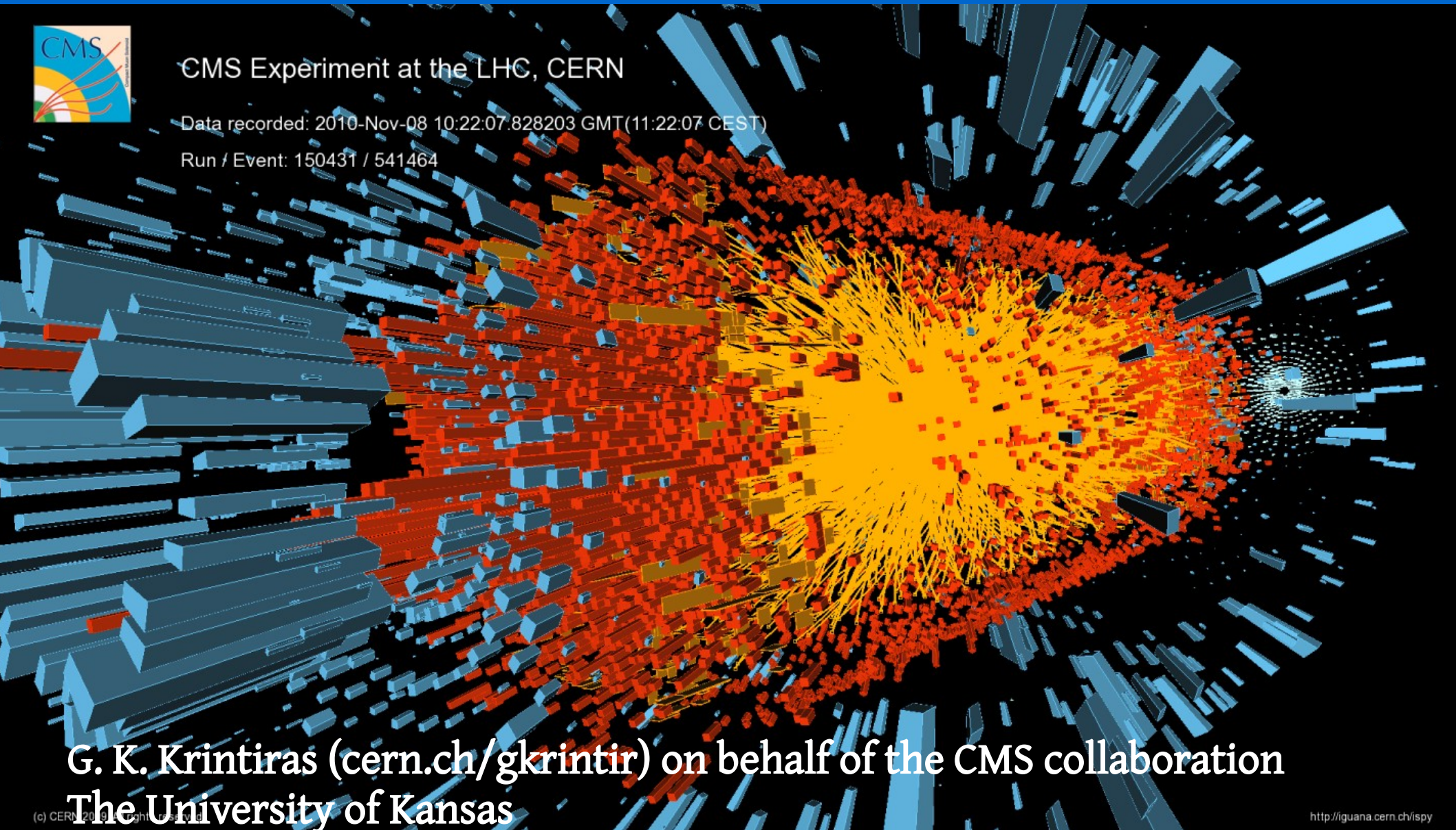
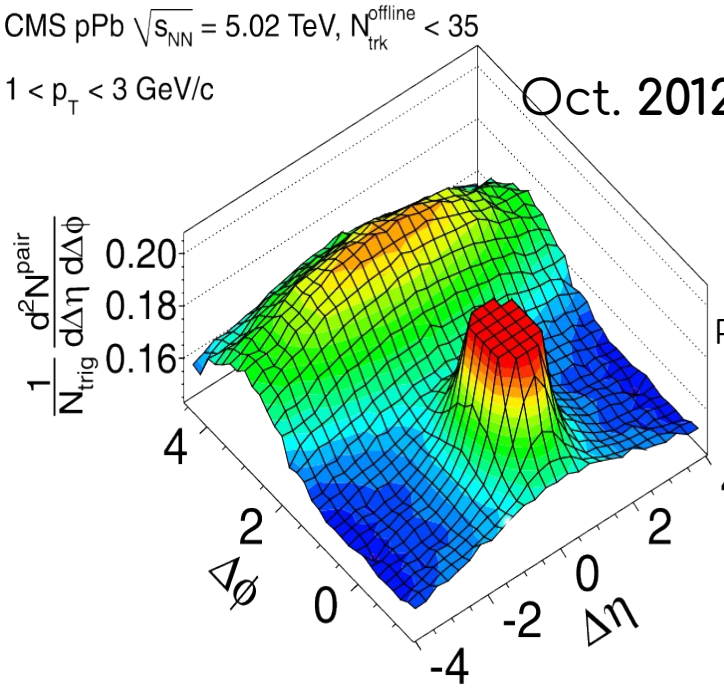
Review of results using heavy ion collisions at CMS



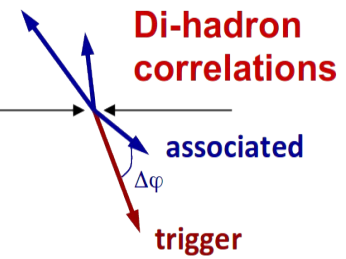
G. K. Krintiras (cern.ch/gkrintir) on behalf of the CMS collaboration
The University of Kansas

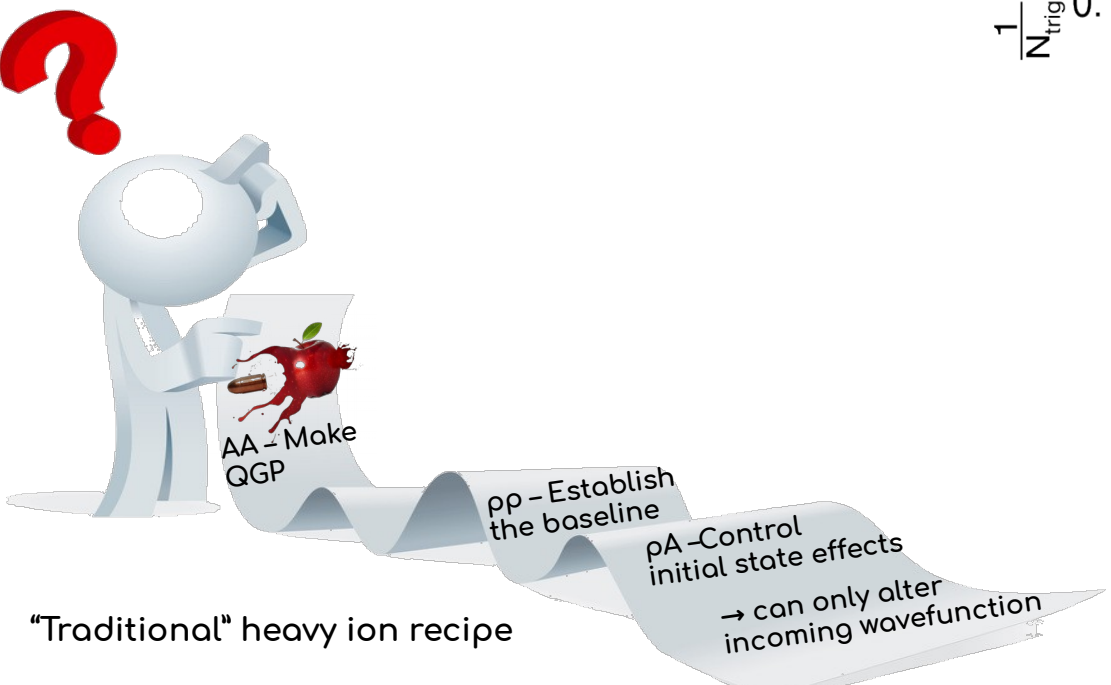
Throwing a bullet through an apple... Why?

- 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!)



Phys. Lett. B **718** (2013) 795





"Traditional" heavy ion recipe

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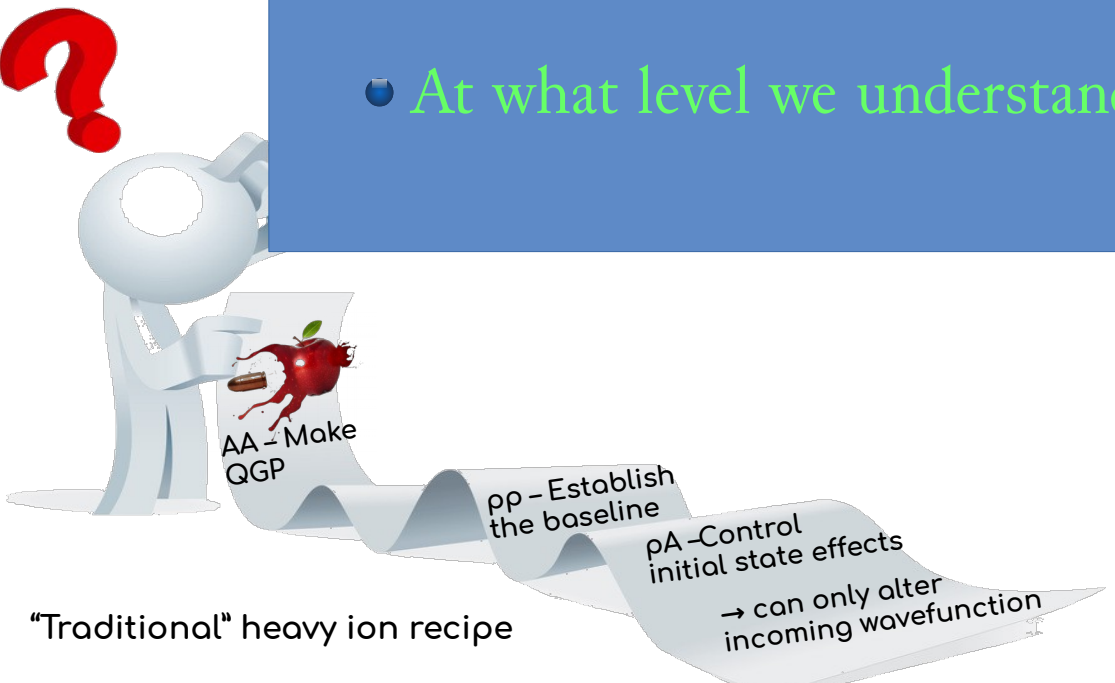
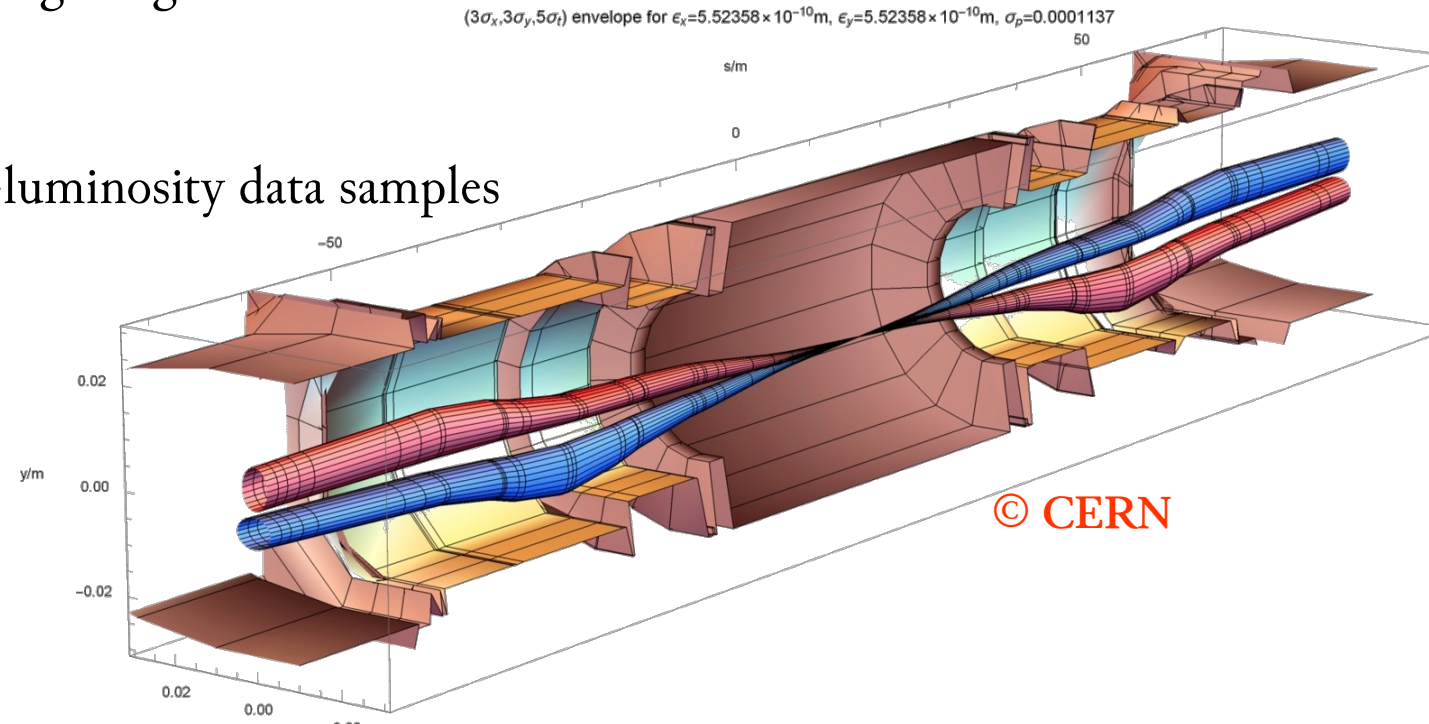
- Are pp and pA collisions AA alike?
- Complementary mechanism(s) for long-range correlations?
- At what level we understand QGP properties at the end?



"Traditional" heavy ion recipe

Studies with heavy ion collisions @ CMS

- Toolbox 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



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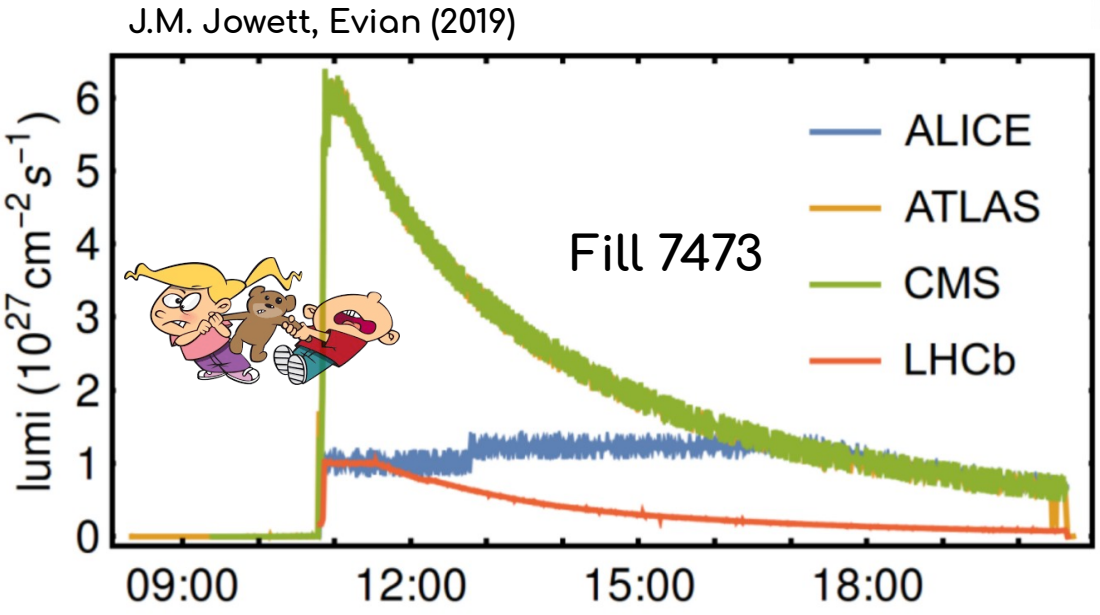
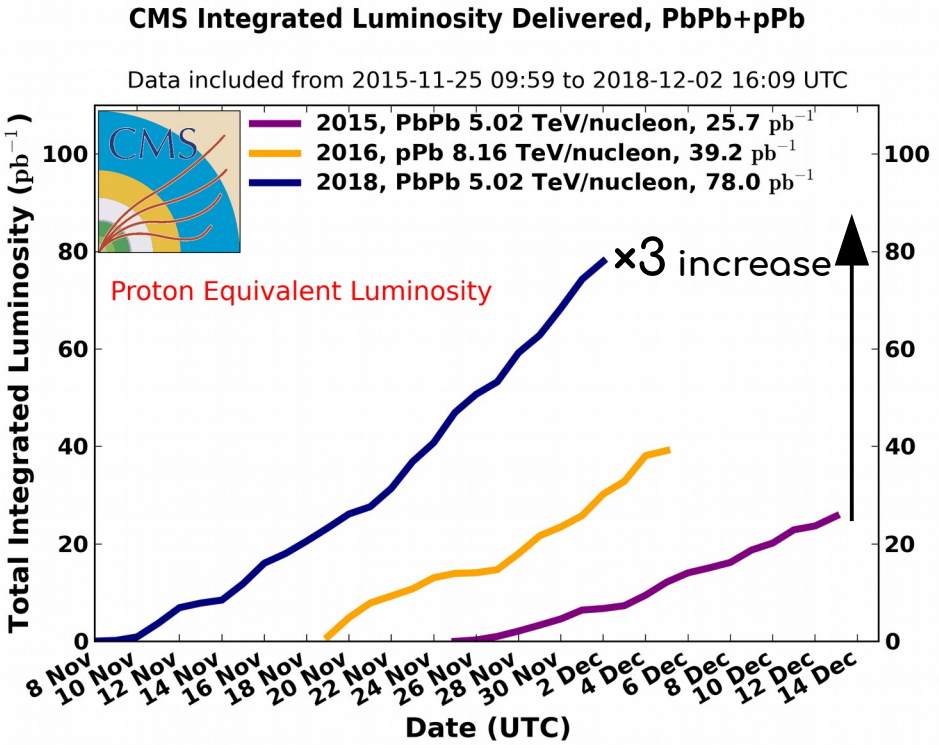
Not exhaustive list: emphasis on latest results

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

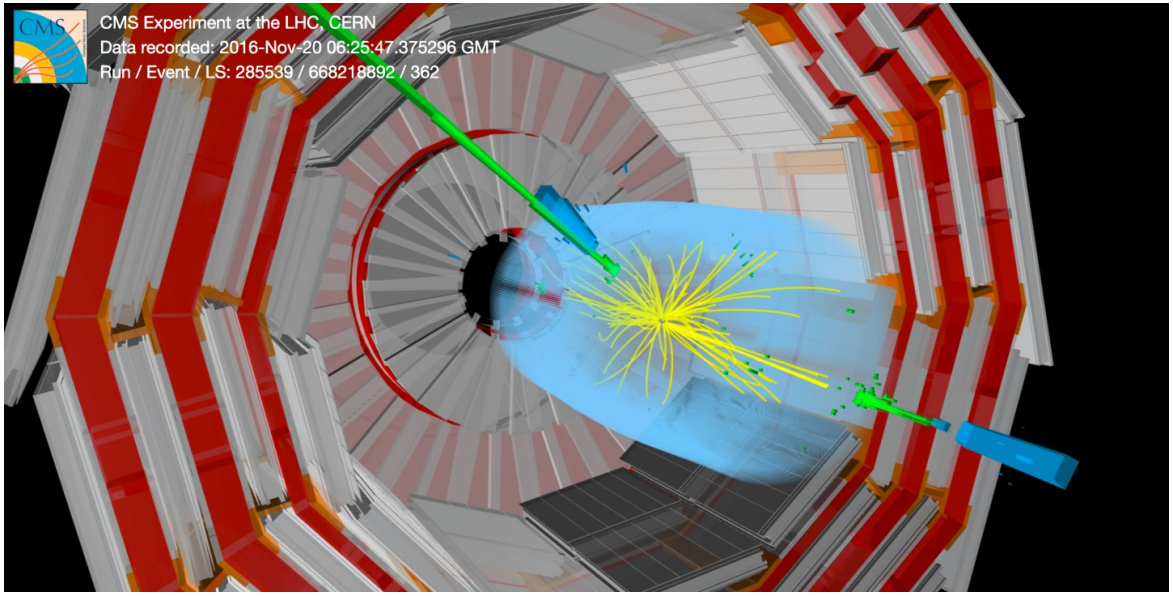




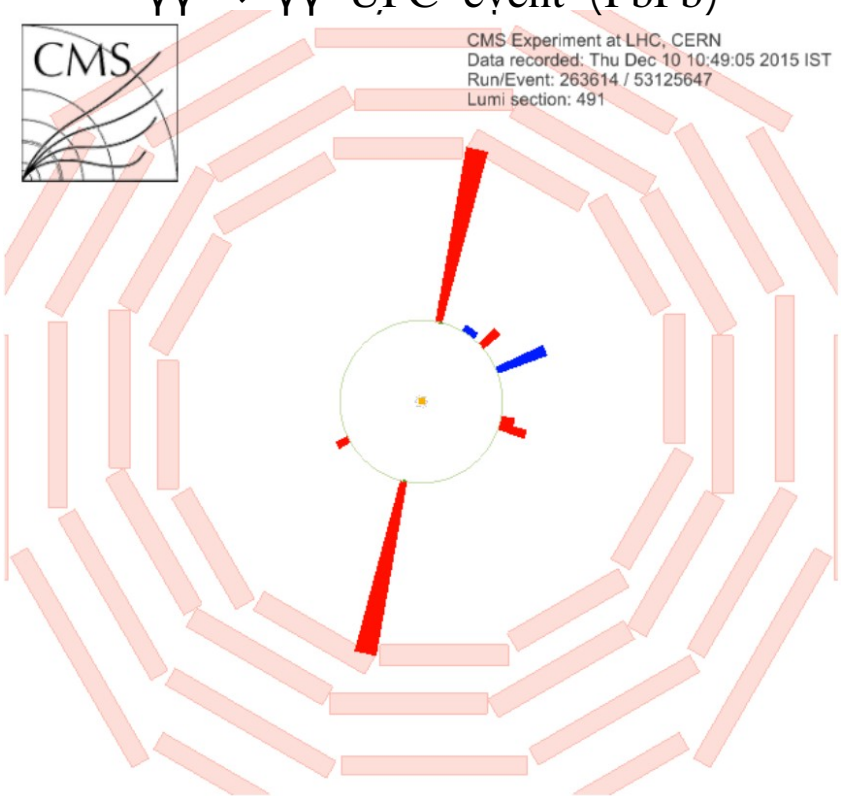
Studies with heavy ion collisions @ CMS

- 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

Dijet event (pPb)



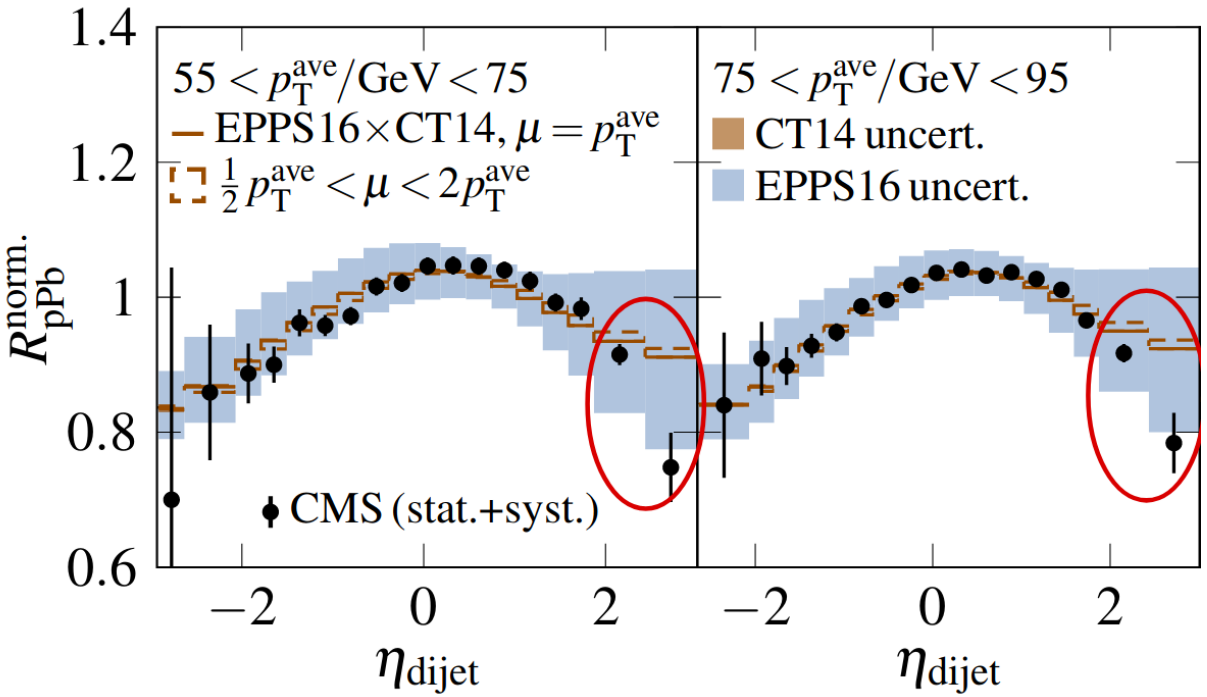
γγ → γγ UPC event (PbPb)

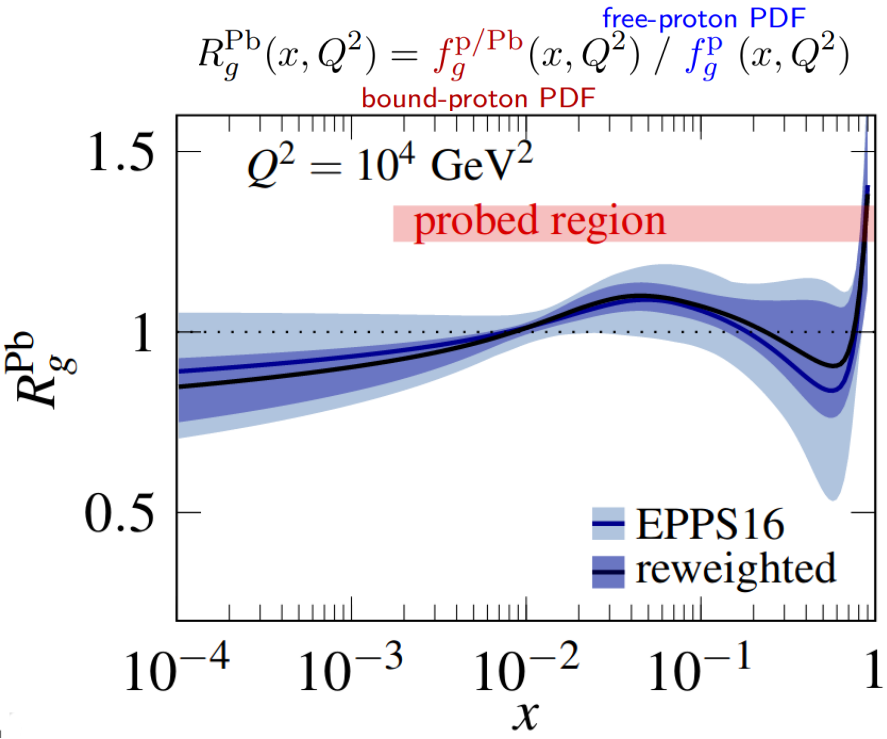


Nuclear gluon PDFs: constraints scarce so far

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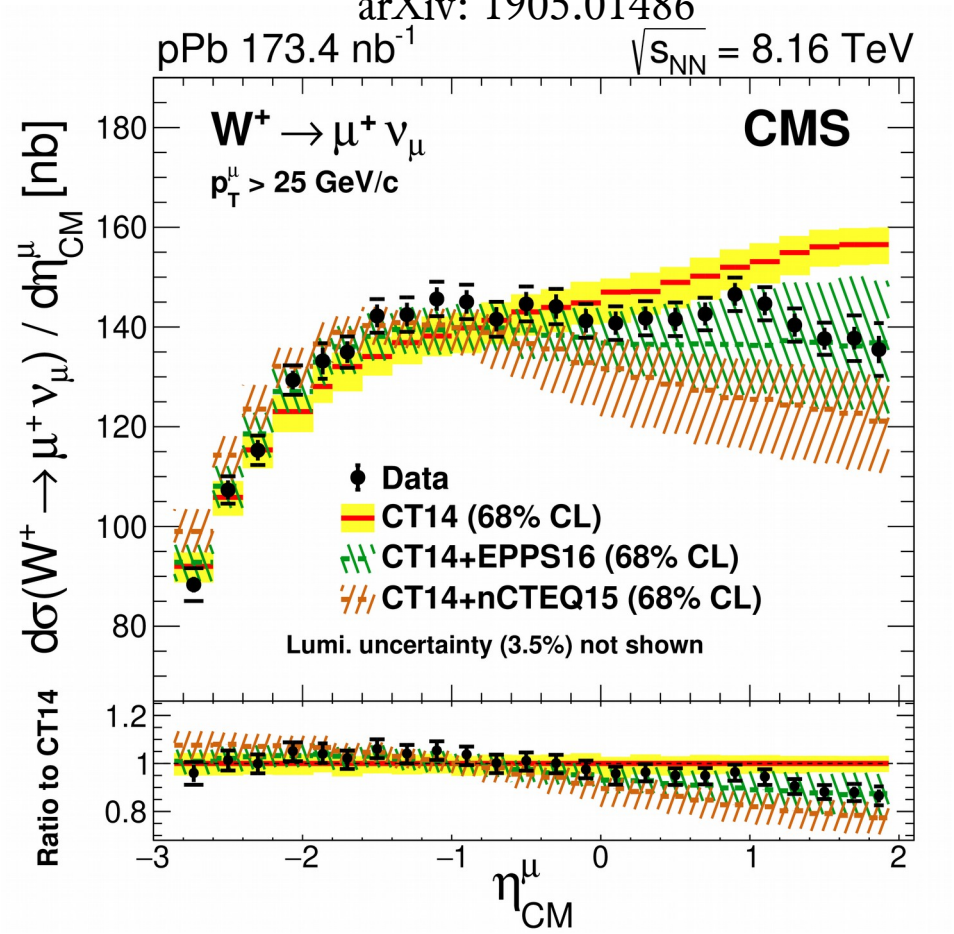
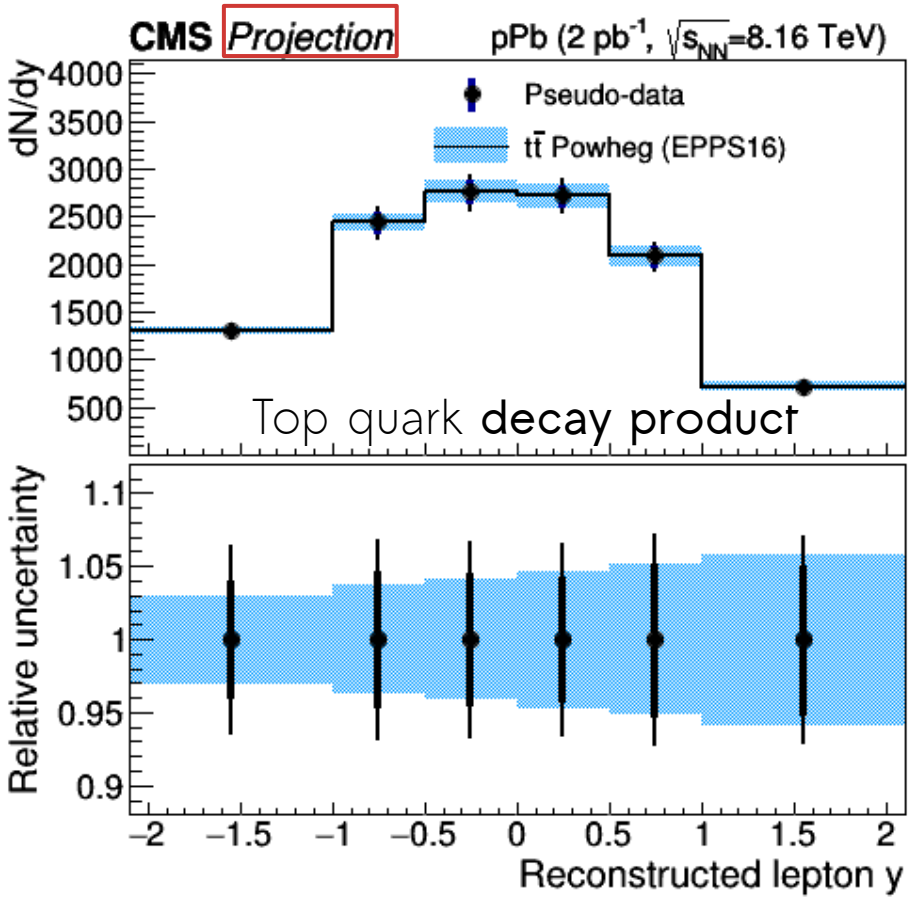
- Data consistent with NLO pQCD predictions with nuclear PDFs (EPPS16)
  - Enhanced suppression at forward y
- Significant reduction in EPPS16 uncertainties after reweighting
  - Complimentary constraints using **W bosons** and **top quarks**

arXiv: 1905.01486



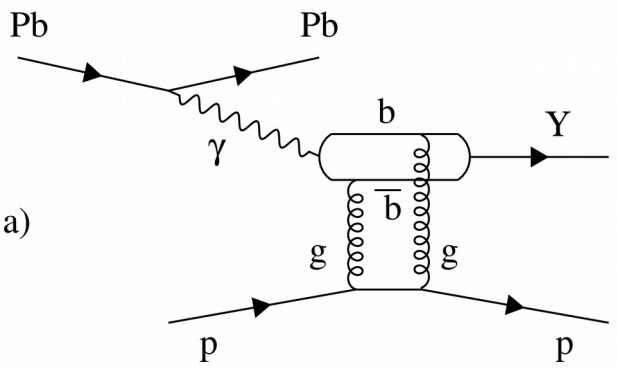
CMS PAS-FTR-18-027

(also in arXiv: 1812.06772)



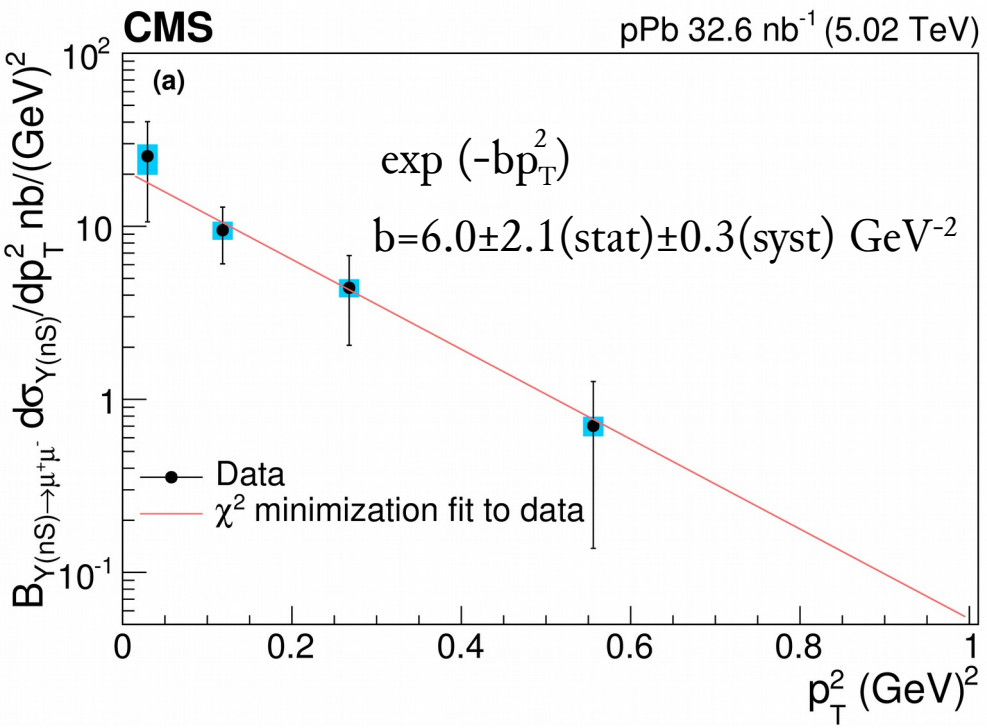
Exclusive vector meson photoproduction in pPb

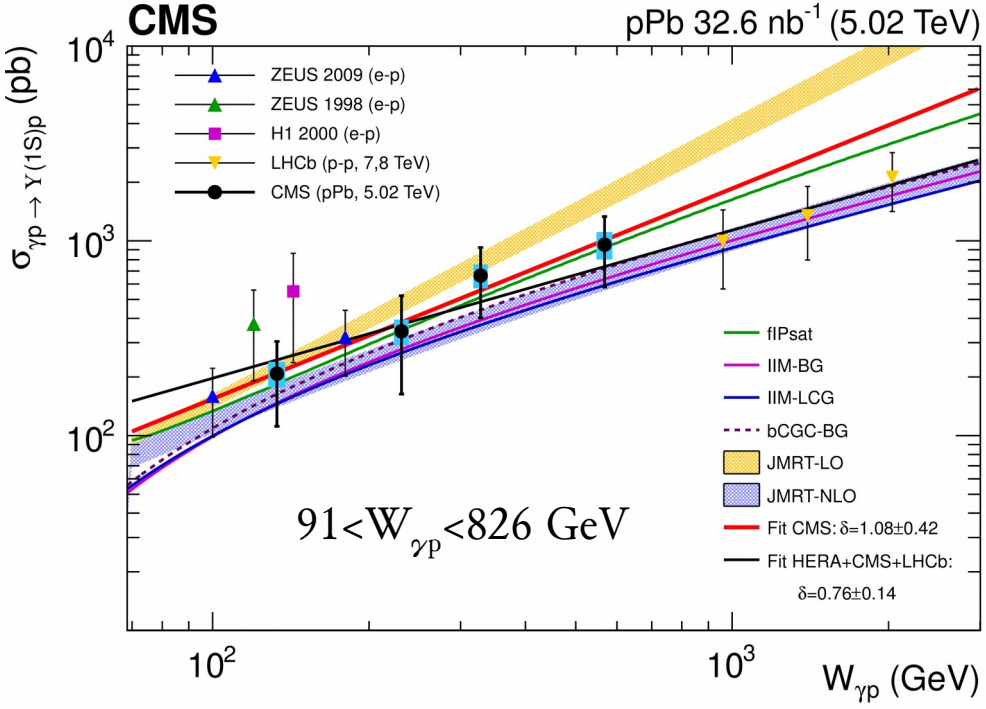
- Idea: Imaging proton using ions as a **photon source**
  - Probe gluon distributions at low $x \approx (M_{VM}/W_{\gamma p})^2$
- $\Upsilon(1S)$ differential in y, p_T^2 and as a function of $W_{\gamma p}$
  - Consistent with
    - b slope parameters at other center-of-mass energies
    - various models of the low-x gluon behavior
    - exponent from HERA and LHCb



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

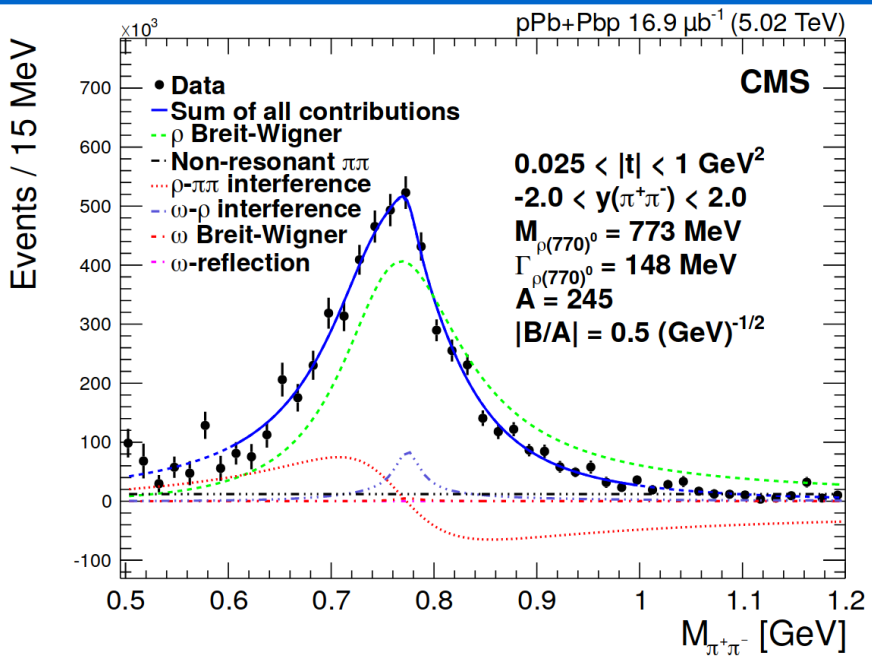
EPJC **79** (2019) 277



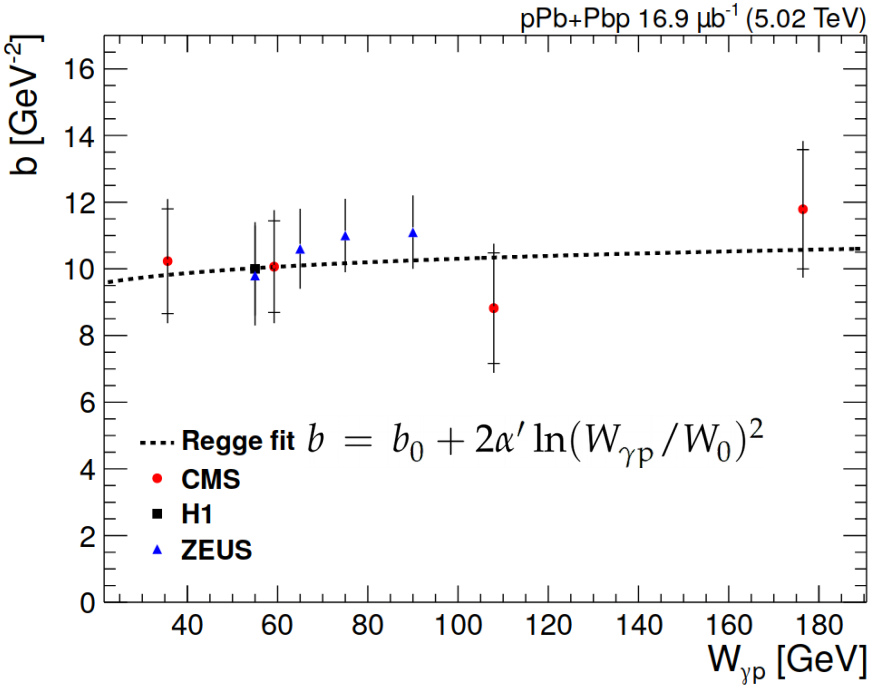


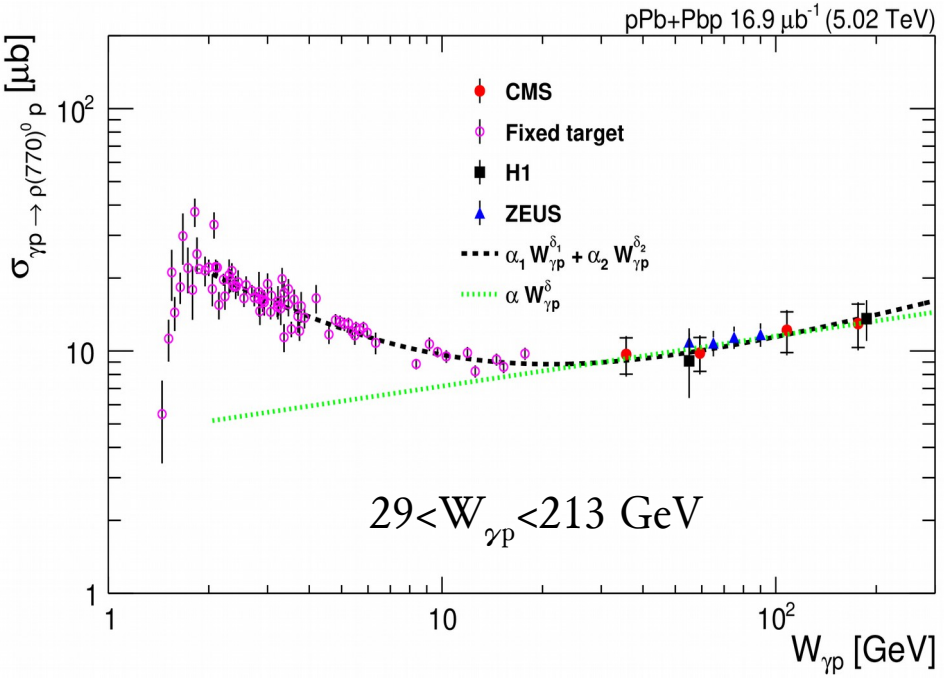
Exclusive vector meson photoproduction in pPb

- First measurement using $\rho(770) \rightarrow \pi^+\pi^-$ exclusive UPC events
  - About 20K candidates from unfolded $M_{\pi^+\pi^-}$
- Consistent with those at HERA
  - indeed ions act as a source of quasi-real photons
- Data (CMS and lower energy) agree with theory-inspired fits



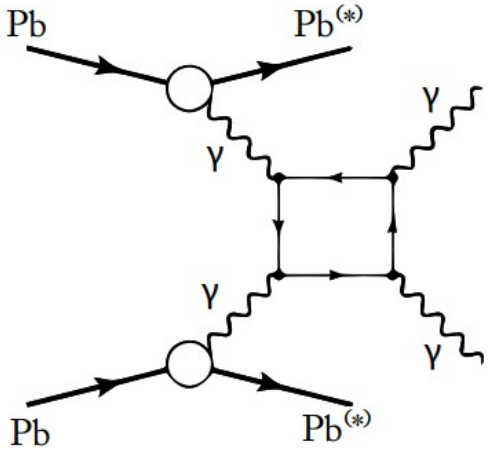
EPJC **79** (2019) 702



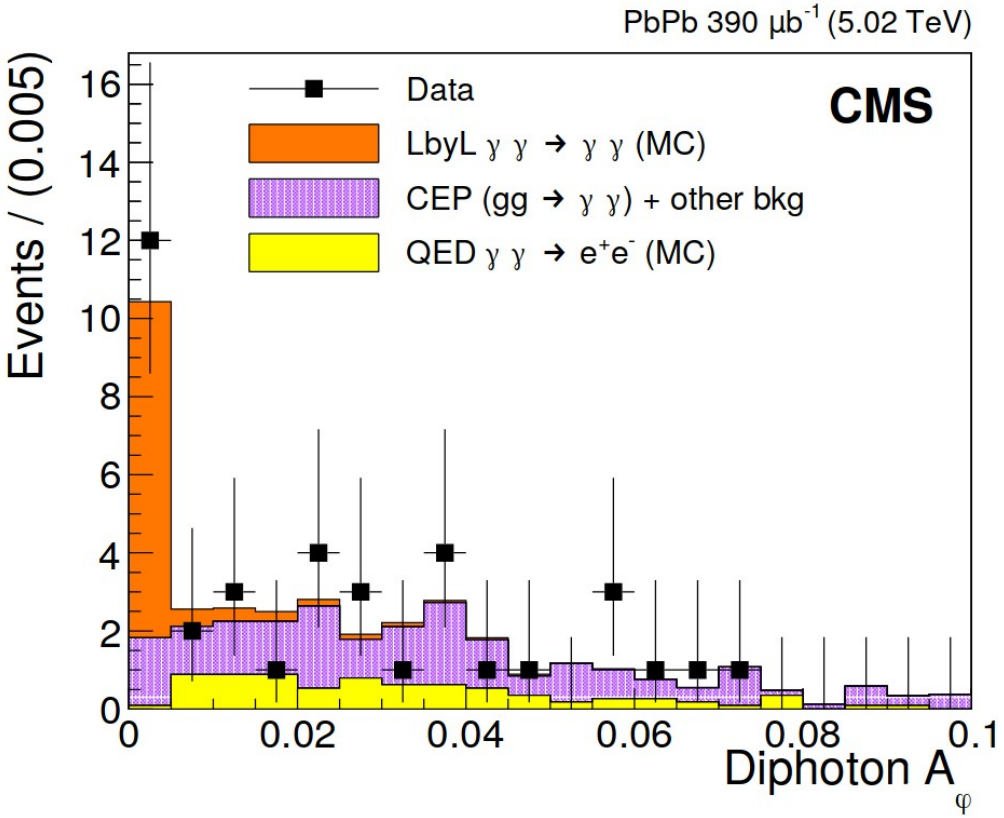


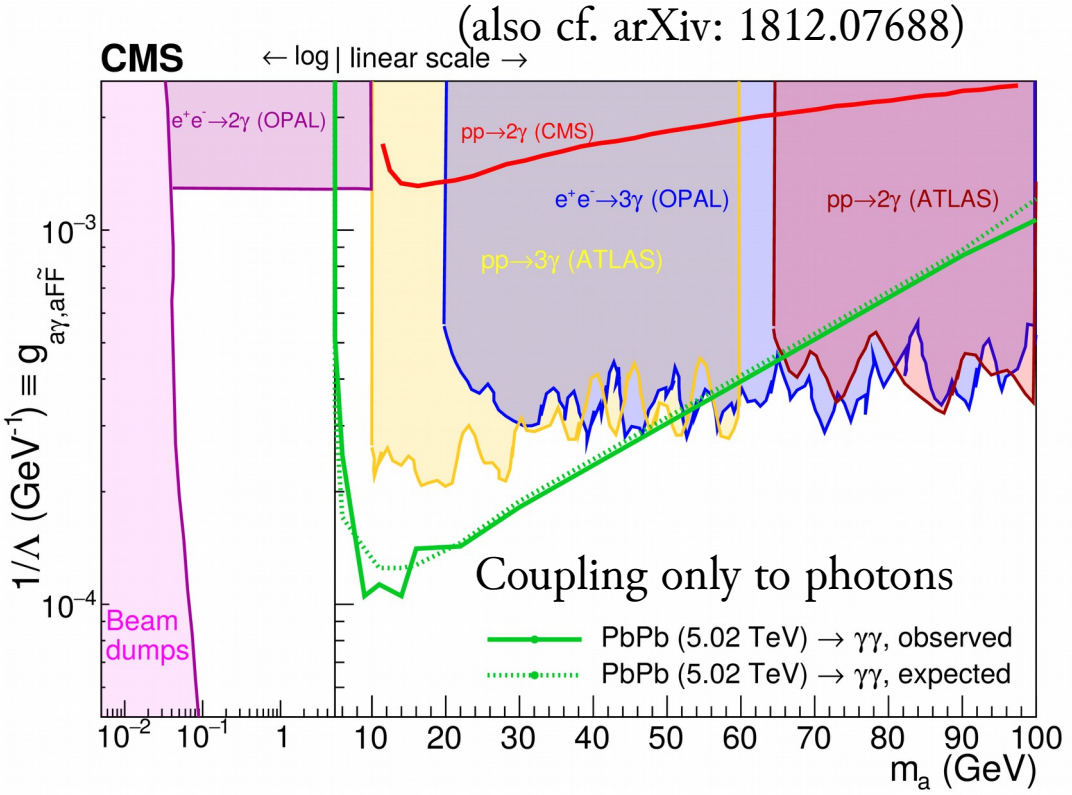
Light-by-light scattering

- Challenging to measure owing to tiny cross section $\mathcal{O}(\alpha^4)$
- Optimized EGM reconstruction for $E_T < 10$ GeV
  - Measured with significance at 4σ level
- 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:
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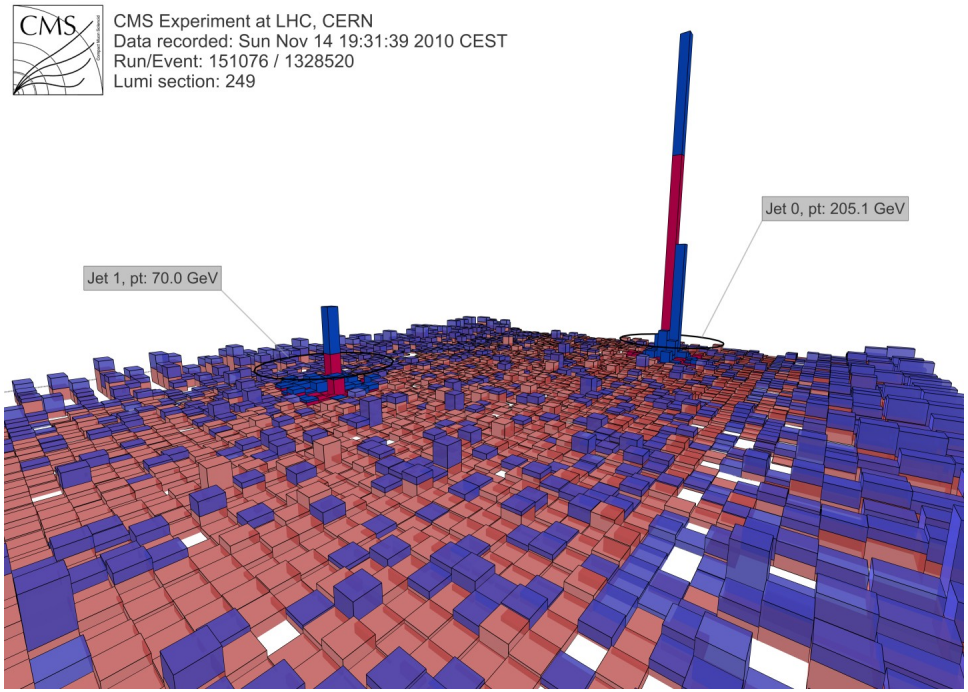
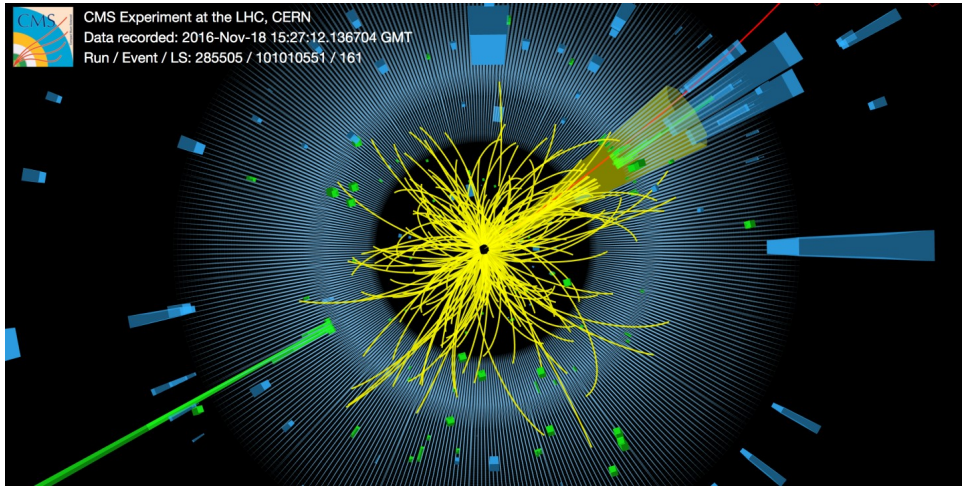
  - **Jet modifications**
  - Heavy quark dynamics
  - New probes

Back-to-back dijet (PbPb)

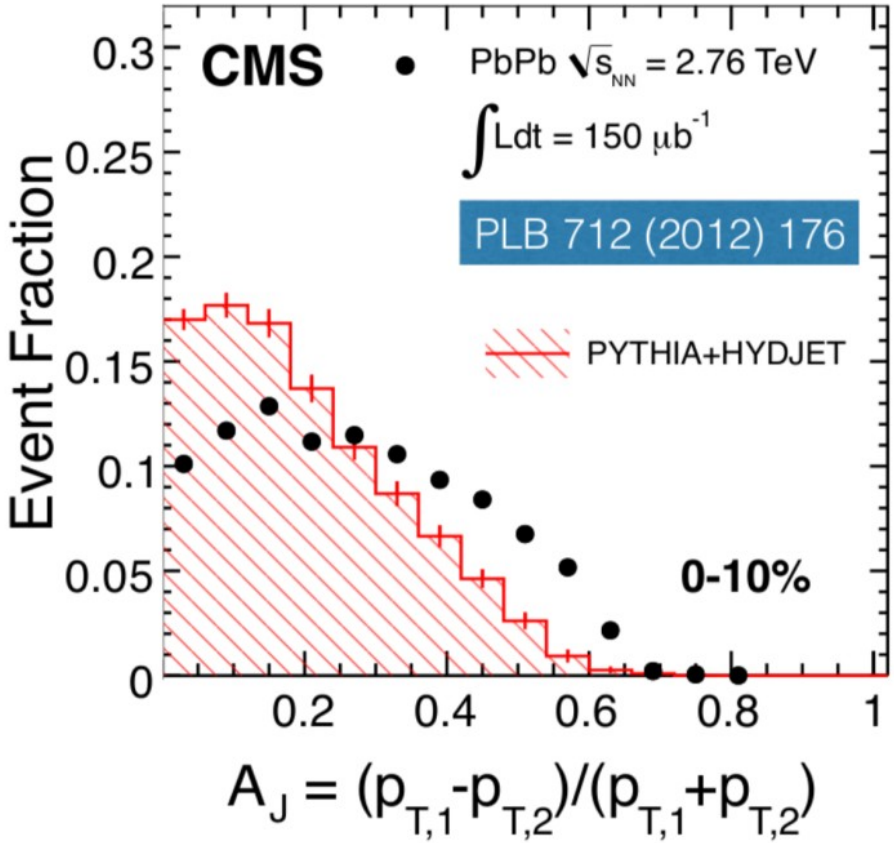


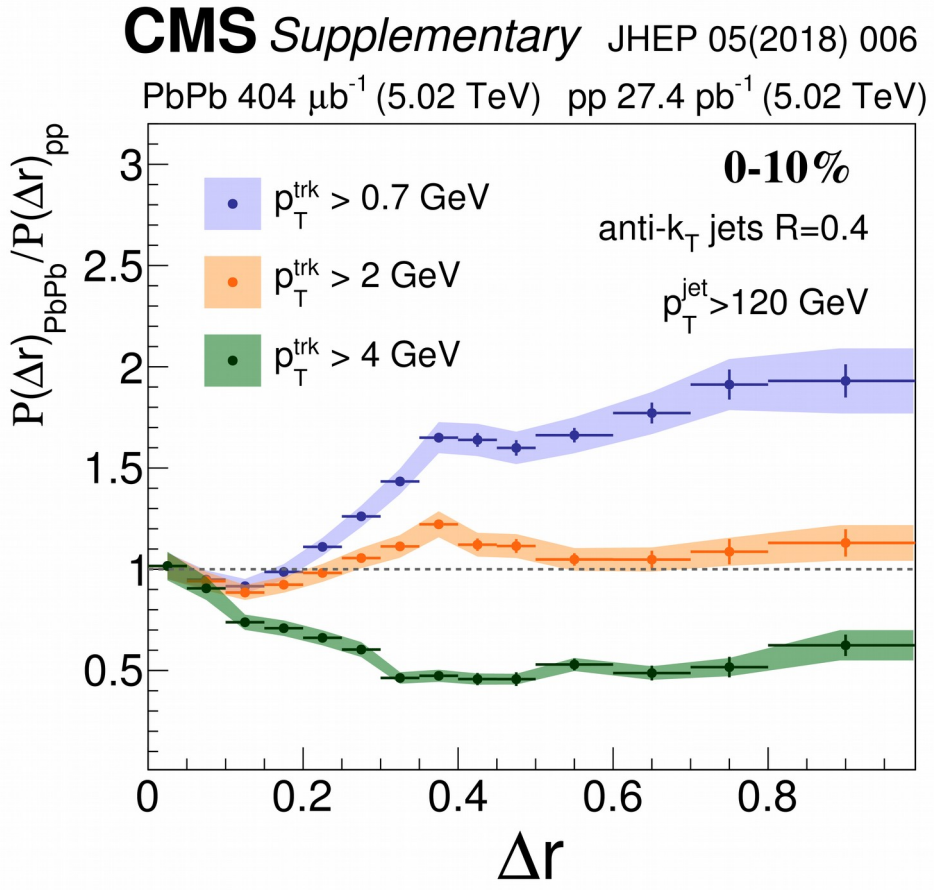
γ+jet (PbPb)



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



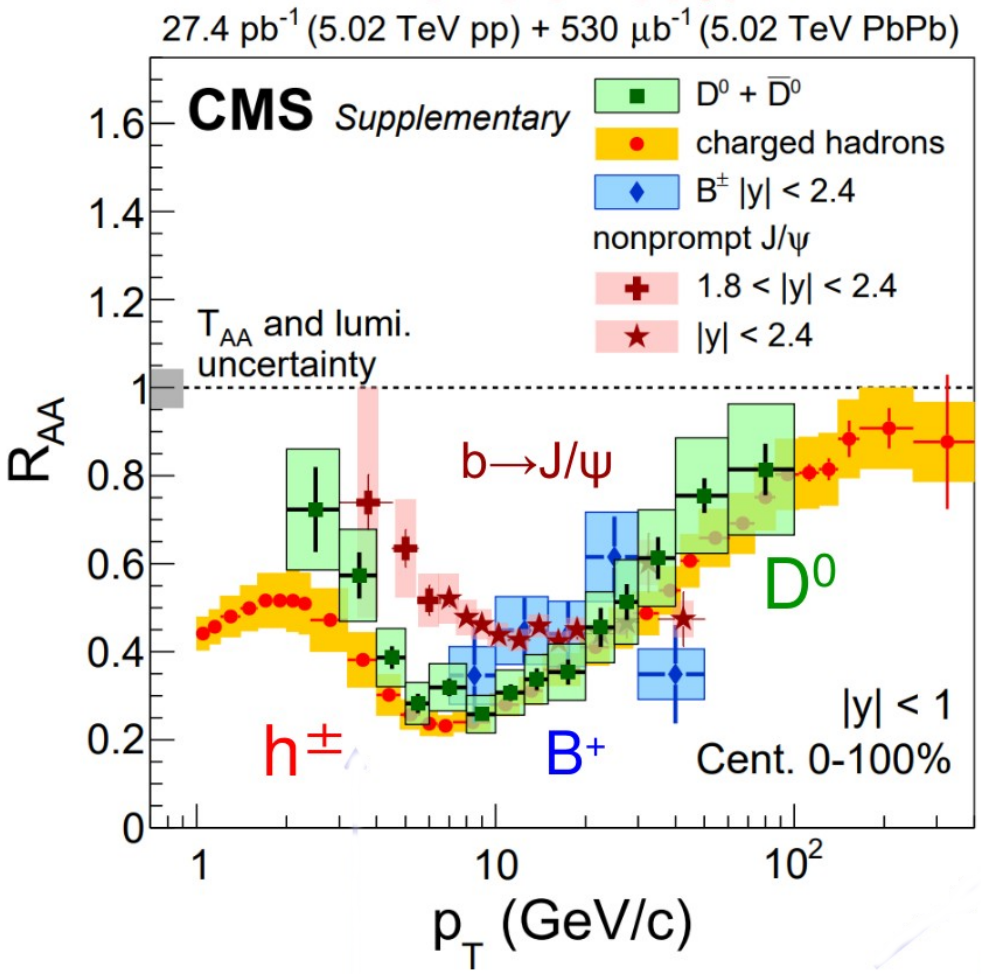


Nuclear modification factor (R_{AA}) of hadrons

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

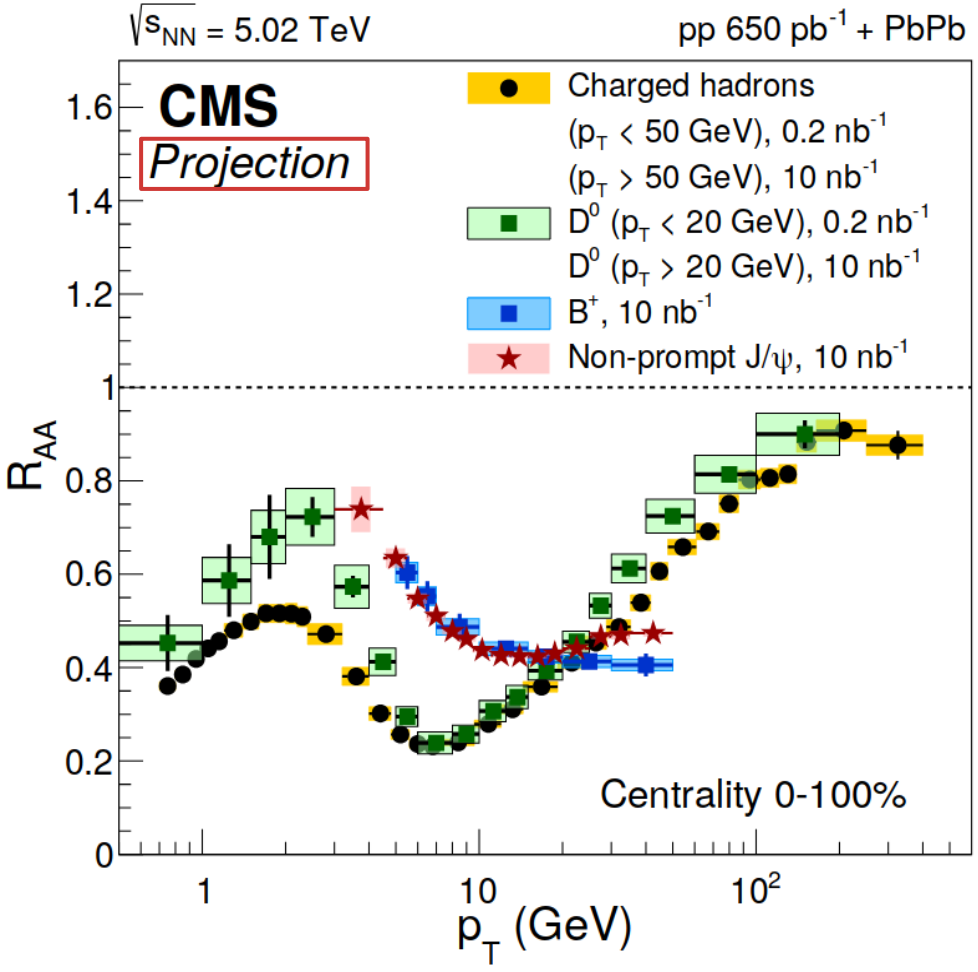
- Energy of partons is lost ('quenched') in QGP
  - Experimentally seen as R_{AA} modifications
  - increases for p_T>10 GeV; independent of flavor
- Significantly better precision with HL-LHC

Phys. Rev. Lett. **123** (2019) 022001



CMS PAS-FTR-17-002

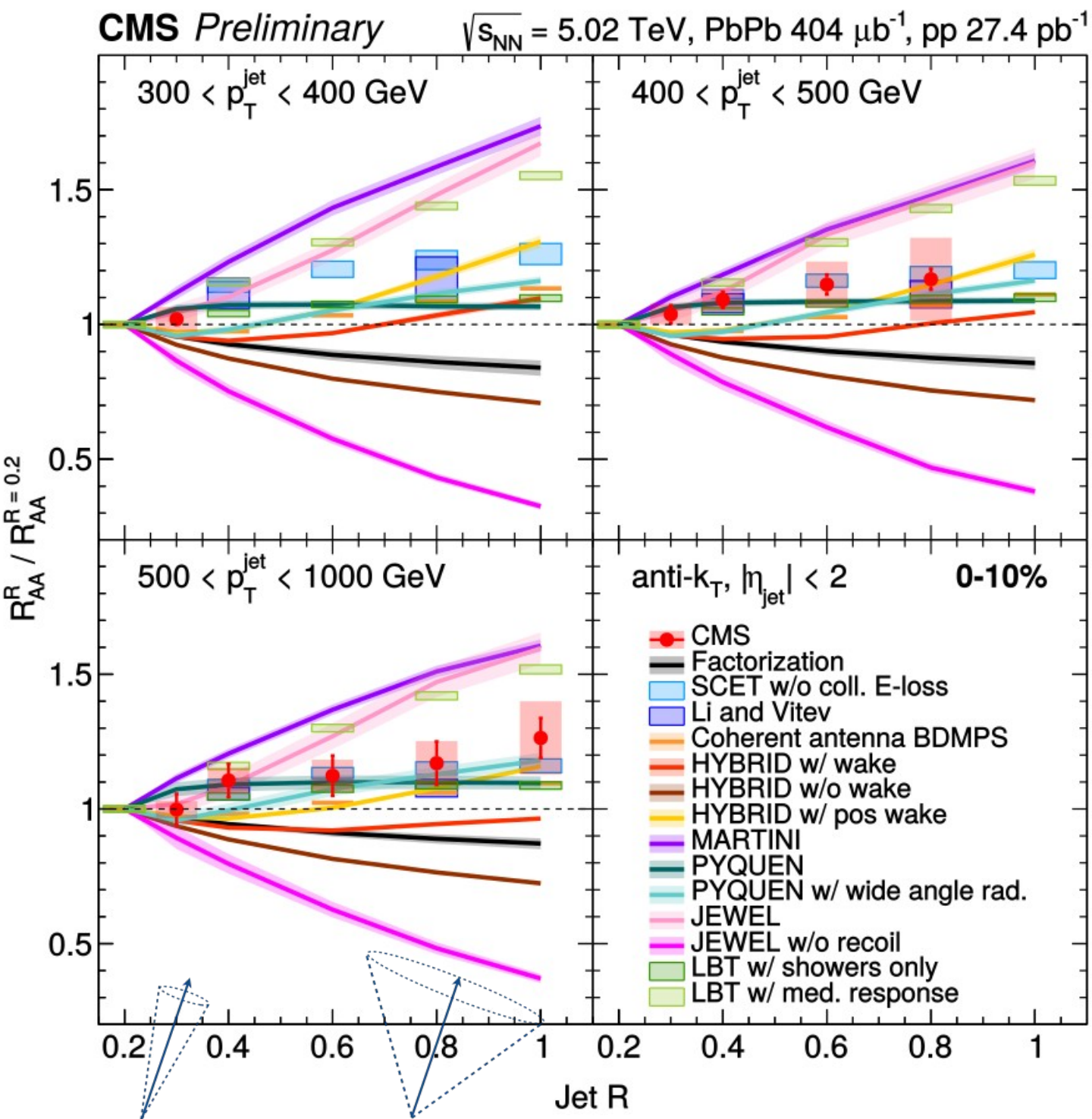
(also in arXiv: 1812.06772)



Jet R_{AA}: the first large radius scan

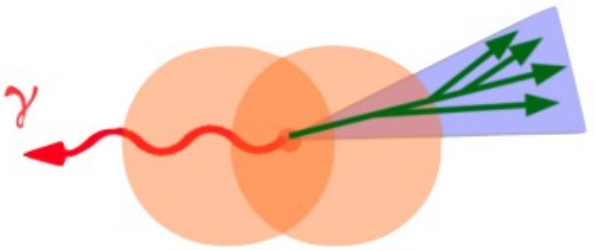
- Up to R = 1.0(!)
  - New phase space
- Competing effects for wide jets
  - **Constraints** on models

CMS PAS-HIN-18-014

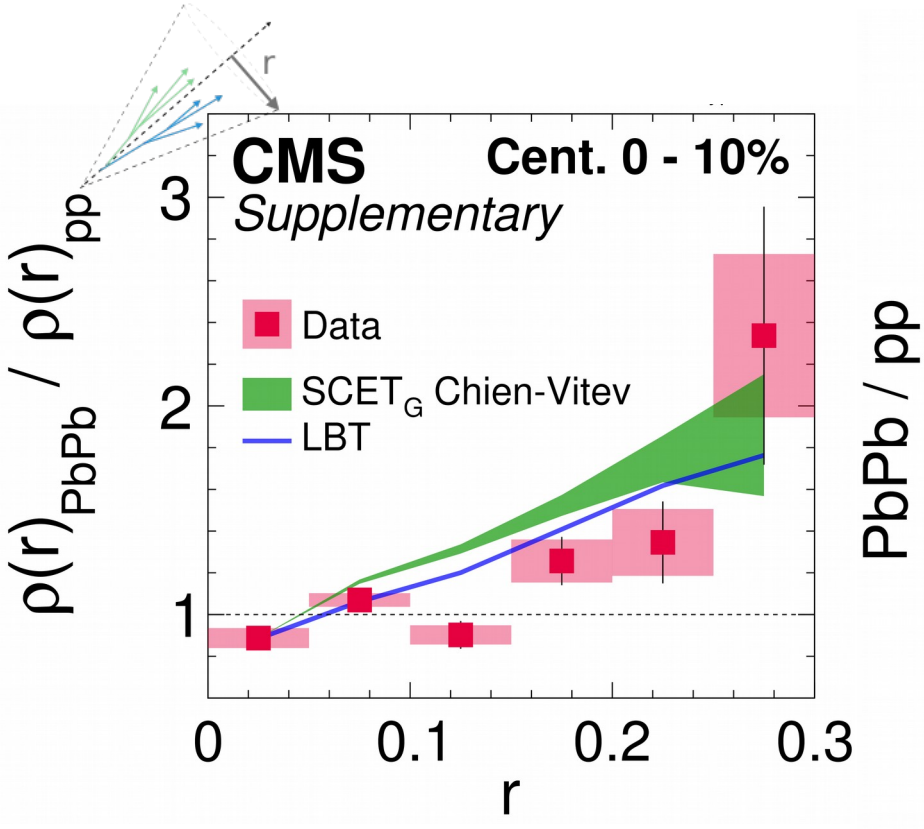


Jet shapes and fragmentation with γ+jet events

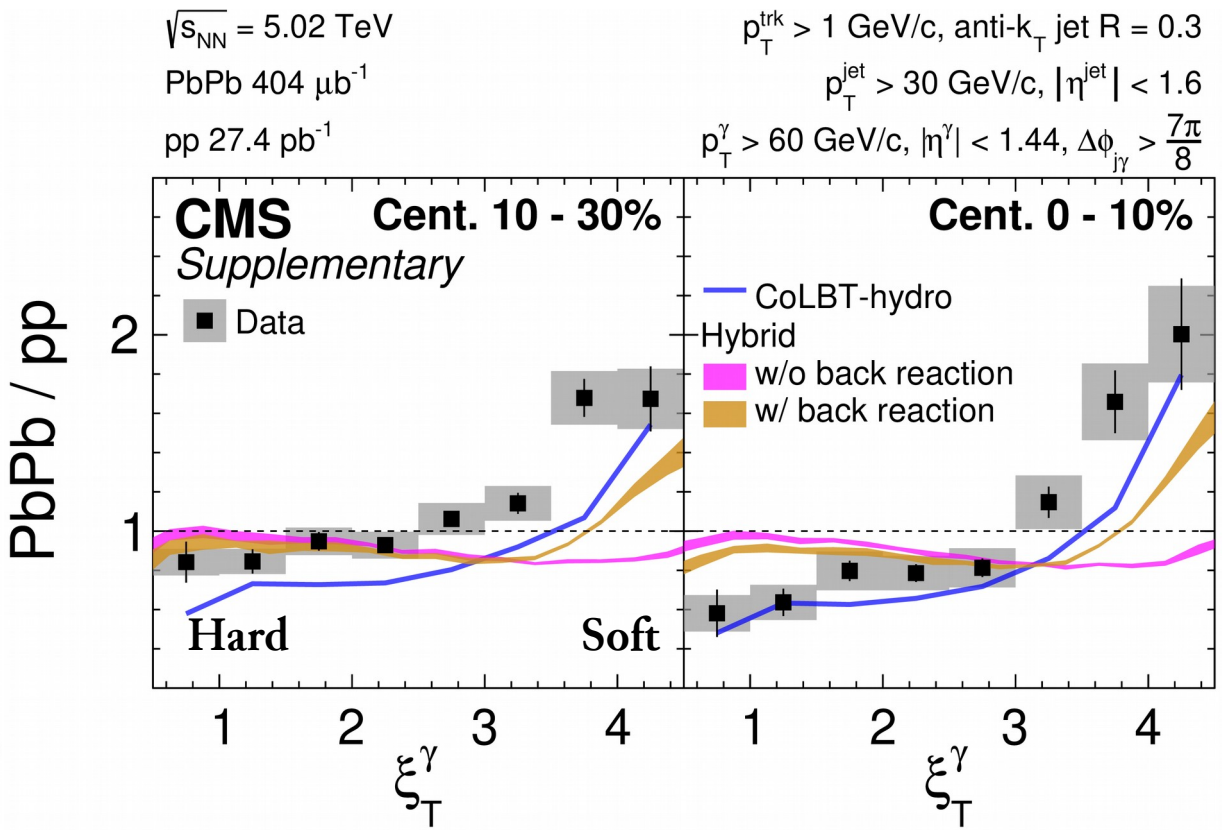
- Initial parton energy better constrained by γ p_T (quark-enriched jets)
  - Jet shape
    - Jets are wider in PbPb than pp
  - Jet fragmentation function
    - Indication of medium-induced modifications



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



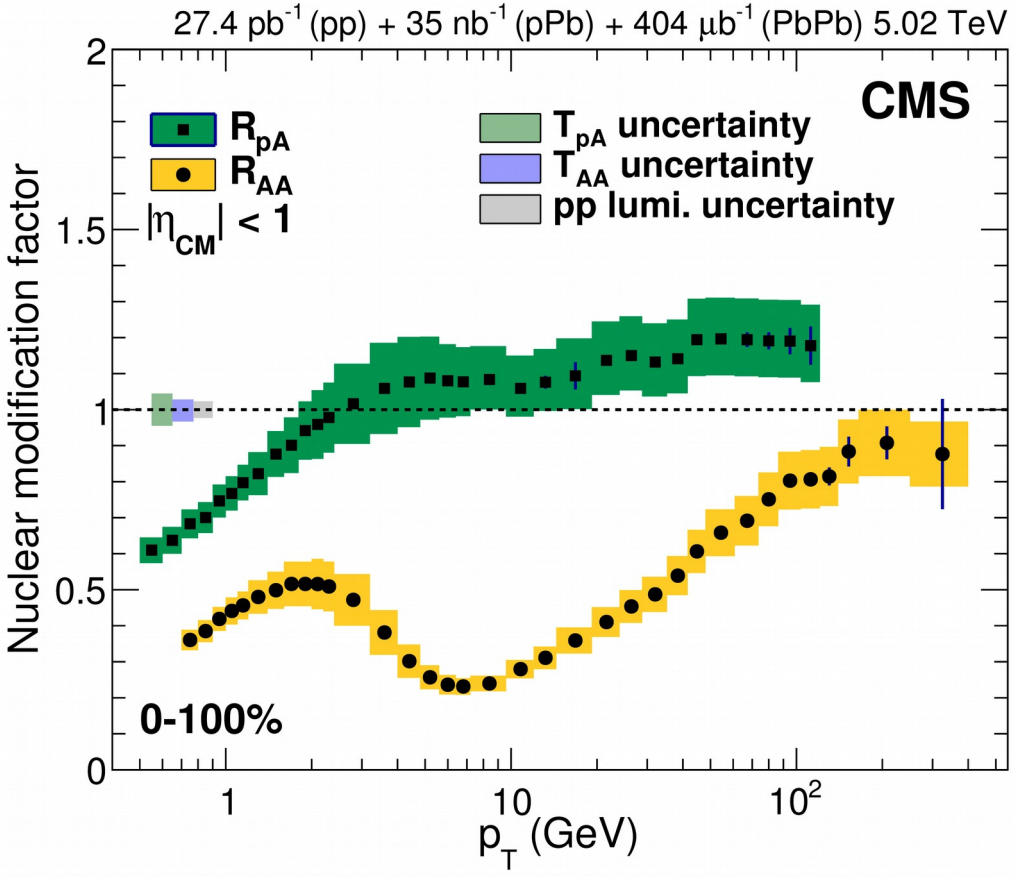
Phys. Rev. Lett. **121** (2018) 242301



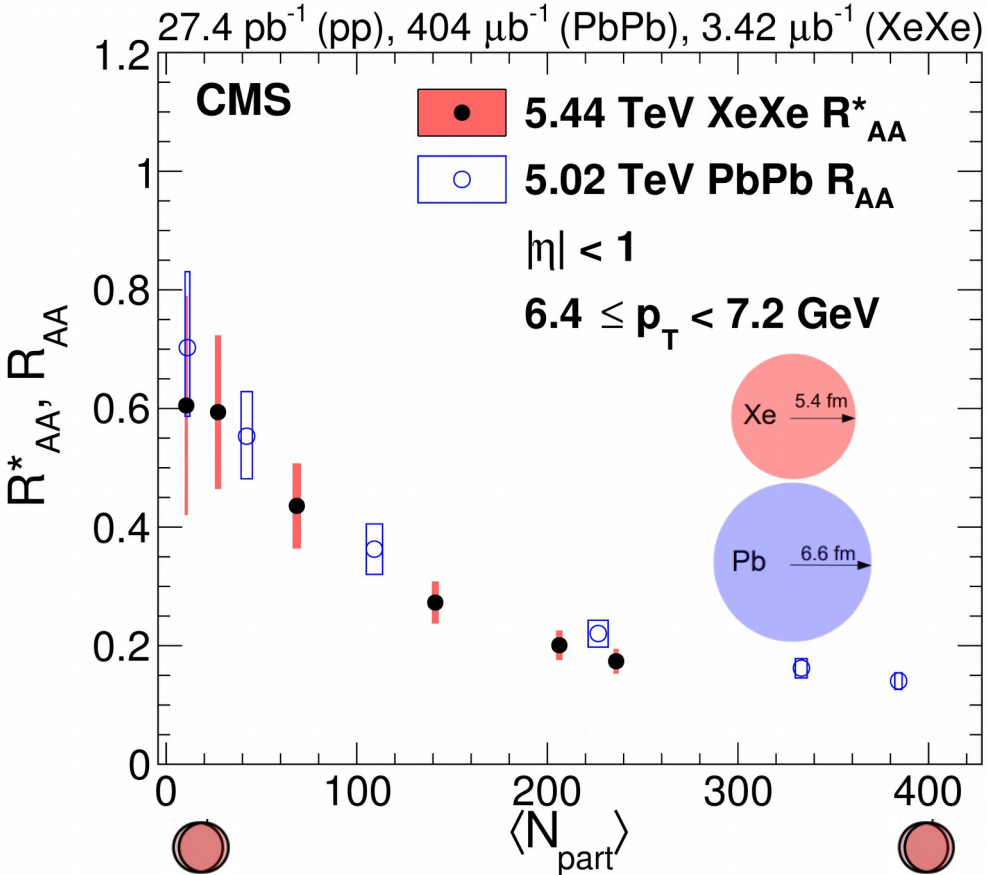
Jet quenching in smaller systems?

- 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

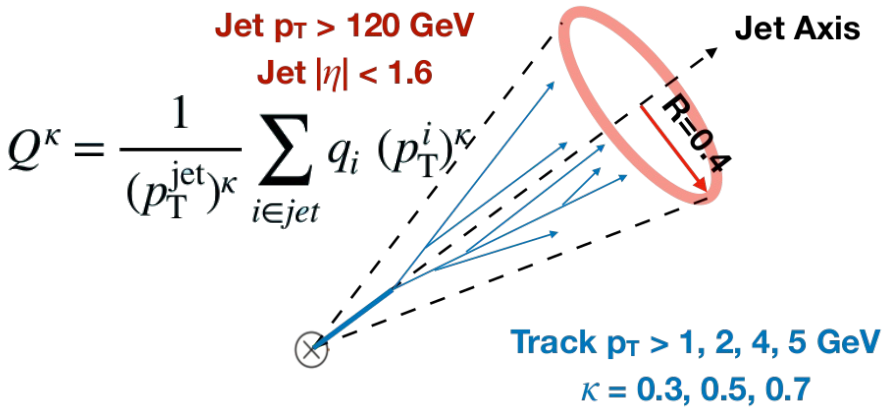


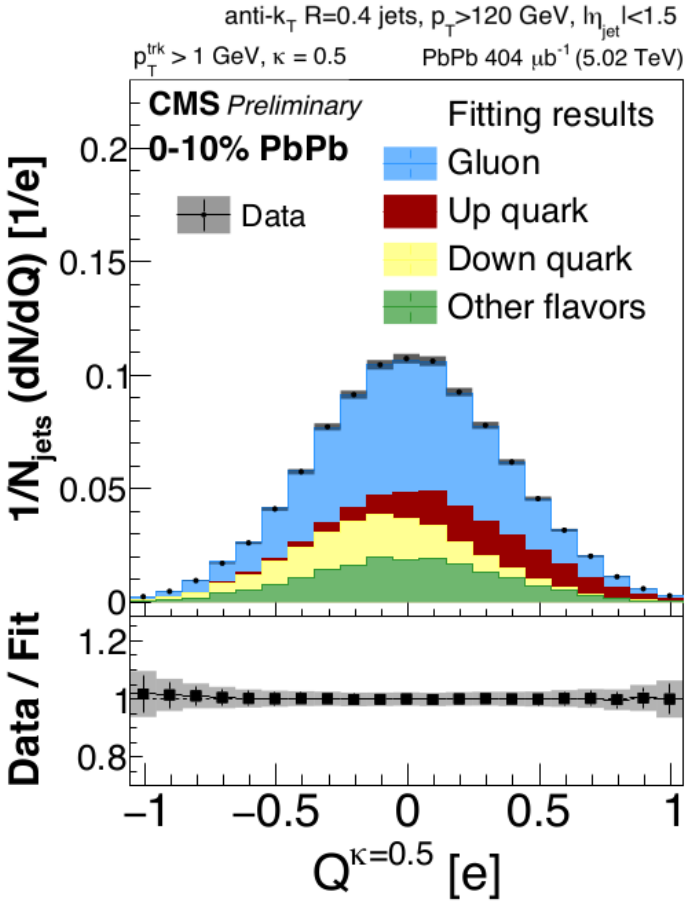
JHEP **10** (2018) 138



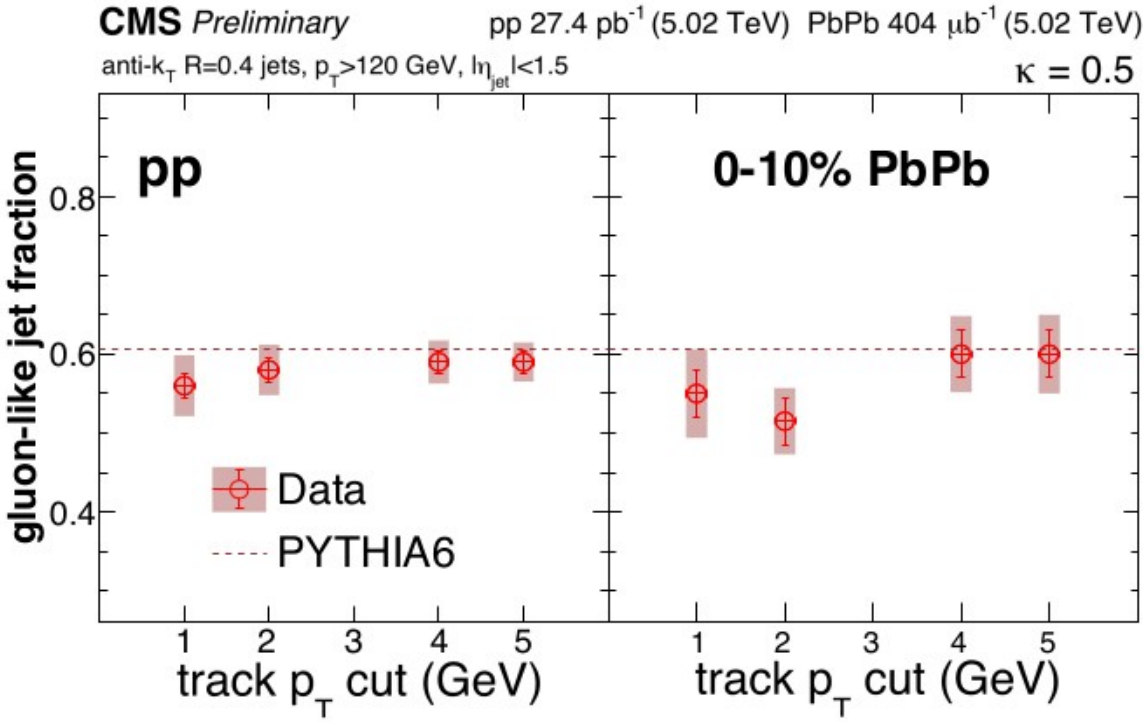
Jet charge in PbPb vs pp

- Extract quark, gluon fractions from a jet charge observable
  - sensitive to the charge of the initiating parton
  - using templates from PYTHIA 8
- **No** modification of jet charge distribution in PbPb
  - consistent fractions with pp





CMS PAS HIN-18-018



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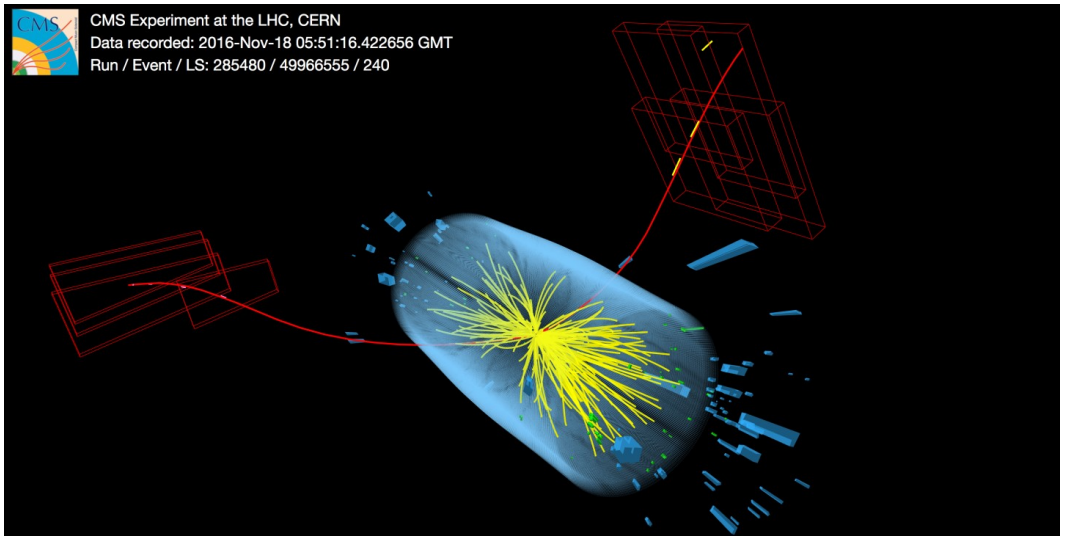
  - Jet modifications
  - **Heavy quark dynamics**
  - New probes

$\Upsilon \rightarrow \mu\mu$ (pPb)



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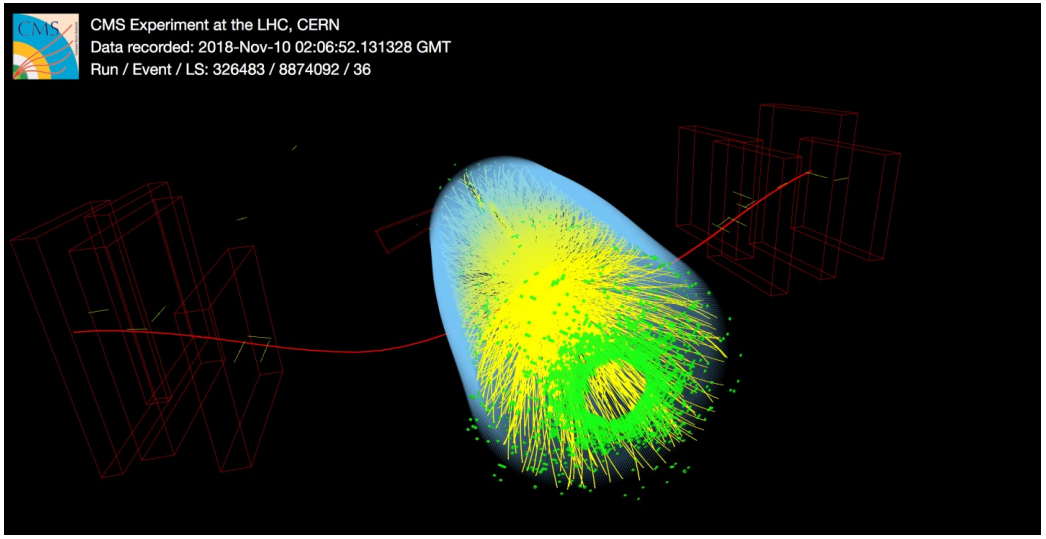
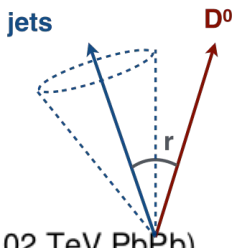


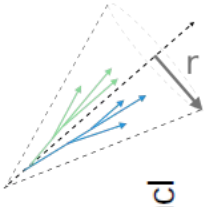
Quenching depends on parton shower and mass?

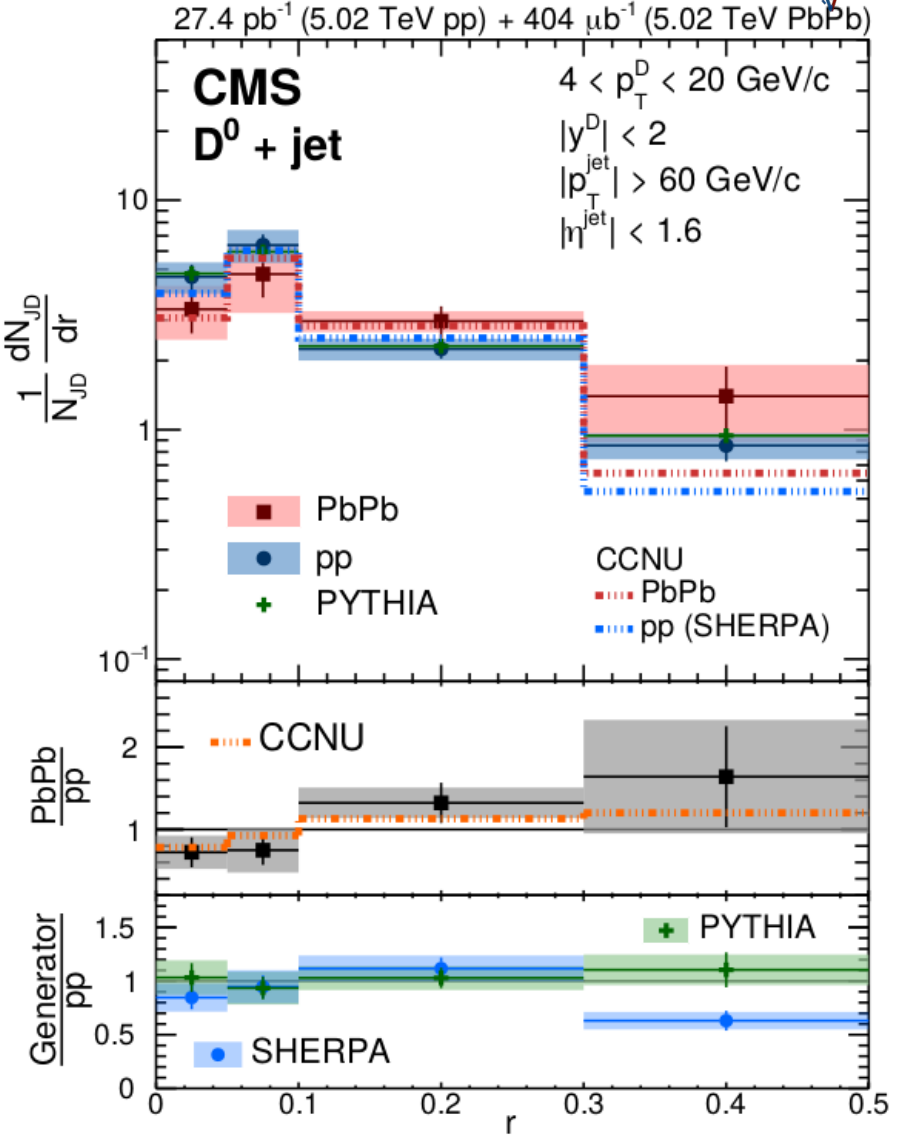
- Study parton showering and particle composition in the large-angle radiation
  - b-jet shapes in pp
    - Flavor-dependence in parton fragmentation
  - Radial profile of D^0 mesons in jets
    - Charm quark diffusion with respect to the jet axis



arXiv:1911.01461

CMS PAS-HIN-18-020





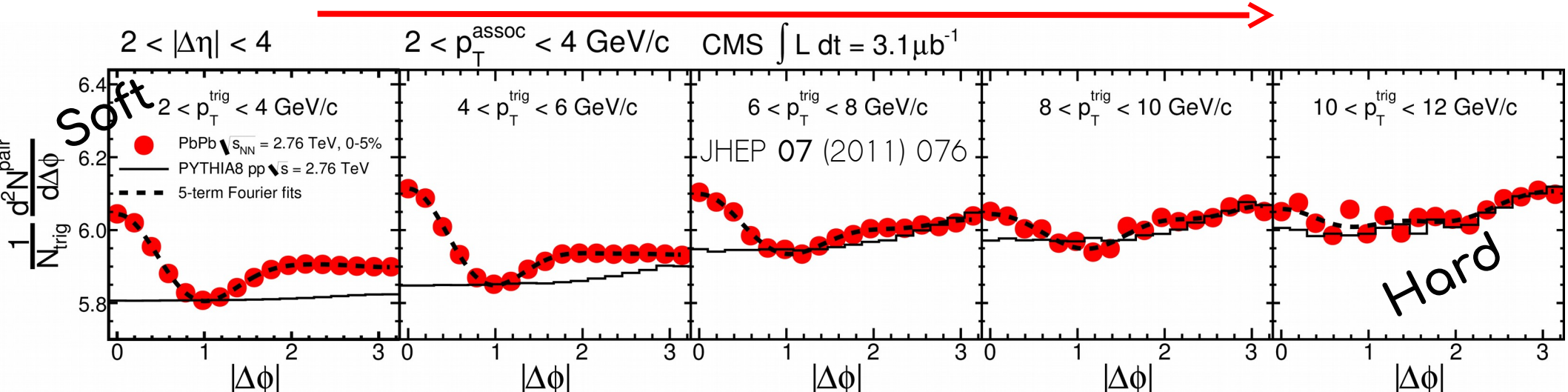
Fourier decomposition of the projected Δφ

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

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

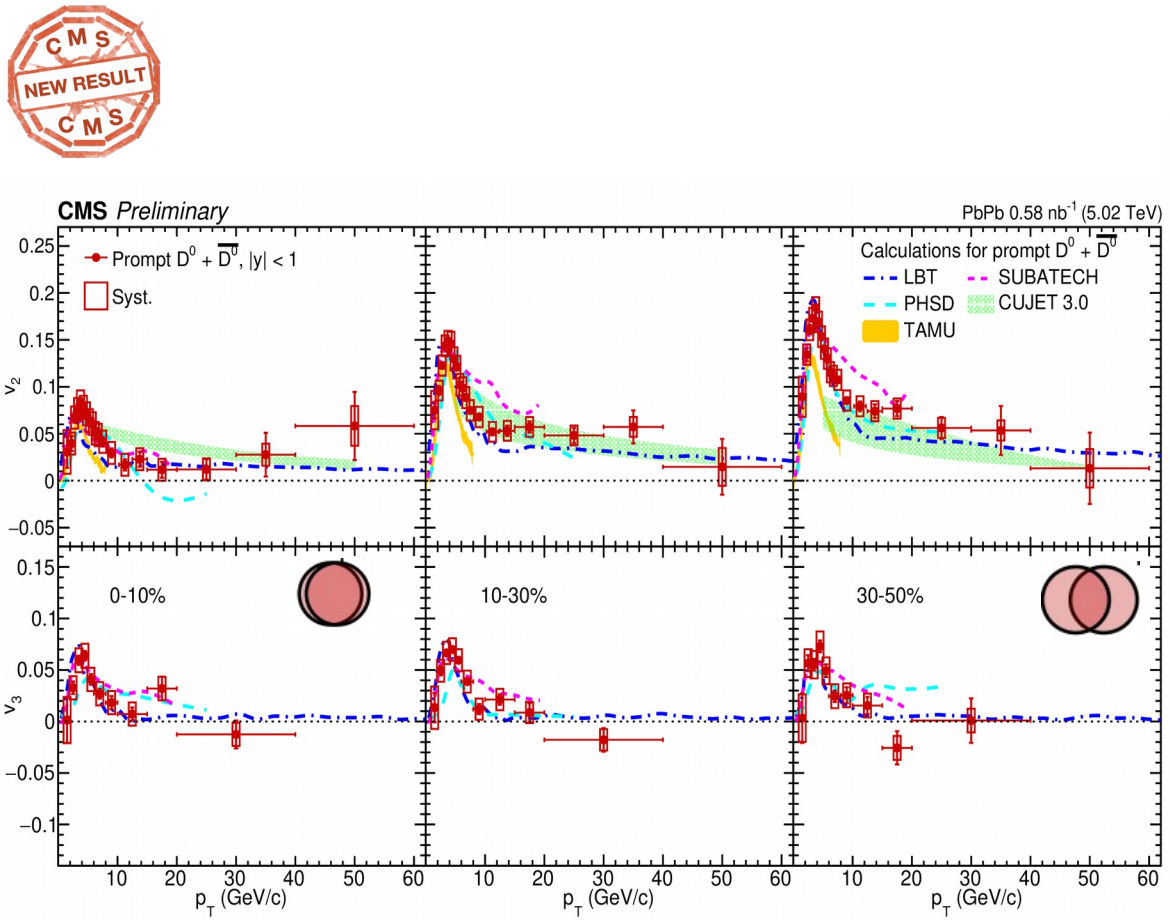
  - single-particle azimuthal anisotropy Fourier coefficients measured as $v_n=\sqrt{v_{n\Delta}}$ (n≥1)
- In hydrodynamic models v_2 and v_3 referred to as "elliptic" and "triangular" flow and related to the
  - initial collision geometry and its fluctuations

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

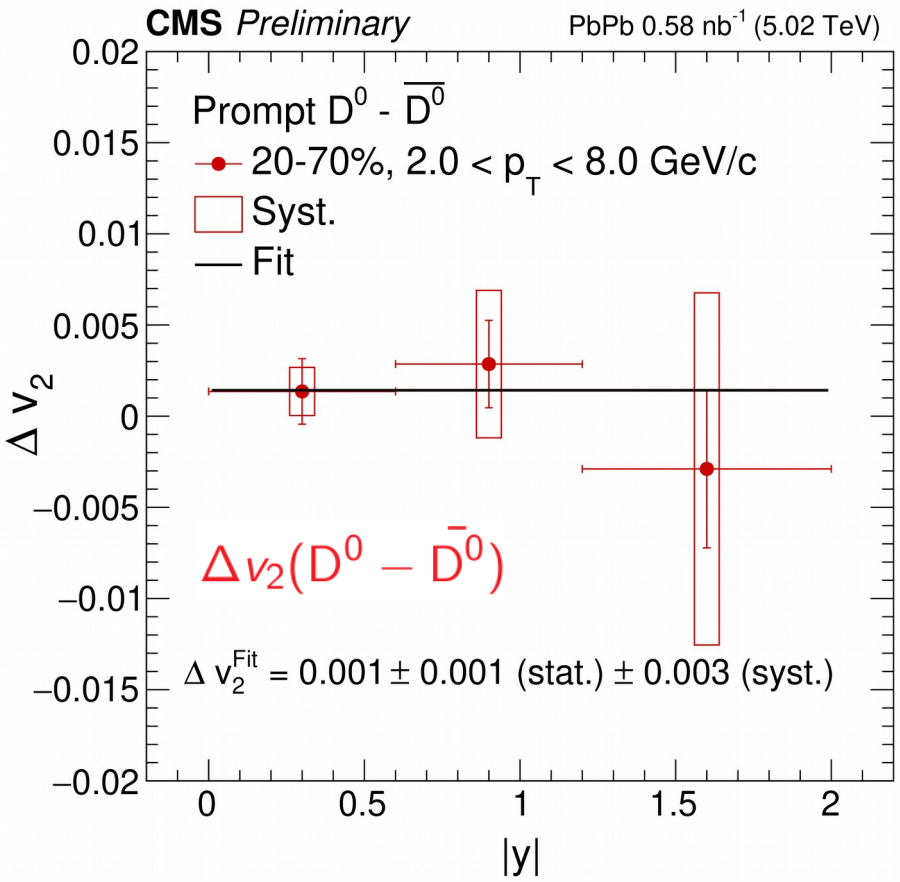


Prompt D^0 v_2 and v_3 in PbPb

- Multidifferential in p_T, |y|, and centrality
  - v_2, v_3 as expected from collision geometry
- Search for strong EM fields effects
  - **no** sign of rapidity dependence of Δv_2 (D^0–$\bar{D}^0$)



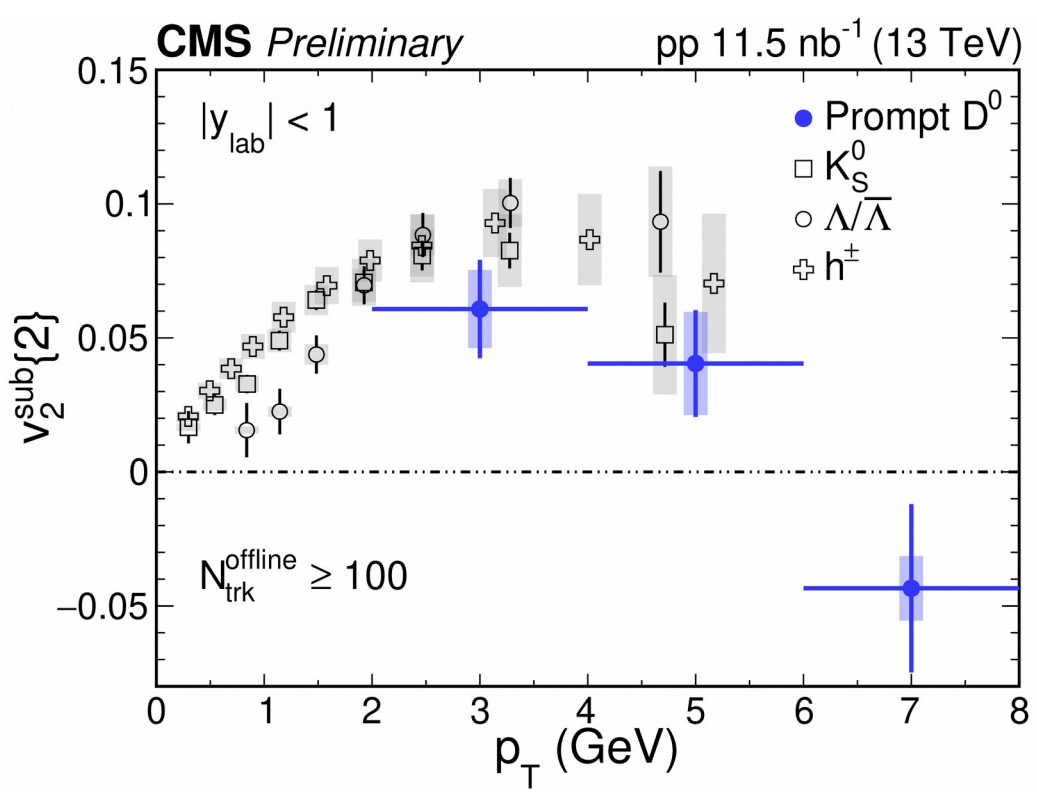
CMS PAS HIN-19-008

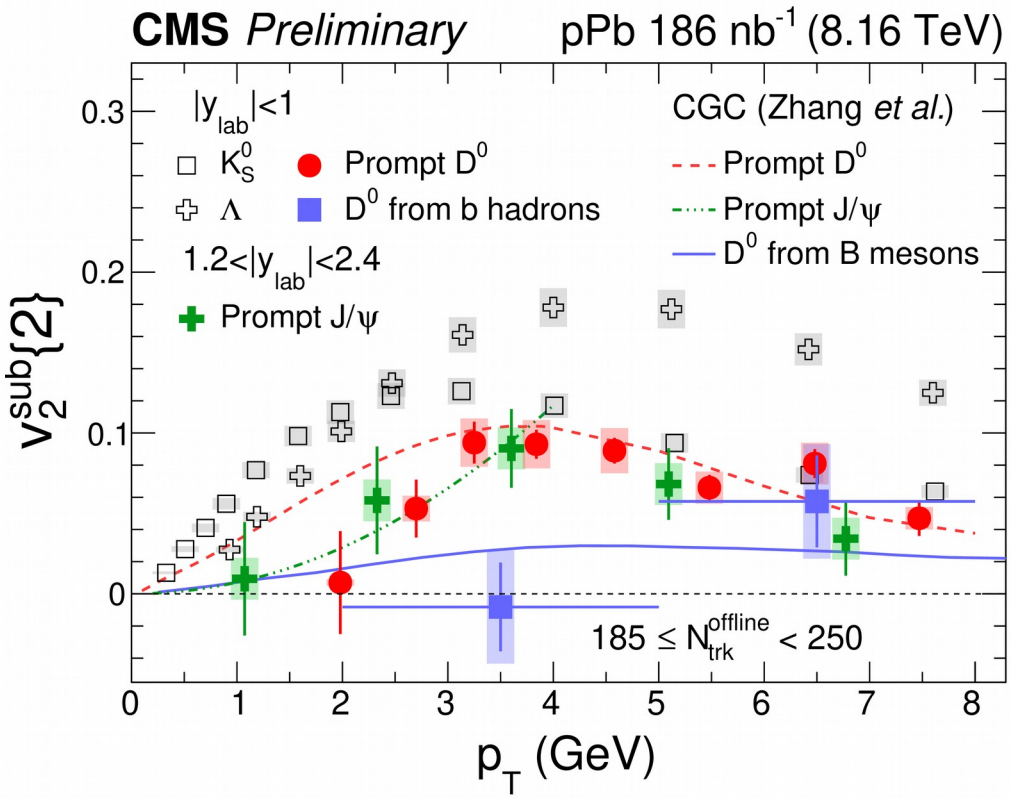


Prompt and nonpromot D^0 v_2 in pp and pPb

- **First** measurement with high-multiplicity events in pp
  - $v_2 \neq 0$; close to the v_2 of light flavors
- **Puzzle** on heavy quark collectivity in small systems
  - Open charm (prompt D^0) similar to hidden charm (prompt J/ψ)
  - Beauty (nonprompt D^0) consistent with 0
    - smaller than prompt D^0 at low p_T

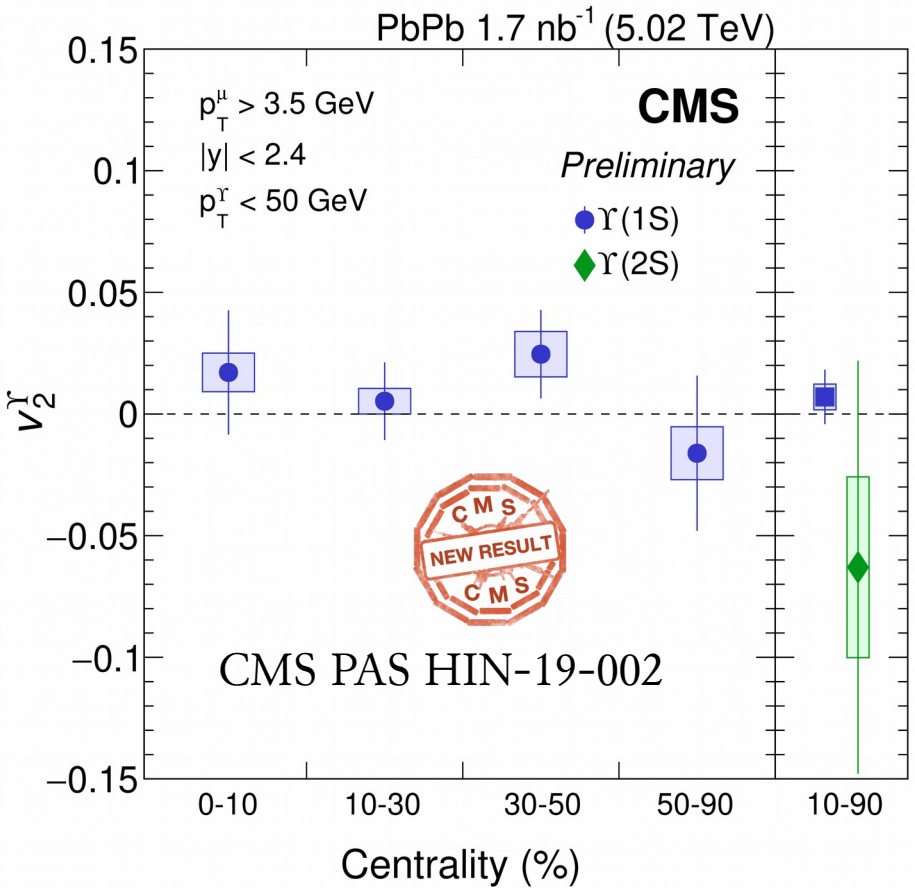
CMS PAS HIN-19-009





Quarkonia: Upsilon family in PbPb and pPb

- 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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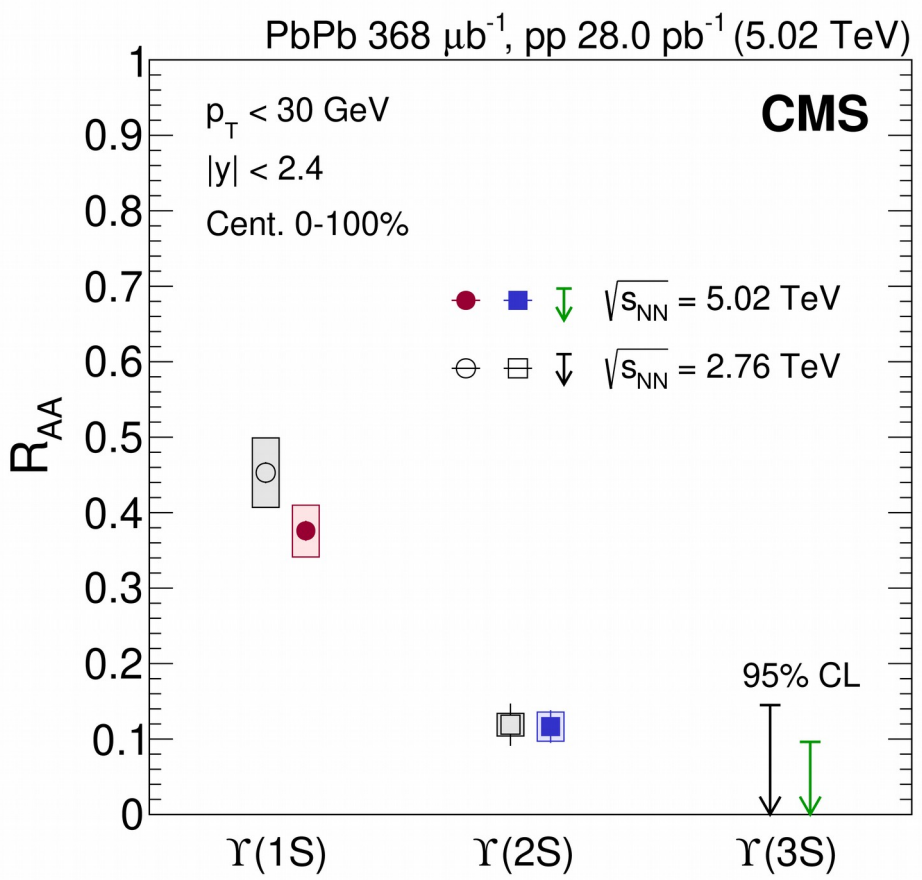
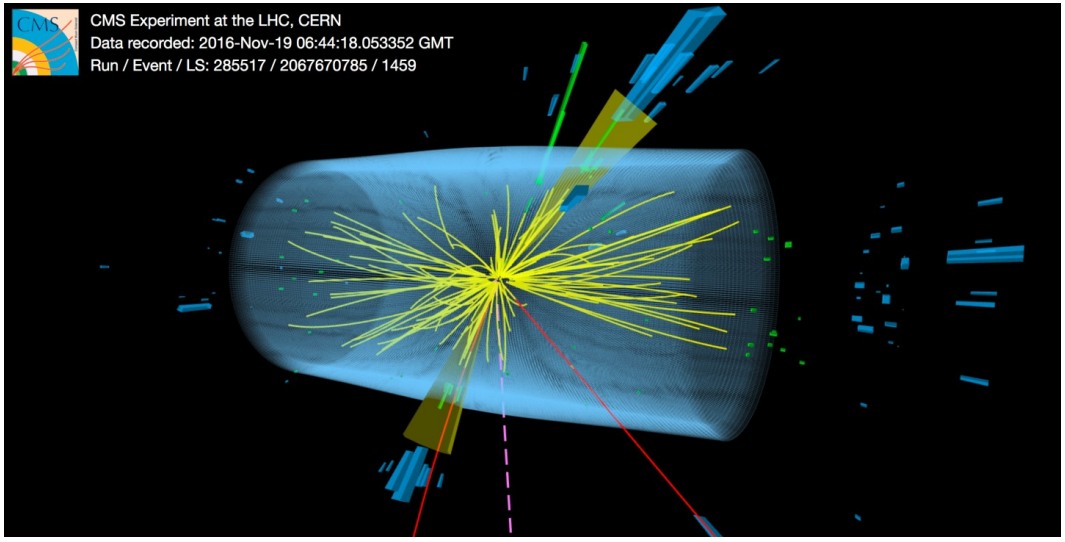


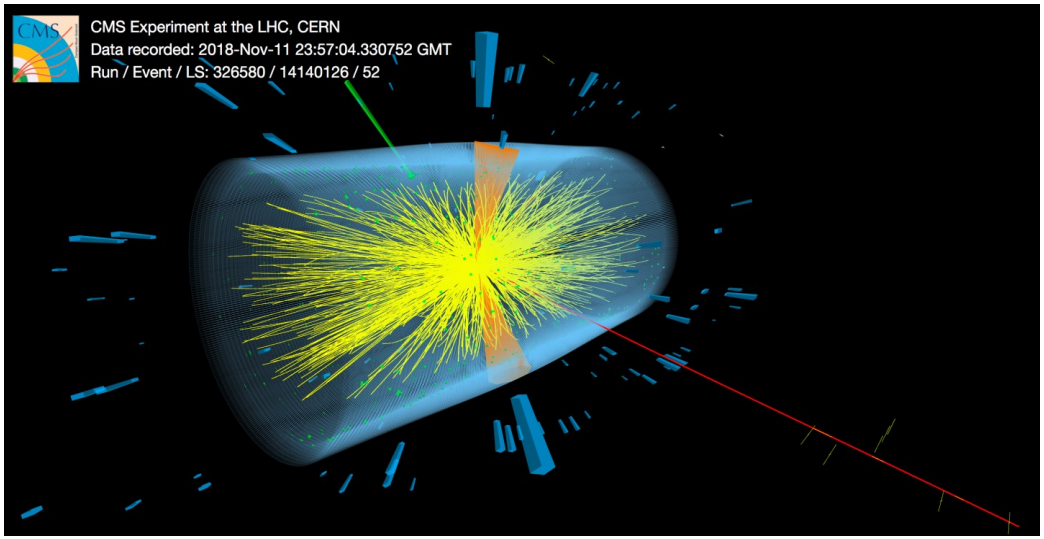
Studies with heavy ion collisions @ CMS

- 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**

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

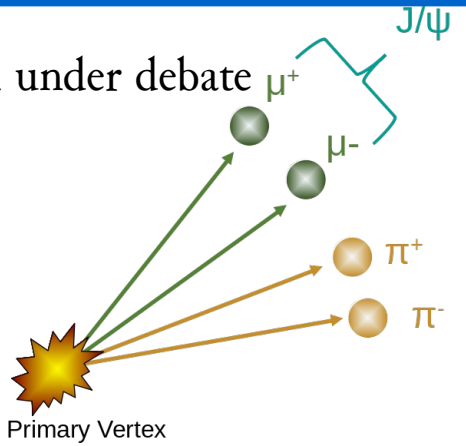


$t\bar{t} \rightarrow W(\mu\nu_\mu)bW(e\nu_e)b$ (PbPb)

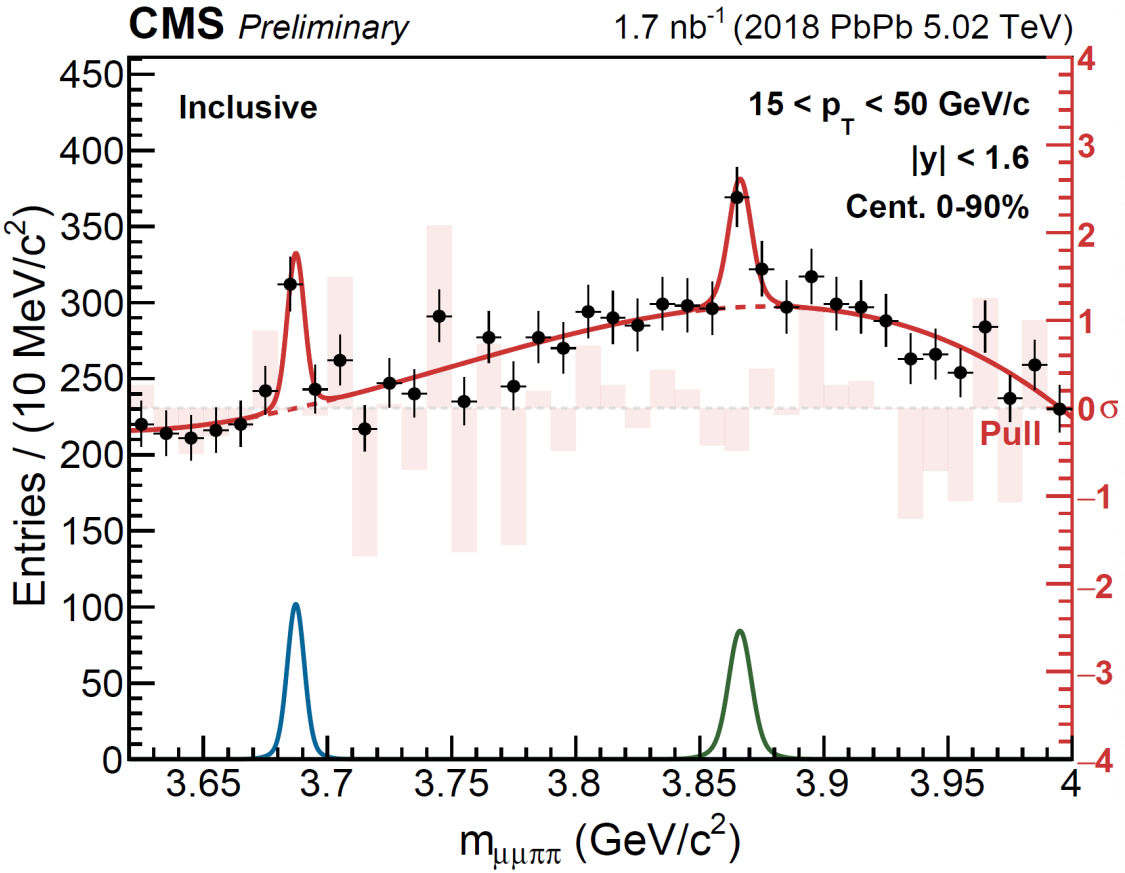


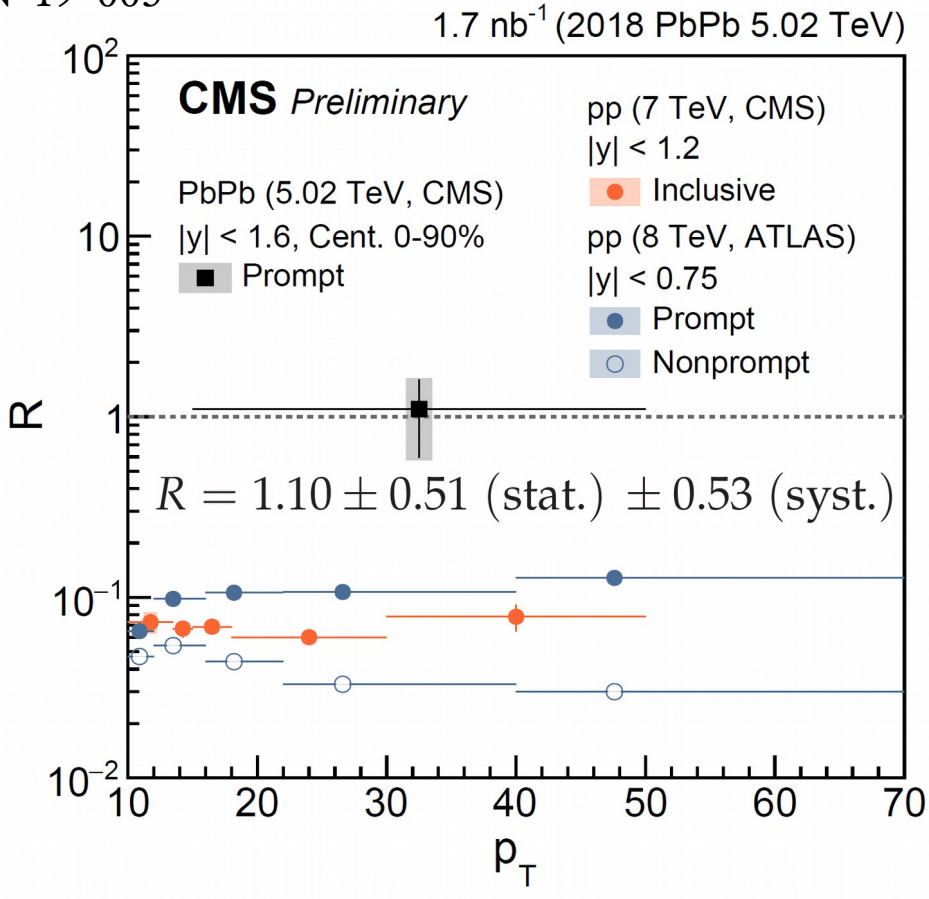
Evidence of X (3872) production in PbPb

- 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 $\psi(2S)$ ratio enhancement in PbPb?



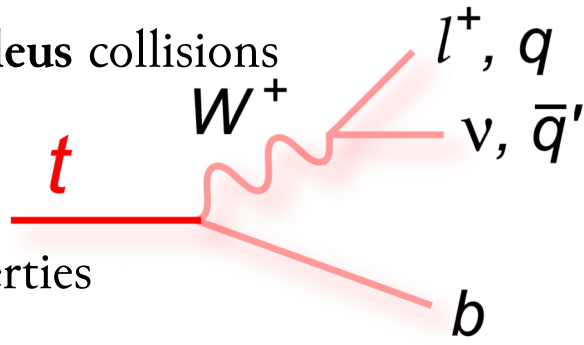
CMS PAS HIN-19-005



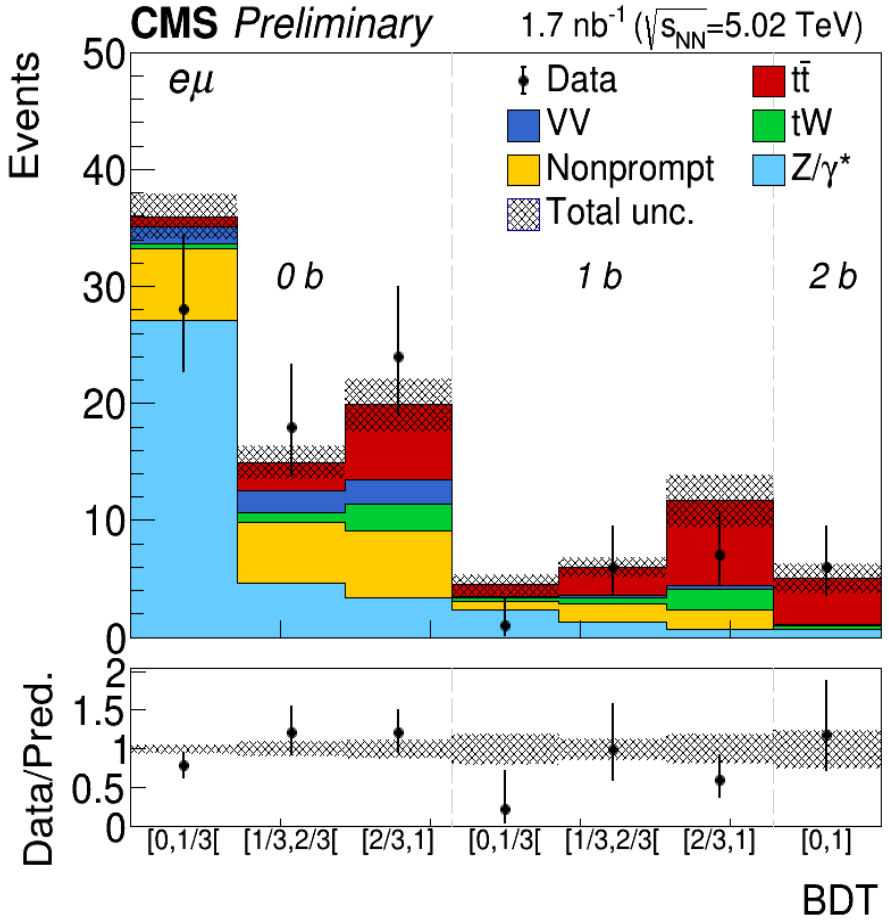


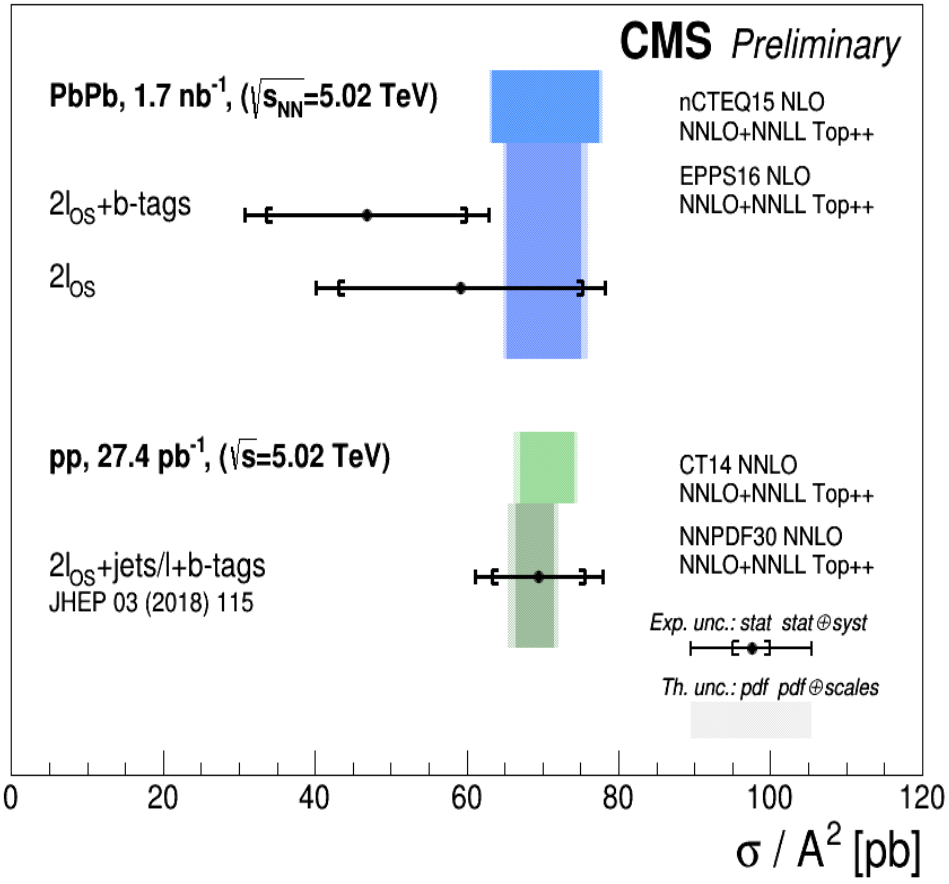
Evidence of $t\bar{t}$ cross section in PbPb

- **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



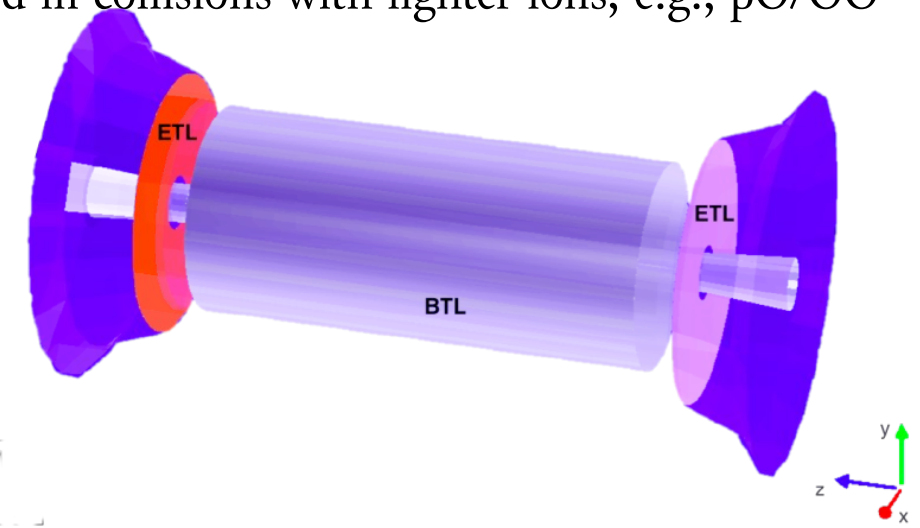
CMS PAS HIN-19-001



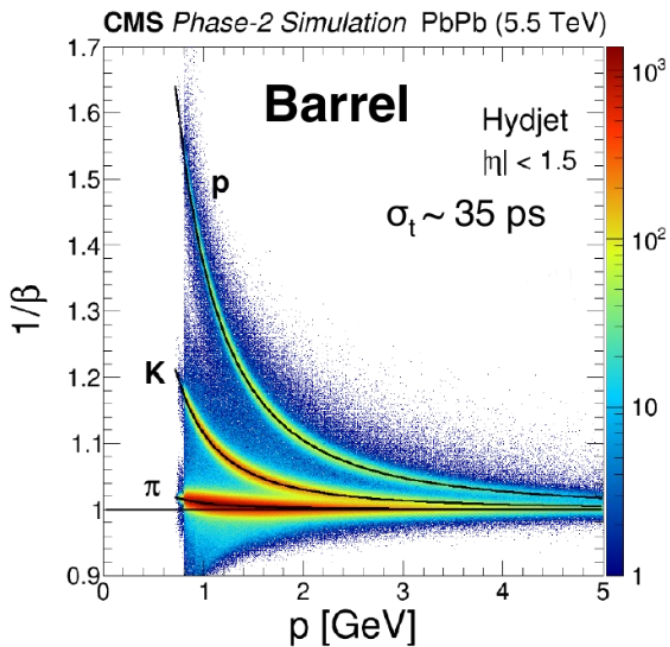


Extending the LHC HI program & CMS LS3 upgrades

- 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

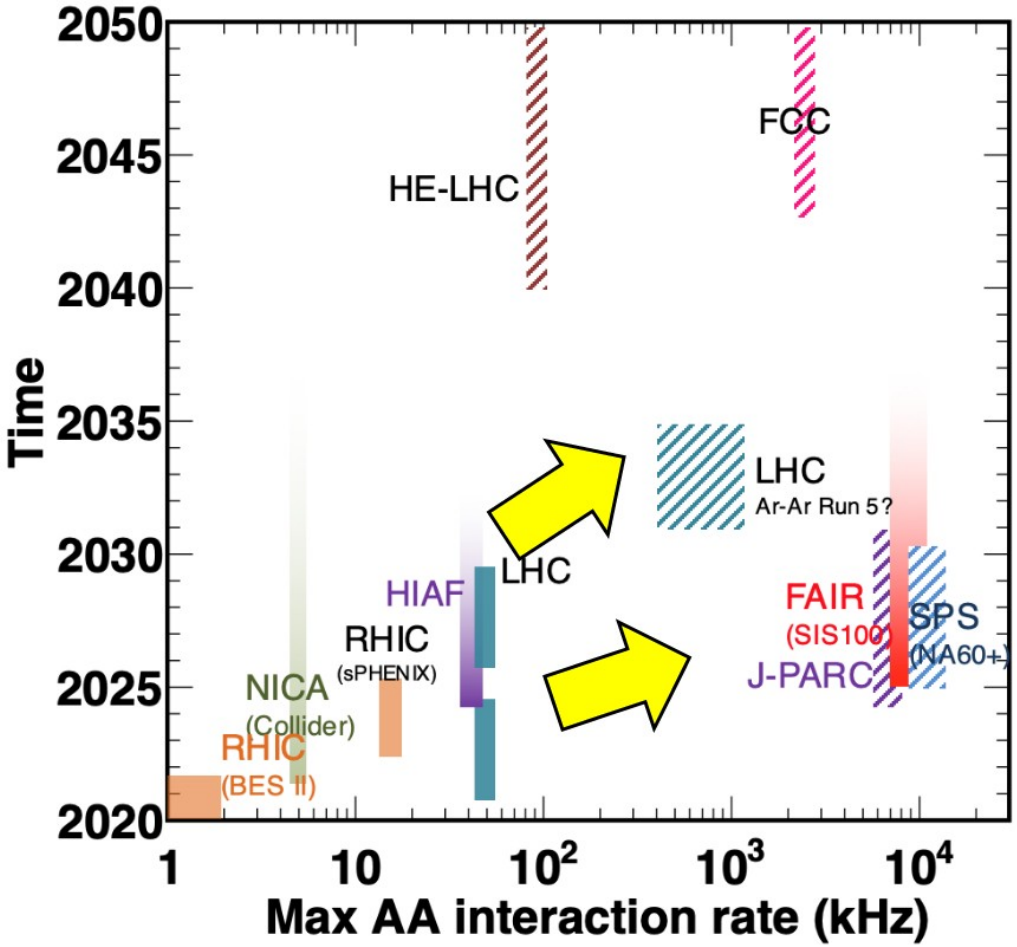


CERN-LHCC-2017-027



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



To shape the long-term plan

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

Decade ahead of us

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

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slides

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 $\Delta\chi^2$	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]

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

Hessian matrix

Parameter variations

arXiv:1704.04036

90% CL defined by the global

As compared to the PDF fitting landscape

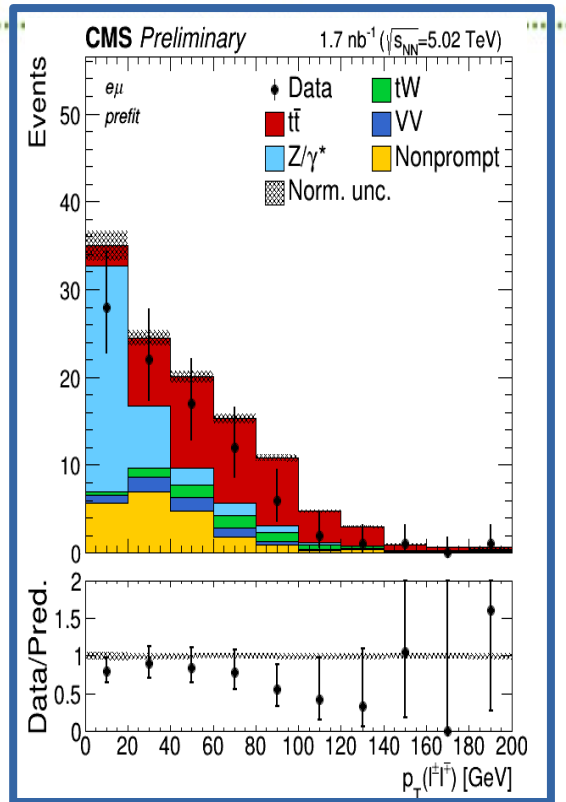
Ubiali, DIS2017

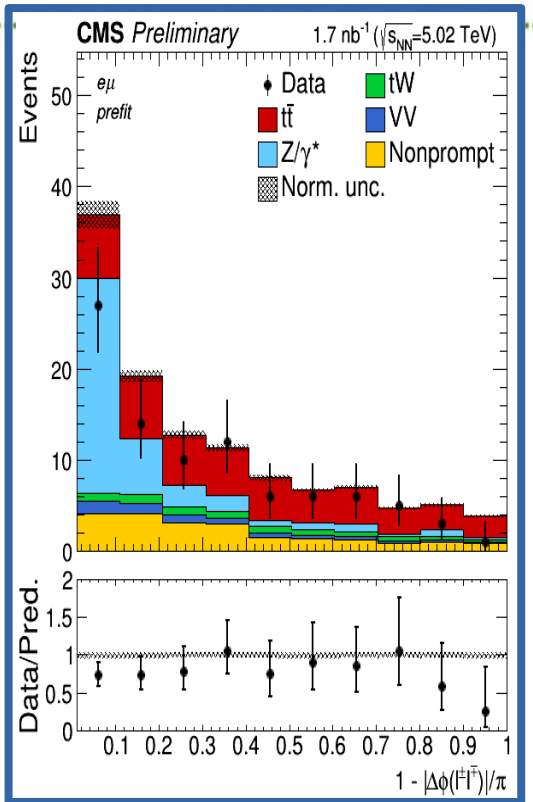
April 2017	NNPDF3.0	MMHT2014	CT14	HERAPDF2.0	CJ15	ABMP16
Fixed Target DIS	✔	✔	✔	✘	✔	✔
JLAB	✘	✘	✘	✘	✔	✘
HERA I+II	✔	✔	✔	✔	✔	✔
HERA jets	✘	✔	✘	✘	✘	✘
Fixed Target DY	✔	✔	✔	✘	✔	✔
Tevatron W,Z	✔	✔	✔	✘	✔	✔
Tevatron jets	✔	✔	✔	✘	✔	✘
LHC jets	✔	✔	✔	✘	✘	✘
LHC vector boson	✔	✔	✔	✘	✘	✔
LHC top	✔	✘	✘	✘	✘	✔
Stat. 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

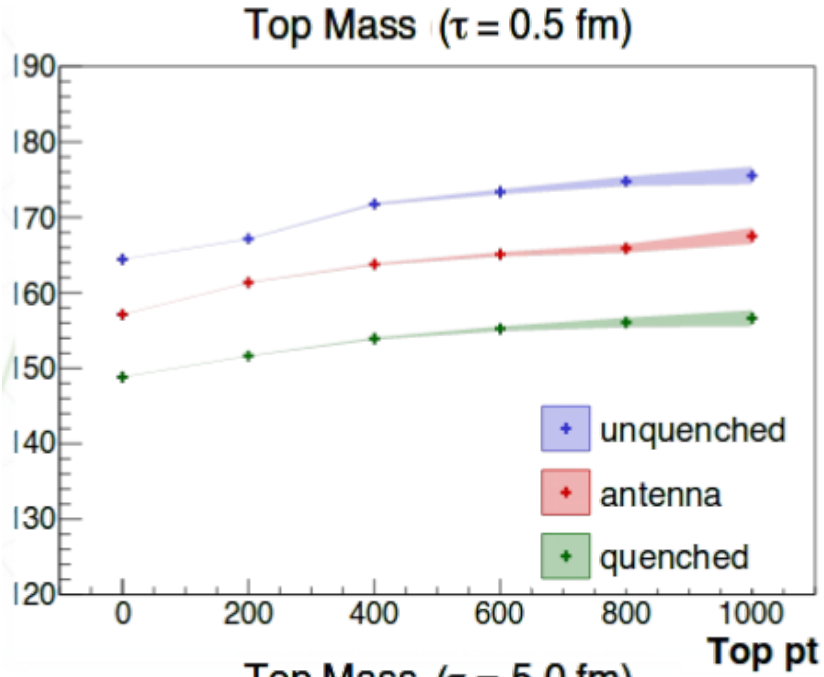
- $p_T(\ell_1)$, the p_T of the highest-p_T lepton,
- A_{p_T}, the asymmetry in the lepton-p_T's, namely $\frac{p_T(\ell_1)-p_T(\ell_2)}{p_T(\ell_1)+p_T(\ell_2)}$,
- $p_T(\ell\ell)$, the p_T of the dilepton system,
- $|\eta(\ell\ell)|$, the absolute η of the dilepton system,
- $|\Delta\phi(\ell\ell)|$, 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.

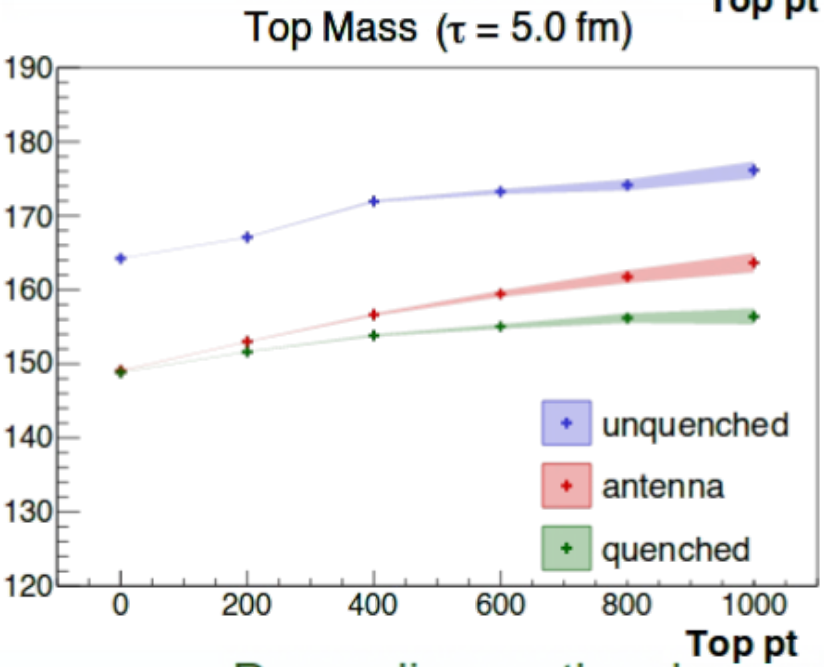


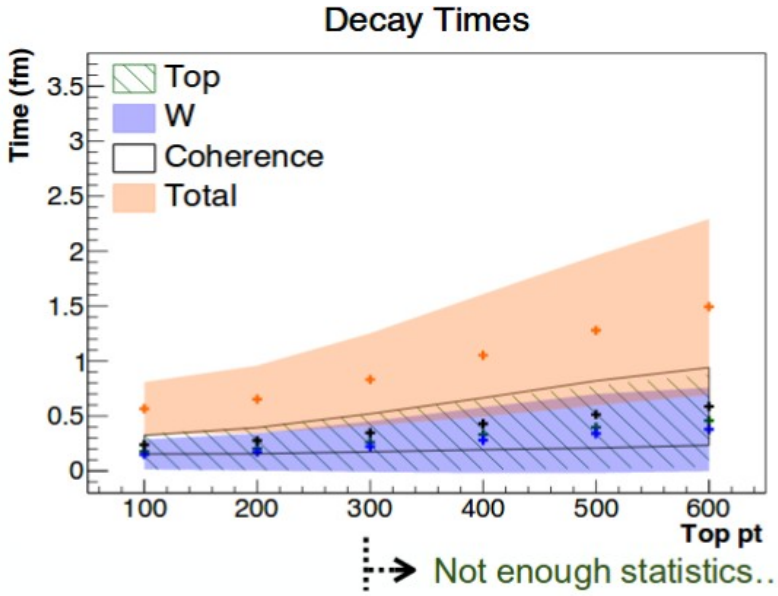


A nice heuristic idea for a yocto-chronometer !

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

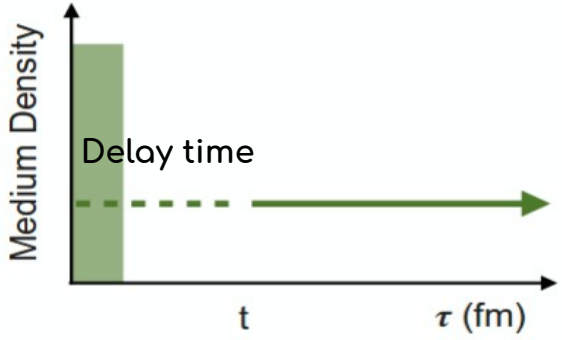


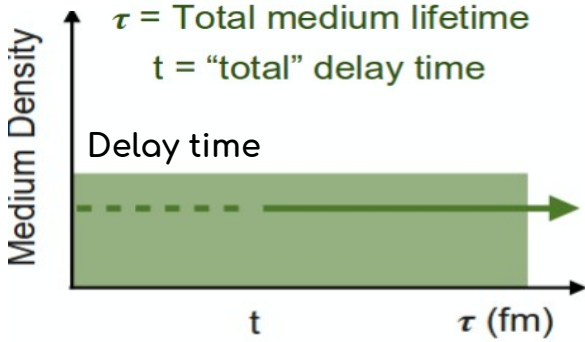




Probe ~ [0.4; 1.2] fm

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





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