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Highlights from LHC Run 2 and prospects for Run 3

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CIEMAT

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Highlights from LHC Run 2 and prospects for Run 3

> 1000 physics publications

- ATLAS and CMS

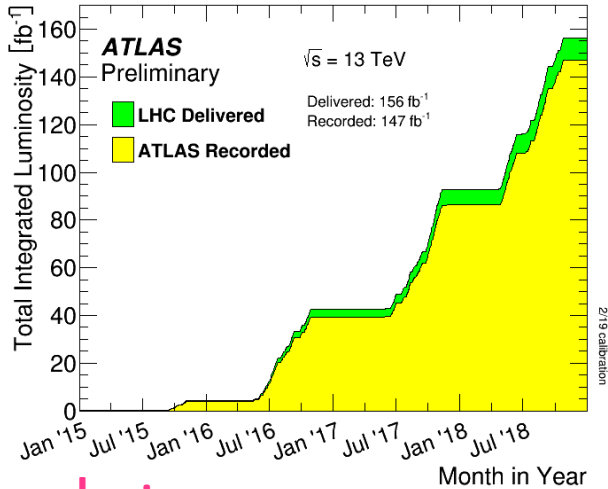
- Higgs boson
- Top quark
- Other SM measurements
- Searches

- LHCb

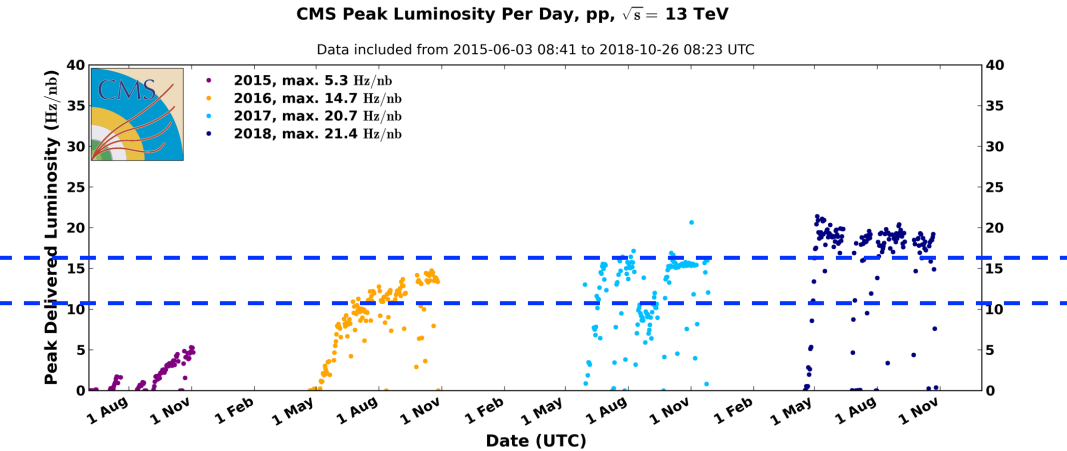
- Prospects for Run 3

The LHC in Run 2

Excellent performance of the machine



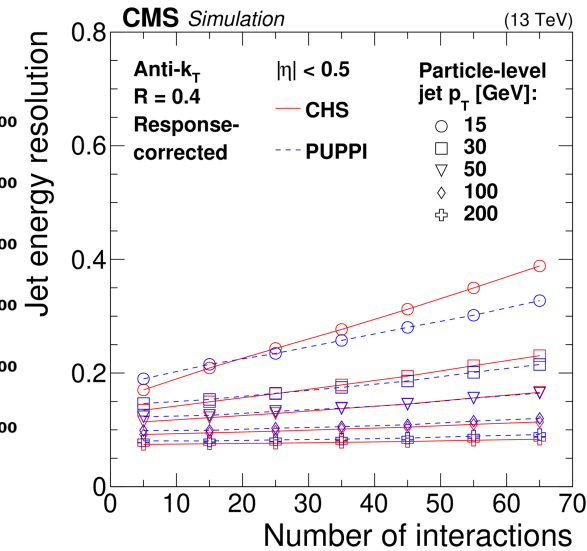
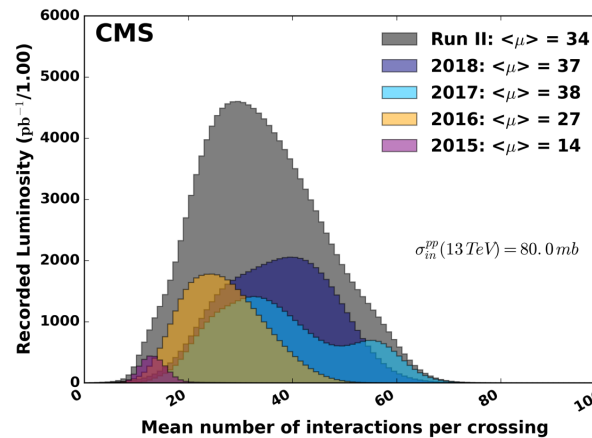
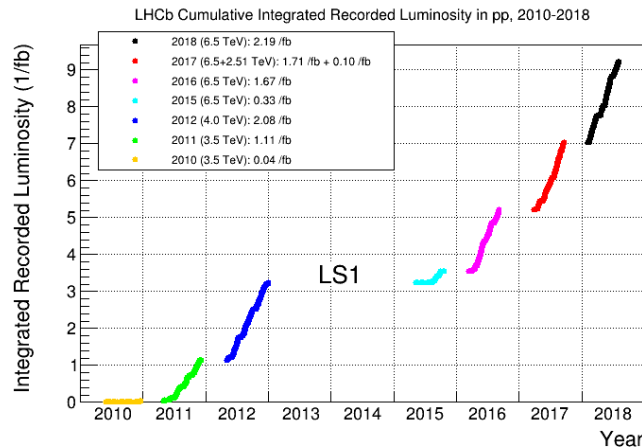
L_{int} :
 ATLAS, CMS: $\sim 150 \text{ fb}^{-1}$
 LHCb: $\sim 6 \text{ fb}^{-1}$



The price to pay (ATLAS & CMS): high pileup
 $\langle \mu \rangle \sim 34$

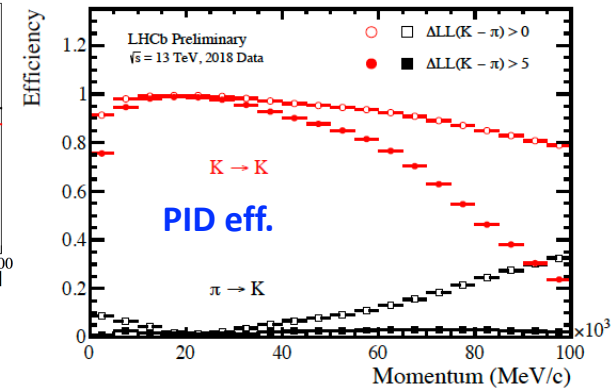
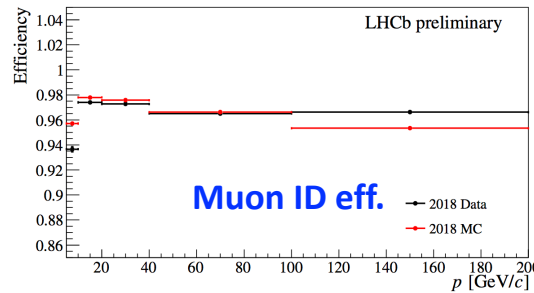
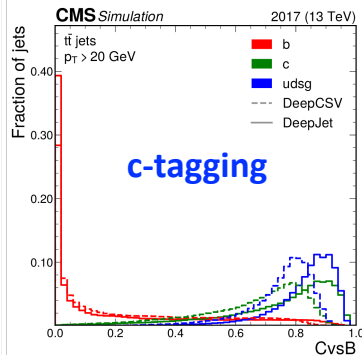
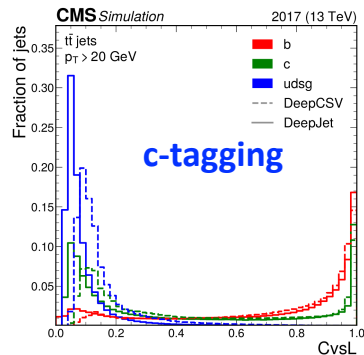
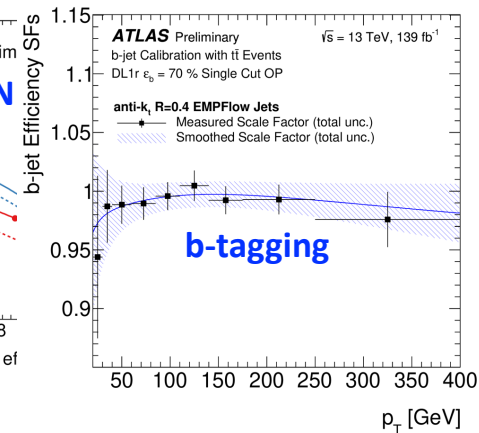
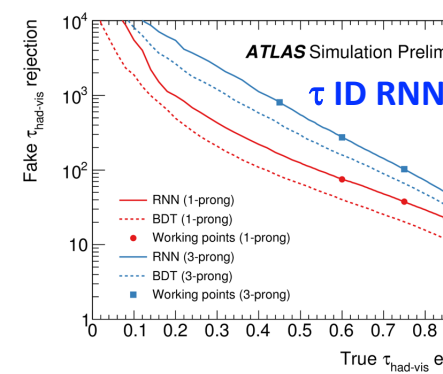
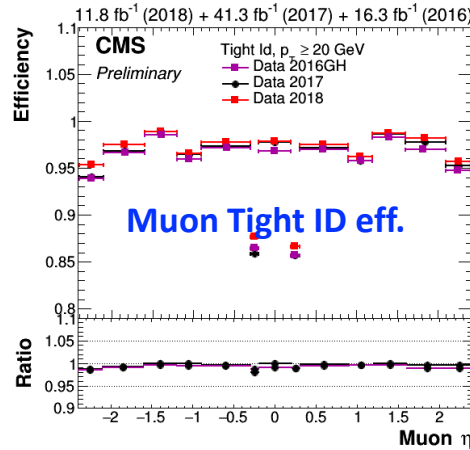
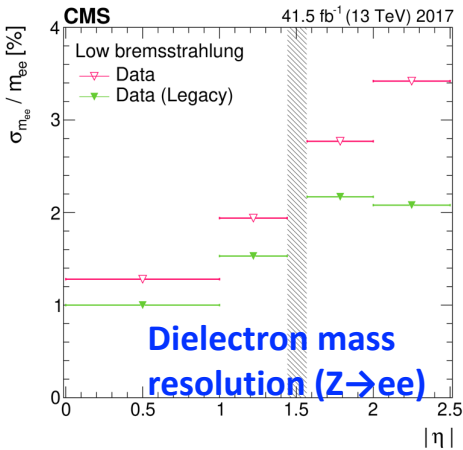
CMS Average Pileup (pp, $\sqrt{s}=13 \text{ TeV}$)

PU mitigation techniques



Excellent performance of the detectors

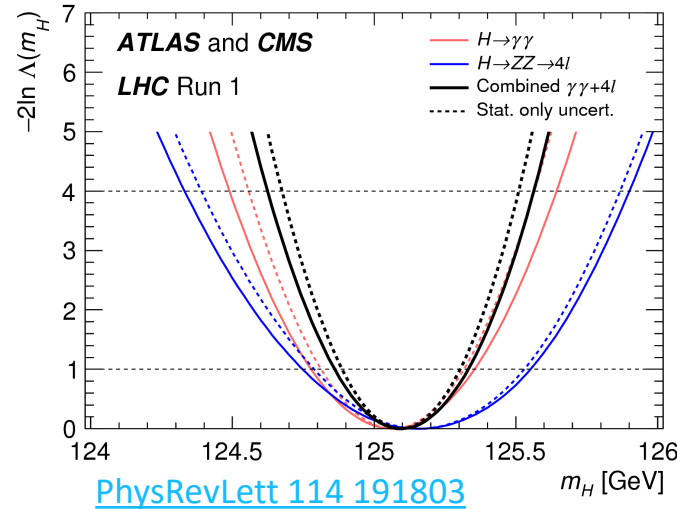
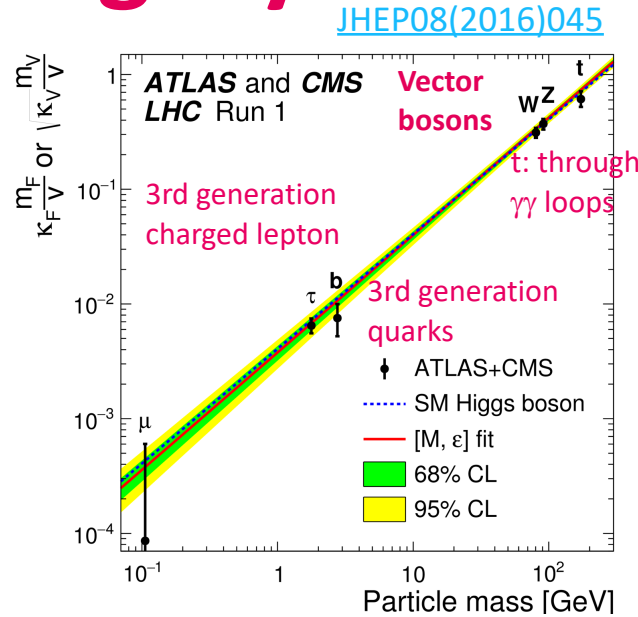
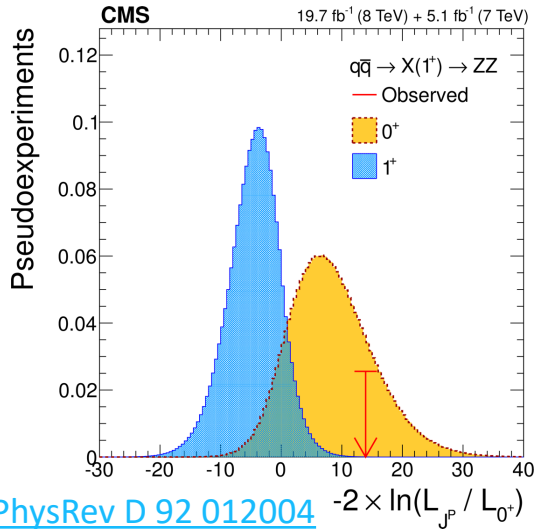
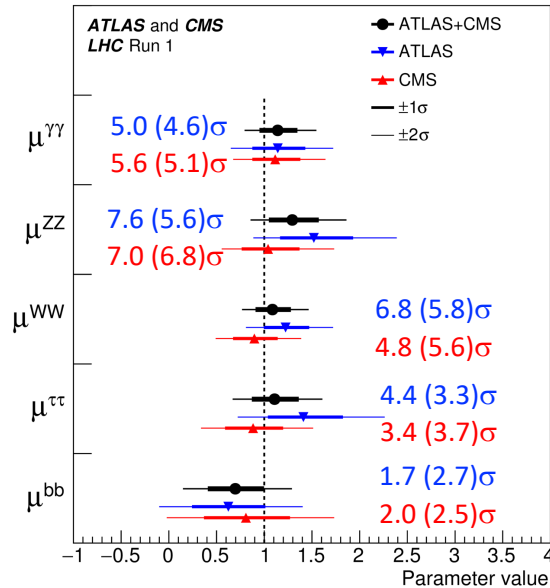
Results from Run 2 only possible thanks to excellent understanding of detector performance, and development of reconstruction and identification algorithms



A very highly efficient object reconstruction, with a percent-level (or better) understanding of this performance in data.

HIGGS BOSON

Higgs Run 1 Legacy



The first Run of LHC firmly established the observation of the Higgs boson:

- independently in the bosonic channels
- coupling to third generation fermions in combination

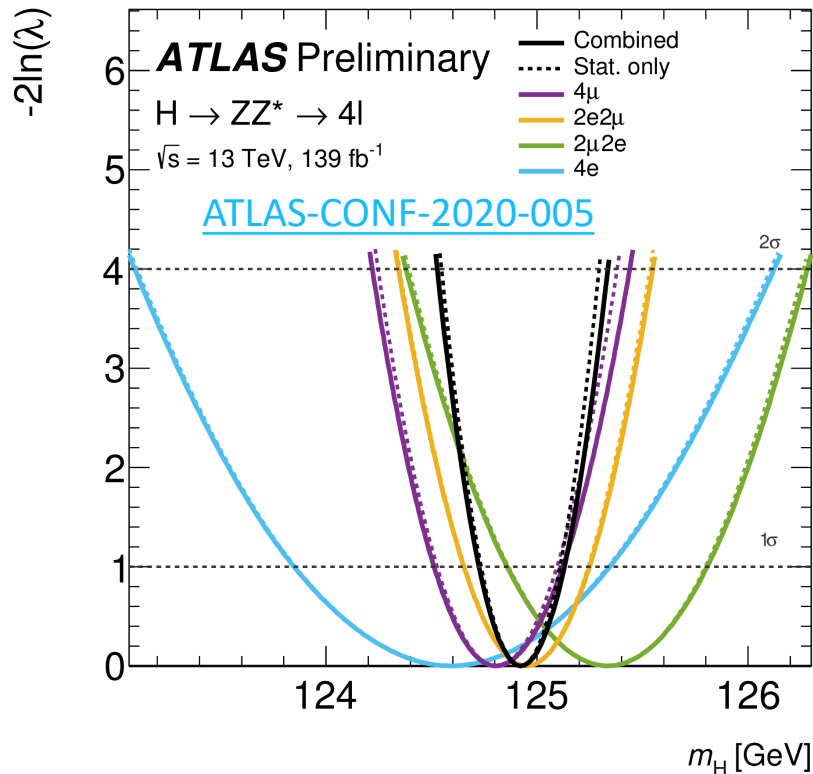
First precision measurements (Cross Sections, Mass)

Scalar nature confirmed (0^+)

First constraints on the total width



Measuring the Higgs Mass and Width

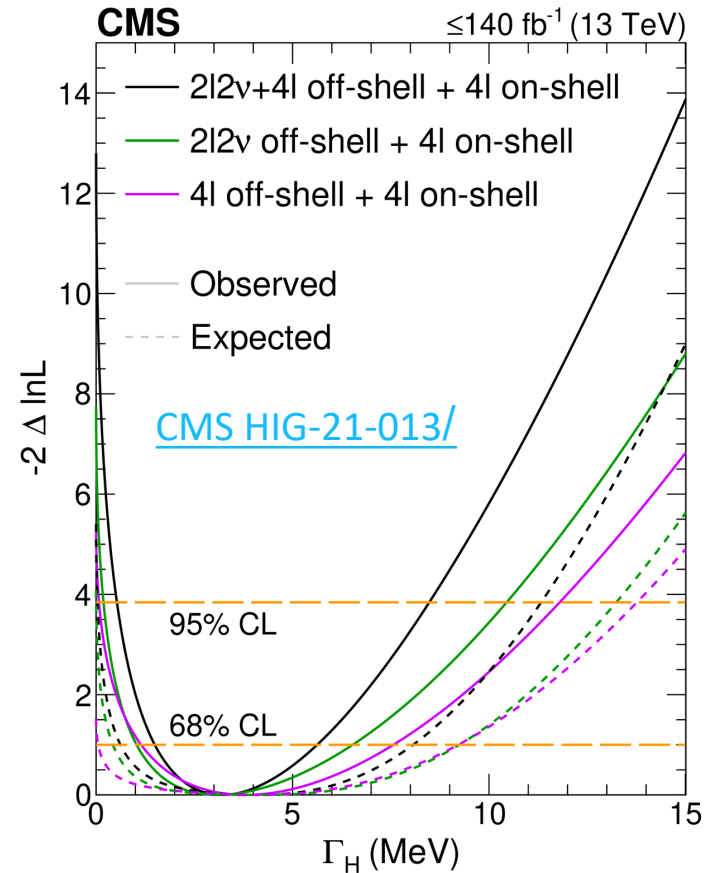


Mass known to the per mil level:

ATLAS (4ℓ): $124.92 \pm 0.19(\text{stat})^{+0.09}_{-0.06}(\text{syst}) \text{ GeV}$

CMS ($4\ell+2\gamma$): $125.38 \pm 0.14 \text{ GeV}$

[\(Phys. Lett. B 805 \(2020\) 135425\)](#)



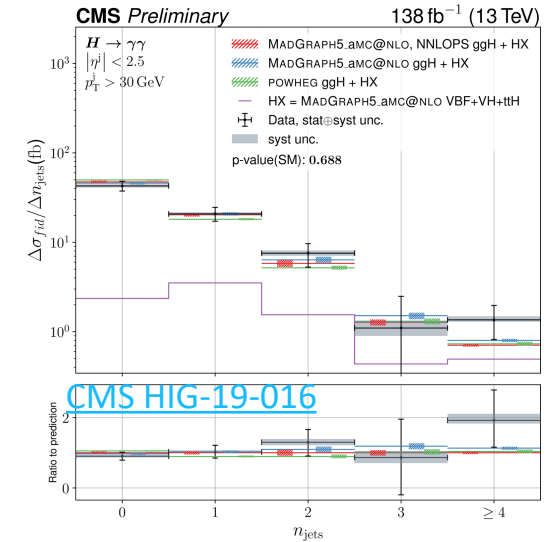
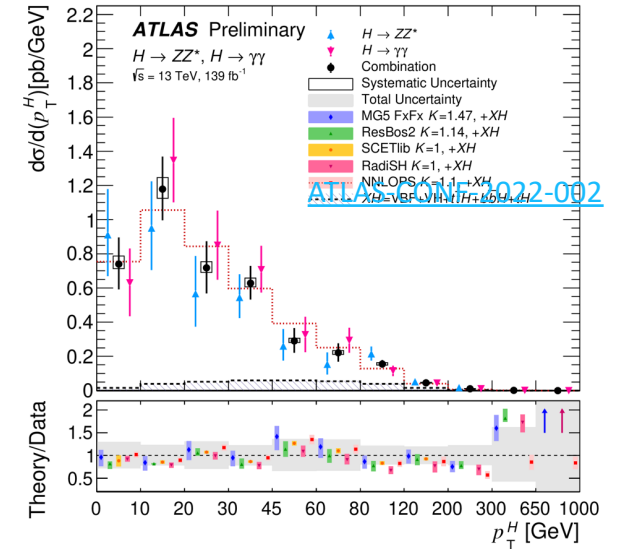
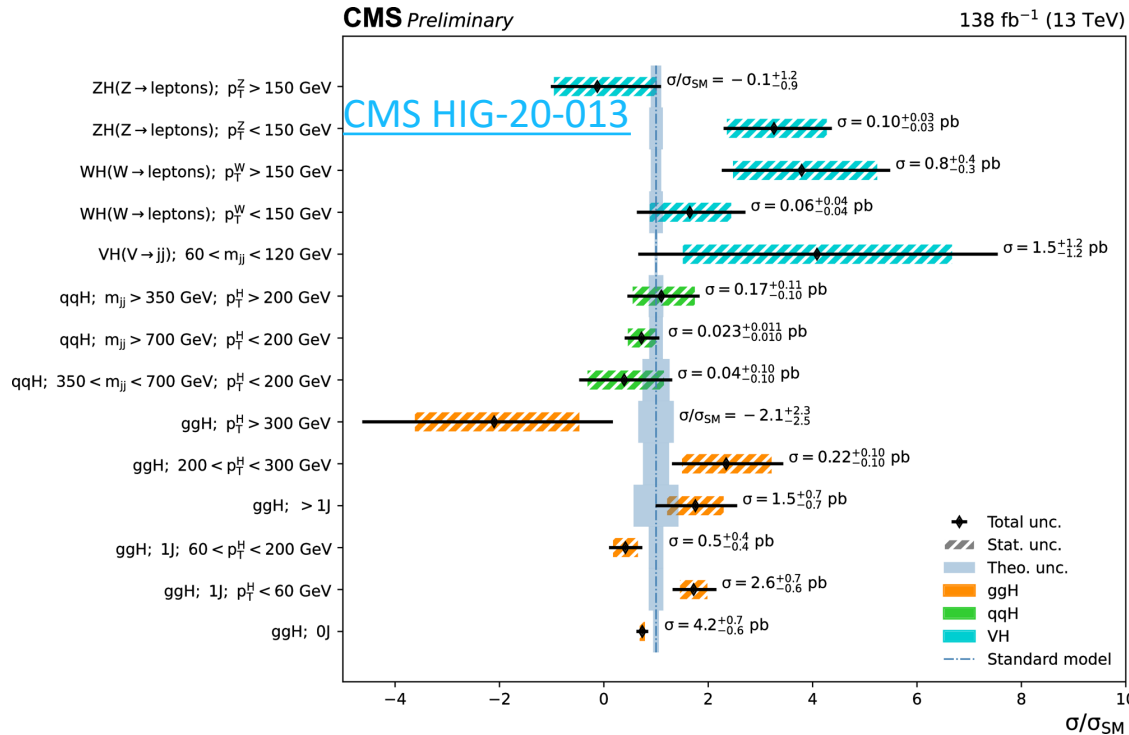
$\Gamma_H = 3.2^{+2.4}_{-1.7} \text{ MeV}$

(Evidence for off-shell HZZ production)

Differential Cross Sections

Moving on from simply quantifying the agreement with the SM, Higgs cross sections are now measured differentially.

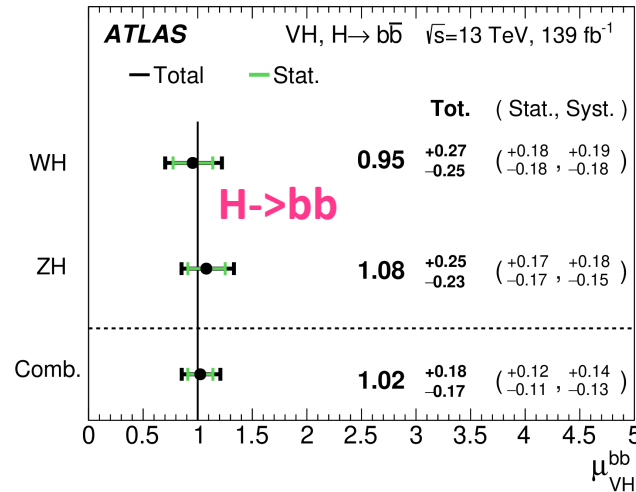
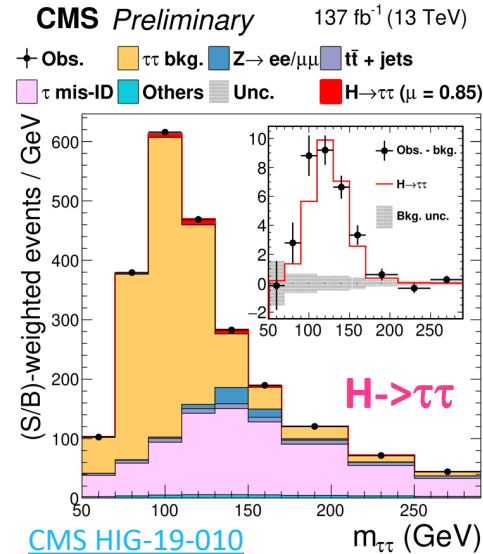
Both in specific bins of fiducial phase-space (STXS) and in terms of kinematic observables (p_T , angles, N_{jets} ,...)



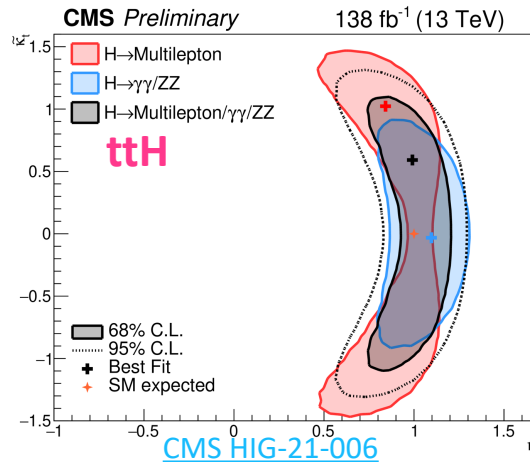
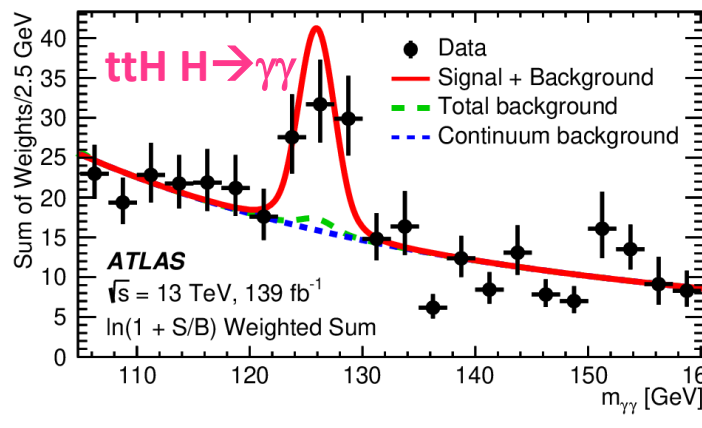
Coupling to Fermions: 3rd Gen

Independent observation of the coupling to b , τ , top

[Eur. Phys. J. C 81, 178 \(2021\)](#)



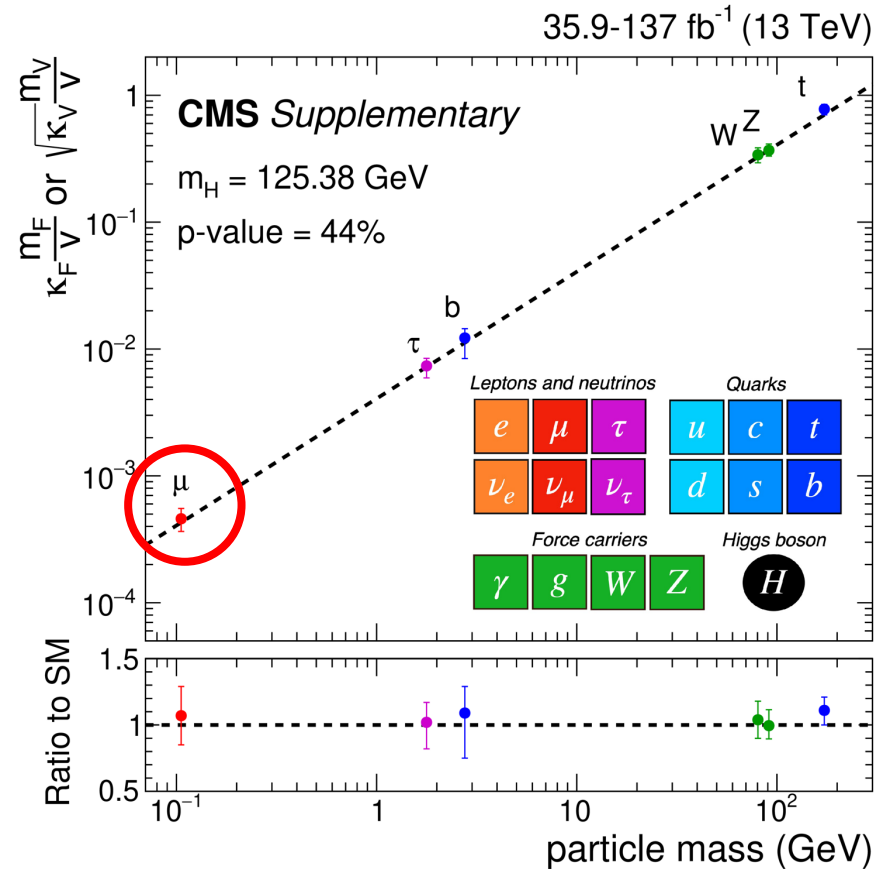
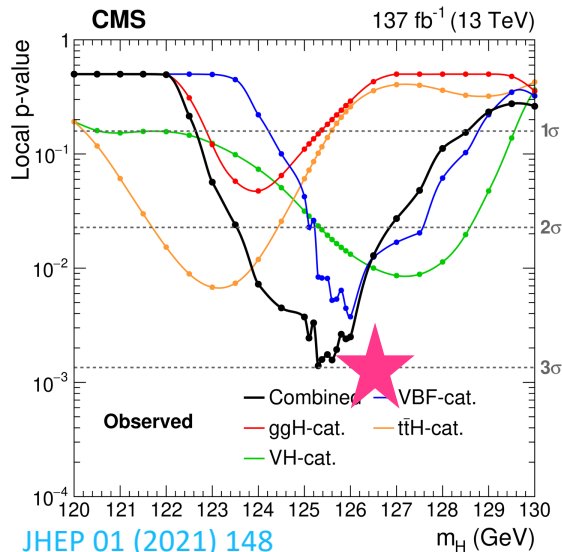
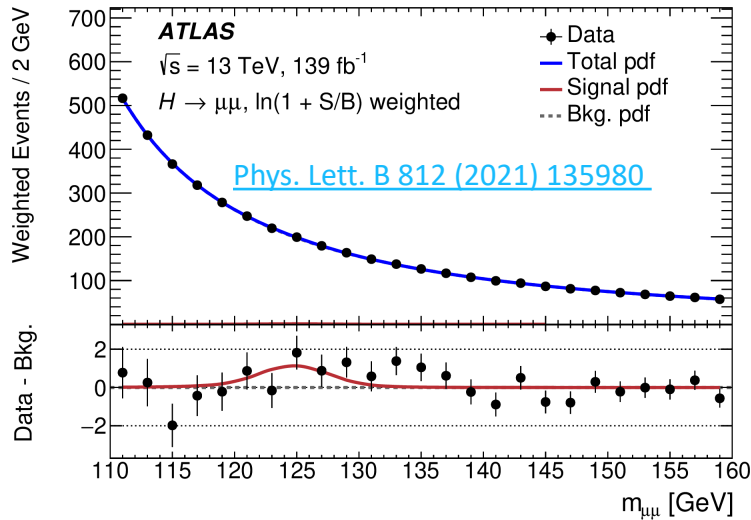
Beyond observation,
decays to fermions of
the 3rd generation have
now also entered the
precision realm



Cross Sections (including
fiducial, differentials and
STXS), CP studies

[PhysRevLett 125 061802](#)

Evidence for the Higgs coupling to muons



Evidence for the Higgs coupling to the 2nd Generation!
 CMS: $\mu = 1.19^{+0.40}_{-0.39} (\text{stat})^{+0.15}_{-0.14} (\text{syst})$
 ATLAS: $\mu = 1.2 \pm 0.6$

TOP QUARK

~ 120M tt pairs,

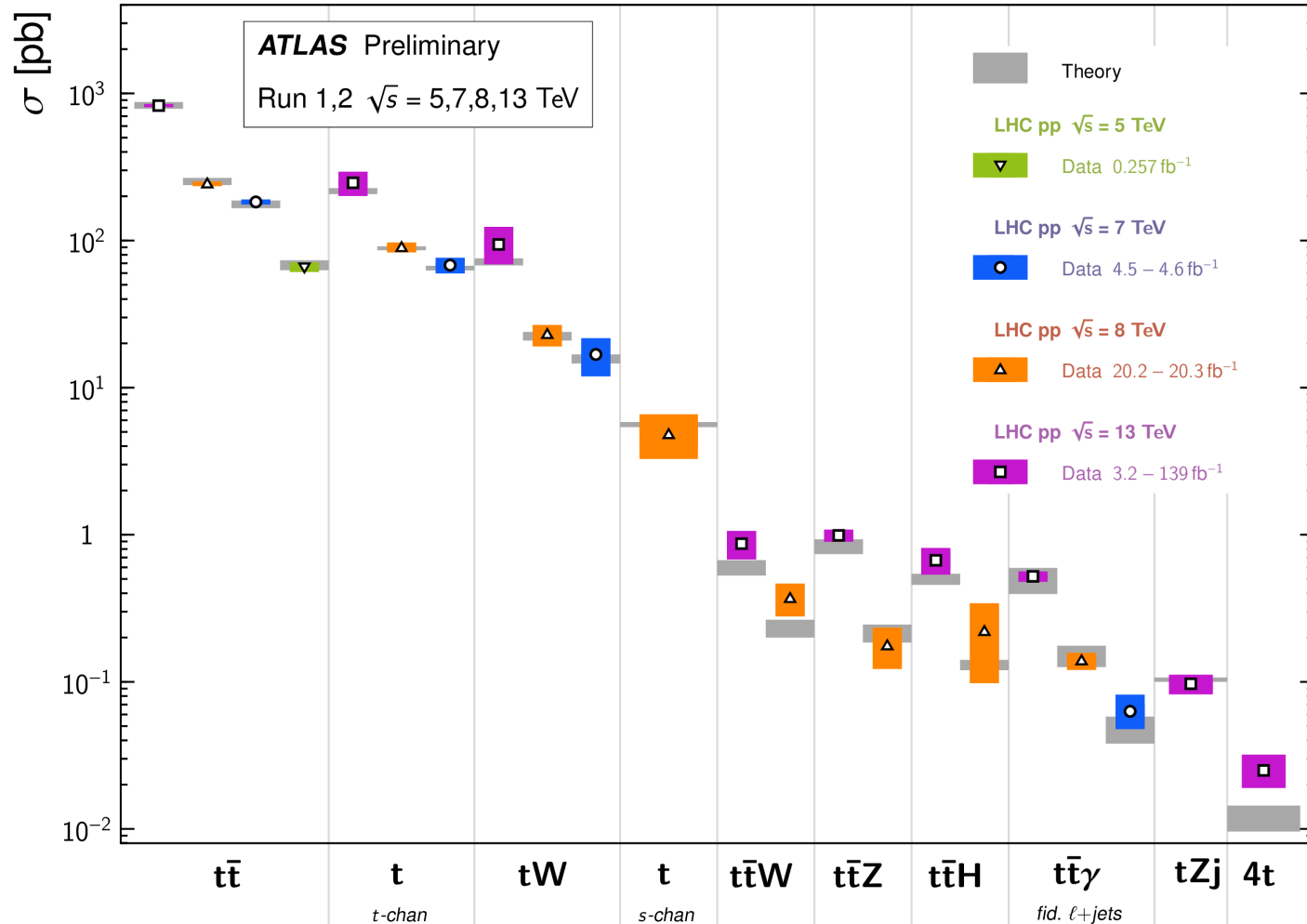
~ 30M single top,

~ 120K ttZ, tZ

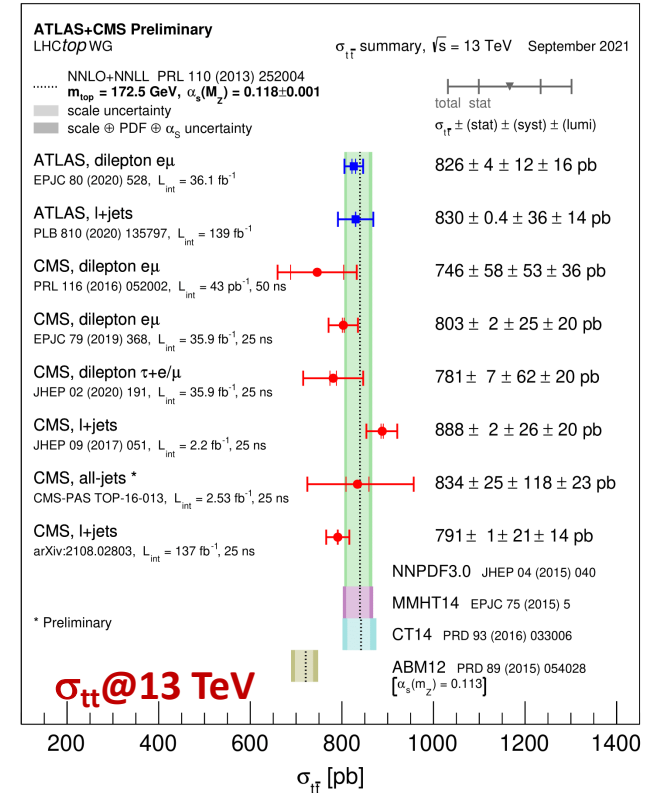
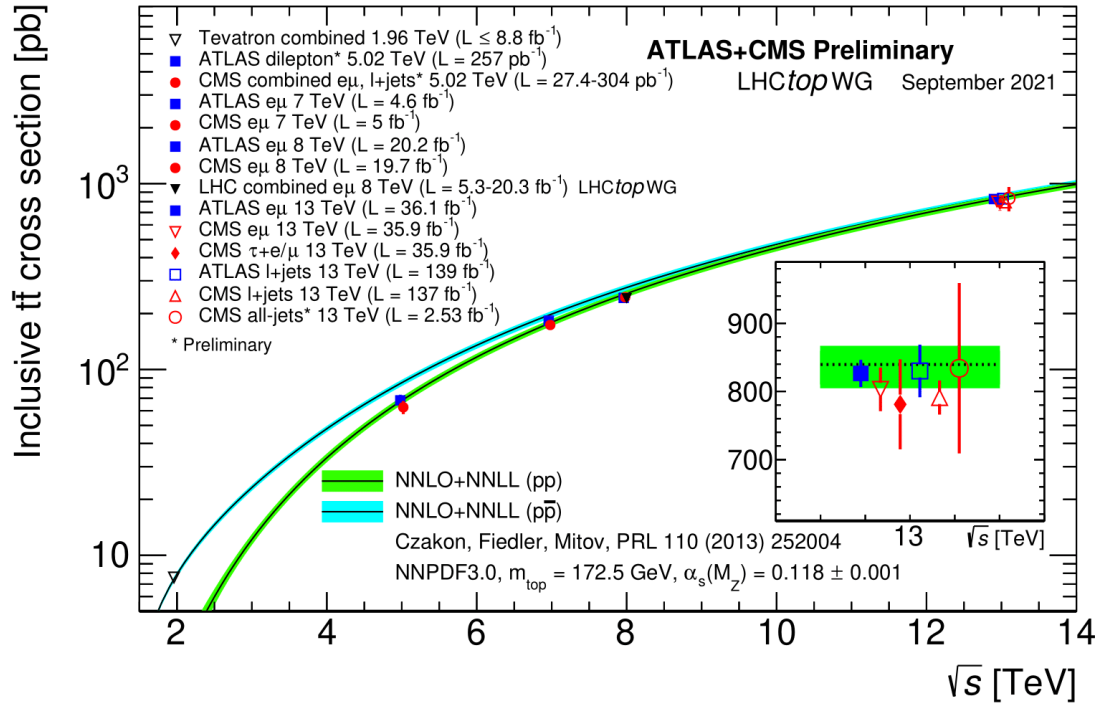
Top quark

Top Quark Production Cross Section Measurements

Status: May 2021



Inclusive tt cross sections



Measured in all channels:

Semi- and di-leptonic final state: unprecedented precision reached

And at all energies:

Reference pp runs @ 5 TeV for heavy ion programme

Next step: Go differential

Do we describe top quark kinematics well?

Provide inputs to the gluon PDF

Extract top mass and α_s

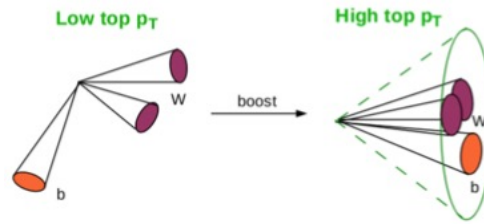
New physics hidden there ?

Differential cross sections

Differential and double-differential cross sections in full kinematic range @13 TeV

Measurements at particle and parton level (effects related to top quark decays, hadronization, and limited detector acceptance corrected)

Exploit **boosted topologies** to extend the phase space to highest p_T region: optimized event selection & reconstruction up to TeV range



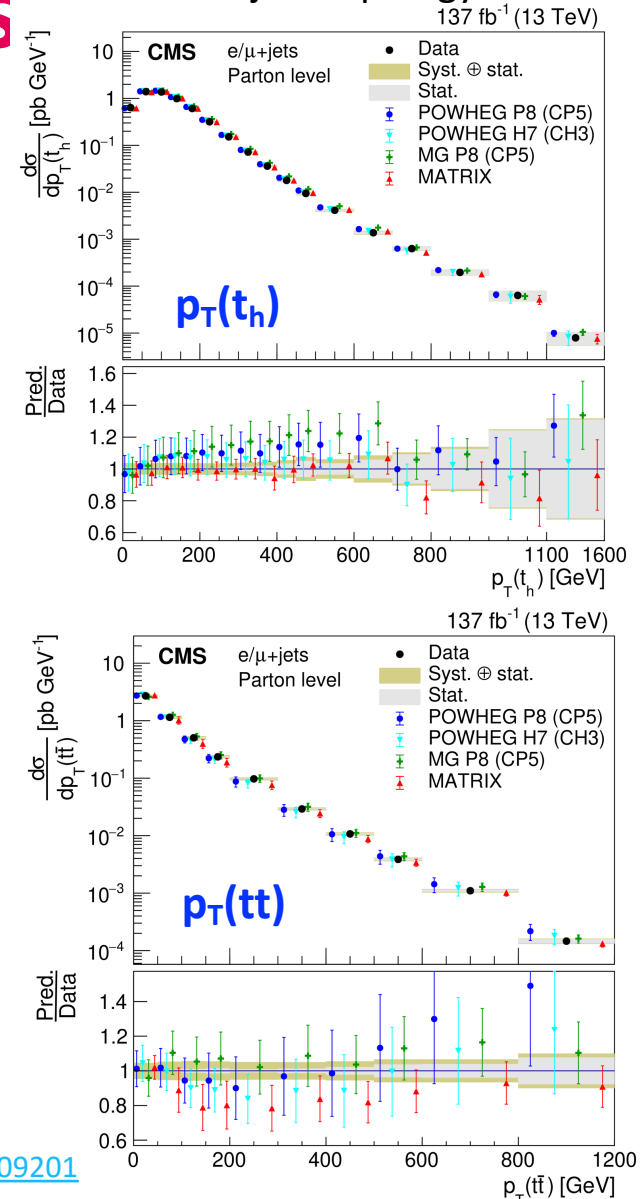
1D and 2D differential cross sections of top, tt and additional jets

Exhaustive comparison to theoretical predictions (NLO ME + PS) and NNLO calculations.

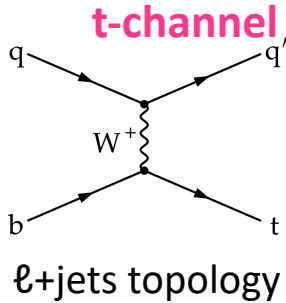
Most measurements are well described by SM predictions, in some cases challenging theory precision but many regions with large mismodelling (in particular, 2D-differential distributions)

[Phys. Rev. D 104 \(2021\) 09201](#)

$\ell + \text{jets}$ topology

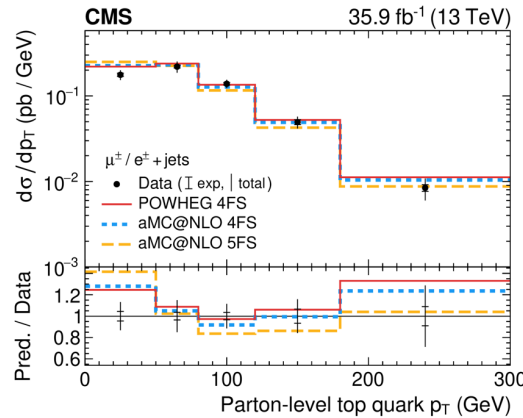


Single top



Inclusive, differential (unfolded) cross sections and charge ratios

Single top cross section at 13 TeV as high as $t\bar{t}$ cross section at 8 TeV

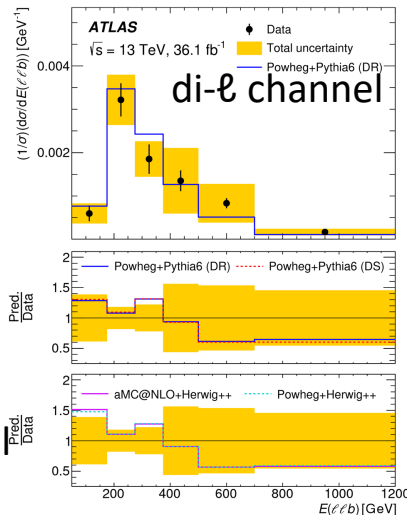
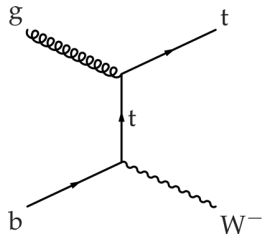


[Eur. Phys. J. C 80 \(2020\) 370](#)

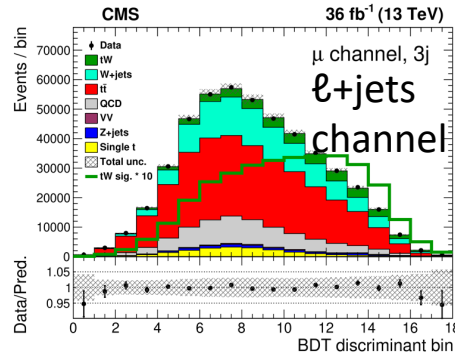
[JHEP 11 \(2021\) 111](#)

[Eur. Phys. J. C 78 \(2018\) 186](#)

tW-channel



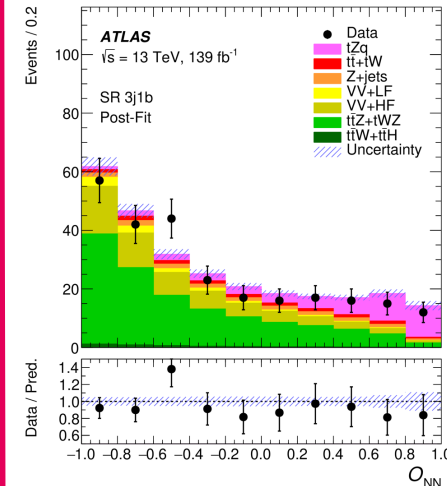
Not yet measurements of the s-channel



First observation of tW in μ or e +jets with $> 5\sigma$

tZq

3ℓ, 2 or 3 jets, ≥ 1 bjet



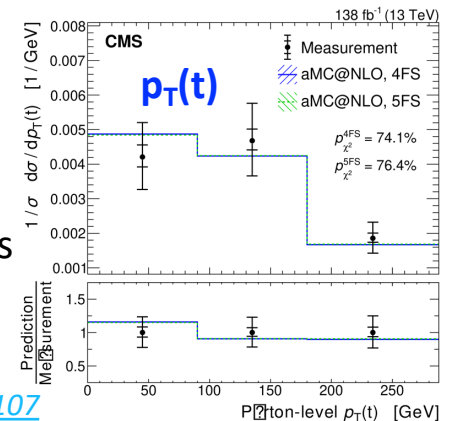
tZq observation reached ($>5\sigma$)

[JHEP 07 \(2020\) 124](#)

First unfolded differential distributions

3ℓ events, binned in jet/btag multiplicities

[JHEP 02 \(2022\) 107](#)

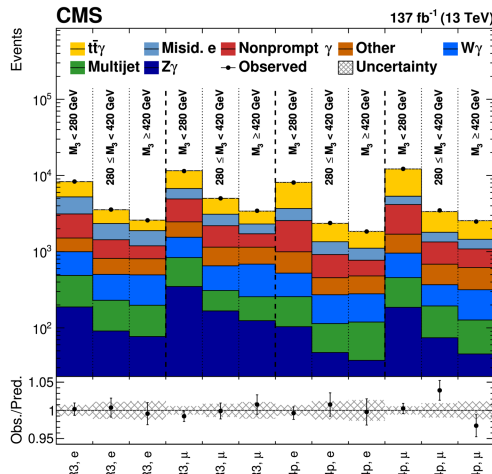


ttV (ttW, tW γ , ttZ, tt γ)

Probing top-electroweak couplings, which can be modified by BSM effects . Inclusive and many differential measurements appearing: parton and particle level, fiducial and full phase space, comparing data to various MC and theory calculations

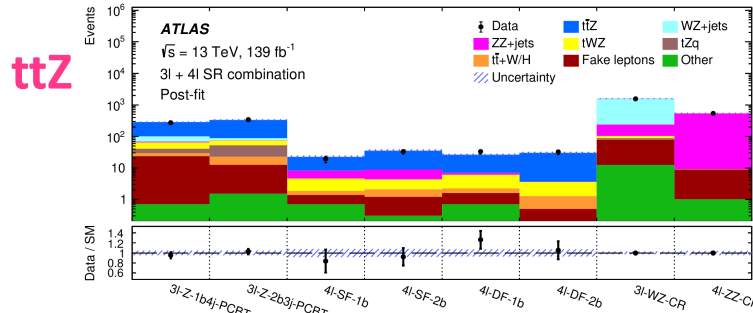
*Multiple analysis regions:
nb. Jets, leptons, tagging...*

tt γ 1 ℓ , 1 γ , ≥ 3 -jet, ≥ 2 -bjets

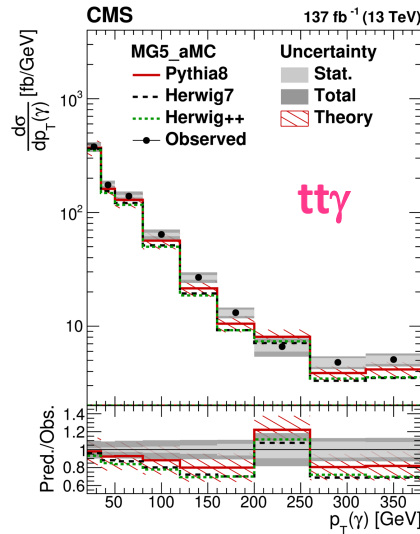


JHEP 12 (2021) 180

(tt γ also in the di- ℓ , 1 γ , ≥ 1 -bjet)

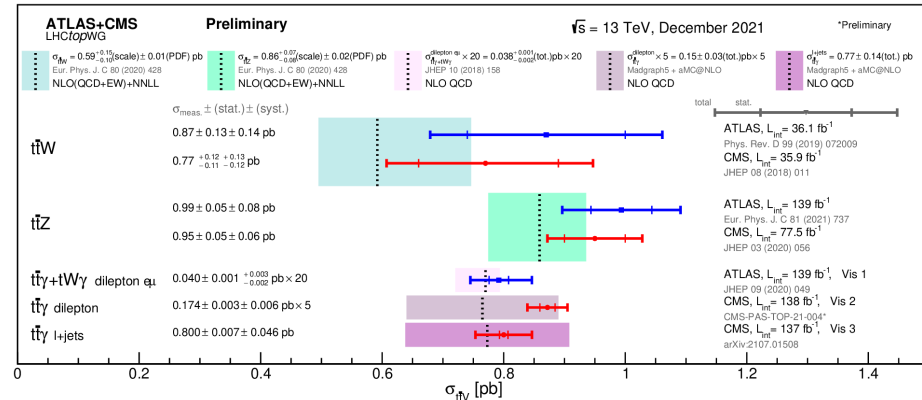
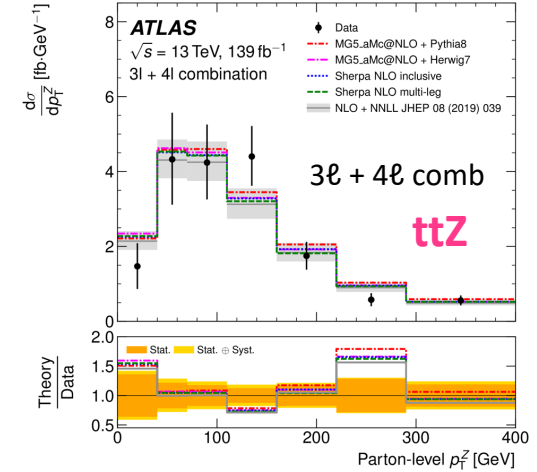


ttZ



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Eur. Phys. J. C 81 (2021) 737



Predictions smaller than measurements

top properties

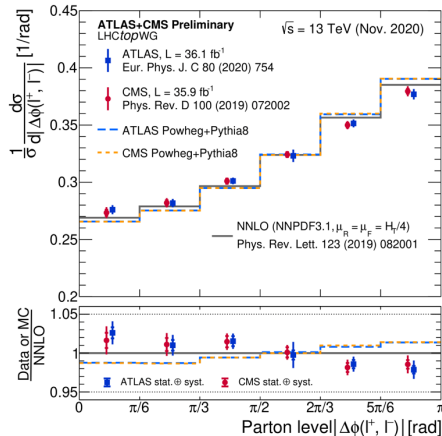
Direct measurement

m_t^{MC} using reconstructed decay products

Indirect measurement

Extract m_t in well defined renormalisation scheme (pole, MS, ...) measuring cross section with direct sensitivity to m_t ,

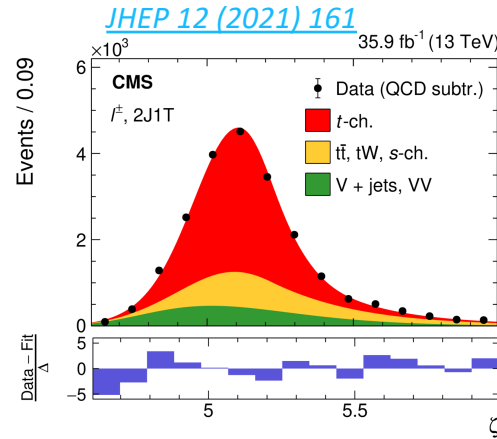
$$m_t^{\text{MC}} = m_t^{\text{pole}} \pm \Delta_{\text{MC}} \text{ O}(1\text{GeV})$$



+ charge and energy asymmetries, Wtb-vertex structure, spin and CP-violation...

Spin correlations

Mass



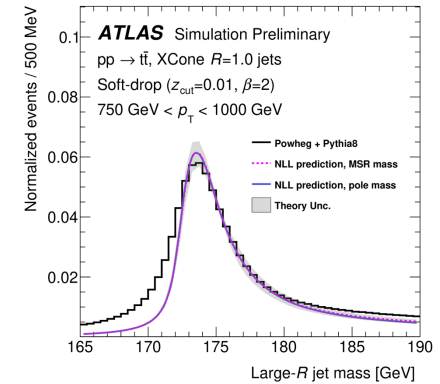
subGeV precision reached in single top (t-channel events)

Polarization in single top t-channel events

From the distributions of the direction cosines of the charged-lepton momentum in the top-quark rest frame

[arXiv:2202.11382](https://arxiv.org/abs/2202.11382)

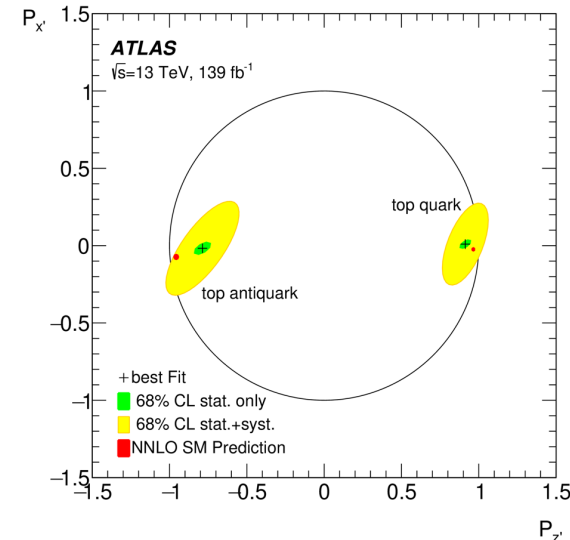
ATL-PHYS-PUB-2021-034



boosted topology

Calibrating m_t^{MC} wrt m_t^{MSR}

$$m_t^{\text{MC}} = m_t^{\text{MSR}} (1\text{GeV}) + 80^{+350}_{-410} \text{ MeV}$$

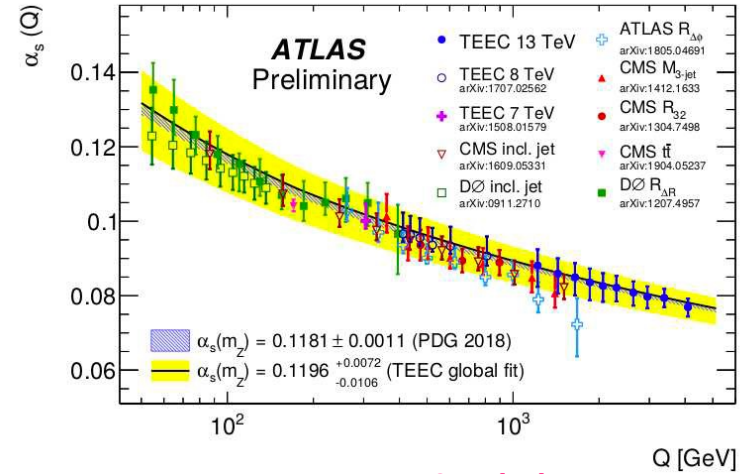
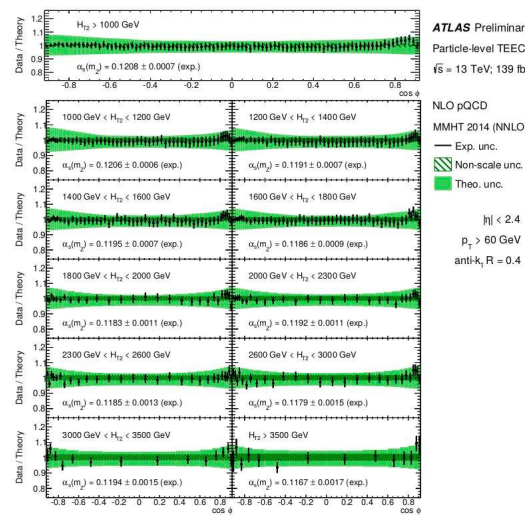
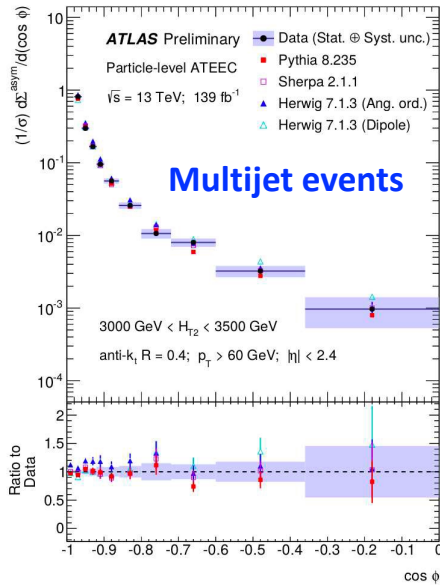


P_z

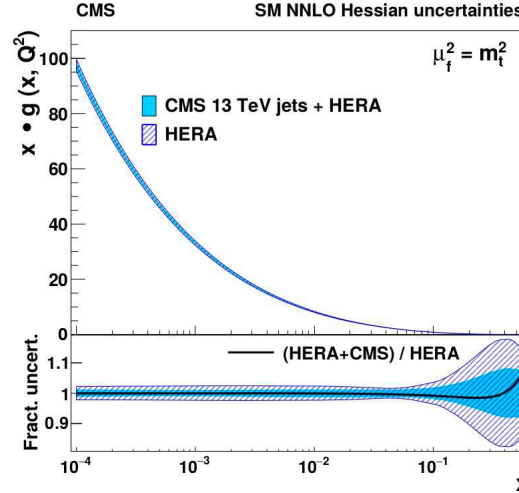
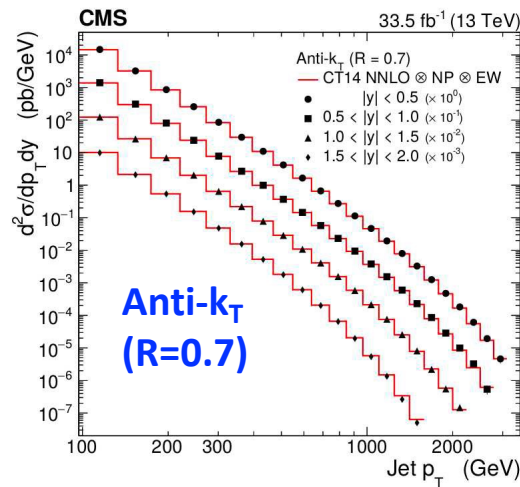
OTHER SM MEASUREMENTS

QCD (α_s and proton PDFs)

ATLAS-CONF-2020-025



Determination of $\alpha_s(Q)$ up to energy scales 4 TeV and test of asymptotic freedom in the multi-TeV regime



Inclusive jet cross sections using anti- k_T algorithm with $R = 0.7$
→ improved determination at NNLO QCD of the proton PDFs and $\alpha_s(m_Z)$ using CMS jet data plus HERA data

JHEP 02 (2022) 142

EWK processes

Overview of CMS cross section results

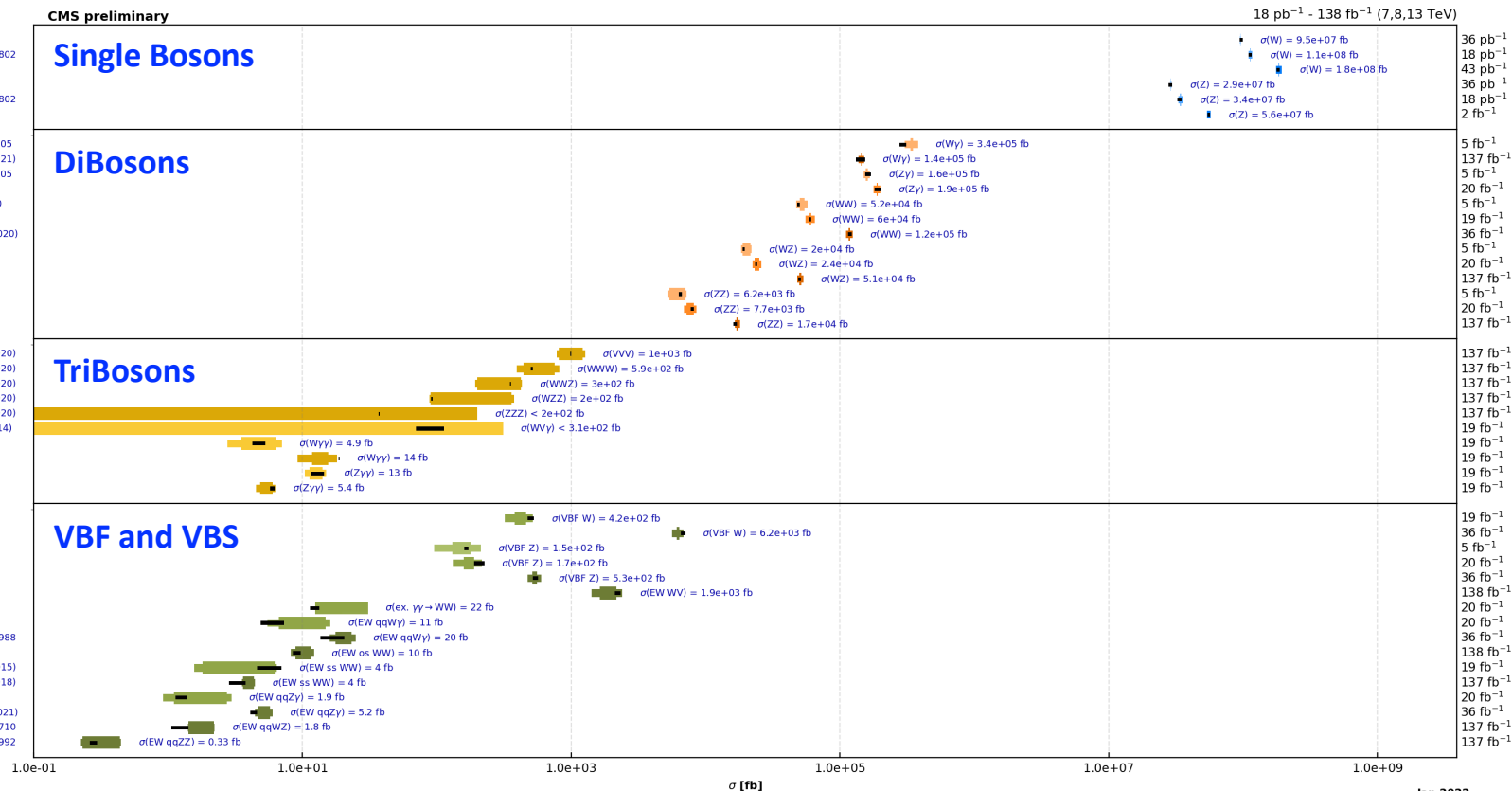
CMS preliminary

Single Bosons

DiBosons

TriBosons

VBF and VBS



Measured cross sections and exclusion limits at 95% C.L.
See here for all cross section summary plots

Jan 2022

Di(multi)bosons

WW, WZ, ZZ processes well established

Precision test of the EWK sector:

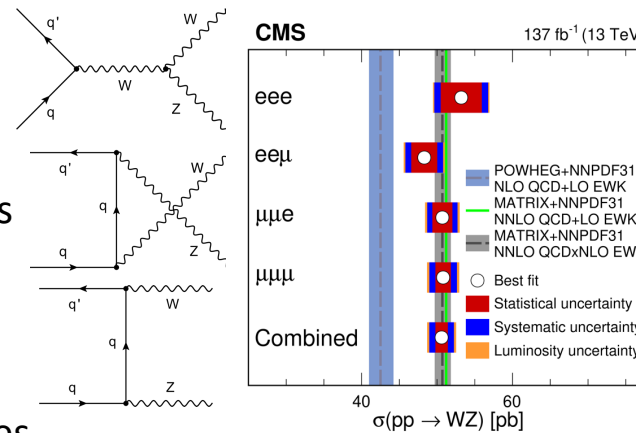
- ✓ Sensitive to higher order QCD/EWK corrections at TeV scale
- ✓ Electroweak Boson self-interactions
- ✓ Background to Higgs and BSM signatures
- ✓ Indirectly probe (model-independent) new physics at high mass scales

Different final states exploited:

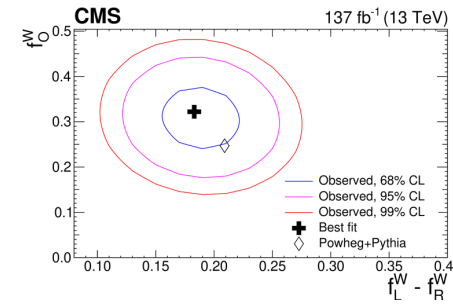
- ✓ full-leptonic and semi-leptonic final states
- ✓ final states with Missing E_T
- ✓ final states with photons

WZ $\rightarrow$ 3 ℓ ν

Total cross section



Polarization of W bosons

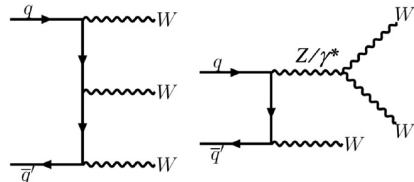


Testing NNLO QCD +NLO EWK predictions
+ diff. distributions

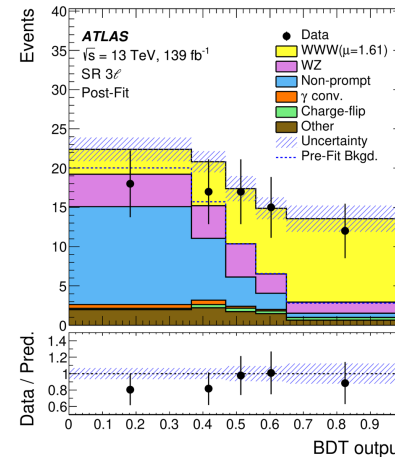
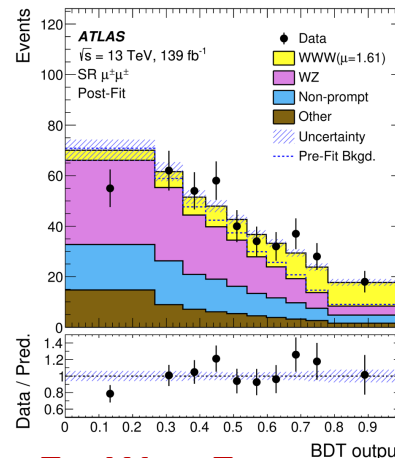
[arXiv:2110.11231](https://arxiv.org/abs/2110.11231)

WWW

(Tribosons) 2SS ℓ + 2jets
3 ℓ



[arXiv:2201.13045](https://arxiv.org/abs/2201.13045)



8.0 (5.4) σ observed
(expected) significance

CMS: Observation of WWW, WWZ, WZZ, and ZZZ

[Phys. Rev. Lett. 125 \(2020\) 151802](https://arxiv.org/abs/2005.01191)

ATLAS: Evidence for WWW, WWZ, WZZ

[Phys. Lett. B 798 \(2019\) 134913](https://arxiv.org/abs/1808.07564)

Much progress also in $W\gamma$, $Z\gamma$, $W\gamma\gamma$, $Z\gamma\gamma$

Vector Boson Fusion and Vector Boson Scattering

Triple and quartic VB gauge self-coupling not yet well known.

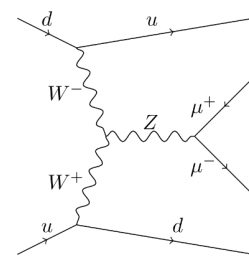
Very clean theoretically: Strengths determined by non-abelian SU(2) structure

At the LHC processes with:

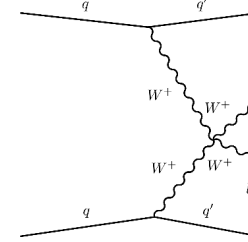
- ✓ Small cross sections
- ✓ Subdominant wrt competing processes.

Purely EWK processes

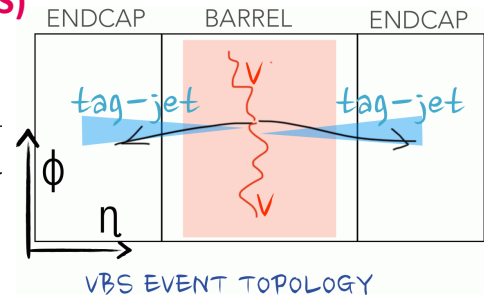
$qq \rightarrow Z qq$ (VBF)



$qq \rightarrow W^+W^+ qq$ (VBS)



Experimental signature

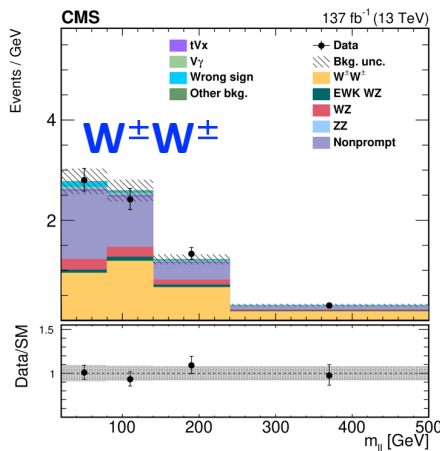


V or VV and 2 jets from the scattered quarks

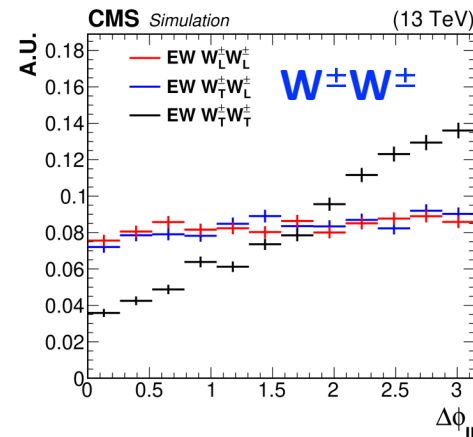
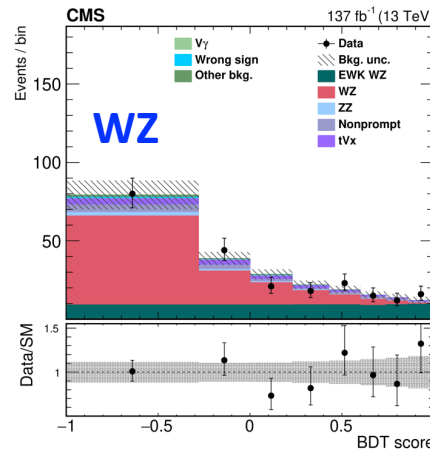
Large dijet rapidity difference $|\Delta\eta_{jj}|$ and/or invariant mass $|m_{jj}|$

TGC and QCG diagrams at the LO (direct access to self-couplings)

VBS $W^\pm W^\pm \rightarrow \ell^\pm \ell^\pm 2\nu$ and $WZ \rightarrow 3\ell\nu$



Simultaneous extraction of both signals



2.6σ obs. significance for $W_L W_X$

[Phys. Lett. B 812 \(2020\) 136018](#)

ZZjj, Zyjj, Wyjj at the level of evidence/first observation: first measurements

[Phys. Lett. B 809 \(2020\) 135710](#)

SEARCHES, SEARCHES, SEARCHES

Supersymmetry

Search program split by SUSY particle production

Strong + stop:

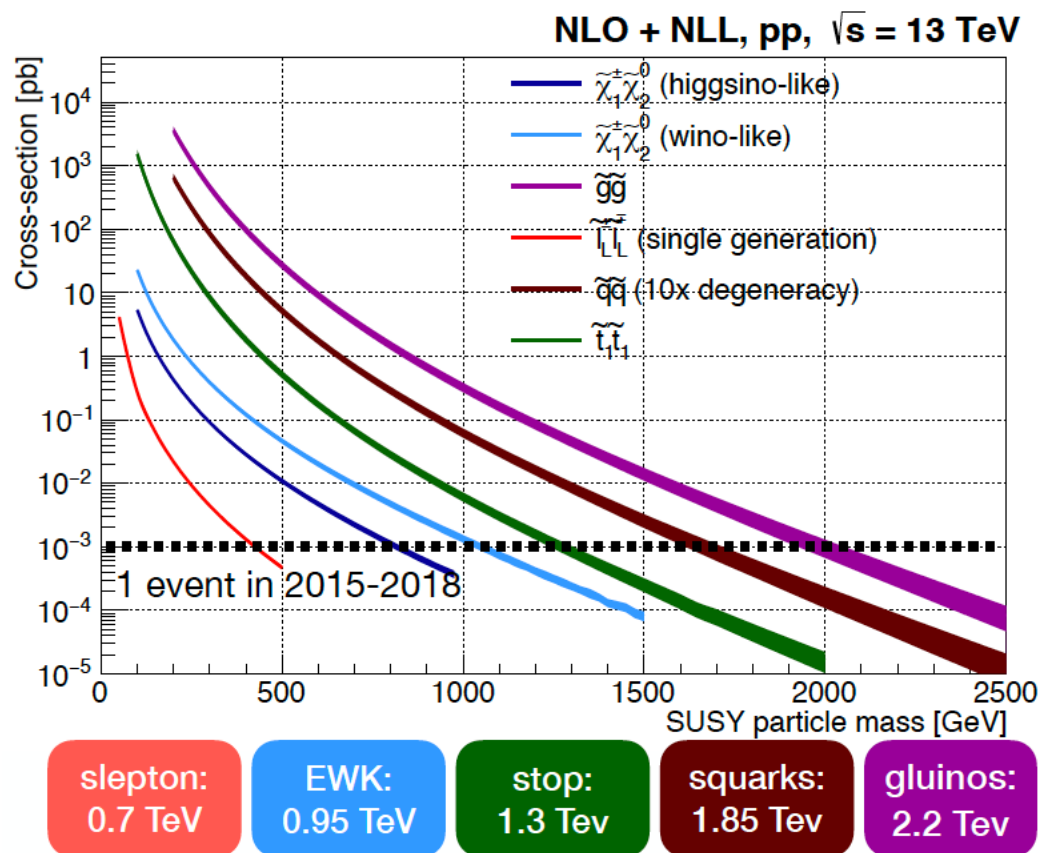
- ✓ Largest cross section
- ✓ Events with many jets in final state

Electroweak + slepton:

- ✓ Smaller cross section
- ✓ Final states depend on decay of bosons
- ✓ Leptonic final state
- ✓ Semileptonic or hadronic

Improving existing tools to increase sensitivity to signal
New decay modes
New final states

Simplified models and new interpretations



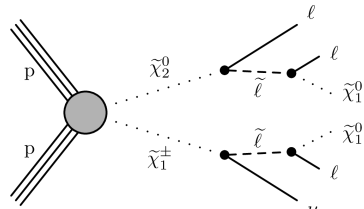
The Higgs boson is now part of the game
Cascade search with additional Higgs bosons

Electroweak production of charginos and neutralinos

Multiple signatures: 3ℓ or 4ℓ with up to two hadronically decaying τ leptons, or two same-sign light leptons

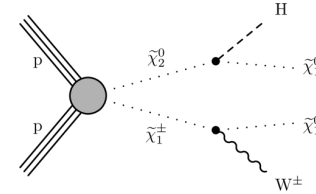
Interpreted in terms of multiple models

[arXiv:2106.14246](https://arxiv.org/abs/2106.14246)



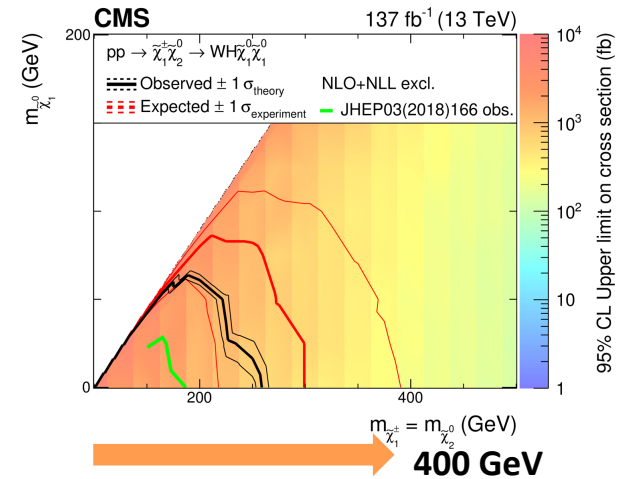
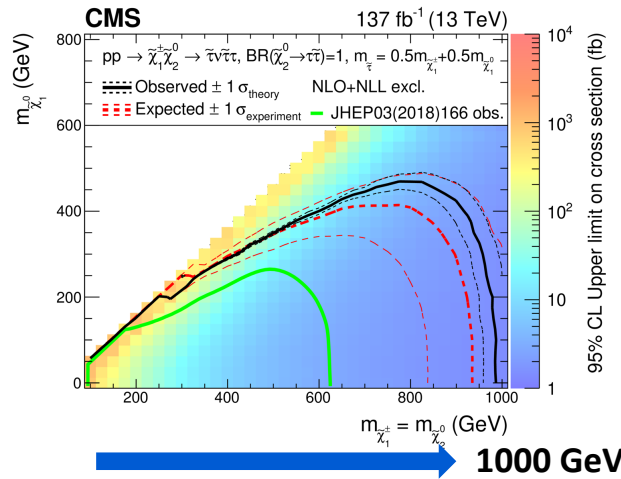
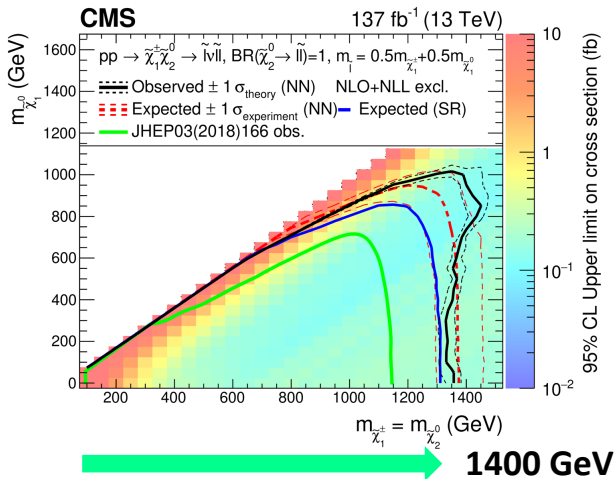
slepton-mediated

τ -enriched slepton-mediated



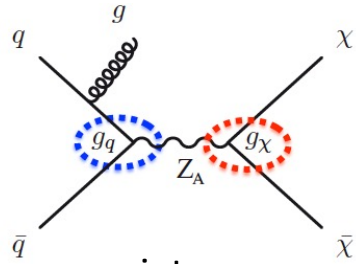
WH-mediated

Category	Requirements
2 ℓ SS	Two light leptons with the same sign
3 ℓ A	Three light leptons including one or more OSSF pairs
3 ℓ B	Three light leptons including no OSSF pairs
3 ℓ C	A pair of light leptons forming an OSSF pair and a τ_h candidate
3 ℓ D	A pair of light leptons of different flavor and opposite sign and a τ_h candidate
3 ℓ E	A pair of light leptons of same sign and a τ_h candidate
3 ℓ F	A light lepton and two τ_h candidates
4 ℓ G	Four light leptons including two independent OSSF pairs
4 ℓ H	Four light leptons including one or less OSSF pairs
4 ℓ I	Three light leptons and a τ_h candidate
4 ℓ J	Two light leptons and two τ_h candidates, including two OSSF pairs
4 ℓ K	Two light leptons and two τ_h candidates, including one or no OSSF pair



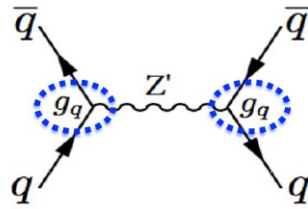
Dark Matter

Mono-X signatures
SM $\rightarrow$ mediator $\rightarrow$ DM



mono-jet, mono-photon, mono-Z, mono-W, mono-H

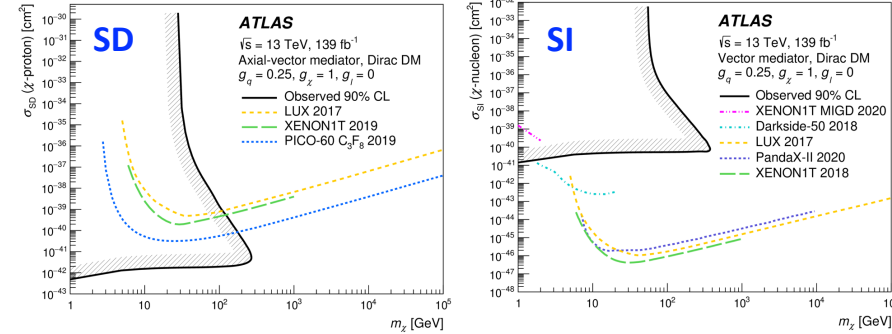
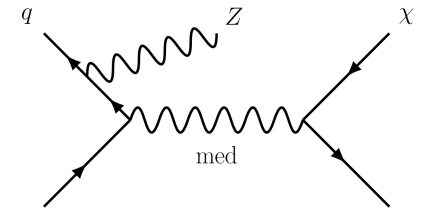
Visible (resonant) signature
SM $\rightarrow$ mediator $\rightarrow$ SM



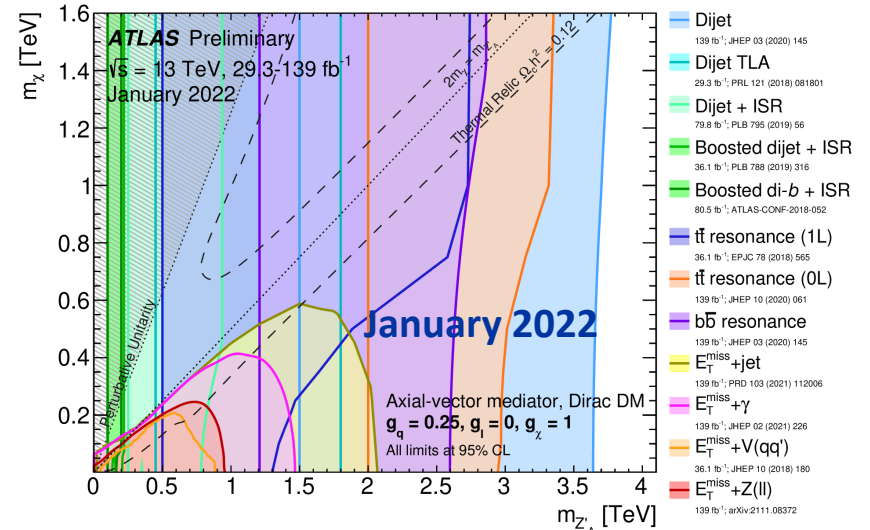
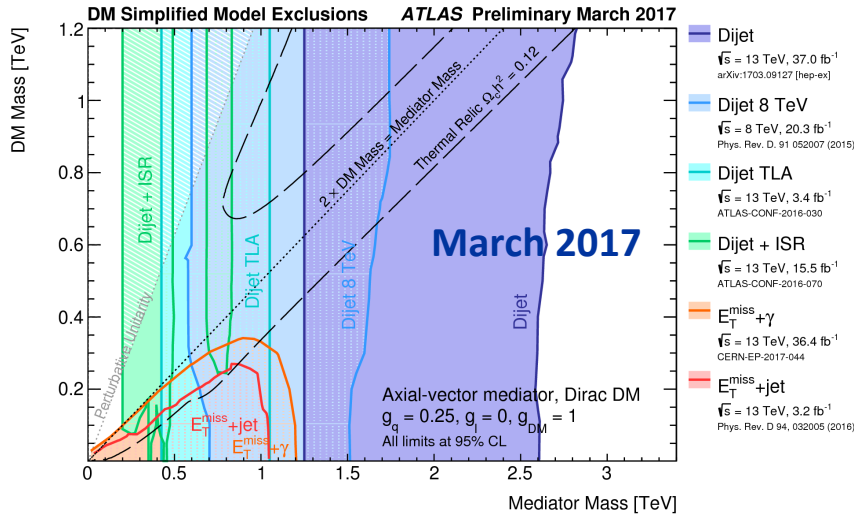
dijet, ditop, dilepton resonances

Mono-Z: $Z + E_T^{\text{miss}}$,
 $Z \rightarrow \ell^+ \ell^-$

[arXiv:2111.08372](https://arxiv.org/abs/2111.08372)

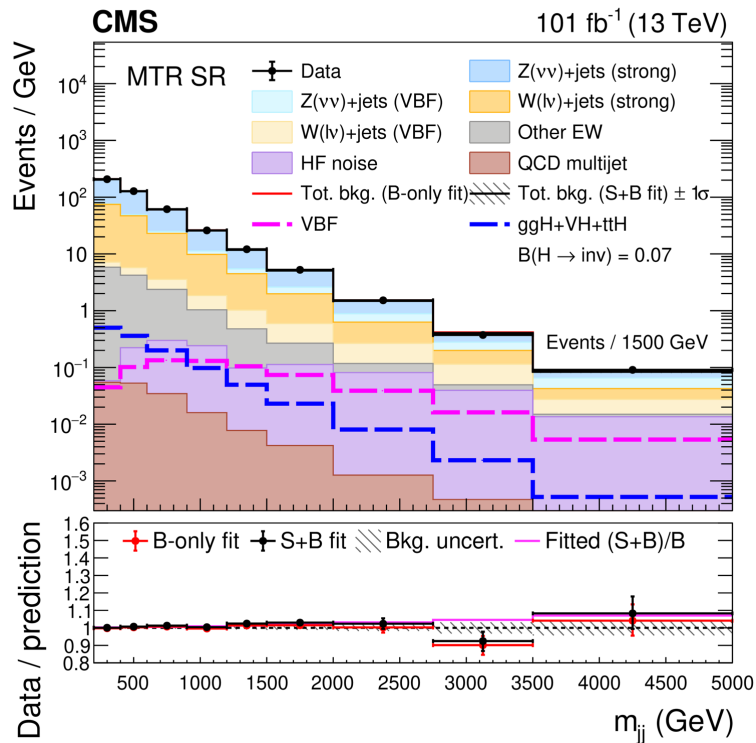


Complementary to Direct searches



Leptophobic axial-vector mediator simplified models

Can the Higgs decay to Dark Matter ?



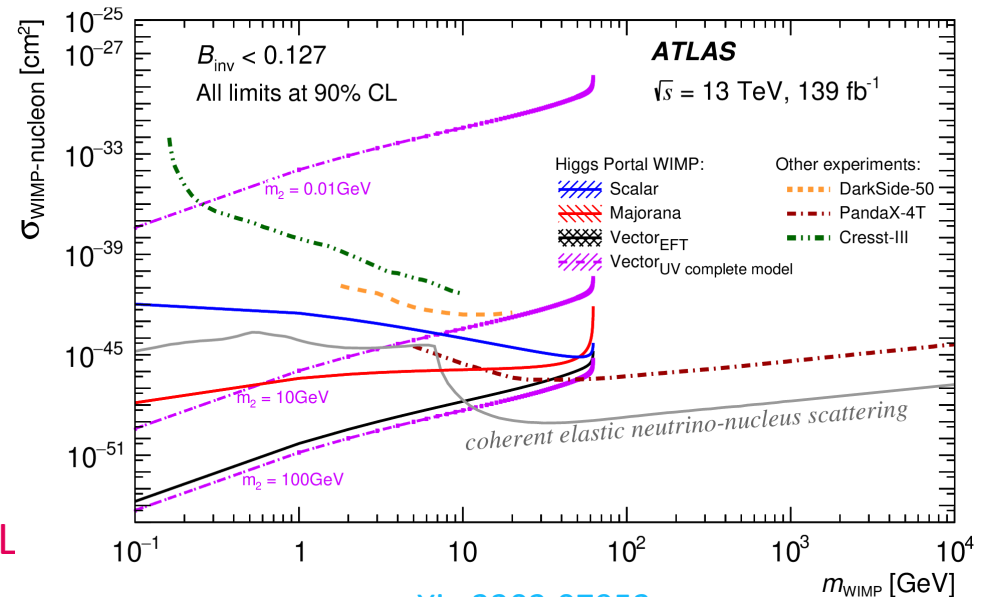
[arXiv:2201.11585](https://arxiv.org/abs/2201.11585)

CMS: $\text{Br}(H_{\text{inv}}) < 0.18$ (0.10) @ 95%CL

ATLAS: $\text{Br}(H_{\text{inv}}) < 0.145$ (0.103) @ 95%CL

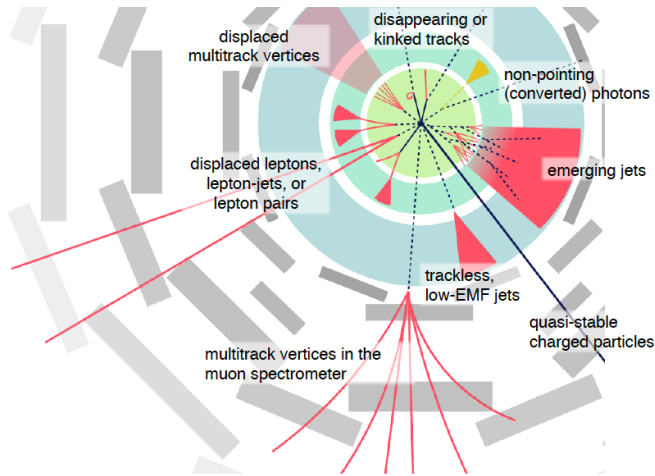
Is the Higgs the SM Higgs? Does it decay unusually?

- Amongst the direct searches for BSM decays ($h \rightarrow aa$, LFV h , ...), Higgs decays to invisible particles have a special role. Very small in the SM ($H \rightarrow ZZ \rightarrow 4\nu$), but prominent in models in which the Higgs can decay to Dark Matter candidates
- Signatures based on Missing Transverse Energy (MET): associated production modes (sp. VBF) dominate



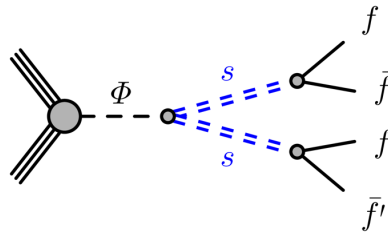
[arXiv:2202.07953](https://arxiv.org/abs/2202.07953)

Searches for Long Lived Particles



*Semi-stable New Particles,
decaying in the detector*

*Complete new program of
searches, where the NP lifetime
is a free parameter*

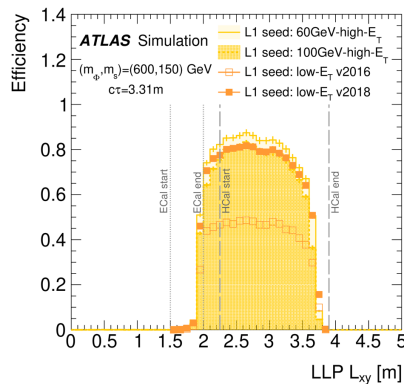


New challenges:

- ✓ Object identification
- ✓ Trigger
- ✓ Backgrounds

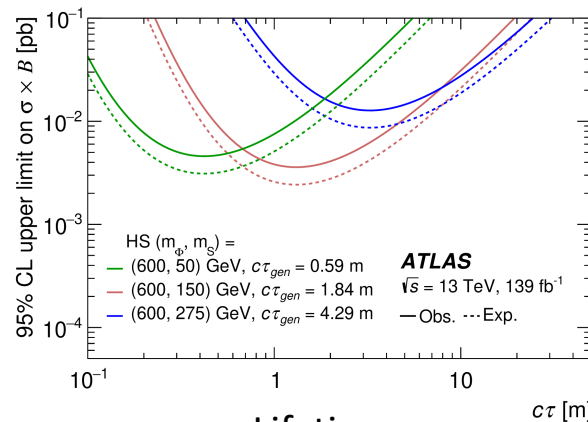
LLP searches interpreted in
the context of many
different models

Displaced jets in the calorimeter

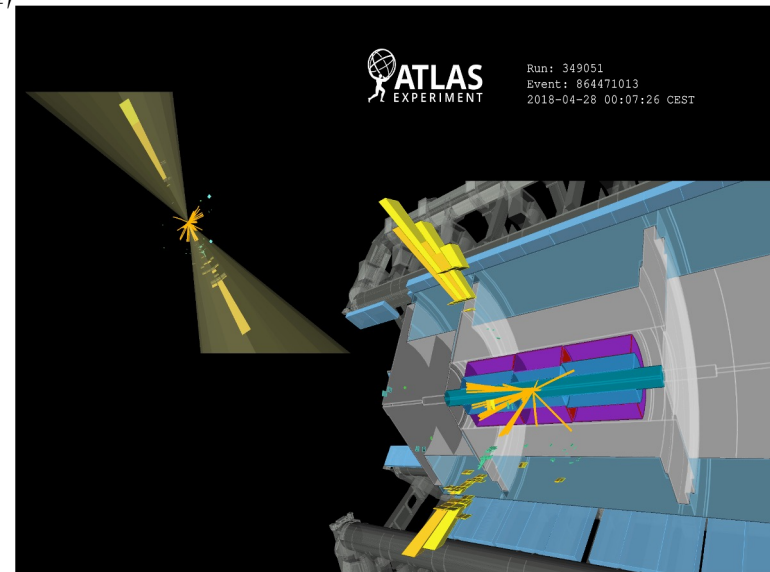


Trigger

[arXiv:2203.01009](https://arxiv.org/abs/2203.01009)



Lifetime

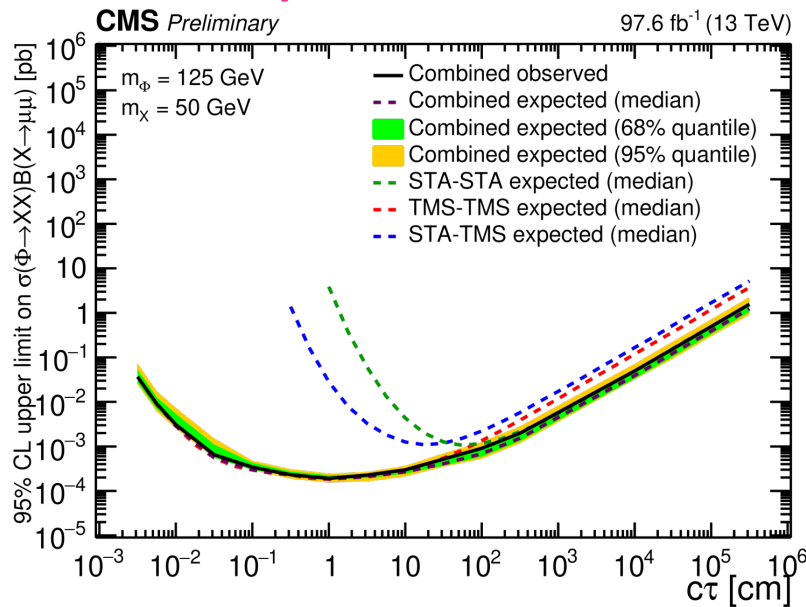


Can the Higgs decay to Long Lived Particles?

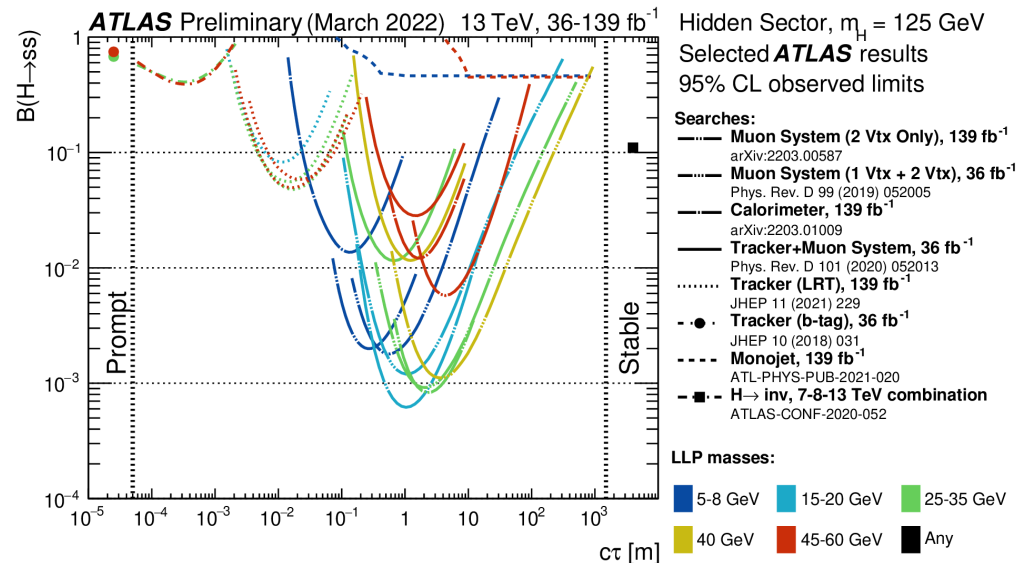
Looking for exotic Higgs decays goes beyond the traditional $h \rightarrow aa/ss$ searches

Expanding to probe for decays to Long Lived particles, Dark Bosons, ALPs... is one of the next frontiers

Displaced muons



[CMS EXO-21-006](#)



[ATL-PHYS-PUB-2022-007](#)

Leptoquarks

LQs new particle with both lepton number L and baryon number B

Scalar particle, $q=-1/3e$ $LQ_S \rightarrow t\tau, b\nu$

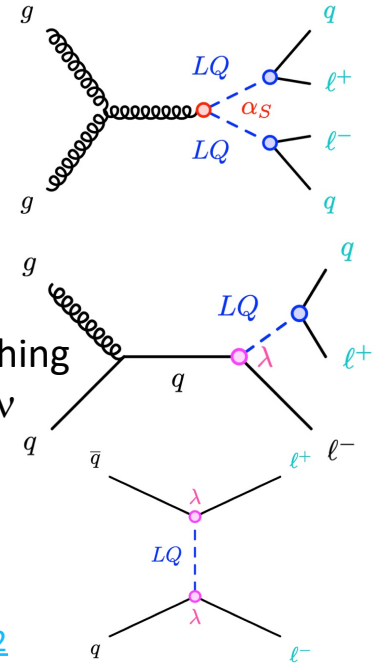
Vector particle, $q=+2/3$, $LQ_V \rightarrow t\nu, b\tau$

Models with third generation LQs and cross-generational mixing are favored by b-anomaly

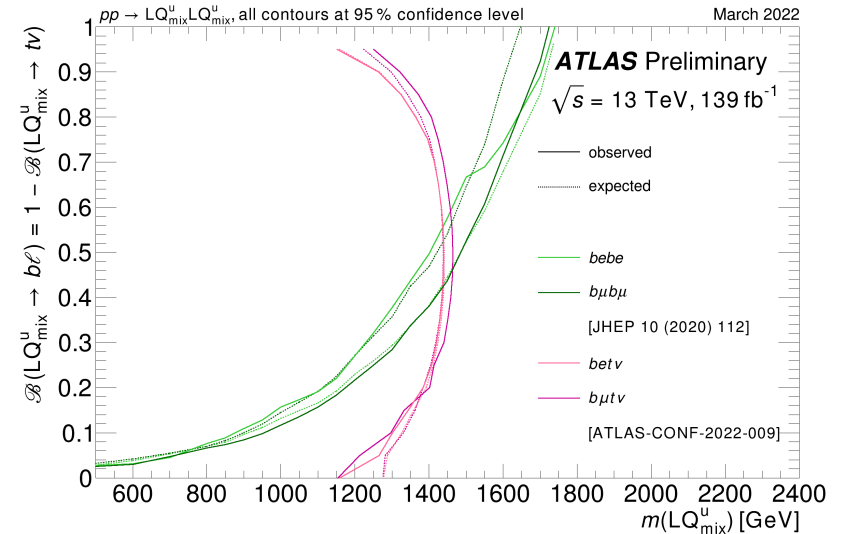
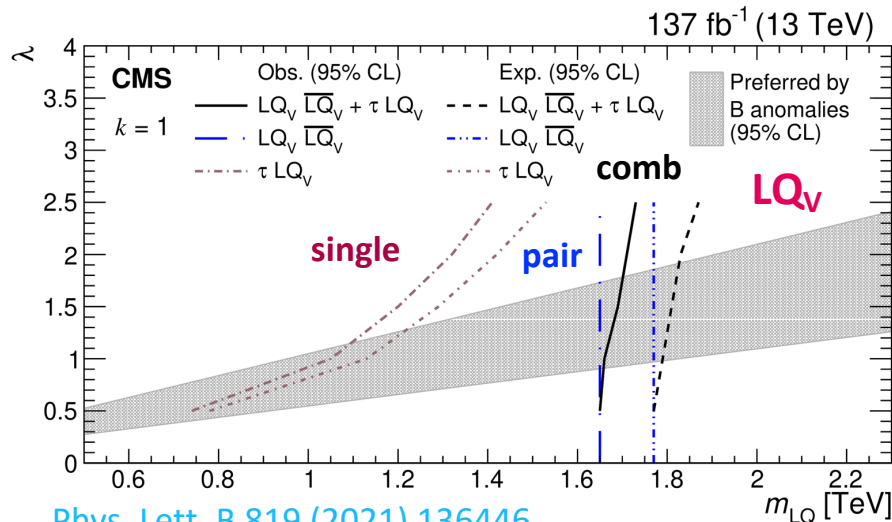
Pair or singly produced **LQ**, $LQ \rightarrow t\tau, b\nu, t\nu$, or $b\tau$
Inclusive hadronic decays of t and τ , and boosted top quark signature

λ = Yukawa coupling to the lepton-quark

β = relative couplings branching fraction $LQ \rightarrow q\ell$ or $LQ \rightarrow q\nu$



[ATL-PHYS-PUB-2022-012](#)



HIGHLIGHTS FROM LHCB

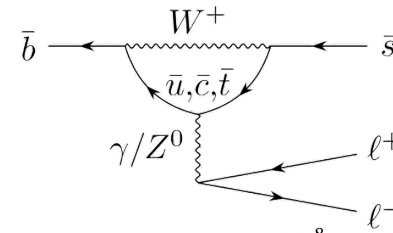
$b \rightarrow s \ell^+ \ell^-$ transitions

A rare decay (decay rate $< 10^{-6}$)

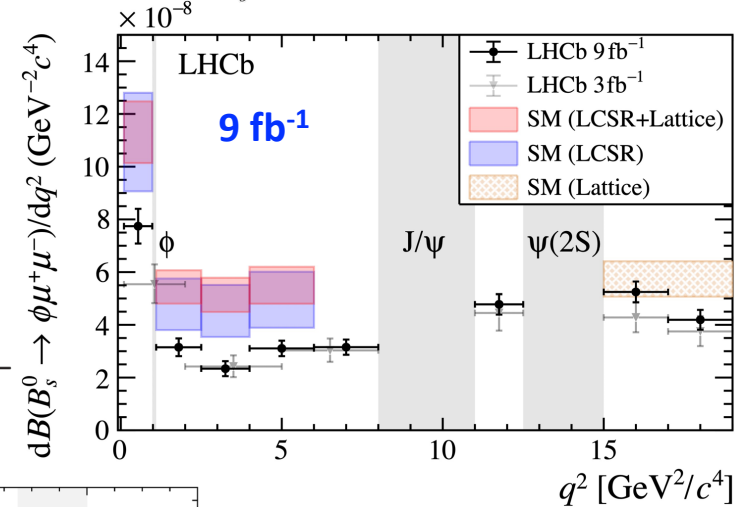
Forbidden at tree-level, proceeds through loop

Heavy NP could enter at the same order as SM

LHCb measurements show increasing tension with SM predictions



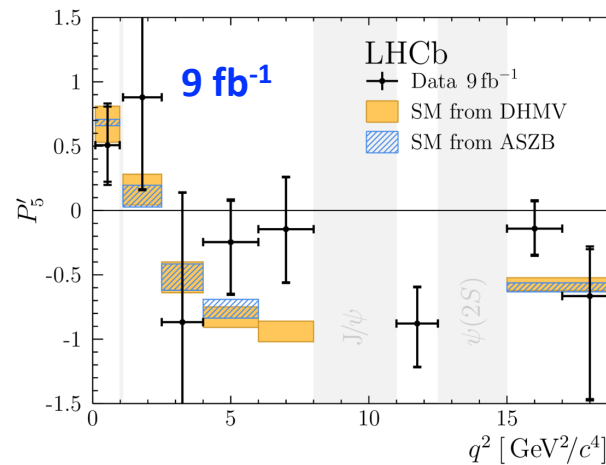
$$\mathcal{H}_{\text{eff}} = \frac{G_F}{\sqrt{2}} V_{tb} V_{ts}^* \sum_i C_i O_i$$



[Phys. Rev. Lett. 126 \(2021\) 161802](#)

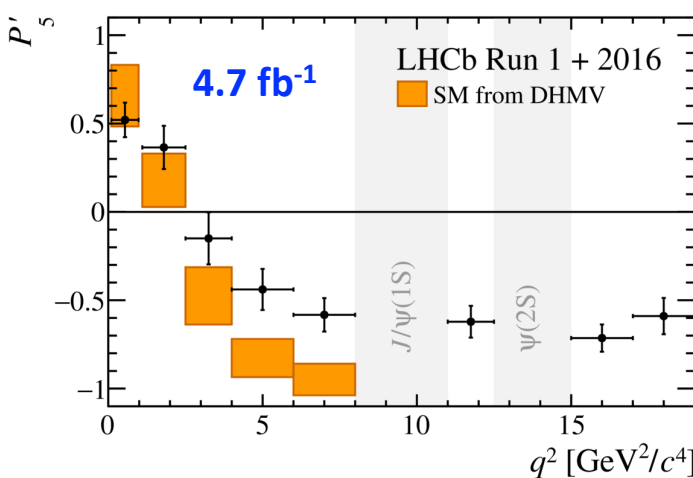
$$B^+ \rightarrow K^{*+} \mu^+ \mu^-$$

Angular analysis



$$B^0 \rightarrow K^{*0} \mu^+ \mu^-$$

Angular analysis



$\sim 3.3\text{-}3.6 \sigma$ tension wrt SM when interpreted in terms of C_9 coeff.

$$B_s^0 \rightarrow \phi \mu^+ \mu^-$$

Branching fractions of $b \rightarrow s \mu^+ \mu^-$ decays

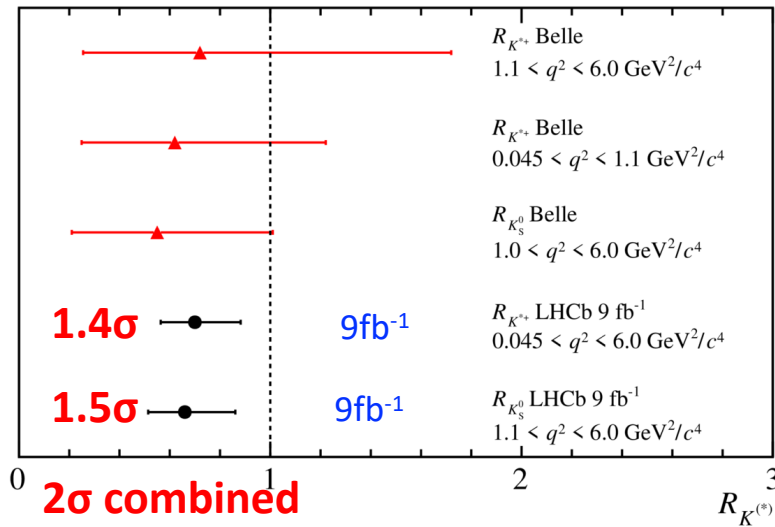
[Phys. Rev. Lett. 127 \(2021\) 151801](#)

$b \rightarrow s \ell^+ \ell^-$ transitions (LFU?) $B^+ \rightarrow K^+ \ell^+ \ell^-$ [arXiv:2103.11769](https://arxiv.org/abs/2103.11769)

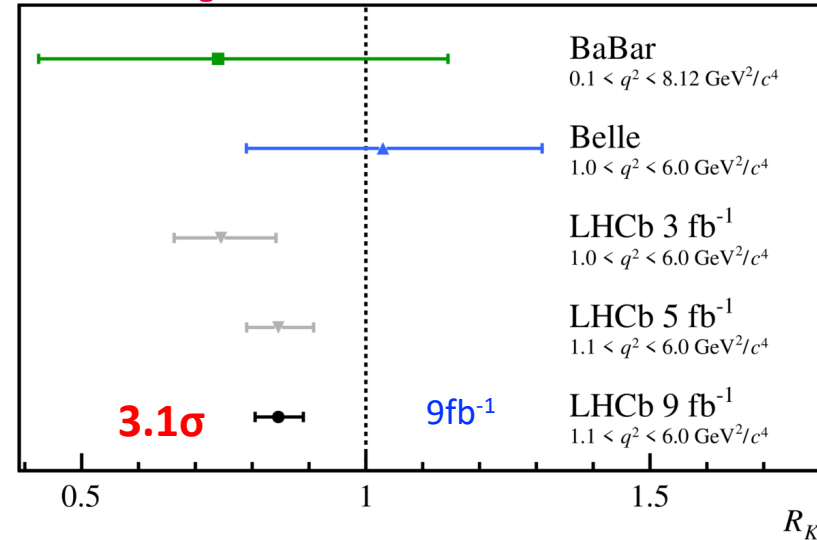
$$R_H = \frac{\int_{q_{\min}^2}^{q_{\max}^2} \frac{d\mathcal{B}(B \rightarrow H \mu^+ \mu^-)}{dq^2} dq^2}{\int_{q_{\min}^2}^{q_{\max}^2} \frac{d\mathcal{B}(B \rightarrow H e^+ e^-)}{dq^2} dq^2} \cong 1$$

$$R_K = 0.846^{+0.044}_{-0.041}$$

[arXiv:2110.09501](https://arxiv.org/abs/2110.09501)



No Run 2 update on $R(D)$ and $R(D^*)$



$$B^+ \rightarrow K^{*+} \ell^+ \ell^-$$

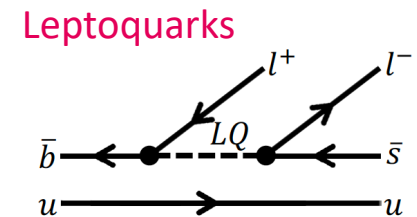
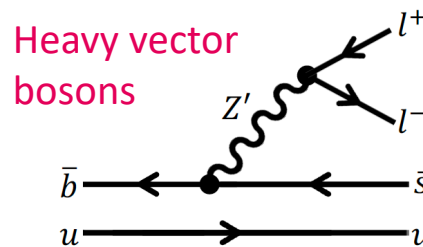
$$B^0 \rightarrow K_S^0 \ell^+ \ell^-$$

Final states

$$K_S^0 \rightarrow \pi^+ \pi^-$$

$$K^{*+} \rightarrow K_S^0 \pi^+$$

Possible coherent explanation involving tree-level new physics competing with SM loop and box diagrams



Rare b-hadron decays and CP-violating processes

$$B_{(s)}^0 \rightarrow \mu^+ \mu^- (\gamma)$$

High suppression in the SM

$$B(B_s^0 \rightarrow \mu^+ \mu^-) = 3.09^{+0.46}_{-0.43} {}^{+0.15}_{-0.11} \times 10^{-9}$$

- Significance > 10 σ
- in agreement with SM

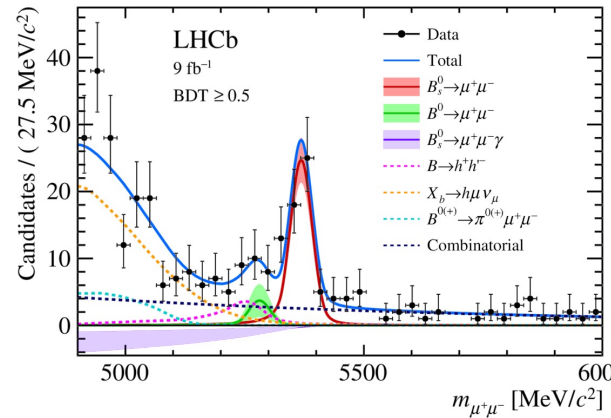
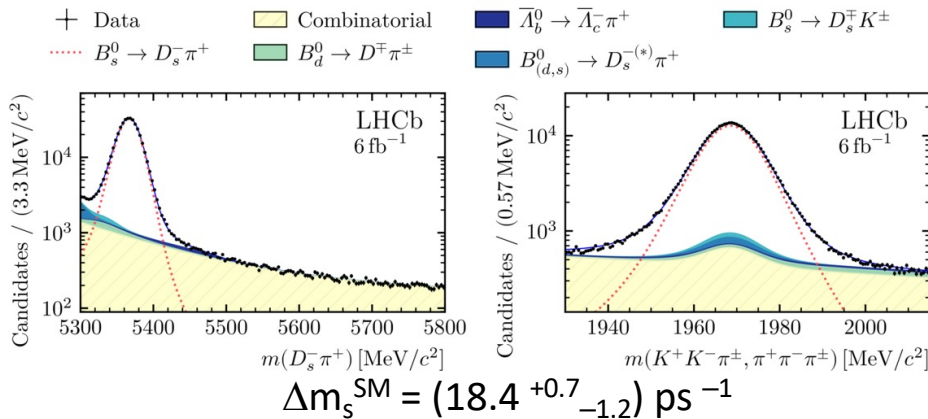
$$B^0 \rightarrow \mu^+ \mu^-$$

$$- B(B^0 \rightarrow \mu^+ \mu^-) < 2.6 \times 10^{-10} \text{ at 95\% CL}$$

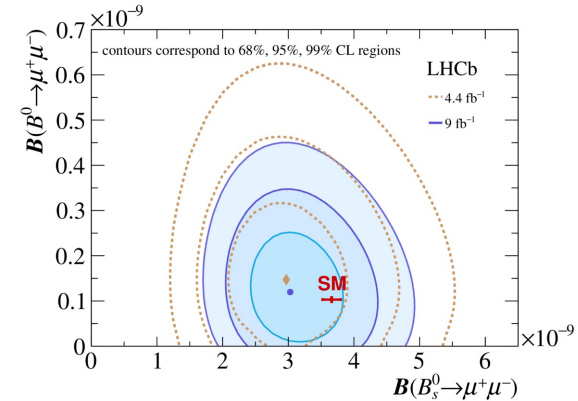
$$B_s^0 \text{ mass difference } \Delta m_s$$

Measured by oscillation frequency with $B_s^0 \rightarrow D_s^- \pi^+$ decays

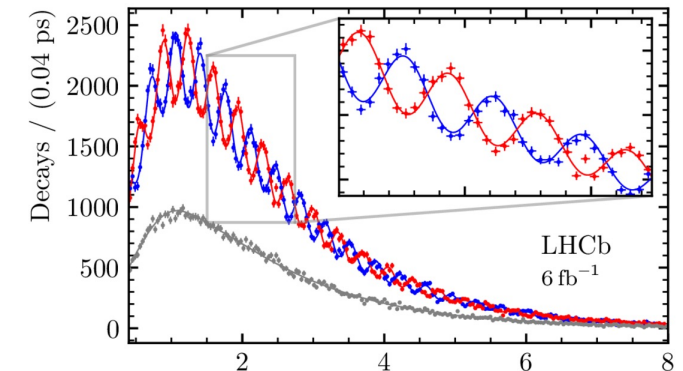
[Nat. Phys. 18, 1-5 \(2022\)](#)



[Phys. Rev. D105 \(2022\) 012010](#)



$$B_s^0 \rightarrow D_s^- \pi^+ \quad \bar{B}_s^0 \rightarrow B_s^0 \rightarrow D_s^- \pi^+ \quad \text{— Untagged}$$



$$\Delta m_s = 17.7683 \pm 0.0051 \pm 0.0032 \text{ ps}^{-1} \text{ [ps]}$$

Precision: 3×10^{-4}

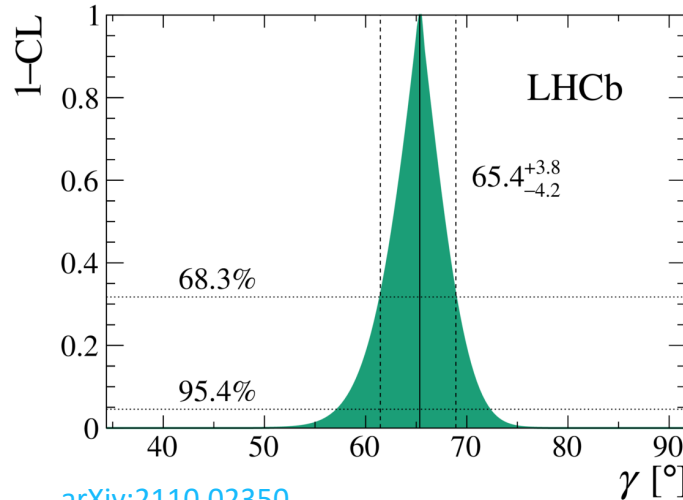
Legacy Measurement (combination)

$$\Delta m_s = 17.7656 \pm 0.0057 \text{ ps}^{-1}$$

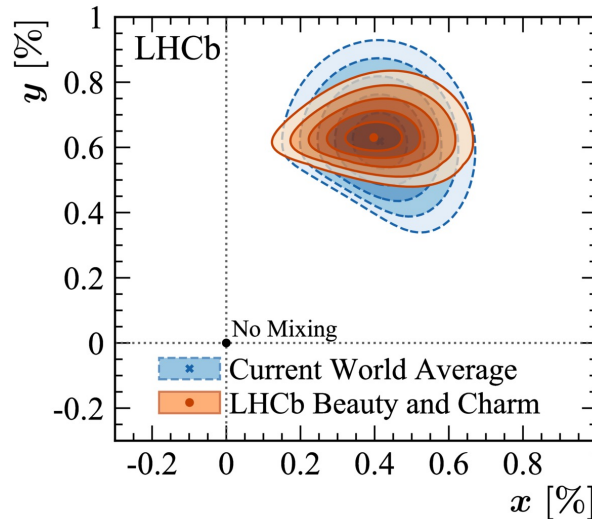
Highlights from LHCb

CKM angle γ

Simultaneous determination of **CKM angle γ** and **charm mixing parameters**



[arXiv:2110.02350](https://arxiv.org/abs/2110.02350)



CKM angle γ

$$\gamma = (65.4^{+3.8}_{-4.2})^\circ$$

Most precise measurement

Charm mixing parameters

$$x = (0.400^{+0.052}_{-0.053})\%$$

$$y = (0.630^{+0.033}_{-0.030})\%$$

Improvement in precision

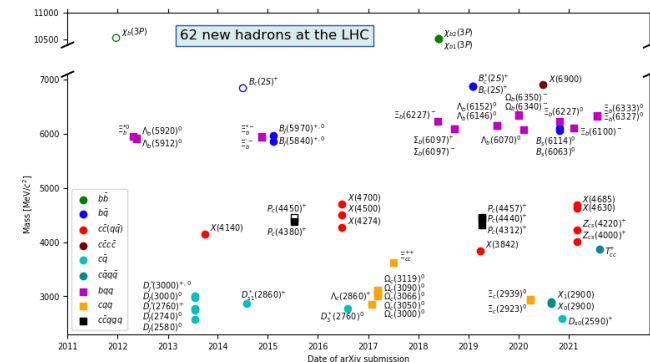
$$x \equiv (m_1 - m_2)/\Gamma$$

$$y \equiv (\Gamma_1 - \Gamma_2)/2\Gamma$$

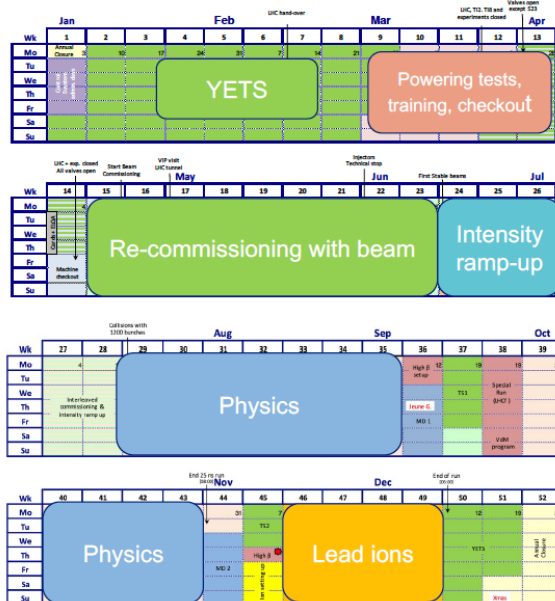
Spectroscopy

Many new states discovered by LHCb
Precise anatomy of conventional and exotic spectroscopy

EWK measurements in the forward region (complementary to ATLAS and CMS)



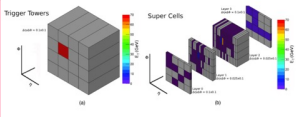
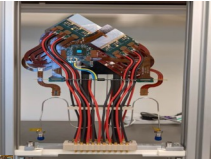
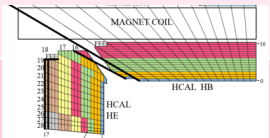
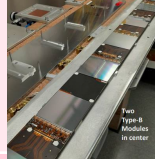
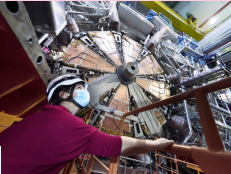
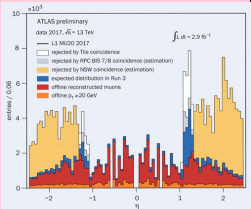
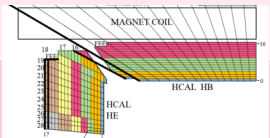
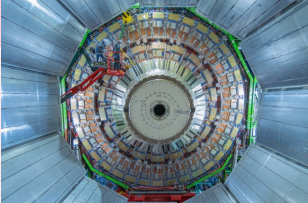
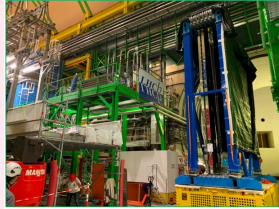
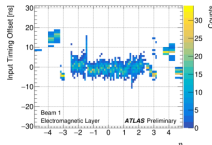
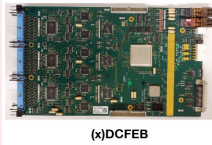
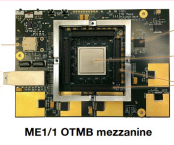
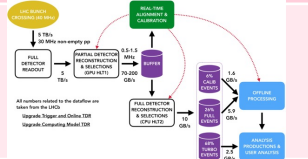
PROSPECTS FOR RUN 3



RUN 3

- ✓ $\sqrt{s} = 13.6$ TeV (14 TeV from 2023)
- ✓ $\mathcal{L} = 2 \times 10^{34} \text{ cm}^{-2}\text{s}^{-1}$ ($2 \times 10^{33} \text{ cm}^{-2}\text{s}^{-1}$ for LHCb)
- ✓ Average pileup $\mu = 50-60$
- Expected integrated luminosity (LHC)
 - ✓ 30 fb^{-1} in 2022 and 80 fb^{-1} in 2023-2025
 - ✓ Total $\mathcal{L}$ Run 3 $\rightarrow L = 270 \text{ fb}^{-1}$
 - ✓ Total $\mathcal{L}$ Run 2 + Run 3 $\sim 0.5 \text{ ab}^{-1}$
 - ✓ Total $\mathcal{L}$ Run 3 (LHCb) $\rightarrow L = 25 \text{ fb}^{-1}$

Upgrades implemented for Run 3

ATLAS	CMS	LHCb
L1-Calorimeter trigger with improved granularity 	New beam pipe, Tracker cooling, CMS opening system and other preparations for HL-LHC 	SiPixel Tk VELO 
New topological L1 trigger	Pixel replaced barrel layer 1 	SiStrip Tk UT 
Muons: New Small Wheel and new “EndCap” trigger  	HCAL BARREL SiPM+5Gbps Readout 	RICH optics & photodetectors 
	GE1/1: 144 GEM chambers Installed in the forward region 	SciCalo 
AFP (forward proton tagger) with new time-of-flight capability	Muon Barrel radiation shielding against neutron background 	New Electronics
Increased performance of software algorithms (Multi-Threading) 	CSC front end electronics for HL-LHC trigger rates  	Muon  Calo 
		RTA 

LHCb physics prospects

Improve the precision in flavour physics observables and in other exploration studies in the forward region by exploiting 5x more instantaneous luminosity with an upgraded detector



[Framework TDR for the LHCb Upgrade II](#)

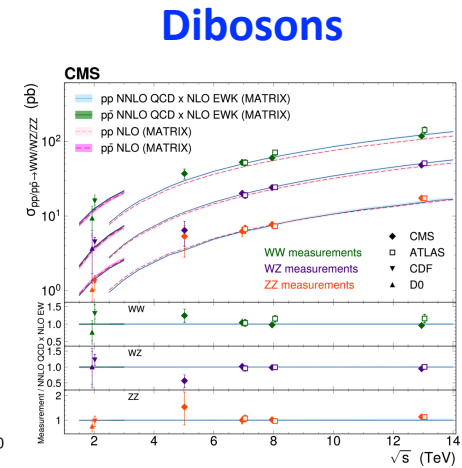
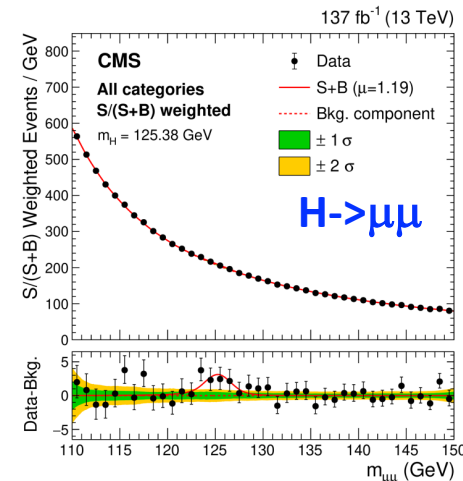
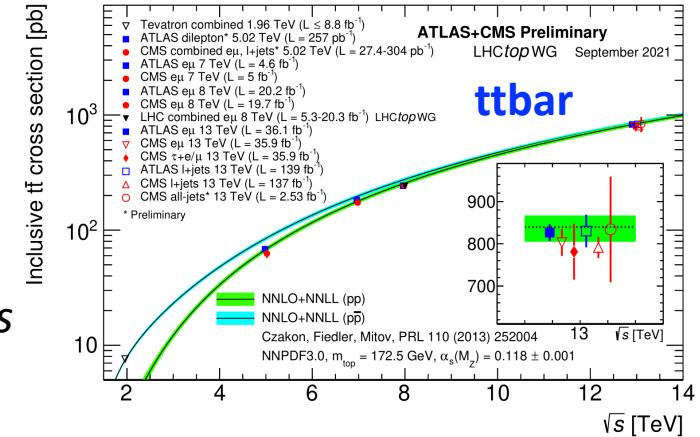
Observable	Current LHCb (up to 9 fb ⁻¹)	Upgrade I (23 fb ⁻¹) (50 fb ⁻¹)	
CKM tests			
γ ($B \rightarrow DK$, <i>etc.</i>)	4° [9,10]	1.5°	1°
ϕ_s ($B_s^0 \rightarrow J/\psi\phi$)	49 mrad [8]	14 mrad	10 mrad
$ V_{ub} / V_{cb} $ ($\Lambda_b^0 \rightarrow p\mu^-\bar{\nu}_\mu$, <i>etc.</i>)	6% [29,30]	3%	—
a_{sl}^d ($B^0 \rightarrow D^-\mu^+\nu_\mu$)	36×10^{-4} [34]	8×10^{-4}	5×10^{-4}
a_{sl}^s ($B_s^0 \rightarrow D_s^-\mu^+\nu_\mu$)	33×10^{-4} [35]	10×10^{-4}	7×10^{-4}
Charm			
ΔA_{CP} ($D^0 \rightarrow K^+K^-, \pi^+\pi^-$)	29×10^{-5} [5]	17×10^{-5}	—
A_Γ ($D^0 \rightarrow K^+K^-, \pi^+\pi^-$)	13×10^{-5} [38]	4.3×10^{-5}	—
Δx ($D^0 \rightarrow K_S^0\pi^+\pi^-$)	18×10^{-5} [37]	6.3×10^{-5}	4.1×10^{-5}
Rare Decays			
$\mathcal{B}(B^0 \rightarrow \mu^+\mu^-)/\mathcal{B}(B_s^0 \rightarrow \mu^+\mu^-)$	71% [40,41]	34%	—
$S_{\mu\mu}$ ($B_s^0 \rightarrow \mu^+\mu^-$)	—	—	—
$A_{\text{T}}^{(2)}$ ($B^0 \rightarrow K^{*0}e^+e^-$)	0.10 [52]	0.060	0.043
A_{T}^{Im} ($B^0 \rightarrow K^{*0}e^+e^-$)	0.10 [52]	0.060	0.043
$\mathcal{A}_{\phi\gamma}^{\Delta\Gamma}$ ($B_s^0 \rightarrow \phi\gamma$)	$^{+0.41}_{-0.44}$ [51]	0.124	0.083
$S_{\phi\gamma}$ ($B_s^0 \rightarrow \phi\gamma$)	0.32 [51]	0.093	0.062
$\alpha_\gamma(\Lambda_b^0 \rightarrow \Lambda\gamma)$	$^{+0.17}_{-0.29}$ [53]	0.148	0.097
Lepton Universality Tests			
R_K ($B^+ \rightarrow K^+\ell^+\ell^-$)	0.044 [12]	0.025	0.017
R_{K^*} ($B^0 \rightarrow K^{*0}\ell^+\ell^-$)	0.10 [61]	0.031	0.021
$R(D^*)$ ($B^0 \rightarrow D^{*-}\ell^+\nu_\ell$)	0.026 [62,64]	0.007	—

ATLAS & CMS

Many analyses will be repeated with up to twice the integrated luminosity, with additional improvements in sensitivity from further developments, including ML techniques, and reduction of the systematic uncertainties

SM processes measured with high precision at the new energy points

- Discovery-through-precision. Work to improve systematics (calibrations and methods)
- Higher statistics will help (stat. in control samples)
- Effort in **modelling** (b,c quarks modelling in $t\bar{t}b\bar{a}$, V+HF jets)
- Consolidate Run-2 observations. Evidence (**$H\mu\mu$** , **VBS**, **tribosons**, **4tops** ...) will reach observation --> differential measurements
- Towards evidence of **rare** (Higgs and others) **processes**
- Strengthen ATLAS & CMS collaboration (generators, MC tunes...), combinations ...



And Effective Field Theory (EFT): towards an integrated Top/Higgs/EW fit

$$\mathcal{L}_{\text{SMEFT}} = \mathcal{L}_{\text{SM}} + \frac{1}{\Lambda} \mathcal{L}_5 + \frac{1}{\Lambda^2} \mathcal{L}_6 + \frac{1}{\Lambda^3} \mathcal{L}_7 + \frac{1}{\Lambda^4} \mathcal{L}_8 + \dots$$

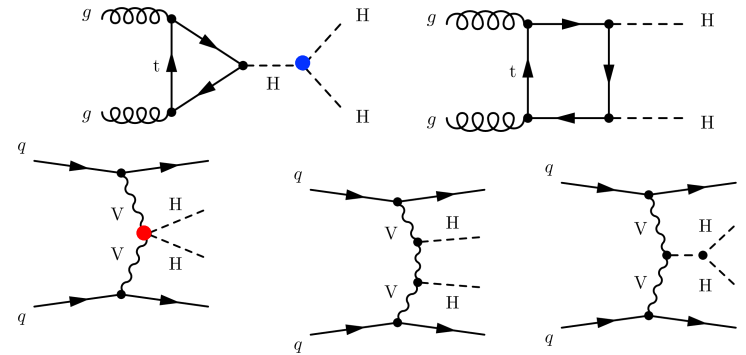
$$\mathcal{L}_n = \sum_i C_i \mathcal{O}_i^{d=n}$$

DiHiggs Production: chasing the Higgs self-coupling

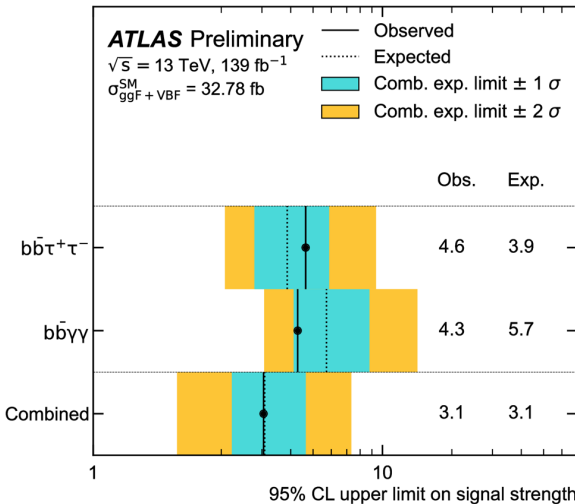
Searching for HH production probes the Higgs self coupling and the **shape of the Higgs potential**

With Run2 data, the golden channels already reach cross sections upper limits of **4-5xSM** per channel per experiment (~3x combined)

ggF and VBF production explored (access κ_λ and κ_{2V})

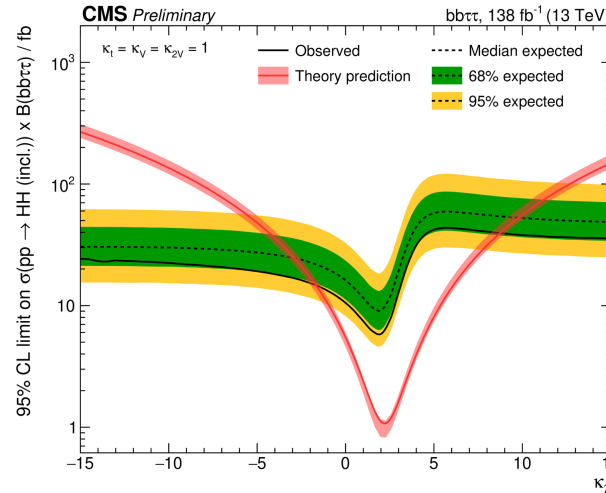


HH $\rightarrow$ bb $\tau\tau$



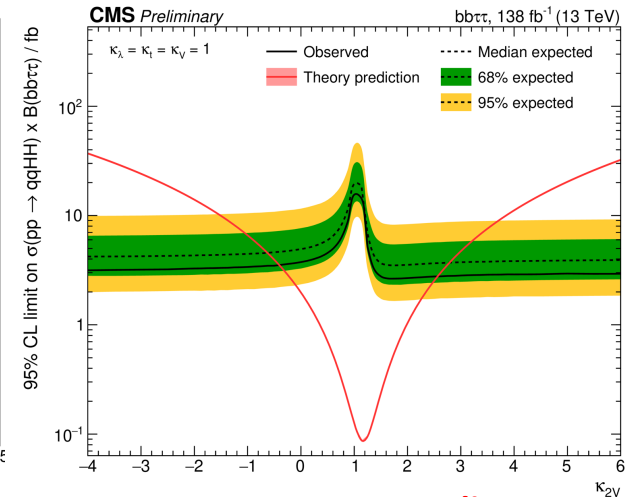
Combined κ_λ [-1.0,6.6] (obs)

[ATLAS-CONF-2021-052](#)



HHH coupling

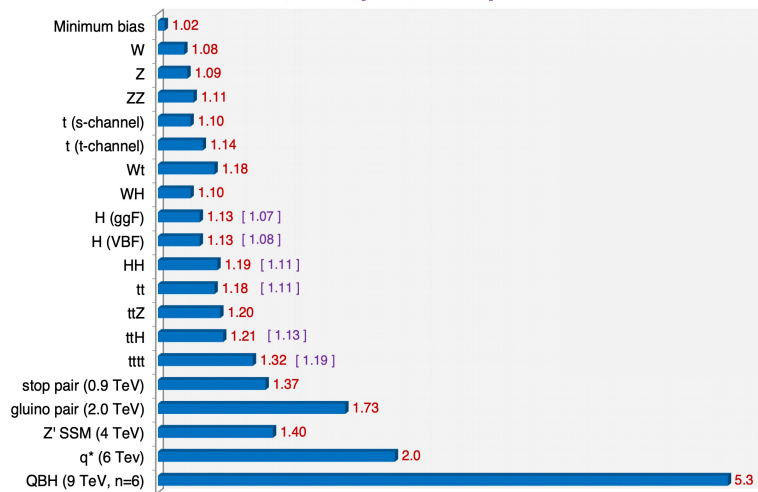
$\mu < 3.3(5.2)\text{xSM}$
 κ_λ [-1.8,8.8] (obs)



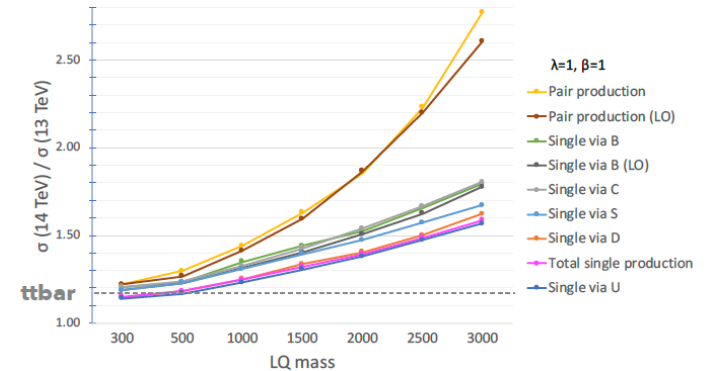
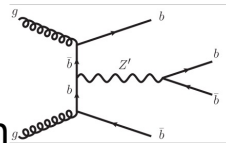
VVHH coupling

[CMS-HIG-20-010](#)

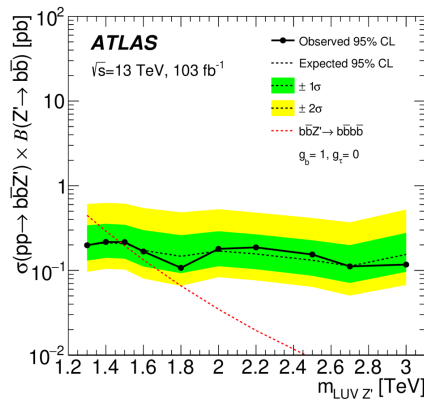
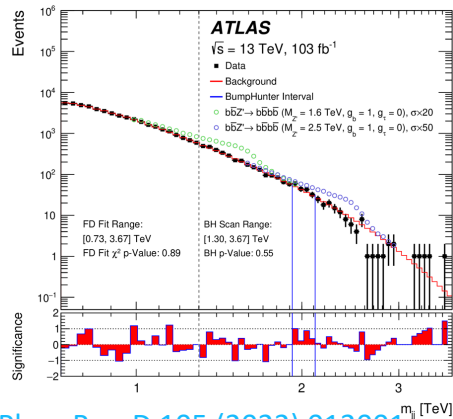
14 / 13 TeV [13.6 / 13 TeV] cross-section ratios



- Higher sqrt(s) --> increase in cross section --> increase in mass reach
 $\sigma \sim \times 2.5$ for high mass pair dijets
- Explore all scenarios favored by the b-anomalies
 $\sigma \sim \times 1.5 - 2.5$ for LQ



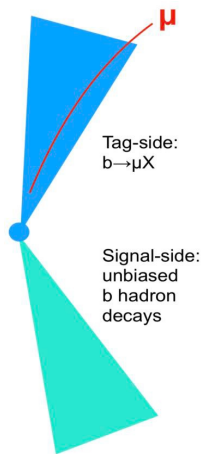
Search for Lepton Universality Violating Z' with enhanced couplings to third generation $bbZ' \rightarrow bbbb$



B-parking

Low p_T displaced triggers to save a sample of unbiased B hadron decays recoiling wrt the triggered muon. Data was reconstructed after the end of the run.

Enables analyses targeting LFU violation (and many others relying on a soft lepton)



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BSM

Make sure the whole parameter space is explored.

Did we overlook anything ?

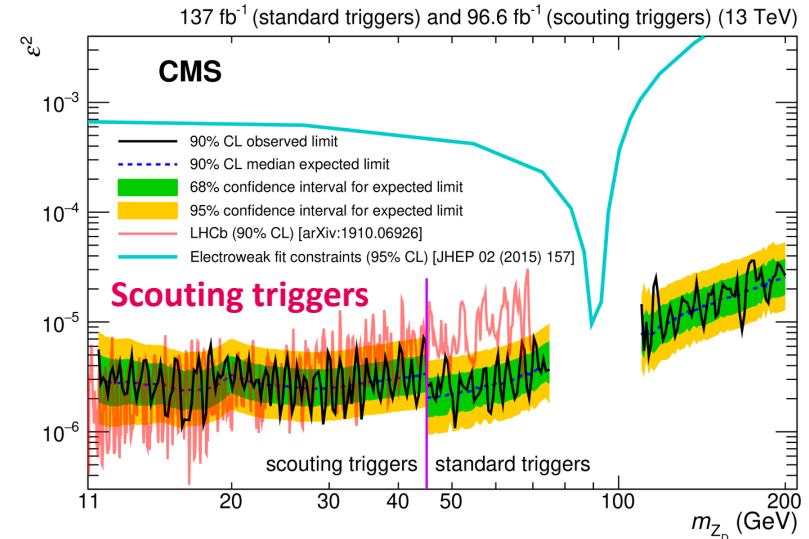
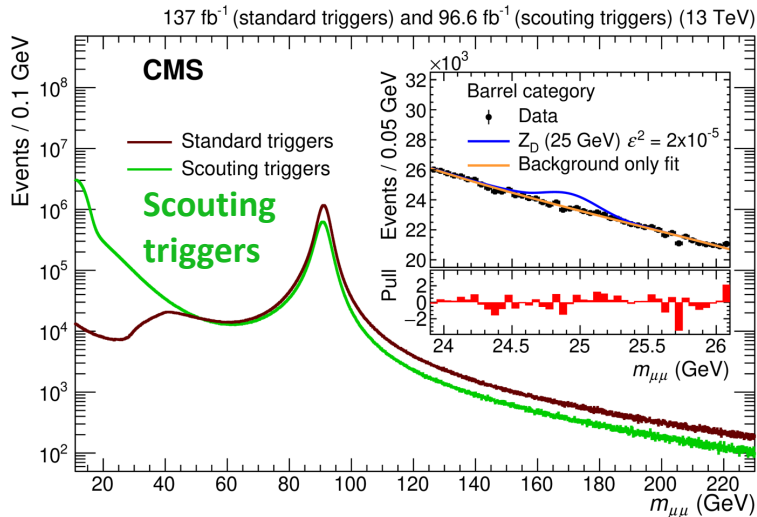
Many motivated scenarios predict resonances at low mass (Dark sectors...). Not well scrutinized before, as searches (triggers) concentrated in high mass regions.

Scouting

Analysis based on a reduced data format and on the online reconstruction in the HLT farm (do not save the full event data).

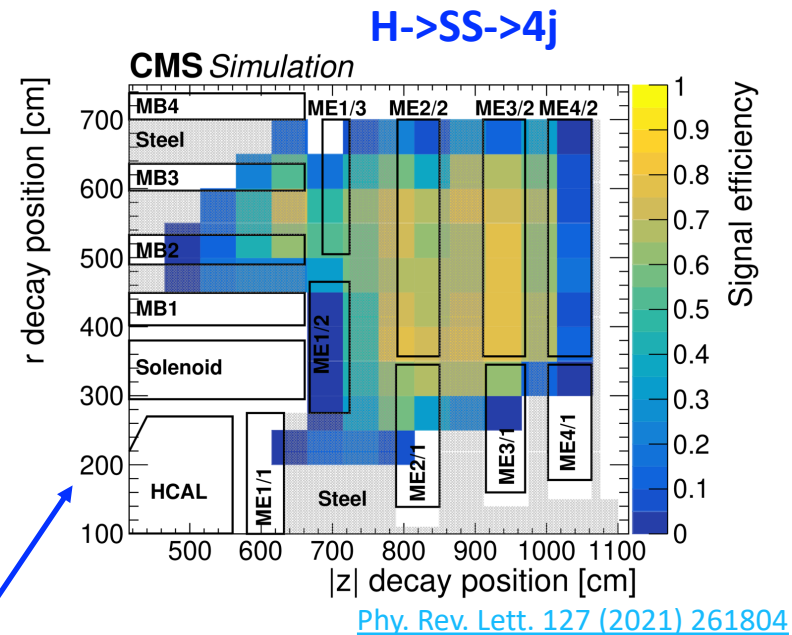
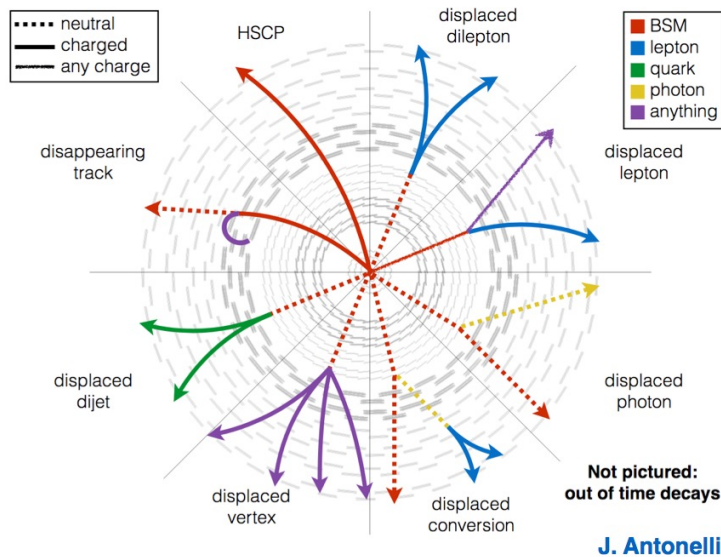
Working on adding additional L1 triggers thanks to the use of GPUs at trigger level

Search for narrow light dimuon resonances with $m_{\mu\mu} > 11.5$ GeV



[Phys. Rev. Lett. 124 \(2020\) 131802](#)

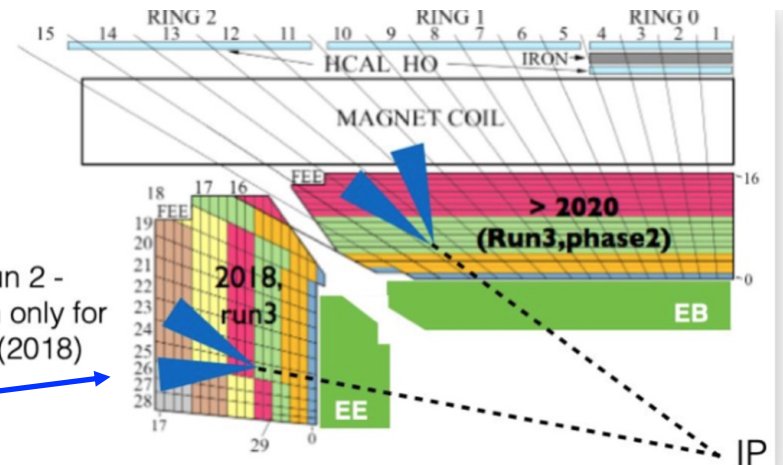
Expanding the LLP reach



New developments in the L1 trigger to increase efficiency for displaced signatures

- ✓ Increase efficiency for displaced muons
- ✓ Extend muon triggers to hadronic showers
- ✓ Exploit timing information
- ✓ Exploit HCAL depth information

Run 2 -
depth only for
HE (2018)



IGFAE

$K_S^0 \rightarrow \mu\mu$, $K_S^0 \rightarrow \pi^0 \mu\mu$, $\Sigma \rightarrow \rho\mu\mu$,
 $B_s^0 \rightarrow J/\psi KK$, $B^+ \rightarrow \pi^+ \pi^+ \pi^-$,
 $B^+ \rightarrow K_S^0 \pi^+ \pi^+ \pi^-$, $B^+ \rightarrow K^+ K^+ K^-$,
 $B_s^0 \rightarrow K^+ K^- K^0$, $B^0 \rightarrow \rho^0 \rho^0$, BSM
Higgses, Dark γ , $R(D^*)$, $RpPb$

UniOvi

HWW, WW, WZ, WWbb, tt,
tW, ttH, tH, EWKino, Stop

IFCA

HWW, WW, W-helicity,
mono-top, mono-H, Dark
H, SUSY charginos and top
squarks, sleptons, general
SUSY

IFAE

ttW, 4t, t Yukawa, H_{inv}, Heavy H, light
scalars, mono-jet, mono-W/Z, SUSY
gluinos, Higgsinos, LQ, VLQ, tH

UAM

γ , γ +jets

CIEMAT

HWW, W/Z+HF, HH,
ttbb, top, dilepton Exo

UAM

Higgs, Diboson
resonances

Ramón Llull, UB,

IFIC

$B_s \rightarrow \phi \gamma$, $\Lambda_b \rightarrow \Lambda \gamma$

IFIC

ttH, ttW, ttg, Htt, Ht, HH,
ExoH, Wtb, LLP



LHC Run 2 extremely fruitful in all fronts!!

*Let´s go for Run 3 with:
Higher precision
And discovery potential*

**Thank you very much
for your attention**



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