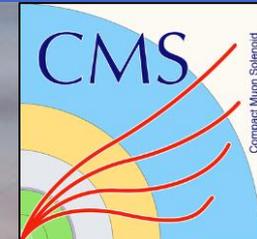


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Inclusive and differential



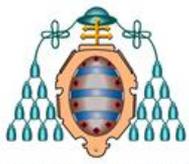
t

\bar{t}

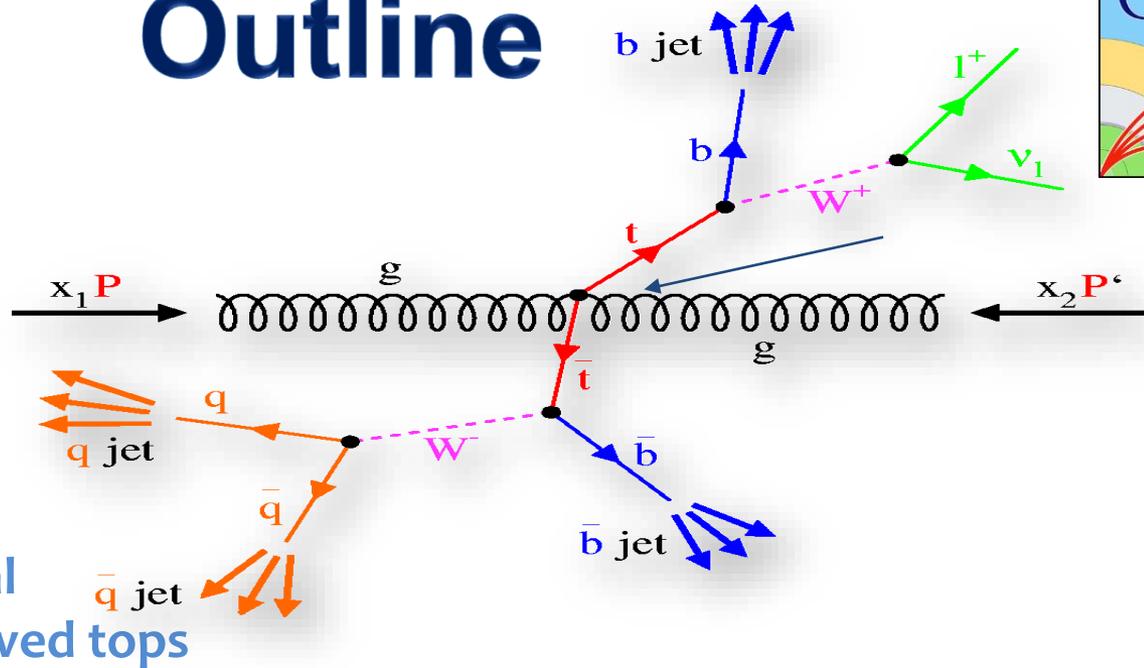
cross-section measurements at CMS

Javier Fernandez, U. Oviedo-ICTEA (Spain),
on behalf of the CMS collaboration

European Physical Society Conference
on High Energy Physics (EPS-HEP)
26 July 2021, DESY-Univ. Hamburg



Outline



- Inclusive
- Differential
- Double-differential
- Boosted and resolved tops

Experimental references:

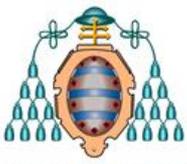
- **CMS:**

<https://twiki.cern.ch/twiki/bin/view/CMSPublic/PhysicsResultsTOP>

- Summary and combinations of **LHC Top results:**

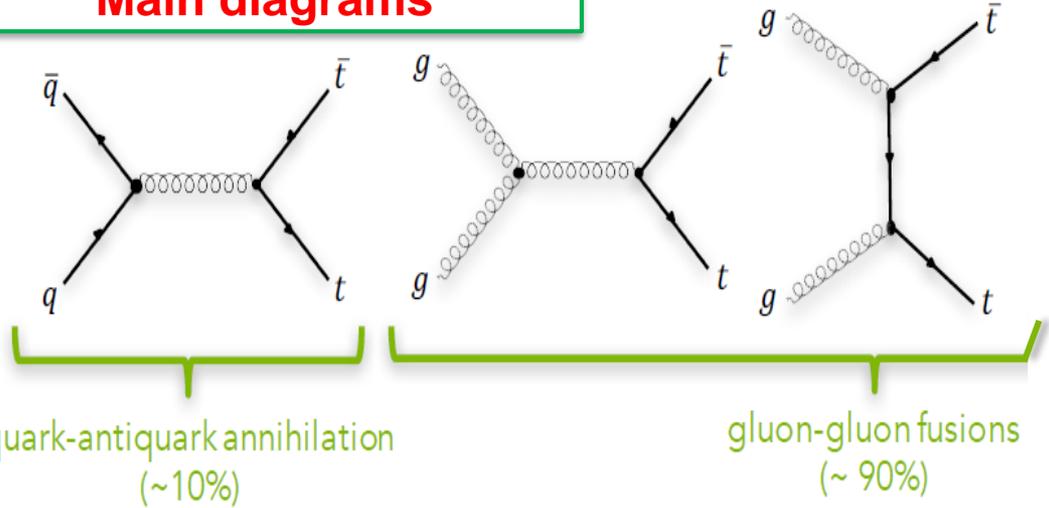
<https://twiki.cern.ch/twiki/bin/view/LHCPhysics/LHCTopWGSummaryPlots>

Brief summary of ONLY latest results on 5.02 and 13 TeV LHC data.



Top quark pair production @LHC

Main diagrams

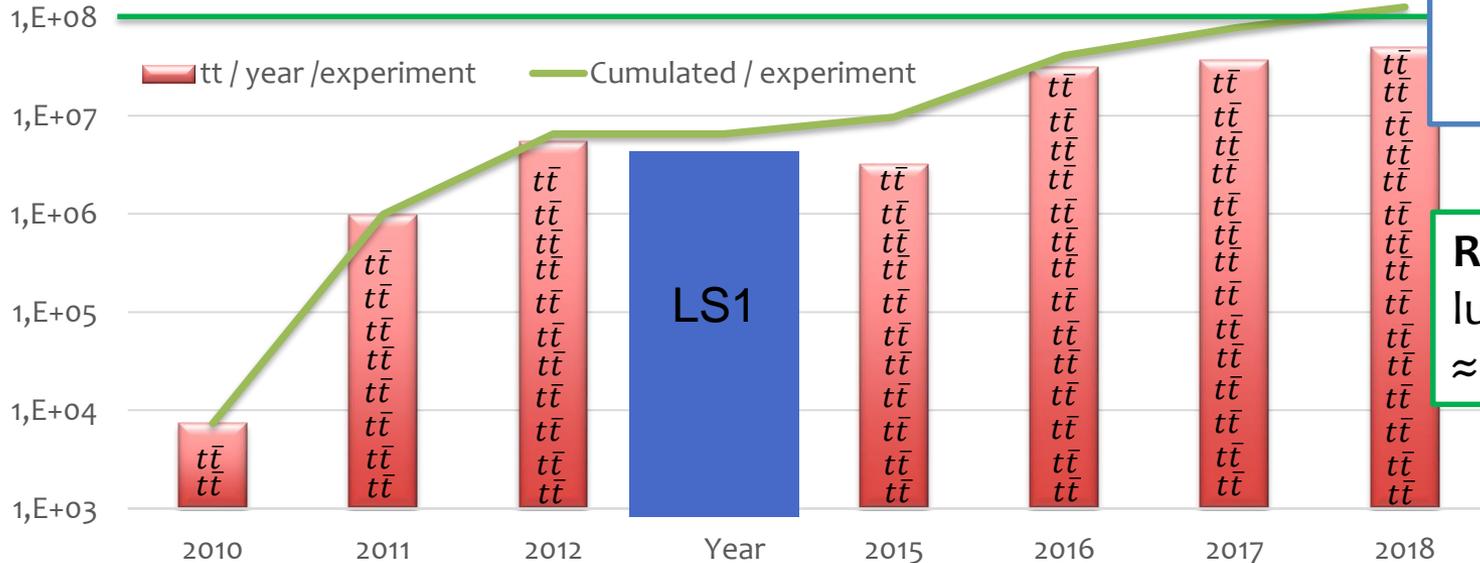


\sqrt{s} (TeV)	σ ($m_t = 172.5$ GeV)
5	$68.9 \pm 1.9(\text{scale}) \pm 2.7(\text{PDF} + \alpha_S)$
7	$177.3^{+4.7}_{-6.0}(\text{scale}) \pm 9.0(\text{PDF} + \alpha_S)$
8	$252.9^{+6.4}_{-8.5}(\text{scale}) \pm 11.7(\text{PDF} + \alpha_S)$
13	$832^{+20}_{-29}(\text{scale}) \pm 35(\text{PDF} + \alpha_S)$

4.8-5.2%

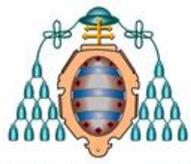
Full NNLO+NNLL calculation
[arXiv:1303.6254]

Number of $t\bar{t}$ events
in ATLAS/CMS



More than 10^8 $t\bar{t}$ pairs!!

Run2: total luminosity $\approx 163 \text{ fb}^{-1}$



The CMS detector



CMS DETECTOR

Total weight : 14,000 tonnes
 Overall diameter : 15.0 m
 Overall length : 28.7 m
 Magnetic field : 3.8 T

STEEL RETURN YOKE
 12,500 tonnes

SILICON TRACKERS
 Pixel ($100 \times 150 \mu\text{m}$) $\sim 16\text{m}^2 \sim 66\text{M}$ channels
 Microstrips ($80 \times 180 \mu\text{m}$) $\sim 200\text{m}^2 \sim 9.6\text{M}$ channels

SUPERCONDUCTING SOLENOID
 Niobium titanium coil carrying $\sim 18,000\text{A}$

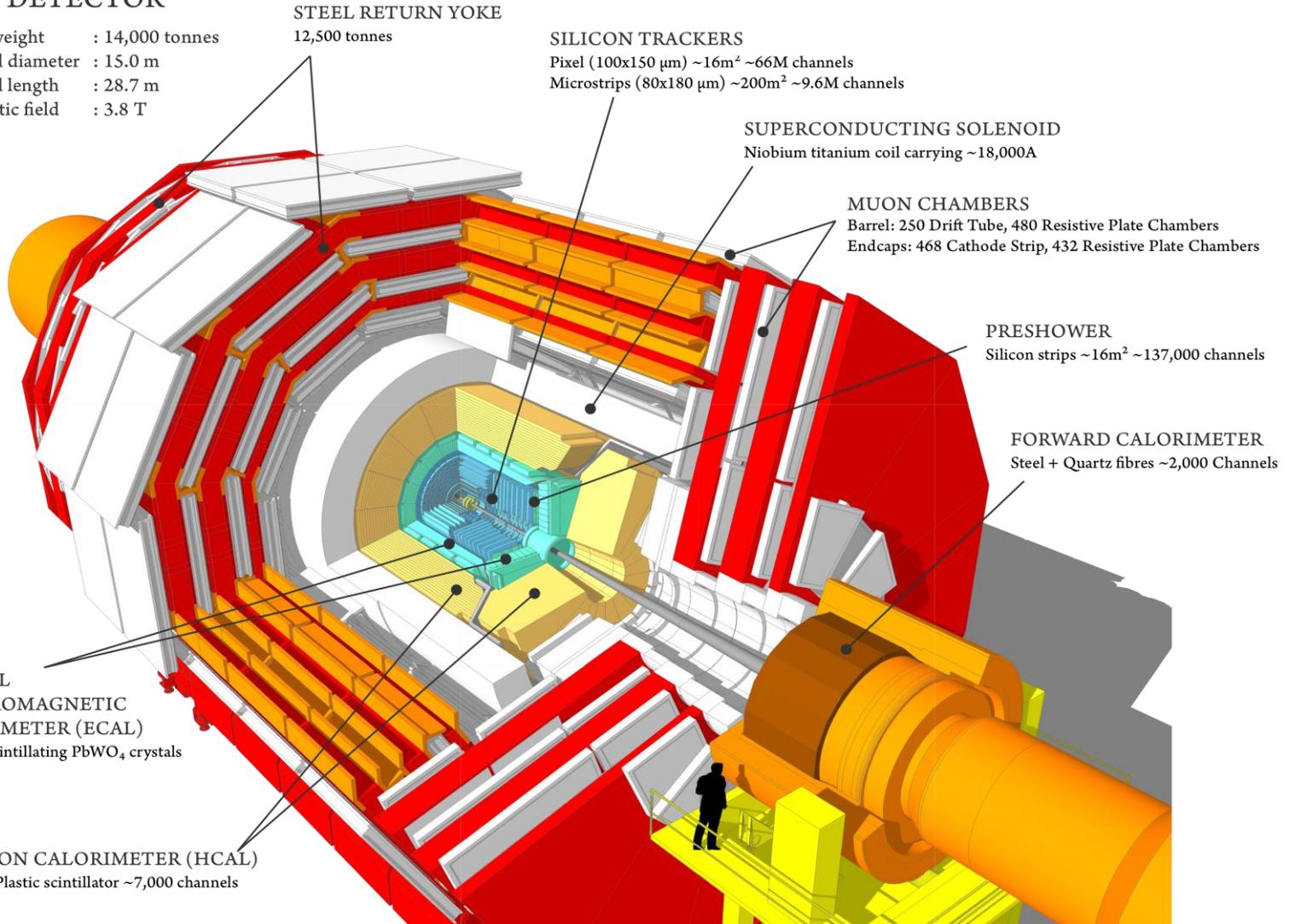
MUON CHAMBERS
 Barrel: 250 Drift Tube, 480 Resistive Plate Chambers
 Endcaps: 468 Cathode Strip, 432 Resistive Plate Chambers

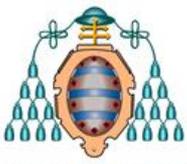
PRESHOWER
 Silicon strips $\sim 16\text{m}^2 \sim 137,000$ channels

FORWARD CALORIMETER
 Steel + Quartz fibres $\sim 2,000$ Channels

CRYSTAL ELECTROMAGNETIC CALORIMETER (ECAL)
 $\sim 76,000$ scintillating PbWO_4 crystals

HADRON CALORIMETER (HCAL)
 Brass + Plastic scintillator $\sim 7,000$ channels





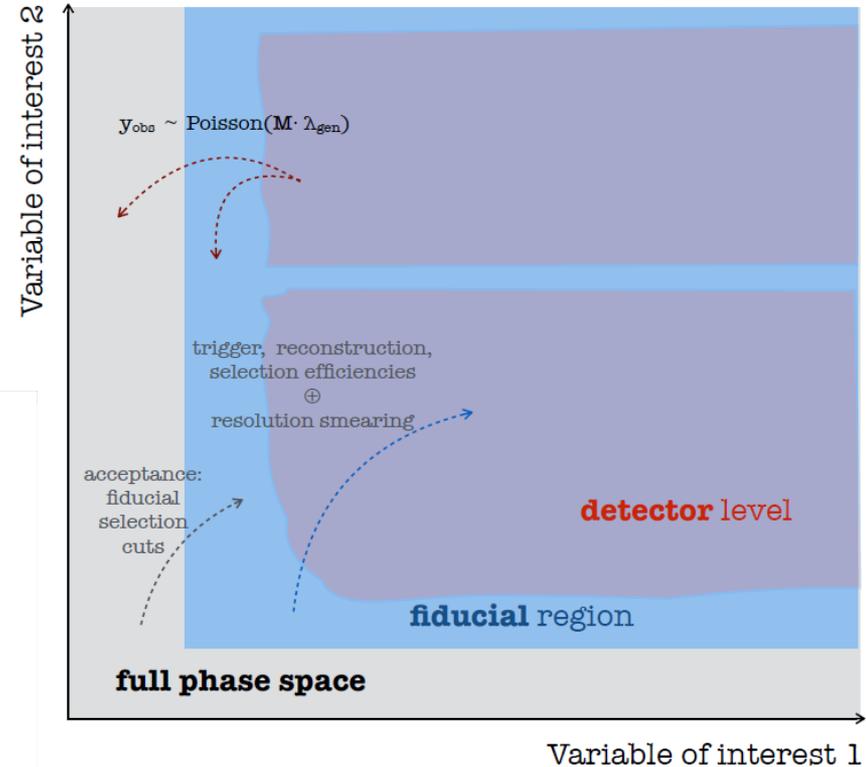
The challenges



All types of objects involved (jets, b-jets, missing transverse momentum, leptons)

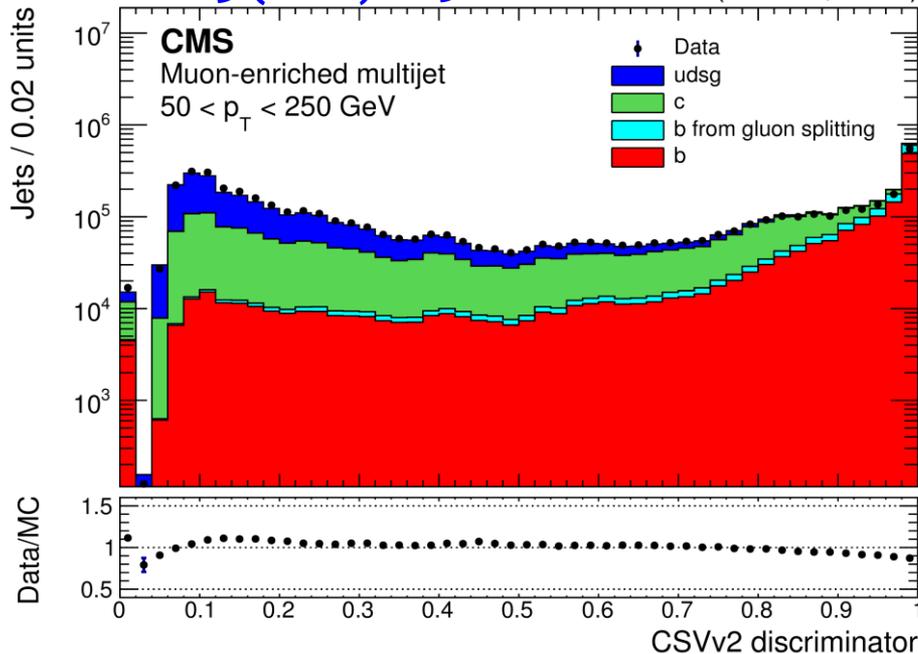
• **Experimental challenges:**

- jet energy scale (< 2%)
- b-tagging efficiency (< 3%) & fake rate
- lepton triggering & identification (< 2%)



JINST 13 (2018) P05011

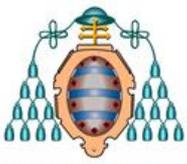
35.9 fb⁻¹ (13 TeV, 2016)



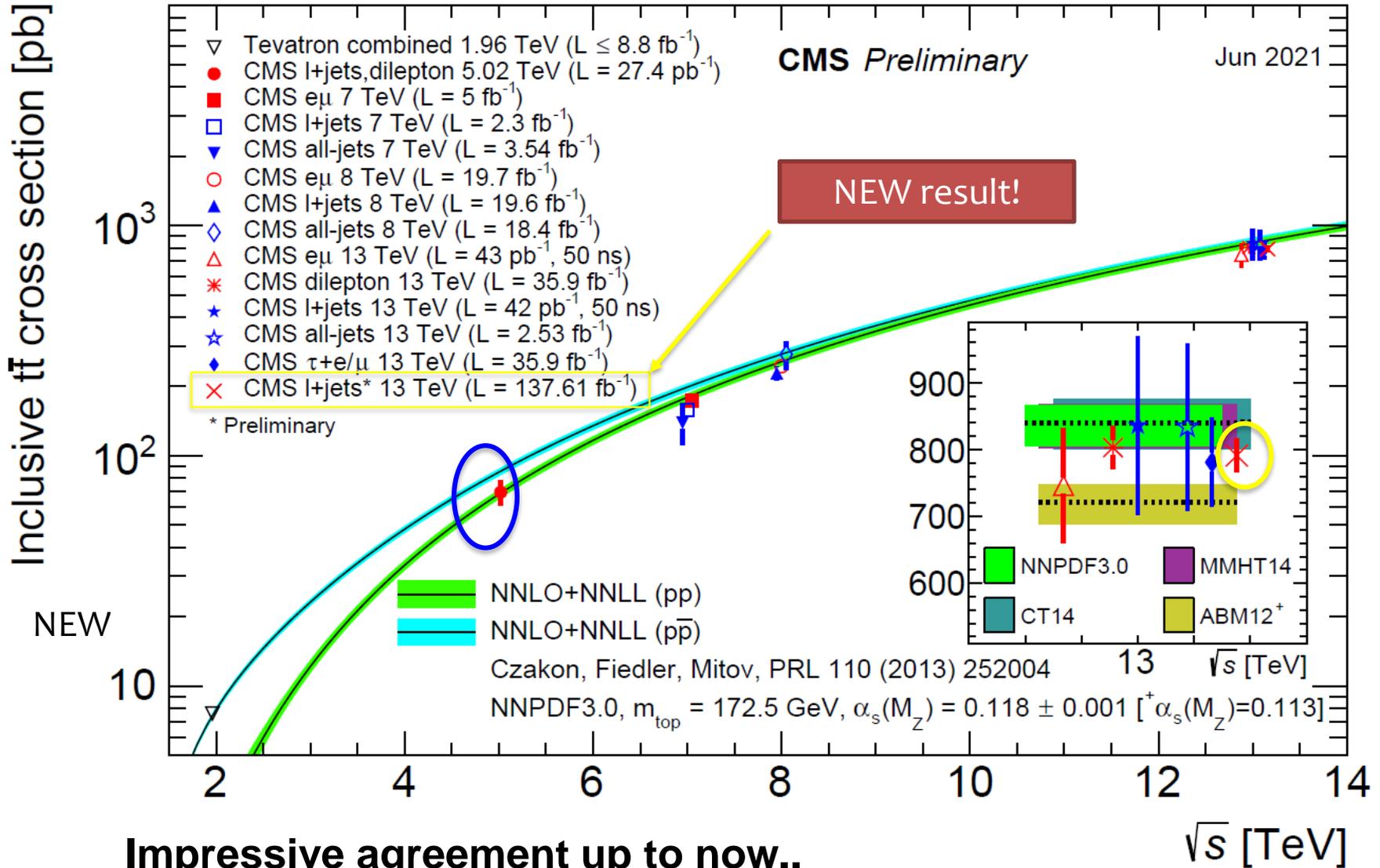
• **Theoretical challenges:**

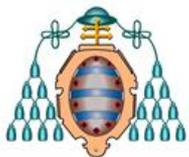
- enter through unfolding to parton & particle level
- parton shower & underlying event modelling

[CMS-NOTE-2017-004](#)

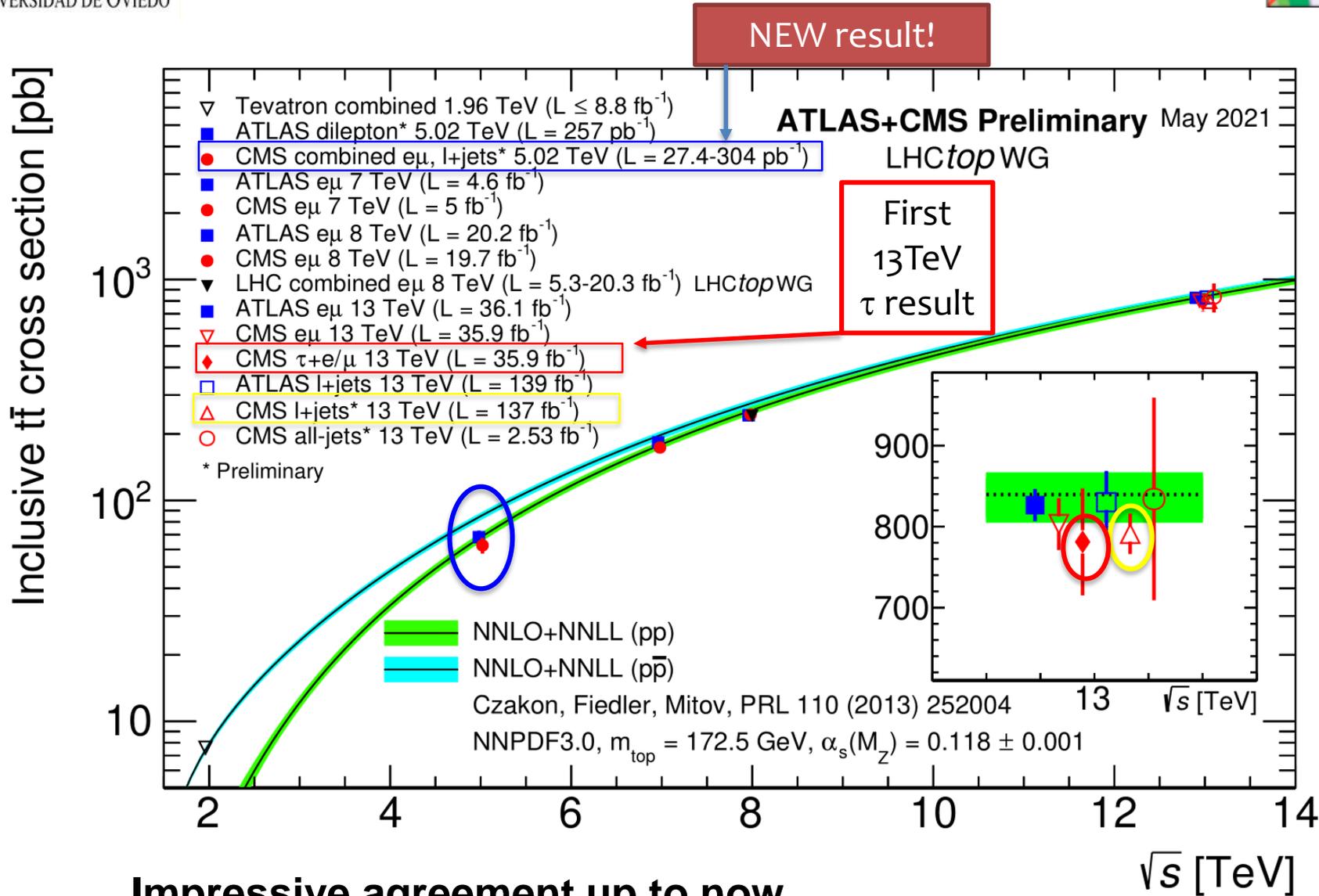


The full picture





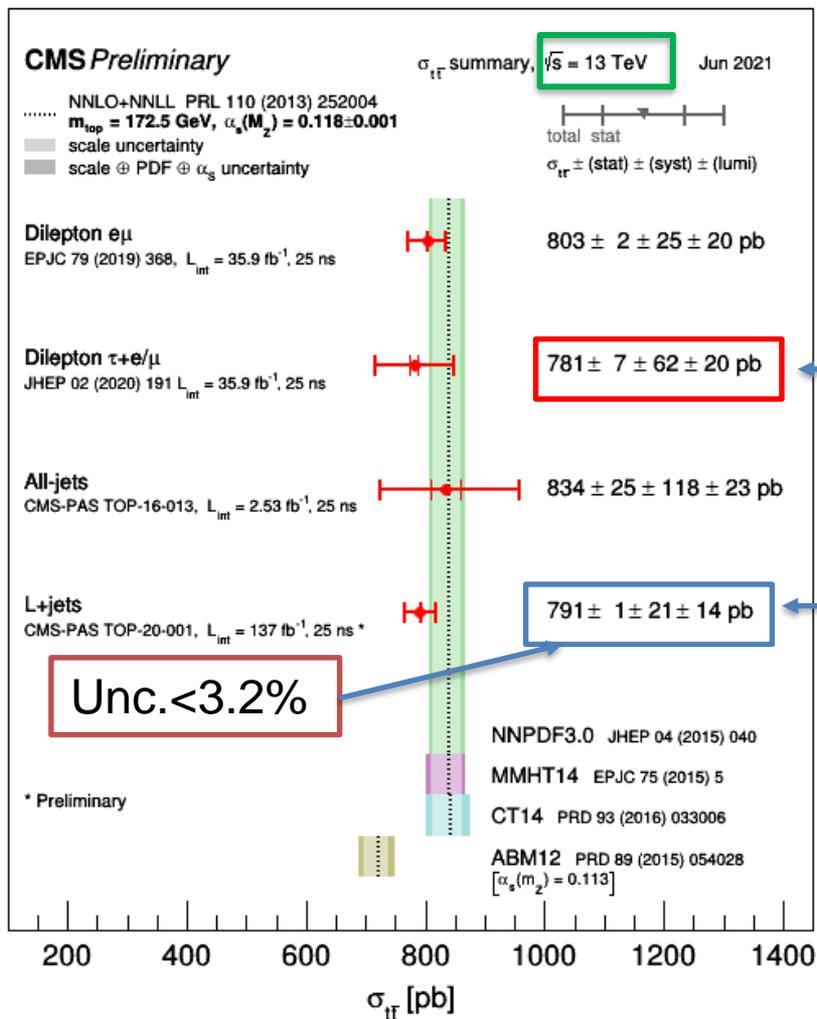
The totally full picture



Impressive agreement up to now..



The detailed 13TeV picture



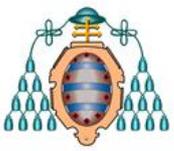
First 13TeV τ result

NEW result!

Unc. < 3.2%

- Inclusive measurements are in good agreement with theory
- Exp. uncertainty comparable to theoretical uncertainty

Need to look at differential measurements!!



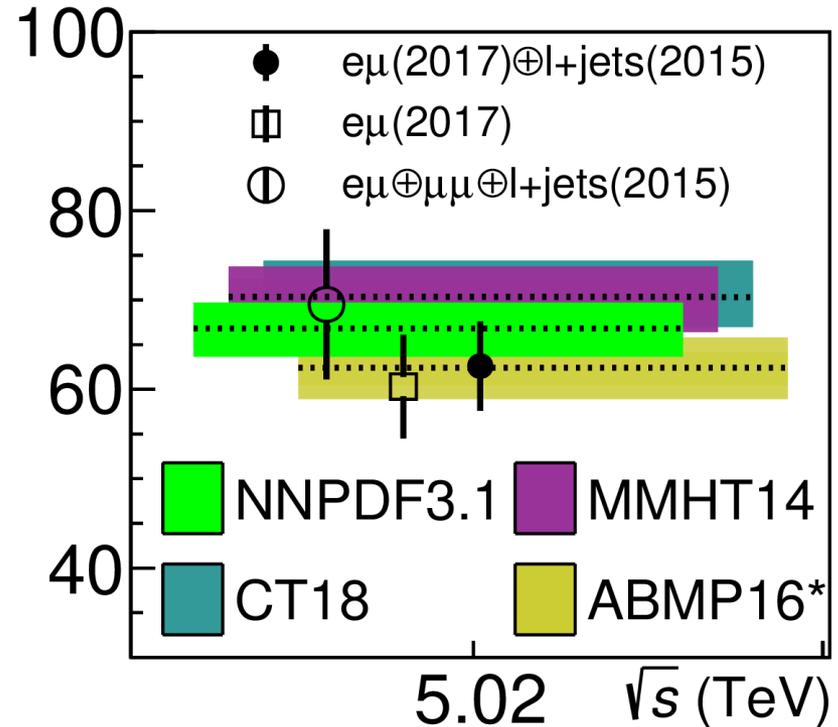
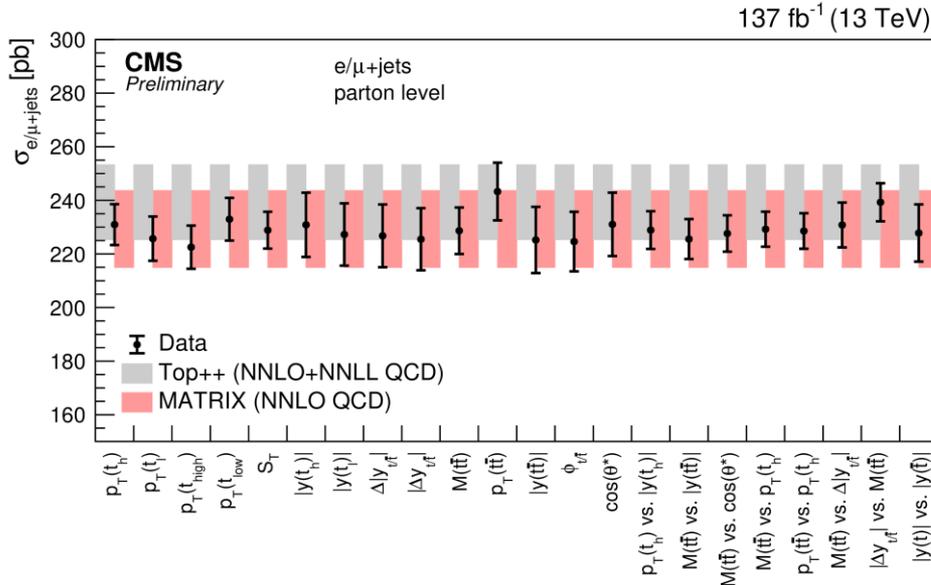
Latest inclusive measurements



Inclusive e/μ + jets $\sqrt{s} = 13$ TeV.
TOP-20-001

Inclusive $e\mu$ dilepton $\sqrt{s} = 5.02$ TeV
(2017 data) TOP-20-004

$\sigma_{d\text{il}} = 60.3 \pm 5.0(\text{stat}) \pm 2.8(\text{syst}) \pm 0.9(\text{lum}) \text{ pb}$
 $= 60.3 \pm 5.5(\text{tot}) \text{ pb}$



- Differential and double-differential in addition to the inclusive (see next slides)

<3.2%

$\sigma_{tt} = 791 \pm 1$ (stat) ± 21 (syst) ± 14 (lumi) pb

$\sigma_{\text{Combined}} = 62.6 \pm 4.1 \pm 3.0 \text{ pb}$ (7.9%)

NNLO + NNLL
 $\sigma_{\text{tt}}^{\text{theo}} = 832_{-29}^{+20}(\text{scale}) \pm 35(\text{PDF} + \alpha_s) \text{ pb}$

$\sigma^{\text{NNLO}} = 68.9_{-2.3}^{+1.9}(\text{scale}) \pm 2.3(\text{PDF}) \pm 1.4_{-1.0}(\alpha_s) \text{ pb}$

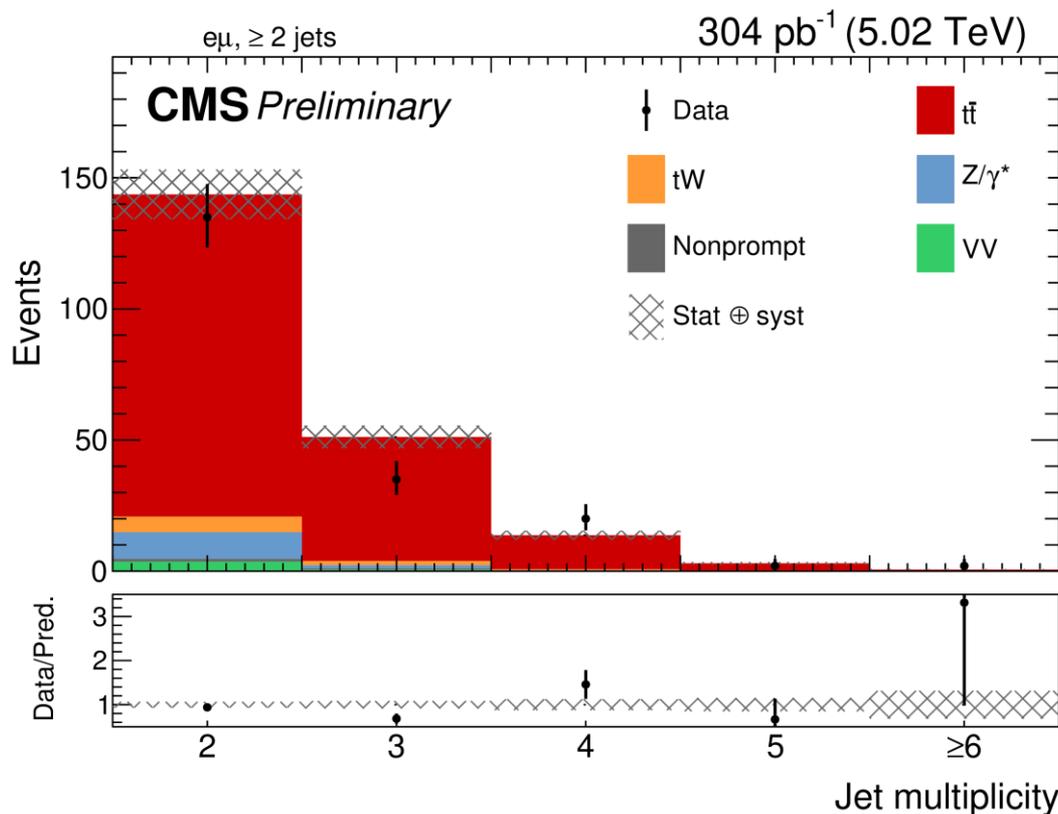


5.02TeV analysis

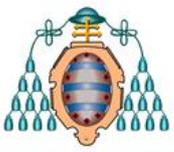
Inclusive $e\mu$ dilepton $\sqrt{s} = 5.02\text{TeV}$
(2017 data) [TOP-20-004](#)

$$\sigma_{\text{dil}} = 60.3 \pm 5.0(\text{stat}) \pm 2.8(\text{syst}) \pm 0.9(\text{lum}) \text{ pb} \\ = 60.3 \pm 5.5(\text{tot}) \text{ pb}$$

- Event selection:
 - Exactly two central, isolated and oppositely charged leptons
 - At least 2 jets (with or without btag)
 - Corresponding same-flavour lepton samples to estimate background
- Counting experiment:
 - Reduced statistical uncertainty after combination with l+jets (2015) analysis (27pb^{-1})



$$\sigma^{\text{NNLO}} = 68.9^{+1.9}_{-2.3}(\text{scale}) \pm 2.3(\text{PDF})^{+1.4}_{-1.0}(\alpha_s) \text{ pb}$$



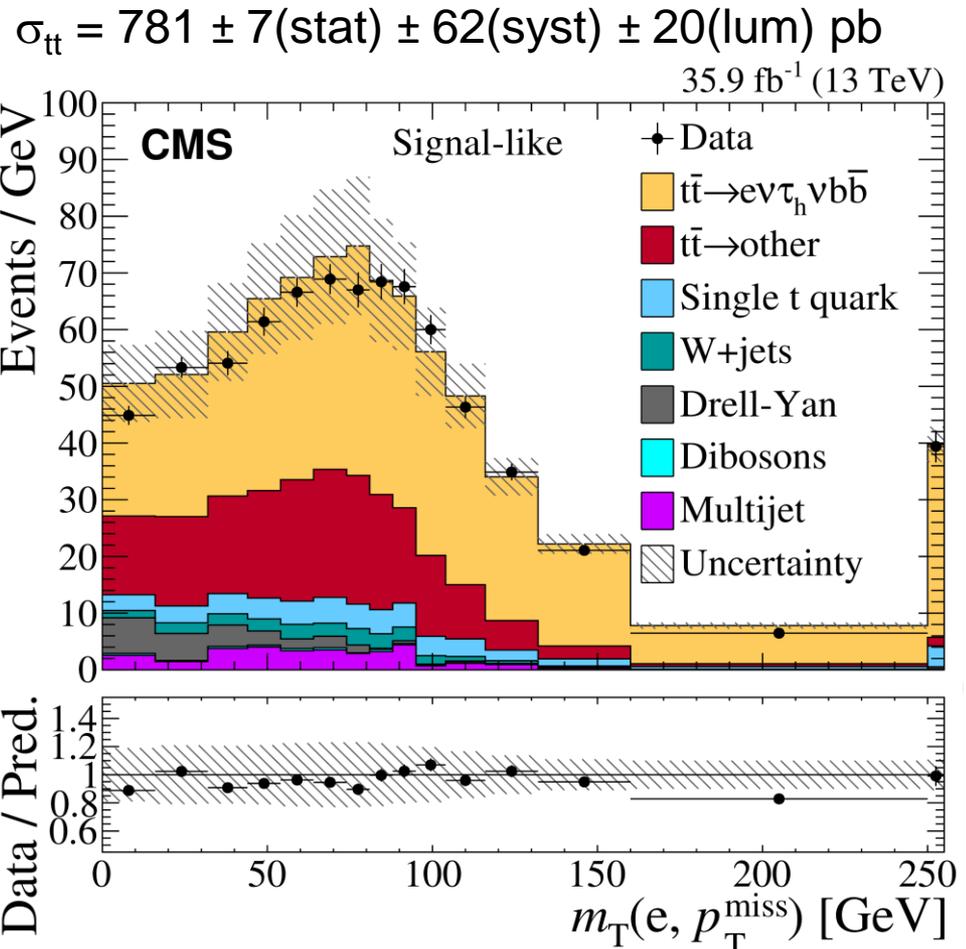
Dilepton with taus



- First measurement at 13TeV including τ 's
 - Improving relative precision of 7 and 8 TeV results
- e/μ and at least 3 jets, of which at least 1 is b-tagged and one identified as hadronic τ
- Background: constrained in a fit to the distribution of $m_T(\text{lepton}, p_T^{\text{miss}})$ in two event categories (e & μ)

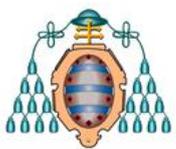
Inclusive dilepton $e/\mu + \tau_h \sqrt{s} = 13\text{TeV}$

JHEP 02 (2020) 191



NNLO + NNLL

$$\sigma_{t\bar{t}}^{\text{theo}} = 832_{-29}^{+20} (\text{scale}) \pm 35 (\text{PDF} + \alpha_S) \text{ pb}$$

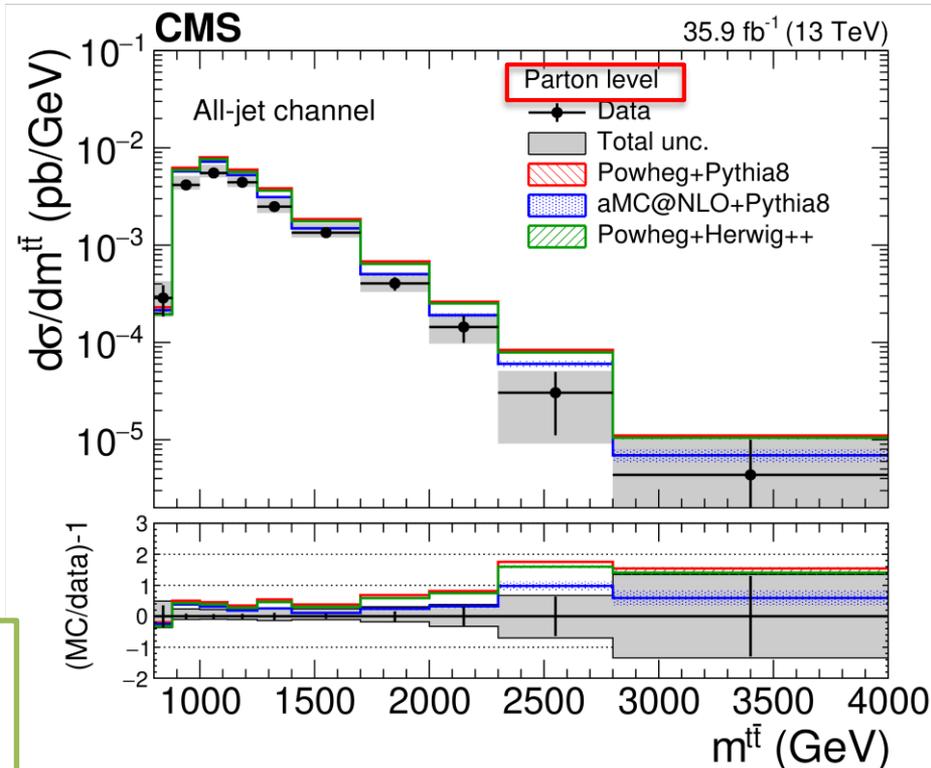
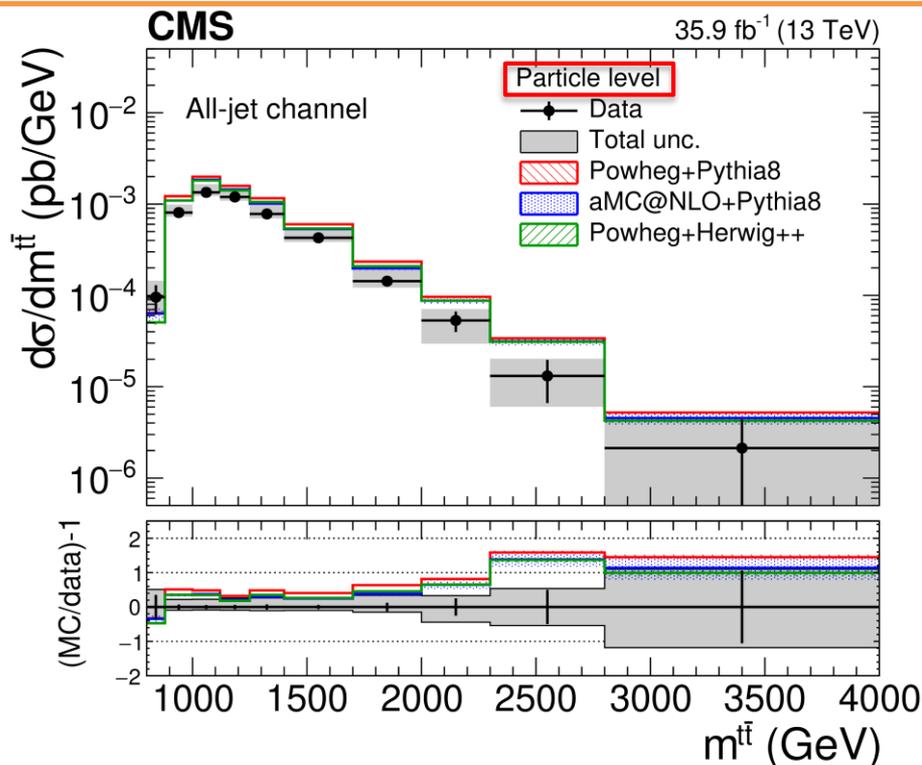


Boosted differential cross sections

Hadronic & e/μ + jets $\sqrt{s} = 13$ TeV, 35.9fb⁻¹

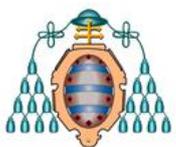
Phys. Rev. D 103 (2021) 052008

- (At least 1) Top reconstructed as a large-radius jet with transverse momentum in excess of 400 GeV
- Other top: isolated e or μ + MET



In both decay channels the observed absolute cross sections are significantly lower than the predictions from theory, while the normalized differential measurements are well described

Notable discrepancies shown

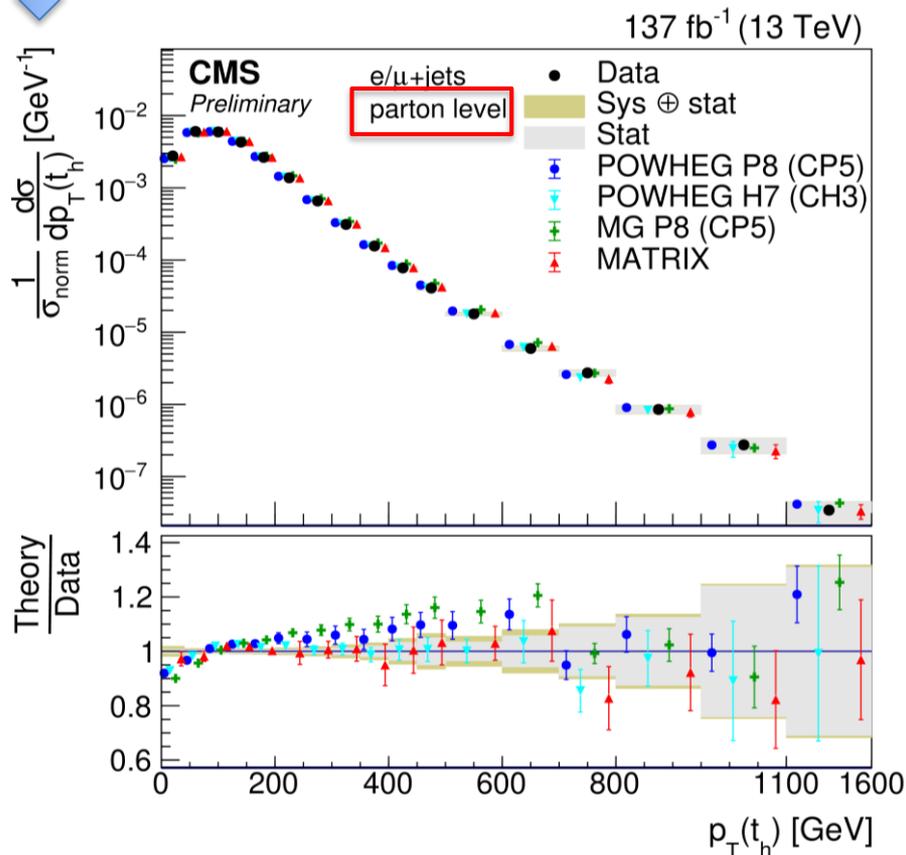
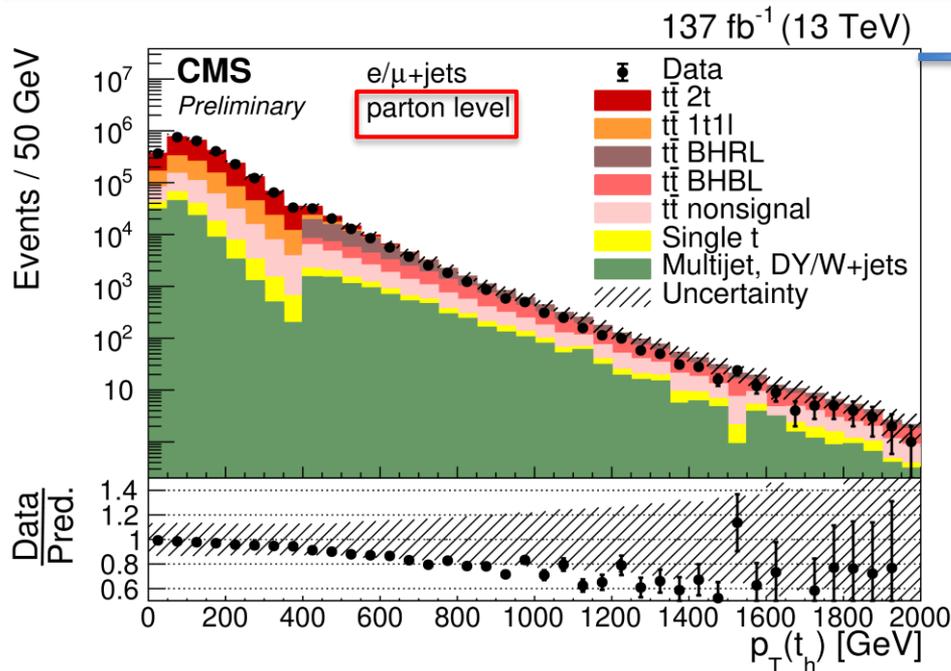


Differential cross sections



$e/\mu + \text{jets}$ $\sqrt{s} = 13 \text{ TeV}$. [TOP-20-001](#)

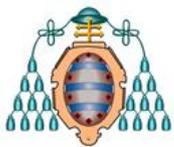
- Exactly 1 central, isolated e or μ
- Differential and double-differential cross sections in full kinematic range



4 event categories based of number of tight (loose) b-tags and resolved or boosted top-quark candidates:

- **2t**: 2 resolved top-candidates with 2 tightly b-tagged jets
- **1t1l**: 2 resolved top-candidates with 1 tight and 1 loose b-tag
- **BHRL**: boosted hadronic top ($p_T > 400 \text{ GeV}$) but resolved leptonic top, 1 tight b-tag
- **BHBL**: both top-candidates boosted, 1 loose b-tag on leptonic side

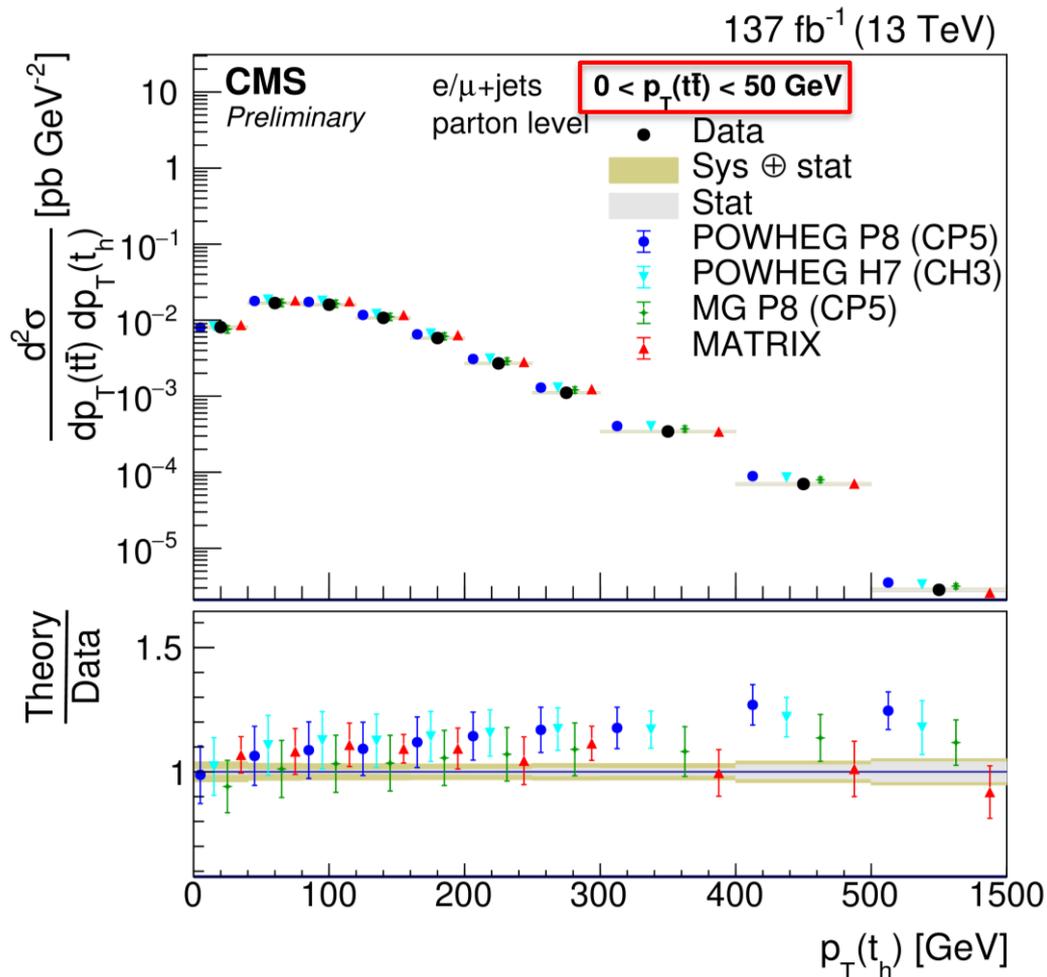
Absolute lower, shapes OK



2D Differential cross sections



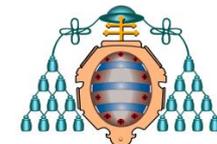
$e/\mu + \text{jets}$ $\sqrt{s} = 13 \text{ TeV}$. [TOP-20-001](#)



- For the first time the cross section of the full spectra are obtained using a combination of resolved and boosted $t\bar{t}$ topologies.
- Kinematic quantities on parton-level for individual top-quarks:
 - $p_T(t_h), p_T(t_l), |y(t_h)|$
 and top-pairs:
 - $|y(t\bar{t})|, m(t\bar{t}), p_T(t\bar{t})$
- The combination of multiple reconstruction categories allows for constraints of systematic uncertainties → significantly improved precision with respect to previous measurements
- Uncertainties in the jet energy scale, luminosity, and $t\bar{t}$ modeling are the dominant sources.



Summary

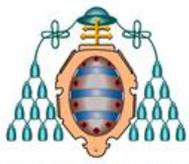


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Top quark pair production measured with high precision at CMS:

- Inclusive results at 5, 7, 8 and 13TeV in **good agreement** with predictions, \rightarrow (multi)differential studies
- Run2 at 13TeV allows to explore the **full phase space** of top production in both boosted and resolved topologies:
 - Most differential distributions **compatible with the SM predictions** of POWHEG +PYTHIA/HERWIG, and mg5_aMC@NLO +PYTHIA
 - A **softer top quark p_T spectrum** is observed compared to most of the NLO predictions, specially at high p_T and $|y|$
 - Parton-level cross sections compared to the **NNLO QCD calculations** obtained with MATRIX (reduced theoretical uncertainty)

BACKUP



Is top quark special?



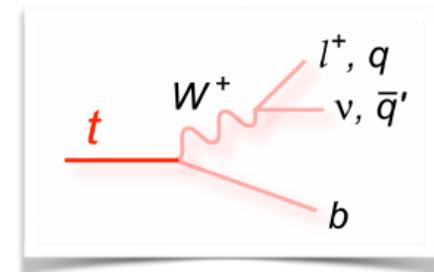
- full hadronic
- semileptonic
- dileptonic

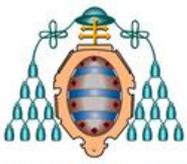
- top quark is the most massive known particle
 - significant contribution of top loops
- the top Yukawa coupling is close to unity
 - coincidence or special dynamics?
- it decays before it can hadronize
 - no bound states with top can be formed
 - its decay products (W, b) largely preserve the top quark spin polarization
- top properties provide critical tests for the SM predictions
 - very sensitive to BSM effects

W^+ / W^-	$\bar{u}d$	$\bar{c}s$	e^-	μ^-	τ^- decay
$\bar{u}d$	jets		e + jets	μ + jets	τ + jets
$\bar{c}s$			e + jets	μ + jets	τ + jets
e^+	e + jets		ee	$e\mu$	e τ
μ^+	μ + jets		$e\mu$	$\mu\mu$	$\mu\tau$
τ^+ decay	τ + jets		e τ	$\mu\tau$	$\tau\tau$
$\bar{u}d$	jets		e+jets	μ +jets	
e^+	e + jets		ee	$e\mu$	
μ^+	μ + jets		$e\mu$	$\mu\mu$	

τ unstable
 not observed experimentally

$$BR(t \rightarrow Wb) = 0.957$$



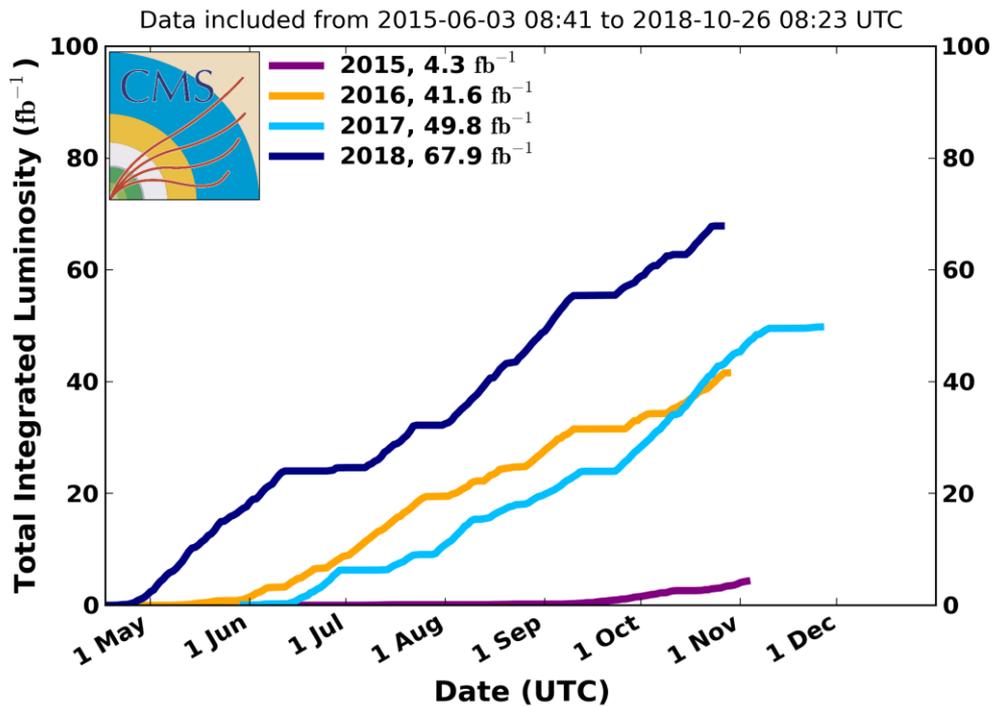


LHC: the perfect machine?

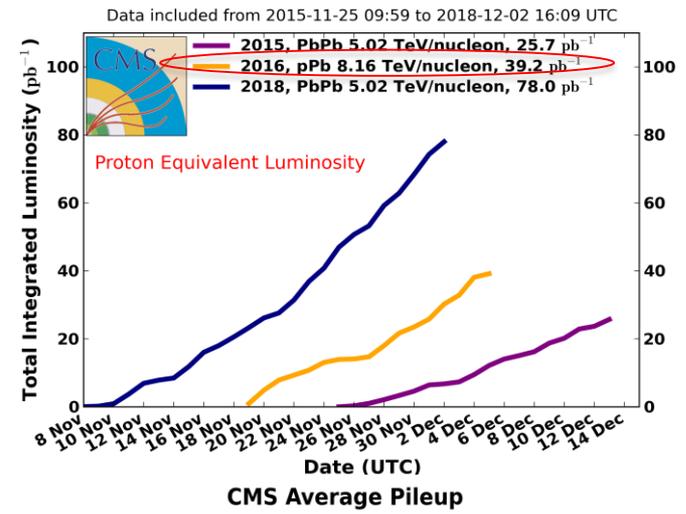


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CMS Integrated Luminosity Delivered, pp, $\sqrt{s} = 13$ TeV

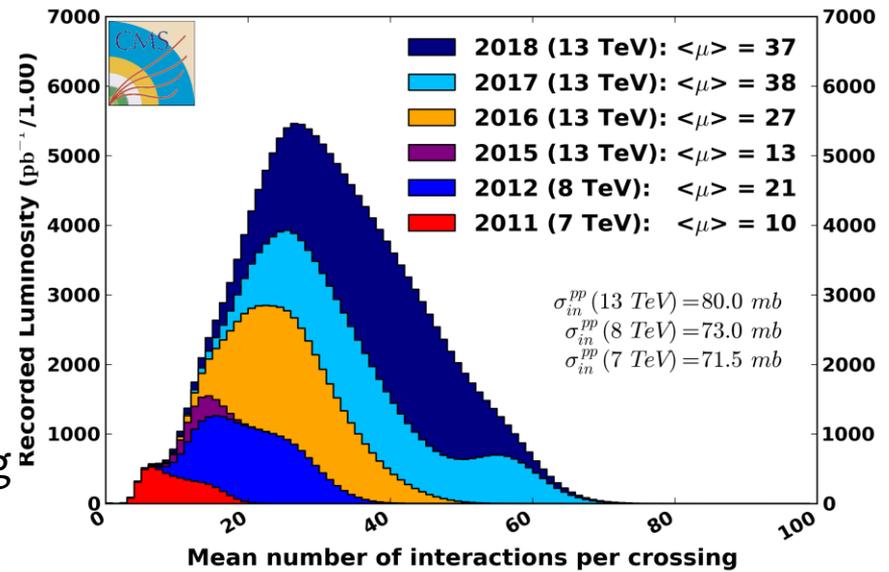


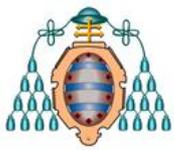
CMS Integrated Luminosity Delivered, PbPb+pPb



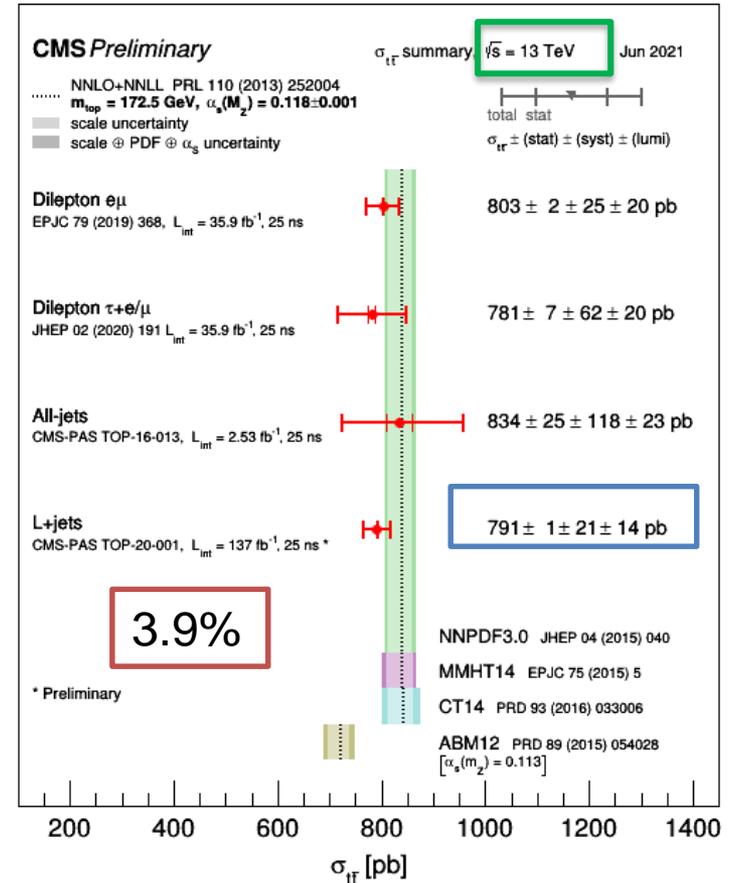
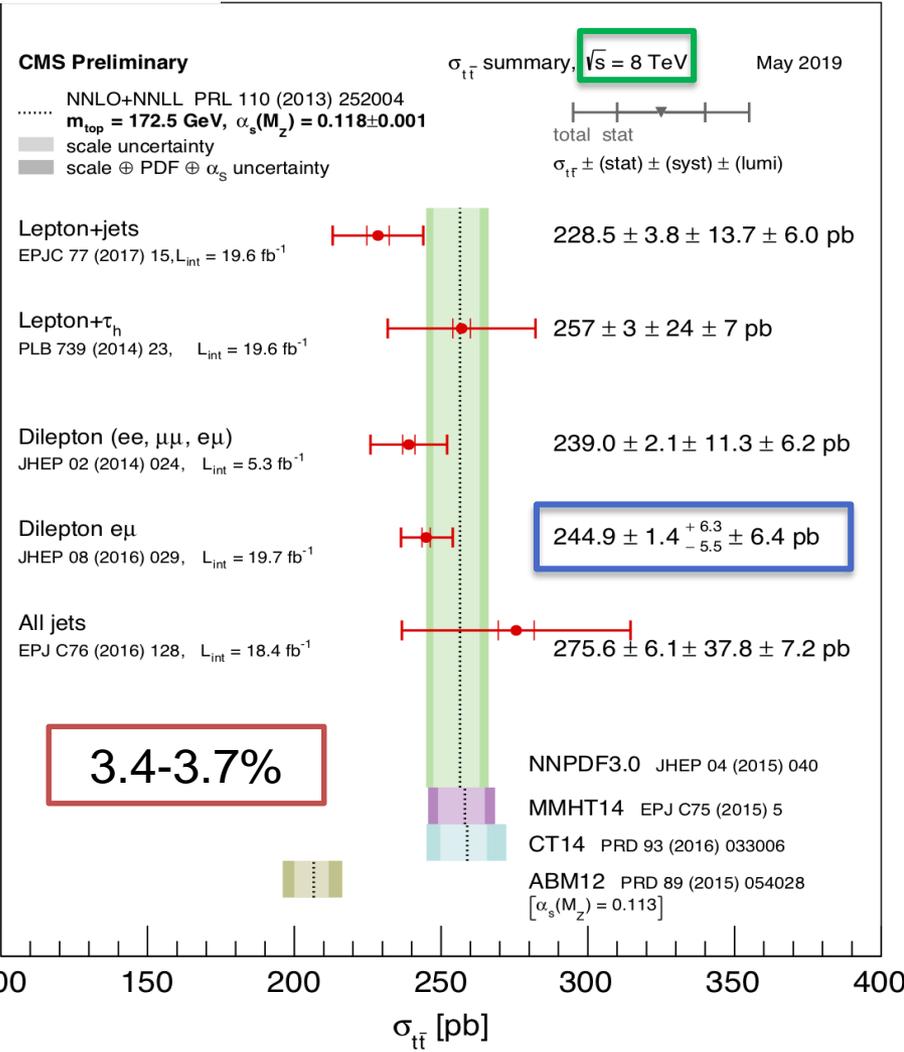
Run2: proton-proton @ 13 TeV in 2015 - 2018

- total luminosity ≈ 163 fb⁻¹
- $\sim 10^8$ top quark pairs produced
- on average 34 interactions per bunch crossing





The detailed picture



- Inclusive measurements are in good agreement with theory
- Exp. uncertainty comparable to theoretical uncertainty

Need to look at differential measurements!!