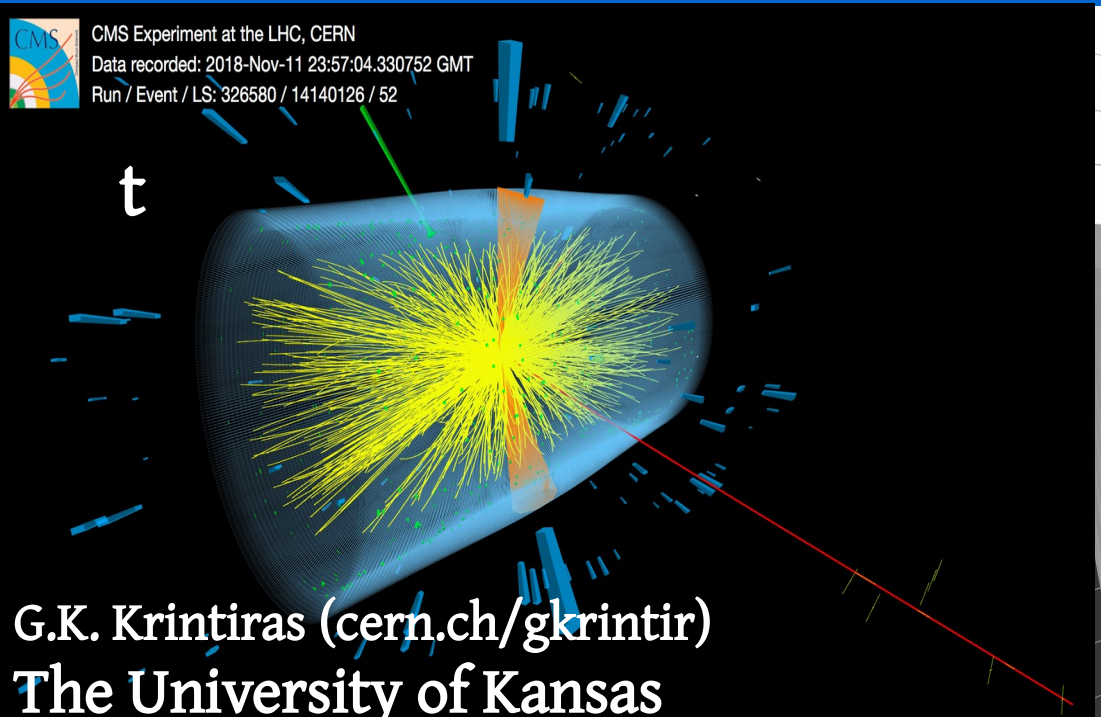
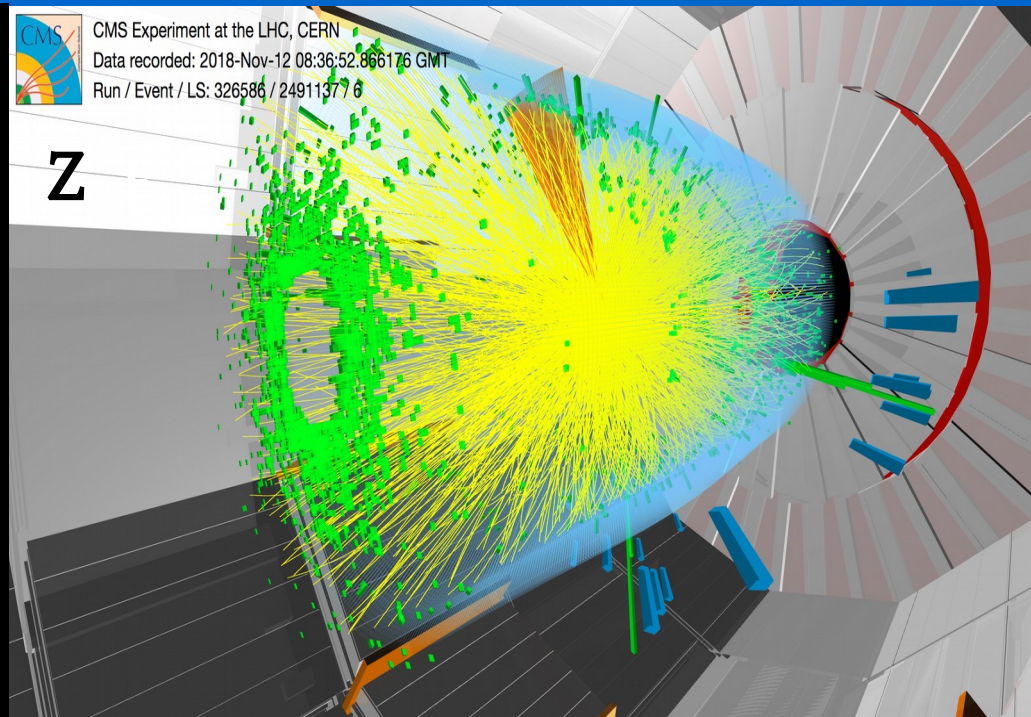
Future physics opportunities with W and Z bosons and top quarks for high-density QCD at LHC

arXiv: 1812.06772





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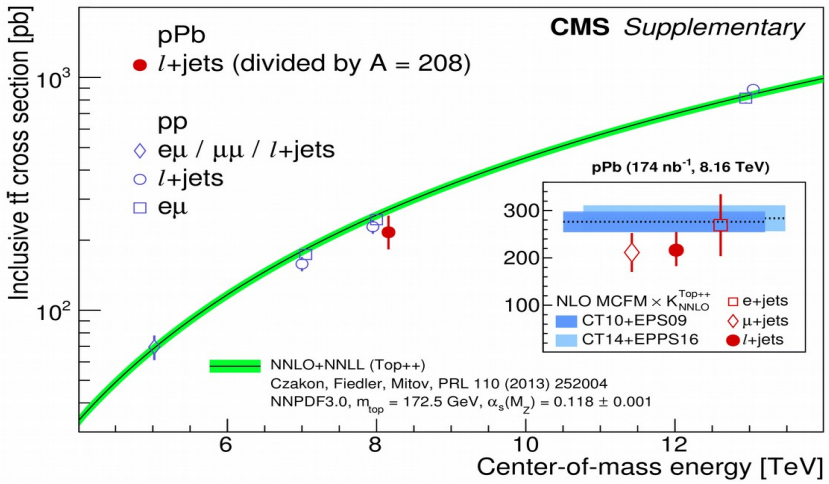
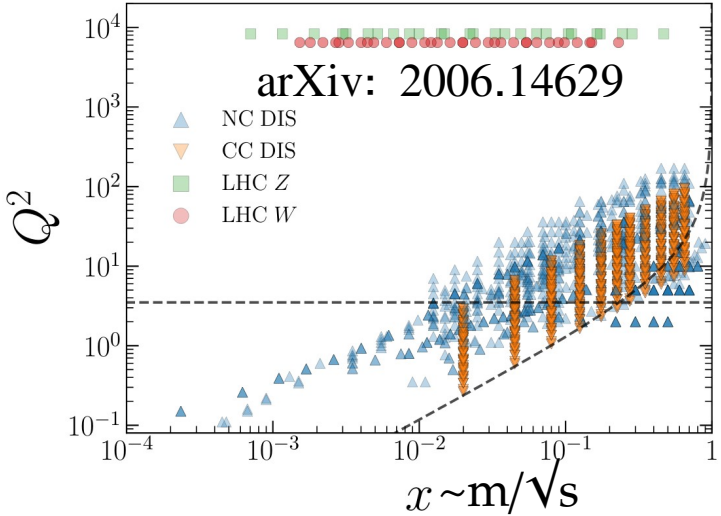
Current studies @ LHC: 4 √s & 3 systems!

- A **wealth** of W and Z boson and $t\bar{t}$ measurements
  - At 5, 7, 8, and 13 TeV
  - In central and forward regions
  - In pp, pPb, and PbPb collisions

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



- A **new era** for nuclear-modification studies
  - Initial state
    - nPDFs at complemenatary (x, Q^2) values
  - Final state
    - tools for parton energy loss

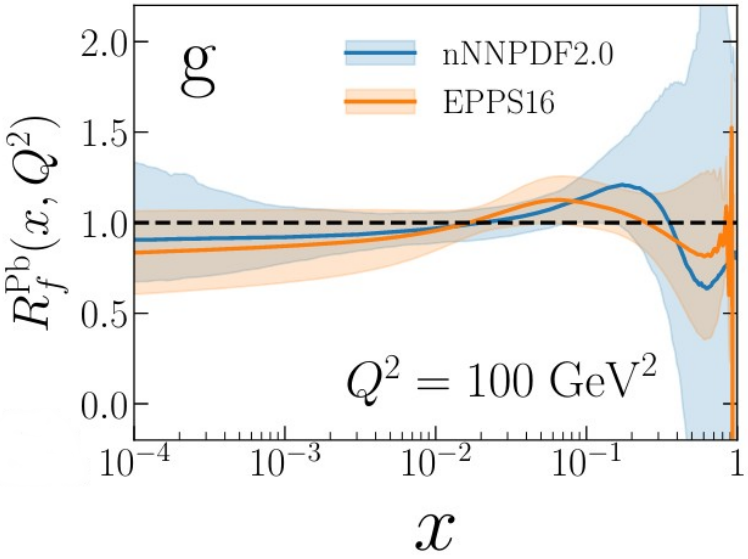


Key characteristics of the nPDF global fits

Nucl. Phys. A **967** (2017) 241

	EPS09	DSSZ12	KA15	NCTEQ15	EPPS16
Order in α_s	LO & NLO	NLO	NNLO	NLO	NLO
Neutral current DIS ℓ+A/ℓ+d	✓	✓	✓	✓	✓
Drell-Yan dilepton p+A/p+d	✓	✓	✓	✓	✓
RHIC pions d+Au/p+p	✓	✓		✓	✓
Neutrino-nucleus DIS		✓			✓
Drell-Yan dilepton π+A					✓
LHC p+Pb jet data					✓
LHC p+Pb W, Z data					✓
Q cut in DIS	1.3 GeV	1 GeV	1 GeV	2 GeV	1.3 GeV
datapoints	929	1579	1479	708	1811
free parameters	15	25	16	17	20
error analysis	Hessian	Hessian	Hessian	Hessian	Hessian
error tolerance $\Delta\chi^2$	50	30	not given	35	52
Free proton baseline PDFs	CTEQ6.1	MSTW2008	JR09	CTEQ6M-like	CT14NLO
Heavy-quark effects		✓		✓	✓
Flavor separation				some	✓
Reference	[JHEP 0904 065]	[PR D85 074028]	[PR D93, 014026]	[PR D93 085037]	[EPJ C77 163]

arXiv: 2006.14629

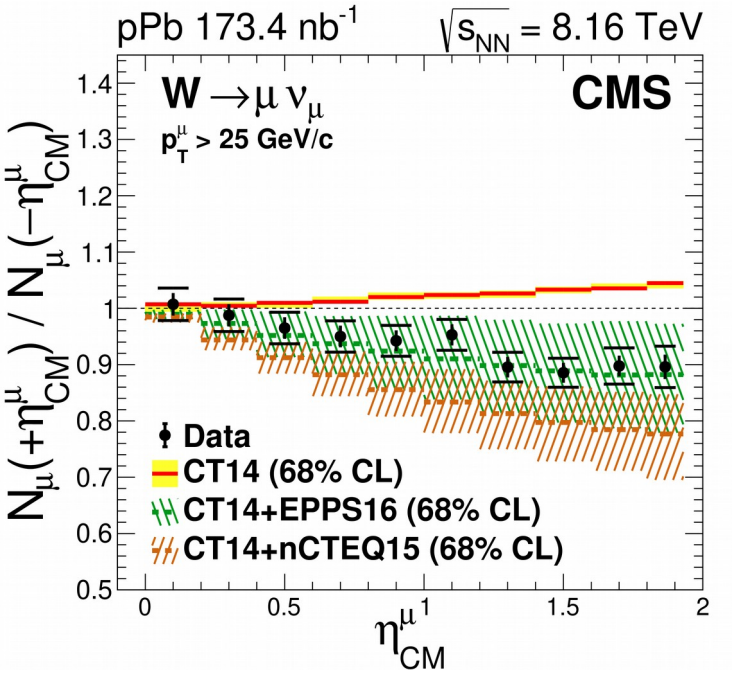


- nPDFs from **several** groups
  - less available data sets compared to the free-nucleon cases
  - different data sets (e.g., pPb LHC data), theoretical assumptions, and methodological settings
  - **not well** understood aspects, e.g., the nuclear modifications of the gluon distribution

Observation of nuclear modifications in W production

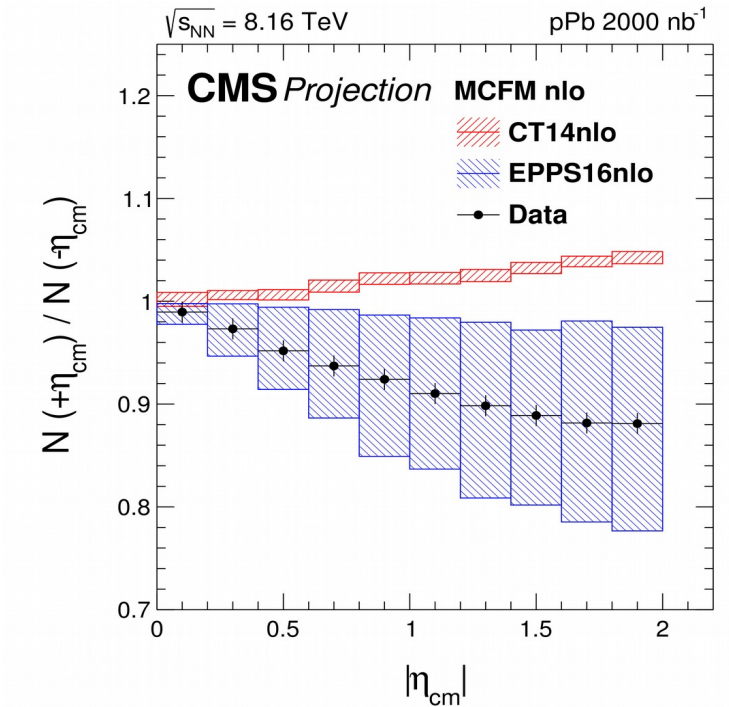
Phys. Lett. B **800** (2020) 135048

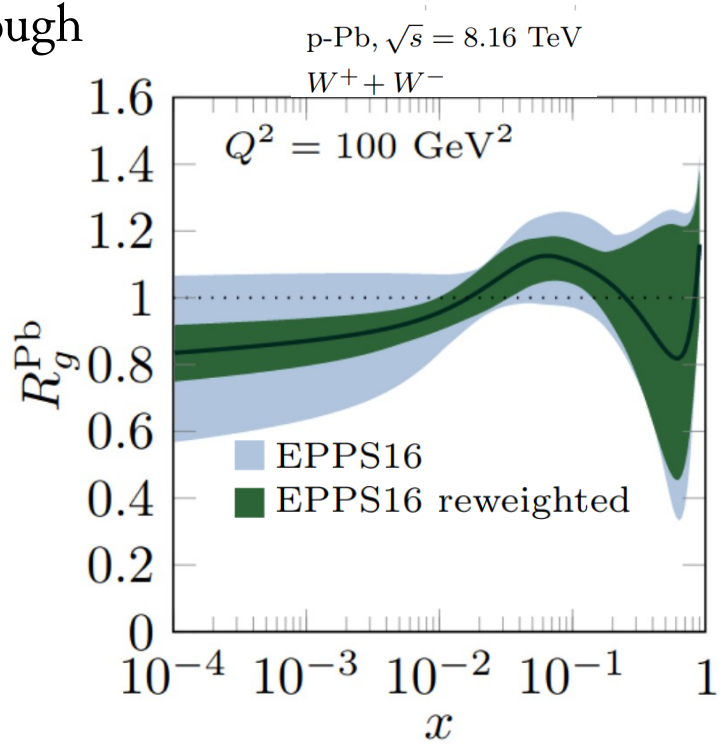
- W boson asymmetry measurement with Run **2** data
  - in pPb collisions at 8 TeV
  - results favour nPDF calculations
  - can provide **constraints** on the nPDF global fits
    - gluons but also light sea quarks



Prospects for W boson forward-to-backward ratios

- Exploit the larger (× 10) pPb data set in Runs 3–4
  - experimental uncertainties much **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

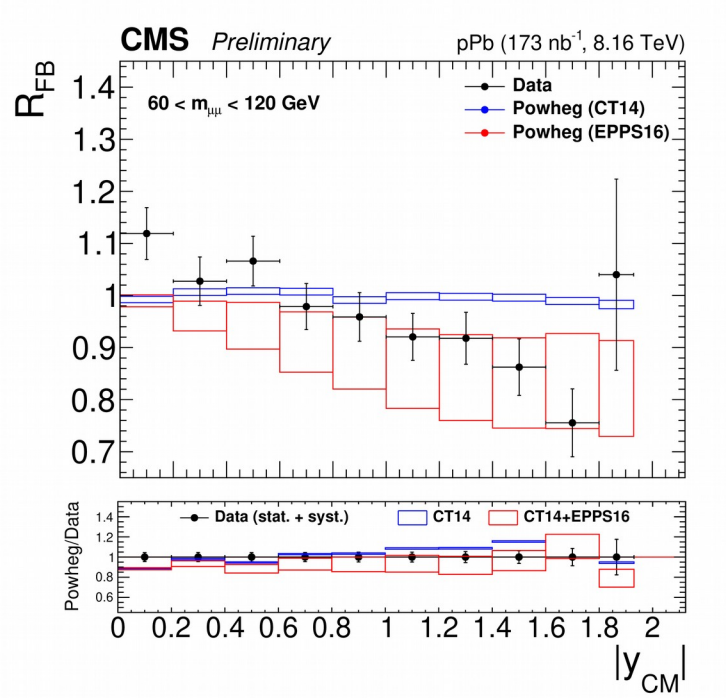


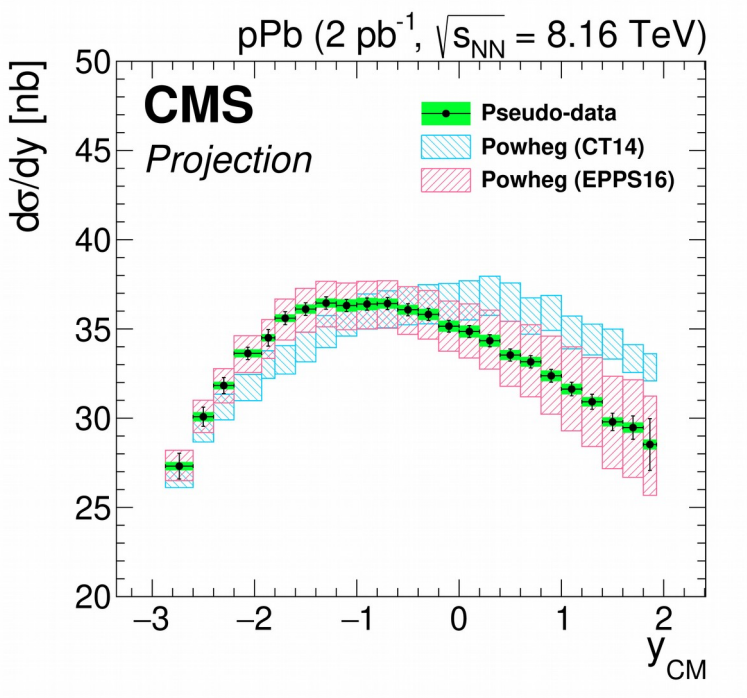


Differential cross sections for the Drell–Yan process

- dσ/dX and proton- over Pb-going ratios with Run **2** data at 8 TeV
  - including, but not restricted to, Z boson production
  - results **already favor** nPDF calculations too

CMS-PAS-HIN-18-003

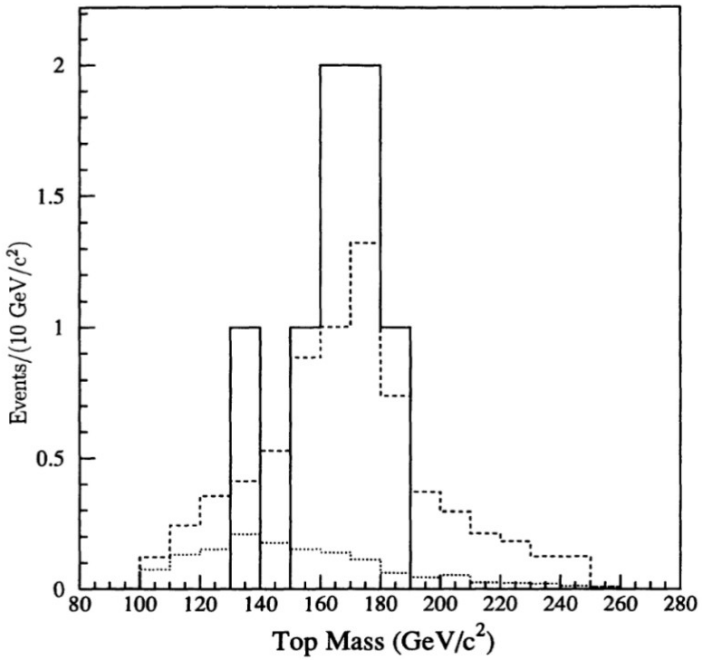




Observation of top quarks in pPb collisions

- Performed in the semileptonic final state with Run **2** data at 8 TeV
  - Events with ≥ 2 b jets: **background-free**
  - results not yet sensitive to nPDF vs PDF difference (we expect a mild increase relative to pp)

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



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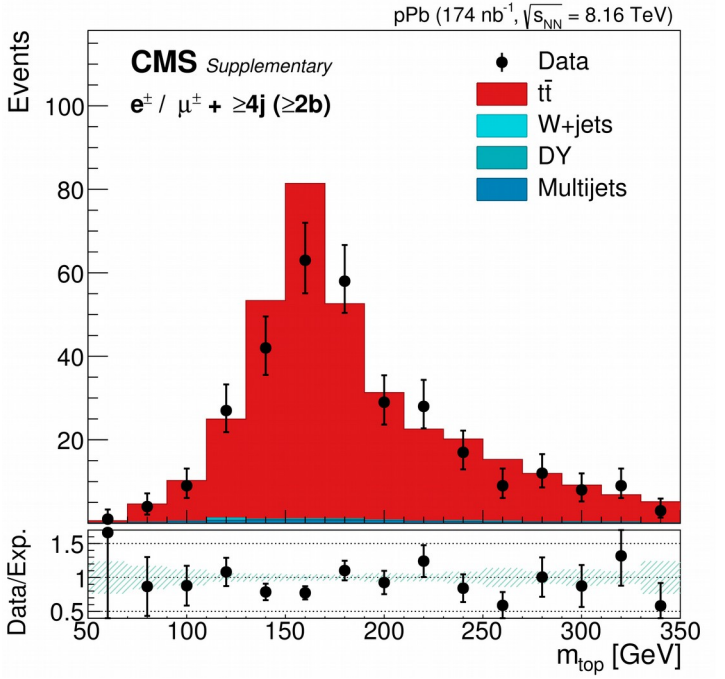
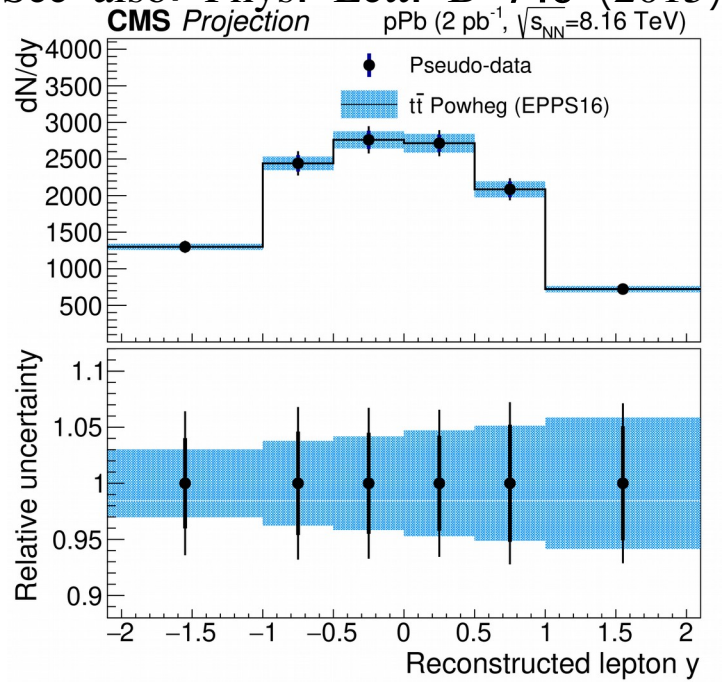
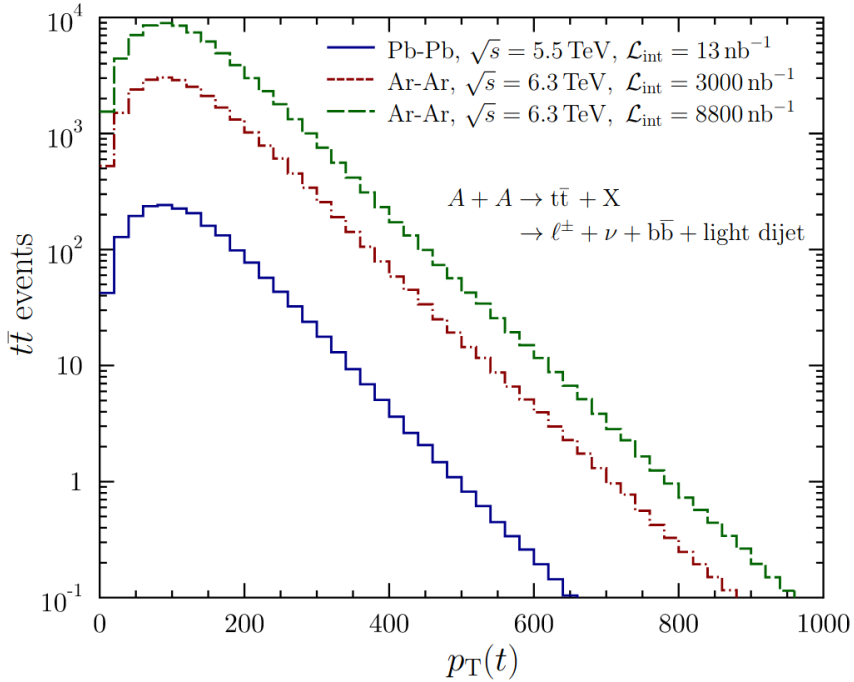


Prospects for top quark production at HL-LHC

- 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

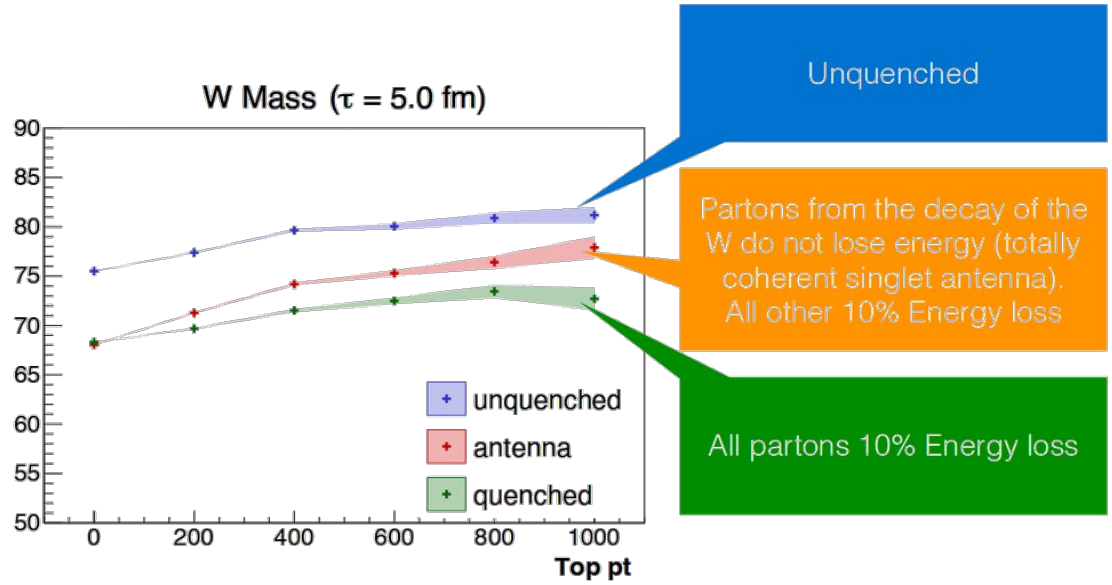
See also: Phys. Lett. B **746** (2015) 64

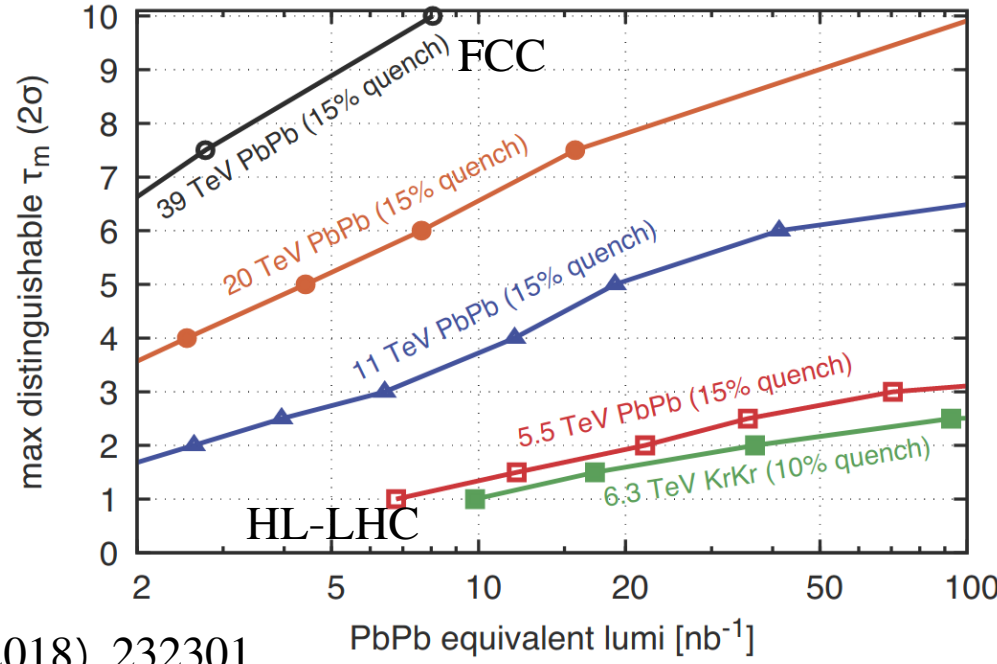




"Unveiling the yoctosec structure of the QGP"

- Top quark via their decay products has the potential to **resolve** the time evolution of the QGP
  - via a series of time delays, correlated with top p_T, we trace the quenching time dependence
    - At HL-LHC, possible to distinguish low-duration scenarios (inclusively)
    - At FCC, possible to assess the QGP density evolution ('triggering on' top quark p_T)

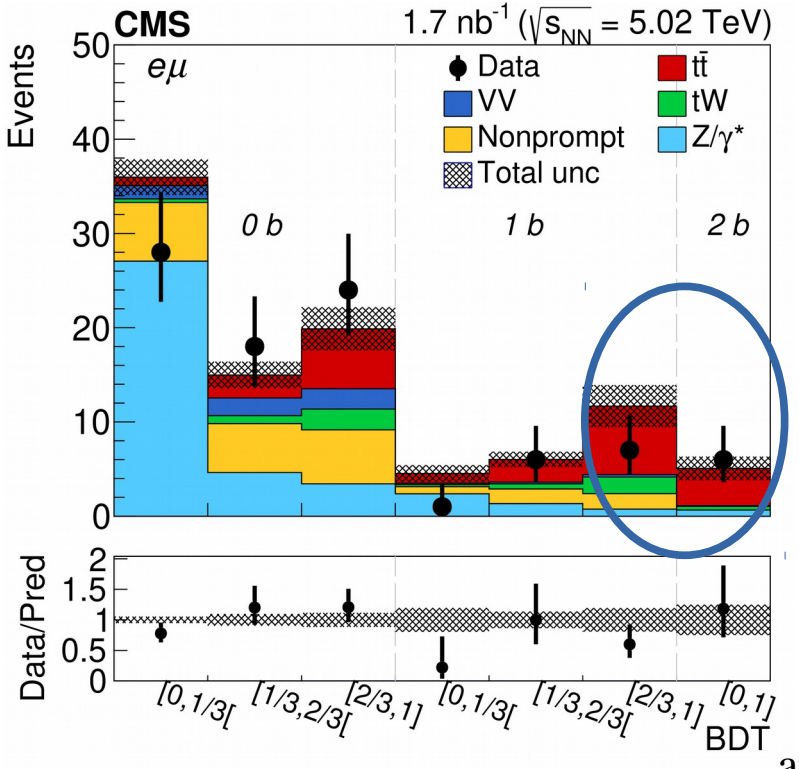


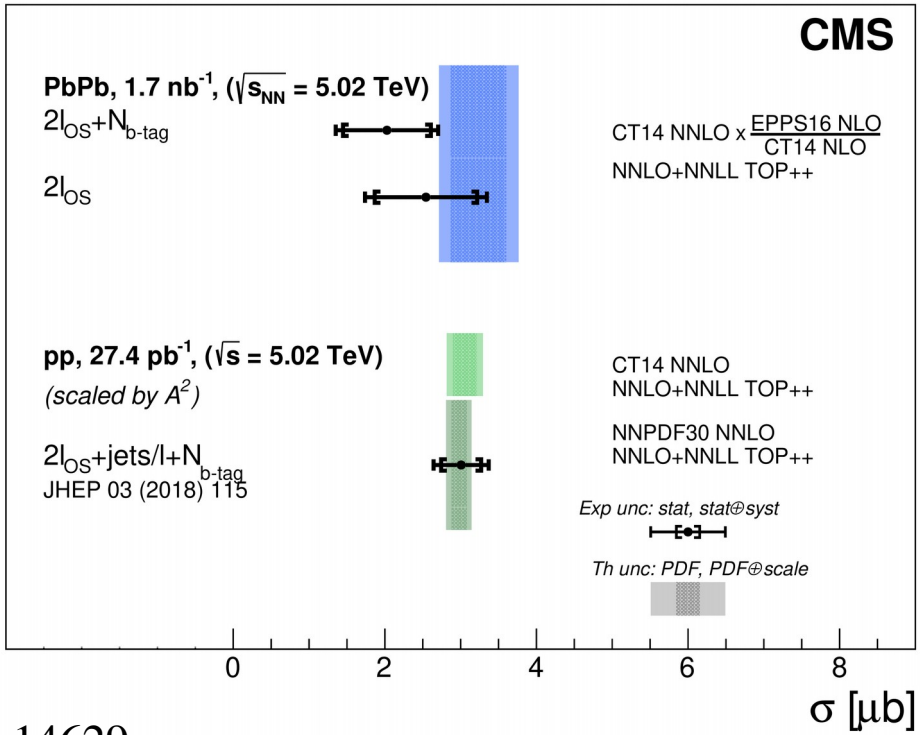


Phys. Rev. Lett. **120** (2018) 232301

Evidence of top quarks in PbPb collisions

- 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

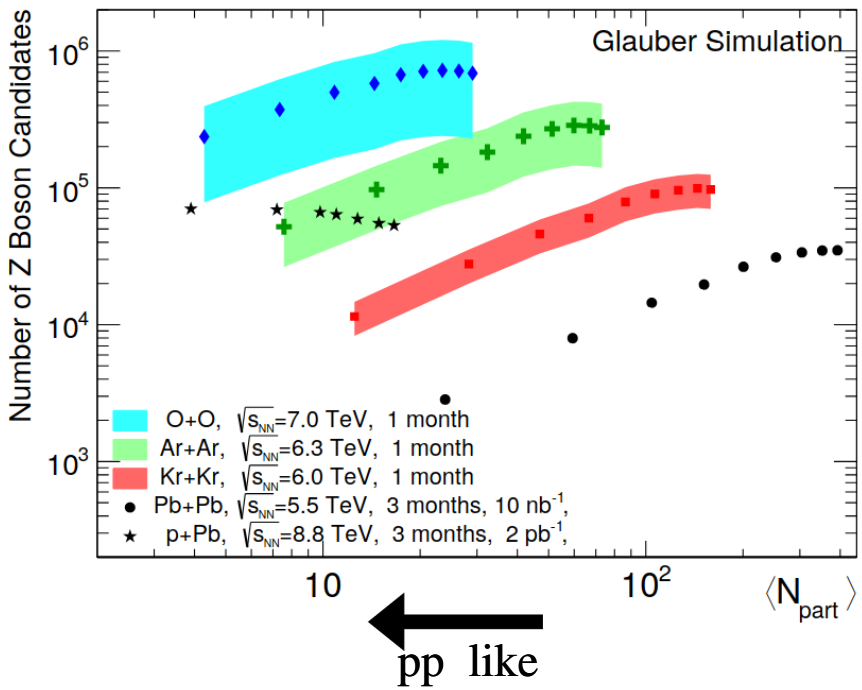


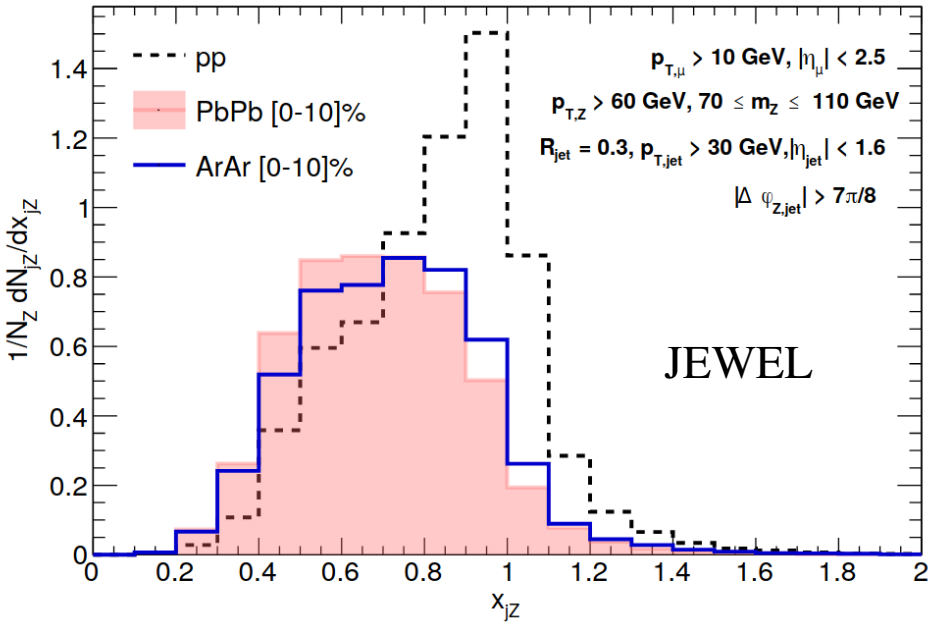


arXiv: 2006.14629

Z physics motivation for collisions with lighter ions

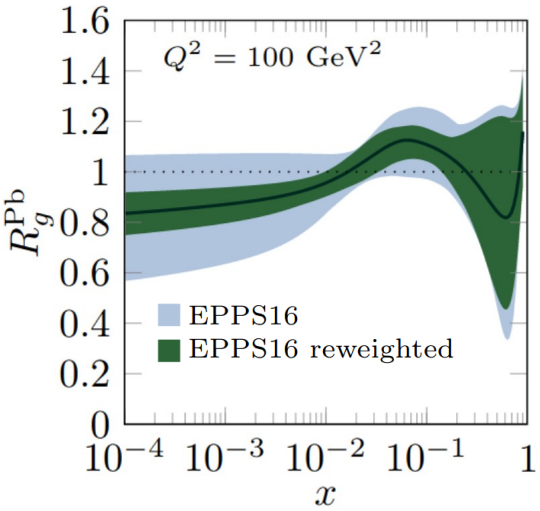
- **1 month** of ArAr > PbPb data set in Runs 3–4
  - coverage of a much broader range in Z p_T → jet-energy differential studies of quenching
- case study: ratio of the jet to Z p_T expected **similar** in ArAr and PbPb collisions

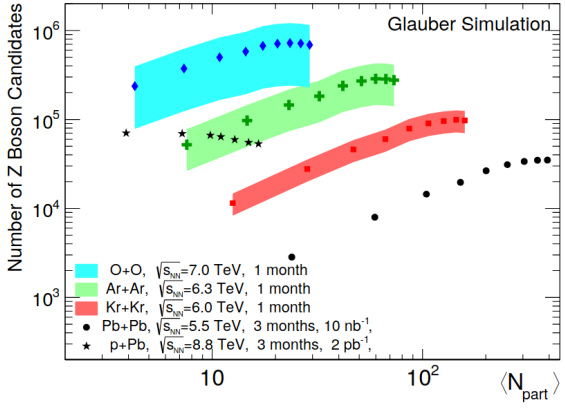




Heavy ion rare probes program @ LHC

- 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 can be a game changer
  - different groups already **include** W/Z boson data in global fits
- Contrary to probes sensitive to QGP integrated lifetime we can assess the QGP density evolution
  - top quark a **new tool** profiting from lighter ions
- To refine modeling of dilute systems and optimize their choice
  - the available info indicates the potential of **lighter** systems
  - of relevance for BSM searches (e.g., J Phys G **47** (2020) 060501)

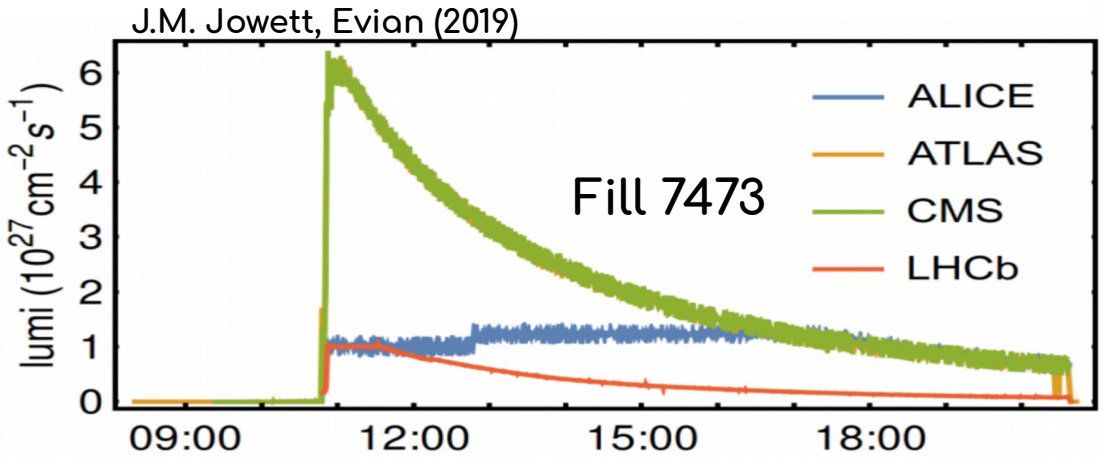


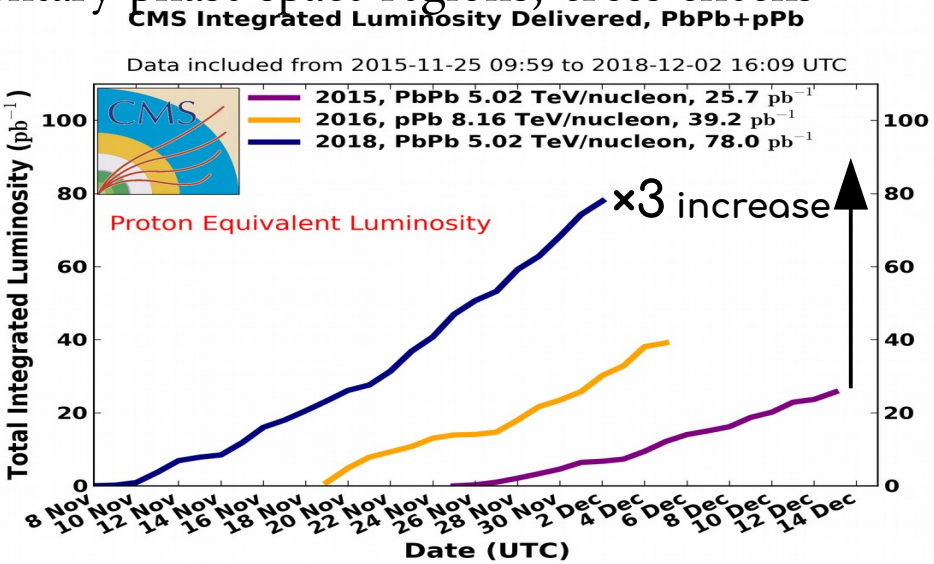


S slides

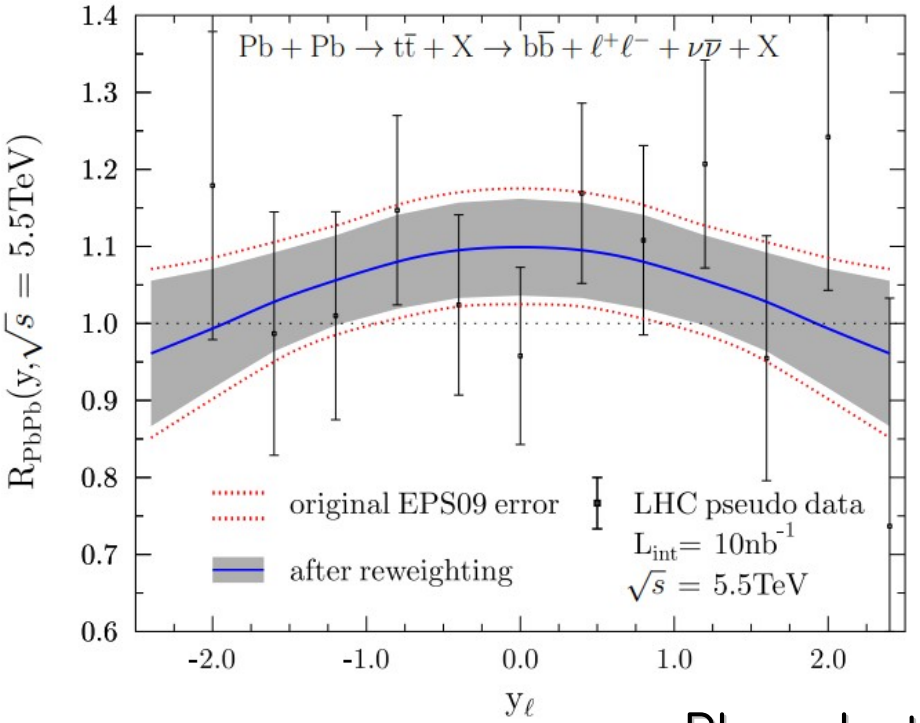
Surpassing the baseline luminosity goals

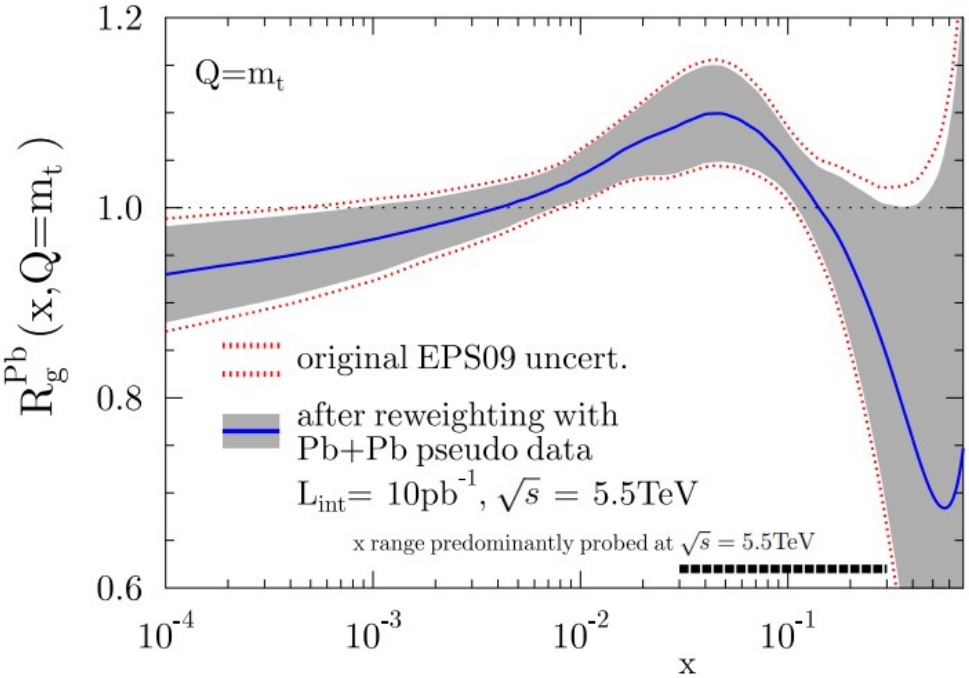
- LHC collided more types of beam, than originally foreseen, with better performance
  - In practice, we've come close to the "HL-LHC" performance with PbPb and pPb collisions
    - In 2018 the peak luminosity at IP1/5 reached **×6** the design **without** magnet quenches
- Opens up further opportunities 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 R_{PbPb} differentially





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

- Nuclear modification factor R_{PbPb} for tt production in the dilepton channels with the central PDF sets of CT10+EPS09 as a function of lepton rapidity

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