Hard probes (mainly jets) at LHC

Yaxian MAO

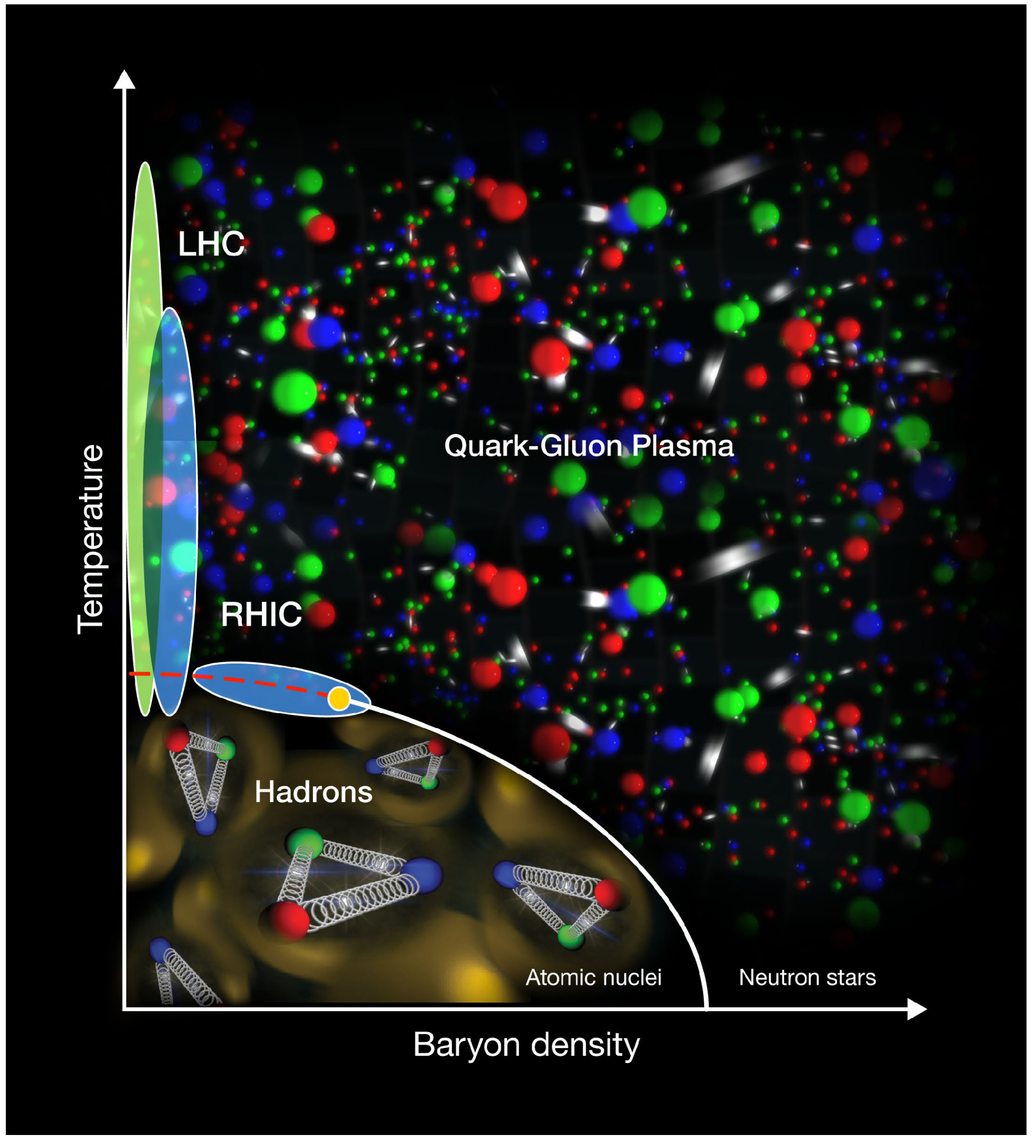
Central China Normal University

Tsukuba Global Science Week
Tsukuba, 2015

The QCD phase transition and HI collision

- QCD calculations (on the lattice) indicate that the phase transition occurs at a critical energy density

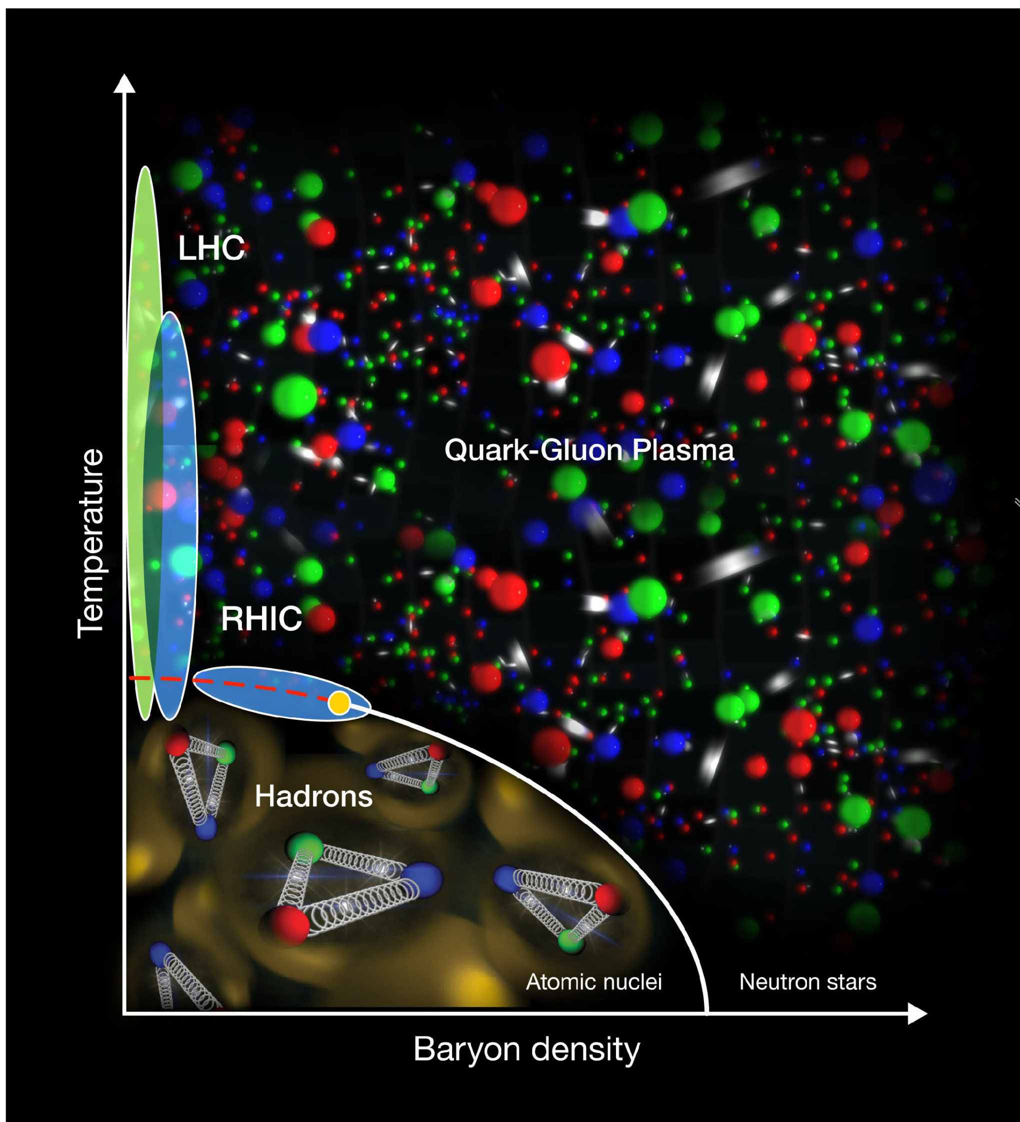
We can thus create a system of deconfined quarks and gluons
➡ by heating (T)
➡ by compression (matter density)

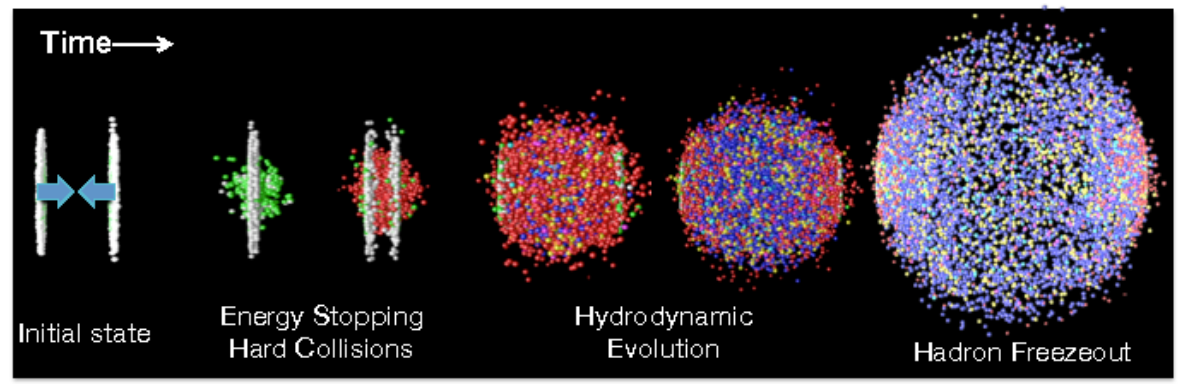


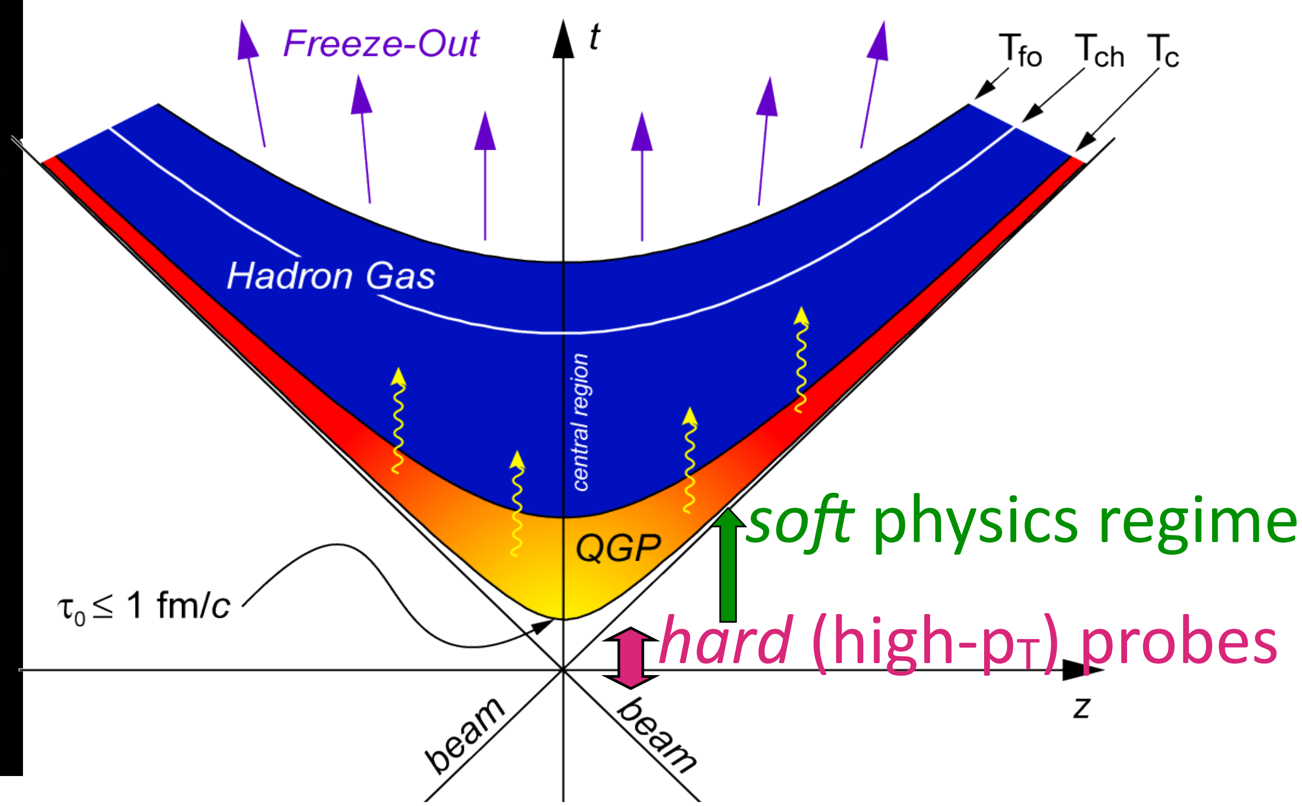
The QCD phase transition and HI collision

- QCD calculations (on the lattice) indicate that the phase transition occurs at a critical energy density

We can thus create a system of deconfined quarks and gluons
- ➡ by heating (T)
- ➡ by compression (matter density)







Two labs to create QGP

AGS : 1986 – 2000

- Si and Au beams ; $\sqrt{s}$ ~ 5 GeV
- only hadronic variables

RHIC : 2000 –

- Au beams ; up to $\sqrt{s}$ = 200 GeV
- 4 experiments (only two remain)

SPS : 1986 – 2003

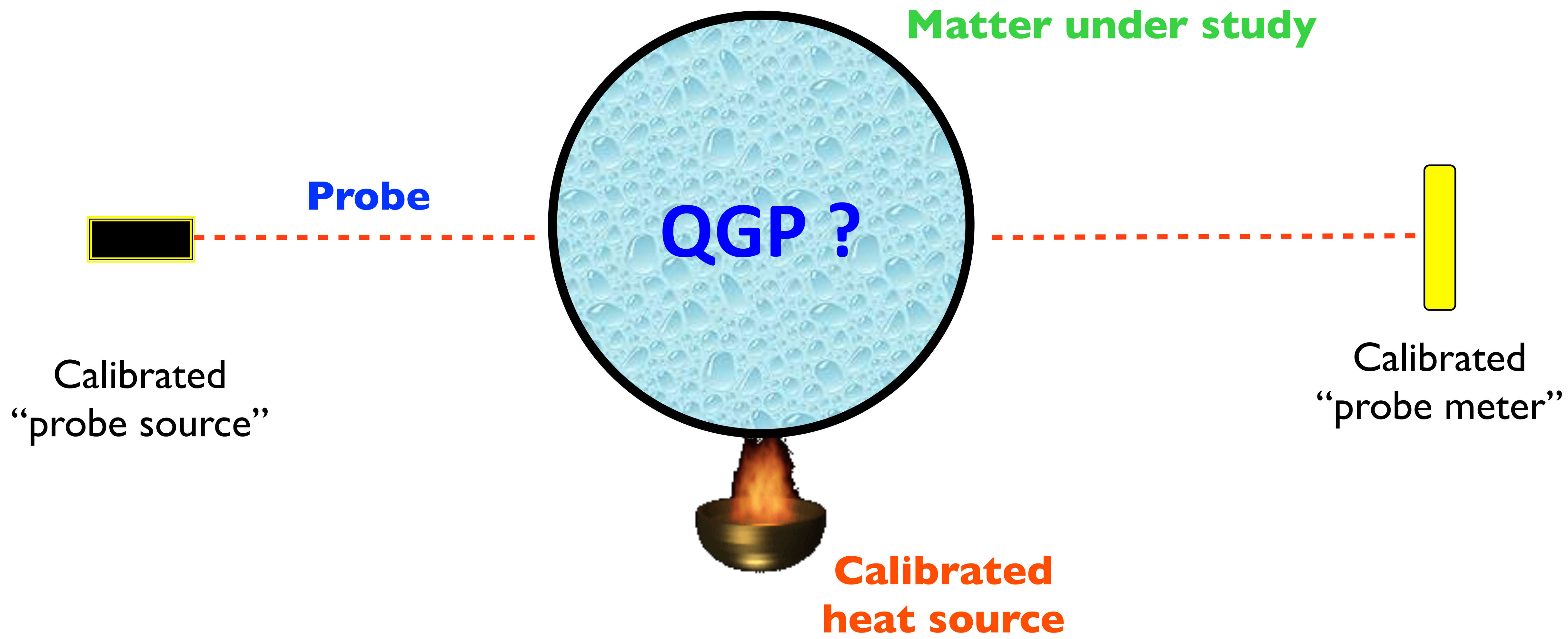
- O, S, In, Pb beams ; $\sqrt{s}$ ~ 20 GeV
- hadrons, photons and dileptons

LHC : 2010 –

- Pb beams ; up to $\sqrt{s}$ = 5500 GeV
- ALICE, CMS and ATLAS

Probing QGP

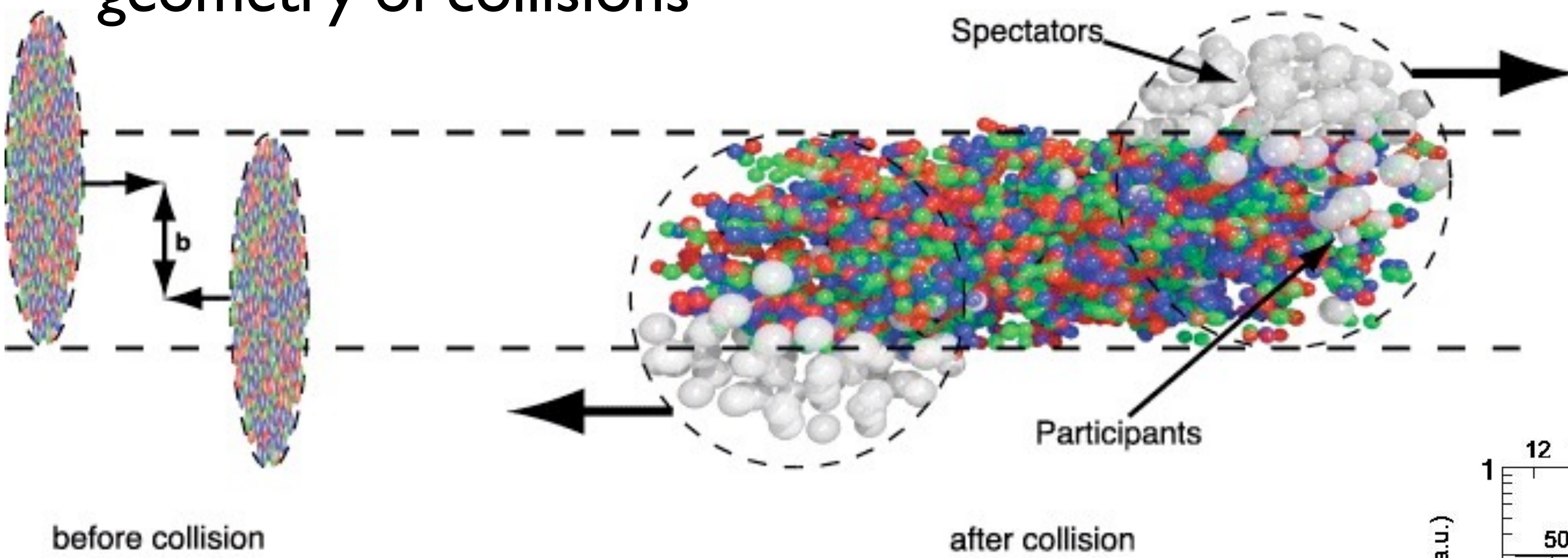
We study the QCD matter produced in HI collisions by looking how the well understood probes are modified, as a function of temperature (centrality of the collisions)

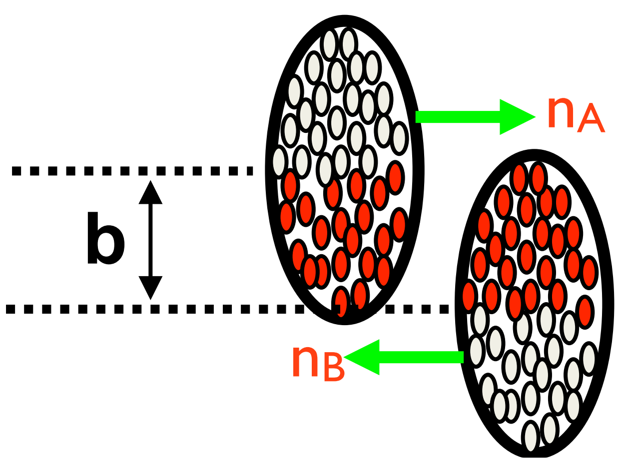


Centrality of the collisions

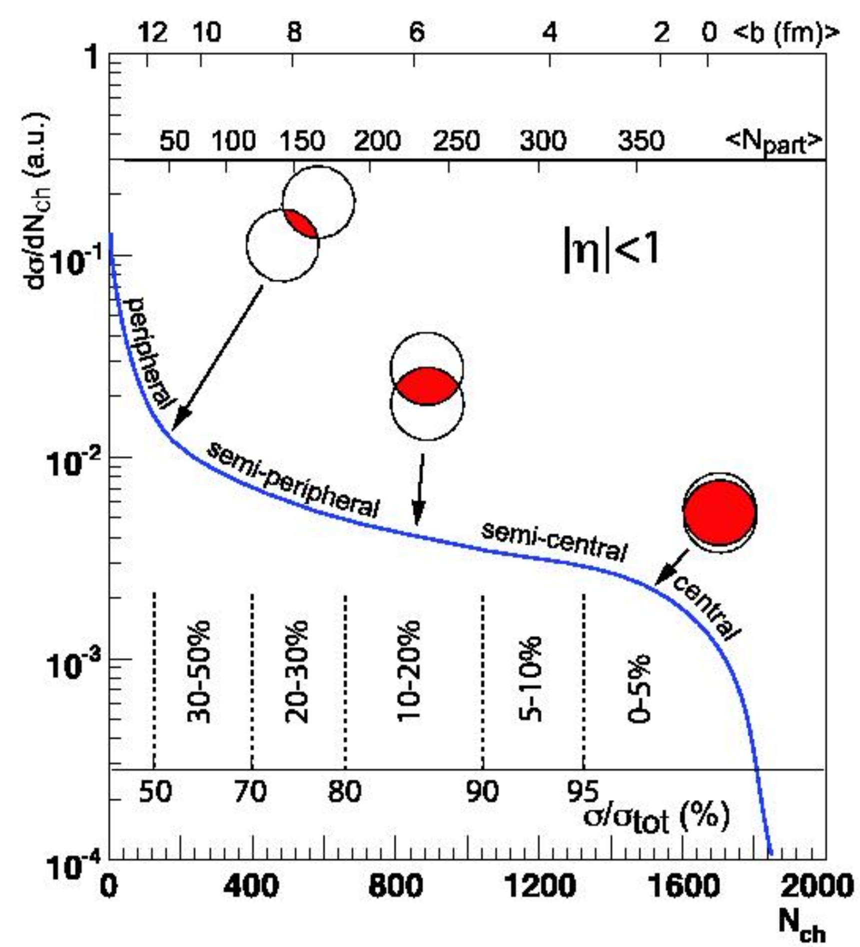
Controls the volume, shape and energy density of the system

➡ Multiplicity and energy of produced particles are correlated with geometry of collisions





$$N_{part} = n_A + n_B$$
$$N_{coll} = n_A \otimes n_B$$

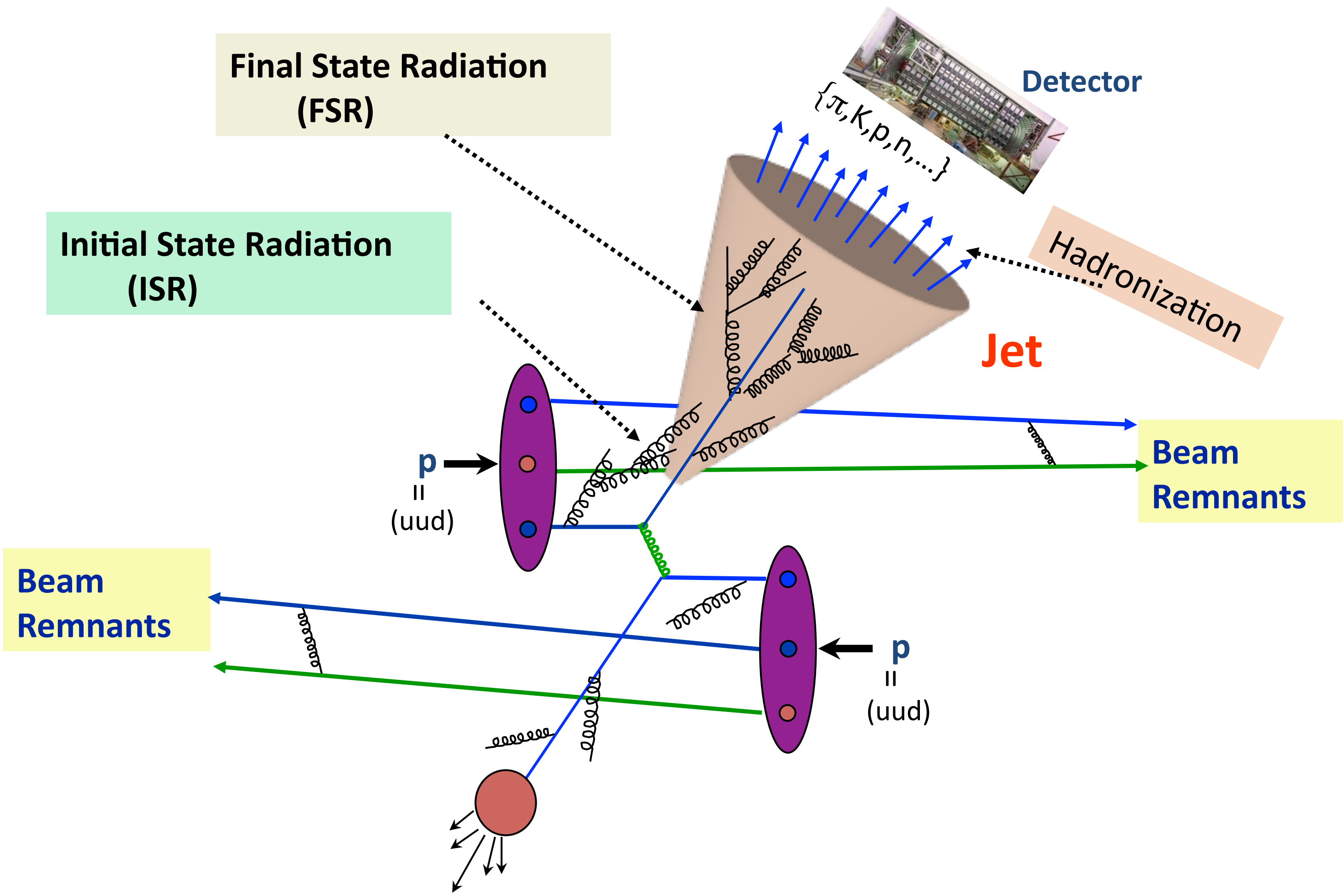


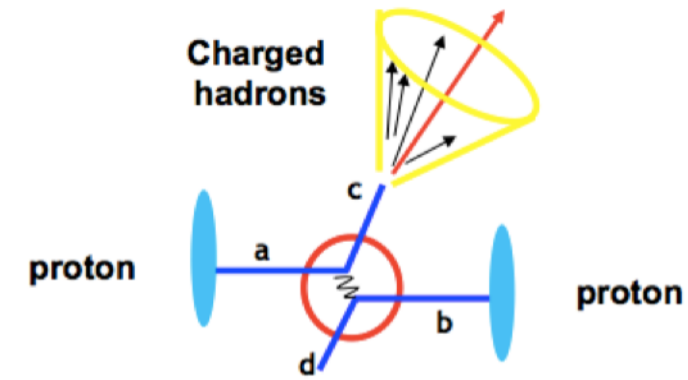
Soft processes: long timescale, large σ, $\sigma_{tot} \propto N_{part}$

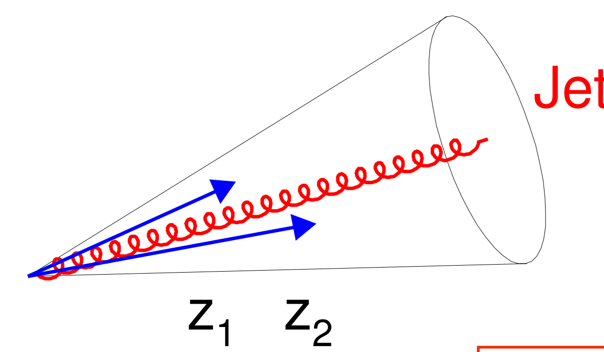
Hard processes: short timescale, large σ, $\sigma_{tot} \propto N_{coll}$

Hard scattering and jet production:QCD

Study the strong force using jet production







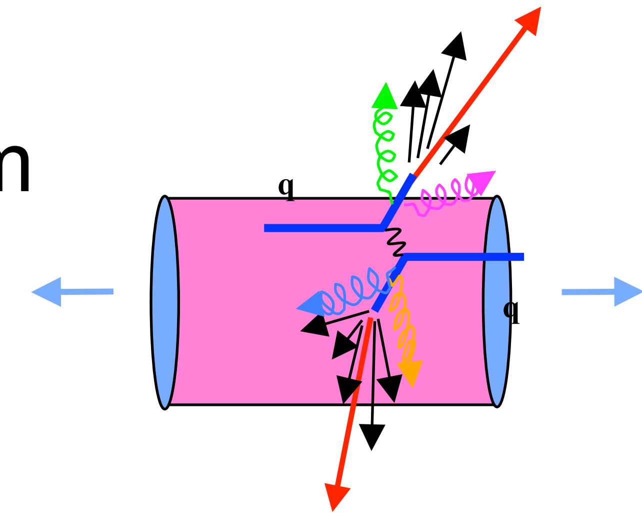
$$z = \frac{p_{\text{hadron}}}{p_{\text{jet}}}$$

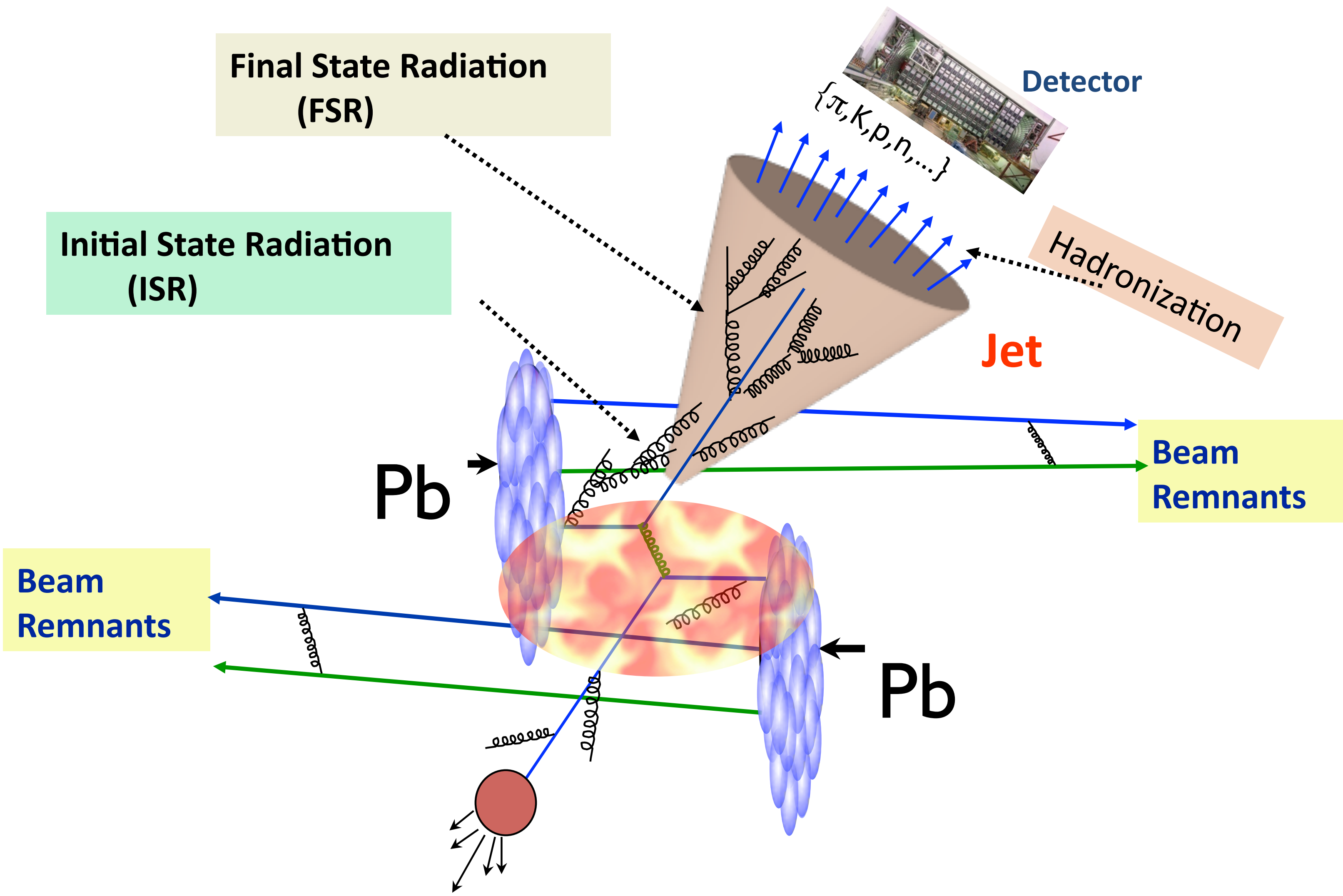
- Jets of particles produced in high energy parton-parton scattering
- Jet fragmentation function (FF): hadron distribution as a function of z, (momentum fraction taken by hadron from the jet)

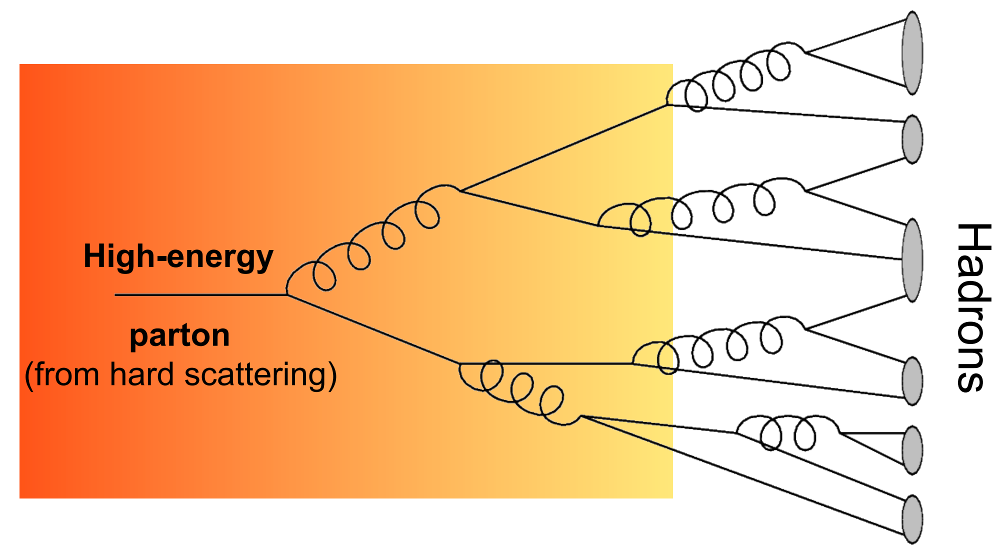
Jet-quenching in QGP

Study the transport properties of the QGP

a color charge (g, q, Q) in a colored medium





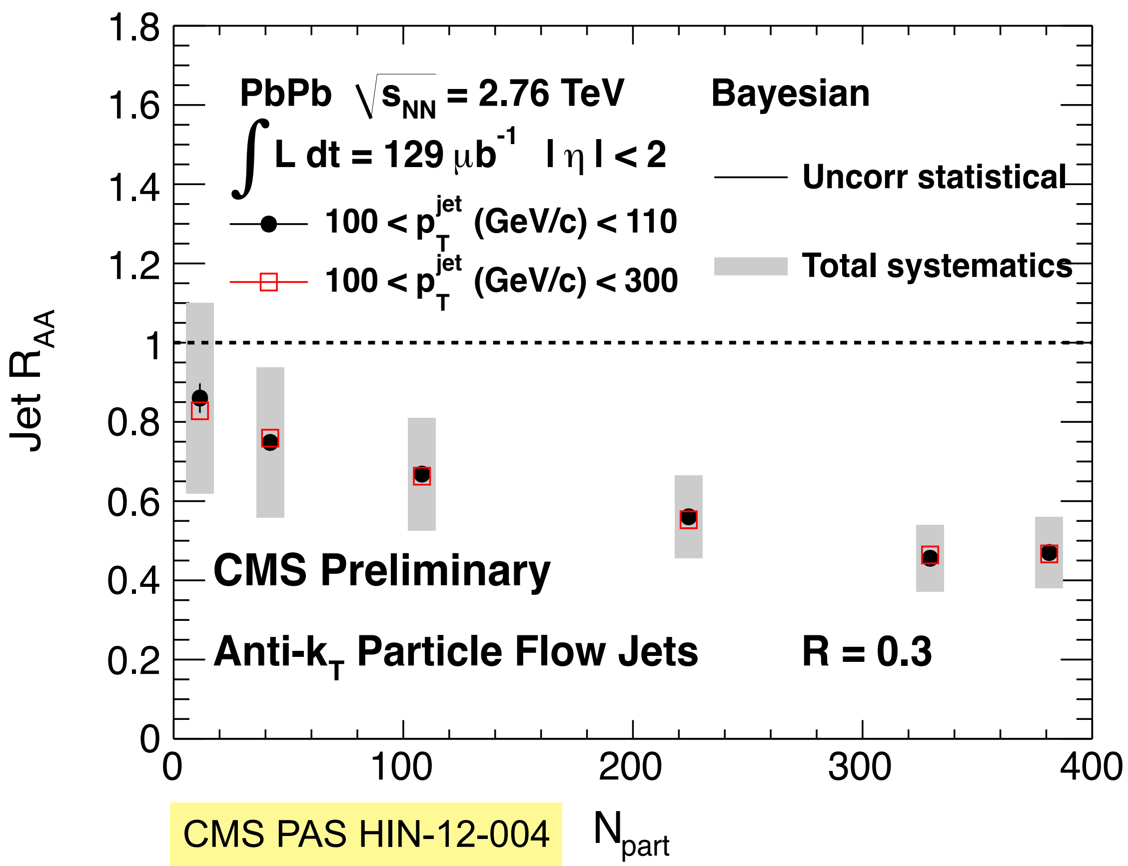


- Partons loose energy ΔE when traversing the medium
  - Jet(E) → Jet (E' = E-ΔE) + soft particles(ΔE)
- Jet quenching measures 'stopping power' of QGP

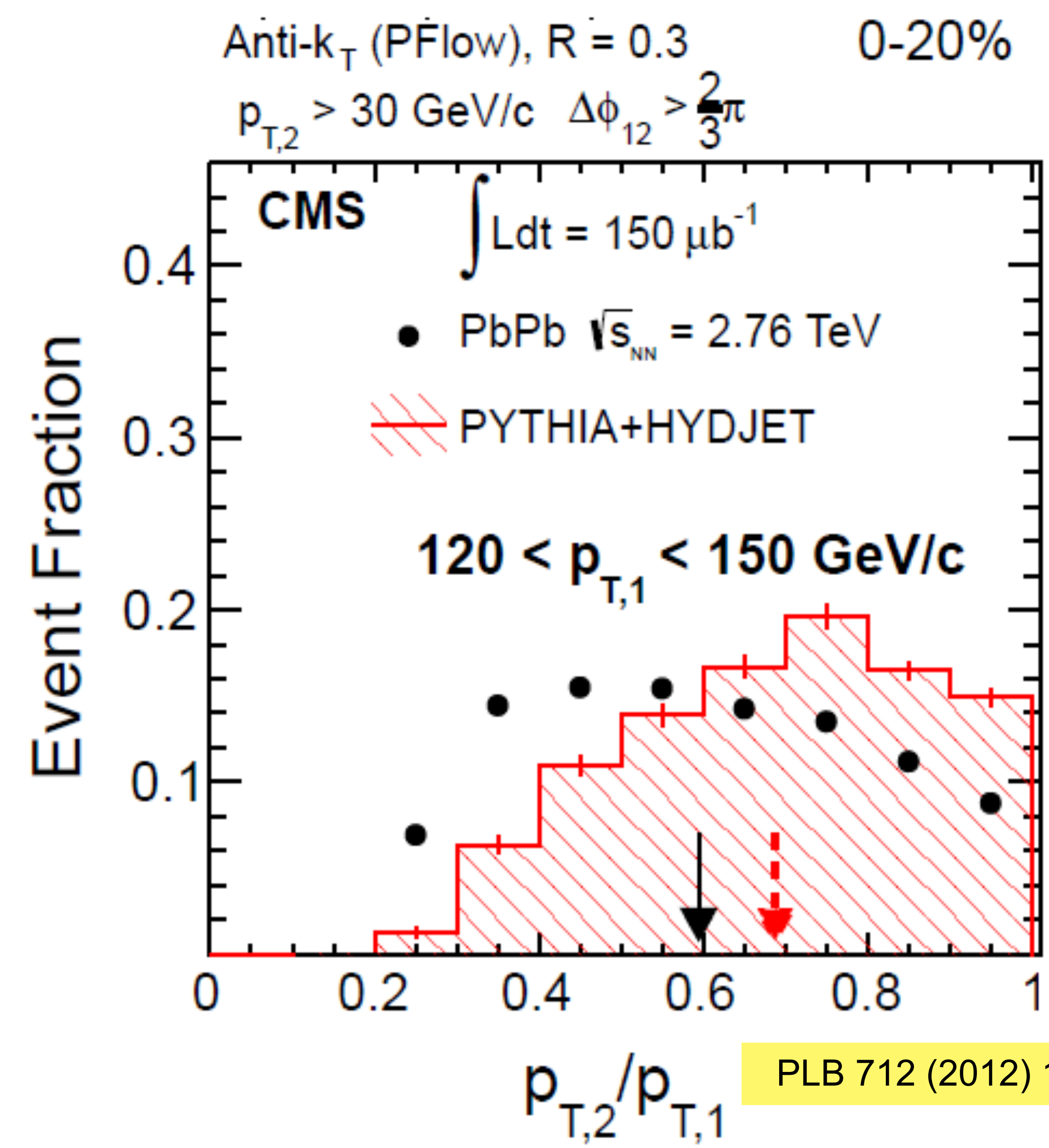
Jet quenching evidences at LHC

- R_{AA}: Nuclear modification factor

$$R_{AA} = \frac{\sigma_{pp}^{inel}}{\langle N_{coll} \rangle} \frac{d^2 N_{AA}/dp_T d\eta}{d^2 \sigma_{pp}/dp_T d\eta}$$



CMS PAS HIN-12-004

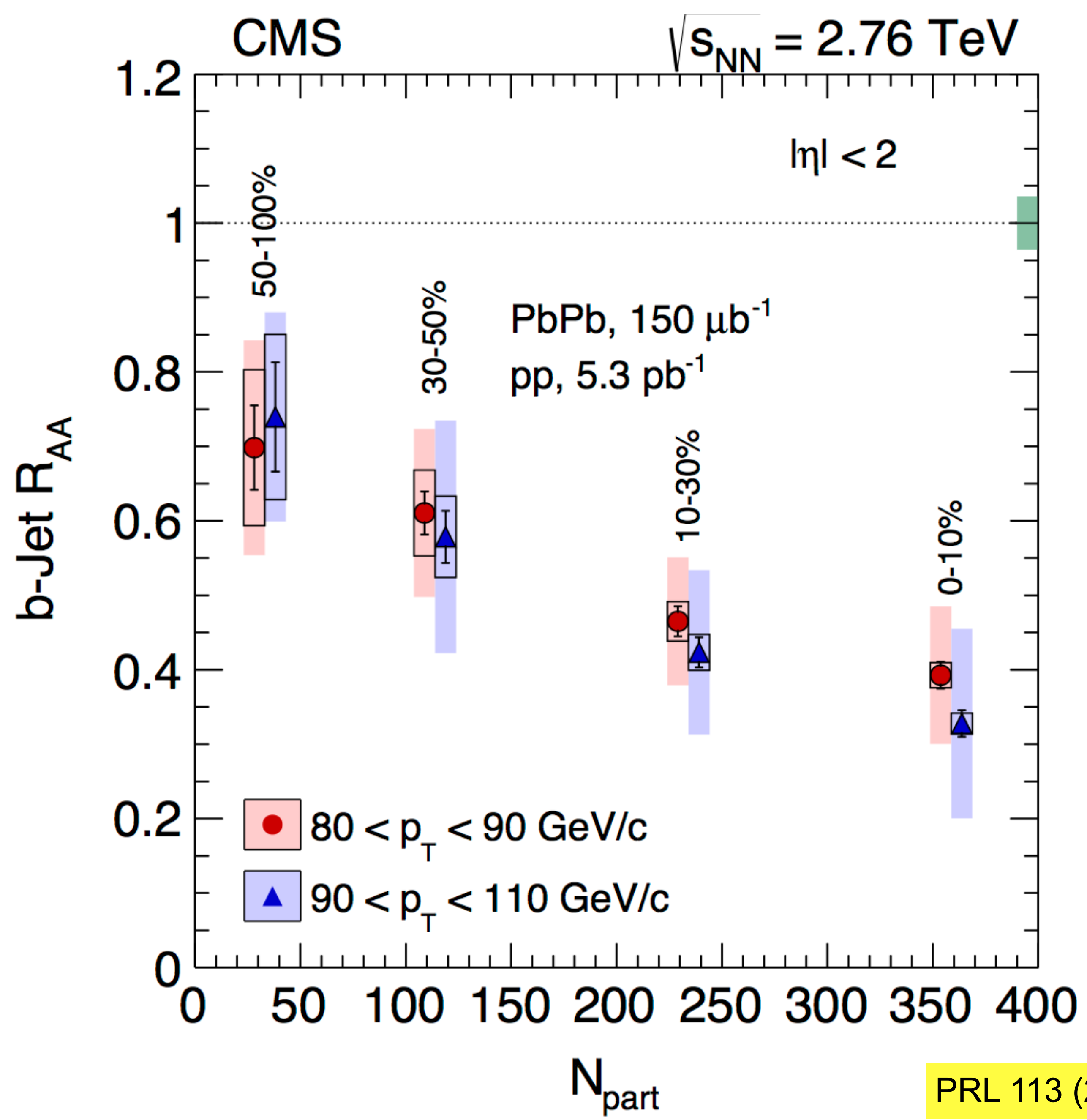


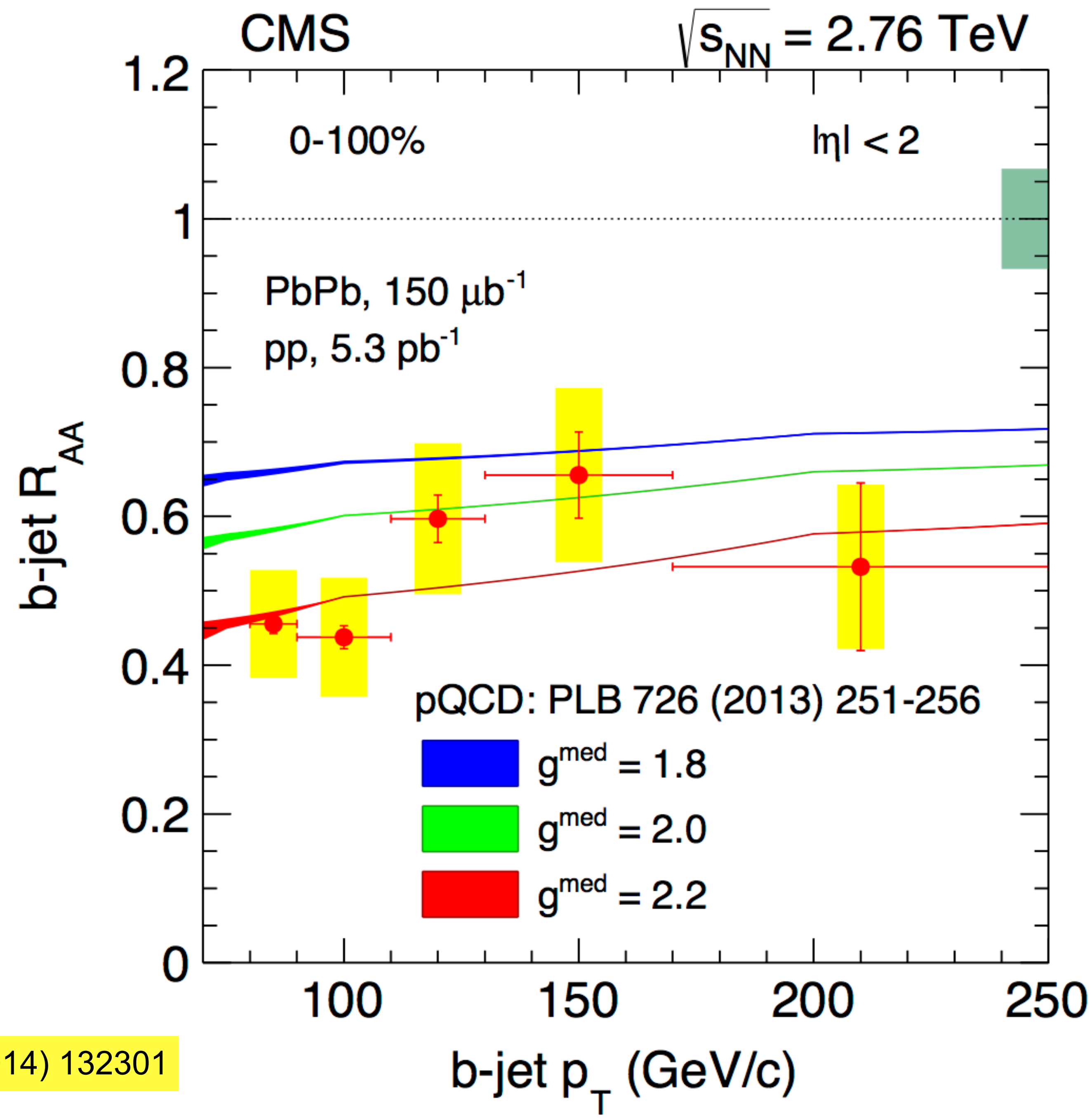
PLB 712 (2012) 176

- About 50% of jets (R_{AA} ~ 0.5) are lost at a given p_T in most central PbPb
- Dijet p_T ratio is imbalanced in most central PbPb collisions

➡ Jets (light flavour) are quenched in central PbPb collisions, how about b-jets?

b-jet suppression



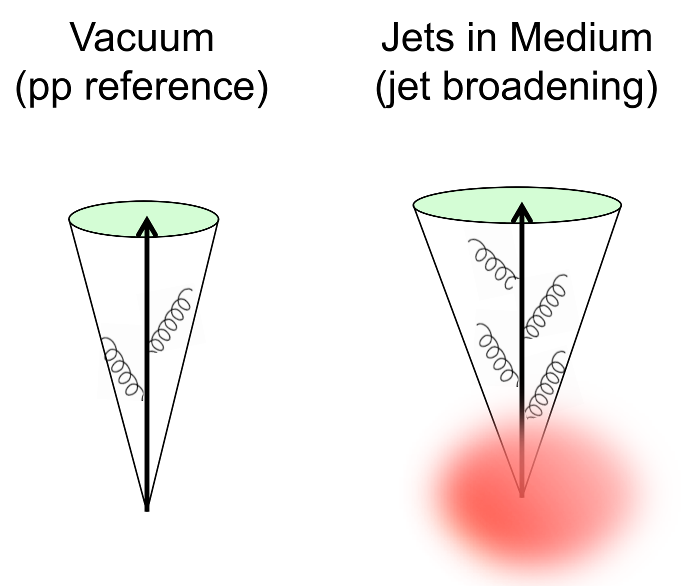


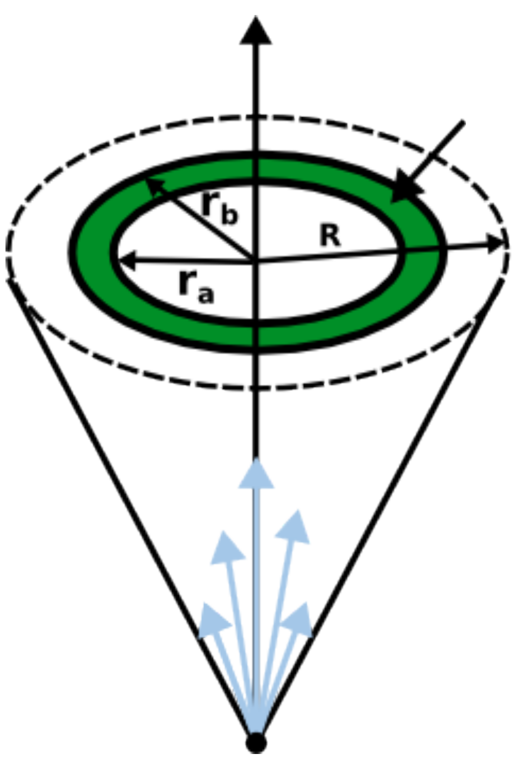
PRL 113 (2014) 132301

- Evidence of b-jet suppression in central PbPb collisions
- b-jet RAA favours strong jet-medium coupling from pQCD model

Anatomy of jets

- Understand how jets interact with the QGP medium by studying the energy flow inside the jet
  - ➡ question to address: is the jet energy in PbPb redistributed radially?





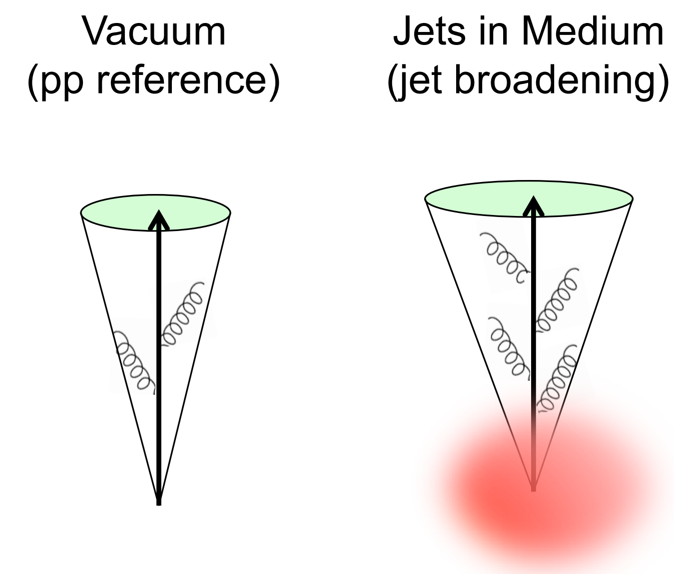
$$r = \sqrt{(\eta_{jet}-\eta_{ch})^2+(\varphi_{jet}-\varphi_{ch})^2}$$

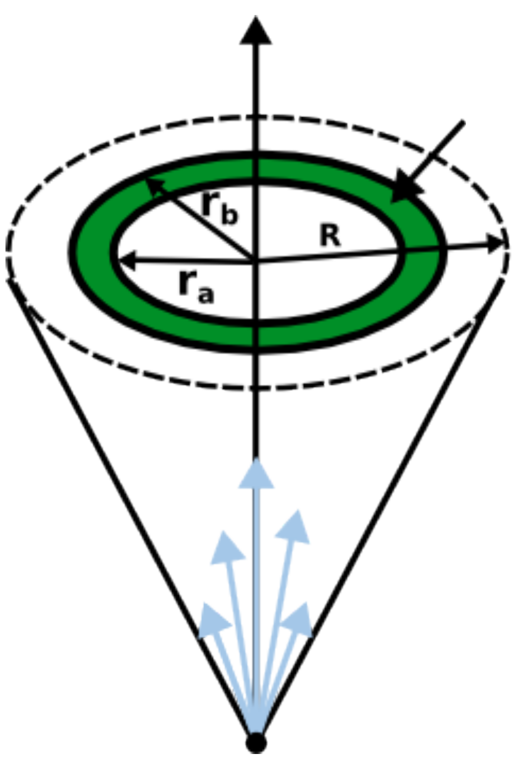
$$\rho(r) = \frac{1}{f_{ch}}\frac{1}{\delta r}\frac{1}{N_{jet}}\sum_{jets}\frac{p_T(r-\delta r/2, r+\delta r/2)}{p_T^{jet}},$$

Anatomy of jets

- Understand how jets interact with the QGP medium by studying the energy flow inside the jet

  ➡ question to address: is the jet energy in PbPb redistributed radially?





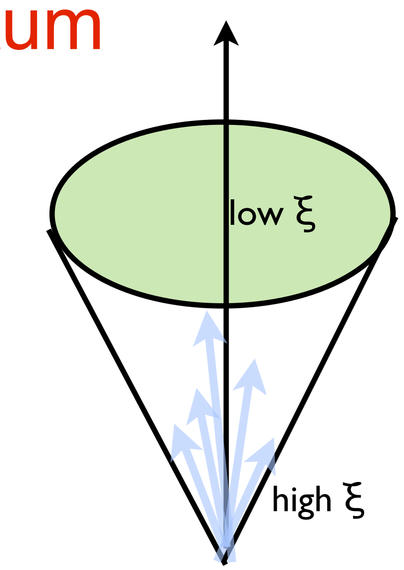
- Understand how jets interact with the QGP medium by studying the particle longitudinal momenta

  ➡ question to address: is the jet energy in PbPb redistributed in momentum space?

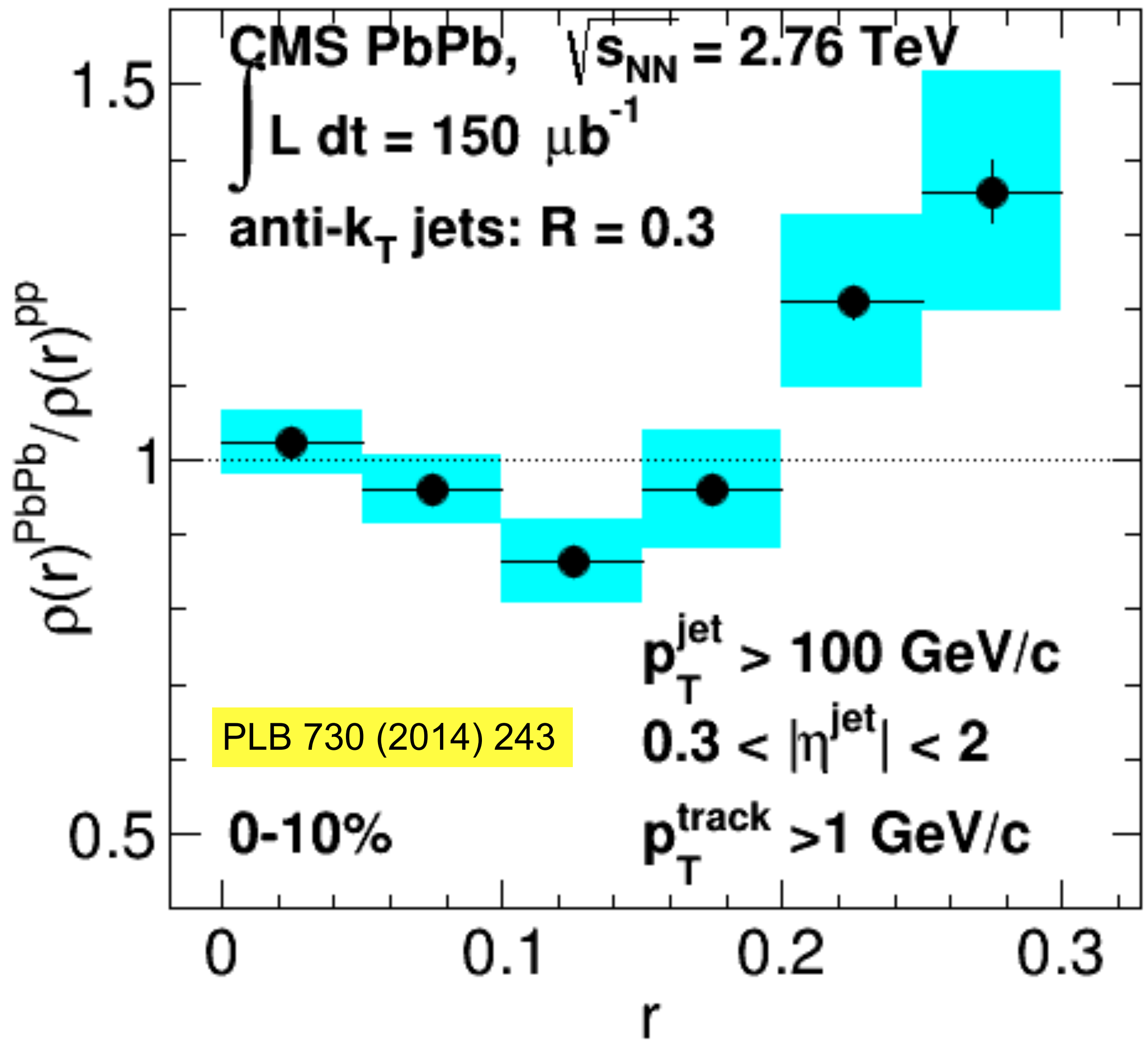
$$r = \sqrt{(\eta_{jet}-\eta_{ch})^2+(\varphi_{jet}-\varphi_{ch})^2}$$

$$\rho(r) = \frac{1}{f_{ch}} \frac{1}{\delta r} \frac{1}{N_{jet}} \sum_{jets} \frac{p_T(r-\delta r/2, r+\delta r/2)}{p_T^{jet}},$$

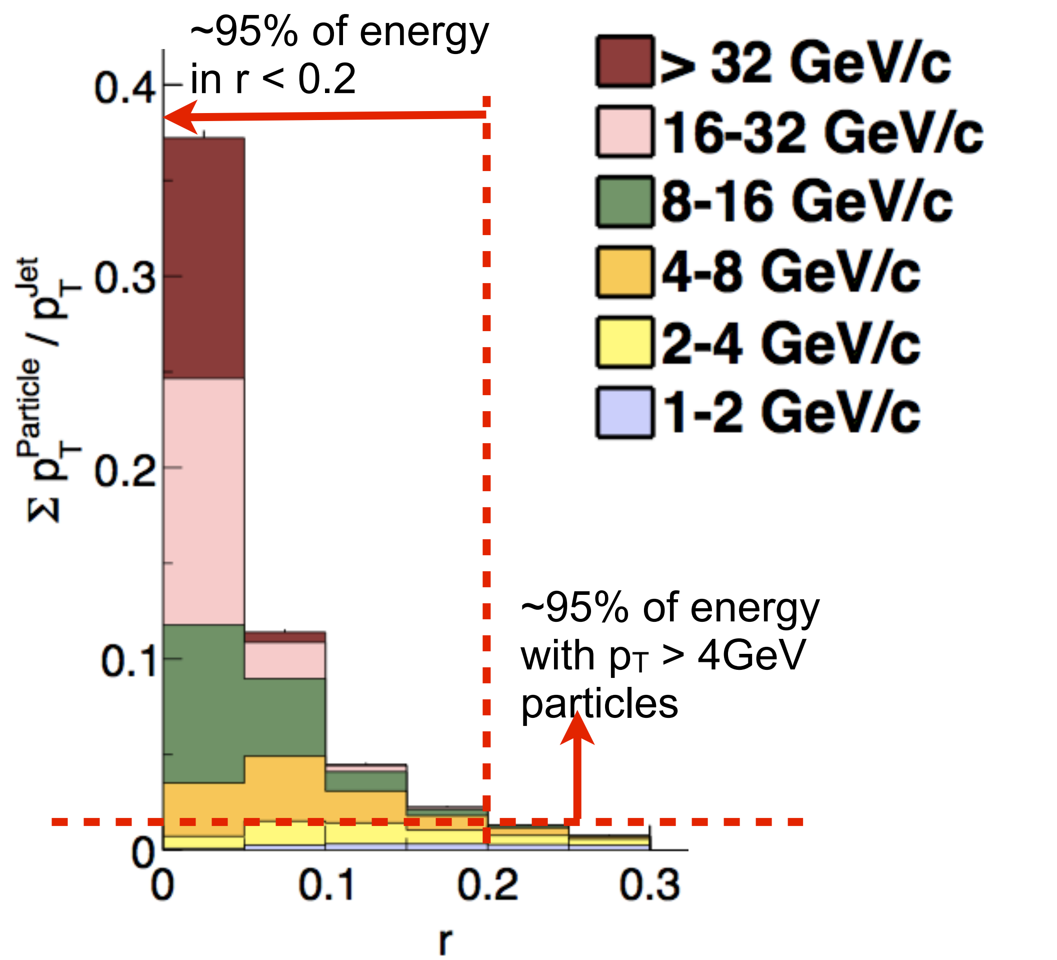
$$\xi = \ln(1/z) = \ln(p^{jet}/p_{||})$$



Jet shape analysis



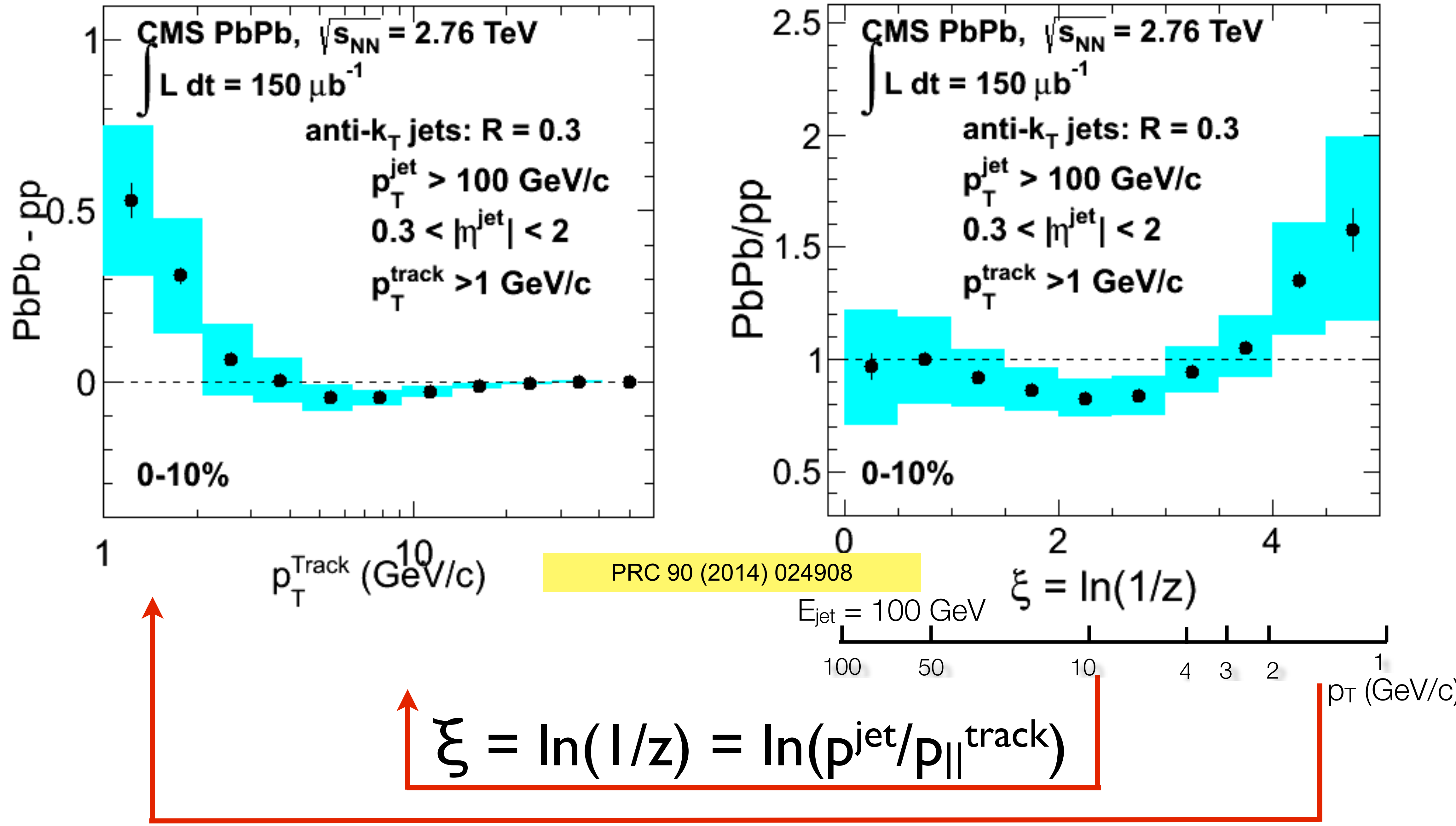
PYTHIA 100 GeV inclusive jet
Anti-k$_T$ R=0.3 jet
Charged particle energy fraction



- Core of the jet (dominated by high p_T particles) → no changes
- Intermediate r (intermediate p_T particles) → depletion/narrower
- Large radii (low p_T particles) →excess/broadening

➡Jet energy is redistributed inside jet cone

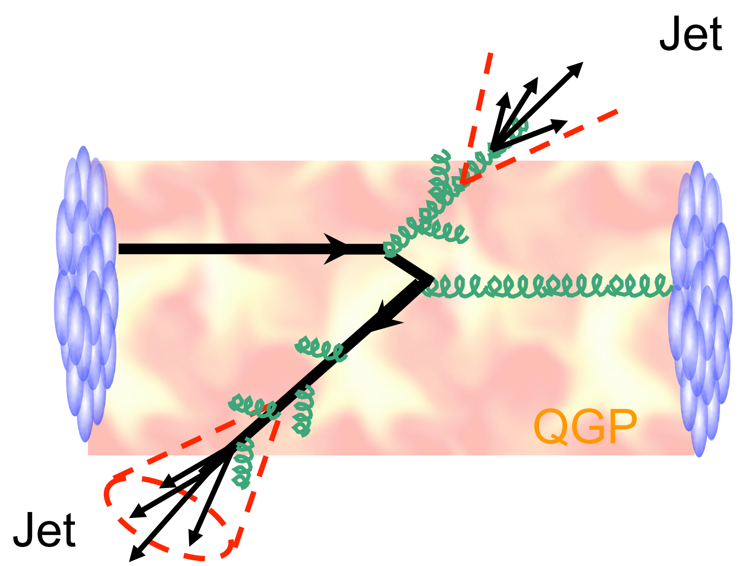
Inclusive jet FF vs. p_T and ξ



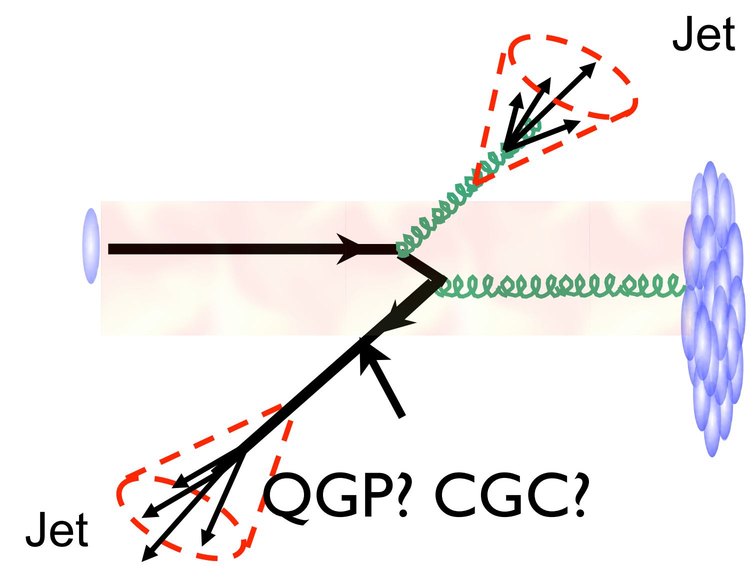
- high p_T particles → no changes
- intermediate p_T particles → depletion
- low p_T particles →excess
  - ➡Jet fragmentation is modified

Controlled Experiment: p + Pb ?

PbPb collisions



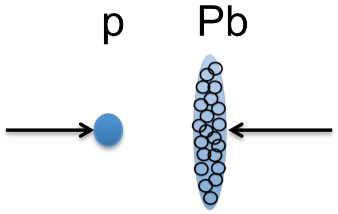
pPb collisions

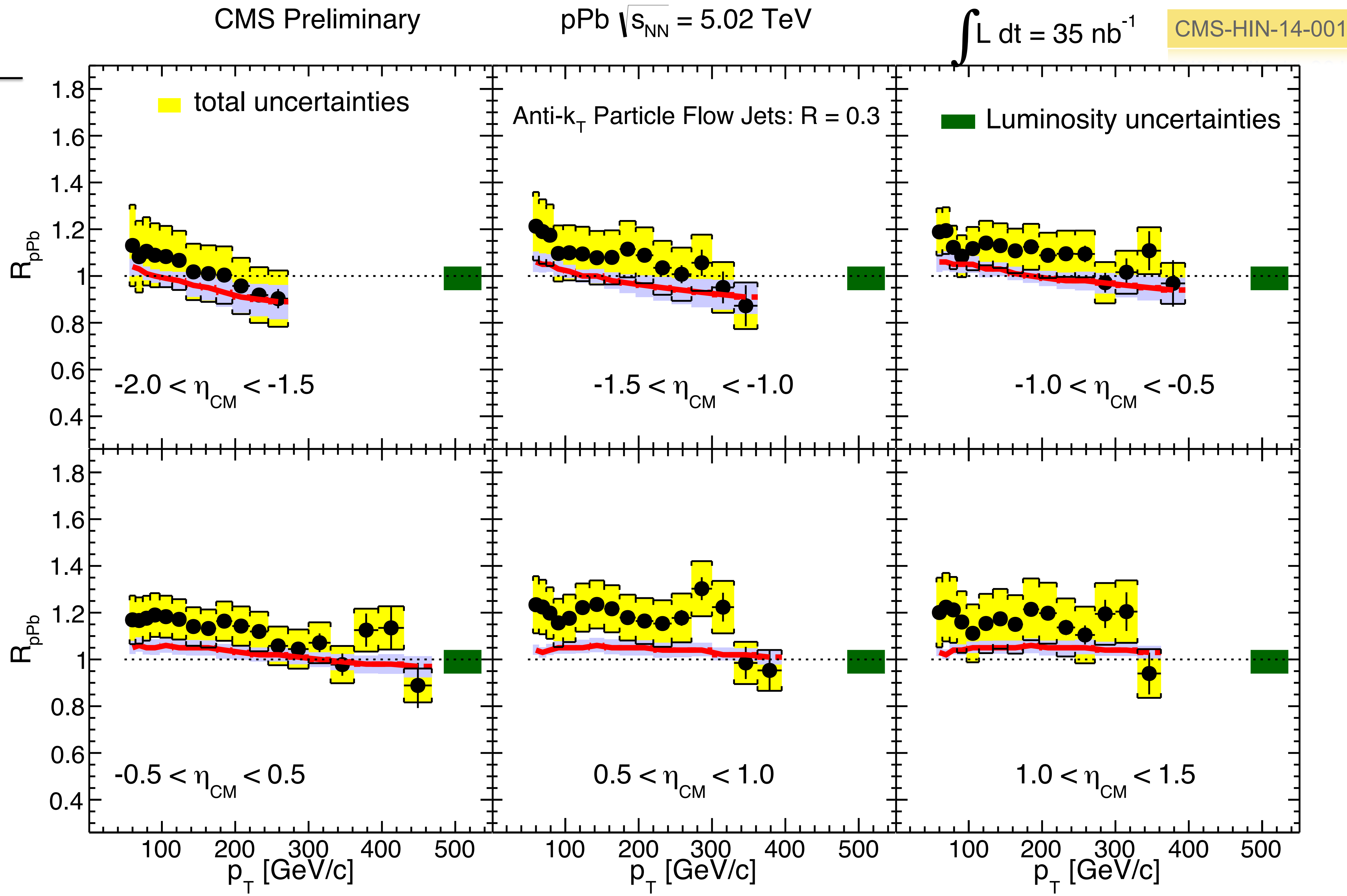


- Clear signs of Quark-Gluon Plasma (QGP)
- Strongly interacting particles affected by the presence of QGP
  - quenched jets and high p_T
  - modified jet structure

- Can we understand the baseline for PbPb?
- How do strongly interacting particles behave in cold nuclear matter? quenching?
- Can we see nuclear structure?

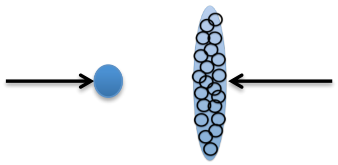
Jet quenching in p + Pb?



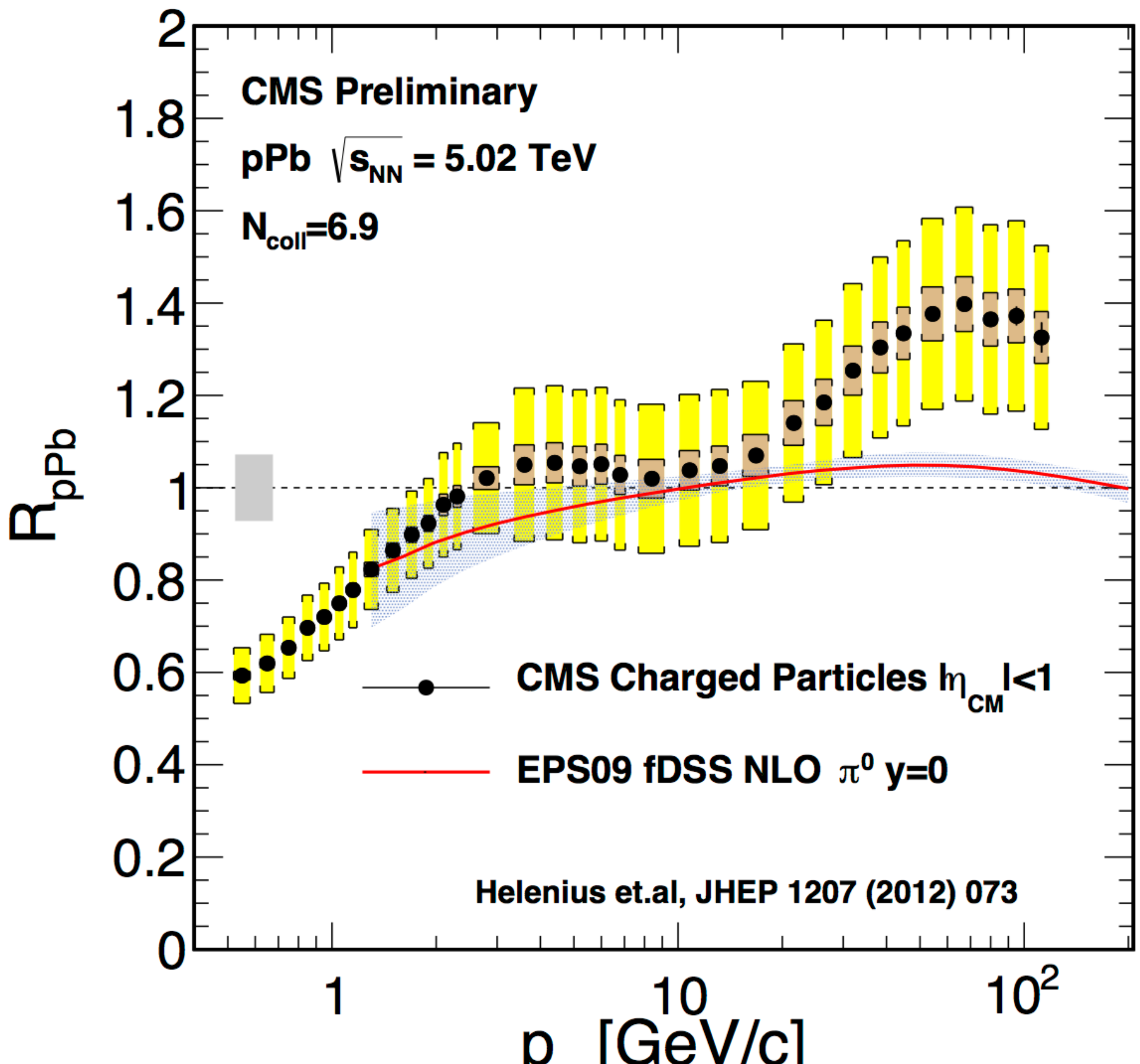


- No strong jet p_T dependence observed
- Consistent with EPS09 description

Charged particles R_{pA}

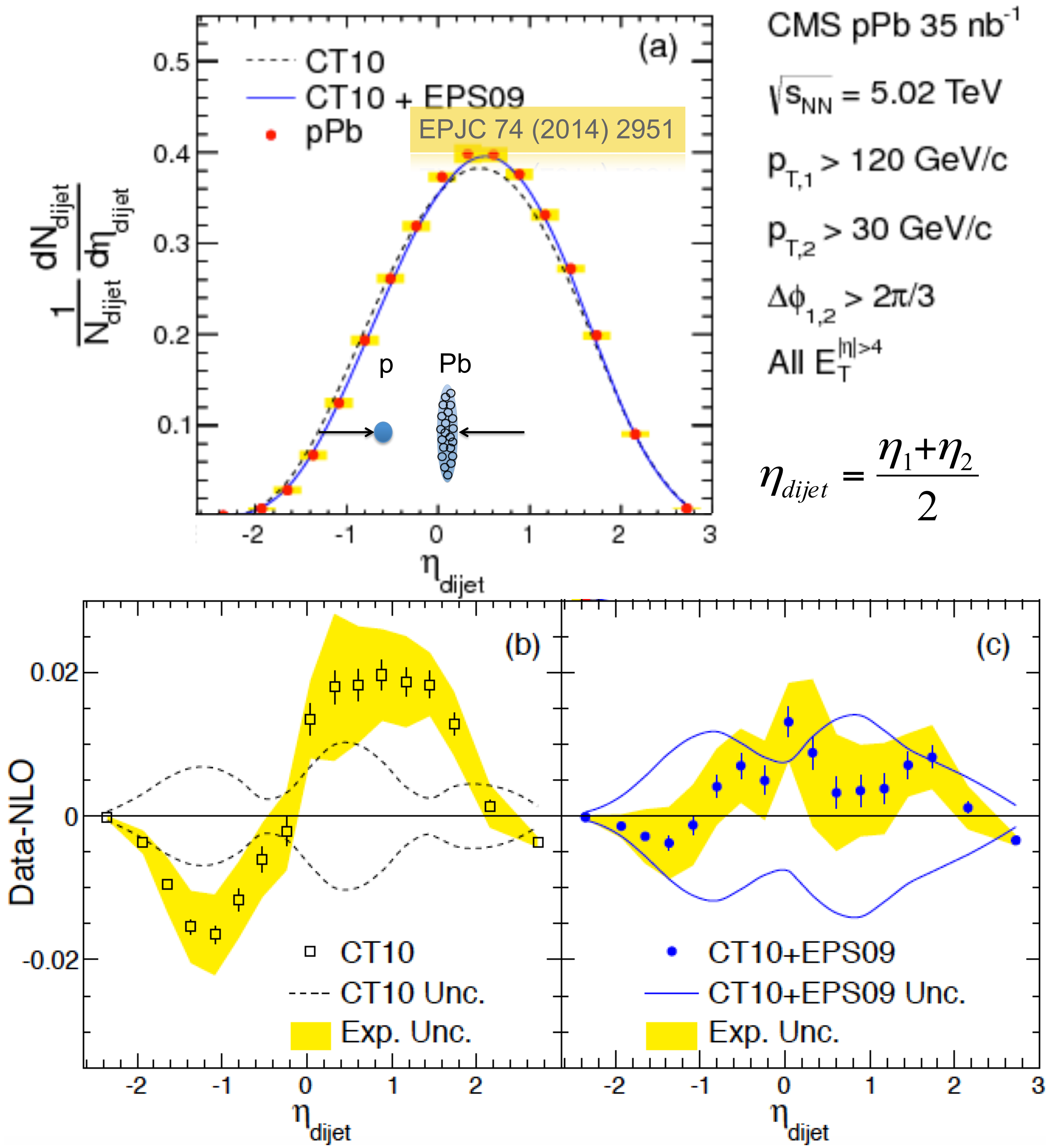


EPJC 75 (2015) 237



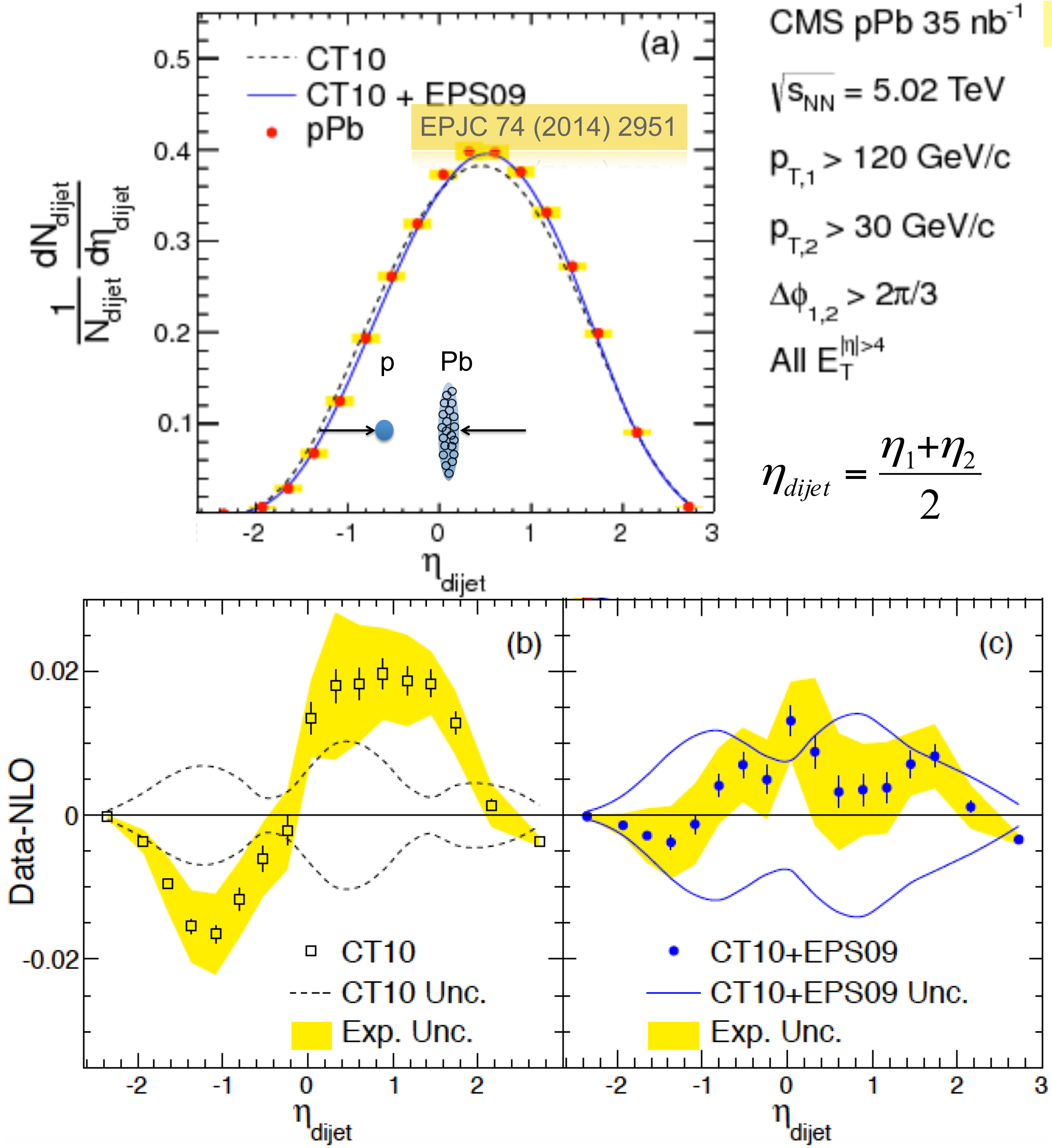
- No suppression observed for charged hadron production in pPb collisions
- High p_T charged particles ($50 < p_T < 100$) $R_{pPb} > 1$ using interpolated pp reference
- EPS09 calculation is under predicted the data → possible baryon/meson difference?

Dijet η asymmetry

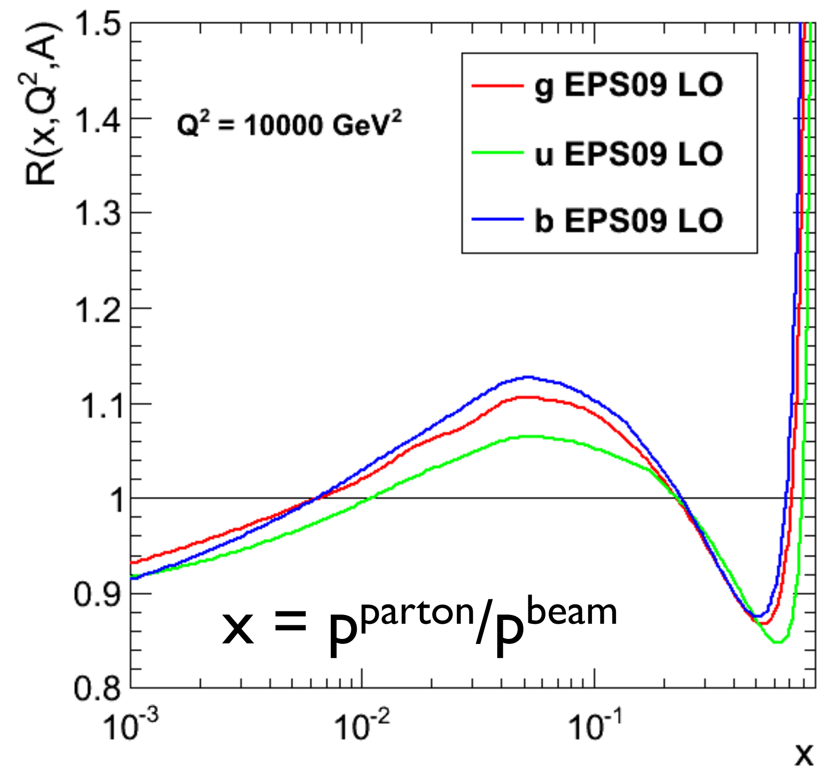


- Agreement between data and EPS09 calculation with systematics

Dijet η asymmetry

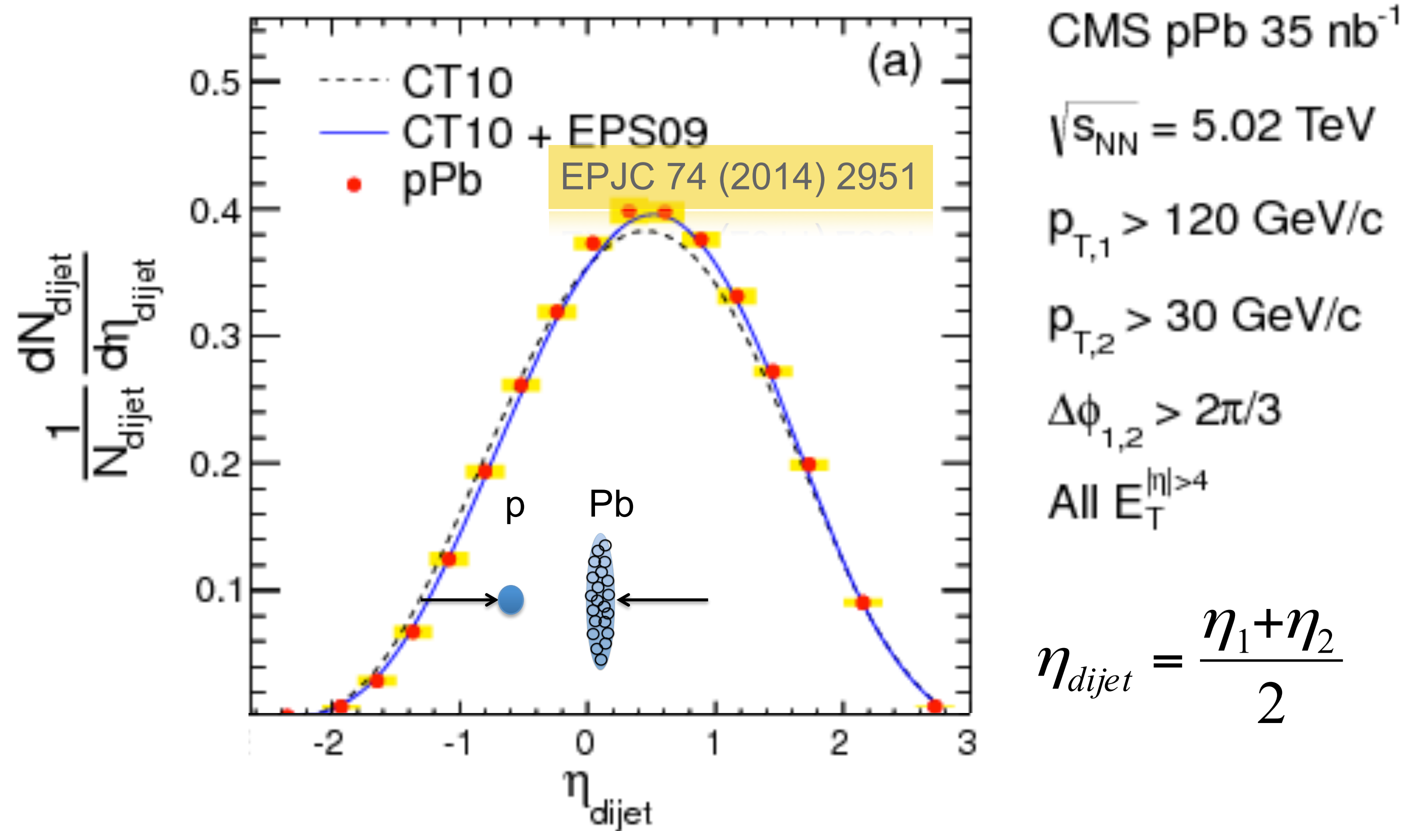


François Arleo and Jean-Philippe Guillet http://lapth.cnrs.fr/npdfgenerator/

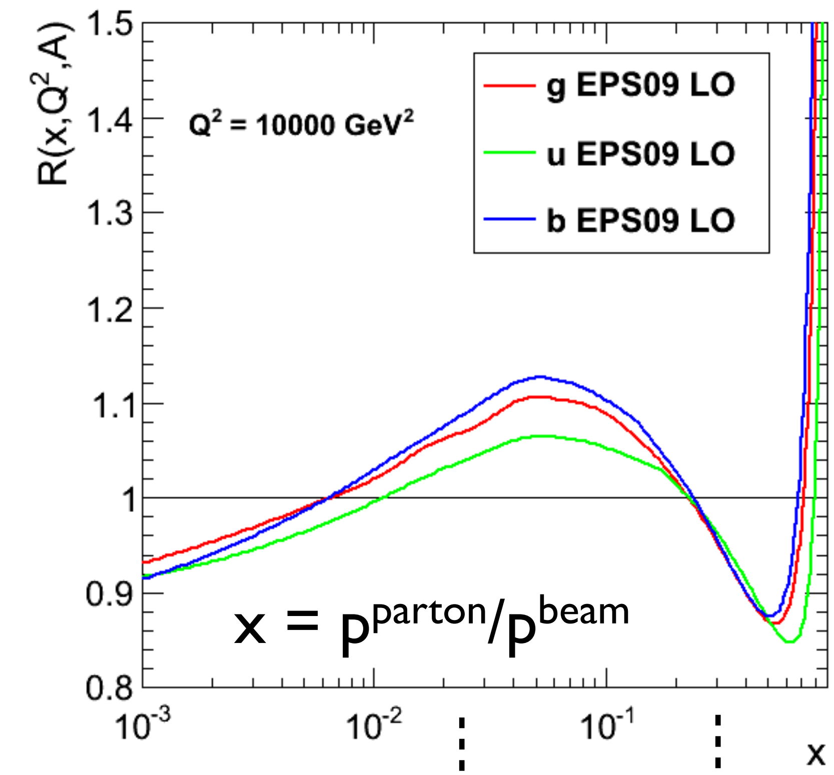


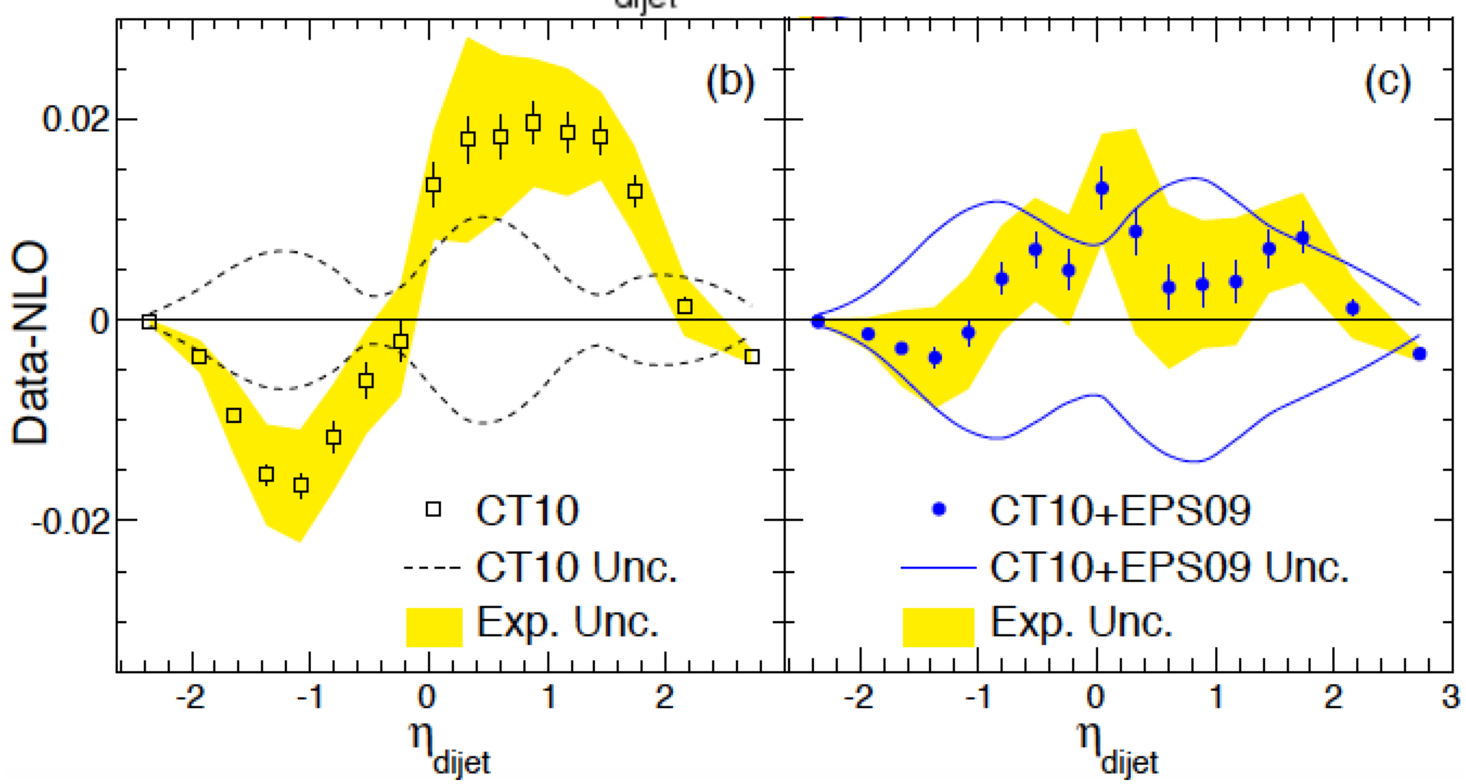
- Agreement between data and EPS09 calculation with systematics

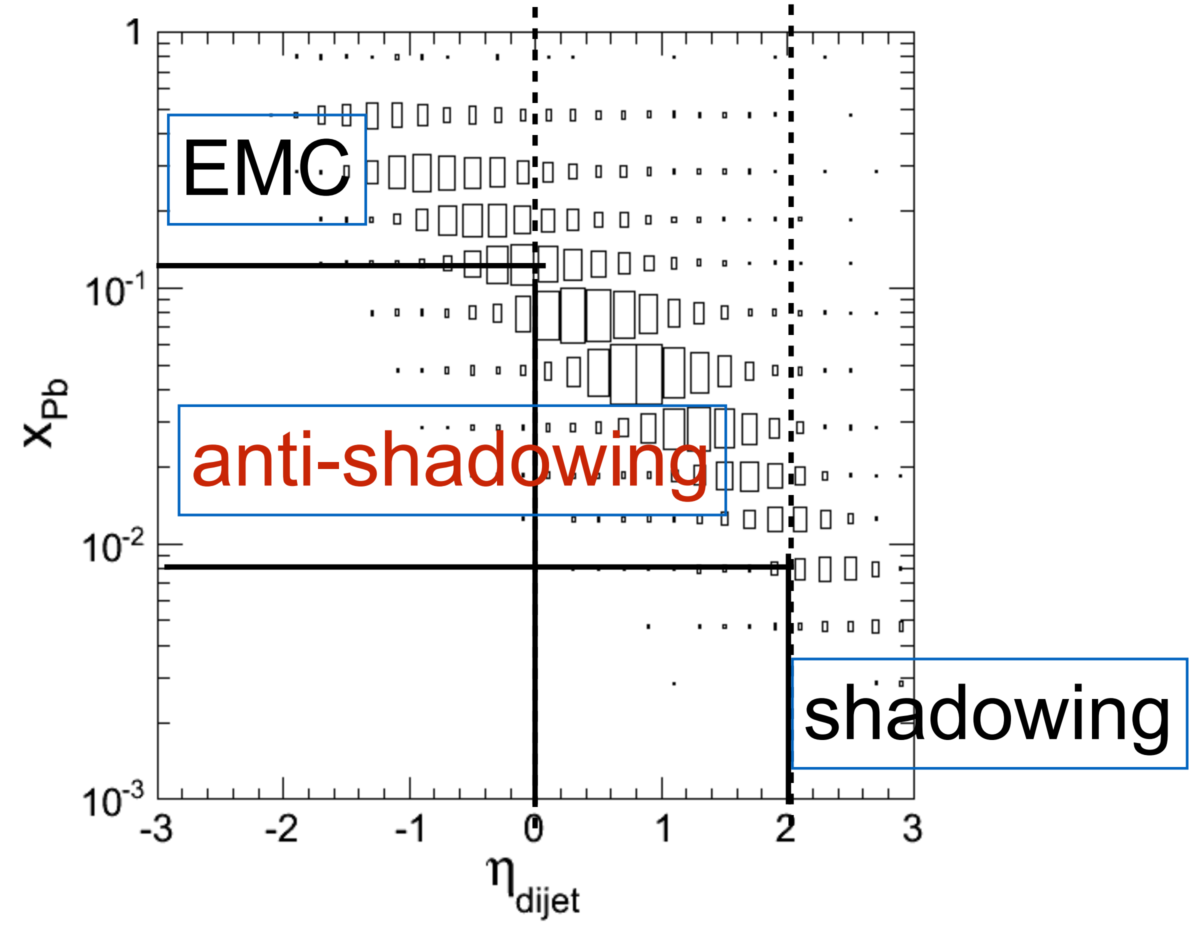
Dijet η asymmetry



François Arleo and Jean-Philippe Guillet http://lapth.cnrs.fr/npdfgenerator/



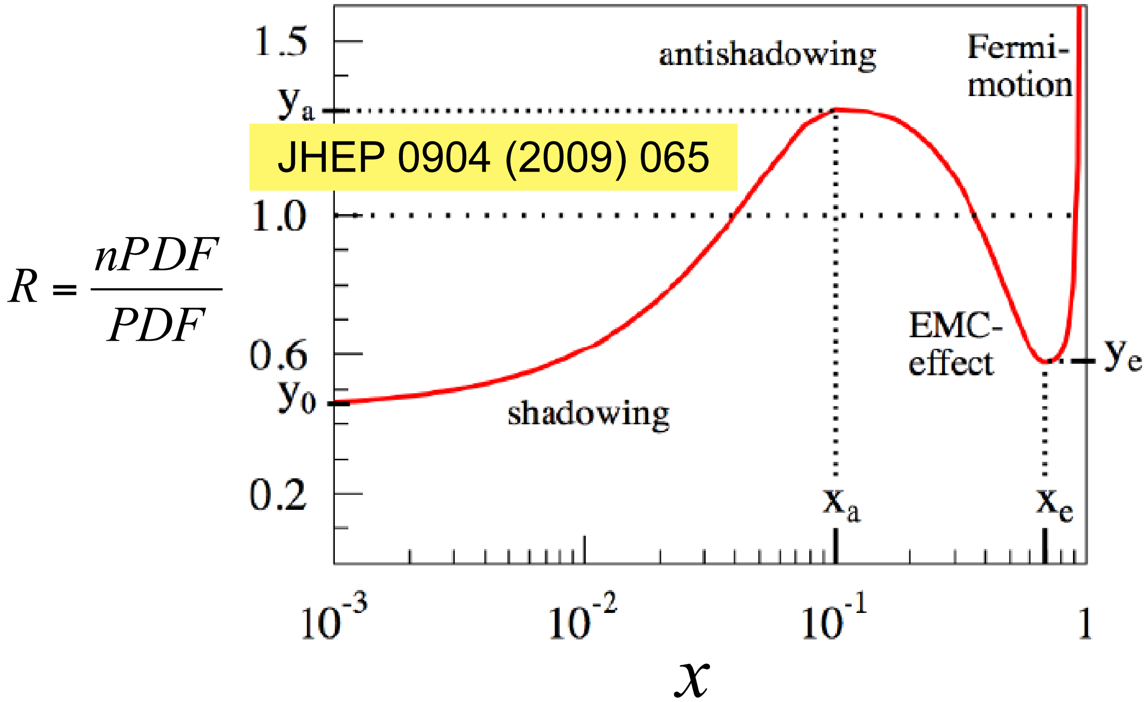




- Agreement between data and EPS09 calculation with systematics

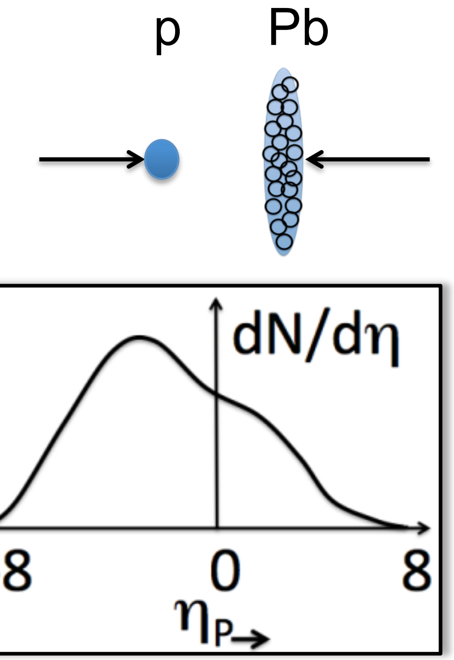
Probing nPDF with jets and hadrons

x - fractional momentum from a colliding nucleon carried by the parton



"backward"

large x from Pb



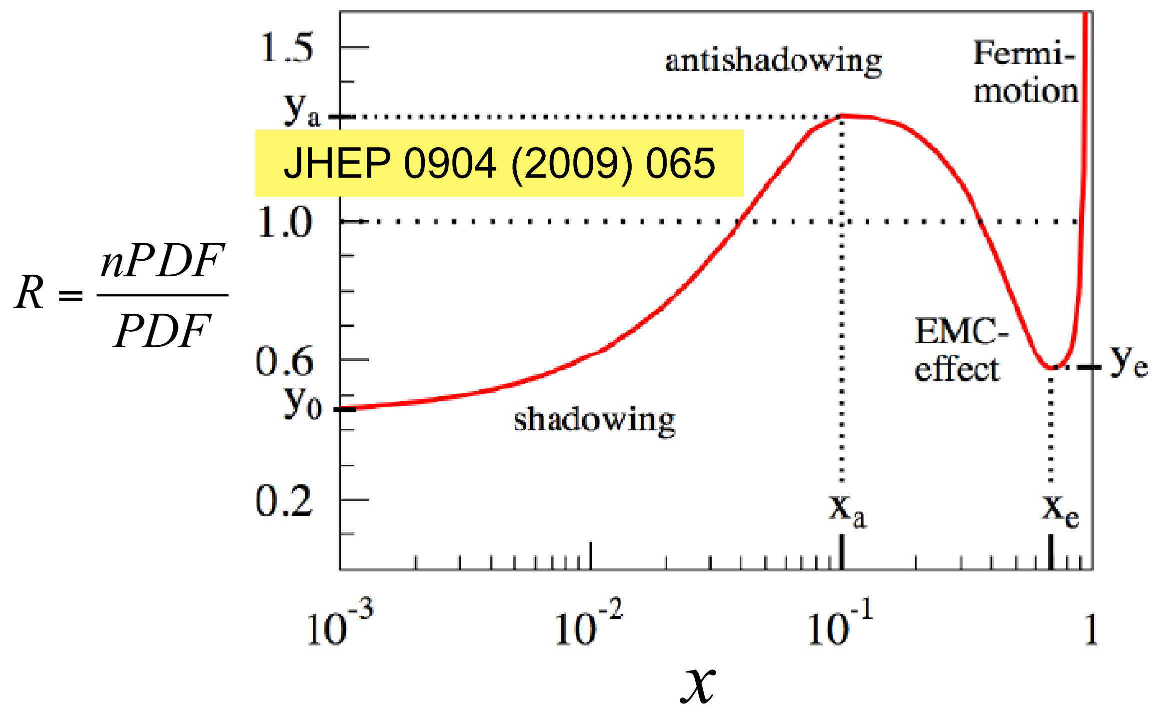
"forward"

small x from Pb

- Different p_T and η region can probe different x-range

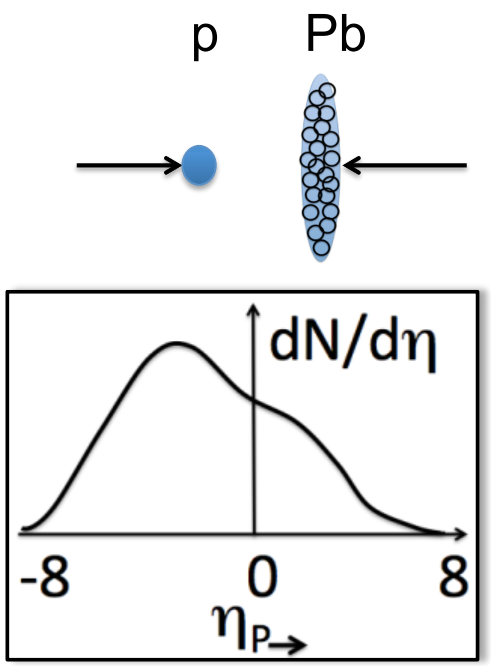
Probing nPDF with jets and hadrons

x - fractional momentum from a colliding nucleon carried by the parton



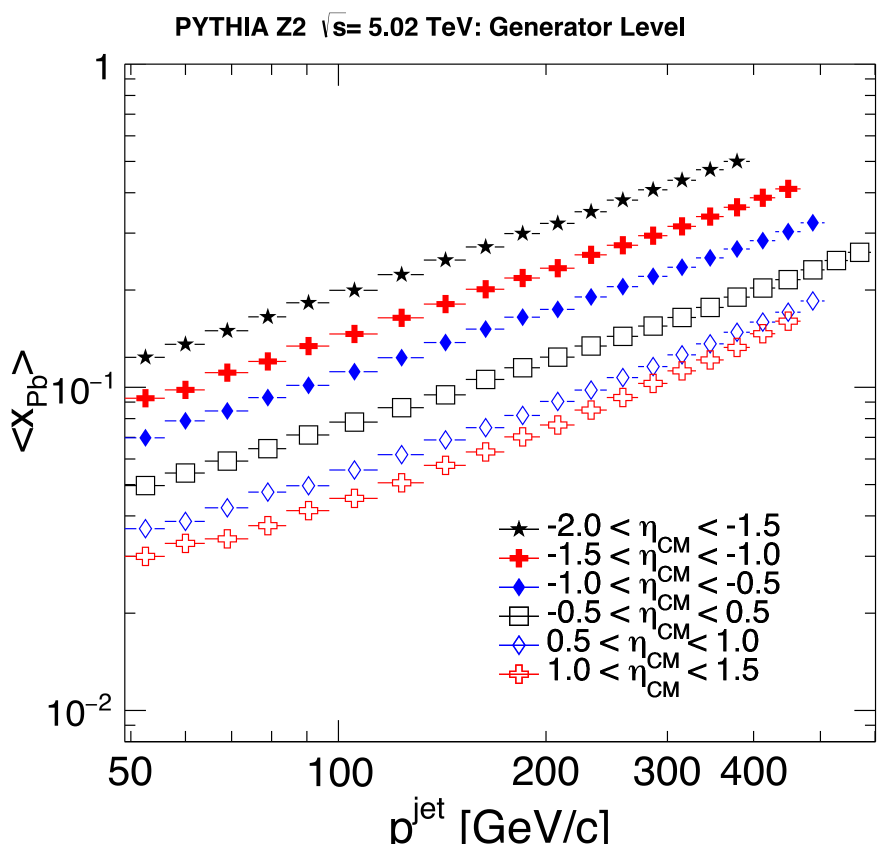
"backward"

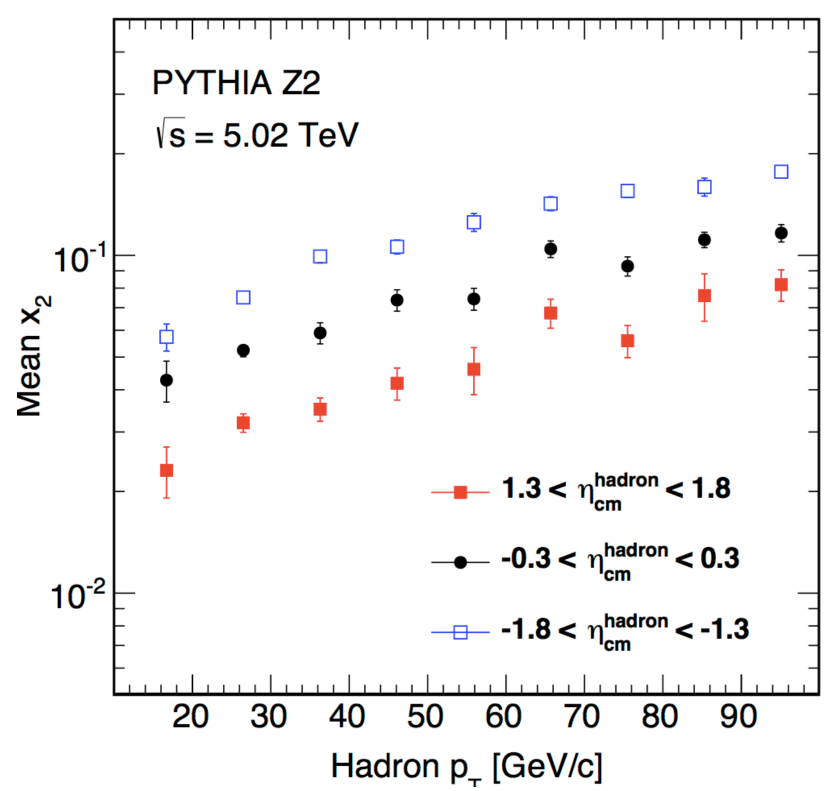
large x from Pb



"forward"

small x from Pb

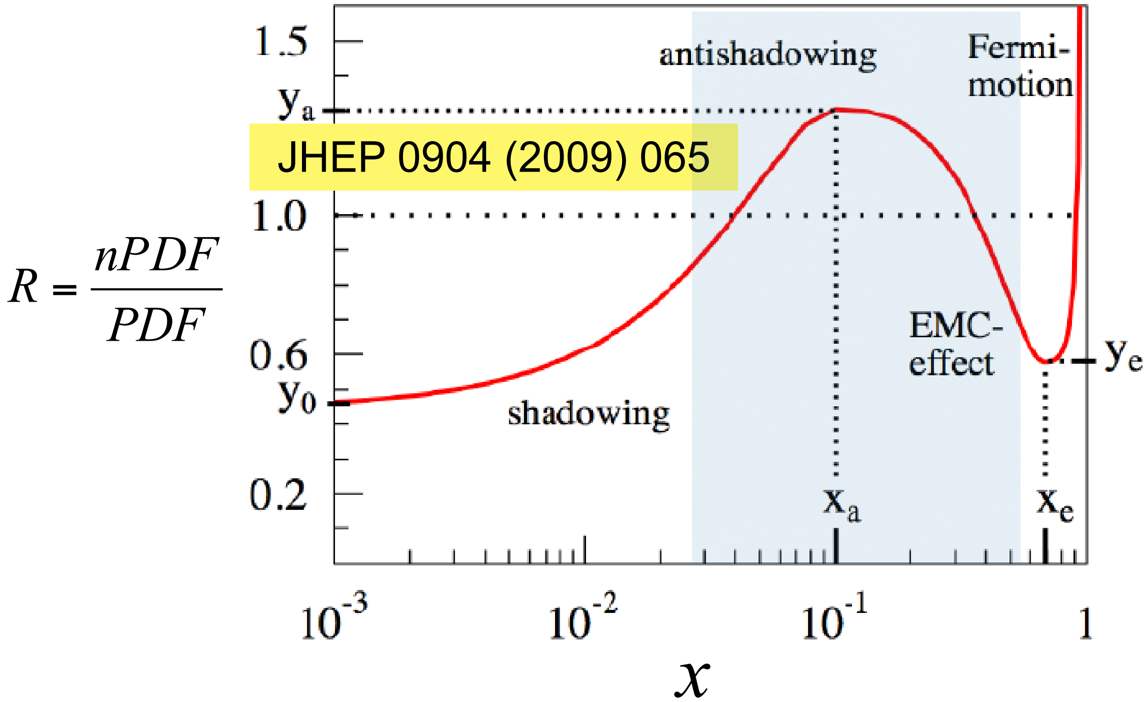




- Different p_T and η region can probe different x-range

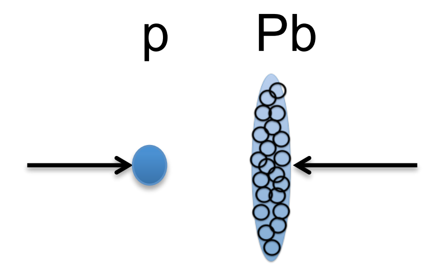
Probing nPDF with jets and hadrons

x - fractional momentum from a colliding nucleon carried by the parton



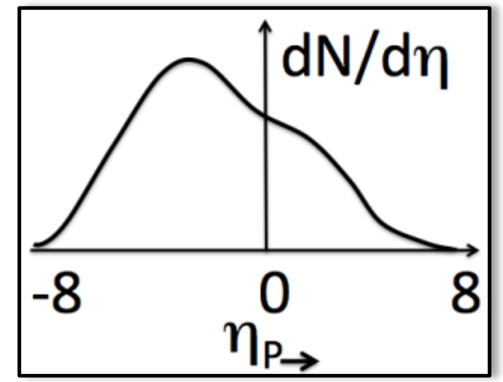
"backward"

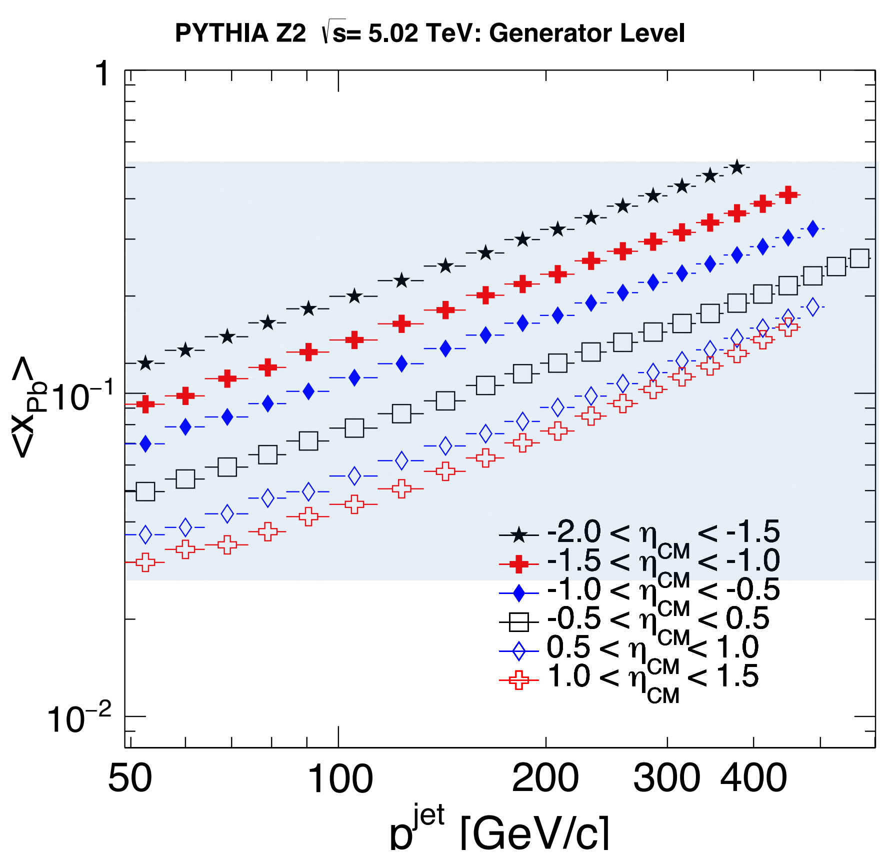
large x from Pb

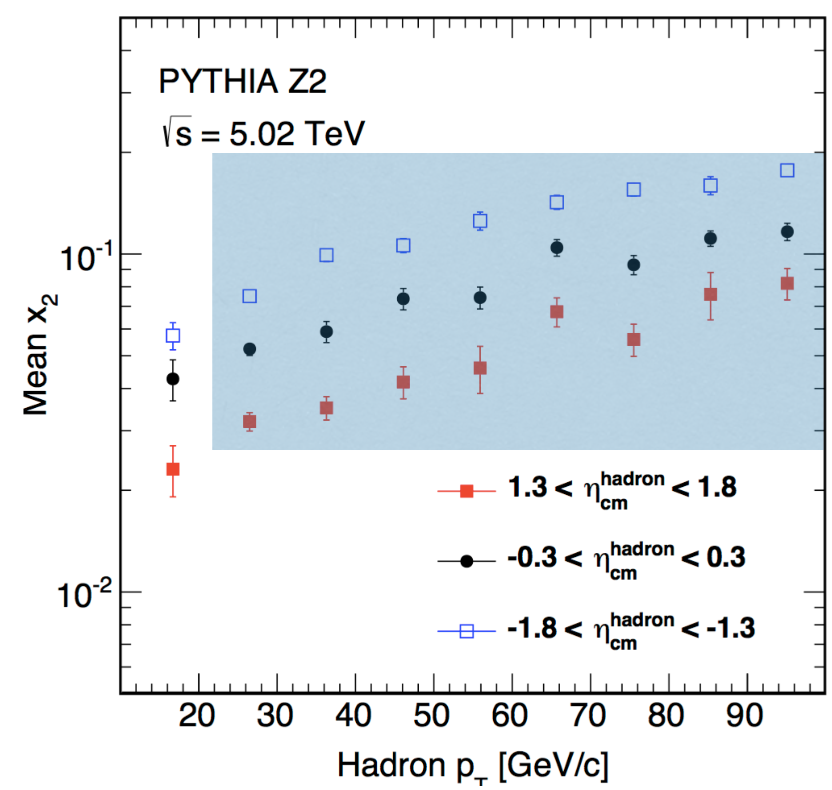


"forward"

small x from Pb

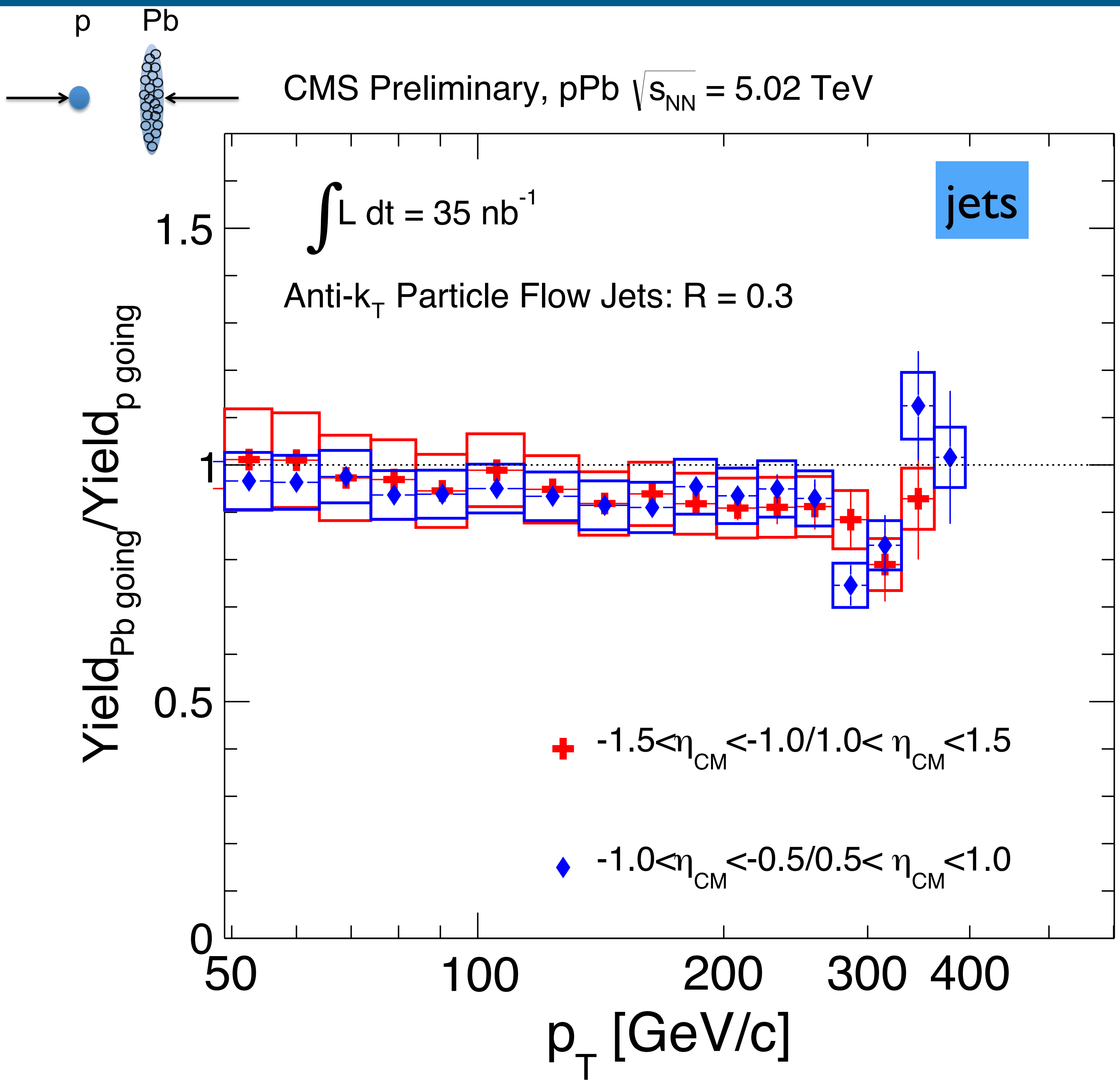


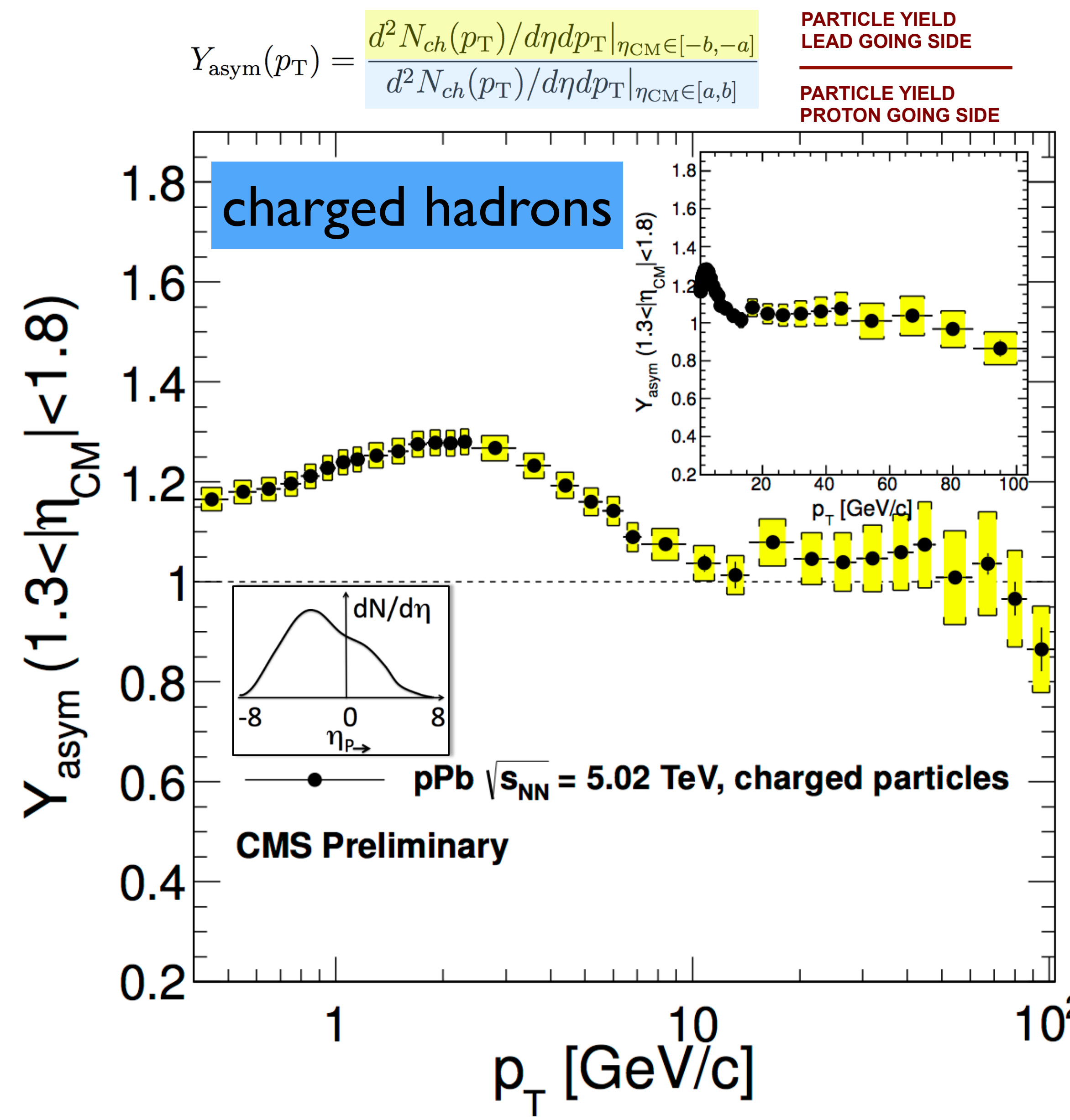




- Different p_T and η region can probe different x-range

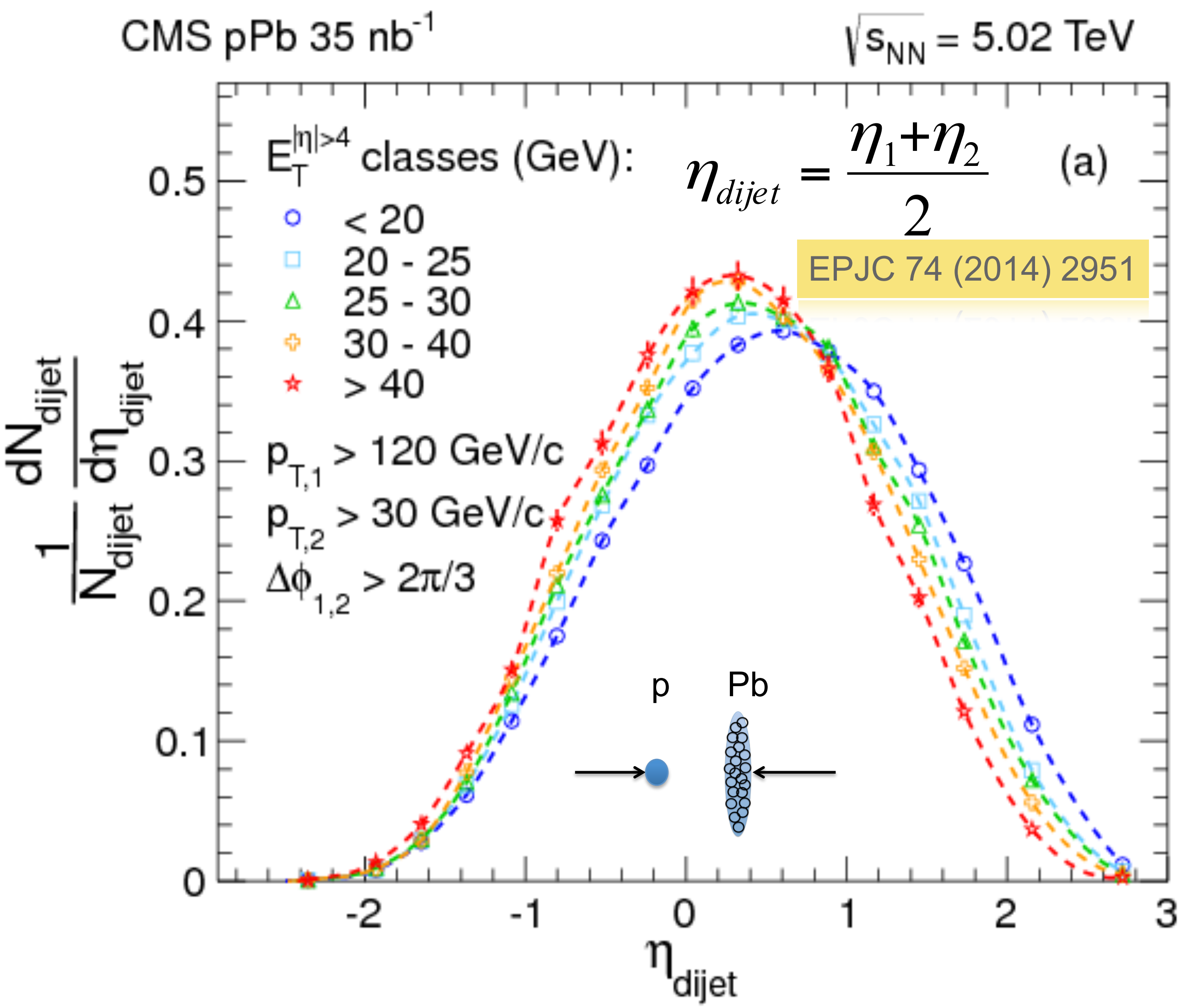
Charged particle and jet production asymmetry





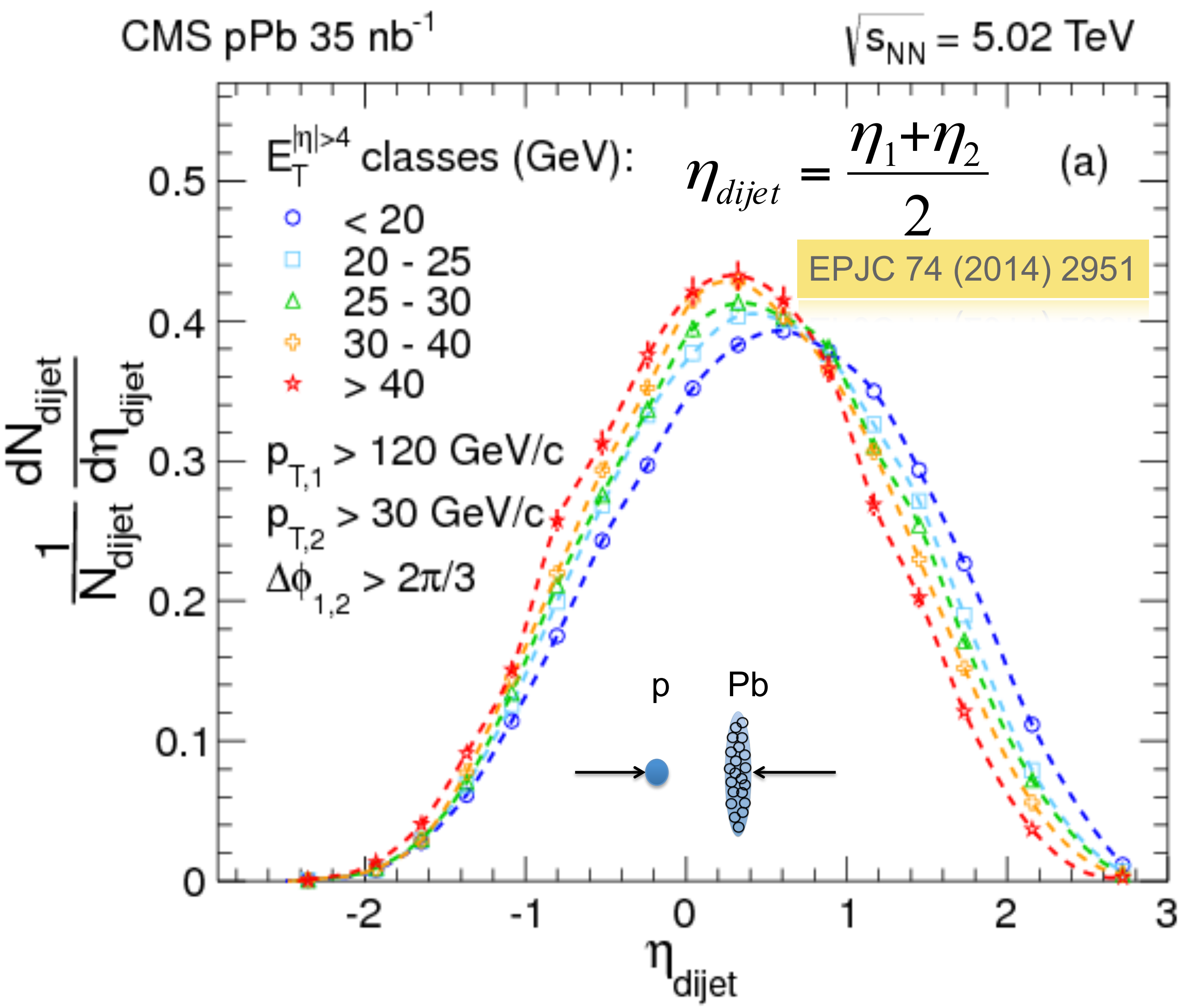
- Charged hadrons: $Y_{asym} > 1$ ($p_T < 10$ GeV/c); $Y_{asym} \sim 1$ ($p_T > 10$ GeV/c)
- Decreasing trend of Y_{asym} for both charged hadron and jets at very high p_T

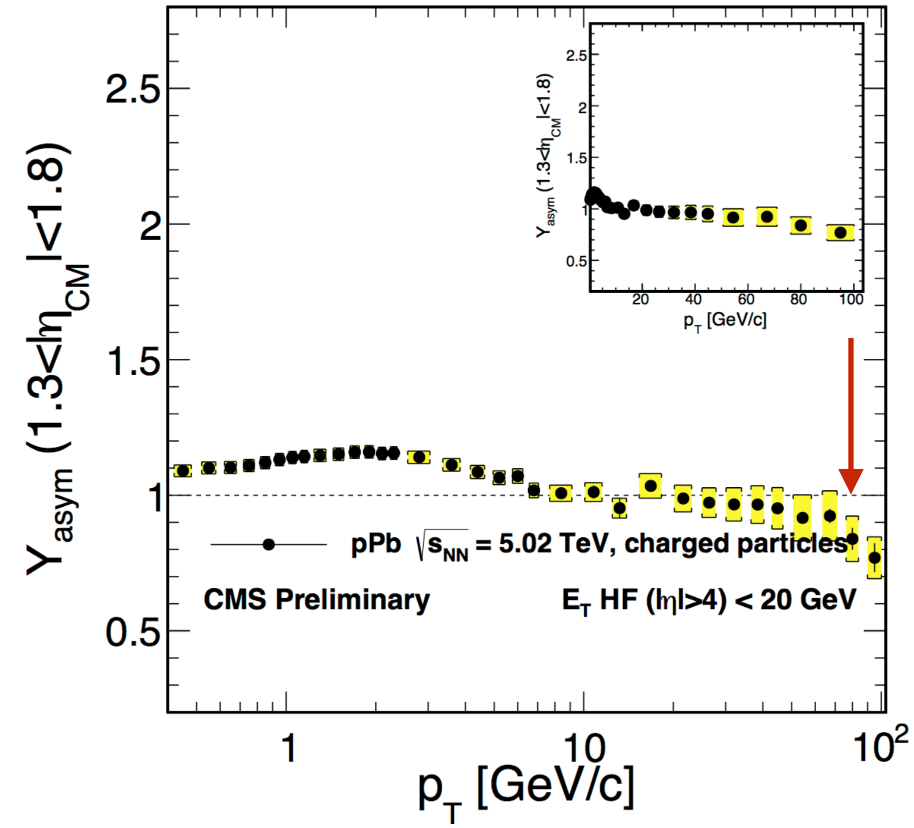
dijet η and charged hadron asymmetry

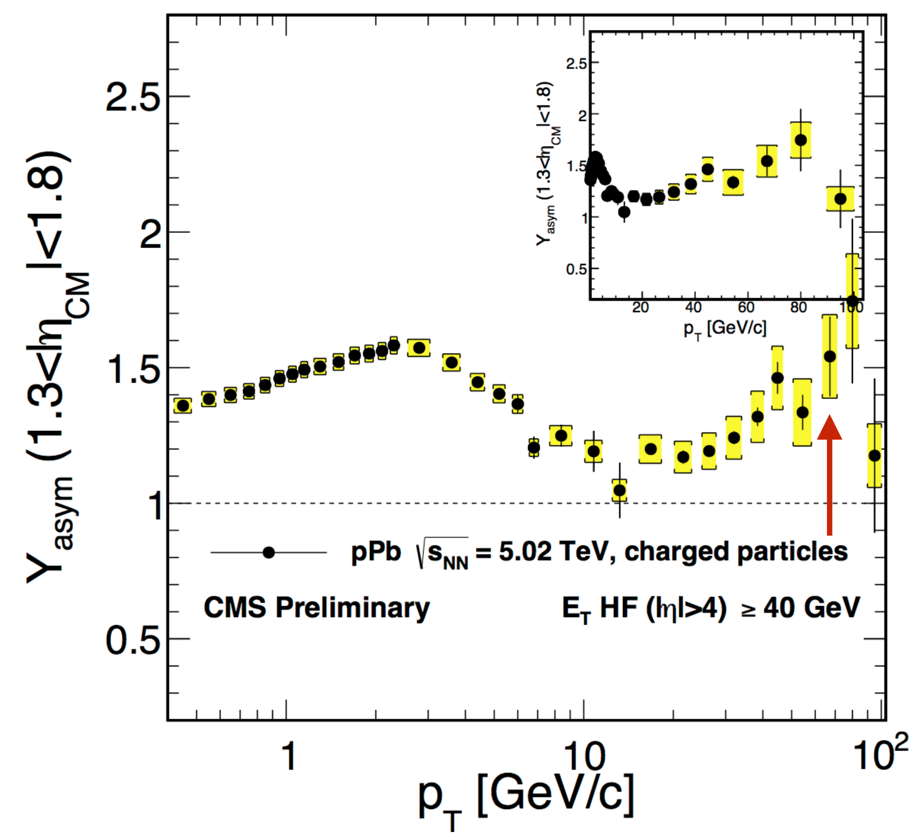


- "Peripheral" (low HF activity): dijets shifted to p-going side, expect $Y_{asym} < 1$
- "Central" (high HF activity): dijets shifted to Pb-going side, expect $Y_{asym} > 1$

dijet η and charged hadron asymmetry







- "Peripheral" (low HF activity): dijets shifted to p-going side, expect $Y_{asym} < 1$
- "Central" (high HF activity): dijets shifted to Pb-going side, expect $Y_{asym} > 1$

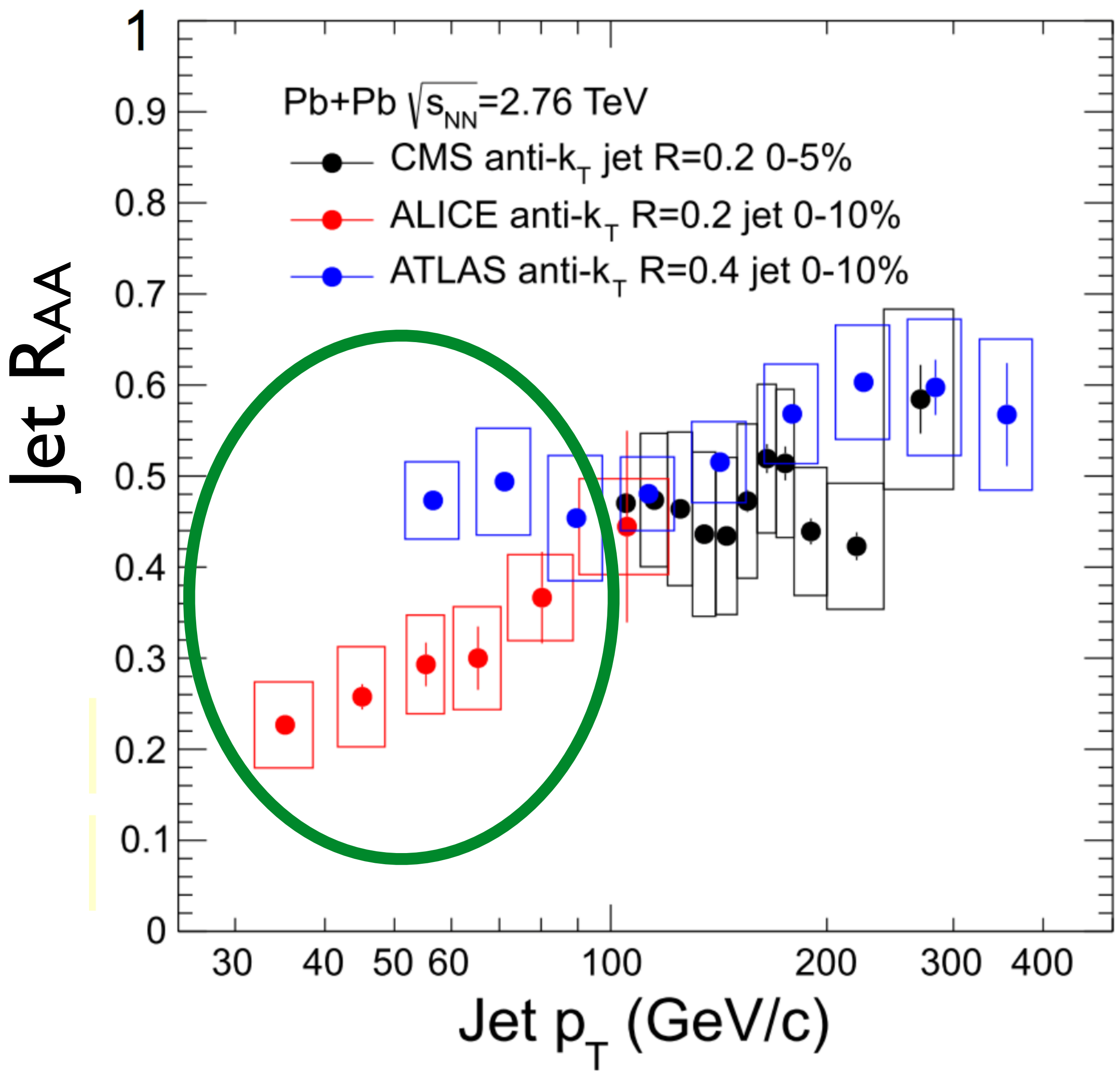
Summary and outlook

- AA: consistent picture about jet quenching in PbPb collisions from different experiments
  - high p_T jets are strongly suppressed
  - heavy quark jets behave similarly as light quark jets
  - Jet fragmentation patterns are modified
- pA: too complex to serve as reference but interesting to explore
  - no jet quenching observed
  - pQCD calculation including nPDF effects can described data in general but not hadrons
- But…still left with questions…
  - can be addressed and checked by higher statistics LHC RunII and RunIII data with more differential measurements

➡ flash in the next few slides with the questions in my mind…

How low p_T Jet quenched?

How are the low p_T jets suppressed?

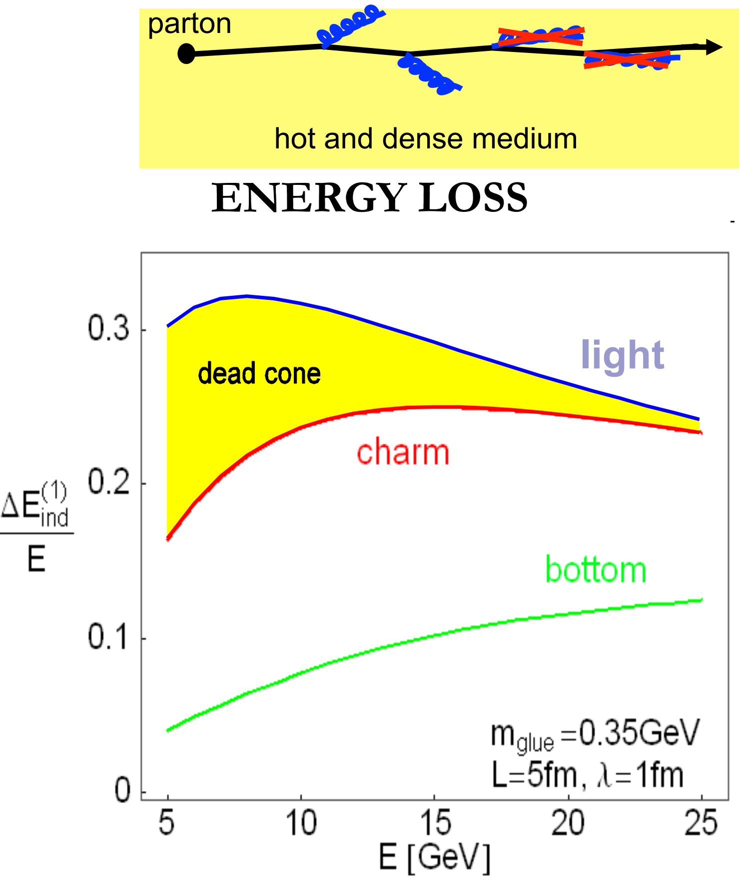


- High p_T R_{AA} is in good agreement, however low p_T behavior is different

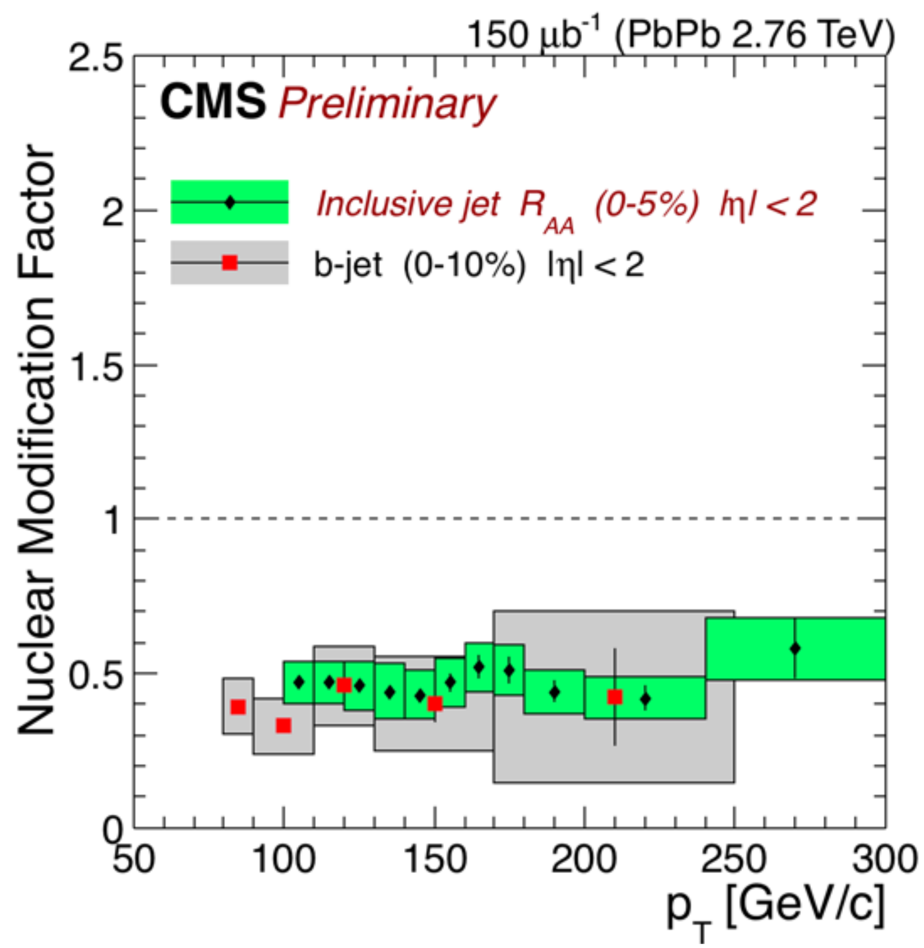
➡ different jet cone size, can be revisited with RunII data under same condition

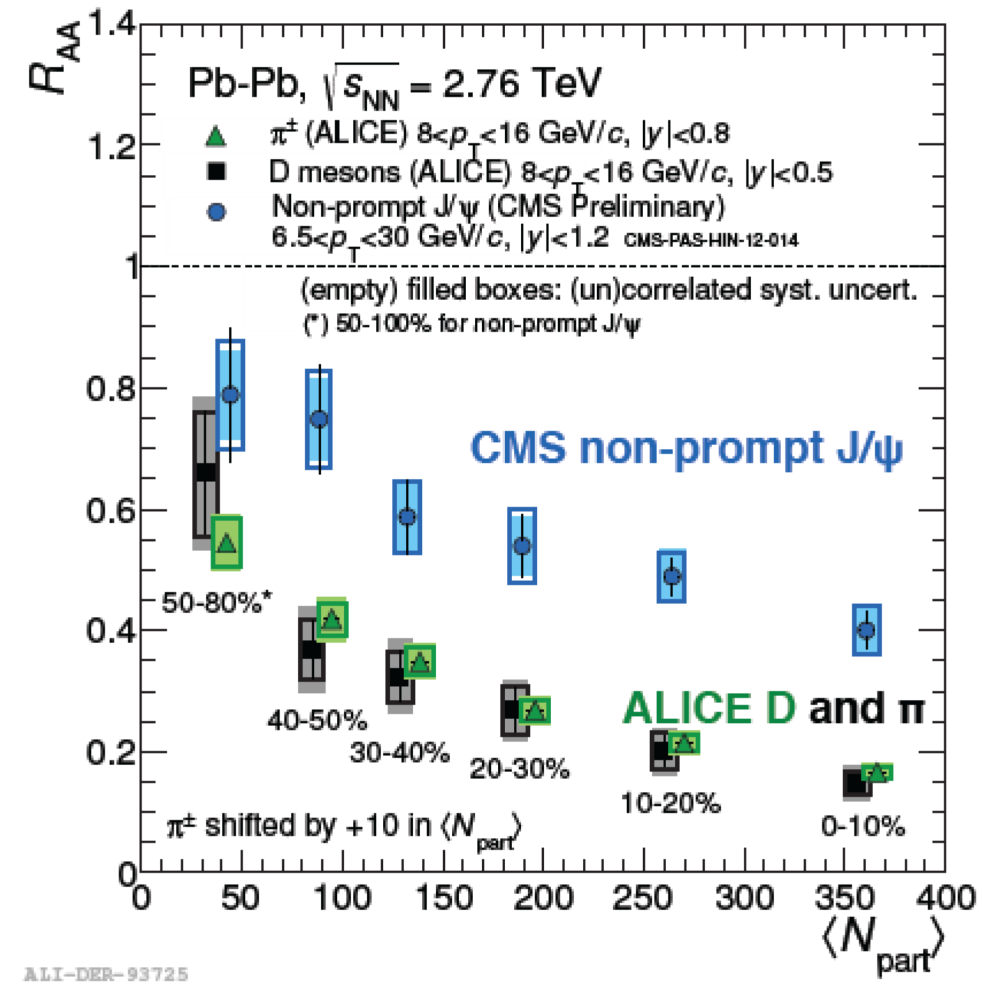
Flavour dependent energy loss?

Is the energy loss depending on the quark flavour as predicted?



M.Djordjevic PRL 94 (2004)

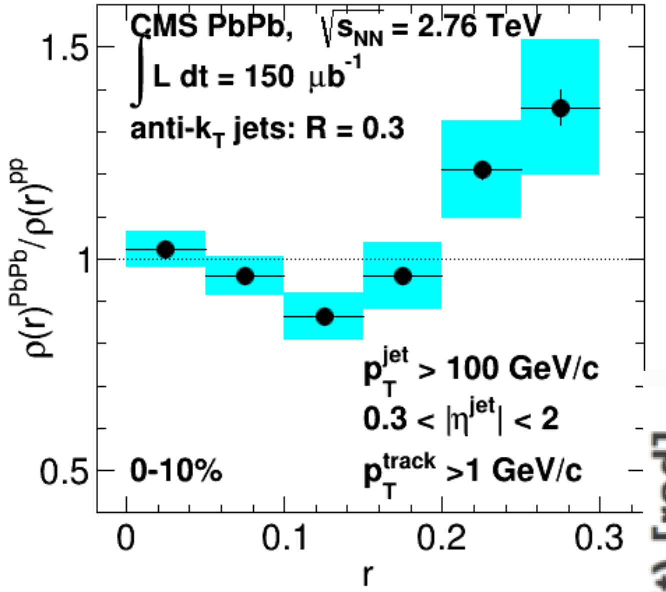




- R_{AA}(b-jet) ≃ R_{AA}(inclusive-jet) at high p_T, no strong flavour dependence
- $R_{AA}(J/\psi \leftarrow B) > R_{AA}(D) \simeq R_{AA}(\pi)$

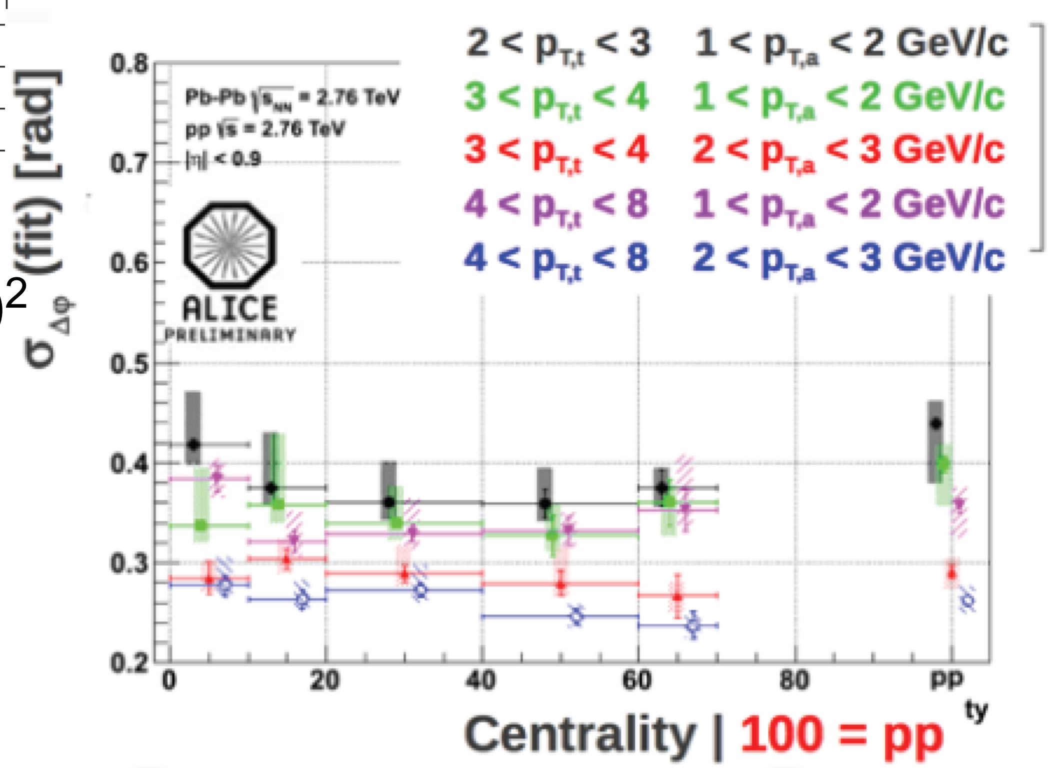
➡ More measurements down to low p_T needed to conclude

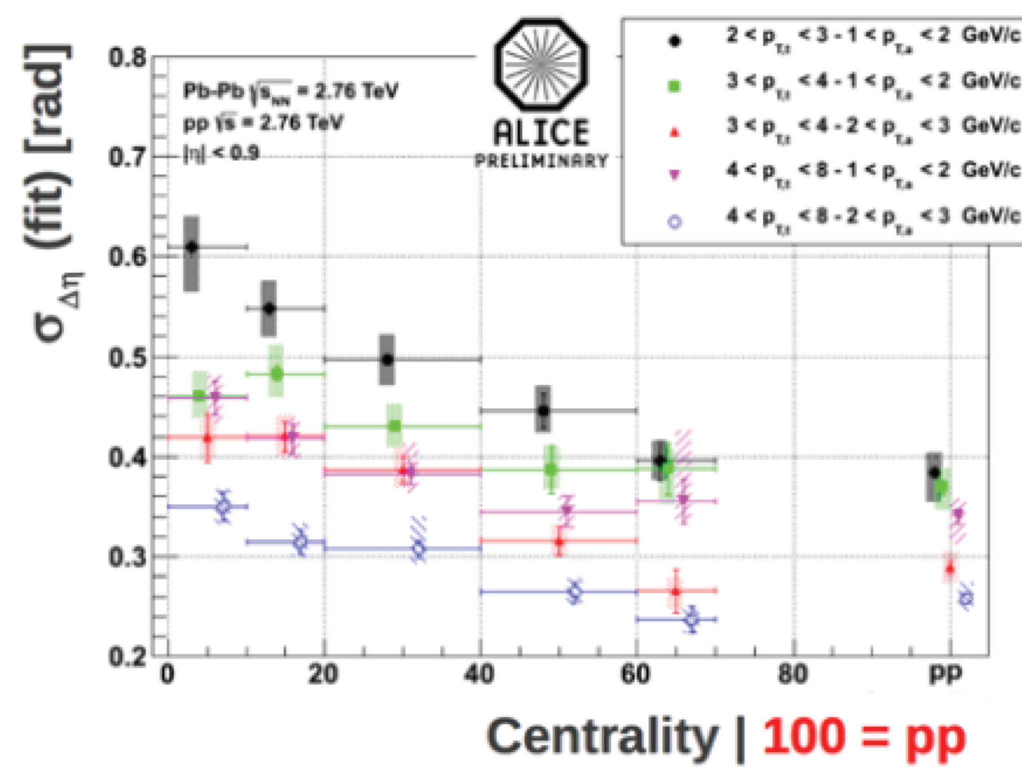
Longitudinal or transverse broadening?



$r = \sqrt{(\eta_{jet}-\eta_{ch})^2+(\varphi_{jet}-\varphi_{ch})^2}$

Which direction of the jet broadening occurred?



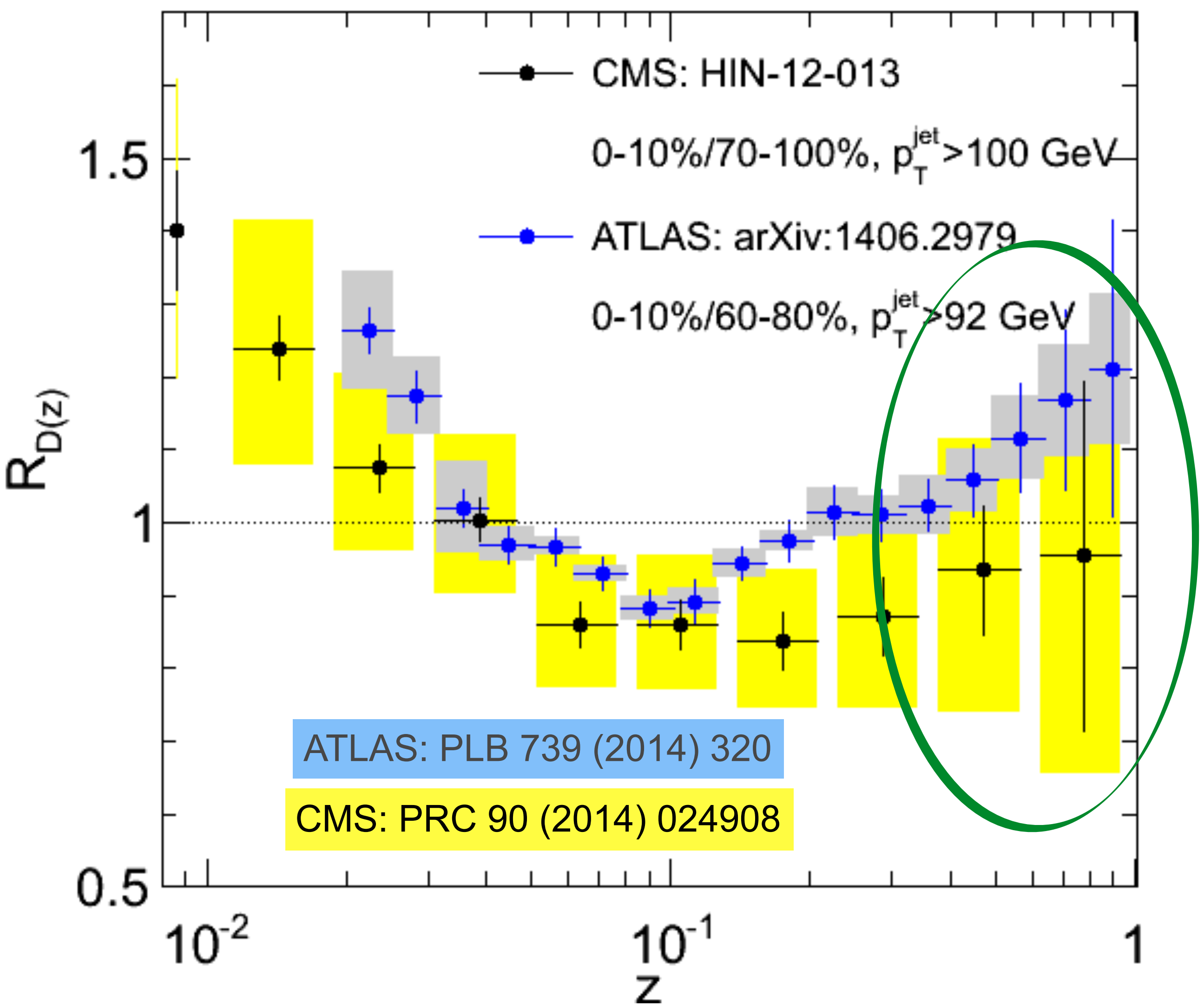


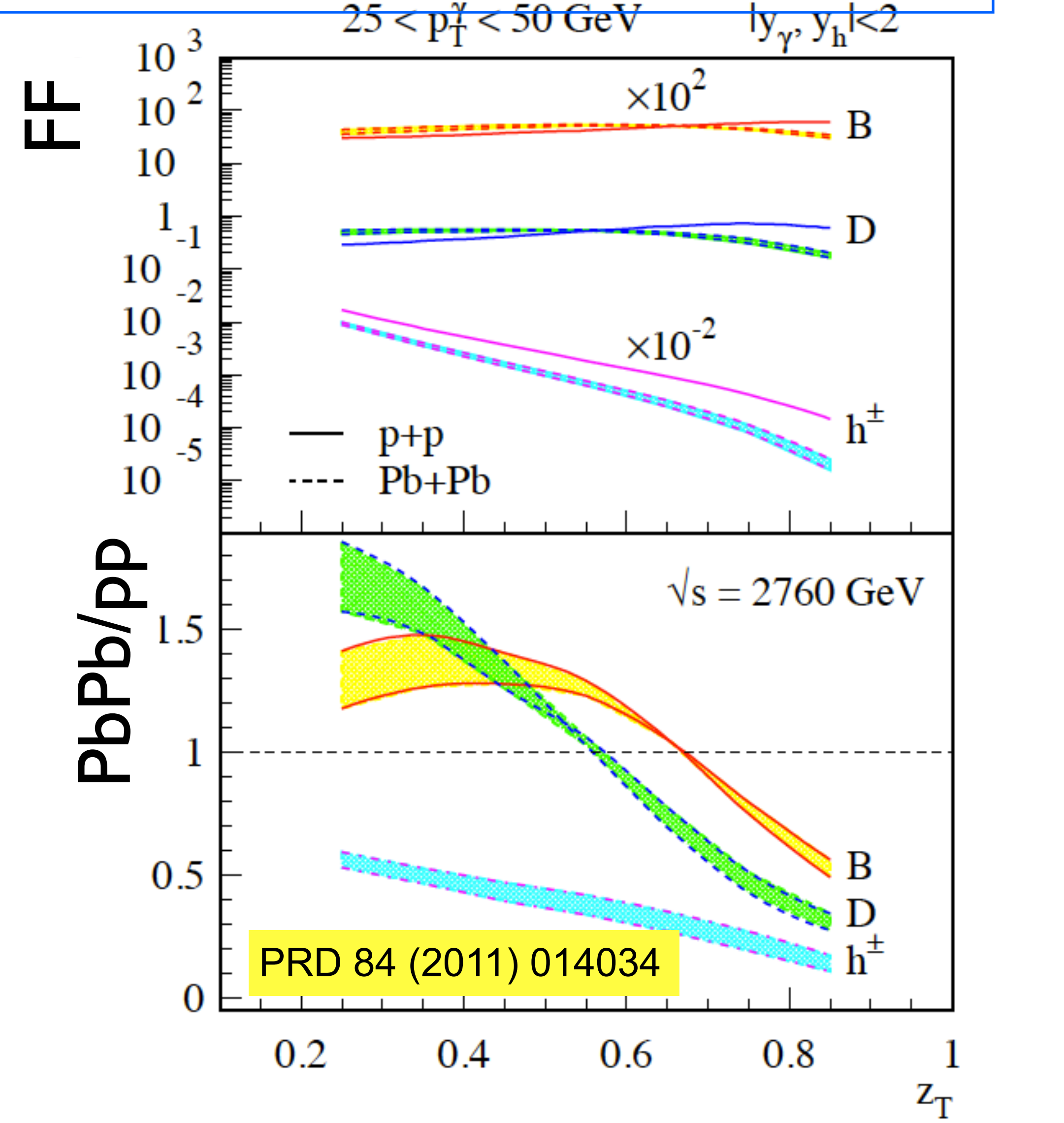
- Di-hadron correlation study observed:
  - Broadening mainly in transverse direction and no increase in longitudinal direction

➡Need precise study with jets for Δη and Δφ broadening

Color charge dependent jet FF and modifications?

High z fragments modified? Different partons have different modification?





- FF Rcp shows difference hints at high z between experiments
  - ➡ need precise measurements with coming LHC data
- Theory predicted jet fragmentation pattern modified differently for different parton mass
  - ➡ can be checked at LHC with coming data

Thank you for your attention!

Of course there are much more …

Please stay tuned…

backup