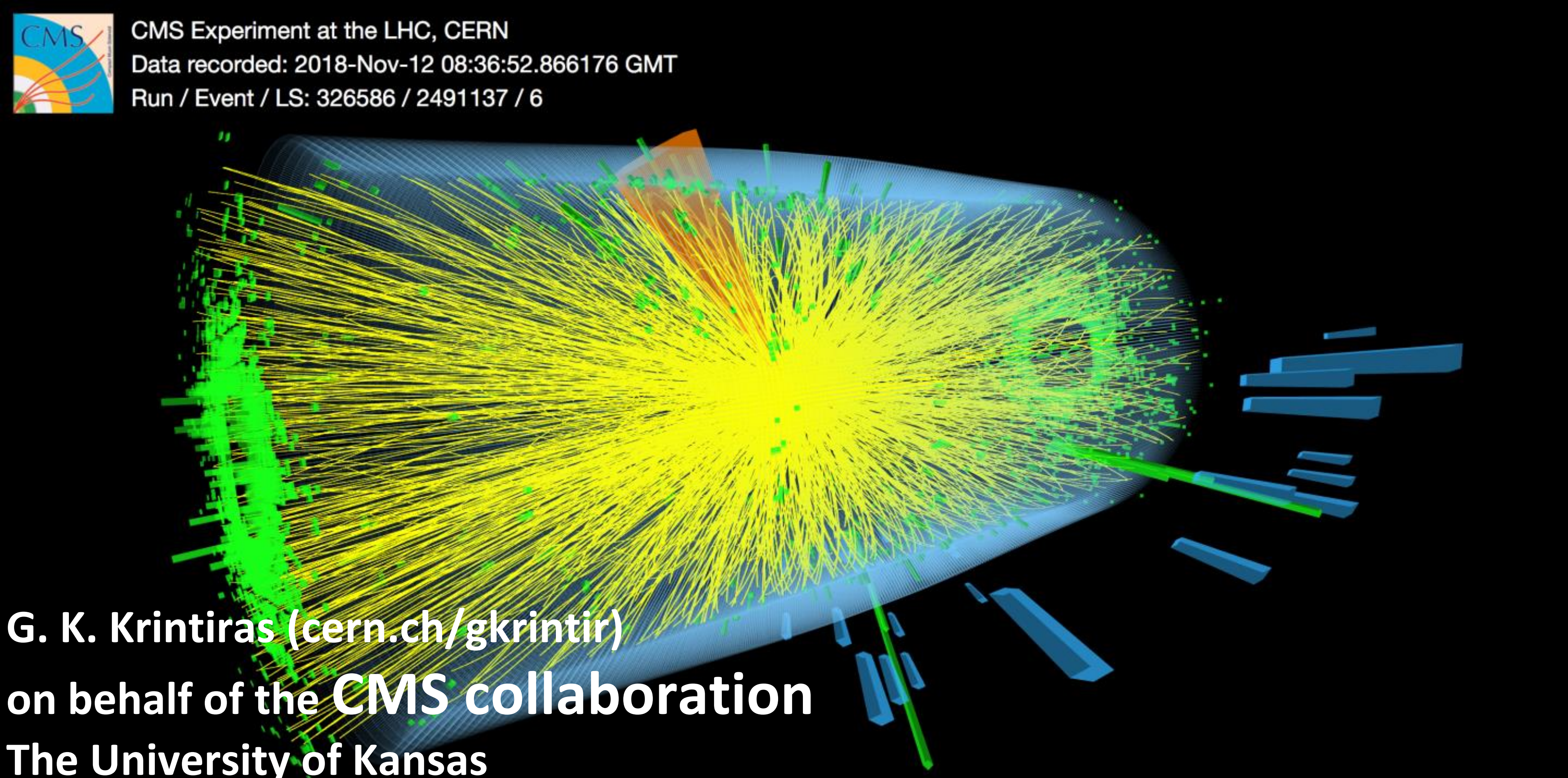
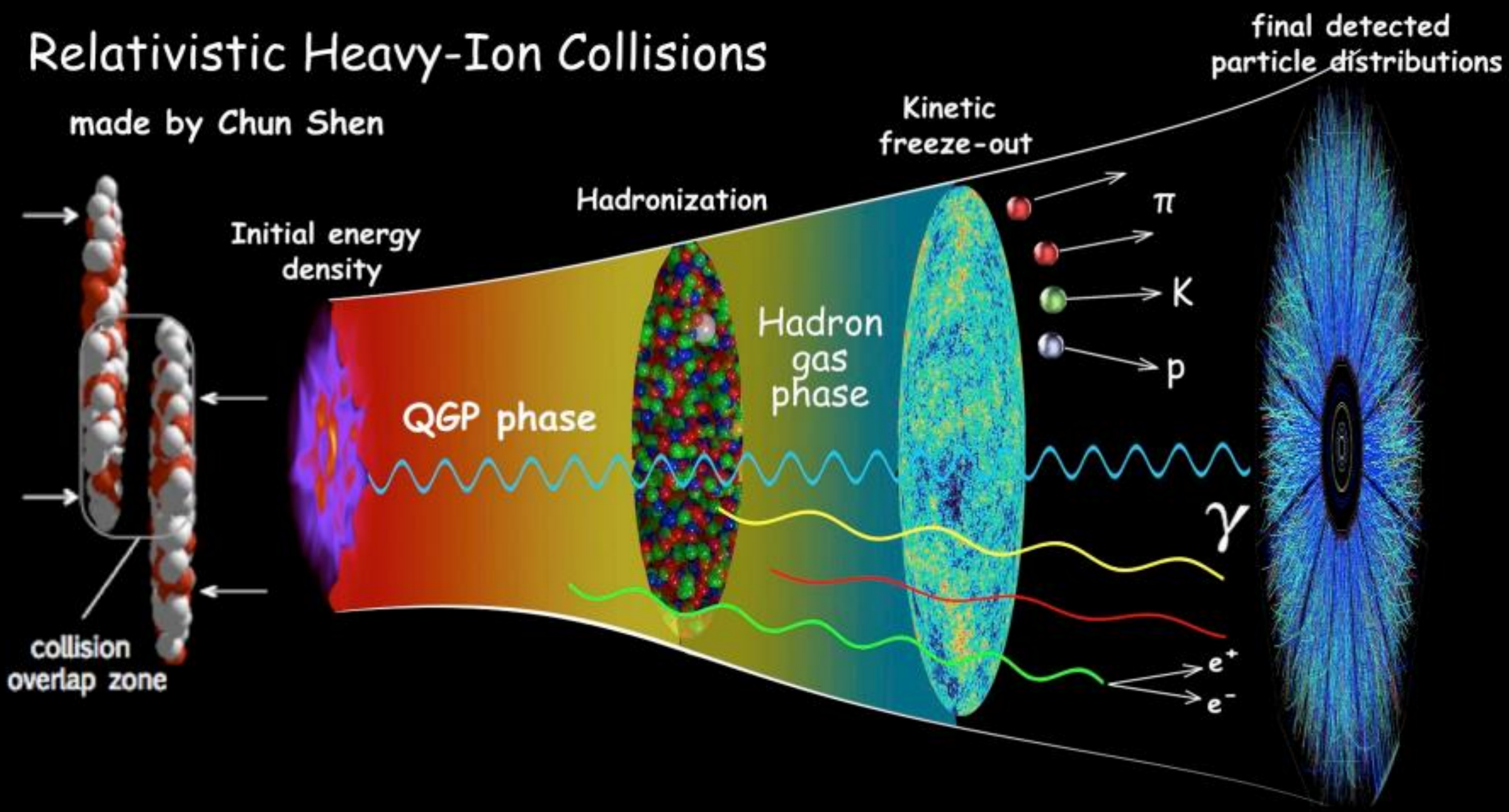
Recent CMS Heavy Ion results
What's the status at MPI 2022

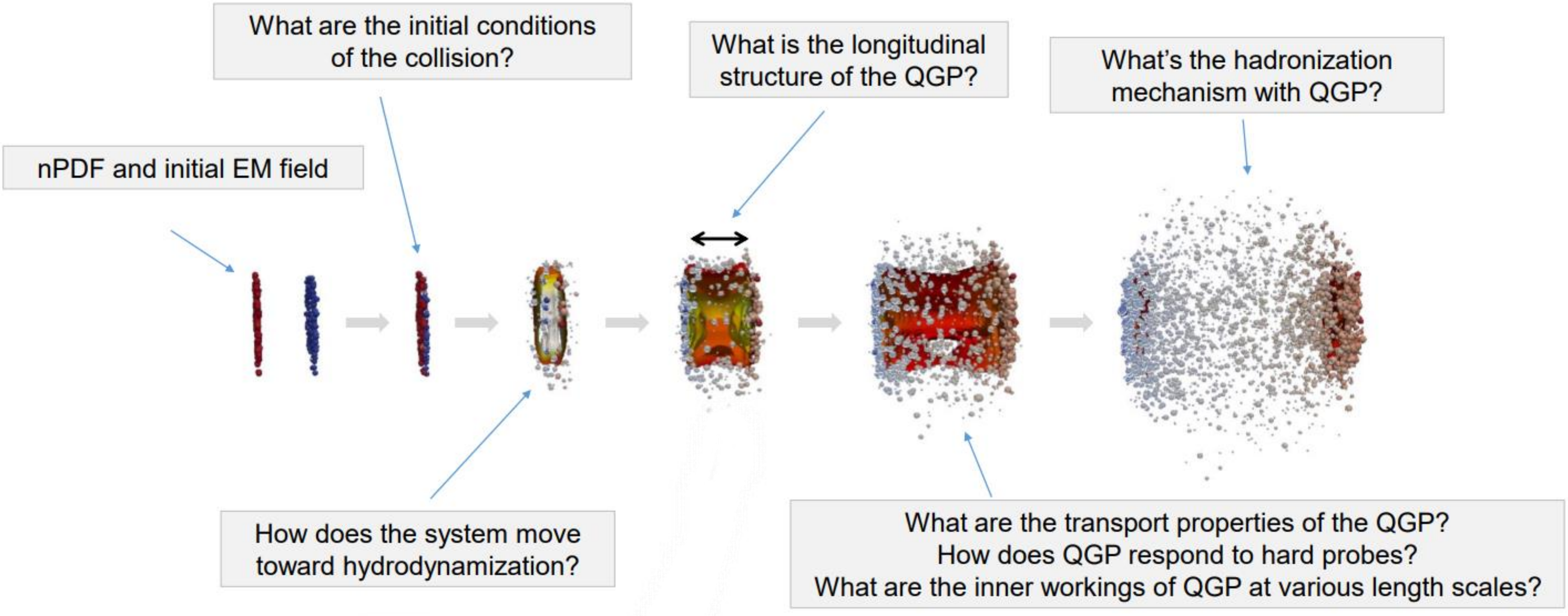


G. K. Krintiras (cern.ch/gkrintir)
on behalf of the CMS collaboration
The University of Kansas

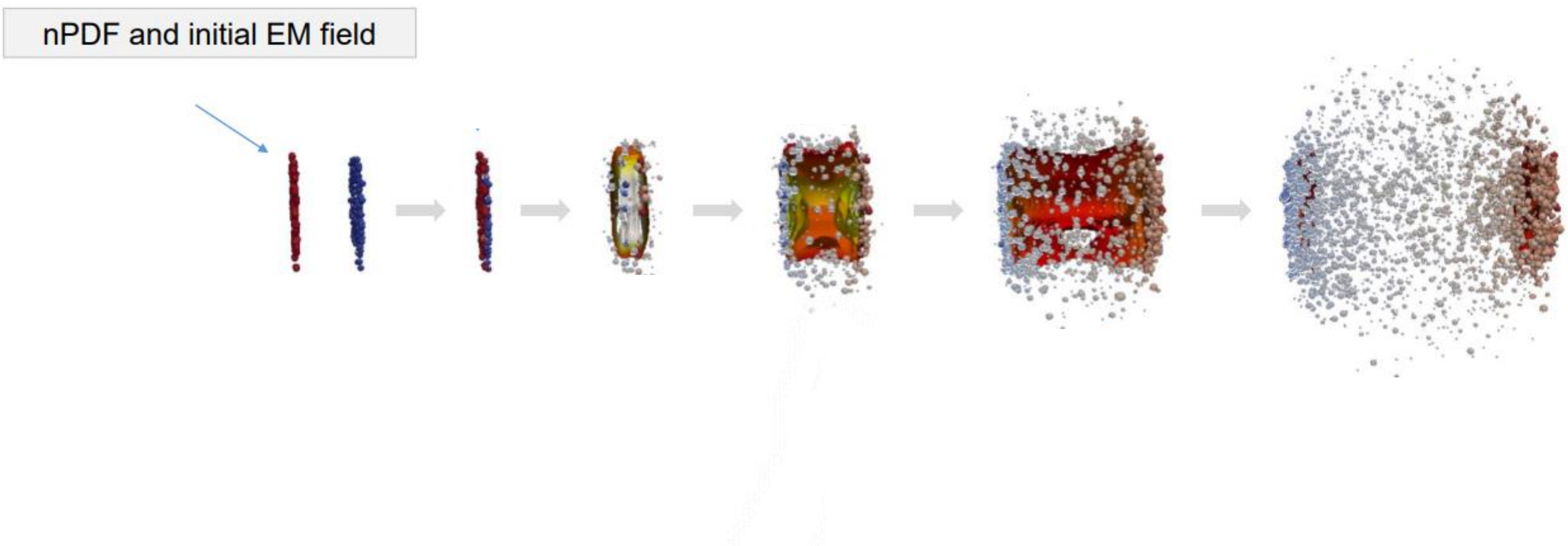


HIC "Standard Model"

Pressing questions and open items

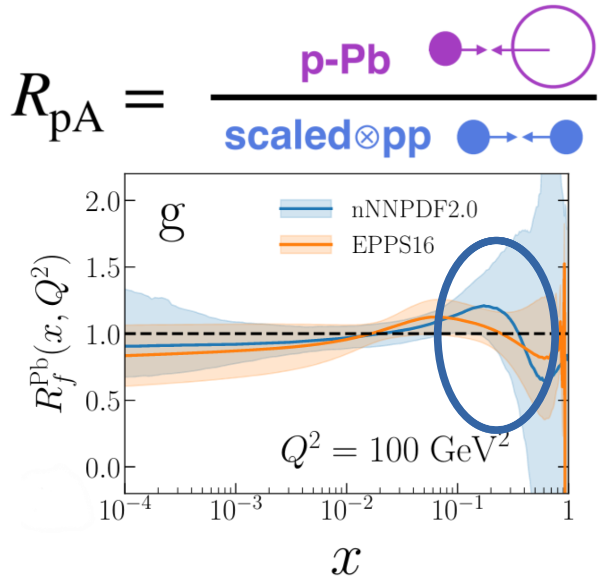


Input from
[EF community workshop (Yen-Jie Lee)]

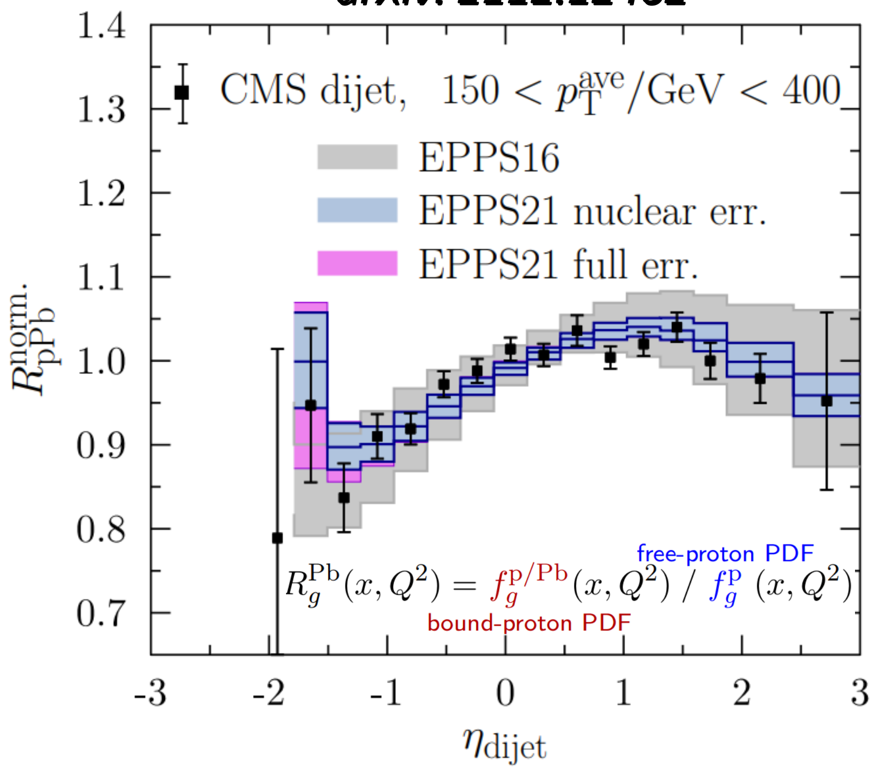

nPDF and initial EM field

Nuclear gluon PDF: constraints scarce so far

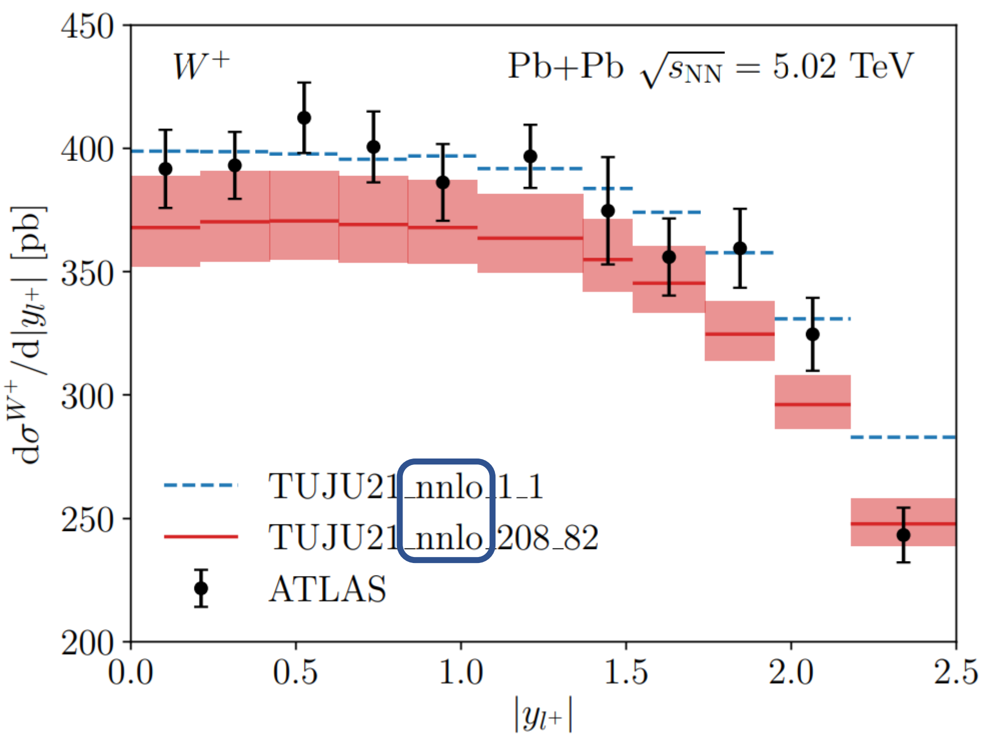
- **State-of-the-art** nPDFs for perturbative QCD calculations
- **Strong constraints** on gluon modifications from dijets and W bosons
- **NNLO** nPDF analyses to include LHC data



arXiv: 2112.12462



arXiv: 2112.11904



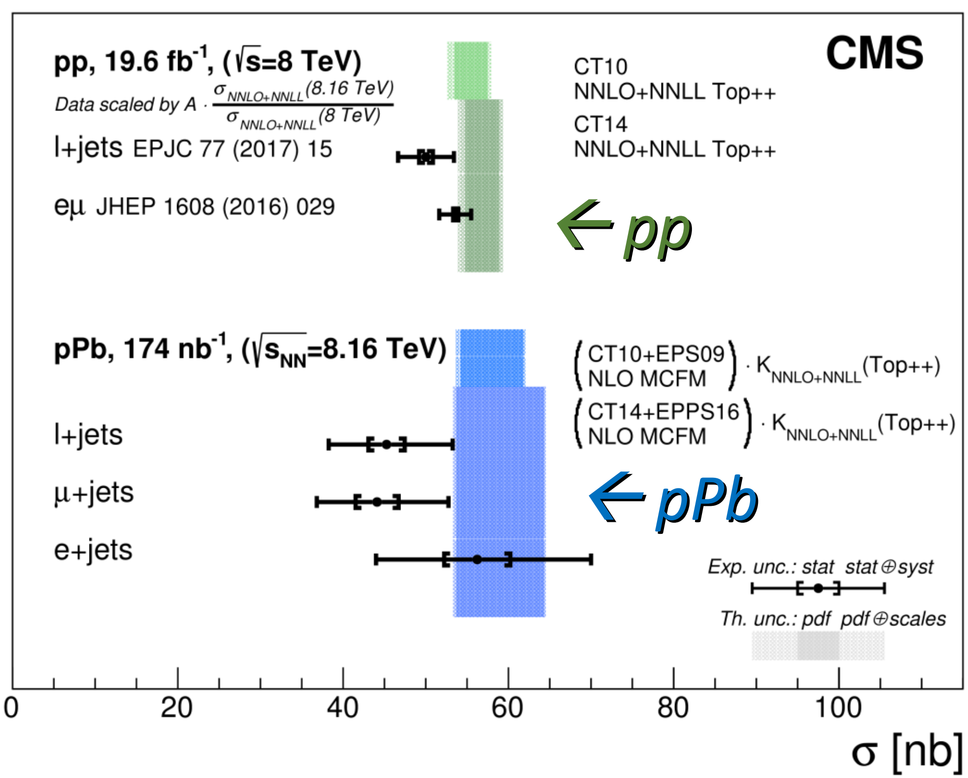
In preparation of EIC, HIC @ LHC provides the **best input to nPDFs**

Nuclear gluon PDF: constraints scarce so far

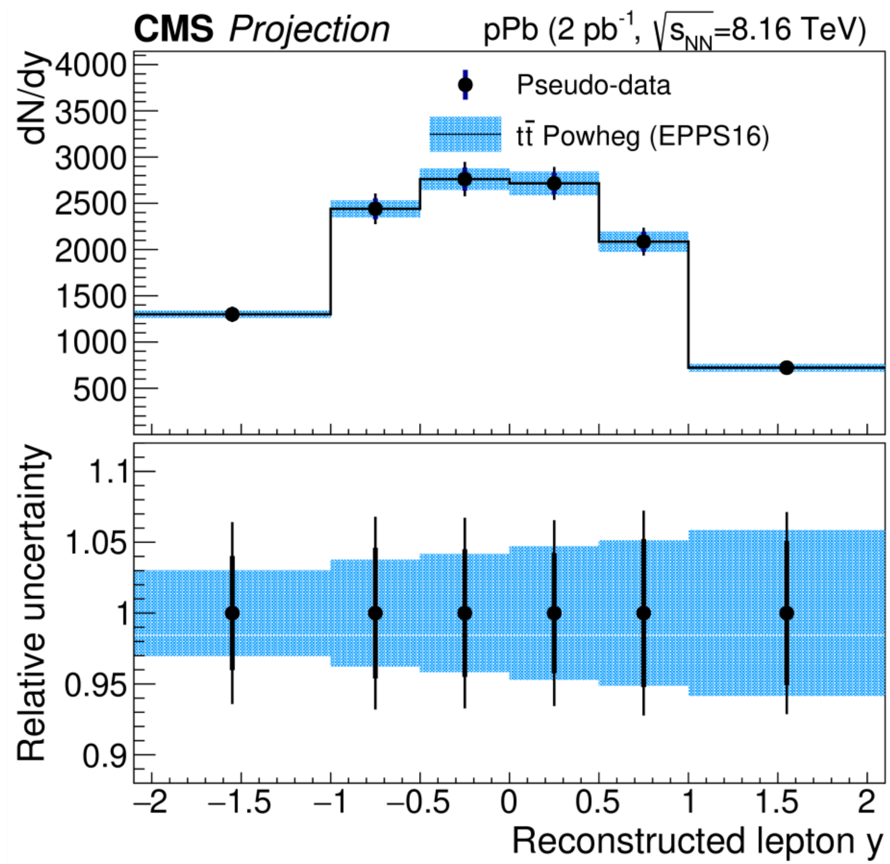
- **State-of-the-art** nPDFs for perturbative QCD calculations
- **Strong constraints** on gluon modifications from dijets and W bosons
  - also possibly from **top quark production**
- **NNLO** nPDF analyses to include LHC data

$$R_{\mathrm{pA}} = \frac{\text{p-Pb}}{\text{scaled}\otimes\text{pp}}$$

arXiv: 1709.07411



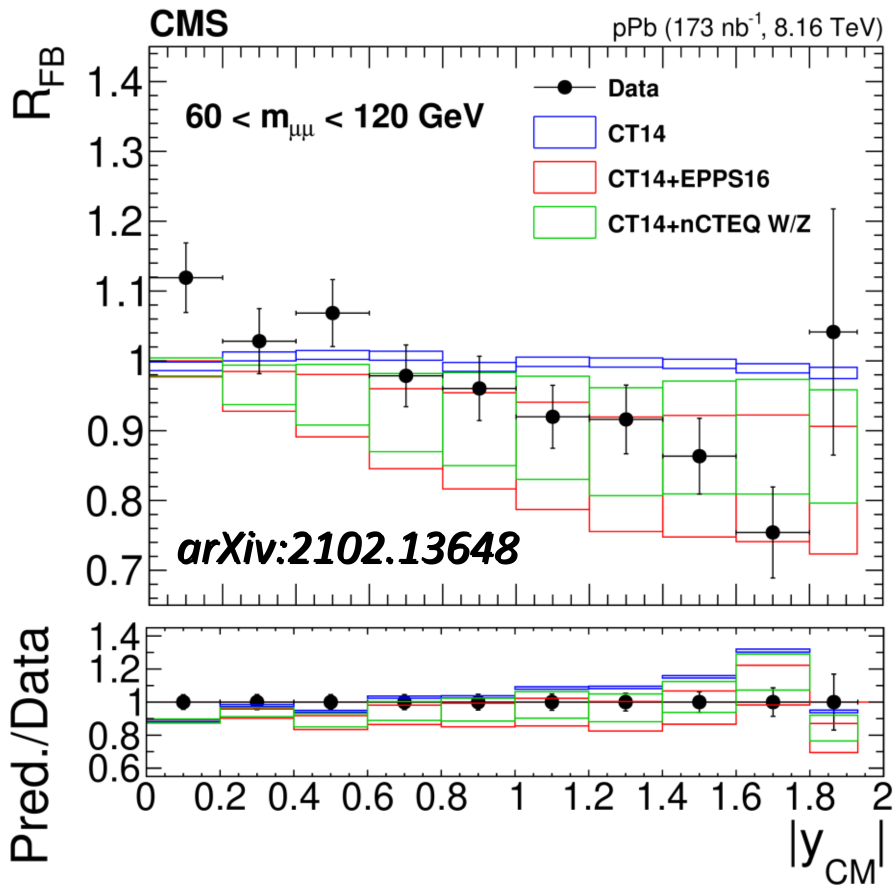
arXiv: 1812.06772



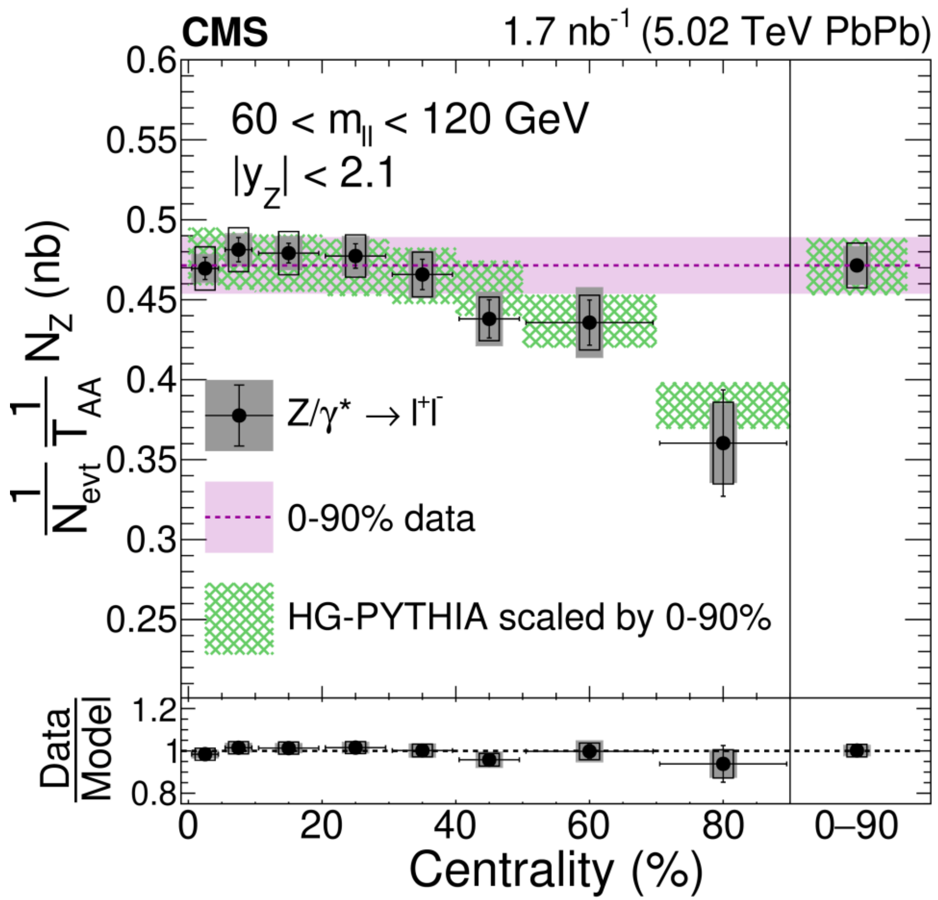
In preparation of EIC, HIC @ LHC provides the **best input to nPDFs**

Probing the initial state with DY: another standard candle

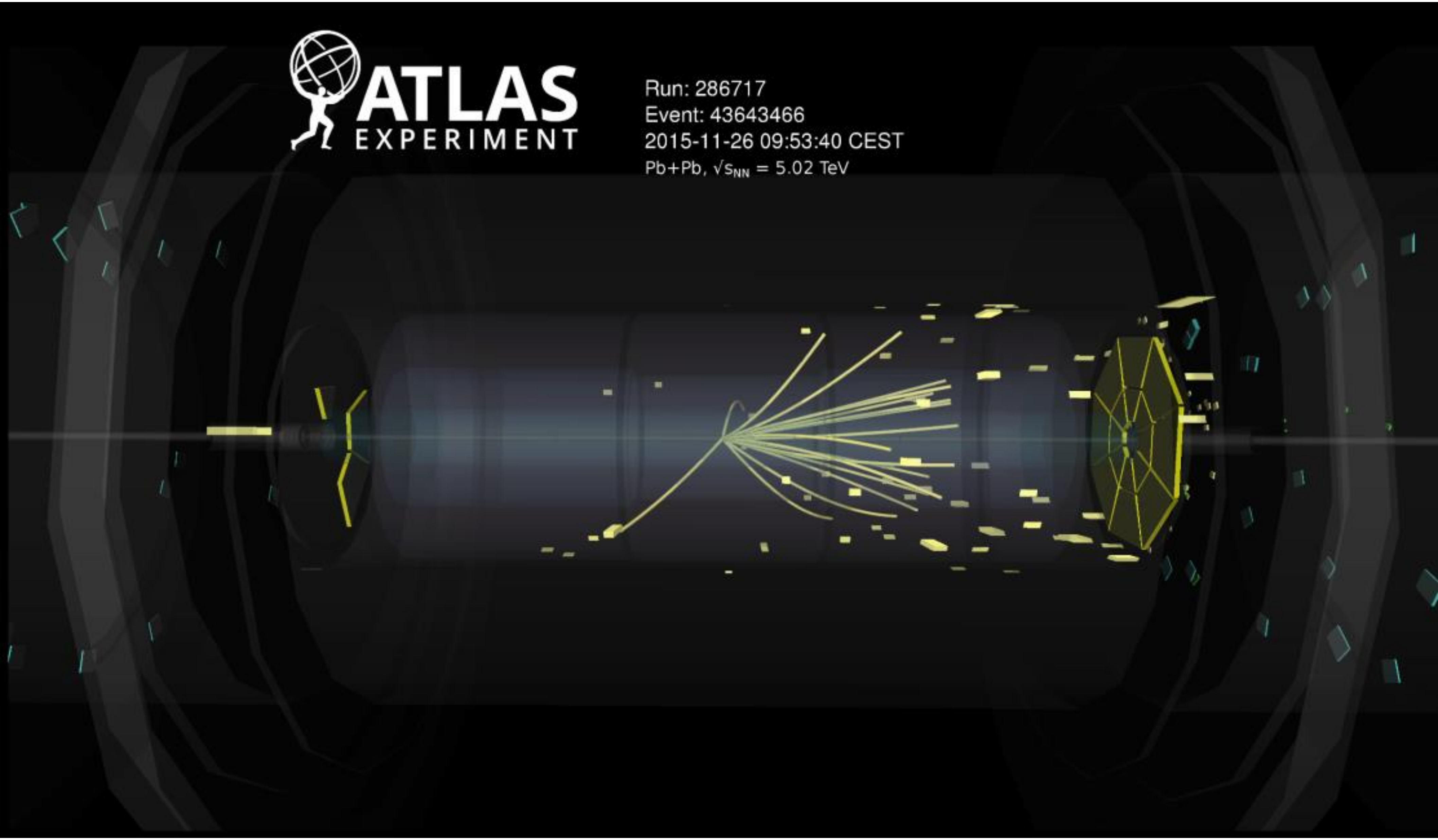
- **Drell-Yan (DY)** inclusive & differential pPb measurement in **extended** 15< $m_{\mu\mu}$ <120 GeV
  - the most precise to date → provide **novel constraints** on the quark nPDFs
- High-precision in PbPb too
  - Deviation from flat centrality dependence described by **HG-PYTHIA**
  - Possibility to **determine NN luminosity** with # of Z boson **counts**



arXiv: 2103.14089



Z boson production could even provide a **new normalization method**!



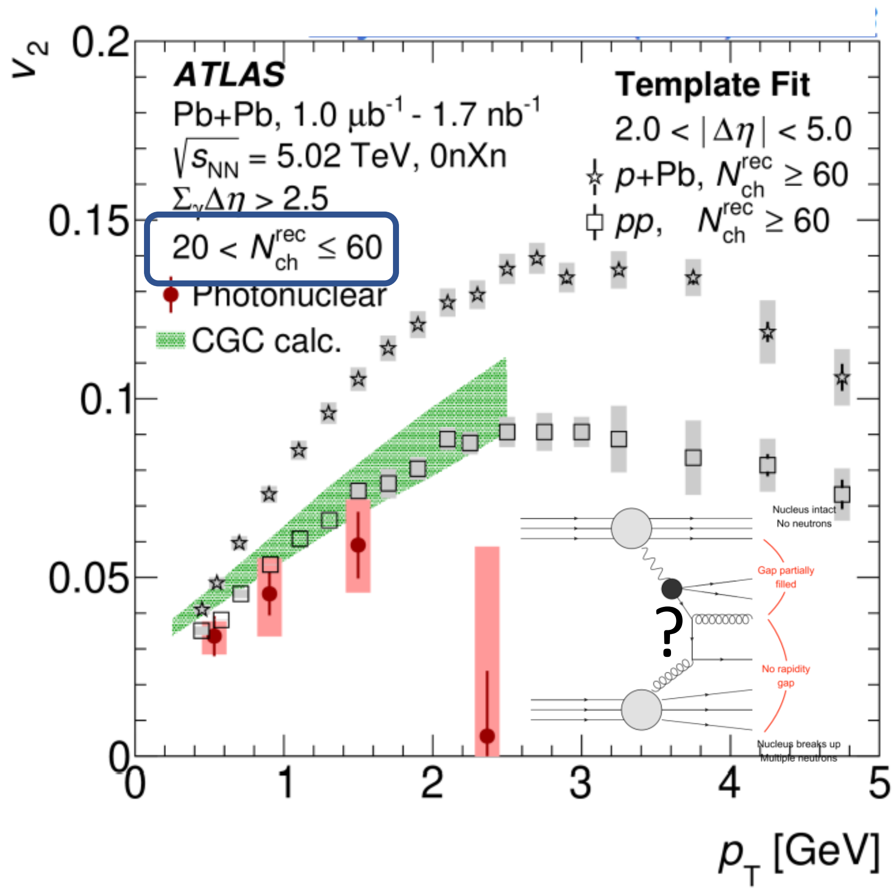
Empty events *full* of physics

Understanding v_n in the smallest systems

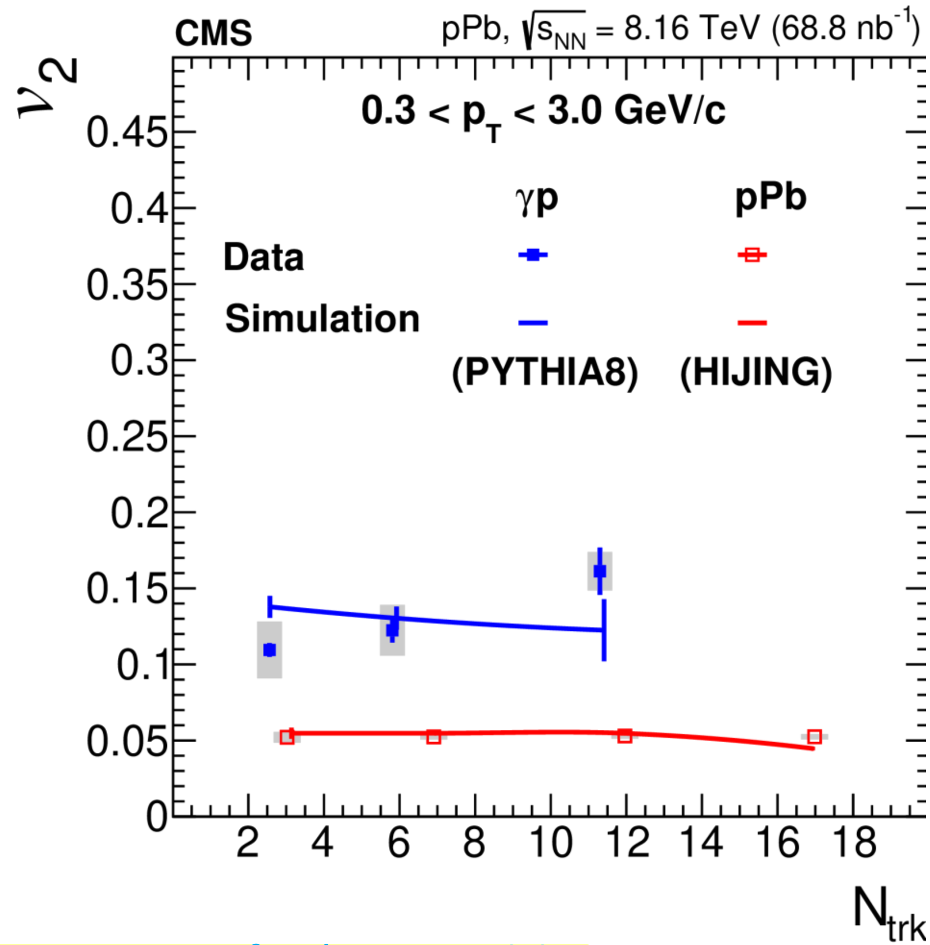
- Do we have systems **smaller than in pp** at LHC?
- γA, γp events good candidates to "bridge the gap" with e+e-
- **Not yet conclusive**: signs of QGP, CGC, γ → vector meson (VM) fluctuation?

cf. Valentina's talk

arXiv:2107.10771



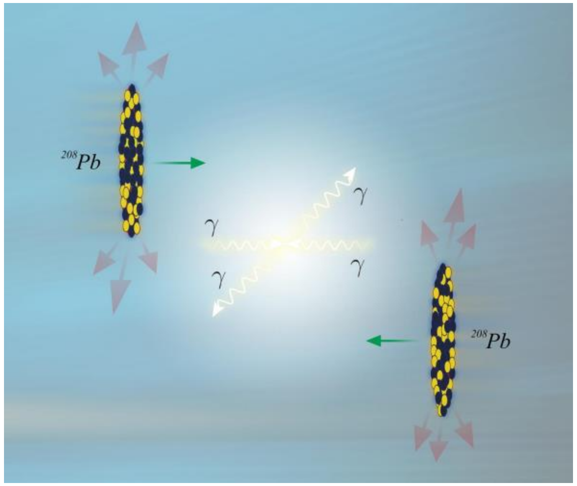
arXiv:2204.13486



In preparation of EIC, alternative use of pPb is **promising**

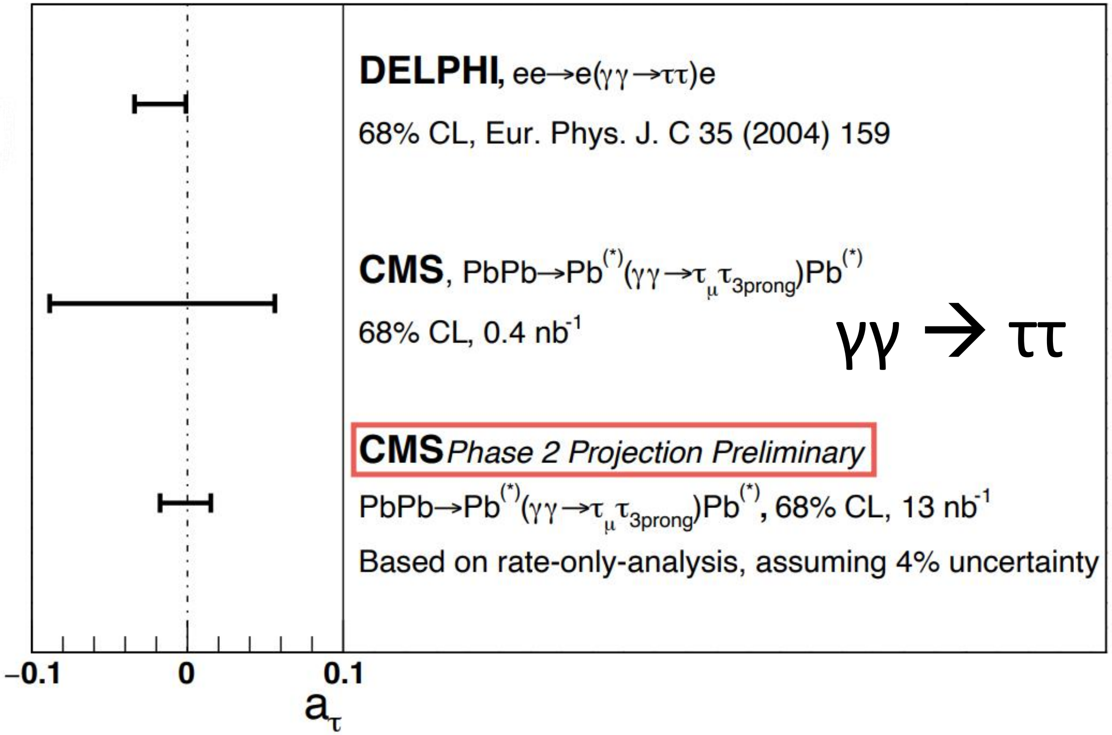
Precision QED and BSM searches

- Processes like $\gamma\gamma \rightarrow \mu\mu$ will be high **precision-like** at HL-LHC
- calibration of photon flux, constrain predictions for $\gamma\gamma \rightarrow ee, \tau\tau$
- Small cross sections, e.g., $\mathcal{O}(\alpha^4)$ for $\gamma\gamma \rightarrow \gamma\gamma$, but Z^4 **enhancement**
- **best** limits on couplings of axion-like particles over m_a =0.1−100 GeV

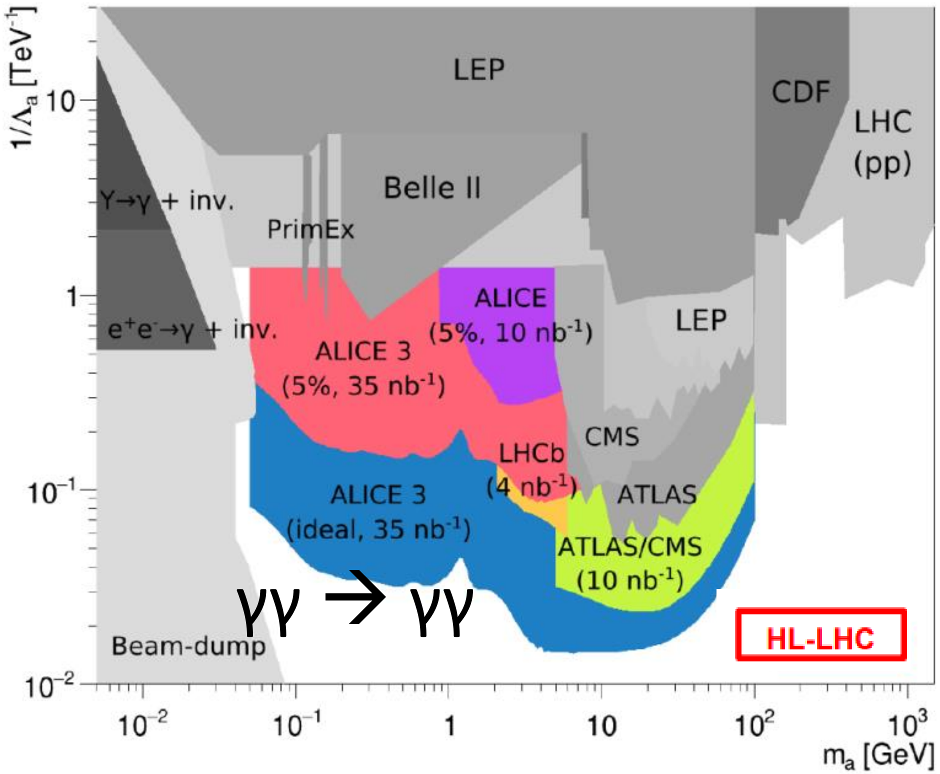


Source: IFJ PAN

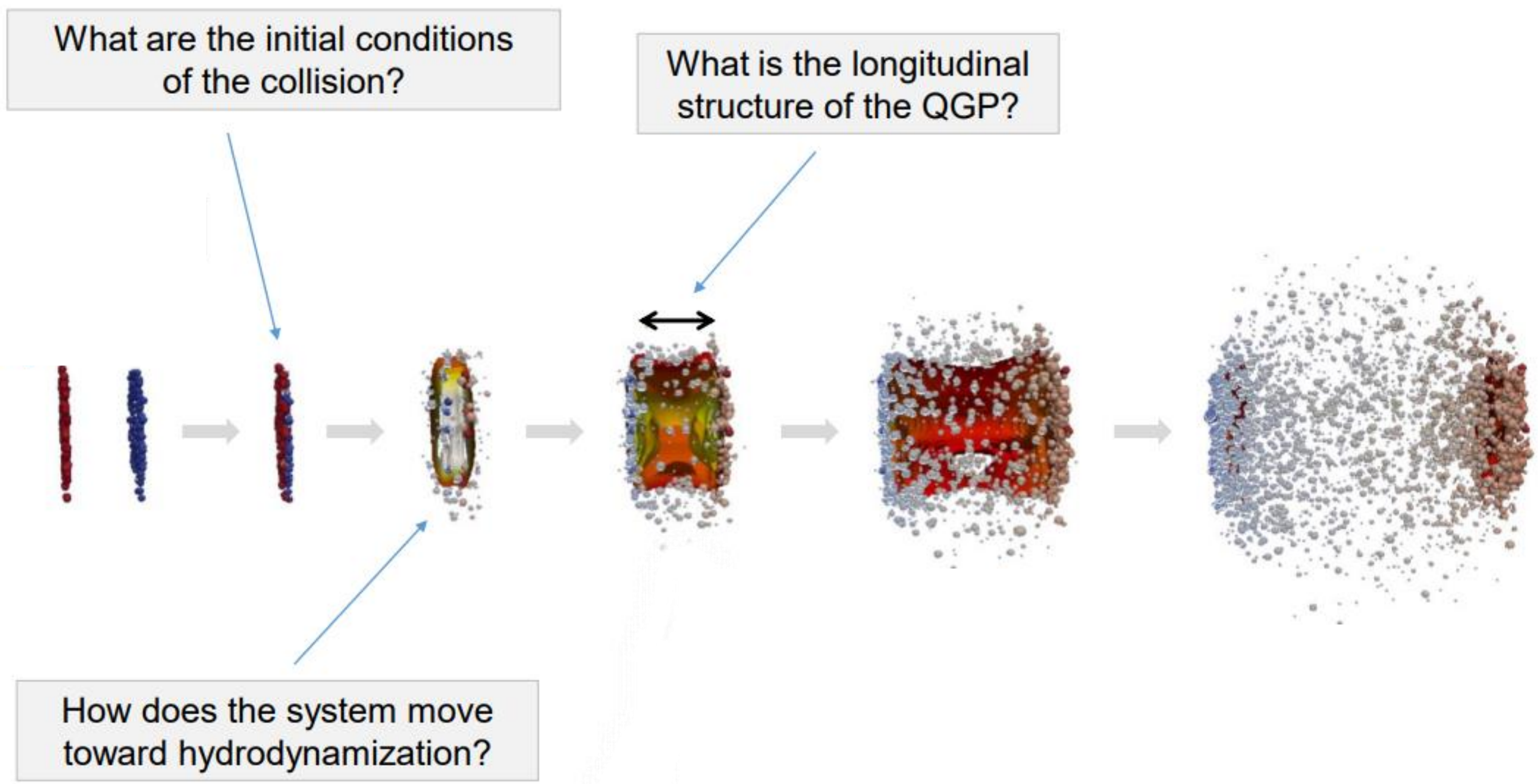
arXiv: 2206.05192



arXiv: 2203.05939

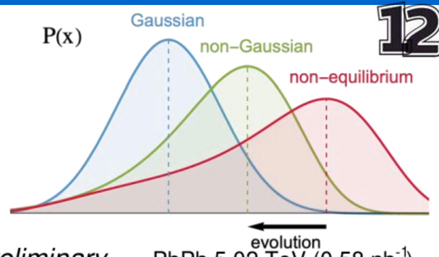


Taking advantage of **huge photon fluxes** from large-A UPC


What are the initial conditions of the collision?
What is the longitudinal structure of the QGP?
How does the system move toward hydrodynamization?

Investigating the initial stages with more elaborate observables

- **Subtle** differences in $v_2\{2k\}(k\leq5)$ → fluctuation-driven **moments** of v_2
  - measured **v2{10}** measured for the first time!
  - constraints on hydro predictions
- High-precision for **sign changes** when correlating $v_n\{2k\}$ with $[p_T]$
  - very sensitive to gluon correlations (CGC): **not seen in data**



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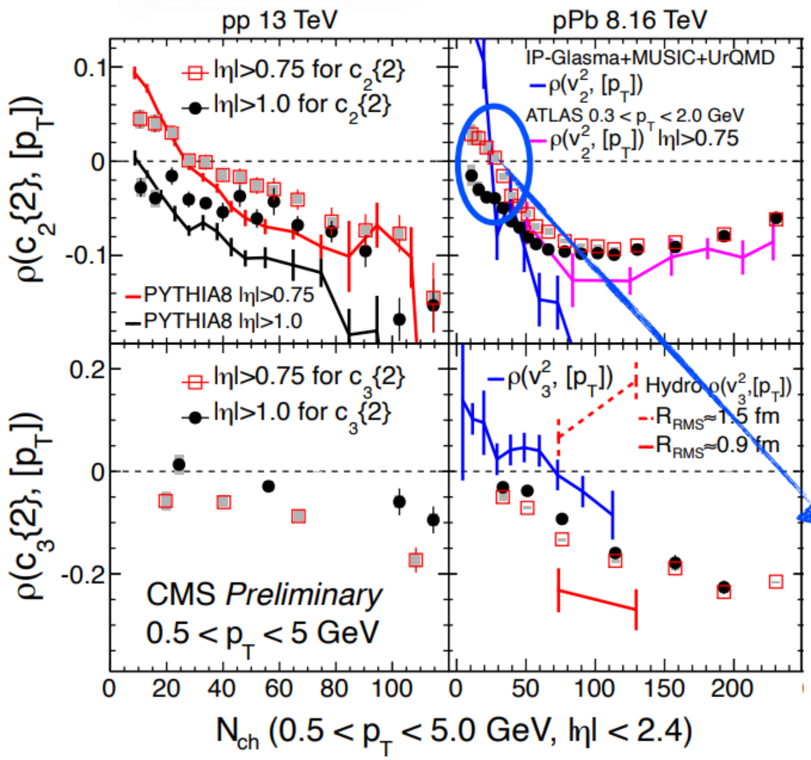


$$\rho(v_n^2,[p_T]) = \frac{\mathrm{cov}(v_n^2,[p_T])}{\sqrt{\mathrm{Var}(v_n^2)_{\mathrm{dyn}}}\sqrt{\mathrm{Var}([p_T])_{\mathrm{dyn}}}}$$

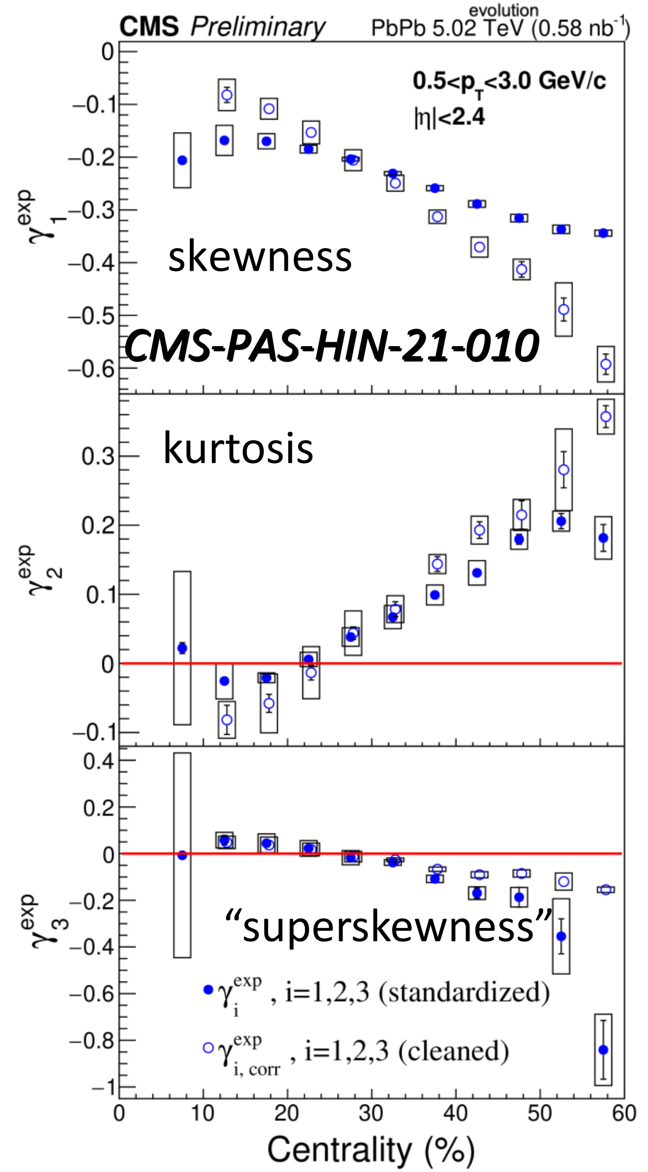
□ small η gap

● large η gap

Reduction of non-flow effects

IP-Glasma+MUSIC+UrQMD

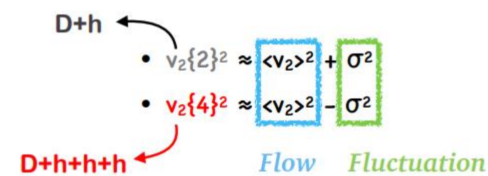
: Sign change predicted by CGC



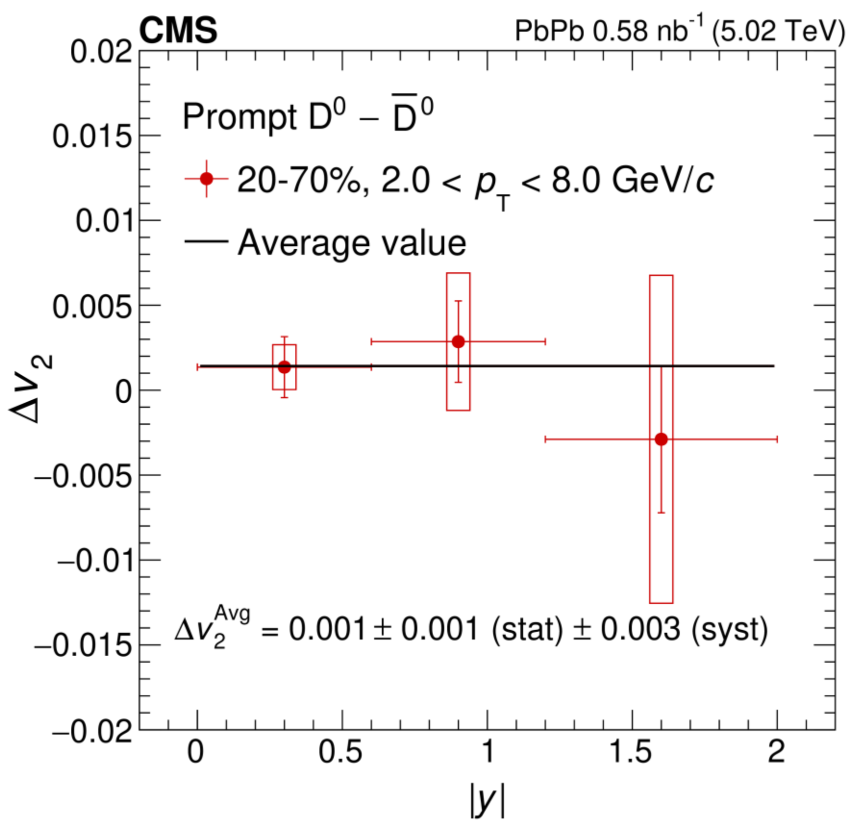
Resolving v_2 event-by-event fluctuations with **unprecedent precision**

Charm quark dynamics via (multi)particle correlations

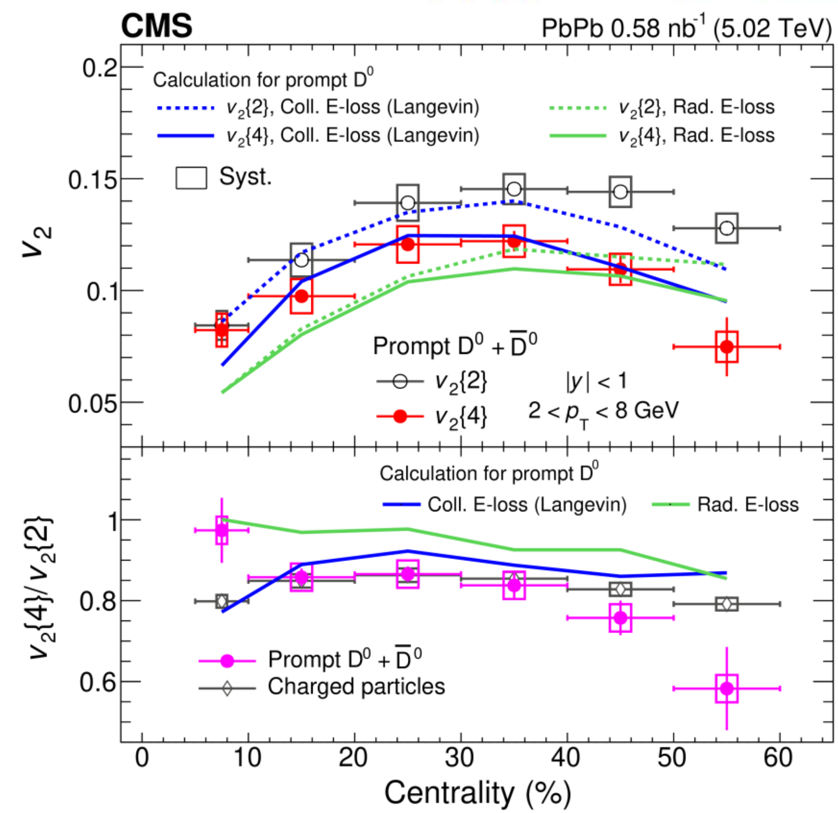
- **First** Δv_2 measurement for D^0 → sensitive to the strong created EM fields
  - **no EM induced charge-dependent splitting** in v_2
- First **high-precision $v_2\{4\}$/ $v_2\{2\}$** also for D^0 → check whether fluctuations on v_2 are **universal**
  - that's the case modulo very central (peripheral) events



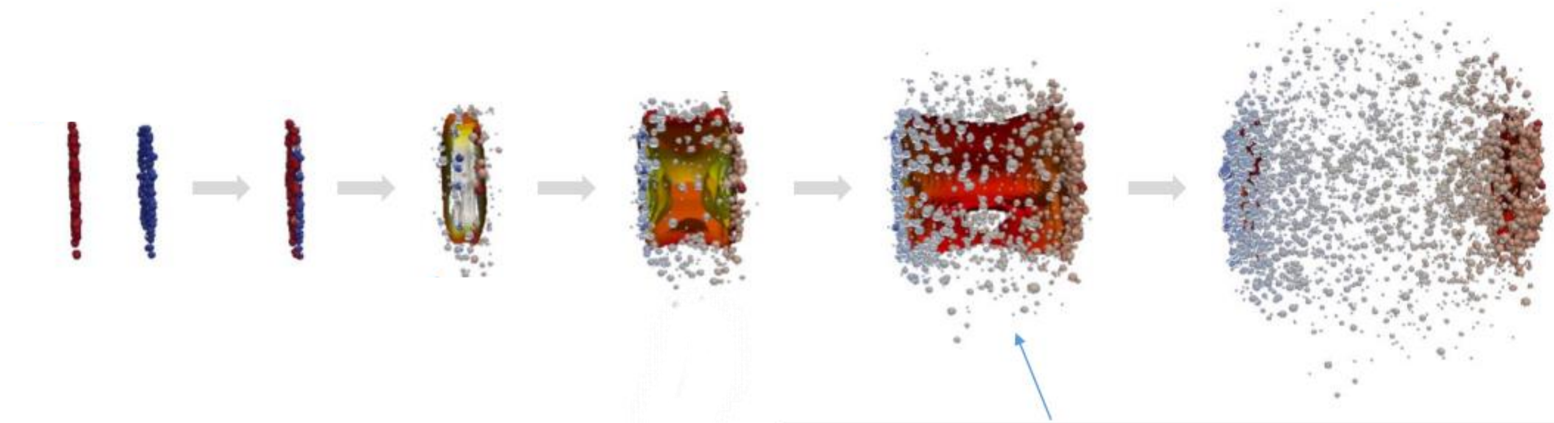
arXiv: 2009.12628



arXiv: 2112.12236



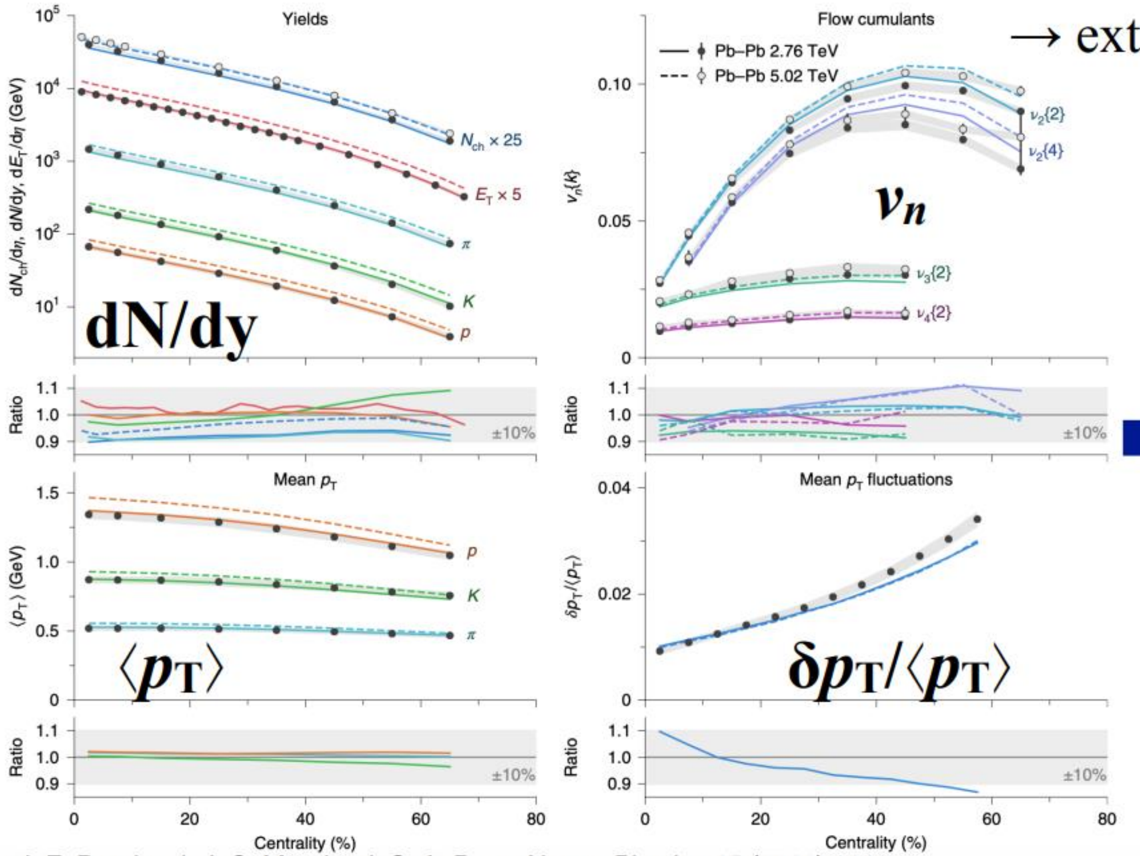
Resolving v_2 event-by-event fluctuations with **identified particle $v_2\{4\}$**



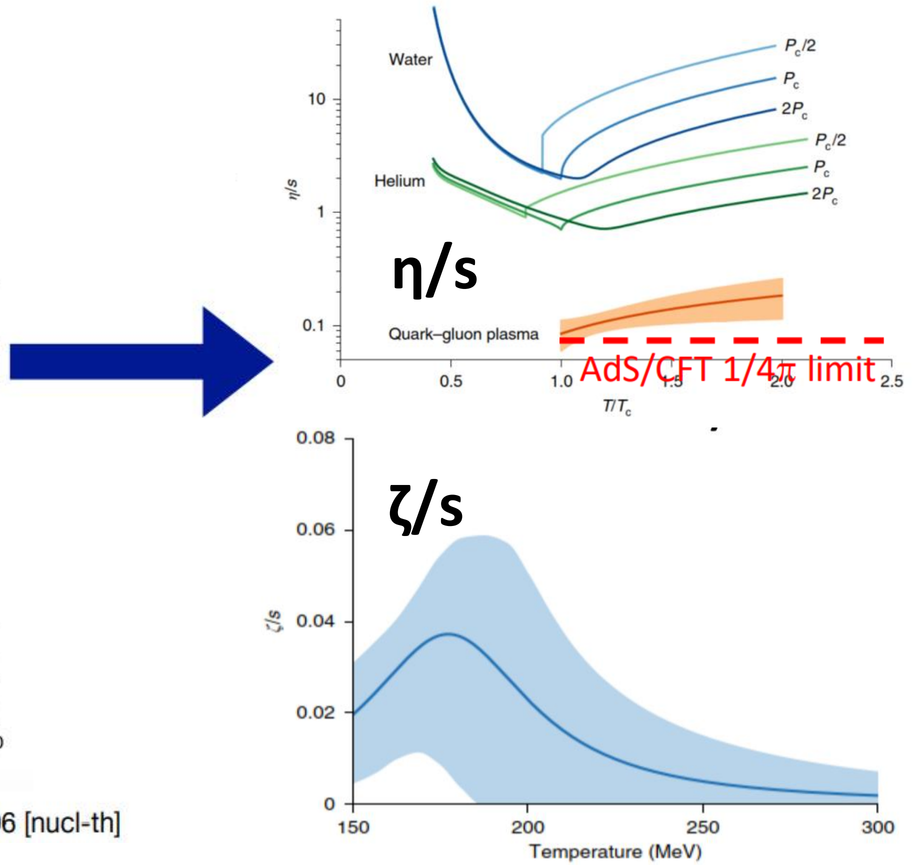
What are the transport properties of the QGP?
How does QGP respond to hard probes?
What are the inner workings of QGP at various length scales?

Extracting QGP thermodynamic properties

- Soft particle production and kinematics give us information about **QGP and its evolution**
- viscosities **η/s** and **ζ/s** control dissipation of energy-momentum perturbations



→ extract shear and bulk viscosity $\eta/s(T)$, $\zeta/s(T)$



J. E. Bernhard, J. S. Moreland, S. A. Bass, Nature Physics 15 (2019) 1113
J. S. Moreland, J. E. Bernhard, S. A. Bass, Phys. Rev. C 101 (2020) 024911, arXiv:1808.02106 [nucl-th]

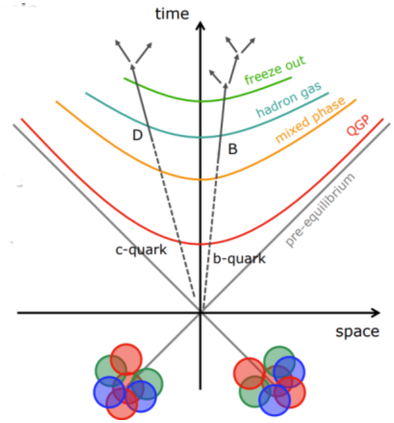
Data from LHC (ALICE and CMS)

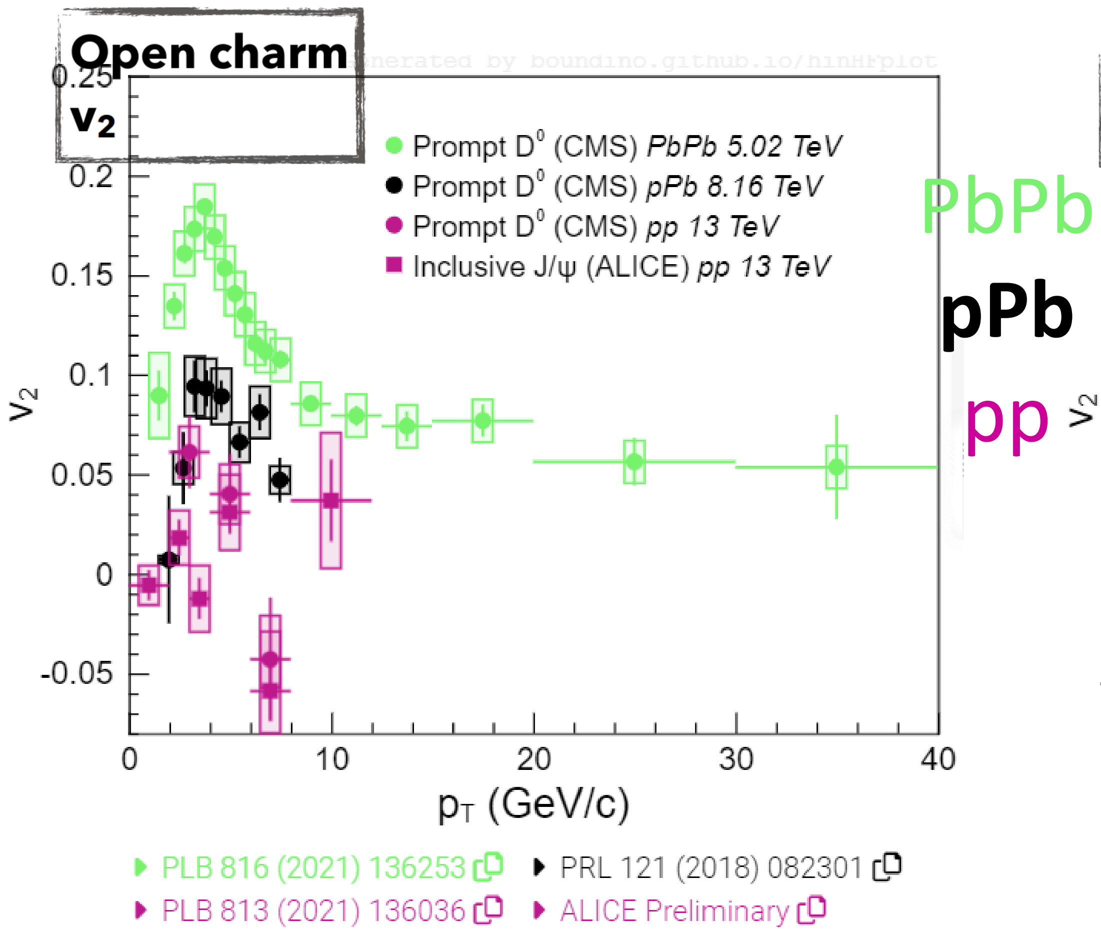
cf. Chun's talk

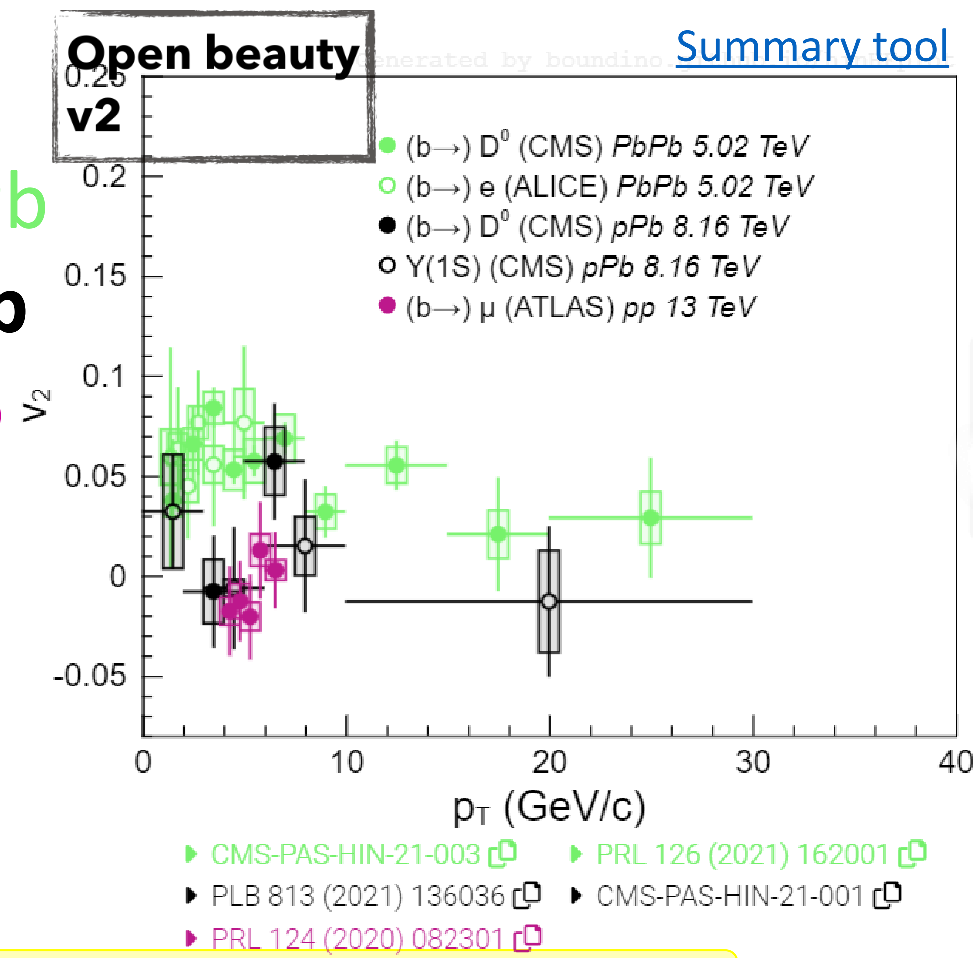
η/s near to AdS/CFT threshold: **almost perfect fluid**!

Comparing heavy flavor particle flow in all systems

- There is charm anisotropy... everywhere
  - 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
  - can HF probes help to answer **whether QGP is formed** in high-multiplicity pPb/pp?





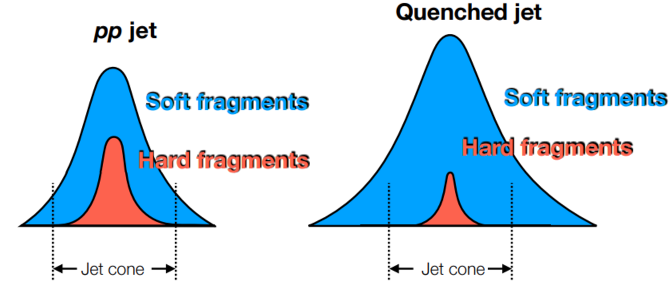


Summary tool

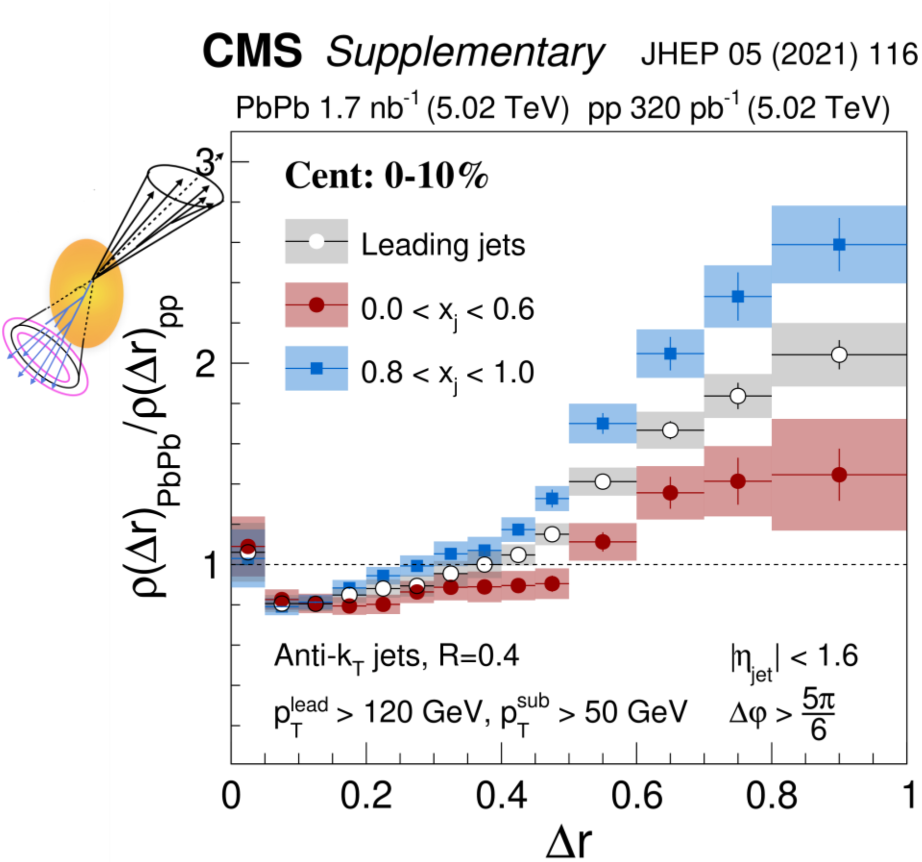
Novel input to the description of heavy-quark transport and energy loss

How energy loss is distributed?

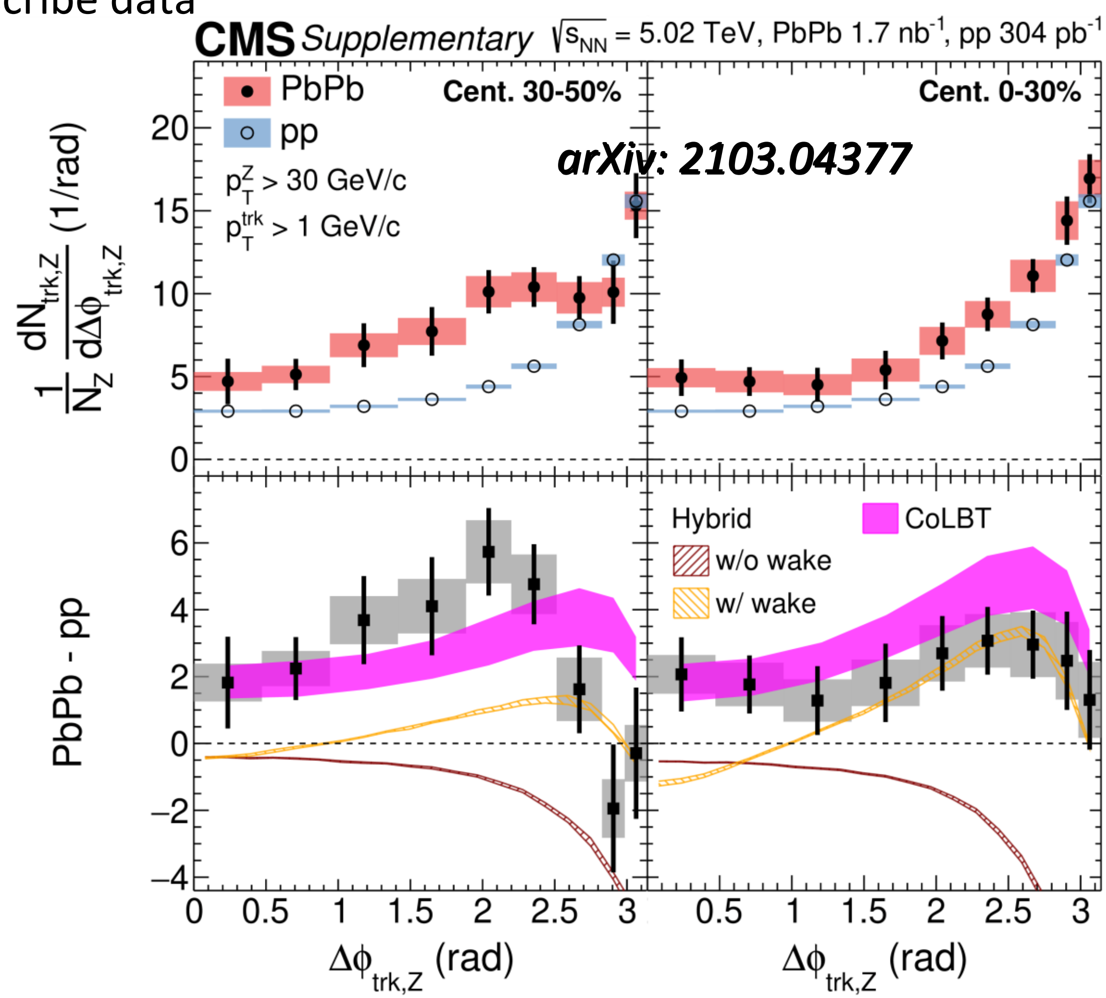
- **Jet shape**: radial profile of particles in jets
  - energy outside jet cone is mostly **low energy** particles
  - energy is transferred to soft particles **at large angles**



- **Similar conclusions** when checking the behavior of particles associated with Z bosons
  - models with **parton-medium interactions** describe data



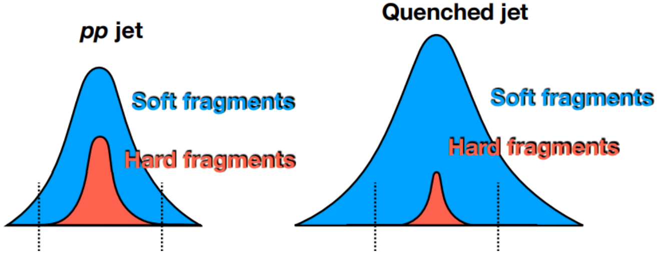
$$\rho(\Delta r) = \frac{1}{\delta r}\frac{1}{N_{\text{jets}}}\frac{\sum_{\text{jets}}\sum_{\text{tracks}\in(\Delta r_a,\Delta r_b)} p_T^{\text{ch}}}{\sum_{\text{jets}}\sum_{\text{tracks}\in\Delta r\leq 1} p_T^{\text{ch}}}$$

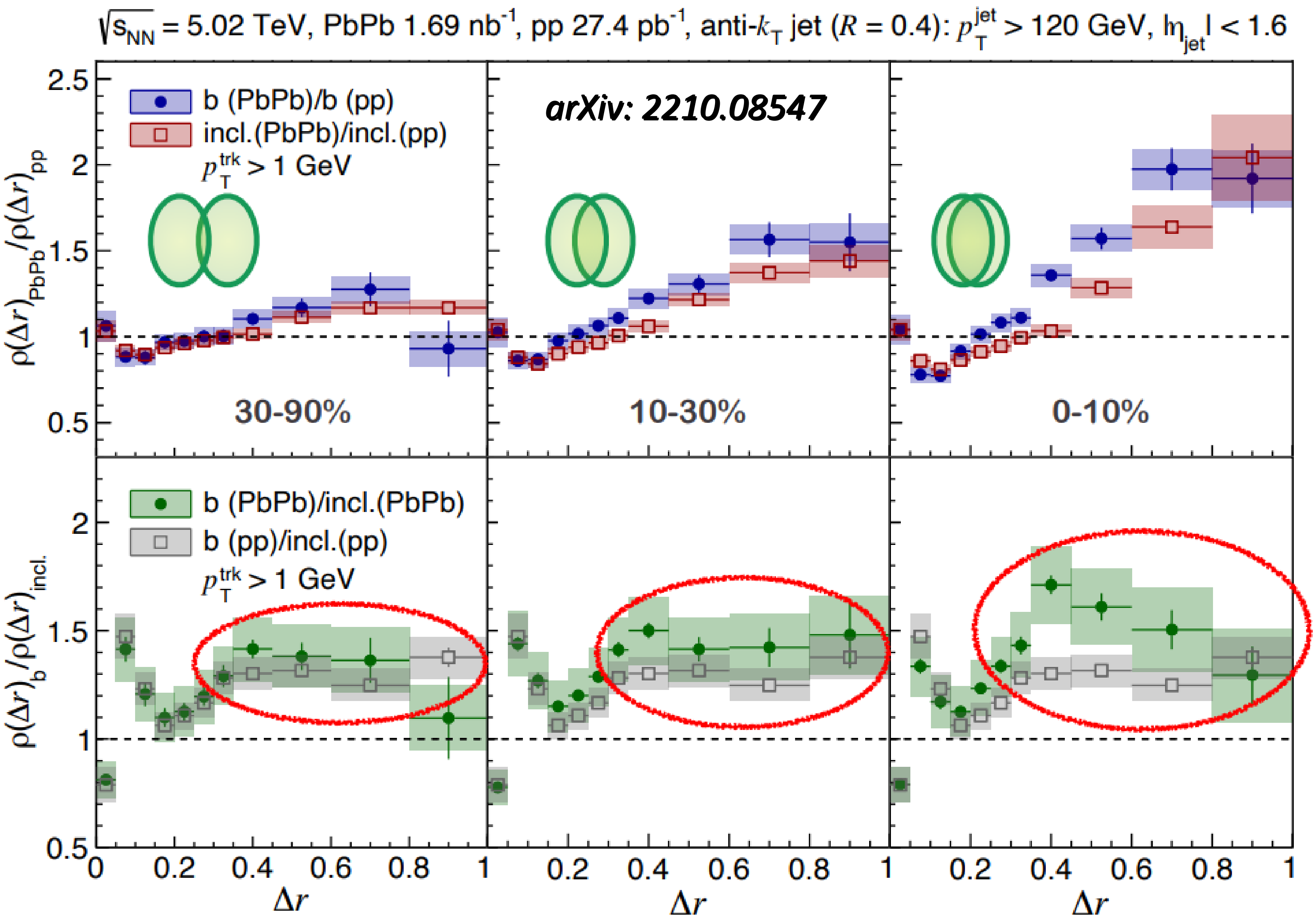


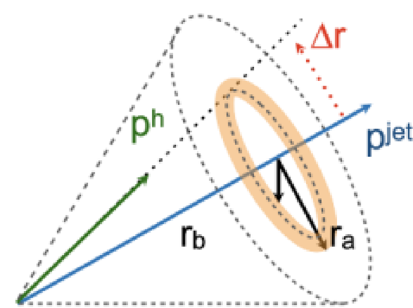
Important to include **medium response** in the modeling

How energy loss is distributed?

- Larger modification **for b than inclusive jets** at large Δr
- Depletion at small Δr : suggestion of **dead-cone effect** for b jets





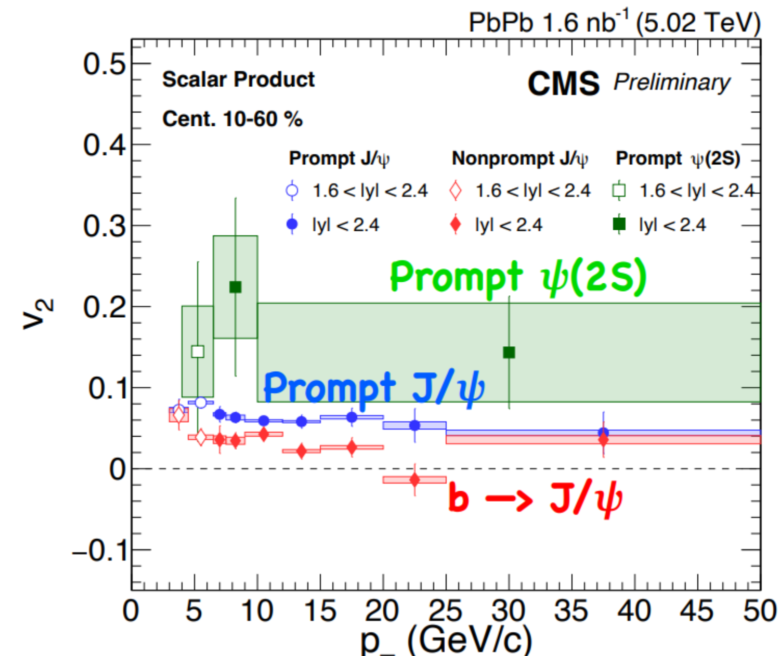


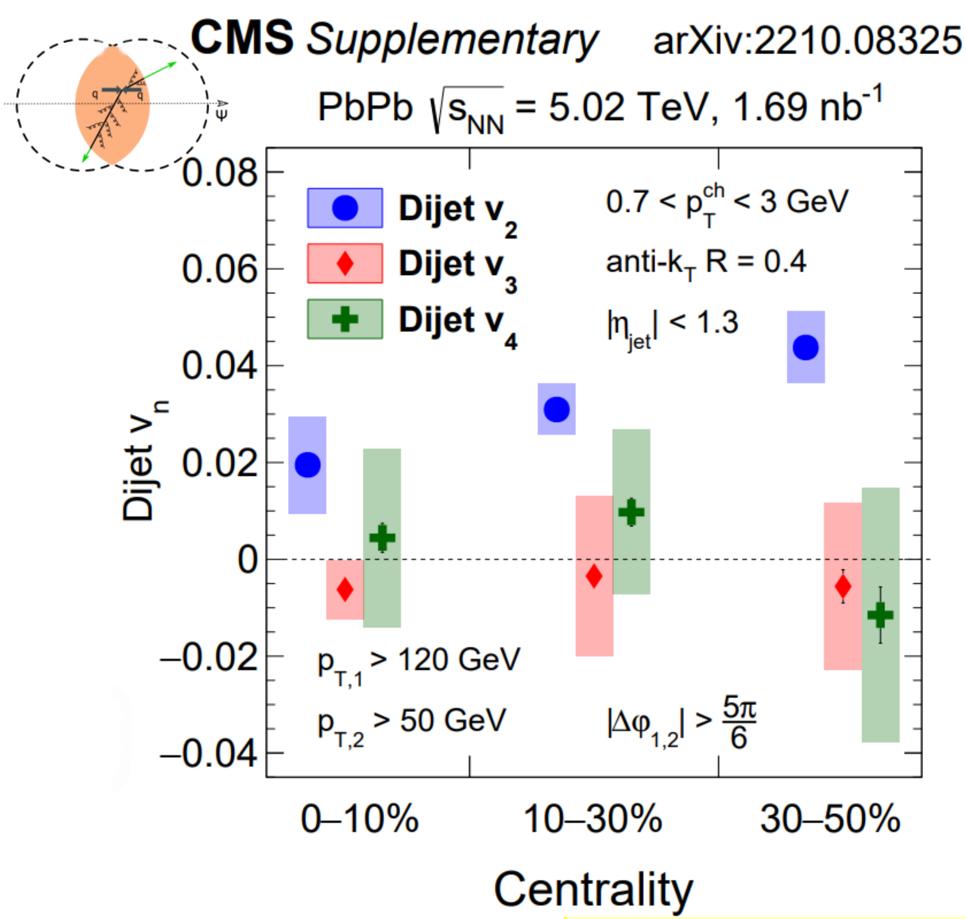
Increased medium response to the propagation of a heavier quark

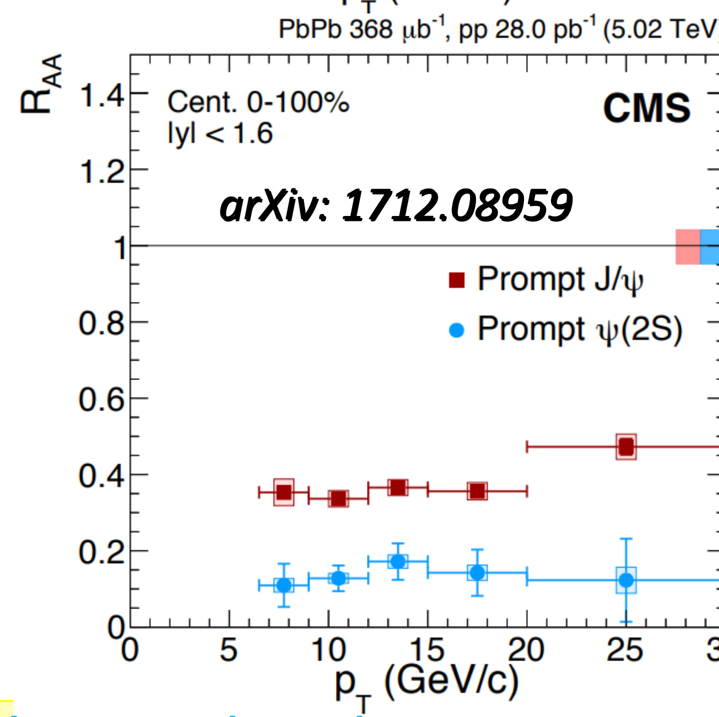
Explore energy loss and QGP expansion **at the same time**

- Measure the rate of jets wrt. collision geometry
  - dijet v_n show the **path length dependence** of energy loss
- **Measurements** of v_2 and R_{AA}
  - **mass splitting** at low p_T but converge at high p_T ($\gg m_b$)
  - v_2 ψ(2S) "out of trend" despite larger suppression

CMS-PAS-HIN-21-008



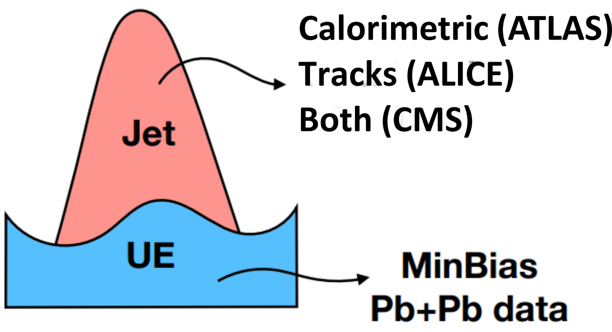




High-p_T probes to become **powerful tomography tools**

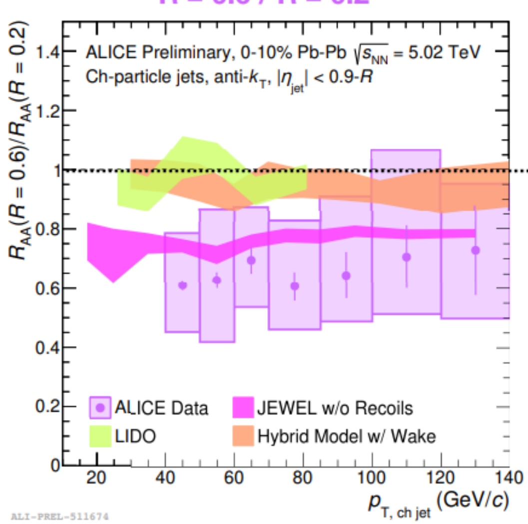
Wait, all these previous conclusions depend on R?

- With **larger jet R** one expects
  - wider area to recover lost energy
  - phase space to open for jets with wider splittings
- Closer look to the R (in)dependent suppression
  - Different **jet collections** and **UE estimations**



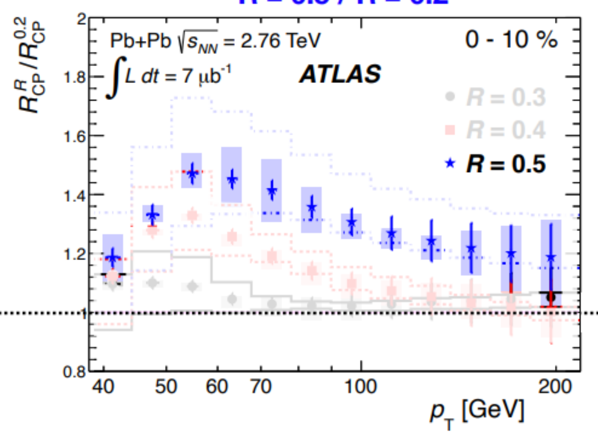
ALI-PREL-511679

R = 0.6 / R = 0.2

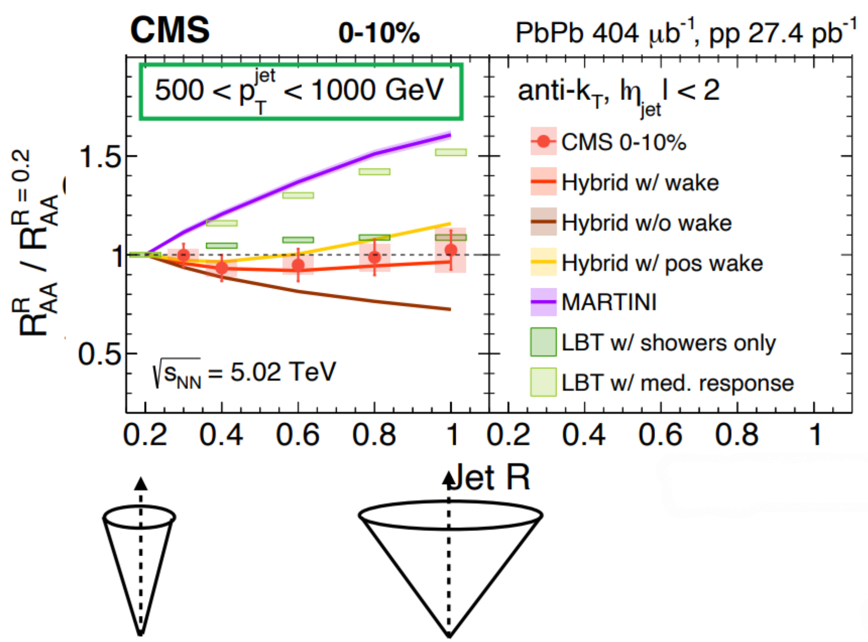


arXiv: 1208.1967

R = 0.5 / R = 0.2



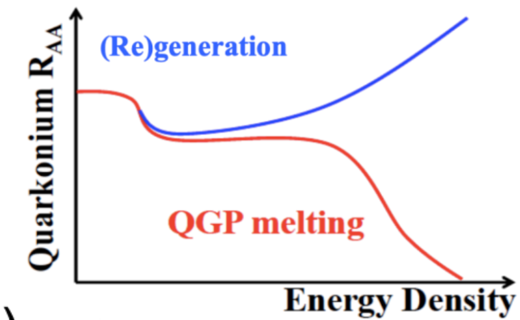
arXiv: 2102.13080



Discriminating power for models and the physics mechanisms at play

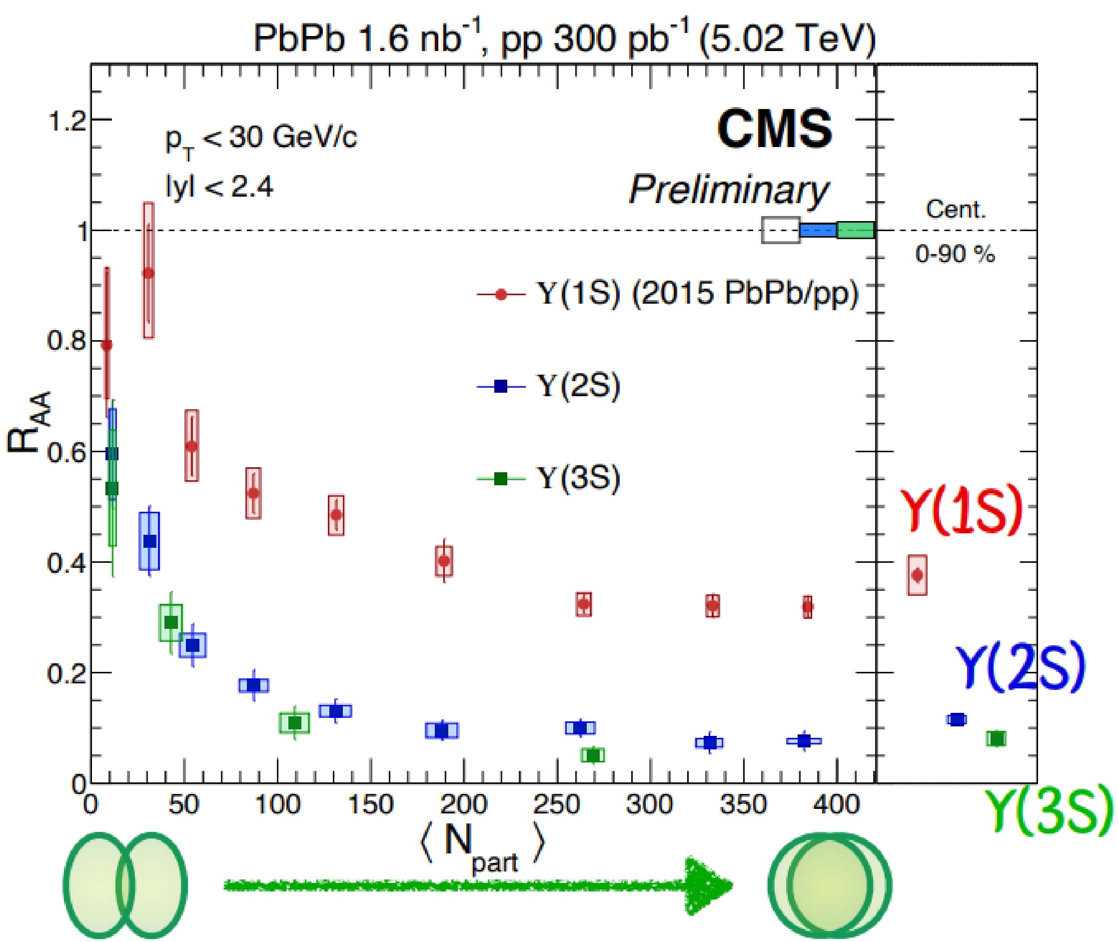
Heavy quarkonia suppression

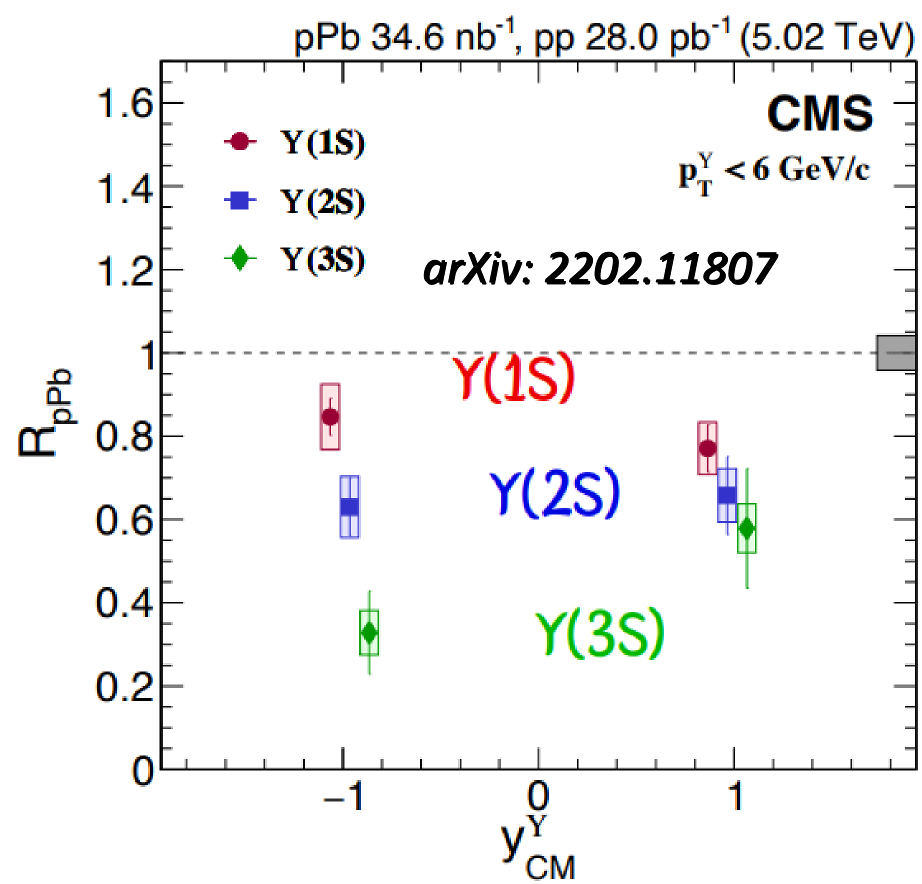
- Observation of the **sequential melting** of ϒ(ns) in **PbPb and pPb**
- Similarly to the **hierarchy suppression** between J/ψ and ψ(2S)
- first time including **Y(3S)** in the picture



$R_{AA}(Y(1S)) > R_{AA}(Y(2S)) > R_{AA}(Y(3S))$

CMS-PAS-HIN-21-007



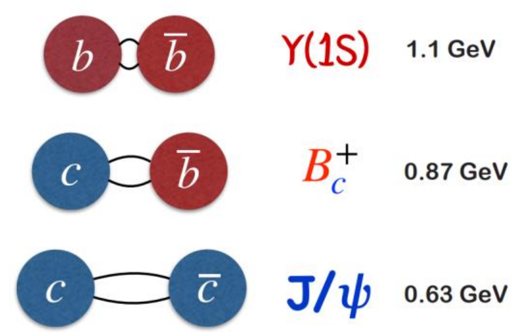


Interplay of **suppression-regeneration** crucial to grasp data

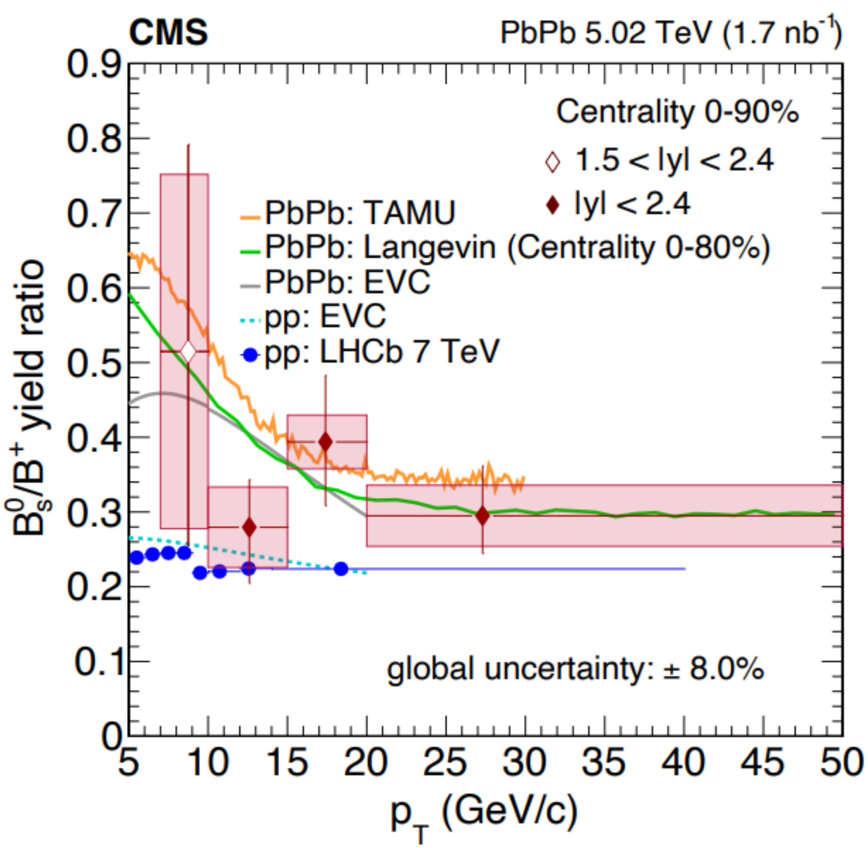
B_s and B_c in PbPb

- For B_s **low-pT enhancement** suggested by models
  - current uncertainty **large** though
- **First observation** of B_c
  - unique state for enhancement (low pT) and suppression (high pT)

Binding energy hierarchy



arXiv: 2109.01908



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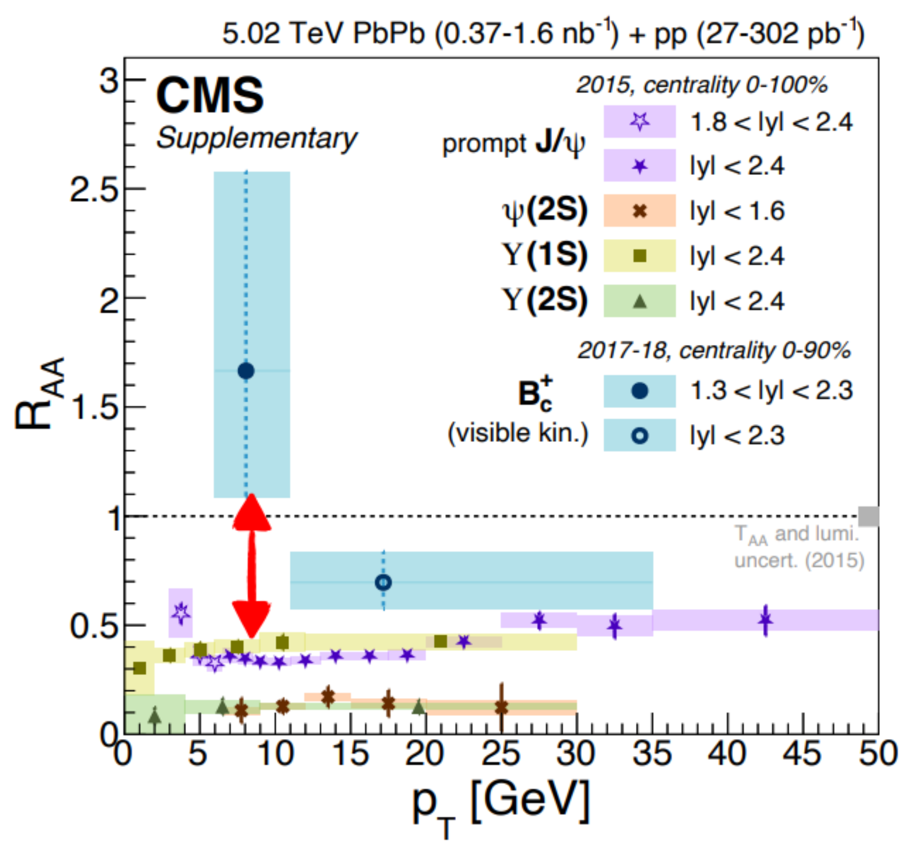
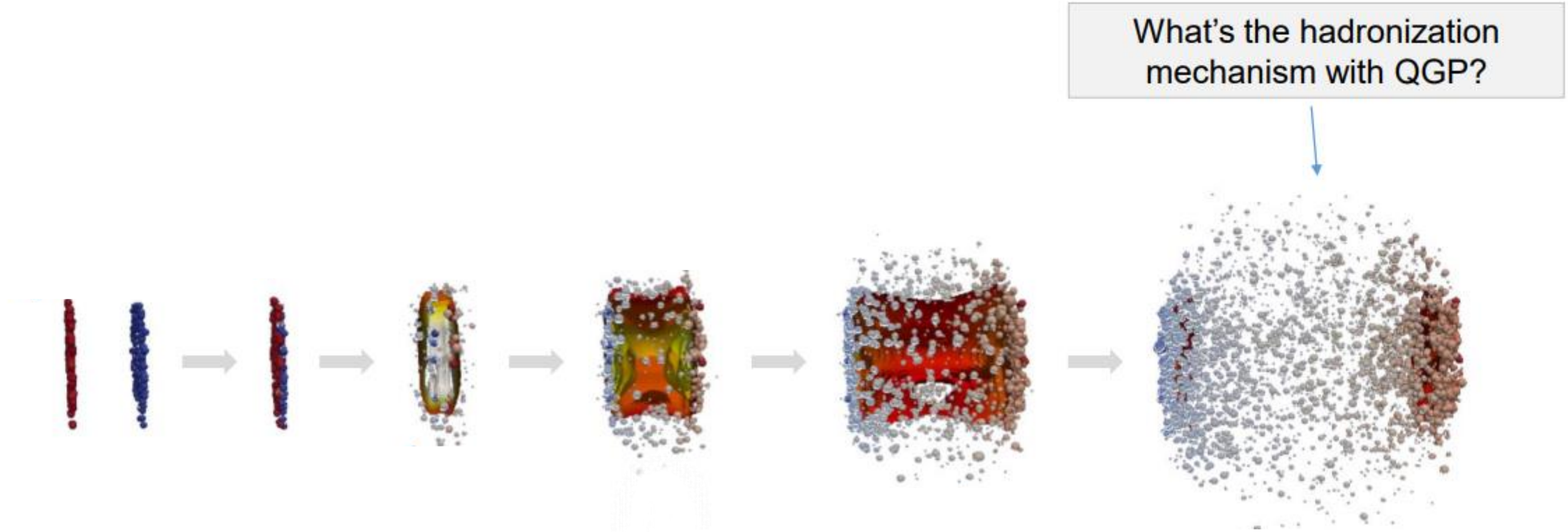
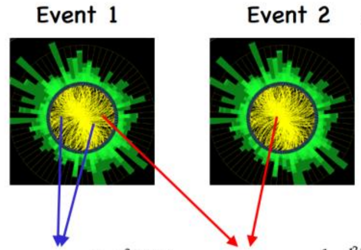


Novel probe **for suppression-regeneration**


What’s the hadronization mechanism with QGP?

Femtoscopic measurements with charged and strange particles

- **Charge-dependent** two-particle "balance" functions in **extended p_T range**
- models can't grasp Δη width vs N_{ch}, **better in Δϕ**



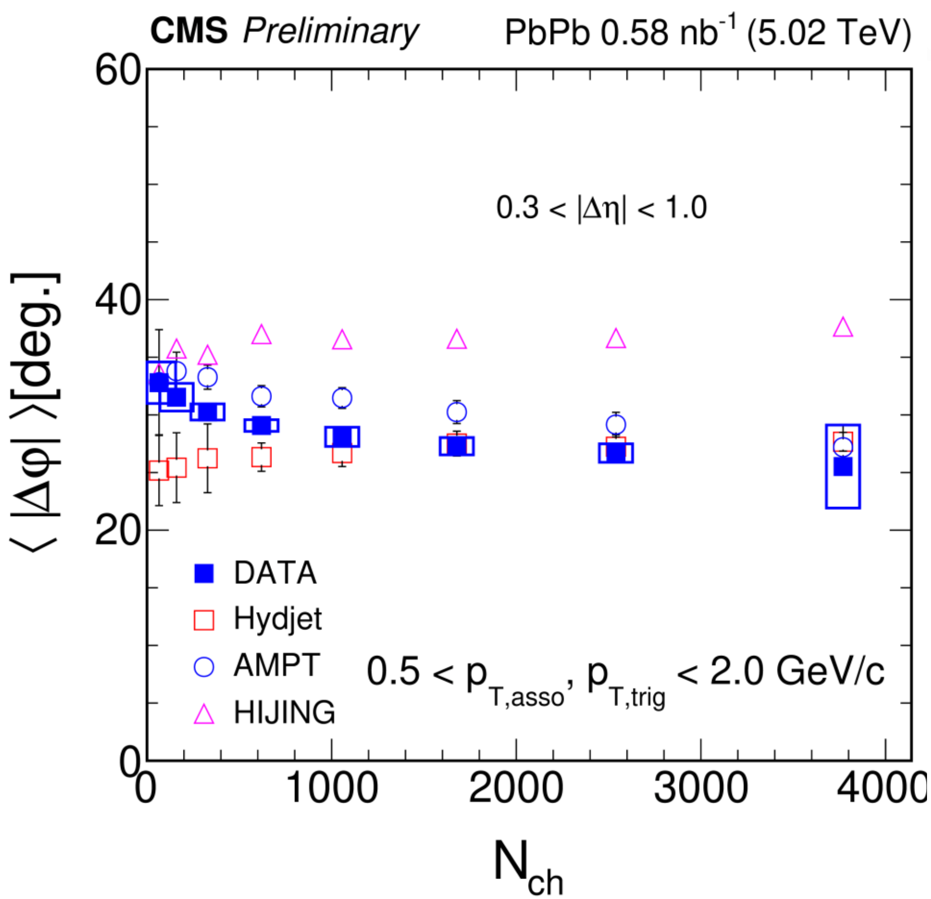
$$S(\Delta\eta,\Delta\varphi) = \frac{1}{N_{trig}}\frac{d^2N^{same}}{d\Delta\eta\Delta\varphi} \qquad M(\Delta\eta,\Delta\varphi) = \frac{1}{N_{trig}}\frac{d^2N^{mix}}{d\Delta\eta\Delta\varphi}$$

2D correlation : $C_2(\Delta\eta,\Delta\varphi) = M(0,0)\frac{S(\Delta\eta,\Delta\varphi)}{M(\Delta\eta,\Delta\varphi)}$

Balance function

$$B(\Delta\eta,\Delta\varphi) = \frac{1}{2}[C_2(+,-)+C_2(-,+)-C_2(+,+)-C_2(-,-)]$$

CMS-PAS-HIN-21-017



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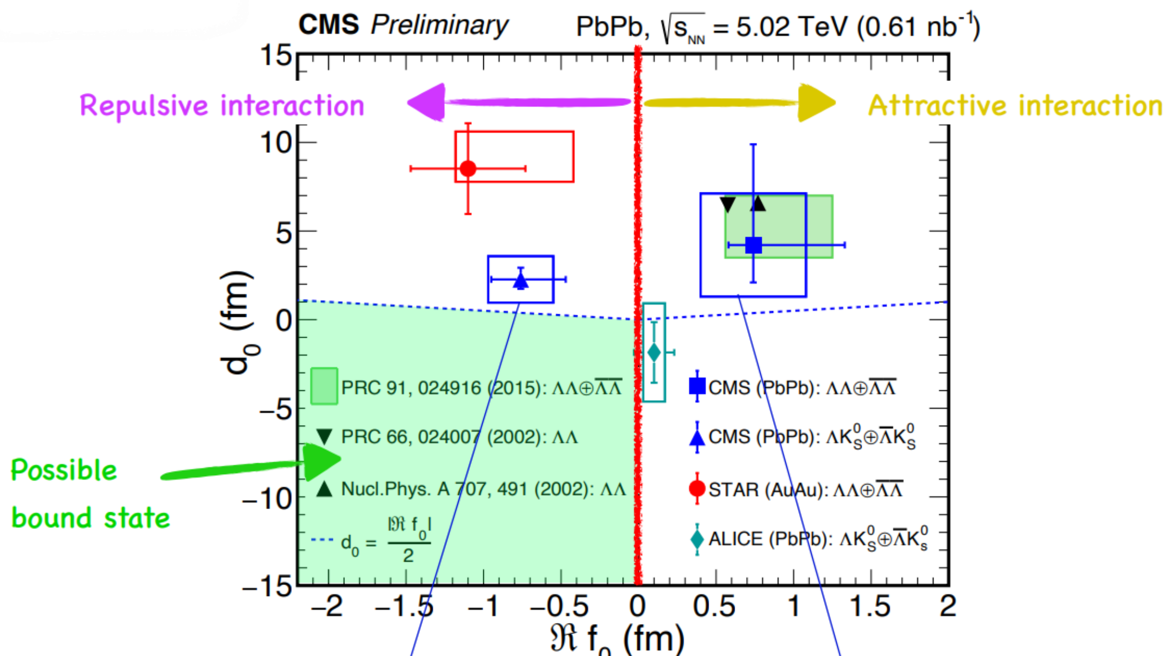


- Two-particle femtoscopic correlation studied with K^0_S and Λ
- Repulsive $\Lambda K^0_S \oplus \overline{\Lambda} K^0_S$ interaction
- No evidence for bound H-dibaryon in PbPb with $\Lambda\Lambda \oplus \overline{\Lambda\Lambda}$ correlation

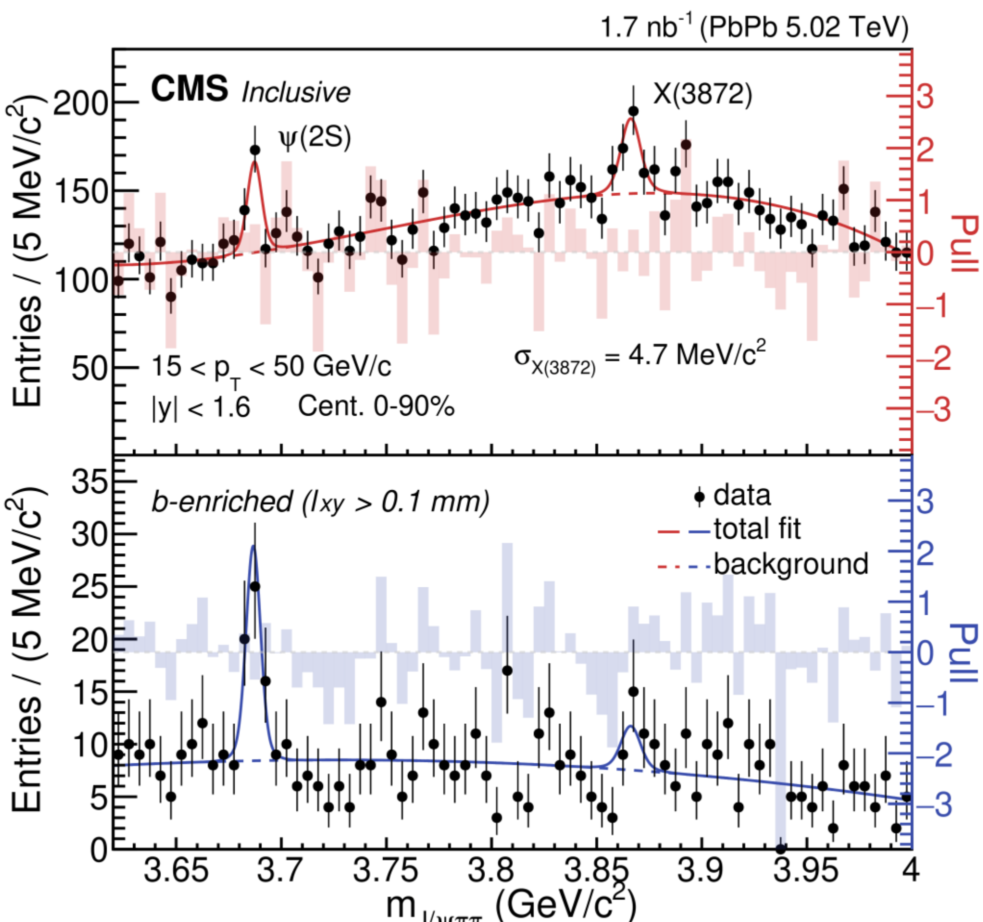
Probing QGP chemical evolution, its size, and baryon (hyperon)-baryon (hyperon) interaction

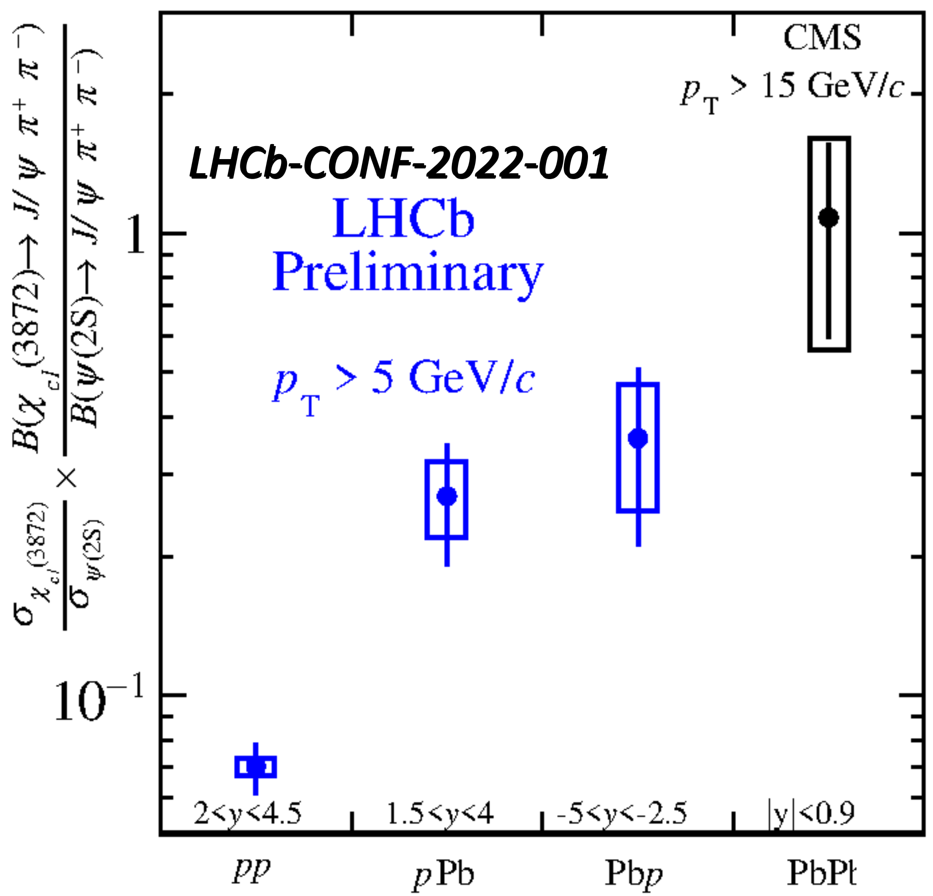
Production of exotic hadrons in HIC

- Exotic states test models in an expanded range of n_{cq}
  - effects are sensitive to size/binding energy of bound state and QGP density

- $\chi_{c1}(3872)/\psi(2S)$: something different for exotic vs conventional hadrons?
  - initial-state effects cancel in the ratio
  - enhancing effects start to **outcompete** breakup (at least at low p_T)

arXiv: 2102.13048





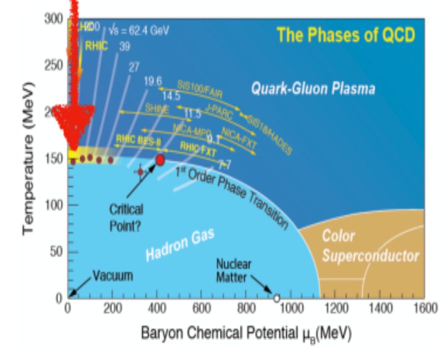
Machine learning techniques increases sensitivity to rare probes

From “smoking guns” to high precision, exotic and new signals

Goals for high-T/low-μ_B QCD matter	Experimental tools
Controlling initial conditions	pA , nPDF fits, flow (de)correlations
From early phase to hydrodynamization	Flow and fluctuations
Quenching and connection to smaller systems	R_{AA}, jet (sub)structure, high-p_T probes
Transport properties and thermalization	Heavy flavor transport, quarkonia, exotics
Pinning down hydro-like behavior	v_n in γA, γp
Precision QED and BSM searches	Photon-induced processes

LHC for heavy-ion physics

- **Unique potential**
  → high T, low μ_B, large HF yields
- **Progress enabled** by
  - increased **luminosity**
  - improved **detector performance**, e.g. vertexing, acceptance

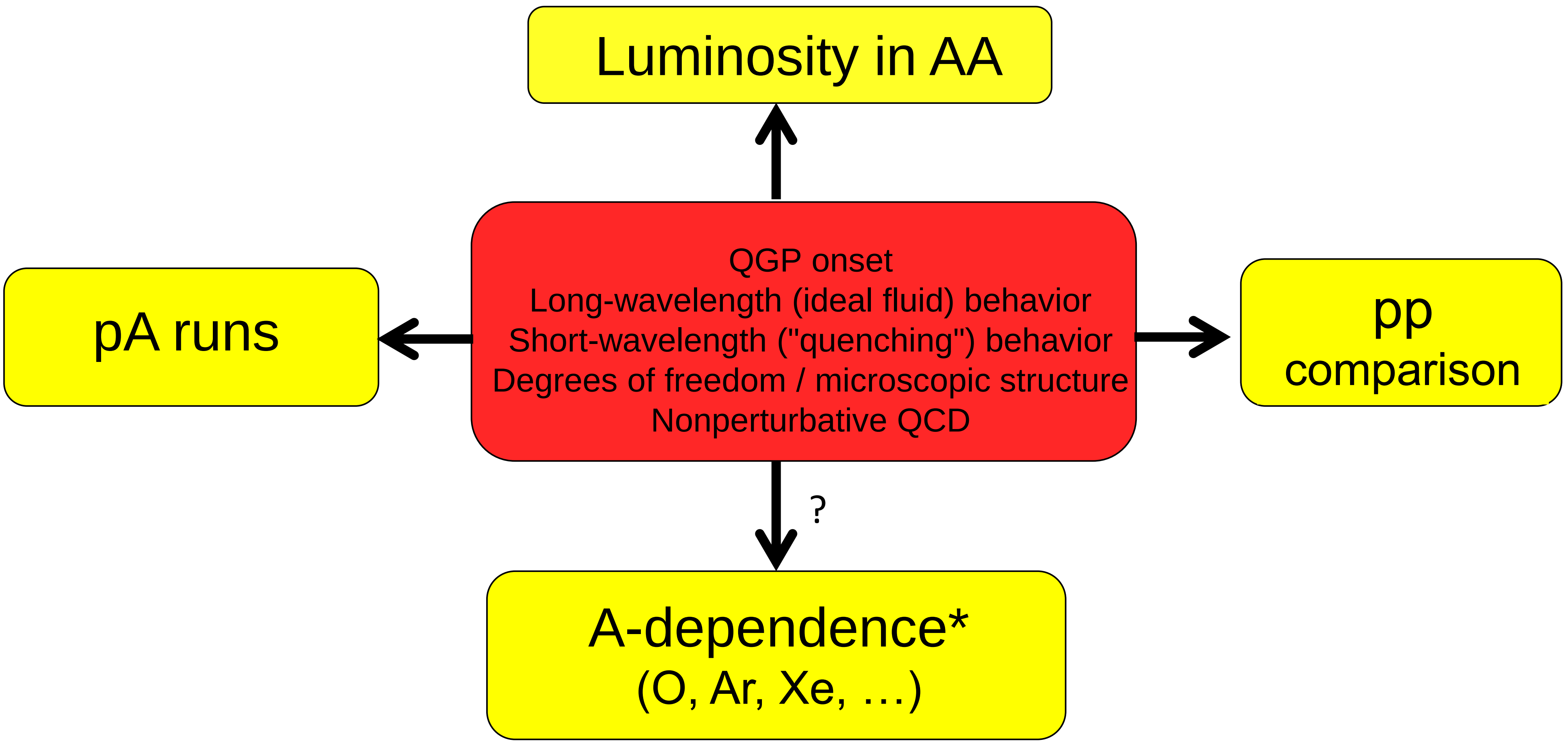


With input from
[Workshop on the physics of HL-LHC (2017)]
[CMS HI Physics at LHC Runs 3+4 and Beyond]

Nonexhaustive list

slides

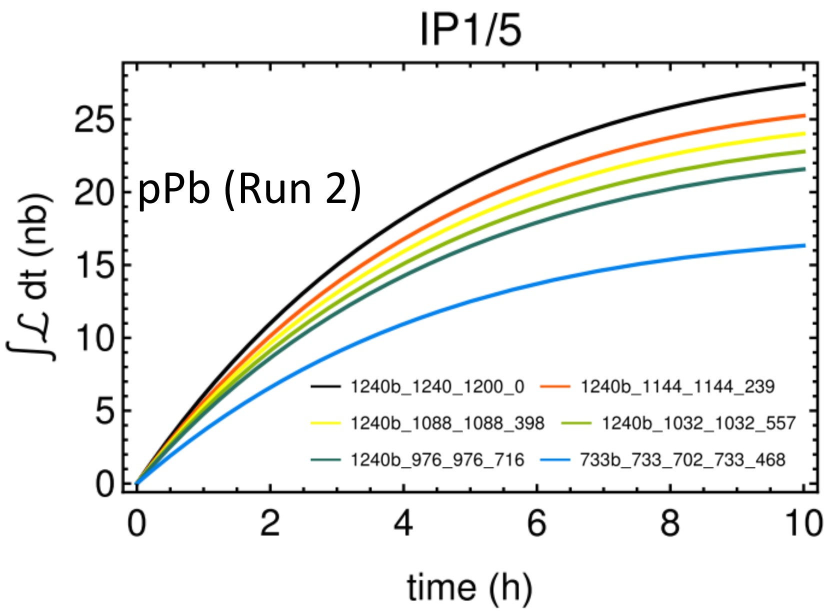
Throwing a bullet through an apple... Why?

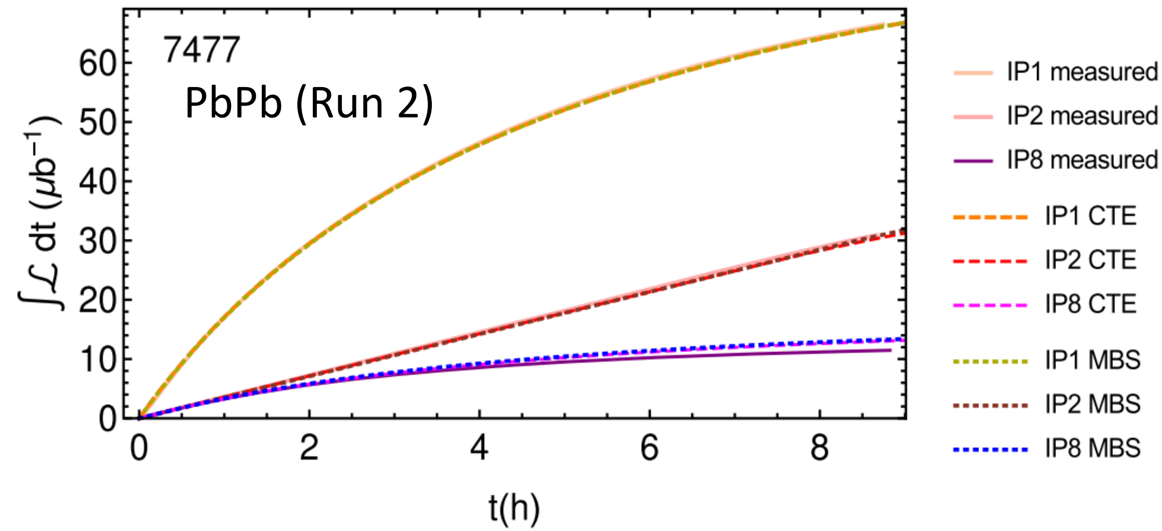


Beyond improvements from detector upgrades and increased luminosity, the YR and Snowmass efforts document the HL-LHC (&beyond) scientific program for understanding **high-density QCD**

With input from
[Workshop on the physics of HL-LHC (2017)]

HL-LHC operational scenarios for pPb and PbPb





- Included in the YR and more recently refined (CERN-ACC-2020-0011, EPJ.Plus 136 (2021) 7)
- scenarios are based on **benchmarked** models (agree remarkably 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

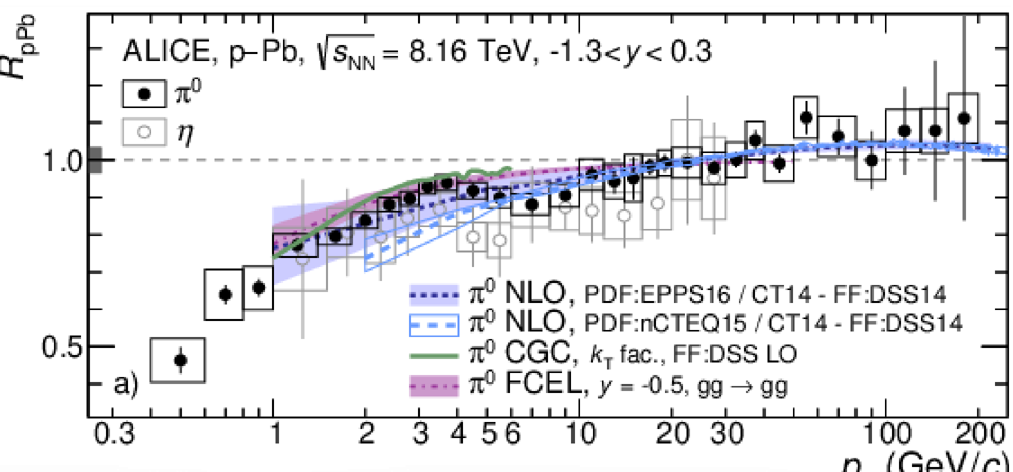
HL-LHC starts at Run 3 for heavy ions

Nuclear PDFs: constraints scarce so far

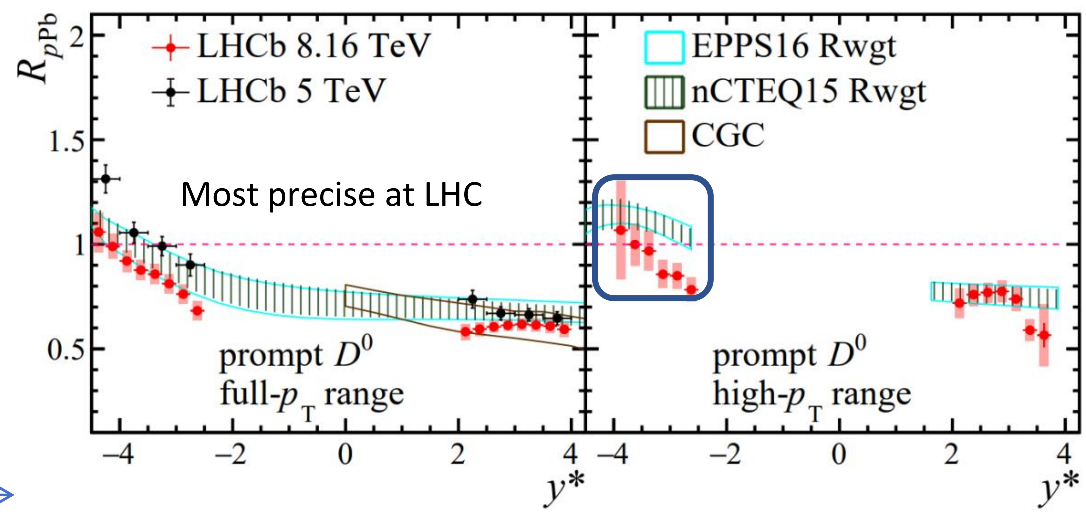
- State-of-the-art nPDFs for perturbative QCD calculations
  - Strong constraints on gluon modifications from dijets and W bosons
  - NNLO nPDF analysis to include LHC data

- Complementarity at very **low-*x*** with π^0, η, and D^0 mesons
  - **Bonus:** saturation models and energy loss constraints

PLB 827 (2022) 136943



arXiv: 2205.03936



2 orders of magnitude!

R_{pPb} stringent test of nPDFs and saturation models **in small-x region**

Key characteristics of the nPDF global fits

	KSASG20	nCTEQ15WZSIH	TUJU21	EPPS21	nNNPDF3.0
Order in α_s	NLO & NNLO	NLO	NLO & NNLO	NLO	NLO
lA NC DIS	✓	✓	✓	✓	✓
νA CC DIS	✓		✓	✓	✓
pA DY	✓	✓		✓	✓
πA DY				✓	
RHIC dAu π^0,$\pi^\pm$		✓		✓	
LHC pPb π^0,$\pi^\pm$,$K^\pm$		✓			
LHC pPb dijets				✓	✓
LHC pPb D^0				✓	✓ reweight
LHC pPb W,Z		✓	✓	✓	✓
LHC pPb γ					✓
Q, W cut in DIS	1.3, 0.0 GeV	2.0, 3.5 GeV	1.87, 3.5 GeV	1.3, 1.8 GeV	1.87, 3.5 GeV
p_T cut in D^0,h-prod.	N/A	3.0 GeV	N/A	3.0 GeV	0.0 GeV
Data points	4353	948	2410	2077	2188
Free parameters	9	19	16	24	256
Error analysis	Hessian	Hessian	Hessian	Hessian	Monte Carlo
Free-proton PDFs	CT18	~CTEQ6M	own fit	CT18A	~NNPDF4.0
Free-proton corr.	no	no	no	yes	yes
HQ treatment	FONLL	S-ACOT	FONLL	S-ACOT	FONLL
Indep. flavours	3	5	4	6	6
Reference	PRD 104, 034010	PRD 104, 094005	arXiv:2112.11904	arXiv:2112.12462	arXiv:2201.12363

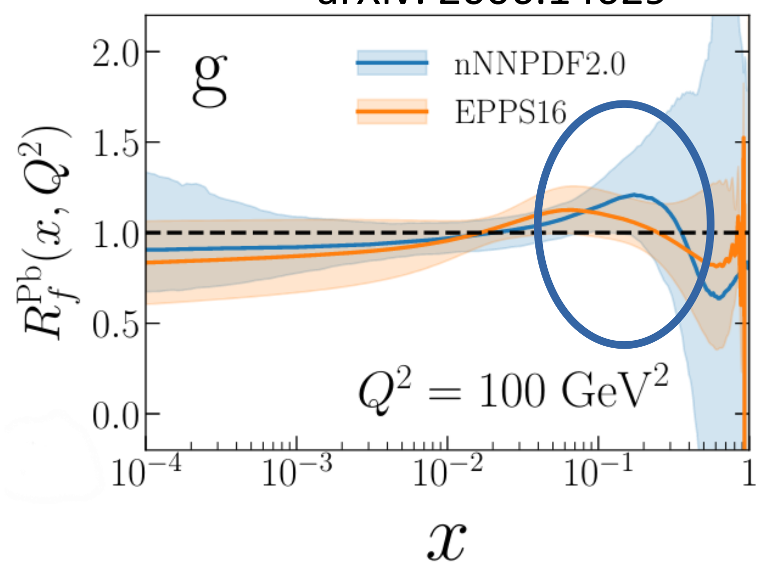
P. Paakkinen (DIS22)

Key characteristics of the nPDF global fits

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

Nuclear (most recent) PDFs	nCTEQ15	EPPS16	nNNPDF2.0 (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 **but**
- 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 for bound nucleons, e.g.,
  - the nuclear modifications of the gluon distribution
  - Measurements at small-x test non-linear QCD evolution at small-x (“parton saturation”)

In preparation of EIC, pPb @ HL-LHC provides the best input to nPDFs

Nuclear gluon PDFs: constraints scarce so far

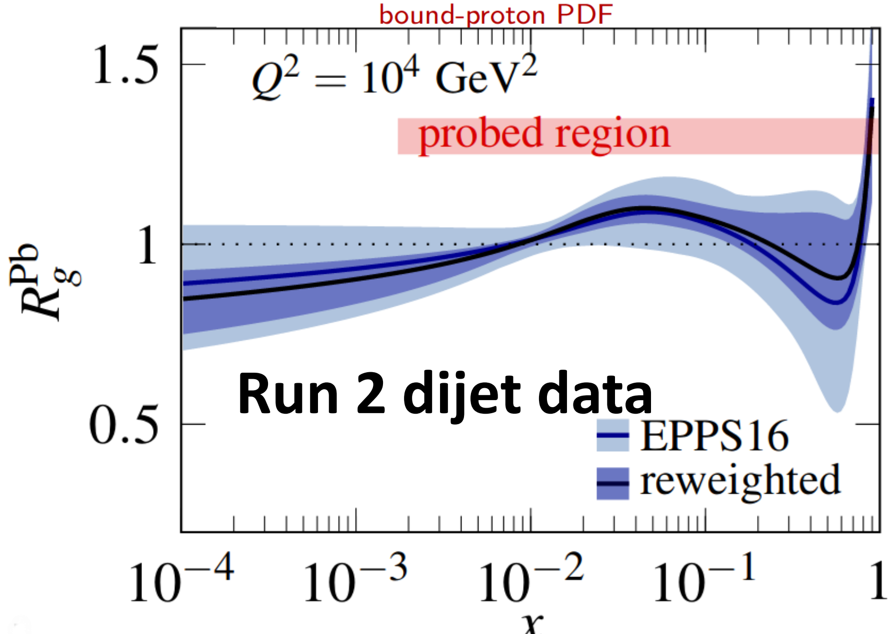
- Stringent constraints with **dijet** production
  - Enhanced **suppression** at forward y
- Significant reduction in EPPS16 uncertainties after reweighting already with Run 2 data (left plot)
- **Improved constraints** with HL-LHC data (right plot)
- Complementarity with W bosons and top quarks, and exclusive vector meson photoproduction

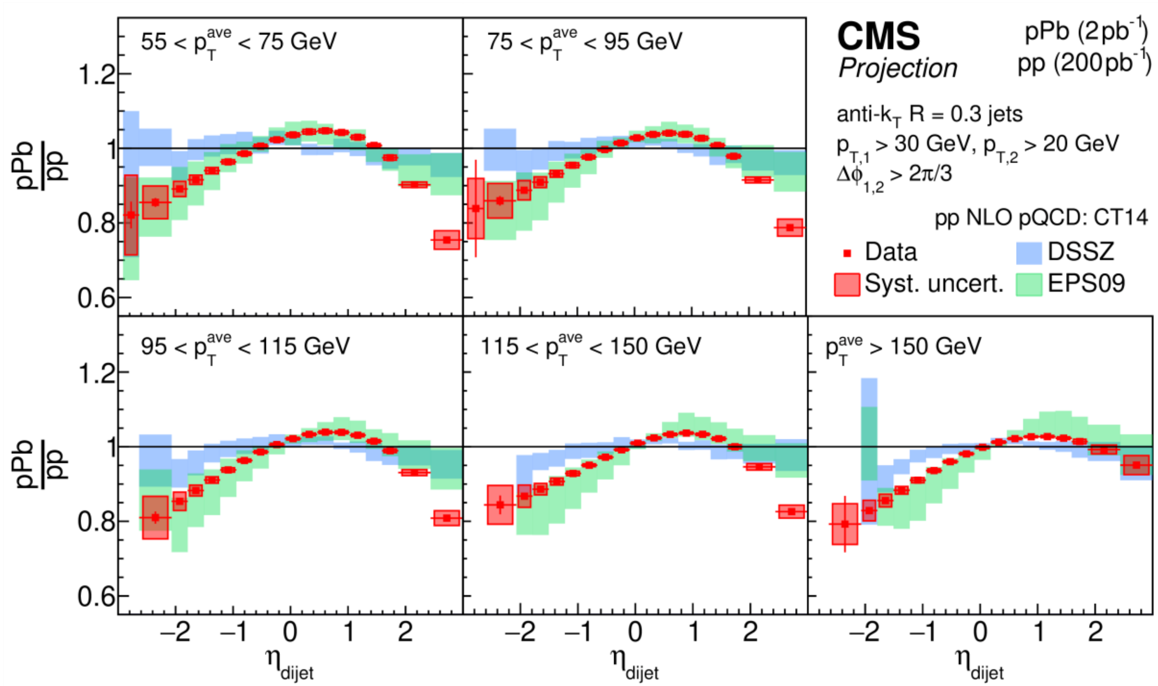
Phys. Rev. Lett. **121** (2018) 062002
EPJC **79** (2019) 511

free-proton PDF

$$R_g^{\mathrm{Pb}}(x,Q^2) = f_g^{\mathrm{p/Pb}}(x,Q^2)\ /\ f_g^{\mathrm{p}}(x,Q^2)$$

bound-proton PDF





HF transport models: ingredients

	Collisional en. loss	Radiative en. loss	Coalescence	Hydro	nPDF
TAMU	✓	✗	✓	✓	✓
LIDO	✓	✓	✓	✓	✓
PHSD	✓	✗	✓	✓	✓
DAB-MOD	✓	✓	✓	✓	✗
Catania	✓	✗	✓	✓	✓
MC@sHQ+EPOS	✓	✓	✓	✓	✓
LBT	✓	✓	✓	✓	✓
POWLANG+HTL	✓	✗	✓	✓	✓
LGR	✓	✓	✓	✓	✓

But more importantly: different **implementations** and **input parameters**.

Input from
QM22 conference (Luuk Vermunt)

Uncertainties in B_s in PbPb

arXiv: 2109.01908

Table 2: Summary of systematic uncertainties in the T_{AA}-scaled yield measurements for B^+ and B_s^0 mesons, in three centrality ranges. The measurements are performed in the B meson kinematic region given by $10 < p_T < 50\,GeV/c$ and $|y| < 2.4$. The relative uncertainty values are shown in percentage.

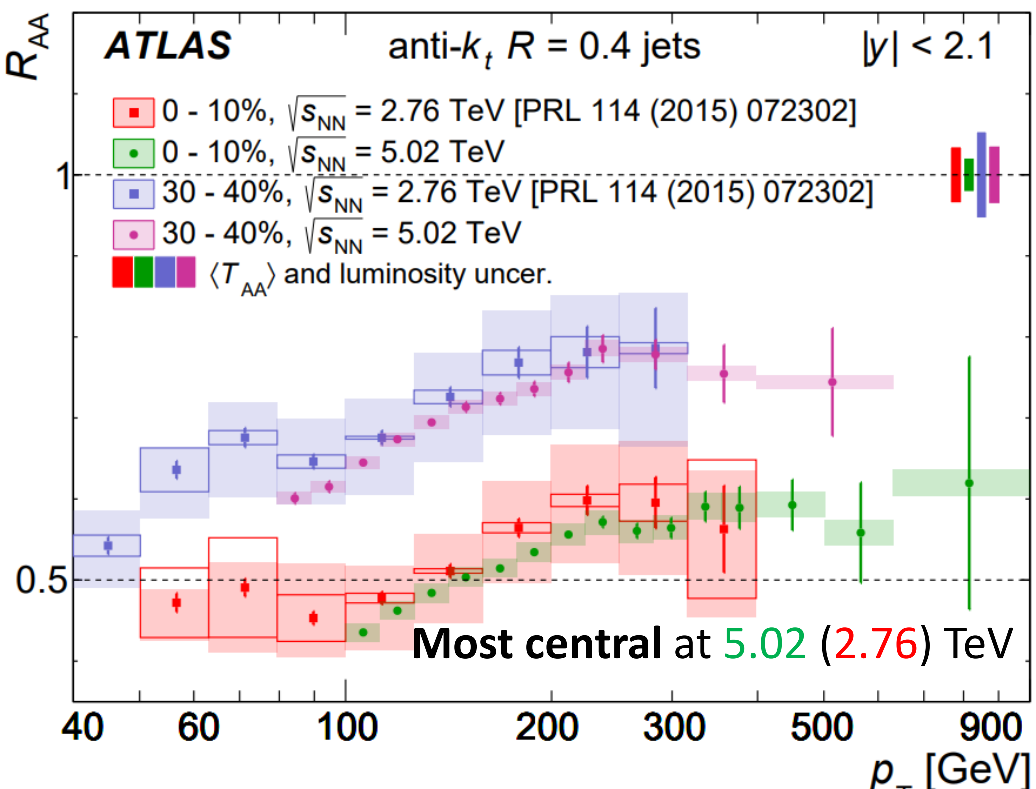
	B^+			B_s^0		
Centrality class	0–30%	30–90%	0–90%	0–30%	30–90%	0–90%
Muon efficiency	$^{+4.2}_{-3.8}$	$^{+4.1}_{-3.8}$	$^{+4.2}_{-3.8}$	$^{+5.5}_{-4.9}$	$^{+4.6}_{-4.2}$	$^{+5.3}_{-4.7}$
Data/MC agreement	13	8.0	12	3.1	3.7	3.2
MC sample size	3.2	2.2	2.4	6.6	2.3	4.4
Fit modeling	2.5	2.8	2.6	2.5	3.2	2.3
Tracking efficiency	5.0	5.0	5.0	10	10	10
T_{AA}	2.0	3.6	2.2	2.0	3.6	2.2
N_{MB}		1.3			1.3	
Branching fraction		2.9			7.5	
Total	$^{+16}_{-15}$	$^{+12}_{-12}$	$^{+15}_{-15}$	$^{+16}_{-16}$	$^{+15}_{-15}$	$^{+15}_{-15}$

Measuring jet quenching

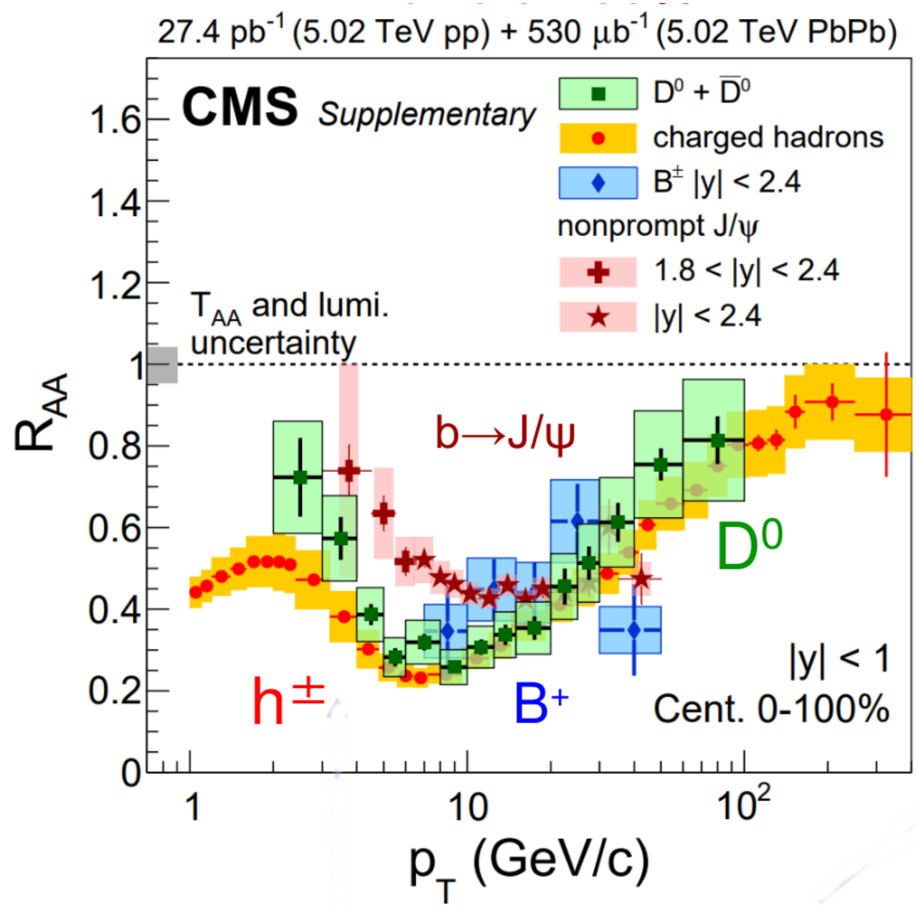
- Energy of partons is redistributed ('quenched') inside QGP
  - Experimentally seen as R_{AA} modifications of **hadrons or jets**
  - **dependent on** centrality, p_{T}, parton mass
- Unprecedented access from **low- to high-p_T**

$$R_{AA} = \frac{\text{Pb-Pb}}{\text{scaled} \otimes \text{pp}}$$

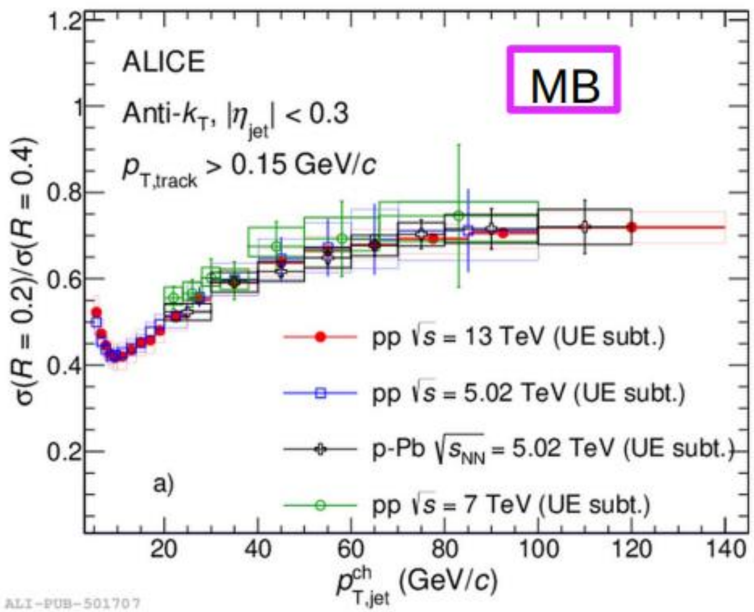
PLB 790 (2019) 108

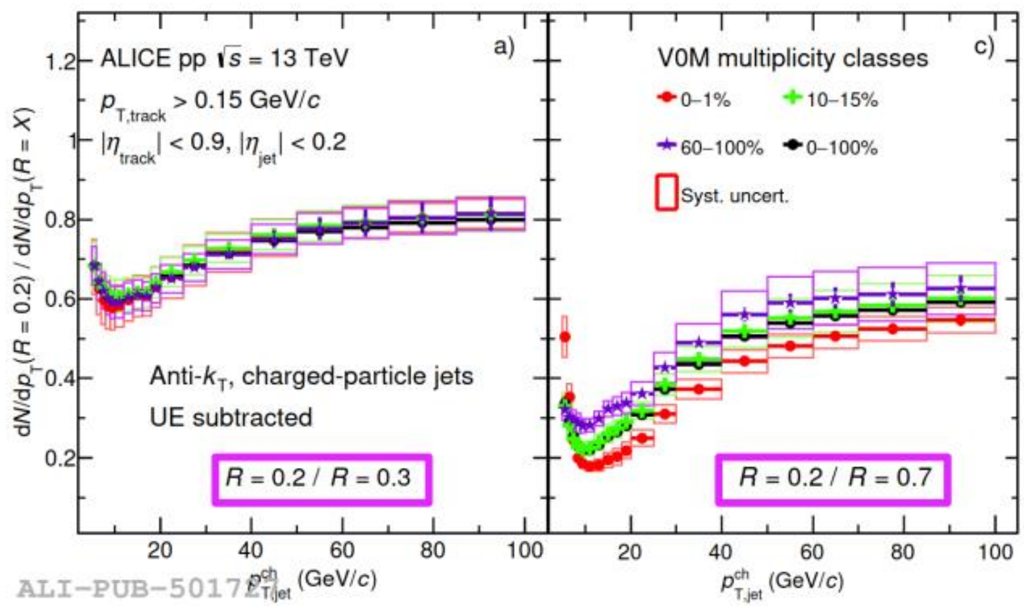


PRL 123 (2019) 022001



Ratios of jet p_T spectra with different R





New

arXiv:2202.01548

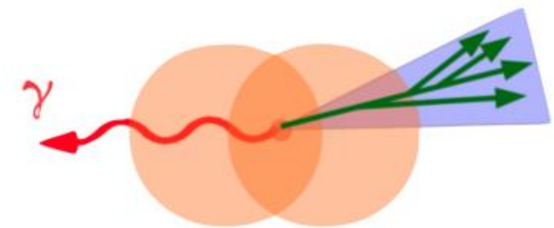
MB ratio of p_T-differential cross section spectra:

independent of $\sqrt{s}$

EA-selected ratio of spectra:
- small R : independent of EA
- large R : hint of EA dependence

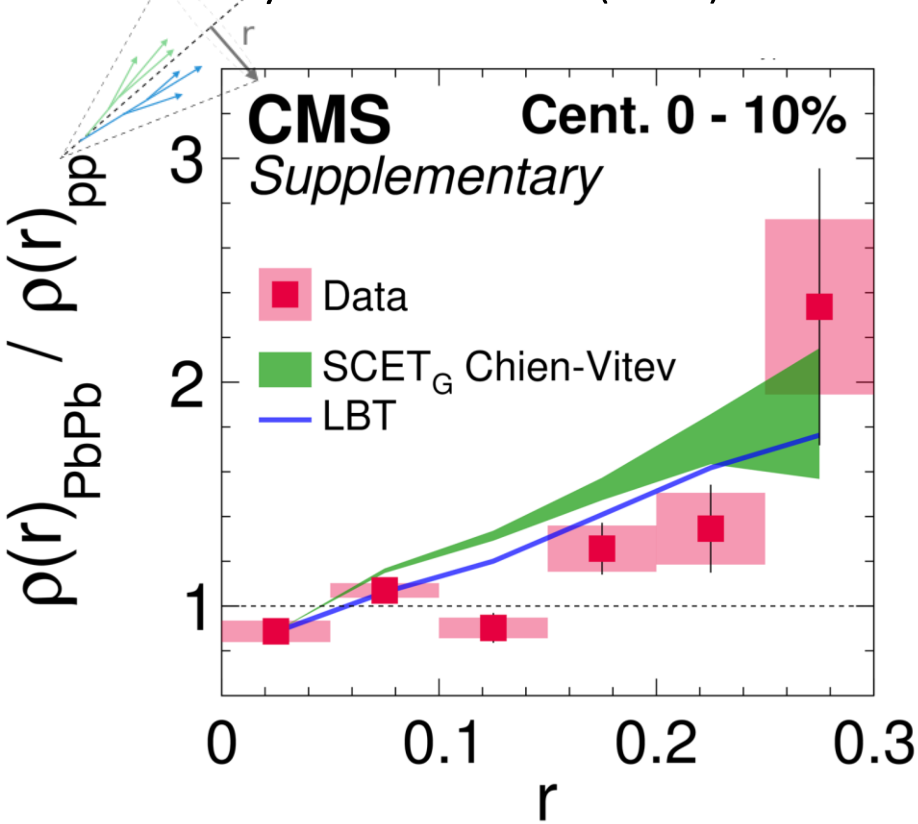
Jet shapes and fragmentation with γ+jet events

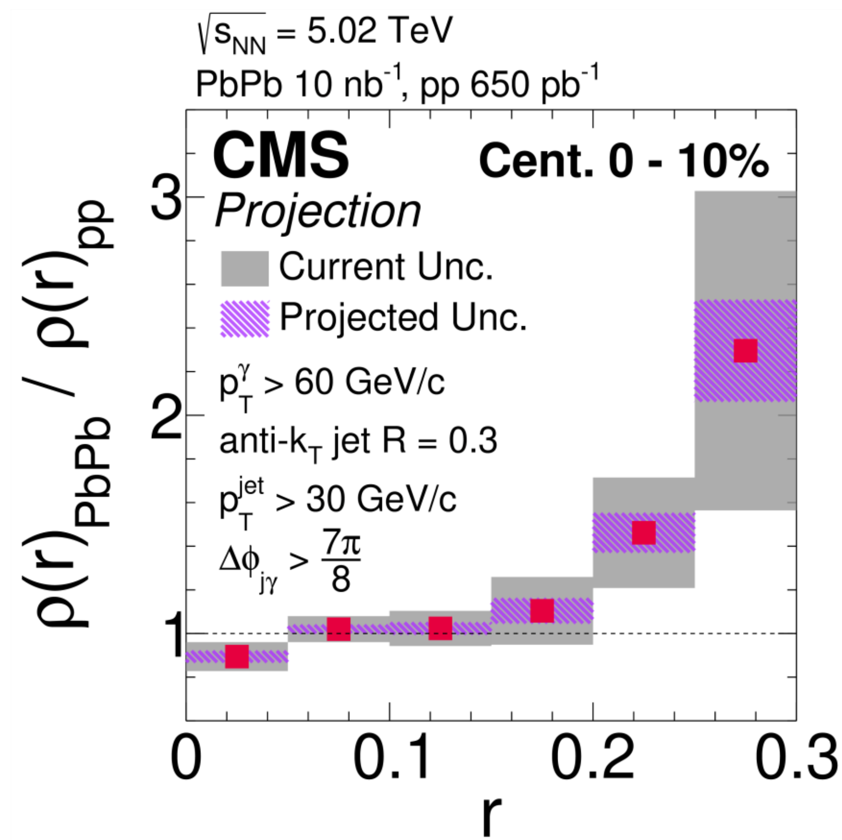
- Initial parton energy better constrained by γ p_T (quark-enriched jets)



- Jet shape
  - **Jets are wider** in PbPb than pp
- Jet fragmentation function
  - Measuring with precision medium-induced modifications

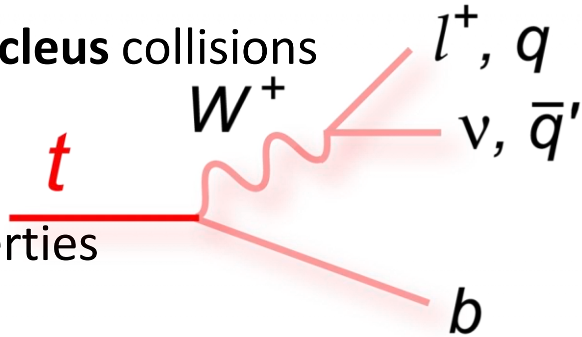
Phys. Rev. Lett. **122** (2019) 152001



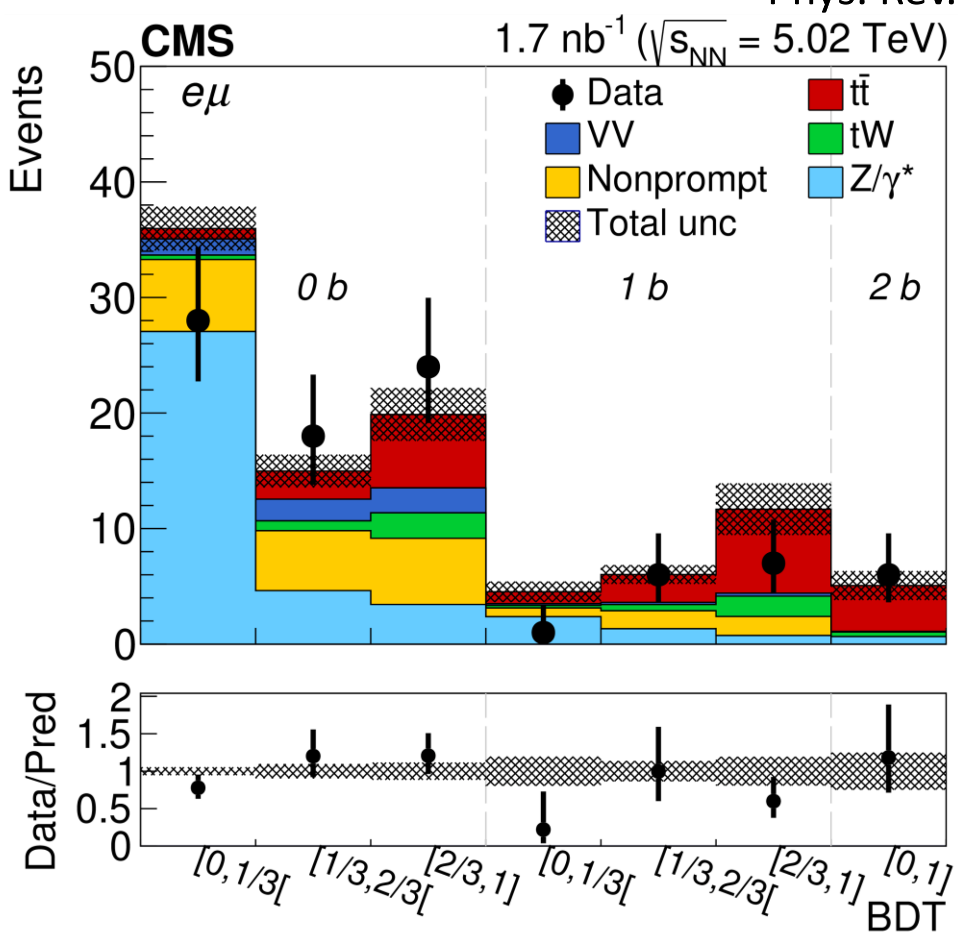


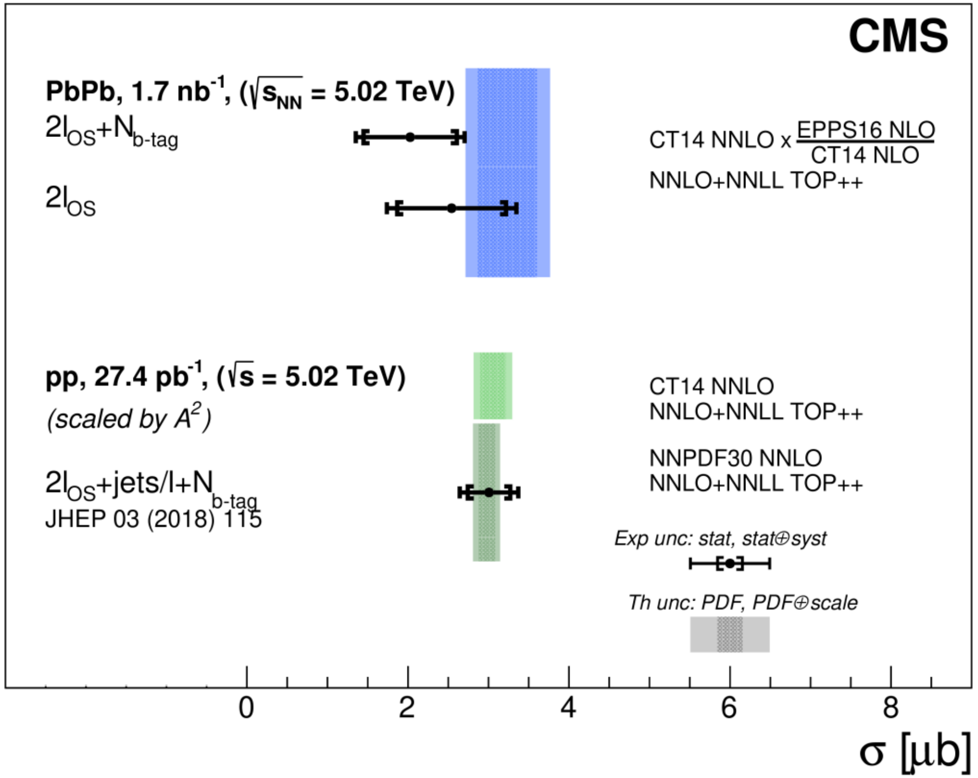
Evidence of $t\bar{t}$ cross section in PbPb

- **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



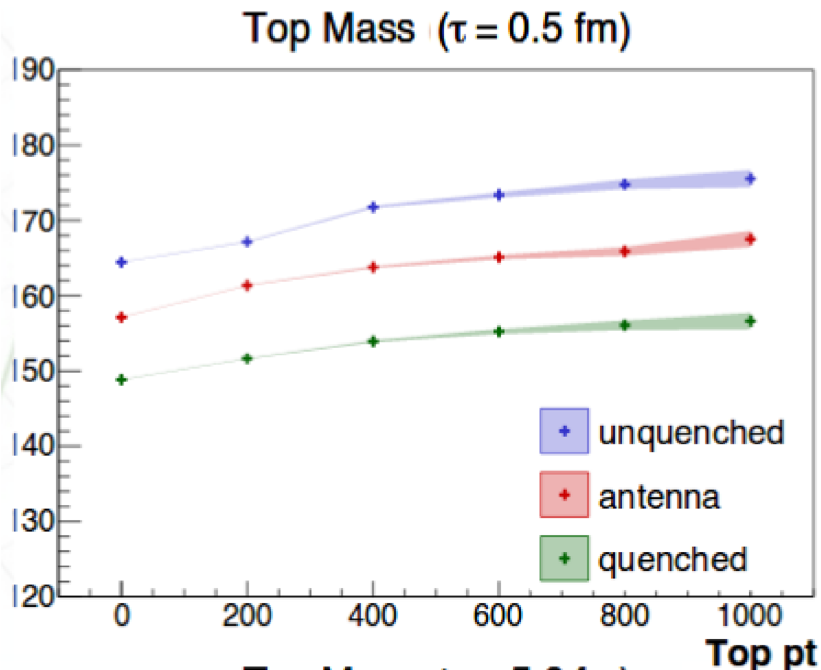
Phys. Rev. Lett. **125** (2020) 222001

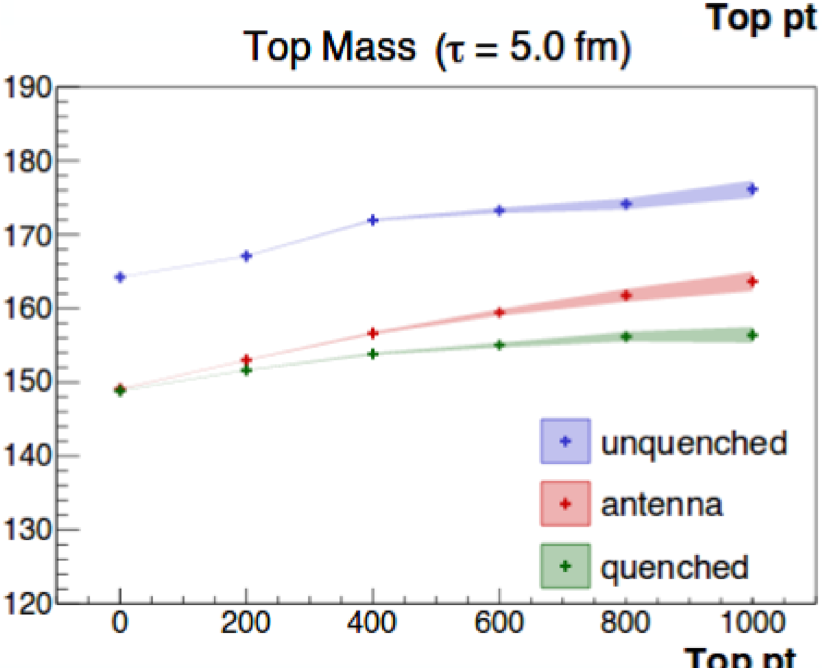


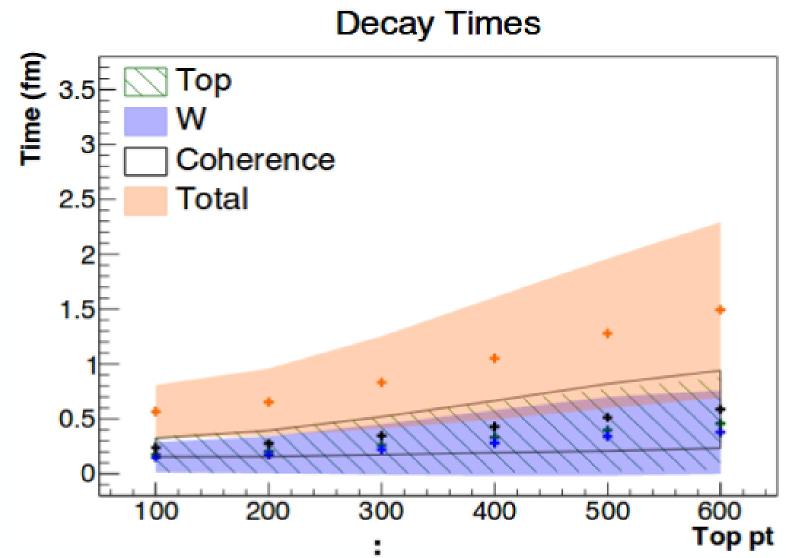


A nice heuristic idea for a yocto-chronometer !

L. Apolinário et al. 4th HIN Jet WKSH (2016)



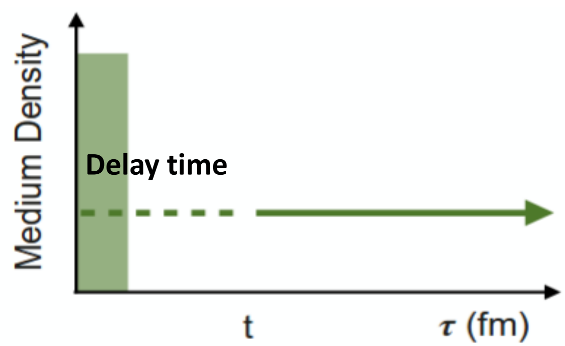


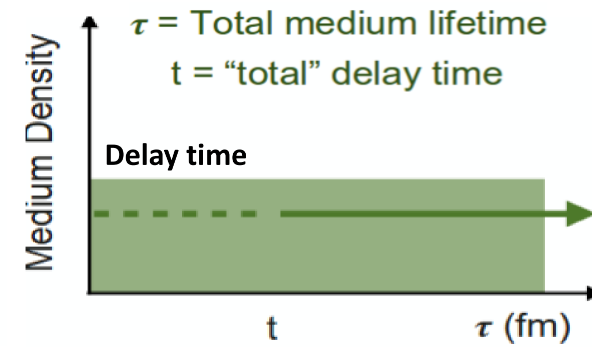


Not enough statistics…

Probe ~ [0.4; 1.2] fm

ΔE/E = [(τ-t)/τ] * 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.