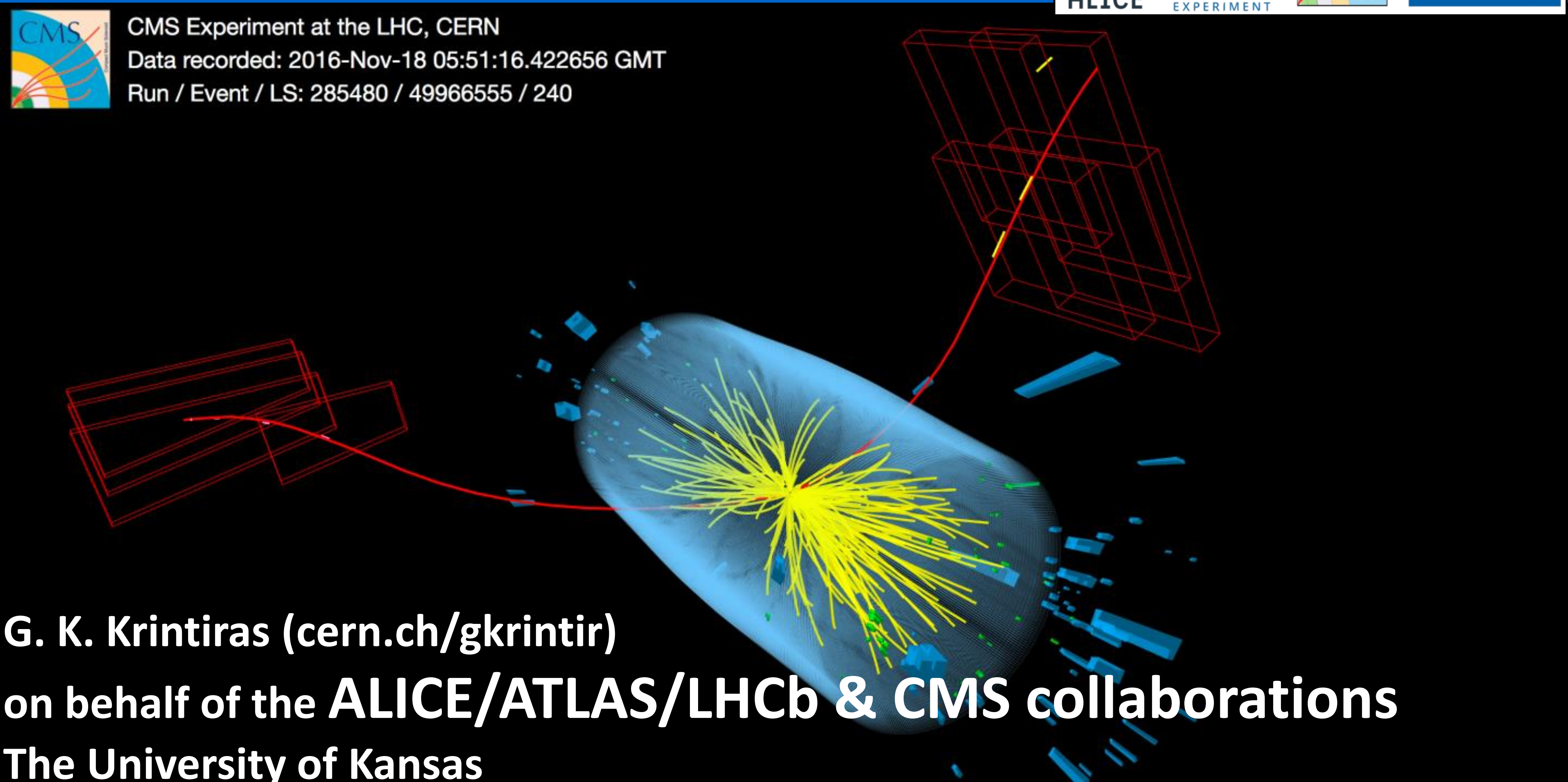
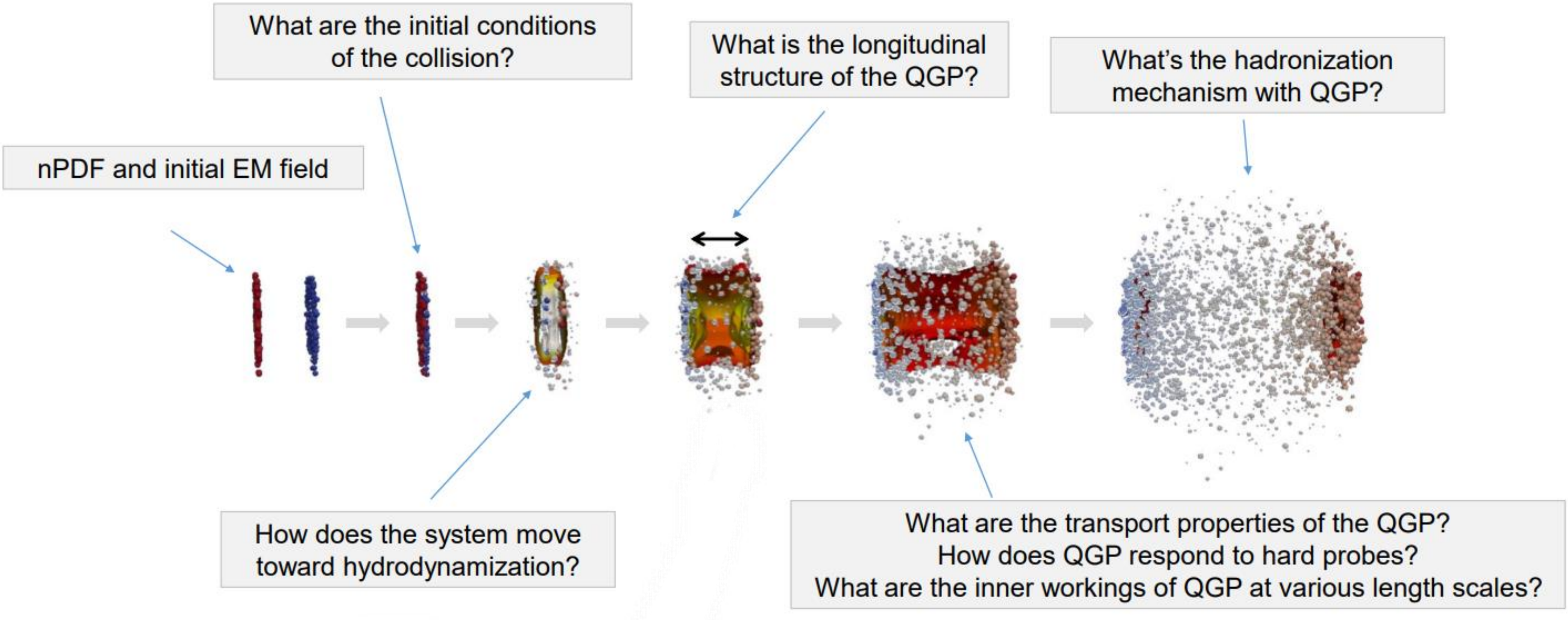
Open HF, quarkonia, Z/W in PbPb

What's the status at QCD@LHC 2022



G. K. Krintiras (cern.ch/gkrintir)
on behalf of the ALICE/ATLAS/LHCb & CMS collaborations
The University of Kansas

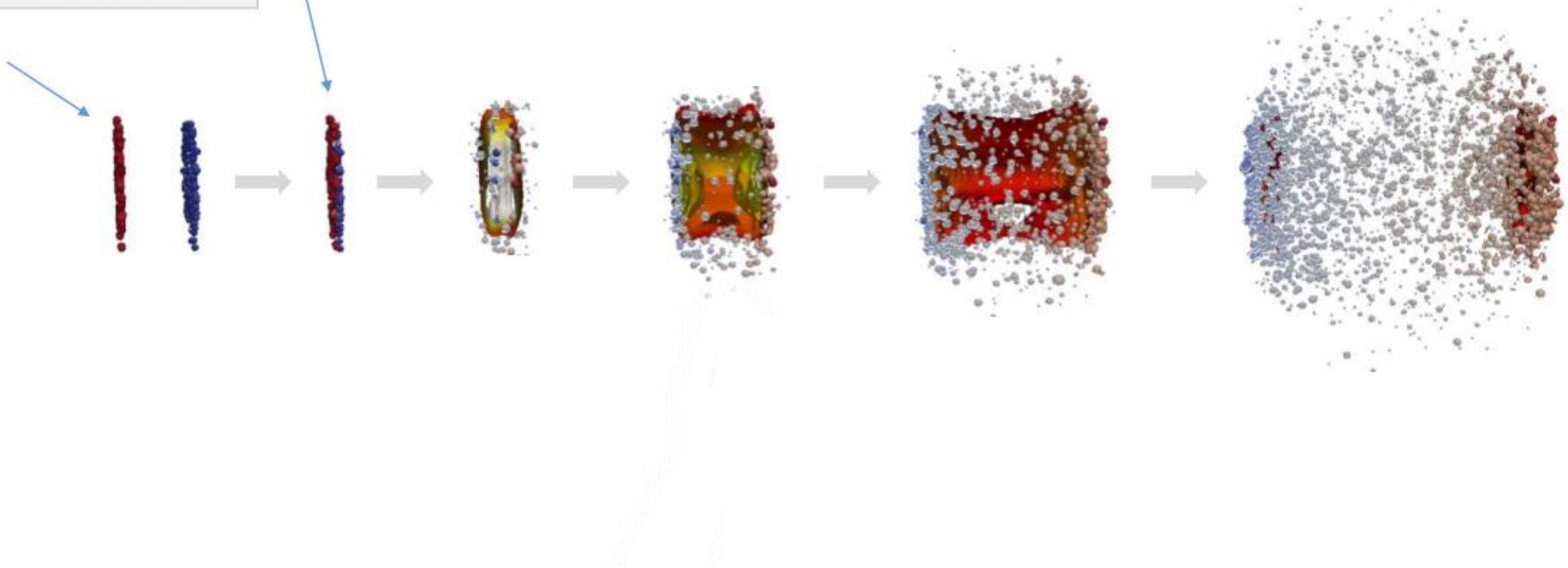
Pressing questions and open items



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

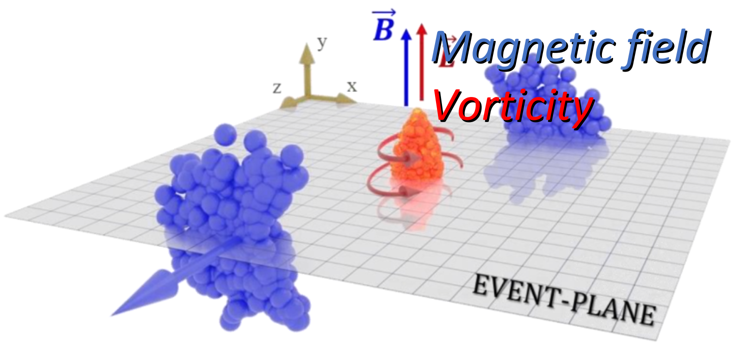
What are the initial conditions
of the collision?

nPDF and initial EM field

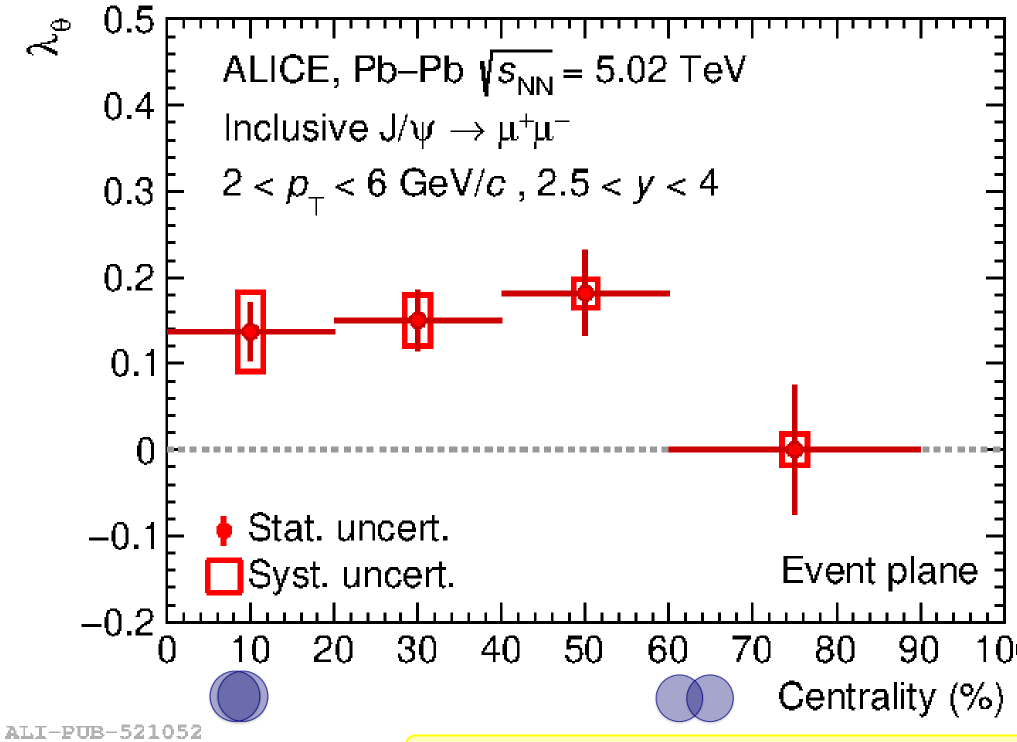


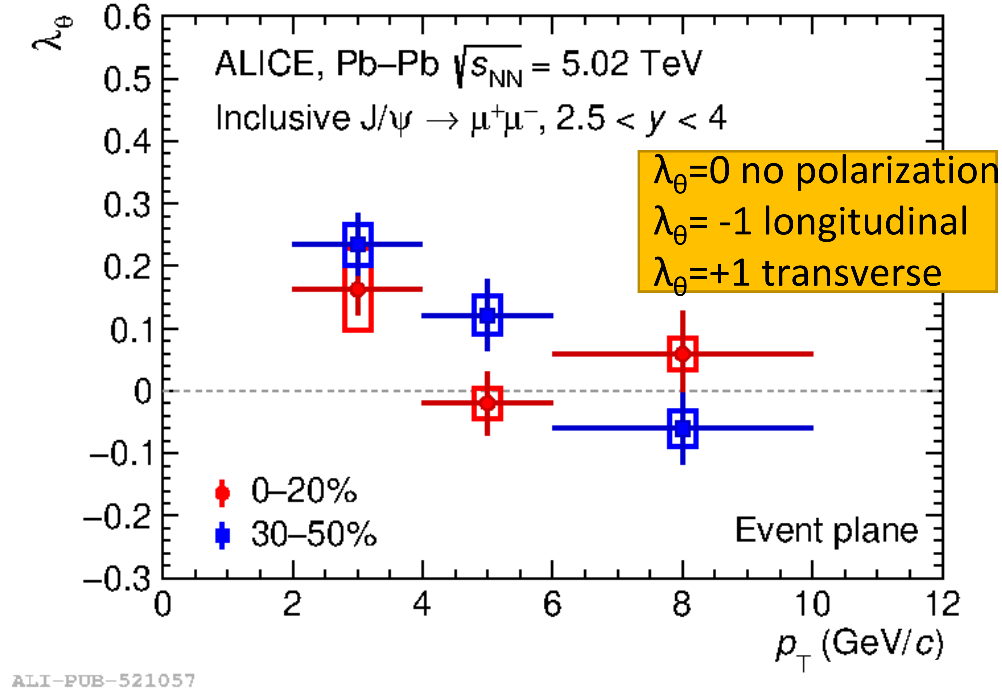
Polarization of quarkonia in PbPb

- Polarization (λ_θ): degree to which **the spin is aligned** w.r.t. a chosen direction
- Evidence of $\lambda_\theta > 0$ (w.r.t the event plane) for **inclusive J/*ψ***
  - **vanishing** λ_θ at larger p_T
  - **significant effect** up to semicentral events



arXiv: 2204.10171

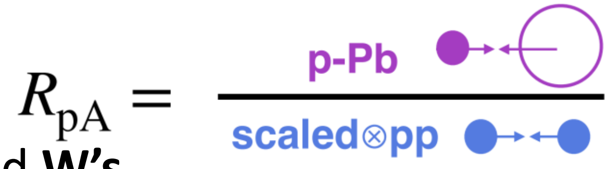




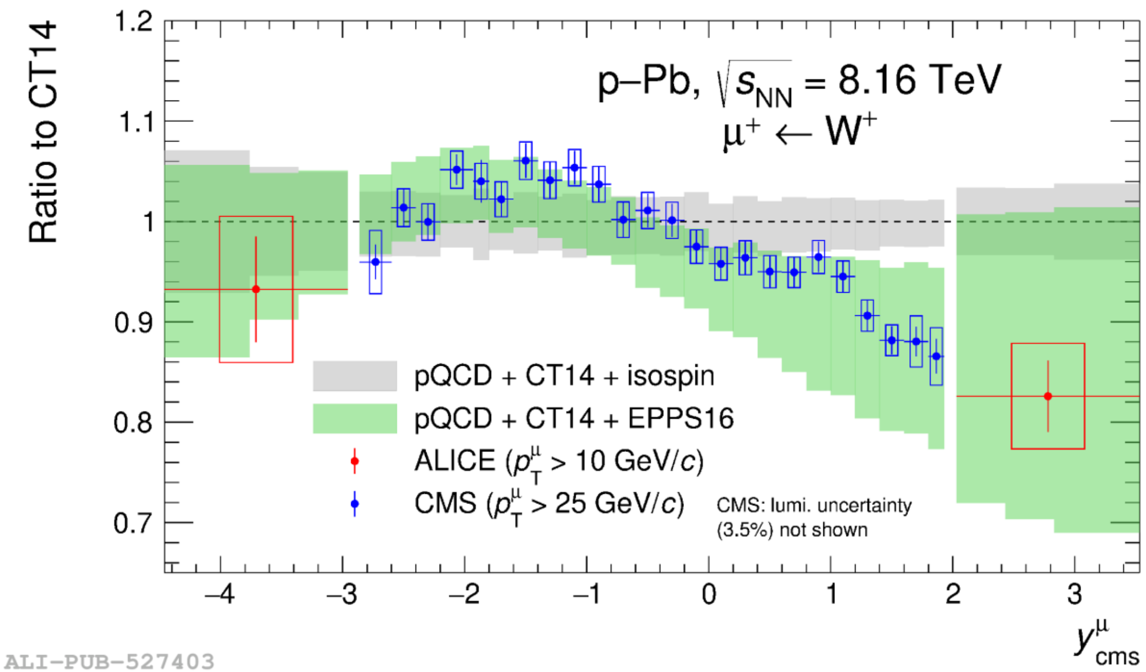
Sensitive to huge **magnetic field** and properties of a **rotating fluid**

Nuclear PDFs: constraints scarce so far

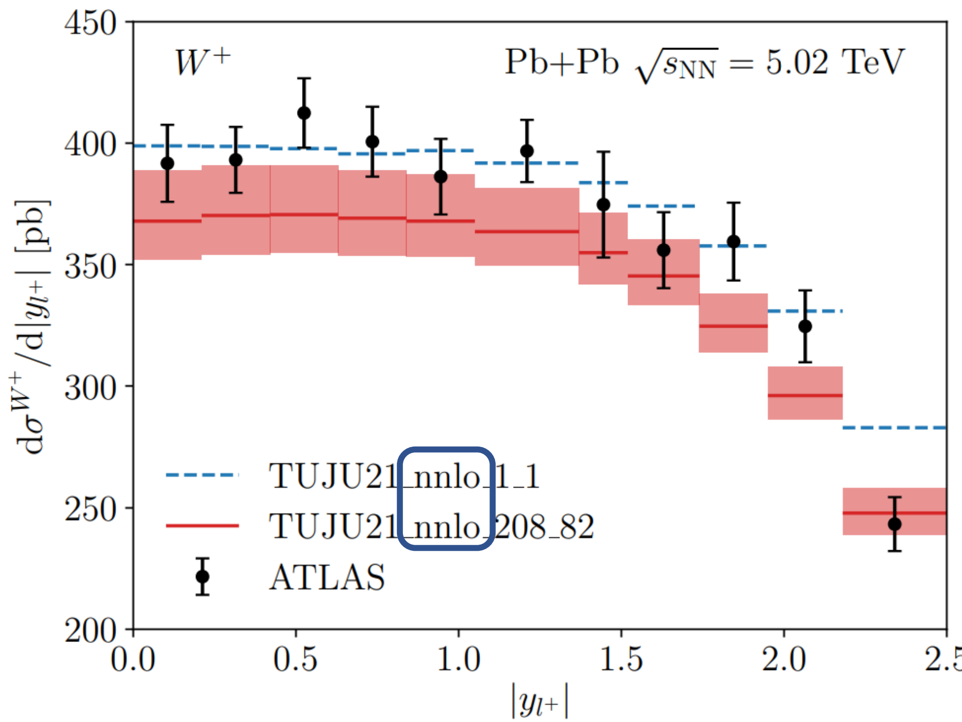
- **State-of-the-art** nPDFs for perturbative QCD calculations
- **Strong constraints** on bound nucleon modifications from dijets and **W's**
- **NNLO** nPDF analyses to include LHC data



arXiv: 2204.10640



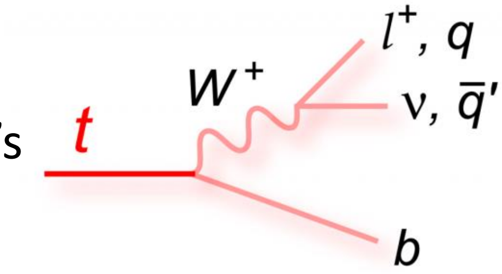
arXiv: 2112.11904



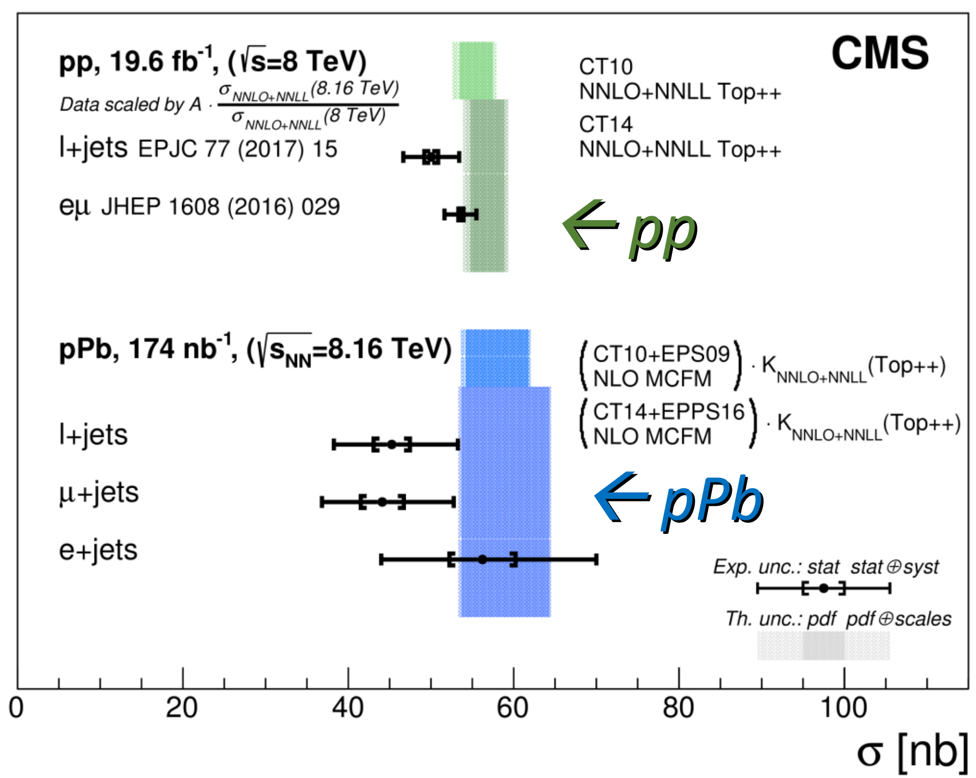
In preparation of EIC, HIC @ LHC provides the **best input to nPDFs**

Nuclear PDF: constraints scarce so far

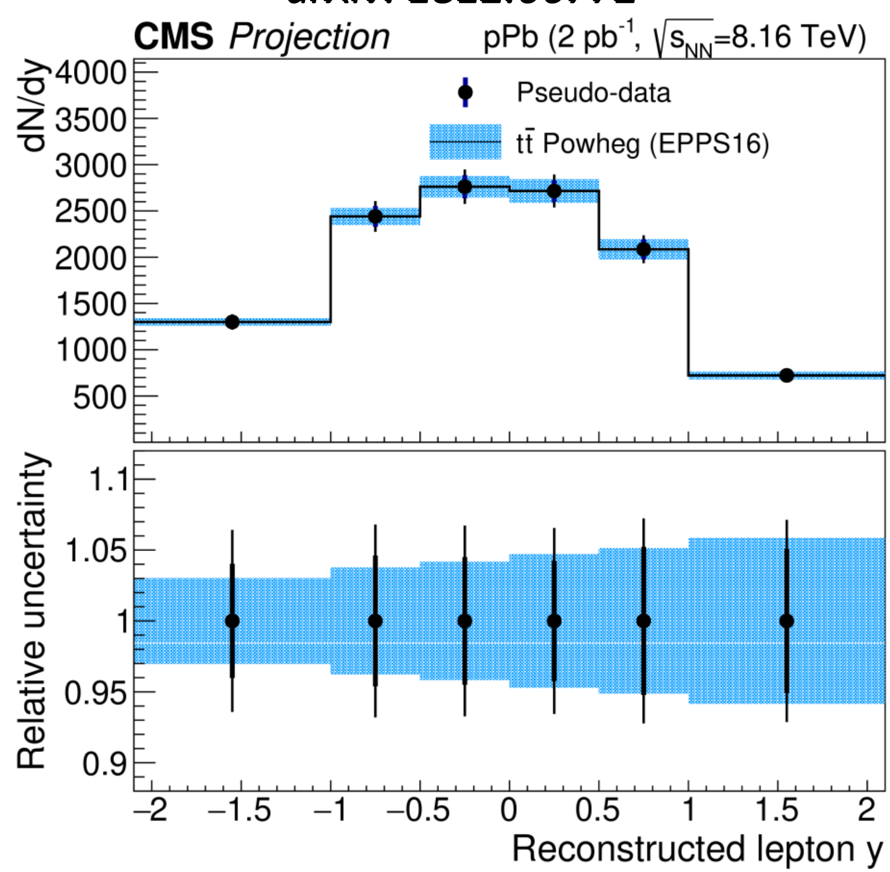
- State-of-the-art nPDFs for perturbative QCD calculations
- Strong constraints on bound nucleon modifications from dijets and W's
  - also possibly from **top quark pair production**
- NNLO nPDF analyses to include LHC data



arXiv: 1709.07411



arXiv: 1812.06772

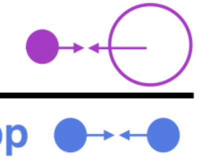


Probing the **unknown very high-*x* and Q^2** region

Nuclear PDFs: constraints scarce so far

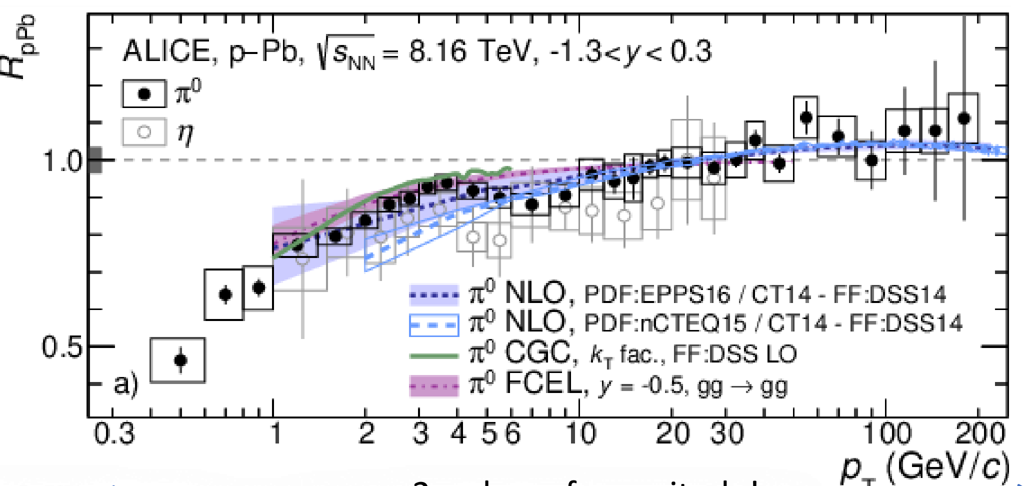
- State-of-the-art nPDFs for perturbative QCD calculations
  - Strong constraints on gluon modifications from dijets and W bosons
  - NNLO nPDF analysis to include LHC data

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

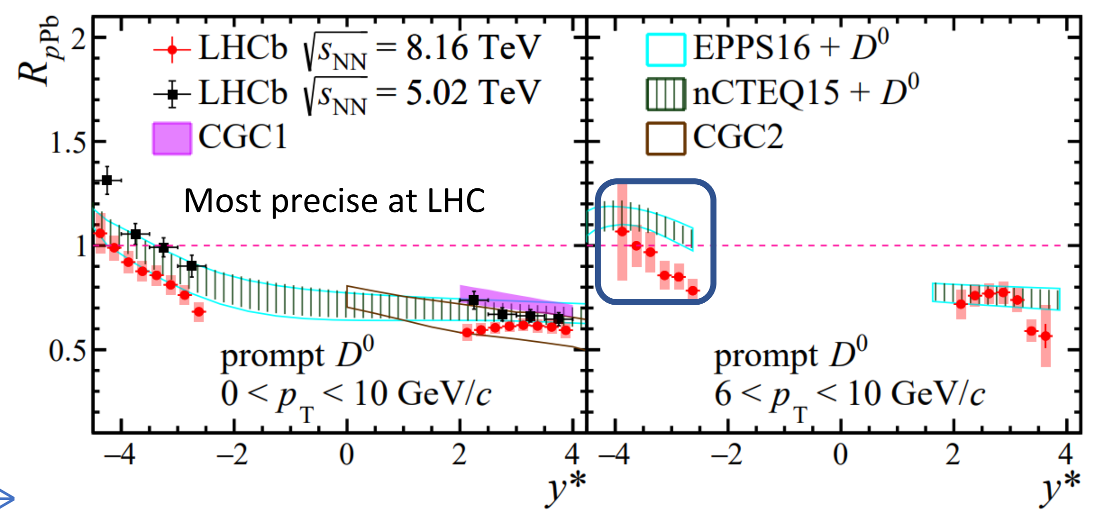


- Complementarity at very **low-*x*** with π^0, η, **and D^0 mesons**
  - **Bonus:** saturation models and energy loss constraints

arXiv: 2104.03116



arXiv: 2205.03936

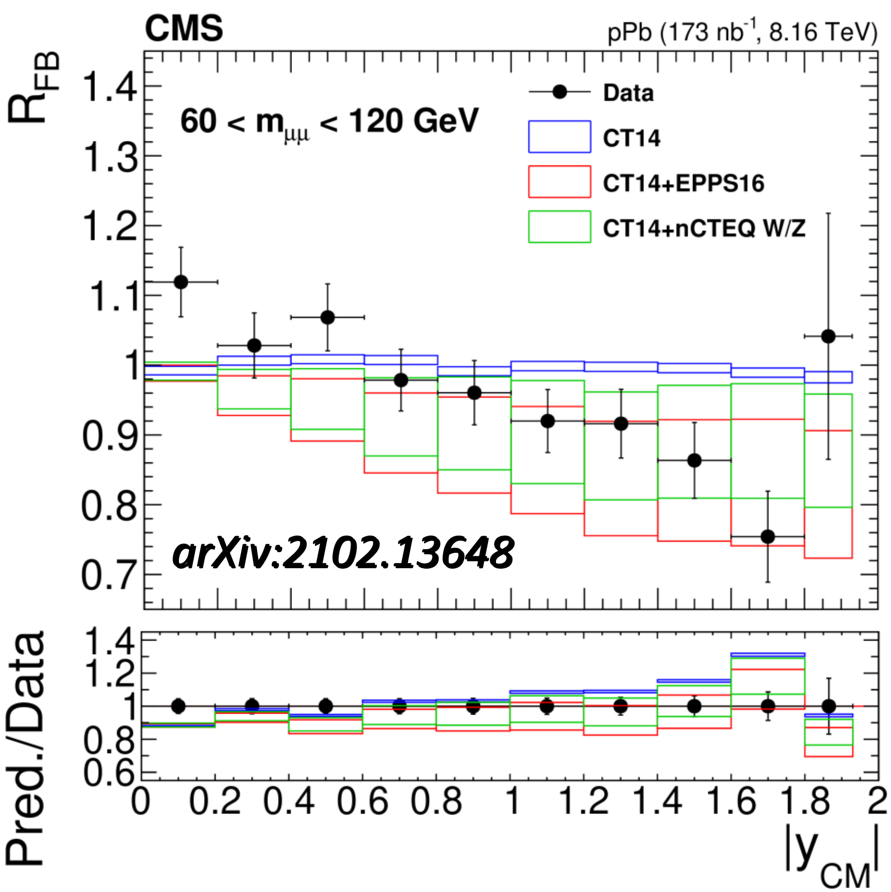


2 orders of magnitude!

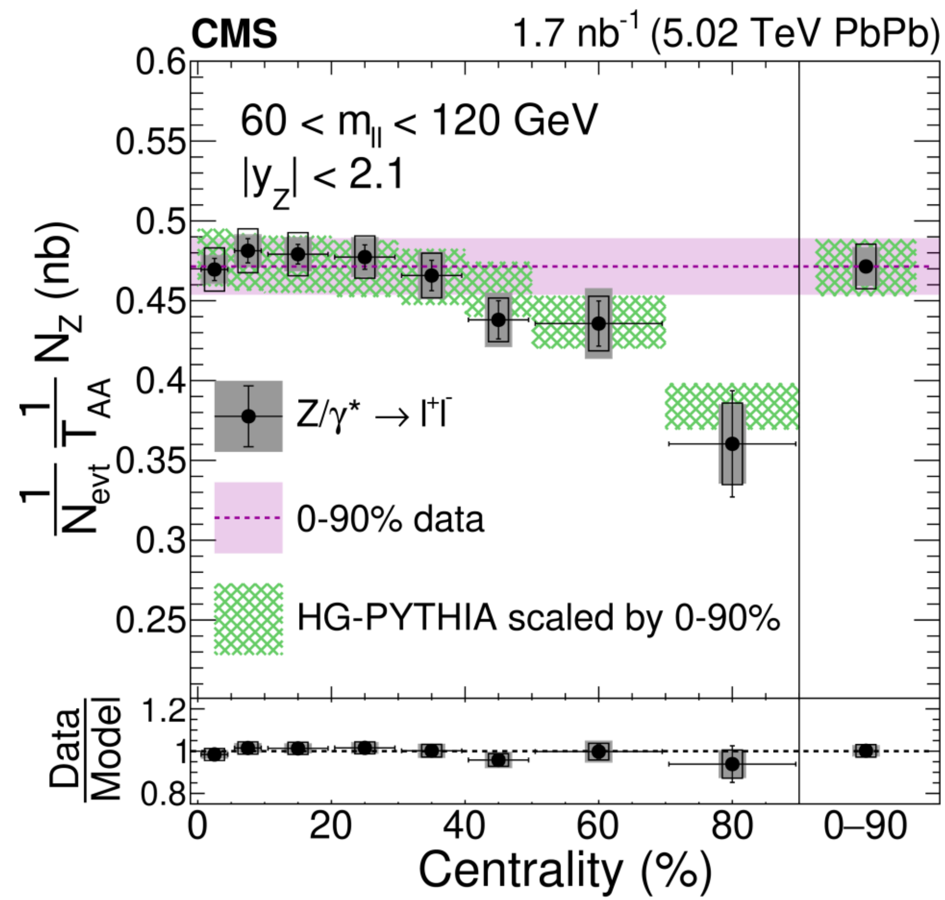
R_{pPb} stringent test of nPDFs and saturation models **in small-x region**

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 → **constraints** on the **quark nPDFs**
- High-precision in PbPb too
  - Deviation from flat centrality dependence described by **HG-PYTHIA** (like ALICE, tension with ATLAS)
  - Possibility to **determine NN luminosity** with # of Z boson **counts**



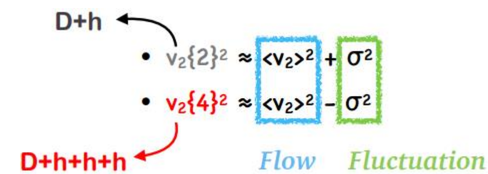
arXiv: 2103.14089



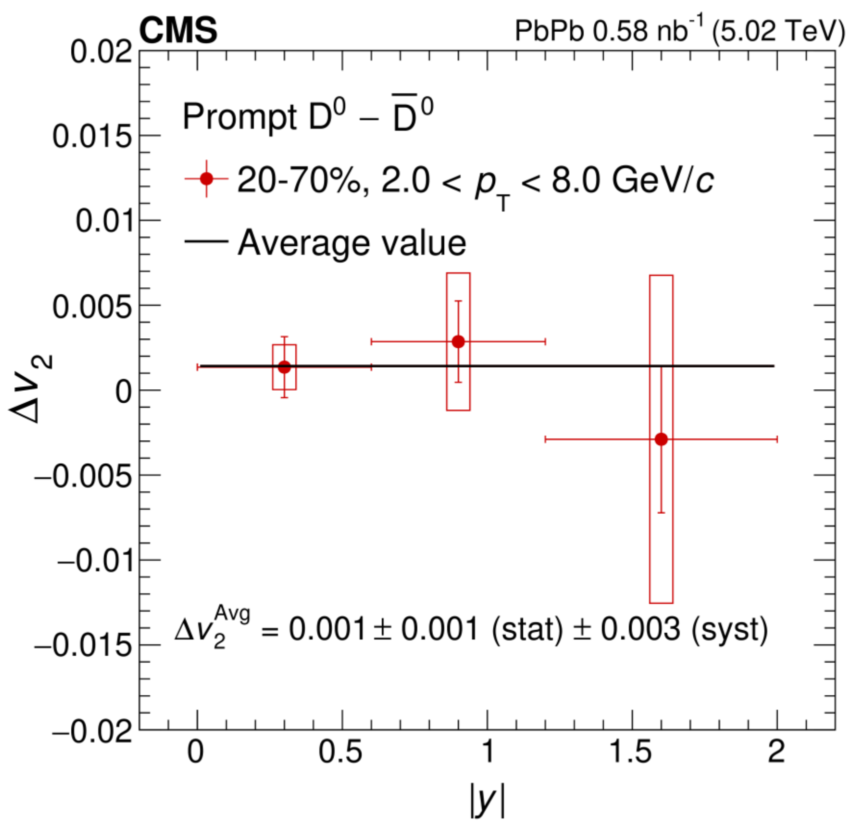
Z boson production could even provide a **new normalization method**!

Charm quark dynamics via (multi)particle correlations

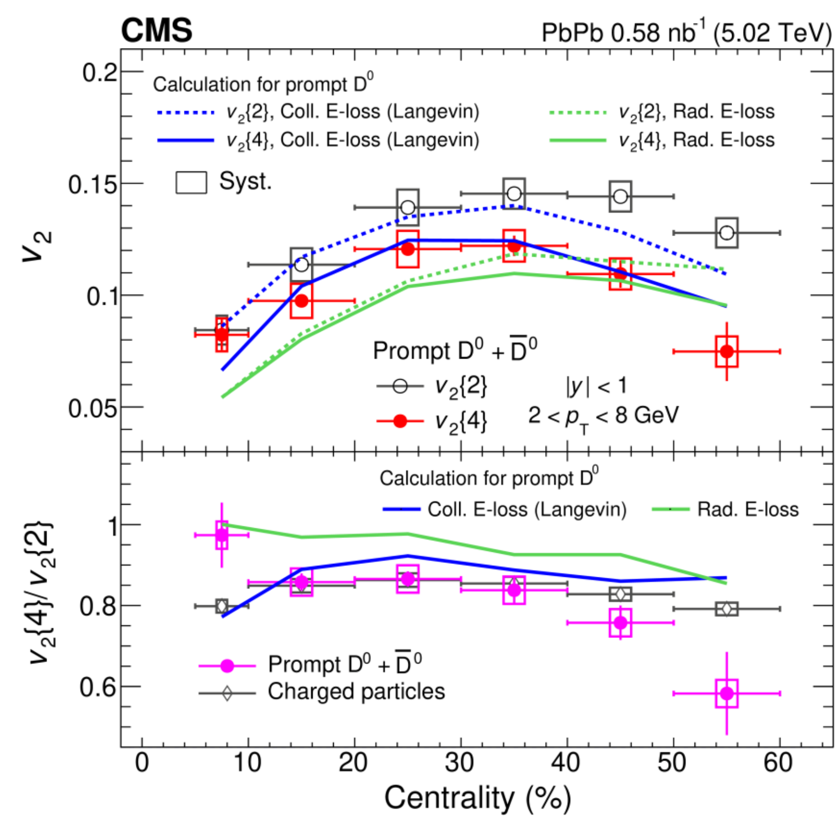
- **First** Δv_2 measurement for D^0 → sensitive to the strong created EM fields
  - **no EM induced charge-dependent splitting** in v_2
- First **high-precision $v_2\{4\}/ v_2\{2\}$** also for D^0 → check whether fluctuations on v_2 are **universal**
  - that's the case modulo very central (peripheral)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



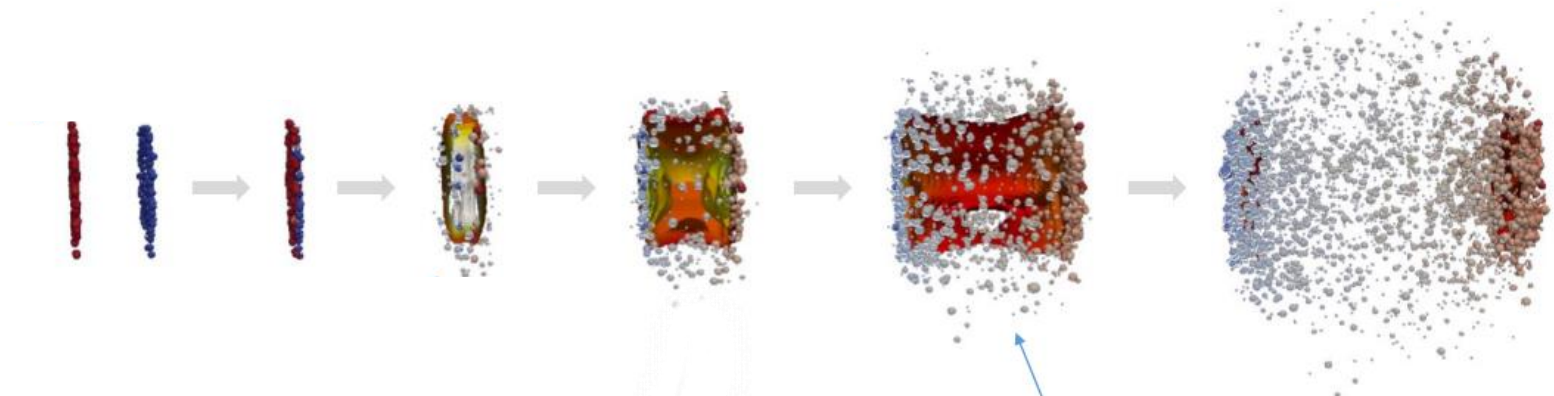
arXiv: 2009.12628



arXiv: 2112.12236



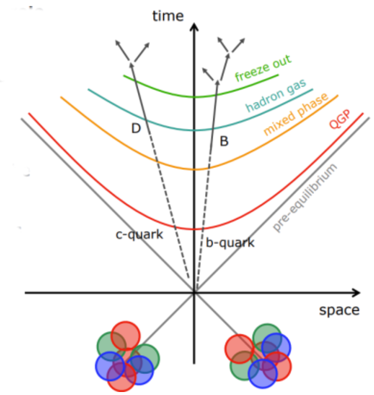
Resolving v_2 event-by-event fluctuations with **identified particle $v_2\{4\}$**



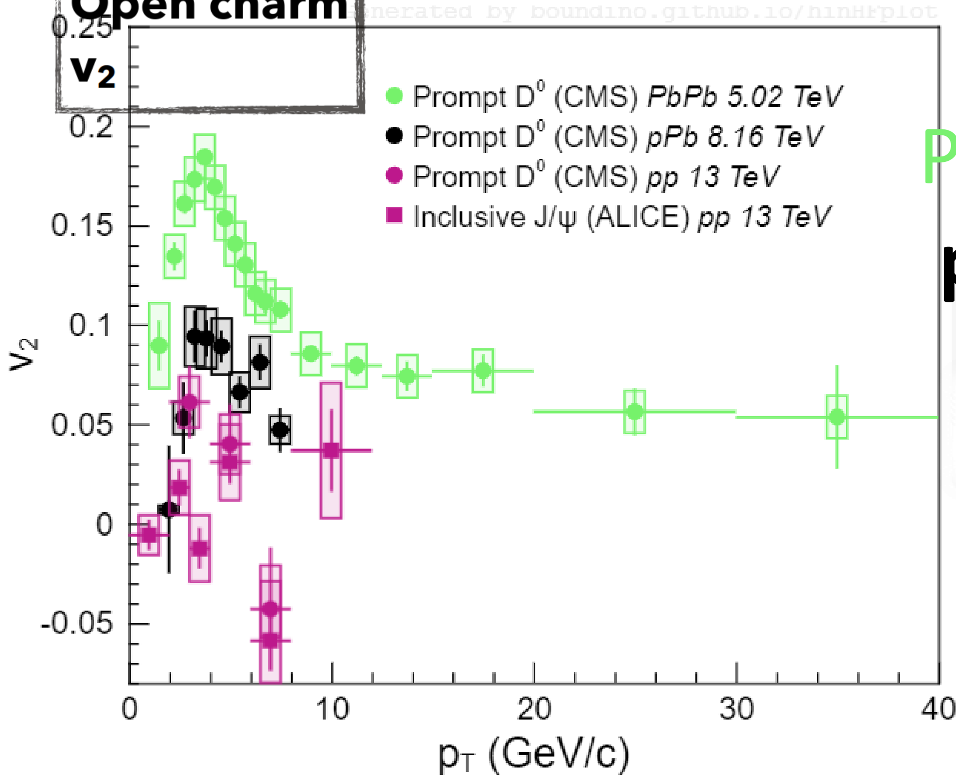
What are the transport properties of the QGP?
How does QGP respond to hard probes?
What are the inner workings of QGP at various length scales?

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
  - HF probes help to answer **whether QGP is formed** in high-multiplicity pPb/pp



Open charm



- PLB 816 (2021) 136253
- PRL 121 (2018) 082301
- PLB 813 (2021) 136036
- ALICE Preliminary

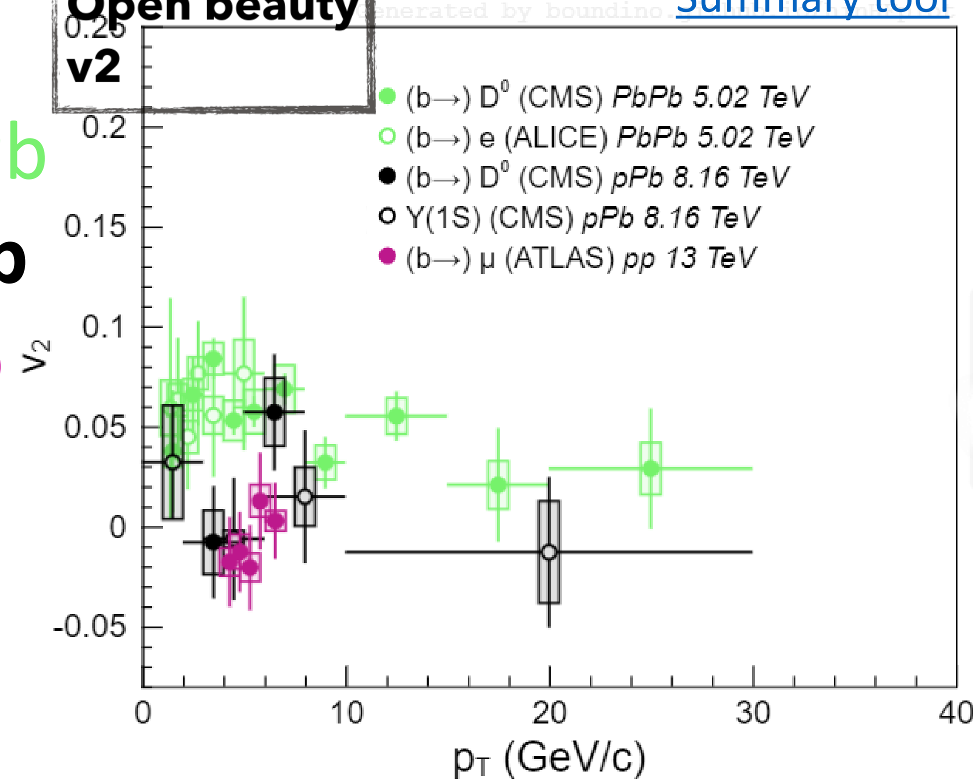
PbPb

pPb

pp

Open beauty

[Summary tool]

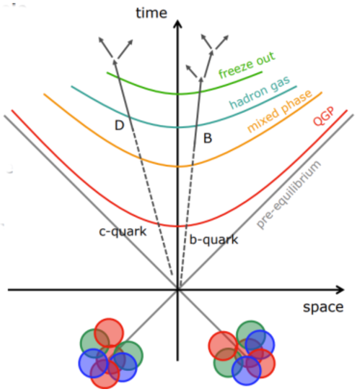


- CMS-PAS-HIN-21-003
- PRL 126 (2021) 162001
- PLB 813 (2021) 136036
- CMS-PAS-HIN-21-001
- PRL 124 (2020) 082301

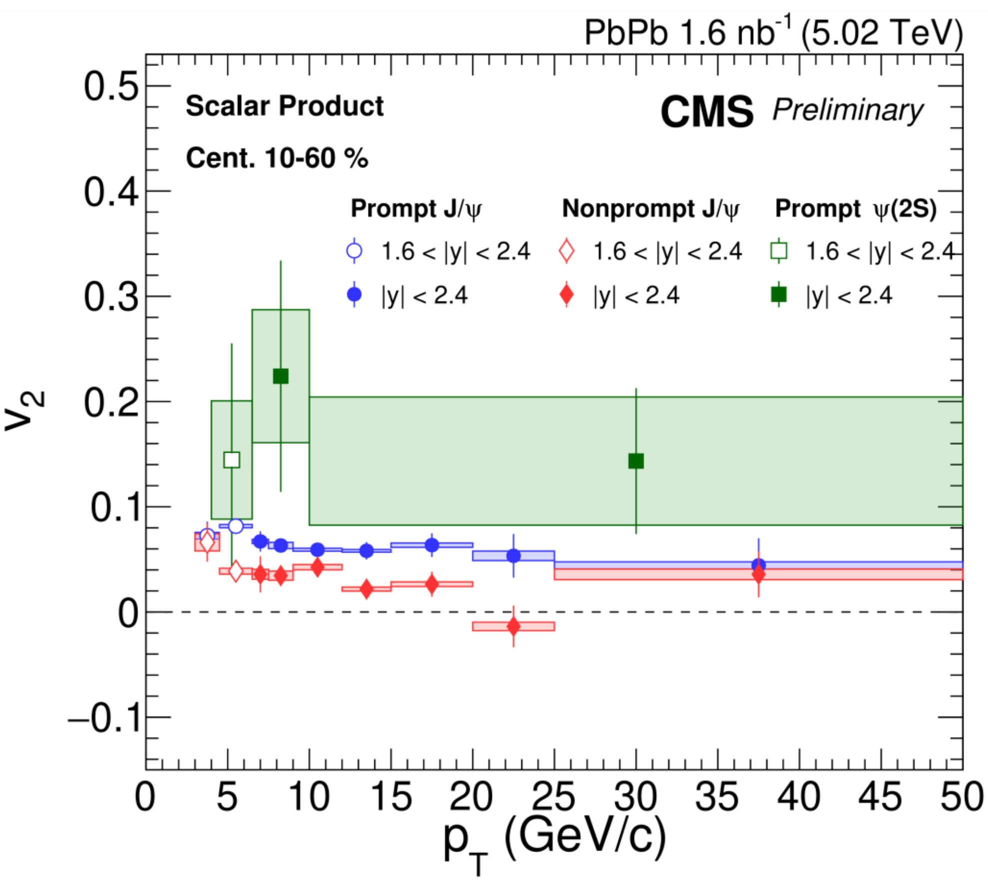
Novel input to the description of heavy-quark transport and energy loss

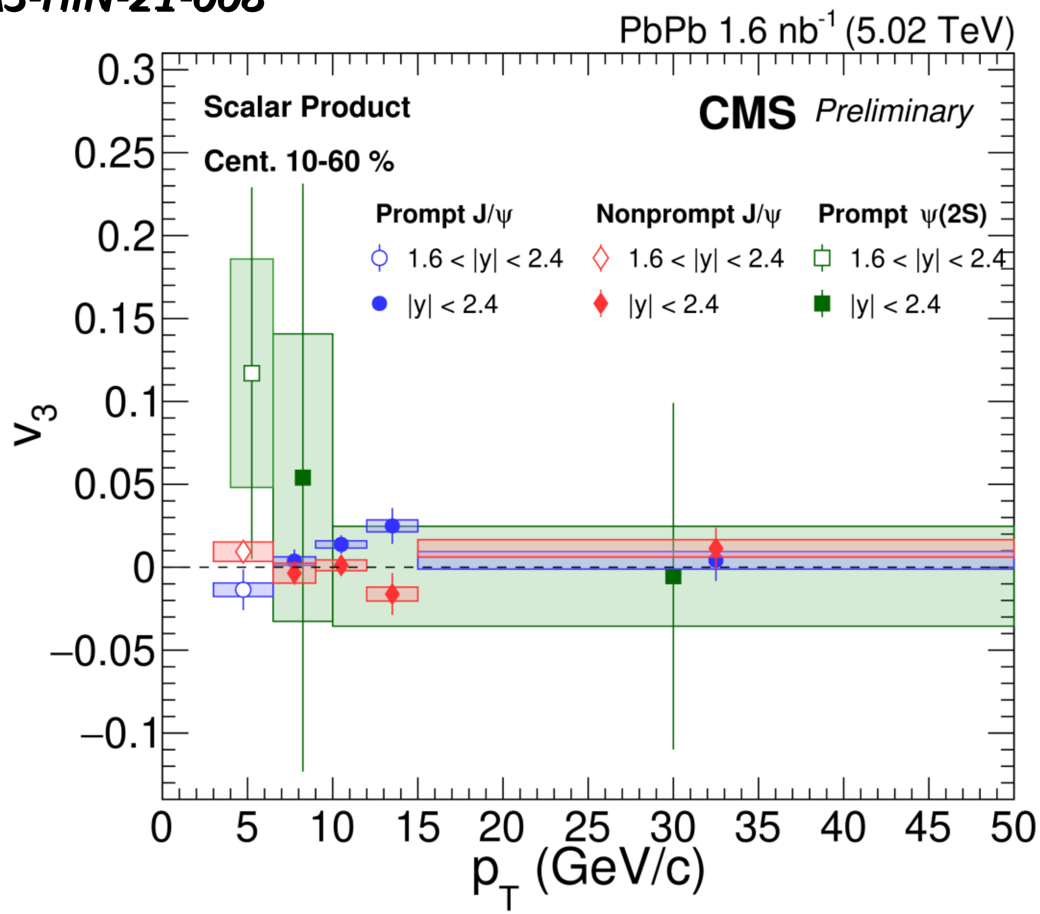
v_2 and v_3 of charmonia in PbPb

- There is finite charm anisotropy... **up to high p_T** → path length dependence
  - v_2 of prompt ψ(2S) **larger than** prompt J/ψ v_2 up to high p_T
  - so different levels of **recombination** for J/ψ and ψ(2S)?
- The measured **v_3 consistent with zero**
  - **not (yet?) sensitive** to event-by-event fluctuations



CMS-PAS-HIN-21-008

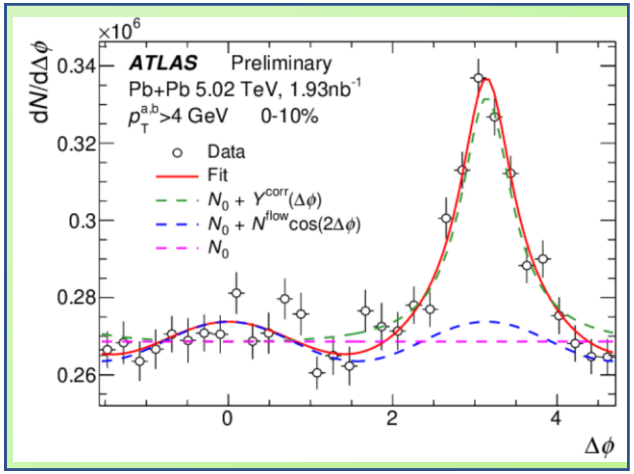




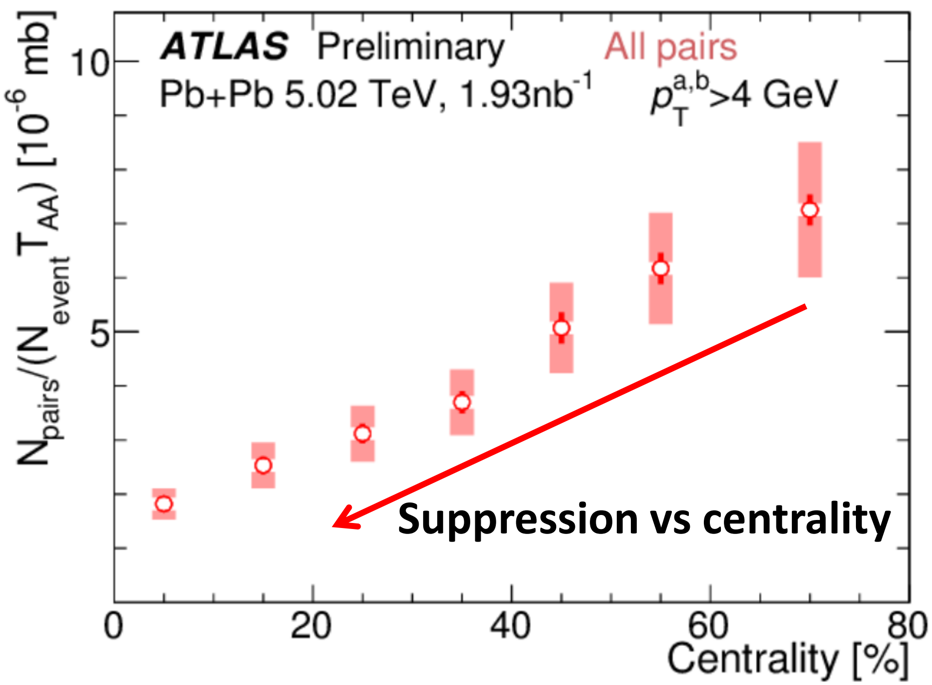
Azimuthal anisotropy for **prompt ψ(2S)** mesons is reported for the first time

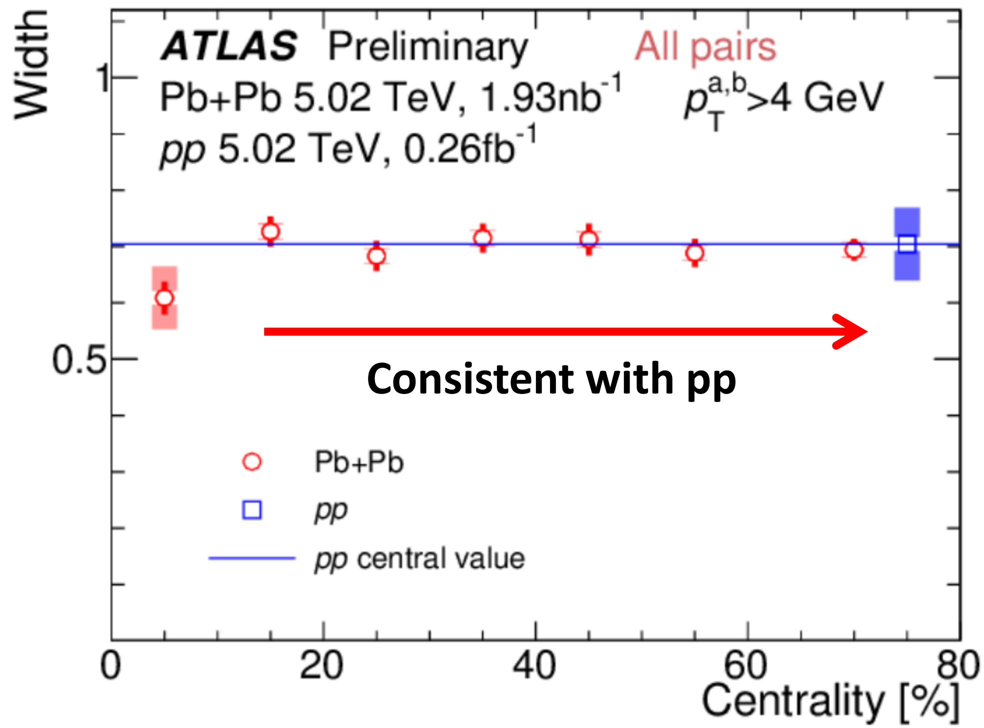
Azimuthal correlations of muon pairs from HF decays

- Can shed light on the **HF energy-loss mechanism**(s)
- opposite- vs same-sign muons: (in principle) ccbar vs bbar
- Observables: **HF yield** and **width** of away-side correlation
- **yield suppression** toward central collisions.
- width quite independent of centrality and **consistent with pp**



ATLAS-CONF-2022-022

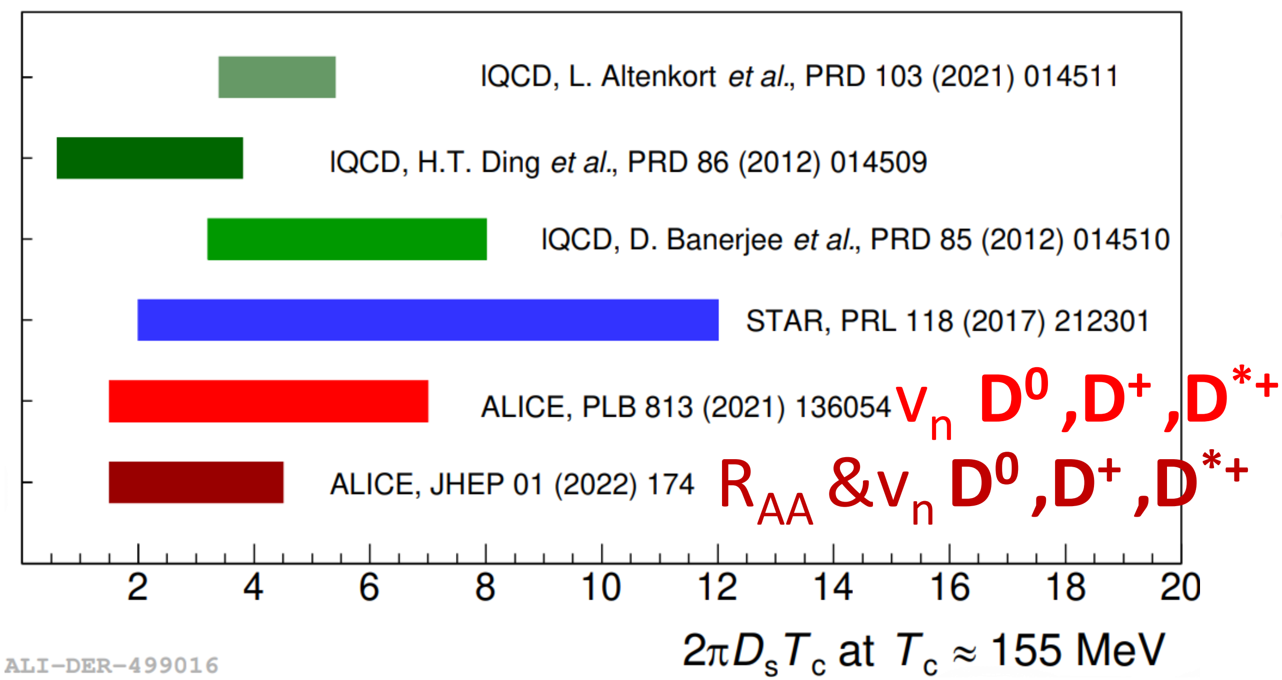


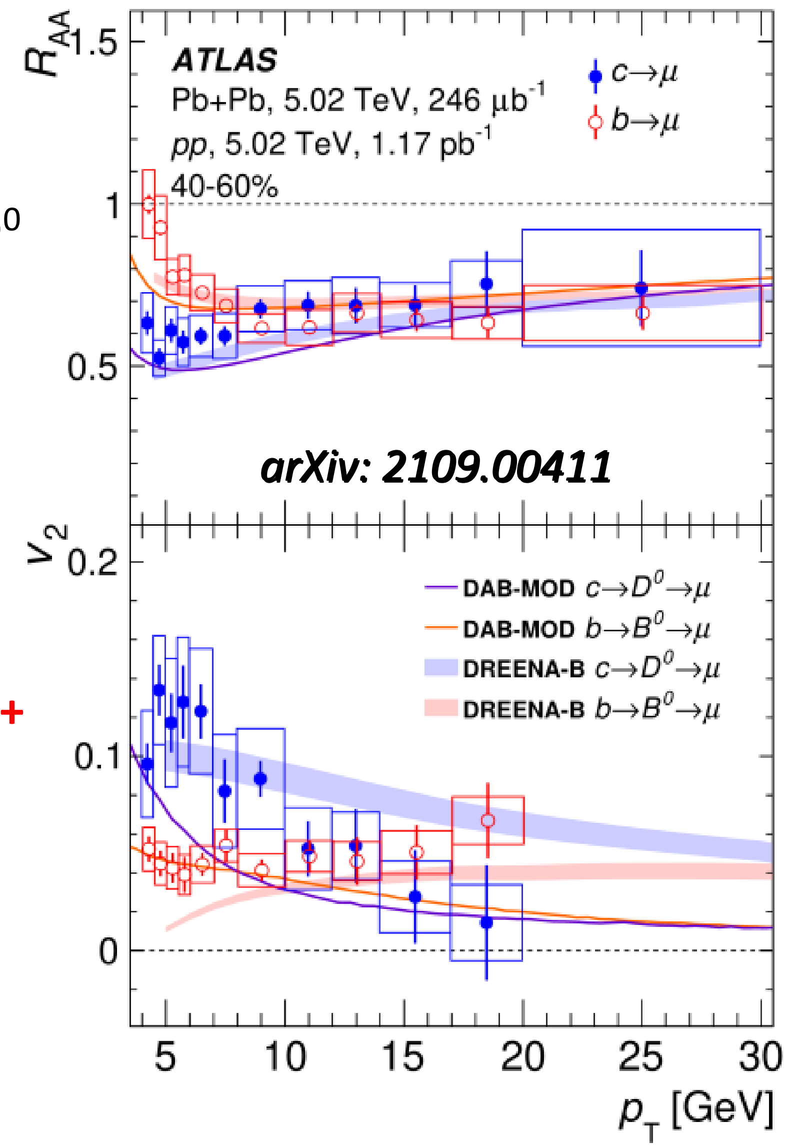


An alternative method for probing HF interactions with QGP

Explore energy loss and QGP expansion at the same time

- **Constraining** the spatial diffusion coefficient via data-to-model comparisons
  - different transport models for energy loss and hadronization ($T > T_c$)
  - simultaneous description of R_{AA} and v_2 → $1.5 < 2\pi D_s T_c < 4.5$ (**best limits** at LHC)
- **Measurement** of R_{AA} **and** v_2 for charm and bottom
  - **mass splitting** at low p_T but converge at high p_T ($\gg m_b$)
  - D_s in R_{AA} &v_2 calculation **in line** with the extraction from D^0

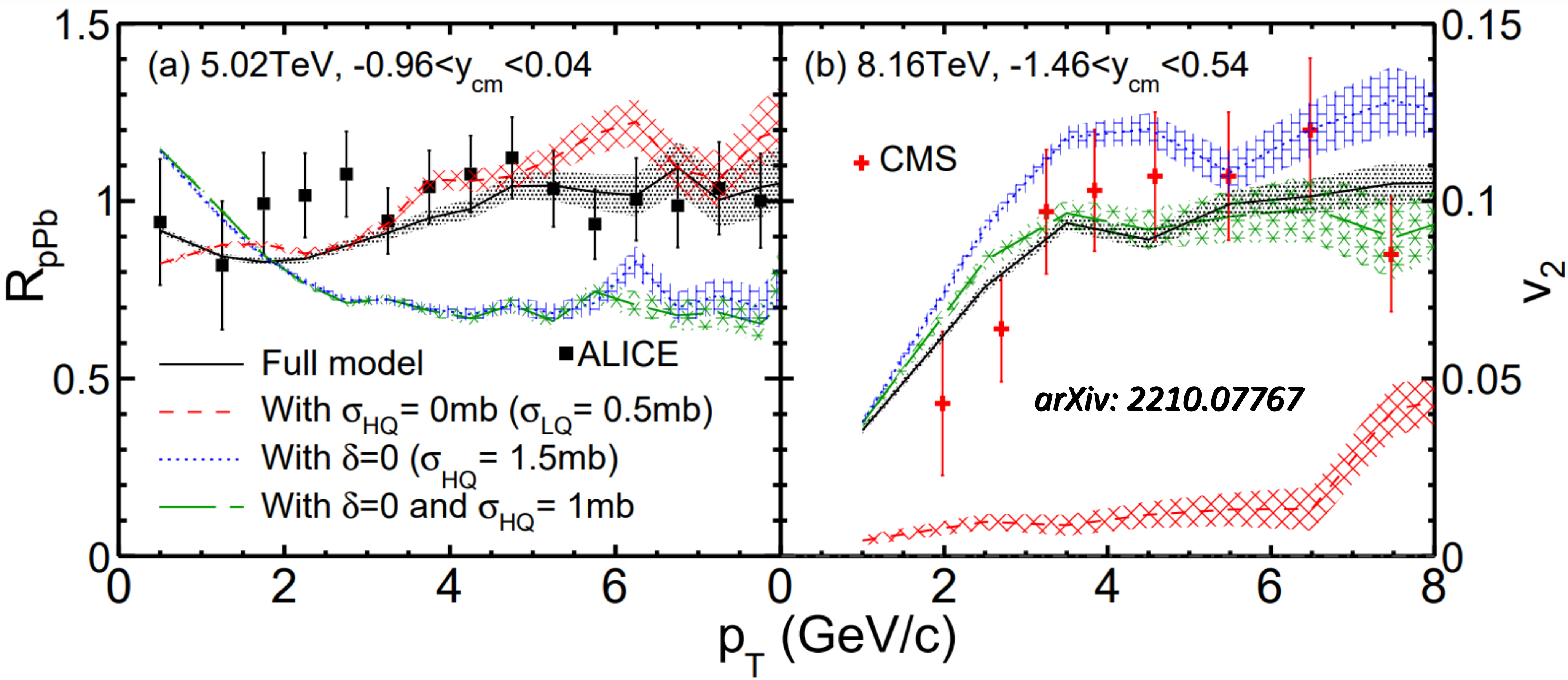




HF probes start to become **powerful tomography tools**

Resolving the p_T and v_2 puzzle of D^0

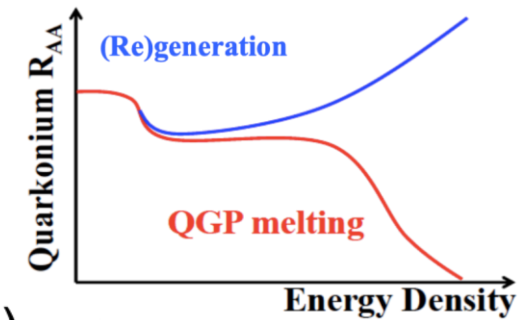
- Challenging to understand the R_{pPb} and v_2 of D^0
  - models describe the HF R_{pPb} but can't v_2 (POWLANG) or can predict only the v_2 (GCC)
- Recently a **simultaneous description** was provided in a modified AMPT version, key findings:
  - **parton interactions+Cronin effect** important for R_{pPb} while
  - parton interactions are mostly responsible for the v_2



Cronin effect could also be important for HF in large systems

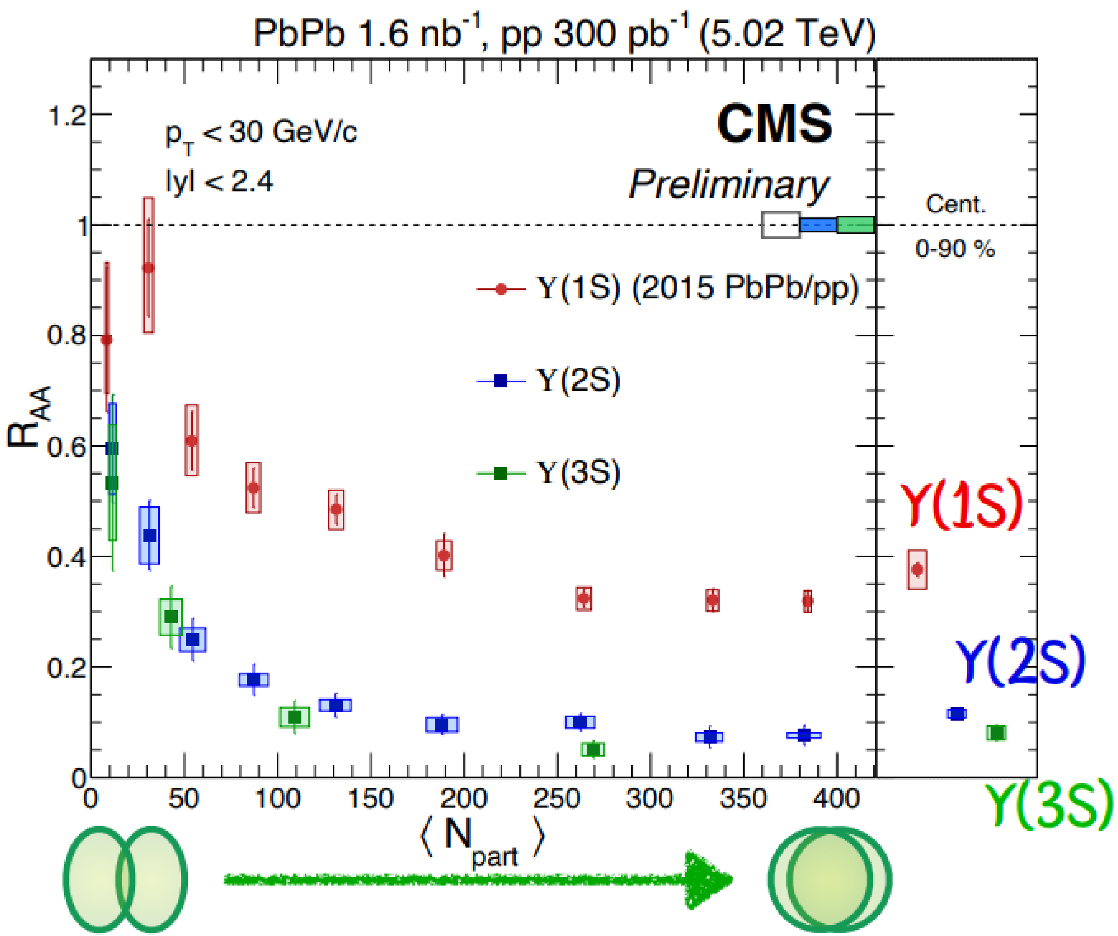
Heavy quarkonia suppression

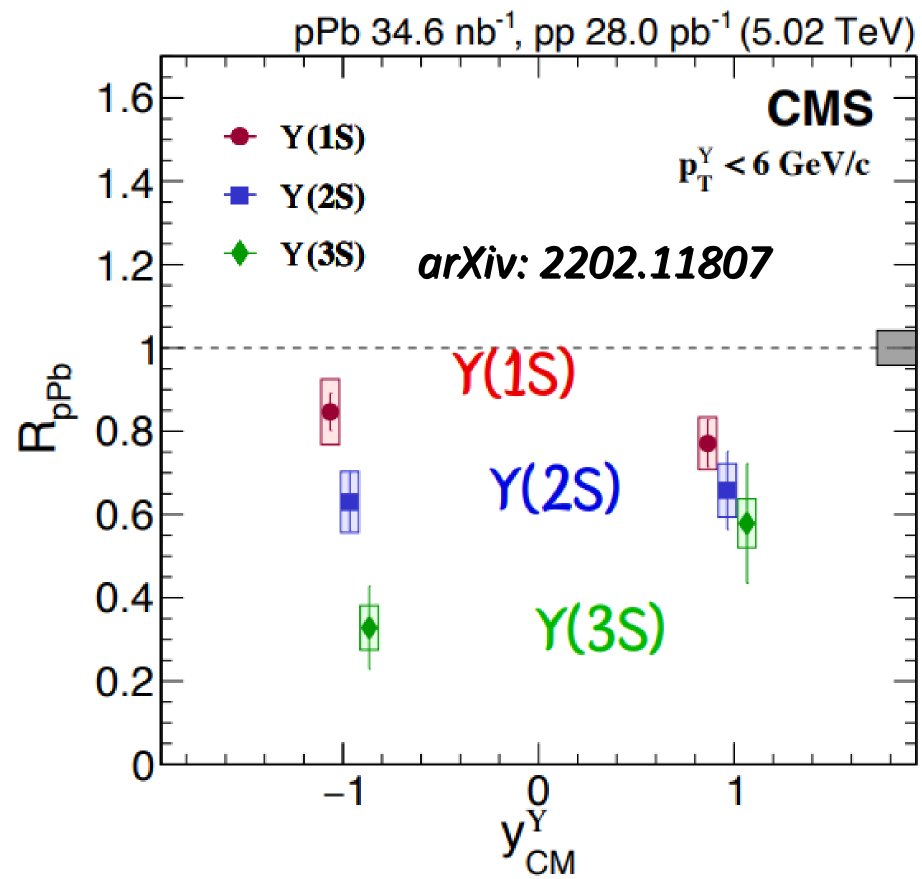
- Observation of the **sequential melting** of ϒ(ns) in **PbPb and pPb**
  - first time including **Y(3S)** in the picture



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

CMS-PAS-HIN-21-007

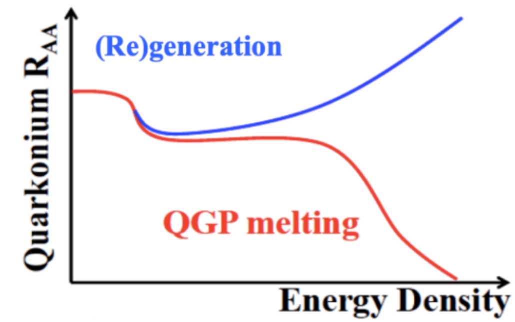




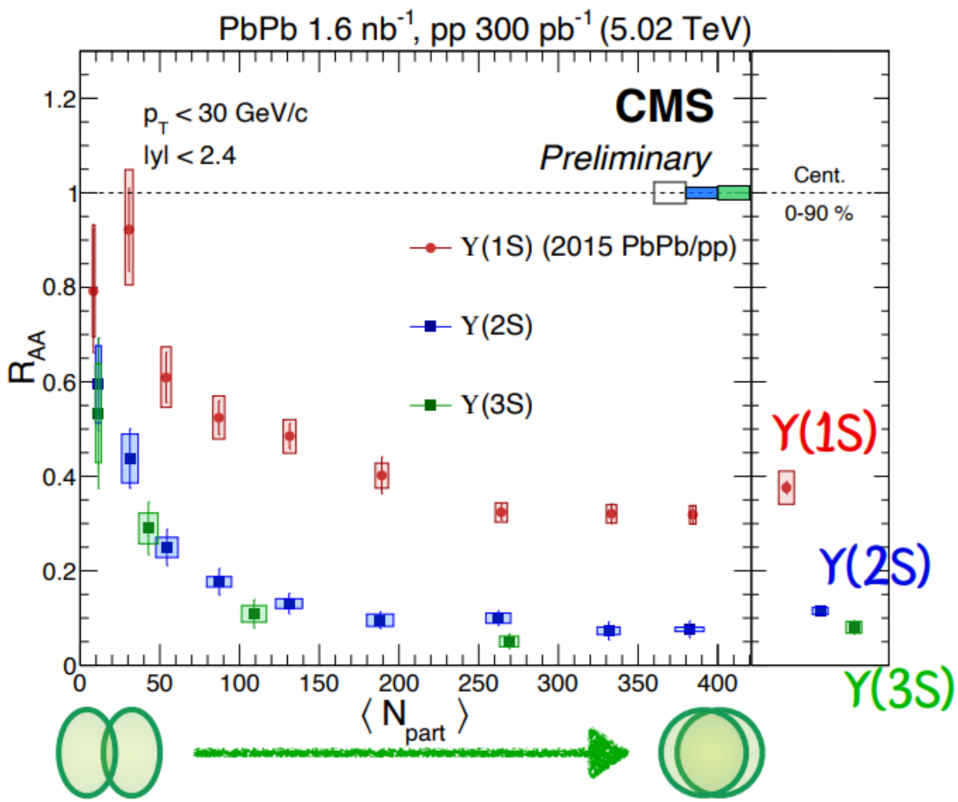
Interplay of **suppression-regeneration** crucial to grasp data

Heavy quarkonia suppression

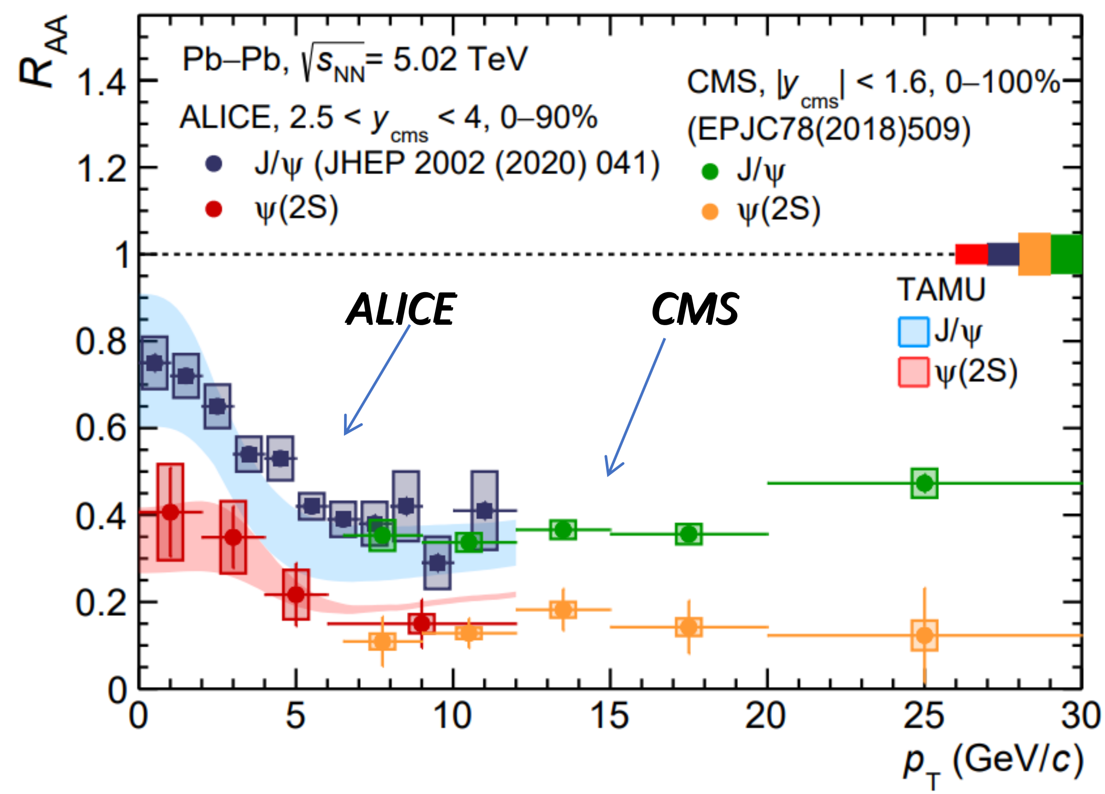
- Observation of the **sequential melting** of ϒ(ns) in **PbPb and pPb**
  - first time including **Y(3S)** in the picture
  - Similarly to the **hierarchy suppression** between J/ψ and ψ(2S)
  - **decreasing R_{AA} vs p_T** connected with charm quark regeneration



CMS-PAS-HIN-21-007



arXiv: 2210.08893

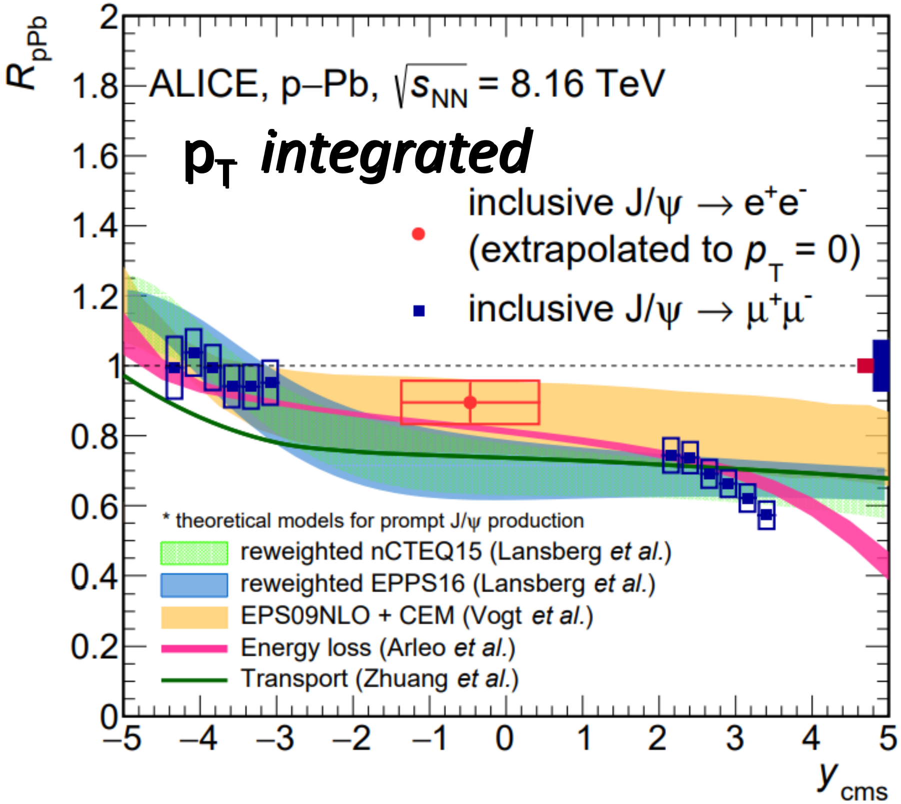


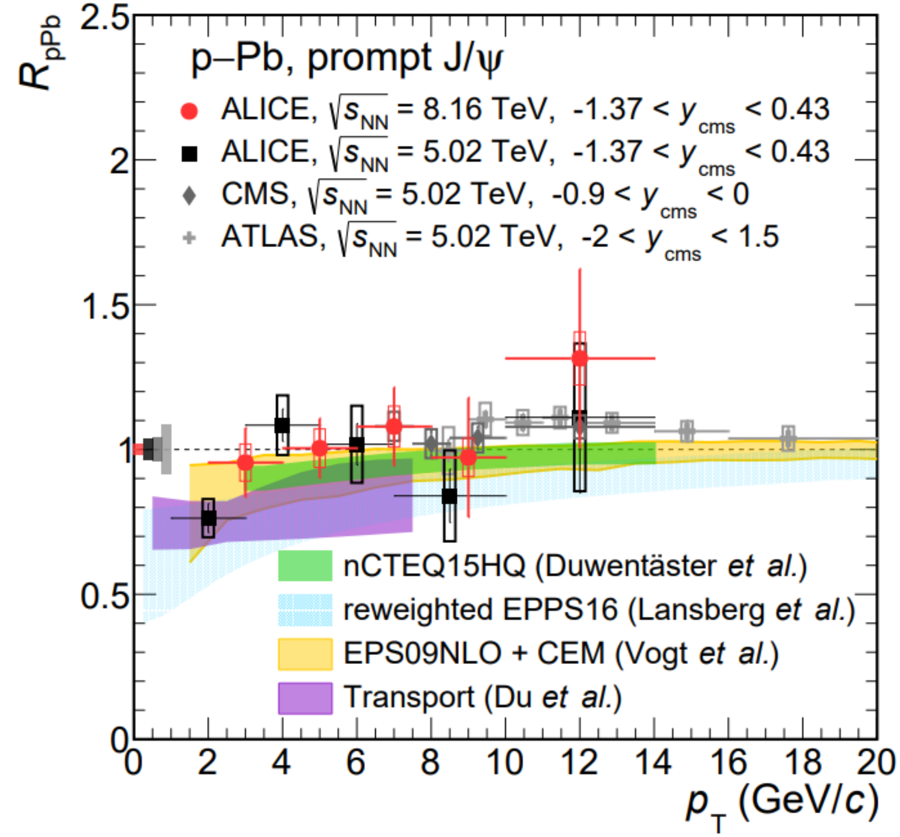
Interplay of **suppression-regeneration** crucial to grasp data

J/ψ production at midrapidity

- The **first measurement** of prompt and nonprompt J/ψ at midrapidity in pPb 8.16 TeV
- thanks to the usage of **electron triggers** in TRD
- Theoretical models describing the forward, backward y results, **also agree at midrapidity**
- $\mathbf{R_{pPb}}$ **vs** $\mathbf{p_T}$ consistent with unity → **CNM effects modest** in the studied kinematic range

arXiv: 2211.14153



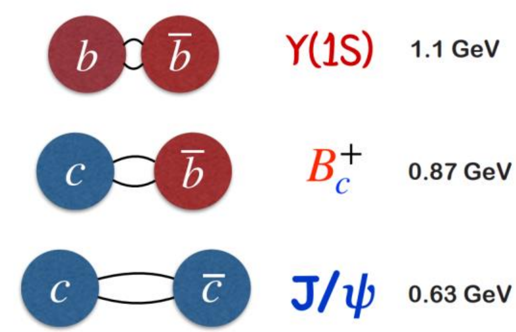


Data can be described with **no final-state effects**

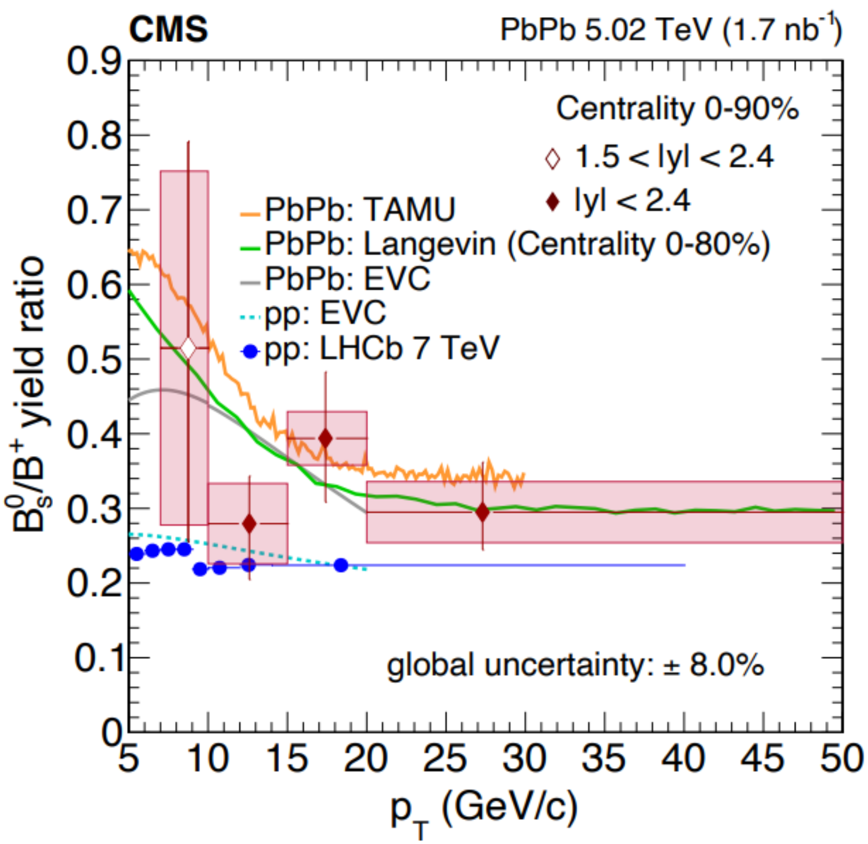
B_s and B_c production PbPb

- For B_s^0 **low-pT enhancement** suggested by models
  - current uncertainty **large** though
- **First observation** of B_c^+
  - unique state for enhancement (**low p_T**) and suppression (**high p_T**)

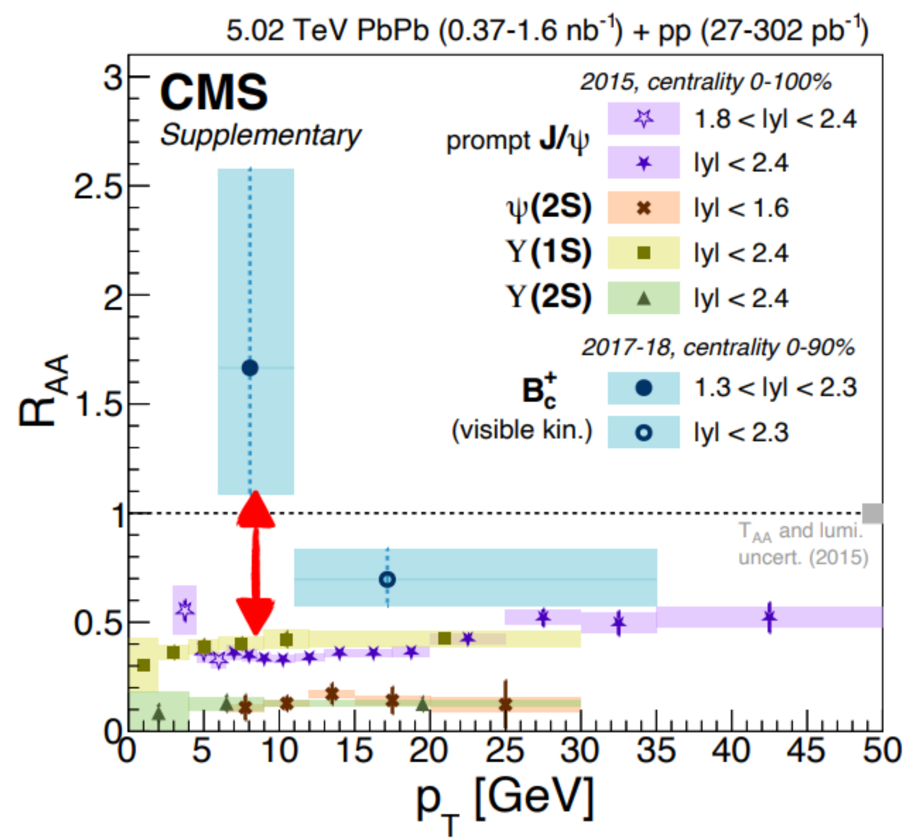
Binding energy hierarchy



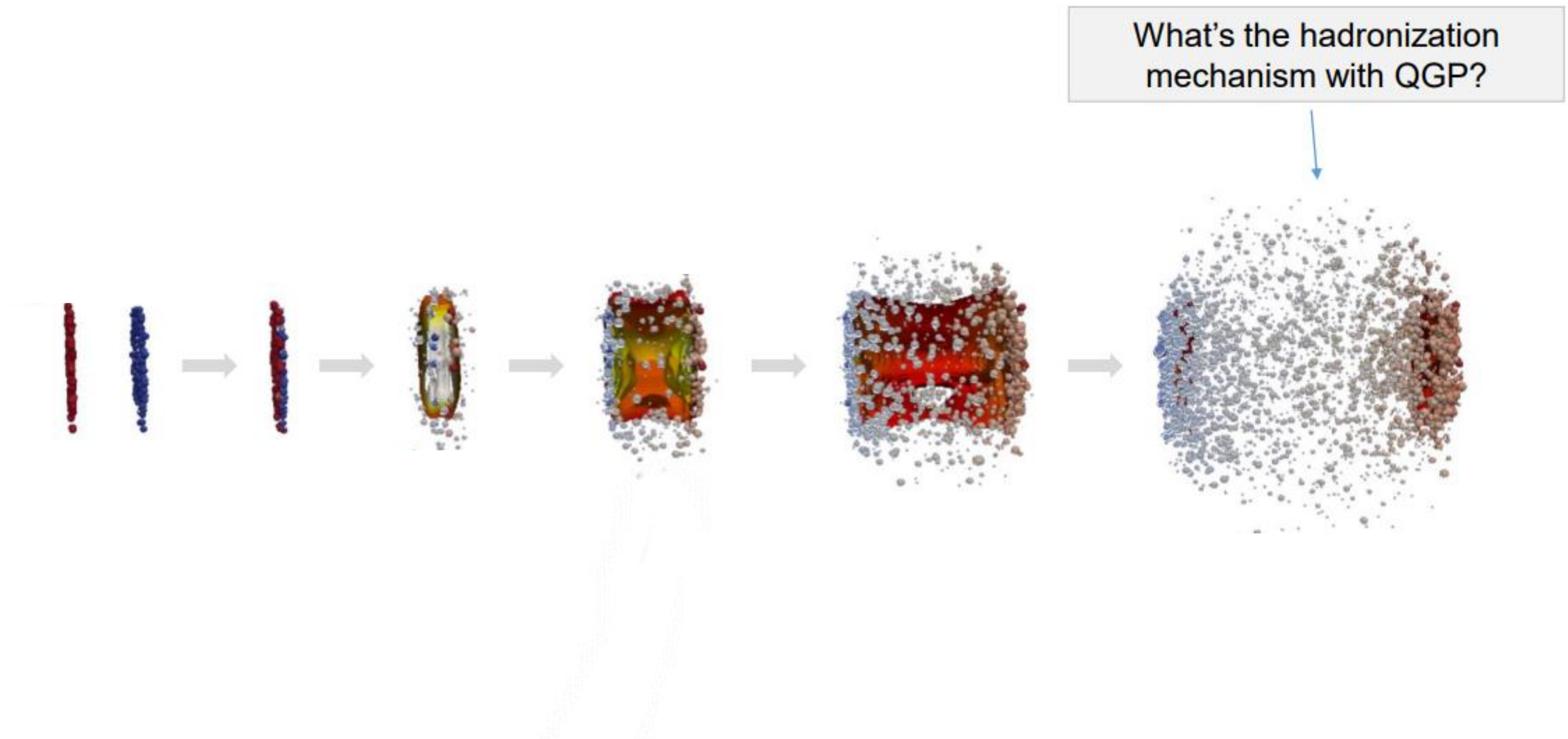
arXiv: 2109.01908



arXiv:2201.02659



Novel probe **for suppression-regeneration**

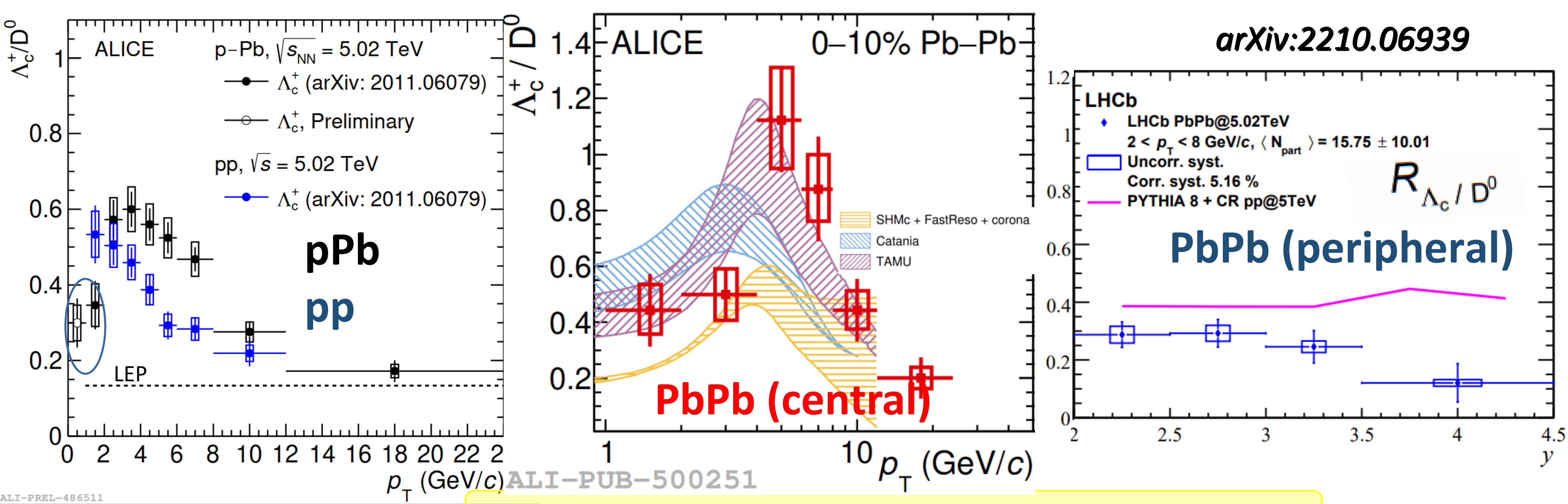

What's the hadronization
mechanism with QGP?

Charmed baryon-to-meson ratio in all systems

- New measurements of Λ_c^+/D^0 down to **p_T= 0** and **central PbPb**
  - difference wrt to pp → radial flow or multiplicity dependence of hadronization?
  - challenging further the **universality** of hadronization process
- So far **significant differences** in mid vs forward y
  - a systematic discrepancy in y **confirmed**
  - motivate improvements in **model predictions** in different phase-space regions

arXiv:2112.08156

arXiv:2210.06939

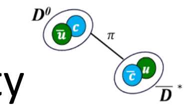


Data in tension with **the Statistical Hadronization model**

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)

$D^0\overline{D}^*$ **Molecule**

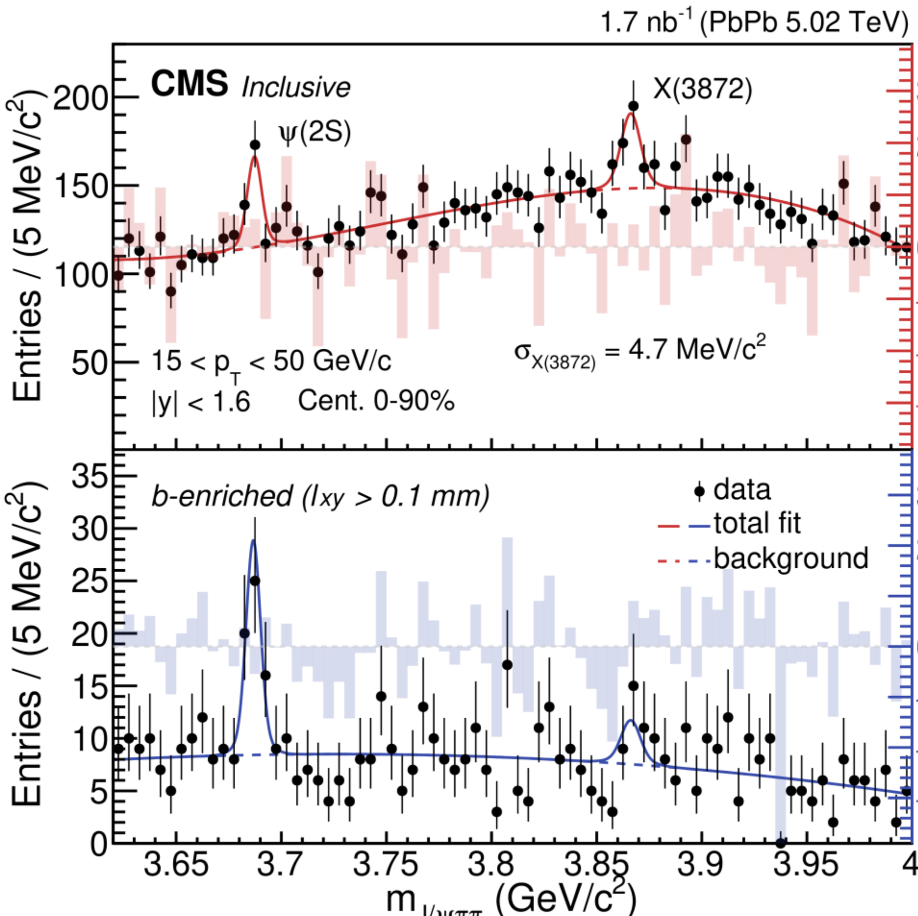


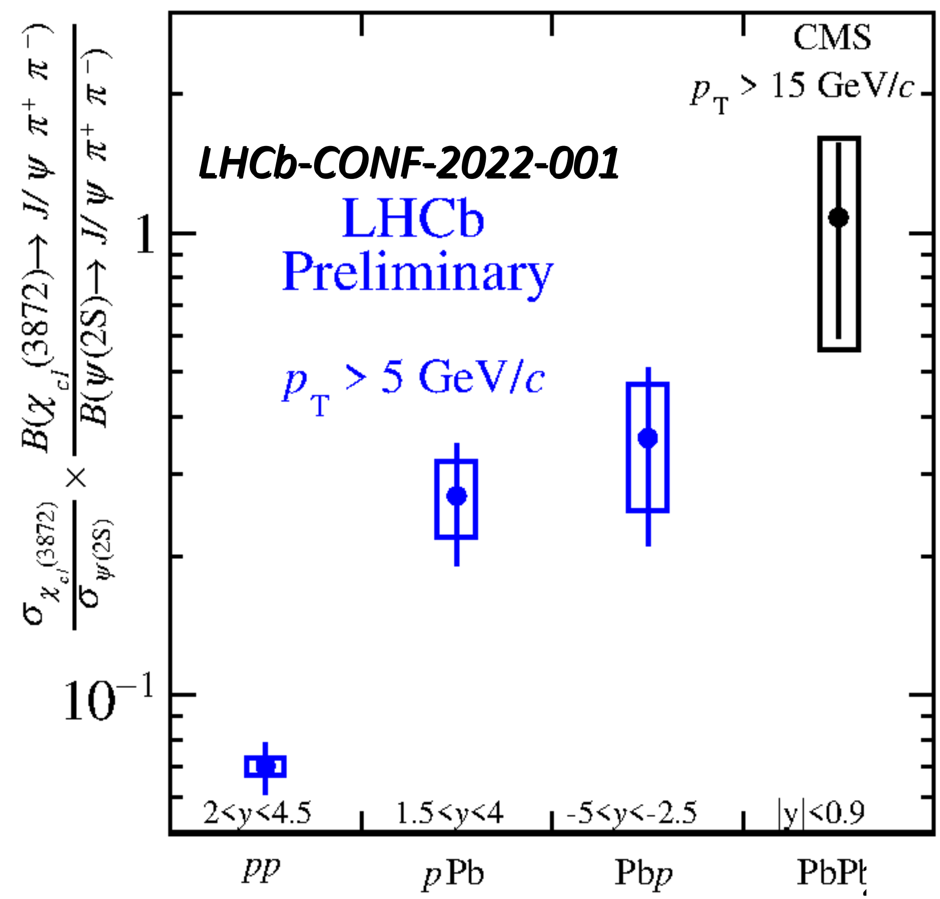
VERY small binding energy
VERY large radius, ~5-10 fm

Compact tetraquark

Tightly bound via color exchange between diquarks
Small radius, ~1 fm

arXiv: 2102.13048

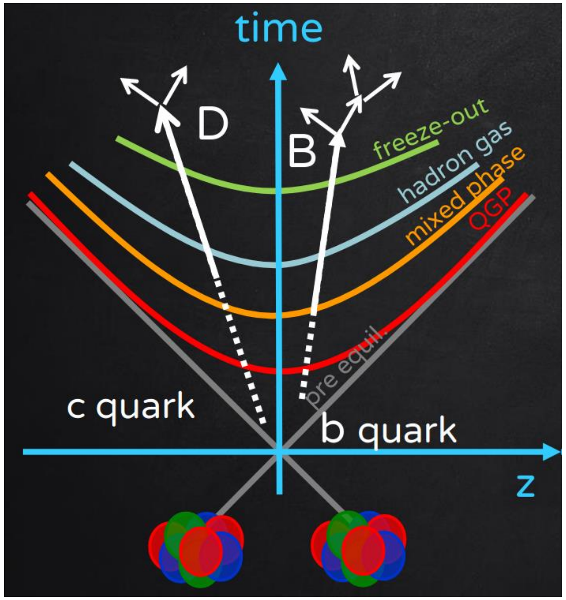




Machine learning techniques increases sensitivity to rare probes

Summary

- LHC nuclear data **are a game changer**
  - **precise extractions of nPDFs** crucial for modeling the initial state needed to characterize the QGP
- Comprehensive studies of heavy flavor collectivity in **all** systems
  - significant charm v_2, bottom flows (?) in PbPb
  - complementary measurements from $\Delta\phi$ correlations of HF decayed leptons
- Explore v_2 & $R_{AA,pA}$ **at the same time**
  - consistently extract D_s, understand p_T broadening, and parton interactions
- A rich program on **quarkonia suppression**
  - J/ψ in extended regions, $\psi(2S)$, $\Upsilon(ns)$, B_s^0, B_c^+
- Future data with improved precision will provide **crucial insights**
  - for example Λ_c^+/D^0 ,exotic mesons, all above



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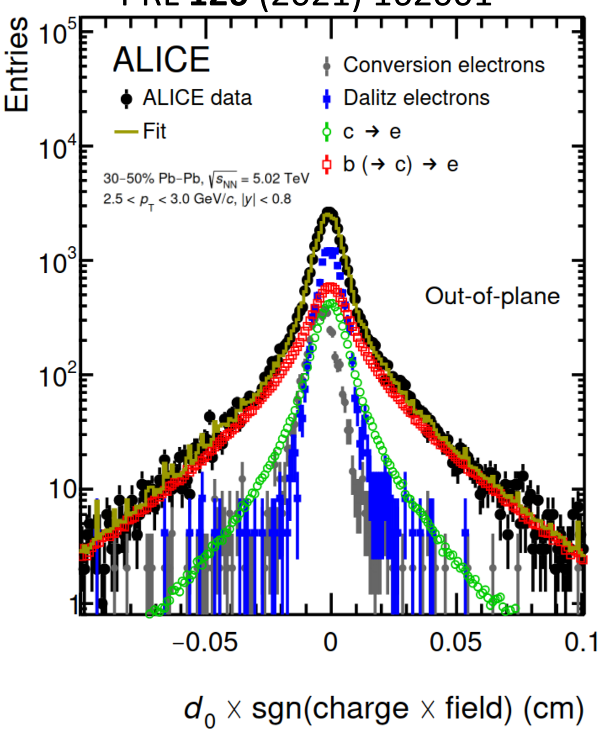
slides

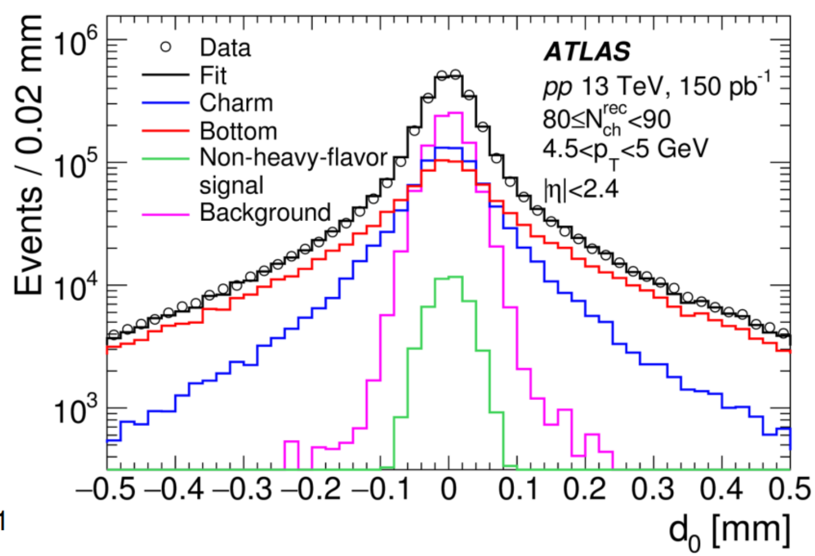
Key features of heavy flavor measurements

- Variety of meson/baryon states with different flavors in a broad kinematic range
  - techniques to **separate** heavy from light flavor decays
- We gain insight on
  - whether heavy quarks **flow** with the bulk
  - **parton interactions** in the QGP (thermalization, energy loss,...)
  - QGP **properties** (transport coeff)
  - pQCD predictions, parton shower modeling, hadronization mechanisms

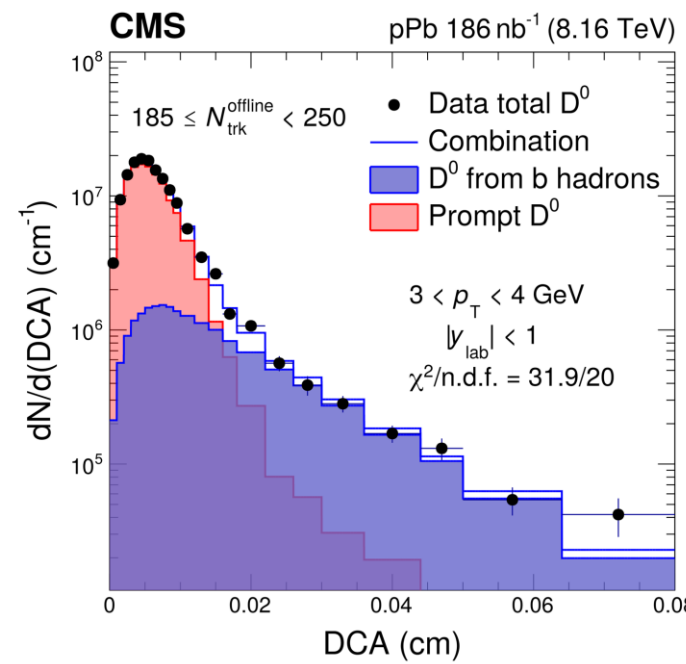
PRL **126** (2021) 162001



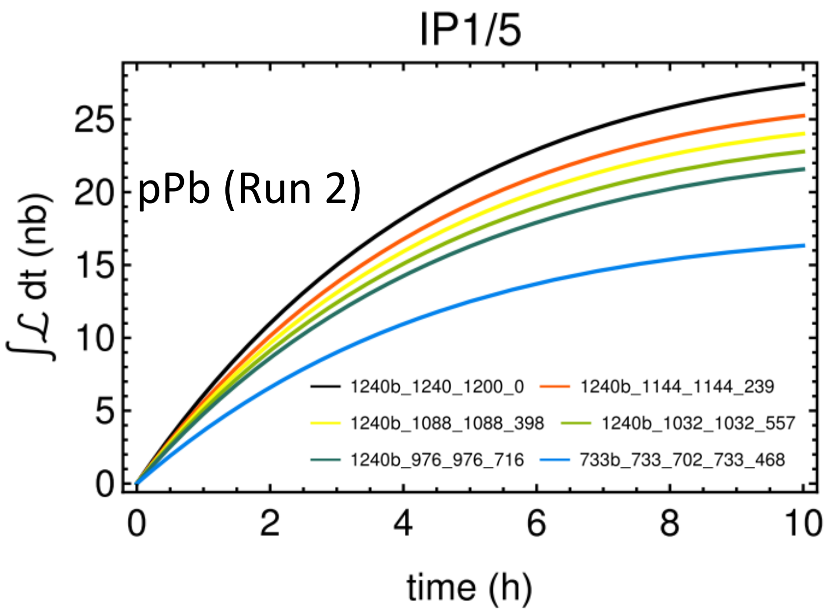
PRL **124** (2020) 082301

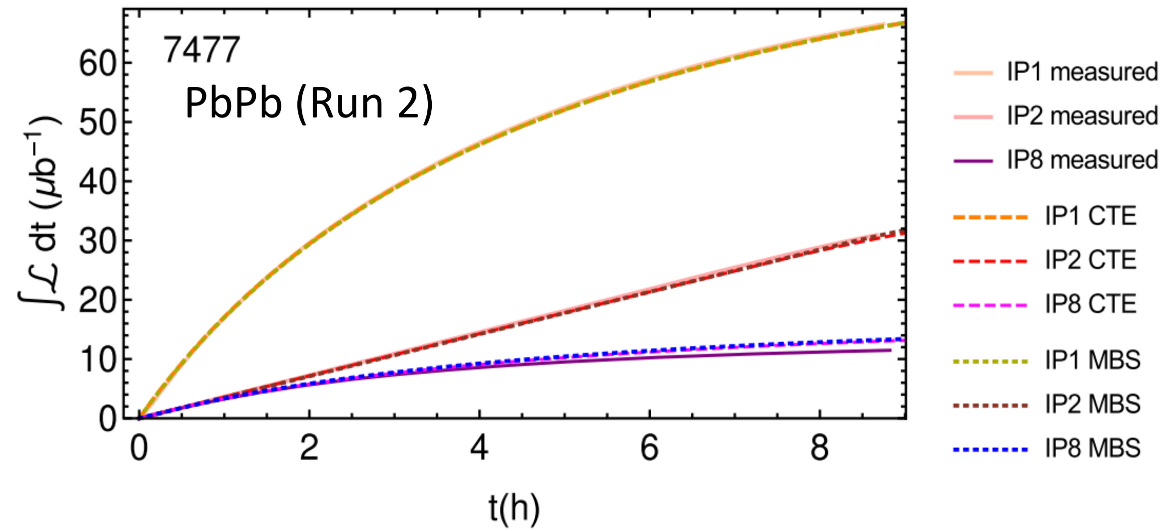


PLB **813** (2021) 136036



HL-LHC operational scenarios for pPb and PbPb



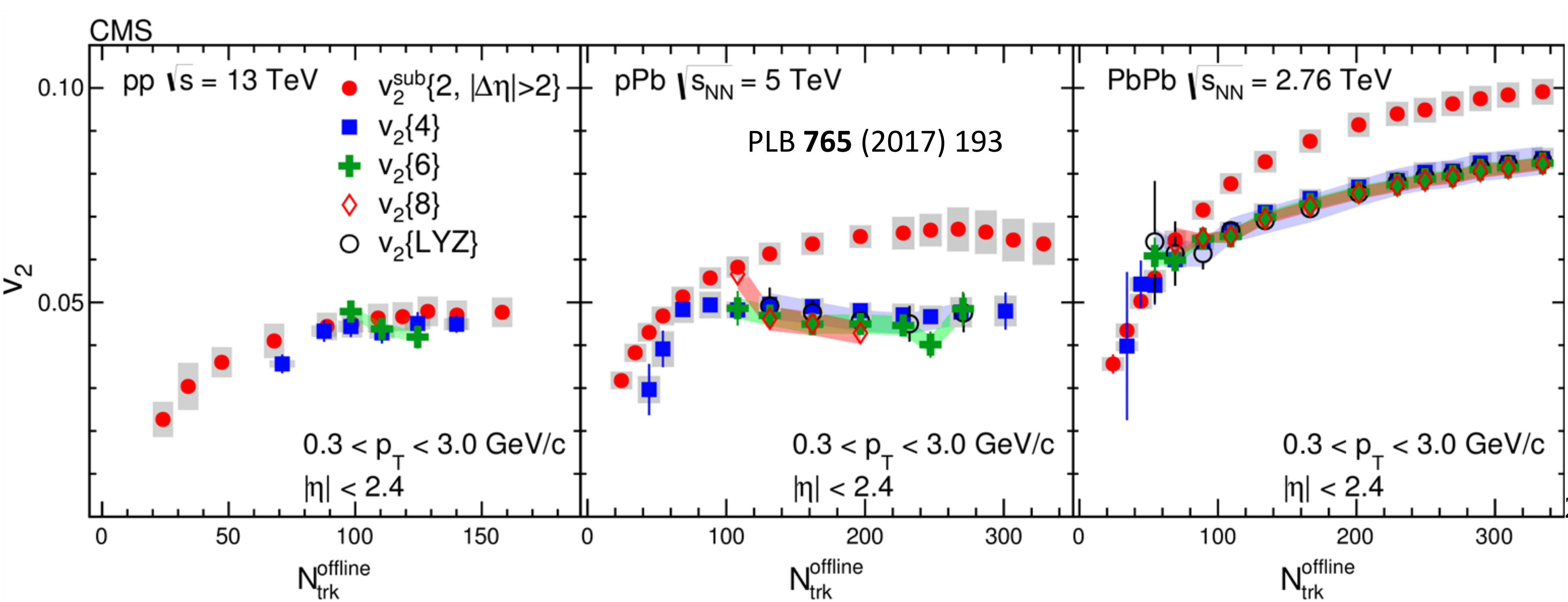


- Included in the YR and more recently refined (CERN-ACC-2020-0011, EPJ.Plus 136 (2021) 7)
- scenarios are based on **benchmarked** models (agree remarkably well with Run 2 LHC data)
- **≈five** one-month runs would be needed to reach **13 /nb** of PbPb
- **≈two** one-month runs would be needed to reach **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

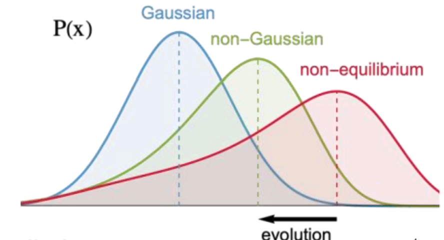
Collectivity in small systems?

- Detailed flow measurements in **pp/pPb** indicate that
  - centrality/event activity and p_T dependence qualitatively **similar** to that in AA
  - identified particle and multiparticle correlation techniques support a **collective origin** of $\mathbf{v_n}$
  - encompassed 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)

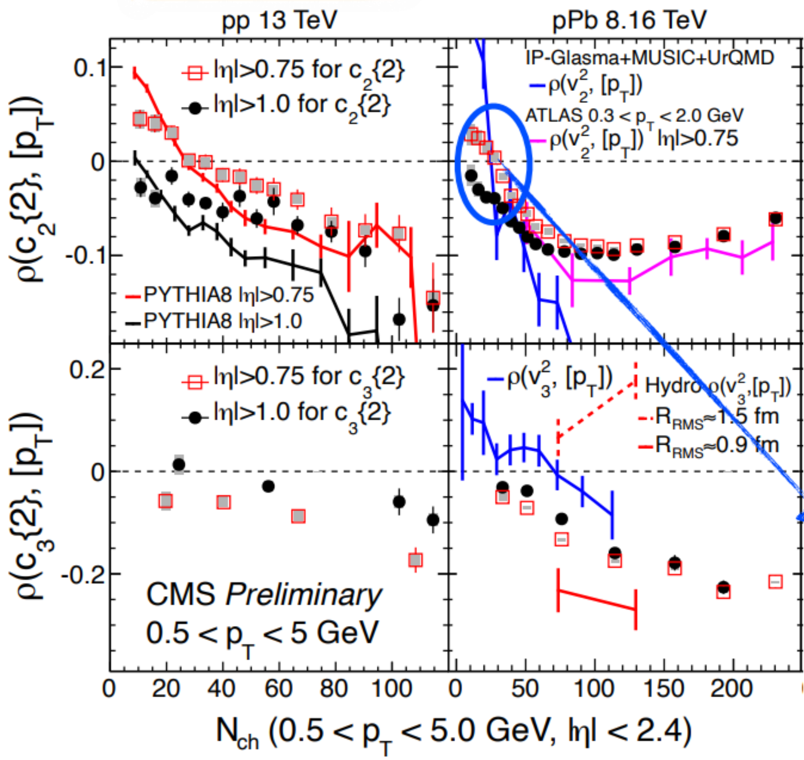


Investigating the initial stages with more elaborate observables

- **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**



CMS-PAS-HIN-21-012



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

□ small η gap

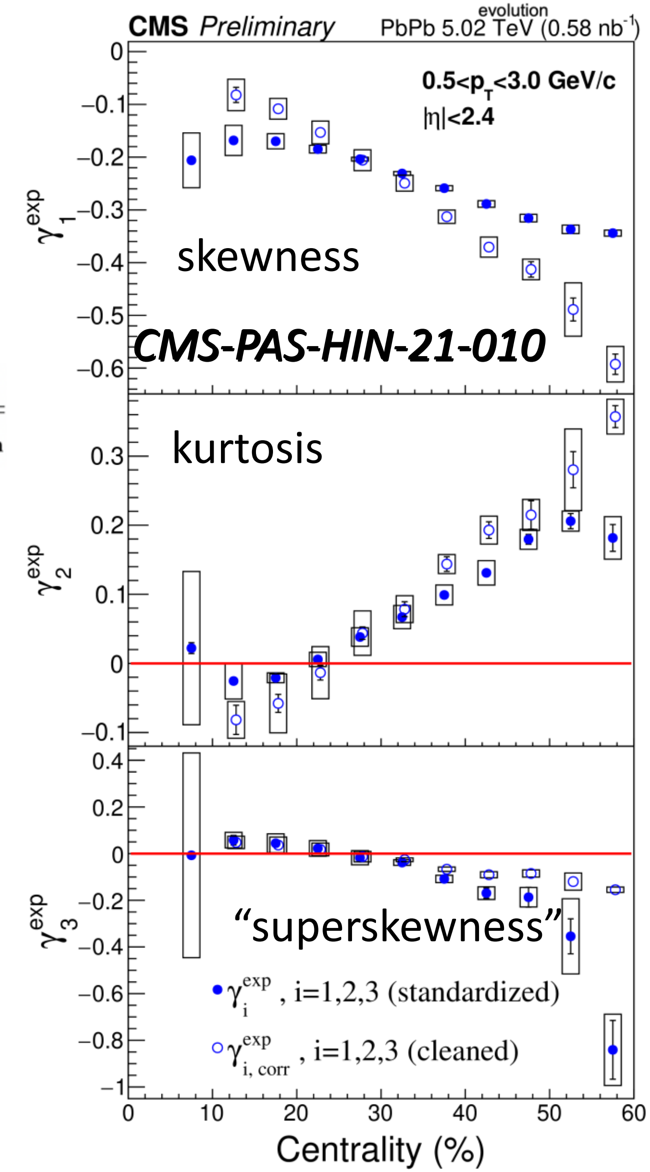
● large η gap

Reduction of non-flow effects

+ IP-Glasma+MUSIC+UrQMD

: Sign change predicted by CGC

CMS-PAS-HIN-21-010



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

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

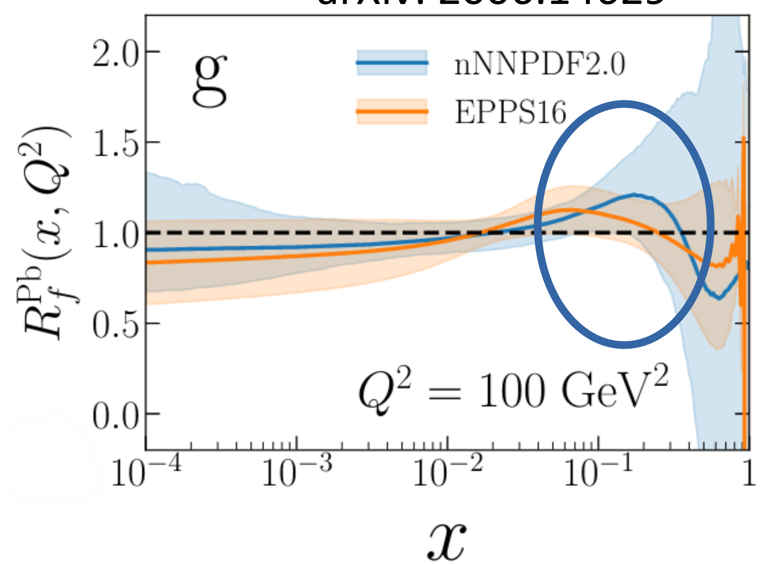
P. Paakkinen (DIS22)

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

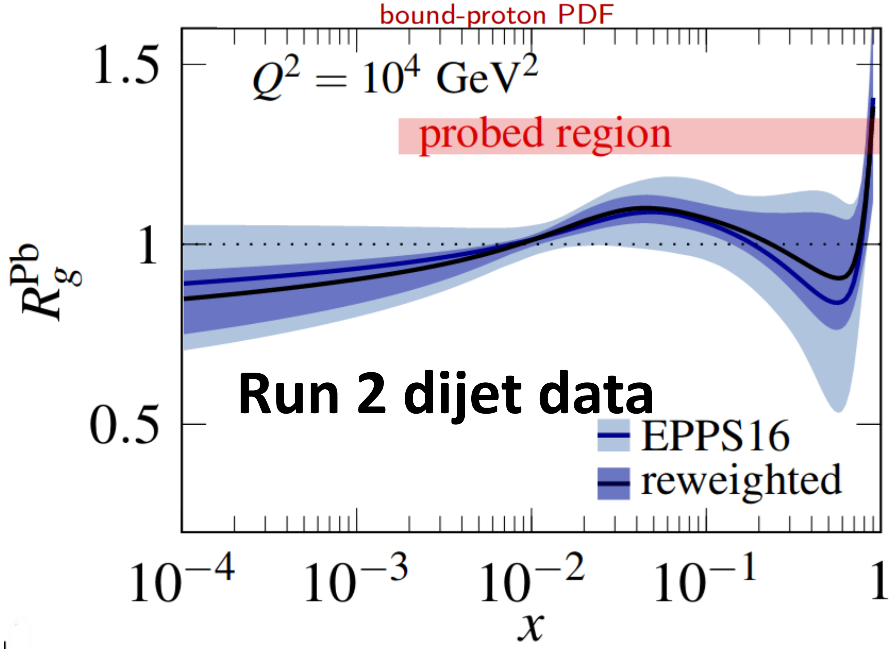
- Stringent constraints with **dijet** production
  - Enhanced **suppression** at forward y
- Significant reduction in EPPS16 uncertainties after reweighting already with Run 2 data (left plot)
- **Improved constraints** with HL-LHC data (right plot)
- Complementarity with W bosons and top quarks, and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

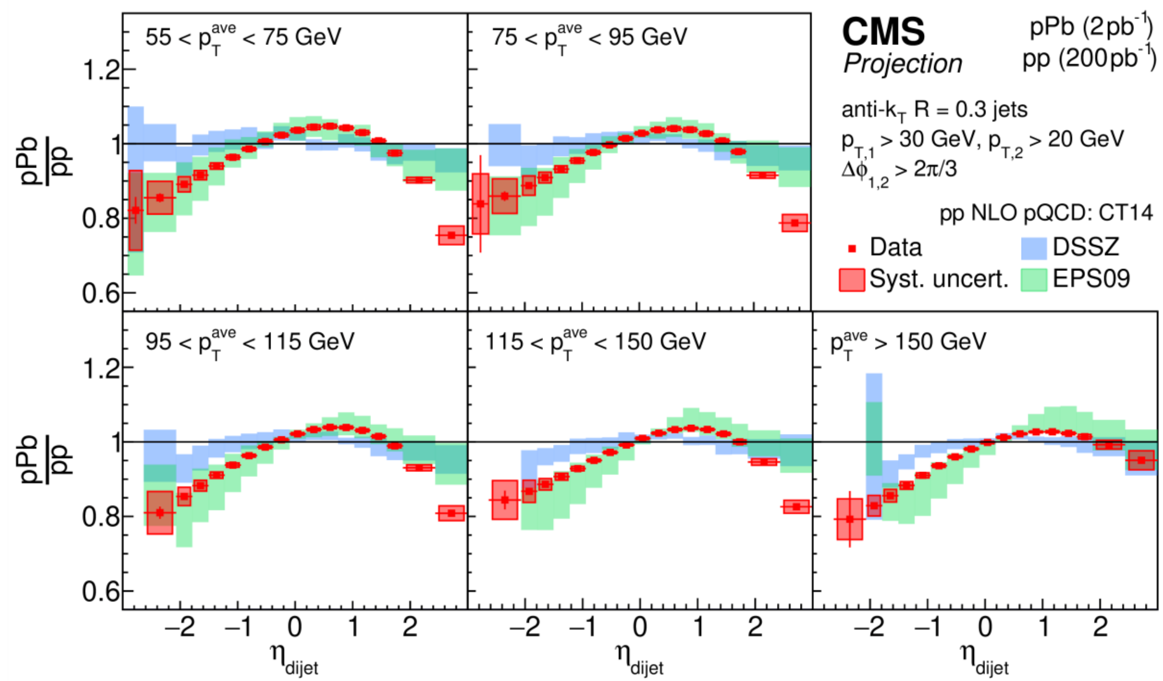
Phys. Rev. Lett. **121** (2018) 062002
EPJC **79** (2019) 511

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.

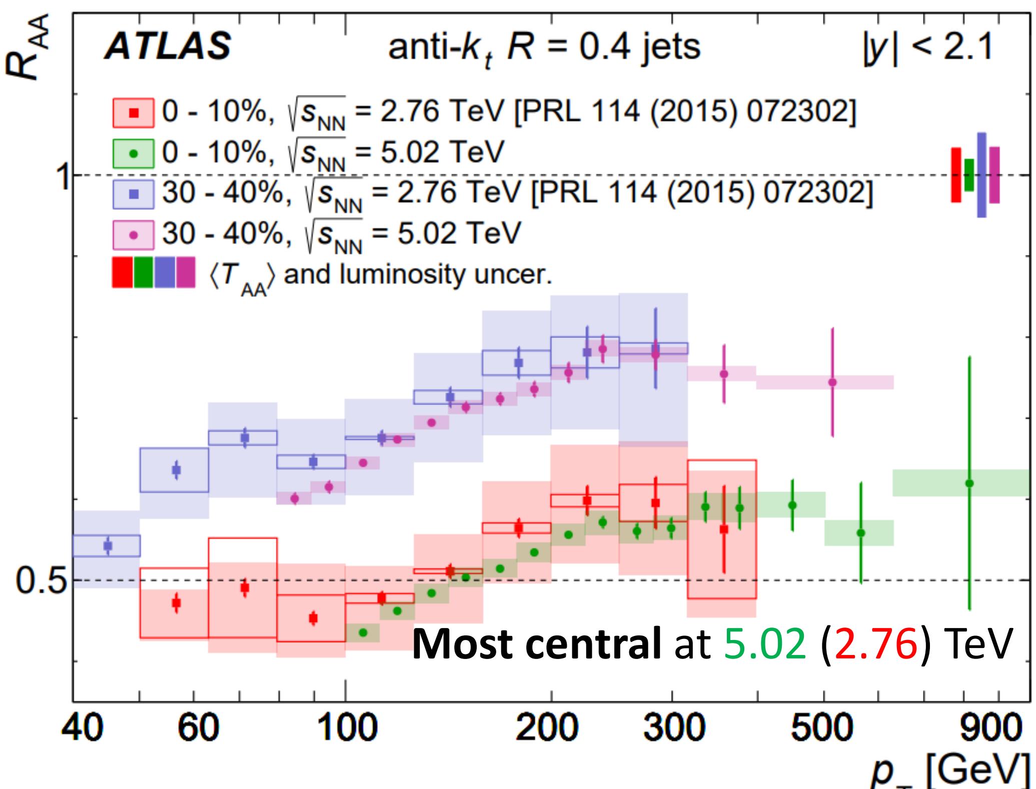
	B^+			B_s^0		
Centrality class	0–30%	30–90%	0–90%	0–30%	30–90%	0–90%
Muon efficiency	$^{+4.2}_{-3.8}$	$^{+4.1}_{-3.8}$	$^{+4.2}_{-3.8}$	$^{+5.5}_{-4.9}$	$^{+4.6}_{-4.2}$	$^{+5.3}_{-4.7}$
Data/MC agreement	13	8.0	12	3.1	3.7	3.2
MC sample size	3.2	2.2	2.4	6.6	2.3	4.4
Fit modeling	2.5	2.8	2.6	2.5	3.2	2.3
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**

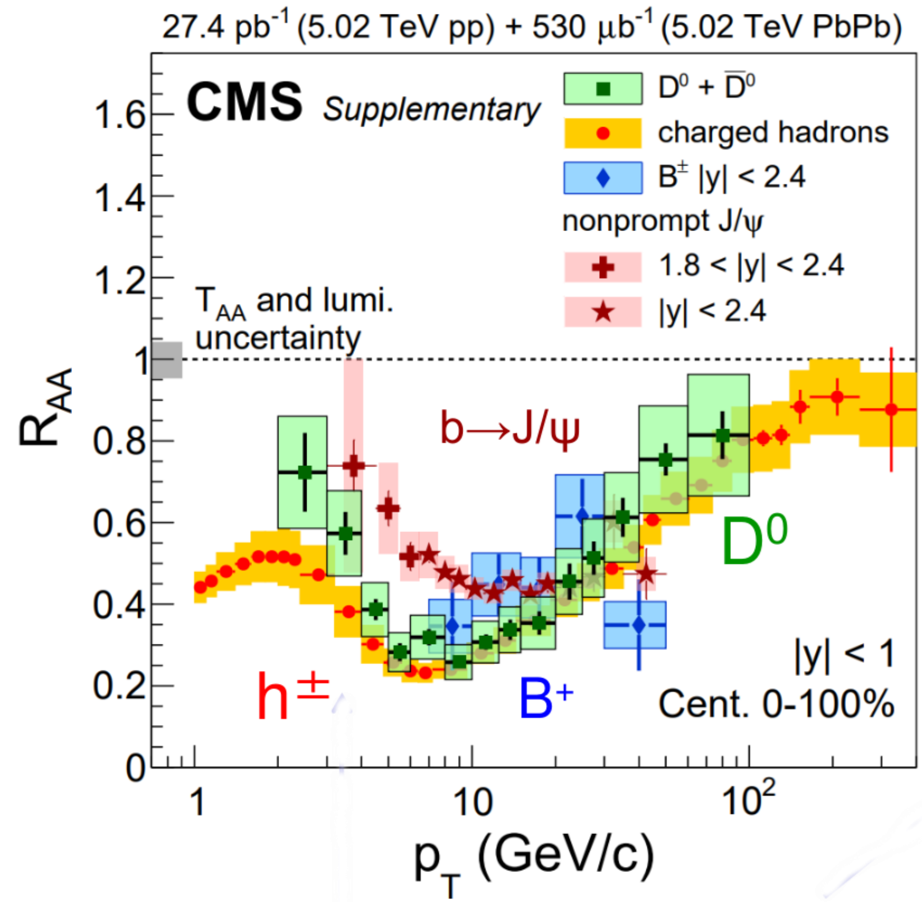
- Energy of partons is redistributed ('quenched') inside QGP
  - Experimentally seen as R_{AA} modifications of **hadrons or jets**
  - **dependent on** centrality, p_{T}, parton mass
- Unprecedented access from **low- to high-p_T**

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

PLB 790 (2019) 108

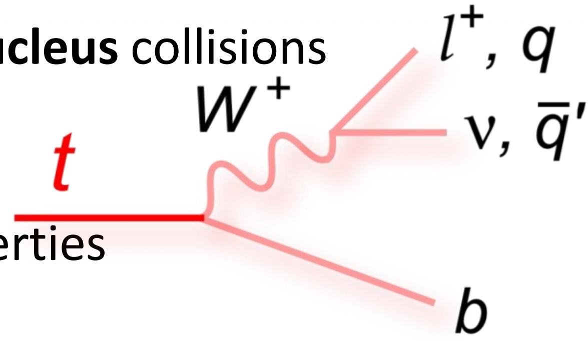


PRL 123 (2019) 022001

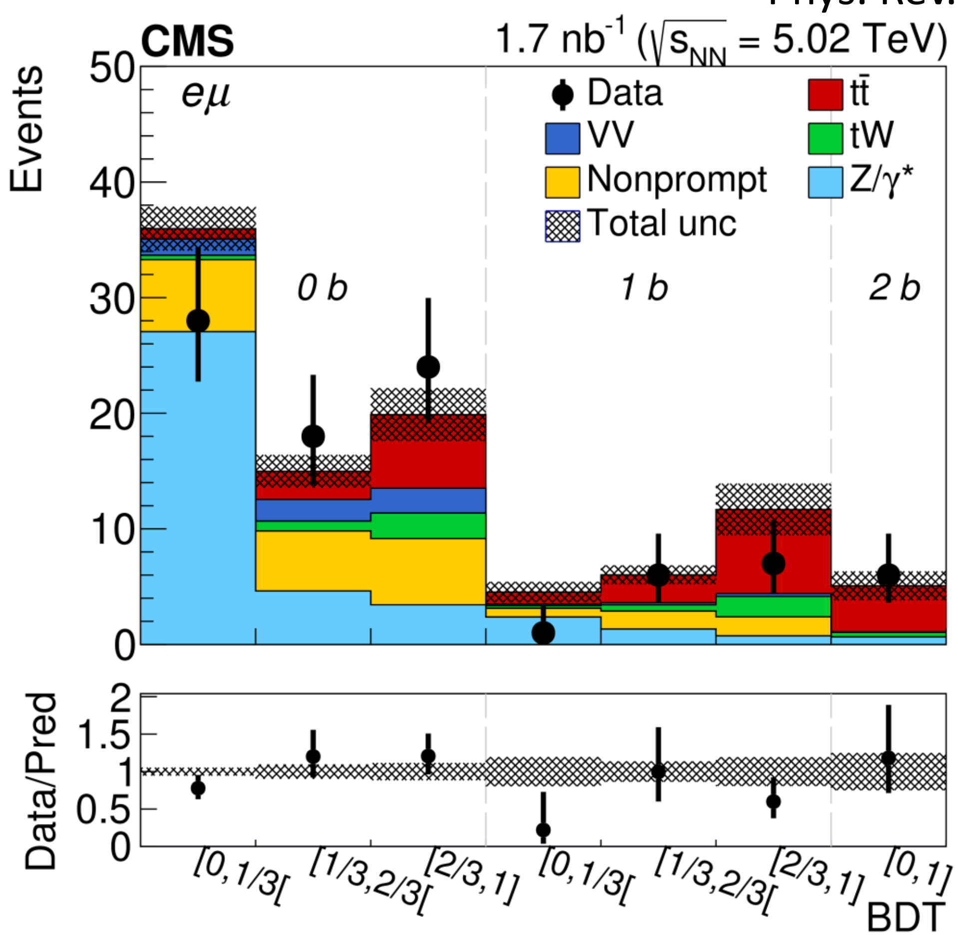


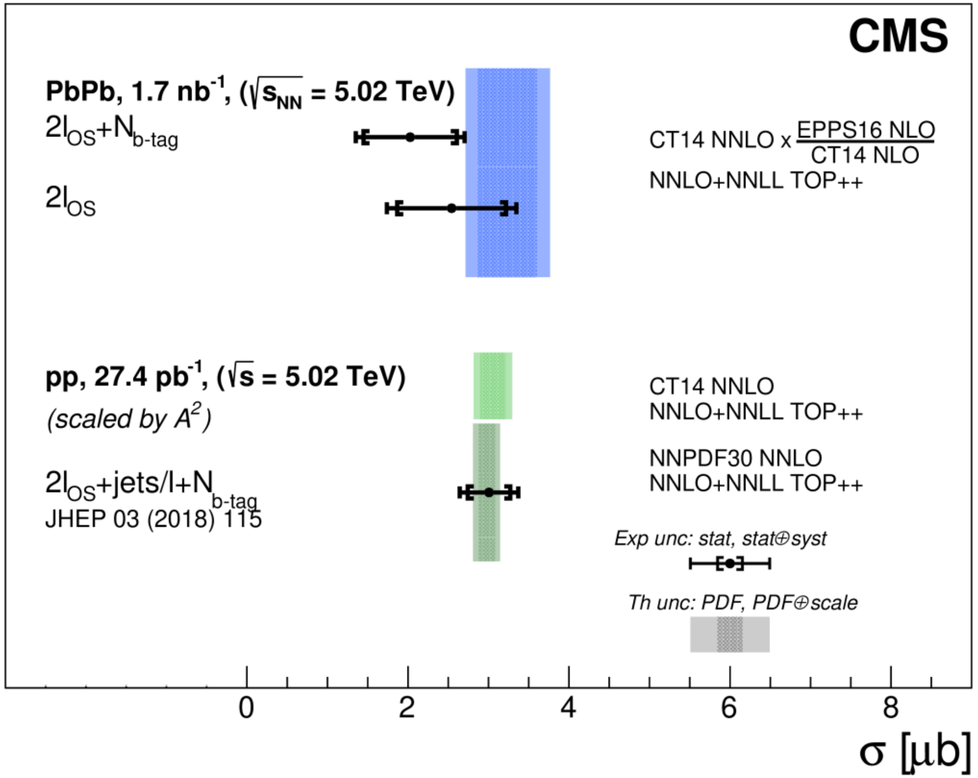
Evidence of $t\bar{t}$ cross section in PbPb

- **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



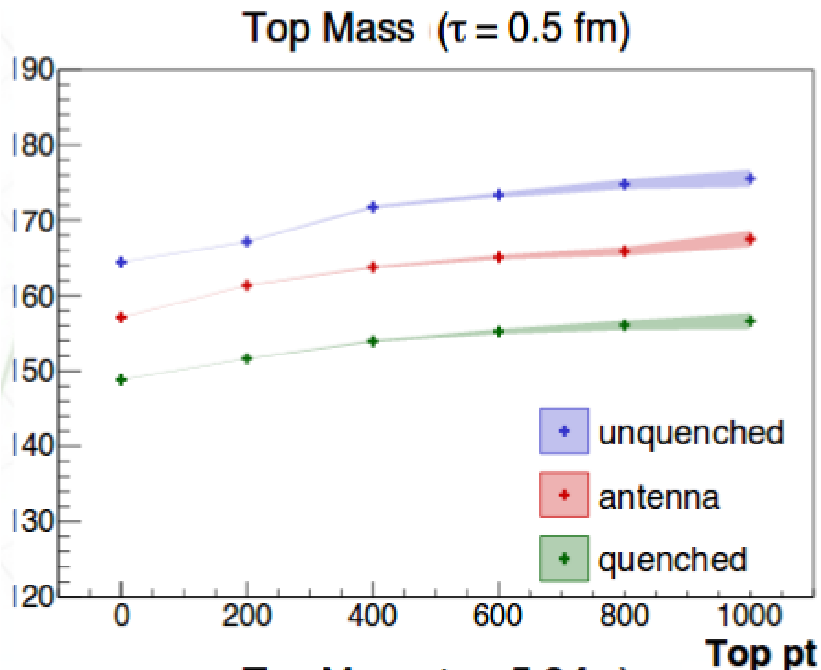
Phys. Rev. Lett. **125** (2020) 222001

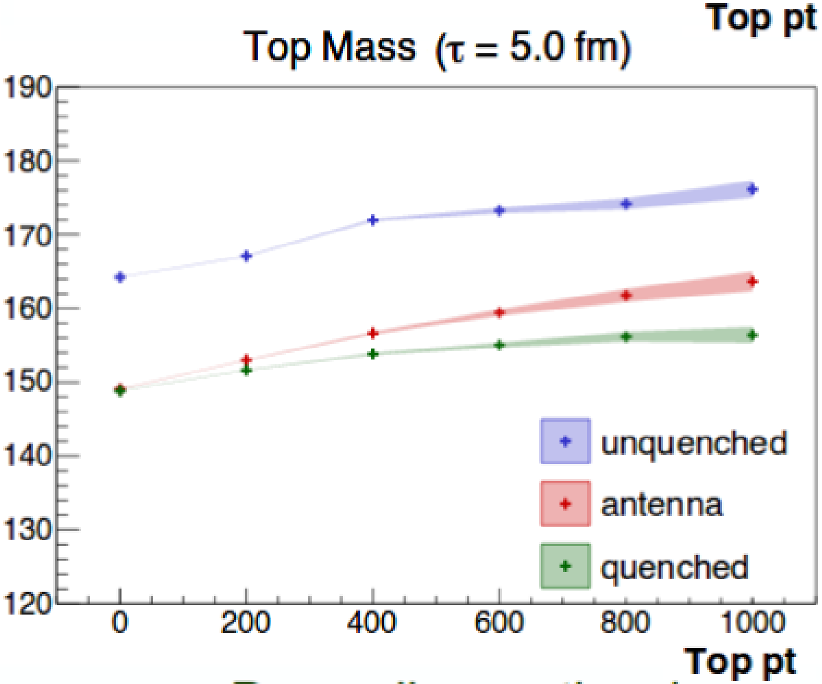


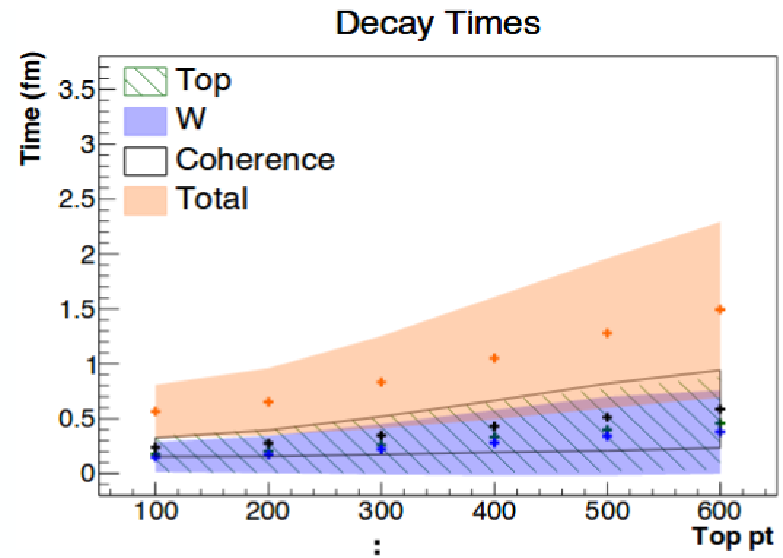


A nice heuristic idea for a yocto-chronometer !

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



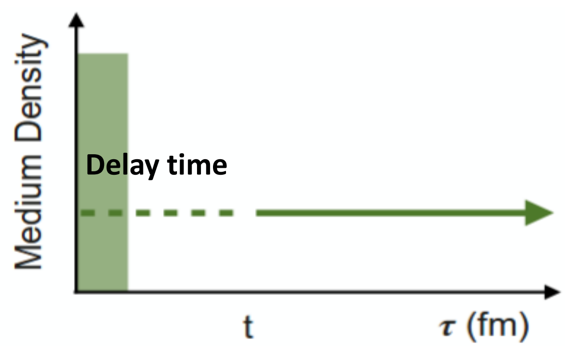




Not enough statistics…

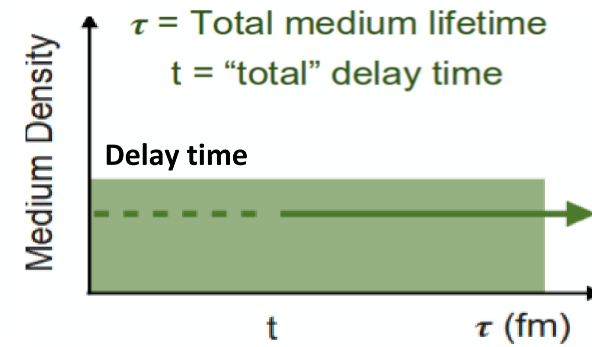
Probe ~ [0.4; 1.2] fm

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



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!