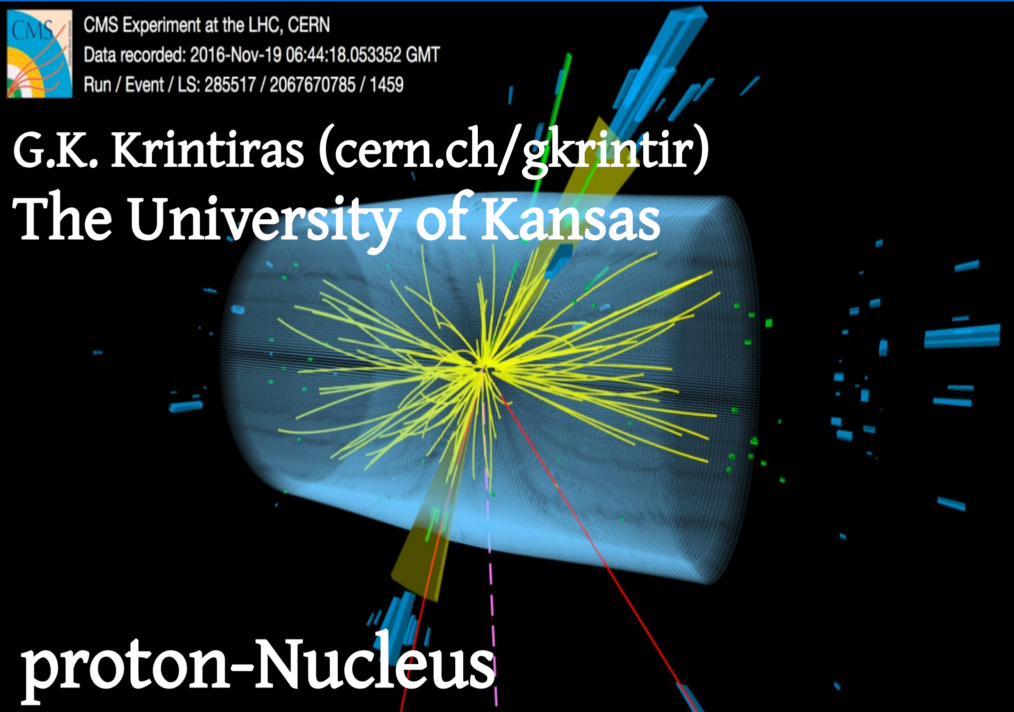
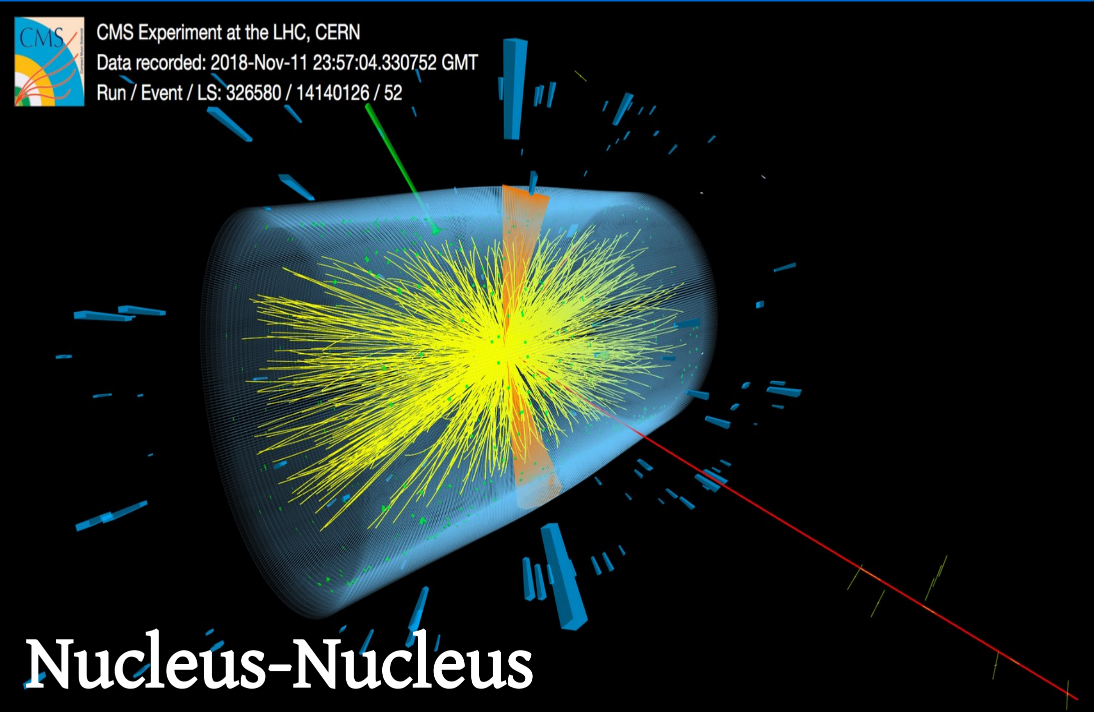
Top Quarks and the "Little Bang Standard Model"

arXiv: 1709.07411, 1711.03143, 2006.11110

G.K. Krintiras (cern.ch/gkrintir)
The University of Kansas



proton-Nucleus



Nucleus-Nucleus

Outline

- Top quark first **observed** at Tevatron 25 years ago
- Studied **in detail** in pp collisions at LHC

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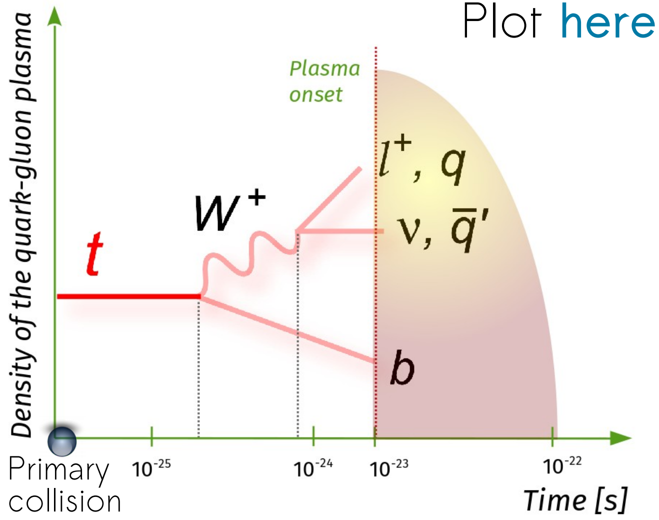
- Nuclear collisions are used to study **QGP**, a strongly-interacting form of matter
  - What is the arrangement of quarks and gluons inside heavy nuclei?
  - Could top quarks provide successive time snapshots of QGP?

Plot here



Outline

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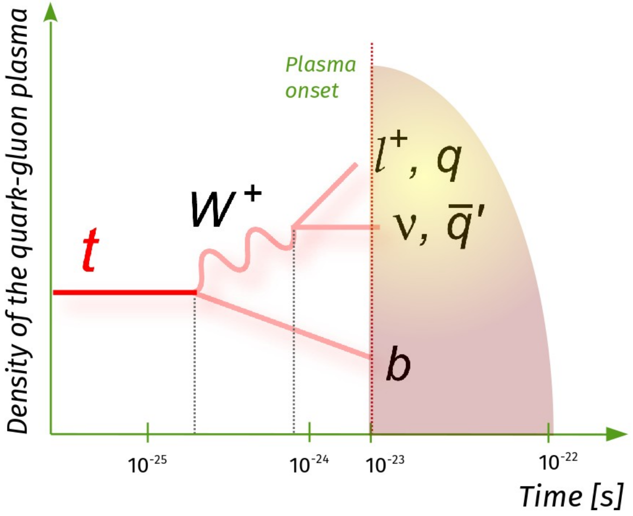
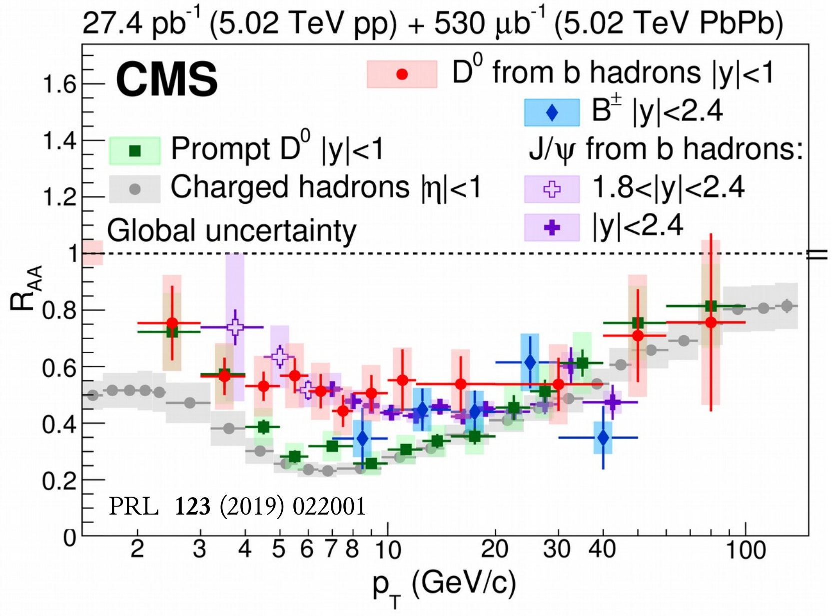
- Nuclear collisions are used to study **QGP**, a strongly-interacting form of matter
  - What is the arrangement of quarks and gluons inside heavy nuclei?
  - Could top quarks provide successive time snapshots of QGP?
- A dedicated study program of $t\bar{t}$ in the “Little Bang Standard Model”
  - going from “reference” **pp** $\longrightarrow$ **pPb** $\longrightarrow$ **PbPb**
- Luminosity is relatively low for those data sets
  - What are the **prospects** at Runs 3–4 & beyond?



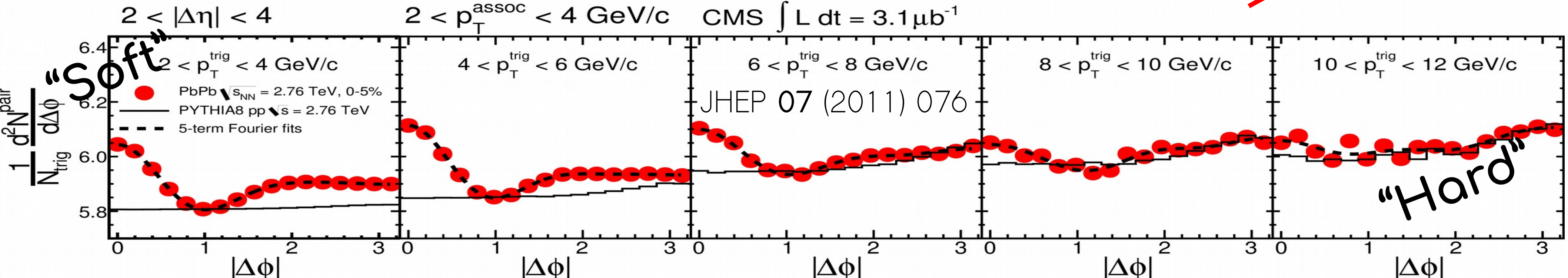
QGP: the form that the early Universe existed in



$$= \frac{\text{PbPb jet yield}}{\text{scaled pp jet yield}}$$

- Energy of partons is lost ('quenched') in QGP
  - experimentally seen as R_{AA} **modifications**
- Different mechnasims for hadron formation
  - p_T-dependent ϕ **correlations**

A fluid that retains its QCD **asymptotic freedom** character!

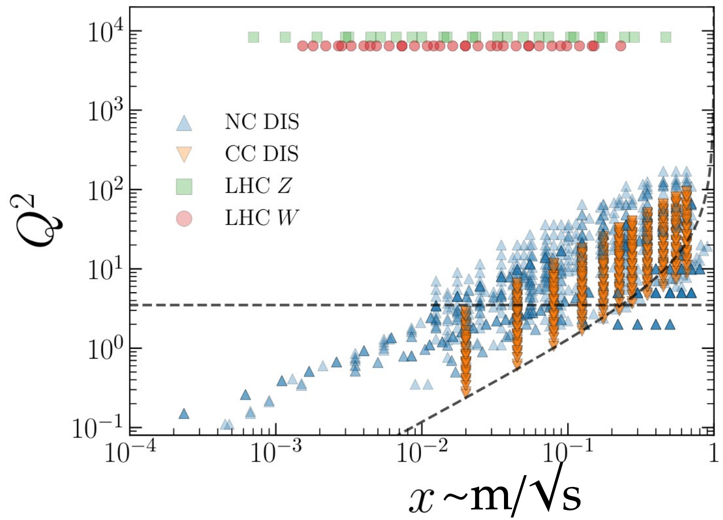


Characterizing the "initial state": nPDF global fits

With input from Annu. Rev. Nucl. Part. Sci. **70** (2020)

Nuclear (most recent) PDFs	nCTEQ15	EPPS16	nNNPDF**2**.0 (**1**.0)	TUJU19
Perturbative order	NLO	NLO	NLO, NNLO	NLO, NNLO
Heavy quark scheme	ACOT	S-ACOT	FONLL	ZM-VFN
Value of $\alpha_s(m_Z)$	0.118	0.118	0.118	0.118
Input scale Q_0	1.30 GeV	1.30 GeV	1.00 GeV	1.69 GeV
Data points	708	1811	1467 (451)	2336
Fixed Target DIS	✓	✓	✓(w/o ν-DIS)	✓
Fixed Target DY	✓	✓		
LHC DY and W		✓	✓(✗)	
Jet and had. prod.	(π^0 only)	(π^0, LHC dijet)		
Independent PDFs	6	6	3	6
Parametrisation	simple pol.	simple pol.	neural network	simple pol.
Free parameters	16	20	256 (178)	16
Statistical treatment	Hessian	Hessian	Monte Carlo	Hessian
Tolerance	$\Delta\chi^2 = 35$	$\Delta\chi^2 = 52$	—	$\Delta\chi^2 = 50$

JHEP **09** (2020) 183



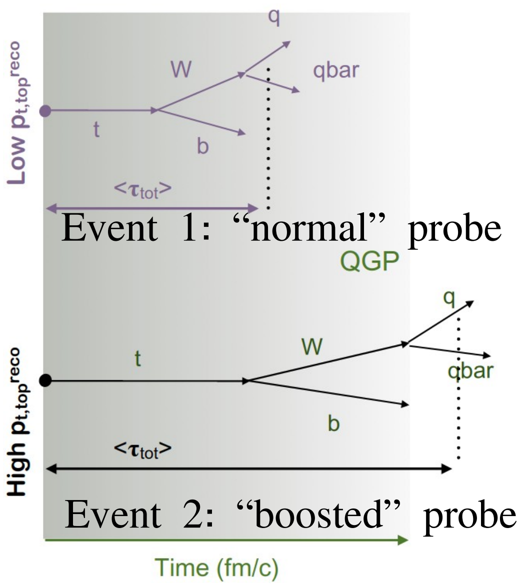
- nPDFs from **several** groups
  - less available data sets compared to the free-nucleon cases
  - different data sets (e.g., pPb LHC data), theoretical assumptions, and methodological settings
  - **not well** understood aspects, e.g., the nuclear modifications of the gluon distribution

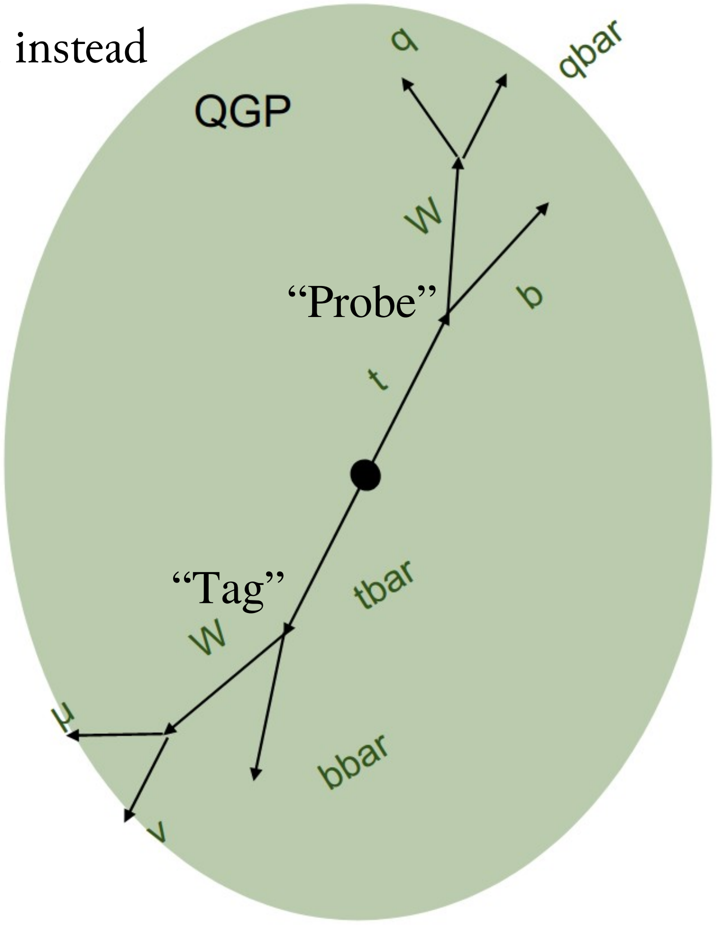
Probing the "final state": the yoctosec QGP lifetime

- Probes for jet quenching, e.g., dijets, Z/γ+jet, are produced **simultaneously** with the collision
- Top decay products have the potential to **resolve** the QGP evolution instead

Probing the "final state": the yoctosec QGP lifetime

- Probes for jet quenching, e.g., dijets, Z/γ+jet, are produced **simultaneously** with the collision
- Top decay products have the potential to **resolve** the QGP evolution instead
  - Leptonic & hadronic branches as "tag" & "probe"
    - qq' start interacting with the medium at **later** times
    - top p_T acts as the "trigger" on the onset of the interaction



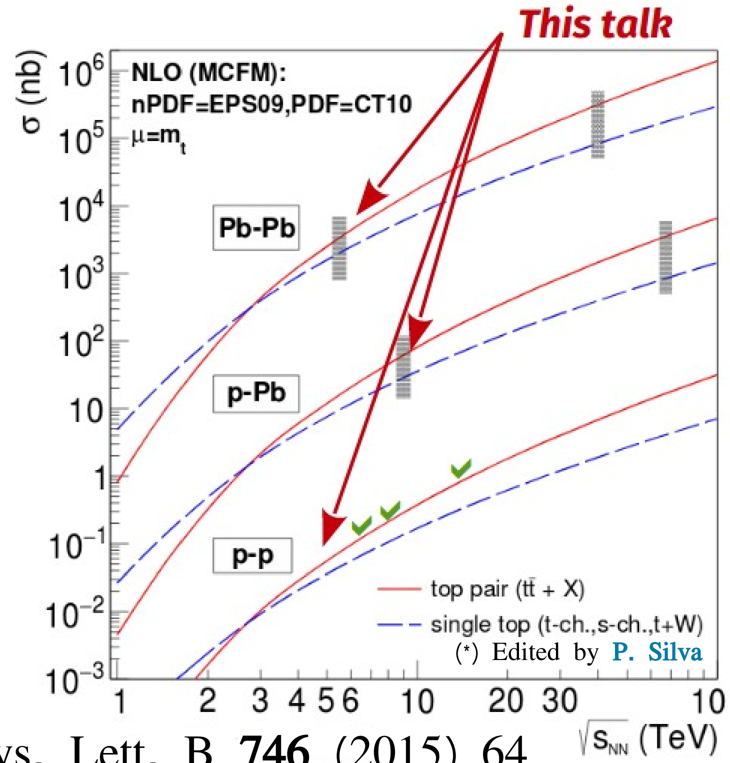


Theoretical expectations: from pp to PbPb

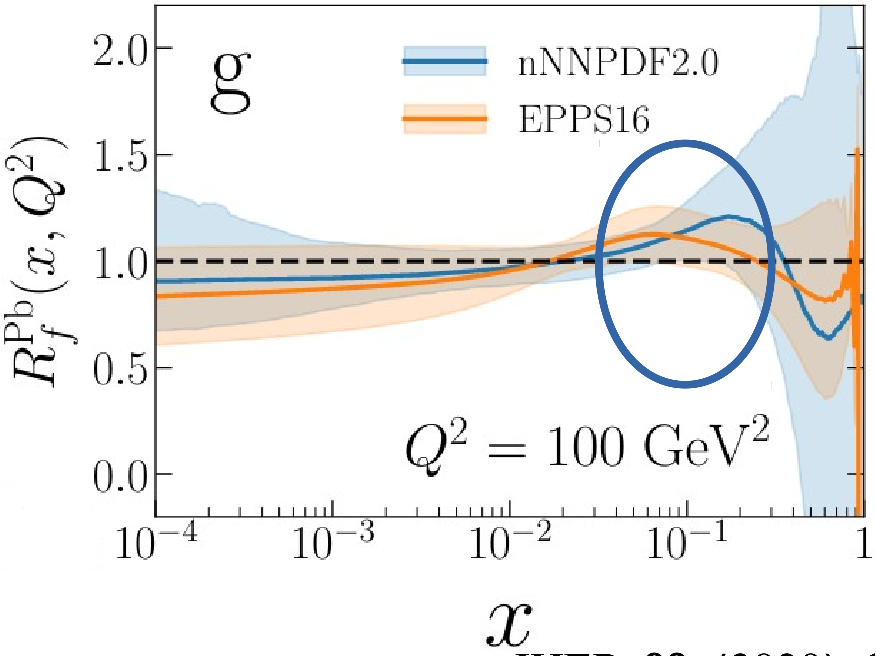
- $t\bar{t}$ pairs mostly produced through gg fusion at LHC
  - $\sigma_{t\bar{t}}$ **enhanced** by the atomic mass
  - a further (yet **mild**) increase relative to pp: region not well known

$$Q^2 \approx m_t^2 \approx 3 \cdot 10^4\ \mathrm{GeV}^2$$

$$x \approx 2m_t/\sqrt{s_{NN}} \approx 0.005 - 0.05$$



Phys. Lett. B **746** (2015) 64



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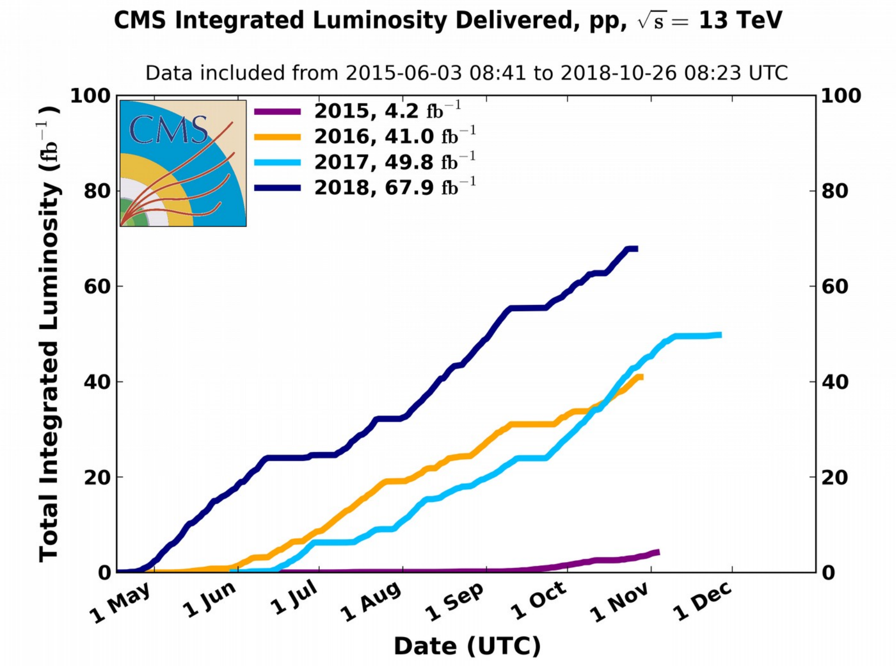
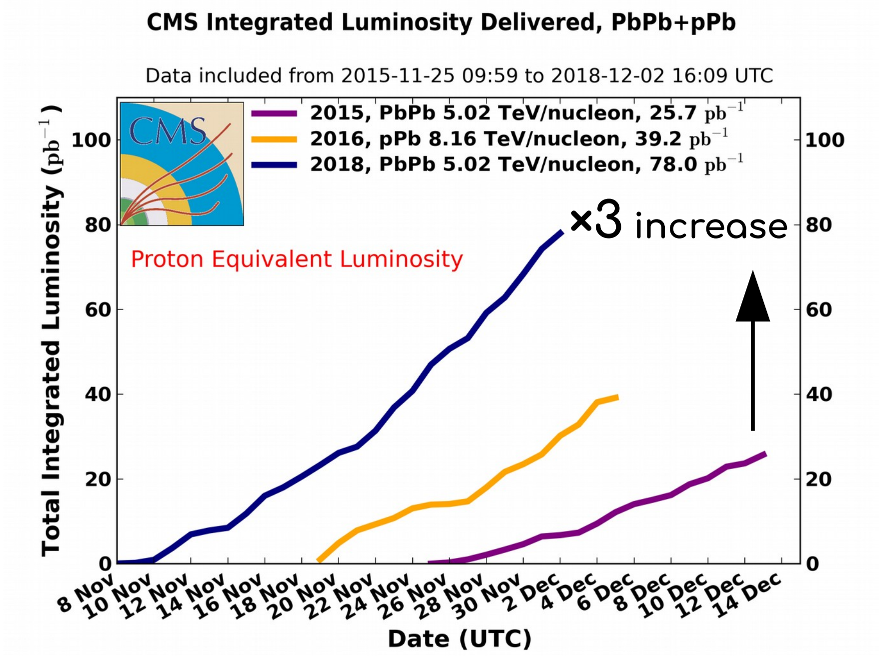
A lot of progress in the accelerator forefront!

proton-proton collisions (Run 2)



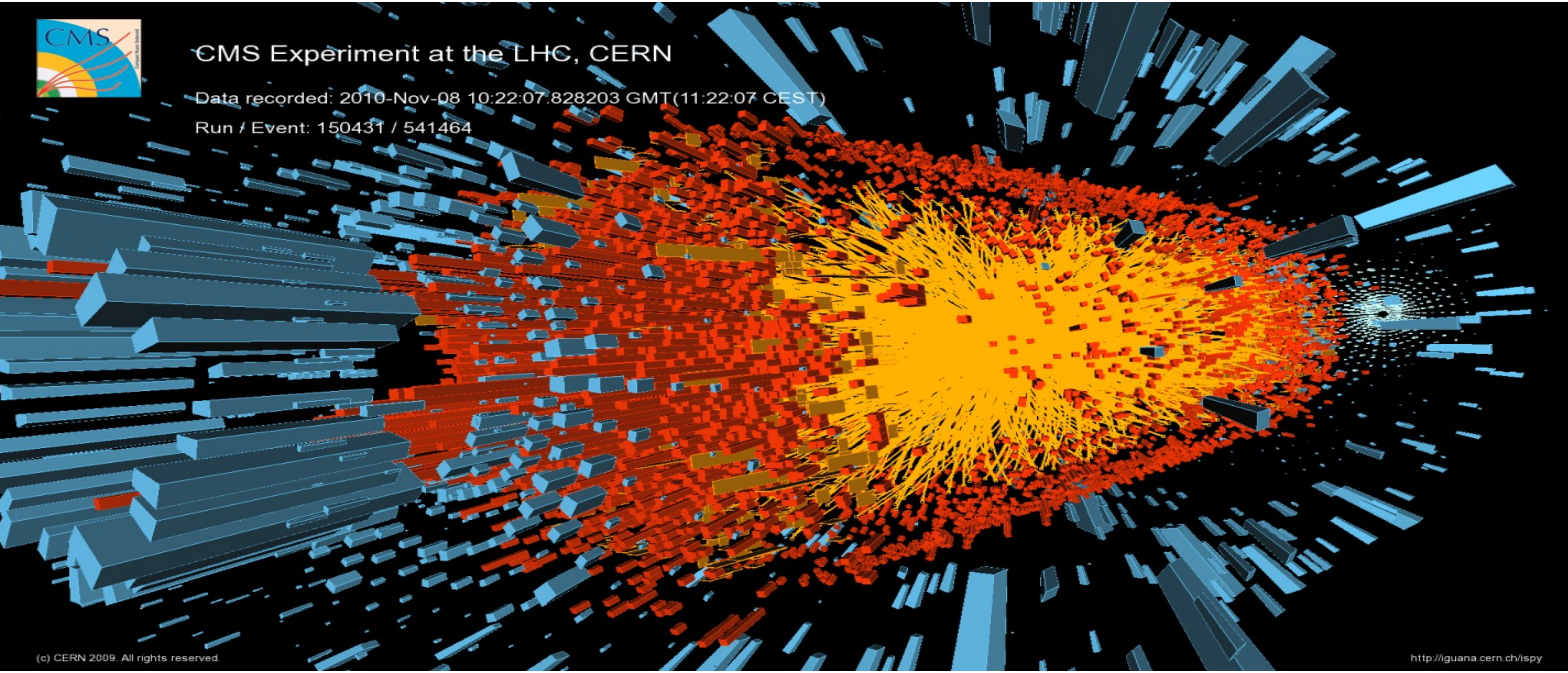
Nuclear collisions (Run 2)



- In 2018, the peak PbPb luminosity at IP1/5 reached ×6 the design without magnet quenches
  - We have about 2000 times **less** nuclear (pPb or PbPb) than pp data
  - Mainly due to acceleration limitations and running time: 4 months **vs** > 4 years!

That's a mess ツ

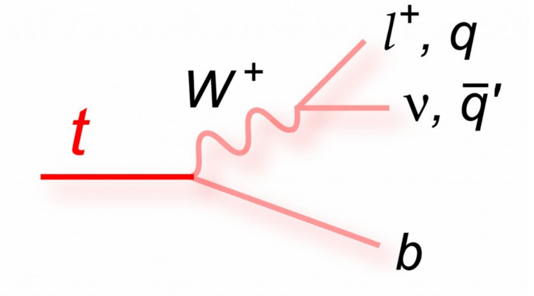
CMS-PHO-EVENTS-2010-002-51



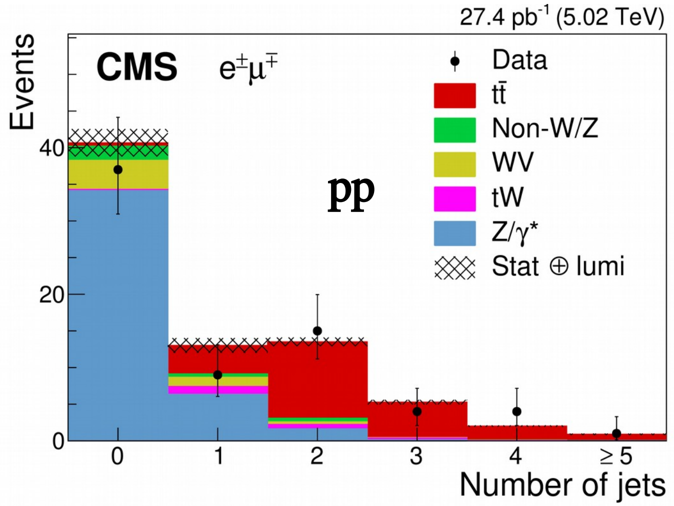
- We search for **distinct** event signatures, characteristic of particle production of some type

Measurement of $t\bar{t}$ cross section: general approach

- Choose the **cleanest** final states
  - (di)leptons +jets
- Define the "visible" phase space
  - Kinematic requirements on physics objects
  - Split in bins of (b) jet multiplicity
- Optimize analysis techniques
  - **MVA** for b tagging and signal extraction
  - data-based bkg estimation
  - using subset of the available data ("blind" approach)
- Perform likelihood fits to **distributions**
  - The cross section ($\sigma_{t\bar{t}}$) is extracted

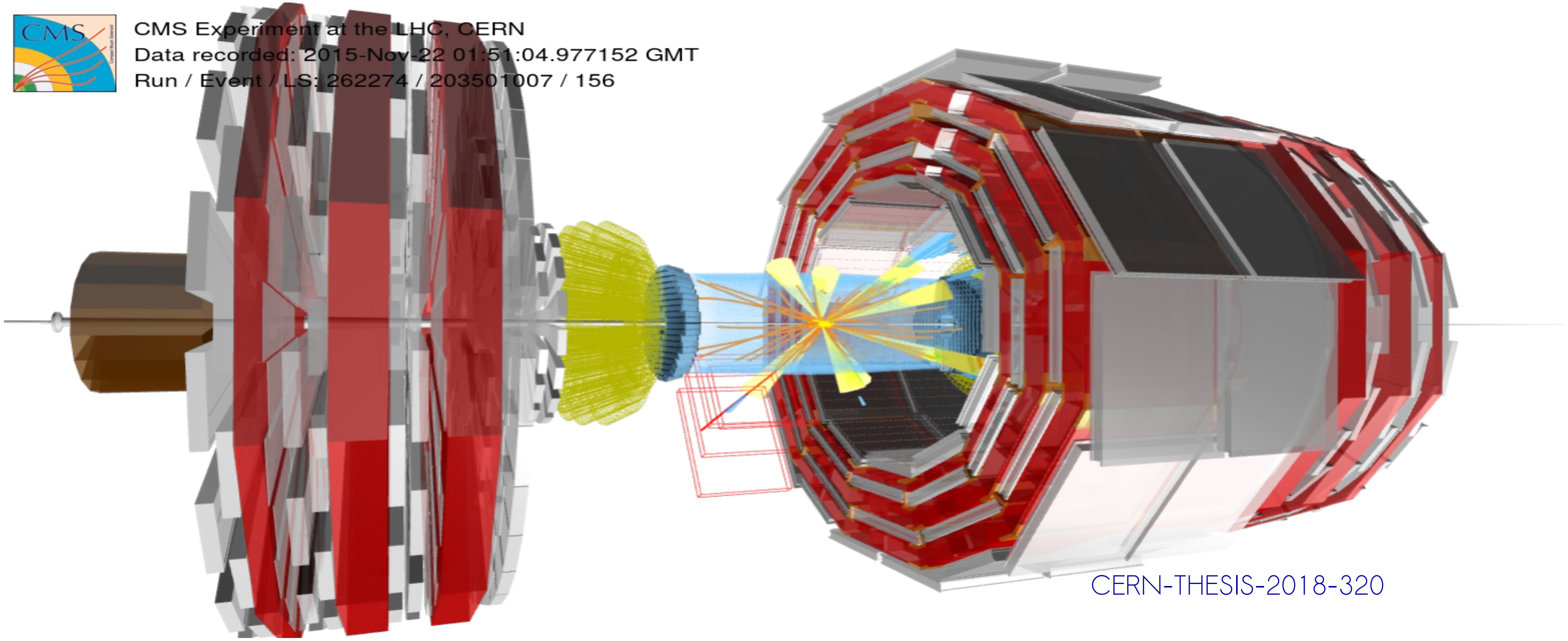


JHEP 03 (2018) 115



The "top in pp @ 5.02 TeV" measurement

A very clean signature in low-pileup conditions:
electron + muon + jets + missing energy

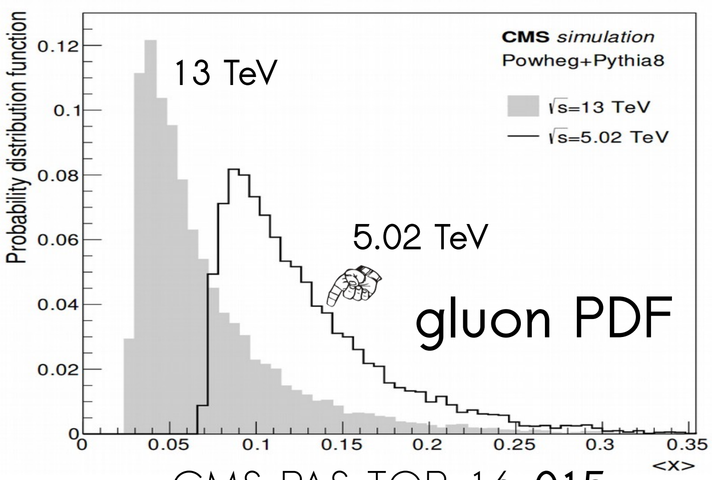


CERN-THESIS-2018-320

arXiv: 1711.03143
(JHEP **03** (2018) 115)

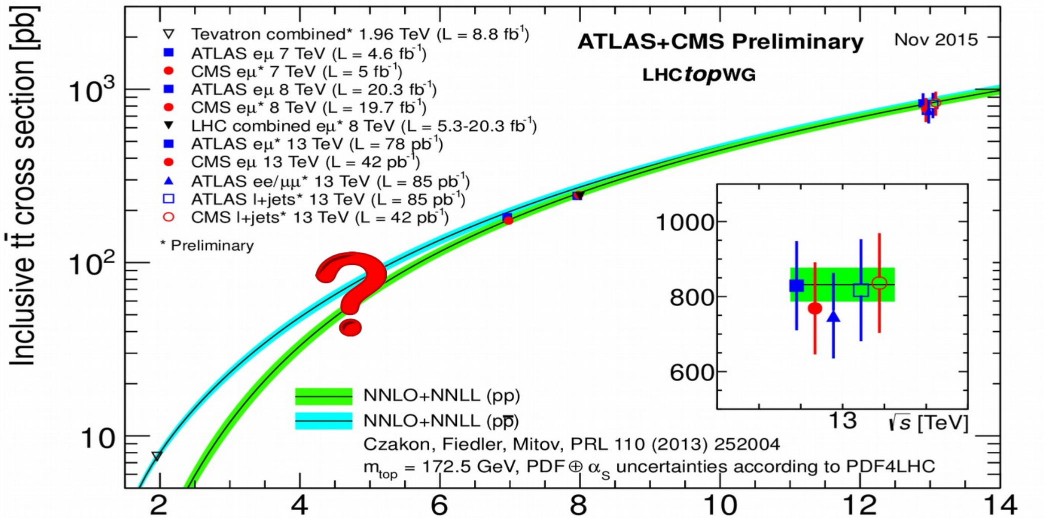
Why TOP @ 5.02 TeV? Any complementarity in place?

- Measurement of the $t\bar{t}$ cross section in pp @ 5.02 TeV
  - **tracks** the √s evolution of the theo expectation
    - at an interesting "corner"
  - **probes** the production of large-$\langle x \rangle$ gluons
    - check the impact on gluon PDF and its uncertainty
  - **paved** the way for the first study in nucleus-nucleus collisions
    - no need to extrapolate from different √s



CMS PAS TOP-16-015

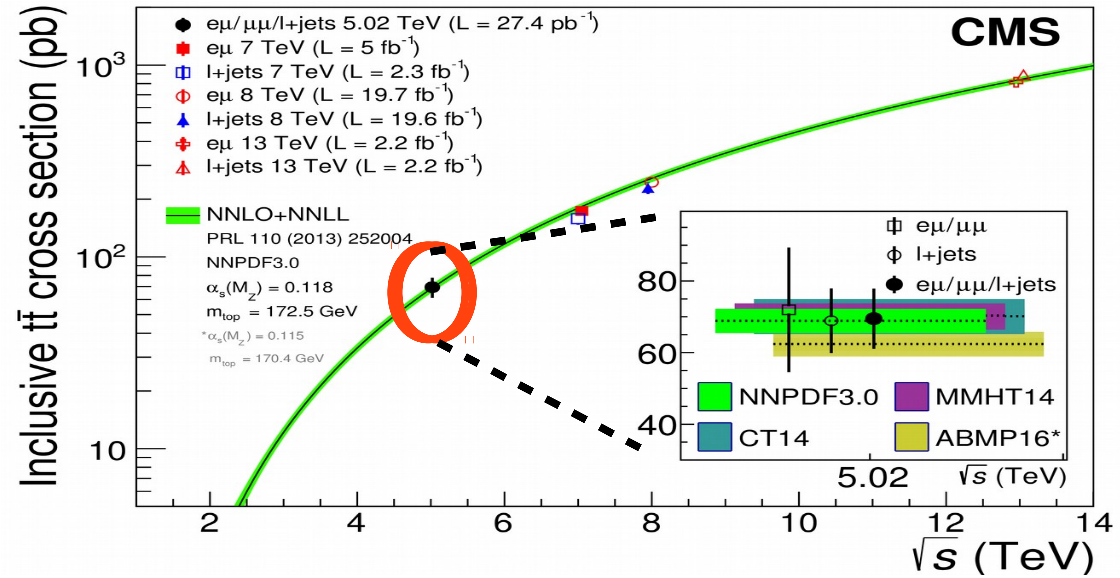
Nov 2015

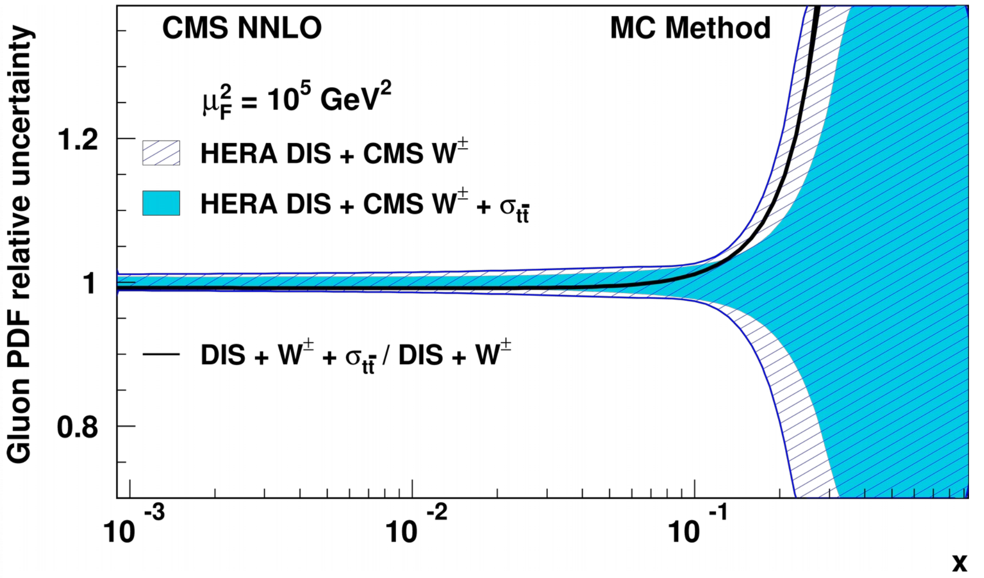


What is the attained precision?

- **First** measurement after which $t\bar{t}$ is established in **4** √s at LHC
  - using **independent** final states
    - total unc of **12%**
    - further **improvement** expected with the 2017 data set (**×**10 higher luminosity)
  - moderate **reduction** of the unc in the gluon PDF at high *x*

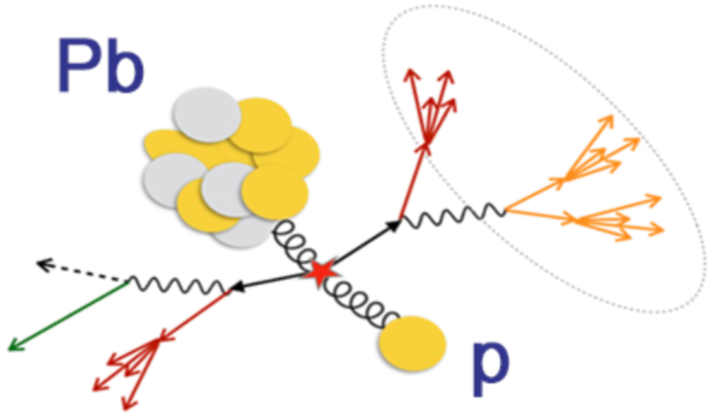
JHEP **03** (2018) 115



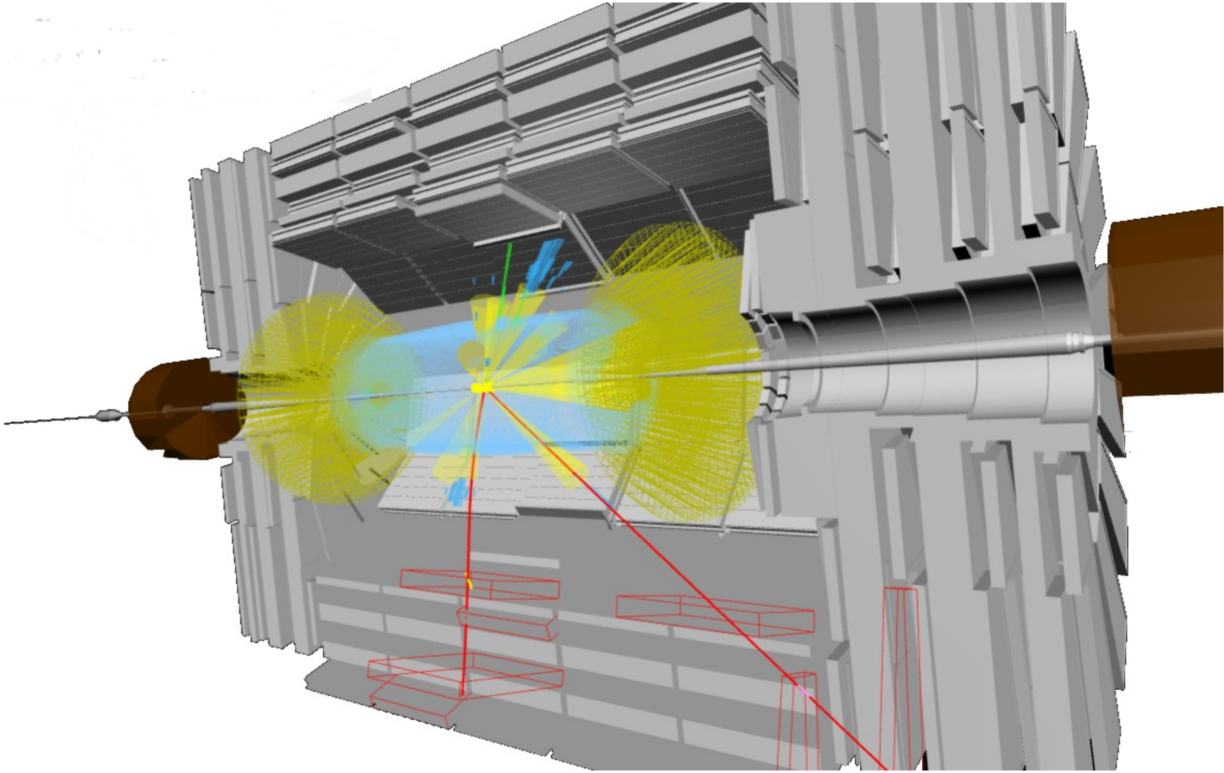


The discovery of “top in nuclear collisions”

Physics SYNOPSIS



Top Quark in Nuclear Collisions



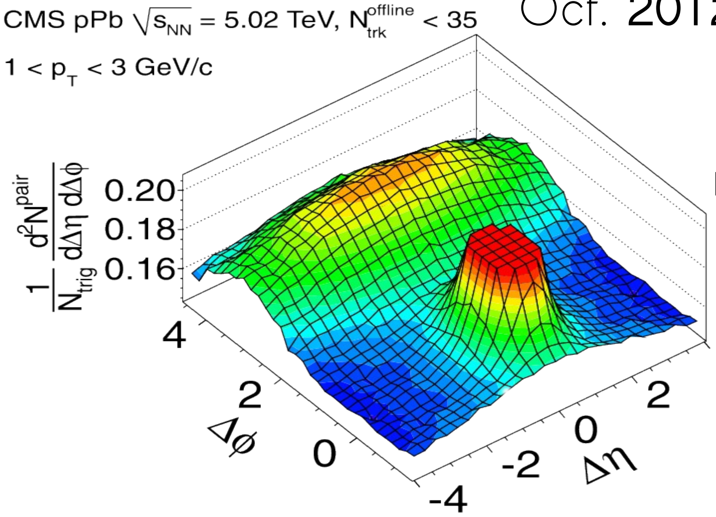
CERN-THESIS-2018-320

arXiv: 1709.07411
(Phys Rev Lett **119** (2017) 242001)

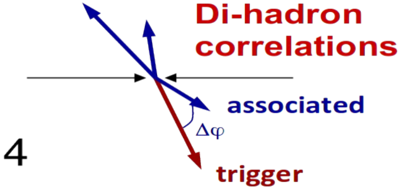
Throwing a bullet through an apple... Why?

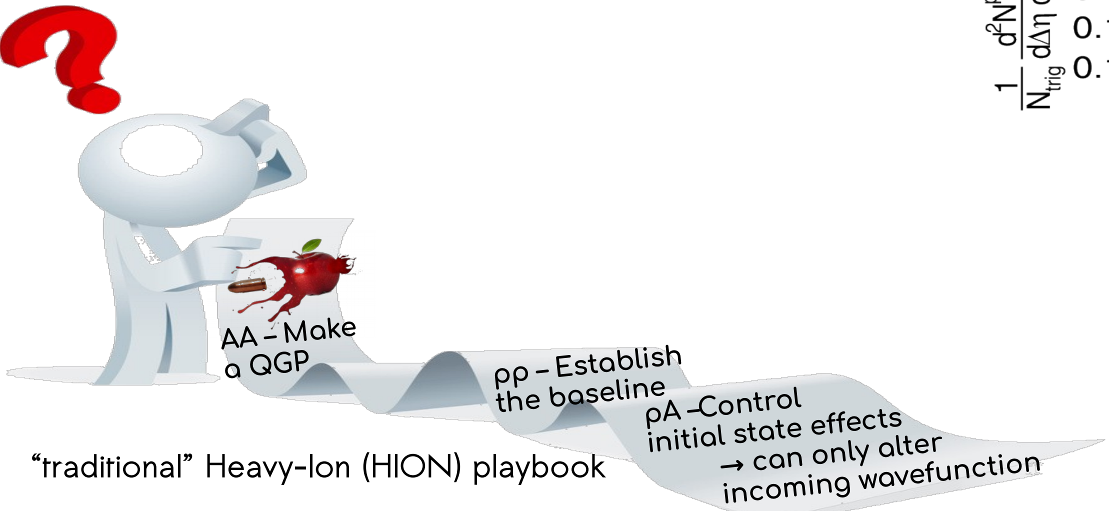
- Initially only thought to gain insight about **cold** QCD matter
  - The first collisions of unequal species @ LHC revealed **surprises**
    - signs **similar** to QGP formation
    - interest exploded (the 3rd most cited CMS paper in PLB!)

Oct. 2012



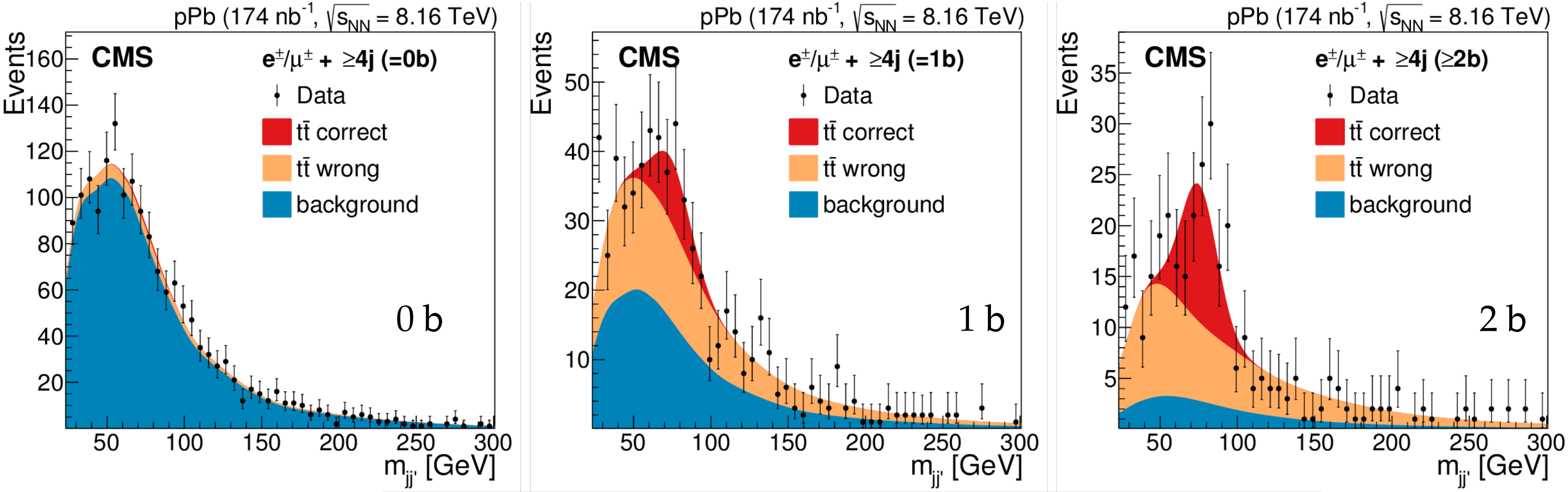
Phys. Lett. B 718 (2013) 795





The first search analysis for $t\bar{t}$ in nuclear collisions!

- Performed in the semileptonic final state with pPb data at 8.16 TeV
  - j,j' jets are paired based on their proximity in the (η,φ) space
    - to construct the variable of interest; here the $\mathbf{m_{jj'}}$ inv mass
  - **Combined** fit in bkg (0 b) and signal (1,2 b) enriched categories

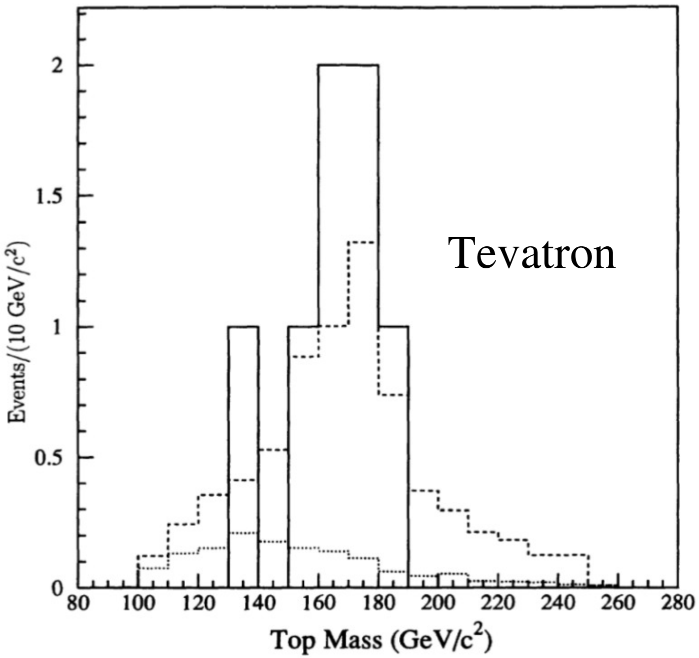


Background completely determined from data

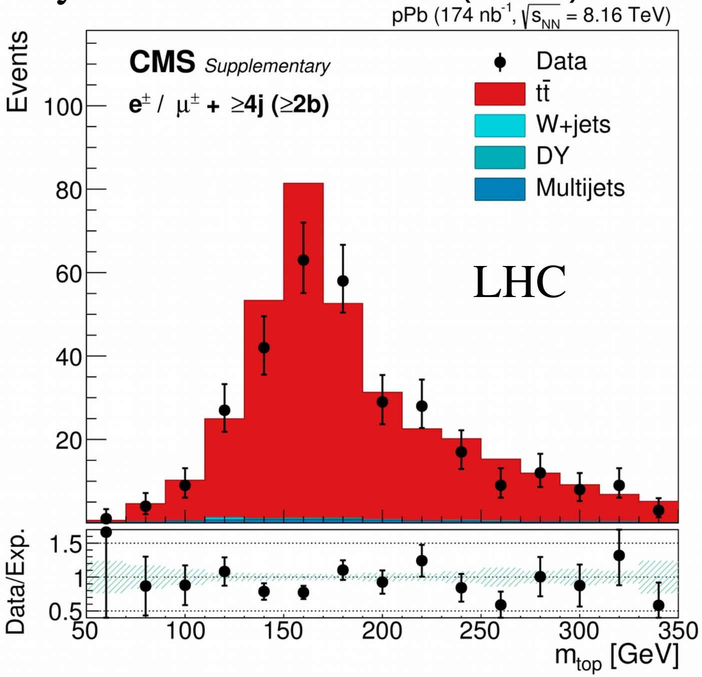
Even a peak is reconstructed close to top mass

- To further support the consistency with the production of top quarks
  - the inv mass of the **jj'b** triplet ("hadronic" top mass) is formed
    - events with ≥ 2 b jets: **background-free**

Phys. Rev. Lett. **73** (1994) 225



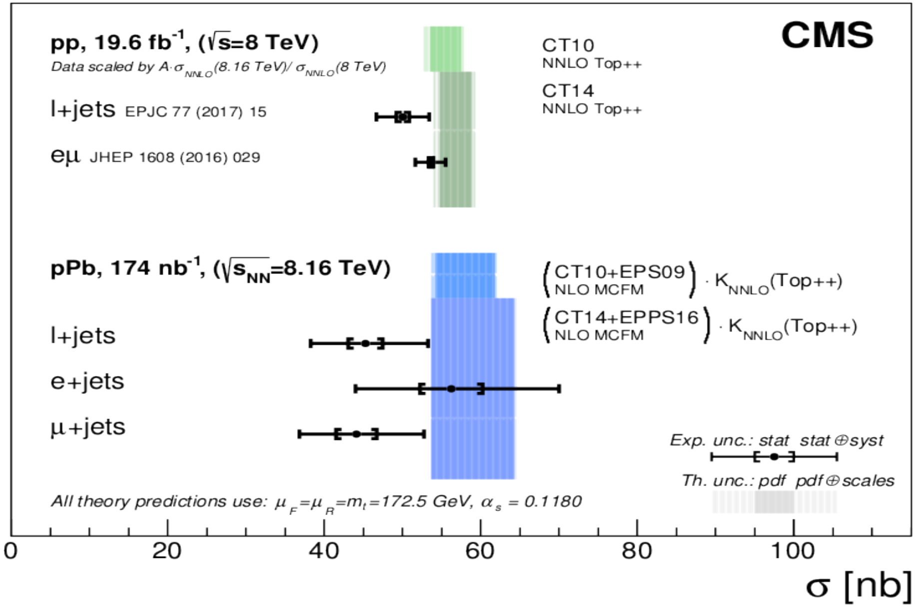
Phys. Rev. Lett. **119** (2017) 242001

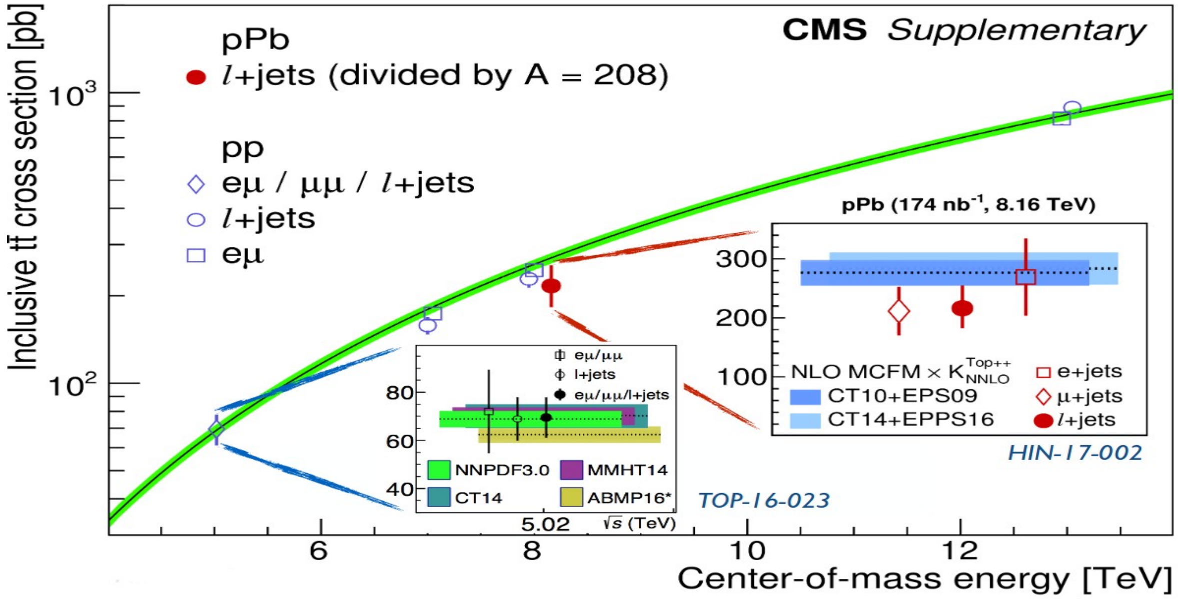


Observation of top quarks in pPb collisions

- First experimental **observation** of the top quark in nuclear collisions
  - $\sigma_{t\bar{t}}$ in **two** independent final states
    - $d\sigma_{t\bar{t}} / \sigma_{t\bar{t}} \approx 17\%$
    - **consistent** with pQCD calculations and scaled pp data
    - not yet sensitive to nPDF vs PDF differences

PRL **119** (2017) 242001

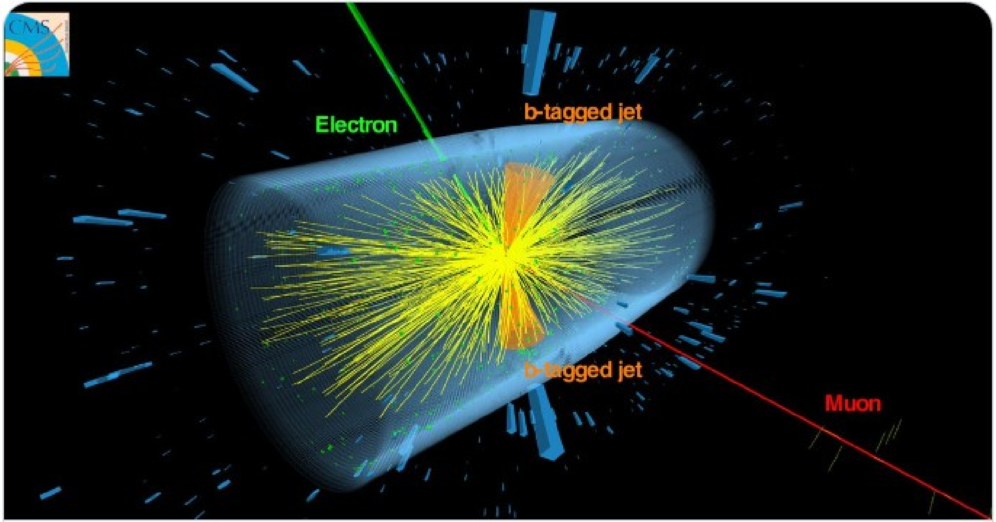




"Heavy metal hits the top"

CERN @CERN

This result from @CMSExperiment, opens the path to study in a new and unique way the extreme state of matter that is thought to have existed shortly after the #BigBang.



CMS sees evidence of top quarks in collisions between heavy nuclei

The CMS collaboration has seen evidence of top quarks in collisions between heavy nuclei at the Large Hadron Collider (LHC). This isn't the first time this ...

home.cern

CMS Experiment at CERN

October 9 at 9:08 AM

For the first time the CMS Collaboration demonstrates evidence that top quarks are produced in nucleus-nucleus collisions! Read more how the top quark interacts with the heavy metal 🎸💥🎸 of the lead-lead collisions in this CMS physics briefing: ➡️ https://cms.cern/news/heavy-metal-hits-top

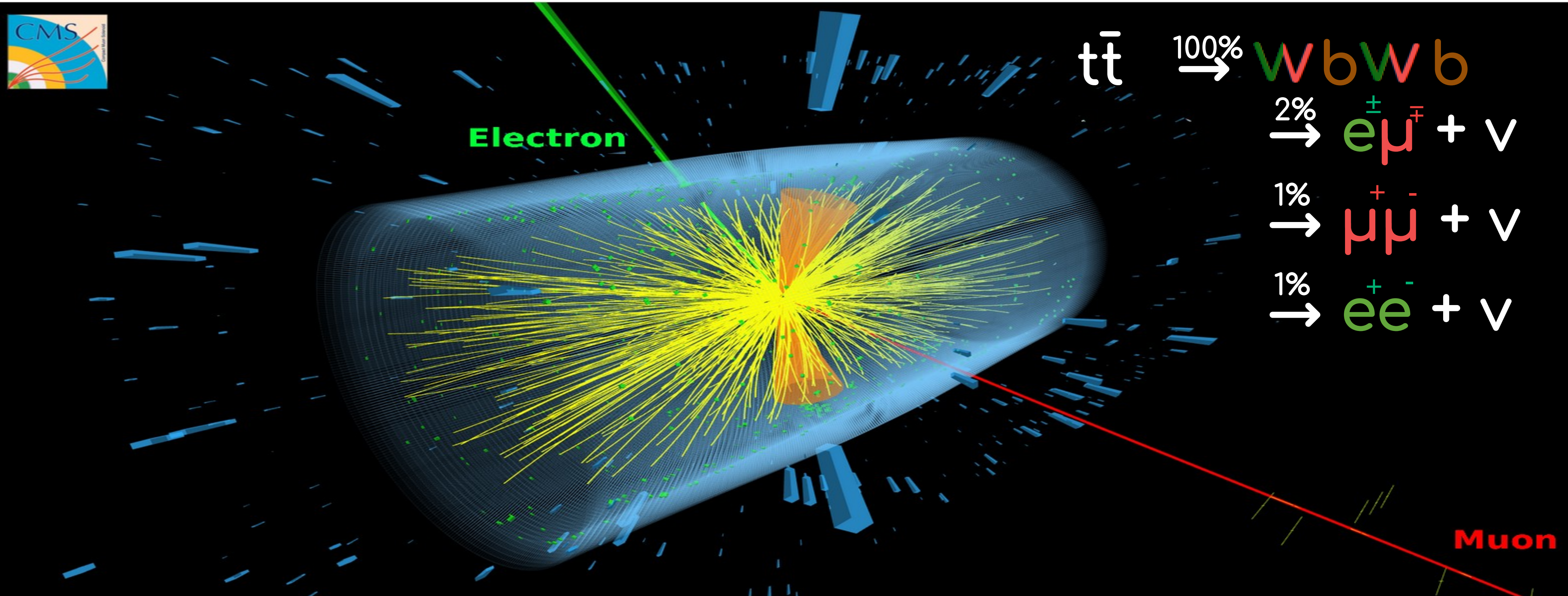
arXiv: 2006.11110
(Phys Rev Lett **125** (2020) 222001)

The first search for $t\bar{t}$ using PbPb collisions

- Dilepton final states have the best S/B but what about the **event count**?

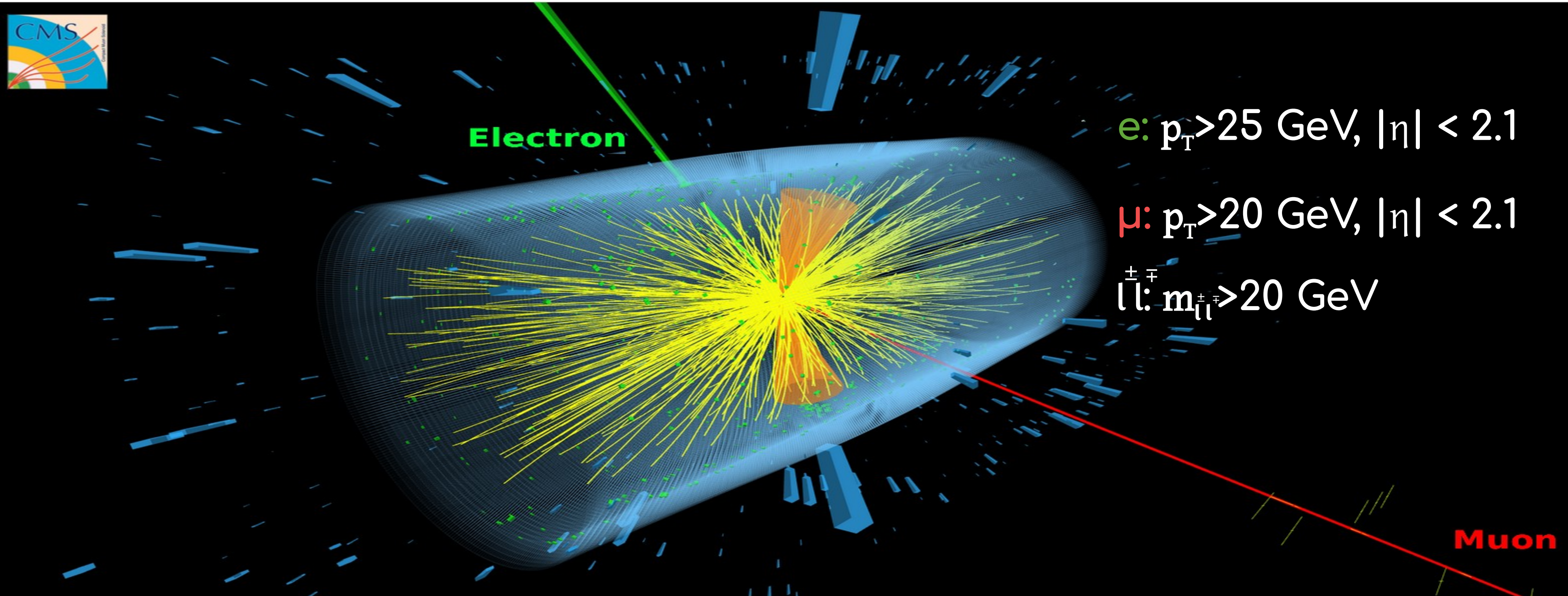
[Phys. Lett. B **746** (2015) 64]

  - perturbative QCD cross section (3.2 μb) × luminosity (1.7 /nb in 2018): $\mathcal{O}(100)$ candidate events
    - accounting for signal acceptance and detection efficiency



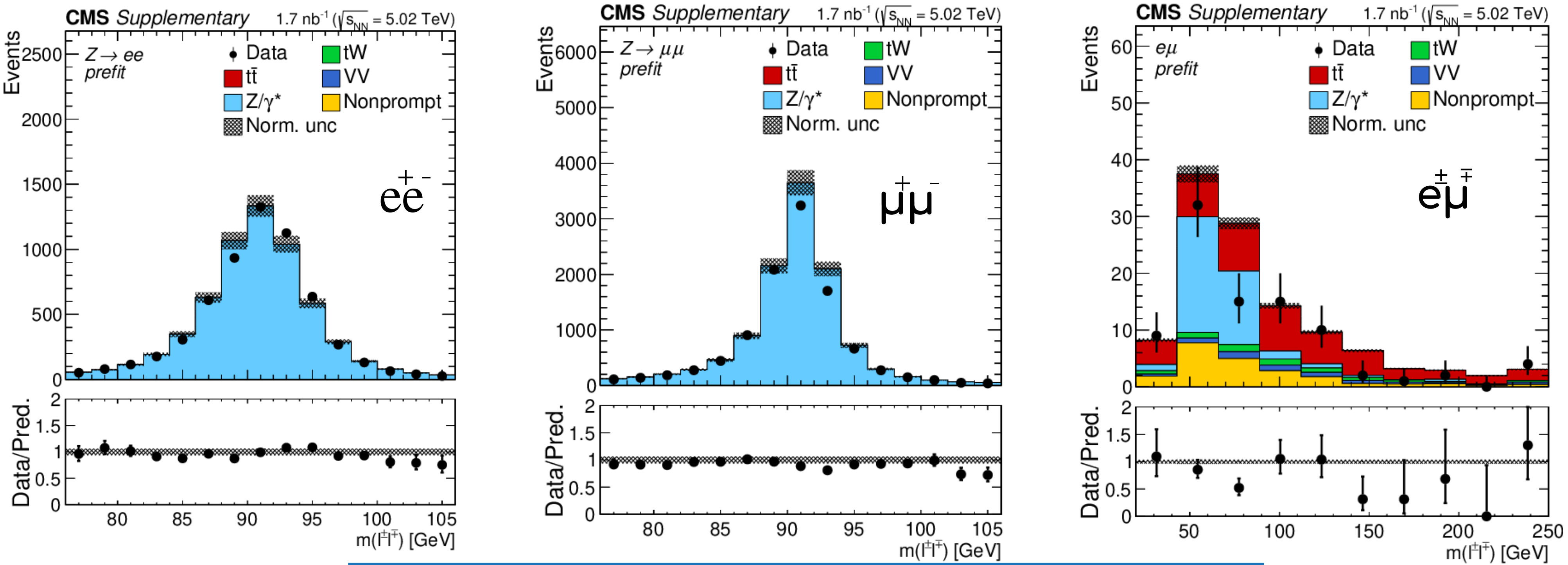
The first search for $t\bar{t}$ using PbPb collisions

- Dilepton final states have a **distinct event signature**
  - Leptons are of **high p_T**, **isolated**, and **opposite charge**
  - Main background from prompt (e.g., Z/γ^*) or nonprompt leptons



The signal and bkg modeling

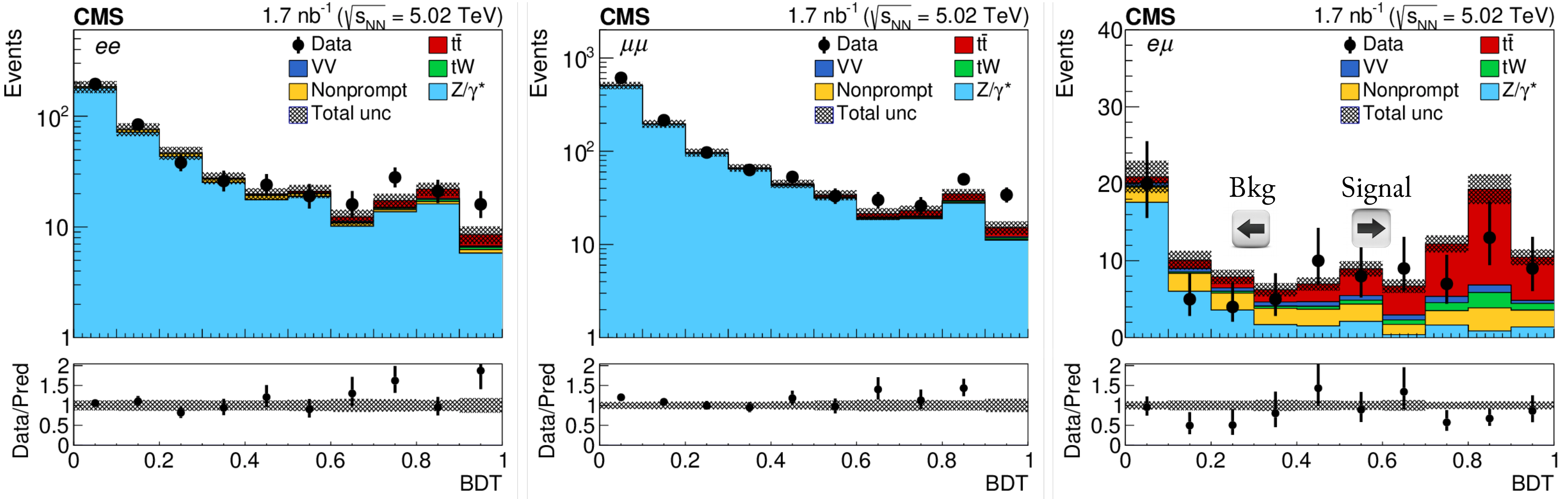
- NN (N=p,n) → $t\bar{t}$, bkg processes at **next-to-leading order** (NLO) in pQCD
  - EPPS16 nPDFs, "embedded" to HYDJET
  - Nonprompt (e.g., QCD multijet, W+jets) bkg from event mixing



The predictions are scaled to luminosity!

Optimizing the $t\bar{t}$ extraction with lepton-only MVA

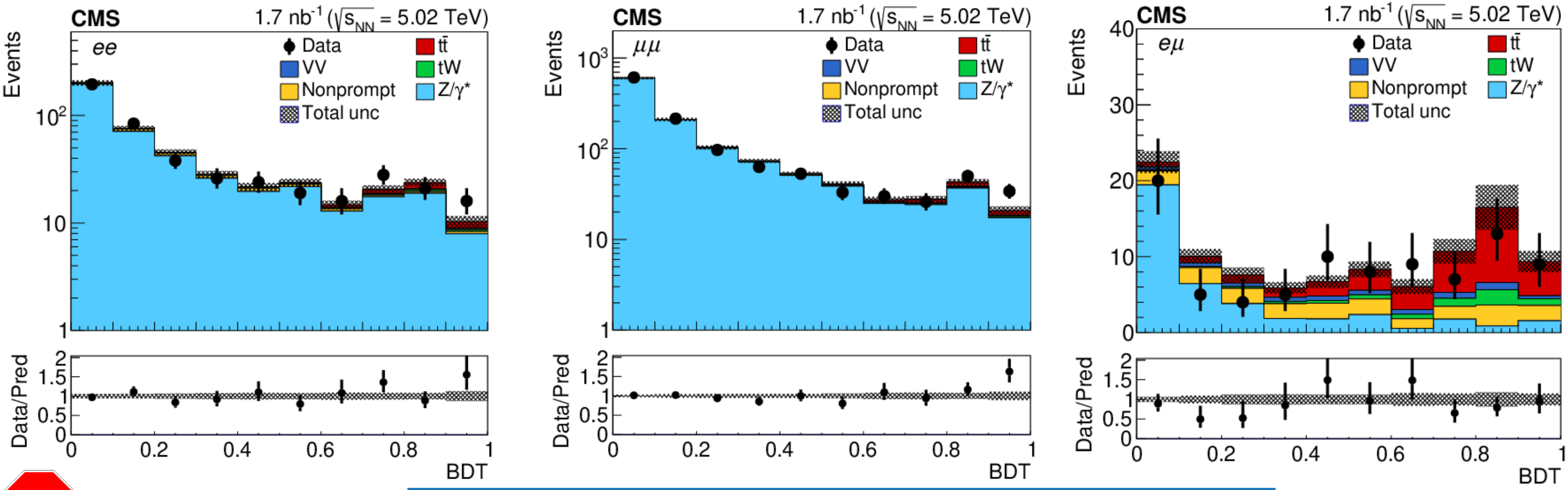
- Boosted Decision Trees (BDTs): kinematics from the two leading-p_T leptons
  - **Easy** to calibrate and **robust** against QGP effects
- Bkg and $t\bar{t}$ signal populate low- and high-BDT scores, respectively



Prefit

The cross-flavor final state the most sensitive, as expected!

- The cross section is measured **2.54** ± **0.69** (stat) ± **0.43** (exp) ± **0.13** (theo) μb
  - The statistical uncertainty is dominant
- Total number of signal events from all three final states: **43**
  - compatible with that we initially expected

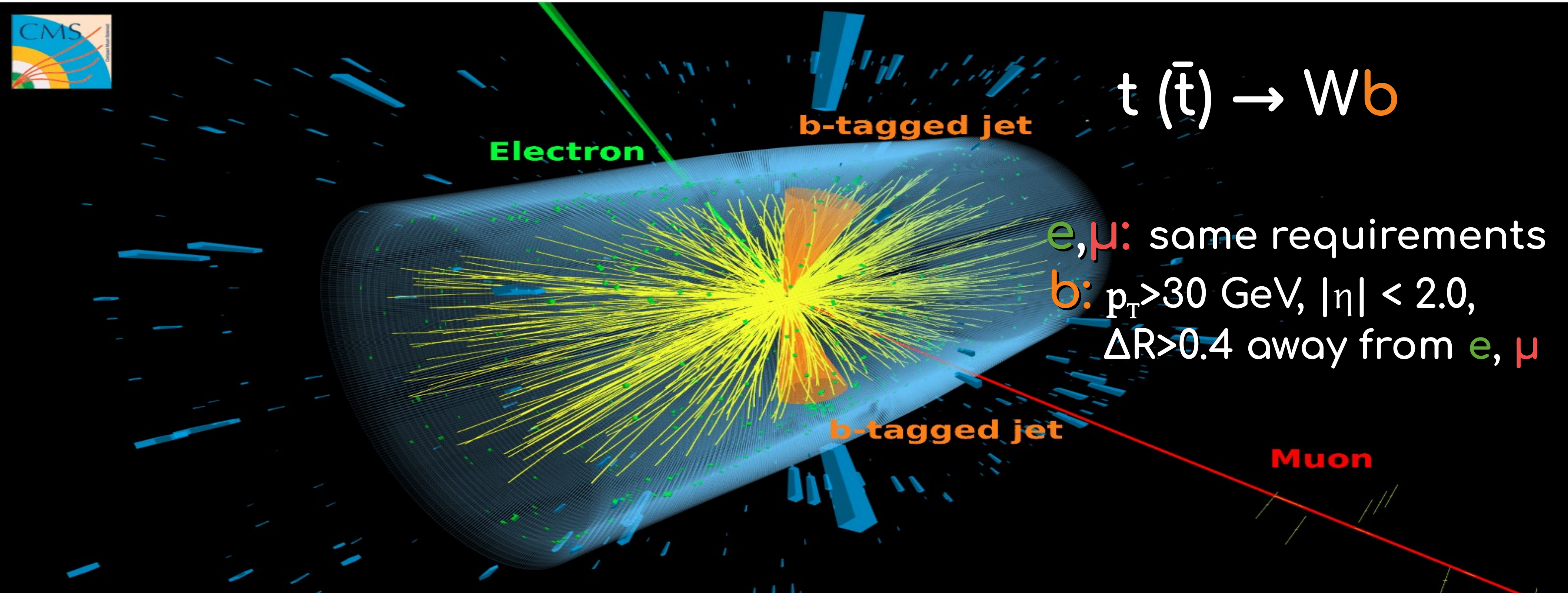


Postfit

The first evidence of top quarks in PbPb!

Including the information from jets

- **Enriching** the final-state topology with the **b jet** info: phase space regions with different signal purity
  - Jets (anti-k_T, 0.4) are also of **high p_T** with falling η distribution
    - An optimized algorithm successfully tags 60–70% of the b jets



$t\ (\bar{t}) \rightarrow Wb$

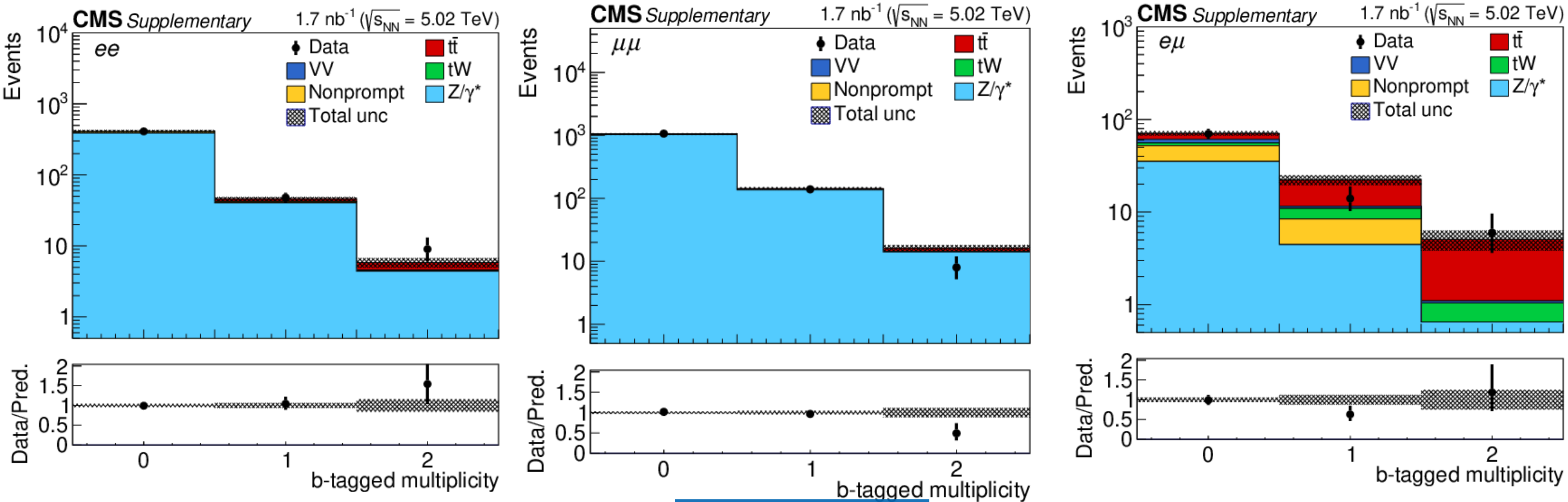
e,μ: same requirements

b: p_T>30 GeV, |η| < 2.0,
ΔR>0.4 away from e, μ

The signal and bkg b jet multiplicity

- We count the number of events in the three final states with 0, 1, and 2 b-tagged jets
  - selecting the jets with the **highest** b tagging score
- Additional systematic uncertainties well under control
  - Experimental (b-tagging efficiency, JES/JER) ⊕ jet quenching parametrization uncertainty in signal

[Phys. Rev. Lett. **119** (2017) 062302]



Z/γ* from data

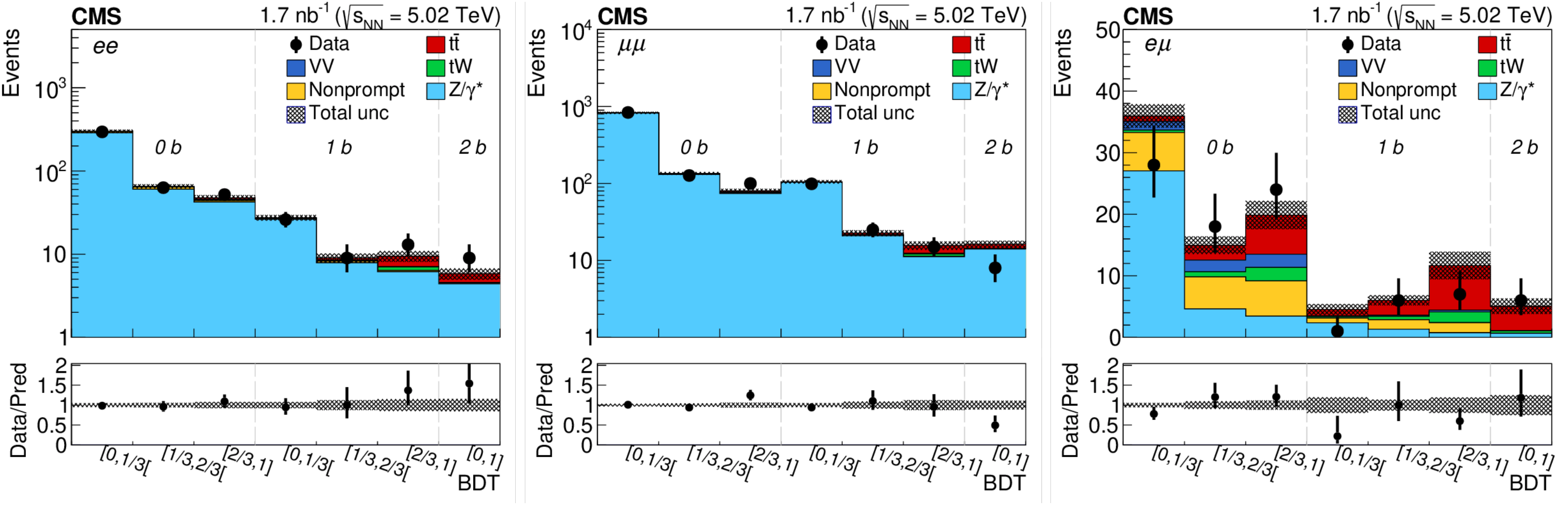
Measuring the $t\bar{t}$ cross section with leptons+b-tags

- We extracted $\sigma_{t\bar{t}}$ with a **similar precision** relative to the lepton-only measurement

$\mathfrak{L}$ =1.7±0.1 /nb

$\sigma_{t\bar{t}}$ = 2.03 ± 0.68 μb

$d\sigma_{t\bar{t}} / \sigma_{t\bar{t}} \approx 33\,\%$



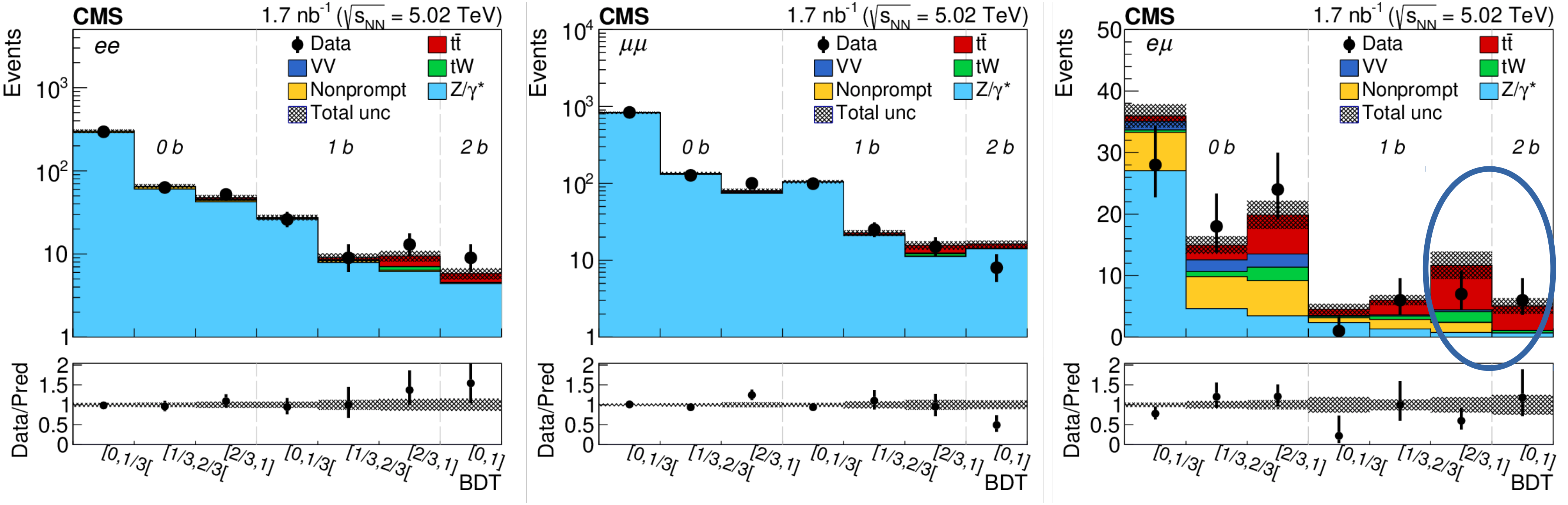
Measuring the $t\bar{t}$ cross section with leptons+b-tags

- We extracted $\sigma_{t\bar{t}}$ with a **similar precision** relative to the lepton-only measurement
- b tagging is a powerful tool to flag $t\bar{t}$ production
  - $t\bar{t}$ provides a **pure** sample of b jets throughout the QGP evolution

$\mathfrak{L}$ =1.7±0.1 /nb

$\sigma_{t\bar{t}} = 2.03 \pm 0.68\ \mu b$

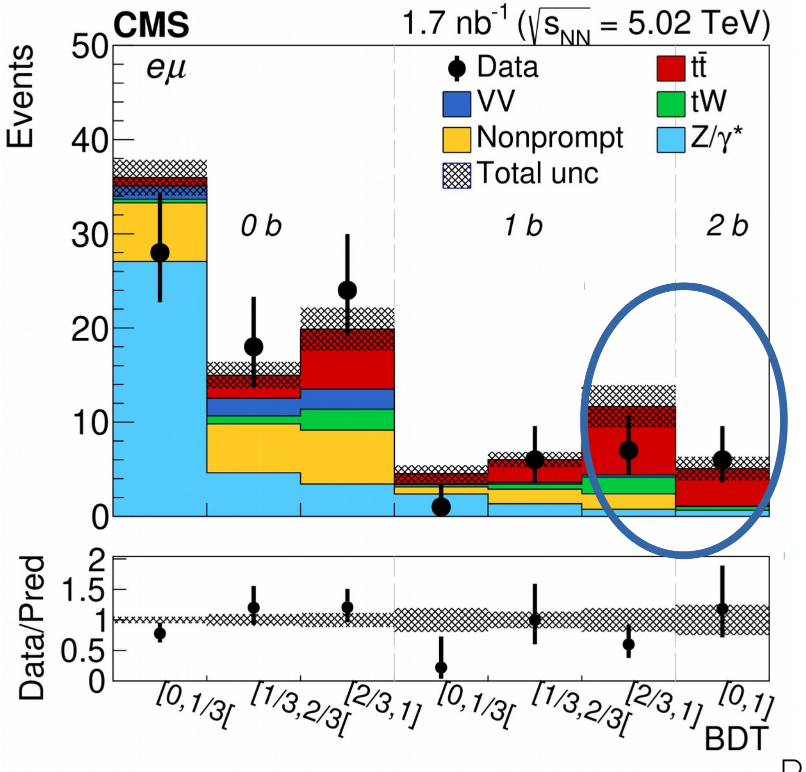
$d\sigma_{t\bar{t}} / \sigma_{t\bar{t}} \approx 33\ \%$

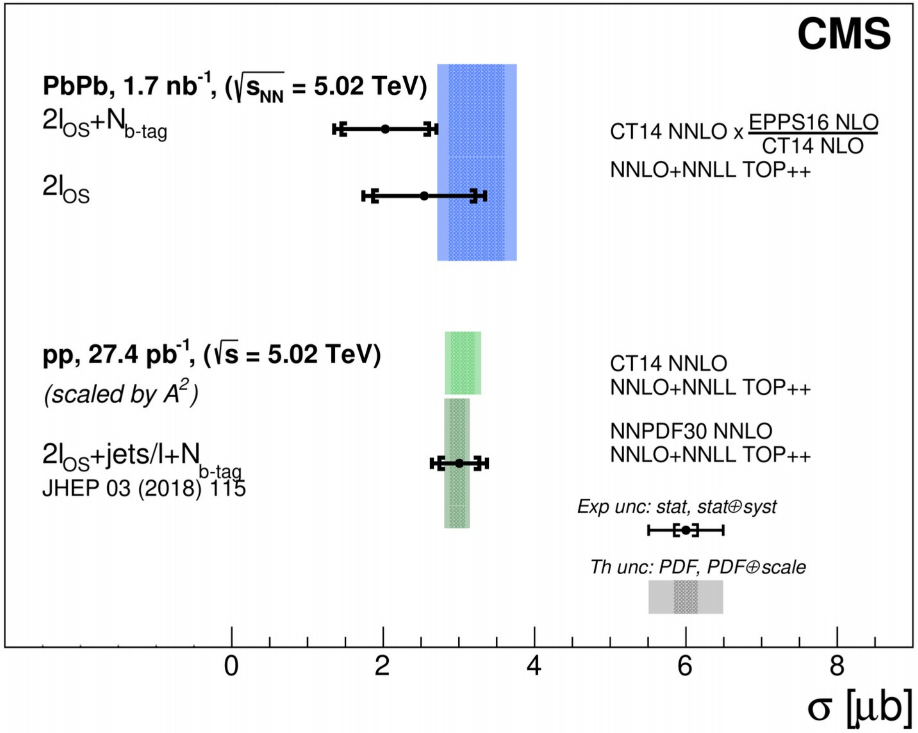


Evidence of top quarks in PbPb collisions

U.S. DEPARTMENT OF ENERGY | Office of Science

- Experimental evidence of the top quark in **nucleus-nucleus** collisions
  - using dileptons only or dileptons+b jets
- First step in establishing a **new tool** for probing nPDFs as well as the QGP properties

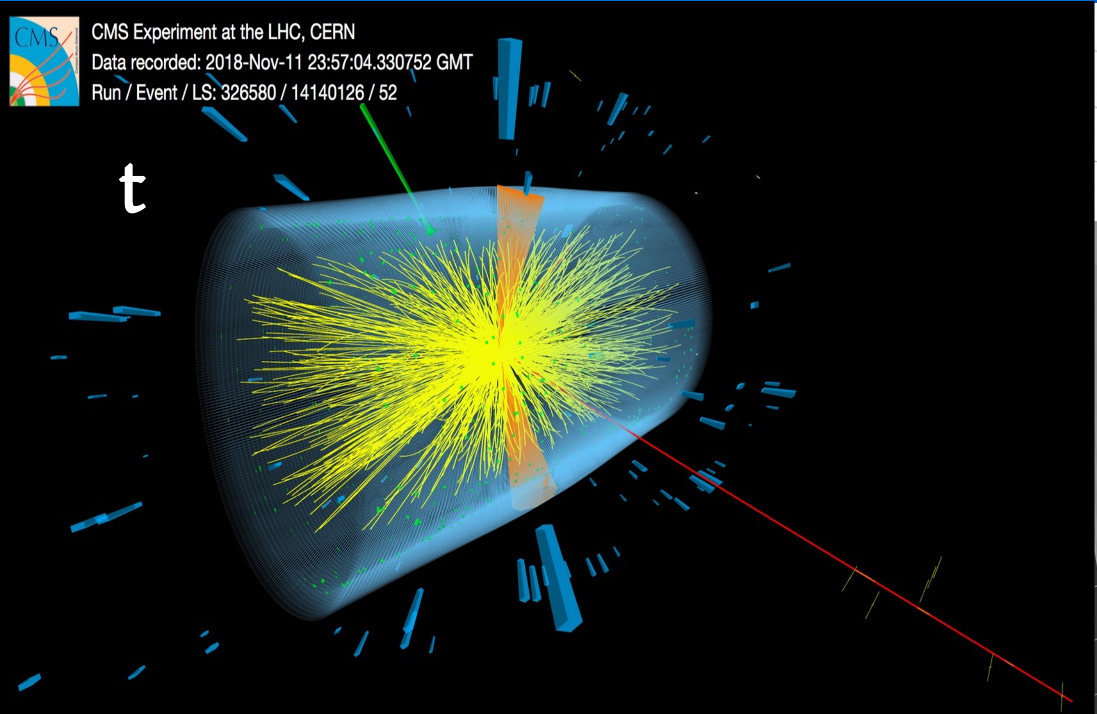


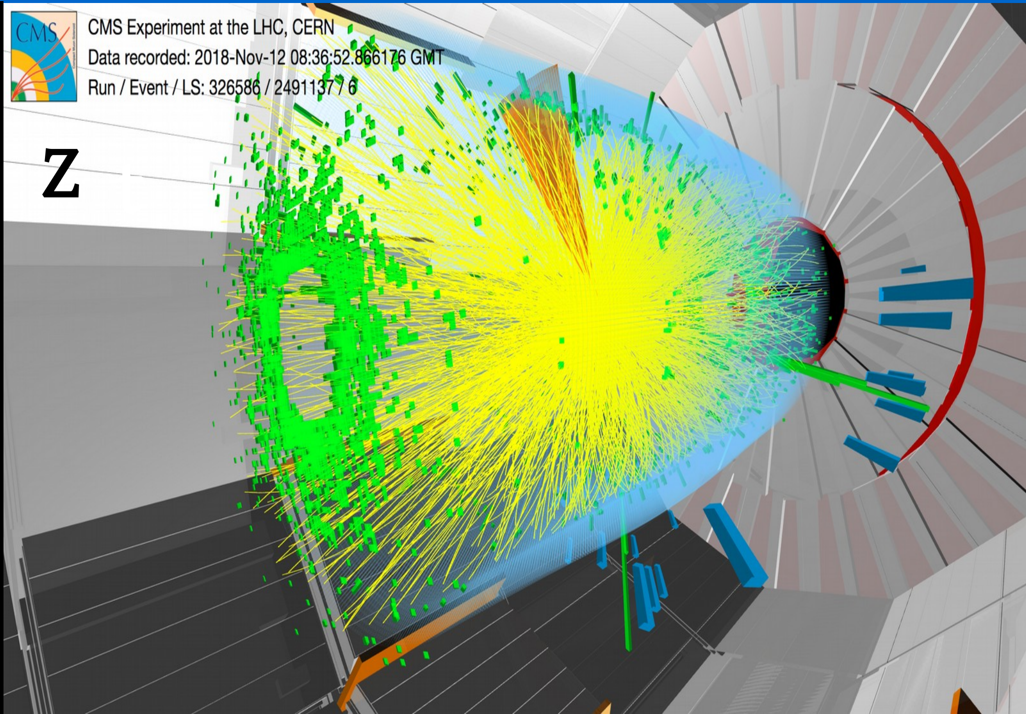


PRL **125** (2020) 222001

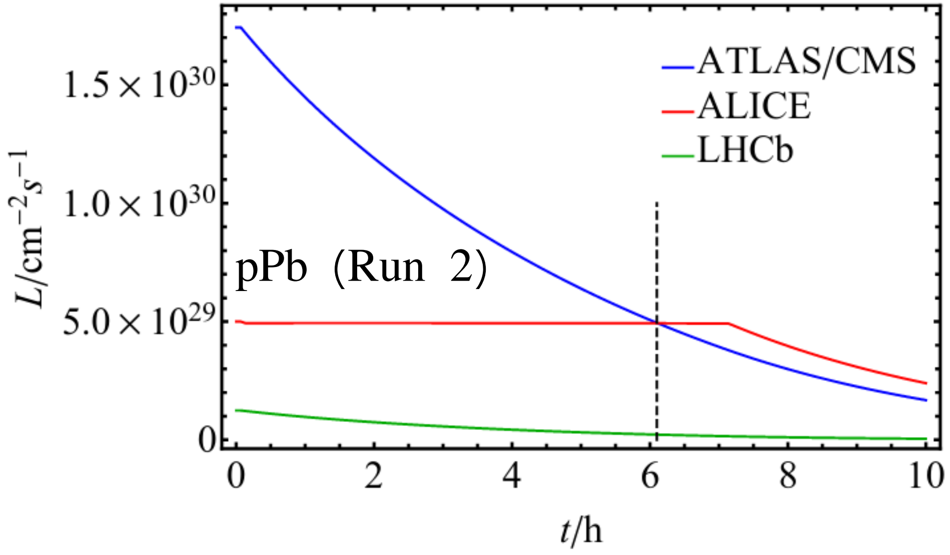
Future physics opportunities with W and Z bosons and top quarks for high-density QCD at LHC

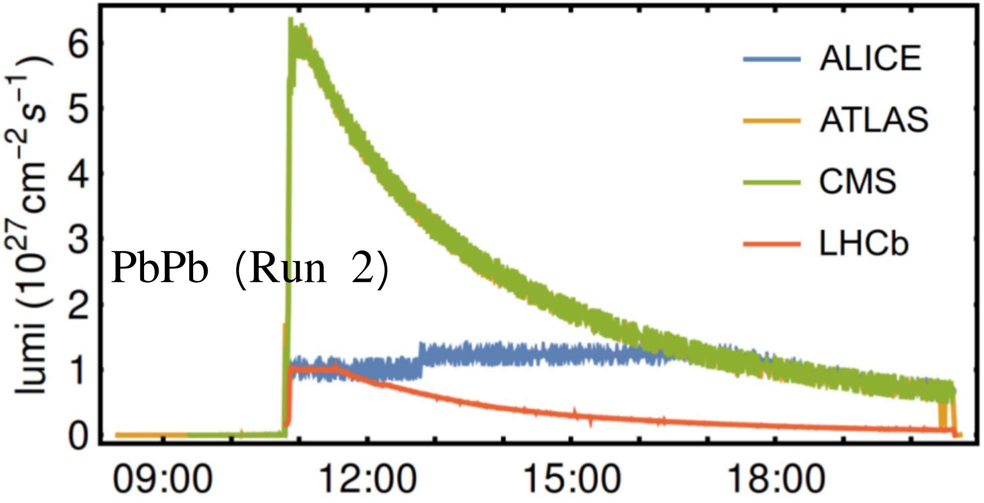
arXiv: 1812.06772





HL-LHC operational scenarios for pPb and PbPb

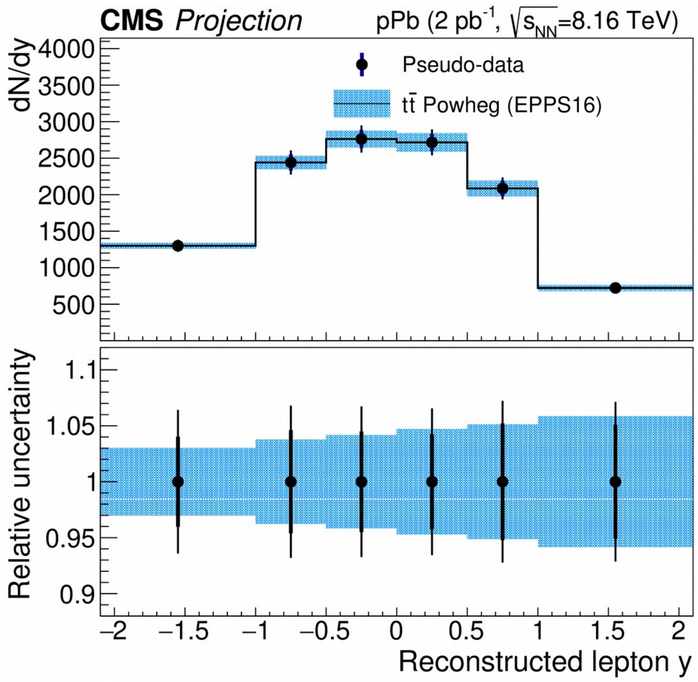


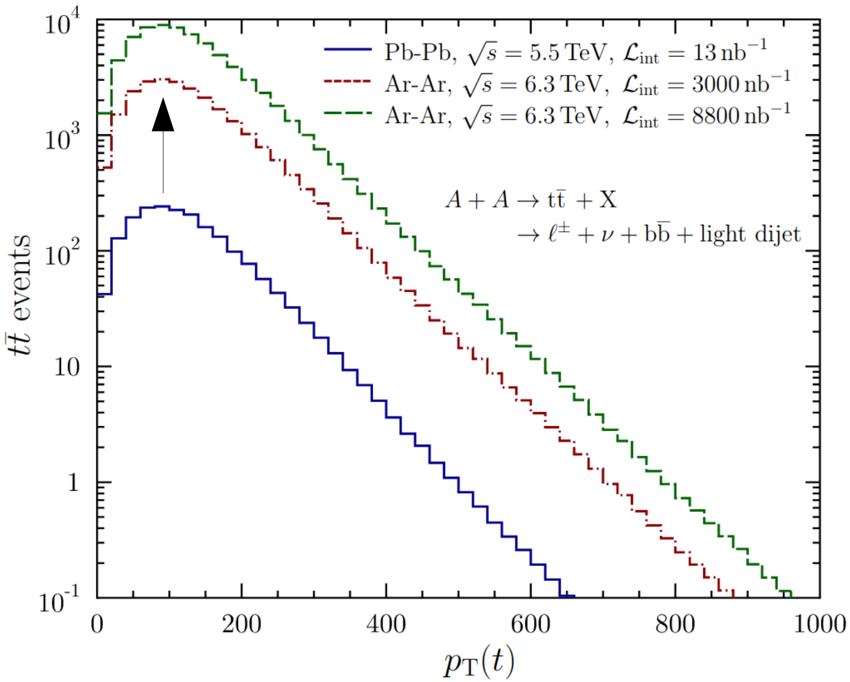


- Included in the YR and recently refined (CERN-ACC-2020-0011)
  - scenarios are based on **benchmarked** models (actually agree remarkaly well with Run 2 LHC data)
  - ≈**five** one-month runs would be needed to reach 13 /nb of PbPb
  - ≈**two** one-month runs would be needed to reach 1.2 /pb of pPb
  - projections could be improved, e.g., due to operational efficiency (>50%), etc

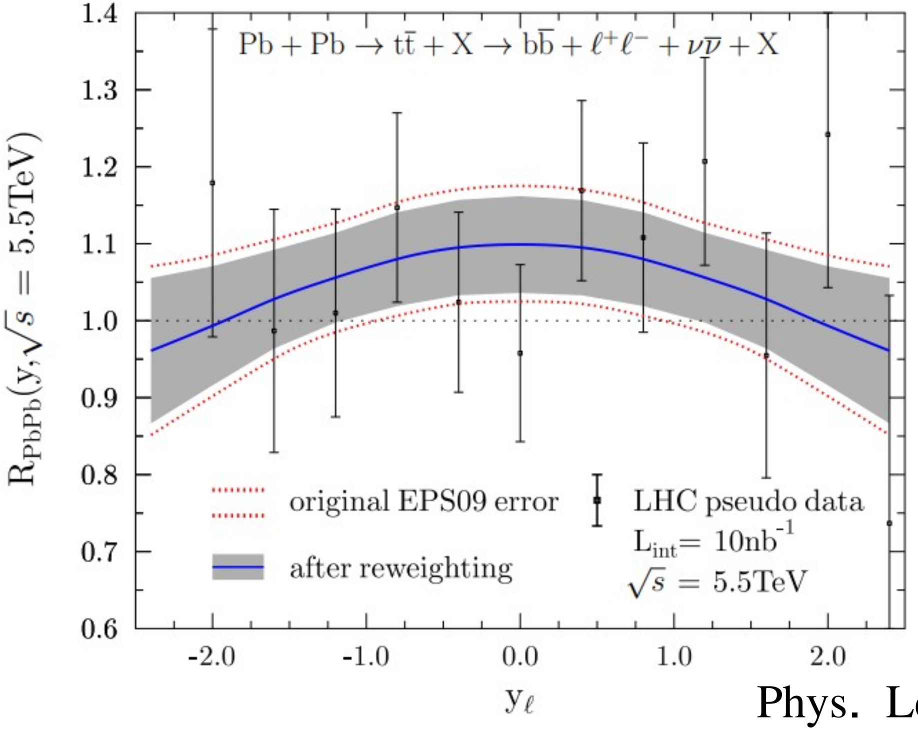
Prospects for top quark production at pA HL-LHC

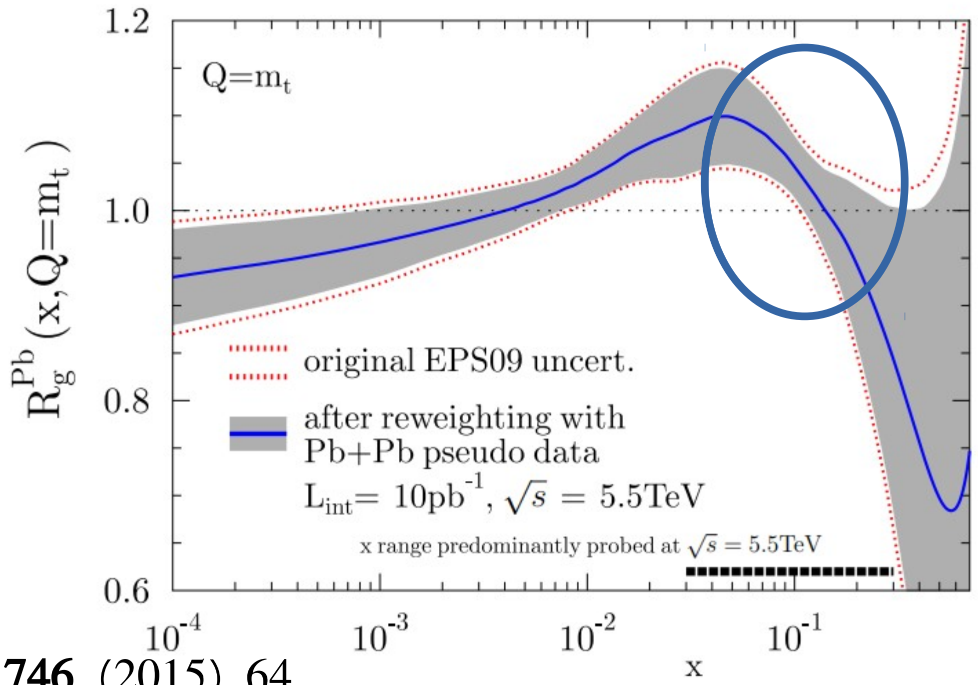
- The y of the decay leptons sensitive probe of the nuclear gluon density
  - **comparable** experimental and nPDF uncertainty with the pPb data set in Runs 3–4
    - depending on the expected systematic error and bin-by-bin correlations
  - to showcase **another potential**: In a pAr mode, the higher √s + lumonsity → increased $t\bar{t}$ yield





Prospects for top quark production at AA HL-LHC



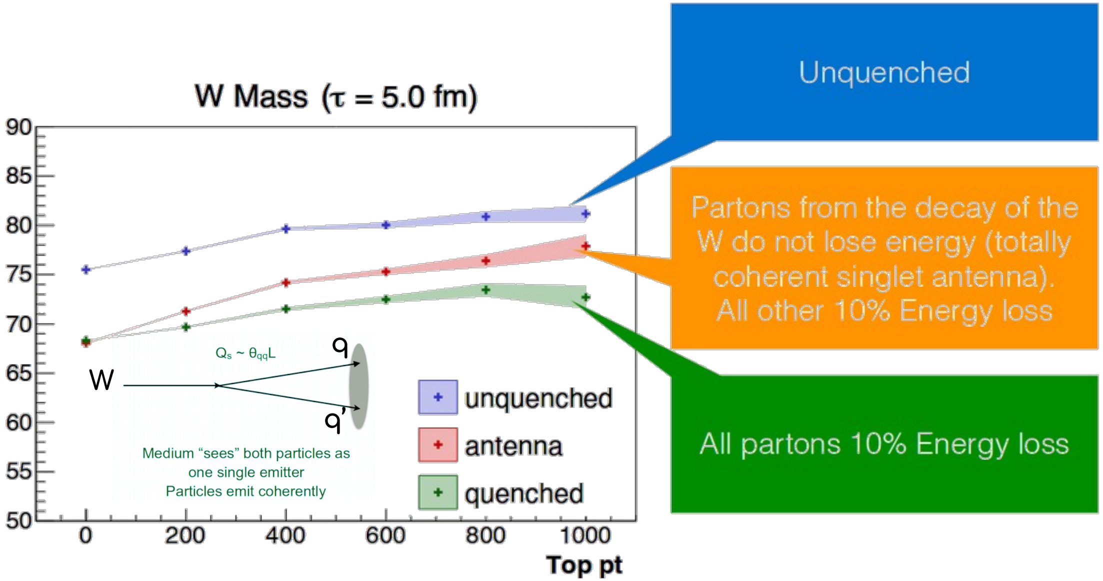


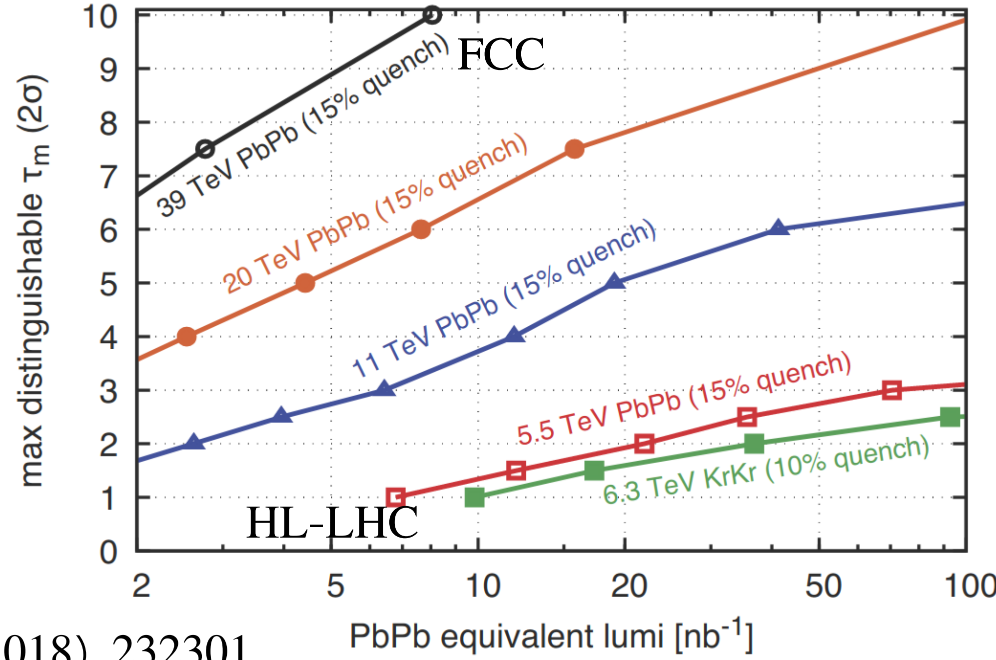
Phys. Lett. B **746** (2015) 64

- nPDF uncertainties increase at large *x* due to the **lack** of direct constraints
  - the region where the predictions for R_g also **differ** between nPDF determinations
  - some constraints from the current LHC dijet measurements (cf. backup)

W mass vs top p_T and QGP lifetime reach

- What would be the observable to measure the amount of energy loss?
  - By reconstructing **W mass vs top p_T** we can trace the quenching time dependence
    - At HL-LHC, possible to distinguish low-duration scenarios (inclusively)
    - At FCC, possible to assess the QGP density evolution (i.e., 'triggering on' top p_T)

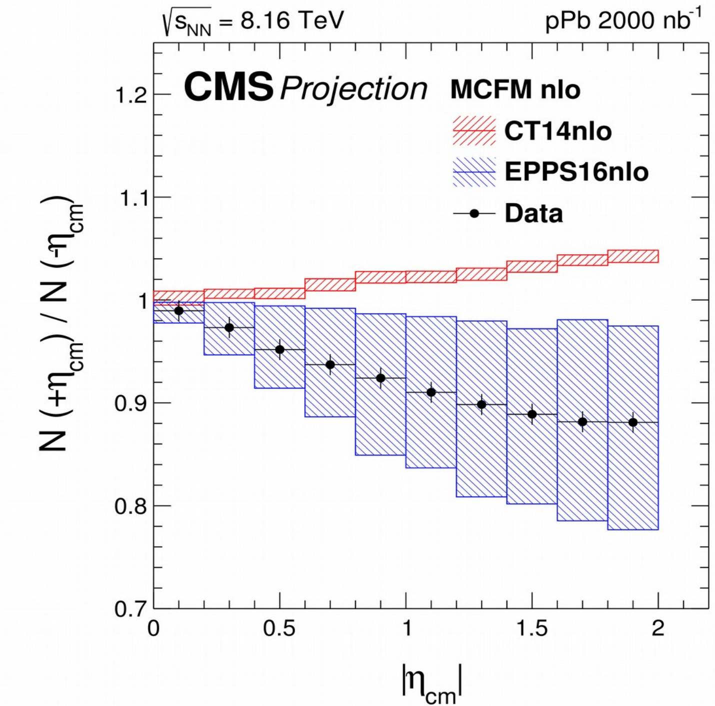


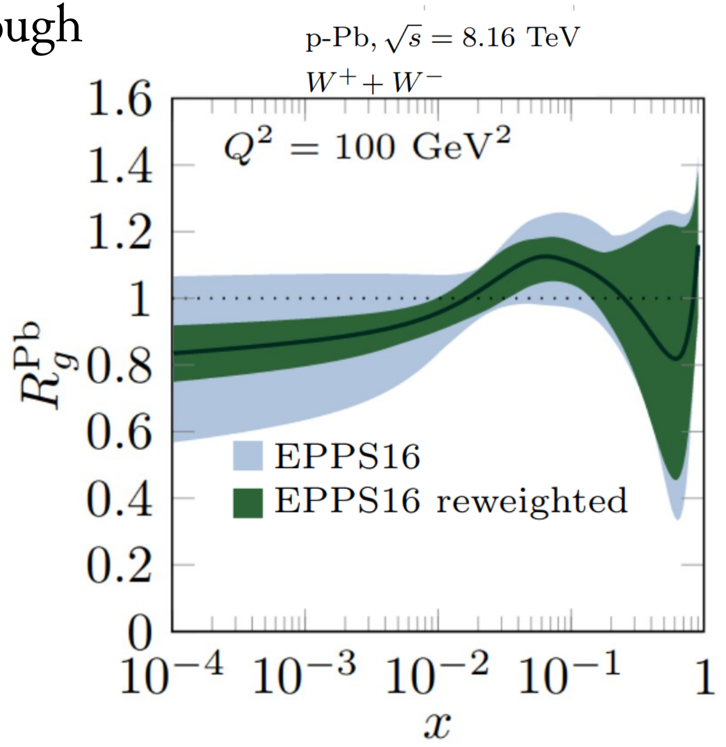


Phys. Rev. Lett. **120** (2018) 232301

Prospects for W boson forward-to-backward ratios

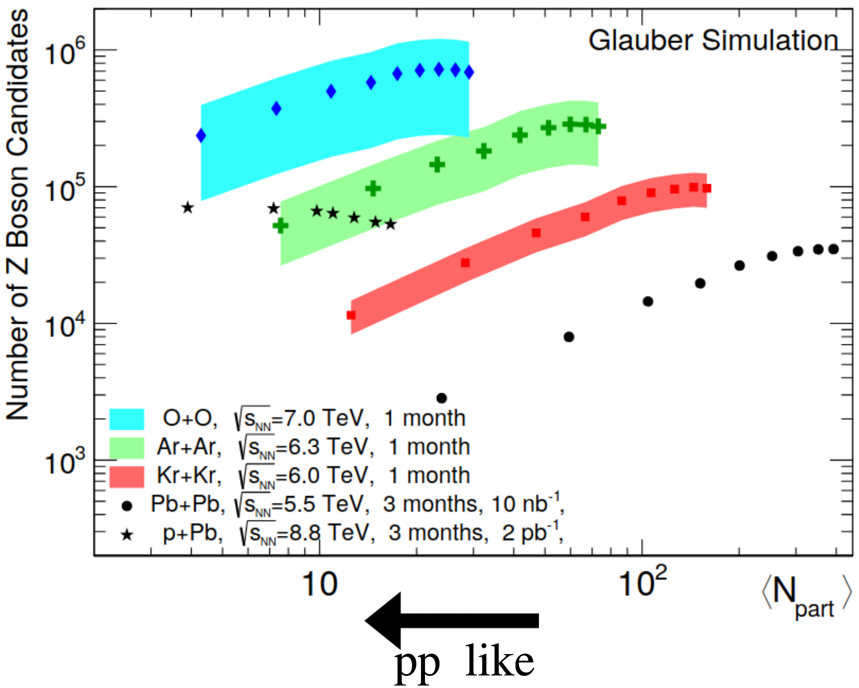
- Exploit the larger (× 10) pPb data set in Runs 3–4
  - experimental uncertainties significantly **smaller** than the nPDF ones
  - to showcase the potential: significant reduction of the uncertainties in the gluon nPDF
    - the large-x (> 0.1) part is **not affected** though

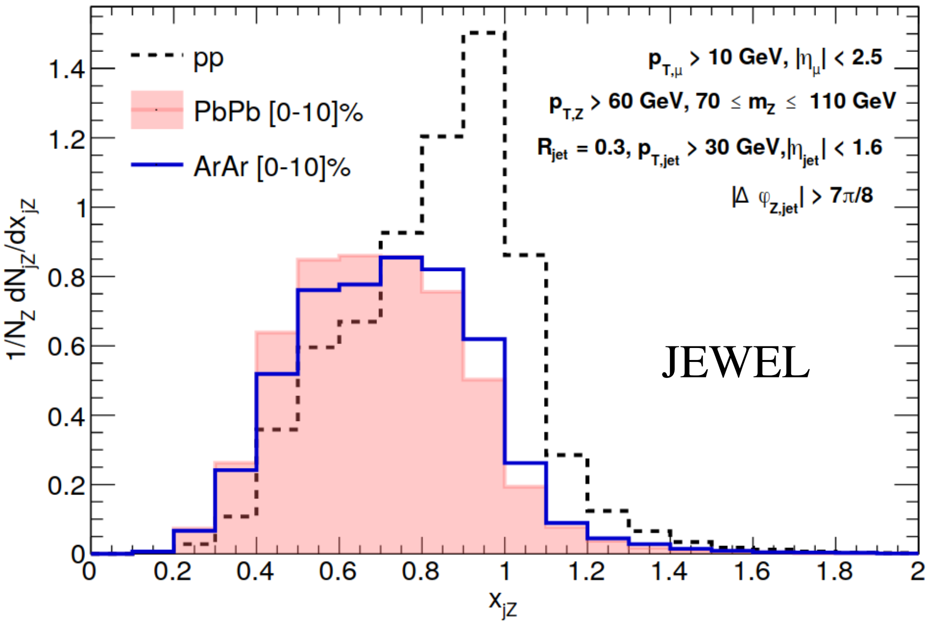




Physics motivations for collisions with lighter ions

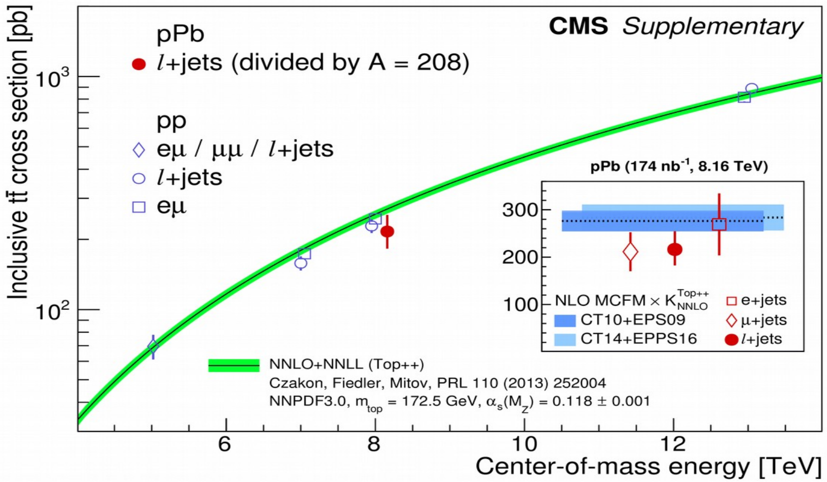
- **1 month** of ArAr > PbPb data set in Runs 3–4
  - coverage of a much broader range in Z p_T → jet-energy differential studies of quenching
- case study: ratio of the jet to Z p_T expected **similar** in ArAr and PbPb collisions

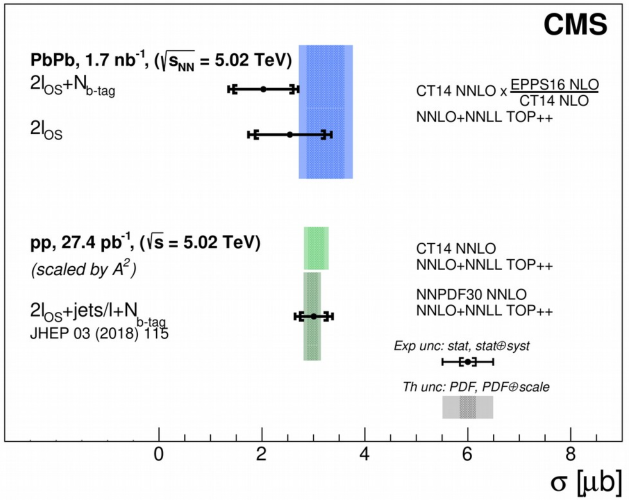




Up-to-date compilation: 4 $\sqrt{s_{NN}}$ & 3 systems @ LHC!

- A **wealth** of $t\bar{t}$ measurements
  - At 5, 7, 8, and 13 TeV
  - In central and forward regions
  - In pp, pPb, and PbPb collisions
- A **new era** for nuclear-modification studies
  - Initial state
    - nPDFs at complemenatary (x, Q^2) values
  - Final state
    - tools for parton energy loss

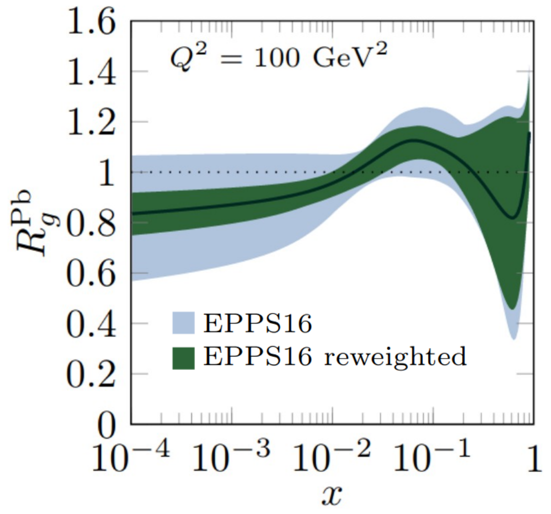


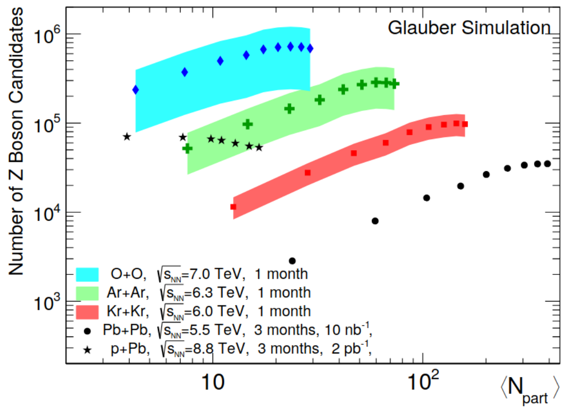


U.S. DEPARTMENT OF ENERGY | Office of Science

Hard and "rare" probes HI program @ HL-LHC

- **Precise** extractions of nPDFs crucial for
  - studying the strong interaction in the high-density regime
  - modeling the initial state needed to characterize the QGP
- LHC nuclear data are a game changer
  - different groups **already** include W/Z boson data in global fits
- We can assess the QGP density evolution
  - top quark a **new tool** profiting from HL-LHC and lighter ions
- To refine modeling of dilute systems and optimize their choice
  - the available info already indicates the potential of **lighter** systems
    - isoscalar beams **complementary** to HL-LHC pp? (cf. backup)
  - of relevance for **BSM** searches too (e.g., J Phys G **47** (2020) 060501)

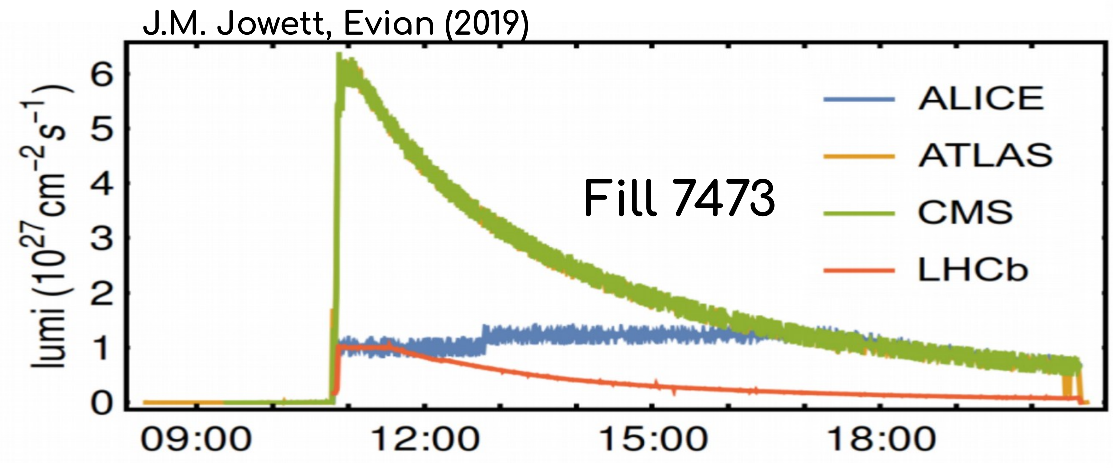


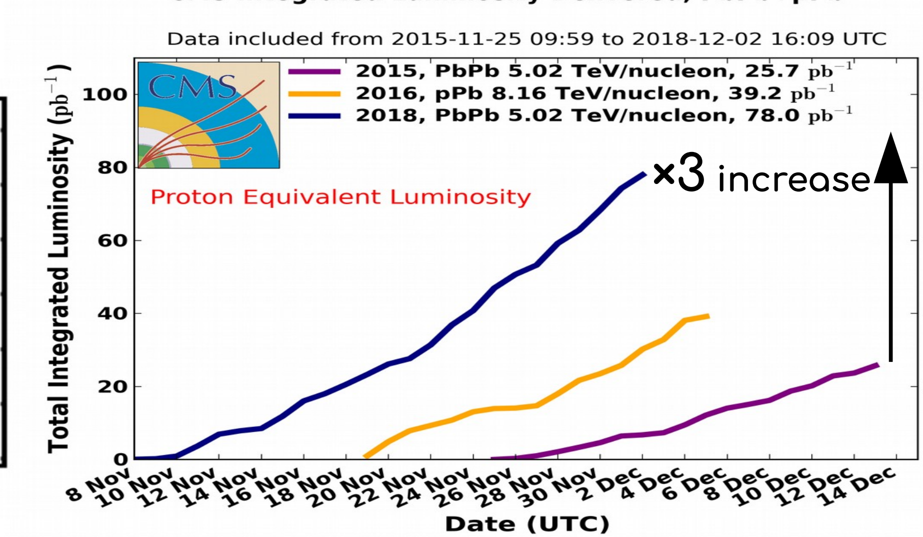


s slides

Surpassing the baseline luminosity goals

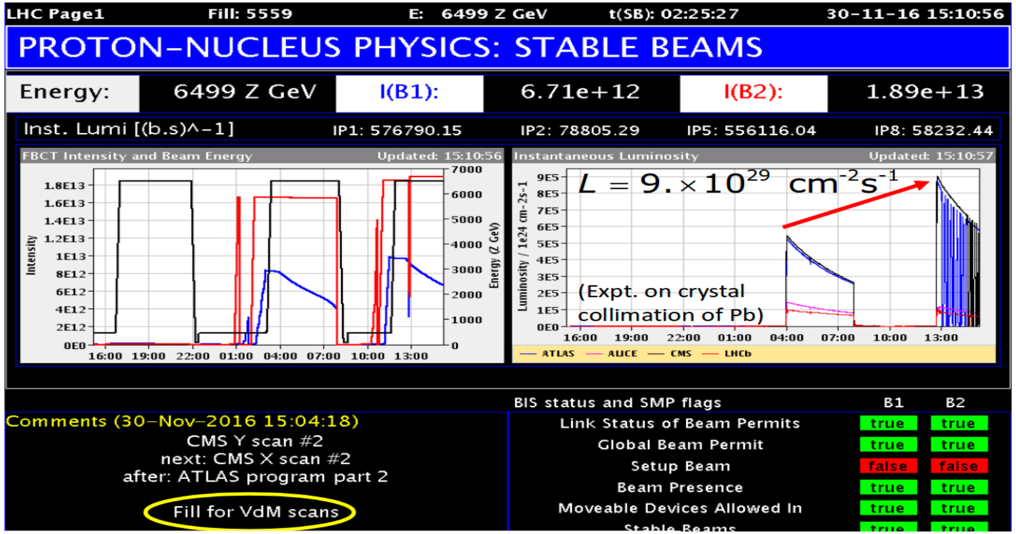
- LHC collided more types of beam, than originally foreseen, with better performance
  - In practice, we've come close to the "HL-LHC" performance with PbPb and pPb collisions
    - In 2018 the peak luminosity at IP1/5 reached **×6** the design **without** magnet quenches
- Opens up further opportunities for high-density QCD studies
  - For probes **not accessible** so far due to lower luminosity or energy
    - **All** 4 experiments participate → complementary phase space regions, cross checks

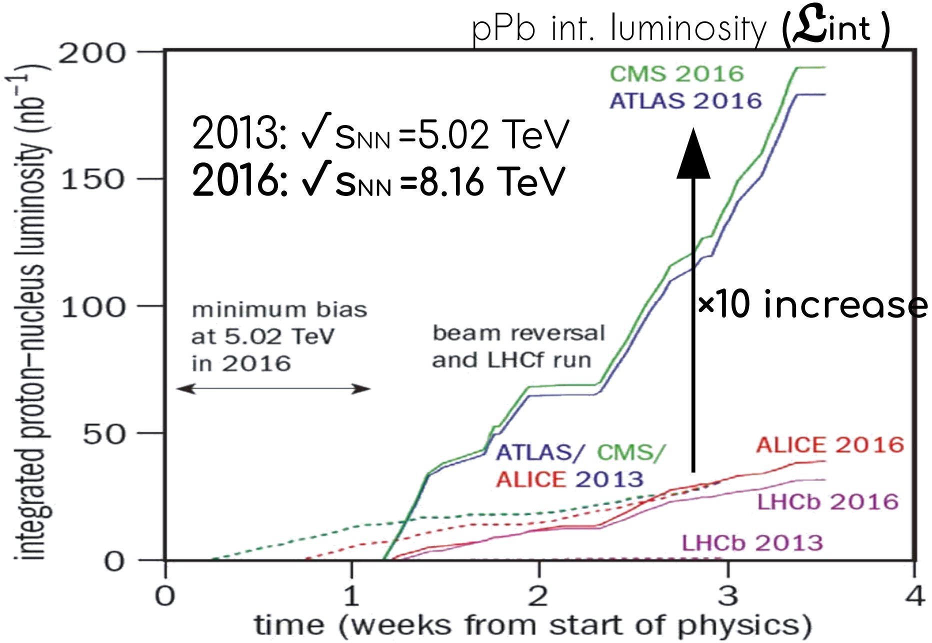




The first system fulfilled high-luminosity requirements!

- One of the primary goals of the **2016 pPb** run, i.e., **>** 100/nb, achieved
  - further data sets delivered parasitically, e.g, beam-gas interactions @ LHCb
- **Record** luminosity and Fill duration
  - instantaneous luminosity **surpassed** the "design" value by almost a factor 8
  - the longest-ever LHC Fill (5510) achieved: 38hr!





Pb **debris** prohibited from going even higher : (

Interest + ingenuity ⇒ $\mathfrak{L}$int =174±6/nb (!)

The first search analysis for $t\bar{t}$ in nuclear collisions!

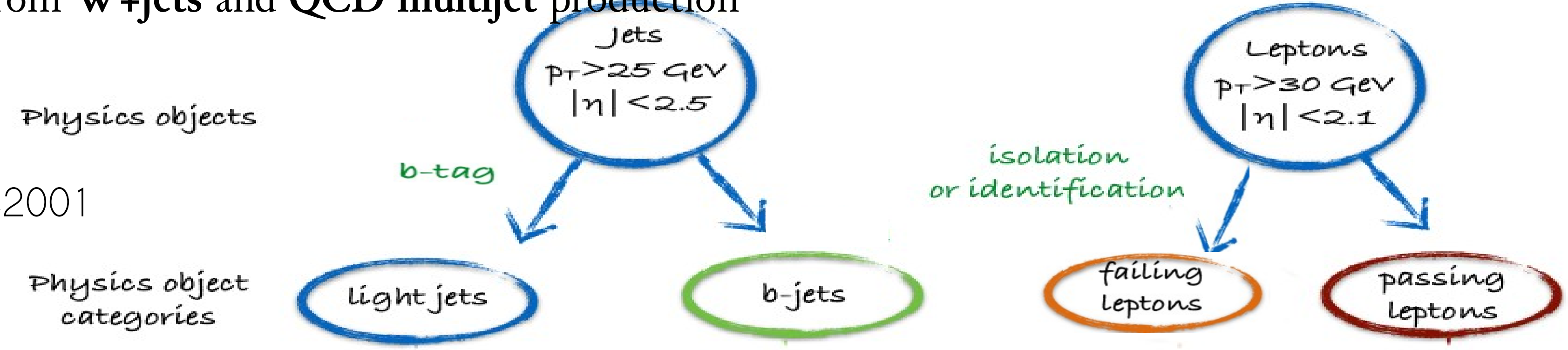
- $t\bar{t} \rightarrow$ bW bW $\rightarrow$ b l b jj'

we search for the lepton (l= e, μ) & the light jets j,j'

- j,j' jets are paired based on their proximity in the (η,φ) space

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

PRL **119** (2017) 242001



1 triggered l (l=e,μ)

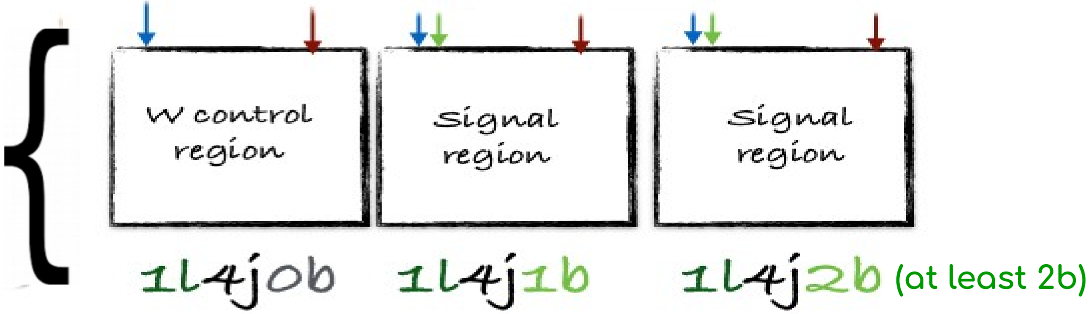
+ 0 extra leptons (offline)

+ 4 jets clustered with anti-kt (R=0.4)

+ systematic uncertainties

excludes *null* > 5σ ?

Combined fit
over 2 × 3 = 6
categories

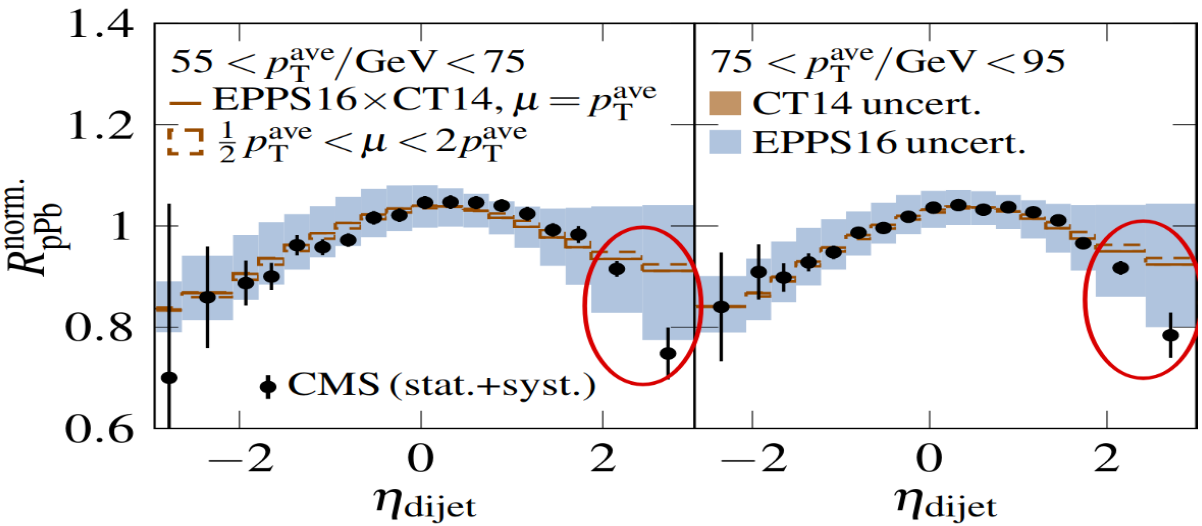


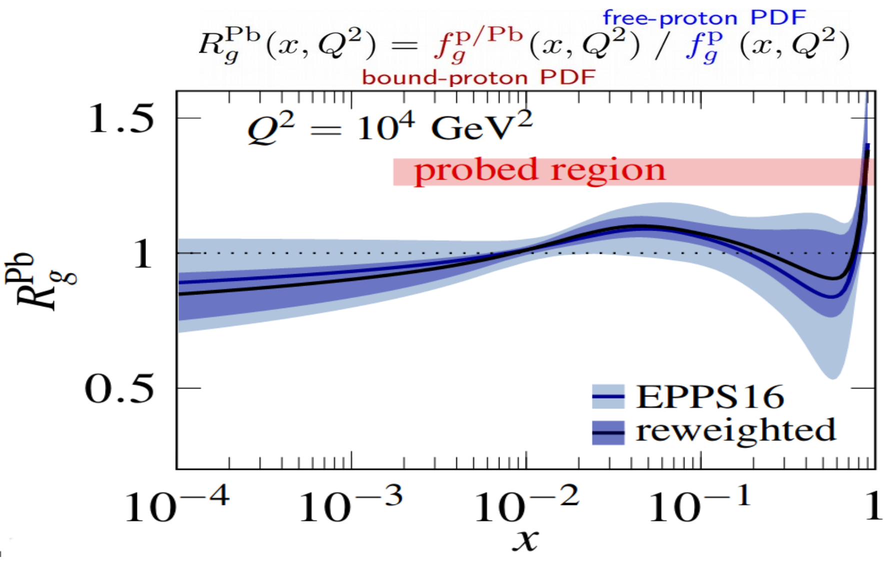
Nuclear gluon PDFs: constraints scarce so far

- Stringent constraints with CMS dijet events
- Data consistent with NLO pQCD predictions with nuclear PDFs (EPPS16)
  - Enhanced **suppression** at forward y
- Significant reduction in EPPS16 uncertainties after reweighting

Phys. Rev. Lett. **121** (2018) 062002

EPJC **79** (2019) 511





The Gamma Factory path to HL-LHC

- Snowmass should also consider the HL-LHC scheme based on the laser Doppler cooling
  - **decrease** the transverse emittance of colliding bunches
  - accelerate and collide fully **stripped ion** beams in the LHC ring
  - relevant also for **FCC-hh** (take advantage of the LHC vacuum)
- The GF path is restricted to a narrow range of nuclei
  - a concrete scenario already with the isoscalar **Ca(+20)**
  - maximizes **partonic** and **photon-photon** luminosity
- The proposed scheme requires further studies
  - and **validation** of the GF laser-cooling simulations at SPS
- A (new) way to maximize luminosity at HL-LHC
  - optimal sharing between pp & AA modes–makes us all happy(?)
  - significantly **enlarges** the physics potential

M. Krasny, ICHEP2020

Parameter	Value
$s^{1/2}$ [TeV]	7.
$\sigma_{BFPP}(Ca)/\sigma_{BFPP}(Pb)$	5×10^{-5}
$\sigma_{had}(Ca)/\sigma_{tot}(Ca)$	0.6
N_b	3×10^{9}
$\varepsilon_{(x,y)n}$ [μm] (1)	0.3 →
IBS [h]	1-2
β* [m]	0.15
L_{NN} [cm-2s-1]	4.2×10^{34}
Nb of bunches	1404
Collisions/beam crossing	5.5

Prog. Part. Nucl. Phys. (2020) 103792

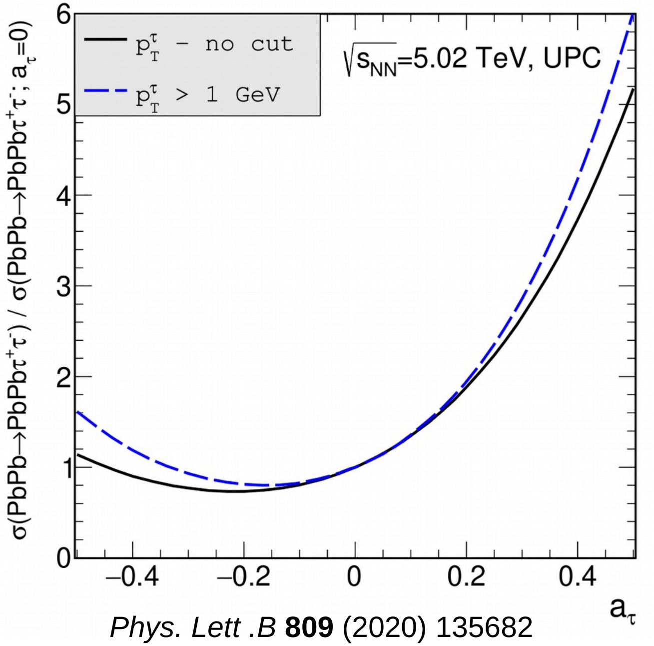
Anomalous moments of τ lepton in γγ→τ+τ−

- Exclusive production of τ leptons by two-photon fusion promising **candidate**
  - for g-2 determination
  - since **90s** and **recent** theory considerations renewed the interest

- This is because the γγ→τ+τ− cross section **strongly** depends on the anomalous magnetic moment $a_τ$
  - **mild** dependence on τ lepton p_T
  - SM ($a_τ$=0) cross section O(1 mb)
    - O(1 M)/O(1 K) events **prior to/after** eff+accep with 2 /nb

- Detection of τ leptons **challenging** especially at low-p_T (<20 GeV)
  - actually **no** measurement with τ leptons in nuclear collisions so far
    - e.g., indirect presence via Z/γ* events in HIN-19-001

- Take advantage of **UPC** events and τ lepton **unique** decay signatures
  - UPC triggers and further "exclusivity" cuts crucial for such a measurement
  - τ decays into lighter leptons (electron or muon) or hadrons



Phys. Lett .B **809** (2020) 135682

Event signatures of γγ→τ+τ−

- The primary τ decay channels result to one charged particle (“one prong”)
  - ~**80**% are one-prong (roughly half lepton half hadron) and the rest are three-prong decays
- τ+τ− signal regions can be then defined based on the lepton and hadron (i.e., track) **multiplicity**
  - **dilepton (eμ, μμ, ee):** cleanest but with low reco efficiency
  - **1l (e/μ)+1 track:** main exclusive bkg due to μμ, ee
  - **1l (e/μ)+3 tracks:** main exclusive bkg due to diquark production