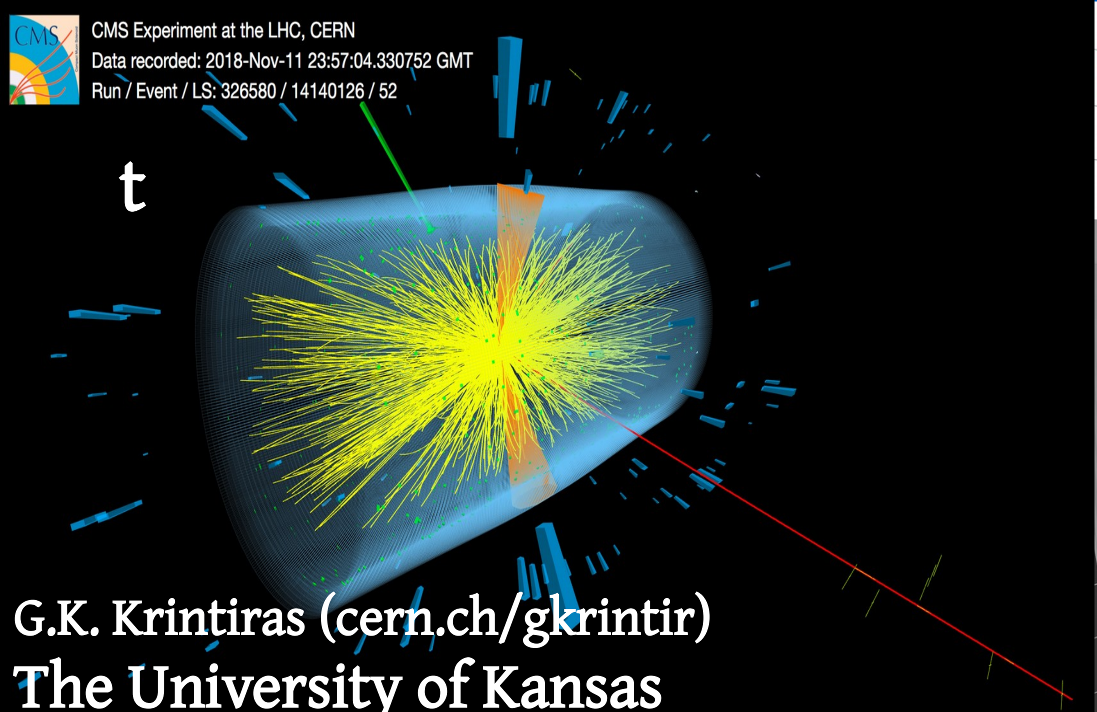
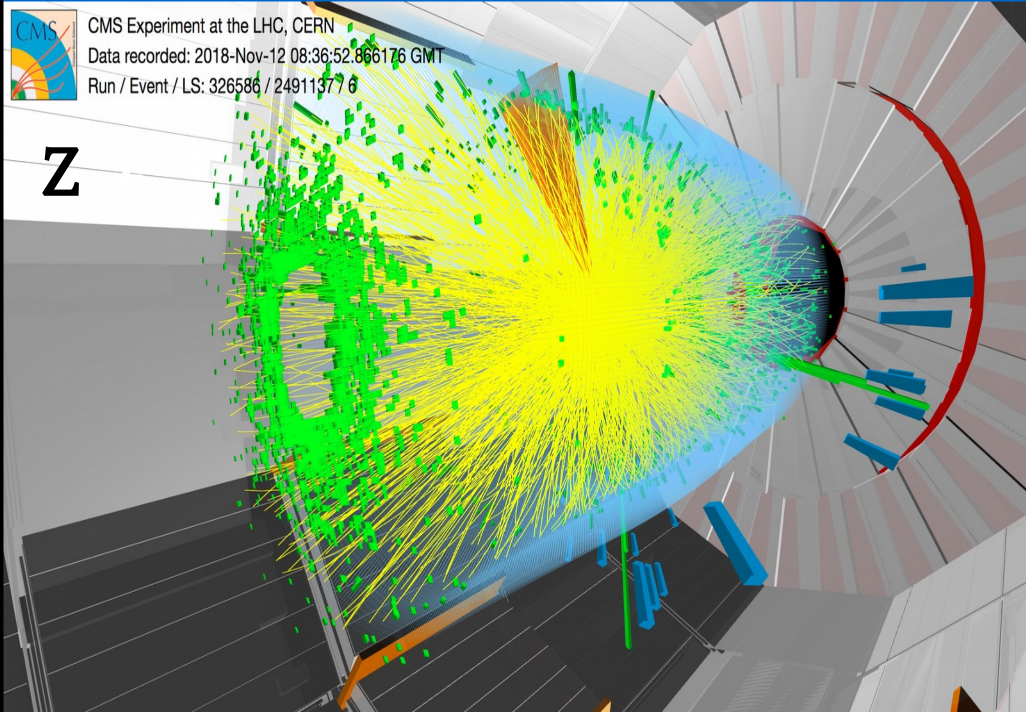
Future physics opportunities with W and Z bosons and top quarks for high-density QCD at HL-LHC

arXiv: 1812.06772





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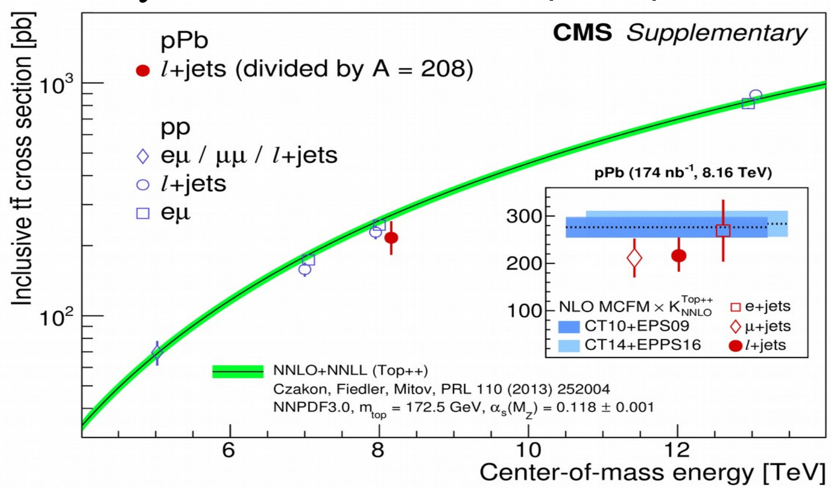
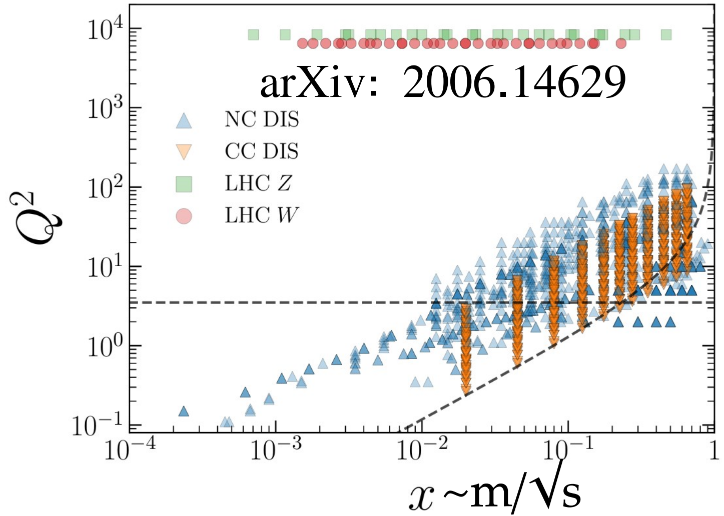
The University of Kansas

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

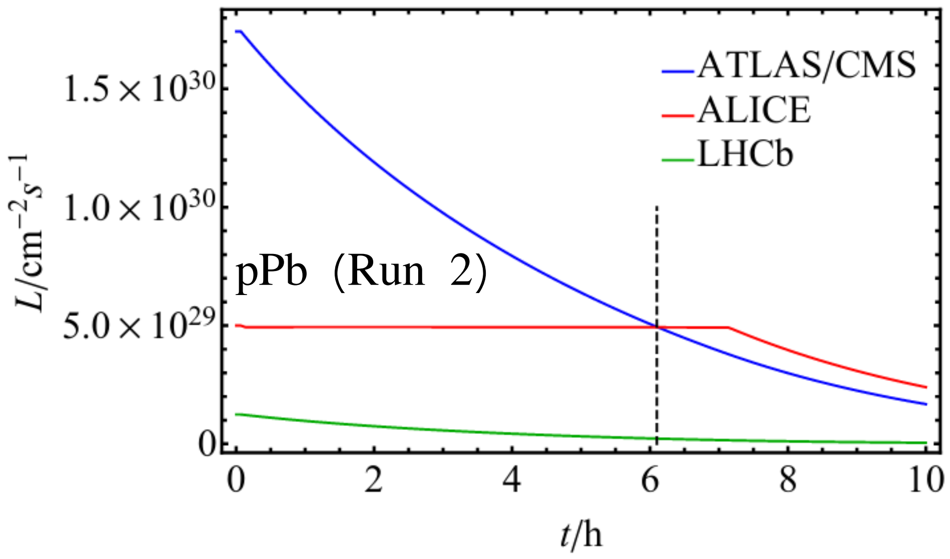
- A **wealth** of W and Z boson and $t\bar{t}$ measurements
  - At 5, 7, 8, and 13 TeV
  - In central and forward regions
  - In pp, pPb, and PbPb collisions
- A **new era** for nuclear-modification studies
  - Initial state
    - nPDFs at complemenatary (x, Q^2) values
  - Final state
    - tools for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

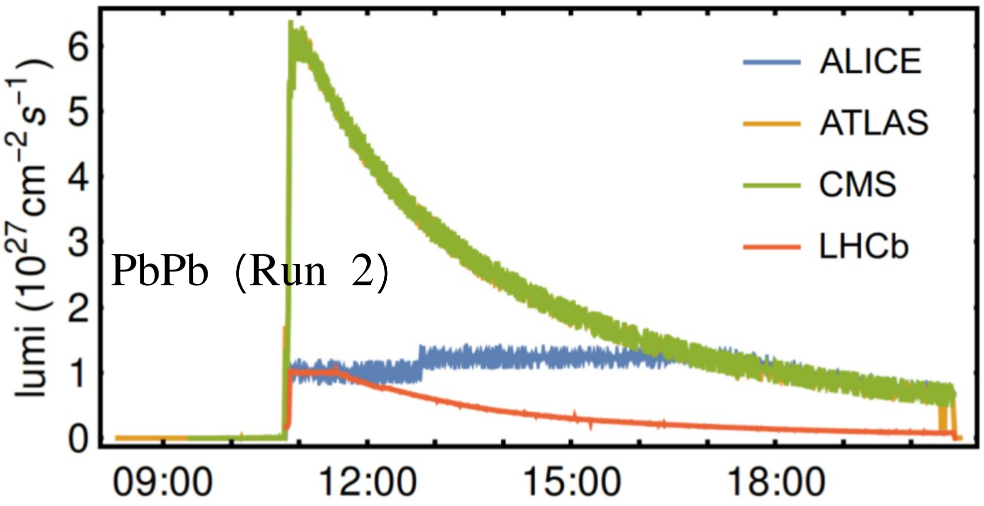
Phys. Rev. Lett. **119** (2017) 242001





HL-LHC operational scenarios for pPb and PbPb





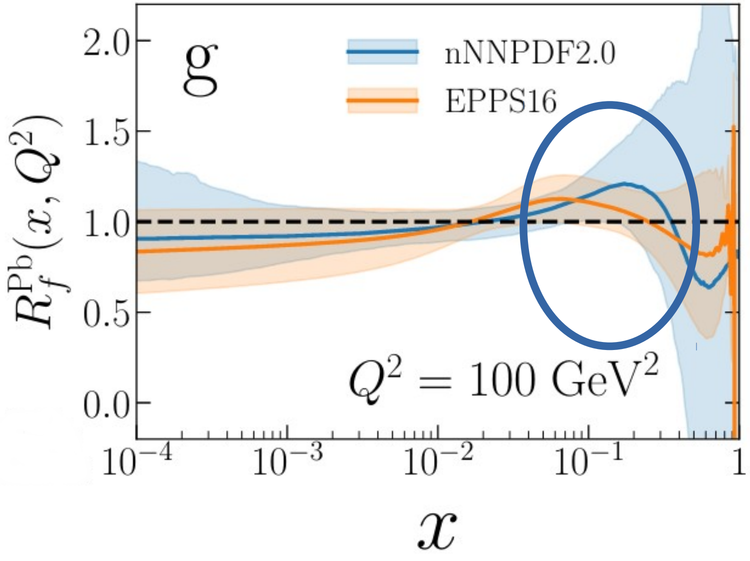
- Included in the YR and recently refined (CERN-ACC-2020-0011, CERN internal)
  - scenarios are based on **benchmarked** models (actually agree remarkaly well with Run 2 LHC data)
  - ≈**five** one-month runs would be needed to reach 13 /nb of PbPb
  - ≈**two** one-month runs would be needed to reach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

Key characteristics of the 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	$\Delta\chi^2 = 35$	$\Delta\chi^2 = 52$	—	$\Delta\chi^2 = 50$

arXiv: 2006.14629

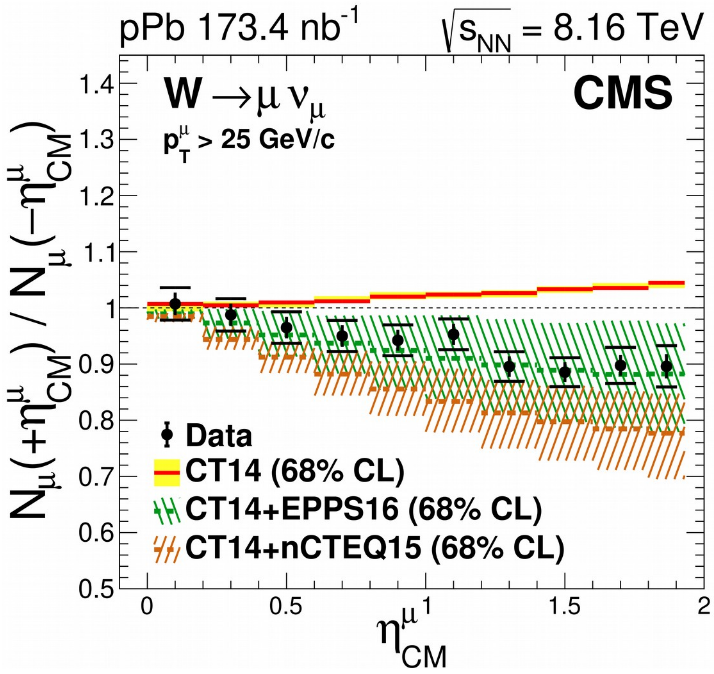


- nPDFs from **several** groups
  - less available data sets compared to the free-nucleon cases
  - different data sets (e.g., pPb LHC data), theoretical assumptions, and methodological settings
  - **not well** understood aspects, e.g., the nuclear modifications of the gluon distribution

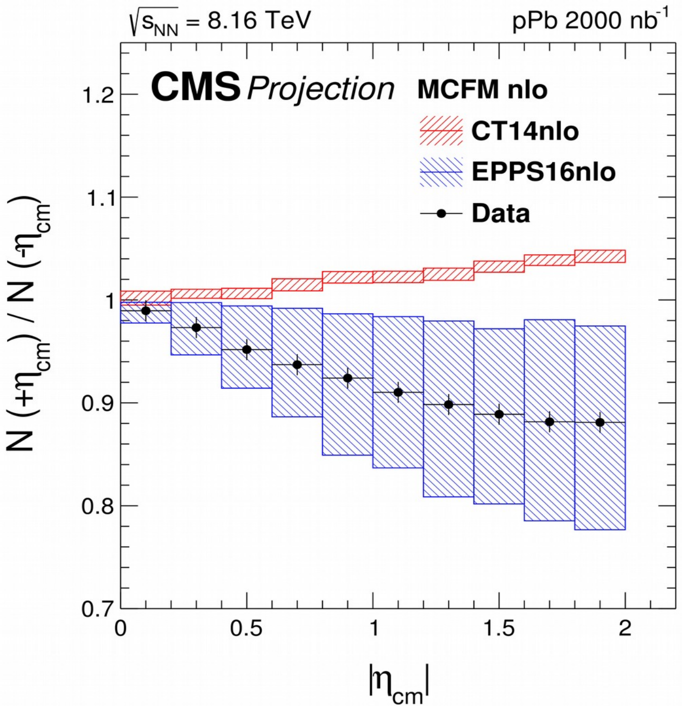
Observation of nuclear modifications in W production

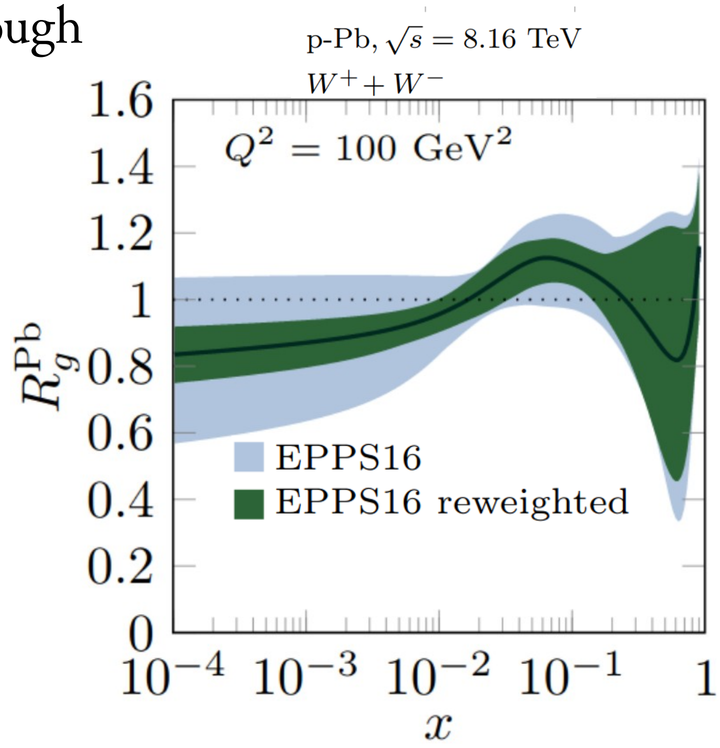
Phys. Lett. B **800** (2020) 135048

- W boson asymmetry measurement with Run **2** data
  - in pPb collisions at 8.16 TeV
  - results favour nPDF calculations
  - can provide **constraints** on the nPDF global fits
    - gluons but also light sea quarks



- 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

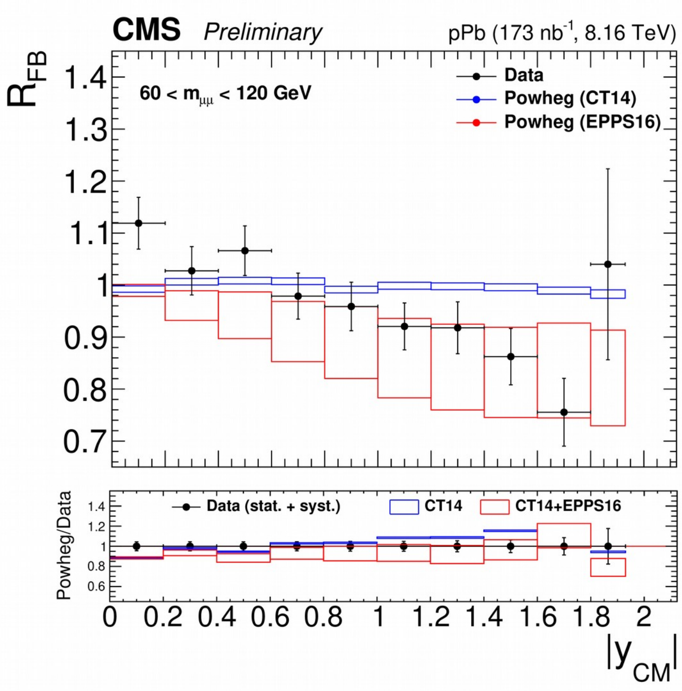


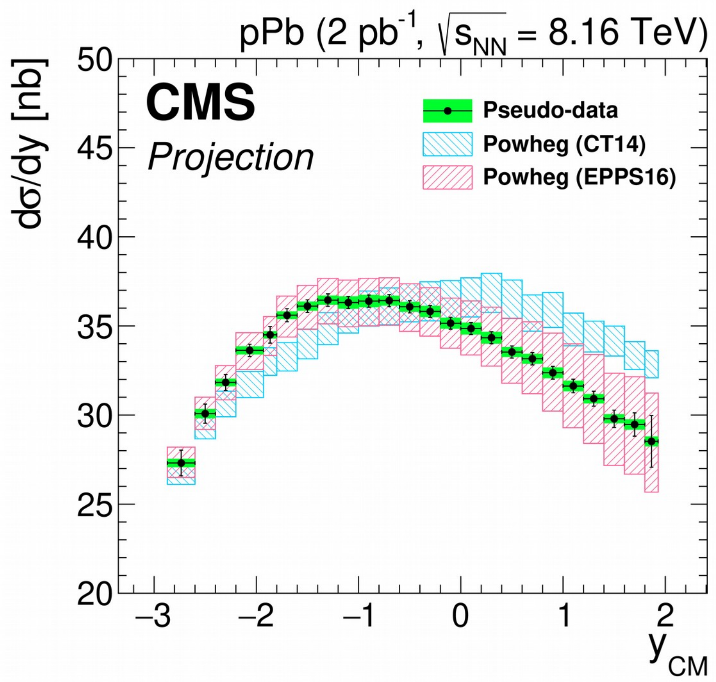


Differential cross sections for the Drell–Yan process

- dσ/dX and proton- over Pb-going ratios with Run **2** data at 8.16 TeV
  - including, but not restricted to, Z boson production
  - results **already favor** nPDF calculations too

CMS-PAS-HIN-18-003

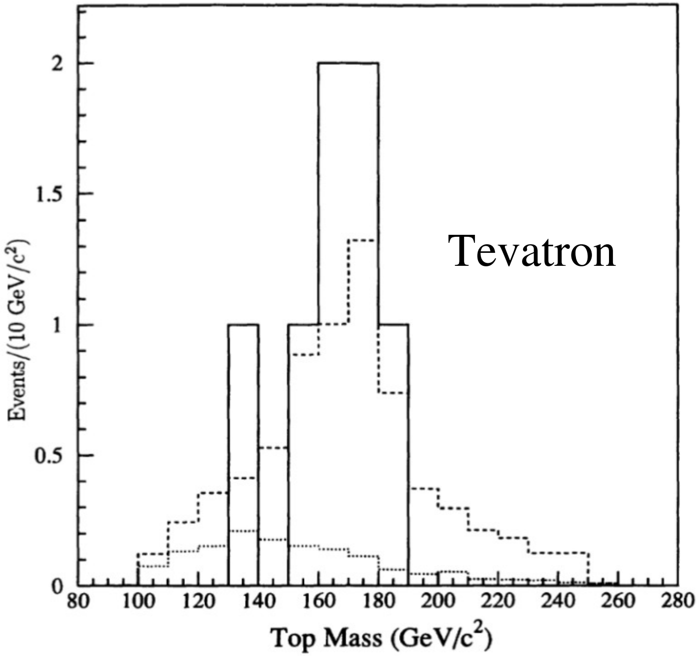




Observation of top quarks in pPb collisions

- Performed in the semileptonic final state with Run **2** data at 8.16 TeV
  - events with ≥ 2 b jets: **background-free**
  - results not yet sensitive to nPDF vs PDF difference (e.g., a mild increase relative to pp)

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



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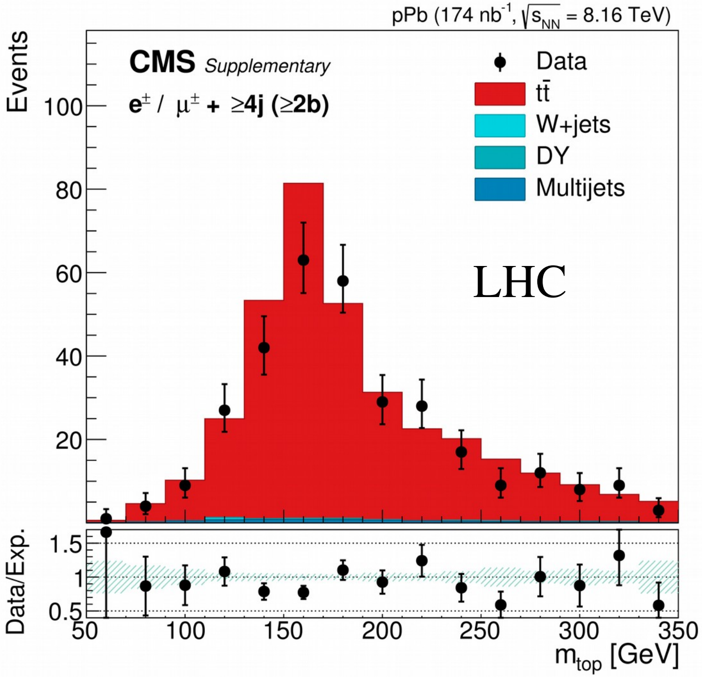
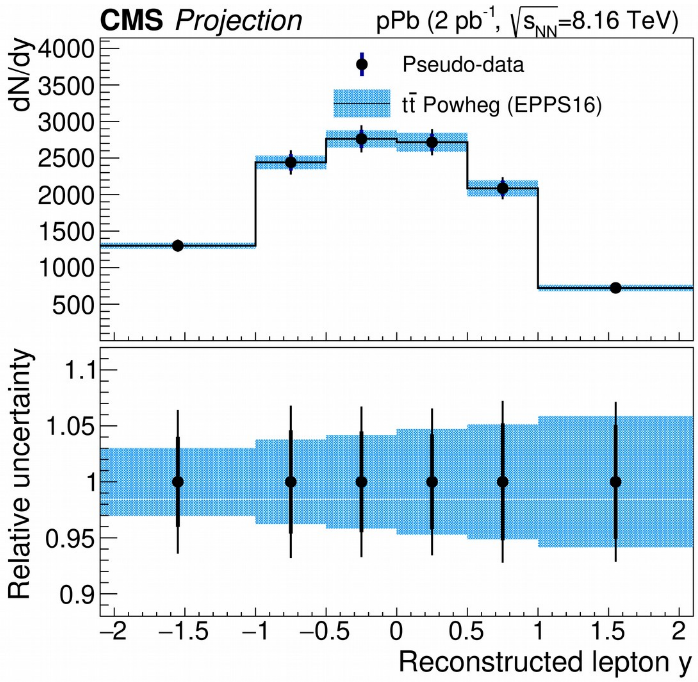
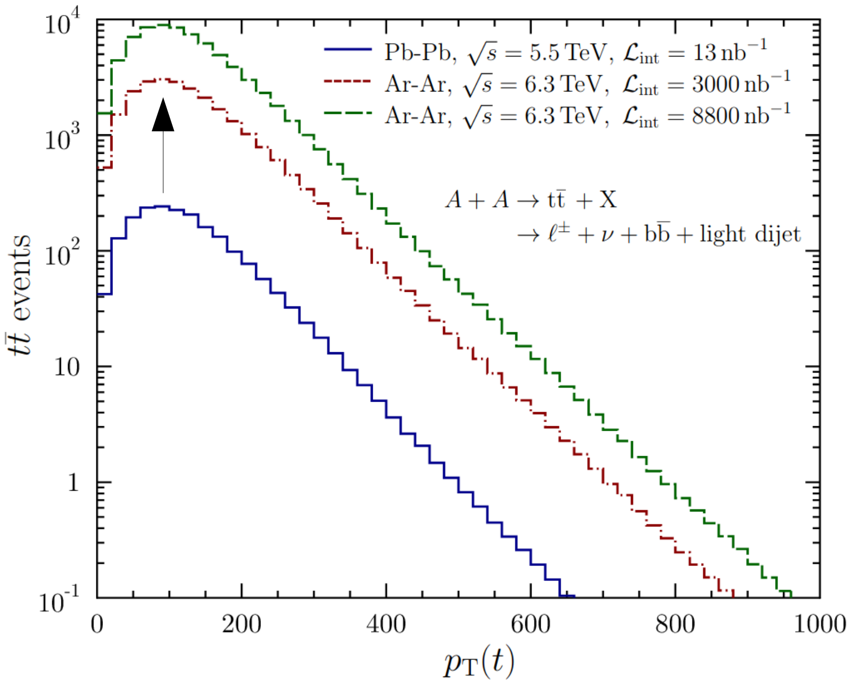


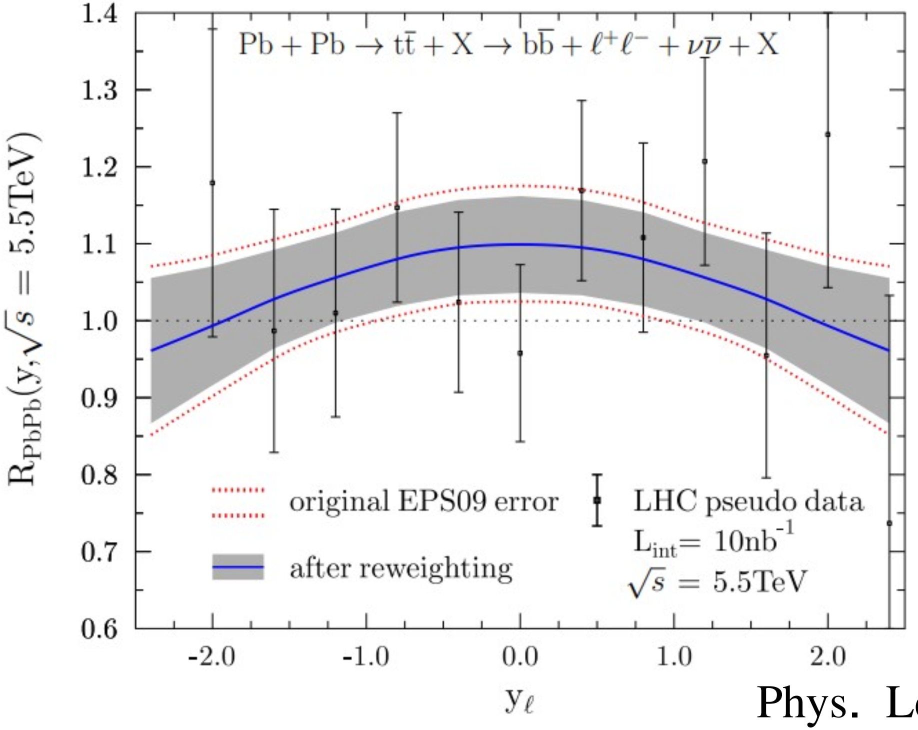
Prospects for top quark production at pA HL-LHC

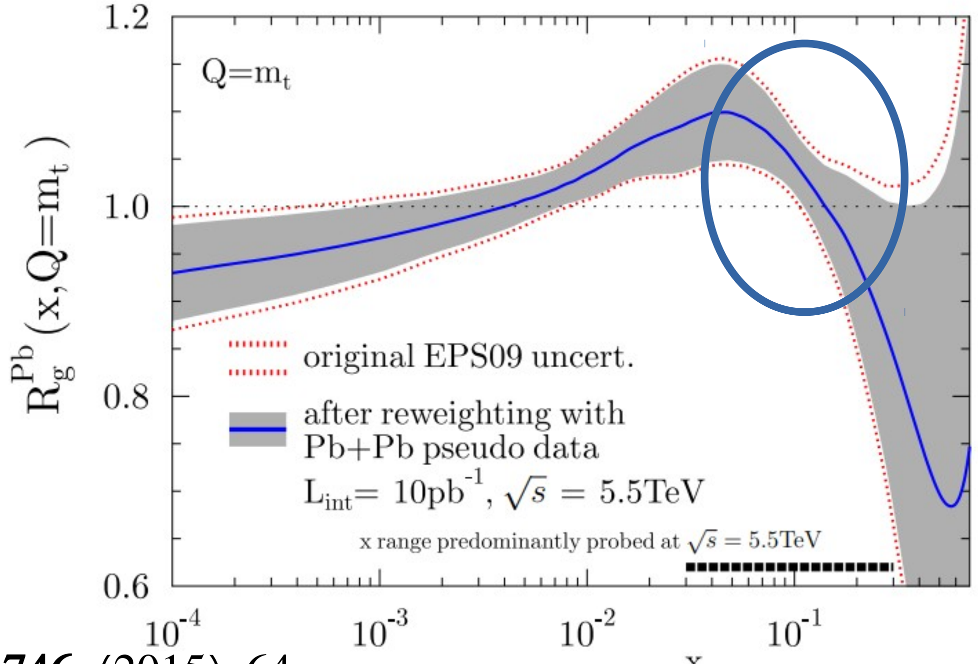
- The y of the decay leptons sensitive probe of the nuclear gluon density
  - **comparable** experimental and nPDF uncertainty with the pPb data set in Runs 3–4
    - depending on the expected systematic error and bin-by-bin correlations
  - to showcase **another potential**: In a pAr mode, the higher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





Prospects for top quark production at AA HL-LHC



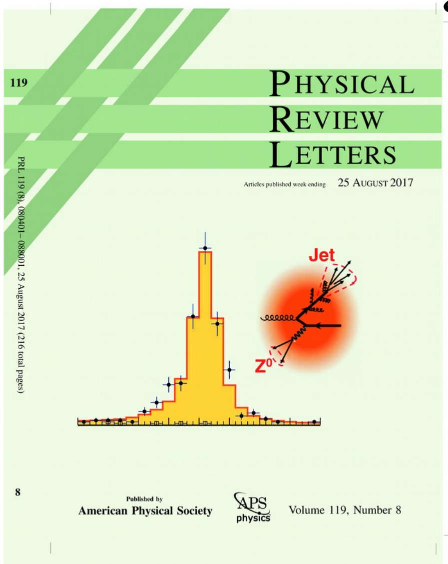


Phys. Lett. B **746** (2015) 64

- 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)

"Unveiling the yoctosec structure of the QGP"

- Jet quenching probes, e.g., so far dijets, Z/ɣ+jet, are produced **simultaneously** with the collision
- Top decay products have the potential to **resolve** the QGP evolution
  - Leptonic & hadronic branches as "tag" & "probe"
    - qq' start interacting with the medium at **later** times
    - but how we trigger on the onset?


119
PHYSICAL REVIEW LETTERS
Articles published week ending 25 August 2017
PRL 119 (8), 080401–088001, 25 August 2017 (216 total pages)
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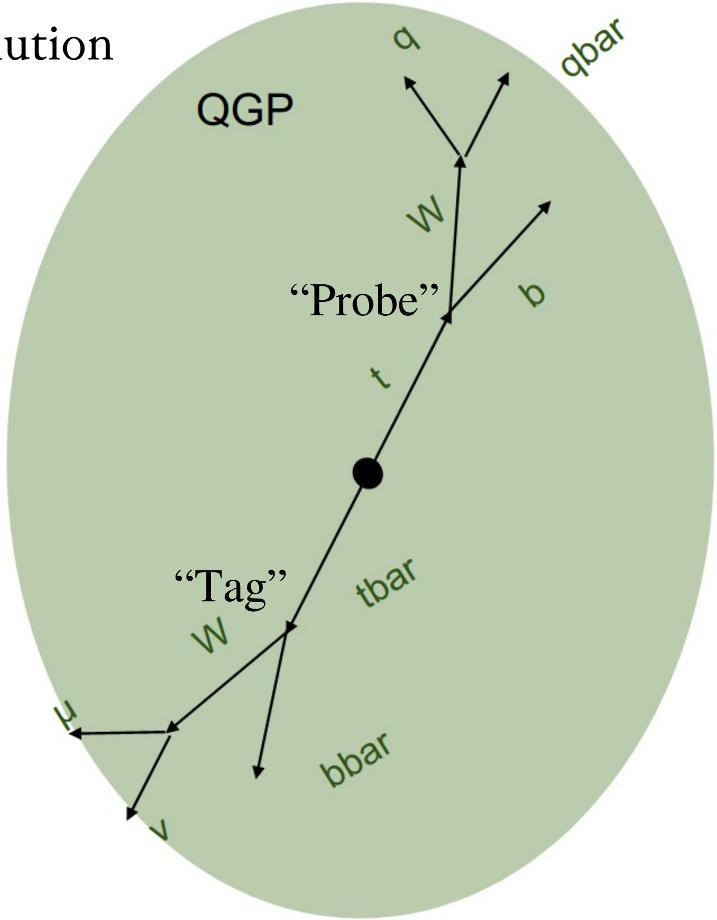
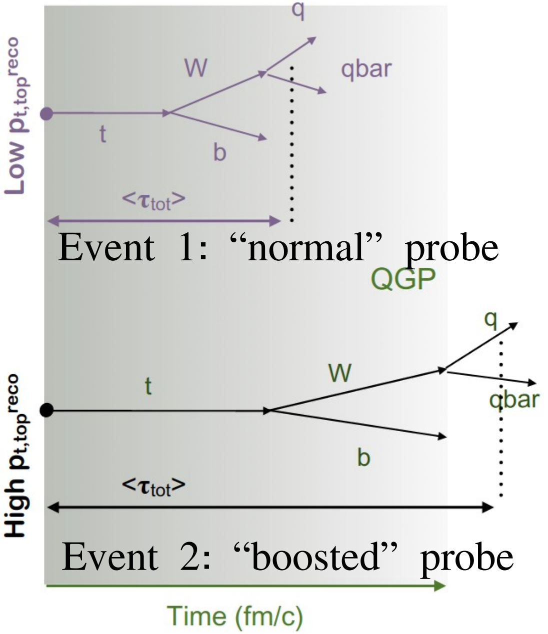
Published by American Physical Society
APS physics
Volume 119, Number 8

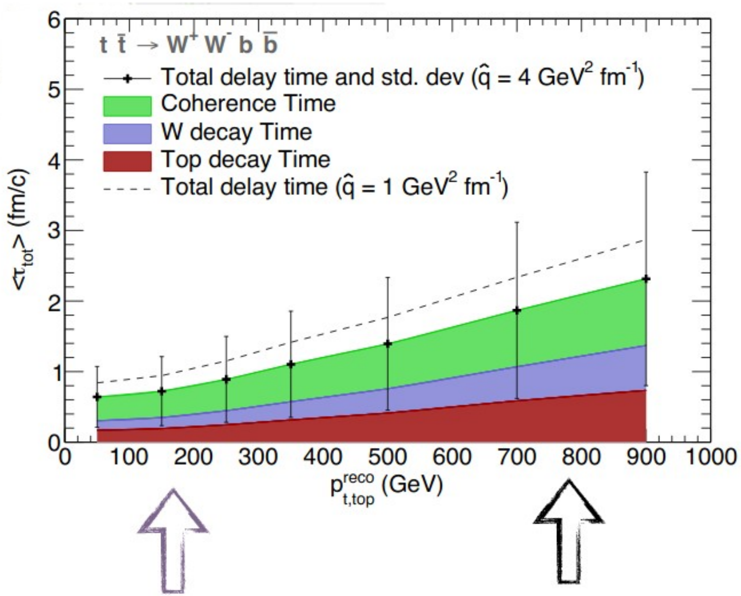
Phys. Rev. Lett. **119** (2017) 082301



The W → qq' "antenna" as time delayed probe

- The series of time delays are **correlated** with top quark p_T
- $t_{tot}\,(p_T) = t_{top} + t_W + t_d$
  - t_d : time at which the qq' decoheres and increases further the delay on top of $t_{top} + t_W$
- Setup a **toy** model in which qq' is allowed or not to loose energy, e.g., ∝ L





Transverse boost factor (top and W):

$$\gamma_{t,X} = \left(\frac{p_{t,X}^2}{m_X^2} + 1\right)^{\frac{1}{2}}$$

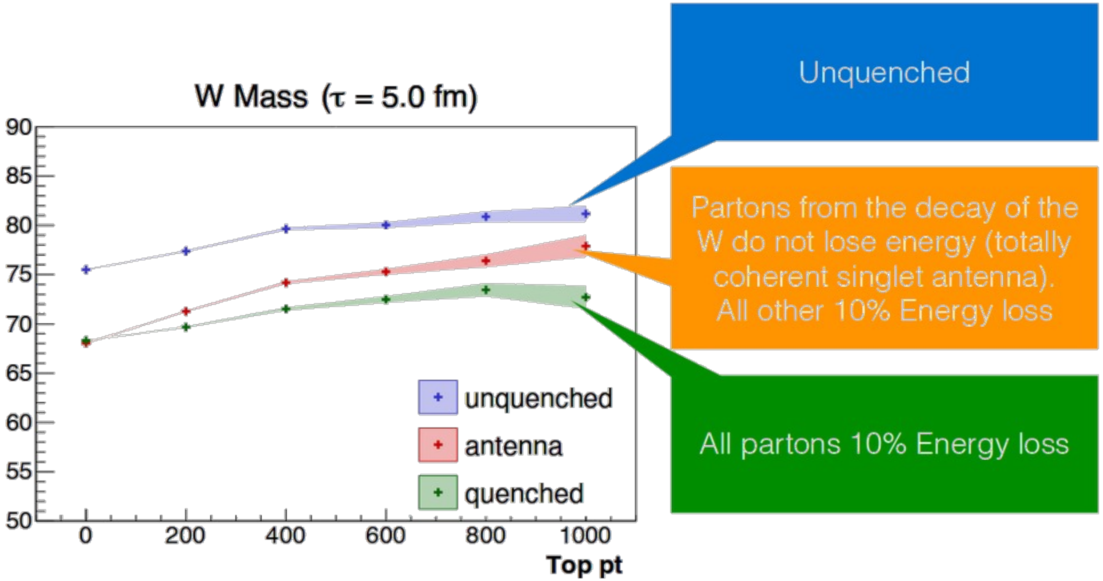
Coherence time (q - qbar antenna):

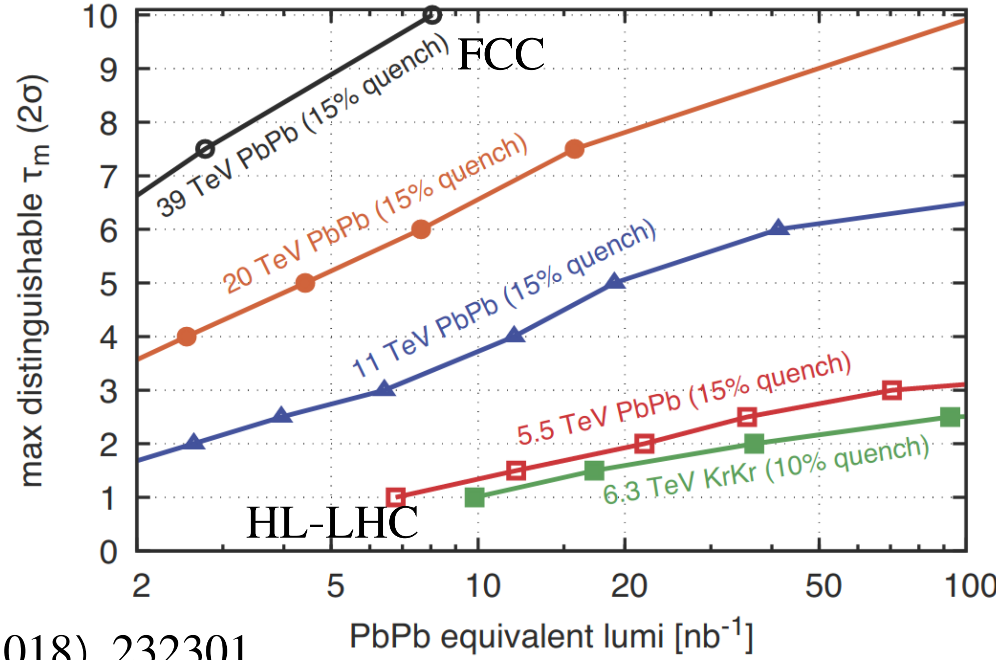
$$t_d = \left(\frac{12}{\hat{q}\theta_{q\bar{q}}^2}\right)^{1/3}$$

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

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)





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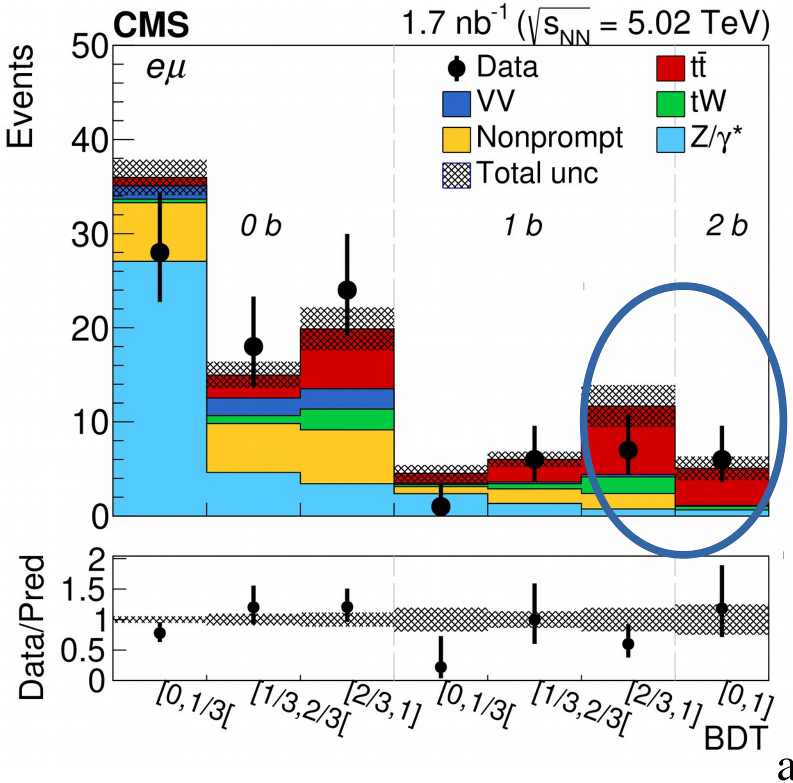
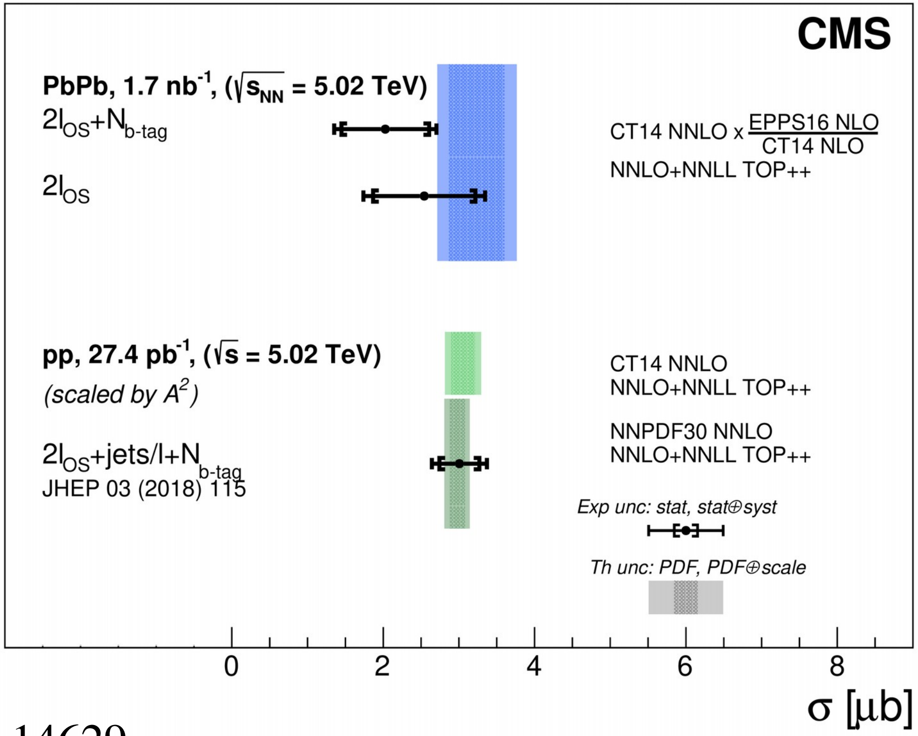
Evidence of top quarks in PbPb collisions

- 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

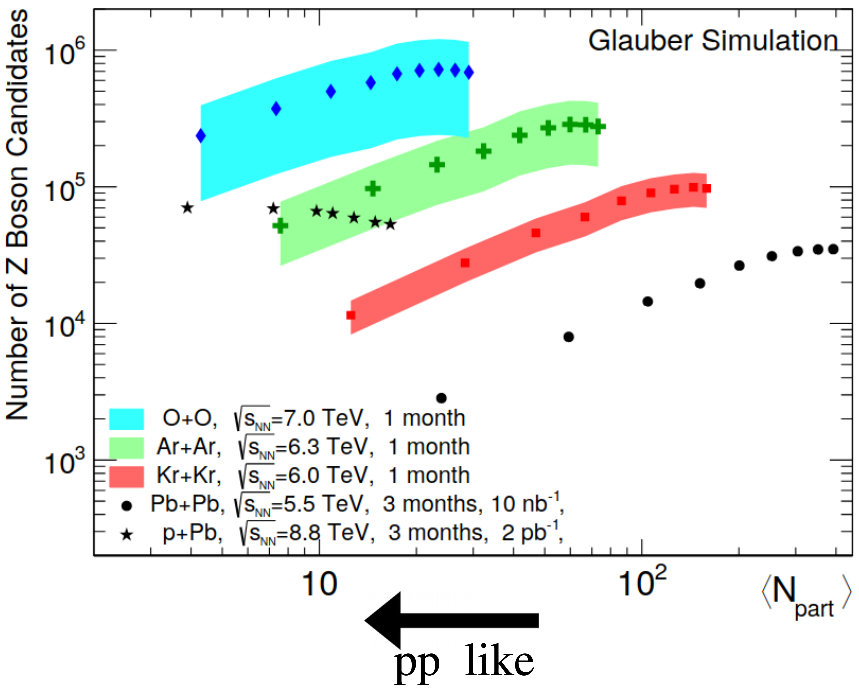


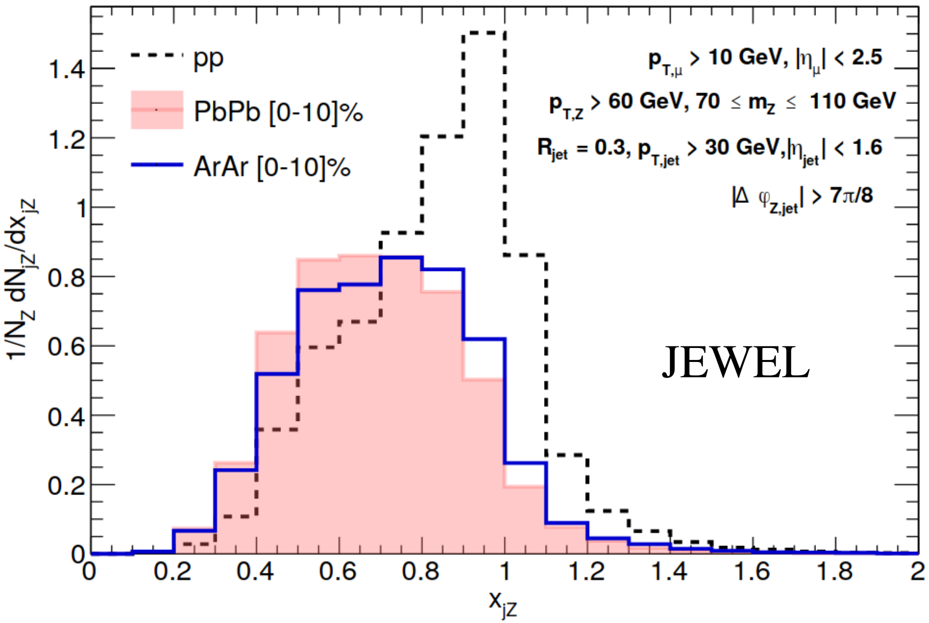


arXiv: 2006.14629

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





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

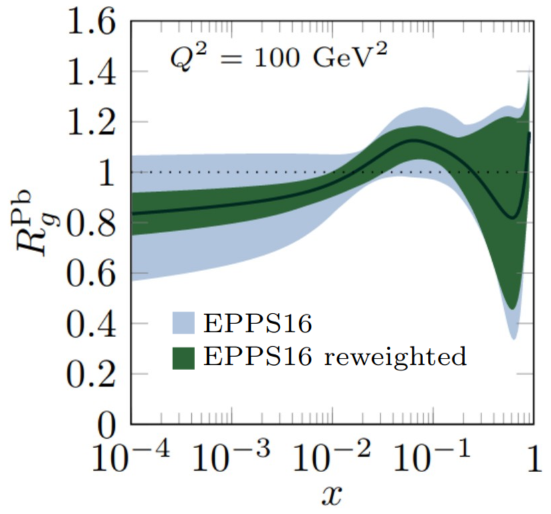
M. Krasny, ICHEP2020

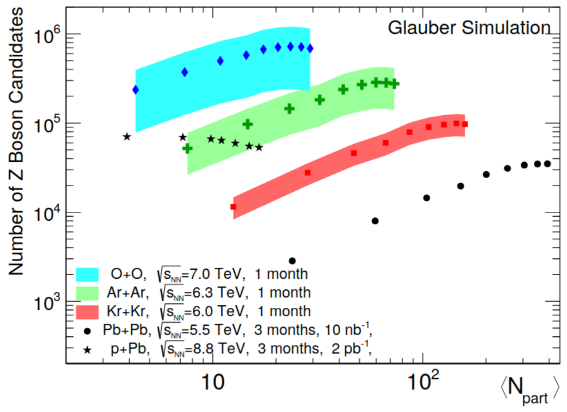
Parameter	Value
$s^{1/2}$ [TeV]	7.
$\sigma_{BFPP}(Ca)/\sigma_{BFPP}(Pb)$	5×10^{-5}
$\sigma_{had}(Ca)/\sigma_{tot}(Ca)$	0.6
N_b	3×10^{9}
$\varepsilon_{(x,y)n}$ [μm] (1)	**0.3** →
IBS [h]	1-2
β* [m]	0.15
L_{NN} [cm-2s-1]	**4.2×10^{34}**
Nb of bunches	1404
Collisions/beam crossing	5.5

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

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 lighter ions
- To refine modeling of dilute systems and optimize their choice
  - the available info already indicates the potential of **lighter** systems
    - isoscalar beams even **complementary** choice to HL-LHC pp
  - of relevance for **BSM** searches too (e.g., J Phys G **47** (2020) 060501)





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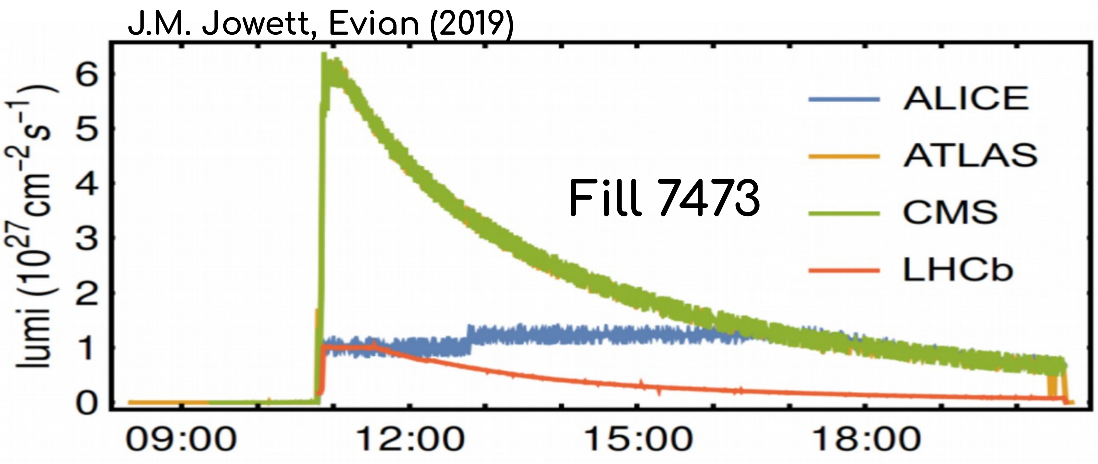
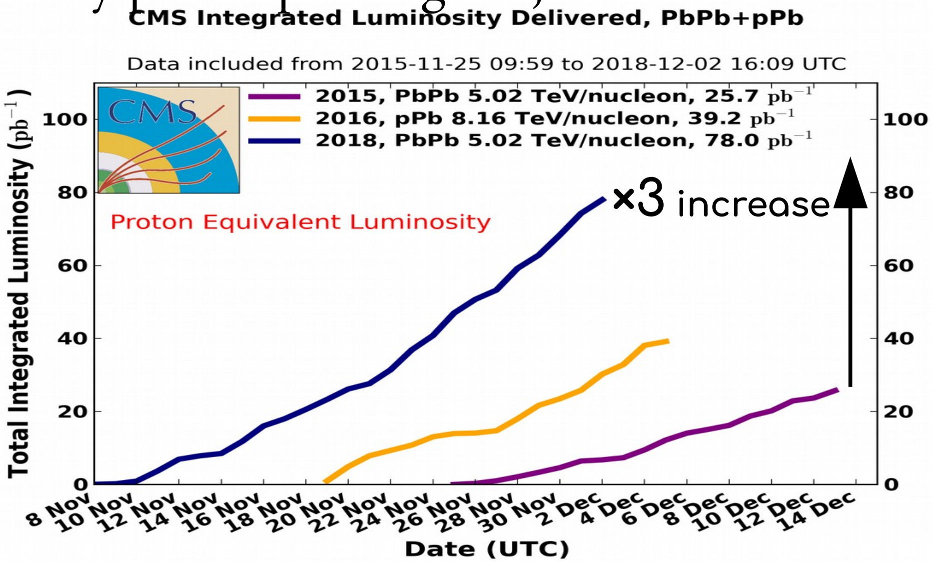
Surpassing the baseline luminosity goals

- 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





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