Observation of top quark production in proton-nucleus collisions

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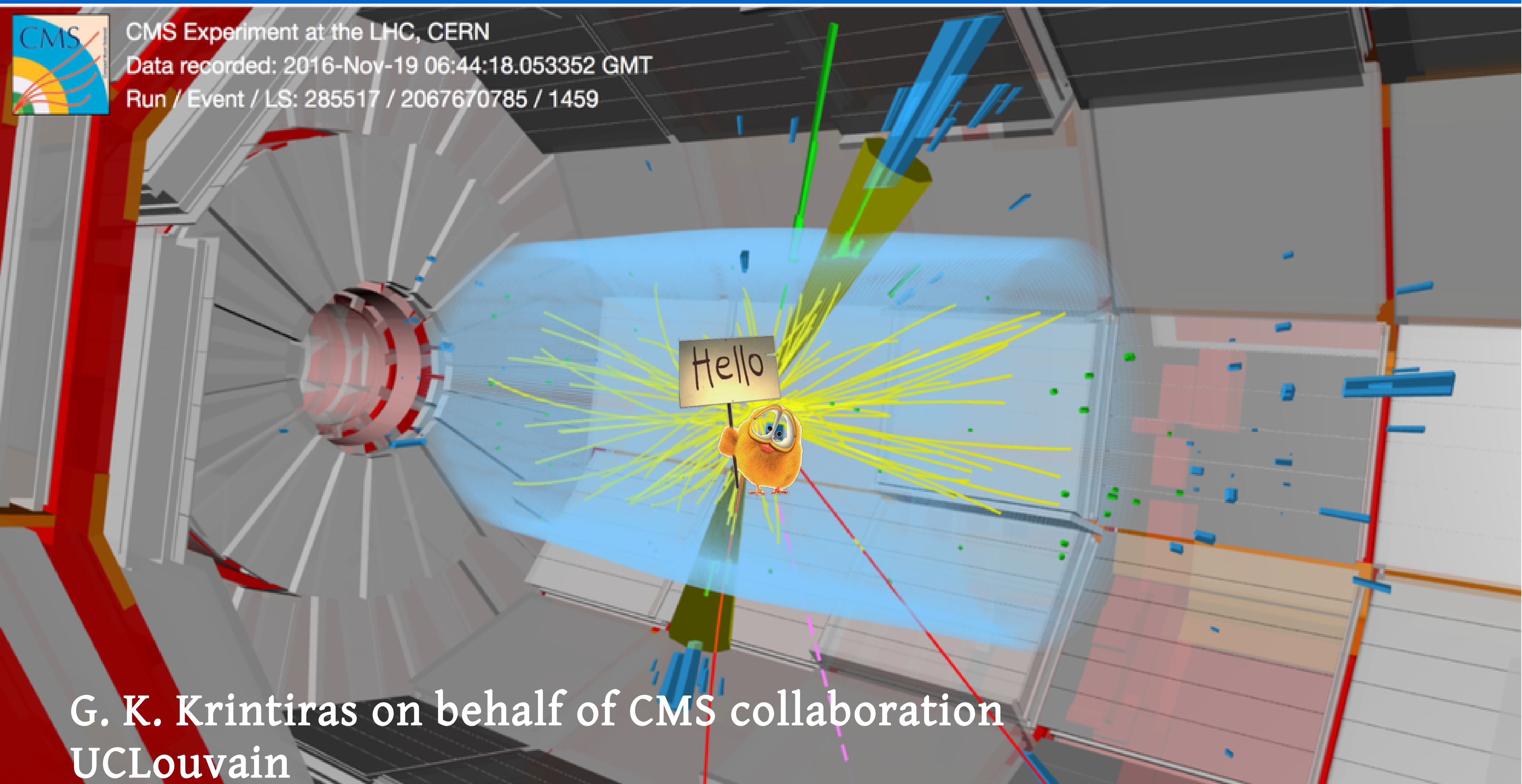

G. K. Krintiras on behalf of CMS collaboration
UCLouvain

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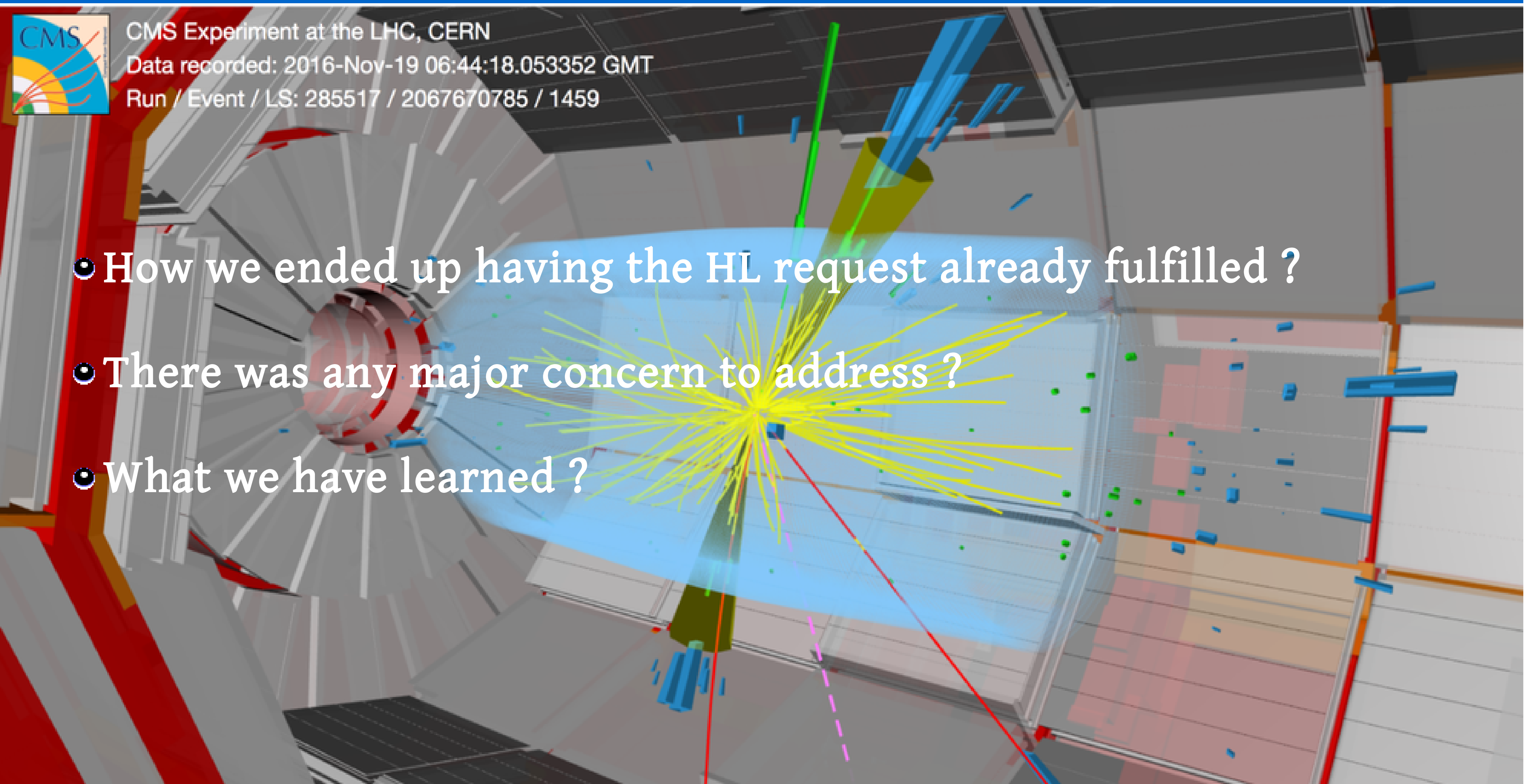
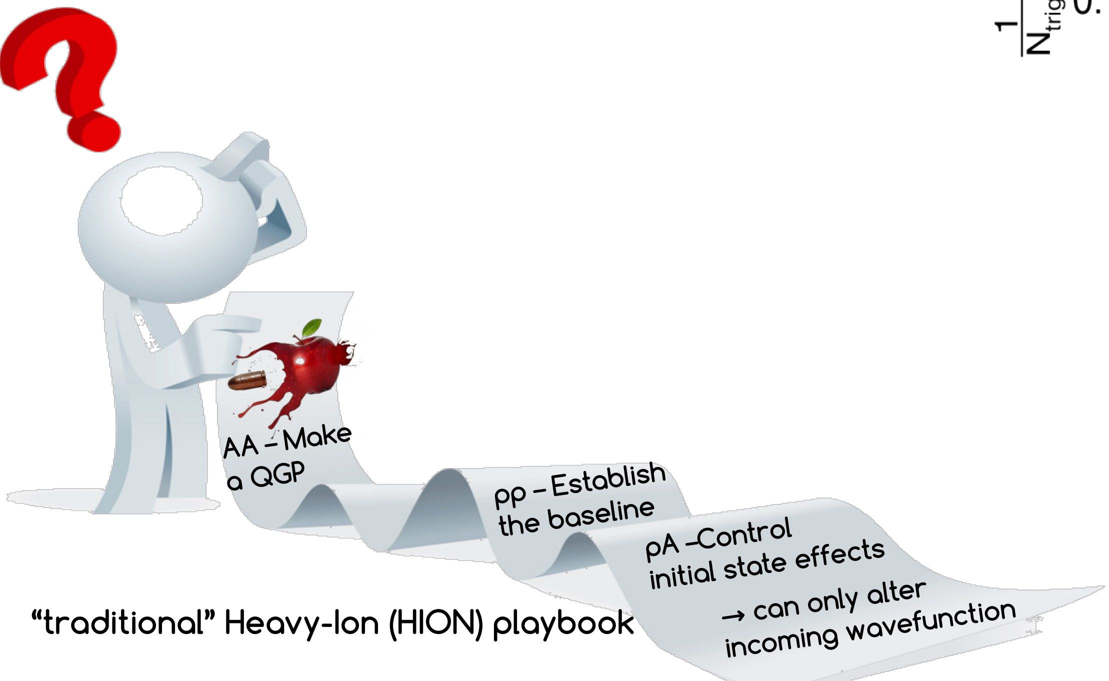


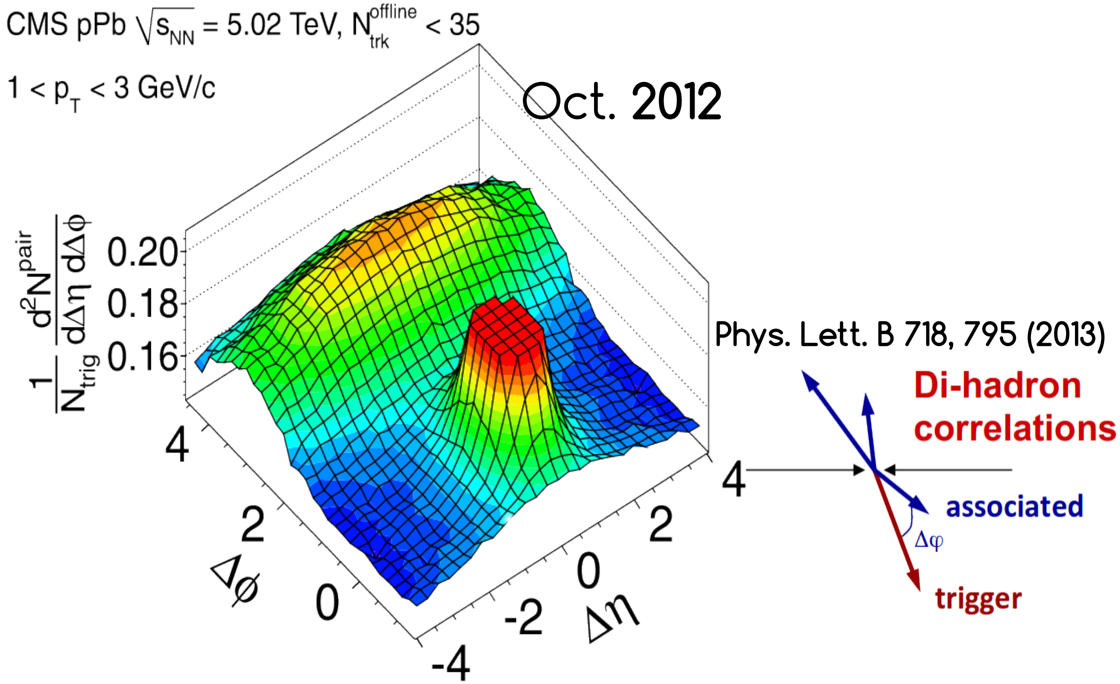
- How we ended up having the HL request already fulfilled ?
- There was any major concern to address ?
- What we have learned ?

Throwing a bullet through an apple… Why ?

- Initially only thought to give answers on **hot** questions about **cold** QCD matter
  - The first collisions of unequal species (**pPb**) @ LHC revealed surprises
    - signs **similar** to those of the Quark-Gluon Plasma (QGP)
    - interest exploded (the 5th most cited CMS paper in PLB !)



"traditional" Heavy-Ion (HION) playbook



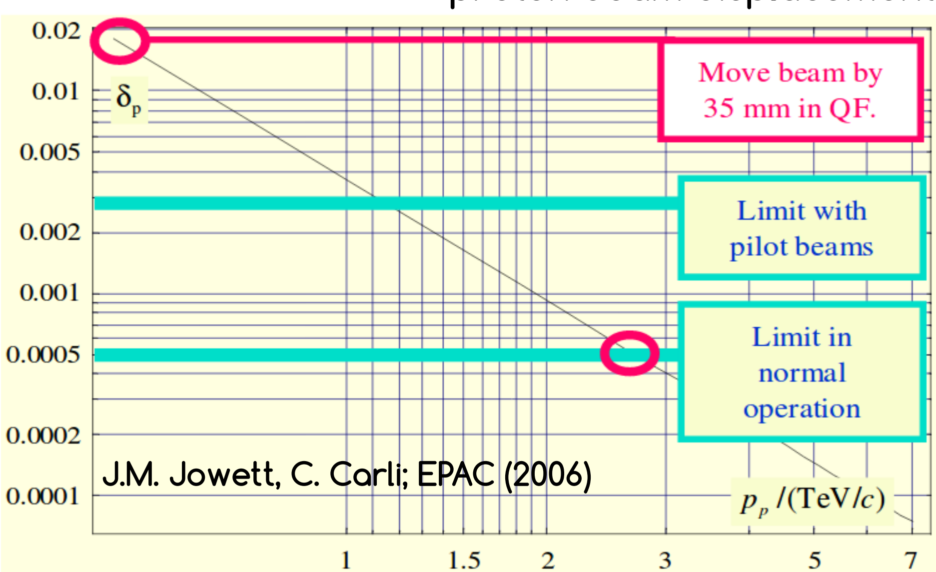
Oct. **2012**

Phys. Lett. B 718, 795 (2013)

Throwing a bullet through an apple... How ?

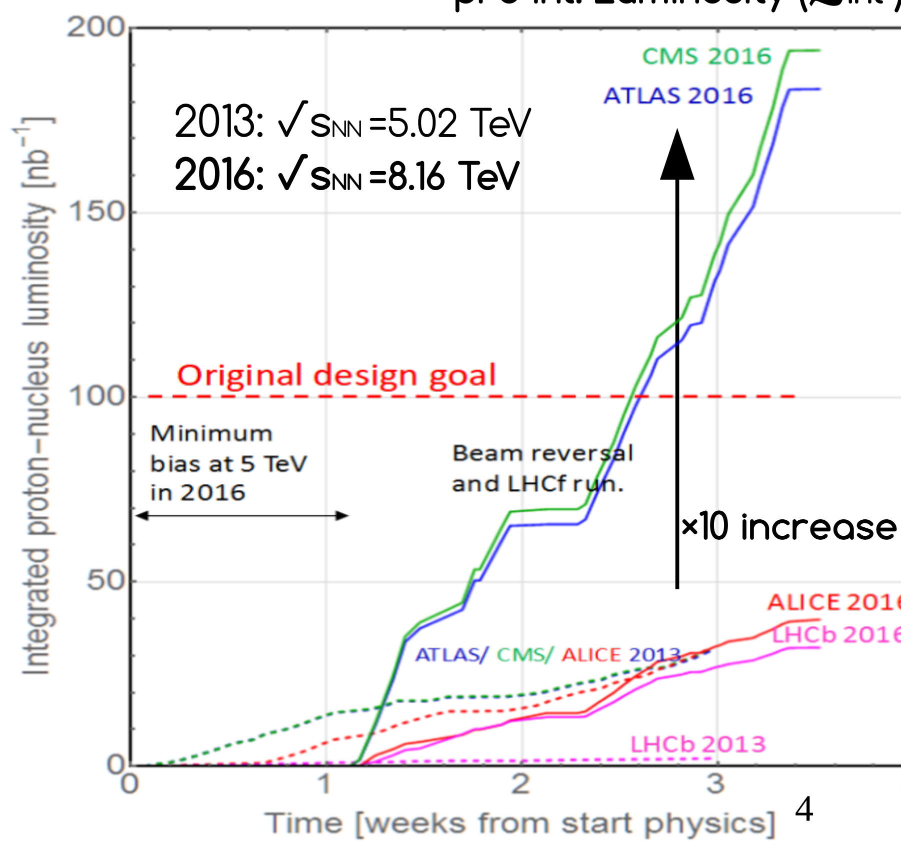
- Initially only thought to give answers on **hot** questions about **cold** QCD matter
  - The first collisions of unequal species (**pPb**) @ LHC revealed surprises
    - signs **similar** to those of the Quark-Gluon Plasma (QGP)
    - interest exploded (the 5th most cited CMS paper in PLB !)
- Ideally LHC is **meant** for equal colliding species
  - its "two-in-one" magnet design gave birth to "cogging" (O.o ?)
    - **no** preceding design (!= BNL RHIC)

proton beam displacement



A **lower** (!) limit on the achieved energy ($\sqrt{s_{NN}}$)

pPb int. Luminosity ($\mathfrak{L}_{int}$)

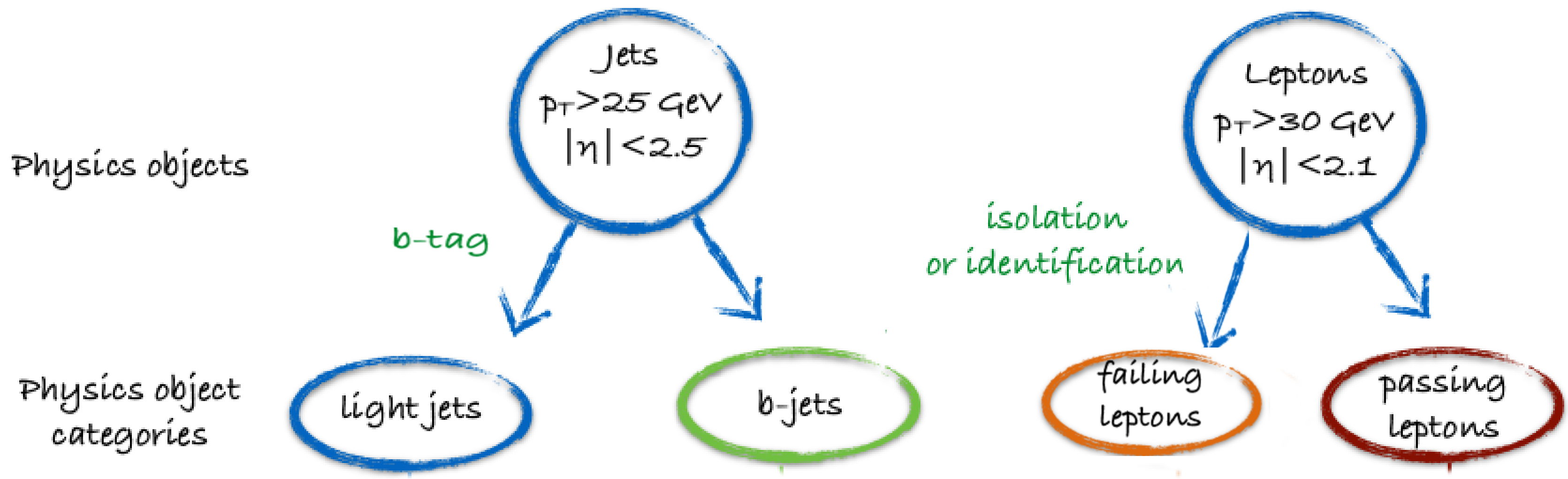


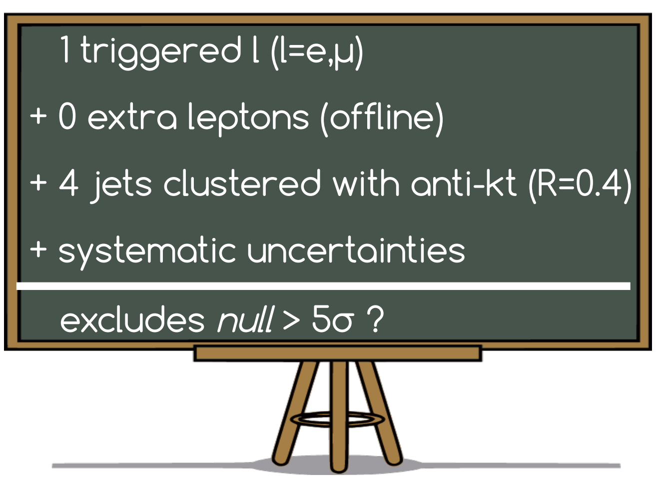
Interest + ingenuity ⇒ $\mathfrak{L}_{int}$ =174±9 nb-1 (!)

The first search analysis for tt in nuclear collisions !

- **l+jets** : t t → bW bW → b l b jj' + missing momentum (MET) i.e., crucial to search for the lepton (l= e,μ) & non-b jets (a.k.a. the light jets j,j')
  - j,j' jets are paired based on their proximity in (η,φ) space (minΔR separation)

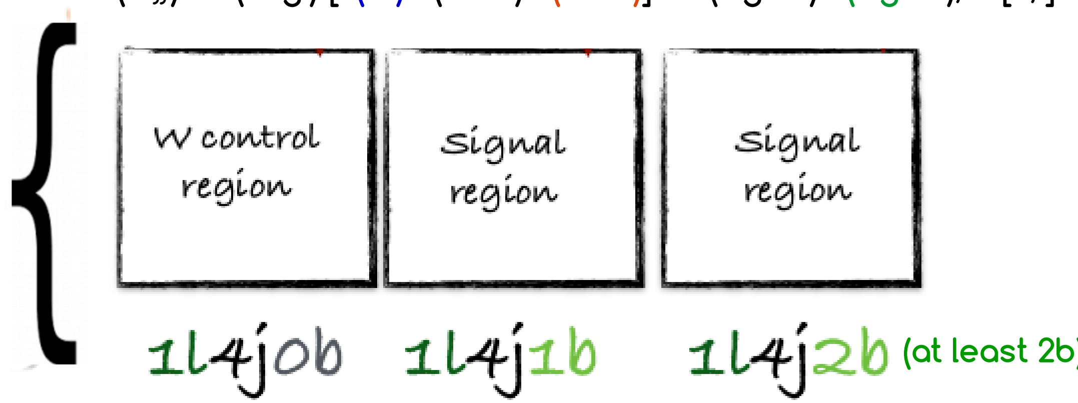
    → to construct the variable of interest; **here the $m_{jj'}$ inv. mass**
  - main backgrounds (bkg.) from **W+jets** and **QCD multijet** production





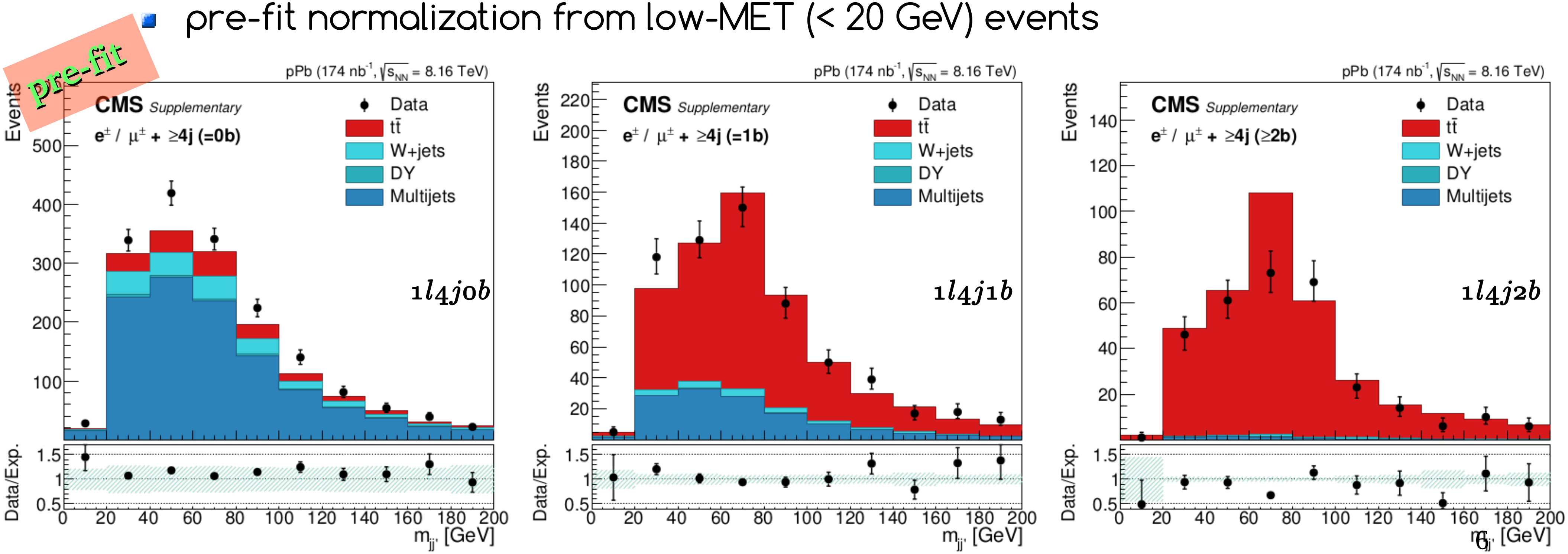
Combined fit over 2 × 3 = 6 categories

N ($m_{jj'}$) = N(bkg.)*[P(W)+f(QCD)*P(QCD)] + N(signal)*P(signal), f∈[0,1]



The data-driven bkg. modeling

- EW processes (W+jets, also DY) modeled with **PYTHIA** (v.6.424, tune Z2*)
  - pN → W + X (**N=p,n**) i.e., a mixture of pp and pn interactions – this is **crucial**
    - **Landau** parameterization found as a proper description (hint: combinatorics)
    - also supported from **POWHEG** (v2) interfaced with CT14+EPPS16
    - effects from nuclear modifications inferred *in-situ*
- QCD multijet process extracted from failed iso (ID) control region in μ(e)+jets channel
    - **kernel** parameterization (hint: non trivial behavior for fake/non prompt l)
    - pre-fit normalization from low-MET (< 20 GeV) events



All samples are tuned to reproduce the global pPb event properties

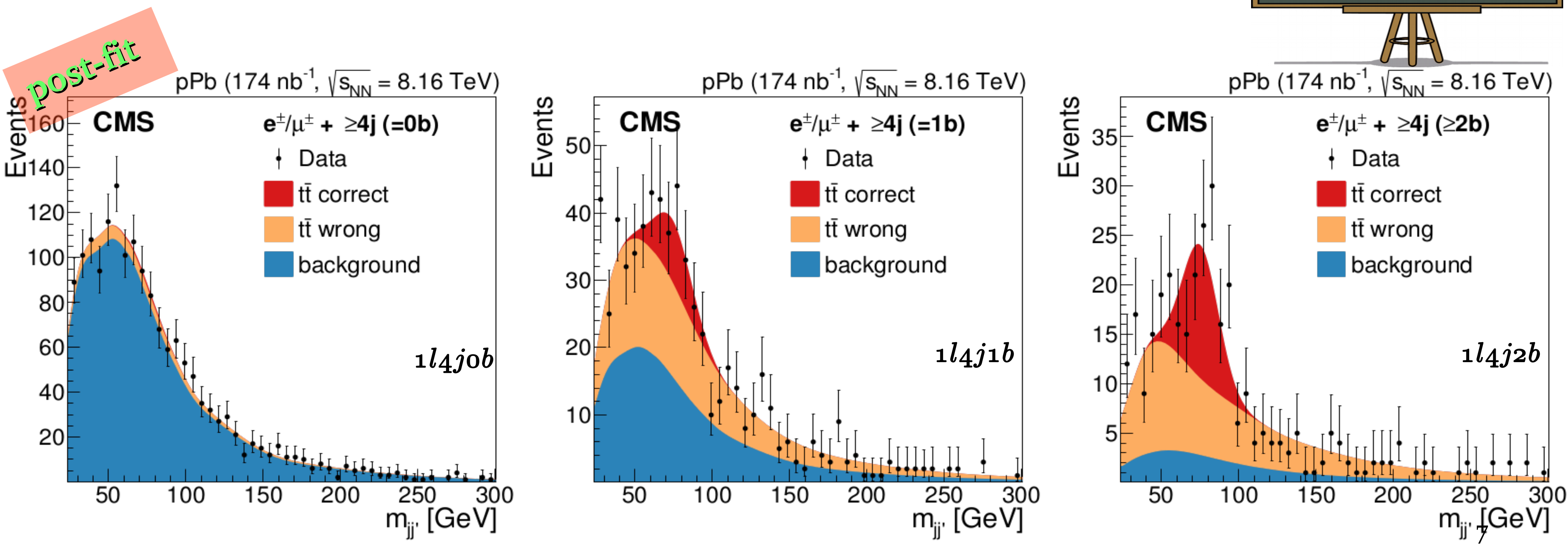
Measuring the tt production cross section (l+jets)

- Basic ingredients: **acceptance** ($\mathcal{A}$) and **efficiency** (ε)
  - $\mathcal{A}$ = 0.060±0.002(tot) (0.056±0.002(tot)) in μ(e)+jets channel
    - determined @ NLO with **POWHEG** (v2) in the fiducial region
  - ε = 0.91±0.04(tot) (0.63±0.03(tot)) in μ(e)+jets channel
    - measured in data with "tag-and-probe" method (Z boson candle)
- Total number of signal (S) events in all 6 cats. : **S = 710 ± 130(tot)**
  - combination dominated by μ+jets channel

$\mathcal{L}_{int}$ =174 nb-1

σ_{tt} = 45±8(tot) nb

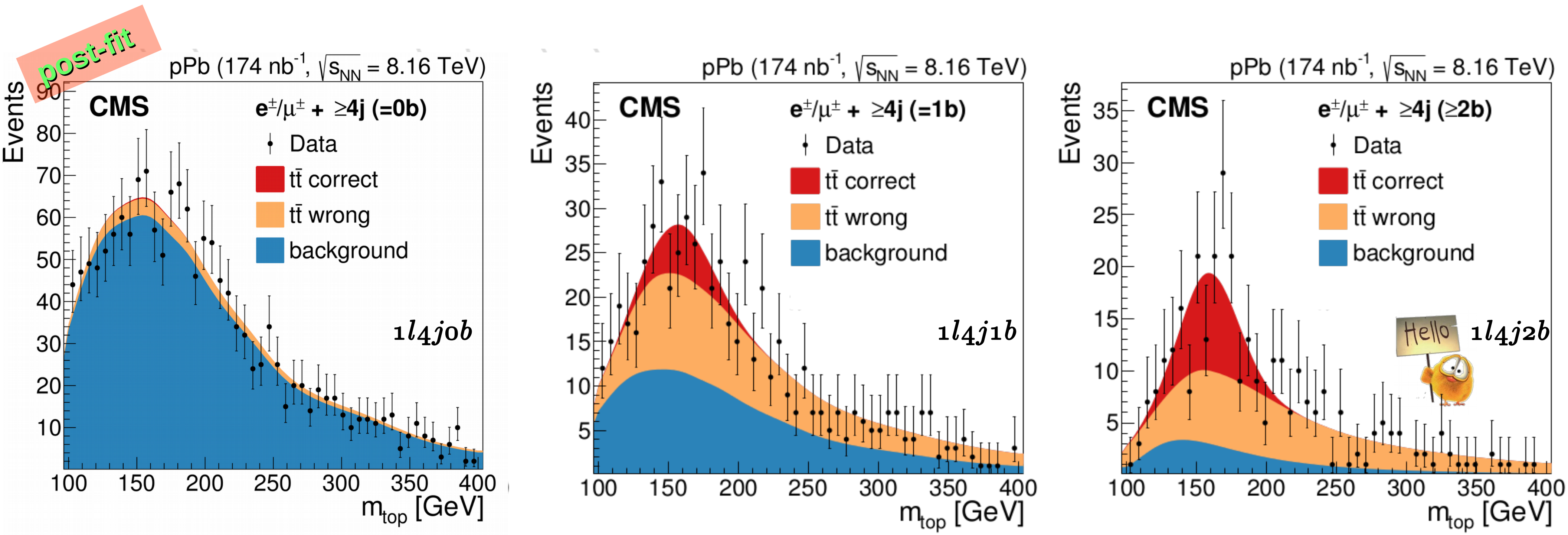
$d\sigma_{tt}$ / σ_{tt} = 17 % (!)



Background completely determined from data !

An "alternative" to the Bayesian posterior

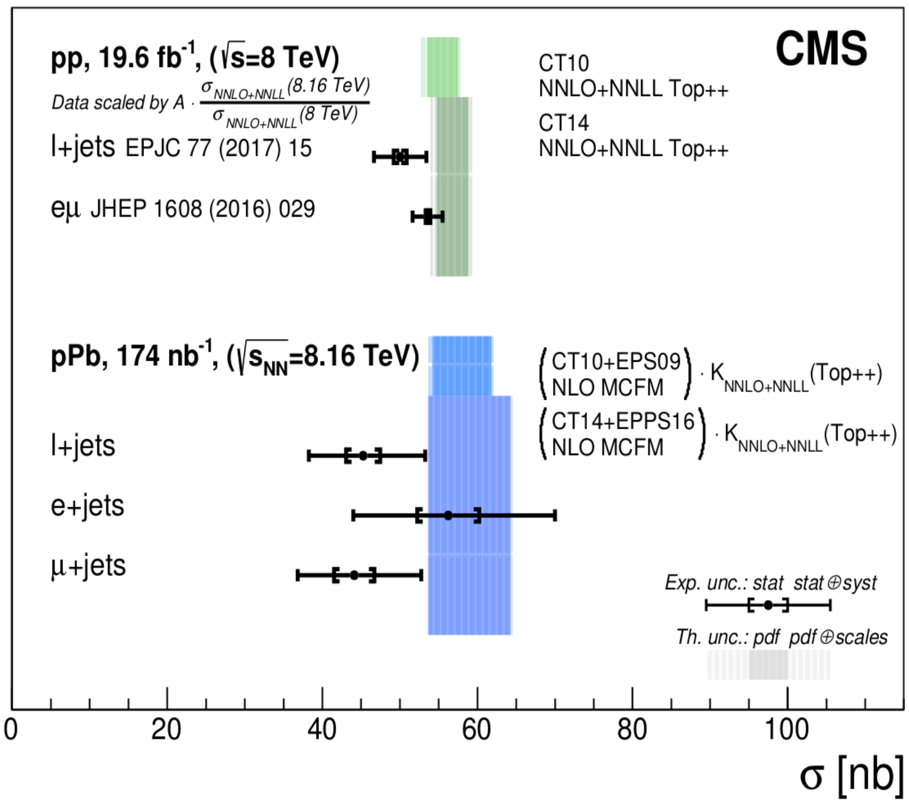
- To further support the consistency with the production of top quarks
  - the inv. mass of **jj'b** triplet (hadronic top mass) is plotted
    - b jet candidate with the highest b-tag discriminator value
    - the minimum difference to inv. mass of **lνb** triplet (leptonic top mass) is considered
  - signal and bkg. contribution scaled to **post-fit** $m_{jj'}$ values

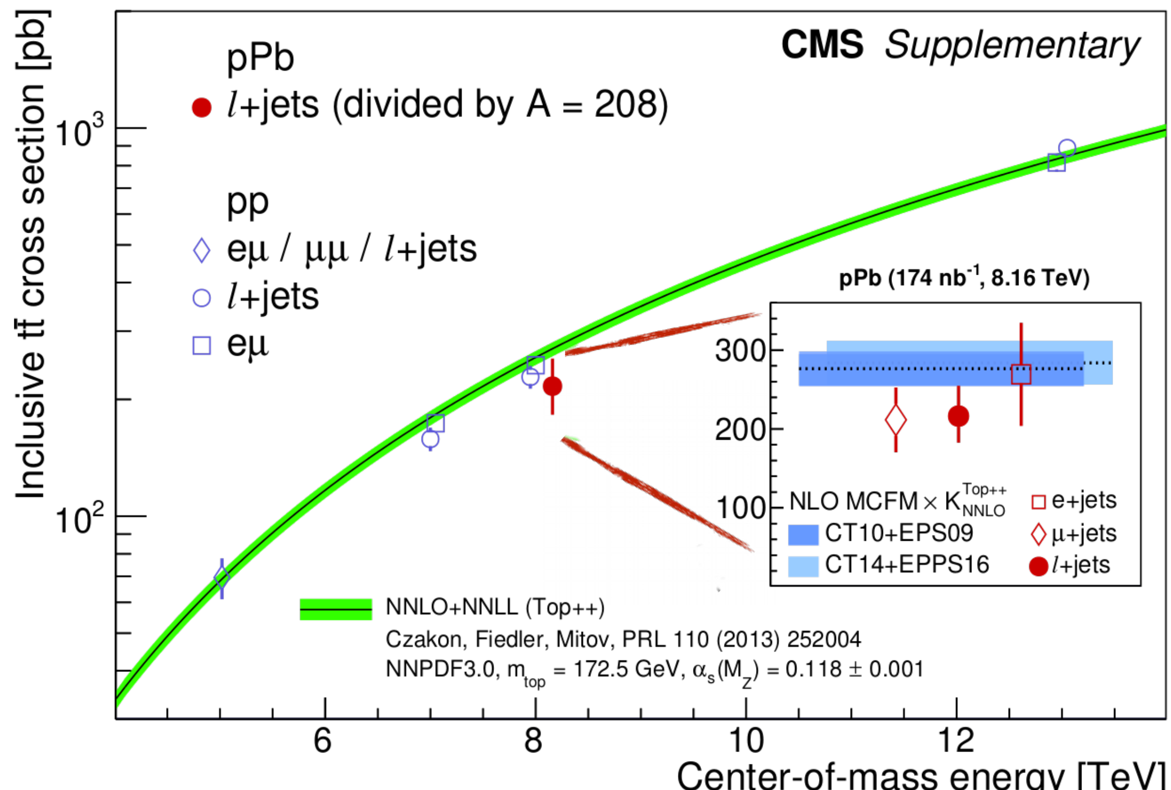


Even a peak is reconstructed close to top mass !

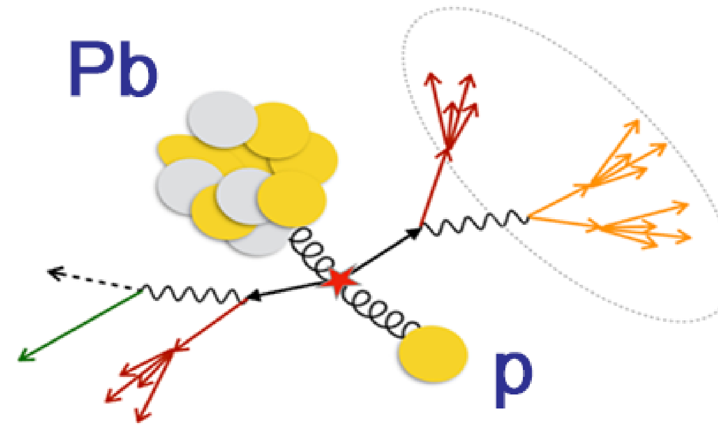
Up-to-date compilation: 4 $\sqrt{s_{NN}}$ & 2 systems @ LHC !

- First experimental **observation** of the top quark in nuclear collisions
  - σ_{tt} measured in two independent decay channels i.e., μ,e+jets
    - $d\sigma_{tt}$ / σ_{tt} = 17% in the l+jets combination
    - **consistent** with the scaled pp data **as well as** pQCD calculations
- **Minimally** relies on assumptions from MC simulation
  - paves the way for the study in AA collisions

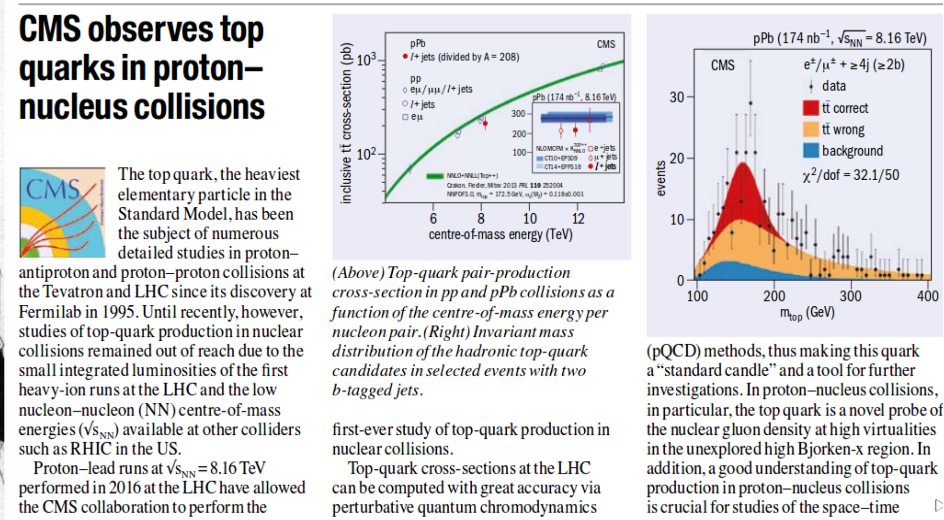




PRL Physics Synopsis, Dec. 2017



CERN Courier, Nov. 2017



CMS observes top quarks in proton–nucleus collisions

The top quark, the heaviest elementary particle in the Standard Model, has been the subject of numerous detailed studies in proton–antiproton and proton–proton collisions at the Tevatron and LHC since its discovery at Fermilab in 1995. Until recently, however, studies of top-quark production in nuclear collisions remained out of reach due to the small integrated luminosities of the first heavy-ion runs at the LHC and the low nucleon–nucleon (NN) centre-of-mass energies ($\sqrt{s_{NN}}$) available at other colliders such as RHIC in the US.

Proton–lead runs at $\sqrt{s_{NN}}$ = 8.16 TeV performed in 2016 at the LHC have allowed the CMS collaboration to perform the first-ever study of top-quark production in nuclear collisions.

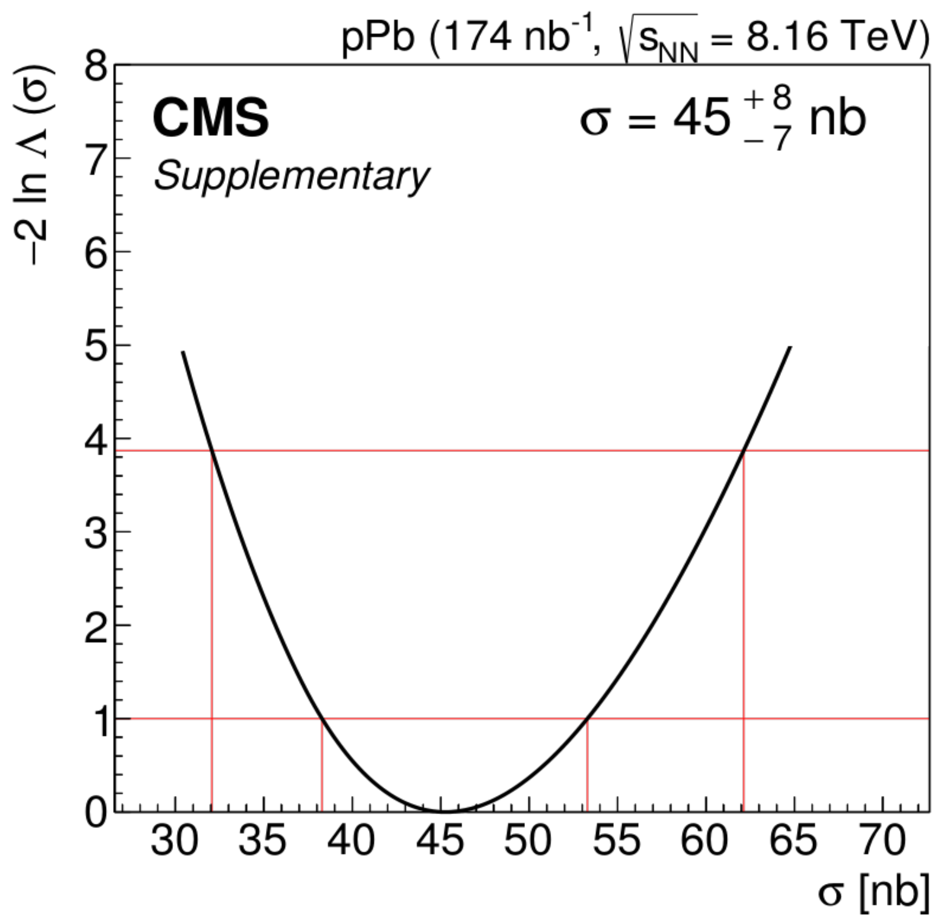
Top-quark cross-sections at the LHC can be computed with great accuracy via perturbative quantum chromodynamics (pQCD) methods, thus making this quark a "standard candle" and a tool for further investigations. In proton–nucleus collisions, in particular, the top quark is a novel probe of the nuclear gluon density at high virtualities in the unexplored high Bjorken-x region. In addition, a good understanding of top-quark production in proton–nucleus collisions is crucial for studies of the space–time

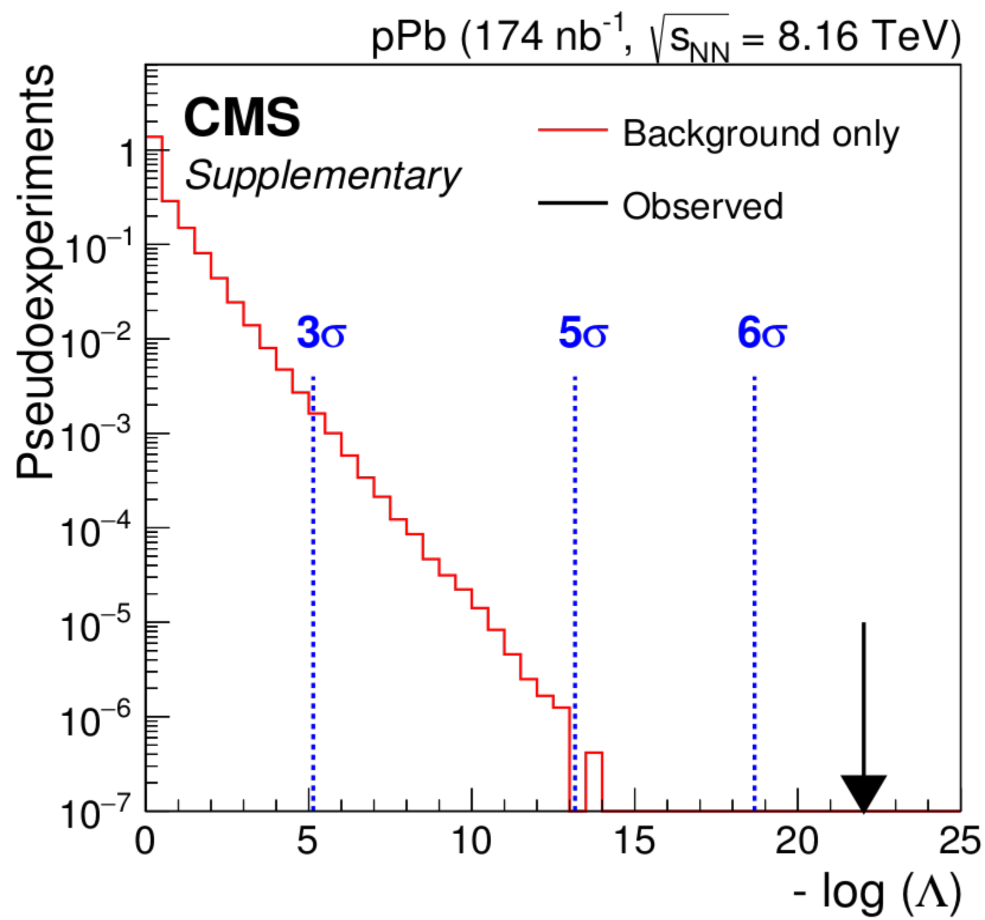
(Above) Top-quark pair-production cross-section in pp and pPb collisions as a function of the centre-of-mass energy per nucleon pair. (Right) Invariant mass distribution of the hadronic top-quark candidates in selected events with two b-tagged jets.

slides

The statistical significance of the measurement

- The *null* hypothesis is excluded at a level of
  - **>5σ** taking into account syst. unc. by:
  - the observed variation of the **likelihood** as a function of the POI
  - PLR from **pseudo-data** generated from the background-only model



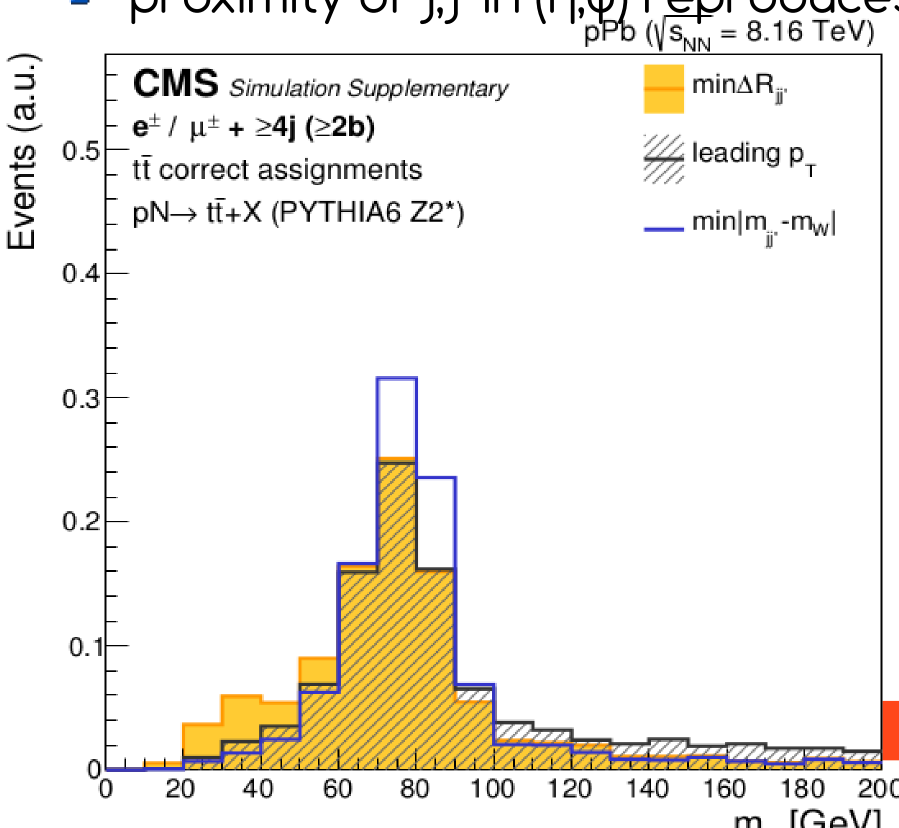


Indeed, the first observation of top quarks in pPb !

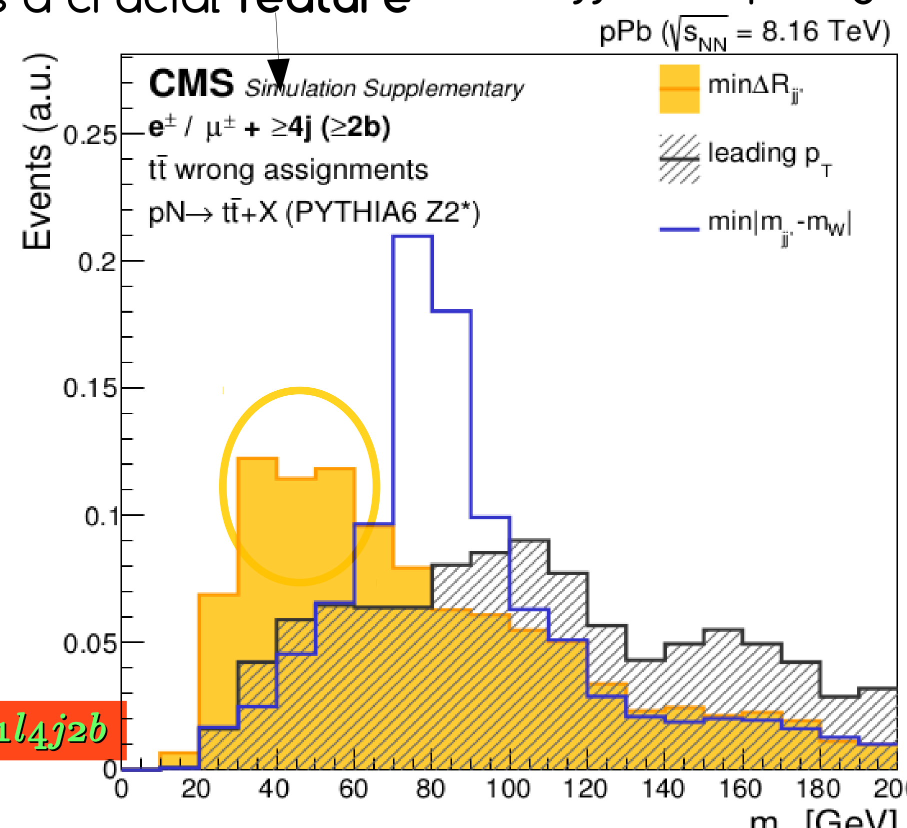
The signal modeling

- tt process modeled with **PYTHIA** (v.6.424, tune Z2*)
  - pN → tt + X (**N=p,n**) i.e., a mixture of pp and pn interactions – not crucial
    - effects from nuclear modifications studied with **POWHEG** (v2) interfaced with CT14+EPPS16
  - split the total contribution in a **resonant** (left Fig.) and a **non resonant** (right Fig.) part
    - resonant: both j,j' (reco) matched with a light flavor parton (truth)
    - proximity of j,j' in (η,φ) reproduces a crucial **feature**

j,j' tested pairing criteria



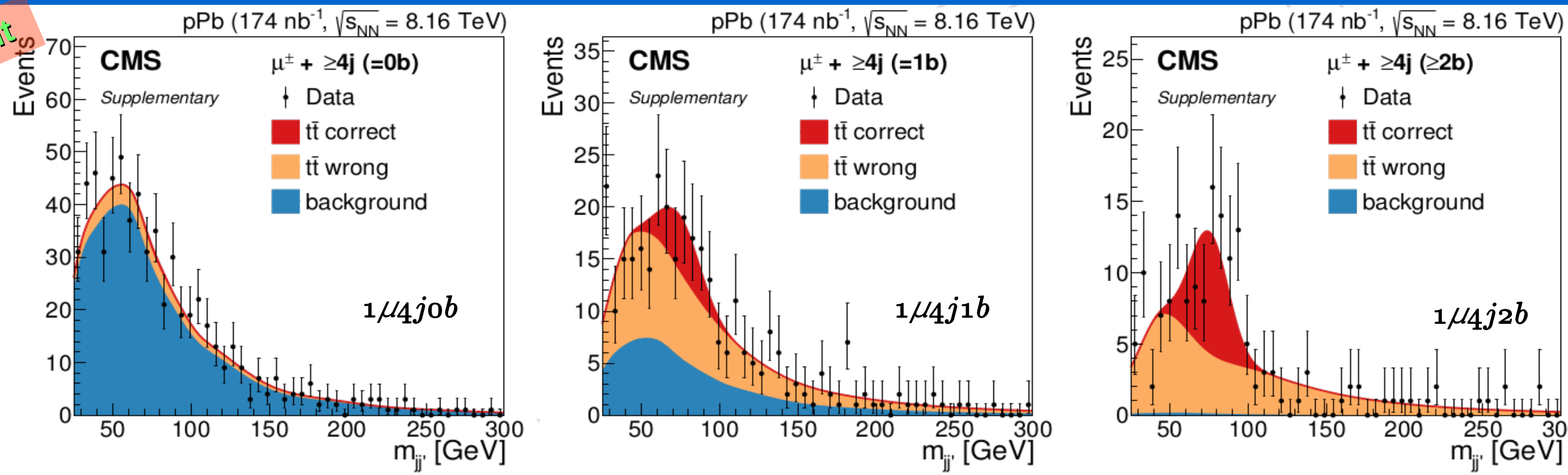
Parameterized with a **CB+gamma**



Parameterized with a **asym. Gaussian+Landau**

Measuring the $t\bar{t}$ production cross section (μ,e+jets)

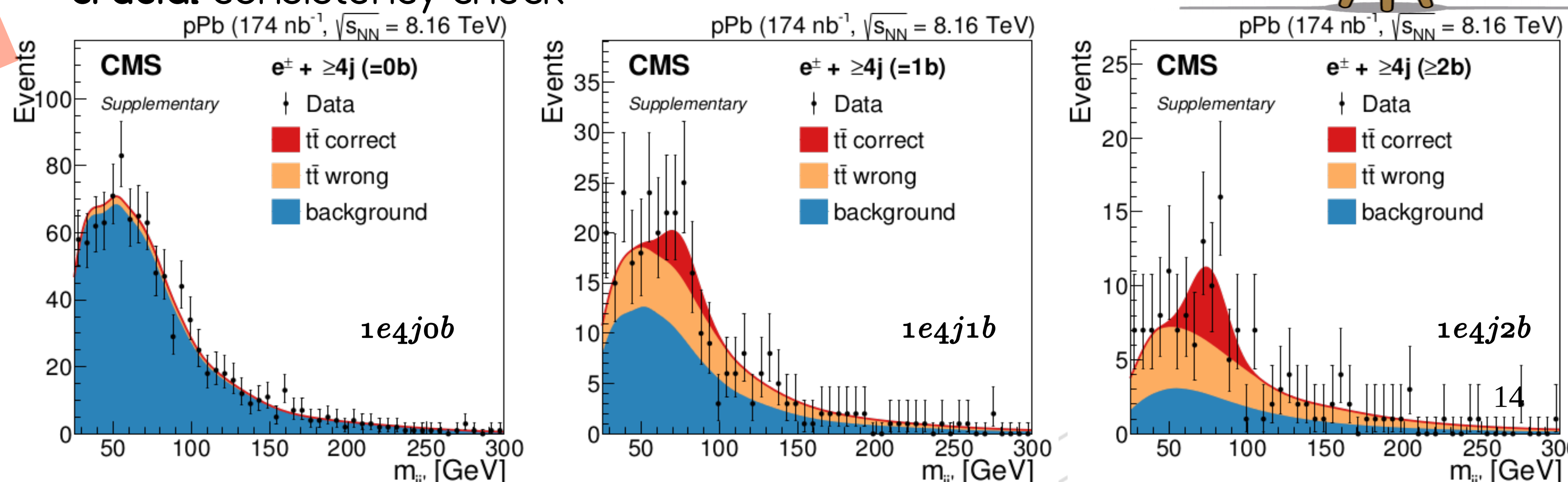
post-fit



- e+jets hampered more by bkg. contamination
  - less precise than μ+jets i.e., $d\sigma_{tt} / \sigma_{tt}$ = **23 %** vs **18 %**
    - **crucial** consistency check

μ+jets:
σ_{tt} = 44±3(stat)±8(syst) nb
e+jets:
σ_{tt} = 56±4(stat)±13(syst) nb

post-fit

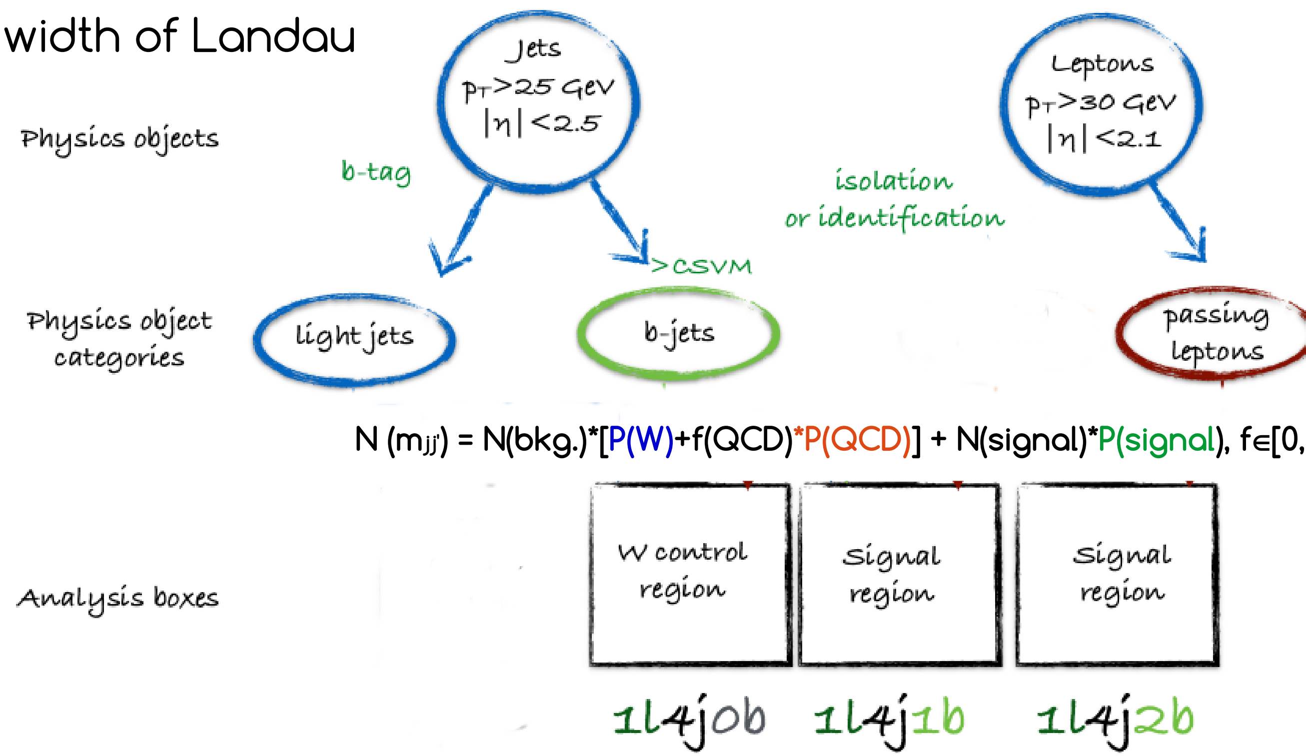


The fit procedure in detail

- In order to ensure stability of the complex fit procedure
  - N(bkg.) floats with N(QCD) constrained with μ, σ from low-MET normalization
  - N(signal) floats with event category coupling based on ε_b., the latter constrained with μ from simulation and conservative σ :
    - $N_{4j2b} = \varepsilon_b \varepsilon_b\, N(\text{signal})$, $N_{4j1b} = 2\,\varepsilon_b(1-\varepsilon_b)\, N(\text{signal})$, $N_{4j0b} = (1-\varepsilon_b)(1-\varepsilon_b)\, N(\text{signal})$
- In order to evaluate the uncertainty on the signal yields
  - profiling of the likelihood is performed over the full set Θ of nuisances

$$\mathcal{L}(\sigma_{t\bar{t}}\,,\Theta) = \prod_l \mathcal{P}\text{oisson}\left(N_l^{\text{obs}}, N_l\right) \cdot \prod_i \mathcal{G}\text{auss}(\theta_i^0, \theta_i, \sigma_{\theta_i})$$

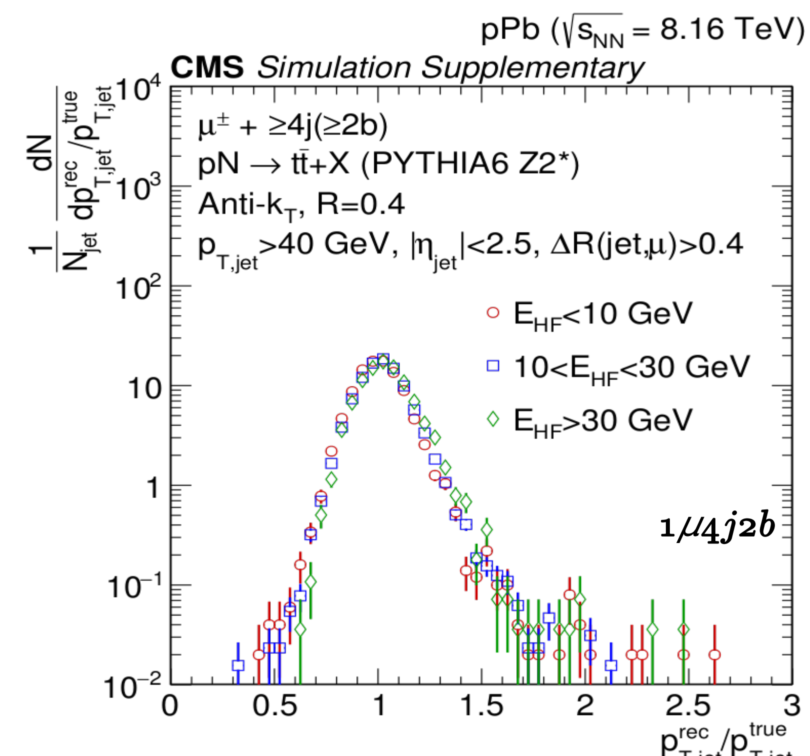
    - N(bkg.), f(QCD), MPV and width of Landau
    - ε_b
    - $\mathcal{A}$, ε, $\mathcal{L}_{\text{int}}$
    - JES effect on $m_{jj'}$



Splitting uncertainty in a stat & syst component

- Neither trivial nor unique task
  - **stat**: fix nuisances to post-fit values and refit with floating σ_{tt}
  - **syst**: $\sqrt{(\text{tot}^2 - \text{stat}^2)}$
- effect of identified sources for systematic variations
  - fix all other nuisances to post-fit values and refit within ±1σ
  - syst != quadratic sum of the effects (hint: mind the correlations)

UNCERTAINTY DESCRIPTION	EFFECT (%)
EVENT COUNT — σ_{tt} floats in the fit and all other parameters fixed to their post-fit values	5
b FINDING EFFICIENCY — the probability that a b jet passes both the kinematic and the b tagging selections	13
BACKGROUND — Shape and normalization uncertainties	7
LUMINOSITY — Preliminary offline calibration for pPb data taking 2016 period	5
JET ENERGY SCALE — 3%-level non-closure of the jet energy corrections in MC events and a 3% residual calibration uncertainty from data	4
LEPTON EFFICIENCY — Dominated by the underlying event dependence	4
ACCEPTANCE — QCD, strong coulping and PDF⊗nPDF (POWHEG)	4



Careful treatment of UE dependence

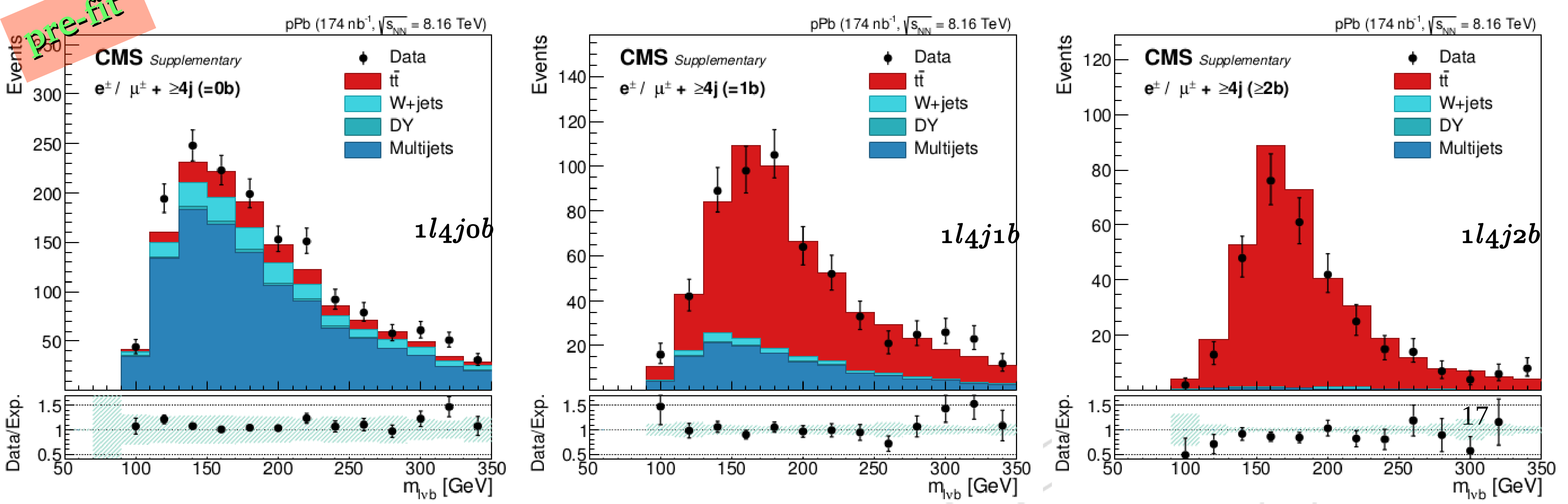
The leptonic top mass

- The longitudinal ν momentum from the 4-momentum conservation in the W(lν) vertex
  - assuming as W boson inv. mass the world average of 80.4 GeV
  - ambiguities raised as
    - two real solutions: the one which minimizes $|p_{z,\nu} - p_{z,l}|$
    - imaginary solutions: real part of the quadratic equation in $p_{z,\nu}$

$$p_{z,\nu} = \frac{\Lambda p_z}{p_{\mathrm{T}}^2} \pm \frac{1}{p_{\mathrm{T}}^2}\sqrt{\Lambda^2 p_z^2 - p_{\mathrm{T}}^2 \left(E^2 \not{E}_{\mathrm{T}}^2 - \Lambda^2\right)},$$

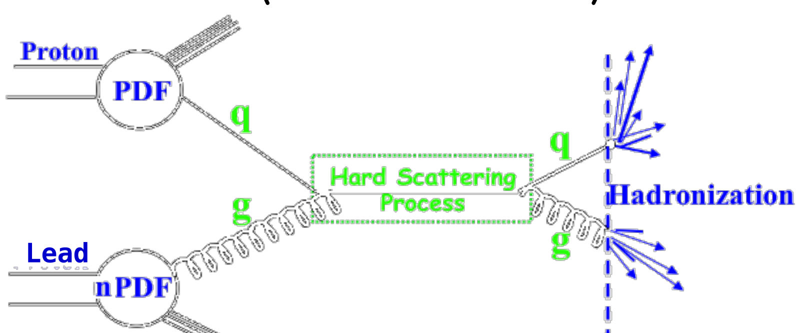
$$\Lambda = \frac{m_{\mathrm{W}}^2}{2} + \vec{p}_{\mathrm{T}} \cdot \vec{\not{p}}_{\mathrm{T}},$$

pre-fit



Theoretical setup for cross section calculation

- Rely on the two fundamental concepts of QCD
  - **factorization** (calculable) and **universality** (input from PDFs)
    - $\sigma_{pA} = A \times \sigma_{pp}$ (A=208 for Pb isotope @ LHC)
- **MCFM** (v8.0, nproc = 141) NLO event calculator with state-of-the-art (n)PDFs
  - bound nucleons' PDF: **EPPS16 NLO** ; baseline free proton PDF: **CT14 NLO**
    - nPDF net effects result in a small +4% modification (R_{pPb}) of $\sigma_{t\bar{t}}$
  - nPDF ⊗ PDF uncertainty from the provided 56+40 eigenvalues → **9%**
  - full calculation repeated with **CT10+EPS09** combination
    - considering the 52+32 error sets → 7%
  - QCD scales choice: $\mu_R = \mu_F =$ **172.5** GeV
    - scale variations by halving/doubling the μ_R, μ_F → **3%**
- **k-factor** (NLO → NNLO) obtained with **TOP++**



cross section ~
PDF ⊗ hard-scattering ⊗ Hadronization

@ $\sqrt{s_{NN}}$=8.16 TeV