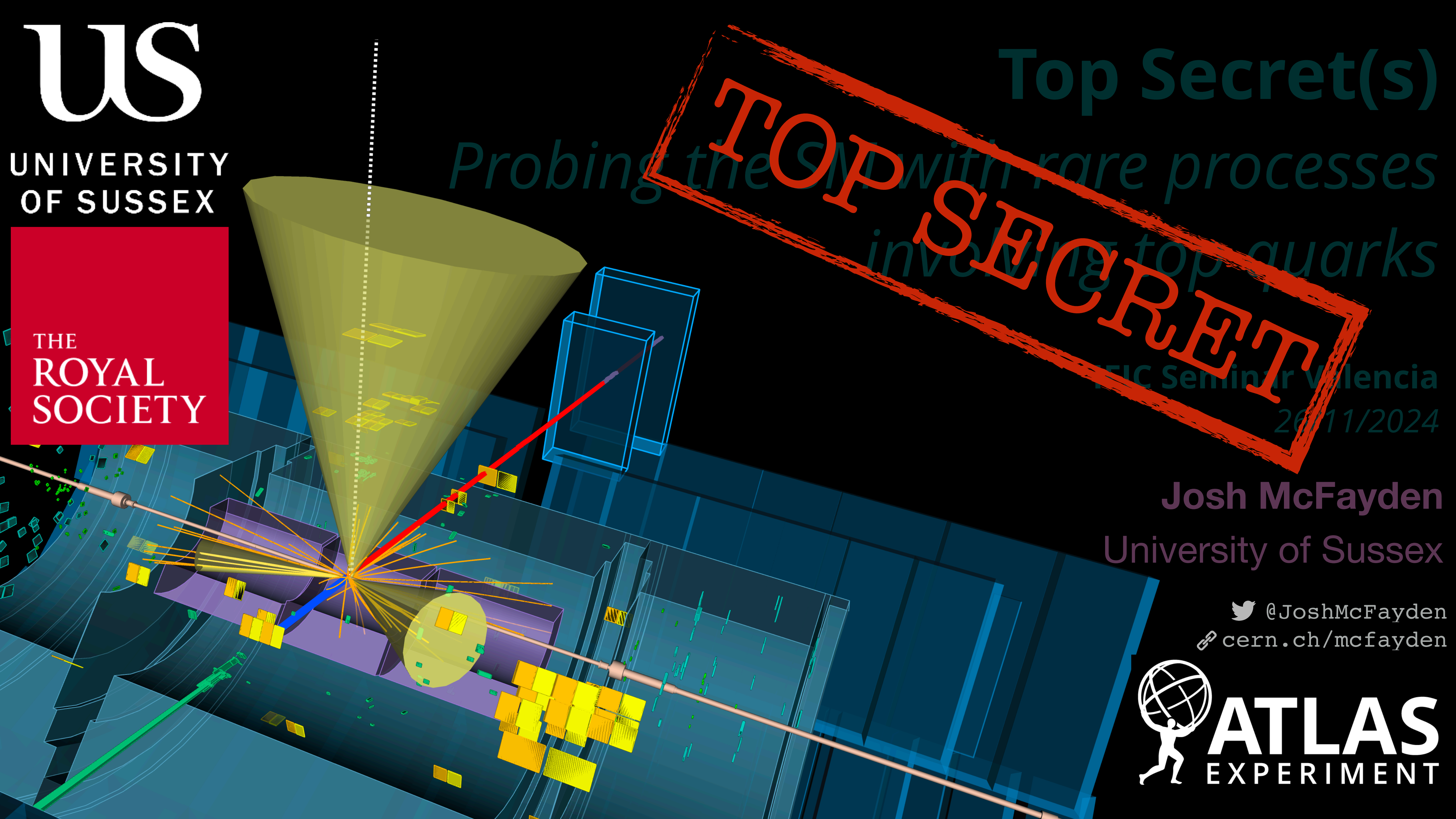




US

UNIVERSITY
OF SUSSEX

THE
ROYAL
SOCIETY

TOP SECRET

Top Secret(s)

Probing the SM with rare processes
involving top quarks

FIC Seminar Valencia

26/11/2024

Josh McFayden
University of Sussex

 @JoshMcFayden
 cern.ch/mcfayden



ATLAS
EXPERIMENT

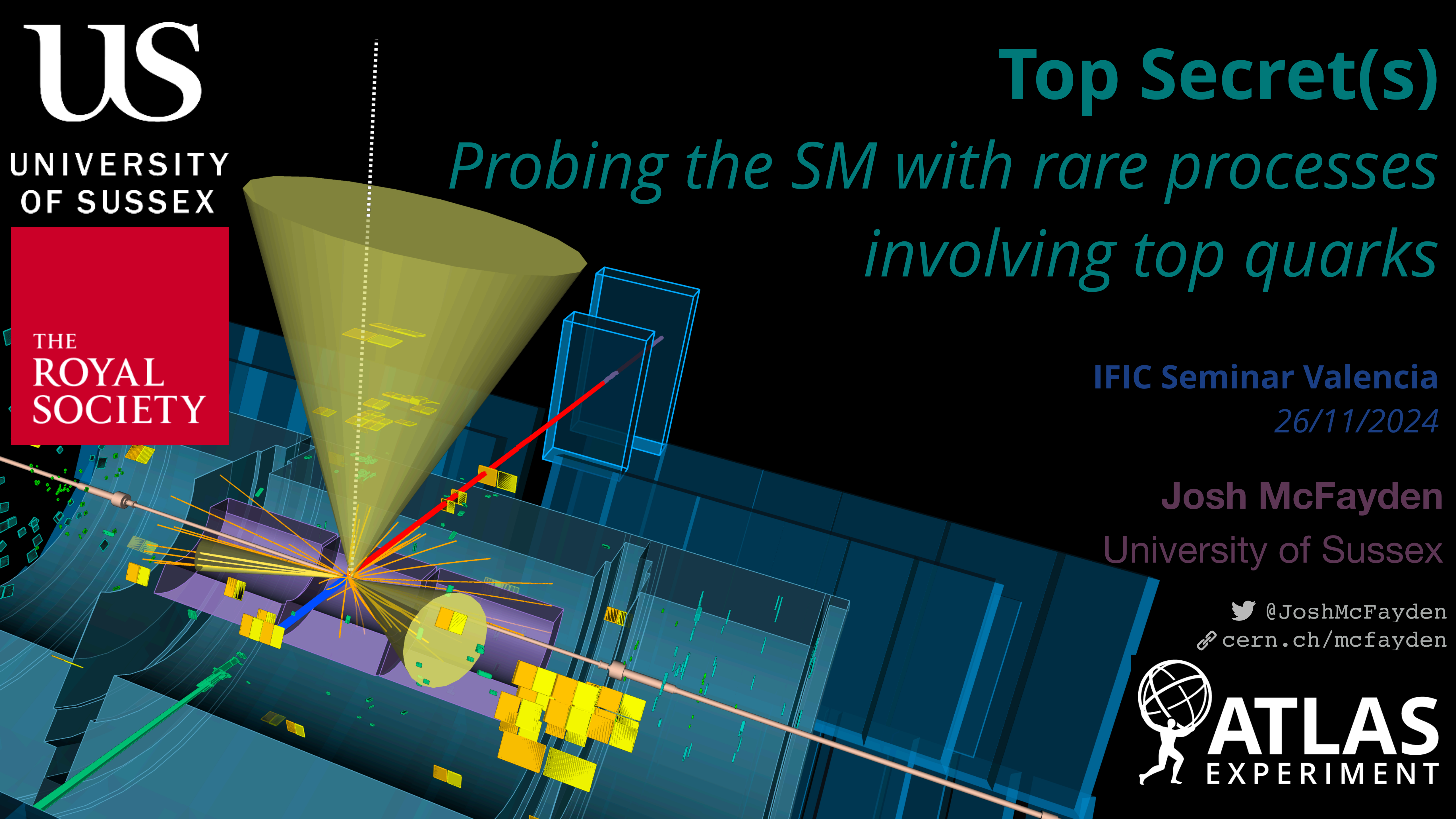
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Why Top Quarks?



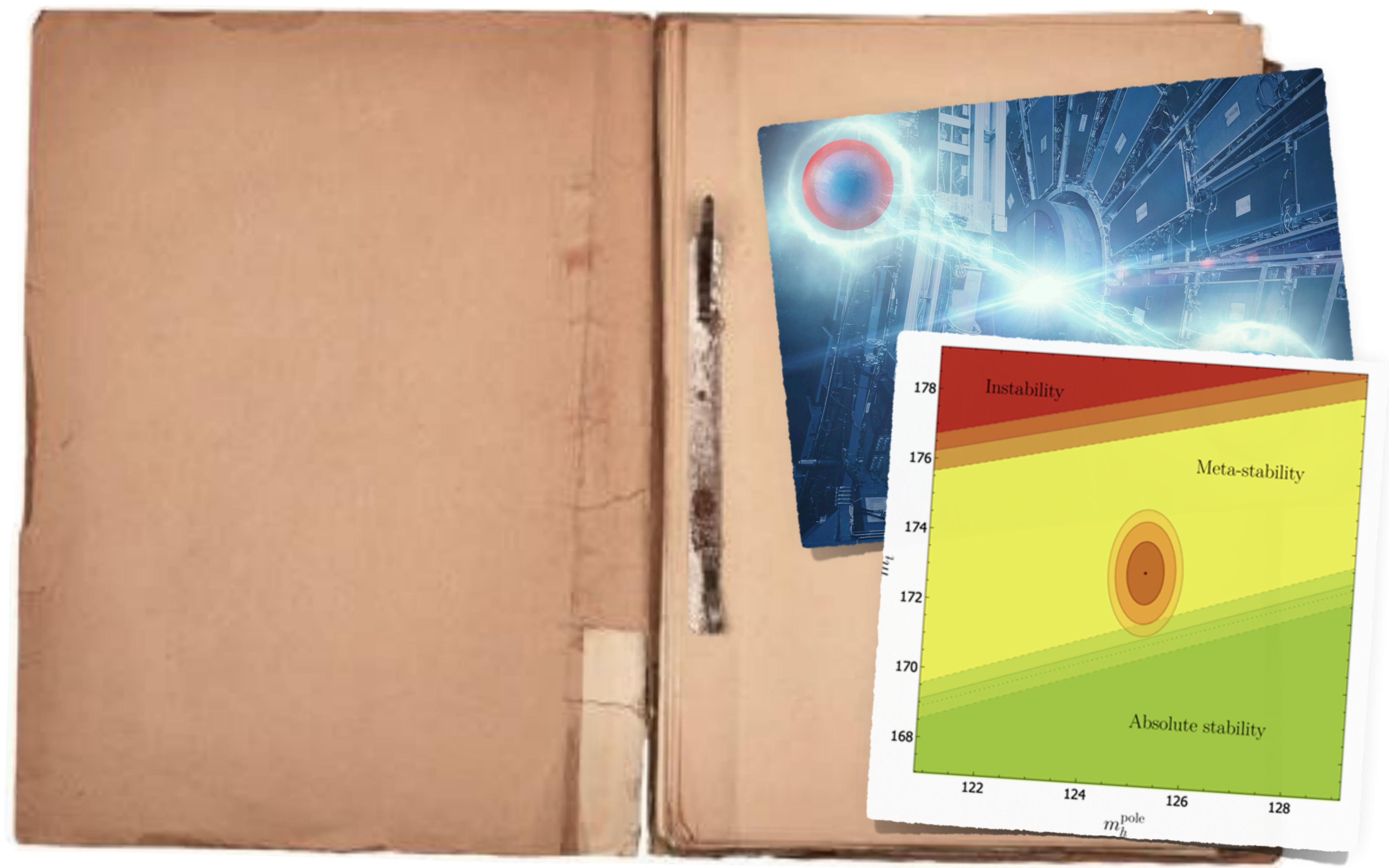
Why Top Quarks?



Why Top Quarks?

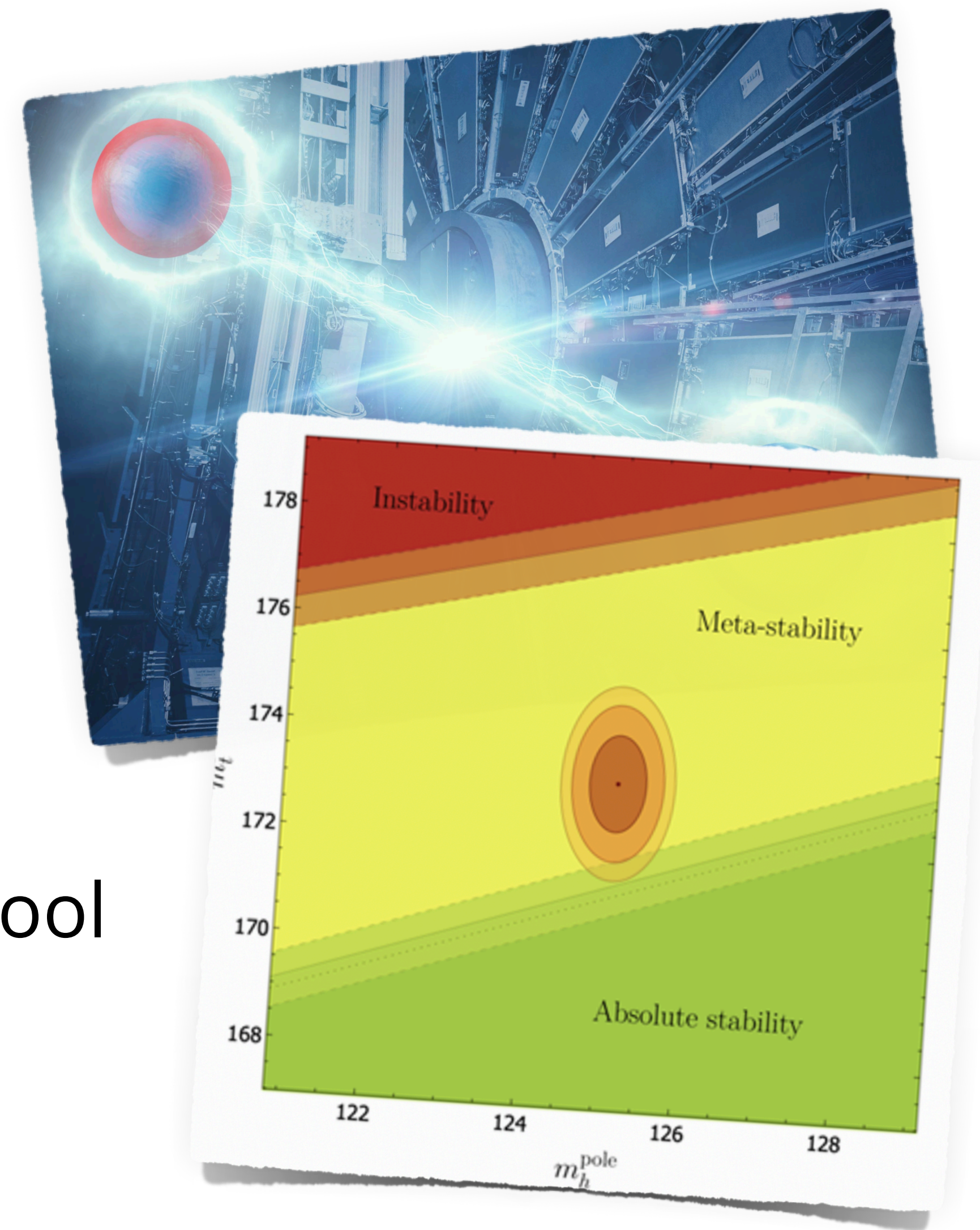


Why Top Quarks?



Why Top Quarks?

- ▶ The heaviest known point-like particle
- ▶ The only quark that decays before hadronising
 - ▶ Gives access to spin through decay products
- ▶ Vital role in EWSB
 - ▶ Largest Yukawa coupling (order 1)
 - ▶ Responsible for Higgs hierarchy problem
 - ▶ Key input to meta/instability of EW vacuum
 - ▶ Also important input to Higgs CP and self-coupling
- ▶ Huge cross section at LHC makes it a precision tool
 - ▶ Tests of SM parameters e.g. LFU in W decays
 - ▶ Search for rare production and decays
 - ▶ Precision test of QCD and MC modelling

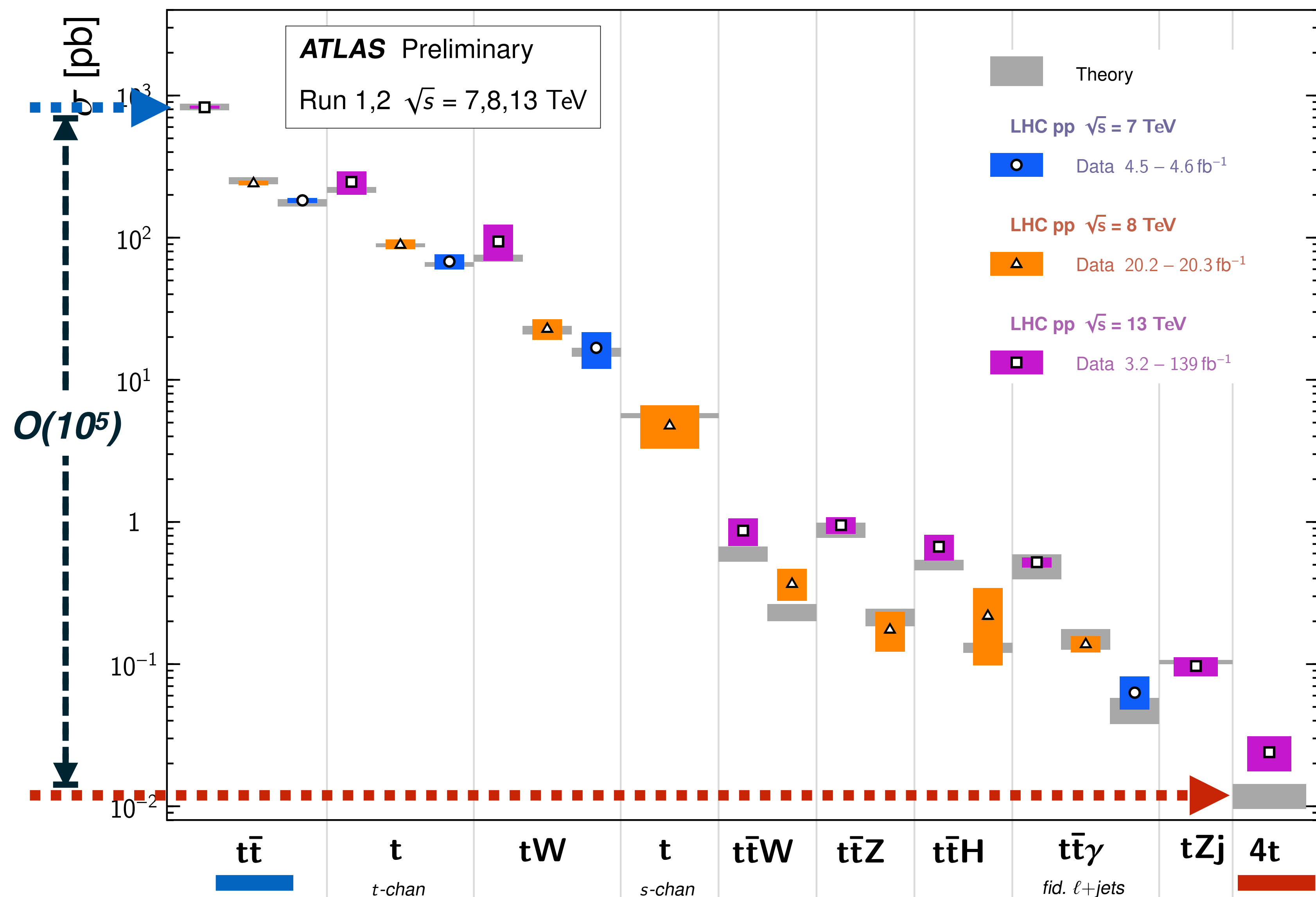


Why Top Quarks?

- ▶ The LHC is a top quark factory
 - ▶ >100 million **top quark pairs** produced Run 2
- ▶ Processes span **5 orders of magnitude** in cross section:
 - ▶ **$O(100M)$ $t\bar{t}$ events**
 - ▶ **$O(1k)$ $t\bar{t}t\bar{t}$ events**
- ▶ Possible decay modes gives rise to a vast array of final states

Top Quark Production Cross Section Measurements

Status: May 2020





Rare top quark associated production

- ▶ Rare Standard Model processes accessible only at the LHC.
 - ▶ Reaching observation for many rare processes
 - ▶ Now achieving sufficient sensitivity for differential measurements
 - ▶ Measurement sensitivity just starting to exceed that of theoretical predictions
- ▶ Important backgrounds to new physics searches
 - ▶ ttW and ttZ backgrounds for ttH in multilepton decay modes
 - ▶ ttZ in top+MET SUSY searches
 - ▶ ttW is major background in any same-sign di-lepton final state
- ▶ Rich phenomenology
 - ▶ Many final states, EFT interpretations



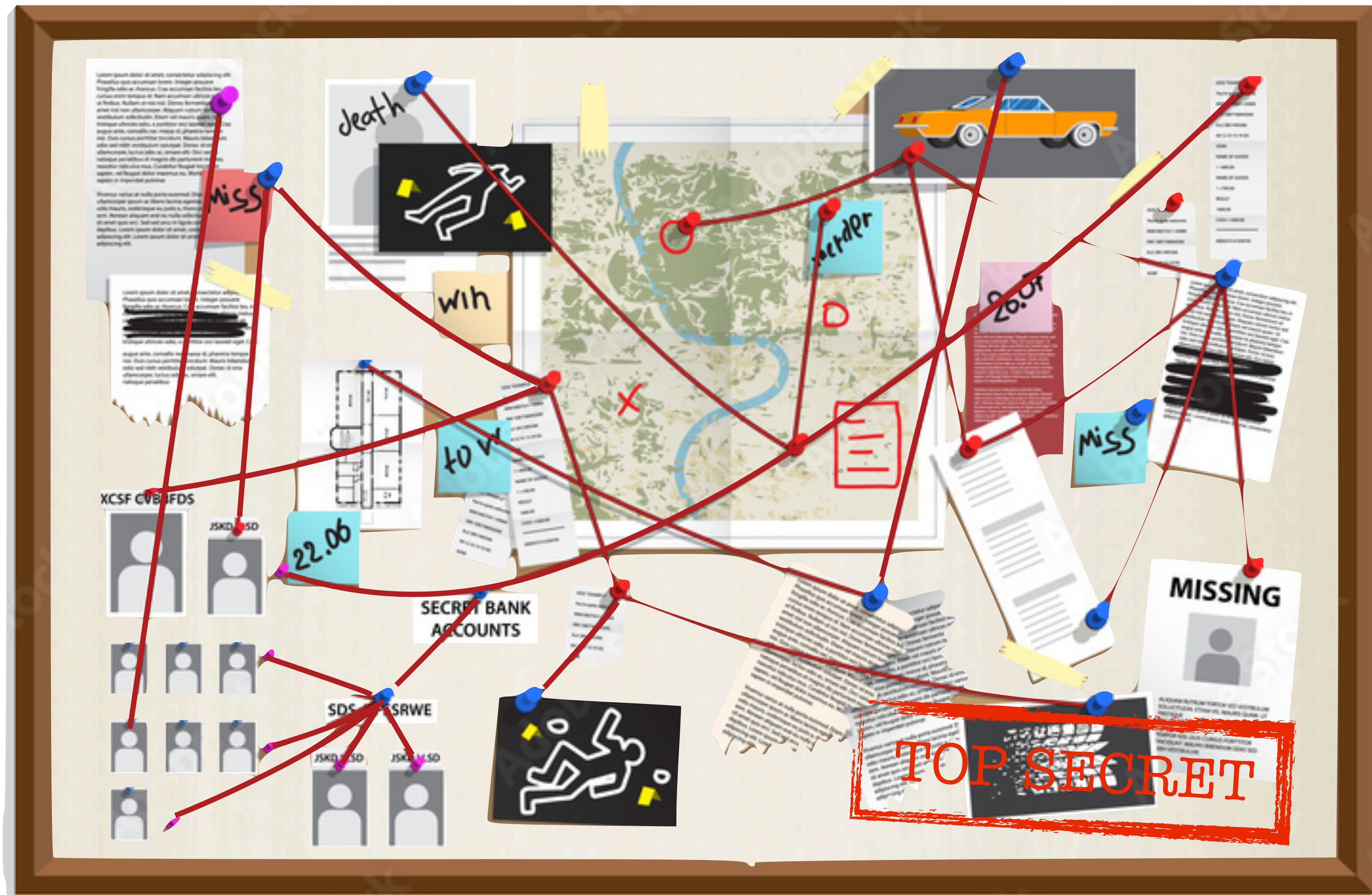
Top Secrets?

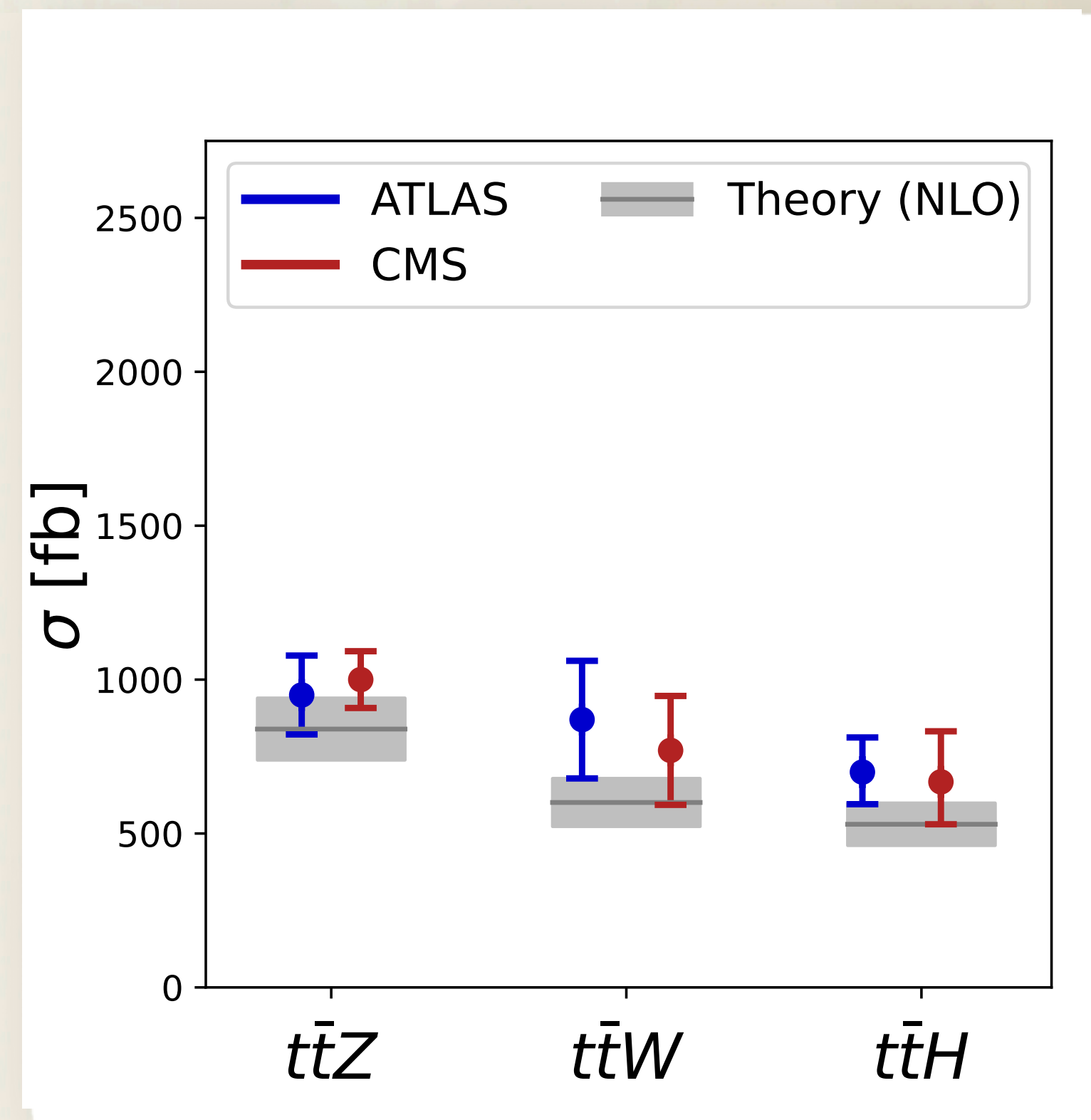
Rare top processes



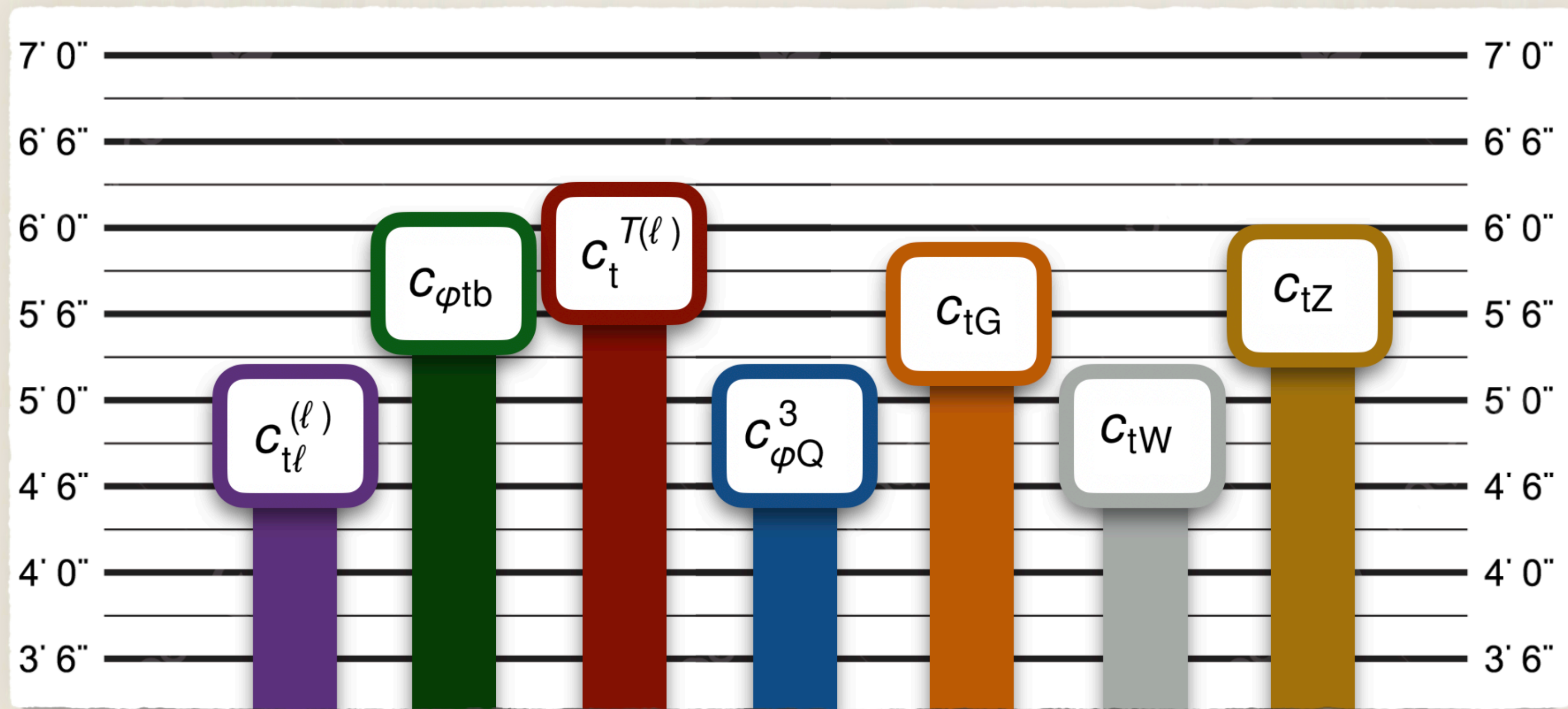
TOP SECRET





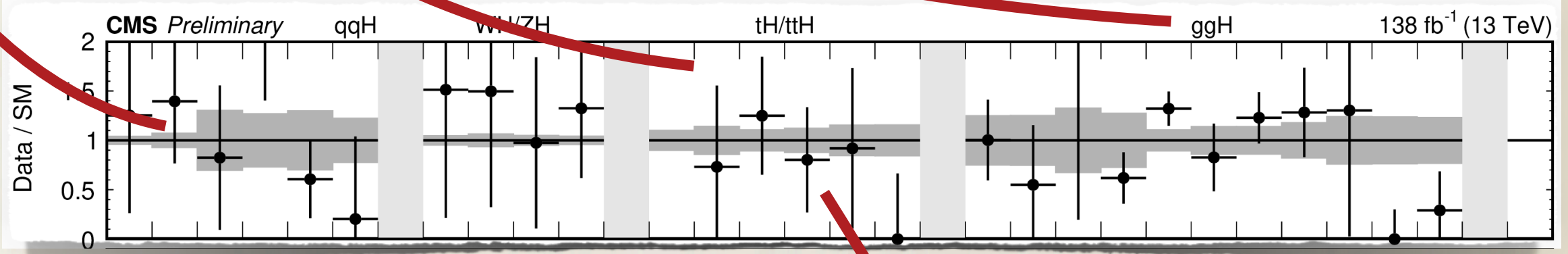
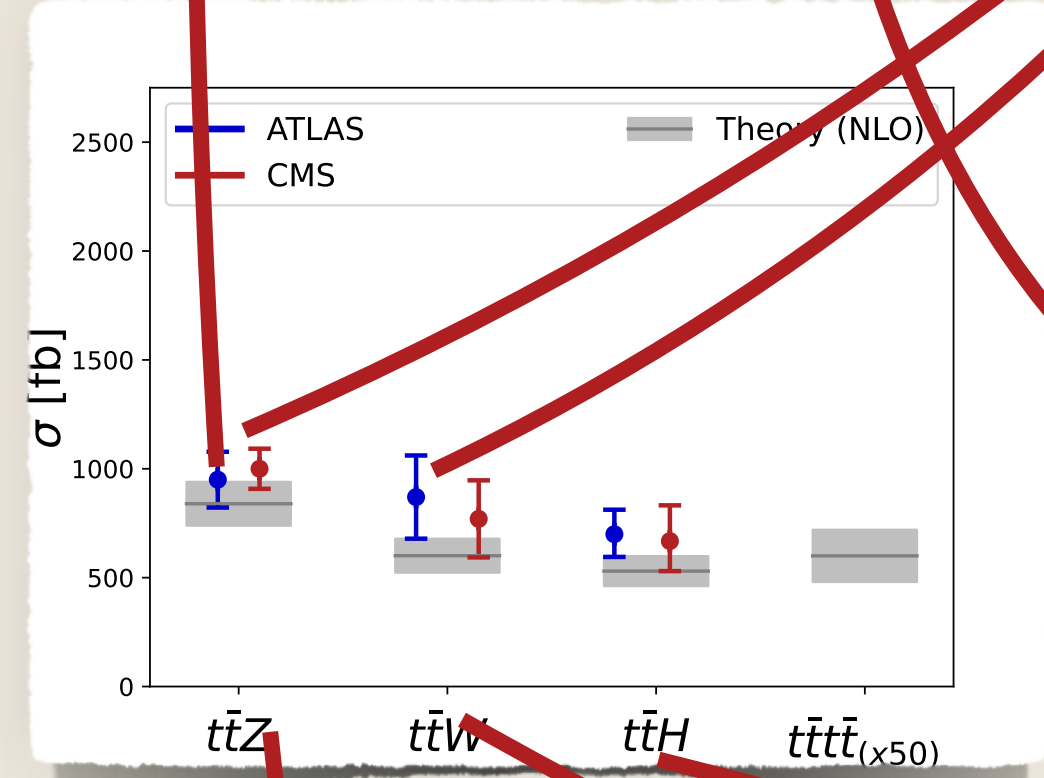
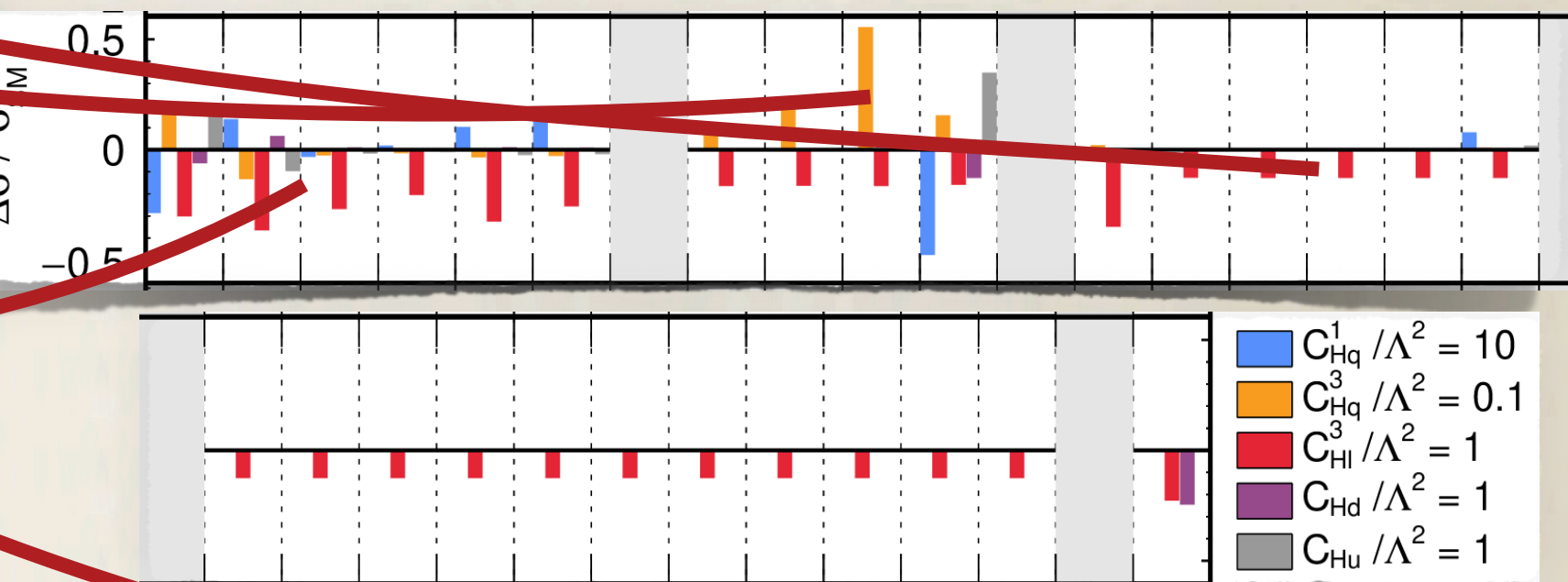
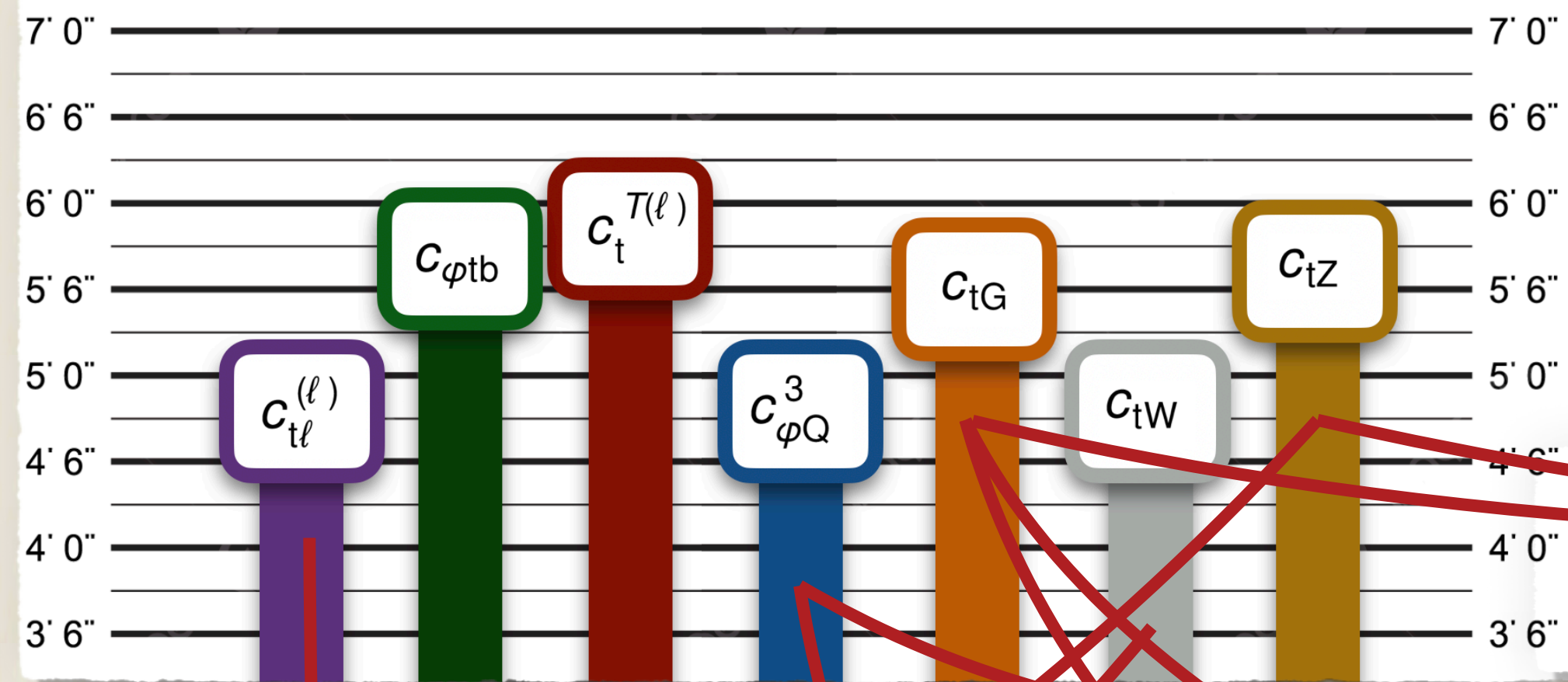


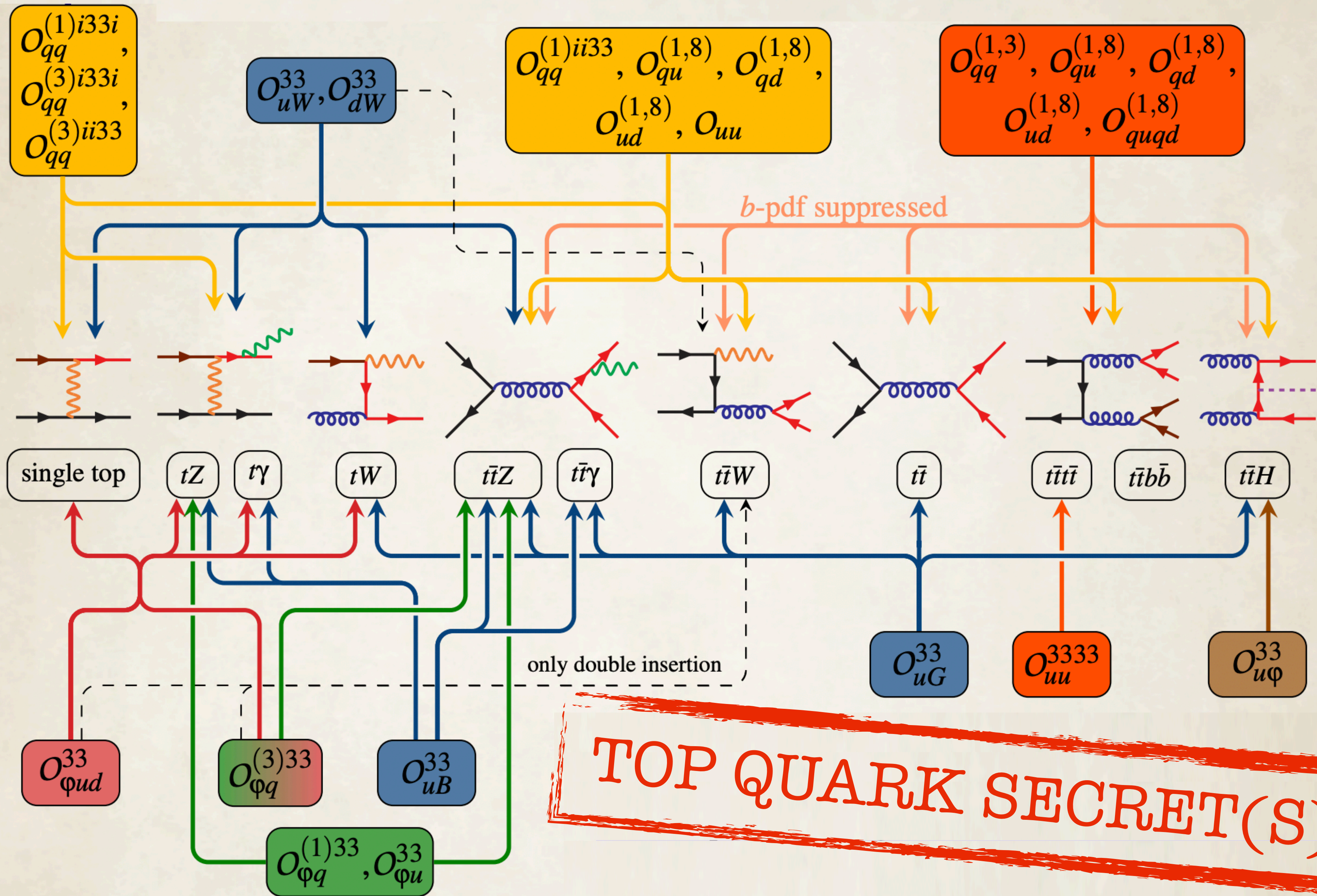
EVIDENCE



SUSPECTS

TOP SECRETS





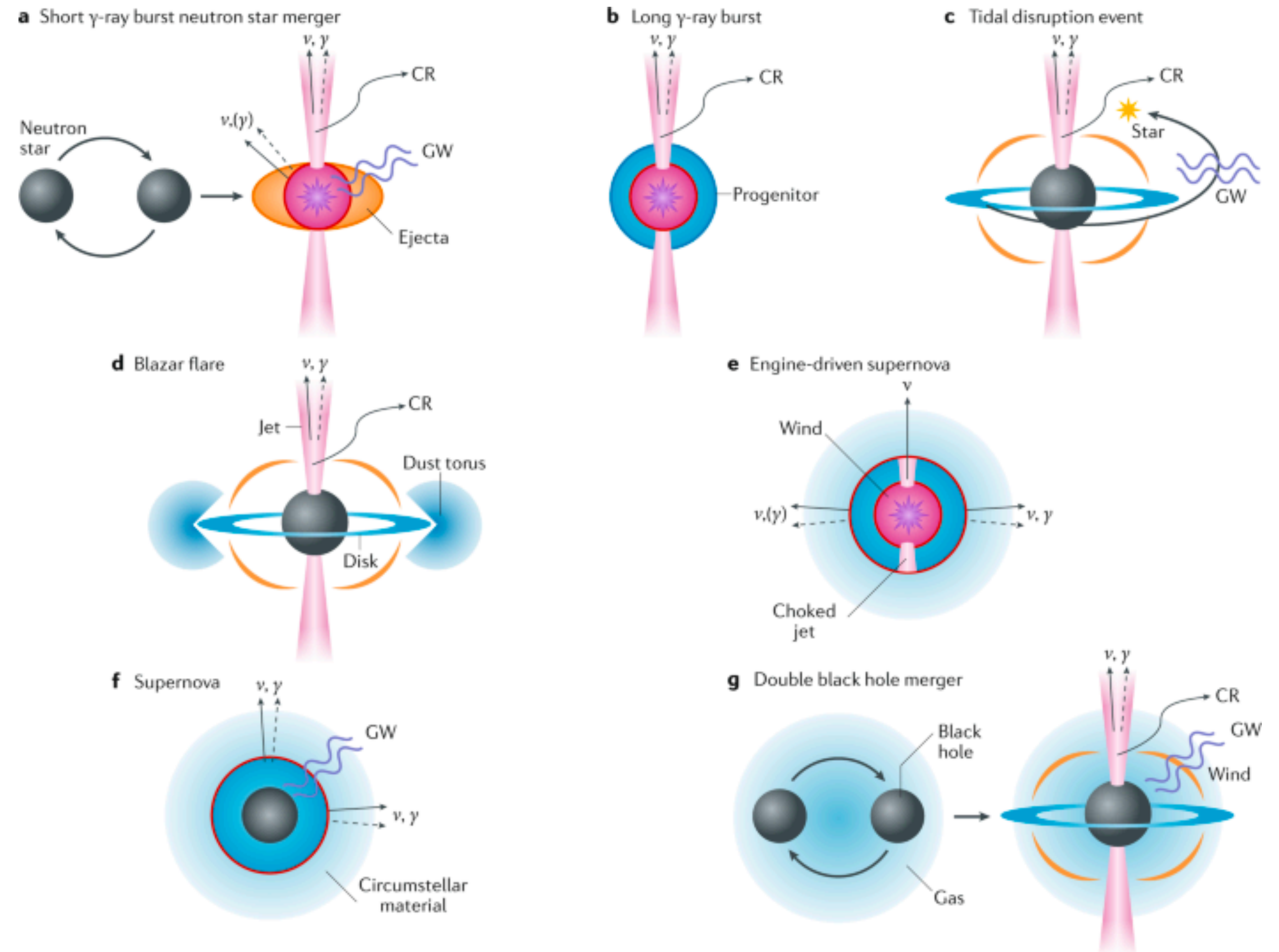
TOP QUARK SECRET(S)

Multi-messenger astrophysics

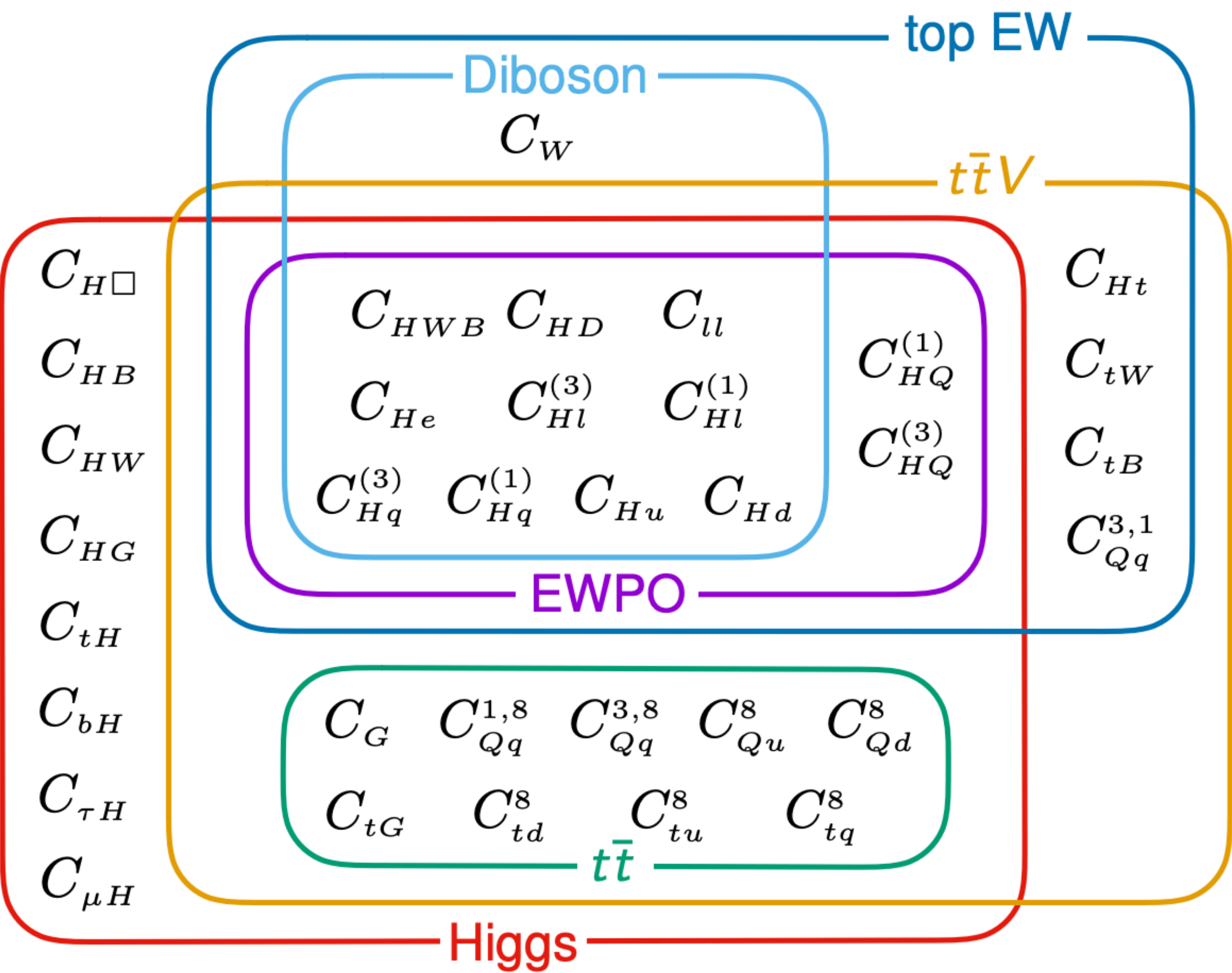
[Péter Mészáros](#) , [Derek B. Fox](#), [Chad Hanna](#) & [Kohta Murase](#)

[Nature Reviews Physics](#) **1**, 585–599 (2019) | [Cite this article](#)

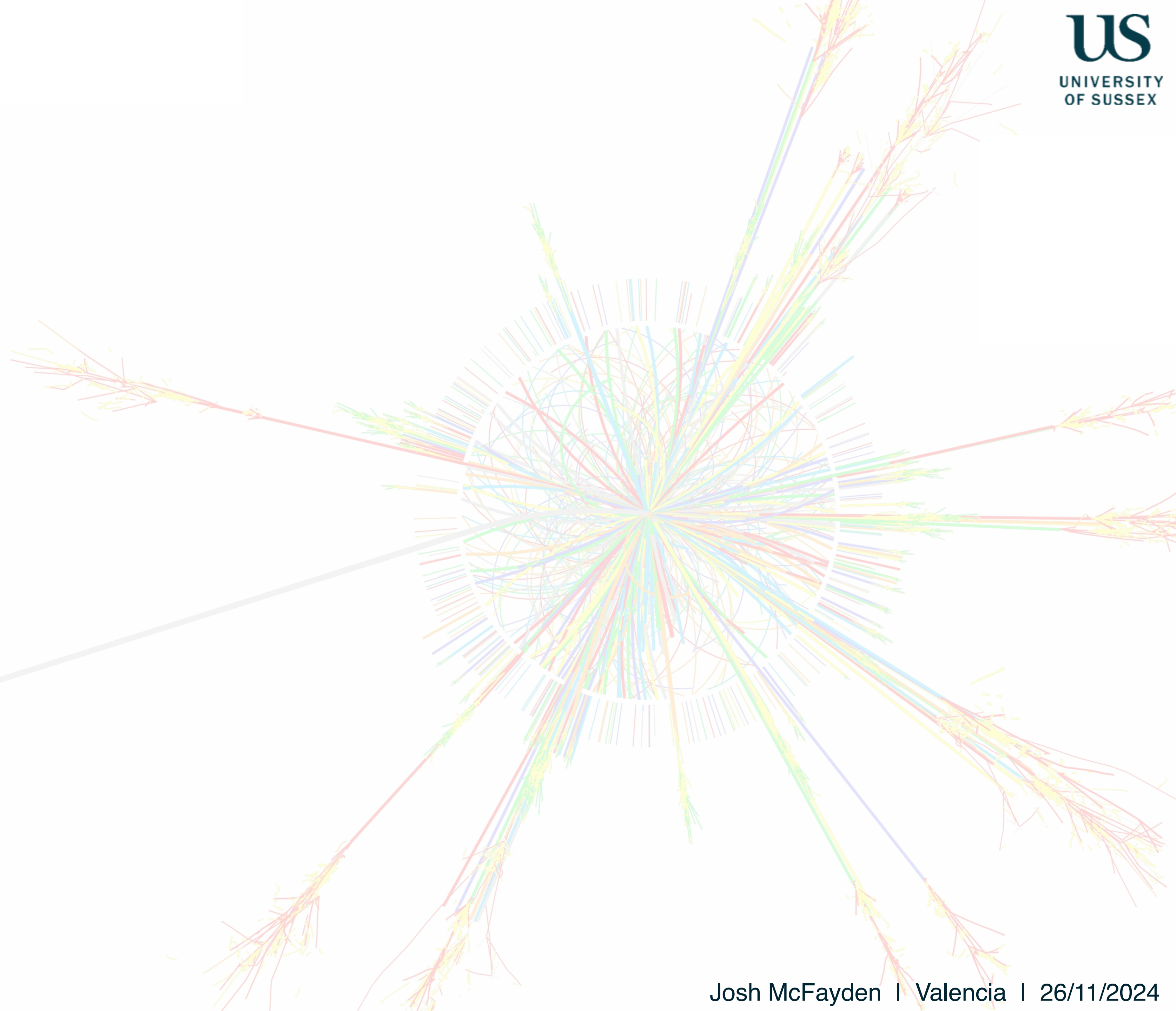
6156 Accesses | **49** Citations | **20** Altmetric | [Metrics](#)



Multi-messenger particle physics



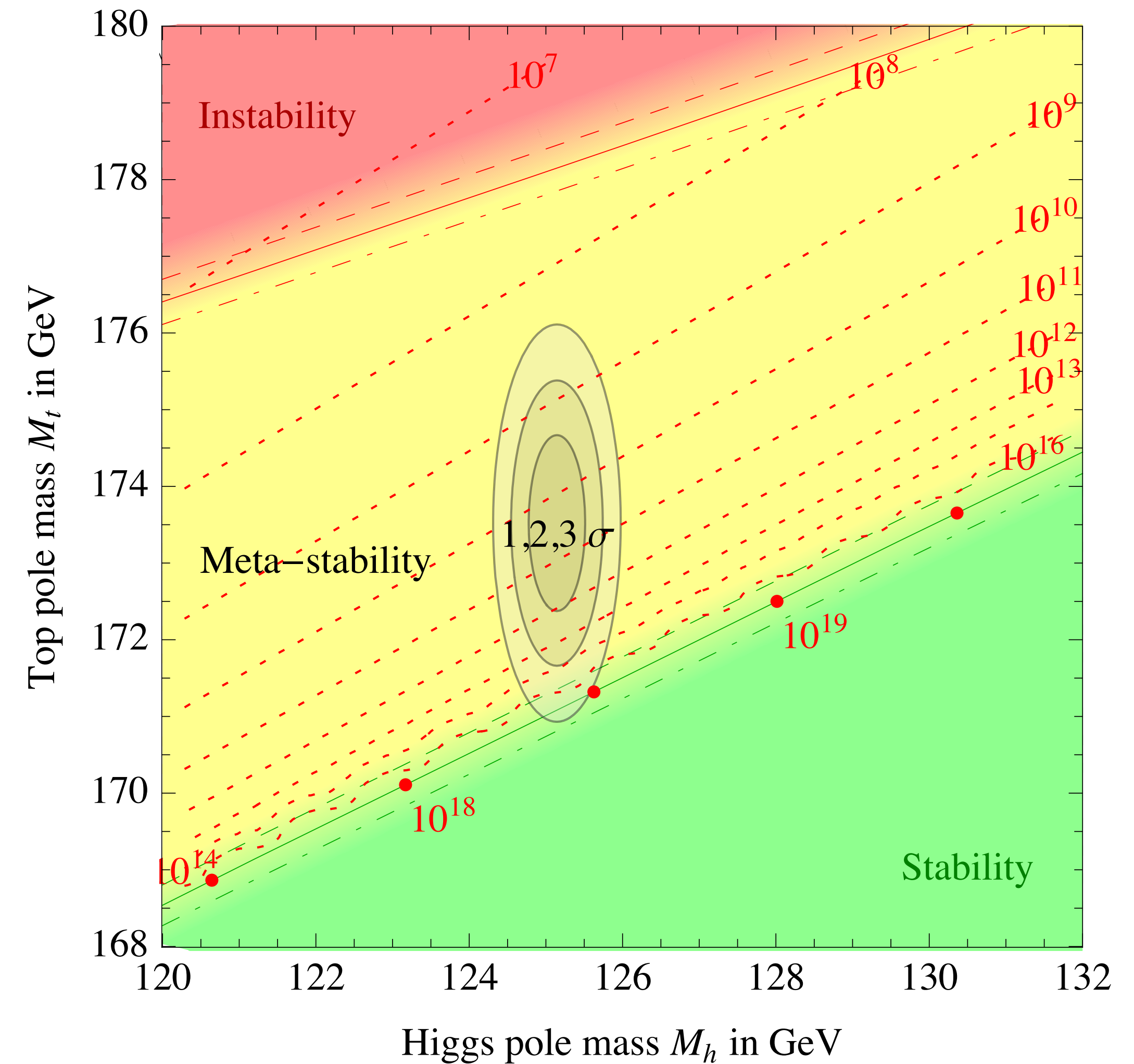
ttH





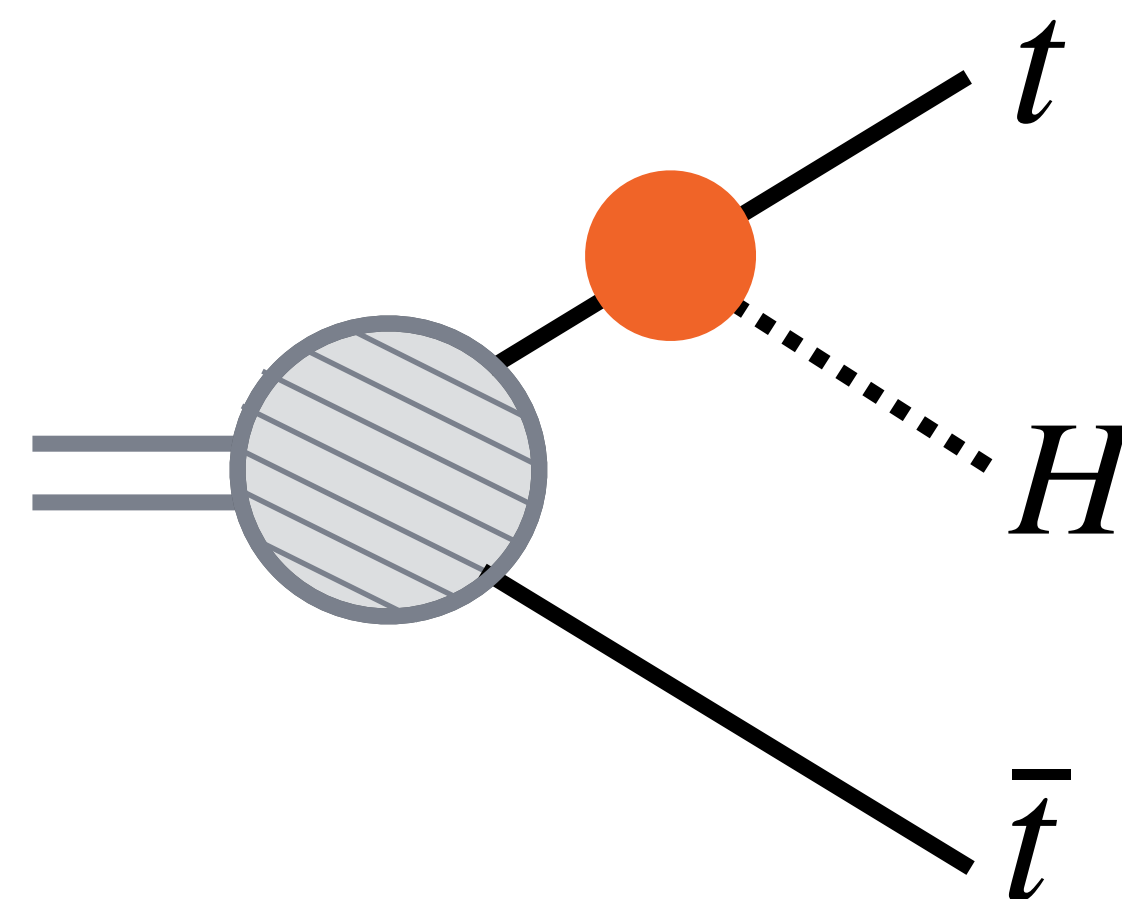
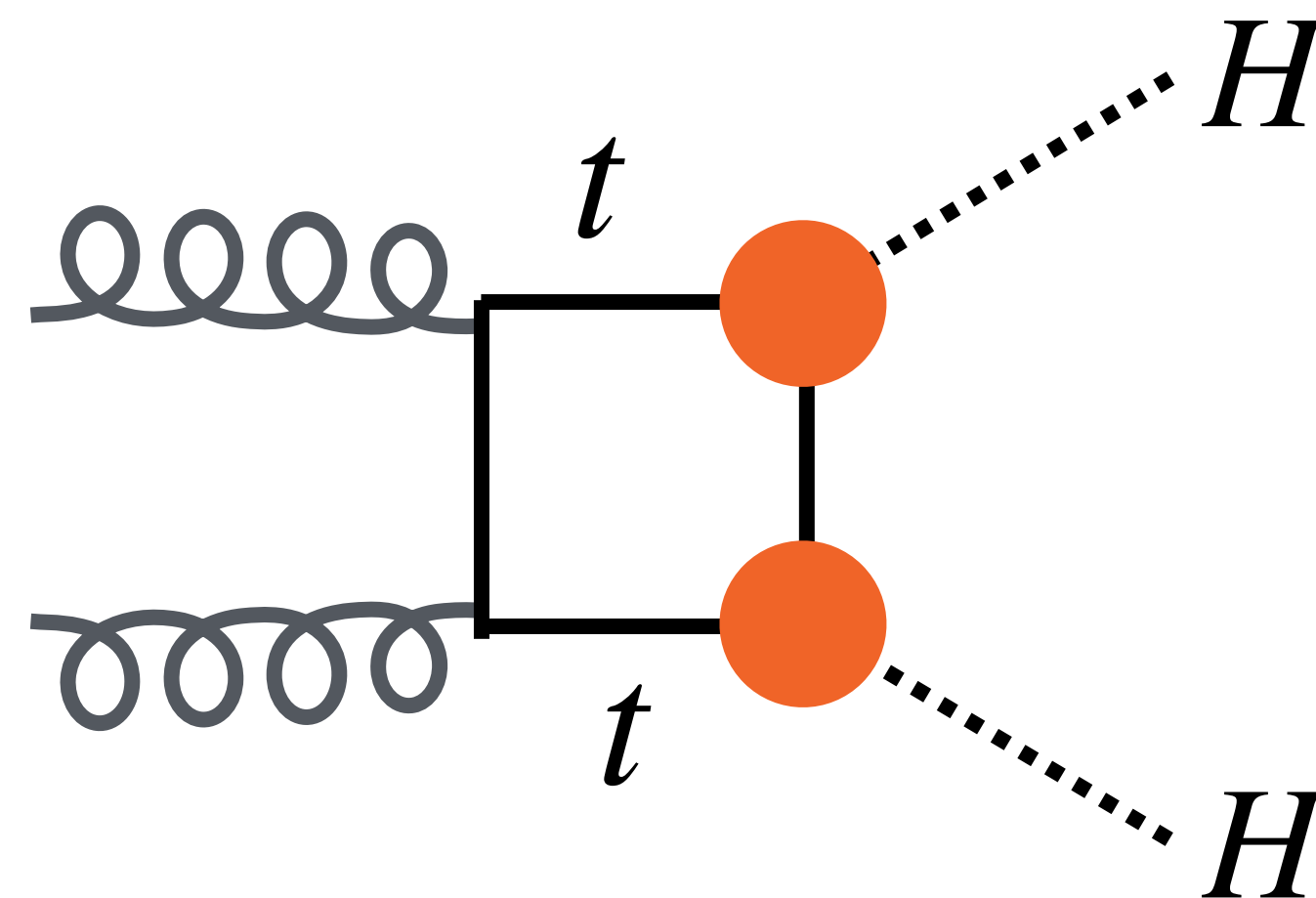
Why ttH?

- ▶ Window into top-Higgs coupling
- ▶ Very important test of EWSB
- ▶ Higgs self-coupling
- ▶ Higgs CP properties



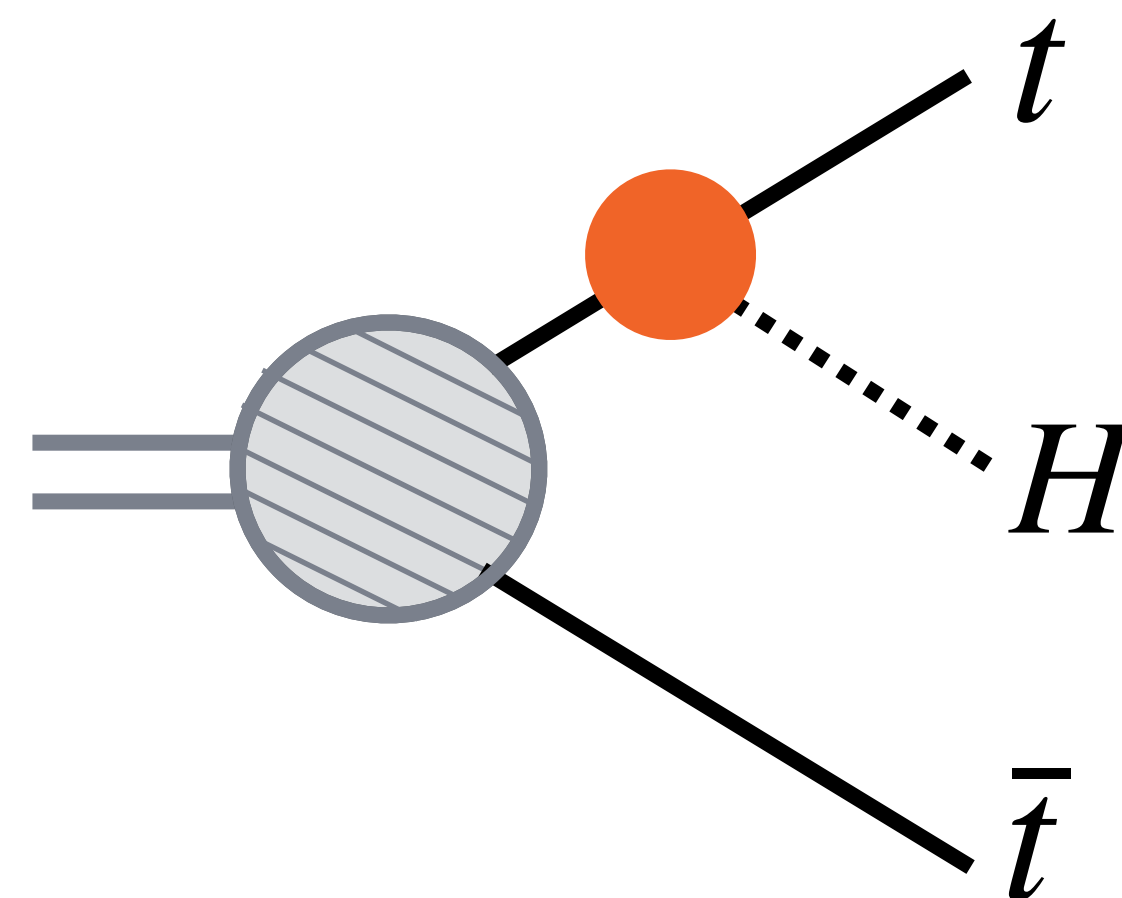
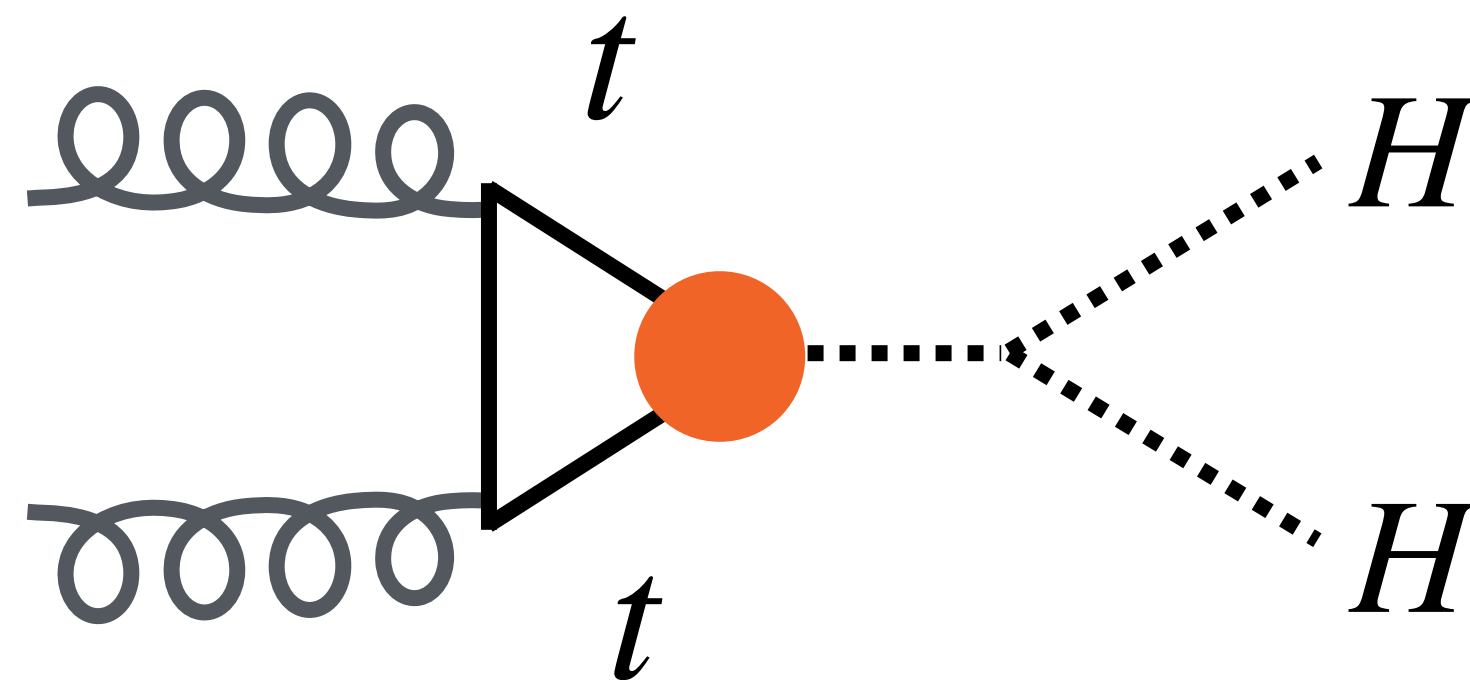
Why $t\bar{t}H$?

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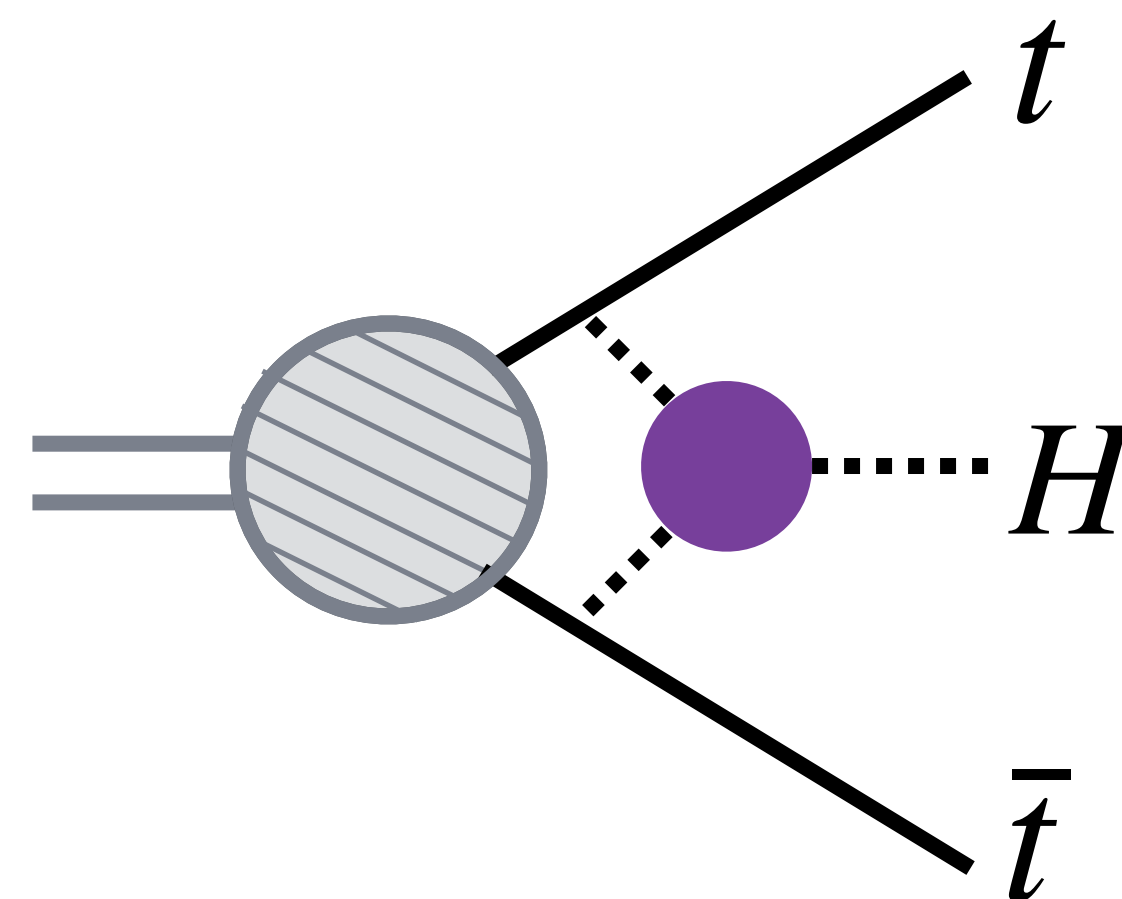
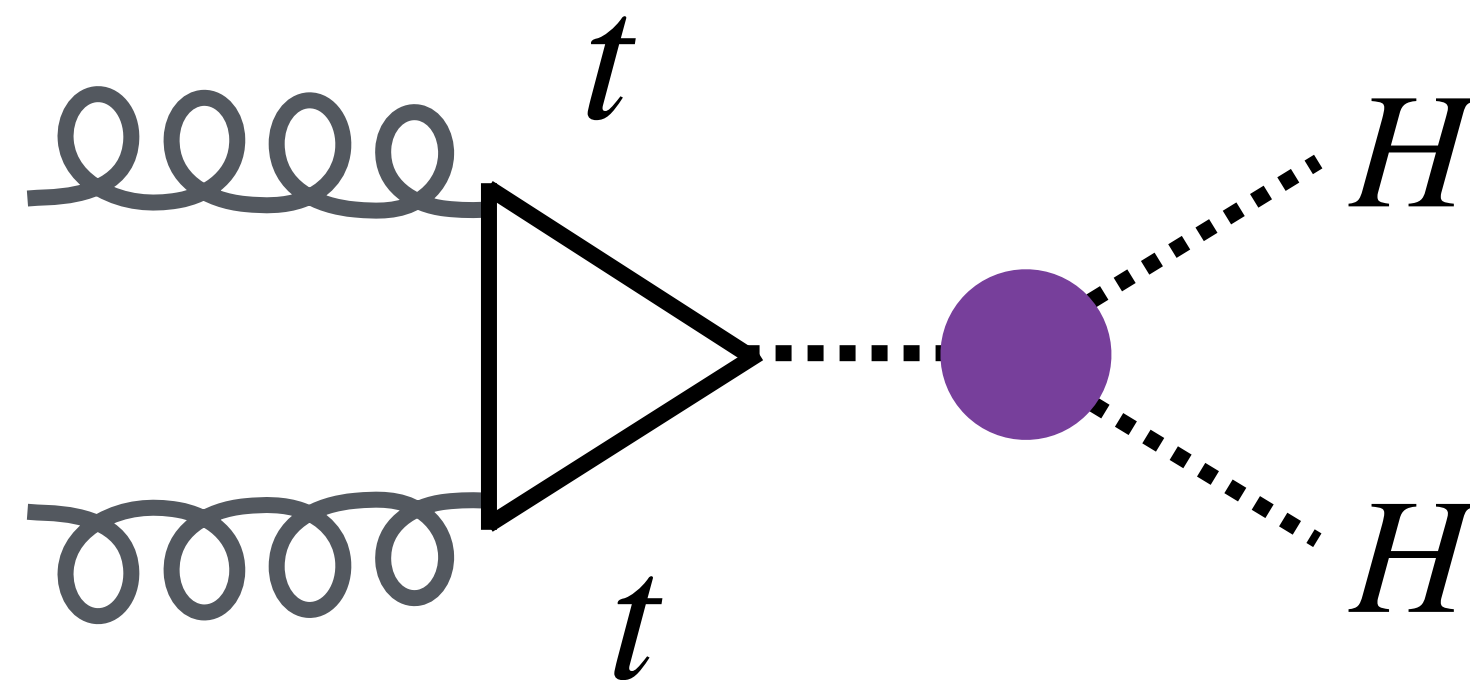
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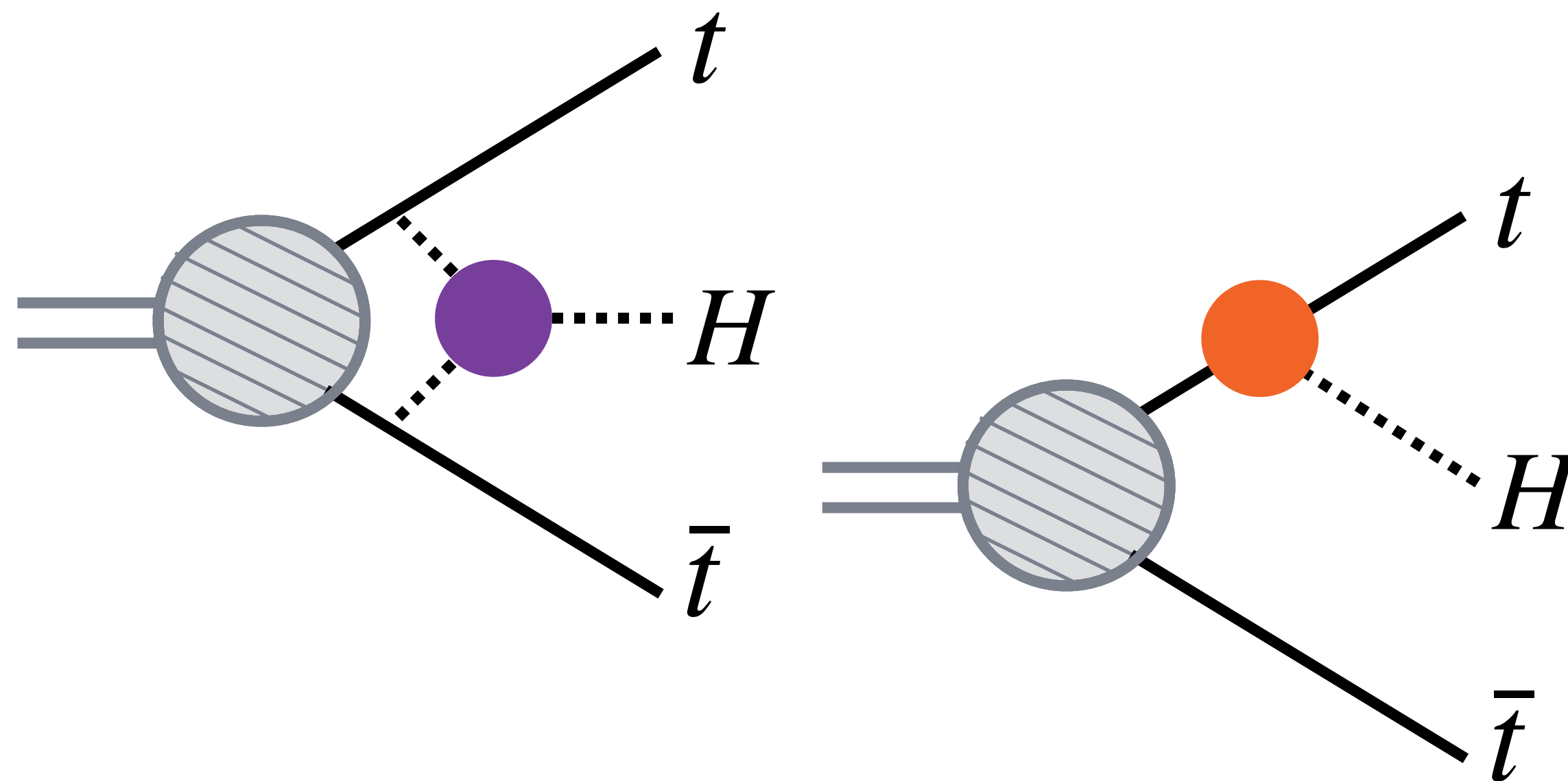
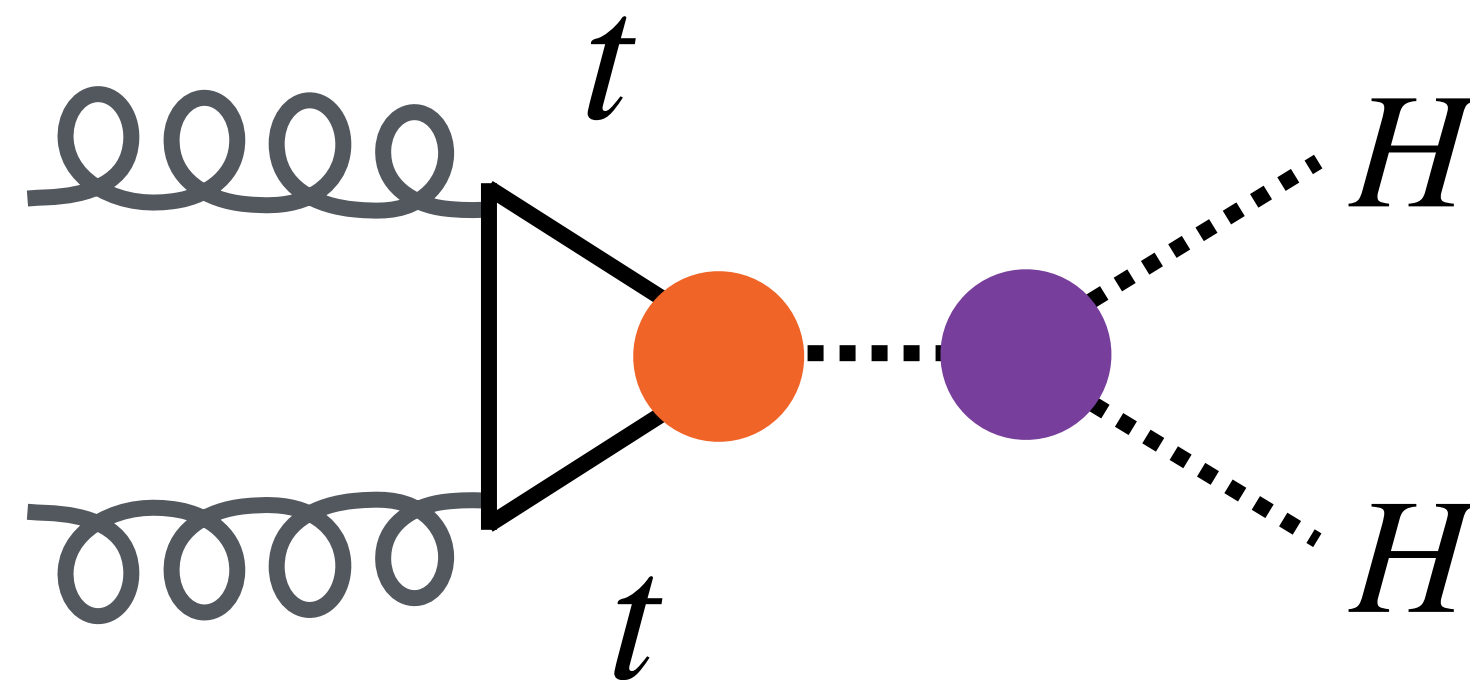
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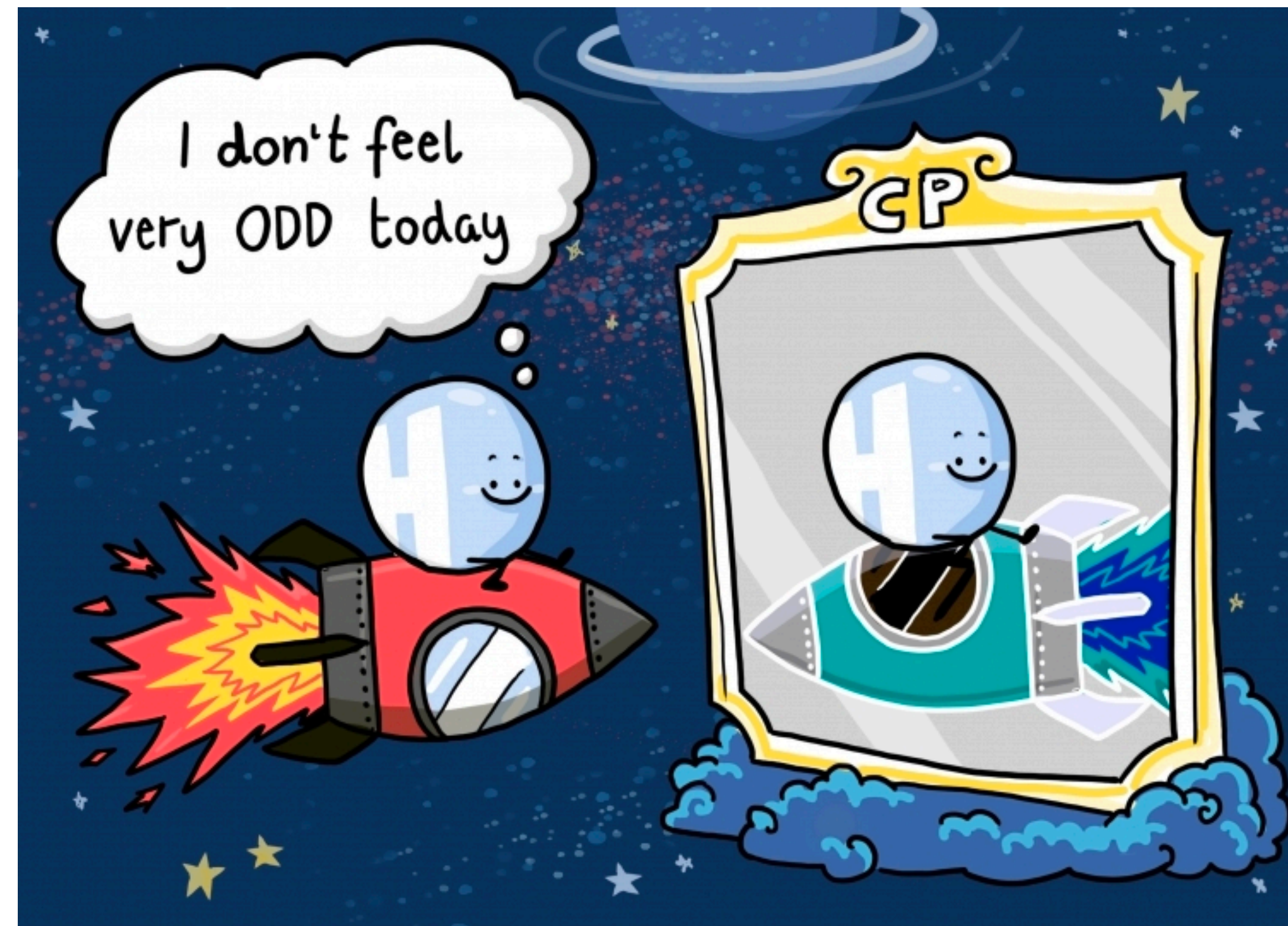
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Why ttH?

► Window into top-Higgs coupling

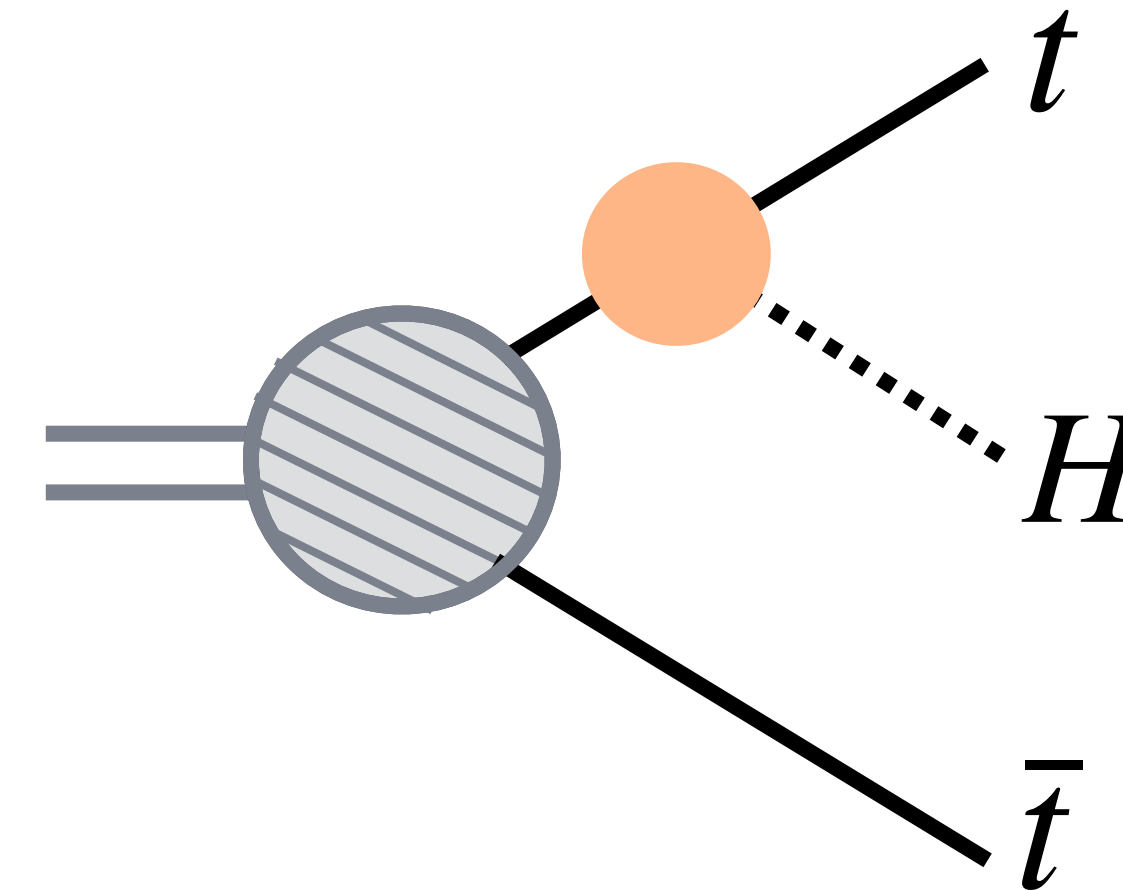


► Very important test of EWSB

► Higgs self-coupling

► Higgs CP properties

CP-even:
No asymmetry



$$\mathcal{L}_{t\bar{t}H} = -\kappa'_t y_t \phi \bar{\psi}_t (\cos \alpha) \psi_t$$

Why ttH?

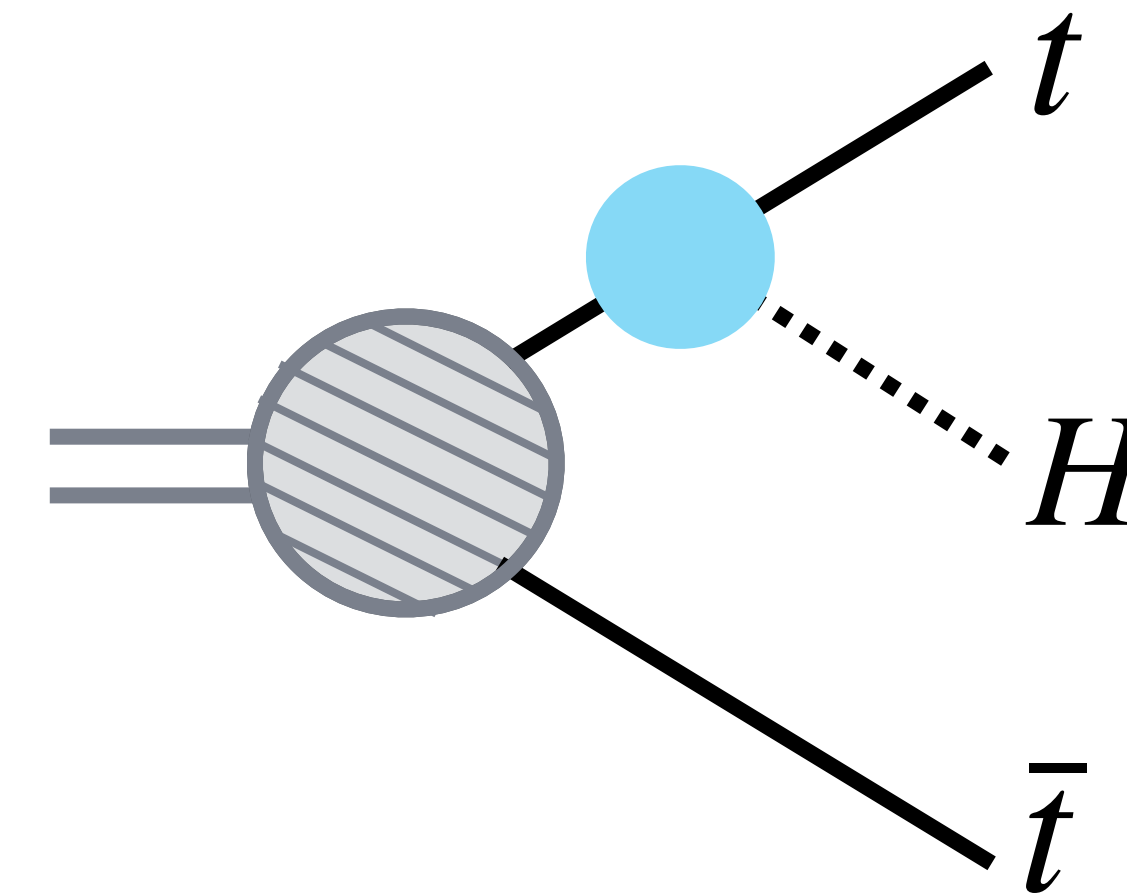
► Window into top-Higgs coupling



► Very important test of EWSB

► Higgs self-coupling

► Higgs CP properties

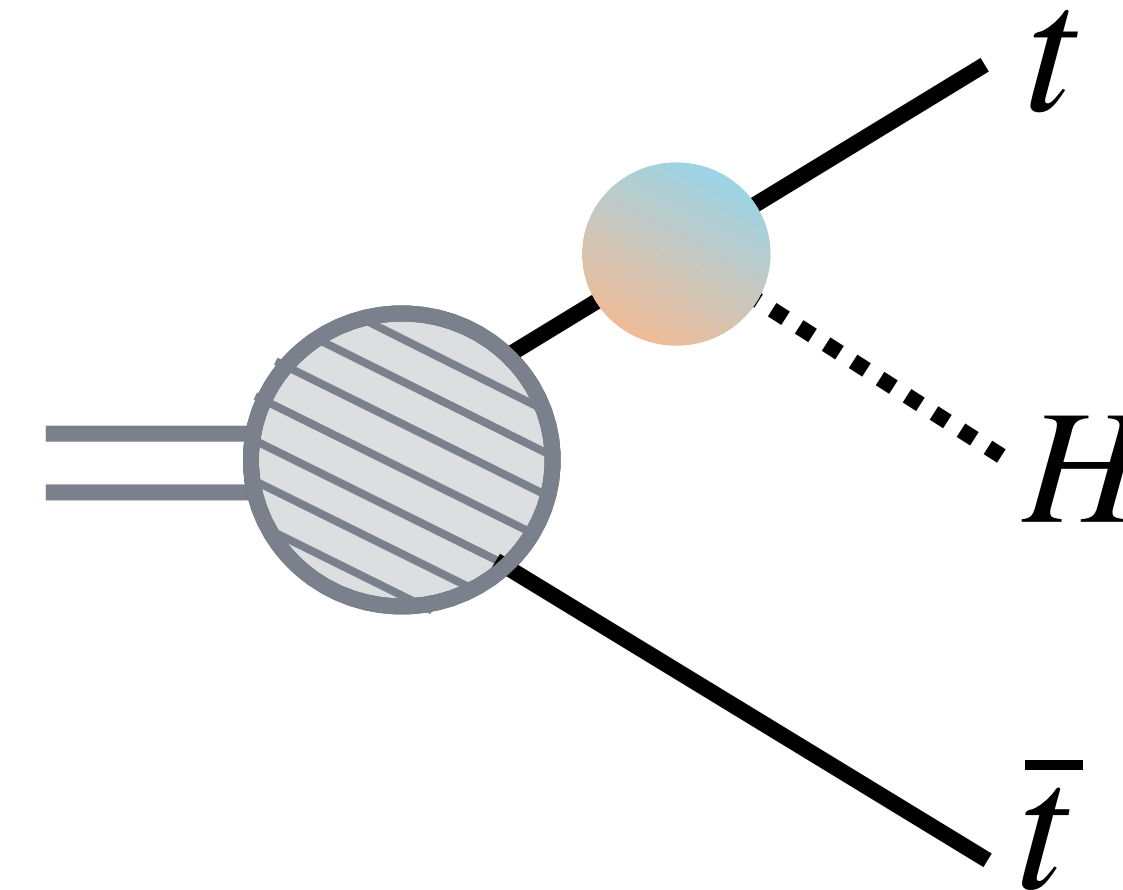


CP-odd:
Maximal asymmetry

$$\mathcal{L}_{t\bar{t}H} = -\kappa'_t y_t \phi \bar{\psi}_t (i\gamma_5 \sin \alpha) \psi_t$$

Why ttH?

- ▶ Window into top-Higgs coupling
- ▶ Very important test of EWSB
- ▶ Higgs self-coupling
- ▶ Higgs CP properties



CP-mixed:
Some asymmetry

$$\mathcal{L}_{t\bar{t}H} = -\kappa'_t y_t \phi \bar{\psi}_t (\cos \alpha + i\gamma_5 \sin \alpha) \psi_t$$



Which ttH?

ttH
($H \rightarrow bb$)

ttH
($H \rightarrow WW, \tau\tau, ZZ$)
'multilepton'

ttH
($H \rightarrow \gamma\gamma, ZZ(\rightarrow 4\ell)$)

Low signal/background (need MVA)

Clear peak (clean bump hunt)

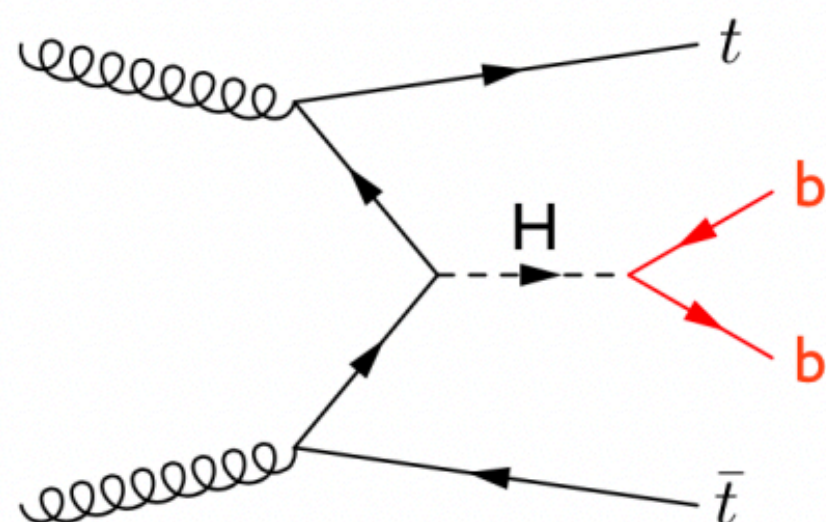
Large branching ratio (yields)

Small branching ratio

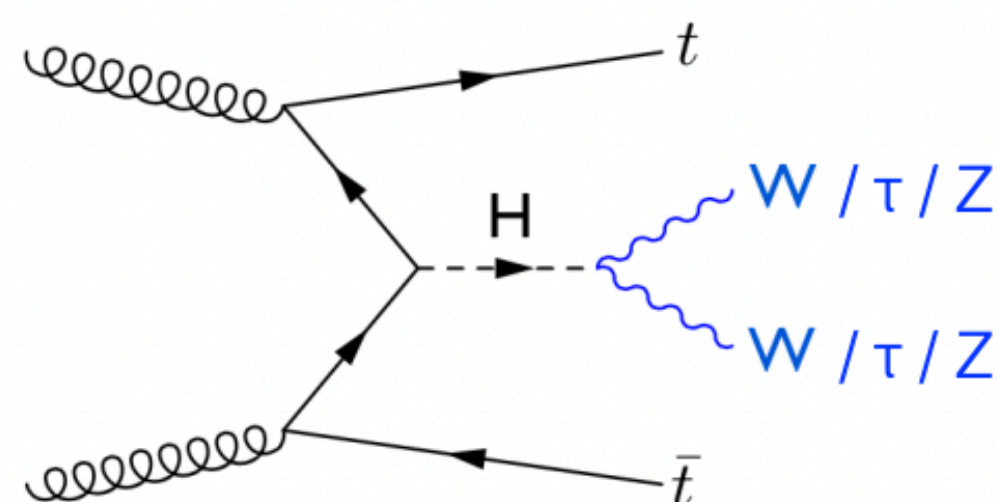
Difficult background modelling

Simple background

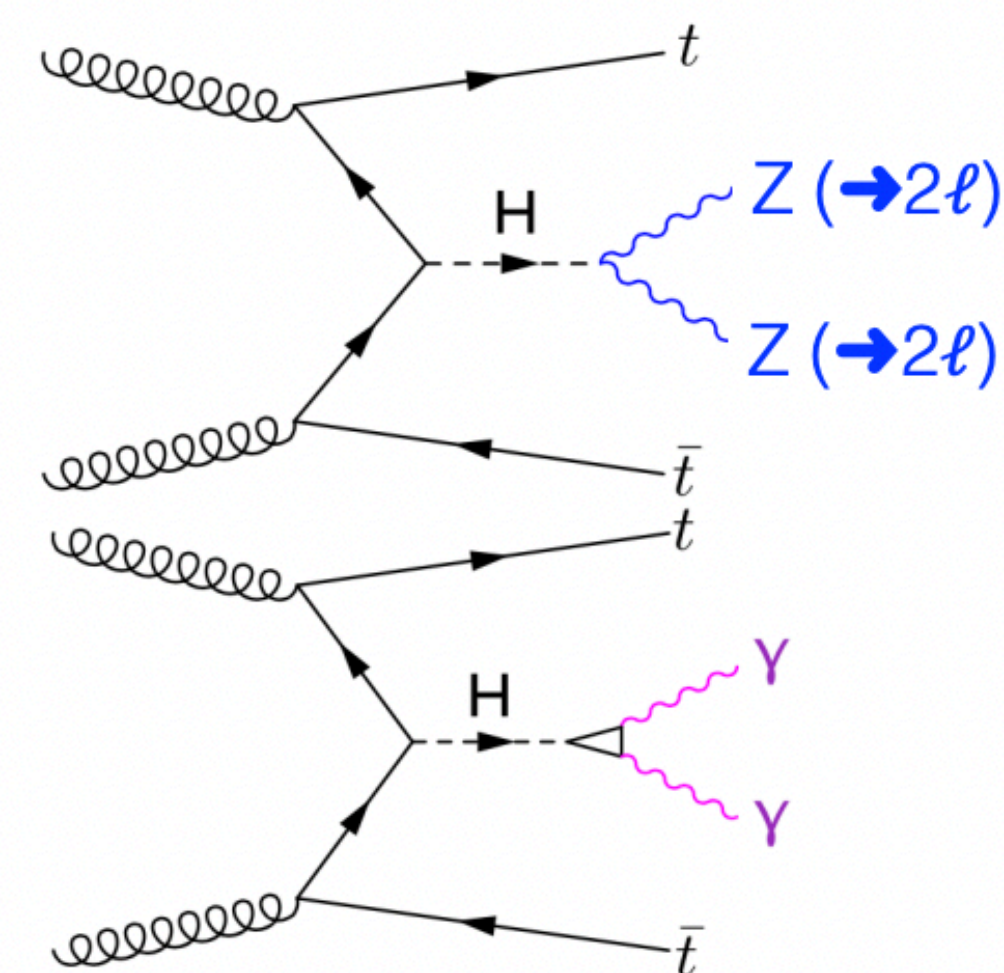
- large irreducible $t\bar{t}$ +jets (HF) background
- final states with **multiple b-jets**



- leptonic decays of W / Z bosons and tau decays can give distinct **multilepton** signatures
- main background from $t\bar{t}Z$ /W and non-prompt leptons



- **resonant** channels





Which ttH?

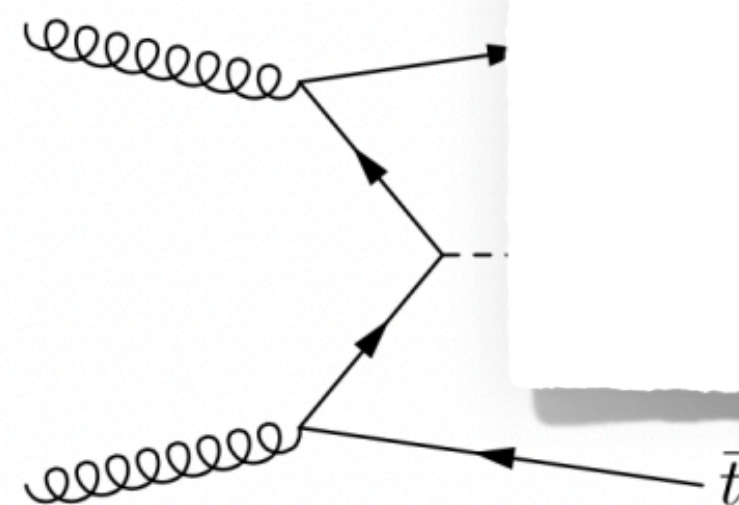
ttH
(H → b $\bar{b}$)

Low signal/

Large branching

Difficult ba

- large irreducible (HF) background
- final states with **multiple b-jets**



ttH

(tot.) (stat. , syst.)

ATLAS

$\sqrt{s}=13$ TeV, 36.1 fb $^{-1}$

— total — stat.

t $\bar{t}$ H ZZ

< 1.9 (68% CL)

t $\bar{t}$ H $\gamma\gamma$

0.6 $^{+0.7}_{-0.6}$ ($^{+0.7}_{-0.6}$, $^{+0.2}_{-0.2}$)

t $\bar{t}$ H b $\bar{b}$

0.8 $^{+0.6}_{-0.6}$ ($^{+0.3}_{-0.3}$, $^{+0.6}_{-0.5}$)

t $\bar{t}$ H ML

1.6 $^{+0.5}_{-0.4}$ ($^{+0.3}_{-0.3}$, $^{+0.4}_{-0.3}$)

t $\bar{t}$ H combined

1.2 $^{+0.3}_{-0.3}$ ($^{+0.2}_{-0.2}$, $^{+0.3}_{-0.2}$)

Best-fit $\mu_{t\bar{t}H}$ for $m_H=125$ GeV

4 ℓ))

ump hunt)

tio

background

els

Z (→2 ℓ)

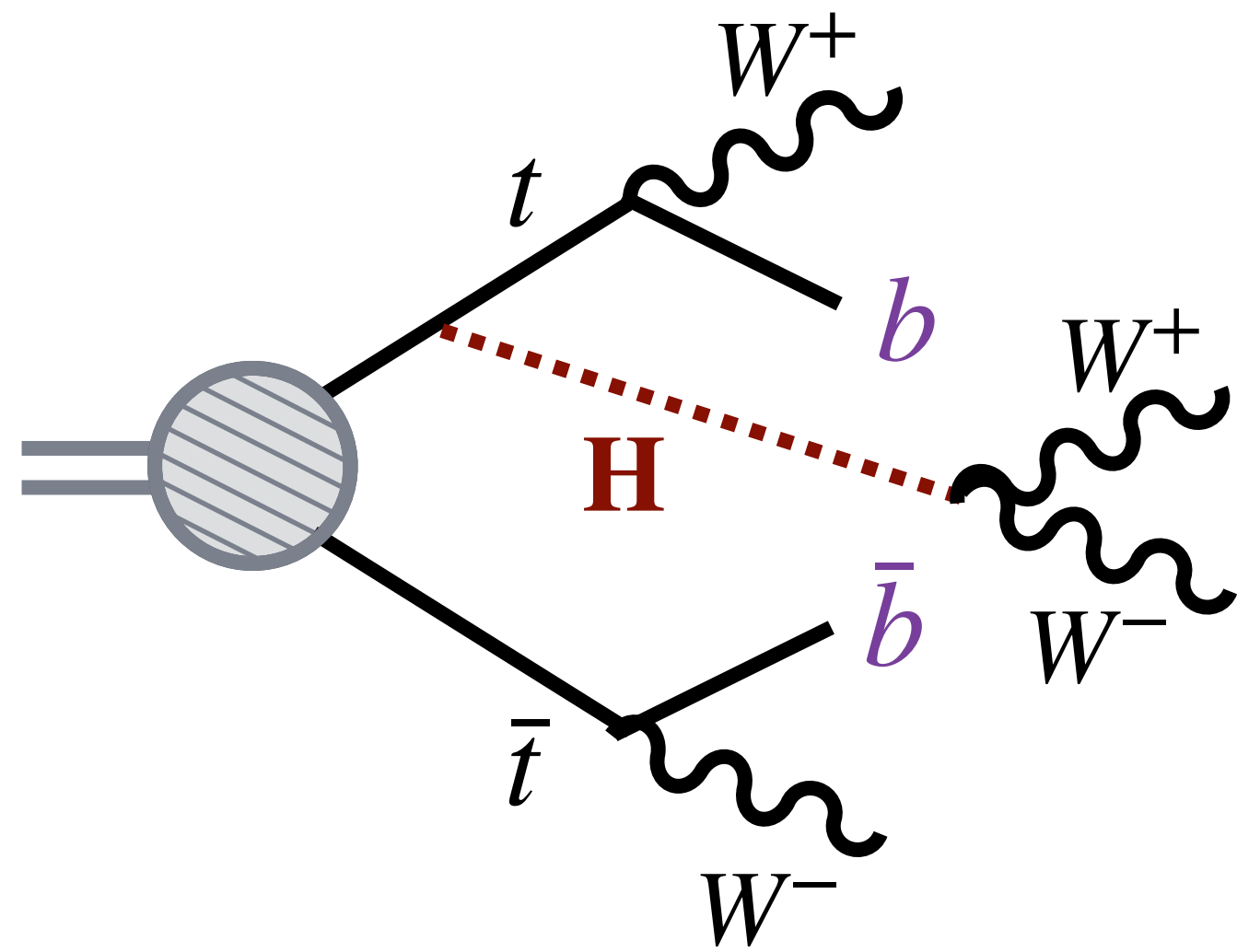
Z (→2 ℓ)

γ

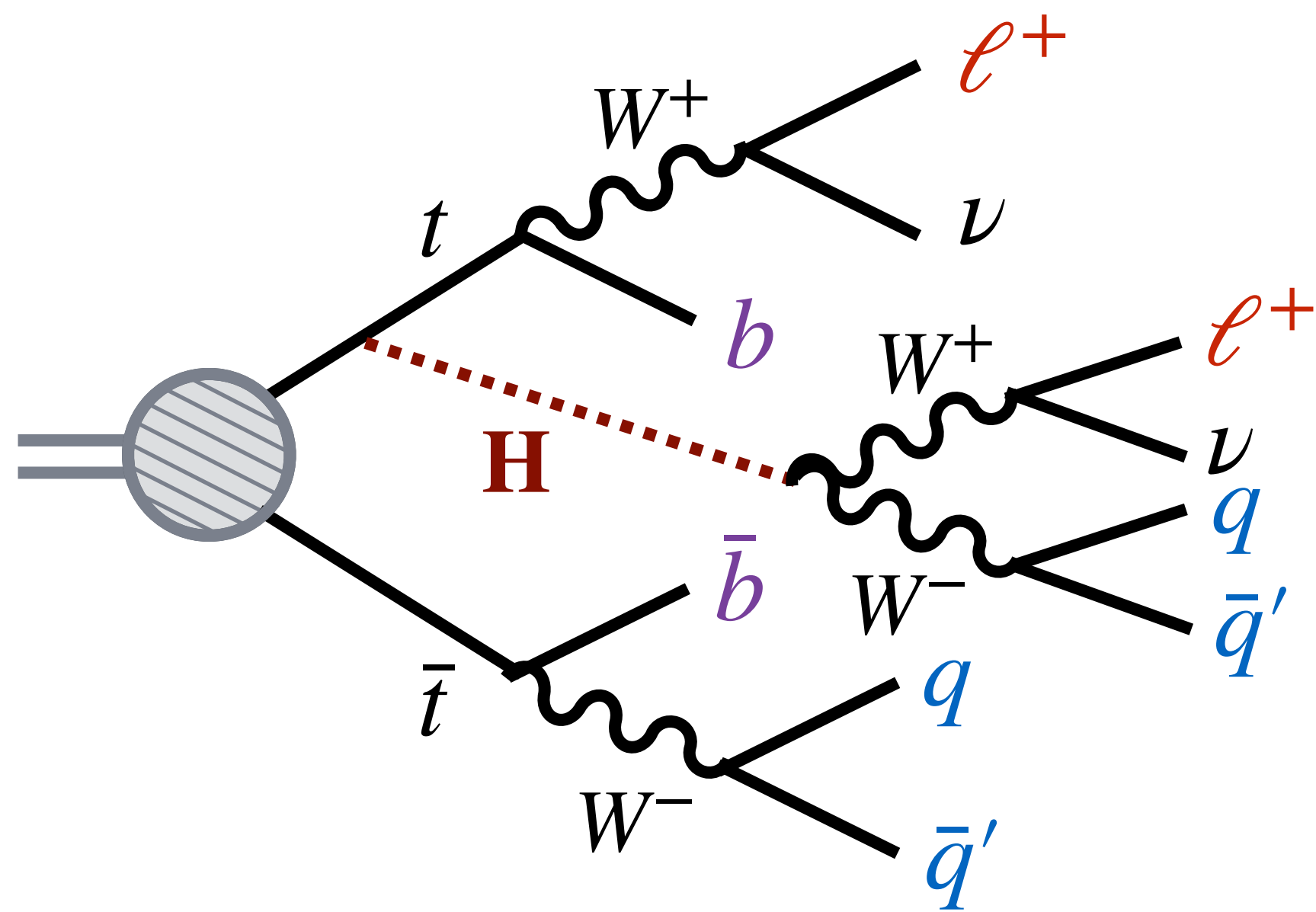
γ



- ▶ In this channel major backgrounds are **ttW**(+jets) and **ttZ**(+jets)



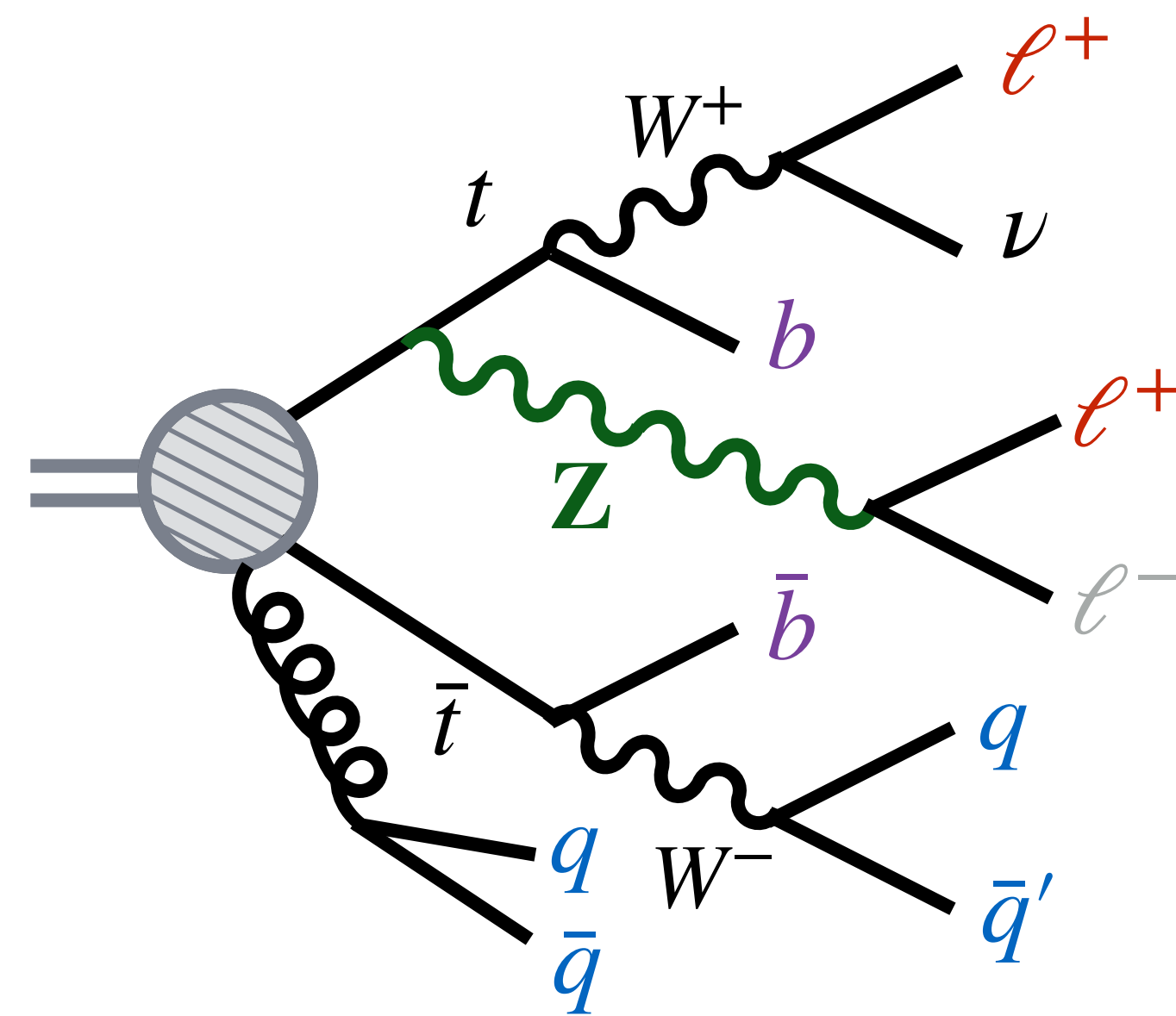
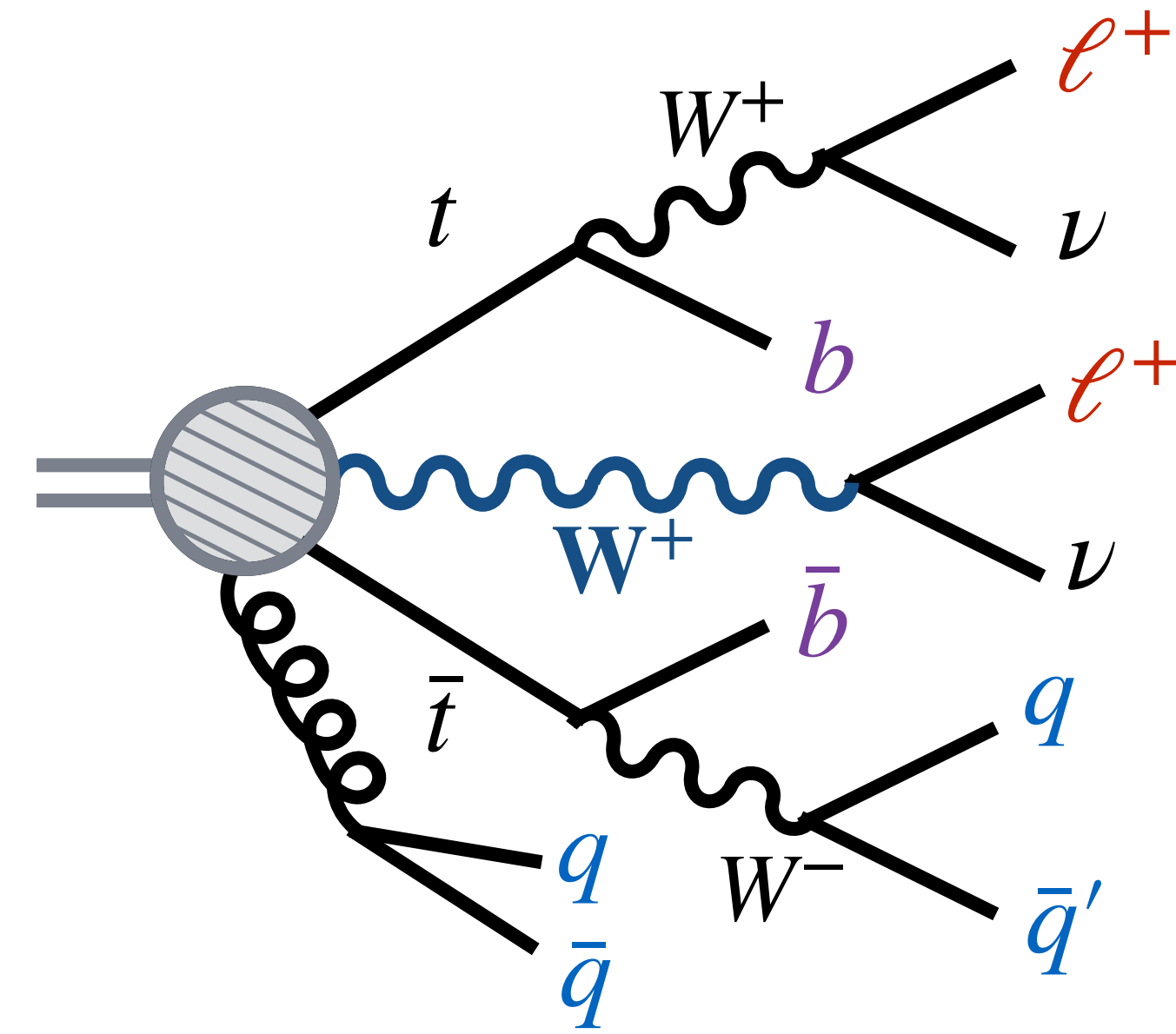
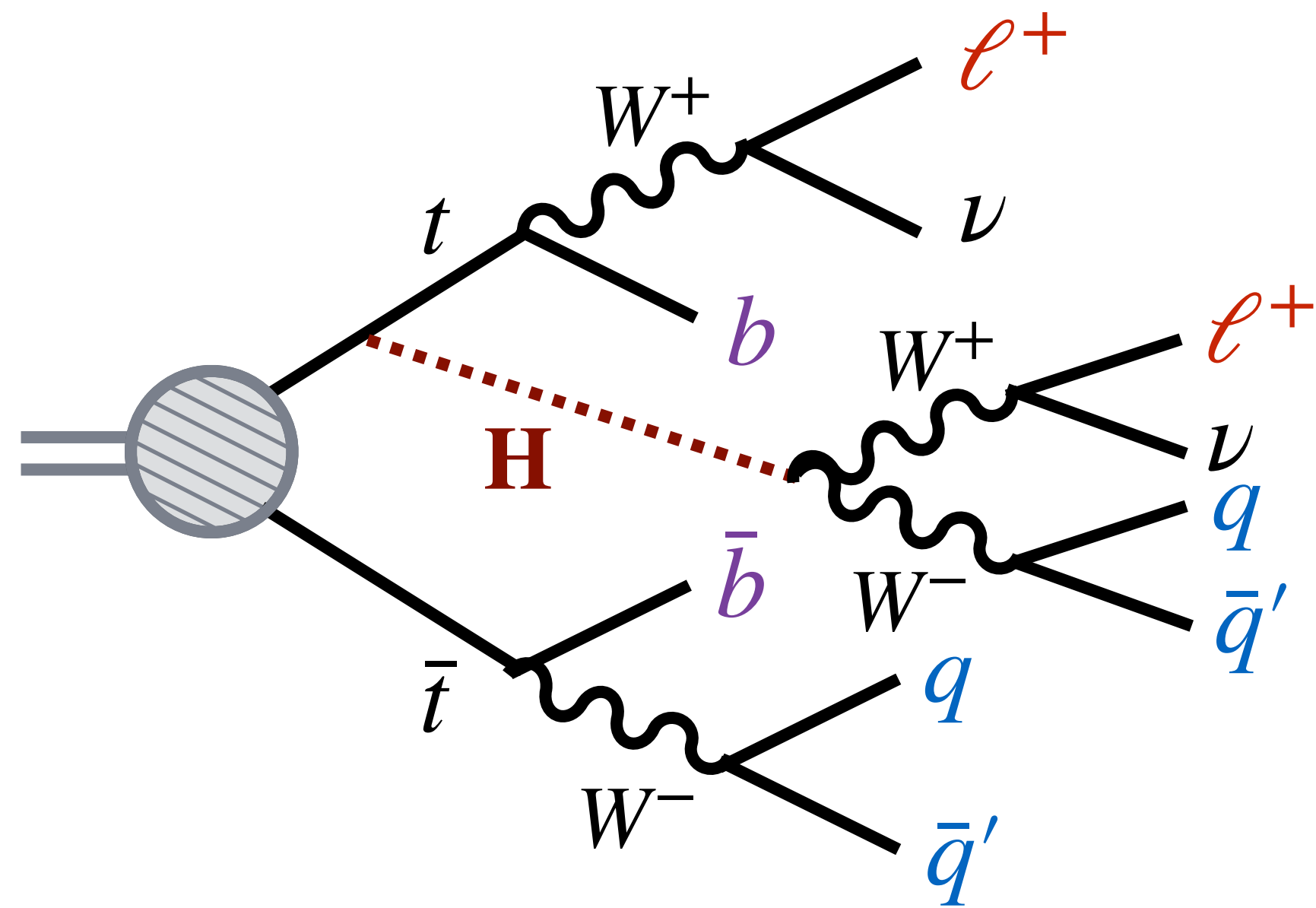
- ▶ In this channel major backgrounds are **ttW**(+jets) and **ttZ**(+jets)
- ▶ 2LSS example:



ttHML | Backgrounds

► In this channel major backgrounds are **ttW**(+jets) and **ttZ**(+jets)

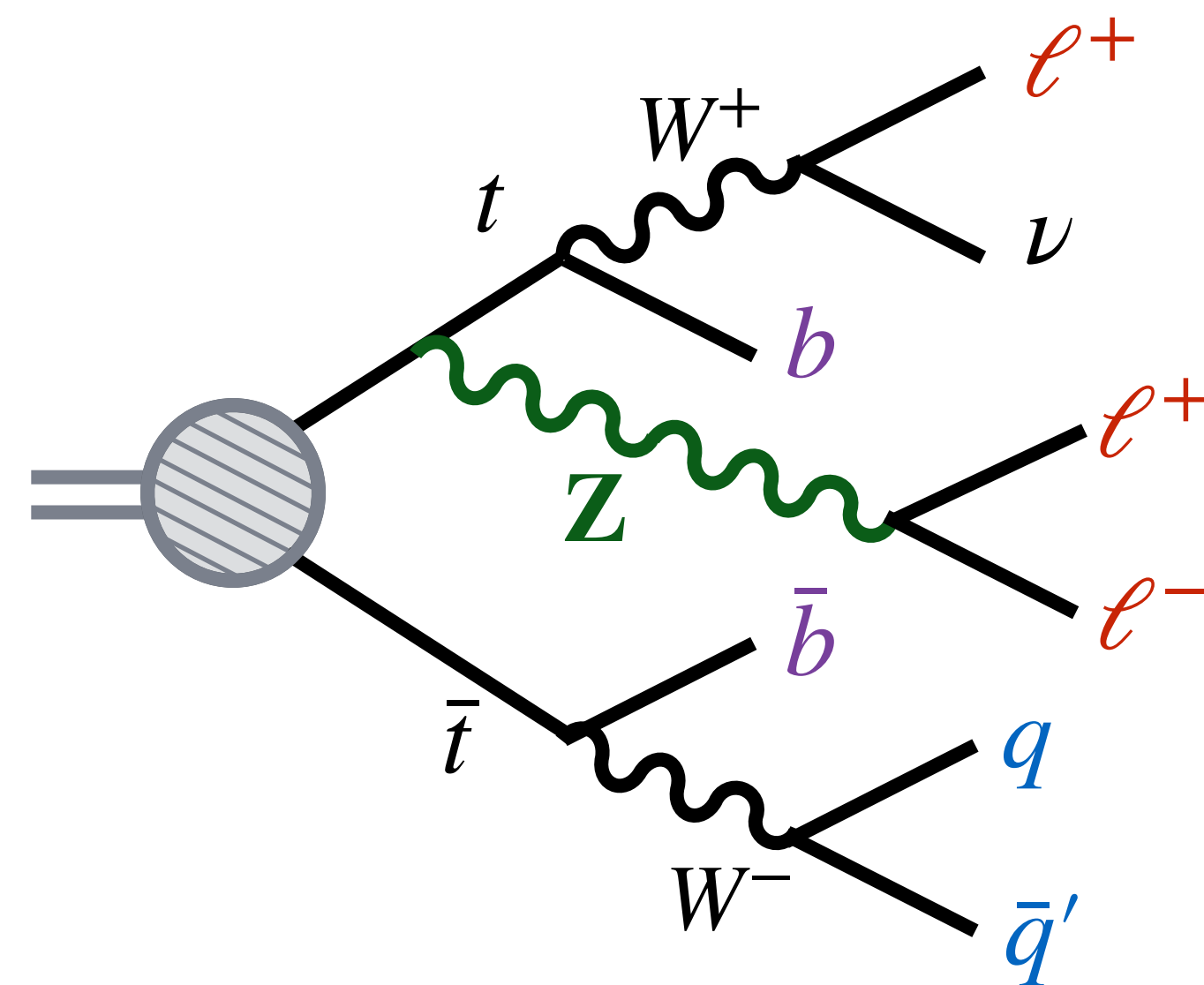
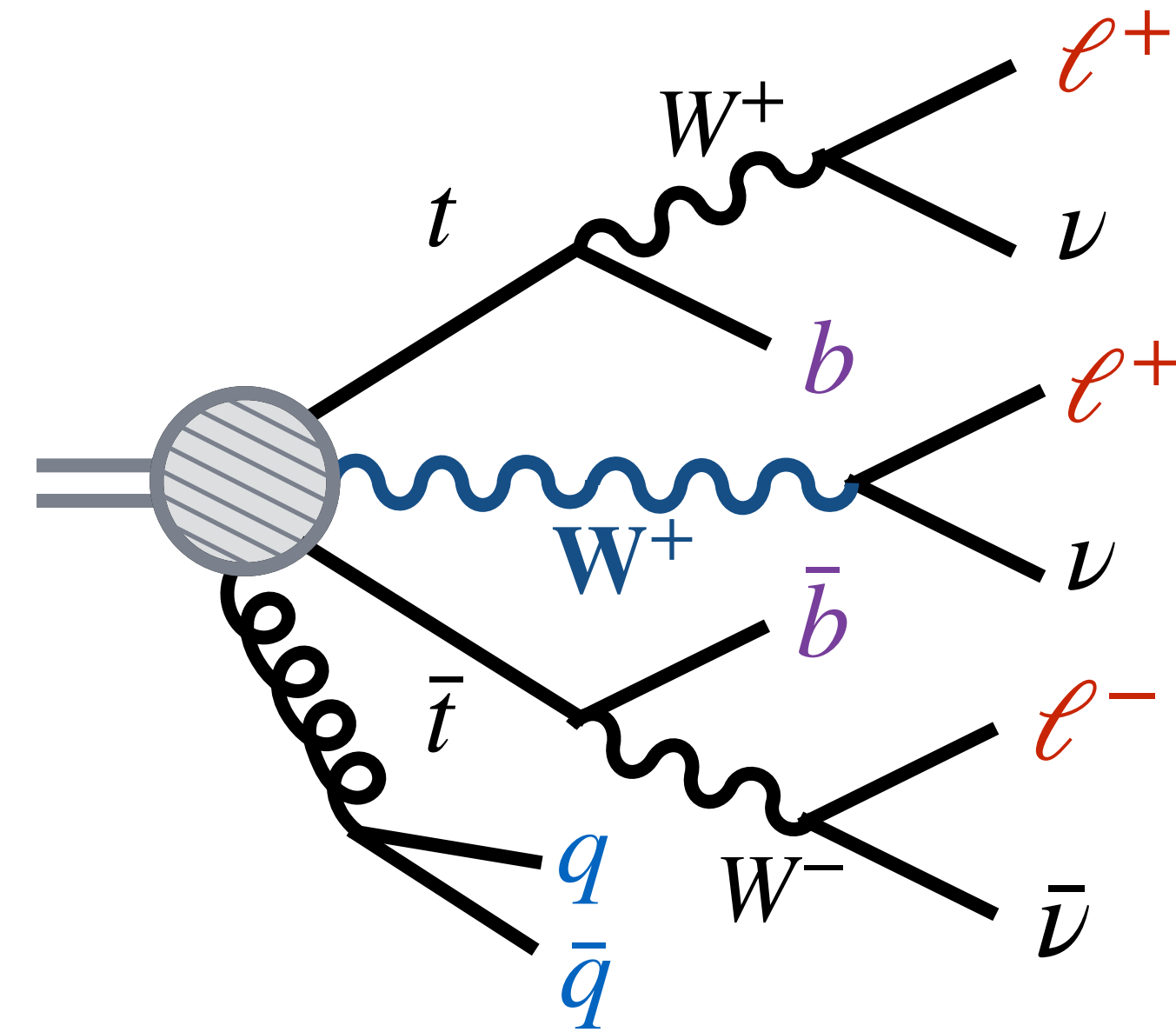
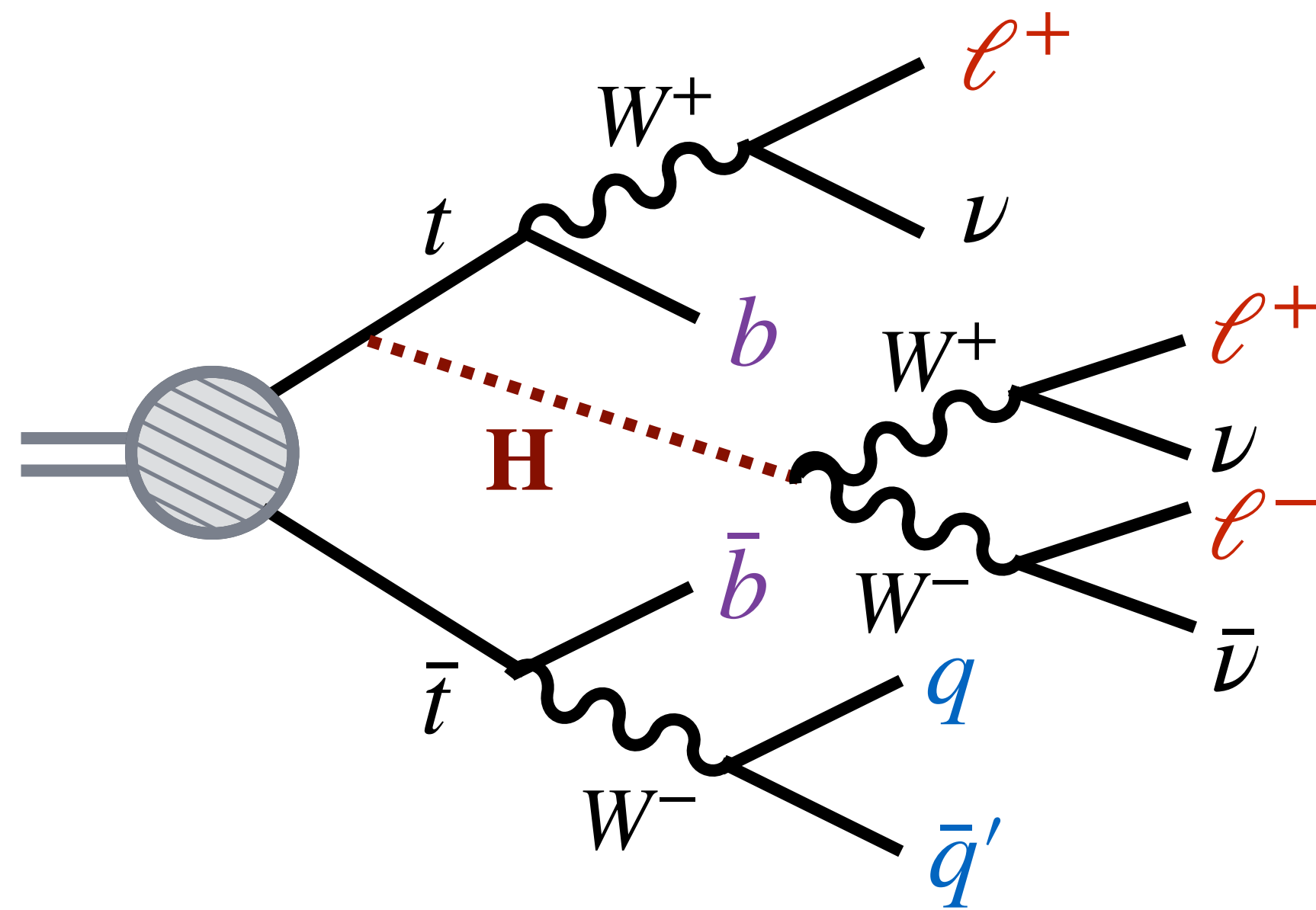
► 2LSS example:



ttHML | Backgrounds

► In this channel major backgrounds are **ttW**(+jets) and **ttZ**(+jets)

► 3L example:

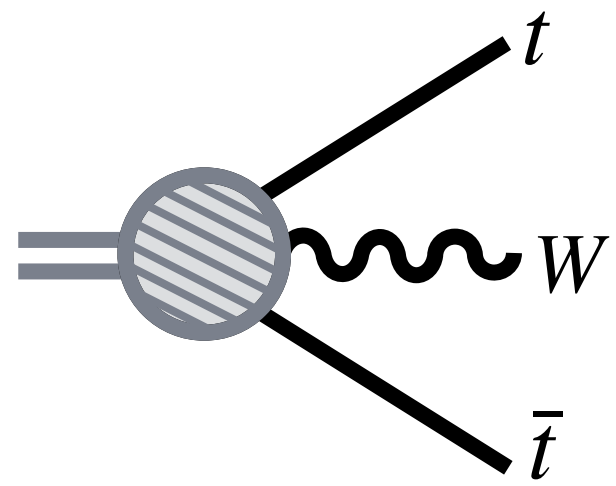


Top+X

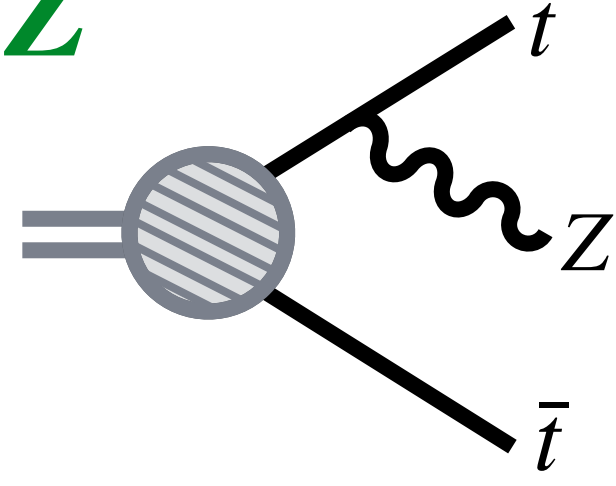
Processes interlinked in multilepton final state



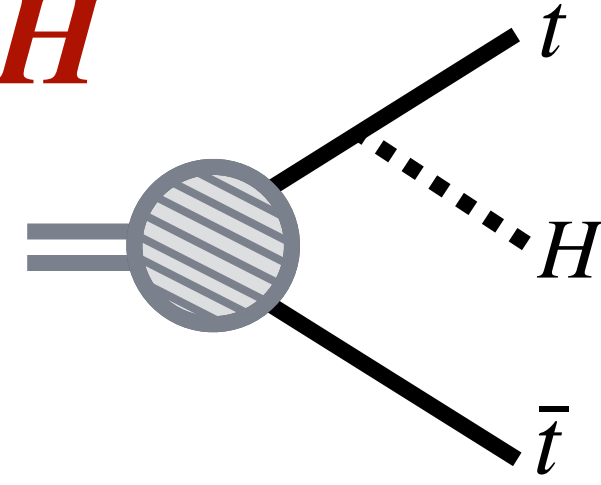
$t\bar{t}W$



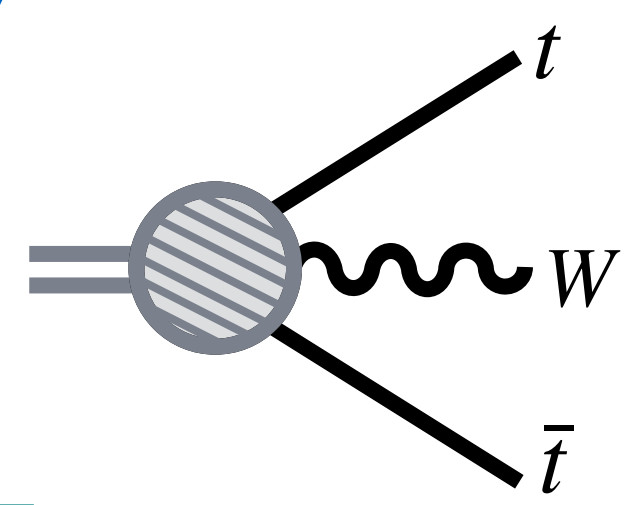
$t\bar{t}Z$



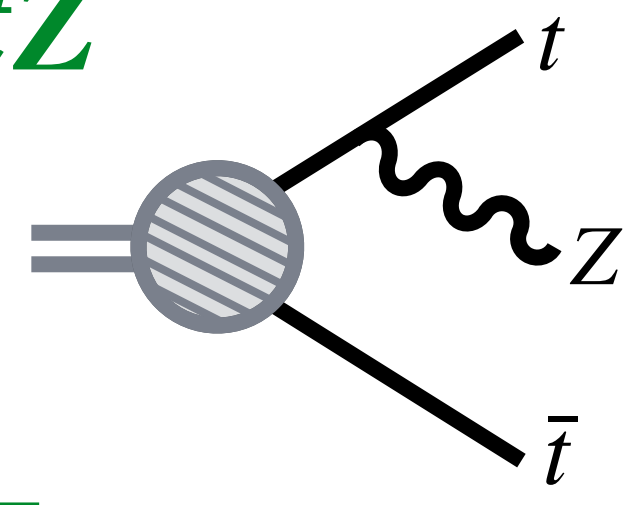
$t\bar{t}H$



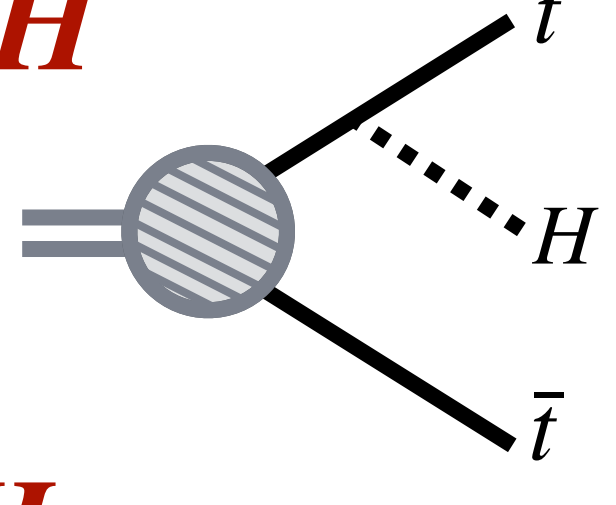
$t\bar{t}W$



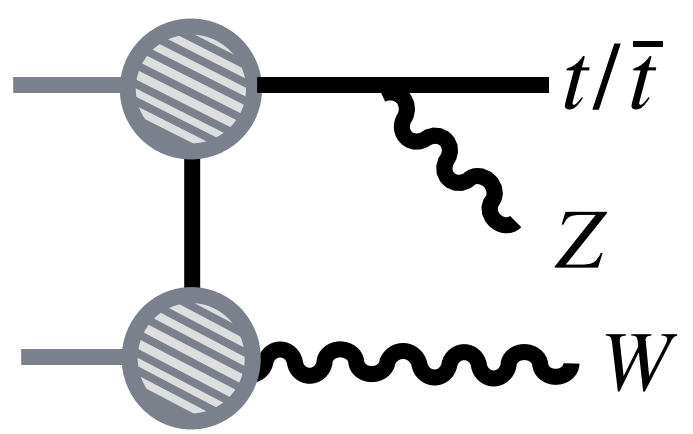
$t\bar{t}Z$



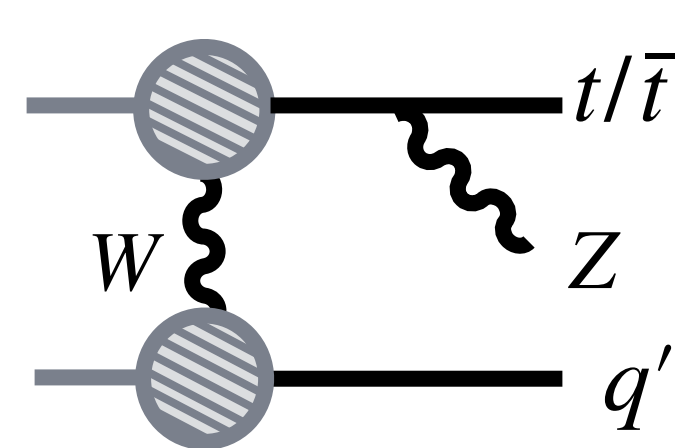
$t\bar{t}H$



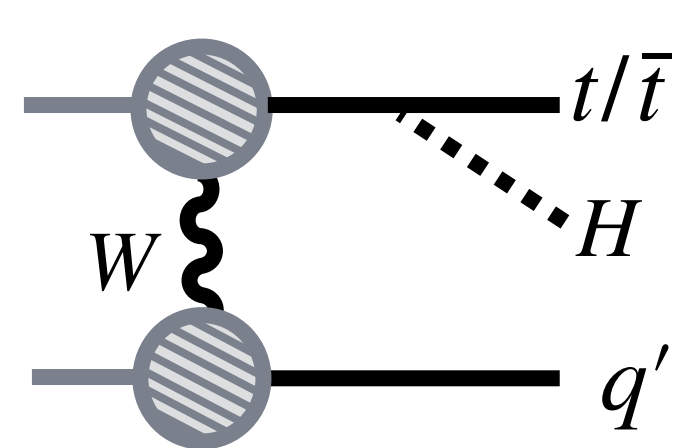
tWZ



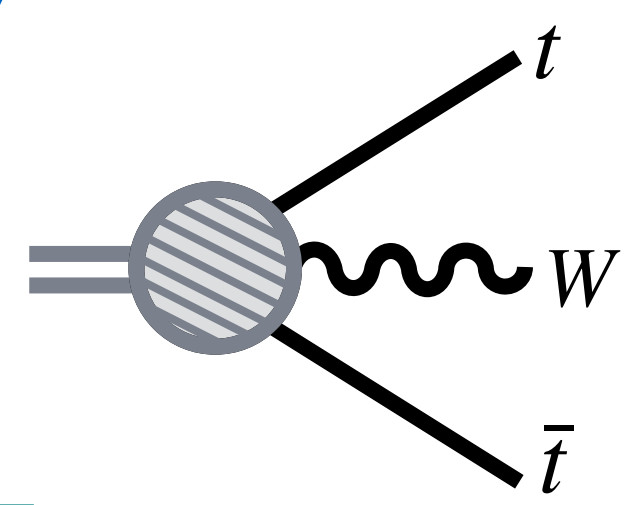
tZq



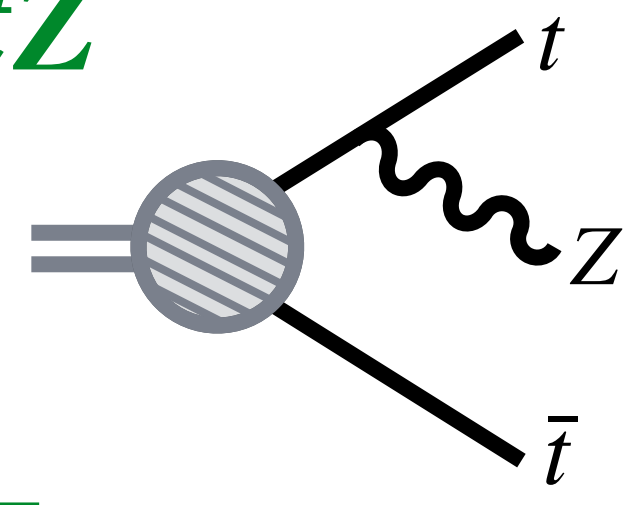
tHq



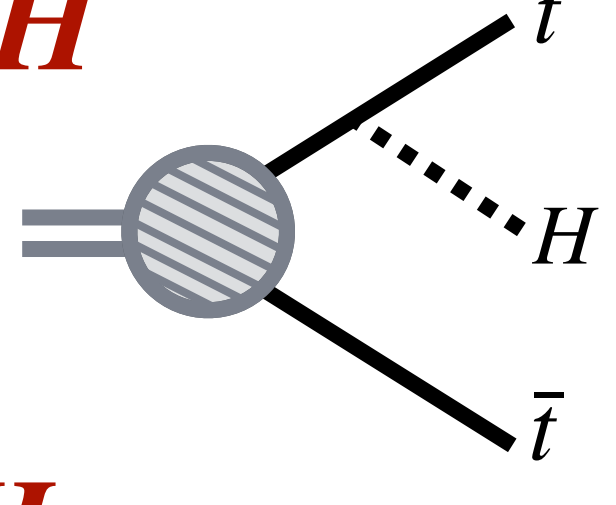
$t\bar{t}W$



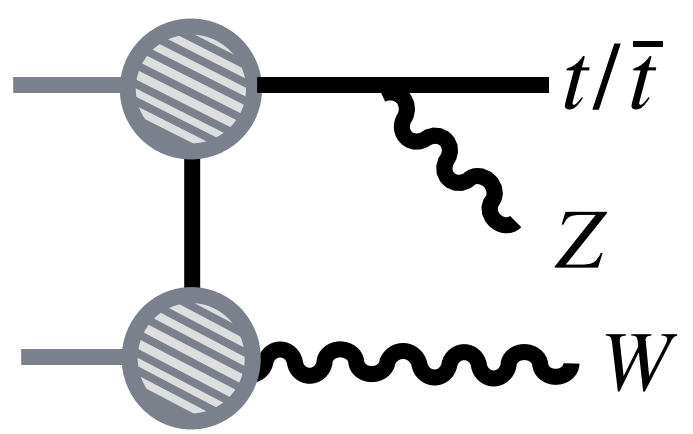
$t\bar{t}Z$



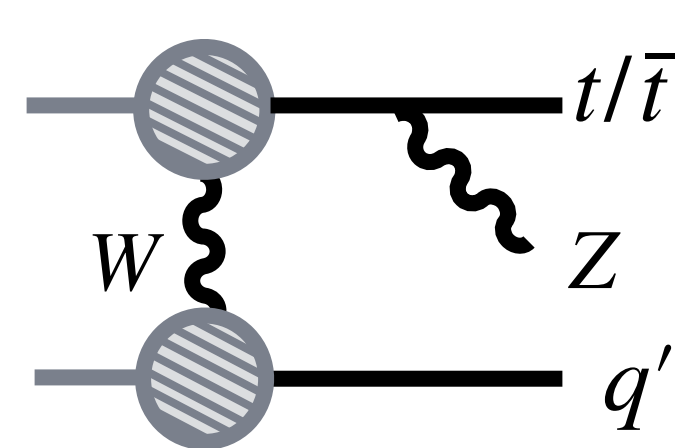
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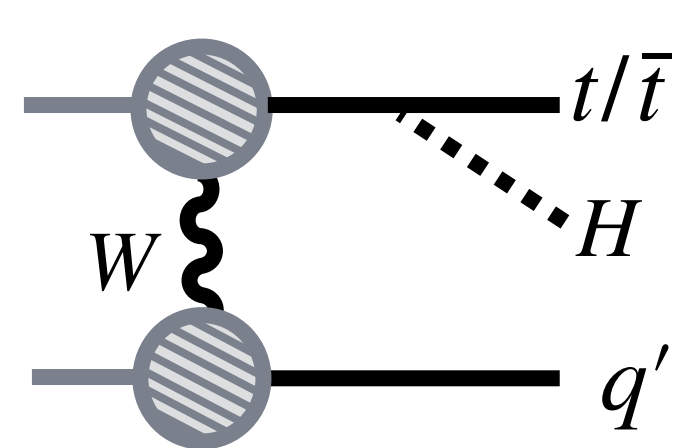
tWZ



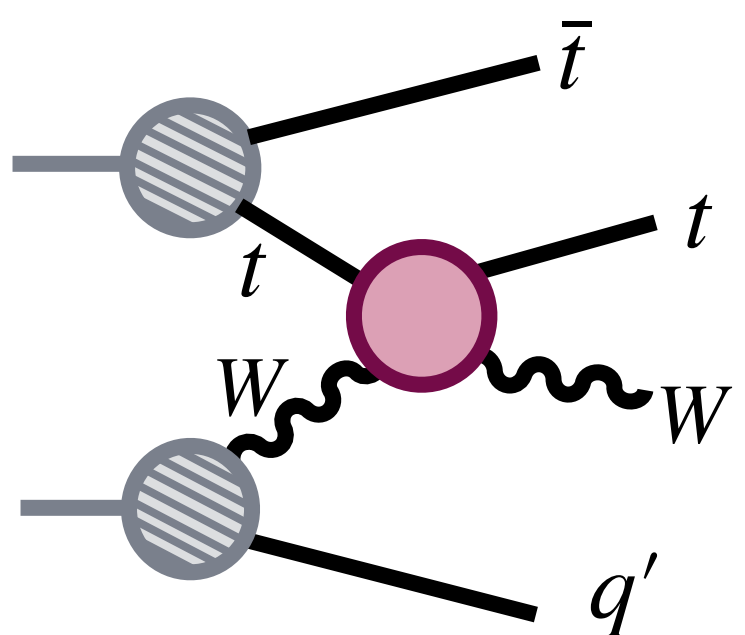
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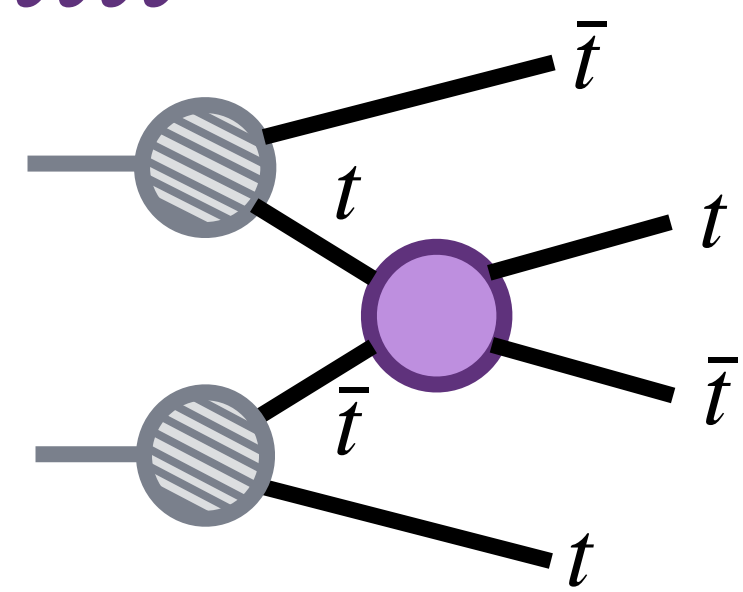
tHq



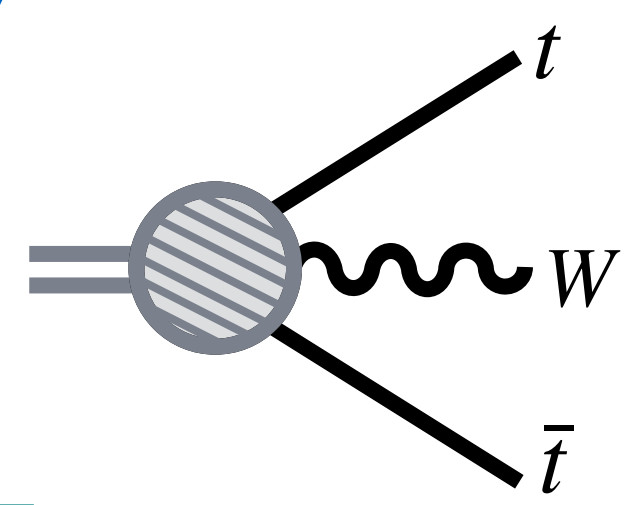
tW -scattering



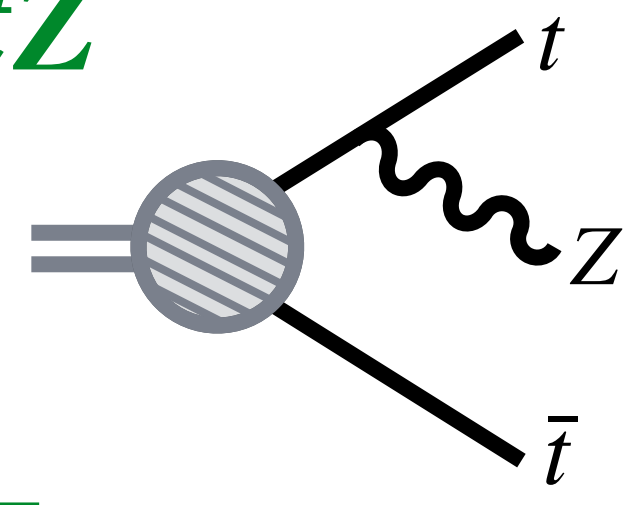
$t\bar{t}t\bar{t}$



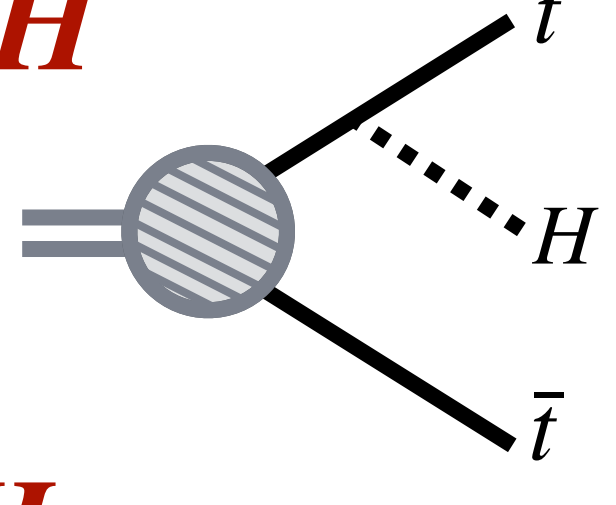
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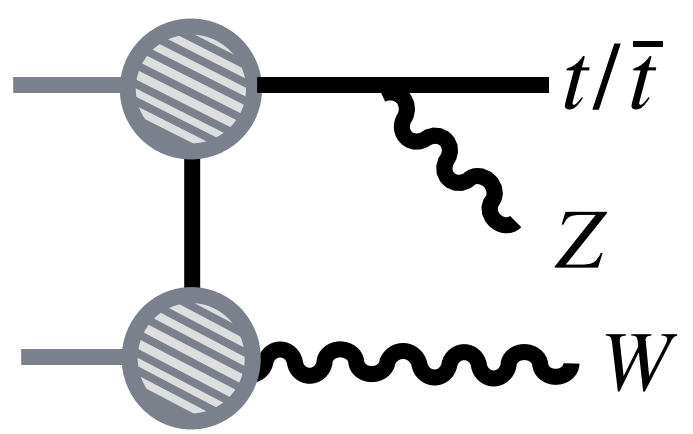
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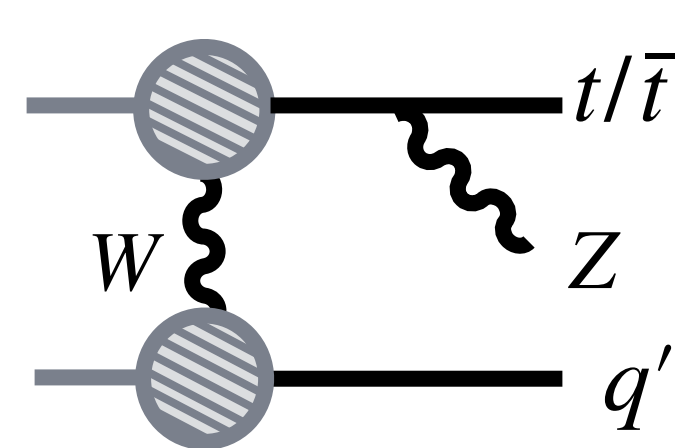
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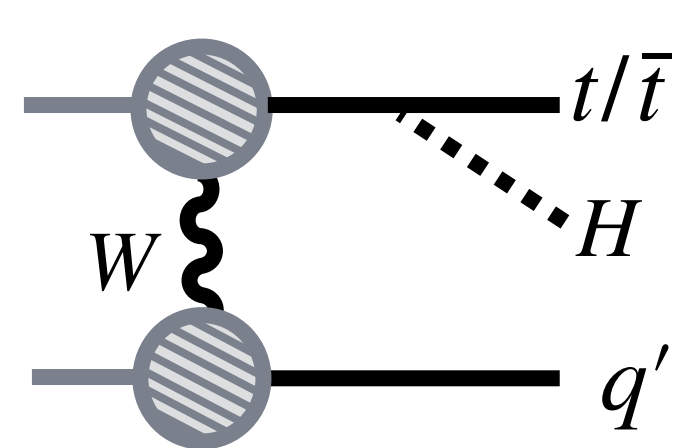
tWZ



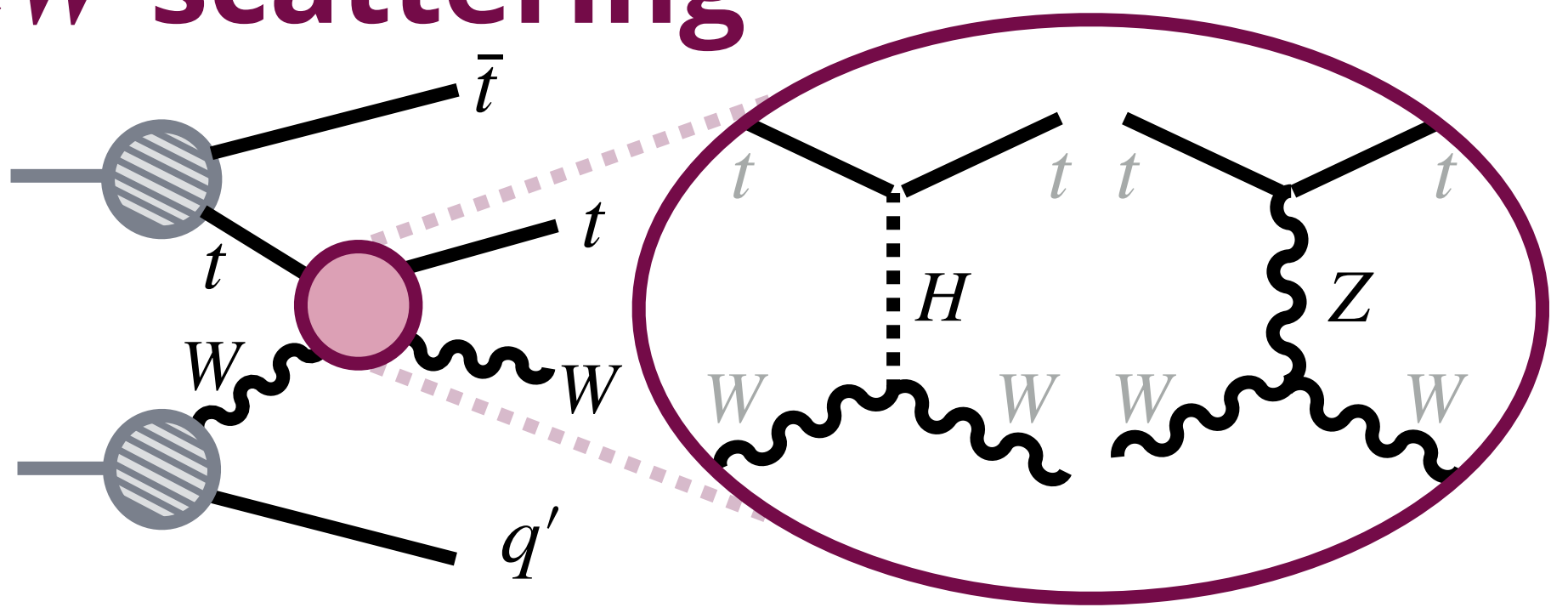
tZq



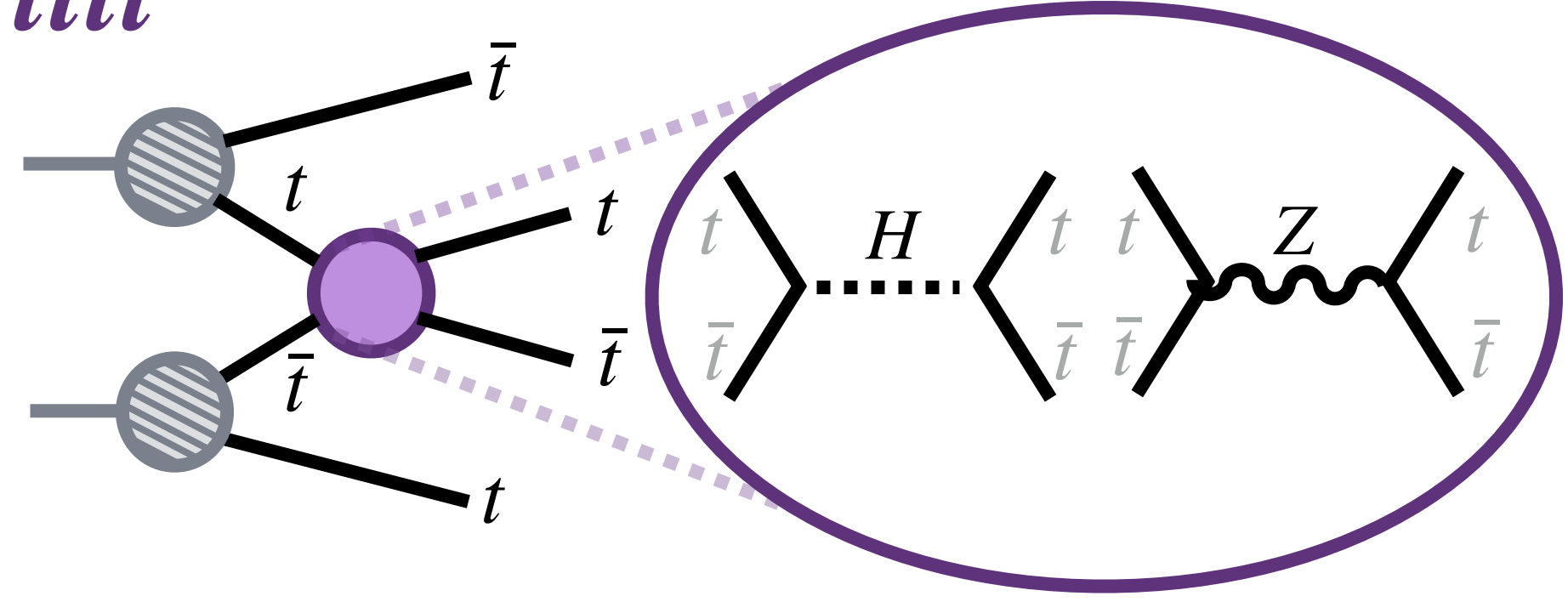
tHq



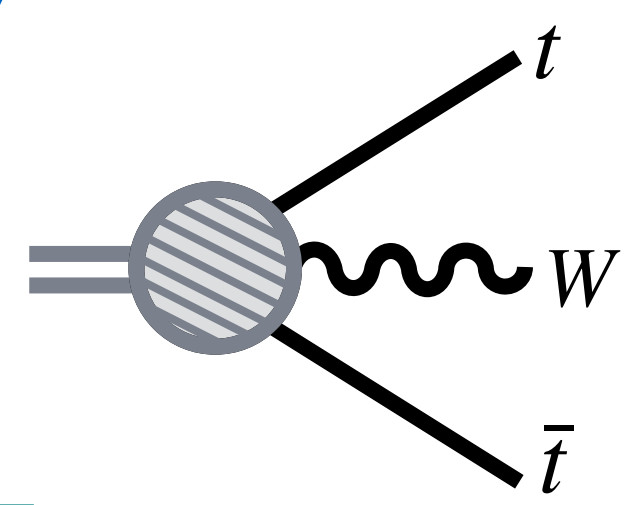
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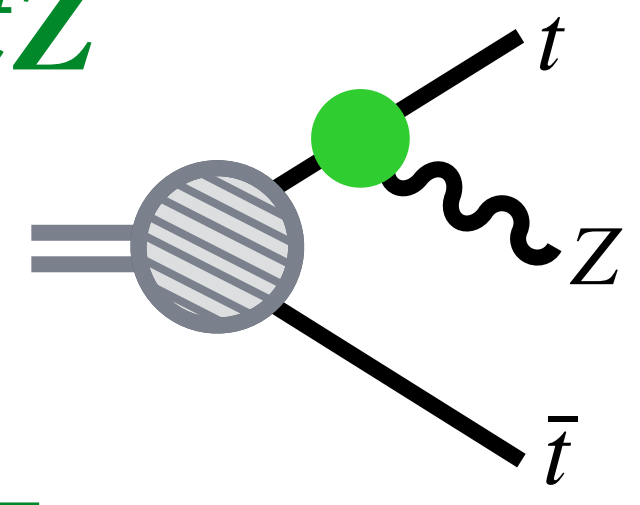
$t\bar{t}t\bar{t}$



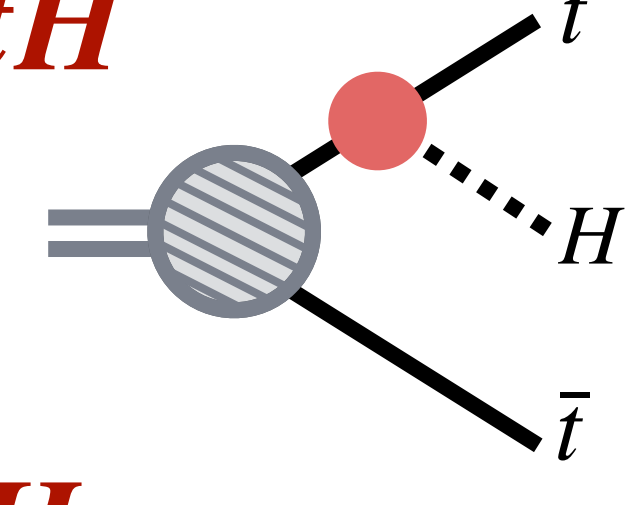
$t\bar{t}W$



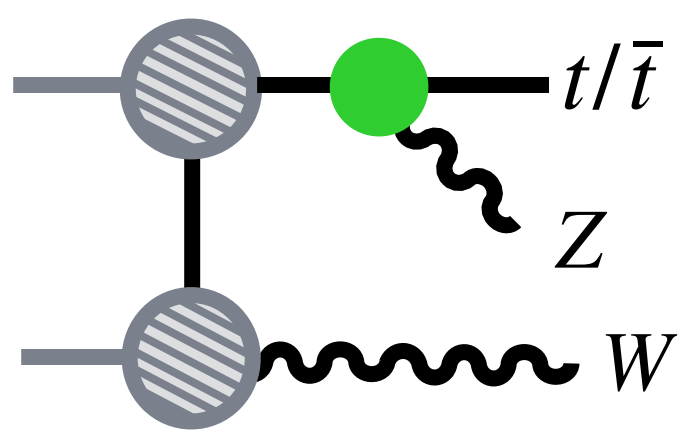
$t\bar{t}Z$



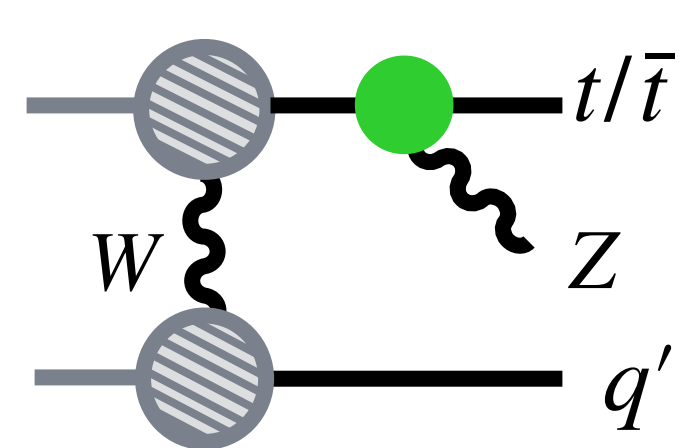
$t\bar{t}H$



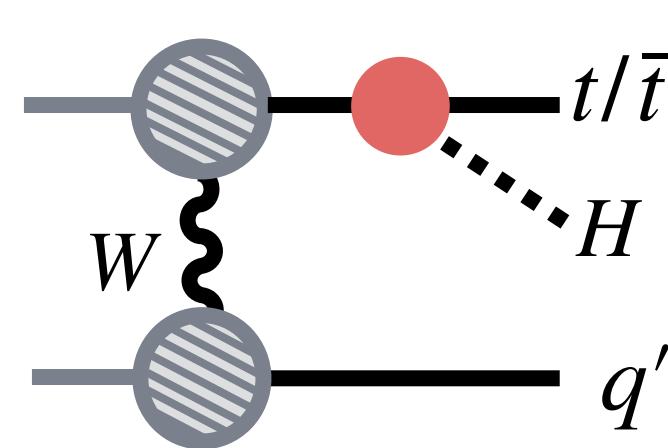
tWZ



tZq



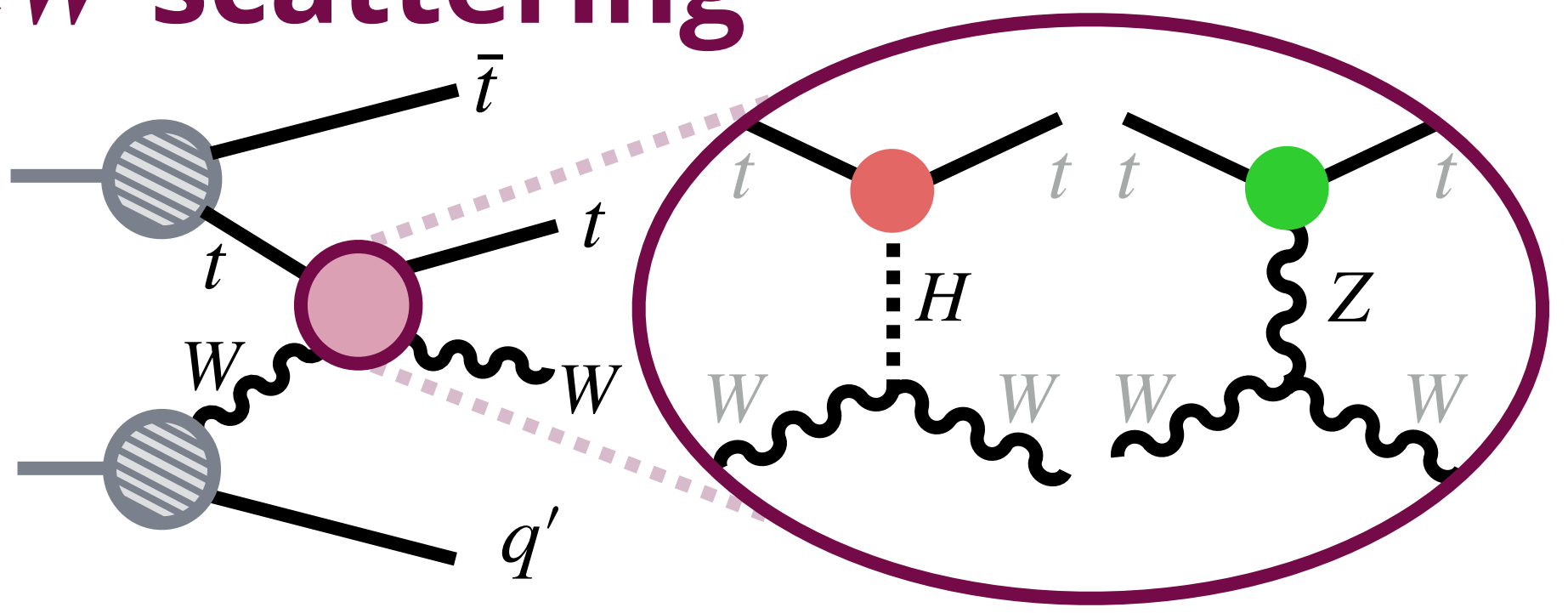
tHq



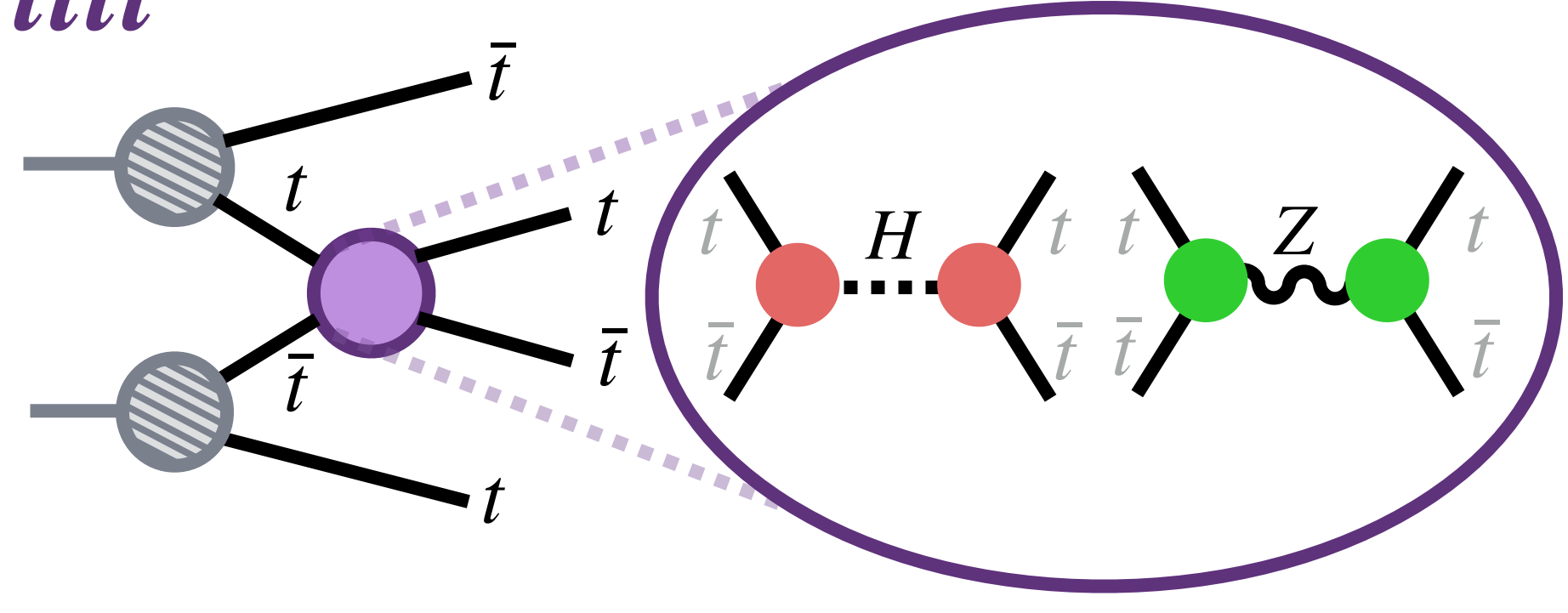
Couplings:

- C_{ttZ}
- C_{ttH}

tW -scattering

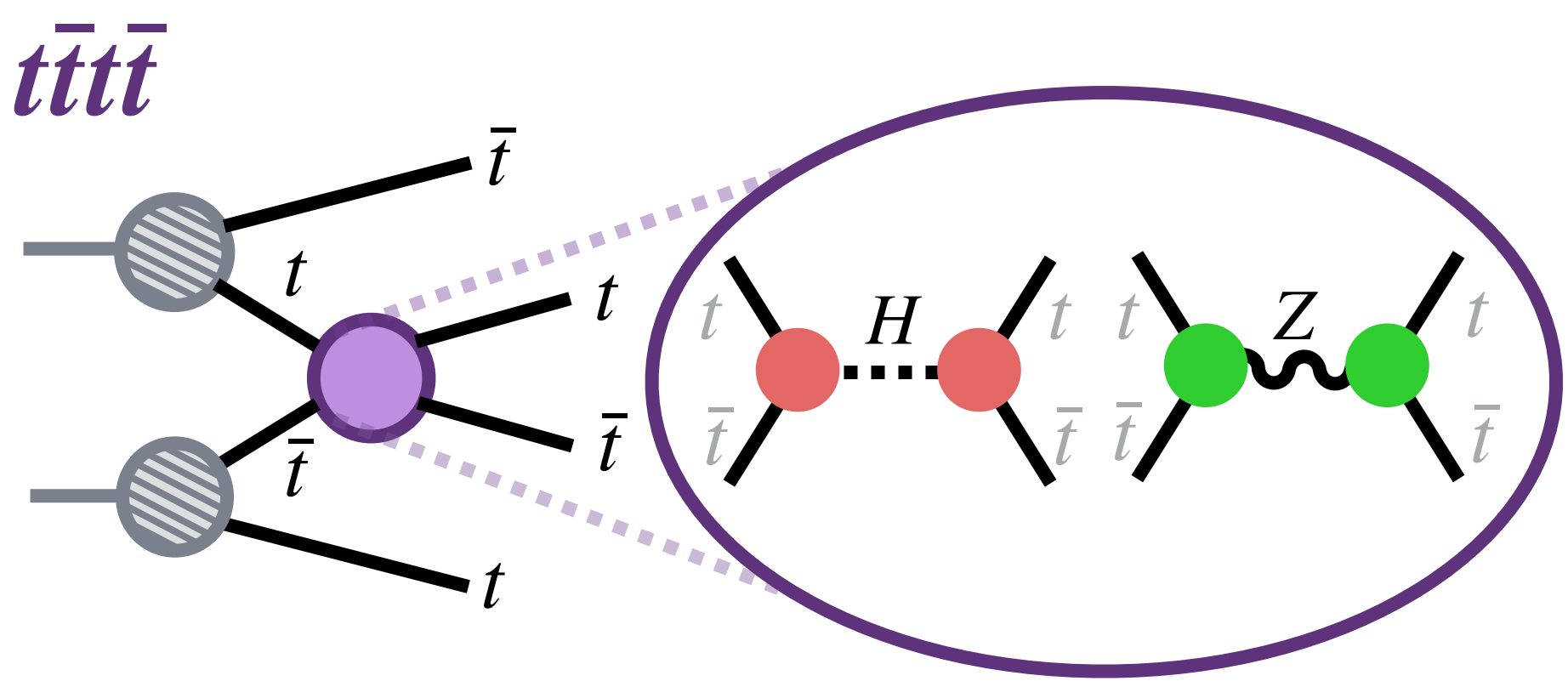
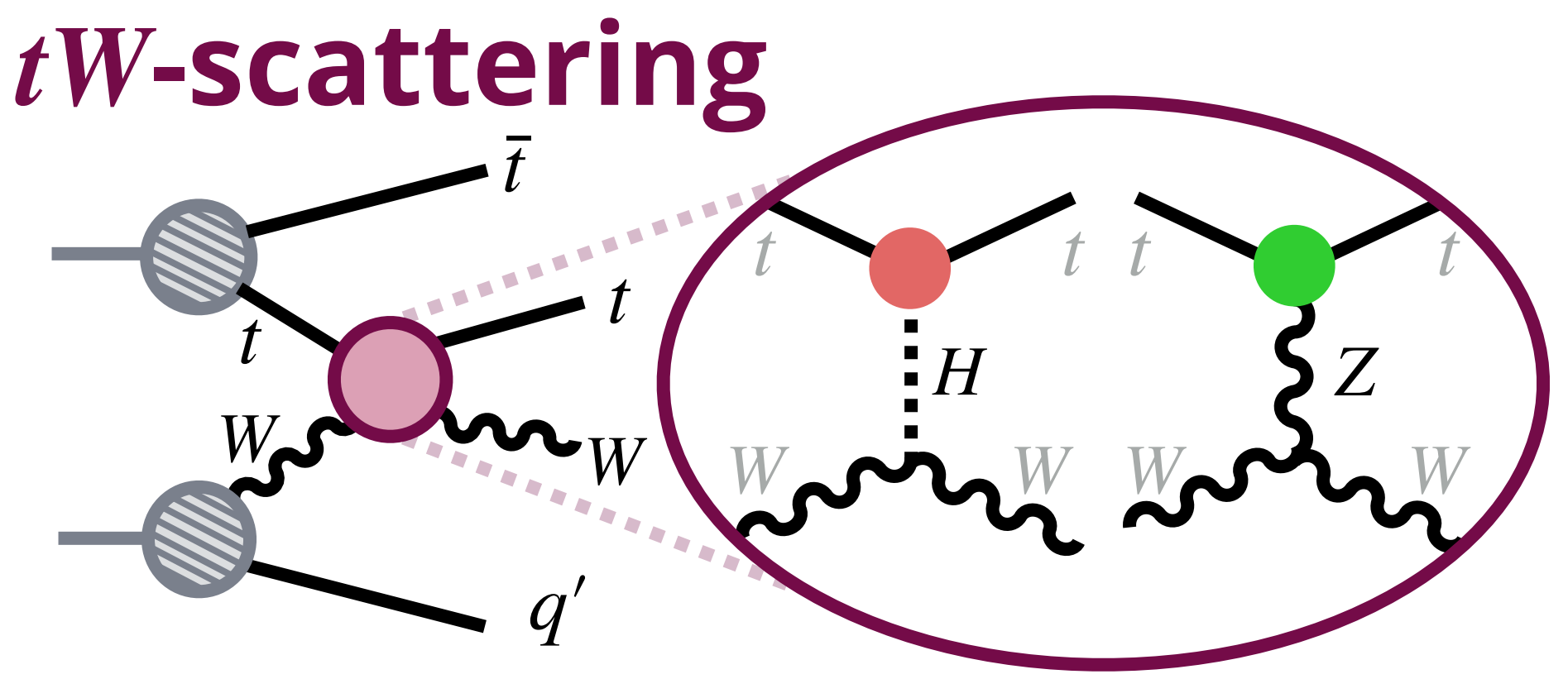
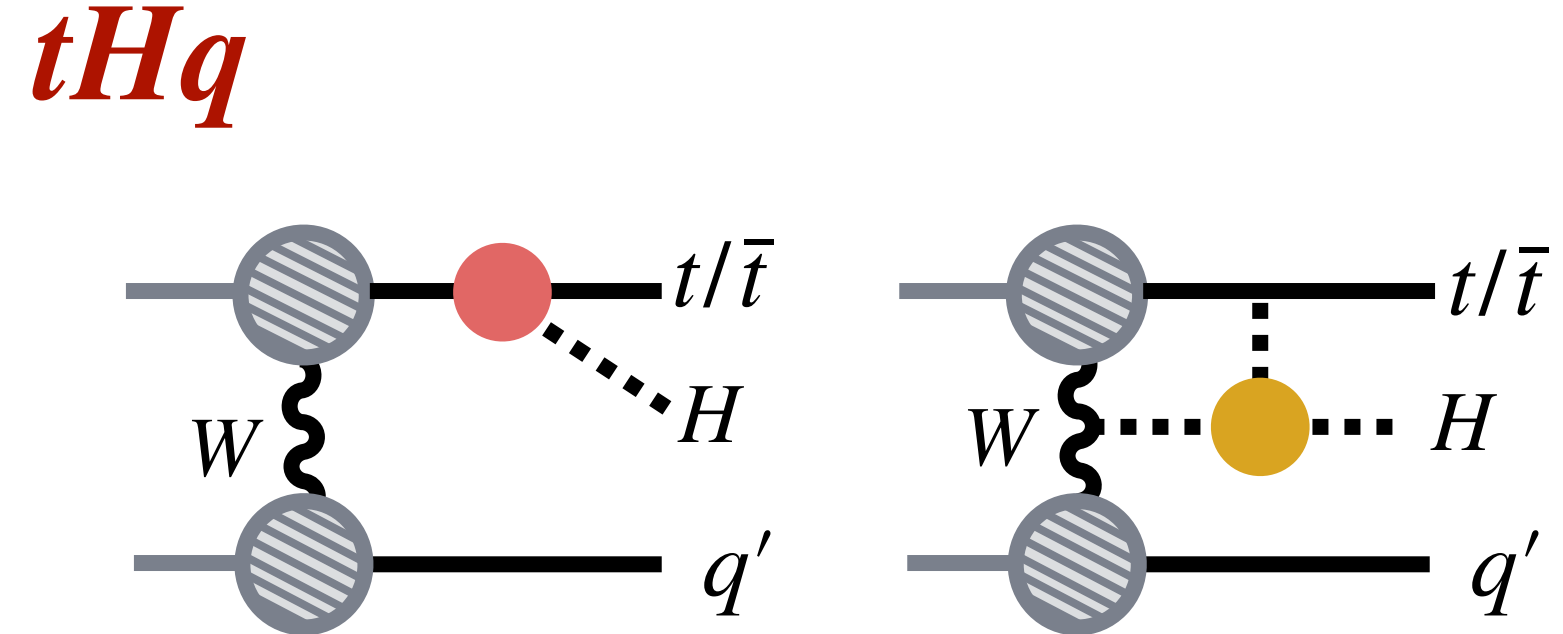
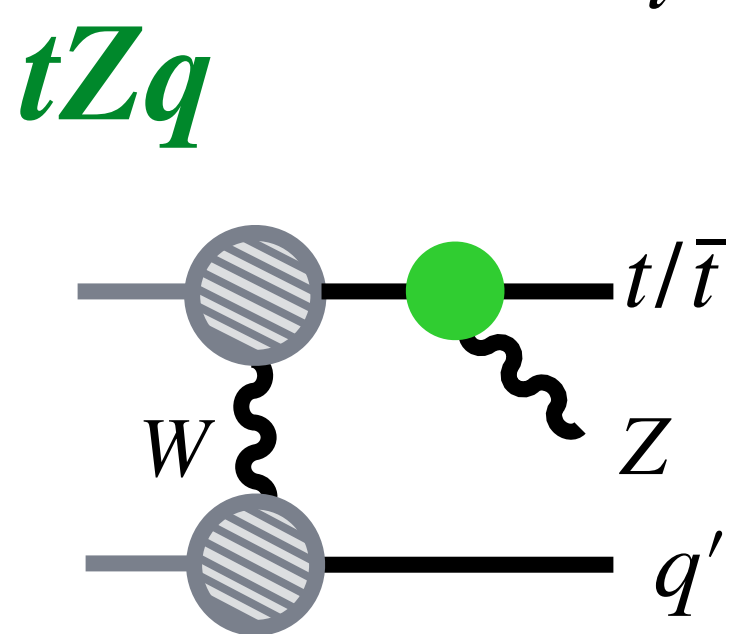
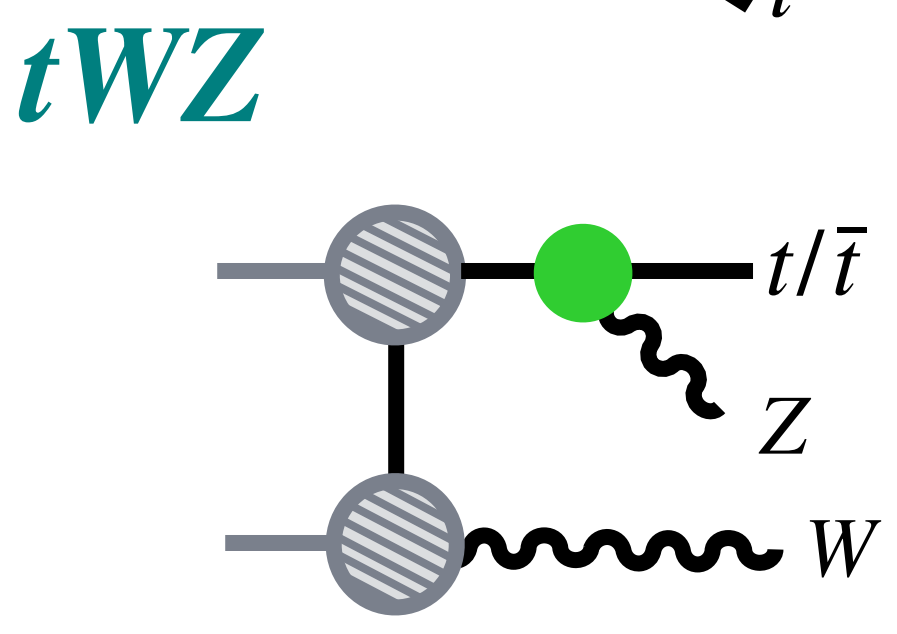
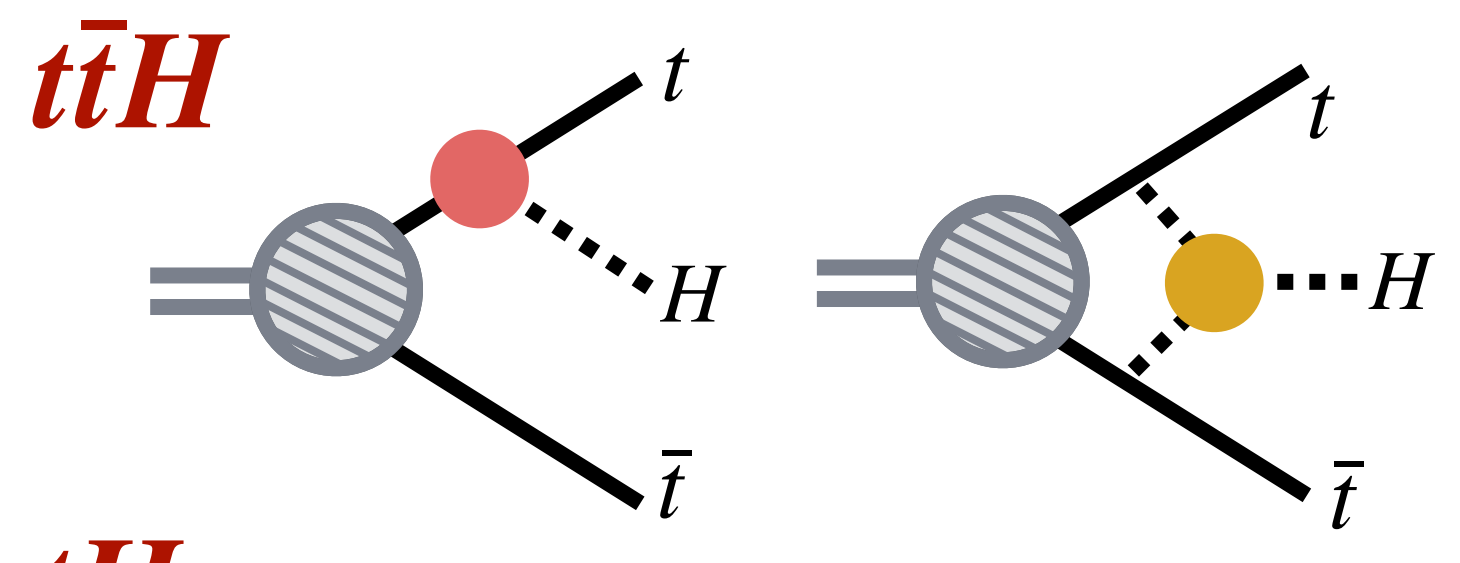
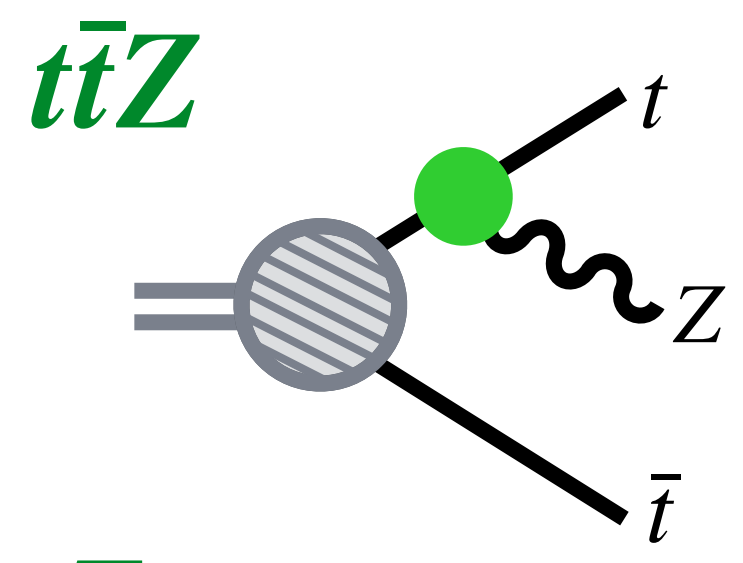
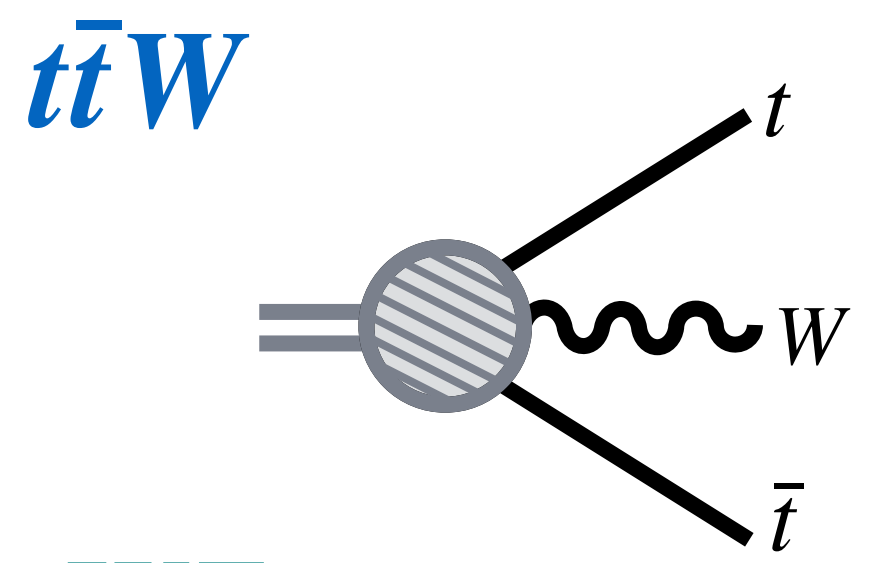


$t\bar{t}t\bar{t}$

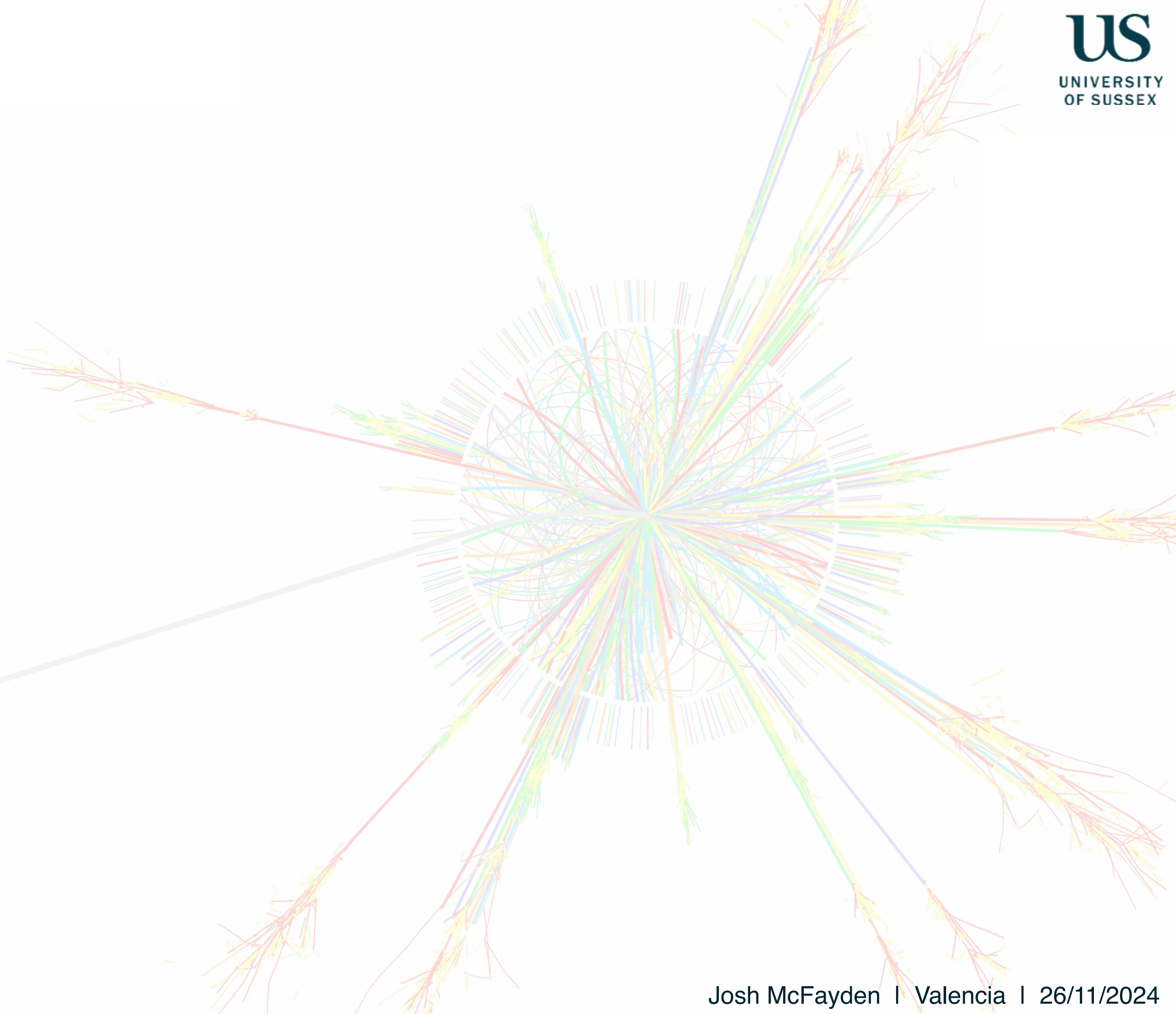


Couplings:

-  C_{ttZ}
-  C_{ttH}
-  C_{HHH}

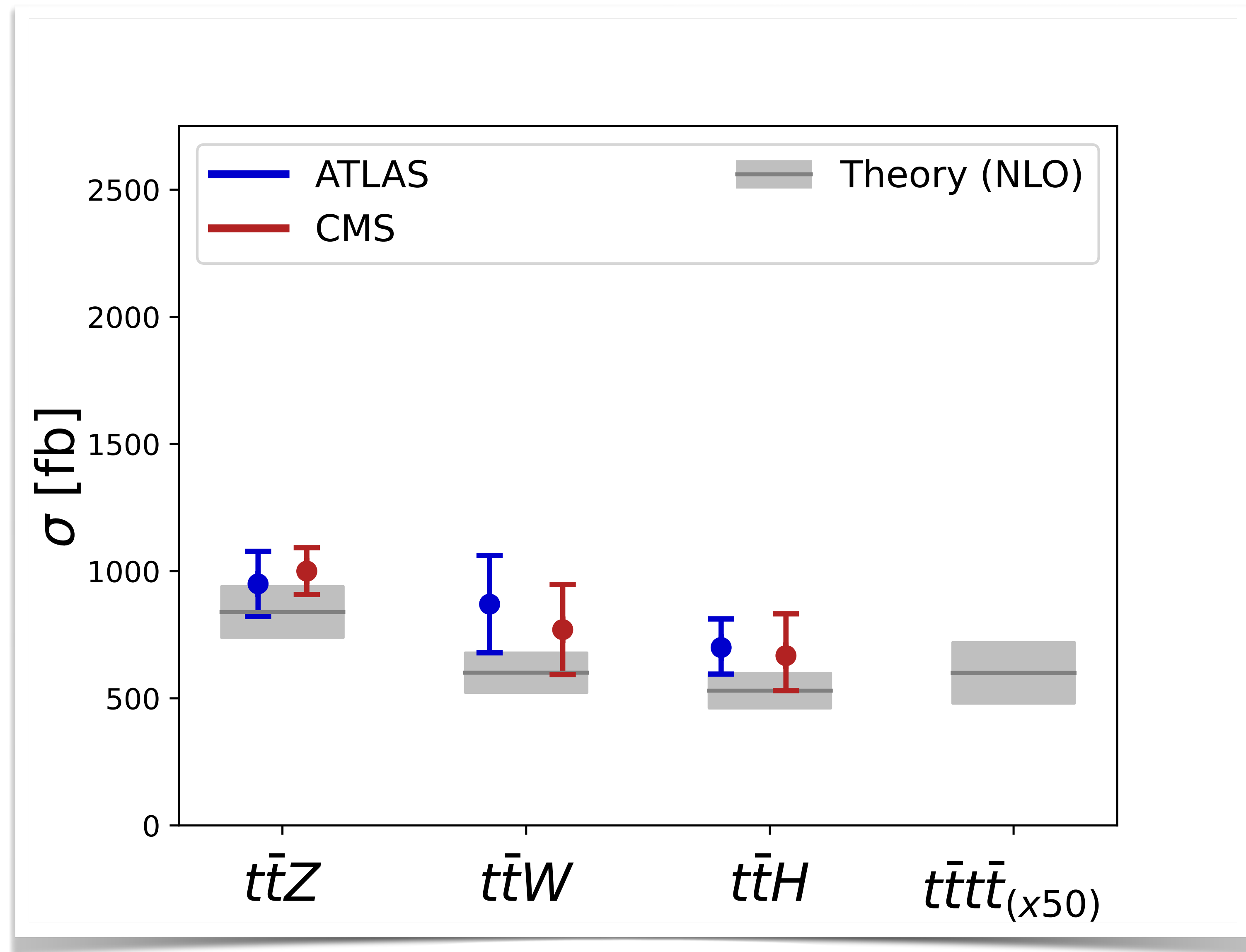


ttW





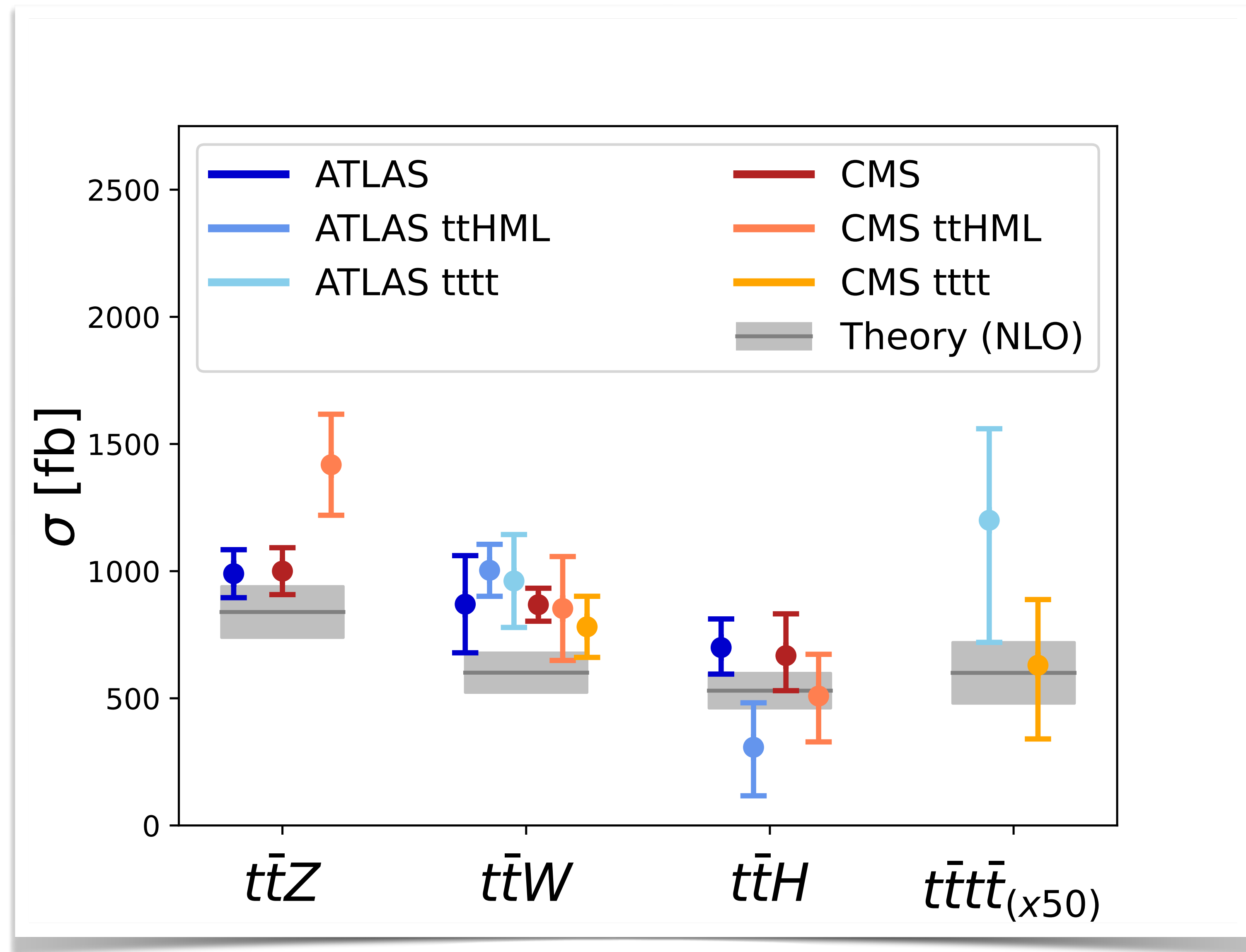
- Started off as barely a hint of deviation from the SM





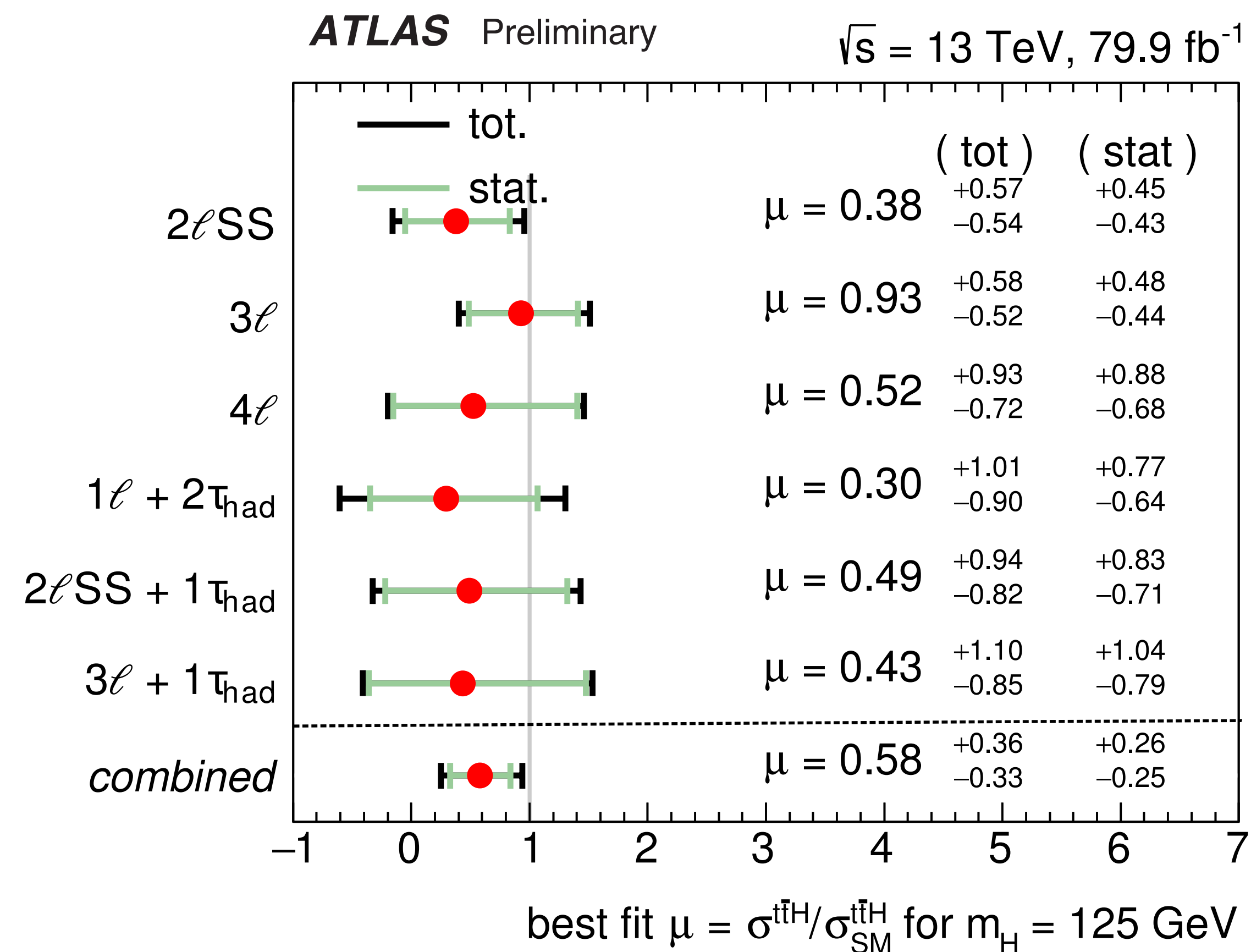
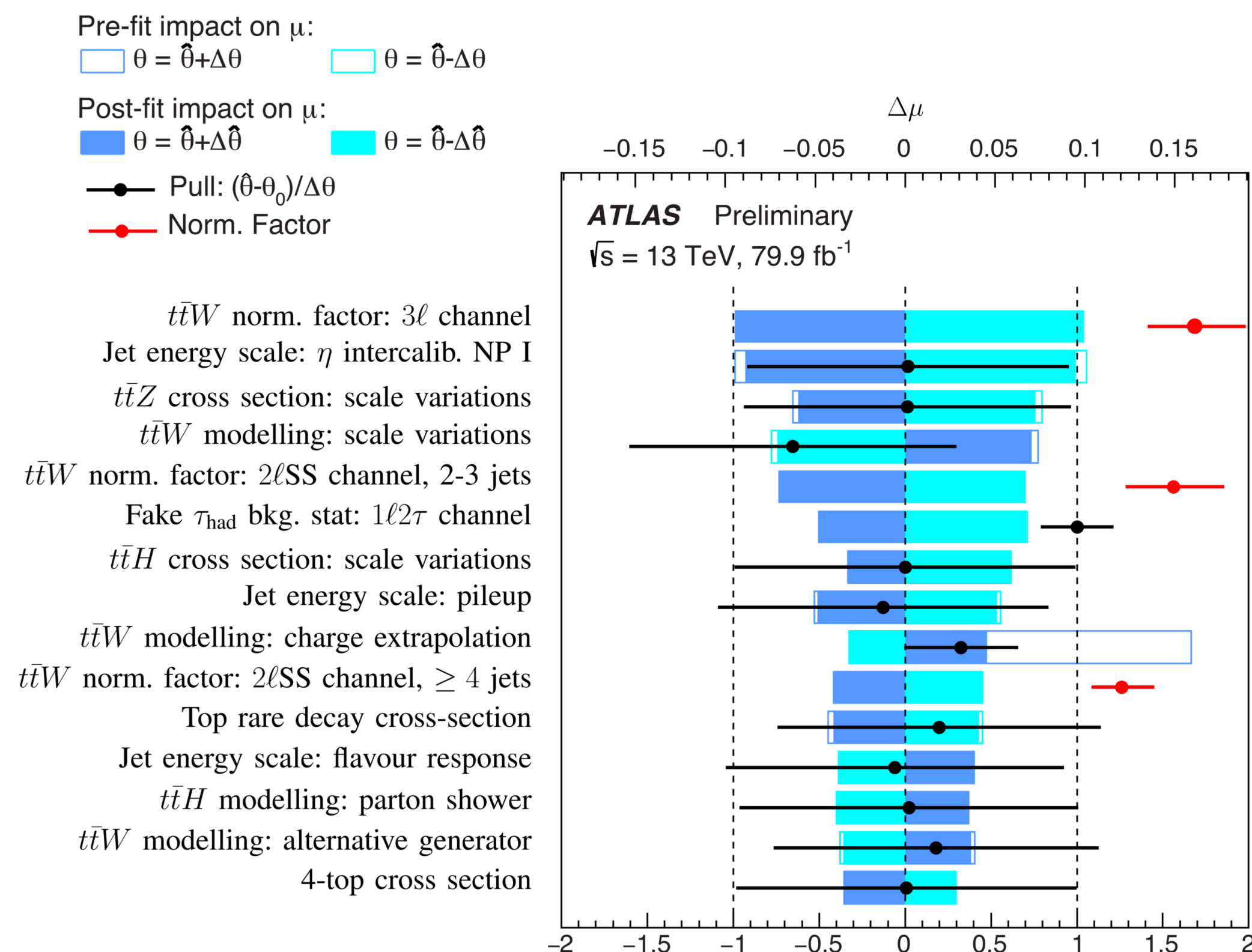
Background | Run 2 results today

- ▶ Started off as barely a hint of deviation from the SM
- ▶ Then seemingly mounting evidence that something is going on with $t\bar{t}W$ (or $t\bar{t}W$ -like final states)

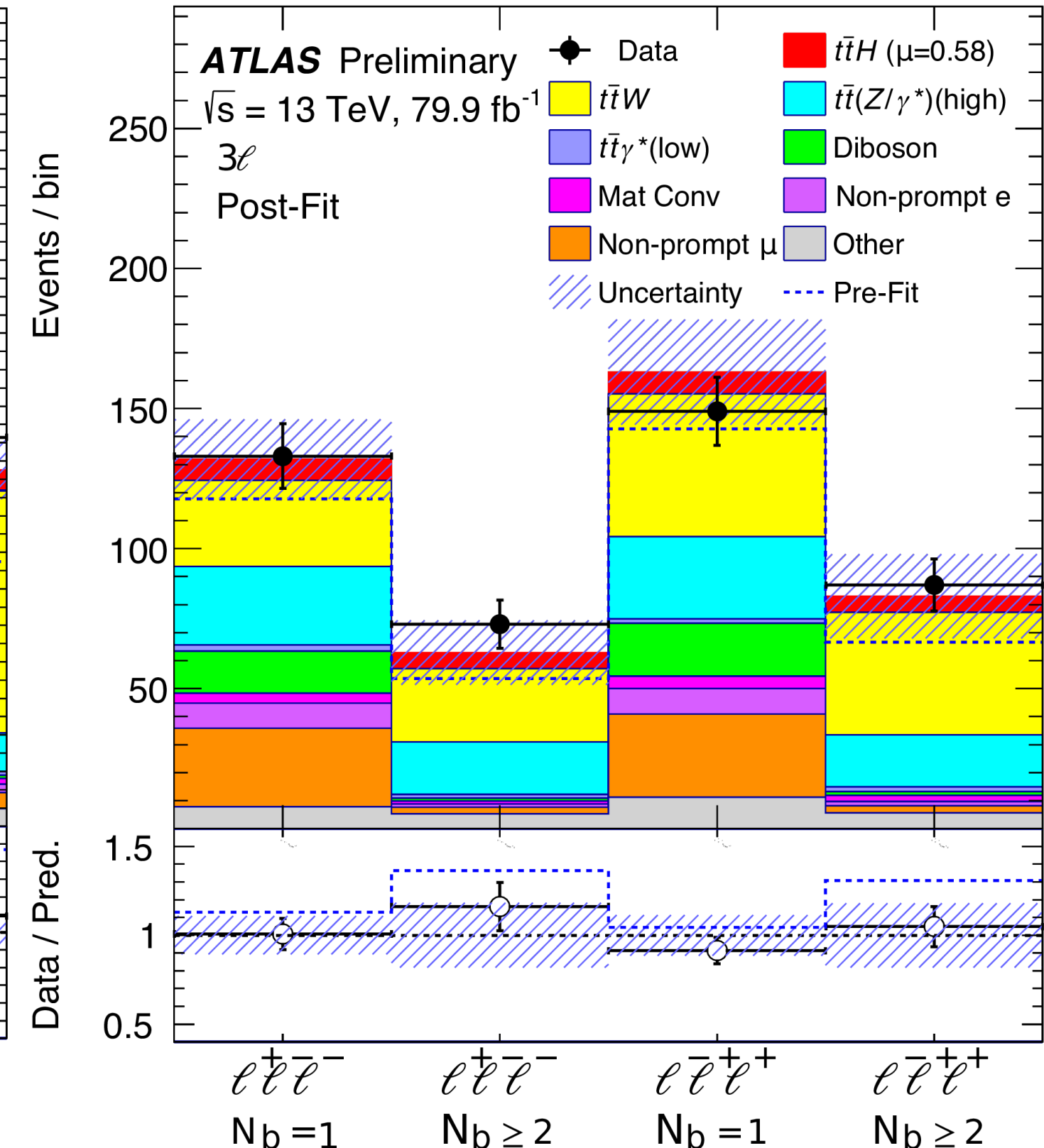
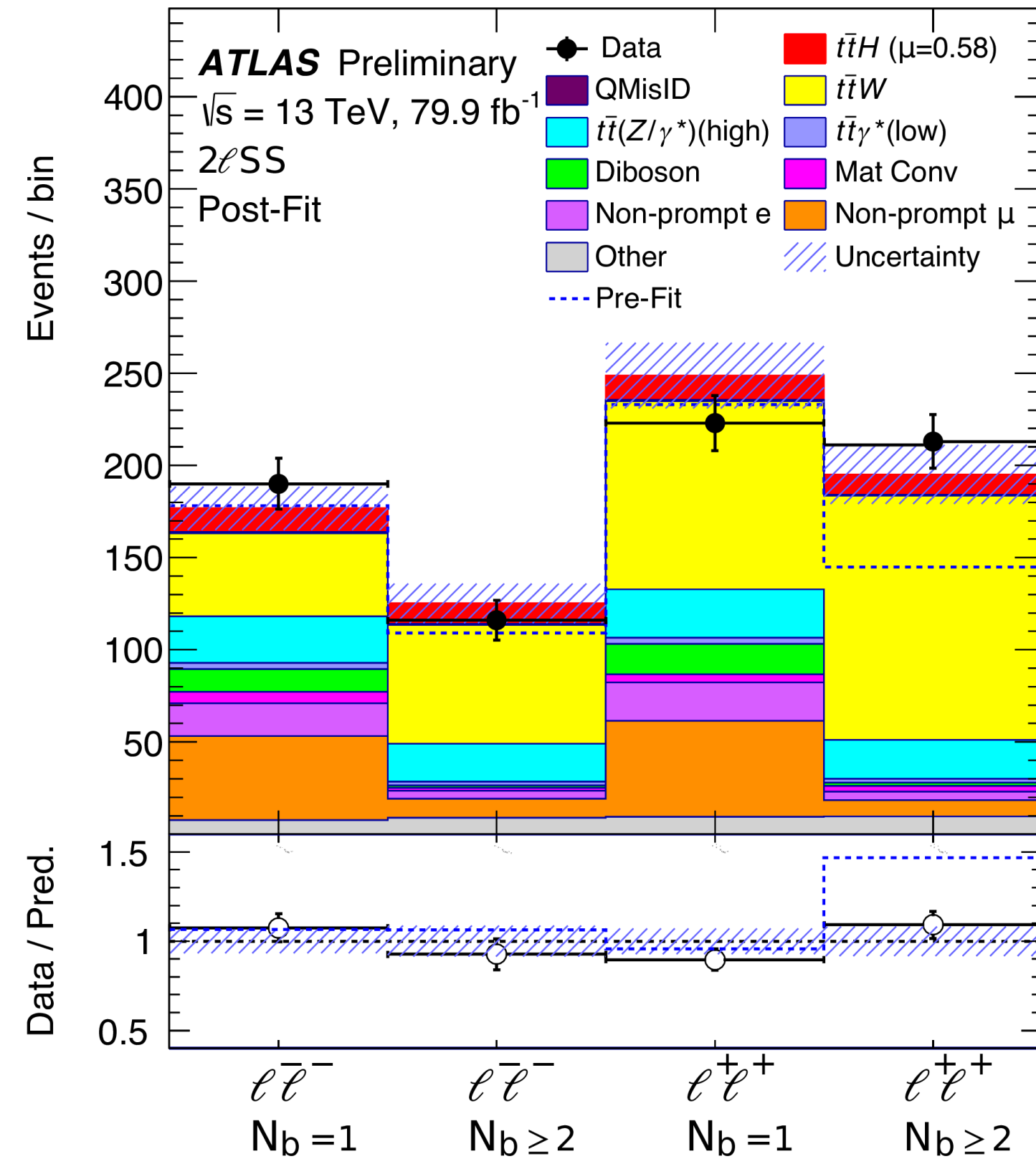
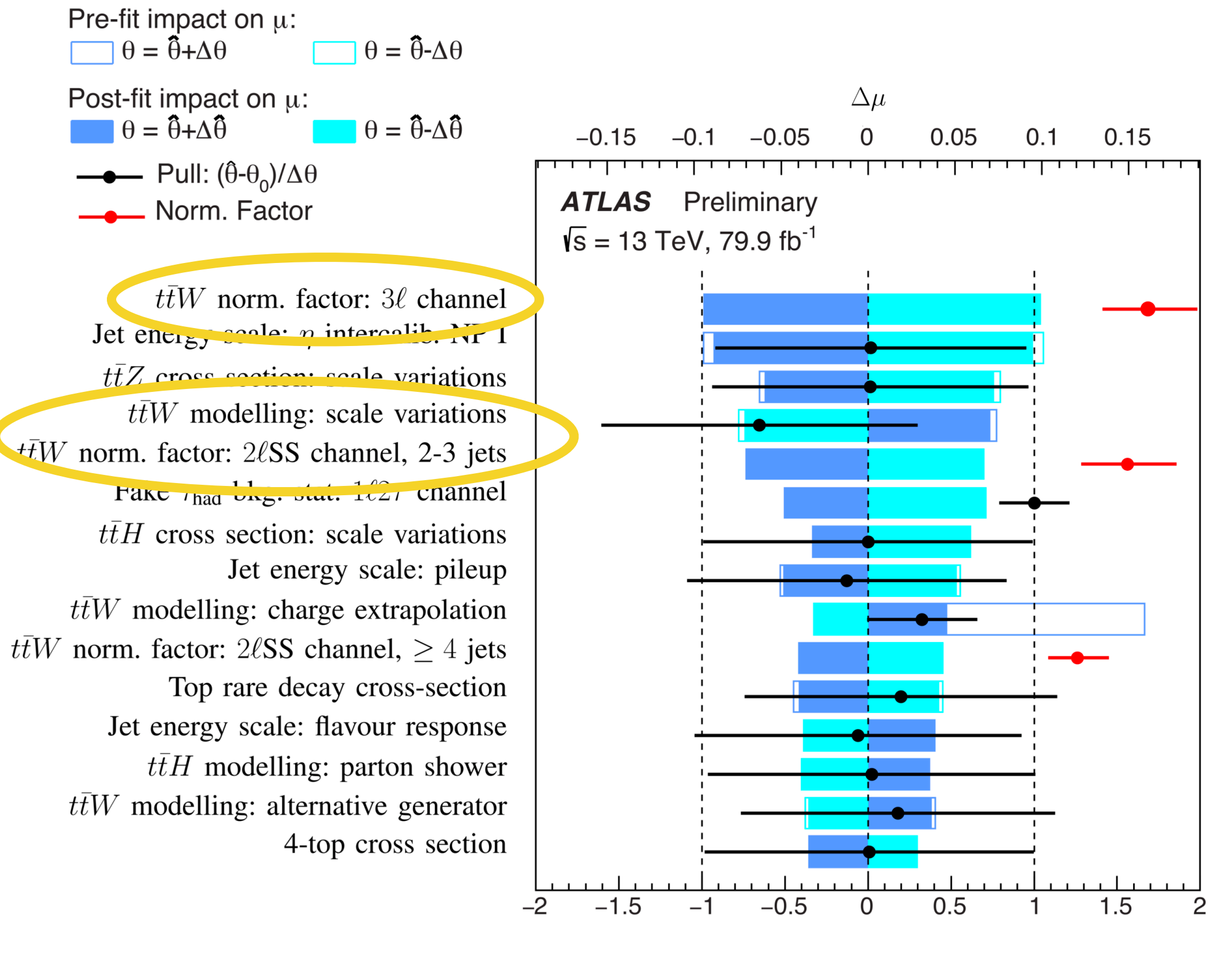


► Previous Run2 result

- NF(ttW) very high (~1.6)
- $\mu(\text{ttH})$ quite low (0.58)
- Observed significance: 1.8σ (expected 3.1σ)



► ttW also a dominant uncertainty:

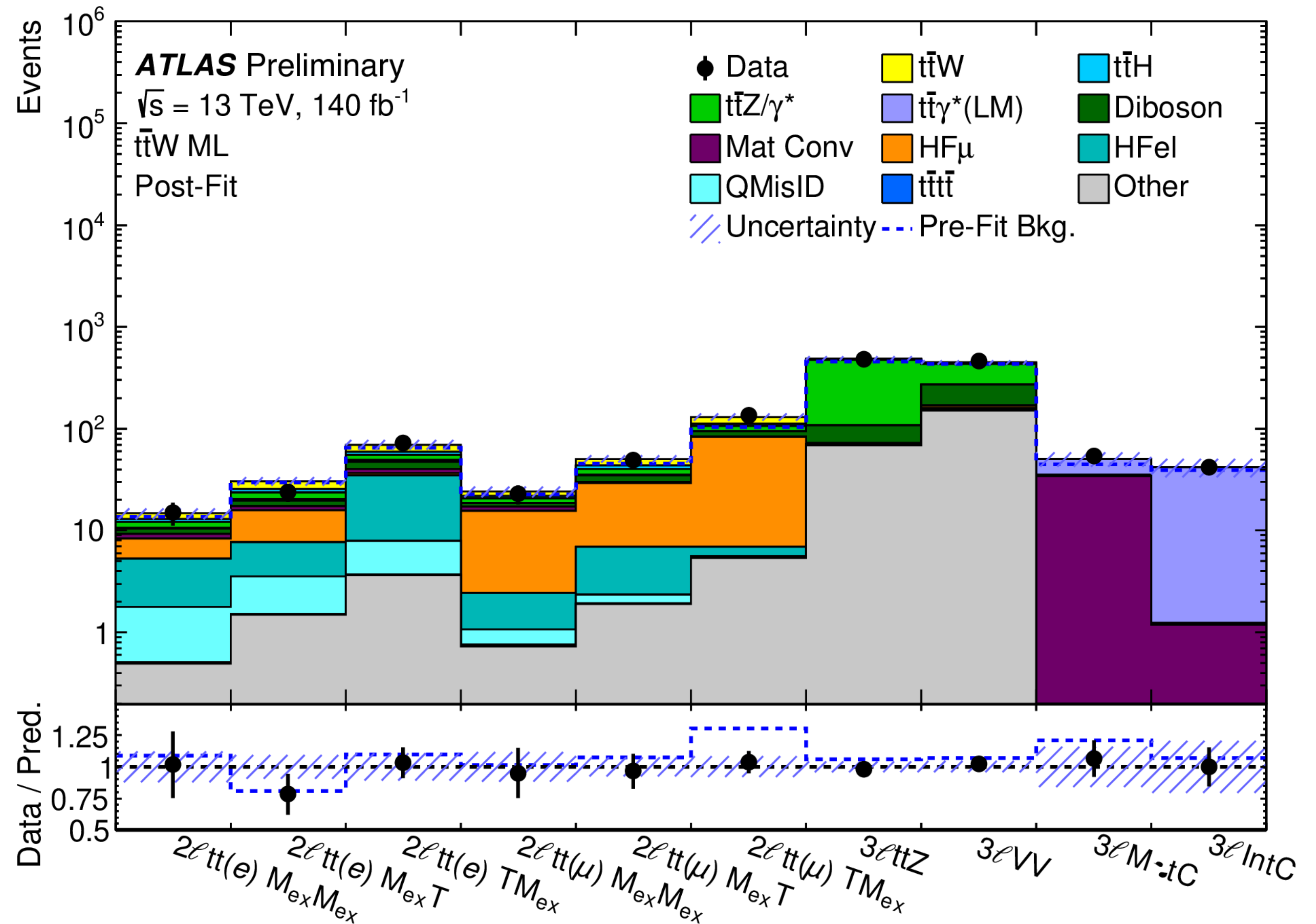
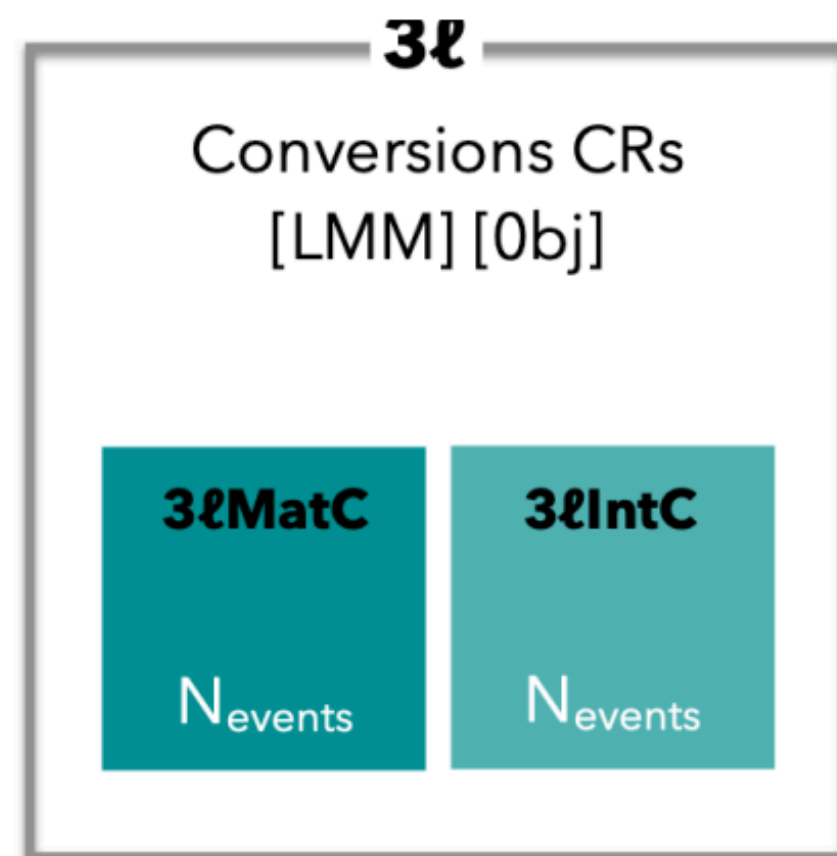
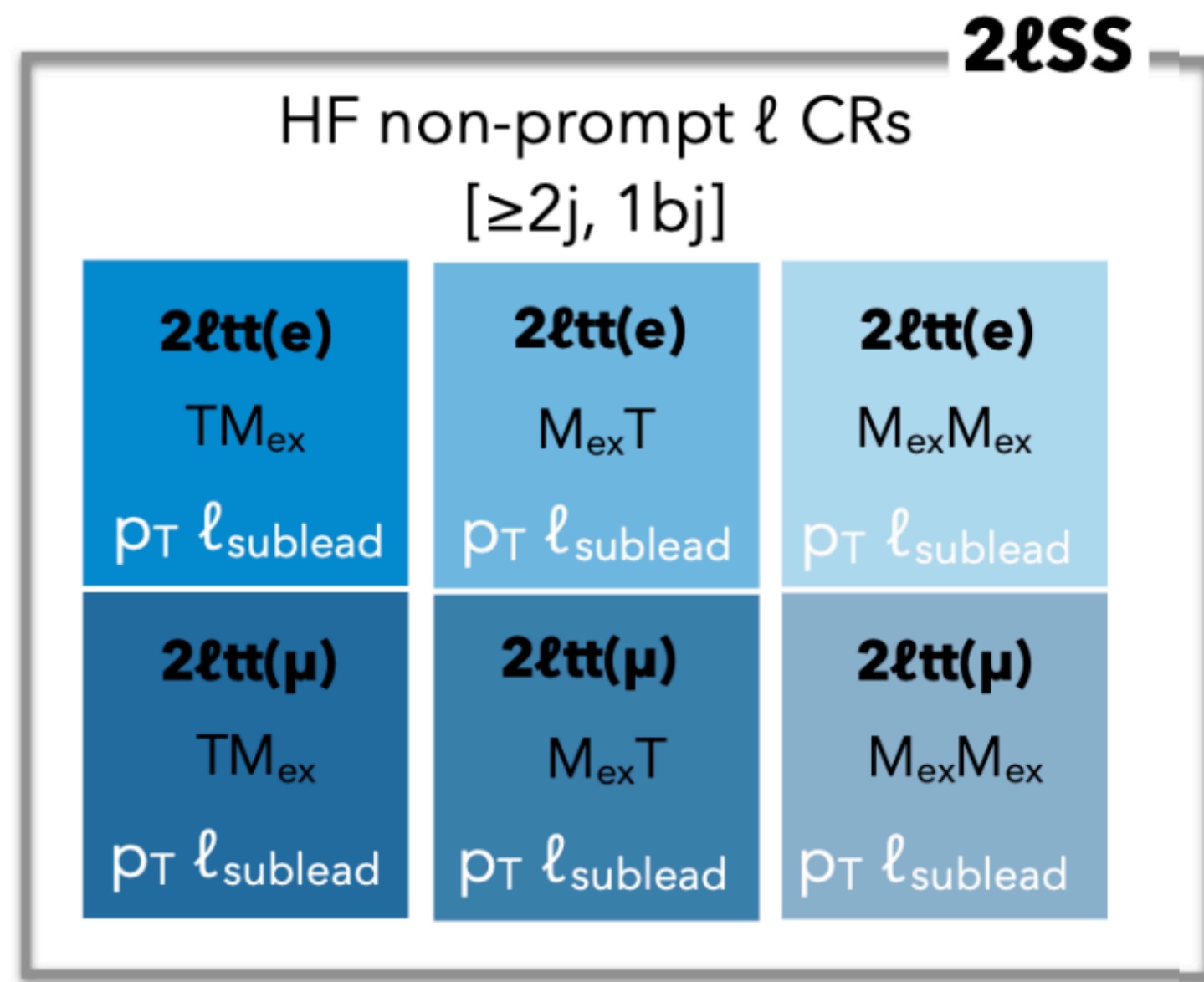


- ▶ Decided that dedicated differential ttW measurement was needed

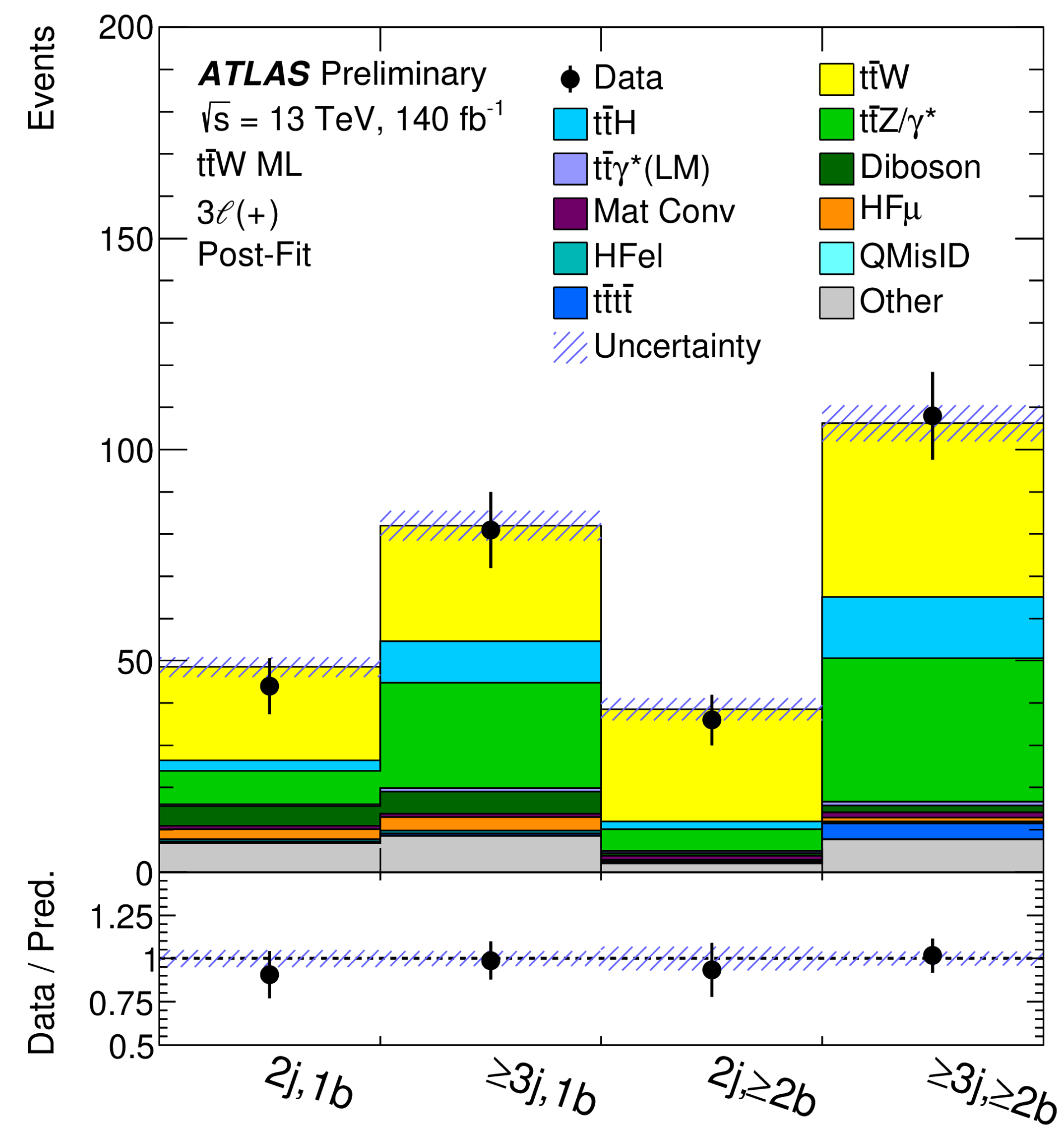
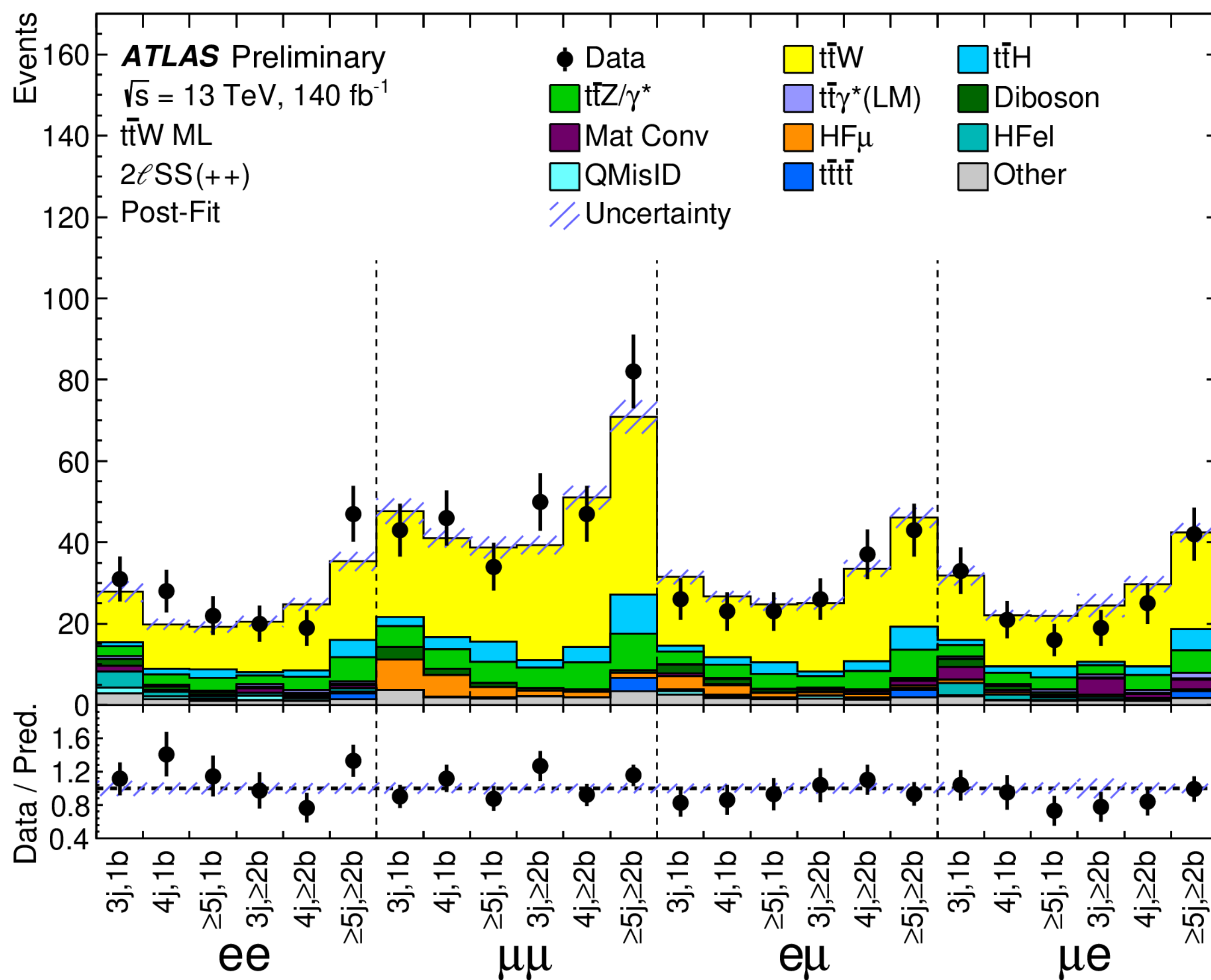


ttW | Background estimation

► Background estimate through "Template fit"



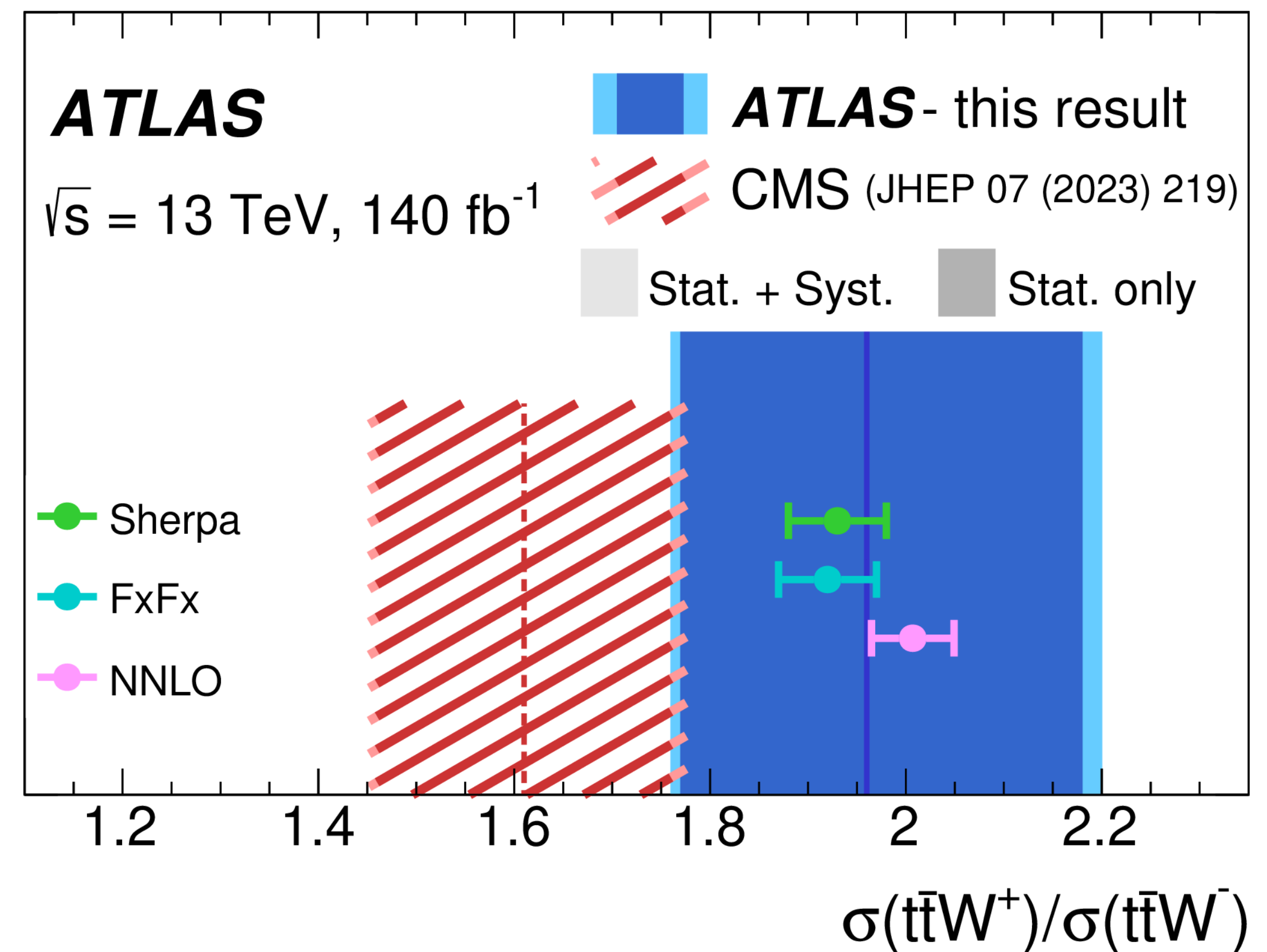
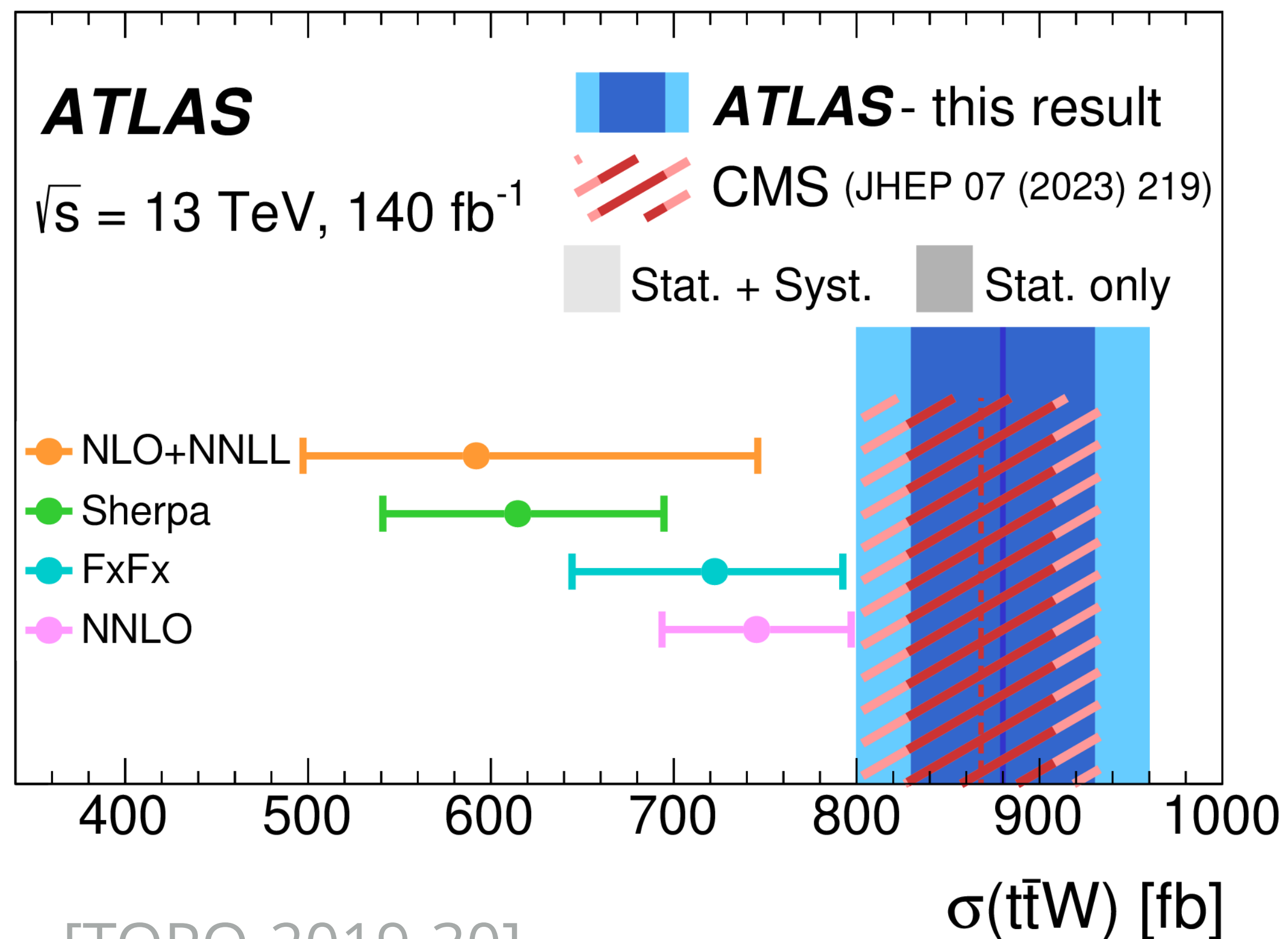
- Split by Njets, Nb and lepton charge and lepton flavour = 48 SS + 8 3L SRs





ttW | Inclusive XS and charge ratio

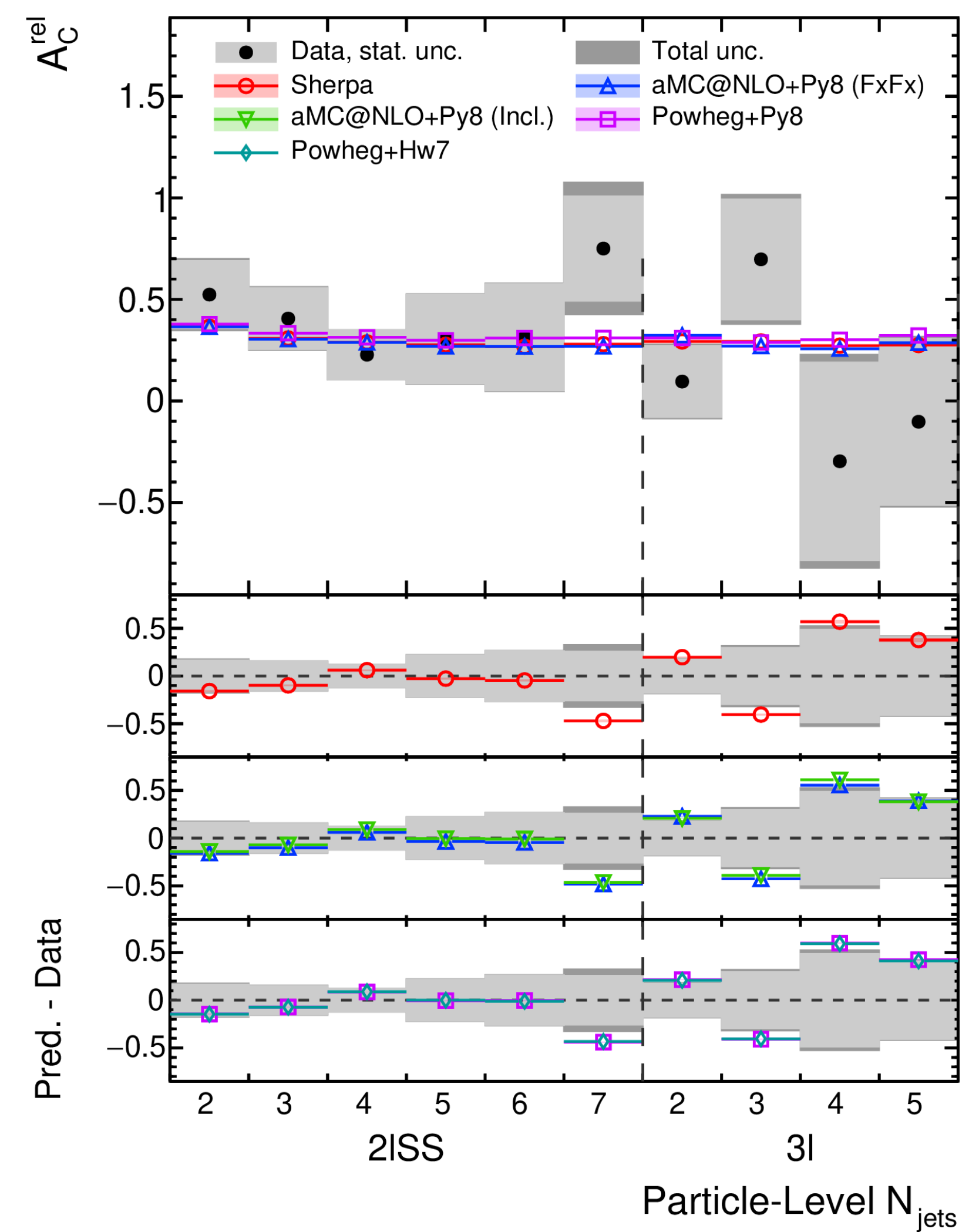
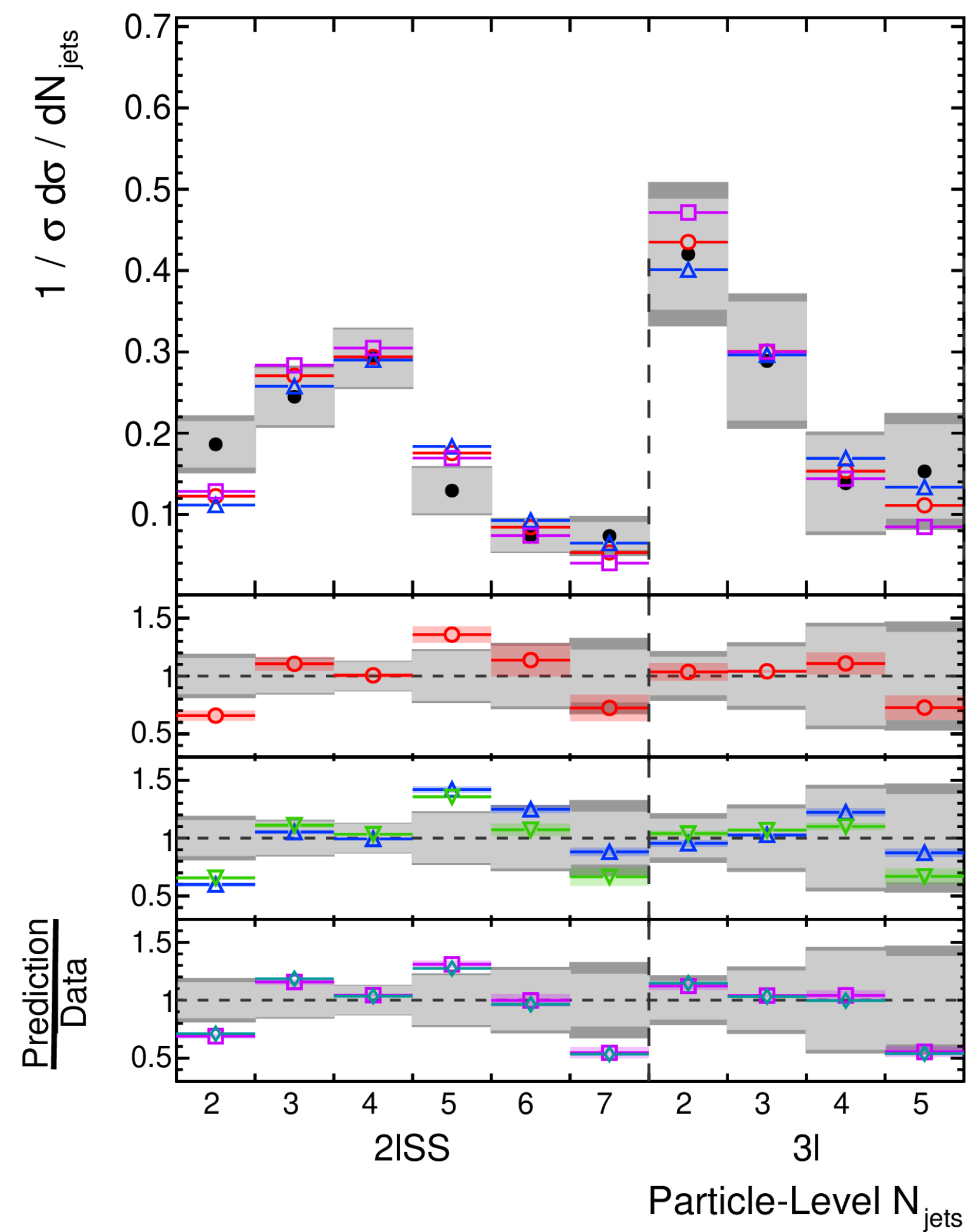
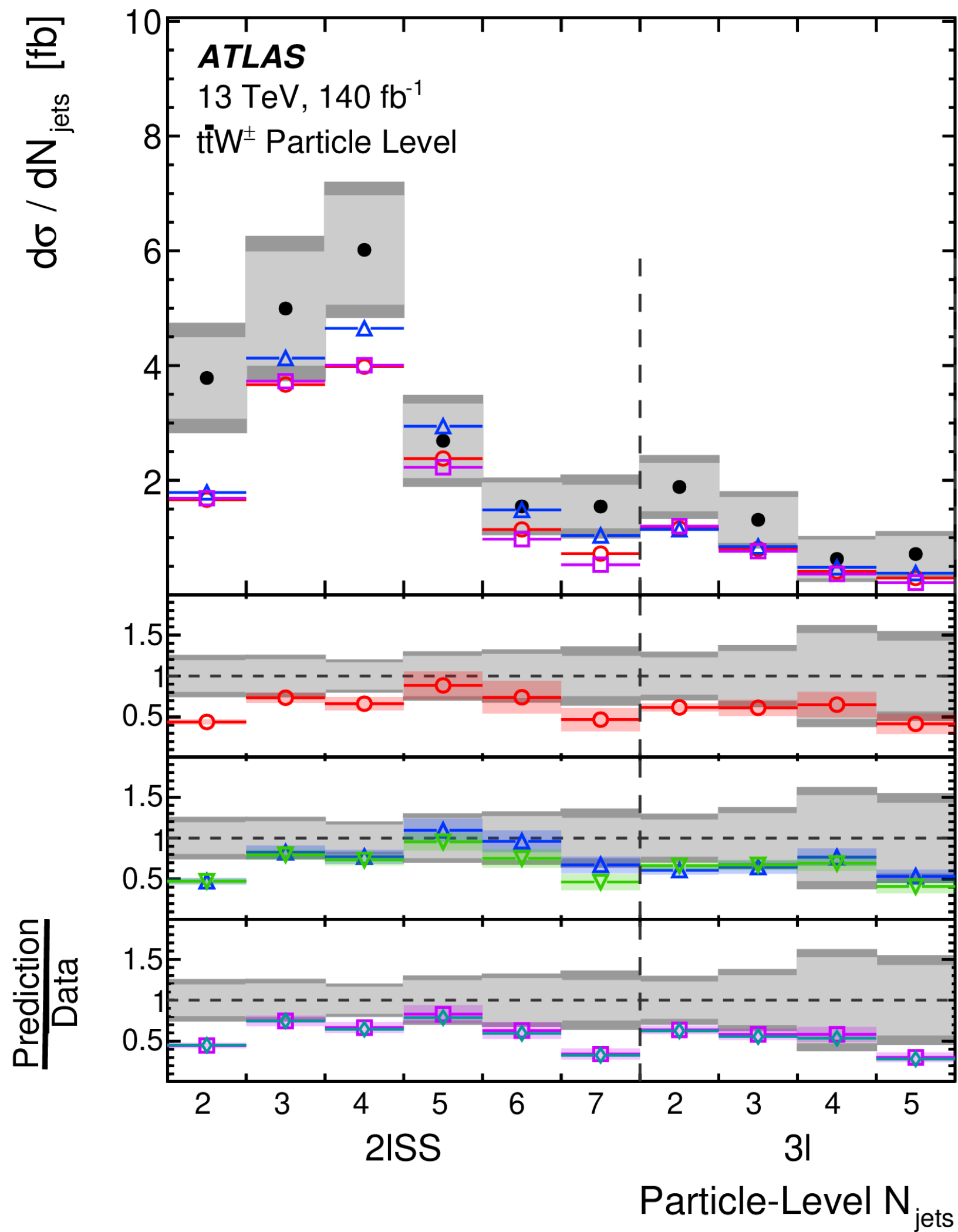
- ▶ $\sigma(\text{ttW}) = 890 \pm 50 \text{ (stat)} \pm 70 \text{ (syst) fb}$ (9% relative uncertainty)
- ▶ **New (approx.) NNLO calculation (2306.16311):** $\sigma(\text{ttW})=745 \text{ fb}$, $\mu(\text{ttW})=1.20$ (Sherpa=1.48)
- ▶ $\sigma(\text{ttW}+)/\sigma(\text{ttW}-) = 1.95 \pm 0.21 \text{ (stat)} \pm 0.16 \text{ (syst)} \rightarrow$ consistent with SM



[TOPQ-2019-30]

ttW | Differential njets

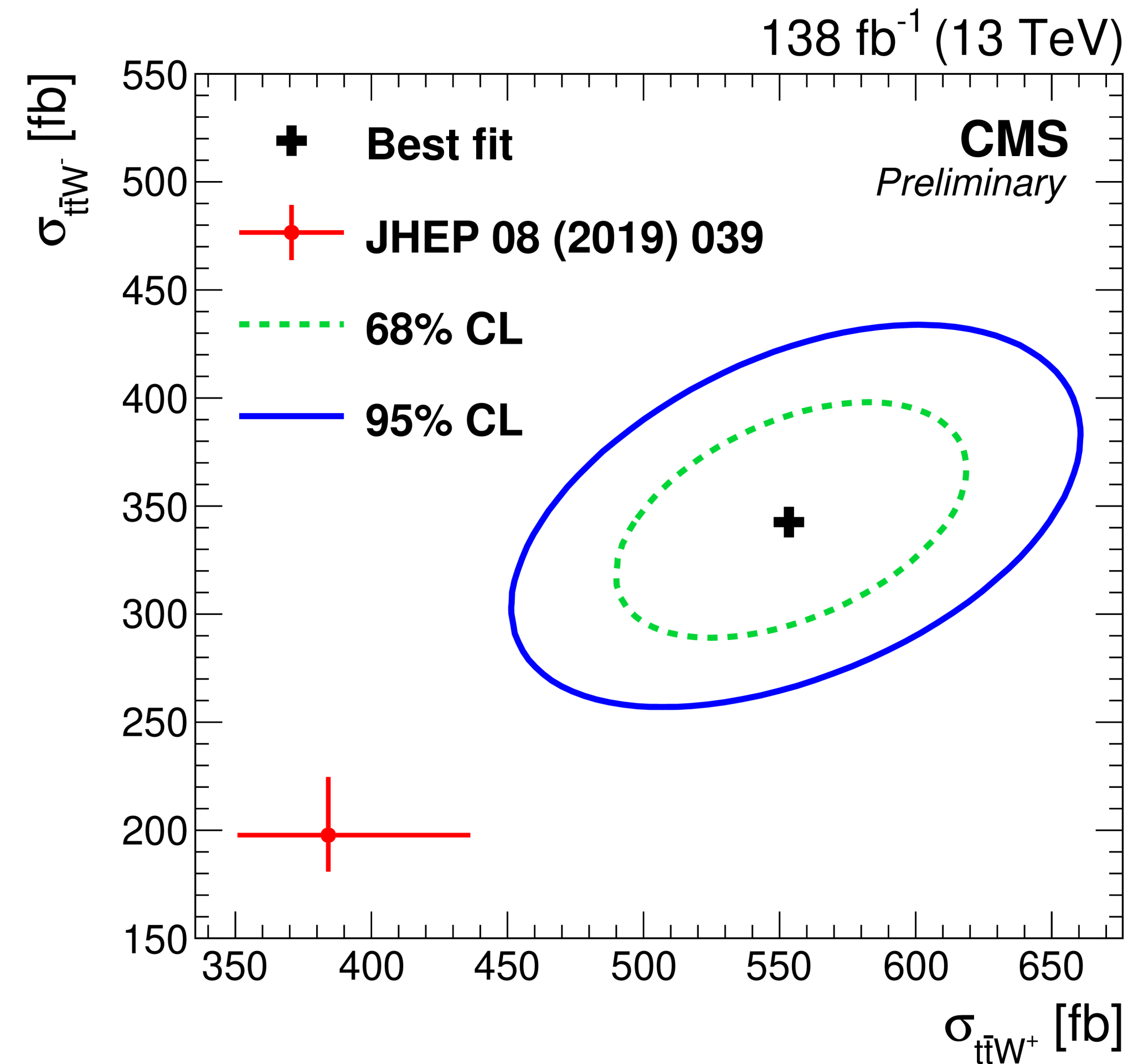
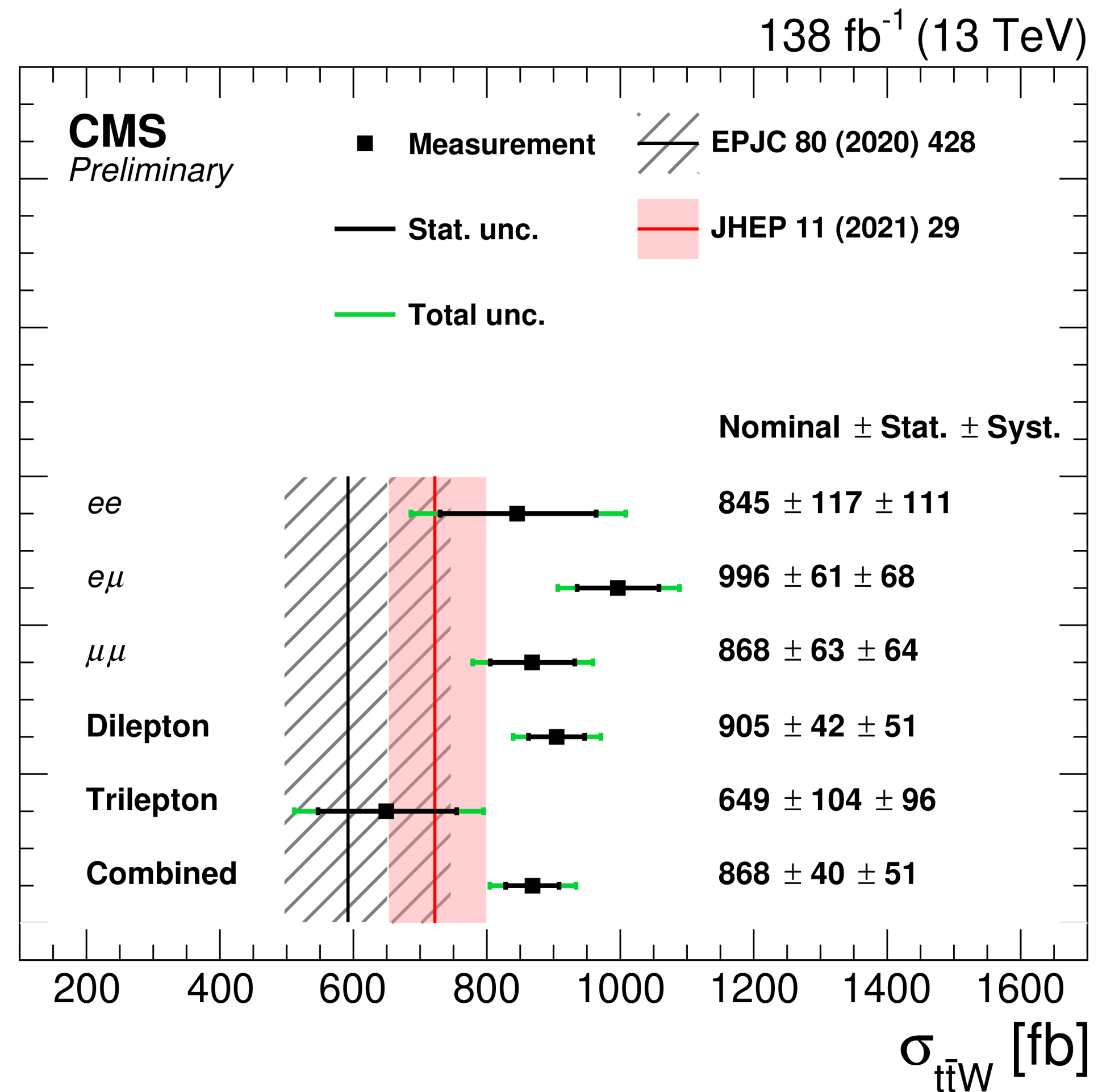
► Unfold 9 observables. Showing here njets:



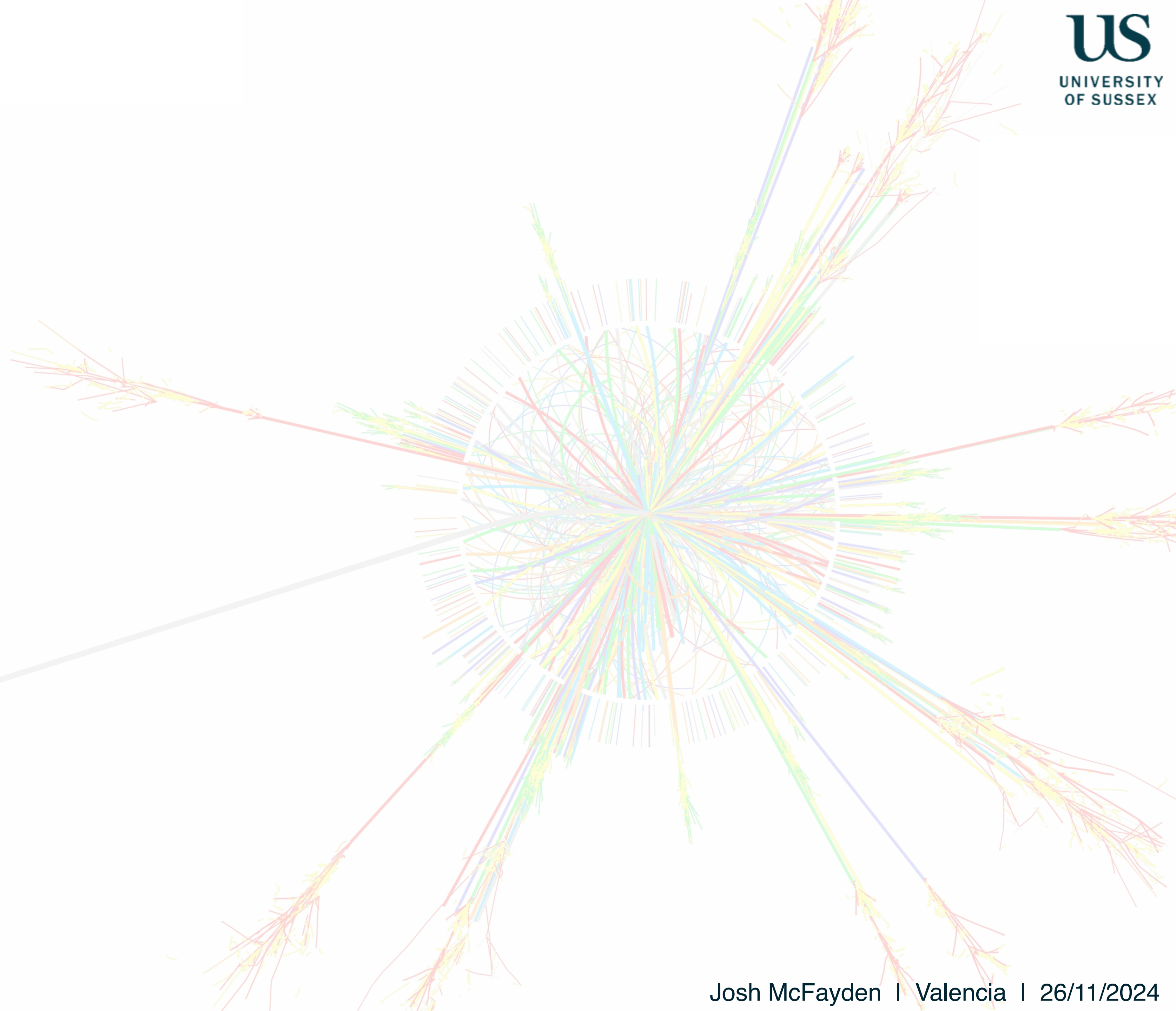
[TOPQ-2019-30]



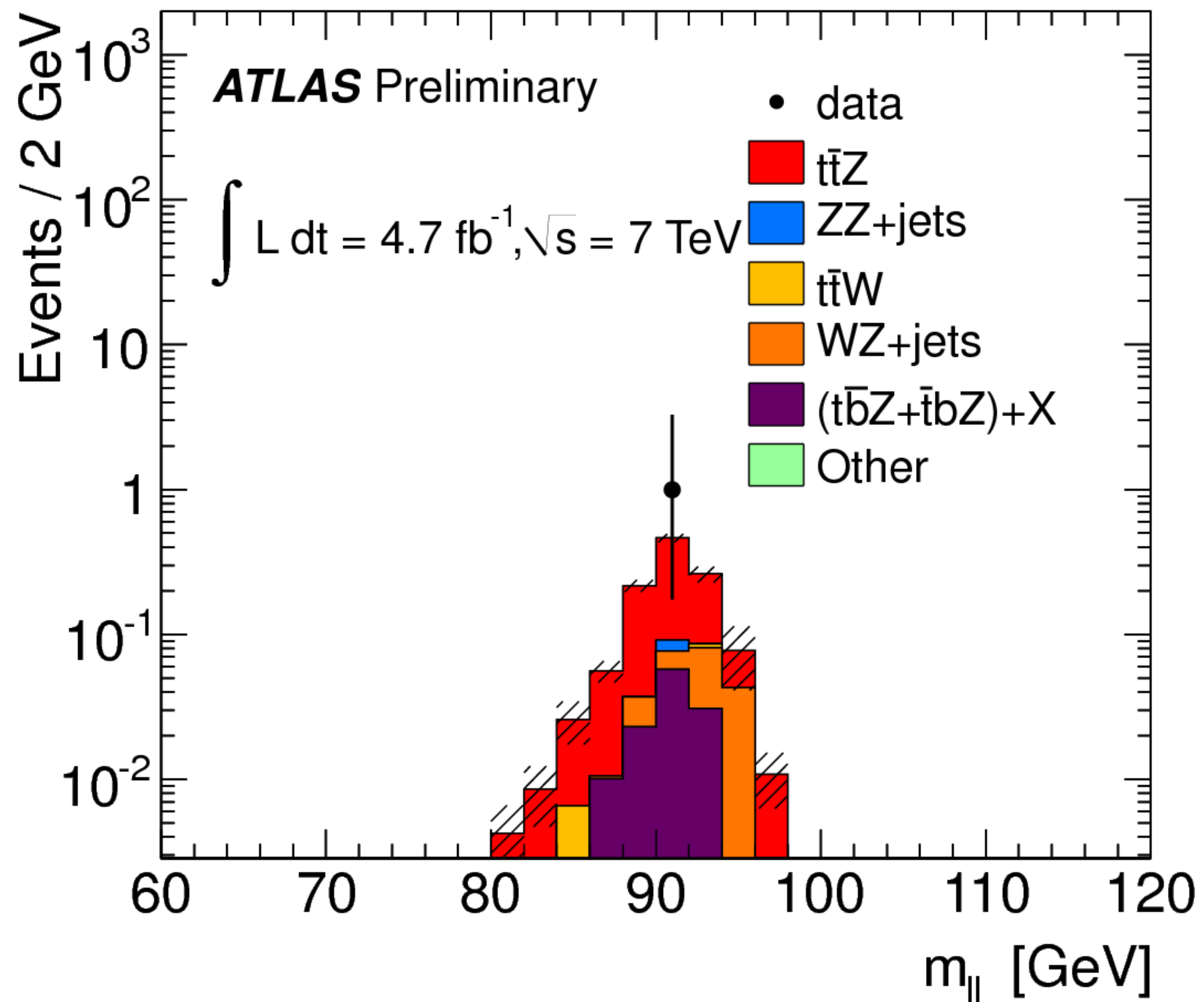
- CMS have full Run 2 inclusive result
- But not yet differential



ttZ



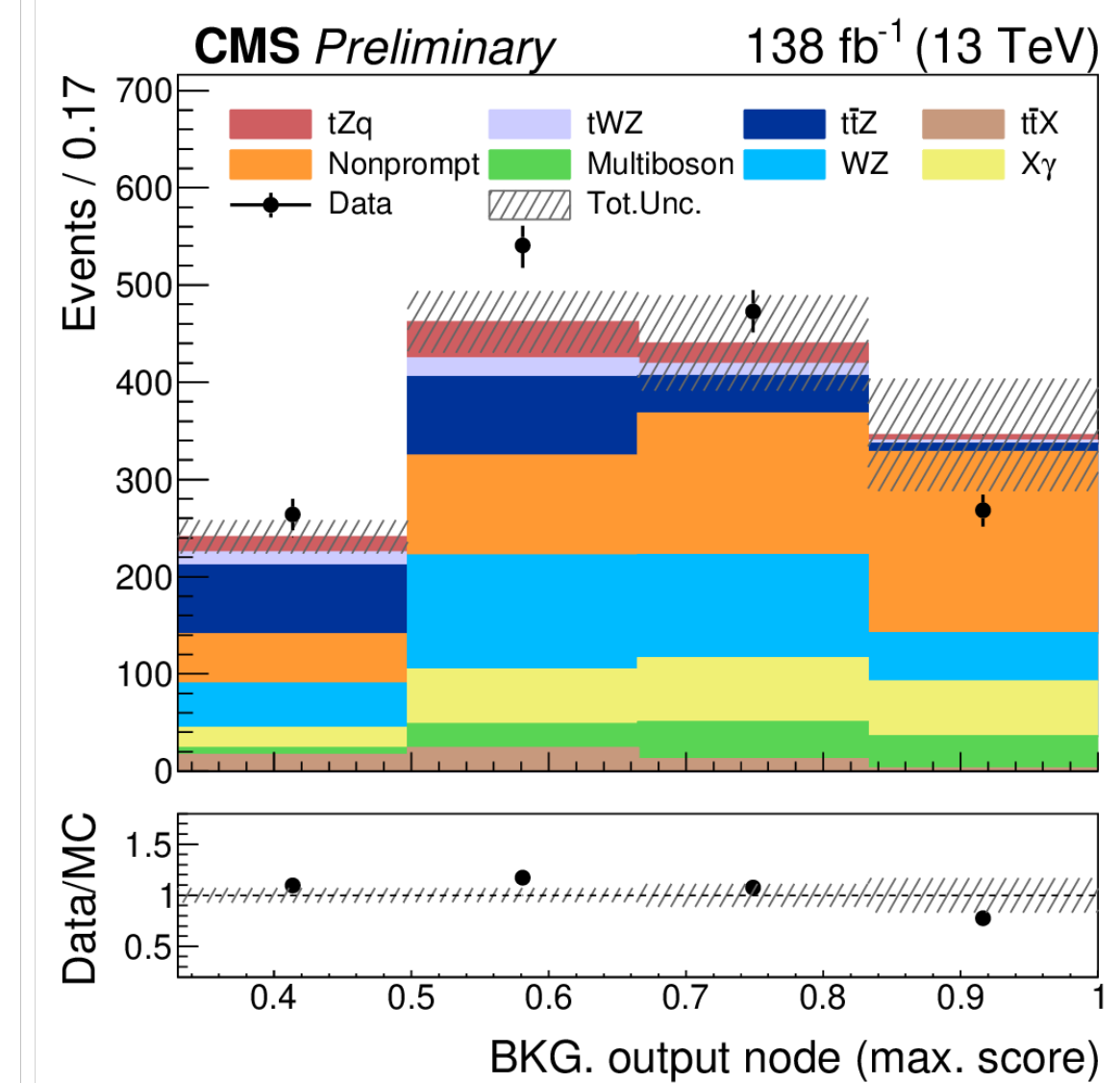
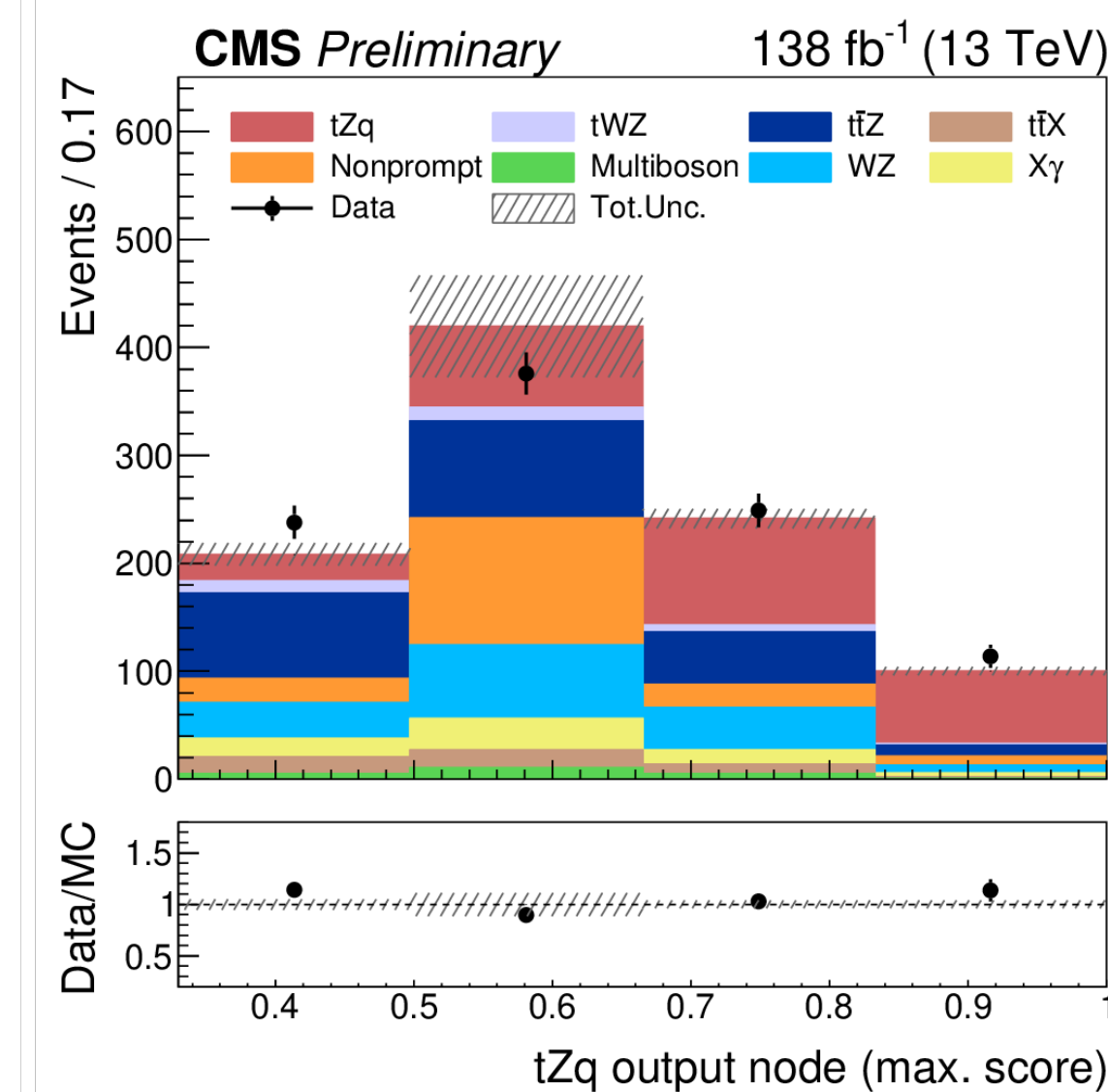
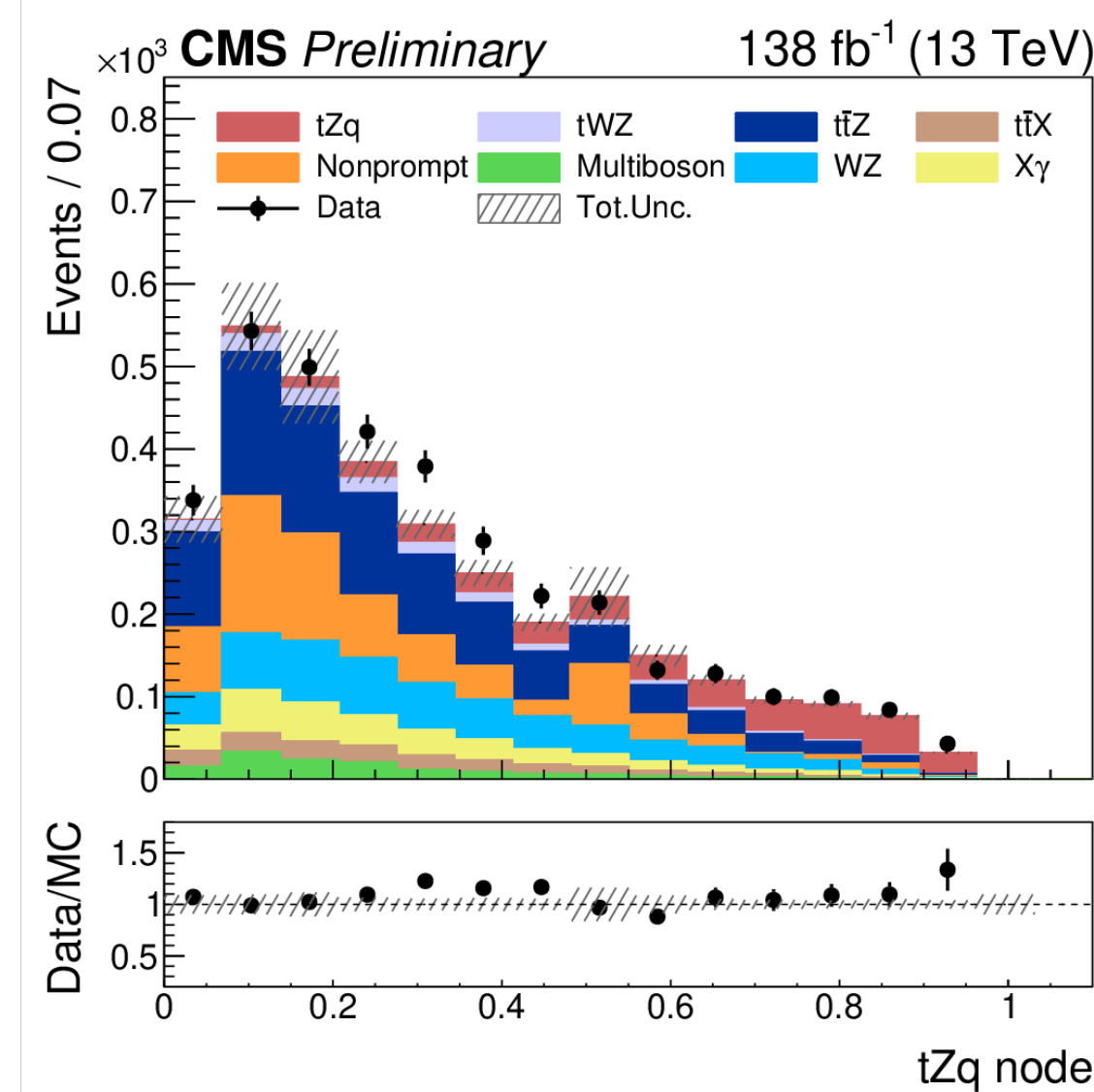
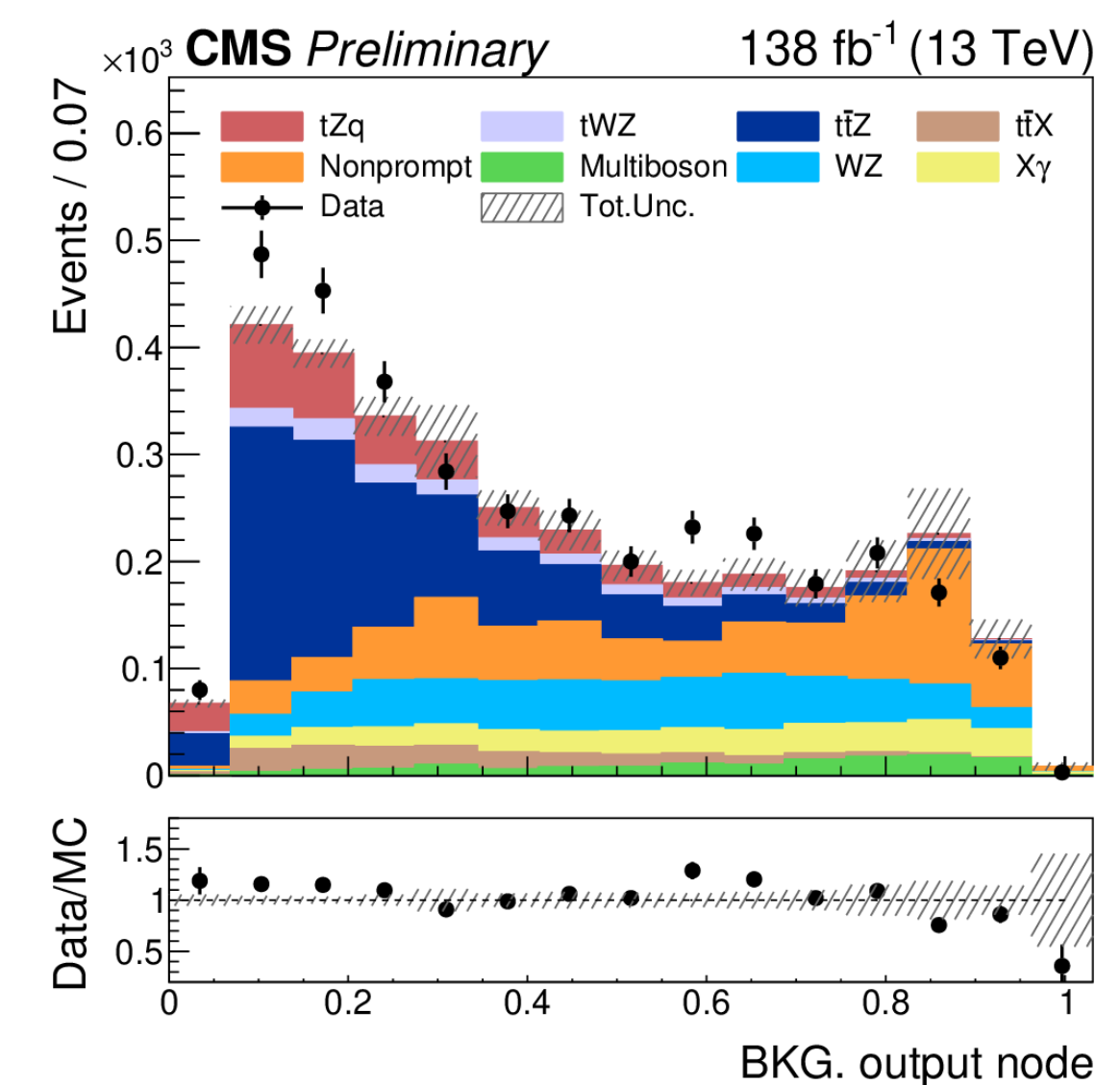
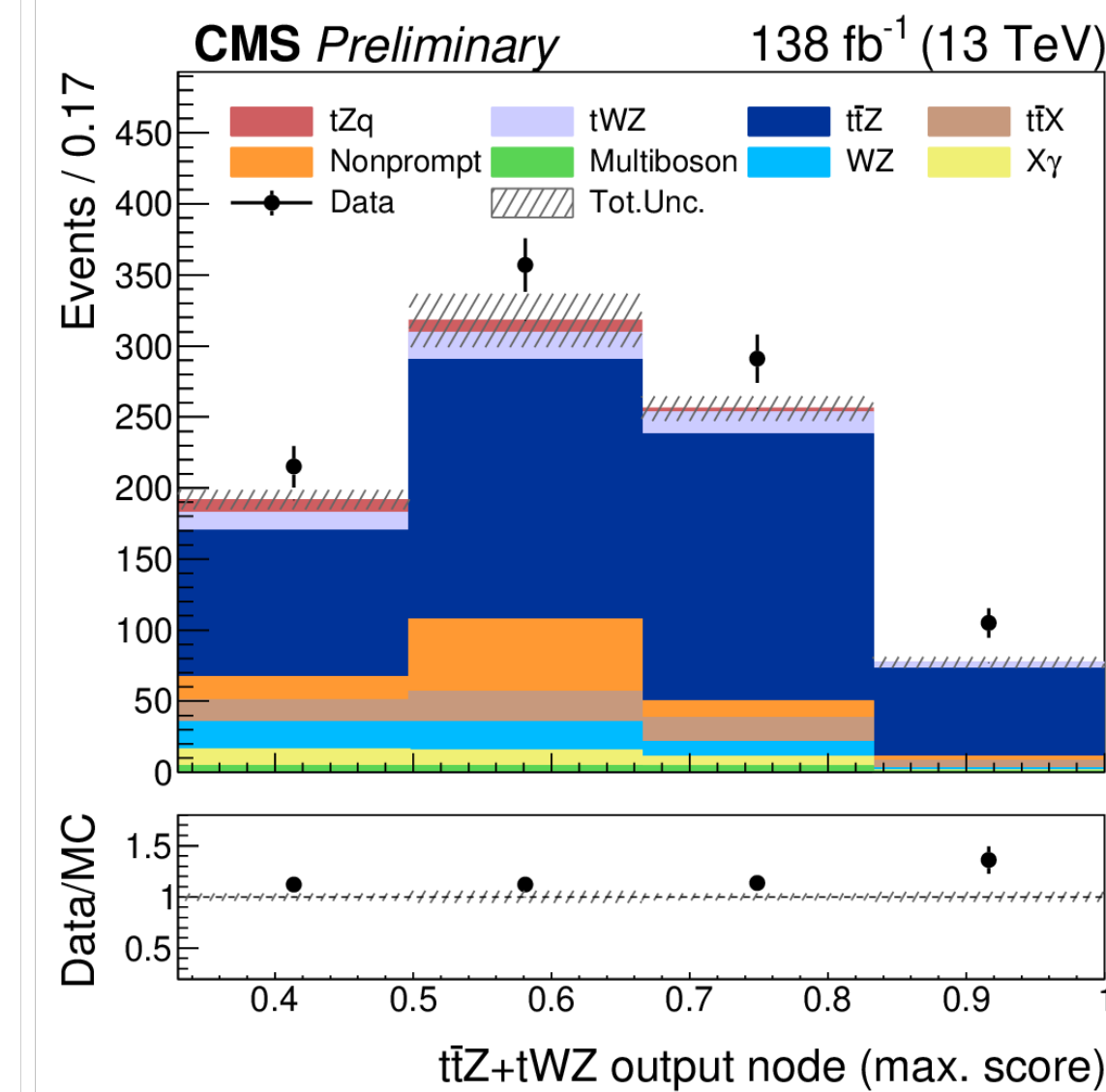
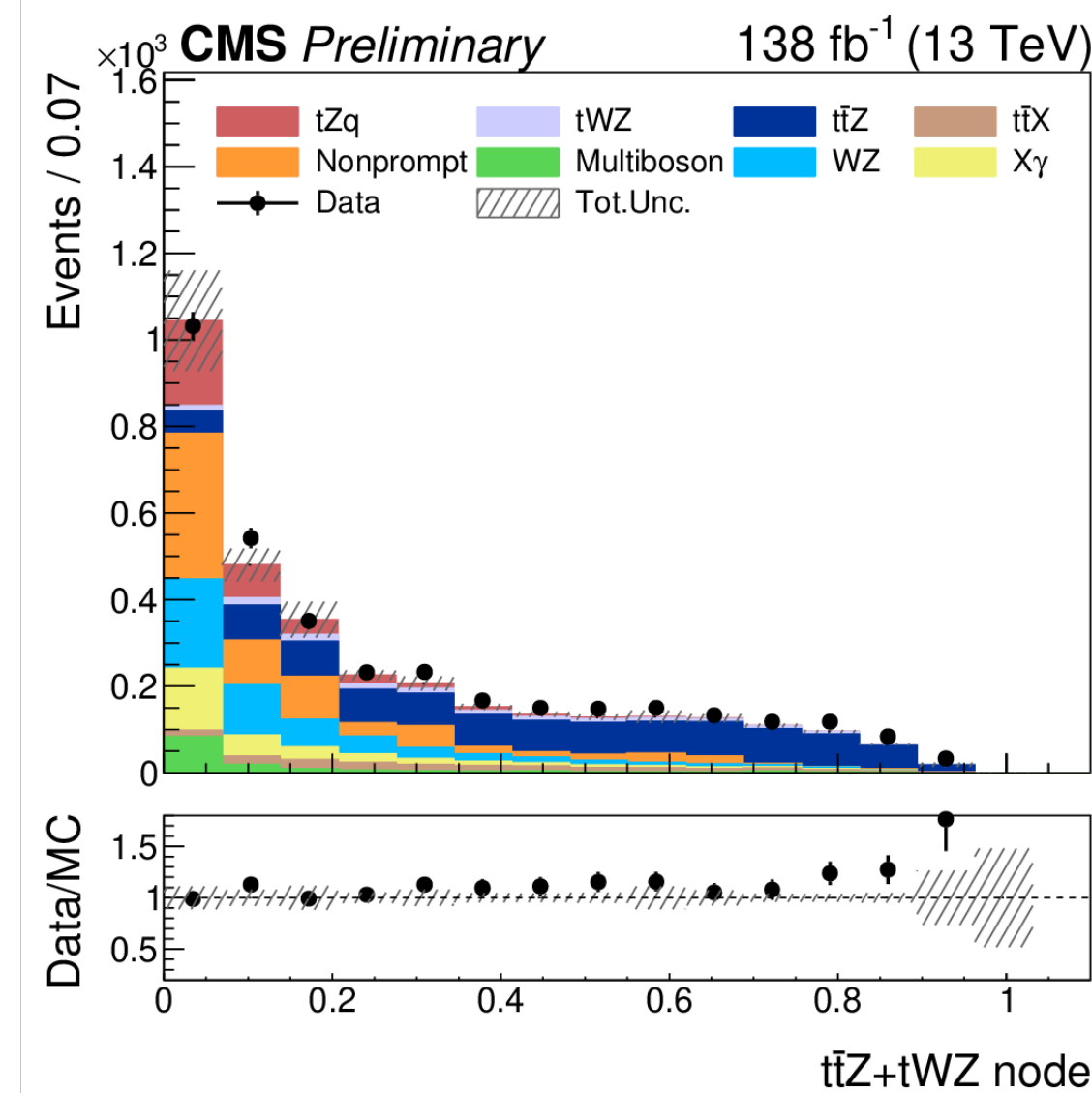
► How it started...





CMS $t\bar{t}Z+tZq$

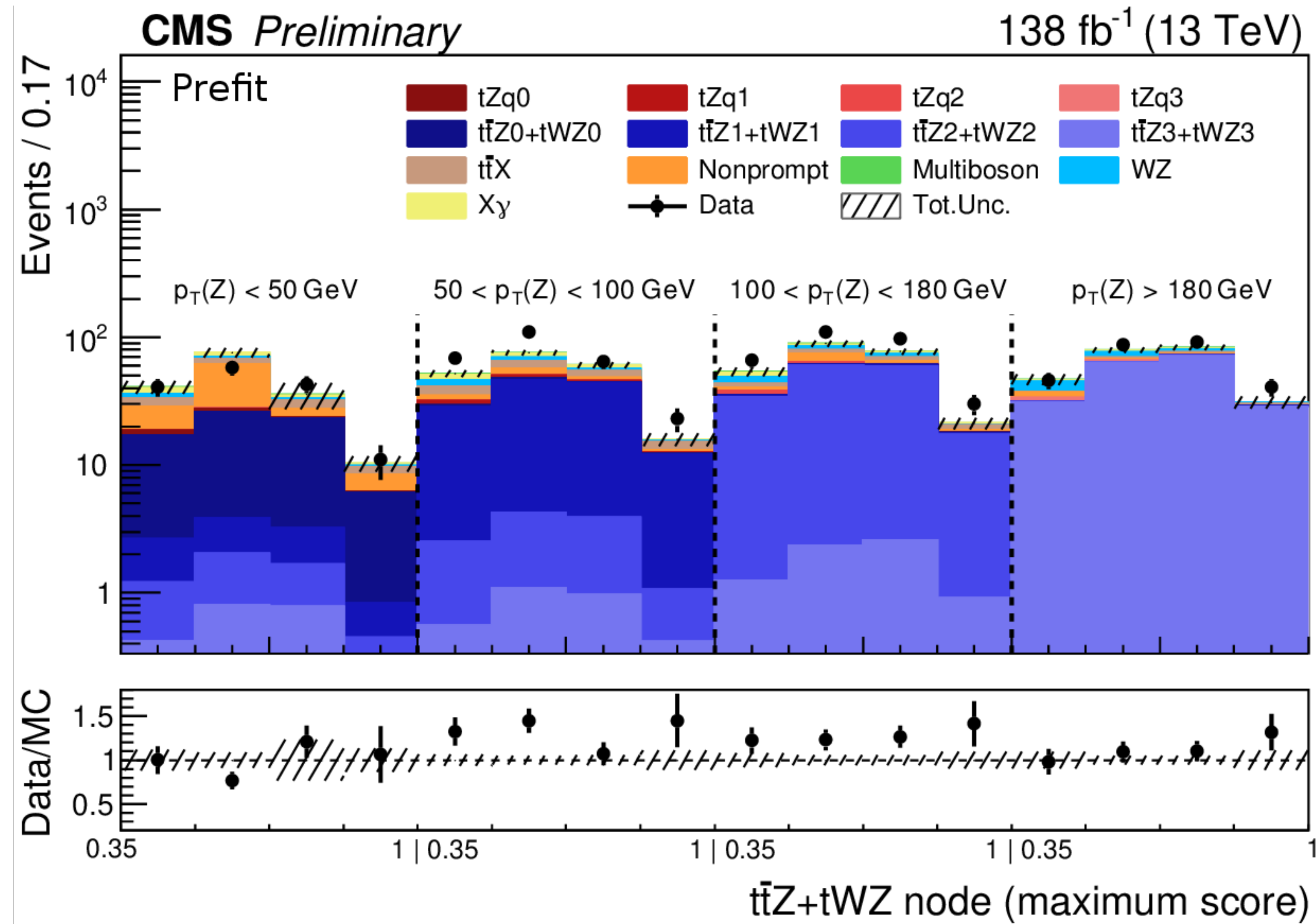
► How it's going...



[TOP-23-004]

► How it's going...

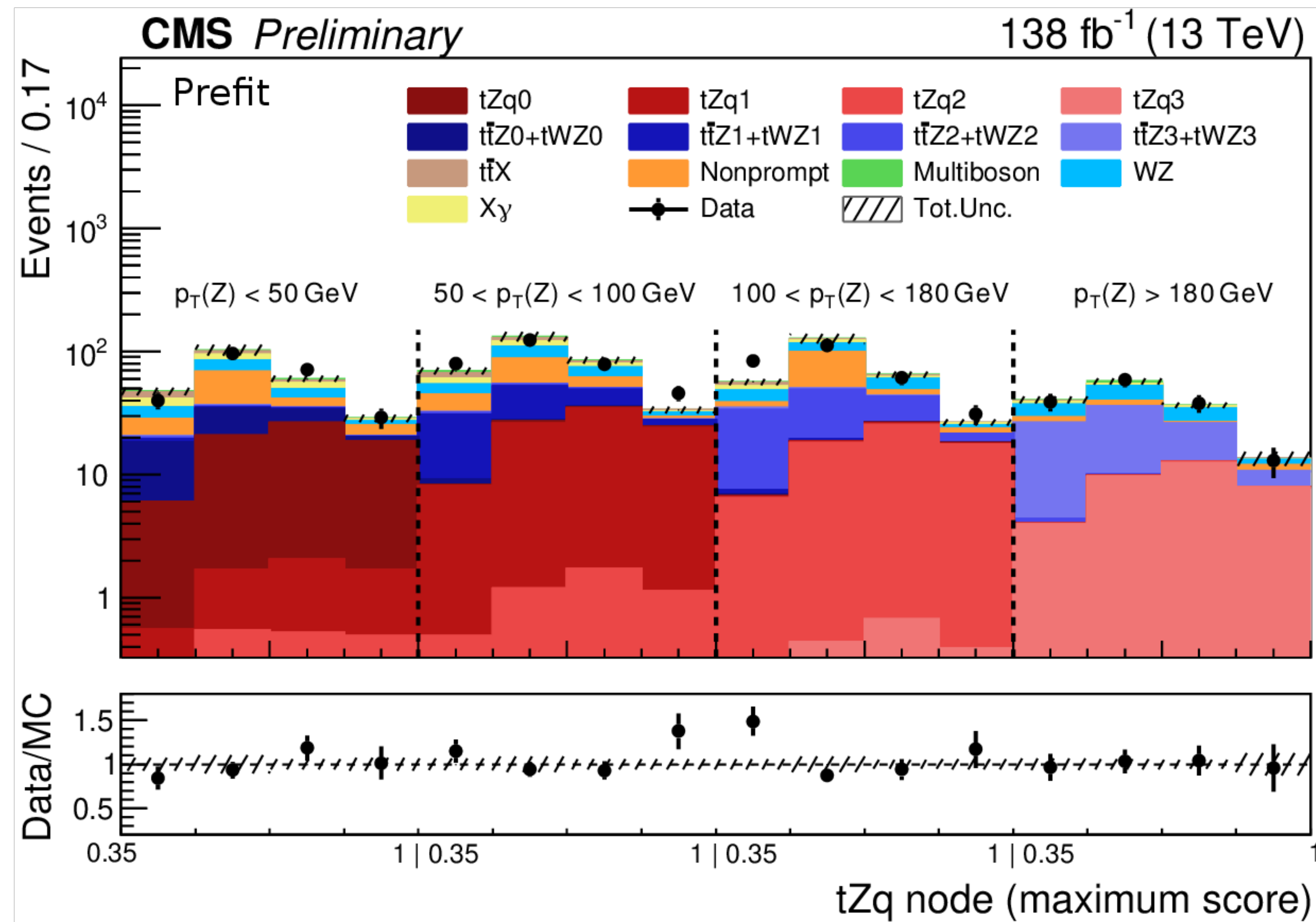
► Now possible to measure differentially ttZ



► How it's going...

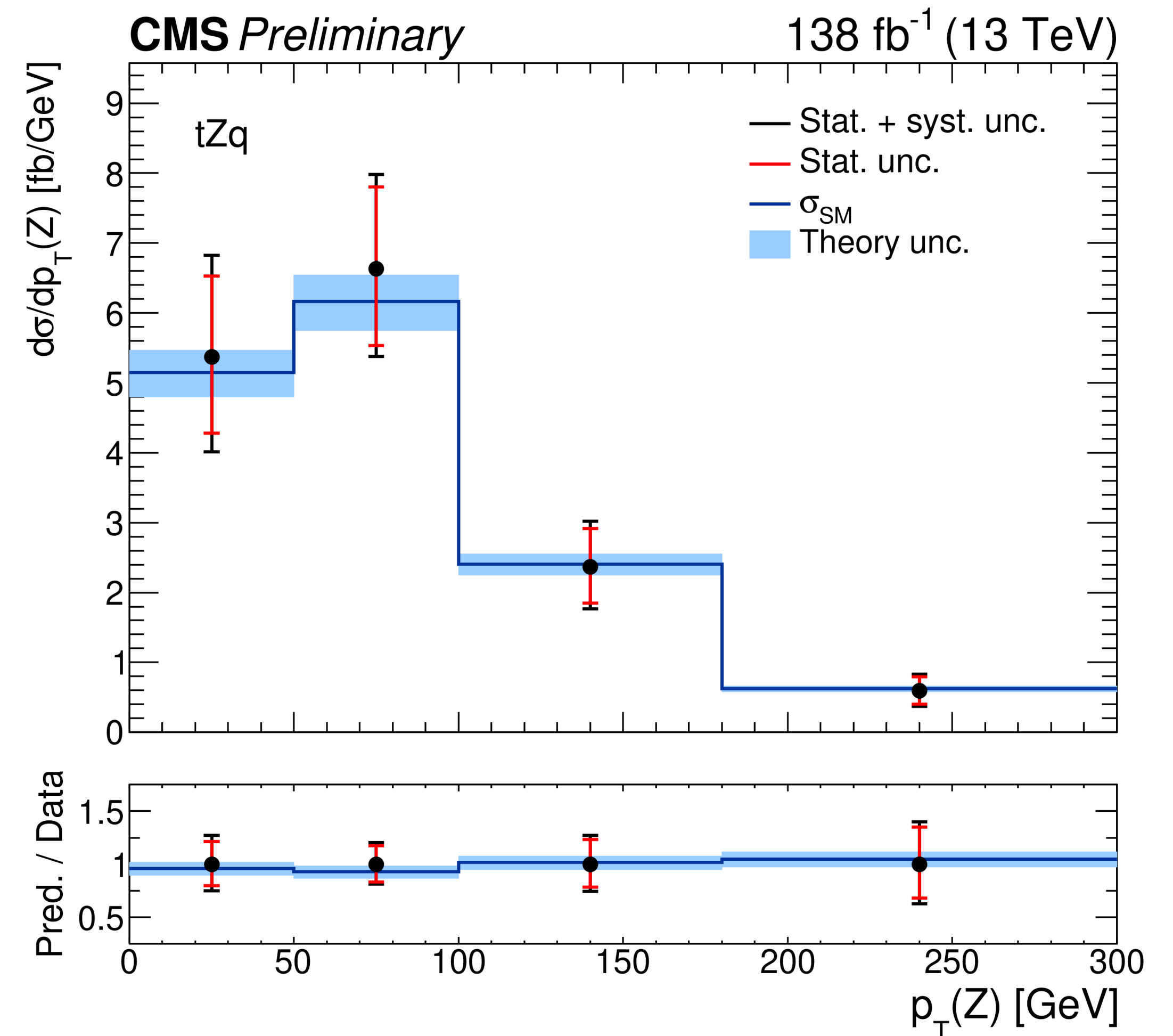
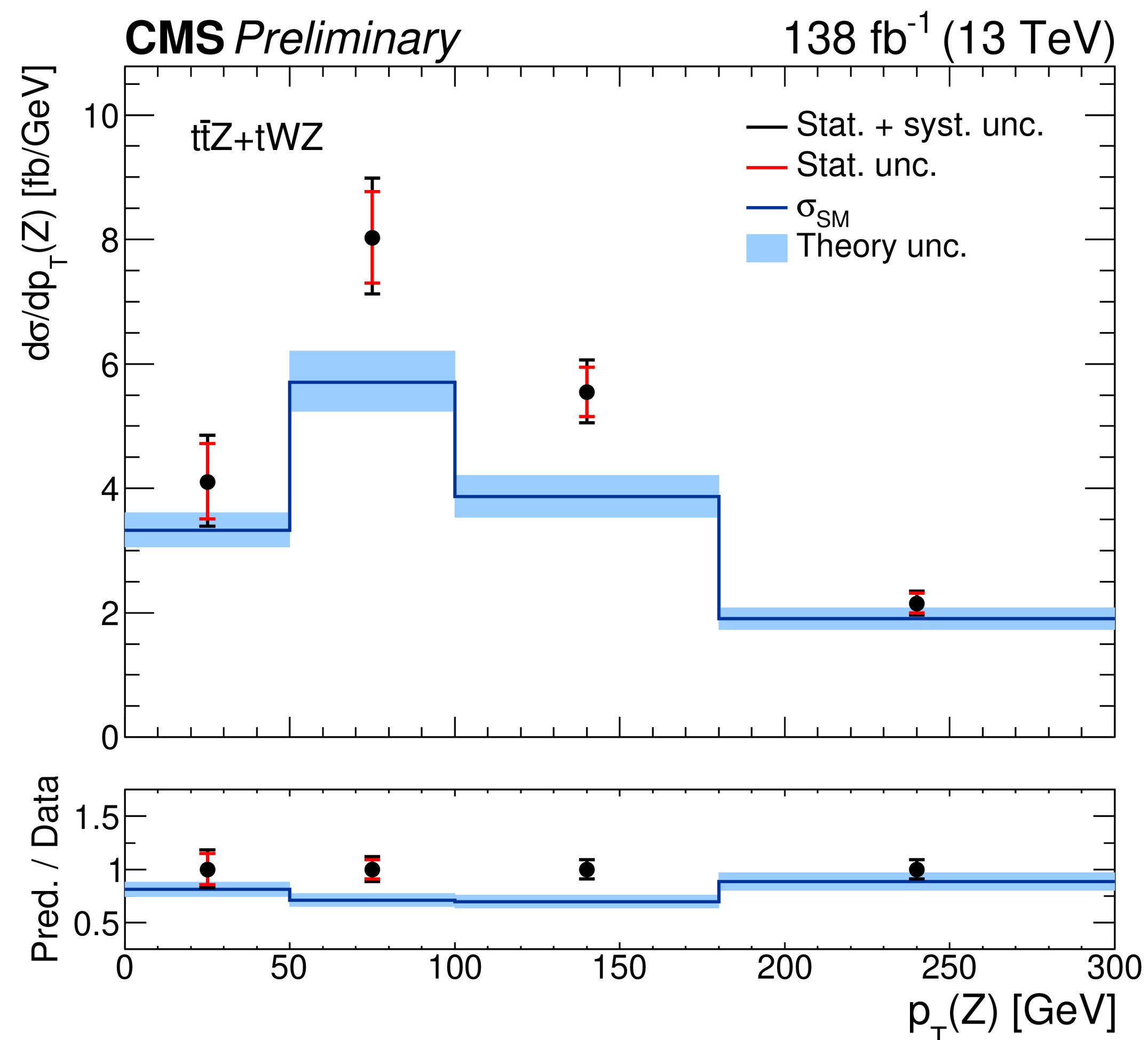
► Now possible to measure differentially ttZ

► And even tZq !





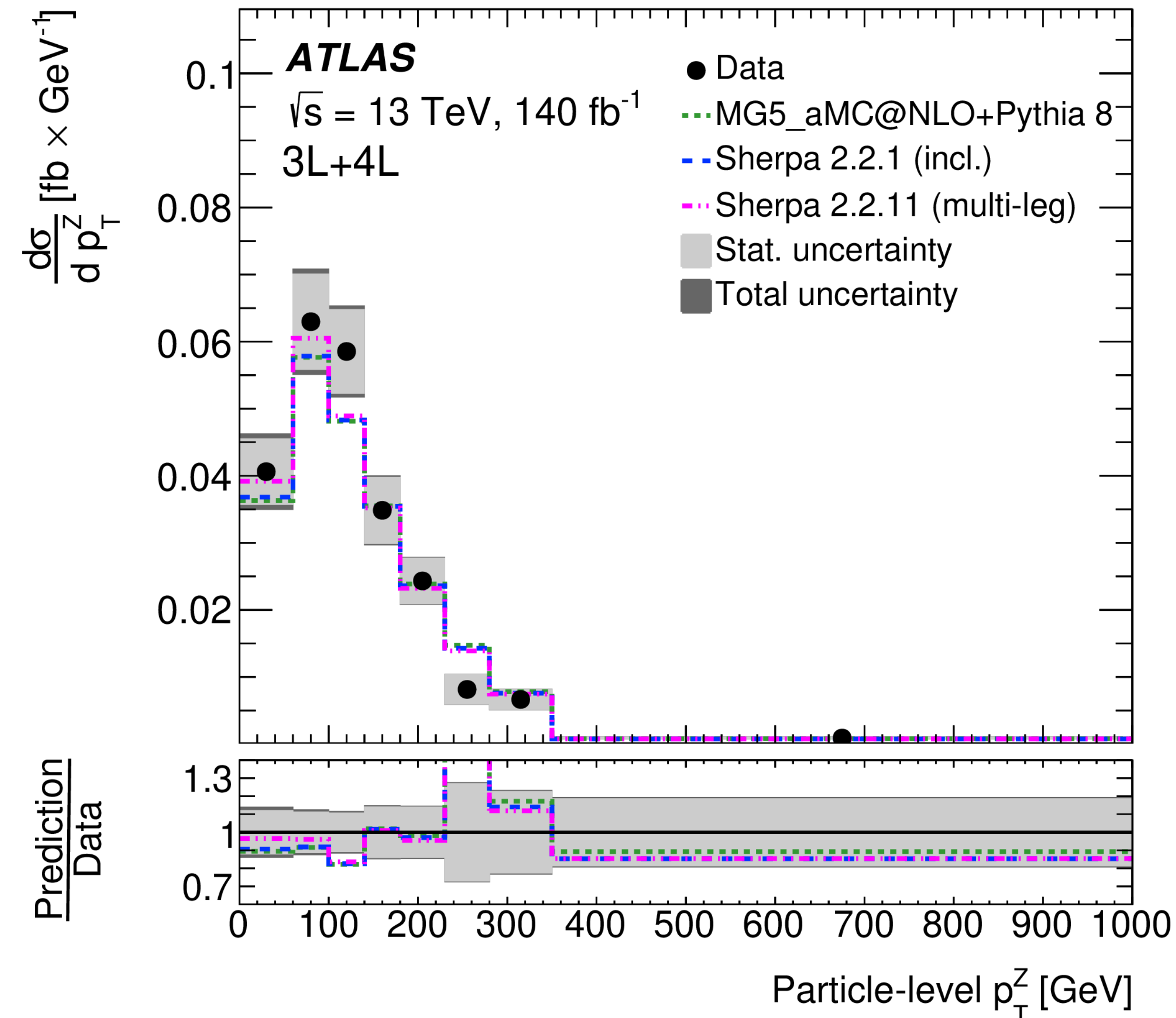
► Unfolded differential cross sections:





- ▶ ATLAS measurement with similar sensitivity
- ▶ ATLAS and CMS both achieve ~6% uncertain on the total cross section:

Channel	$\sigma_{t\bar{t}Z}$
Dilepton	$0.84 \pm 0.11 \text{ pb} = 0.84 \pm 0.06 \text{ (stat.)} \pm 0.09 \text{ (syst.) pb}$
Trilepton	$0.84 \pm 0.07 \text{ pb} = 0.84 \pm 0.05 \text{ (stat.)} \pm 0.05 \text{ (syst.) pb}$
Tetralepton	$0.97^{+0.13}_{-0.12} \text{ pb} = 0.97 \pm 0.11 \text{ (stat.)} \pm 0.05 \text{ (syst.) pb}$
Combination ($2\ell, 3\ell$ & 4ℓ)	$0.86 \pm 0.05 \text{ pb} = 0.86 \pm 0.04 \text{ (stat.)} \pm 0.04 \text{ (syst.) pb}$

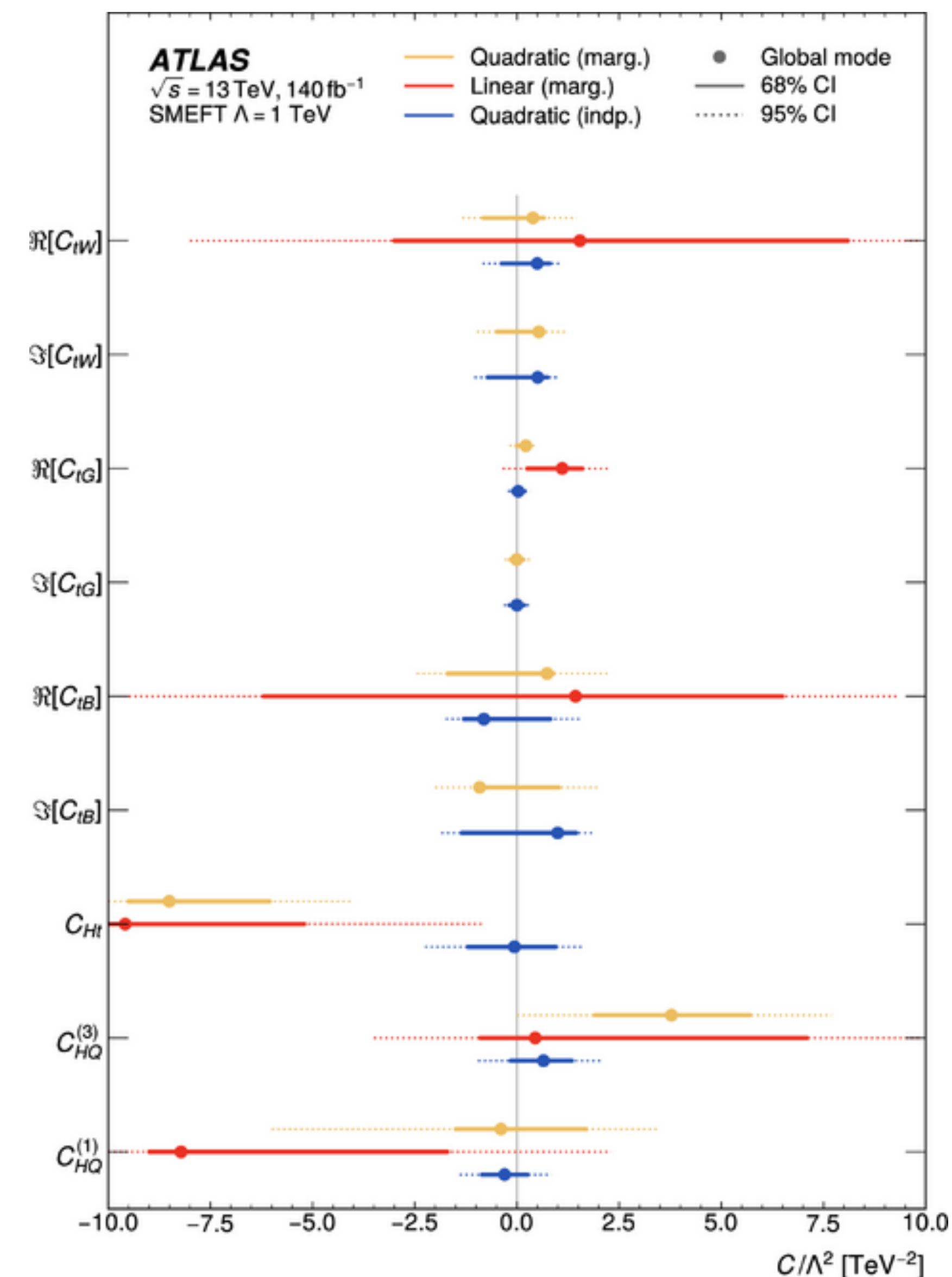


[TOPQ-2020-20]

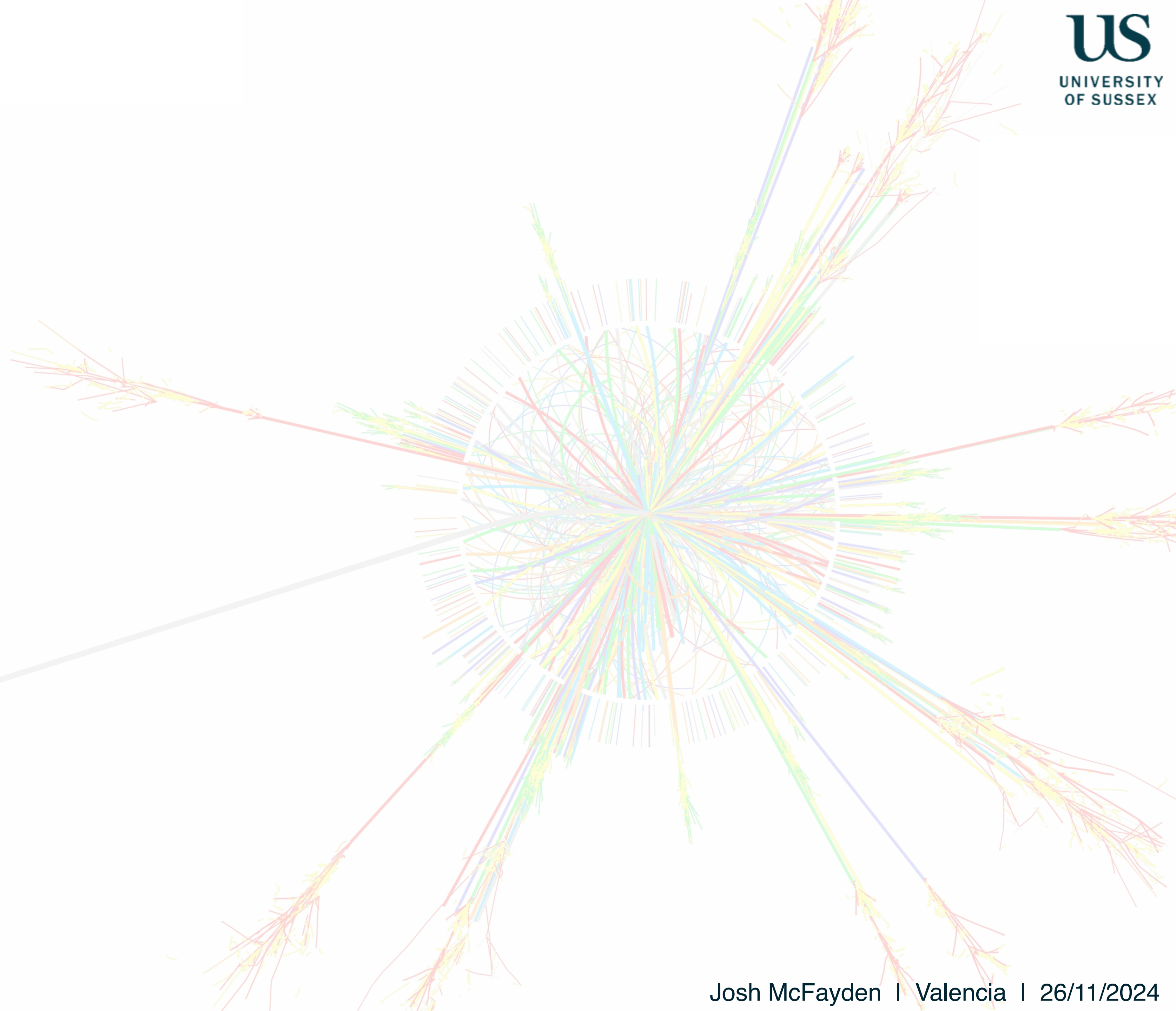


ATLAS ttZ + EFT

- ▶ ATLAS measurement with similar sensitivity
- ▶ ATLAS and CMS both achieve $\sim 6\%$ uncertain on the total cross section
- ▶ ATLAS also directly set limits on EFT operators from unfolded cross sections

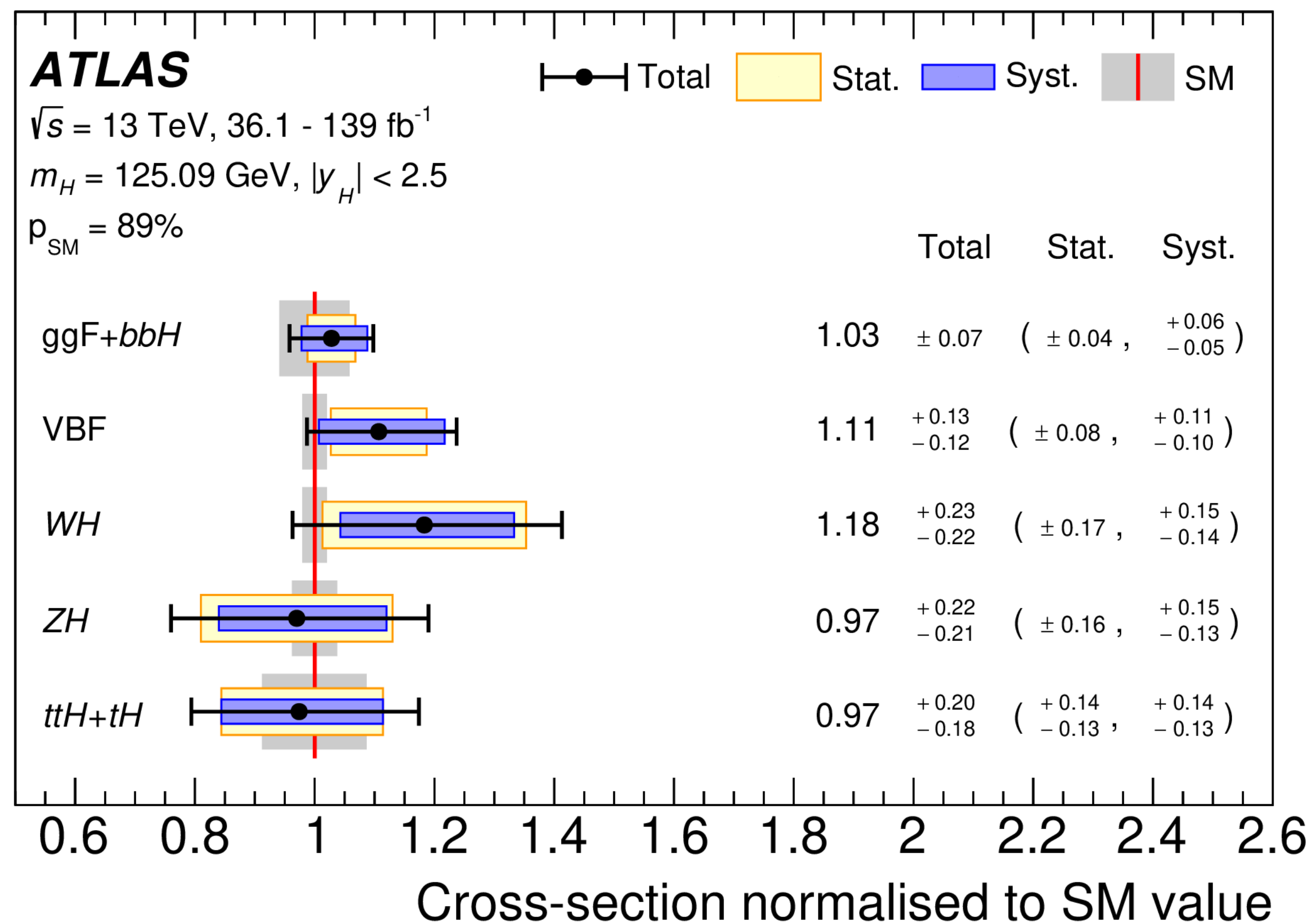


Back to ttH...





- Combined inclusive cross section of ttH+tH known to ~20% → 6σ

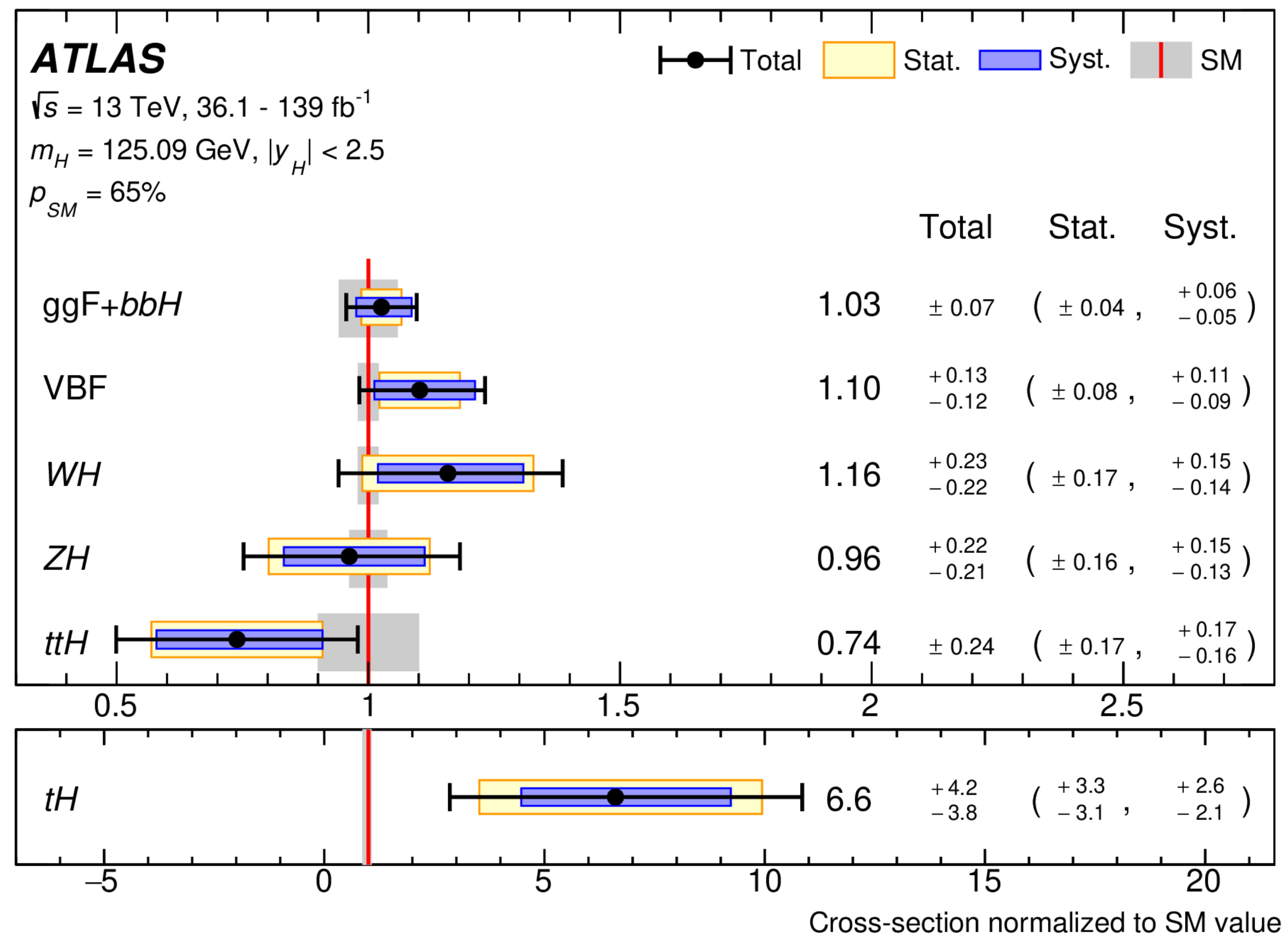


Cross-section normalized to SM value

[HIGG-2021-23]



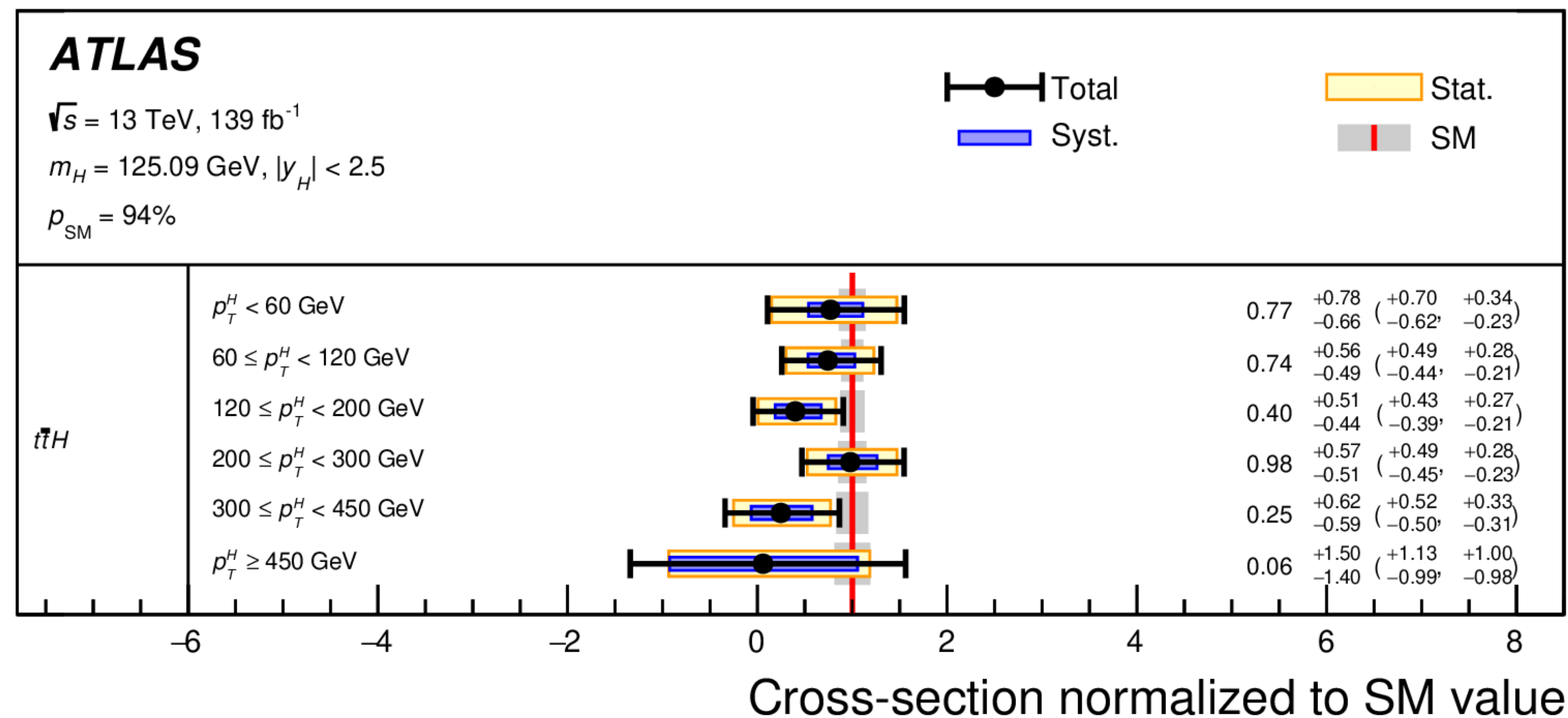
- ▶ Combined inclusive cross section of ttH+tH known to $\sim 20\% \rightarrow 6\sigma$
- ▶ Hard to separate tH:
 - ▶ Large anti-correlation with ttH



[HIGG-2021-23]

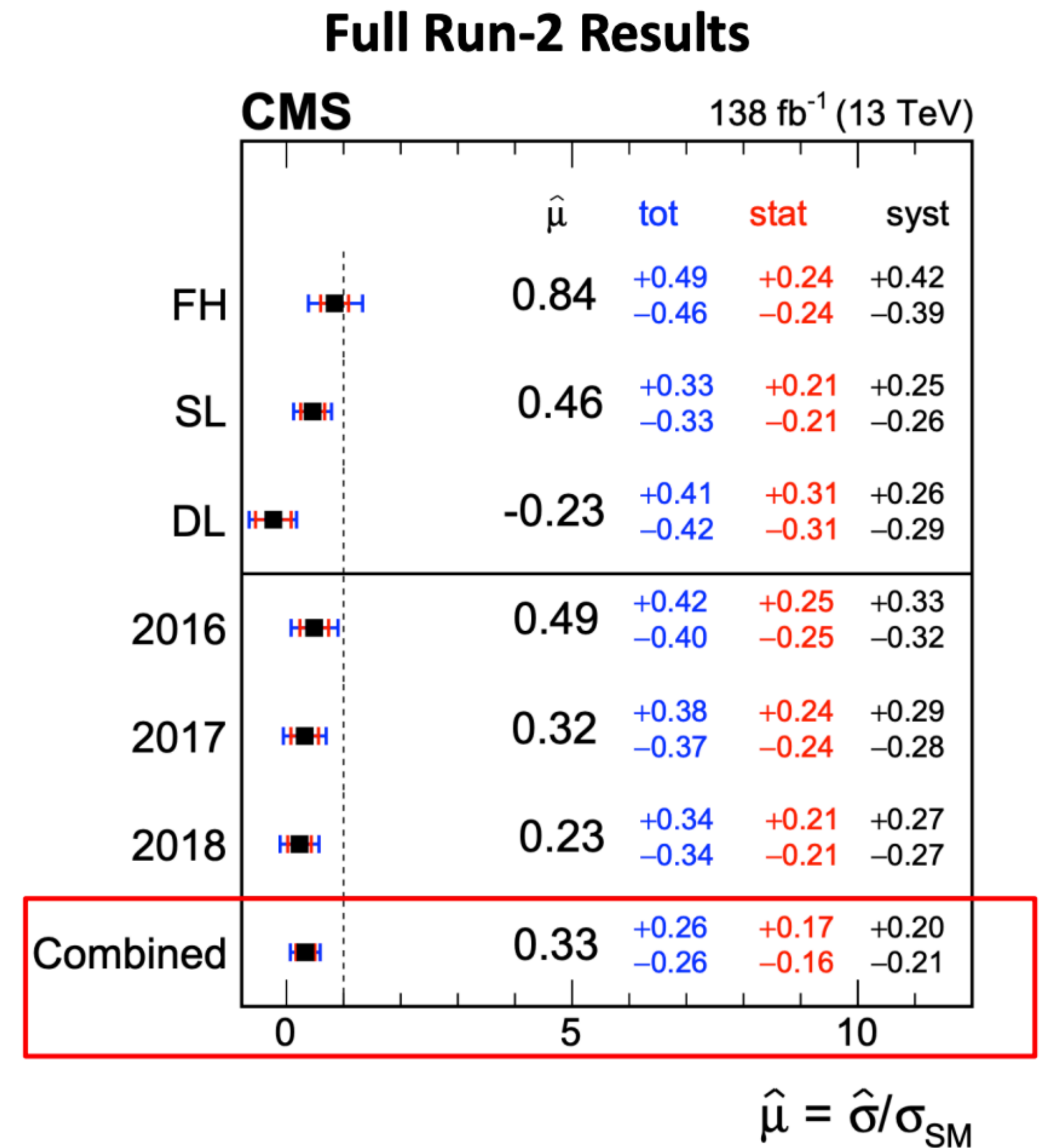
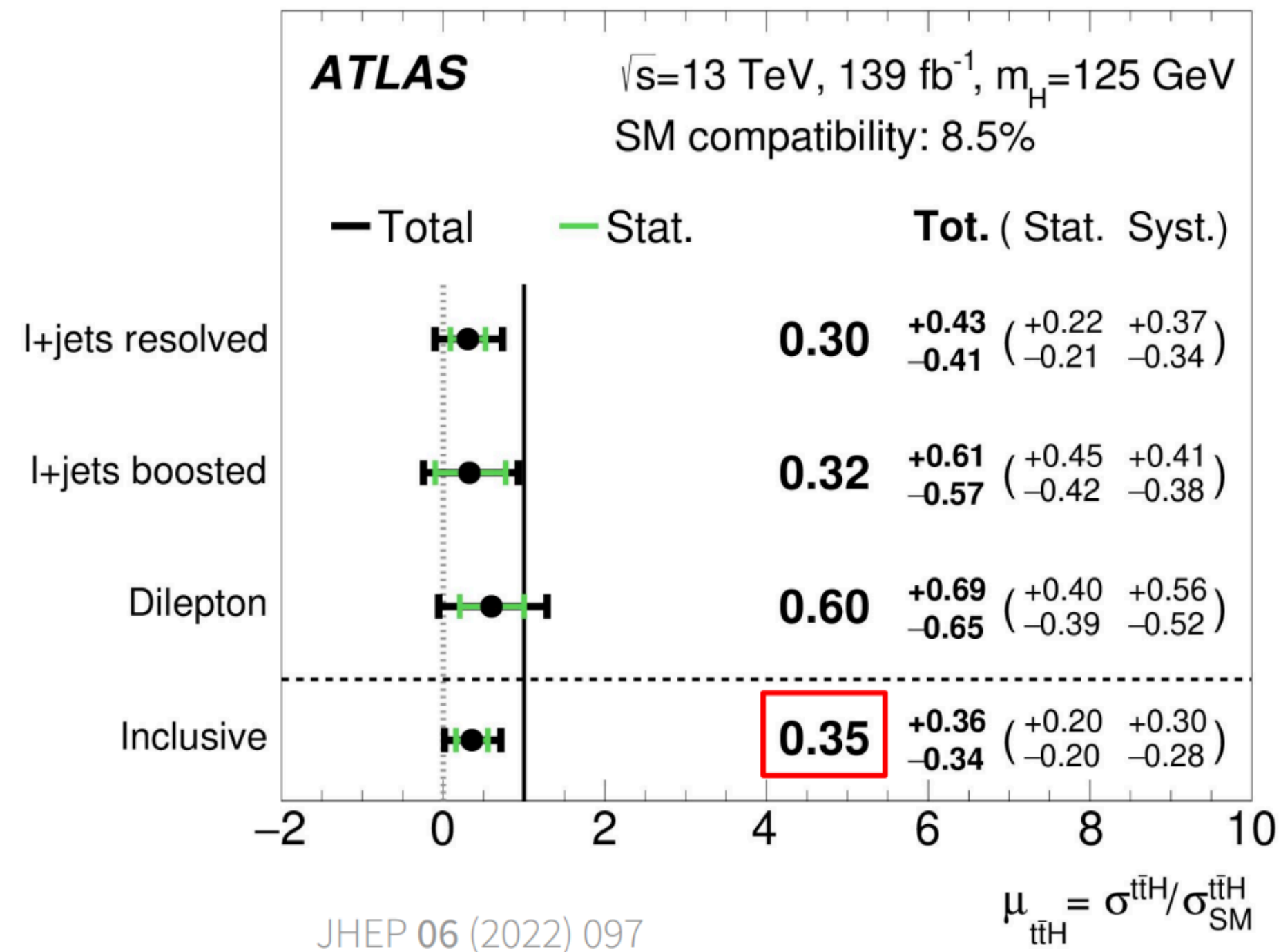


- ▶ Combined inclusive cross section of ttH+tH known to $\sim 20\% \rightarrow 6\sigma$
- ▶ Hard to separate tH:
 - ▶ Large anti-correlation with ttH
- ▶ $\sim 50\%$ uncertainty per STXS bin as a function of $p_T(H)$

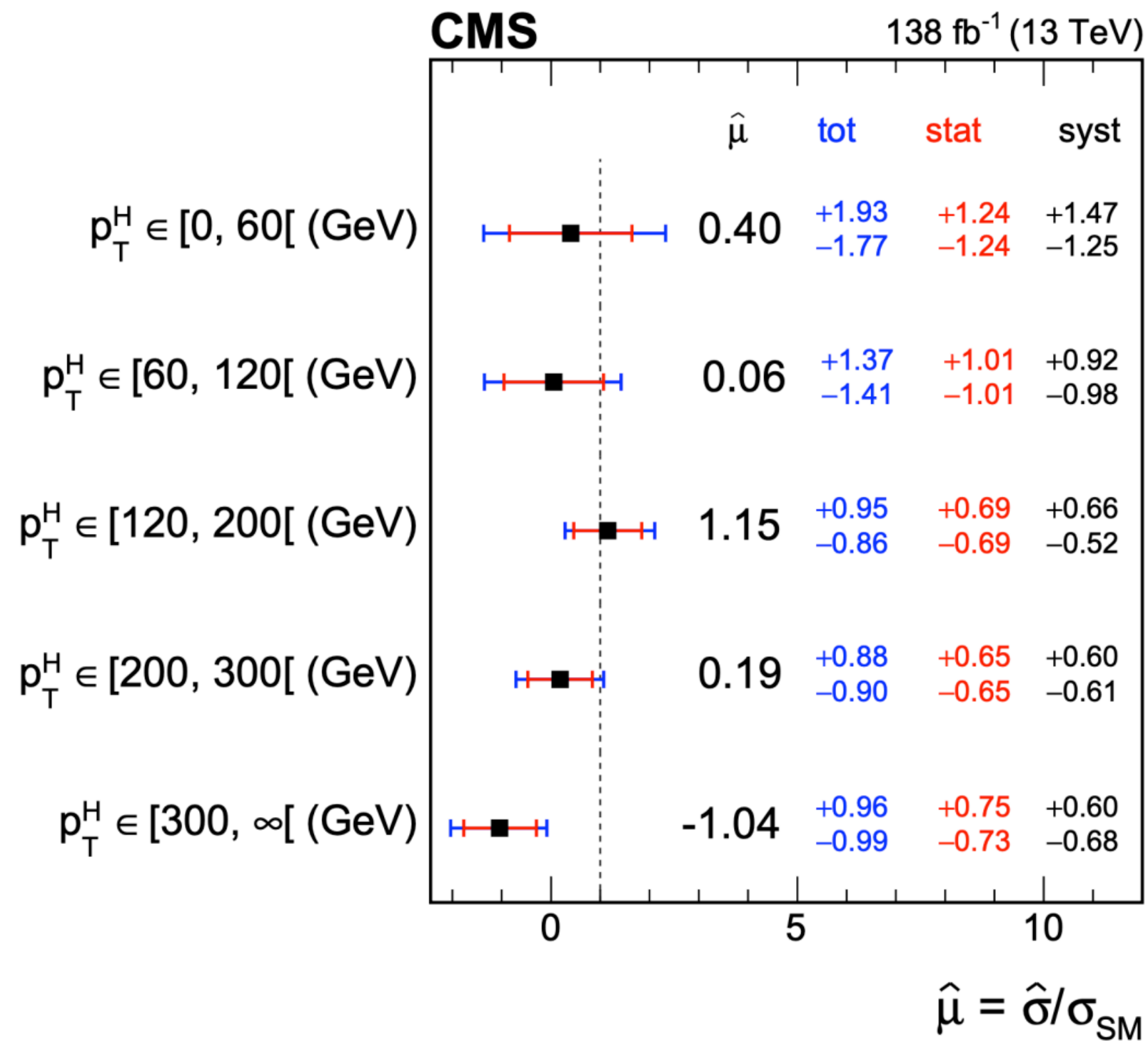


[HIGG-2021-23]

- Interesting tension in previous ATLAS and CMS ttH(bb) inclusive cross section results:



► Latest differential results:



$p_T^H \in [0, 60)$ GeV

$p_T^H \in [60, 120)$ GeV

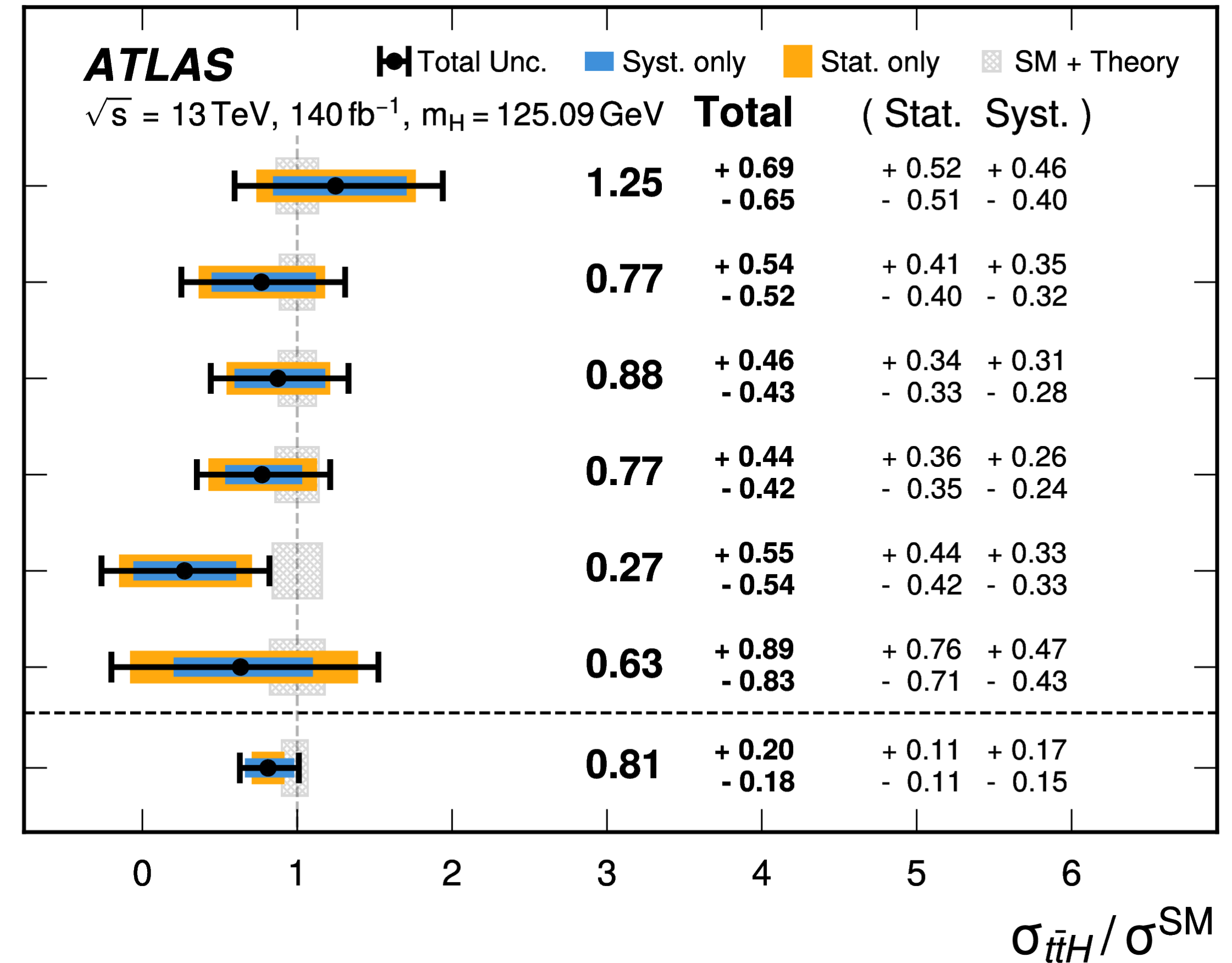
$p_T^H \in [120, 200)$ GeV

$p_T^H \in [200, 300)$ GeV

$p_T^H \in [300, 450)$ GeV

$p_T^H \in [450, \infty)$ GeV

Inclusive

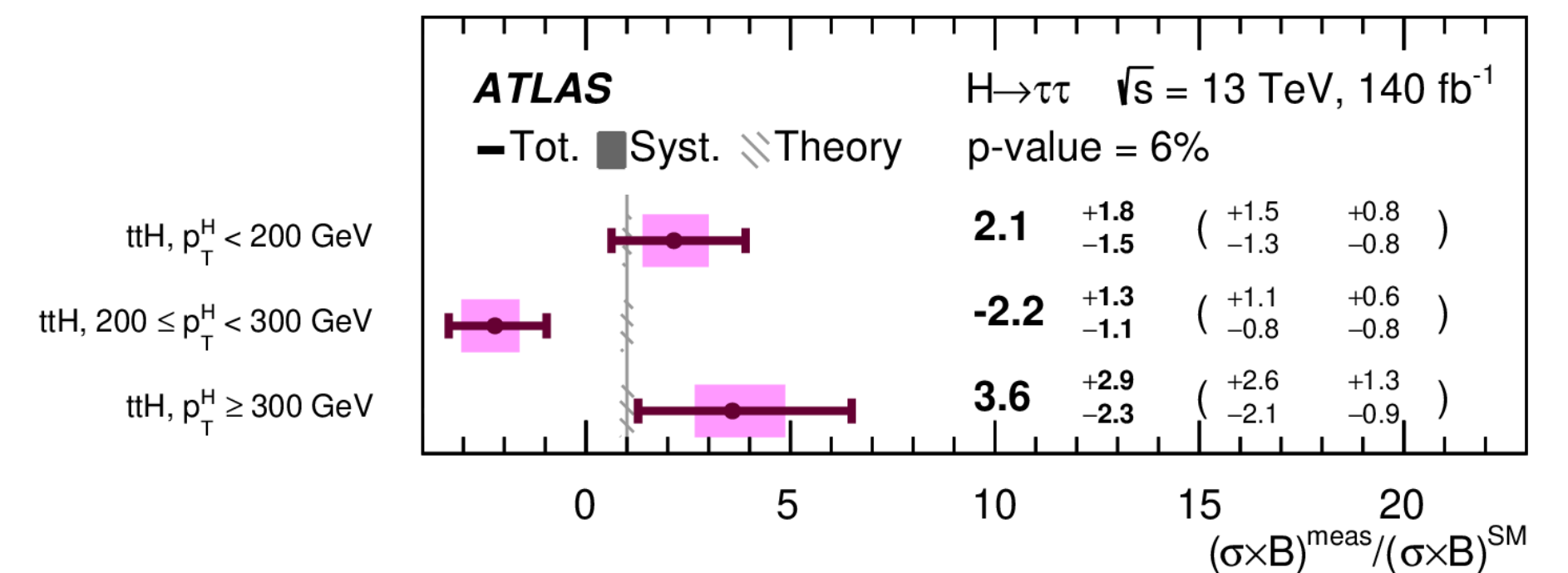
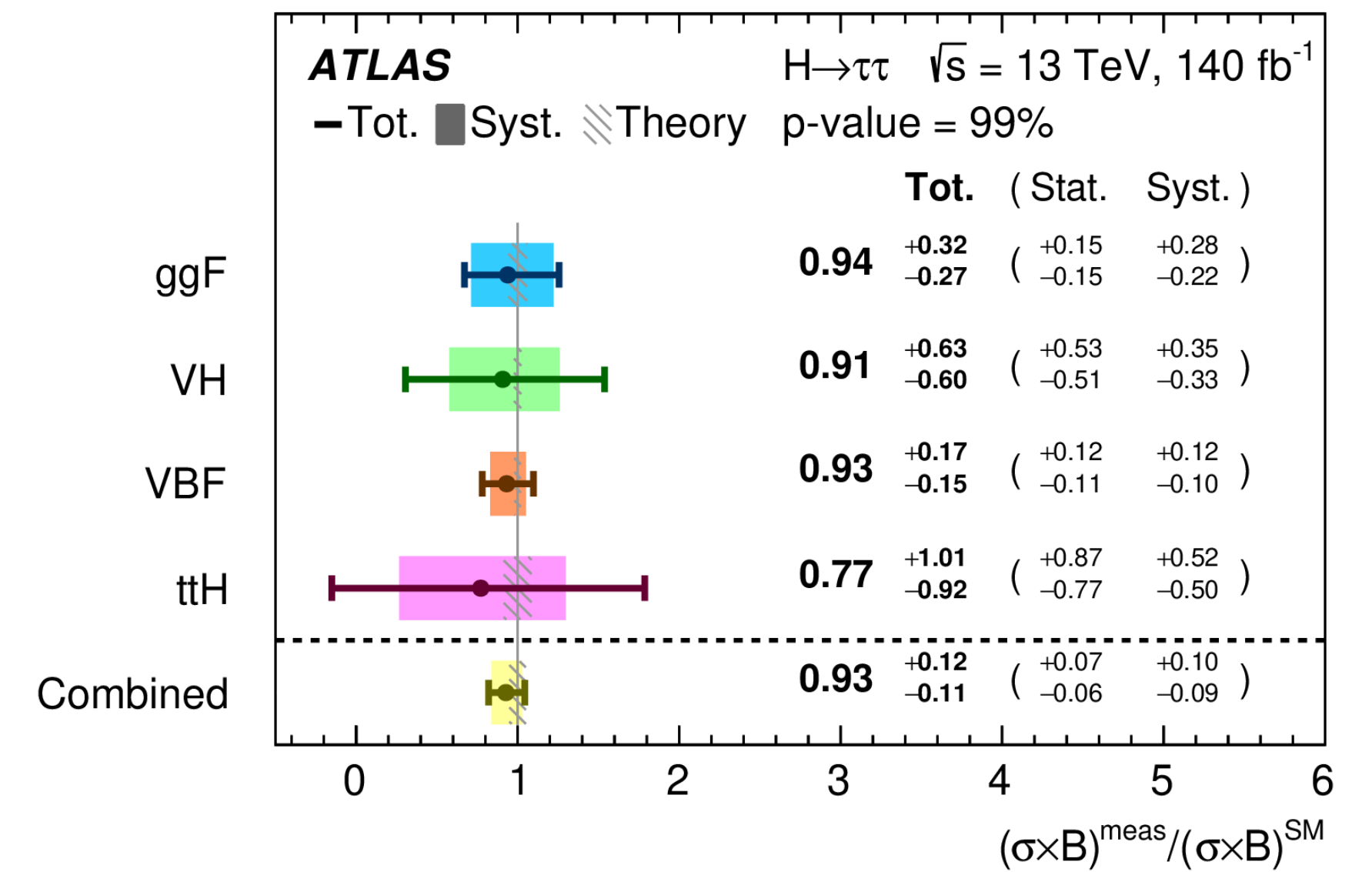
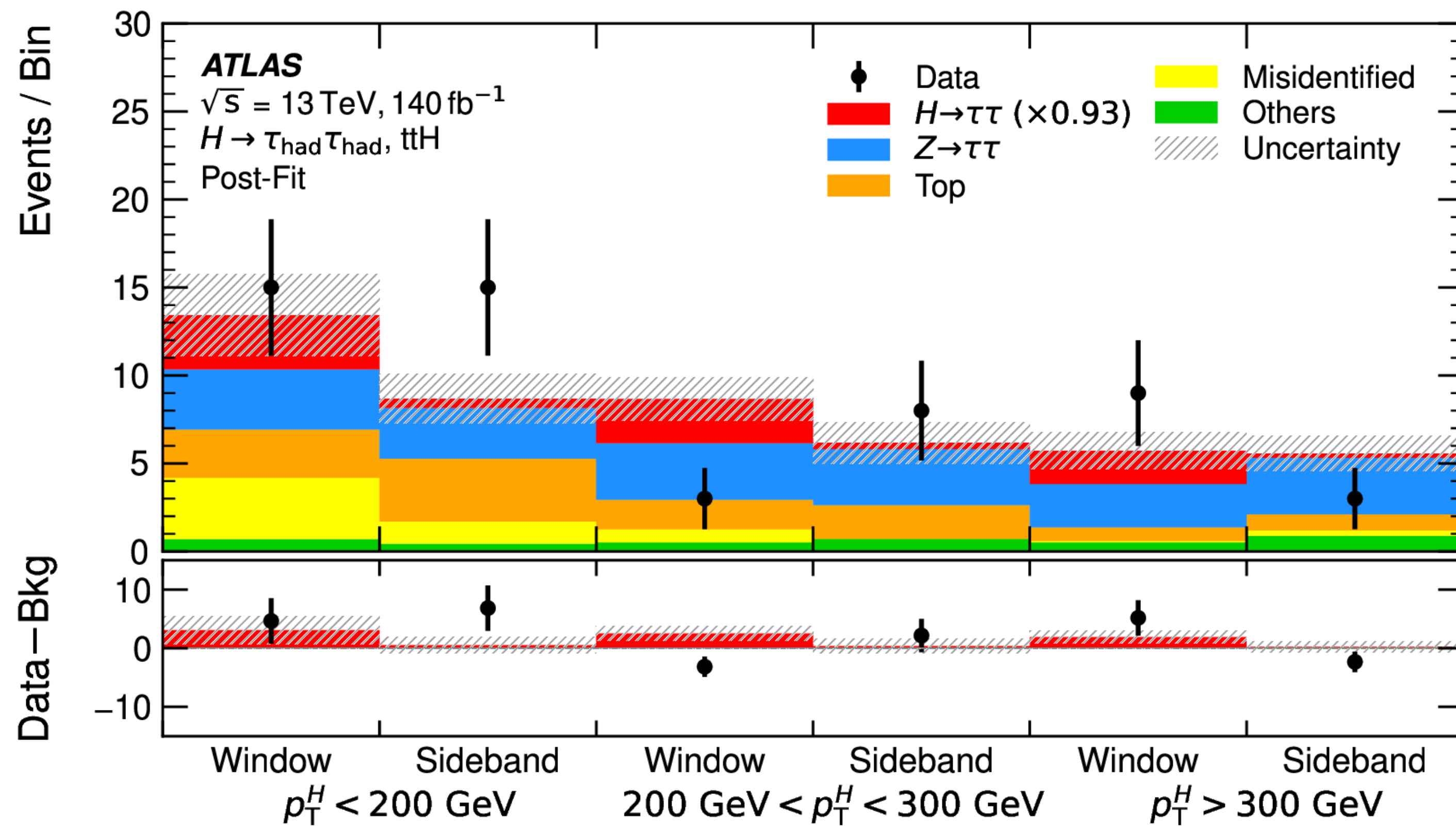


► Significant improvement in $t\bar{t}+b\bar{b}$ background modelling in ATLAS analysis



ATLAS $ttH(\tau\tau)$

Recent ATLAS $ttH(\tau\tau)$ result including differential measurement:

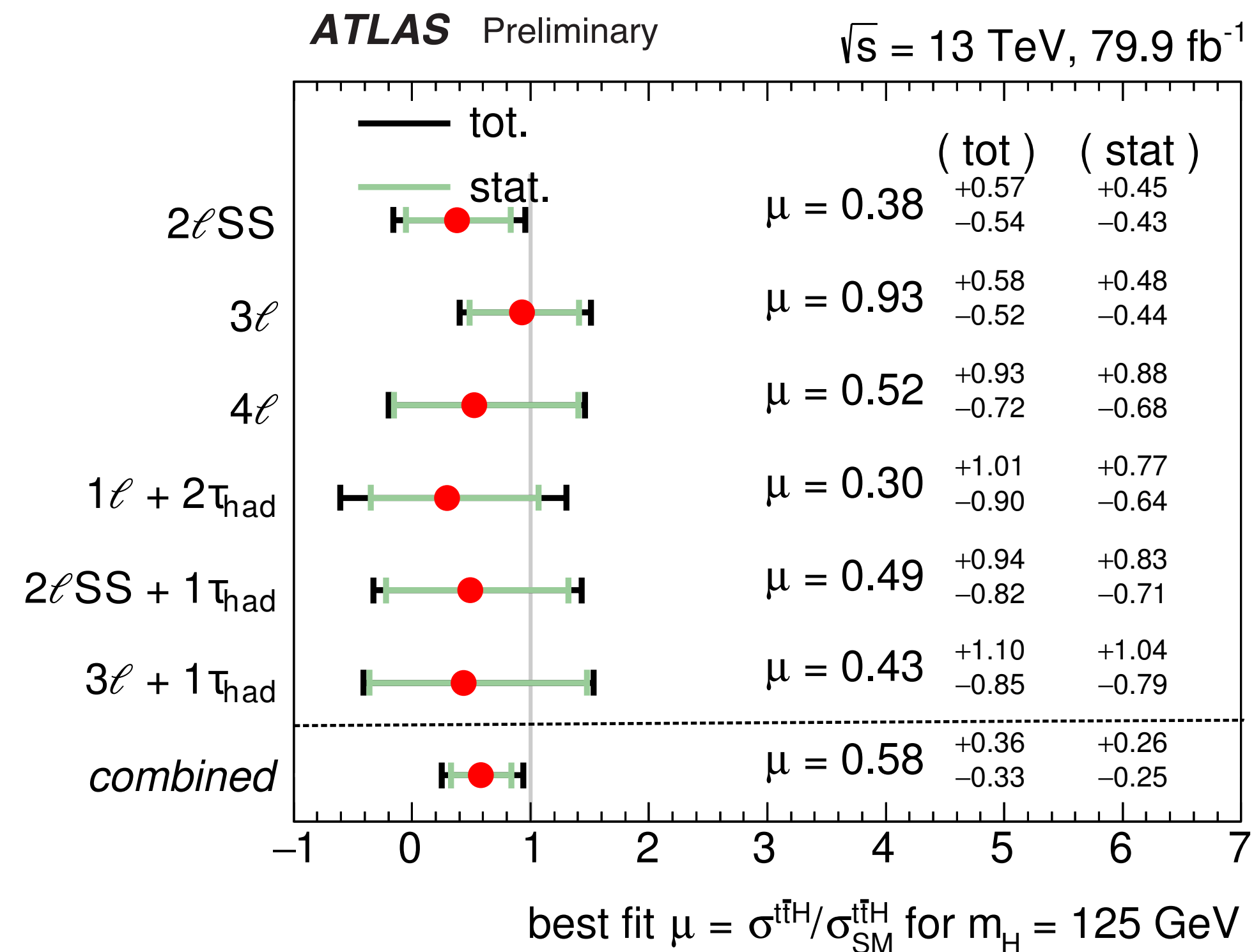


[HIGG-2022-07]



ATLAS $t\bar{t}H \rightarrow \text{multi-leptons}$

- ▶ ATLAS $t\bar{t}H$ ML CONF note (80 fb⁻¹)
- ▶ Observed significant mismodelling attributed to $t\bar{t}W$ background
- ▶ Very important for overall sensitivity
- ▶ **Work ongoing for Full Run 2 result!**

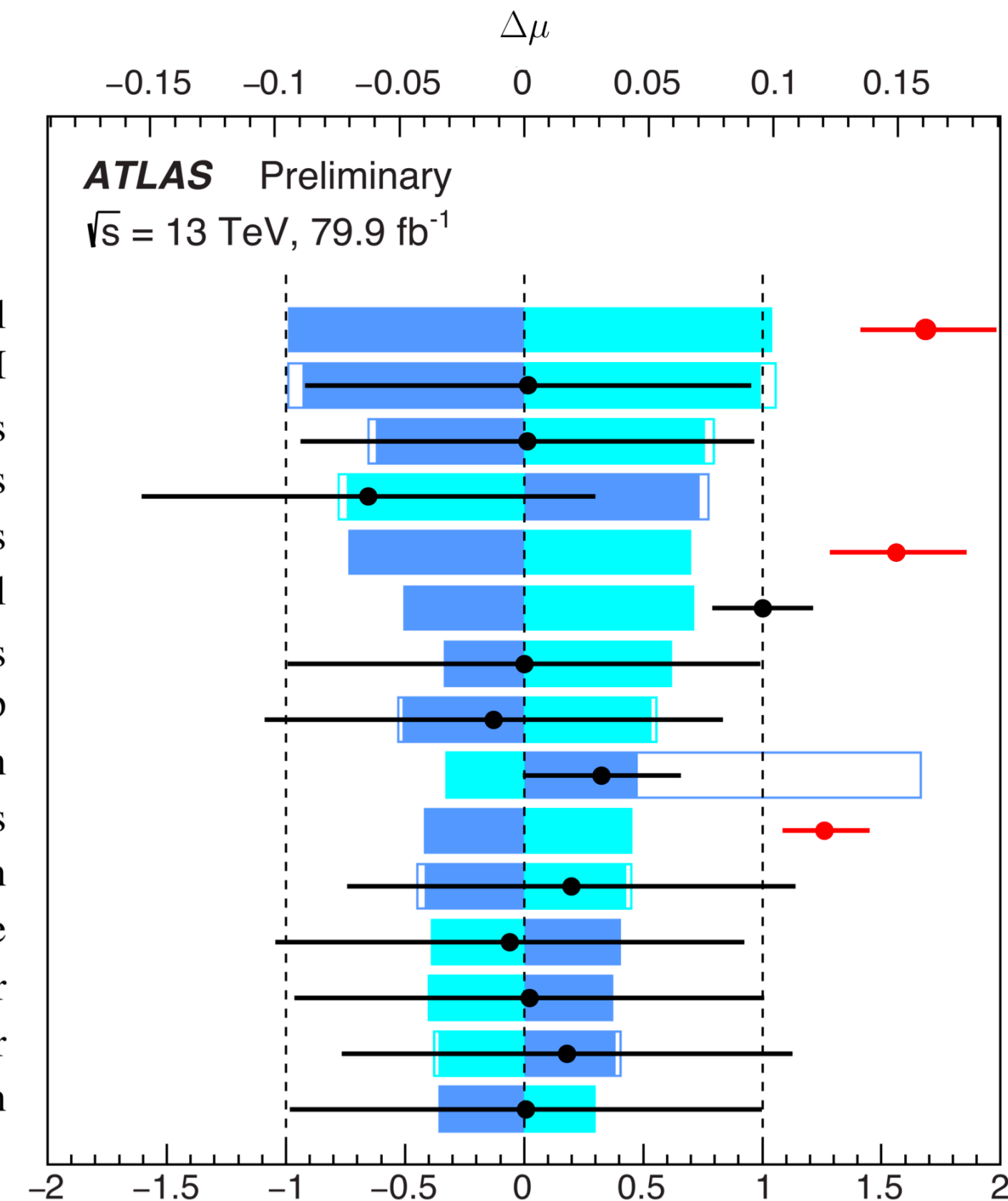


Pre-fit impact on μ :
 $\square \theta = \hat{\theta} + \Delta\theta$ $\square \theta = \hat{\theta} - \Delta\theta$

Post-fit impact on μ :
 $\square \theta = \hat{\theta} + \Delta\hat{\theta}$ $\square \theta = \hat{\theta} - \Delta\hat{\theta}$

—●— Pull: $(\hat{\theta} - \theta_0)/\Delta\theta$
 —●— Norm. Factor

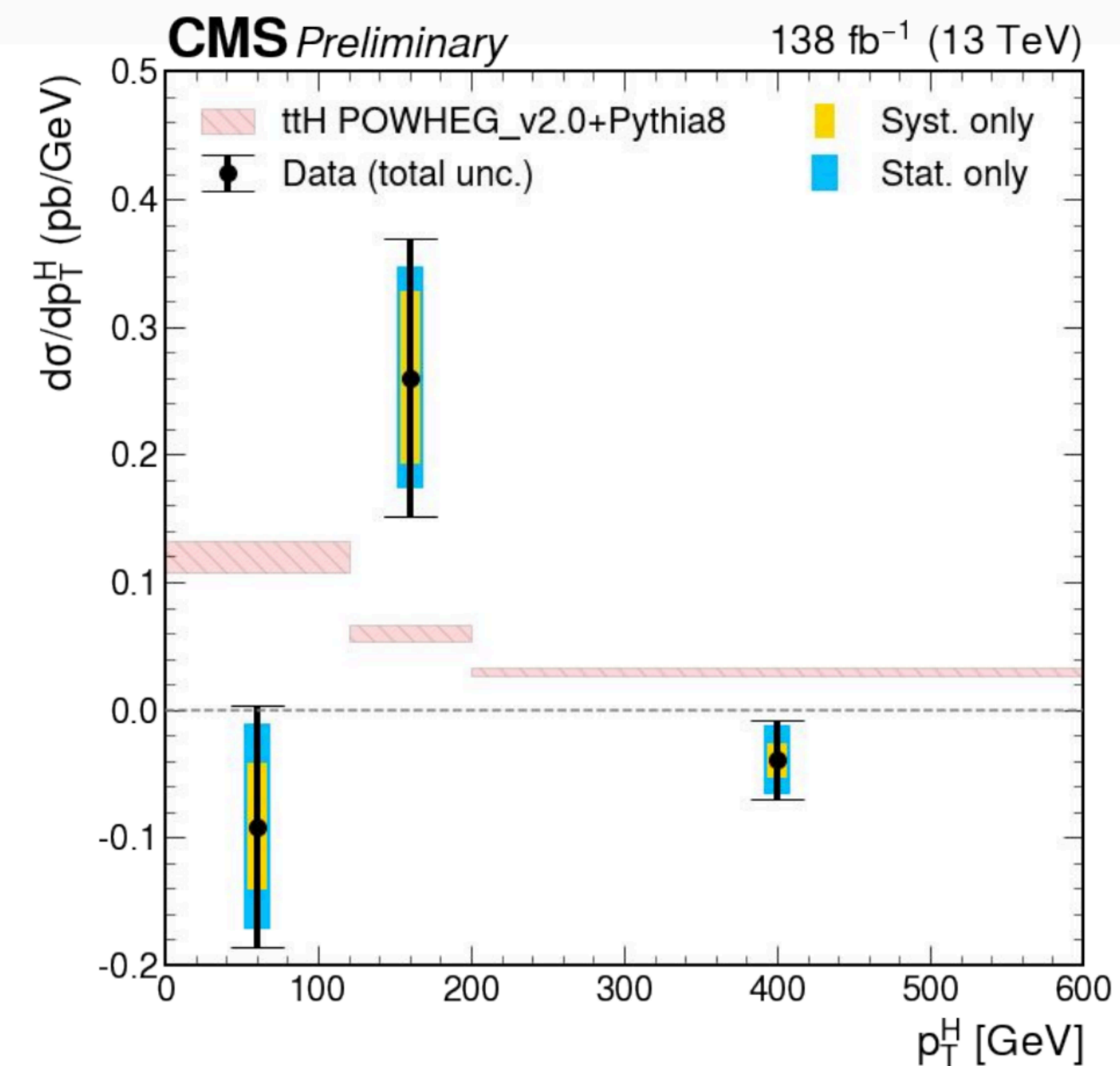
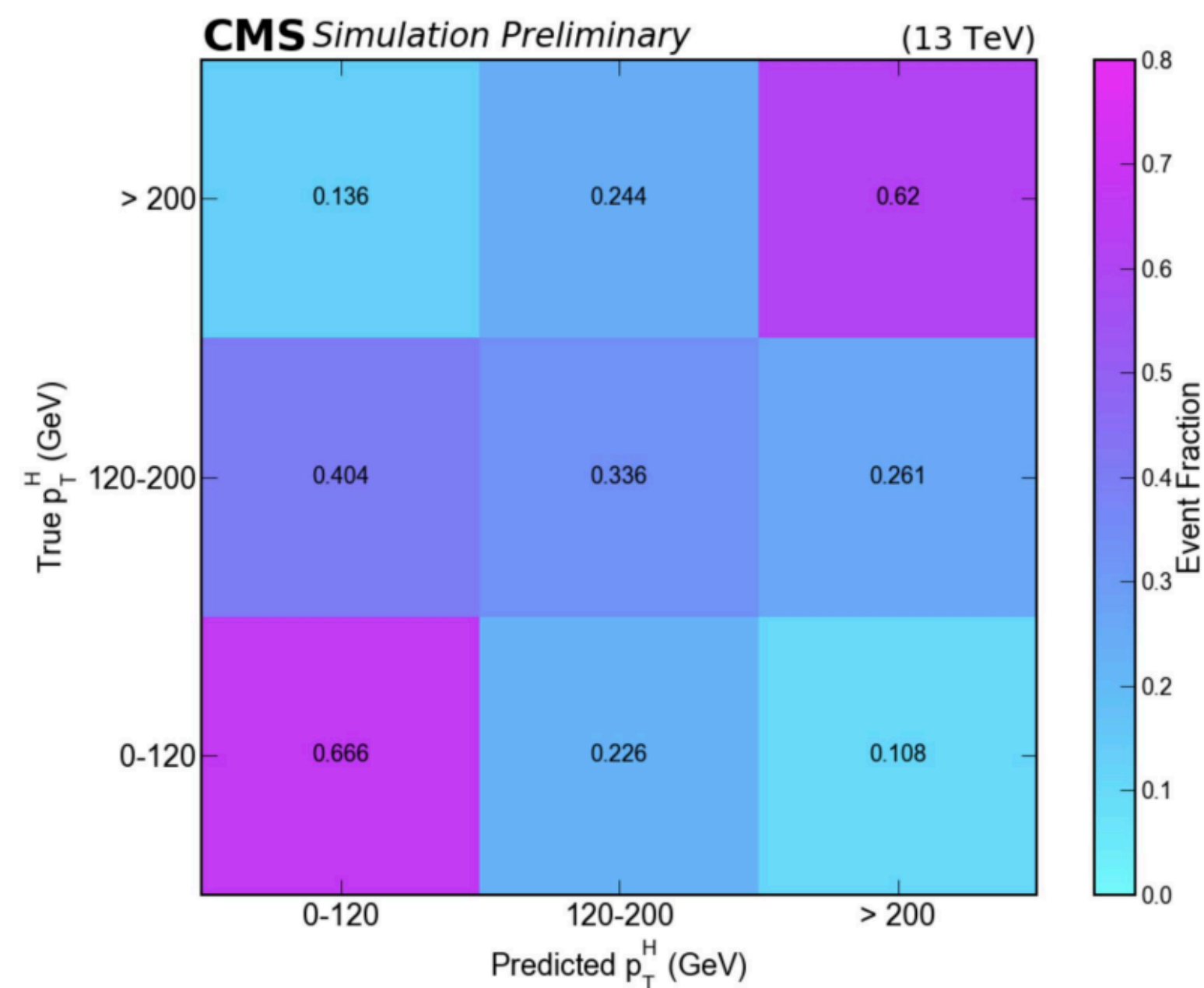
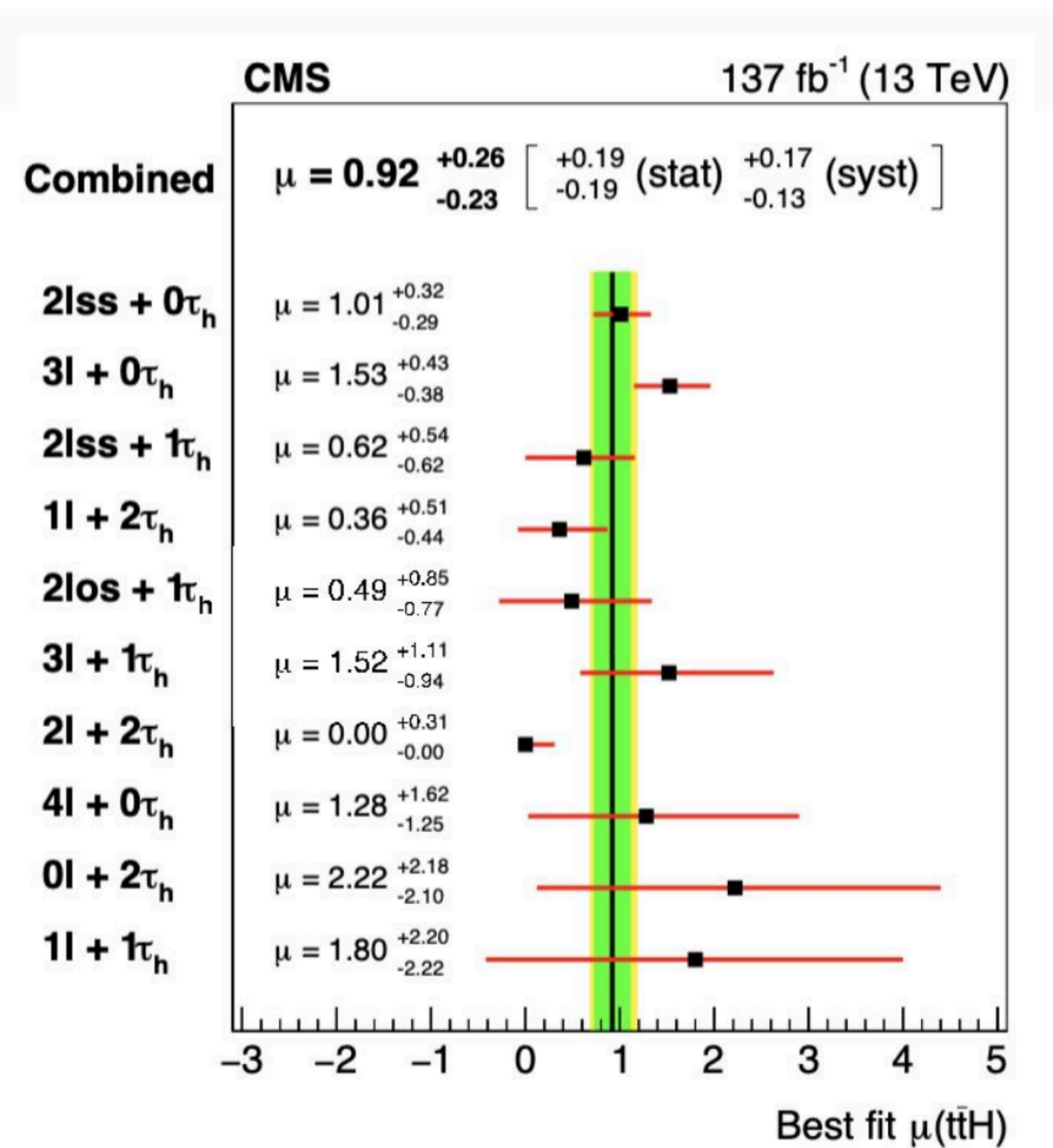
$t\bar{t}W$ norm. factor: 3 ℓ channel
 Jet energy scale: η intercalib. NP I
 $t\bar{t}Z$ cross section: scale variations
 $t\bar{t}W$ modelling: scale variations
 $t\bar{t}W$ norm. factor: 2 ℓ SS channel, 2-3 jets
 Fake τ_{had} bkg. stat: 1 ℓ 2 τ channel
 $t\bar{t}H$ cross section: scale variations
 Jet energy scale: pileup
 $t\bar{t}W$ modelling: charge extrapolation
 $t\bar{t}W$ norm. factor: 2 ℓ SS channel, ≥ 4 jets
 Top rare decay cross-section
 Jet energy scale: flavour response
 $t\bar{t}H$ modelling: parton shower
 $t\bar{t}W$ modelling: alternative generator
 4-top cross section



[ATLAS-CONF-2019-045]

Recent CMS ttHML

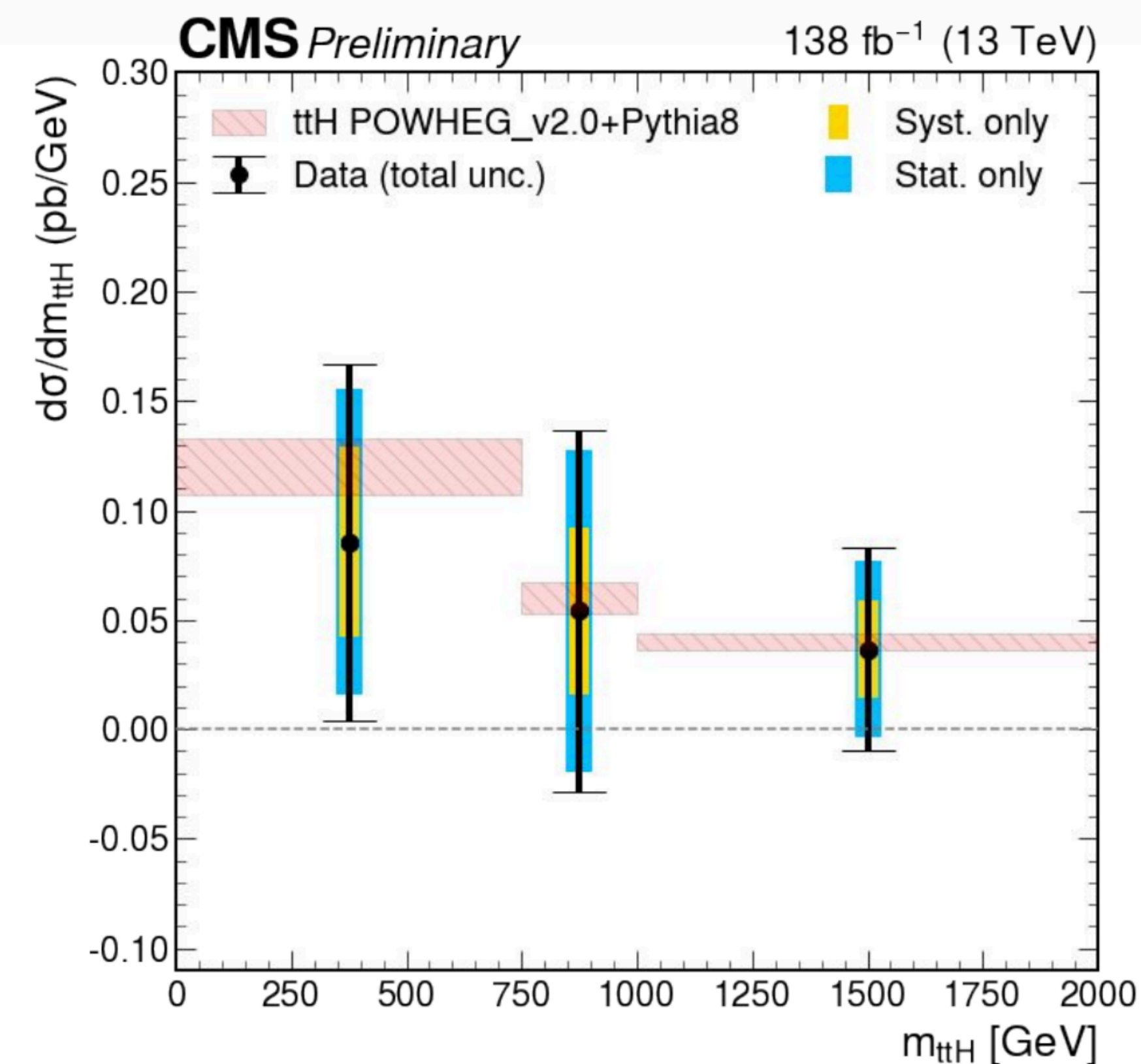
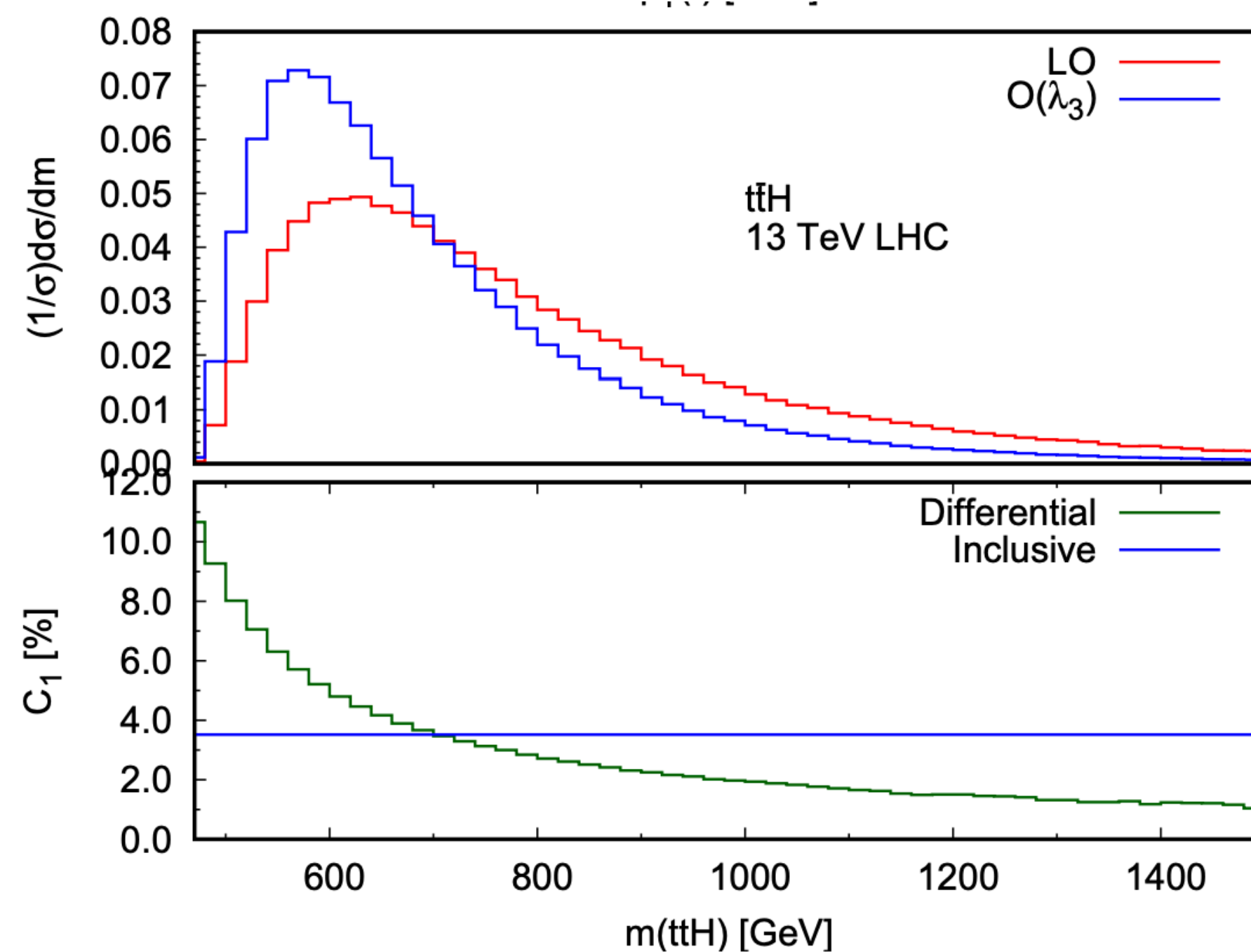
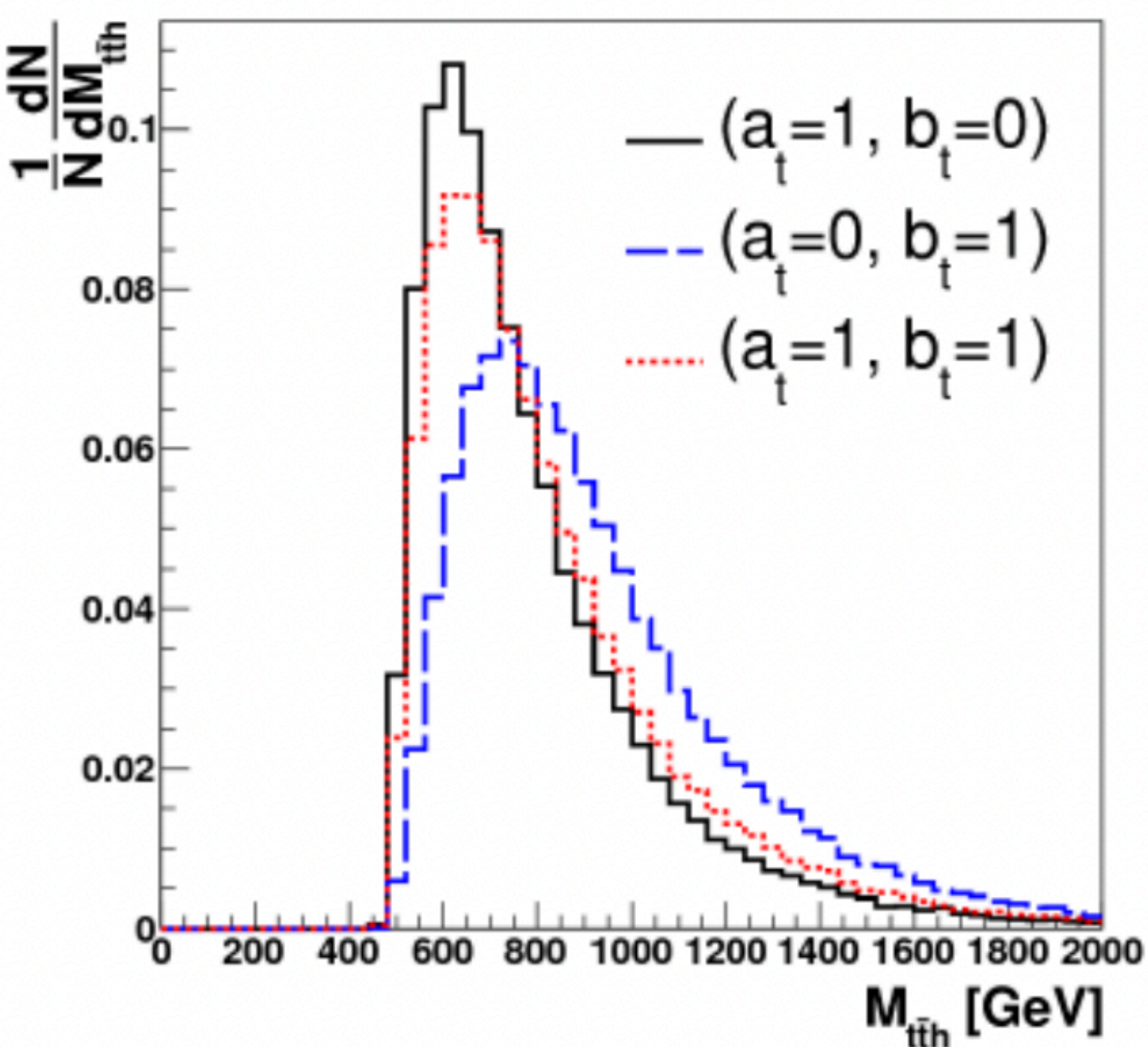
- ▶ New CMS measurement with differential ttH measurement
- ▶ Focus on two most sensitive channels 2LSS+0 τ and 3L+0 τ



[Higgs 2024 Talk]

Recent CMS ttHML

- ▶ New CMS measurement with differential ttH measurement
- ▶ Focus on two most sensitive channels 2LSS+0 τ and 3L+0 τ
- ▶ Includes measurement of $m(\text{ttH})$
 - ▶ Potentially interesting for CP and self-coupling



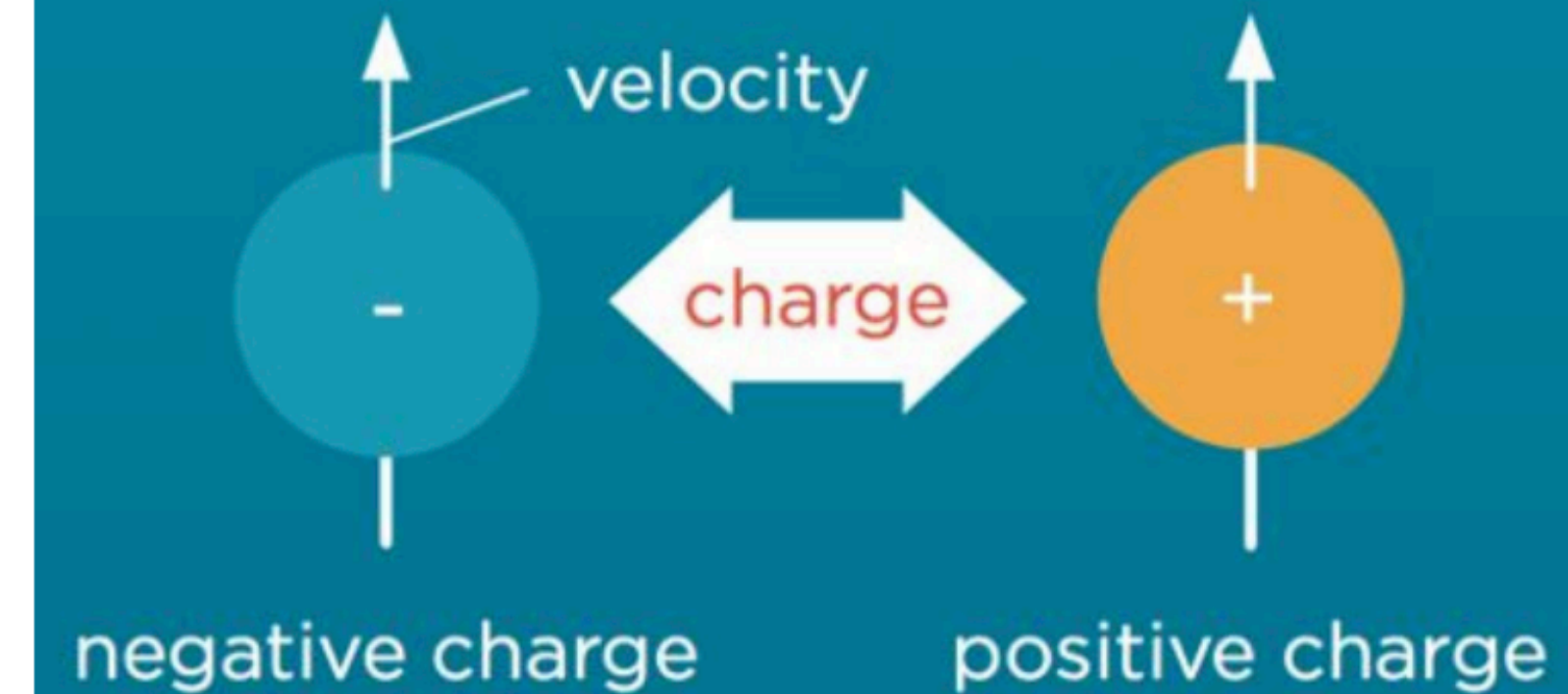
[Higgs 2024 Talk]



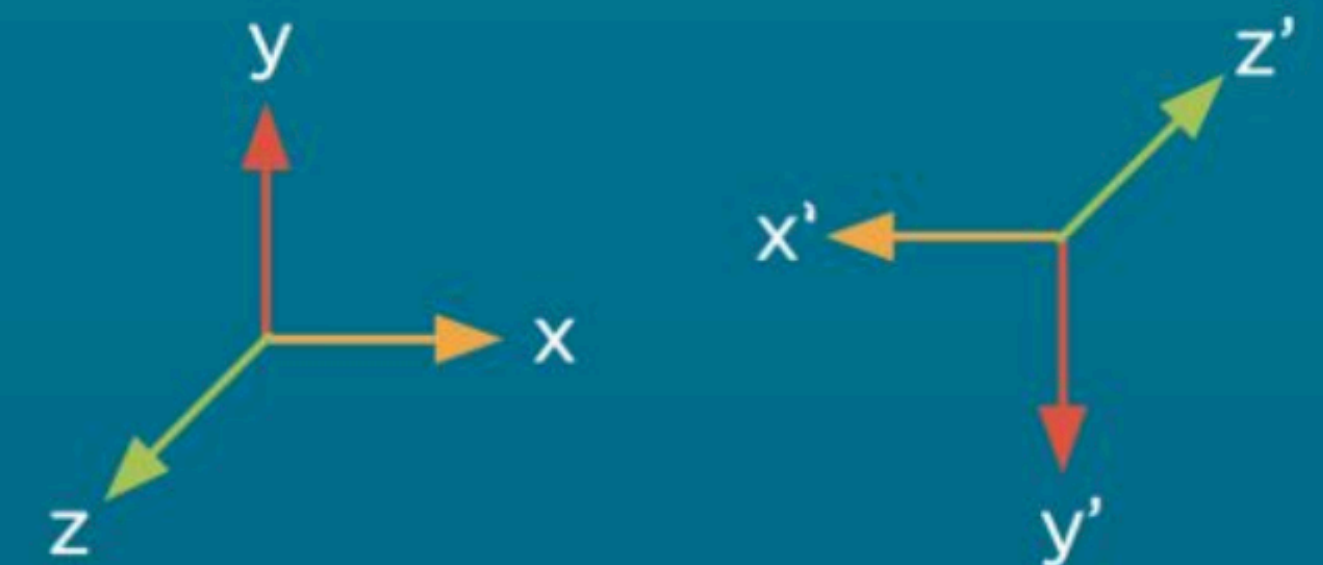
Higgs CP

- ▶ Known CPV far too small to match observed cosmological matter-antimatter imbalance.
 - ▶ Search for additional sources of CPV beyond the SM
 - ▶ Higgs sector is one of several possible hiding places!
-
- ▶ According to the SM, the Higgs boson is “CP-even”
 - ▶ The presence of a CP-odd component would imply CPV
 - ▶ Altering the kinematic properties of the $t\bar{t}H$ process and modifying tH production.

Charge symmetry



Parity symmetry





- ▶ Known CPV far too small to match observed cosmological matter-antimatter imbalance.
 - ▶ Search for additional sources of CPV beyond the SM
 - ▶ Higgs sector is one of several possible hiding places!
-
- ▶ According to the SM, the Higgs boson is “CP-even”
 - ▶ The presence of a CP-odd component would imply CPV
 - ▶ Altering the kinematic properties of the $t\bar{t}H$ process and modifying tH production.
 - ▶ Introduction via CP-odd coupling $\tilde{\kappa}_t$ or CP-angle α

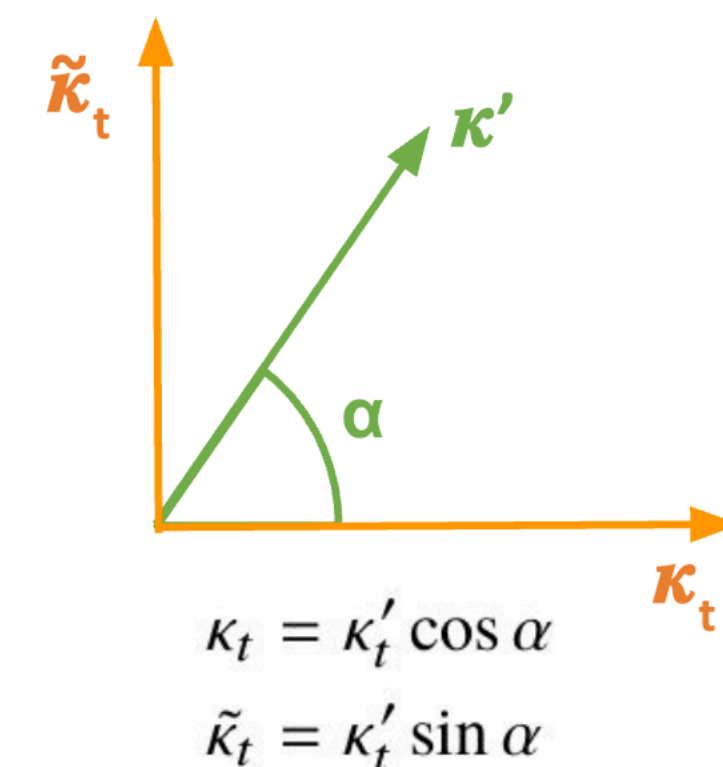
$$\mathcal{L}_{t\bar{t}H} = -\kappa_t y_t \phi \bar{\psi}_t \psi_t$$

SM Interaction Terms



$$\mathcal{L}'_{t\bar{t}H} = -y_t \phi \bar{\psi}_t (\kappa_t + i\gamma_5 \tilde{\kappa}_t) \psi_t$$

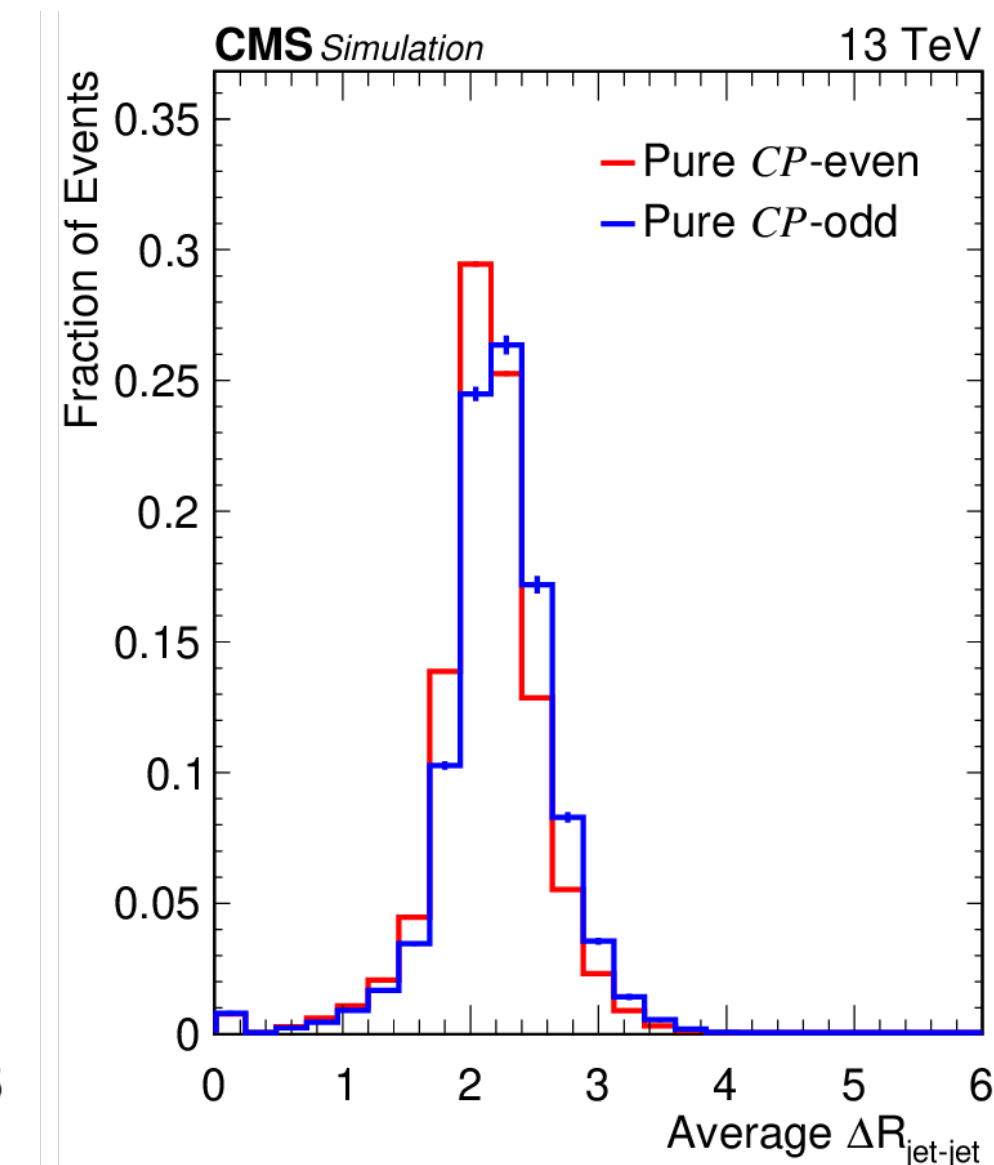
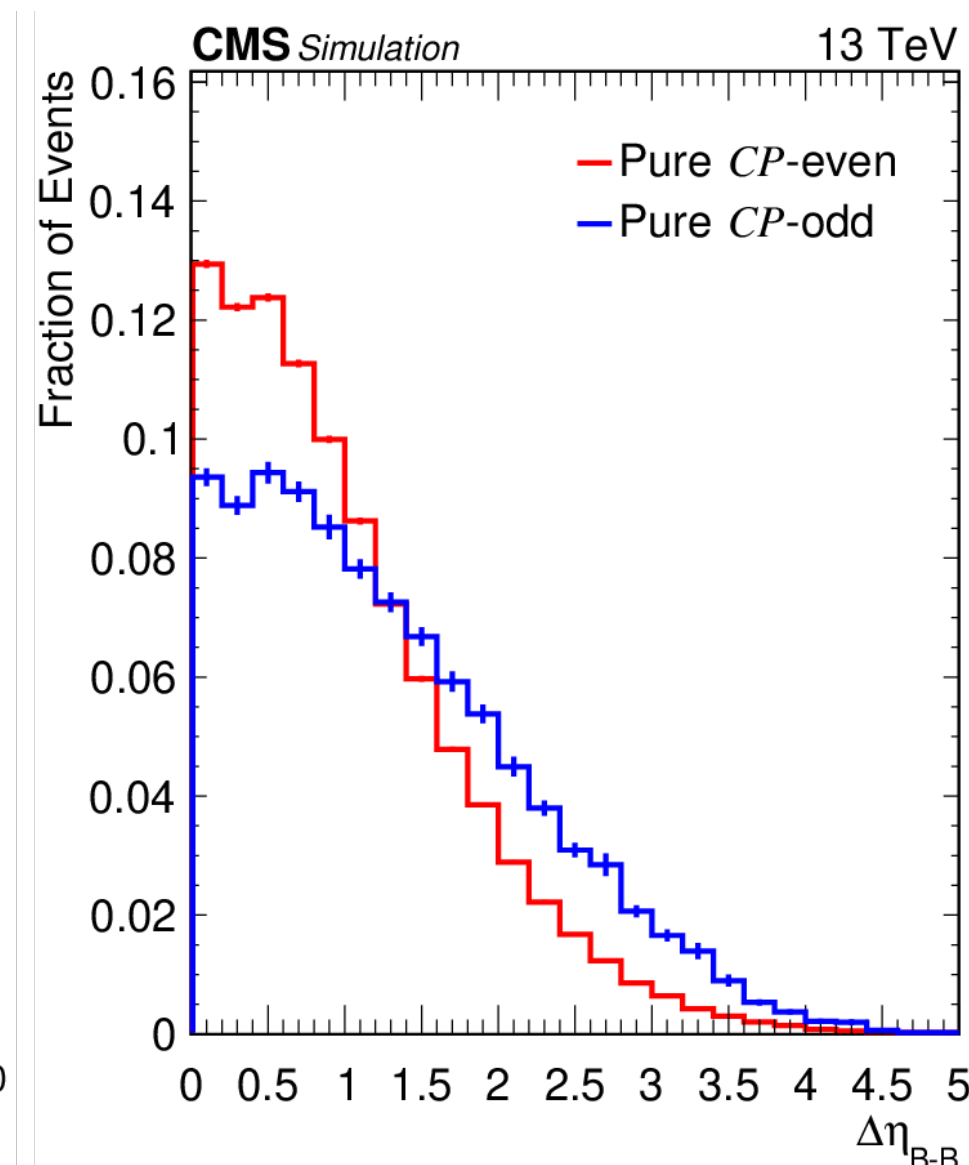
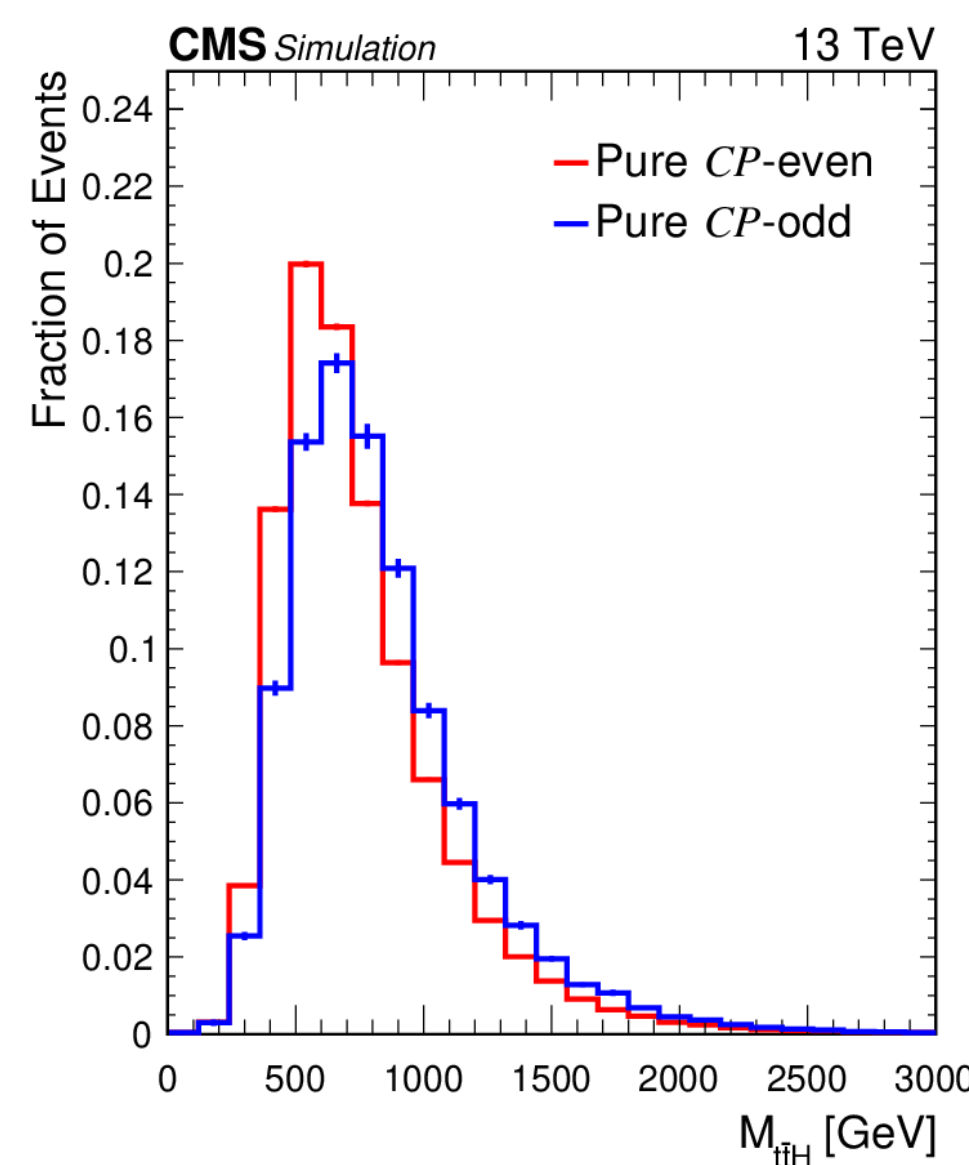
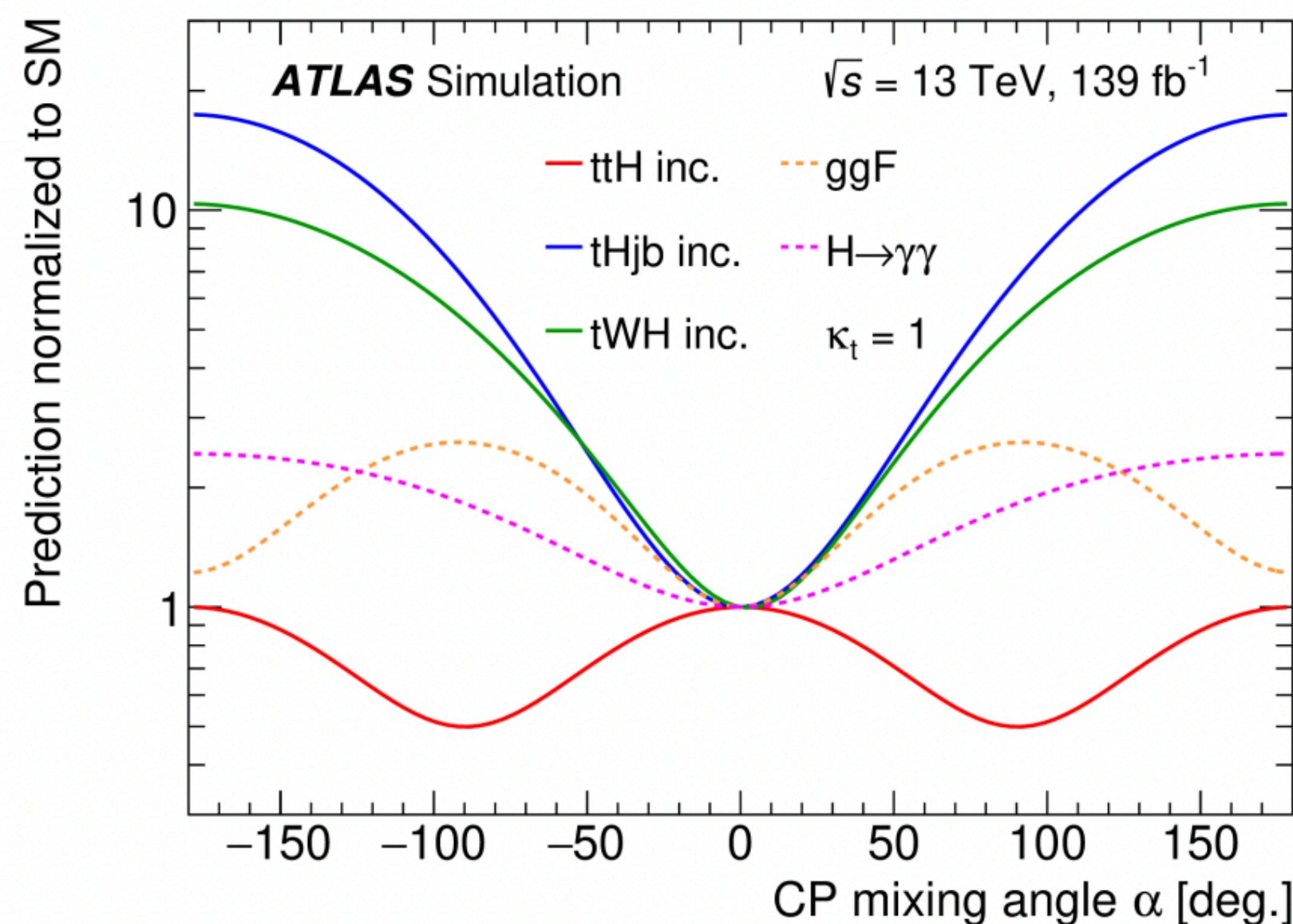
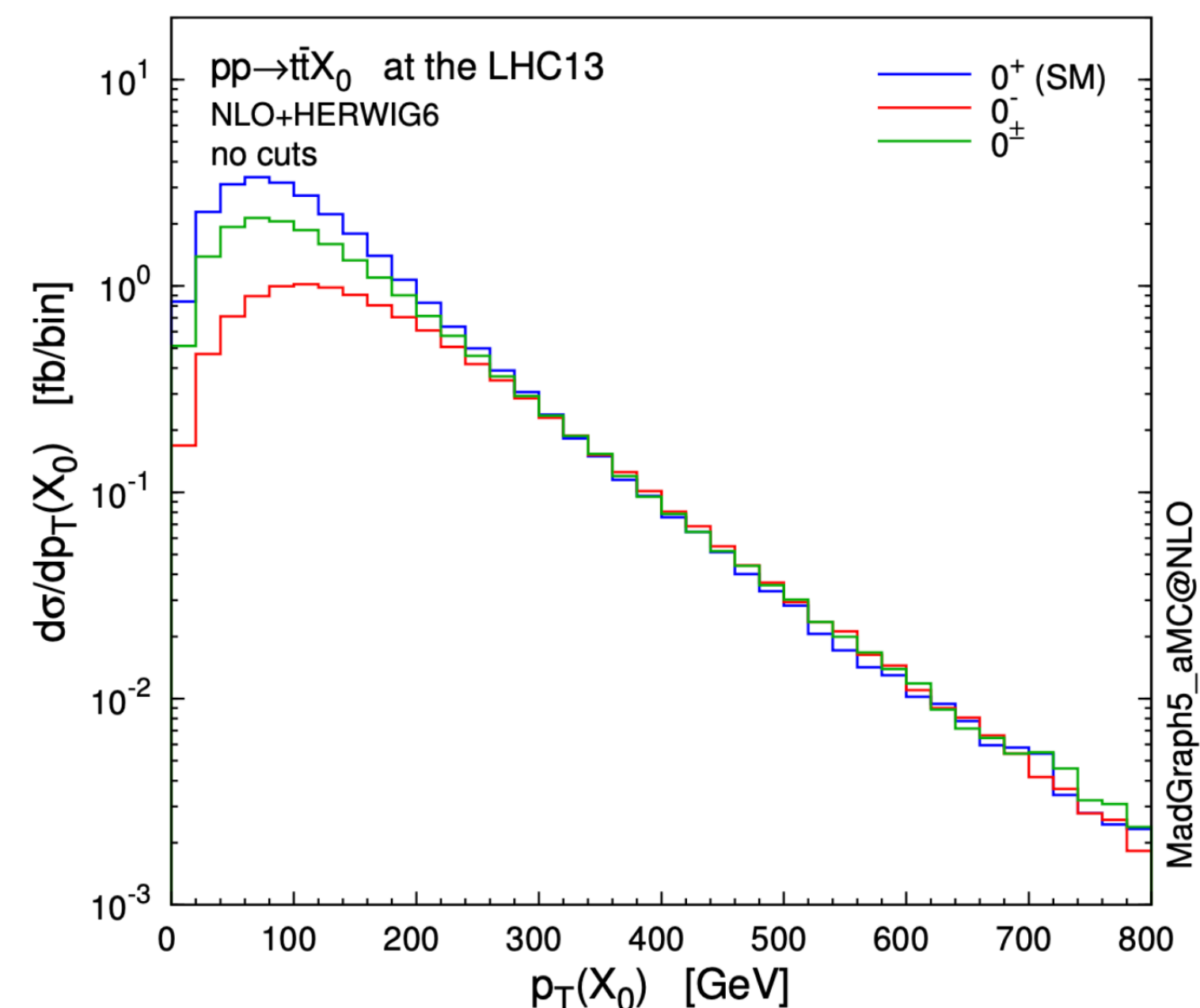
$$\mathcal{L}'_{t\bar{t}H} = -\kappa'_t y_t \phi \bar{\psi}_t (\cos \alpha + i\gamma_5 \sin \alpha) \psi_t$$





Higgs CP

- ▶ Rate information
 - ▶ high sensitivity from $t\bar{t}H$
- ▶ Shape information
 - ▶ Many variables constructed in $t\bar{t}H$
 - ▶ sensitive to spin correlations of process
 - ▶ MVA used

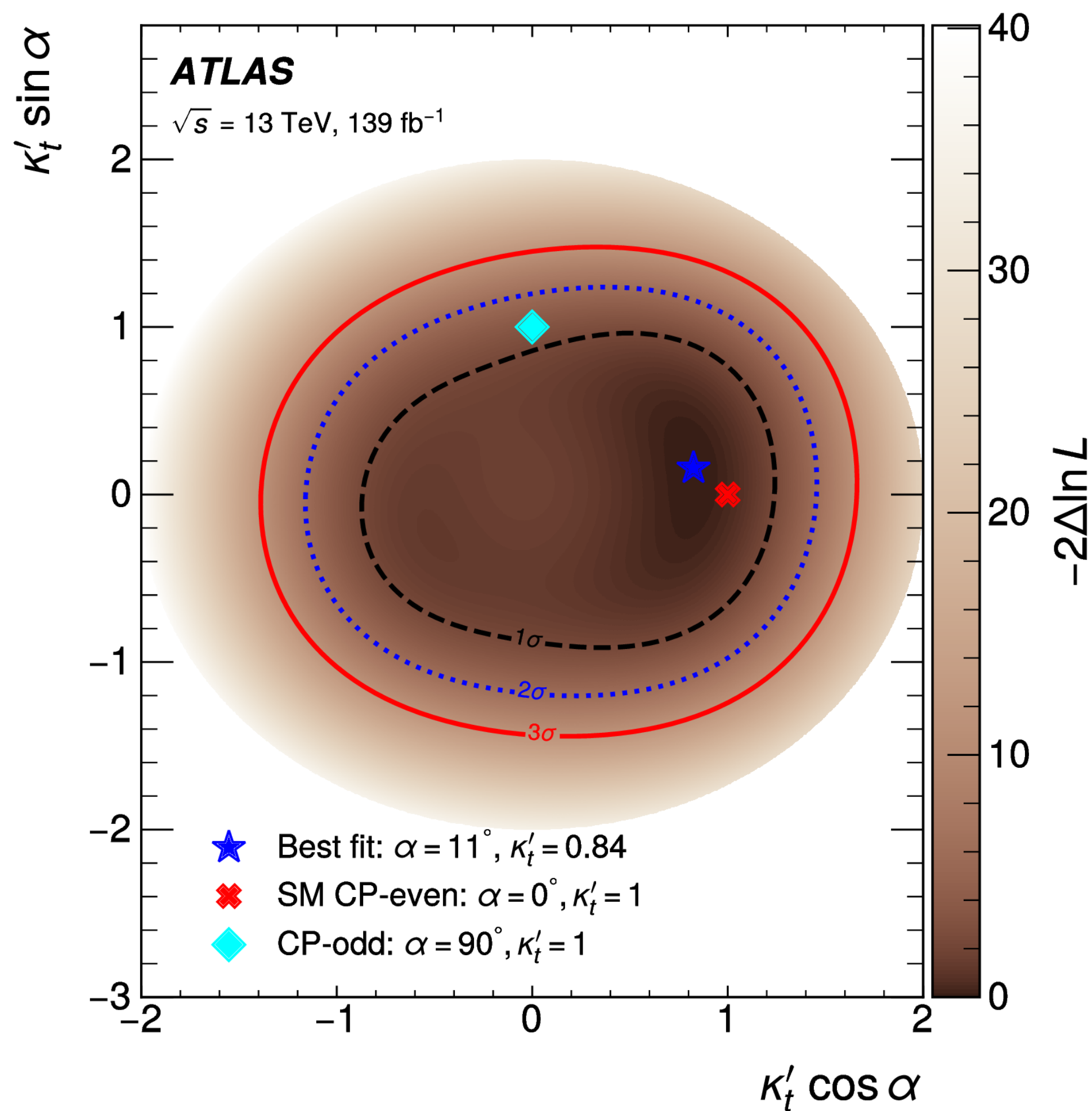




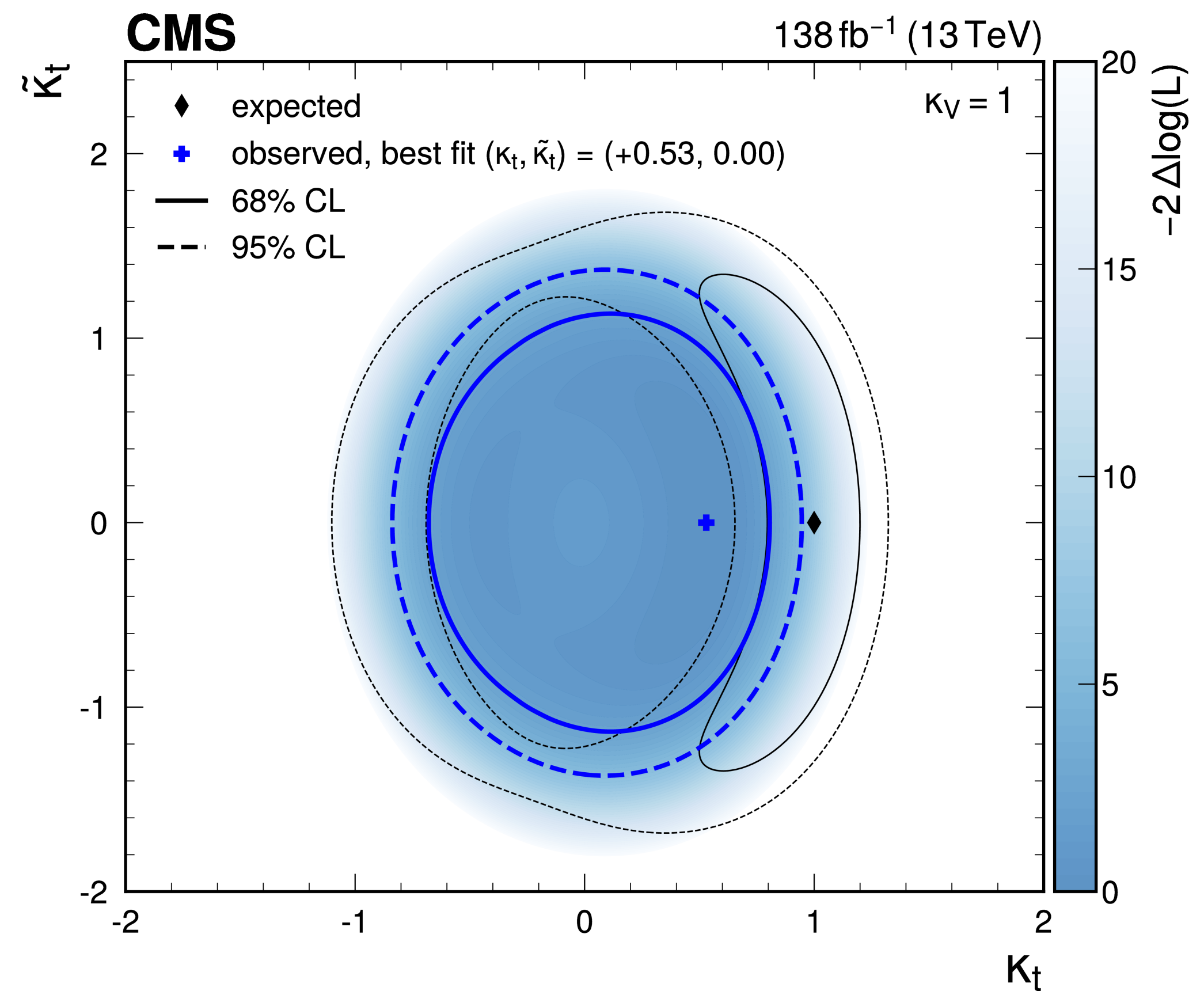
Higgs CP

► ATLAS+CMS $t\bar{t}Hbb$ CP results:

► Use information about the kinematics of the tops to construct CP-sensitive observables



[HIGG-2020-03]

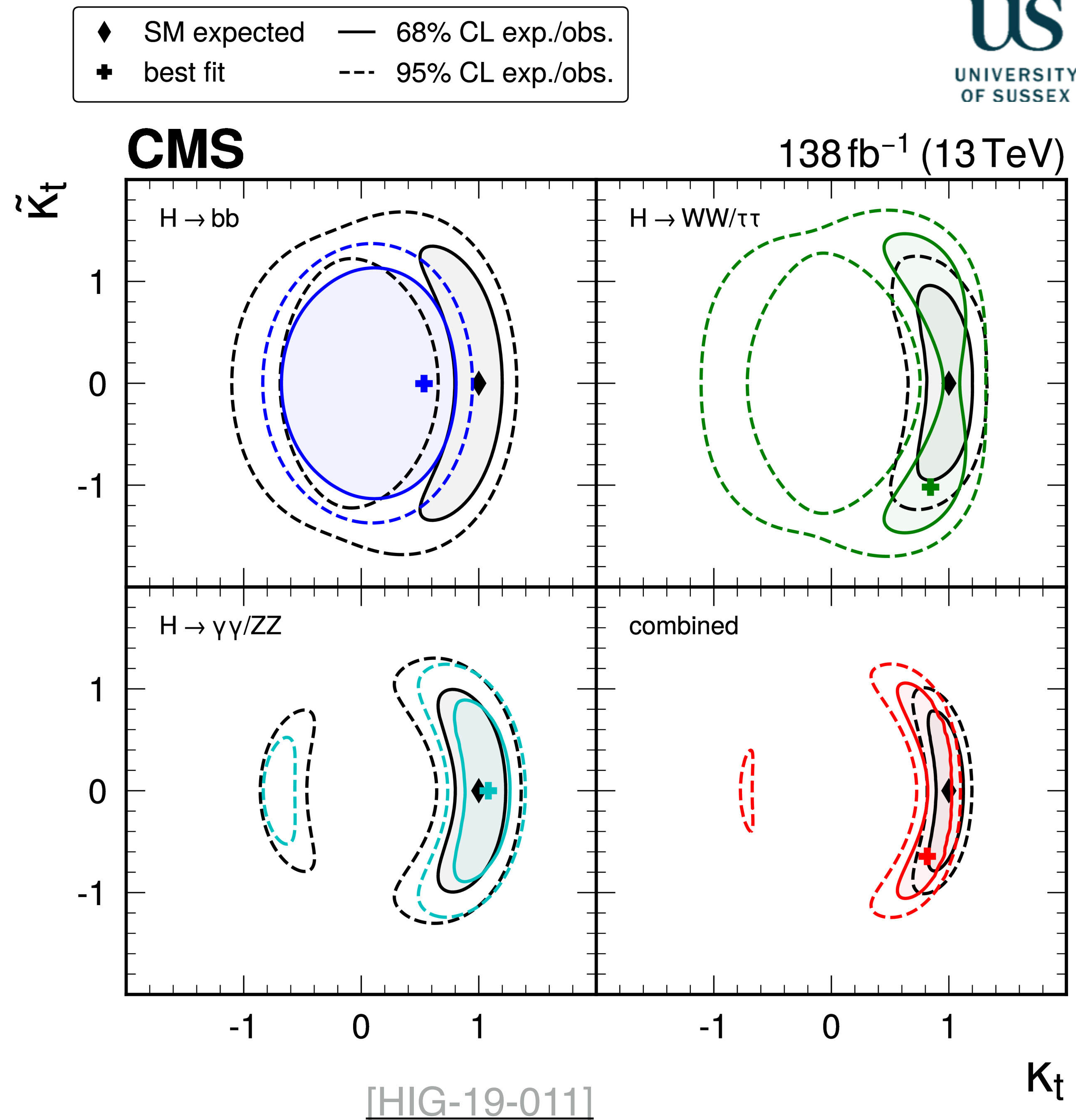


[HIG-19-011]



Higgs CP

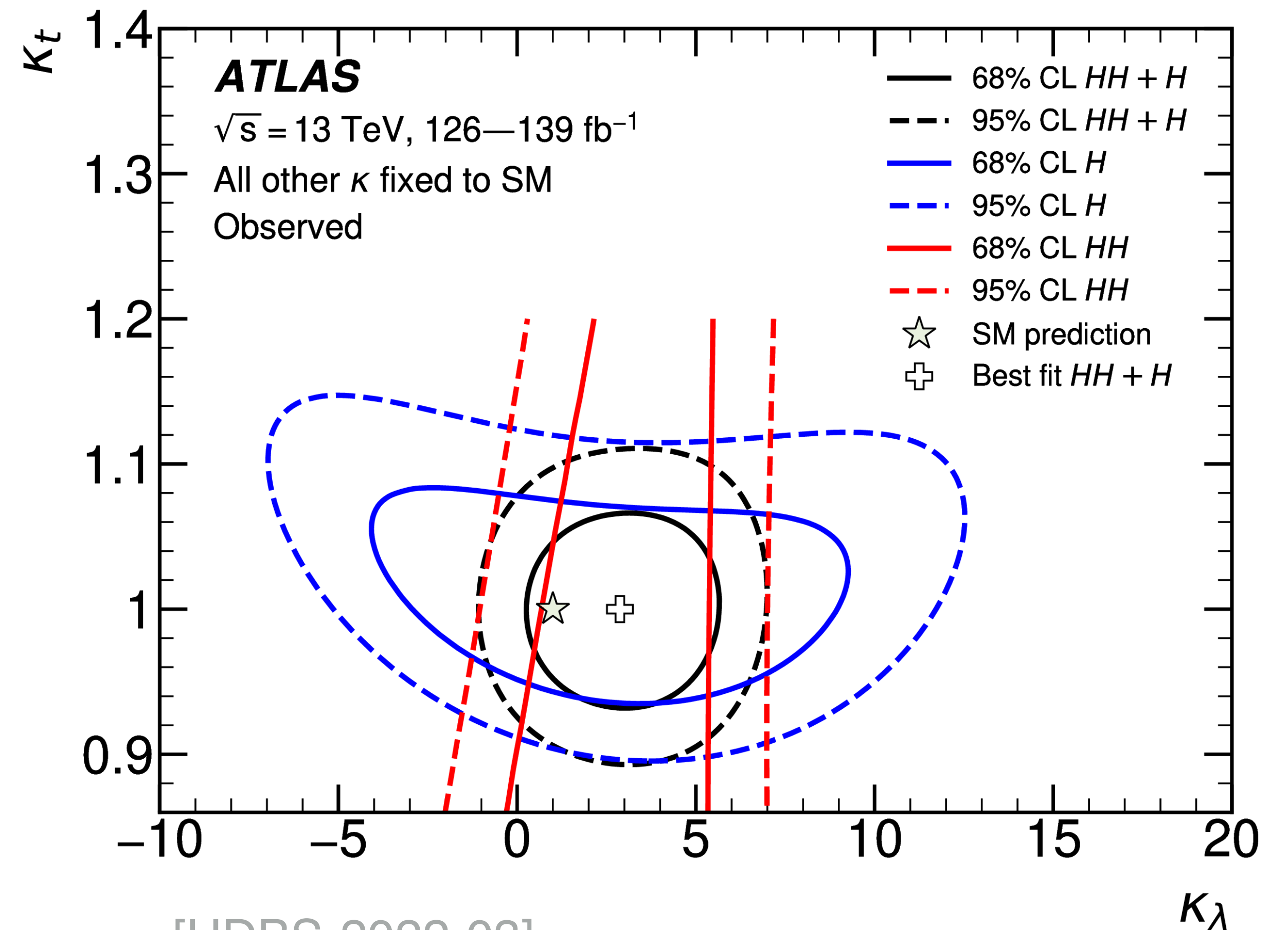
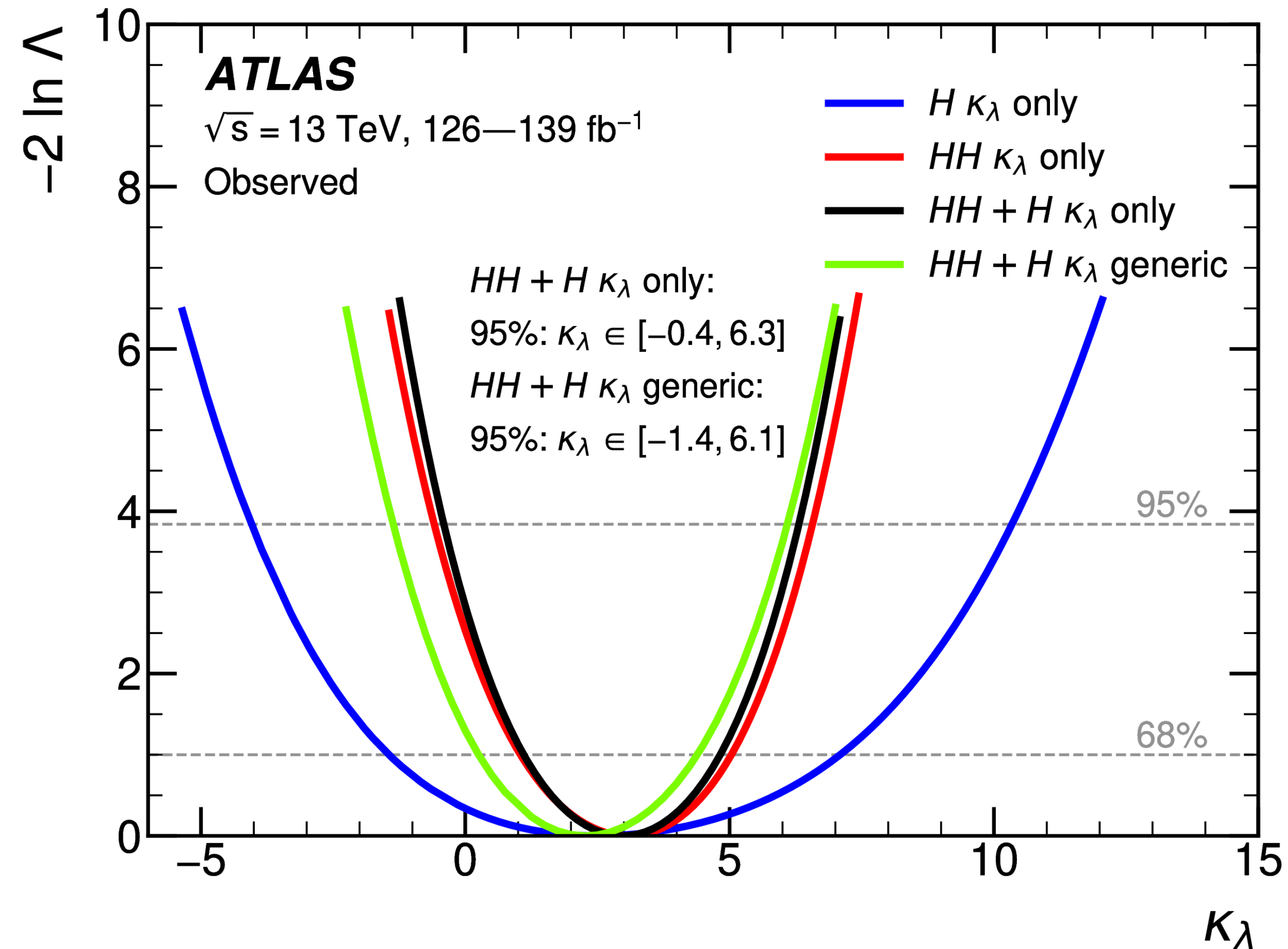
- ▶ ATLAS+CMS $t\bar{t}Hb\bar{b}$ CP results
- ▶ Use information about the kinematics of the tops to construct CP-sensitive observables
- ▶ CMS CP combination shows relative precision of different channels



Higgs self-coupling

► Single+Di-Higgs complementarity

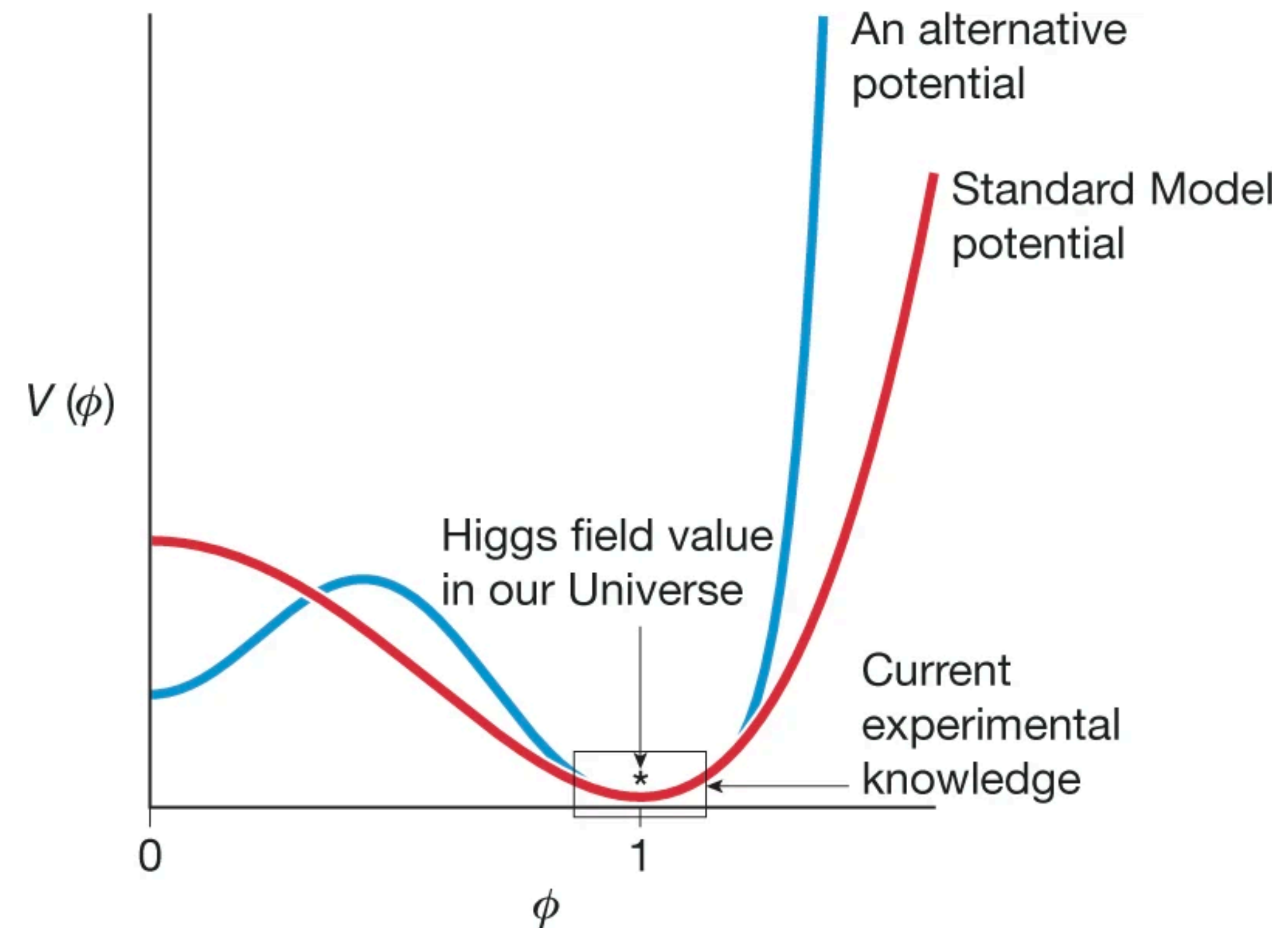
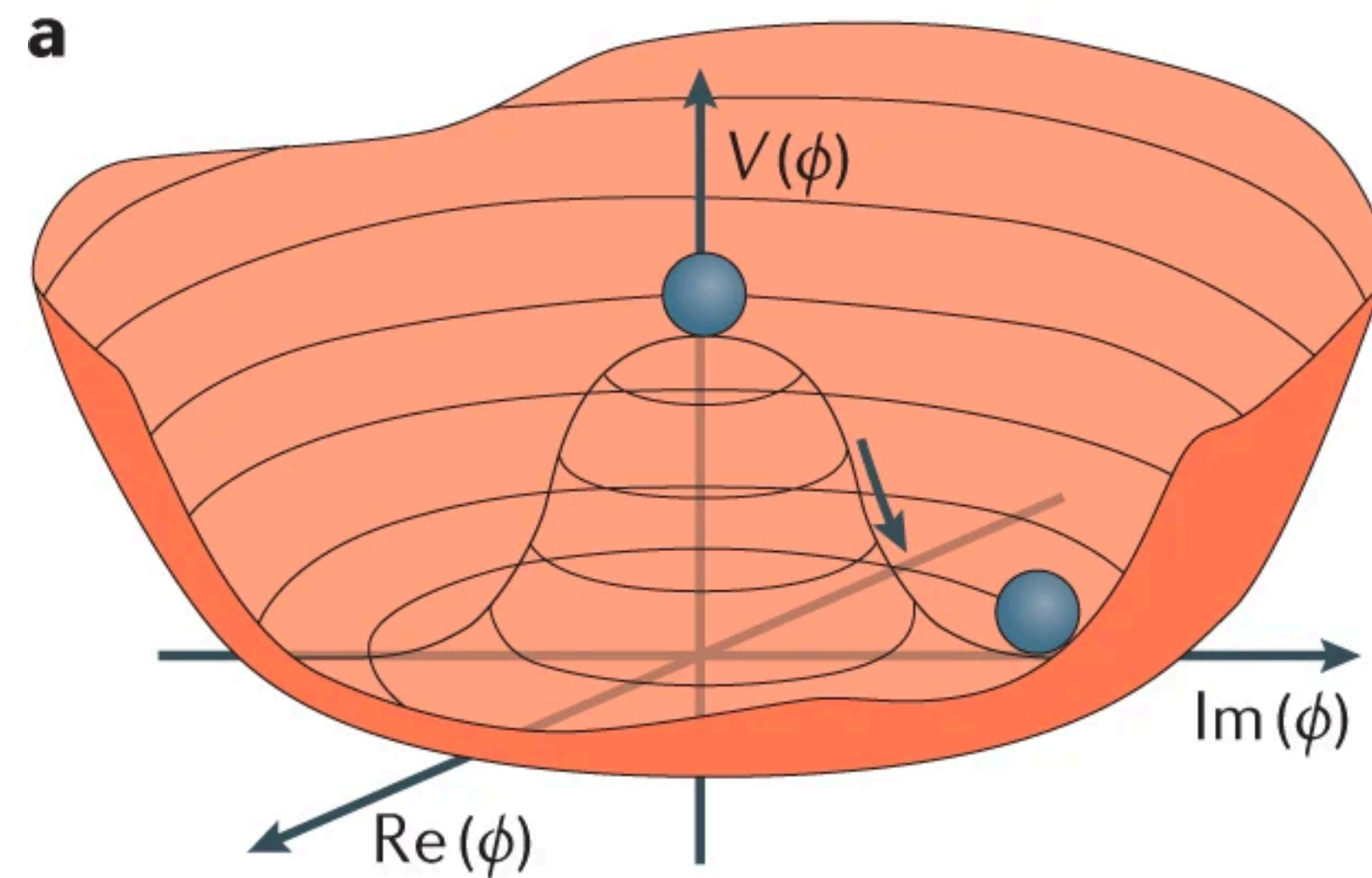
► In dedicated κ_λ fit HH dominates. Single-Higgs vital for separation with κ_t .



[HDBS-2022-03]

Higgs self-coupling

- ▶ Single+Di-Higgs complementarity
 - ▶ In dedicated κ_λ fit HH dominates. Single-Higgs vital for separation with κ_t .
- ▶ What we currently know:

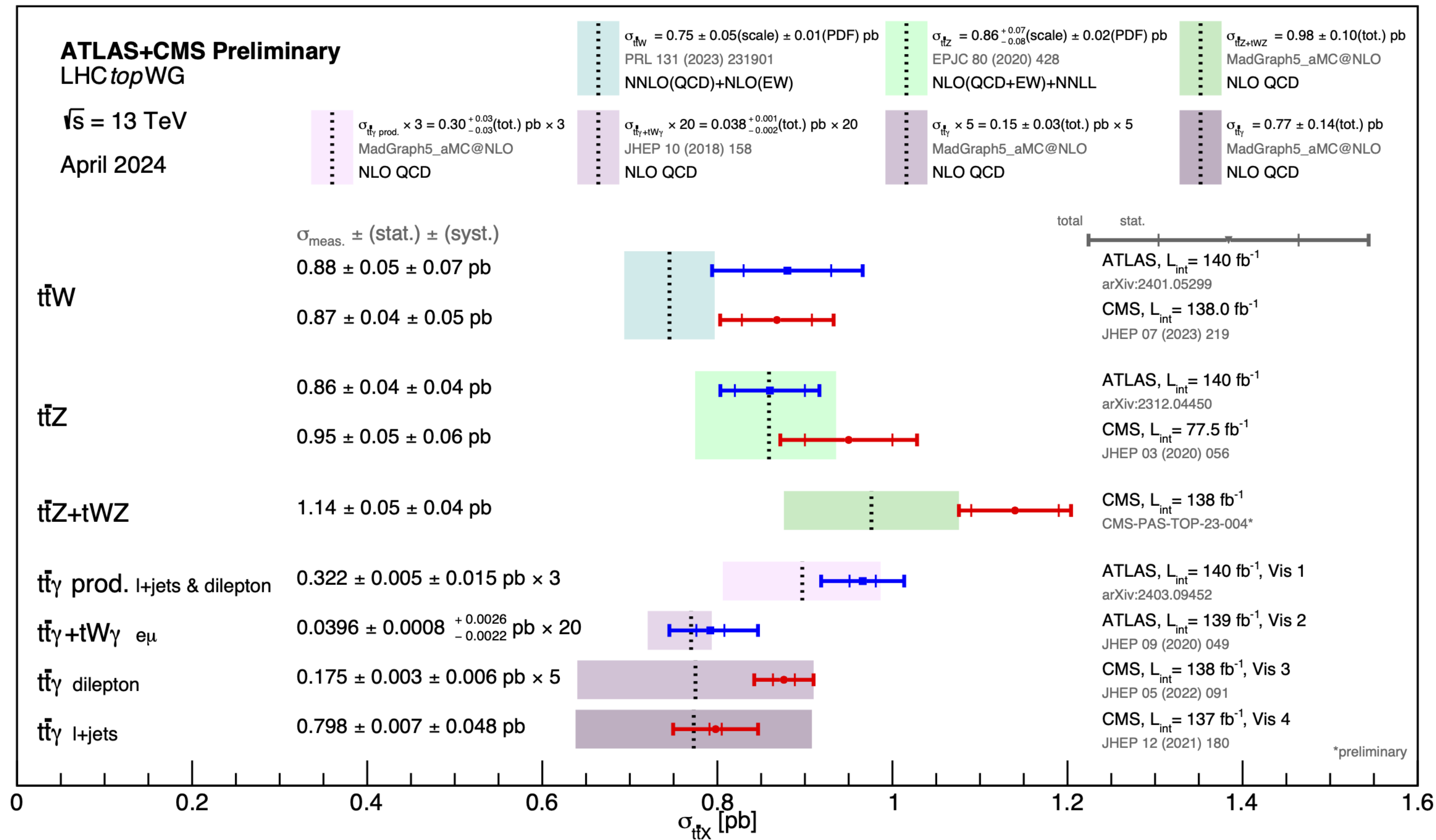


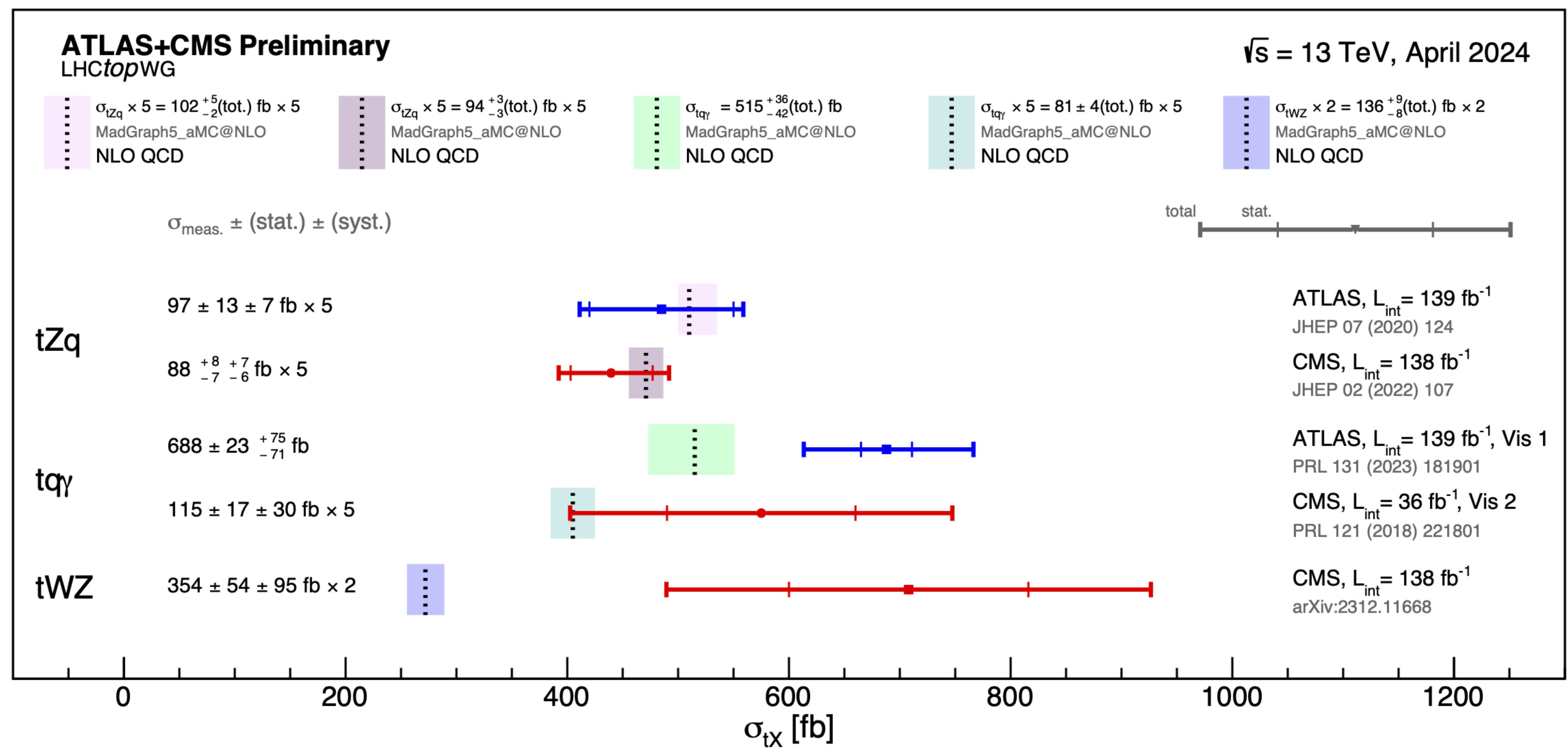
Nature 607, 41–47 (2022)

Observation/Evidence

Status of rarer/harder to identify processes





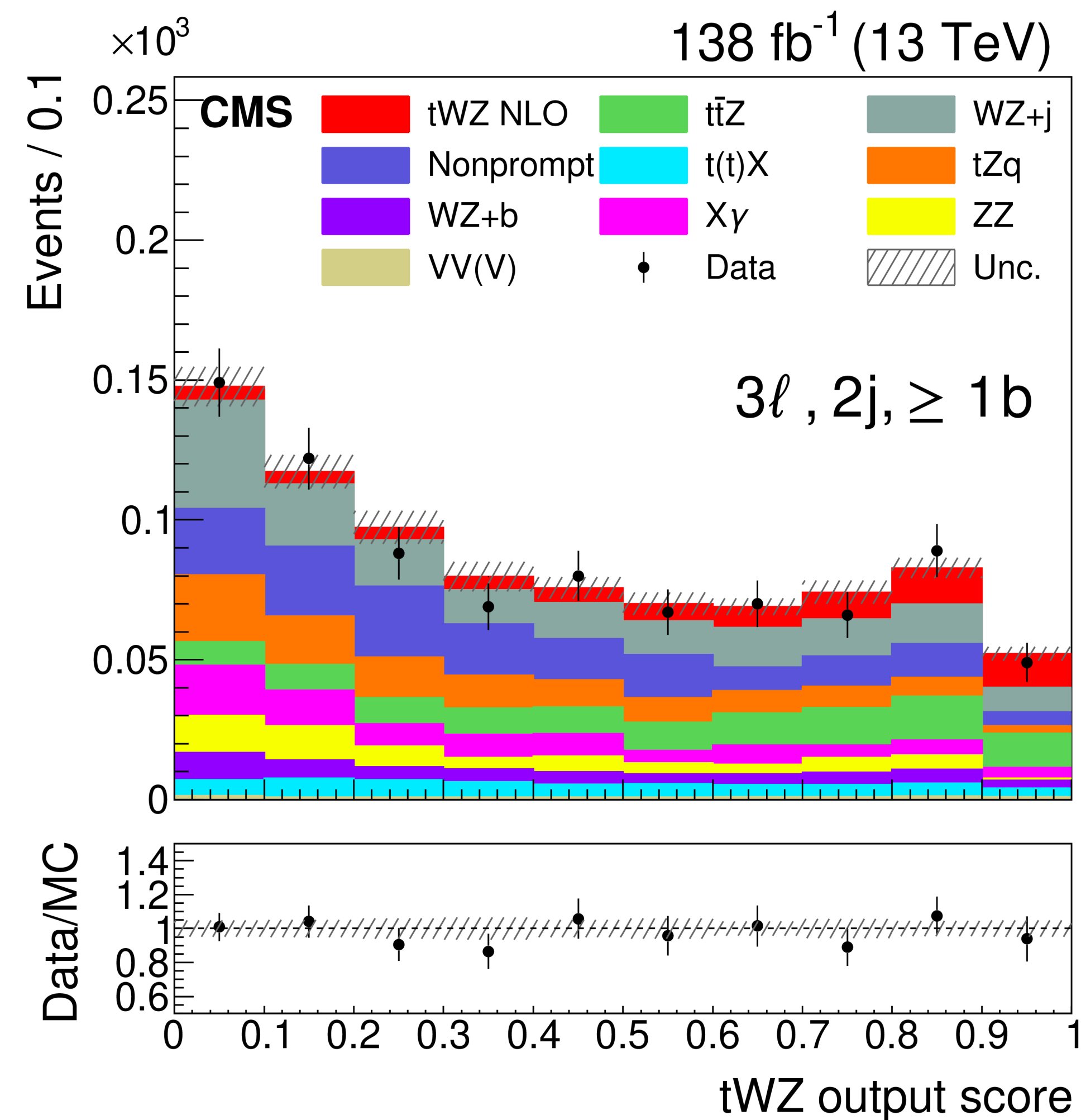
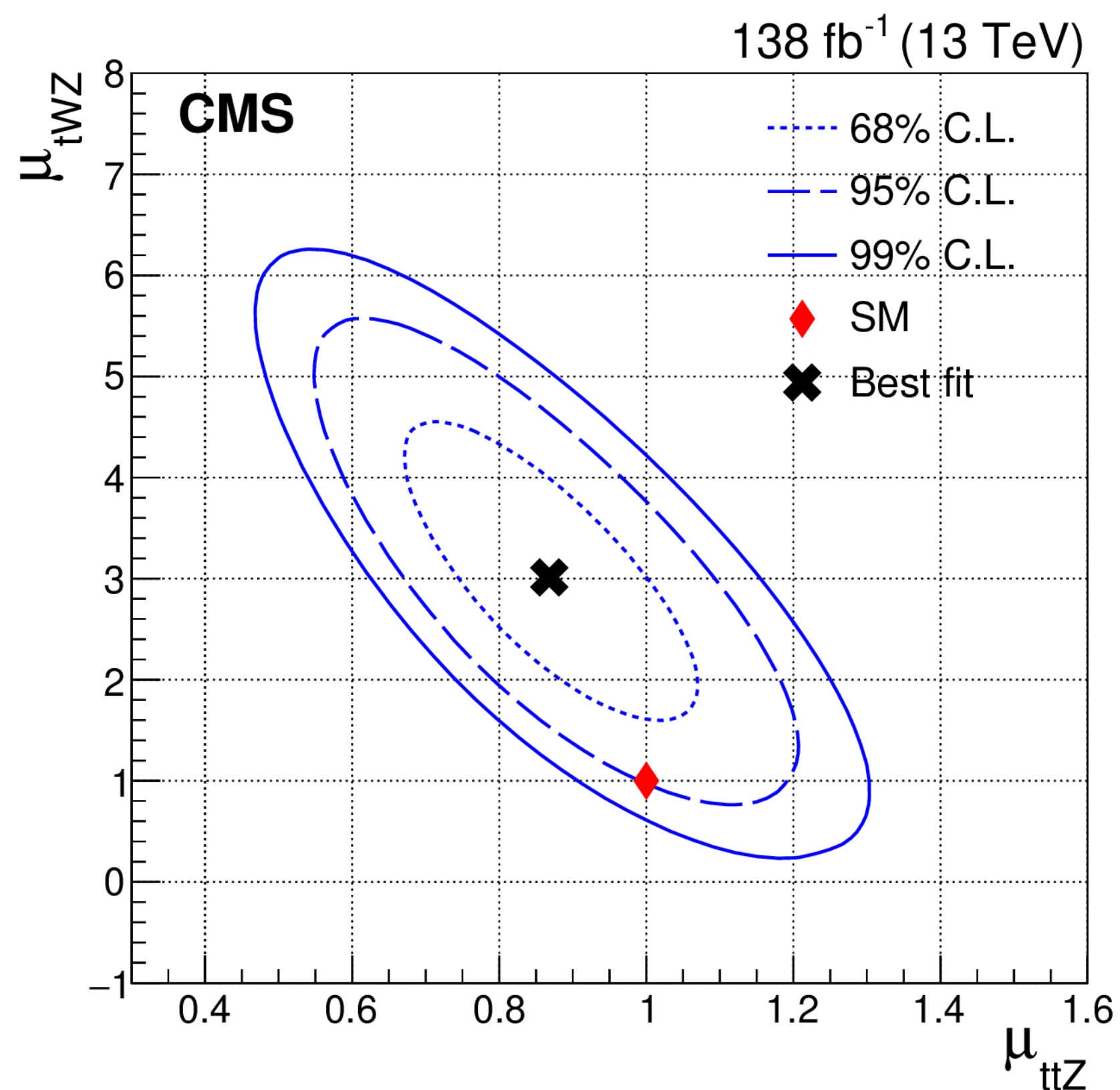




► CMS see evidence for tWZ

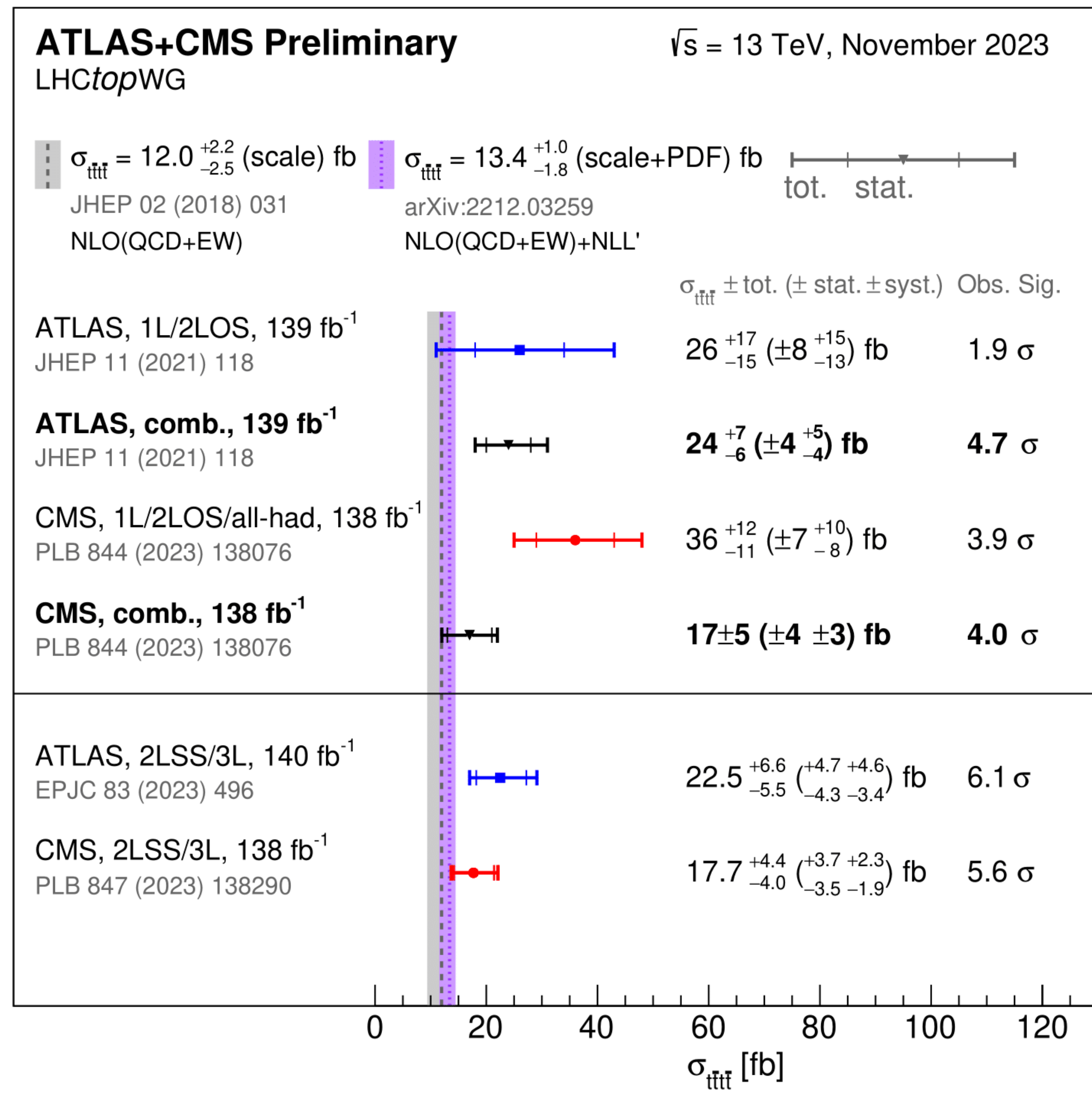
► Significance of 3.4σ (1.4σ expected)

► $\mu(\text{tWZ}) = 2.6 \pm 0.4 \text{ (stat)} \pm 0.7 \text{ (syst)}$



[TOP-22-008]

► 4-top production observed by ATLAS and CMS!

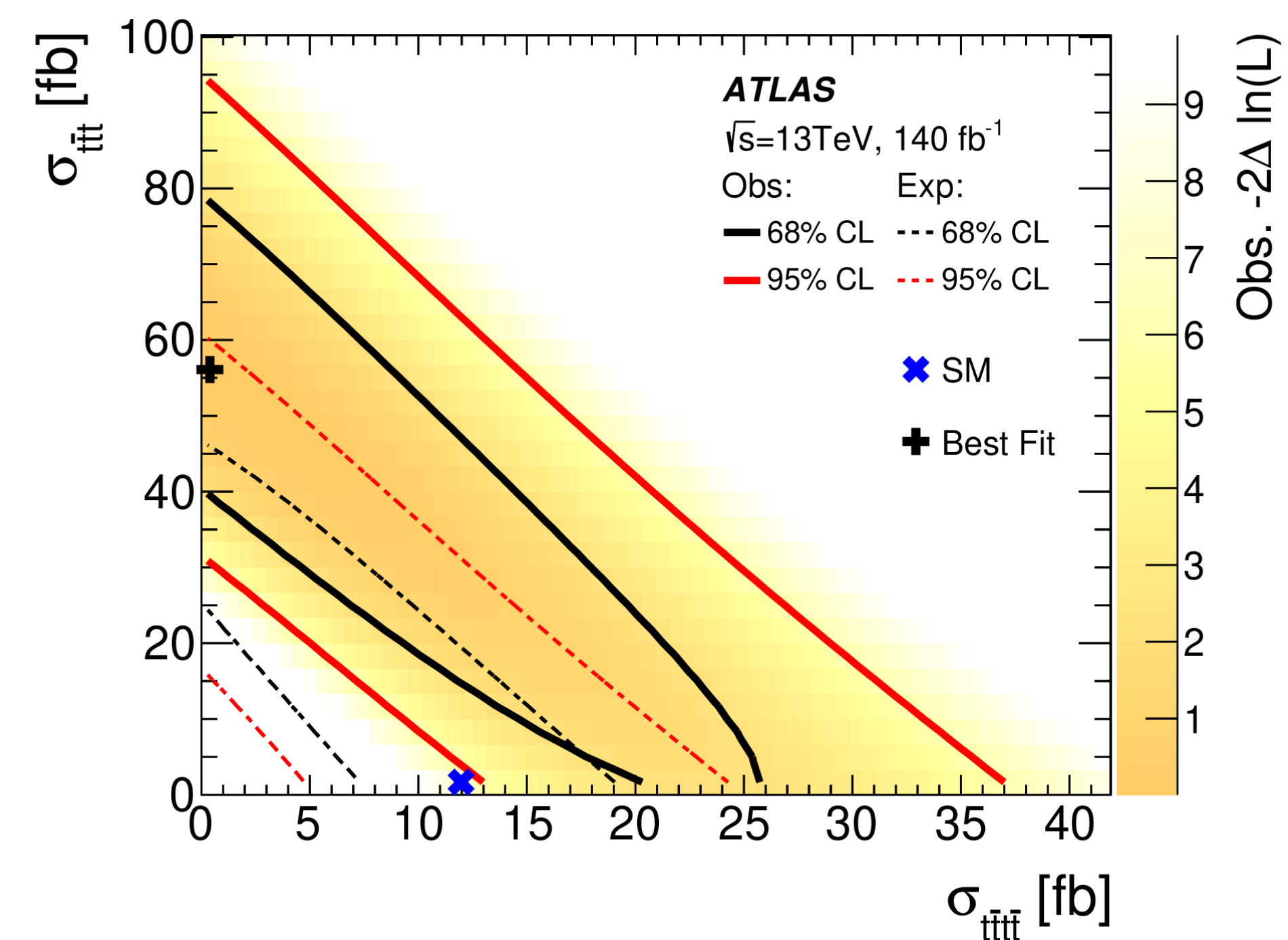
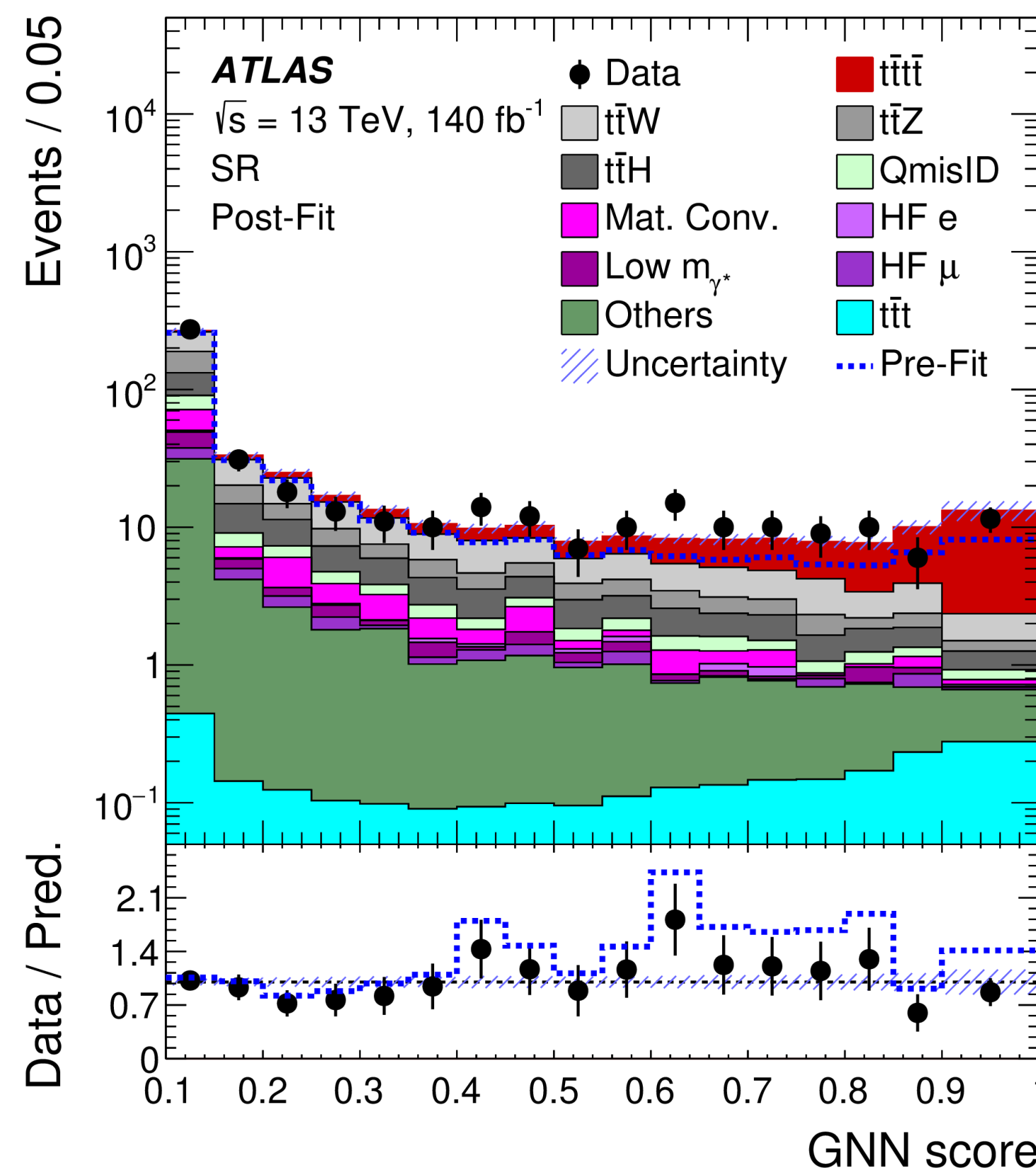


► 4-top production observed
by ATLAS and CMS!

► ATLAS

► 6.1σ (4.3σ expected)

► $\mu = 1.9 +0.8/-0.5$



[TOPQ-2021-08]

4-tops

► 4-top production observed by ATLAS and CMS!

► ATLAS

► 6.1σ (4.3σ expected)

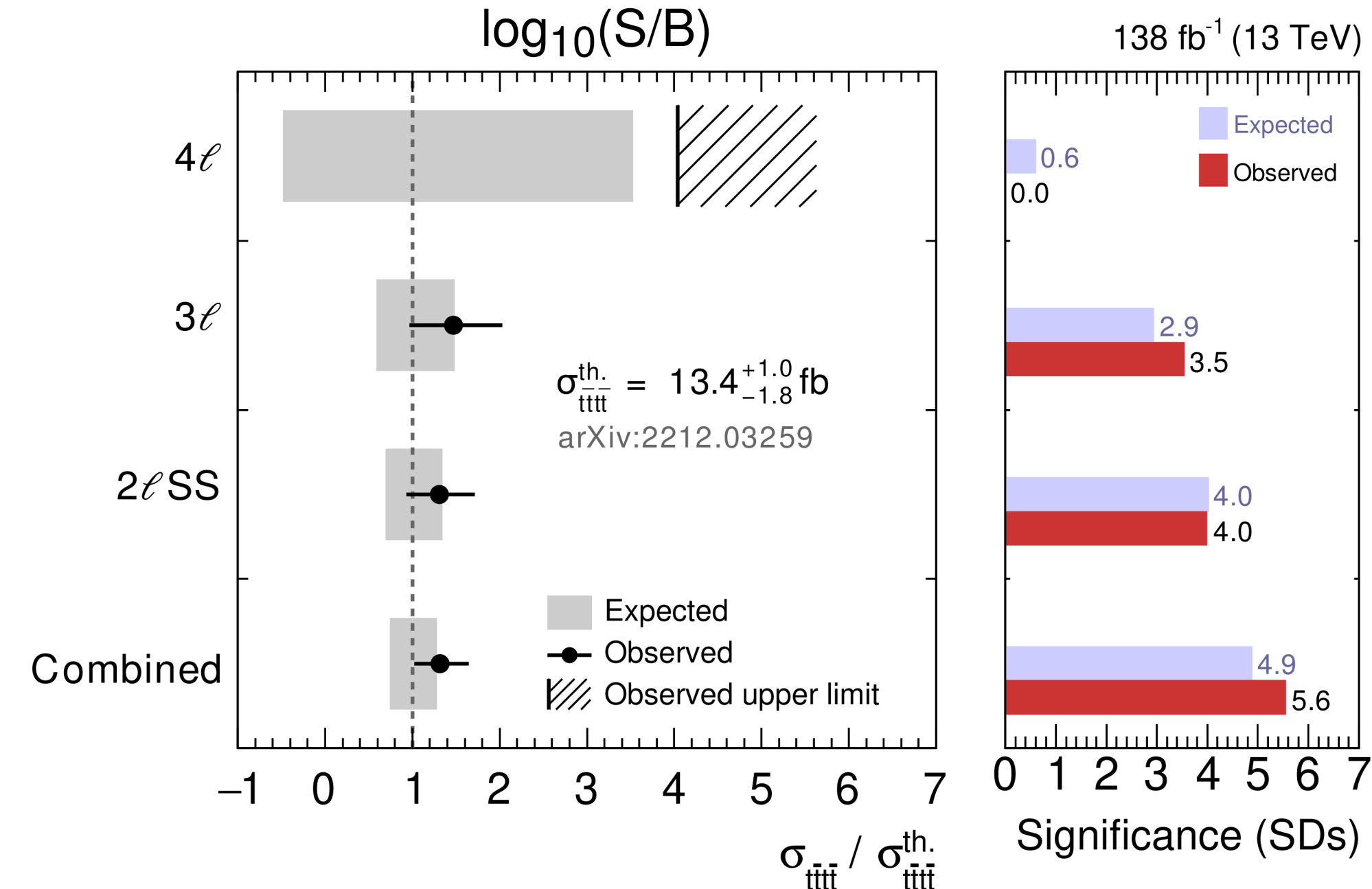
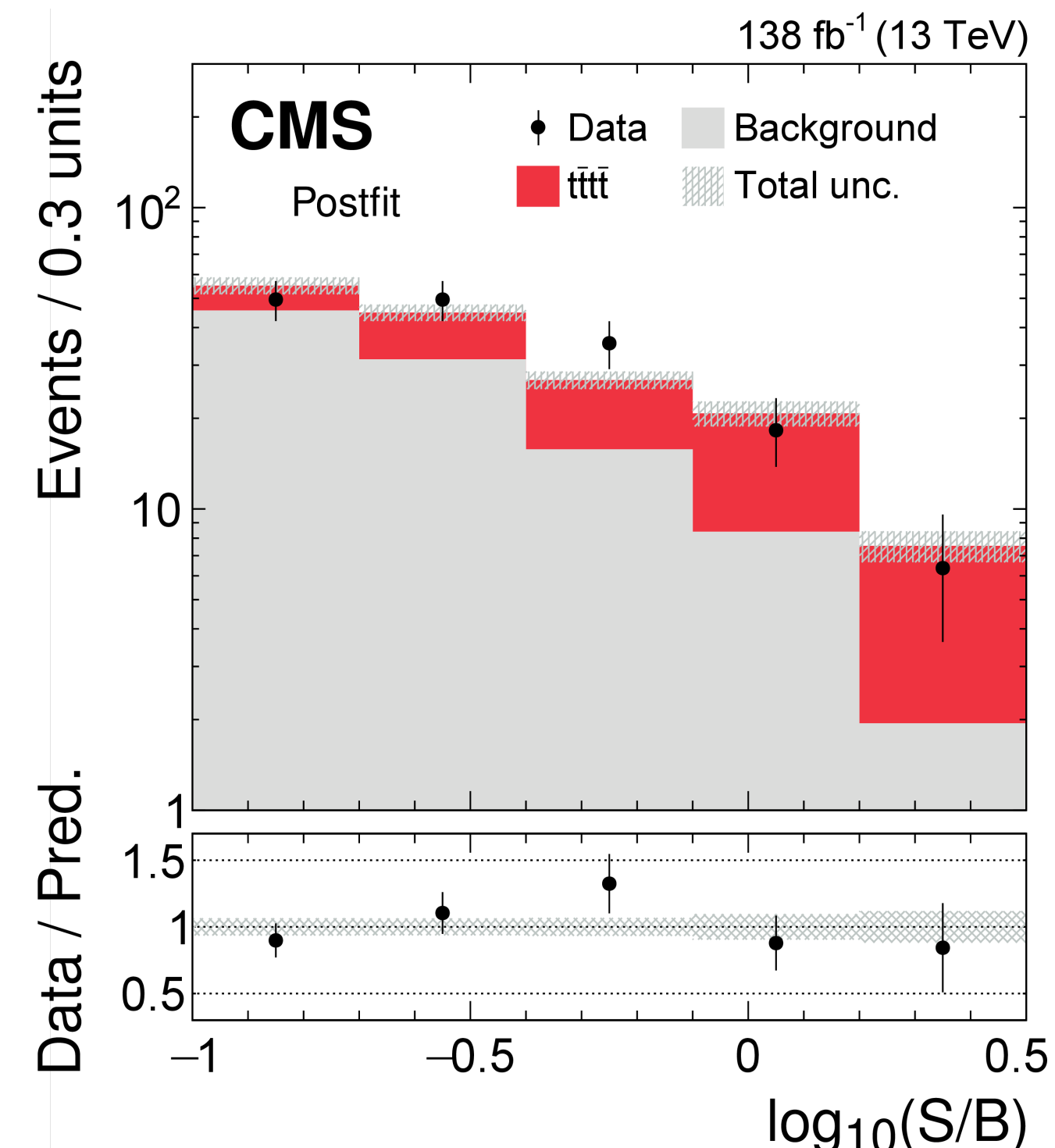
► $\mu = 1.9 +0.8/-0.5$

► CMS

► 5.6σ (4.9σ expected)

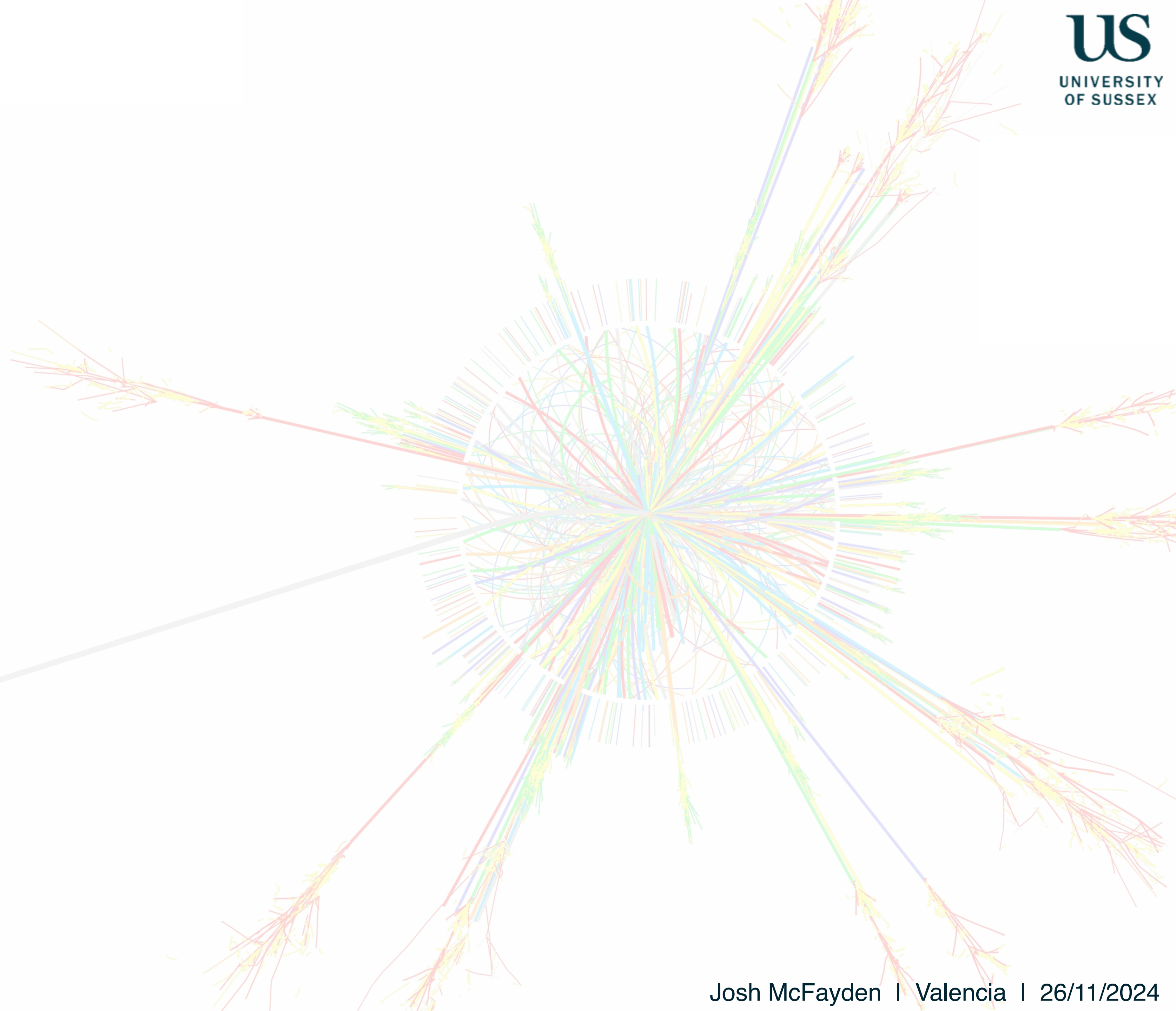
► $\mu = 1.32 +0.33/-0.30$

► In agreement with SM ($13.4 +1.0/-1.8$ fb) at 1σ (including both uncertainties)



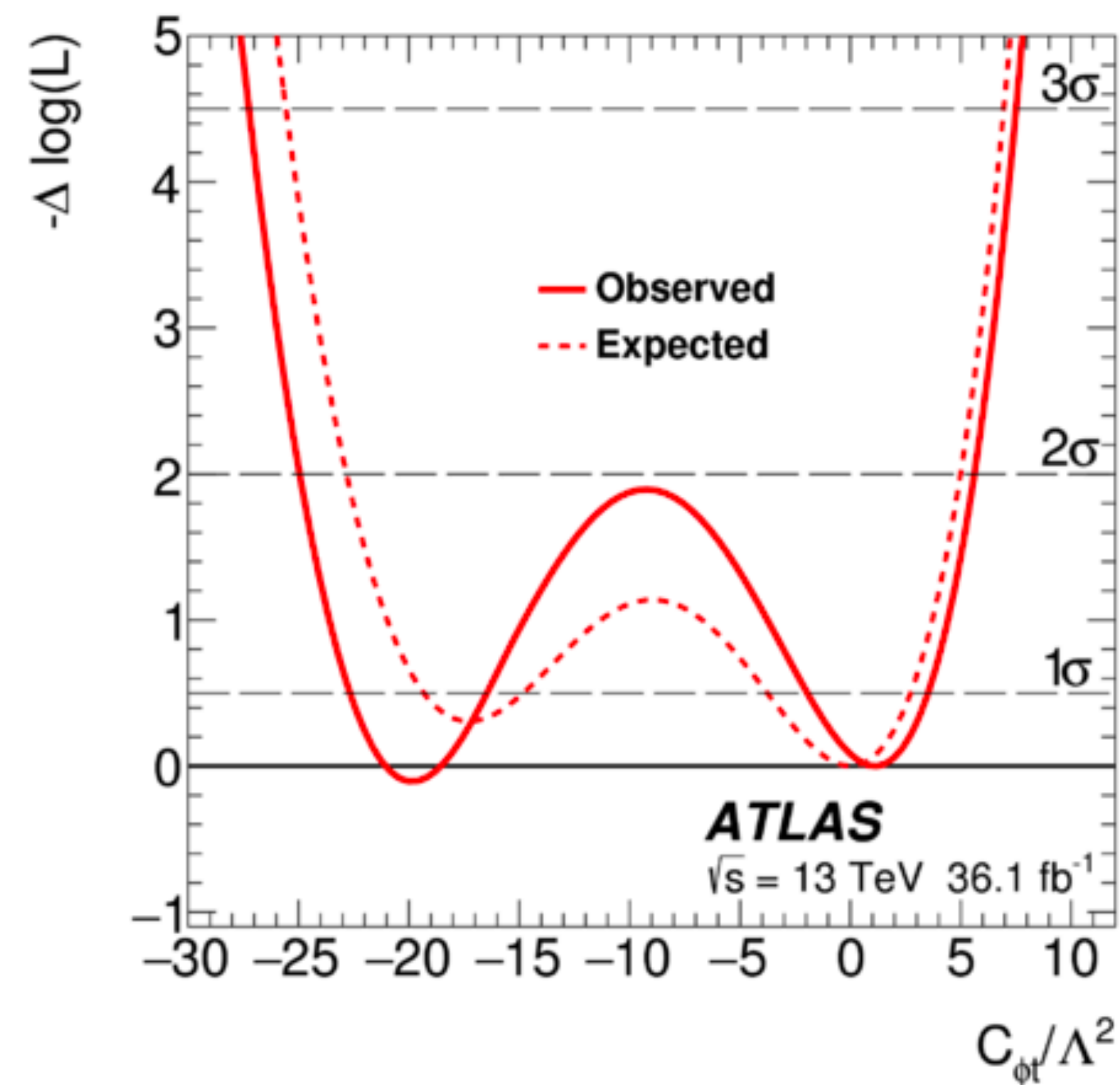
[TOP-22-013]

Top+X EFT



Mini history of EFT in top

- ▶ Single process one operator at a time

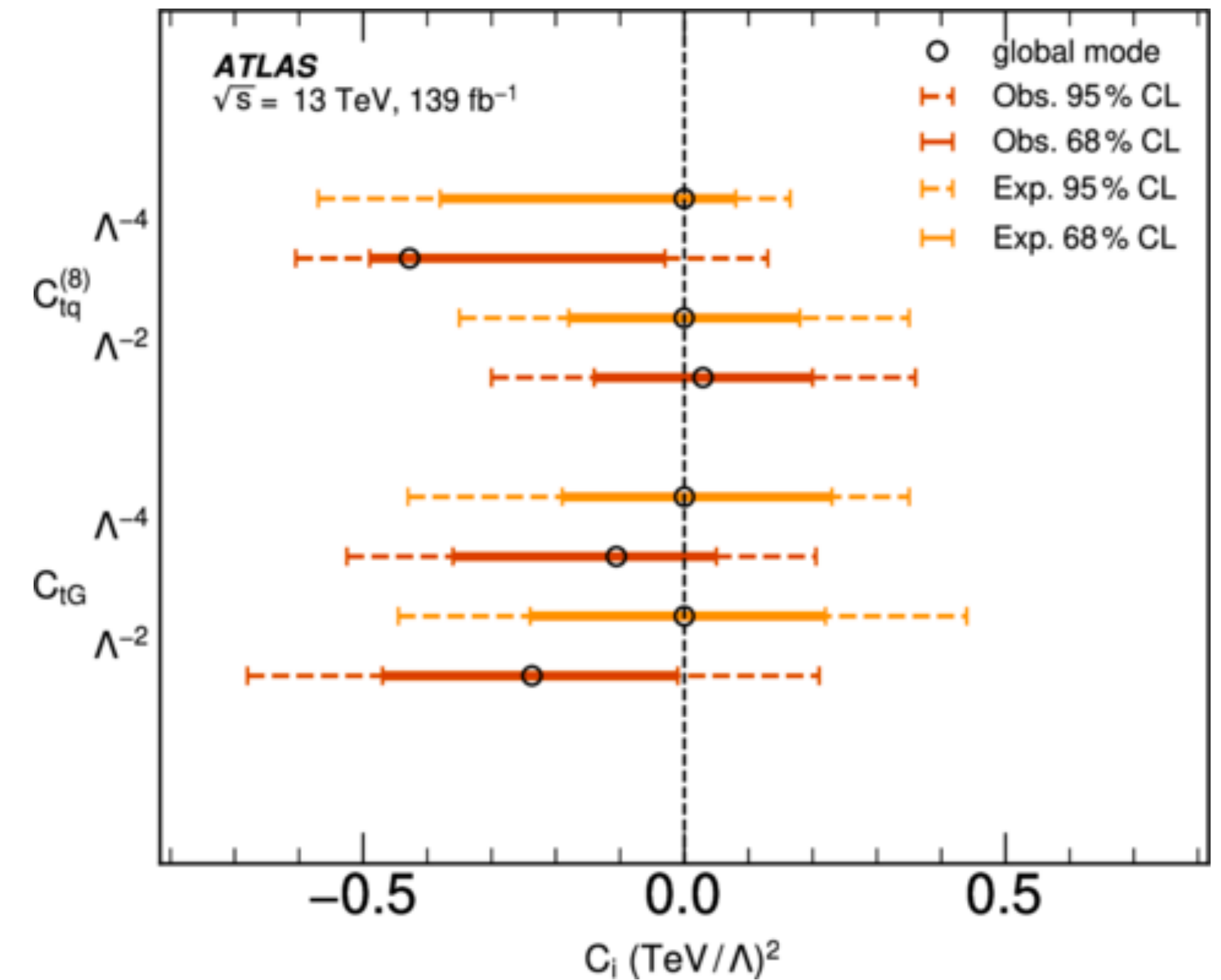


[TOPQ-2016-11]



Mini history of EFT in top

- ▶ Single process one operator at a time
- ▶ Single process multiple operators

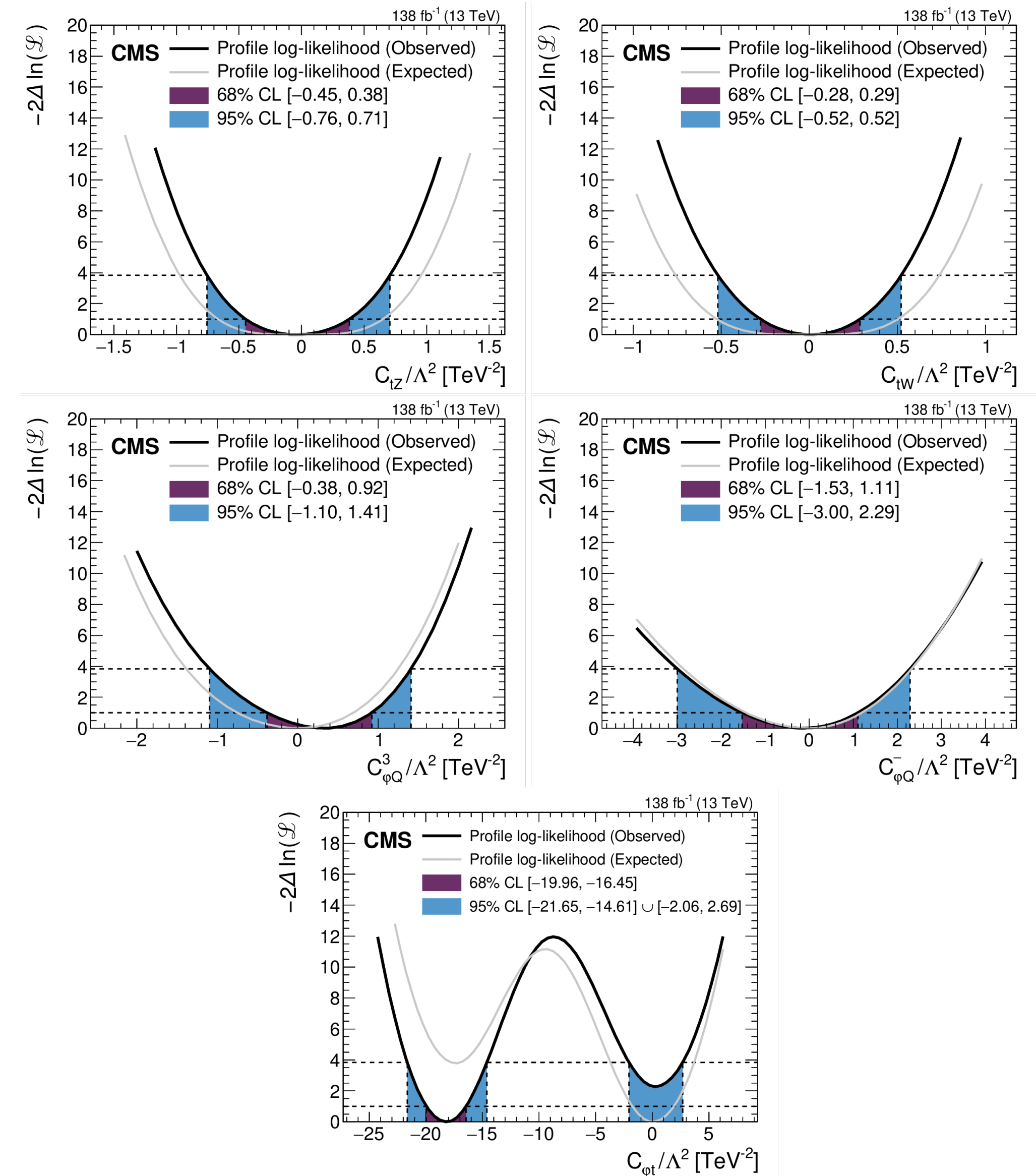


[TOPQ-2019-23]



Mini history of EFT in top

- ▶ Single process one operator at a time
- ▶ Single process multiple operators
- ▶ Multiple processes single operators

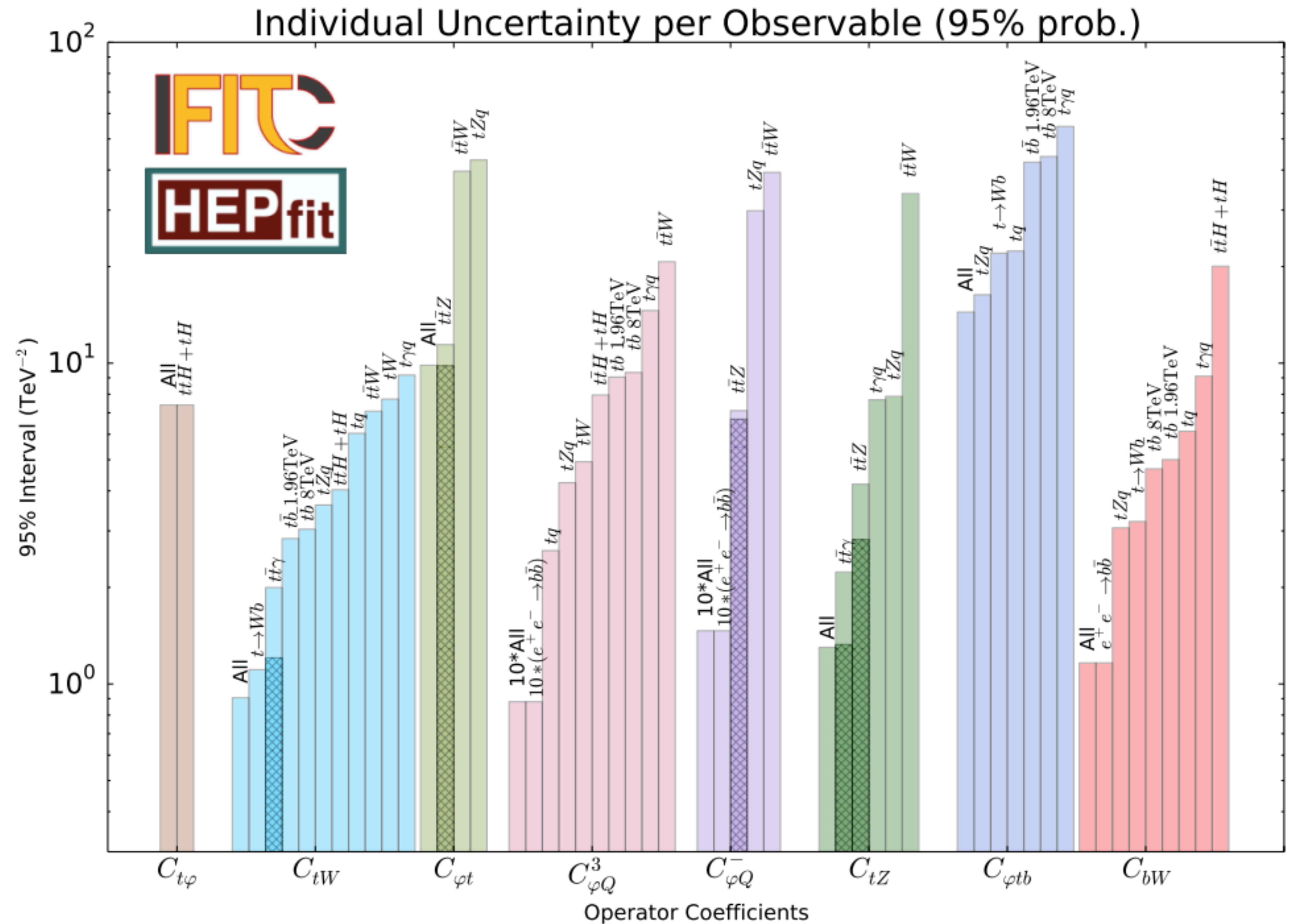


[TOP-21-001]



Mini history of EFT in top

- Studies (by this group!) show that sensitivity comes from many different processes
- As previously discussed very hard to gain pure regions for a single process
- Especially in multi-lepton final state
- Important to look at many processes simultaneously

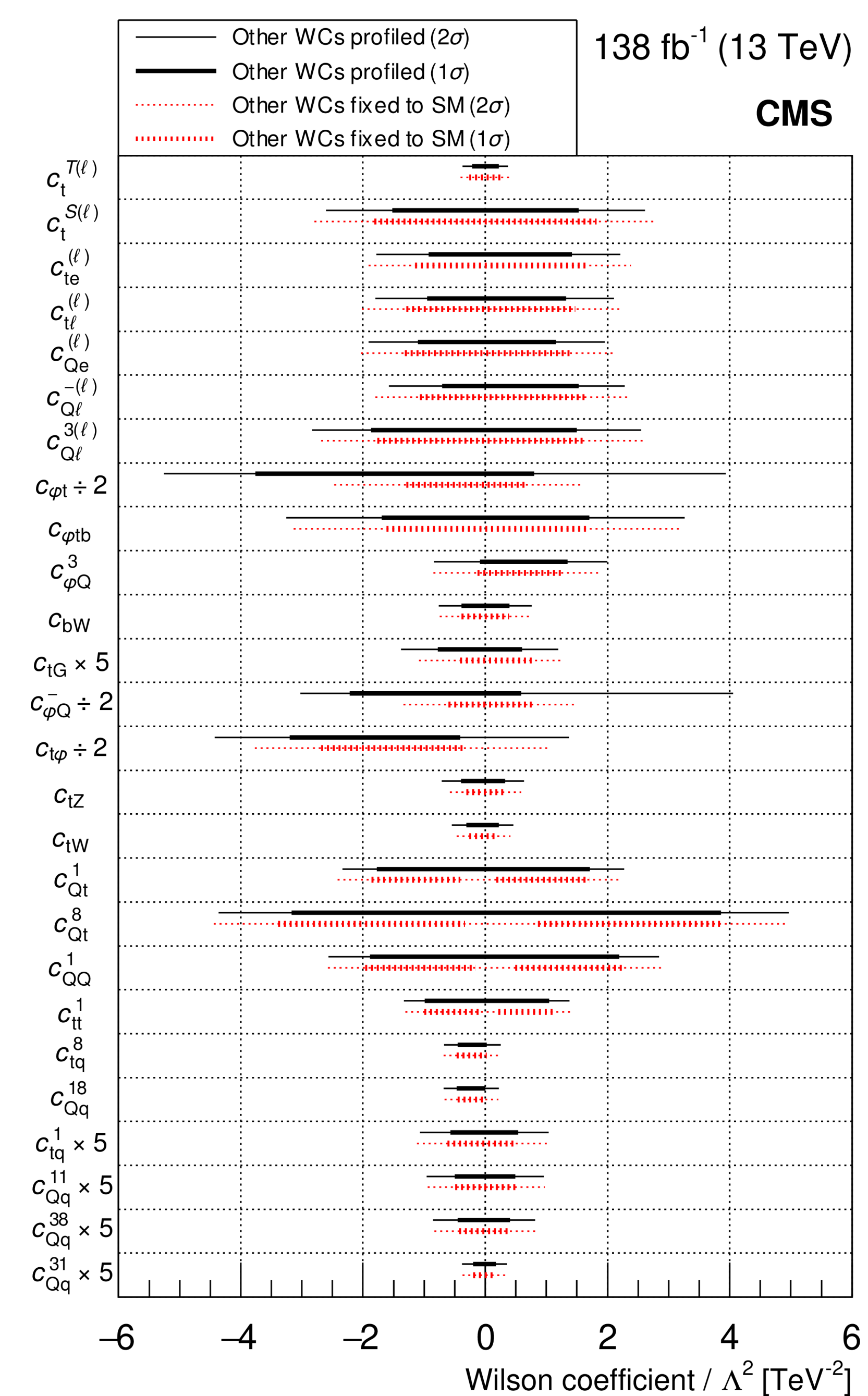
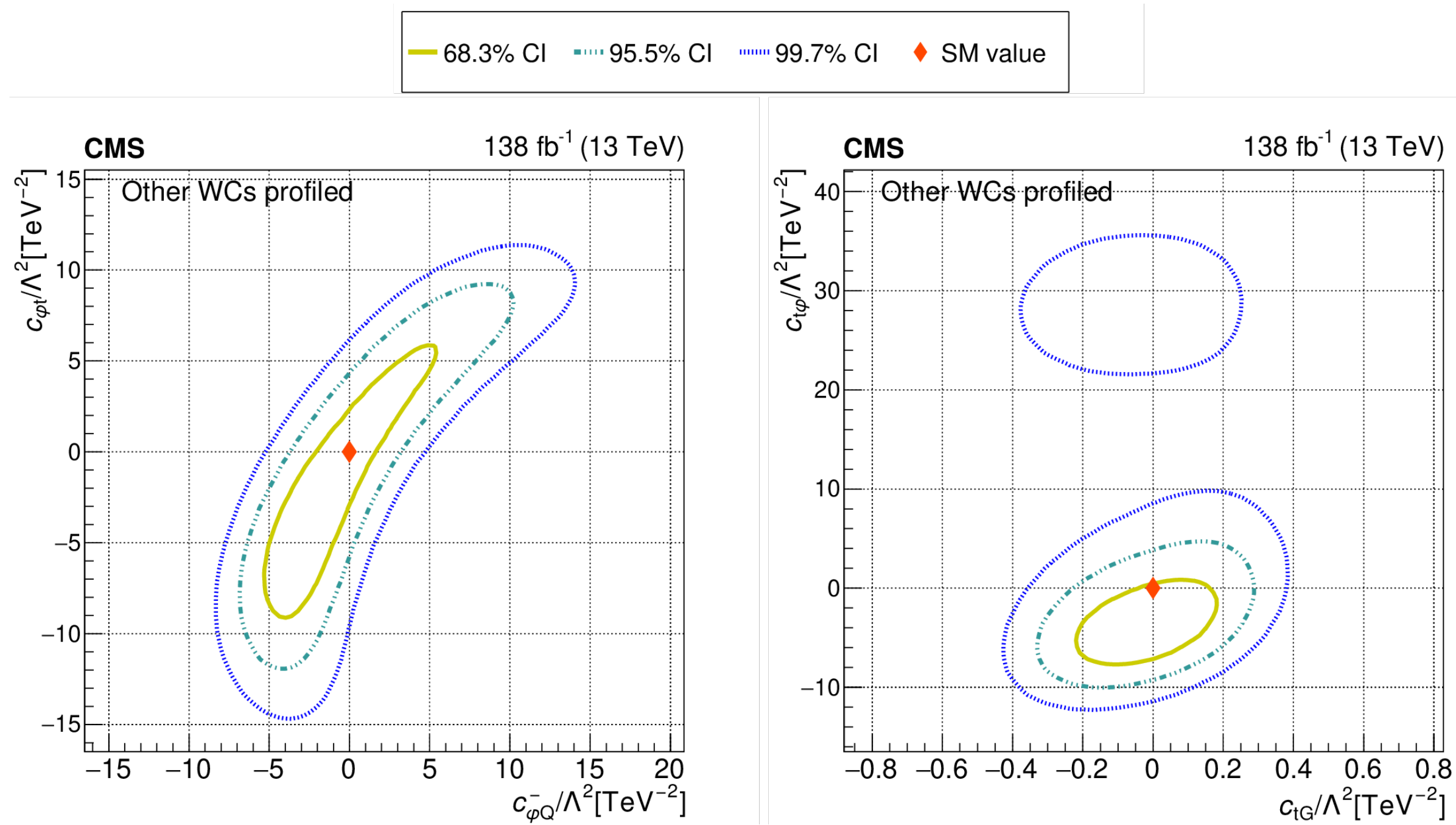


[arXiv:2107.13917]



CMS Top+X EFT

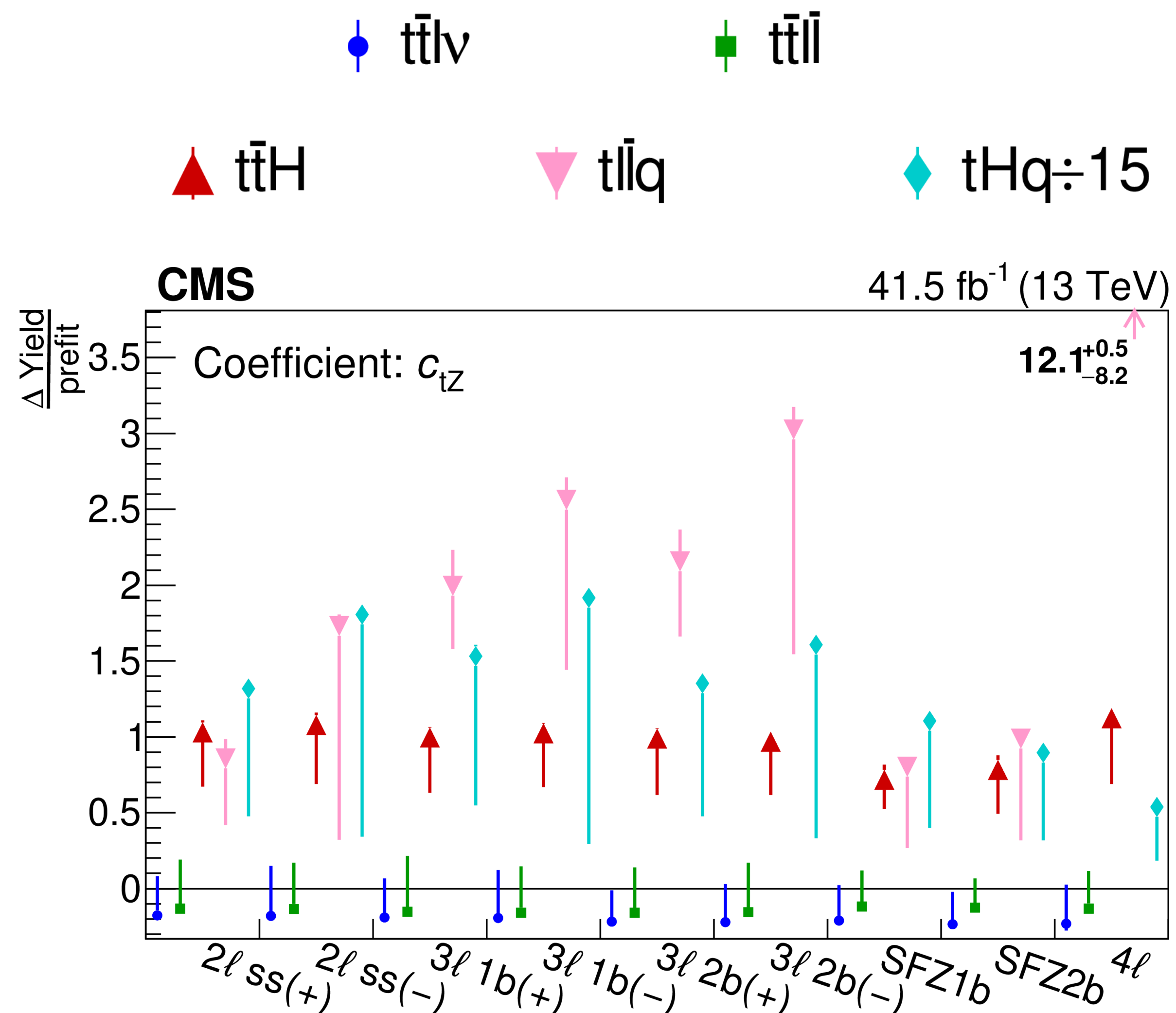
- CMS have complex multi-leptons analysis
- Impressive constraining power even in multi-operator fit
- Able to probe correlations between operators
- No significant deviation from SM



[TOP-22-006]

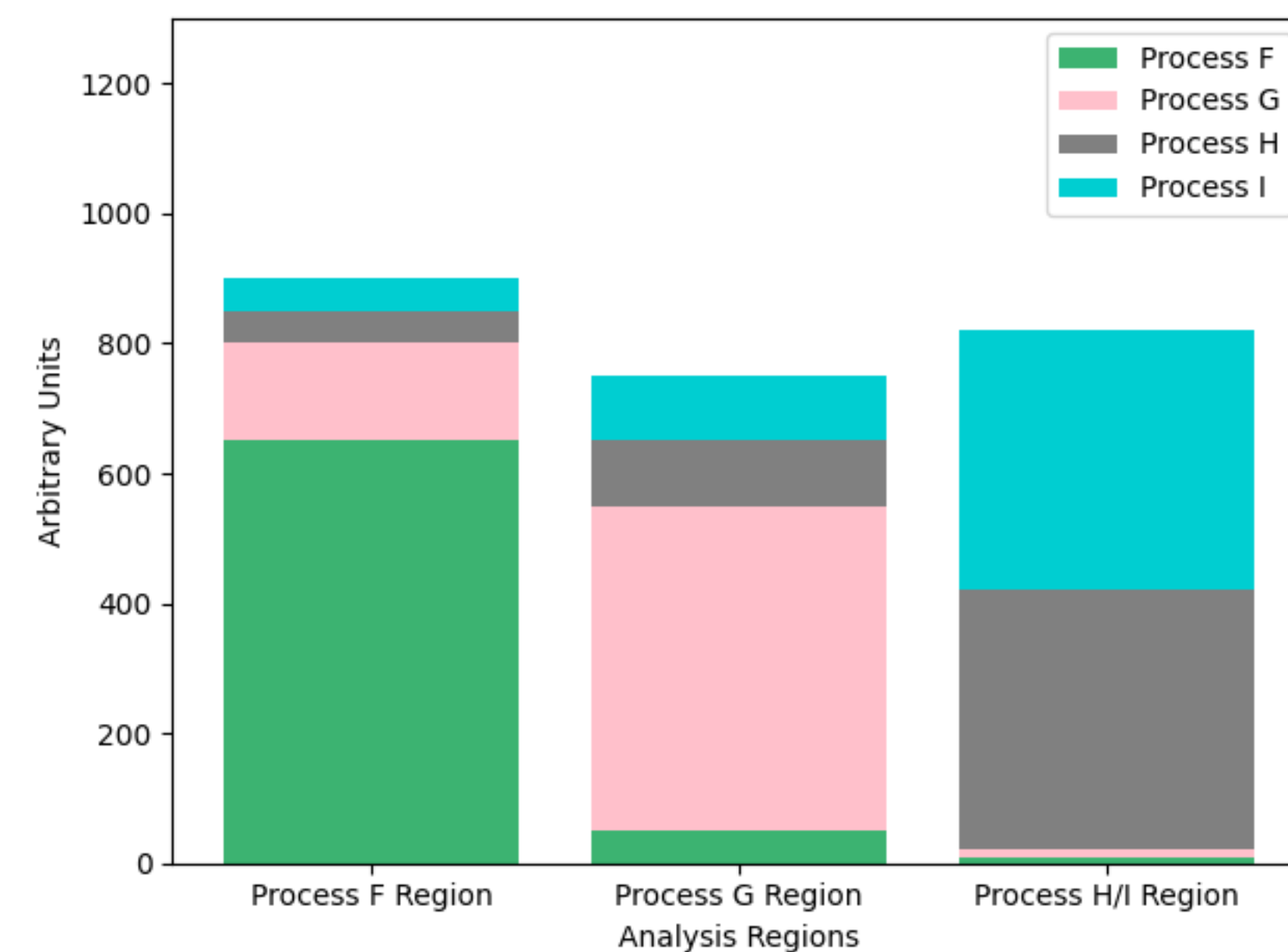
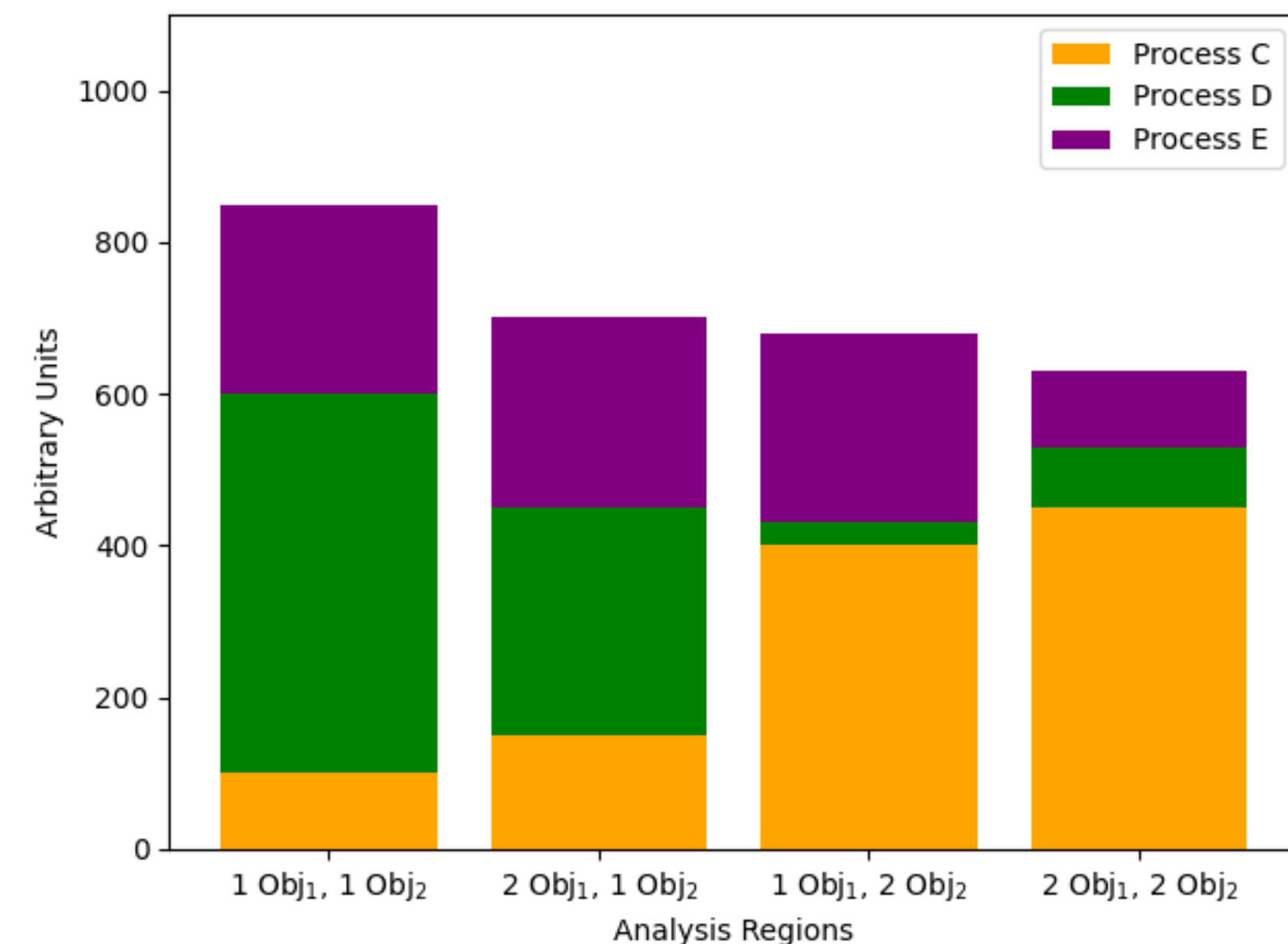


- ▶ CMS have complex multi-leptons analysis
- ▶ Impressive constraining power even in multi-operator fit
- ▶ Able to probe correlations between operators
- ▶ No significant deviation from SM
- ▶ A word of caution:
 - ▶ Can be very hard to understand everything that happens in these fits!

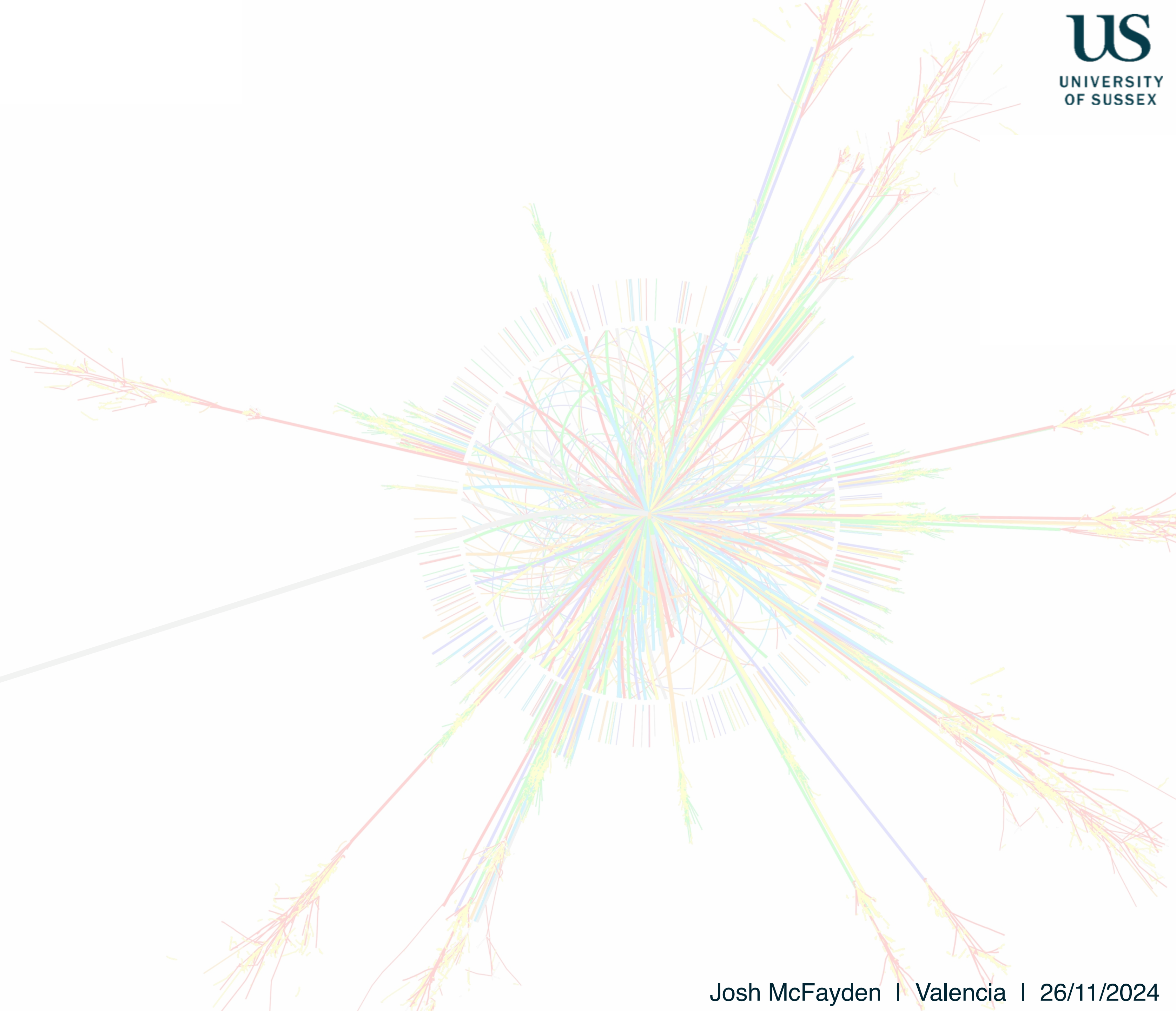


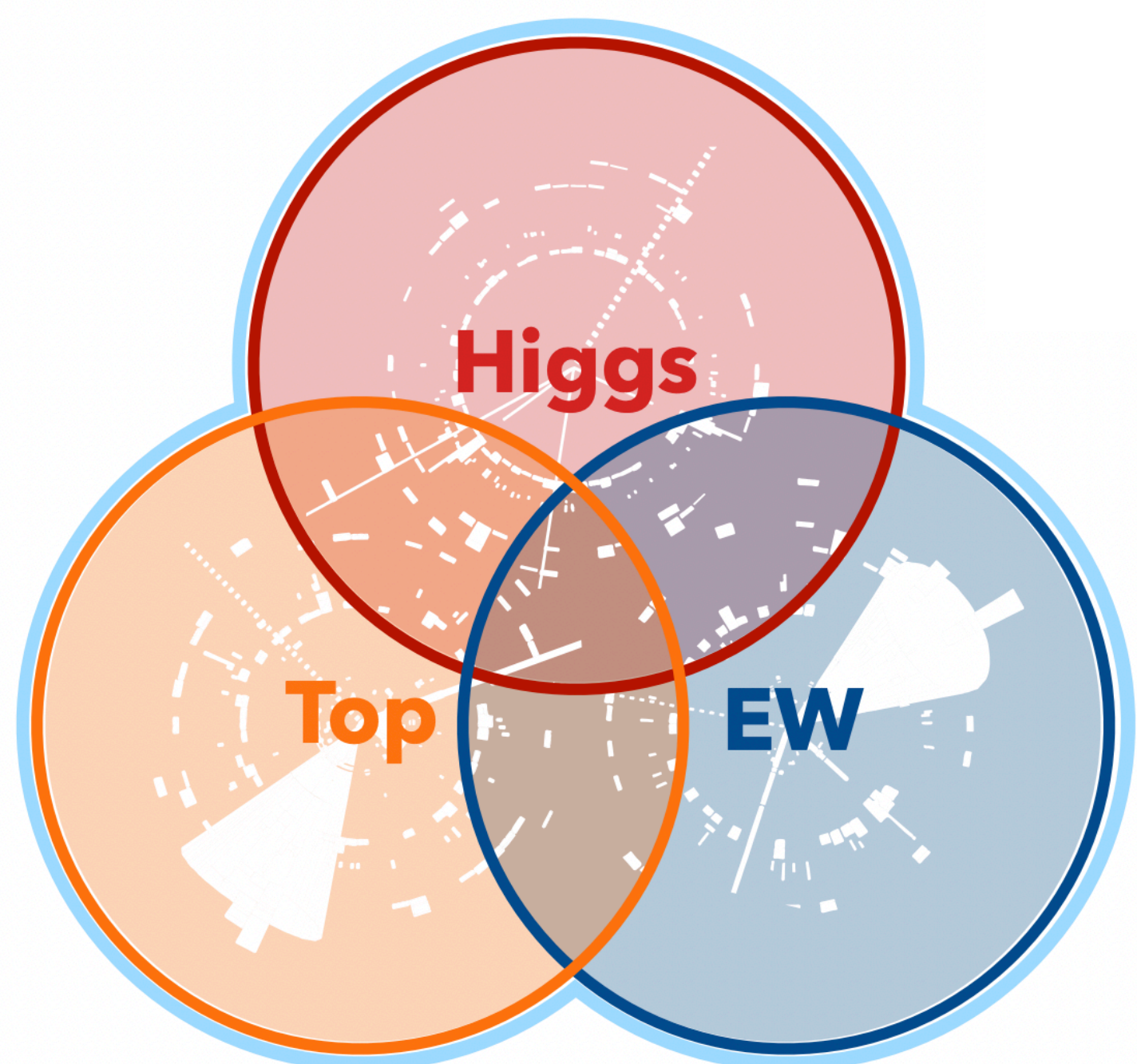
ATLAS Top+X EFT

- ▶ Work underway on strategy for ATLAS Top+X EFT fit
- ▶ But no results yet! 😞
- ▶ Idea is to investigate how different sensitivity can be for analyses with different focus
 - ▶ A) Focus on EFT-sensitive observables
 - ▶ And don't worry too much about what processes contribute
 - ▶ B) Focus on process-sensitive observables
 - ▶ And see how good the EFT sensitivity can be

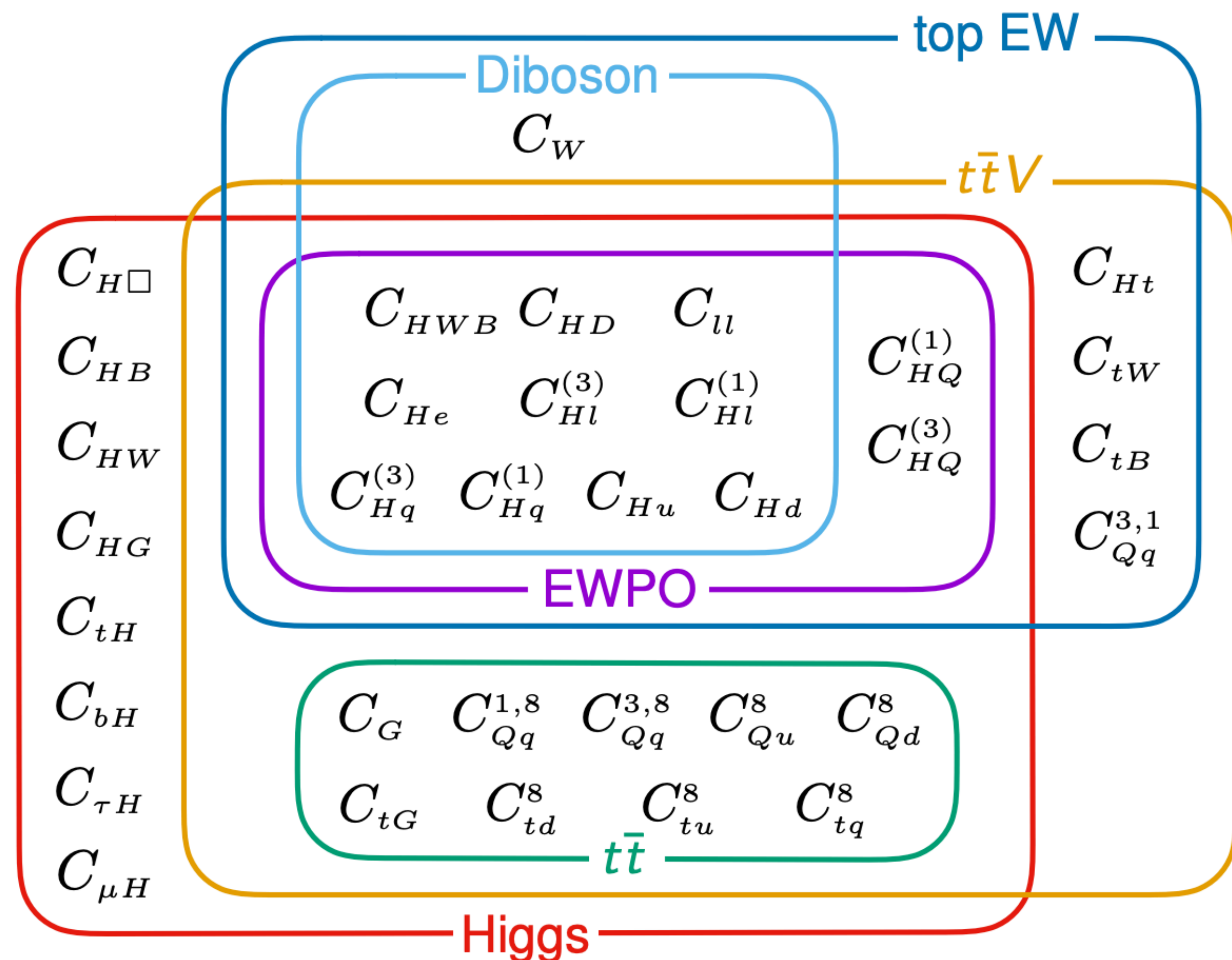


Global EFT



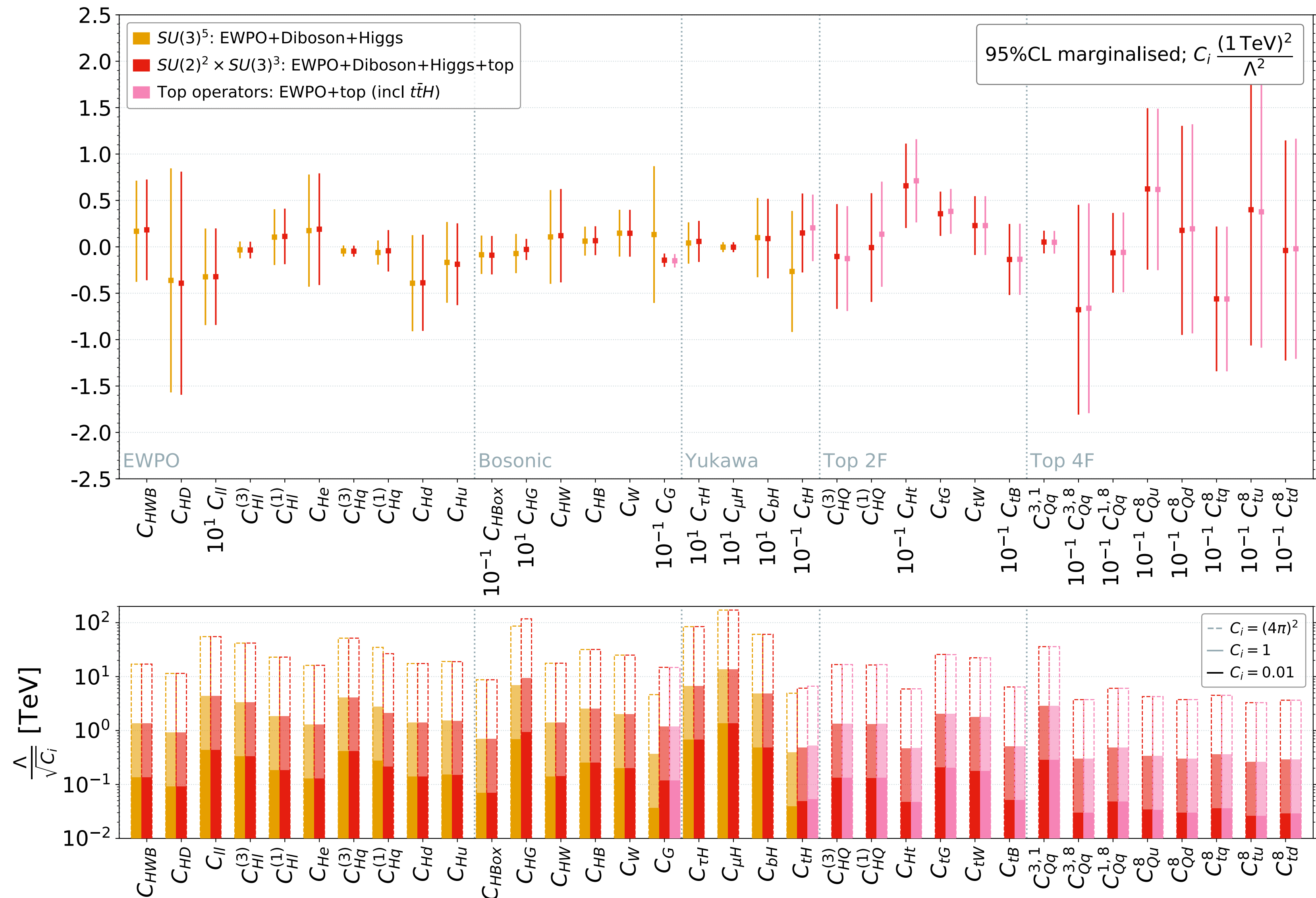


- Measurements of several processes
 - Including from different experiments
- Many operators
- Complementarity improves sensitivity
- Historically performed mainly in pheno community
 - Using available experimental data/information



[arXiv:2012.02779]

- Global fit
- Shows impact of different datasets
 - All data except top
 - Full global fit
 - Top data alone
- In some cases worsened sensitivity
- More freedom in the fit

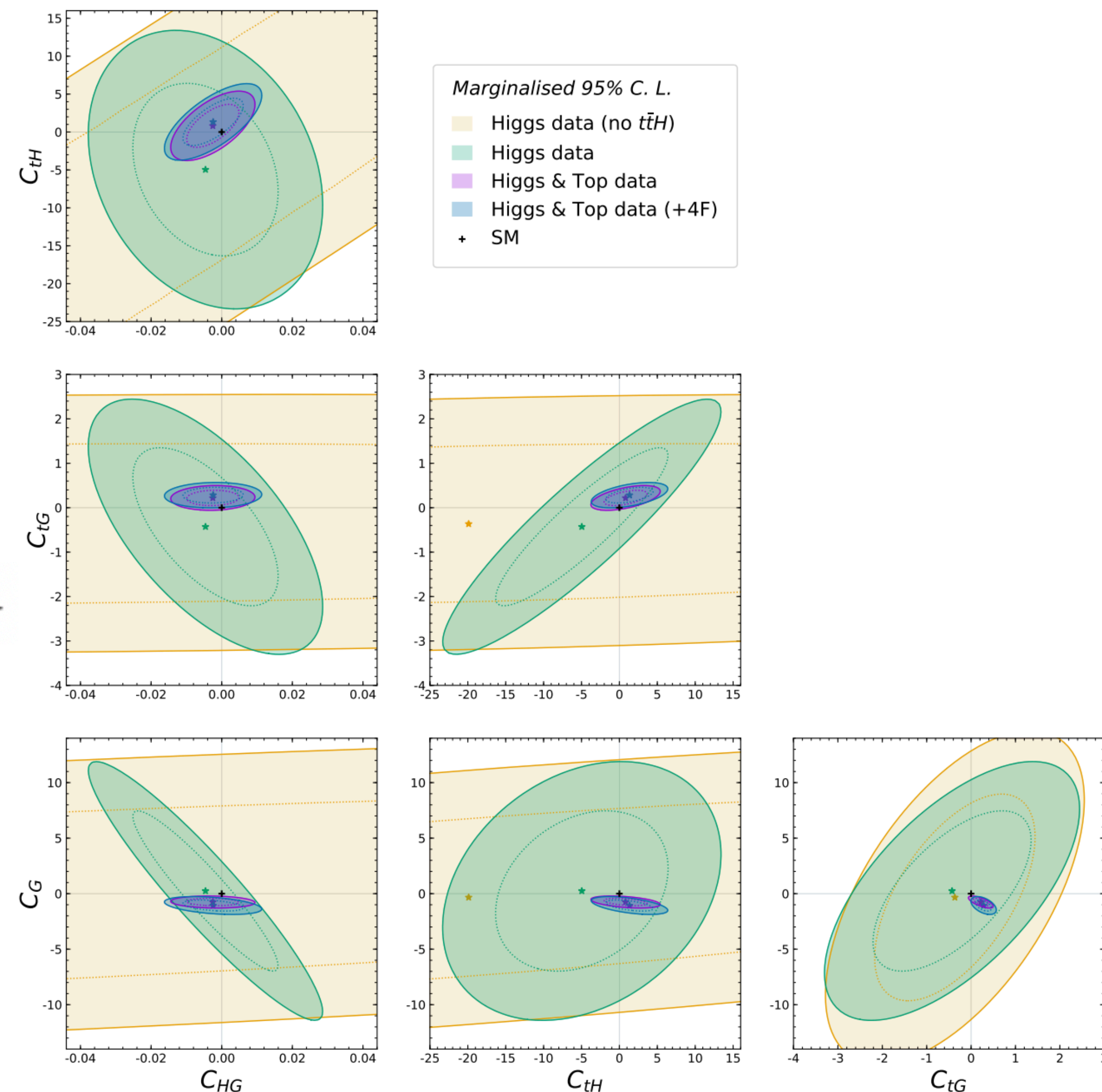


- Some correlations between Top vs Higgs and EWKPO observables.
- Interesting to see e.g. Higgs and Top complementarity

- Fit to subset of operators:

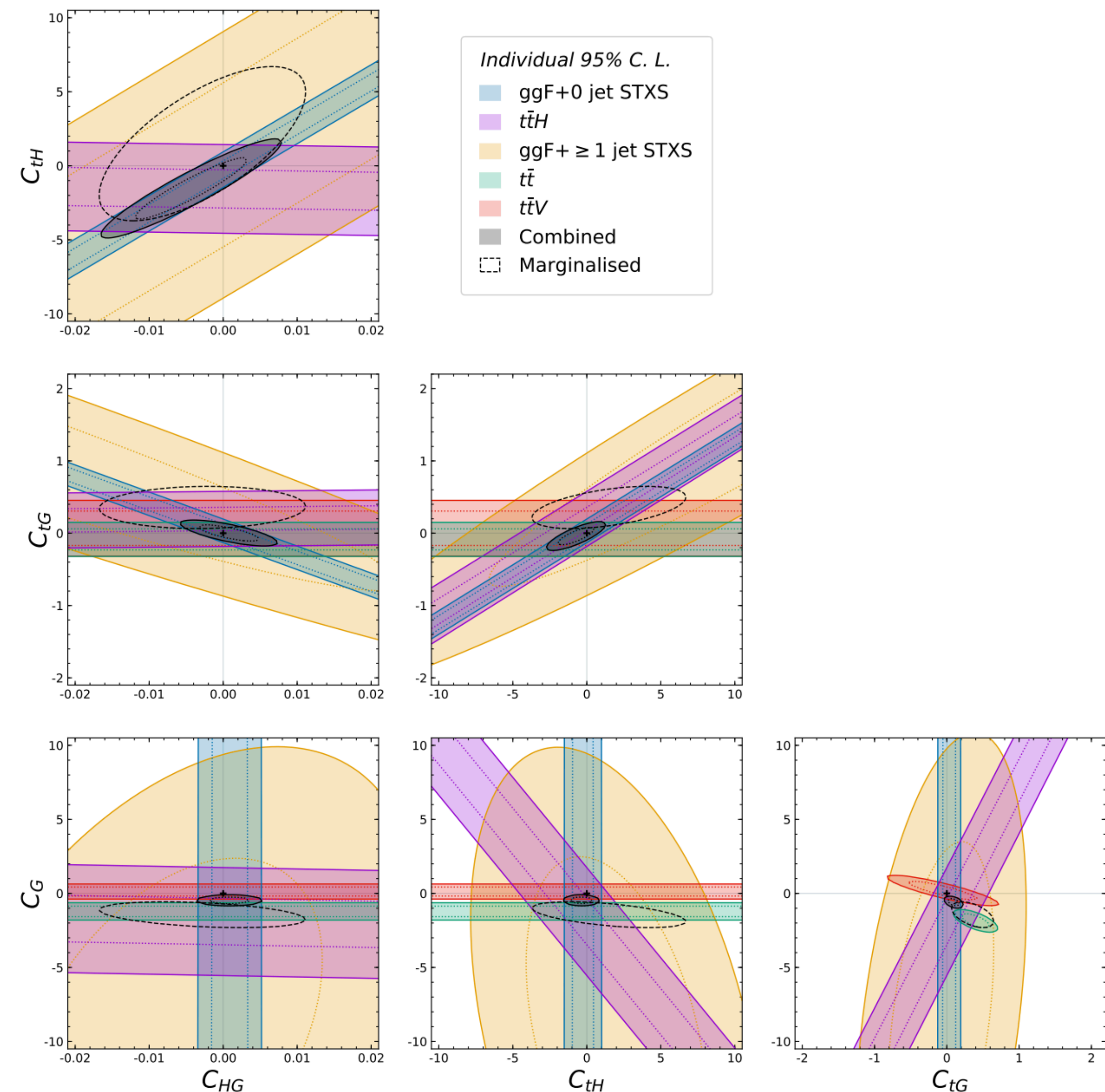
$$\{C_{H\Box}, C_{HG}, C_{HW}, C_{HB}, C_{tH}, C_{bH}, C_{\tau H}, C_{\mu H}, C_G \text{ and } C_{tG}\}$$

- Effect of including both Higgs and top data clearly reduces the allowed parameter space and reduces correlations



[arXiv:2012.02779]

- Some correlations between Top vs Higgs and EWKPO observables.
- Interesting to see e.g. Higgs and Top complementarity
- Fit only 2 operators at a time:
 - 2D fits show what is driving the marginalised constraints
 - Shows contribution of individual measurements
 - STXS on its own not yet very sensitive
 - Including top data helps a lot**

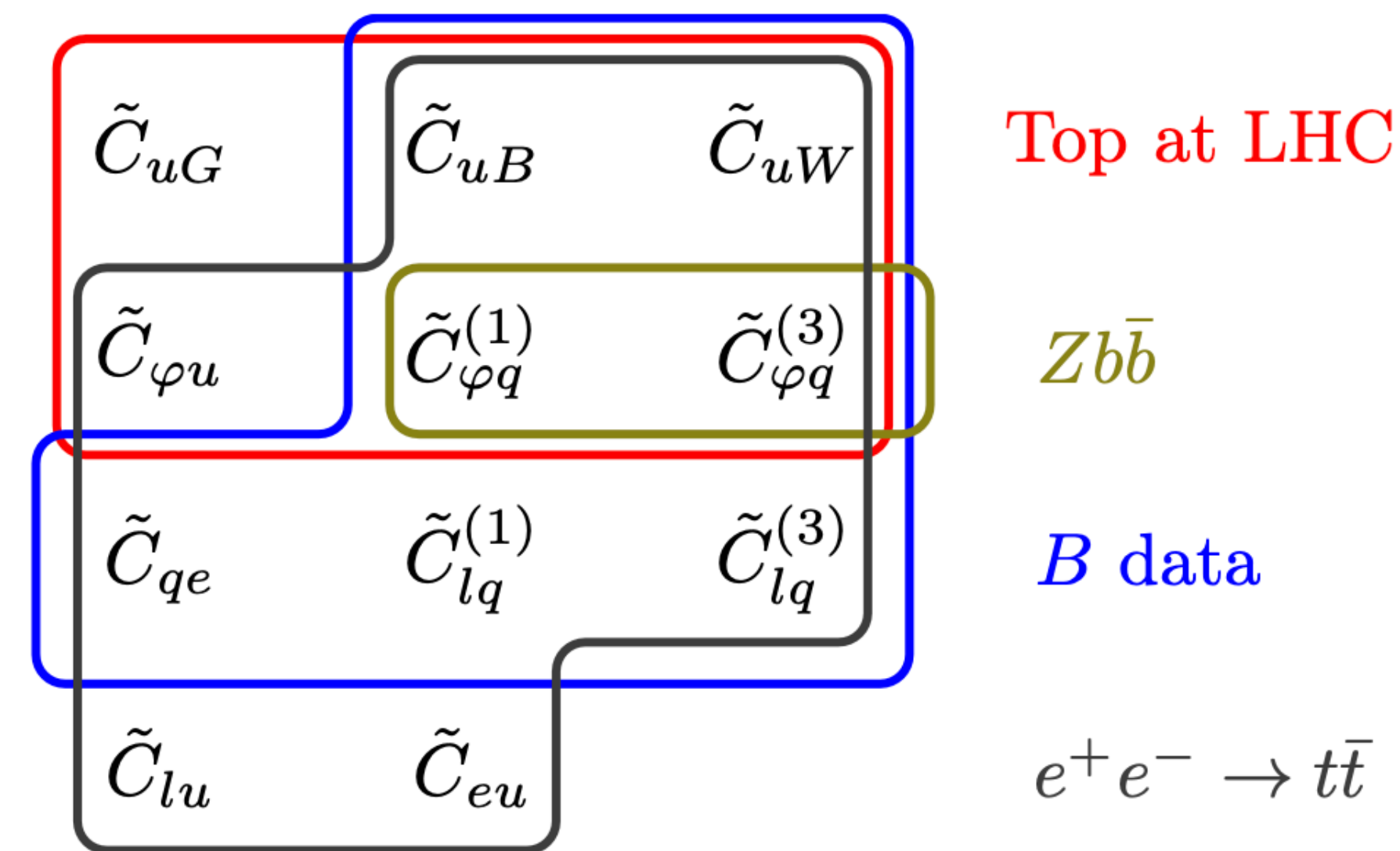
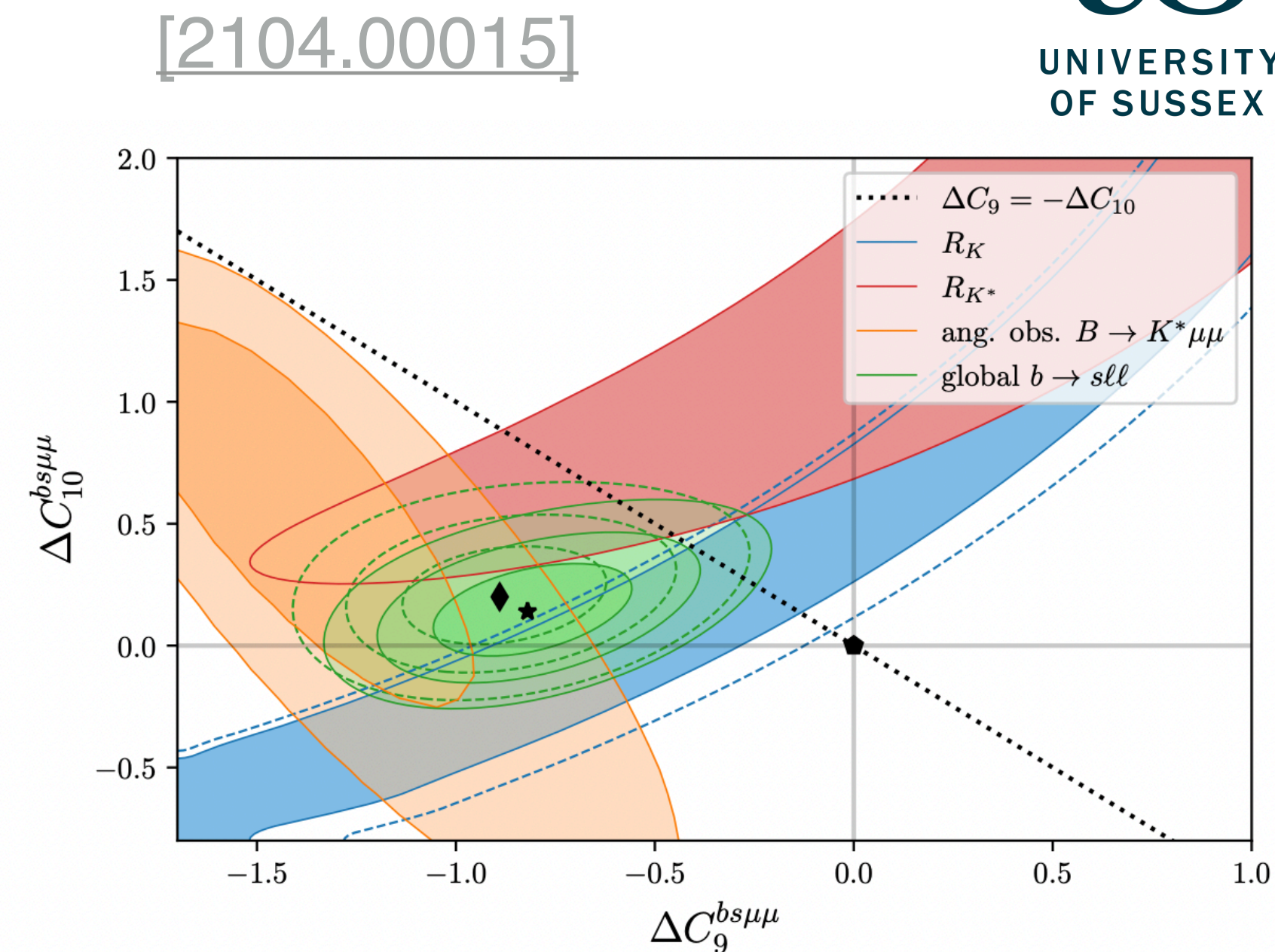
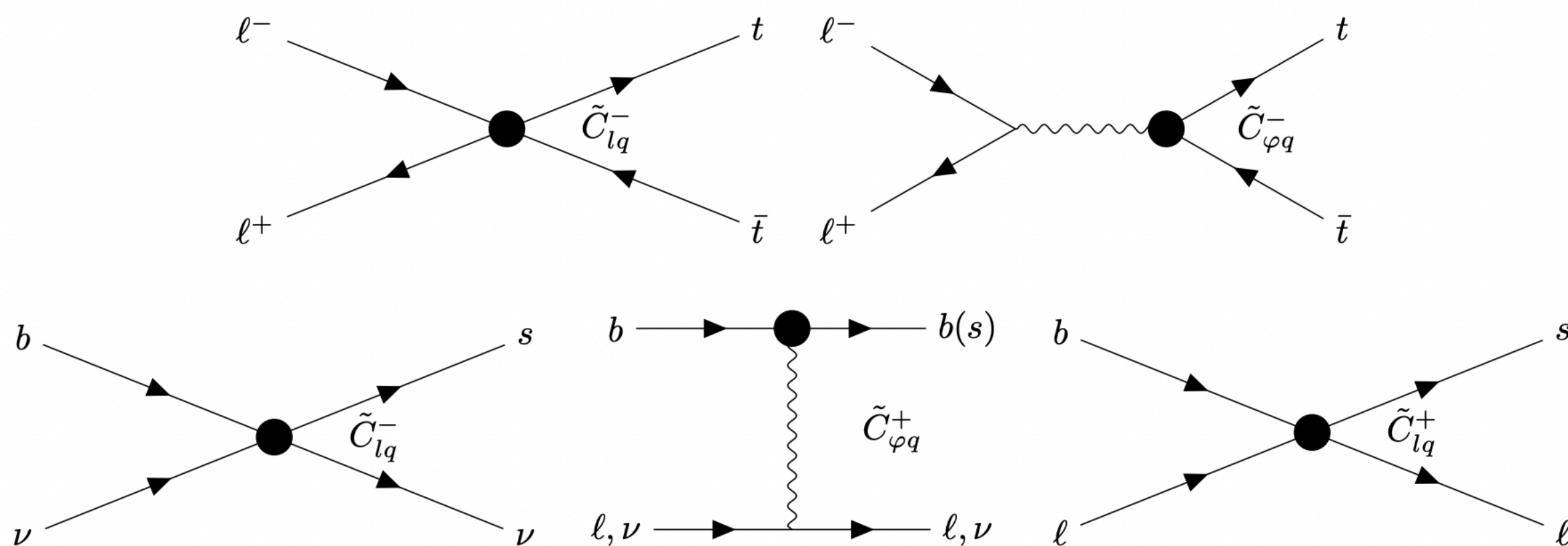


[arXiv:2012.02779]

Link to B-anomalies

- ▶ EFT already used in interpretation of B-anomalies
- ▶ Links between b and top:
 - ▶ B-anomalies require NP in semileptonic 4-fermion operators
 - ▶ Can also use SMEFT to include tops:

$$\bar{s}_L \gamma_\mu b_L \bar{\mu}_L \gamma^\mu \mu_L \quad \longrightarrow \quad \begin{aligned} O_{lq}^{(1)} &= \bar{Q} \gamma_\mu Q \bar{L} \gamma^\mu L, \\ O_{lq}^{(3)} &= \bar{Q} \gamma_\mu \tau^I Q \bar{L} \gamma^\mu \tau^I L \end{aligned}$$



[2012.10456]

Link to B-anomalies

► EFT already used in interpretation of B-anomalies

► Links between b and top:

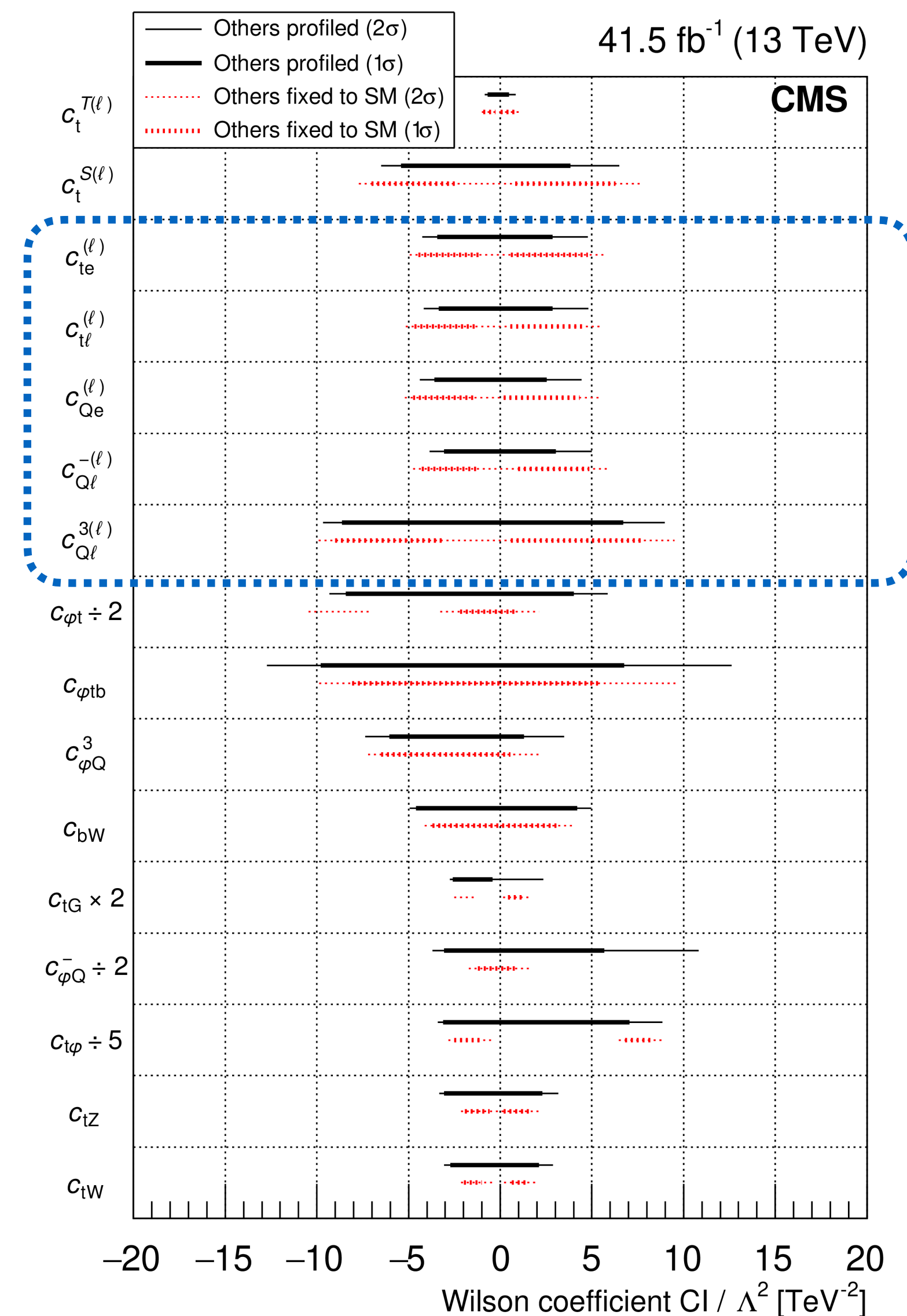
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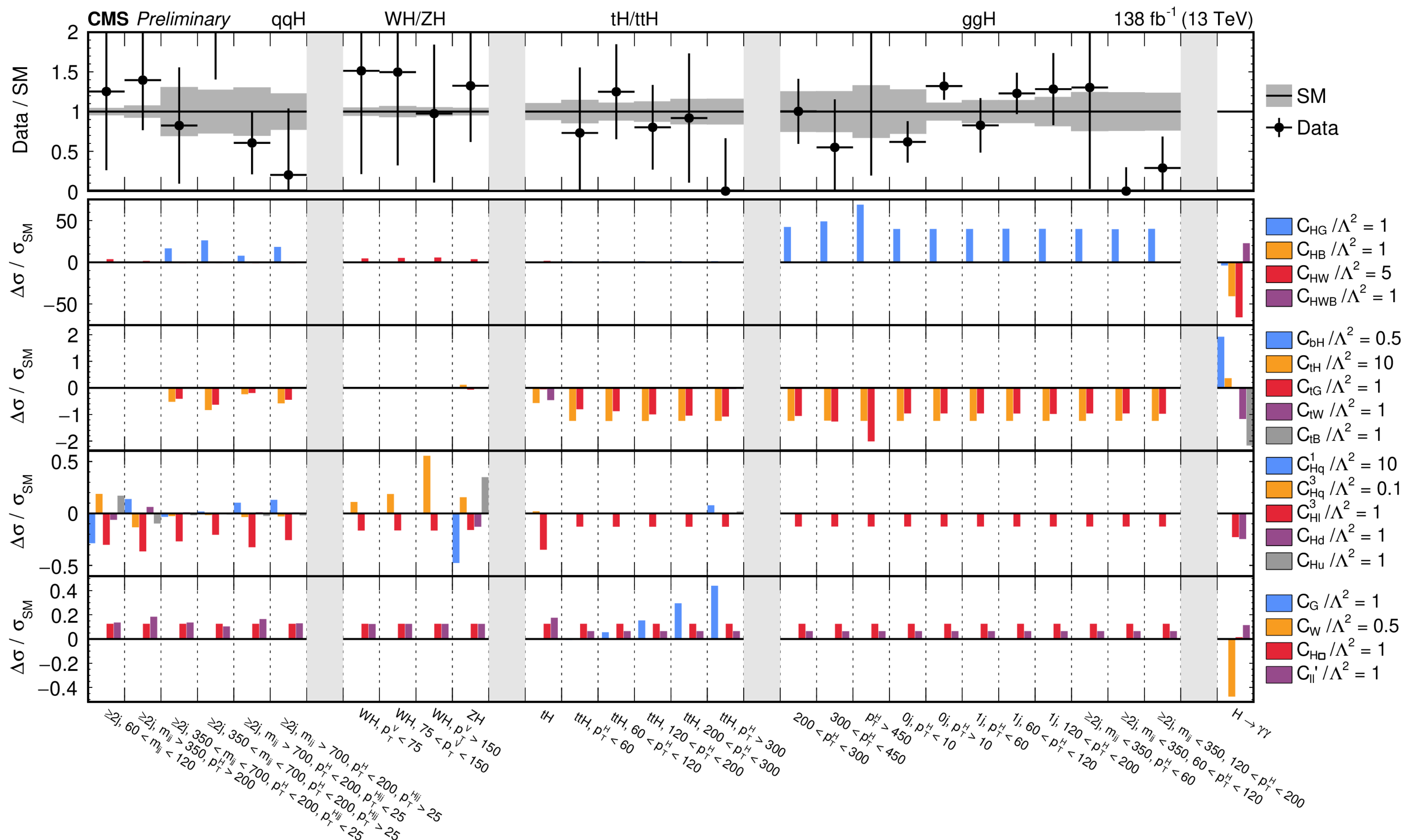
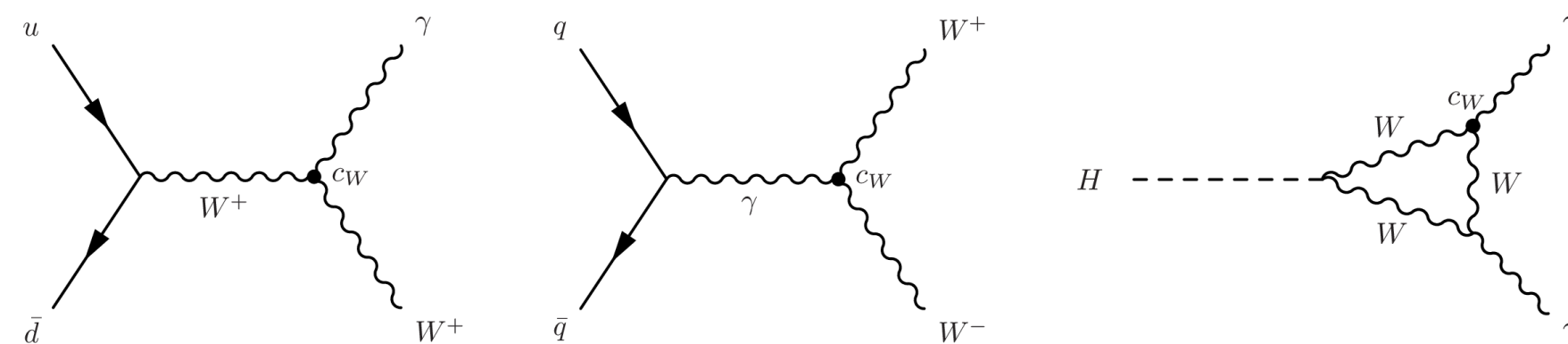
► Top data particularly complementary wrt B + Zbb for some coefficients

► CMS Top+X fit already gives constraints on semileptonic four-fermion operators



► Recently CMS released a global EFT combination including

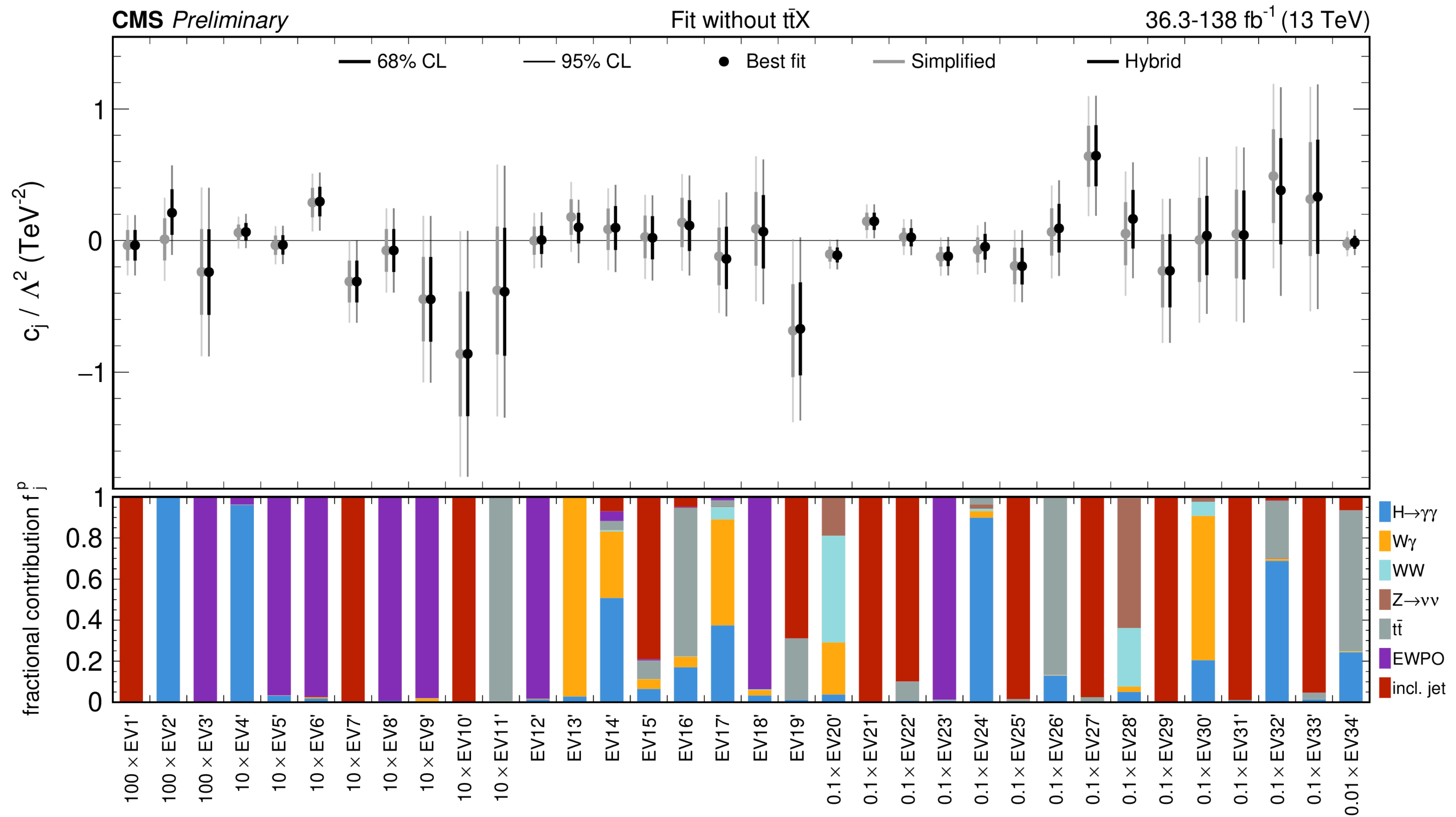
- EWPO
- Jets
- EWK
- Higgs
- ttbar
- Top+X



[SMP-24-003]



Fit without Top+X

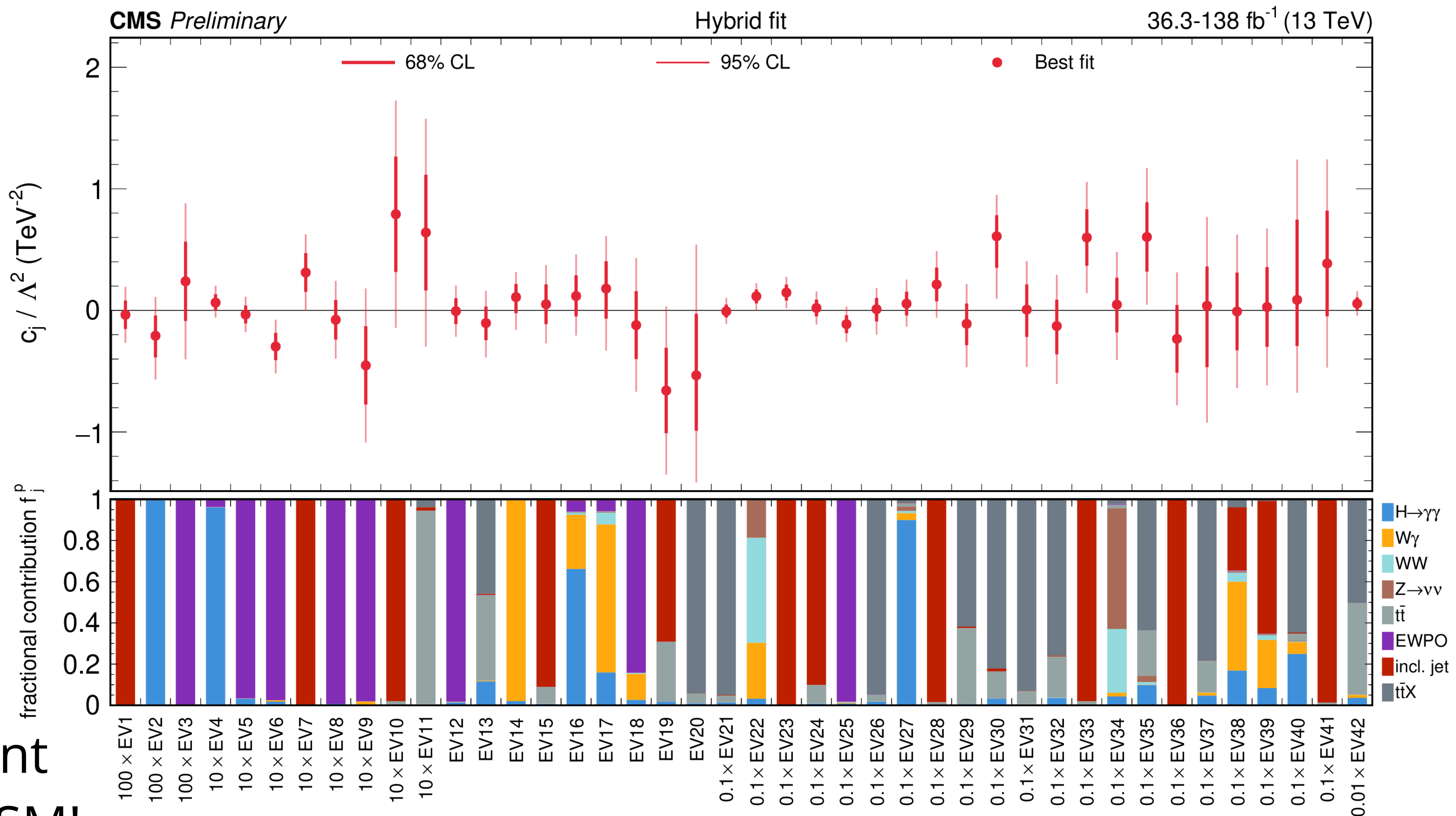




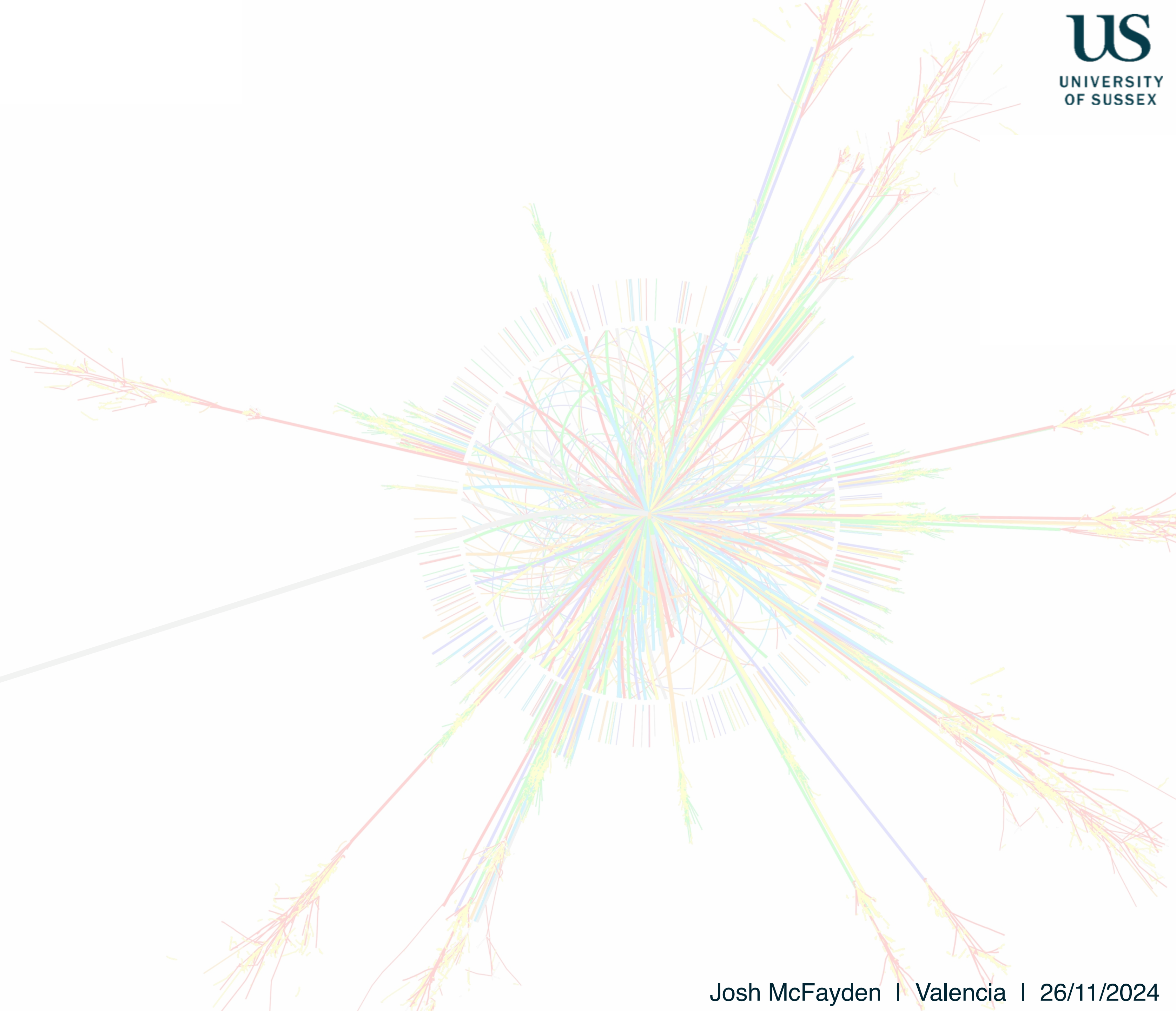
► Fit without
Top+X

► Inclusion
of Top+X
allows many
more
directions
to be
constrained!

► Still no significant
deviation from SM!



Summary





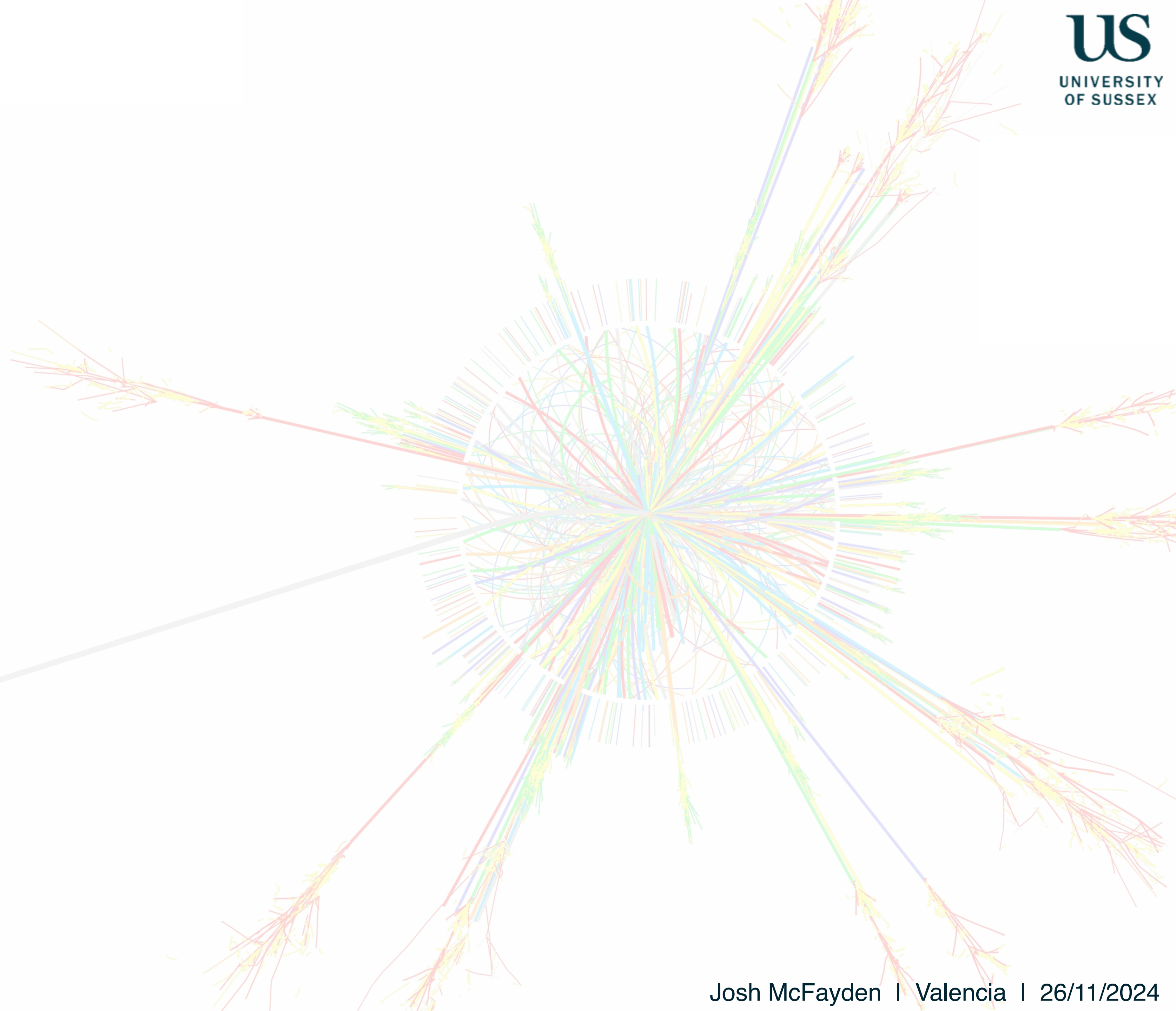
Summary

- ▶ Lots of progress in recent years in Top+X measurements with Run 2 data
- ▶ Observation of the tZq , ttH and 4-tops processes, evidence for tWZ
- ▶ Now sufficient data to measure rare processes differentially, e.g. ttW , ttZ and ttH production.
- ▶ Some tantalising discrepancies wrt the SM predictions...
- ▶ Top+X is sensitive to a wide range of EFT operators, more and more complex fits are in preparation.
 - ▶ Also a vital input to global EFT fits
- ▶ An exciting area with a lot of promise with Run 3 and HL-LHC!

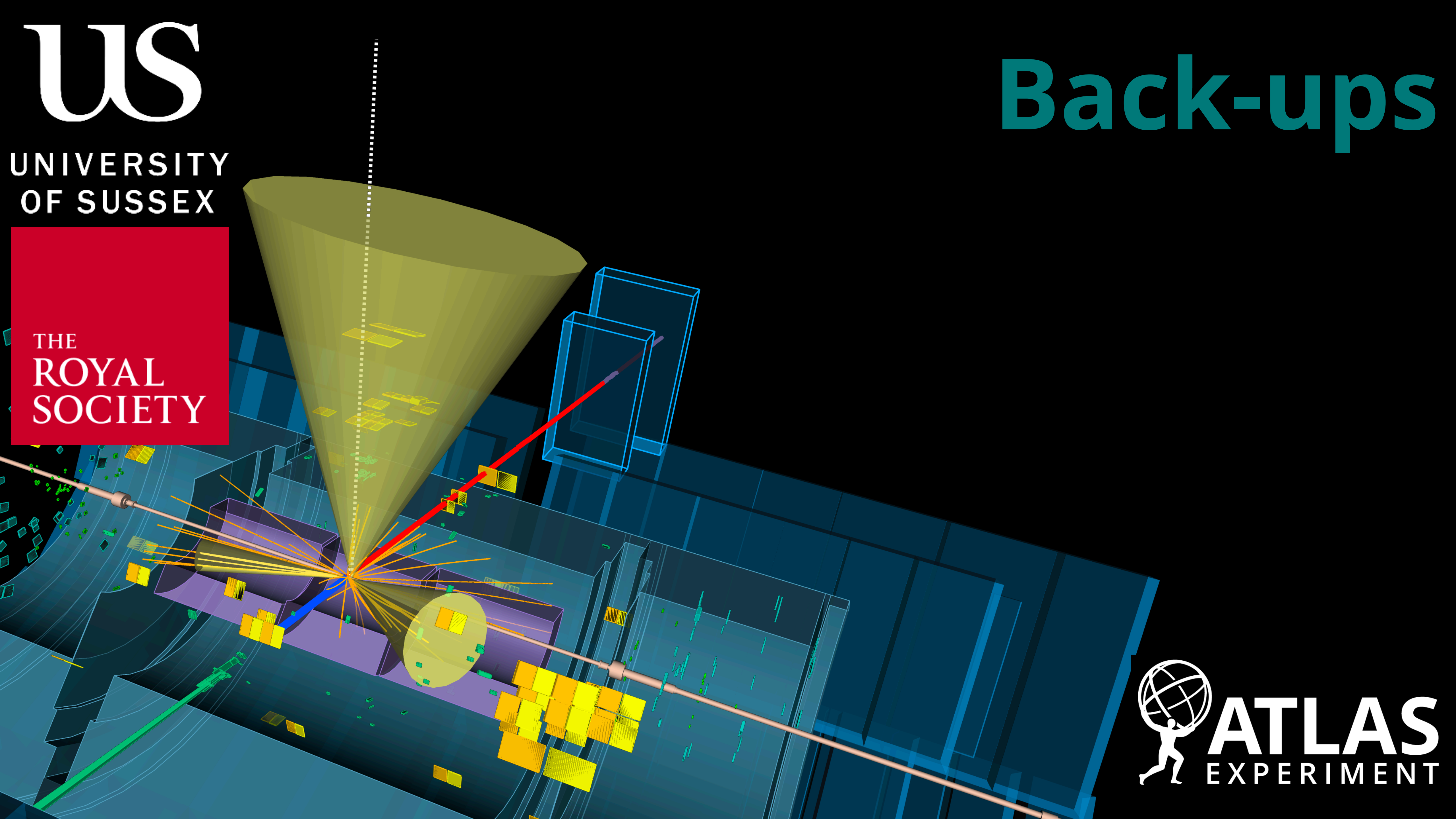
Thanks for your attention!



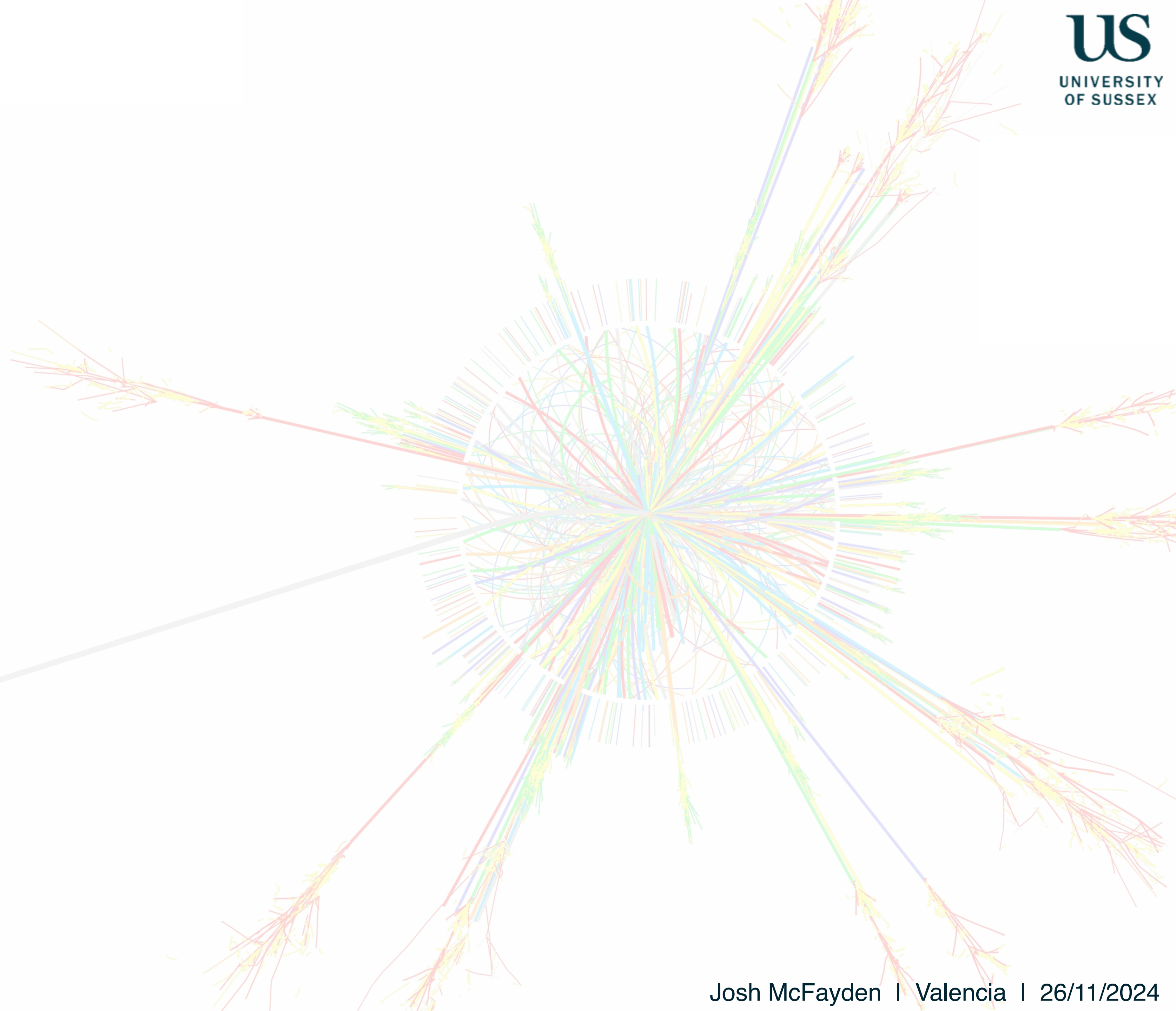
Back-ups



Back-ups

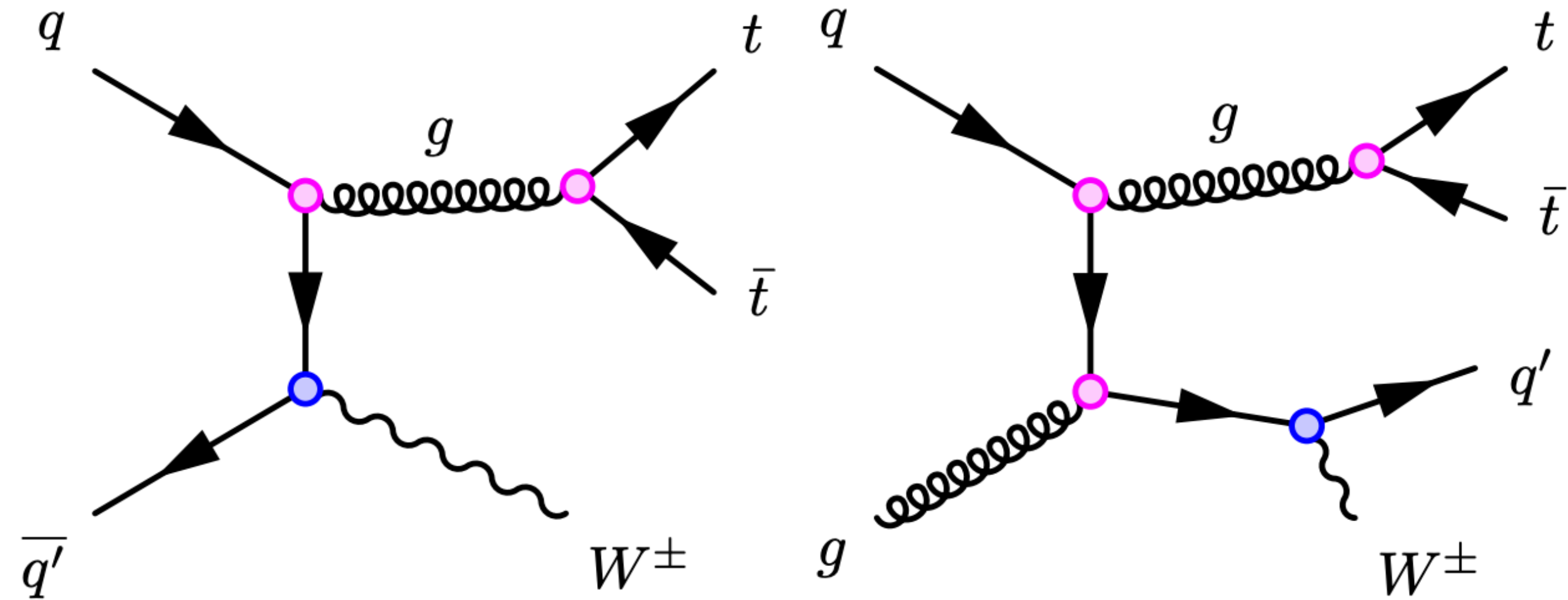


ttW

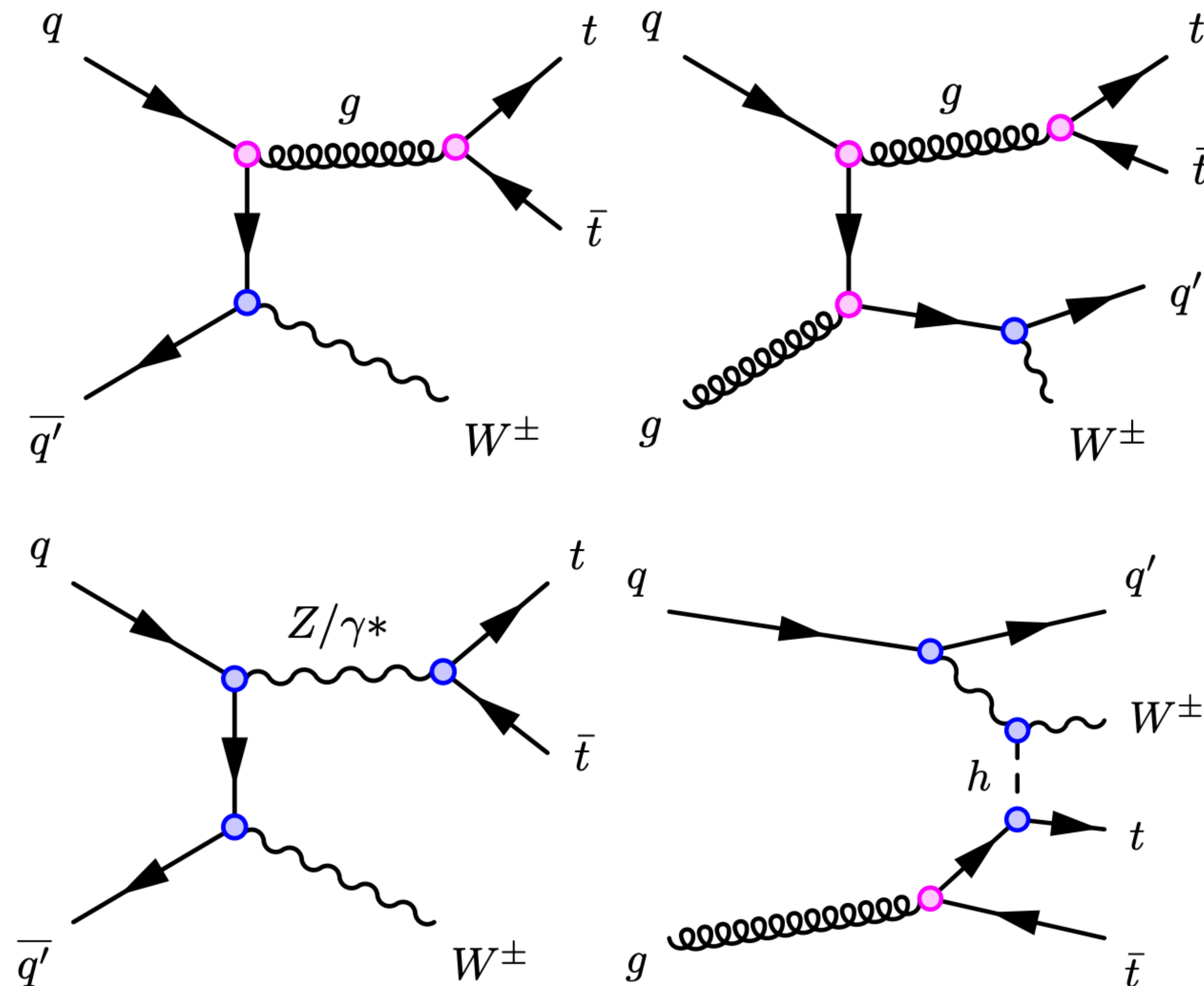


-
- A Feynman diagram illustrating a process involving a quark q and a top quark t . The quark q and top quark t interact via a gluon g exchange (represented by a curly line). The quark q then splits into a quark q' and a $W^\pm$ boson (represented by a wavy line) at a vertex (blue circle). The top quark t continues as a top quark t .

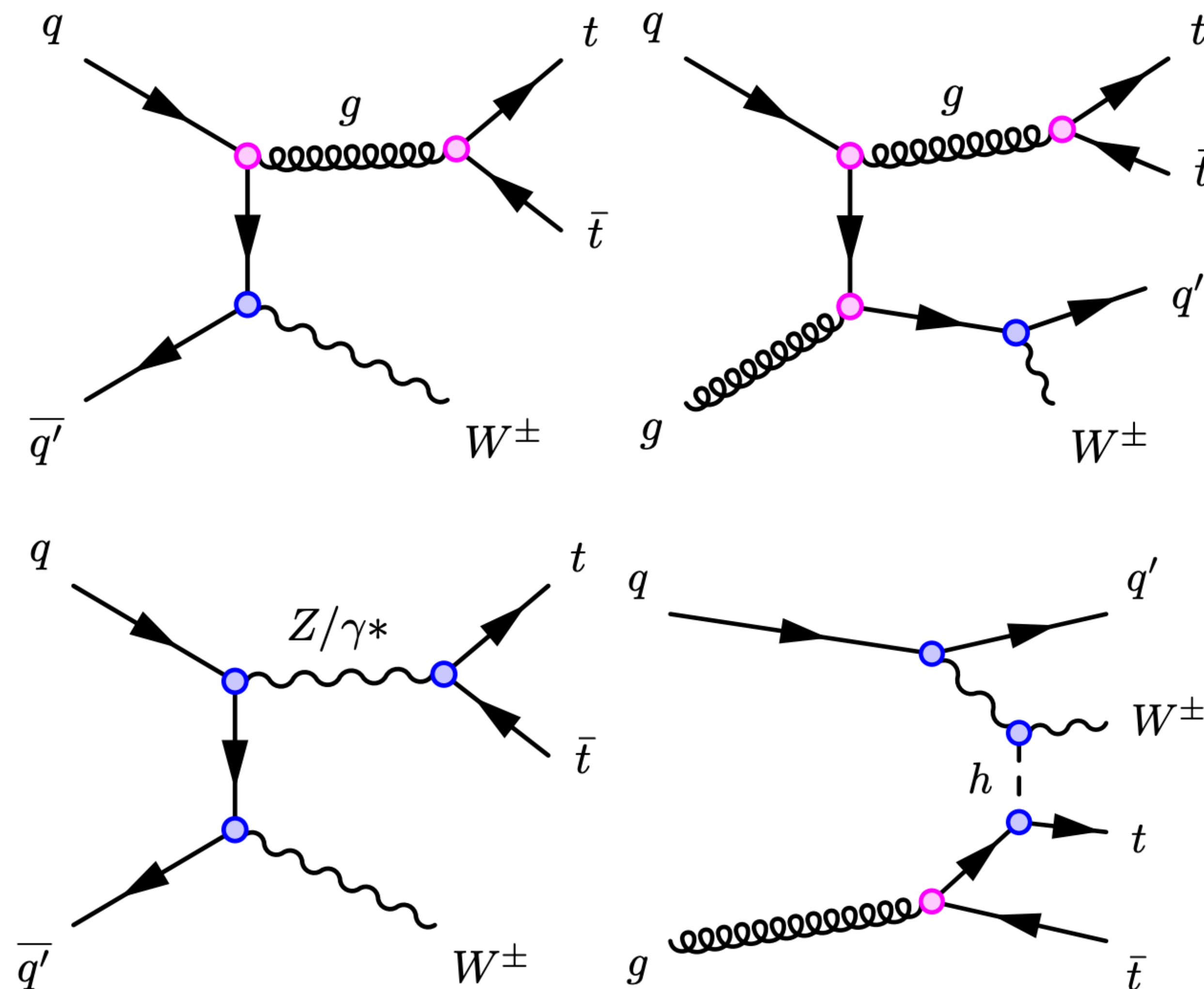
- ▶ qq-initiated process
- ▶ Large NLO QCD corrections
 - ▶ NLO multi-leg merging is important



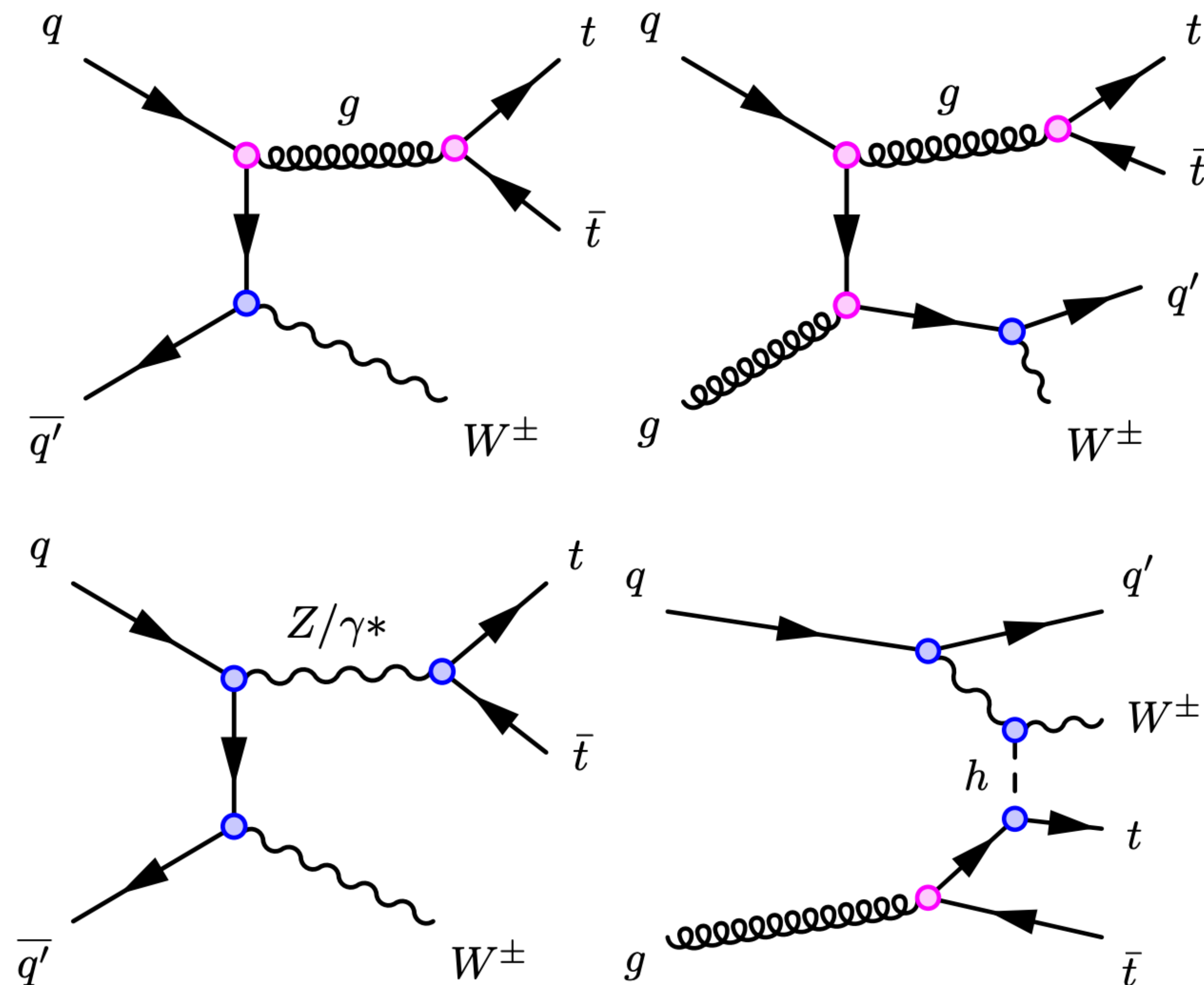
- ▶ qq-initiated process
- ▶ Large NLO QCD corrections
 - ▶ NLO multi-leg merging is important
- ▶ Large NLO EWK corrections



- ▶ qq-initiated process
- ▶ Large NLO QCD corrections
 - ▶ NLO multi-leg merging is important
- ▶ Large NLO EWK corrections
- ▶ Effects of resummation are small
- ▶ No NNLO calculations!



- ▶ qq-initiated process
- ▶ Large NLO QCD corrections
 - ▶ NLO multi-leg merging is important
- ▶ Large NLO EWK corrections
- ▶ Effects of resummation are small
- ▶ **New (a)NNLO calculations!**



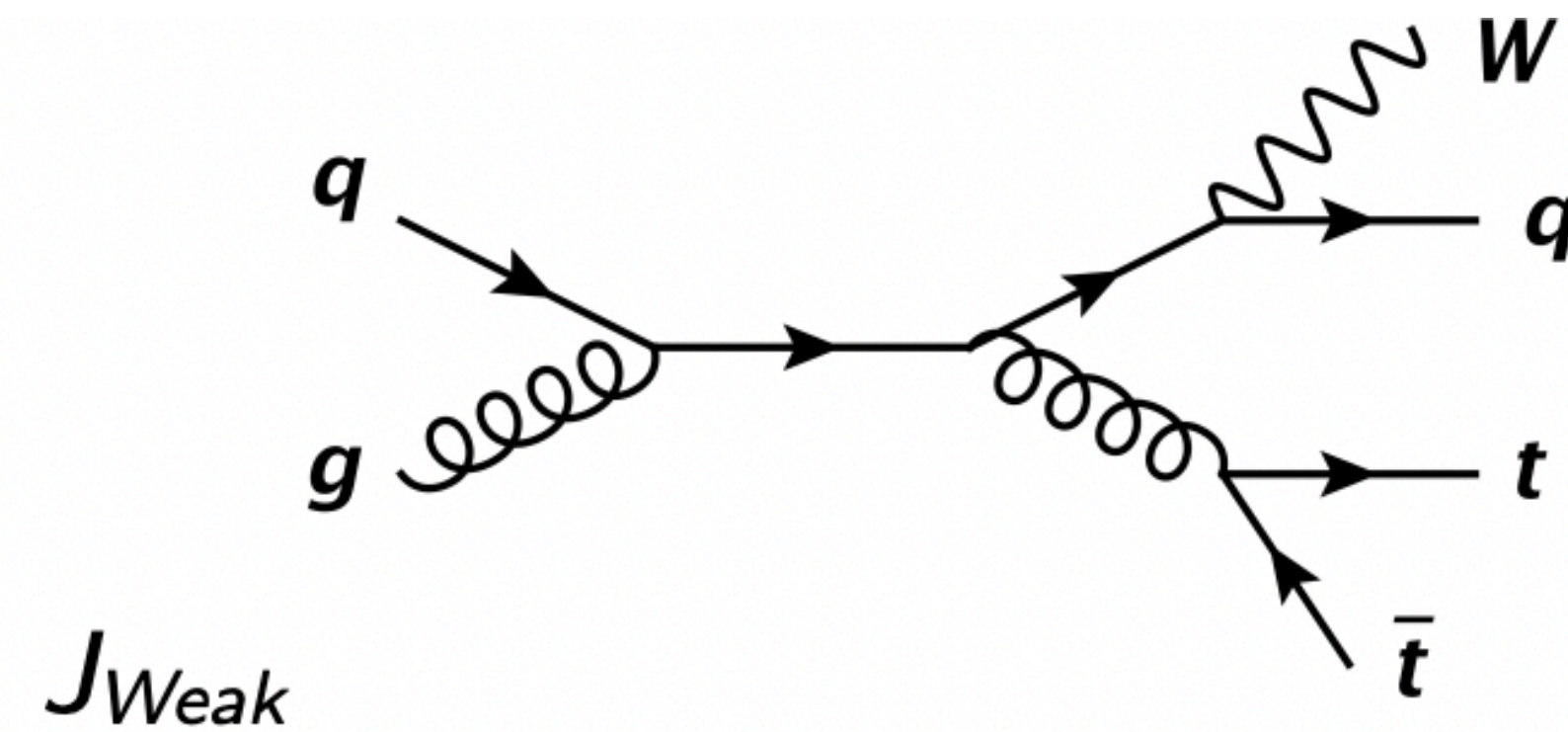
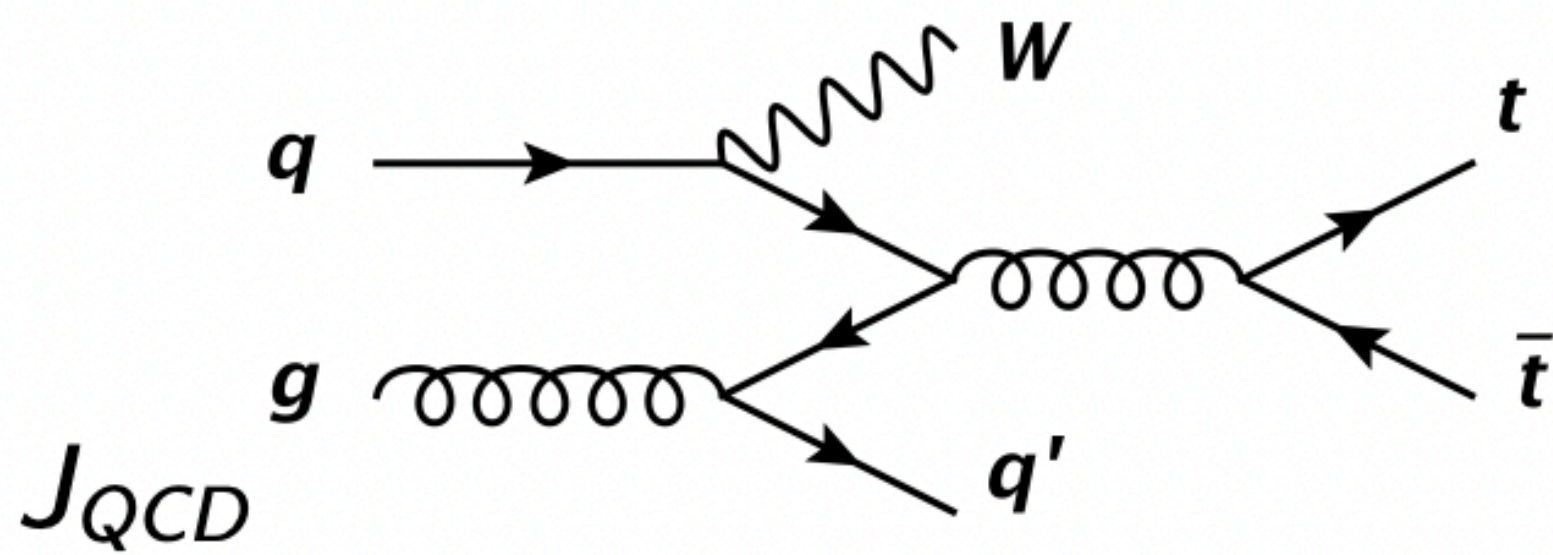


$pp \rightarrow t\bar{t} W^\pm$	$p p > t t \sim \text{wpm}$	$3.777 \pm 0.003 \cdot 10^{-1}$	$+23.9\%$ -18.0%	$+2.1\%$ -1.6%	$5.662 \pm 0.021 \cdot 10^{-1}$	$+11.2\%$ -10.6%	$+1.7\%$ -1.3%
$pp \rightarrow t\bar{t} Z$	$p p > t t \sim z$	$5.273 \pm 0.004 \cdot 10^{-1}$	$+30.5\%$ -21.8%	$+1.8\%$ -2.1%	$7.598 \pm 0.026 \cdot 10^{-1}$	$+9.7\%$ -11.1%	$+1.9\%$ -2.2%
$pp \rightarrow t\bar{t} \gamma$	$p p > t t \sim a$	$1.204 \pm 0.001 \cdot 10^0$	$+29.6\%$ -21.3%	$+1.6\%$ -1.8%	$1.744 \pm 0.005 \cdot 10^0$	$+9.8\%$ -11.0%	$+1.7\%$ -2.0%
$pp \rightarrow t\bar{t} W^\pm j$	$p p > t t \sim \text{wpm } j$	$2.352 \pm 0.002 \cdot 10^{-1}$	$+40.9\%$ -27.1%	$+1.3\%$ -1.0%	$3.404 \pm 0.011 \cdot 10^{-1}$	$+11.2\%$ -14.0%	$+1.2\%$ -0.9%
$pp \rightarrow t\bar{t} Z j$	$p p > t t \sim z j$	$3.953 \pm 0.004 \cdot 10^{-1}$	$+46.2\%$ -29.5%	$+2.7\%$ -3.0%	$5.074 \pm 0.016 \cdot 10^{-1}$	$+7.0\%$ -12.3%	$+2.5\%$ -2.9%
$pp \rightarrow t\bar{t} \gamma j$	$p p > t t \sim a j$	$8.726 \pm 0.010 \cdot 10^{-1}$	$+45.4\%$ -29.1%	$+2.3\%$ -2.6%	$1.135 \pm 0.004 \cdot 10^0$	$+7.5\%$ -12.2%	$+2.2\%$ -2.5%

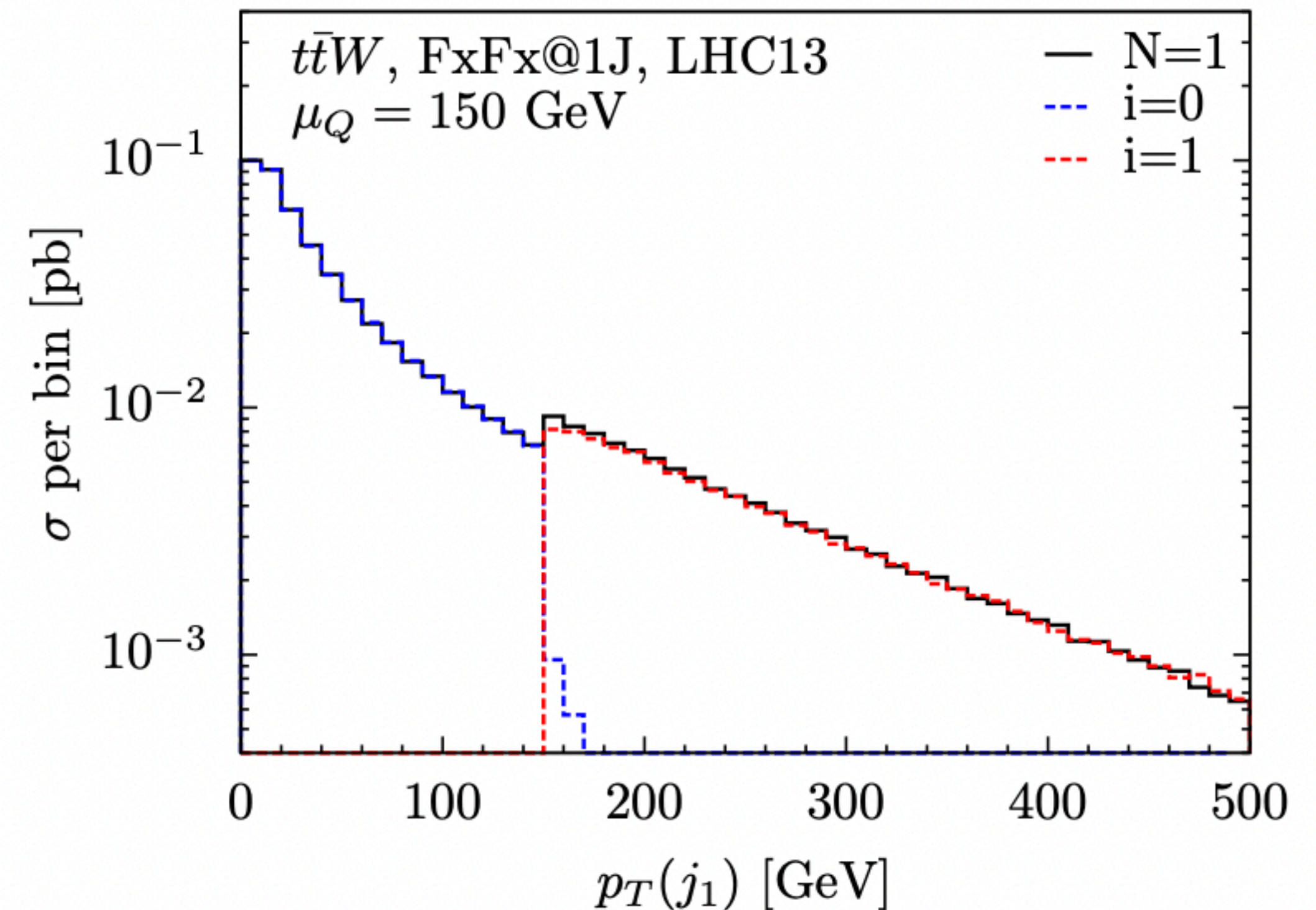
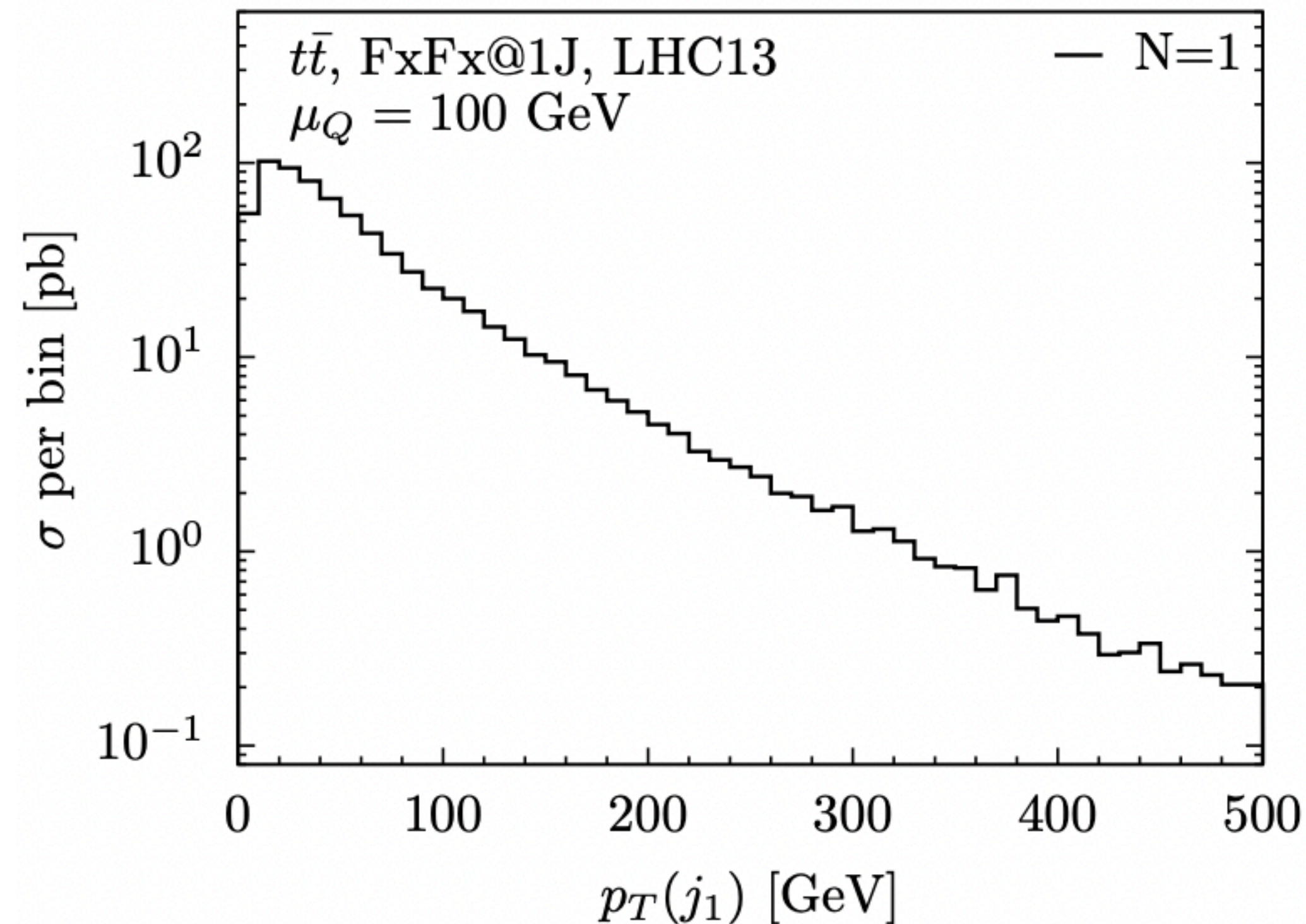
- ▶ MG5_aMC numbers ([arXiv:1405.0301](https://arxiv.org/abs/1405.0301)):
 - ▶ **ttW LO→NLO k-factor = 1.50**
 - ▶ **ttWj LO→NLO k-factor = 1.44** ← This is missing from both existing samples
- ▶ ATLAS production
 - ▶ ttW+0j@NLO = 0.5483 pb
 - ▶ **ttW+0,1j@NLO FxFx = 0.6110 pb → “k-factor” = 1.11**



► Incorrect treatment of “weak” contributions breaks merging:



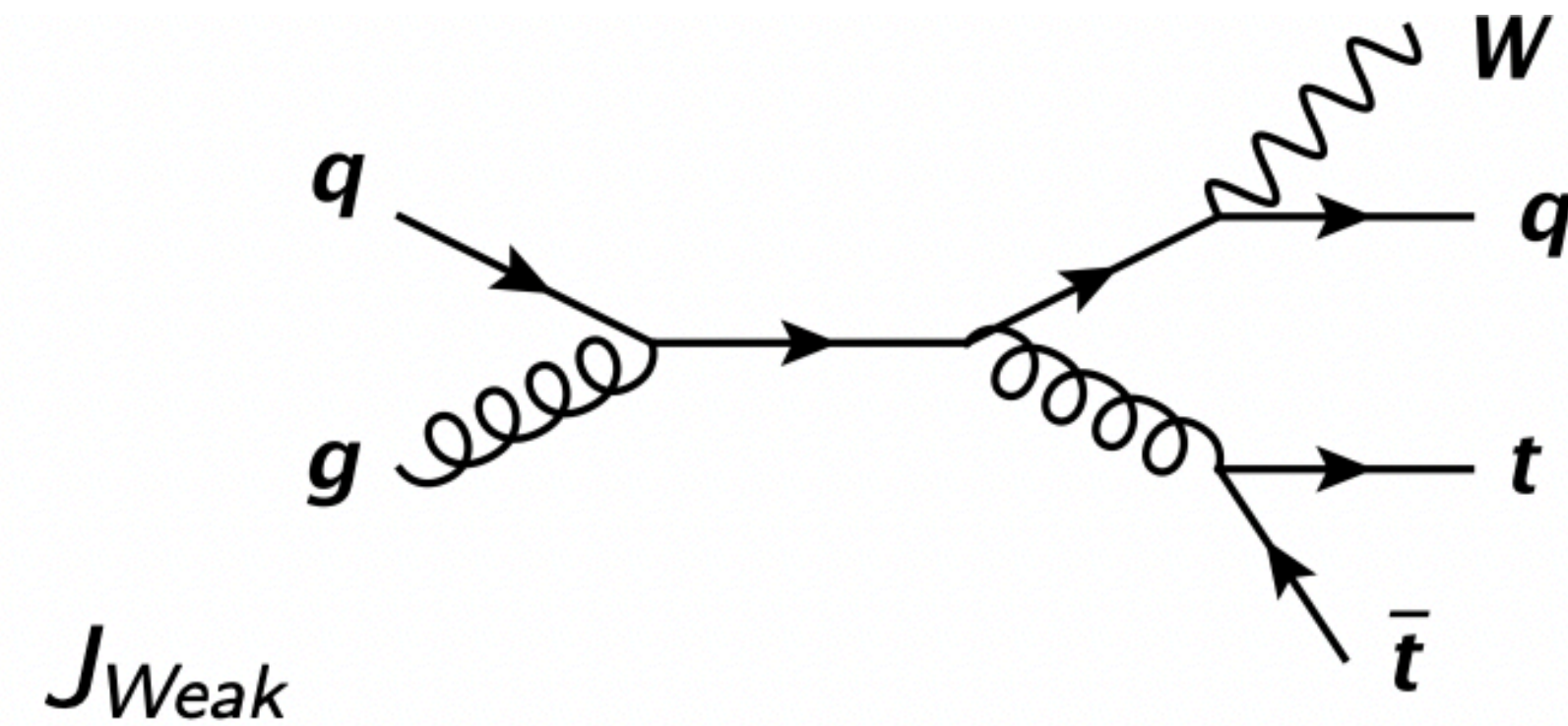
2009.00032	
μ_Q	$\sigma[\text{fb}]$
90 GeV	664
110 GeV	655
110 GeV	655
150 GeV	644
250 GeV	622
350 GeV	602



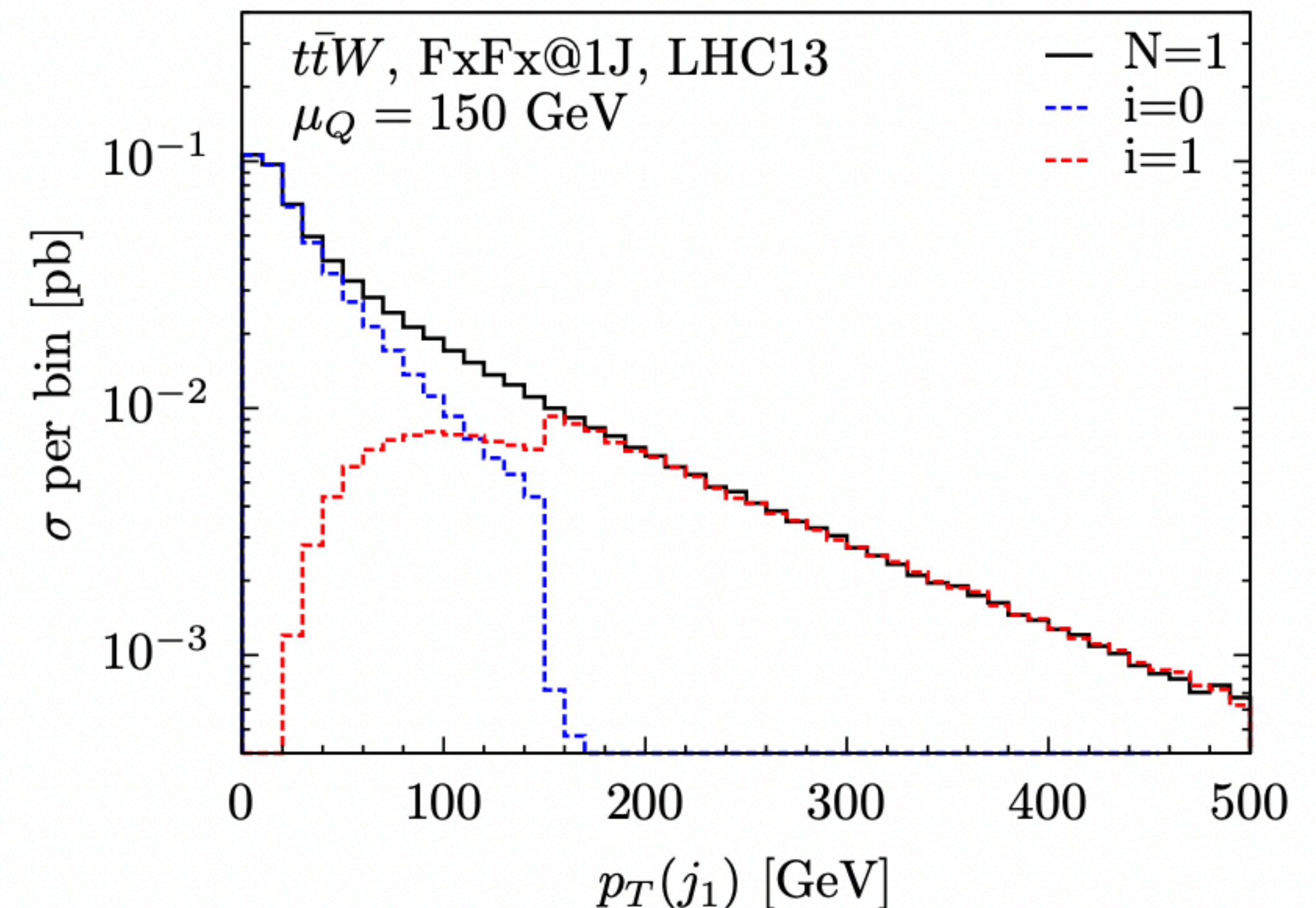
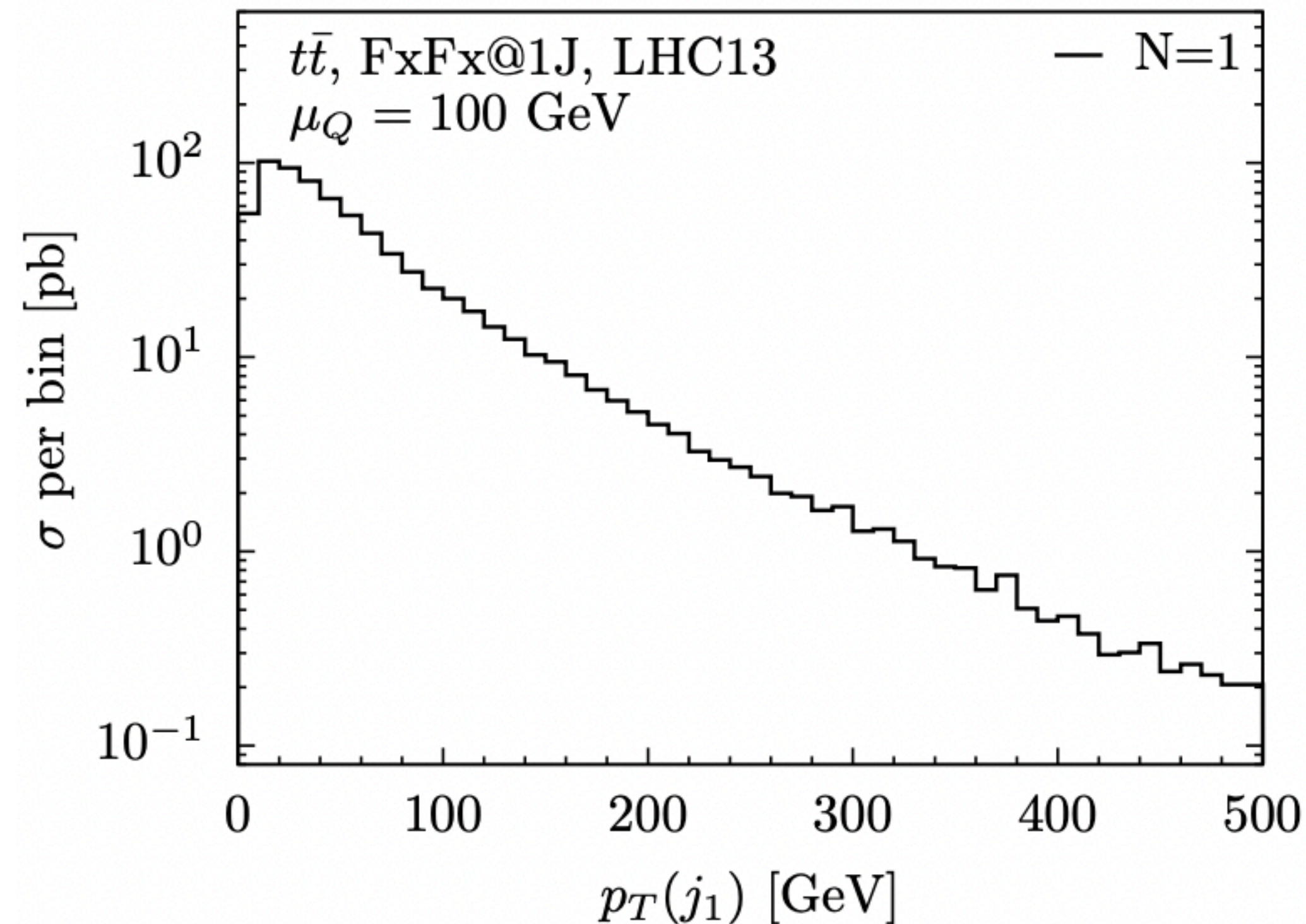


► Incorrect treatment of “weak” contributions breaks merging

- Fix by identifying “weak” events and exclude them from matching
- Restores expected behaviour
- MG5_aMC fix in preparation: **Must check our M**



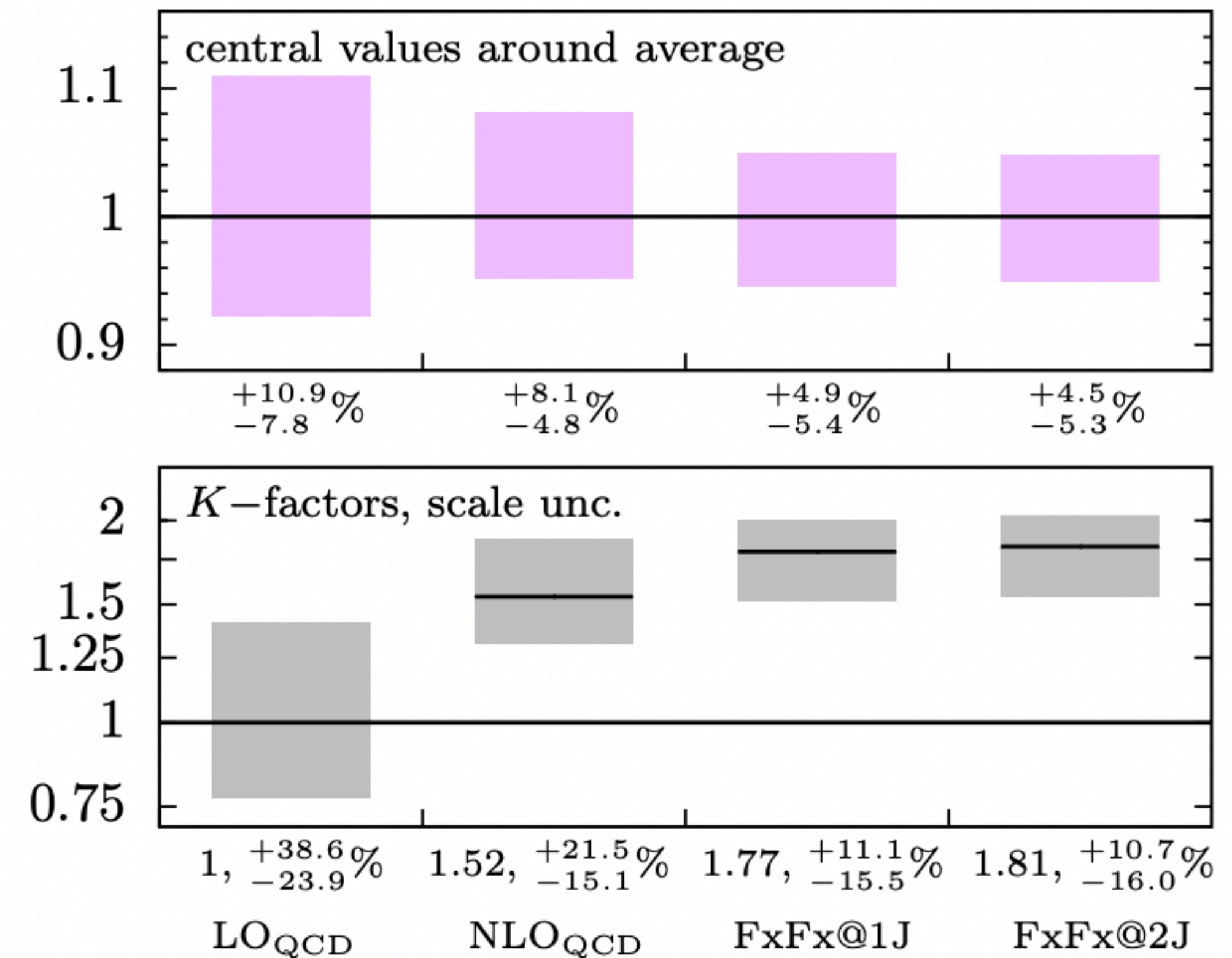
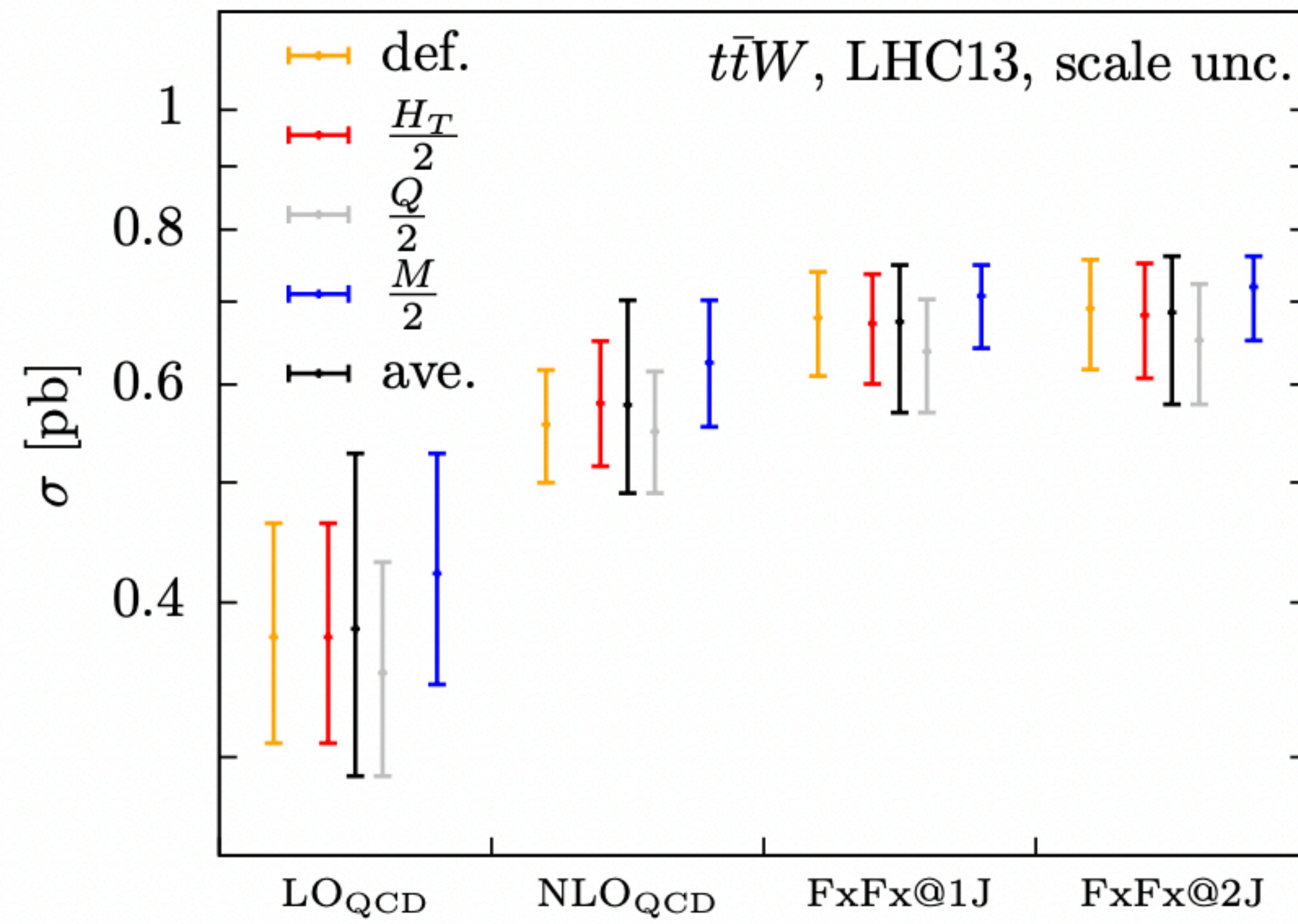
μ_Q [GeV]	σ [fb]
100	678(1)
150	679(1)
200	679(1)
250	679(1)
300	678(1)





► Study of the QCD corrections:

- Known increase in k-factor from $\text{NLO}_{\text{QCD}} \rightarrow \text{FxFx@1j}$, $\text{NLO}_{\text{QCD}} \rightarrow \text{FxF@2j} = 1.2$.
- Decrease in scale uncertainty.



QCD perturbative orders

- Can generate EWsub component and match to the PS:

Order (default scale)	$\sigma \pm \text{scale} \pm \text{PDF}$ [fb]
FxFx@1J	$679.2(6)^{+60.5(+8.9\%)}_{-69.7(-10.3\%)} \quad +7.6(+1.1\%)_{-7.6(-1.1\%)}$
FxFx@2J	$691.1(8)^{+65.7(+9.5\%)}_{-74.1(-10.7\%)} \quad +7.3(+1.1\%)_{-7.3(-1.1\%)}$
FxFx@2J+EW _{sub}	$738.8(8)^{+75.0(+10.1\%)}_{-81.3(-11.0\%)} \quad +7.5(+1.0\%)_{-7.5(-1.0\%)}$

- Only possible to estimate the NLO EW corrections:

- $\widetilde{\text{NLO}}_{\text{EW}} \sim -4\% \text{LO}_{\text{QCD}}$ scale independent at NLO $t\bar{t}W$ (1711.02116)
- $\sim -5.5\% \text{LO}_{\text{QCD}}$ at NLO $t\bar{t}W \rightarrow \text{trilepton}$ (2102.03246)

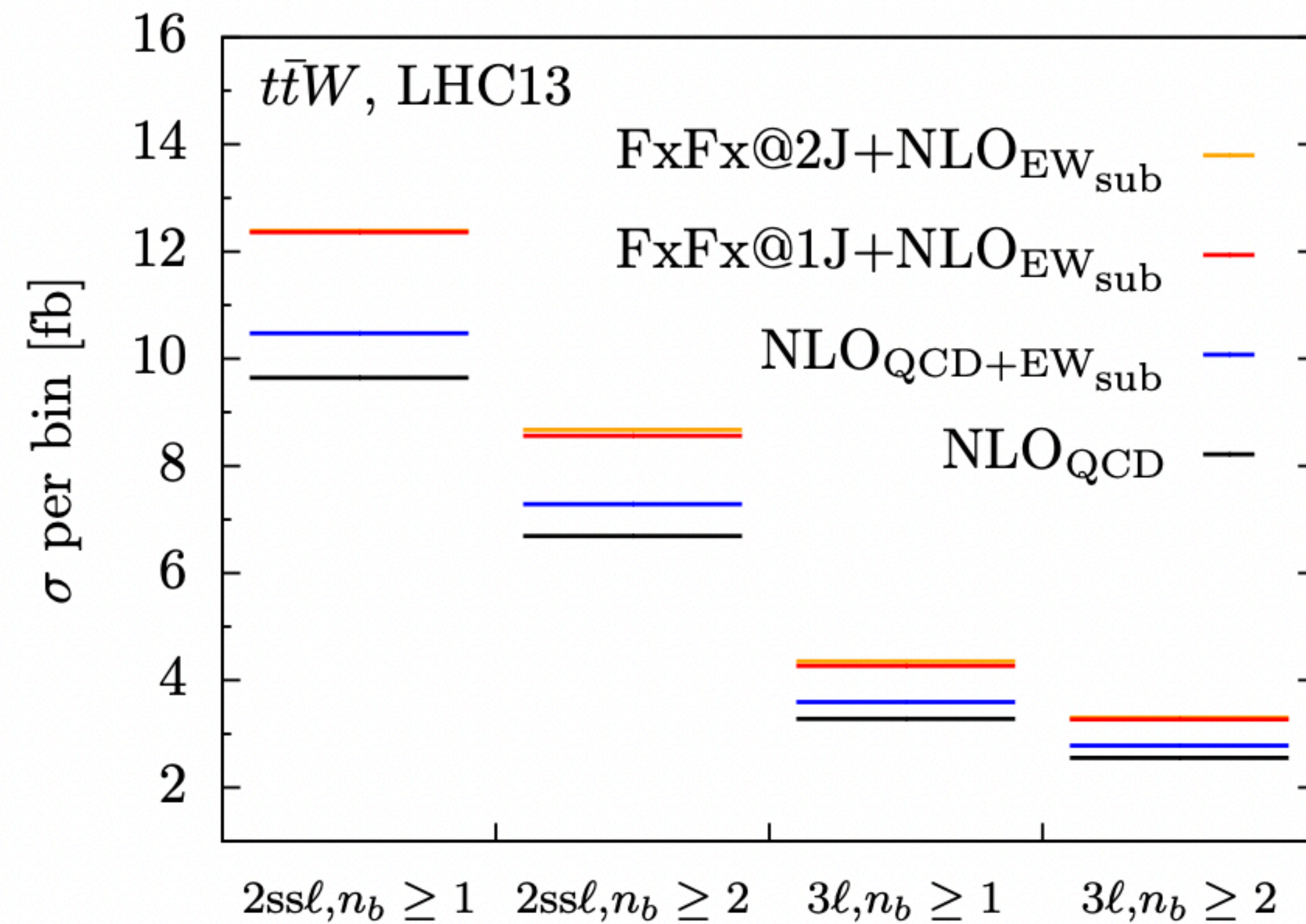
- Total cross section:

Order (default scale)	$\sigma \pm \text{scale} \pm \text{PDF}$ [fb]
FxFx@2J+EW _{sub} + $\widetilde{\text{NLO}}_{\text{EW}}$	$723(1)^{+73.0(+10.1\%)}_{-79.5(-11.0\%)} \quad +7.2(+1.0\%)_{-7.2(-1.0\%)}$

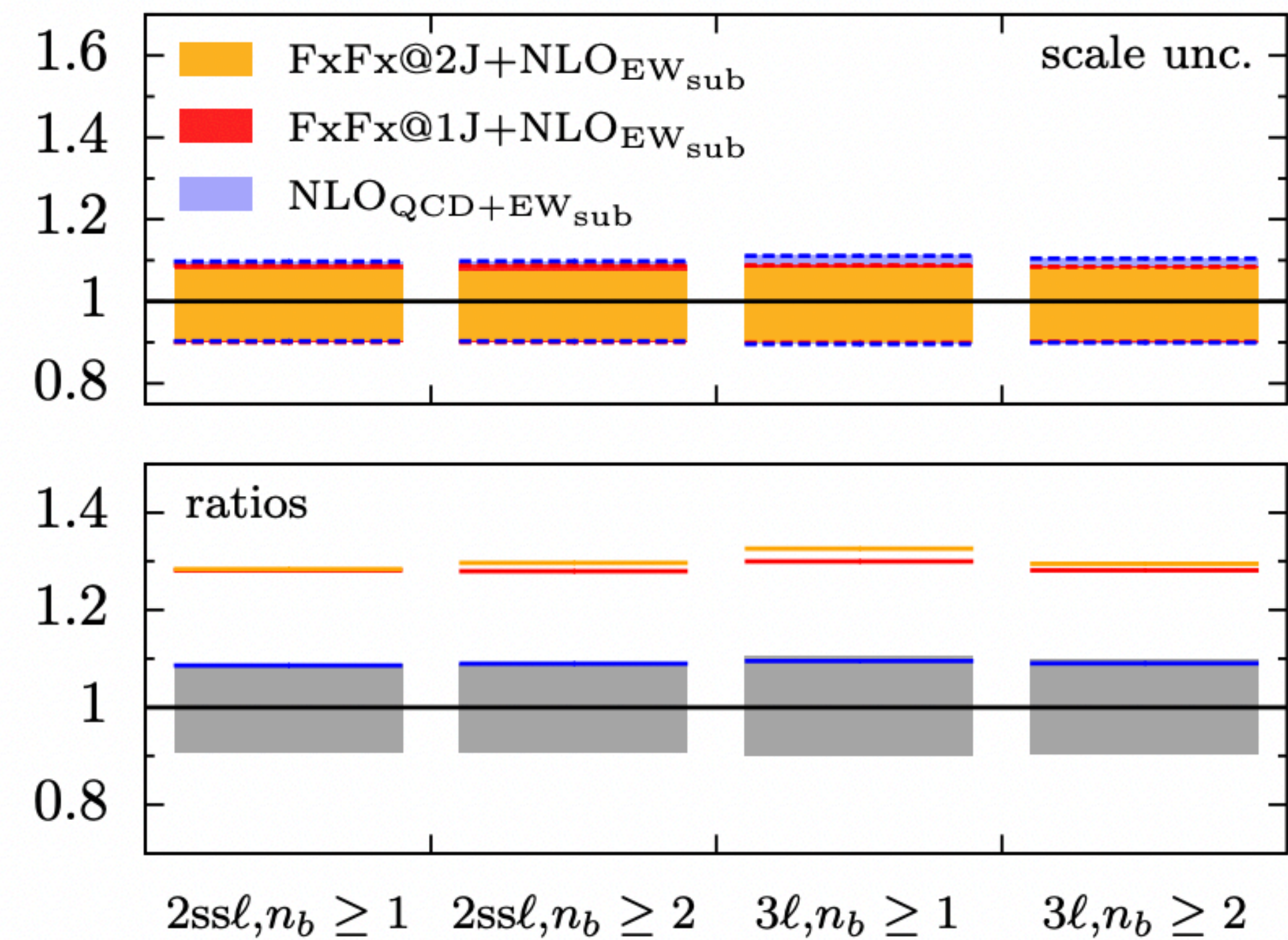
1.2*YR4



- ▶ 10% effects from EWK_{sub} contributions
- ▶ Additional ~20% effect from FxFx@2j additional QCD corrections:
 - ▶ Fairly constant across regions...



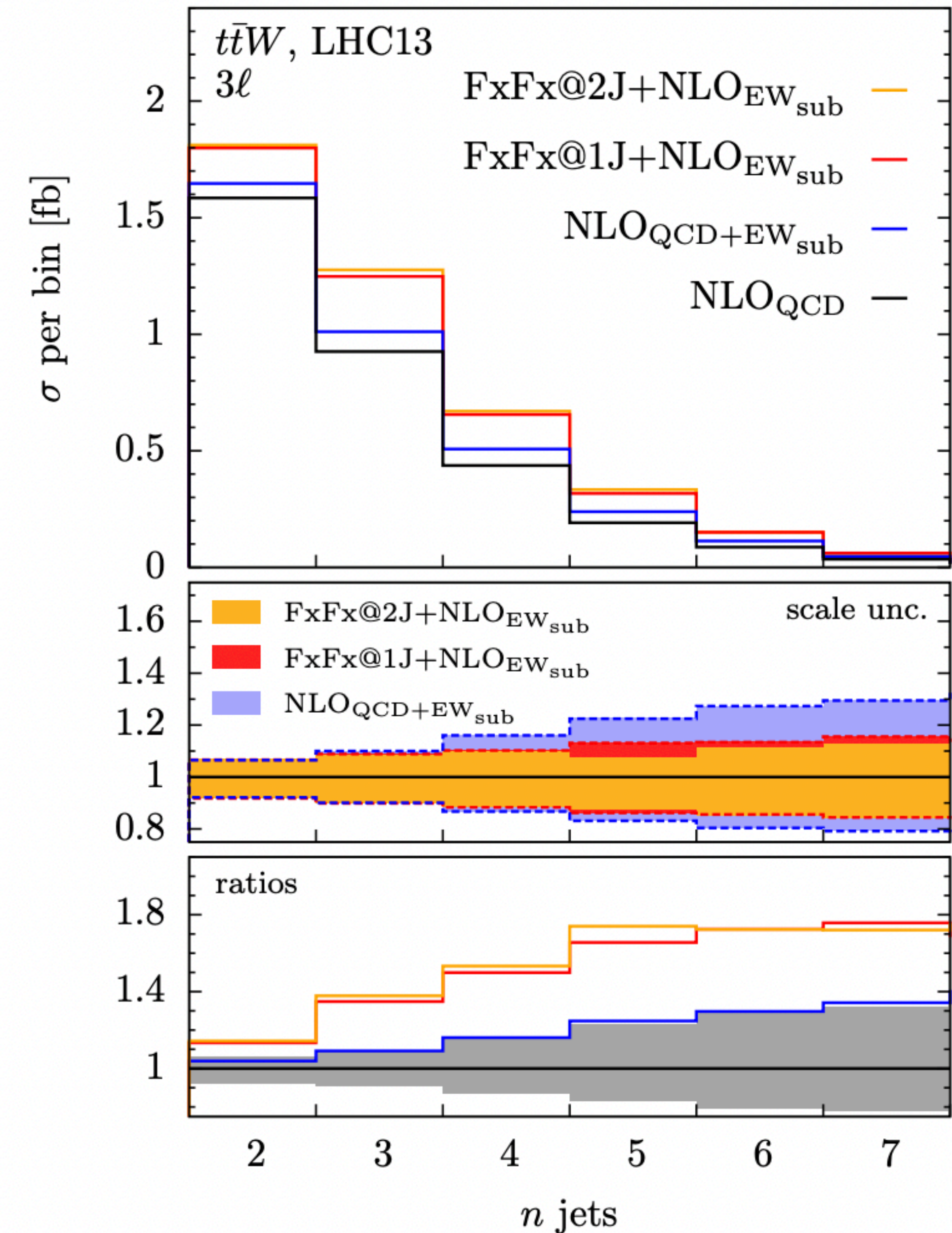
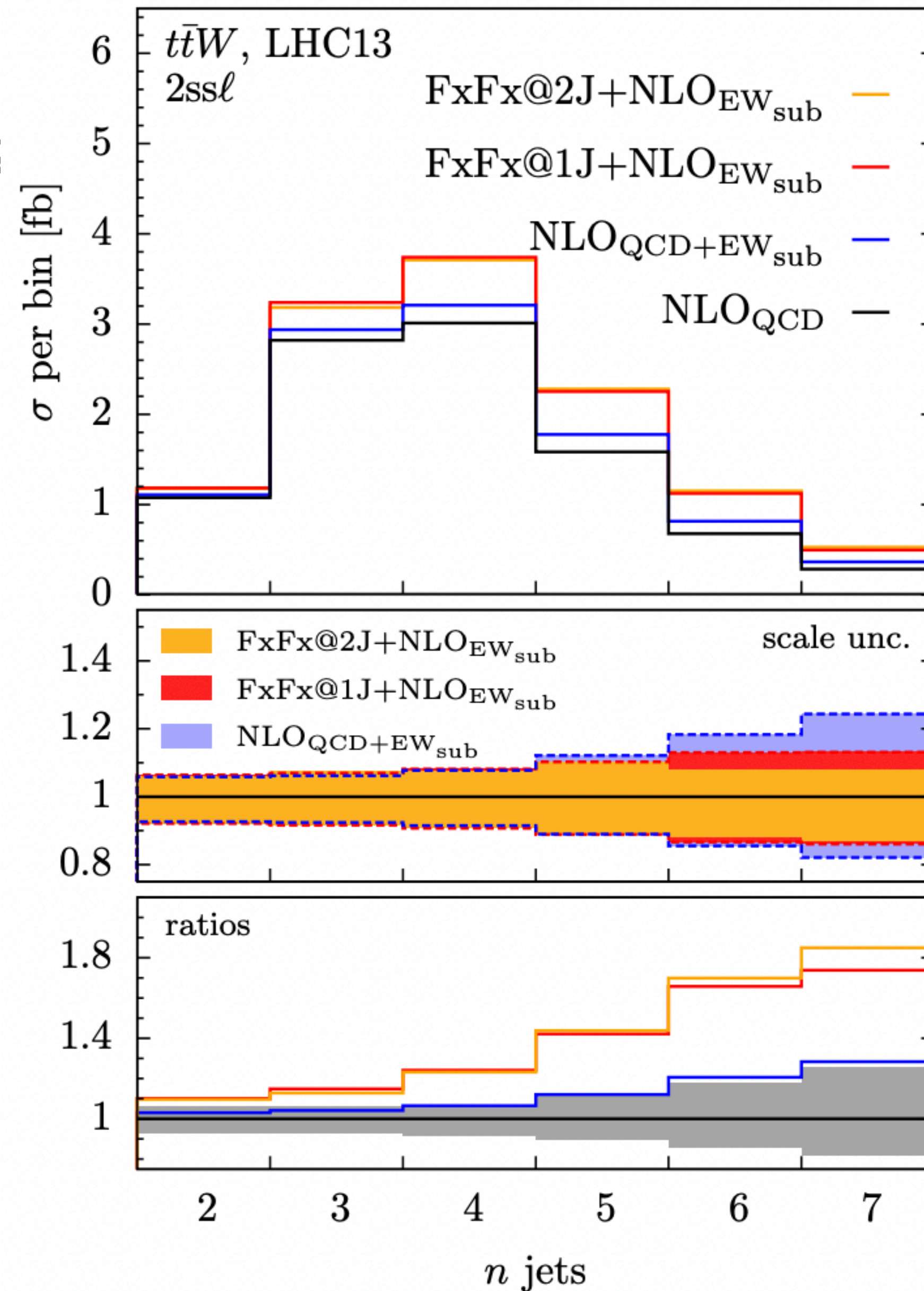
Multilepton signatures





FxFx | Realistic ML analysis

- Not constant difference
- Clear effect in Njets





Off-shell 1

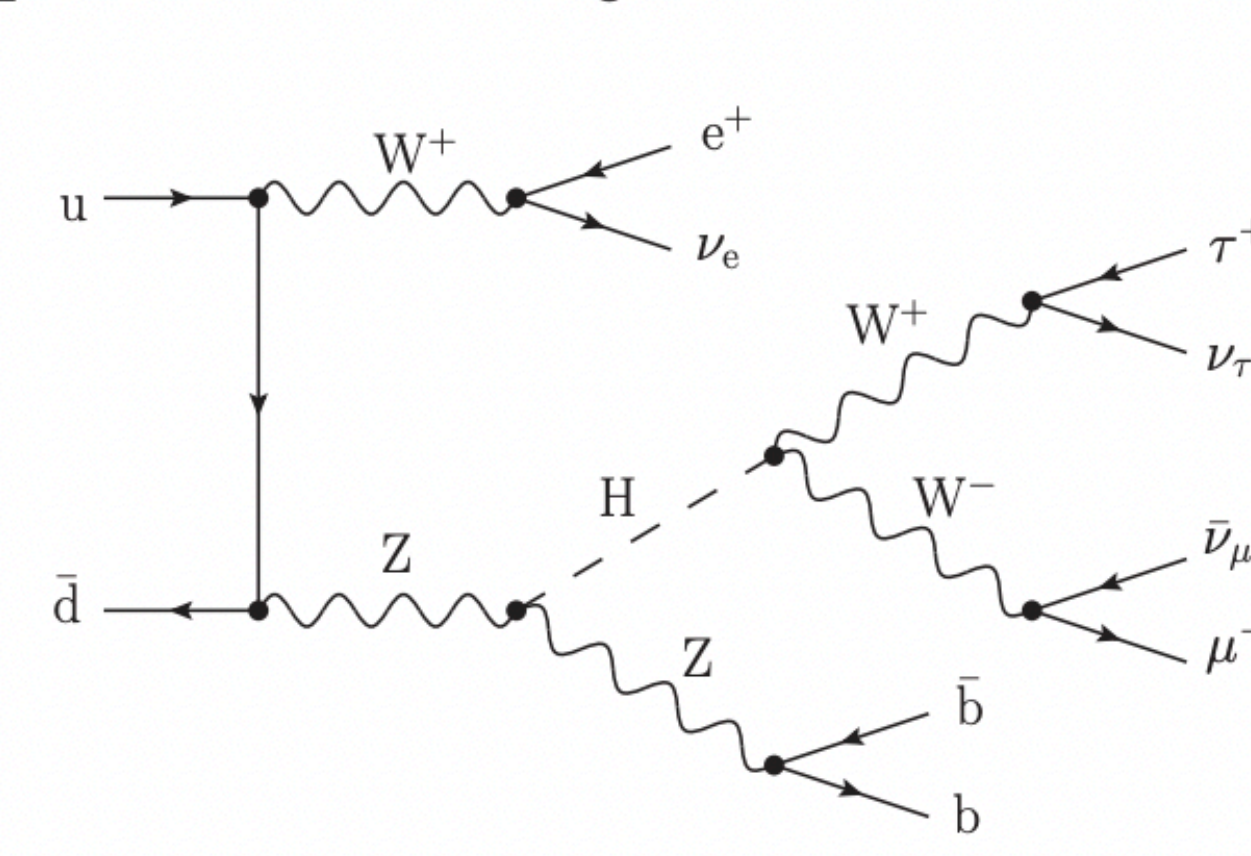
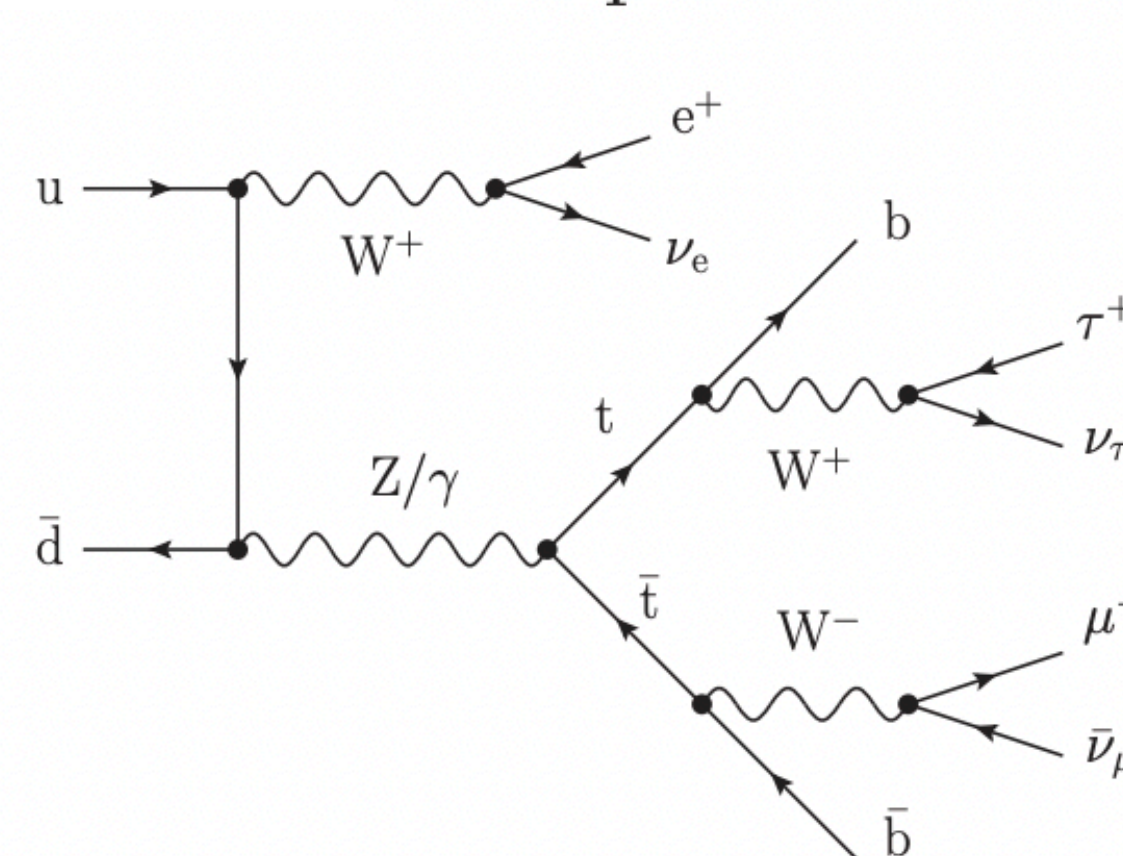
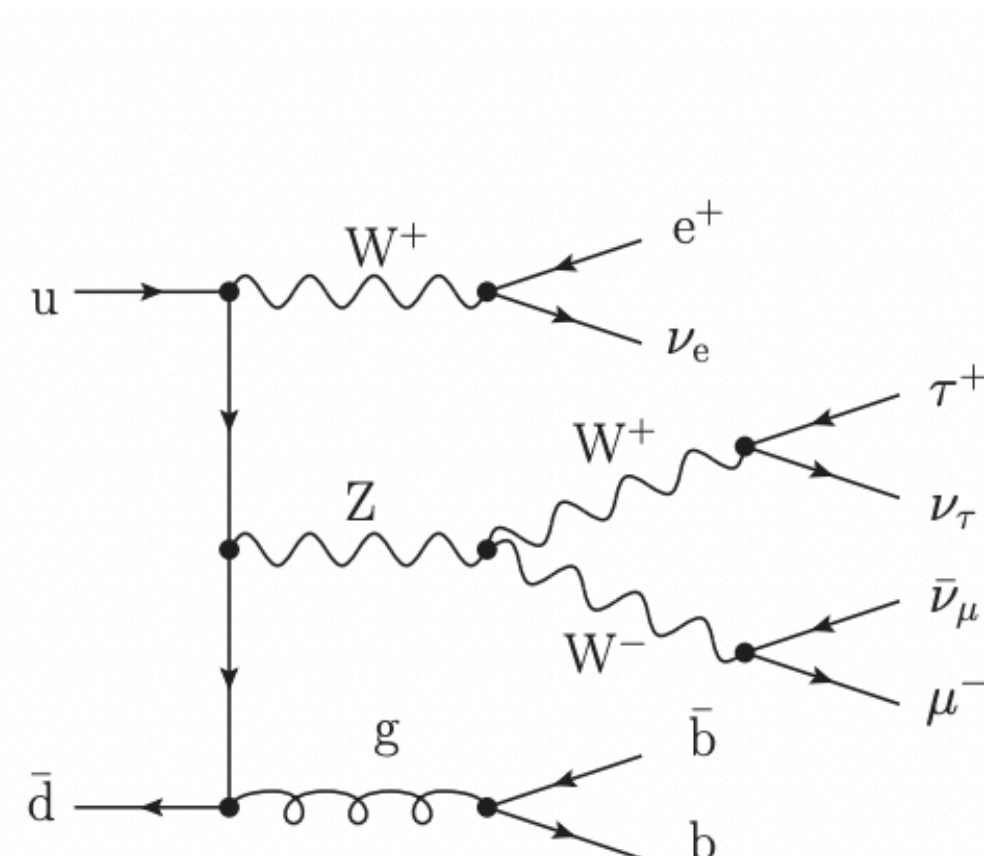
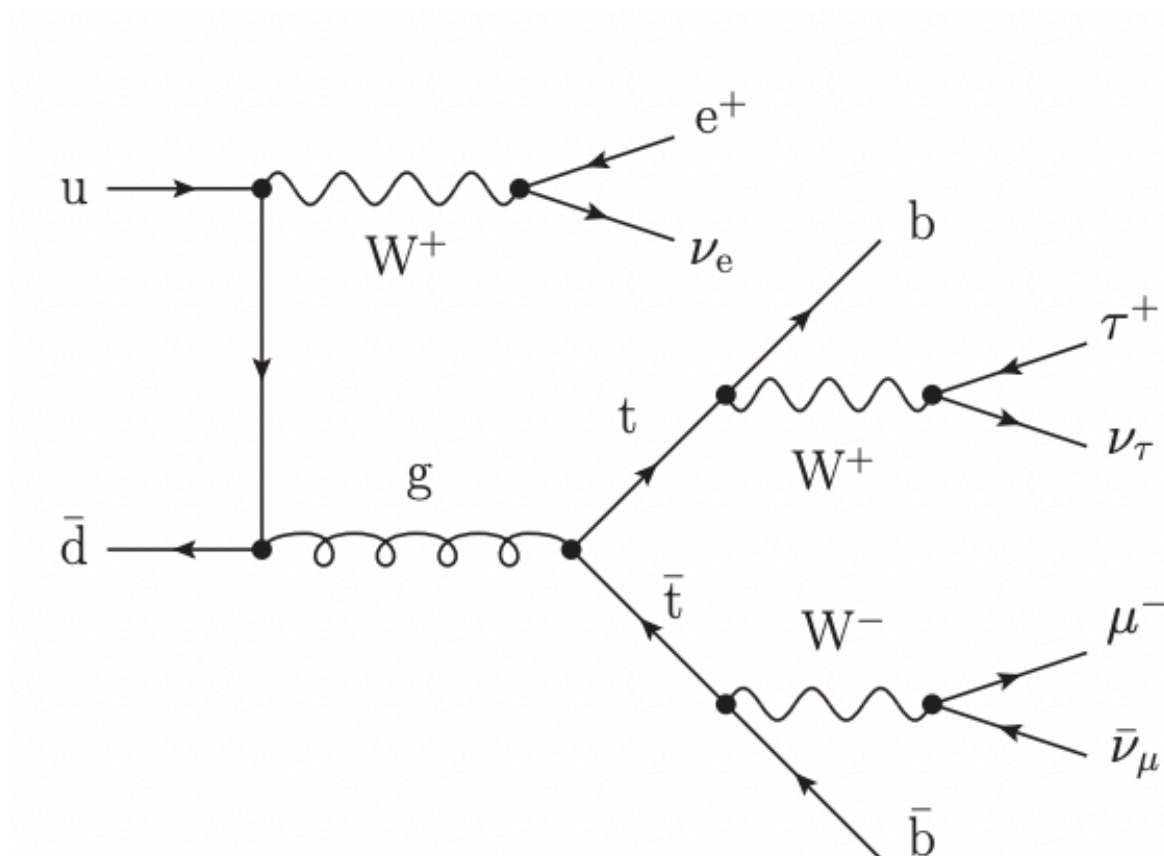
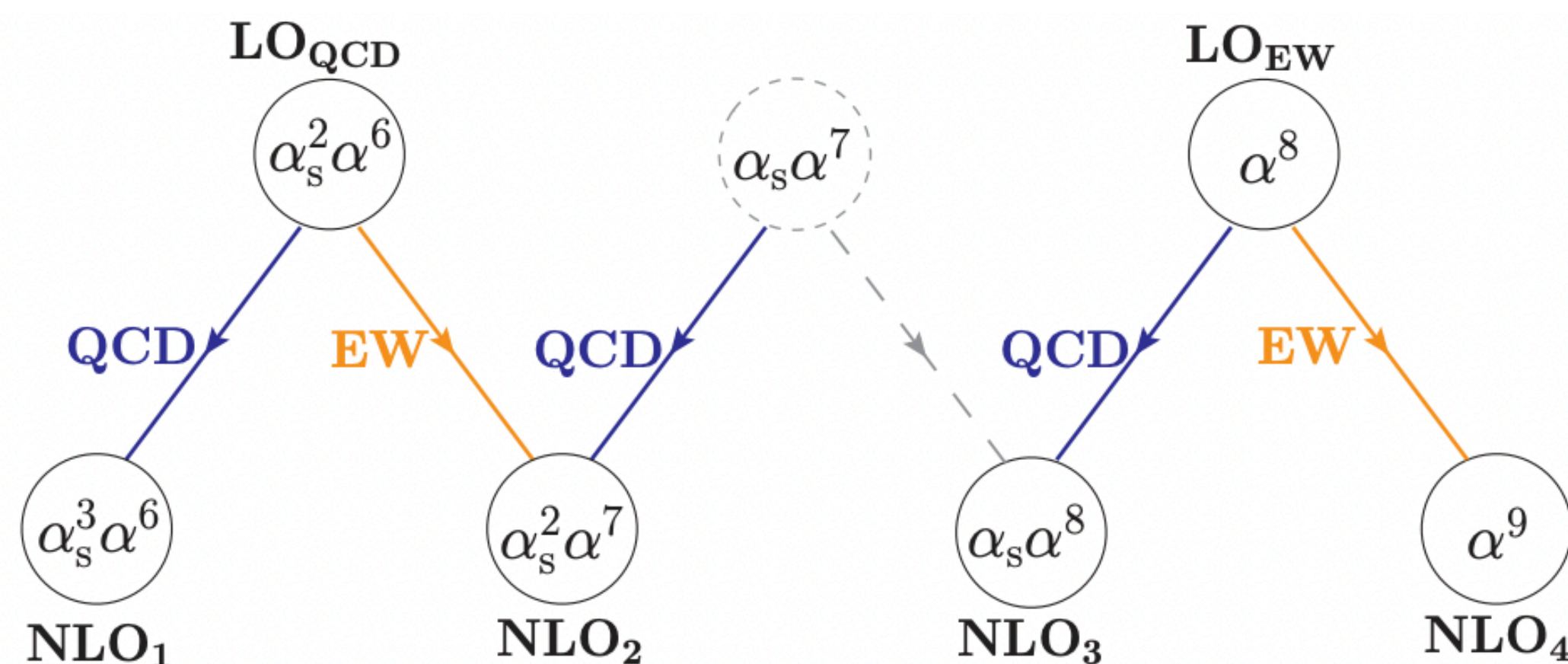
► Status of full NLO off-shell calculations:

► NLO QCD [Bevilacqua et al. 2005.09427 & 2012.01363, Denner GP 2007.12089]

► **Subleading NLO orders [Denner GP 2102.03246] in the 3l channel**

► **$pp \rightarrow b \bar{b} e^+ \nu_e \mu^- \bar{\nu}_\mu \tau^+ \nu_\tau + X$ at NLO accuracy:**

► Many contributions!



Selections, mimic those of [ATLAS 1901.03584]:

$$\mu_0^{(c)} = H_T/3, \mu_0^{(d)} = \sqrt{M_{T,t}M_{T,\bar{t}}}, \mu_0^{(e)} = \sqrt{M_{T,t}M_{T,\bar{t}}}/2$$

2 b-jets (anti- k_t , $R = 0.4(0.1)$ for jet (photon) clustering, $p_{T,b} > 25$ GeV, $|\eta_b| < 2.5$),
3 ch. leptons ($p_{T,\ell} > 27$ GeV, $|\eta_\ell| < 2.5$, $\Delta R_{\ell b} > 0.4$).

	$\mu_0^{(c)}$		$\mu_0^{(d)}$		$\mu_0^{(e)}$	
order	σ (fb)	ratio	σ (fb)	ratio	σ (fb)	ratio
LO _{QCD} ($\alpha_s^2 \alpha^6$)	0.2218(1) ^{+25.3%} _{-18.8%}	1	0.1948(1) ^{+23.9%} _{-18.1%}	1	0.2414(1) ^{+26.2%} _{-19.3%}	1
LO _{EW} (α^8)	0.002164(1) ^{+3.7%} _{-3.6%}	0.010	0.002122(1) ^{+3.7%} _{-3.6%}	0.011	0.002201(1) ^{+3.7%} _{-3.6%}	0.009
NLO ₁ ($\alpha_s^3 \alpha^6$)	0.0147(6)	0.066	0.0349(6)	0.179	0.0009(7)	0.004
NLO ₂ ($\alpha_s^2 \alpha^7$)	-0.0122(3)	-0.055	-0.0106(3)	-0.054	-0.0134(4)	-0.056
NLO ₃ ($\alpha_s \alpha^8$)	0.0293(1)	0.131	0.0263(1)	0.135	0.0320(1)	0.133
LO _{QCD} +NLO ₁	0.2365(6) ^{+2.9%} _{-6.0%}	1.066	0.2297(6) ^{+5.5%} _{-7.3%}	1.179	0.2423(7) ^{+3.5%} _{-5.2%}	1.004
LO _{QCD} +NLO ₂	0.2094(3) ^{+25.0%} _{-18.7%}	0.945	0.1840(3) ^{+23.8%} _{-17.9%}	0.946	0.2277(4) ^{+25.9%} _{-19.2%}	0.944
LO _{EW} +NLO ₃	0.03142(4) ^{+22.2%} _{-16.8%}	0.141	0.02843(6) ^{+20.5%} _{-15.6%}	0.146	0.03425(7) ^{+22.8%} _{-17.0%}	0.142
LO+NLO	0.2554(7) ^{+4.0%} _{-6.5%}	1.151	0.2473(7) ^{+6.3%} _{-7.6%}	1.270	0.2628(9) ^{+4.3%} _{-5.9%}	1.089

- ▶ NLO₁ corr. impact depends a lot on scale choice (from +0.5% to +18%)
- ▶ NLO₂ and NLO₃ relative corr. are scale-independent: -5% and +13% resp.
- ▶ LO_{EW} is 1% of LO_{QCD}, NLO₃ corr. 10 times larger than its LO (tW scattering)
- ▶ Scale-uncertainties dominated by NLO₁: **$\approx \pm 5\%$ for combined NLO result (~1/2 YR4?!)**

Off-shell 1 | Differential

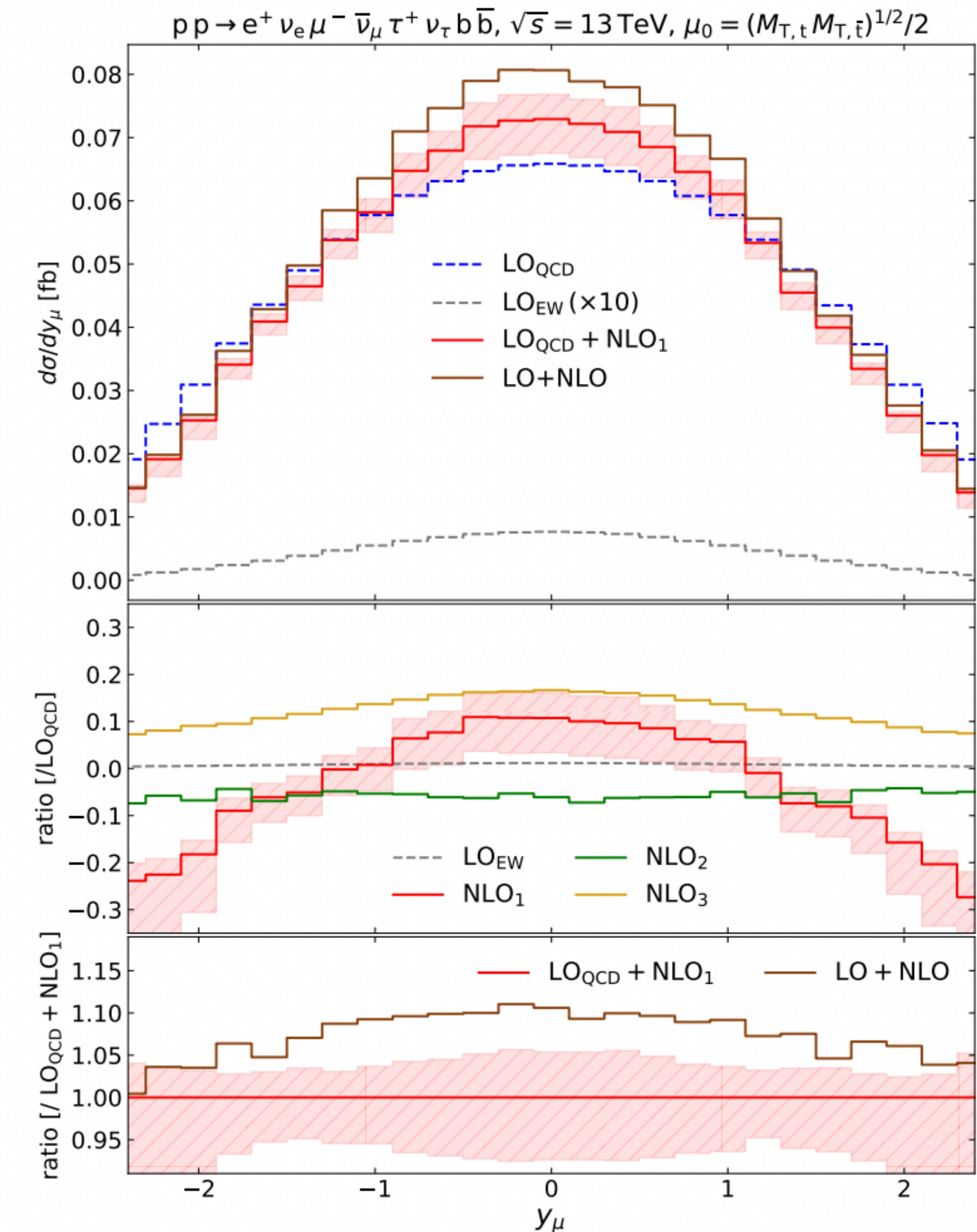
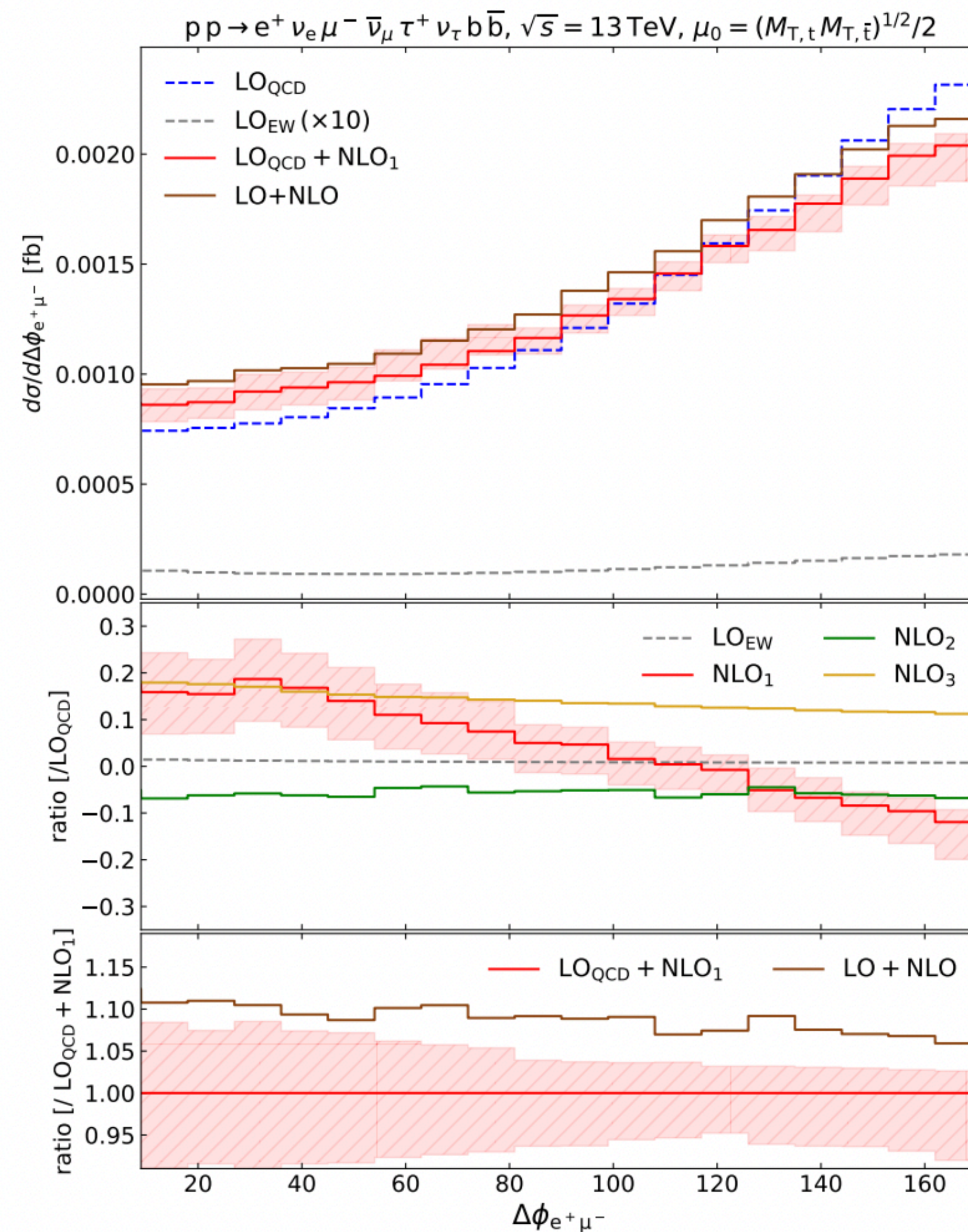
► NLO1 with constant slope

► NLO2+NLO3 give

► NLO1 large variation

► NLO3 diminish fr

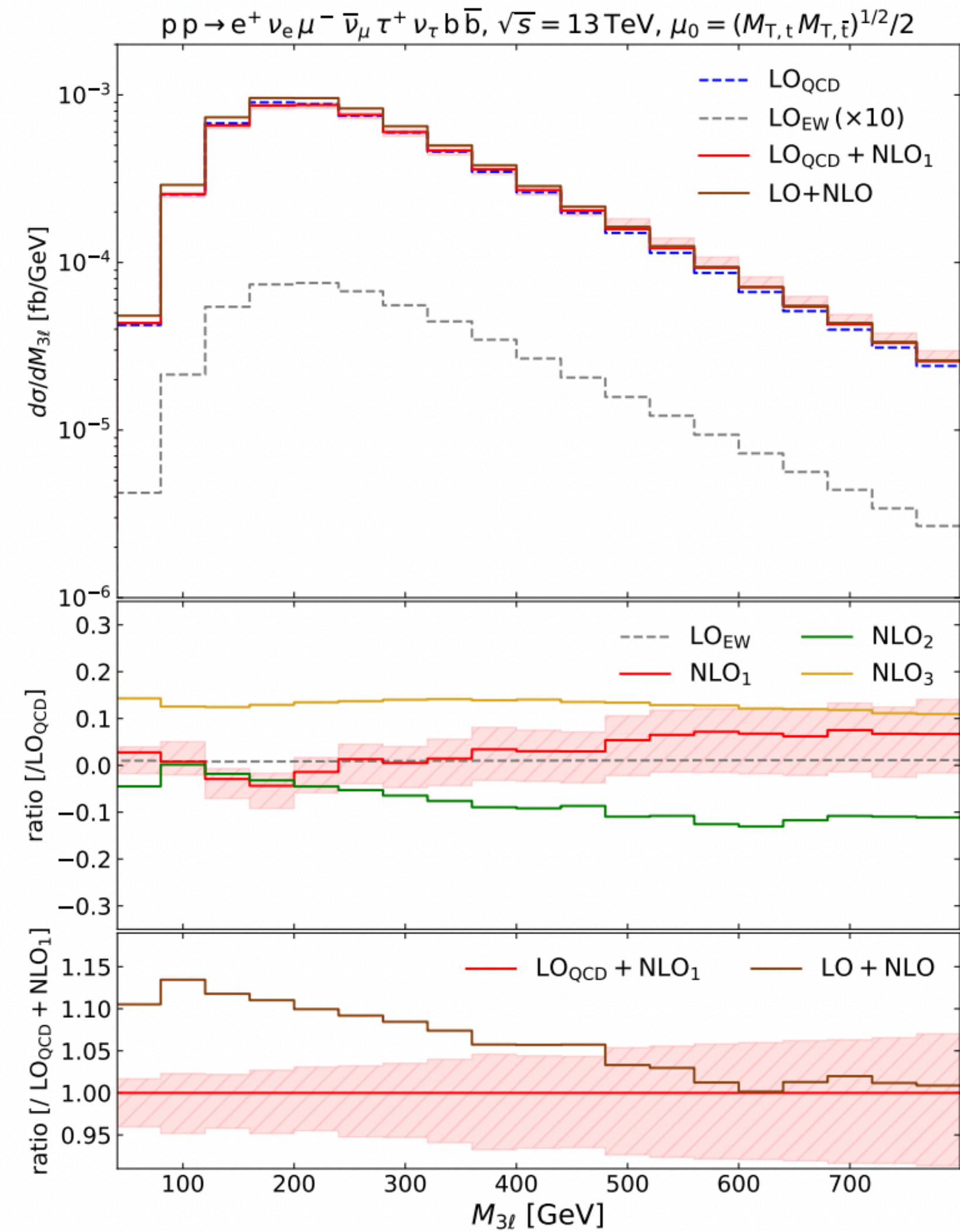
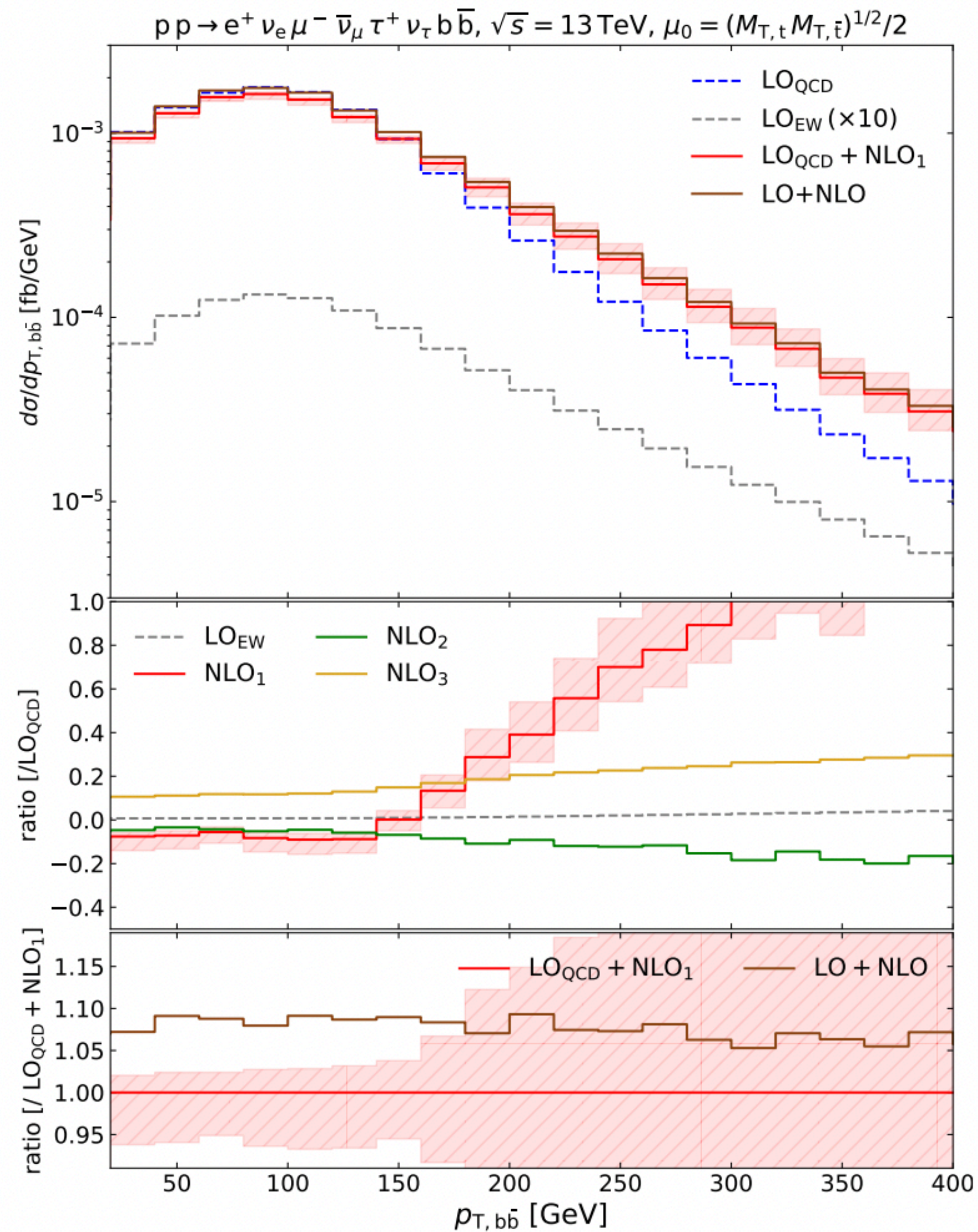
► EWK corrections



Off-shell 1 | Differential

► pT(bb) sensitive to QCD effects

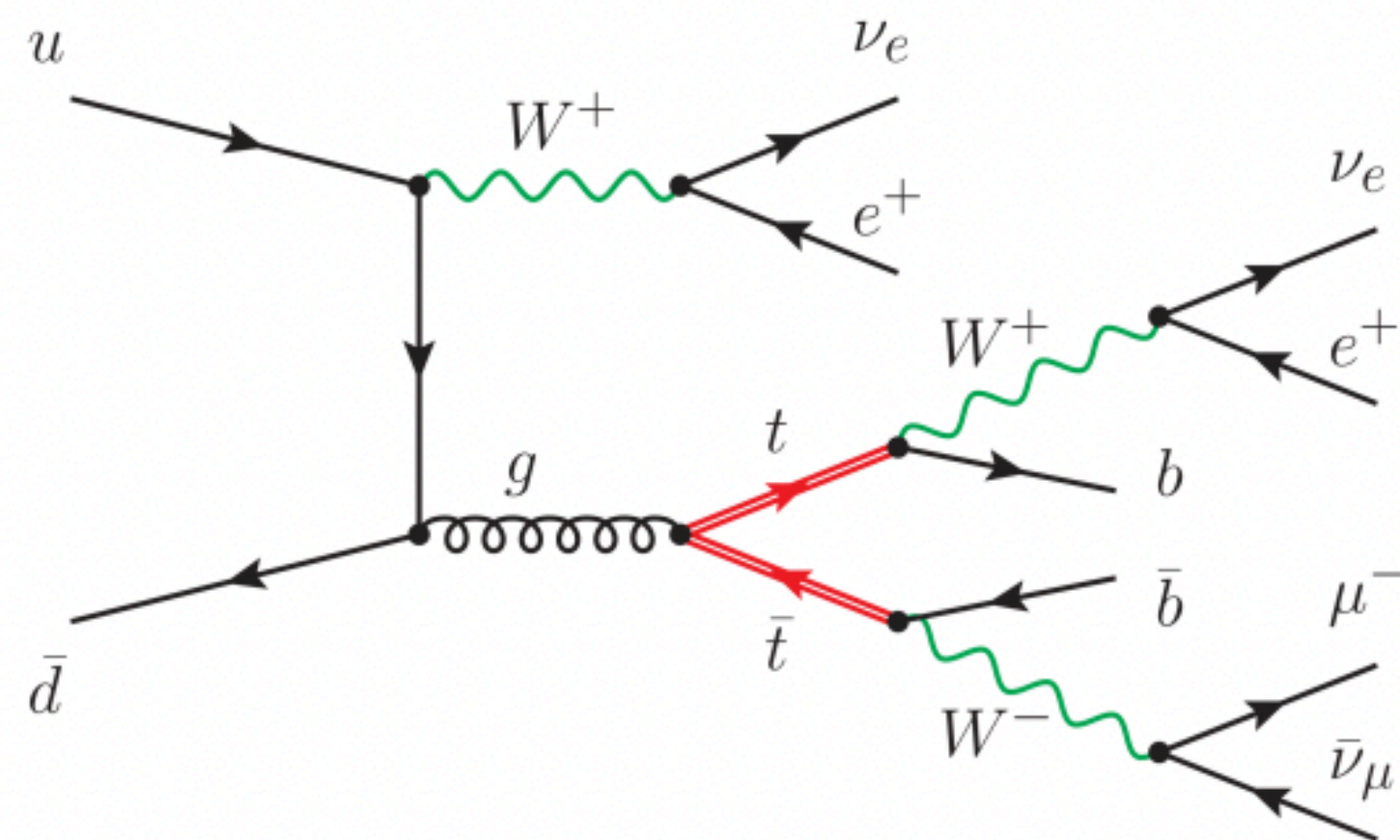
► M3l rather sensit



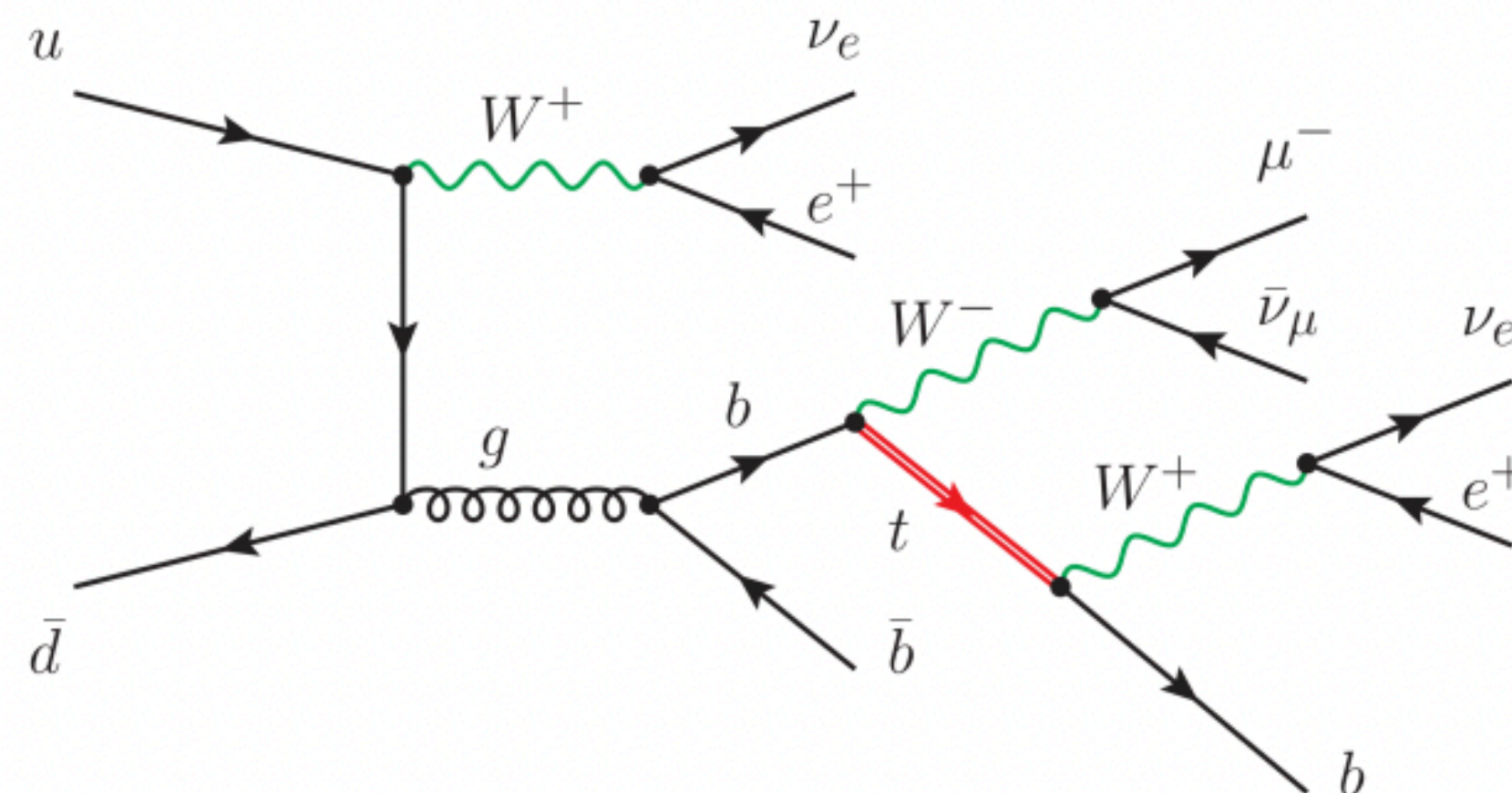


Off-shell 2

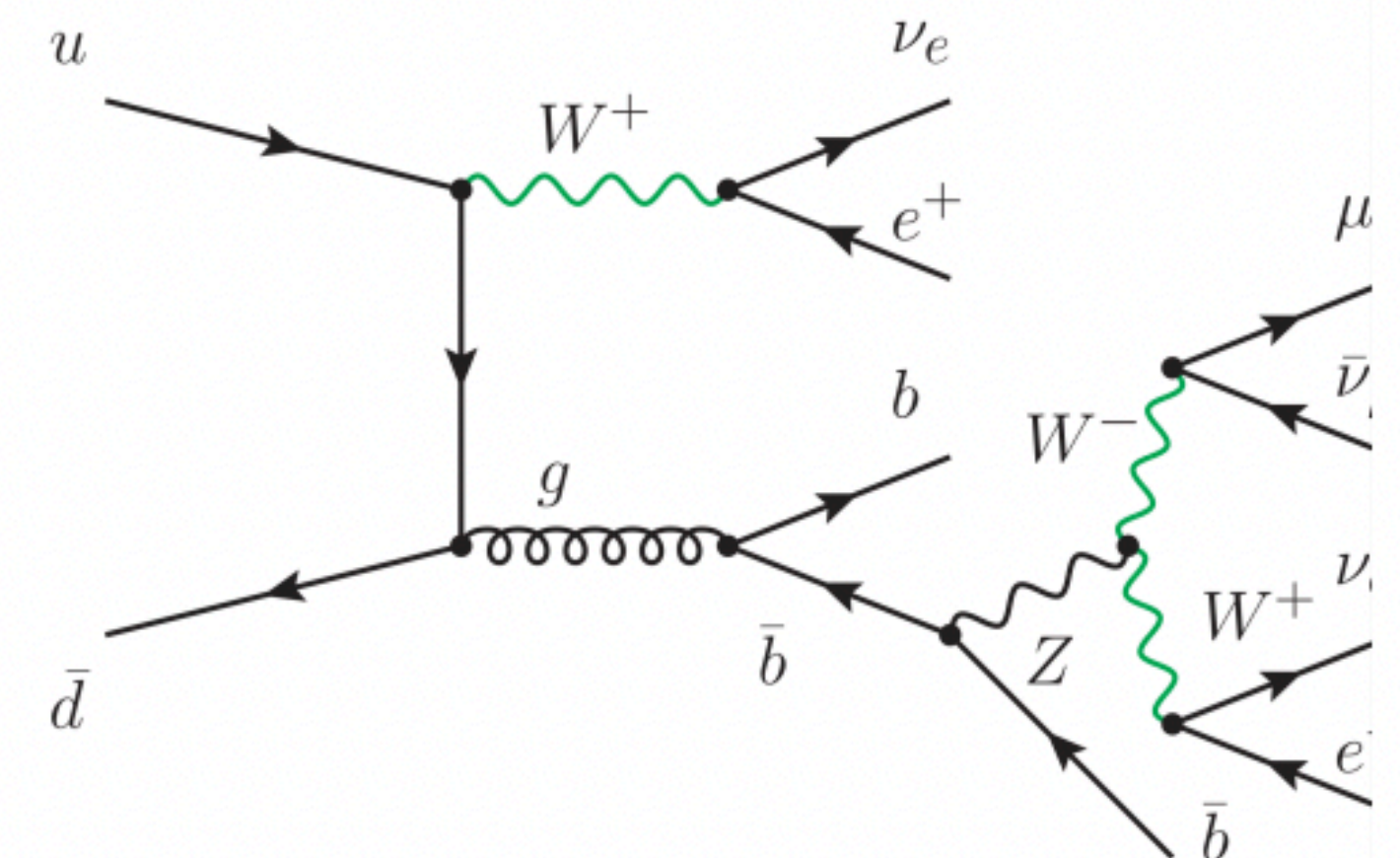
- ▶ Another group are working on off-shell NLO predictions
- ▶ Their study went more into comparisons of different off-shell treatments and comparison with ME+PS generators.



Double resonant



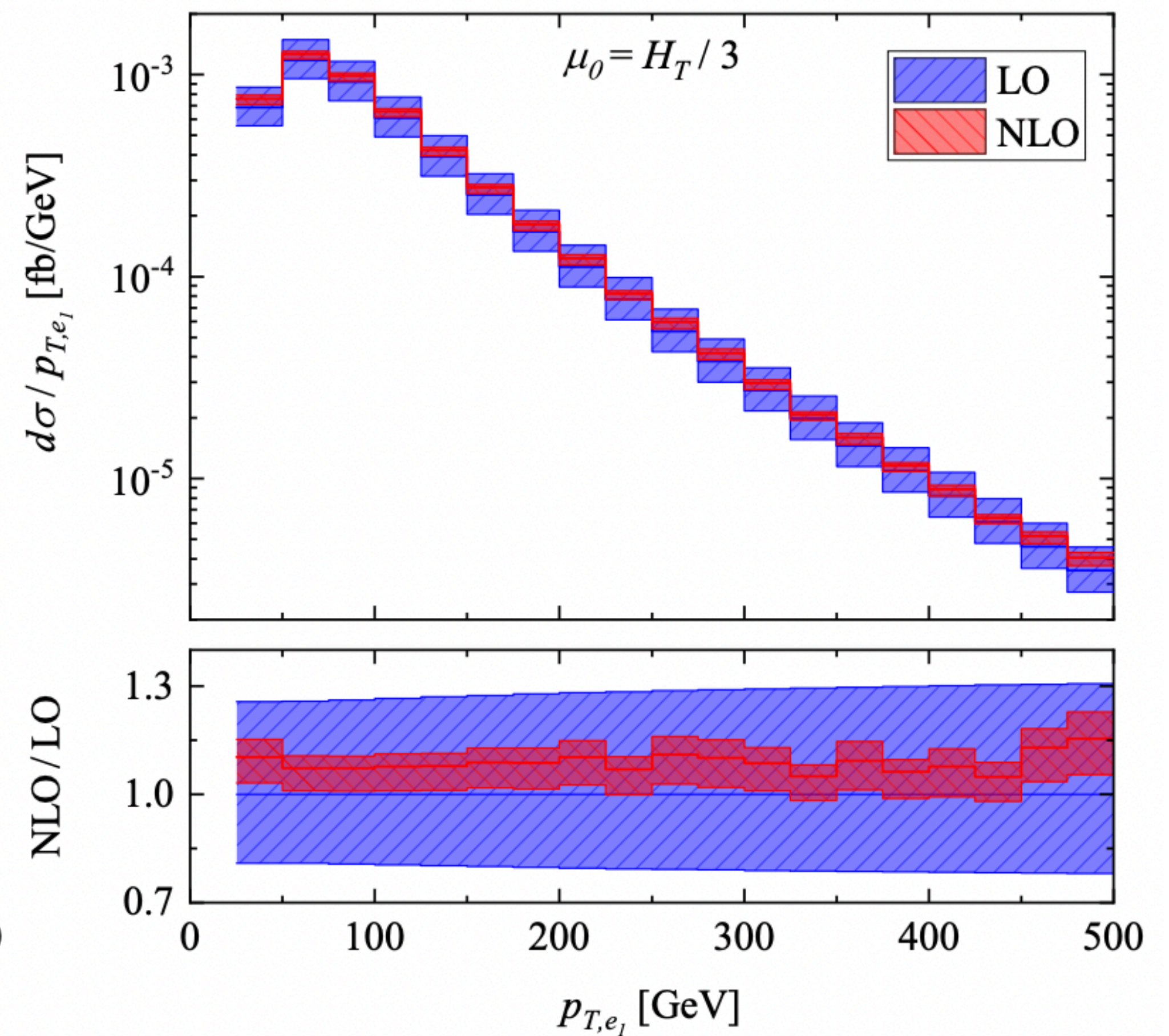
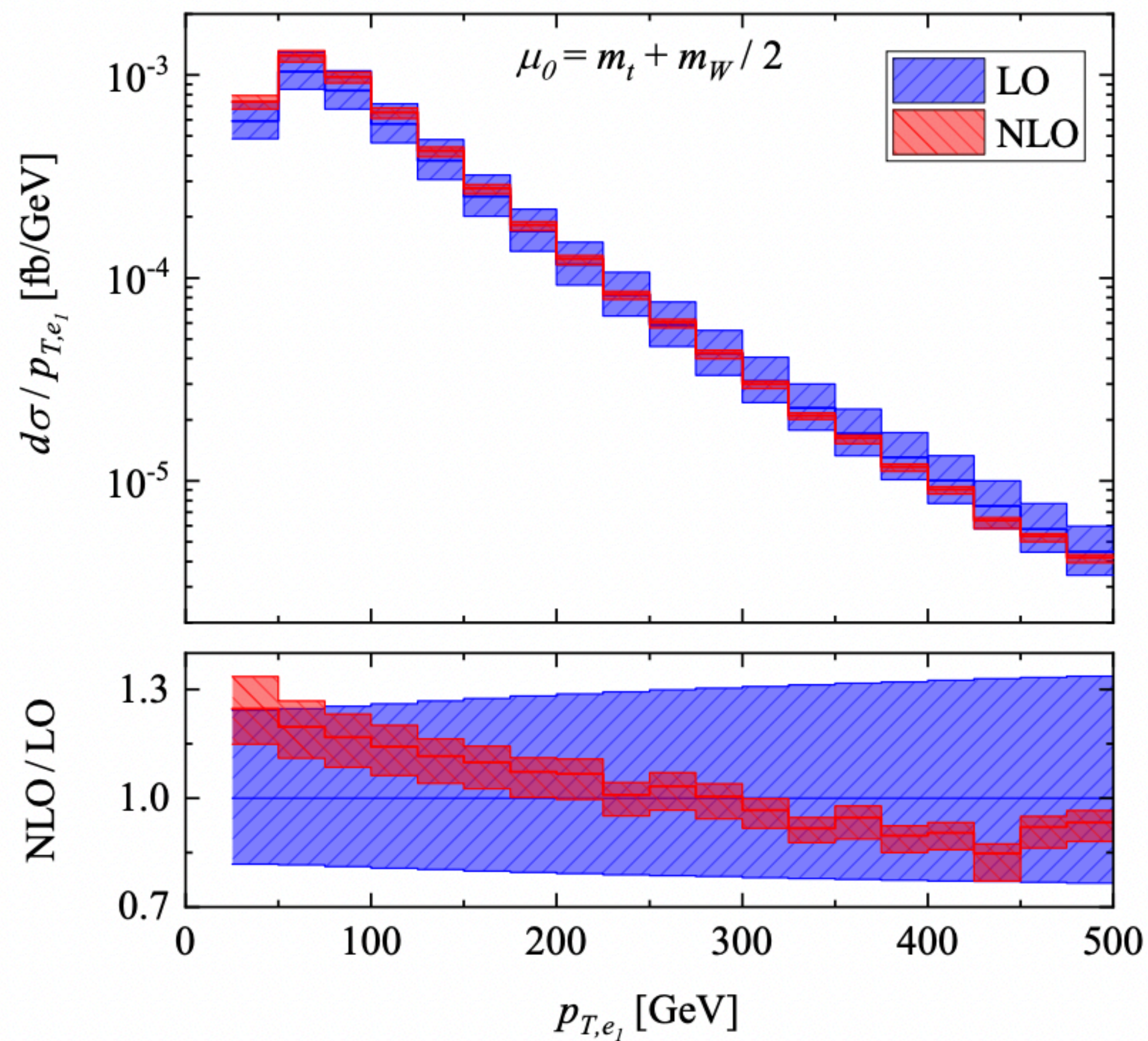
Single resonant



Non-resonant

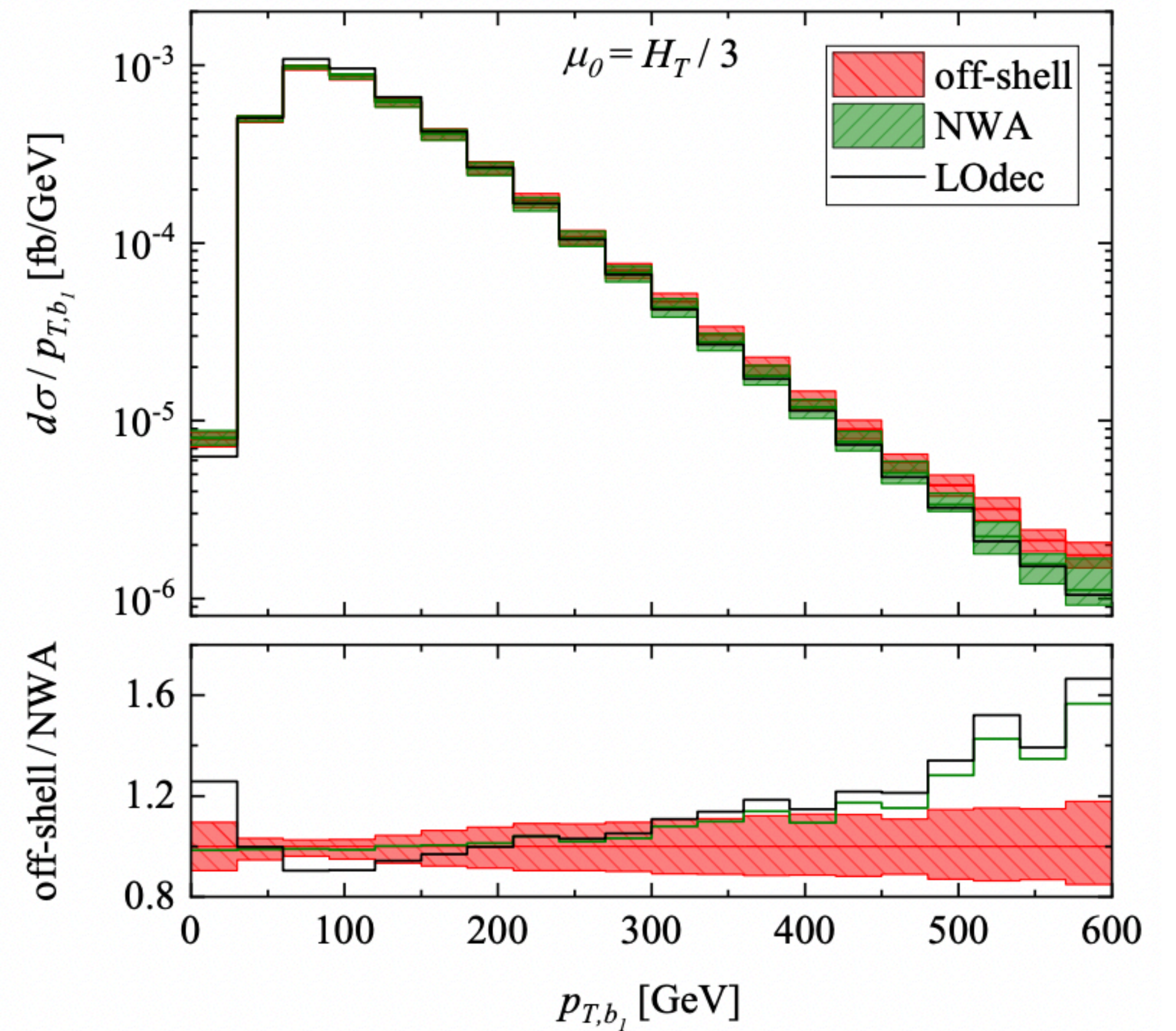
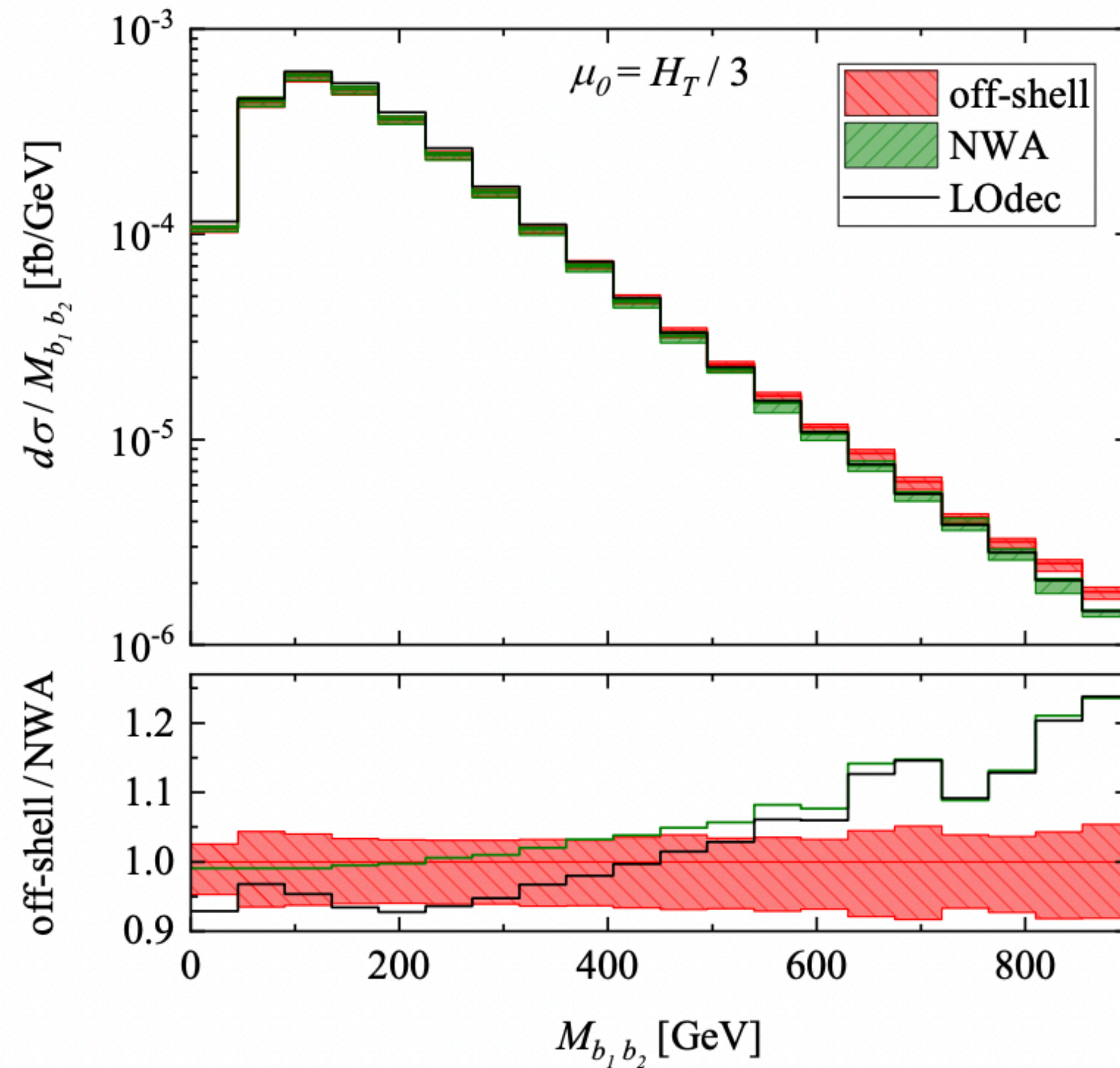
Off-shell 2 | NLO effects

- Impact of NLO effects
- ~10% uncertainty regardless of the scale choice



Off-shell 2 | Off-shell effects

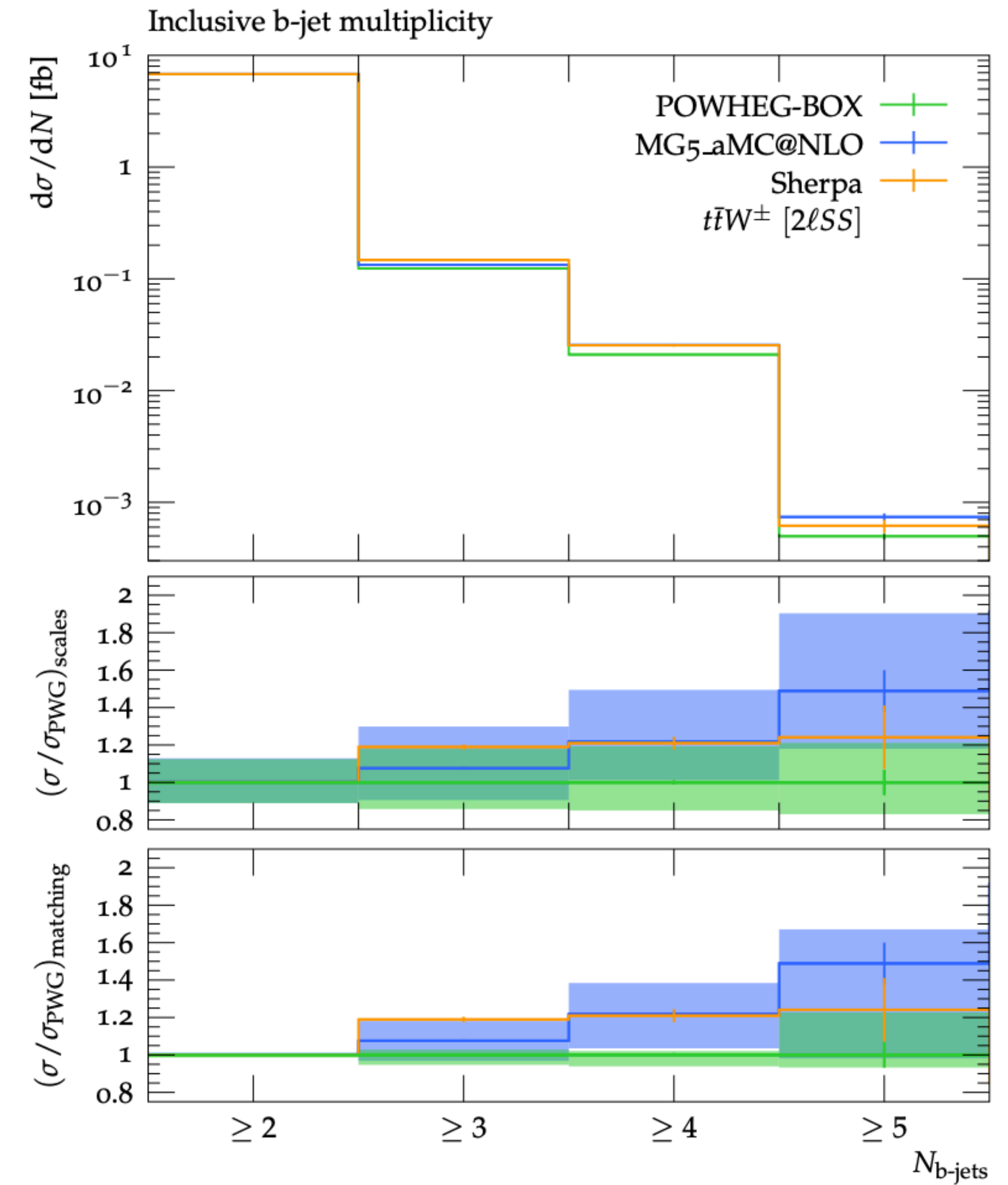
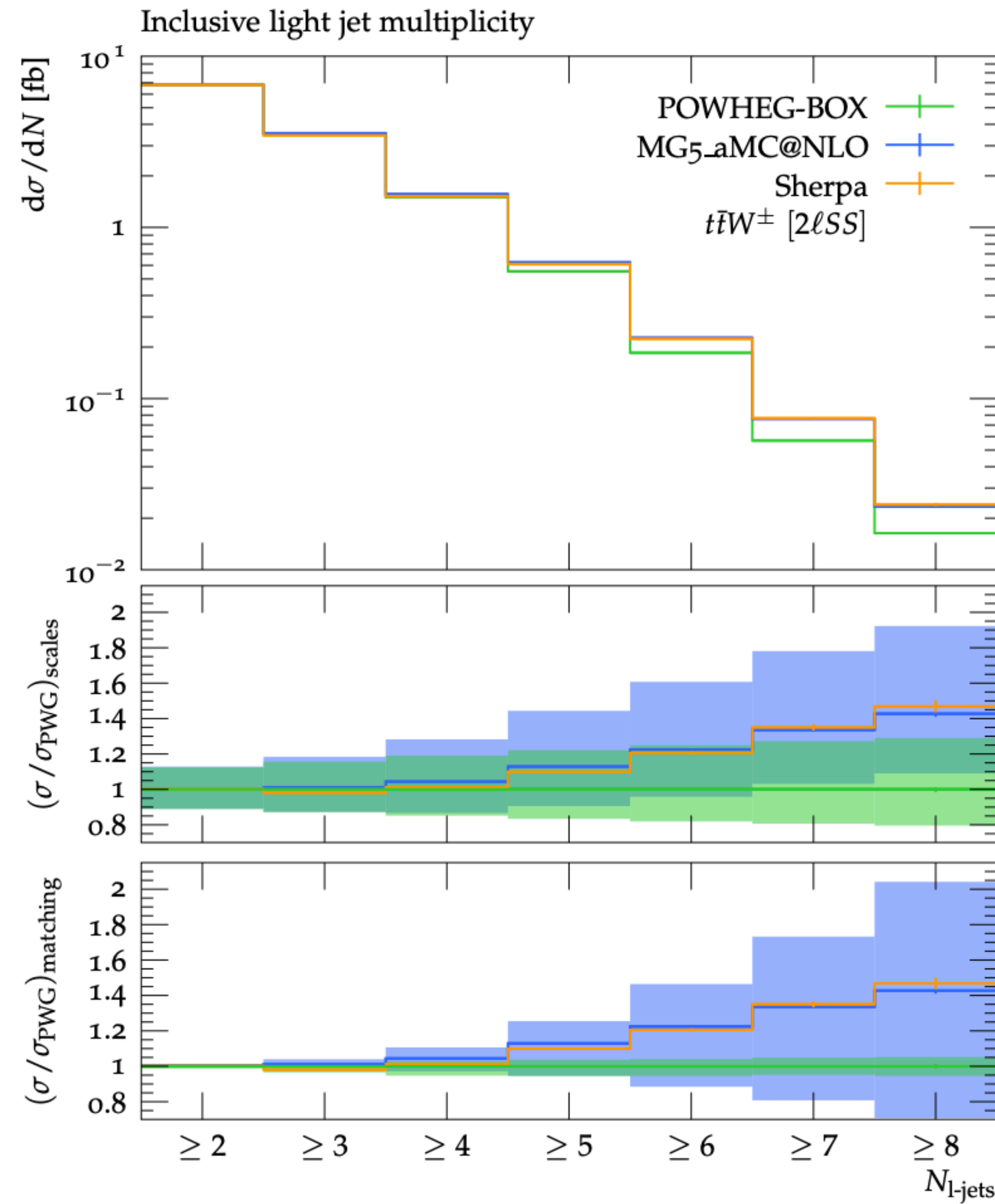
- ▶ Large off-shell effects in the tails of the distributions
- ▶ Differences between NWA and $\text{NWA}_{\text{LOdec}}$ are $\mathcal{O}(10\%)$ in the bulk





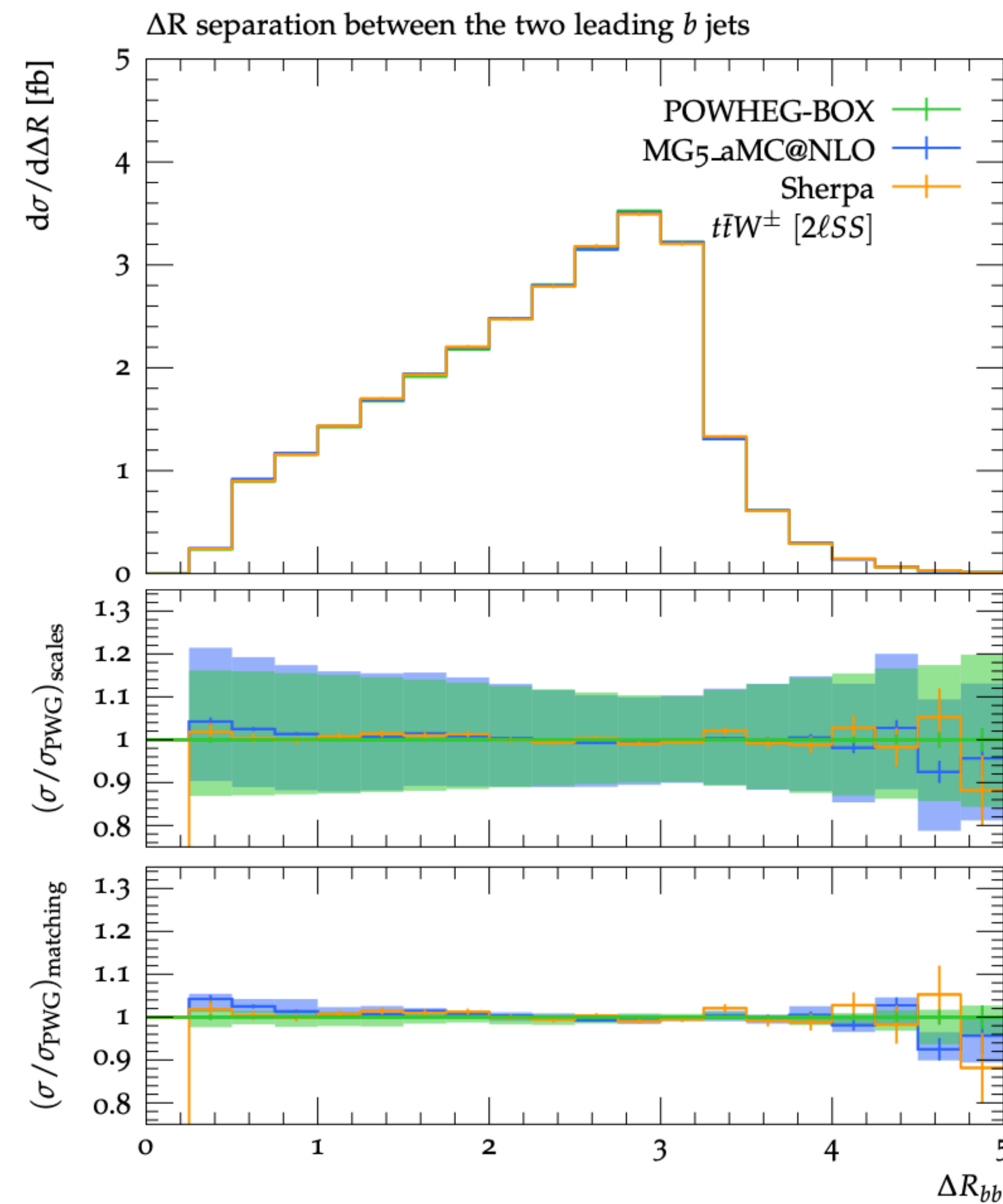
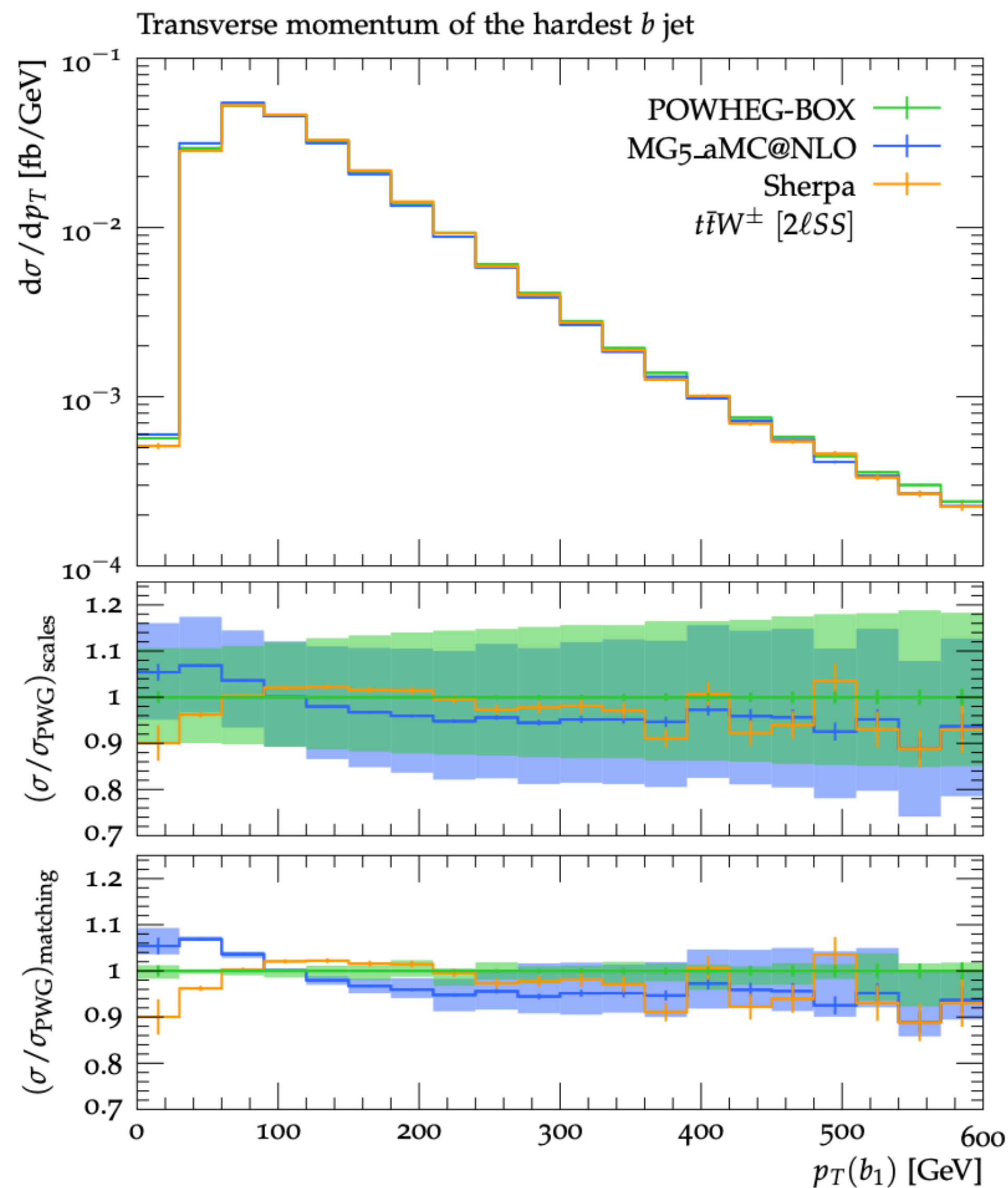
Off-shell 2 | ME+PS results

► Good agreeme



Off-shell 2 | ME+PS results

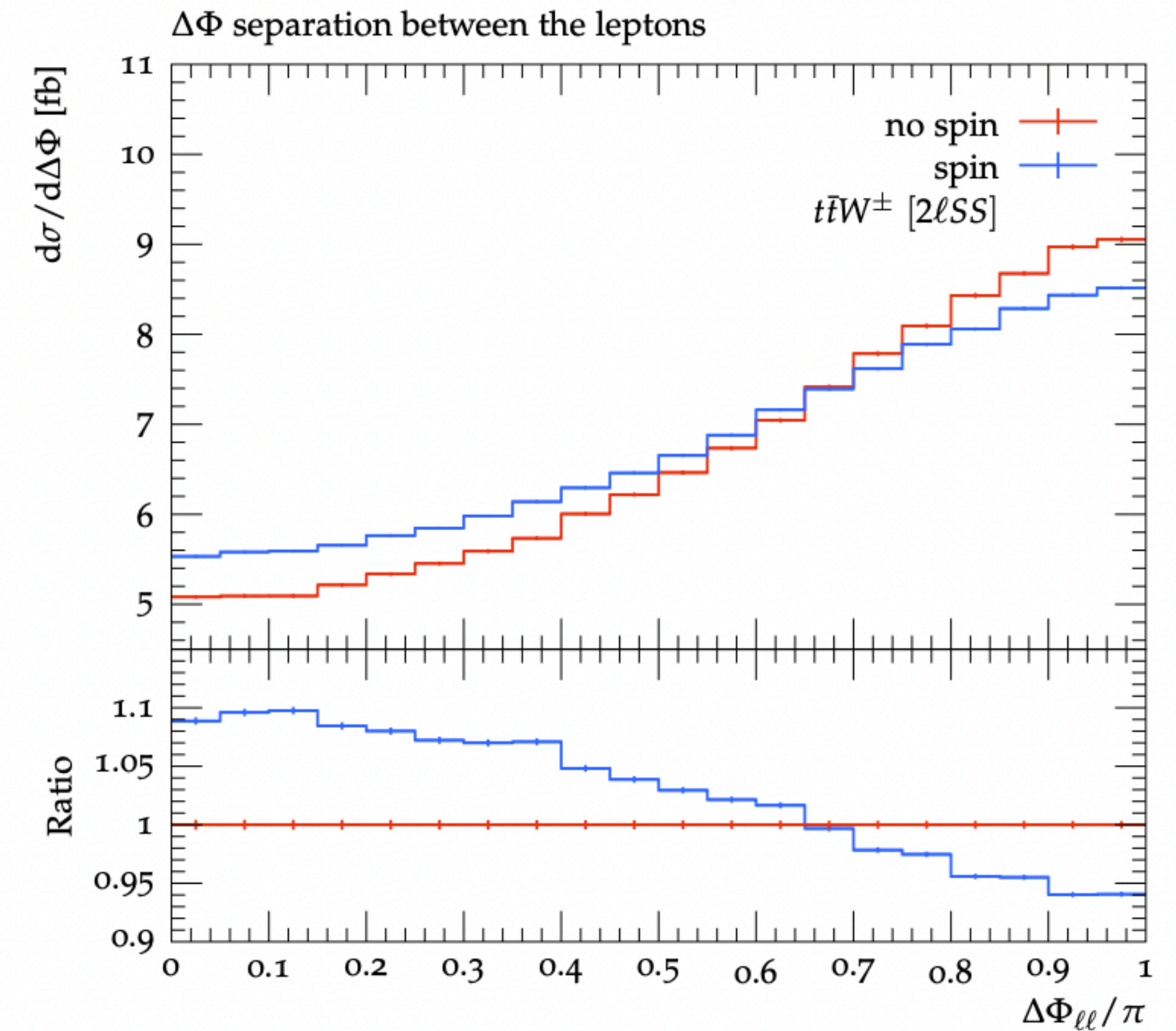
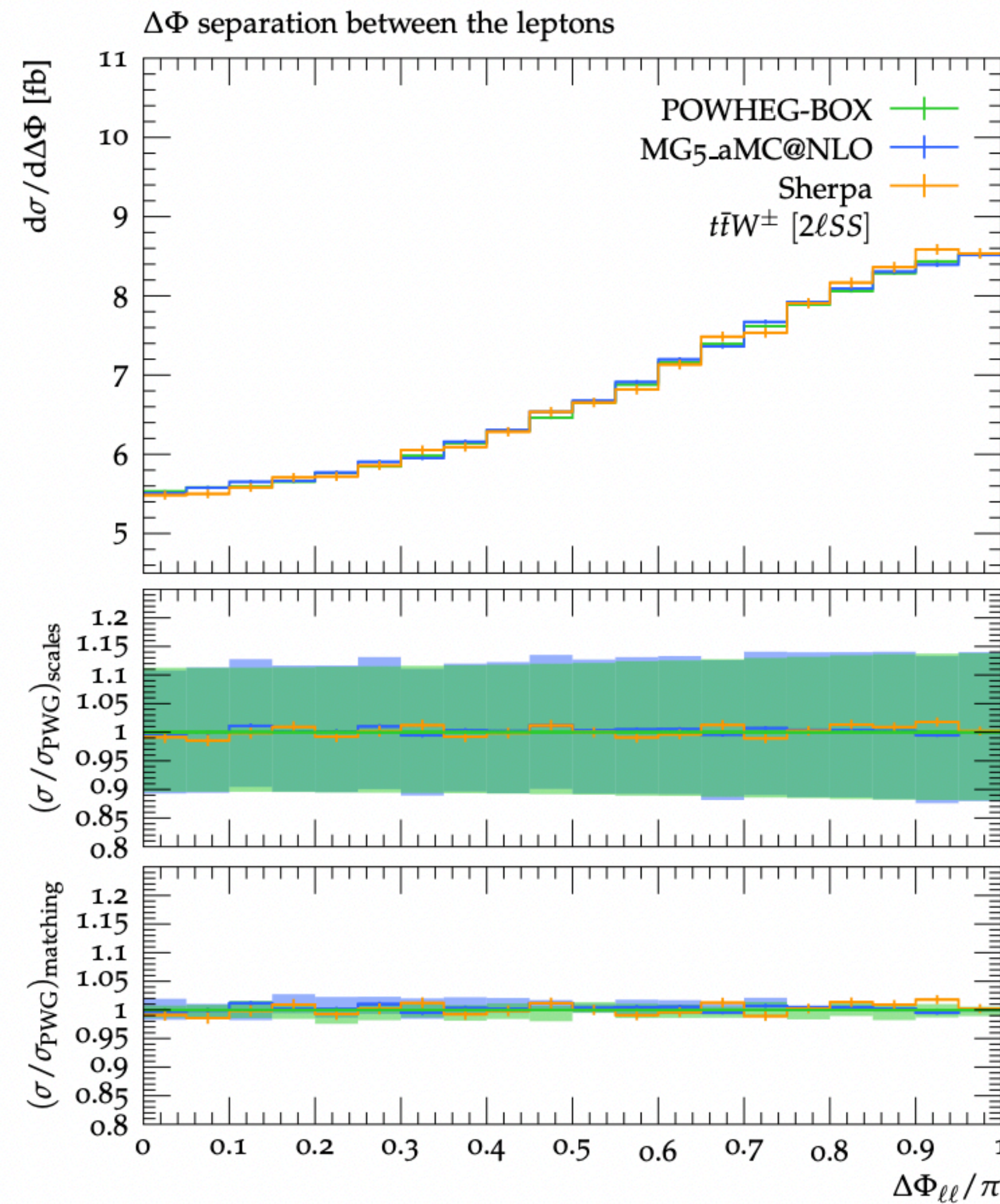
- Good agreement
- Even better in (
- Small shape dif





Off-shell 2 | ME+PS results

- Polarization eff
- **Stronger effect**
- Effect in opposi



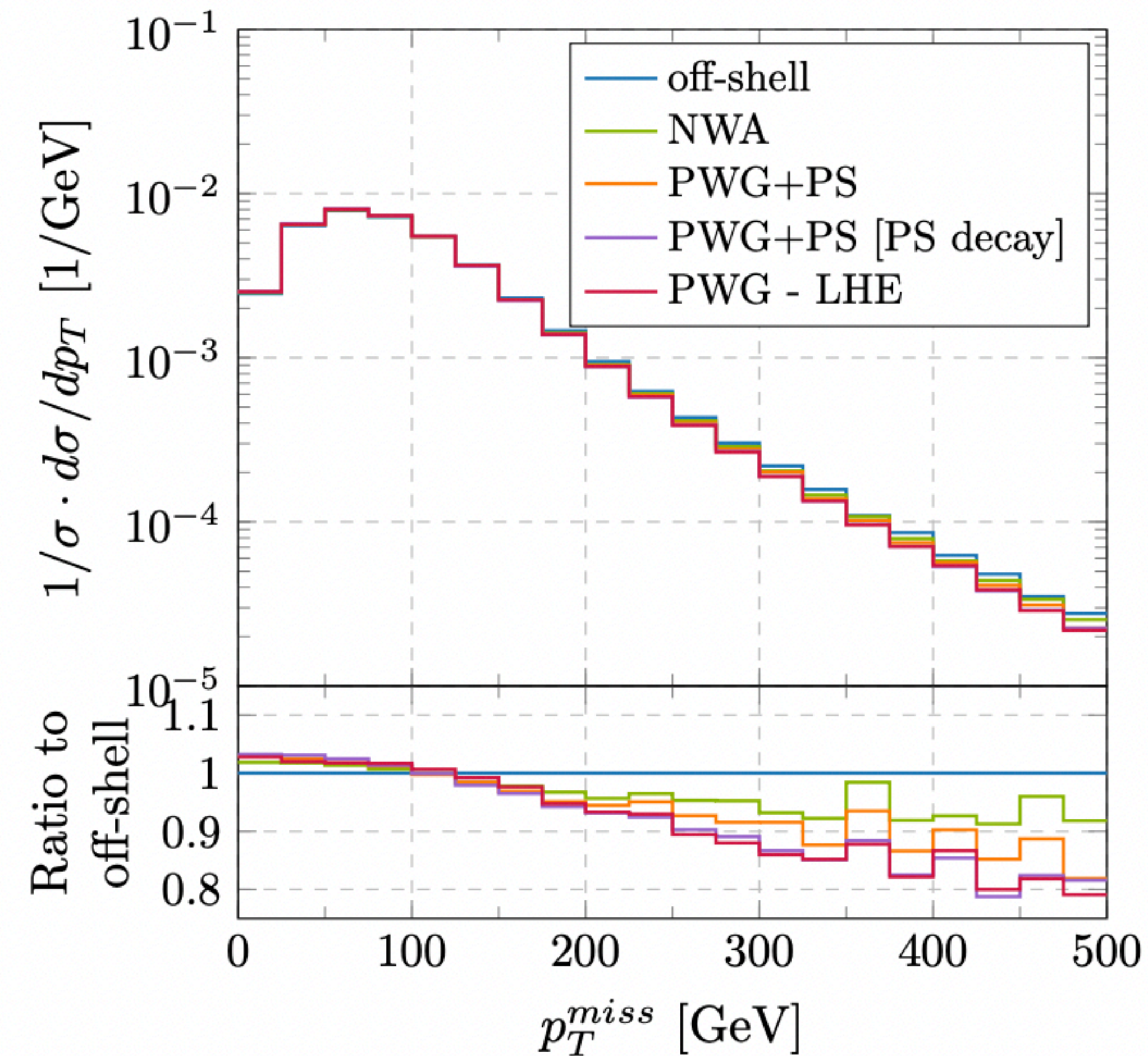
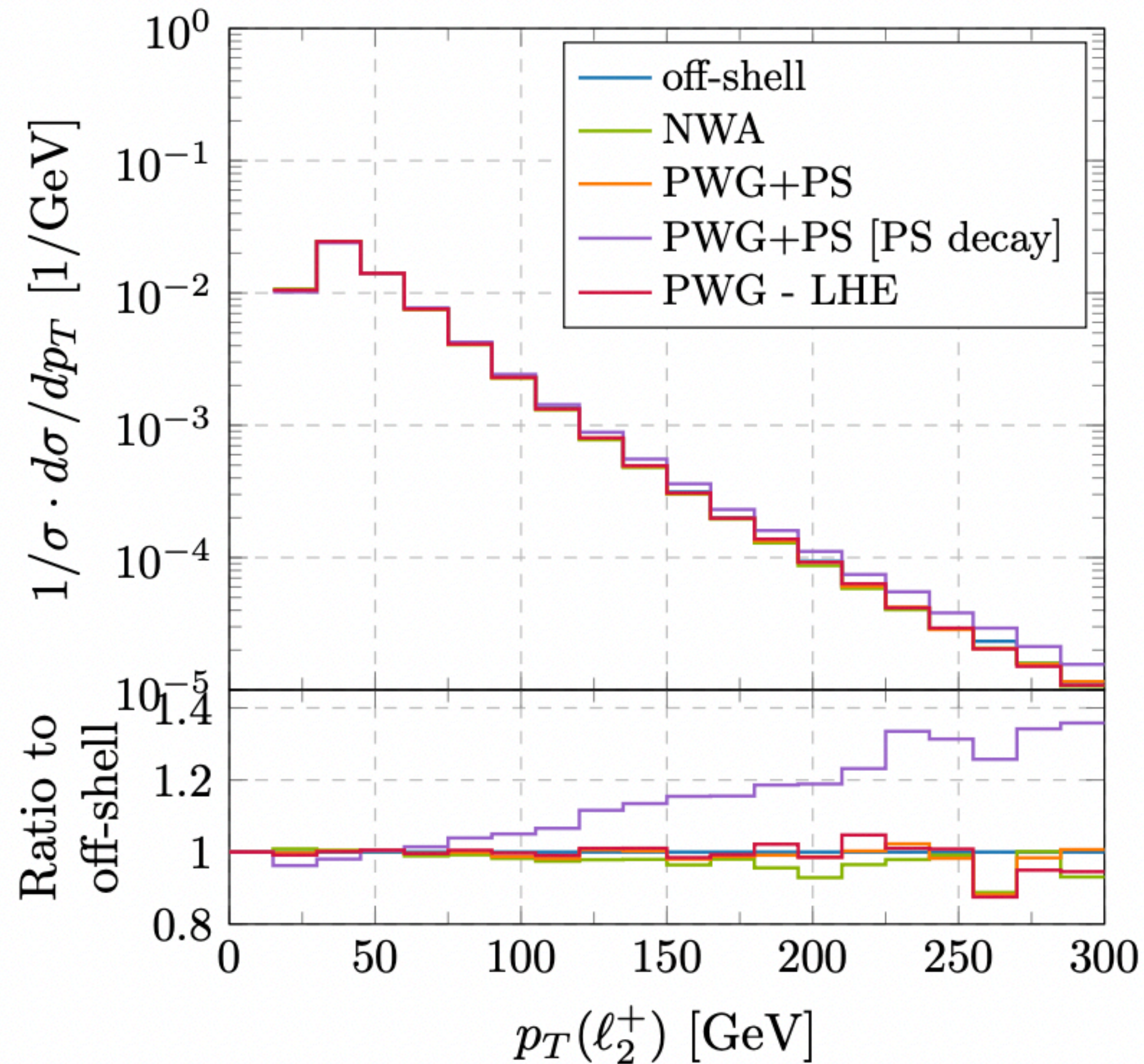


Off-shell 2 | Comparing approaches

► Sizeable differences for certain approximations

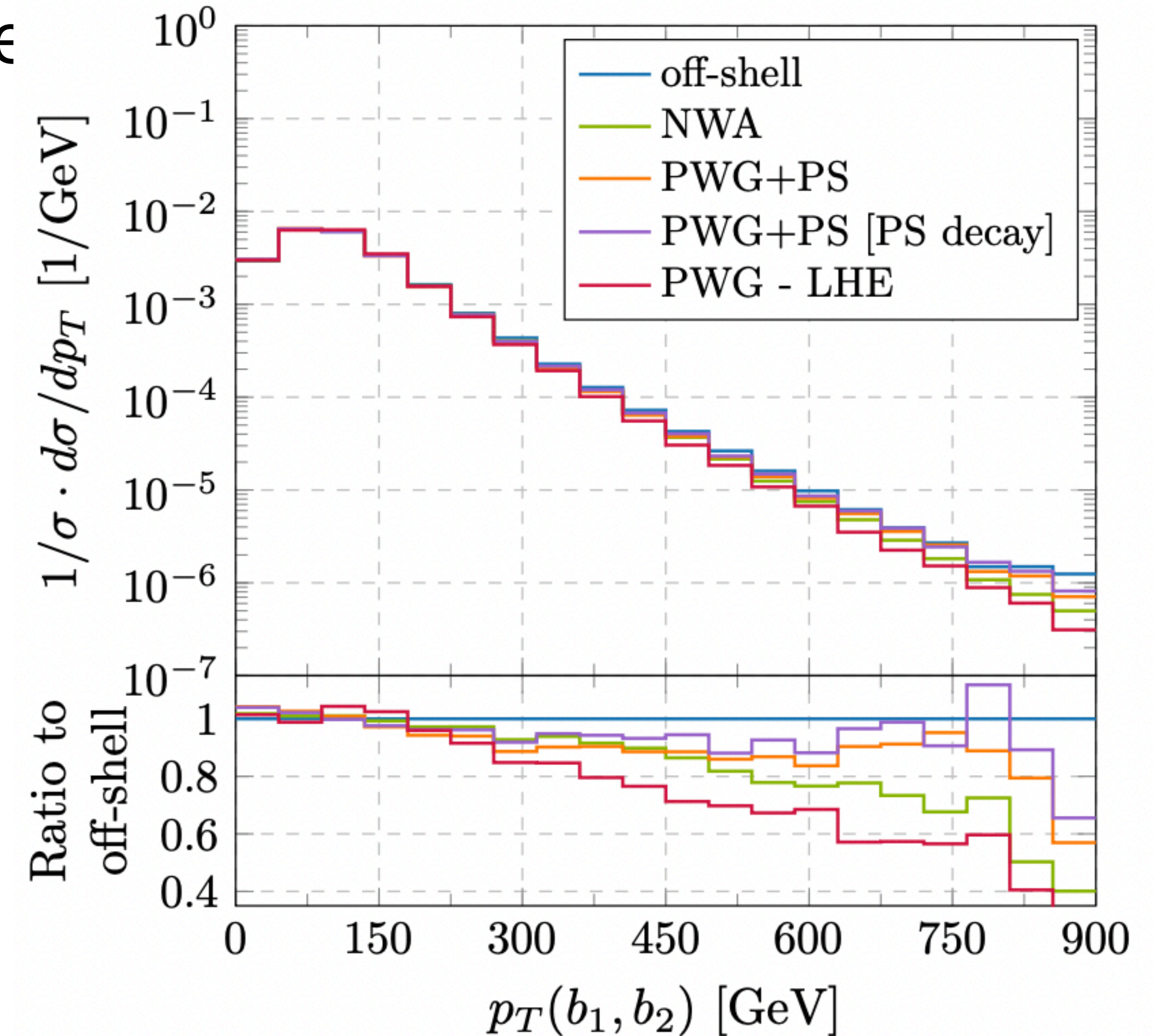
► PS-decay = no spin correlations

► p_T^{miss} has some sensitivity to details of calculation

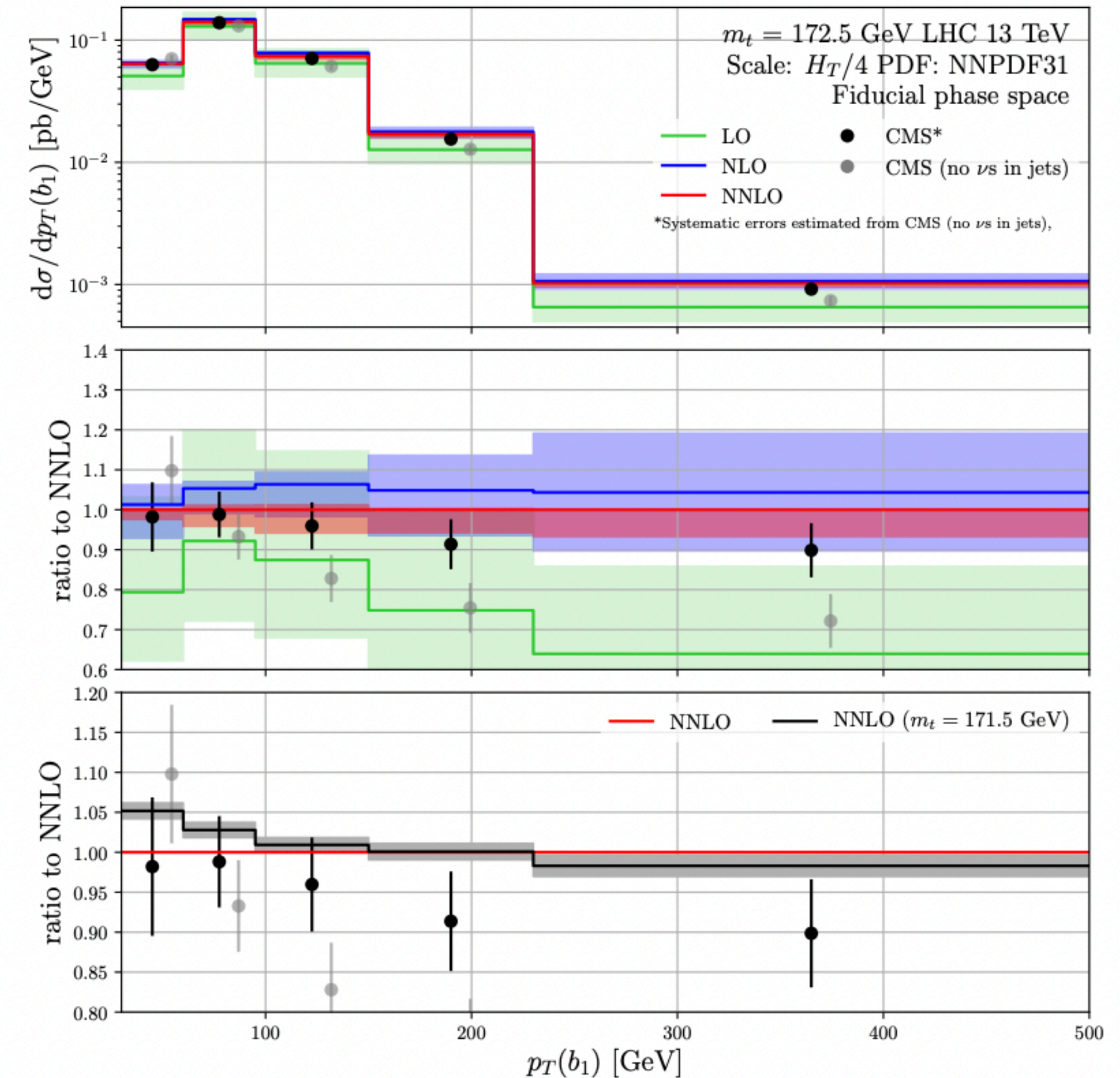


Off-shell 2 | PS effects

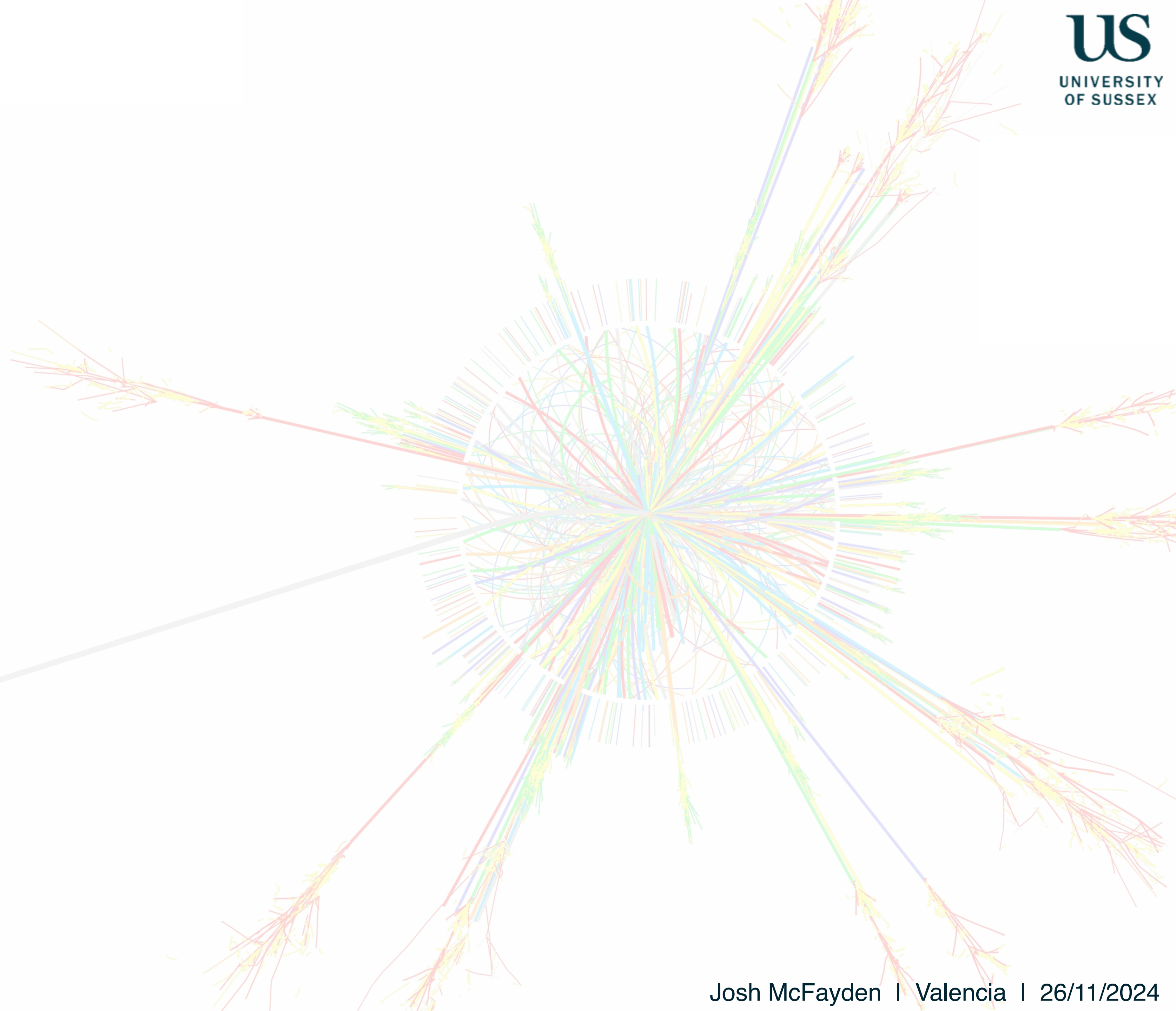
- They were worried about large parton shower effects in the tails and to what extent this is a problem of defining ϵ and PS predictions...



- ▶ They were worried about large parton shower effects in the tails and to what extent this is a problem of defining and PS predictions...
- ▶ c.f. CMS results for different jet definitions...
- ▶ Essentially they were asking “Is it possible parton-level”?



EFT Basics





- ▶ SMEFT describes ~all BSM models characterised by a scale Λ ($\gg v(E)$)
- ▶ Additions to the SM built from $\text{dim}>4$ operators based on SM fields
- ▶ Schematically the Lagrangian is:

$$\mathcal{L}_{SMEFT} = \mathcal{L}_{SM} + \mathcal{L}_5 + \mathcal{L}_6 + \mathcal{L}_7 + \mathcal{L}_8 + \dots$$



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SM (dim 4)



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1 lepton number
violating parameter



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~100-1000 parameters
depending on flavour
structure



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30 operators
violating lepton/
baryon number



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~1000 operators
for $N_f=1$ scenario



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Scale-suppressed
terms



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- ▶ In practise (for simplicity) we often only consider the dimension 6 operators



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- ▶ In practise (for simplicity) we often only consider the dimension 6 operators
- ▶ In terms of operators and coefficients

$$\frac{\mathcal{L}_6}{\Lambda^2} = \sum_i \frac{C_i \mathcal{O}_i^{d=6}}{\Lambda^2}$$



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- ▶ In practise (for simplicity) we often only consider the dimension 6 operators
- ▶ In terms of operators and coefficients
 - ▶ **Scale of new physics**
 - ▶ **Wilson coefficients**
 - ▶ **Dimension 6 operators**

$$\frac{\mathcal{L}_6}{\Lambda^2} = \sum_i \frac{C_i \mathcal{O}_i^{d=6}}{\Lambda^2}$$

► Given these Lagrangian terms

$$\frac{\mathcal{L}_6}{\Lambda^2} = \sum_i \frac{C_i \mathcal{O}_i^{d=6}}{\Lambda^2}$$

the corresponding observables are:

$$\mathcal{A} = \mathcal{A}_{SM} + \mathcal{A}_6$$



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$$\mathcal{A} = \mathcal{A}_{SM} + \mathcal{A}_6 \quad \rightarrow \quad |\mathcal{A}_{SM}|^2 + 2\text{Re}\mathcal{A}_{SM}\mathcal{A}_6^\dagger + |\mathcal{A}_6|^2$$



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$$\frac{C_i a_i}{\Lambda^2}$$

“Interference terms”



► Given these Lagrangian terms

$$\frac{\mathcal{L}_6}{\Lambda^2} = \sum_i \frac{C_i \mathcal{O}_i^{d=6}}{\Lambda^2}$$

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$\frac{C_i a_i}{\Lambda^2}$
"Interference terms"

$\frac{C_i C_j b_{ij}}{\Lambda^4}$
"Quadratic terms"



- ▶ Given these Lagrangian terms

$$\frac{\mathcal{L}_6}{\Lambda^2} = \sum_i \frac{C_i \mathcal{O}_i^{d=6}}{\Lambda^2}$$

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$$\mathcal{A} = \mathcal{A}_{SM} + \mathcal{A}_6 \rightarrow |\mathcal{A}_{SM}|^2 + 2\text{Re}\mathcal{A}_{SM}\mathcal{A}_6^\dagger + |\mathcal{A}_6|^2$$

- ▶ The C_i are what we try to constrain in measurements.

$$\frac{C_i a_i}{\Lambda^2}$$

“Interference terms”

$$\frac{C_i C_j b_{ij}}{\Lambda^4}$$

“Quadratic terms”



- ▶ Given these Lagrangian terms

$$\frac{\mathcal{L}_6}{\Lambda^2} = \sum_i \frac{C_i \mathcal{O}_i^{d=6}}{\Lambda^2}$$

the corresponding observables are:

$$\mathcal{A} = \mathcal{A}_{SM} + \mathcal{A}_6 \rightarrow |\mathcal{A}_{SM}|^2 + 2\text{Re}\mathcal{A}_{SM}\mathcal{A}_6^\dagger + |\mathcal{A}_6|^2$$

- ▶ The C_i are what we try to constrain in measurements.

- ▶ (For a given Λ , conventionally set to 1 TeV)

$$\frac{C_i a_i}{\Lambda^2}$$

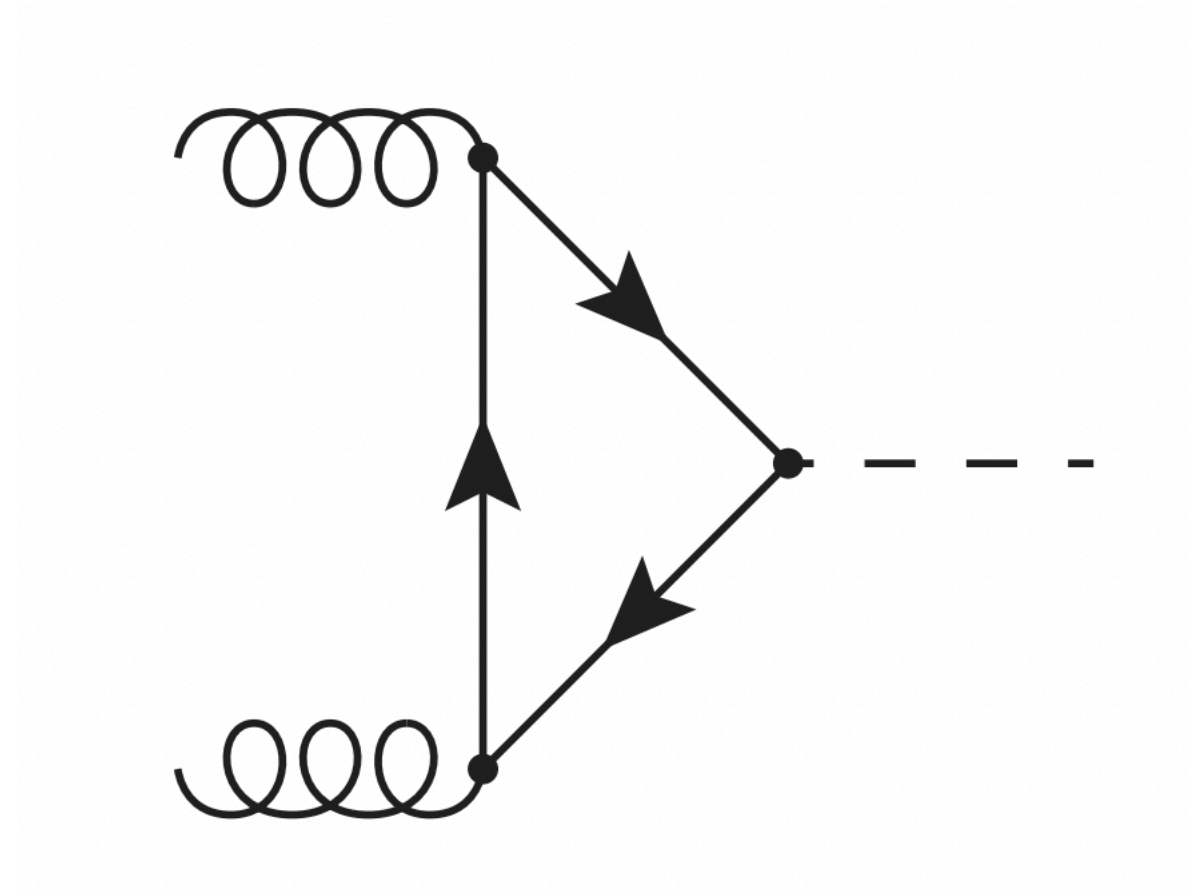
“Interference terms”

$$\frac{C_i C_j b_{ij}}{\Lambda^4}$$

“Quadratic terms”



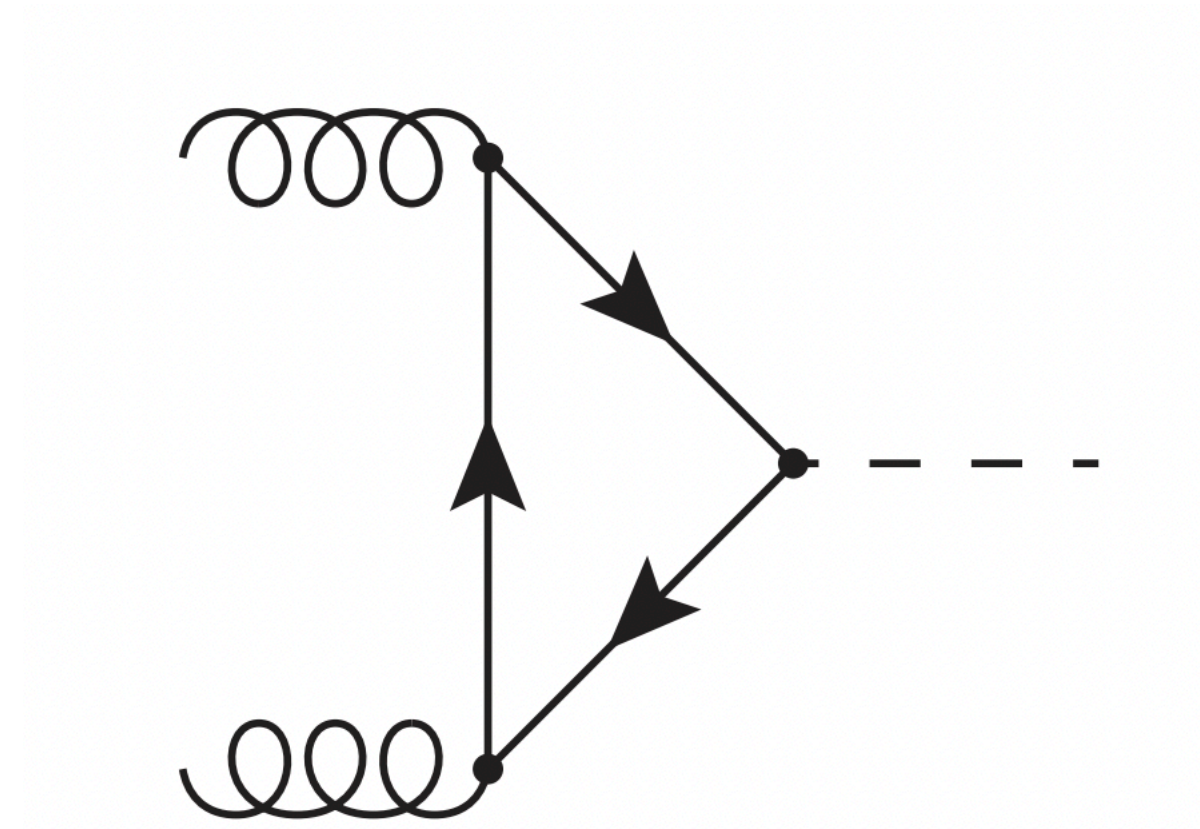
- ▶ Standard Model ggH production only has one tree-level diagram:



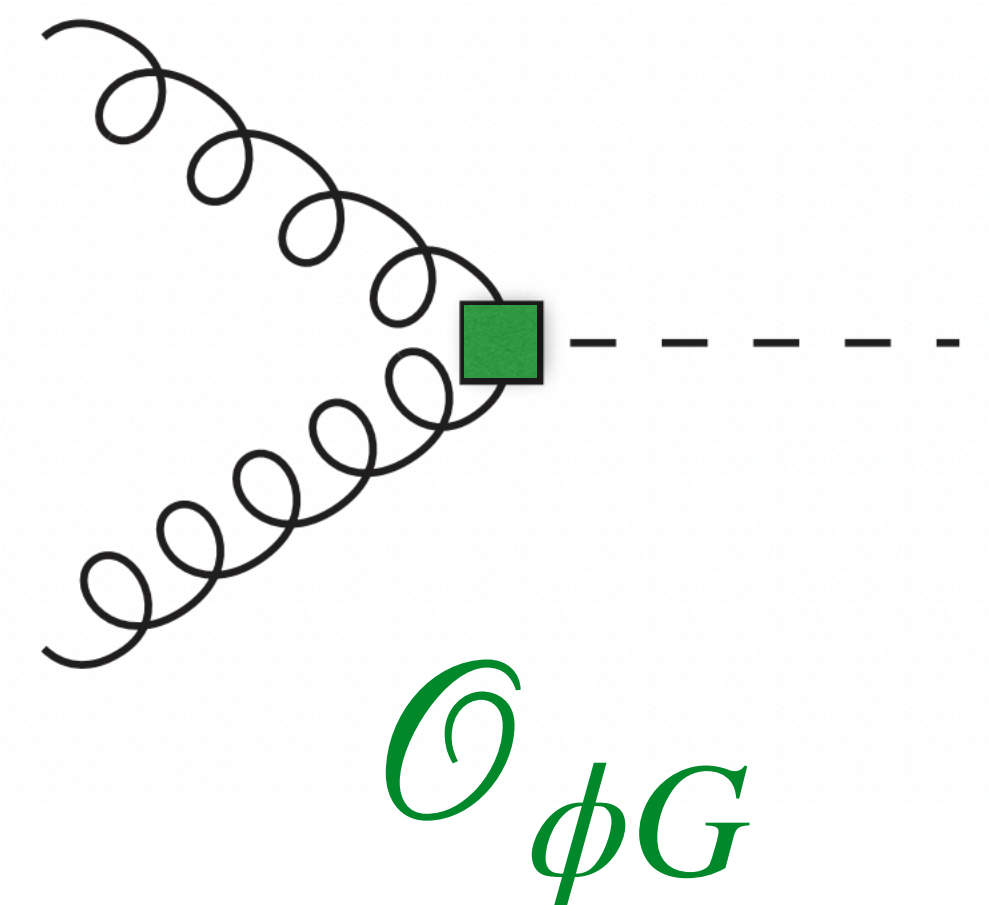
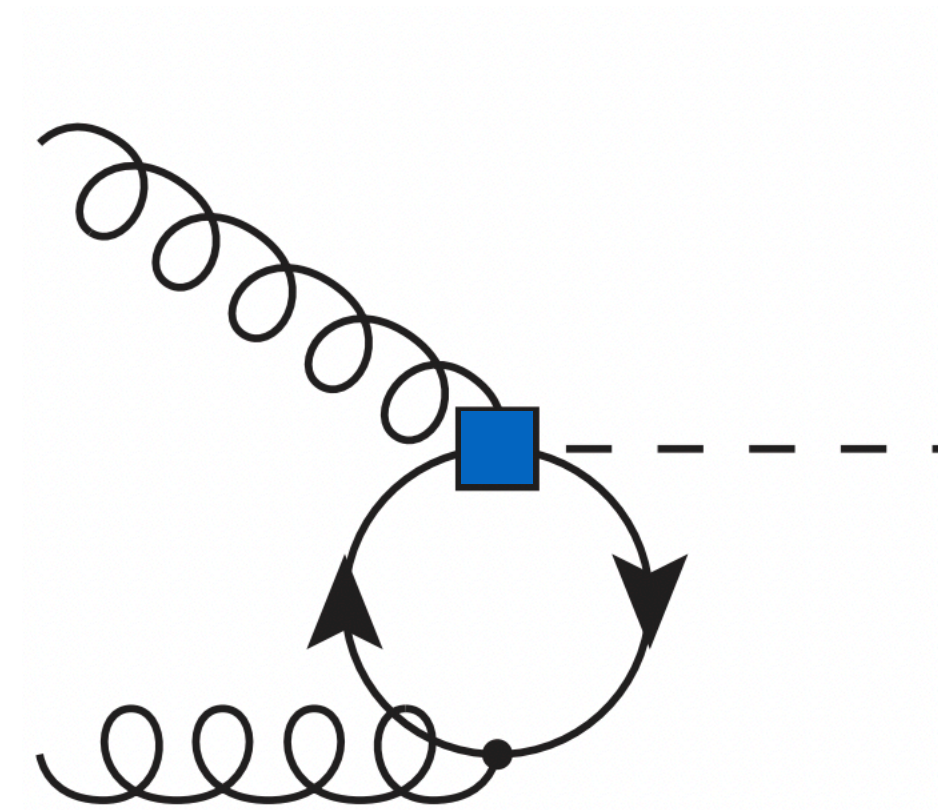
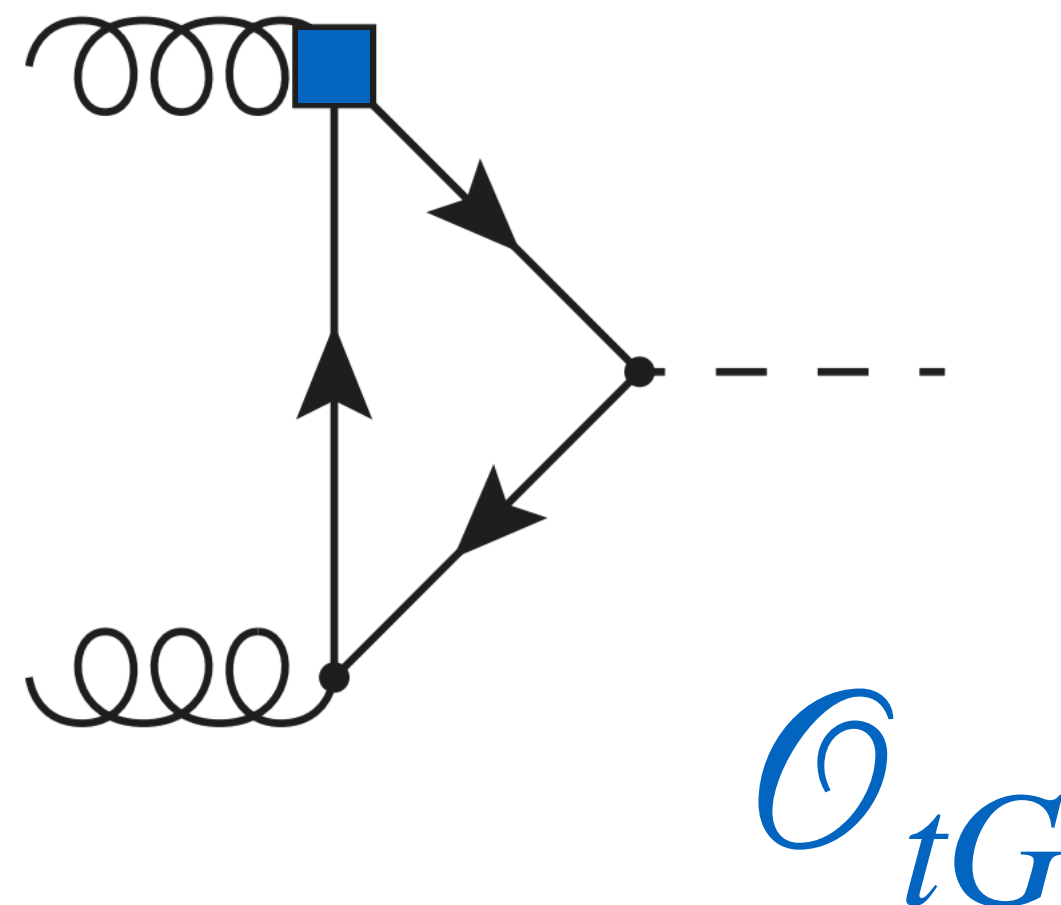
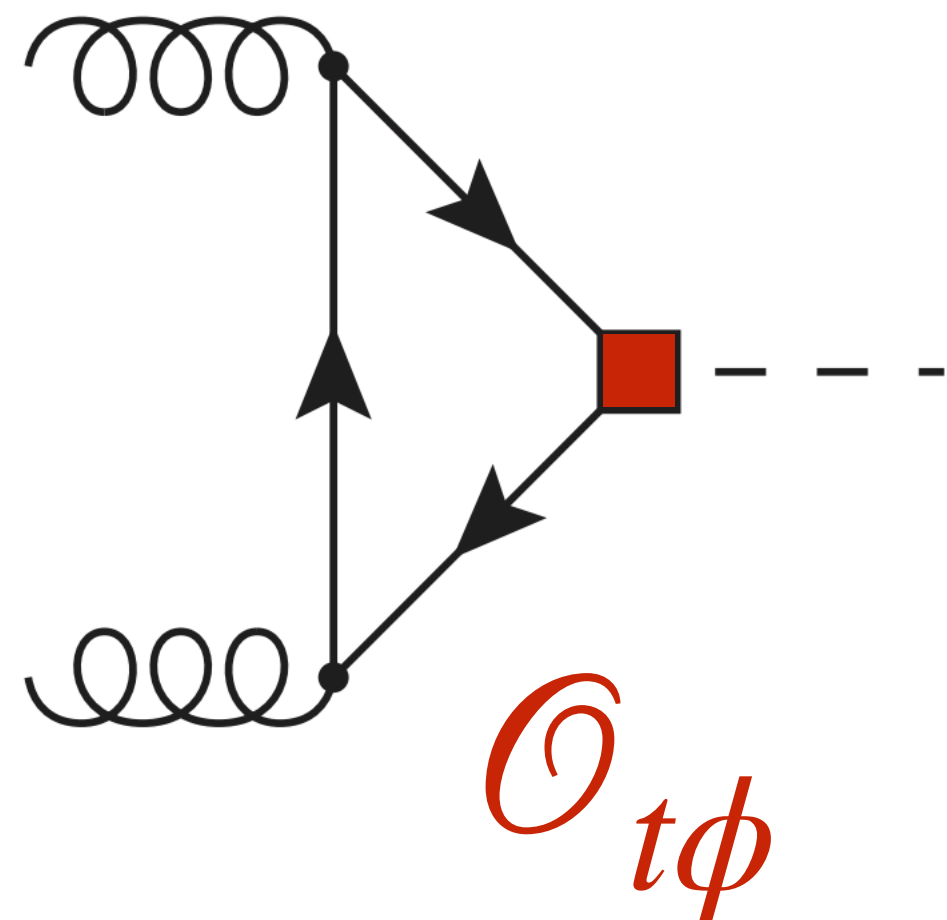


EFT | Basics

- ▶ Standard Model ggH production only has one tree-level diagram:

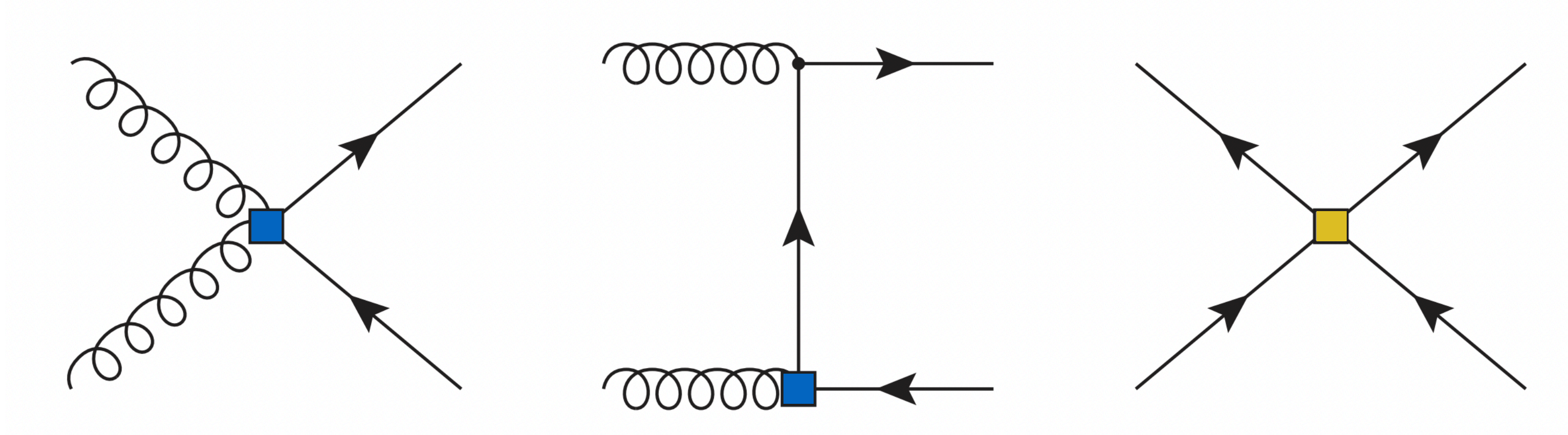


- ▶ In the SMEFT there are contributions from 3 operators:

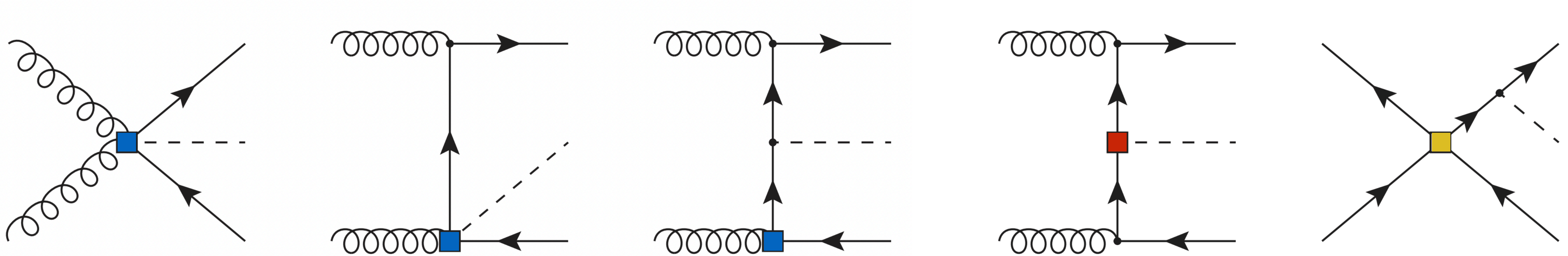




► Ttbar production:



► ttH production:



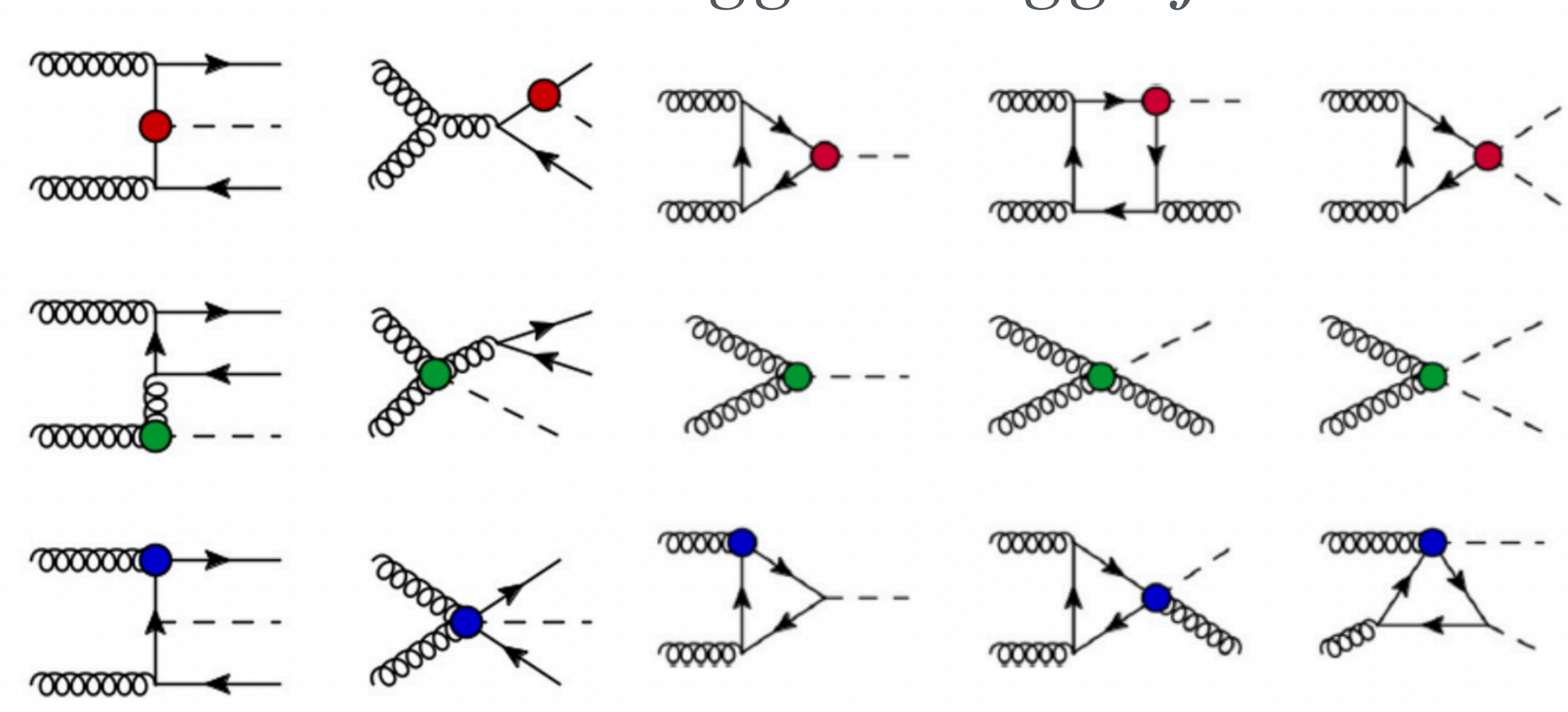


$t\bar{t}H$

ggH

$ggHj$

HH



$$\underline{O_{t\phi} = y_t^3 (\phi^\dagger \phi) (\bar{Q}t) \tilde{\phi}}$$

$$\underline{O_{\phi G} = y_t^2 (\phi^\dagger \phi) G_{\mu\nu}^A G^{A\mu\nu}}$$

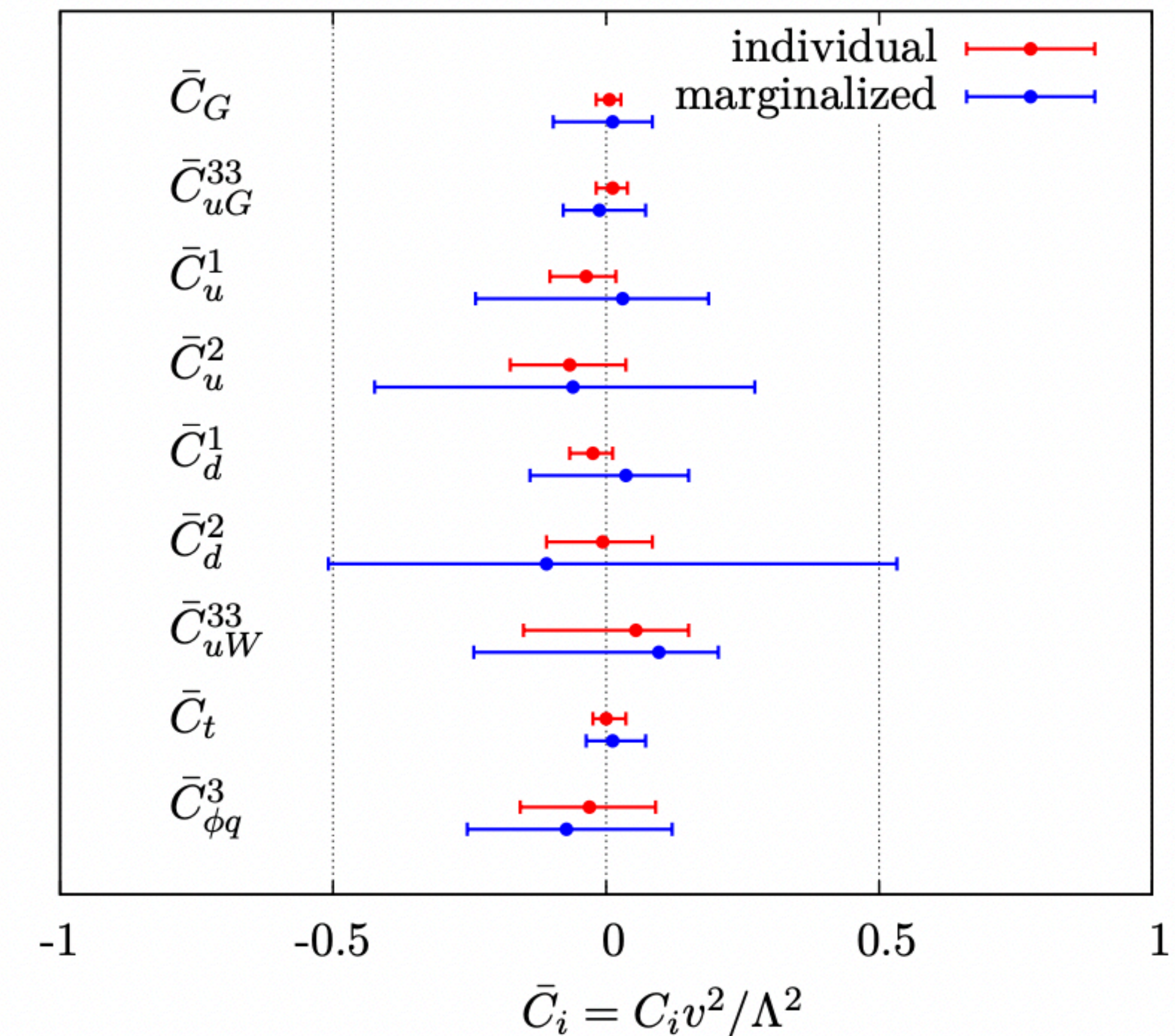
$$\underline{O_{tG} = y_t g_s (\bar{Q} \sigma^{\mu\nu} T^A t) \tilde{\phi} G_{\mu\nu}^A}$$



- ▶ **Individual**: All operator coefficients but one set to zero
- ▶ **Marginalised**: Vary all coefficients simultaneously in the fit.
- ▶ These are often profiled rather marginalised in the traditional Bayesian meaning.

▶ Considering all coefficients at once is more realistic, as all EFT operators are potentially present.

▶ Informative to present both.

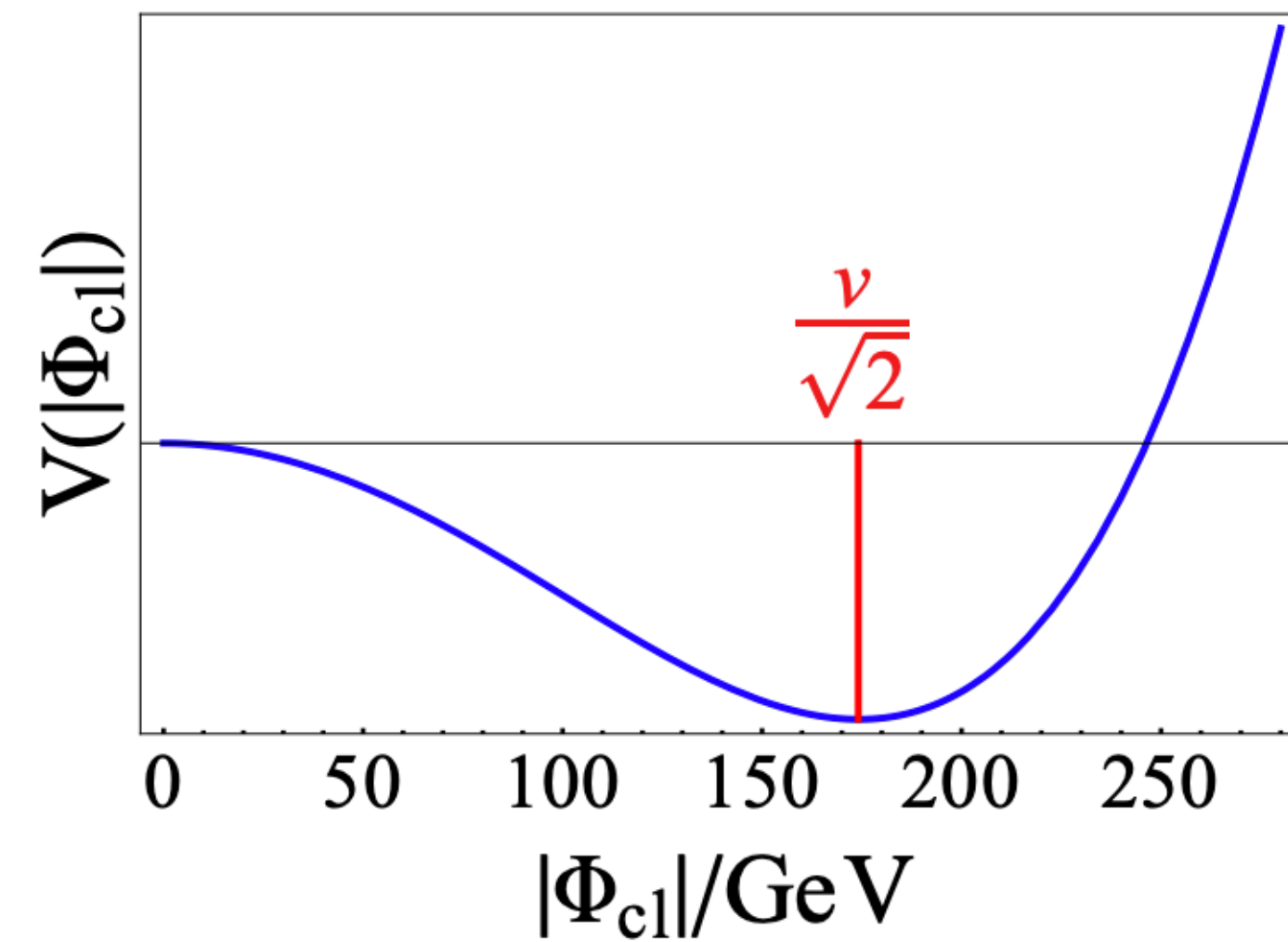


Higgs self-coupling

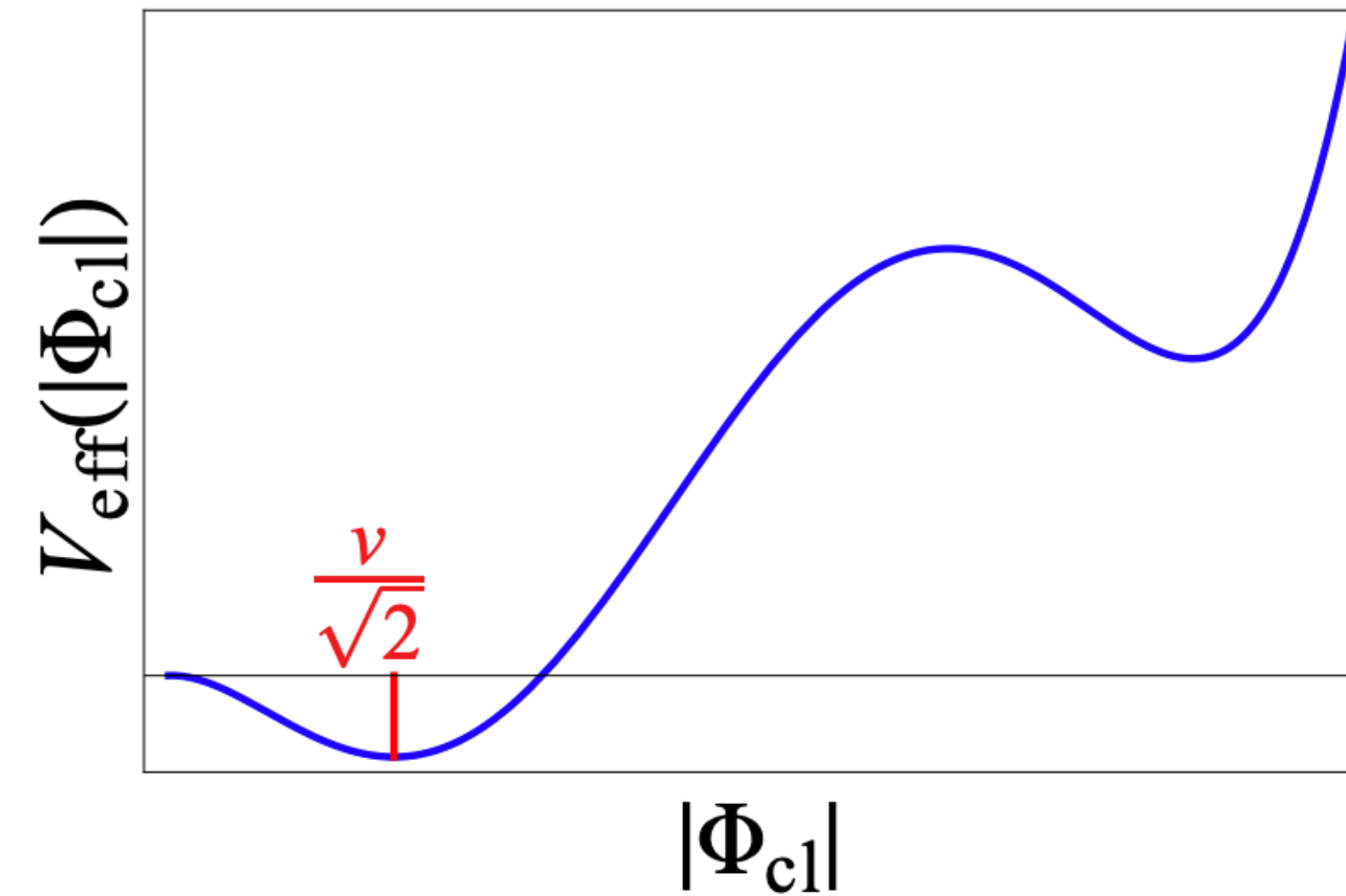


Higgs self-coupling

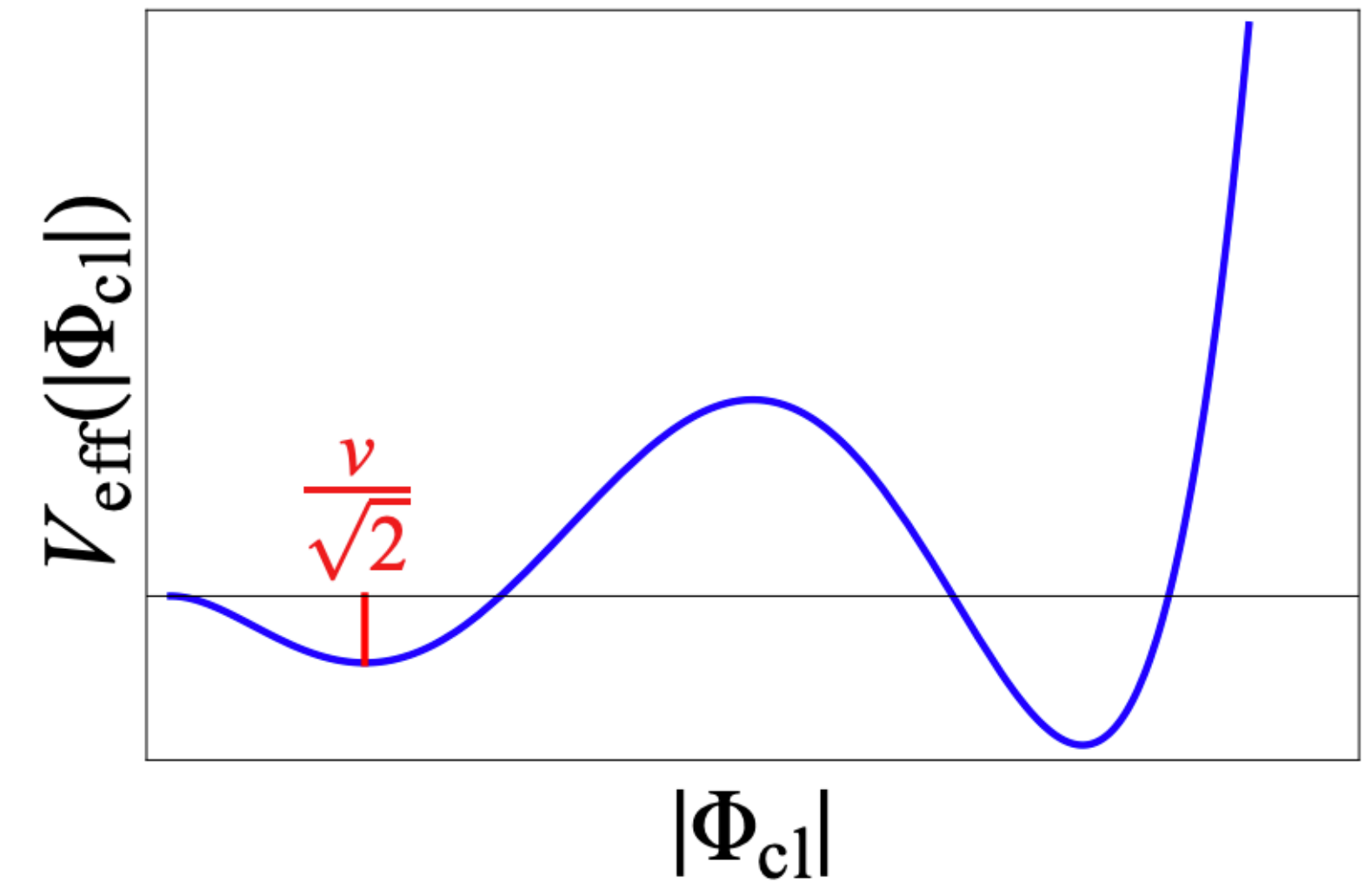
► Vacuum stability:



classical Higgs potential



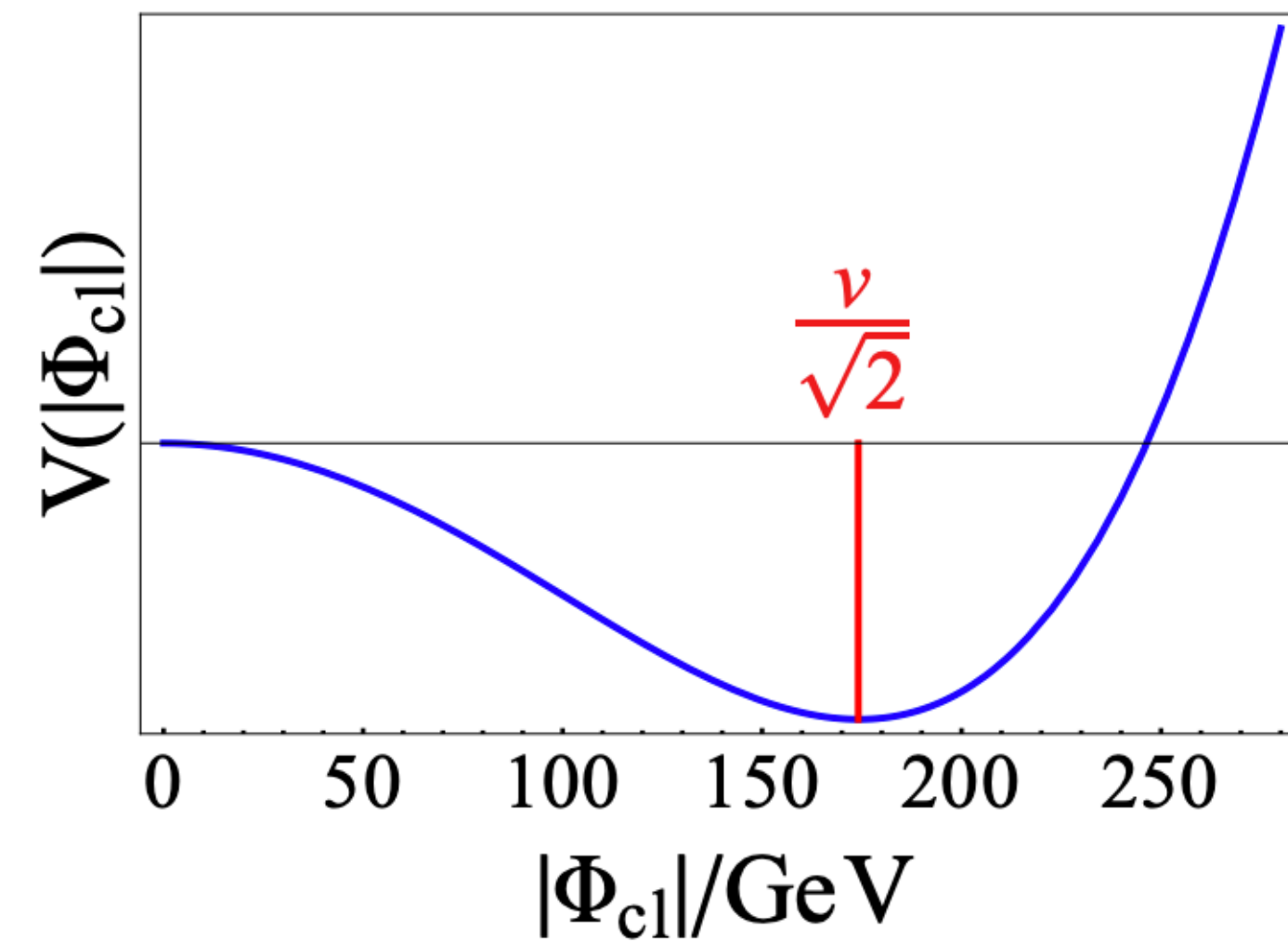
stable



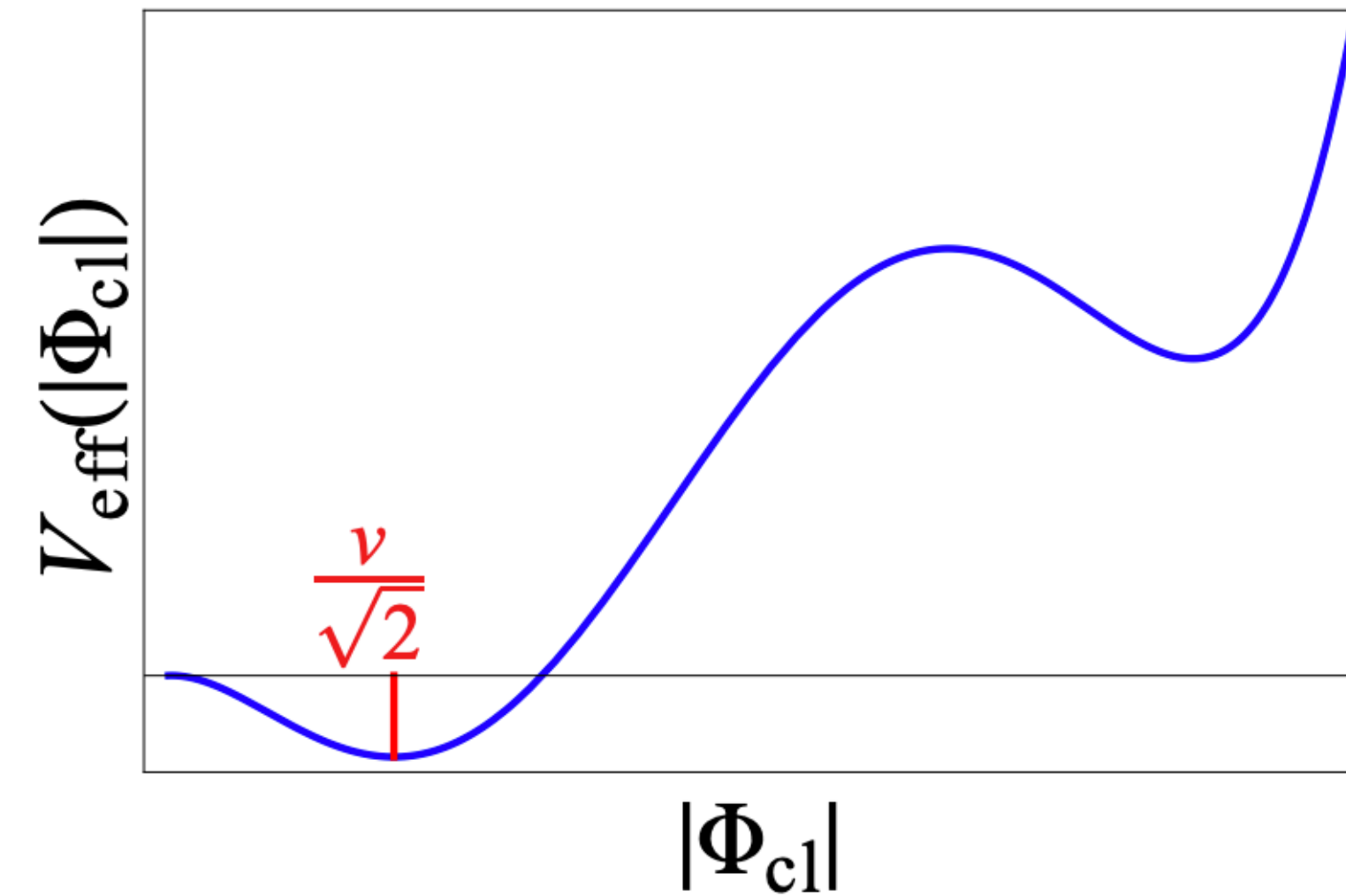
unstable/metastable

Higgs self-coupling

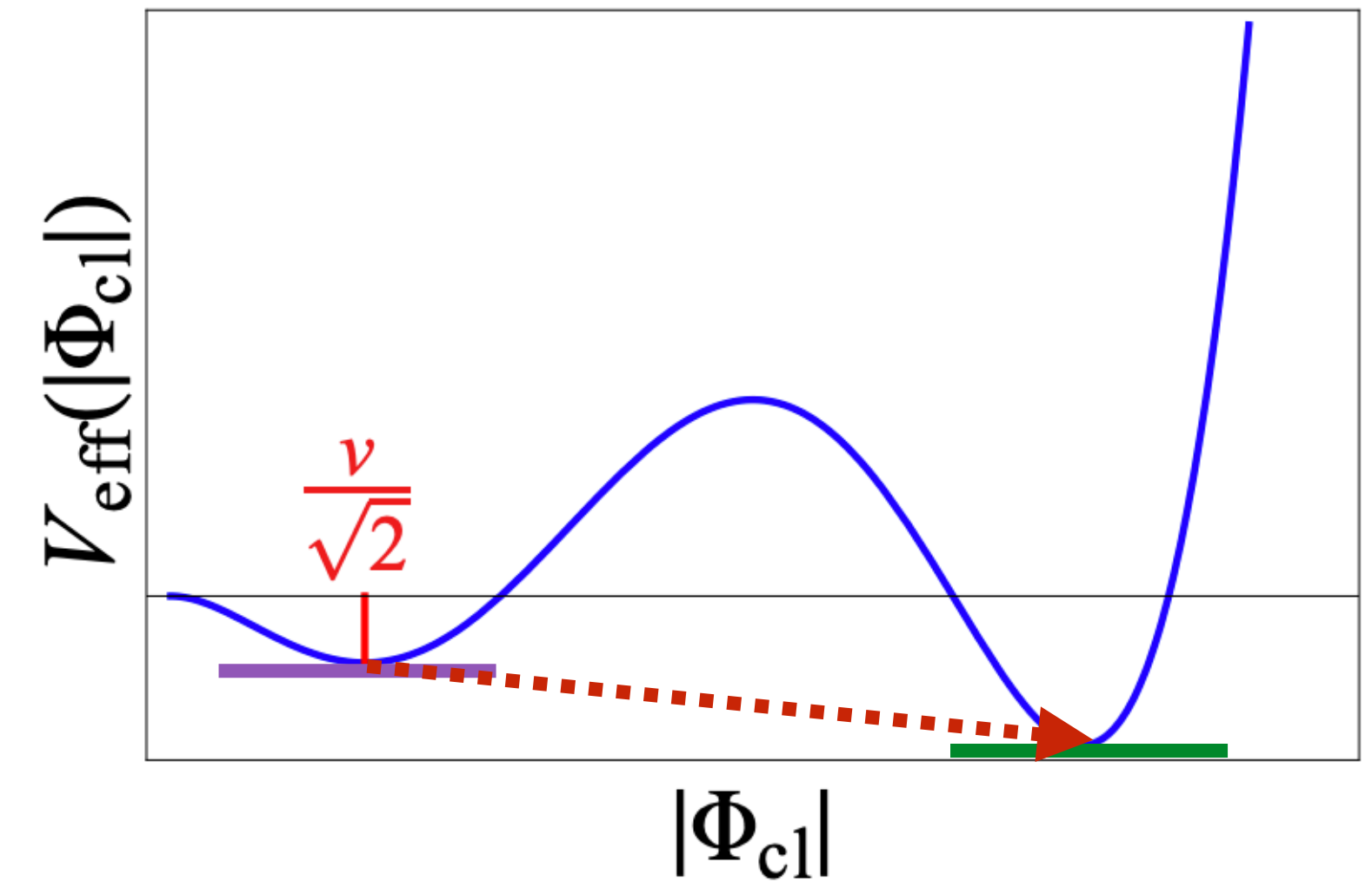
► Vacuum stability:



classical Higgs potential



stable



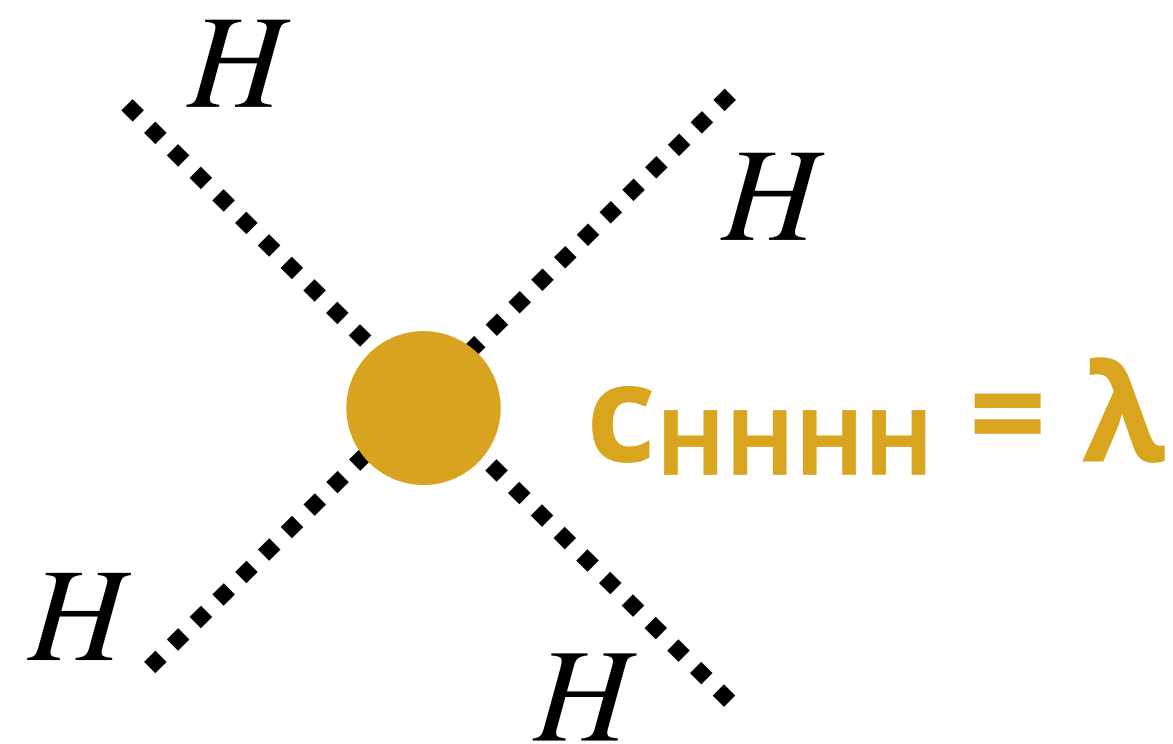
unstable/metastable

- Vacuum is “metastable” if there is some probability for a state in the **false minimum** to **tunnel** into the **true minimum**.
- Depending on whether the lifetime of the electroweak vacuum state is **shorter or longer than the age of the universe** this is called **unstable or metastable**.



WRF Research Proposal | Why?

► So how does this relate to the proposed measurements?!



$$V_{\text{class}} = -\frac{1}{2}m^2\phi^2 + \lambda\phi^4$$

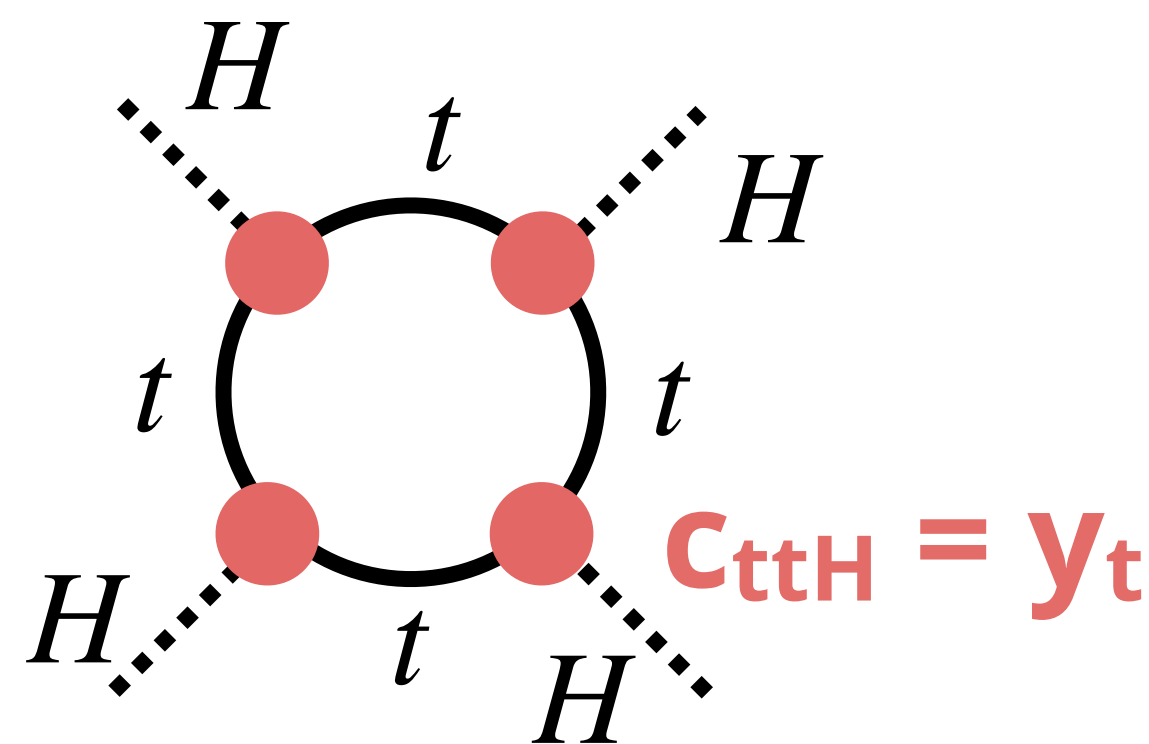
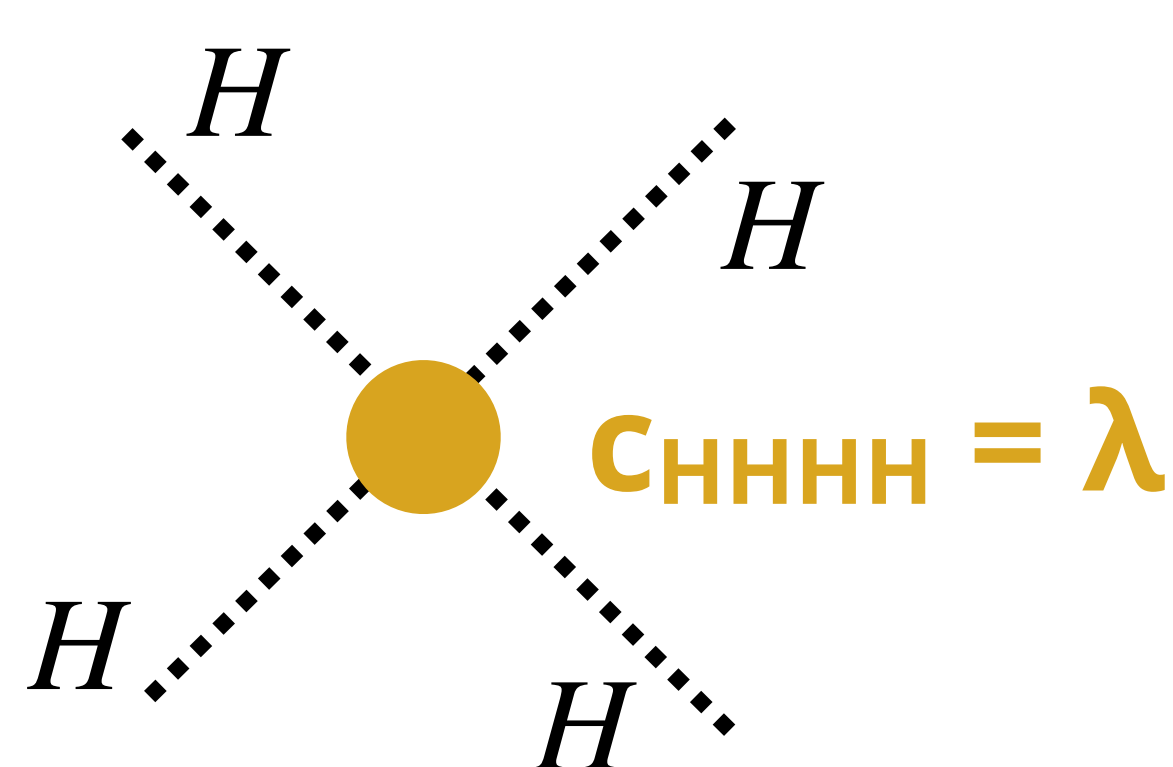
$$V_{\text{eff}} \sim -\frac{1}{2}m^2(\mu)\phi^2(\mu) + \lambda(\mu)\phi^4(\mu)$$

$$\phi \sim \mu \gg v \sim 246 \text{ GeV} \rightarrow V_{\text{eff}} \sim \lambda(\mu)\phi^4(\mu)$$



WRF Research Proposal | Why?

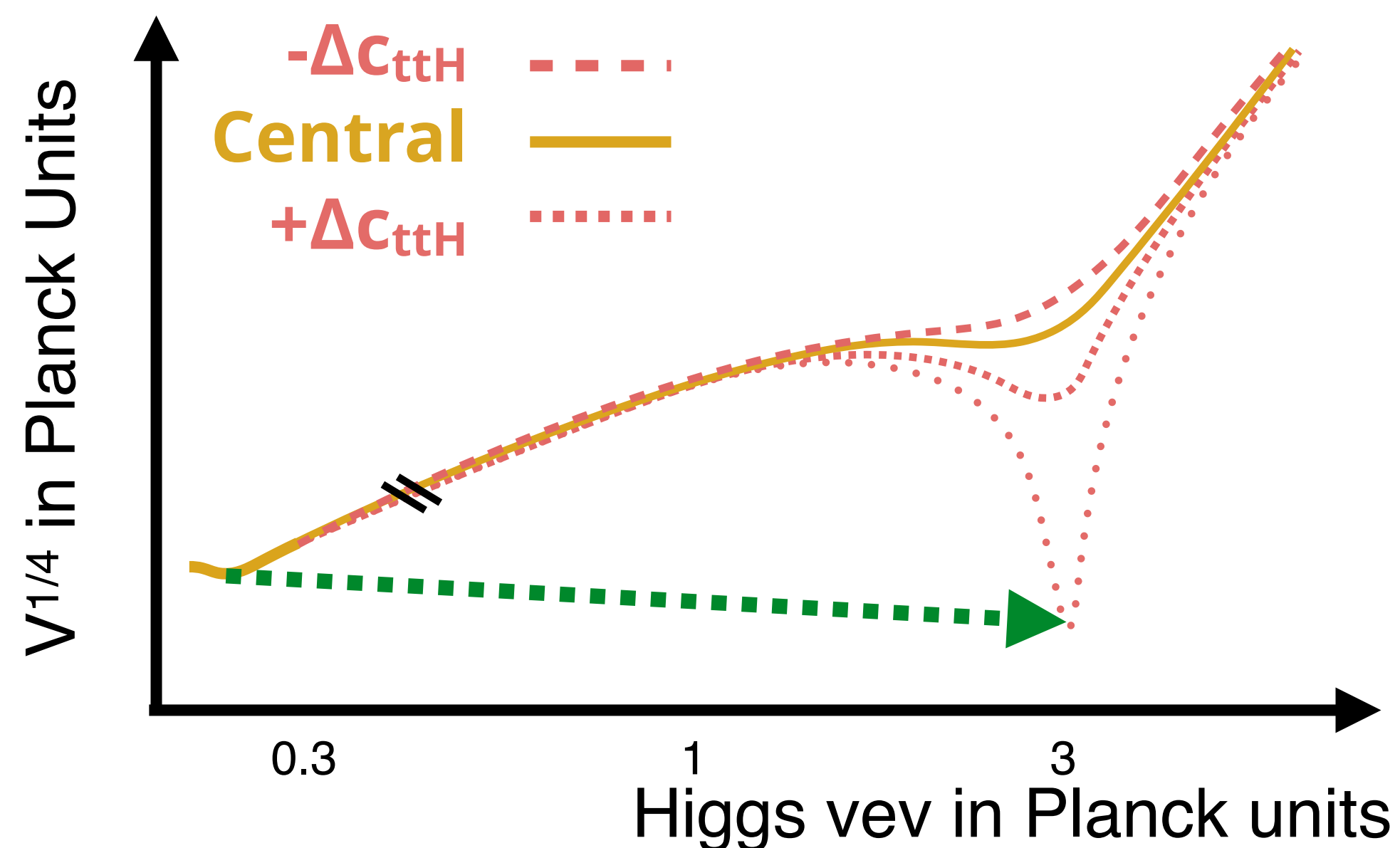
► So how does this relate to the proposed measurements?!



$$V_{\text{class}} = -\frac{1}{2}m^2\phi^2 + \lambda\phi^4$$

$$V_{\text{eff}} \sim -\frac{1}{2}m^2(\mu)\phi^2(\mu) + \lambda(\mu)\phi^4(\mu)$$

$$\phi \sim \mu \gg v \sim 246 \text{ GeV} \rightarrow V_{\text{eff}} \sim \lambda(\mu)\phi^4(\mu)$$



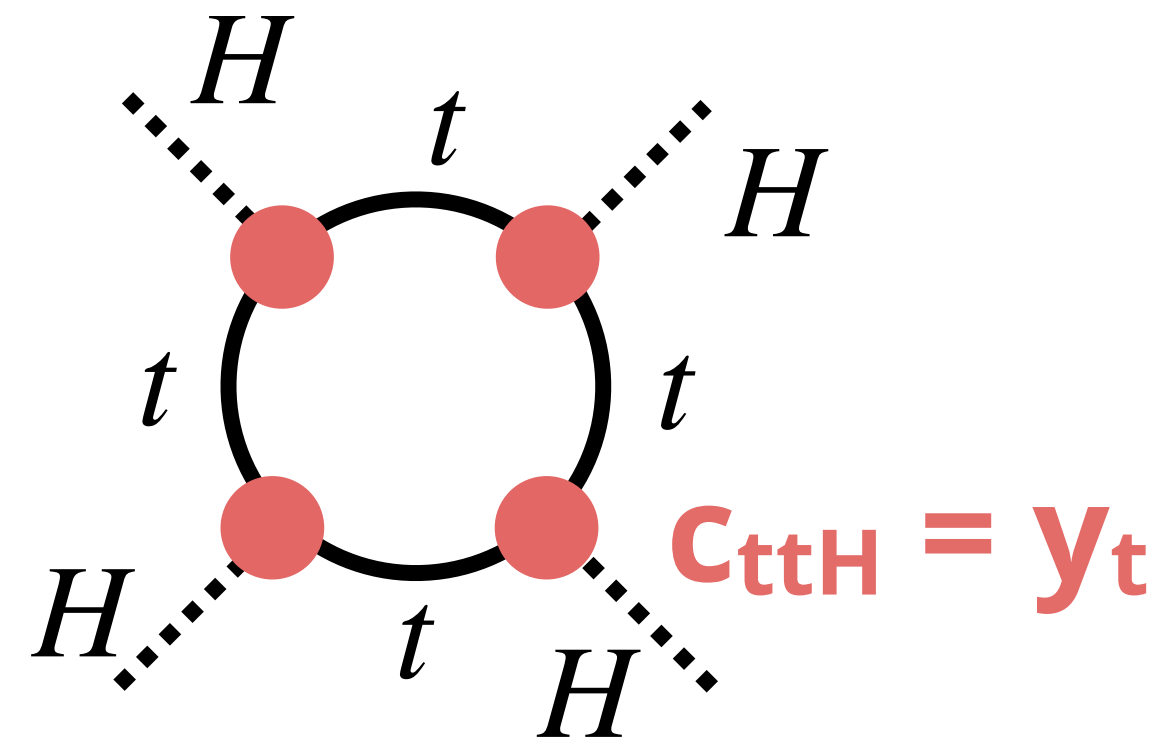
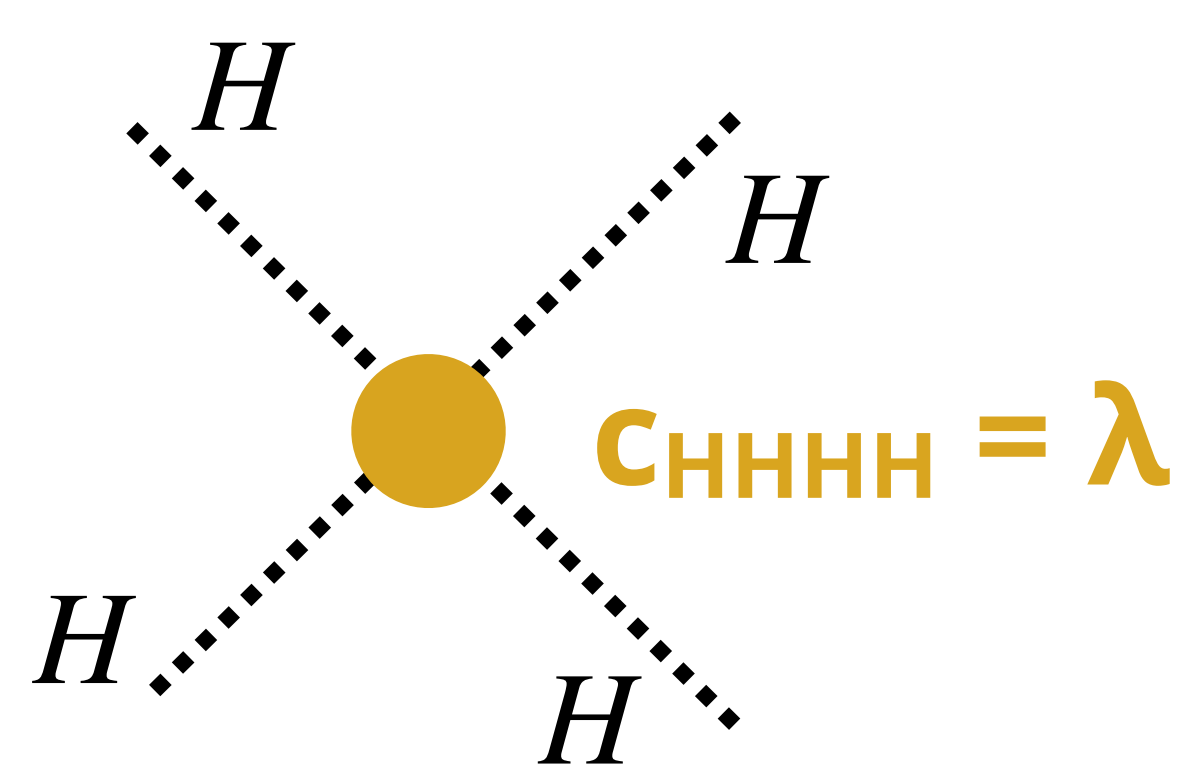
$$\frac{d\lambda}{d \ln \mu} = +\frac{3\lambda^2}{2\pi^2} - \frac{3y_t^4}{8\pi^2} + \dots$$

► The minus sign and is responsible for appearance of the extra minimum of the effective potential at large values of the Higgs field.



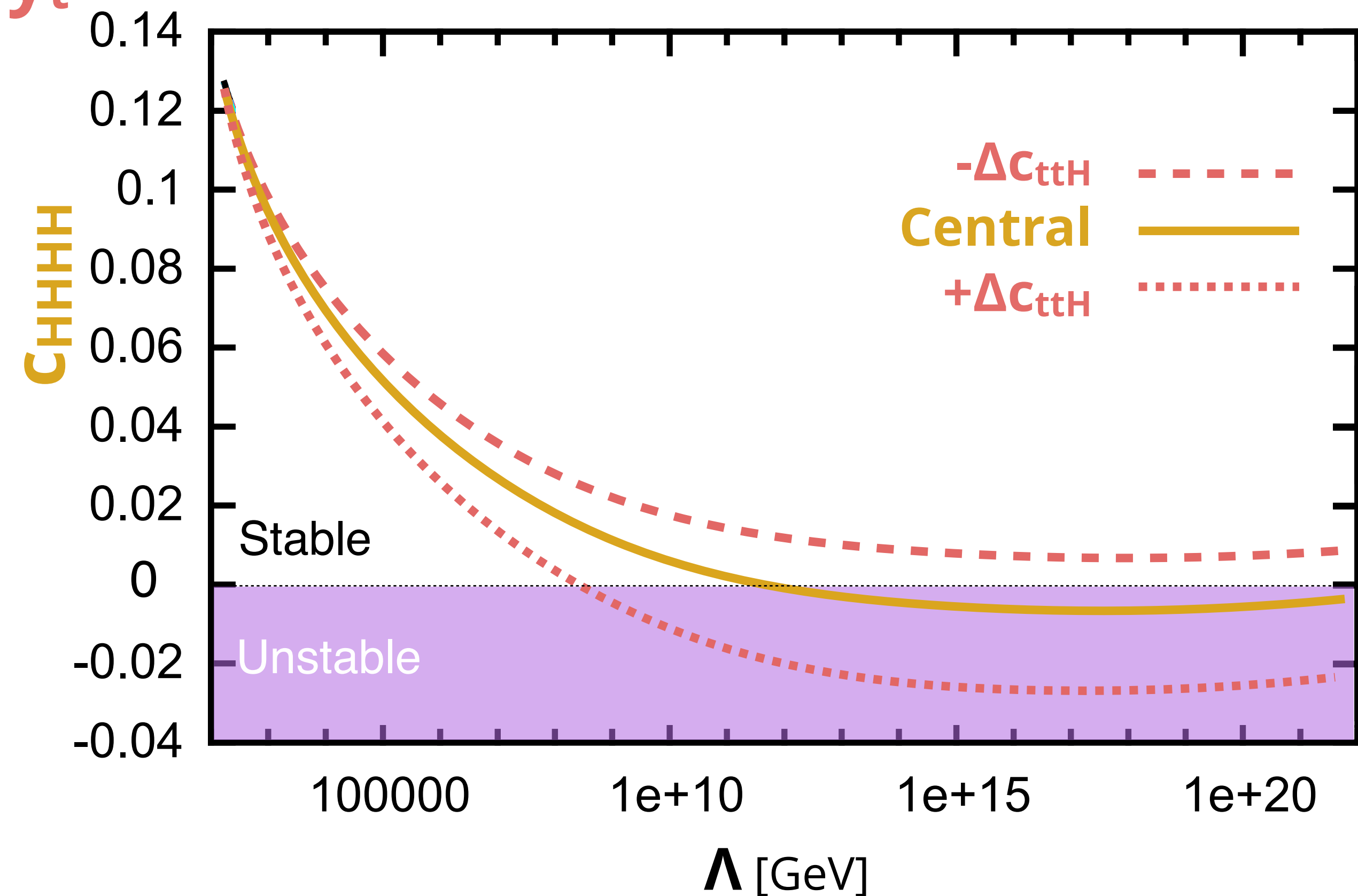
WRF Research Proposal | Why?

► So how does this relate to the proposed measurements?!



$$\frac{d\lambda}{d\log\mu} = +\frac{3\lambda^2}{2\pi^2} - \frac{3y_t^4}{8\pi^2} + \dots$$

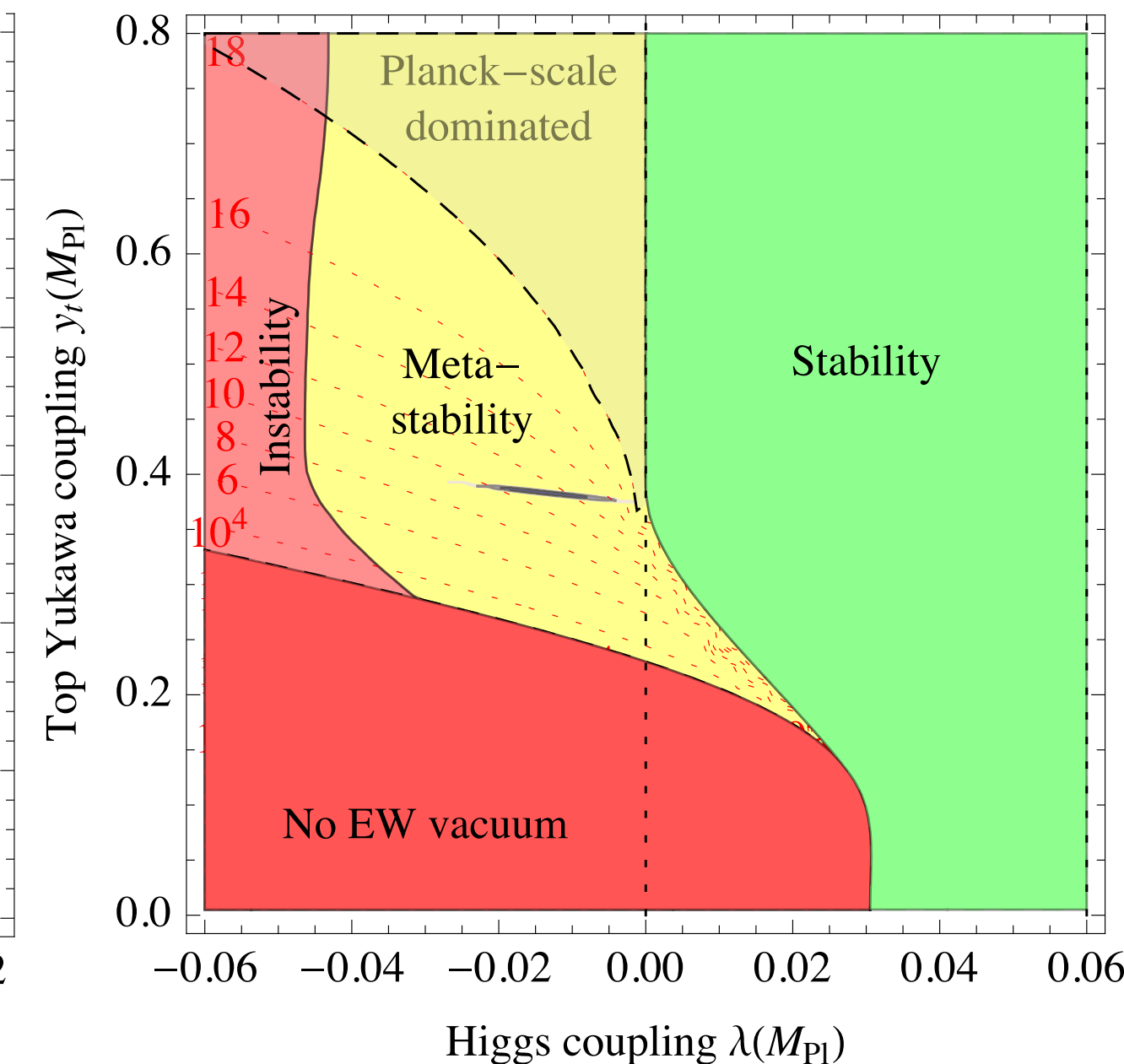
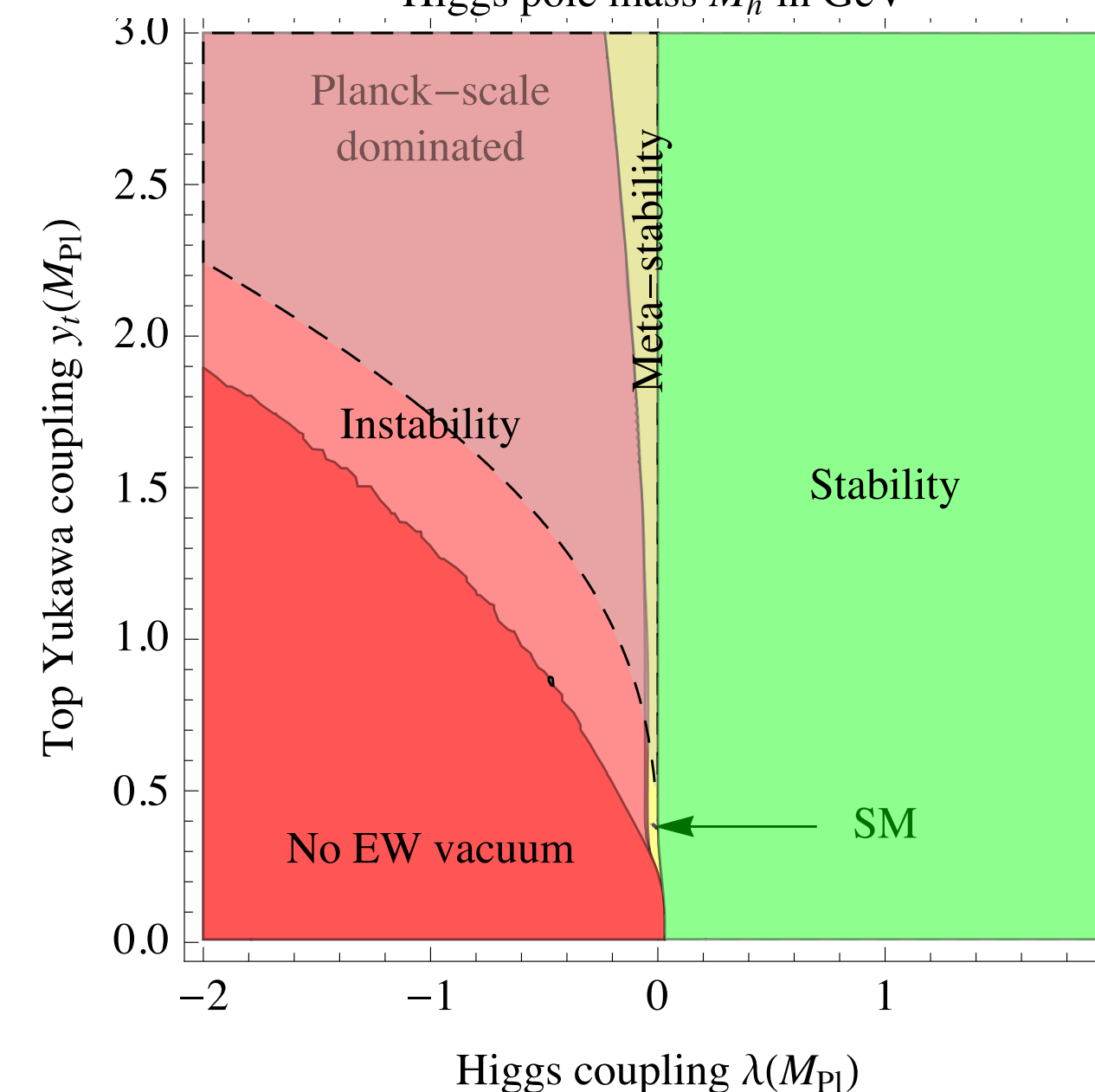
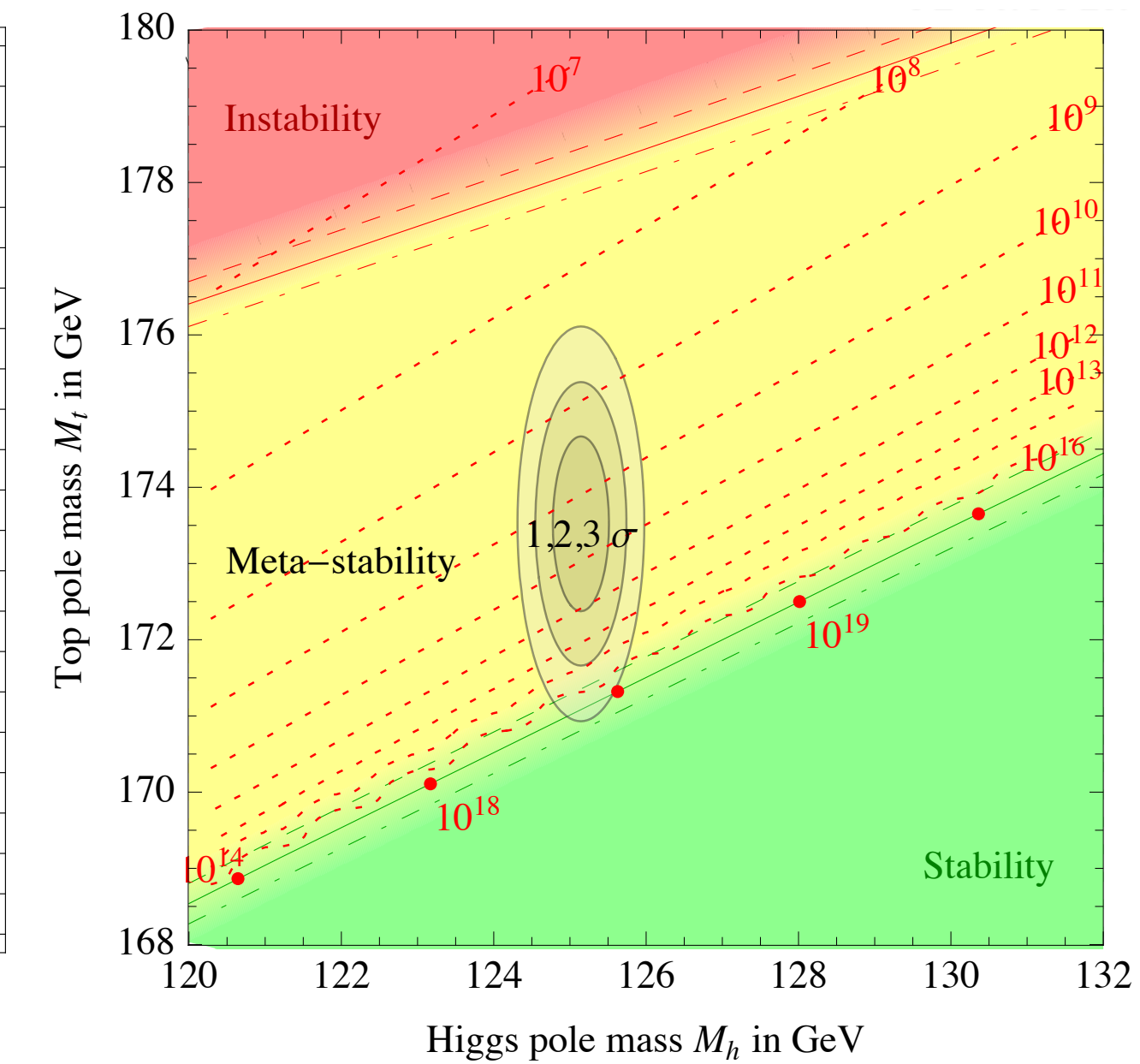
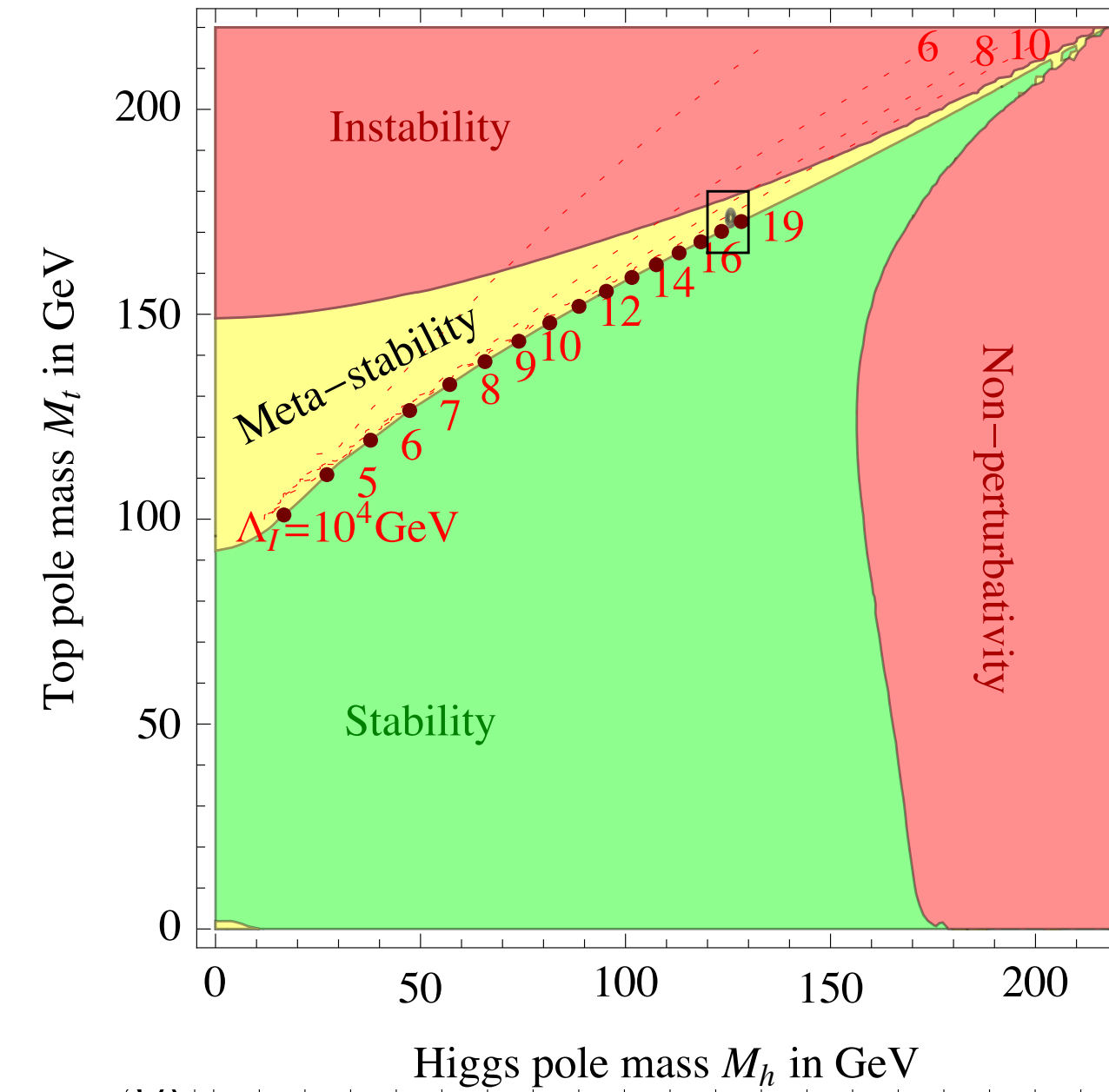
► The **stability** of the Standard Model vacuum is ~equivalent to asking whether λ stays positive up to the maximum validity scale of the theory, e.g. the Planck scale.





URF Research Proposal | Why?

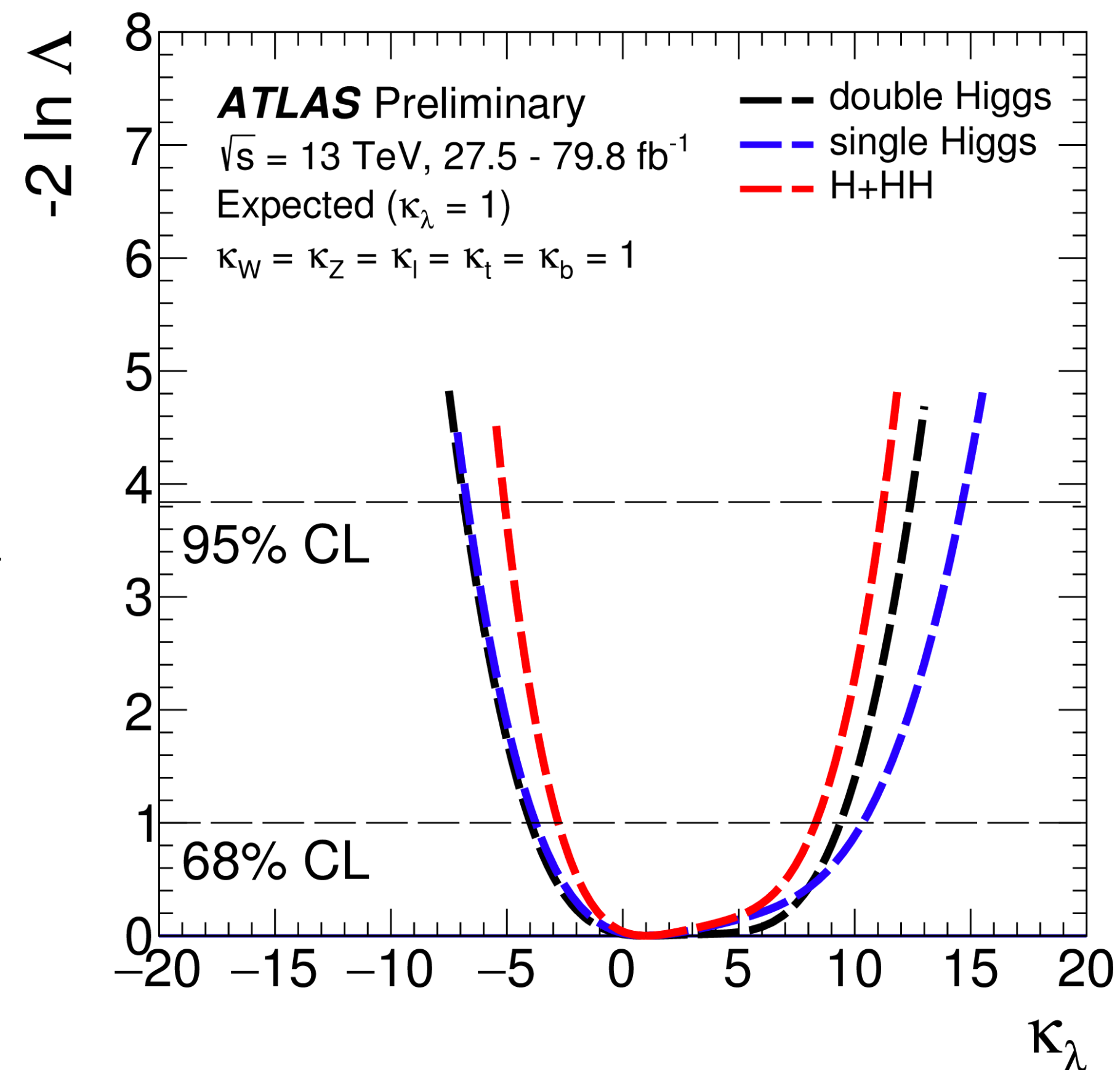
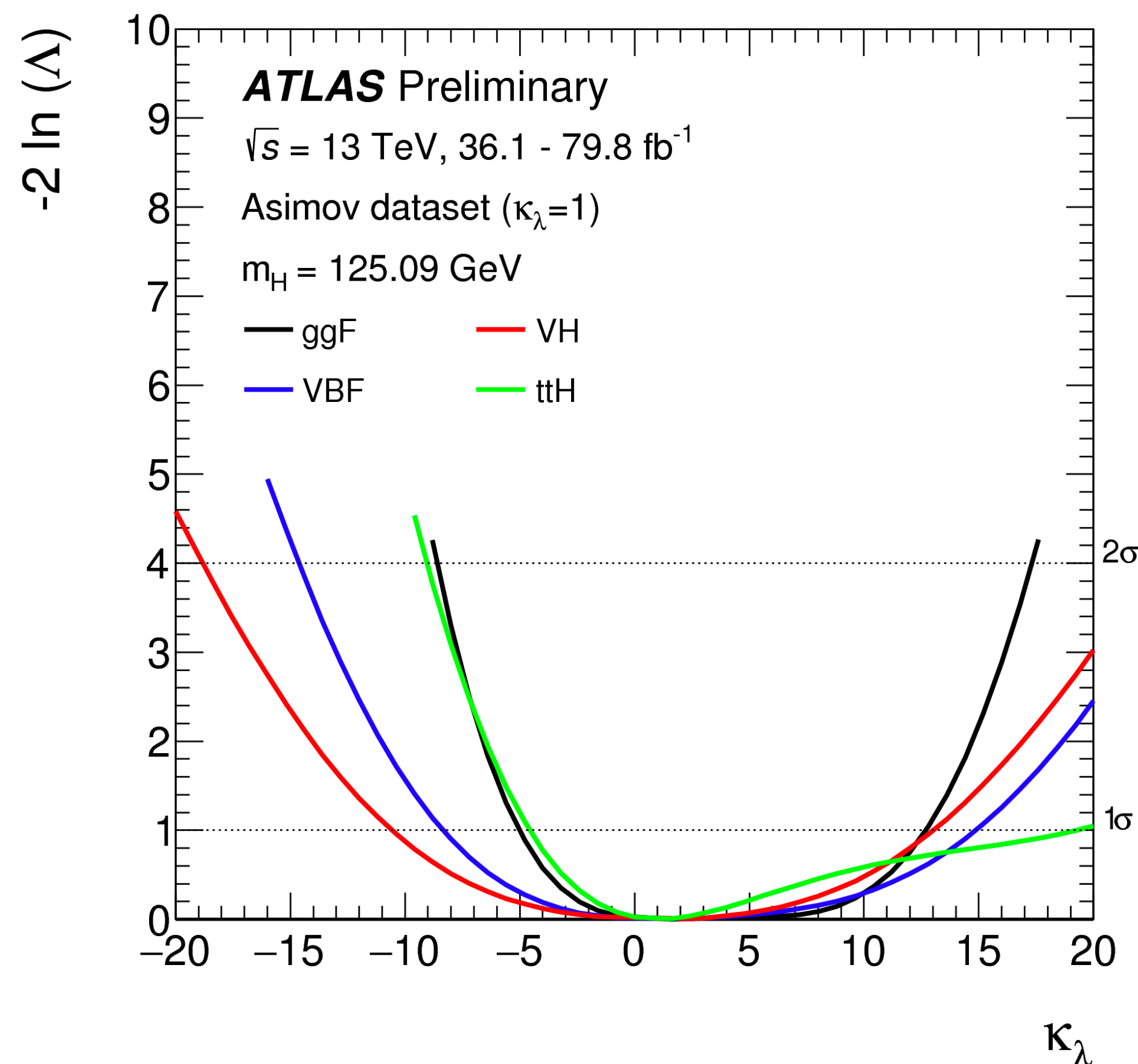
- ▶ Some quotes on this:
 - ▶ “We are (probably) doomed, unless some new physics intervenes” - [\[1704.02821\]](#)
 - ▶ “We believe that near-criticality of the SM vacuum is the most important message we have learnt so far from experimental data on the Higgs boson. Near-criticality gives us a unique opportunity to obtain information about physics taking place at energy scales well beyond the reach of any collider experiment.” - [\[1307.3536\]](#)



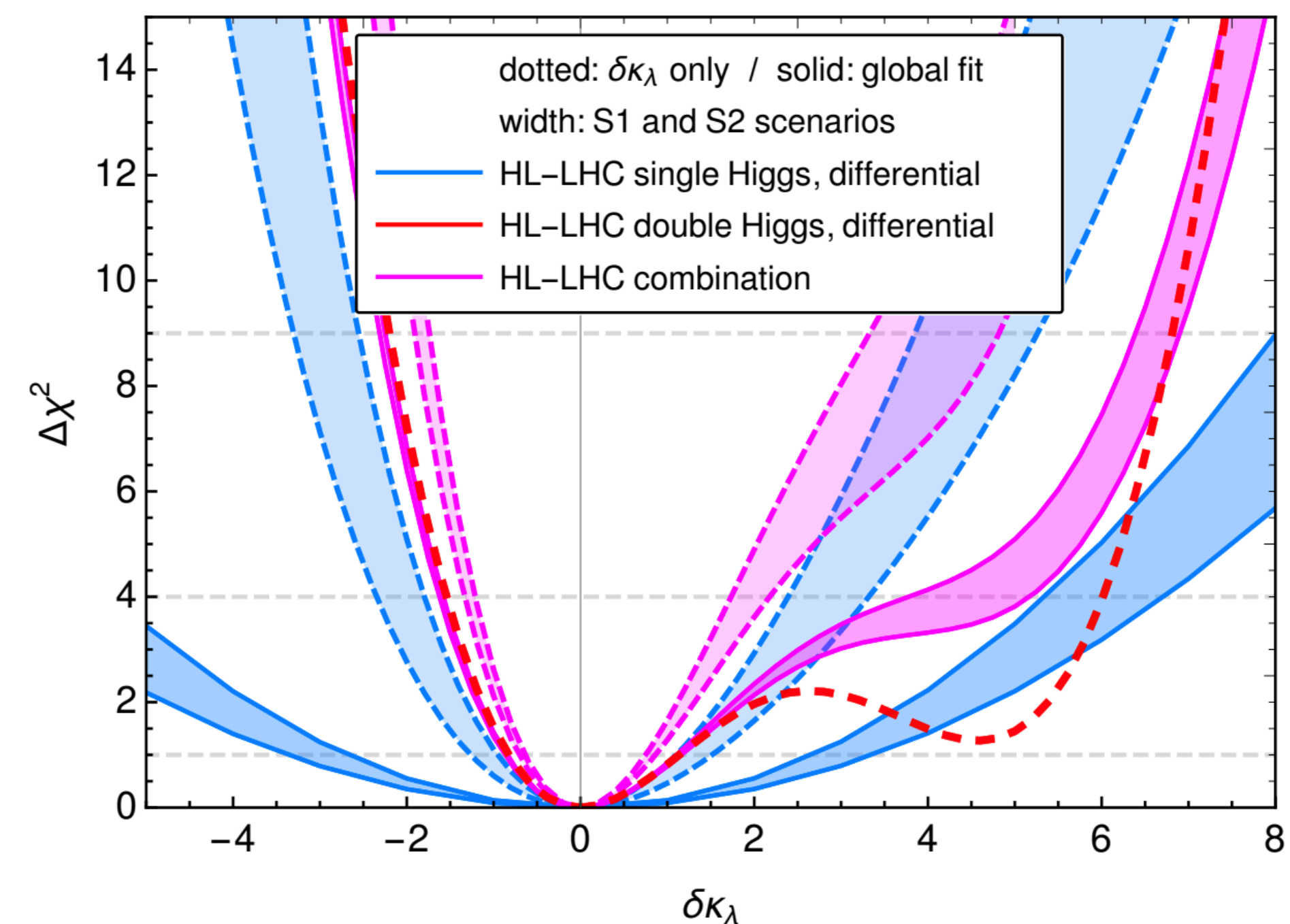
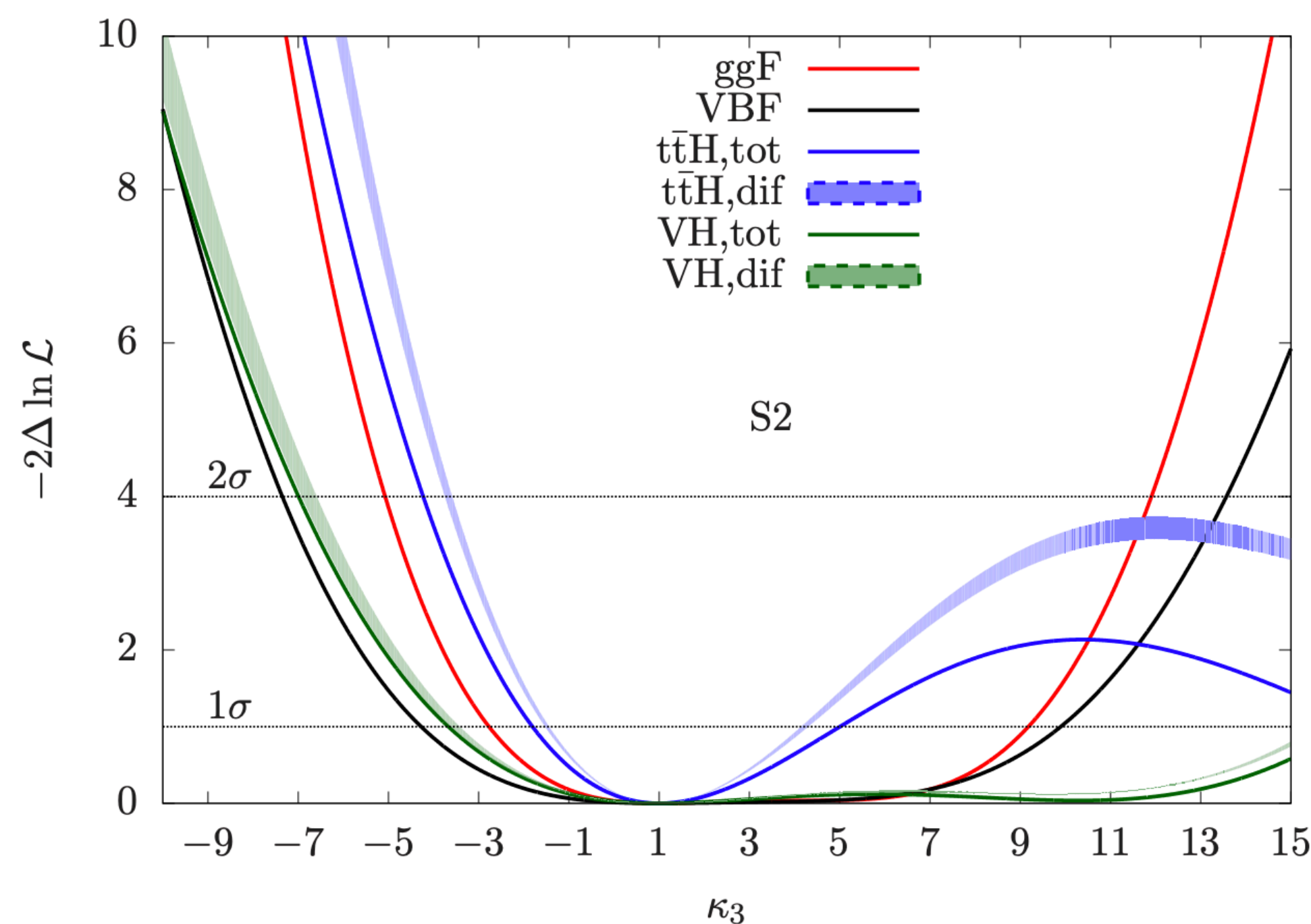


Competitiveness of H vs HH

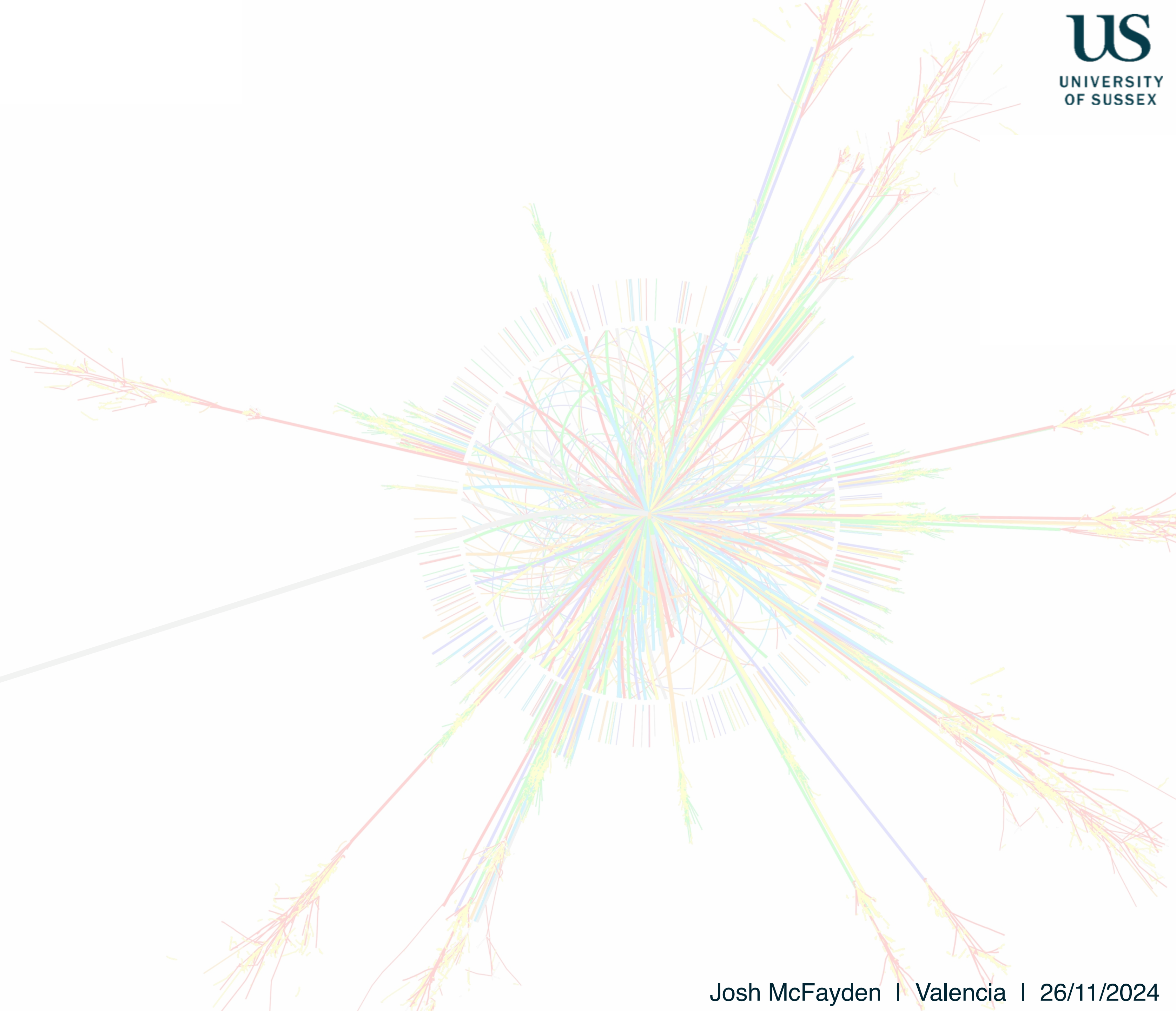
- ▶ In Run2 and Run3 single Higgs measurements are competitive with Higgs pair production.
- ▶ Of these ggH and ttH give the best constraint at low $k\lambda$
- ▶ But this doesn't include differential information for ttH which should be the most sensitive.



- ▶ At HL-LHC while double-Higgs is driving the bound, differential single-Higgs data is relevant as it can help lift the degenerate minima around $\kappa\lambda \sim 5$.
- ▶ At HL-LHC $t\bar{t}H$ is still one of the most constraining measurements at low values but ggH is stronger at high κ_3



Miscellanea



► tt+>=1b model

► PowhegBoxRes+Py8

- Factorisation scale:
$$\frac{1}{2}\sum_{i=t,\bar{t},b,\bar{b},j}m_{T,i}$$
- Renormalisation scale:
$$\sqrt[4]{m_T(t)\cdot m_T(\bar{t})\cdot m_T(b)\cdot m_T(\bar{b})}$$
- hdamp scale:
$$\frac{1}{2}\sum_{i=t,\bar{t},b,\bar{b},j}m_{T,i}$$

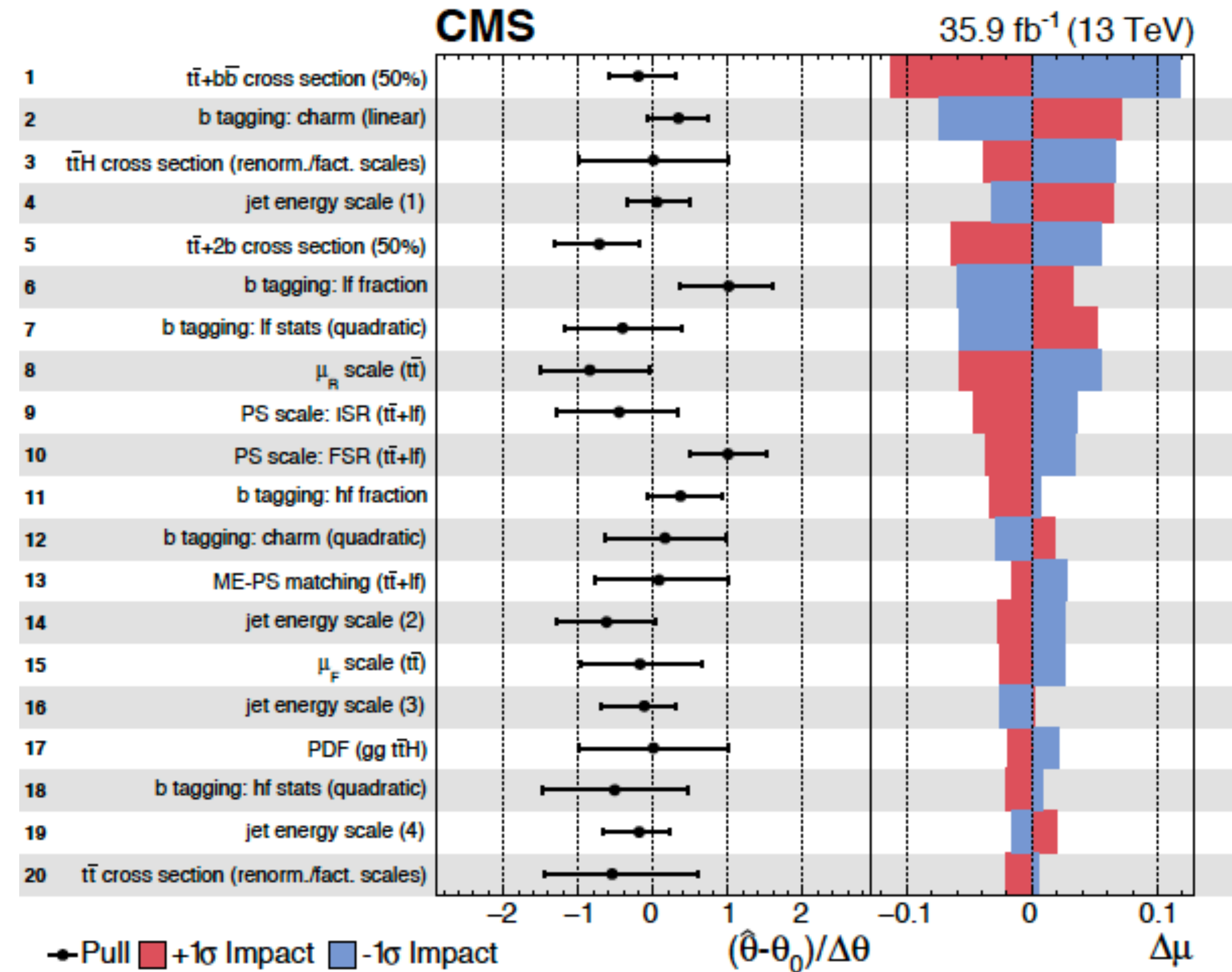
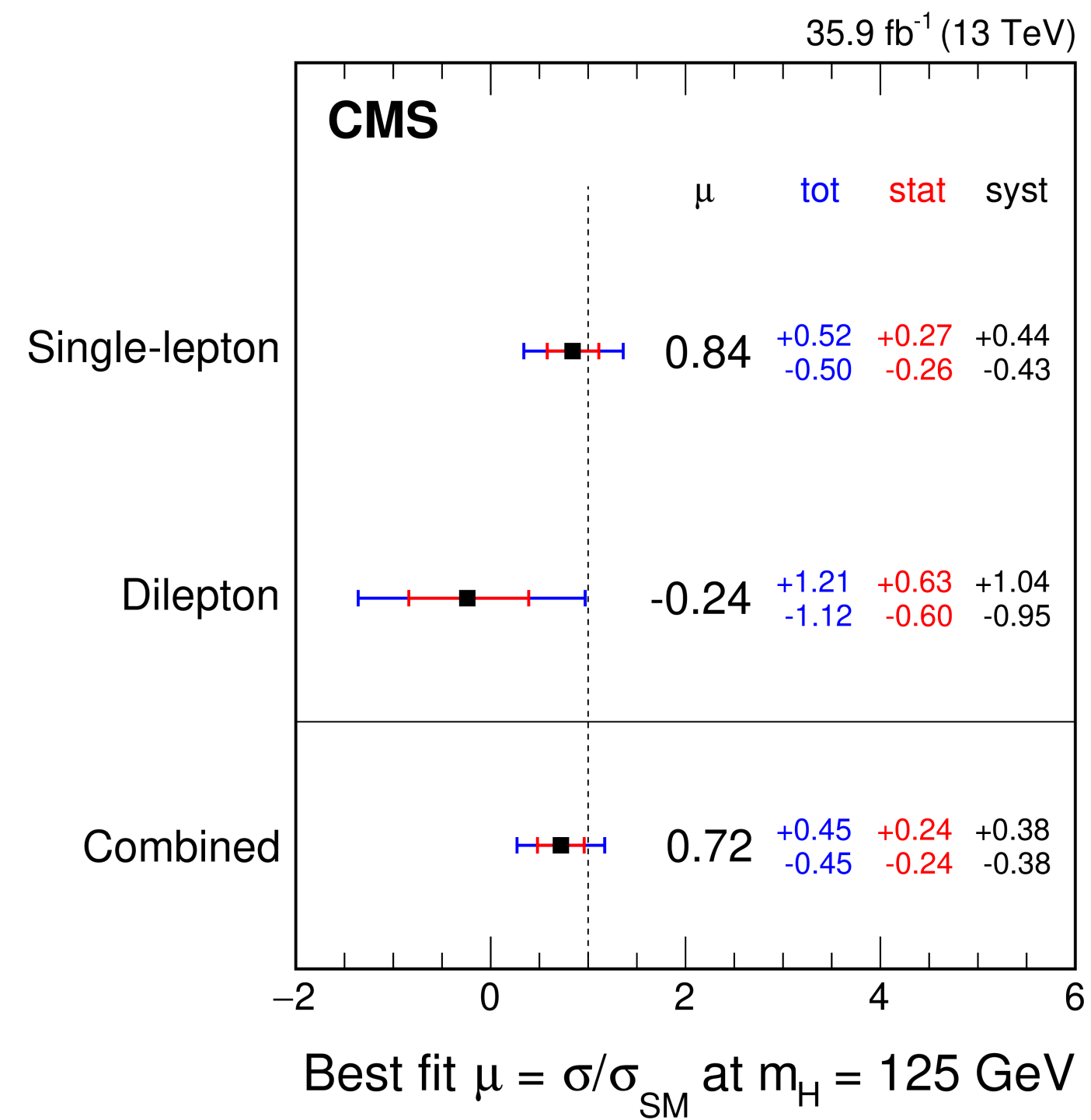
Uncertainty source	Description	Components
$t\bar{t}$ cross-section	Up or down by 6%	$t\bar{t}$ + light
$t\bar{t} + \geq 1b$ normalisation	Free-floating	$t\bar{t} + \geq 1b$
$t\bar{t} + \geq 1c$ normalisation	Up or down by 100%	$t\bar{t} + \geq 1c$
ISR	Varying μ_R^{ISR} (PS), μ_R & μ_F (ME)	in PowHEGBox+PYTHIA8 $t\bar{t}b\bar{b}$ (4FS) in PowHEGBox+PYTHIA8 $t\bar{t}$ (5FS) $t\bar{t} + \geq 1b$
FSR	Varying μ_R^{FSR} (PS)	in PowHEGBox+PYTHIA8 $t\bar{t}b\bar{b}$ (4FS) in PowHEGBox+PYTHIA8 $t\bar{t}$ (5FS) $t\bar{t} + \geq 1c, t\bar{t}$ + light
NLO matching	MADGRAPH5_AMC@NLO +PYTHIA8 $t\bar{t}$ (5FS)	vs. PowHEGBox+PYTHIA8 $t\bar{t}$ (5FS) All
PS & hadronisation	PowHEGBox+HERWIG7 $t\bar{t}$ (5FS)	vs. PowHEGBox+PYTHIA8 $t\bar{t}$ (5FS) All
$p_T^{b\bar{b}}$ shape	Correction from data of $p_T^{b\bar{b}}$ shape in signal regions	$t\bar{t} + \geq 1b$
$t\bar{t} + \geq 1b$ fractions	Variation of the relative fractions of $t\bar{t} + \geq 2b$ and $t\bar{t} + 1b/1B$	$t\bar{t} + \geq 1b$

Uncertainty source	$\Delta\mu$	
Process modelling		
$t\bar{t}H$ modelling	+0.13	−0.05
$t\bar{t} + \geq 1b$ modelling		
$t\bar{t} + \geq 1b$ NLO matching	+0.21	−0.20
$t\bar{t} + \geq 1b$ fractions	+0.12	−0.12
$t\bar{t} + \geq 1b$ FSR	+0.10	−0.11
$t\bar{t} + \geq 1b$ PS & hadronisation	+0.09	−0.08
$t\bar{t} + \geq 1b$ p_T^{bb} shape	+0.04	−0.04
$t\bar{t} + \geq 1b$ ISR	+0.04	−0.04
$t\bar{t} + \geq 1c$ modelling	+0.03	−0.04
$t\bar{t}$ + light modelling	+0.03	−0.03
tW modelling	+0.08	−0.07
Background-model statistical uncertainty	+0.04	−0.05
b -tagging efficiency and mis-tag rates		
b -tagging efficiency	+0.03	−0.02
c -mis-tag rates	+0.03	−0.03
l -mis-tag rates	+0.02	−0.02
Jet energy scale and resolution		
b -jet energy scale	+0.00	−0.01
Jet energy scale (flavour)	+0.01	−0.01
Jet energy scale (pile-up)	+0.00	−0.01
Jet energy scale (remaining)	+0.01	−0.01
Jet energy resolution	+0.02	−0.02
Luminosity	+0.01	−0.00
Other sources	+0.03	−0.03
Total systematic uncertainty	+0.30	−0.28
$t\bar{t} + \geq 1b$ normalisation	+0.04	−0.07
Total statistical uncertainty	+0.20	−0.20
Total uncertainty	+0.36	−0.34



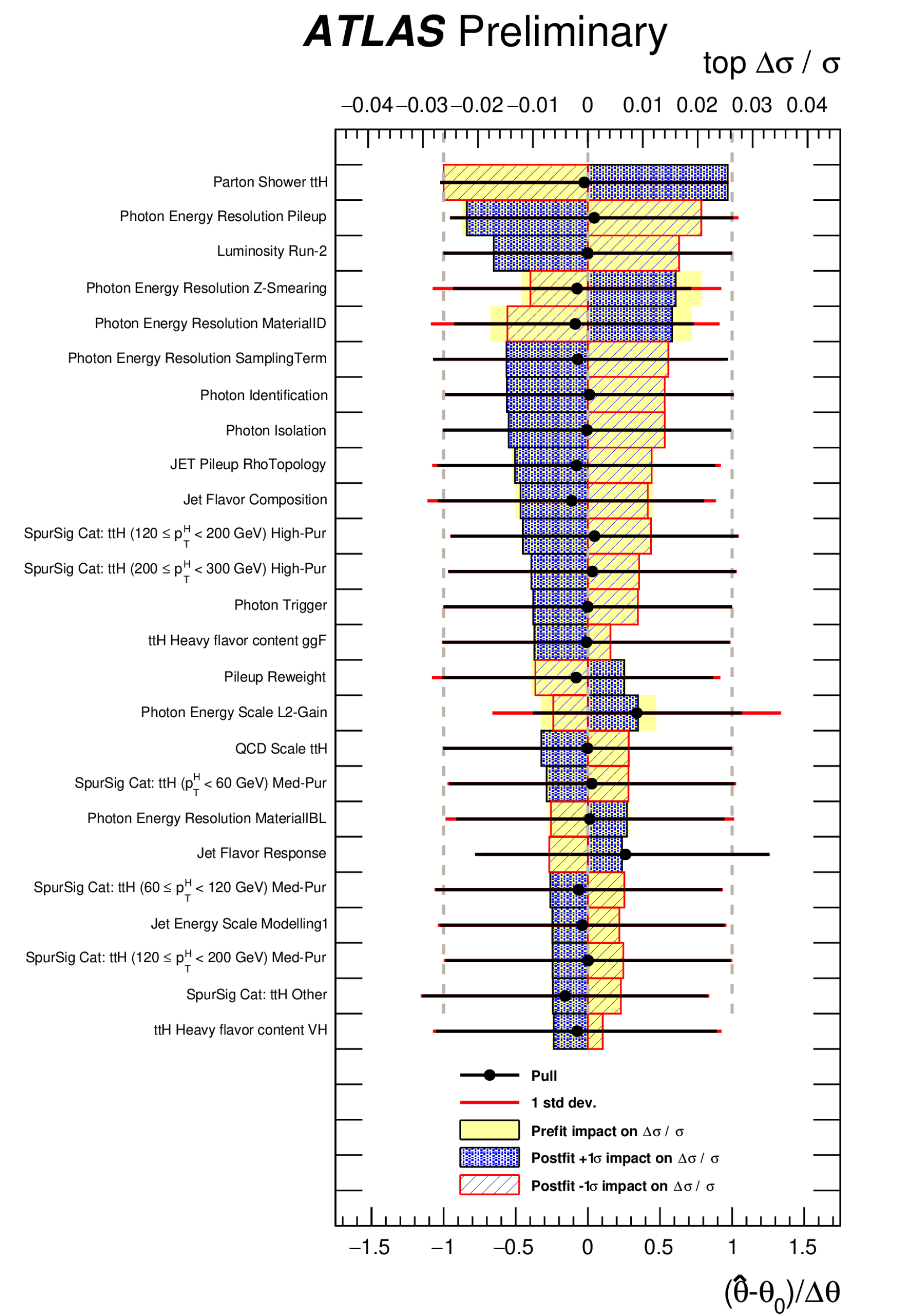
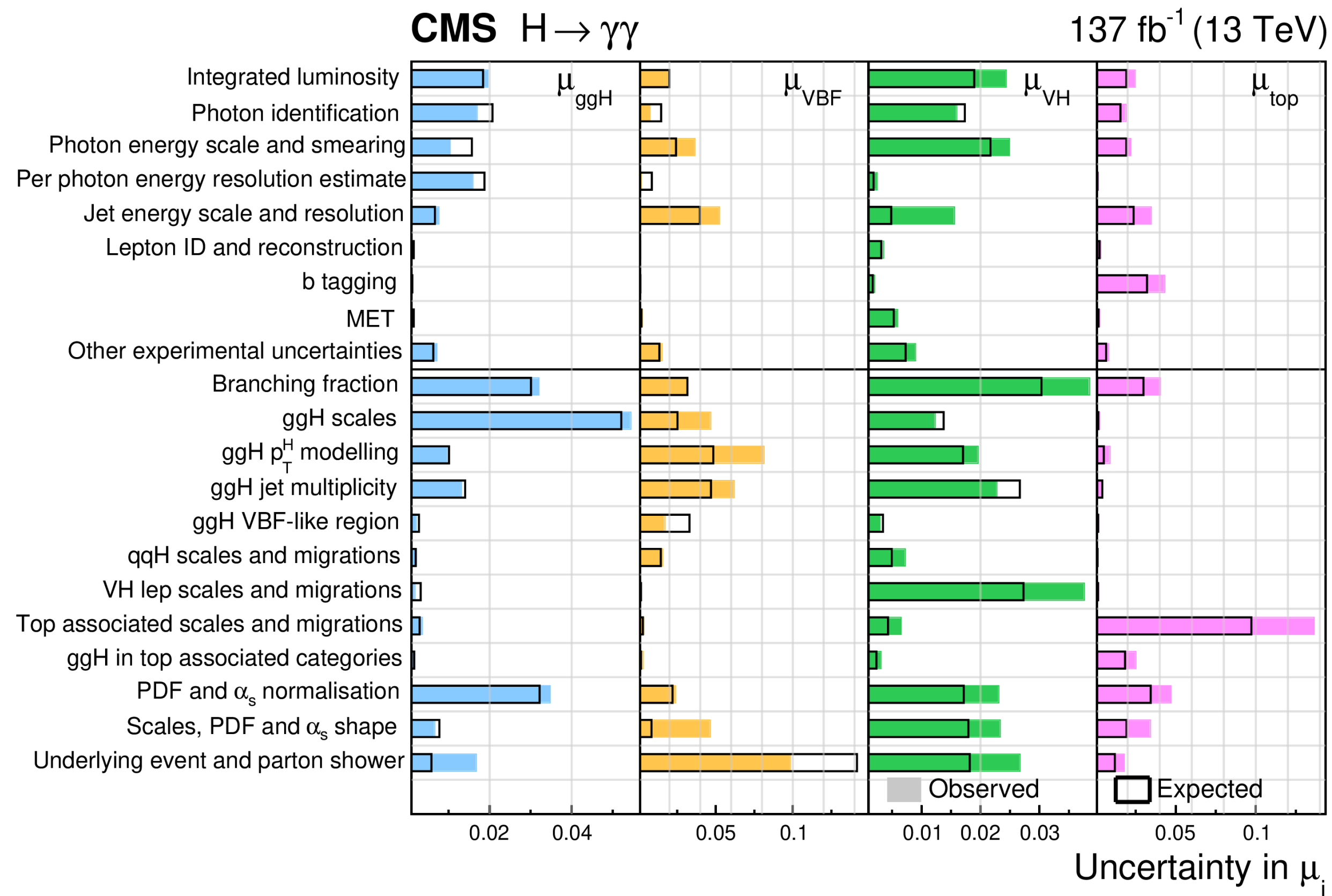
CMS $t\bar{t}Hb\bar{b}$ result 36 ifb

► JHEP 03 (2019) 026



► <https://atlas.web.cern.ch/Atlas/GROUPS/PHY>
[CONF-2020-026/](https://atlas.web.cern.ch/Atlas/GROUPS/PHY)

► <http://cms-results.web.cern.ch/cms-results/p>
[HIG-19-015/index.html](http://cms-results.web.cern.ch/cms-results/p)



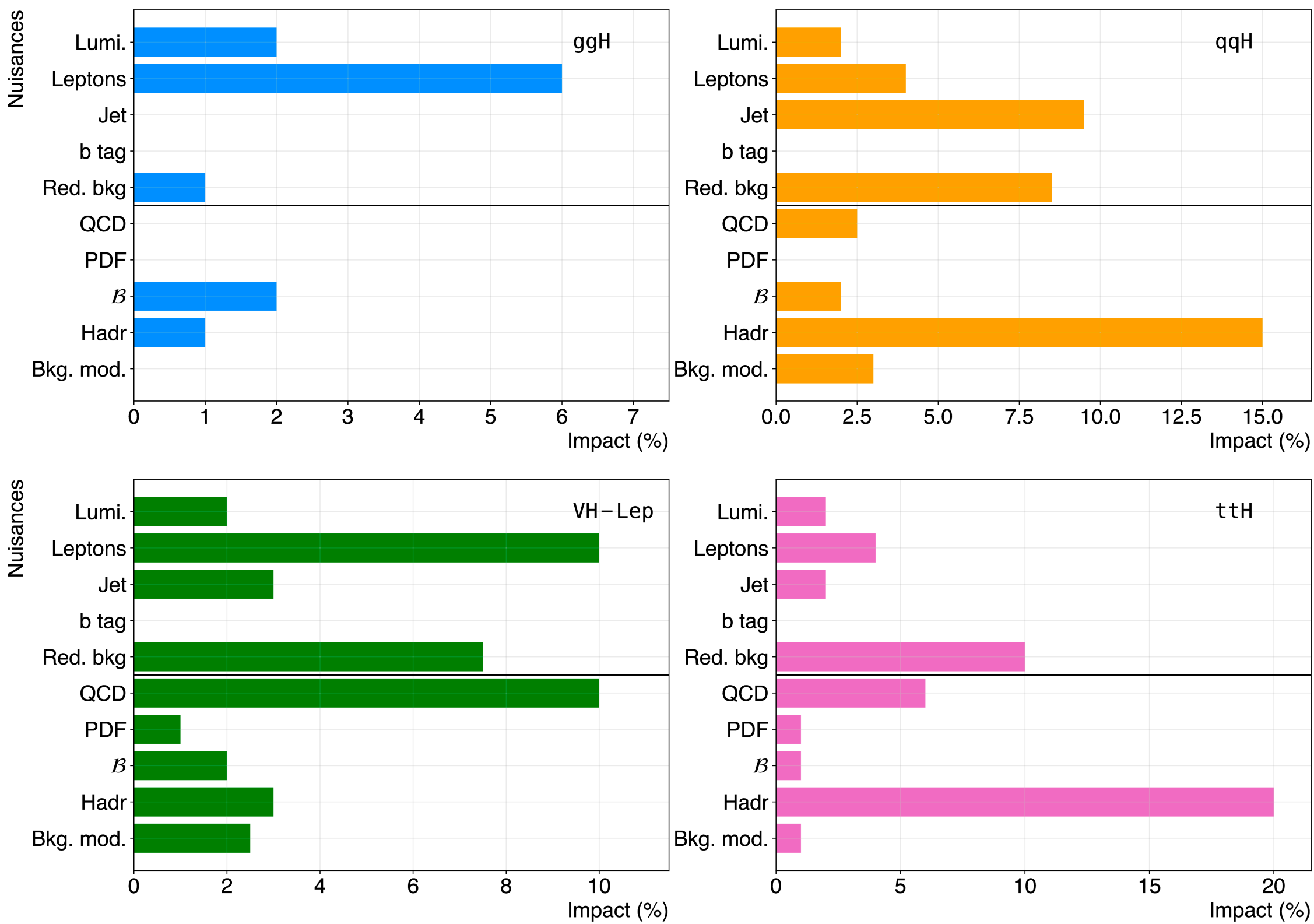


CMS ttH4l result 36 ifb



► <https://atlas.web.cern.ch/Atlas/GROUPS/PHYSICS/PAPERS/HIGG-2018-28/>

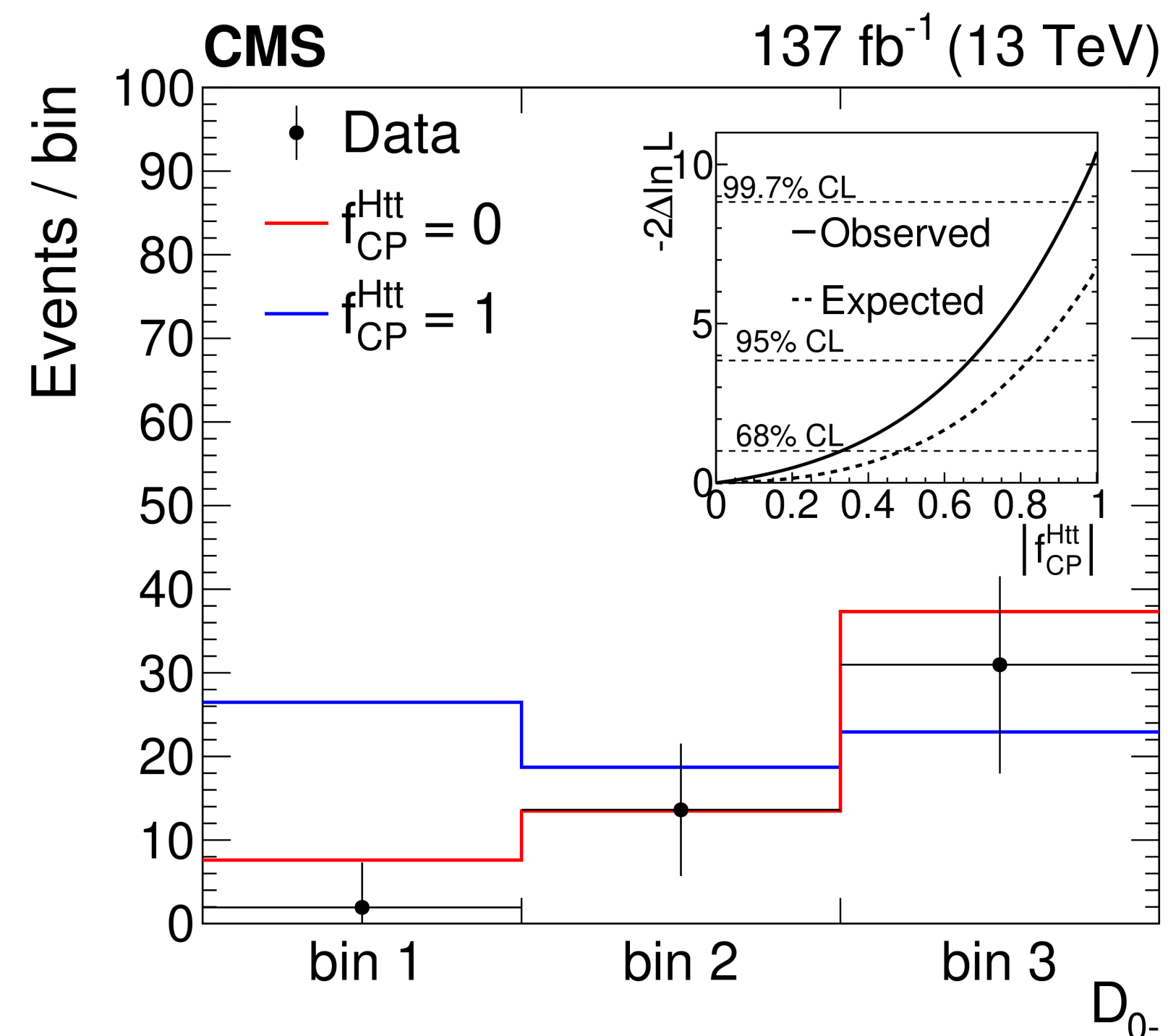
► <http://cms-results.web.cern.ch/cms/HIG-19-001/>



Measurement	Experimental uncertainties [%]				Theory uncertainties [%]				
	Lumi.	e, μ , pile-up	Jets, flav. tag	Reducible bkg	Background		Signal		
					ZZ^*	tXX	PDF	QCD	Shower
Inclusive cross-section									
	1.7	2.5	0.5	< 0.5	1	< 0.5	< 0.5	1	2
Production mode cross-sections									
ggF	1.7	2.5	1	< 0.5	1.5	< 0.5	0.5	1	2
VBF	1.7	2	4	< 0.5	1.5	< 0.5	1	5	7
VH	1.9	2	4	1	6	< 0.5	2	13.5	7.5
ttH	1.7	2	6	< 0.5	1	0.5	0.5	12.5	4
Reduced Stage-1.1 production bin cross-sections									
$gg2H-0j-p_T^H$ -Low	1.7	3	1.5	0.5	6.5	< 0.5	< 0.5	1	1.5
$gg2H-0j-p_T^H$ -High	1.7	3	5	< 0.5	3	< 0.5	< 0.5	0.5	5.5
$gg2H-1j-p_T^H$ -Low	1.7	2.5	12	0.5	7	< 0.5	< 0.5	1	6
$gg2H-1j-p_T^H$ -Med	1.7	3	7.5	< 0.5	1	< 0.5	< 0.5	1.5	5.5
$gg2H-1j-p_T^H$ -High	1.7	3	11	0.5	2	< 0.5	< 0.5	2	7.5
$gg2H-2j$	1.7	2.5	16.5	1	12.5	0.5	< 0.5	2.5	10.5
$gg2H-p_T^H$ -High	1.7	1.5	3	0.5	3.5	< 0.5	< 0.5	2	3.5
$qq2Hqq-VH$	1.8	4	17	1	4	1	0.5	5.5	8
$qq2Hqq-VBF$	1.7	2	3.5	< 0.5	5	< 0.5	< 0.5	6	10.5
$qq2Hqq-BSM$	1.7	2	4	< 0.5	2.5	< 0.5	< 0.5	3	8
VH -Lep	1.8	2.5	2	1	2	0.5	< 0.5	1.5	3
ttH	1.7	2.5	5	0.5	1	0.5	< 0.5	11	3



Higgs CP



From Haichen Wang

CMS

ATLAS

$$\mathcal{A}(Htt) = -\frac{m_t}{v} \bar{\psi}_t \left(\underbrace{\kappa_t}_{\text{red}} + i \underbrace{\tilde{\kappa}_t}_{\text{blue}} \gamma_5 \right) \psi_t$$

$$\mathcal{L} = -\frac{\sqrt{2}m_t}{v} (\bar{\psi}_t \kappa_t (\cos(\alpha) + i \sin(\alpha) \gamma_5) \psi_t) H$$

CMS

ATLAS

$$\kappa_t$$

$$\Leftrightarrow$$

$$\kappa_t \cos \alpha$$

$$\tilde{\kappa}_t$$

$$\Leftrightarrow$$

$$\kappa_t \sin \alpha$$

$$\kappa_t > 0$$

$$\Rightarrow$$

$$-90^\circ < \alpha < 90^\circ$$

$$|f_{CP}^{Htt}| = \frac{|\tilde{\kappa}_t|^2}{|\tilde{\kappa}_t|^2 + |\kappa_t|^2}$$

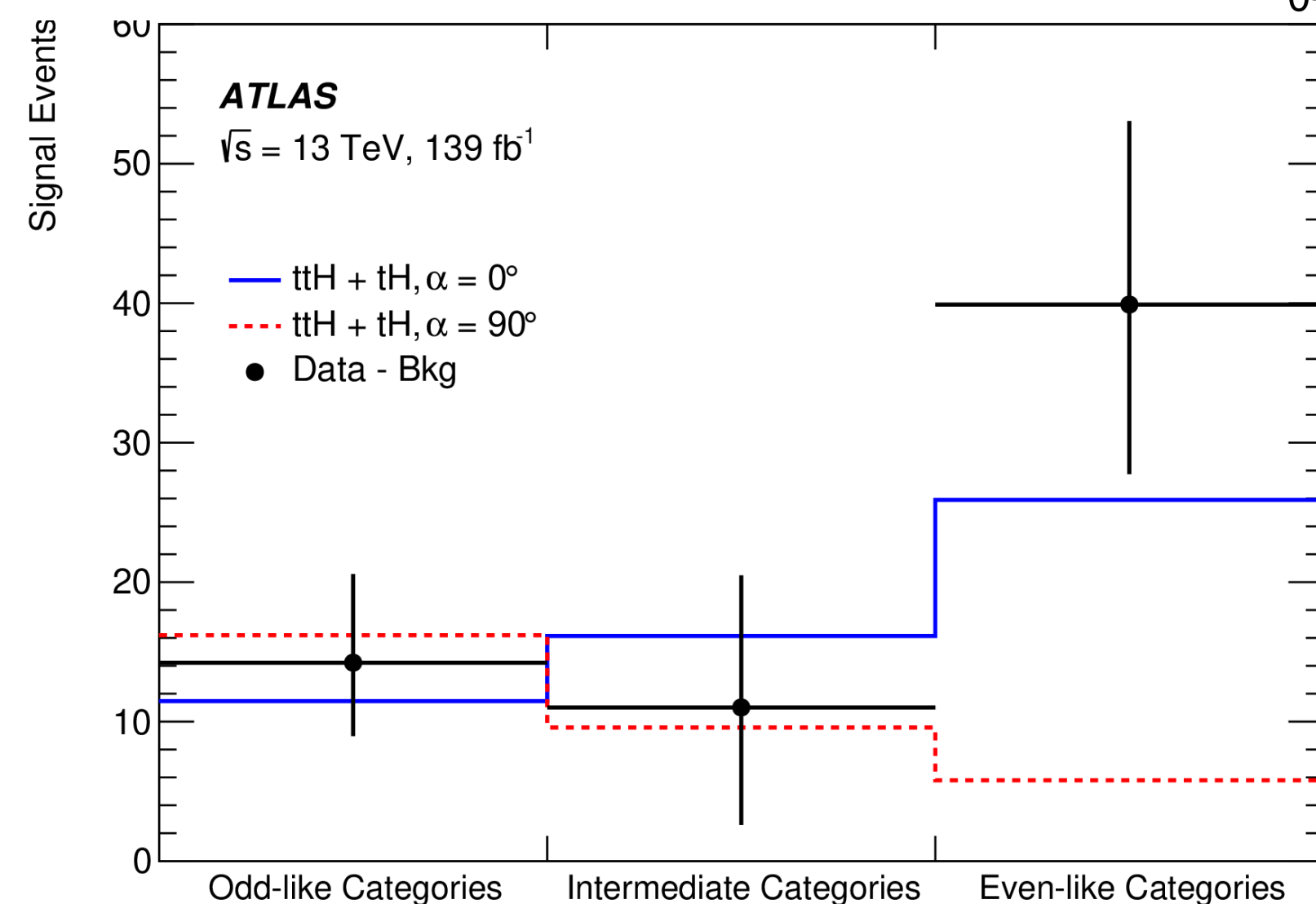
$$\Leftrightarrow$$

$$\sin^2 \alpha$$

$$\mu_{ttH}$$

$$\Leftrightarrow$$

$$\kappa_t^2$$





CMS $t\bar{t}H \rightarrow$ multi-leptons

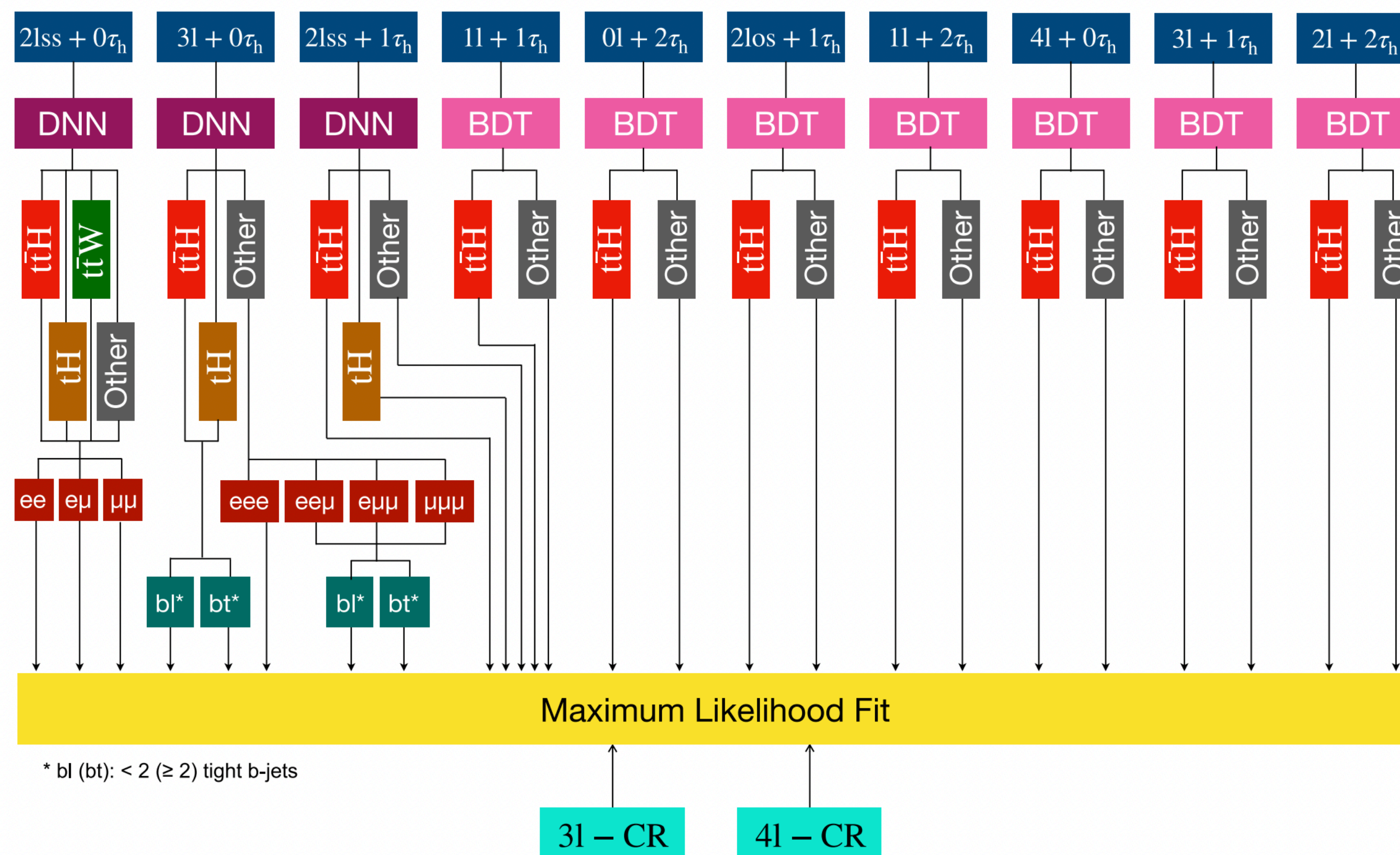
► $t\bar{t}H$ and tH production in $e, \mu, \tau_{\text{had}}$ final state: Eur. Phys. J. C 81 (2021) 378

► Nice that so much is combined into a single coherent analysis:

► $t\bar{t}H$, tH , $t\bar{t}W$, $t\bar{t}Z$ and correlations

► Kappa framework

► Complex
categorisation strategy

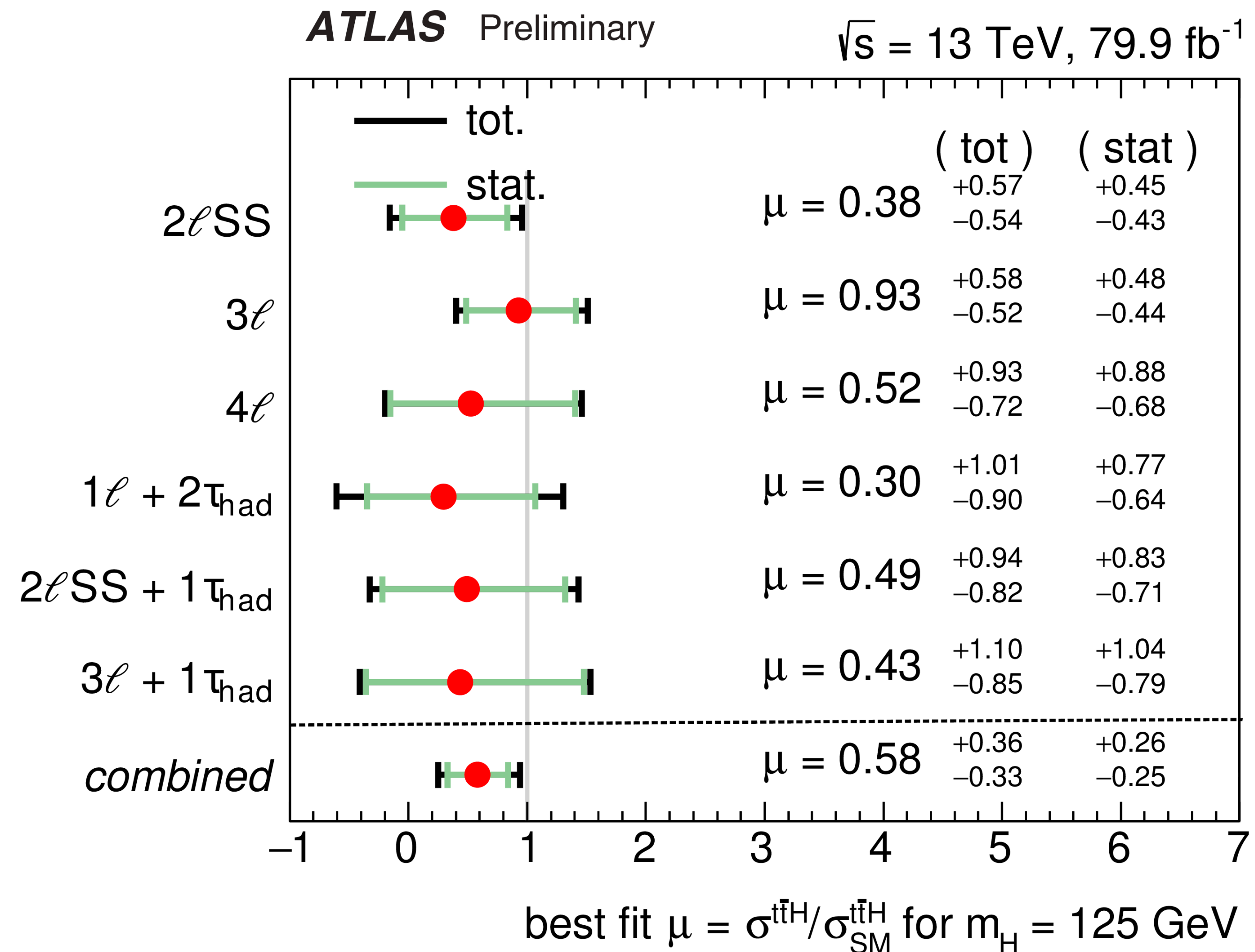


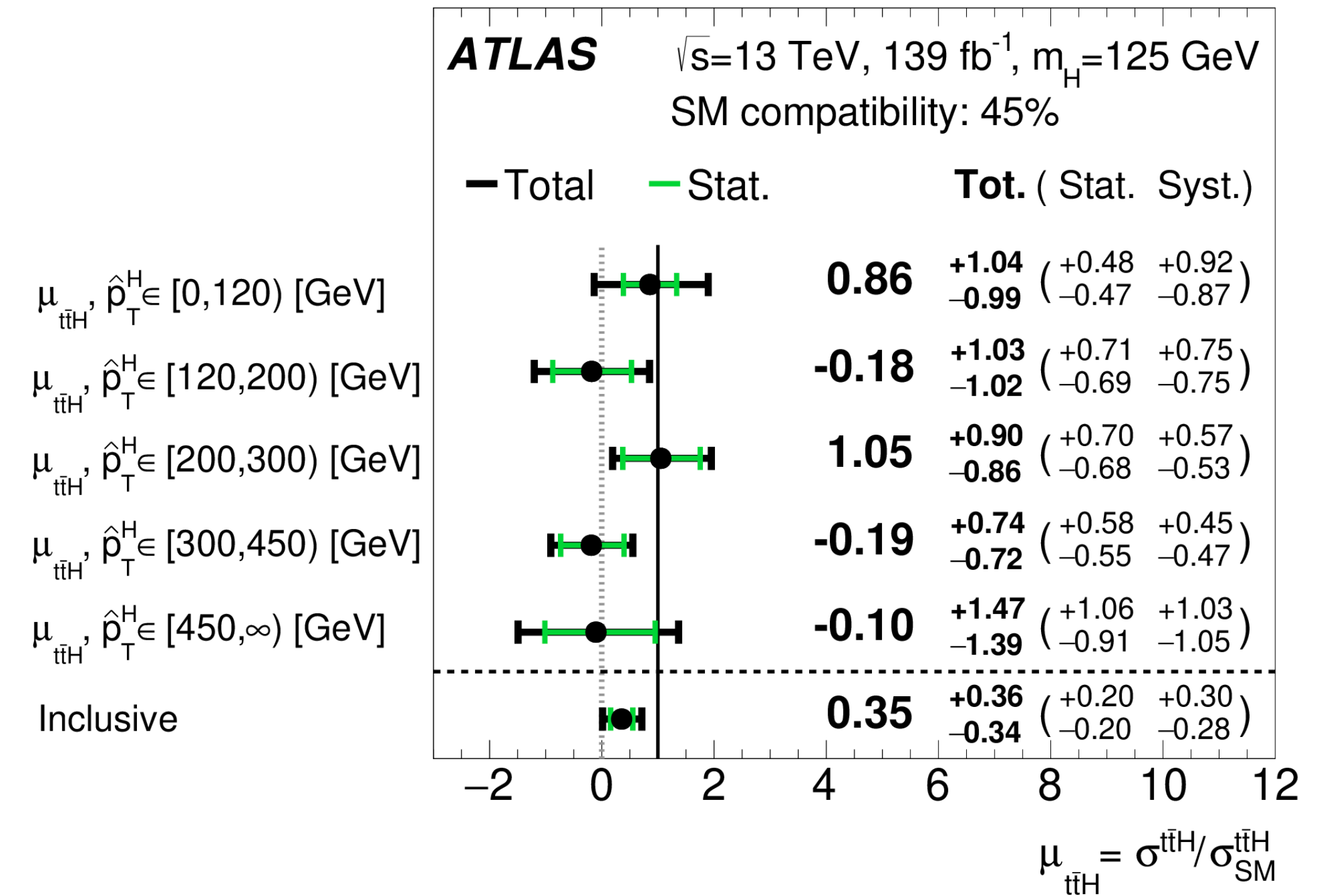
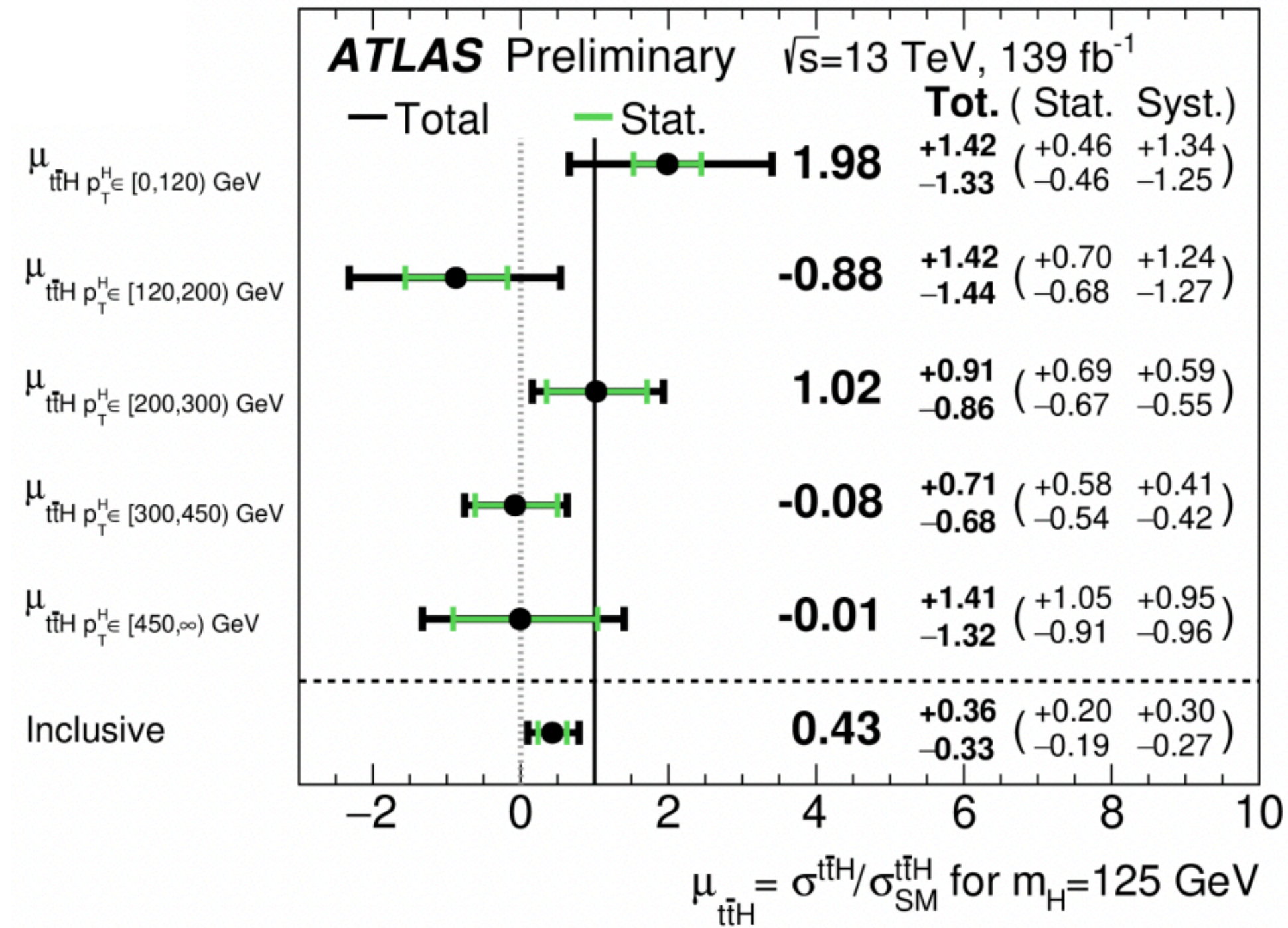


ATLAS $t\bar{t}H \rightarrow$ multi-leptons

► ATLAS $t\bar{t}H$ ML CONF note (80 fb⁻¹): [ATLAS-CONF-2019-045](#)

- Observed significant mismodelling attributed to $t\bar{t}W$ background
- Need $t\bar{t}W+2j$ for 2LSS region
- Very important for overall sensitivity

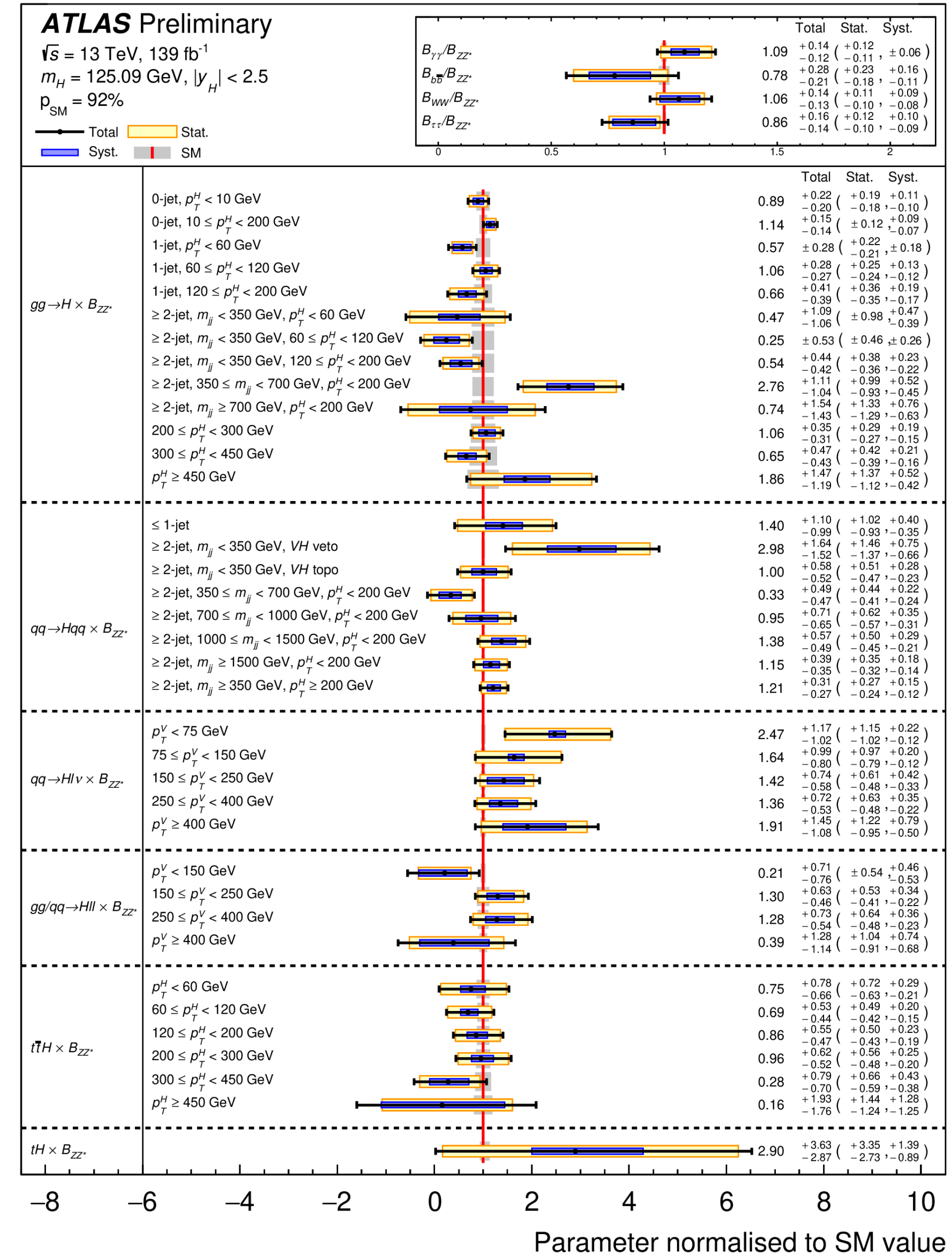
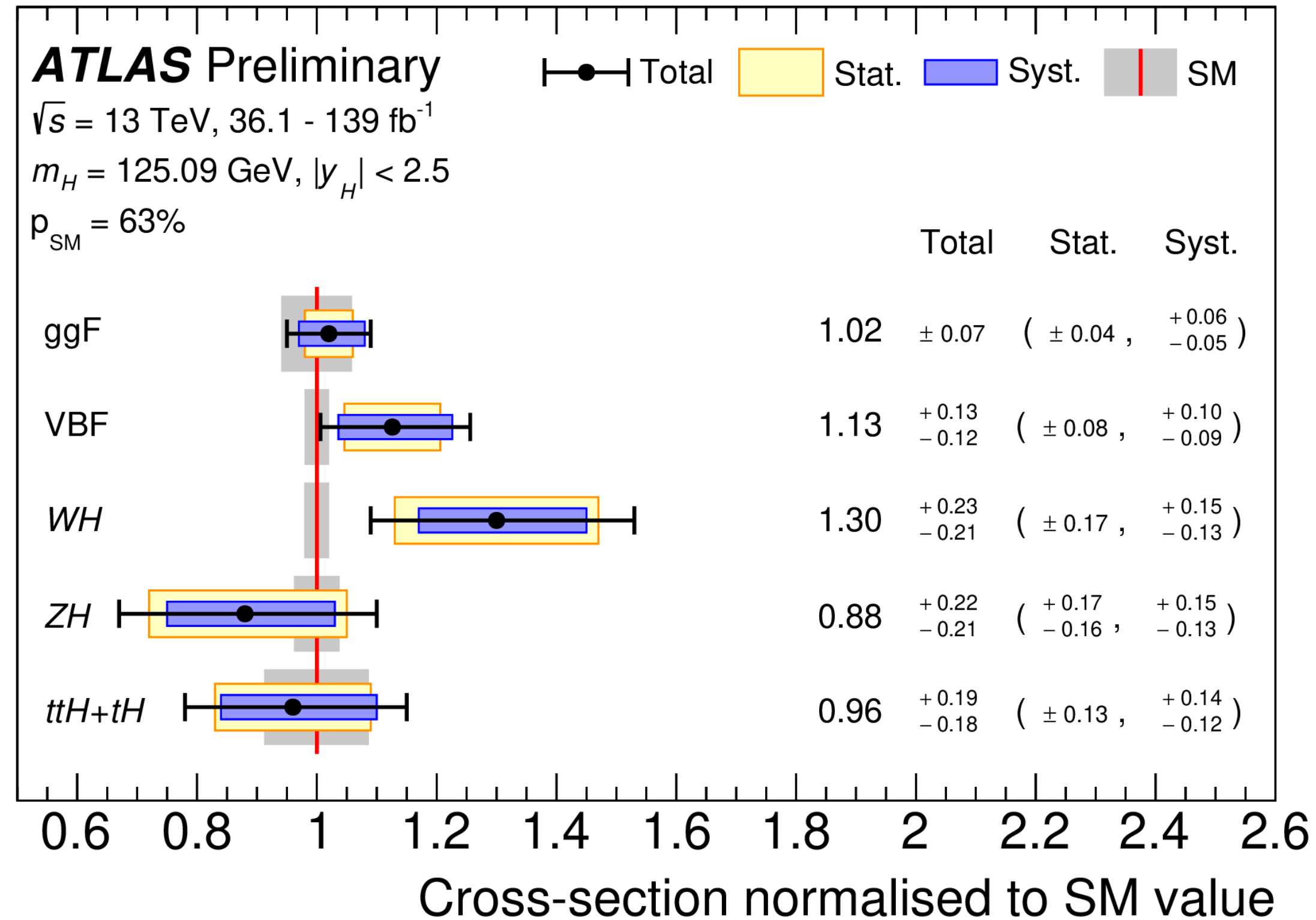




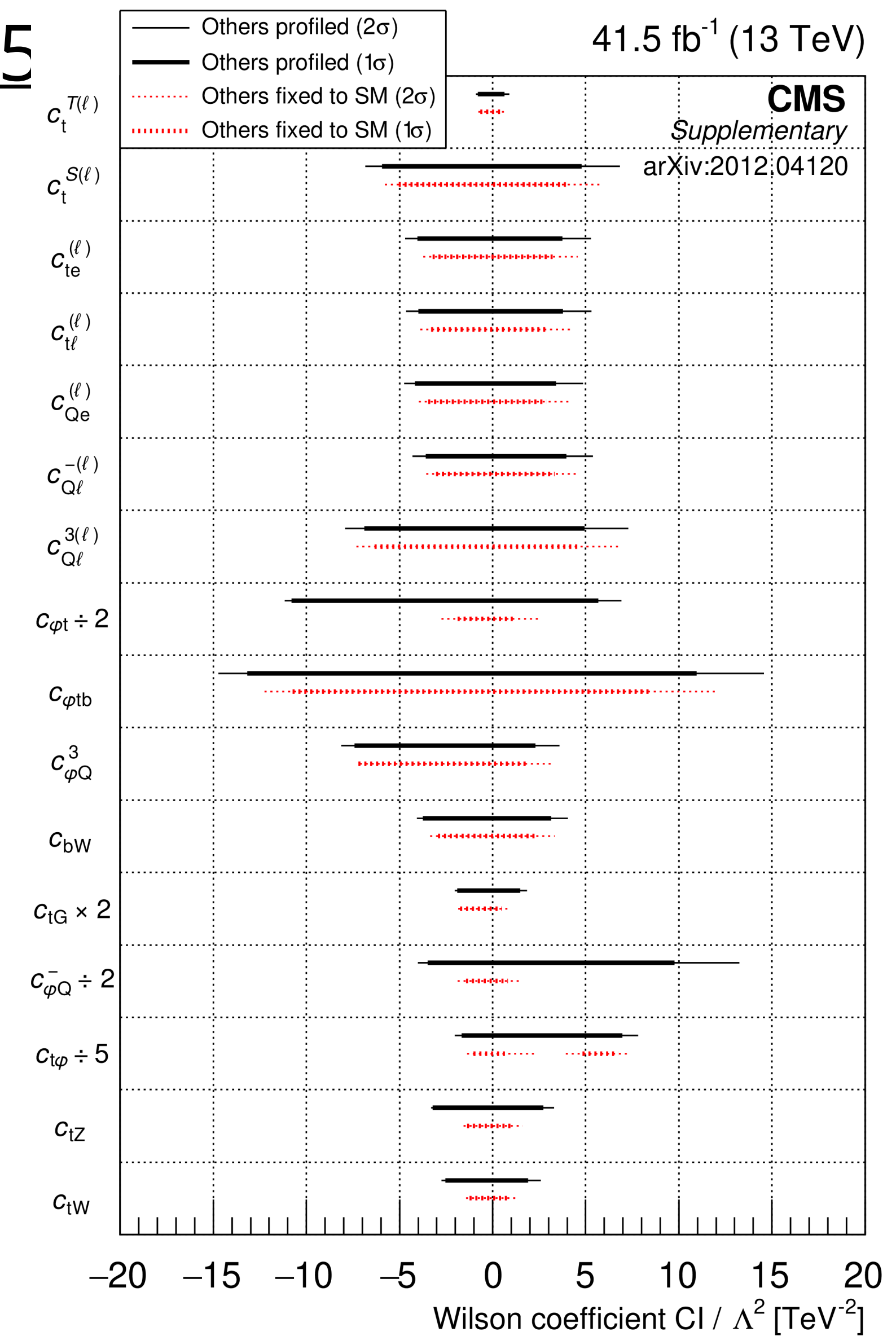


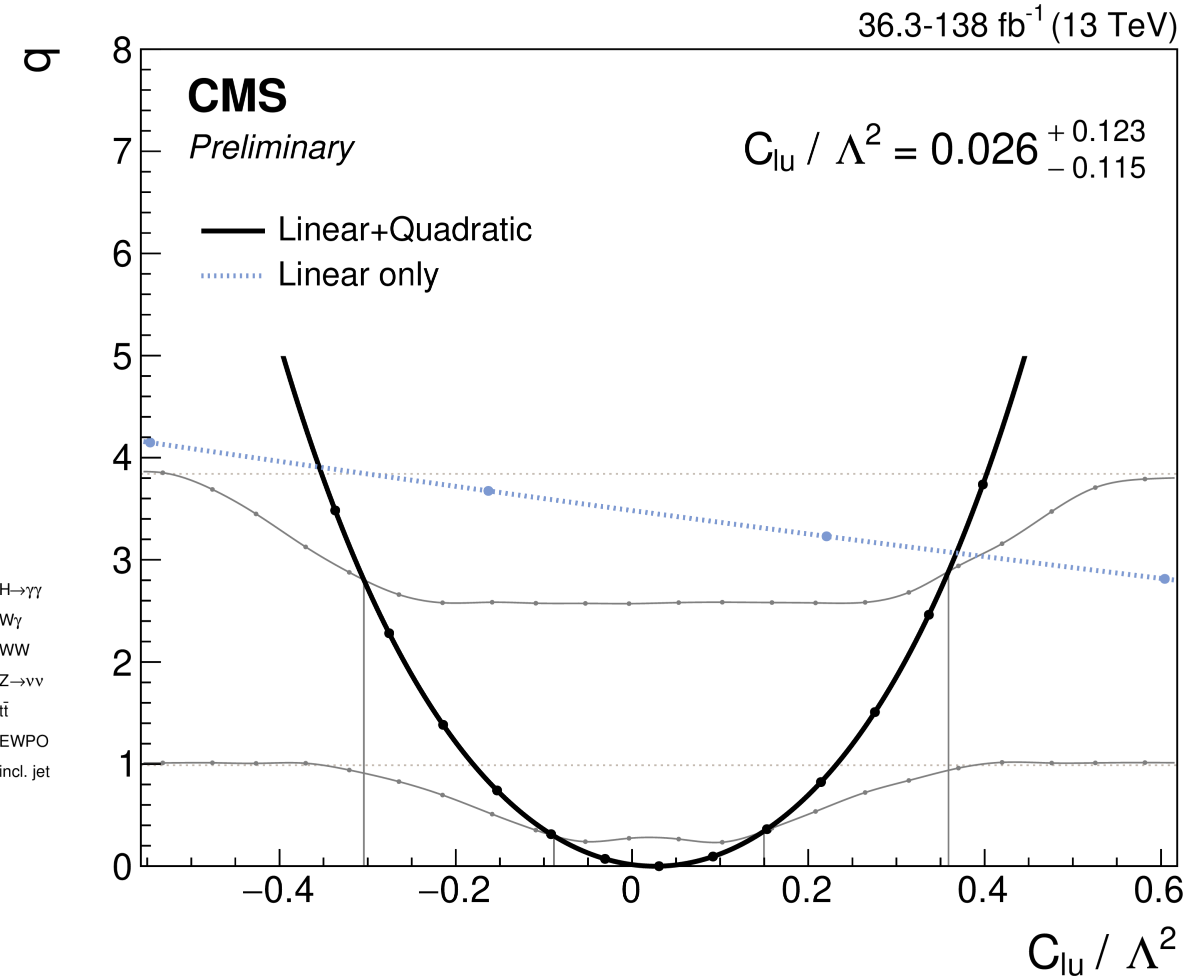
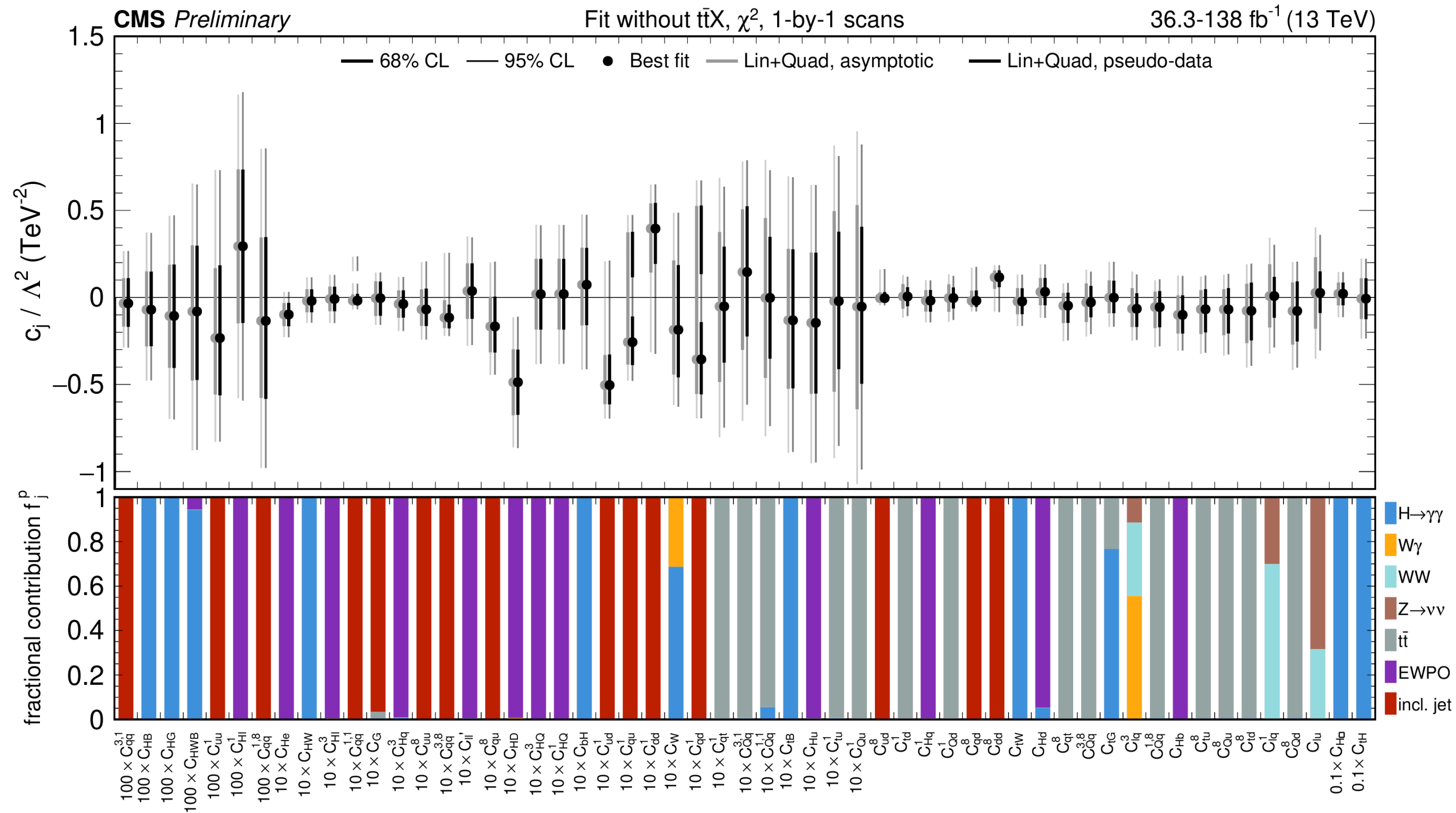
ATLAS ttH combination

ATLAS-CONF-2021-053



- CMS top+X multi-lepton EFT fit: JHEP 2103 (2021) 095
- Top+X “global” EFT fit
- Interpretation in several EFT operators



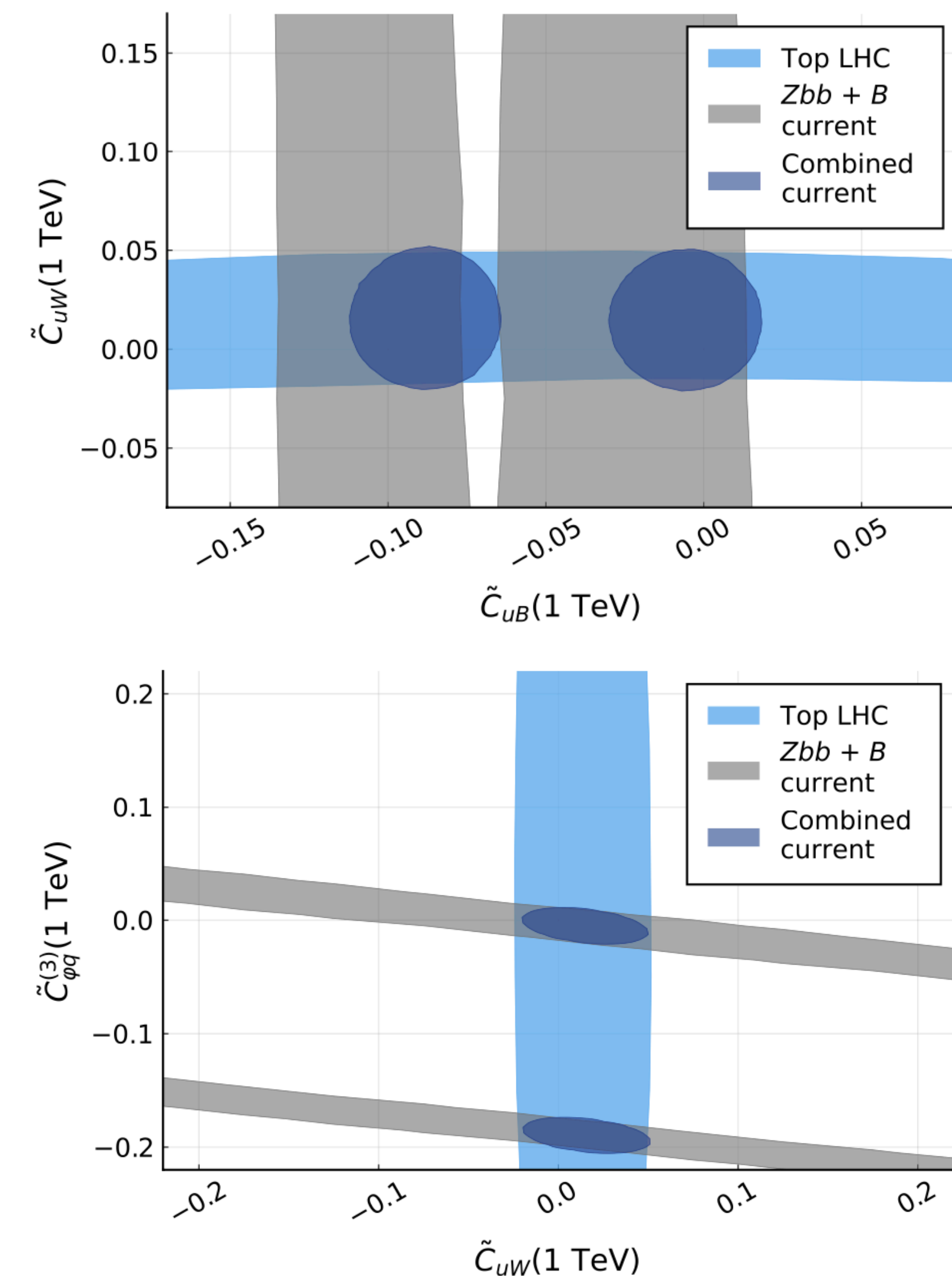


Link to B-anomalies

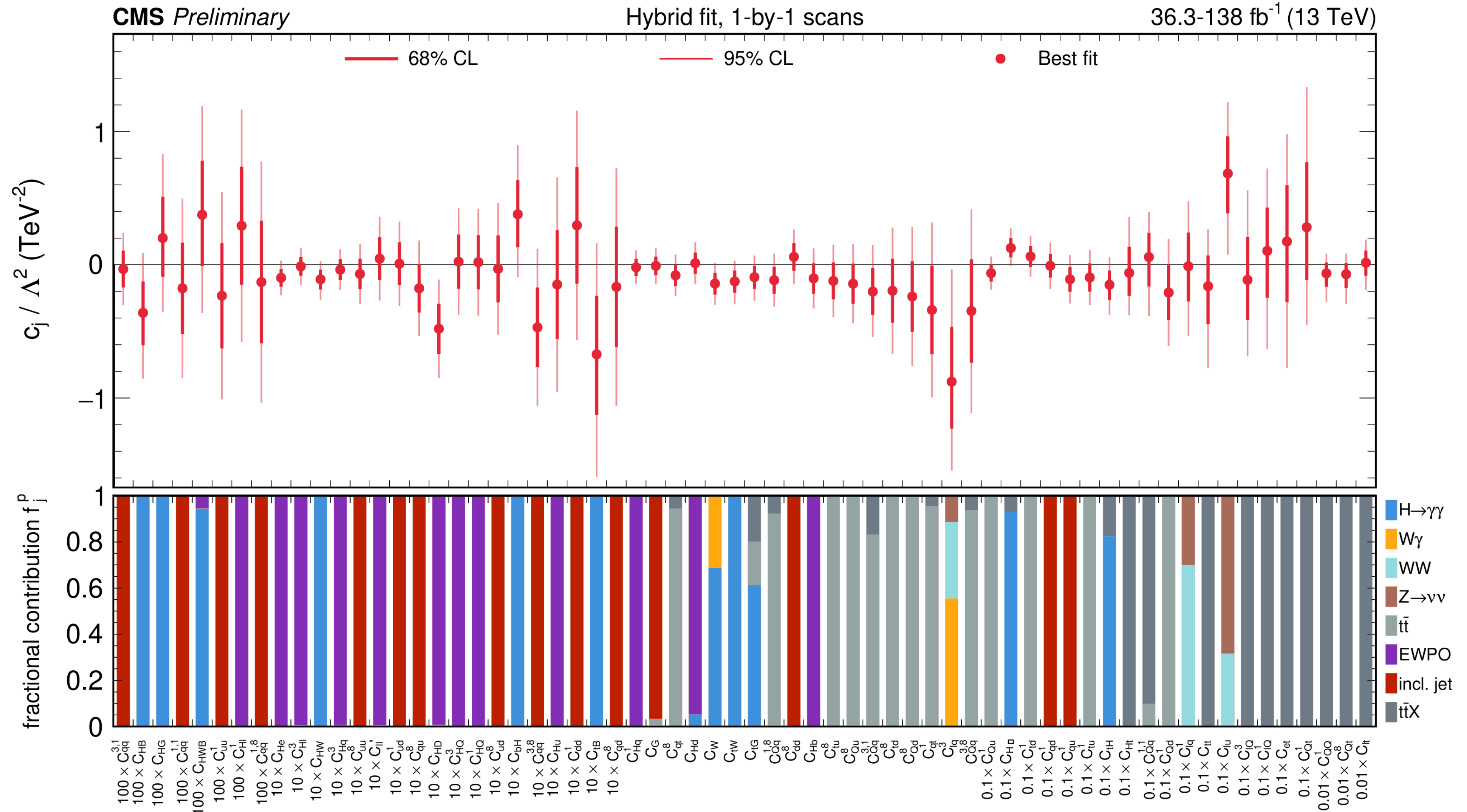
- ▶ EFT already used in interpretation of B-anomalies
- ▶ Links between b and top:
 - ▶ B-anomalies require NP in semileptonic 4-fermion operators
 - ▶ Can also use SMEFT to include tops:

$$\bar{s}_L \gamma_\mu b_L \bar{\mu}_L \gamma^\mu \mu_L \quad \longrightarrow \quad \begin{aligned} O_{lq}^{(1)} &= \bar{Q} \gamma_\mu Q \bar{L} \gamma^\mu L, \\ O_{lq}^{(3)} &= \bar{Q} \gamma_\mu \tau^I Q \bar{L} \gamma^\mu \tau^I L \end{aligned}$$

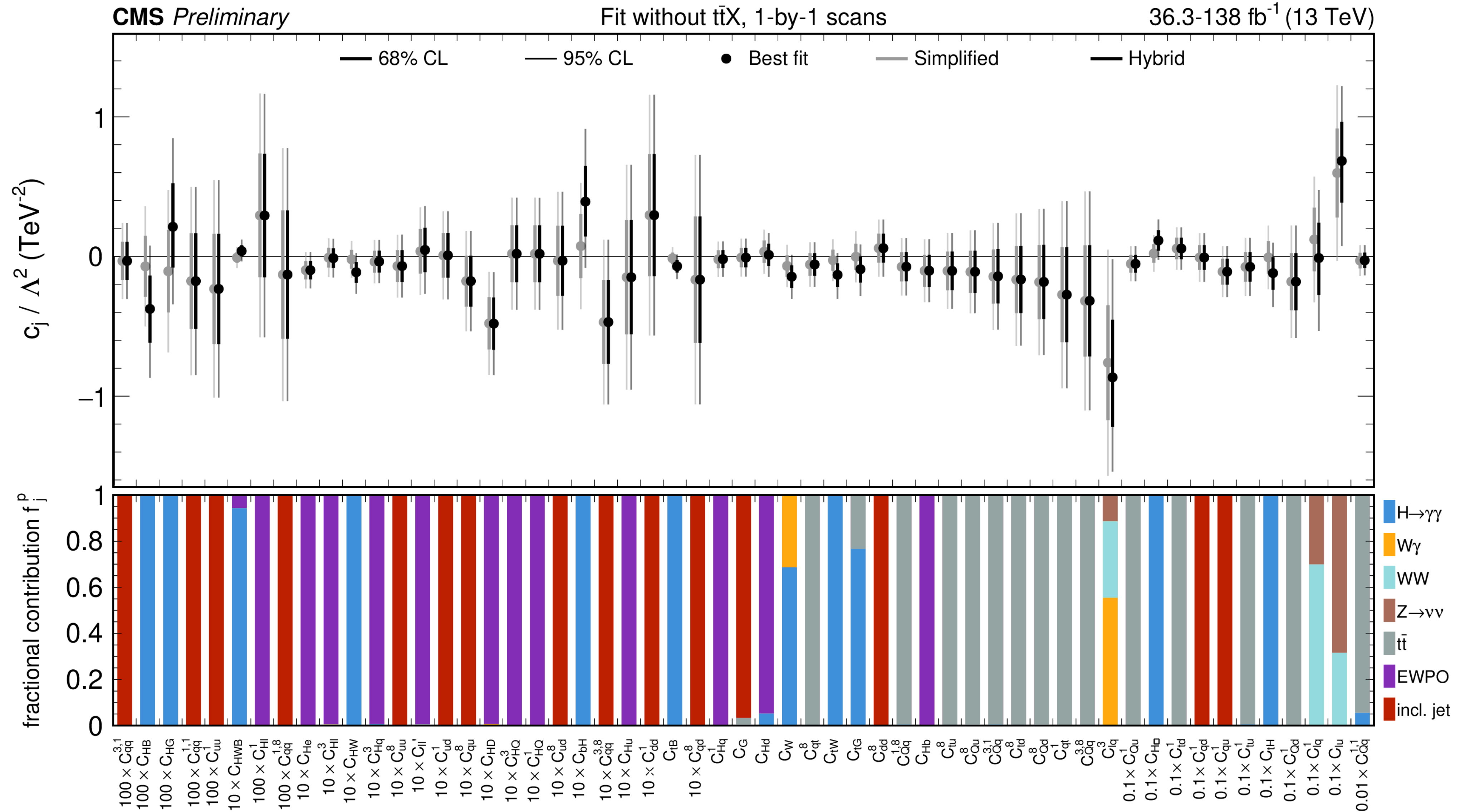
- ▶ Top data particularly complementary wrt B + Zbb for some coefficients



[2012.10456]



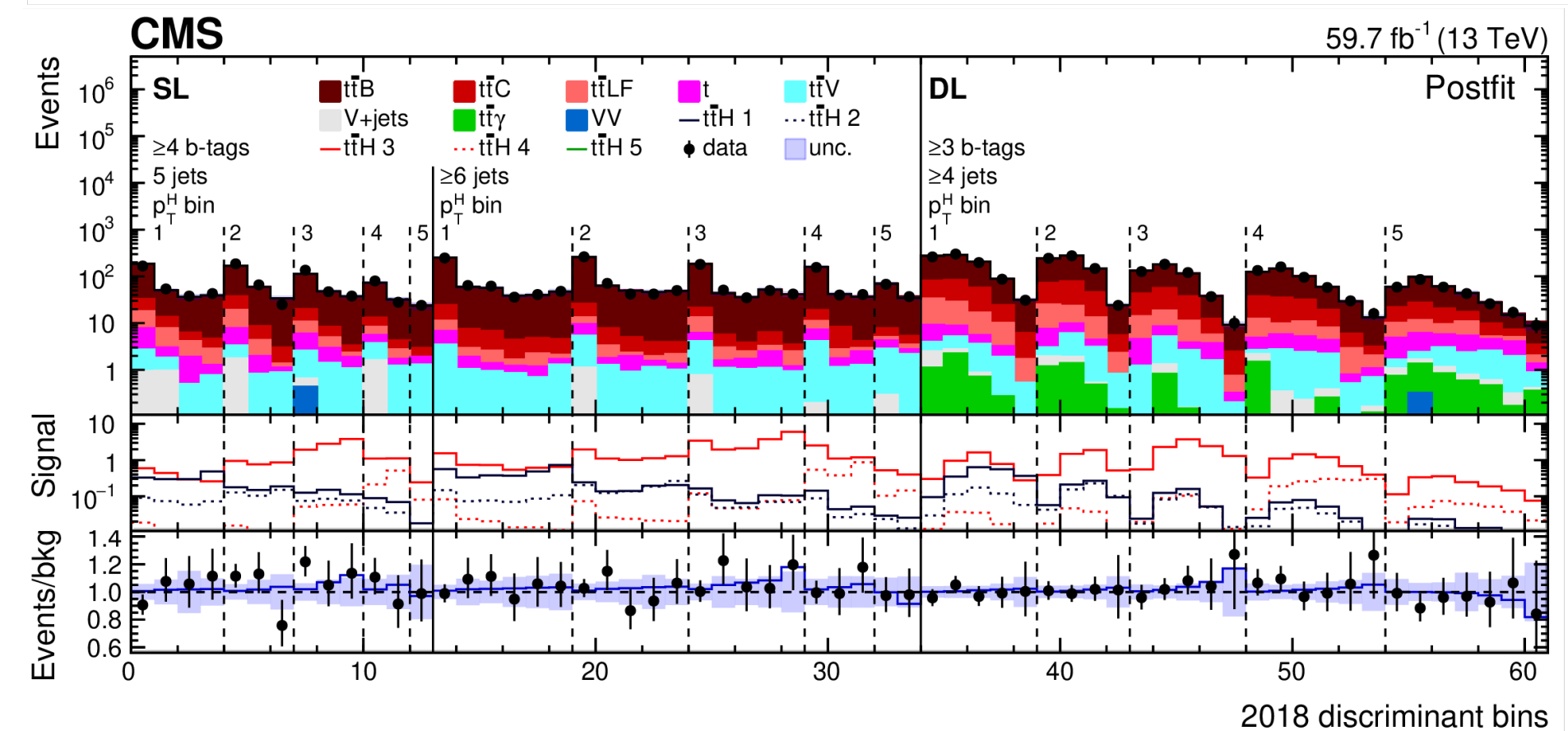
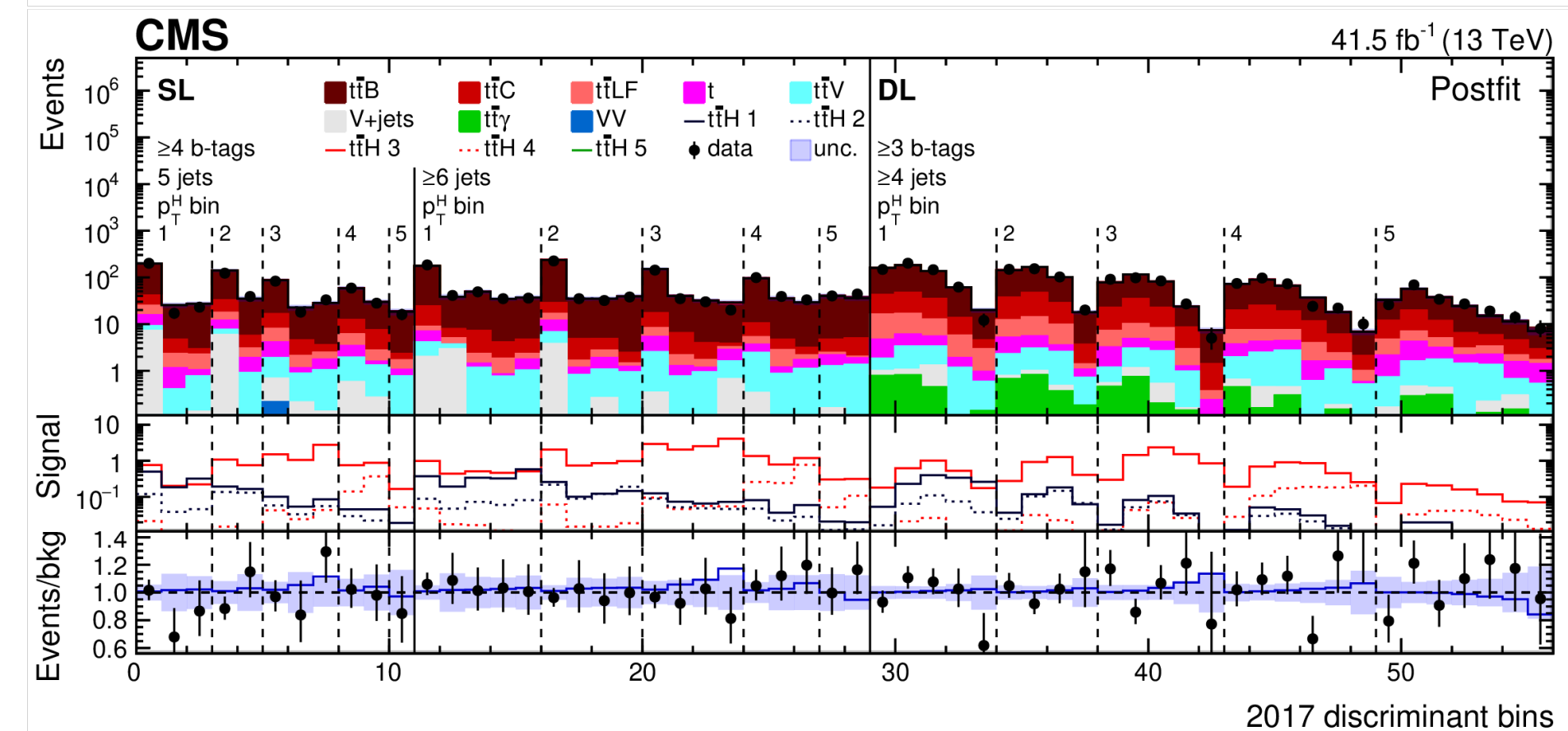
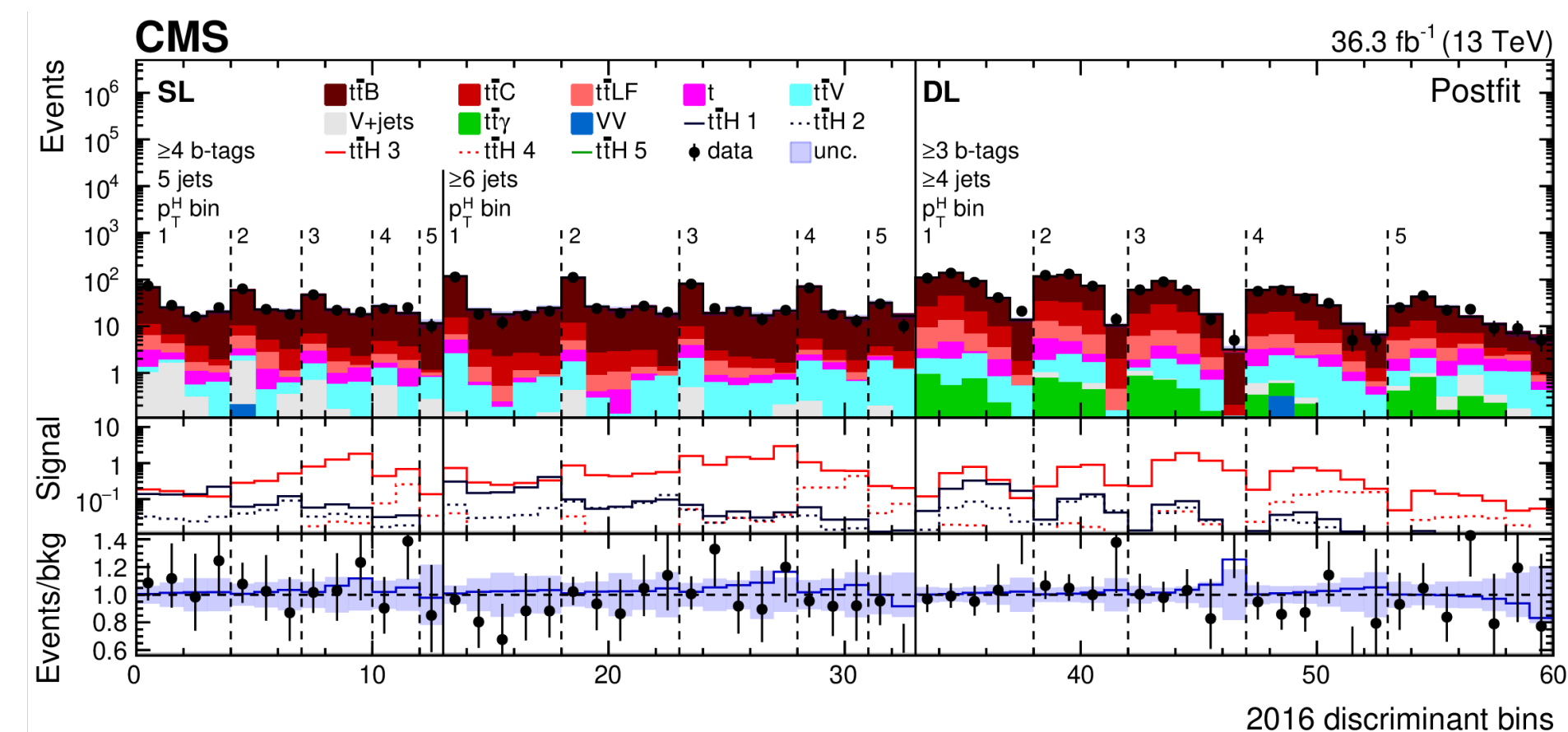
[SMP-24-003]



[SMP-24-003]

ATLAS+CMS $t\bar{t}H(bb)$

► Latest differential results:



CMS ttH(multi-leptons)

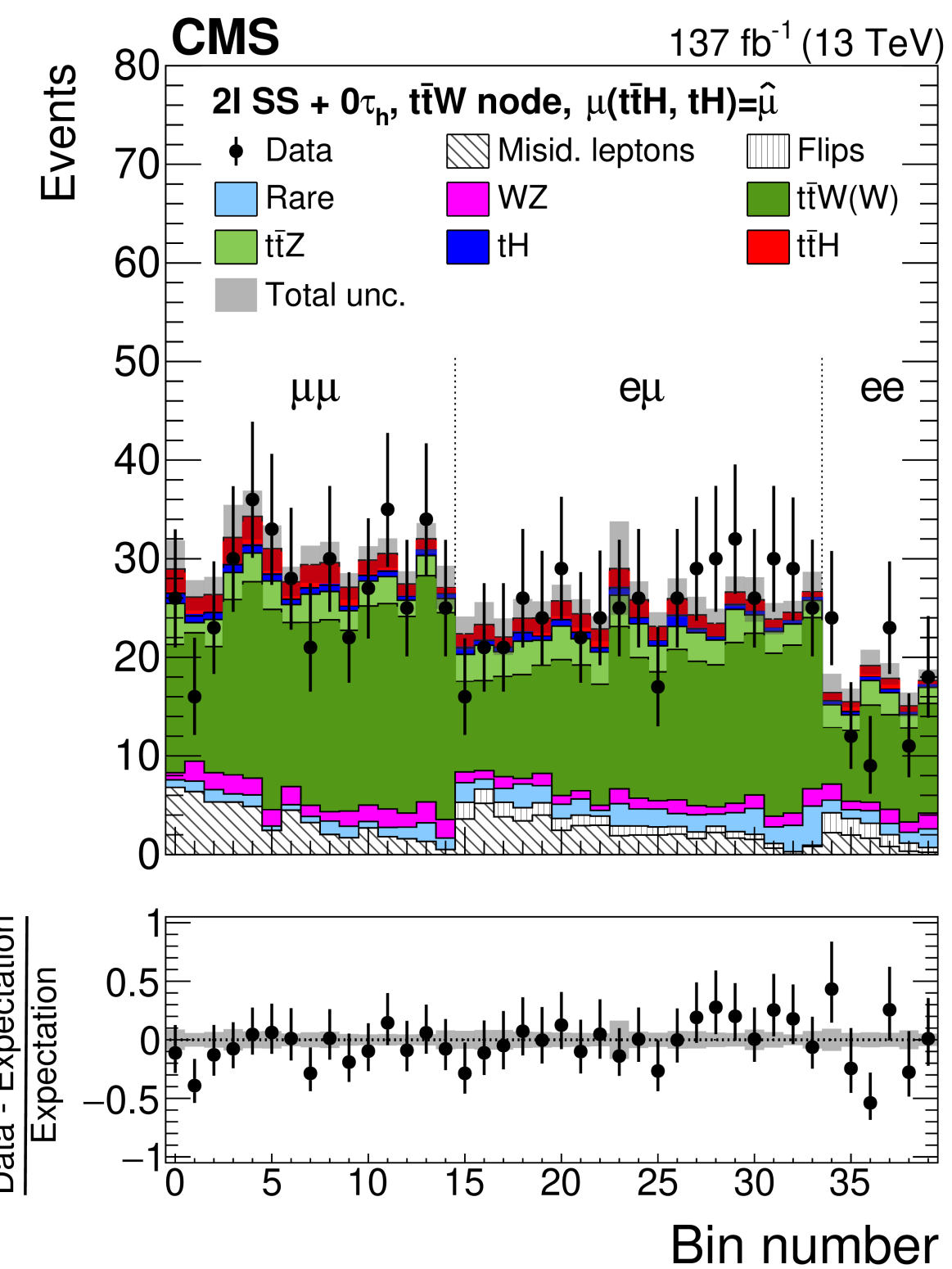
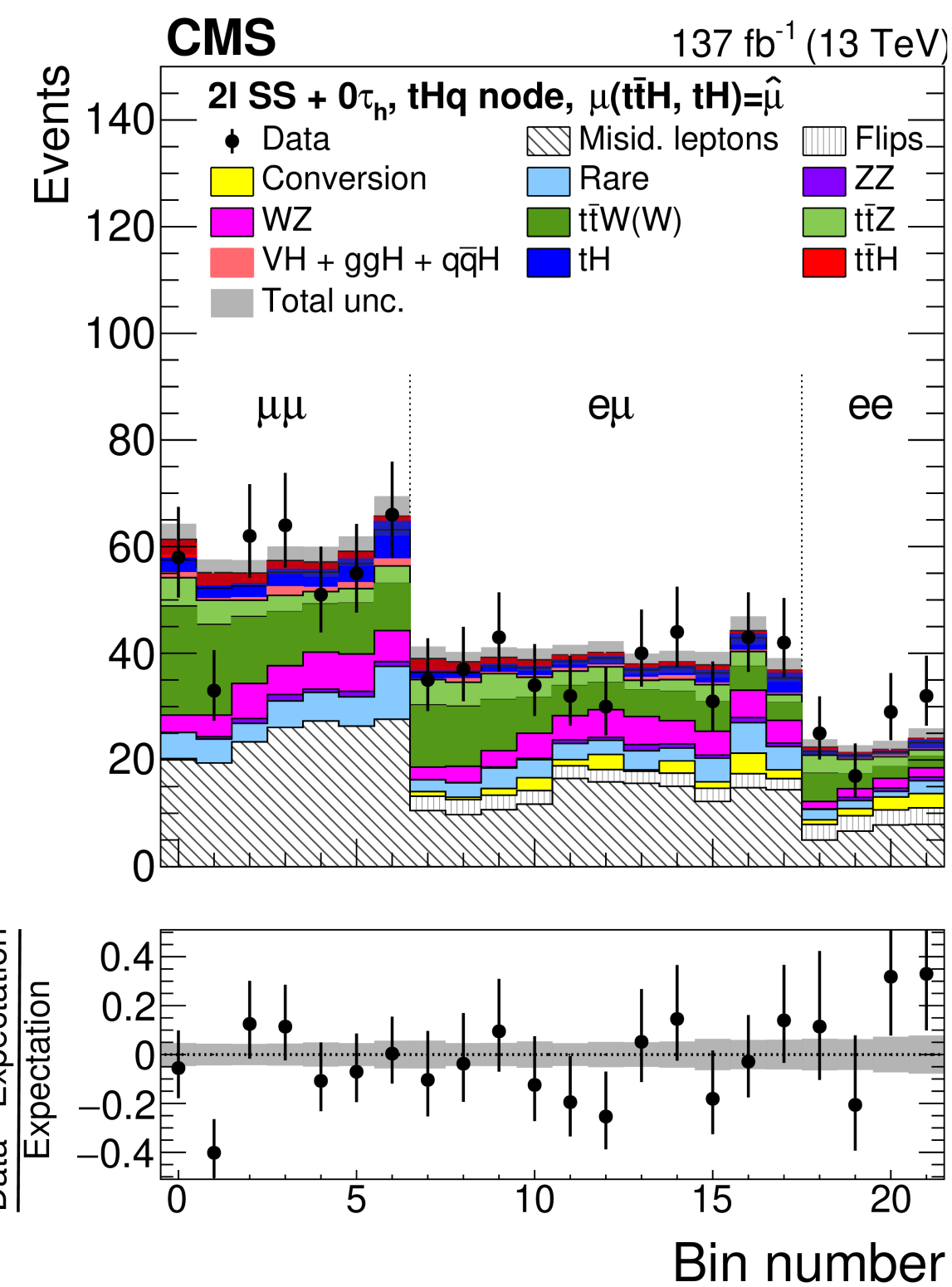
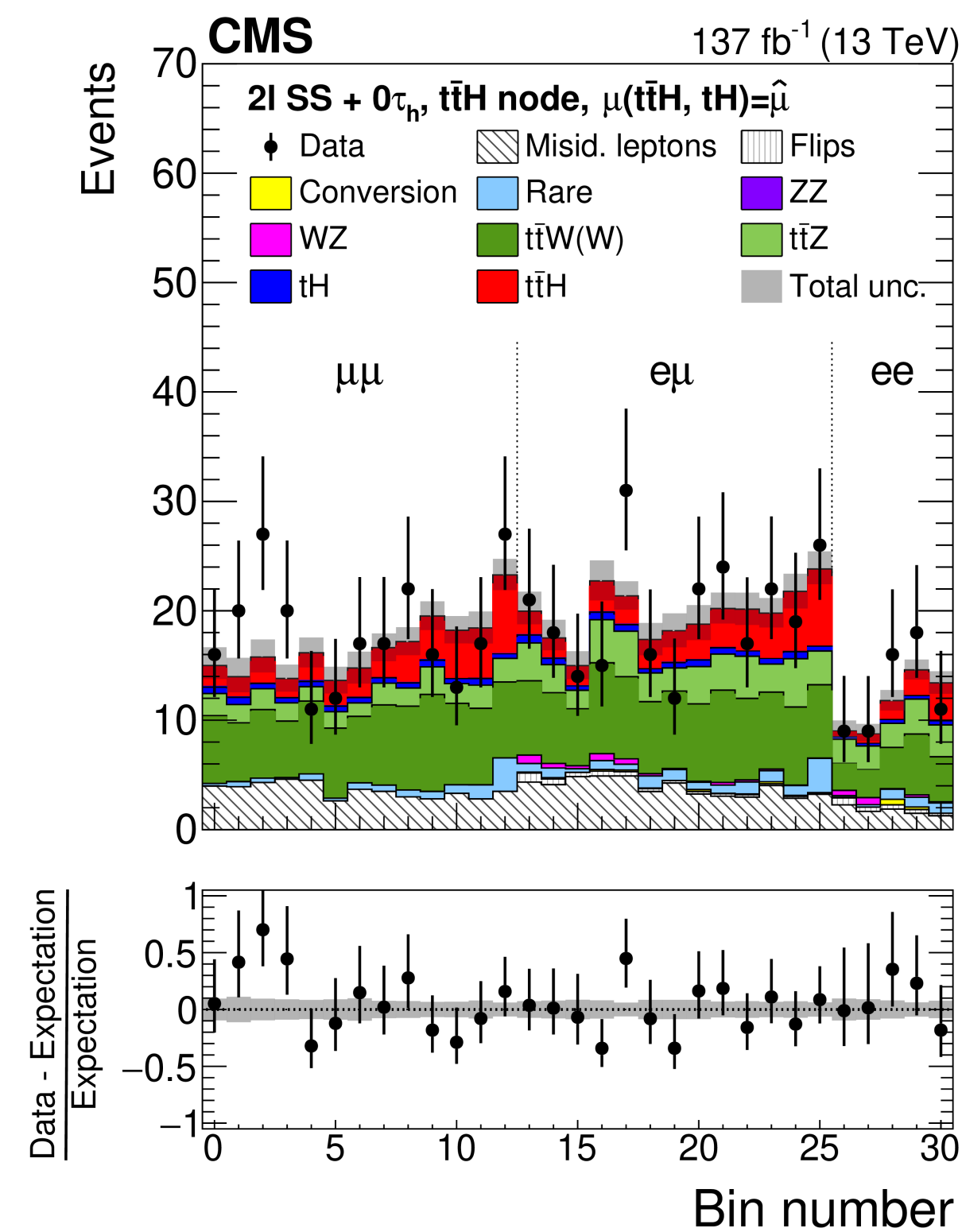
► ttH and tH production in e, μ , τ_{had} final state: Eur. Phys. J. C 81 (2021) 378

► Nice that so much is combined into a single coherent analysis:

► ttH, tH, ttW, ttZ and correlations

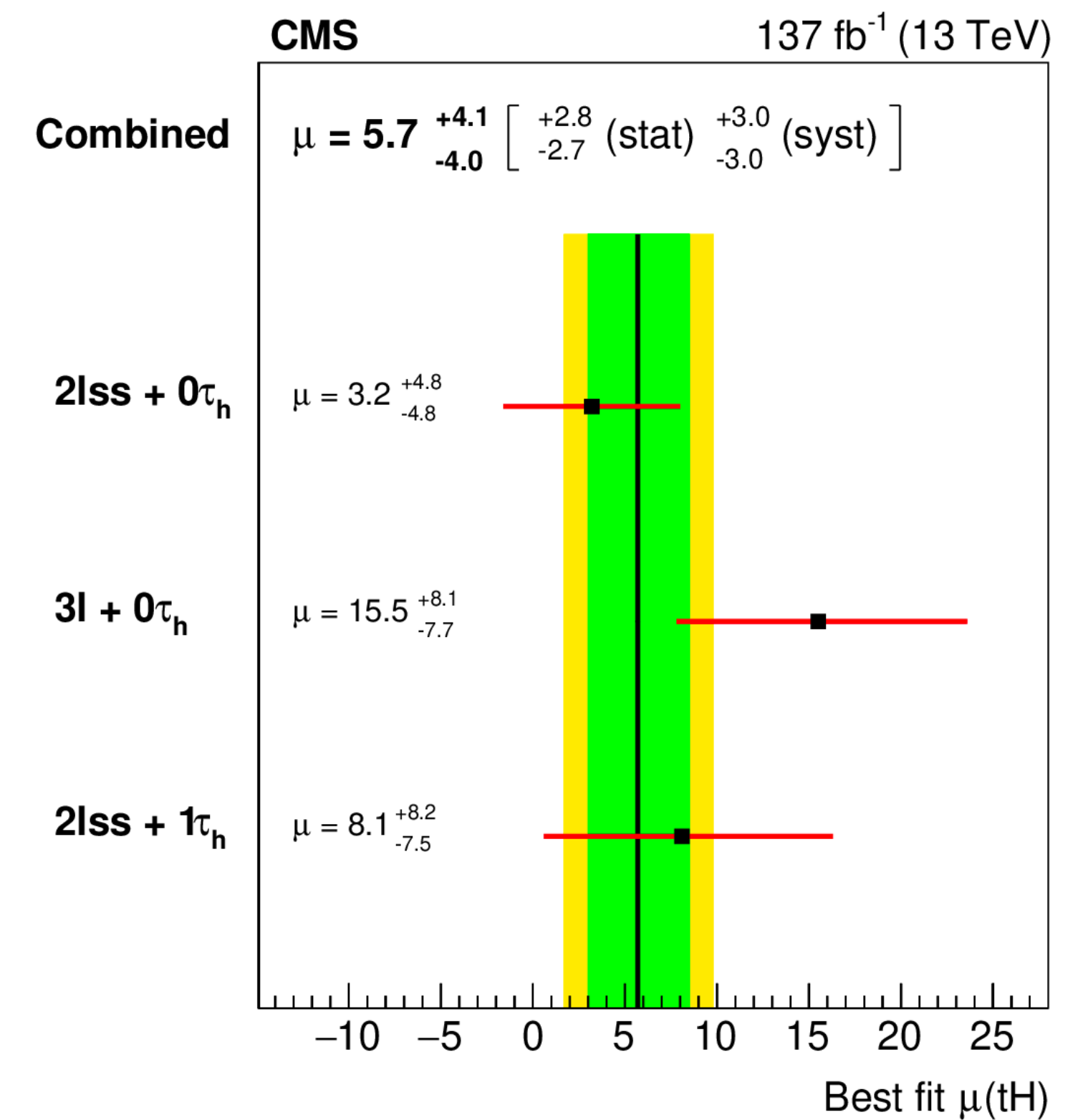
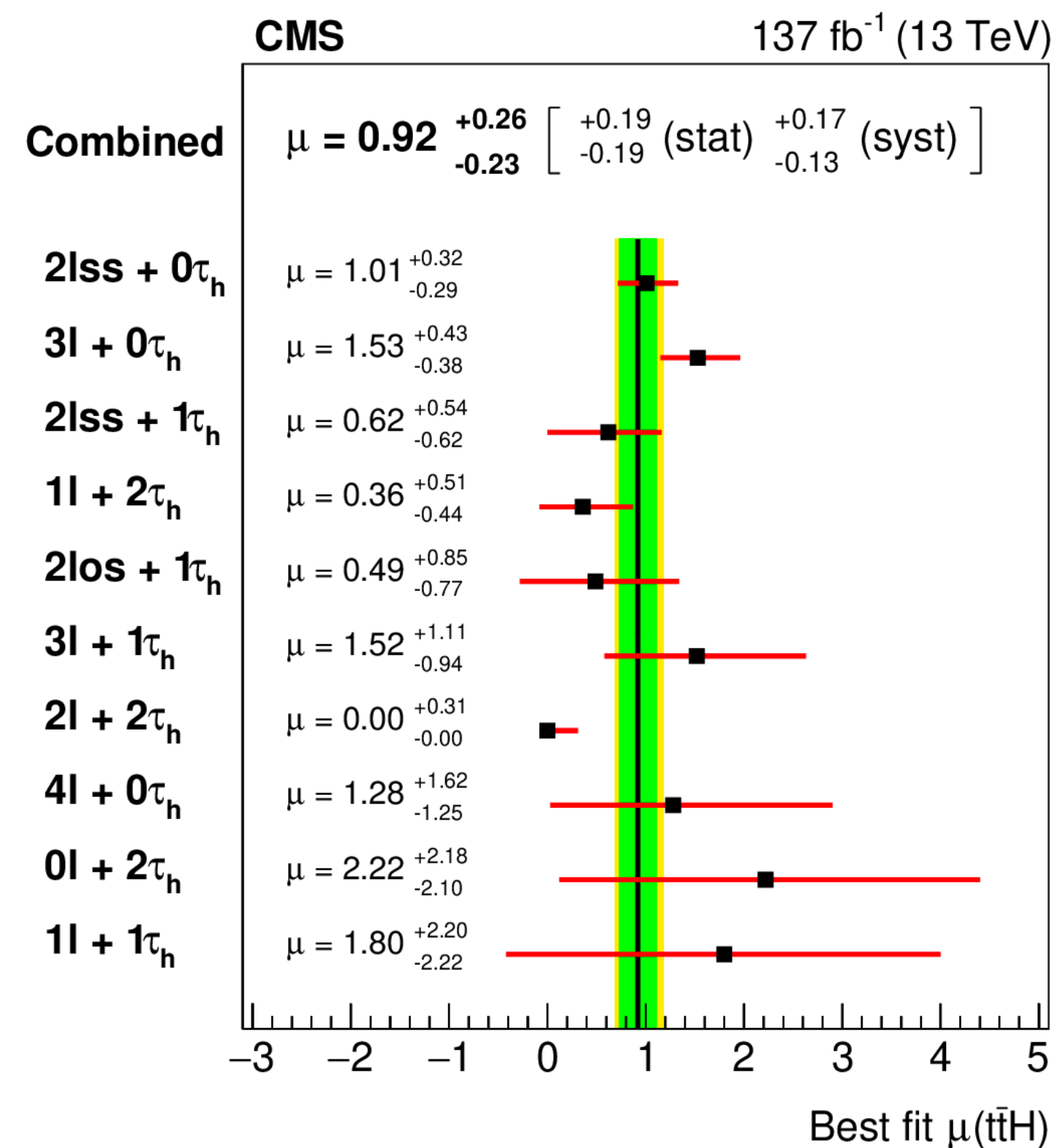
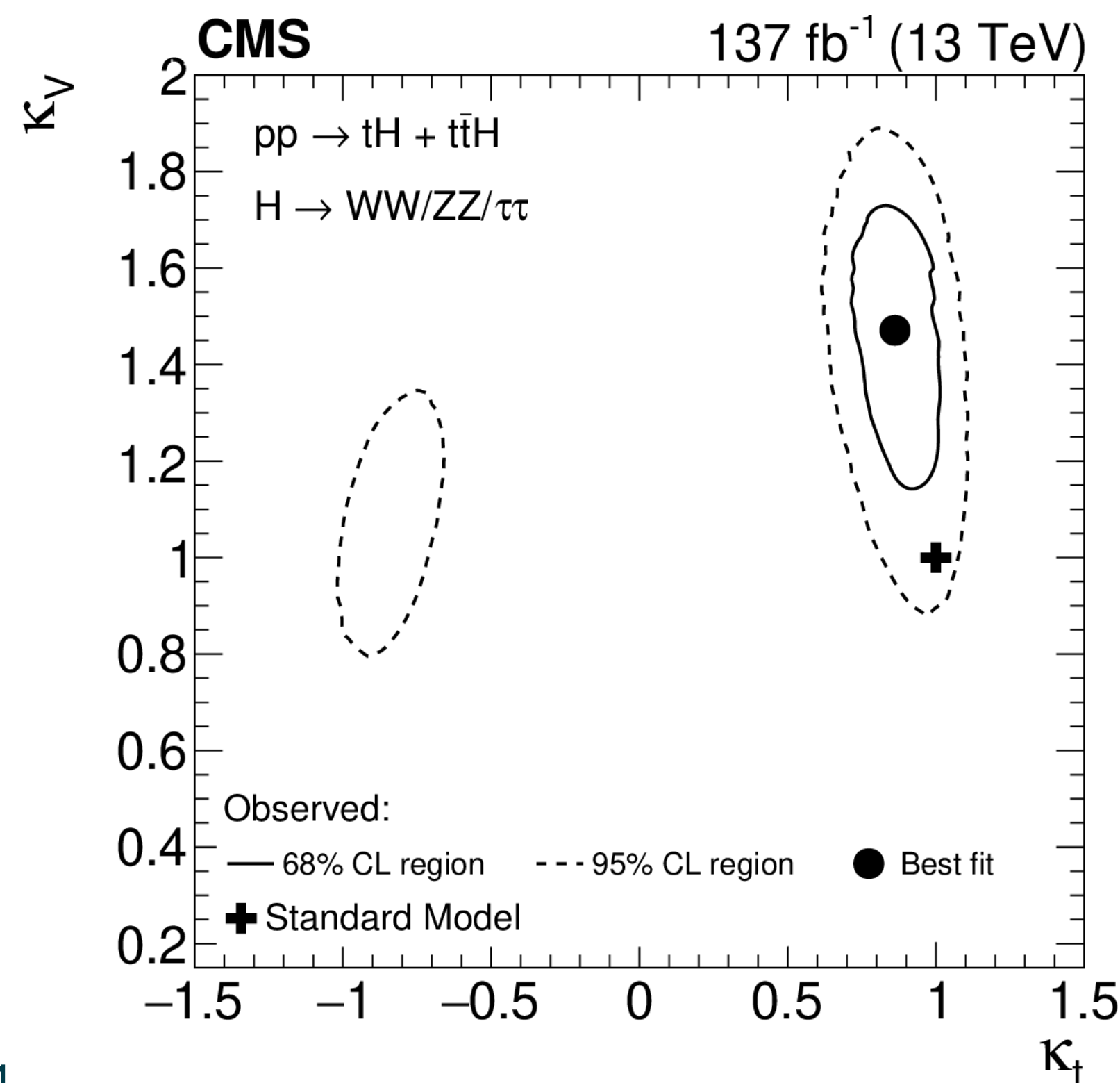
► Kappa framework

► Complex categorisation strategy



CMS $t\bar{t}H \rightarrow \text{multi-leptons}$

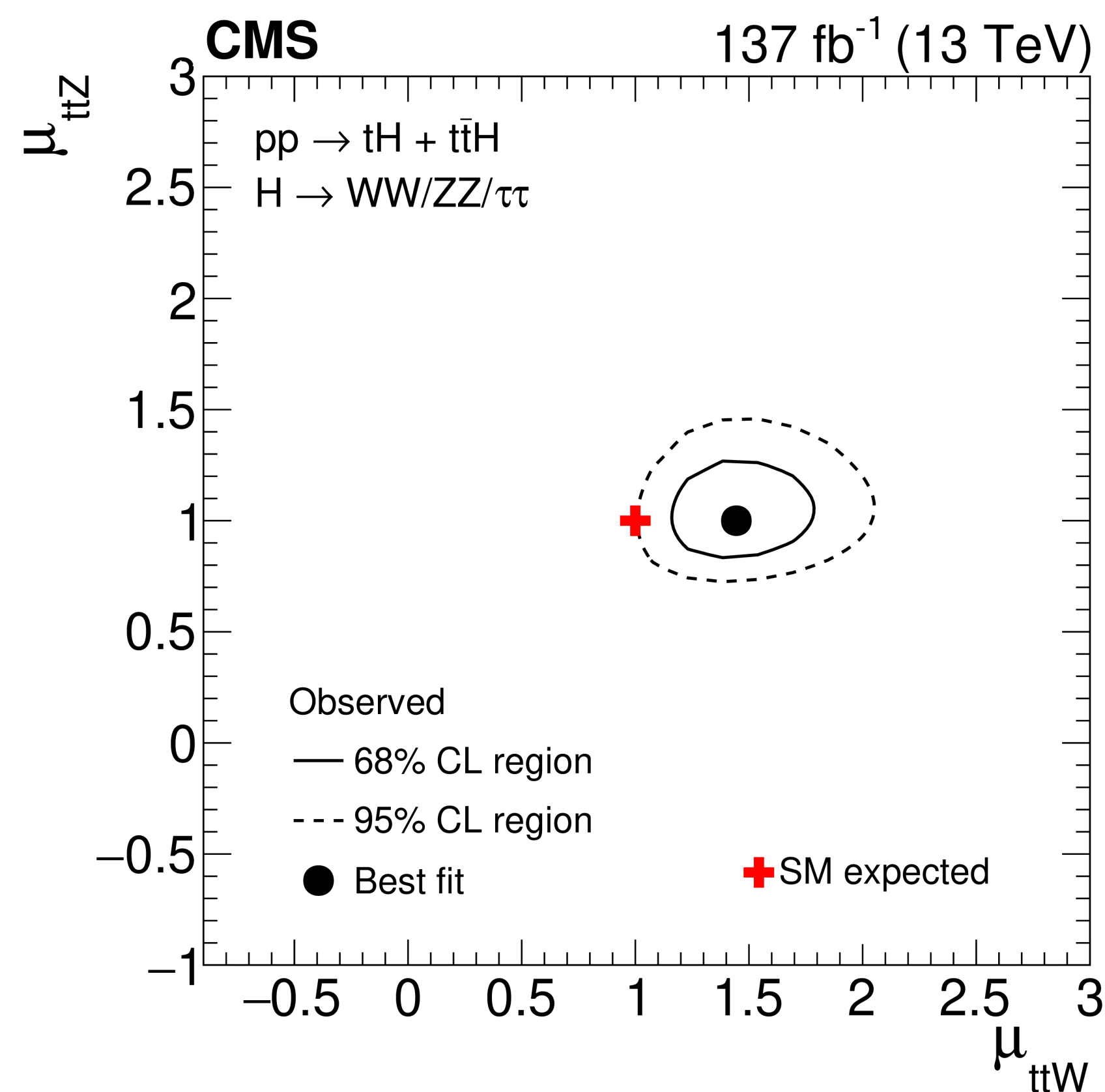
- ▶ $t\bar{t}H$ and tH production in $e, \mu, \tau_{\text{had}}$ final state: Eur. Phys. J. C 81 (2021) 378
- ▶ tH signal strength not yet very precise (as expected).
- ▶ But has some power to distinguish sign of κ_t .





CMS $ttH \rightarrow$ multi-leptons

- ▶ ttH and tH production in $e, \mu, \tau_{\text{had}}$ final state: Eur. Phys. J. C 81 (2021) 378
- ▶ ttW extraction very important for analysis sensitivity
- ▶ Fitted ttW normalisation higher than SM prediction

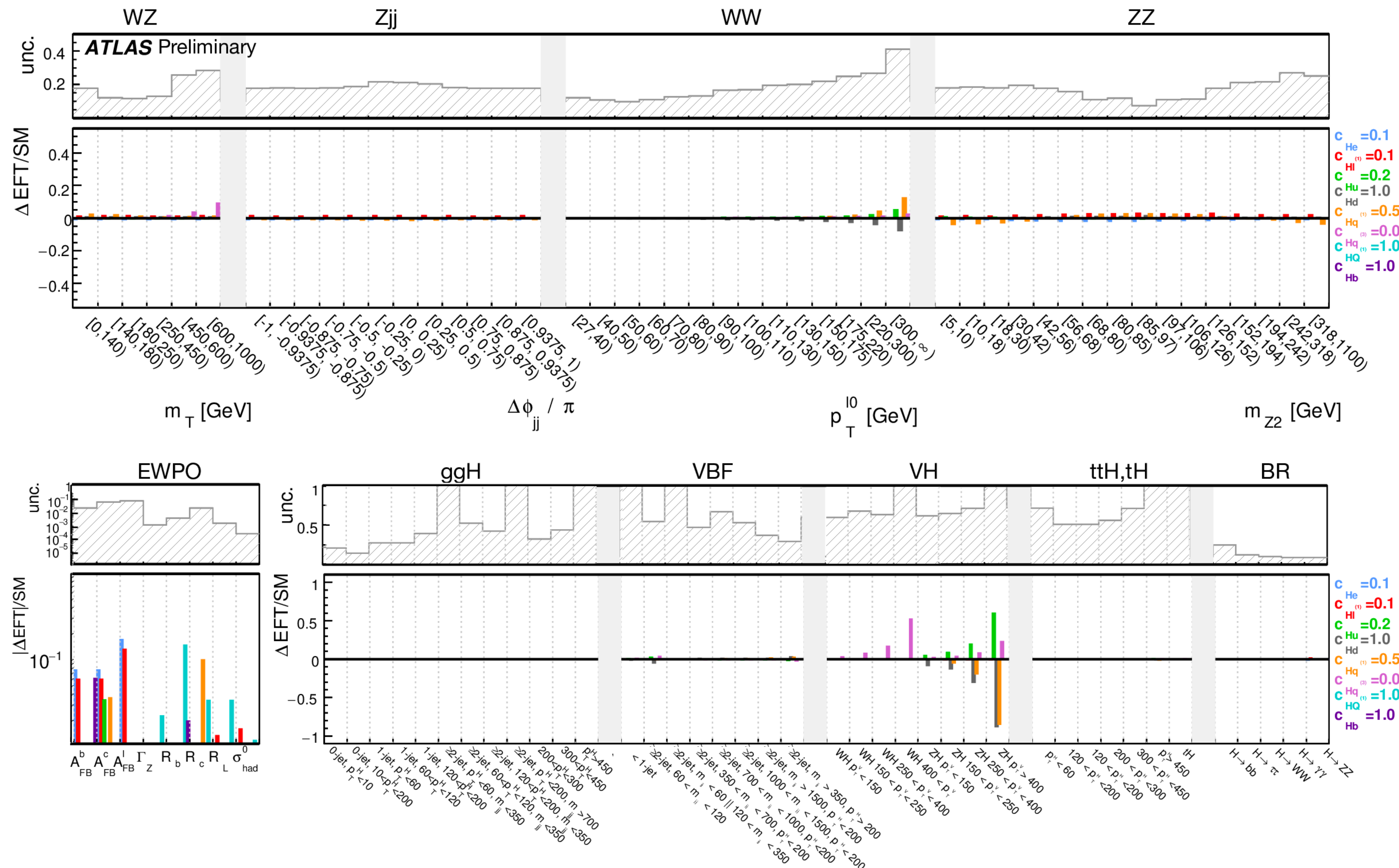


Source	$\Delta\mu_{t\bar{t}H}/\mu_{t\bar{t}H}$ [%]	$\Delta\mu_{tH}/\mu_{tH}$ [%]	$\Delta\mu_{t\bar{t}W}/\mu_{t\bar{t}W}$ [%]	$\Delta\mu_{t\bar{t}Z}/\mu_{t\bar{t}Z}$ [%]
Trigger efficiency	2.3	8.1	1.2	1.9
e, μ reconstruction and identification efficiency	2.9	7.1	1.7	3.2
τ_h identification efficiency	4.6	9.1	1.7	1.3
b tagging efficiency and mistag rate	3.6	13.6	1.3	2.9
Misidentified leptons and flips	6.0	36.8	2.6	1.4
Jet energy scale and resolution	3.4	8.3	1.1	1.2
MC sample and sideband statistical uncertainty	7.1	27.2	2.4	2.3
Theory-related sources affecting acceptance and shape of distributions	4.6	18.2	2.0	4.2
Normalization of MC-estimated processes	13.3	12.3	13.9	11.3
Integrated luminosity	2.2	4.6	1.8	3.1
Statistical uncertainty	20.9	48.0	5.9	5.8

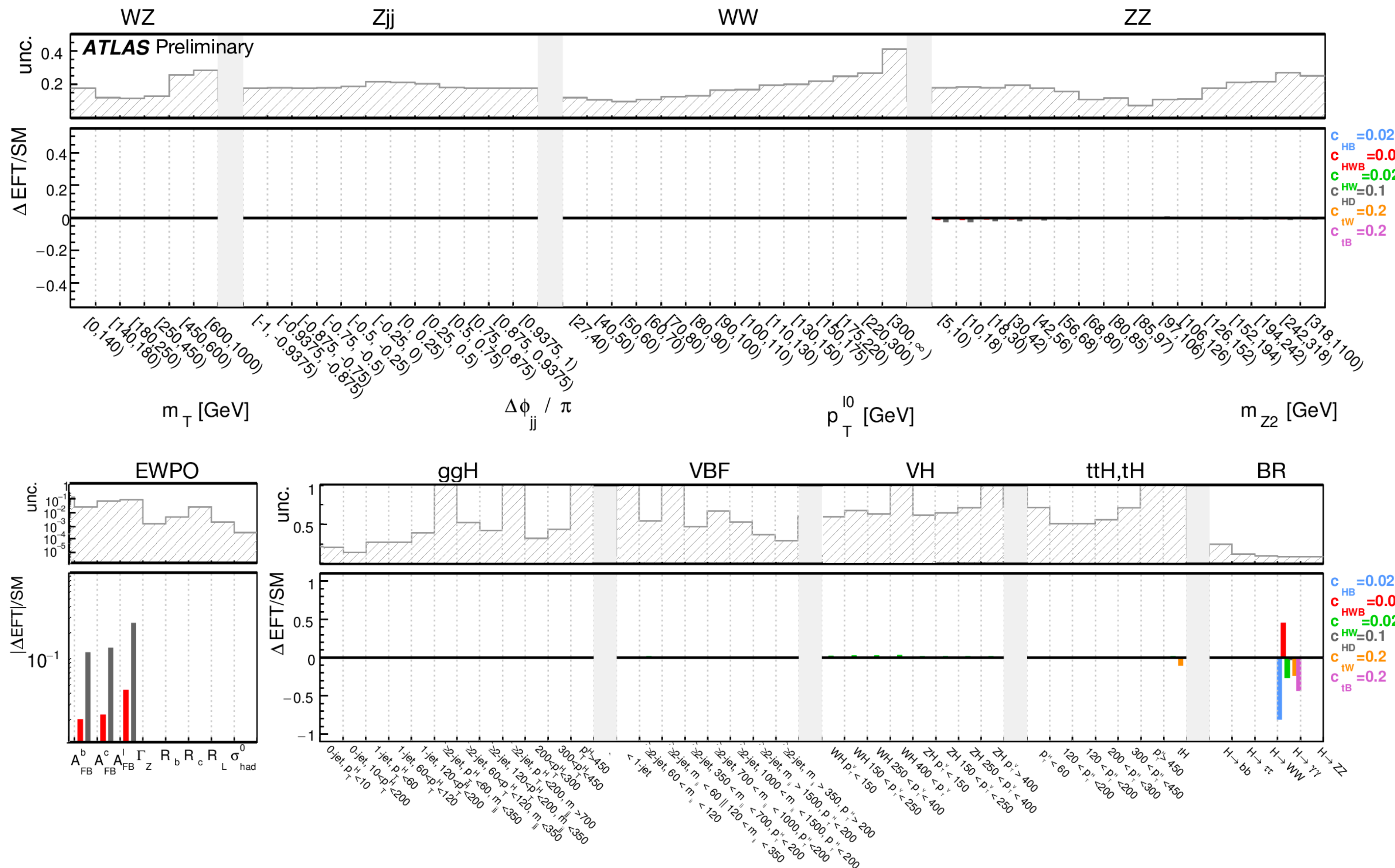
ATLAS Global EFT



- Sensitivity to numerous EFT operators
- Complementarity between different observables



- Sensitivity to numerous EFT operators
- Complementarity between different observables



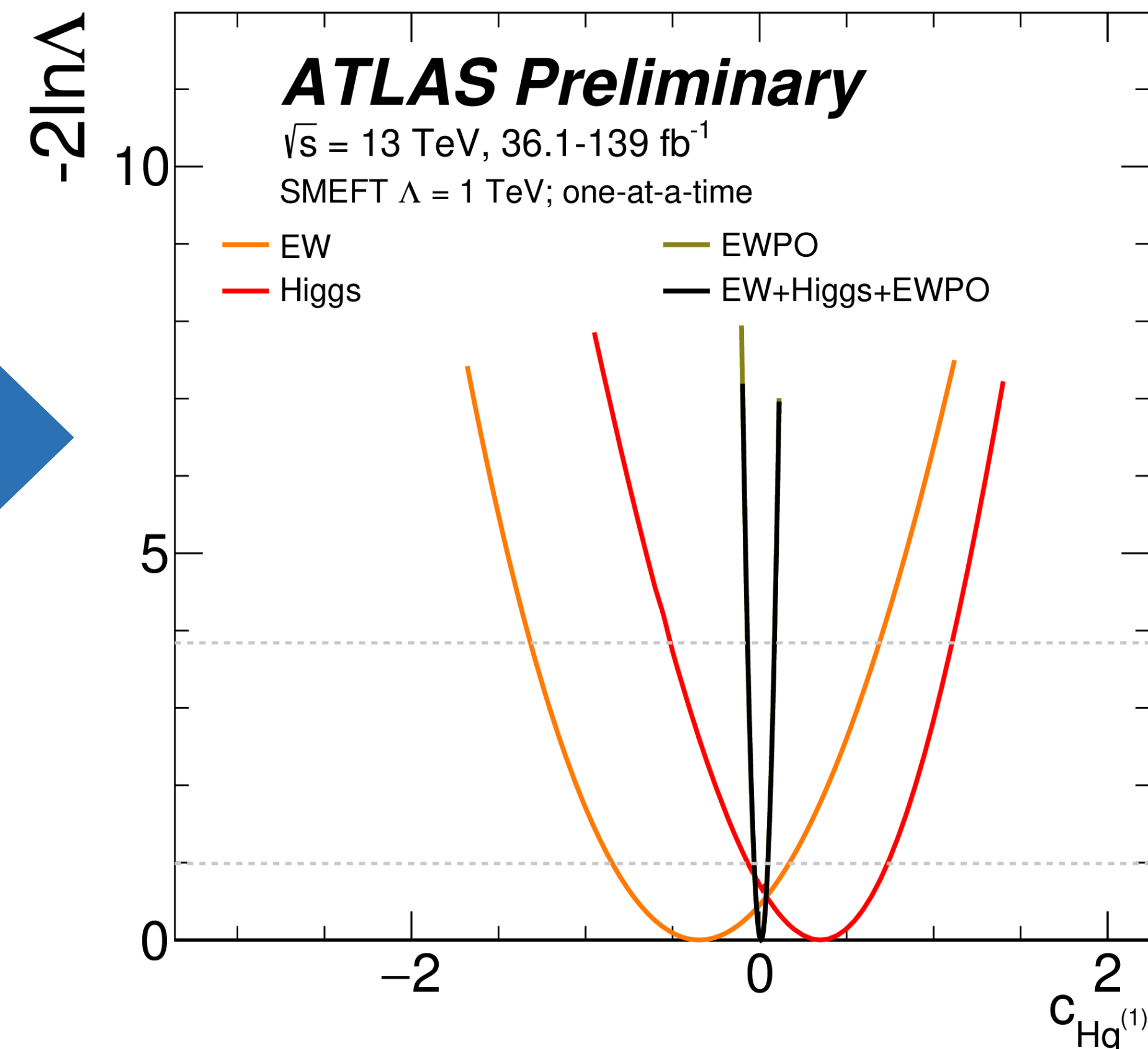
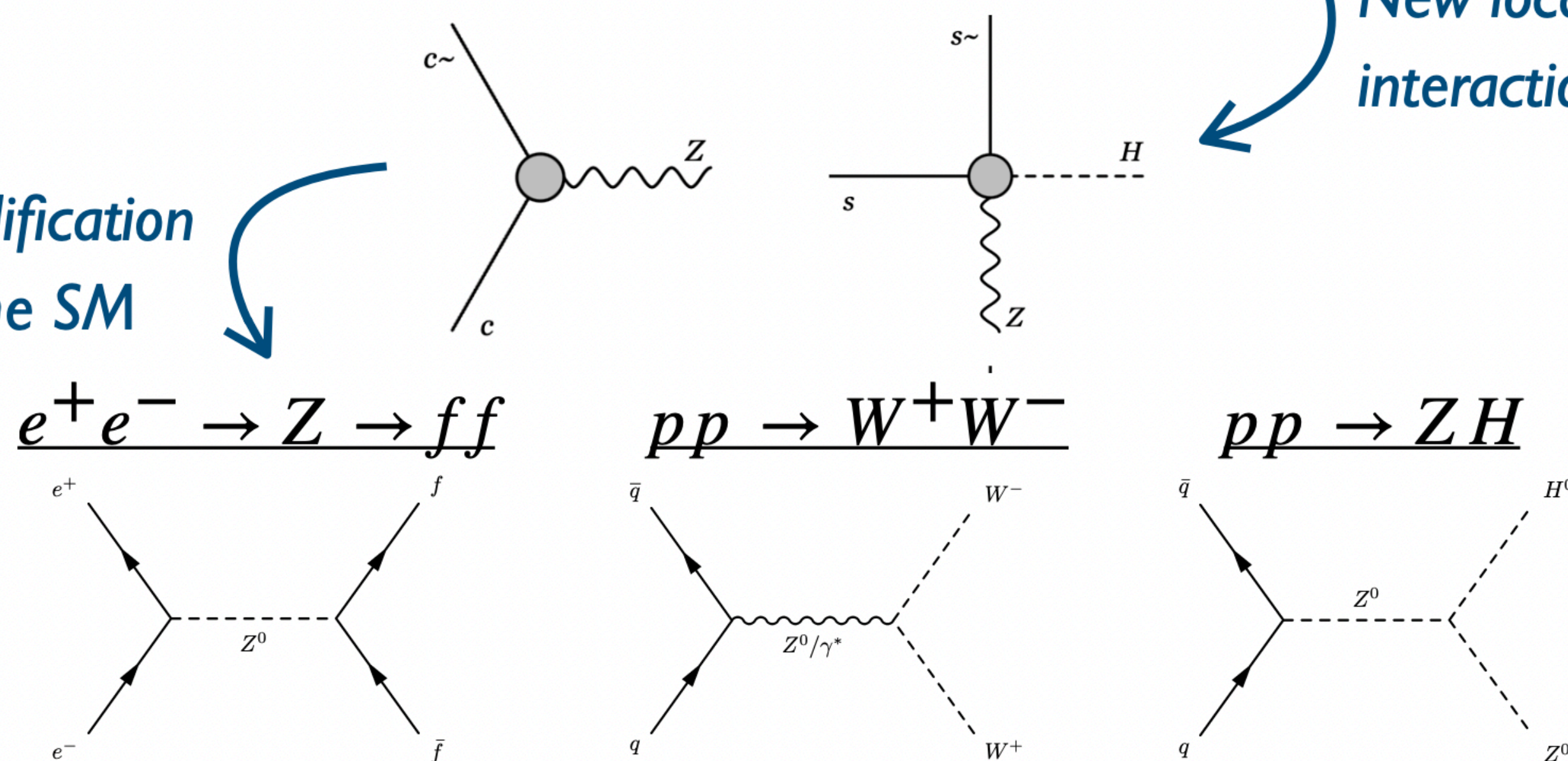
► Single operator fits used to assess impact of different datasets

► For example O_{Hq} :

$$Q_{Hq}^{(1)} = (H^\dagger i \overleftrightarrow{D}_\mu^i H) (\bar{q}_p \gamma^\mu q_r)$$

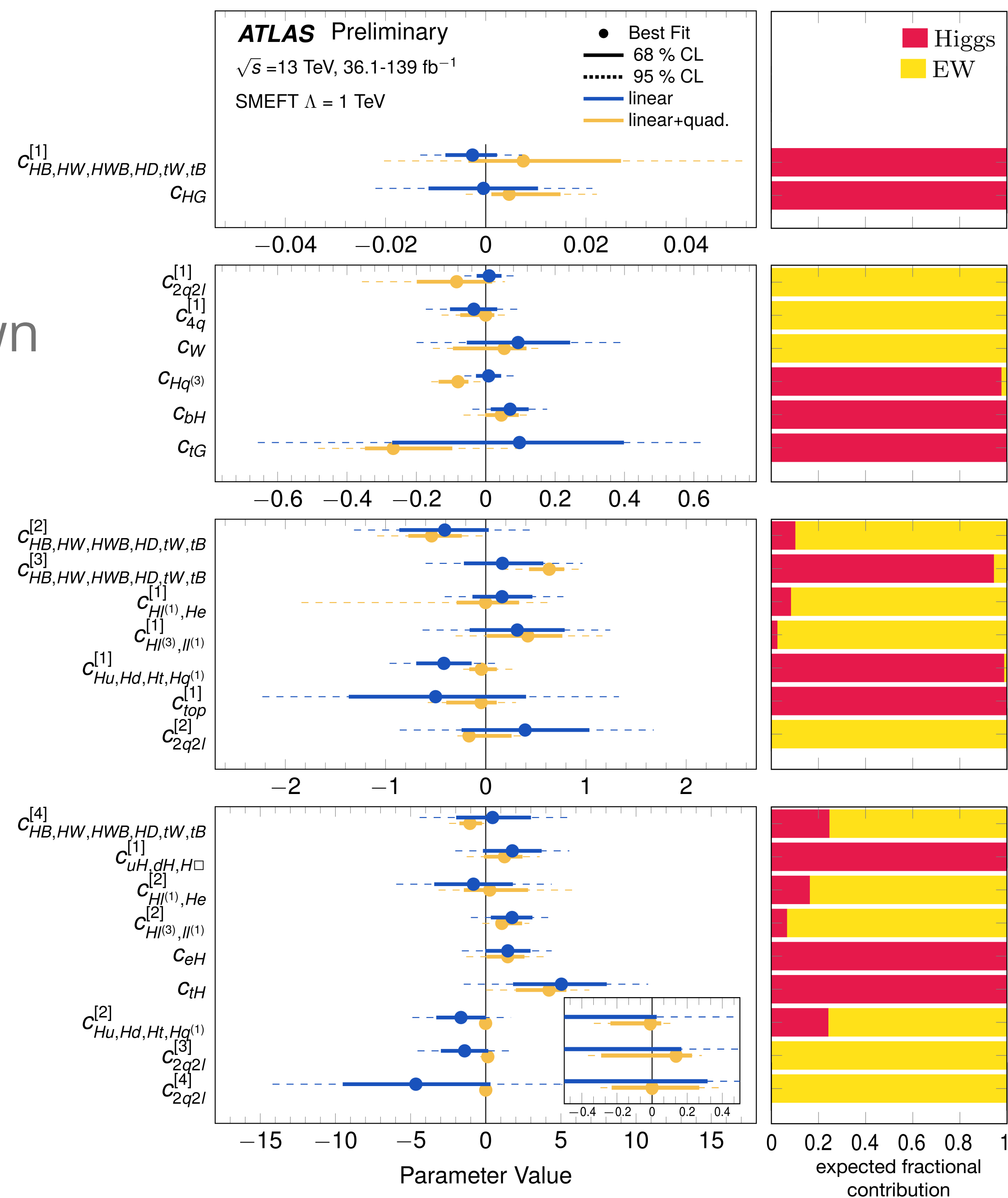
New local interactions

Modification to the SM



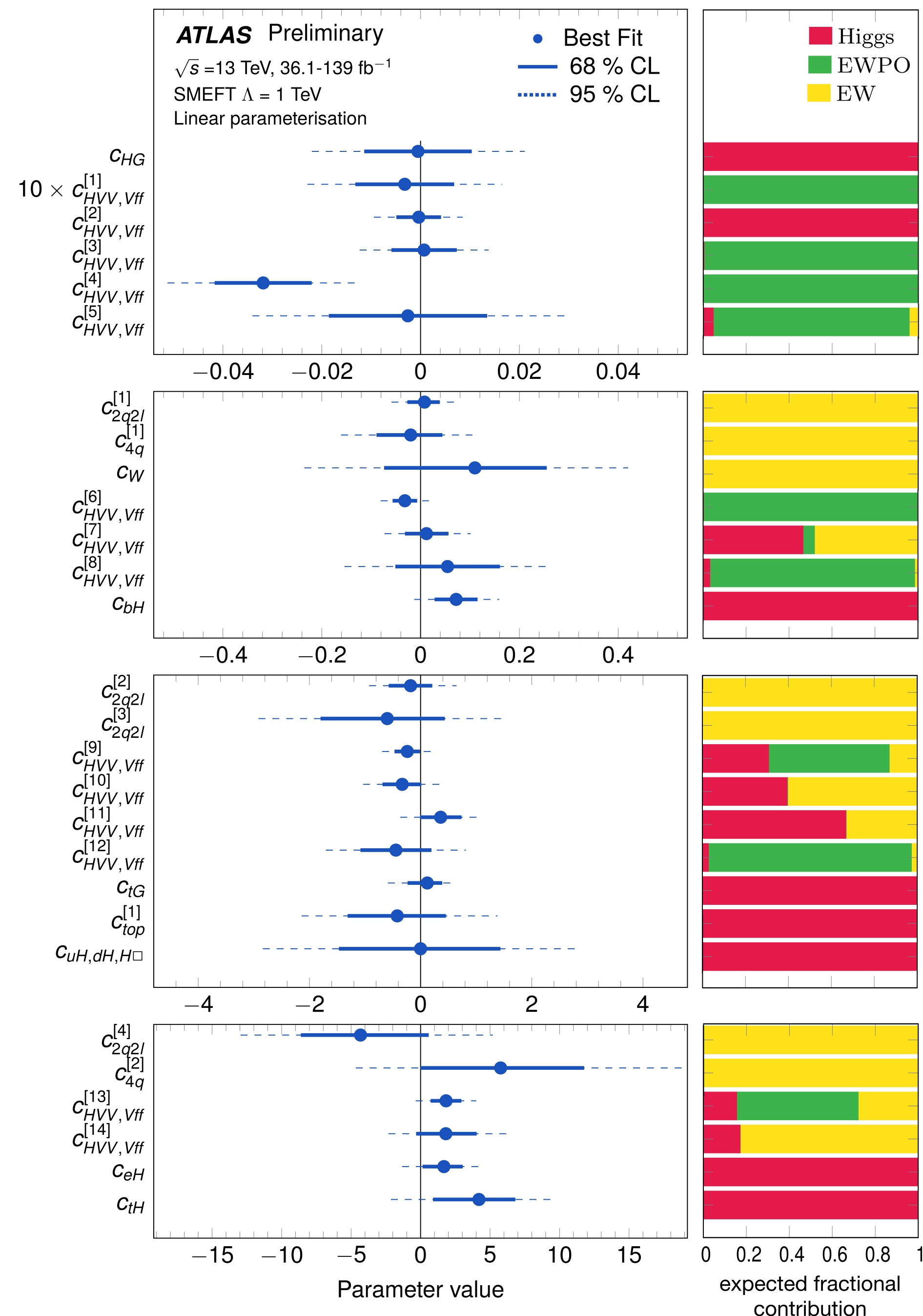
ATLAS Global EFT fit

- ▶ Start by looking at Higgs+EW fit
- ▶ Linear and quadratic parameterisations
- ▶ Expected contribution to sensitivity shown



ATLAS Global EFT fit

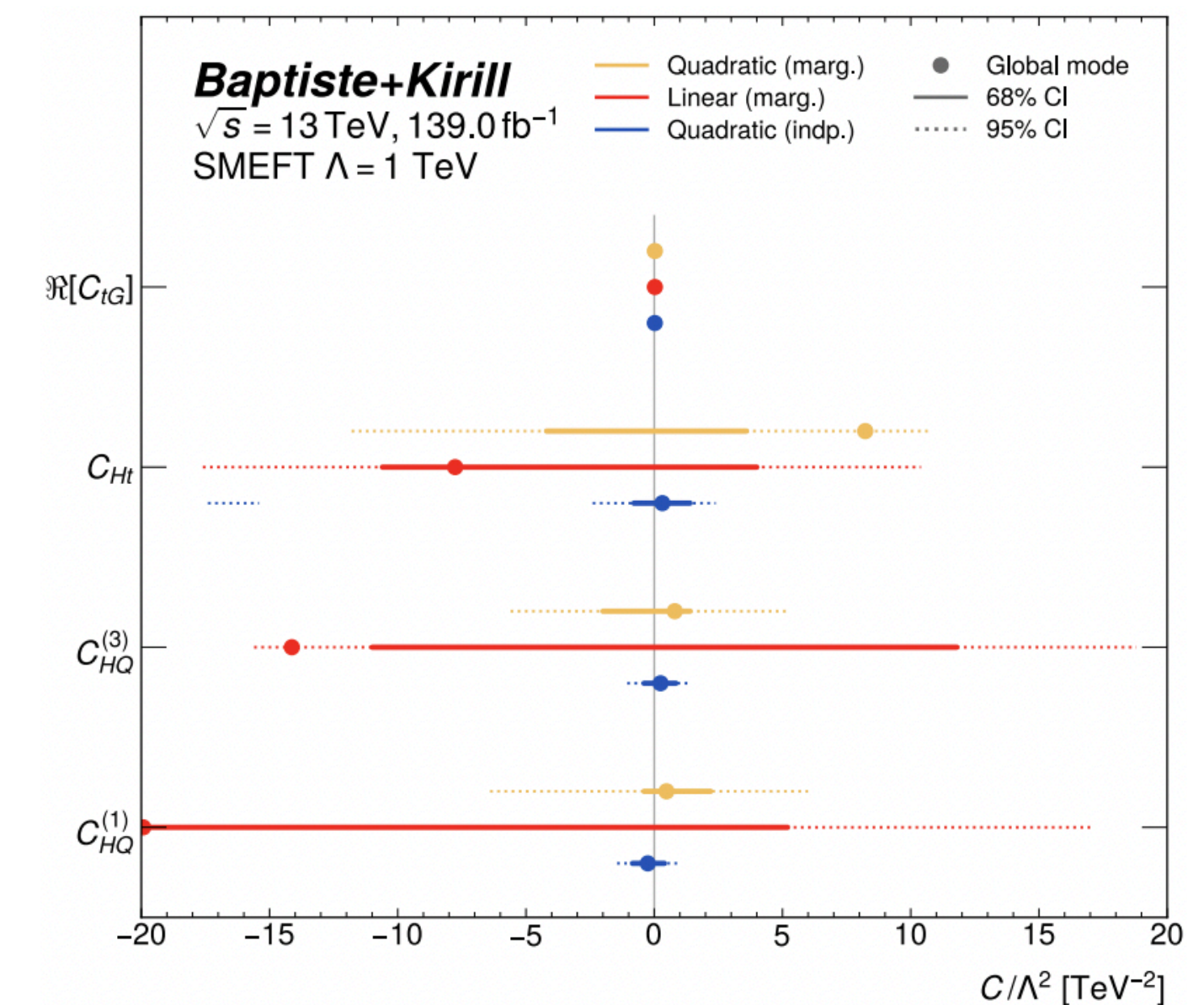
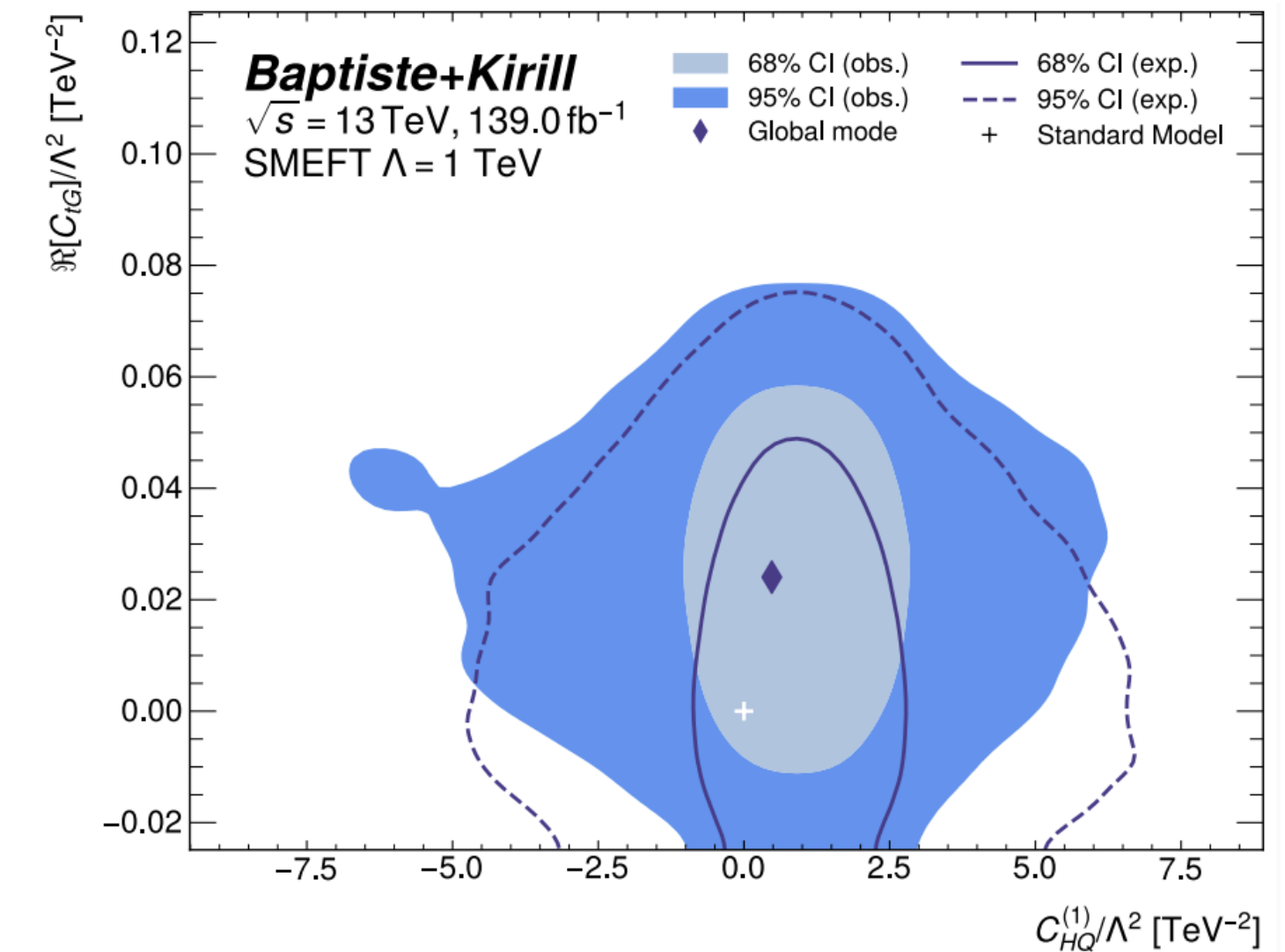
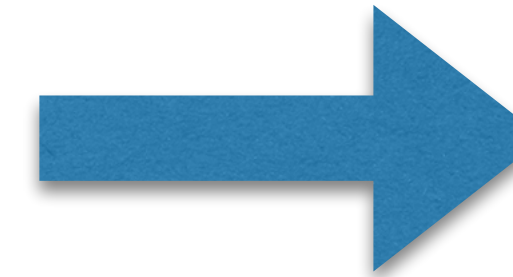
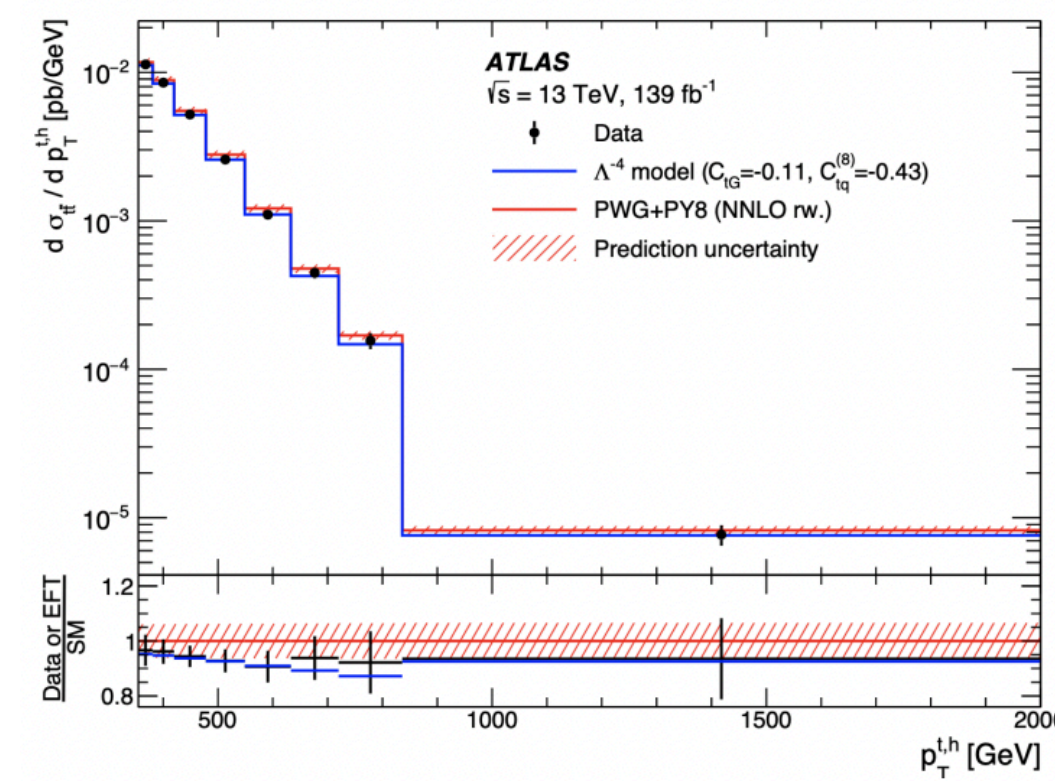
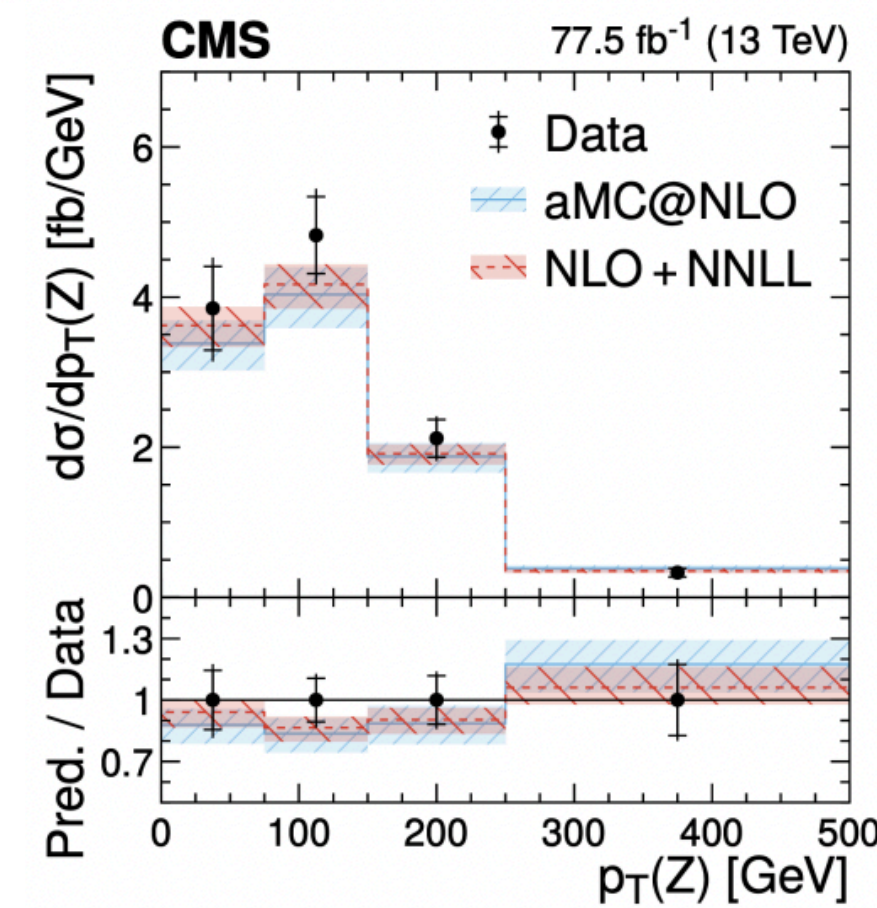
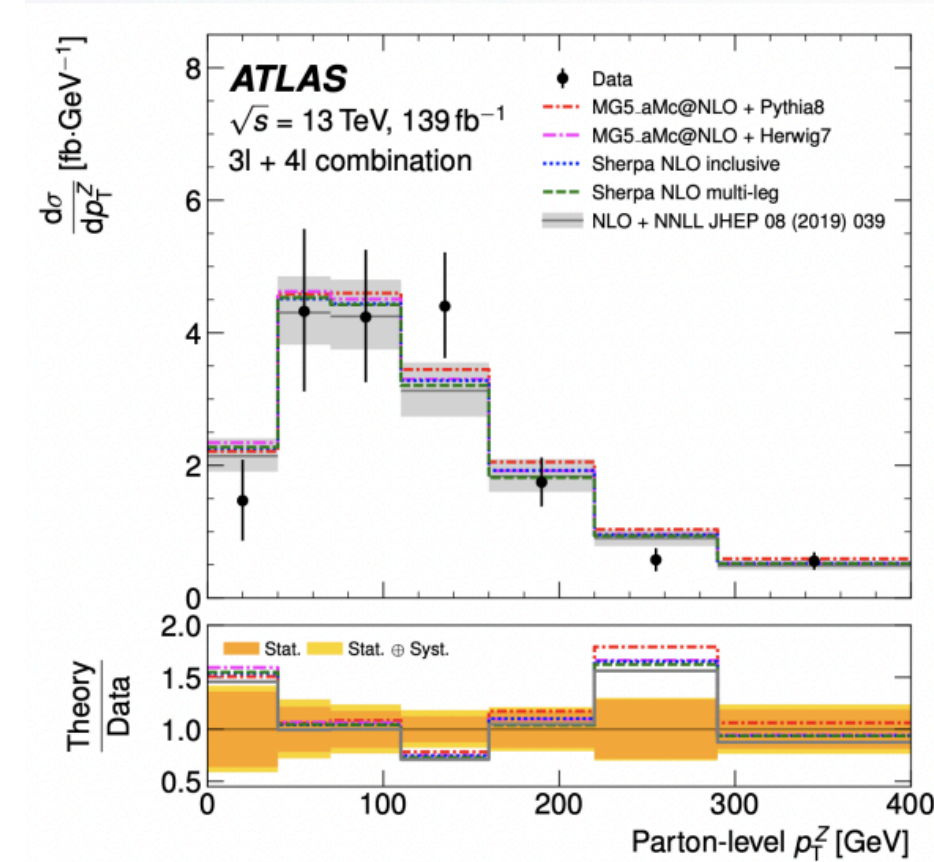
- ▶ Start by looking at Higgs+EW fit
 - ▶ Linear and quadratic parameterisations
 - ▶ Expected contribution to sensitivity shown
- ▶ Full fit to EWPO+EW+Higgs
 - ▶ Results largely compatible with SM
 - ▶ σ^0_{had} , $H \rightarrow \gamma\gamma$, Γ_Z , A_{fb} , and $gg \rightarrow H$ giving largest constraints
 - ▶ In some cases significant constraints come EWPD with important contributions from VH, VBF Higgs and VV production
 - ▶ Contributions of the Higgs and EW measurements expected to become more important with larger datasets



LHC Top WG efforts

► ATLAS+CMS combination of top measurements and EFT interpretation

► Using unfolded data:

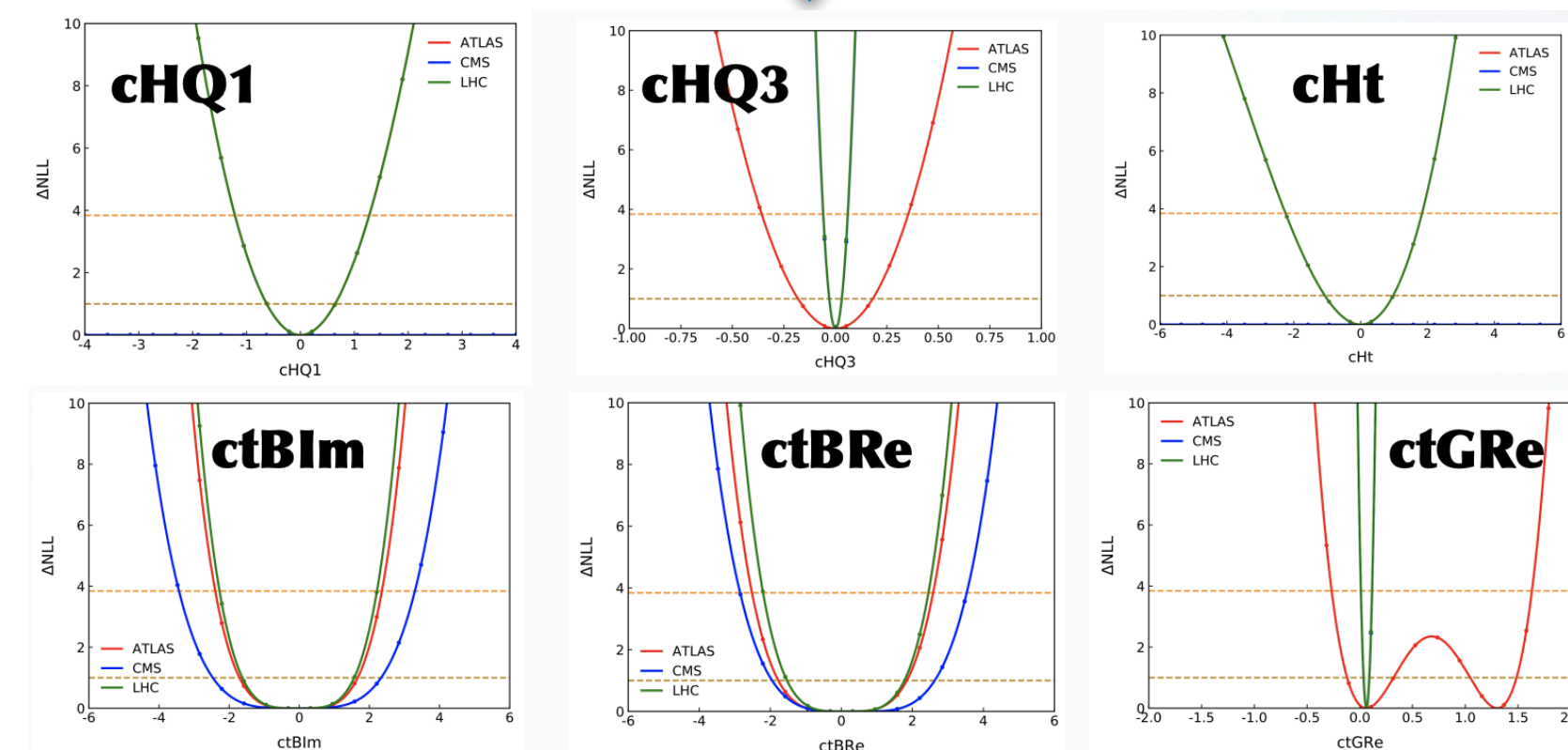
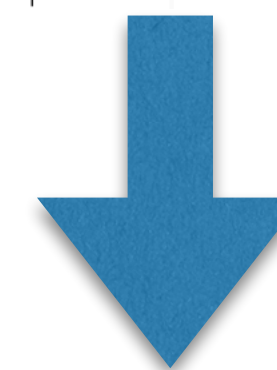
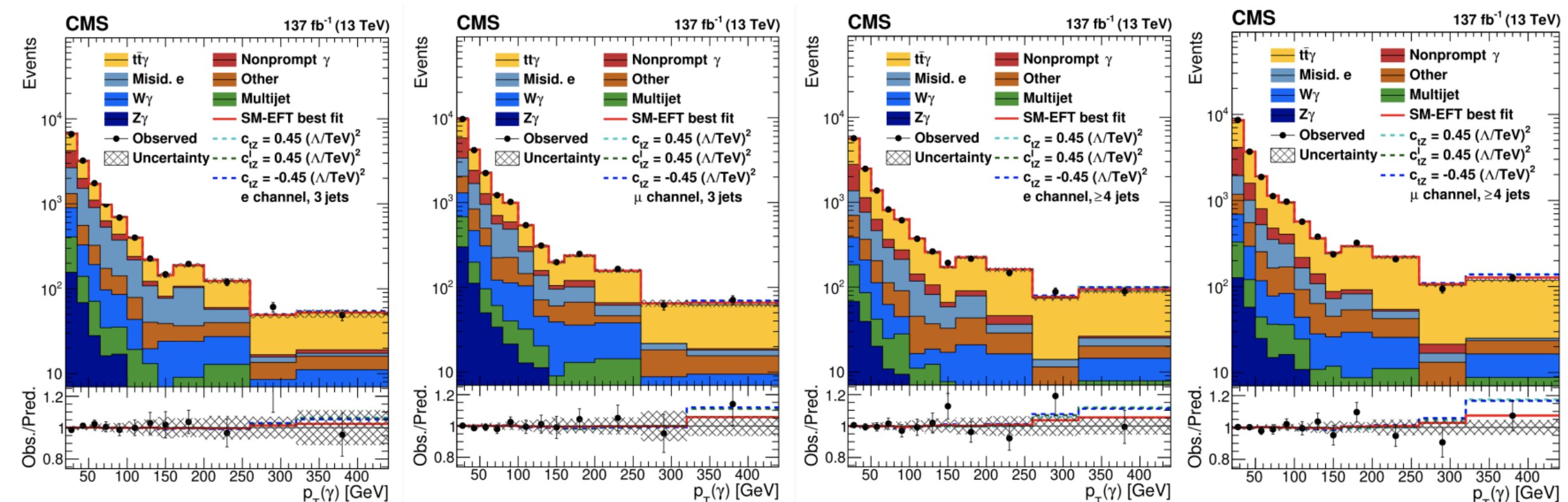
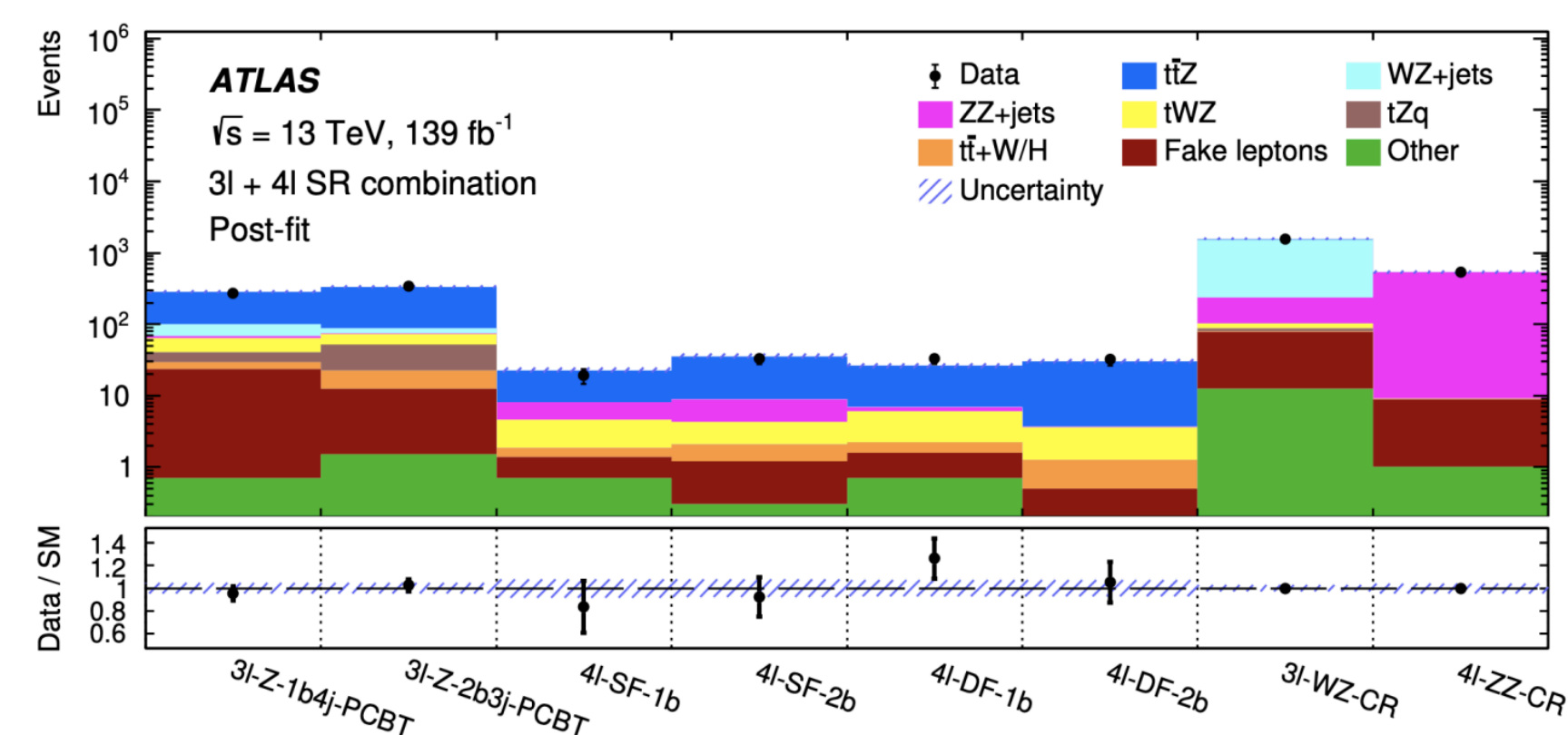


LHC Top WG efforts

► ATLAS+CMS combination
of top measurements and
EFT interpretation

► Using unfolded data

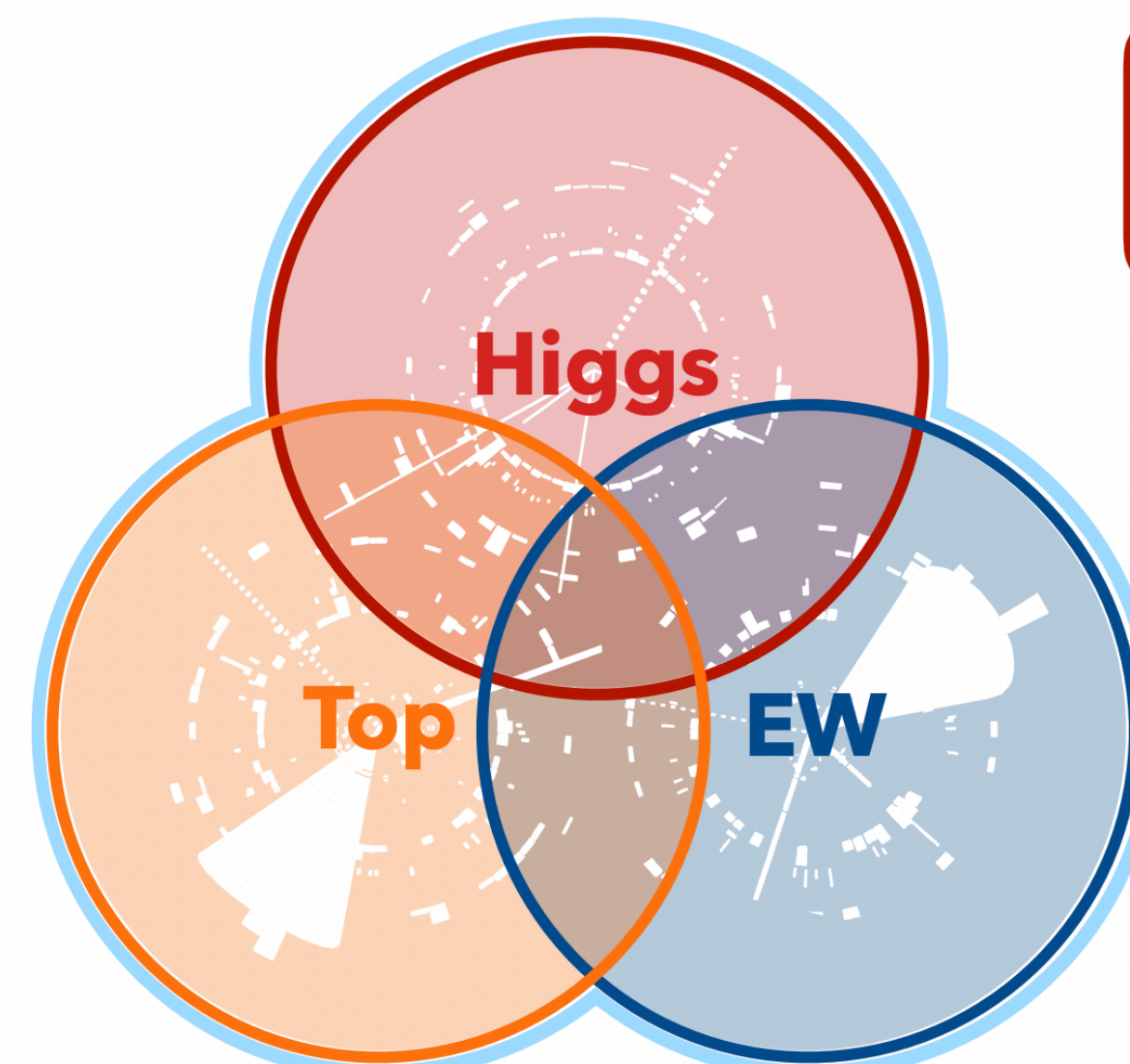
► Using reconstruction-level
information:



► LHC EFT WG already starting work on wider fits

- WG to provide EFT recommendations
- Currently looking at ATLAS+CMS fitting exercise (latest update [here](#))
- Includes Top data!

Single Top (t-channel)



$H \rightarrow \gamma\gamma$
 $H \rightarrow \gamma\gamma + H \rightarrow ZZ^* \rightarrow 4l$
 $+ VH, H \rightarrow b\bar{b}$

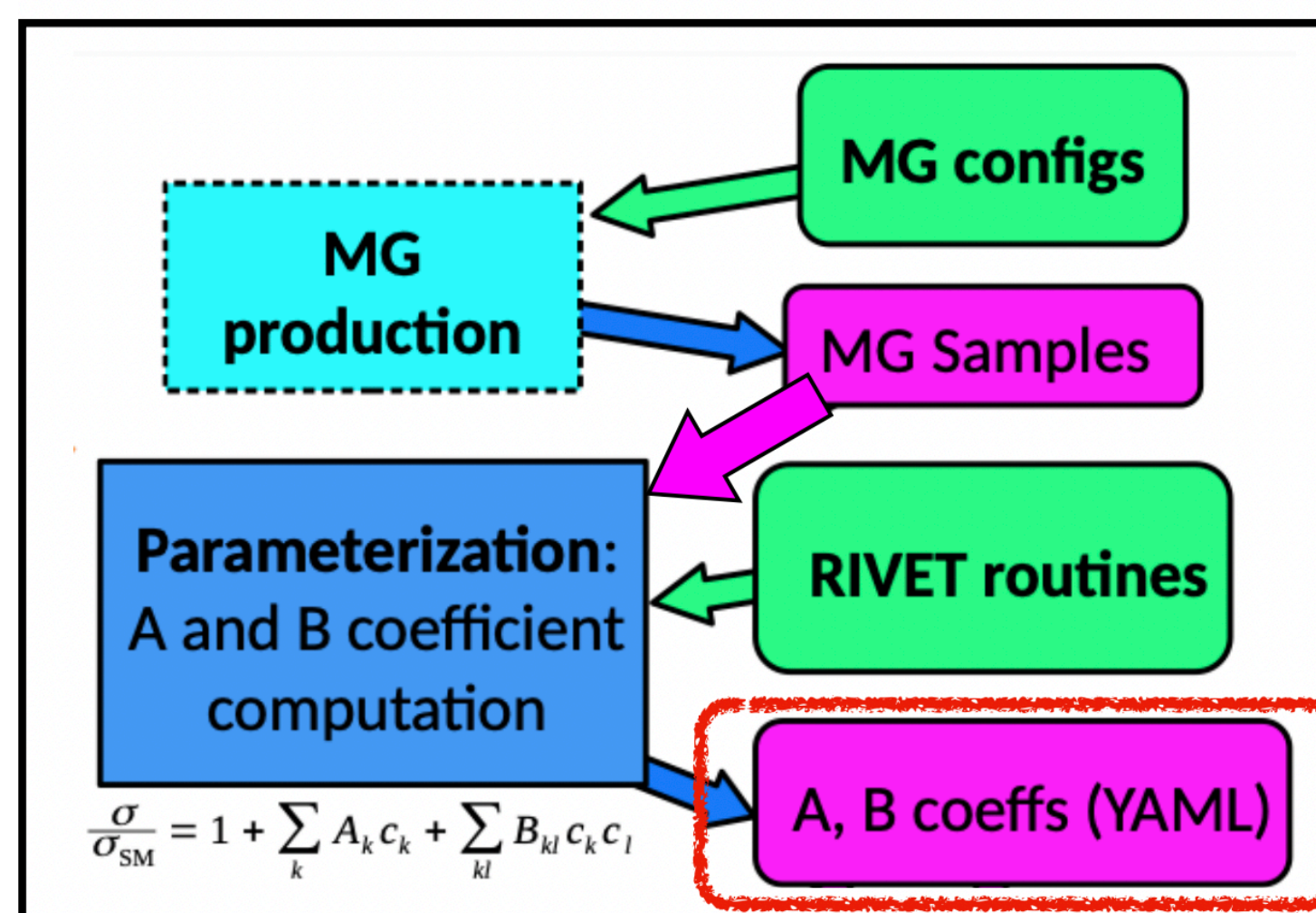
$W\gamma$ production
 WW production
 WZ production
 EW Zjj production
 EWPO - Zpole data

Sketch inspired from Ken Mimasu

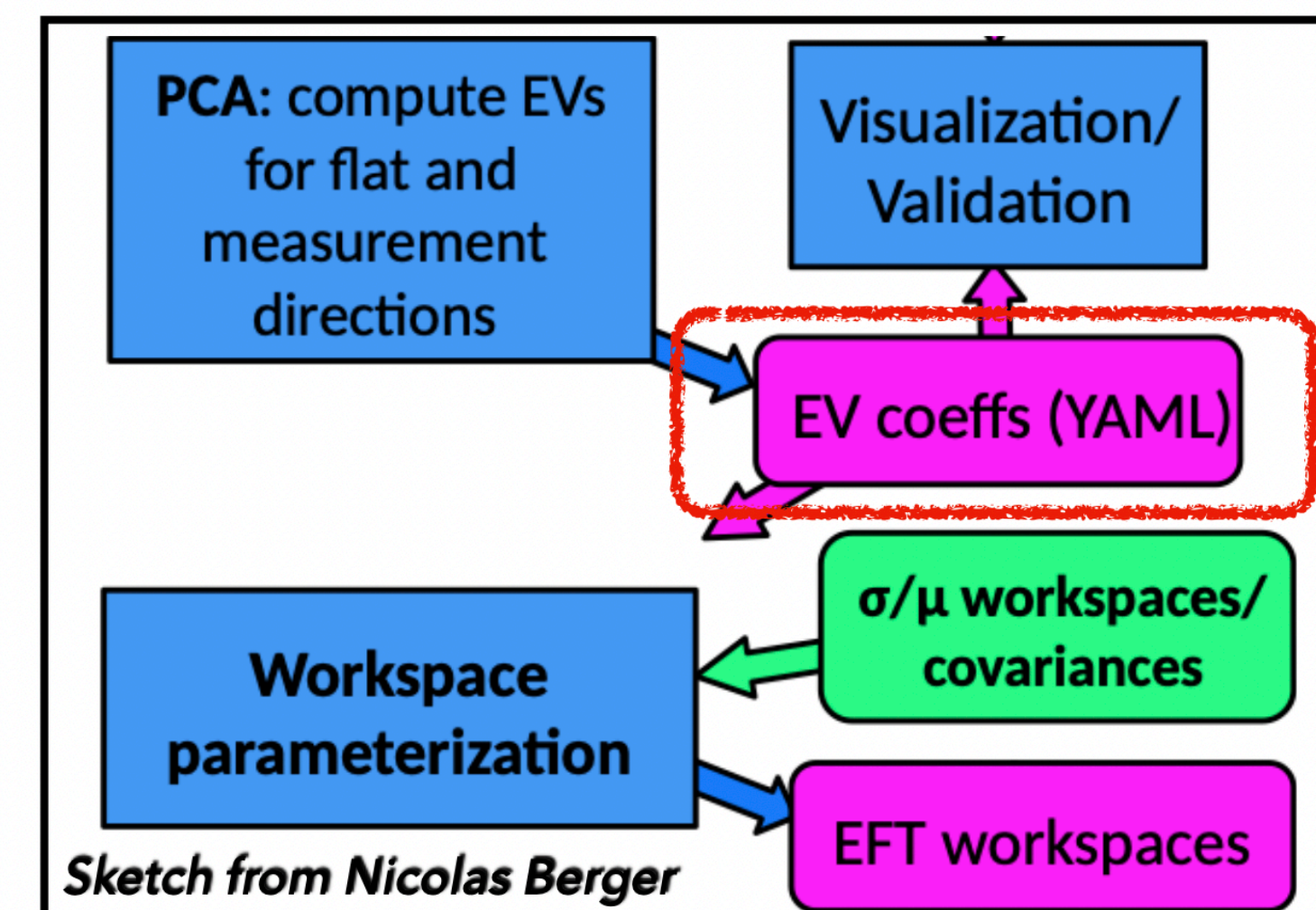
► Workflow defined

- Rivet used to extract parameterisation
- Input based on YAML
- Fit performed with RooFit

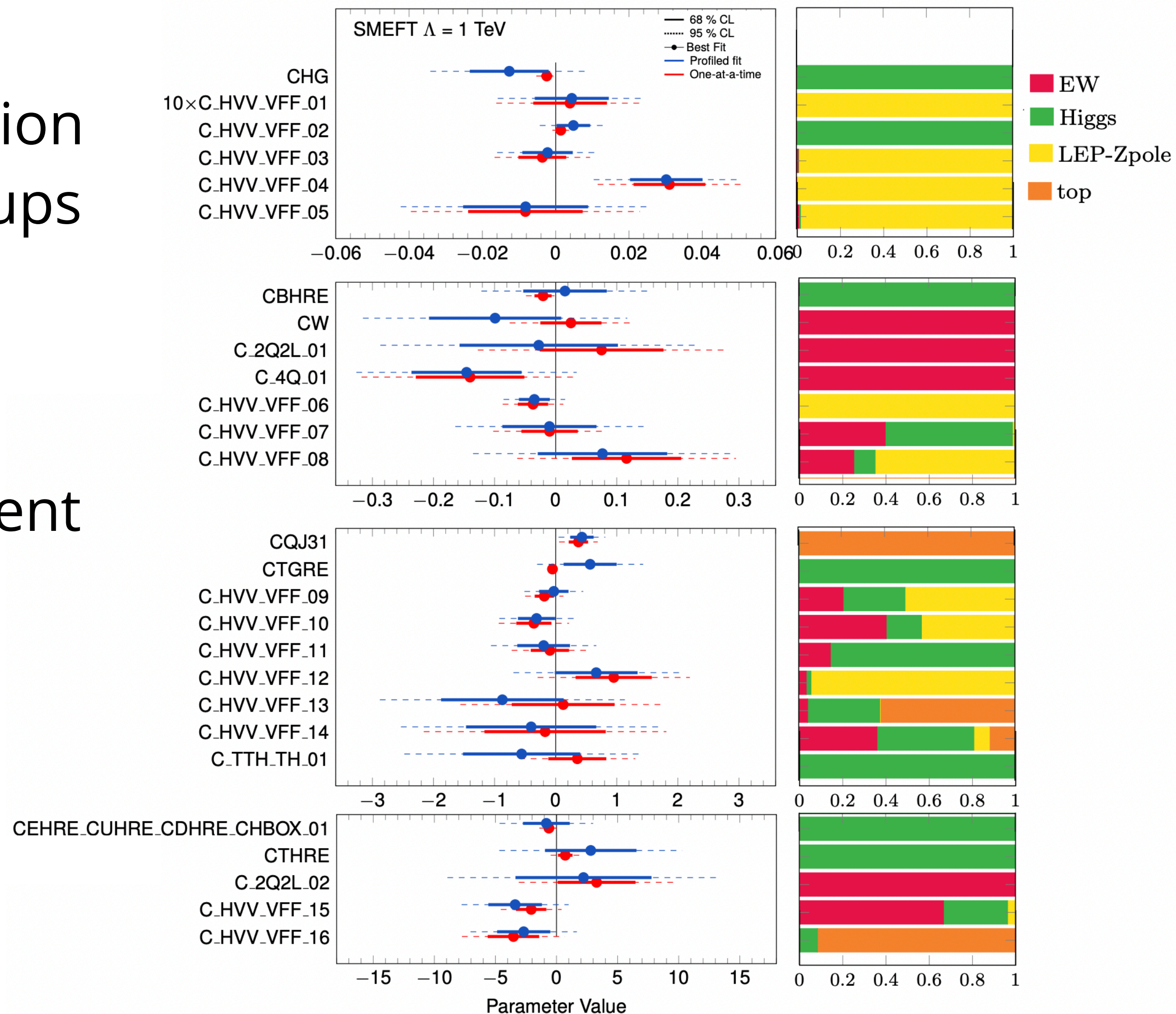
Parameterisation



Statistical model



- ▶ Perform eigenvector decomposition and PCA to identify operator groups
- ▶ Small correlation between groups
- ▶ Able to identify expected contributions of each measurement
- ▶ Fitting exercise in a good shape
- ▶ Everything in place to perform the different steps in a flexible manner





Coordination/Organisational Challenges

► General approach

- Combine input measurements & interpret or directly interpret simultaneous fit of measurements?
- Detector level fits vs unfolded data?

► Practical difficulties

- Different statistical methods (IBU vs FBU, PL vs toys, ...)
- Proper treatment of statistical and systematic correlations
- Measurements delivered on different timelines
- Interpretations: different assumptions on “backgrounds”
→ EFT effects - Hard without coordination!

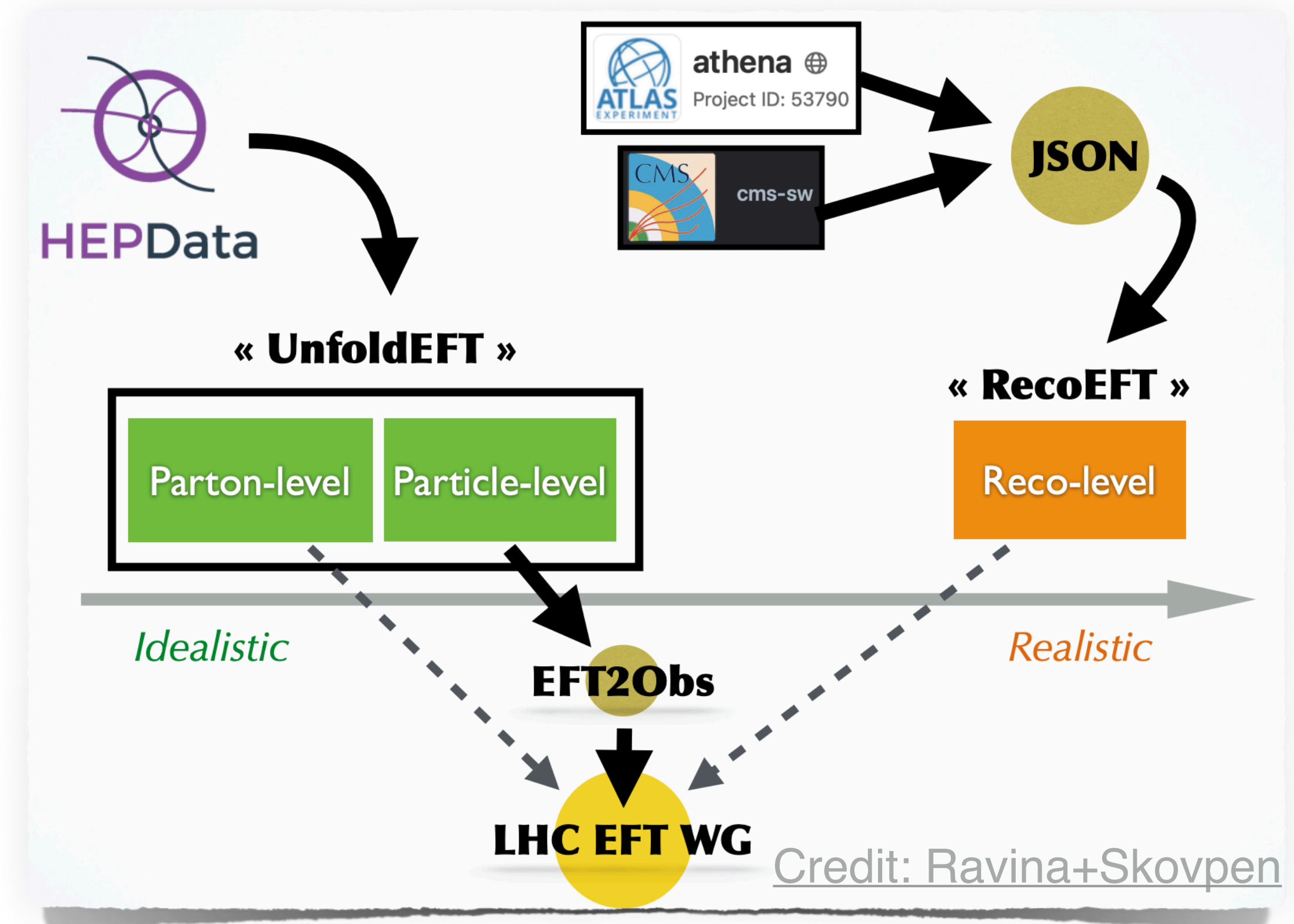
► What to store?

- Store bootstrap replicas for data - estimate stat. correlations
- Stat only results
- Impact of systematic uncertainties:

► Full likelihood (at least: full ranking and NPs correlations), cov. matrix for each unc. incl. stat only. Metadata.

► Signal model

- SMEFT@LO or @NLO? Which operators? Linear/quadratic terms. EFT uncs & validity constraints.





- ▶ Quite comprehensive global fits exist from the theory/pheno community
 - ▶ The importance of including Top data in these is clear
- ▶ Now it's time to think about next steps for adding Top data to experimental global fits
 - ▶ CMS has published a “global” Top+X fit
 - ▶ ATLAS has a recent PUB note on a “global” EWPO/Higgs/EW fit
 - ▶ LHC Top WG exercise looking at unfolded at detector level combinations
 - ▶ LHC EFT WG fitting exercise includes LEP+ATLAS+CMS EWPO/Higgs/EW/**Top** fit
- ▶ Many coordination/organisational challenges
 - ▶ Much of the technical machinery is there and existing fits can serve as starting point