QGP Physics:

How could heavy ion physics at the energy frontier profit from new electron collider measurements (experiment perspective)

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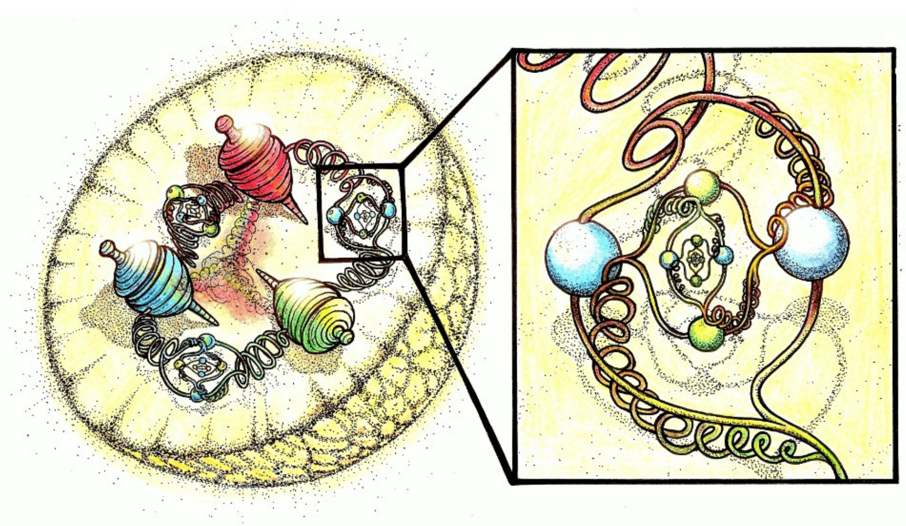
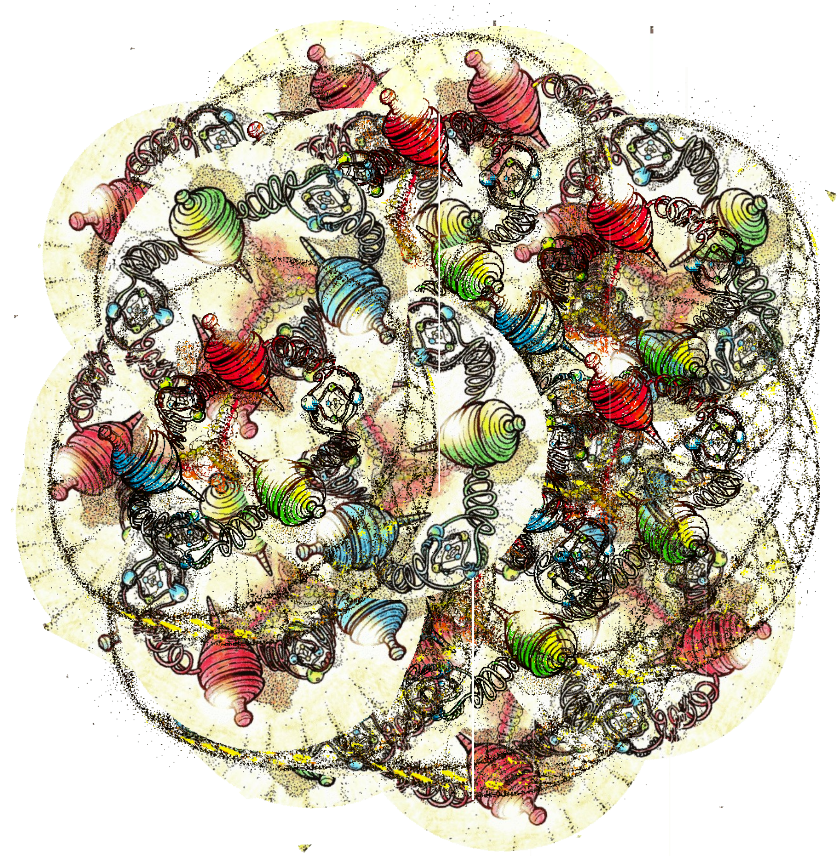
IGDORE and IMT-Atlantique

Electrons for the LHC Workshop
LAL Orsay, France
June 27 2018

QCD is expected to describe building blocks of visible matter (nucleons) and their binding in nuclei

Strongly interacting non-abelian gauge theory which has implications far from being fully understood





QCD studies lead to discovery

40 years of continuous discovery
40 years of powerful R&D to help us elucidate it.

Heavy Ion Collisions and the discovery of the formation of a Quark Gluon Plasma:

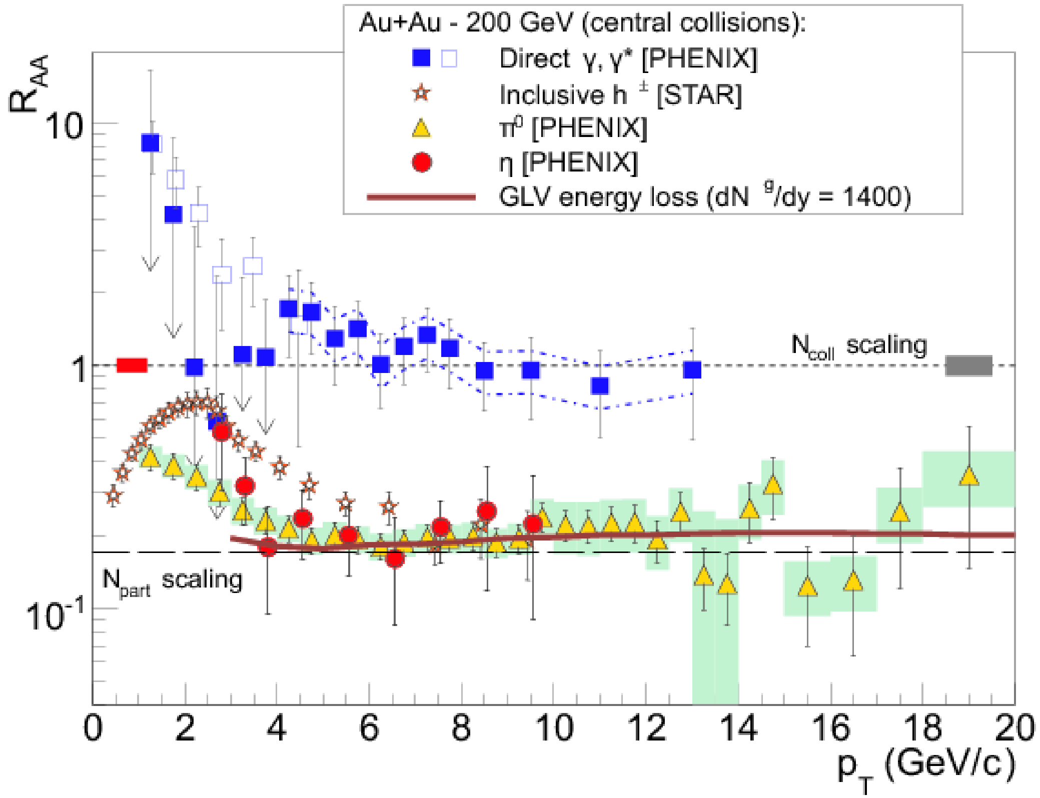
Jet production and quenching

-Viscosity

-Transport properties

-Collectivity

-QGP onset



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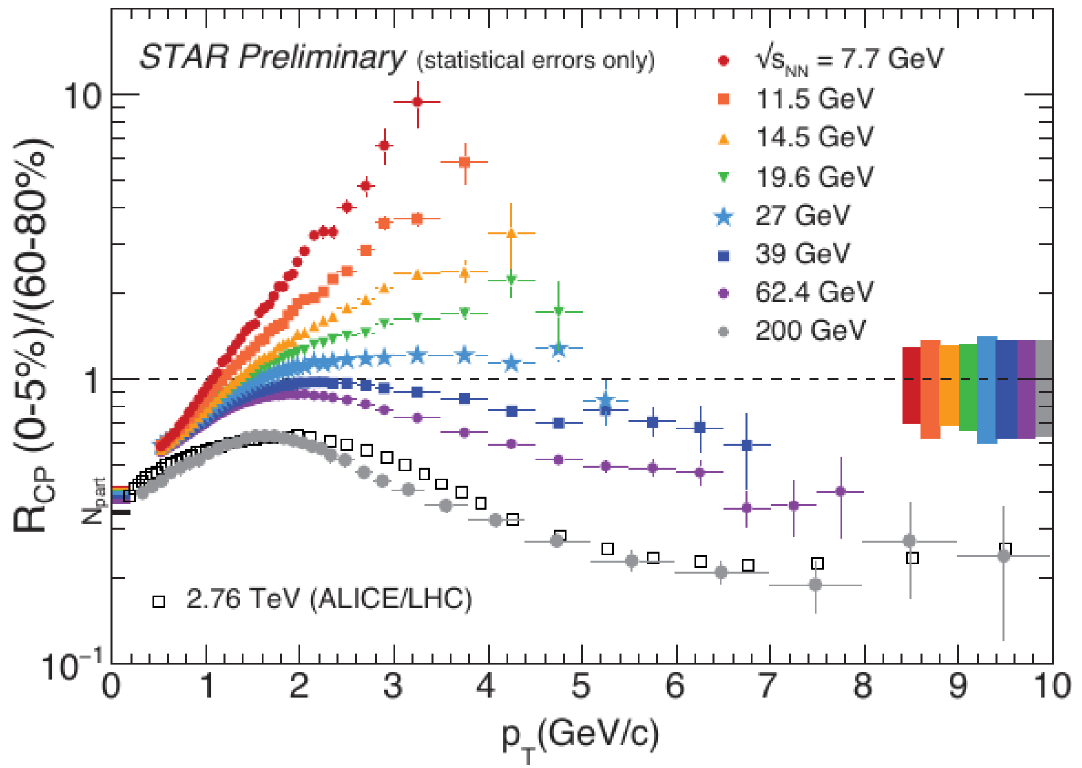
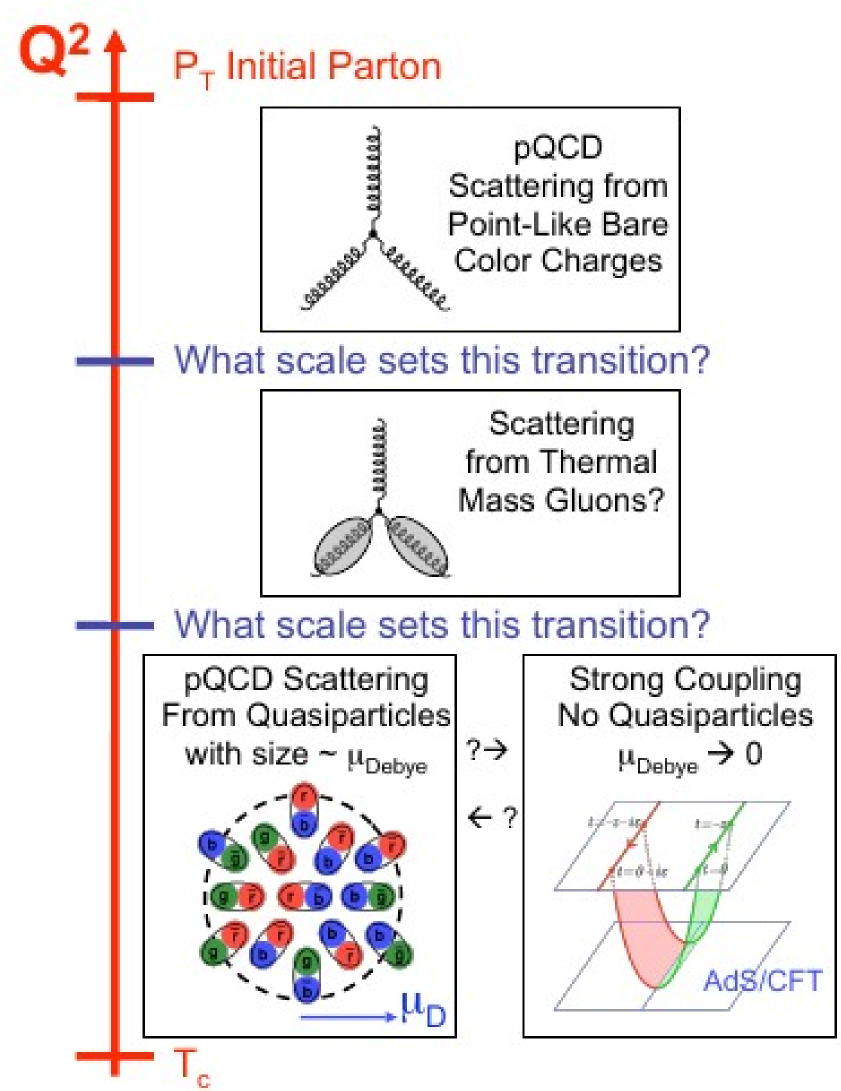


Quark and gluon as quasi particles?



-How do we transition from point like to non-point like physics. How do arrive at a perfect liquid?

-How do color charged-quarks gluons and colorless jets interact with a nuclear medium

-How do the confined hadronic states emerge from these quarks and gluons.

Many open questions we need to address

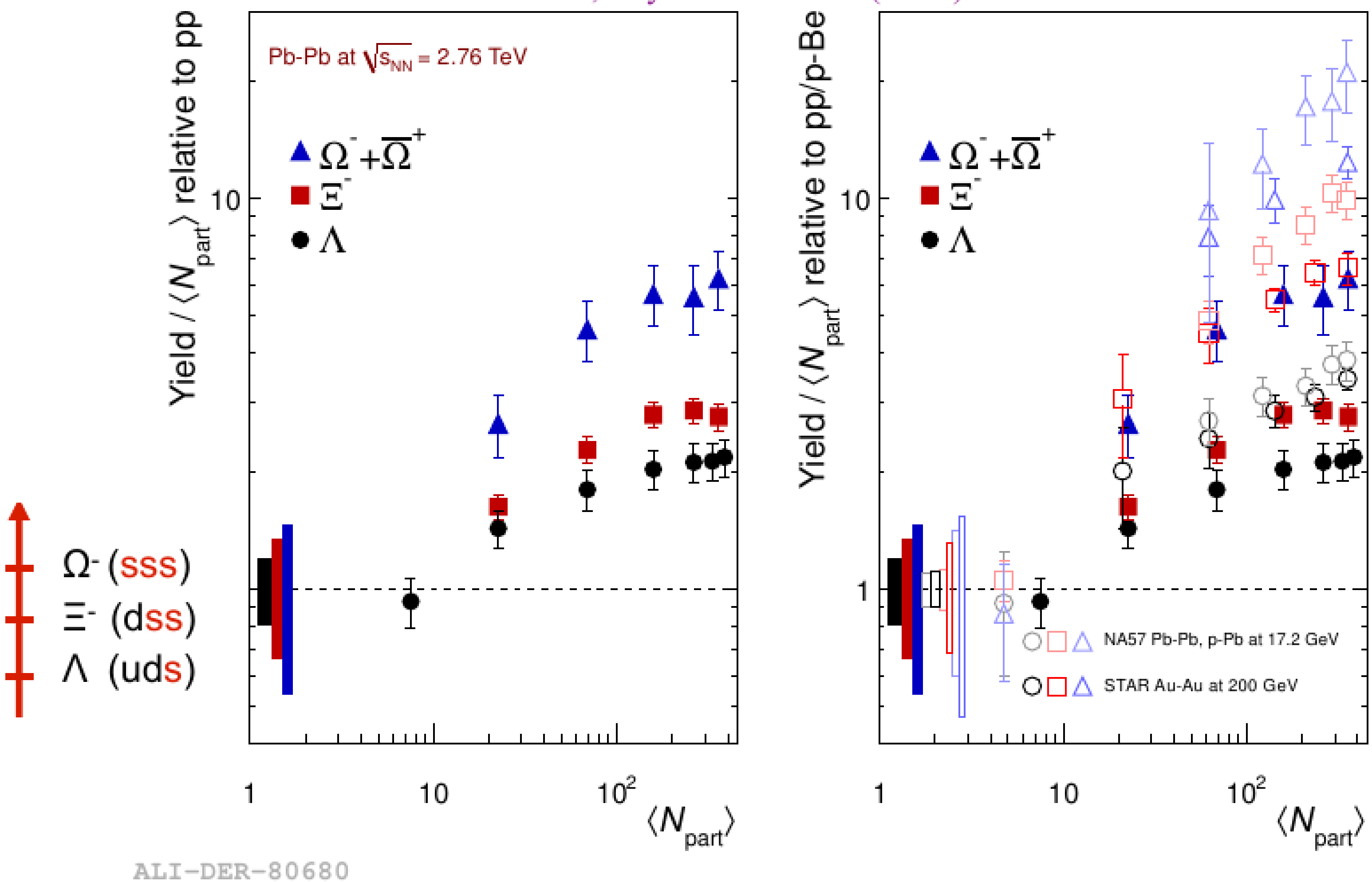
https://arxiv.org/abs/1501.06197 and https://arxiv.org/abs/0903.4379

1. Hadronization, particle spectra and abundances

QGP Onset: Strangeness enhancement

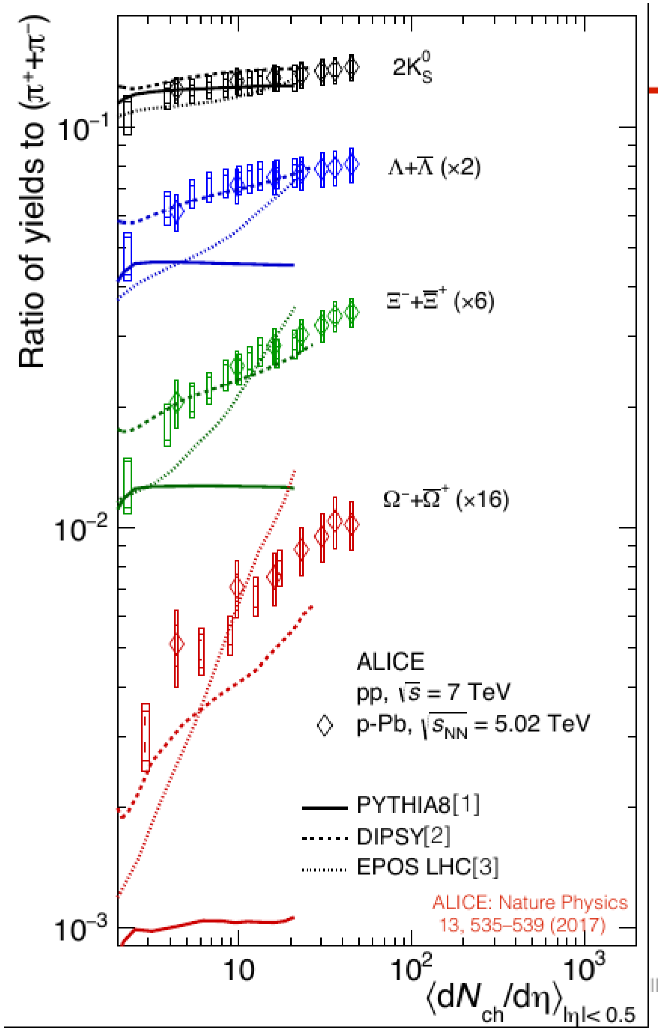
Among the first proposed signatures of the QGP PRL48(1982)1066
Observed in A-A at SPS, RHIC, LHC

ALICE, Phys. Lett. B 728 (2014) 216



QGP Onset: Strangeness enhancement

Enhancement of strange particles with respect to non-strange yield **is also observed** for high multiplicity **pp** and **p-Pb** collisions



-Smooth transition connecting small and larger systems.

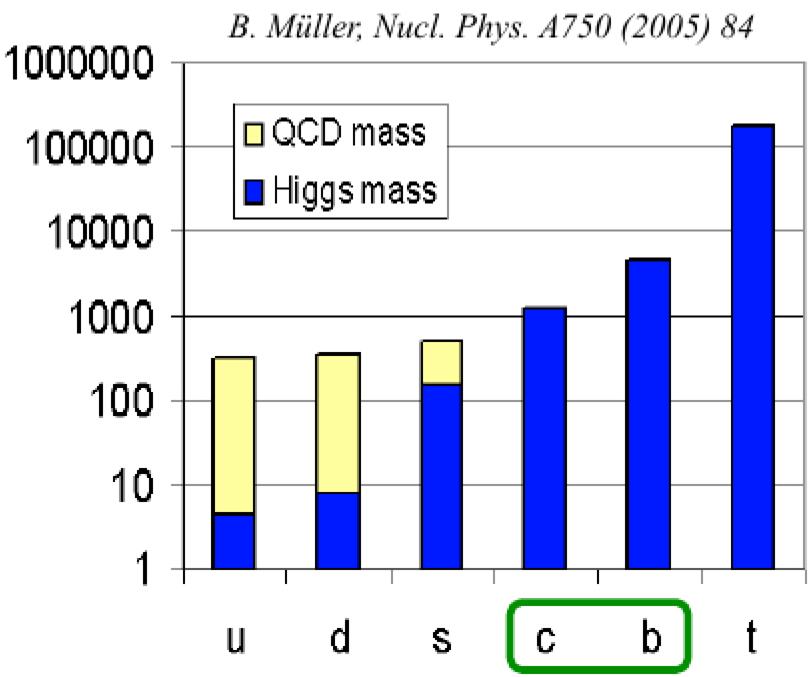
-These measurements may give us insights about the underlying dynamics. Is pp the correct reference for AA?

-eA could provide a more robust reference.

-More experimental insight is needed to interpret the final state strangeness we are observing in large and small systems

https://arxiv.org/pdf/1305.0609
https://cds.cern.ch/record/2302756

Heavy flavor vs multiplicity: quarkonia



The contribution of the QCD vacuum condensates to the masses for the three light quark flavours u, d, s considerably exceed the mass believed to be generated by the Higgs field.

Blue: masses generated by electroweak symmetry breaking (current quark mass)

Yellow: additional masses of the light quark flavors generated by spontaneous chiral symmetry breaking in QCD (constituent quark masses)

- Charm and beauty quark masses are not affected by QCD vacuum (ideal probes to study QGP)
- Charm and beauty quarks provide hard scale for QCD calculations
- **Charmonium production proceeds from hard initial processes and no strong correlations with event activity are expected**

Heavy flavor vs multiplicity: quarkonia

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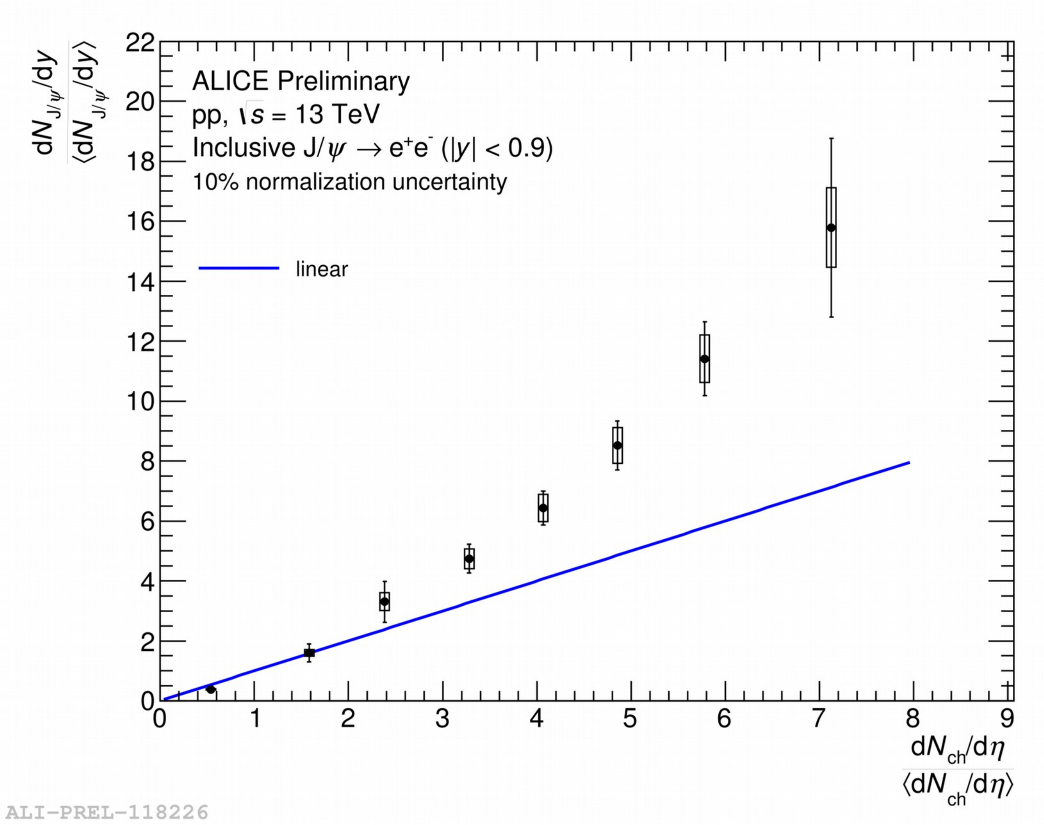

pp collisions

Linear: MPI?

Initial stages 2017 Presentation

Heavy flavor vs multiplicity: quarkonia

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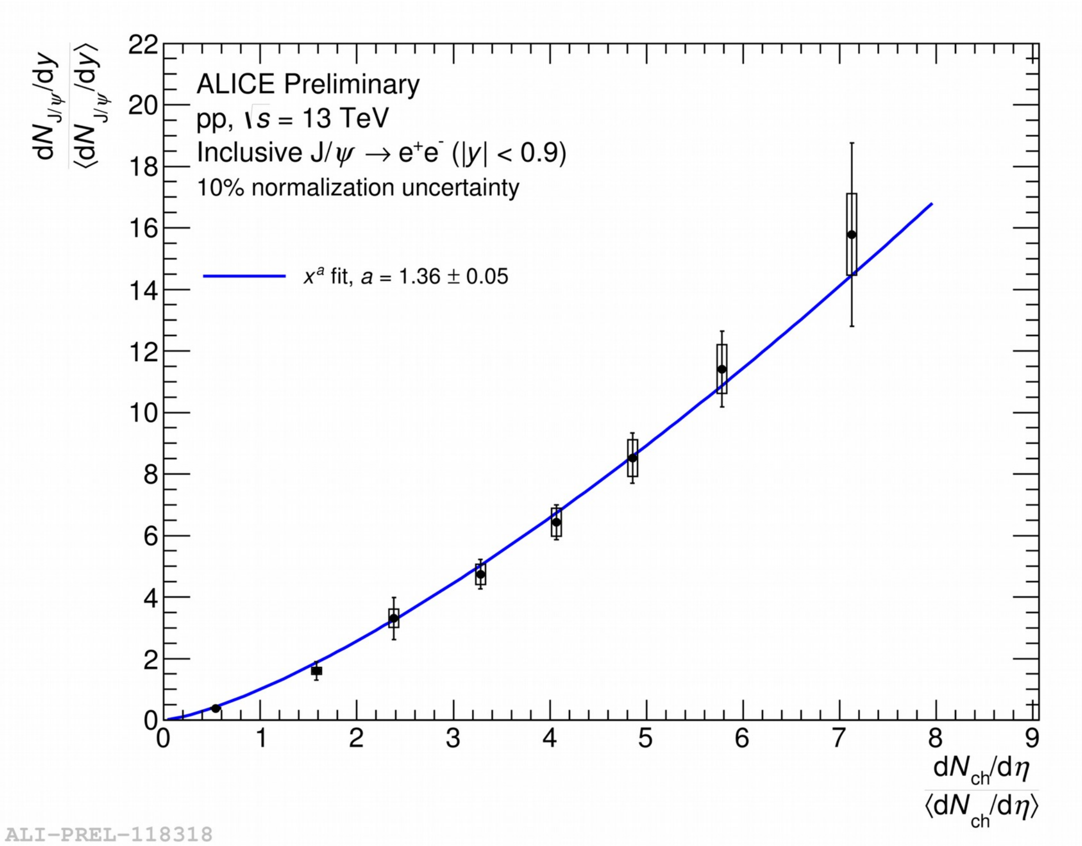


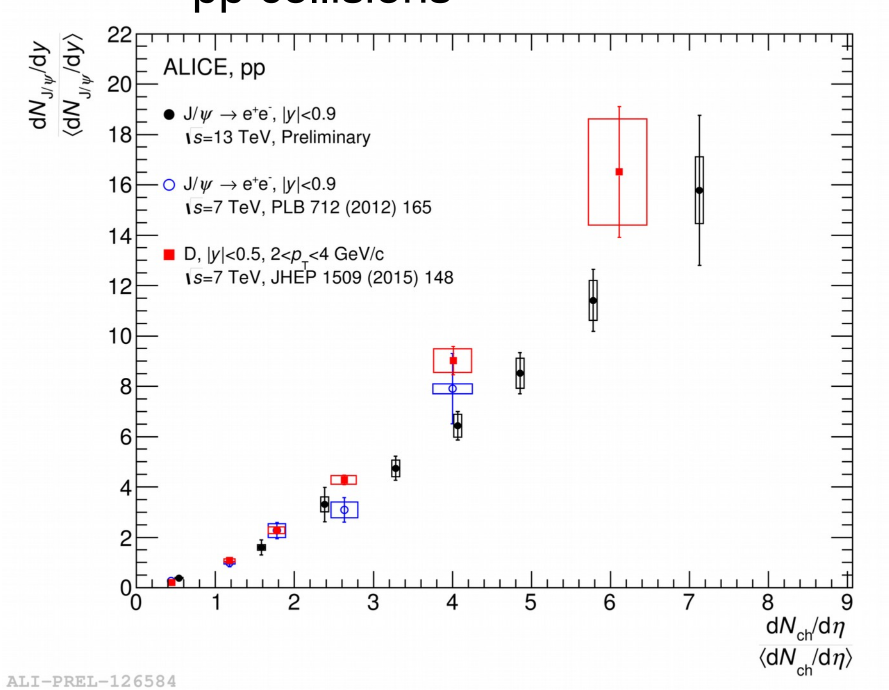
pp collisions

Increase is not linear: highlights importance of other physical processes.

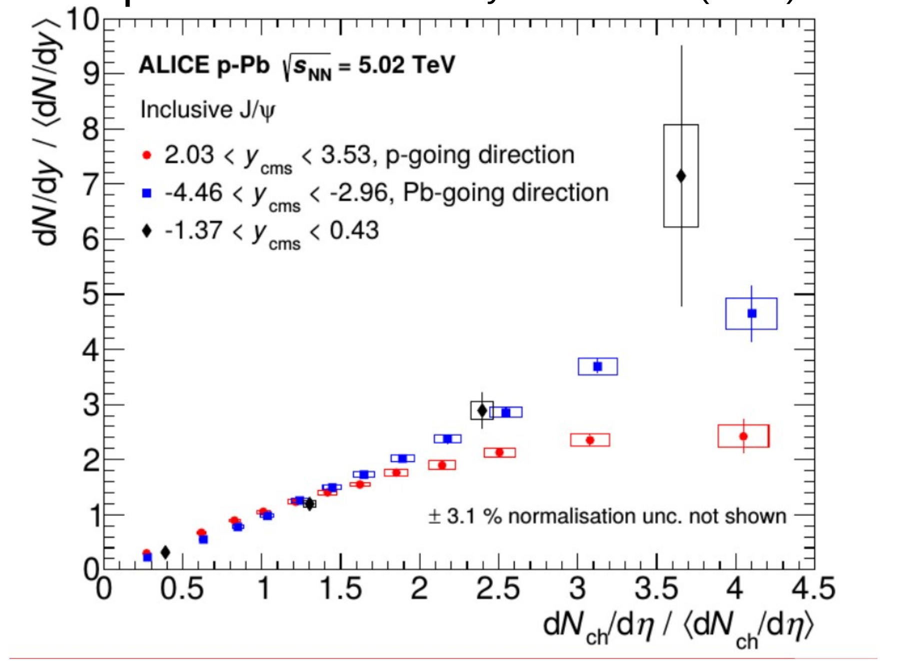
Initial stages 2017 Presentation

Heavy flavor vs multiplicity

pp collisions



p-Pb collisions Phys.Lett. B776 (2018) 91-104



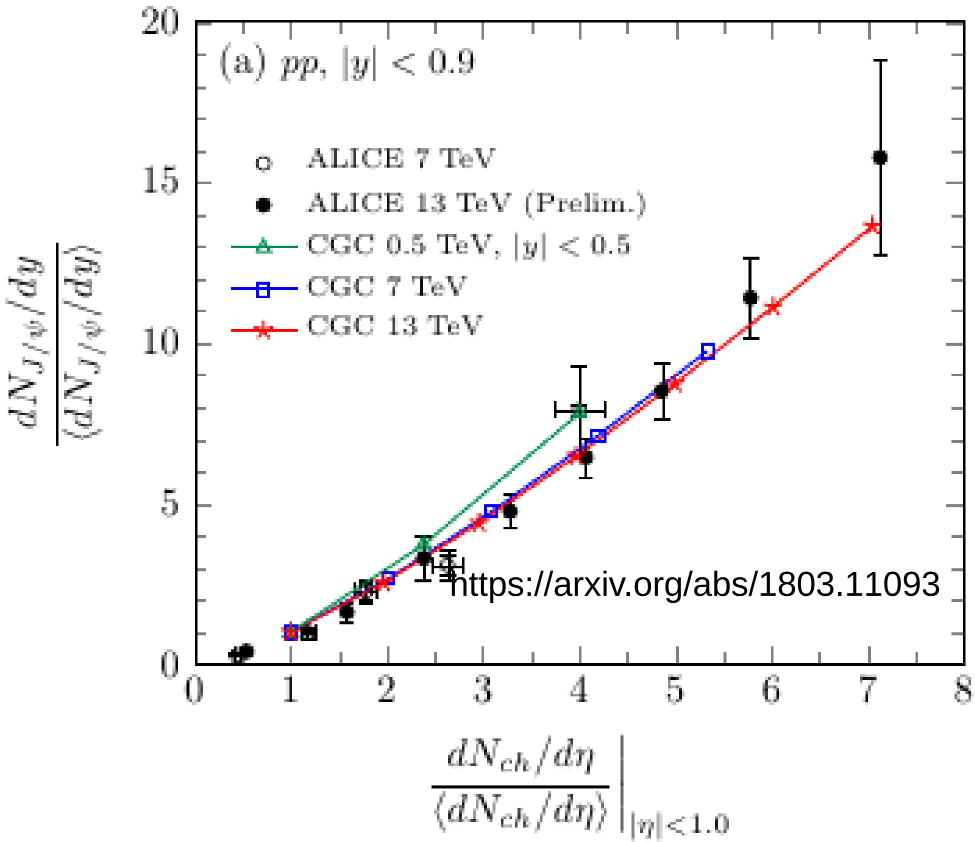
-Similar effects observed for D's
-Hadronization doesn't seem
to play a role

Mid-and backward rapidity (Pb-going):
-Qualitatively similar behavior as in pp collisions

Forward rapidity (p-going): Saturation at high multiplicities?
Bjorken-x range in the domain of shadowing / saturation?

A novel regime of QCD?

Large parton densities
What happens to the gluon density in nuclei? Does it saturate at high energy?
Are we observing a hint of universal properties in all nuclei? (small and large).



-With the LHeC we can access a much lower *x*-region (10^{-6})
-With the EIC we have enhanced color density with nuclear targets: access the non-linear evolution in the high gluon density region via nuclear diffraction.

2. Collective Expansion

Hydrodynamical flow

Radial Flow:
Affects shape of low p_T particle spectra

Elliptic Flow:
Sensitive to initial geometry
Requires early thermalization of the medium

Baryon to meson ratio

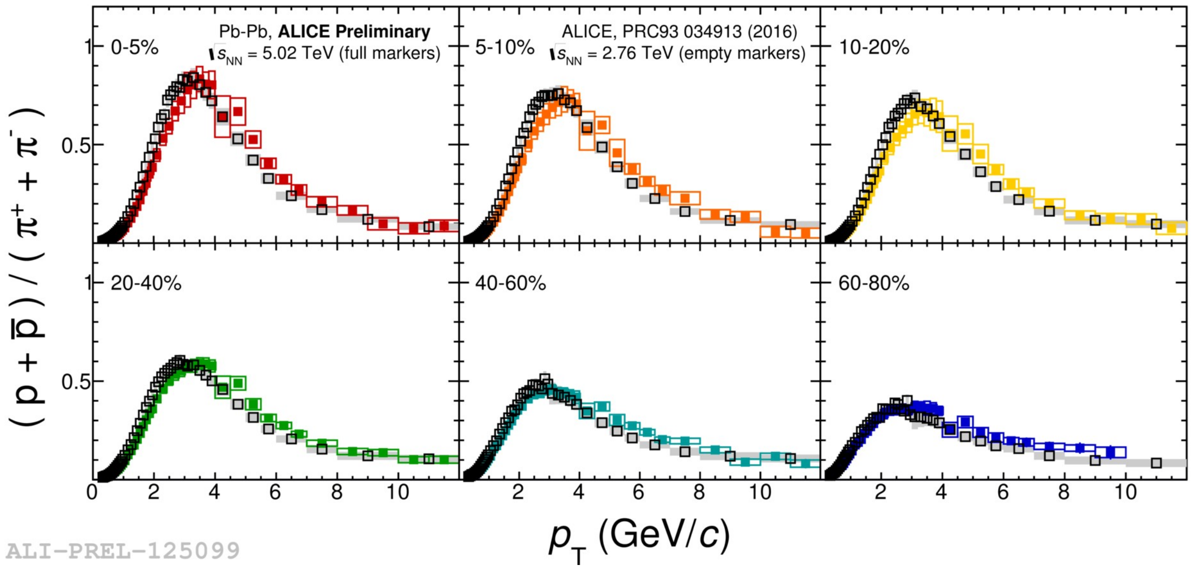
-Pb-Pb no significant energy dependence

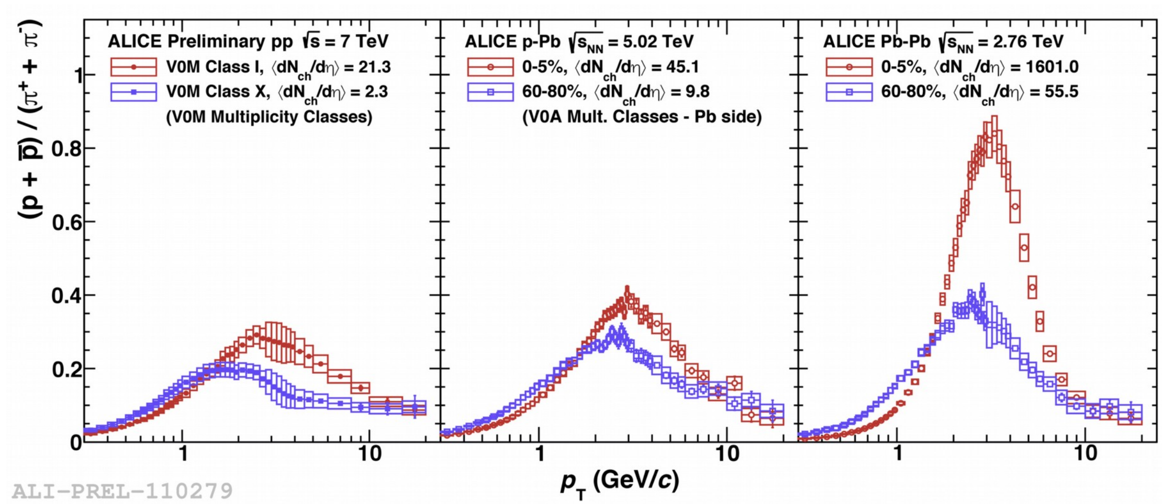
- Radial flow pushes protons to intermediate p_T and depletes low p_T

- Stronger radial flow in central Pb–Pb collisions

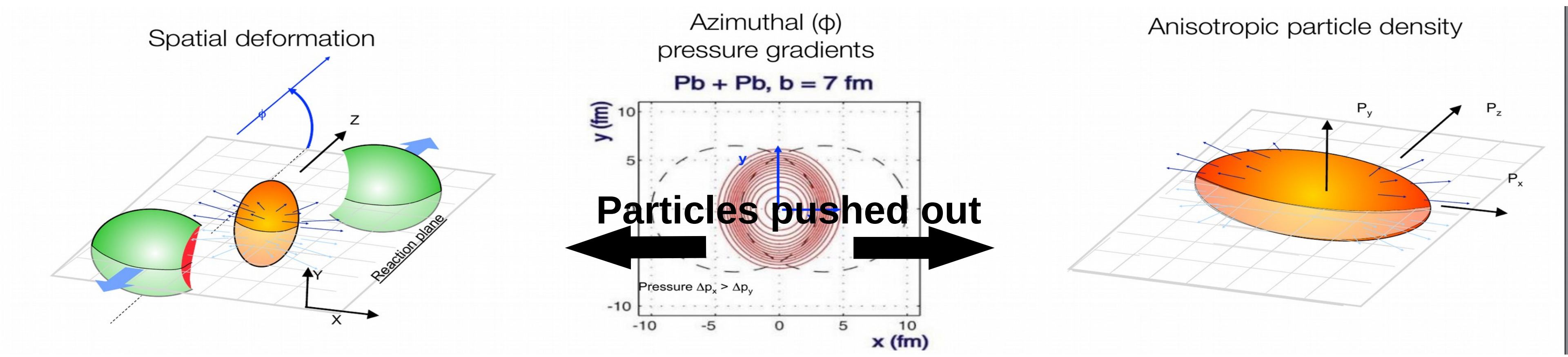
-Low to mid-p_T described by hydrodynamic models

- Similar effects observed in high-multiplicity pp and p–Pb collisions



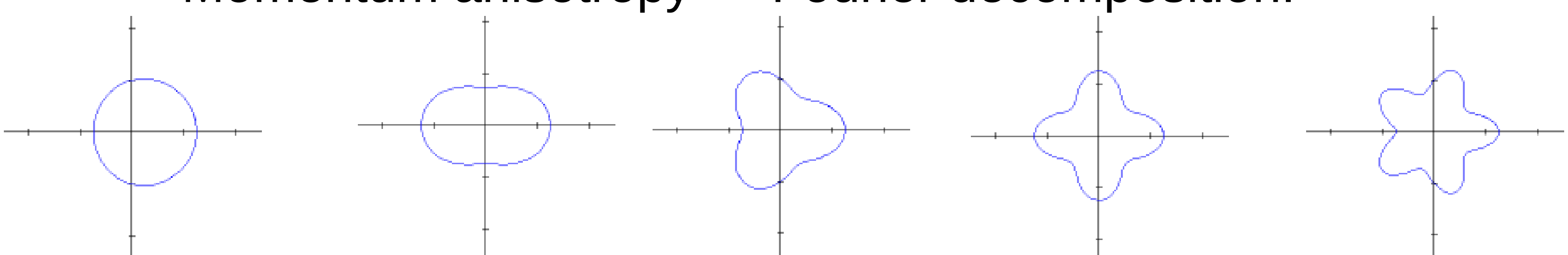


Anisotropic flow



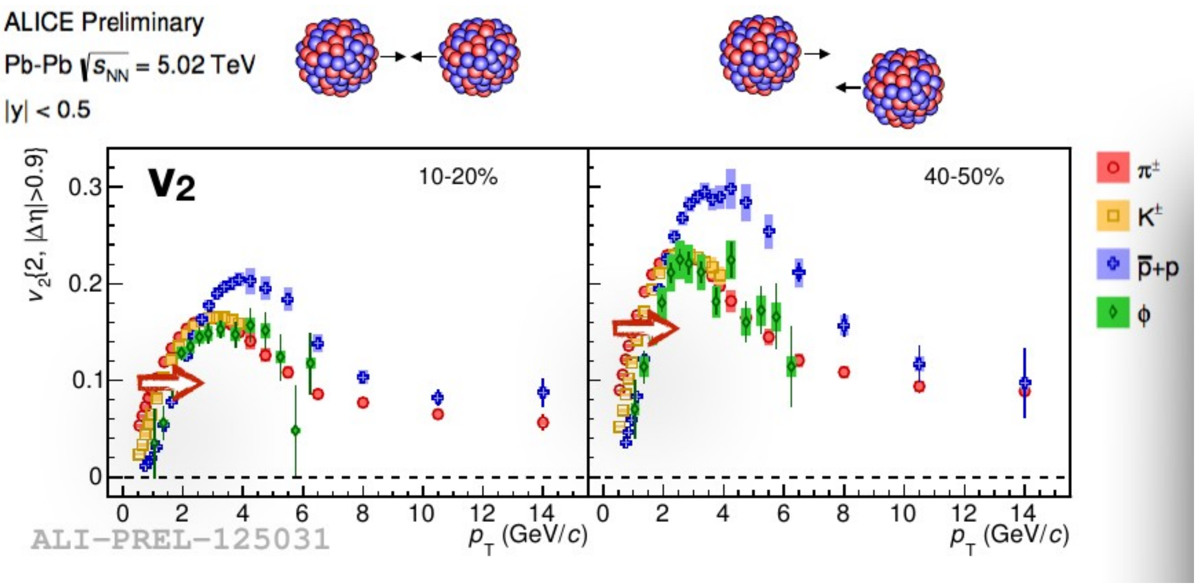
Initial overlap asymmetric → pressure gradients

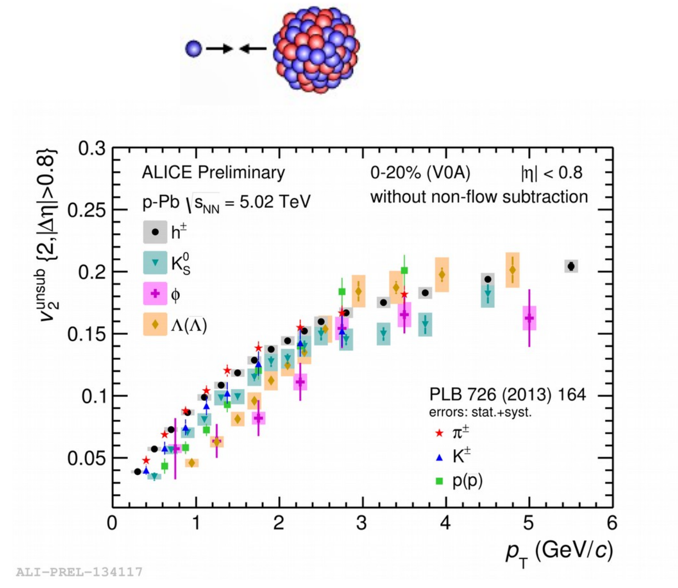
Momentum anisotropy → Fourier decomposition:



$$\frac{d^2N}{dp_T\, d\phi} \approx 1 + 2v_1\cos(d\phi) + 2v_2\cos(2d\phi) + 2v_3\cos(3d\phi) + 2v_4\cos(4d\phi) + 2v_5\cos(5d\phi) + \ldots$$

Light meson flow





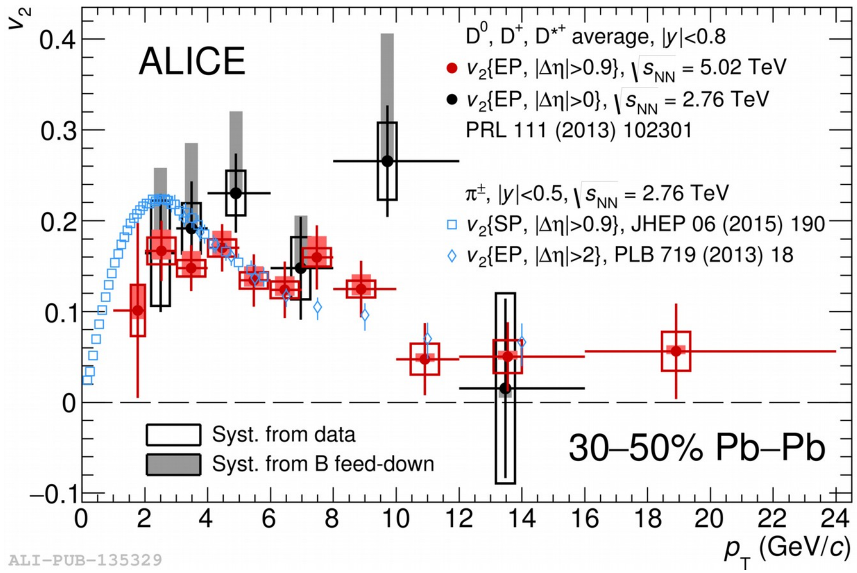
-Low p_T : Mass ordering expected in a collective expansion scenario.

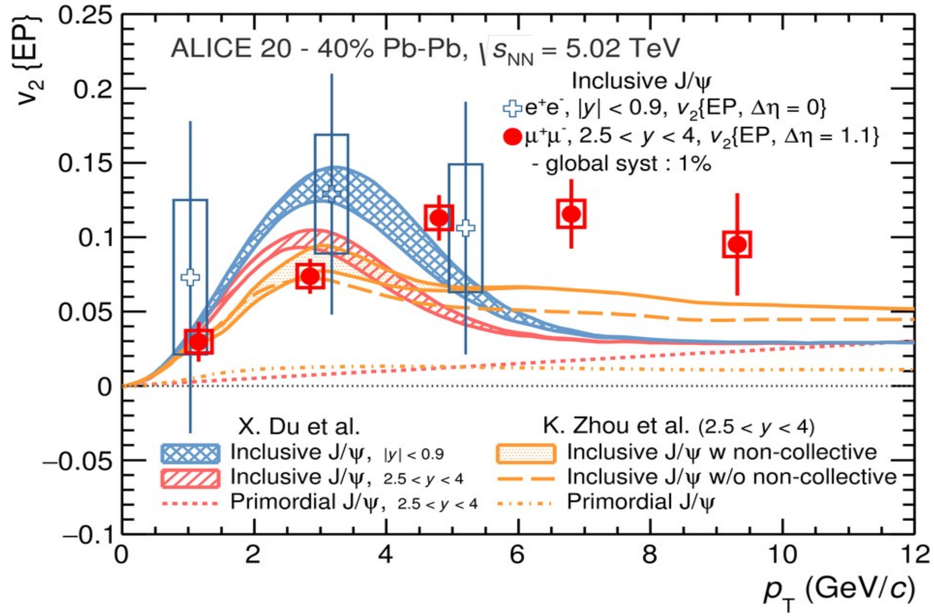
-Low-p_T : v_2 sensitive to hydrodynamic expansion and initial conditions (geometry).

-Similar results observed in a high multiplicity p-Pb environment.

-Effect in these systems may be due to initial state (saturation?) or final state effects (expansion and/or thermal equilibrium ?)

Charm flows





Non zero v_2 for D-meson

Non zero v_2 for J/ψ's

Strong coupling of c-quark with the medium

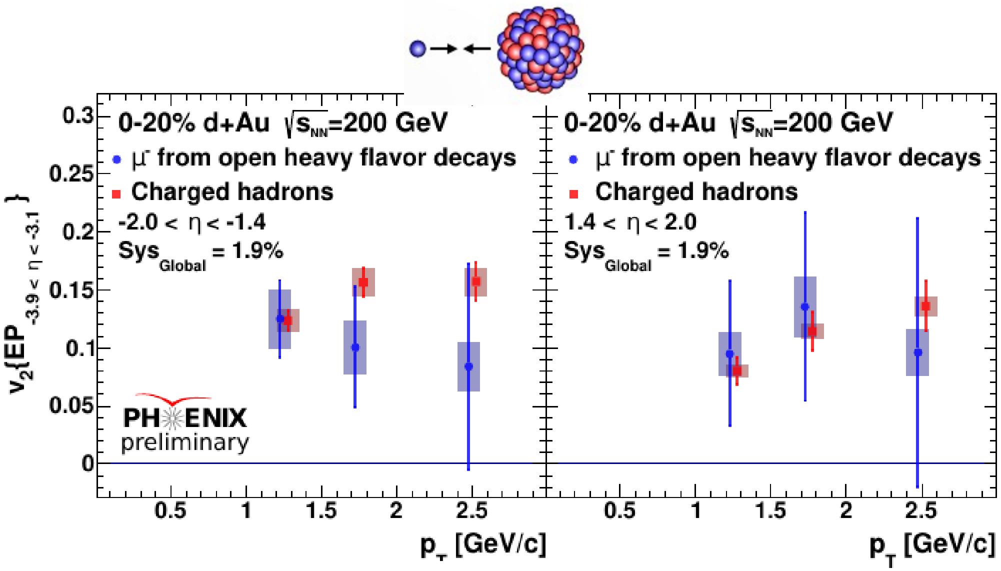
Participation of low p_T charm to collective motion in the QGP

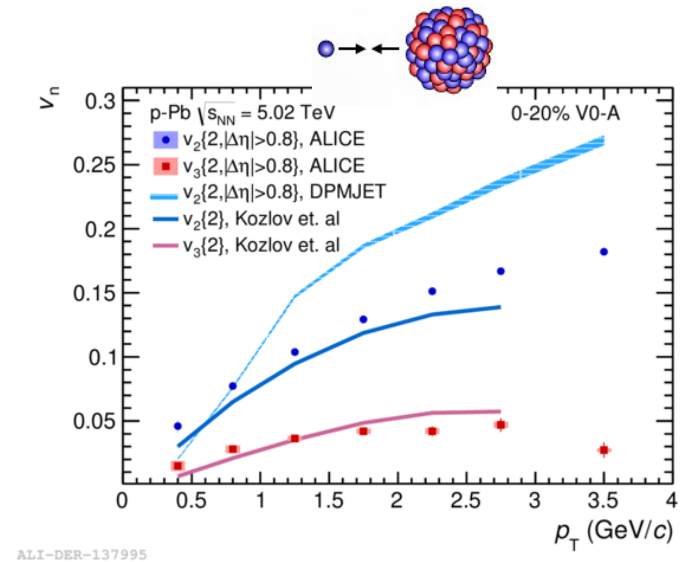
Additionally for the J/ψ this is interpreted as proof of recombination.

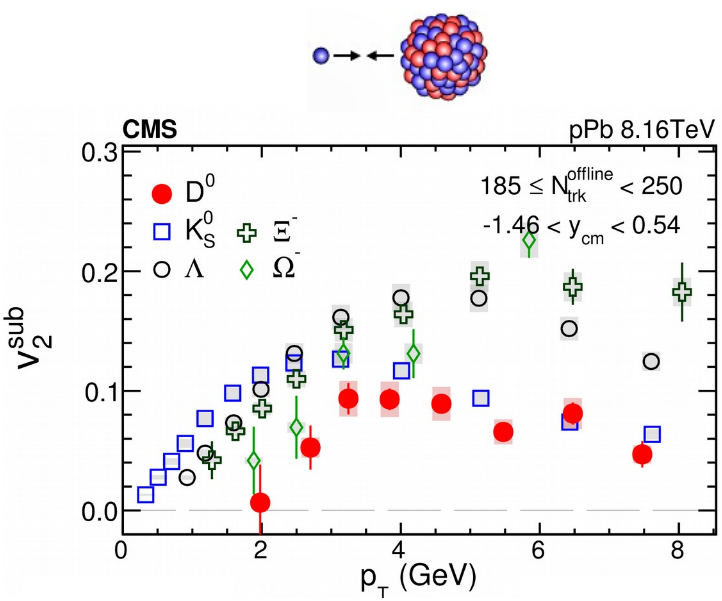
Phys. Rev. Lett. 120.102301 (2018)

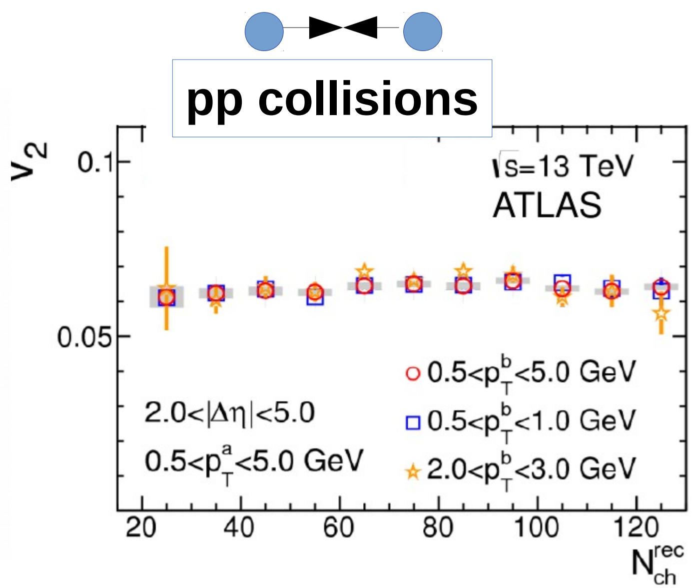
Phys. Rev. Lett. 119, 242301 (2017)

Flow in small systems?









$\sqrt{s_{pA}}$=200 GeV PHENIX
QM2018 Talk

$\sqrt{s_{pA}}$=5.02 TeV ALICE
JHEP 09 (2017) 032

$\sqrt{s_{pA}}$=8.16 TeV CMS:
arxiv:1804.09767

$\sqrt{s}$=13 TeV ATLAS:
PRL116, 172301 (2016)

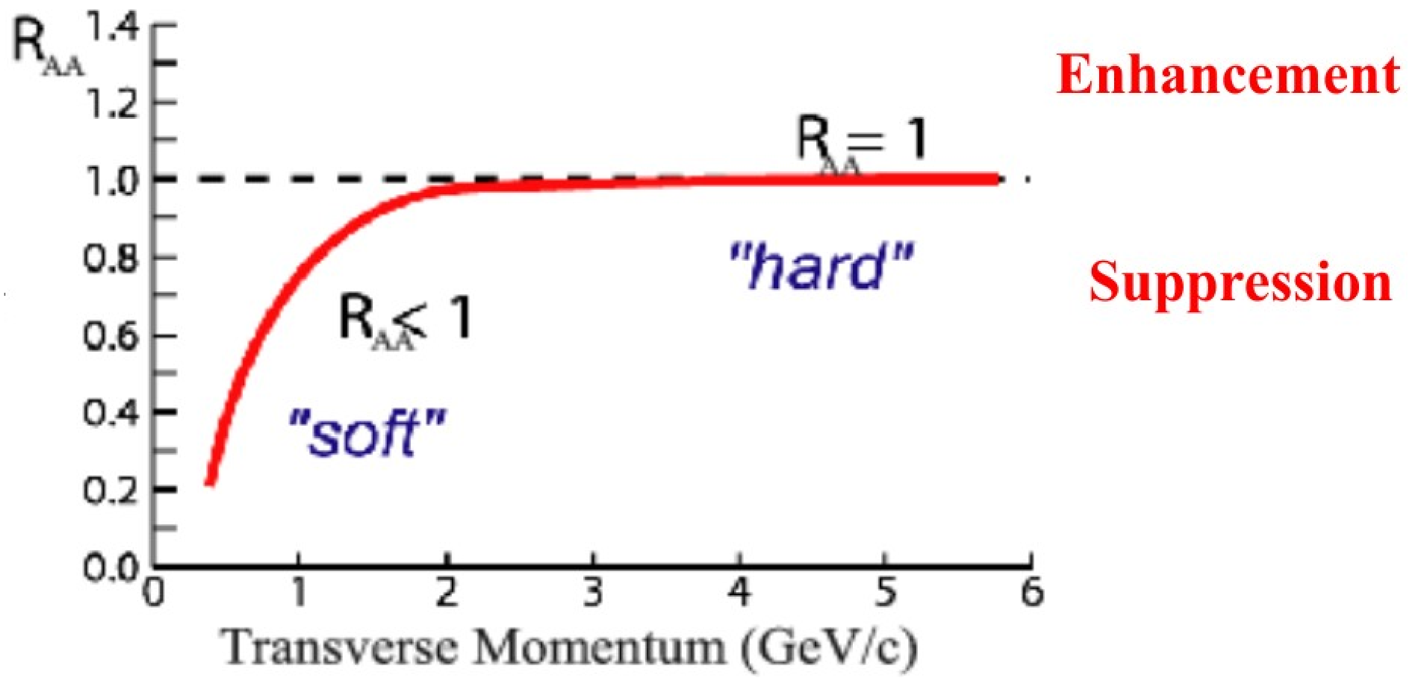
These effects have not seen at LEP nor HERA

3. Hard Processes

Nuclear modification factor

Measure spectra of probe and compare to those in pp collisions or A-A collisions

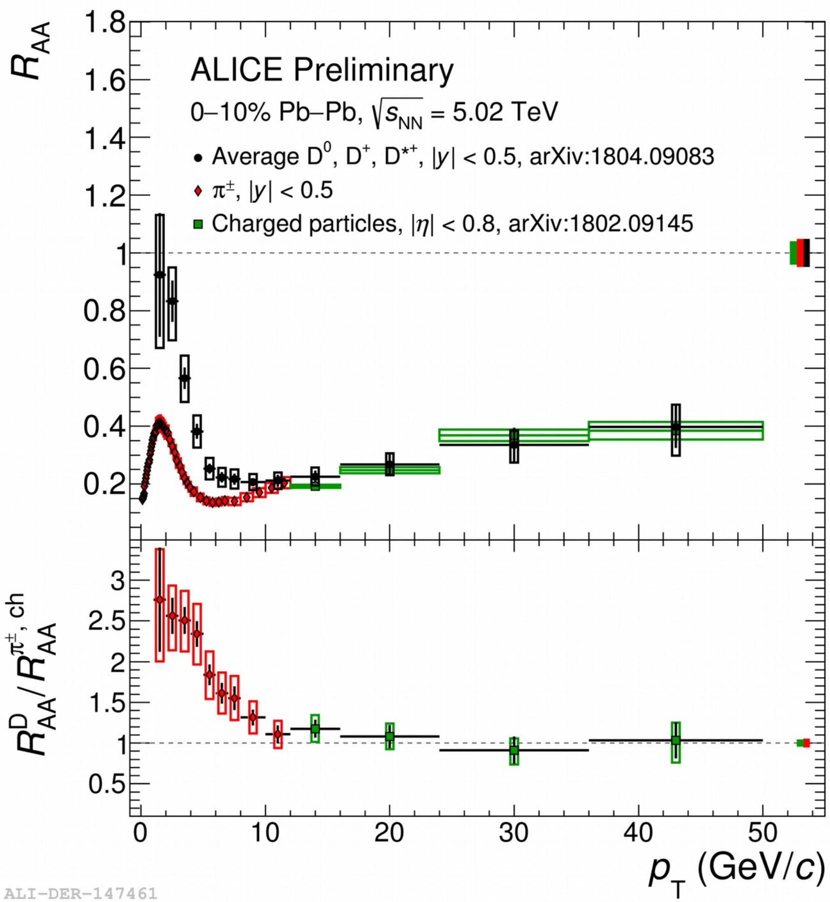
$$R_{\mathrm{AA}} = \frac{\mathrm{AA}}{\mathrm{scaled\ pp}} = \frac{\mathrm{d}^2 N_{\mathrm{AA}}/\mathrm{d}p_{\mathrm{T}}\mathrm{d}y}{\langle N_{\mathrm{coll}}\rangle \mathrm{d}^2 N_{pp}/\mathrm{d}p_{\mathrm{T}}\mathrm{d}y}$$

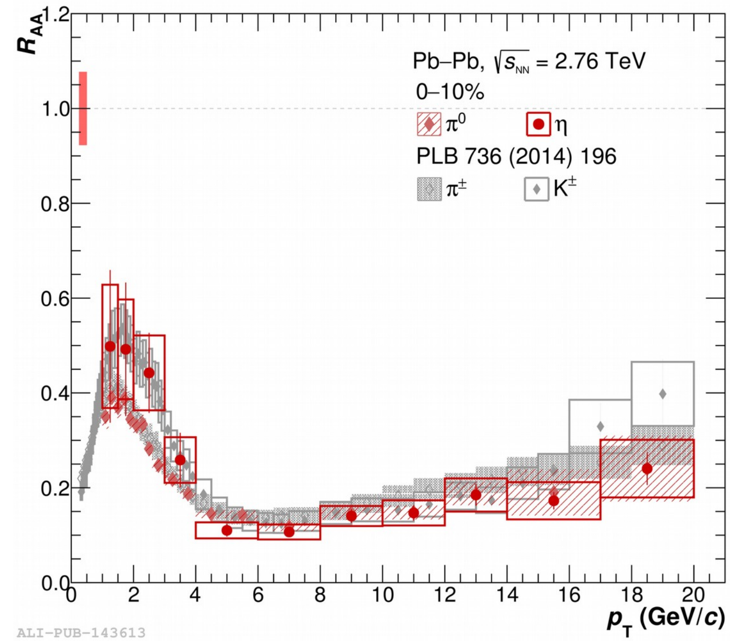


Energy loss in the medium

-High momentum partons lose energy while propagating through the QGP
-Energy loss depends on parton type properties of the medium.
-It can modify color flow

$$R_{AA} = \frac{AA}{\text{scaled pp}} = \frac{d^2N_{AA}/dp_T dy}{\langle N_{coll}\rangle d^2N_{pp}/dp_T dy}$$





Pb-Pb suppression
- Similar to that of pions (at high enough p_T)

-ALICE-PUBLIC-2017-003
-https://arxiv.org/abs/1803.05490

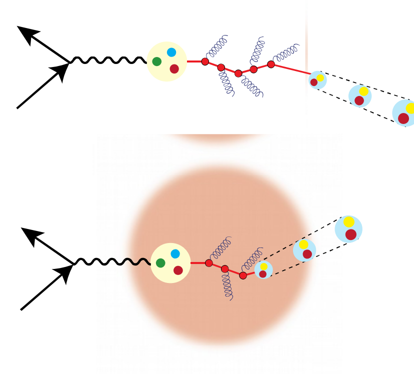
Energy loss in the medium

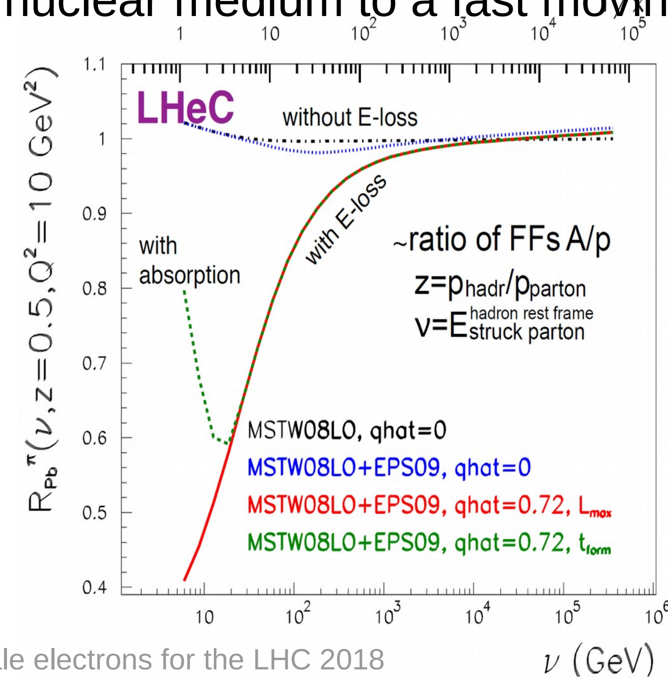
eA provides a stable nuclear medium (CNM):
-Controlled kinematics of hard scattering

-Final state particle with known properties.

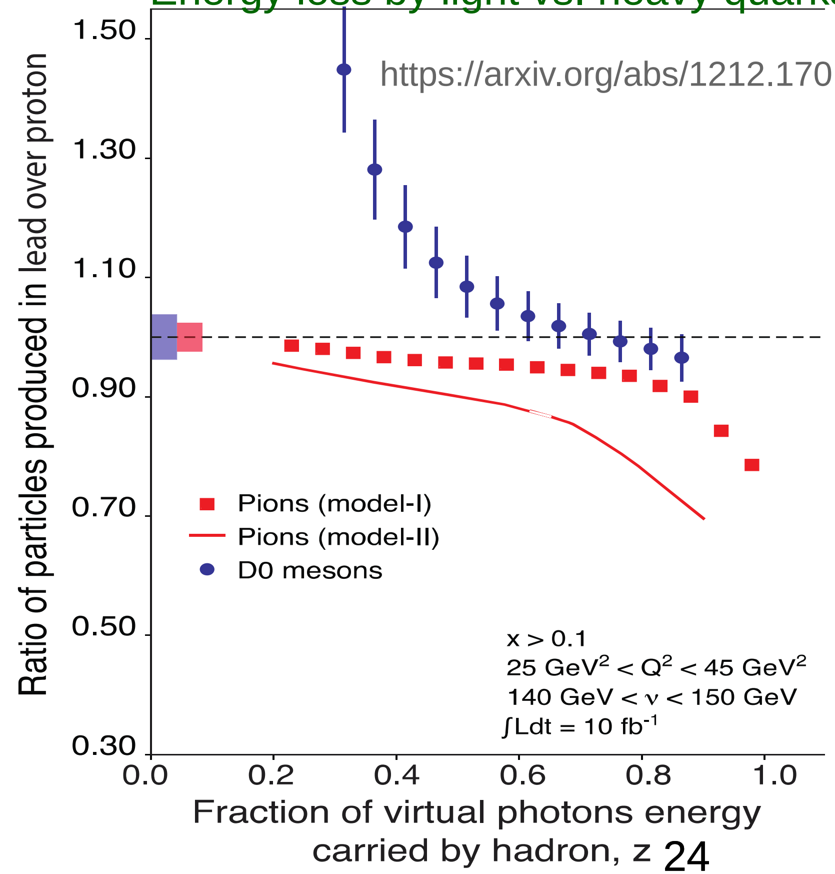
-Varying nuclei size and initial parton energy control fragmentation' length.

-Independent and complementary information essential for the understanding the response of the nuclear medium to a fast moving quark.

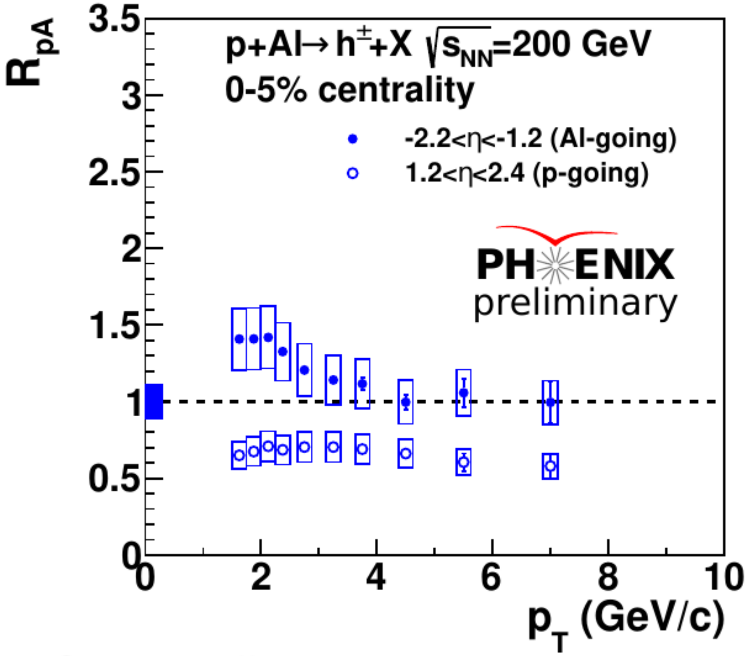


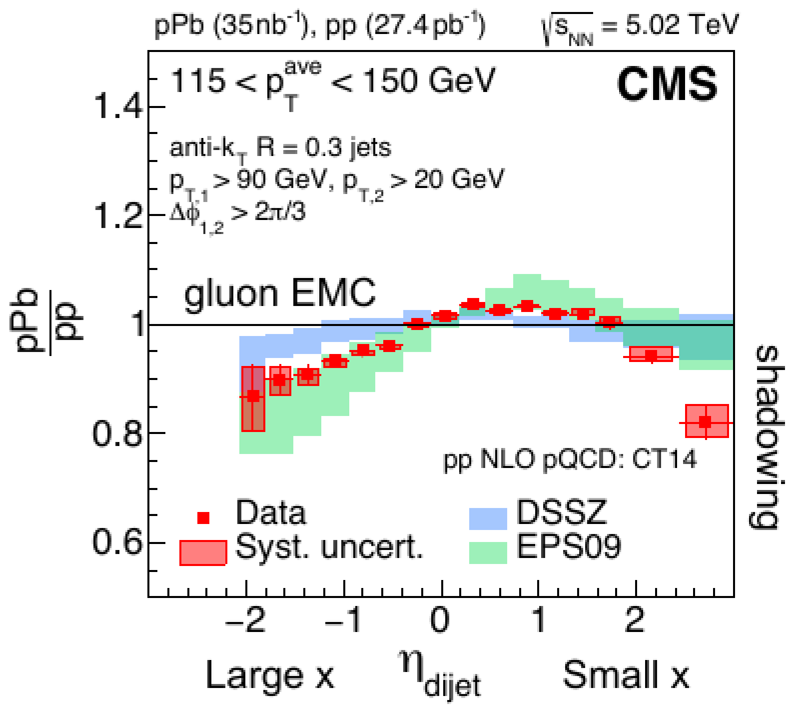


Energy loss by light vs. heavy quarks



nPDF effects?





PHENIX reports an enhancement observed at backward rapidity in p-Al (and p-Au) collisions.

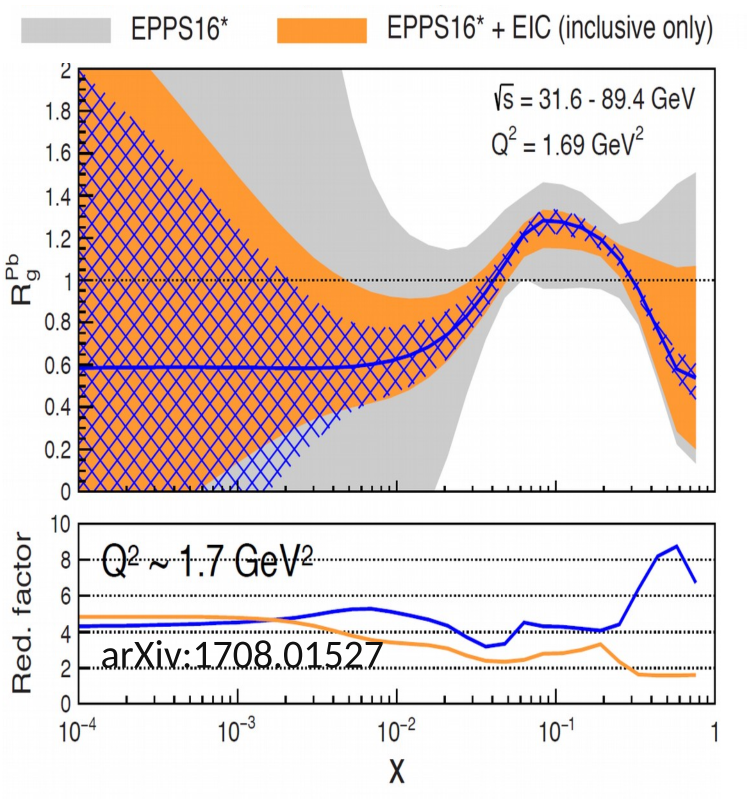
CMS dijet results support the observation of the gluon's EMC effect as well as quark modification

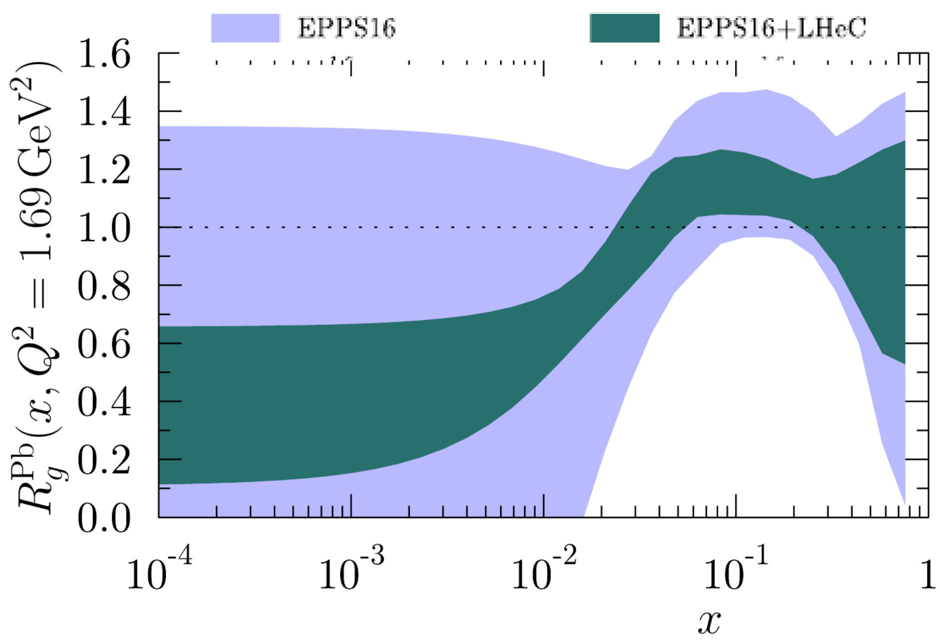
PHENIX: QM2018 J. Bryslawskyj

CMS: https://arxiv.org/abs/1805.04736

Current knowledge on nPDF's

Electron- Ion collisions:
Reduced sea/gluon nPDF uncertainties significantly
Reaching down to x~10^{-4} for EIC and 10^{-6} for LHeC
HF in *e*+A collision constraints at large-*x* gluon





This will be discussed by Elena next

Summary

QCD studies have given us decades of discoveries, and not just the QGP.

Many open questions remain on how the transition from a small system to a dense system occurs: this information is needed to fully understand the properties of the QGP.

Essential experimental bibliography from this presentation:

-Strangeness enhancement in pp collisions:
Nature Physics 13 (2017) 535-539

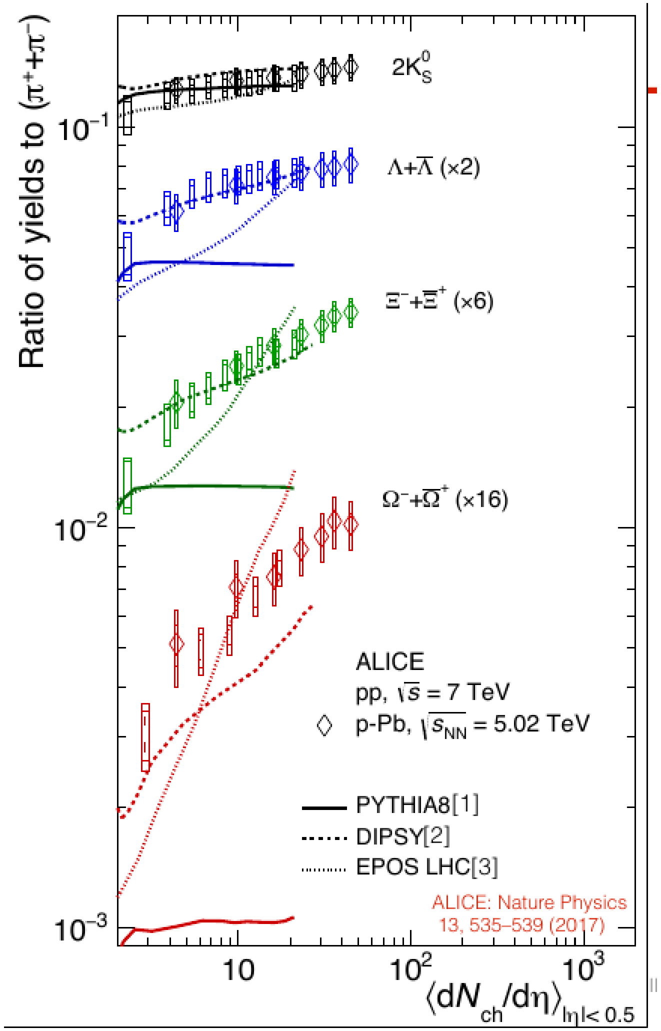
-Particle production vs multiplicity
Phys. Lett. B 776 (2018) 91
Phys. Lett. B 724 (2013) 213

-Flow in large and small systems:
PbPb: Phys. Rev. Lett. 120.102301 (2018)
pPb: arxiv:1804.09767, JHEP 09 (2017) 032
pp: PRL116, 172301 (2016)

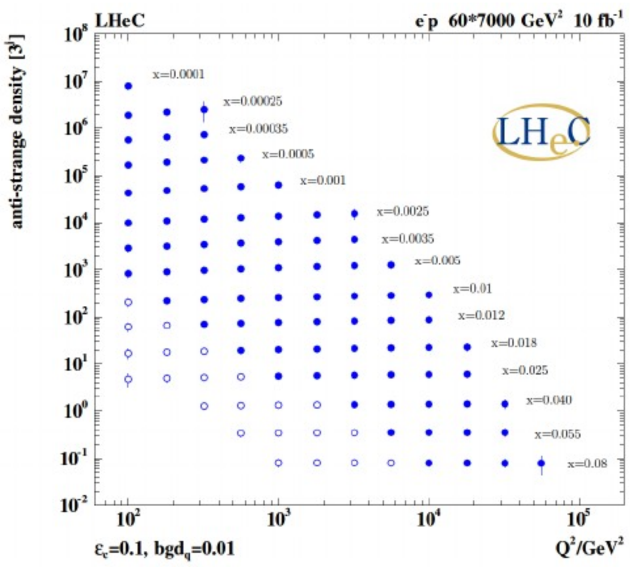
-Nuclear PDFs with dijets:
pA: arXiv:1805.04736

QGP Onset: Strangeness enhancement

Enhancement of strange particles with respect to non-strange yield **is also observed** for high multiplicity **pp** and **p-Pb** collisions



-Smooth transition connecting small and larger systems.
-These measurements may give us insights about the underlying dynamics
-eA can provide a more robust reference.

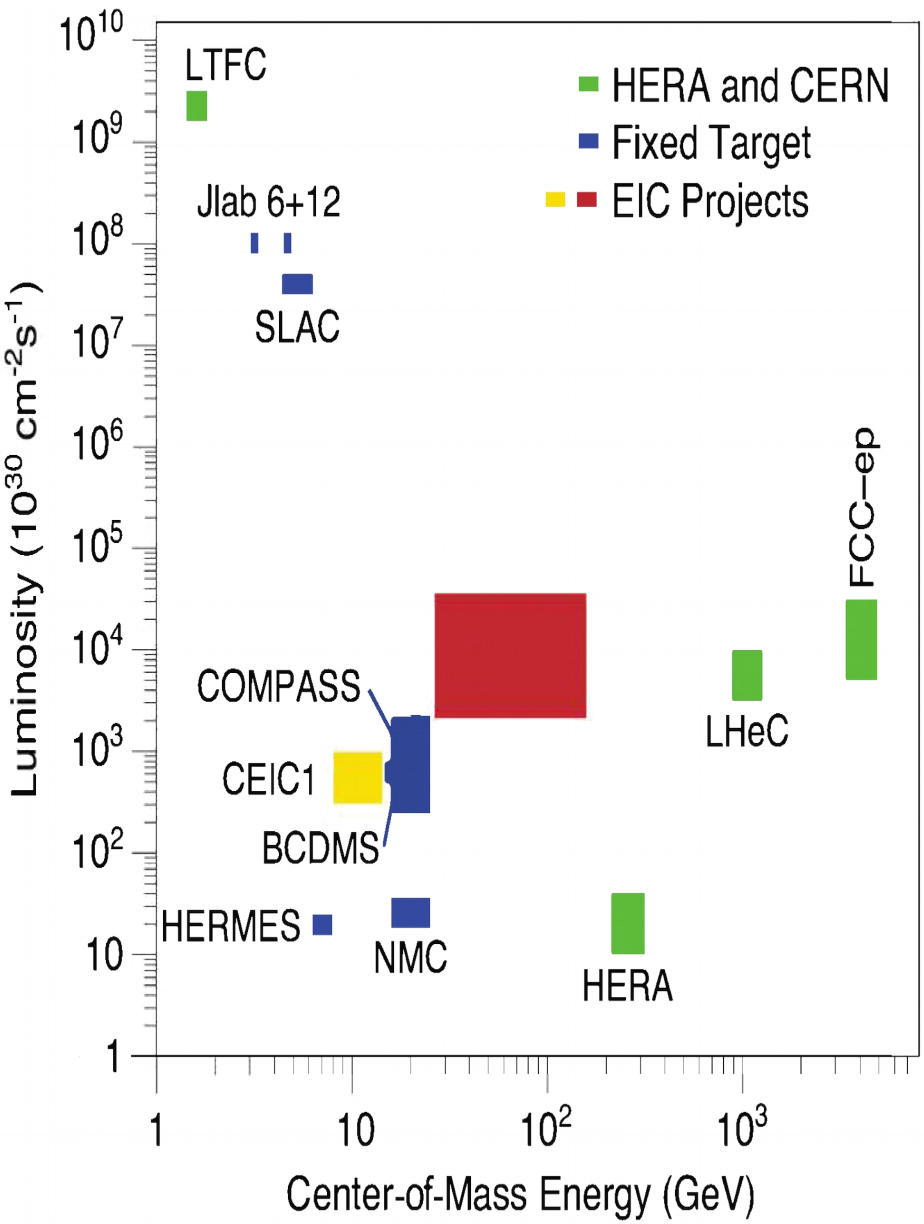


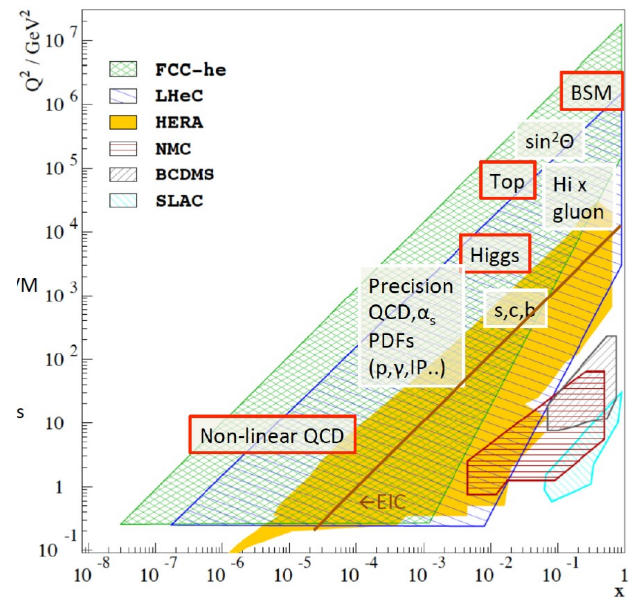
More experimental insight is needed to interpret the final state strangeness we are observing in large and small systems

https://arxiv.org/pdf/1305.0609 and https://cds.cern.ch/record/2302758

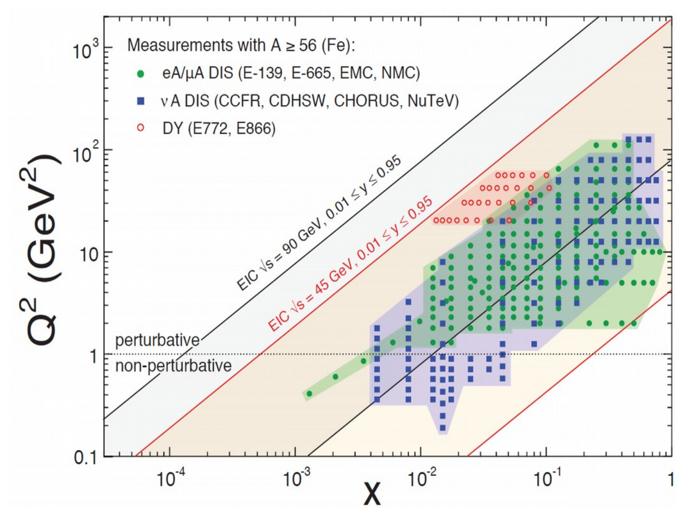
28

Kinematic reach





LHeC



EIC