DIS 2019 TORINO
8-12 April
XXVII International Workshop on Deep Inelastic Scattering and Related Subjects

Heavy Ion Physics
(QCD —> QGP)

QCD at high temperature and density

Bias: Selected topics: jets, heavy flavor, small systems

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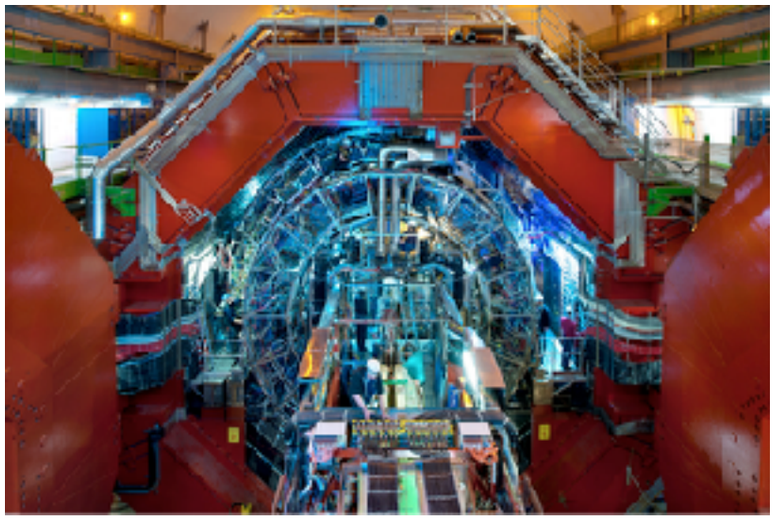
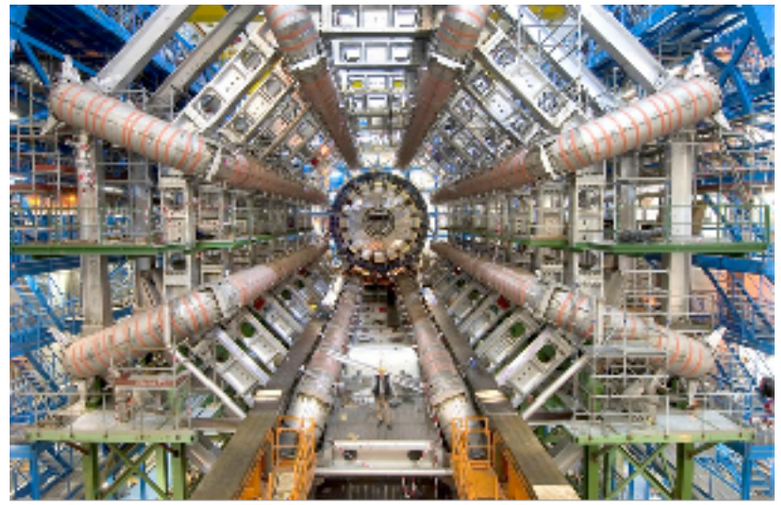
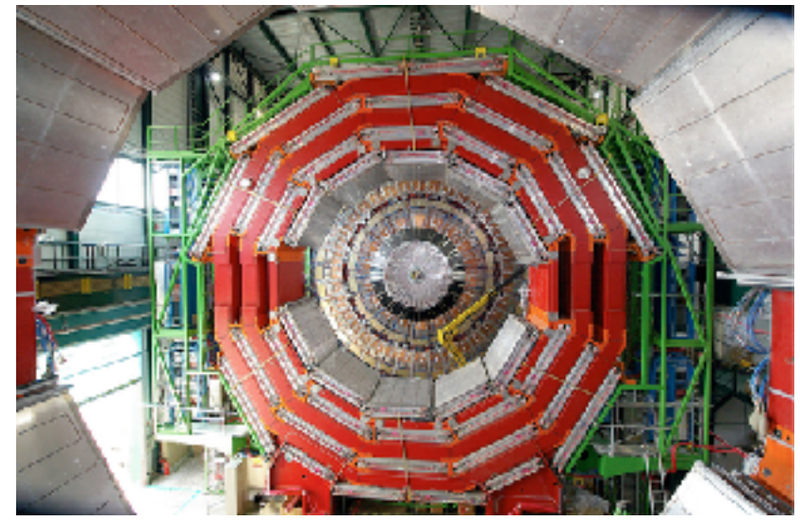
High Energy Heavy Ion Experiments



ALICE

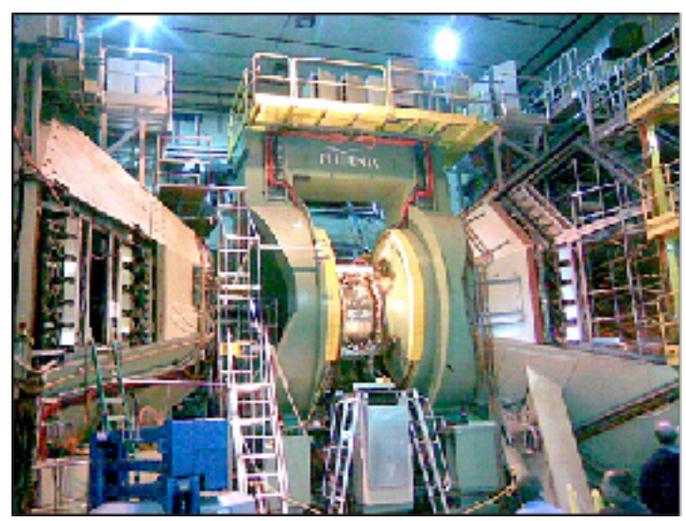


ATLAS

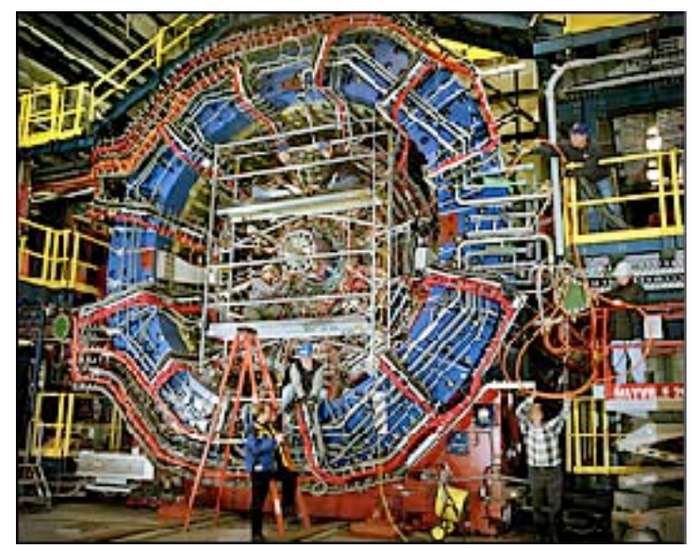


CMS

LHCb



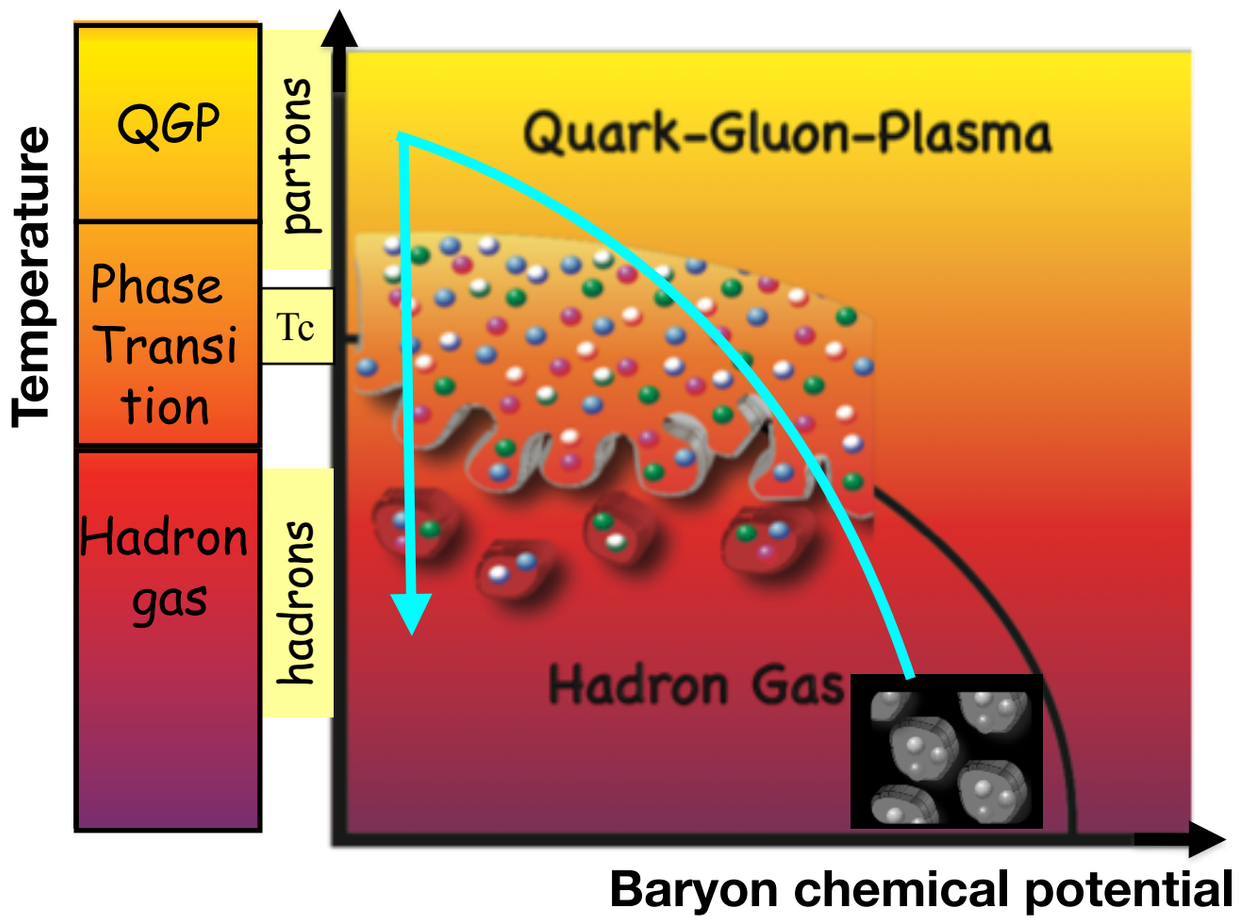
PHENIX



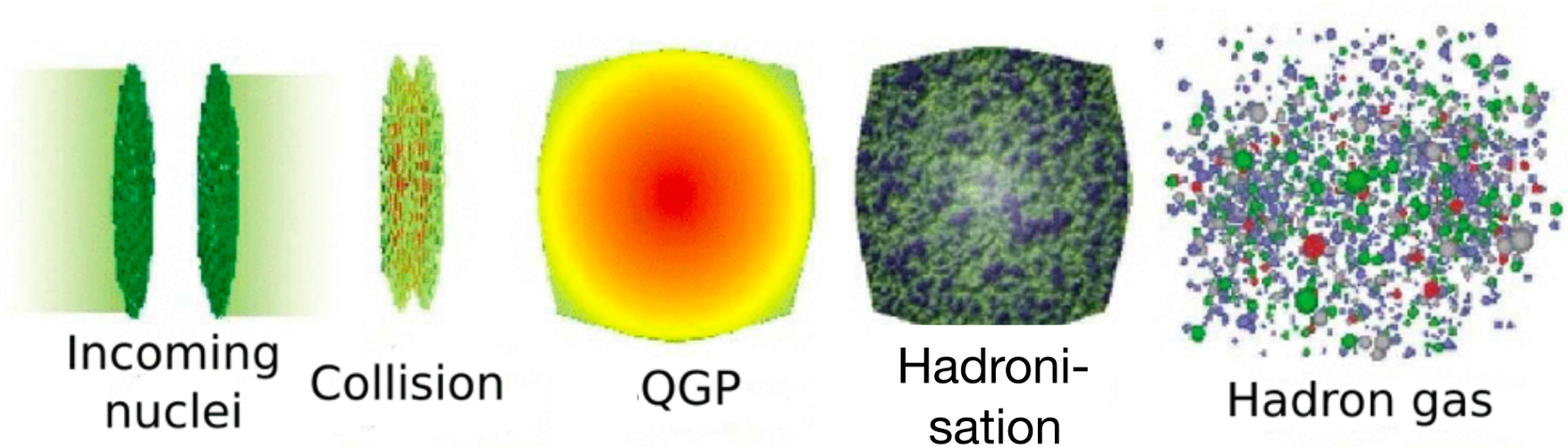
STAR

Energy range: ~10 GeV to ~10 TeV (center of mass energy / nucleon pair)
Collision systems: p+p, p+A, A+A (A = Au, Al, Pb)

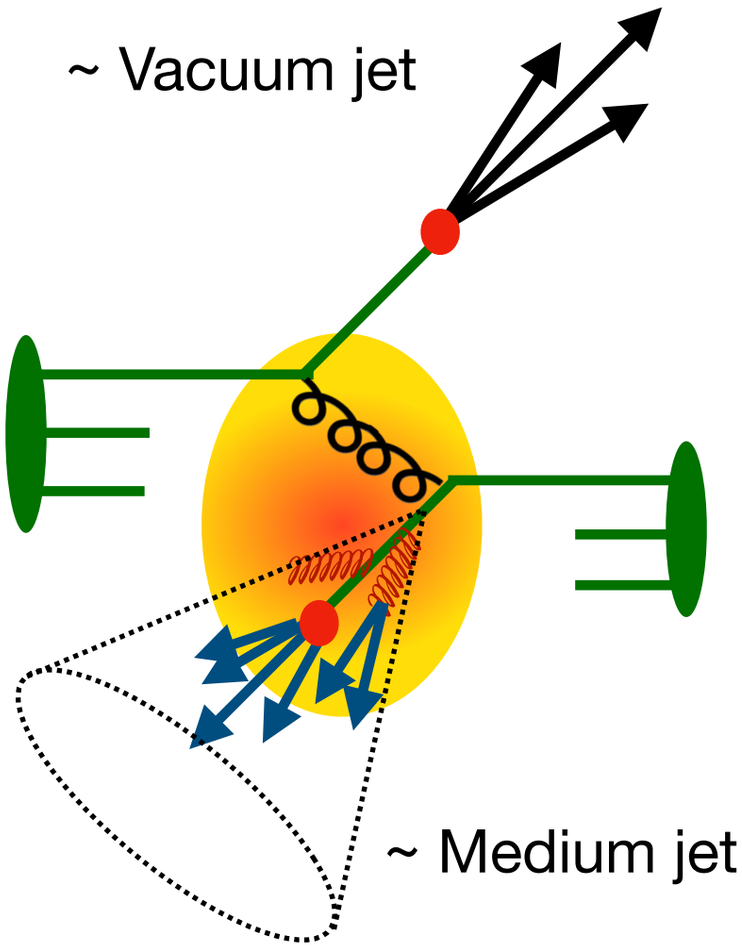
Temperature conditions



- Hard scattering
- QCD medium: elastic and inelastic collisions (+radiation)
- Hadronisation
- Decoupling
  Freeze-outs (chemical + kinetic)

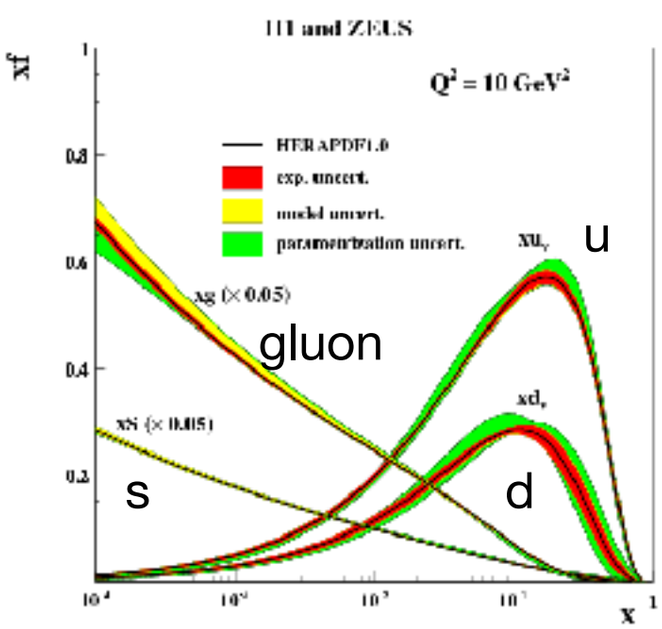


Hard scattering in medium



- Initial conditions (+geometry)
- Initial hard and soft scatterings (qq,qg,gg) depending on: x (momentum fraction) gluon density (not well known)
- Energy dissipation by gluon radiation or parton scattering
- Modification of fragmentation ?

} jet

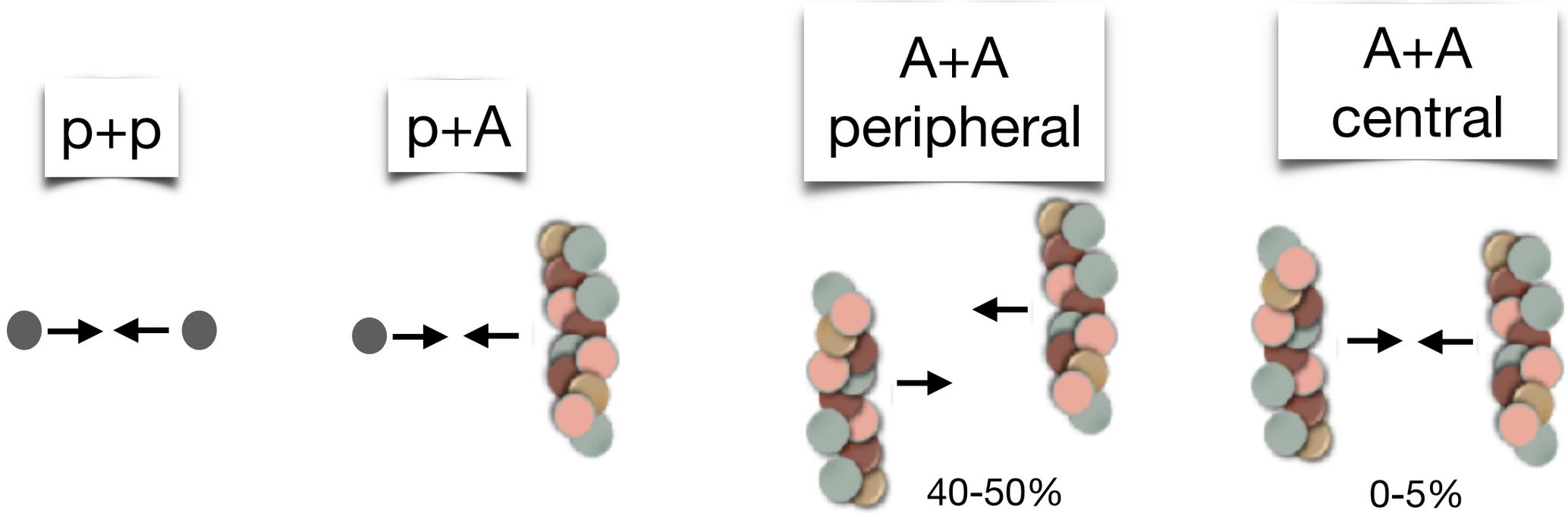


Energy dissipation: Where does the energy go?
—> It changes momentum of particles ?
—> It changes the particle angular distribution ?
—> It changes particle species ?

Questions:
What is the medium ?
How is the medium influenced by the jet ?
How is the jet influenced by the medium ?

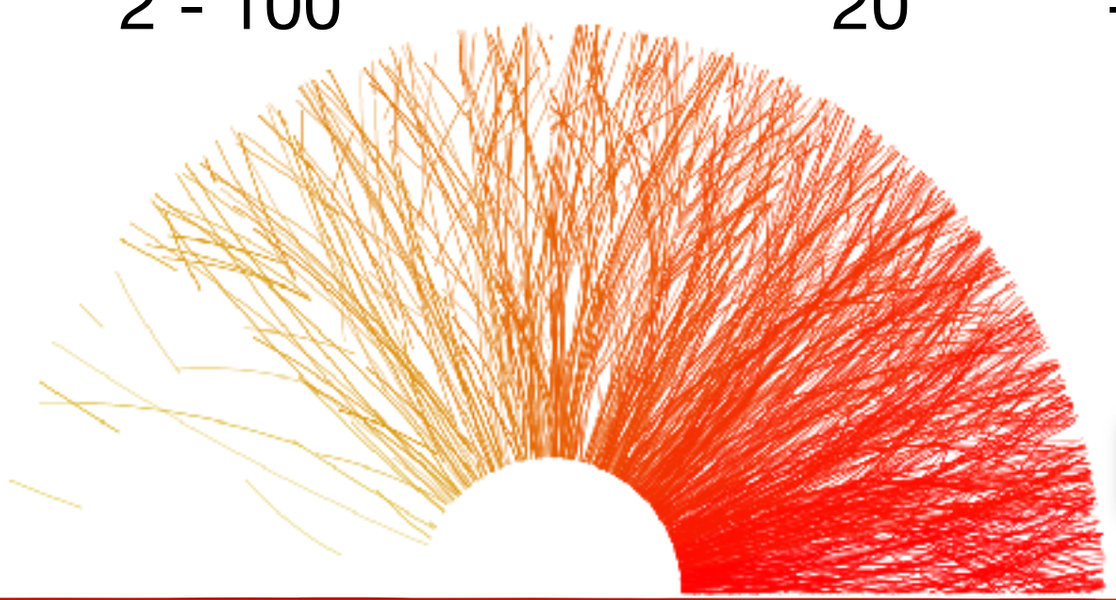
Vary system size of collision

(medium size)



Measure particle multiplicity (activity) at LHC energies (e.g. in TPC |eta| < 0.5)

2 - 100 2 - 100 20 - 2000



n_charge
N_part
centrality in %

—>measurements: AA/pp

General Particle Production

Time and mass dependence

Phys.Rev.Lett.101:232301,2008

— **Hard scattering (jet), high p_T = early**

parton-parton scattering with large Q^2

— **Heavy flavor = early production**

short formation time

~1% of yield

— **Low p_T = medium = late**

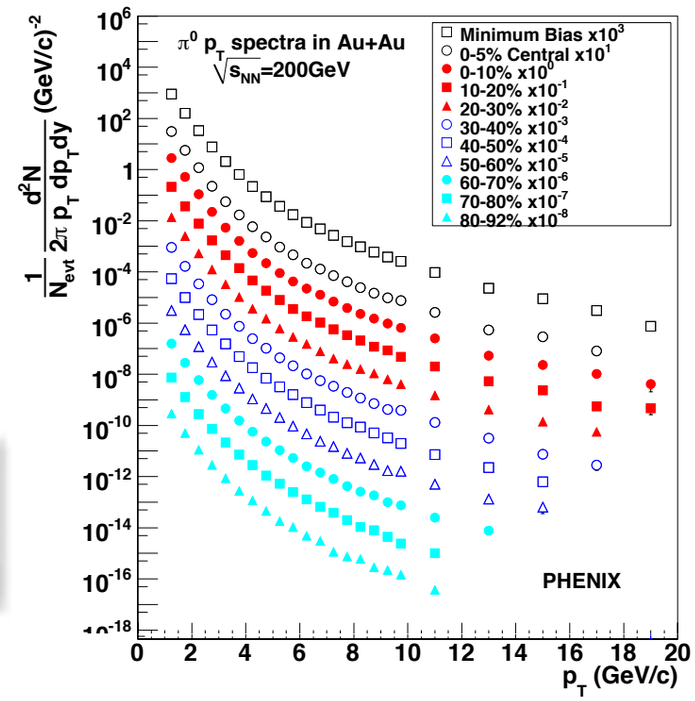
fragmentation and further interactions

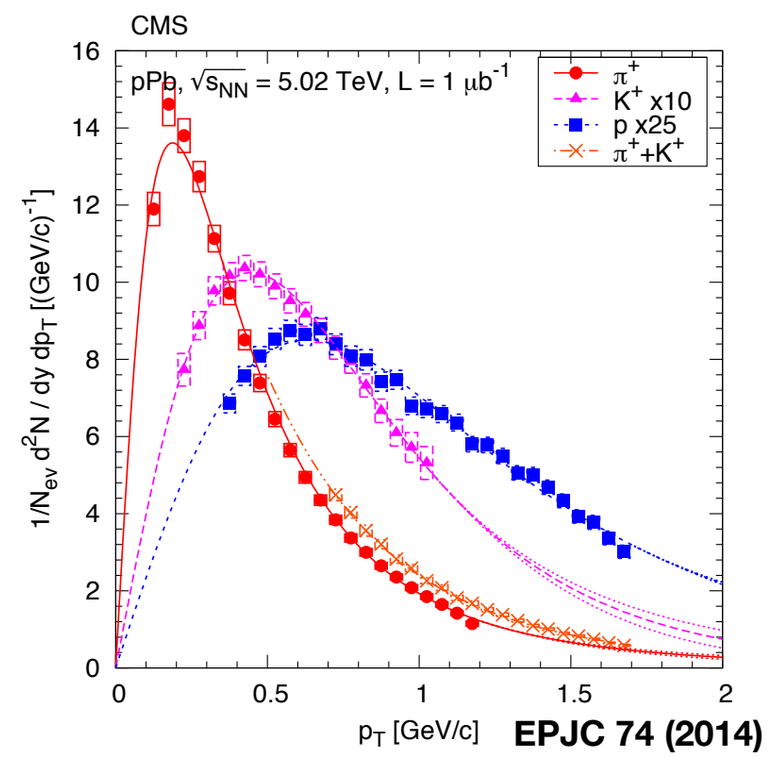
— **Low mass = medium (late)**

multiple interactions

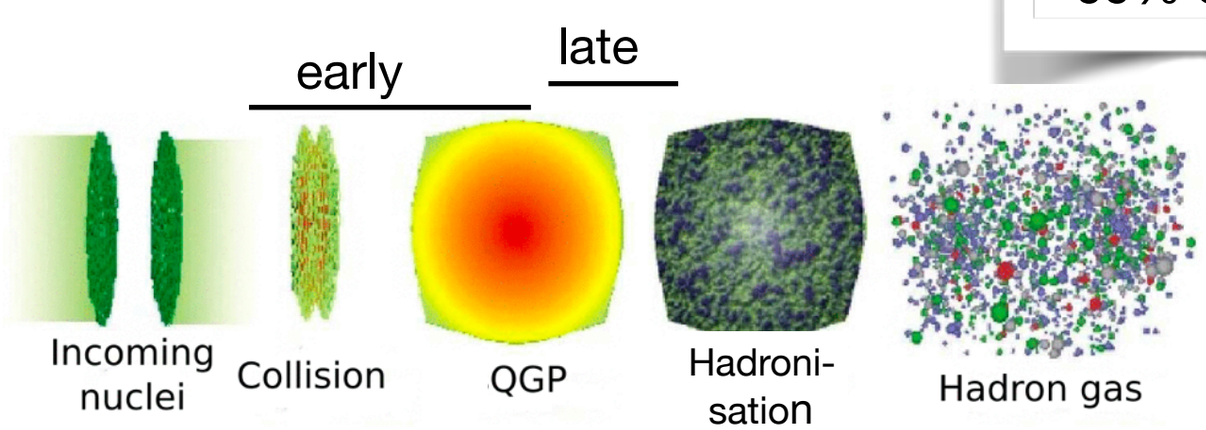
-> thermalized medium

~99% of yield





EPJC 74 (2014) 2847



Outline

Energy dissipation in medium

Jet shape

Baryon/meson production

Correlations (jet + medium)

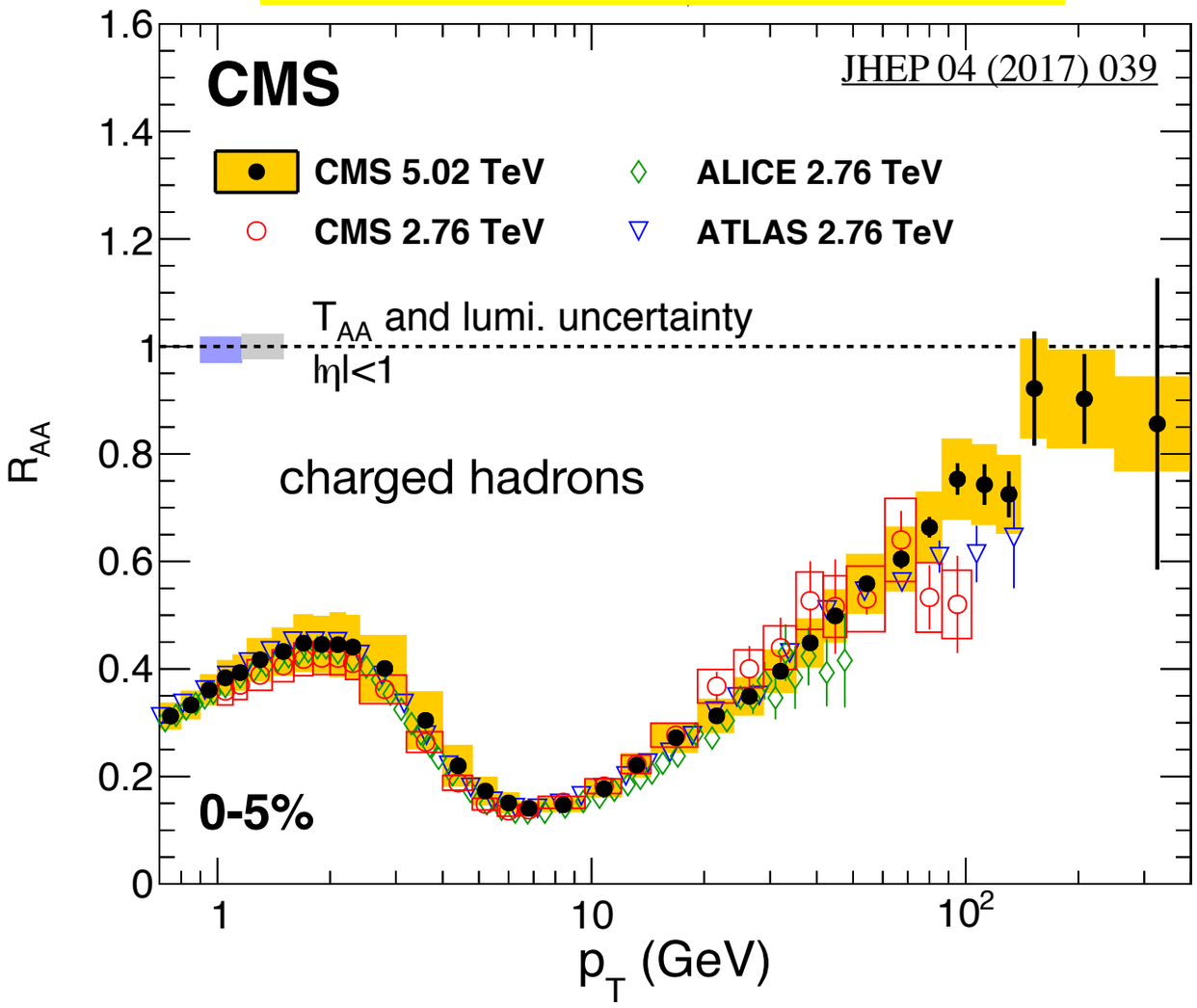
Strangeness production

Small collision systems

Relative momentum distribution (AA/pp)

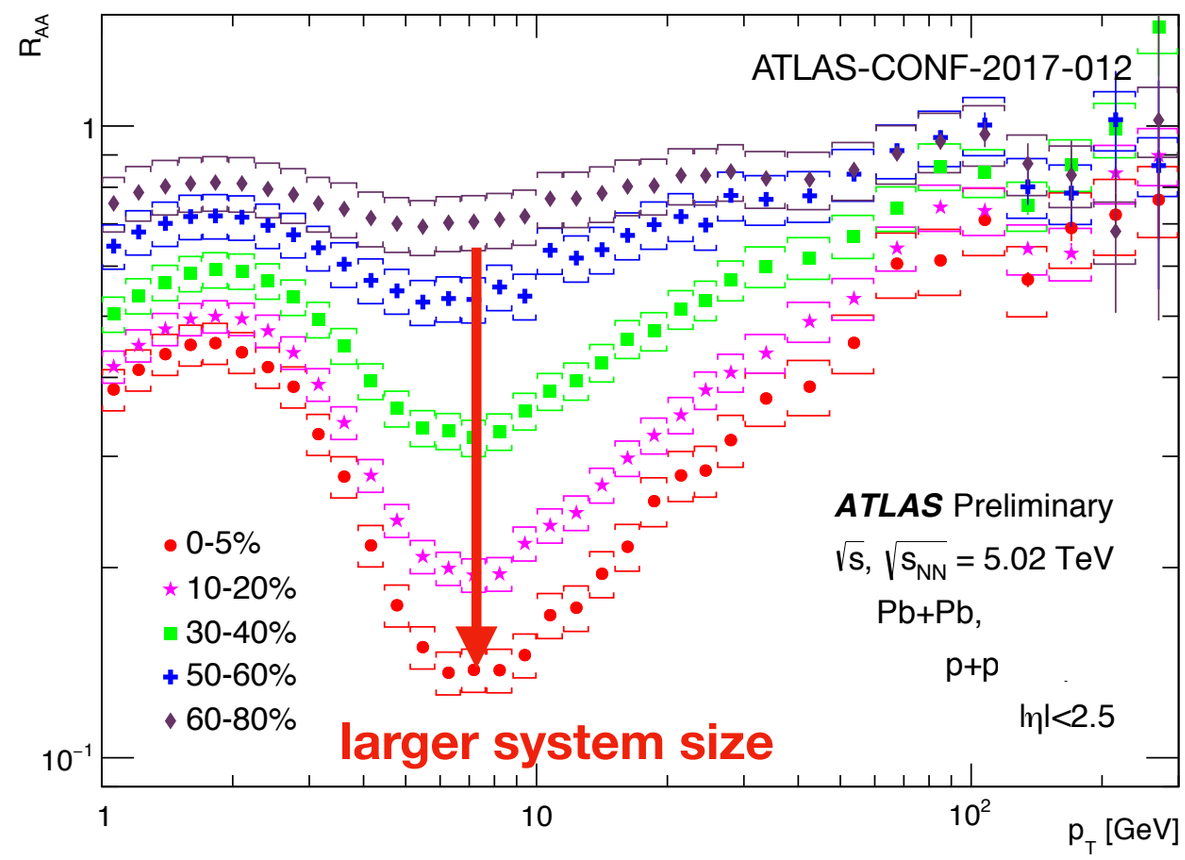
charged hadrons

Pb-Pb 5.02 TeV (pp 5.02 TeV)
central collision = large system size



Nuclear modification factor

$$R_{AA}(p_T) = \frac{dN^{AA}/dp_T}{\langle N_{coll}\rangle\, dN^{pp}/dp_T}$$



Interaction with medium —> energy dissipation —> **energy loss of initial parton**
—> suppression of high momentum hadrons (p~10 GeV/c)

System size or path length dependent energy loss:
larger medium size —> larger energy loss—> smaller R_{AA}

Gluon density RHIC $dN_{glue}/dy \simeq 1000$

Phys.Lett.B579:299-308,2004

Heavy flavor - mass dependent energy loss

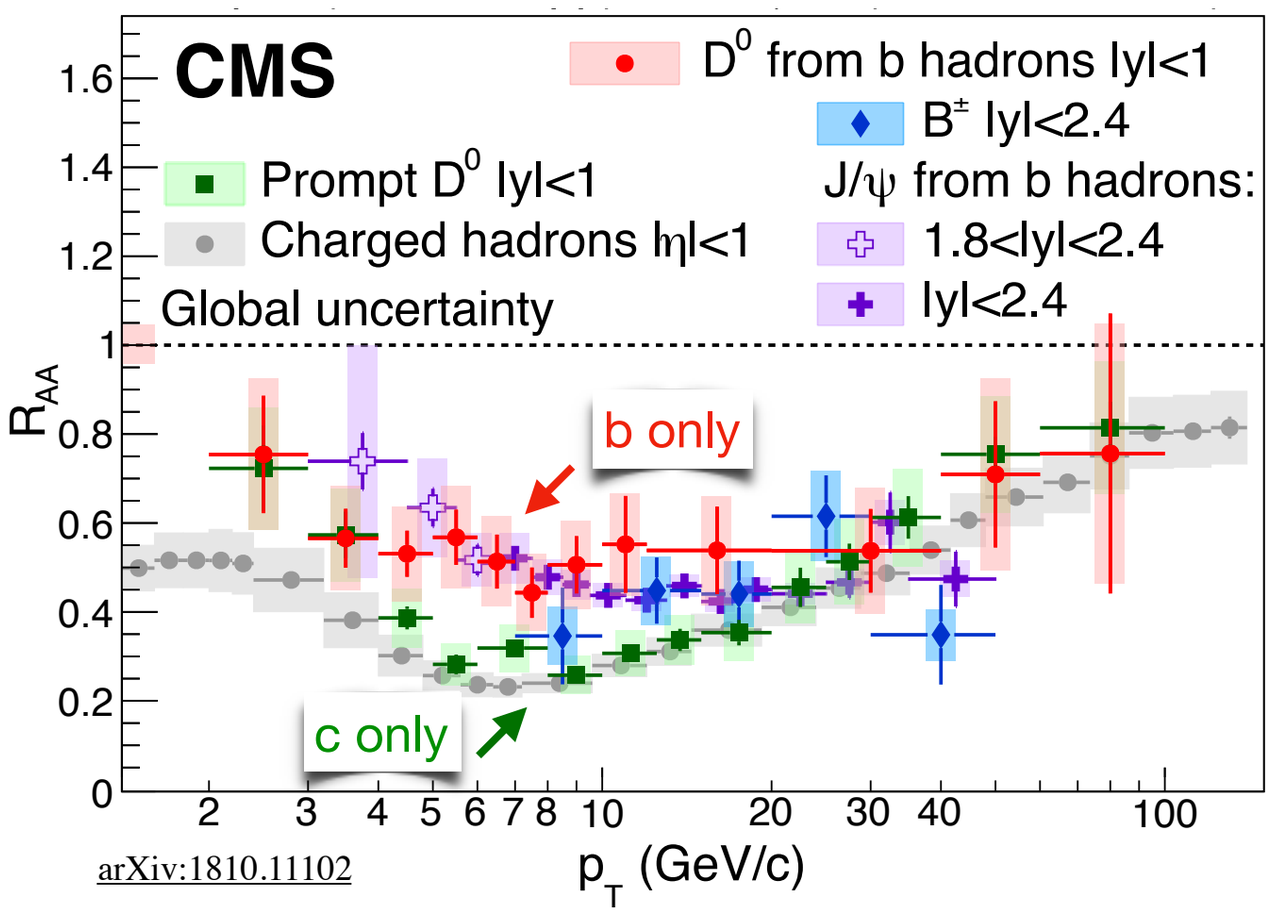
B^{+-} (bu)
D^0 (cu)

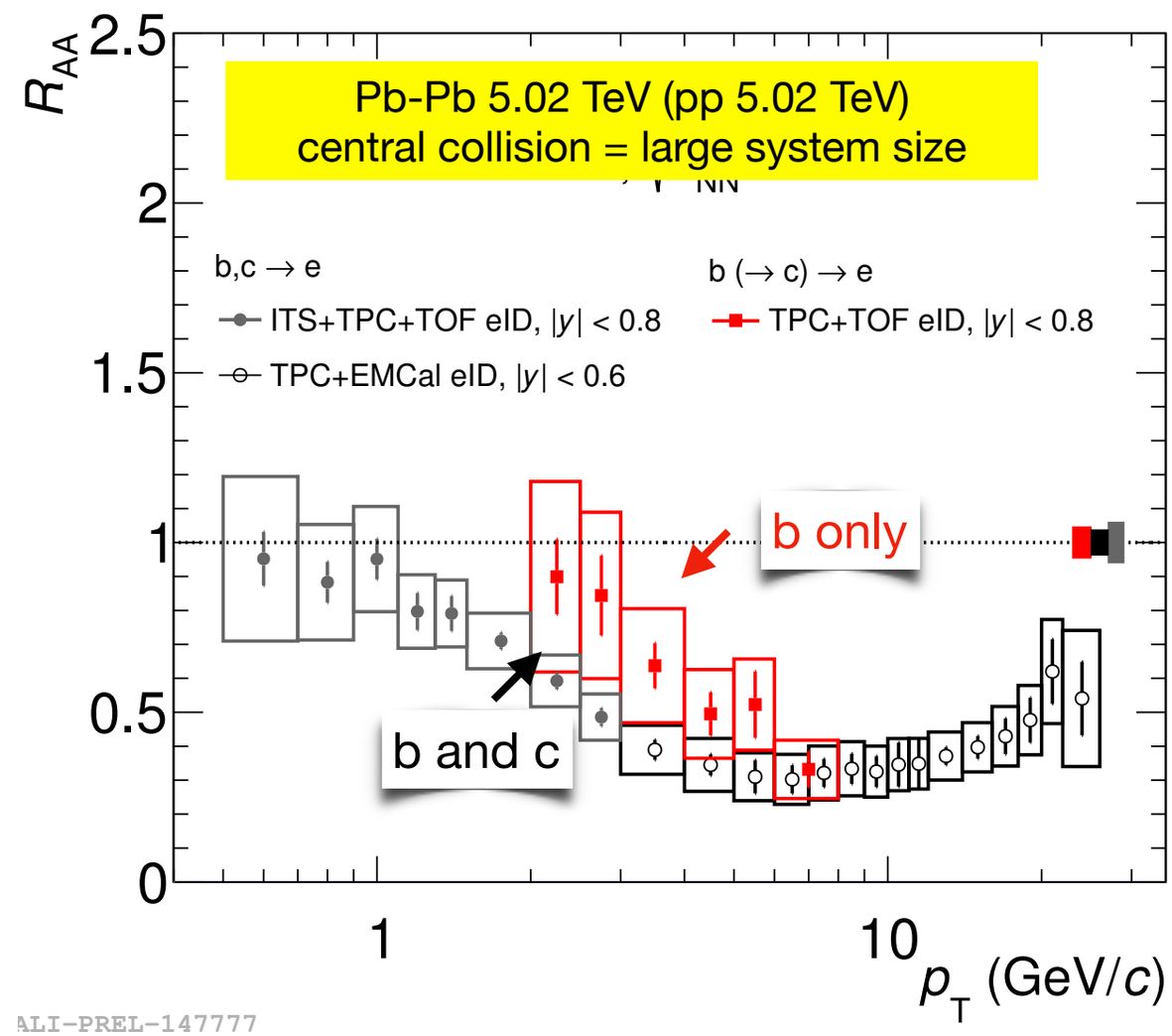
u mass ~ 2 MeV/c^2
c mass ~ 1.3 GeV/c^2
b mass ~ 4.2 GeV/c^2

$M_{gluons} < M_{u,d,s} < M_c < M_b$

$\Delta E_{gluons} > \Delta E_{u,d,s} > \Delta E_c > \Delta E_b$

Pb-Pb 5.02 TeV (pp 5.02 TeV)
central collision = large system size





Heavier b-quark smaller RAA -> lose less energy than c-quark in partonic medium.

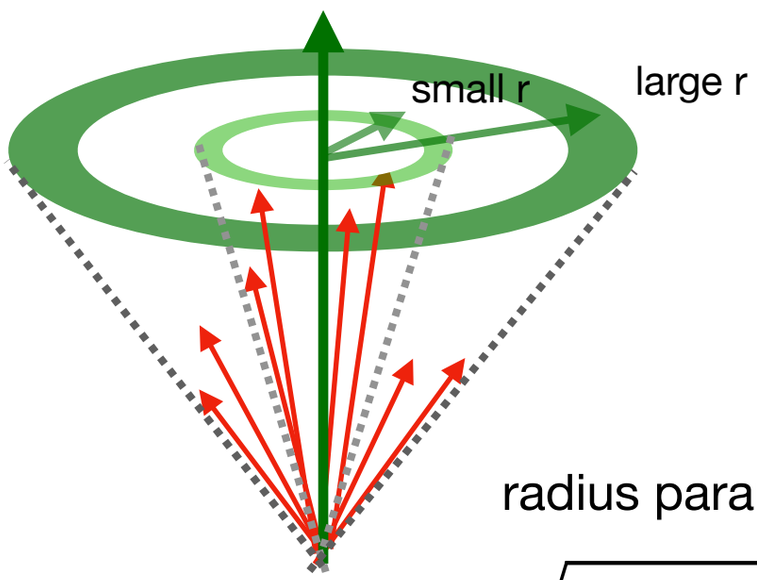
c-quark energy loss is similar to light quark (u,d) energy loss.

Jet Shapes

Jet shape (radius)

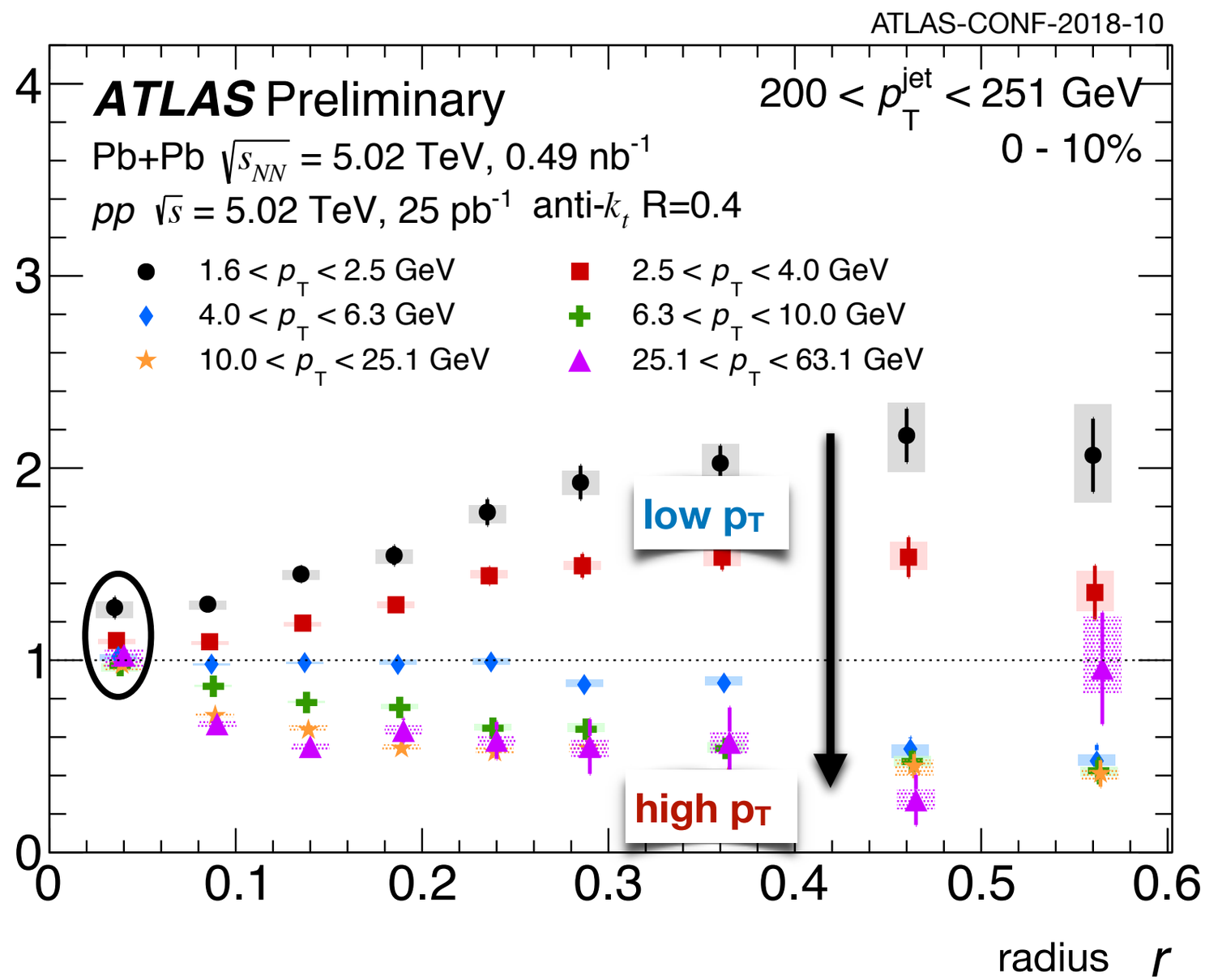
$$R_{D(p_T,r)} - \frac{D(p_T,r)_{\mathrm{Pb+Pb}}}{D(p_T,r)_{pp}}$$

$R_{D\,(p_T,\,r)}$



radius parameter

$$r = \sqrt{\Delta\phi^2 + \Delta\eta^2}$$



- High momentum particles stay closer to jet axis
- Low momentum particles are enhanced at larger radius
  —> Energy loss —> transferred to low momentum particles with large radial distance
- Question: Is this a contribution from gluon rather than quark interaction ?

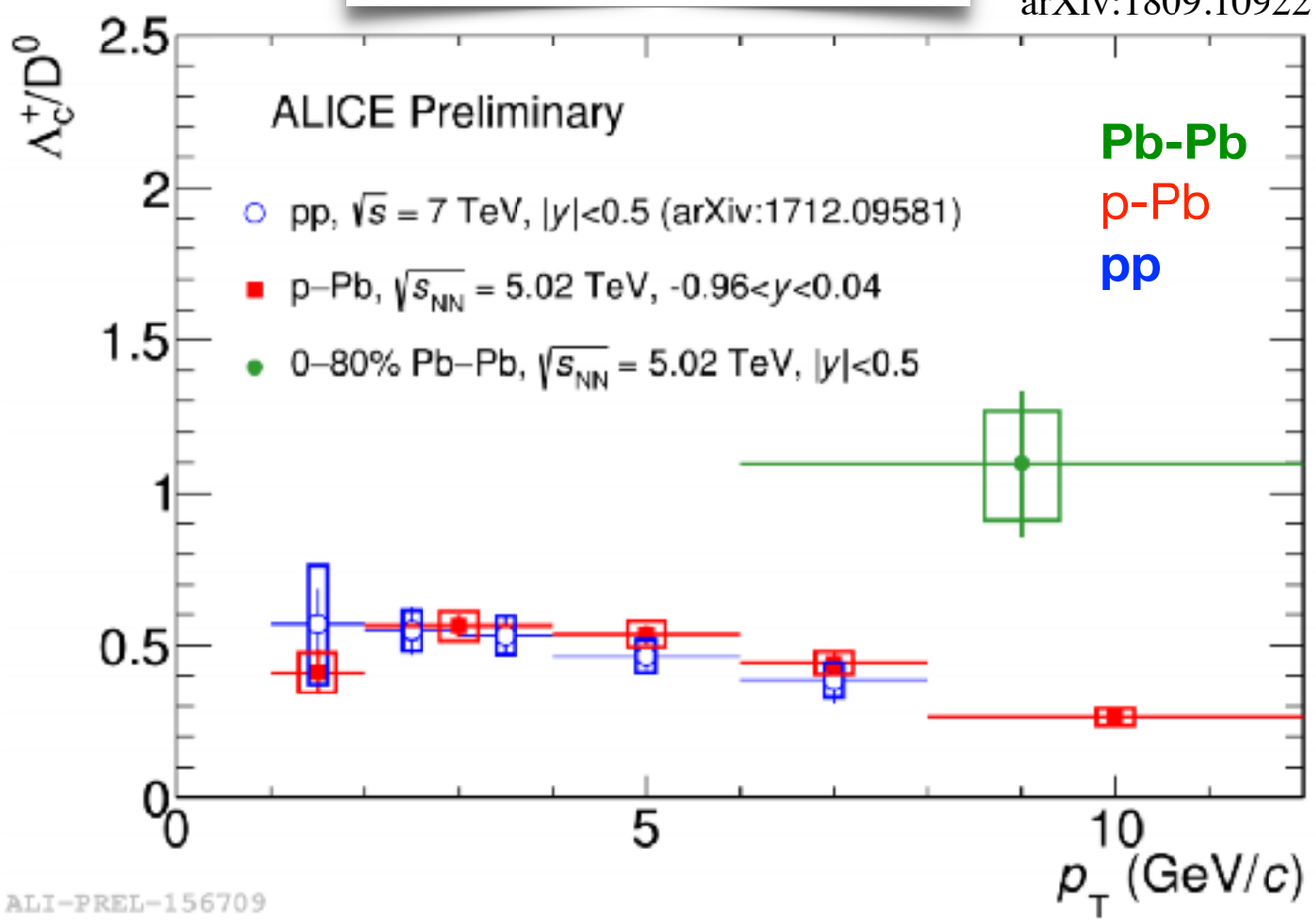
Baryon Production

Baryon production (Λ^+_c/D^0) (early)

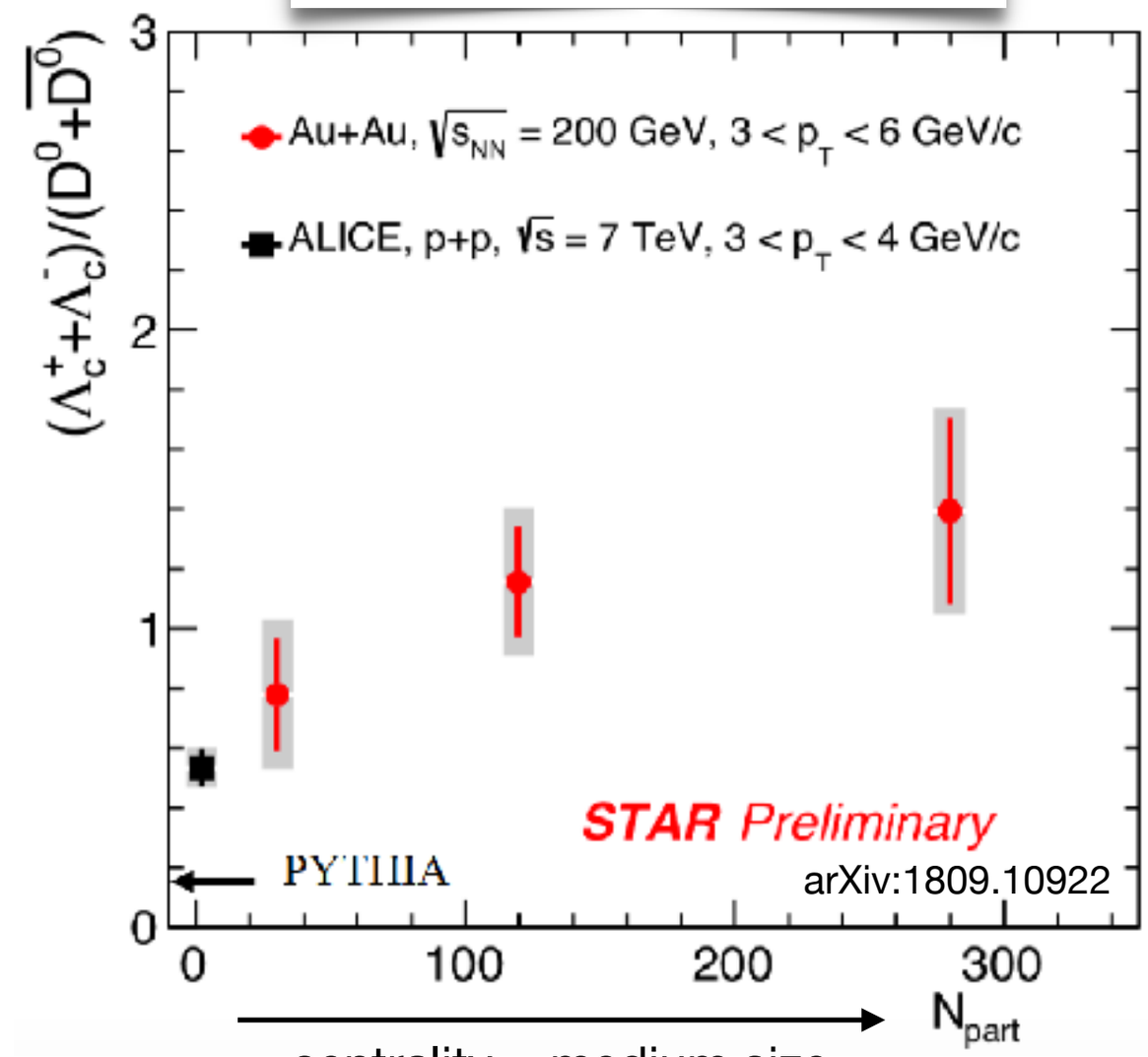
Λ^+_c : udc D^0 :|uc|

Λ^+_c/D^0 vs p_T, 0-80% Pb-Pb

arXiv:1809.10922



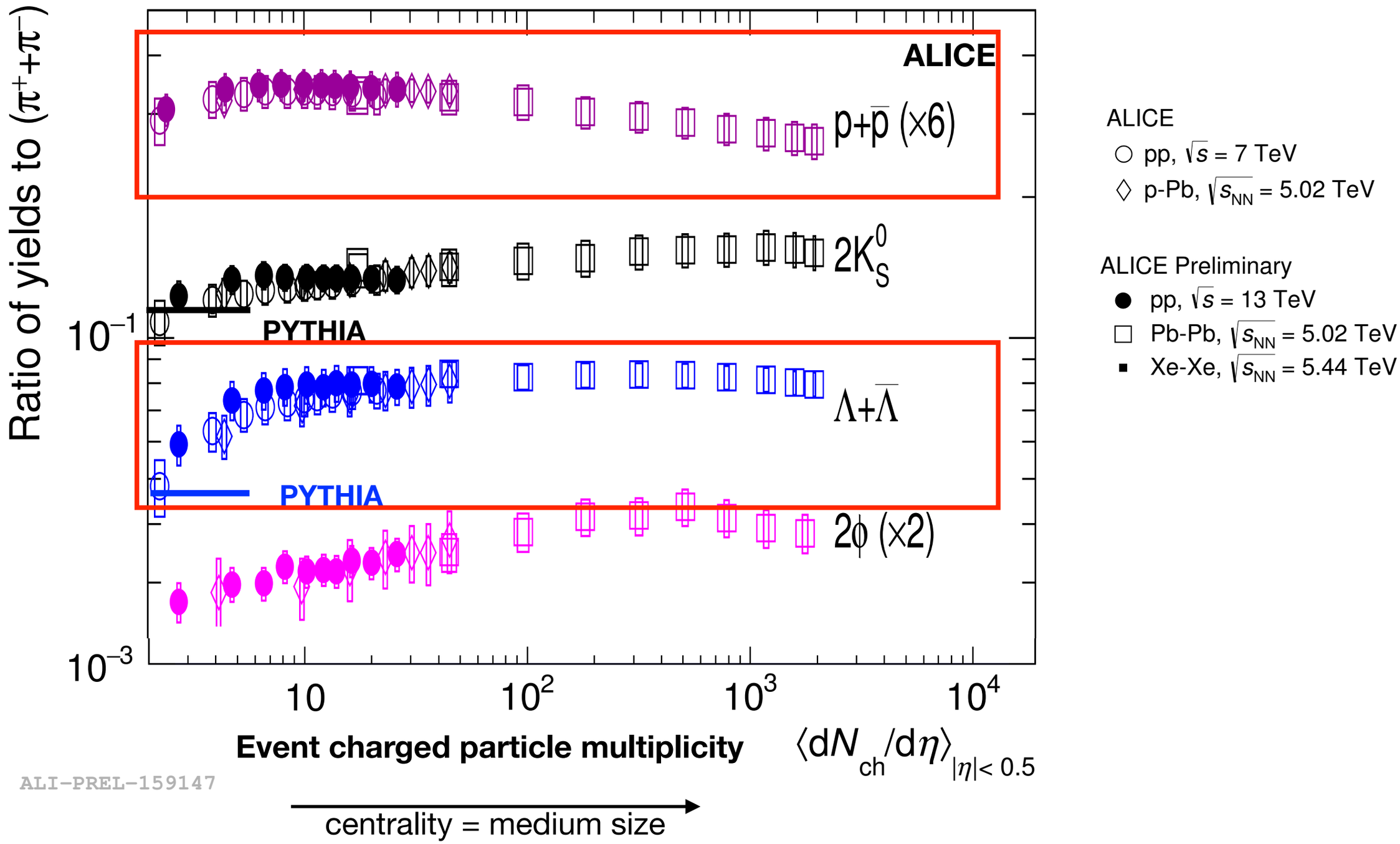
Λ^+_c/D^0 vs N_{part}, $3< p_T < 6$ GeV/c



centrality = medium size

- Enhanced charm baryon/meson at LHC energies (Pb+Pb)
- Enhancement is increasing with larger system size at RHIC energies (Au+Au)
- Significant enhancement observed with respect to PYTHIA for small and large collision systems

Light flavor baryon/meson production (late)



- Λ^+_c/D^0 ratio comparable to Λ/pion light flavour.
- However proton/pion is rather flat
- Low multiplicity pp is in agreement with PYTHIA

Jet (parton)

+

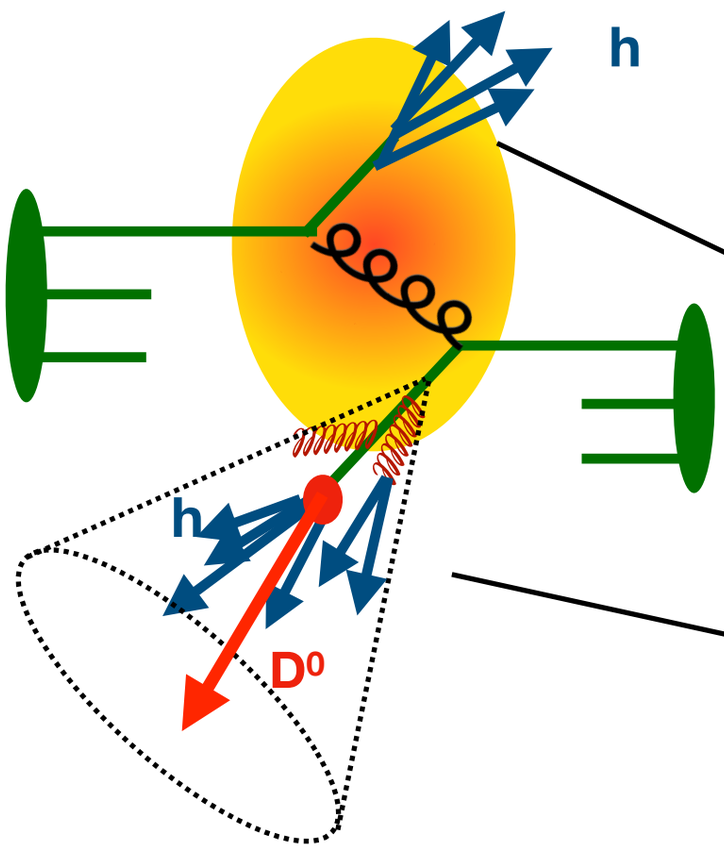
Medium

—> particle correlations

c-quark - fragmentation (D^0-h)

Reminder: triggered correlation -> same-side sees a little bit of the medium

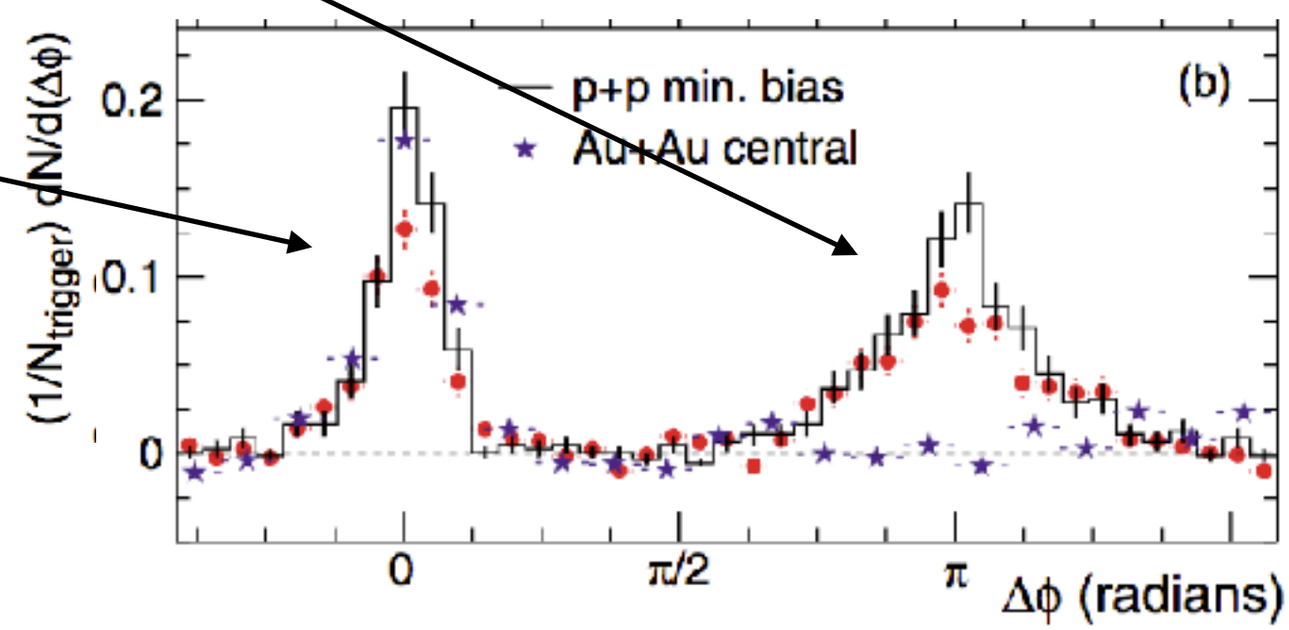
away-side correlation
More medium on the away-side



same-side correlation
Still medium on the same-side

$\Delta\phi$ - h-h correlation

same-side away-side



$$\Delta\eta = \eta_{D^0} - \eta_h$$
$$\Delta\phi = \phi_{D^0} - \phi_h$$

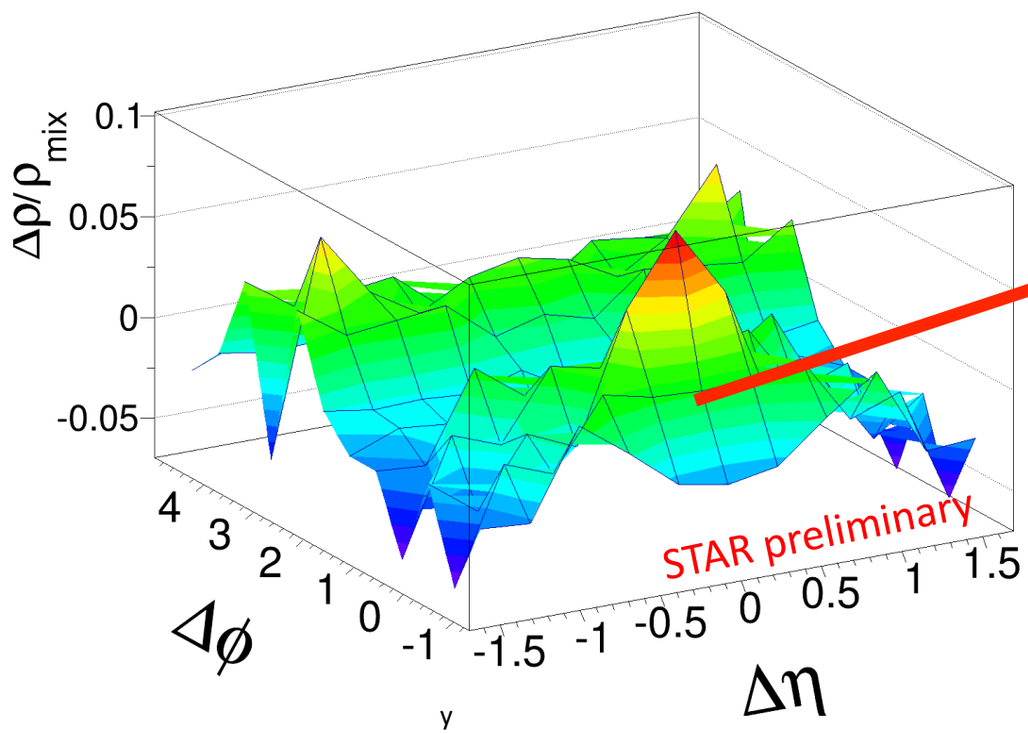
STAR collaboration PhysRevLett.91.072304

Correlation components (D^0-h)

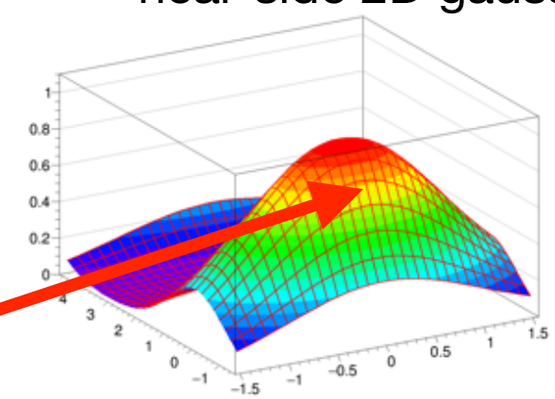
trigger D^0 : p_T = 2-10 GeV/*c*

associate $h^{\pm}$: p_T>0.15 GeV/*c*

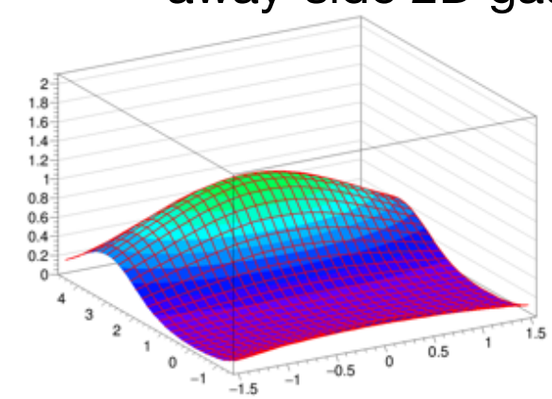
Au+Au 200 GeV



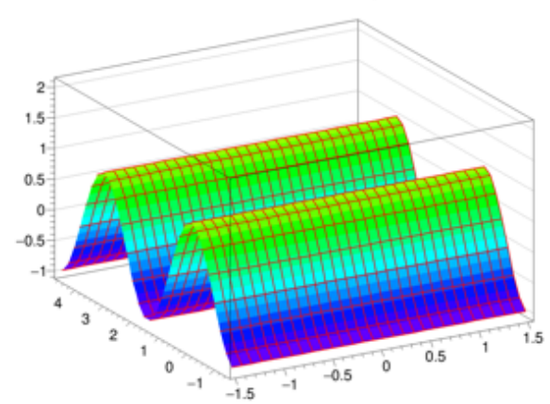
jet (+medium)
near-side 2D gauss



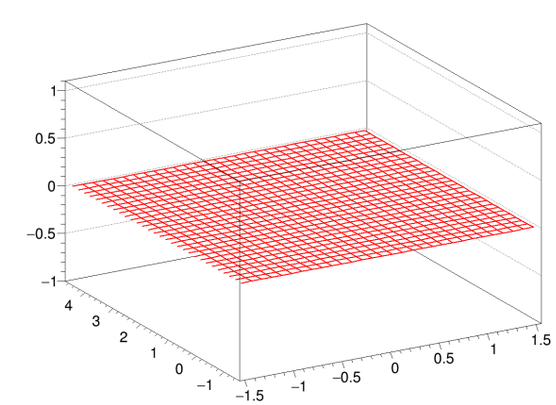
jet (+medium)
away-side 2D gauss

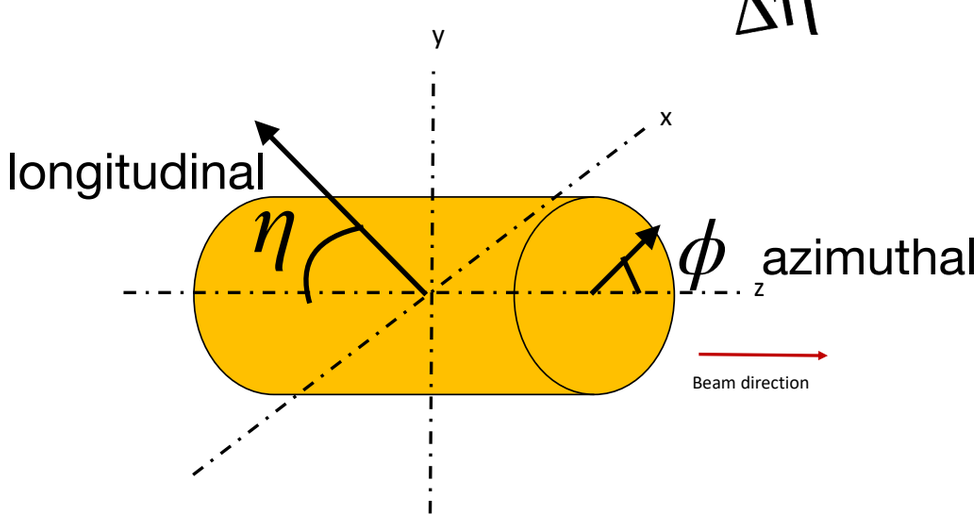


medium
cos2 Δϕ



medium
offset





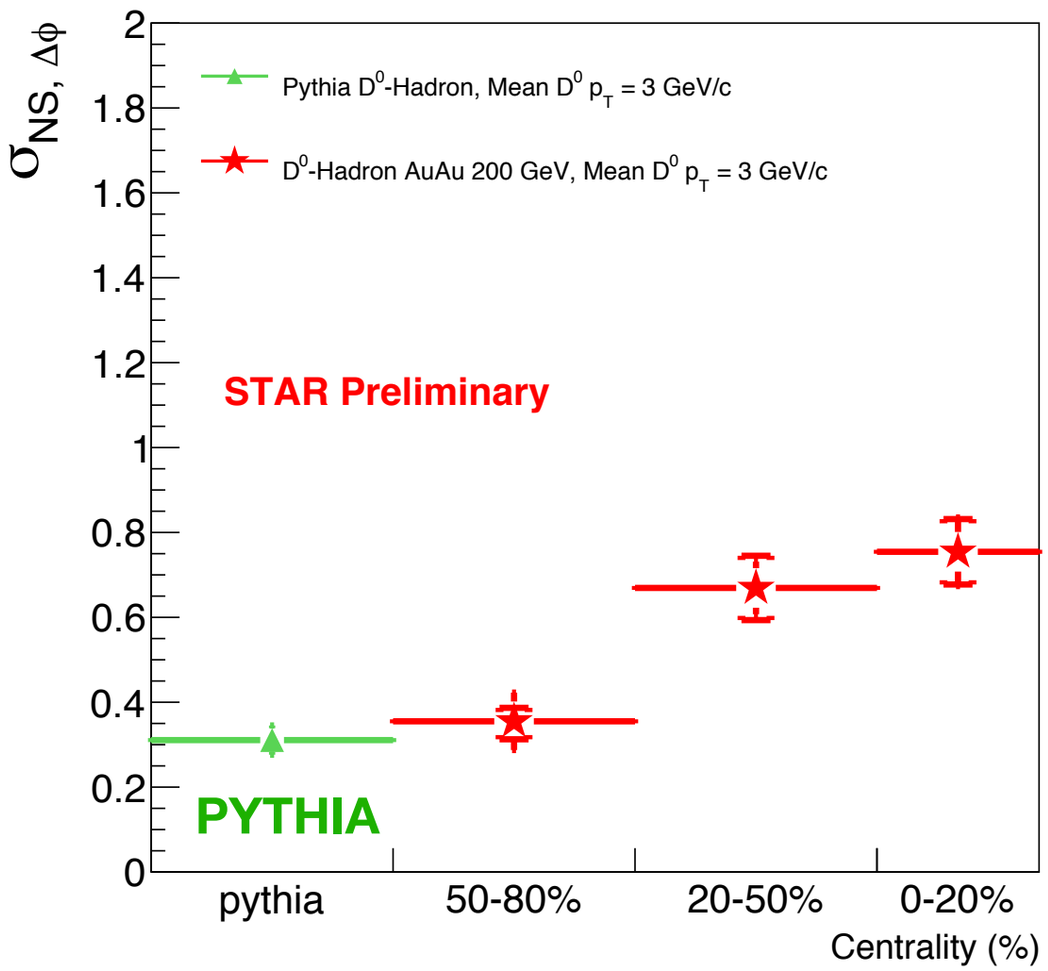
c-quark - fragmentation (D^0-h)

Reminder: triggered correlation -> near side experiences a little bit of the medium

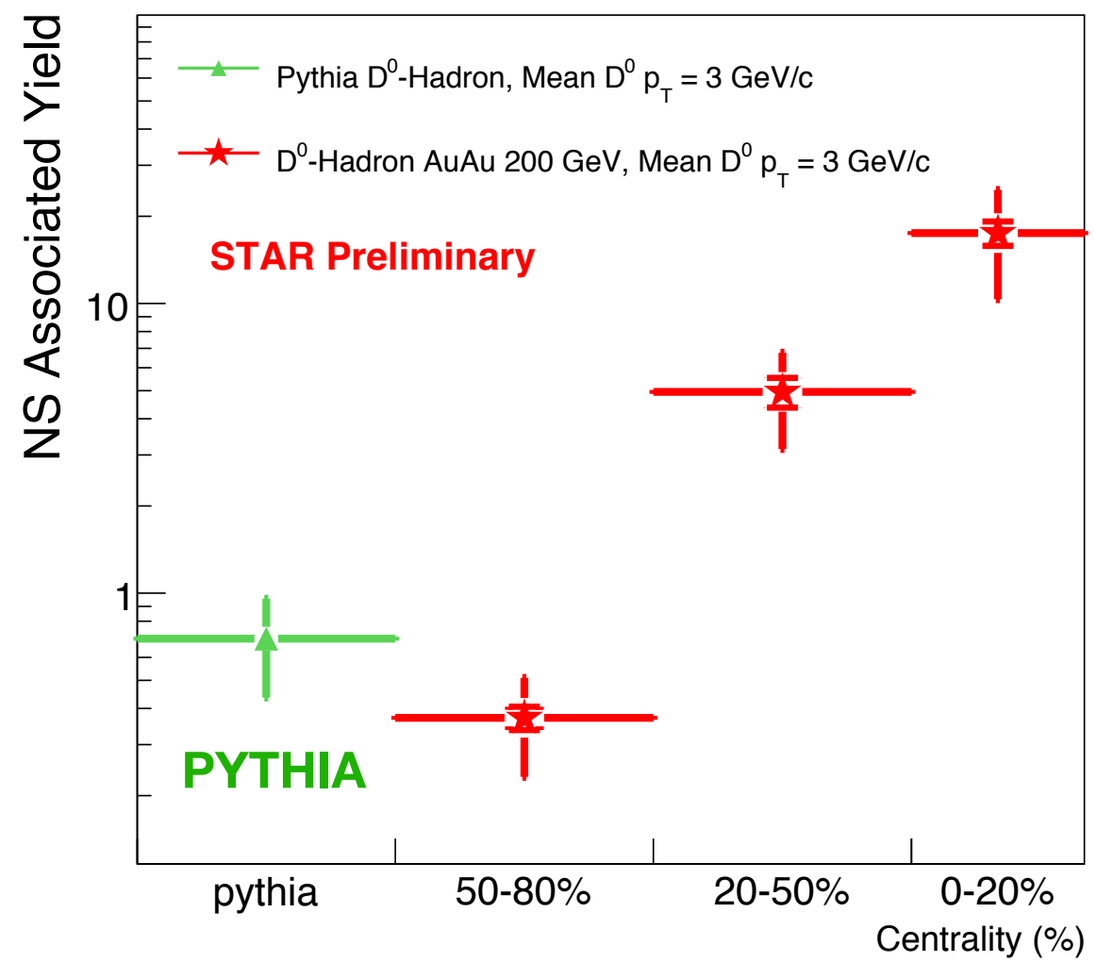
D^0 : p_T^{D0} = 2-10 GeV/c h: p_T^h > 0.15 GeV/c

Au+Au 200 GeV

Near Side Δϕ-width



Near Side hadron yield



- Broadening of near-side hadron distribution with increasing centrality (medium size)
- Associated hadron yield (~pions) is increasing
- PYTHIA in agreement with small medium (peripheral)
- Large medium (central)—> More hadrons and spread out further.

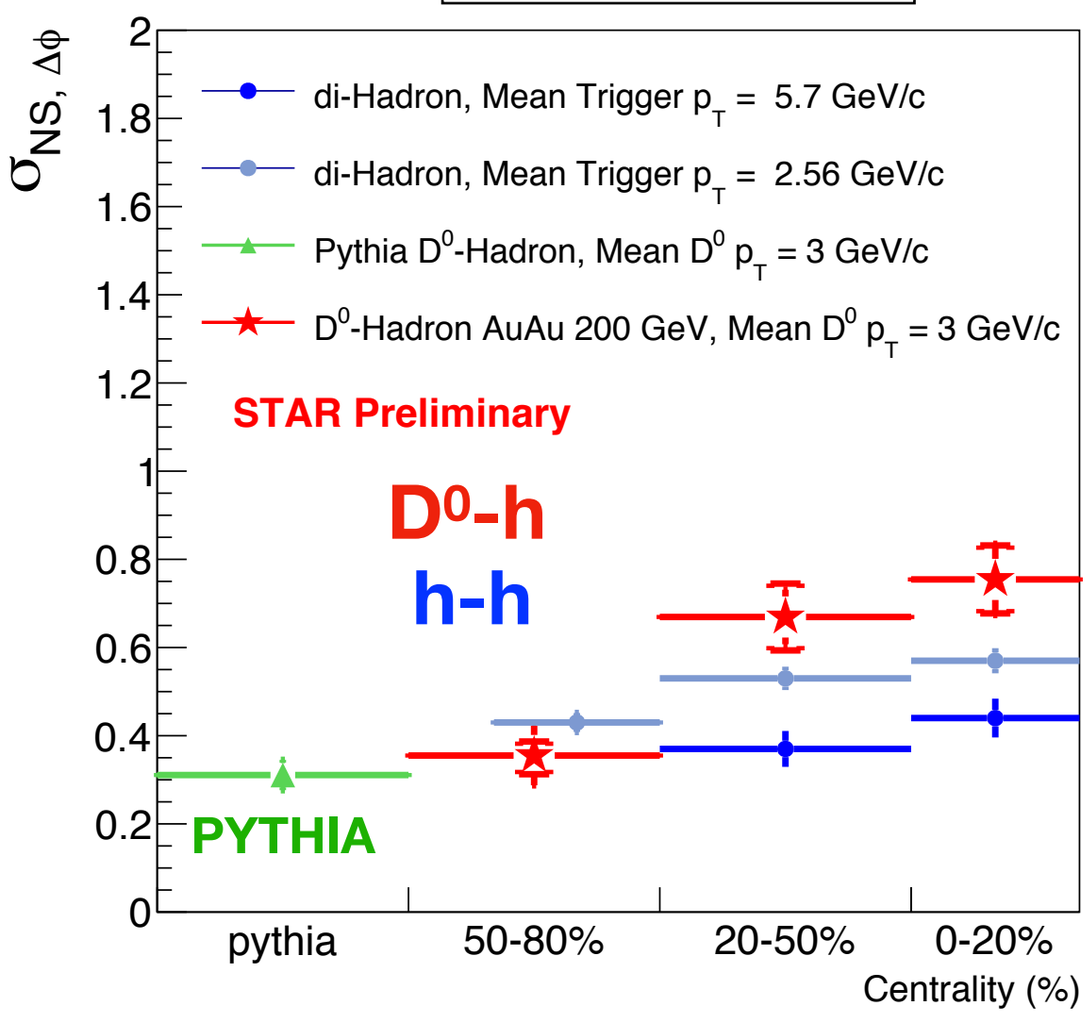
c-quark - fragmentation (D^0-h,h-h)

Reminder: triggered correlation -> near side experiences a little bit of the medium

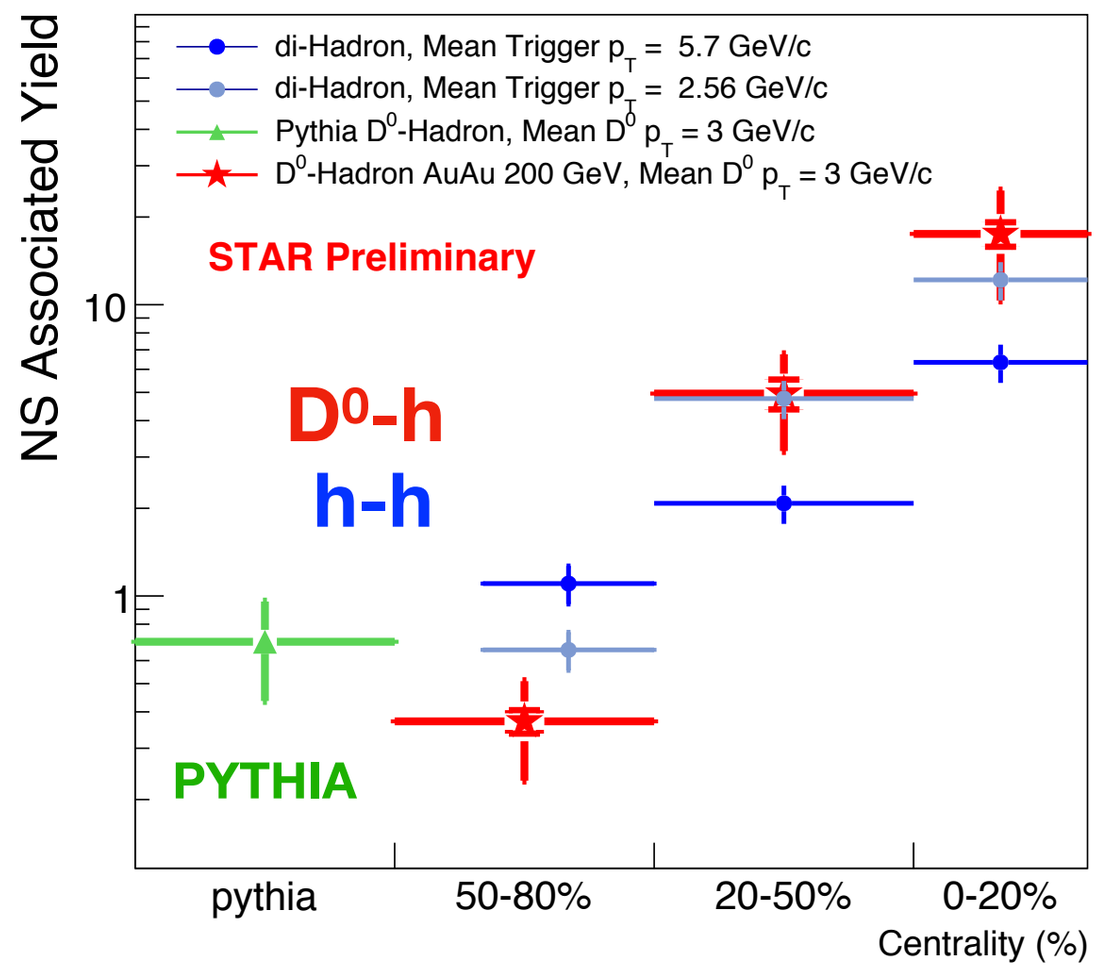
D^0 : p_T^{D0} = 2-10 GeV/c h: p_T^h > 0.15 GeV/c

Au+Au 200 GeV

Near Side Δϕ-width



Near Side hadron yield



Phys. Rev. C **91**, 064910 (2015)

- Same for D^0 and hadron triggered distribution

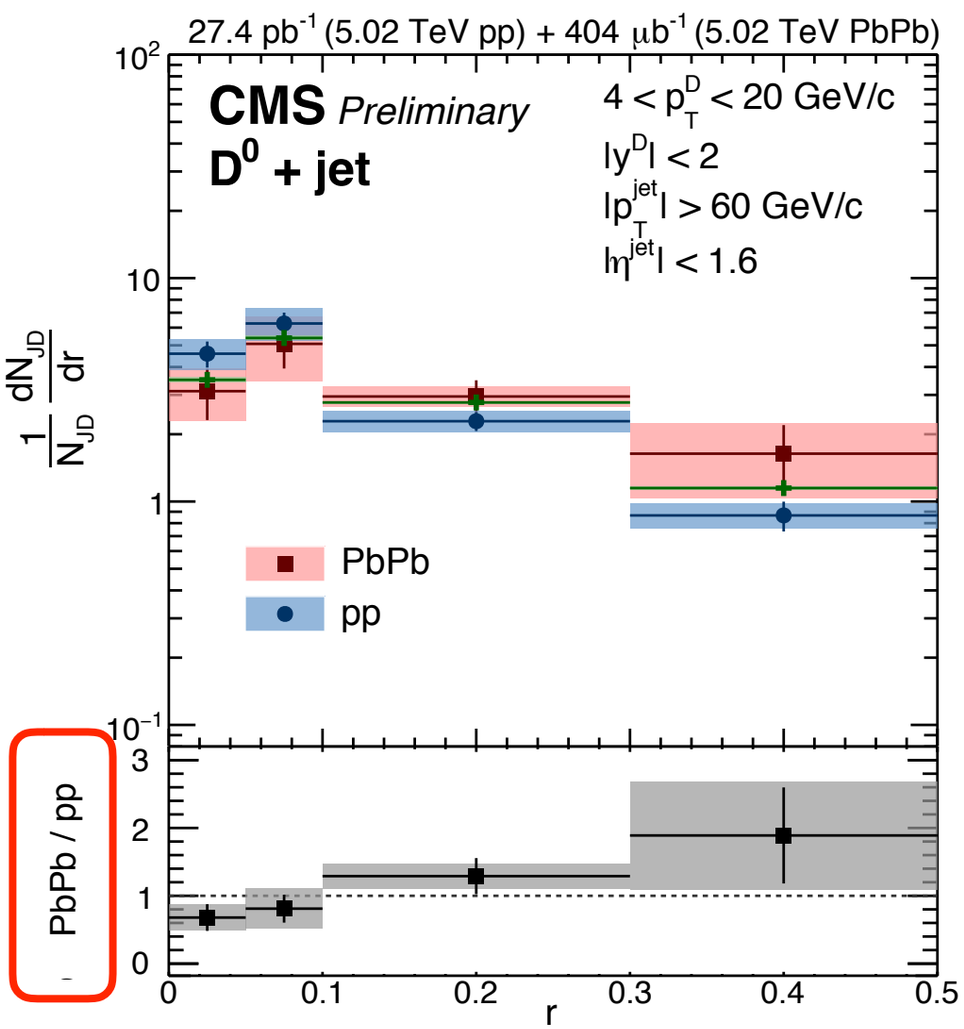
—> similar energy loss for heavy and light quarks ? Theory is needed !

Heavy flavor (D^0) tagged jets

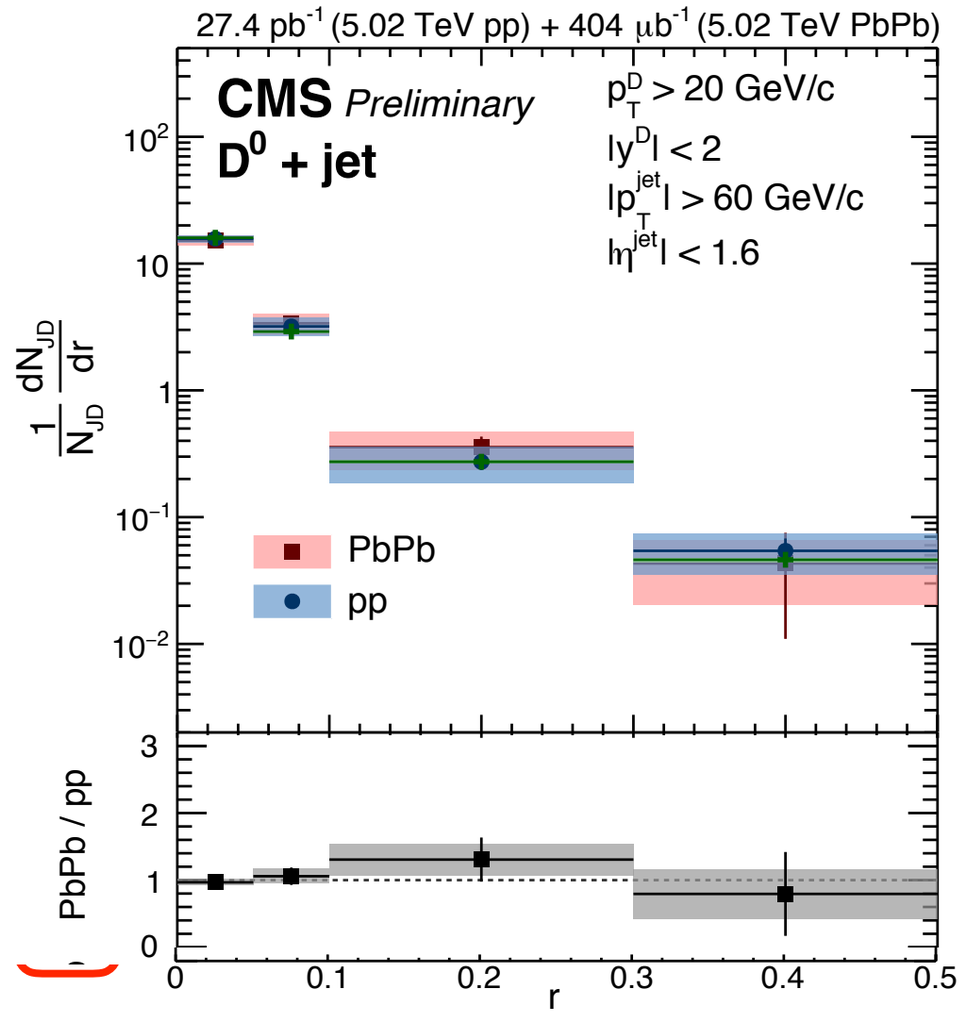
Study the modification of jet fragmentation and modification of jet radial profile

Radial distribution of D^0 in jets -> angular distribution of D^0 w.r.t jet axis

Low-p_T D^0 : $4 < p_T^{D0} < 20$ GeV/c

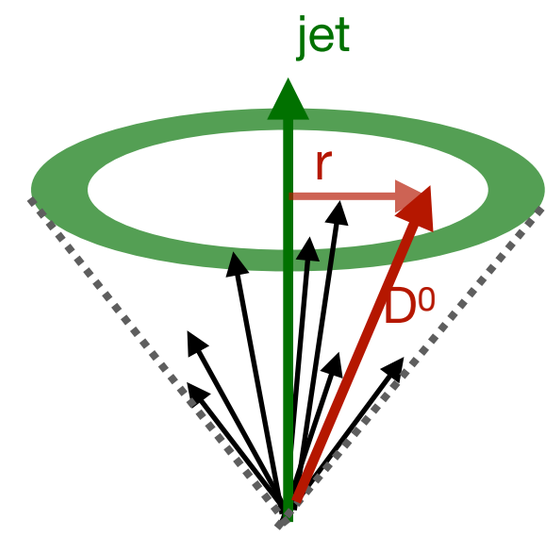


High-p_T D^0: $p_T^{D0} > 20$ GeV/c



radius parameter

$$r = \sqrt{\Delta\phi^2 + \Delta\eta^2}$$



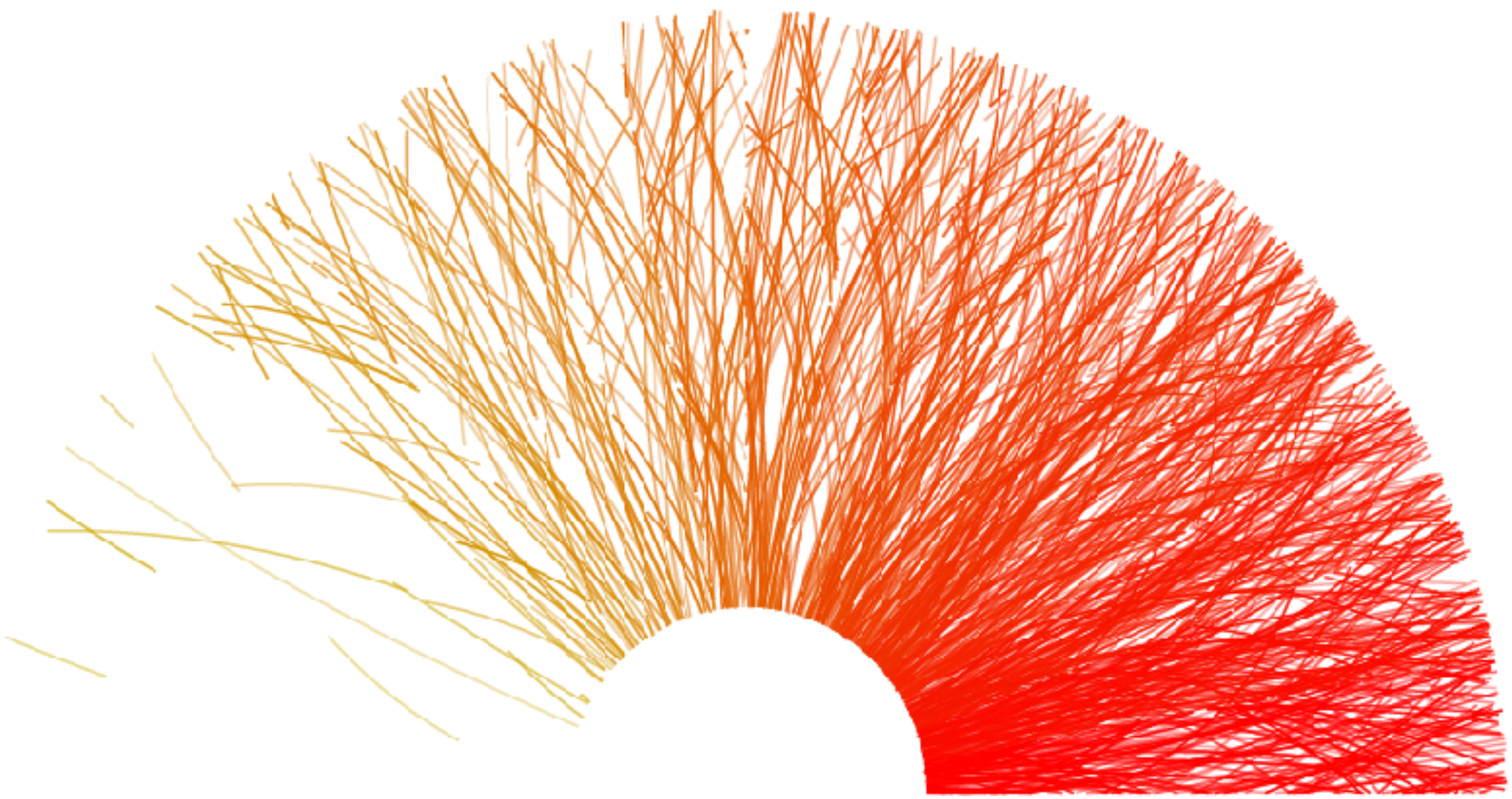
- Low p_T D^0: increasing trend with r

—> could indicate D^0 further away from jet-axis in Pb-Pb compared to pp.

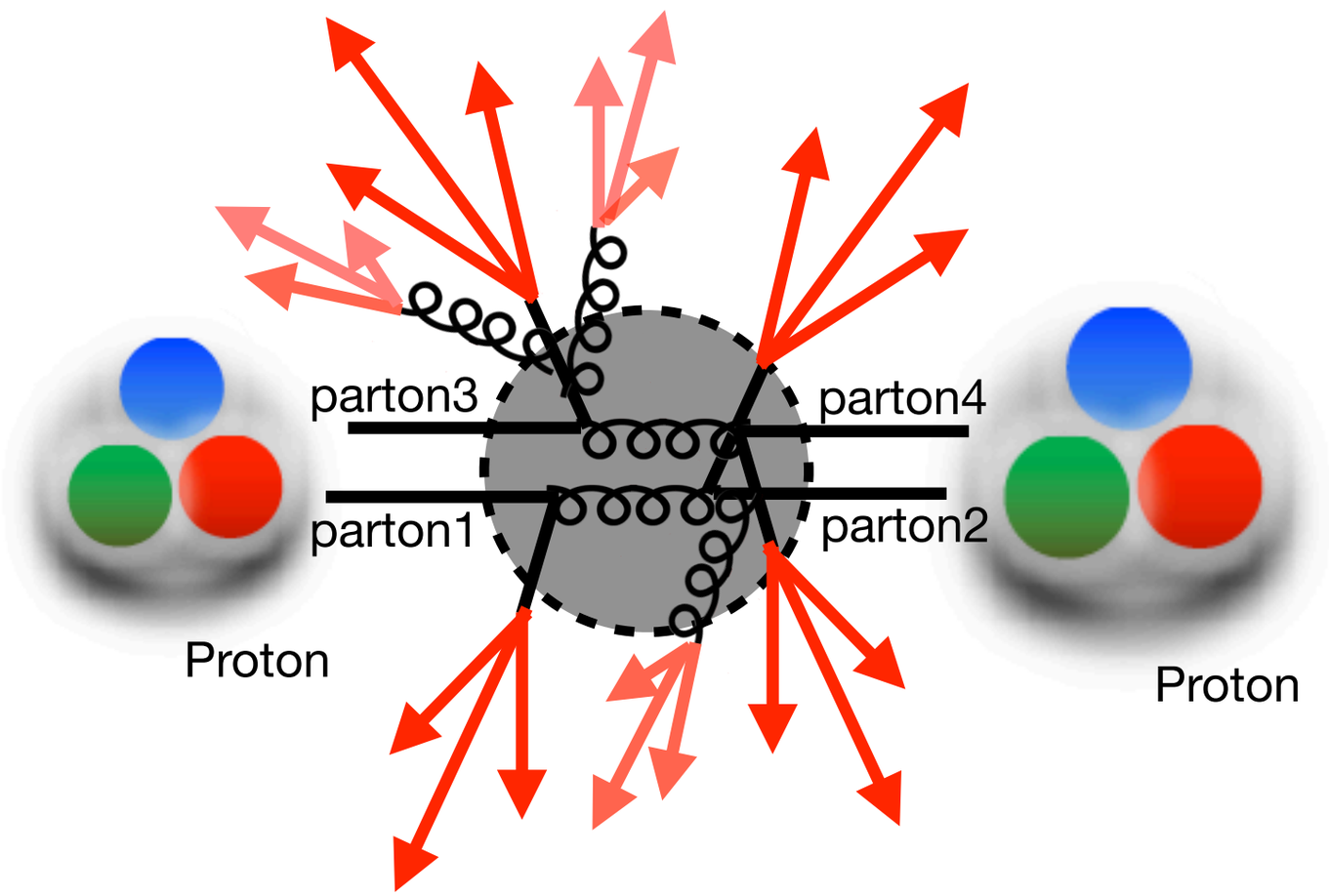
- High p_T D^0: ratio consistent with unity —> D^0 distribution not changed by medium

Medium : small -> large (size)

- Smooth transition of small to large medium with multiplicity (event activity) of hadrons in collision
- In pp, pA and AA collisions



Multiple interactions in pp —> medium



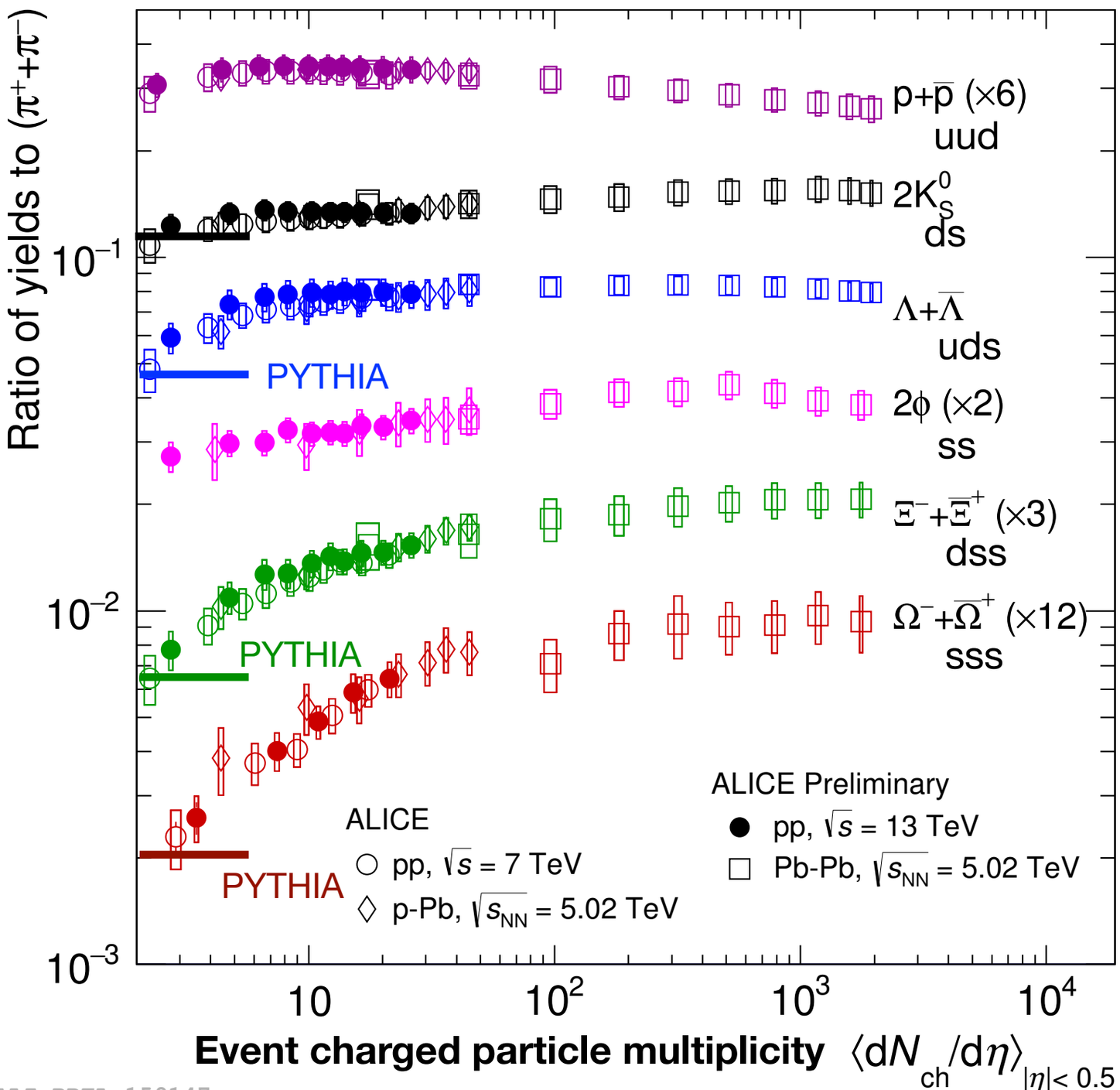
scattering 1

scattering 2

—>multiple parton interactions
—>gluon radiation

—> higher event multiplicity

Strangeness/pion production (pp, pA, AA)



ALI-PREL-159147

and Nature Phys. 13 (2017) 535-539

Pb-Pb 70-80% = p-Pb 0-5% = 45

- **Strangeness enhancement in AA with respect to pp scales with strange quark content**

—> coming from multiple parton interactions (not hadronic)

- smooth transition from pp, pA to AA

- in small systems: (small QGP ?)

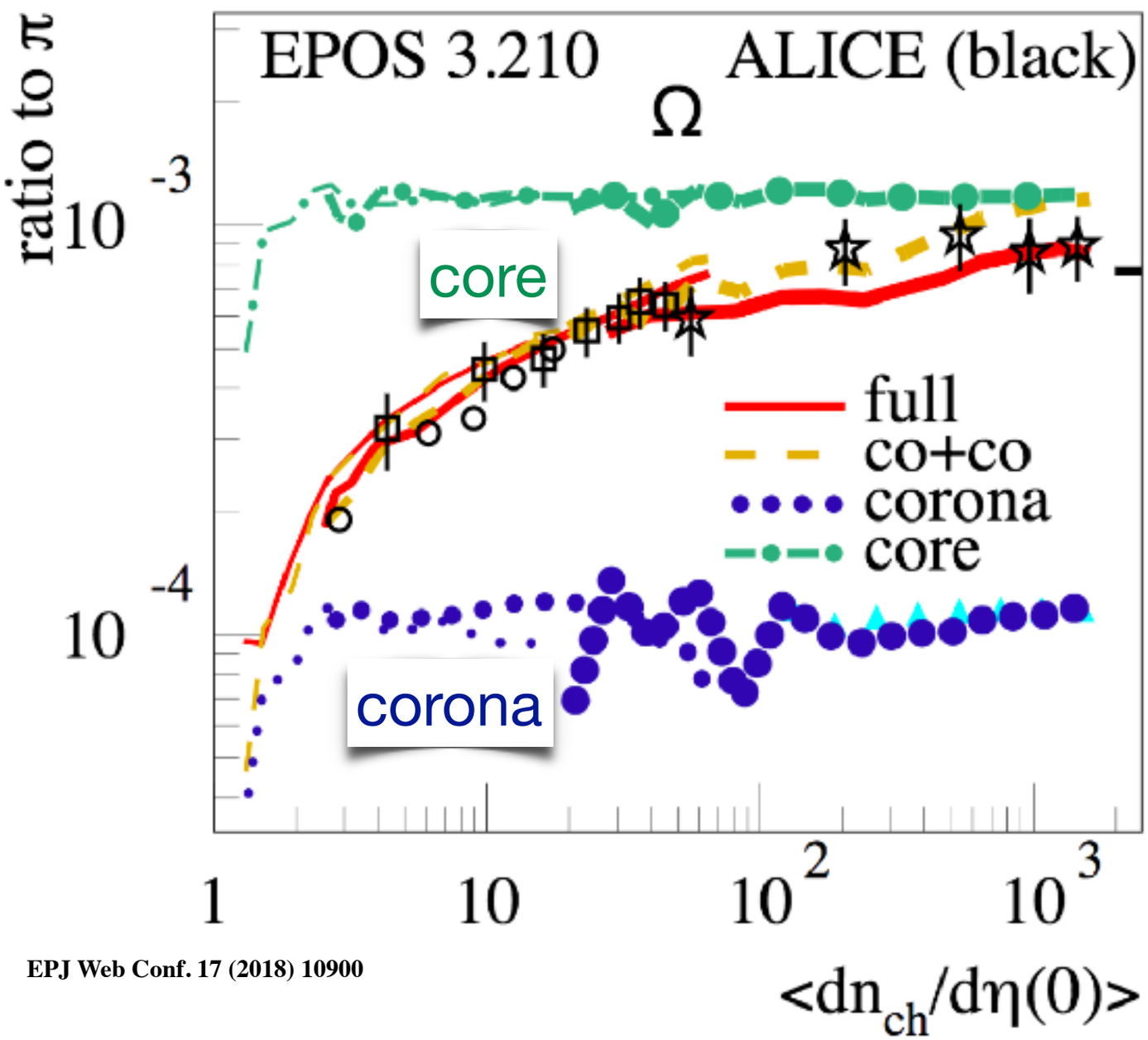
—> modified hadron production in small systems?

—> modified fragmentation function ?

- Described with PYTHIA (string frag) in low multiplicity pp collisions

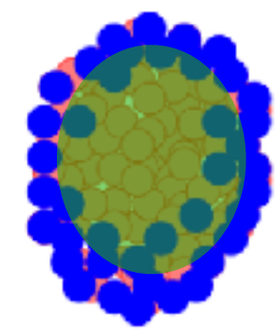
Omega/pion vs event activity

EPOS: Multiple pomeron exchange via Gribov-Regge theory
Hard interactions based on pQCD



EPJ Web Conf. 17 (2018) 10900

Core-Corona approach
with multiple parton scattering



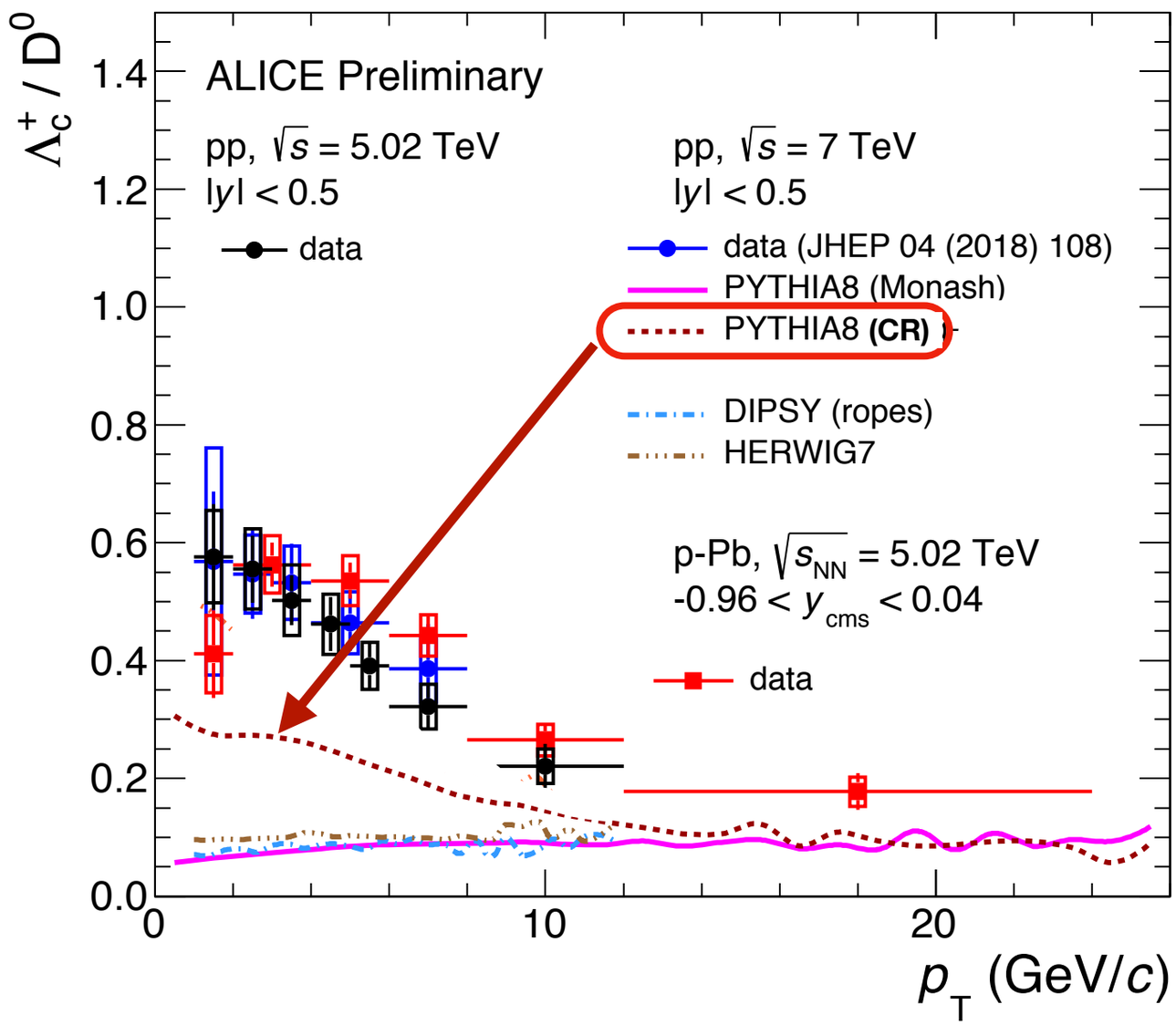
Corona (blue)
= "partons" with no interactions
—> string decay
—> VACUUM
(consistent with PYTHIA)

Core (green)
= "partons" with multiple interactions
—> conservation laws (hydro)
—> statistical decay
—> MEDIUM

- Enhanced strangeness production in core medium
- Strangeness enhancement from partonic medium

—> partonic medium (QGP?) in small systems (pp and pA)

Baryon production (Λ^+_c/D^0) p+p and p-Pb

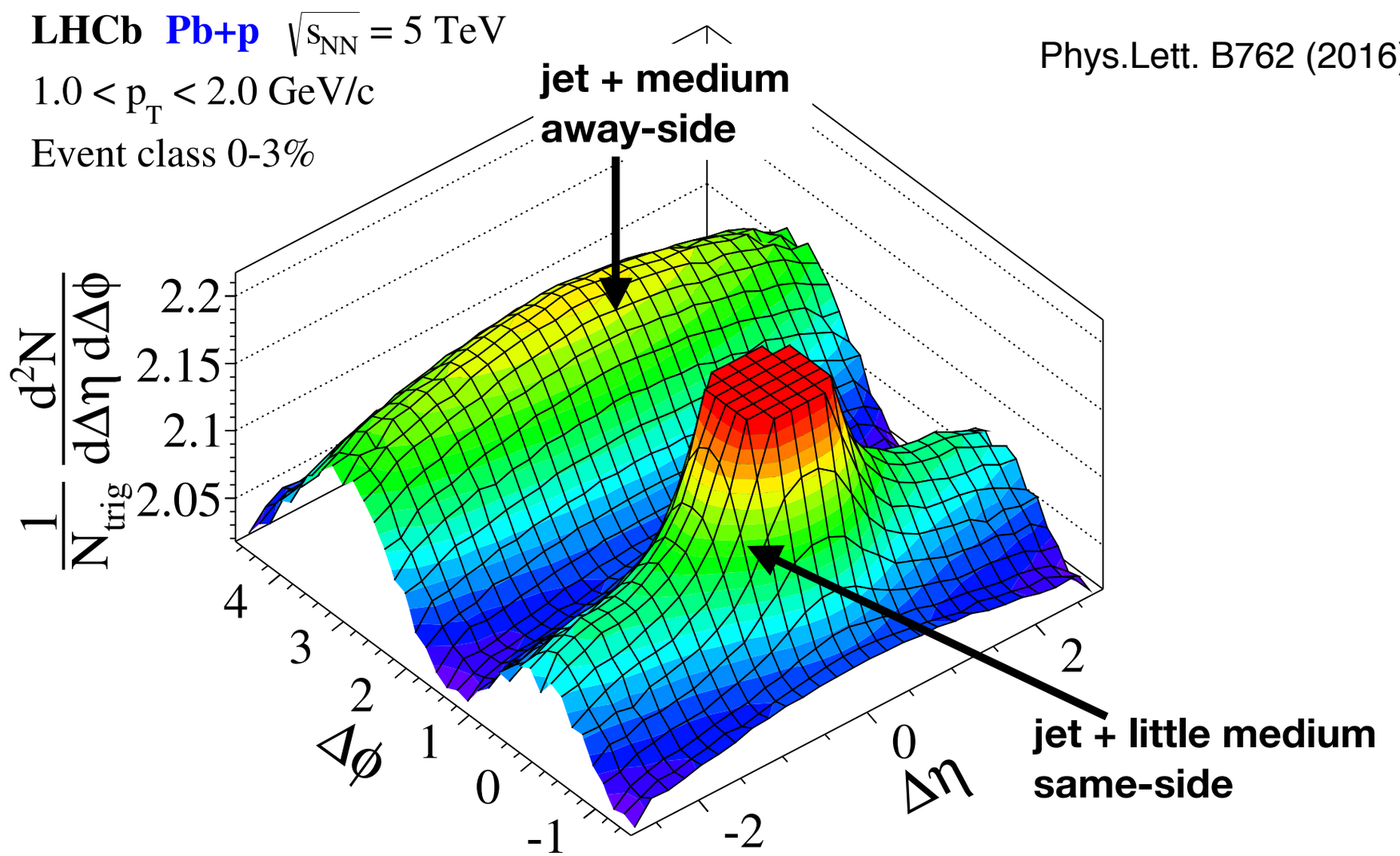


PYTHIA, DIPSY, HERWIG are not describing the data in
min bias pp and pPb events (not lowest multiplicity events !)

NEW: PYTHIA including color reconnection (CR) for multiple strings in medium
(junctions for string-string reconnection) —> closer to data in low p_T region

Correlations in small systems

Pb+p 5 TeV 0-3%



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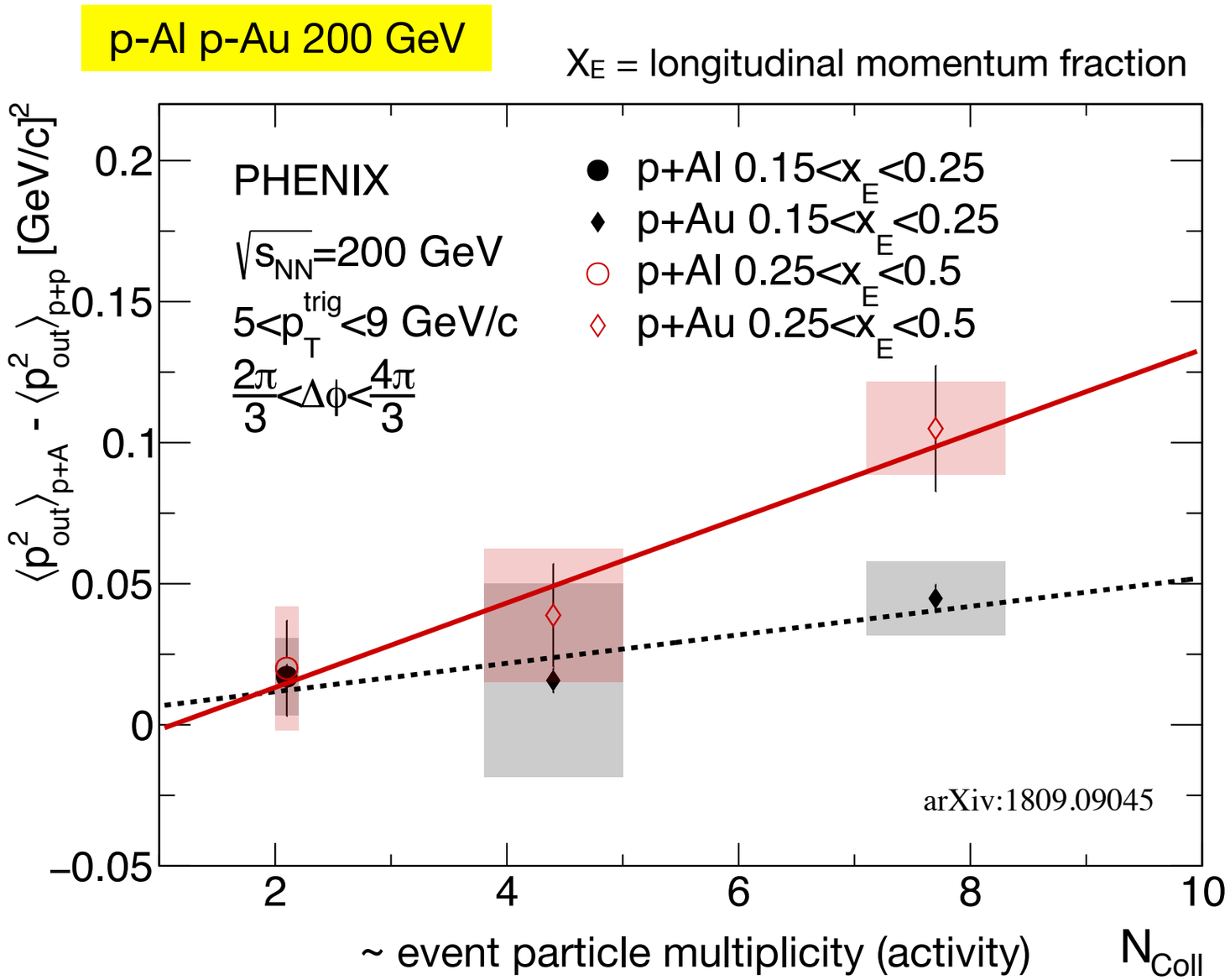
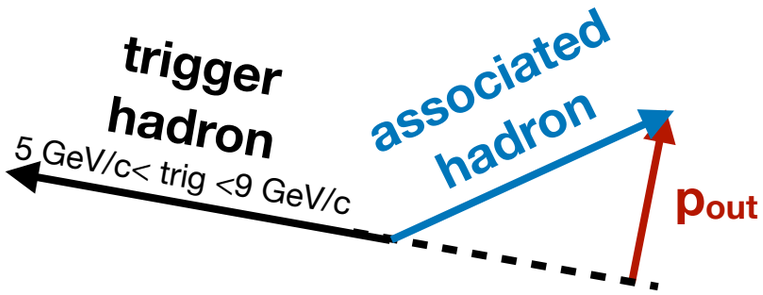
- Correlations similar to AA collisions
- Broadening on the away-side

Jet broadening in small (p+A)





$$p_{out} = p_T^{assoc} sin\Delta\phi$$

- Larger broadening on the away-side in high multiplicity events

—> more collisions —> larger broadening

—> **scattering in partonic medium**

—> **broadening is system size dependent**

Summary

- Energy dissipation is medium size and mass dependent
- Jet modification due to medium interactions
- Enhanced baryon production in larger systems
- Enhanced strangeness production
- Partonic medium in small collision systems
- (Theory needed)
- Important to understand gluon density, distributions and gluon interactions —> EIC

Thanks !