tt production at CMS

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(on behalf of the CMS Collaboration)

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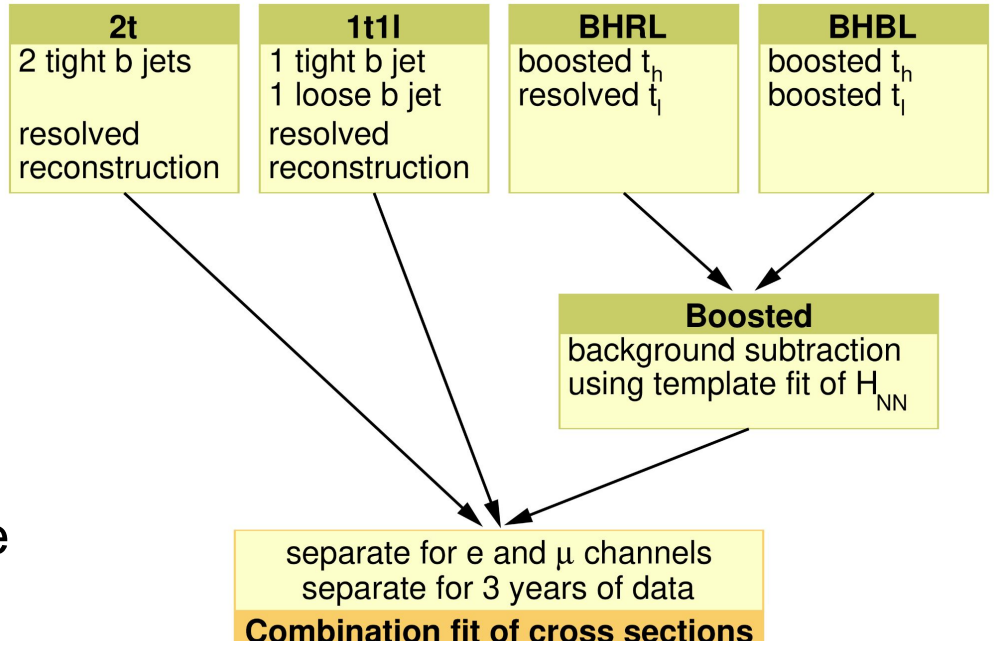
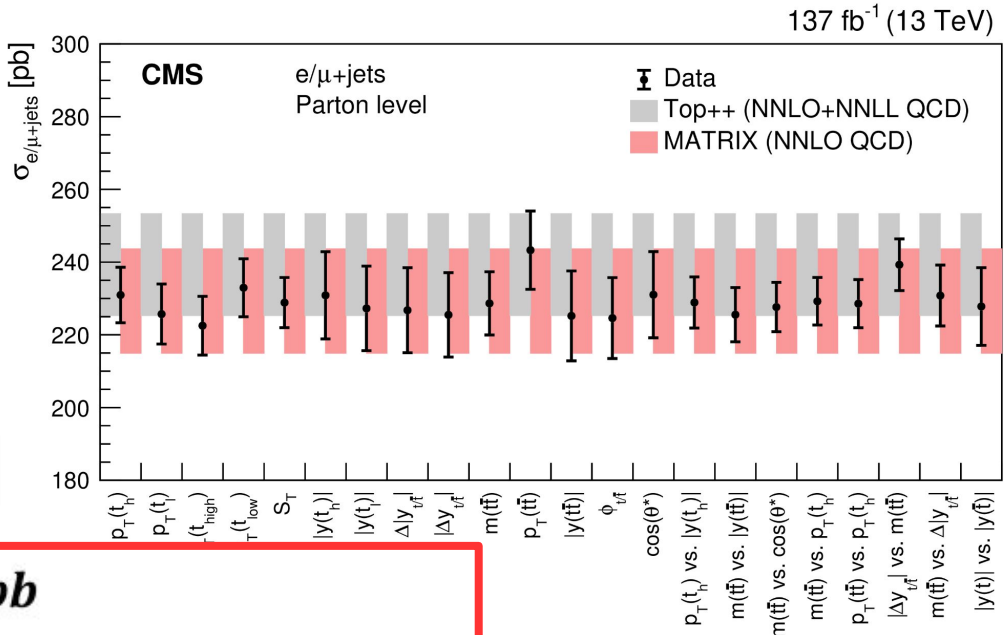
tt inclusive in l+jets - 137 fb^{-1} - Phys. Rev D 104 (2021) 092013

- For the first time, a combination of resolved and boosted tt topologies is used
  - ➢ provides constraints on the systematic uncertainties improving the precision



- χ^2 fit to find the cross-section considering the migration matrices
- Uncertainties are constrained by χ^2 fit
- Inclusive = sum of all bins (parton level)
- JES (1.38%) dominant systematic

$$\sigma(\text{MATRIX}) = 797^{+39}_{-51}(\text{scale}) \pm 39(\text{PDF})\ \text{pb}$$



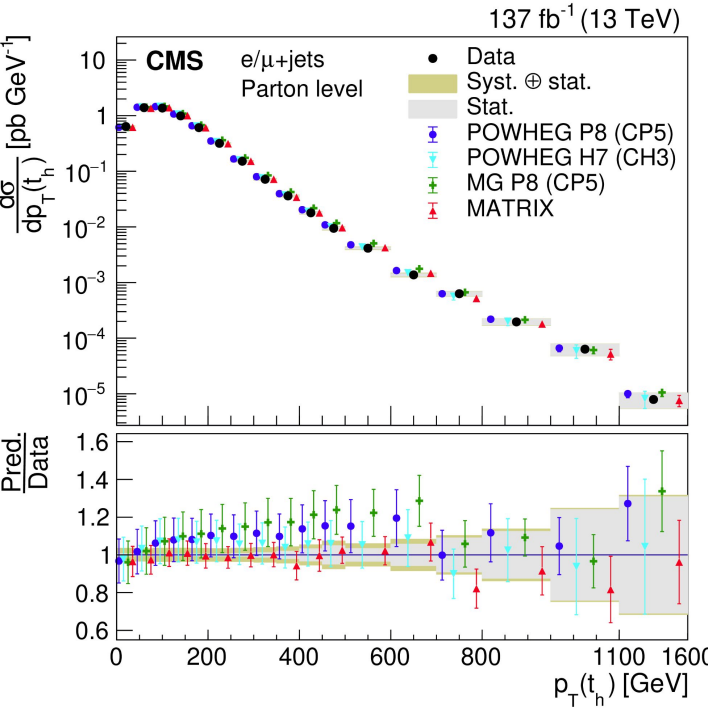
$$\sigma = 791 \pm 1\,(stat) \pm 21\,(syst) \pm 14\,(lumi)\ pb$$

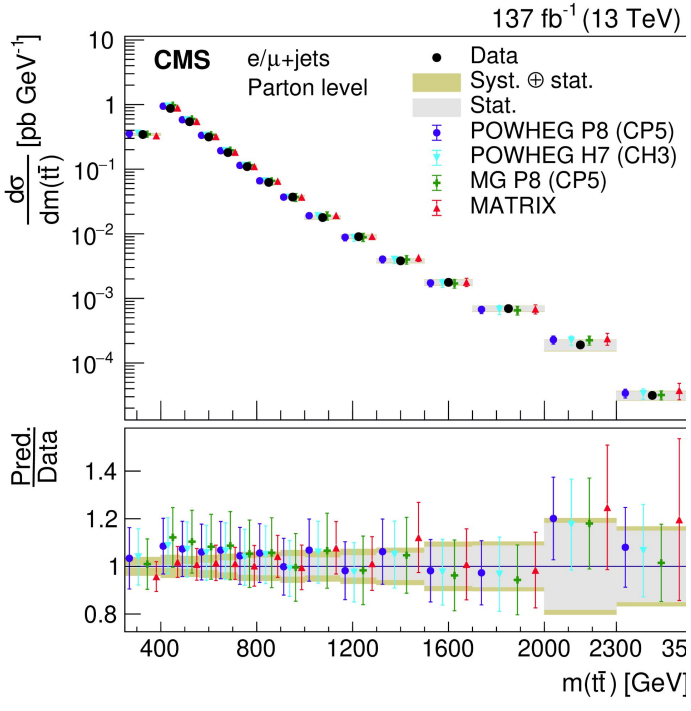
total relative uncertainty of 3.19%

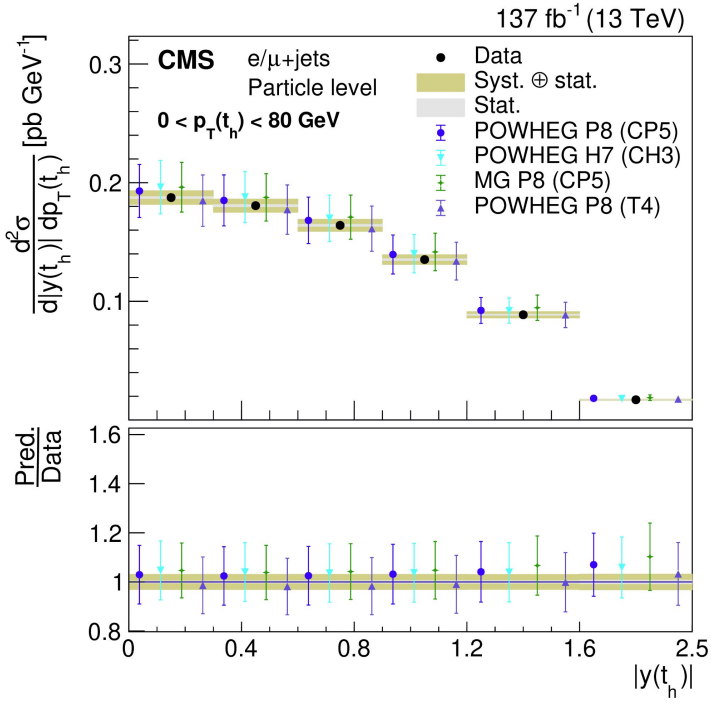
tt differential in l+jets - 137 fb^{-1} - Phys. Rev D 104 (2021) 092013

- Single and double differential measured as a function of many kinematic properties of the top quarks and the tt system, at the parton and particle levels
  - ➢ the latter reduces extrapolations based on theoretical assumptions

- Parton-level cross sections are compared to MATRIX (NNLO)
  - ➢ with a significantly reduced theoretical uncertainty

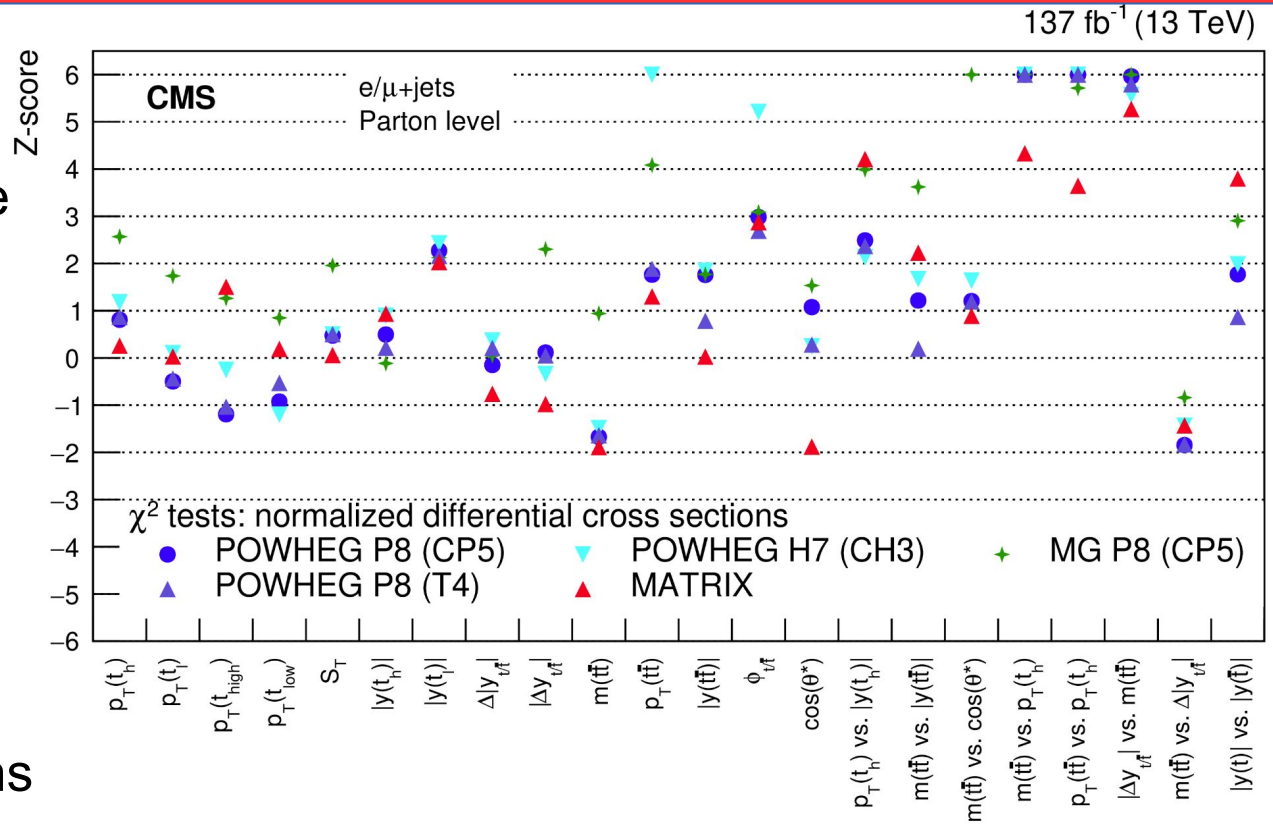






tt differential in l+jets - 137 fb^{-1} - Phys. Rev D 104 (2021) 092013

- Most differential distributions are found to be compatible with the SM predictions



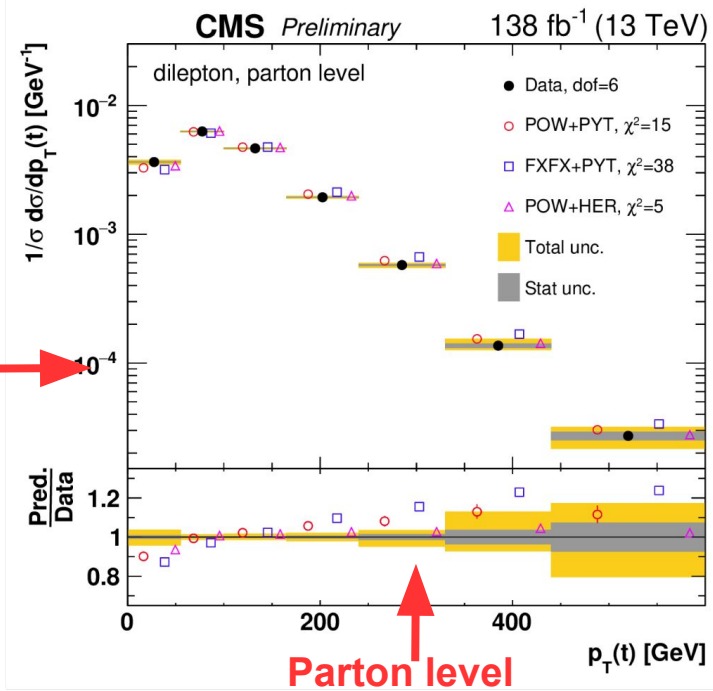
- Top quark p_T spectrum is softer than most of the NLO predictions

- Deviations are observed when the top quark p_T is measured in bins of the m(tt)

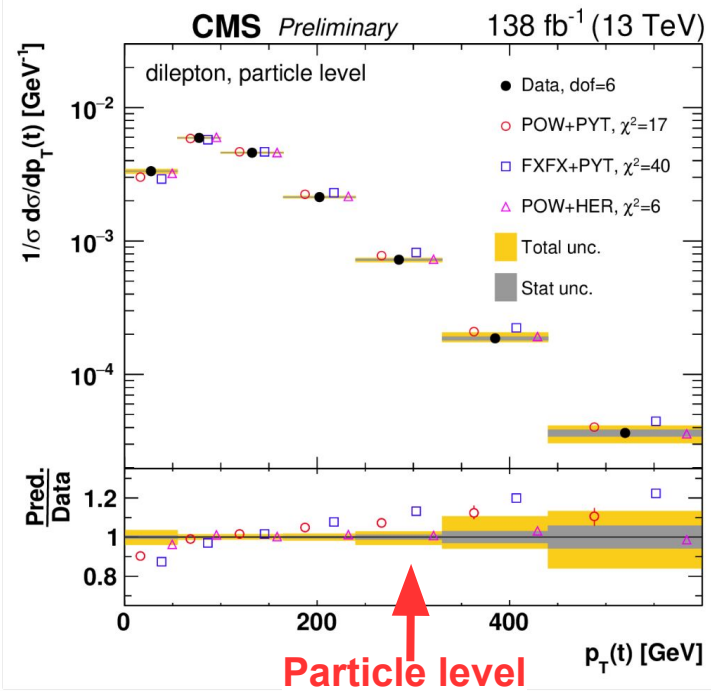
- POWHEG+HERWIG and MG5_aMC@NLO+PYTHIA do not describe well jet multiplicities and related observables

tt differential in dilepton - 138 fb^{-1} - CMS-PAS-TOP-20-006

Top quark

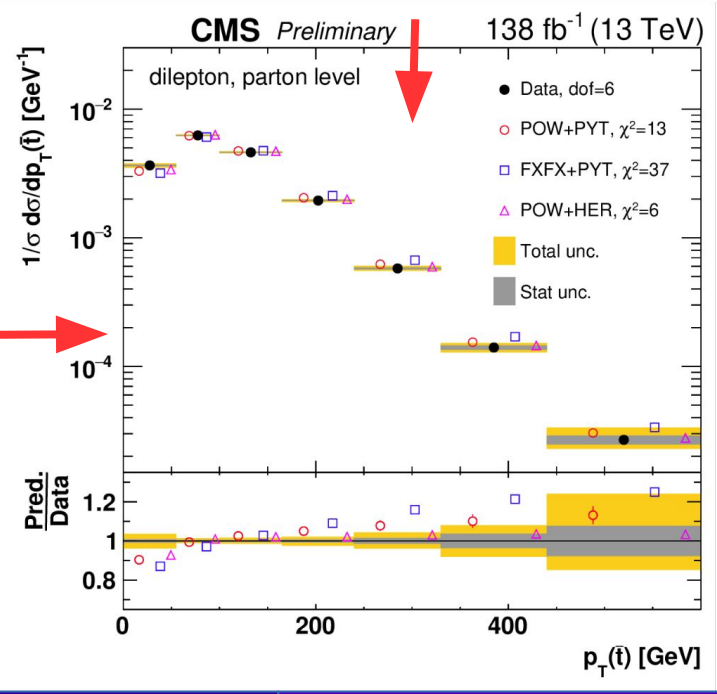


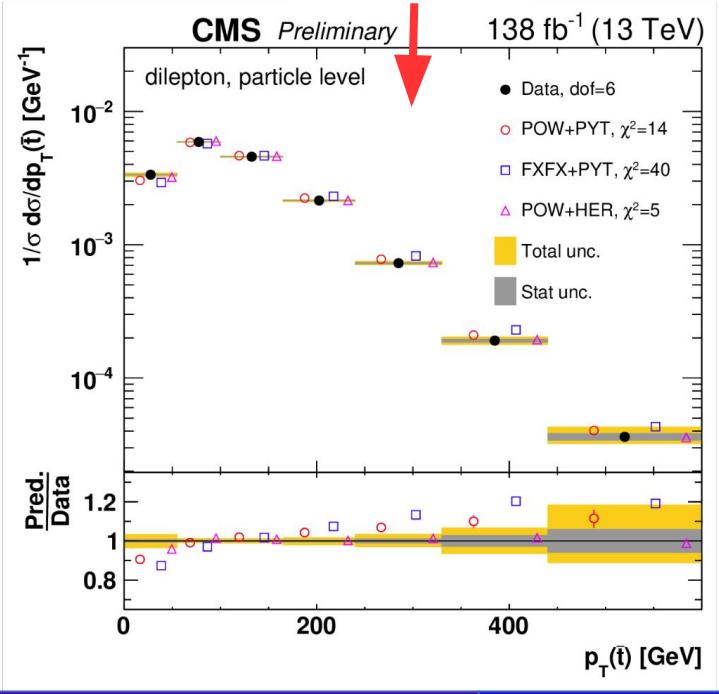
Parton level



Particle level

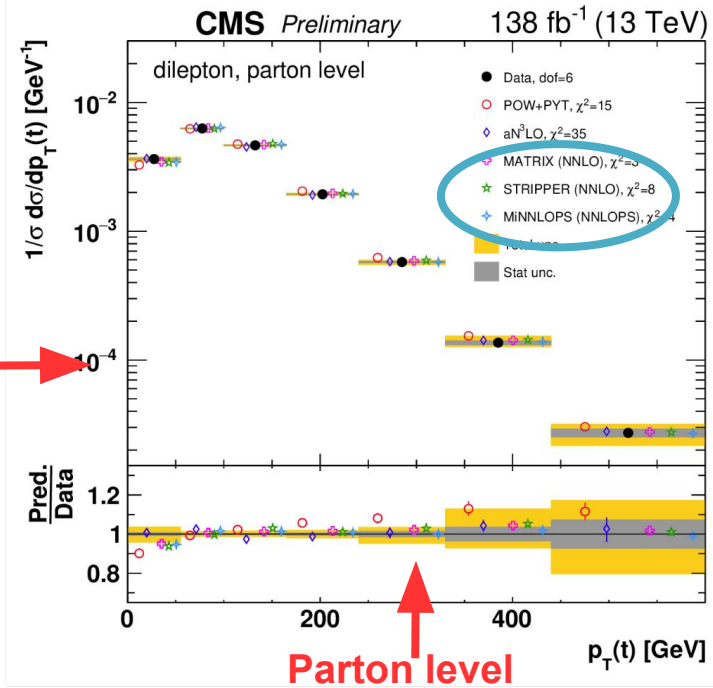
Antitop quark



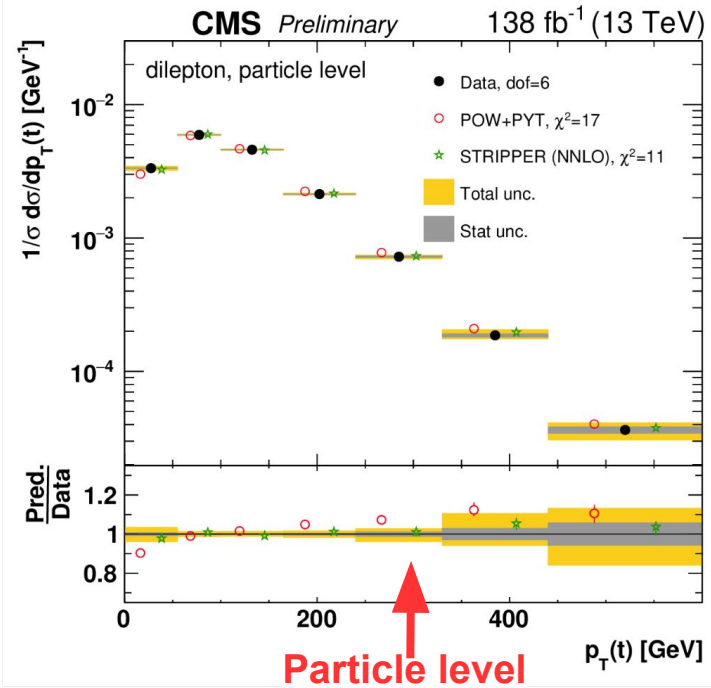


tt differential in dilepton - 138 fb^{-1} - CMS-PAS-TOP-20-006

Top quark

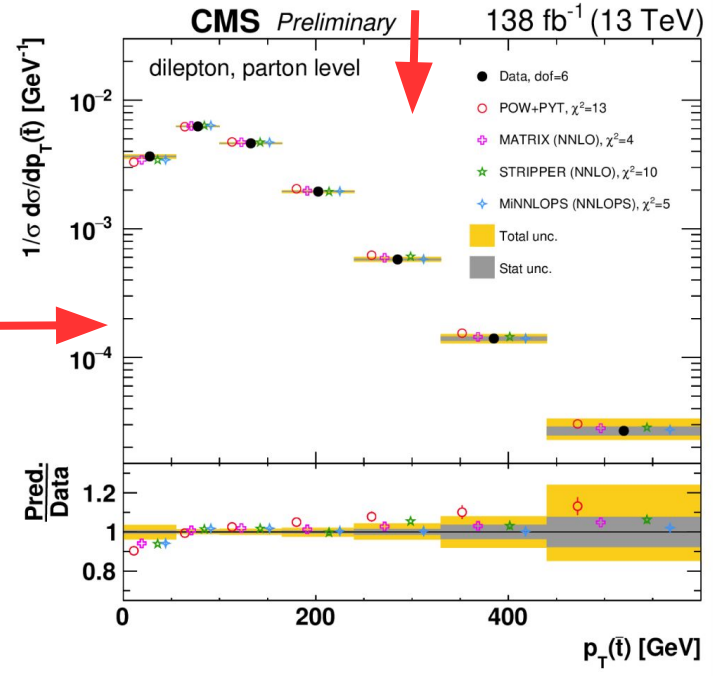


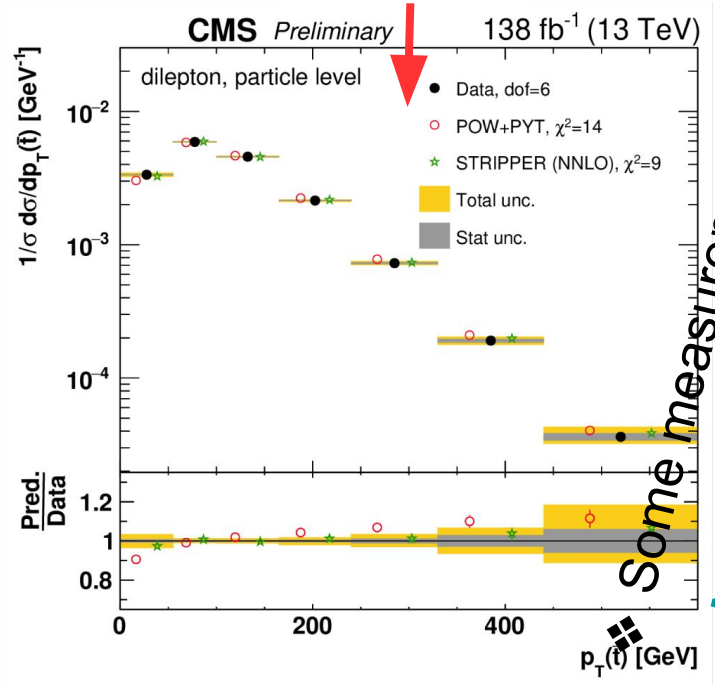
Parton level



Particle level

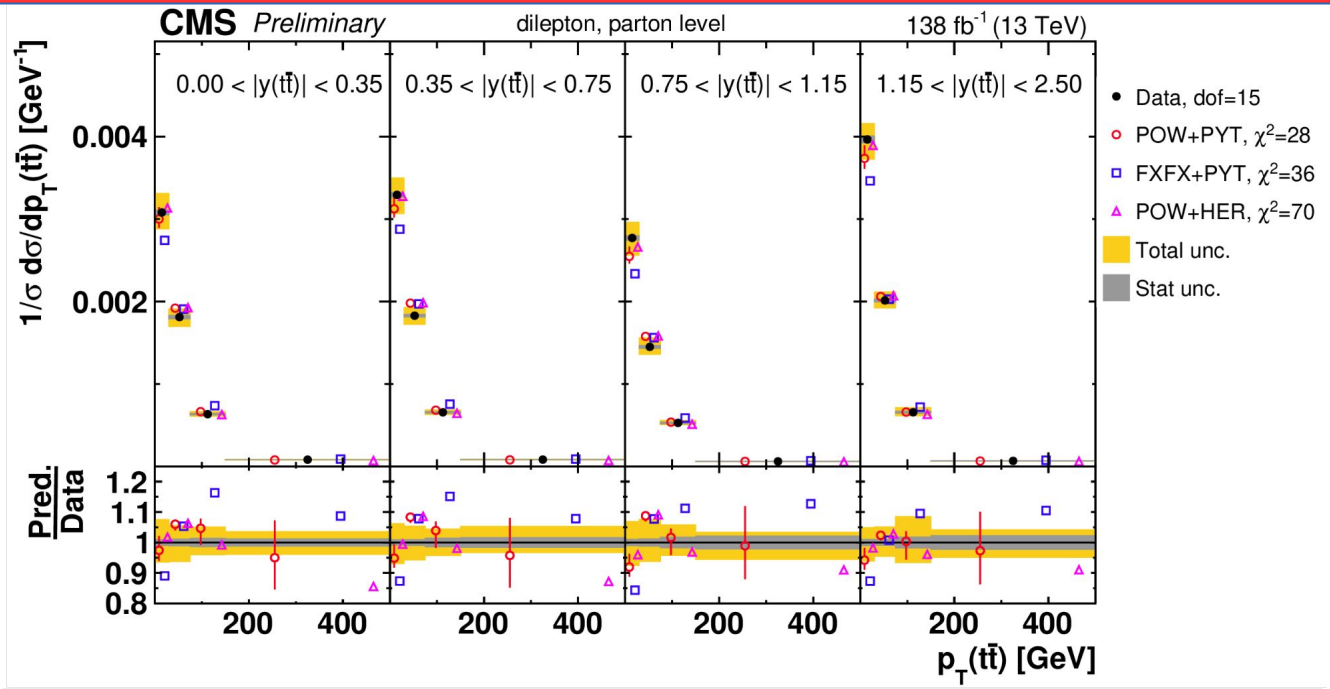
Antitop quark

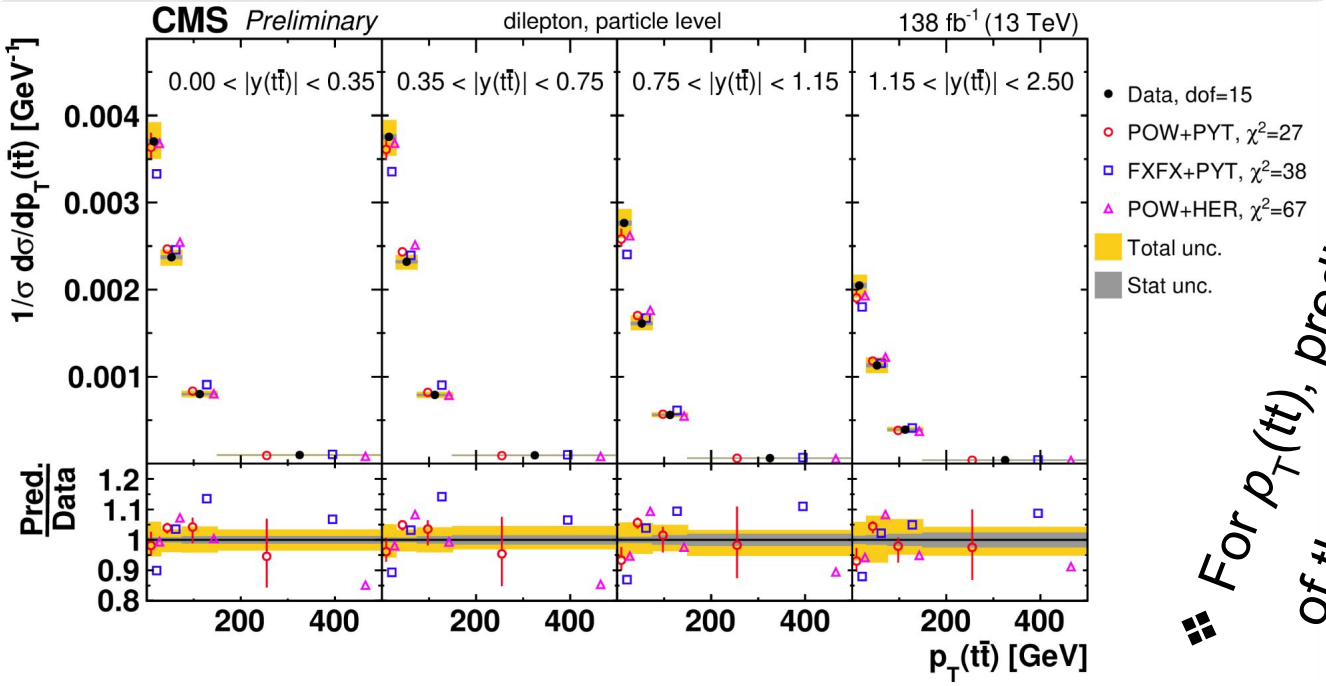




Some measurements are also confronted with **beyond NLO predictions** (MATRIX, STRIPPER, MINNLOOPS)

tt differential in dilepton - 138 fb^{-1} - CMS-PAS-TOP-20-006

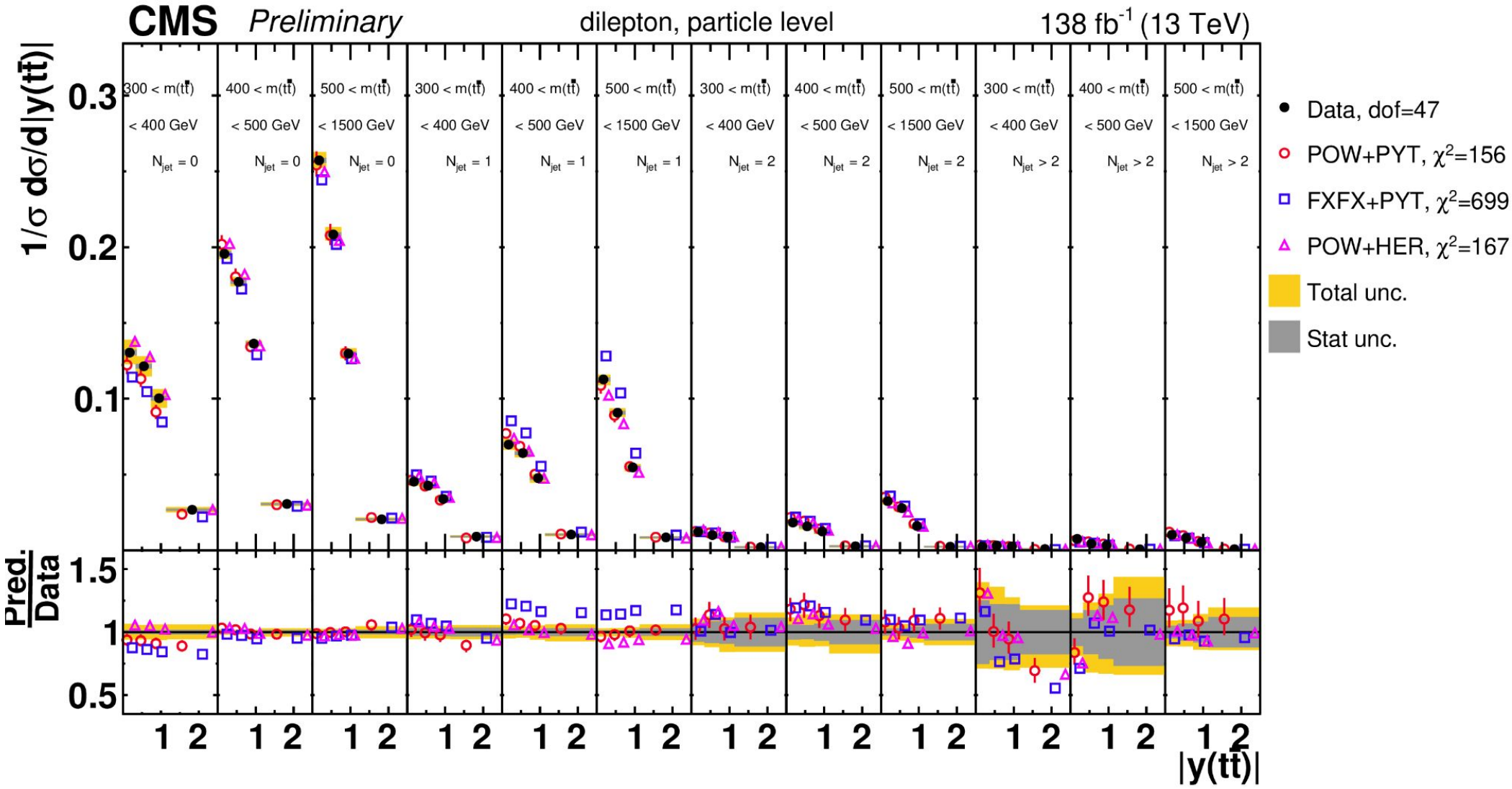




- For p_T(tt), predictions have larger differences and none of them provides a good description of the data
- m(tt) and y(tt) reasonably well described

tt differential in dilepton - 138 fb^{-1} - CMS-PAS-TOP-20-006

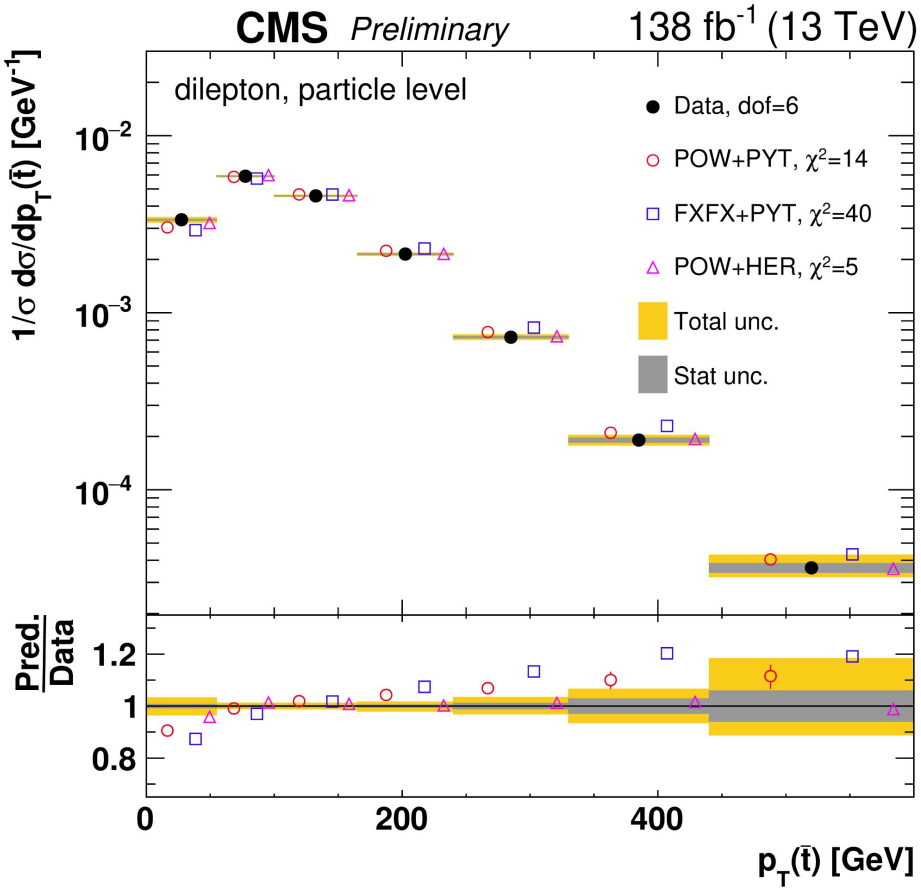
- Differential cross sections are measured as function of one, two, or **three variables** at the parton and particle levels

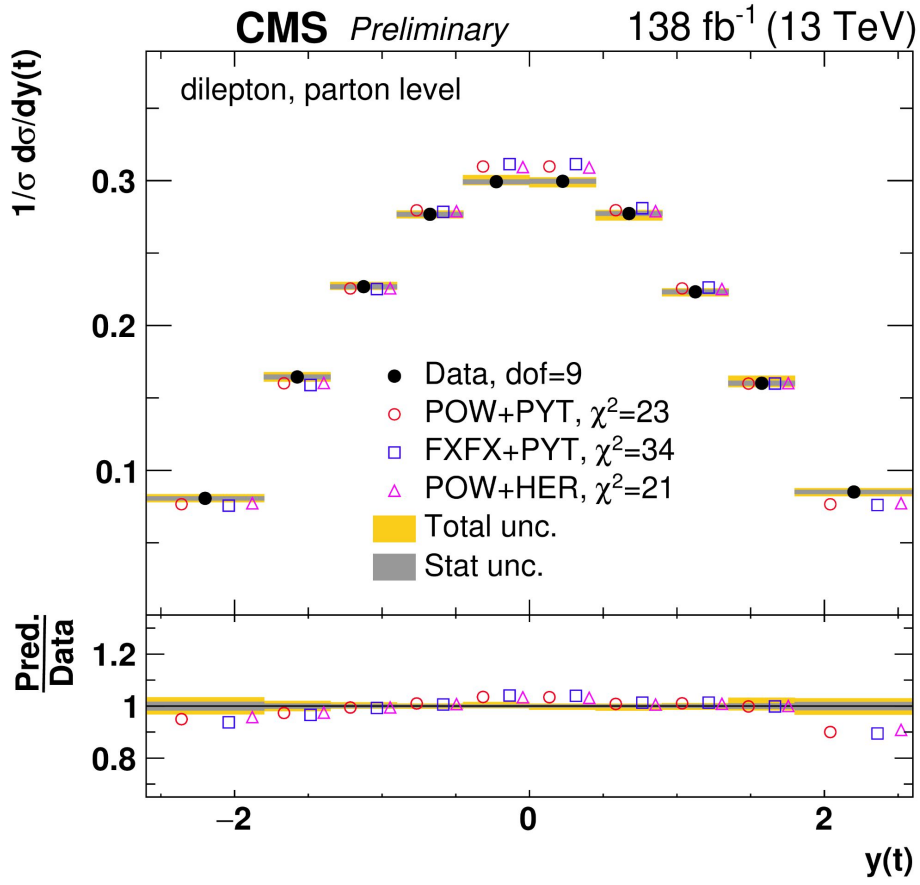


tt differential in dilepton - 138 fb^{-1} - CMS-PAS-TOP-20-006

- Nominal predictions, neglecting theoretical uncertainties, do not describe well several of the measured cross sections
  - ➢ deviations larger for the multi-differential cross sections

- Calculations predict harder p_T(t) and more-central rapidity distributions than data

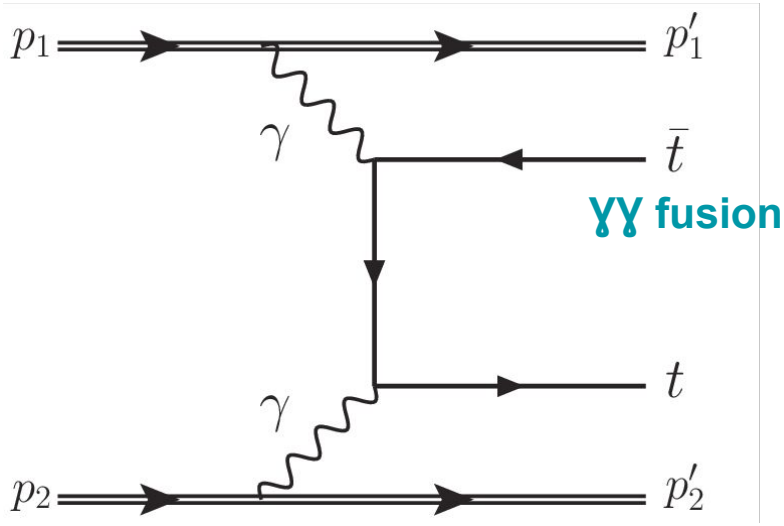


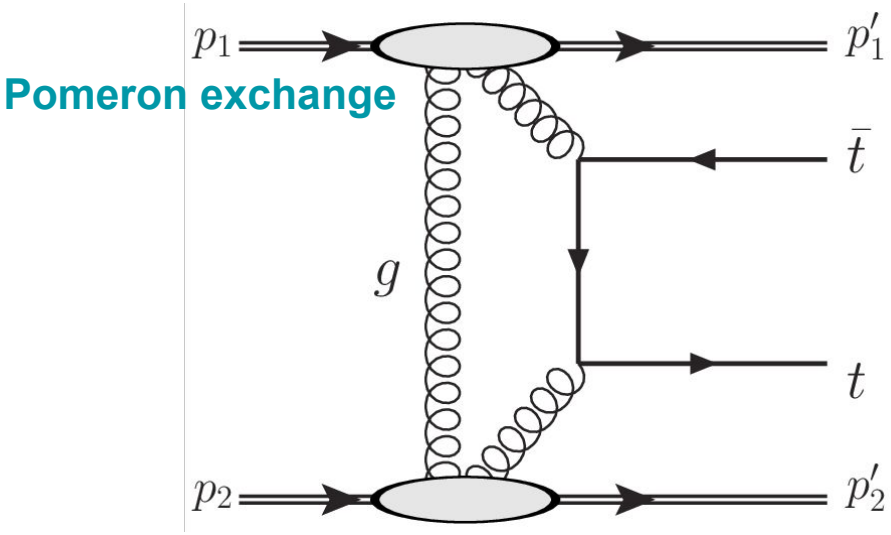


Central exclusive tt production

- Standard tt production measurements performed via strong interaction processes

- A different mechanism can lead to the production of tt pairs in pp scattering via the exchange of colourless particles such as photons or pomerons (≈0.1 fb)
  - ➢ one or both protons may remain intact after the interaction, while part of their energy is transferred to the tt pair





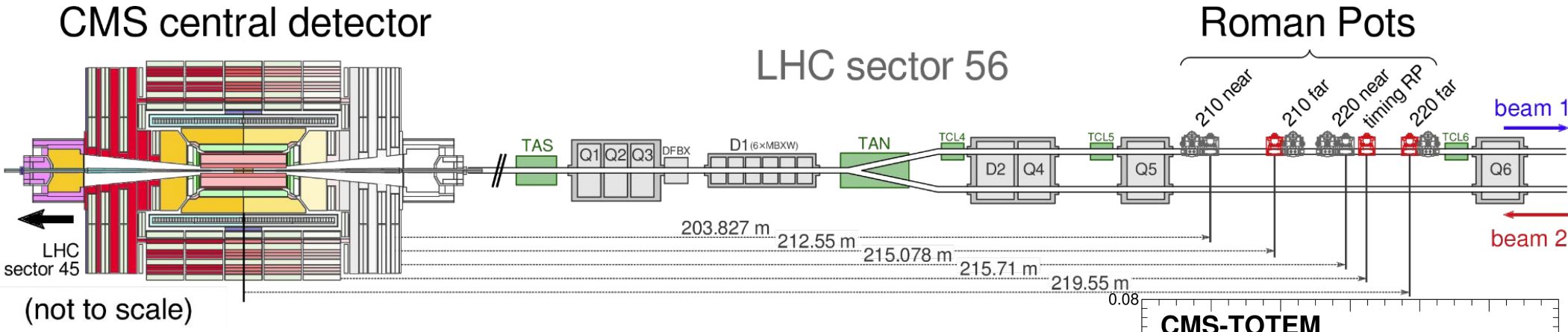
- Process where the two protons survive the collision, i.e. the reaction pp → pttp, is called central exclusive production

Search for central exclusive tt production - 29.4 fb^{-1}

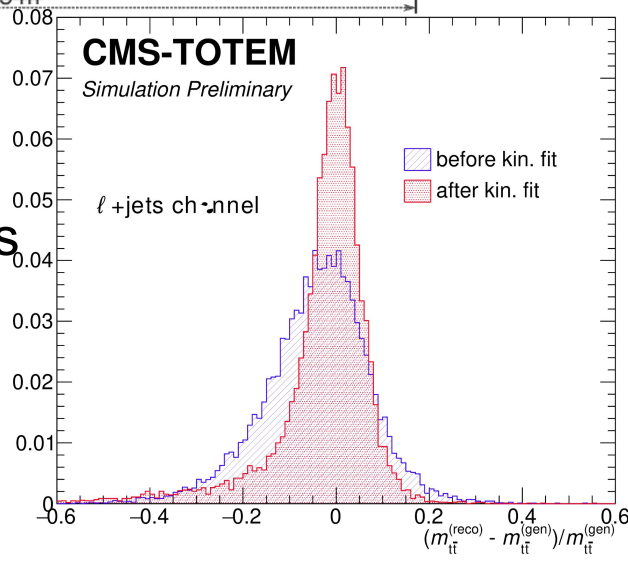
CMS-PAS-TOP-21-007

- Using proton-tagged events in proton-proton collisions at the LHC at 13 TeV

- Forward protons are detected with the CMS-TOTEM Precision Proton Spectrometer, one on each side of the interaction region



- tt decay products are reconstructed using the CMS central detector either in the dilepton or the lepton+jets decay modes



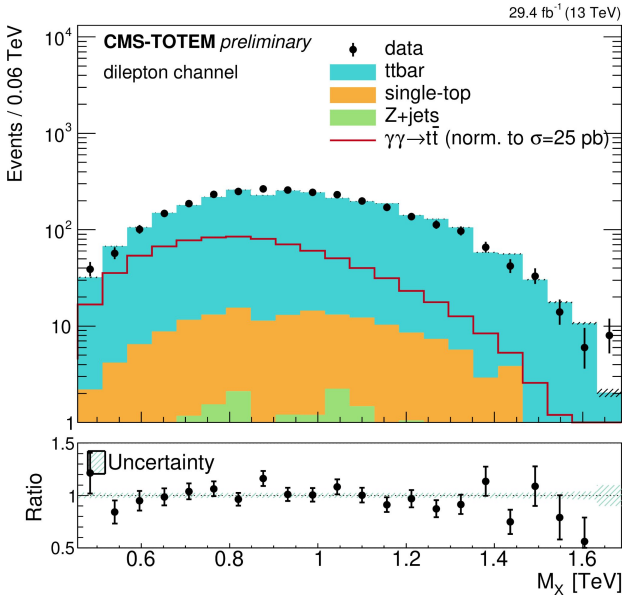
- Search conducted separately for the two modes, and the results are combined

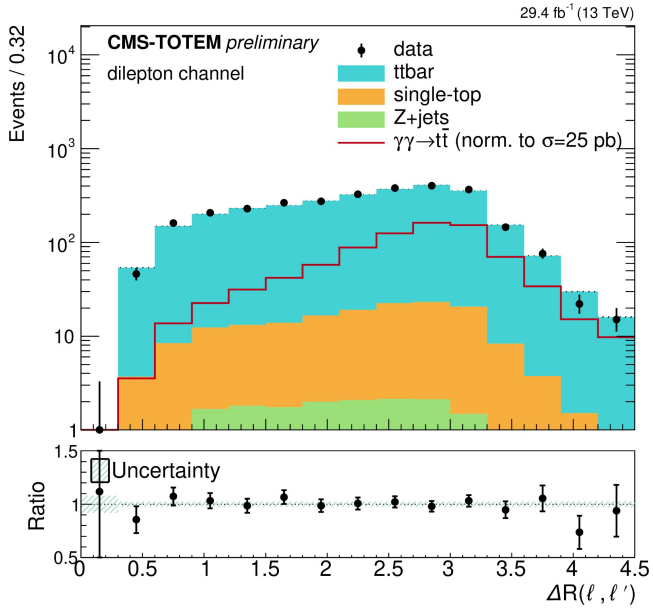
Search for central exclusive tt production - 29.4 fb^{-1}

CMS-PAS-TOP-21-007

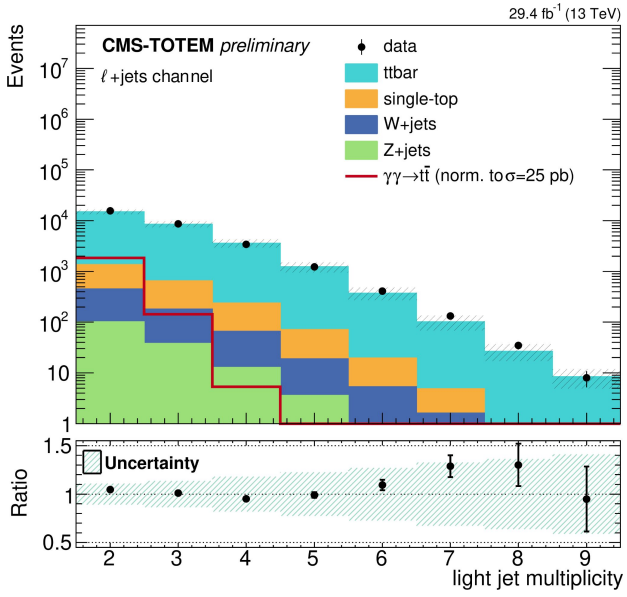
❖ In order to enhance the signal content of the selected samples, MVA is used

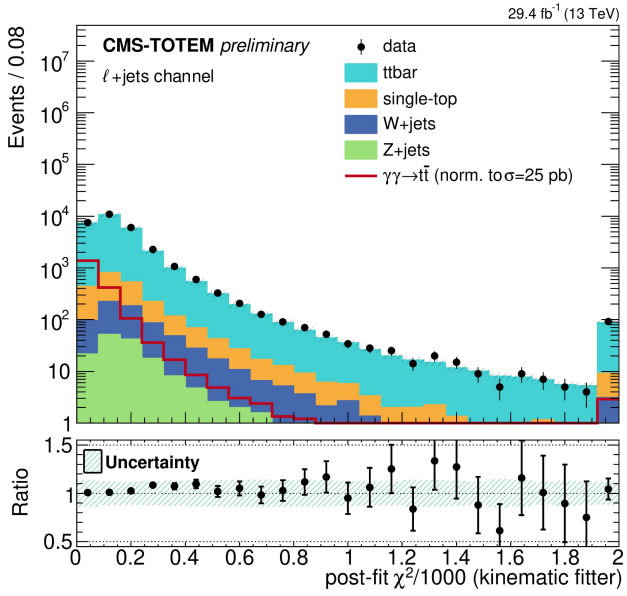
Dilepton →





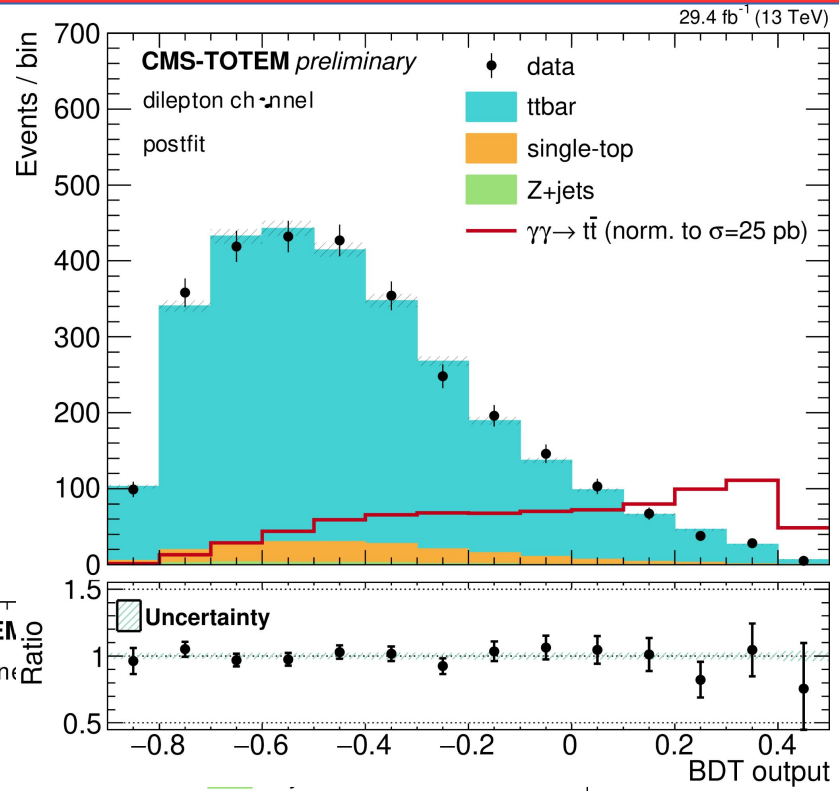
l + jets →

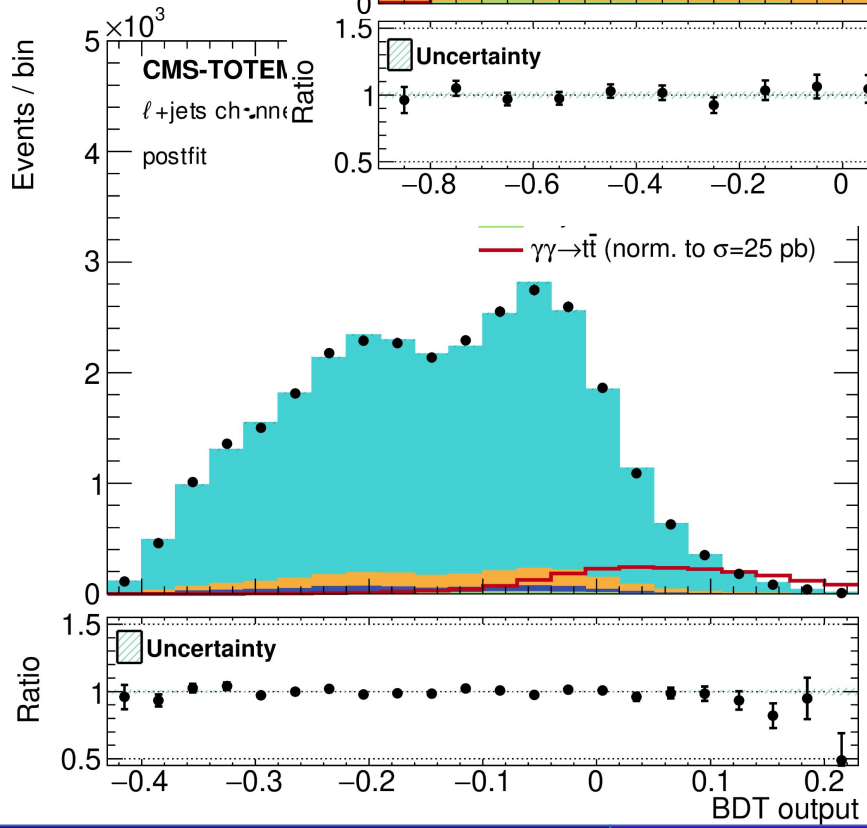


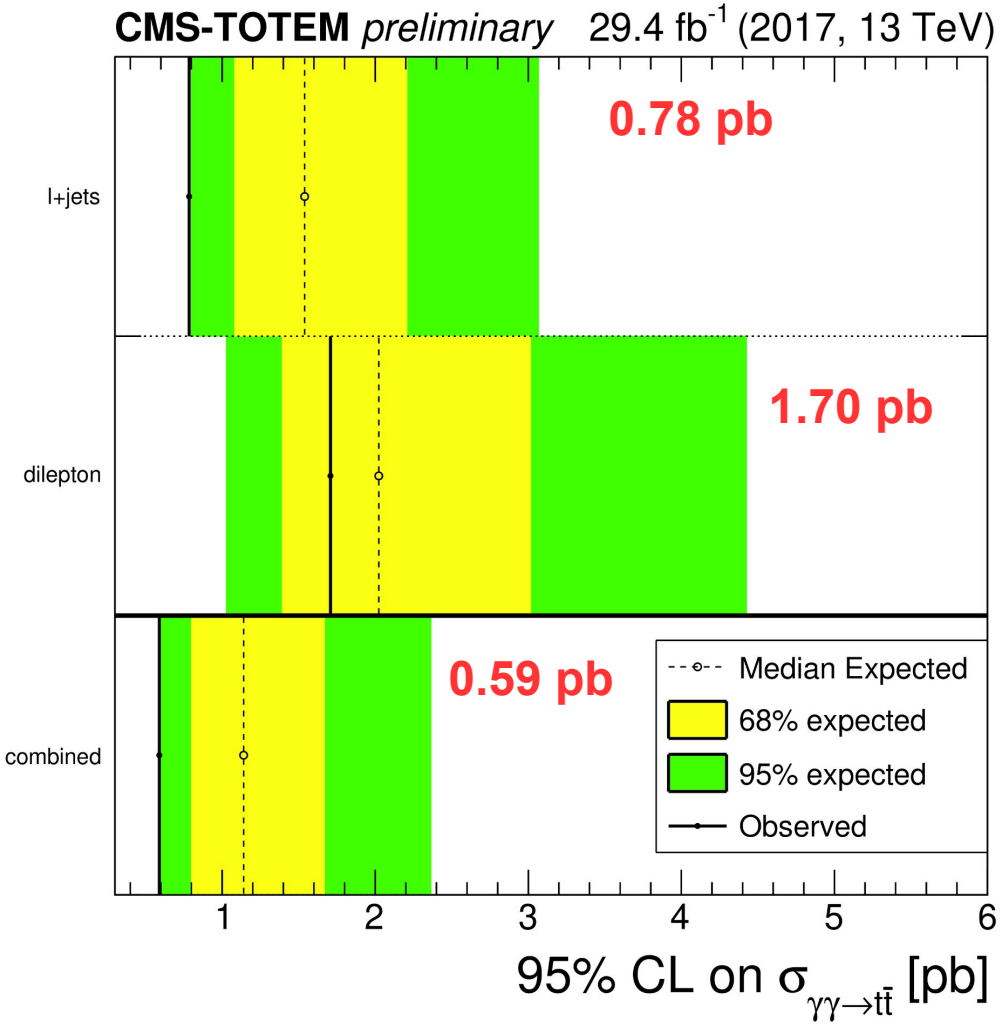


Search for central exclusive tt production - 29.4 fb^{-1}

CMS-PAS-TOP-21-007





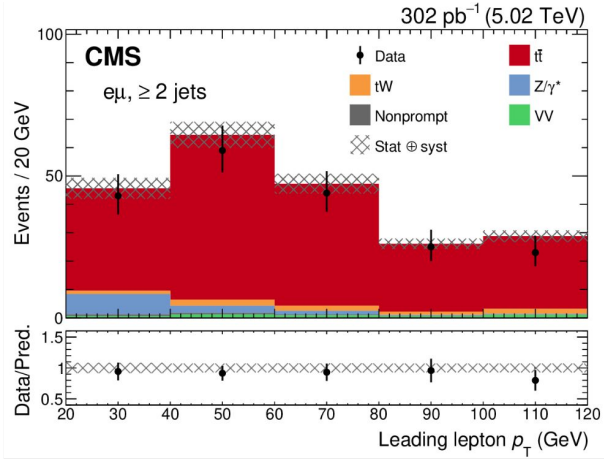


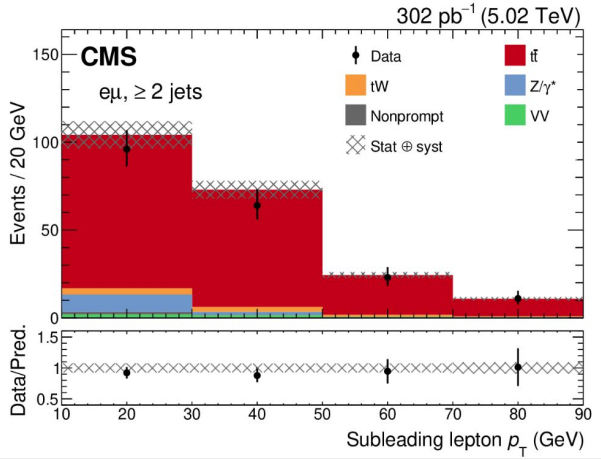
tt inclusive @ 5 TeV - 302 pb^{-1} - JHEP 04 (2022) 144

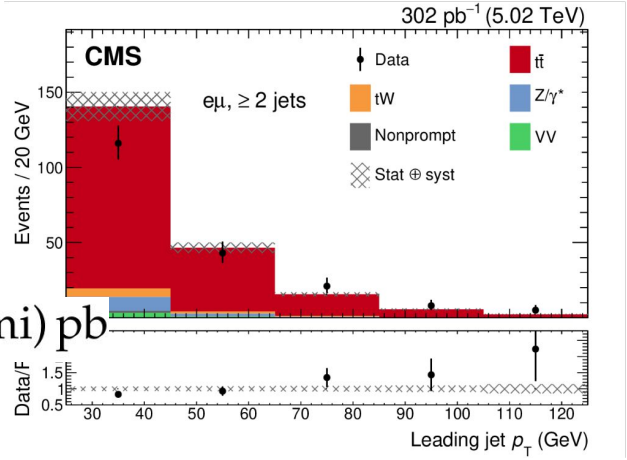
- Data collected in a special LHC low-energy and low-intensity run in 2017

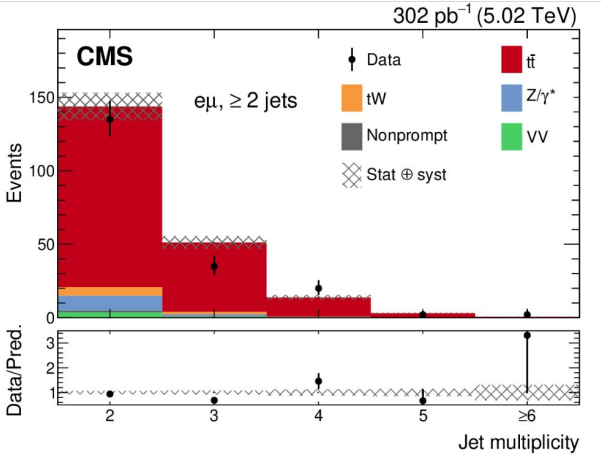
- Events with one electron and one muon of opposite charge, and at least two jets

$$\sigma_{t\bar{t}} = 60.7 \pm 5.0\,(\text{stat}) \pm 2.8\,(\text{syst}) \pm 1.1\,(\text{lumi})\ \text{pb}$$







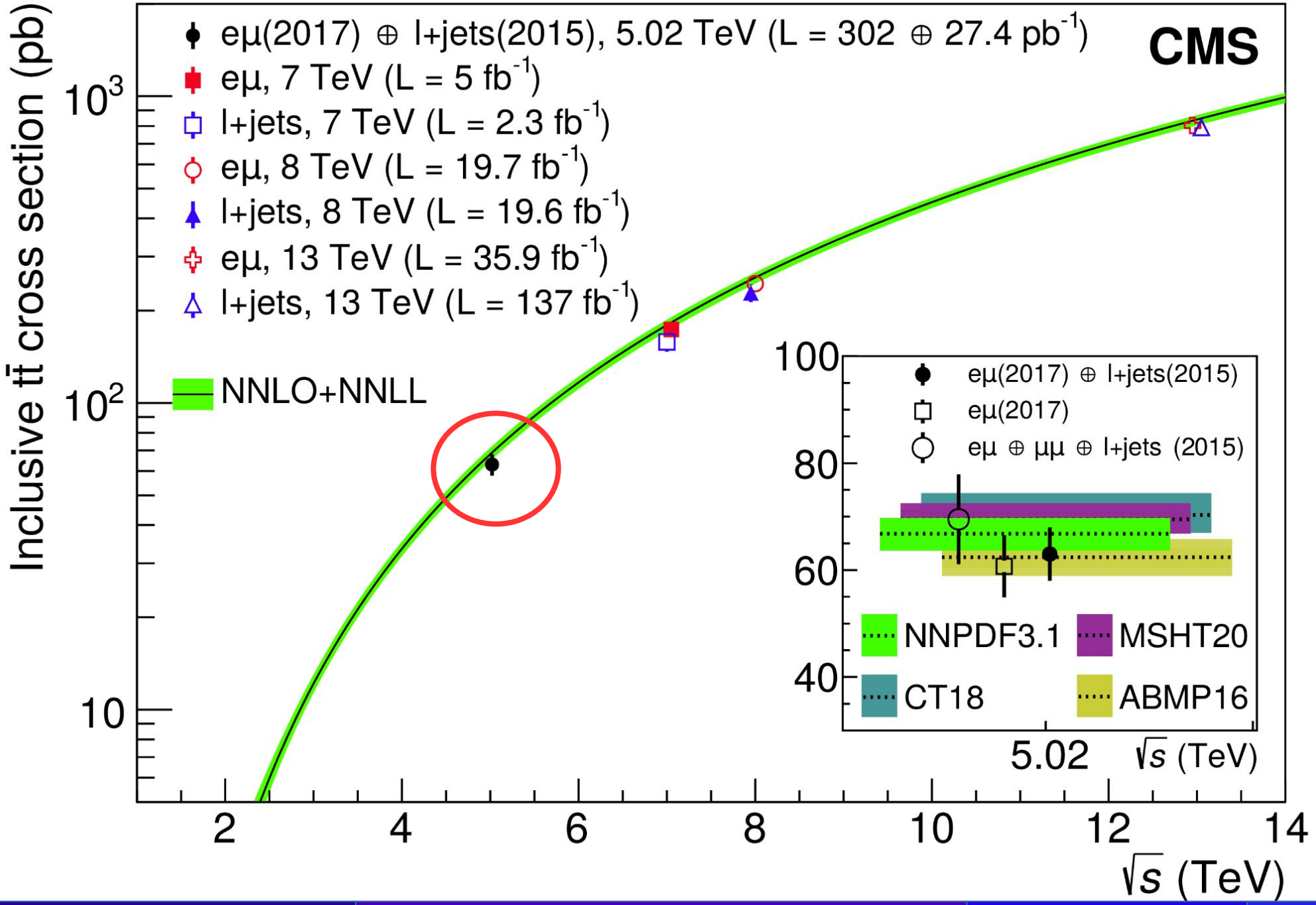


- To reduce the statistical uncertainty: (302 fb^{-1}, 2017, dil) ⊕ (27.4 fb^{-1}, 2015, l+jets)

$$\sigma_{t\bar{t}}^{\text{comb}} = 63.0 \pm 4.1\,(\text{stat}) \pm 3.0\,(\text{syst+lumi})\ \text{pb}$$

  - In agreement with σ(SM) = $66.8^{+2.9}_{-3.1}$ pb.

tt @ 5 TeV - 302 pb^{-1} - JHEP 04 (2022) 144



Summary

- The large amount of LHC data recorded up to date allows us to perform **extremely precise inclusive measurements**

- Multi differential measurements in all channels for resolved and boosted topologies as a function of many observables of tt, jets and leptons kinematics, at particle and parton level

- First search for **central exclusive tt** production

- In general, results are in good agreement with **SM** prediction
  - Some **tension** observed with the NLO predictions on double-differential distributions and variables related to the **top p_T**

- **Stay tuned:** New results with more data are on their way…

http://cms-results.web.cern.ch/cms-results/public-results/preliminary-results/TOP/index.html

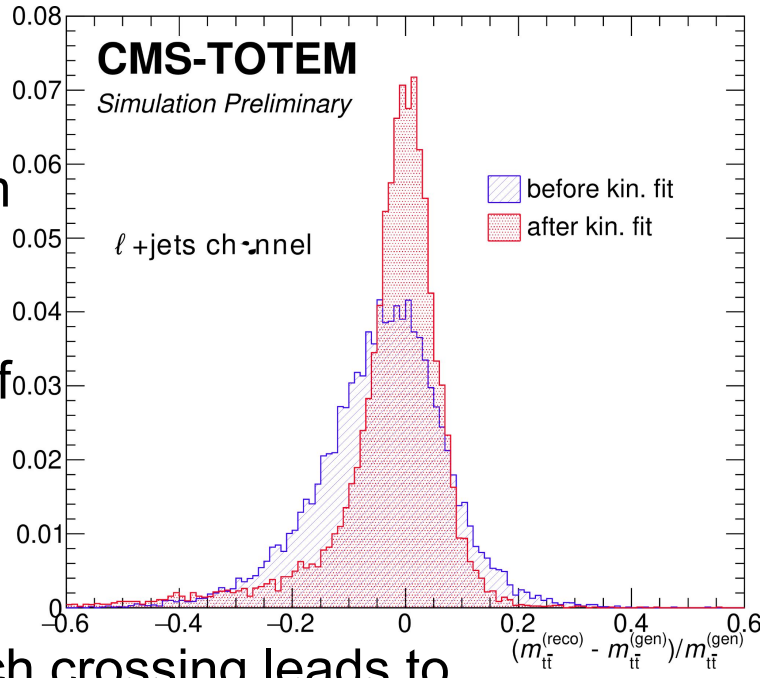
Back-up Slides

Search for central exclusive tt production - 29.4 fb^{-1}

CMS-PAS-TOP-21-007

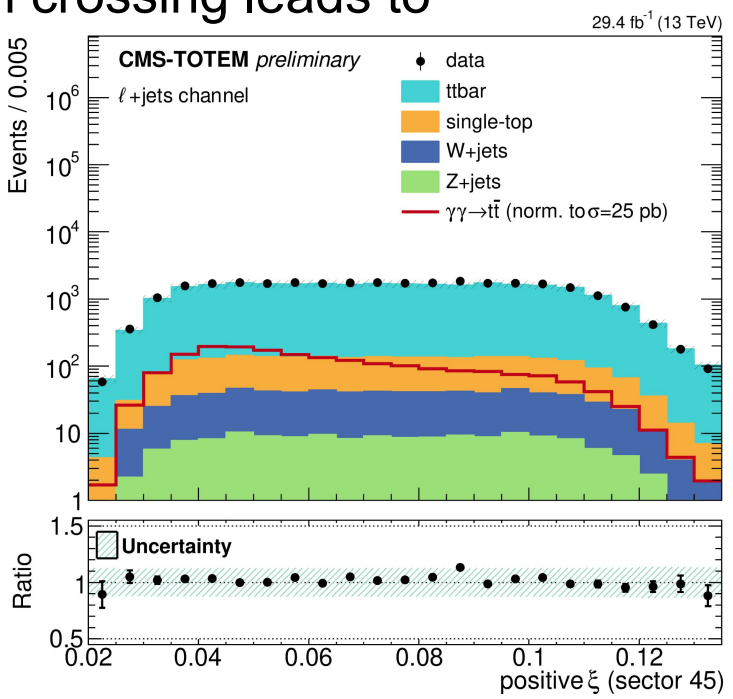
- Both the dilepton and the l+ jets analysis require one multi-RP proton track to be reconstructed in each arm

- Full reconstruction of the tt pair allows the correlation of its kinematics with that of the forward protons

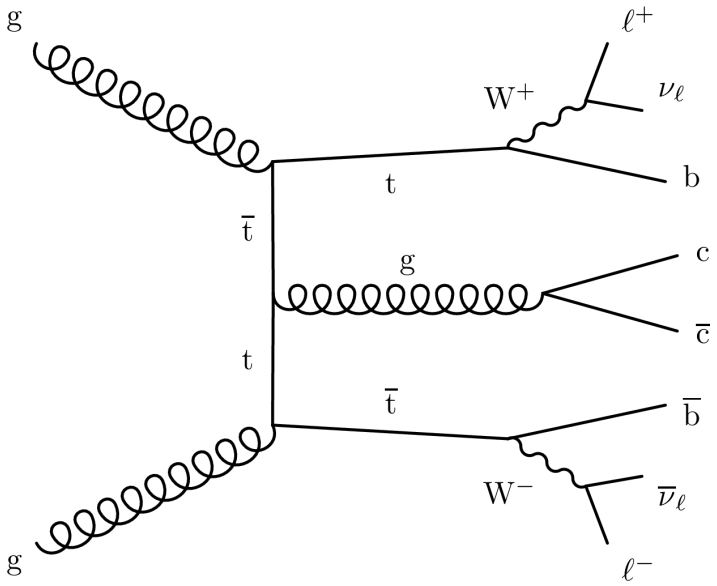


- Requiring multiple proton interactions in the same bunch crossing leads to superposition of objects from different primary vertex:
  - ➢ background event maybe selected as signal
  - ➢ signal event maybe rejected

- In order to take this correctly into account, a pool of proton pairs reconstructed in real data is collected to be used as pileup protons



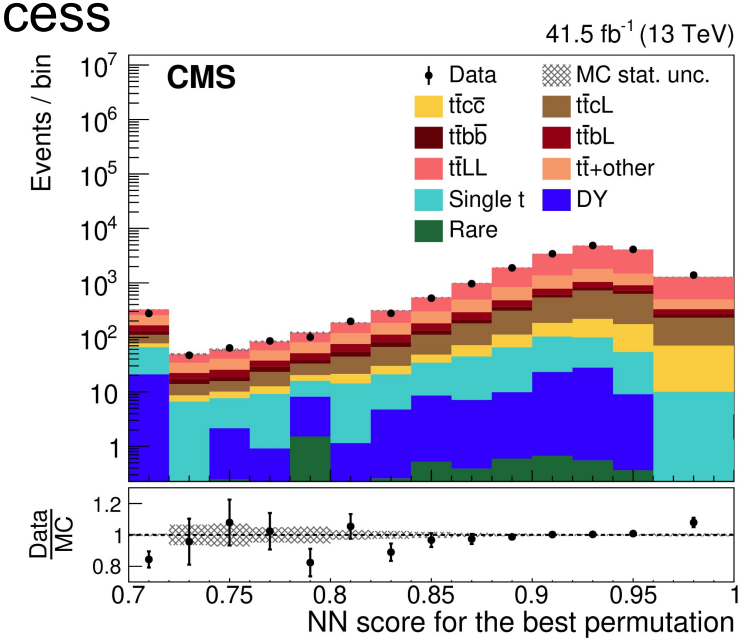
ttcc Production



- Calculations of the production cross section for ttbb are available at NLO in QCD but suffer from large uncertainties
  - Due to the choice of factorization and renormalization scales
- ttcc production is much harder
  - More difficult to experimentally distinguish c than b jets from light-flavour (LF) or gluon jets
  - Challenge of simultaneously separating ttcc and ttbb events from tt with additional LF or gluon jets (ttLL)

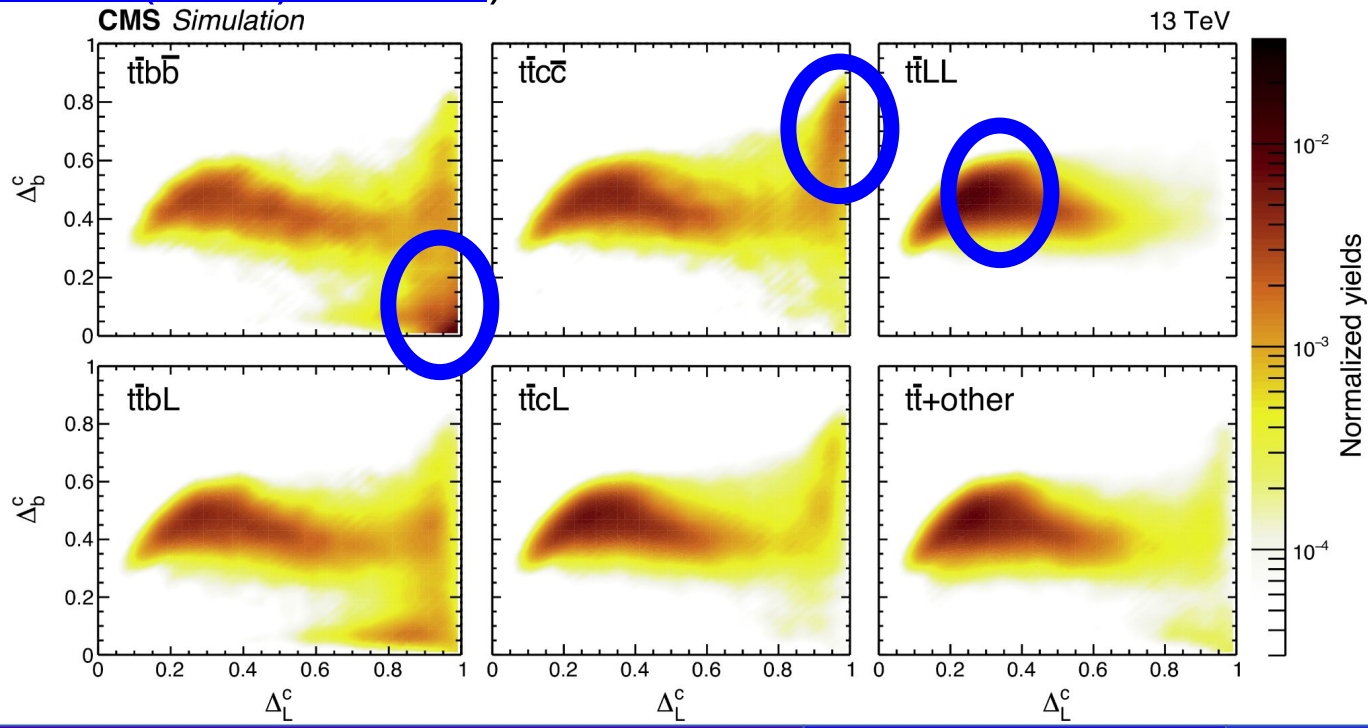
ttcc Production - 41.5 fb^{-1} - Phys. Lett. B. 820 (2021) 136565

- **First dedicated measurement** of this production process
- Dileptonic final states with at least two additional jets
- Training a NN to identify the correct jet-parton assignment
- A new charm jet identification algorithm provides input to a neural network that is trained to distinguish among ttcc, ttbb and tt (JINST 13 (2018) P05011)
- Train multiclass NN to separate ttcc / ttbb / ttLF



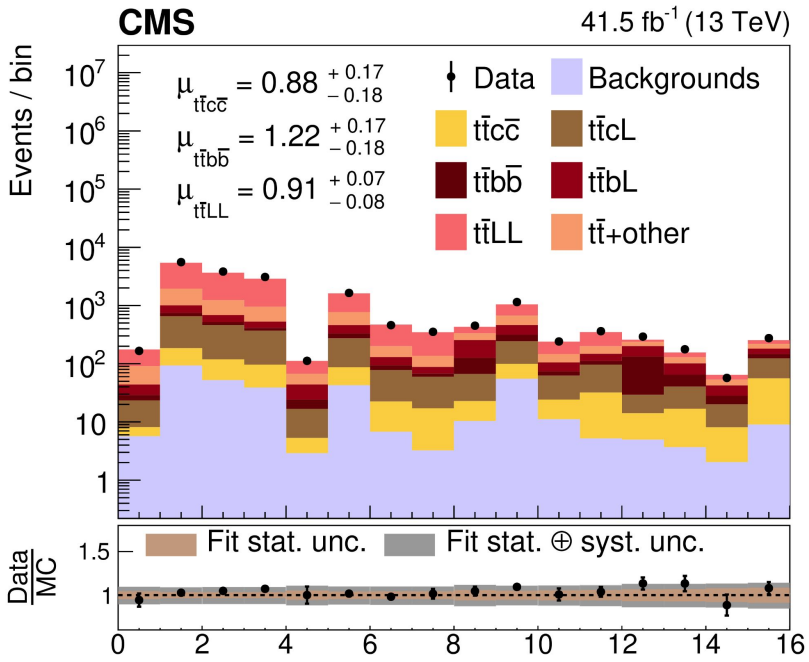
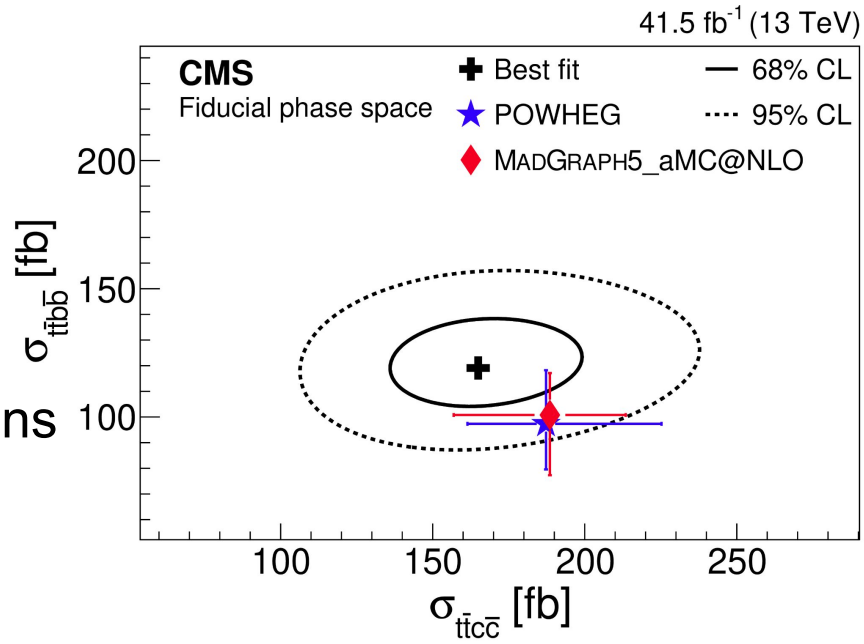
$$\Delta_b^c = \frac{P(t\bar{t}c\bar{c})}{P(t\bar{t}c\bar{c}) + P(t\bar{t}b\bar{b})}$$

$$\Delta_L^c = \frac{P(t\bar{t}c\bar{c})}{P(t\bar{t}c\bar{c}) + P(t\bar{t}LL)}$$



ttcc Production - 41.5 fb^{-1} - Phys. Lett. B. 820 (2021) 136565

- Template fit to the unrolled 2D distribution
- Inclusive ttcc, ttbb, and ttLL cross sections are simultaneously measured, together with their ratios to the inclusive tt + two jets cross section

	Result	POWHEG	MADGRAPH5_aMC@NLO
	Full phase space		
$\sigma_{t\bar{t}c\bar{c}}$ [pb]	$8.0 \pm 1.1 \pm 1.3$	9.1 ± 1.8	8.9 ± 1.5
$\sigma_{t\bar{t}b\bar{b}}$ [pb]	$4.09 \pm 0.34 \pm 0.55$	3.34 ± 0.72	3.39 ± 0.66
$\sigma_{t\bar{t}LL}$ [pb]	$231 \pm 5 \pm 21$	255 ± 43	261 ± 37
R_c [%]	$2.69 \pm 0.36 \pm 0.32$	2.81 ± 0.20	2.72 ± 0.19
R_b [%]	$1.37 \pm 0.11 \pm 0.14$	1.03 ± 0.08	1.03 ± 0.09

- The measured values and theoretical predictions agree at the level of one to two standard deviations