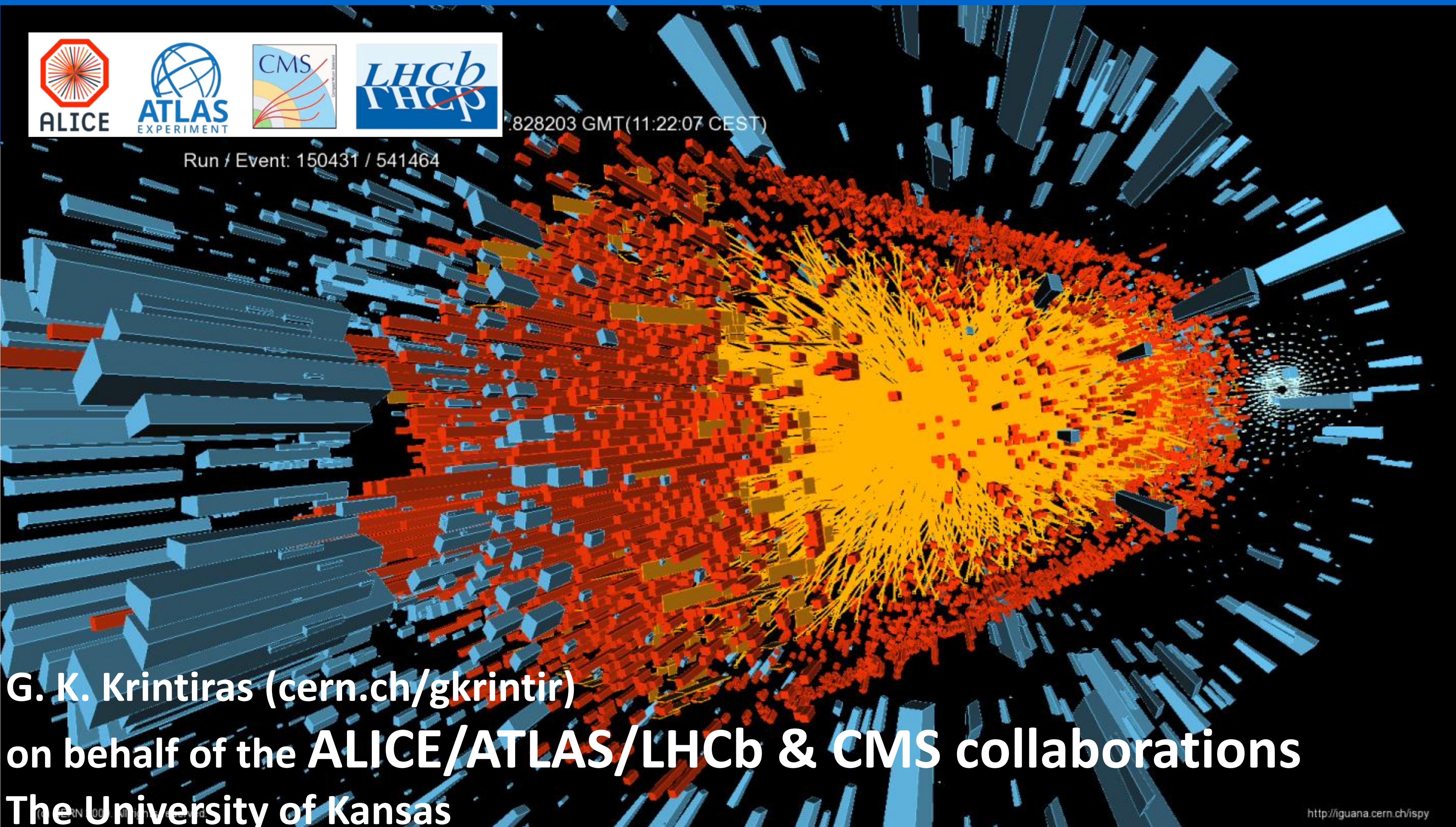
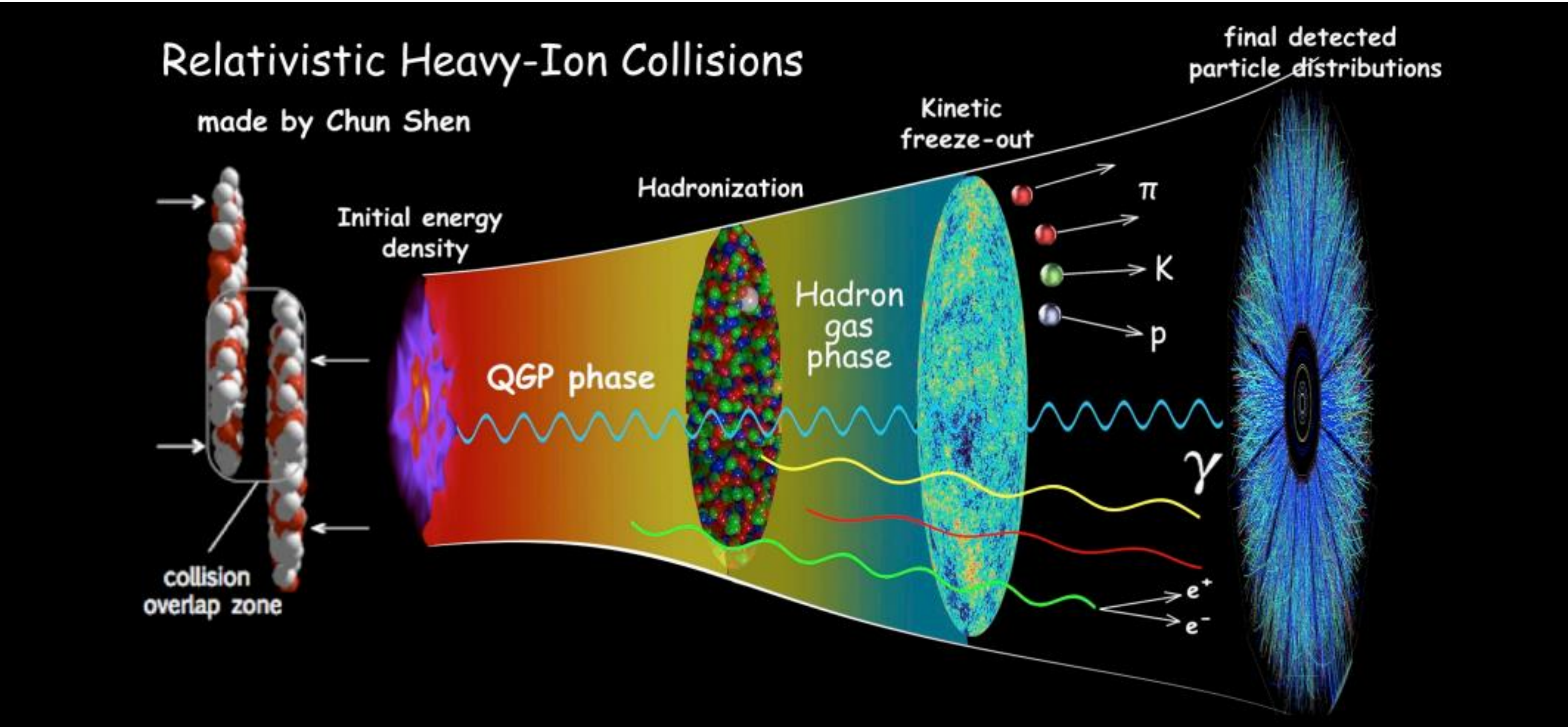
Pinning down the QGP properties
What's the status at LHCP 2022

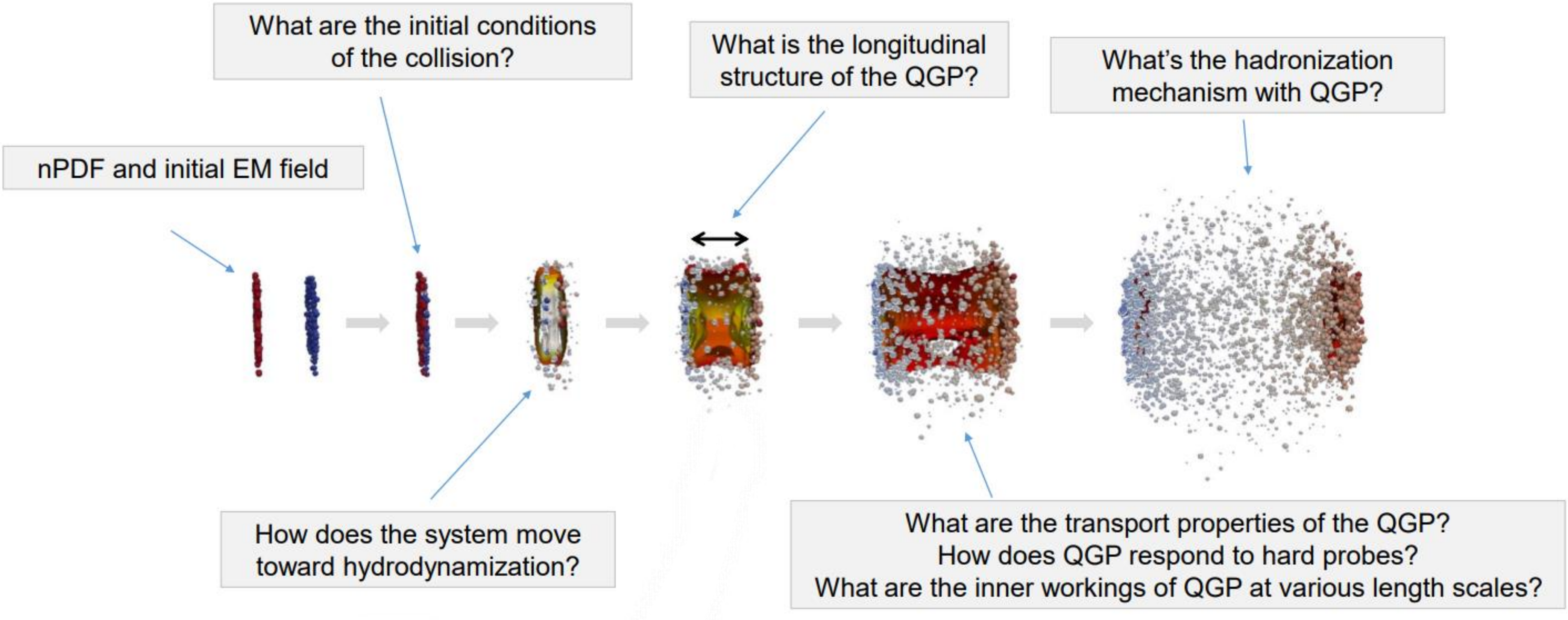


G. K. Krintiras (cern.ch/gkrintir)
on behalf of the ALICE/ATLAS/LHCb & CMS collaborations
The University of Kansas



HIC "Standard Model"

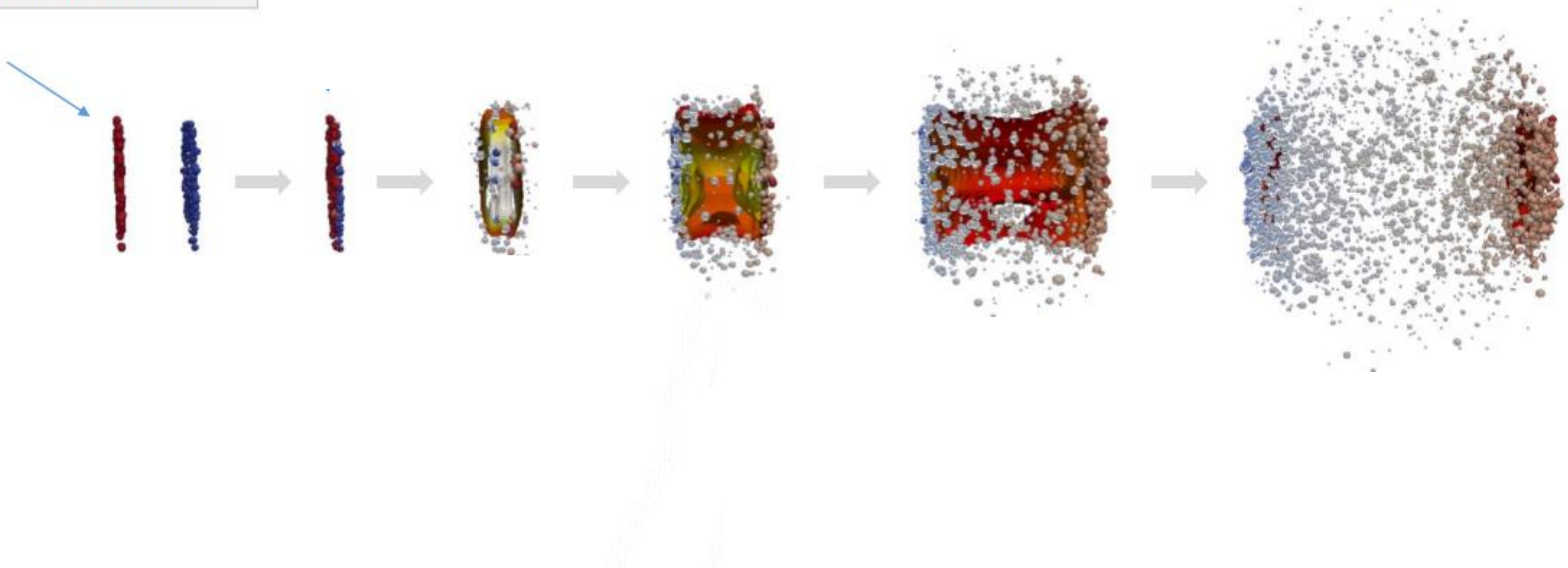
Pressing questions and open items



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

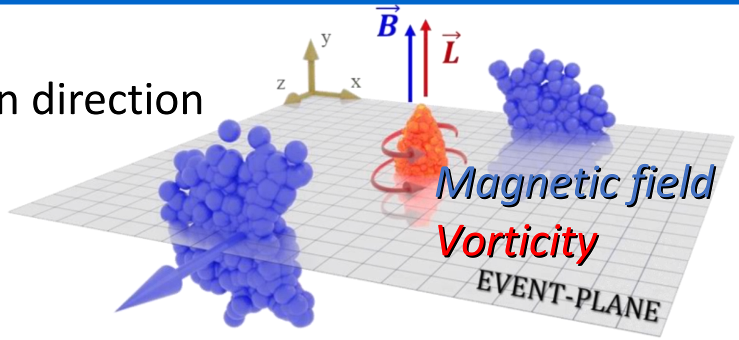
cf. Petja’s talk

nPDF and initial EM field

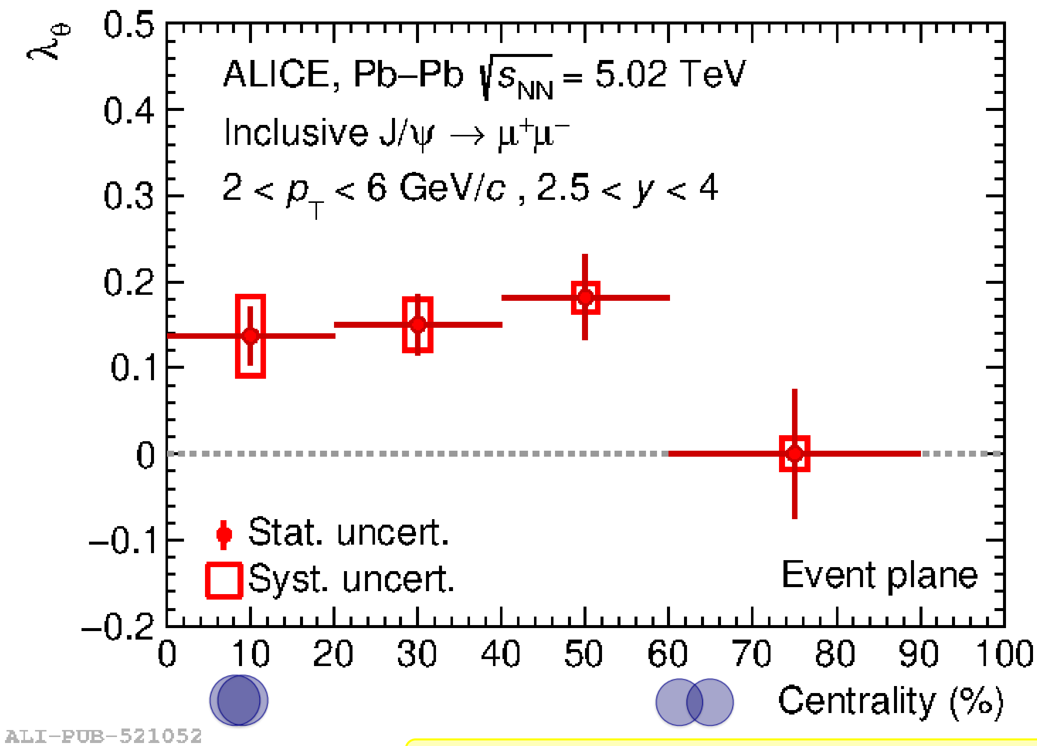


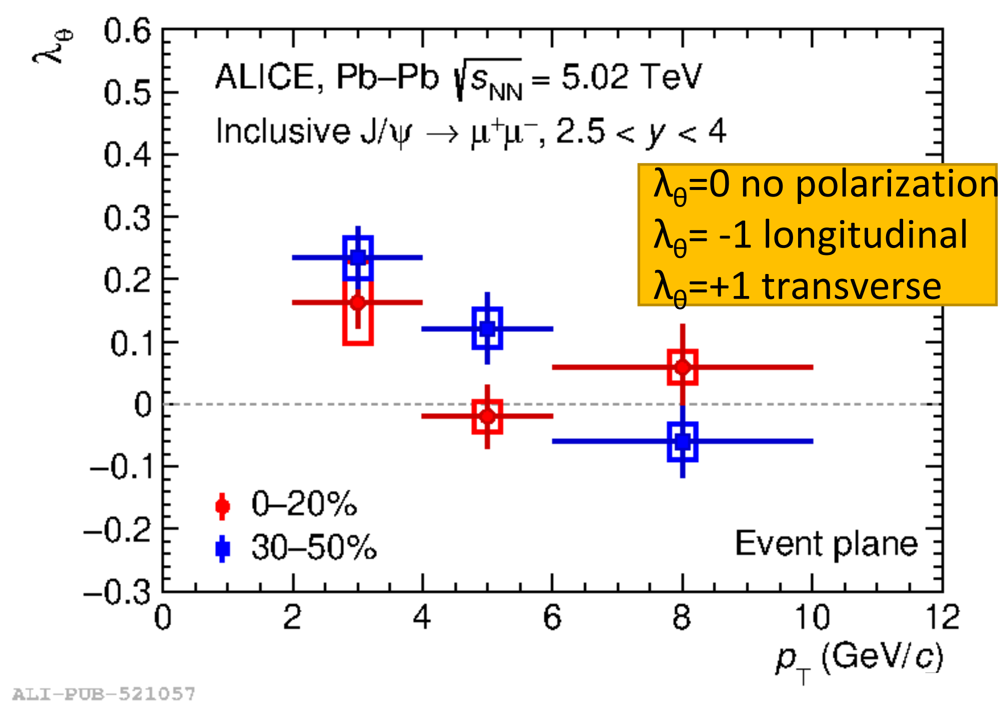
Polarization of quarkonia in PbPb

- 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

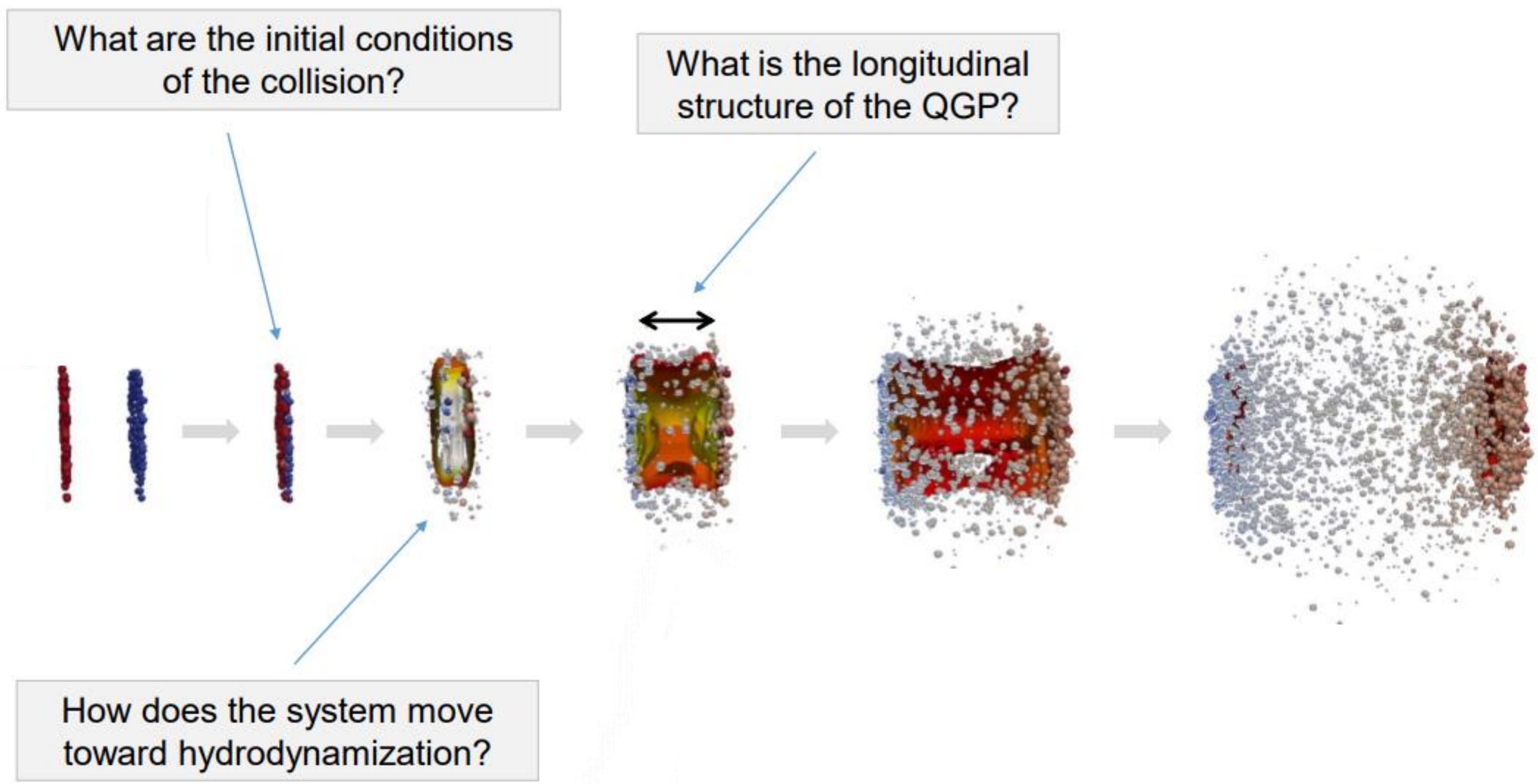


arXiv: 2204.10171

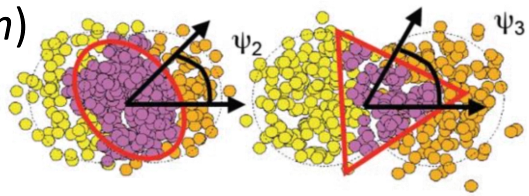




Sensitive to huge **magnetic field** and properties of a **rotating fluid**


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

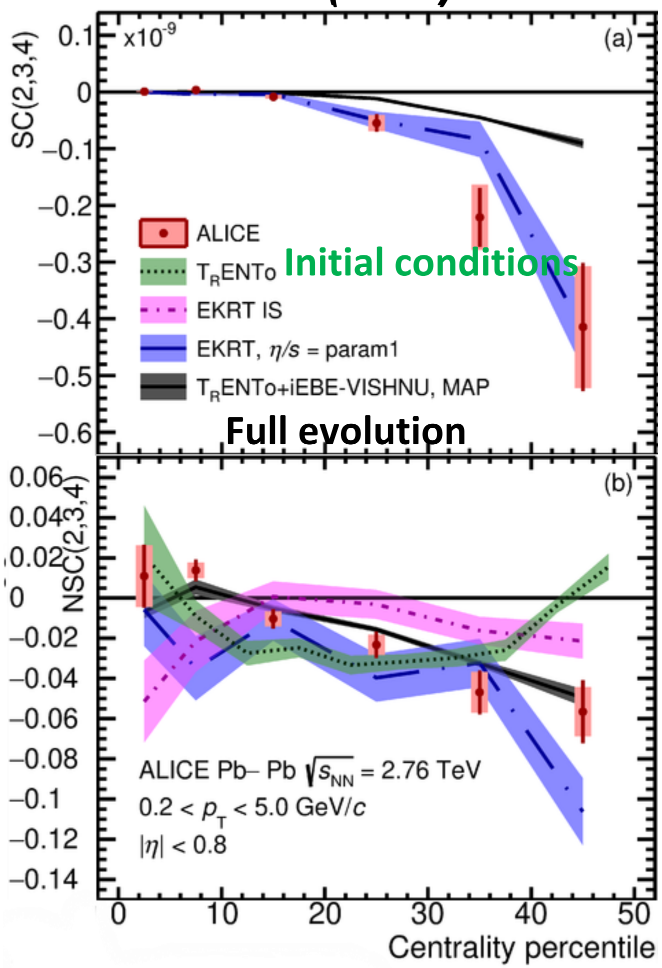
Investigating the initial stages with flow (de)correlations



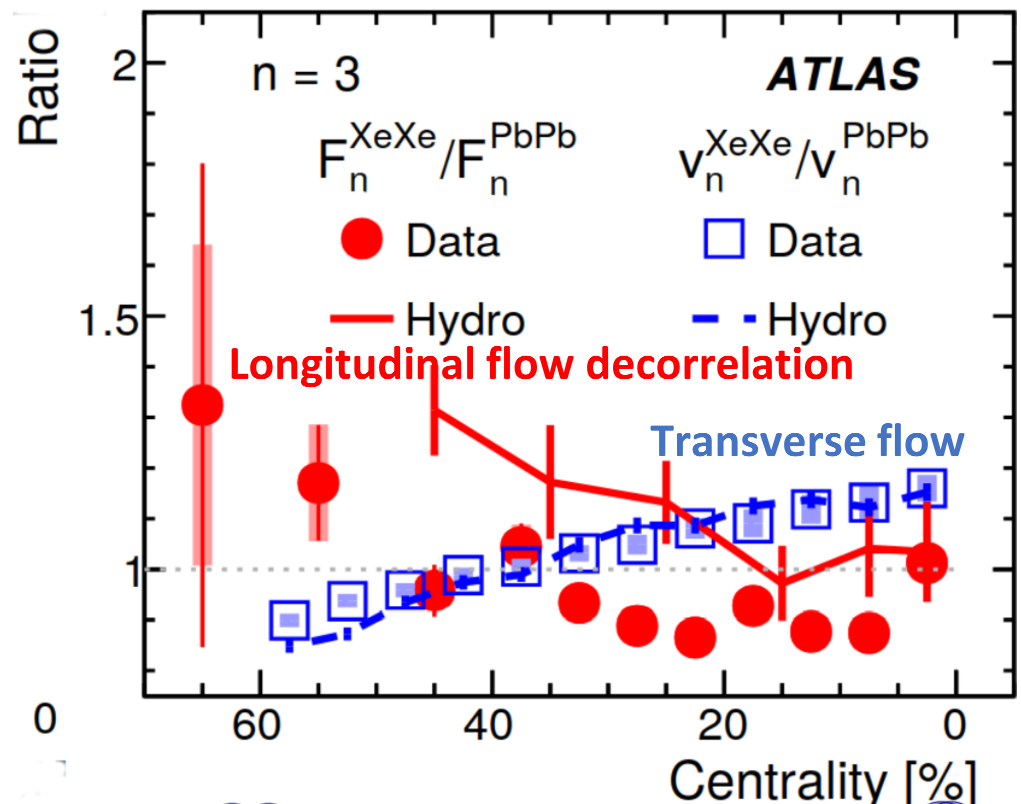
- Multi-harmonic "**cross talk**", e.g., higher order symmetric cumulants SC(*k, l, m*)
  - sensitive to disentangling effects from the **initial state vs QGP evolution**
- Flow **decorrelation**: rapidity dependence of the factorization breaking
  - input to **3D modeling** of initial conditions and QGP

cf. Fabio's talk

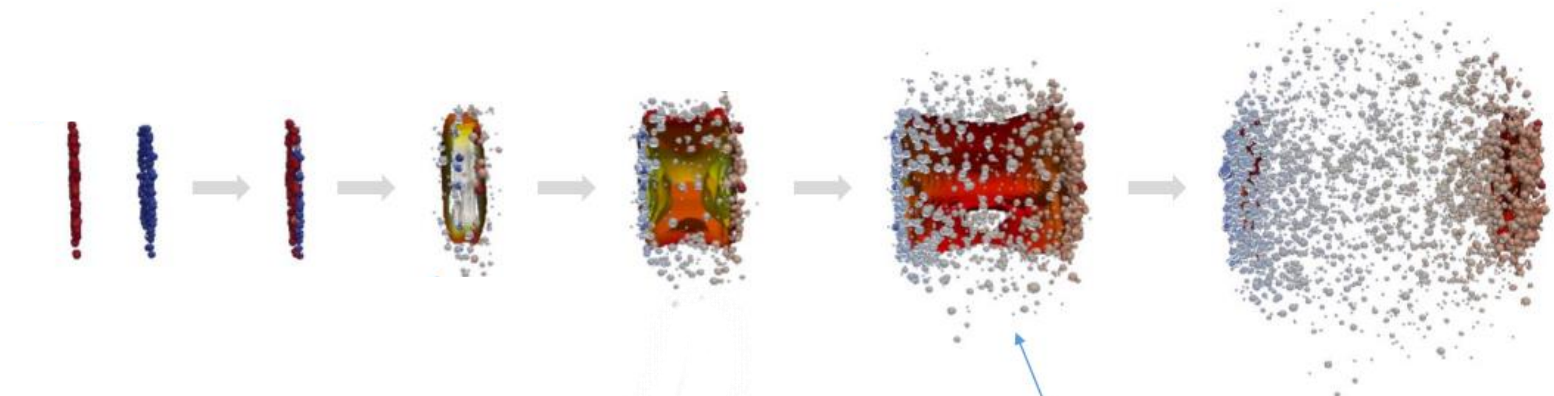
PRL 127 (2021) 092302



PRL 126 (2021) 122301



Understanding initial conditions and early-time effects vital for **modeling**



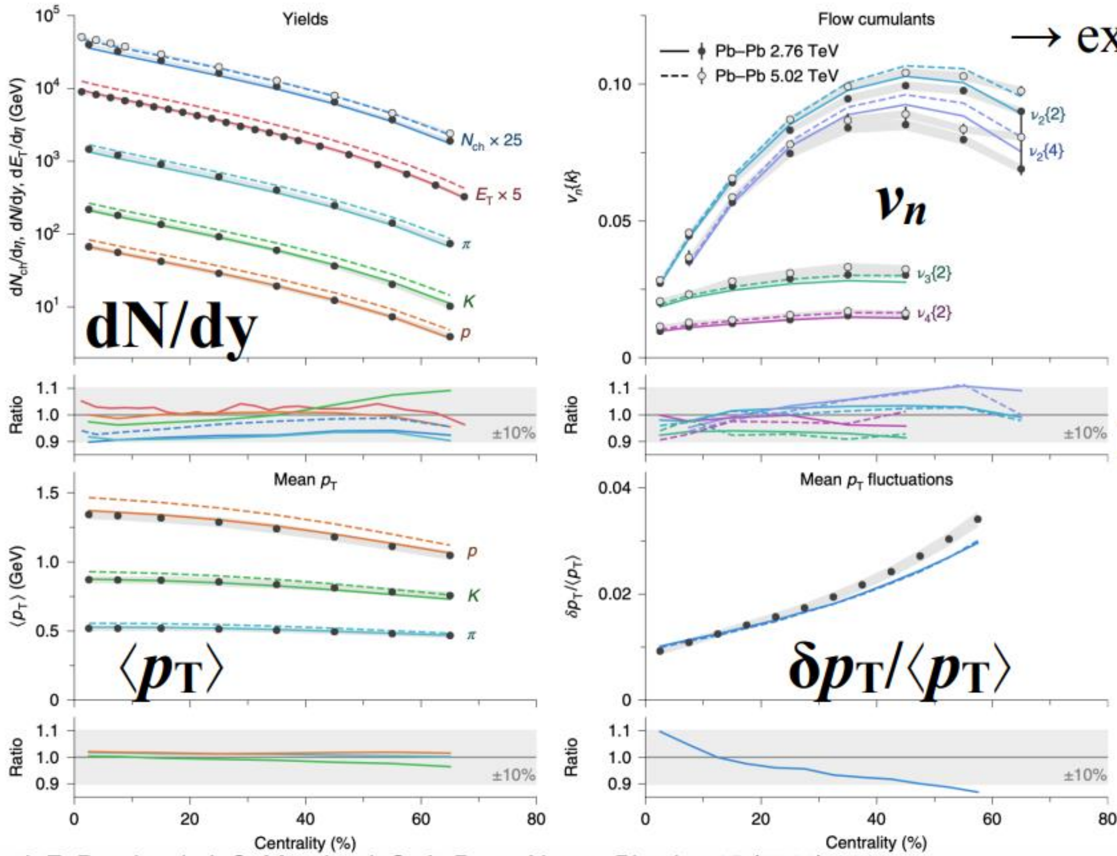
What are the transport properties of the QGP?
How does QGP respond to hard probes?
What are the inner workings of QGP at various length scales?

Extracting QGP thermodynamic properties

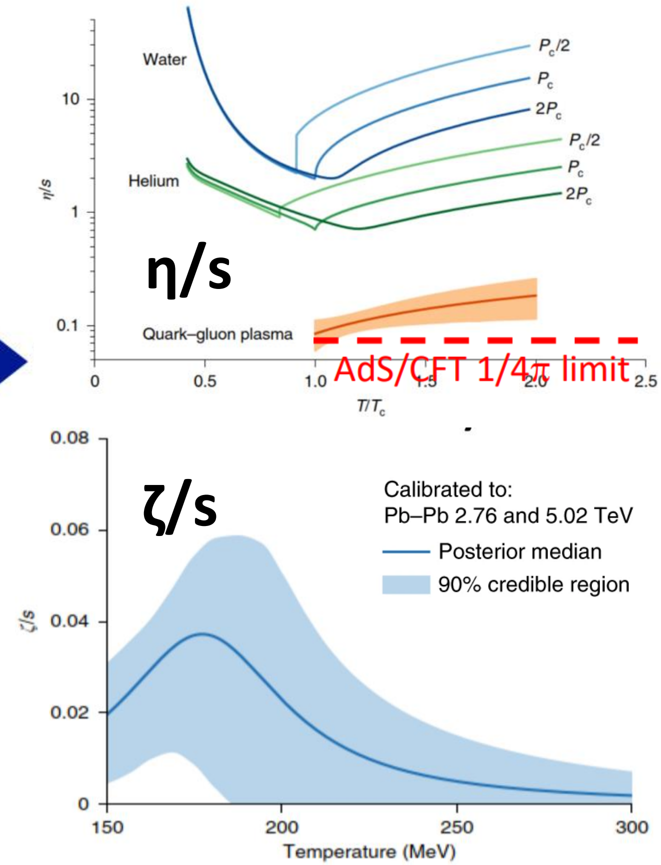
- Soft particle production and kinematics give us information about **QGP and its evolution**
- viscosities **η/s** and **ζ/s** control dissipation of energy-momentum perturbations

cf. Siyu's talk

→ 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

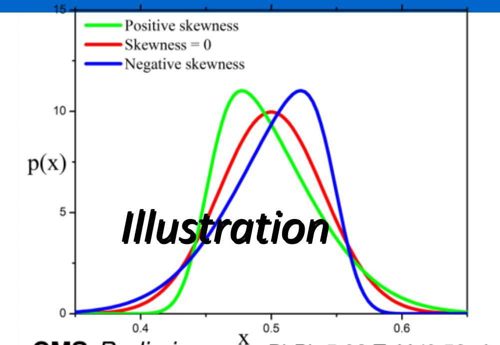


Data from LHC (ALICE and CMS)

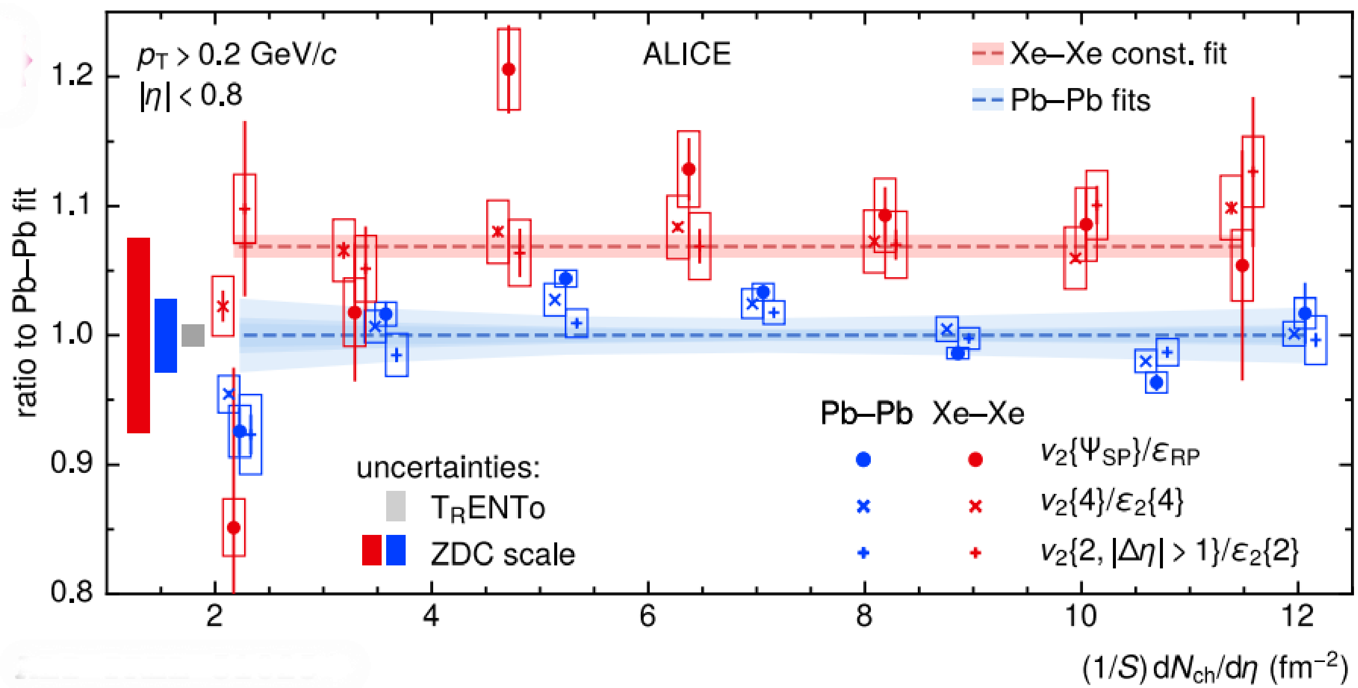
η/s near to AdS/CFT threshold: **almost perfect fluid**!

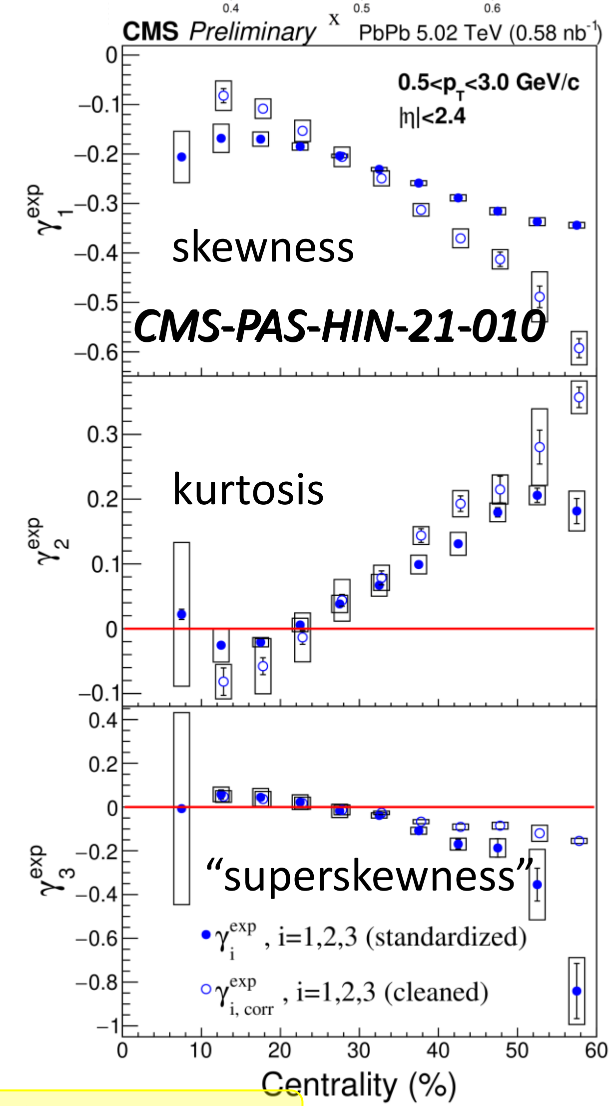
More elaborate flow observables

- Ideal fluid evolution $v_2 \propto k\, \varepsilon_2$ ($k \equiv$ hydrodynamic response of QGP)
- **system size** dependence of v_2/ε_2 sensitive to η/s
- **subtle** differences in $v_2\{2k\}(k \leq 5)$ → fluctuation-driven **moments** of v_2
- constraints on hydro predictions of the QGP evolution



arXiv:2204.10240



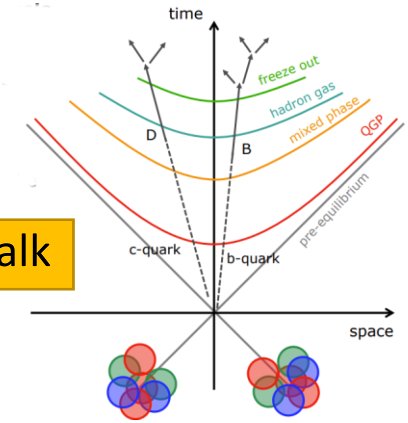


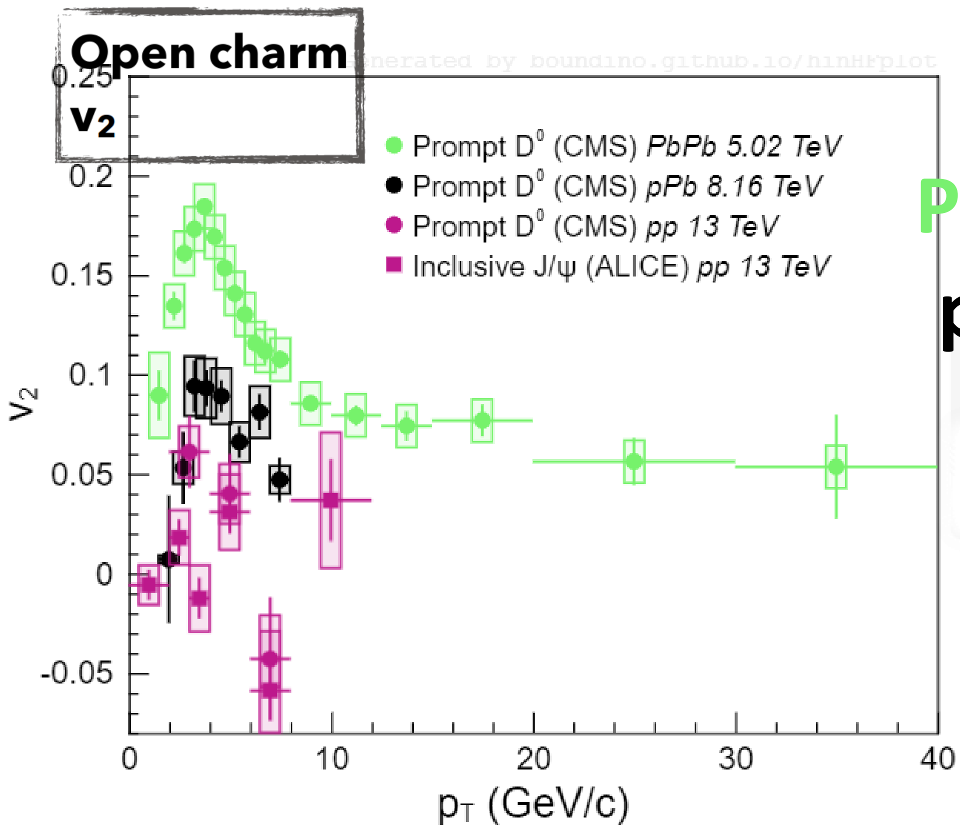
Resolving v_2 event-by-event fluctuations with **unprecedent precision**

Comparing heavy flavor particle flow in all systems

- There is charm anisotropy... everywhere
  - apparent ordering: v_2 (PbPb) > v_2 (pPb) > v_2 (pp)
  - so **system size** should play a role?
- For open bottom hadrons: v_2 (PbPb) > 0 but v_2 (pPb) ~ v_2 (pp) ~ 0
  - do we hit some **threshold** between charm and beauty processes?

cf. Milan's talk





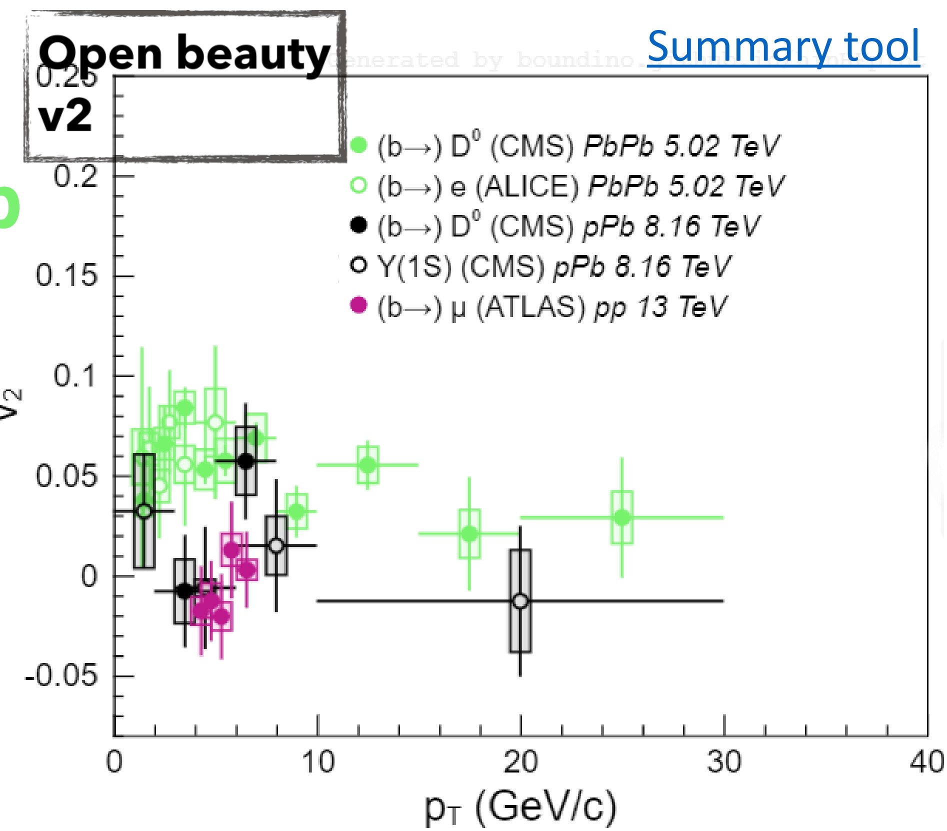
- PLB 816 (2021) 136253
- PRL 121 (2018) 082301
- PLB 813 (2021) 136036
- ALICE Preliminary

PbPb

pPb

pp

[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

Measuring jet quenching (I)

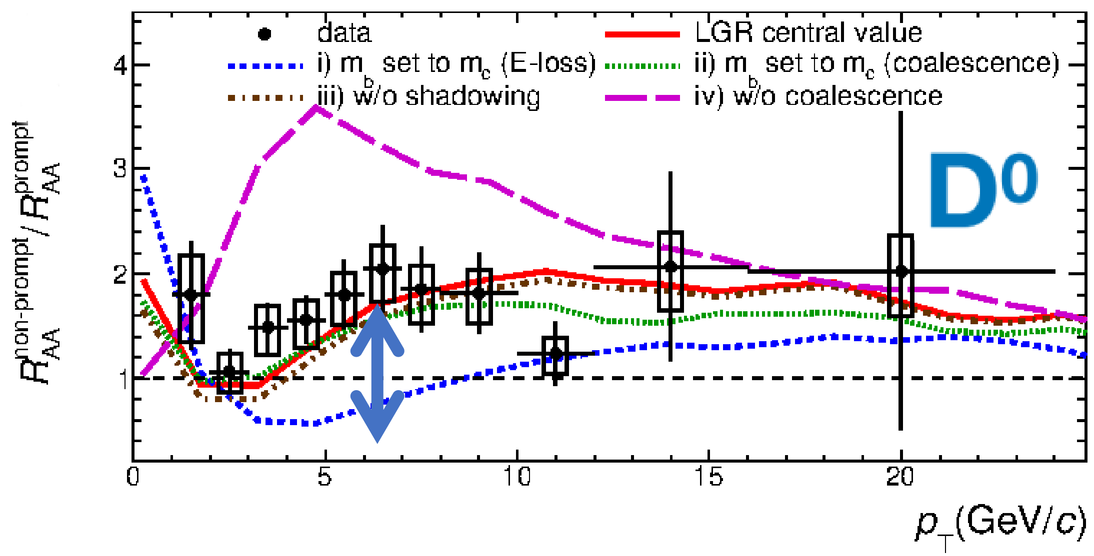
- Energy of partons is redistributed ('quenched') inside QGP
  - Experimentally seen as R_{AA} modifications of **jets** (or hadrons)

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

- Evidence of **mass** dependence
  - nonprompt D^0 **>** prompt D^0 R_{AA}
  - b jets **less suppressed** than inclusive jets

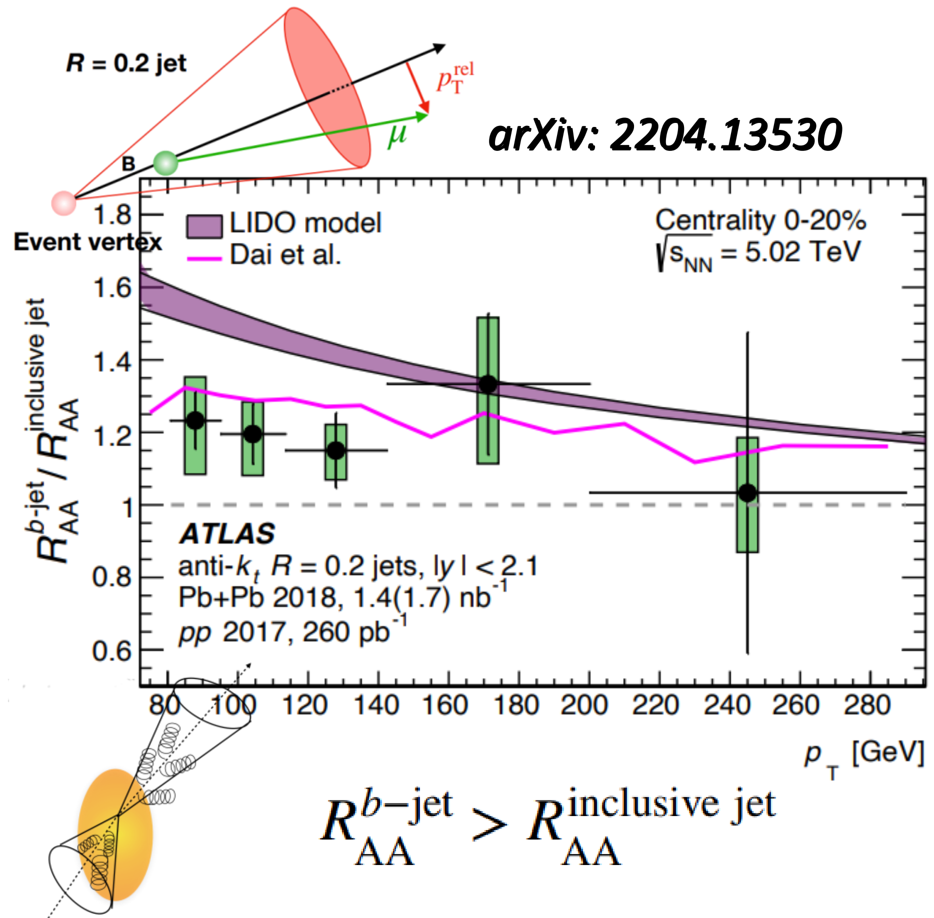
cf. Andre's & Yaxian's talks

arXiv: 2202.00815



$m_b \rightarrow m_c$: ratio of $R_{AA}^{pred} < R_{AA}^{meas}$

arXiv: 2204.13530



$$R_{AA}^{b-\text{jet}} > R_{AA}^{\text{inclusive jet}}$$

Measuring **jet quenching (II)**

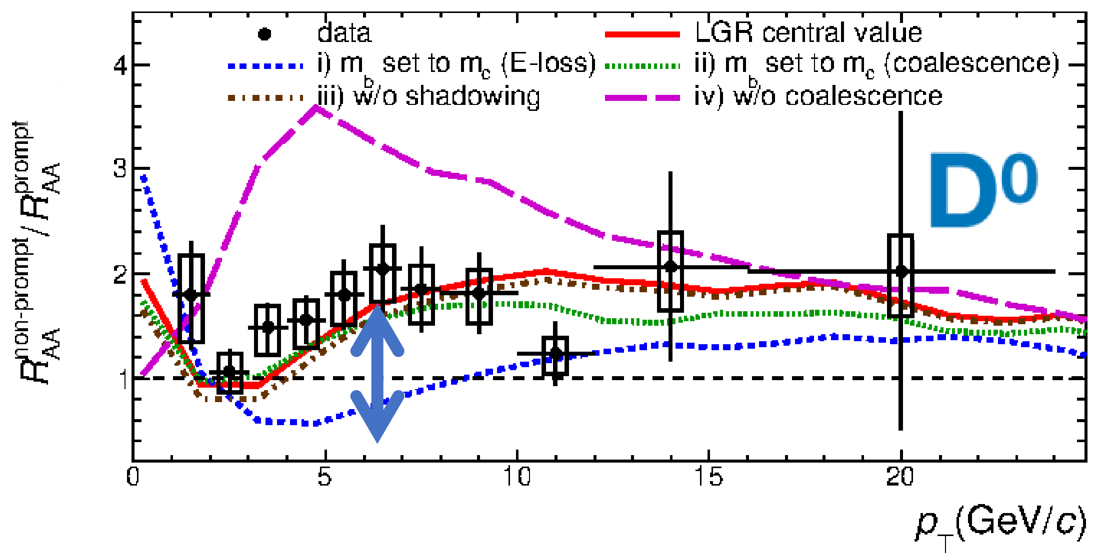
- Energy of partons is redistributed ('quenched') inside QGP
  - Experimentally seen as R_{AA} modifications of **jets** (or hadrons)

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

- Evidence of mass **and color-charge** dependence
  - γ-tagged (i.e., quark-initiated) jets **less suppressed** than inclusive jets

cf. Andre's & Yaxian's talks

arXiv: 2202.00815



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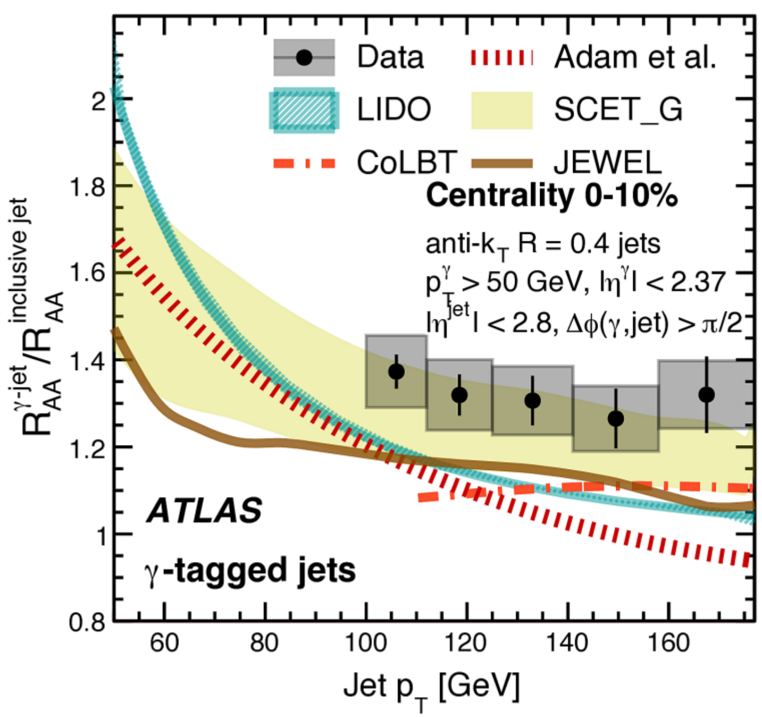
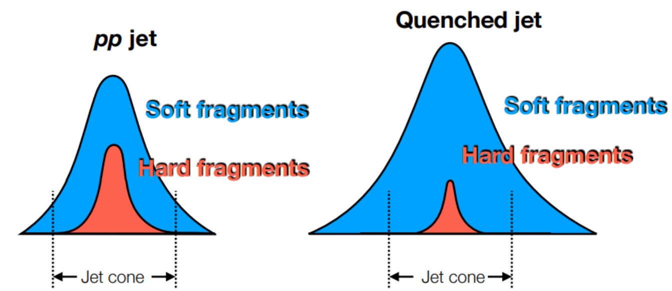
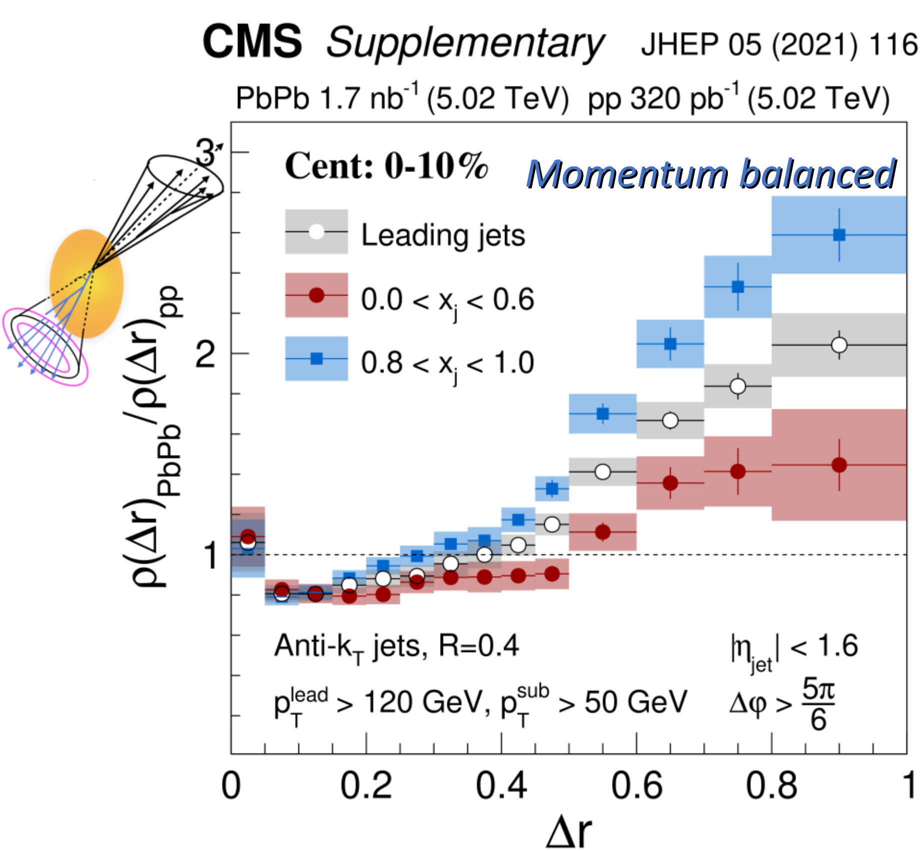


Parton mass and color-charge dependence play a major role in energy loss

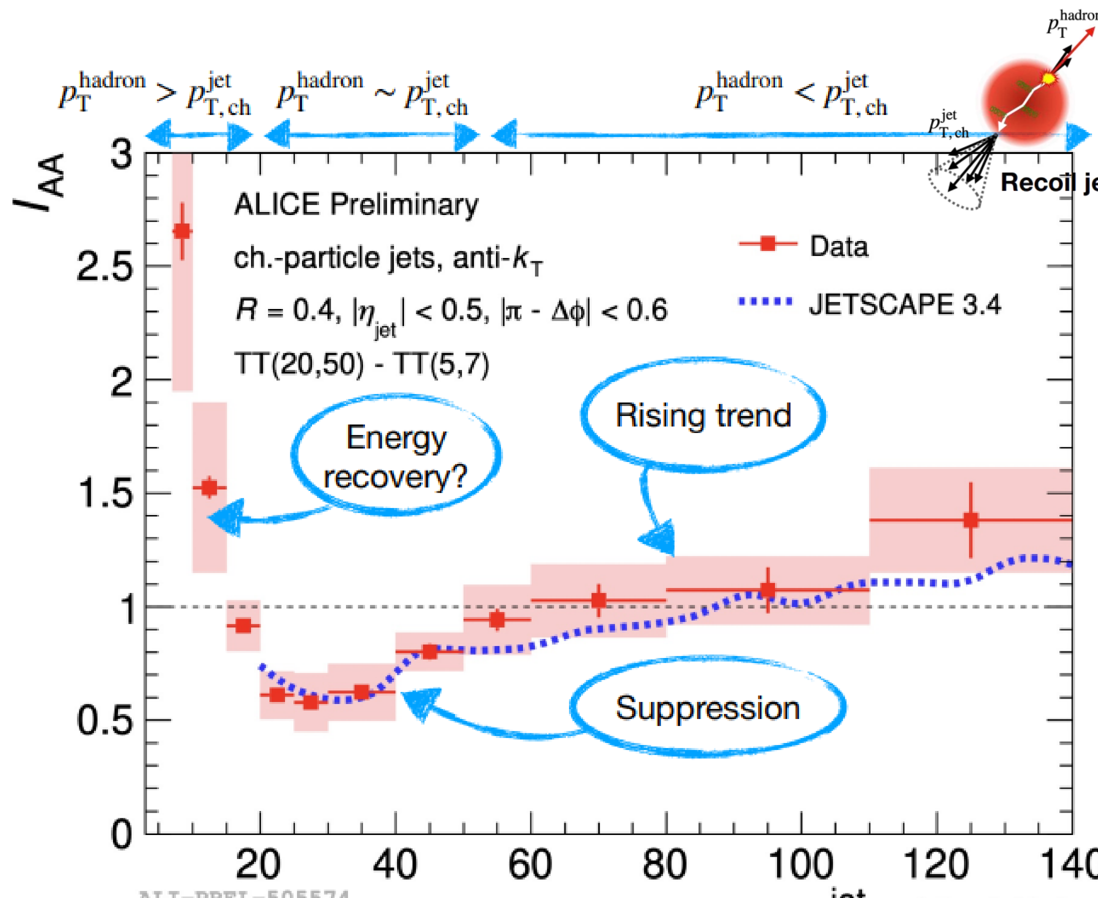
How energy loss is distributed?

- **Jet shape**: radial profile of particles in jets
  - energy outside jet cone is mostly **low energy** particles
  - energy is transferred by soft particles **at large angles**
- $\mathbf{I_{AA}}$: check the behavior of associated particles (jets, Z bosons, ..)
  - **suppression (recovery)** of high (low) momentum associated yield



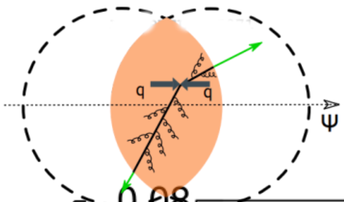


$$\rho(\Delta r) = \frac{1}{\delta r}\frac{1}{N_{\text{jets}}}\frac{\sum_{\text{jets}}\sum_{\text{tracks}\in(\Delta r_a,\Delta r_b)} p_T^{\text{ch}}}{\sum_{\text{jets}}\sum_{\text{tracks}\in\Delta r\leq 1} p_T^{\text{ch}}}$$

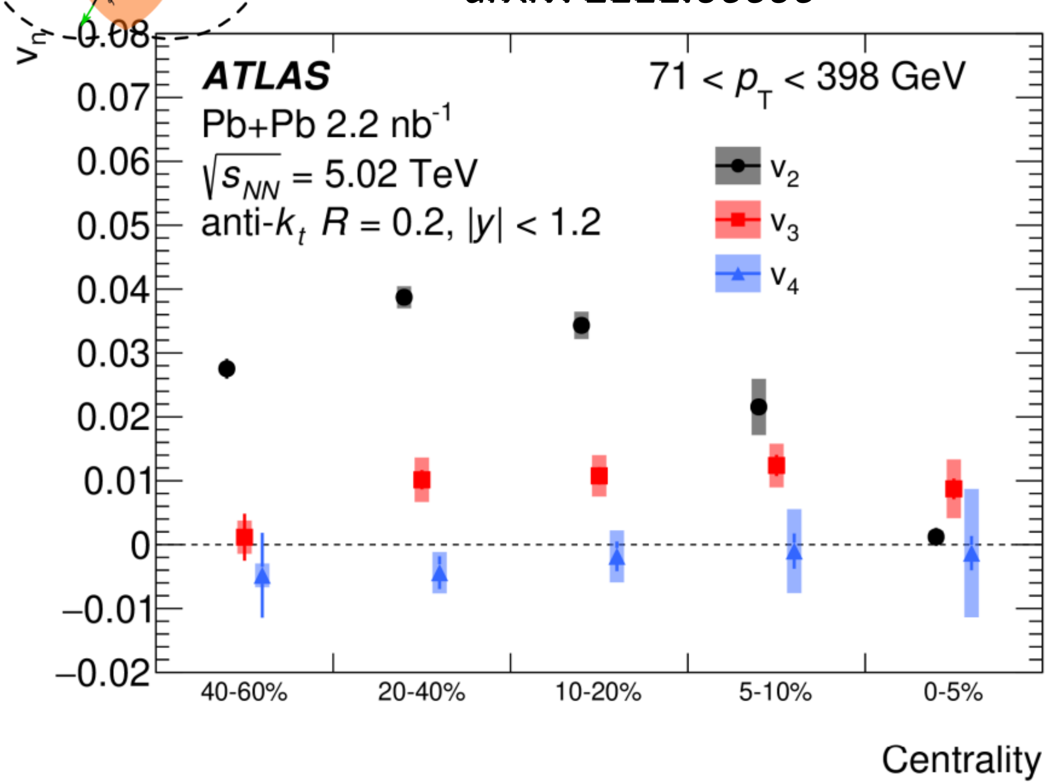


Important to include **medium response** in the modeling

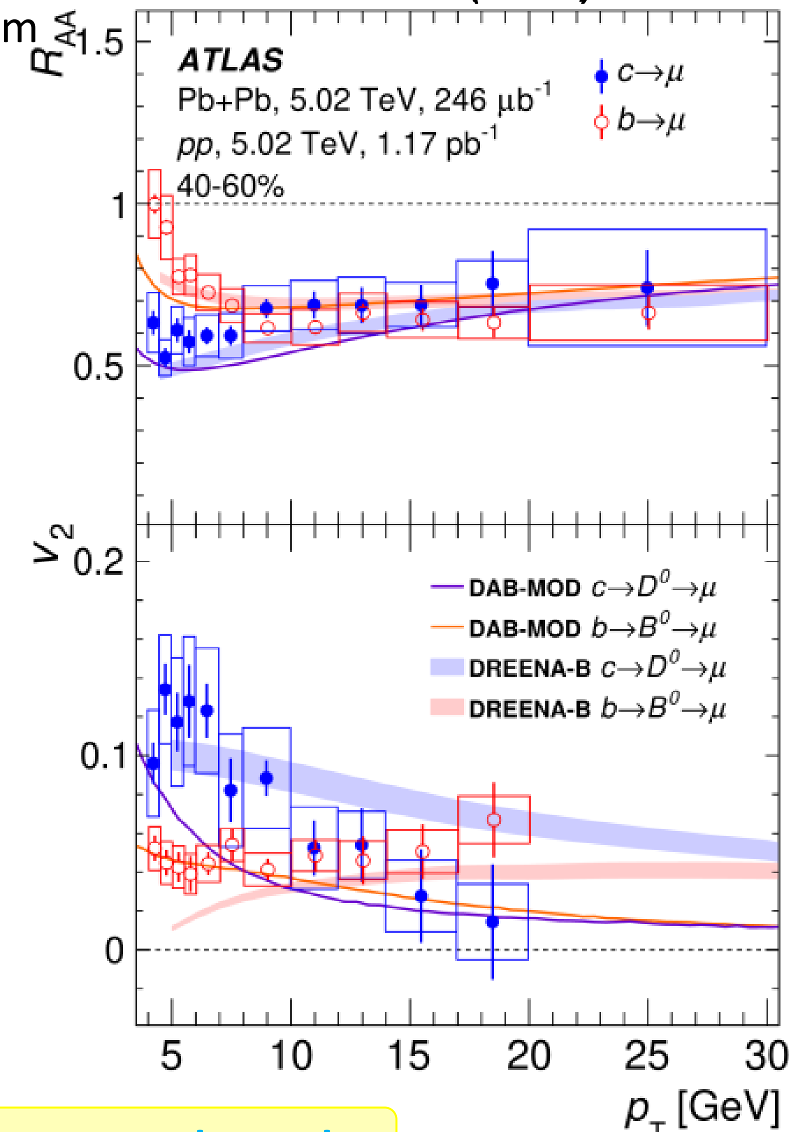
- Measure the rate of jets wrt. collision geometry: varies the amount of QGP that the jet sees
  - jet v_n show the **path length dependence** of jet quenching
  - jet $\mathbf{v_3}$ **>0** sensitive to the fluctuations in the initial state
- **Simultaneous measurement** of R_{AA} and v_2 for charm and bottom
  - **mass splitting** at low p_T but converge at high p_T ($\gg m_b$)



arXiv: 2111.06606



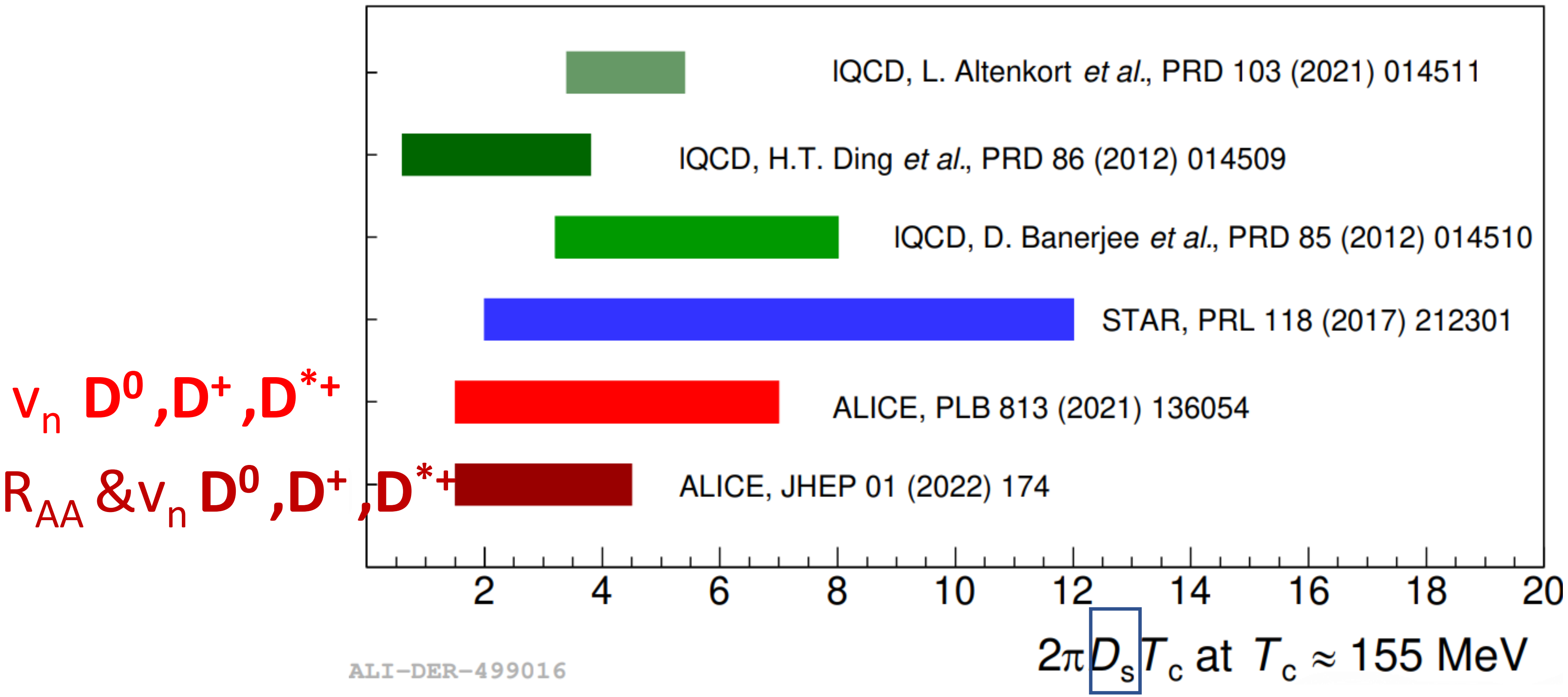
PLB 829 (2022) 137077



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

Explore energy loss and QGP expansion at the same time (II)

- **Constraining** the spatial diffusion coefficient via data-to-model comparisons
- different transport models for energy loss and hadronization ($T > T_c$) mechanisms
- simultaneous description of R_{AA} and v_2 → $1.5 < 2\pi D_s T_c < 4.5$ (current best limit at LHC)
- **in agreement** with D_s from other v_2 measurements and the ones used to describe c,b → μ



First constraints on the **spatial diffusion coefficient** at LHC

Repeating the same procedure in pPb **fails**?

- Positive v_n seen in pPb up to high p_T
  - **reproduced** by jet quenching model
- No suppression observed in pPb
  - **contrary** to the prediction from the very same model
  - supported by **no modifications** of hadron yields in central pPb
- Use smaller systems (e.g., γA) or lighter ions
  - Does RAA simply scale with initial 'geometry'?
  - OO collisions could provide **key guidance** for jet quenching in lighter systems

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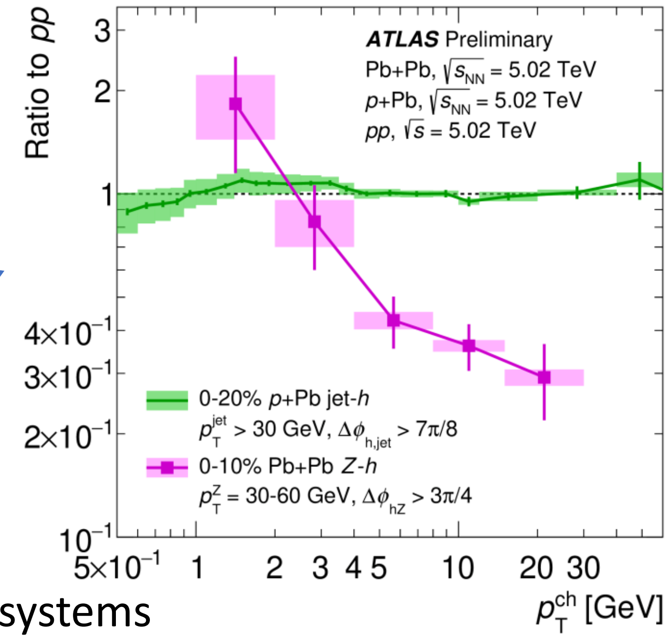
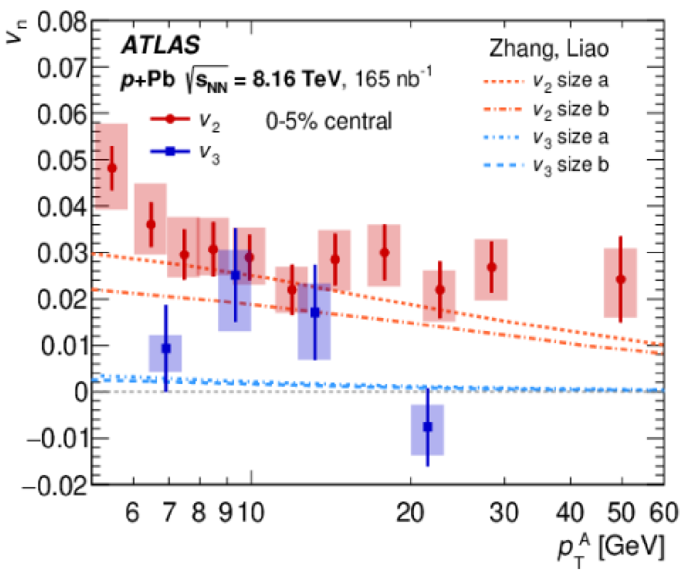


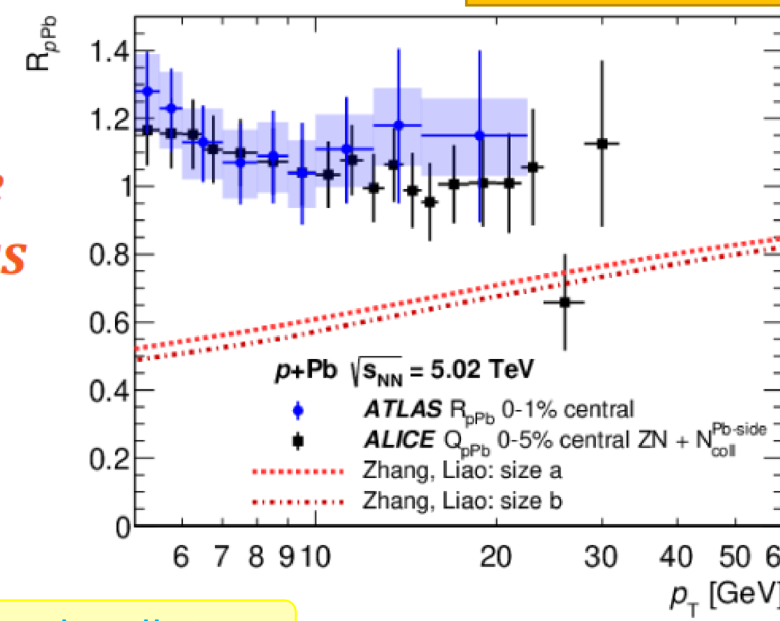
cf. Katerina's & Aleksas's talks

EPCJ C 80 (2020) 73

Significant Elliptic Flow



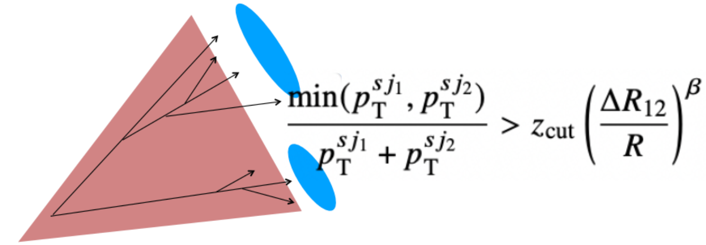
Negligible Energy Loss



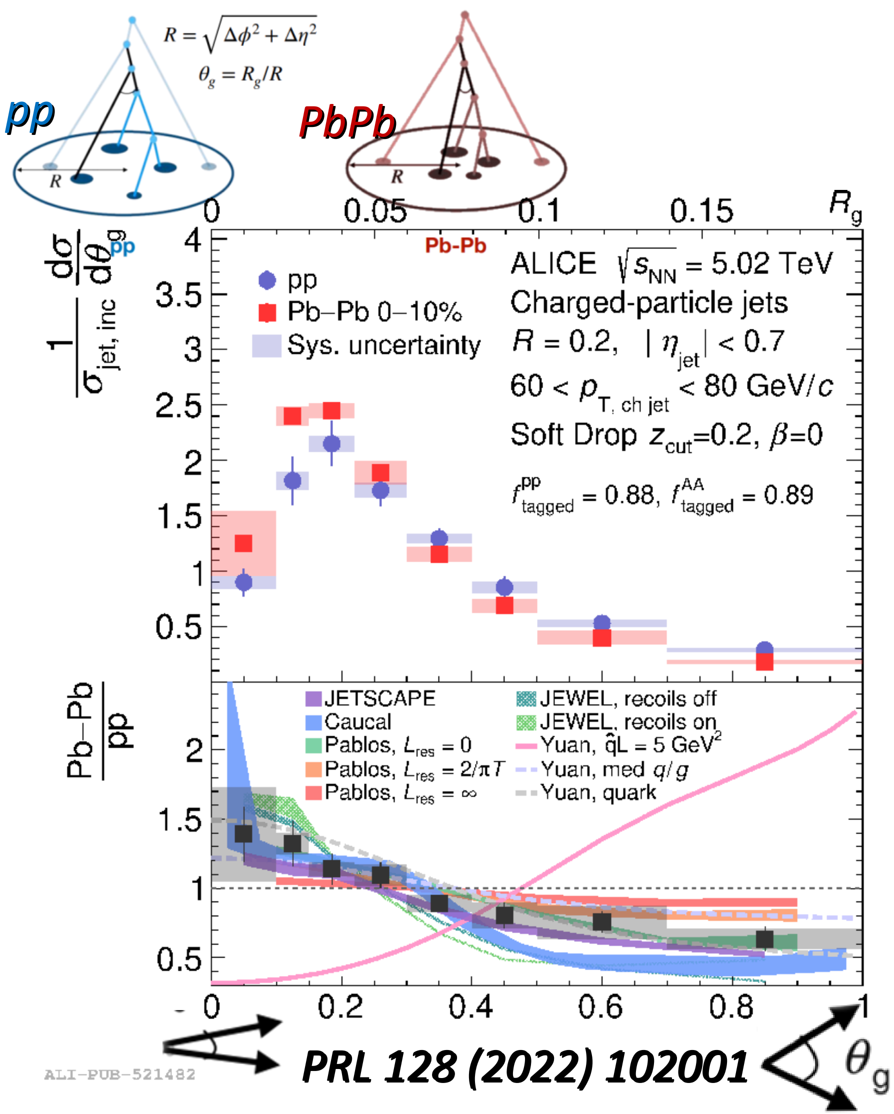
Pinning down the **energy loss limit** in pPb collisions

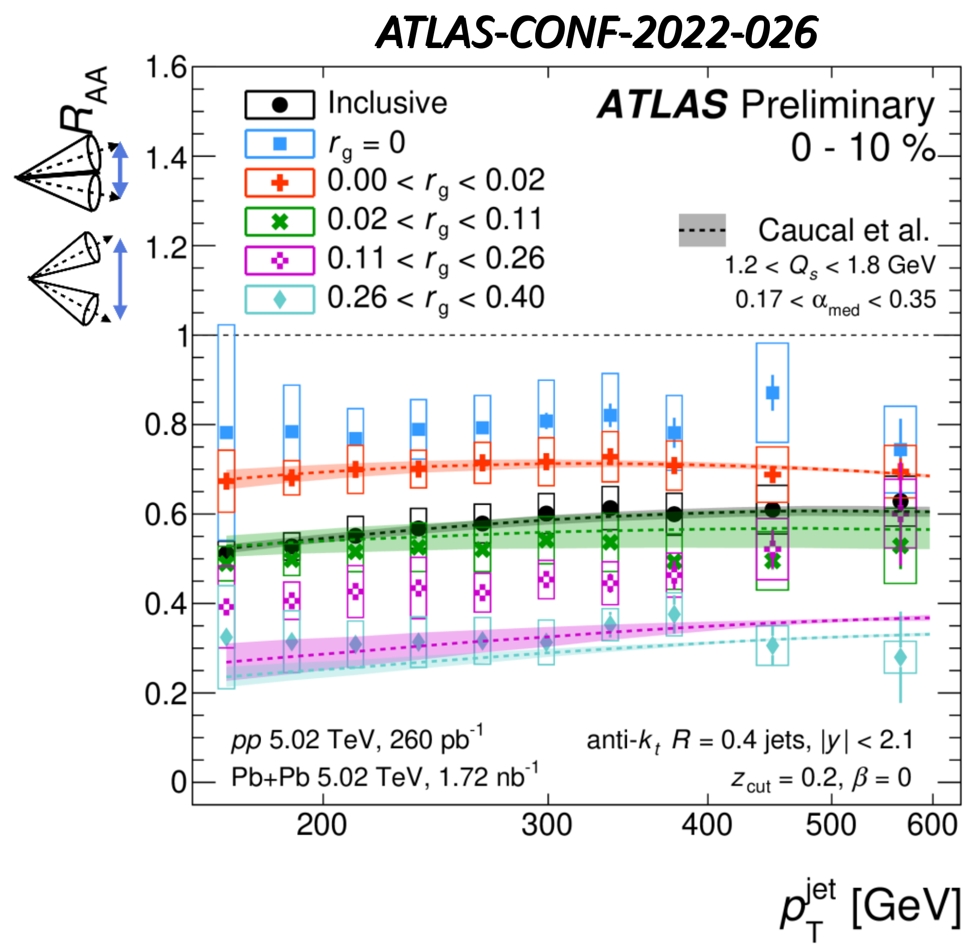
Can the QCD medium resolve the jet internal structure?

- A series of variables probe different aspects **of jet substructure**
- θ_g : jet core **more collimated** in PbPb than pp
- A critical angle (r_g) above which jets lose energy **incoherently?**



cf. Martin's talk





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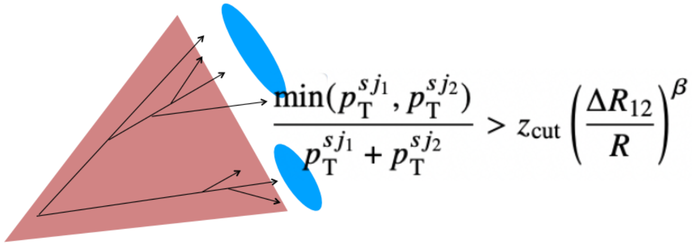

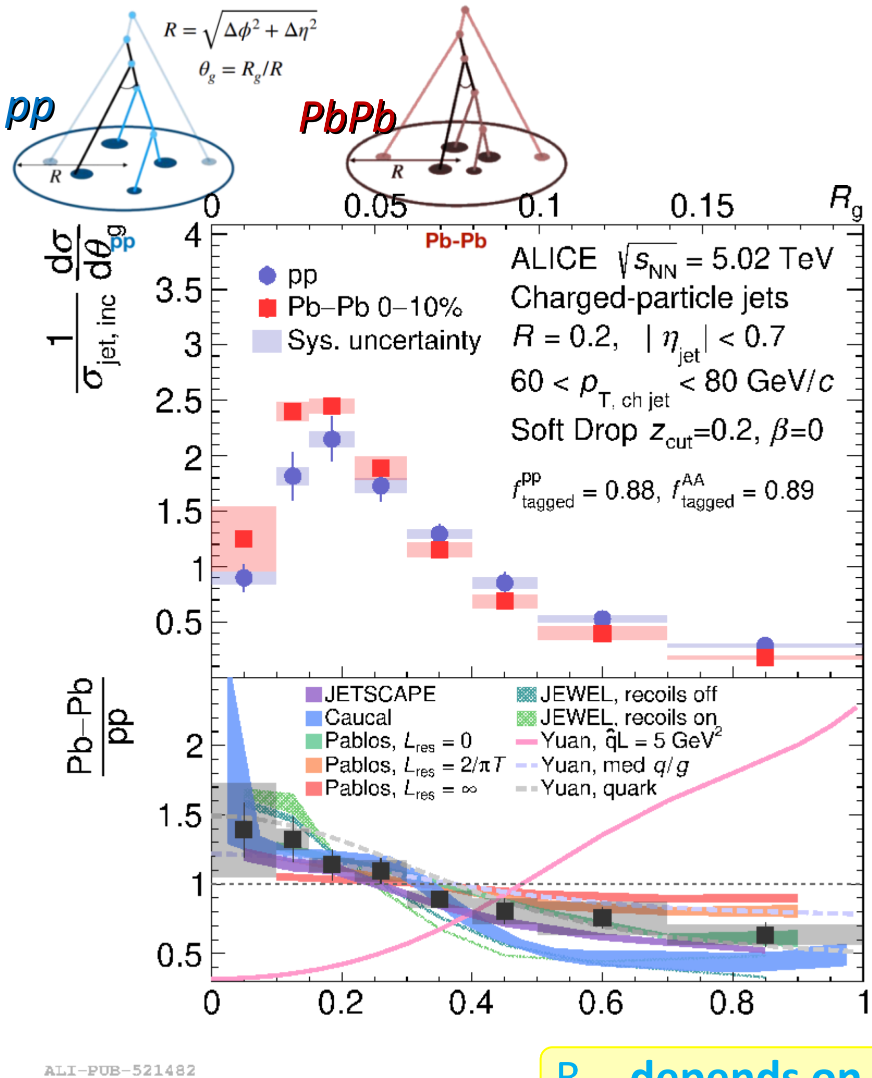

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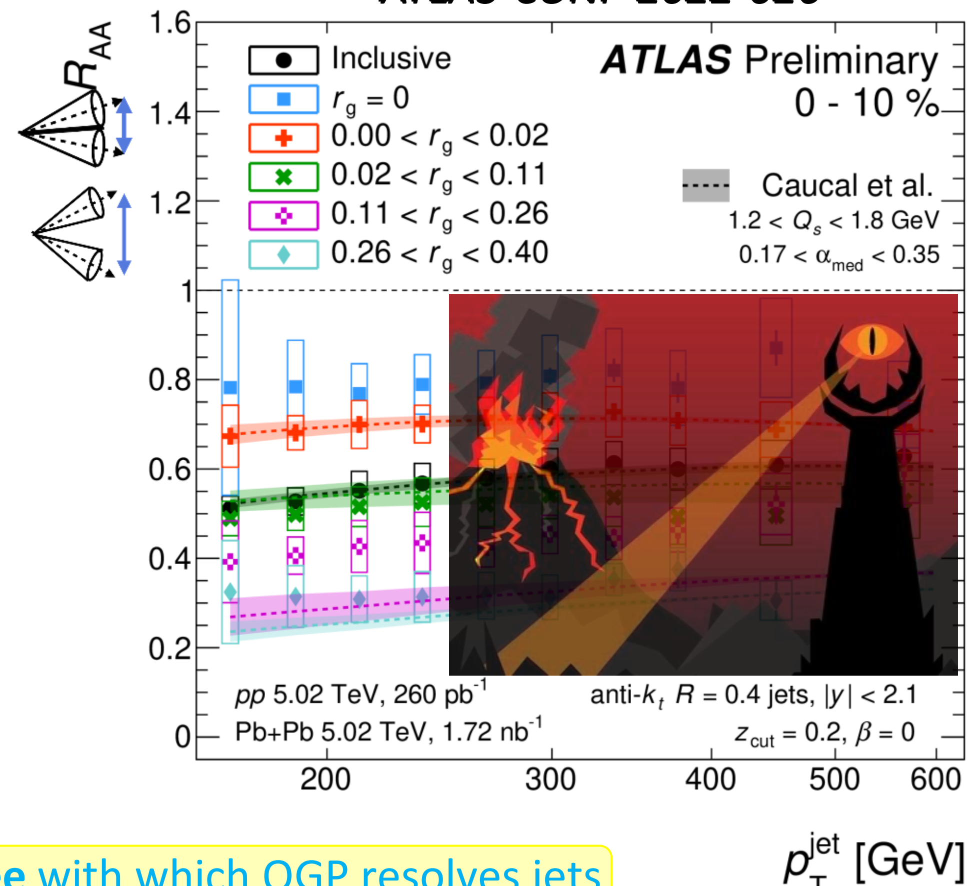
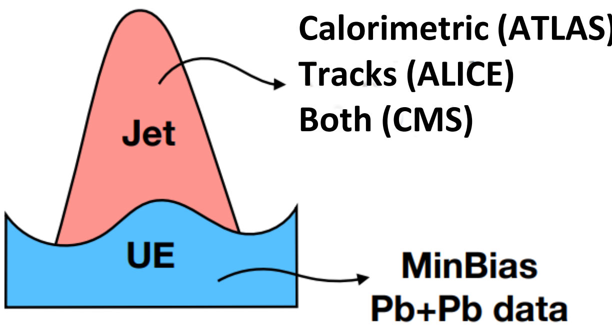


R_{AA} **depends on the degree** with which QGP resolves jets

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**



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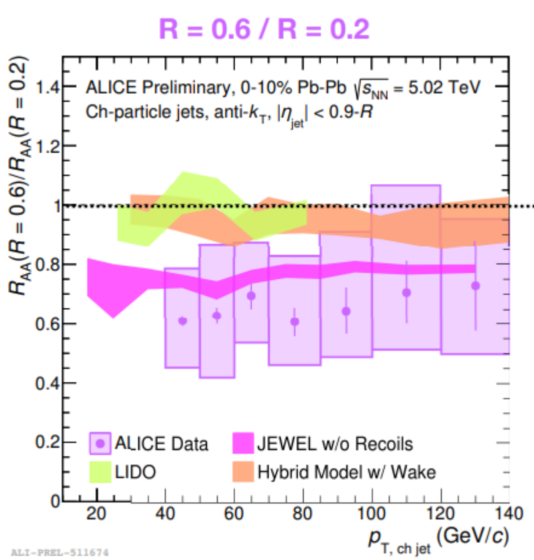

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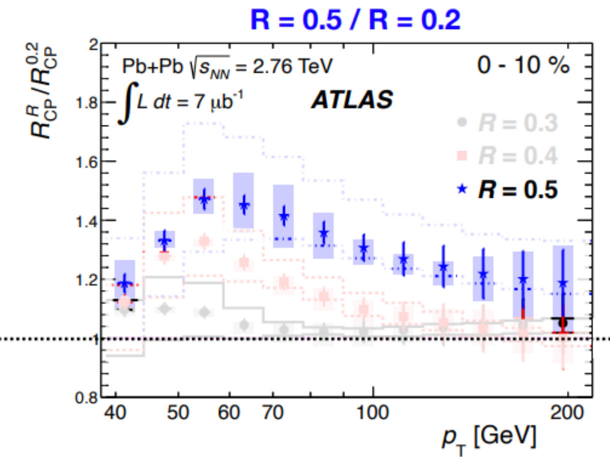
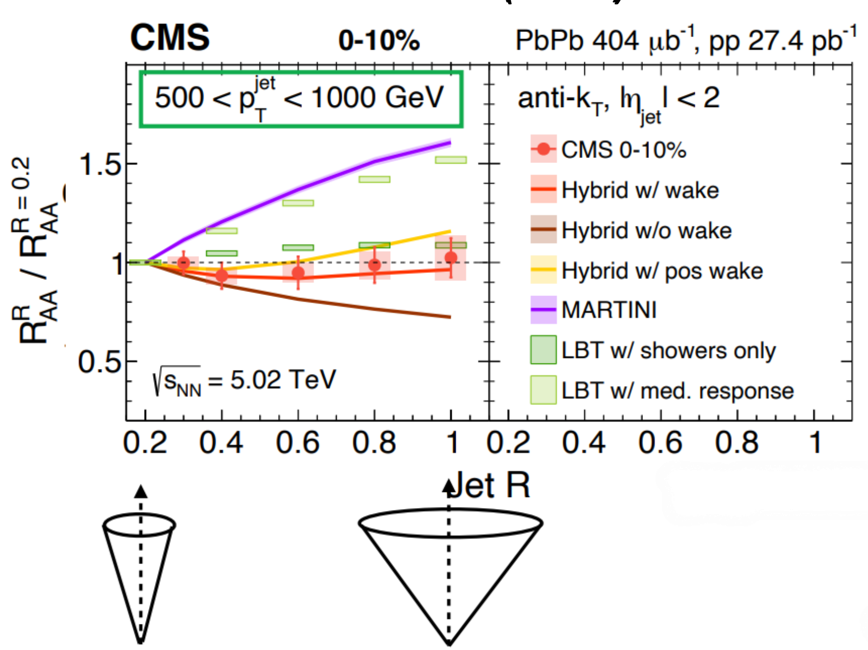


JHEP 05 (2021) 284

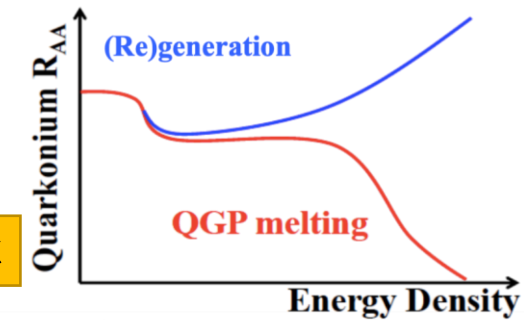


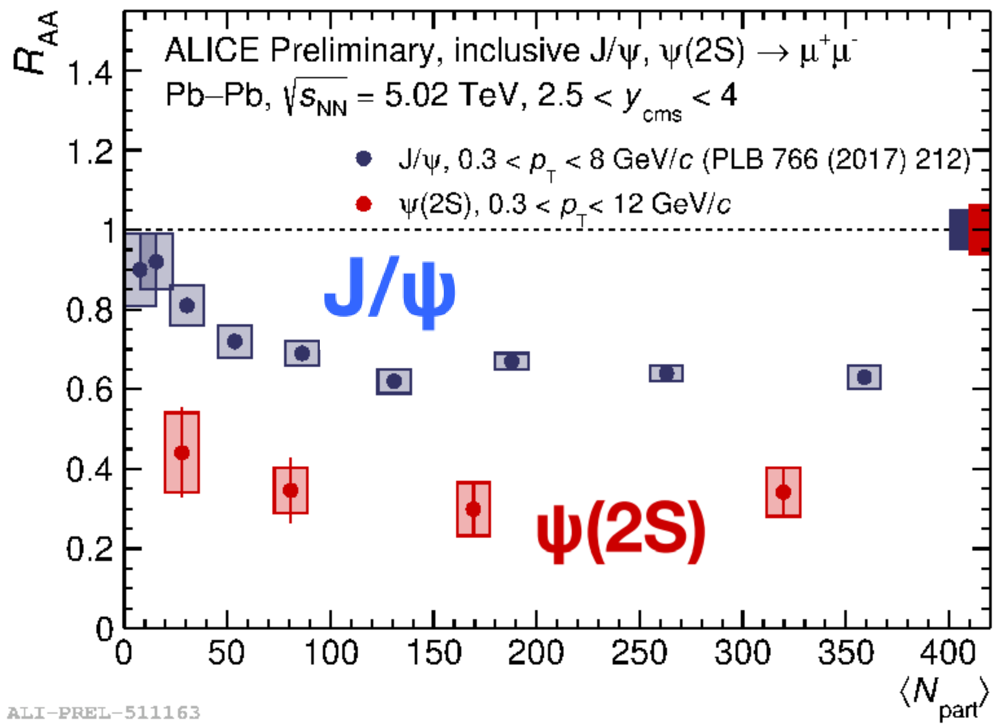
Discriminating power for models and the physics mechanisms at play

Heavy quarkonia suppression-regeneration

- Clear **hierarchy of suppression** between J/ψ and ψ(2S)
  - consistently for all studied p_T and centrality
- Observation of the **sequential melting** of ϒ(ns) states
  - first time including **Υ(3S)** in the picture

cf. Robin's talk





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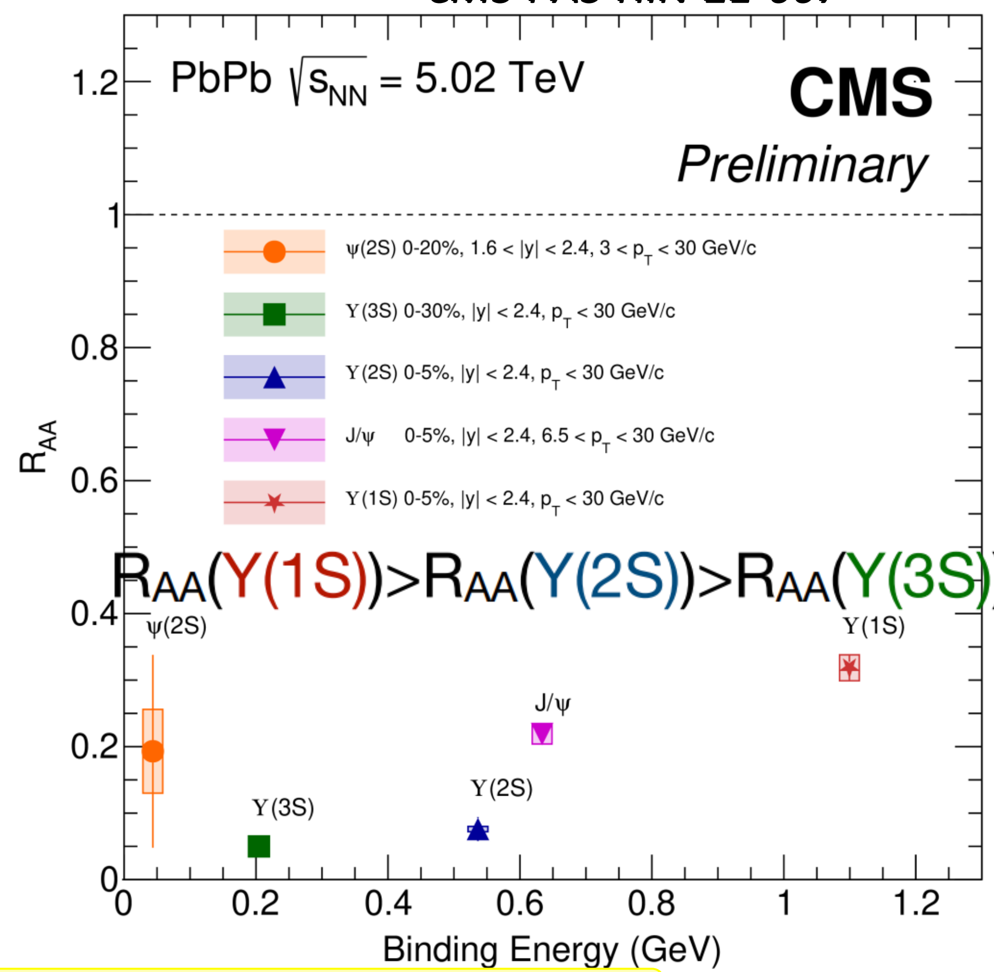
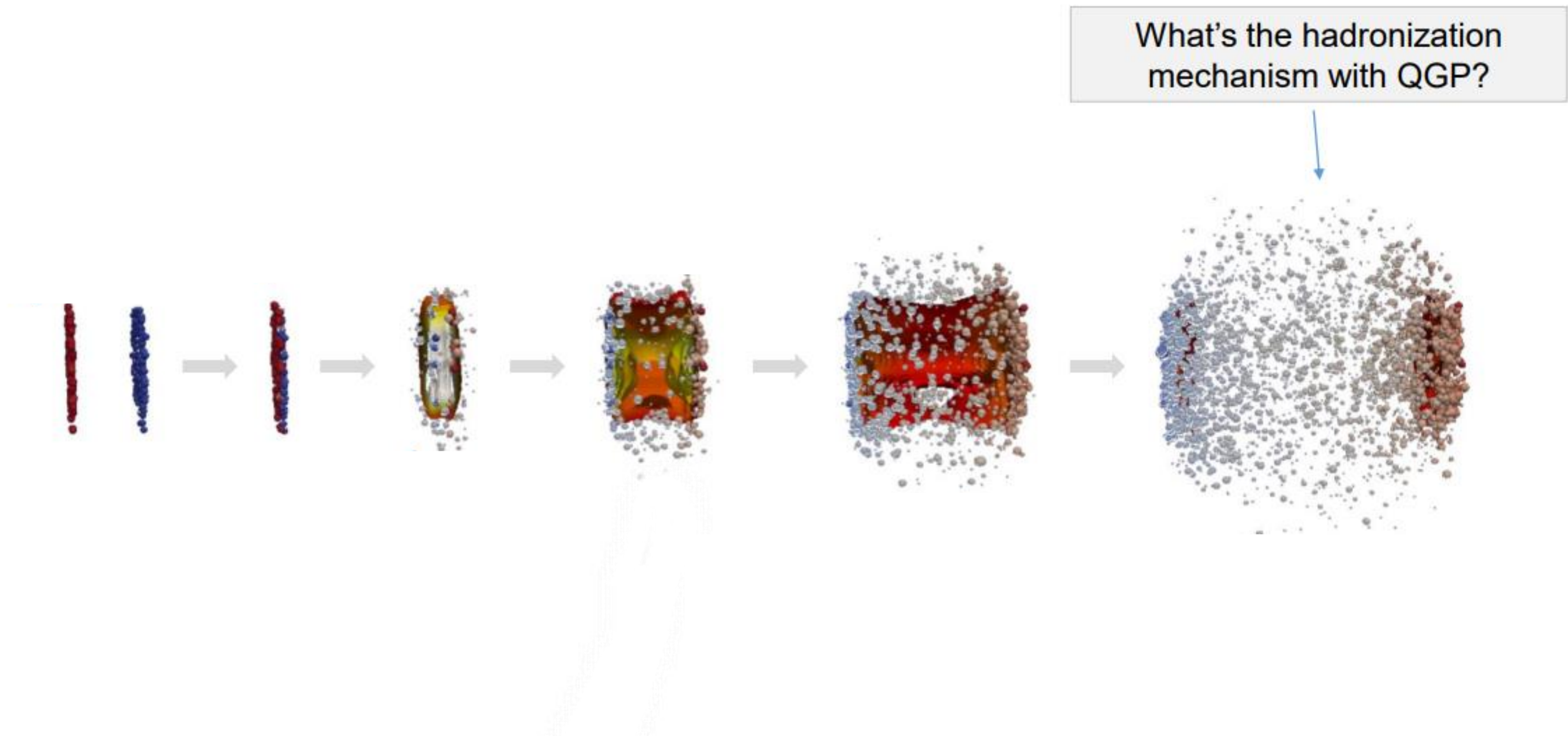


Interplay of **suppression-regeneration** crucial to grasp data

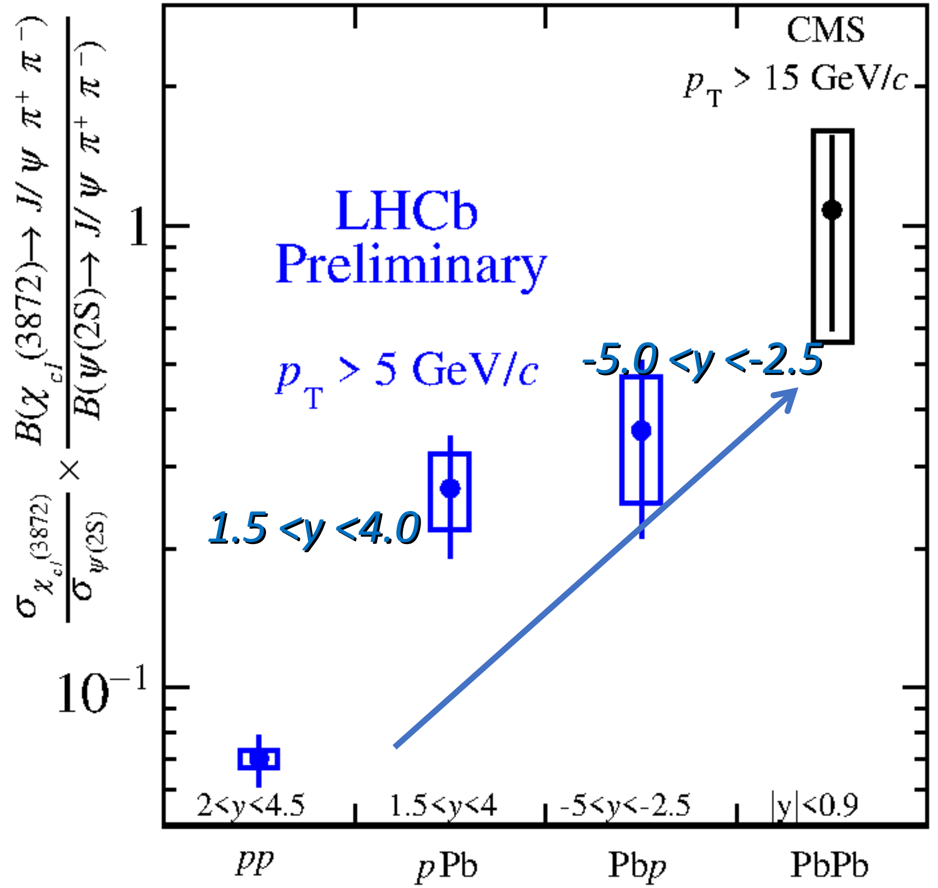

What’s the hadronization
mechanism with QGP?

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

cf. Fabio's talk



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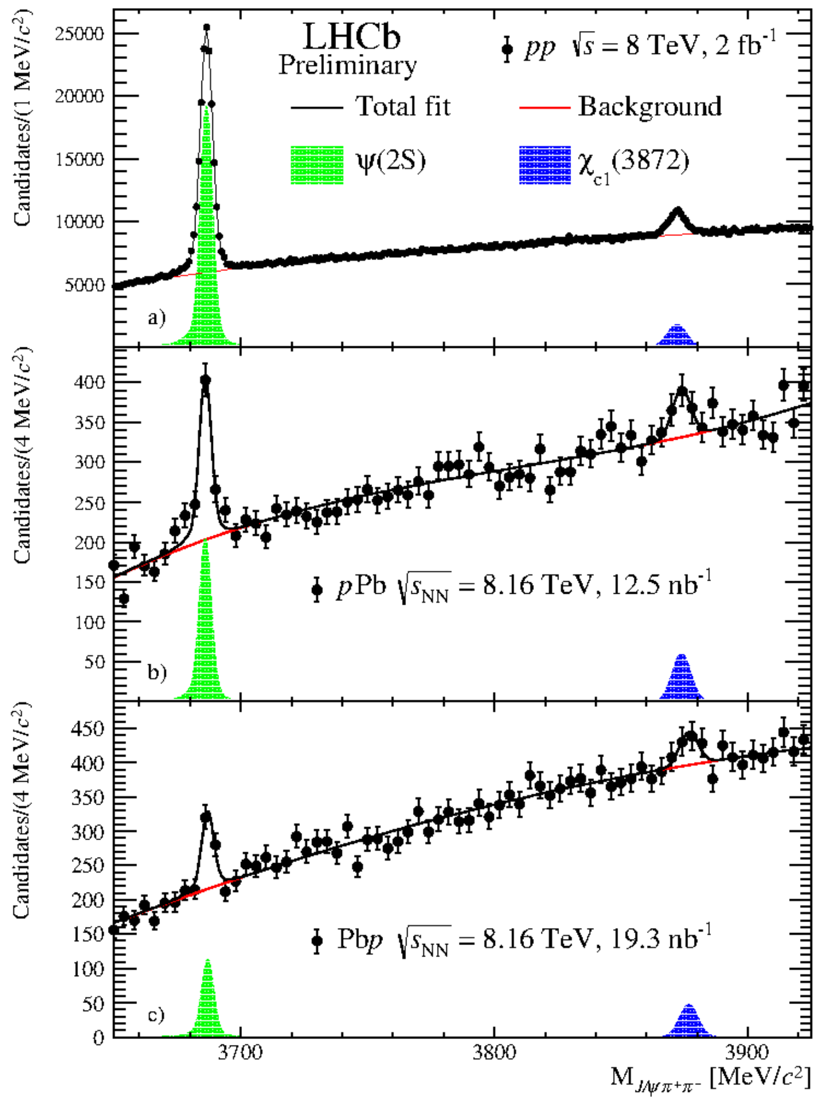

Crossover between suppressing (comover breakup) and enhancing effects (coalescence)

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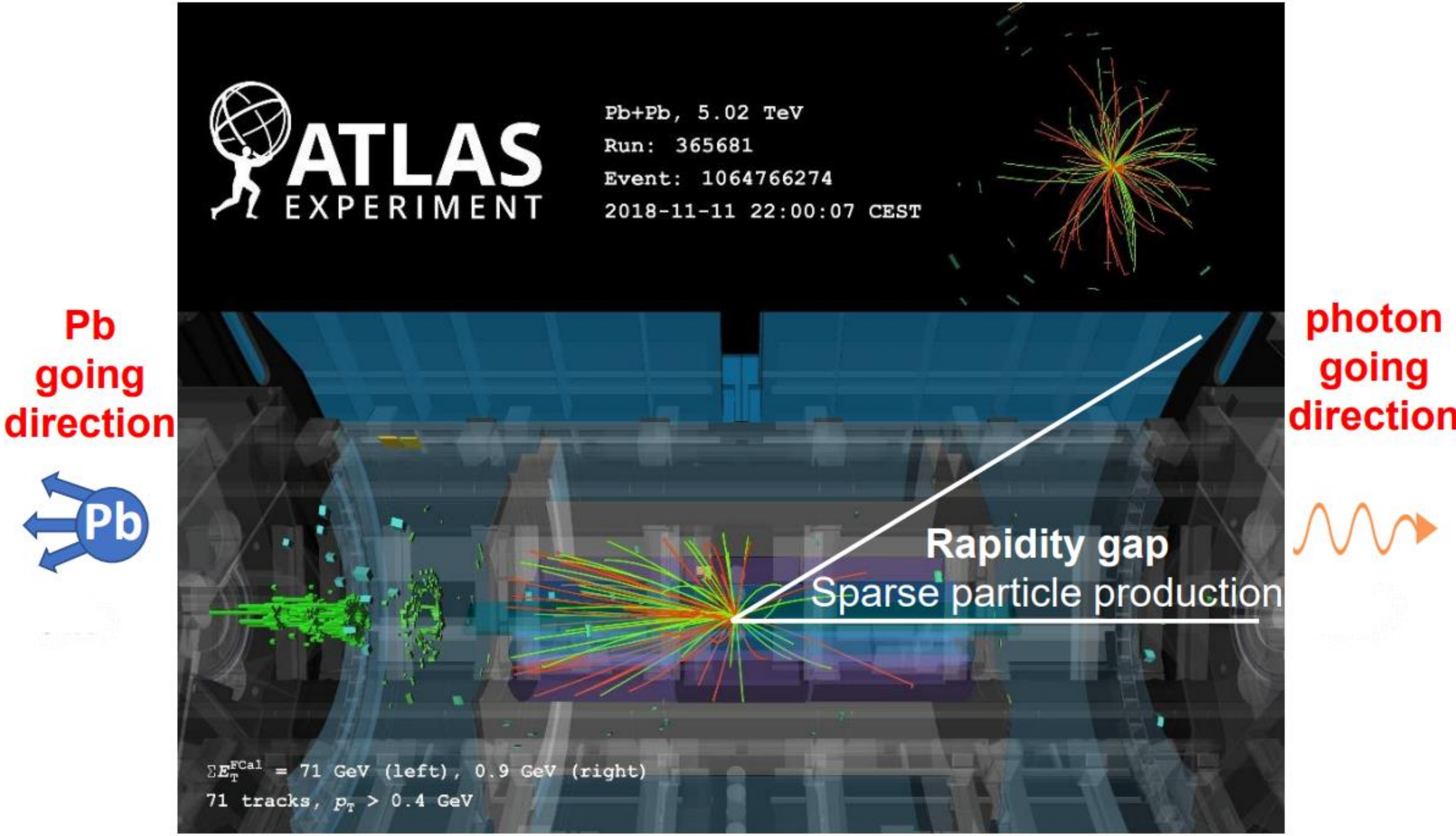


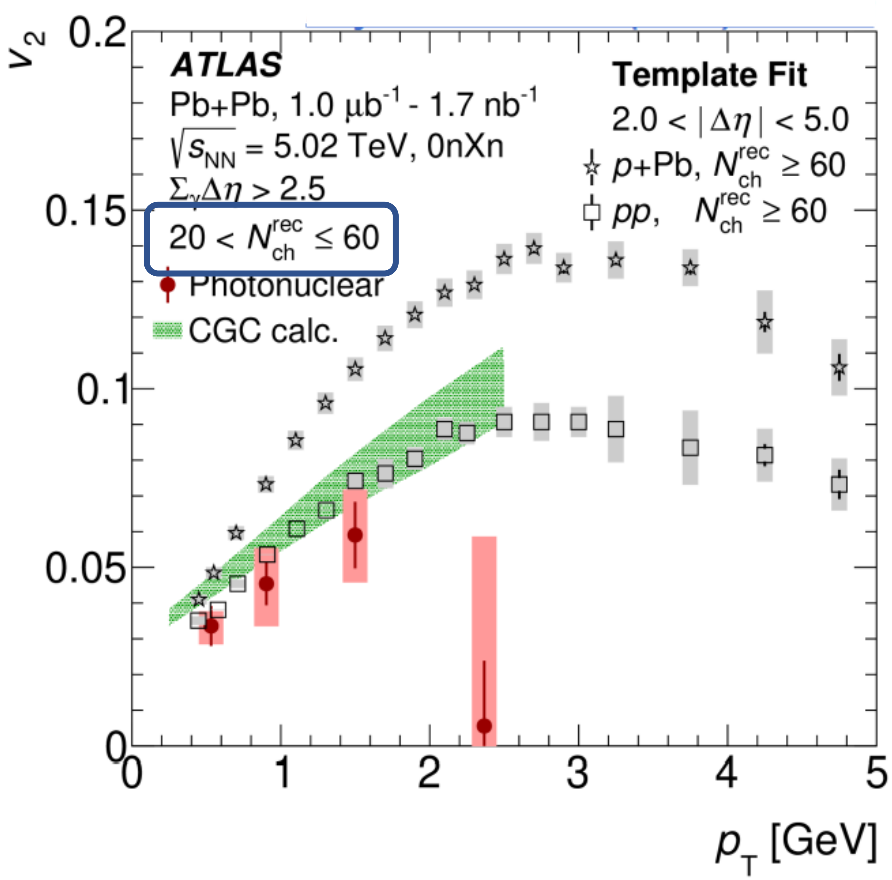
Empty events full of physics

Understanding Vn in the smallest systems

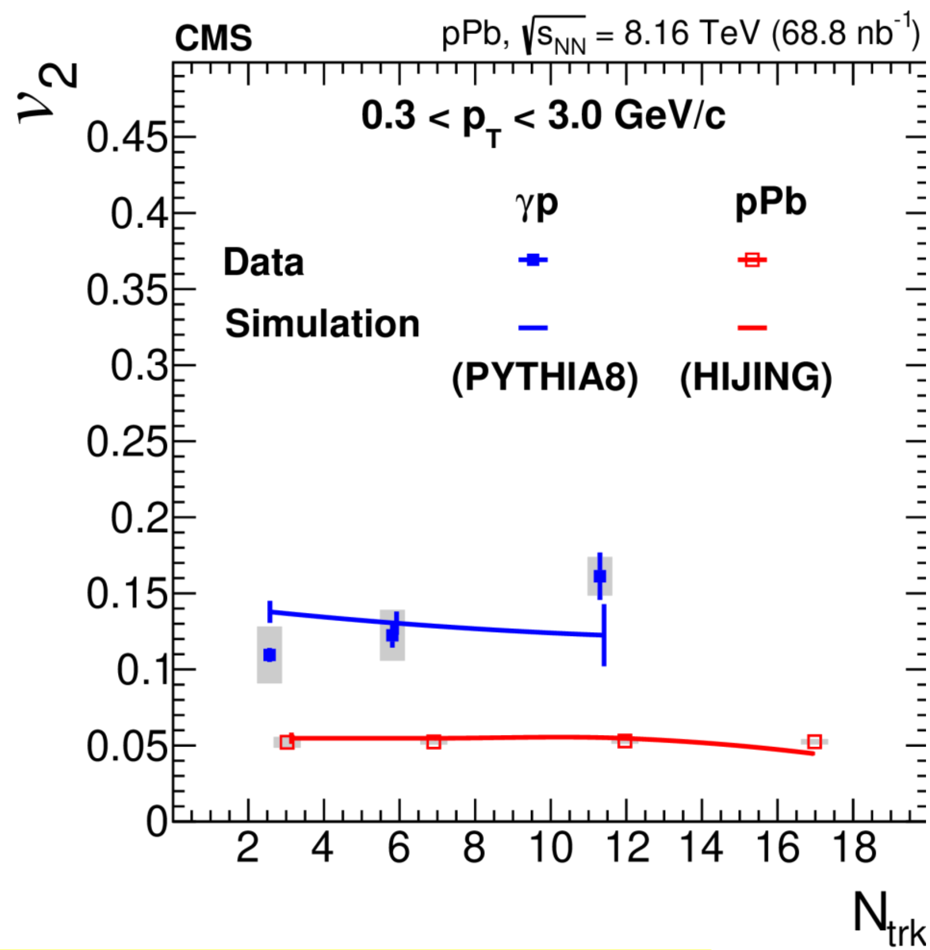
- Do we have systems **smaller than in pp** at LHC?
- γA, γp events good candidates to "bridge the gap" with e+e-
- **Not yet conclusive**: signs of QGP or CGC?

cf. Katarina's & Blair's talks

Phys. Rev. C 104 (2021) 014903



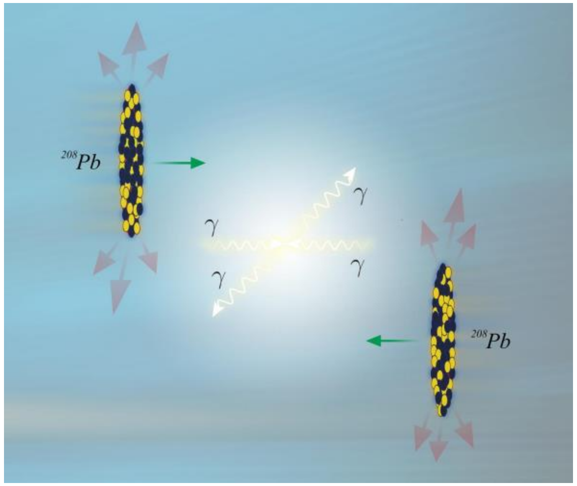
arXiv:2204.13486



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

Precision QED and BSM searches

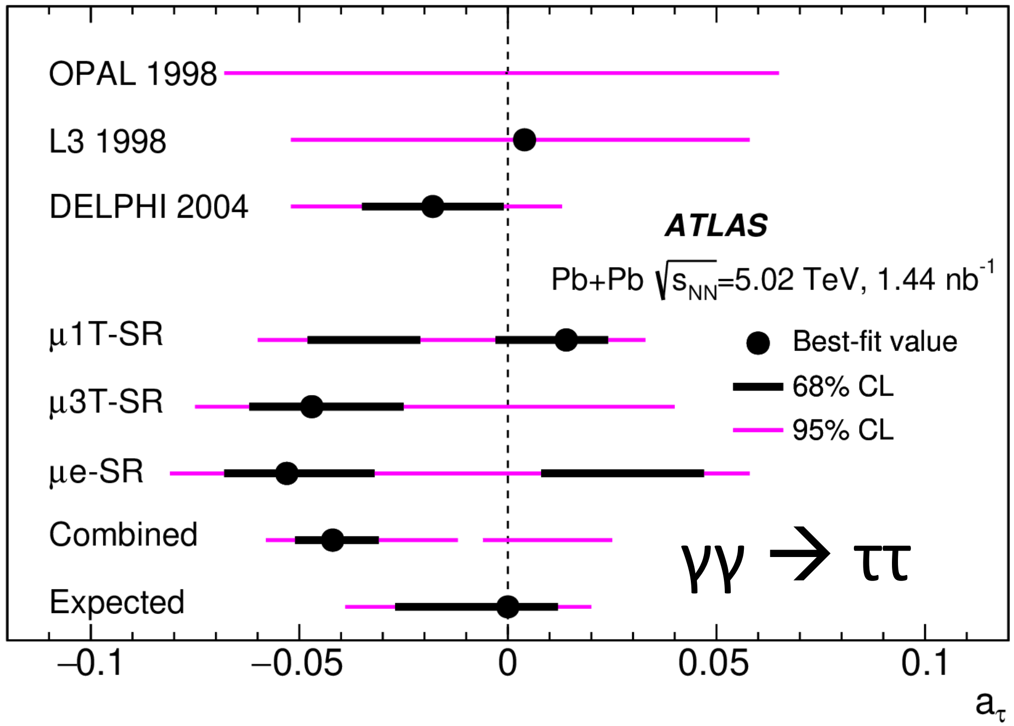
- Processes like $\gamma\gamma \to \mu\mu$ will be high **precision-like** at HL-LHC
  - calibration of photon flux, constrain predictions for $\gamma\gamma \to ee$, **$\tau\tau$**
- Small cross sections, e.g., $\mathcal{O}(\alpha^4)$ for $\gamma\gamma \to \gamma\gamma$, but Z^4 **enhancement**
  - **best**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



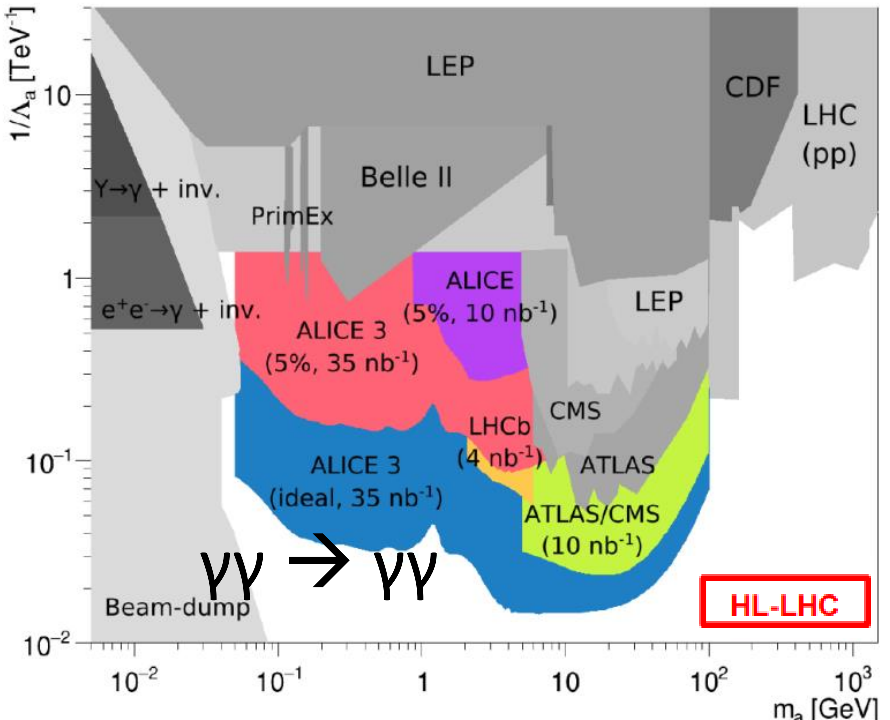
Source: IFJ PAN

cf. Mateusz's talk

arXiv: 2204.13478



arXiv: 2203.05939

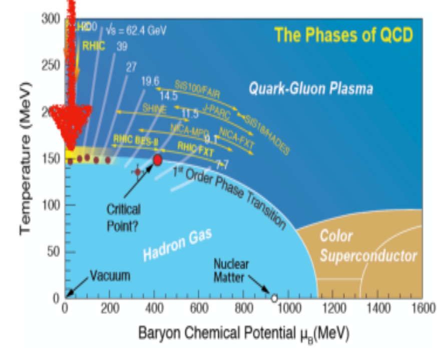


Taking advantage of **huge photon fluxes** from large-A UPC

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

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



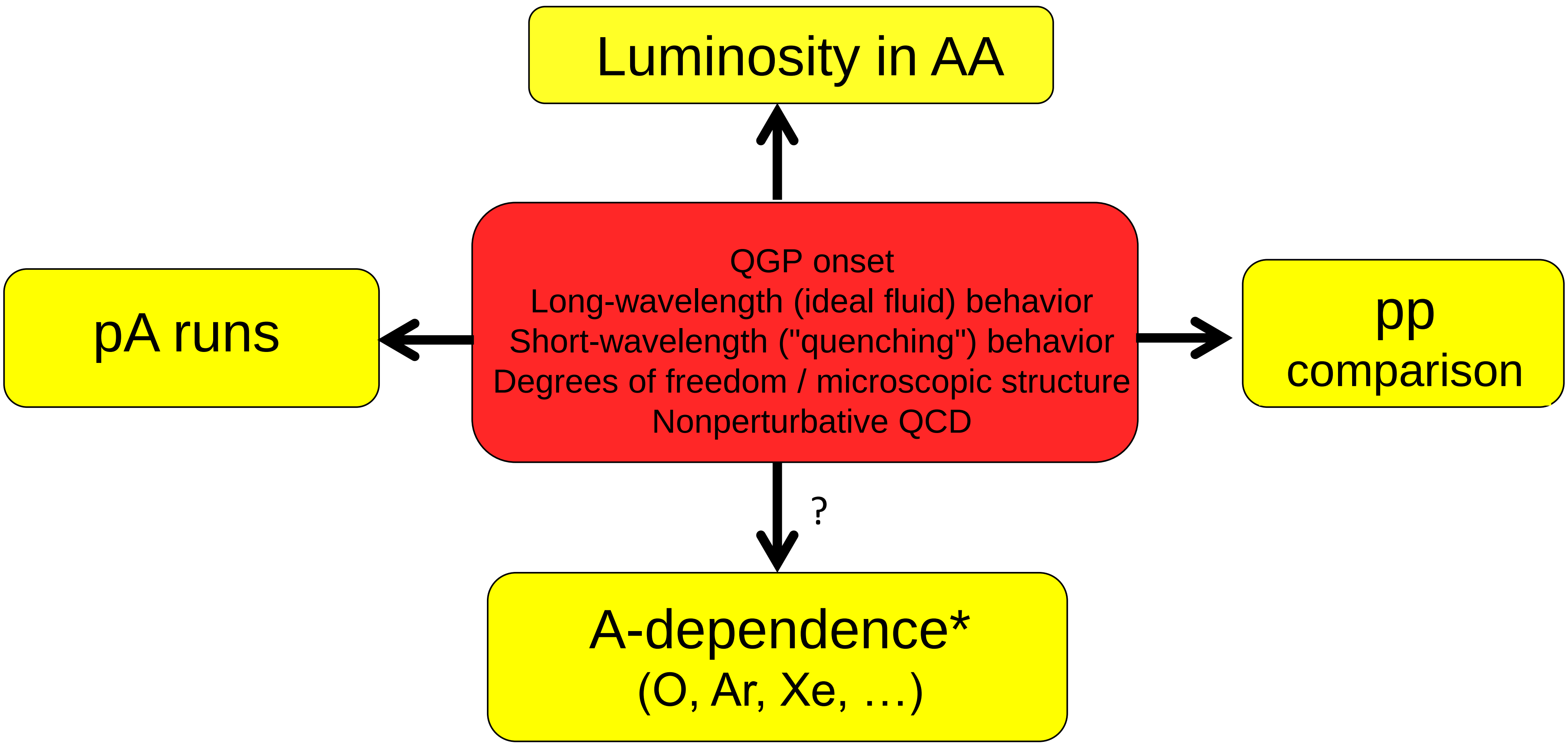
Goals for high-T/low-μ_B QCD matter	Experimental tools
Controlling initial conditions	pA , nPDF fits, flow (de)correlations
From early phase to hydrodynamization	Flow and fluctuations
Quenching and connection to smaller systems	R_{AA}, jet (sub)structure, high-p_T probes
Transport properties and thermalization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

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

Nonexhaustive list


BONUS

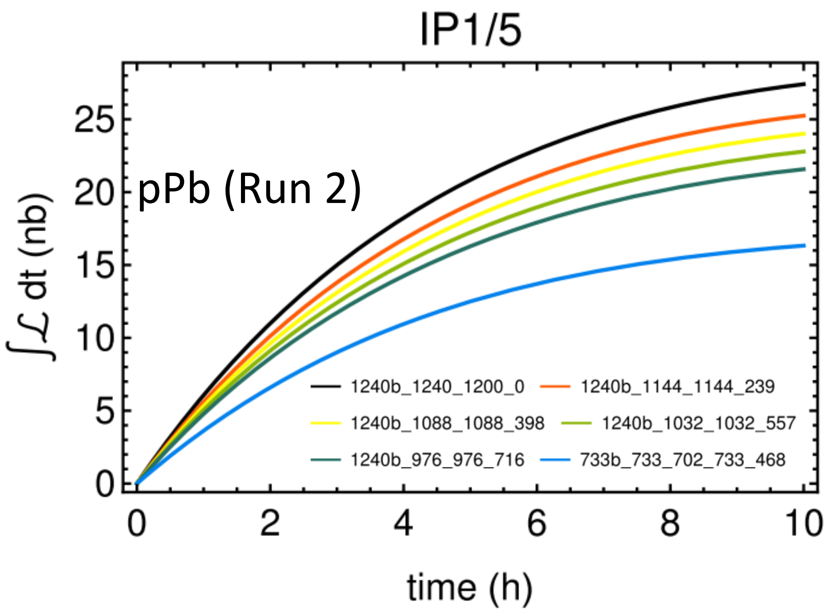
Throwing a bullet through an apple... Why?

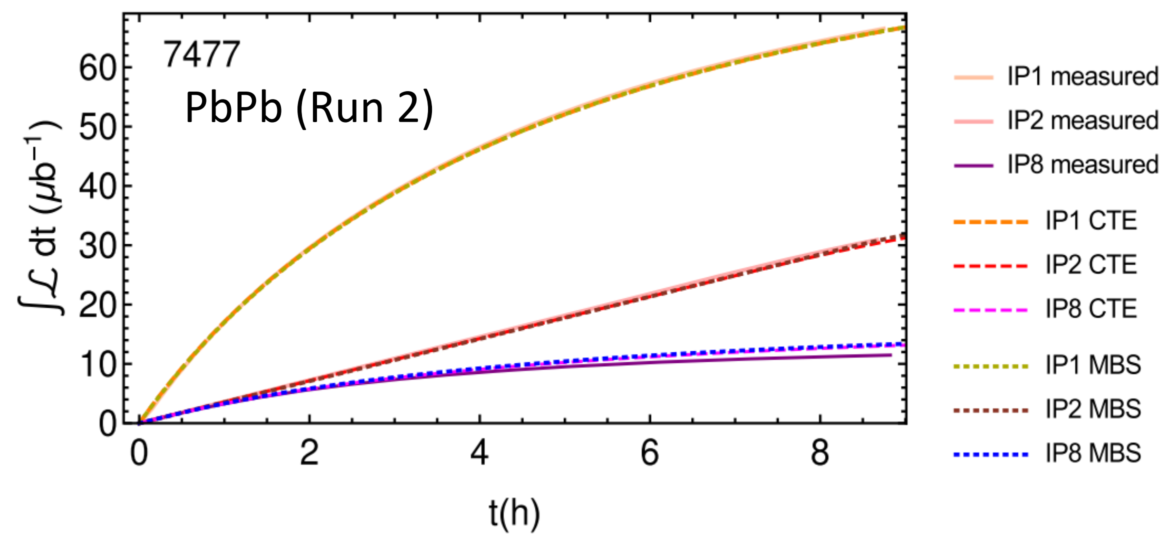


Beyond improvements from detector upgrades and increased luminosity, the YR and Snowmass efforts document the HL-LHC (&beyond) scientific program for understanding **high-density QCD**

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

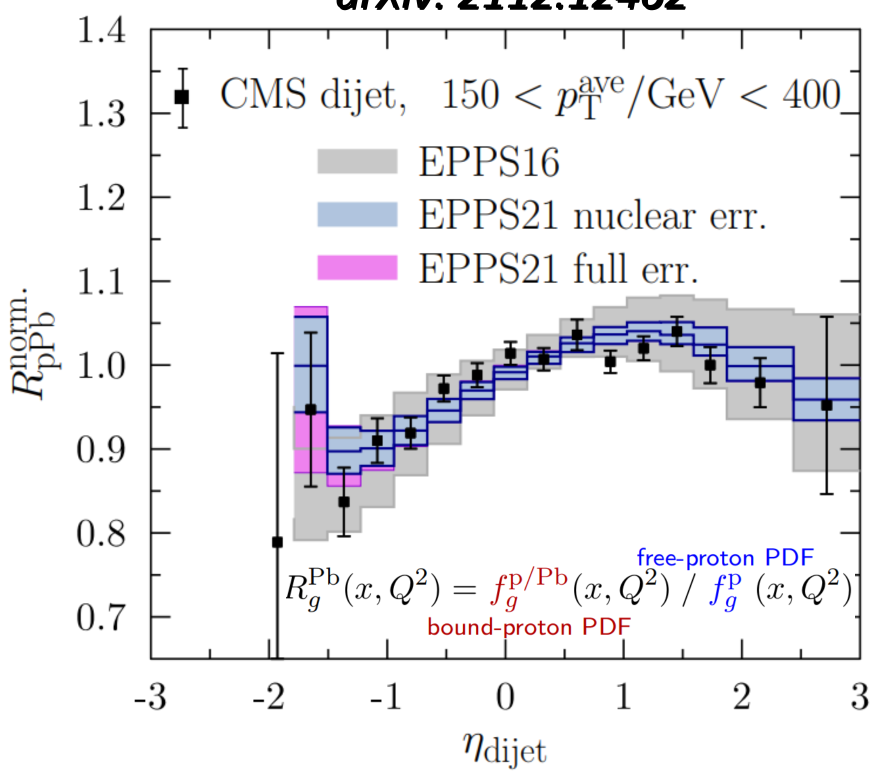
Nuclear PDFs: constraints scarce so far

- **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

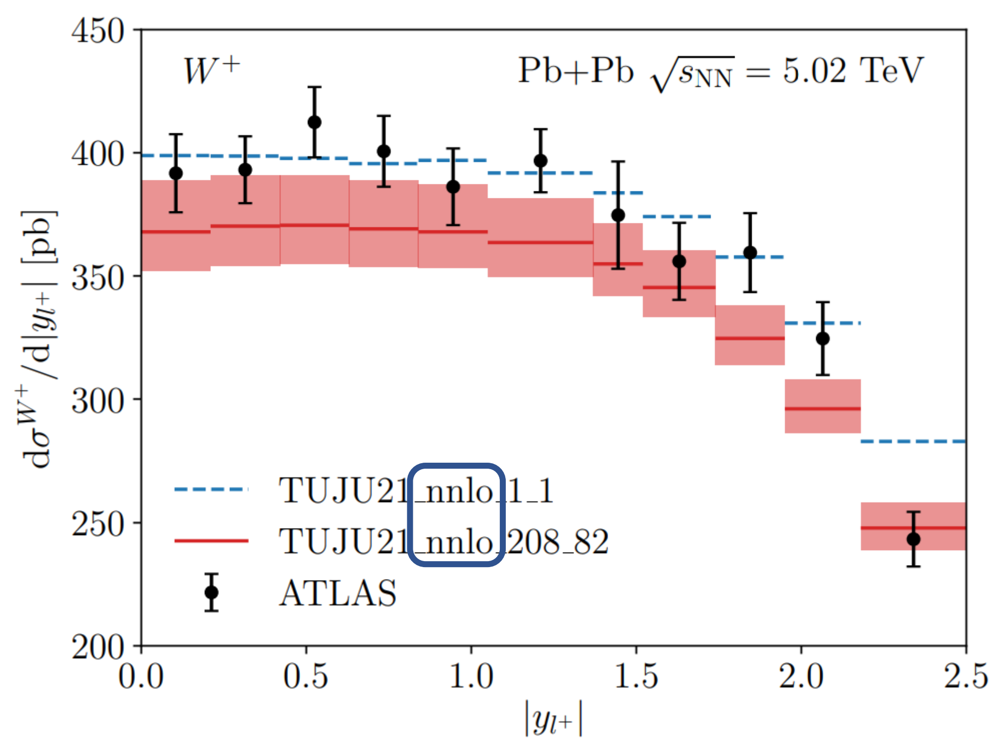
$$R_{\mathrm{pA}} = \frac{\text{p-Pb}}{\text{scaled}\otimes\text{pp}}$$

cf. Petja's talk

arXiv: 2112.12462



arXiv: 2112.11904



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

Nuclear PDFs: constraints scarce so far

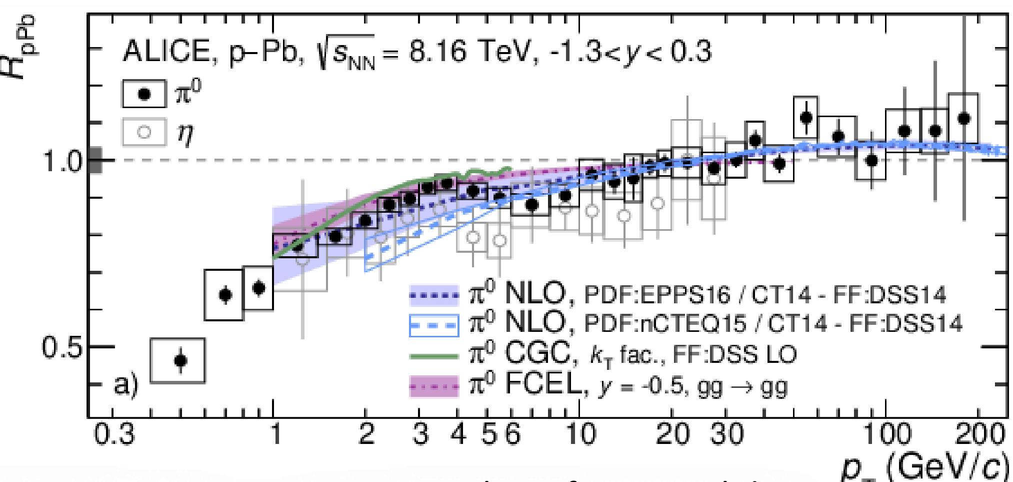
- State-of-the-art nPDFs for perturbative QCD calculations
  - Strong constraints on gluon modifications from dijets and W bosons
  - NNLO nPDF analysis to include LHC data

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

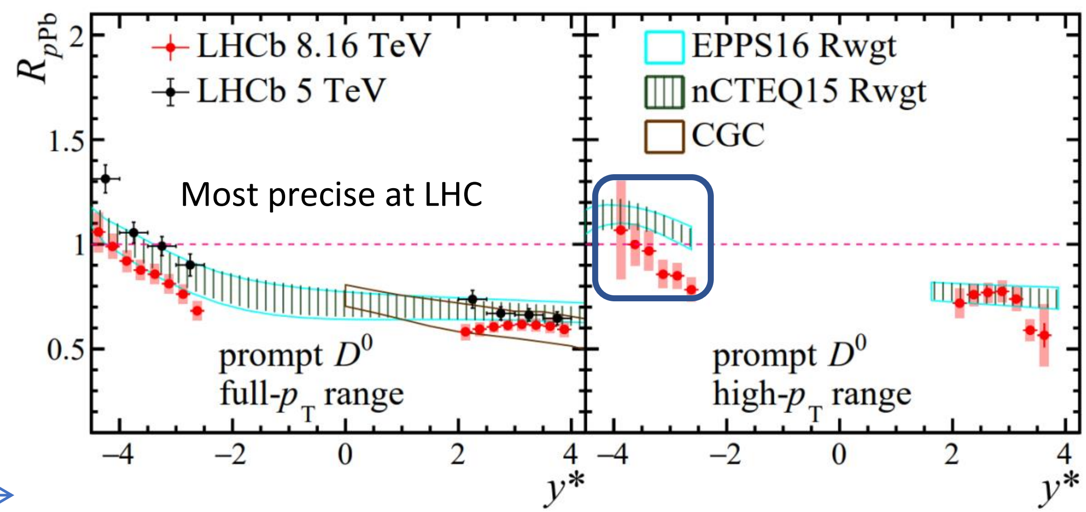
- Complementarity at very **low-*x*** with π^0, η, and D^0 mesons
  - **Bonus:** saturation models and energy loss constraints

cf. Petja's talk

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	$\sim$CTEQ6M	own fit	CT18A	$\sim$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

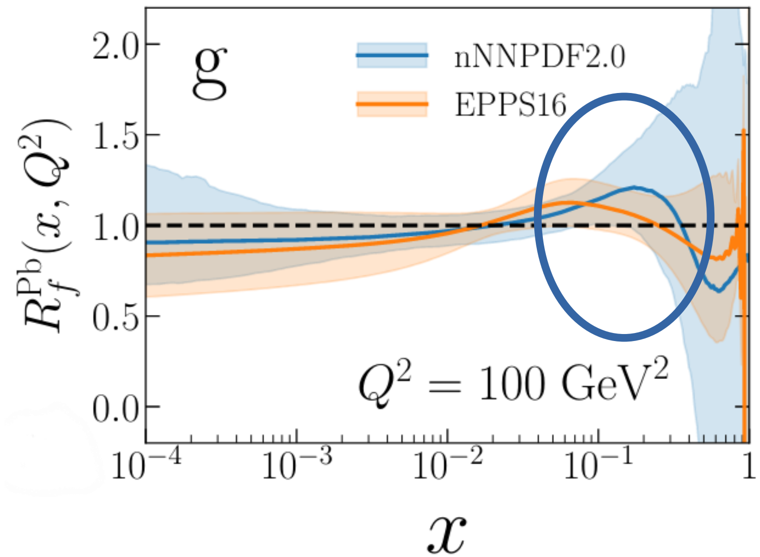
P. Paakkinen (DIS22)

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

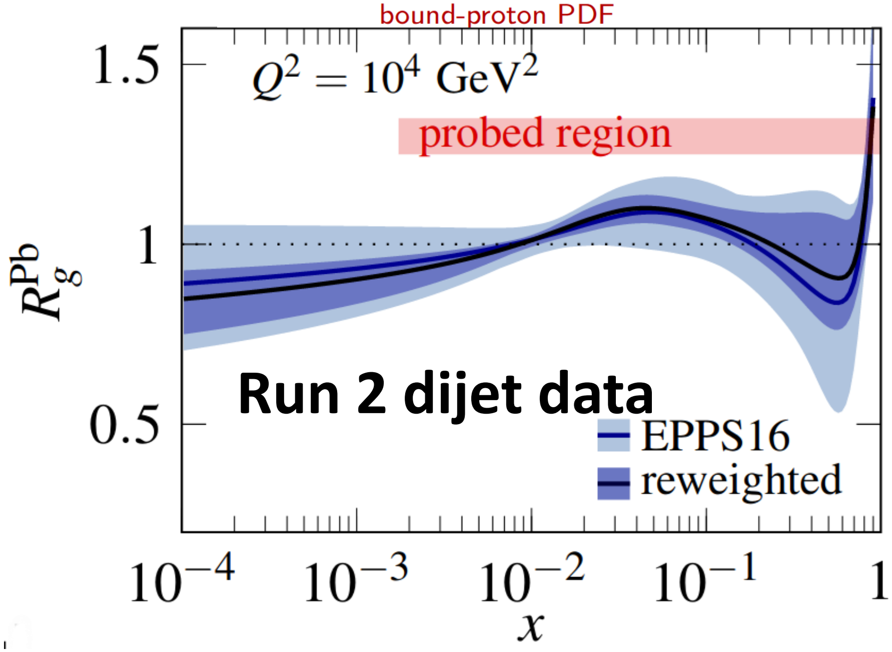
Nuclear gluon PDFs: constraints scarce so far

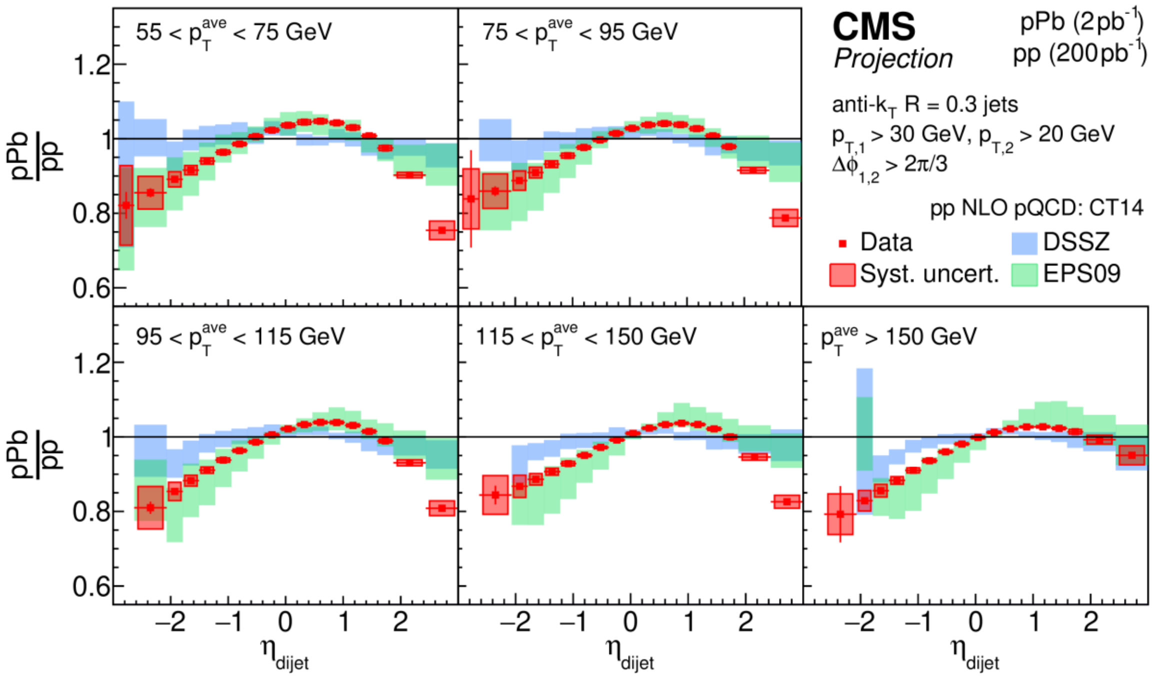
- Stringent constraints with **dijet** production
  - Enhanced **suppression** at forward y
- Significant reduction in EPPS16 uncertainties after reweighting already with Run 2 data (left plot)
- **Improved constraints** with HL-LHC data (right plot)
- Complementarity with W bosons and top quarks, and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

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

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

free-proton PDF
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**.

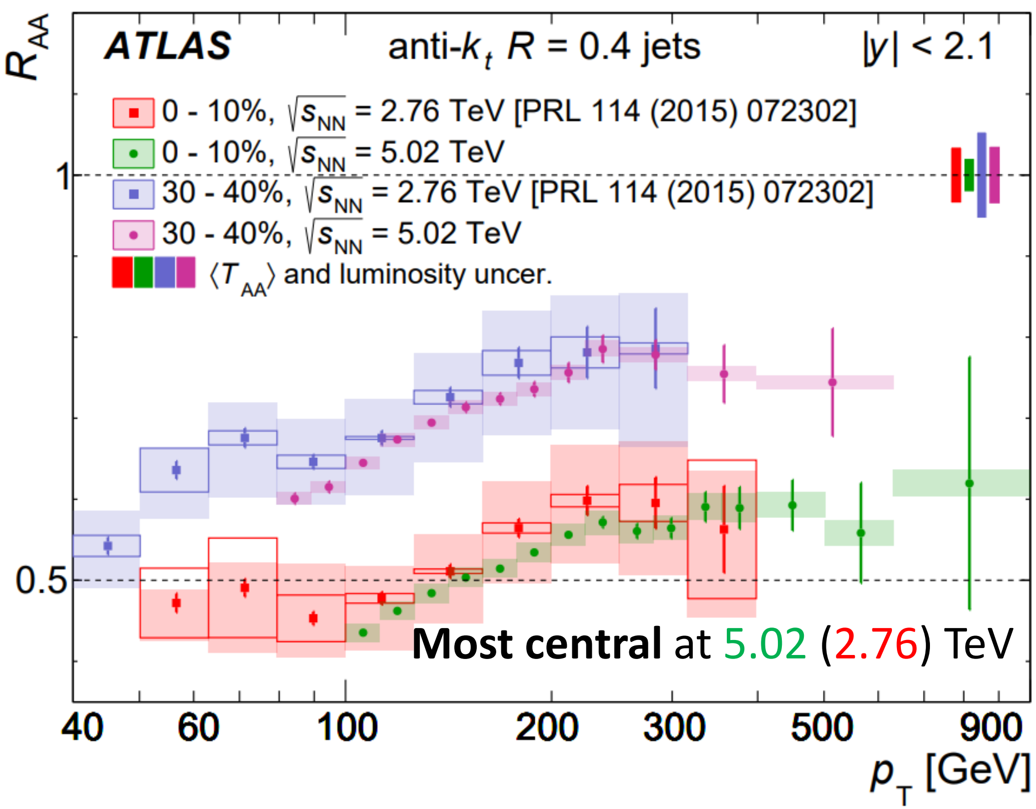
Input from
[QM22 conference (Luuk Vermunt)]

Measuring jet quenching

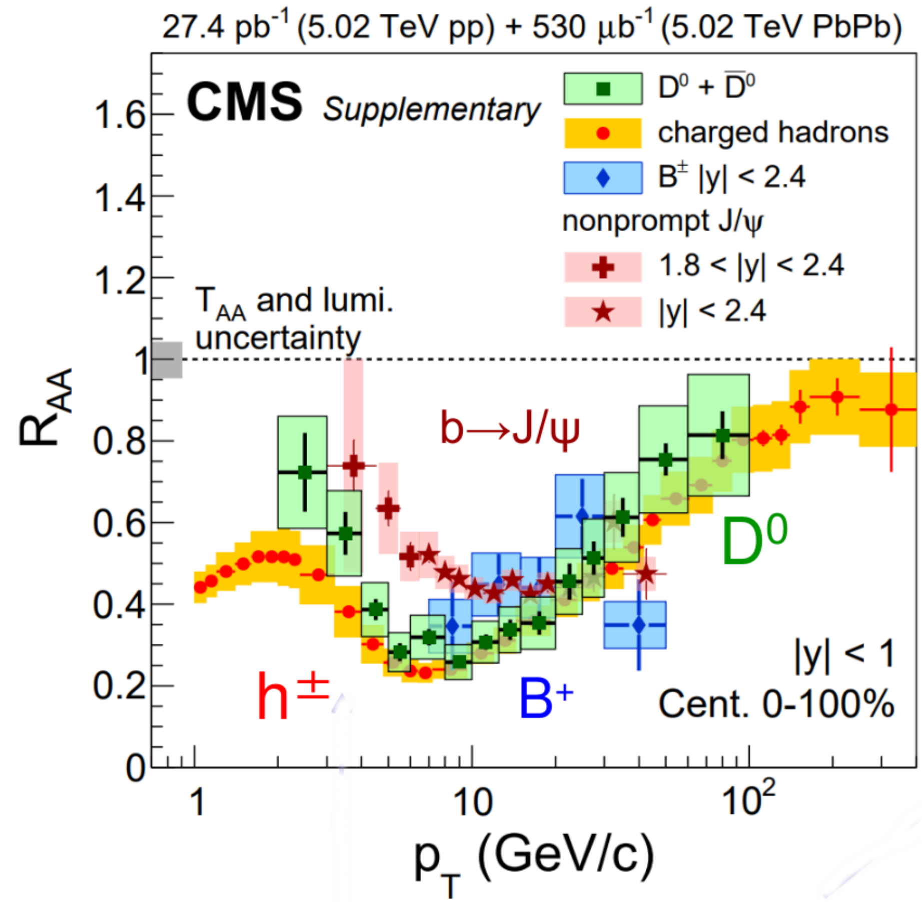
- Energy of partons is redistributed ('quenched') inside QGP
  - Experimentally seen as R_{AA} modifications of **hadrons or jets**
  - **dependent on** centrality, p_{T} , parton mass
- Unprecedented access from **low- to high-p_T**

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

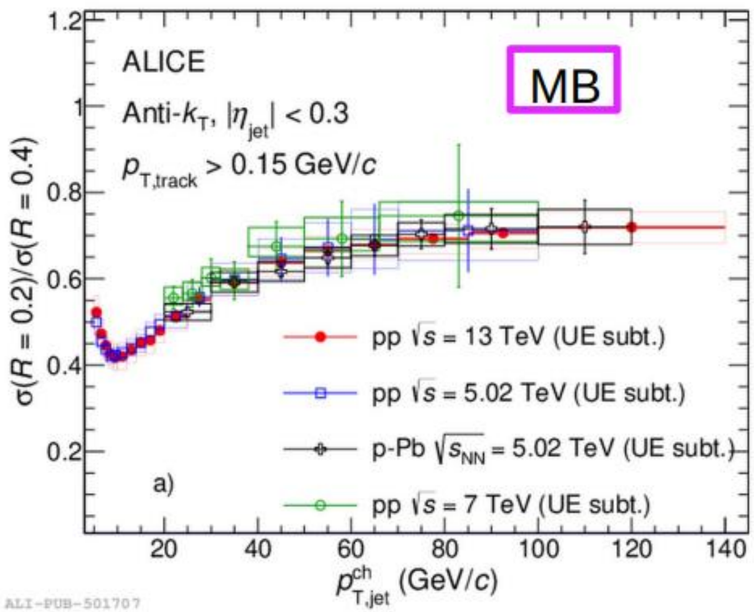
PLB 790 (2019) 108

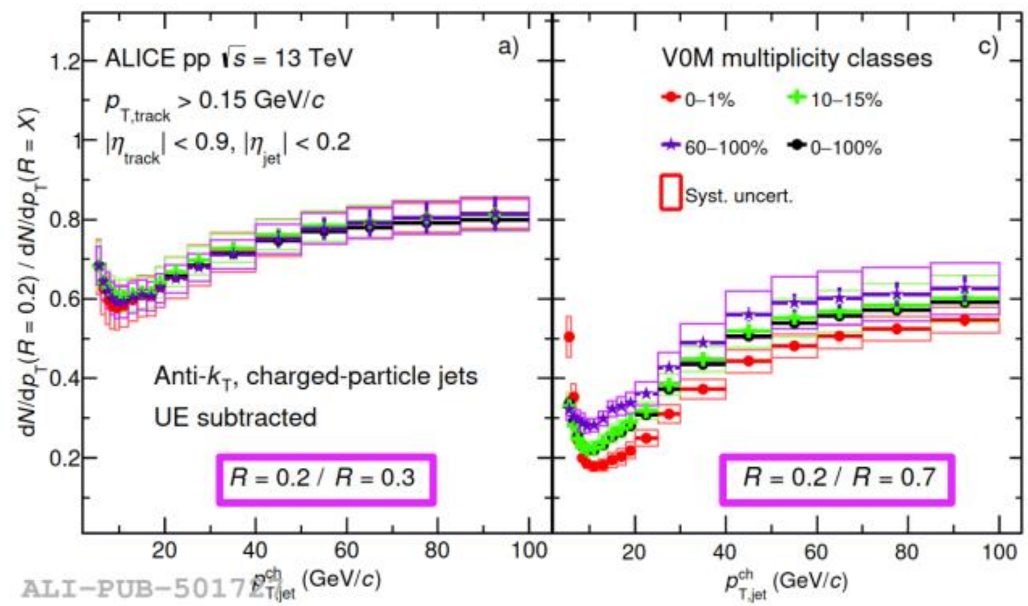


PRL 123 (2019) 022001



Ratios of jet p_T spectra with different R





New

arXiv:2202.01548

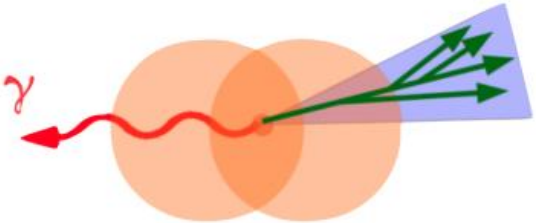
MB ratio of p_T-differential cross section spectra:

independent of $\sqrt{s}$

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

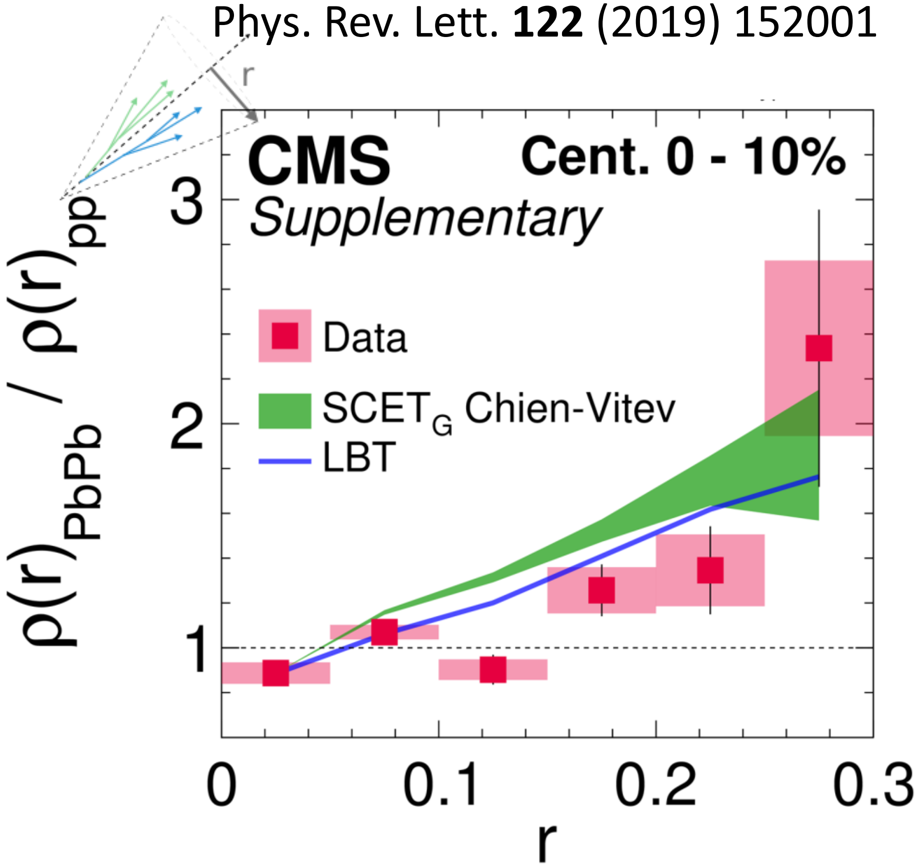
Jet shapes and fragmentation with γ+jet events

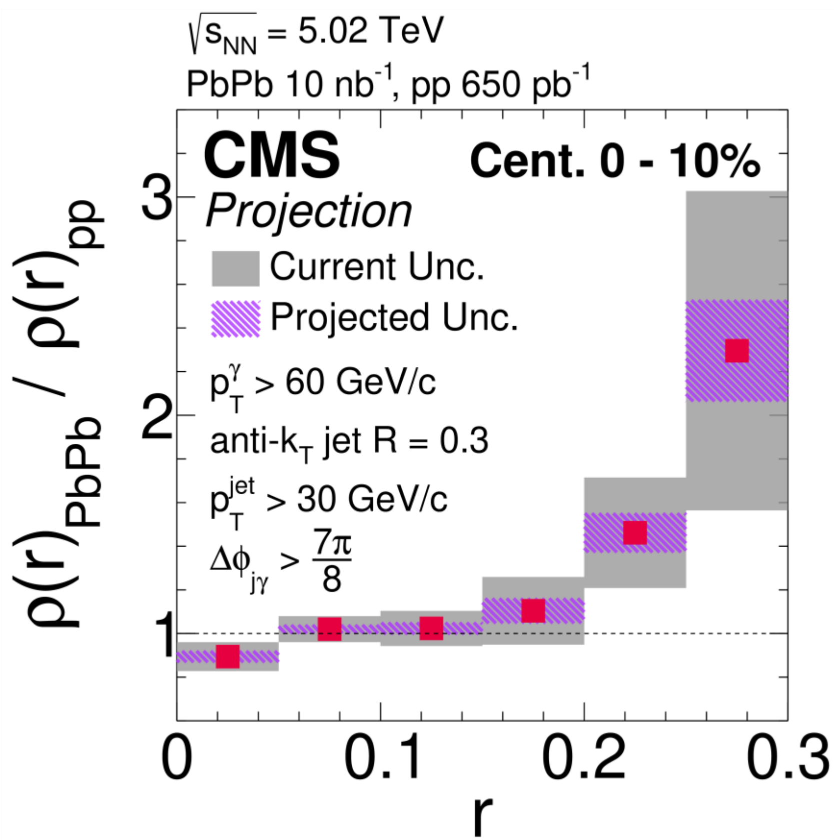
- Initial parton energy better constrained by γ p_T (quark-enriched jets)



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

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





Jet shapes and fragmentation with γ+jet events

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- Jet shape
  - Jets are wider in PbPb than pp
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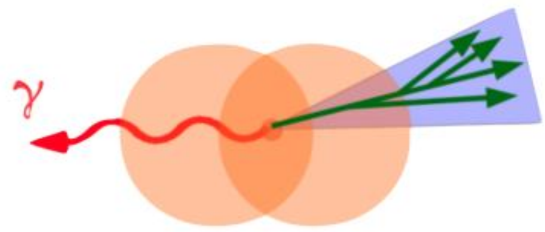
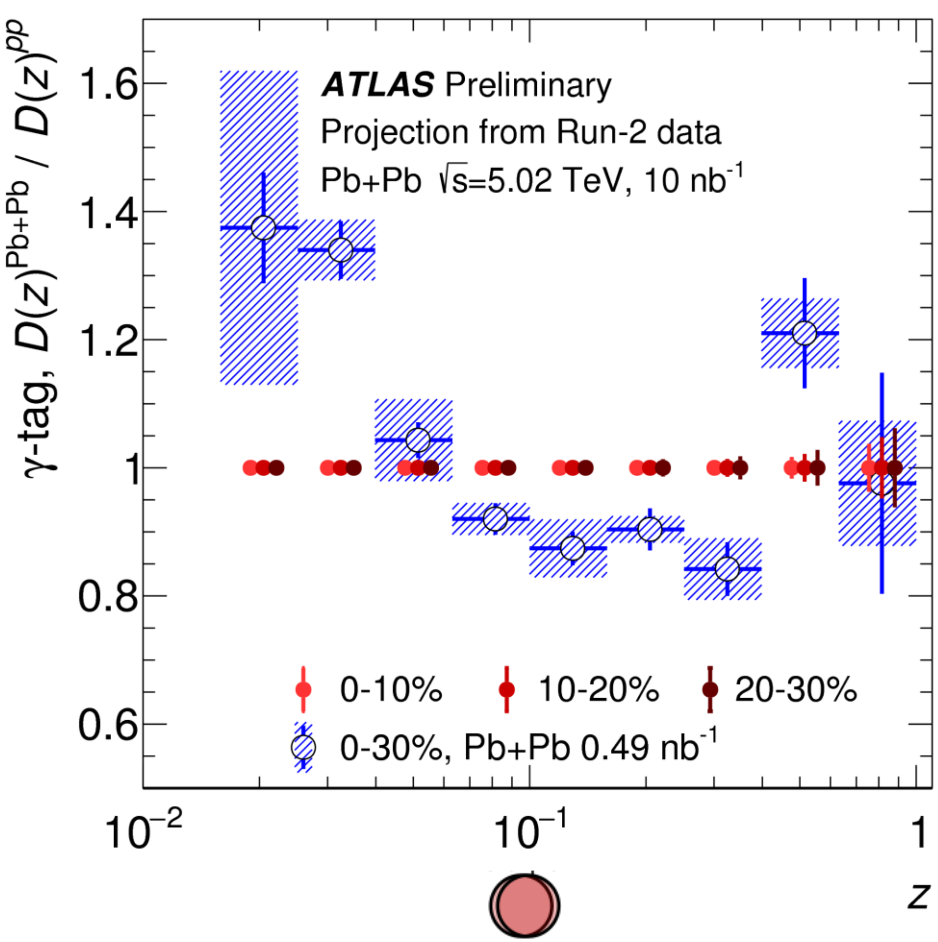
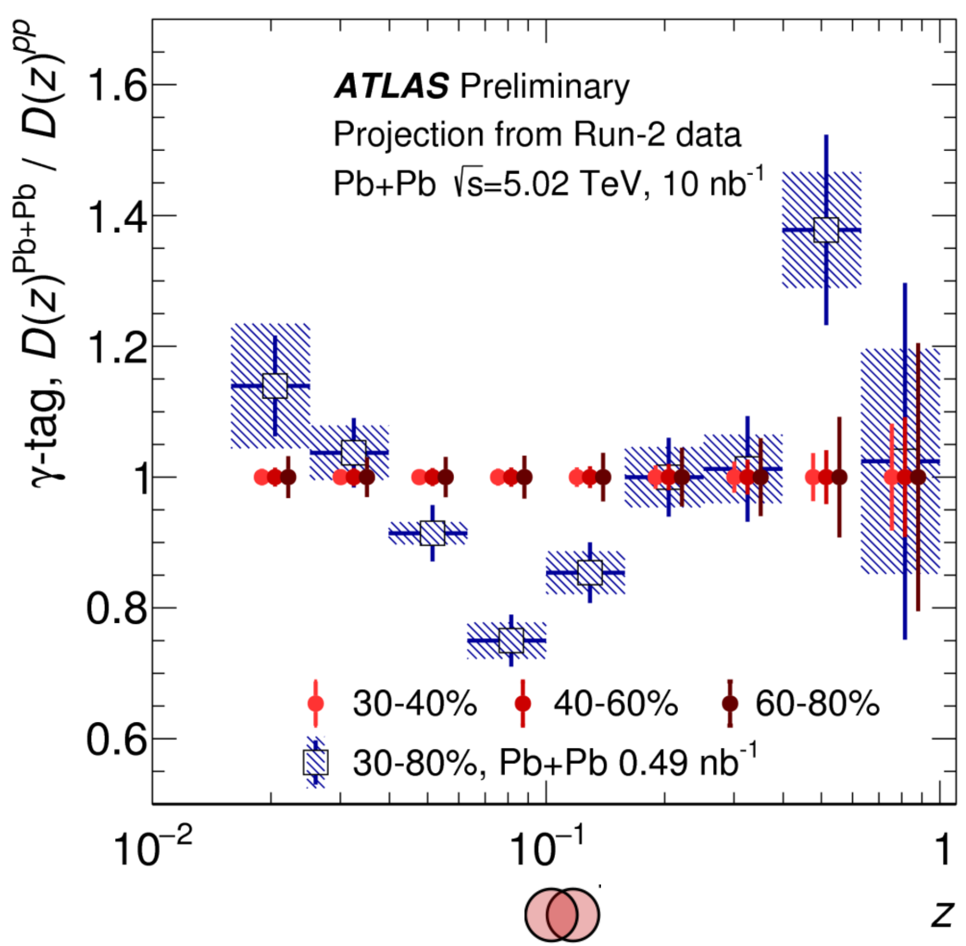
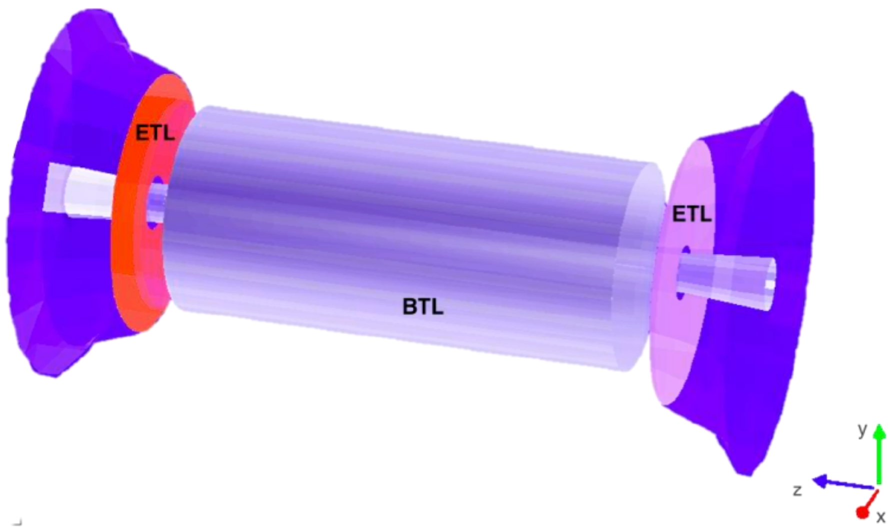




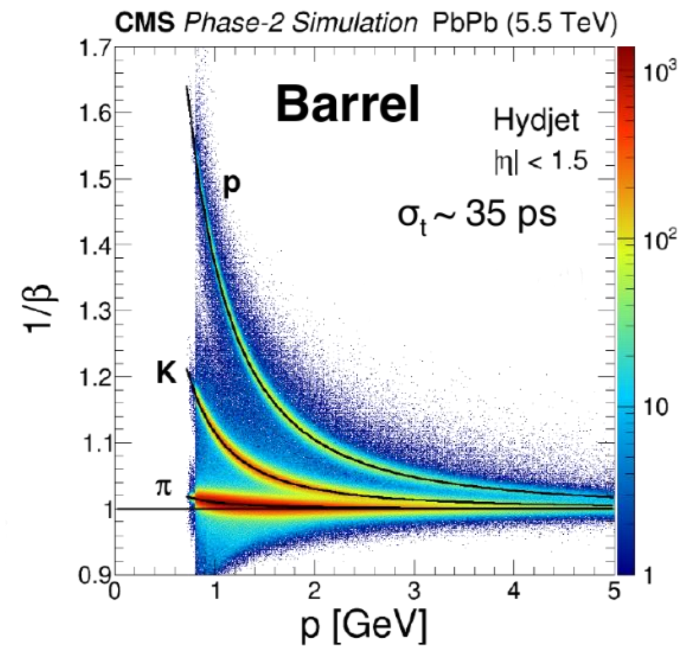


Extending the LHC HI program & Phase 2 upgrades

- 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 |η|<2.5 to < 4.0 (3.0), etc.
- ATLAS 2.5 < | η | < 5
- 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



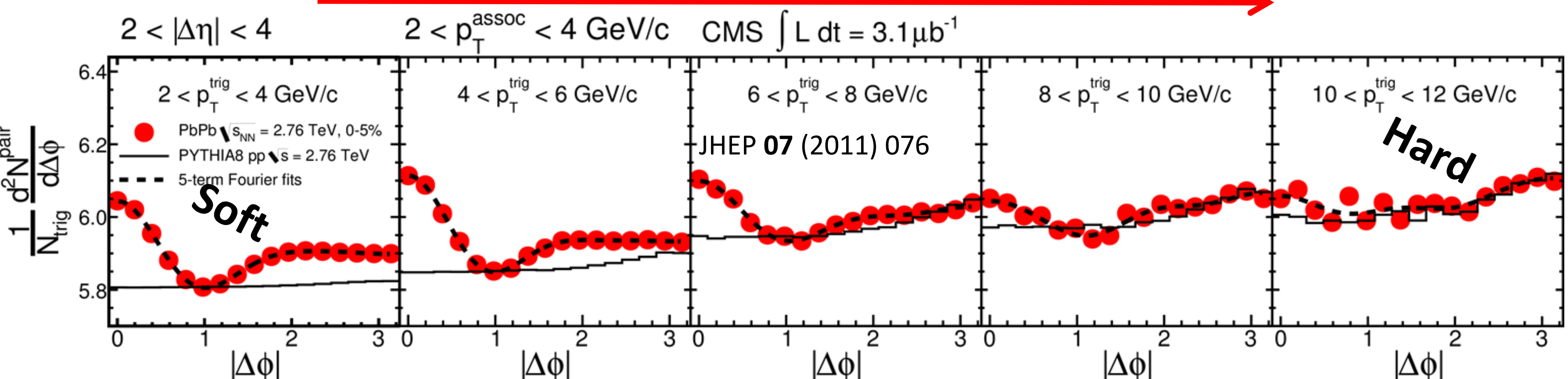
Fourier decomposition of the projected Δϕ

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

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

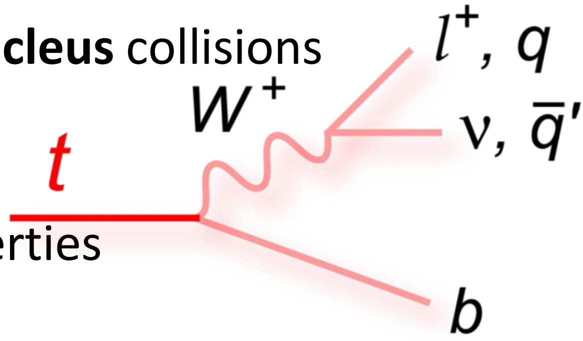
- single-particle azimuthal anisotropy Fourier coefficients measured as v_n=v$v_{n\Delta}$ (n≥1)
- In hydrodynamic models v_2 and v_3 referred to as "elliptic" and "triangular" flow and related to the
- Initial collision geometry and its fluctuations

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

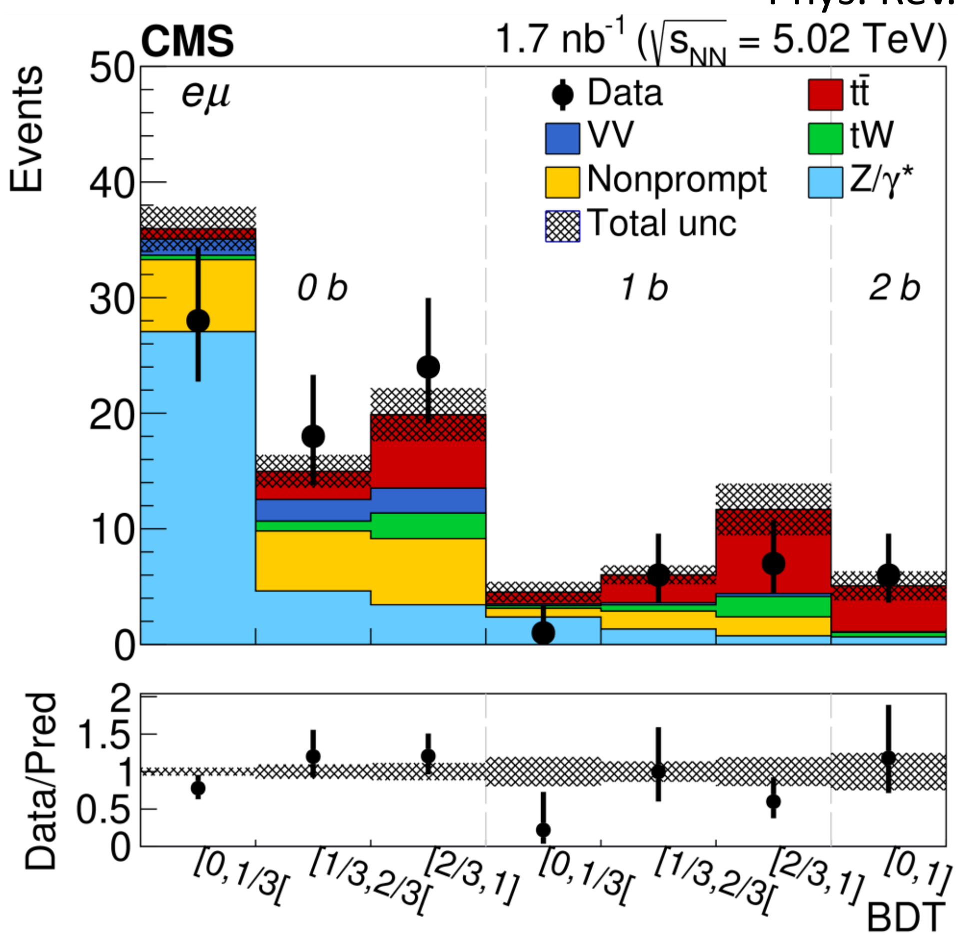


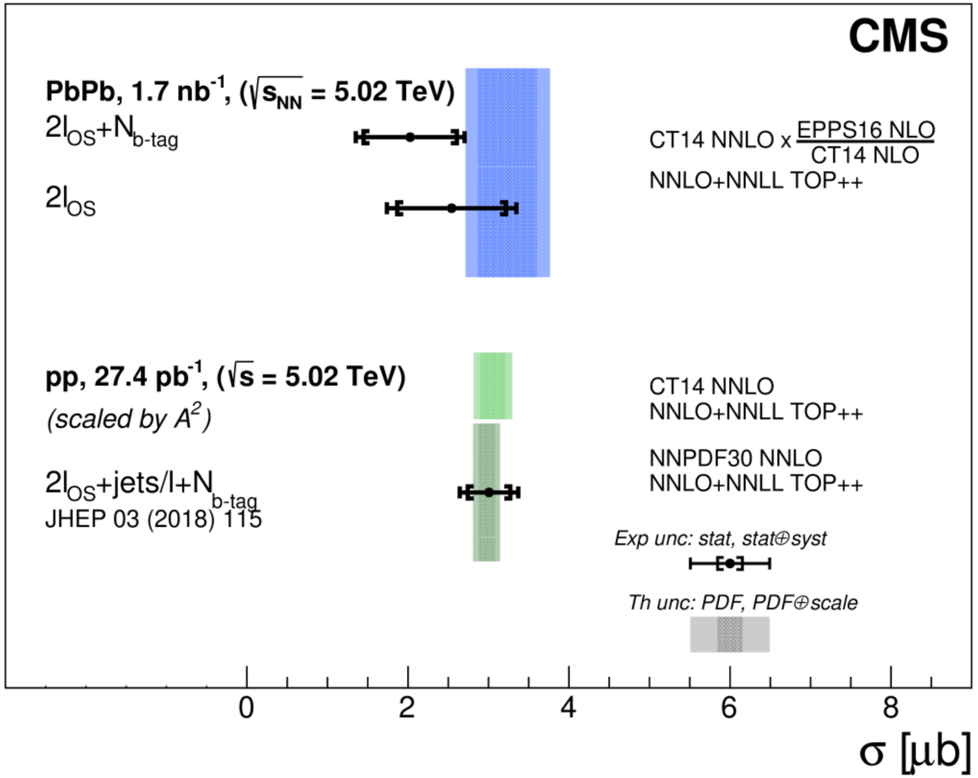
Evidence of $t\bar{t}$ cross section in PbPb

- **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

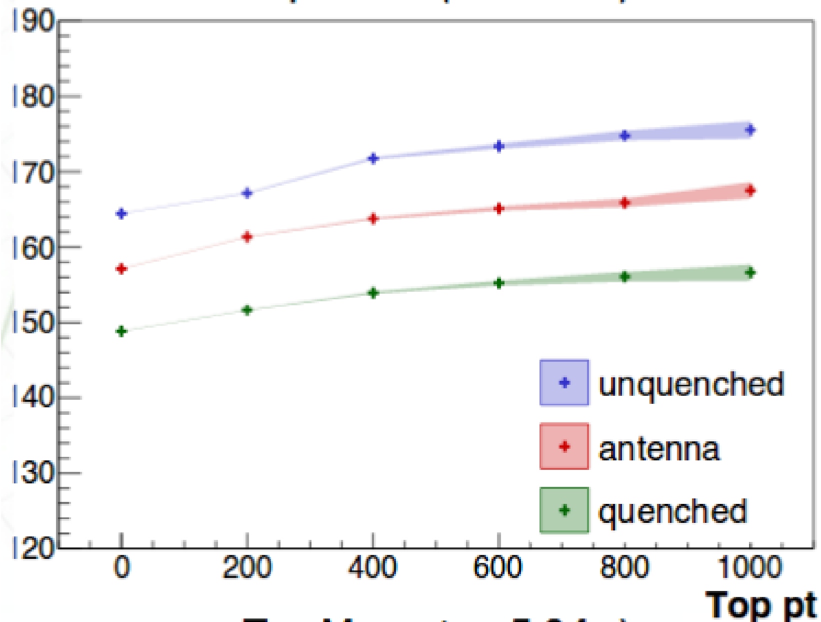




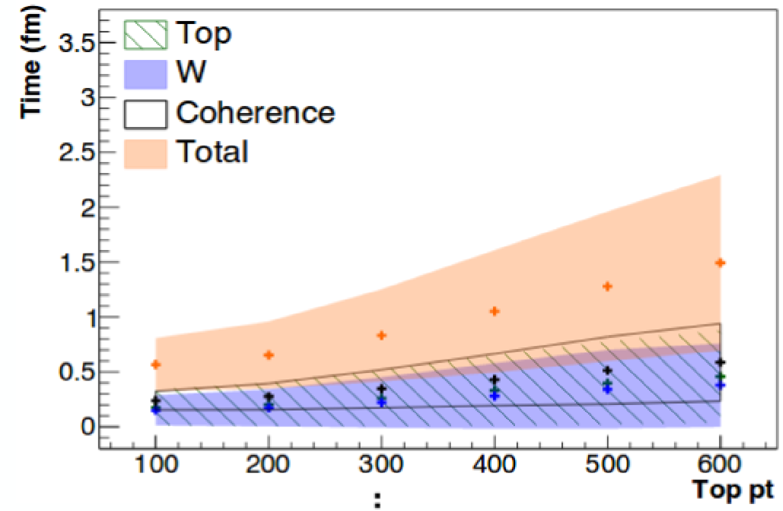
A nice heuristic idea for a yocto-chronometer !

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

Top Mass ($\tau = 0.5$ fm)

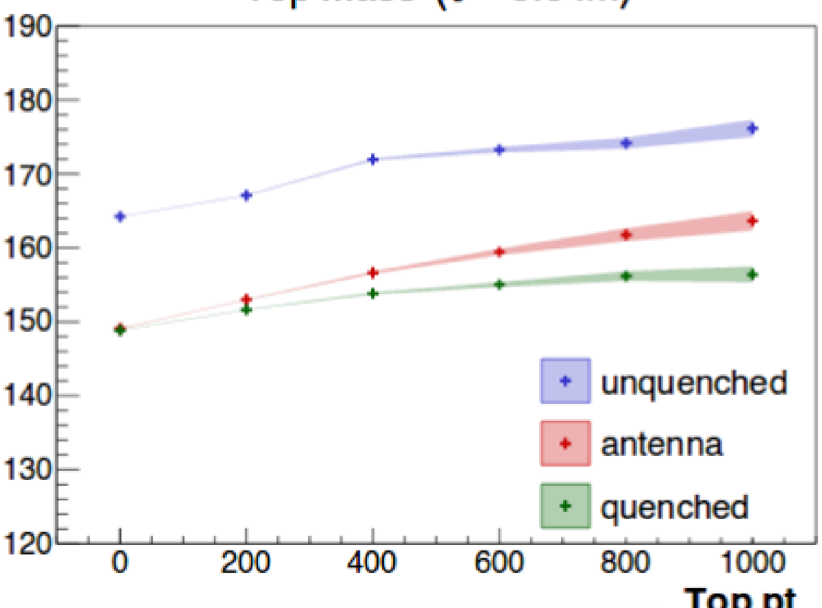


Decay Times



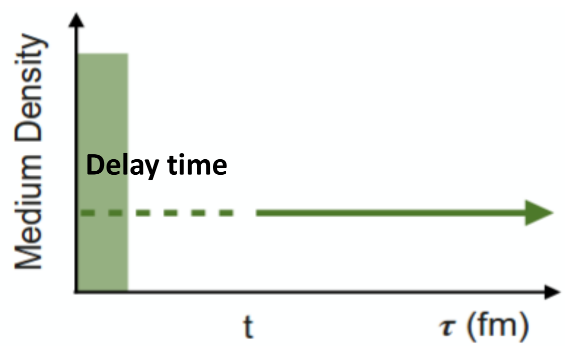
Not enough statistics…

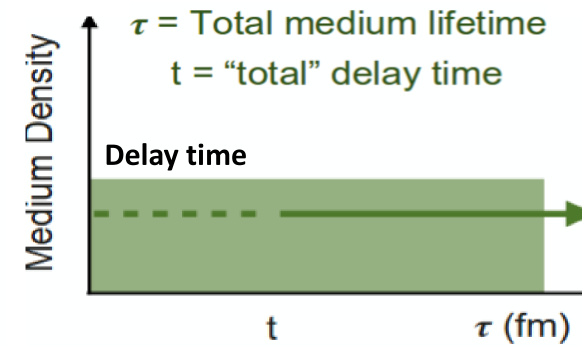
Top Mass ($\tau = 5.0$ fm)



Probe ~ [0.4; 1.2] fm

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





τ = Total medium lifetime

t = "total" delay time

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

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

BSM searches with heavy ion collisions at the LHC

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

arXiv: 1812.07688

Production mode	BSM particle/interaction	Remarks
Ultraperipheral	Axion-like particles	$\gamma\gamma \to a$, $m_a \approx 0.5$–$100\,\mathrm{GeV}$
	Radion	$\gamma\gamma \to \phi$, $m_\phi \approx 0.5$–$100\,\mathrm{GeV}$
	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	$m_{A'} \lesssim 1\,\mathrm{GeV}$, advanced particle ID
	Long-lived particles (heavy ν)	$m_{\mathrm{LLP}} \lesssim 10\,\mathrm{GeV}$, 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.