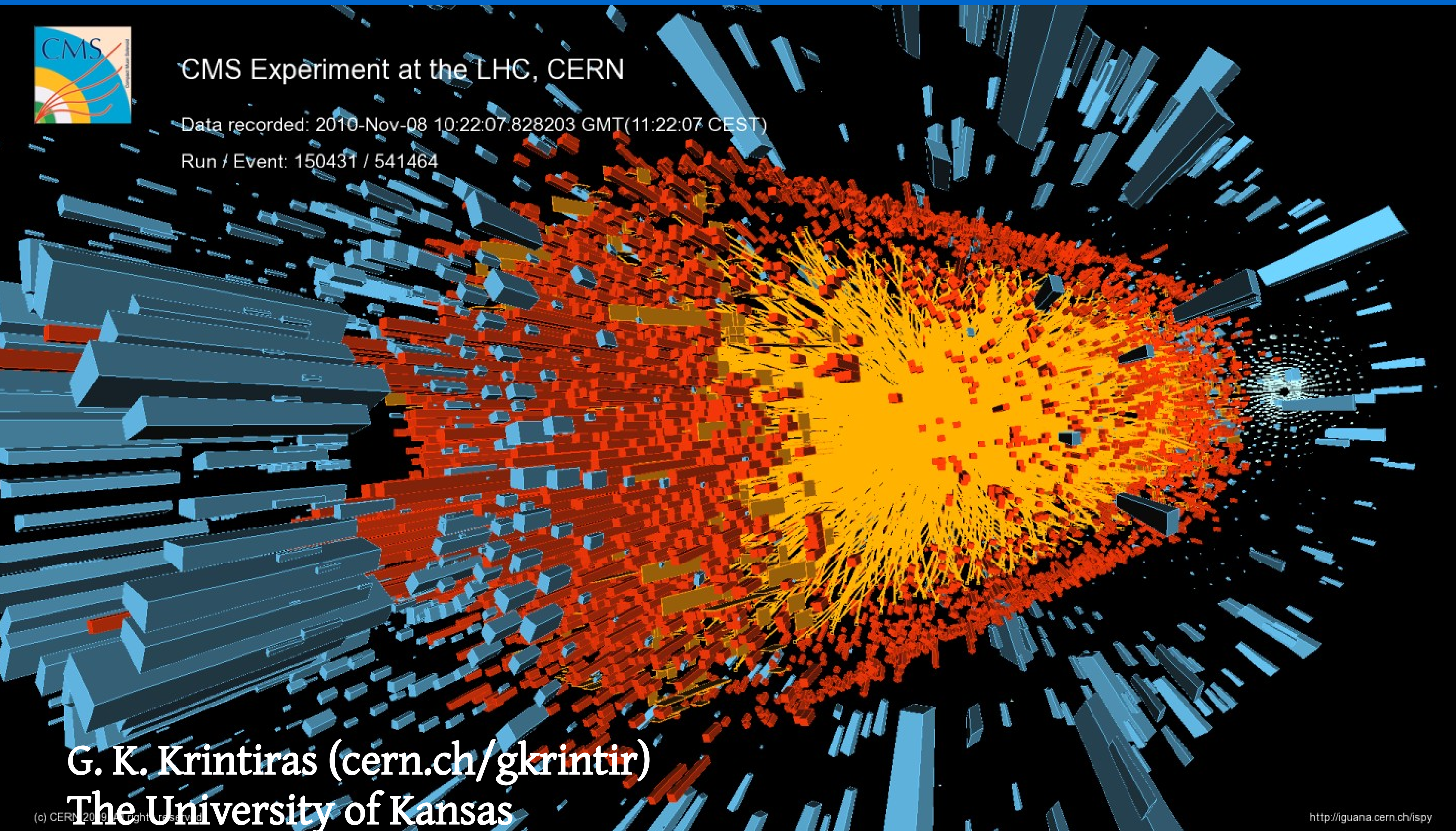
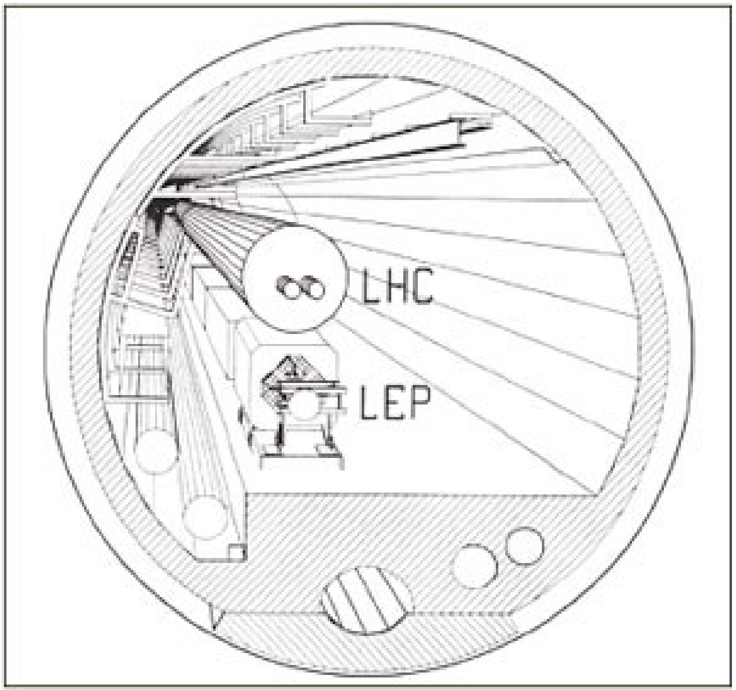
Heavy ion collisions at LHC (with focus on CMS results)

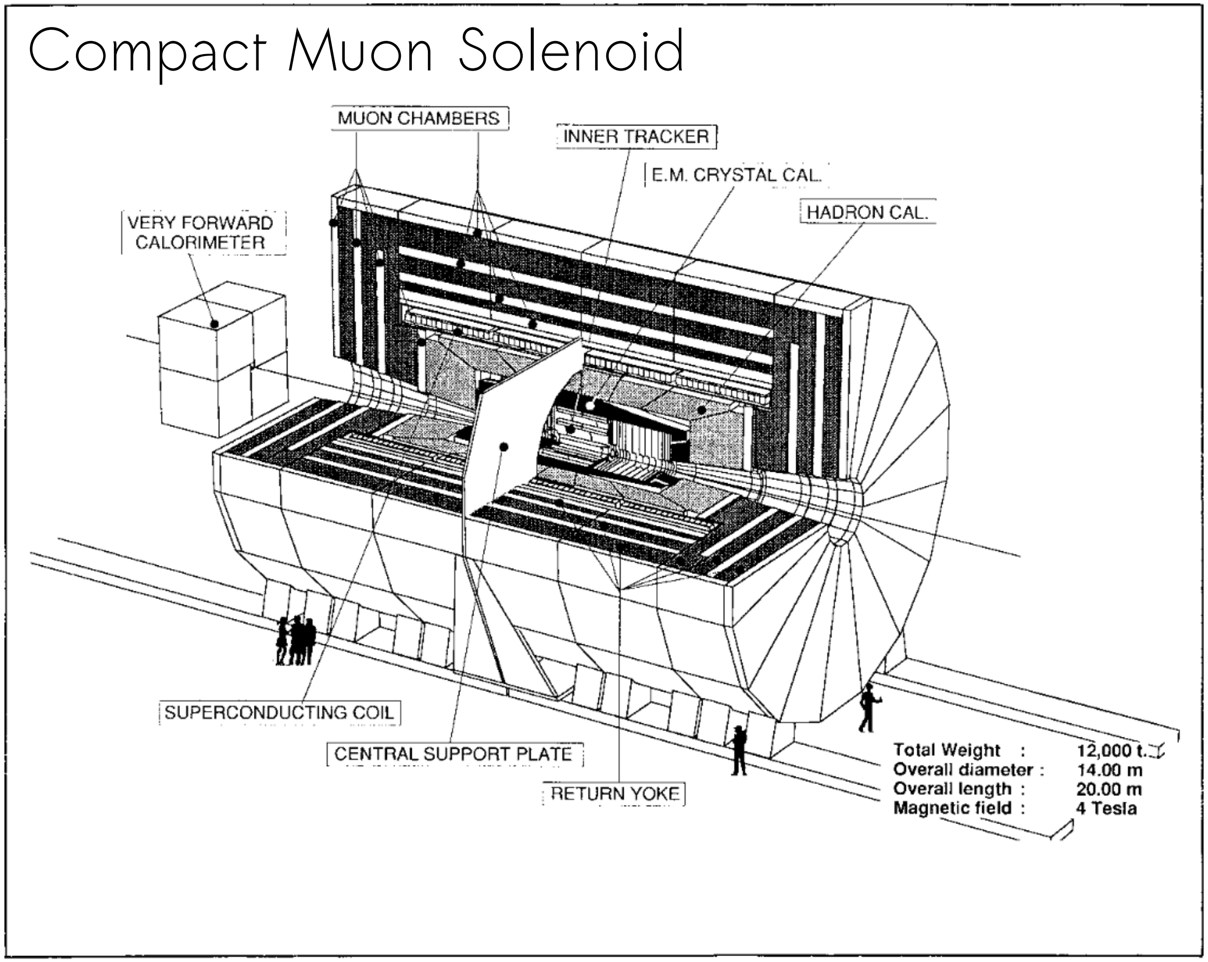


G. K. Krintiras (cern.ch/gkrintir)
The University of Kansas

What's after the Large Electron–Positron Collider (1989-2000)?



Lausanne LHC workshop (1984)



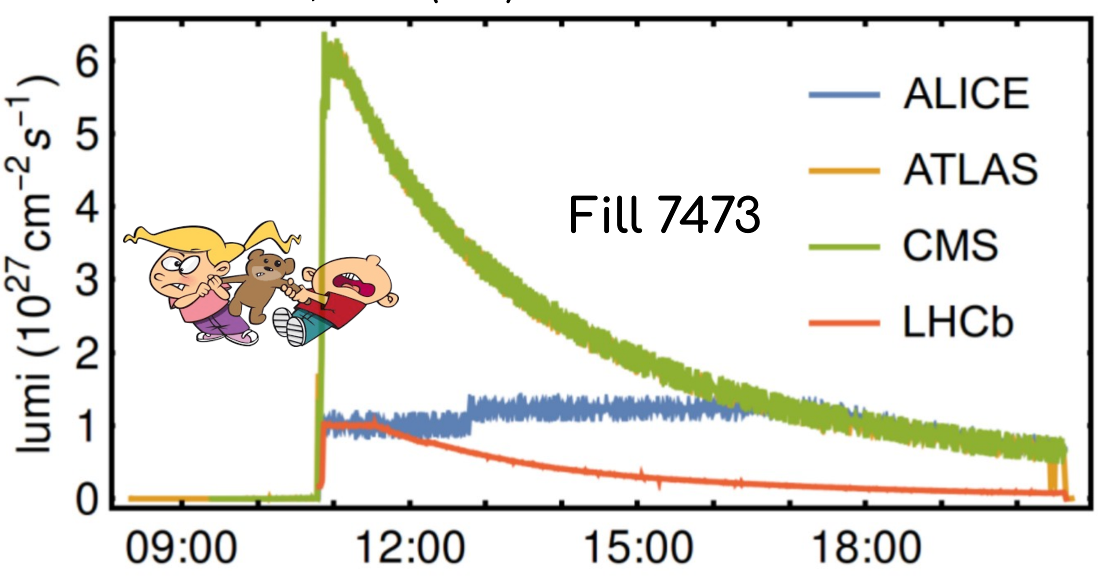
Evian "debut" (1992)

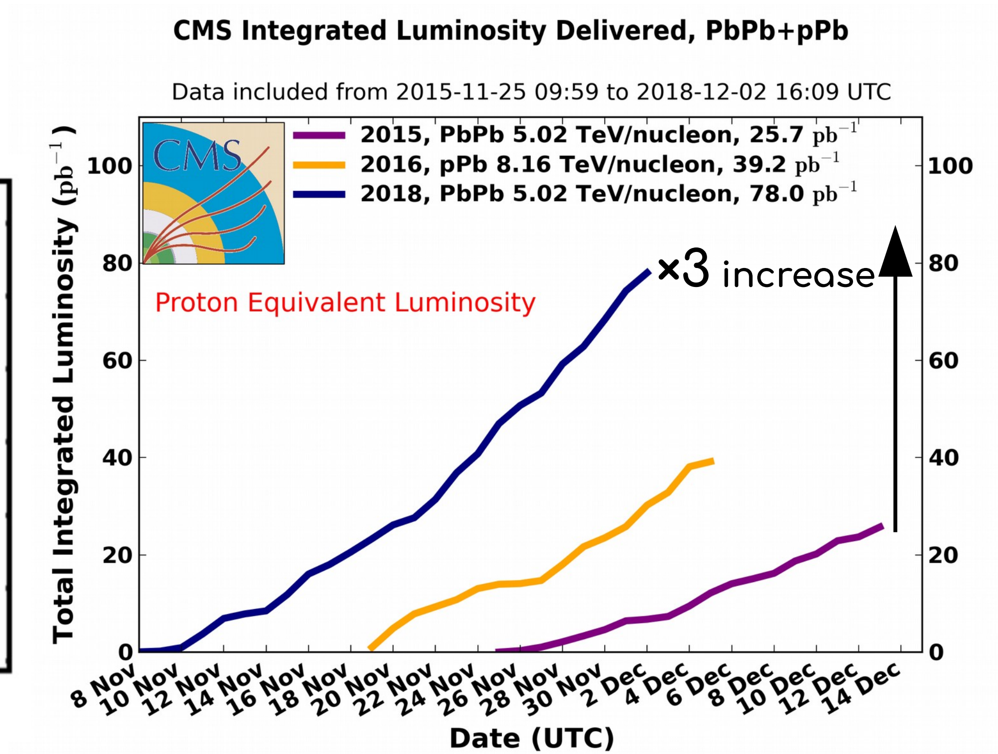
- The infrastructure for *a* **Large Hadron Collider** (LHC), if any, would be driven by
  - the existed tunnel (radius and size) and its injectors: "Multipacket" collider + **10 T** magnets
  - *Expressions of Interest* in 1992: LHC to handle proton and lead **ions**

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

J.M. Jowett, Evian (2019)

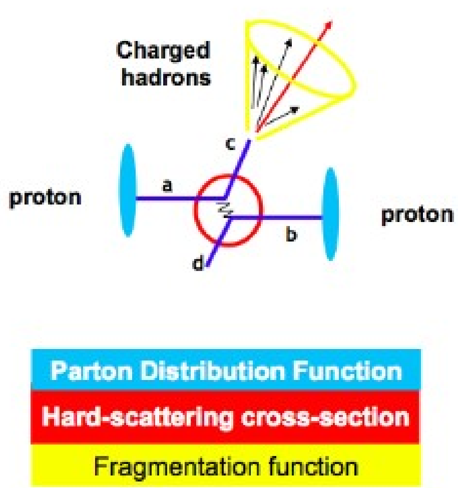




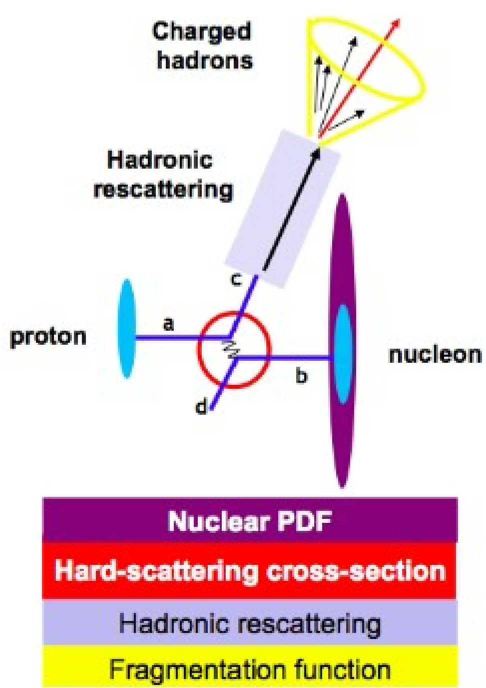
Searches for high-density QCD phenomena

- Look at “elementary” pp and pA collisions
  - Measure an observable, e.g., p_T-dependent ϕ correlations (“soft”), jet production (“hard”), etc
- Look at heavy ion (AA) collisions
  - Measure the very same observable as in pp, pA collisions
- Compare them: Is there something new, e.g., **modified** particle production in the bulk/within jets?

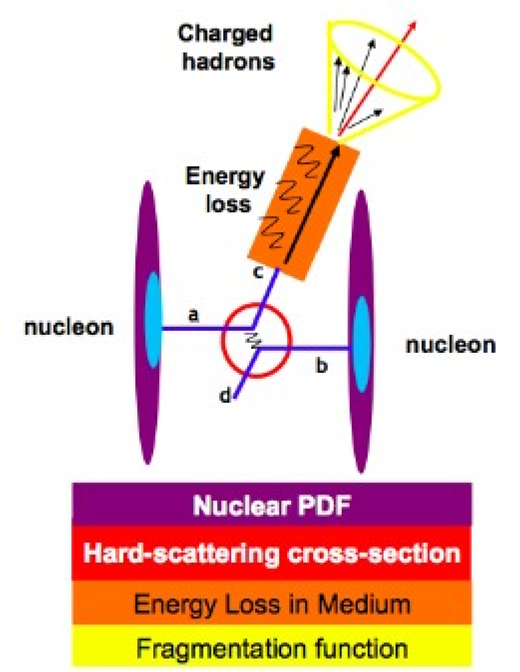
pp



pA

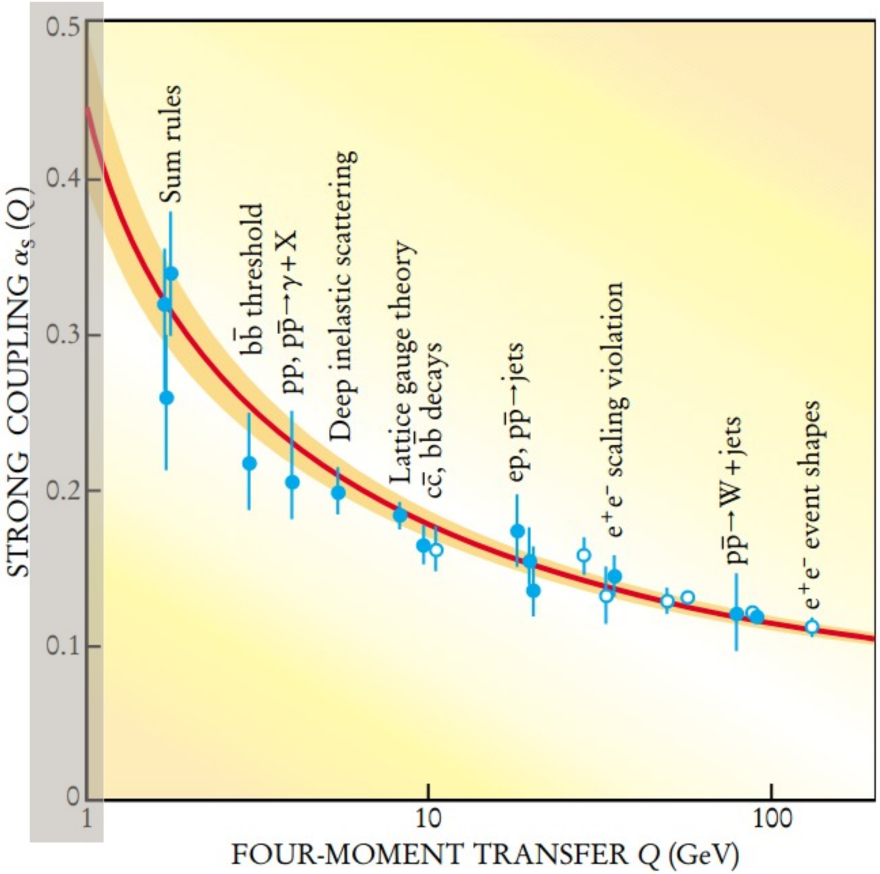


AA



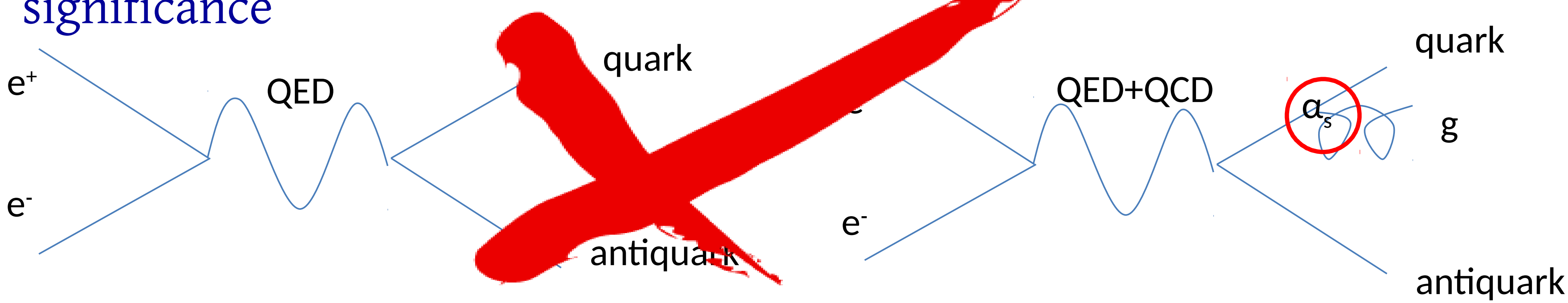
But why QCD is called the strong interaction?

Physics Today **53** (2000) 8

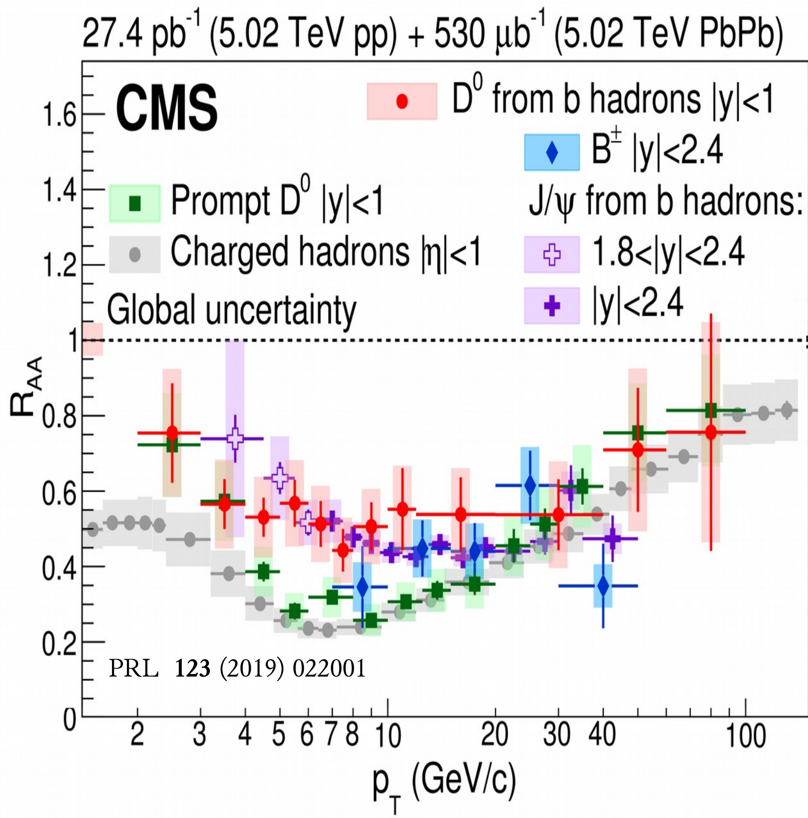


- Hard scattering cross sections calculable
  - **provided** the scale μ is chosen large
- Does the large-distance behavior of QCD implies
  - a transition region where "color" degrees of freedom dominate?
  - I.e., a **deconfinement** phase exists?

Large coupling → we cannot verify by sequentially adding terms of lower significance



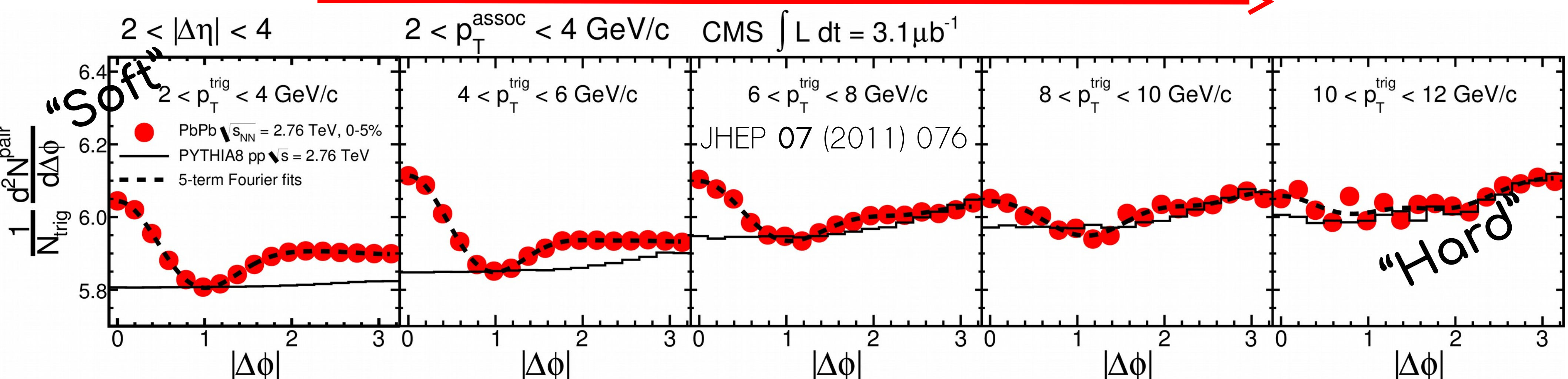
QGP: the form that the early Universe existed in



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

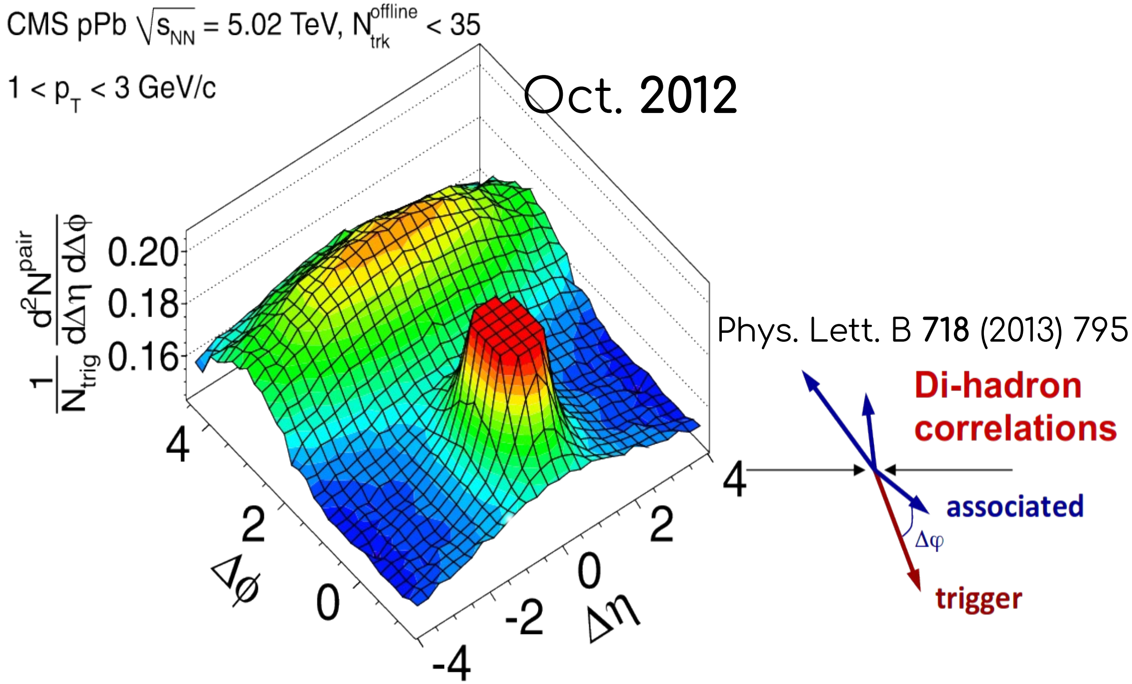
- Energy of partons is lost ('quenched') in QGP
  - experimentally seen as R_{AA} **modifications**
- Different mechnasims for hadron formation
  - p_T -dependent ϕ **correlations**

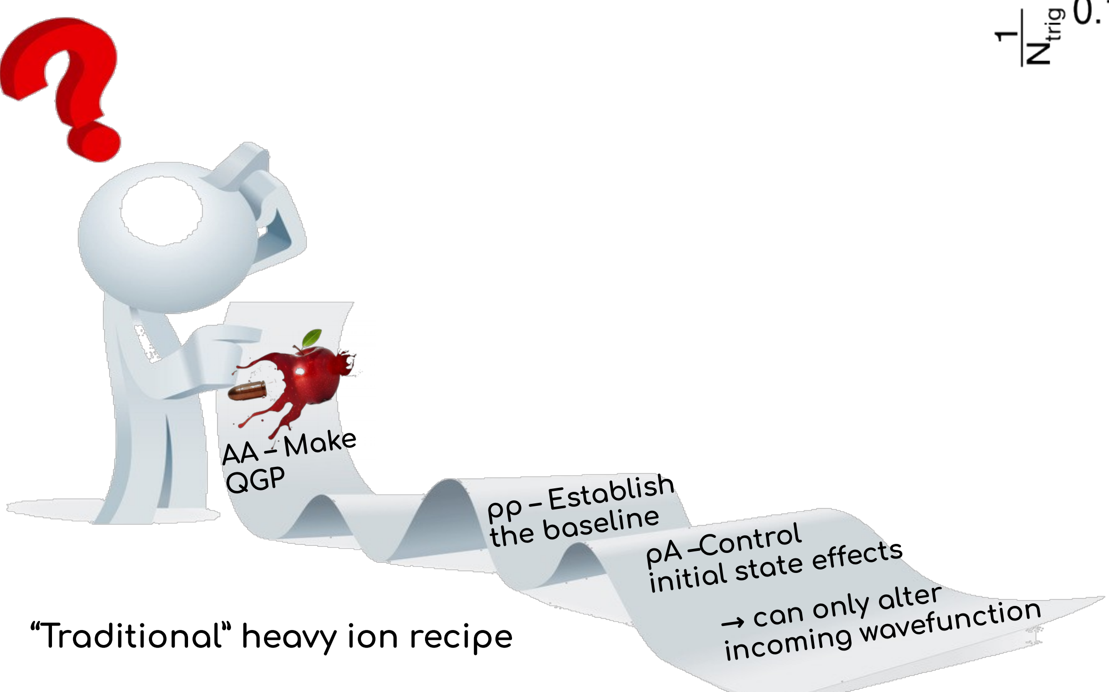
A fluid that retains its QCD **asymptotic freedom** character!



Throwing a bullet through an apple... Why?

- To probe **cold** QCD matter
  - Collisions of unequal species (proton-lead) @ LHC revealed **surprises**
    - signs reminiscent of a quark-gluon plasma (QGP)
    - interest exploded (the 5th most cited CMS paper in PLB!)





"Traditional" heavy ion recipe

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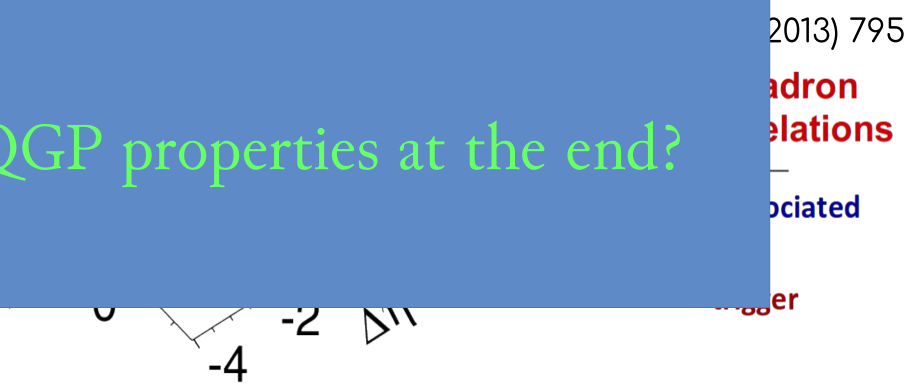
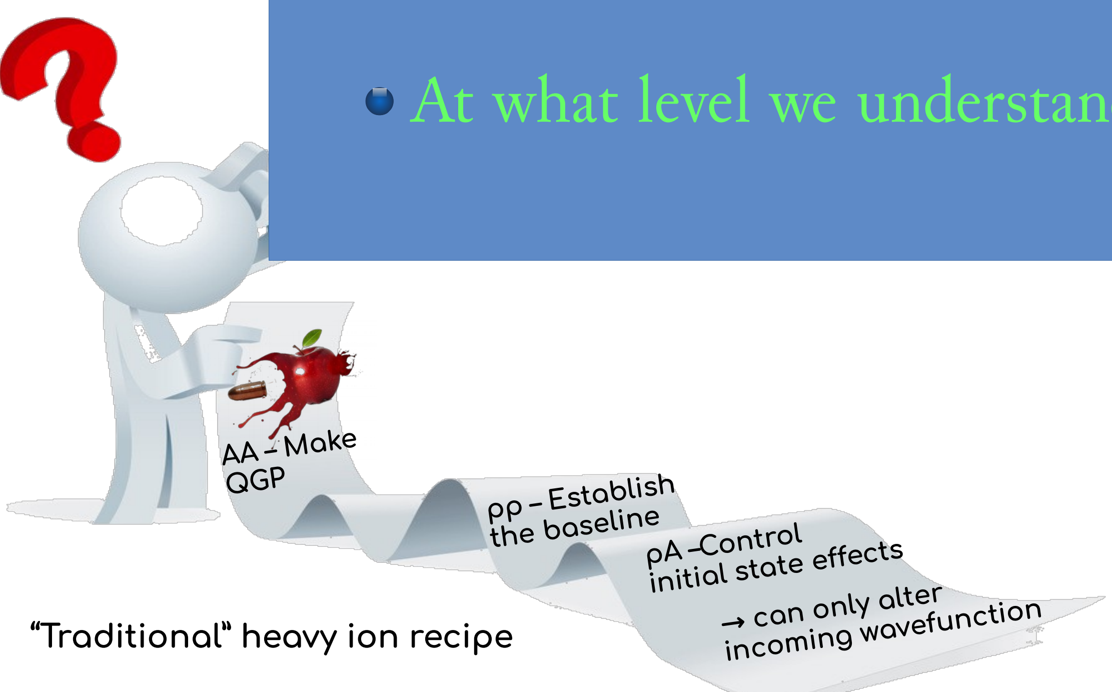


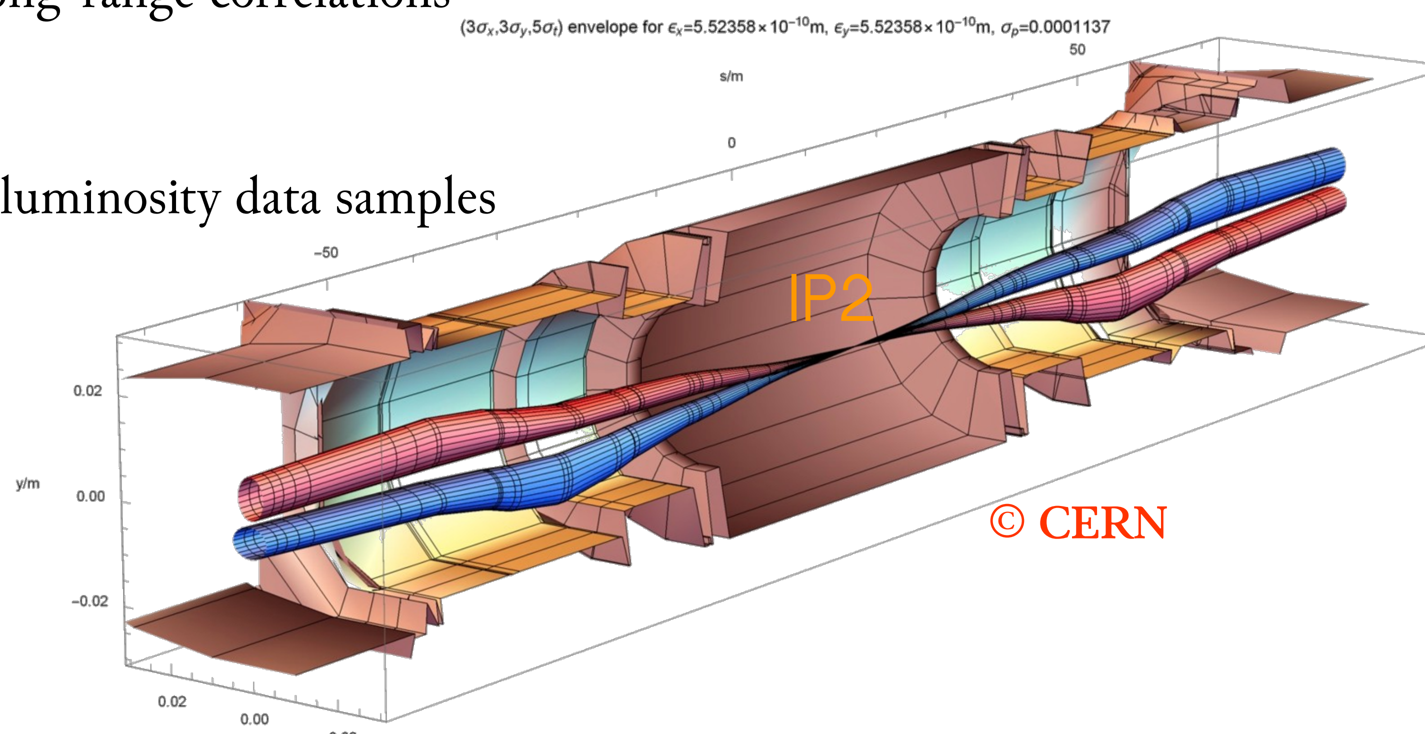
- Are pp and pA collisions AA alike?
- Complementary mechanism(s) for long-range correlations?
- At what level we understand QGP properties at the end?



“Traditional” heavy ion recipe

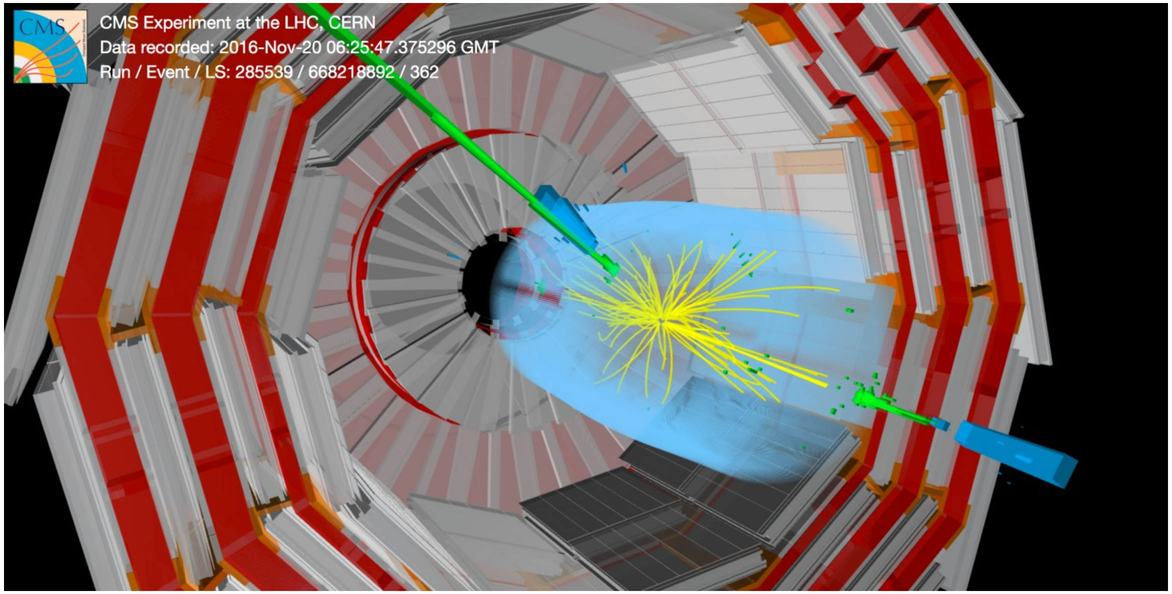
Studies with heavy ion collisions @ LHC

- Toolbox (**not exhaustive**) to infer from heavy ion and their "reference" collisions:
  - Hard probes and photon-induced processes
    - Nuclear PDFs, gluon saturation, BSM physics, etc.
  - Jet modifications
    - In-medium parton energy loss and medium response
  - Heavy quark dynamics
    - Hadronization and long-range correlations
  - New probes
    - accessible with high-luminosity data samples

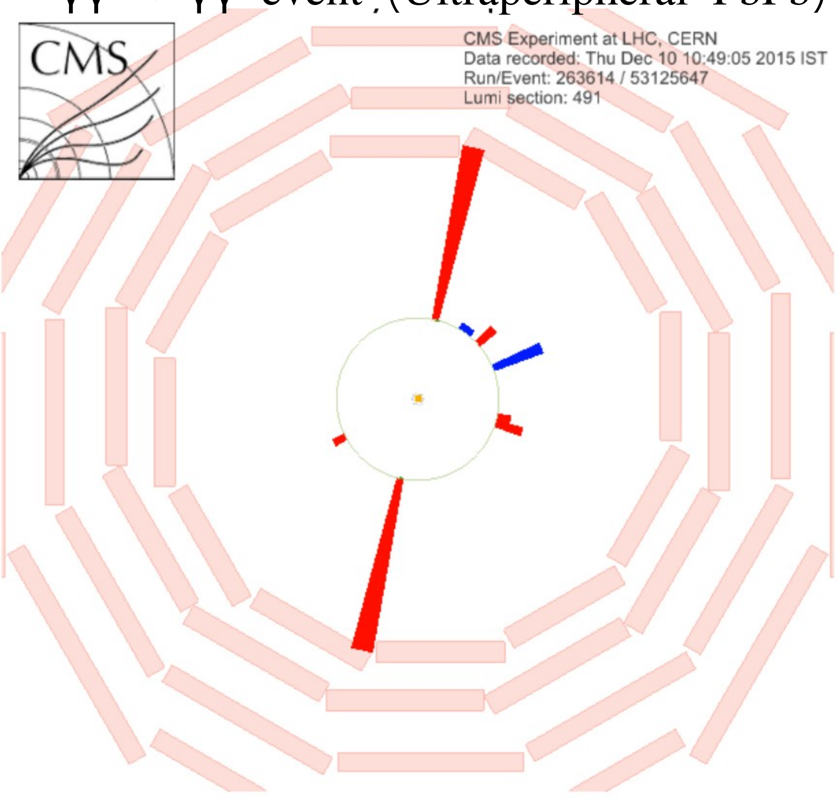


- Extended experimental toolbox to infer from heavy ion and their "reference" collisions:
  - **Hard probes and photon-induced processes**
  - Jet modifications
  - Heavy quark dynamics
  - New probes

Dijet event (pPb)



$\gamma\gamma \rightarrow \gamma\gamma$ event (Ultraperipheral PbPb)

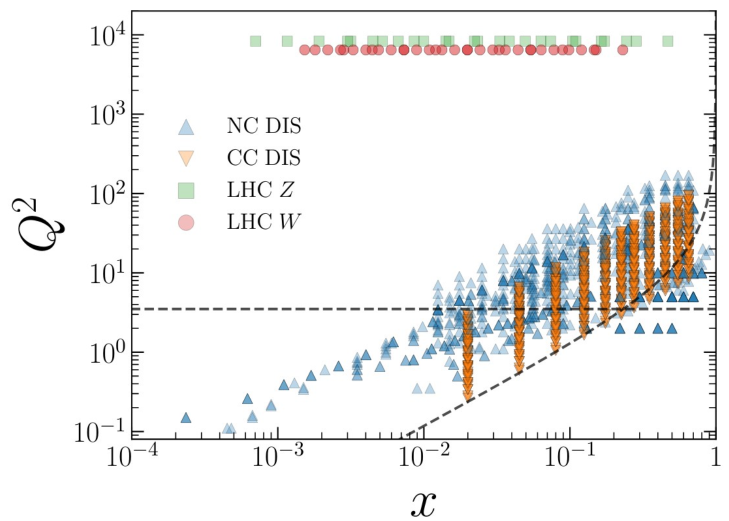


Key characteristics of the nPDF global fits

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	$\Delta\chi^2 = 35$	$\Delta\chi^2 = 52$	—	$\Delta\chi^2 = 50$

JHEP **09** (2020) 183



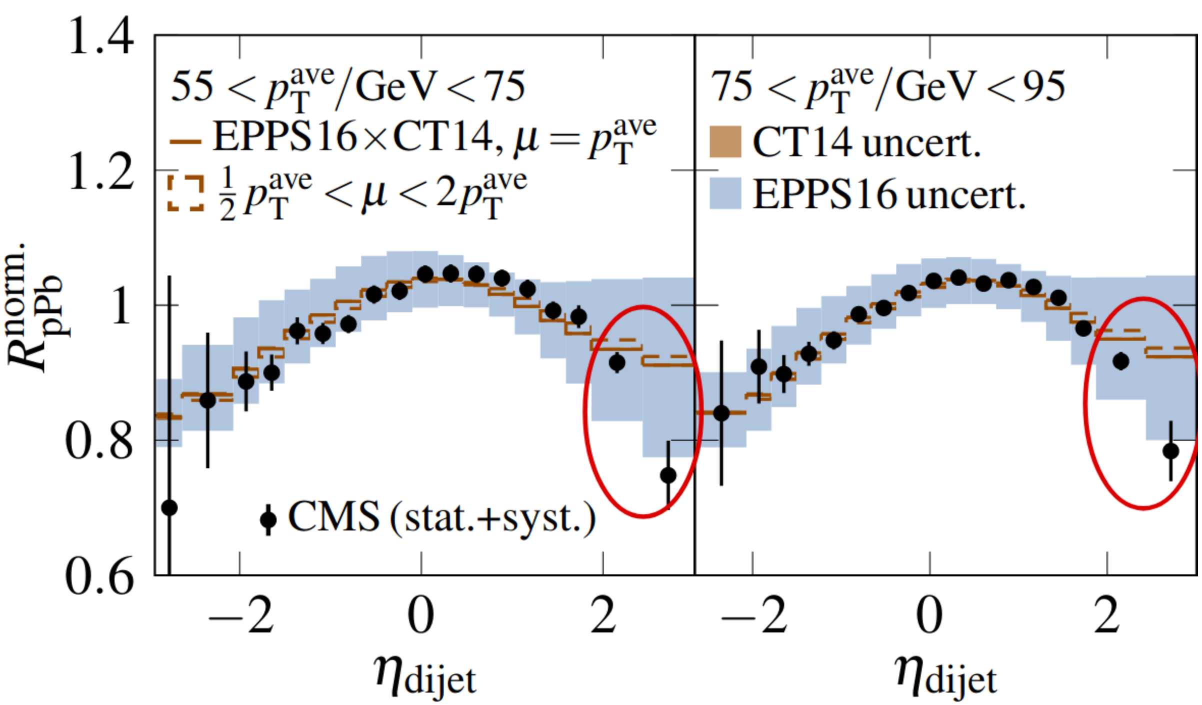
- nPDFs from **several** groups
  - less available data sets compared to the free-nucleon cases
  - different data sets (e.g., pPb LHC data), theoretical assumptions, and methodological settings
  - **not well** understood aspects, e.g., the nuclear modifications of the gluon distribution

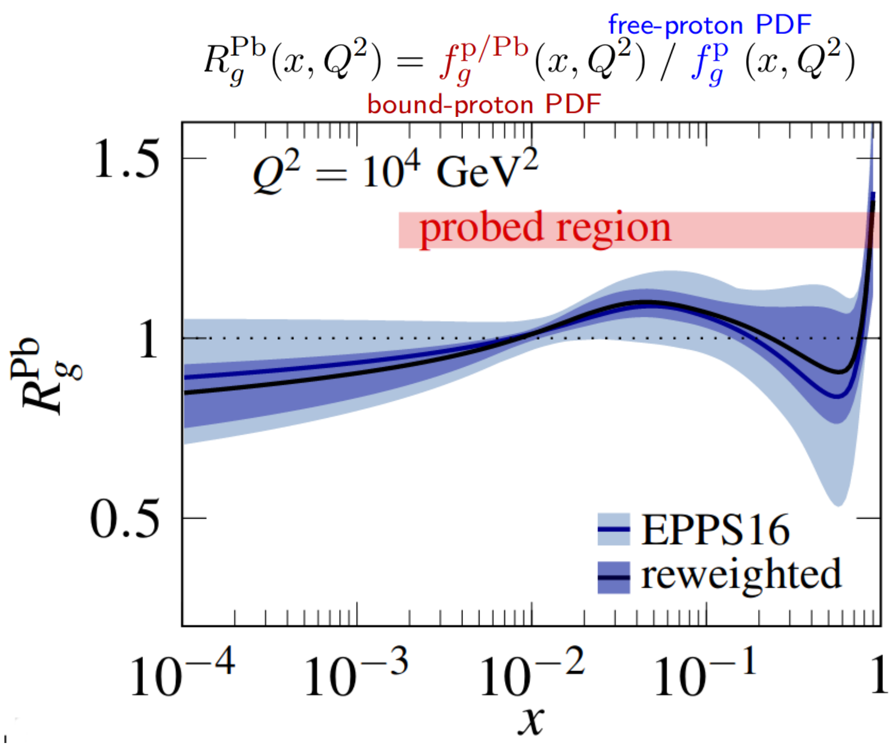
Nuclear gluon PDFs: constraints scarce so far

- 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





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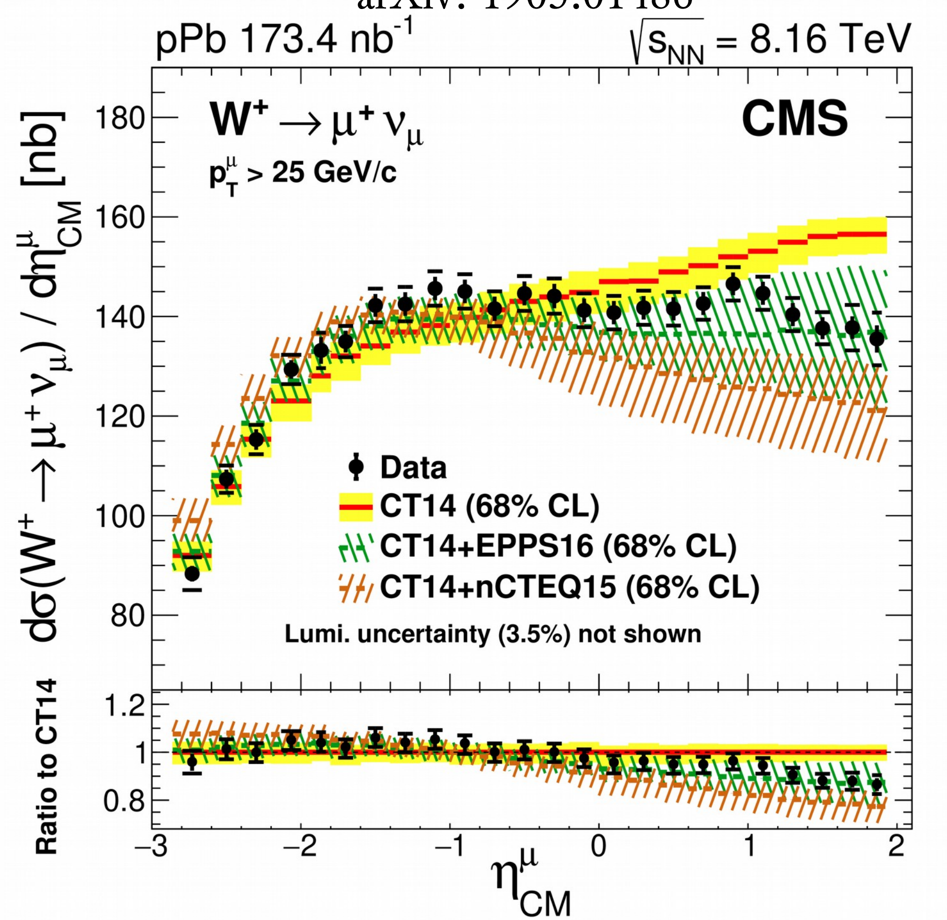
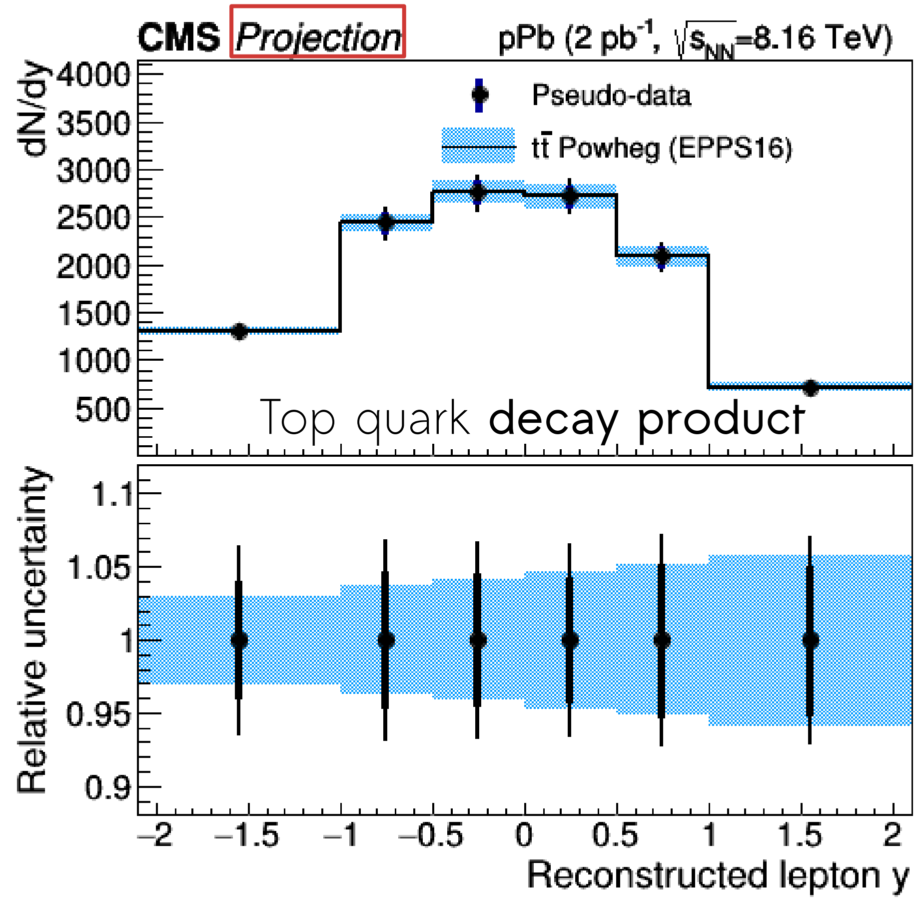
- Stringent constraints with CMS dijet events
- Data consistent with NLO pQCD predictions with nuclear PDFs (EPPS16)
  - Enhanced suppression at forward y
- Significant reduction in EPPS16 uncertainties after reweighting
  - Complimentary constraints using **W bosons** and **top quarks**

arXiv: 1905.01486



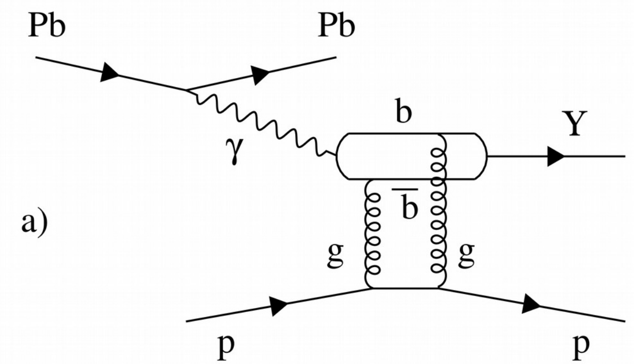
CMS PAS-FTR-18-027

(also in arXiv: 1812.06772)



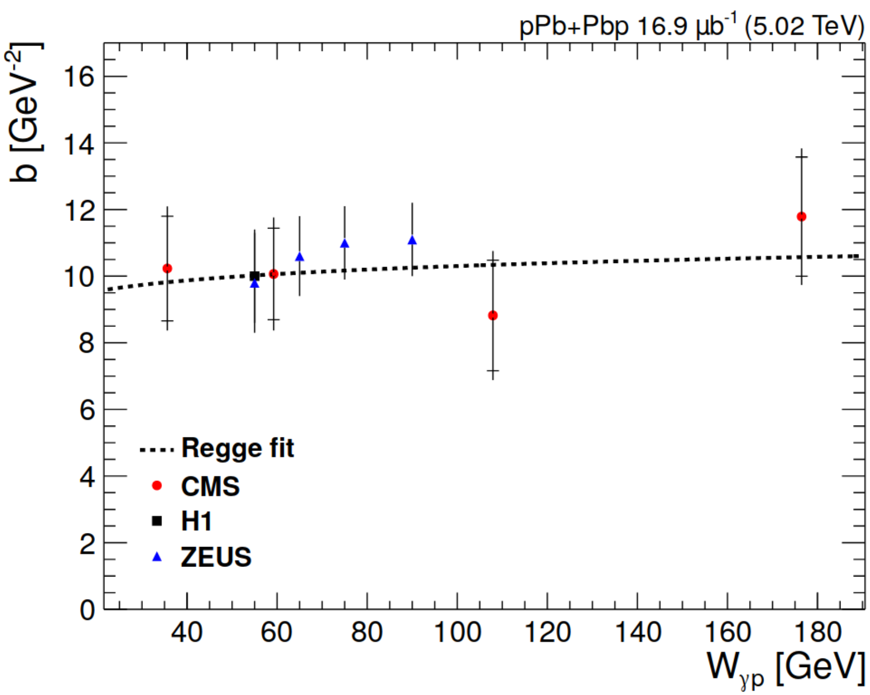
Exclusive vector meson photoproduction in pPb

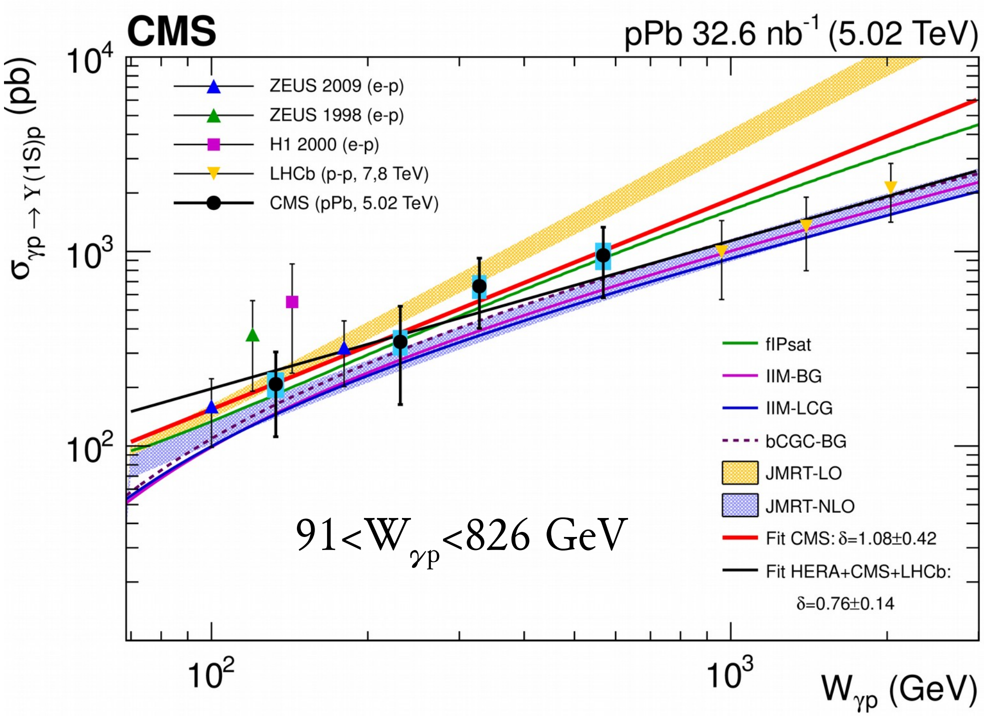
- Idea: Imaging proton using ions as a **photon source**
  - Probe gluon distributions at low $x \approx (M_{VM}/W_{\gamma p})$
- $\rho(770) \rightarrow \pi^+\pi^-$ exclusive UPC events consistent with those at HERA
  - indeed ions act as a source of quasi-real photons
- Using $\Upsilon(1S)$ differentially in y, p_T and as a function of $W_{\gamma p}$ to test
  - various models of the low-x gluon behavior



$\gamma p \rightarrow \Upsilon(nS)p$ (n = 1, 2, 3)

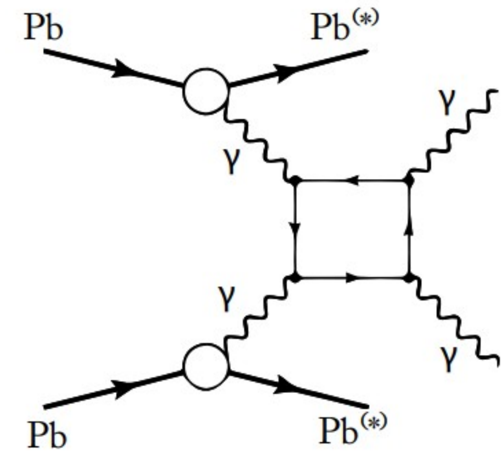
EPJC **79** (2019) 277





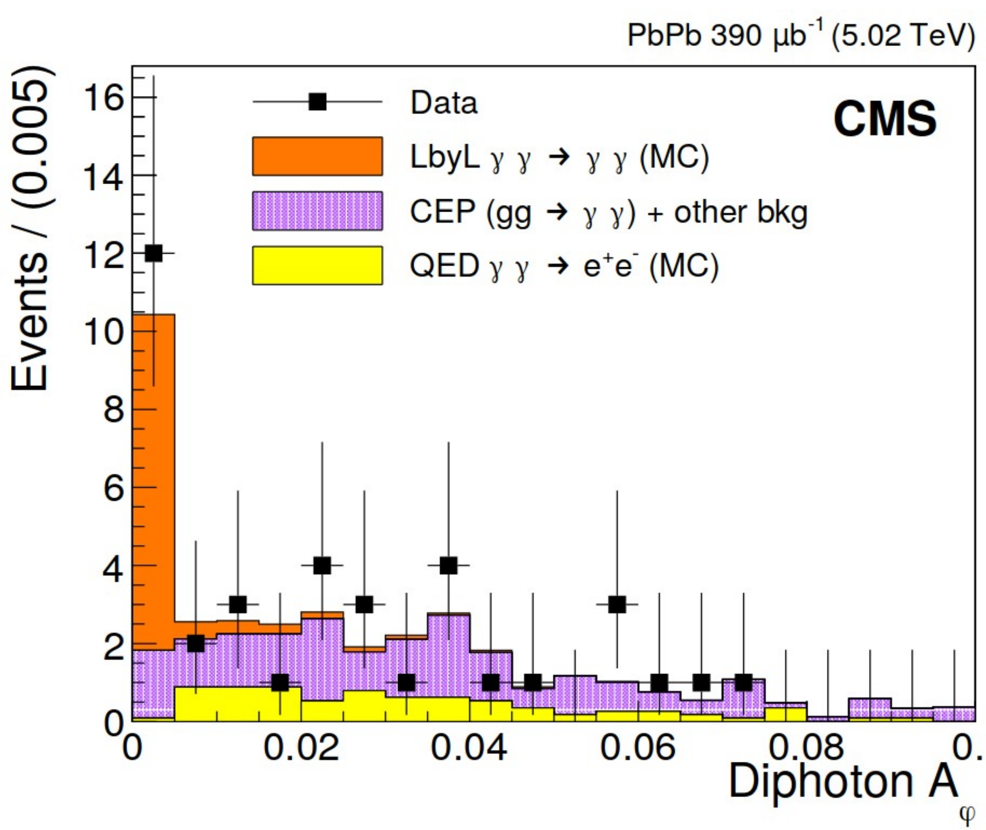
Light-by-light scattering

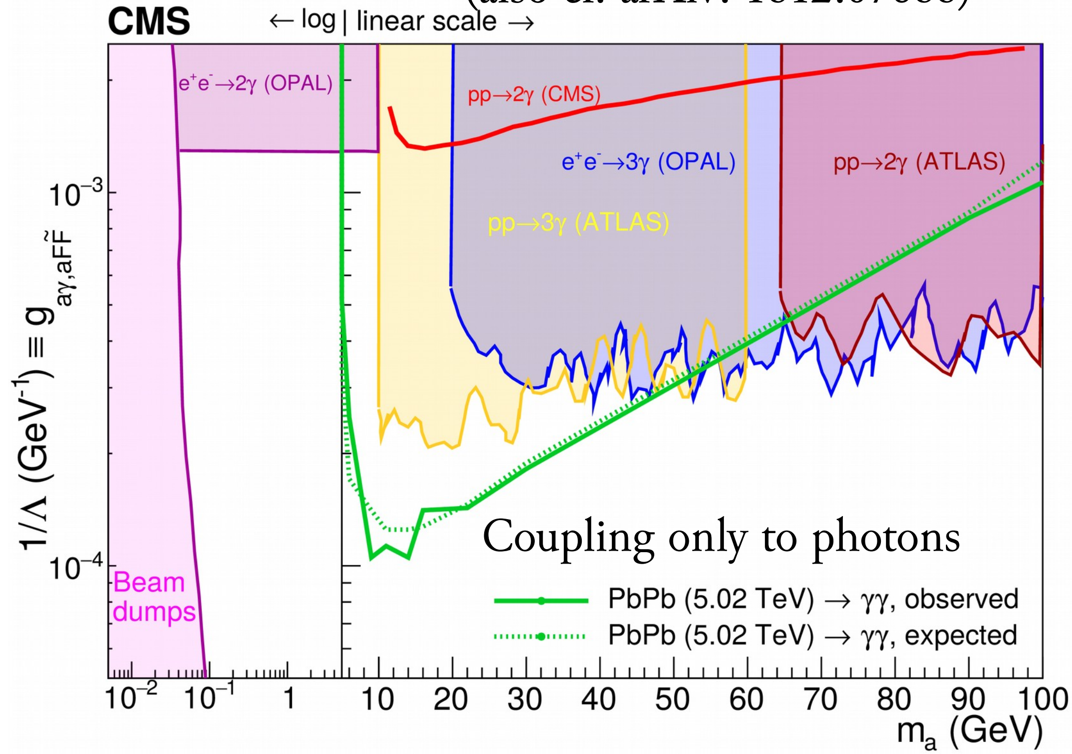
- Challenging to measure owing to a tiny cross section of $\mathcal{O}(\alpha^4)$
- Optimized EGM reconstruction for $E_T < 10$ GeV
  - Measured with significance at 4σ level
  - Good candidate to perform **combined** LHC measurements
- Limits on coupling of axion-like particles to photons (or hypercharge)
  - **Best** exclusion limits over m_a =5–50 (5–10) GeV



Phys. Lett. B **797** (2019) 134826

(also cf. arXiv: 1812.07688)

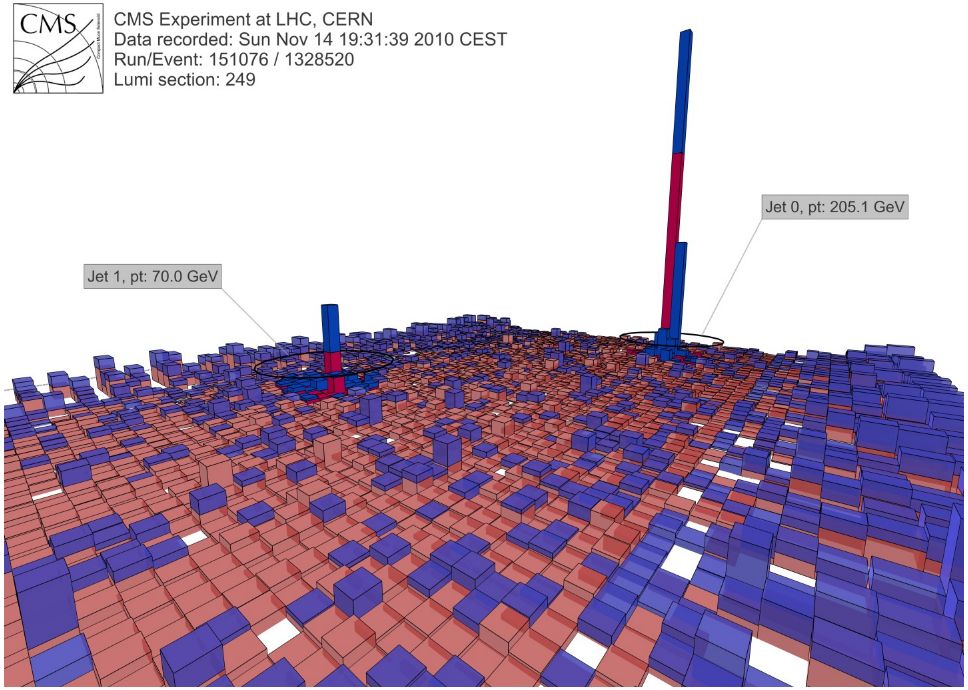




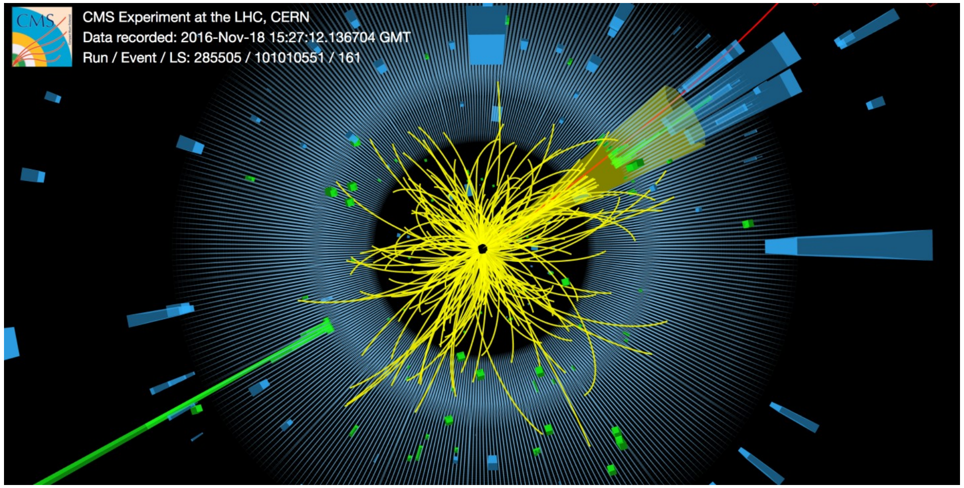
Studies with heavy ion collisions @ CMS

- Extended experimental toolbox to infer from heavy ion and their 'reference' collisions:
    - Hard probes and photon-induced processes
    - **Jet modifications**
    - Heavy quark dynamics
    - New probes

Back-to-back dijet (PbPb)

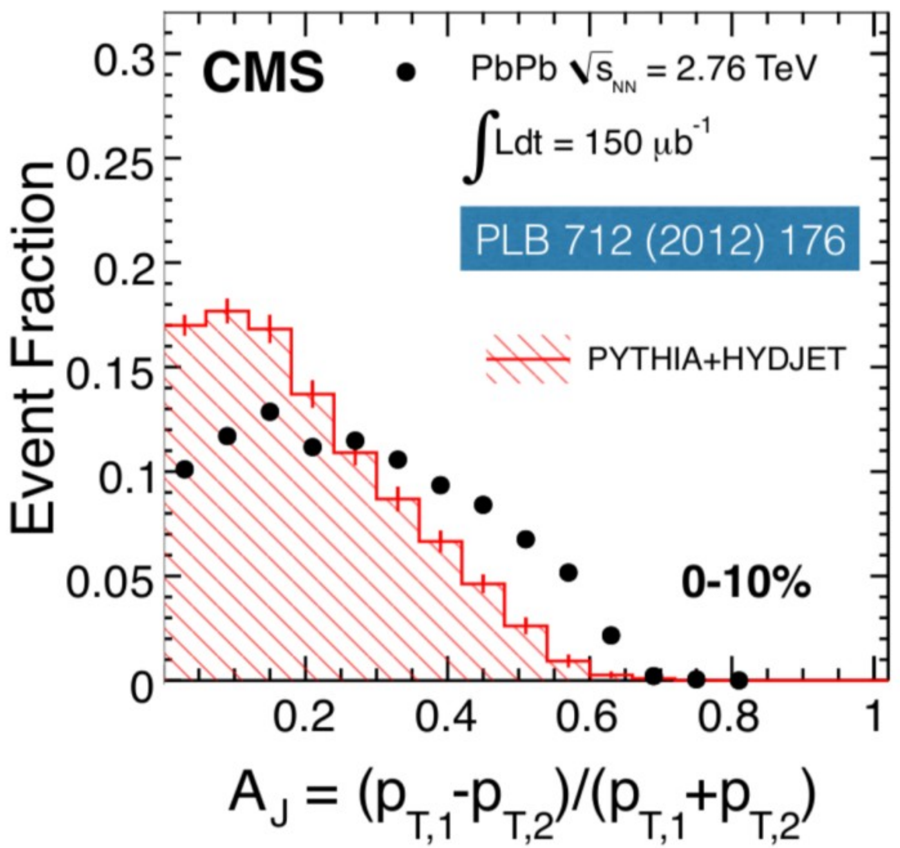


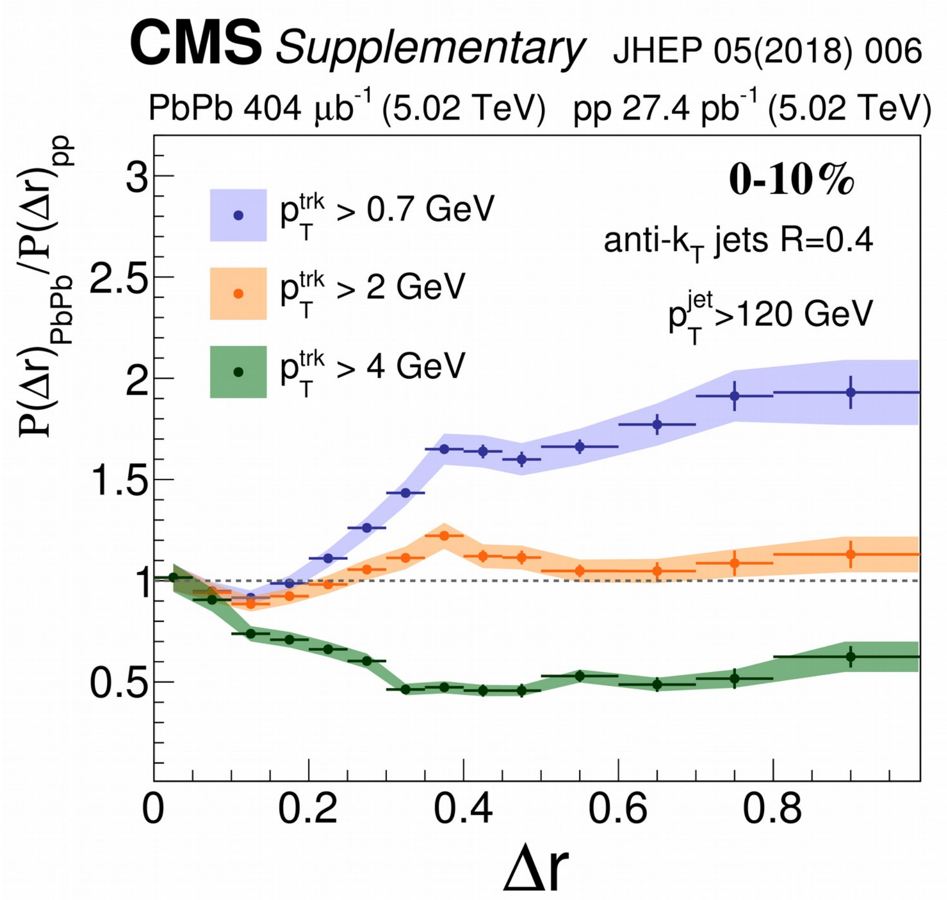
γ+jet (PbPb)



Jet quenching

- Jets are tomographic probes of the QGP
- We characteristically measure
  - Changes in the dijet p_T balance for the most central (head-on collision) events
  - Reshuffling of energy in and out of jet cone in PbPb compared to pp events



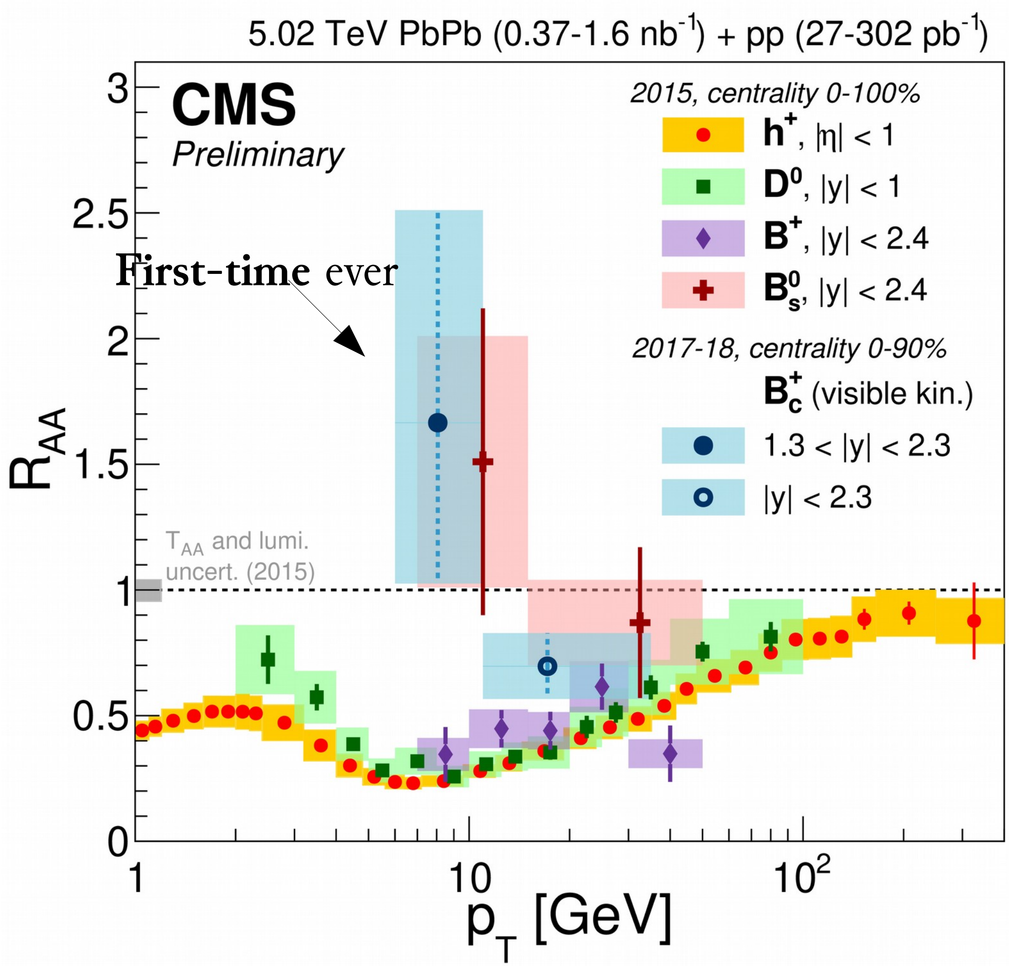


Nuclear modification factor (R_{AA}) of hadrons

$$R_{AA}(p_T) = \frac{\text{PbPb jet yield}}{\text{scaled pp jet yield}}$$

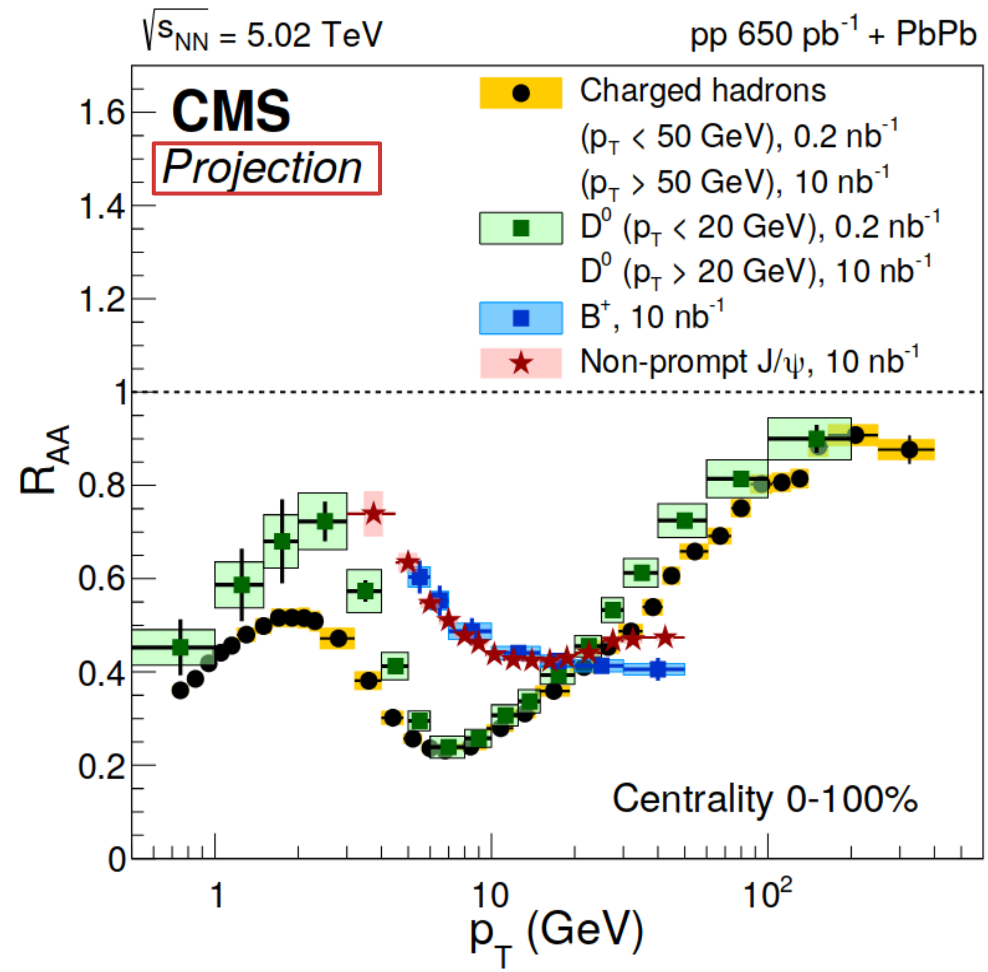
- Energy of partons is lost ('quenched') in QGP
  - Experimentally seen as R_{AA} modifications
  - increases for p_T>10 GeV; independent of flavor
- Significantly better precision with HL-LHC

CMS PAS HIN-20-004



CMS PAS-FTR-17-002

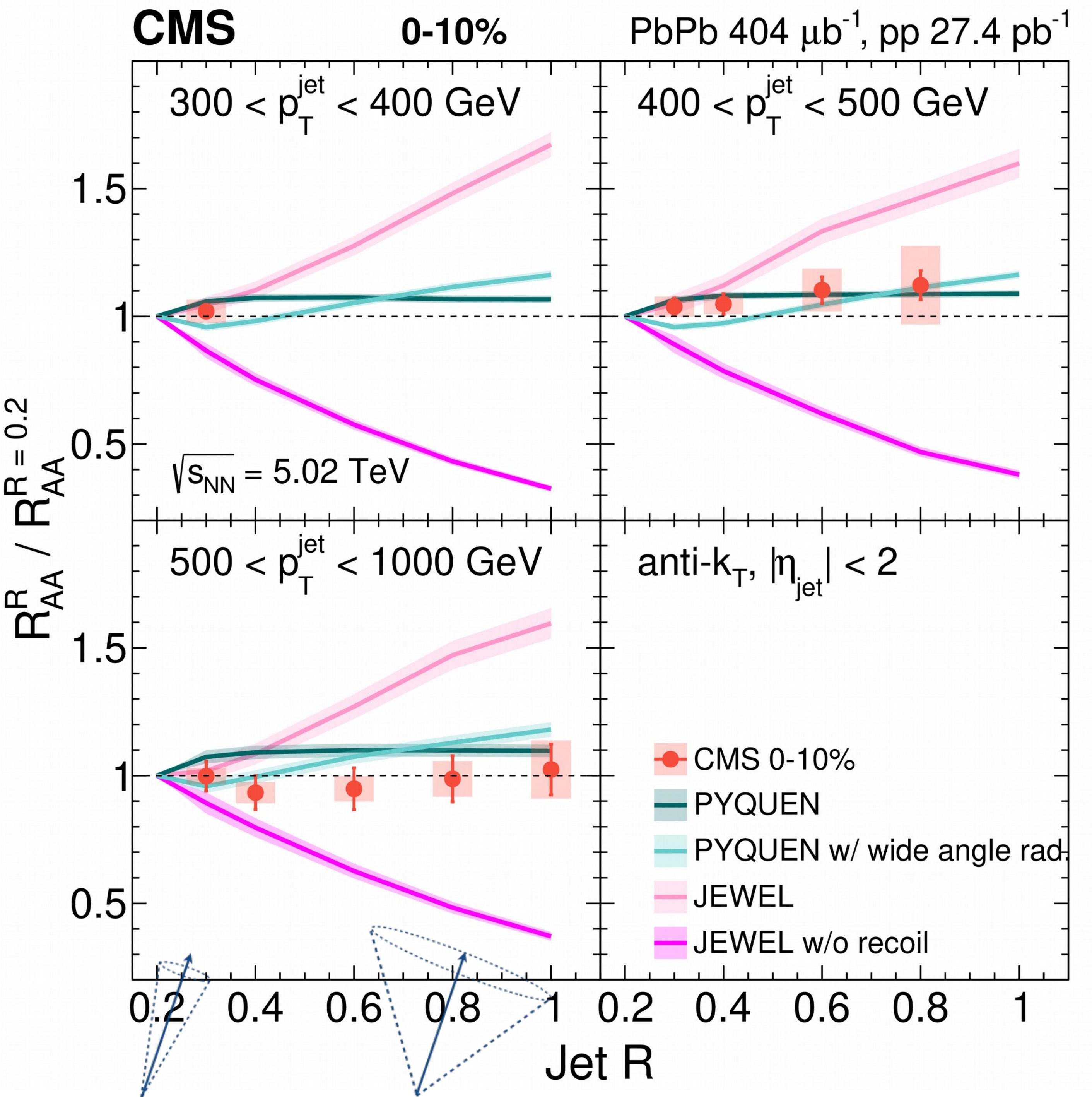
(also in arXiv: 1812.06772)



Jet R_{AA}: the first large radius scan

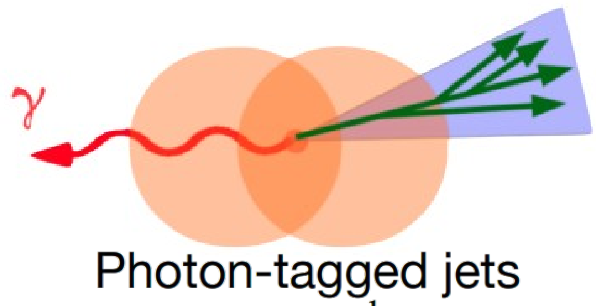
- Up to R = 1.0(!)
  - New phase space
- Competing effects for wide jets
  - **Constraints** on models

JHEP 05 (2021) 284



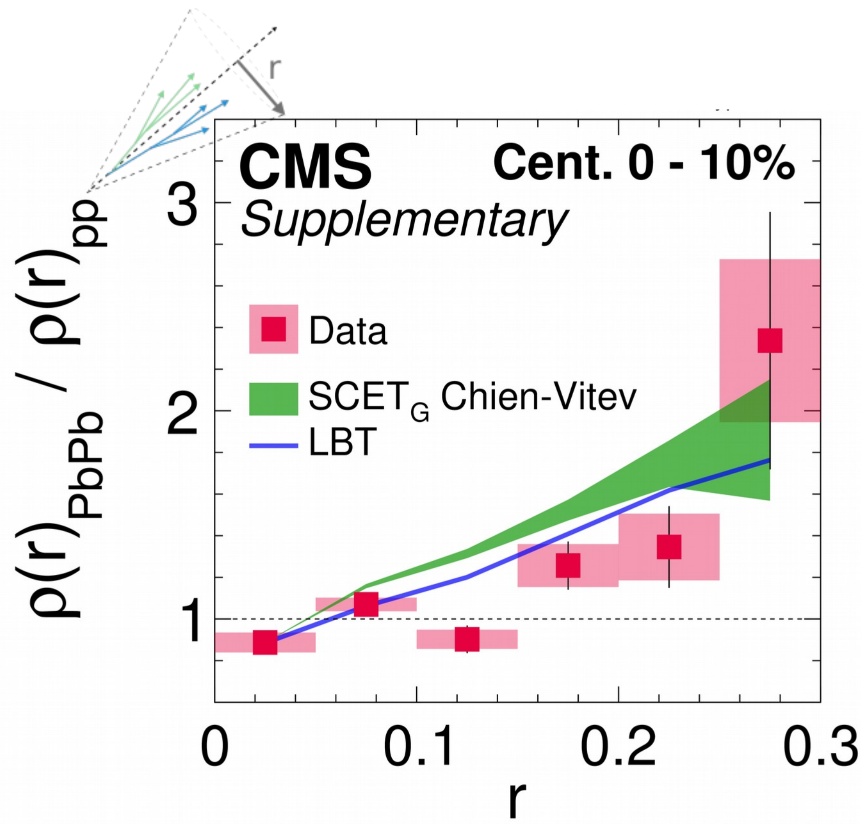
Jet shapes and fragmentation with γ+jet events

- Initial parton energy better constrained by γ p_T (quark-enriched jets)
  - Jet shape
    - Jets are wider in PbPb than pp
  - Jet fragmentation function
    - Indication of medium-induced modifications

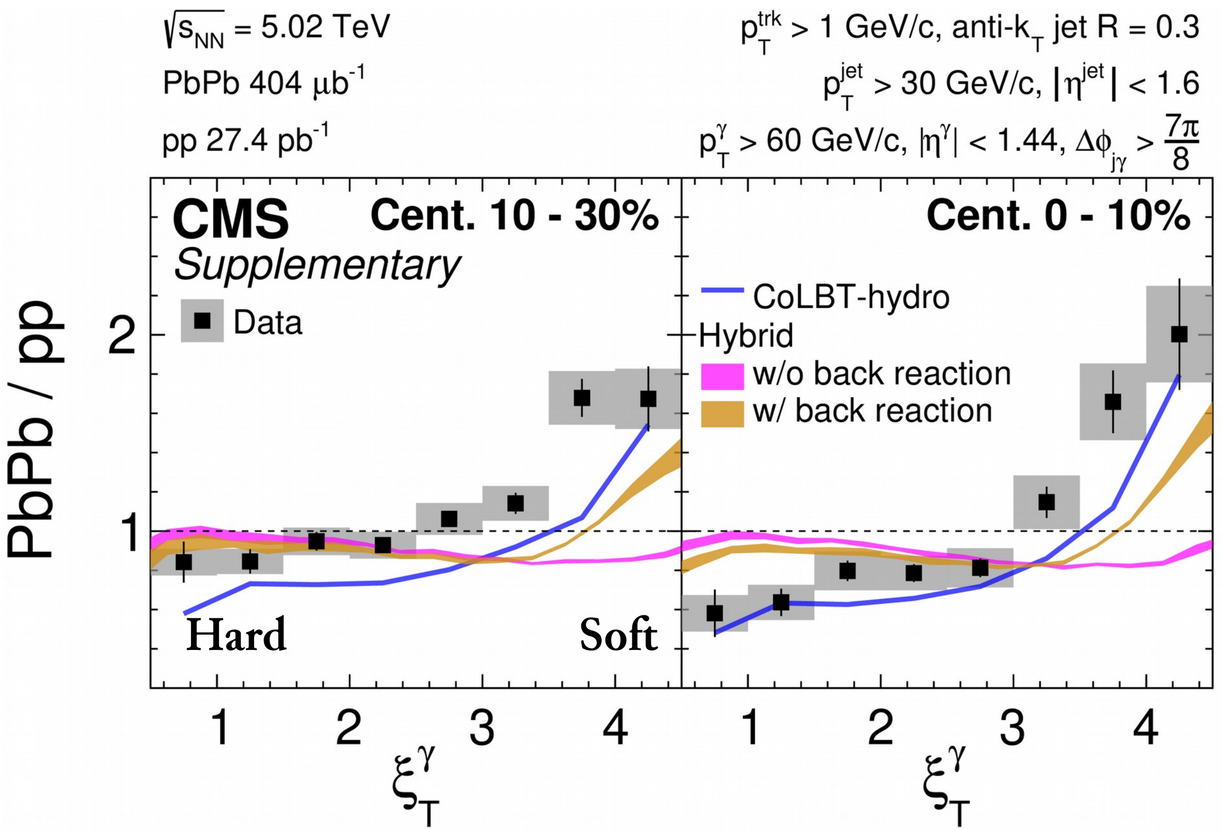


$$\xi_T^\gamma = -\ln(p_T^h / E_\gamma)$$

Phys. Rev. Lett. **122** (2019) 152001



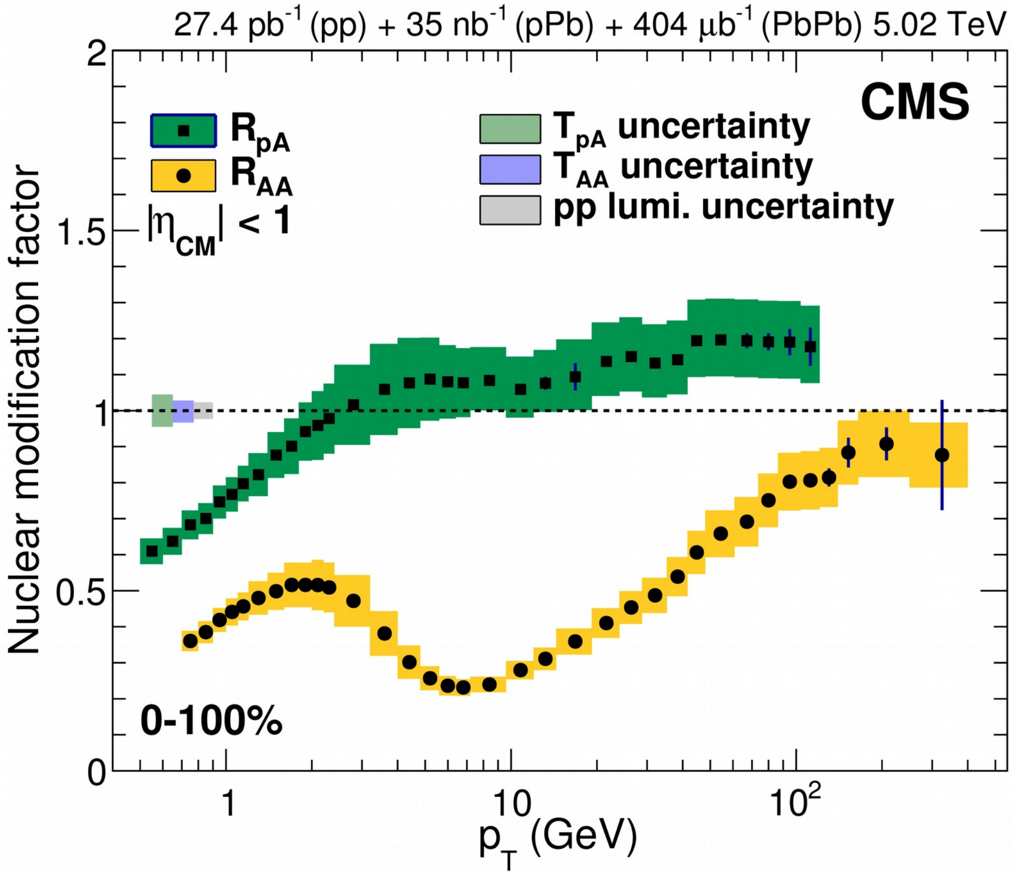
Phys. Rev. Lett. **121** (2018) 242301



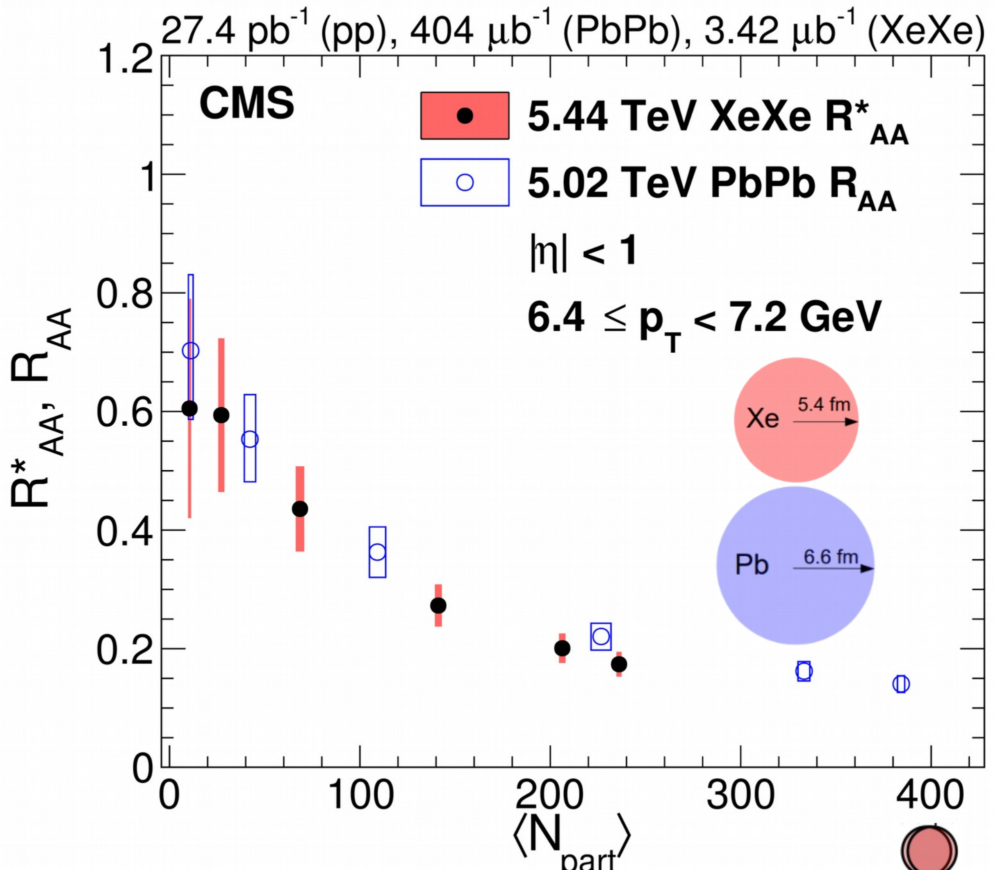
Jet quenching in smaller systems?

- Crucial to understand the minimum requirement(s) for jet quenching
  - Final state effect in high multiplicity pPb
    - No suppression observed in pPb collisions for $p_T > 2$ GeV
  - Use smaller ions
    - Charged particle R_{AA} simply scales with initial 'geometry' (N_{part})

JHEP **04** (2017) 039



JHEP **10** (2018) 138



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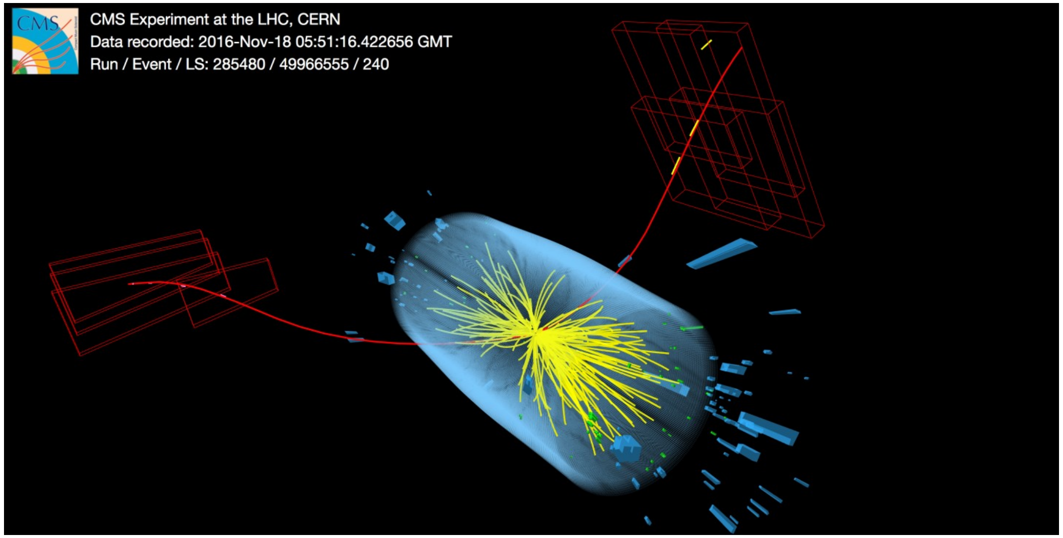
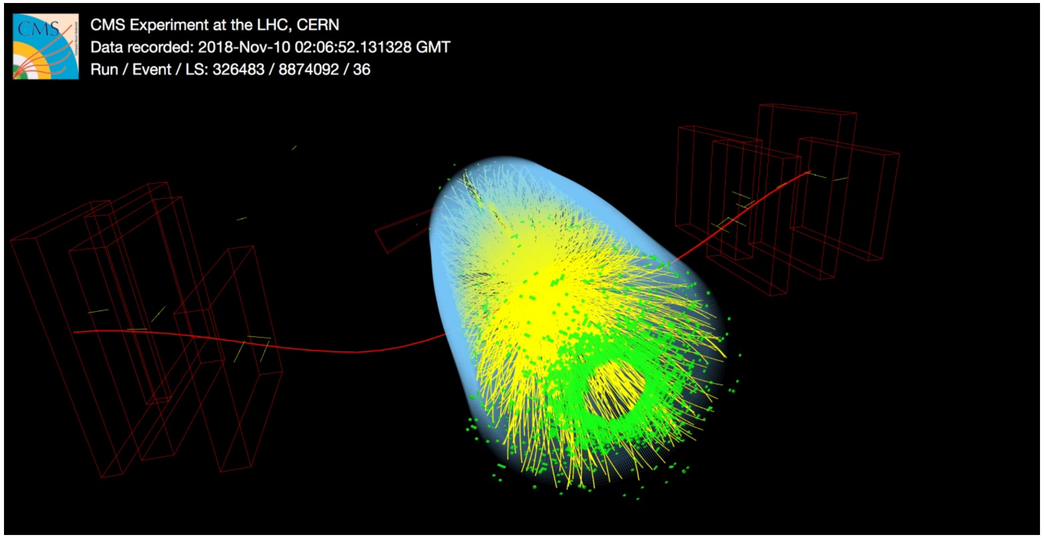


$\Upsilon \rightarrow \mu+\mu-$ (PbPb)



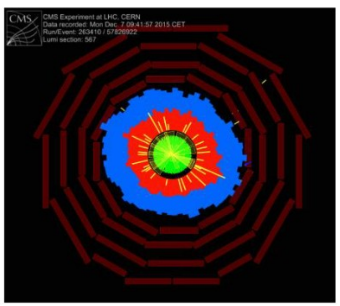
Fourier expansion of the projected Δφ

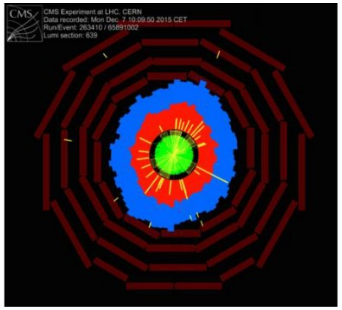
- Azimuthal correlations of particle pairs are decomposed via a Fourier expansion:

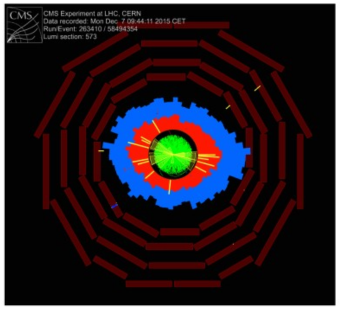
$$\frac{1}{N_{\mathrm{trig}}}\frac{dN^{\mathrm{pair}}}{d\Delta\phi} = \frac{N_{assoc}}{2\pi}\left[1+\sum_{n} 2V_{n\Delta}\cos(n\Delta\phi)\right]$$

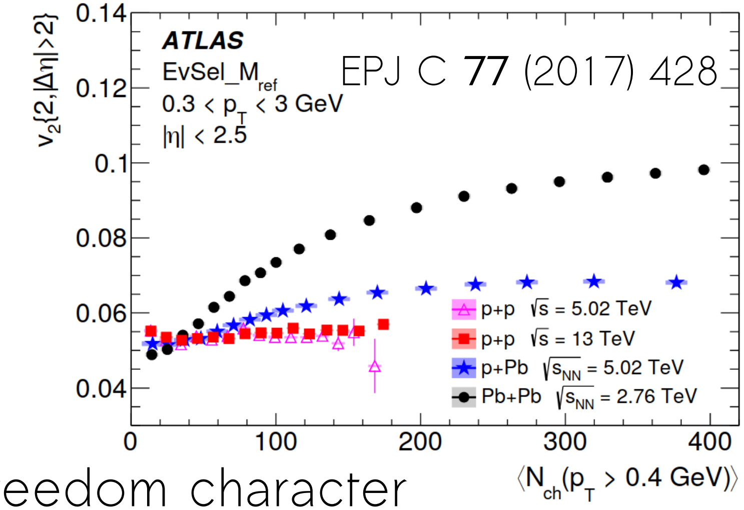
  - single-particle azimuthal anisotropy Fourier coefficients measured as $v_{n\geq1}=\sqrt{v_{n\Delta}}$

- Harmonics (e.g., v_2, v_3) can be interpreted as **flow** (e.g., elliptic, triangular) that are related to
  - **collision geometry,** its **fluctuations,** and **system's evolution**

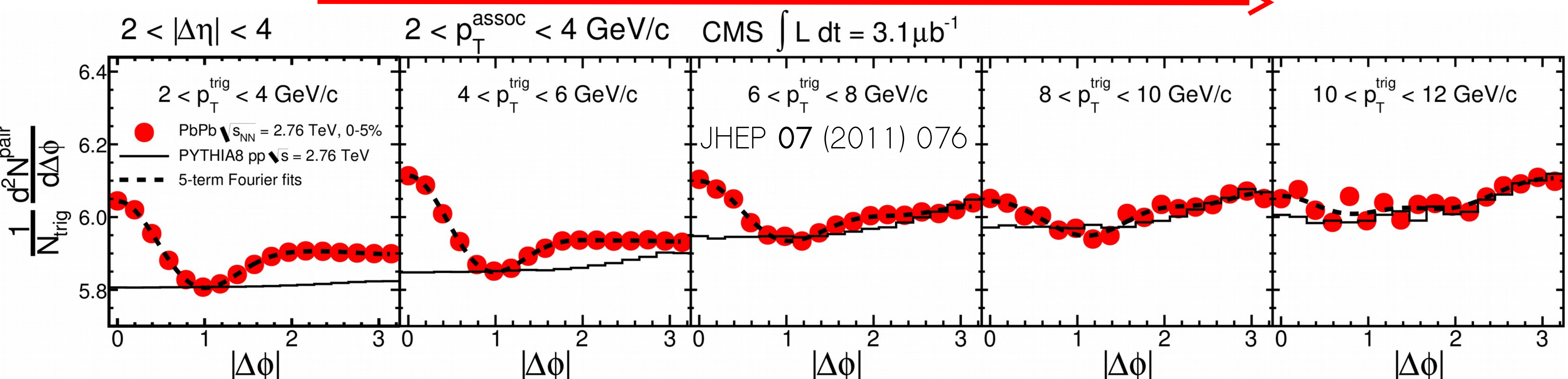






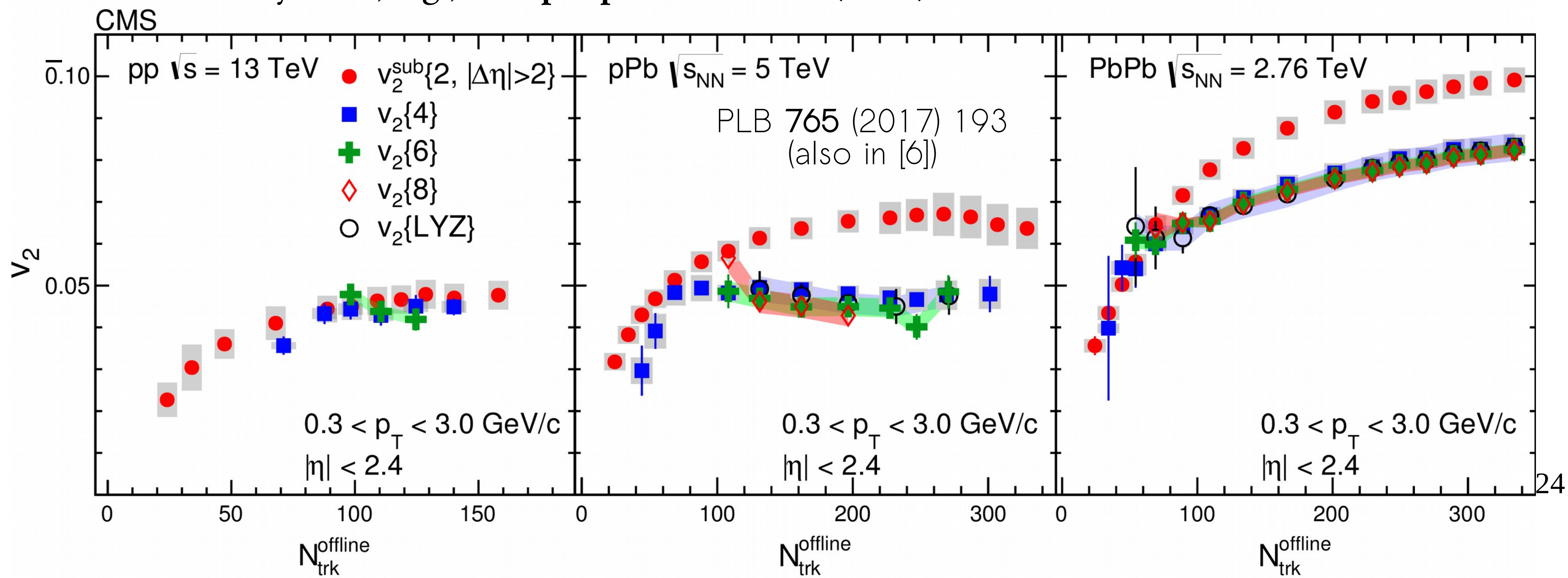


A fluid that retains its QCD asymptotic freedom character

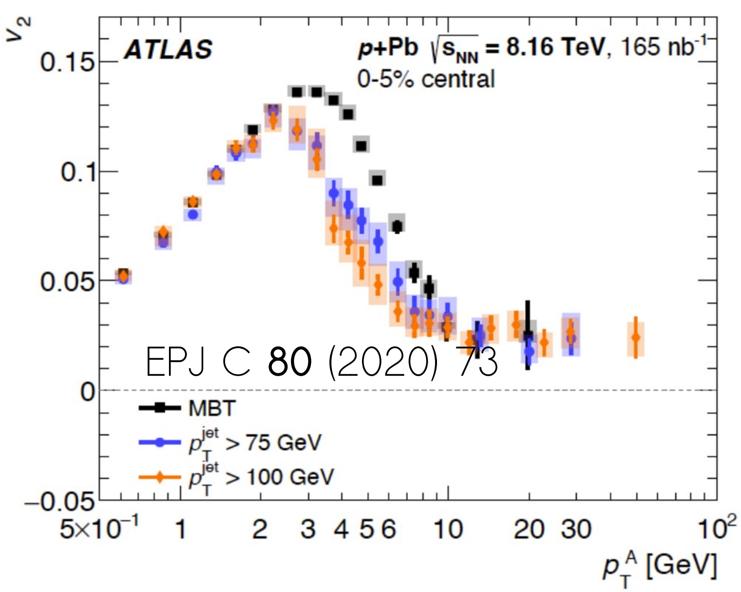


Measuring collectivity in small systems

- Detailed measurements of $\mathbf{v_2}$&$\mathbf{v_3}$
  - centrality/event activity and p_T dependence qualitatively **similar** to that in heavy ions
  - identified particle and multiparticle correlation techniques support a **collective origin** of $\mathbf{v_n}$
    - encompased by hydrodynamical models, but **not a unique** description
- We start answering whether a collective component in $\mathbf{v_n}$ exists by studying
  - the role of the **initial conditions**
  - the impact of **hard-scattering** processes and **energy loss**
  - alternative systems, e.g., **ultraperiphal collisions** (UPC)

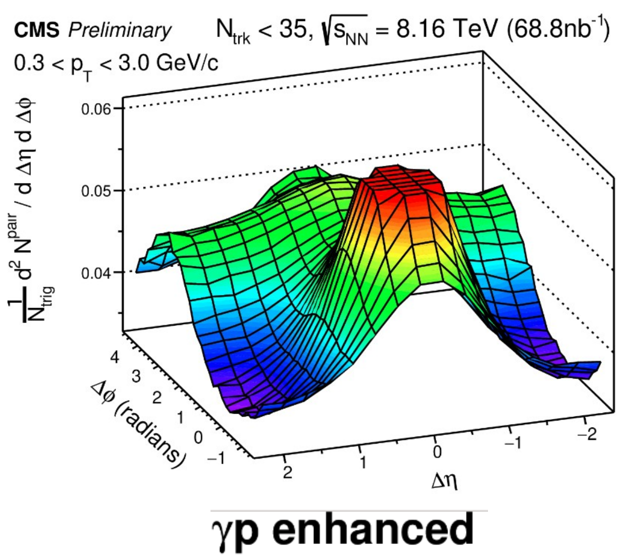


- **Process-dependent v_n** can distinguish complementary particle production mechanisms
  - $v_{2,3}$ similarity (ordering) in MB vs jet-triggered pPb events indicative of flow (soft+hard admixture)
  - $v_{2\text{-}4}$ largely independent of whether measured in jet enriched/depleted pp events [7]
- Photonuclear **collisions in UPC** offer an alternative dynamics of small systems
  - competing explanations can be tested in cases one of the "beams" has a **simpler** initial state
  - both ATLAS and CMS see **significant v_2** in UPC PbPb [8] and pPb collisions, respectively



EPJ C 80 (2020) 73

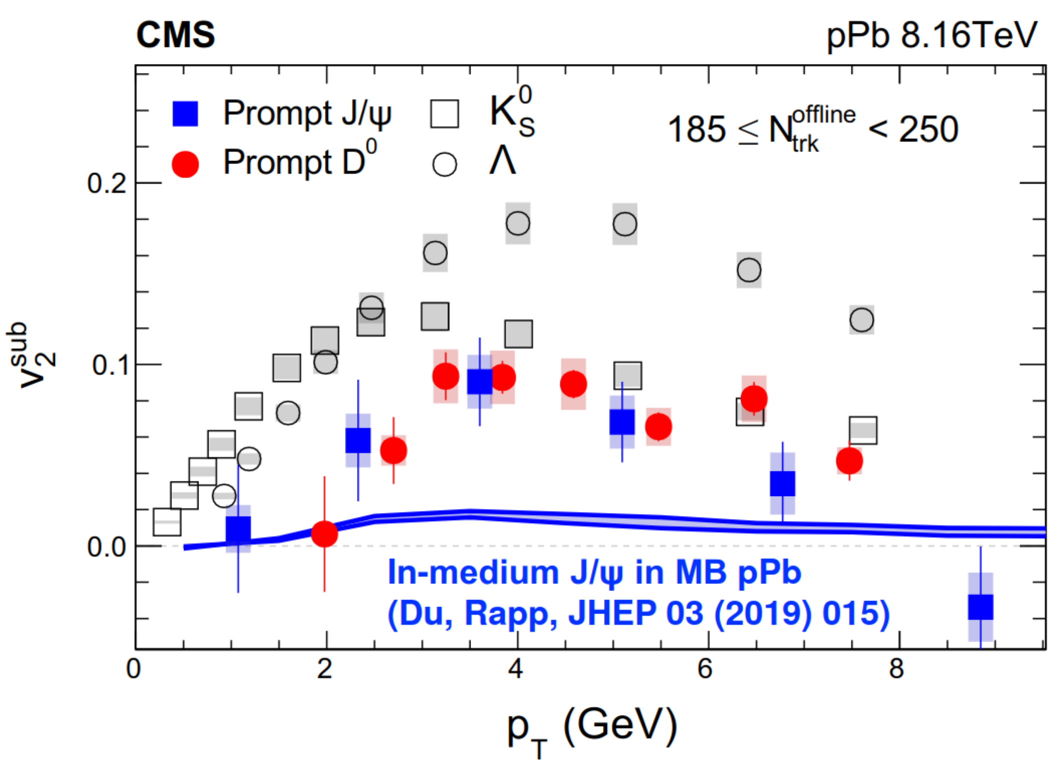
CMS-PAS-HIN-18-008



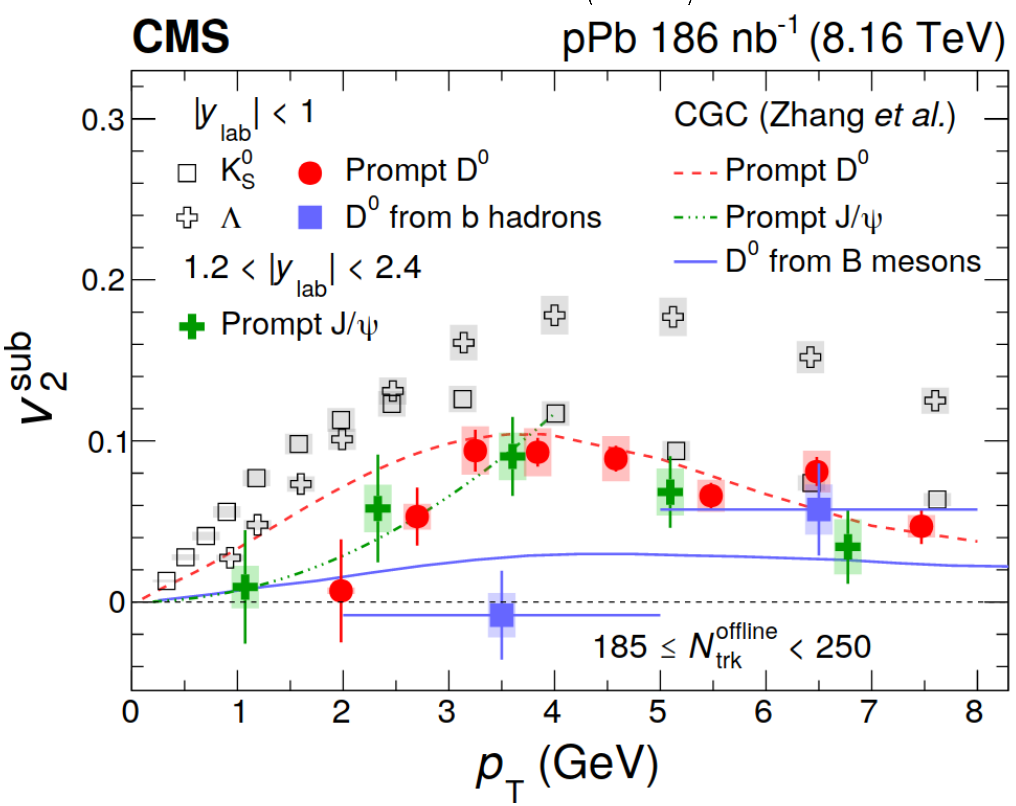
Measuring HF particle flow in pPb

- Observation of **c flow**
  - the number-of-constituent-quark (n_q) scaling holds for KE_T/n_q < 1 GeV
  - model with final-state interactions underestimates the v_2 signal
- First measurements of **b flow**
  - indication of flavor hierarchy between light, charm, and beauty at low p_T
  - qualitative agreement with CGC calculations and data → an important role for initial-state effects?

PLB **791** (2019) 172



PLB **813** (2021) 136036



Quarkonia: Upsilon family in PbPb

- Flow of bottomonia in PbPb
  - Precise $\Upsilon(1S)$ v_2 consistent with 0
  - **First** $\Upsilon(2S)$ v_2 measurement consistent with 0 too
    - in contrast to larger J/ψ v_2
- Sequential suppression of Υ family
  - stronger in PbPb than pPb

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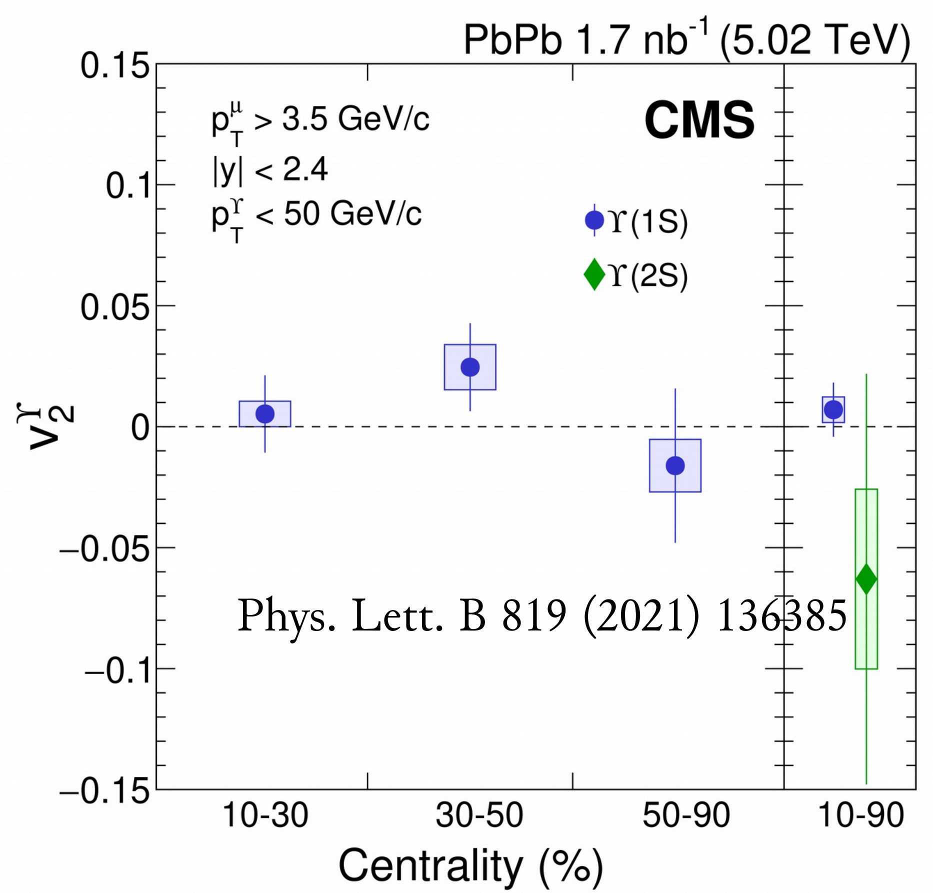
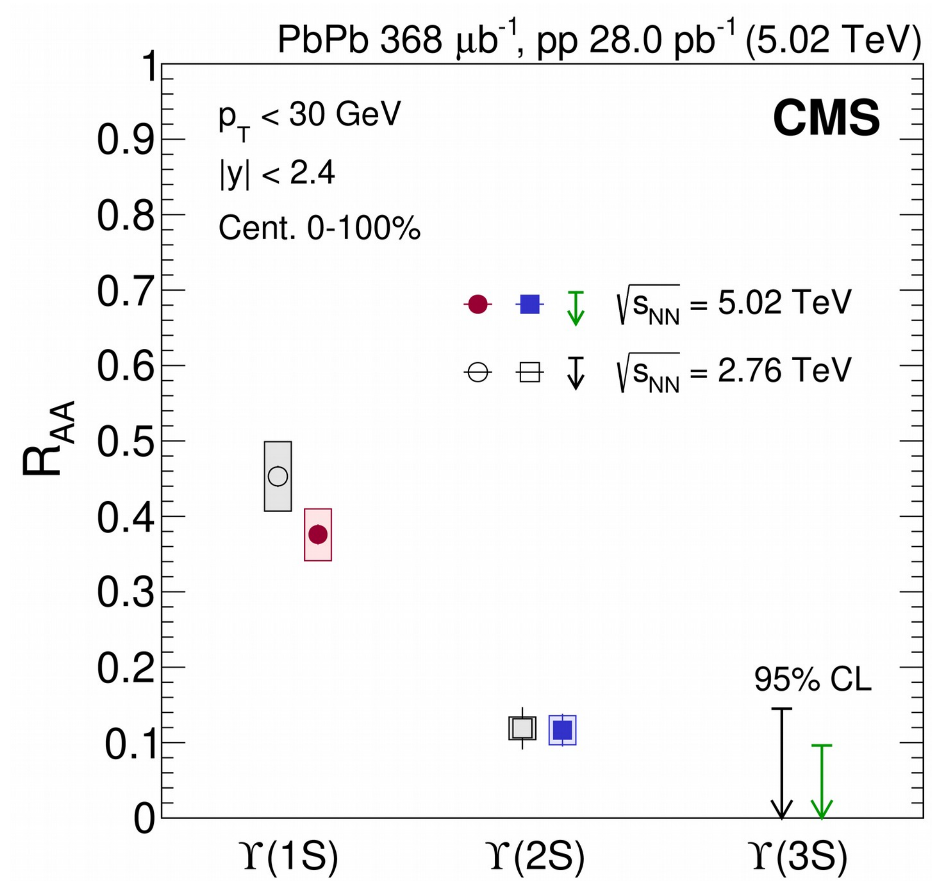


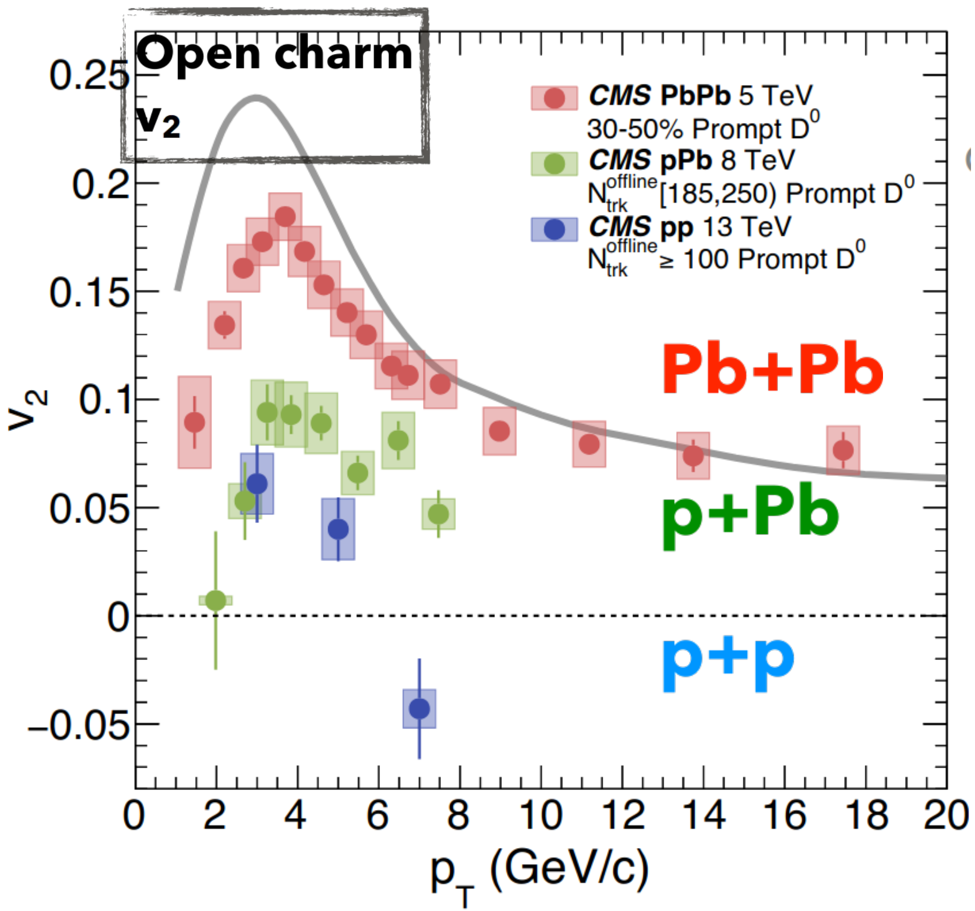
Phys. Lett. B 819 (2021) 136385

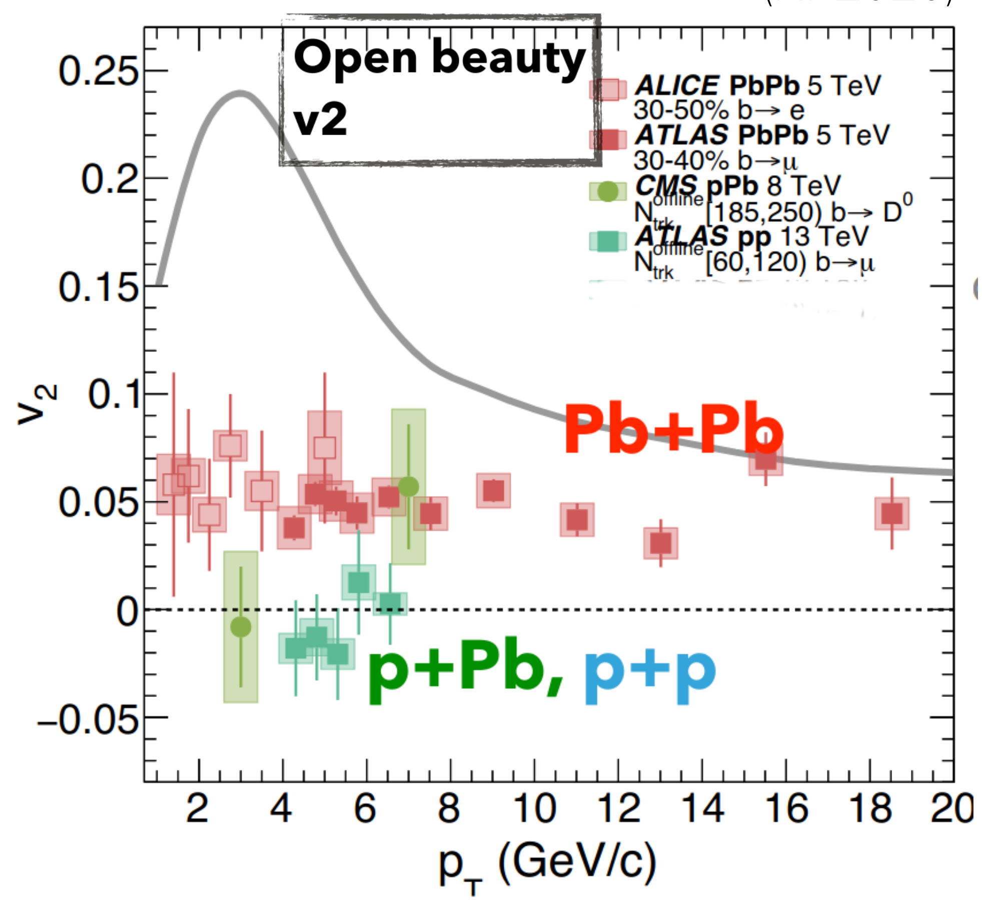


Comparing HF particle flow in all systems

- There is charm anisotropy… everywhere
  - apparent ordering: v_2 (PbPb) > v_2 (pPb) > v_2 (pp)
    - so **system size** should play a role?
- For open bottom hadrons: v_2 (PbPb) > 0 but v_2 (pPb) ~ v_2 (pp) ~ 0
  - do we hit some **threshold** between charm and beauty processes?
- **Novel input** to the description of heavy-quark transport and energy loss in small systems

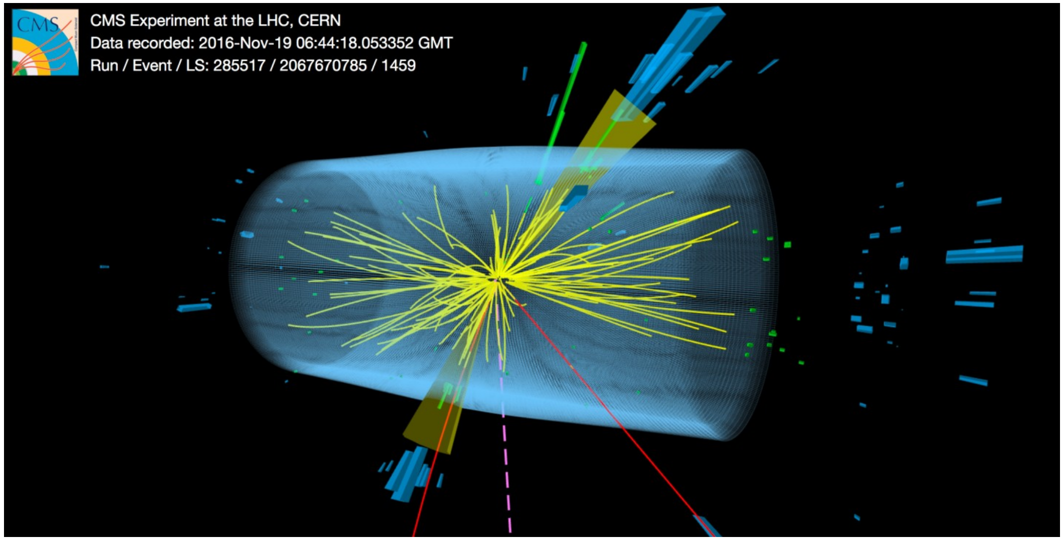
C. Mironov (HP2020)



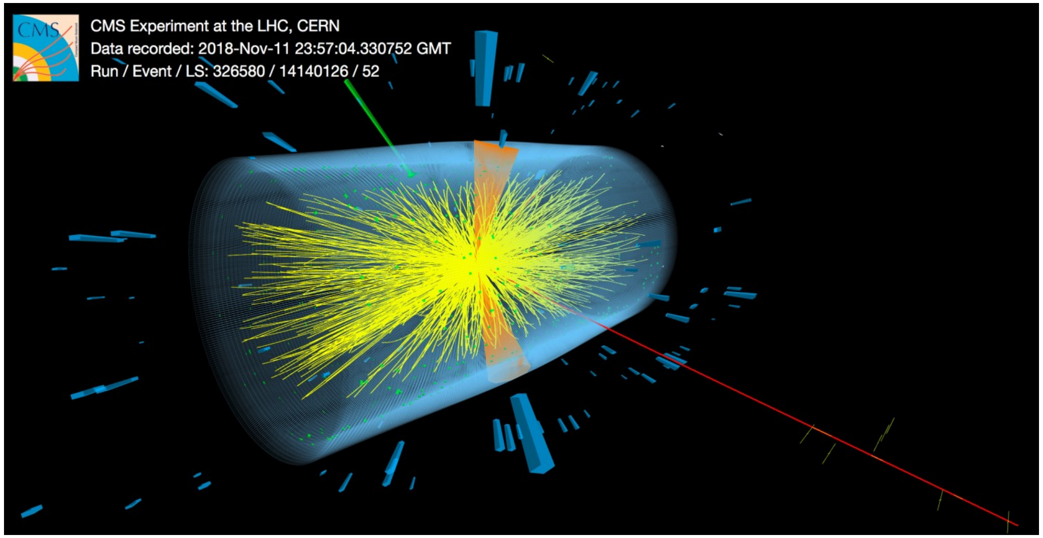


- Extended experimental toolbox to infer from heavy ion and their ‘reference’ collisions:
  - Hard probes and photon-induced processes
  - Jet modifications
  - Heavy quark dynamics
  - **New probes**

$t\bar{t} \rightarrow W(\mu\nu_\mu)bW(e\nu_e)b$ (pPb)

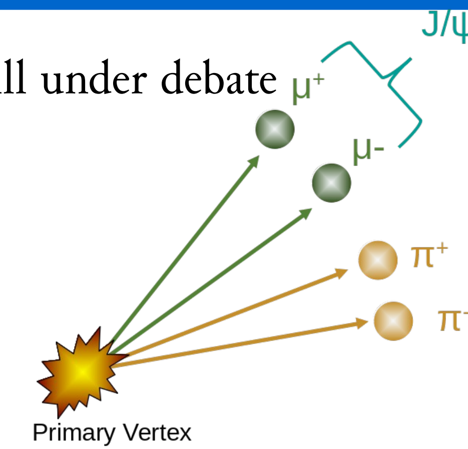


$t\bar{t} \rightarrow W(\mu\nu_\mu)bW(e\nu_e)b$ (PbPb)



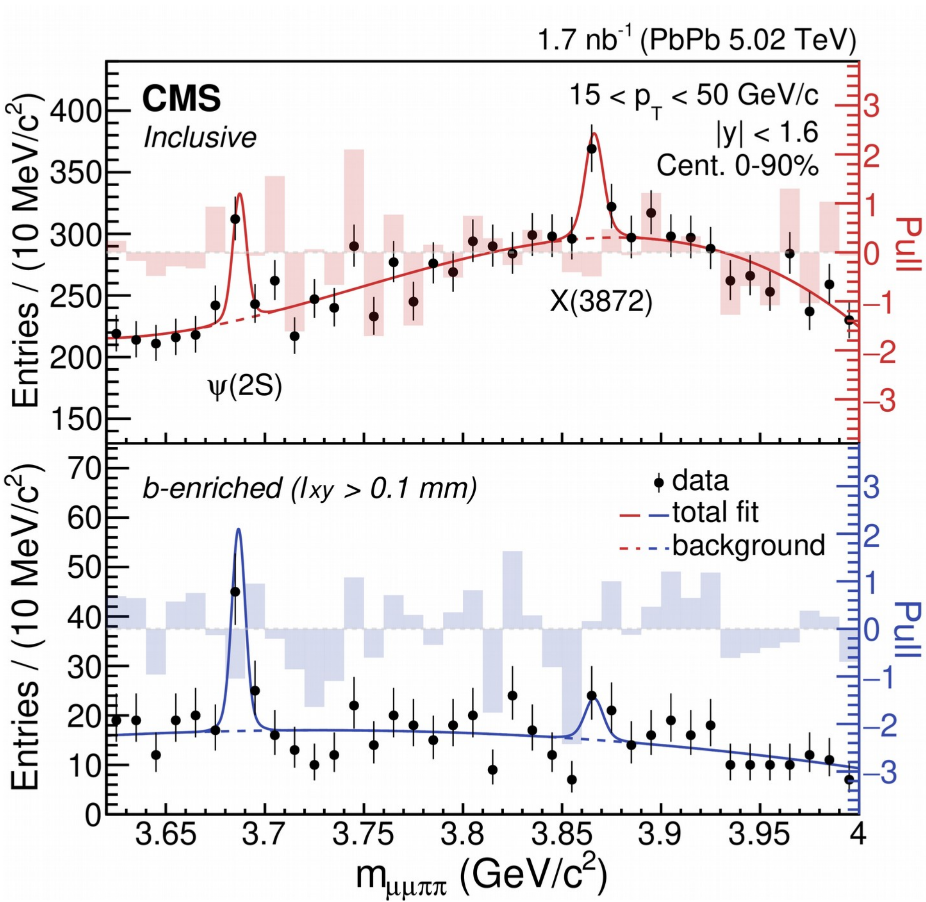
Evidence of X (3872) production in PbPb

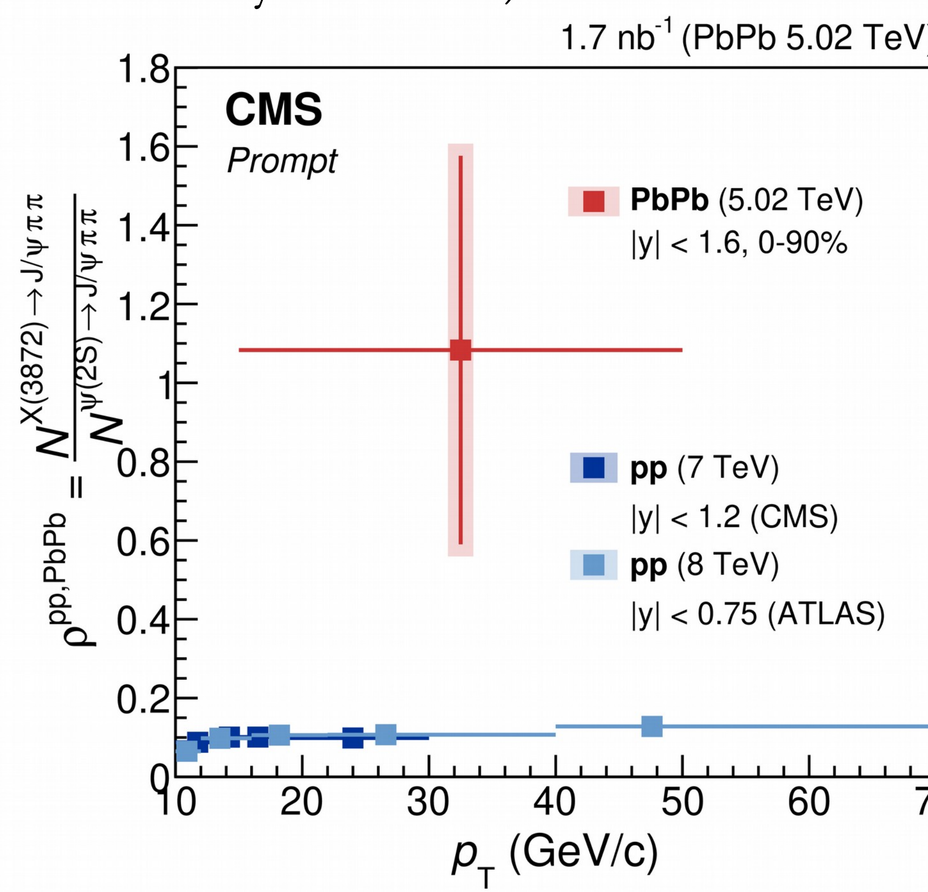
- X(3872) (or $\chi_{c1}(3872)$): Observed by BELLE (2003), its internal structure is still under debate
  - extended, compact four-quark or mixed molecule-charmonium state?
  - Production in QGP probes its structure, e.g., coalescence models



- Measured with significance at 4σ level
  - X(3872) to ψ(2S) ratio enhancement in PbPb?

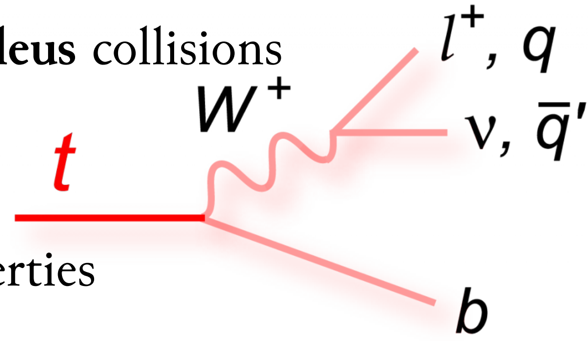
2102.13048 (submitted to Phys. Rev. Lett.)

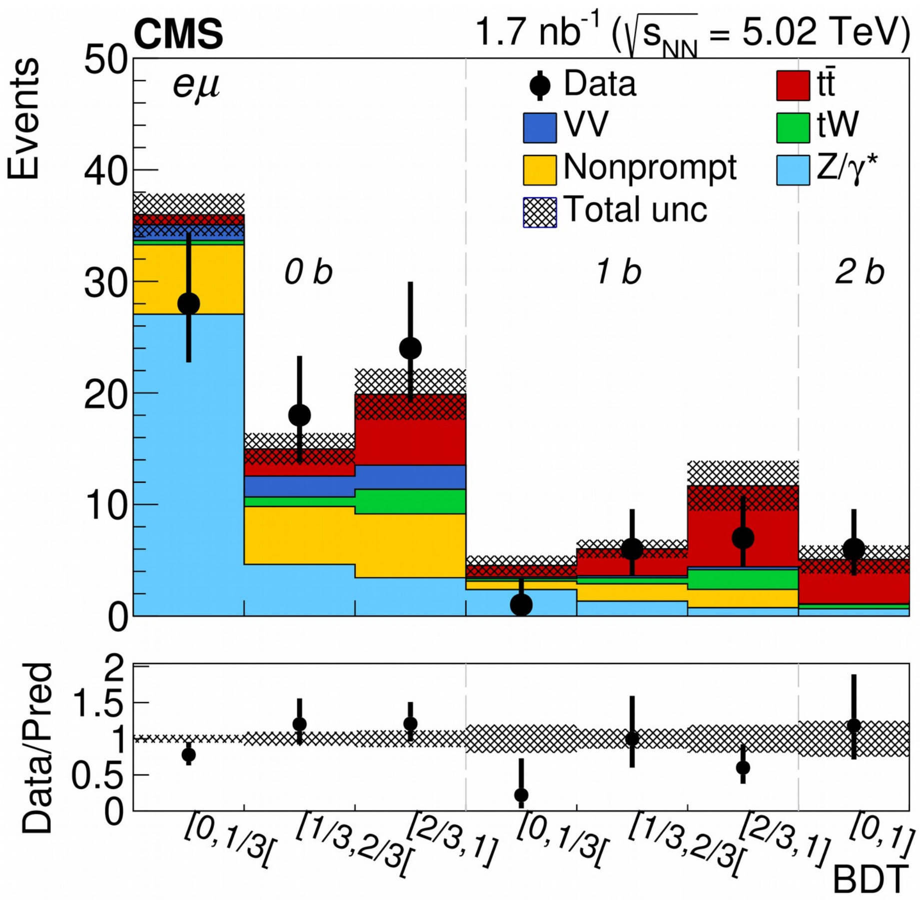


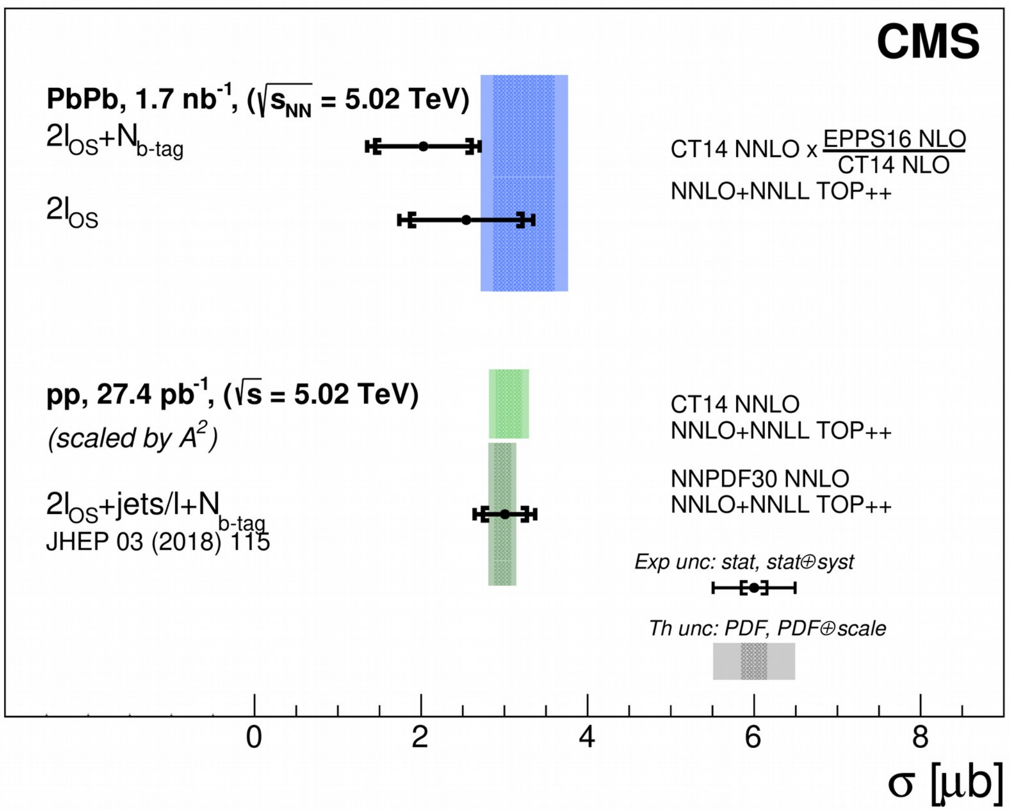


Evidence of $t\bar{t}$ cross section in PbPb

- **First** experimental evidence (4σ level) of the top quark in **nucleus-nucleus** collisions
  - using leptons only and leptons+b jets
- It establishes a **new tool** for probing nPDFs as well as the QGP properties

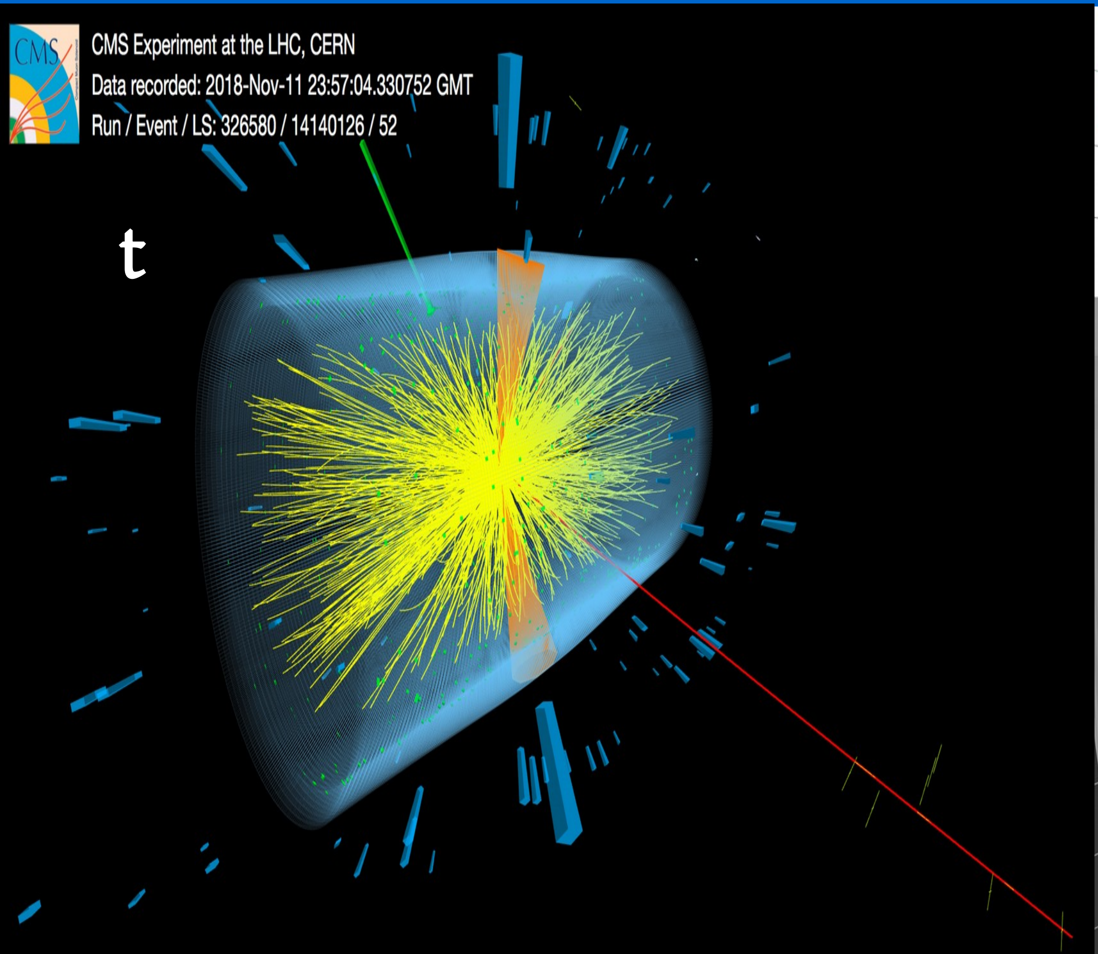


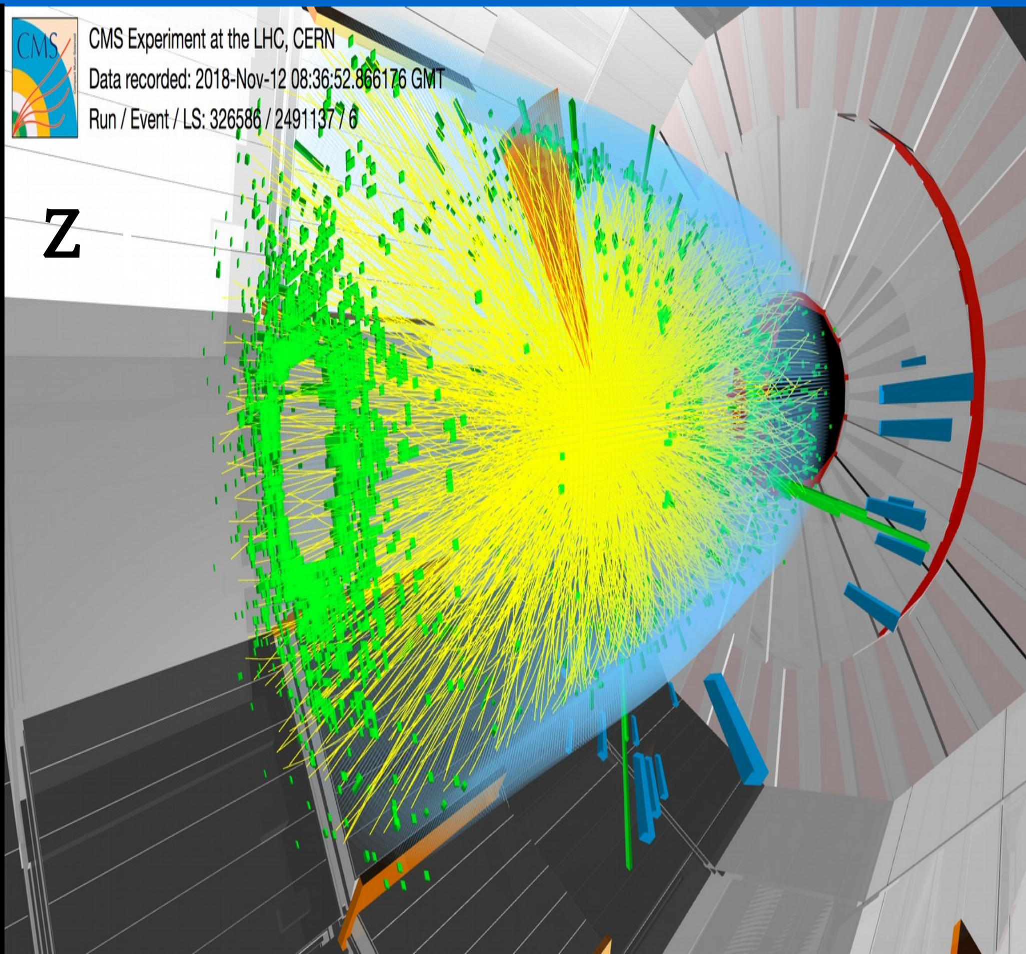




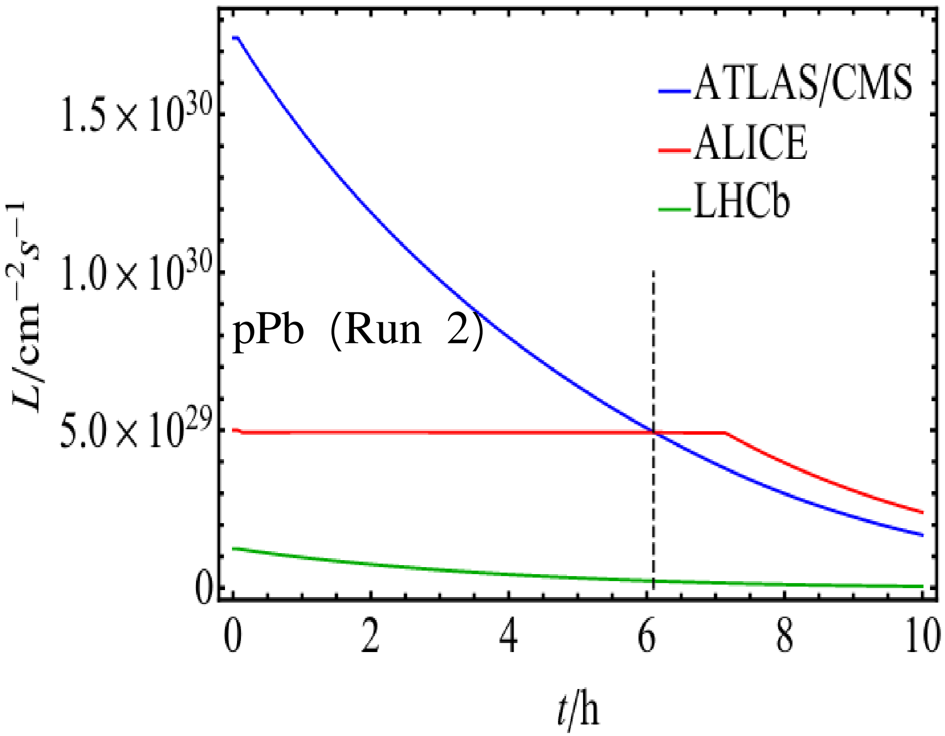
Future physics opportunities with W and Z bosons and top quarks for high-density QCD at LHC

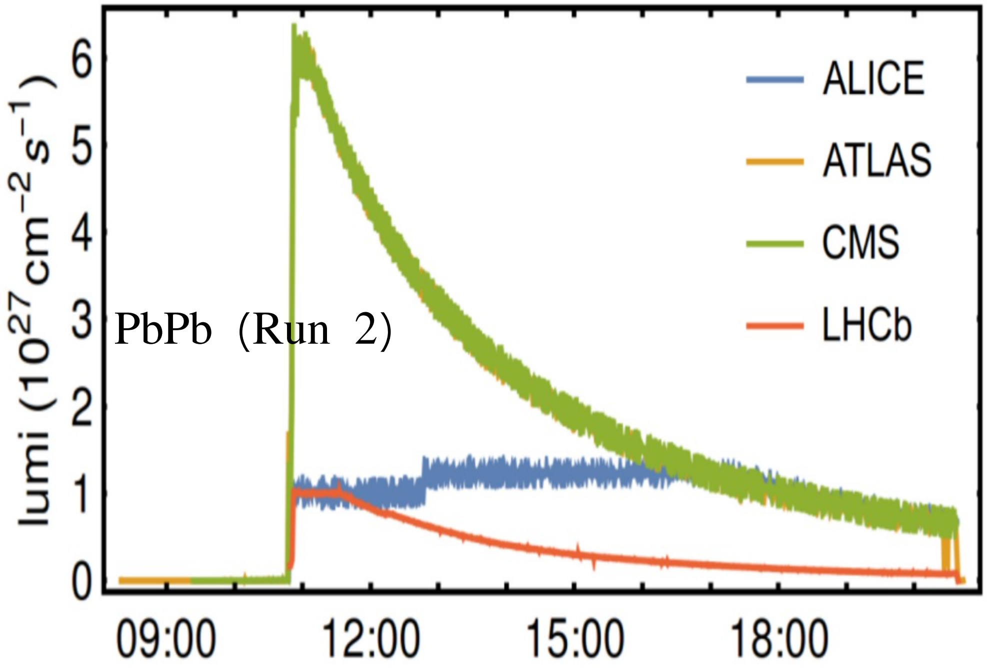
arXiv: 1812.06772





HL-LHC operational scenarios for pPb and PbPb

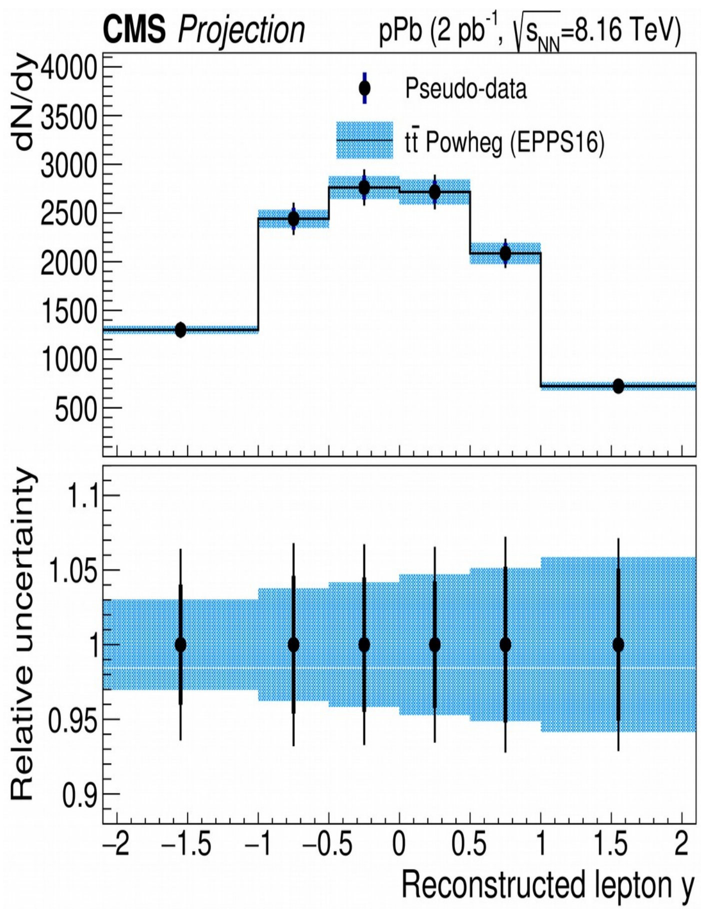


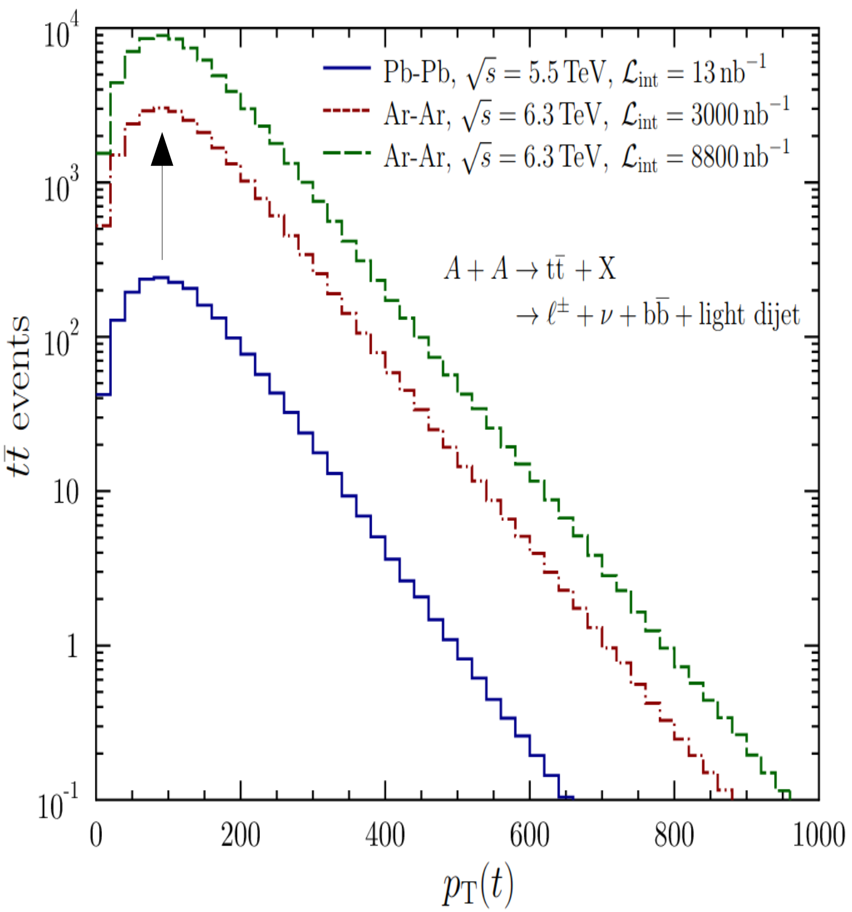


- Included in the YR and recently refined (CERN-ACC-2020-0011)
  - scenarios are based on **benchmarked** models (actually agree remarkaly well with Run 2 LHC
  - ≈**five** one-month runs would be needed to reach 13 /nb of PbPb
  - ≈**two** one-month runs would be needed to reach 1.2 /pb of pPb
  - projections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

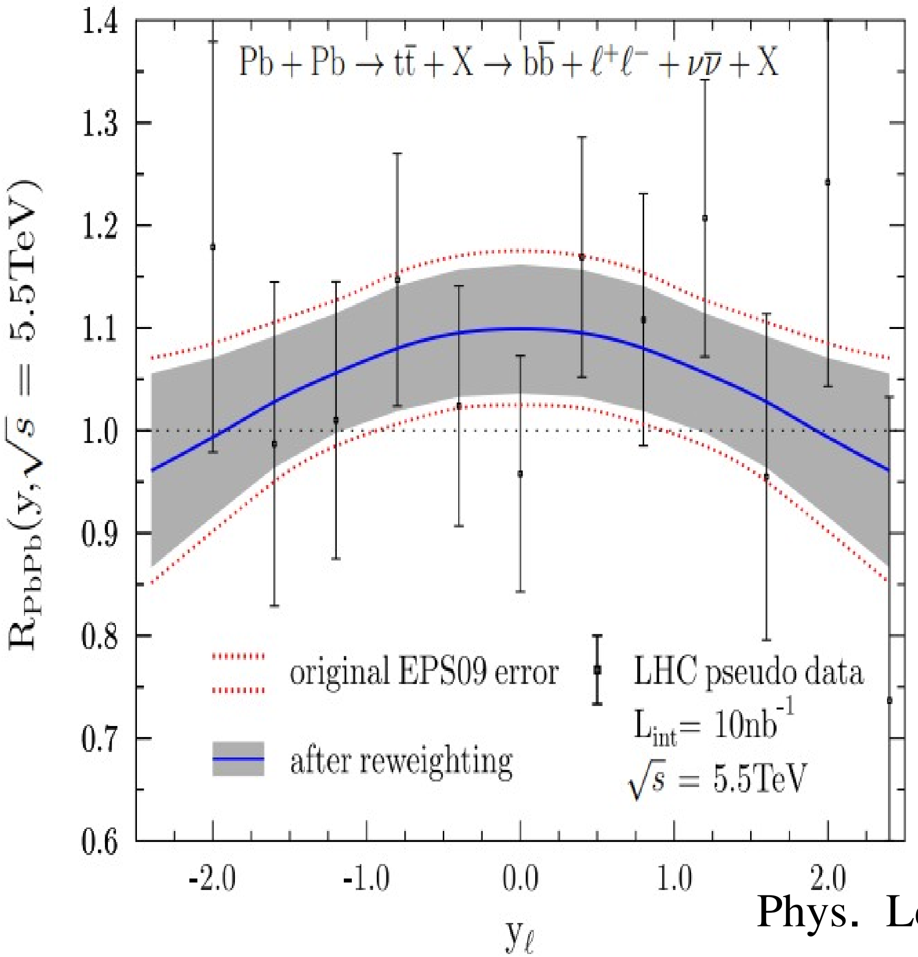
Prospects for top quark production at pA HL-LHC

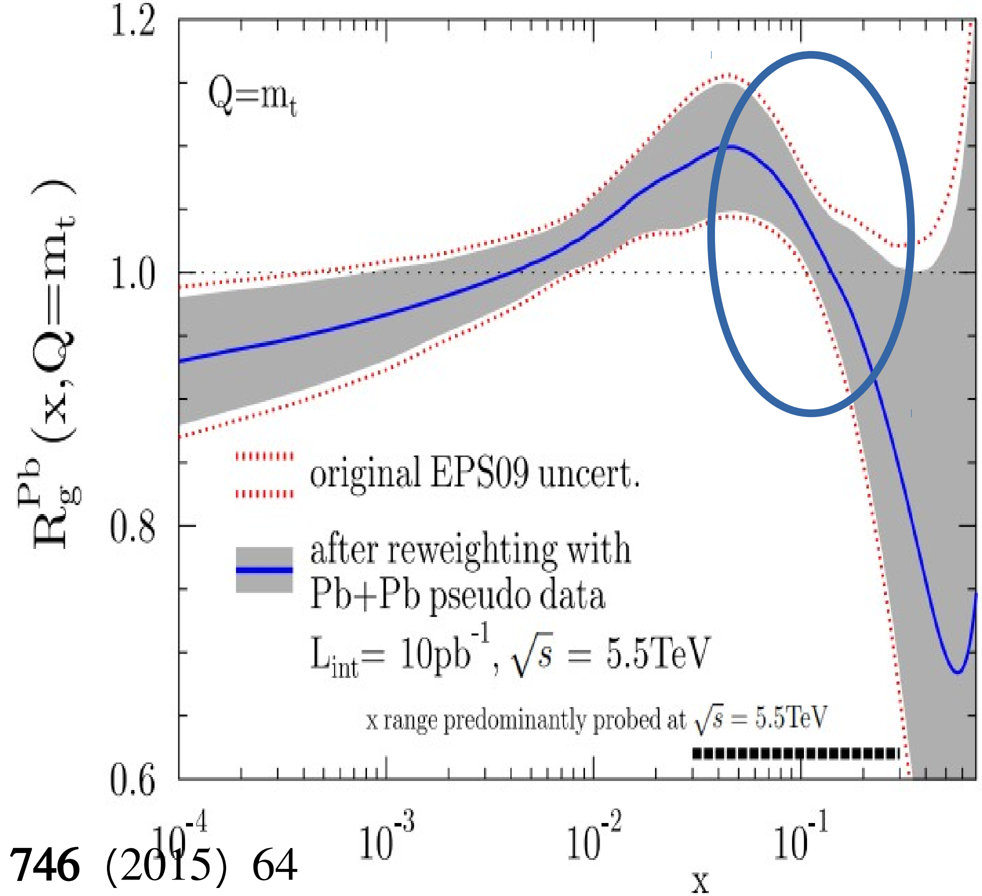
- The y of the decay leptons sensitive probe of the nuclear gluon density
  - **comparable** experimental and nPDF uncertainty with the pPb data set in Runs 3–4
    - depending on the expected systematic error and bin-by-bin correlations
  - to showcase **another potential**: In a pAr mode, the higher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





Prospects for top quark production at AA HL-LHC





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

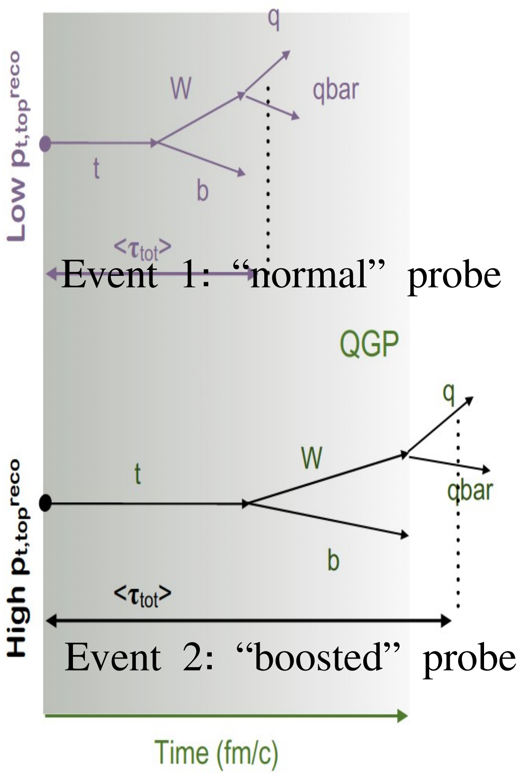
- nPDF uncertainties increase at large *x* due to the **lack** of direct constraints
  - the region where the predictions for R_g also **differ** between nPDF determinations
  - some constraints from the current LHC dijet measurements (cf. backup)

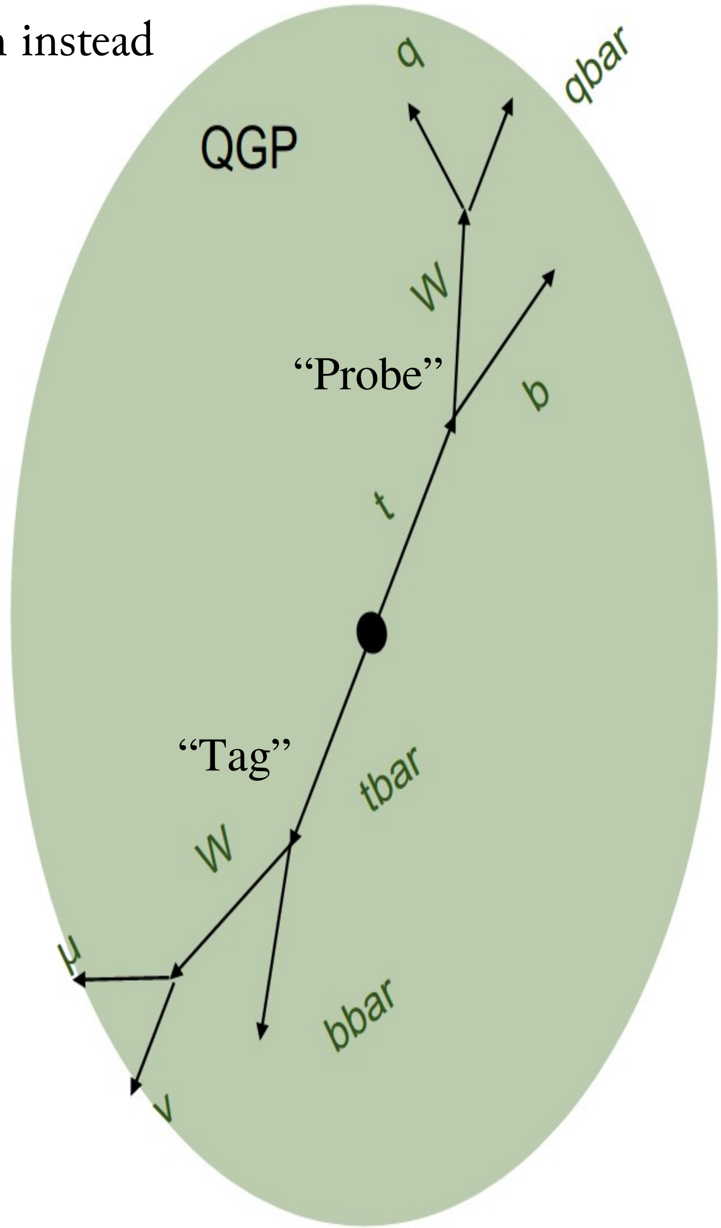
Probing the “final state”: the yoctosec QGP lifetime

- 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

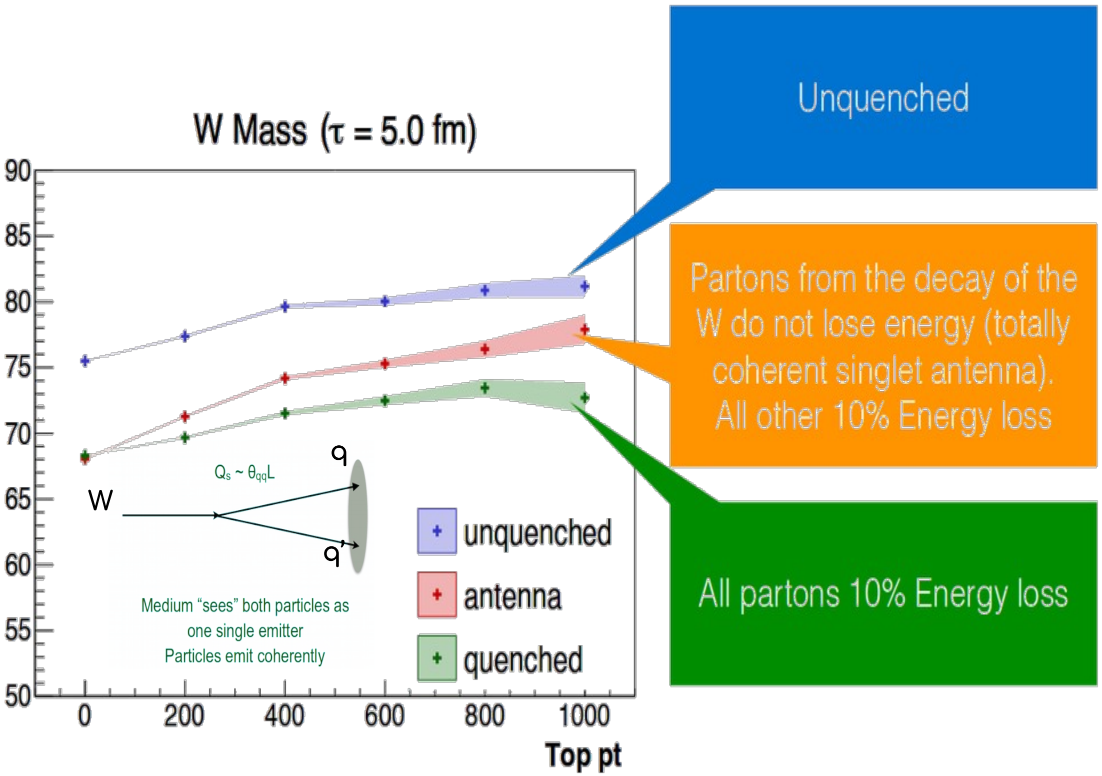
- Probes for jet quenching, e.g., dijets, Z/γ+jet, are produced **simultaneously** with the collision
- Top decay products have the potential to **resolve** the QGP evolution instead
  - Leptonic & hadronic branches as “tag” & “probe”
    - qq’ start interacting with the medium at **later** times
  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

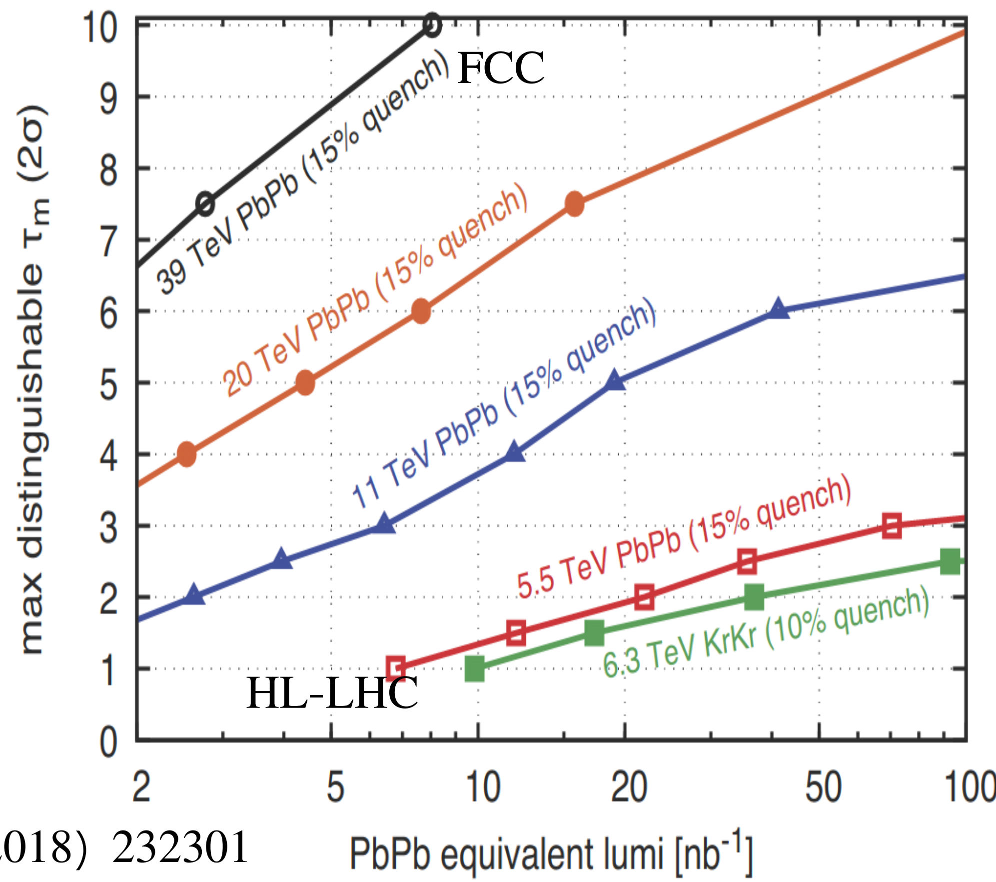




W mass vs top p_T and QGP lifetime reach

- 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)

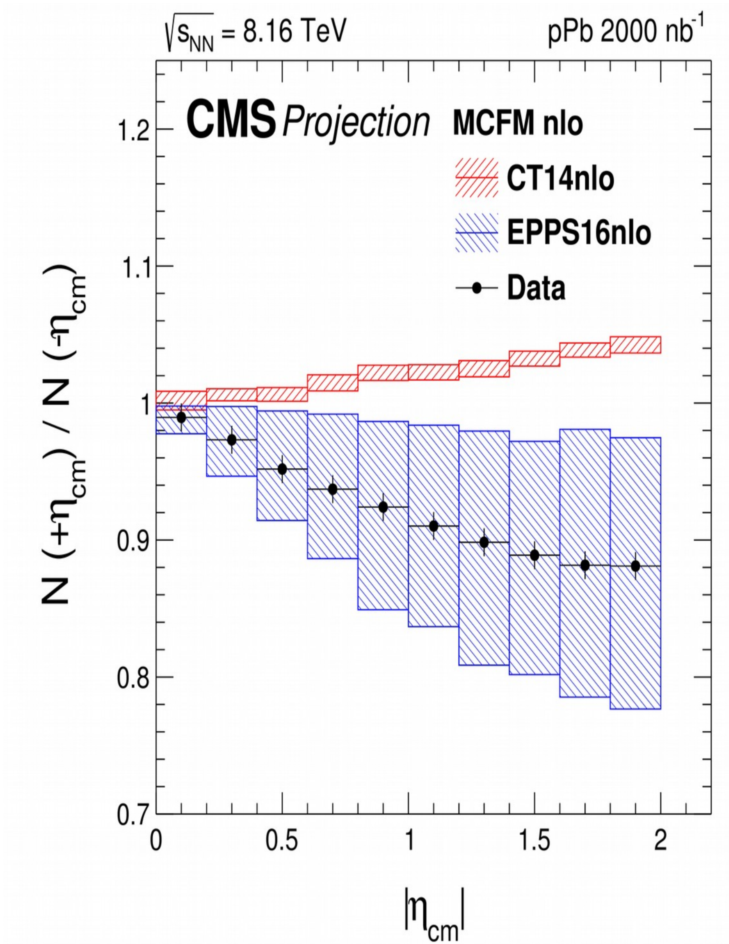


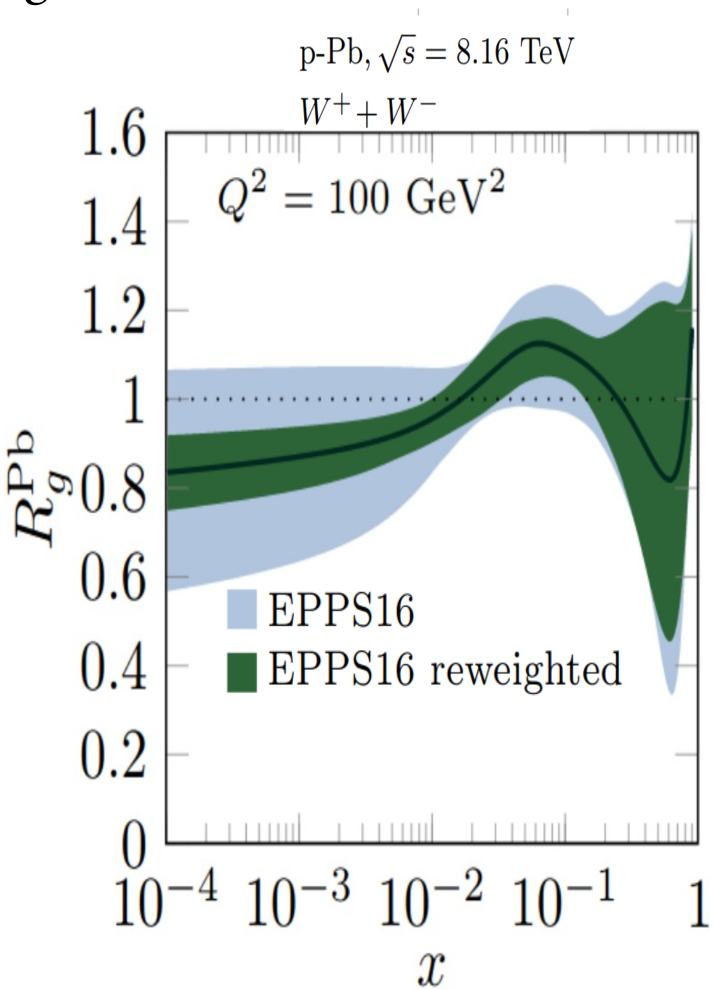


Phys. Rev. Lett. **120** (2018) 232301

Prospects for W boson forward-to-backward ratios

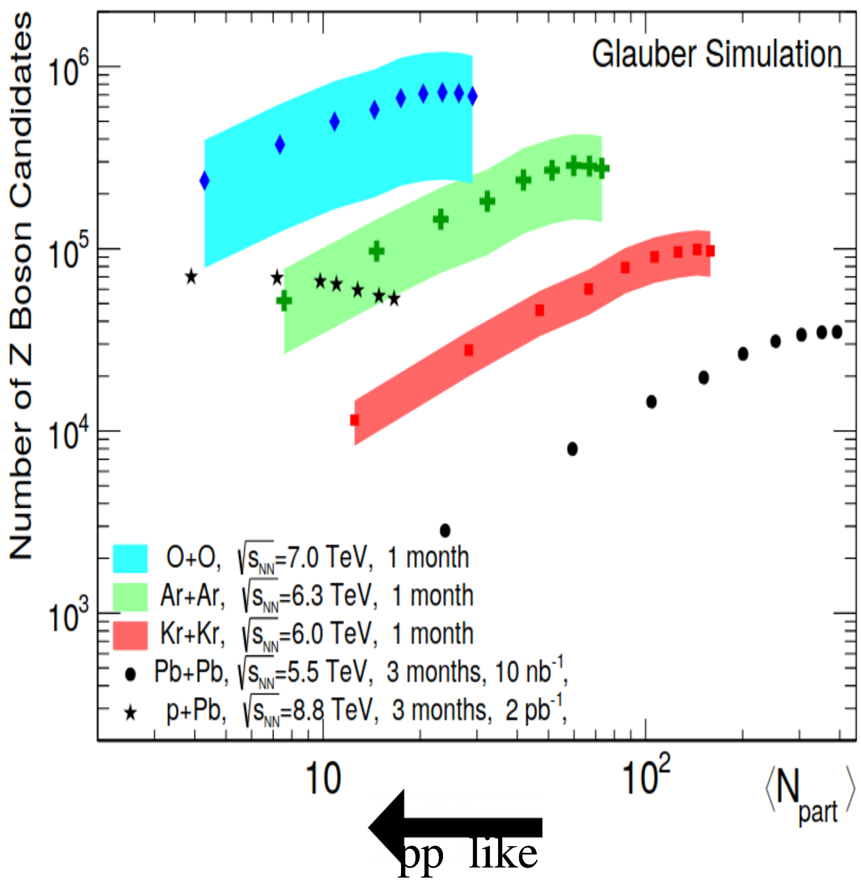
- Exploit the larger (× 10) pPb data set in Runs 3–4
  - experimental uncertainties significantly **smaller** than the nPDF ones
  - to showcase the potential: significant reduction of the uncertainties in the gluon nPDF
    - the large-x (> 0.1) part is **not affected** though

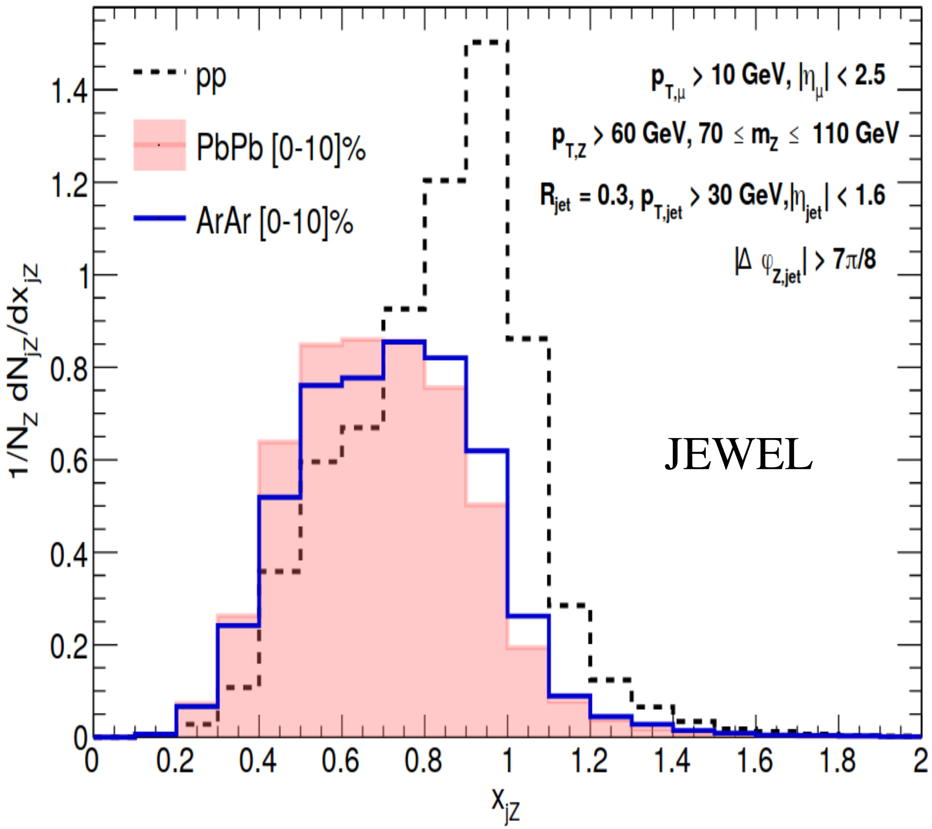




Physics motivations for collisions with lighter ions

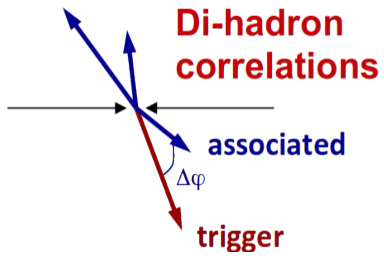
- **1 month** of ArAr > PbPb data set in Runs 3–4
  - coverage of a much broader range in Z p_T → jet-energy differential studies of quenching
- case study: ratio of the jet to Z p_T expected **similar** in ArAr and PbPb collisions

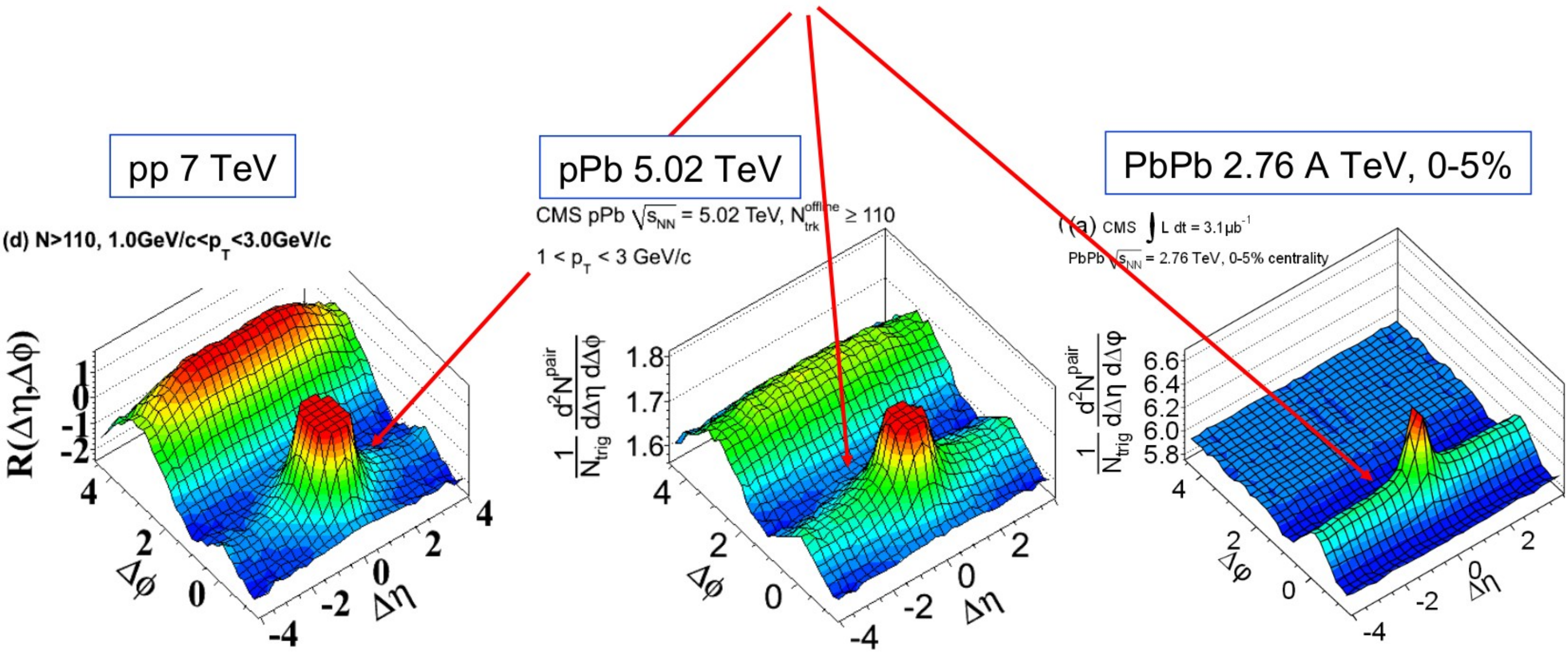




"Everything...flows"(?)

- Long-range ($2 < |\Delta\eta| < 4$), near-side ($\Delta\varphi \approx 0$) angular correlations are seen at LHC at various $\sqrt{s}$ in
  - heavy ion (XeXe and PbPb), **and**
  - "small systems", i.e., high-multiplicity pPb and pp collisions
- Signs reminiscent of **collective behavior** of a quark-gluon plasma (QGP)

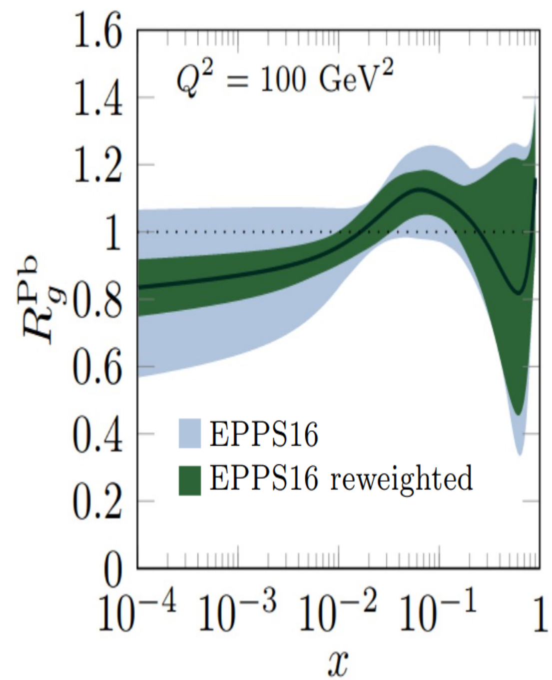


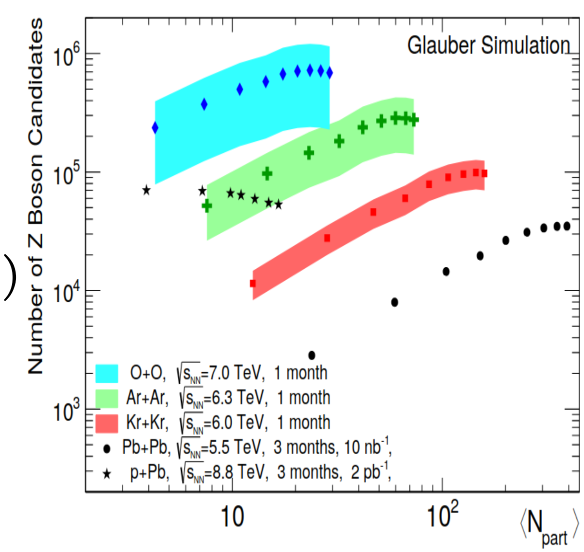


JHEP **09** (2010) 091 | PLB **718** (2013) 795 | JHEP **07** (2011) 076

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)

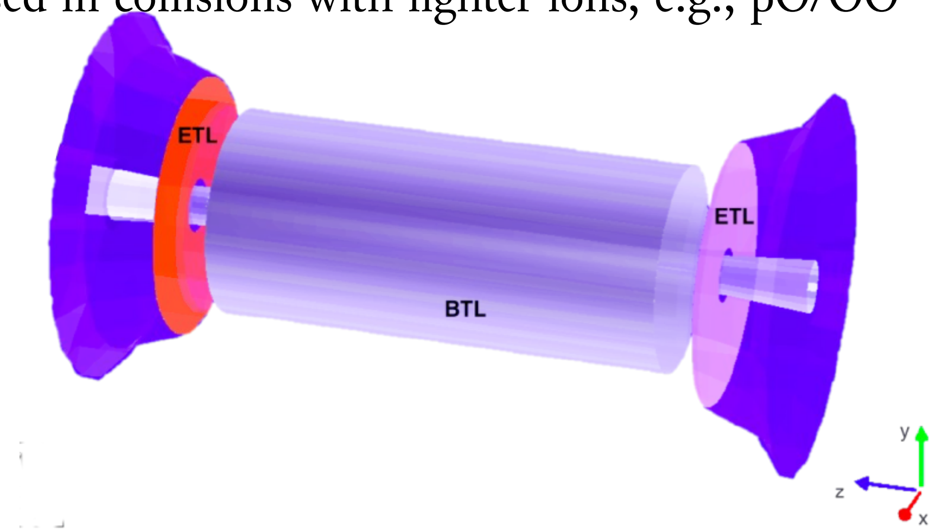




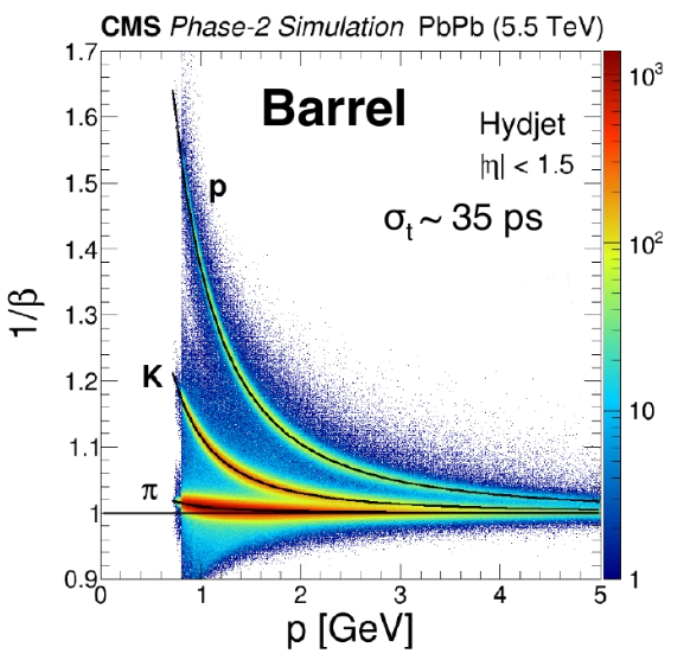
S slides

Extending the LHC HI program & CMS LS3 upgrades

- Runs 3+4: main **goal** of >10/nb PbPb
  - focus on rare triggers
  - even larger minimum-bias event sample
    - > 6 kHz at HLT in Run 3, goal to increase for Run 4
- Major Phase-2 upgrades for HL-LHC (2026+)
  - Extension of tracker (muon systems) acceptance from $|\eta|<2.5$ to < 4.0 (3.0), etc.
  - Precise timing detectors for pileup rejection
    - byproduct TOF PID
- Radiation-hard zero degree calorimeter (2021+)
  - Can also be used in collisions with lighter ions, e.g., pO/OO

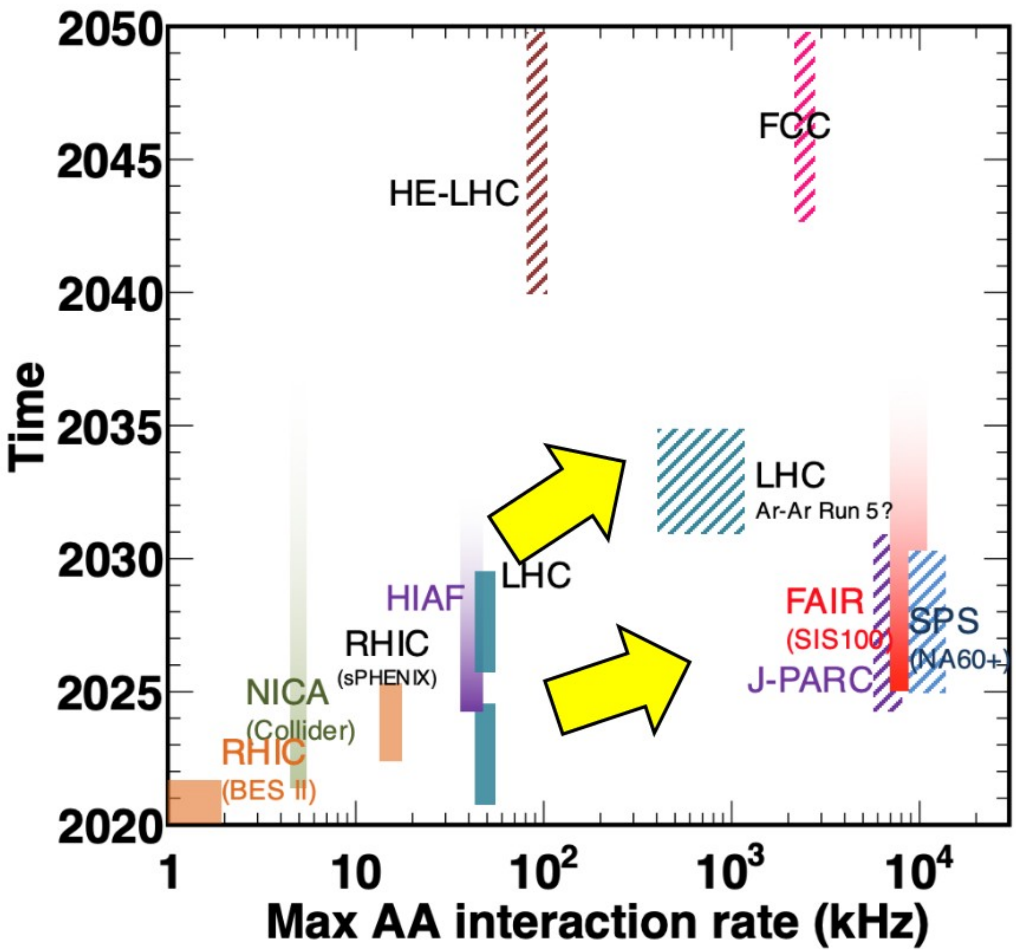


CERN-LHCC-2017-027



Outlook: General goals in HL-LHC & beyond

- **Parton densities** in broad kinematic range and search for **saturation**
- **Macroscopic** long-wavelength QGP properties with unprecedented precision
- **Collectivity** across colliding systems
- **Microscopic** parton dynamics underlying QGP properties



Decade ahead of us

- Data from 6–7 facilities
- Up to ×100 higher rates

To shape the long-term plan

- LHC Run 5 HI
  - not a simple extension
- EIC cold QCD program

Key characteristics of the latest fits of nPDFs (in chronological order from left to right)

arXiv:1704.04036

	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 $\Delta\chi^2$ (90% CL defined by the global)	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]

$$\chi^2_{\rm global} \approx \chi^2_0 + \sum_{i,j} (a_i - a_i^0) H_{ij} (a_j - a_j^0) = \chi^2_0 + \sum_i z_i^2$$

Hessian matrix

Parameter variations

arXiv:1704.04036

As compared to the PDF fitting landscape

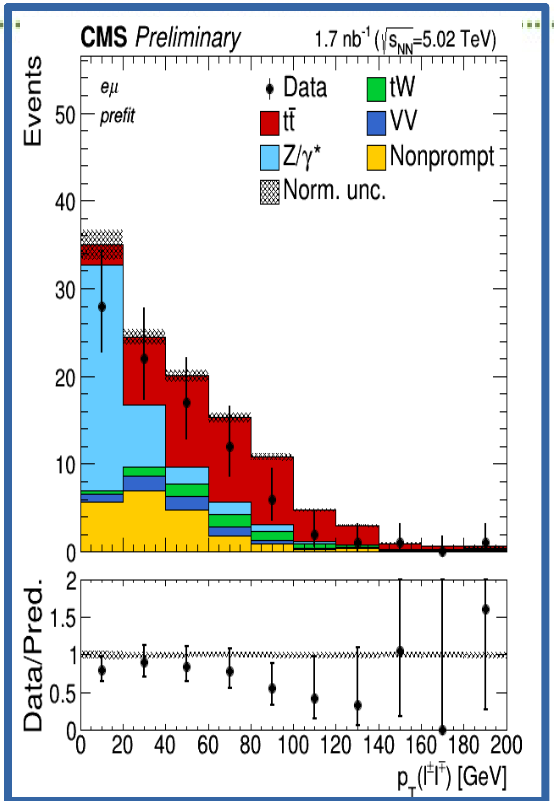
Ubiali, DIS2017

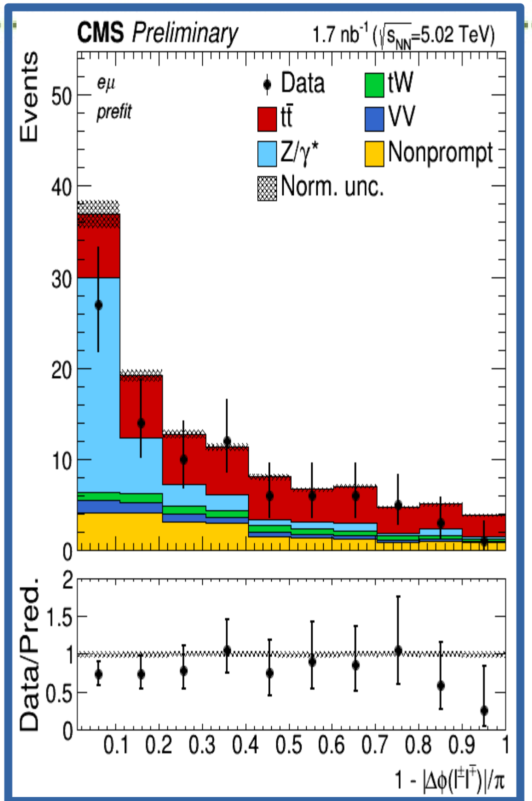
April 2017	NNPDF3.0	MMHT2014	CT14	HERAPDF2.0	CJ15	ABMP16
Fixed Target DIS	✔	✔	✔	✘	✔	✔
JLAB	✘	✘	✘	✘	✔	✘
HERA I+II	✔	✔	✔	✔	✔	✔
HERA jets	✘	✔	✘	✘	✘	✘
Fixed Target DY	✔	✔	✔	✘	✔	✔
Tevatron W,Z	✔	✔	✔	✘	✔	✔
Tevatron jets	✔	✔	✔	✘	✔	✘
LHC jets	✔	✔	✔	✘	✘	✘
LHC vector boson	✔	✔	✔	✘	✘	✔
LHC top	✔	✘	✘	✘	✘	✔
Stat. treatment	Monte Carlo	Hessian $\Delta\chi^2$ dynamical	Hessian $\Delta\chi^2$ dynamical	Hessian $\Delta\chi^2=1$	Hessian $\Delta\chi^2=1.645$	Hessian $\Delta\chi^2=1$
Parametrization	Neural Networks (259 pars)	Chebyshev (37 pars)	Bernstein (30-35 pars)	Polynomial (14 pars)	Polynomial (24 pars)	Polynomial (15 pars)
HQ scheme	FONLL	TR'	ACOT-χ	TR'	ACOT-χ	FFN (+BMST)
Order	NLO/NNLO	NLO/NNLO	NLO/NNLO	NLO/NNLO	NLO	NLO/NNLO

Signal separation: measuring $t\bar{t}$ with leptons only

- Use the kinematics of the two leading-p_T leptons to train a BDT

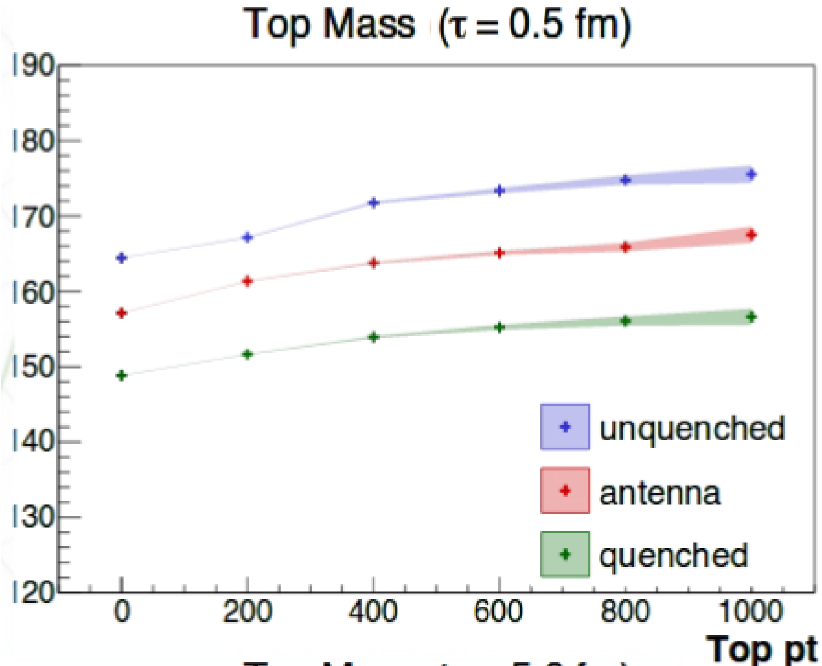
- $p_T(\ell_1)$, the p_T of the highest-p_T lepton,
- A_{p_T}, the asymmetry in the lepton-p_T's, namely $\frac{p_T(\ell_1)-p_T(\ell_2)}{p_T(\ell_1)+p_T(\ell_2)}$,
- $p_T(\ell\ell)$, the p_T of the dilepton system,
- $|\eta(\ell\ell)|$, the absolute η of the dilepton system,
- $|\Delta\phi(\ell\ell)|$, the absolute value of the separation in ϕ of the two leptons, and
- $\Sigma|\eta_i|$, the sum of the absolute η's of the leptons.

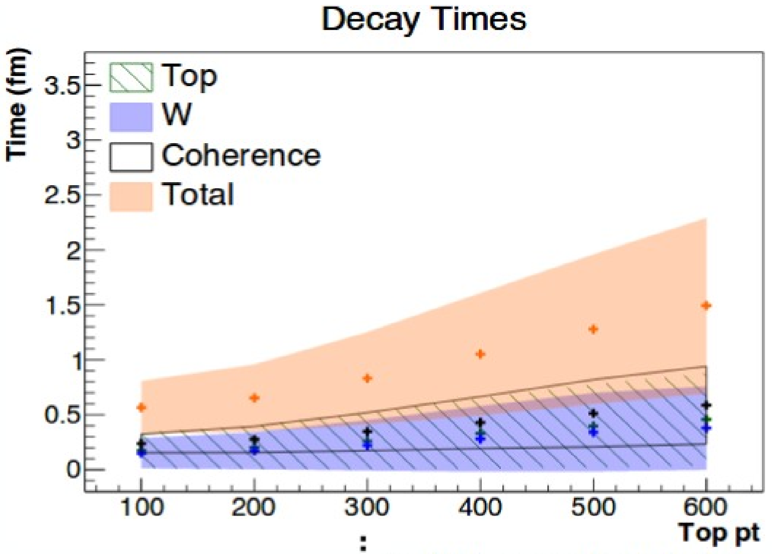




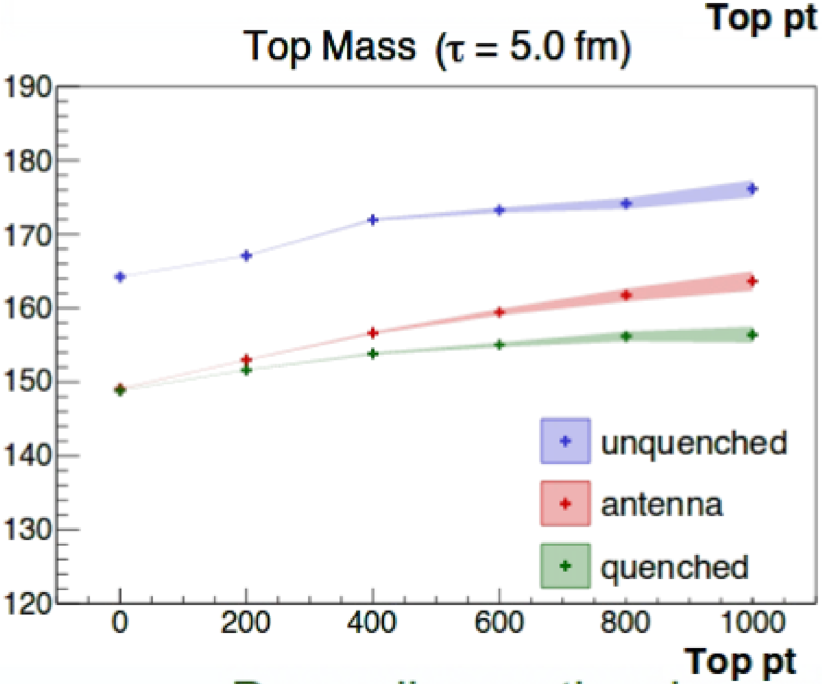
A nice heuristic idea for a yocto-chronometer !

L. Apolinário et al. 4th HIN Jet WKSH (2





Not enough statistics…

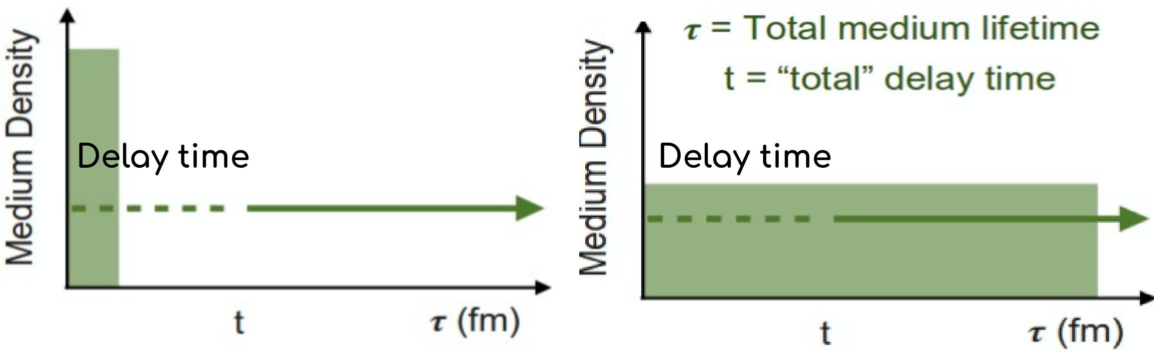


Probe ~ [0.4; 1.2] fm

$\Delta E/E = [(\tau - t)/\tau] * 0.1$

τ = Total medium lifetime

t = "total" delay time



Depending on the chosen p_T, the antenna may still lose some energy.

Knowing the energy loss, it is possible to build the density evolution profile of the medium!

BSM searches with heavy ion collisions at the LHC

- Submitted as input to the update of the European Particle Physics Strategy (EPPS)

arXiv: 1812.07688

Production mode	BSM particle/interaction	Remarks
Ultraperipheral	Axion-like particles	$\gamma\gamma \to a$, $m_a \approx 0.5$–$100\,\text{GeV}$
	Radion	$\gamma\gamma \to \phi$, $m_\phi \approx 0.5$–$100\,\text{GeV}$
	Born-Infeld QED	via $\gamma\gamma \to \gamma\gamma$ anomalies
	Non-commutative interactions	via $\gamma\gamma \to \gamma\gamma$ anomalies
Schwinger process	Magnetic monopole	Only viable in HI collisions
Hard scattering	Dark photon	$m_{A'} \lesssim 1\,\text{GeV}$, advanced particle ID
	Long-lived particles (heavy ν)	$m_{\text{LLP}} \lesssim 10\,\text{GeV}$, improved vertexing
Thermal QCD	Sexaquarks	DM candidate

Table 1: Examples of new-physics particles and interactions accessible in searches with HI collisions at the LHC, listed by production mechanism. Indicative competitive mass ranges and/or the associated measurement advantages compared to the *pp* running mode are given.

- Also not exhaustive list
  - e.g, tau g–2 using LHC heavy ion collisions in arXiv: 1908.05180