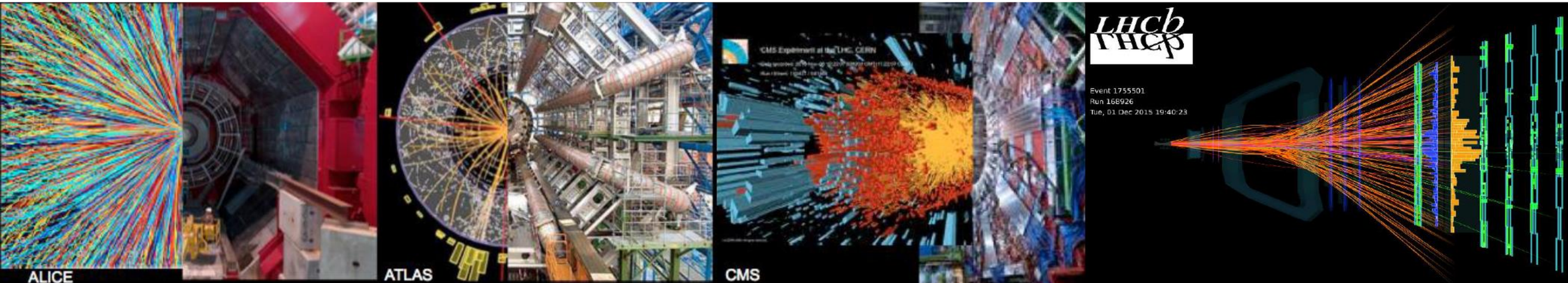
Review of Physics with LHC Run 3 and 4

Yen-Jie Lee (MIT)

ALICE 3 Workshop

Oct 19, 2021



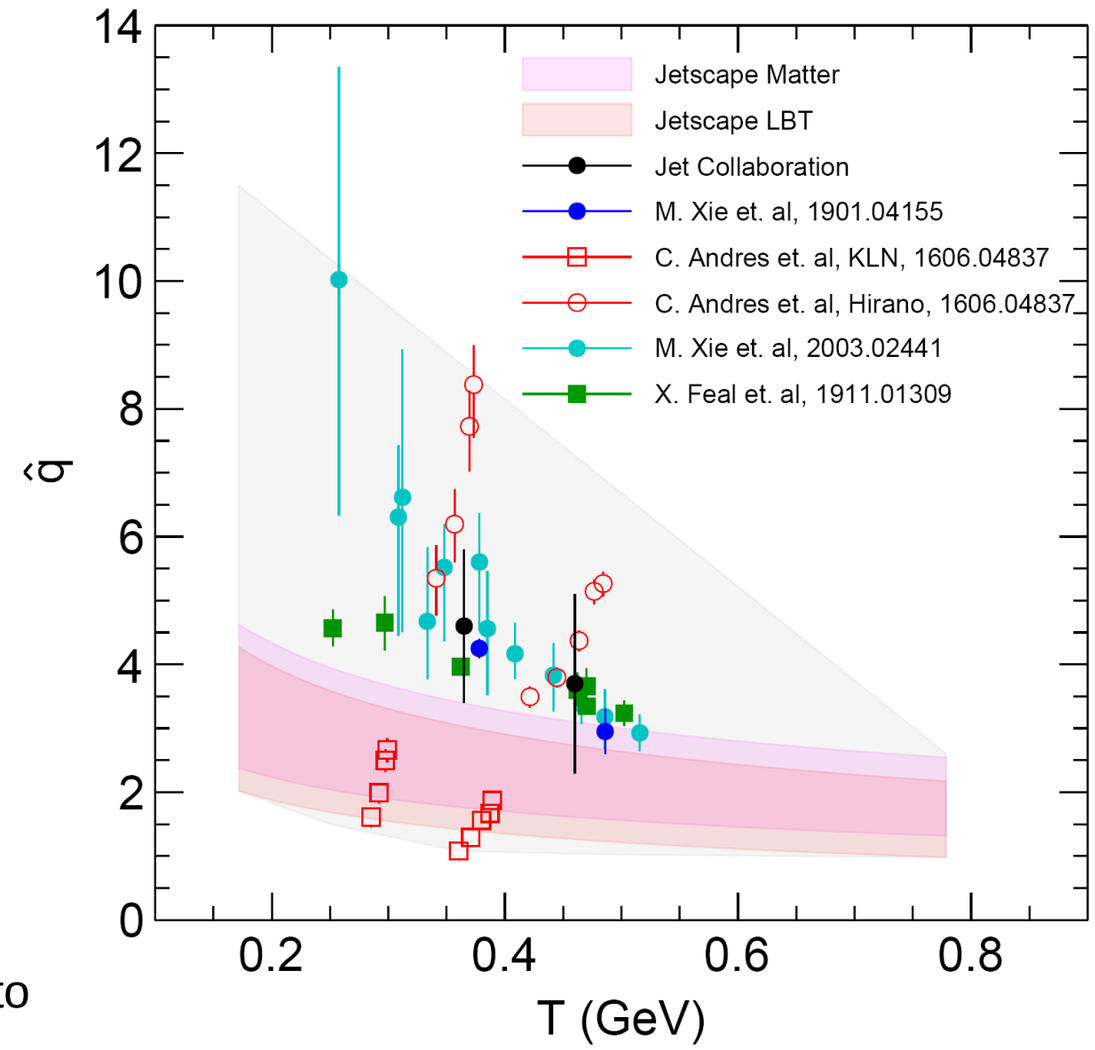
QGP Transport Properties with RHIC and LHC Run 2 Data

Jet Quenching Parameter $\hat{q}$

- Extracted **only** from charged hadron spectra R_{AA}
- Decreasing trend vs. T
- Extracted values differ by up to a factor of 5

Remaining Issues:

- Different jet quenching mechanisms in theoretical models
- Different QGP media used in various calculations
- Hadronization of fast moving partons
- Need theoretical progress on the QGP properties from **jets** to catch up with the experimental efforts



Compilation by YJL, Michael Winn, Liliana Apolinario
Working in progress

QGP Transport Properties with RHIC and LHC Run 2 Data

Charm diffusion coefficient D_s

See Steffen A. Bass's talk

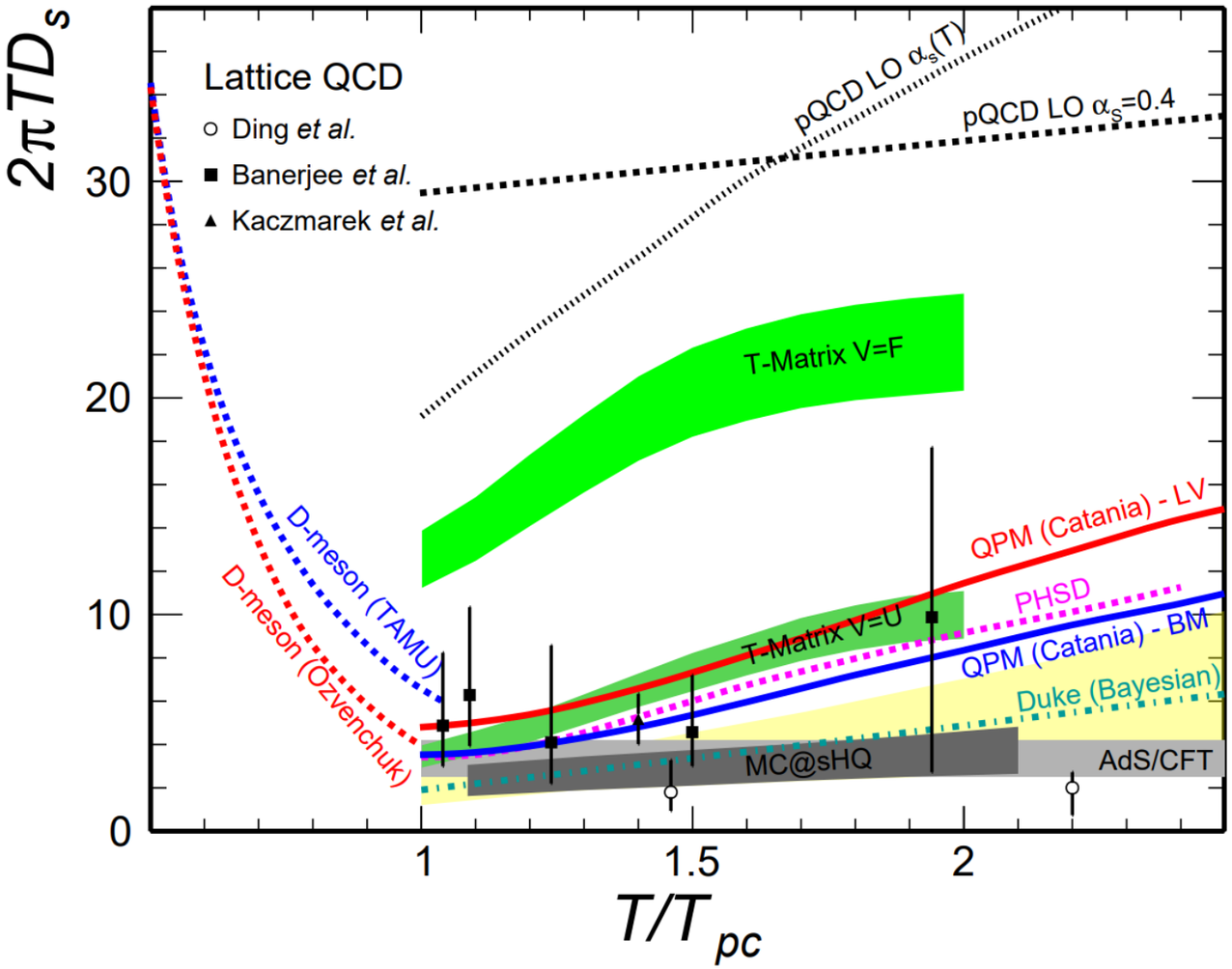
- Data-driven extraction from D meson R_{AA} and v_2
- pQCD calculations at LO are ruled out by the data
- Non-perturbative calculations with a potential close to the HQ free energy from LQCD are not viable
- Increasing trend of D_s vs. T in various models

Remaining Issues:

- Hadronization of charm quarks

See Francesco Prino's talk

- Charm diffusion mechanism
- Different QGP media used in various calculations
- Precision of the experimental data



Xin Dong, YJL, Ralf Rapp, Ann.Rev.Nucl.Part.Sci. 69 (2019) 417-445

Medium Properties from Soft and Hard Probes

Specific viscosity has been extracted from soft probes

See Steffen A. Bass's talk

- Via identified hadron dN/dη, $\langle p_T \rangle$, v_2, v_3 and v_4
- Main uncertainties from initial state and early time dynamics

To get the big picture of the QGP properties with Run 2 + RHIC data, one could compare the inputs from soft and hard probes:

- **HQ D_s** could be related to specific viscosity by

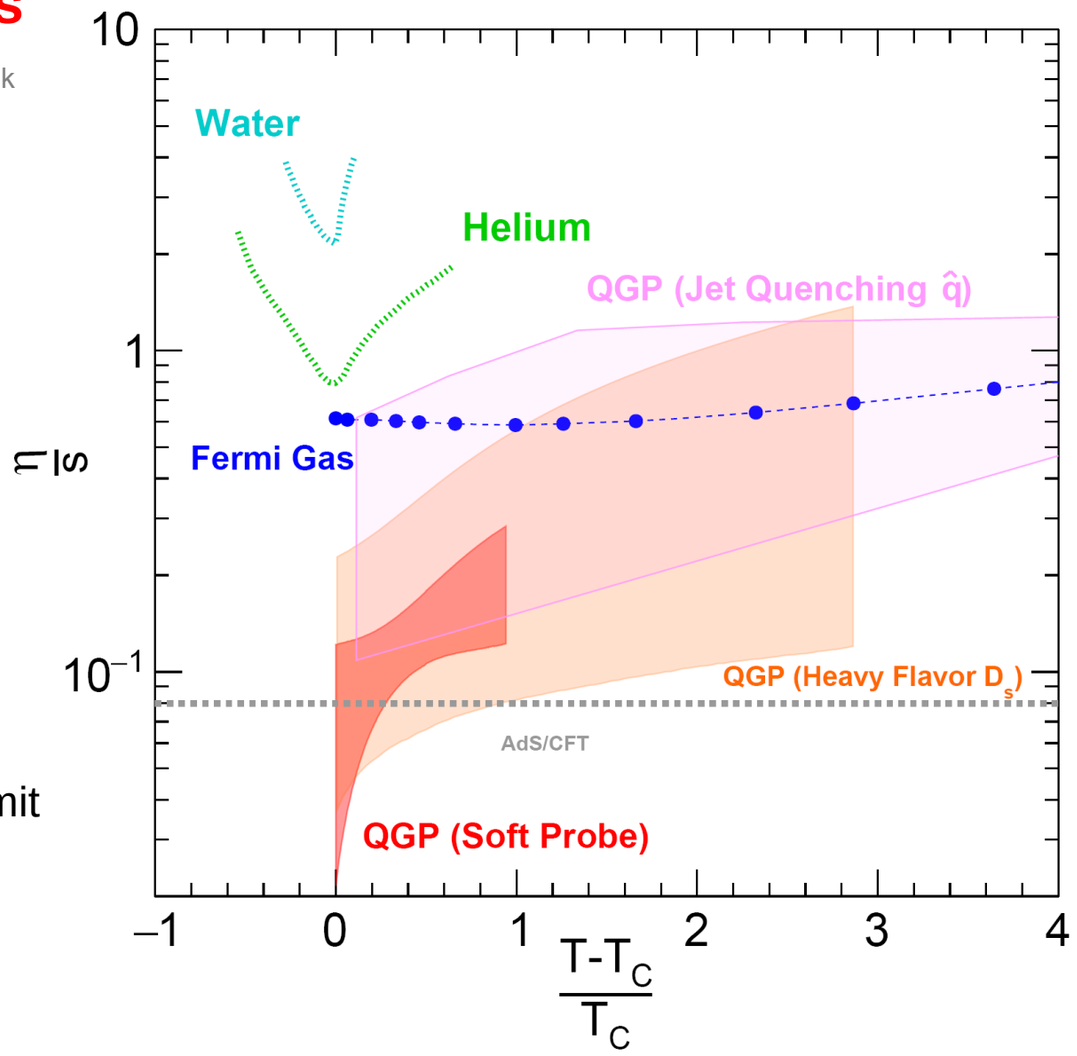
$$\frac{\eta}{s} = \frac{D_s(2\pi T)}{4\pi k}$$

arXiv:0903.1096

Where the scale factor ranges between 1 (strong-coupling limit) and 2.5 (weak coupled)

- **Jet quenching parameter $\hat{q}$** could be related to specific viscosity in the limit of multiple soft scattering by

$$\frac{\eta}{s} = 1.25\frac{T^3}{\hat{q}}$$



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QGP properties extracted from **hard probes are consistent with the results from soft probes, but within rather large uncertainties**

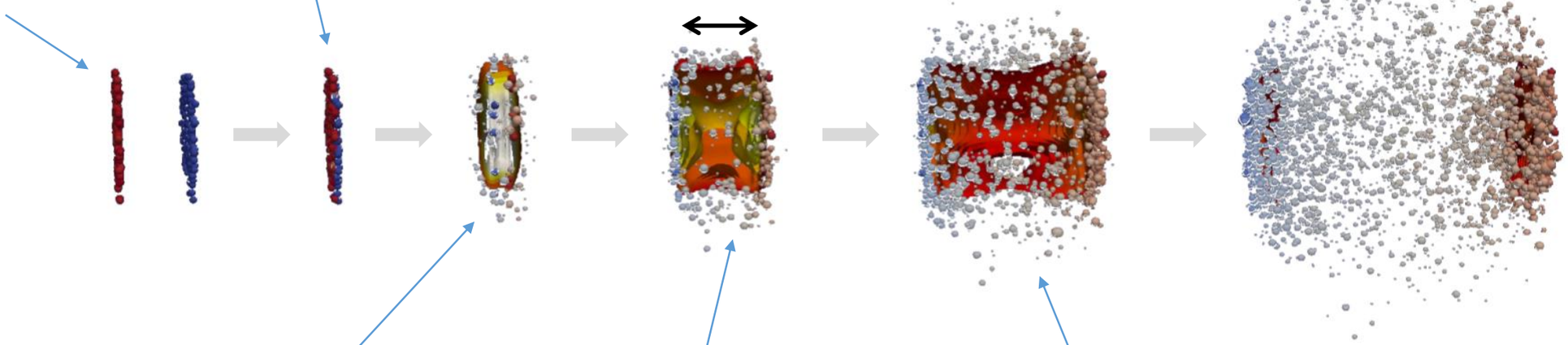
Open Questions to be Addressed with Run 3 and 4 Data

What are the initial conditions of the collision?

What is the longitudinal structure of the QGP?

What's the hadronization mechanism with QGP?

nPDF and initial EM field



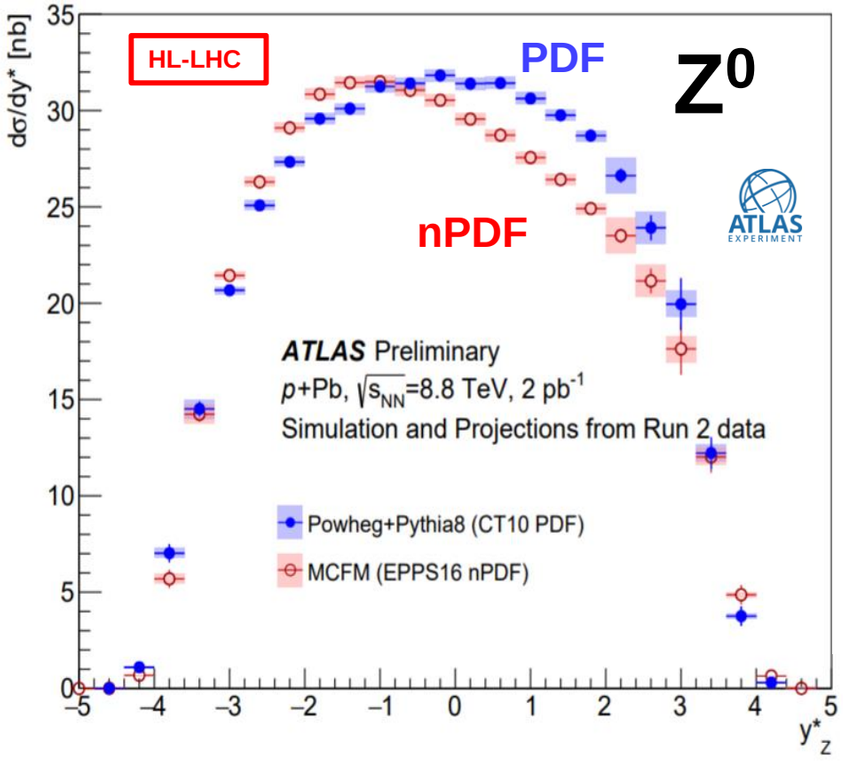
How does the system move toward hydrodynamization?

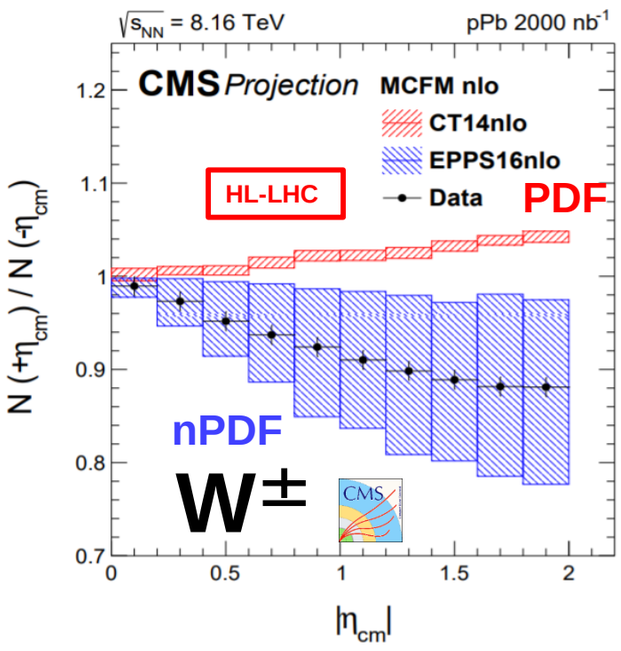
What are the transport properties of the QGP?
How does QGP respond to hard probes?
What are the inner workings of QGP at various length scales?

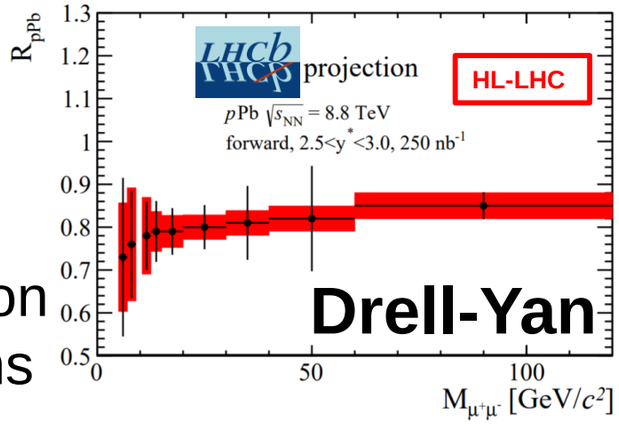
What is the in-medium color force?

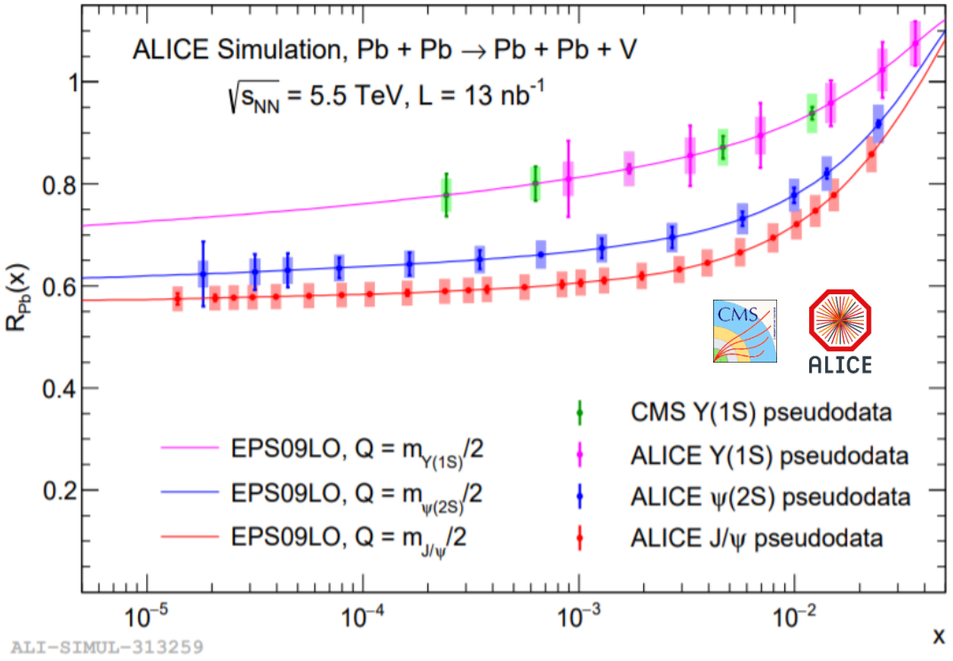
Visualization taken from Jonah E. Bernhard
arXiv:1804.06469

nPDF Constraint from pPb Collisions





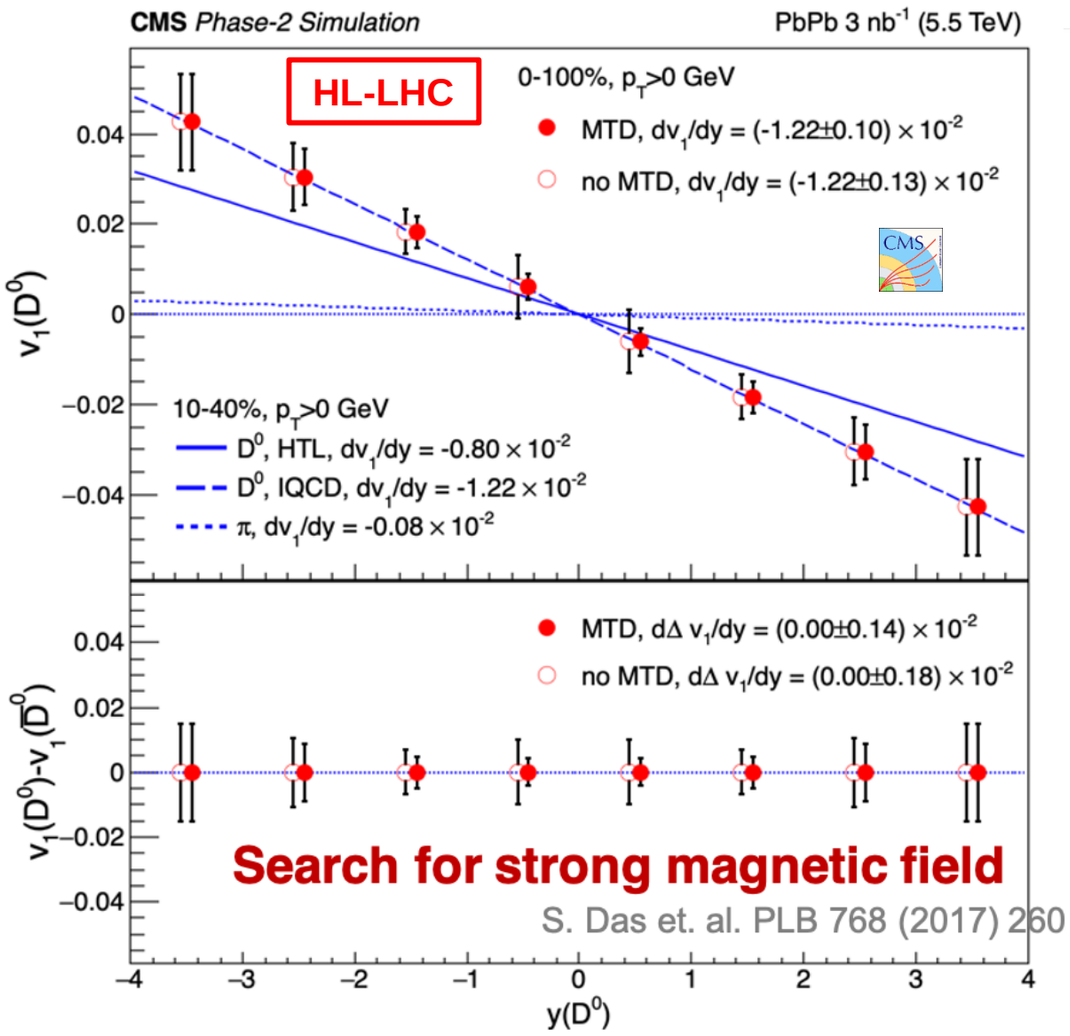




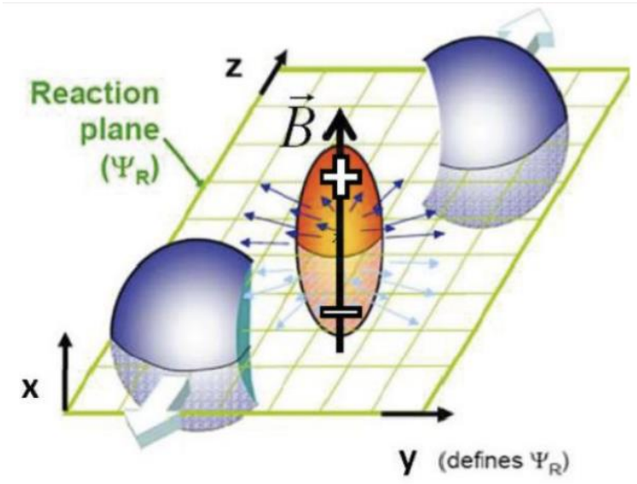
- Strong constraints on nPDF from electroweak boson, Drell-Yan and dijet cross-section measurements in pPb collisions

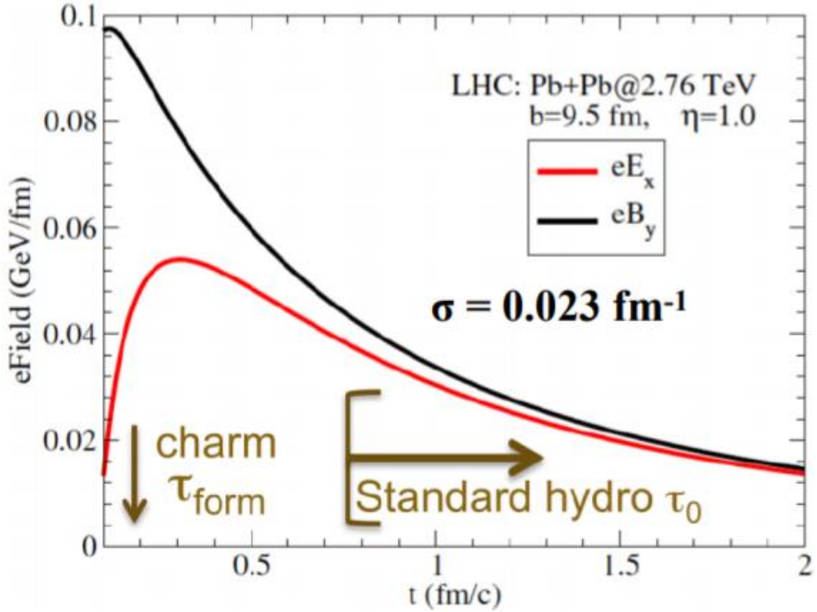
- Ultra-Peripheral PbPb Collisions (UPC): **γ+Pb** collisions!
- HL-LHC data: Precise measurements of Υ(1S), J/ψ and ψ(2S) over a **very wide x range**, test **Q dependence** of nuclear modifications

Magnetic Field with D^0 Directed Flow v_1



$$\frac{2\pi}{N}\frac{dN}{d\phi} = 1 + \sum_{n=1}^{\infty} \boxed{2v_n} \cos[n(\phi - \Psi_n)]$$

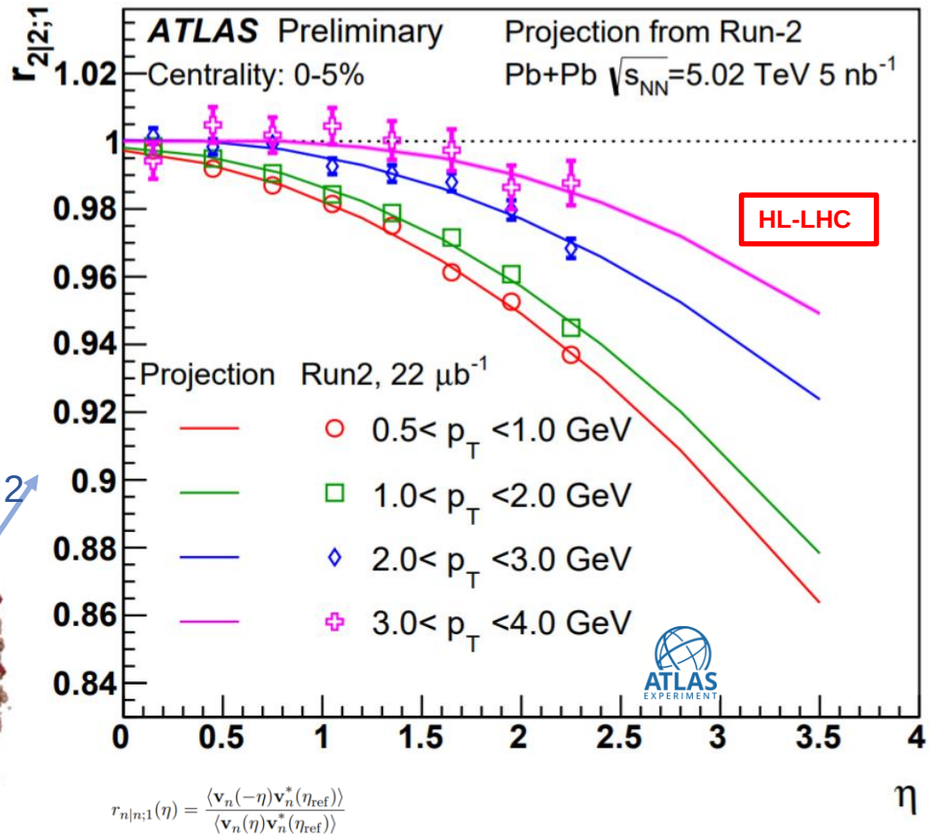


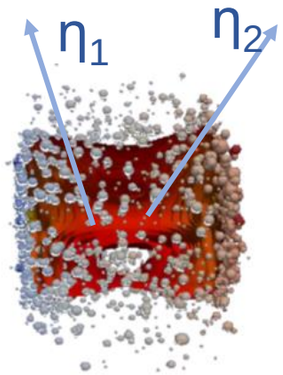


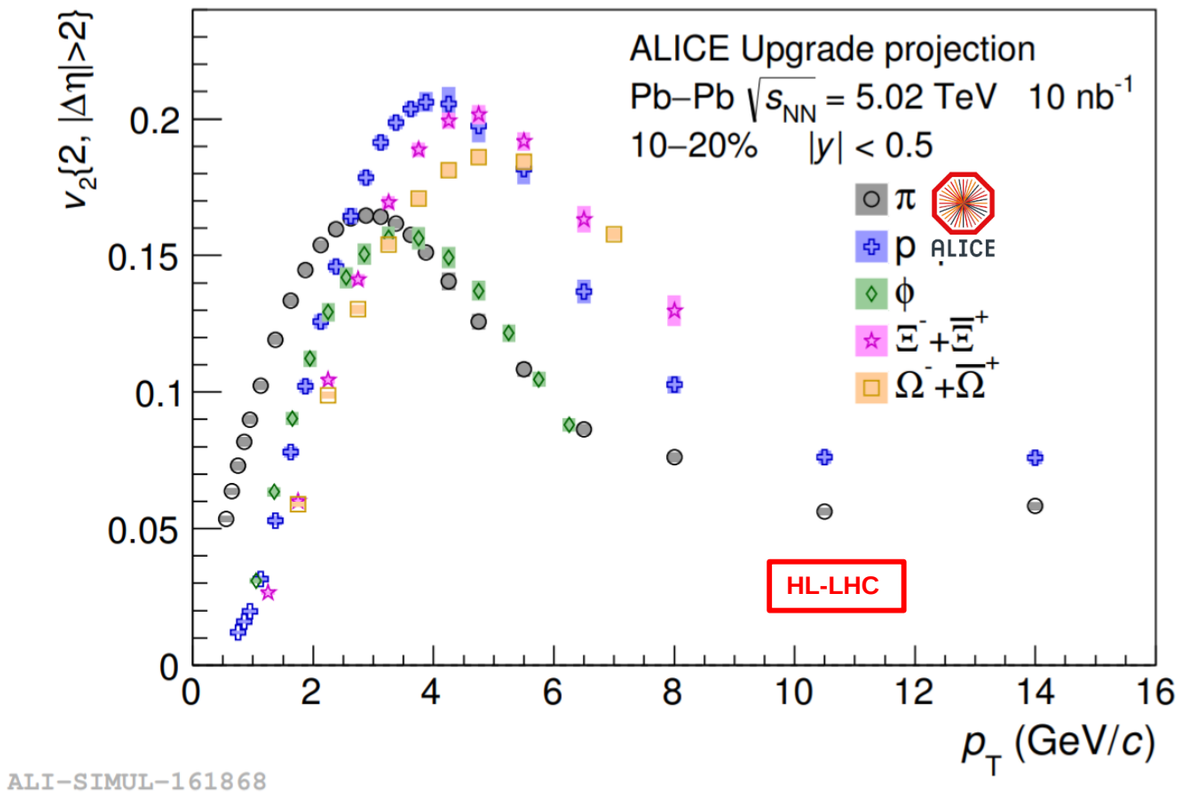
- Strong initial electromagnetic field in heavy ion collisions inducing a vorticity in the reaction plane.
- The resultant effects entails a significant directed flow (v_1) and the effects increase vs. D^0 rapidity
- MTD and the large acceptance CMS tracker could provide high precision measurement of D^0 v_1 over 8 units of D^0 rapidity.

Prospects for Flow Measurements in PbPb

- Unprecedented high precision and differential measurements of flow harmonics and their event-by-event fluctuations
  New constraints on the QGP initial density profile, formation time, properties and hadronization





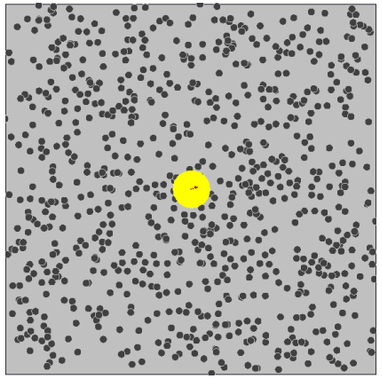


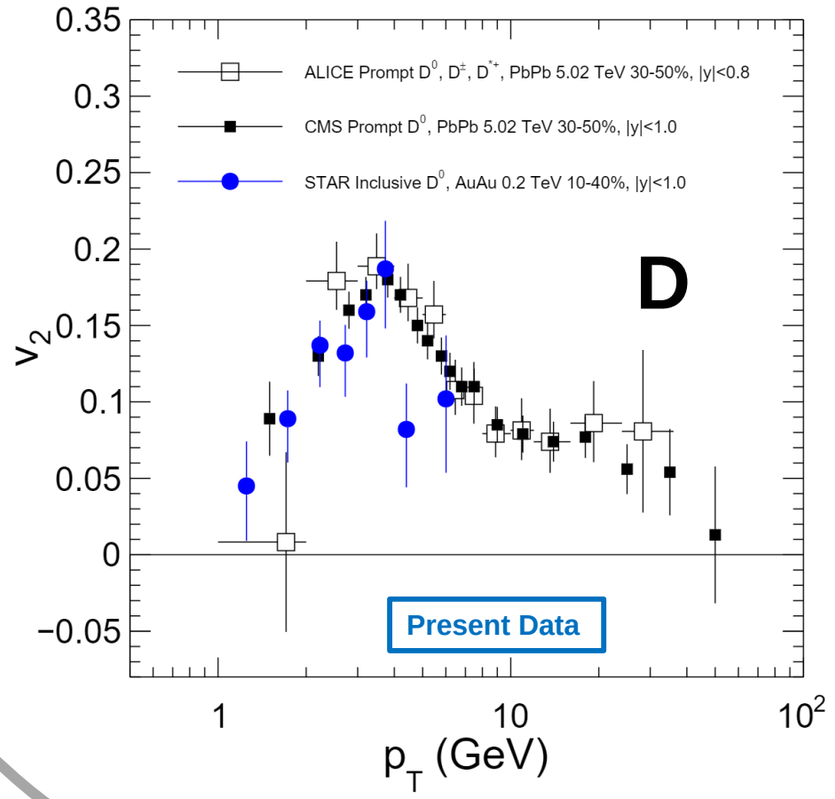
- Pseudorapidity dependence of the flow measurements over **a wide η window** enabled by ATLAS and CMS tracker upgrade
  New insights into the longitudinal structure of QGP (event-plane decorrelation)

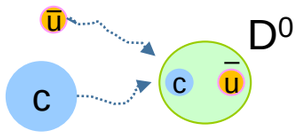
Open Heavy Flavor

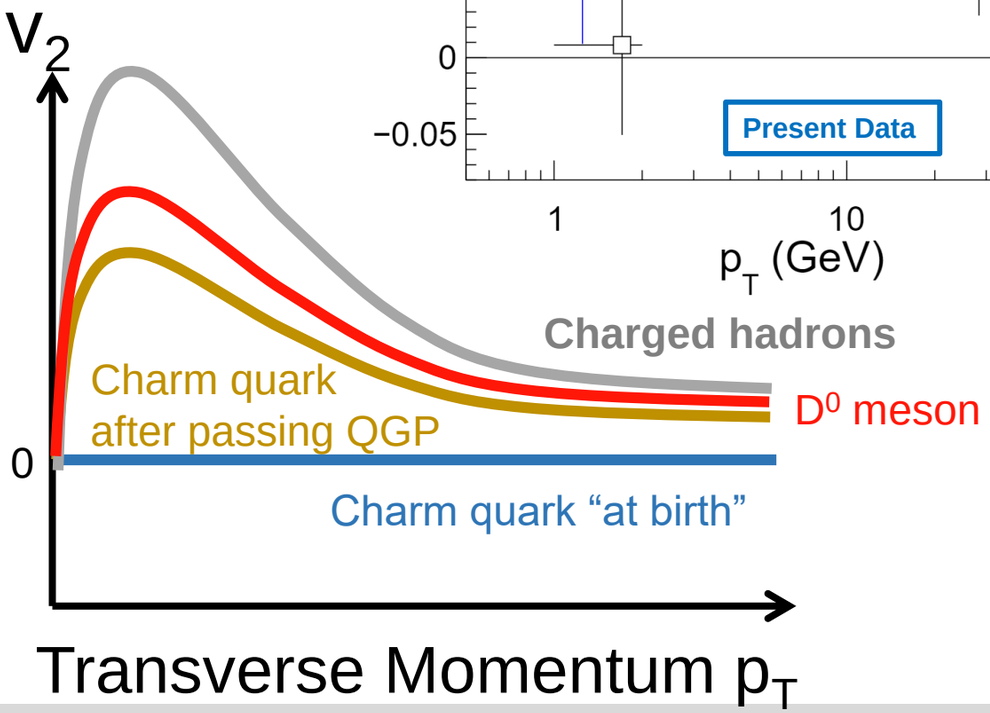
- Produced **before** the QGP formation
- Low momentum heavy quarks (HQ) are then "kicked around" by quasi-particles in a pQCD picture (like Brownian Motion)
- Heavy quark diffusion coefficient (D_s) provides a direct window on the in-medium QCD force
- Since the **QGP expands radially**, QCD force (like "wind") will increase the v_2 of the heavy quarks in the QGP bath
- Hadronization of heavy quarks could also pick up v_2 from light flavors

See also: Alexander Kalweit's talk
Gian Michelle Innocenti's talk

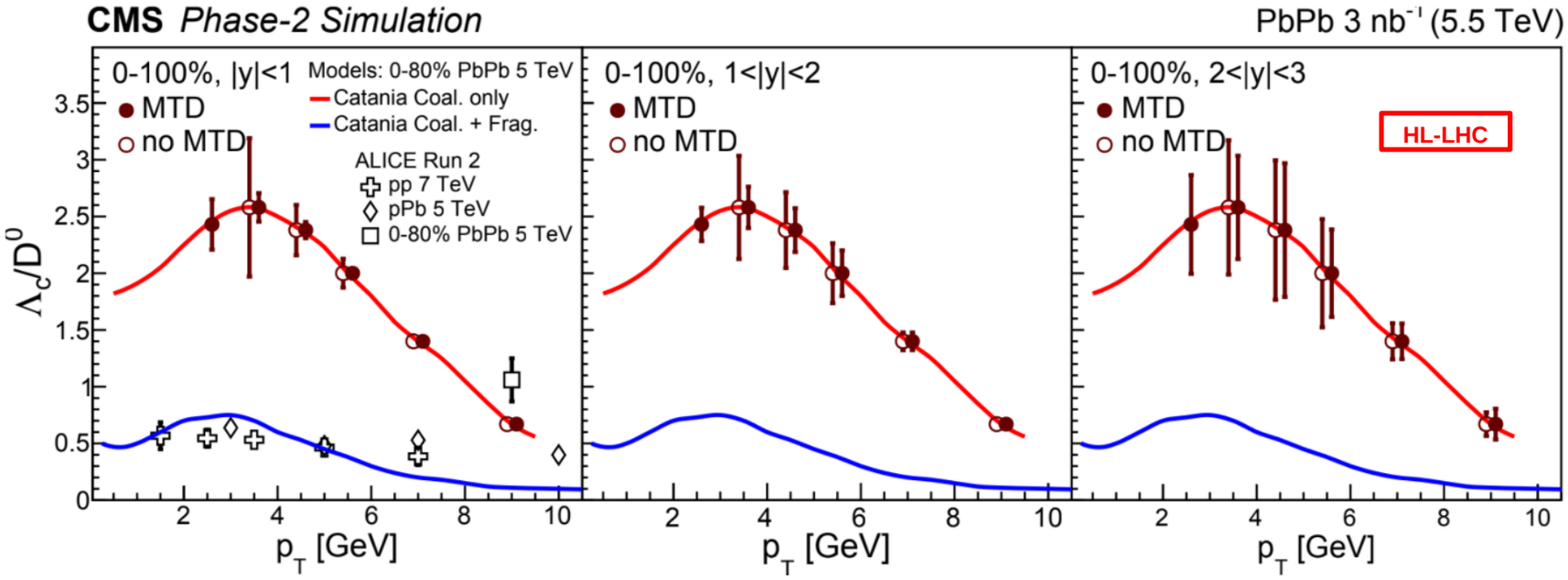


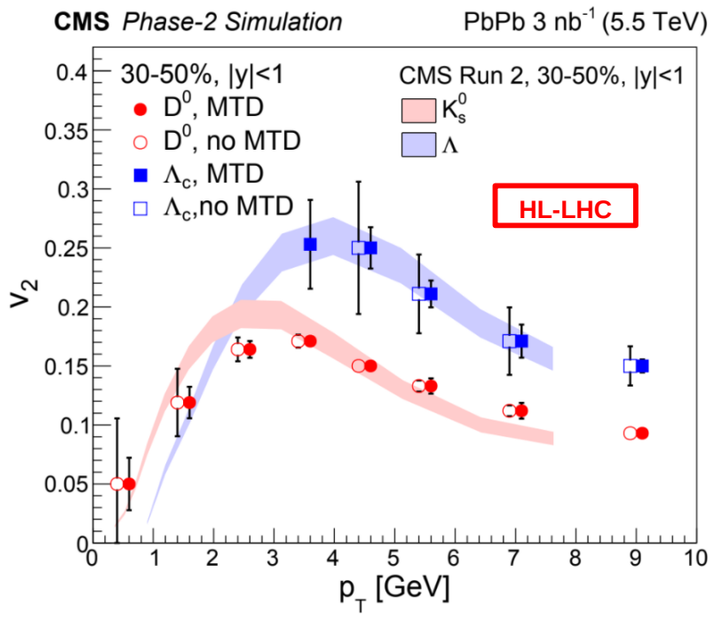




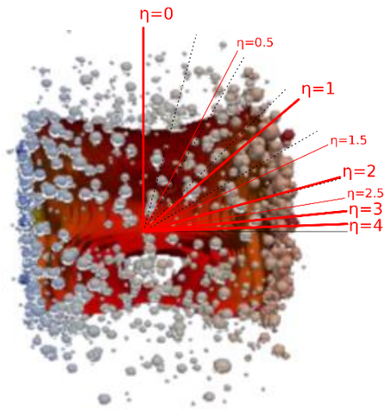


Wide Rapidity Coverage of Λ_c^+/D^0 and v_2 measurement

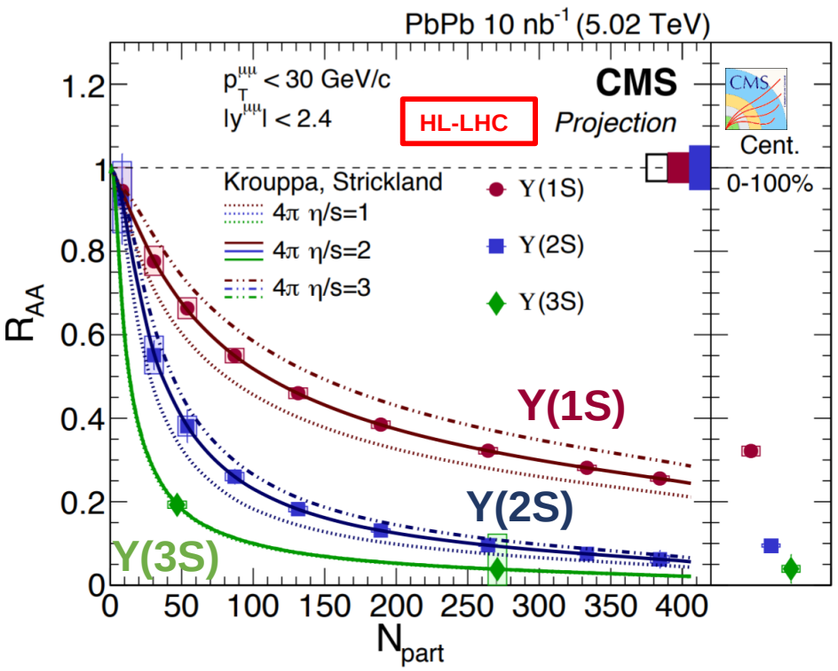


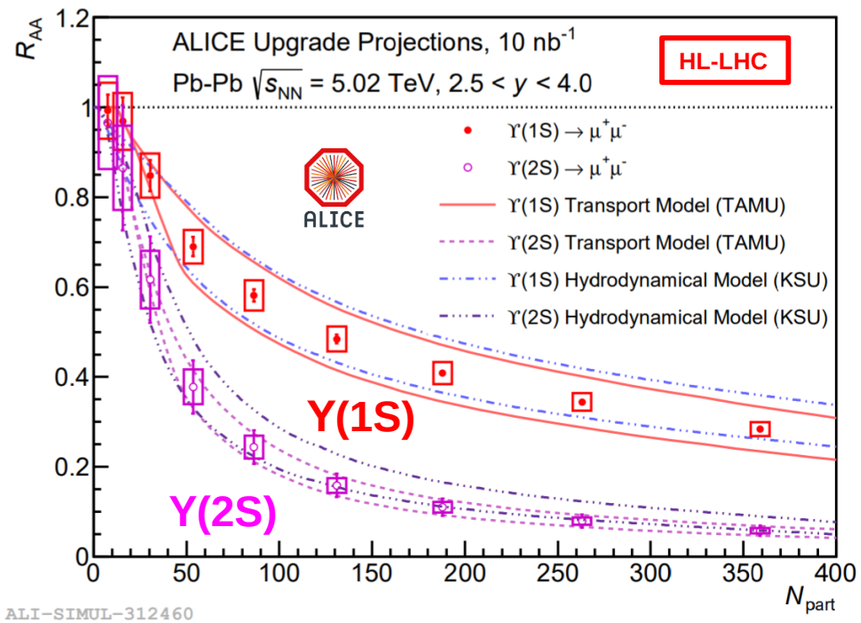


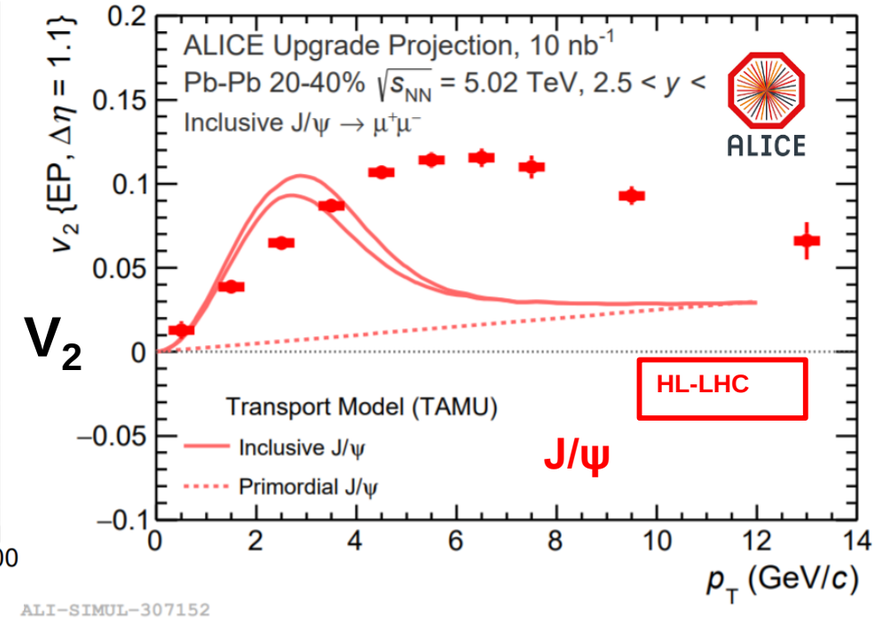
- Measurement of Λ_c^+/D^0 and Λ_c^+ v_2 over a large pseudorapidity interval
- Together with other measurements: provide **the strongest constraint** on the heavy quark hadronization mechanism



Quarkonia Production in HL-LHC



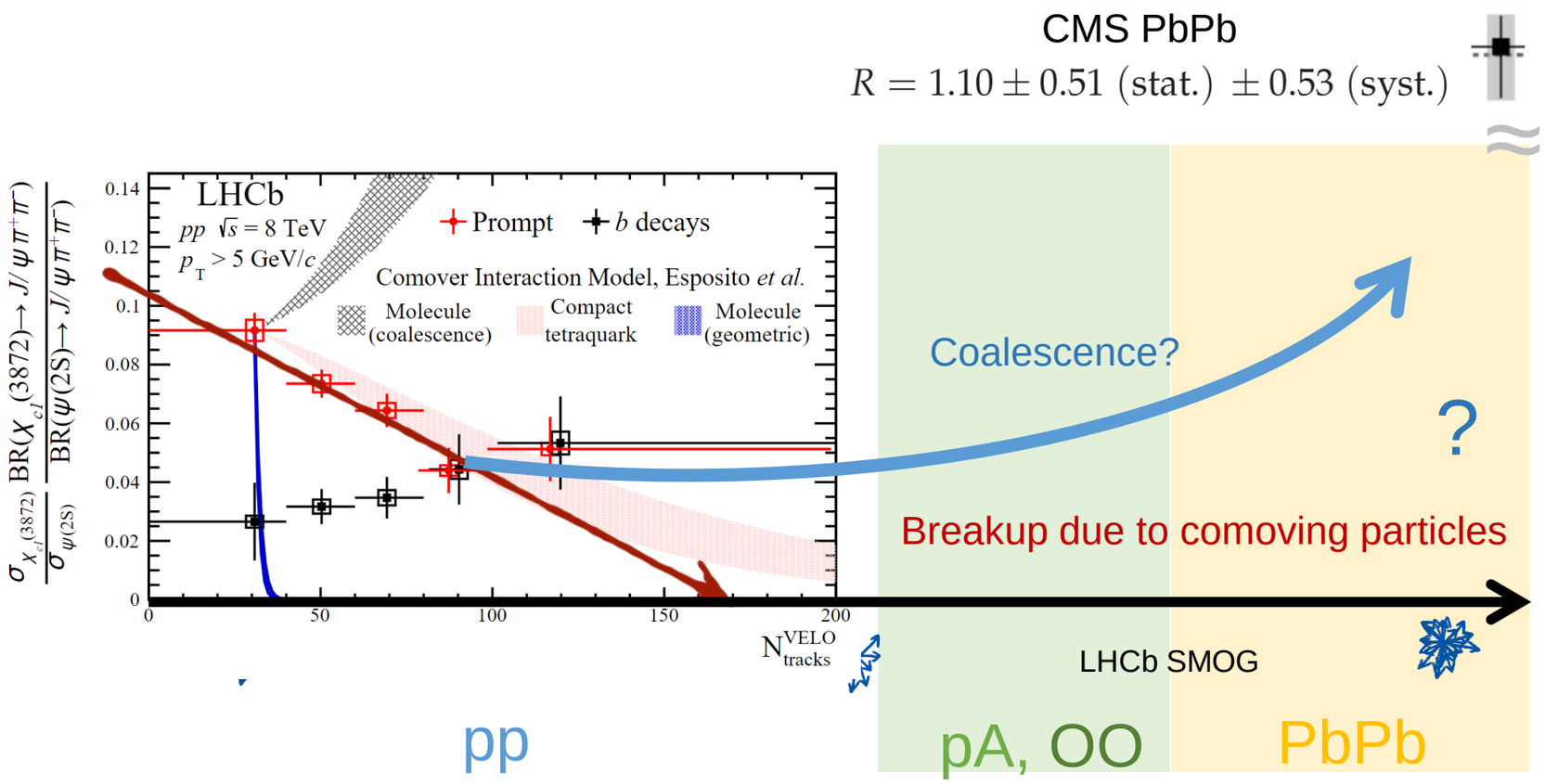


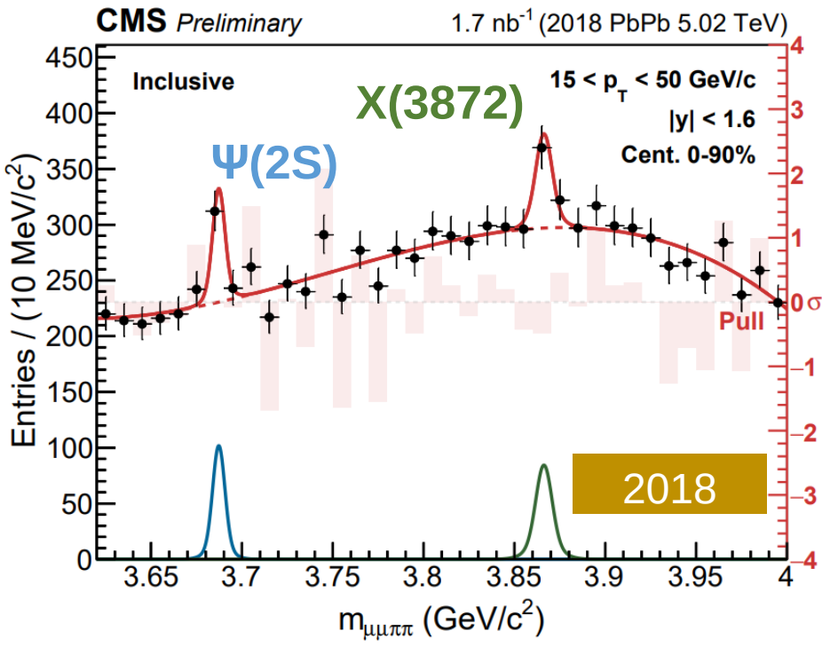


- Precise measurement of Υ(nS), J/ψ and ψ(2S) R_{AA} as a function of centrality, p_T and rapidity
  - **Observation of Υ(3S) production in PbPb**
  - Precise measurement at large rapidity from ALICE
  - Sensitive to QCD in-medium potential

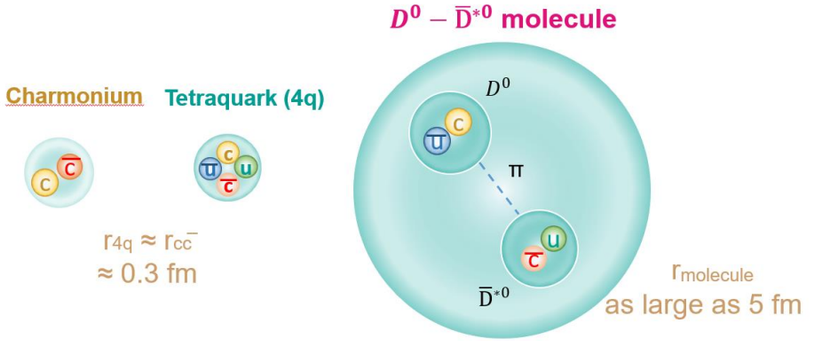
- High precision measurement of J/ψ elliptic flow: Probe the QCD interaction of deconfined c and $\bar{c}$

Probe the Inner Structure of X(3872) with QGP





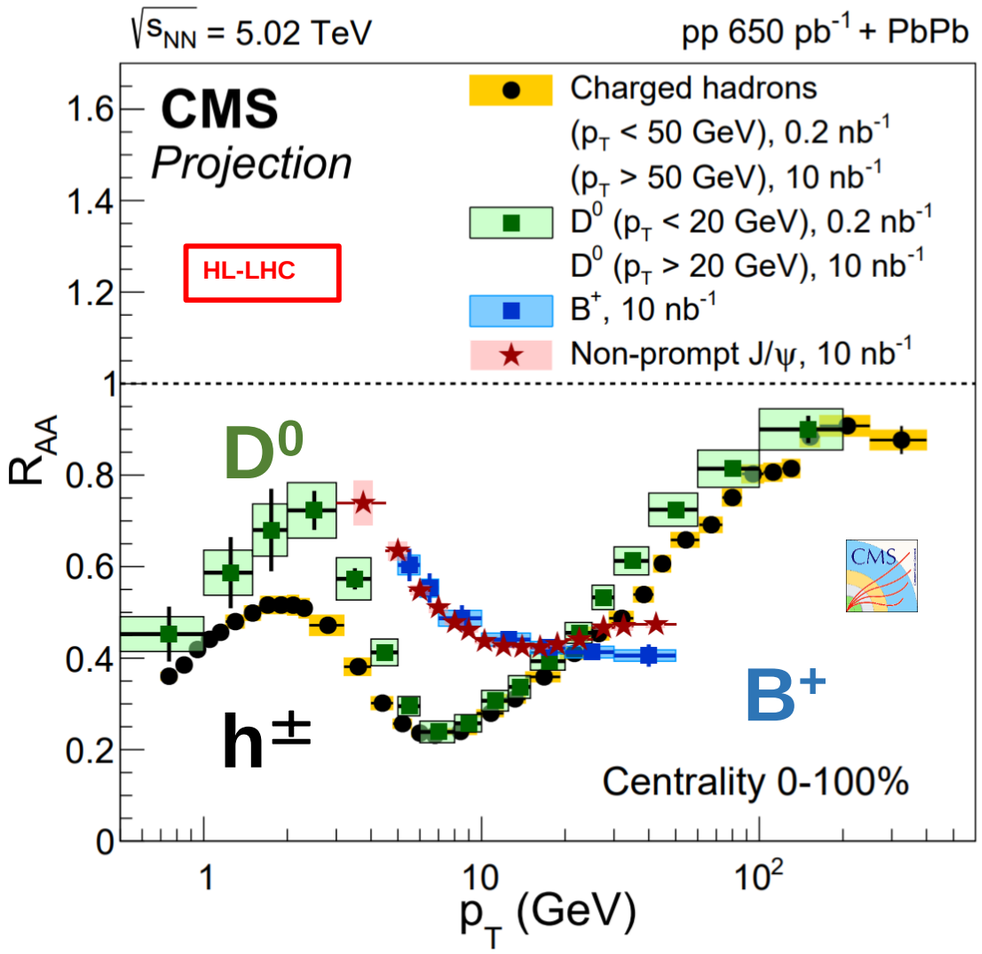
The first evidence of X(3872) in HI



- Observation **of X(3872) in PbPb is expected (>5 σ) in Run3**
- Run3+4: Enables more differential studies (vs. p_T and centrality)
- Low p_T reach limited by combinatorial background
  - → ALICE3 and/or LHCb with central event capability upgrade

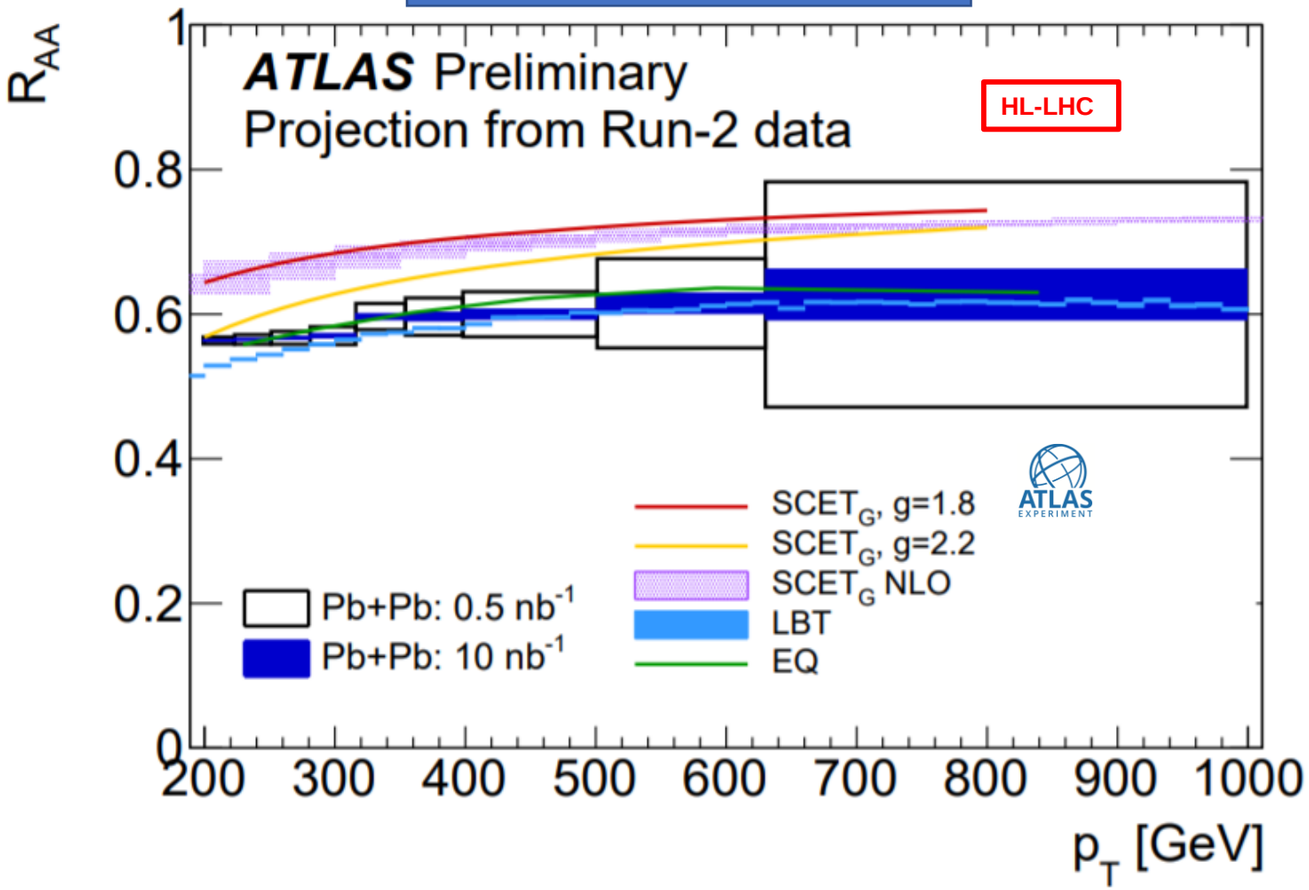
Jet Quenching up to 1 TeV in PbPb

(Heavy Flavor)Hadron R_{AA}



- Precise measurement of light and heavy flavor hadron R_{AA} up to **0.4** to **1 TeV**

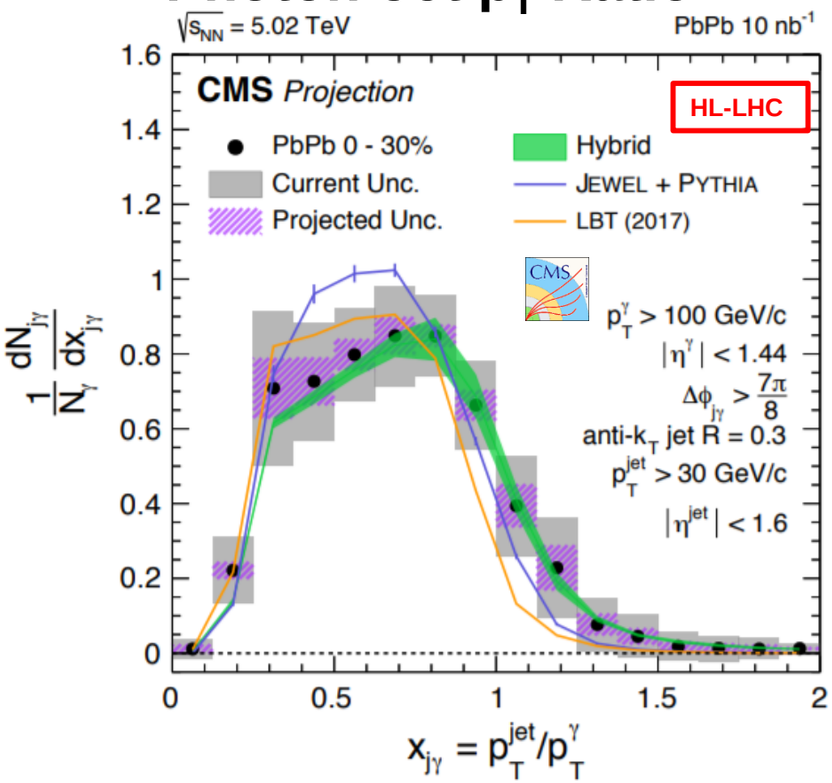
Jet R_{AA}



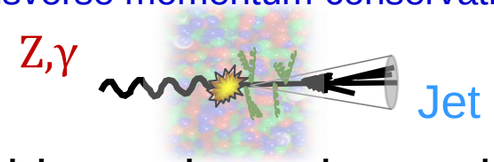
- High p_T reach of charged hadrons and jet R_{AA} up to **~ 1 TeV**
- The excitement is that the quenched energy will be significant compared to underlying event energy density!

Photon-Jet and Hadron-Jet Correlations in PbPb

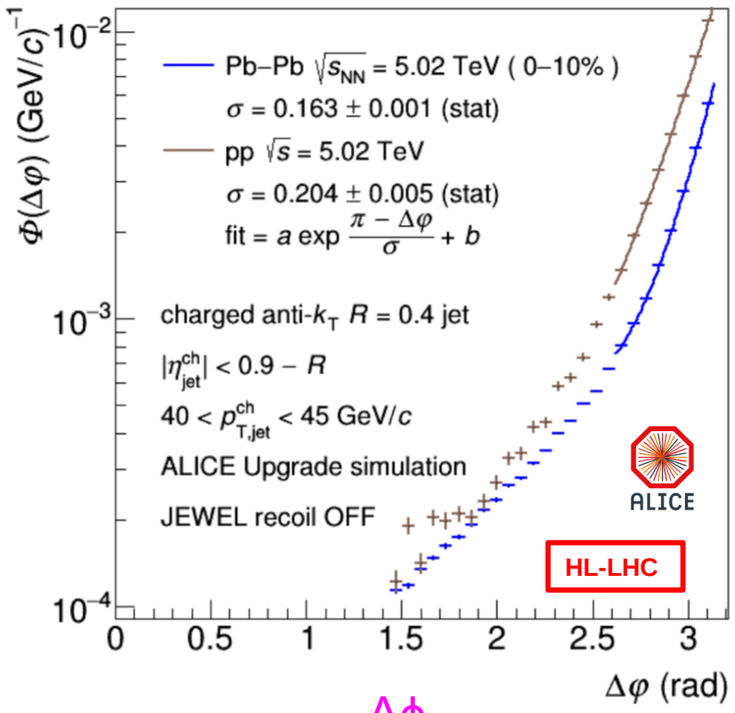
Photon-Jet p_T Ratio

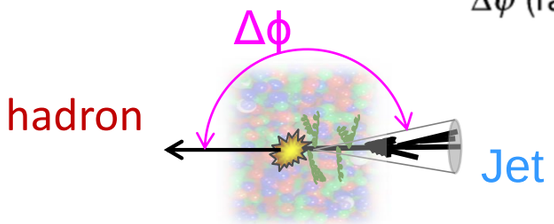


Transverse momentum conservation

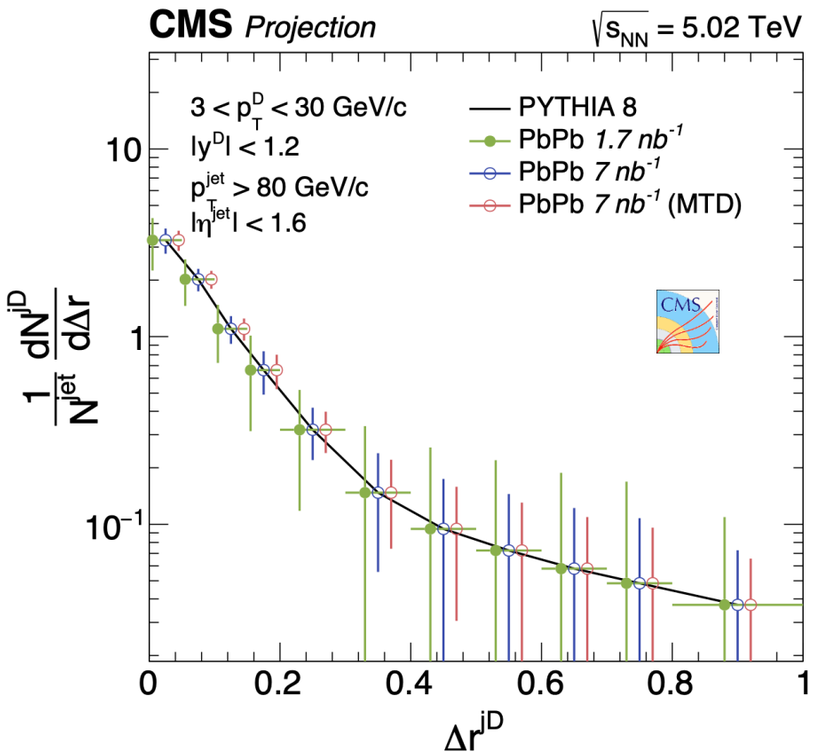


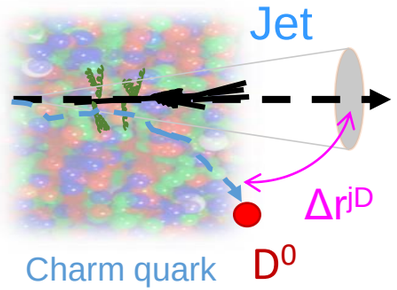
Hadron-Jet Correlation





D^0-Jet Correlation

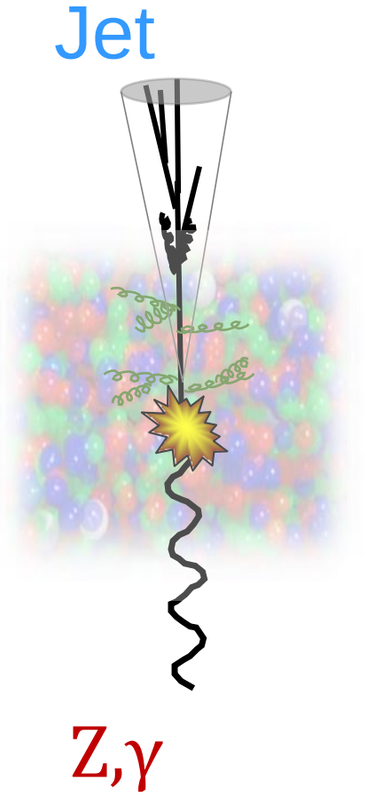




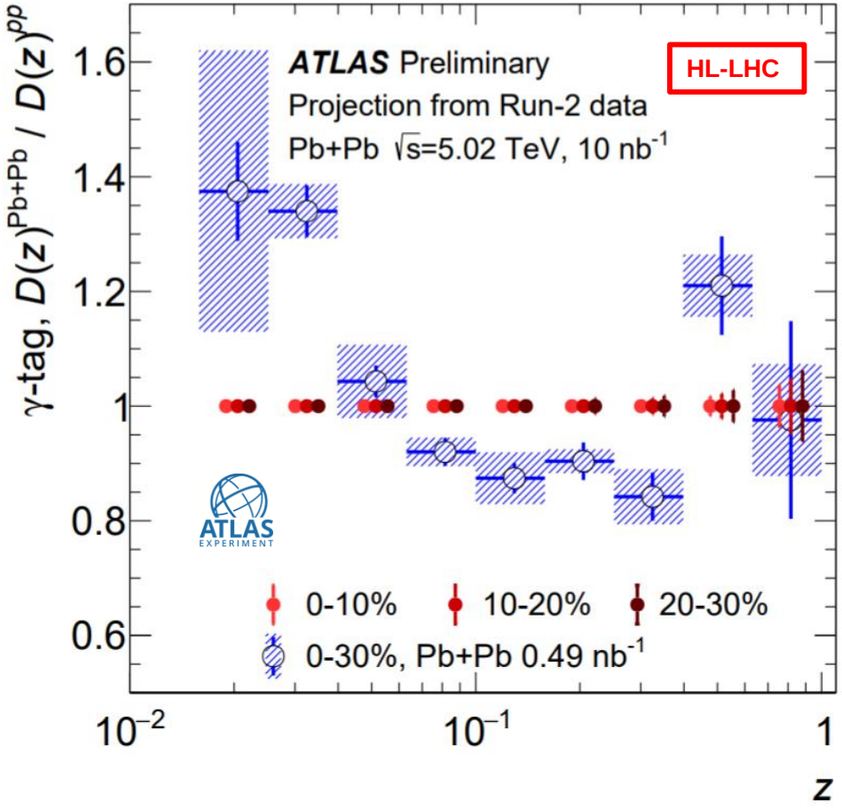
- Quenching reduces boson-jets p_T ratio
- High precision "**absolute energy loss**" measurement at HL-LHC

- Hadron-Jet and D-Jet Angular Correlation: search for **large angle scattering**, study of QGP scattering power and substructure

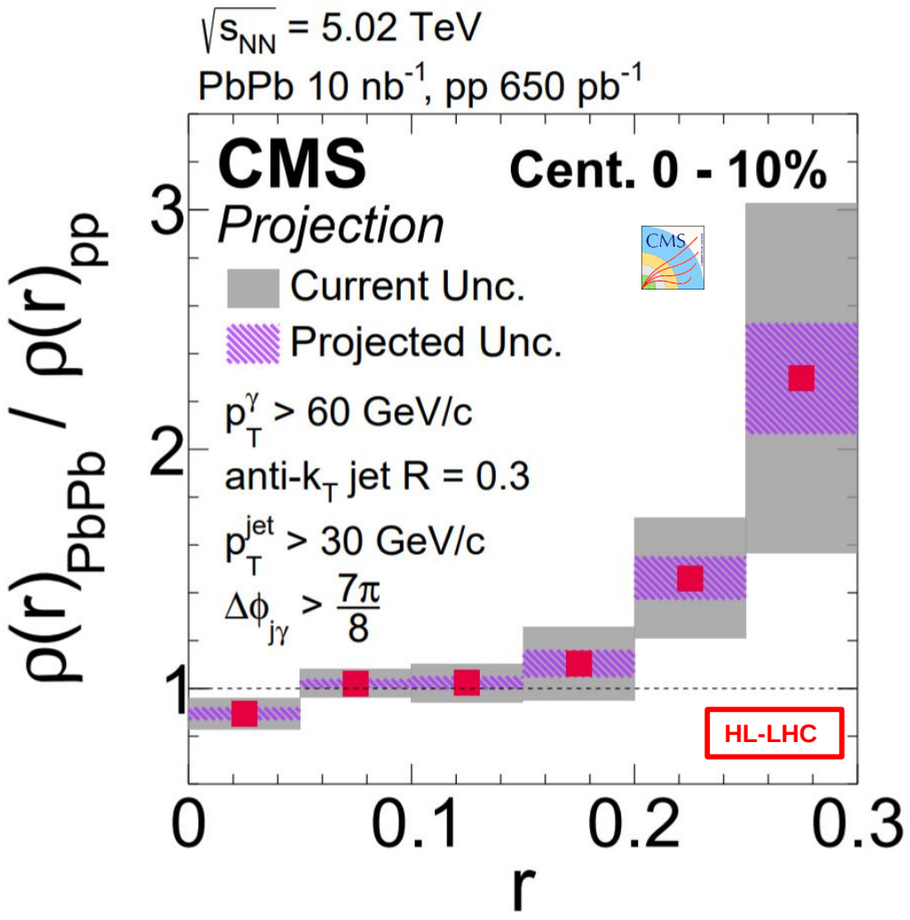
Photon-Tagged Jet Structure in PbPb



Modification of Jet Fragmentation Function



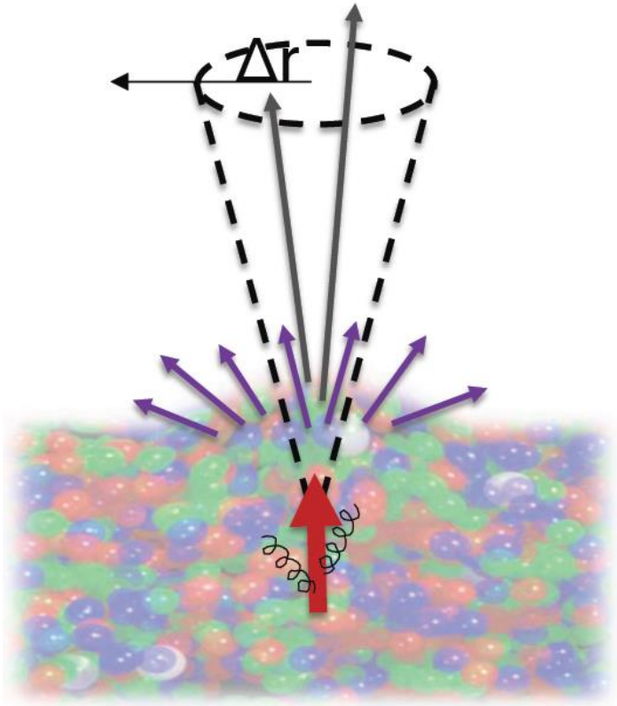
Modification of Jet Shape

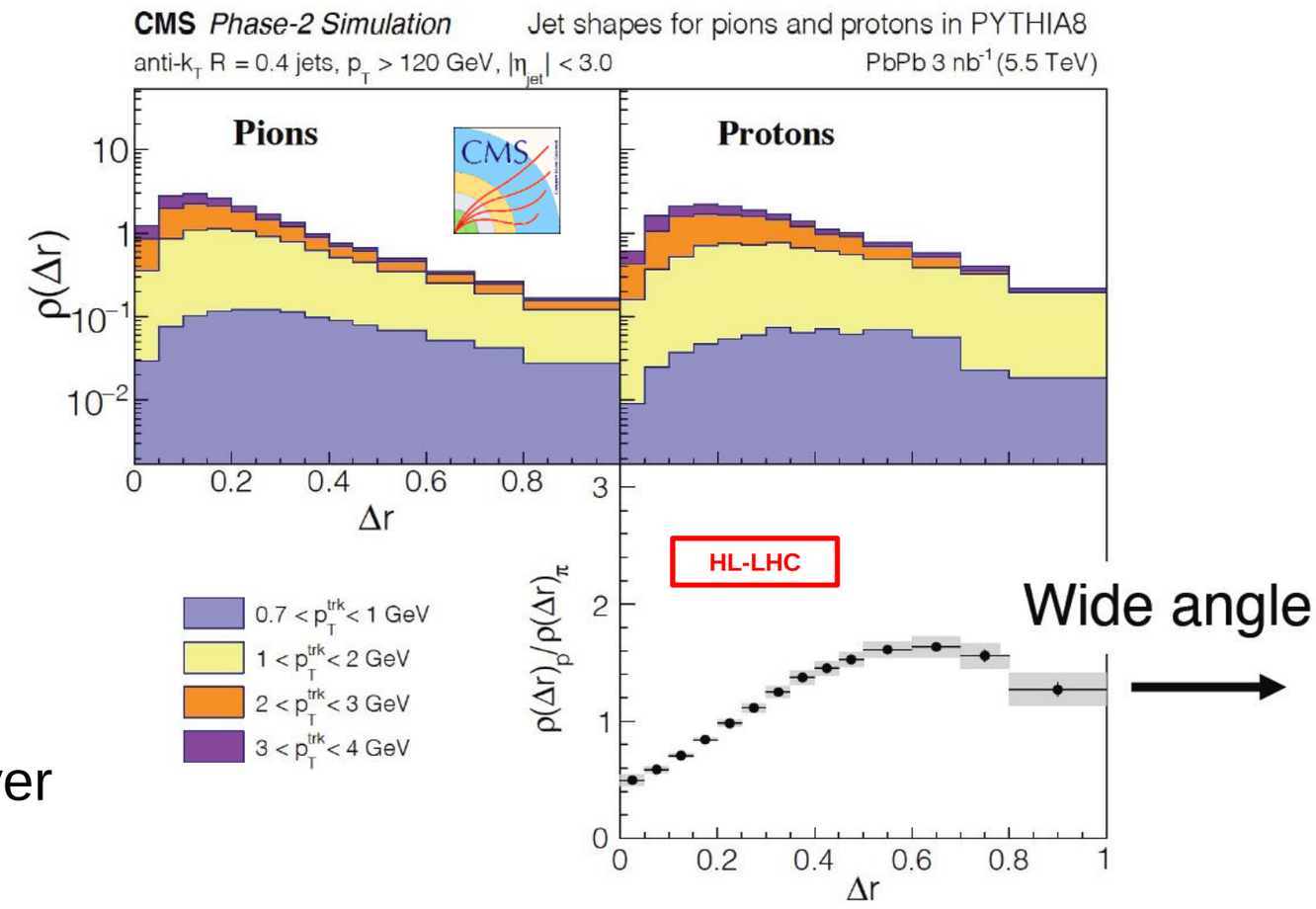


- High precision measurement of photon-tagged jet substructure
- Study of medium response and “jet thermalization”

Jet Hadronization and Medium Response

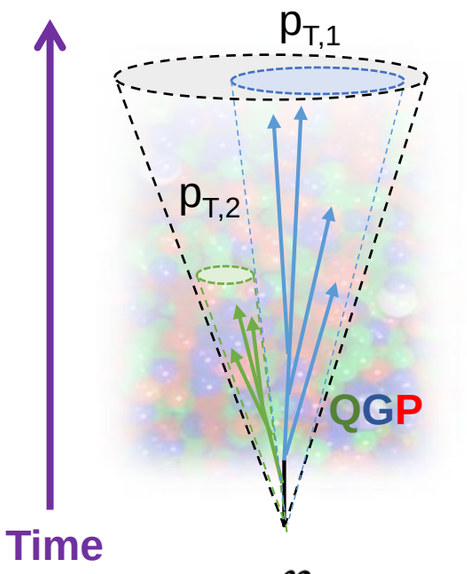
What are properties of wide angle radiations? Medium-like vs. jet-like?



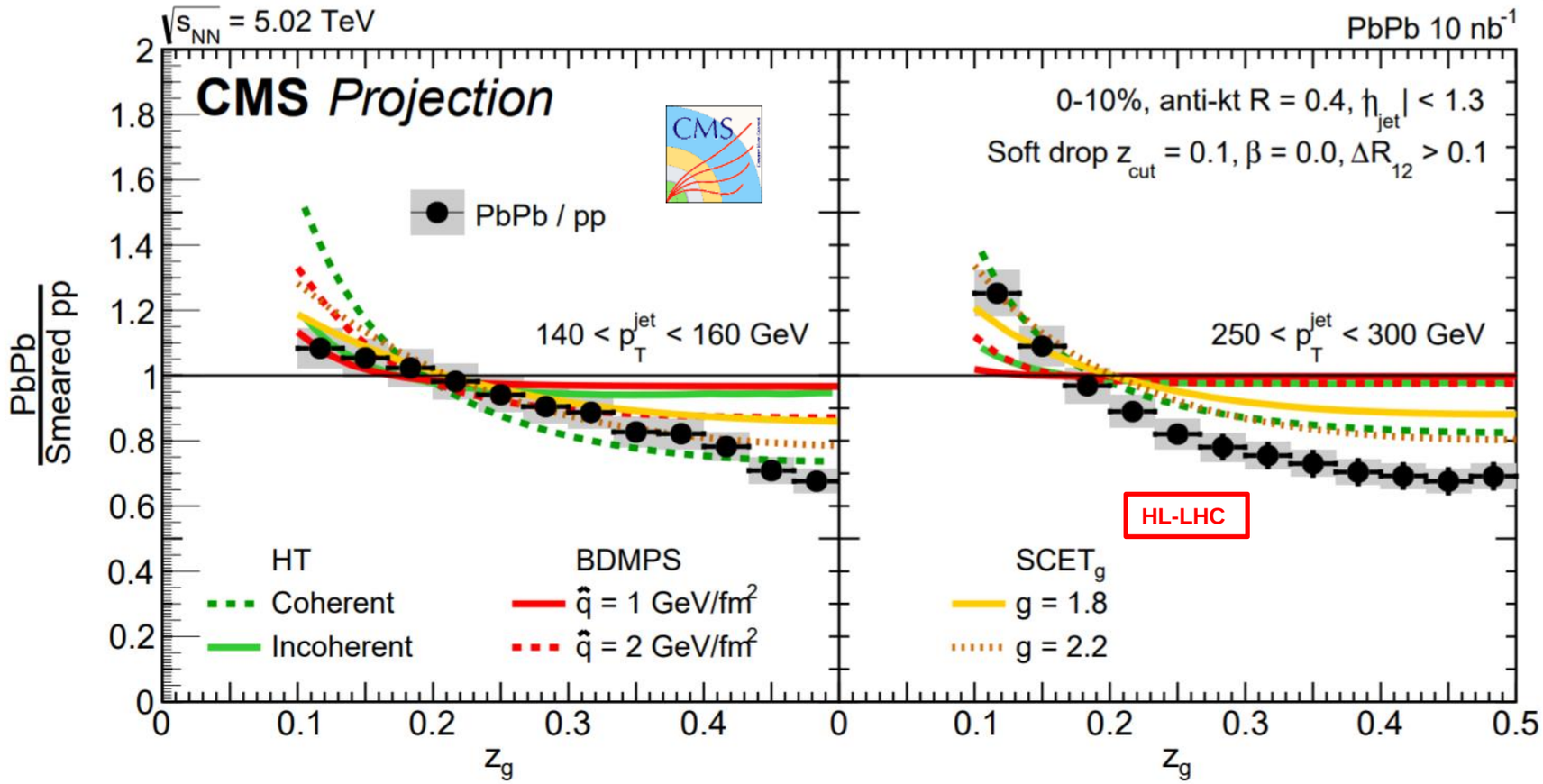


With CMS Run 3+4 data and PID capability over a wide rapidity interval, we aim to perform detailed investigation of the quenched energy

Subjet Momentum Sharing in PbPb

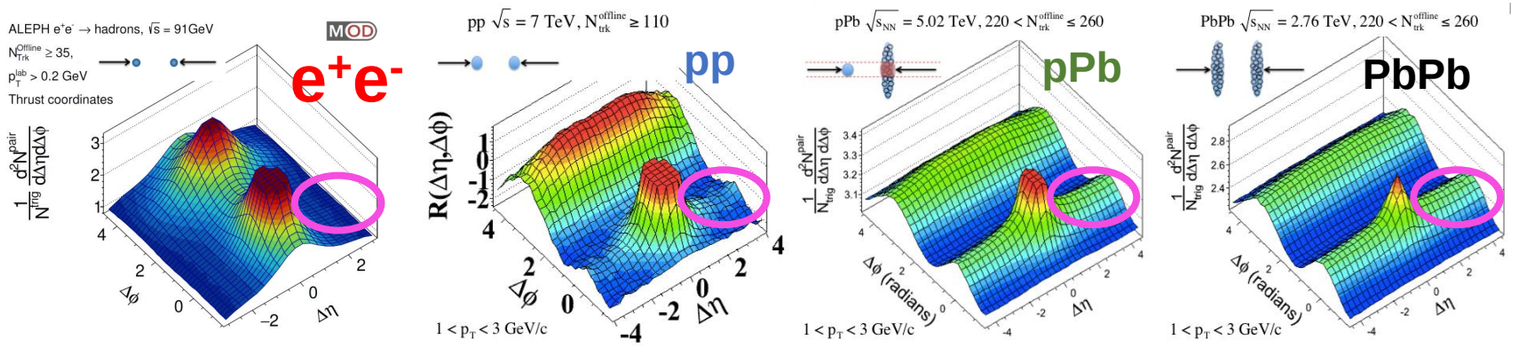


$$z_g = \frac{p_{T,2}}{p_{T,1} + p_{T,2}}$$



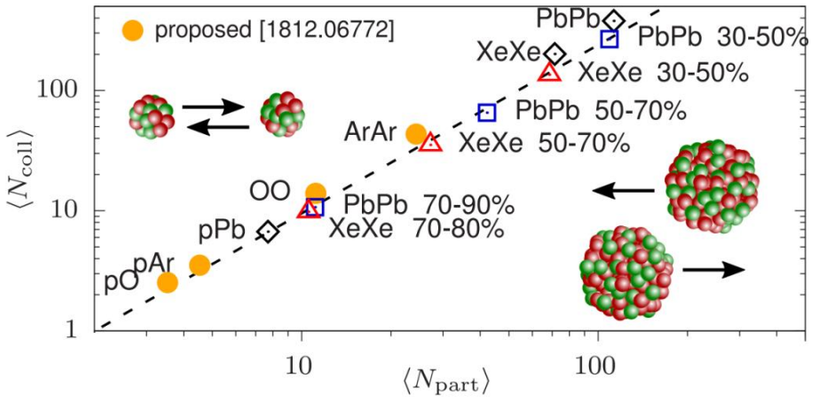
- New era of jet substructure fluctuation studies: **constraints on the QGP scattering power with a completely orthogonal observable** (vs. jet or hadron spectra)
- Grooming techniques enable us to classify jets and to study **"Parton Shower Shape Dependence of Jet Quenching"**

Small System



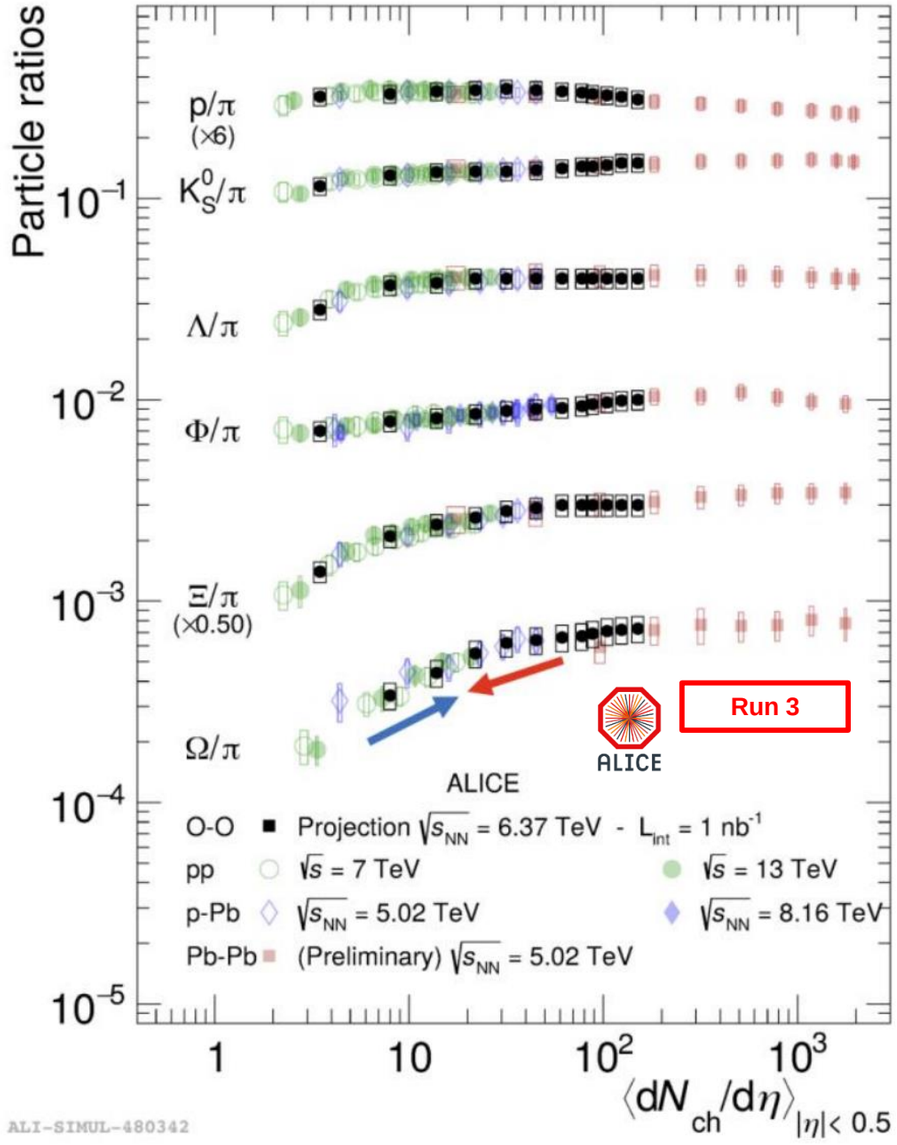
PRL 123 (2019) 21, 212002

- Flow-like phenomena in high multiplicity pp and pPb collisions, not yet observed in ee and eA



- Strangeness enhancement from ALICE particle ratios measurements

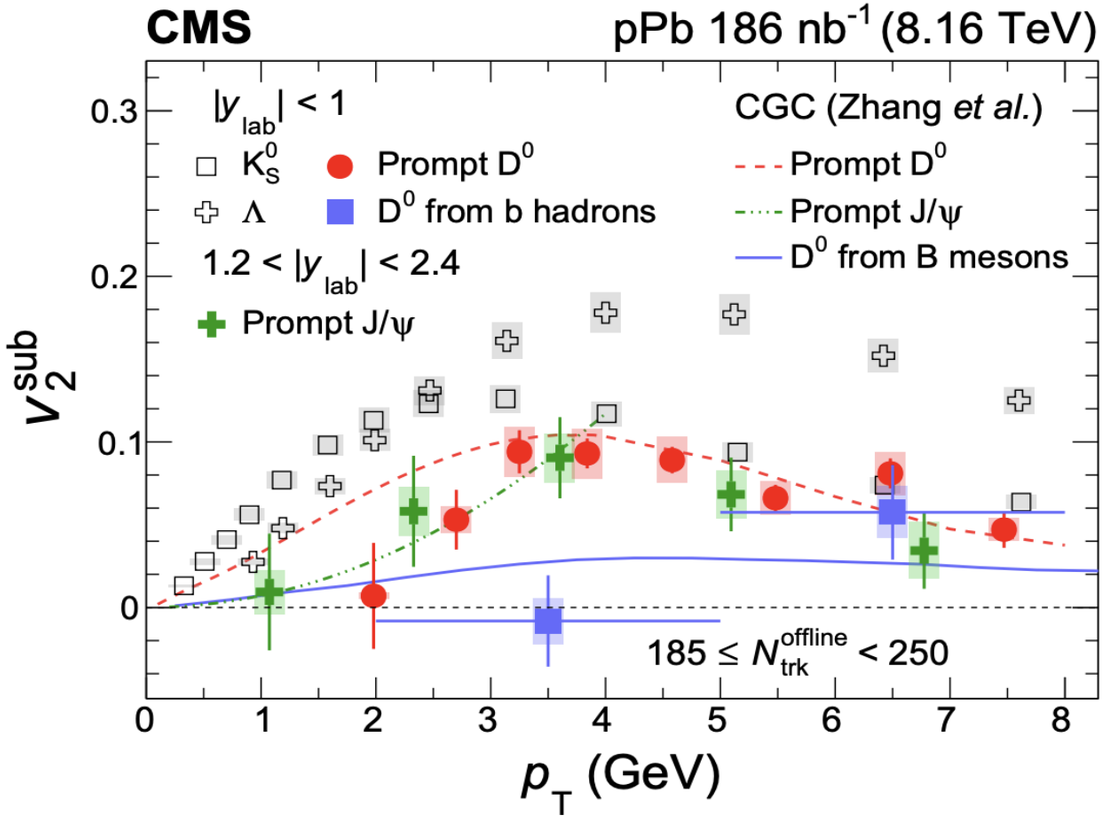
- OO: provide unique opportunity to smoothly connect pPb and PbPb



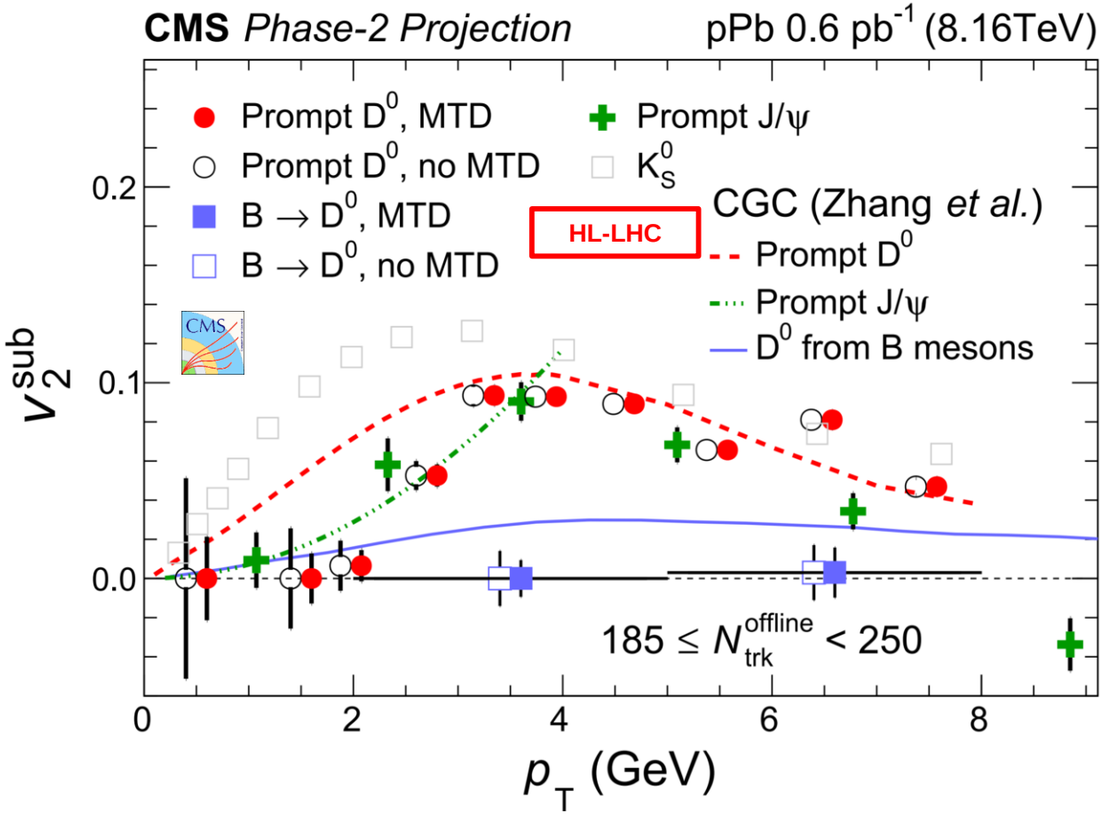
Collectivity in Small System

pPb

CMS Run 2

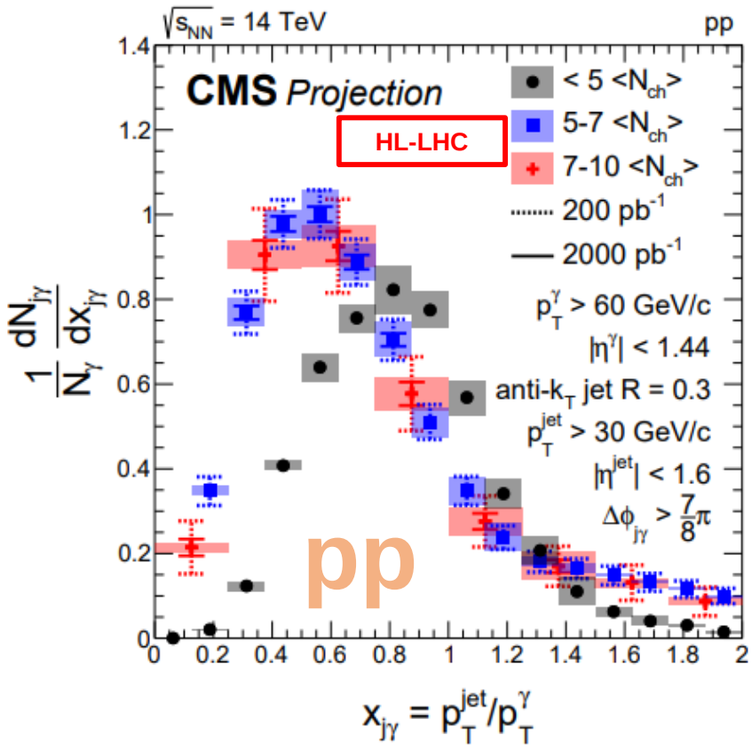


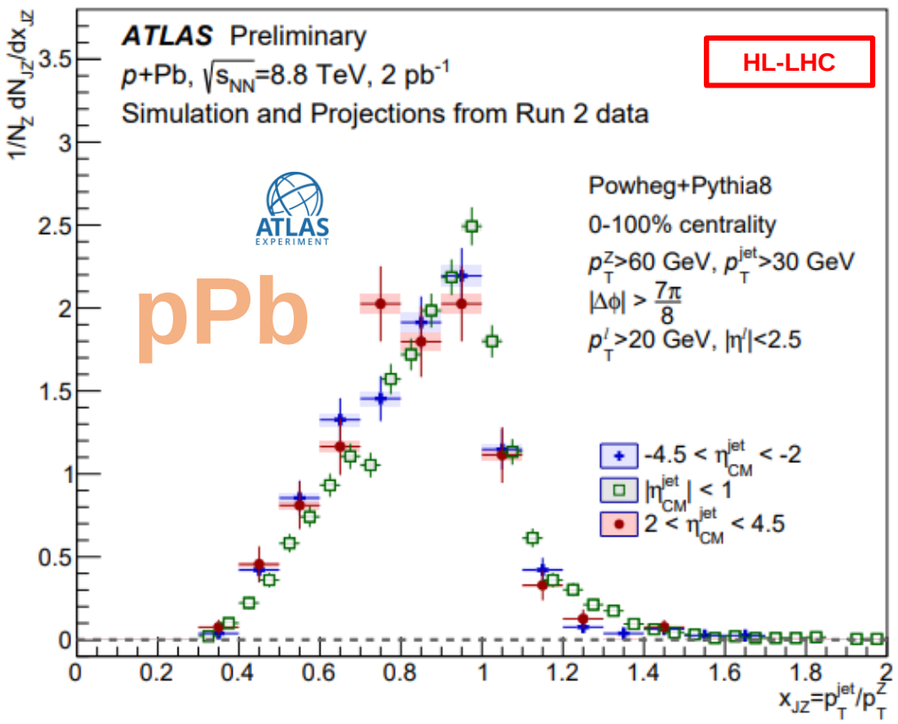
CMS 1-year with MTD

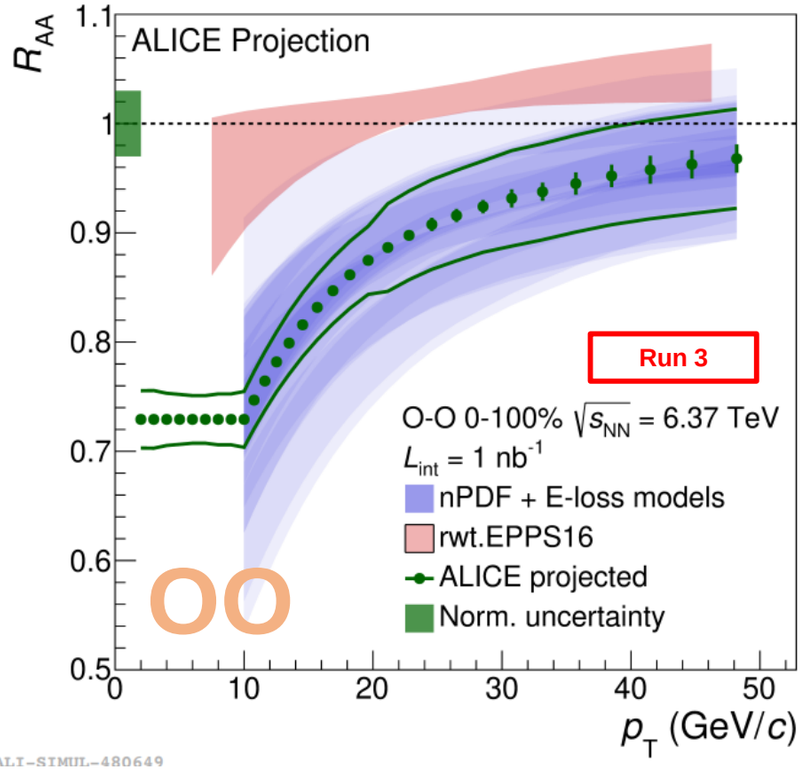


- With MTD: Unprecedented precision could be achieved with fast CMS tracking and DAQ system
- Detailed characterization of the heavy flavor hadron collective behavior in high multiplicity proton-proton and proton-lead collisions

Search for Jet Quenching in Small Systems



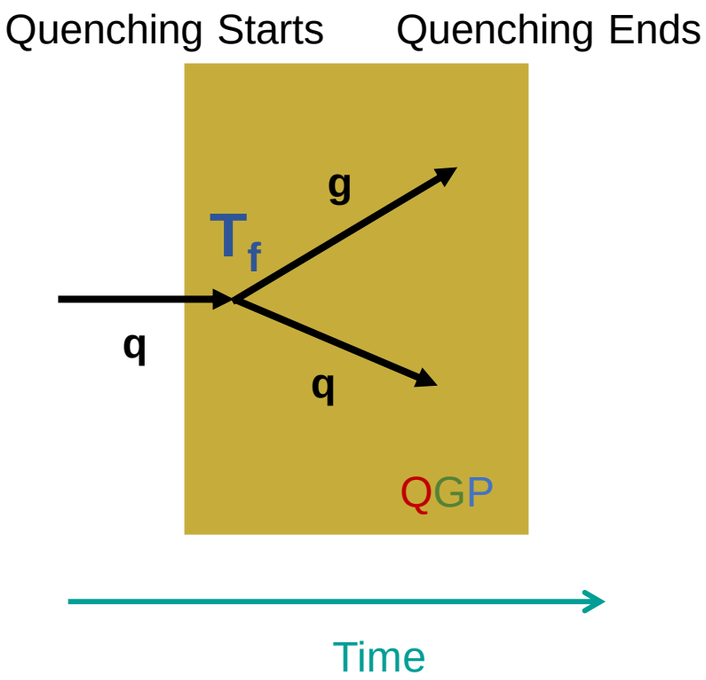




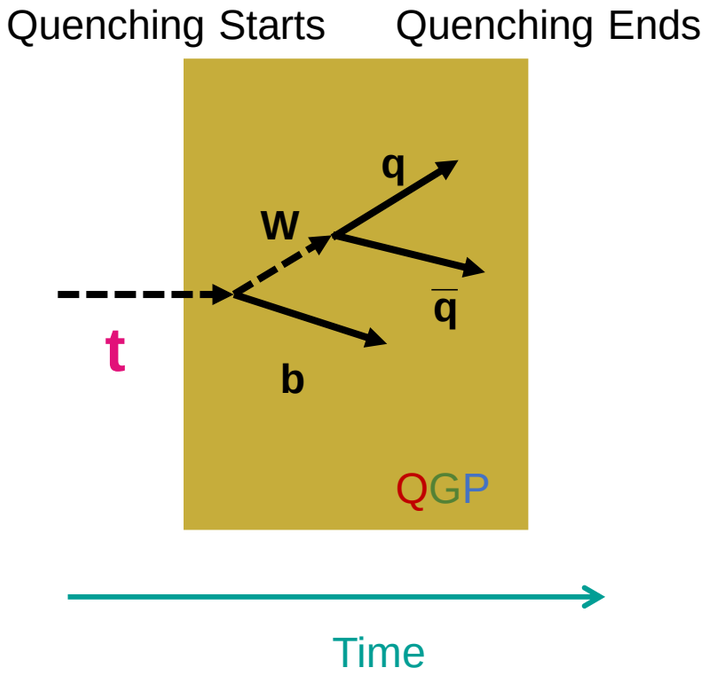
- High statistics pp and pPb data could provide a large sample of electroweak boson-tagged jets for the study of jet quenching in small systems.
- OO collisions: opportunity to search for jet quenching in small AA system

Probing the QGP Evolution

Formation Time (T_f) Tagging

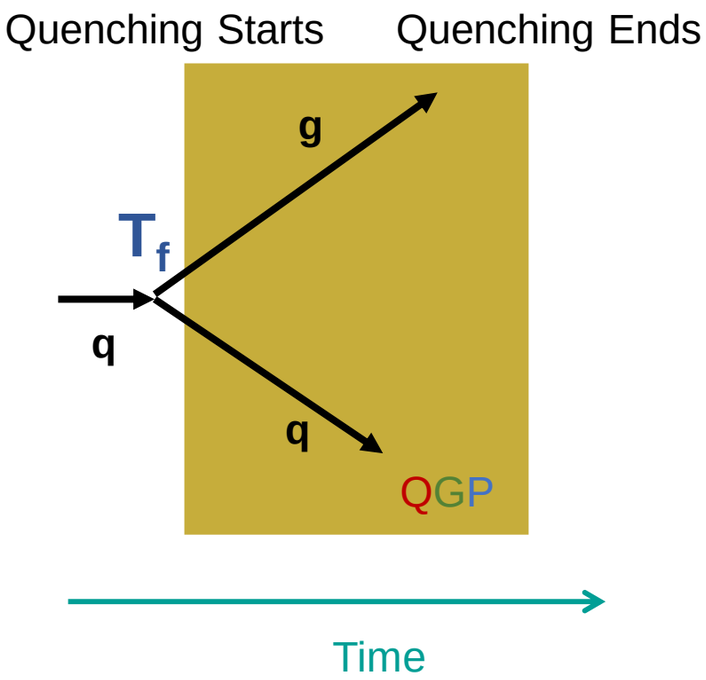


Boosted Top



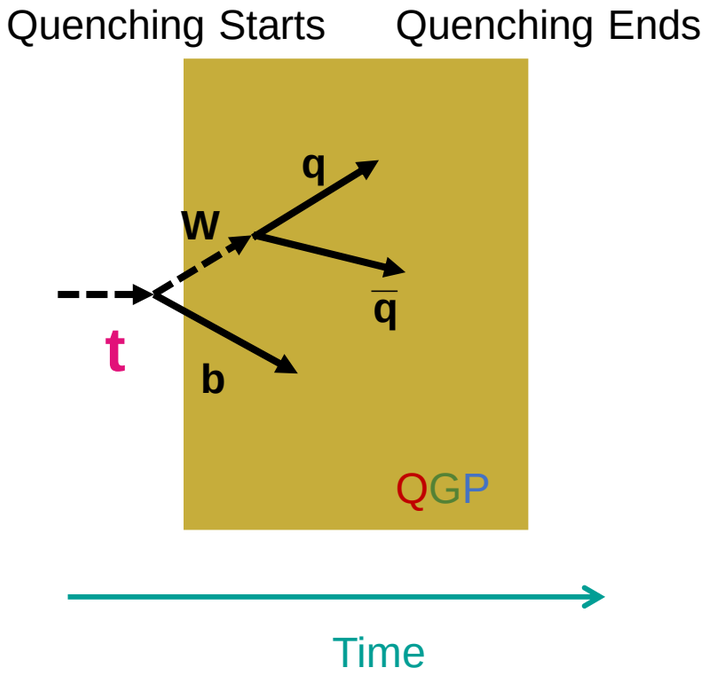
Probing the QGP Evolution

Formation Time (T_f) Tagging



Short formation time

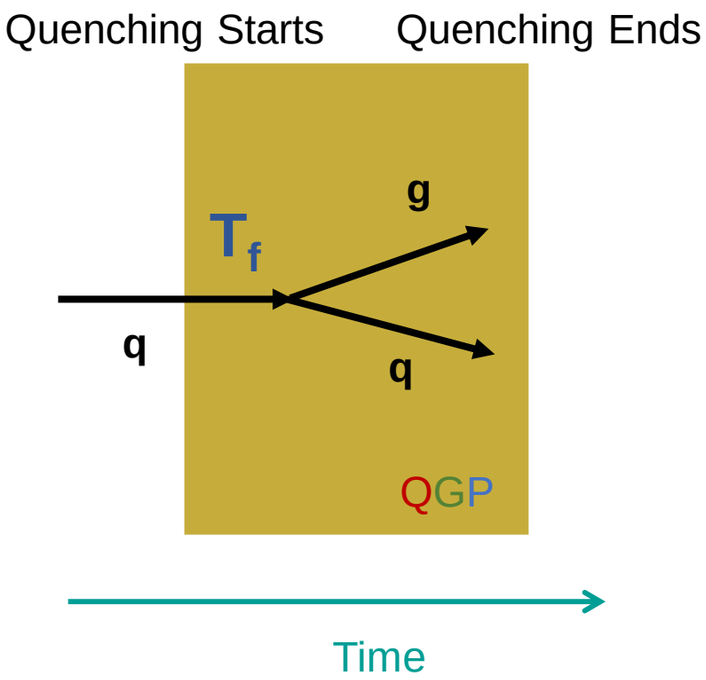
Boosted Top



Low p_T top

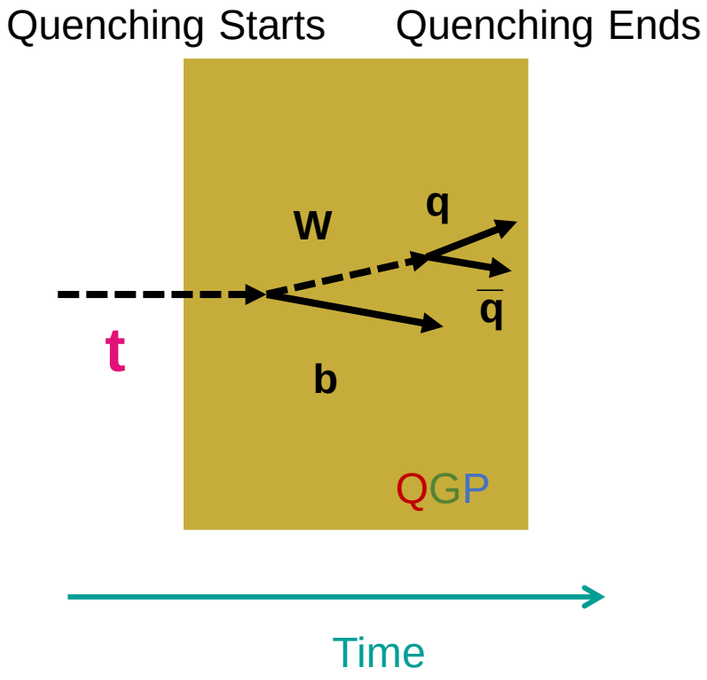
Probing the QGP Evolution

Formation Time (T_f) Tagging



Long formation time

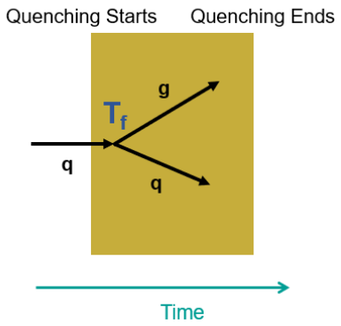
Boosted Top



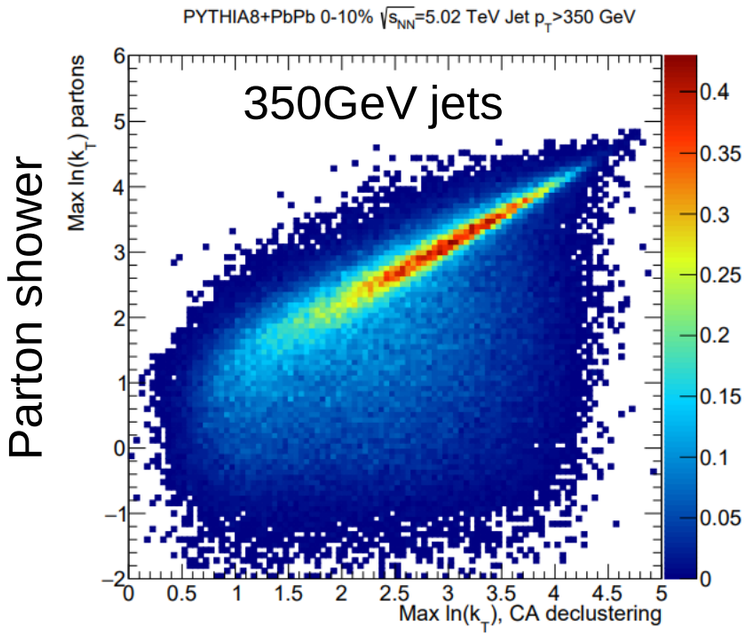
High p_T top

Probing the QGP Evolution

Formation Time (T_f) Tagging

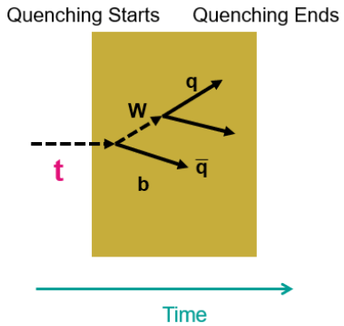


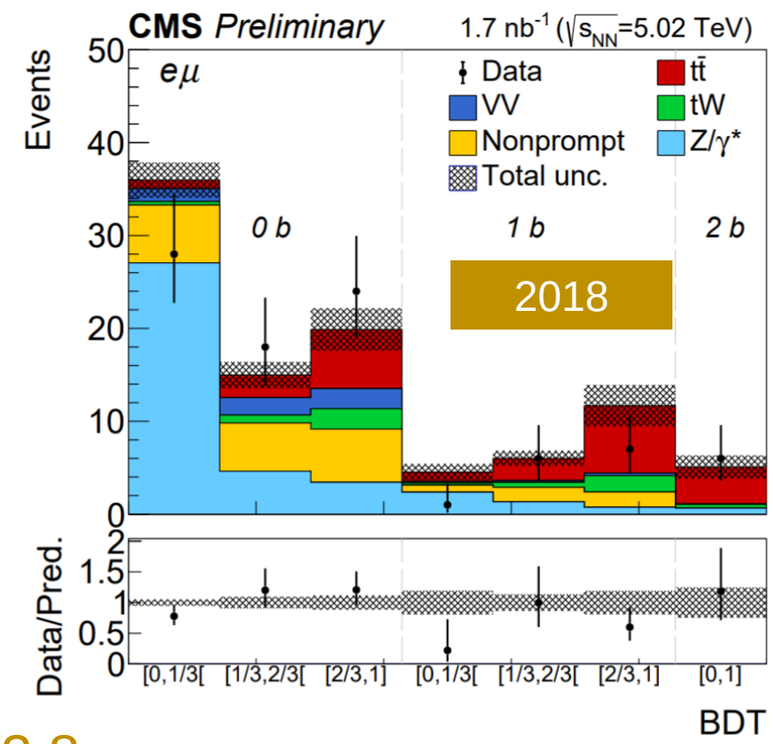
Yi Chen, YJL,
EMMI Jet RRTF



Hadron level (C-A declustering)

Boosted Top





Modification of jet structure and correlations through interactions with QGP constituents

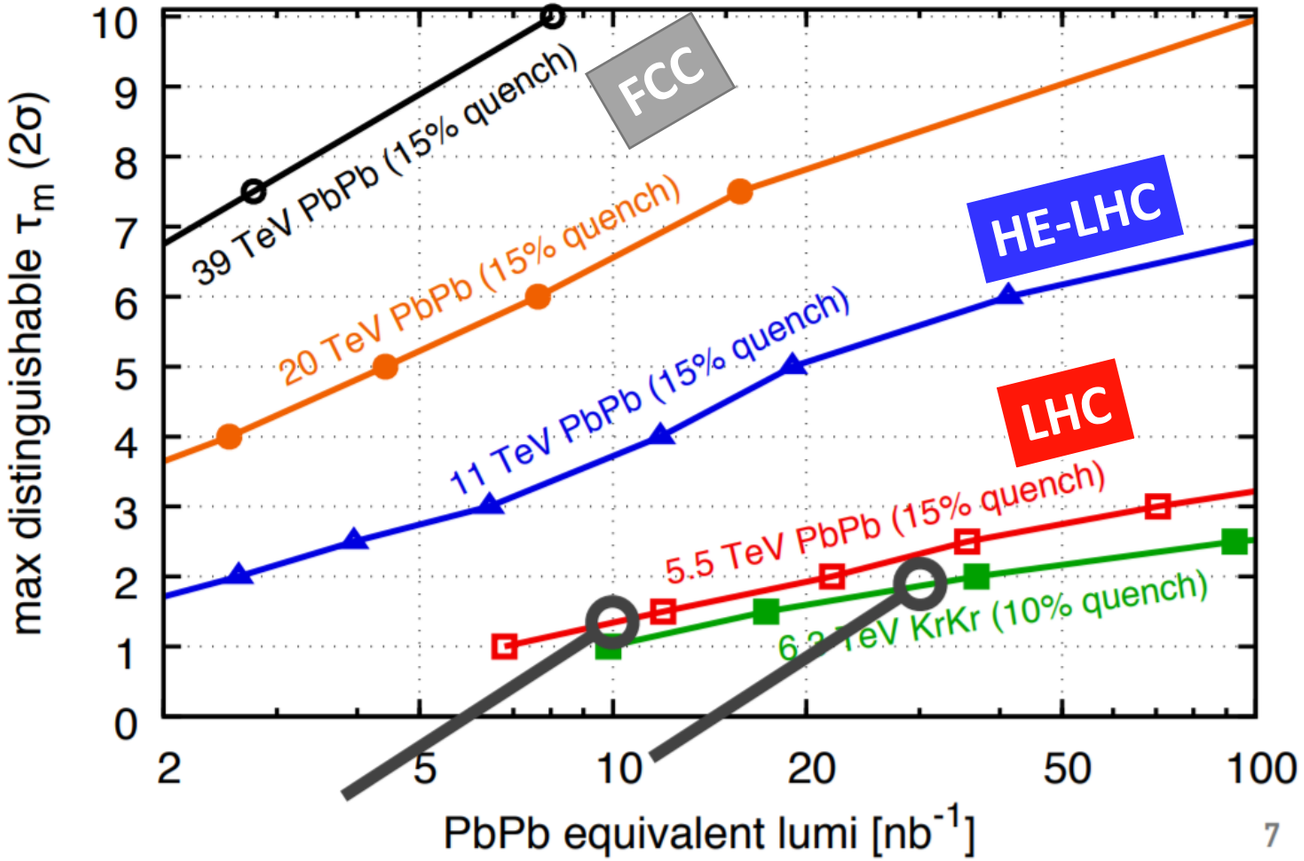
2018 data: 3.8σ

Observation of Top production in Run 3

- First proof-of-principle measurement with Run 3 and 4 data.
- To fully exploit the top and high p_T jet probes, much higher statistics needed

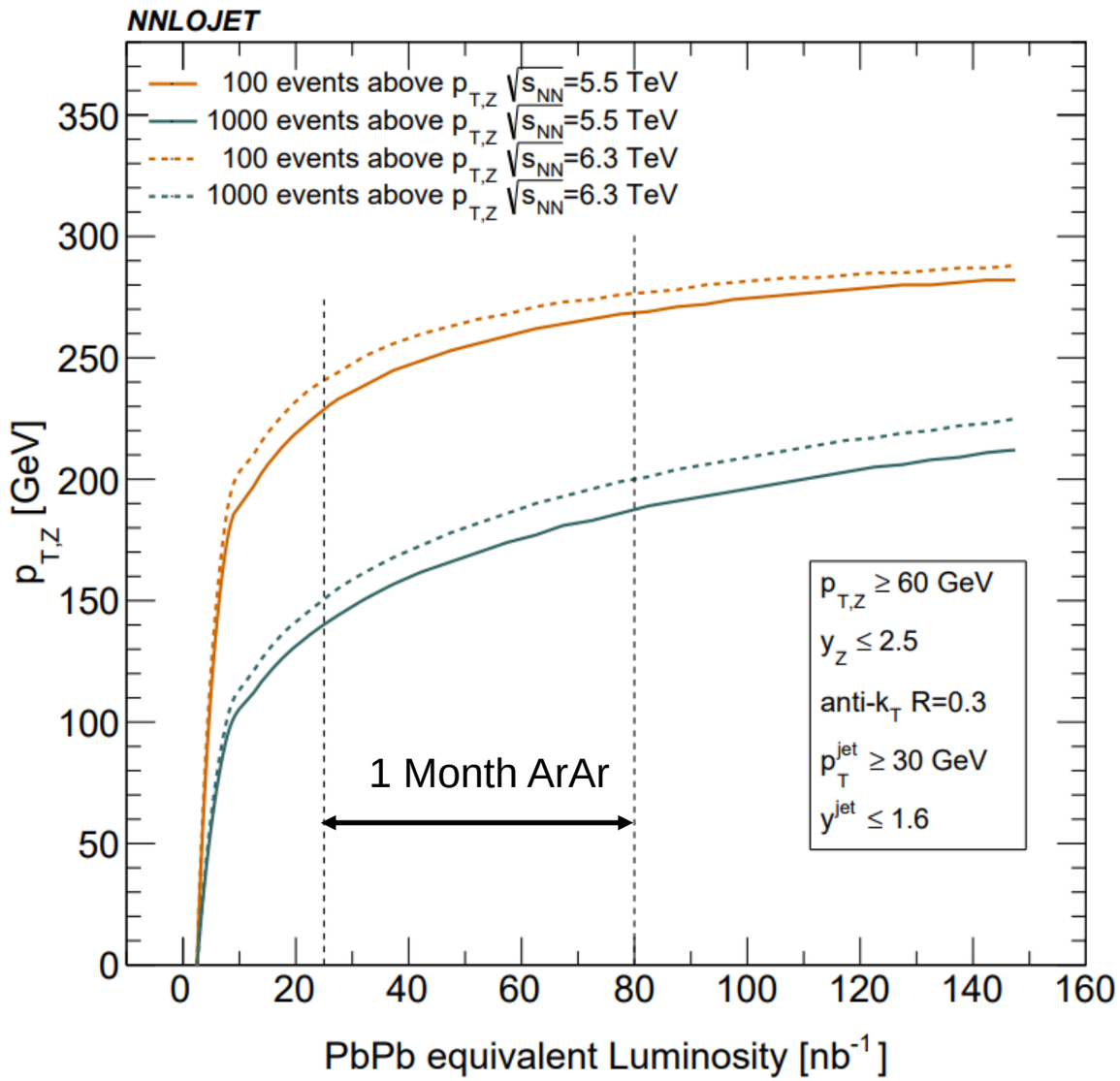
Sensitivity to the Medium End Time

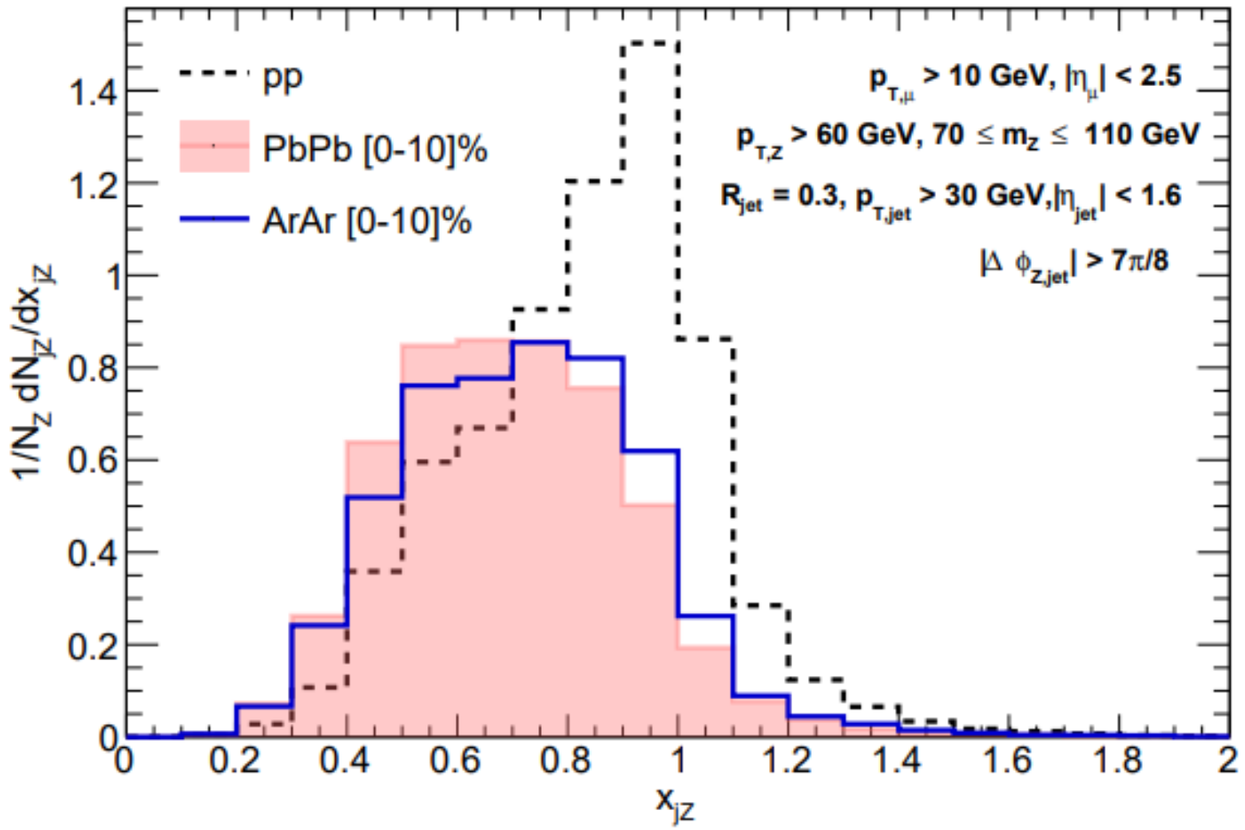
- Sensitivity to medium end time (τ_m):
  - HL-LHC PbPb Program (10 nb^{-1}): 1.4 fm/c
  - 1 month KrKr (30 nb^{-1}): 1.8 fm/c



Full exploitation of this probe only at **FCC energies**

Expected Performance with Lighter Ions in Run 5

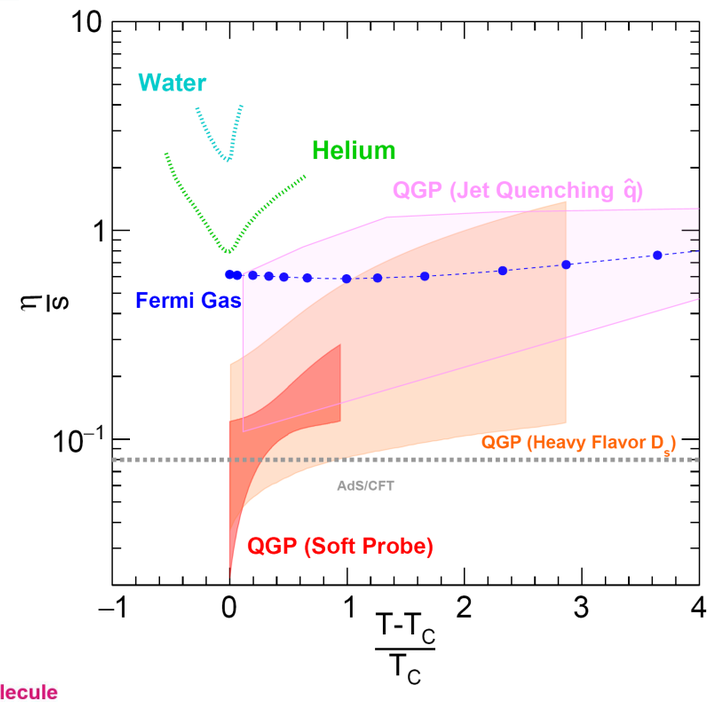


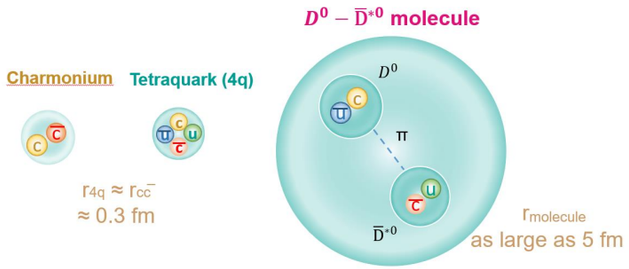


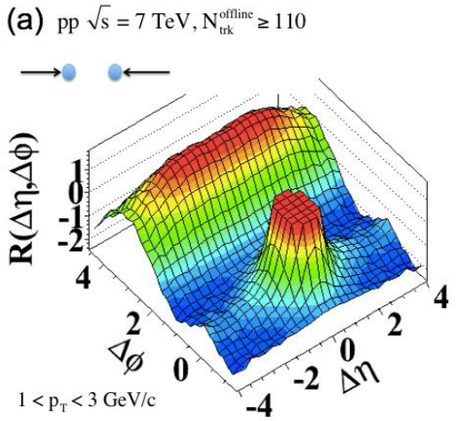
ArAr: a smaller collision system with still sizable jet quenching based on JEWEL

Summary

- Run 3+4 data will provide
  - **New constraints on the nPDF** from high precision electroweak bosons, UPC Quarkonia in PbPb, forward HF hadrons and dijets in pPb
  - Improve the understanding of **initial energy density profile** and the **underlying dynamics of hydrodynamization**
  - **Precise determination of medium properties** such as temperature, viscosity and transport coefficients through multiple probes
  - Study the **microscopic structure of QGP** at different length scales
  - Probe the **nature of X(3872)** with QGP and high multiplicity pp and pPb collisions
  - Initial studies of **time-dependent evolution of QGP**







- Stress tests to the heavy ion standard model:
  - Constraining QGP properties from soft and hard probes
  - Establish a firm foundation to the new discovery in smaller systems

- Backup slides

Label

HL-LHC 13 nb^{-1} of PbPb sample + up to 2 pb^{-1} of pPb data to be collected in Run 3 + 4

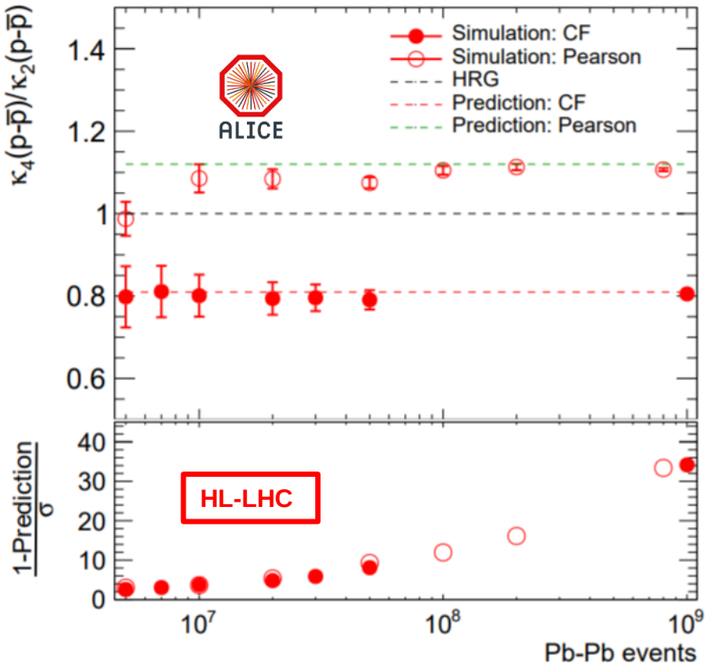
Present Data Analyzed Run 1 + 2015 data (up to 0.5 nb^{-1} of PbPb data)

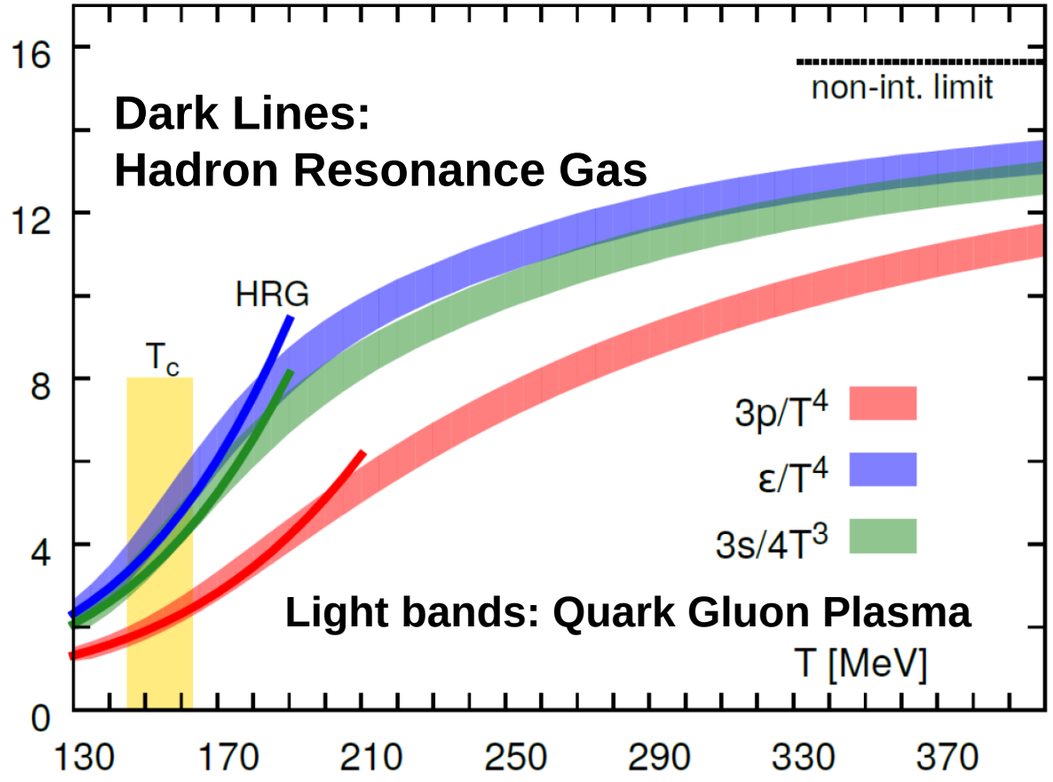
QCD Equation of State at μ_B=0

Can we "measure" the QCD Equation of State?

High precision flow measurement enabled by HL-LHC data

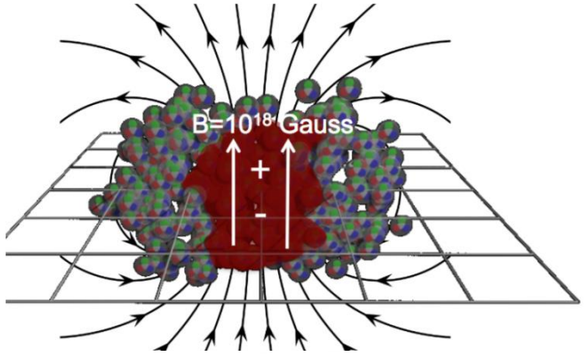
Net-baryons fluctuation

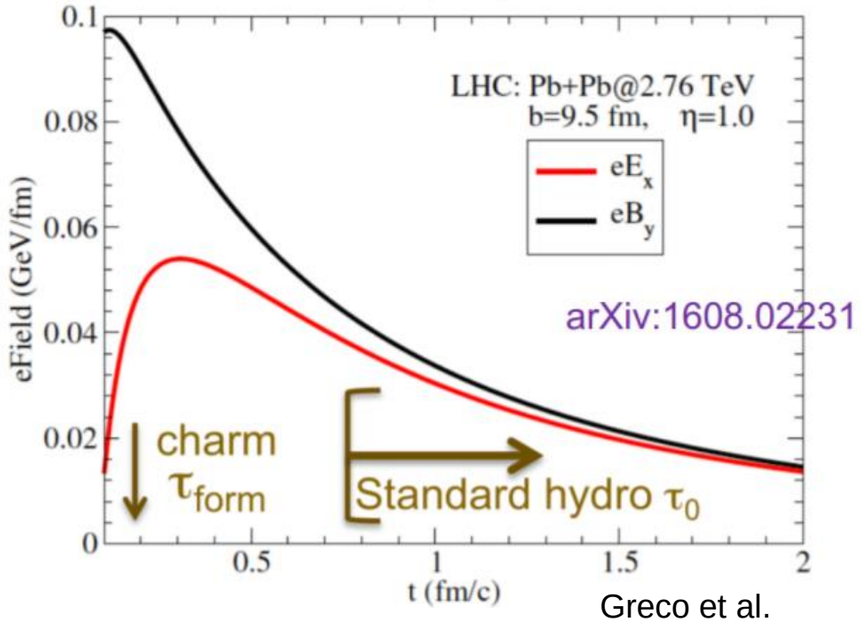




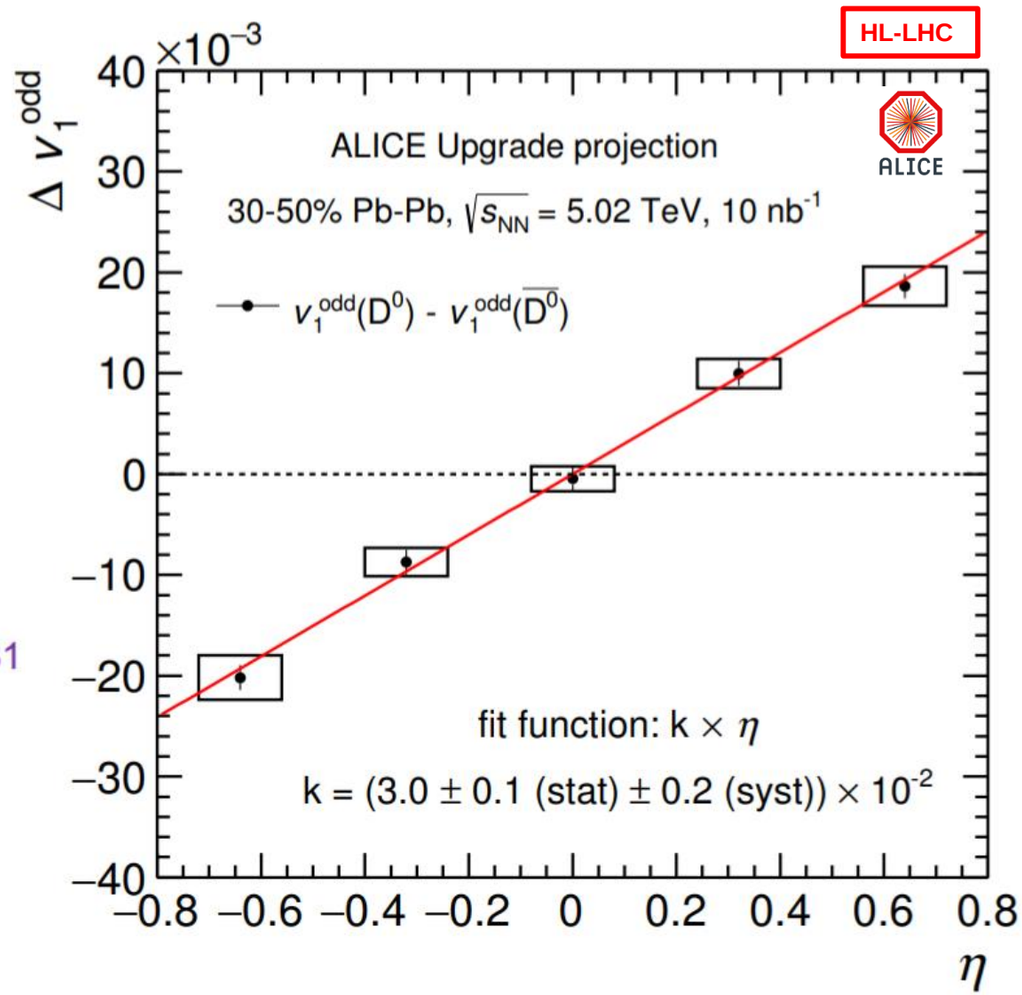
… and many more observables enabled by HL-LHC data

Magnetic Field with Charm Meson





Greco et al.



- Charm Quarks:
  - More sensitive (than light flavor) to early magnetic fields and vorticity
- High precision measurement could be performed for the first time with HL-LHC data

Outline of WG5 Yellow Report

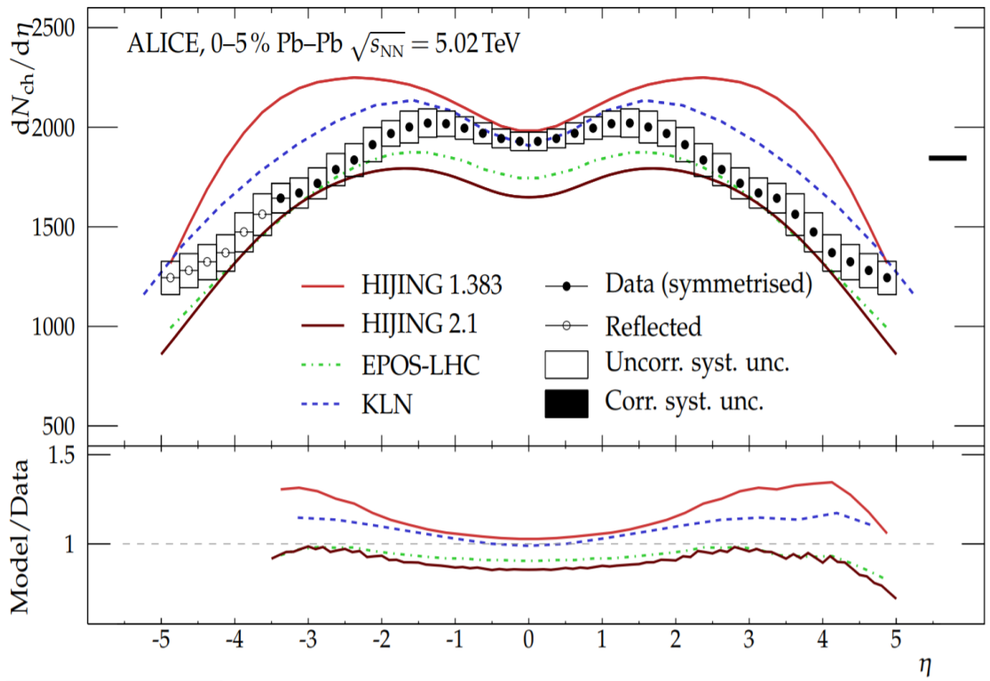
Future physics opportunities for high-density QCD with ions and proton beams at LHC

- 185 contributors to 13 chapters
- Final version submitted to arXiv:1812.06772

	Chapter	Coordinator
1	Introduction	WG5 Conveners
2	Heavy-Ion Performance of LHC, HL-LHC and HE-LHC	John Jowett (LHC)
3	(anti-)(hyper-)nuclei and fluctuations of conserved charges	Francesca Bellini (ALICE)
4	Flow/Correlations	Soumya Mohapatra (ATLAS)
5	Open Heavy Flavor	Elena Bruna (ALICE) Gian Michele Innocenti (CMS)
6	Jets and parton energy loss	Marta Verweij (CMS)
7	Quarkonia	Anton Andronic (ALICE) Emilien Chapon (CMS)
8	Electromagnetic radiation	Michael Weber (ALICE)
9	Emergence of Hot and Dense QCD in Small Systems	Jan Fiete Grosse-Oetringhaus (ALICE) Constantin Loizides (ALICE)
10	High energy QCD with proton-nucleus collisions and UPC	Michael Winn (LHCb)
11	Other opportunities with ion and proton beams at the LHC	Zvi Citron (ATLAS) Iwona Grabowska-Bold (ATLAS) Hans Dembinski (LHCb)
12	Luminosity requirement and proposed run schedule	WG5 Conveners
13	High Energy LHC (HE-LHC)	Andrea Dainese (ALICE) David d'Enterria (CMS) Carlos A. Salgado (Theory)

Global Event Properties

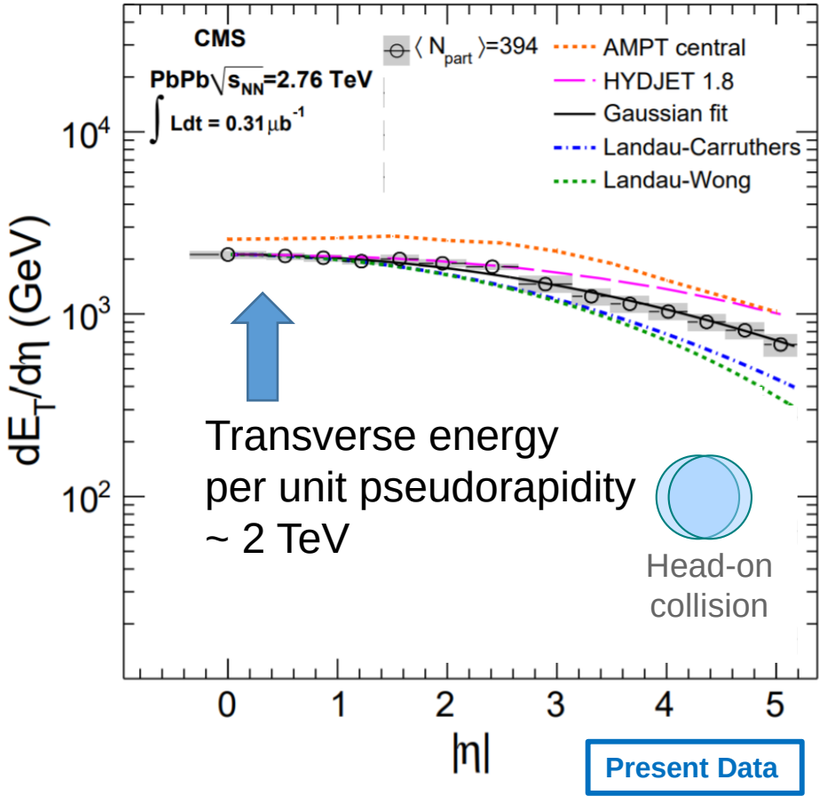
Charged Particle Pseudorapidity Distribution



Present Data

η

Transverse Energy Density



Present Data

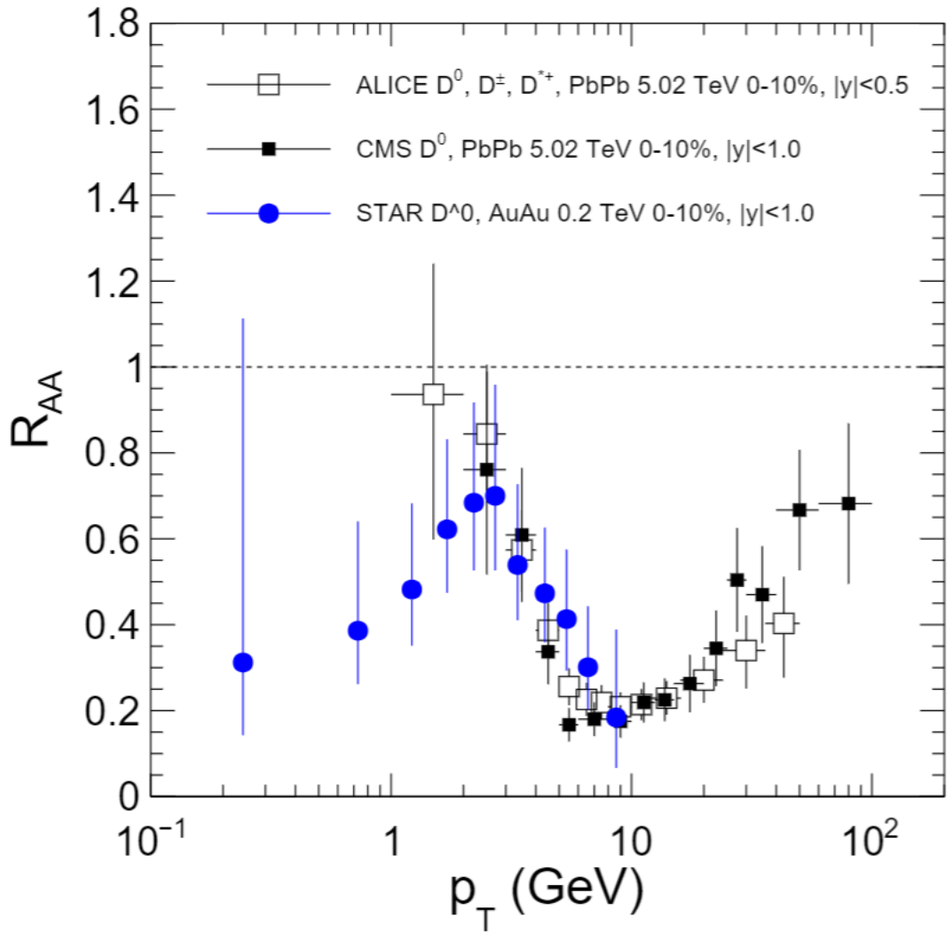
Particle density in Lead+Lead
~ **400x** of that in proton+proton

At **t~ 1fm/c:** energy density of the medium ~ 13 GeV/fm^3

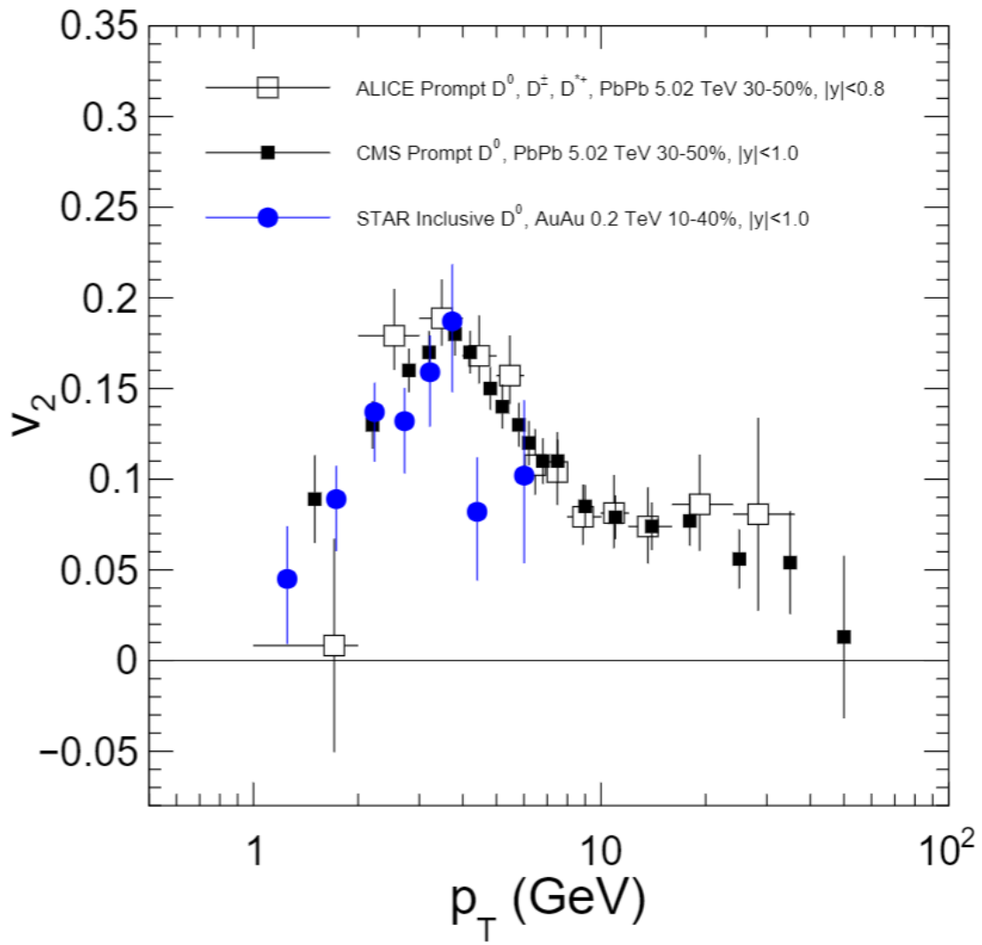
>20x denser than the proton

D^0 v_2 and R_{AA} in PbPb at 5.02 TeV

Present Data

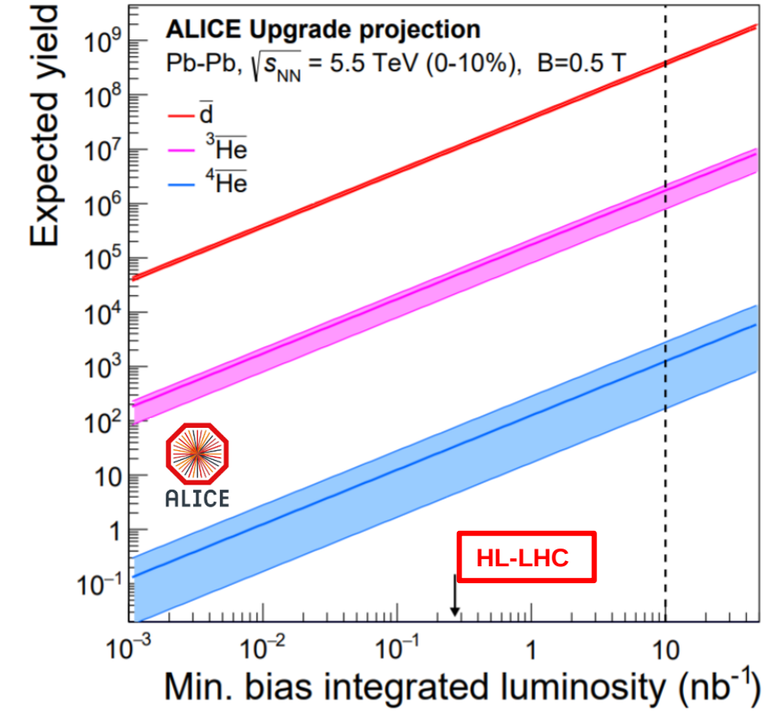


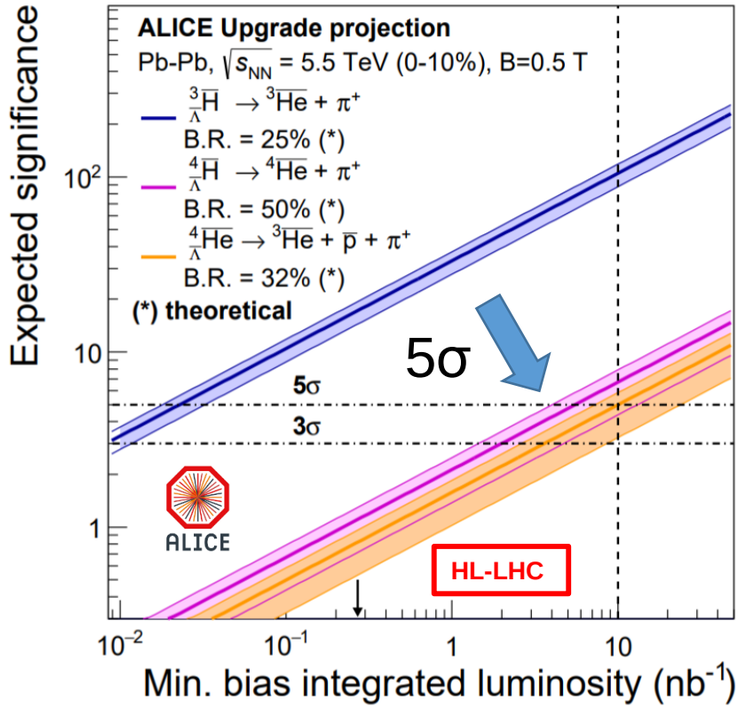
Present Data



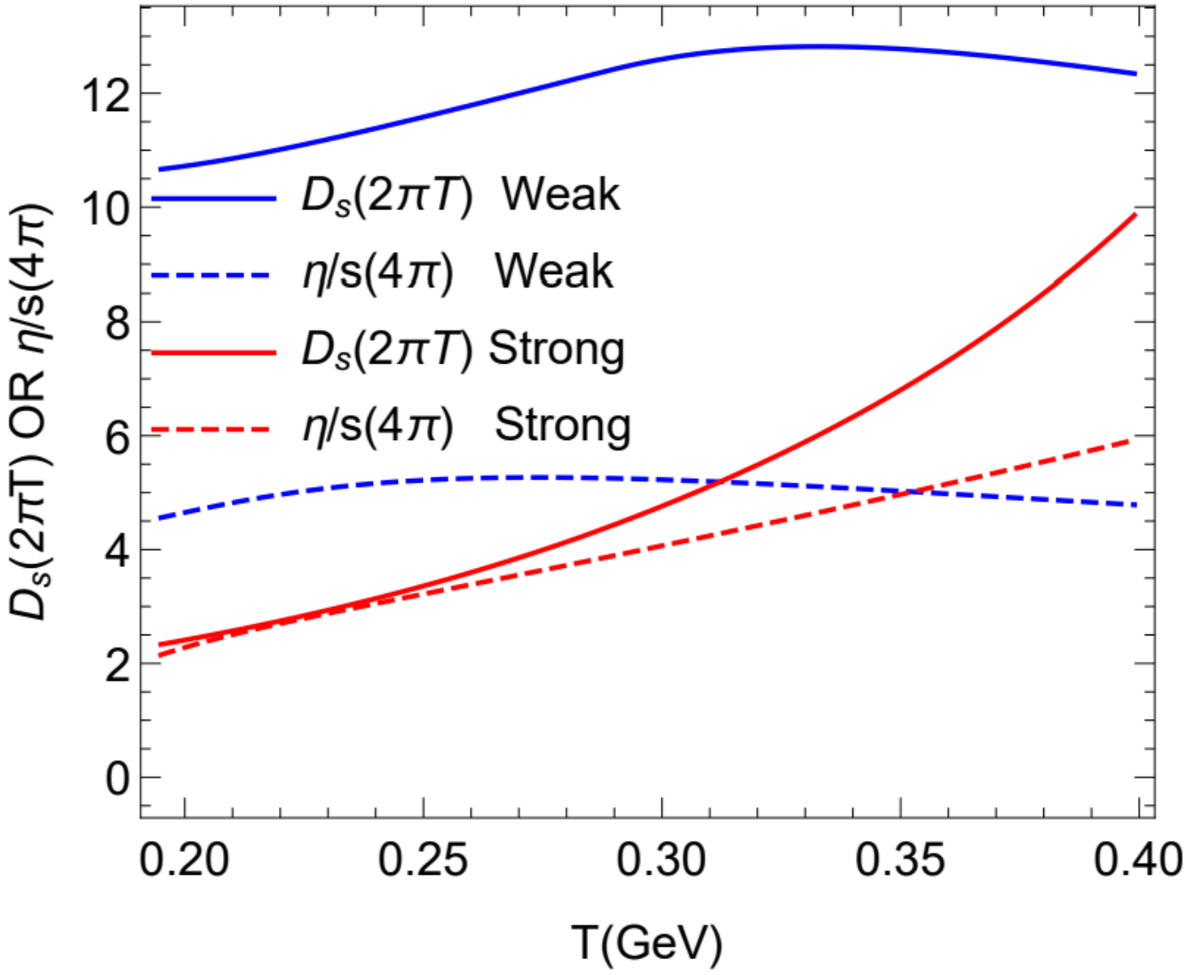
(Anti-)(hyper-)nuclei Production

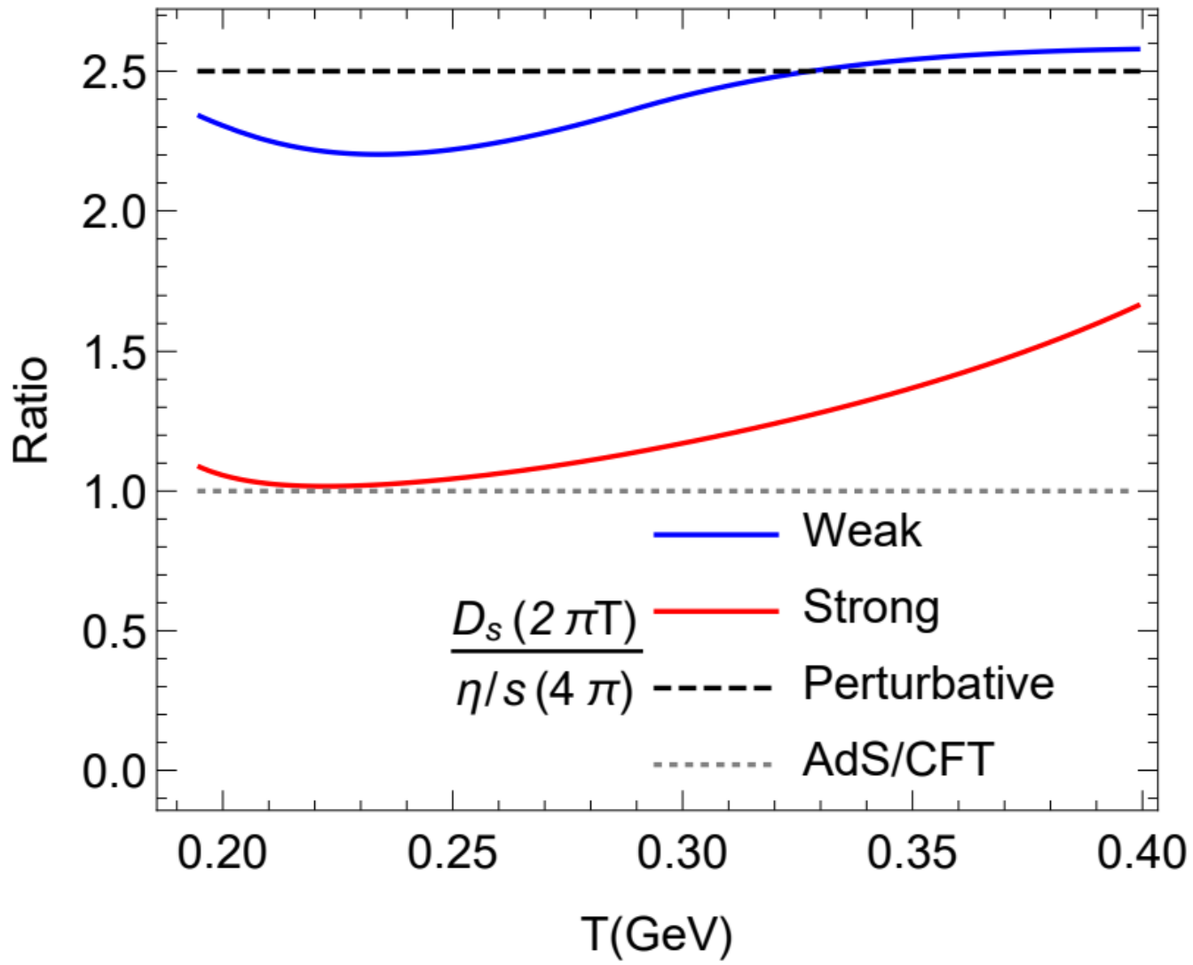
- **Precision test of coalescence / thermal production models**
  Sensitive to size ratio of the object and the source
- **Search** for rarely produced **anti-** and hyper-matter: Insights on the **strength of the hyperon-nucleon interaction**, relevant for nuclear physics and neutron stars. HL-LHC: first observation for anti-hyper-nuclei with A = 4
- **Constrain** models with pp measurements:
  Estimates of **astrophysical background** for dark matter searches





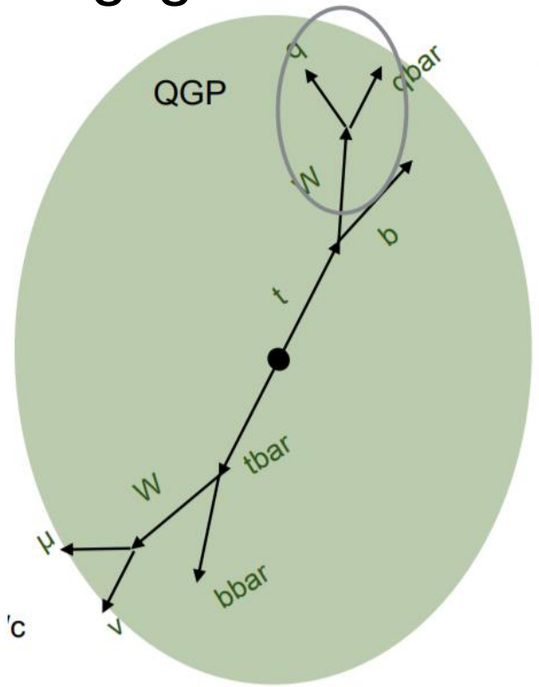
Comparison of the Charm Diffusion Coefficient and Specific Viscosity





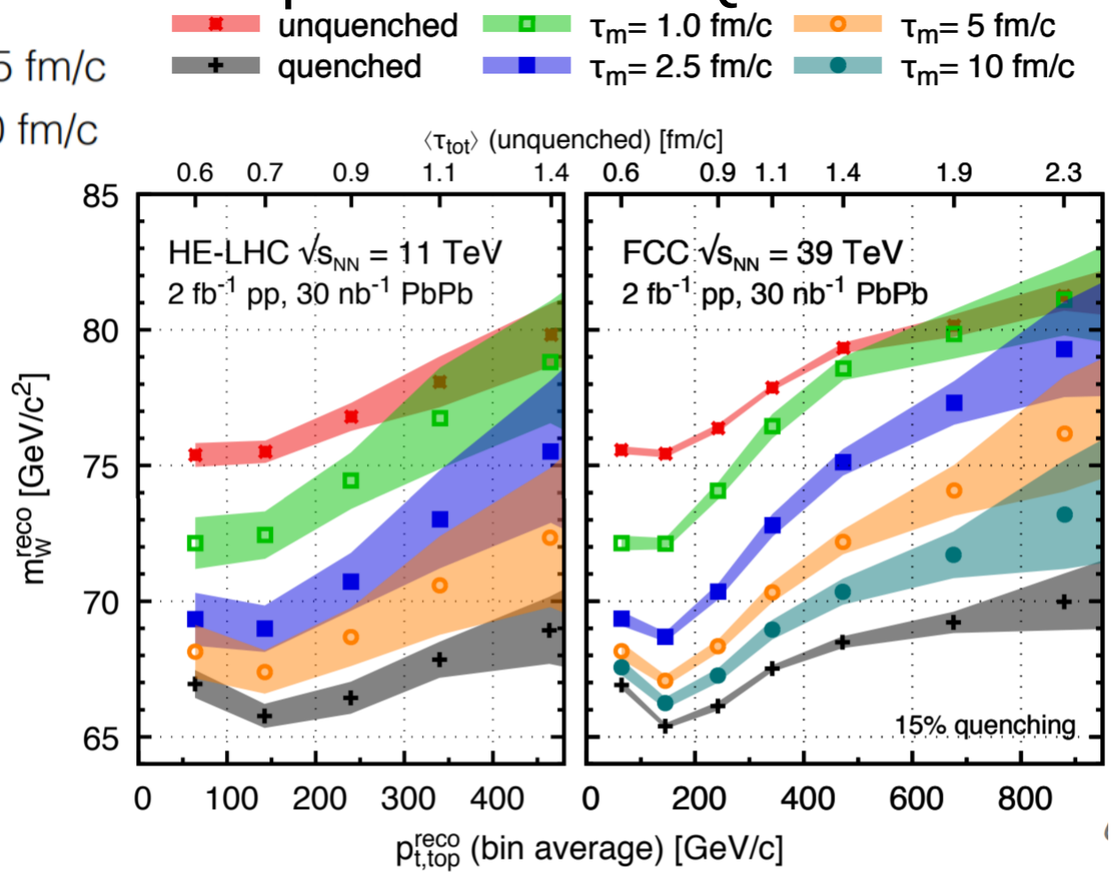
Modification of W mass in Top event

Negligible interaction between Top / W and the QGP



τ_{top}=0.15 fm/c

τ_W=0.10 fm/c

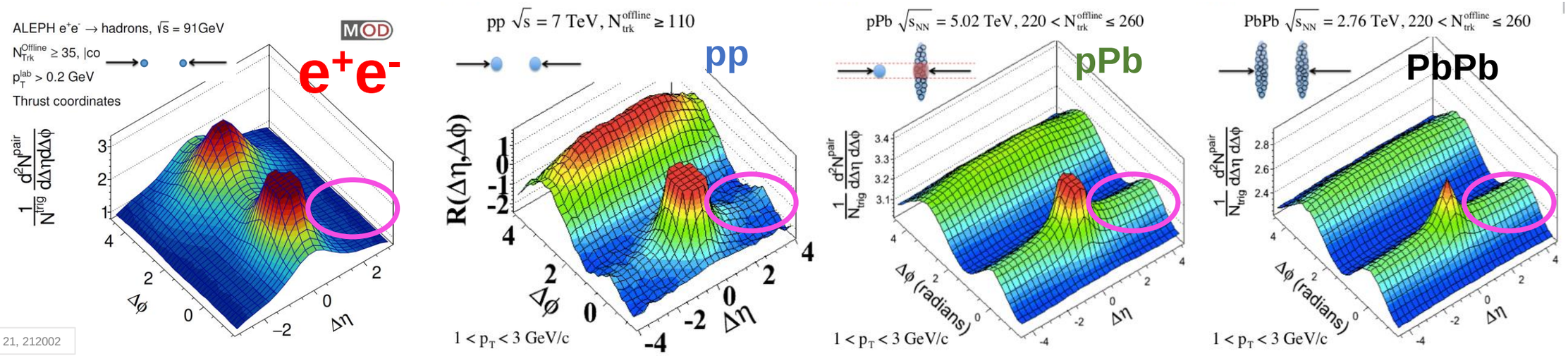


τ_m : quenching end time

- Longer total delay time of the W (τ_{tot}) leads to smaller modification of W mass in heavy ion collisions
- Probe the "start" and "end" time of the QGP!!

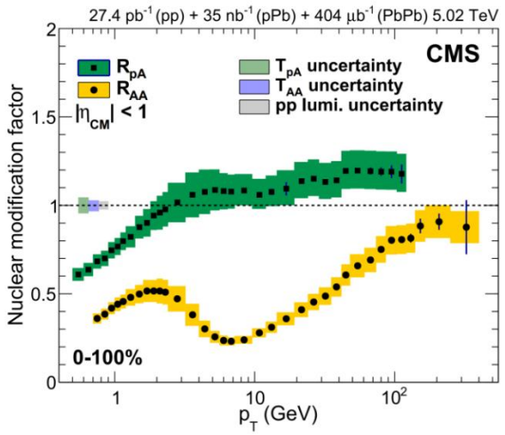
"A Yoctosecond Chronometer." (Gavin Salam)

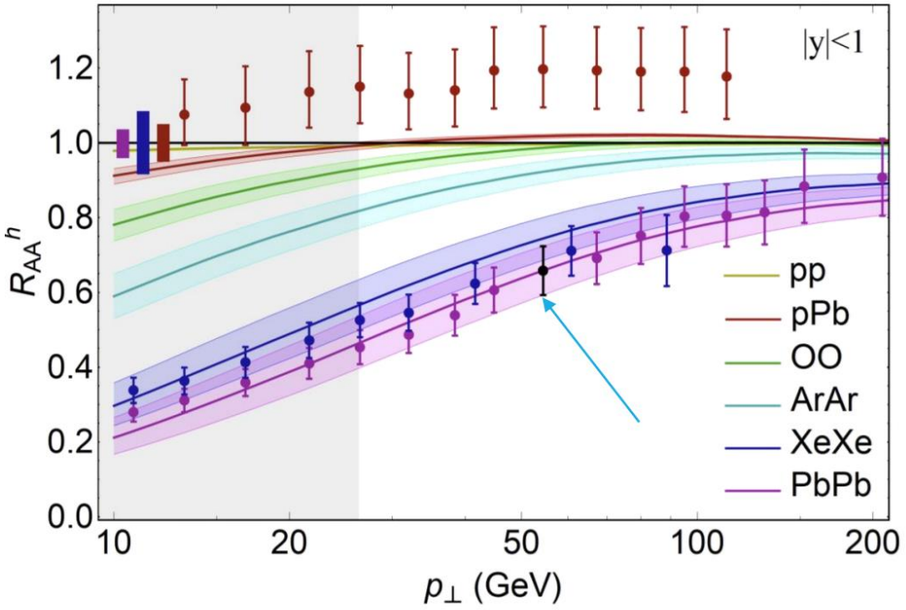
pO and OO: Jet Quenching in Small System?



PRL 123 (2019) 21, 212002

1. There seems to be flow
   - Quite some modeling, but everything consistent with hydro (does not prove hydro!)
2. But: nuclear modification > 1: **no (naive) jet/hadron energy loss**

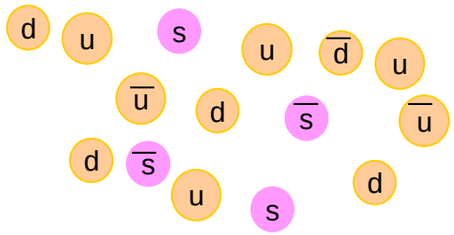




Wilke van der Schee

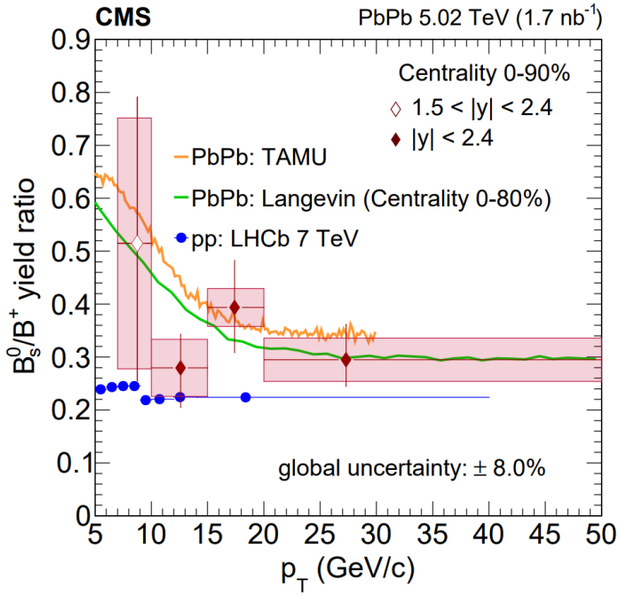
Hadronization of Heavy Quarks in QGP

Strange quark content is enhanced in QGP (Due to the high temperature)



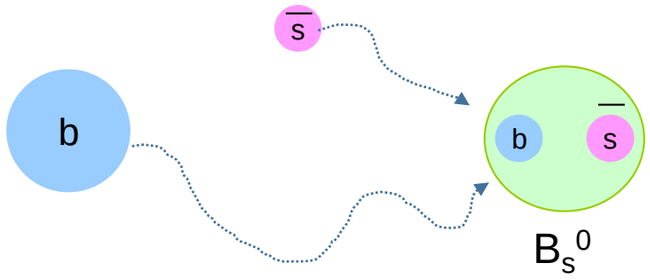
Present Data

B_s/B^+



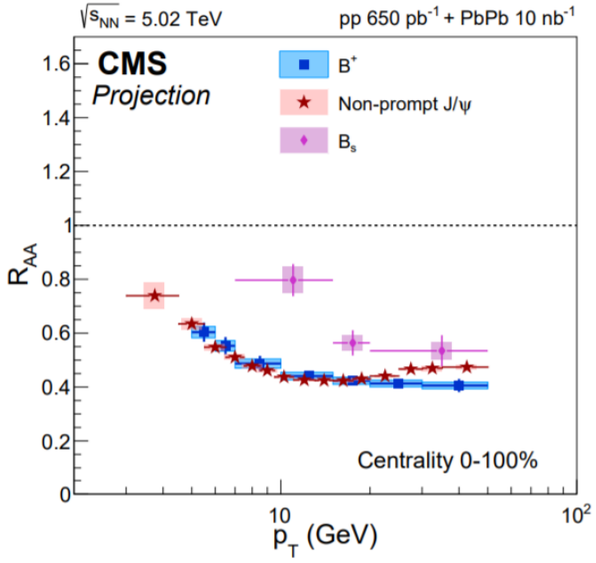
Idea: Probe the partonic QGP by heavy quarks!

Ex: D_s , B_s and Λ_c could be **enhanced via coalescence**



HL-LHC

R_{AA}



B_s^0 arXiv:1810.03022	$B^\pm$ PRL 119 (2017) 152301

Relation between Specific Viscosity in MSS

The transport coefficient, in the limit of multiple soft scattering:
Where ρ is the density of scattering centers

$$\hat{q} \overset{MSS}{\equiv} \rho \int dq_\perp^2 \, q_\perp^2 \, \frac{d\sigma}{dq_\perp^2}$$

Within the framework of kinetic theory: $\eta \sim \frac{1}{3} \langle p \rangle \lambda \rho$ $\qquad \lambda = (\rho \sigma_{tr})^{-1}$

The total transport cross-section when soft scattering dominates:

$$\sigma_{tr} \approx \frac{4}{\hat{s}} \int dq_\perp^2 q_\perp^2 \frac{d\sigma}{dq_\perp^2} = \frac{4\hat{q}}{\hat{s}\rho} \Rightarrow \lambda = \left(\frac{\hat{s}}{4\hat{q}} \right)$$

Taking the medium as a gas of massless thermal particles:

$$\langle p \rangle \approx 3T, \langle \hat{s} \rangle \approx 18T^2 \qquad s \approx 3.6\rho$$

We could get

$$\frac{\eta}{s} \approx 1.25 \frac{T^3}{\hat{q}}$$