Quark-Gluon Plasma Studies in Run 3 and 4

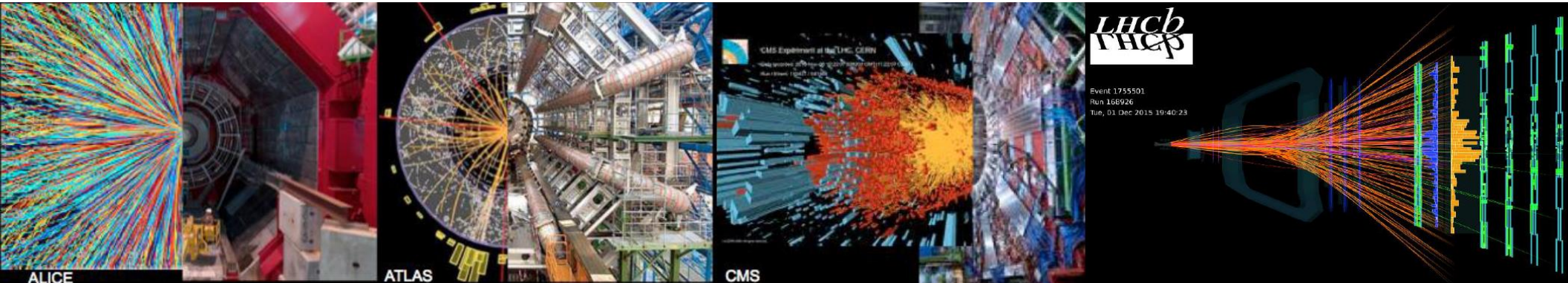
Yen-Jie Lee (MIT)

On behalf of WG5

HL/HE-LHC Physics Workshop

CERN, March 1, 2019

Conveners: Zvi Citron (ATLAS), Jan Fiete Grosse-Oetringhaus (ALICE), John Jowett (LHC)
Yen-Jie Lee (CMS), Urs Wiedemann (Theory), Michael Winn (LHCb)



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)

Label

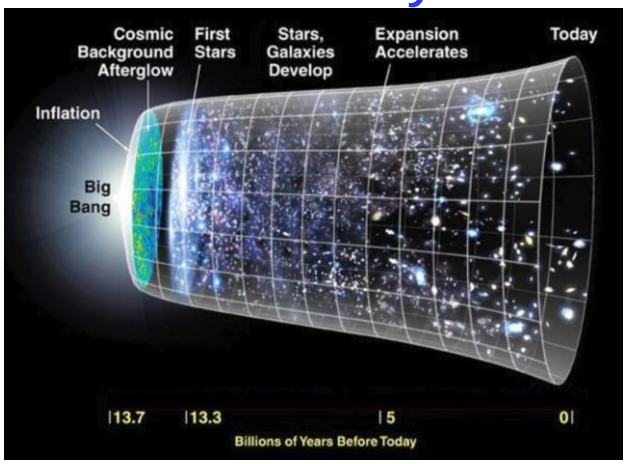
HL-LHC 13 nb^{-1} of PbPb sample + up to 2 pb^{-1} of pPb data to be collected in Run 3 + 4

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

Performance studies with data in Run 5 and beyond will be covered in Guilherme Milhano's talk

QCD Phase Diagram

Expansion of Early Universe



Temperature

Quark-Gluon Plasma

Hadron Gas

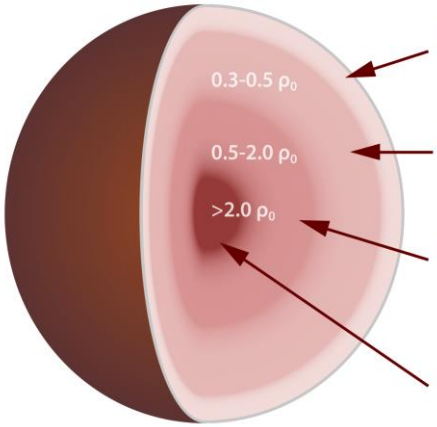
Color Superconductor

Nuclei

Neutron Star

Baryon Density

Neutron Star Formation



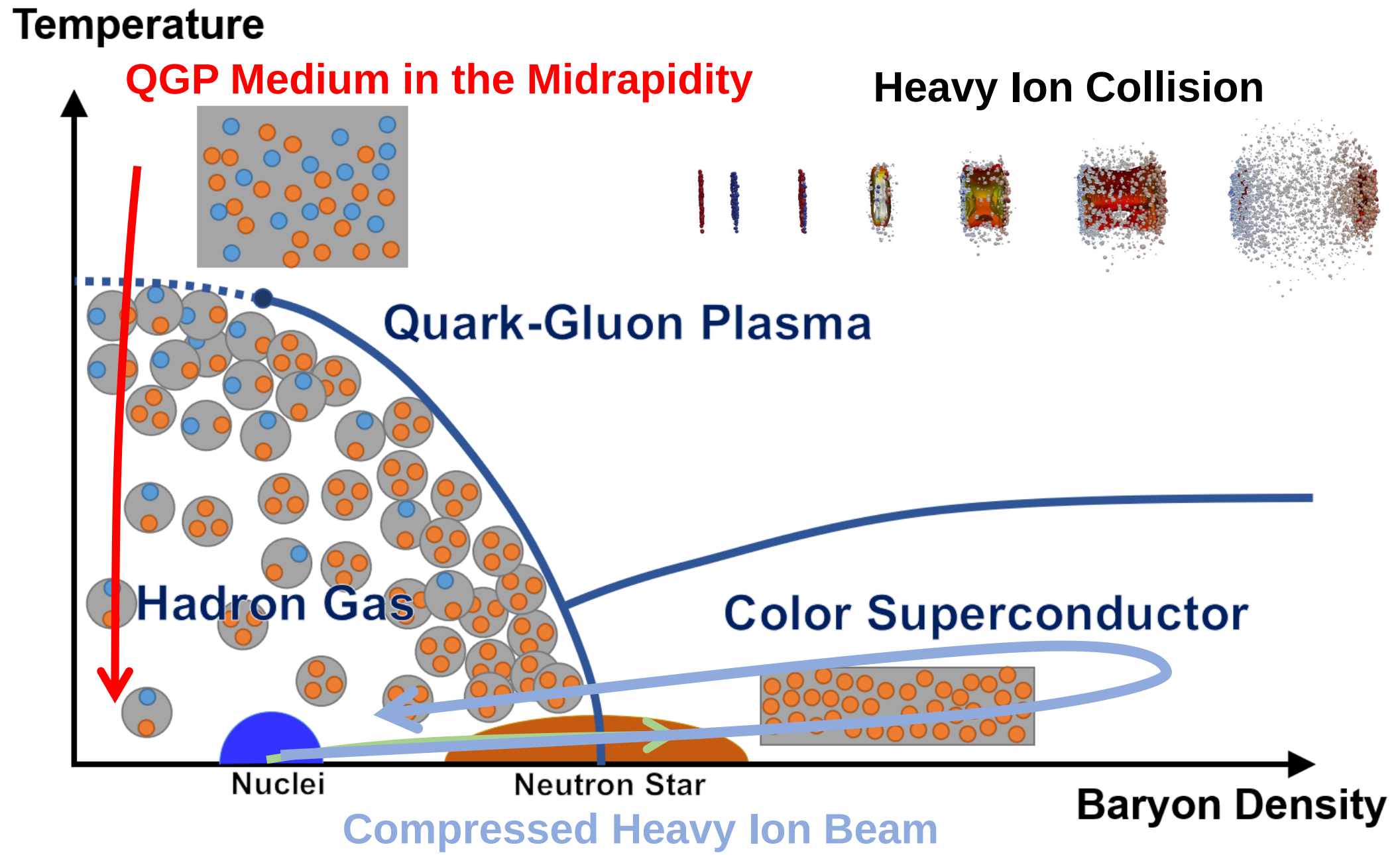
outer crust 0.3-0.5 km
ions, electrons

inner crust 1-2 km
electrons, neutrons, nuclei

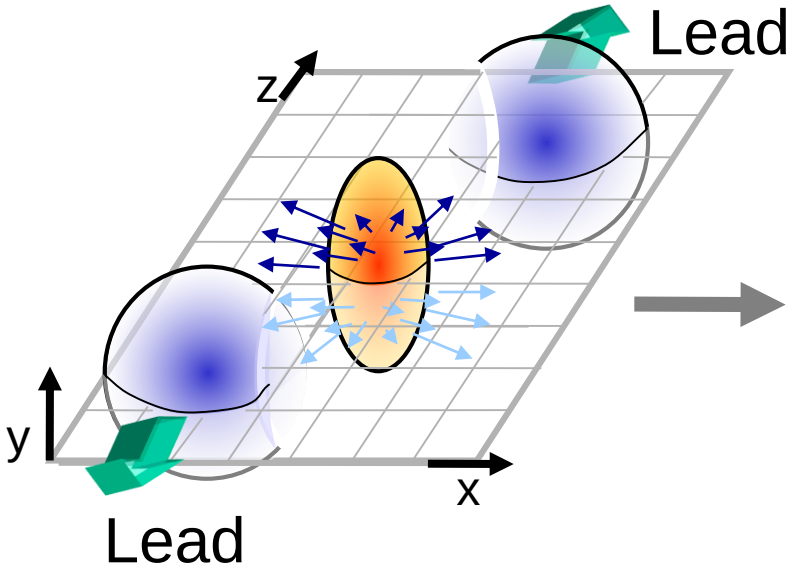
outer core ~ 9 km
neutron-proton Fermi liquid
few % electron Fermi gas

inner core 0-3 km
quark gluon plasma?

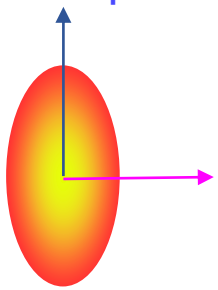
QCD Phase Diagram



Collectivity from Hydro Evolution

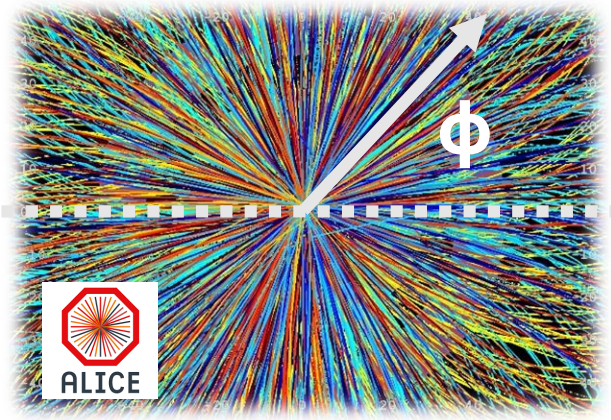


small pressure gradient

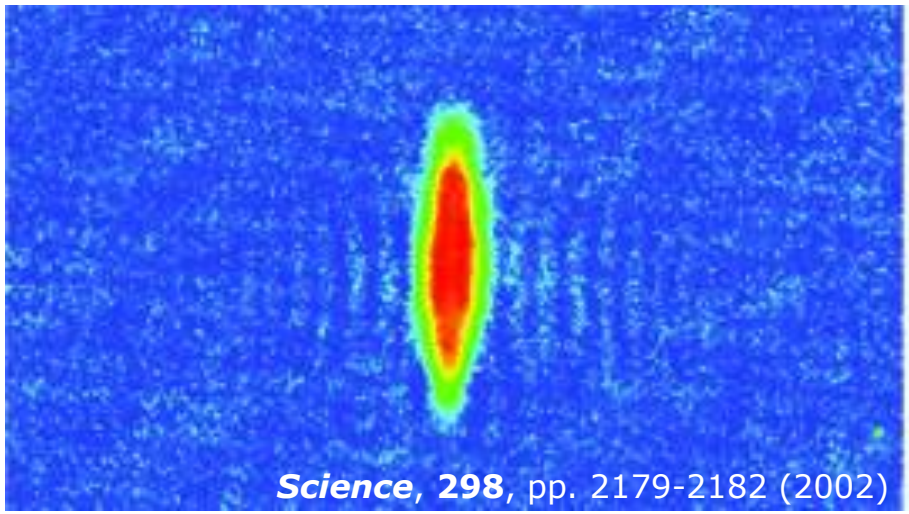


Large pressure gradient

Charged particles



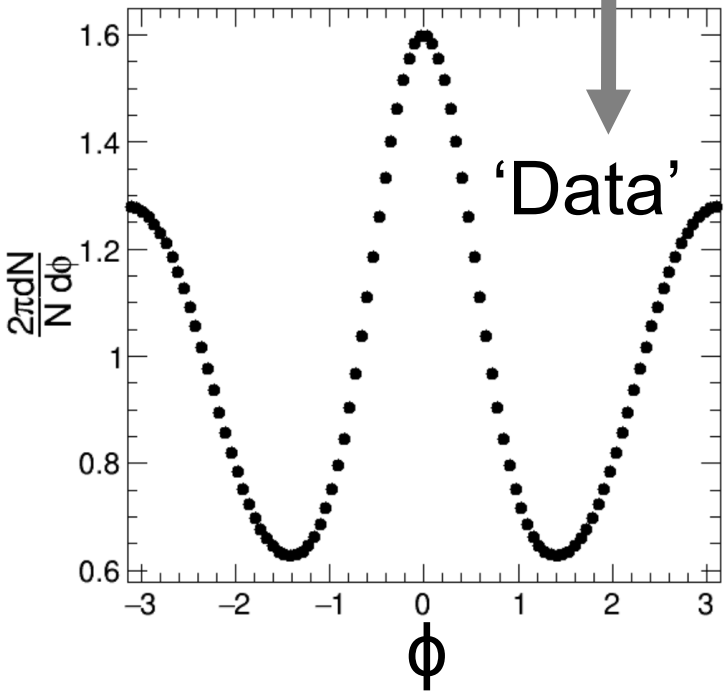
Expansion of **Ultra-cold atoms (Li-6)** released from trap



100 μs

Collective motion is observed

→ **Early hydrodynamization!**



Particle Azimuth Angle Distribution

Final State Particle Azimuthal Anisotropy

Magnitude

v_2 Ψ_2

+ Ψ_3

v_3

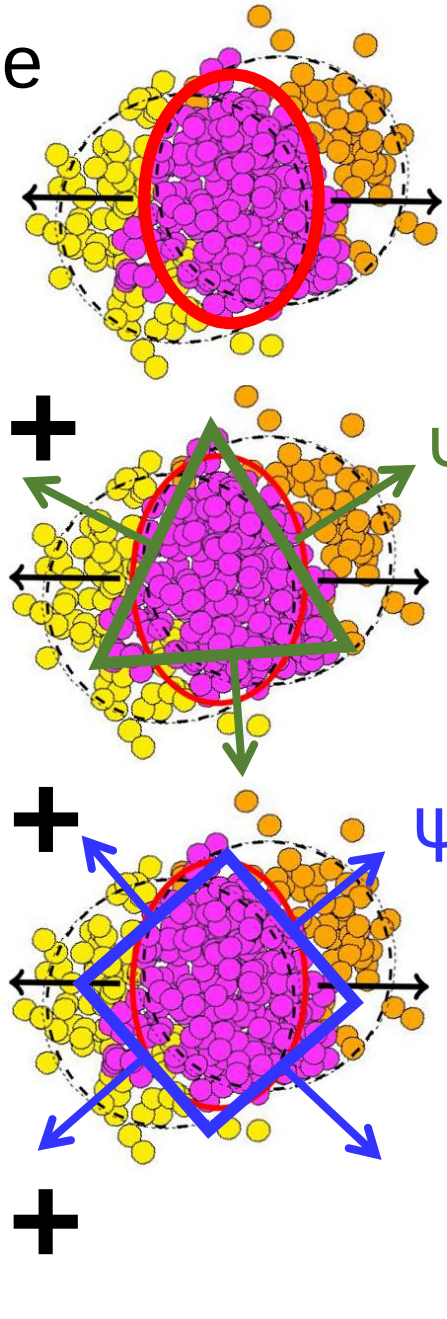
+ Ψ_4

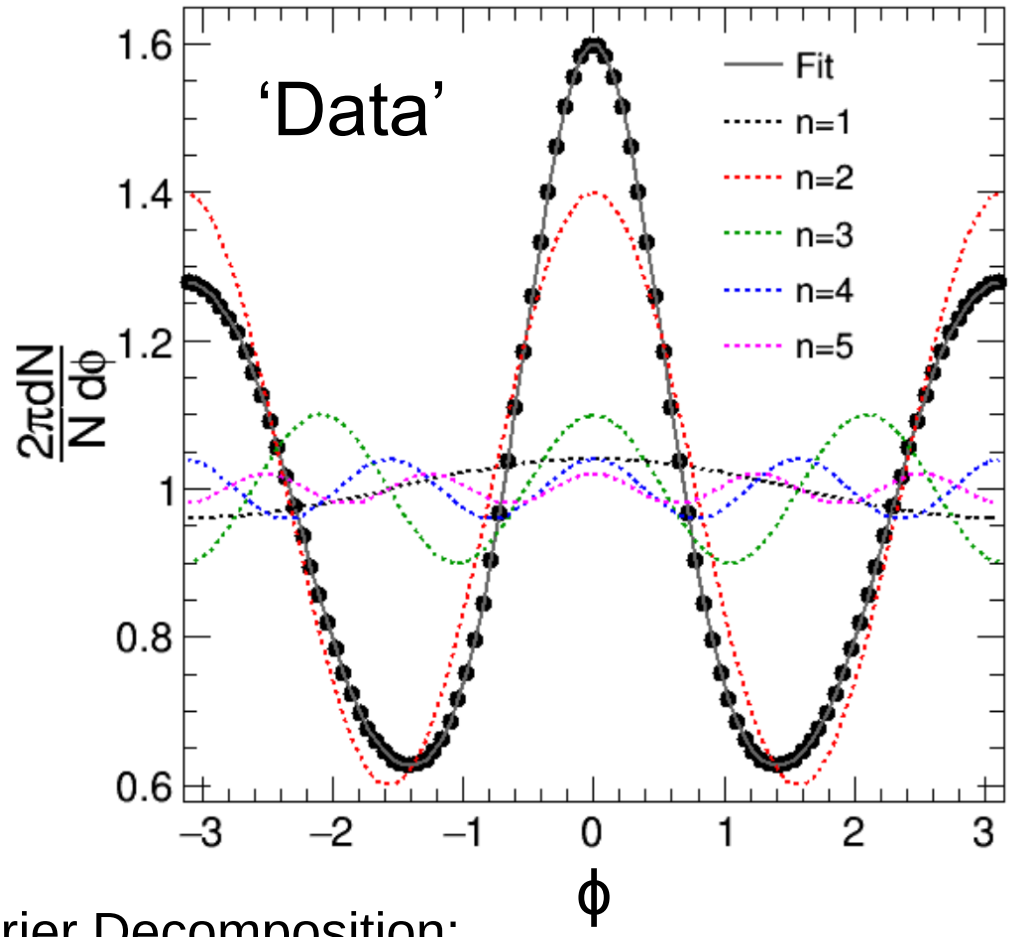
v_4

⋮

+

v_n ...





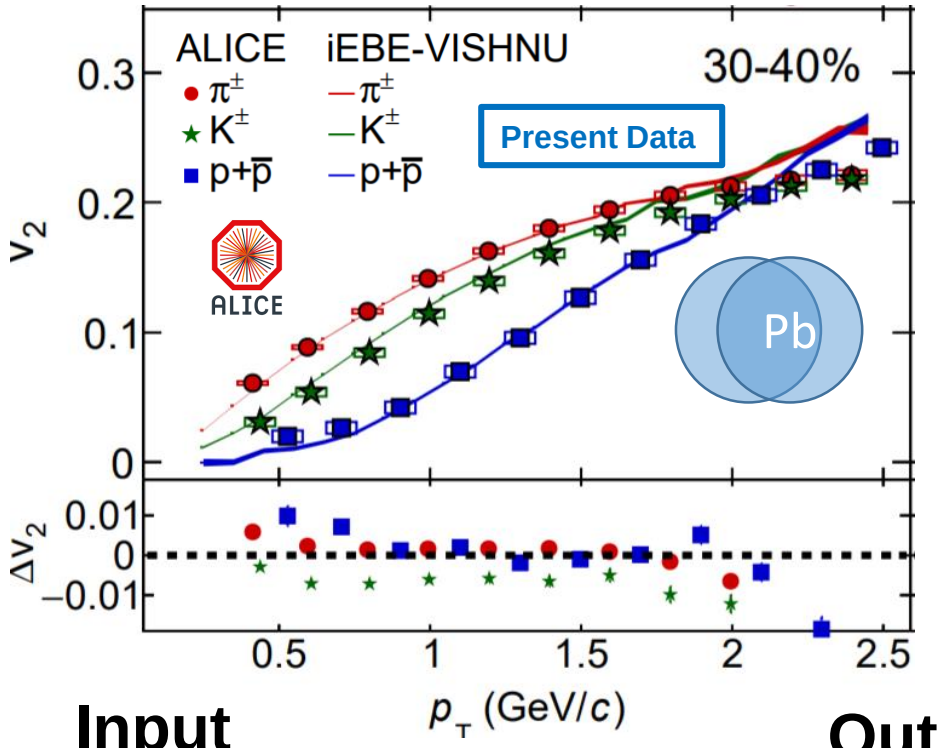
Fourier Decomposition:

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

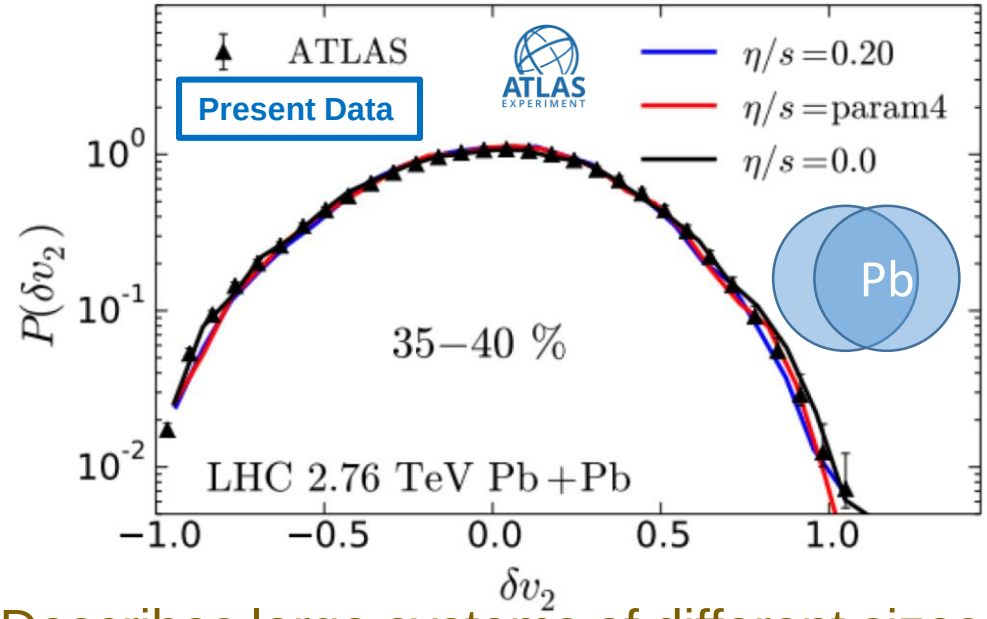
Alver and Roland (MITHIG)
"Collision geometry fluctuation"
PRC82 (2010) 039903

Relativistic Hydrodynamics Calculations

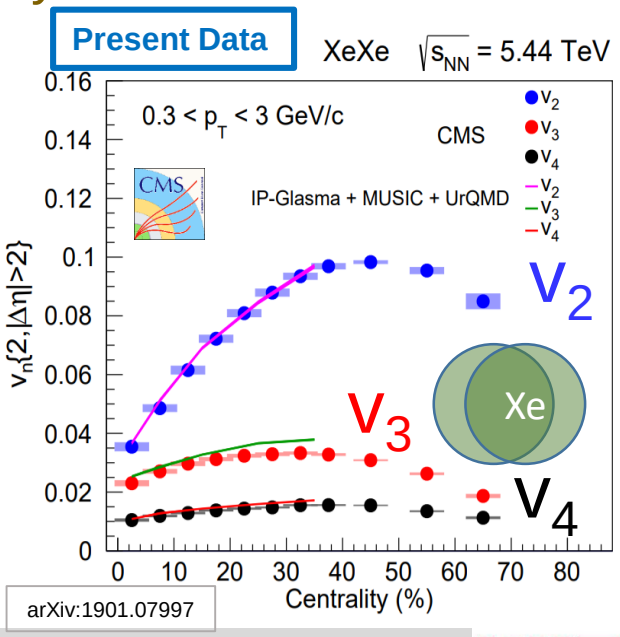
Describes flow of identified particles



Describes the elliptic flow (v_2) fluctuation



Describes large systems of different sizes



Input

Lattice QCD Equation of State

Output (from Global fit)

Medium Properties

$$T_{\mu\nu} = \varepsilon u_\mu u_\nu + p[\varepsilon]\Delta_{\mu\nu} - \eta[\varepsilon]\sigma_{\mu\nu} - \zeta[\varepsilon]\Delta_{\mu\nu}\nabla_\mu u^\mu + \mathcal{O}(\partial^2),$$

$$\sigma_{\mu\nu} = \Delta_{\mu\alpha}\Delta_{\nu\beta}(\nabla^\alpha u^\beta + \nabla^\beta u^\alpha) - \frac{2}{3}\Delta_{\mu\nu}\Delta_{\alpha\beta}\nabla^\alpha u^\beta,$$

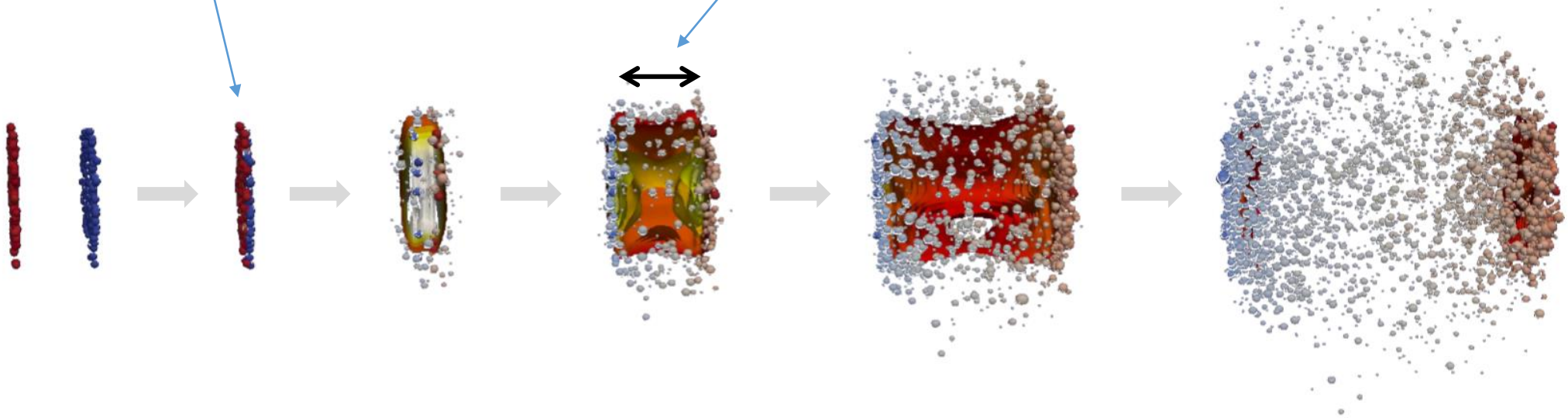
$$\Delta_{\mu\nu} = g_{\mu\nu} + u_\mu u_\nu,$$

hydrodynamic evolution equations, $\nabla_\mu T^{\mu\nu} = 0$

Big Questions

What are the initial conditions of the collision?

What is the longitudinal structure of the QGP? What is the equation of state of QGP?



Visualization taken from Jonah E. Bernhard
arXiv:1804.06469

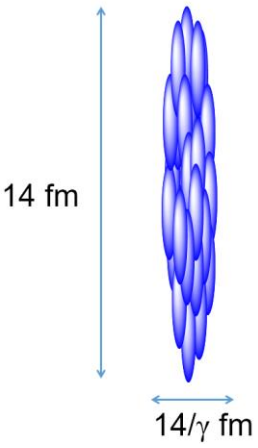
Parton Distribution Function (PDF)

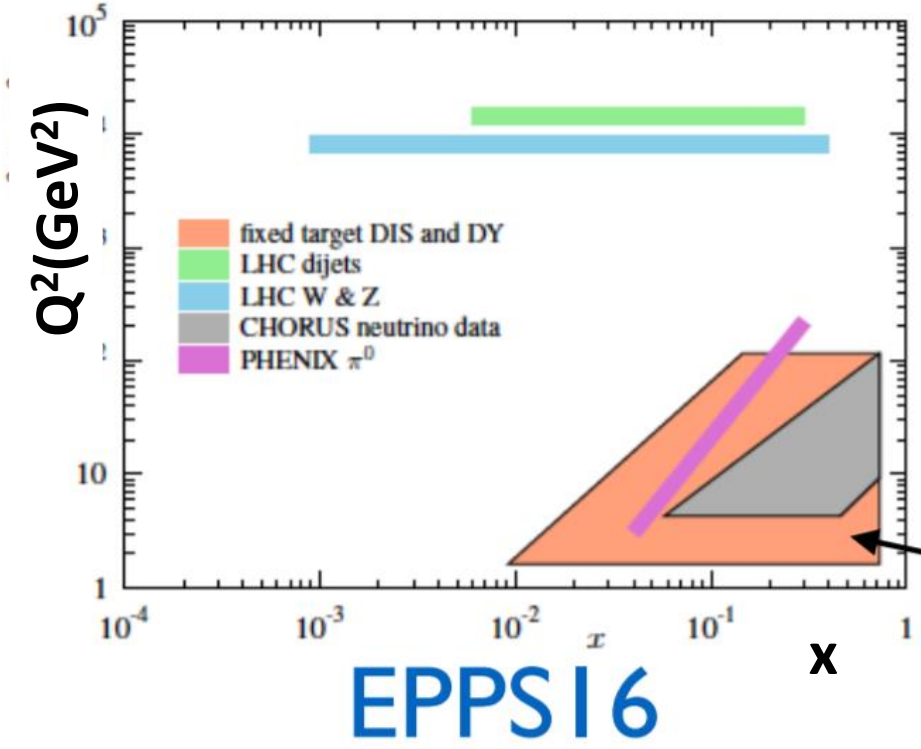
Lead Ion ≠ Superposition of **Neutrons** and **Protons**

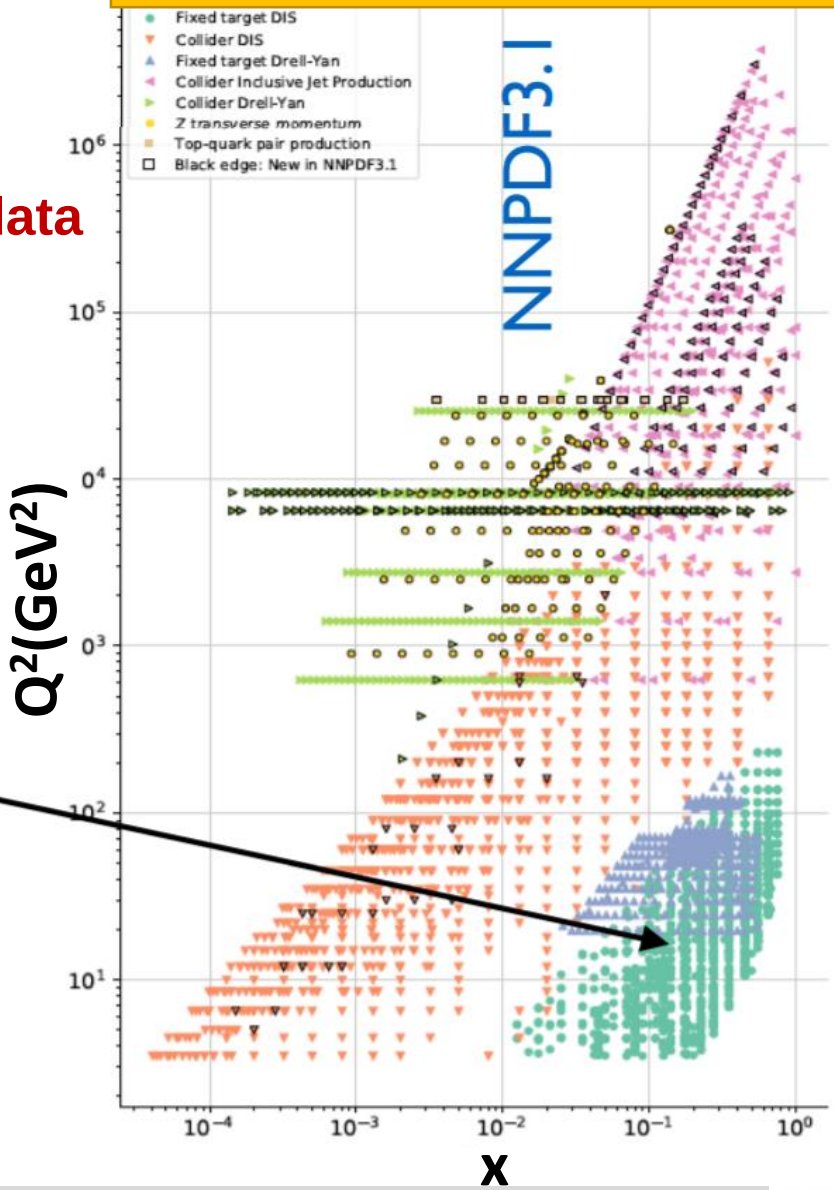
Input Data for Nucleon PDF

Input Data for Ion PDF

45 Pb collider data vs. **1200 proton collider data**

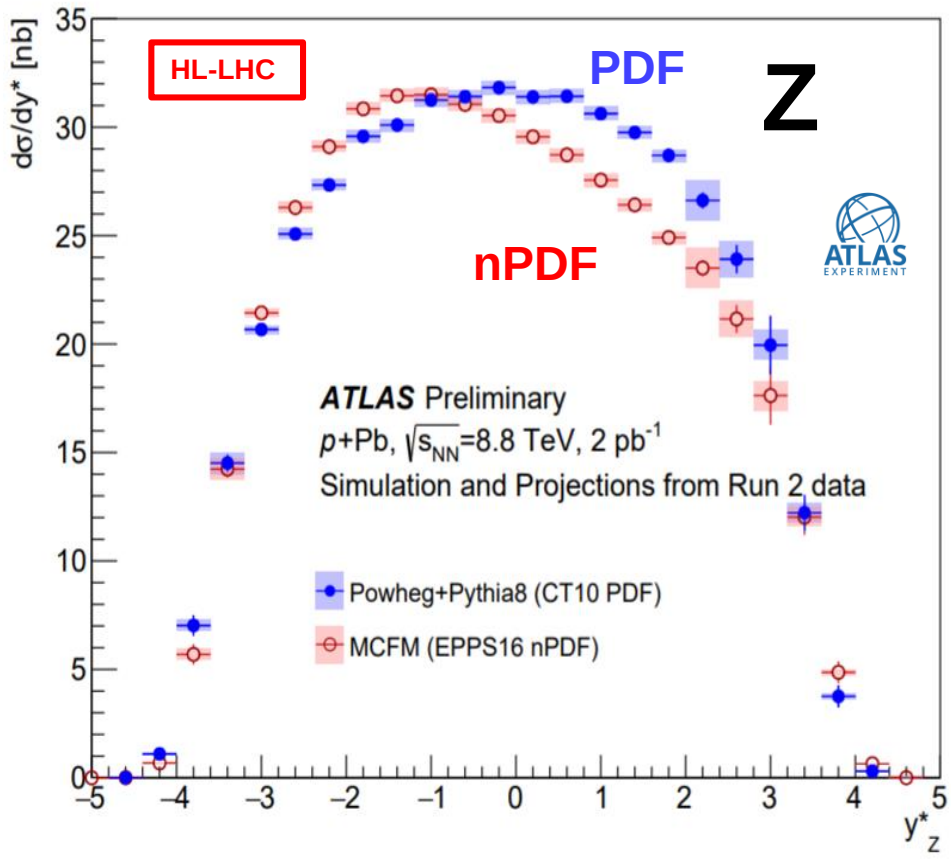


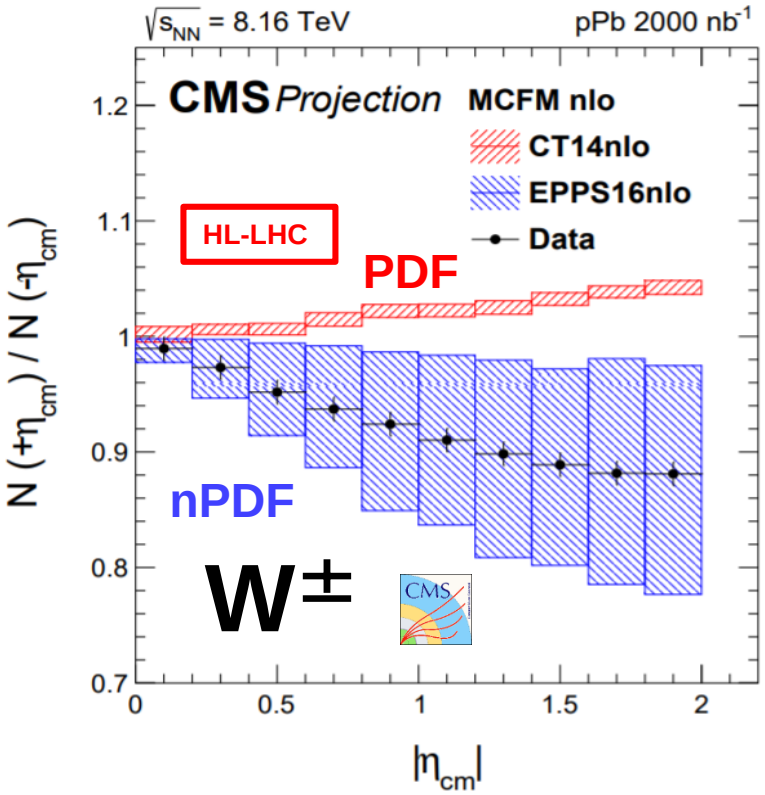


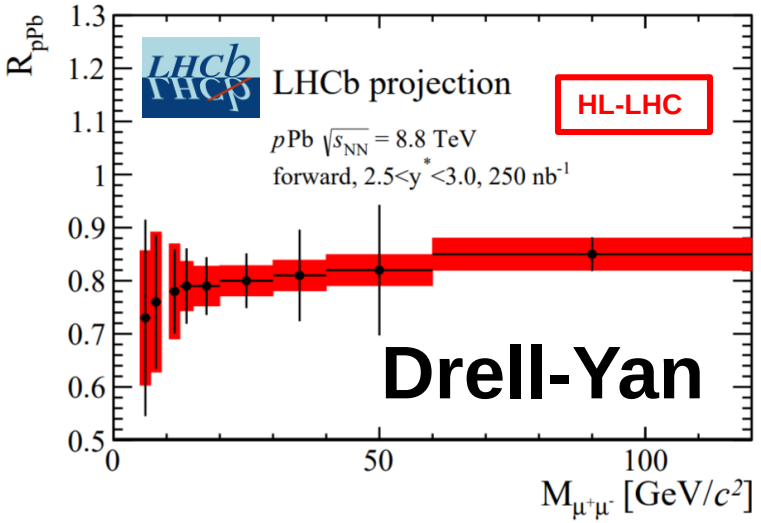


Poor understanding of PDF due to the limited amount of ion data

nPDF Constraint from pPb Collisions



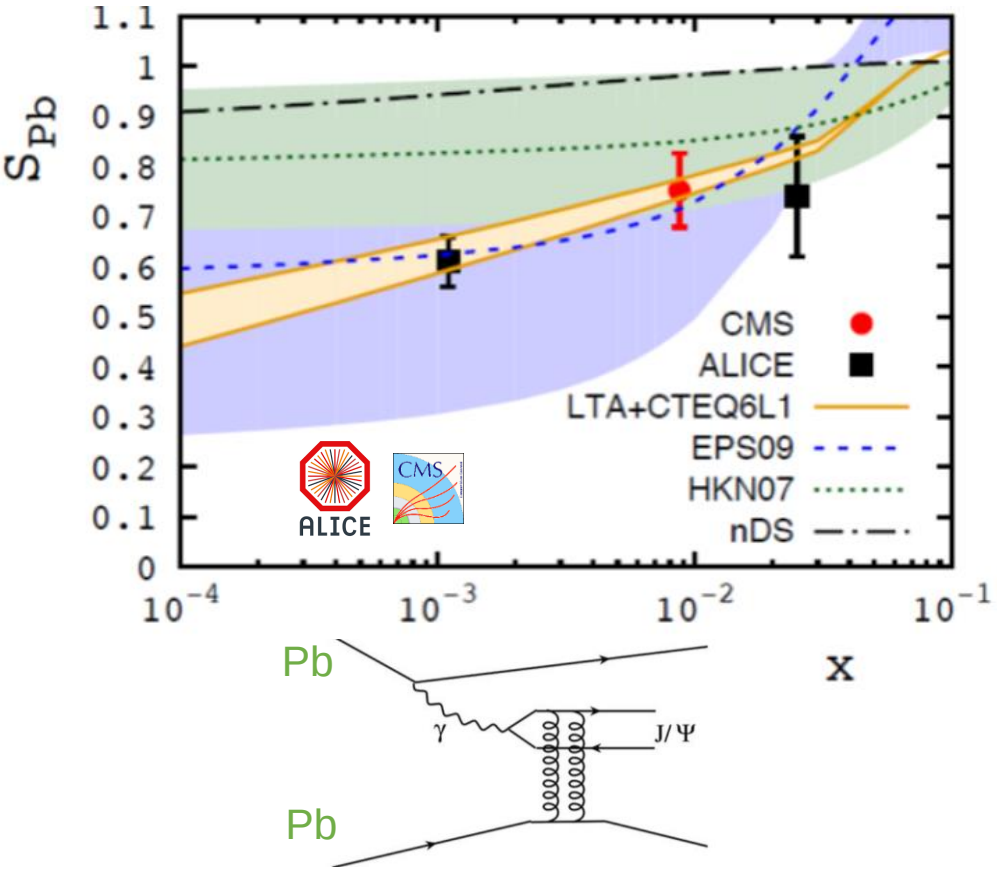




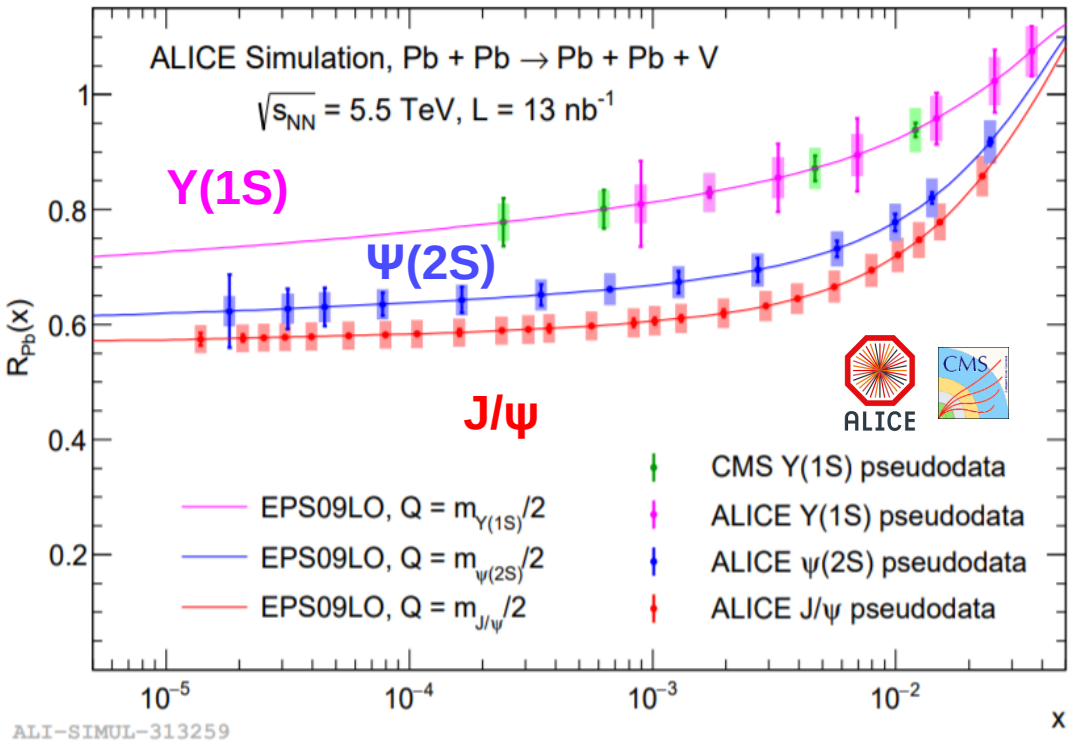
Strong constraints on (quark) nPDF from electroweak boson, Drell-Yan and dijet cross-section measurements in pPb collisions

nPDF from Ultra-Peripheral PbPb Collisions

UPC J/ψ in Run 1 + 2015 Data **Present Data**

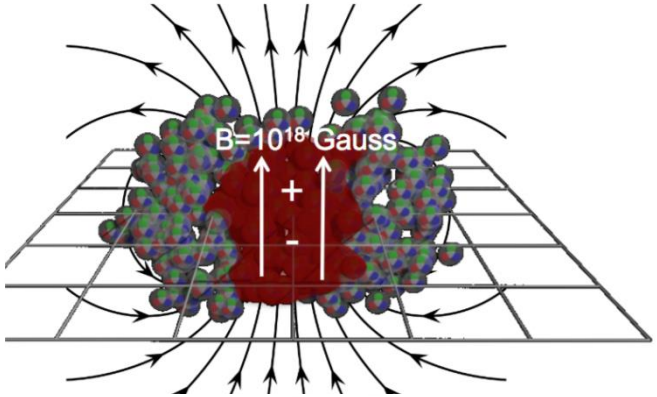


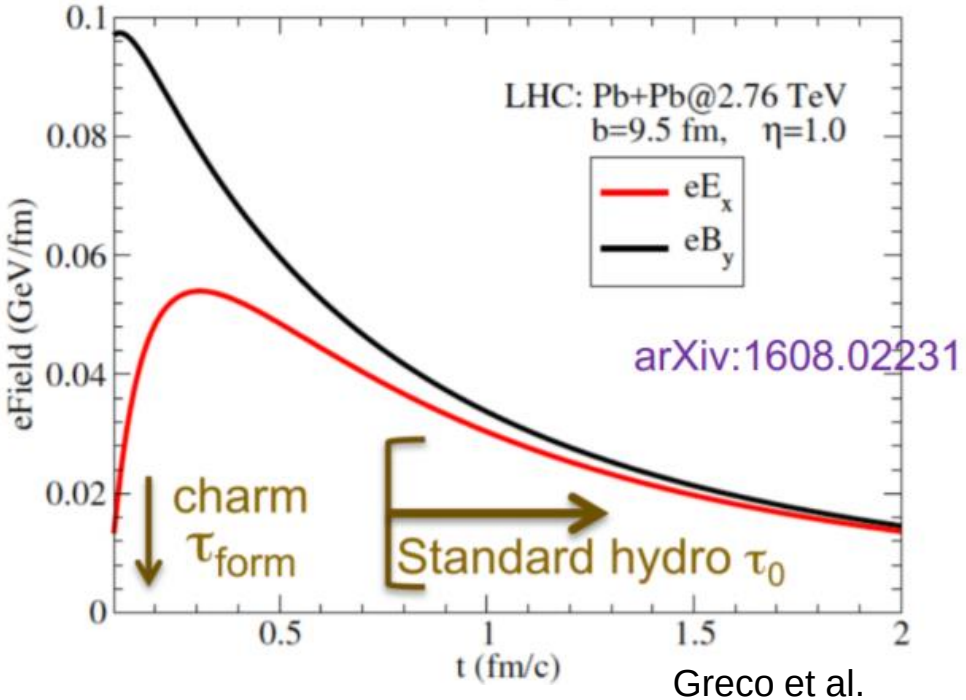
Performance of UPC Quarkonia **HL-LHC**



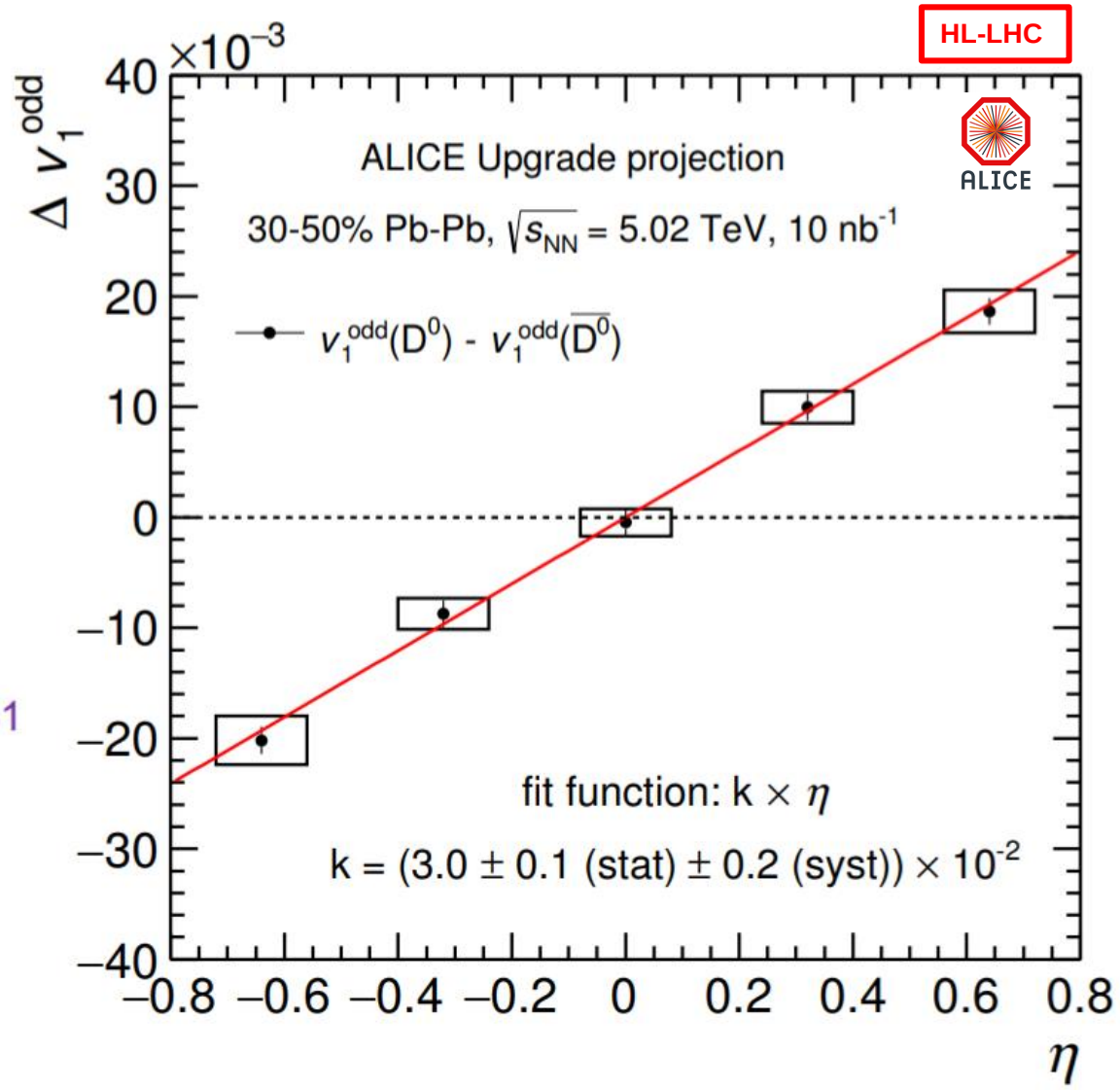
- Ultra-Peripheral PbPb Collisions(UPC): **γ+Pb** collisions!
- HL-LHC data: Precise measurements of Υ(1S), J/ψ and ψ(2S) over a **very wide x range**, test **Q dependence** of nuclear modifications
- Together with (di-)jet data in UPC PbPb and pPb collisions: strong constraint on the gluon nuclear PDF

Magnetic Field with Charm Meson





Greco et al.

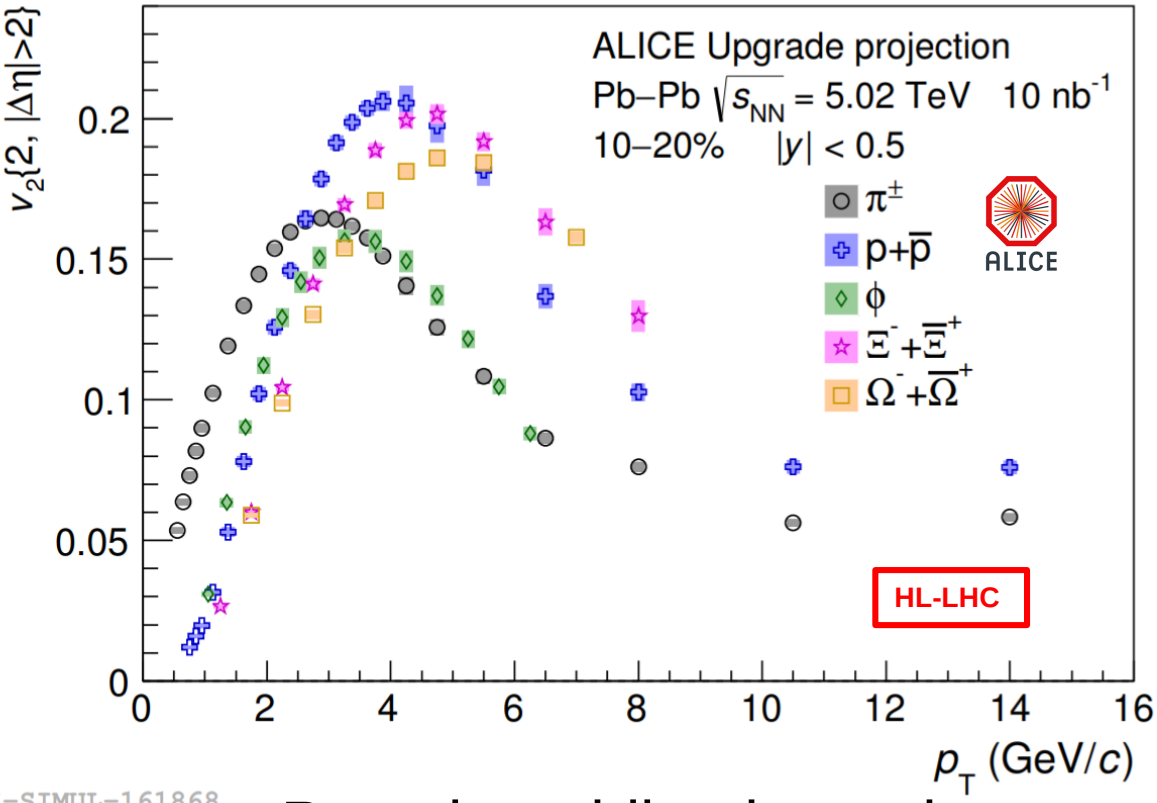


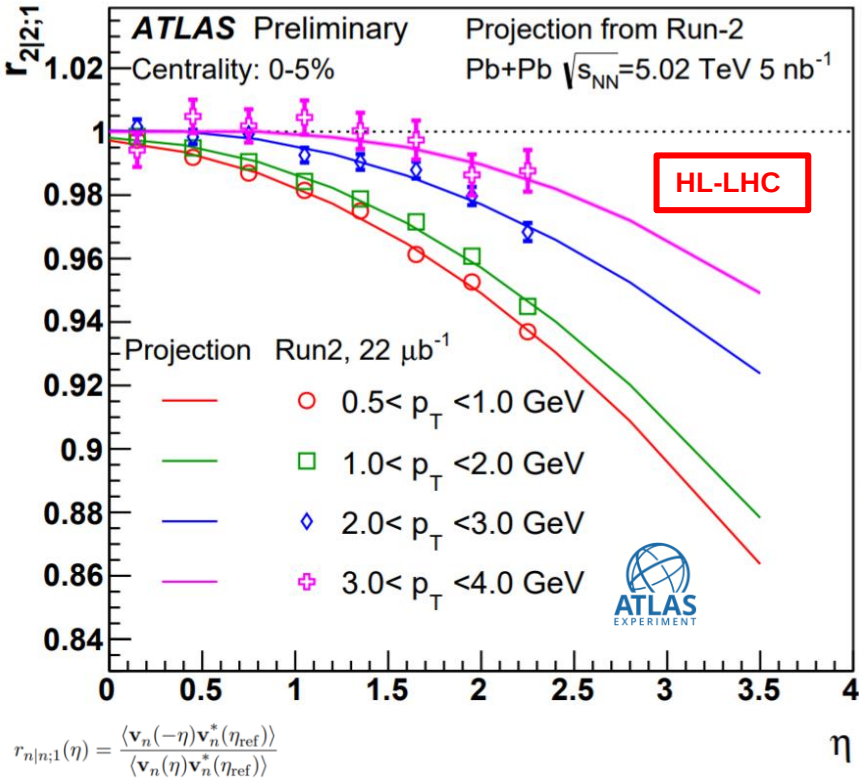
ALI-SIMUL-140060

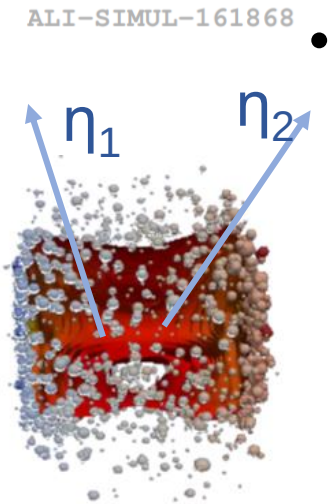
- Charm Quarks:
  - More sensitive (than light flavor) to early magnetic fields and vorticity
- High precision measurement could be performed for the first time with HL-LHC data

Prospects for Flow Measurements

- 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







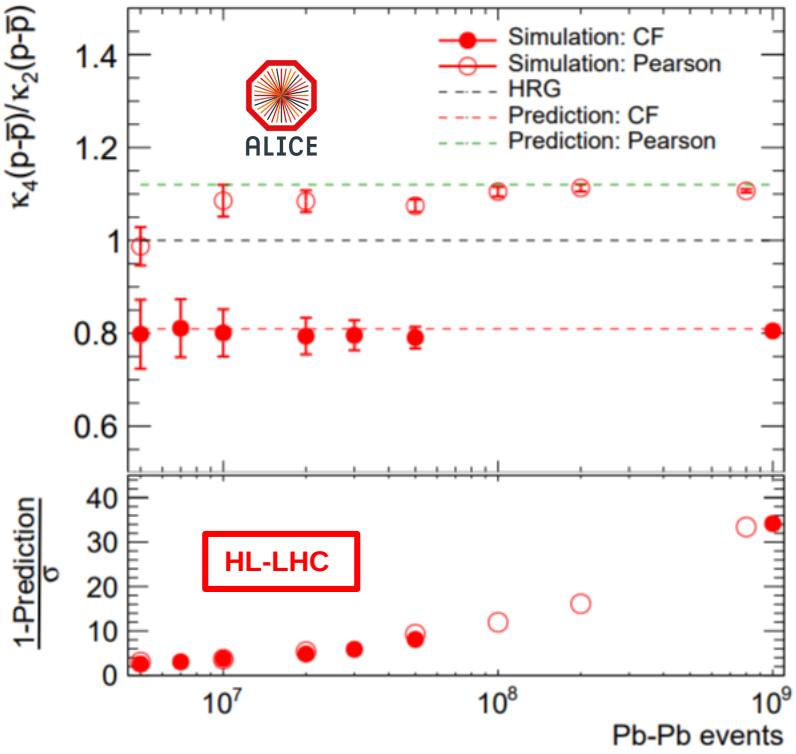
- Pseudorapidity dependence of the flow measurements over **a wide η window** enabled by ATLAS and CMS tracker upgrade
  New insights into the longitudinal structure of QGP (event-plane decorrelation)

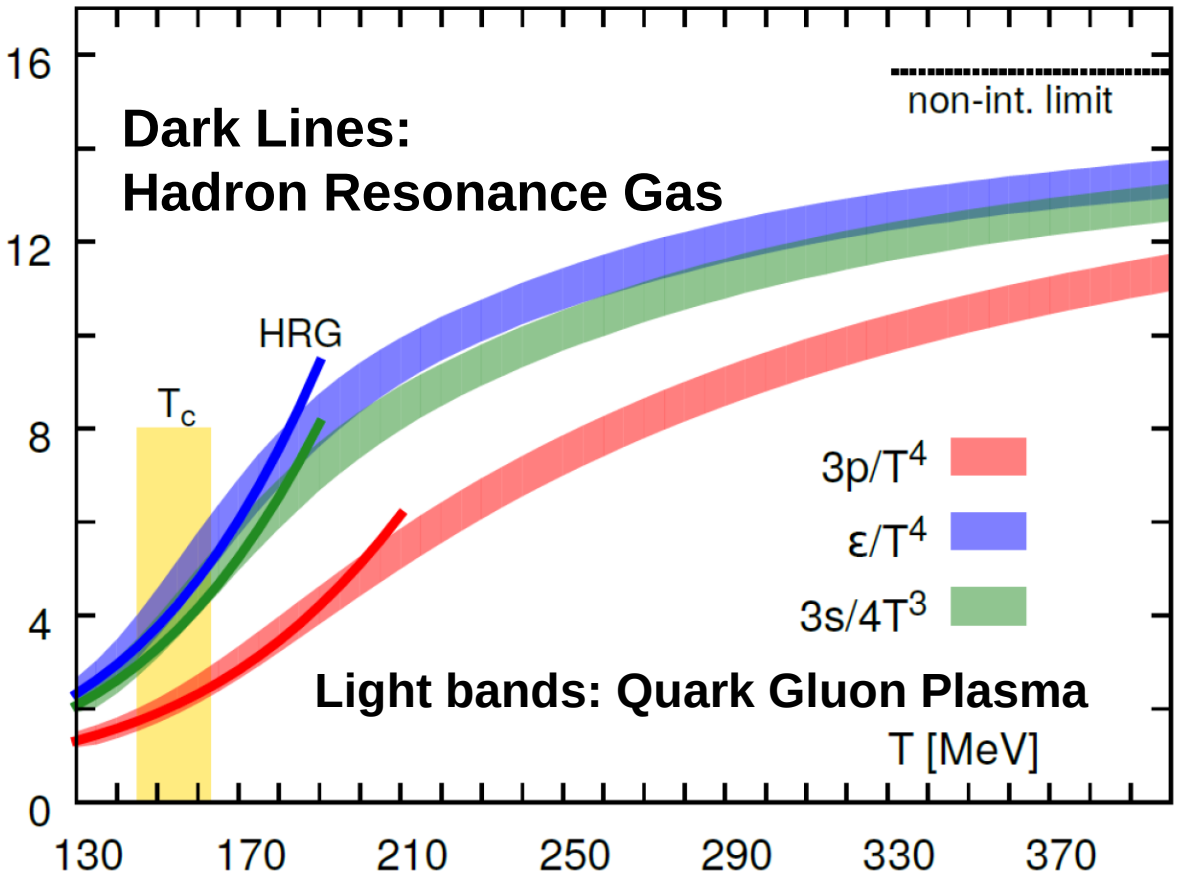
QCD Equation of State at μ_B=0

Can we "measure" the QCD Equation of State?

High precision flow measurement enabled by HL-LHC data

Net-baryons fluctuation



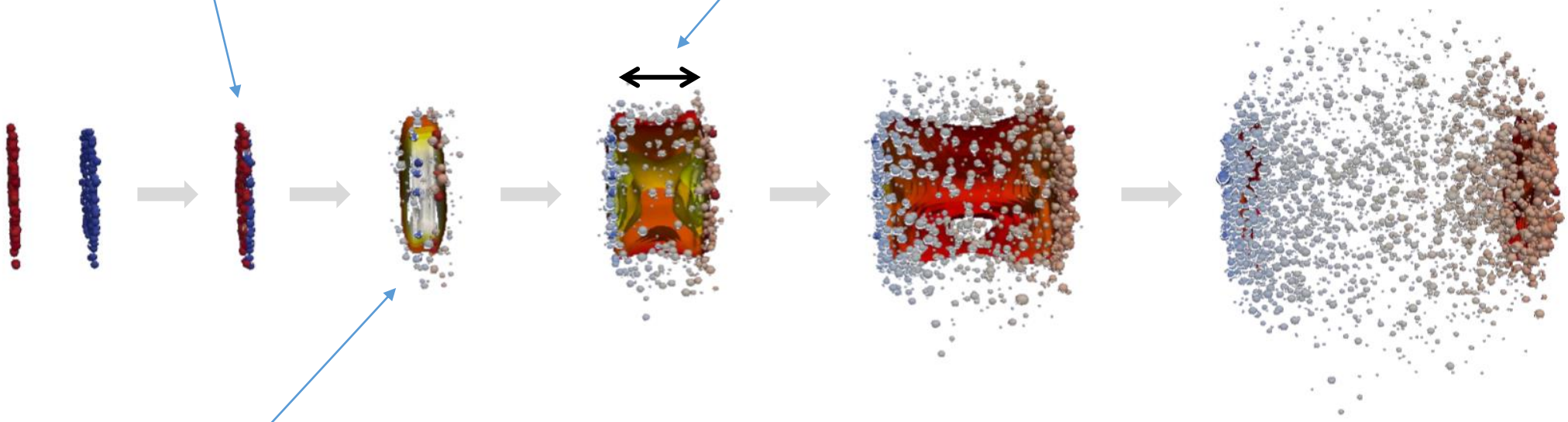


… and many more observables enabled by HL-LHC data

Big Questions

What are the initial conditions of the collision?

What is the longitudinal structure of the QGP? What is the equation of state of QGP?

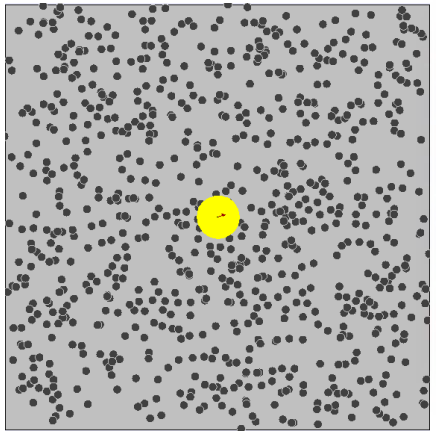


How does the system move toward hydrodynamization?

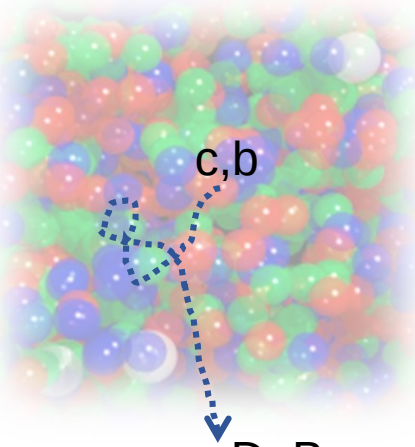
Visualization taken from Jonah E. Bernhard
arXiv:1804.06469

Open Heavy Flavor

- Produced **before** the QGP formation
- Low momentum heavy quarks (HQ) are then "kicked around" by quasi-particles (Brownian Motion)
- Heavy quark diffusion coefficient (D_s) provides a direct window on the in-medium QCD force



Brownian Motion



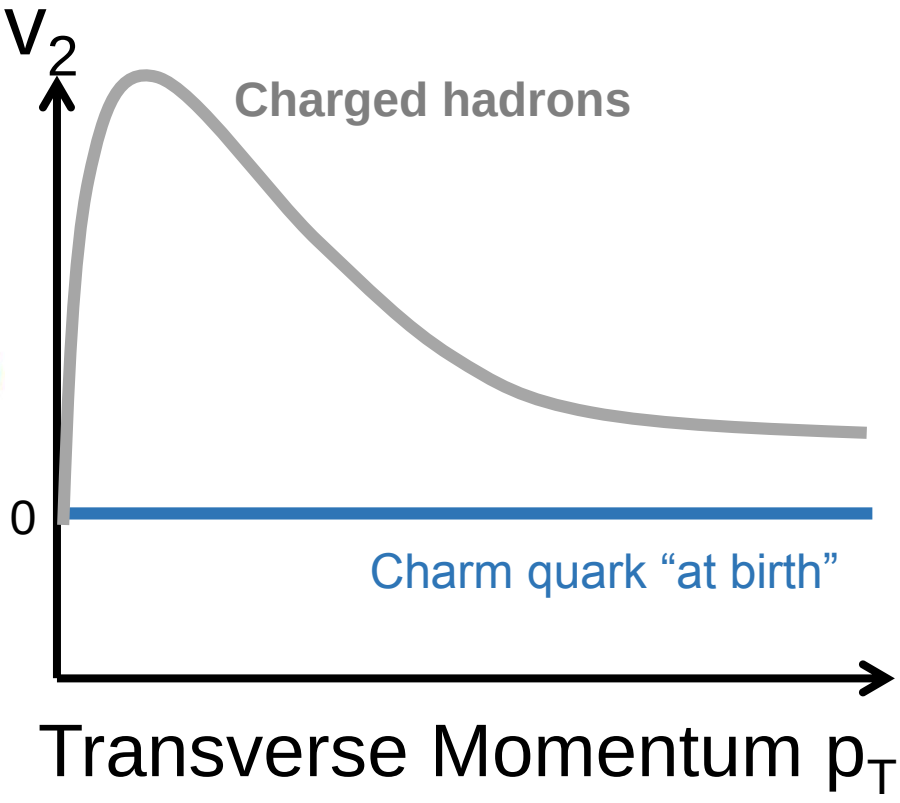
Fokker-Planck equation:

$$\frac{\partial}{\partial t} f_Q(t,p) = \frac{\partial}{\partial p} pA(p) f_Q(t,p) + \frac{\partial^2}{\partial^2 \vec{p}} B(p) f_Q(t,p)$$

Heavy Quark Diffusion Coefficient:

$$\mathcal{D}_s = \frac{T}{m_Q A(p=0)}$$

Long-wavelength limit of HQ transport



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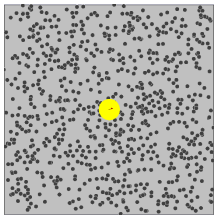
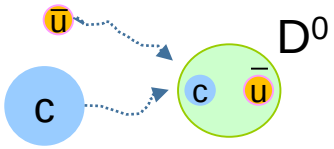
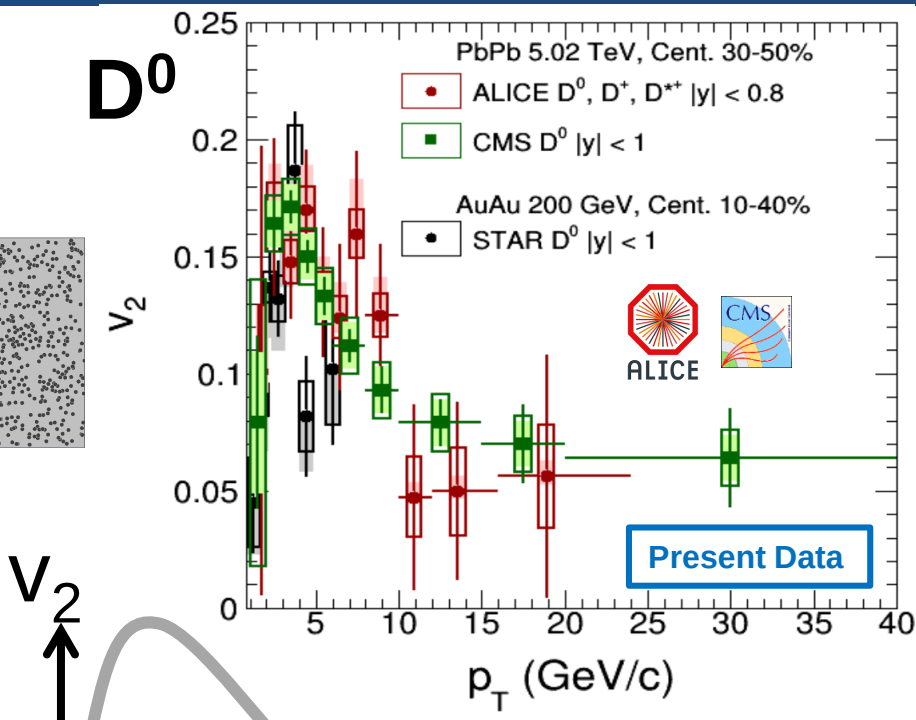
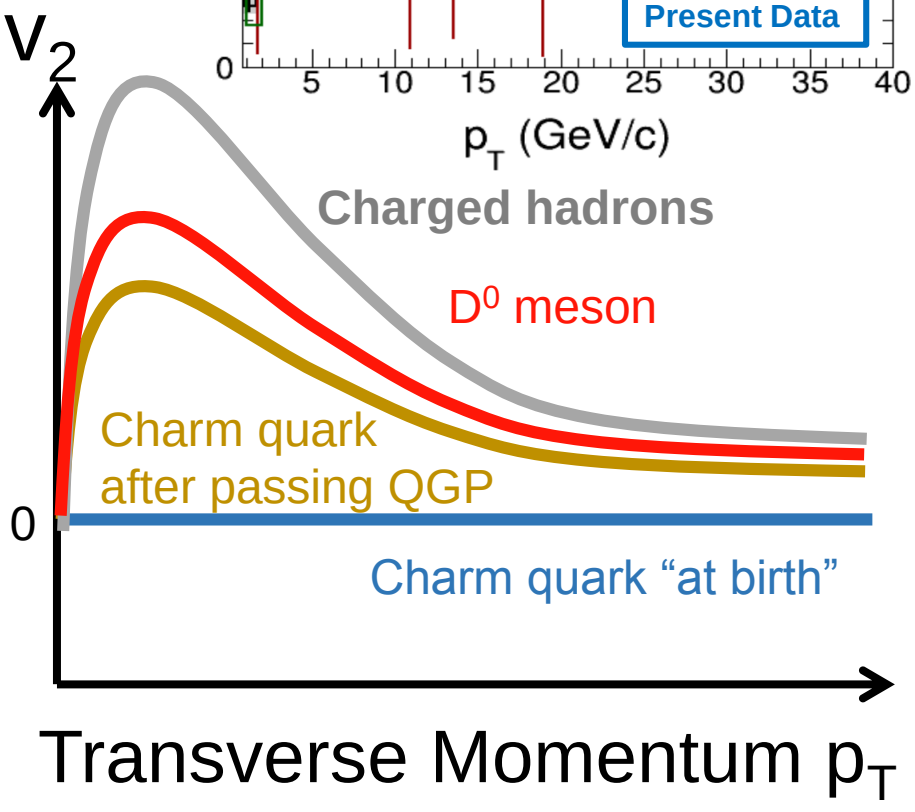


- Heavy quark diffusion coefficient (D_s) provides a direct window on the in-medium QCD force
- Since the **QGP expands radially**, QCD force (like 'wind') will increase the v_2 of the heavy quarks in the QGP bath

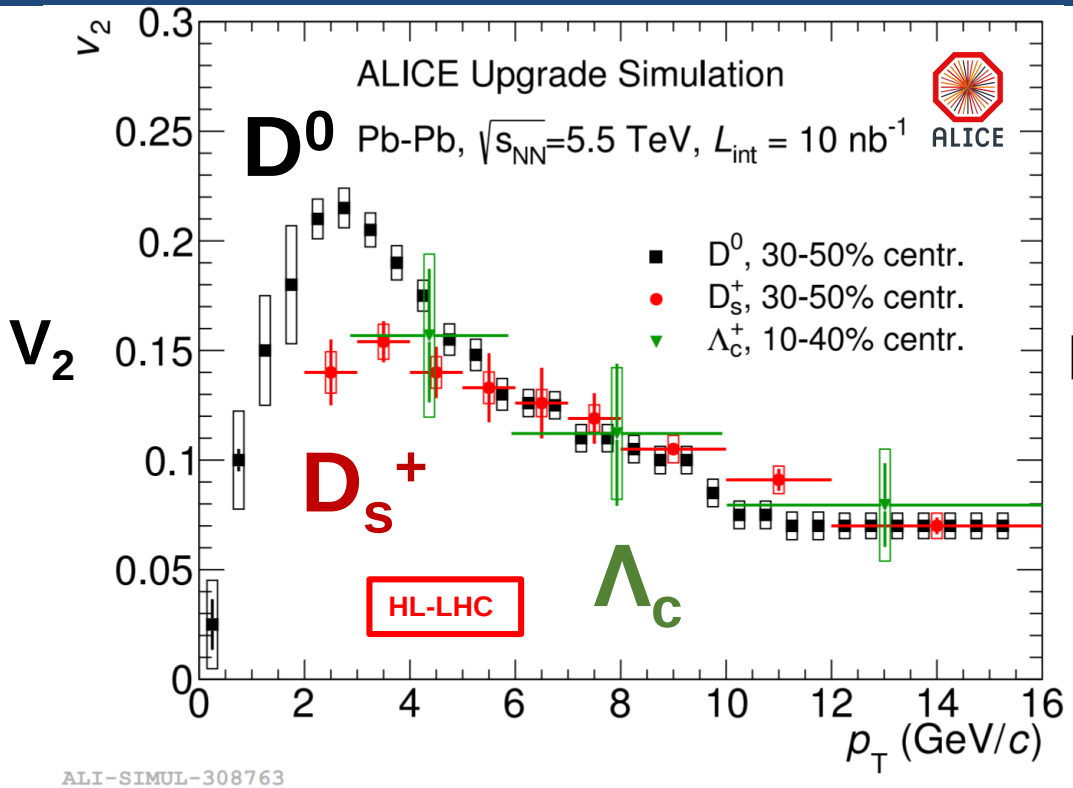


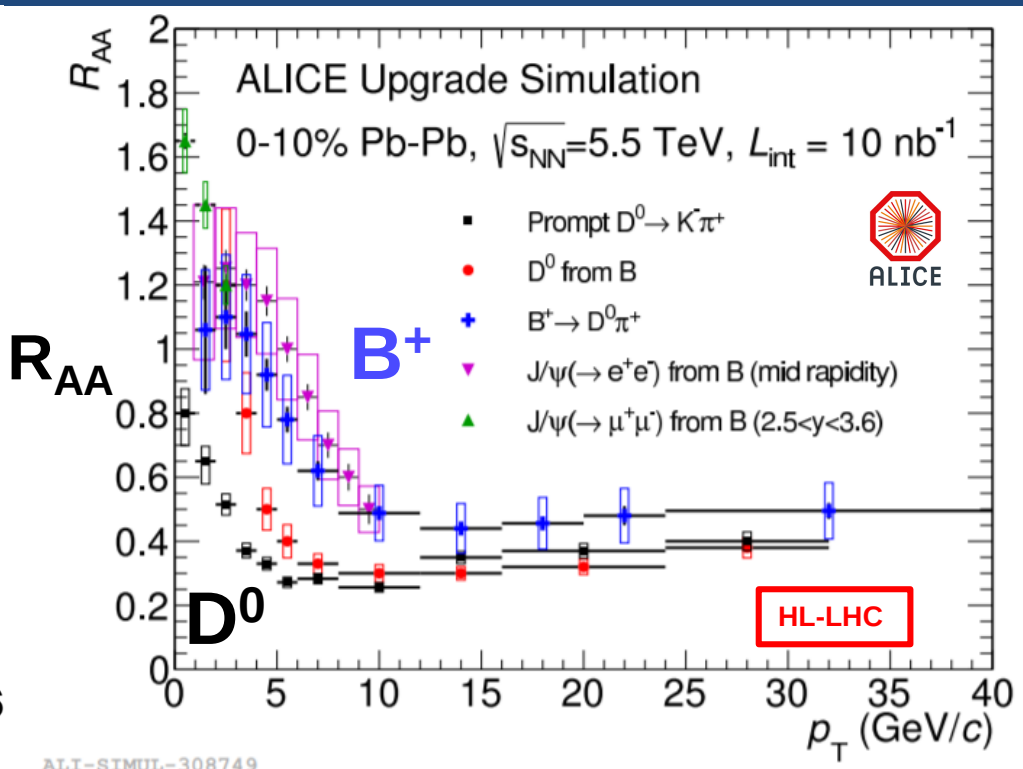
- Hadronization of heavy quarks (through coalescence) also pick up v_2 from light flavors





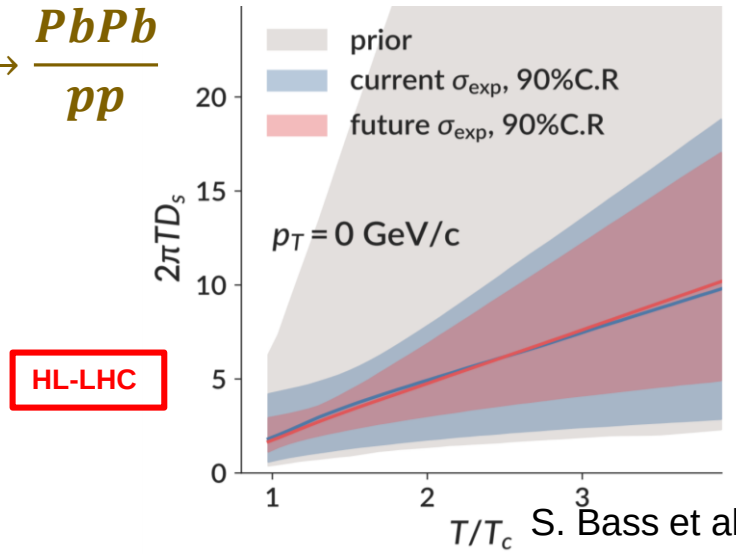
Heavy Flavor Hadron in PbPb at 5.02 TeV





- High precision measurement of heavy flavor hadron v_2 and spectra (from high p_T to p_T~0): **Total charm cross-section** which provide strong constrains on the models of charmonium recombination
- Strong constraints on the heavy quark diffusion coefficient D_s

$$R_{AA} \rightarrow \frac{PbPb}{pp}$$



S. Bass et al.

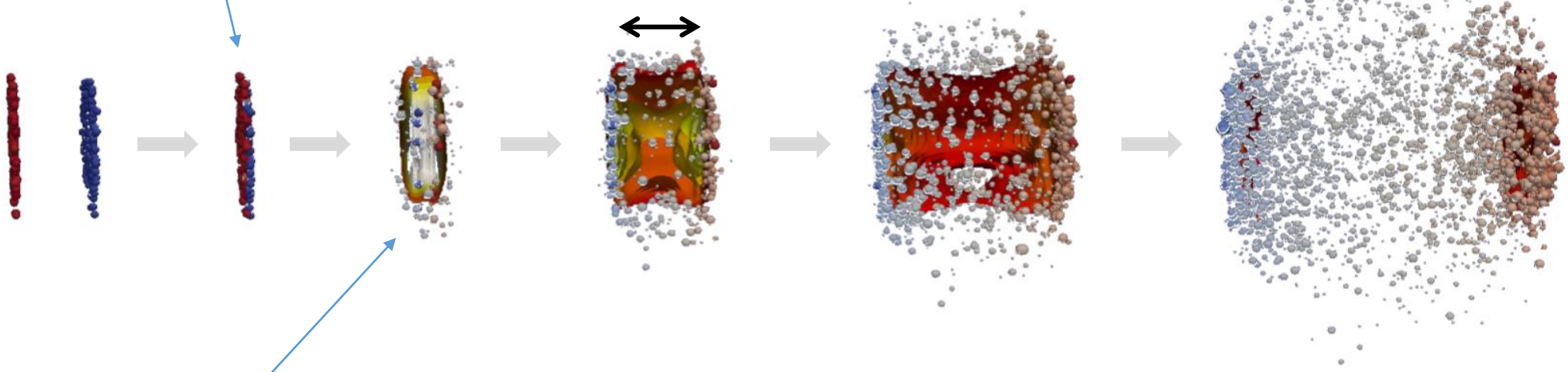
Constrains using a Bayesian analysis

Big Questions

What are the initial conditions of the collision?

What is the longitudinal structure of the QGP? What is the equation of state of QGP?

How does the QGP hadronize?

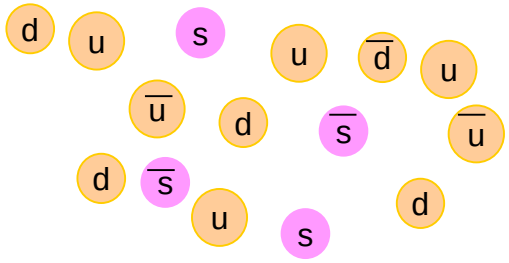


How does the system move toward hydrodynamization?

Visualization taken from Jonah E. Bernhard
arXiv:1804.06469

Hadronization of Heavy Quarks in QGP

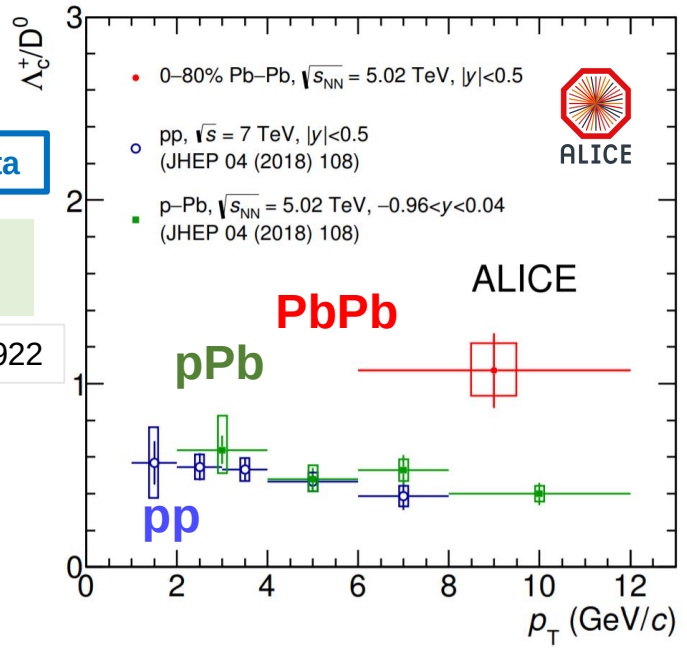
Strange quark content is enhanced in QGP (Due to the high temperature)



Present Data

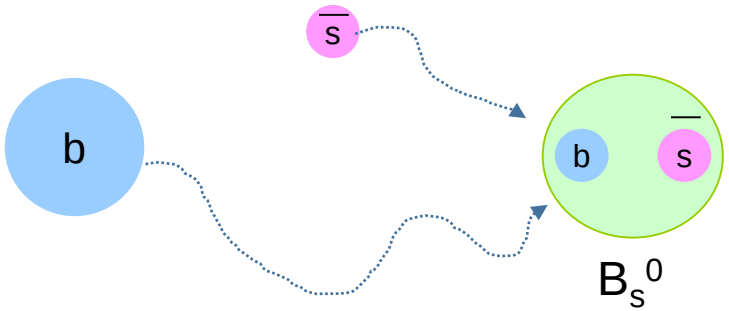
Λ_c/D

arXiv:1809.10922



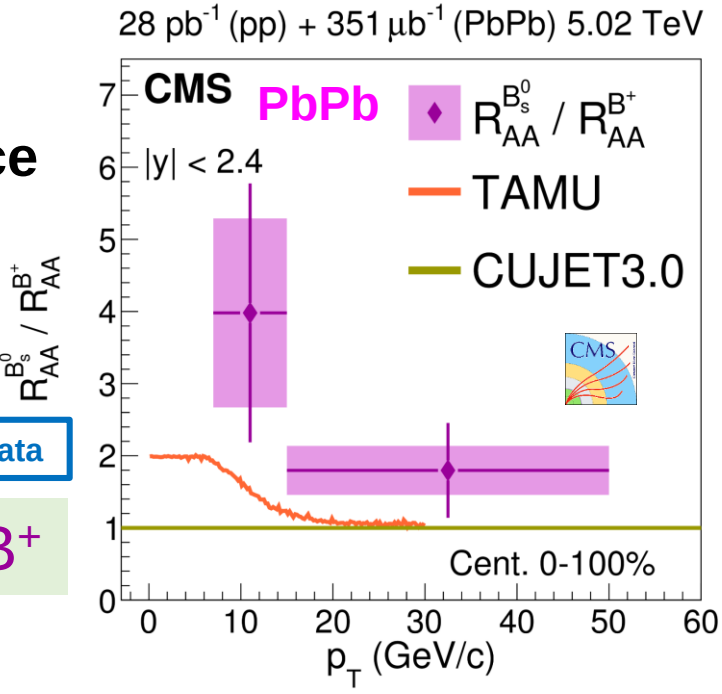
Idea: Probe the partonic QGP by heavy quarks!

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



Present Data

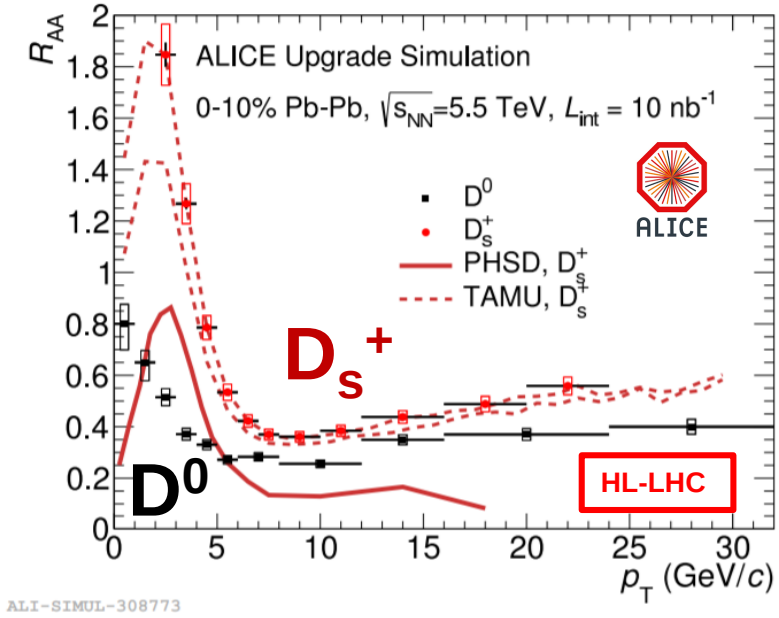
B_s/B^+



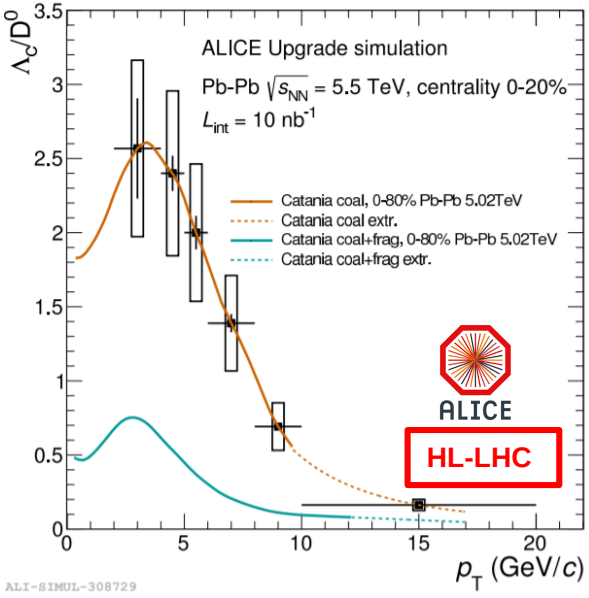
B_s^0 arXiv:1810.03022	$B^{\pm}$ PRL 119 (2017) 152301

Heavy Quark Hadronization

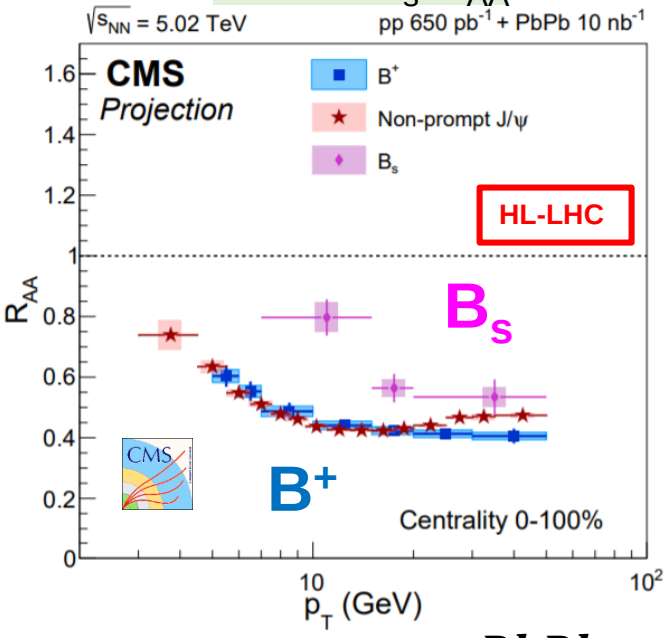
D_s R_{AA}



Λ_c/D



B^+ and B_s R_{AA}

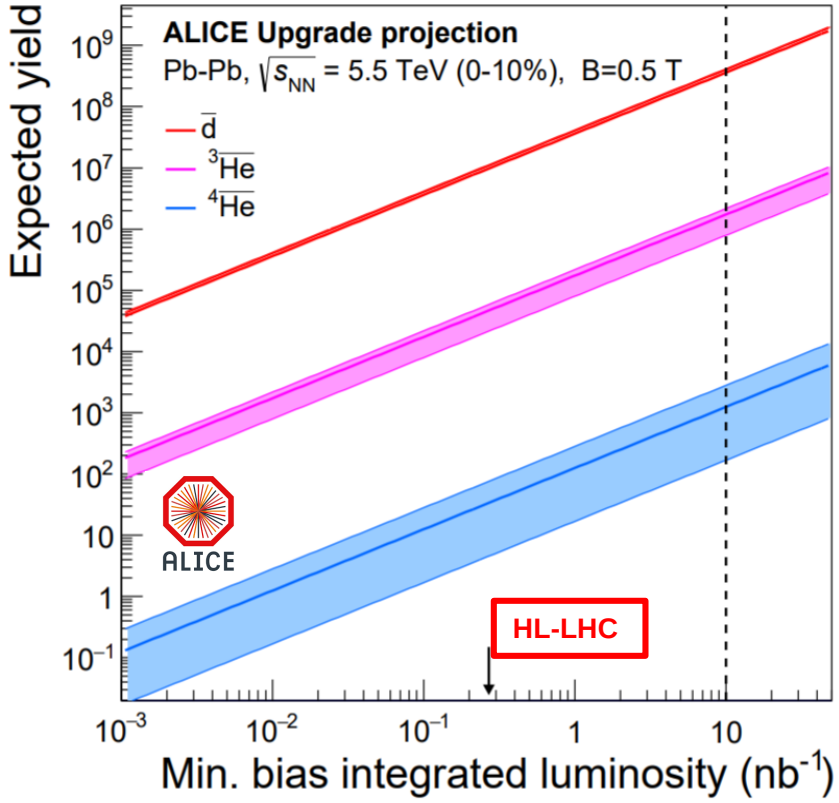


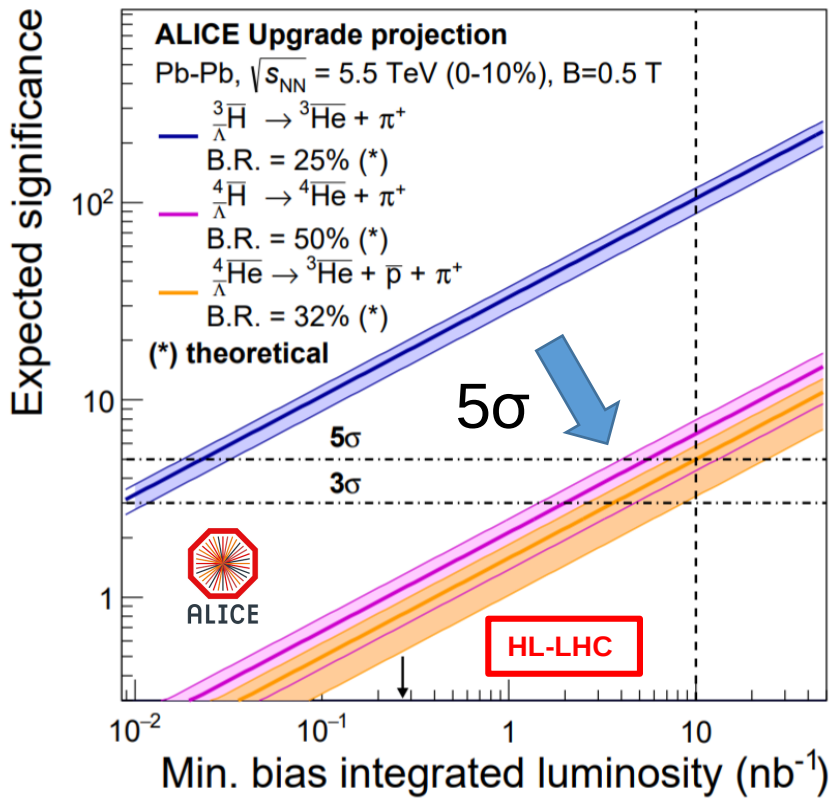
$$R_{AA} \rightarrow \frac{PbPb}{pp}$$

- Charm quark number is **conserved** in strong interaction
  - Hadronization chemistry: crucial for the interpretation of the heavy flavor hadron spectra ("keep track of all the c quarks")
- Run 3+4 data will allow the first comprehensive survey of this effect
  - D_s, B_s and Λ_c spectra from low to high p_T in pp and PbPb
  - Provide the necessary statistical accuracy to see the emergence of the effect at low p_T

(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



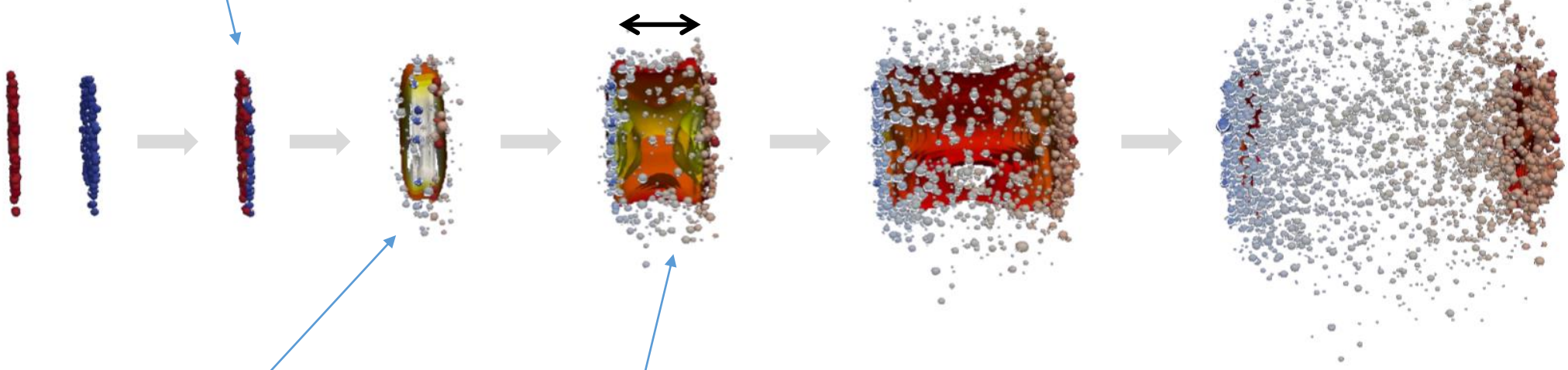


Big Questions

What are the initial conditions of the collision?

What is the longitudinal structure of the QGP?

How does the QGP hadronize?

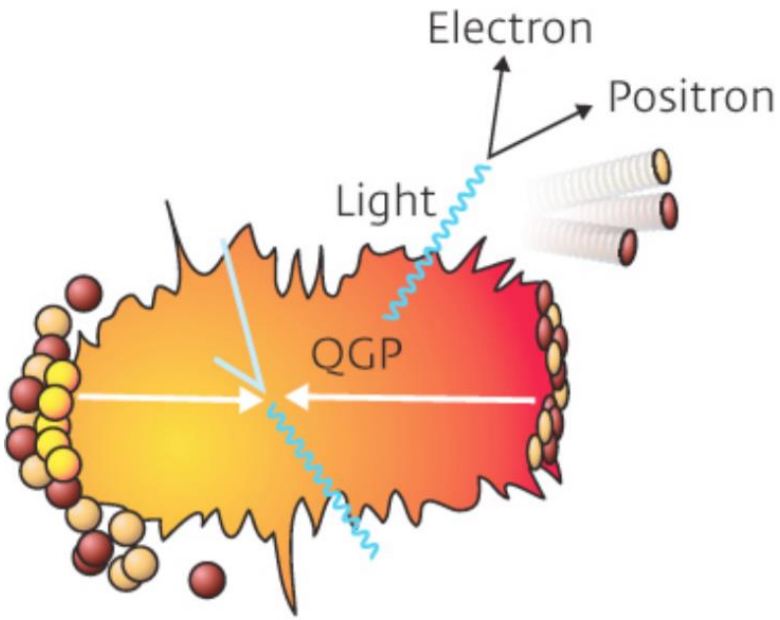


How does the system move toward hydrodynamization?

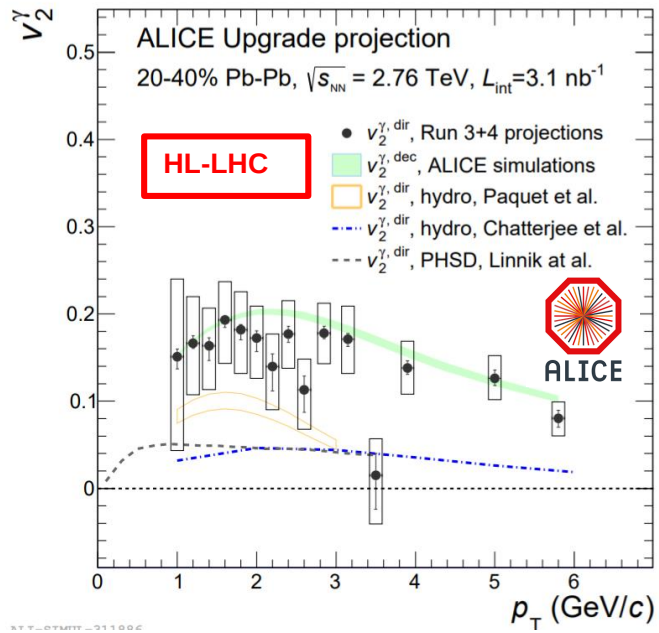
What is the temperature of the QGP?

Visualization taken from Jonah E. Bernhard
arXiv:1804.06469

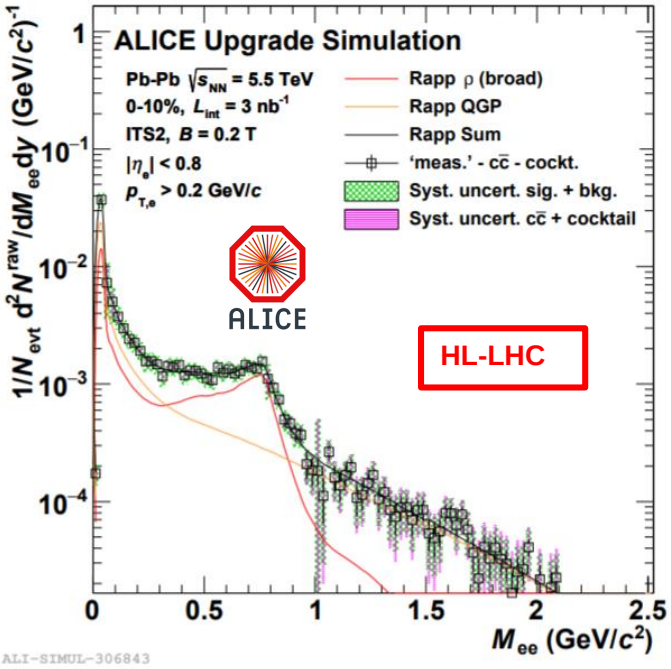
Temperature of QGP: Thermal Photons / Dilepton



Photon Azimuthal Anisotropy



Dielectron invariant mass



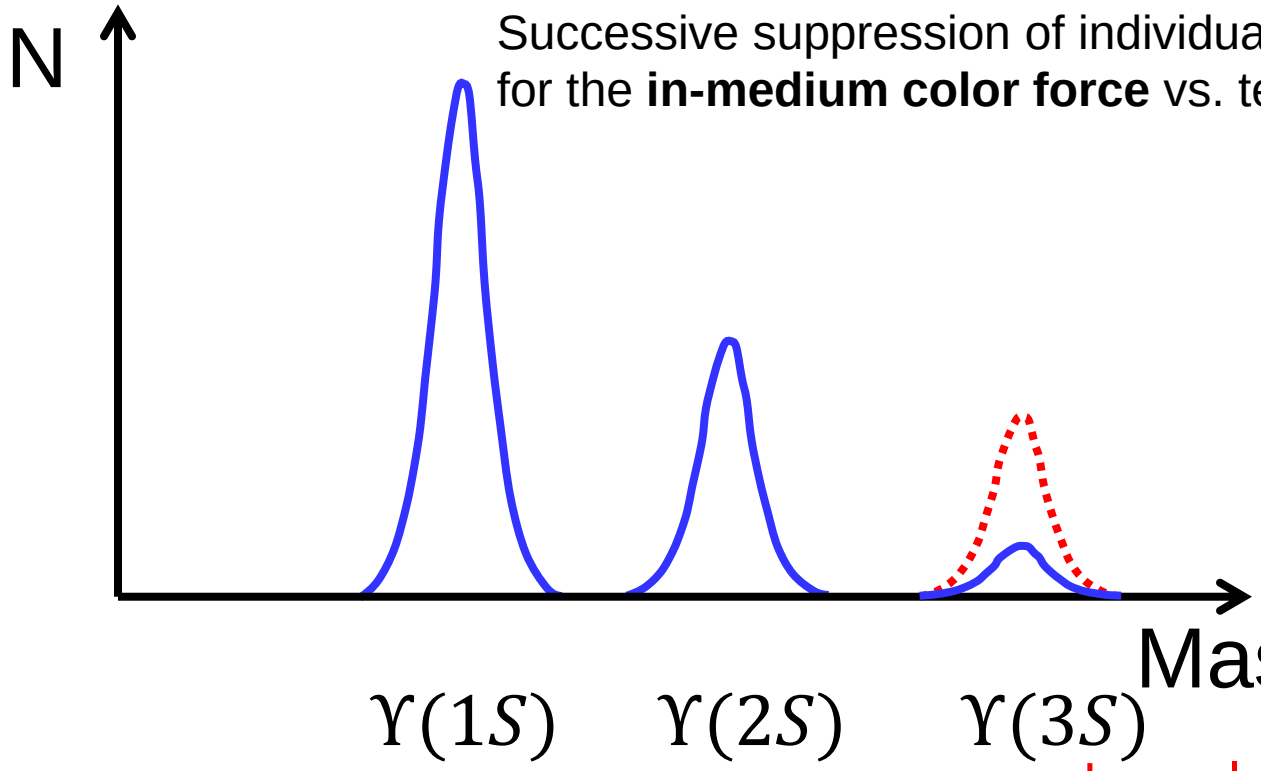
Photons:

- Thermal radiation

Dileptons:

- Thermal radiation
- Effective T with uncertainty of ~20%
- Vector meson spectral shape
- Beyond SM particles with $J^{PC}=1^{--}$ (e.g. dark photons)
- 3 nb^{-1} PbPb collisions with B=0.2 T (instead of B=0.5T) at ALICE

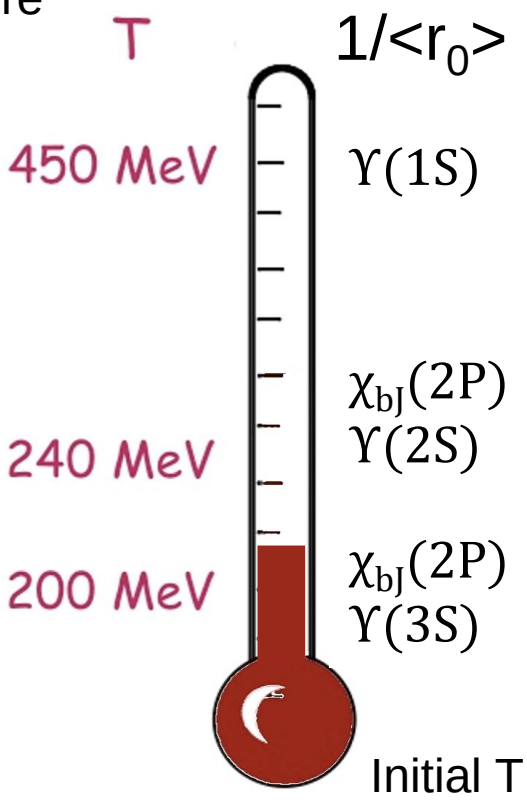
In QGP (lower Energy AA collisions)



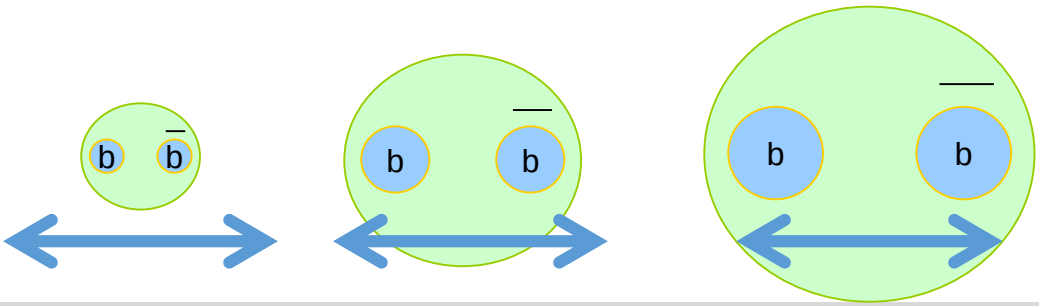
Successive suppression of individual states provides a window for the **in-medium color force** vs. temperature

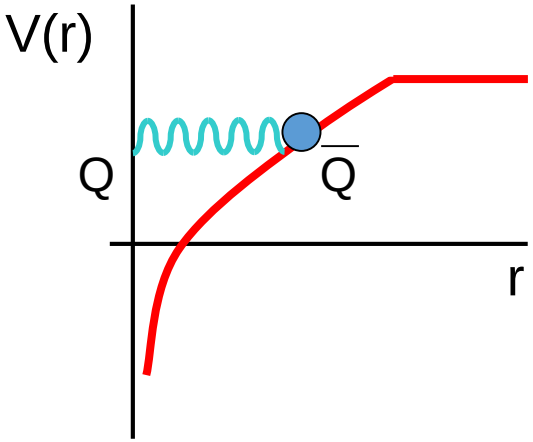
Tightly bound
Small in radius

Loosely bound
Small in radius

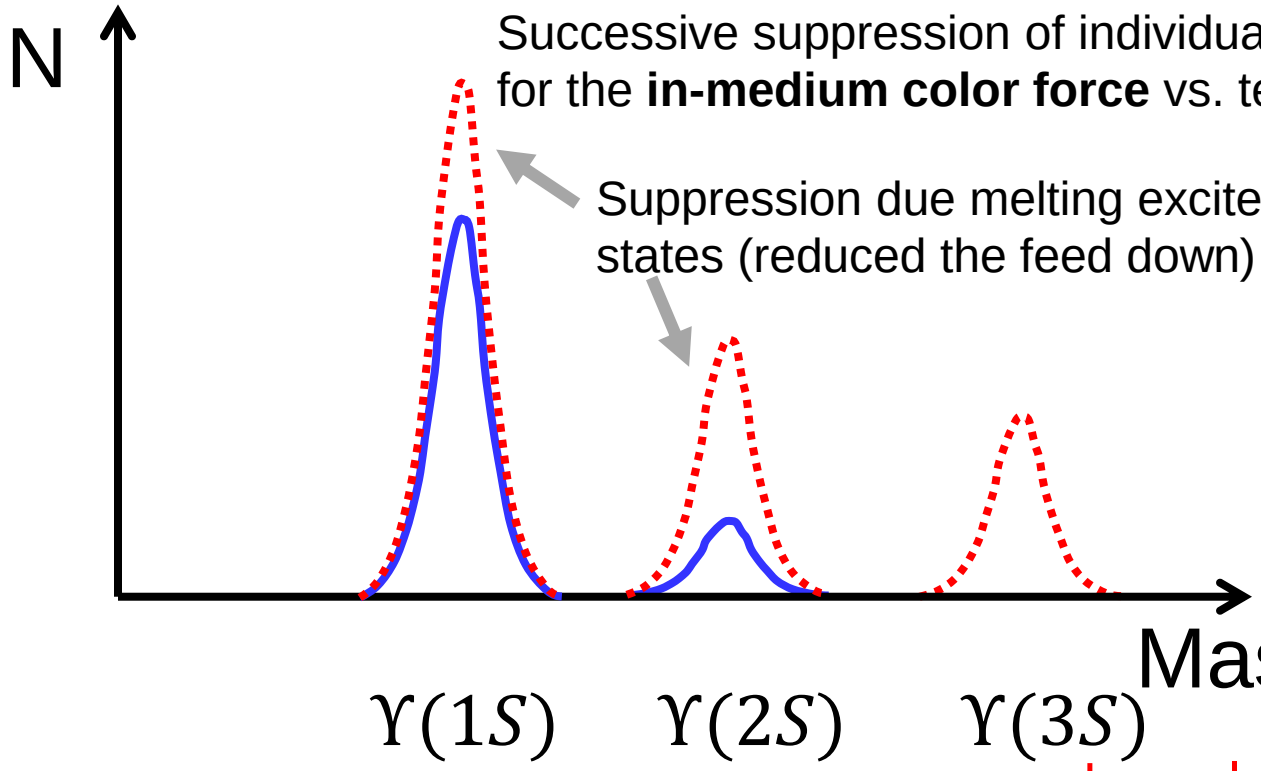


Debye Screening Length



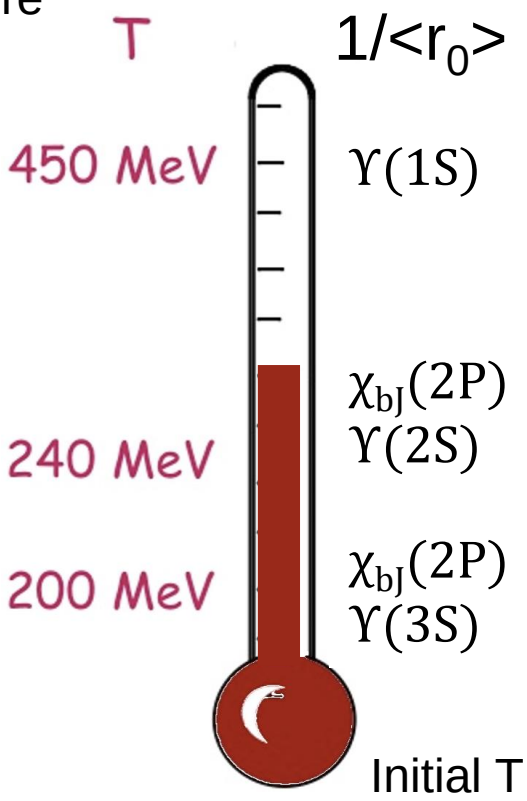


In QGP (AA collisions)

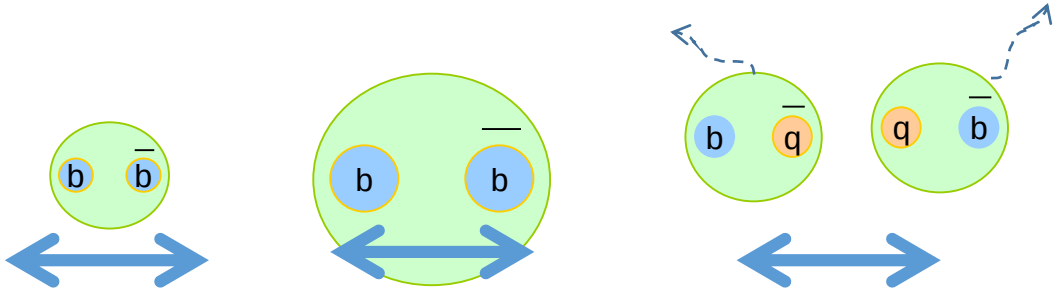


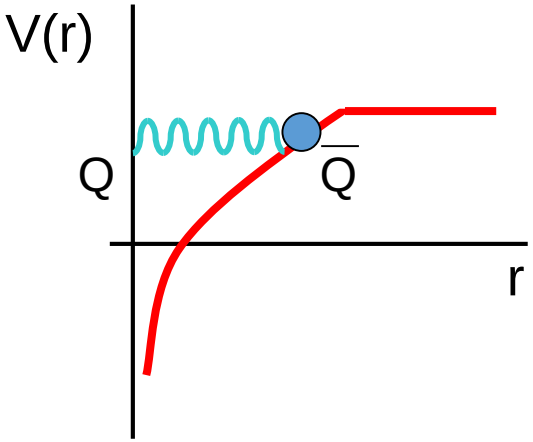
Tightly bound
Small in radius

Loosely bound
Small in radius

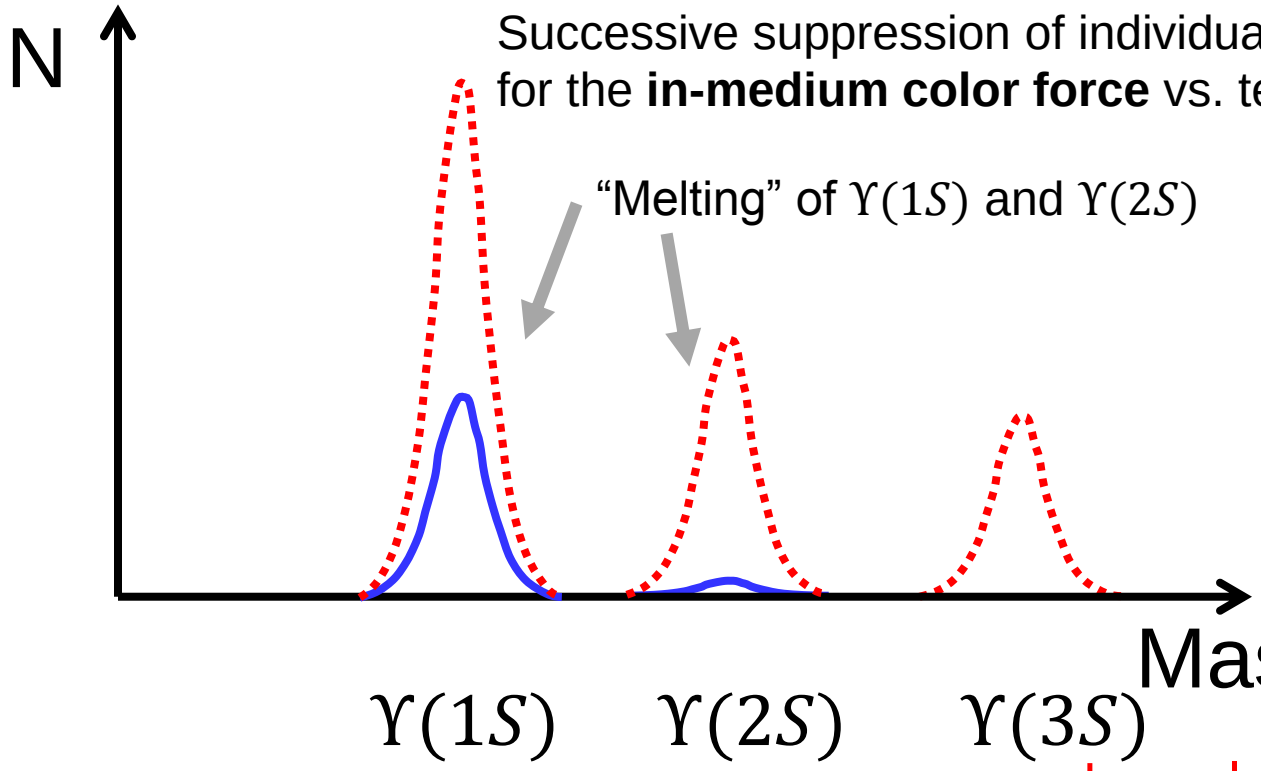


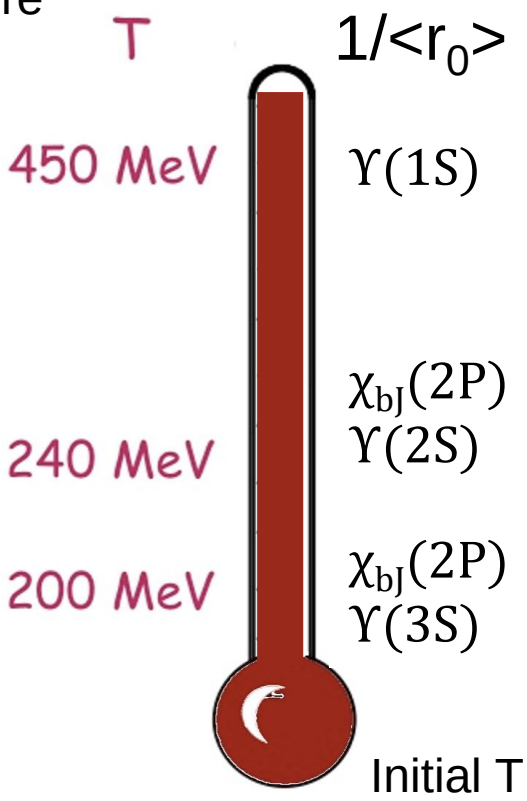
Debye Screening Length



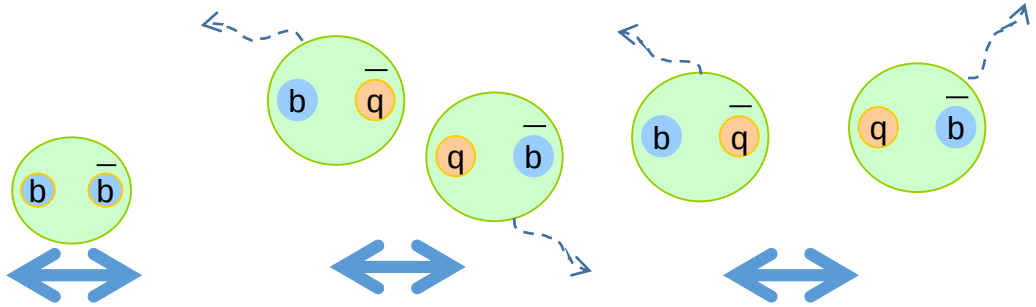


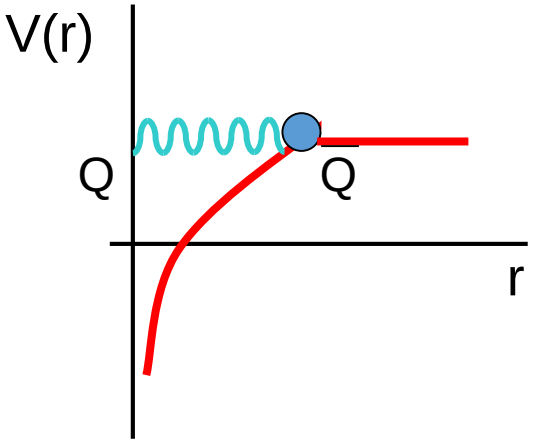
In QGP (AA collisions at LHC)



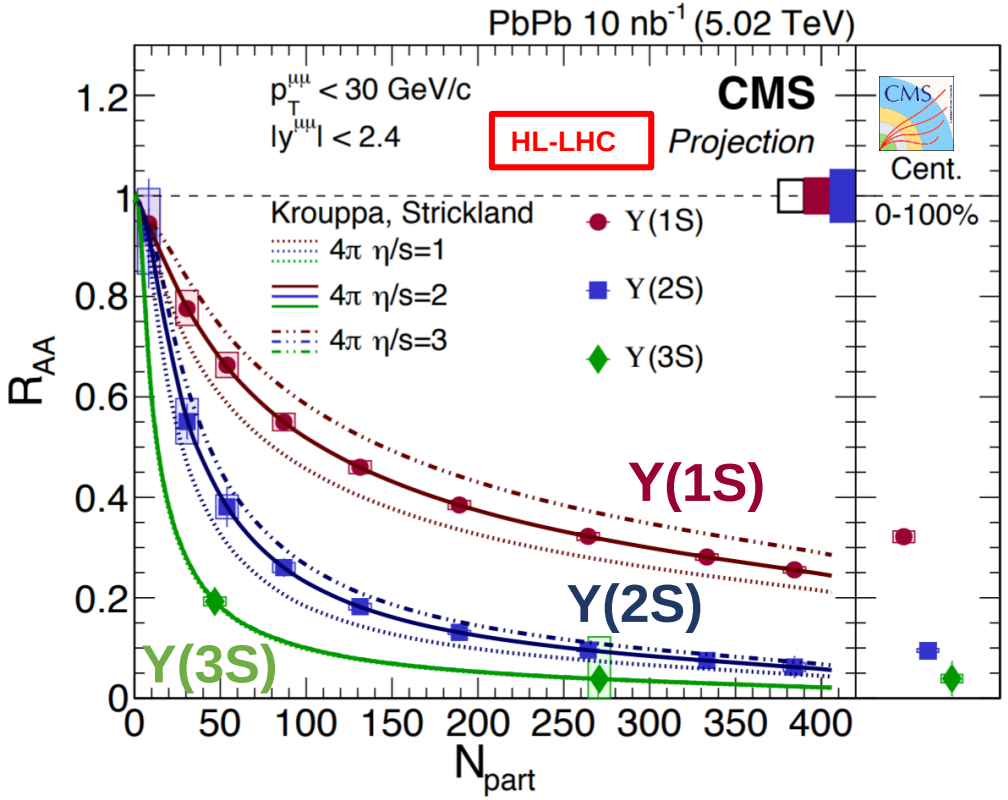


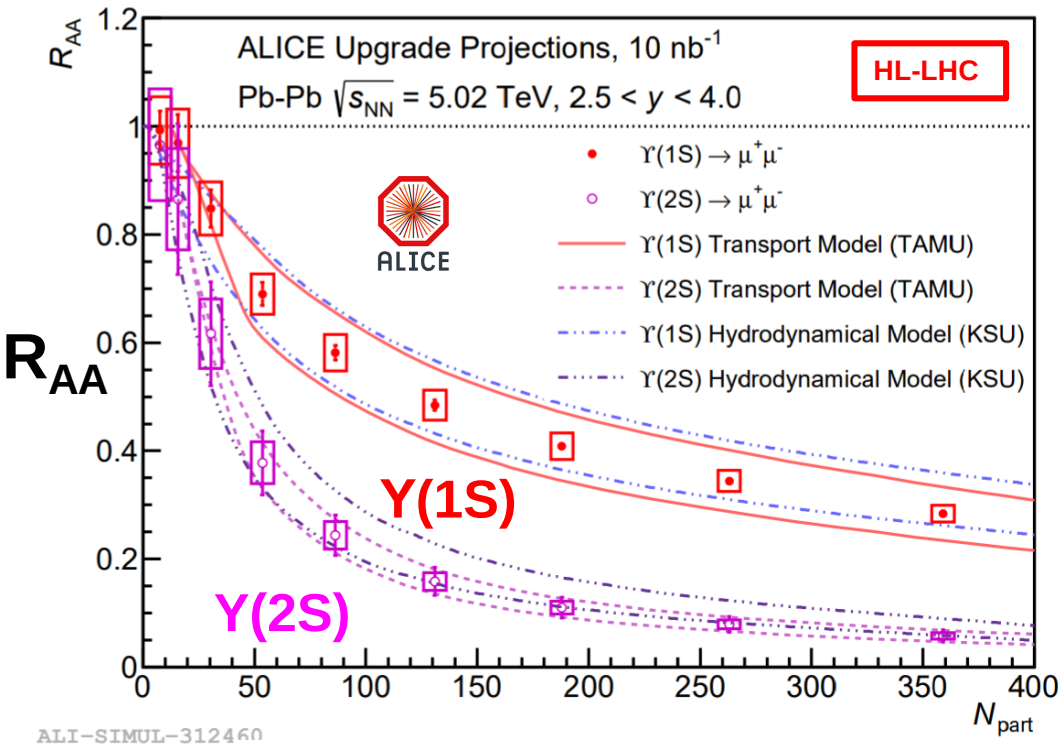
Debye Screening Length



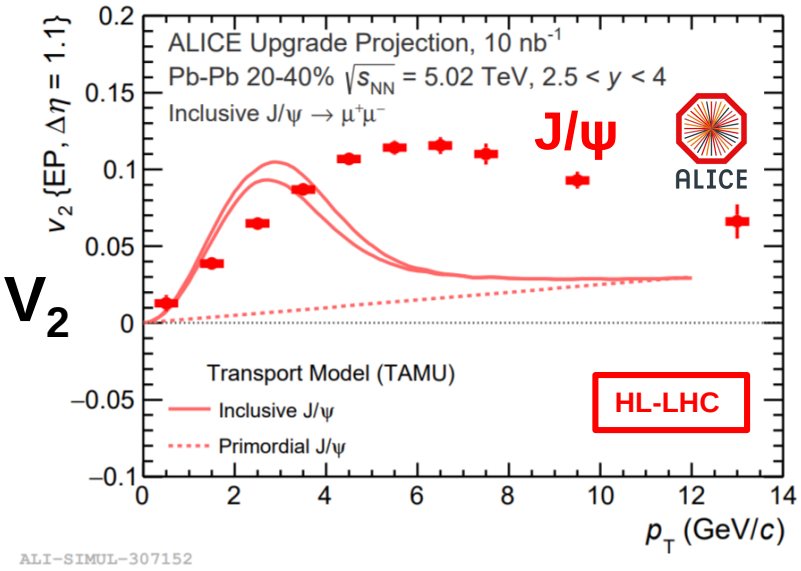


Quarkonia Production in HL-LHC





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



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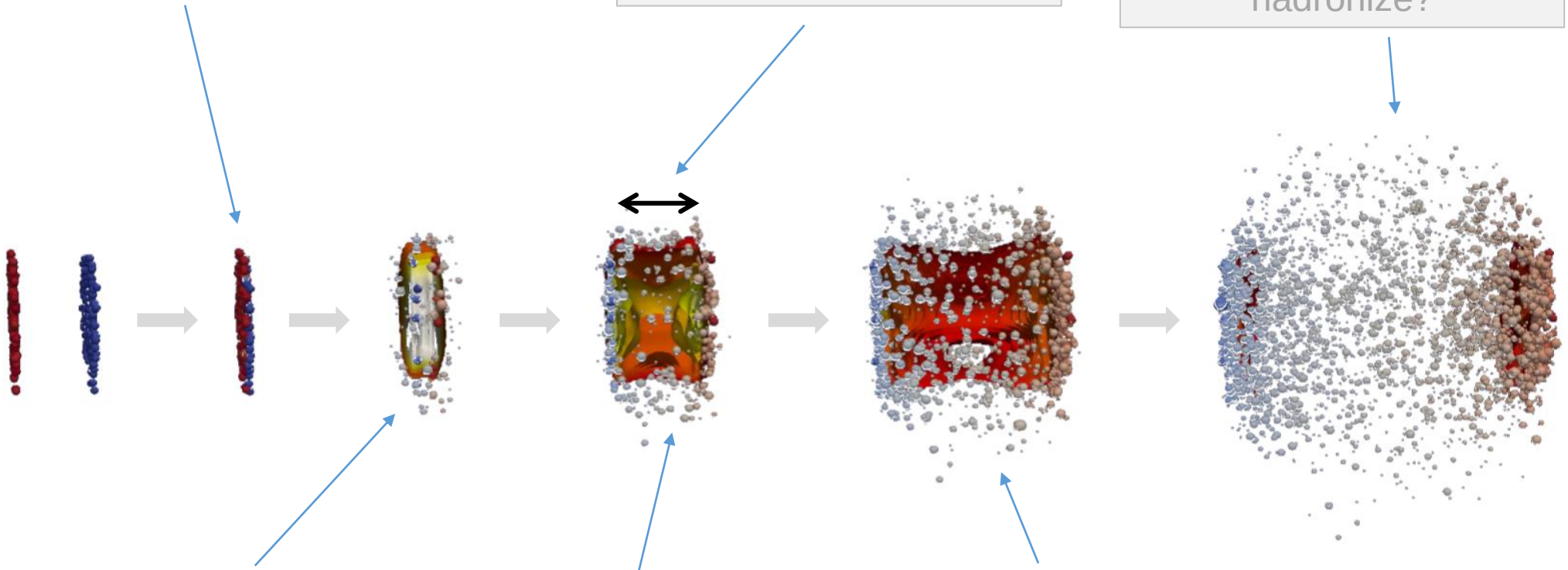


How does the system move toward hydrodynamization?

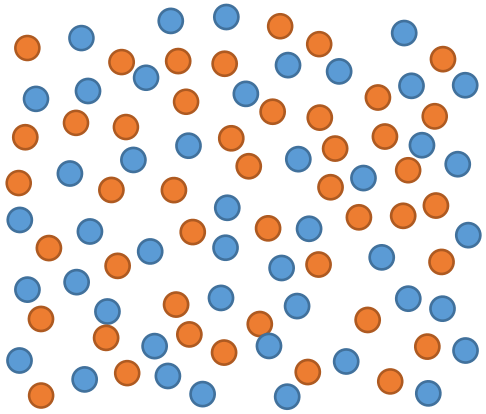
What is the temperature of the QGP?

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?

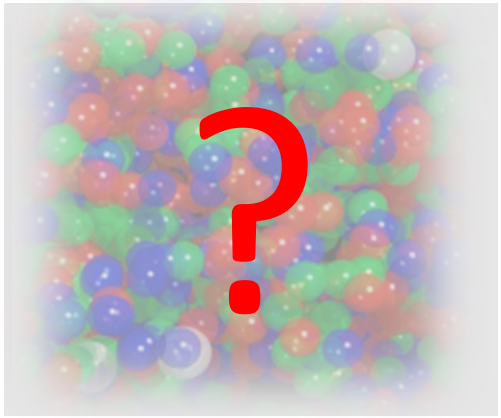
Visualization taken from Jonah E. Bernhard
arXiv:1804.06469

Quark Gluon Plasma Substructure

Quarks and Gluons



Thermal Mass Gluons?



QGP Fluid

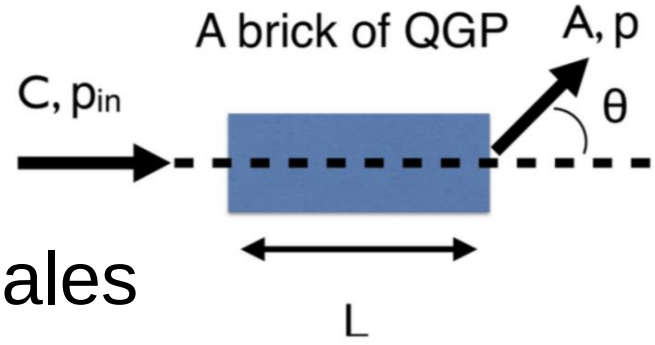
AdS/CFT low viscosity goo

Short Wavelength

What is the structure of QGP at intermediate length scale ?

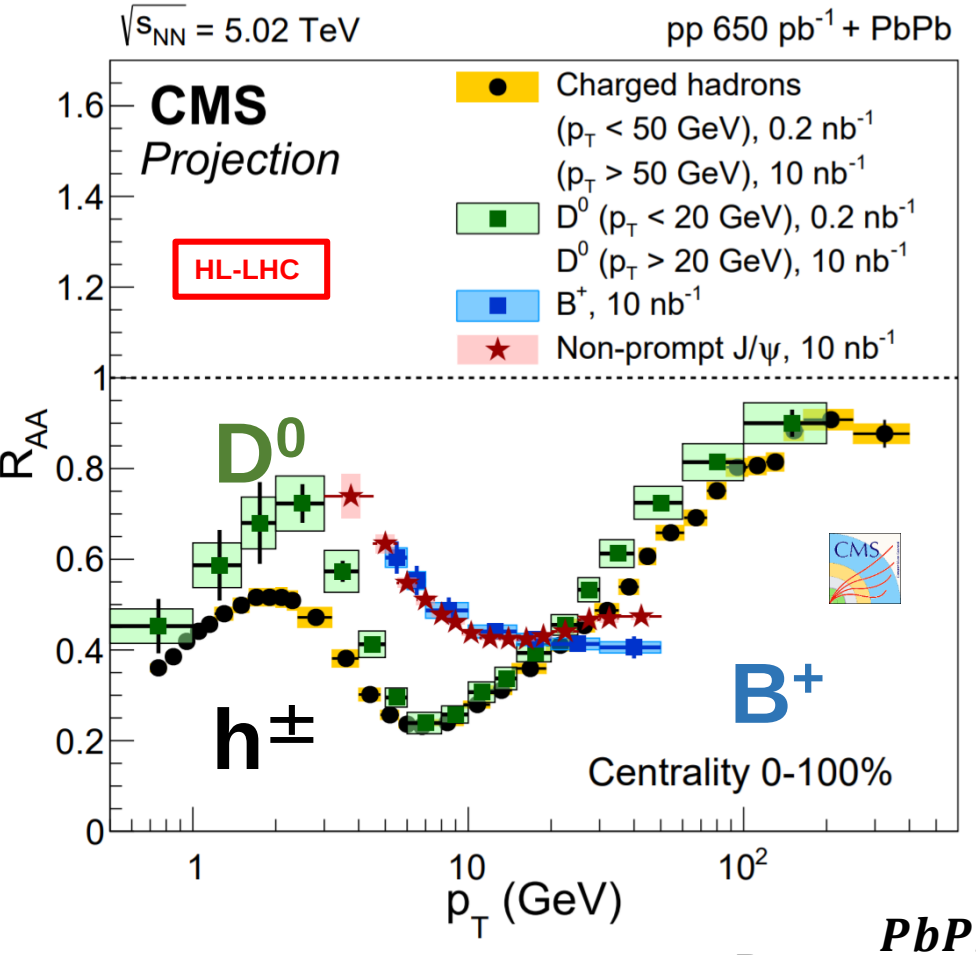
Long Wavelength

Use hard probes which reveal QGP structure at various length scales



Jet Quenching up to 1 TeV

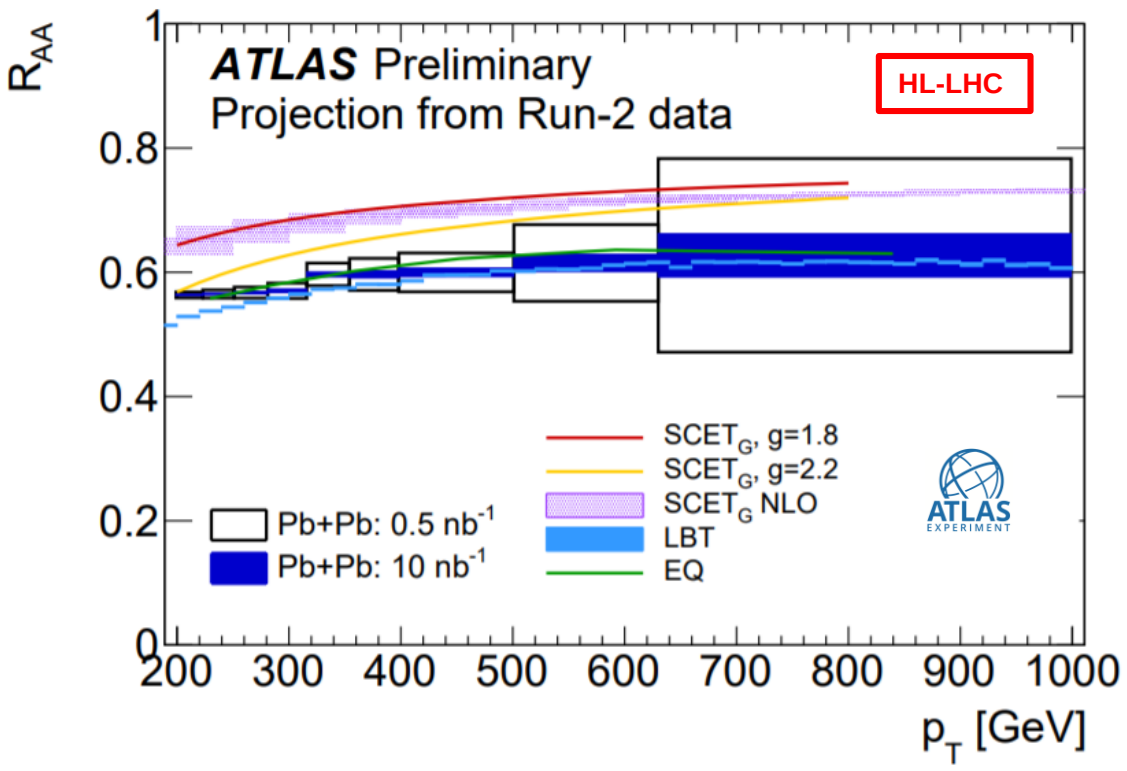
(Heavy Flavor)Hadron R_{AA}



$$R_{AA} \rightarrow \frac{PbPb}{pp}$$

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

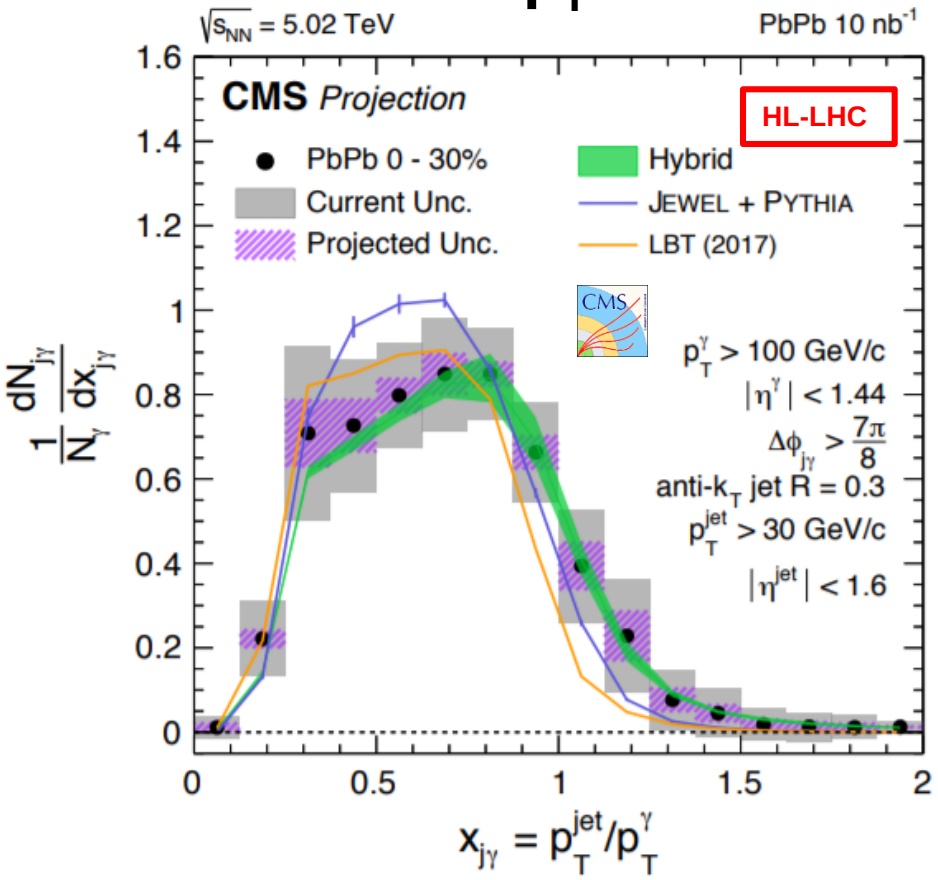
Jet R_{AA}



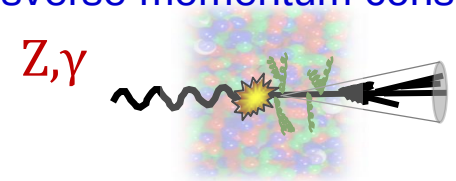
- High p_T reach of charged hadrons and jet R_{AA} up to **~ 1 TeV**
- The excitement is that the quenched energy will be significant compared to underlying event energy density!

Photon-Jet and Hadron-Jet Correlations

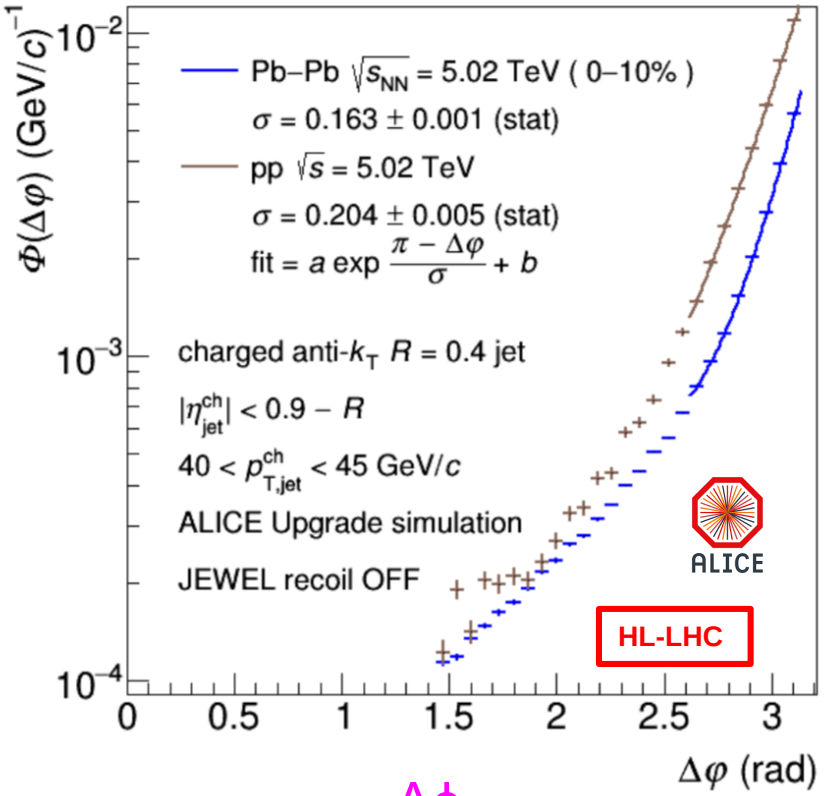
Photon-Jet p_T Ratio

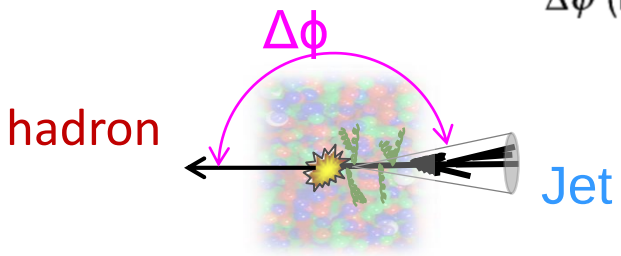


Transverse momentum conservation



Hadron-Jet Correlation



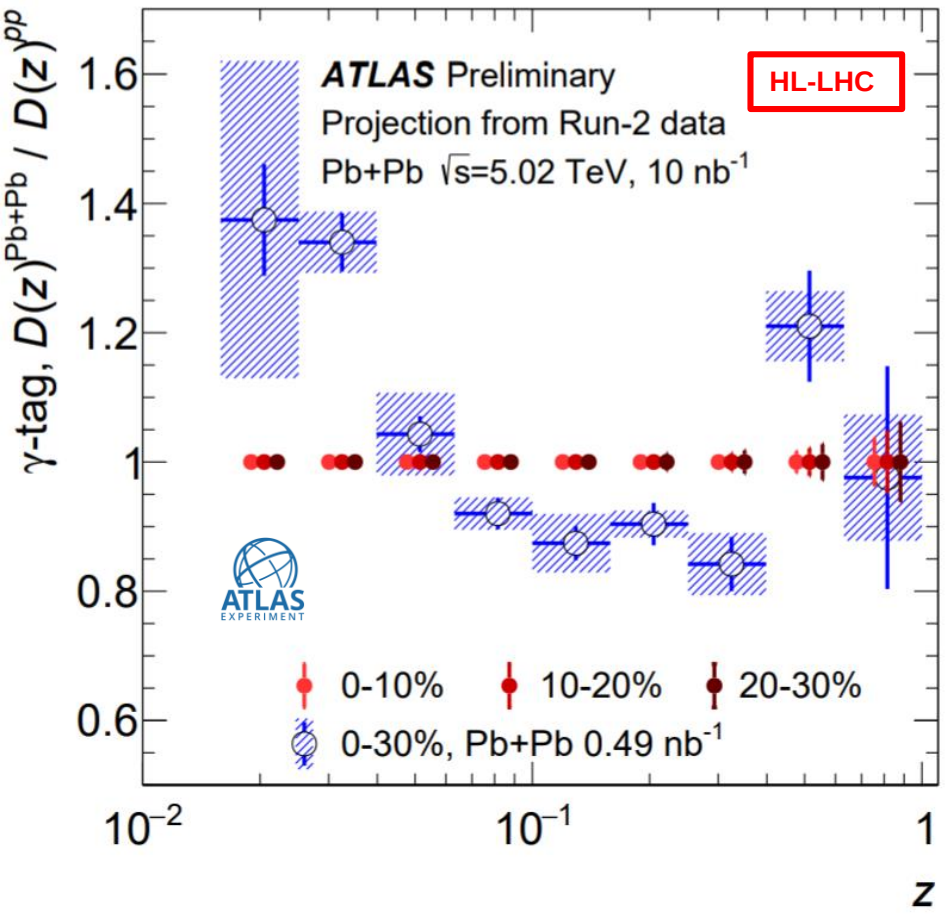


- Quenching reduces boson-jets p_T ratio
- High precision "**absolute energy loss**" measurement at HL-LHC

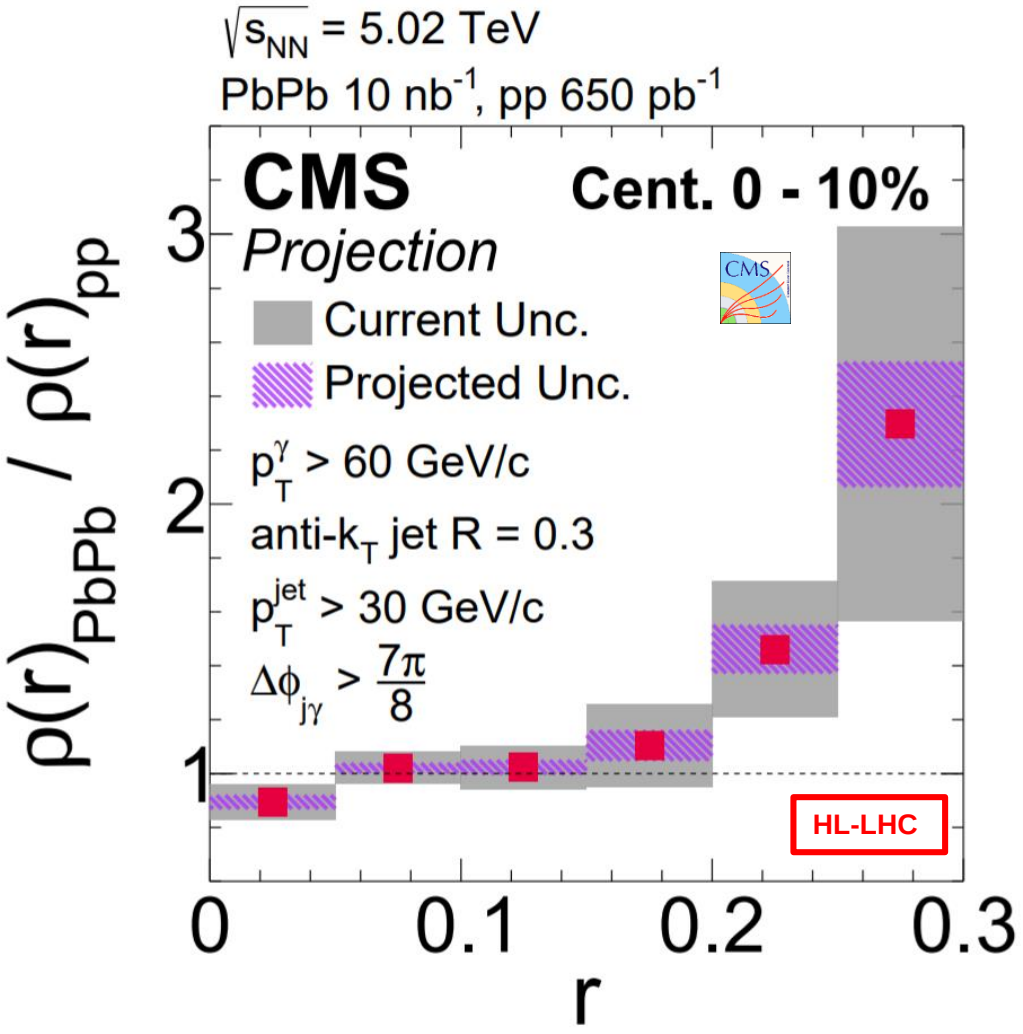
- Hadron-Jet Angular Correlation: search for **large angle scattering** study of QGP substructure

Photon-Tagged Jet Structure

Modification of Jet Fragmentation Function

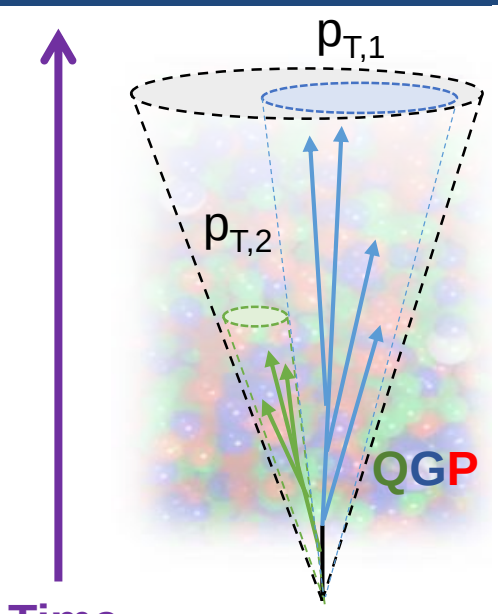


Modification of Jet Shape

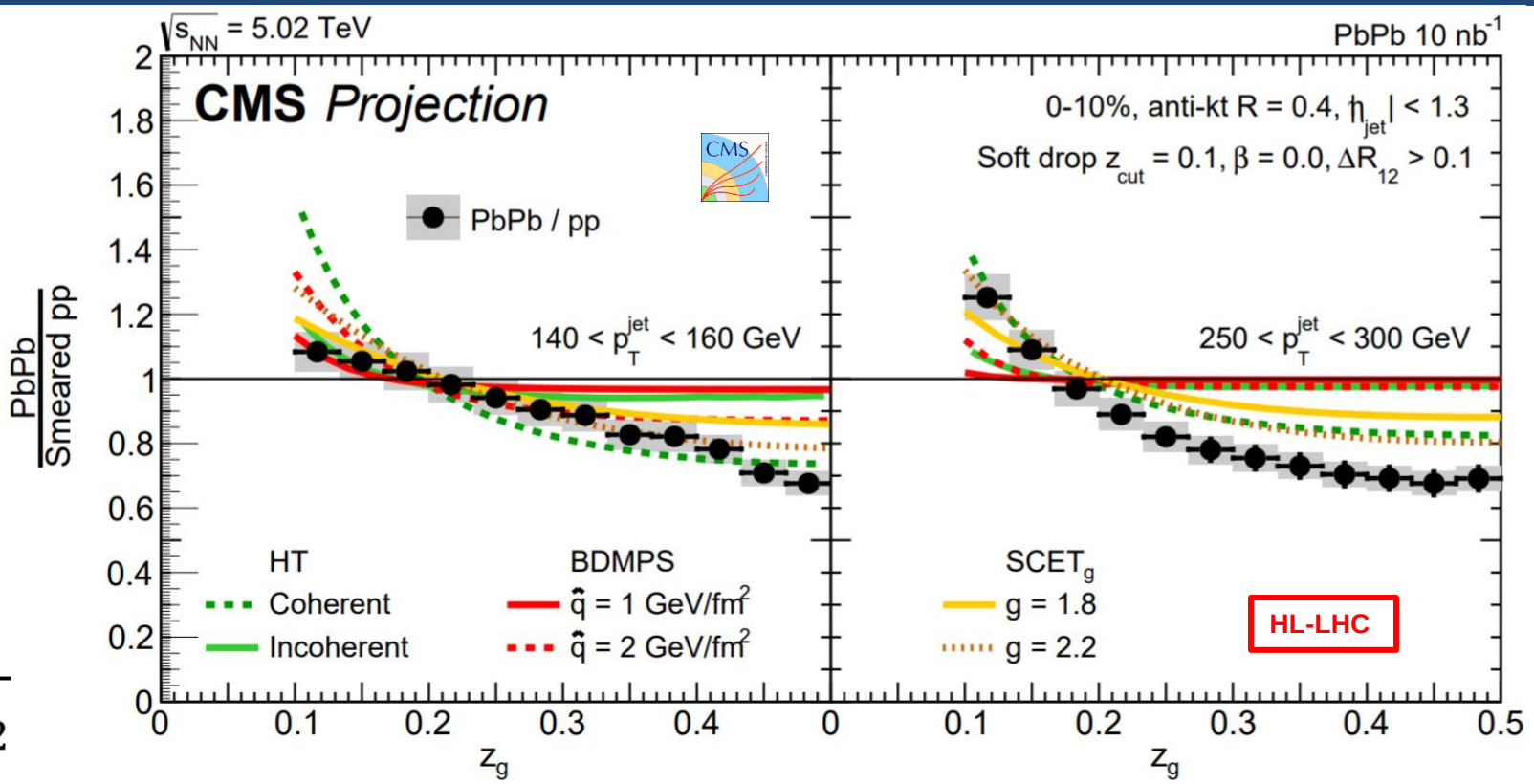


- High precision measurement of photon-tagged jet substructure
- Study of medium response and “jet thermalization”

Subjet Momentum Sharing



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



- Parton energy loss in QGP: **space-time evolution of the parton shower matters** since QGP is cooling down vs. time
- 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"**

Summary

- Significant progress on all the WG5 chapters, exploit the high statistics pp, pPb and PbPb data in Run 3+4
  - New constraints on the nPDF
  - Understand initial energy density profile and the underlying dynamics of hydrodynamization
  - Search for critical behavior with conserved charge fluctuation and improved sensitivity to QCD EoS
  - Precise determination of medium properties such as temperature, viscosity and transport coefficients
  - Probe the relevant the degrees of freedom / microscopic structure of QGP at different length scales

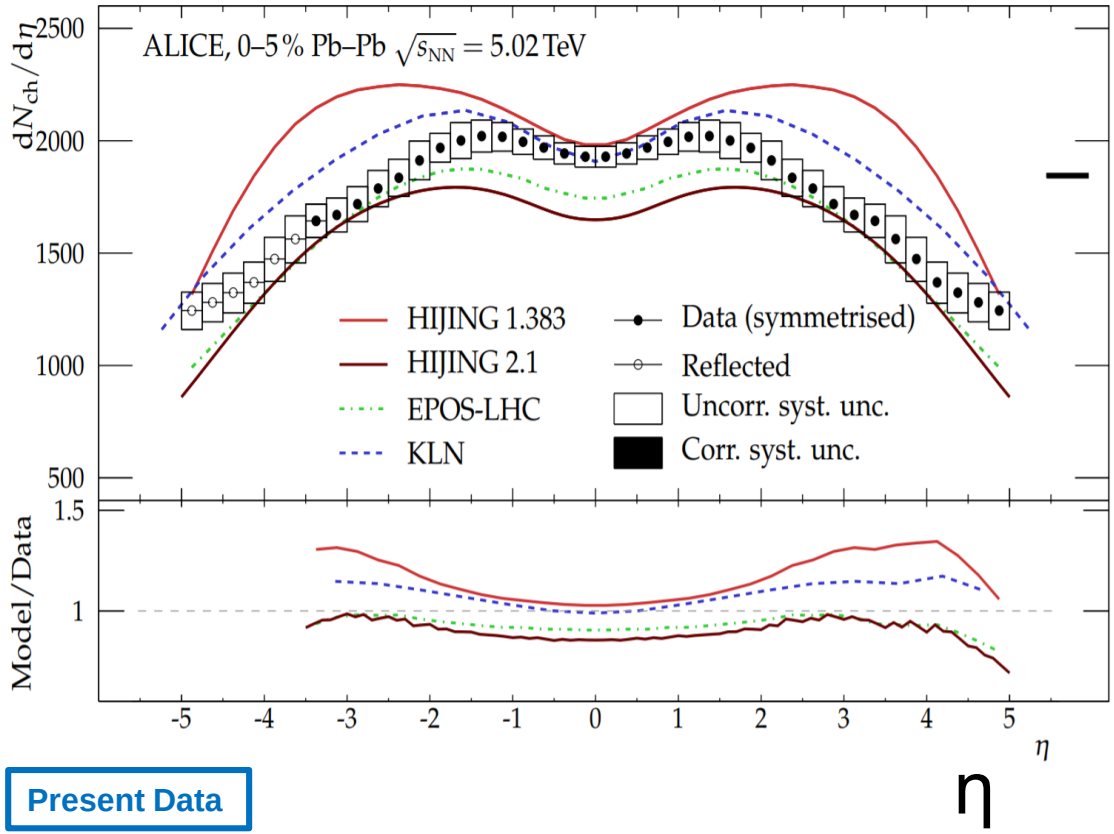
- Provide stress tests to the heavy ion standard model as a firm foundation to the new discovery in smaller systems

- Many thanks to all the contributors to the WG5 chapters!

- Backup slides

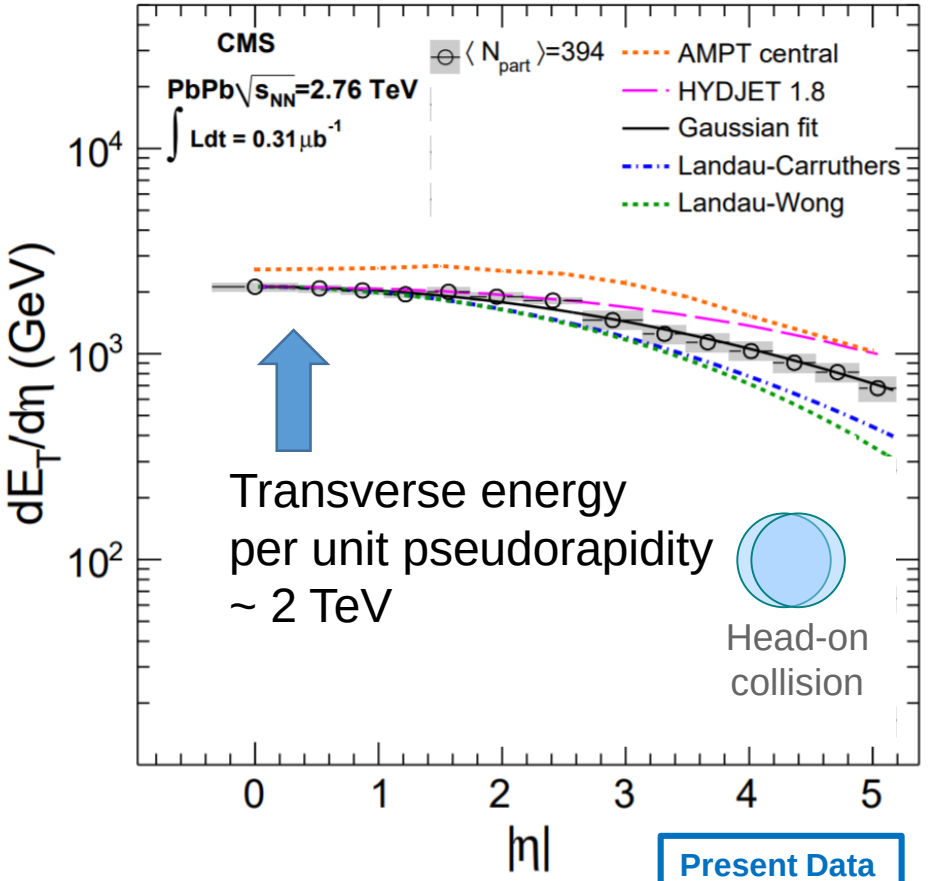
Global Event Properties

Charged Particle Pseudorapidity Distribution



Present Data

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