Top quark mass & co

Theory-Experimental Workshop DESY-CERN-IFIC & friends

Marcel Vos (IFIC, CSIC/UV, Valencia)

Valencia, November 12th 2025

IFIC INSTITUT DE FÍSICA CORPUSCULAR · CSIC CONSEJO SUPERIOR DE INVESTIGACIONES CIENTÍFICAS · VNIVERSITAT DE VALÈNCIA · GENERALITAT VALENCIANA · AITANA

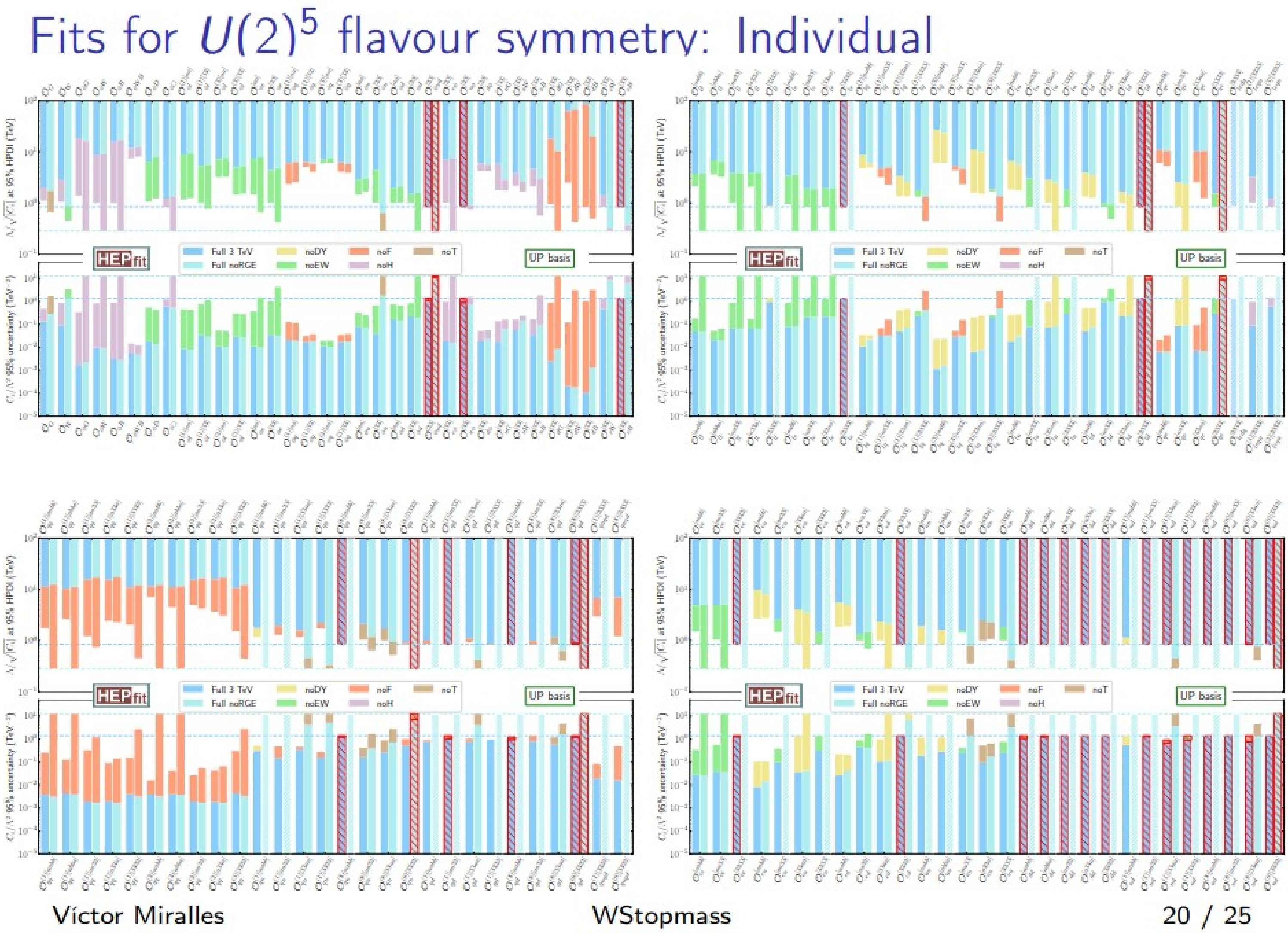
Slightly off-topic: bottom quark mass (Juan)

Conclusion & Outlook

- **Scale evolution** of QCD parameters is **experimentally testable**.
- **Updated measurement** of bottom quark mass at high scale → $m_b(m_H) = 2.38\,^{+0.24}_{-0.21}$ GeV
  - Full Correlation matrix allows to **significantly decrease uncertainty** (**33%**) via **combination.**
  - Provides **proof for running of quark masses**; **no running ruled out by 9σ**.
- **Future Colliders** have a **high potential for improvement**, particularly **Linear** Facilities: **experimental uncs. projected to reach the level of today's theoretical ones!**
- **Near Future:**
  - **Integrate within ATLAS** analysis groups to further develop & refine the measurement
  - Address the **elephant in the room**: we inevitably **assume SM for Higgs decays**
    - Simultaneous measurement of b-Yukawa & m_b
    - Design scenarios for different effects of new physics
  - **Refine the prediction for LCF**, reproduce "covariance matrix treatment" (Junping Tian & Jorge De Blas).

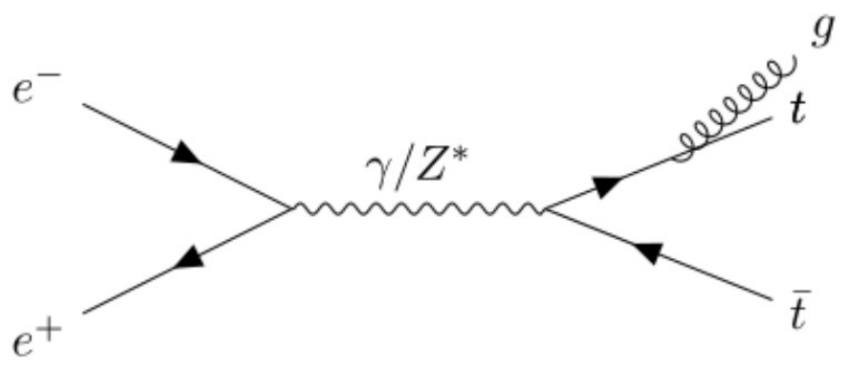
Juan Ramírez Alfaro || Top mass workshop 2025 || 10 Nov 2025 **24**

Top/Higgs/EW SMEFT fits (Victor)



A bit further off-topic: entanglement & decoherence (Maria)

J.M. Camacho, MV, Maria Moreno, U. Valencia ‘25



Start from an entangled top quark pair and study the impact of Final State Radiation

Radiation has small effect in inclusive analysis (Aoude et al., arXiv:2504.07030)

In events with a hard gluon emission, the tt concurrence changes strongly

Dn (e+e- → tt) ~ -0.5 [full phase space]
Dn (e+e- → ttg) → 0 [pT(gluon) > 200 GeV)]

Difference can be made 5σ significant, if all final states are used (hadronic polarimetry)

Quantum decoherence is accessible at colliders

Experimental demonstration of decoherence due to FSR is possible

Belle II with today's data, Z-pole run at LCF/FCCee/CEPC/LEP3

Top quark pair production at high-energy e+e- collider and (possibly) the LHC

Huge samples

Strong decoherence

Machine	$\sqrt{s}$ [GeV]	$\int \mathcal{L}dt$ [ab^{-1}]	final state	# $t\bar{t}$ events	concurrence C[ρ] $e^+e^- \rightarrow$ $t\bar{t}$	$t\bar{t}g$	R ($C^{t\bar{t}g}/C^{t\bar{t}}$)	signifi (R $\neq$
linear e^+e^-	500	8	(ee, $e\mu$, $\mu\mu$)	$5 \cdot 10^6 \times 4\%$	0.13	0.06 ($p_T > 20$ GeV)	0.43	3.1
(LCF [13])	500	8	all channels	$5 \cdot 10^6$	idem	idem	idem	15
linear e^+e^-	1000	8	(ee, $e\mu$, $\mu\mu$)	$10^6 \times 4\%$	0.25	0.06 ($p_T > 150$ GeV)	0.23	4.0
(LCF [13])	1000	8	all channels	10^6	idem	idem	idem	20
Machine	$\sqrt{s}$ [GeV]	$\int \mathcal{L}dt$ [ab^{-1}]	final state	# $\tau^+\tau^-$ events	concurrence $e^+e^- \rightarrow$ $\tau^+\tau^-$	$\tau^+\tau^-\gamma$	R ($C^{\tau\tau\gamma}$ / $C^{\tau\tau}$)	signifi (R $\neq$
Belle II 2025 [20]	10.579	0.5	single-prong	5×10^8	0.73	0.15 ($p_T > 2$ GeV)	0.33	34
Belle II target [21]	10.579	50	idem	5×10^{10}	idem	idem	idem	341
Z-pole (GigaZ [13])	91.2	0.1	idem	10^8	0.48	0.21 ($p_T > 20$ GeV)	0.44	14
Z-pole (TeraZ [22, 23])	91.2	300	idem	2×10^{11}	idem.	idem.	idem	75

Pretty entangled

The top quark mass, how are we doing?

The bottom quark $\overline{\text{MS}}$ mass $m_b(m_b)$ is known to about 0.5 %
The top quark pole mass is known to 0.2 % (direct, with some CAVEATs)
The top quark pole mass is known to 0.4 % (from cross sections, other CAVEATs)
The top quark $\overline{\text{MS}}$ mass $m_t(m_t)$ is known to about 1 % (from cross sections)
No MSR mass yet, but this can be done using the same cross sections

b

$I(J^P) = 0(\frac{1}{2}^+)$

$m_b = 4.18^{+0.03}_{-0.02}$ GeV   Charge $= -\frac{1}{3}\ e$ Bottom $= -1$

t

$I(J^P) = 0(\frac{1}{2}^+)$

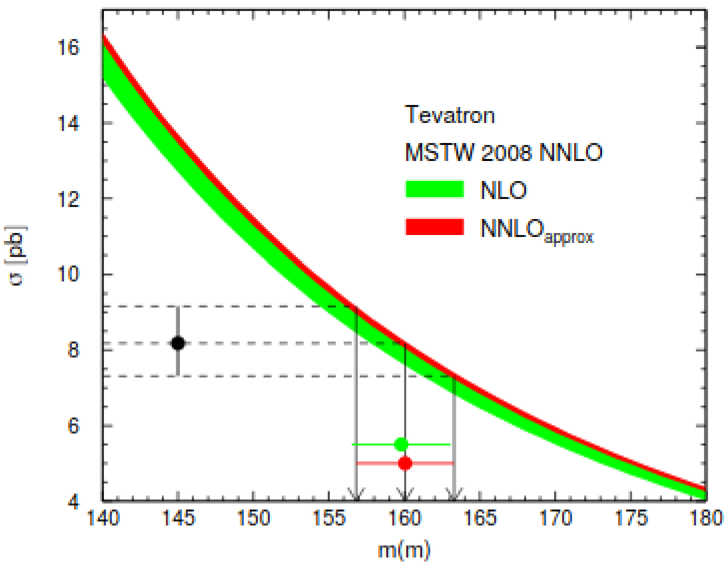
Charge $= \frac{2}{3}\ e$ Top $= +1$

Mass (direct measurements) $m = 172.69 \pm 0.30$ GeV [a,b] $(S = 1.3)$
Mass (from cross-section measurements) $m = 162.5^{+2.1}_{-1.5}$ GeV [a]
Mass (Pole from cross-section measurements) $m = 172.5 \pm 0.7$ GeV
$m_t - m_{\bar{t}} = -0.15 \pm 0.20$ GeV $(S = 1.1)$
Full width $\Gamma = 1.42^{+0.19}_{-0.15}$ GeV $(S = 1.4)$
$\Gamma(W b)/\Gamma(W q(q = b, s, d)) = 0.957 \pm 0.034$ $(S = 1.5)$

R.L. Workman et al. (Particle Data Group), Prog.Theor.Exp.Phys. 2022, 083C01 (2022)
2025 edition: https://pdg.lbl.gov/2025/listings/rpp2025-list-t-quark.pdf

Warning: PDG selection of measurements and averaging procedure are debatable

Mass measurements from the x-section



Differential cross sections

Can we have both – mass sensitivity and a robust interpretation?

Differential cross section measurements!

A combination can reach well below 1 GeV

(as per discussion on Tuesday, talks by Sven, Taras, Sasha, Davide, Sebastian)

More is possible…, with better theory

- NNLO predictions for tt+jet
  C. Brancaccio
- Full calculations, including top decay 2 → 6 (+jet)
  M. Worek at previous worshops
- “threshold” corrections due to Coulomb potential
  G. Limatola

QCD fit to all data

ABMPtt PDF fit Alekhin, Garzelli, S.M., Zenaiev '24

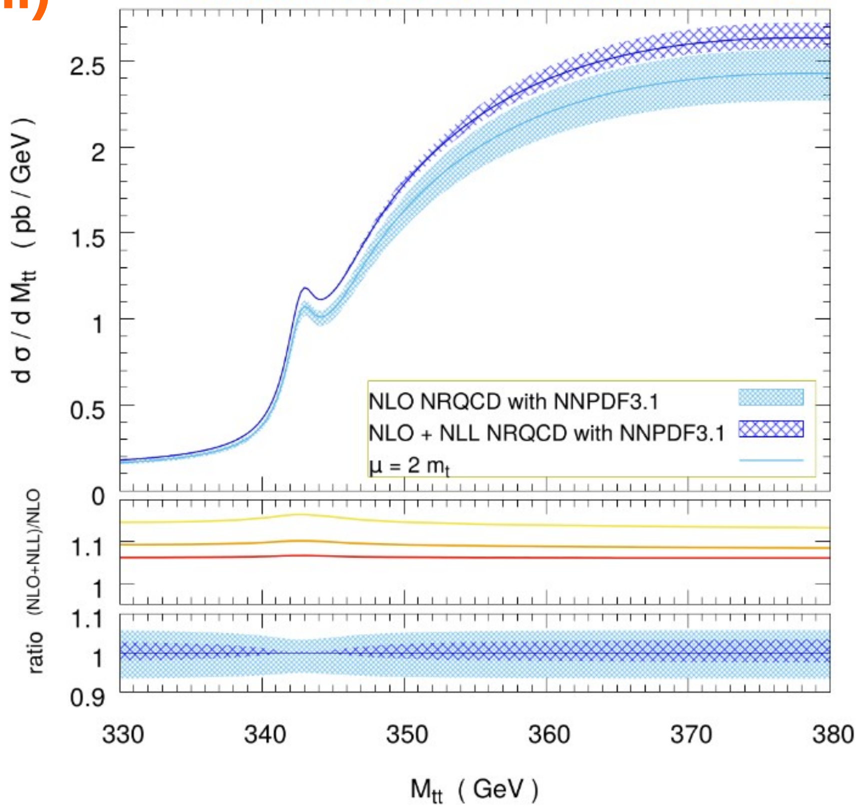
- New PDF fit with differential LHC top-quark data in ABMP framework
  - differential $t\bar{t} + X$ cross sections in $M(t\bar{t})$, $y(t\bar{t})$ $(NDP = 112)$
- Results
  - top-quark $\overline{\text{MS}}$ mass $m_t(m) = 160.6 \pm 0.6$ GeV
  - pole mass $m_t(m) = 170.2 \pm 0.7$ GeV
  - strong coupling $\alpha_s(M_Z) = 0.1150 \pm 0.0009$

High-precision mass extraction in well-defined renormalization scheme is possible with the data collected at the LHC

Joint "QCD" fit of PDFs, strong coupling and top mass should remain the long-term goal for the experiments

Threshold corrections (Giovanni)

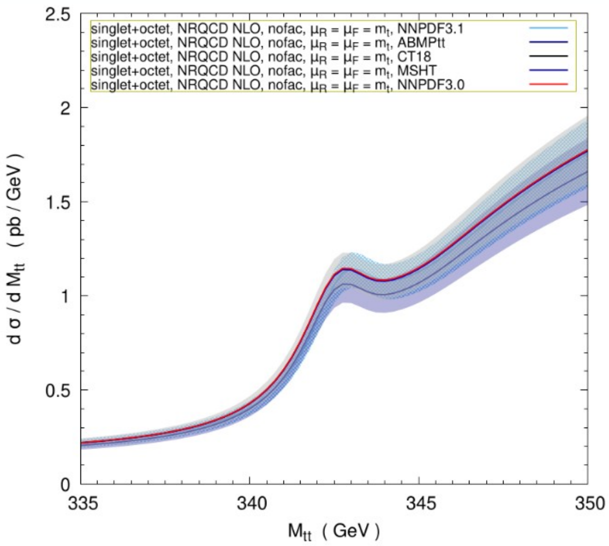
[Garzelli, GL, Moch, Steinhauser, Zenaiev '24]



Quasi-bound-state effects are important for LHC analyses

-- top mass & yukawa
-- entanglement
-- toponium search

Lot of interest from theory community to develop fixed-order predictions (G. Limatola) and MC tools (Fuks, Nason,…)
Note: "toponium" day at CERN, 14/01/2026



A lot of work to define a credible set of uncertainties for the threshold region
(c.f. "toponium" cross section measured to ~15%
https://cms-results.web.cern.ch/cms-results/public-results/publications/TOP-24-007/index.html)

NNLO for ttbar+jet

NNLO QCD corrections to top-quark pair production in association with a jet

Colomba Brancaccio

Based on: JHEP 03 (2025) 070, arXiv:2511.xxxxx

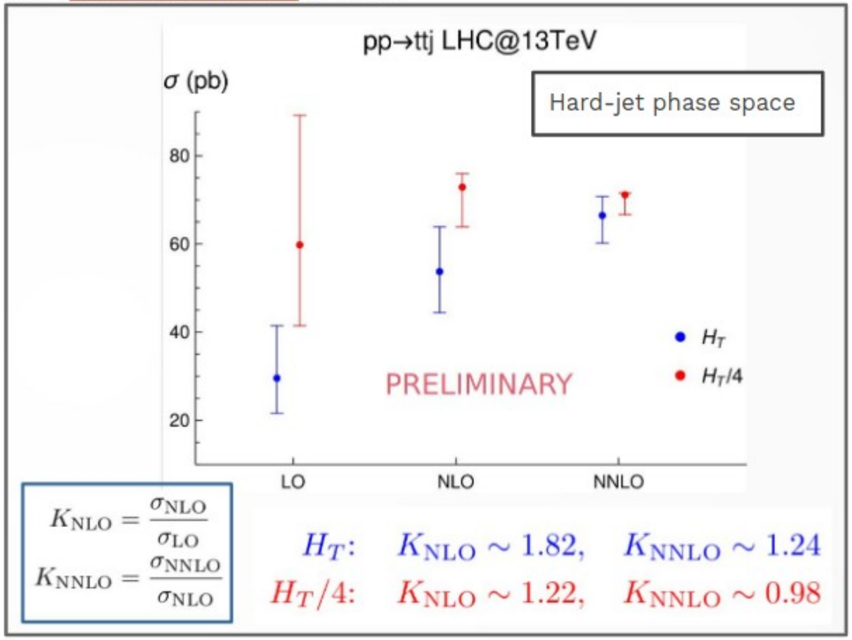
With: S. Badger, M. Becchetti, M. Czakon, H. B. Hartanto, R. Poncelet, S. Zoia

Amazing that we now have access to NNLO, delivered on time and with fully differential predictions!

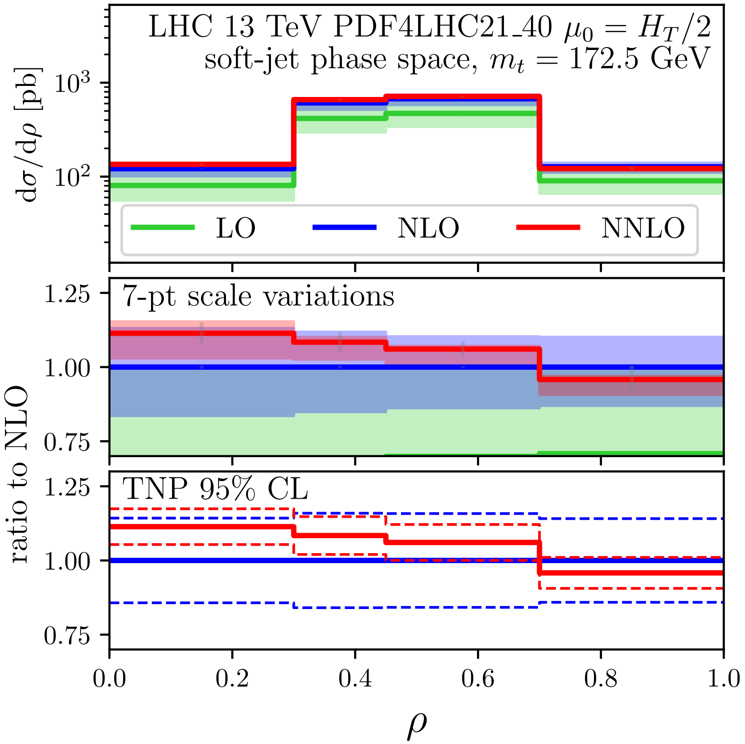
NNLO tt+jet

New!

From H. B. Hartanto's talk at TOP25



NNLO K-factor is small when the usual relatively small dynamic scale is used



NNLO K-factor has a slight slope in the mass-sensitive observable rho_s

→ non-negligible impact on mass?

→ improve compatibility across sqrt(s)?

→ improve stability w.r.t. gluon pT?

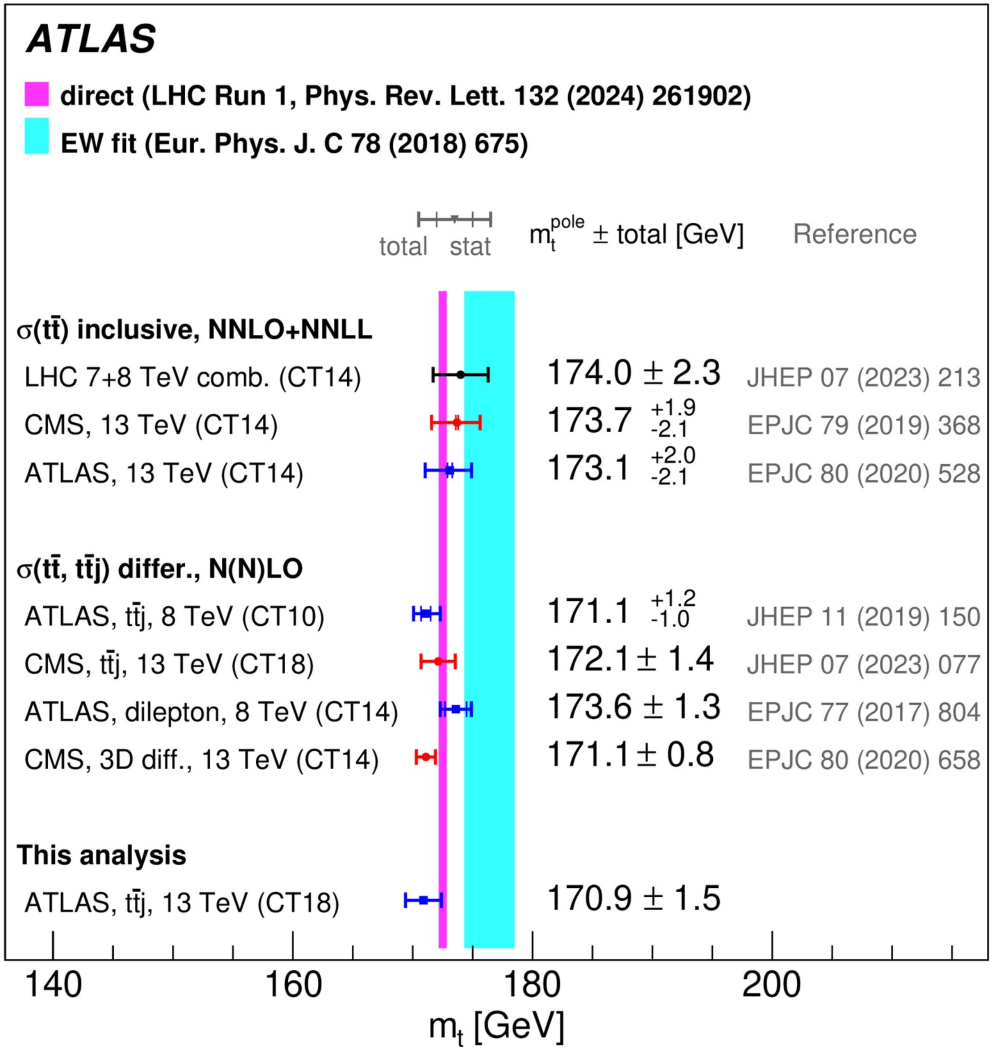
NNLO calculation should be the basis of the LHC top WG pole mass combination

LHC pole masses (Davide)

Run 2 program is unfolding

Still in the ttj pipeline:
-- CMS full run 2 (di-lepton)
-- ATLAS full run 2 (l+jets)
Both sub-GeV results!!

Further pole masses:
-- inclusive cross section
(via $\overline{\text{MS}}$ mass?)
-- ttbar differential
-- dilepton differential



The struggle

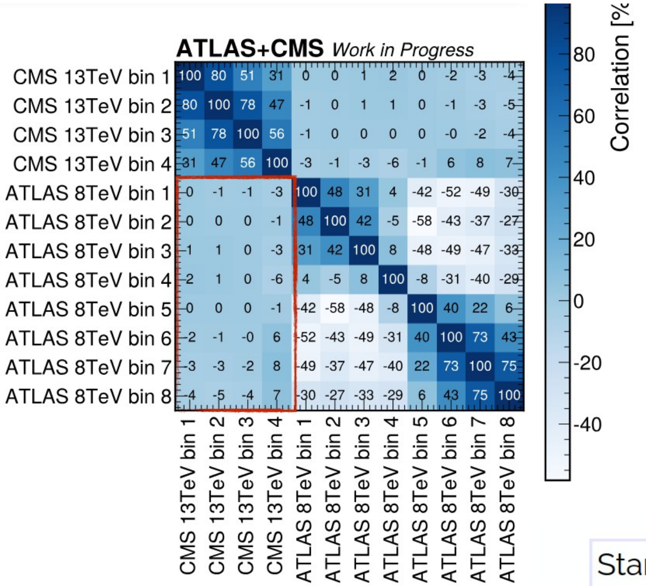
The struggle is real

Jets remain difficult
-- pile-up adding new challenges
-- improve in-situ techniques (Miguel)

New modelling uncertainties
-- ATLAS recoil uncertainty!!

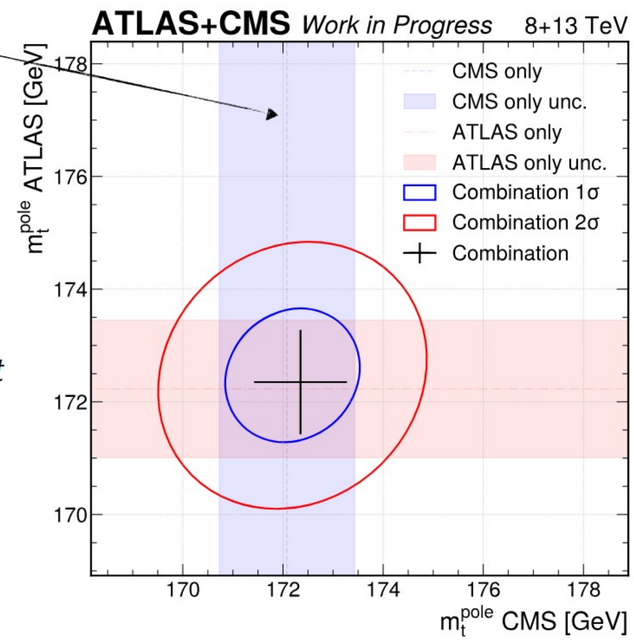
Uncertainty source	$\Delta m_t^{\mathrm{pole}}$ [GeV]	MC stat. unc. [GeV]
Data statistics	0.33	-
Detector unc.		
b-tagging and mistag	0.44	0.06
Jets	0.65	0.06
Leptons	0.25	0.06
Others	0.18	0.06
Modeling unc.		
MC statistical uncertainty	0.08	-
Backgrounds normalization	0.02	-
Single-top modeling	0.03	0.06
m_t^{MC} dependence	0.10	0.09
PS Recoil model	0.68	0.06
Parton shower	0.43	0.14
Underlying event	0.39	0.12
Color reconnection	0.13	0.08
ME+PS matching: $p_{\mathrm{T}}^{\mathrm{hard}}$	0.09	0.06
ME+PS matching: h_{damp}	0.26	0.06
ME+PS matching: line shape	0.38	0.12
3D NNLO reweight	0.21	0.06
PDF	0.26	0.06
Initial-state radiation	0.24	0.06
Final-state radiation	0.04	0.16
Factorization scales	0.09	0.06
Renormalization scales	0.03	0.06
Theory unc.		
Scale variations	+0.34 -0.28	+0.05 -0.06
PDF $\oplus$ α_S	0.24	+0.06 -0.06
Total	+1.47 -1.44	-

The combination: ATLAS 8 TeV + CMS 13 TeV



A lot of work by Andrej, Davide, Sebastian & Matteo
-- correlations from run 1 mass combination
-- harmonized theory predictions + fit setup
-- unification of two very, very different measurements

Standalone CMS



Standalone ATLAS

Adding ATLAS 13 TeV result breaks the combination

Contour from the 2D fit

Focus on result that is ready and adopting the NNLO theory, work on 3rd, 4th and 5th measurement in parallel

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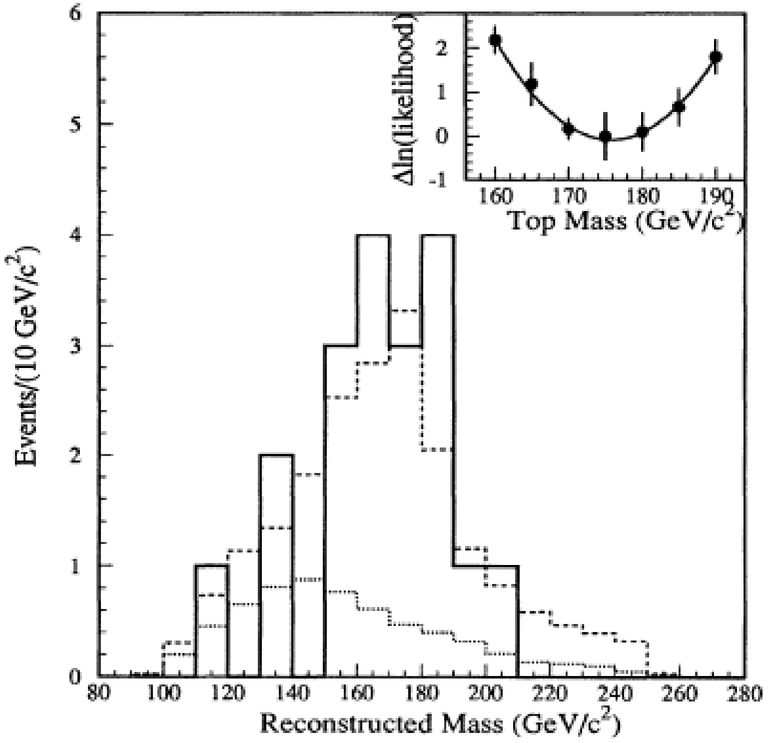
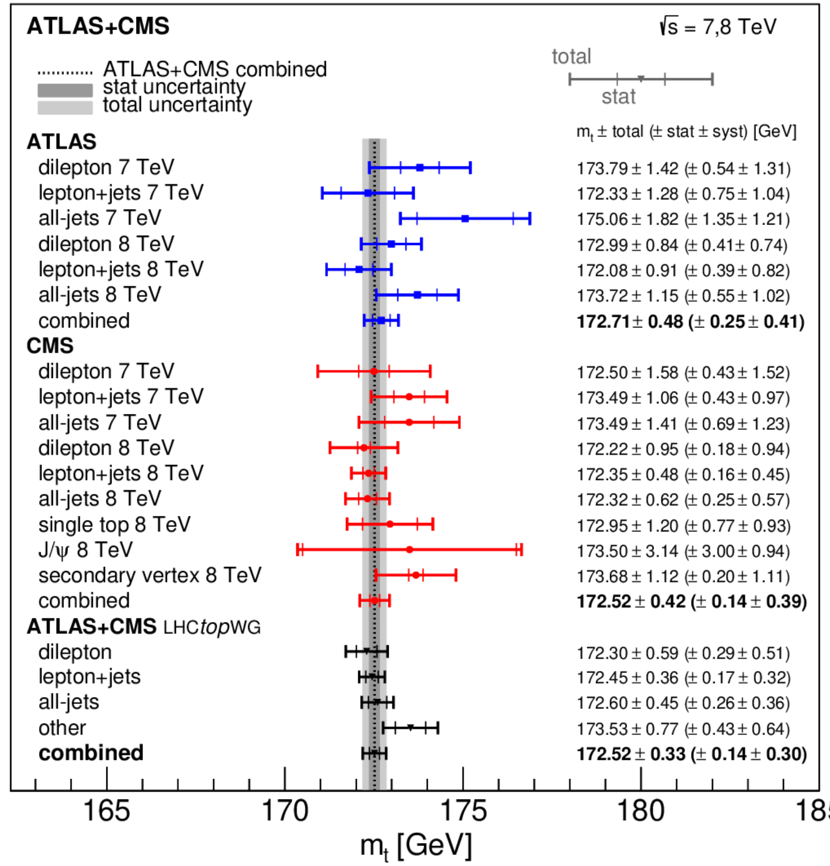
Direct mass measurements



Top is a “naked” quark

Direct mass today



ATLAS+CMS run 1 combination,
PRL 132 (2024)

Multiple (15!) direct measurements
using different techniques

Combination yields 330 MeV uncertainty,
with best measurement of ~600 MeV (link)

- average is dominated by "standard" template methods,
- alternative results provide "robustness" and reduce the total uncertainty

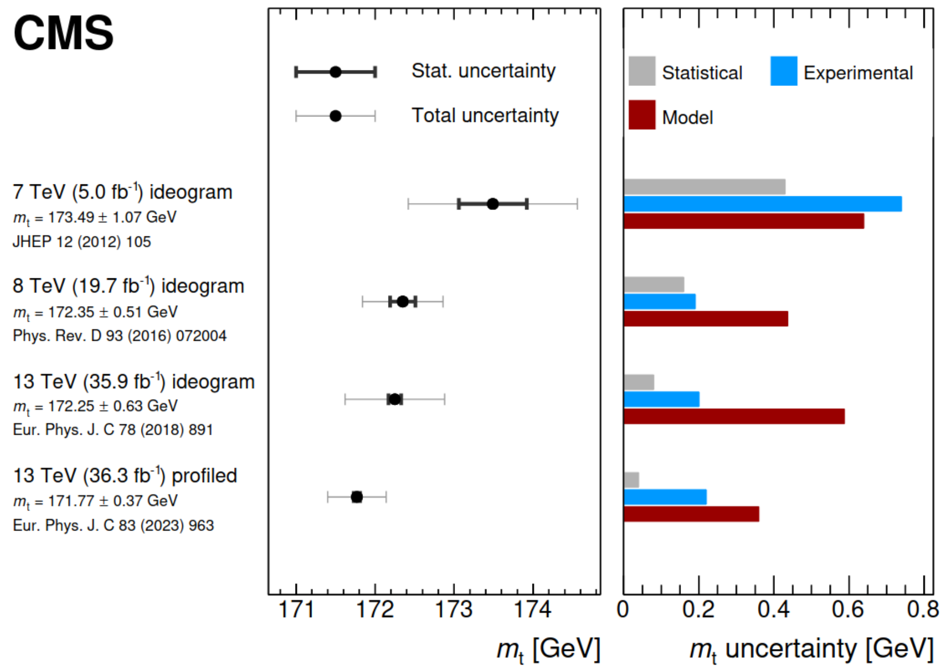
IMHO, this should be your reference for direct top mass measurements (until run 2 analyses take over)

i

CMS l+jets analyses - (r)evolution

Hybrid 2D fit

PL fit, 5 inputs



Two approaches on same data and similar (a priori) uncertainties

PL fit uncertainty: 370 MeV ↔ Classical: 630 MeV

PL fit central value: 171.8 GeV ↔ Classical: 172.3 GeV

(0.5 GeV, 0.8σ wrt classical result, 1.3σ wrt itself)

PL fit: what's m_t for fitted NP ↔ Classical: idem, for nominal NP

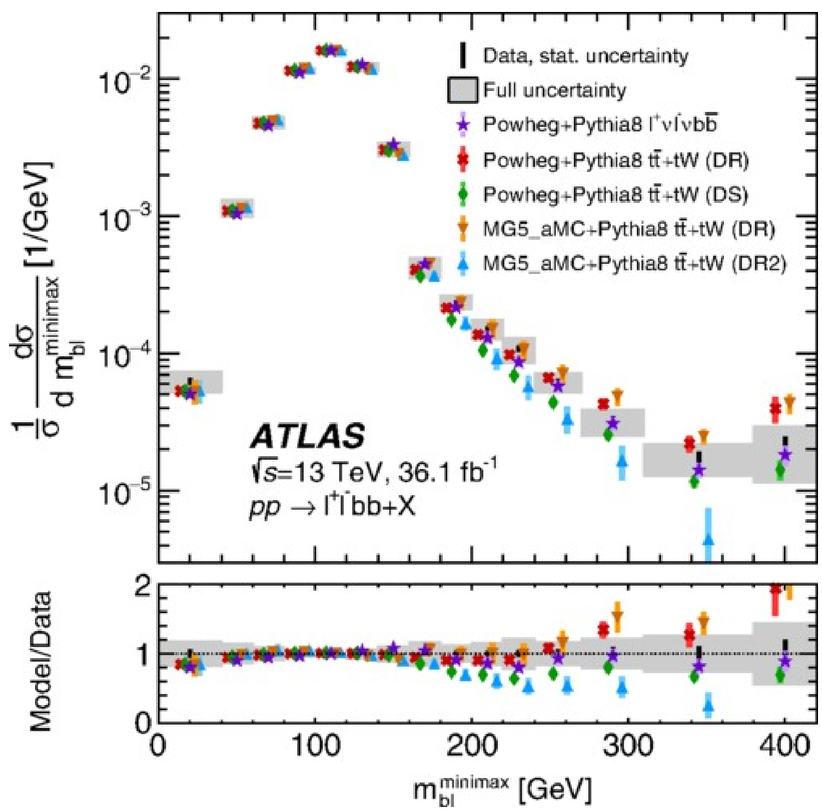
Classical templates are consistent if experiments adopt same MC.

In PL fits the constrained post-fit model will generally be different.

Direct mass+width measurements (Jiwon, Katharina, Miguel)

Both collaborations are preparing next-generation 2D profile-likelihood analyses, that extract the top quark mass and width

-- improved calibrations (ATLAS; W-mass constraint and flavour-specific in-situ)
-- improved MC (bb4l, see talks by Jonas, Jiwon and Katharina)
-- improved modelling uncertainties (CMS+ATLAS; splitting scales in PS)



ATLAS, PRL 121 (2018)

Powheg-bb4l

"new" MCs: bb4l theory

An NLO+PS generator for $t\bar{t}$ and Wt production and decay including non-resonant and interference effects

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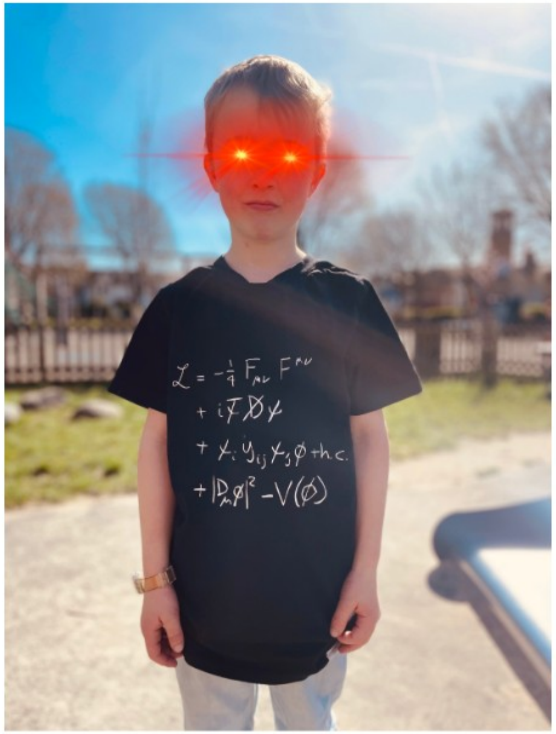


Why does it take 10 years for experiments to adopt a new MC?

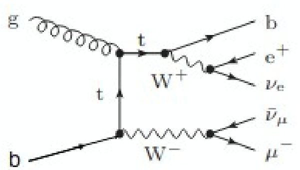
Powheg-bb4l (Jonas)

Interplay between top-pair and Wt

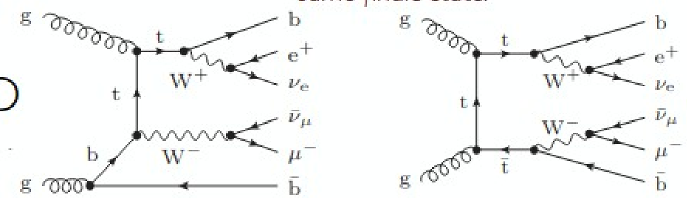
same finale state!

5FS

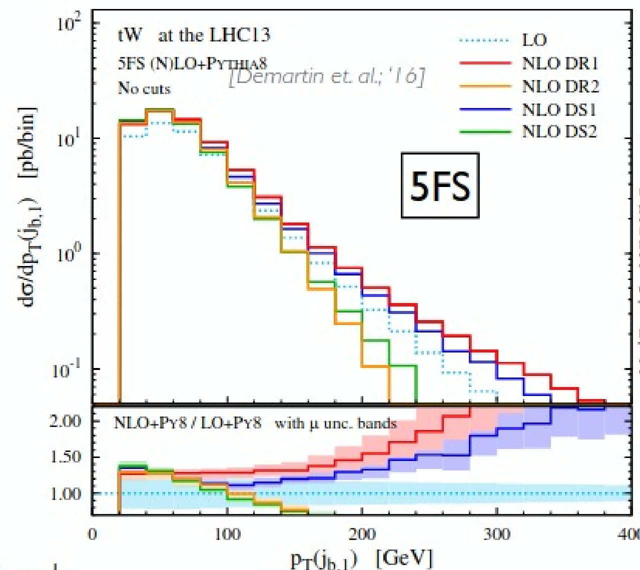
LO



NLO

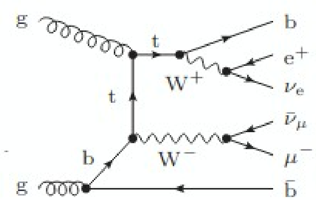


- **NLO corrections to Wt swamped by LO tt+decay**
- requires ad-hoc subtraction prescription:
  (Diagram Removal = DR vs. Diagram Subtraction = DS)
- NLO+PS for Wt available in MC@NLO *[Frixione, et. al.; '08]*, POWHEG *[Re; '11]* and Madgraph_aMC@NLO *[Demartin et. al.; '16]*

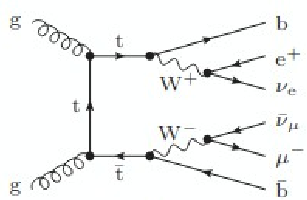


4FS

LO



Wt



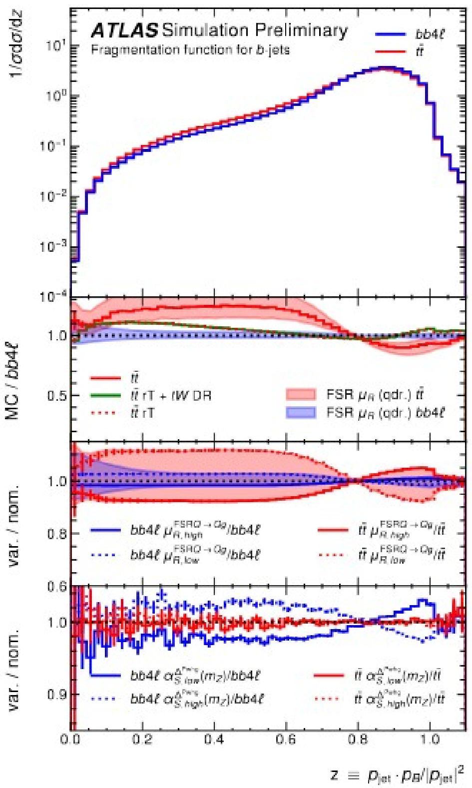
$t\bar{t}$

same finale state!

- **unified treatment of top-pair and Wt including interference**
- Wt enhanced in phase-space regions where one b becomes unresolved/vetoed
- requires off-shell WWbb calculation (with massive b's)

Powheg-bb4l deployment in ATLAS (Katharina)

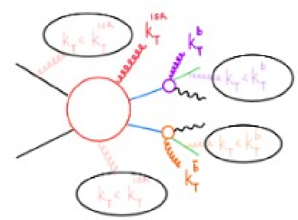
$bb4\ell$ systematics: FSR μ_R and α_S in Powheg Sudakov



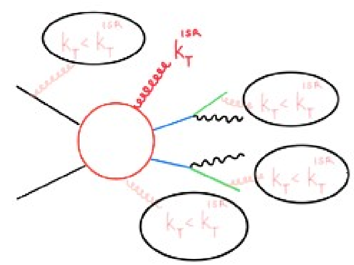
→ same influence of all μ_R splitting kernel variations except for FSR $Q \to Qg$ splitting kernel ($Q \in \{b, t\}$)

Possible explanation: NLO top decay description in $bb4\ell$

$bb4\ell =$

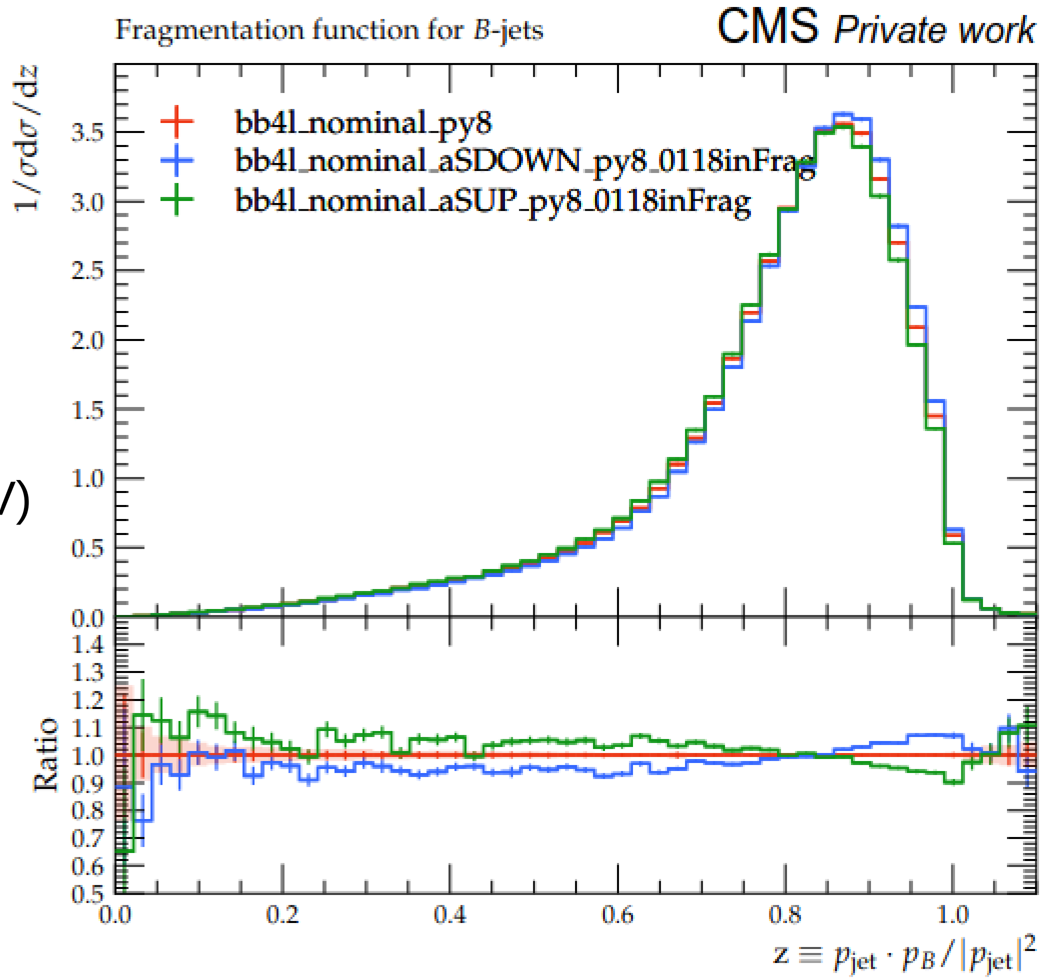


$t\bar{t} =$



→ larger variation in $t\bar{t}$+PS ✓

Powheg-bb4l deployment in CMS (Jiwon)



Developing uncertainty model
(± harmonized with ATLAS)

Total uncertainty on mass (500 MeV) and width (200 MeV) is very promising!!

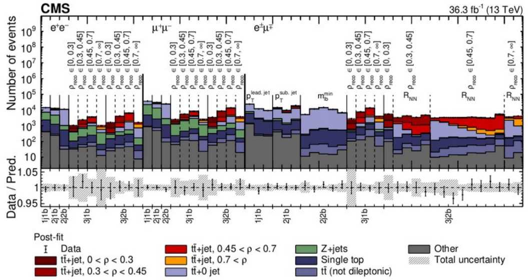
Impact can be estimated now and will guide mitigation strategies

Combination with other direct measurements: need tools for a meaningful estimate of compatibility of the post-fit models, even if nominal MC model is different

PL fit: ATLAS philosophy

There is no clearly spelled-out recommendation from ATLAS management or the statistics forum, but the top group seems to be converging to the following rules:

Use relatively few constraints (#bins « #df)
- 15 bins in l+jets boosted top mass, 21 in mass from m_{bl}, see Katharina’s talk)
- cf. 52? in Sebastian’s tt+jet measurement, 20-30 in Alberto’s version
- cf. 5 (mJ) + 4x30 (W-peak) + 2x20 (t3/2) in CMS boosted measurement
- cf. 5 x 40 in CMS 5D PL fit



Port constraints only when understood
- de-correlation of convoluted PP8-vs-PH7 across regions (more than 1 effect)
- keep FSR correlated between W- and top-peak (one leading physical effect?)

Validate post-fit model explicitly
- if the uncertainty model is too simplistic it will fail somewhere
- could in principle cross-validate over different analyses/experiments

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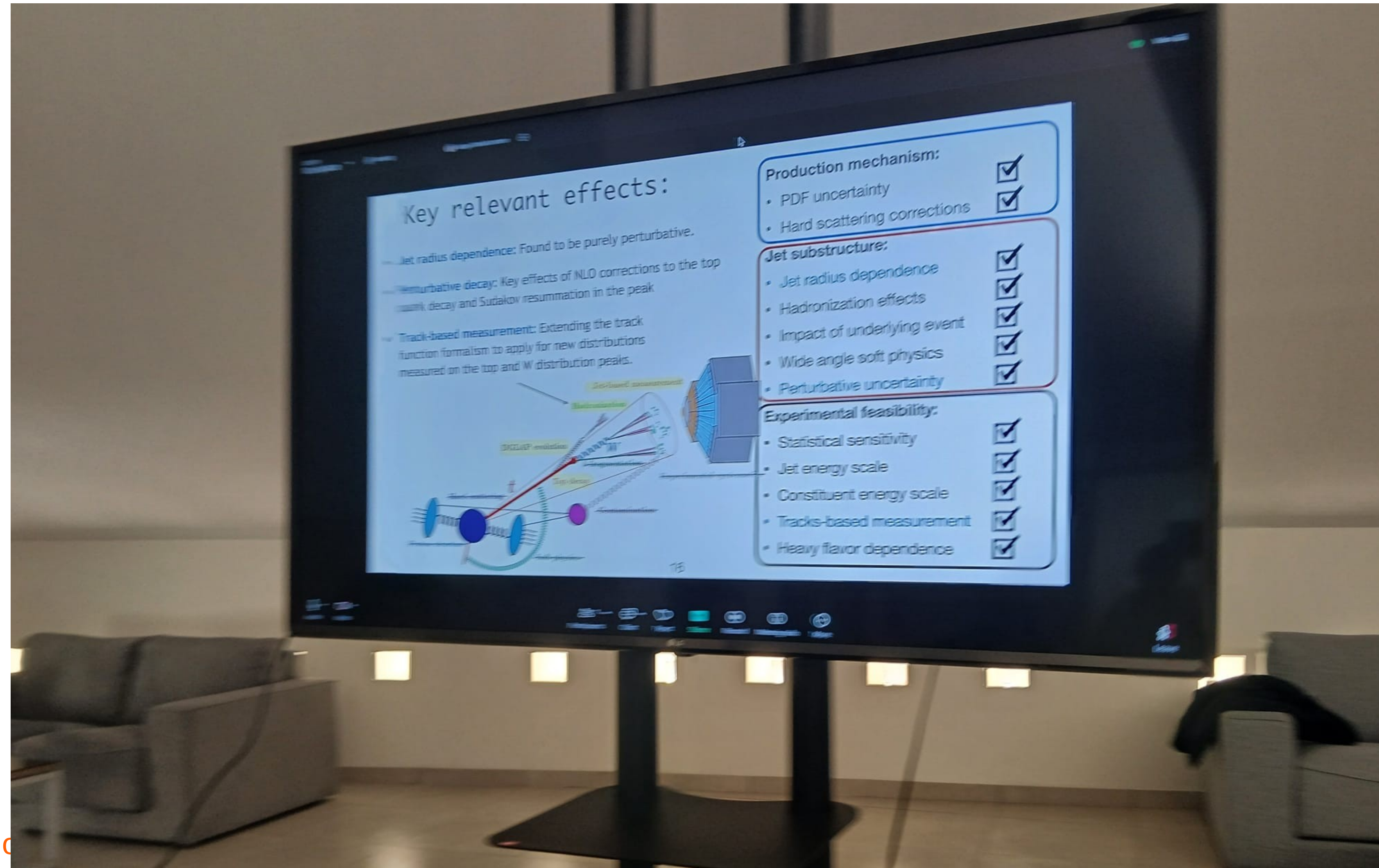
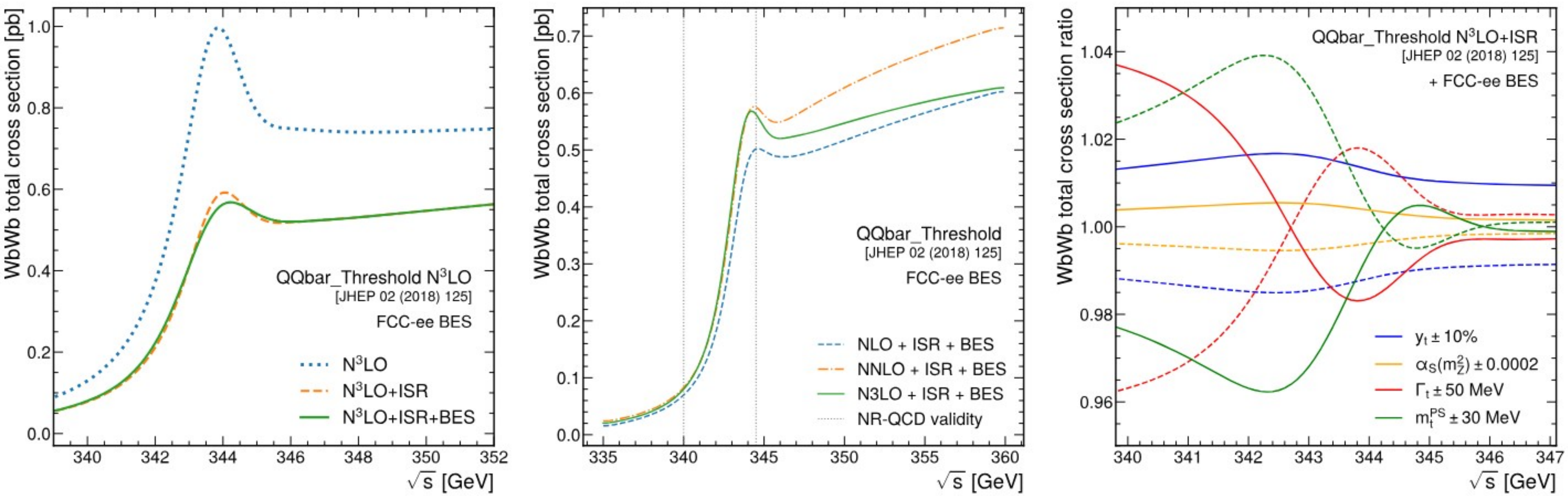
Future mass determinations: LHC run 3 + HL-LHC (Aditya)

Proposal to measure the top quark mass with negligible impact of soft stuff
-- natural evolution of boosted top quark mass measurements?



Future mass determinations: e+e- threshold (Matteo)



Experimental uncertainties much better understood; found to be sub-dominant

A “threshold-continuum” matching is needed to estimate Yukawa potential

Theory progress will determine the precision!!

Uncertainty source	m_t^{PS} [MeV]	Γ_t [MeV]	y_t [%]
Experimental (stat. ×1.2)	4.2	10.0	1.5
Parametric m_t	–	5.3	1.2
Parametric Γ_t	3.0	–	0.8
Parametric y_t	3.8	4.8	–
Parametric α_S	2.2	1.6	0.2
Luminosity calibration (uncorr.)	0.6	1.1	0.2
Luminosity calibration (corr.)	1.0	0.7	0.9
Beam energy calibration (uncorr.)	1.3	1.9	0.1
Beam energy calibration (corr.)	1.3	< 0.1	< 0.1
Beam energy spread (uncorr.)	0.3	0.9	< 0.1
Beam energy spread (corr.)	< 0.1	1.1	< 0.1
Total profiled	6.5	11.7	2.1
Theory	**35**	**25**	**?**

Future mass determinations: e+e- boosted (André)

First Numerical Results

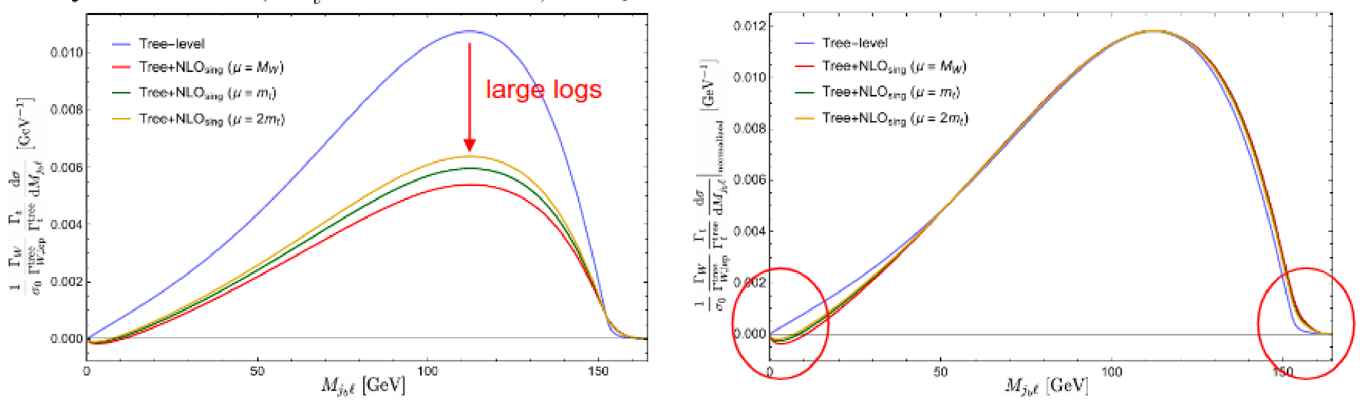
- Resummation of logarithms and implementation of hadronization effects are very involved due to the complexity of the convolutions.

→ NLO fixed-order results for the b-jet lepton invariant mass

$$\frac{\mathrm{d}\sigma}{\mathrm{d}M_{j_b\ell}}(\Delta M_t)\Big|_{\mathrm{NLO,sing}} \equiv \int_{(m_t-\Delta M_t)^2}^{(m_t+\Delta M_t)^2} \mathrm{d}M_t^2 \int_{(m_t-\Delta M_t)^2}^{(m_t+\Delta M_t)^2} \mathrm{d}M_{\bar{t}}^2 \, \frac{\mathrm{d}^3\sigma}{\mathrm{d}M_t^2\,\mathrm{d}M_{\bar{t}}^2\,\mathrm{d}M_{j_b\ell}}\Big|_{\mathrm{NLO,sing}}$$

$$Q = 700\ \mathrm{GeV},\ m_t^{\mathrm{pole}} = 173\ \mathrm{GeV},\ \Delta M_t = 10\ \mathrm{GeV}$$

Predictions including top decay; get one step closer to data



- Resummation of large logarithms is essential
- NLO effects in the endpoint regions due to corrections of the hemisphere resonance mass (M_t) and the b-jet mass ($M_{b\text{-jet}}$).

Summary

Top quark mass: the road to precision

(1) Hard work on Monte Carlo, fixed-order predictions and jet calibrations
(2) Responsible use of PL fits on improved uncertainty model
(3) Variety of methods and topologies (data will warn us when pushed too far)
(4) New methods with reduced/complementary systematics
(5) Improved understanding of limitations MC + fixed order
(6) Beyond the LHC: e+e- threshold scan + ….

If we manage to make progress on these points,
it will benefit the overall top physics program