Titans clash: the top quark meets Pb ions

F. Goya, Saturno devorando a su hijo, printed on a coffee mug...

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Wednesday, 21st October 2020

Ciclo de seminários “Café com Física”

Outline

Introduction

(re-) establishing the pp reference

First observation in pPb collisions

First evidence in PbPb collisions

Conclusions*

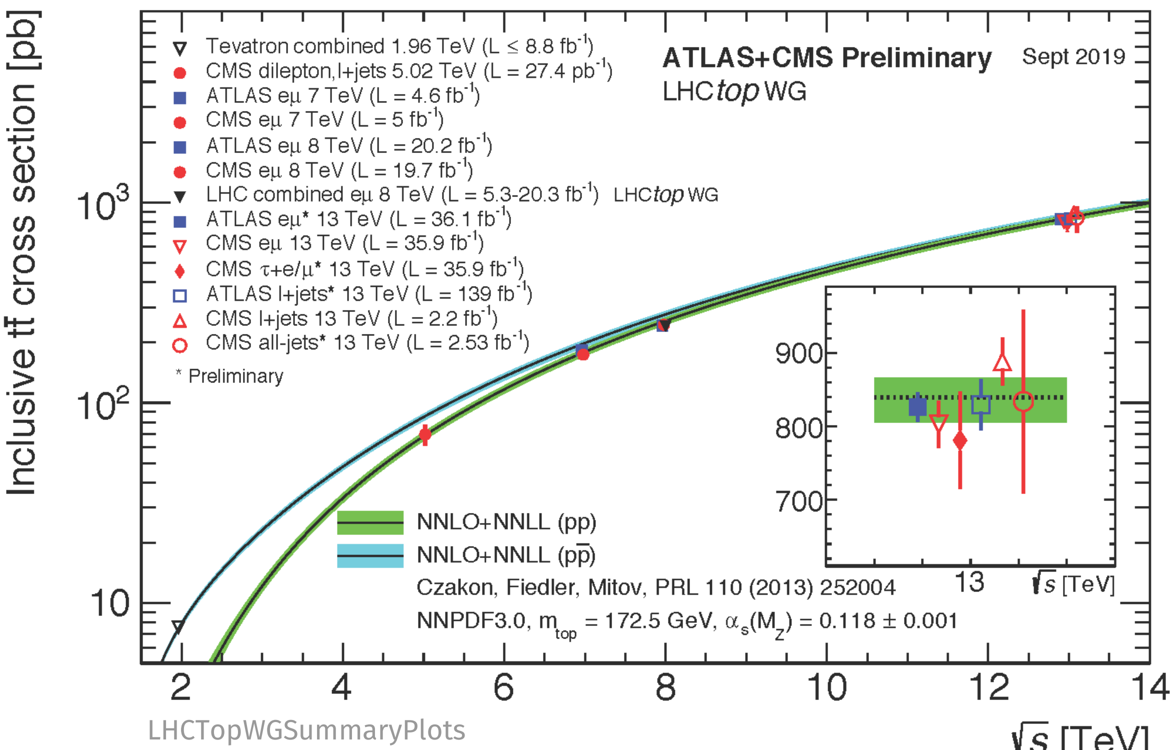
** with a reprise of Goya's "Saturn devouring his son"*

Introduction

Top quarks still interesting 25 years after

- **At the LHC top quarks are predominantly produced by strong interactions**
  - cross section is sensitive to mass and strong-coupling constant

$$\hat{\sigma} \propto \left(\frac{\alpha_S}{m_t}\right)^2 f(\alpha_S, \beta)$$



LHCTopWGSummaryPlots

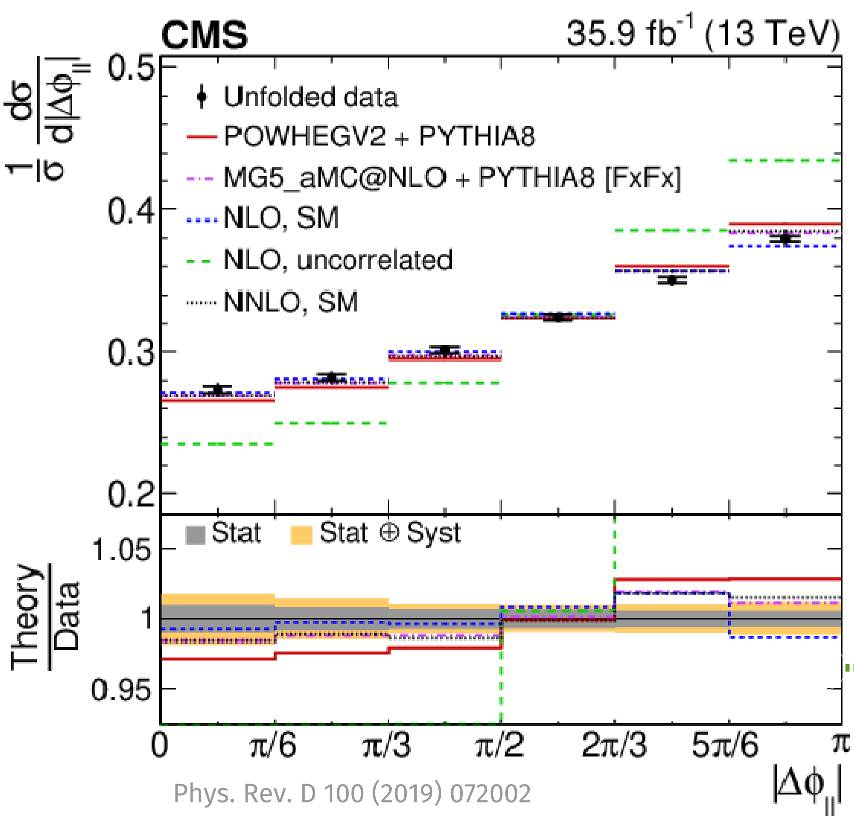
$$\delta m_t^{pole} / m_t^{pole} \approx 1.2\%$$

$$\delta \alpha_S / \alpha_S \approx 3.4\%$$

Eur. Phys. J. C 79 (2019) 368

Top quarks still interesting 25 years after

- **At the LHC top quarks are predominantly produced by strong interactions**
  - cross section is sensitive to mass and strong-coupling constant
  - differential distributions are sensitive to width, EW corrections, BSM couplings



Phys. Rev. D 100 (2019) 072002

NLO QCD uncorrelated

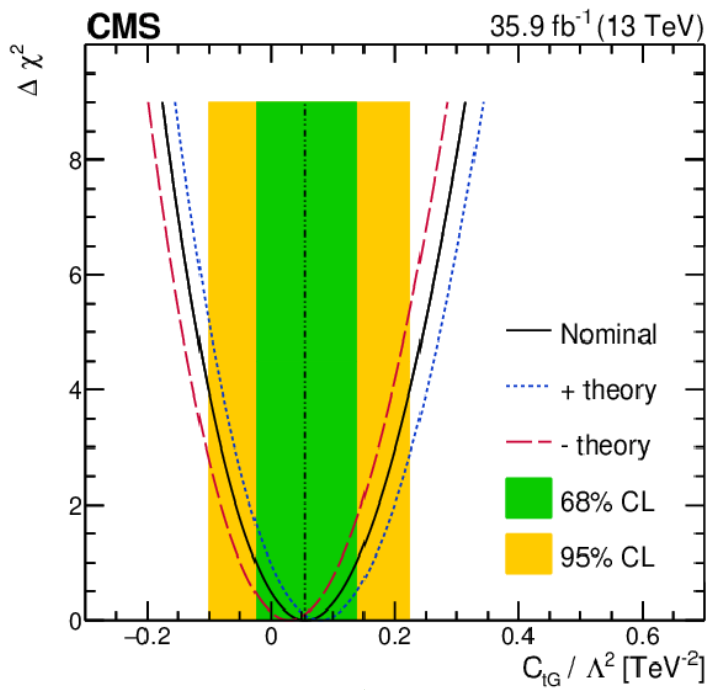
$$\chi^2/dof = 190/5$$

$$\chi^2/dof = 9/5$$

NLO QCD SM

$$\chi^2/dof = 4/5$$

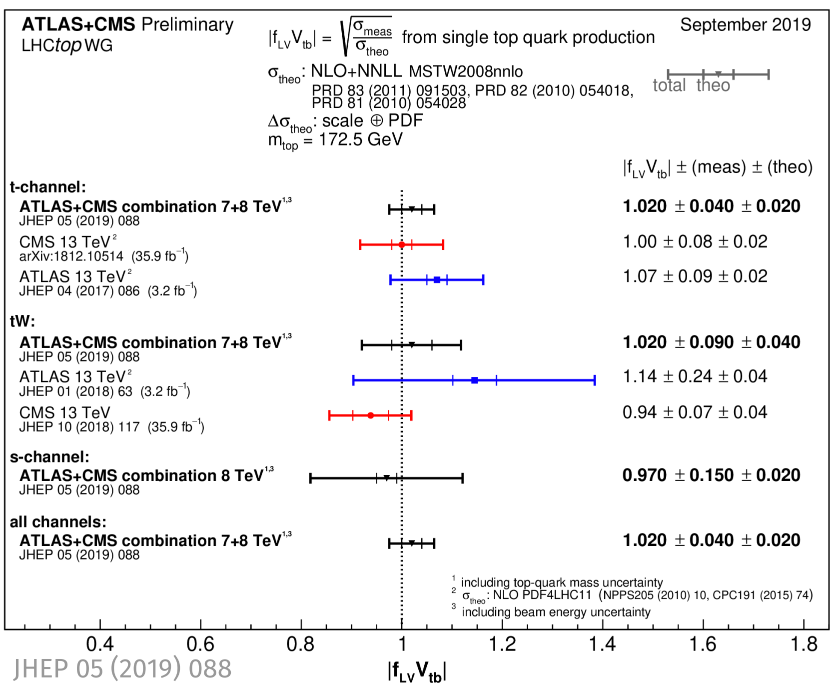
NLO QCD + parton shower



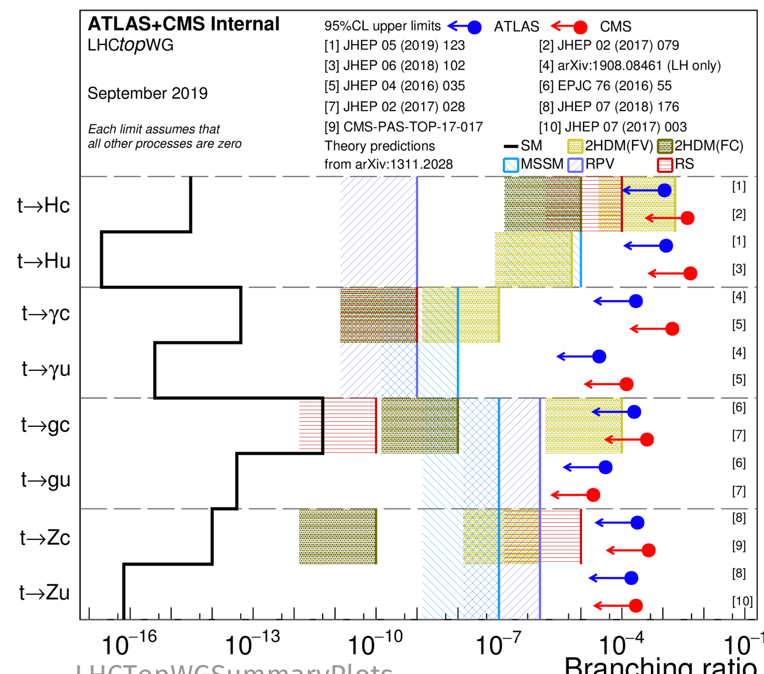
explore sensitivity to anomalous chromo-magnetic moments

Overall status of top quark physics at the LHC

- **In general data are in good agreement with NNLO QCD+NLO EW**
  - good precision reached in V_{tb} (4%), α_s (3%), and m_t (0.3%)
  - up to $d^3\sigma/dX$ measured! exploring production, decay, resolved and boosted regimes
  - rich programme of measuring rarer processes
    (associated productions with heavy flavours, bosons, other top quarks,…)
  - searches for FCNCs, anomalous couplings, charge asymmetry, CP violation, …



JHEP 05 (2019) 088



LHCTopWGSummaryPlots

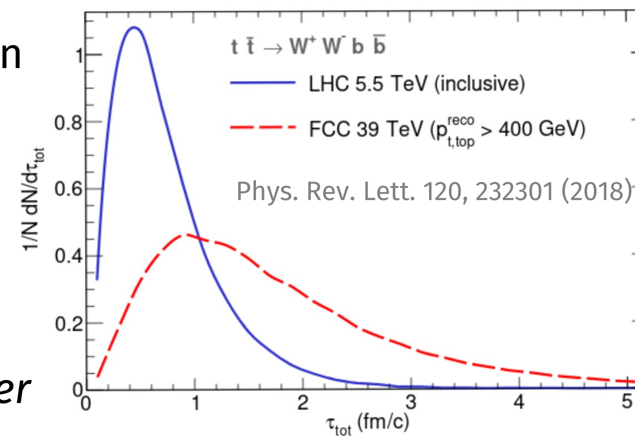
Top quarks as (the) hard(est) probes in heavy-ions

- **Top quarks have typical time scales which are smaller than QCD time scales**

$$\underbrace{\frac{1}{m_t}}_{\substack{\text{production}\\ 10^{-27}\text{ s}}} < \underbrace{\frac{1}{\Gamma_t}}_{\substack{\text{lifetime}\\ 10^{-25}\text{ s}}} < \underbrace{\frac{1}{\Lambda_{QCD}}}_{\substack{\text{hadronization}\\ 10^{-24}\text{ s}}} < \underbrace{\frac{m_t}{\Lambda^2}}_{\substack{\text{spin-flip}\\ 10^{-21}\text{ s}}}$$

  - most top quarks will promptly decay after production
  - decay products are color-coherent for “long” time
  - with high statistics explore different time scales: boosted tops will live longer $\Delta t \to \Delta t / \sqrt{1-\beta^2}$

    ⇨ *probe time structure of the QGP with a chronometer*



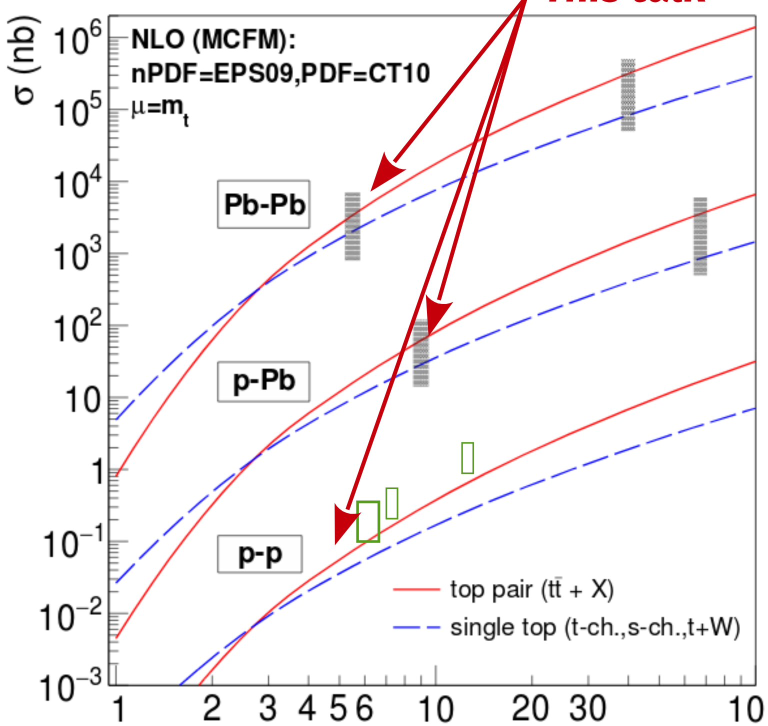
- **Given the precision reached in top quark physics: potential to be a reference**
  - experimentally view it's used already for tagging efficiencies, jet energy scale
  - use it as standard model candle in (large statistics) heavy ion collisions

From pp to PbPb

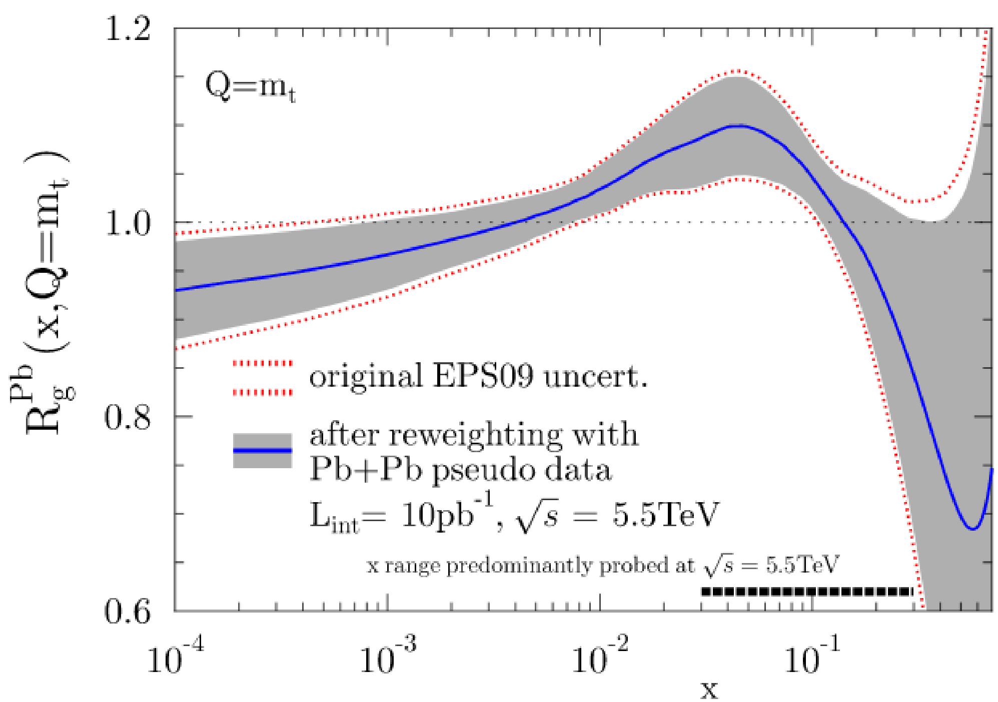
- **tt pairs mostly produced through gg fusion**
  - with respect to pp, production cross section enhanced by A^n (n=# nuclei)
  - positive (yet small) anti-shadowing region in nuclear PDFs, poorly known

$$Q^2 \approx m_t^2 \approx 3 \cdot 10^4 \text{ GeV}^2 \qquad x \approx 2m_t/\sqrt{s_{NN}} \approx 0.005 - 0.05$$

This talk



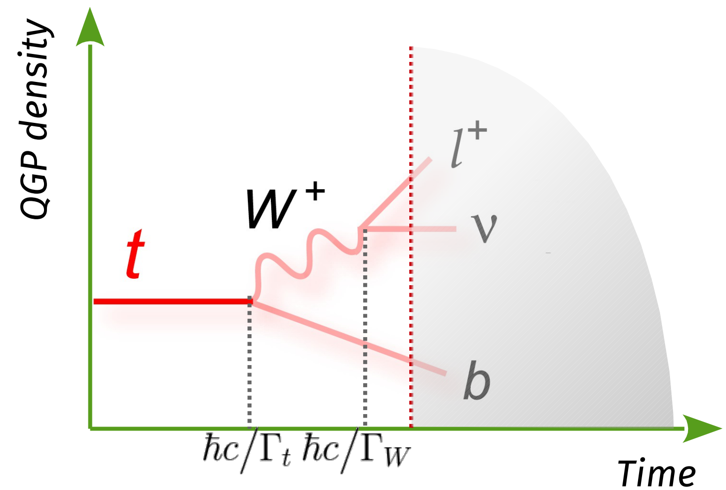
arXiv:1501.05879



Experimental challenges

- **Top quark carries colour**
  - $\hbar c/\Gamma_t \gg c\tau_{QGP}$ ⇨ decays before QGP is formed
  - decay products pass through medium:
    - charged leptons are unaffected
    - jets may probe it
      (quenching effects may occur,
      maybe surpressed due to
      color coherence, and EWK origin)

  ⇨ *avoid entangling different effects in a first measurement*

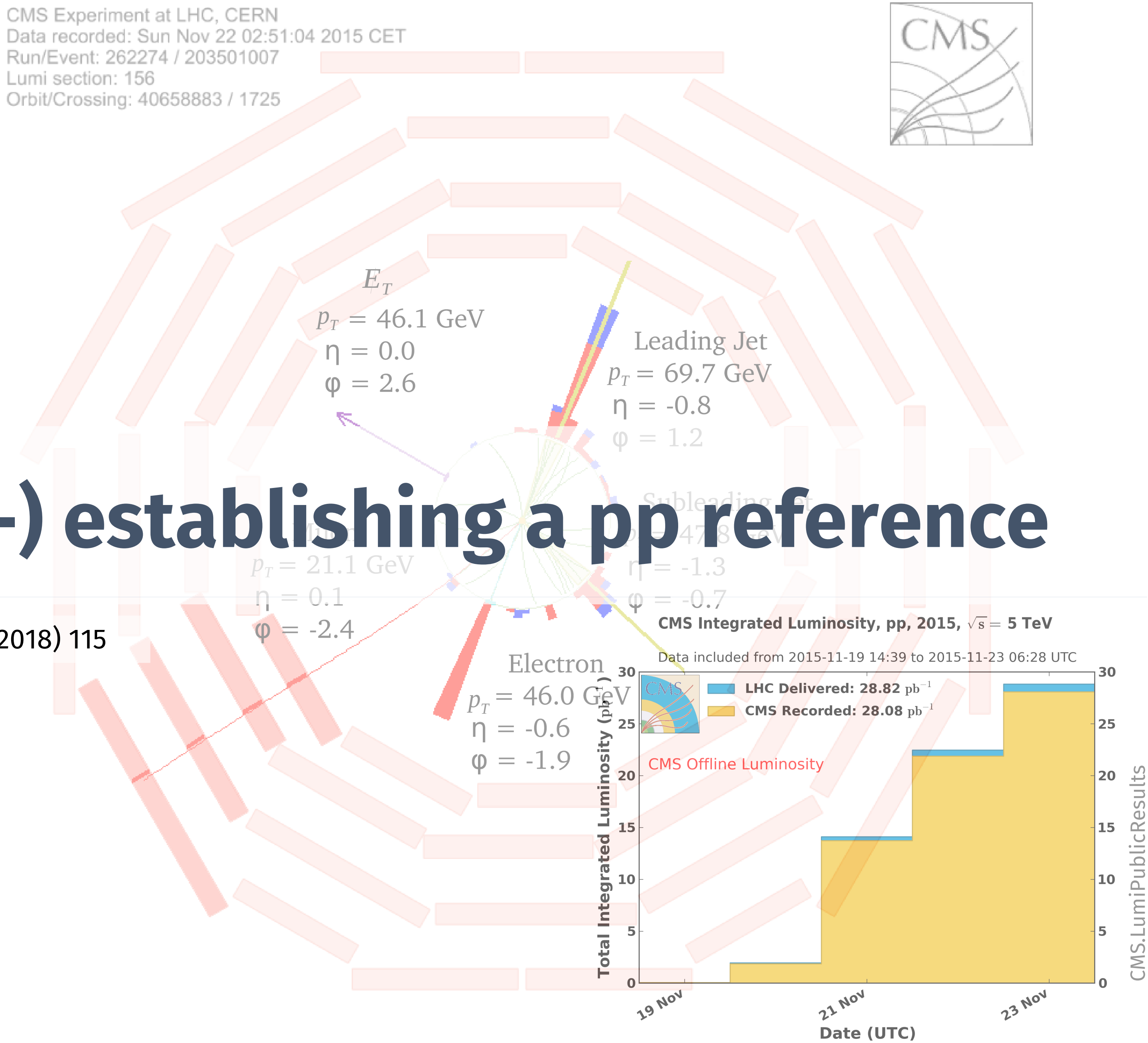


- **pp reference, pPb and PbPb runs have low integrated luminosity**
  - hard to calibrate precisely jet energy scale, b-tagging efficiencies
  - care with selection of top signals from W+jets, Drell-Yan and multijet backgrounds

  ⇨ *need "aggressive" discrimination and "in-situ" calibrations whenever possible*

(re-) establishing a pp reference

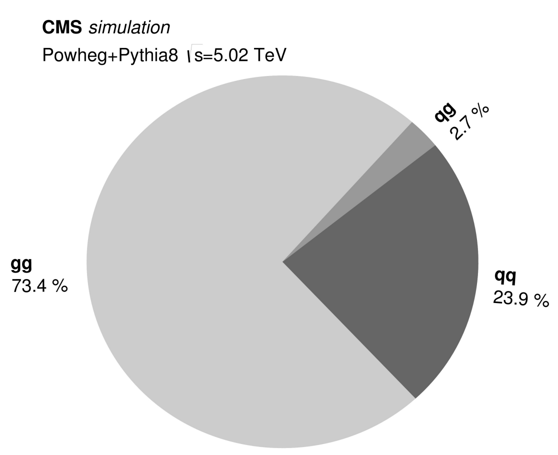
JHEP 03 (2018) 115



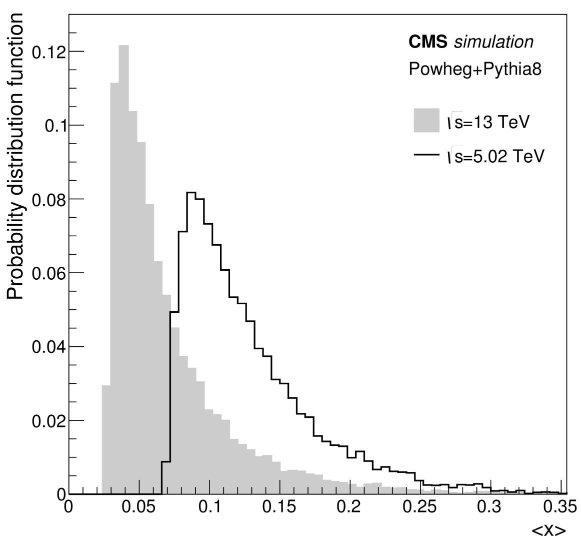
Measuring σ(tt) at $s^{1/2}$=5.02 TeV

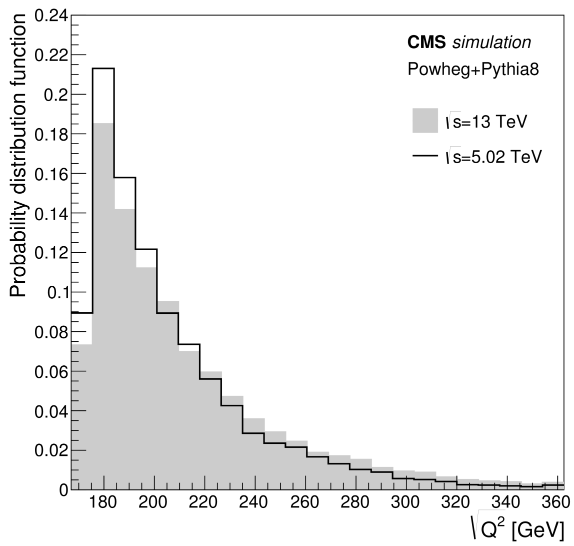
- **Why should we bother in the first place?**
  - *experimentally*:
    - same nucleon-nucleon c.o.m. energy as PbPb (no rescaling needed)
    - employ selections/variables which could be interesting in PbPb
    - never done before (bridge the gap between Tevatron and LHC)
  - *theory*:
    - lower $s^{1/2}$ pushes PDFs to higher x at the same Q^2, enhanced qq' contribution

      (with more statistics could be competitive for α_S and m_t^{pole}, charge asymm.)



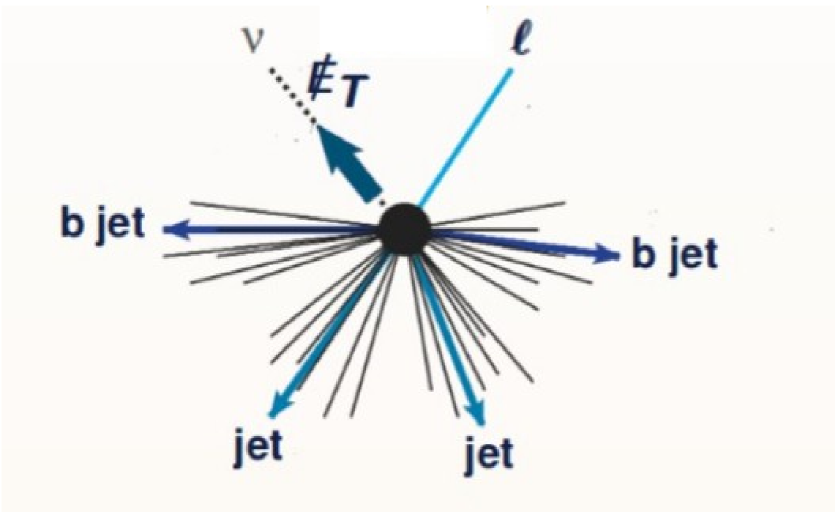
CMS-PAS-TOP-16-015





Measurement strategy

- **Combine final states with at least one charged lepton**
  - high combined BR (35%) and S/B (50-95%) with simple selections



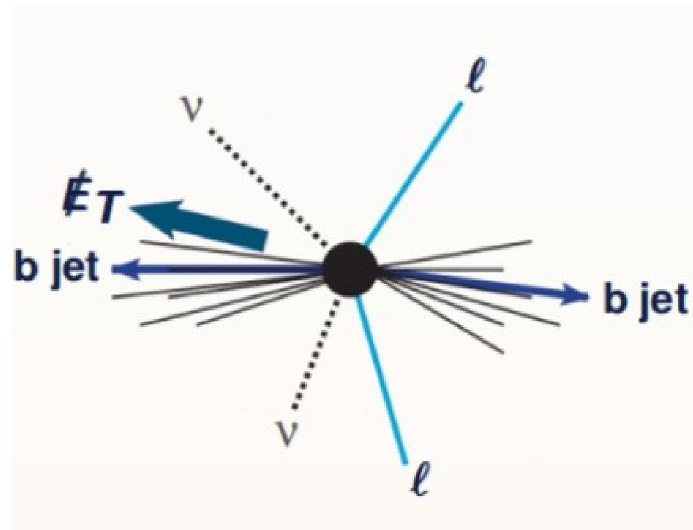
lepton+jets

=1 e (μ) p_T>40 (25) GeV |η|<2.1 I_{rel}<15%

>=4 jets p_T>30 GeV |η|<2.4

b-tagging (ε_b~70% ε_g~1%) used in counting

and to identify jets from W→qq' decays



dileptons

1e1μ or 2μ p_T>20 (18) GeV for e(μ)

reject if m(ll)<20 GeV

≥2 jets p_T>25 GeV |η|<3

μμ-specific |m(ll)-91|>15 GeV + E_T^{miss}>35 GeV

Dilepton

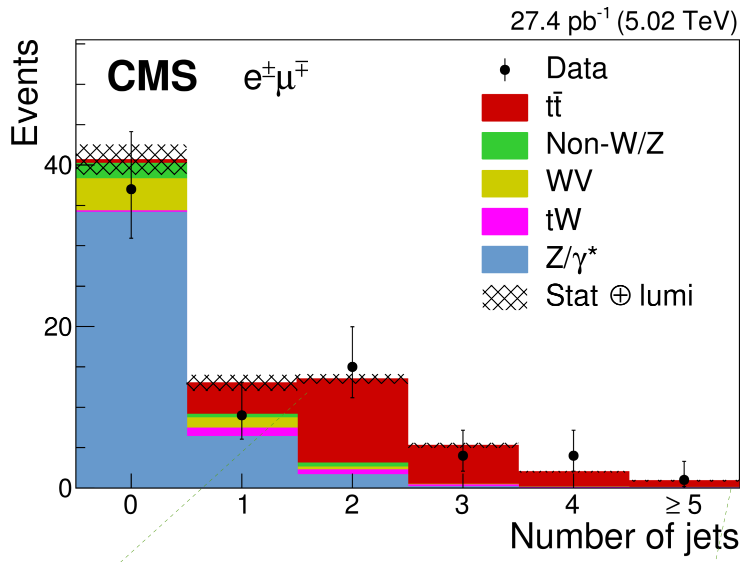
- **Apply simple cut and count**

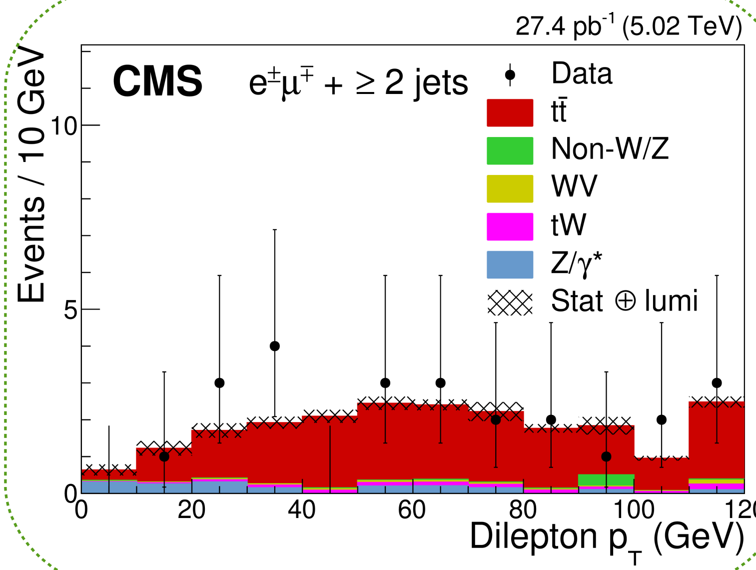
$$\sigma = \frac{N_{obs} - N_{bkg}}{A \cdot \varepsilon \cdot \mathcal{L}}$$

- **Residual backgrounds mostly from data**
  - DY yields scaled using Z peak (extrapolation to outside peak)
  - W+jets estimated from same-sign dileptons
  - both predictions compatible with simulation ~20-90% unc. ⇨ dσ/σ~3%
- **Trigger/selection eff. measured with Z→ll**
  - tag-and-probe method limited by statistics
  - ~1-3% uncertainty per lepton
- **Luminosity measurement known to 2.3%**

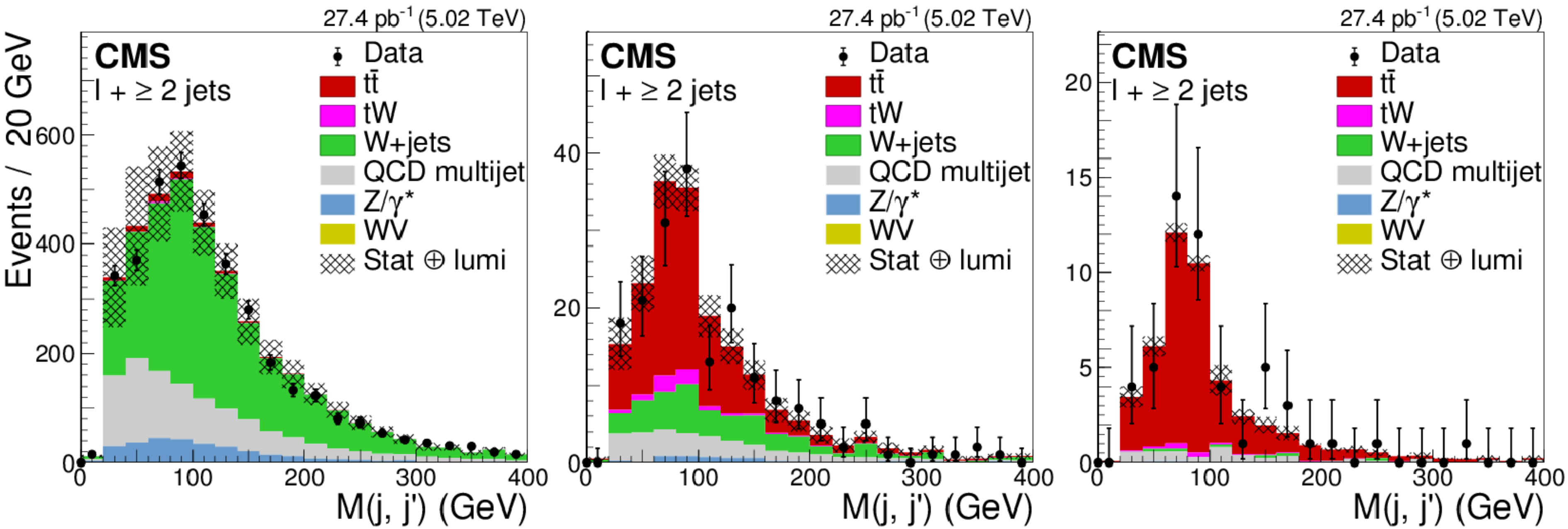
25% unc.

$$\sigma_{t\bar{t}} = 77 \pm 19\,(\text{stat}) \pm 4\,(\text{syst}) \pm 2\,(\text{lumi})\,\text{pb}$$



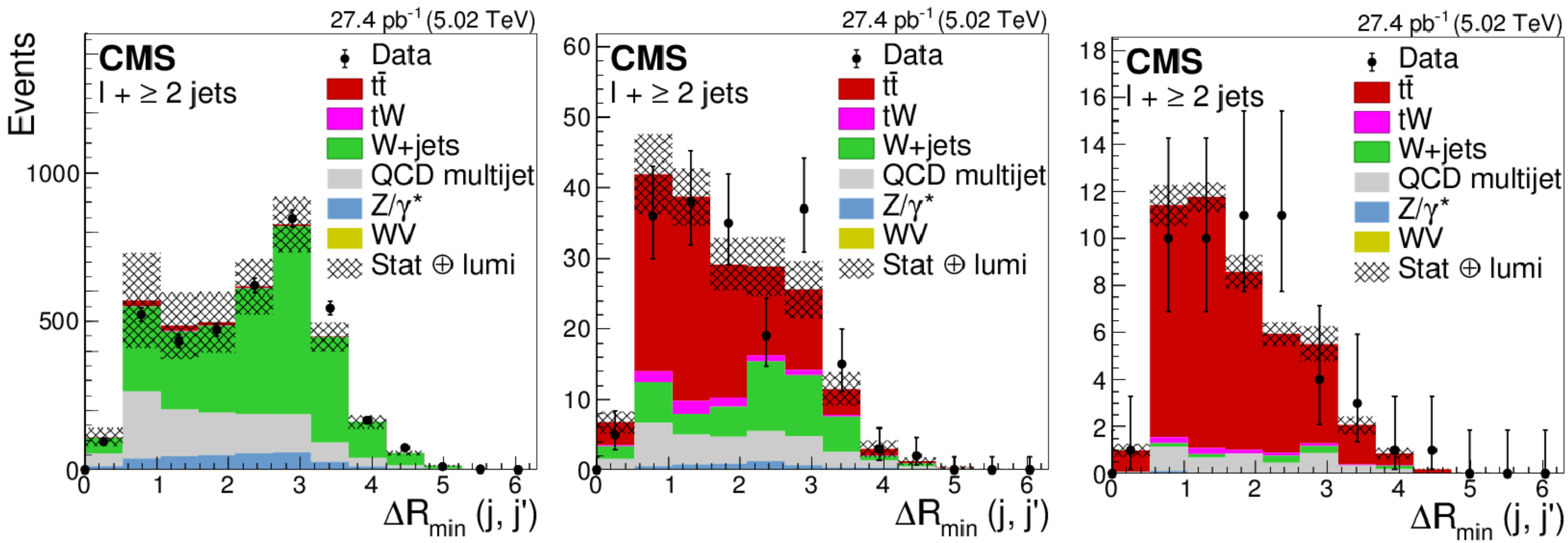


Lepton+jets I



- **Profit from W → qq' resonance only present in tt decays**
  - Non-b-tagged jets closer - minimize ΔR(j,j') (keep this in mind later for pPb)
- **Categorize the events according number of b-jets to separate signal**
  - W+jets modelled from simulation (MG5_aMC@NLO FxFx)
  - QCD modelled from inverting the μ isolation or e-id criteria

Lepton+jets II

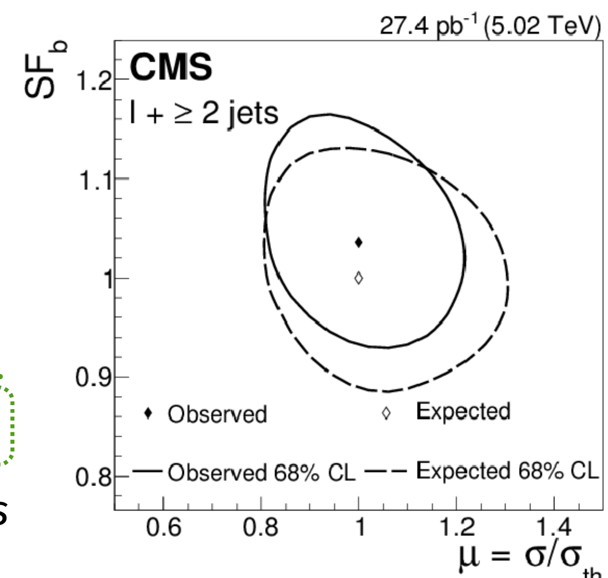


- **Fit min ΔR(j,j') in several categories**
  - reduced sensitivity to jet energy scale uncertainties
  - fairly robust against theory uncertainties
- **Combined extraction of σ(tt) and b-tag efficiency →**

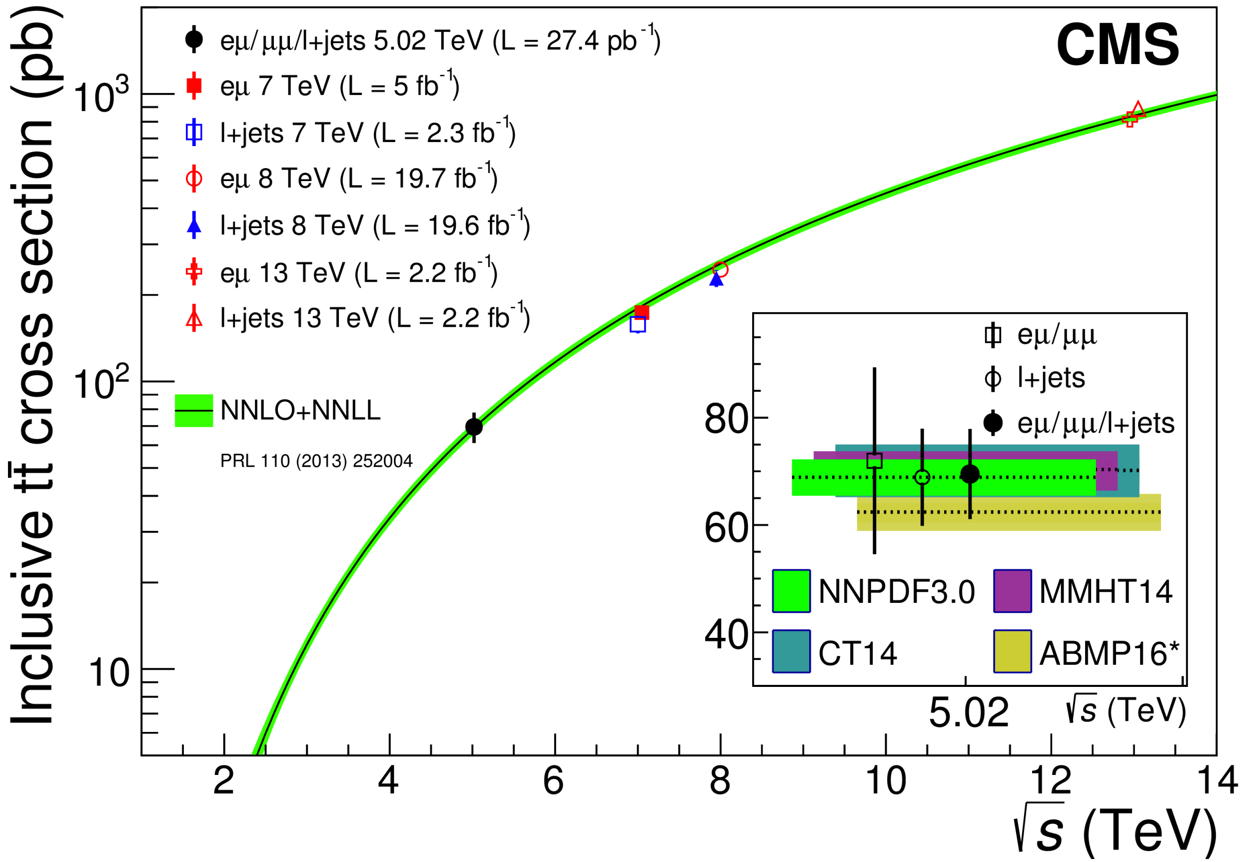
13% unc.

$$\sigma_{t\bar{t}} = 68.9 \pm 6.5\,(\text{stat}) \pm 6.1\,(\text{syst}) \pm 1.6\,(\text{lumi})\,\text{pb}$$

main syst. uncertainties: ε_b, QCD and W+jets estimations



Combined result



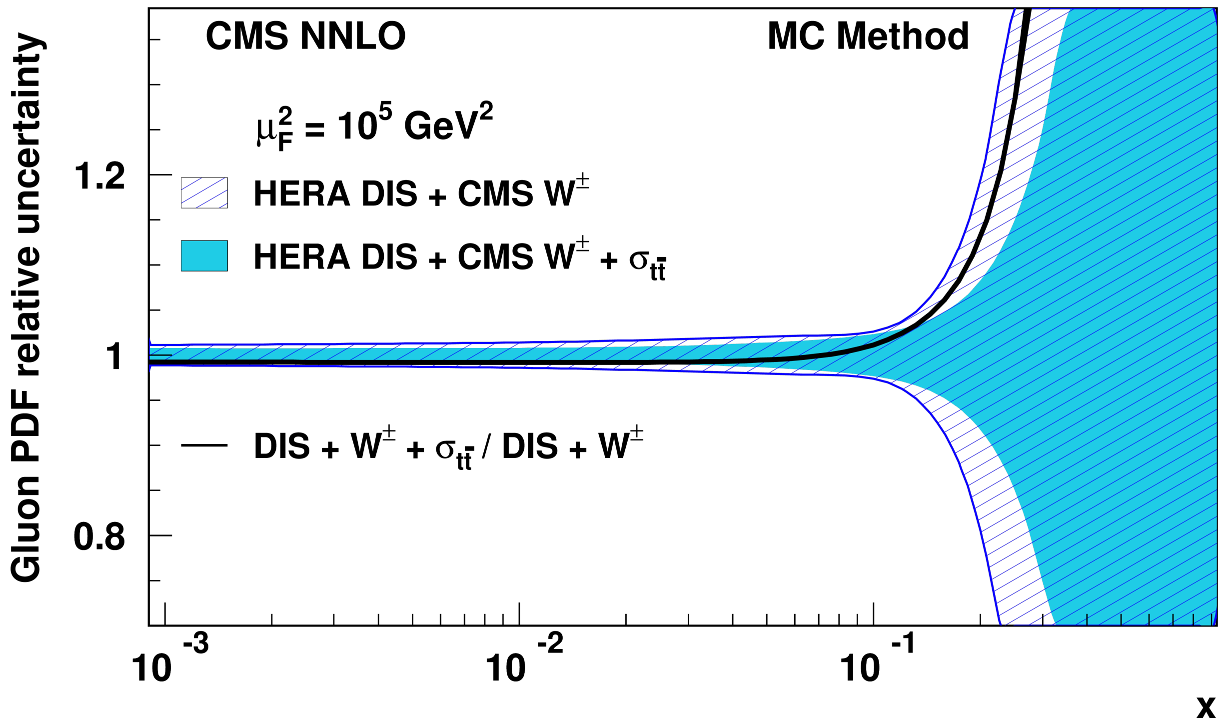
$$\sigma_{t\bar{t}} = 69.5 \pm 6.1\,(\mathrm{stat}) \pm 5.6\,(\mathrm{syst}) \pm 1.6\,(\mathrm{lumi})\,\mathrm{pb}$$

12% unc.

- **In good agreement with NNLO+NNLL QCD prediction**

$$\sigma^{\mathrm{NNLO}} = 68.9\ ^{+1.9}_{-2.3}\,(\mathrm{scale}) \pm 2.3\,(\mathrm{PDF})\ ^{+1.4}_{-1.0}\,(\alpha_s)\,\mathrm{pb}$$ (NNPDF3.0, α_S=0.118, m_t=172.5 GeV)

Impact on PDFs



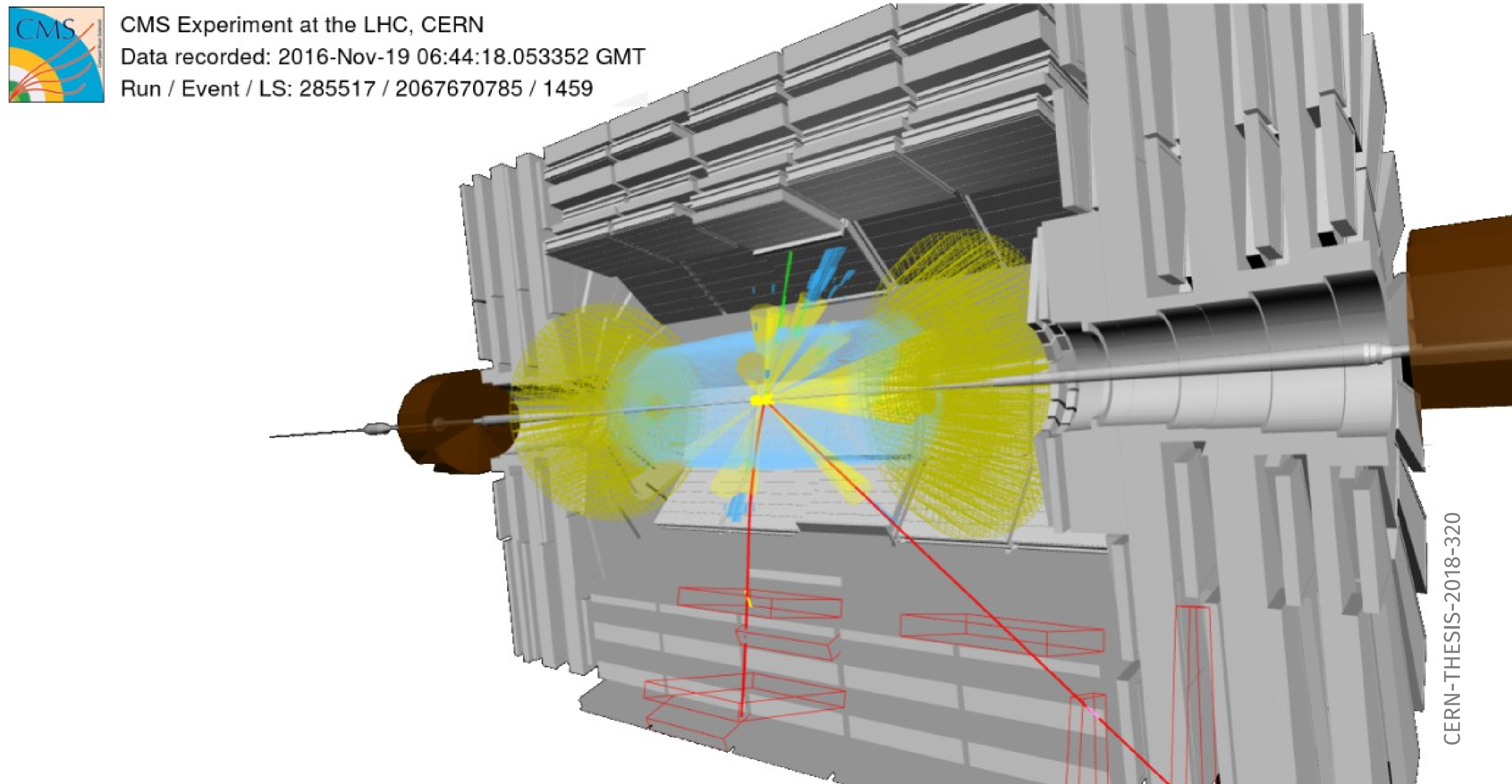
- **Nice complementarity of low $s^{1/2}$ tt measurements, constraint PDF by**
  - assuming a functional form for the PDFs
  - using DGLAP evolution at NNLO
  - combine with HERA and CMS W asymmetry using *xFitter*

$$xg(x) = A_g x^{B_g} (1-x)^{C_g} (1 + D_g x).$$

QCD sum rules *Low x* *high-x* *additional dof*

- **Modest improvement at high x still limited by large statistical uncertainty…**

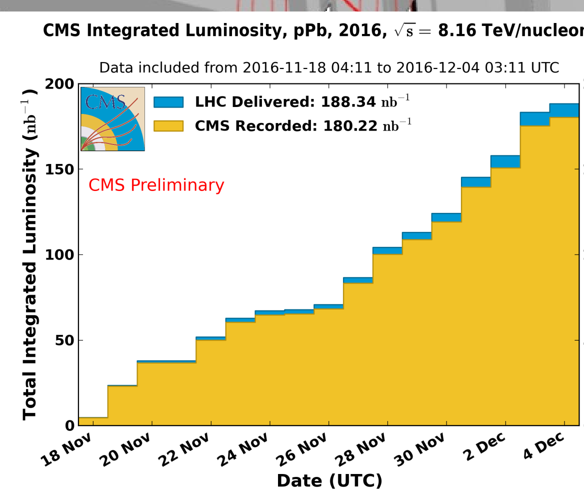
  … to be topped up with 10x more data from low pileup 2017 run :)



CERN-THESIS-2018-320

pPb observation

Phys. Rev. Lett. 119, 242001 (2017)



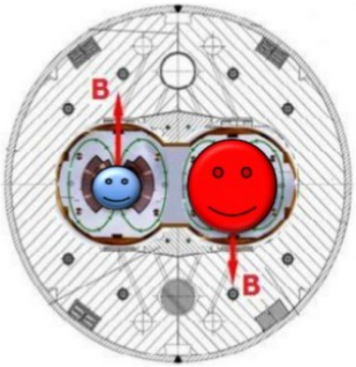
CMS.LumiPublicResults

Colliding different species at the LHC

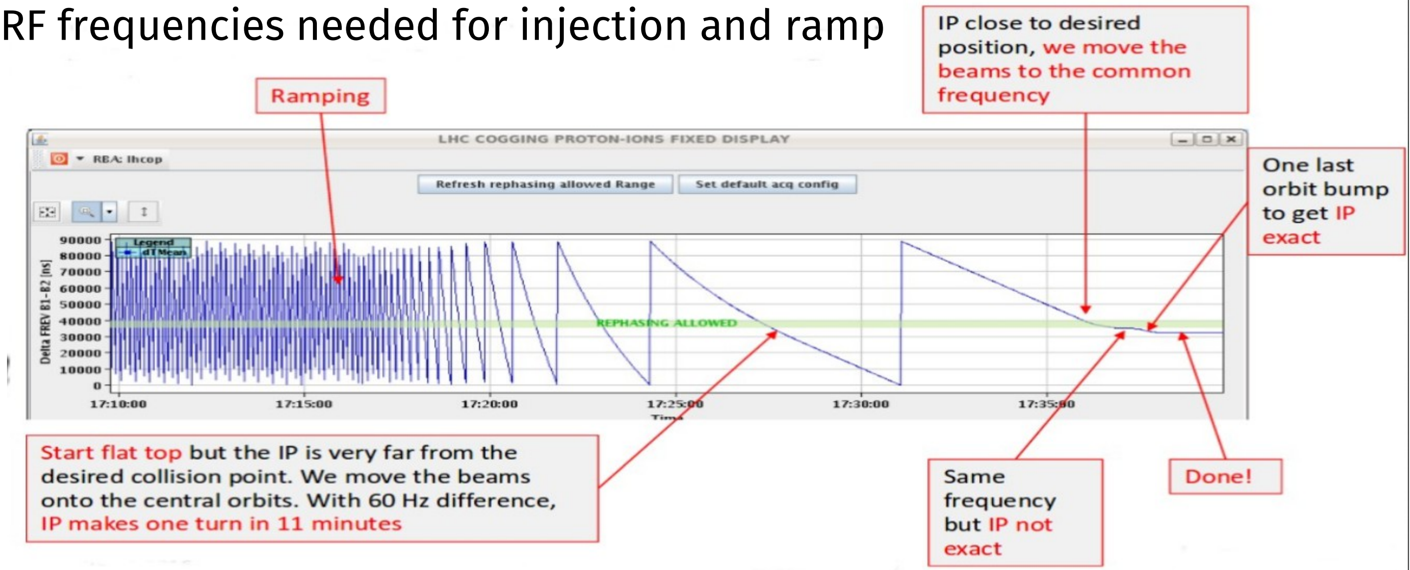
- **Two-in-one design of the LHC magnets requires equal magnetic rigidity $p_{Pb}=Zp_p$**
- **Different revolution time needs to be compensated by adjusting f_{RF}**

$$T = \frac{C}{c}\sqrt{1+(Am_p/Zp_p)^2}(1+\eta\delta)$$

orbit length — *light speed* — *phase-slip factor* — *Fractional momentum deviation*



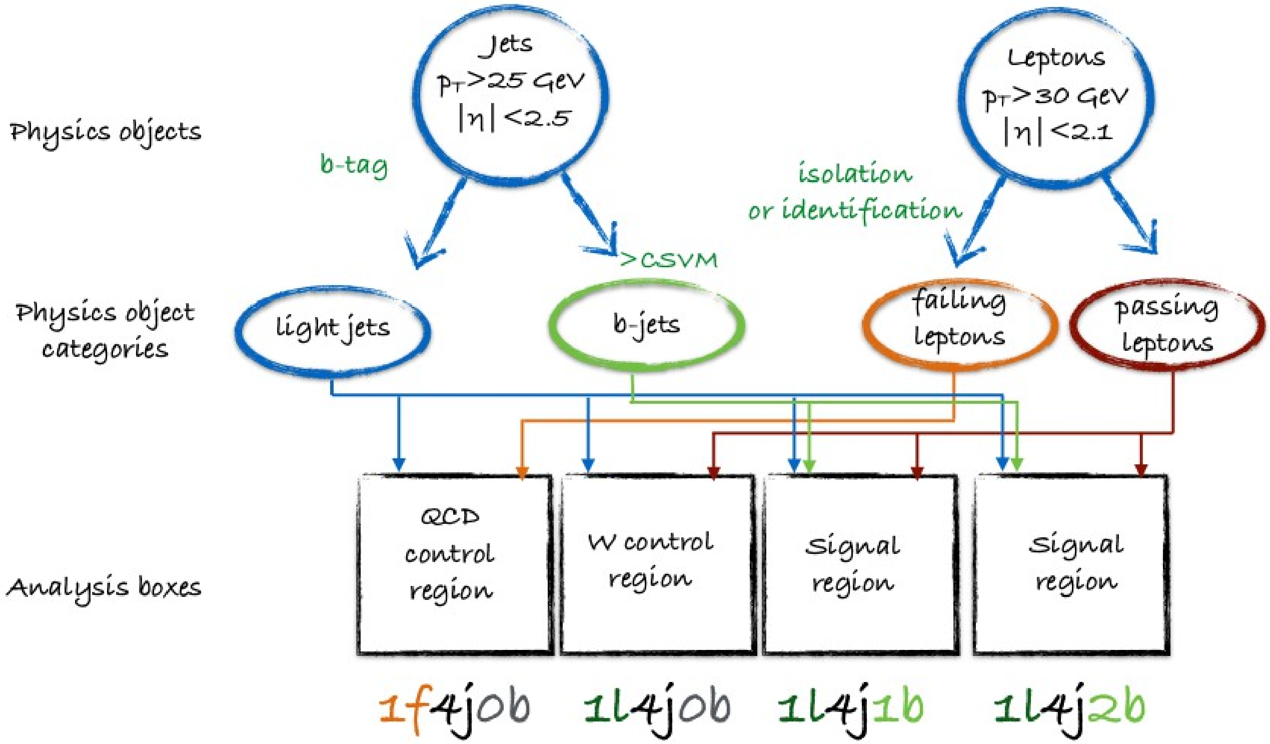
  - beam *cogging* needed at the LHC (different operation from RHIC)
  - as reference: at injection time p make 8 more turns than Pb
  - different RF frequencies needed for injection and ramp



see J. Jowett @ CAS2018

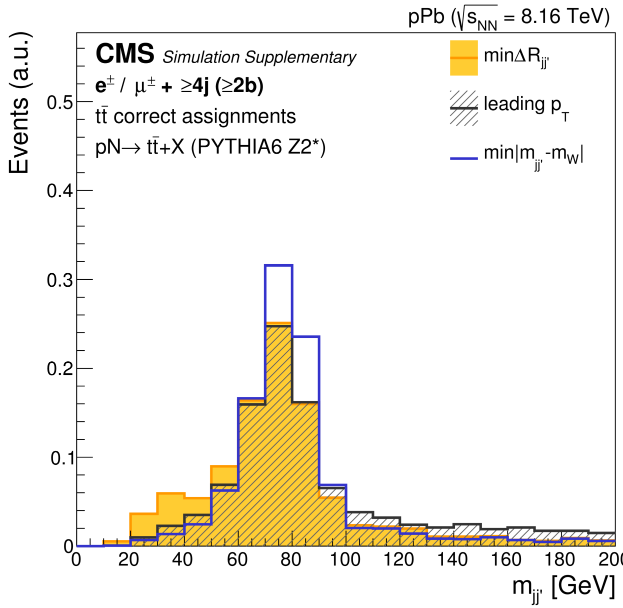
Searching for pPb → tt: analysis strategy

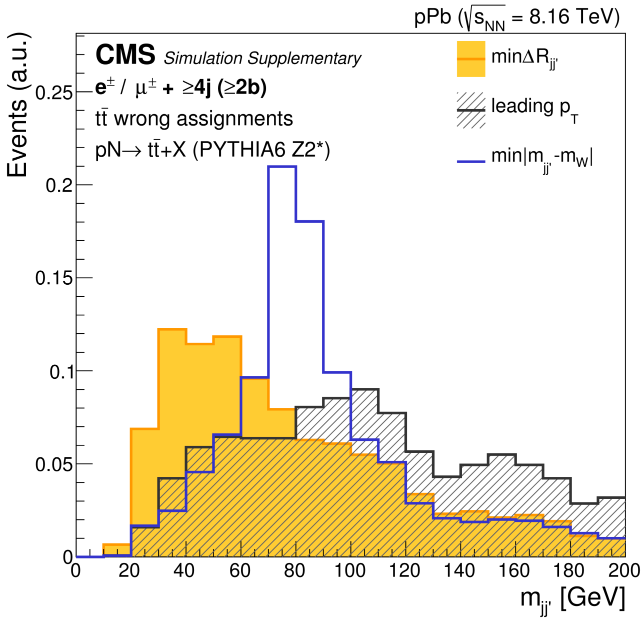
- **pPb collisions are relatively "clean", slightly asymmetric in pseudo-rapidity**
- **Use highest BR and high S/B channel (l+jets) to establish tt**
  - Pair non b-tagged jets based minimizing ΔR(jj')
  - Fit resonant W→qq' to extract σ(tt) with minimal reliance on theory/MC



Signal and background modelling

- **Signal has resonant and non-resonant components**
  - pairing strategy is instrumental in preserving main characteristics
  - also contributes to avoid shaping the background

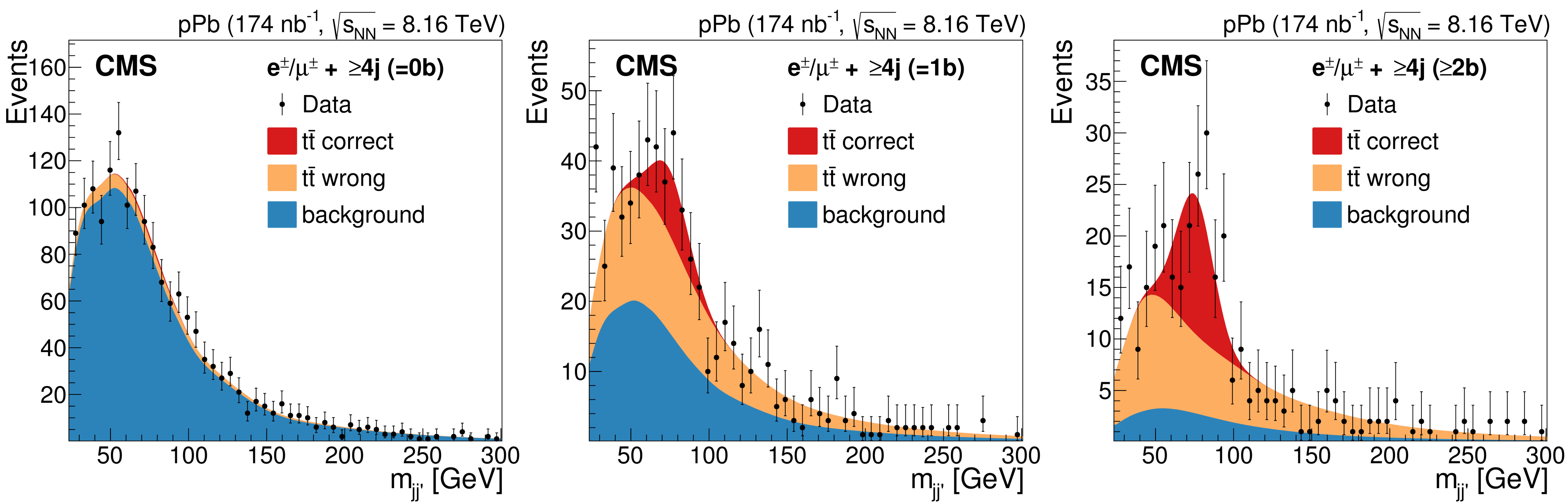




- **Backgrounds are determined from data**
  - Multijets-like background modelled by inverting lepton requirements
  - W+jets-like modelled with Landau-like spectrum (MC-inspired)

    (Fine-adjustement of parameters in-situ from non-b-tagged control region)

Measuring W → qq' (in pPb conditions)



- **Can be compared visually with pp-case of slide 14**
- **Use fully parametric approach to fit total signal events, profiling**
  - background normalization / shape distortions
  - b-finding efficiency →
  - jet energy scale →

$$N_0(\mathrm{S}) = (1-\varepsilon_\mathrm{b})^2 N(\mathrm{S})$$
$$N_1(\mathrm{S}) = 2\varepsilon_\mathrm{b}(1-\varepsilon_\mathrm{b}) N(\mathrm{S})$$
$$N_2(\mathrm{S}) = \varepsilon_\mathrm{b}^2 N(\mathrm{S})$$

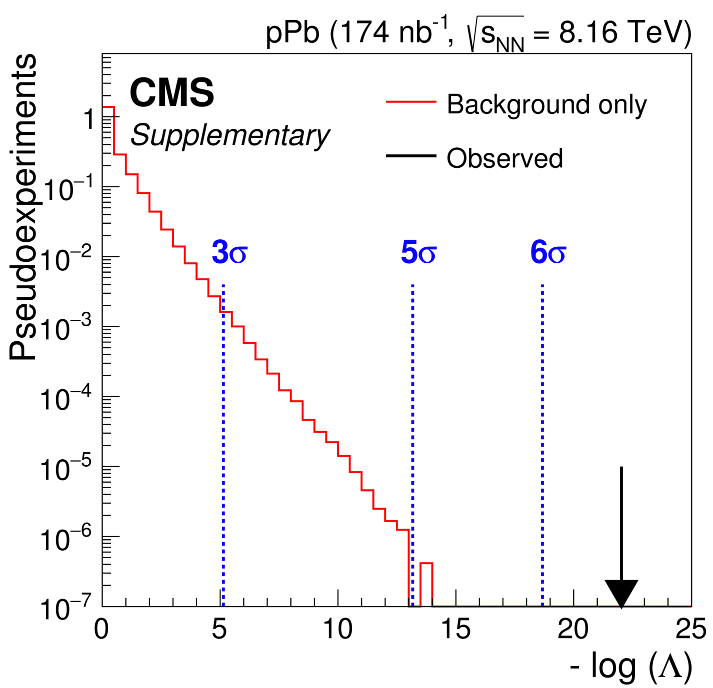
ε_b~0.595

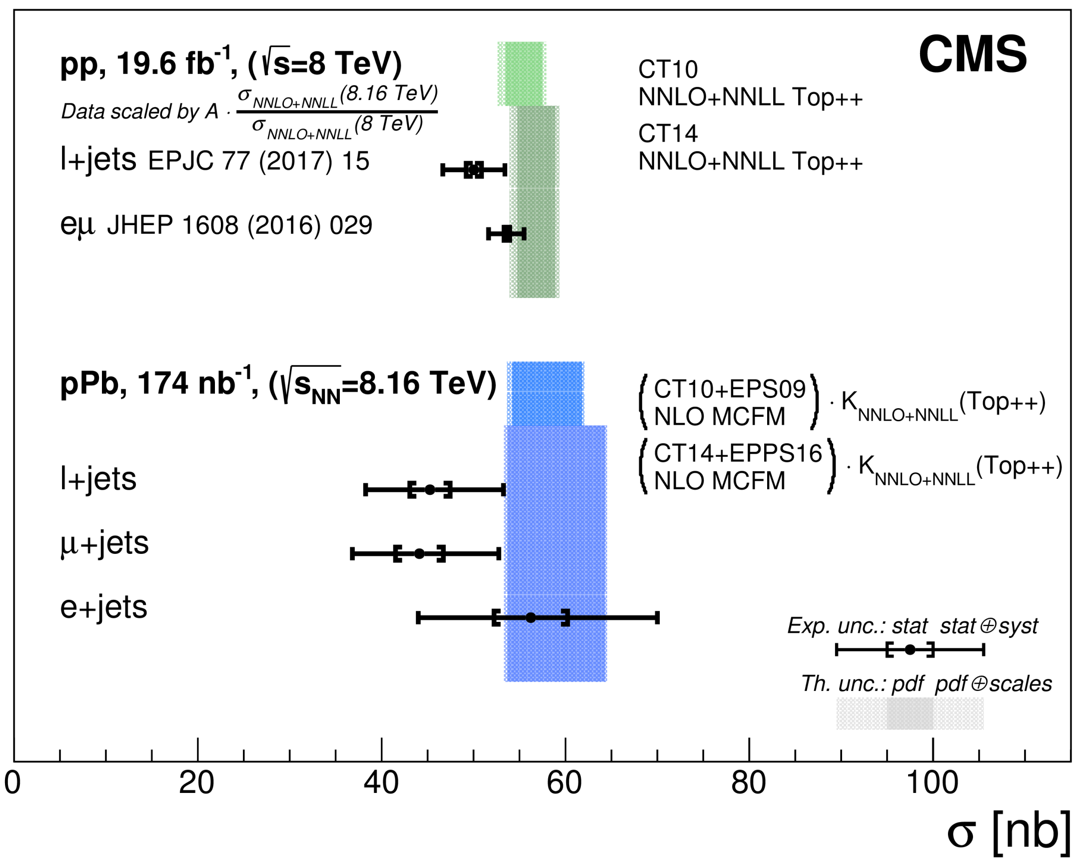
$$\widetilde{m}_{\mathrm{W(jj)}} = (1 + \delta_{JSF} \cdot \theta_{JSF}) \cdot m_{\mathrm{W(jj)}}$$

- **Estimated acceptance of ≈6% and efficiency of ≈63-90% for e (μ)**
  - based on PYTHIA simulations (small nuclear modif. factors predicted by POWHEG)

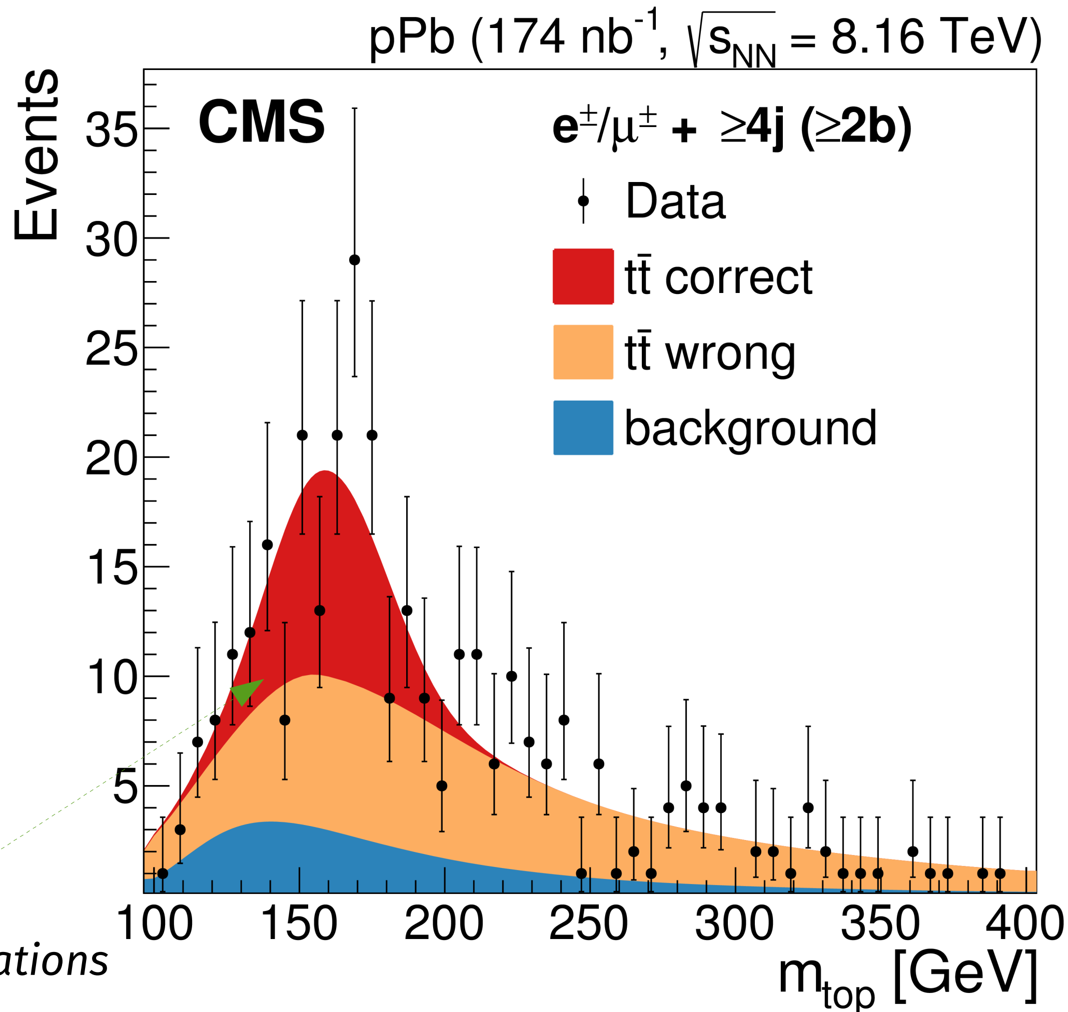
Result

- **Clear observation of pPb → tt well above 5σ**
- **Cross section measured to be** $\sigma_{t\bar{t}} = 45 \pm 8\,(\text{total})\,\text{nb}$ 17% unc.
  - in good agreement with the NLO prediction $59.0 \pm 5.3\,(\text{PDF})\,^{+1.6}_{-2.1}\,(\text{scale})\,\text{nb}$





An “alternative” to a Bayesian posterior using m_{top}



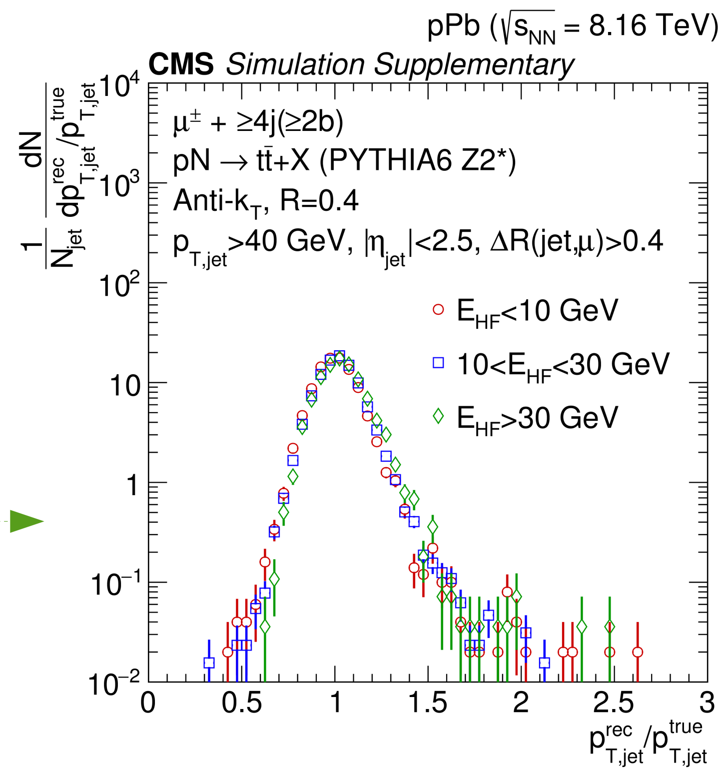
Post-fit normalizations from fit to m(jj')

Using leading b-tagged jets
Pairing after minimizing |m(bjj')-m(blv)|

Main uncertainties

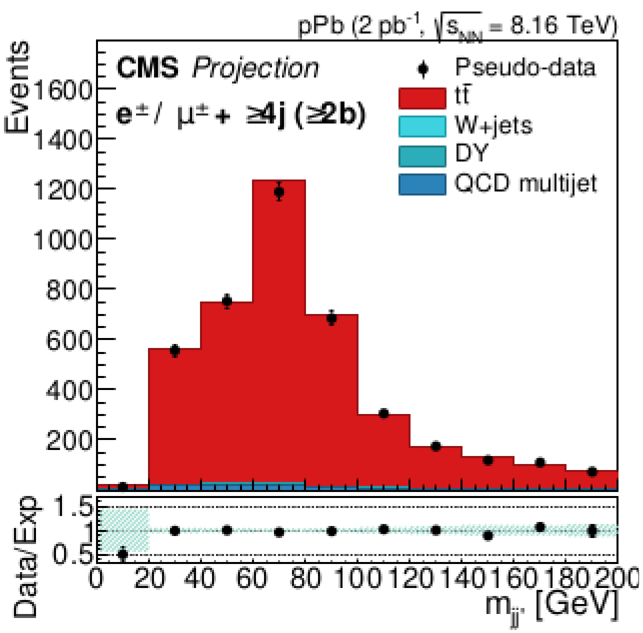
- **Fitting strategy is expected to scale most uncertainties with luminosity$^{1/2}$!**
  - determine in-situ crucial ingredients: JES, ε_b, background normalization
  - more careful assessment of background shapes needed with higher stats

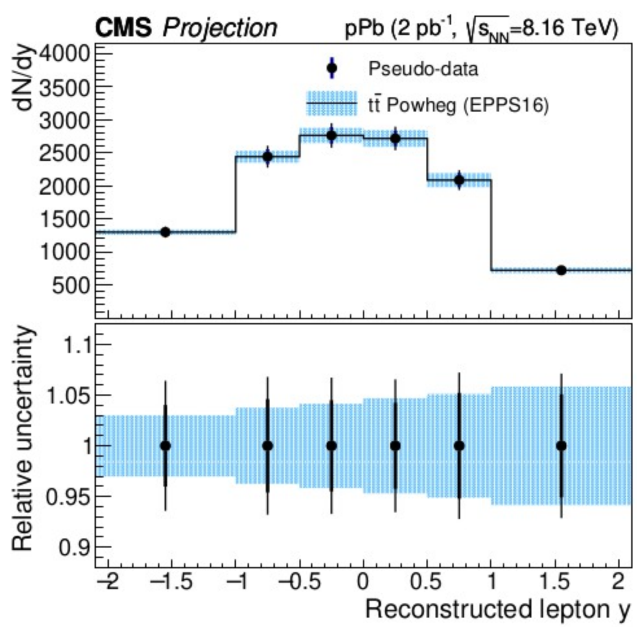
Source	**Δσ/σ [%]**
Statistical	5
b-finding efficiency	13
Backgrounds (shapes/normalization)	7
Integrated luminosity	5
Jet energy scale	4
Lepton efficiencies	4
Acceptance (QCD scales, nPDFs)	4



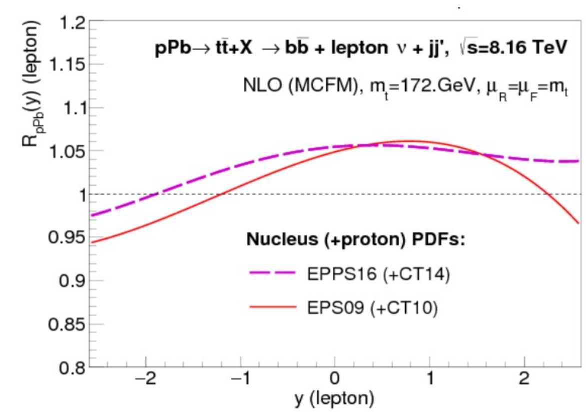
Projections for the HL-LHC

- **With 2/pb of data of future runs, expect to contribute effectively to probe nPDFs**
  - resonant W→qq' can be used to obtain background-subtracted distributions
  - Using a *sPlot* technique (just like B-physics)
  - projected uncertainty expected to be competitive with current EPPS16 unc.
  - ratio to pp reference expected to probe anti-shadowing region of nPDFs

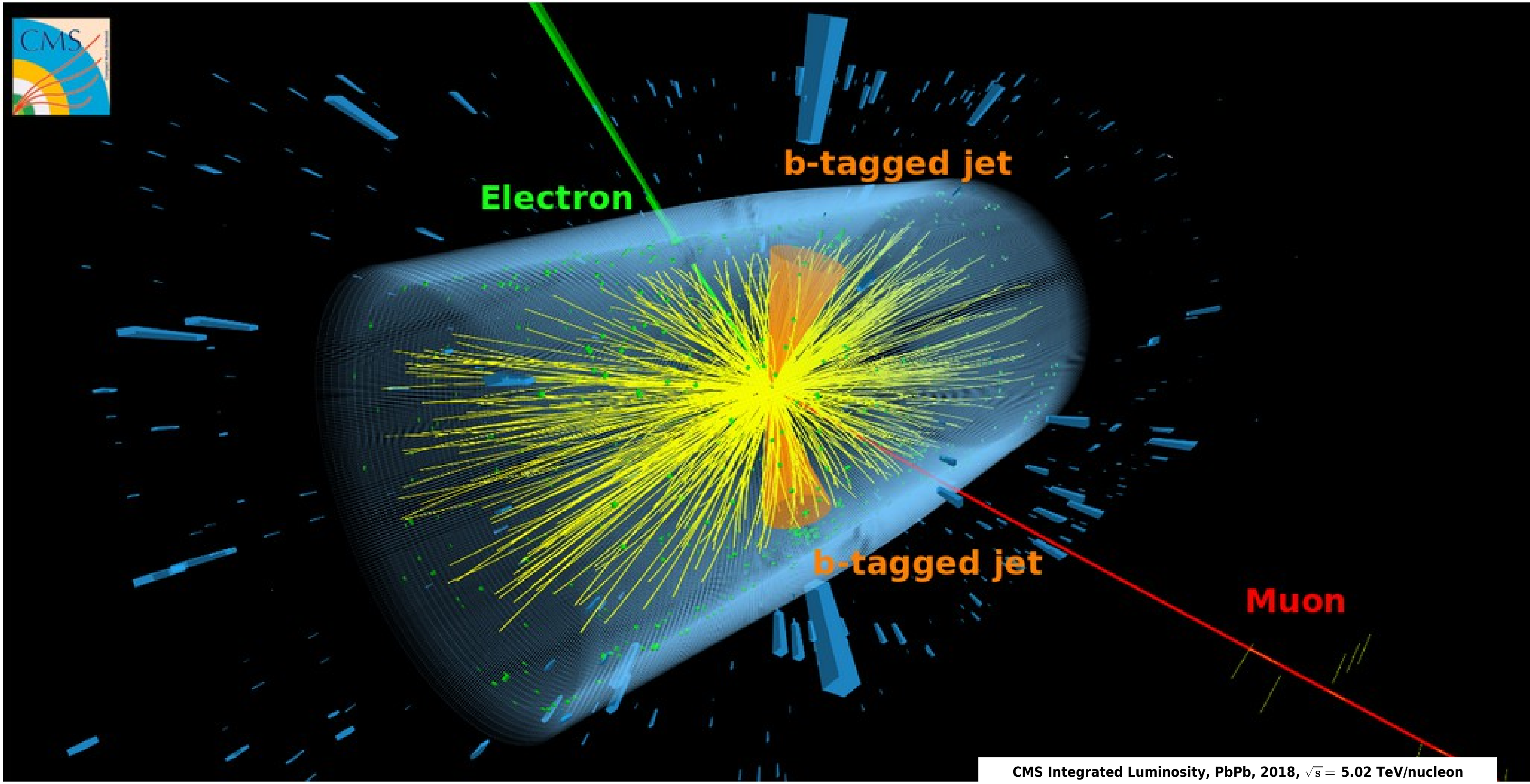




CMS-PAS-FTR-18-027

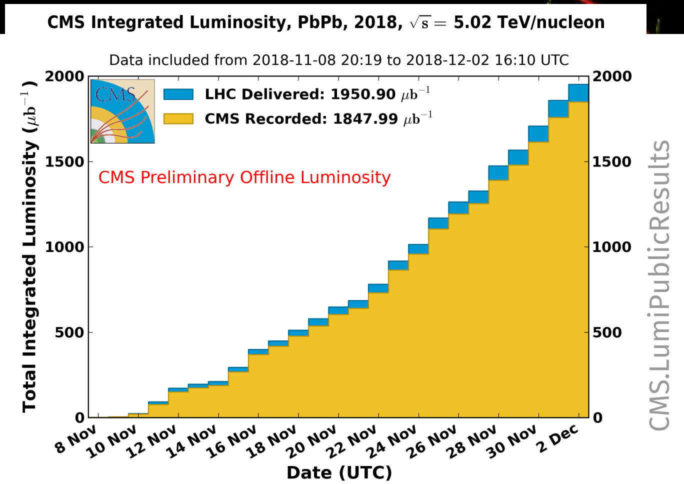


Nucl. Phys. A 982 (2019) 75--80



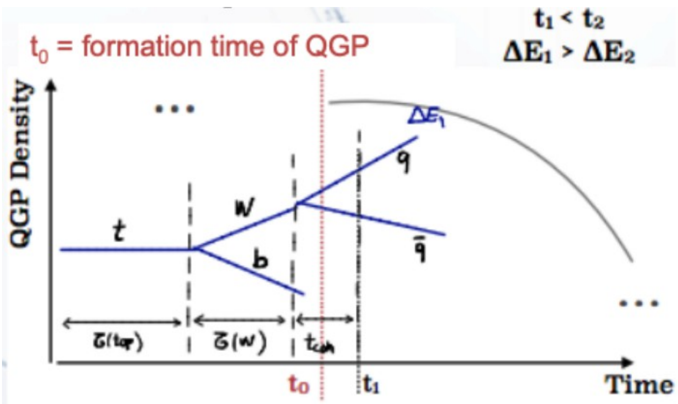
First evidence in PbPb

arXiv:2006.11110, *acc. in Phys. Rev. Lett.*



How?

- **Most top quarks will be produced nearly at rest**
  - decay products will pass through the medium
  - rely on charged leptons as clean probes

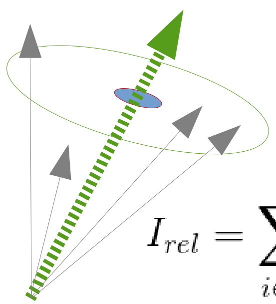


- **Select at least two leptons**
  - Single lepton triggers, p_T>20 (15) GeV for e(μ)
  - Offline require **p_T>25 (15) GeV |η|<2.1 (2.4) for e(μ)**
  - op. charged leptons with m_{ll}>20 GeV

    (vetoeing 15 GeV around Z→ll pole for same-flavour dileptons)
  - veto back-to-back dilepton requiring A = |1-Δϕ/π| > 0.01
  - **identification and isolation specifically tuned** for heavy-ion collisions

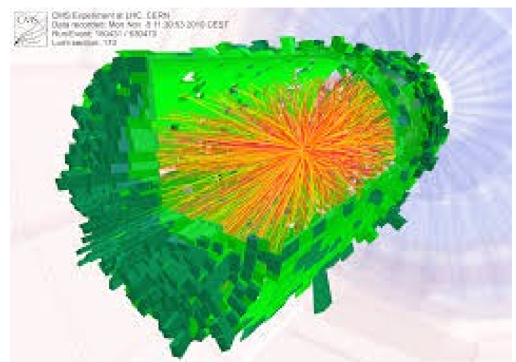
Lepton isolation

- **Main contribution from the underlying event (UE)**
  - large event-to-event fluctuations + varying collision centrality
  - need a fine-grained estimation of average energy flowing around leptons



R=[Δη²+Δϕ²]^1/2=0.2

$$I_{rel} = \sum_{i \in R} p_{T,i}/p_T(\ell) - 1$$

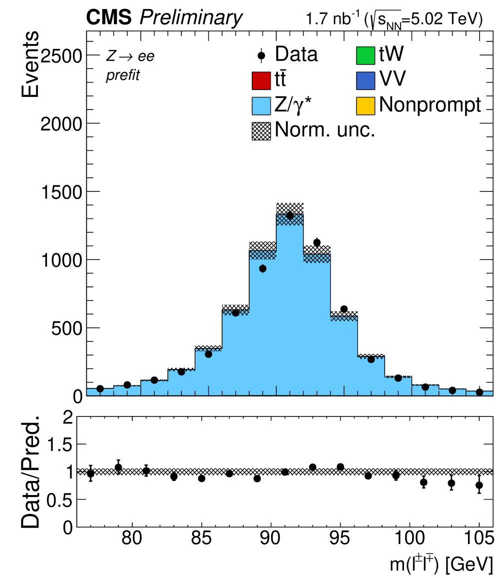


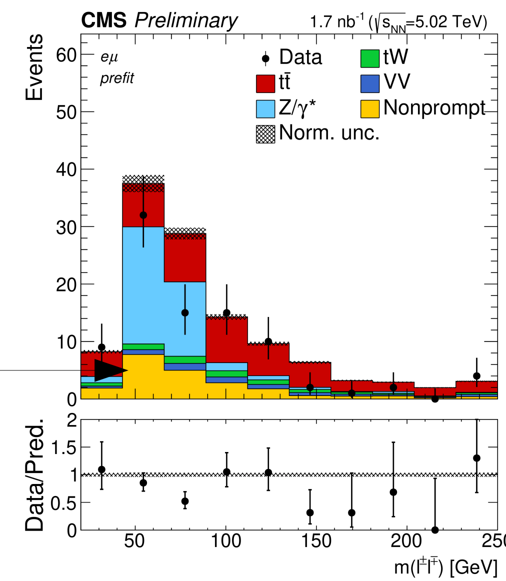
$$\rho = \text{median}\left[\left\{\frac{p_{tj}}{A_j}\right\}\right]$$

- **Use FastJet to compute median energy density (ρ)**
  - for each event ρ is computed in 5 different η slices
  - use slice corresponding to the reconstructed lepton η
  - subtract UE contribution from initial isolation estimation: $I_{rel} \rightarrow I_{rel} - UE(\rho)/p_T(l)$
  - UE(ρ) parameterization found from data, using Z→ll events
  - **flattens dependency of isolation on the centrality of the collision**

Main backgrounds

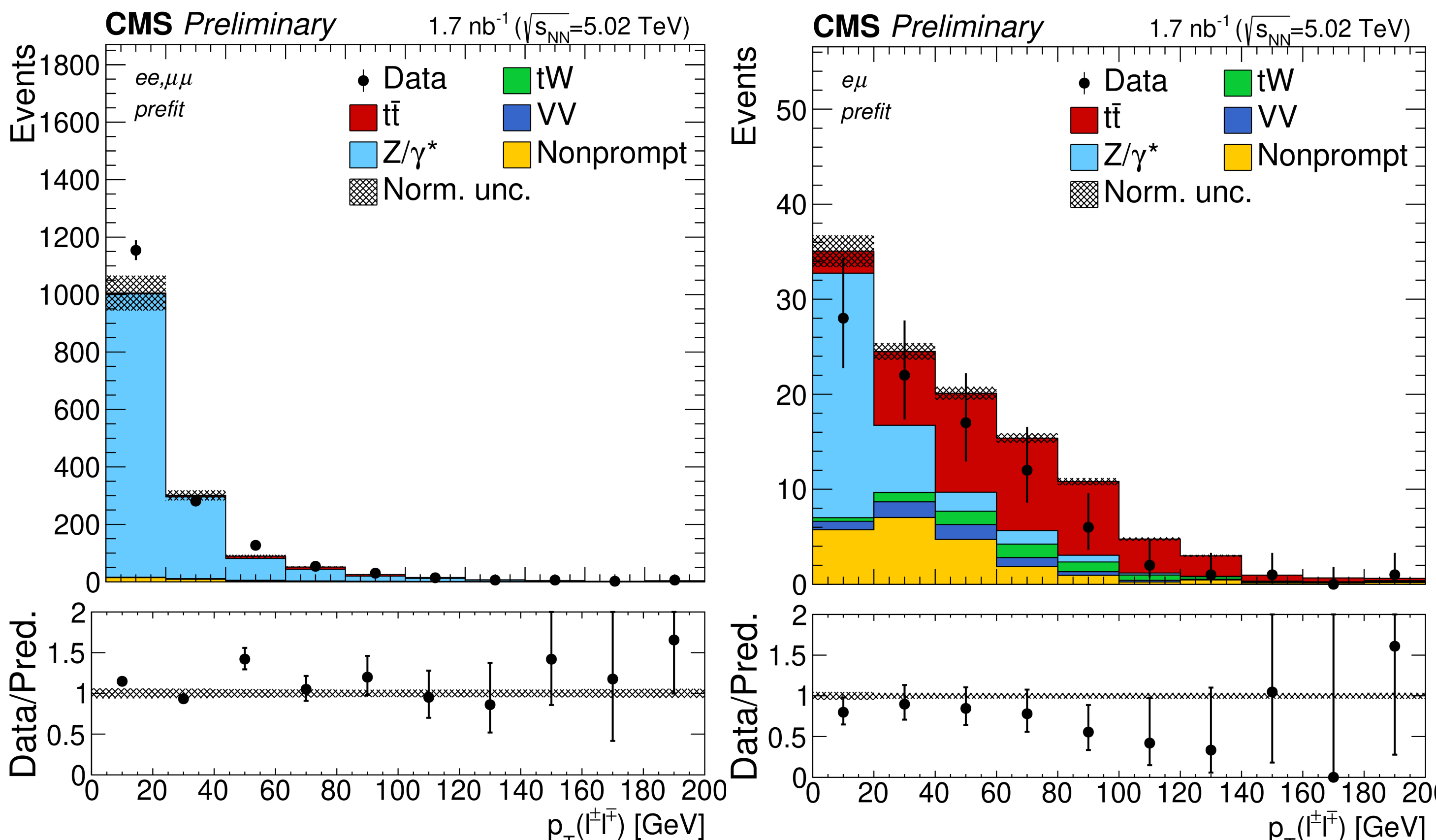
- **Event selection is relatively simple**
  - not many backgrounds left
- **Drell-Yan production is expected to dominate →**
  - Start with NLO QCD prediction (MG5_aMC@NLO)
  - Fair agreement in rate for Z → ll selection
  - Off-shell Z/γ* contributions in same-flavor
  - On-shell Z → ττ → eμ in op. flavor
  - Correct dilepton p_T using Z → μμ data/MC ratio
- **Non-prompt backgrounds are trickier**
  - expect W+jets and QCD multijets with heavy flavors
  - use event-mixing technique
  - rank mixed events in distance wrt to original event
    (k-NearestNeighbor algorithm: centrality, isolation,...)
  - use nearest neigbors (1st out of 100), repeat several times





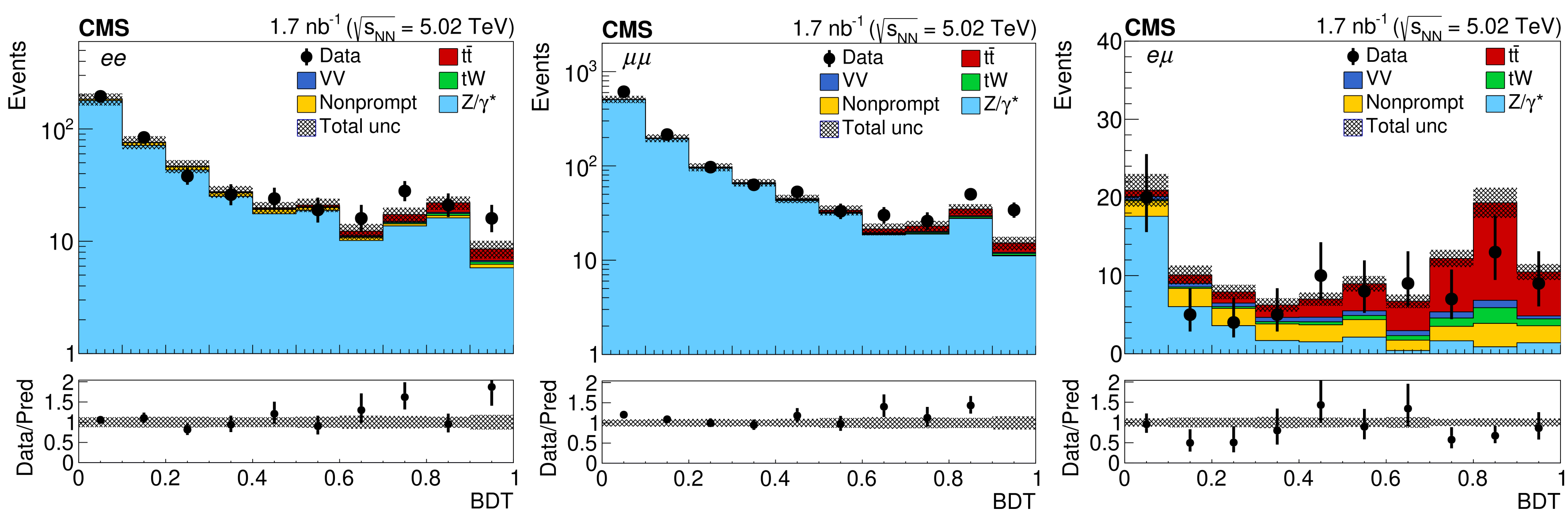
Dilepton p_T (prior to fit)

- **Single leptonic-only most-discriminating variable**
- **Data below prediction in signal region ⇨ hints signal strength <1**
  - off-shell DY fairly well modeled



Dilepton BDT (prior to fit)

- **Combine several leptonic variables in a multivariate discriminator (BDT)**
  - $p_T(ll)$, $\eta(ll)$, $\Delta\phi(ll)$ pT(l1),$\delta p_T/\Sigma p_T$, $\Sigma\eta$
  - train on MC to separate DY from tt
  - Variable is transformed to be approx. uniform for non-prompt background
- **Data/MC agreement: similar observations as made for previous slide**

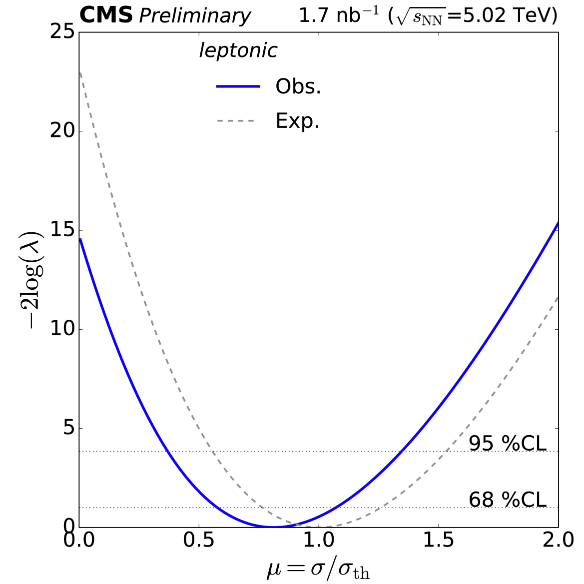


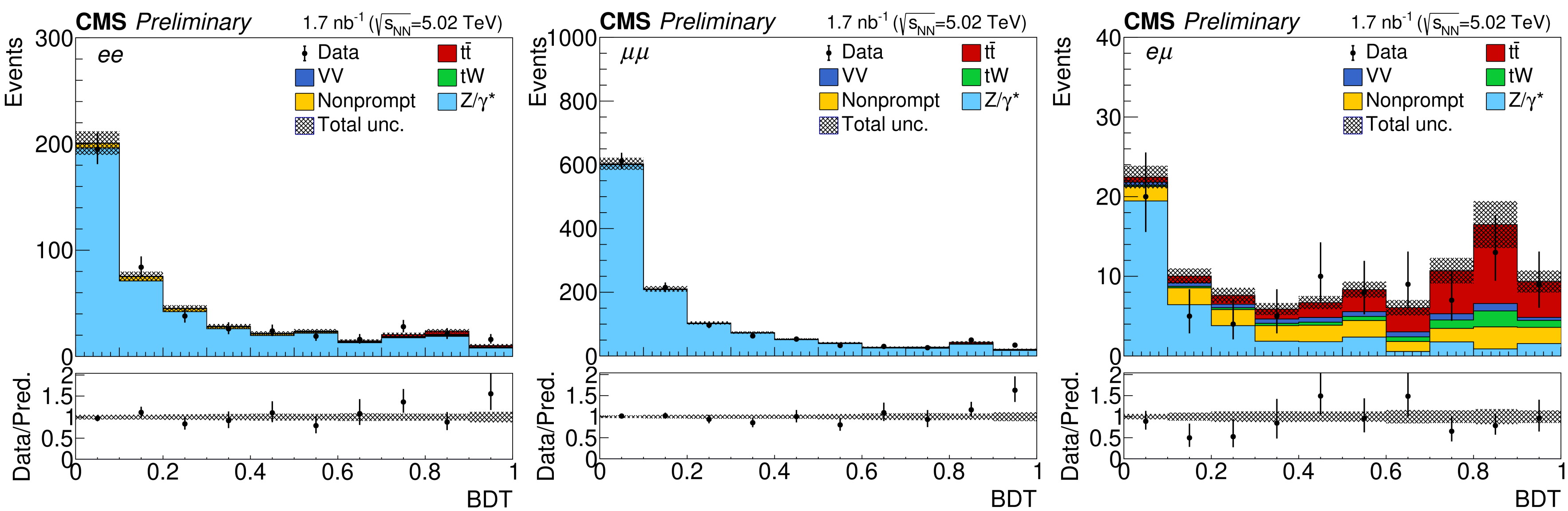
Signal extraction

- **A profile likelihood method is used to extract the signal strength**
- **Uncertainties include the following sources:**
  - *Experimental*
    - 5% luminosity
    - centrality/p_T/η-dependent trigger/id/iso scale factors from tag-and-probe
    - Non-prompt normalization based on same-sign data counts ($\delta N/N$~20%)
      shape based on a variation of the kNN distance
    - Shape statistical uncertainties (Barlow-Beeston)
  - *Theory*
    - Nuclear PDFs/QCD scales affect negligibly shapes but are included
    - Top p_T modeling based on pp prescription
    - $\Delta m_t = \pm 1$ GeV based on Breit-Wigner re-weighting
    - Z p_T modeling based on data/MC uncertainty, normalization freely floating
    - 30% uncertainty on residual backgrounds: tW, WW, WZ, ZZ

Fit results

- **Pre-fit deficits drive final μ=0.79±0.26**
- **Significance: 3.8 (obs.) 4.8 (exp.) 18% p-val**
- **Post-fit distributions in very good agreement**
  - Fit does not alter significantly shapes
  - background normalization barely changes





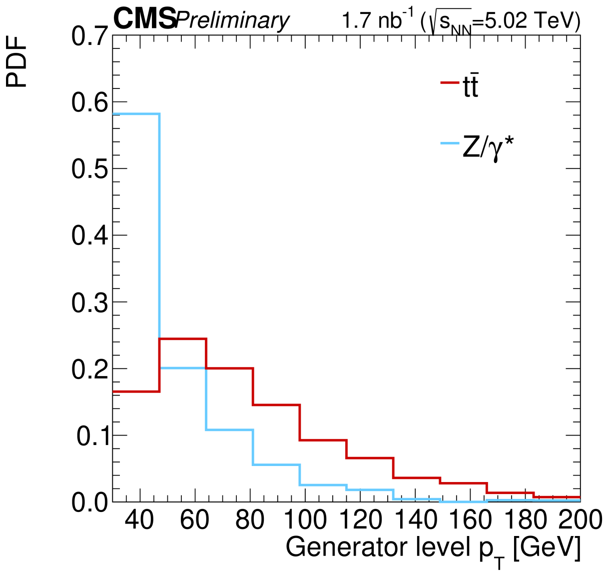
Adding b-jet information

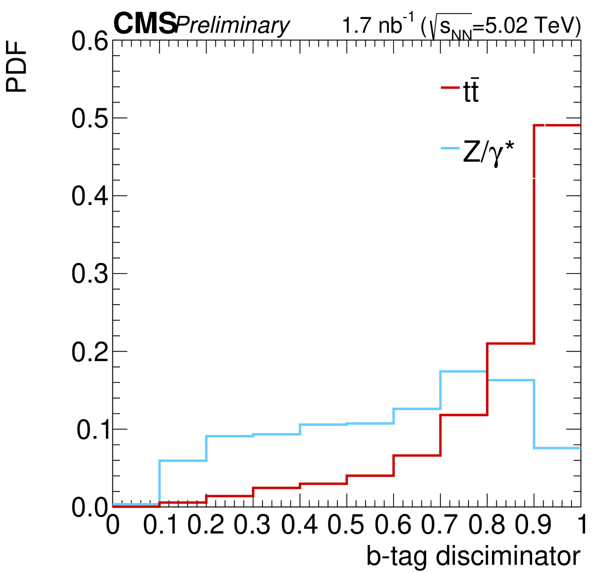
- **Use particle-flow jets with constituent subtraction**
  - using fine-grained η FastJet-ρ computation
  - remove/correct energy of jet constituents based on ρ

    (cf. arXiv:1708.09429, arXiv:1403.3108)
- **anti-k_T R=4 jets with p_T>30 GeV $|\eta|$<2.0 $\Delta R(j,l)$>0.4**
  - dedicated b-tag discriminator training for heavy ions
  - tune working point to yield approx.

    65% (5%) efficiency for b- (other-) jets
  - dependency on centrality from "track confusion"
- **Consider only the two jets with highest b-tag discr.**
  - count how many pass pass the threshold
  - Use counting to categorize events

    (similar to what was done for pp and pPb analyses)





b-jet counting related uncertainties

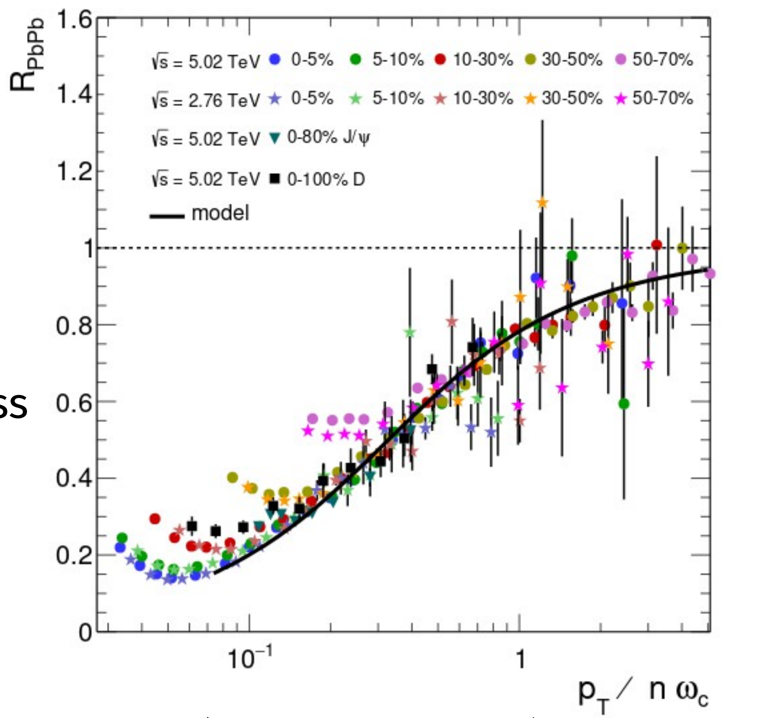
- **No measurement of efficiencies and mistag in data…**
  - too low statistics to constraint eb in-situ as in the pp/pPb cases
  - expect however that mistags are negligible after b-tag discr. ranking
  - use inflated efficiency uncertainties in the fit ($\delta\varepsilon_b$~10% $\delta\varepsilon_q$~30%)

- **In addition, expect jet quenching to occur**
  - based R_{AA} fits to different spectra
  - scaling behavior $f(p_T/\omega_c)$ from arXiv:1703.10852 →
  - data indicates universal high-p_T behavior

    use to parameterize mean constituent energy loss

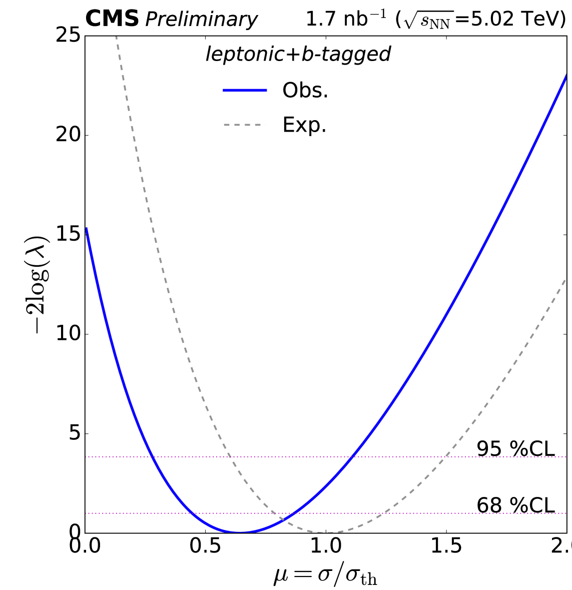
    (1-7 GeV depending on the centrality)
  - use estimate to dampen jet energy in MC
  - *moves jets out-of-threshold leading to*

    decreased probability of finding the b jets from top decays (5-10% variations)



Fit results (b-tagged)

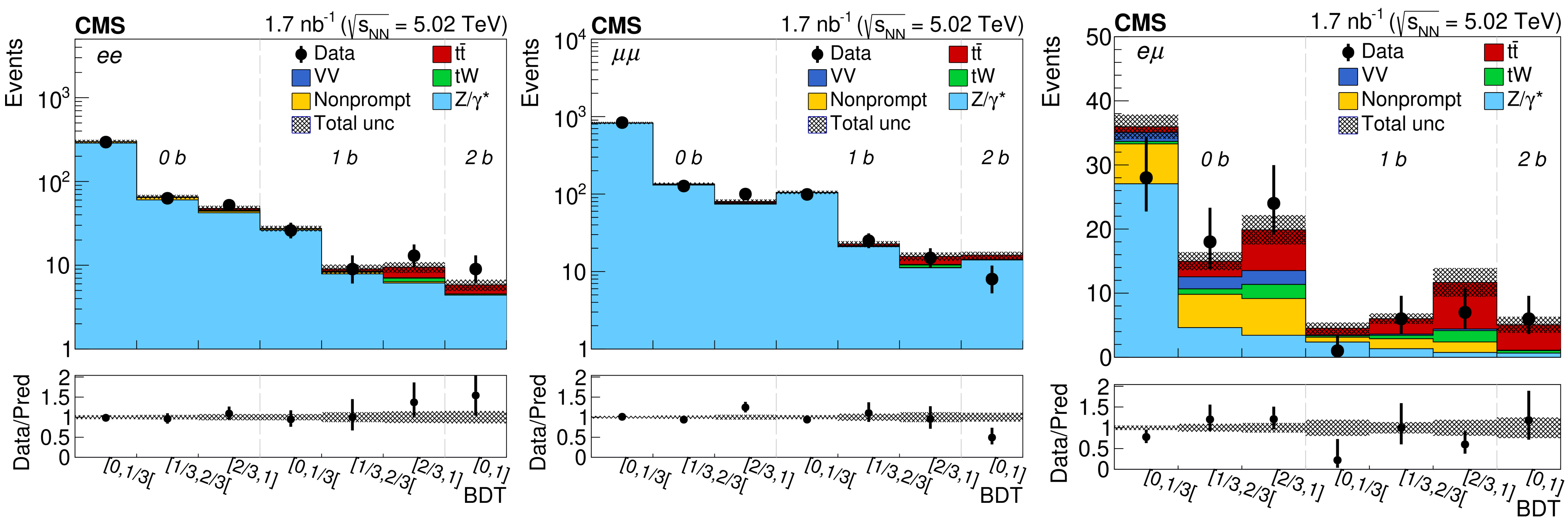
- **Repeat the fit to the BDT discriminator in #b-tags**
- **Deficit is slightly enhanced: μ=0.63±0.22**
  - still compatible with inclusive analysis
- **Significance: 4.0 (obs.) 5.8 (exp.) 5% p-val**
- **Fit finds 43±11 signal events (out of 1768 selected)**



Process	Final state e^+e^- 0b	1b	2b	$\mu^+\mu^-$ 0b	1b	2b	$e^\pm\mu^\mp$ 0b	1b	2b
Z/γ^*	389.8±15.4	40.4±2.7	4.4±0.8	1027.5±27.3	136.1±5.7	14.1±1.7	35.1±1.7	4.4±0.9	0.7±0.2
Nonprompt	17.3±2.2	1.4±0.2	$\leq$ 0.1	7.6±1.0	0.8±0.1	$\leq$ 0.1	17.1±1.9	4.0±0.4	$\leq$ 0.1
tW	1.1±0.2	0.9±0.2	$\leq$ 0.1	1.8±0.4	1.3±0.3	0.2±0.1	3.4±0.7	2.5±0.5	0.4±0.1
VV	1.9±0.3	0.2±0.1	$\leq$ 0.1	3.3±0.6	0.4±0.1	$\leq$ 0.1	5.4±0.9	0.6±0.1	$\leq$ 0.1
Total background	410.2±15.1	42.8±2.7	4.5±0.8	1040.2±27.1	138.6±5.7	14.4±1.8	61.1±2.9	11.5±1.3	1.1±0.2
$t\bar{t}$ signal	2.8±0.8	3.2±0.8	1.3±0.4	4.5±1.2	5.1±1.2	1.9±0.6	9.7±2.5	10.7±2.4	4.0±1.2
Observed (data)	410	48	9	1064	139	8	70	14	6

Post-fit distributions

- **Found in very good agreement with the data**
  - events with 2 b-tagged jets are solely counted



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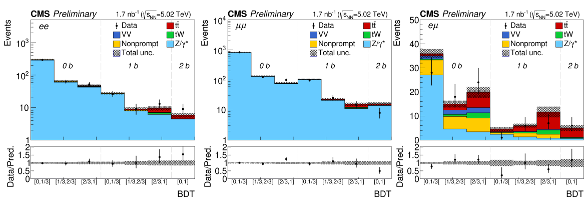
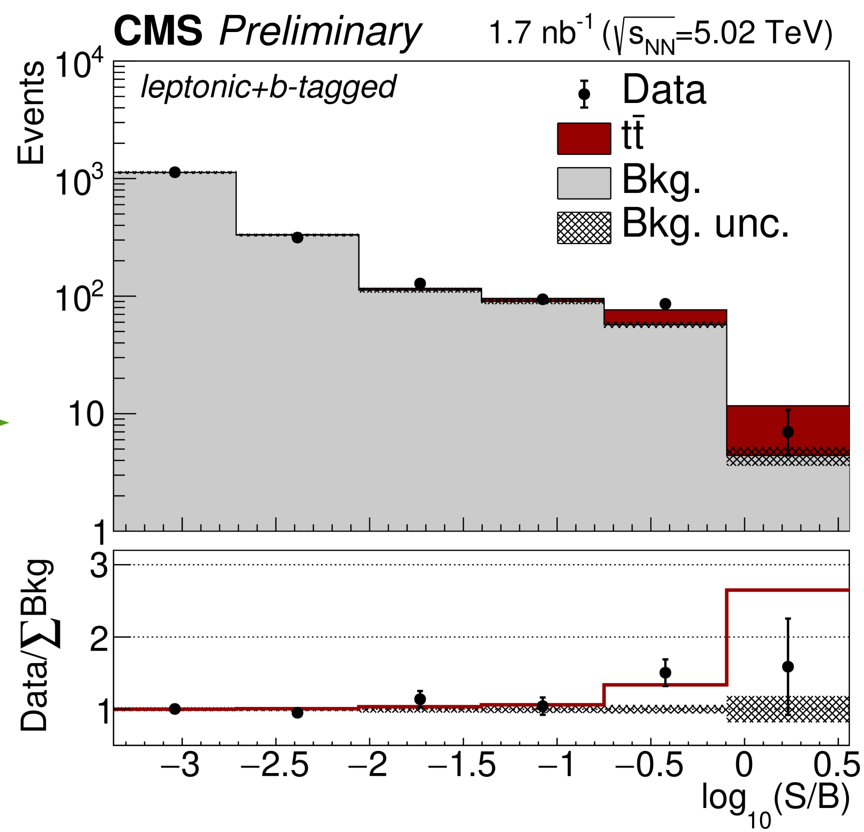


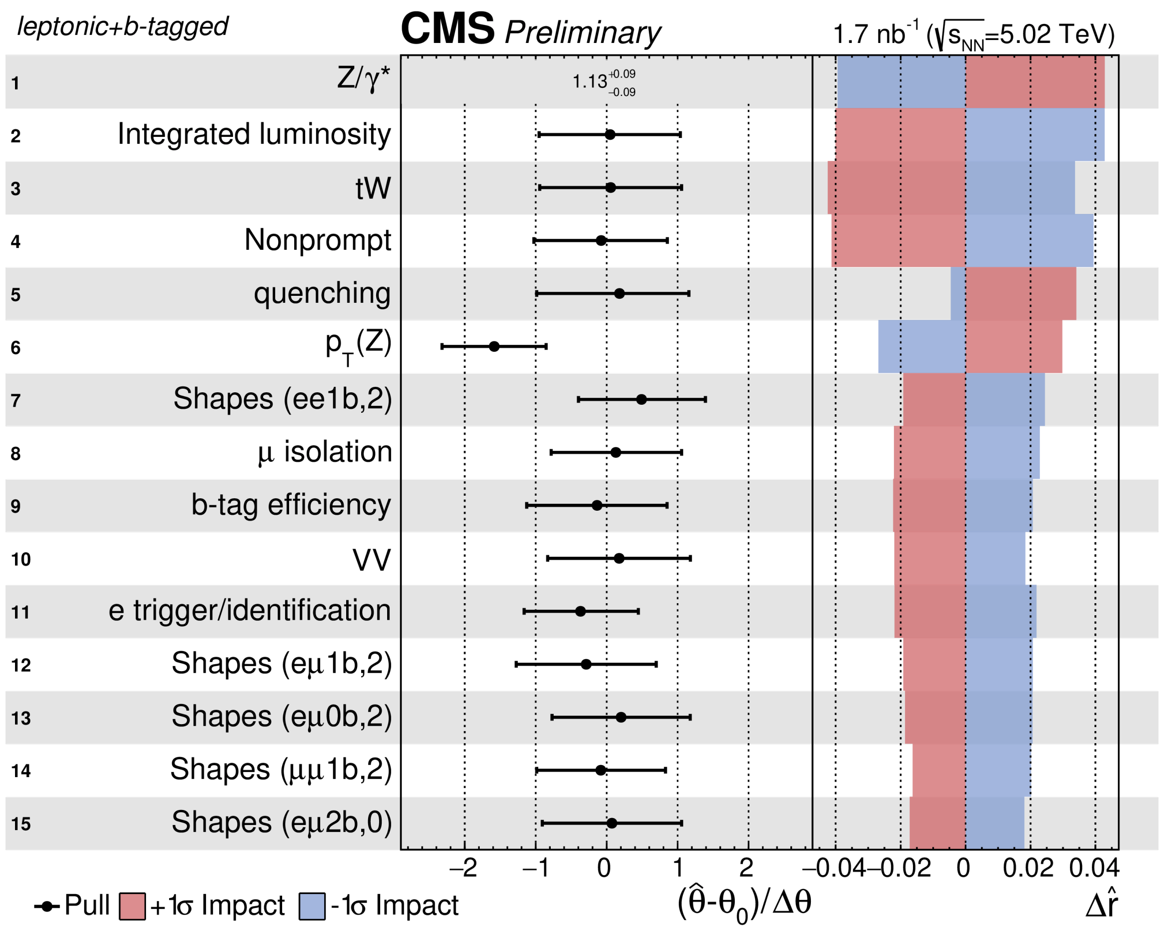


Systematic uncertainty impacts I

- **Statistical uncertainty is** by far **the dominant source**
  - Several uncertainties to scale with luminosity (efficiencies, backgrounds)
  - Jet related uncertainties are sub-leading with respect to background norm.
  - Small theory uncertainty at this point, mostly dominated by Z p_T

Source	$\Delta\mu/\mu$ Dilepton only	$\Delta\mu/\mu$ Dilepton plus b-tagged jets
Total statistical uncertainty	0.27	0.28
Total systematic experimental uncertainty	0.17	0.19
Background normalization	0.12	0.12
Background and $t\bar{t}$ signal distribution	0.07	0.08
Lepton selection efficiency	0.06	0.06
Jet energy scale and resolution	—	0.02
b jet identification (ε_b)	—	0.06
Integrated luminosity	0.05	0.05
Total theoretical uncertainty	0.05	0.05
nPDF, μ_R, μ_F scales, and $\alpha_S(m_Z)$	<0.01	<0.01
Top quark and Zboson p_T modelling	0.05	0.05
Top quark mass	<0.01	<0.01
Total uncertainty	0.32	0.34

Systematic uncertainty impacts II



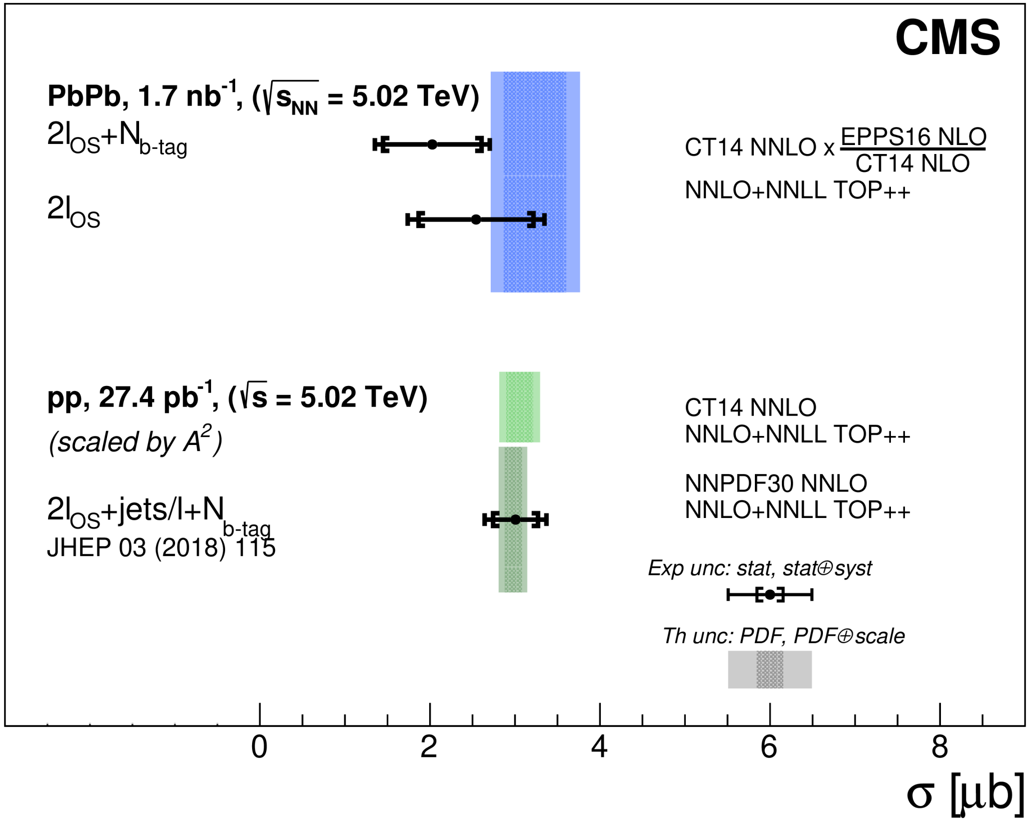
Off-shell DY preferred to have higher strength and even lower p_T

Single-sided impact from quench modeling

Post-fit: most nuisances barely change or get constrained

Grand-summary

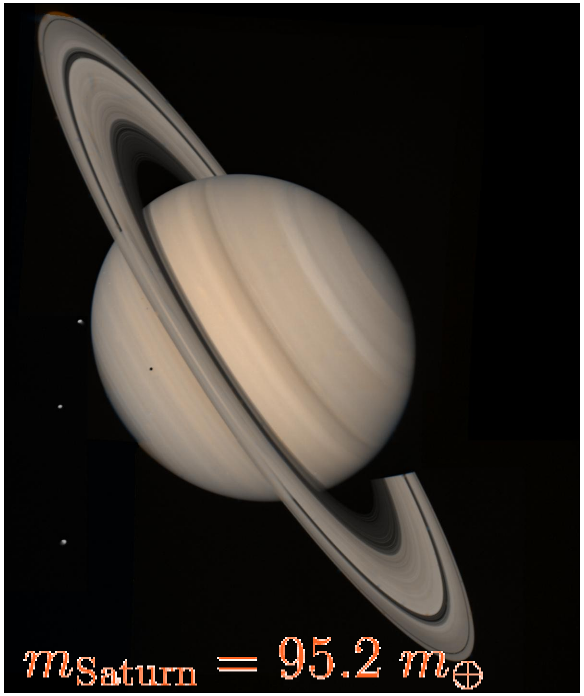
- **We have evidence for tt production in PbPb collisions at 4σ**
- **We measure** $\sigma_{t\bar{t}} = 2.03^{+0.71}_{-0.64}\ \mu b$ ($\sigma_{t\bar{t}} = 2.54^{+0.84}_{-0.74}\ \mu b$ without b-tags)
  32-34% unc.
- **"Close enough" to theory prediction** $\sigma^{NNLO+NNLL}_{PbPb \to t\bar{t}+X} = 3.22\ ^{+0.38}_{-0.35}\,(\text{nPDF} \oplus \text{PDF})\ ^{+0.09}_{-0.10}\,(\text{scale})\,\mu b$

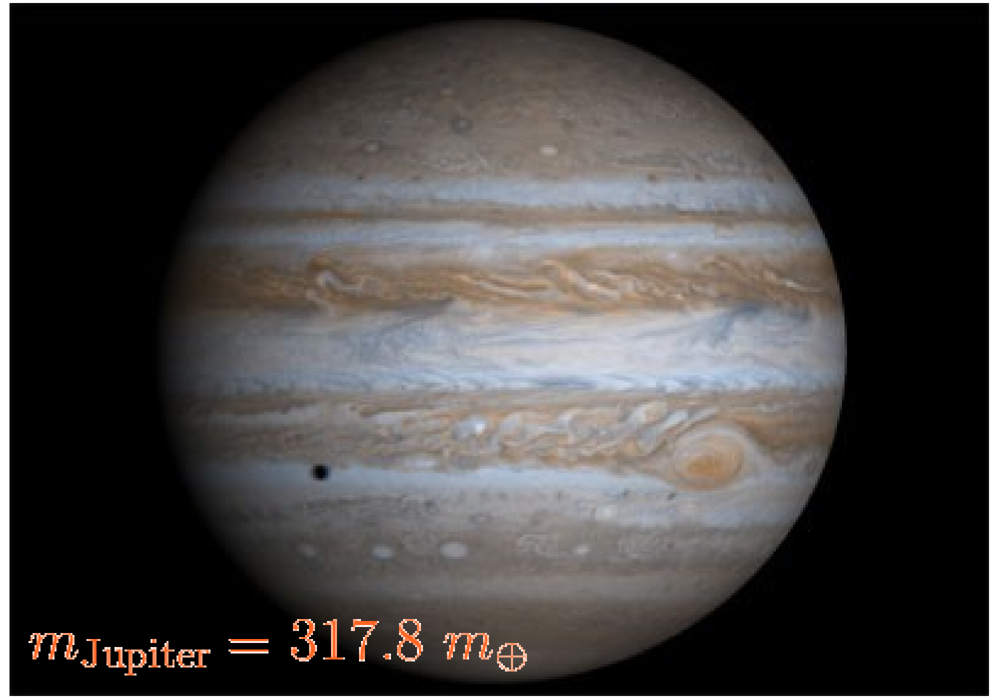


Conclusions

… with a reprise of Goya's “Saturn devouring his son”

From mythology...





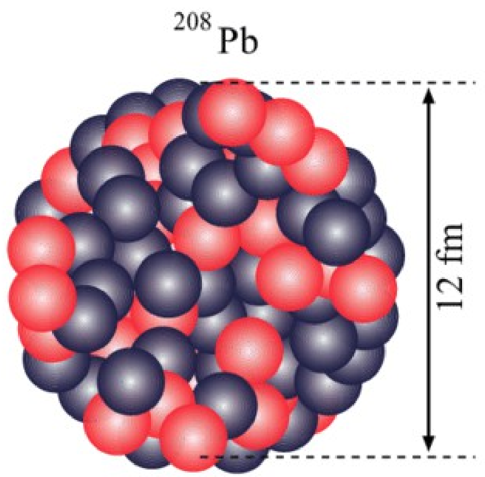
Legend has it as Saturn would predate his own children moments after birth.

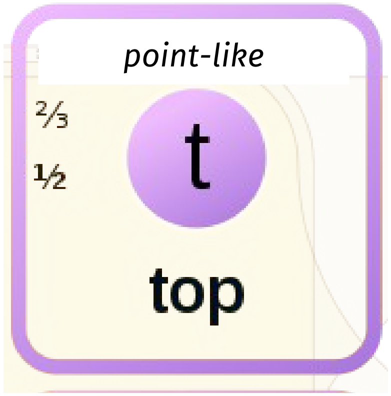
Opis decided to hide their 3rd son in Crete deceiving Saturn with a wrapped stone.

The child grew up and eventually supplanted his father, as the prophecy predicted.

Jupiter was his name.

...to reality...





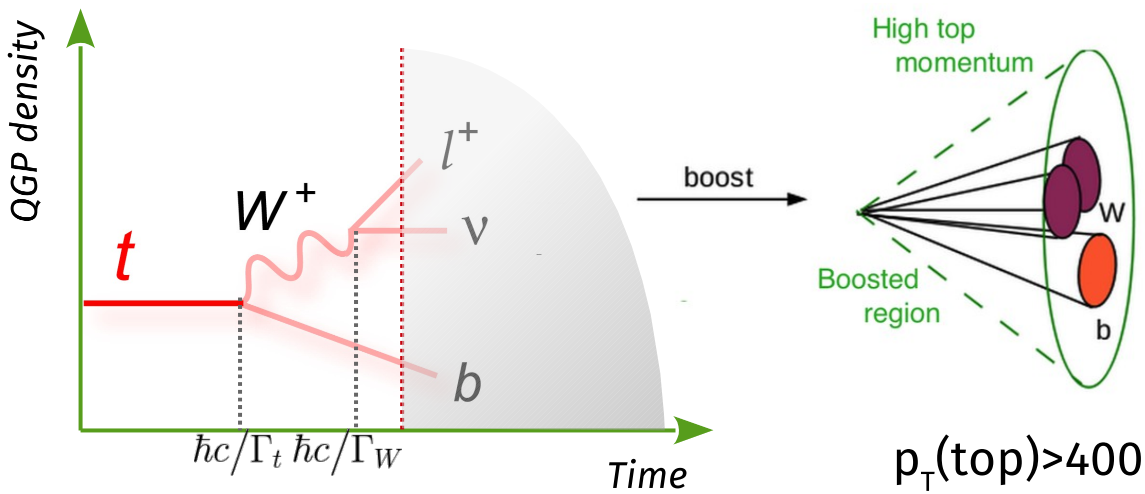
$$m_{\mathrm{Pb}} = 193.8\ \mathrm{GeV}$$

$$m_{\mathrm{t}} = 172.5\ \mathrm{GeV}$$

Different observations show the QGP after Pb ion collisions “predating” colored particles.

Recently CMS found evidence for the heaviest of the 3rd generation quarks in Pb collisions.

...and back to prophecies



p_T(top)>400 GeV

$m_{\mathrm{T,t}}/m_{\mathrm{Pb}} \sim \mathcal{O}\left(m_{\mathrm{Jupiter}}/m_{\mathrm{Saturn}}\right)$

In the future this child will boost up and eventually outlive the QGP.

May the prophecy (FCC-hh) be fulfilled for top quarks in heavy ions.

Outlook

- **CMS has concluded a series of measurements of $\sigma(t\bar{t})$ with special runs**
  - pp and PbPb at 5.02 TeV/nucleon, pPb at 8.16 TeV/nucleon
  - simple yet innovative ways of measuring a simple quantity
    (signal extraction, background estimations, in-situ constraints, stat. limited)
  - first and only measurements so far
  - culminate in the first evidence of PbPb → $t\bar{t}$ production

- **The door to top as a new hard probe in heavy-ions has been opened**
  - Look forward for higher luminosity runs
  - Combination with future measurements from other experiments
  - Exploring the QGP properties from a new perspective...
    ... but also use PbPb to search for new physics! (see arXiv:1812.07688)