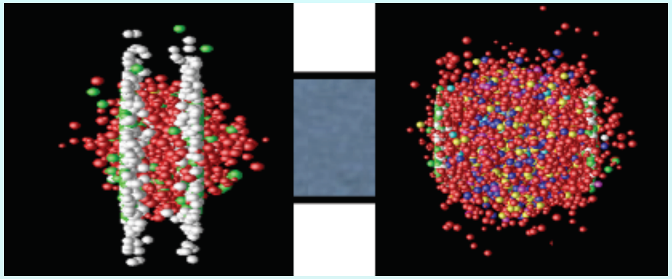
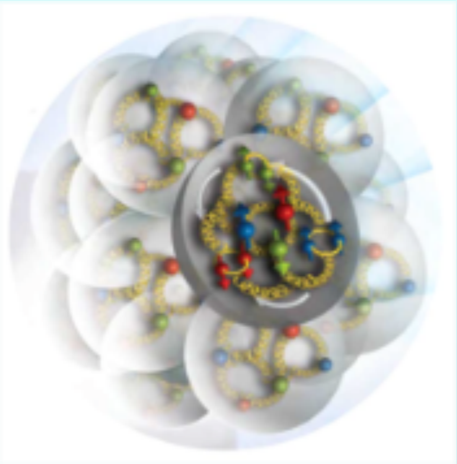
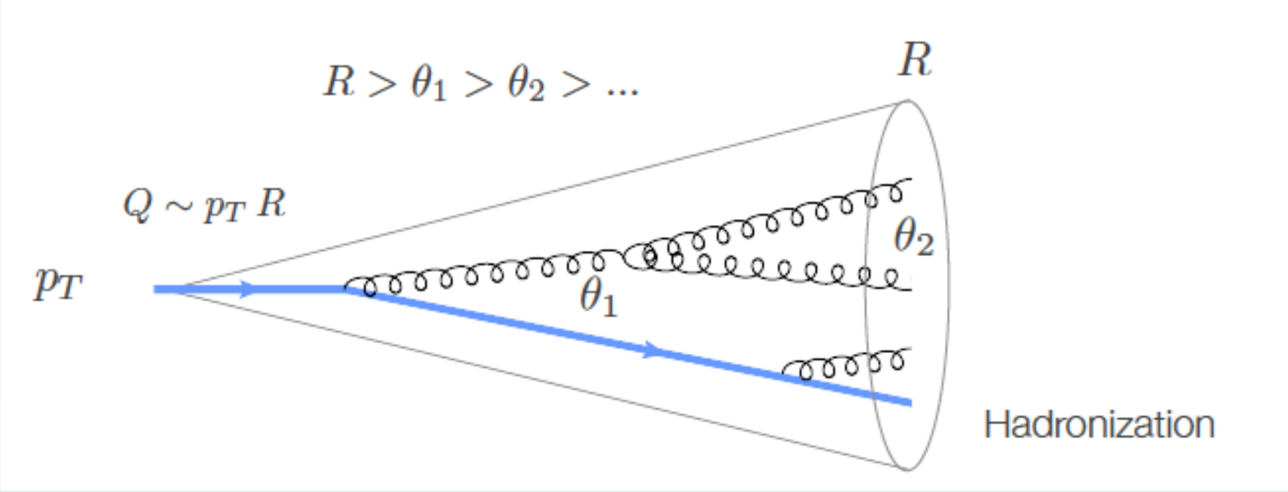
Probing QCD Matter, hot and cold







Symposium for Wick Haxton

Barbara Jacak, UC Berkeley & LBNL

January 7, 2020

In honor of Wick Haxton

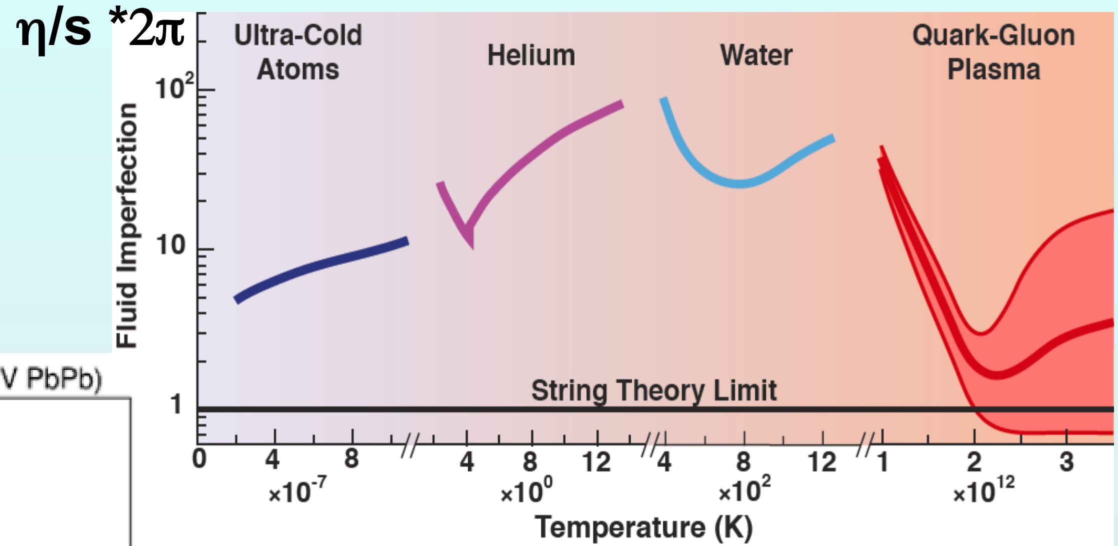
Chair of the UCB Physics Department

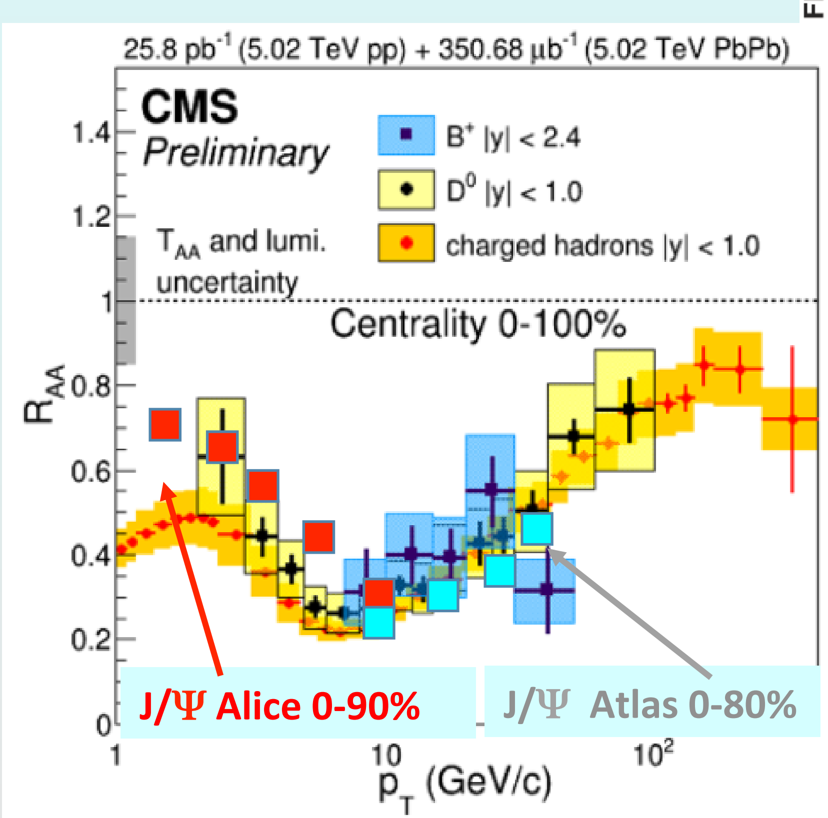
Senior Staff Member at LBNL Nuclear Science Division

Cheerful skeptic who keeps us on our toes…

Quark Gluon Plasma: strongly coupled hot QCD matter

- QGP flows as a nearly perfect liquid





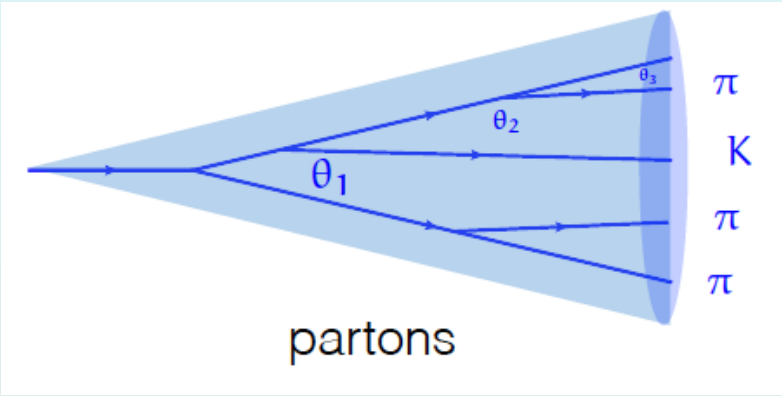
- QGP is very opaque to color-charged particles

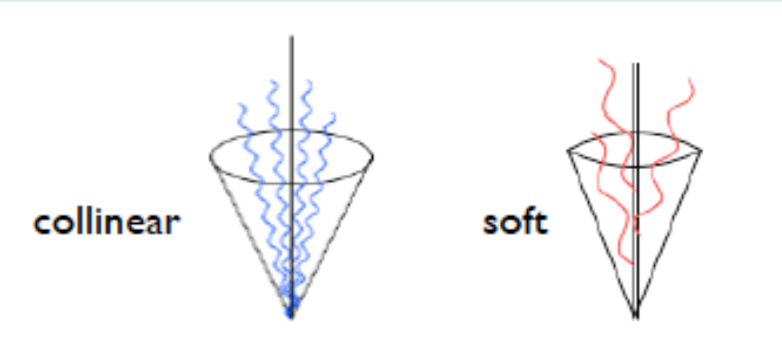
- What are its transport properties?

Probe of coice: jet (a coherent "object")

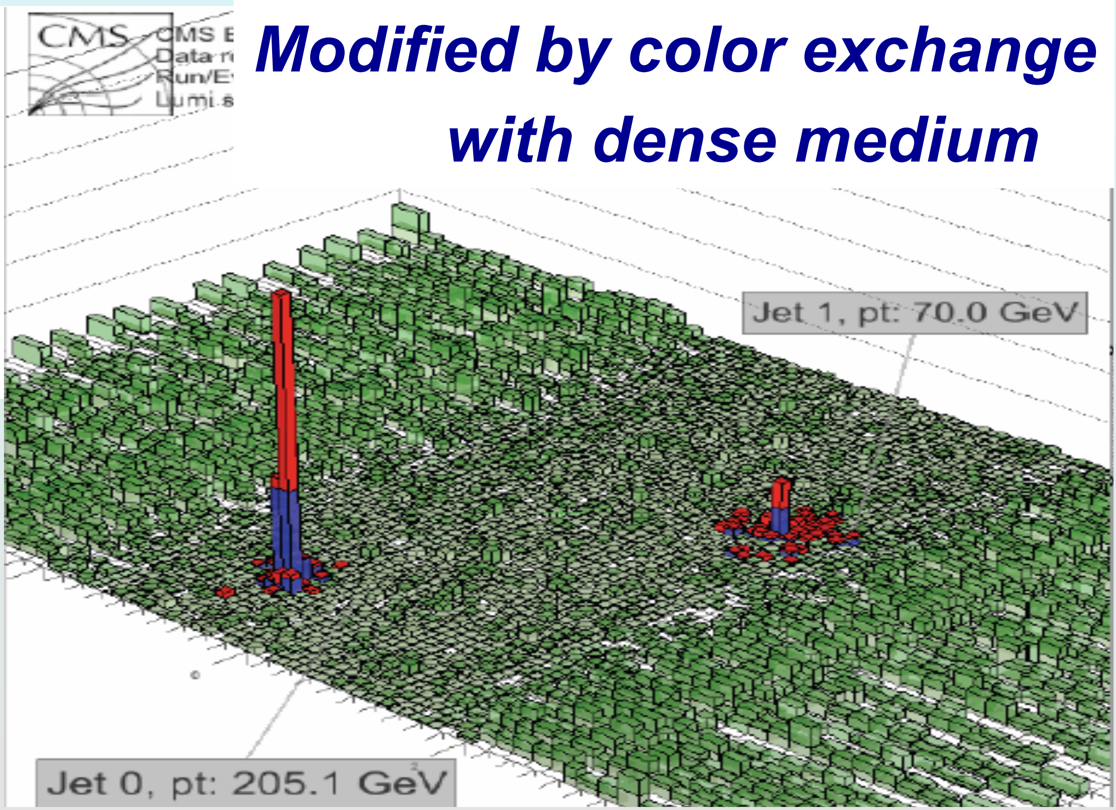
- q,g undergo probabilistic cascade of g emissions
- Total color charge & flavor are conserved
- Successive branchings are ordered in angle
- Color coherence suppresses large angle soft radiation

$$\theta_{jet} > \theta_1 > \dots > \theta_n$$





Modified by color exchange with dense medium

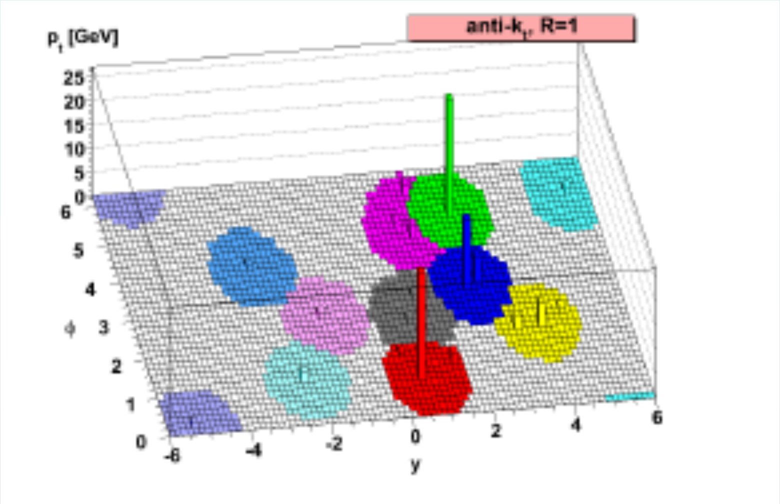


What’s in a jet?

- **Which hadrons belong to the same jet?**
  In ion collisions: underlying event of particles from other sources than this parton
- **Jet algorithm of choice: “anti-k_T”** *arXiv:1802.1189*
  Seed is hardest hadron or calorimeter tower
  Calculate distance to other particles:

$$d_{ij} = \min(k_{Ti}^{-2} k_{Tj}^{-2}) \frac{\Delta_{ij}^2}{R^2} \quad \textbf{and} \quad \Delta_{ij}^2 = (y_i - y_j)^2 + (\phi_i - \phi_j)^2$$

  Clusters softer particles with harder ones, until no more remain within distance of 2R



Typically, use R ~ 0.4 to allow statistical subtraction of the underlying event. But this misses some of the parton’s energy.

R = 1.0 is better. Feasible in e+A

Some Mysteries in hot QCD

- **Where does the energy lost by fast particles go?**

  How does strongly coupled QCD plasma transport energy?

- **Why does hydrodynamics work so well?**

  Hydrodynamic flow sets in very fast

  Even very small systems exhibit flow

  How does (cold) QCD matter transport energy?

Parton energy loss

- **Quantify using q-hat**

  $\hat{q} = \sqrt{\mu^2/\lambda}$ λ=mean free path; μ=typical p_T transfer per scatter

  $\sim k_T^2/l$

- **For a 10 GeV parton**

  $\hat{q}$ = **1.9 +/- 0.7 GeV^2/fm @ T=470 MeV**

  1.2 +/-0.3 GeV^2/fm @ T=370 MeV

  JET Collaboration PRC90, 014909 (2014)

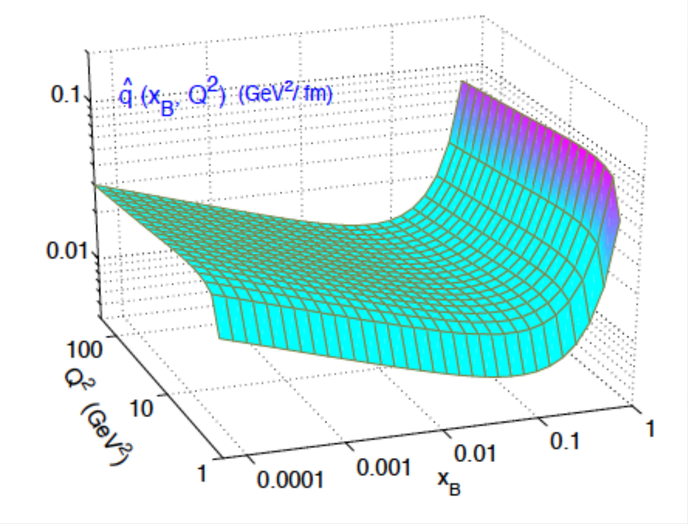
  0.38 GeV^2/fm @ 150 MeV(hot hadron gas)

  arXiv:1910.07027: Dorau, Rose, Pablos & Elfner

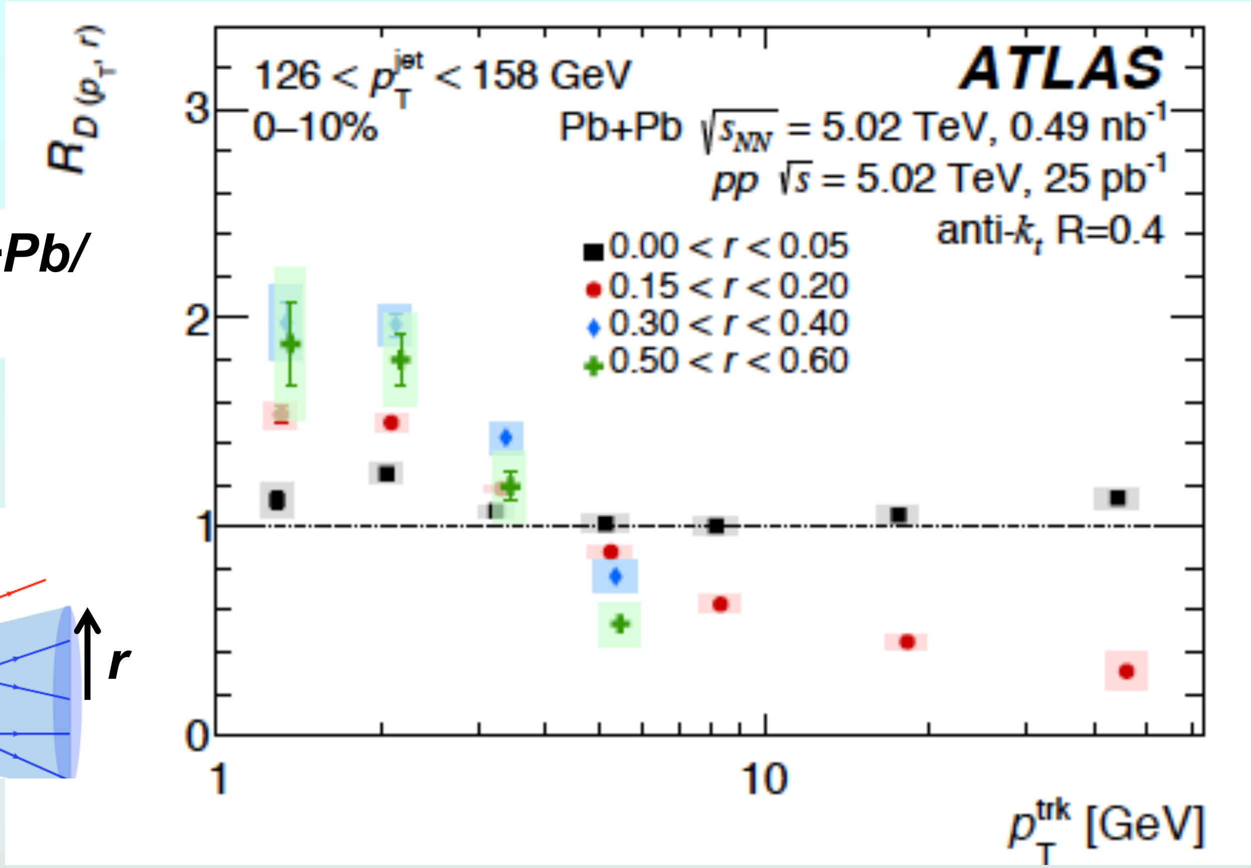
- **Many body q,g interactions!**
- **In cold nuclear matter**

  $\hat{q}$ **~ 0.02 GeV^2/fm**

  arXiv:1907.11808:
  Ru, Kang, Wang,
  Xing & Zhang



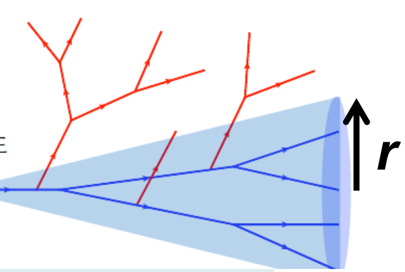
Looking differentially inside jets



arXiv: 1908.05264

See also: CMS arXiv: 1803.00042

Pb+Pb/ p+p



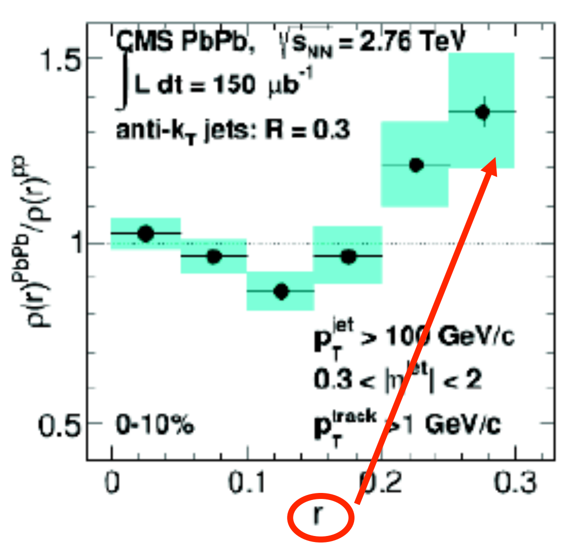
- **Excess soft particles at large jet radius**
- **Narrowing of higher p_T particle density**
- **Energy loss vs. medium response?**

quantify: compare theory to the differential data

CoLBT-hydro, Hybrid, SCET$_G$

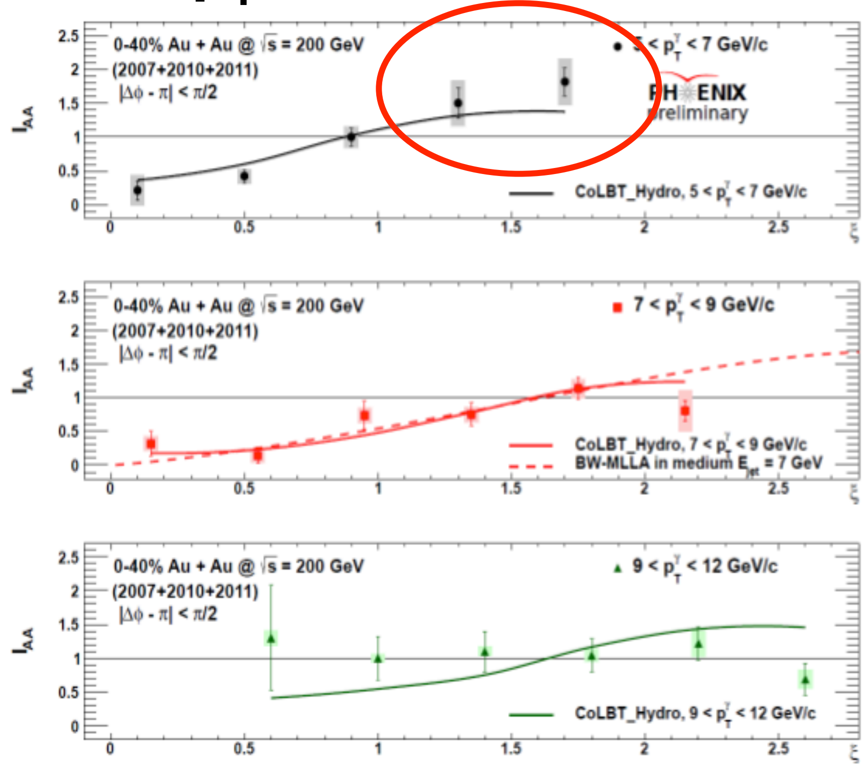
Jets get wider & "softer" in QGP

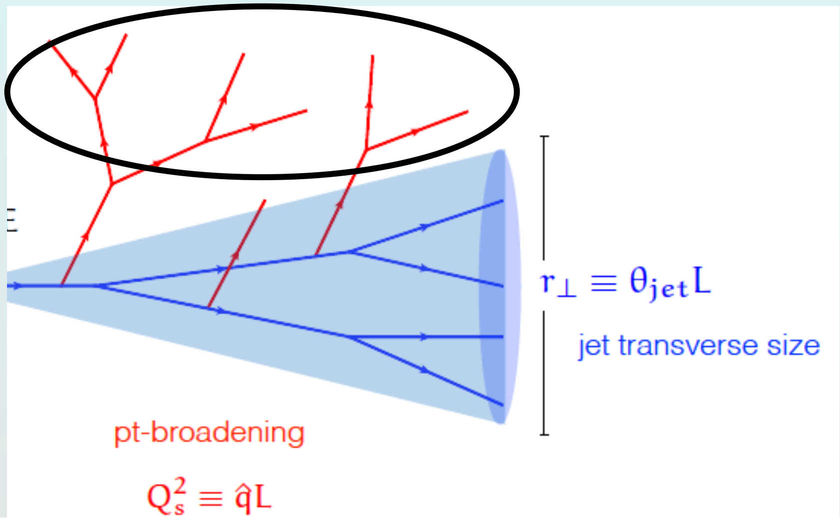
Pb+Pb/p+p:
Extra low momentum particles; high momenta suppressed



Pb+Pb/ p+p: Jets are wider in Pb+Pb

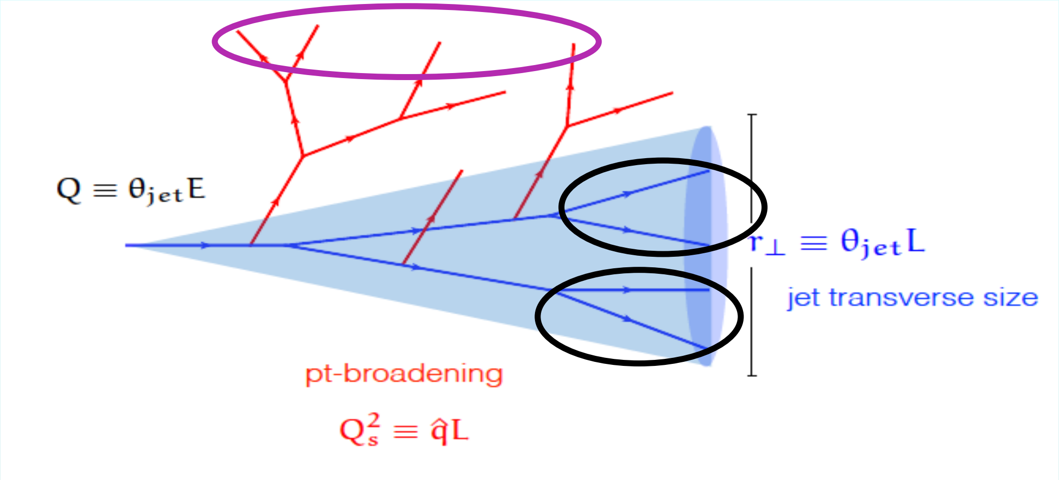
$\leftarrow p_T$





Medium induced radiation!
+ medium response

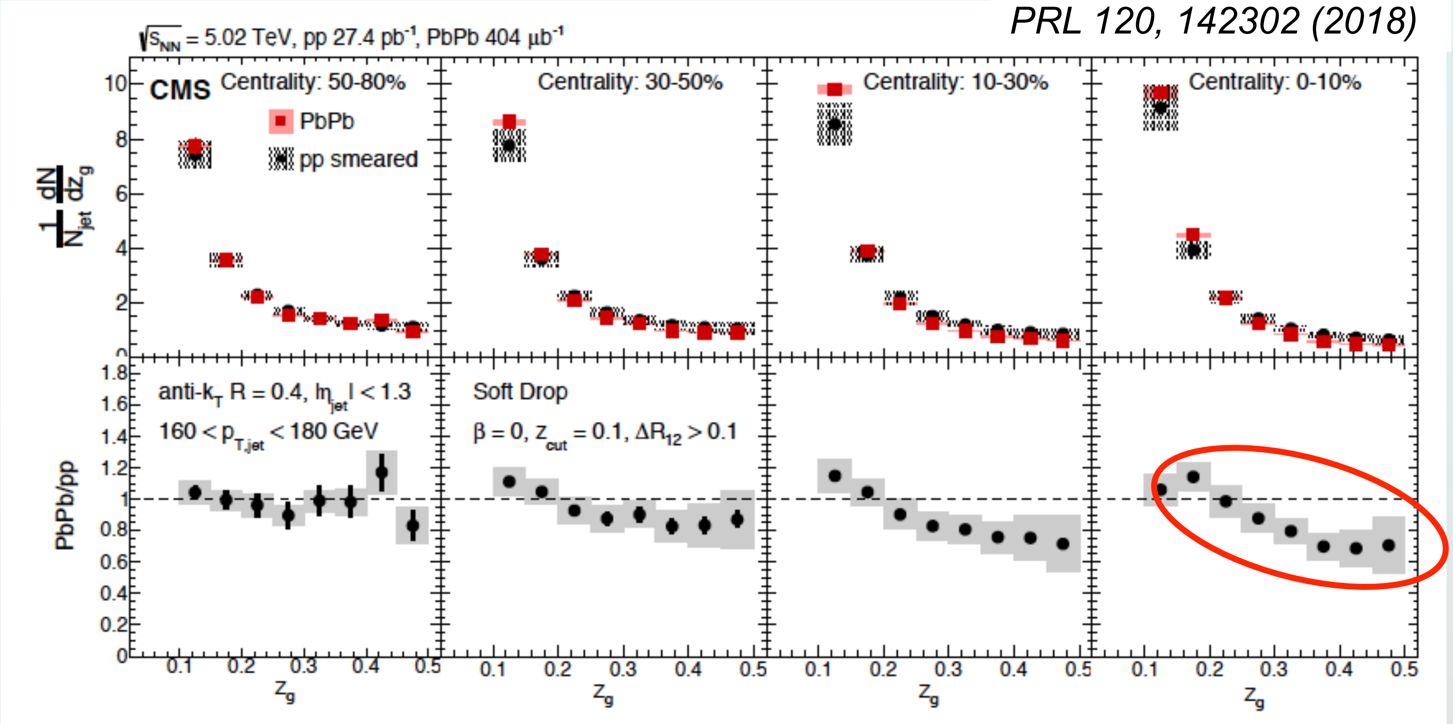
Medium induced gluon splitting?



Groom away soft stuff, look for the 2 highest p_T objects

$$z_g = \frac{p_{T2}}{p_{T1} + p_{T2}}$$

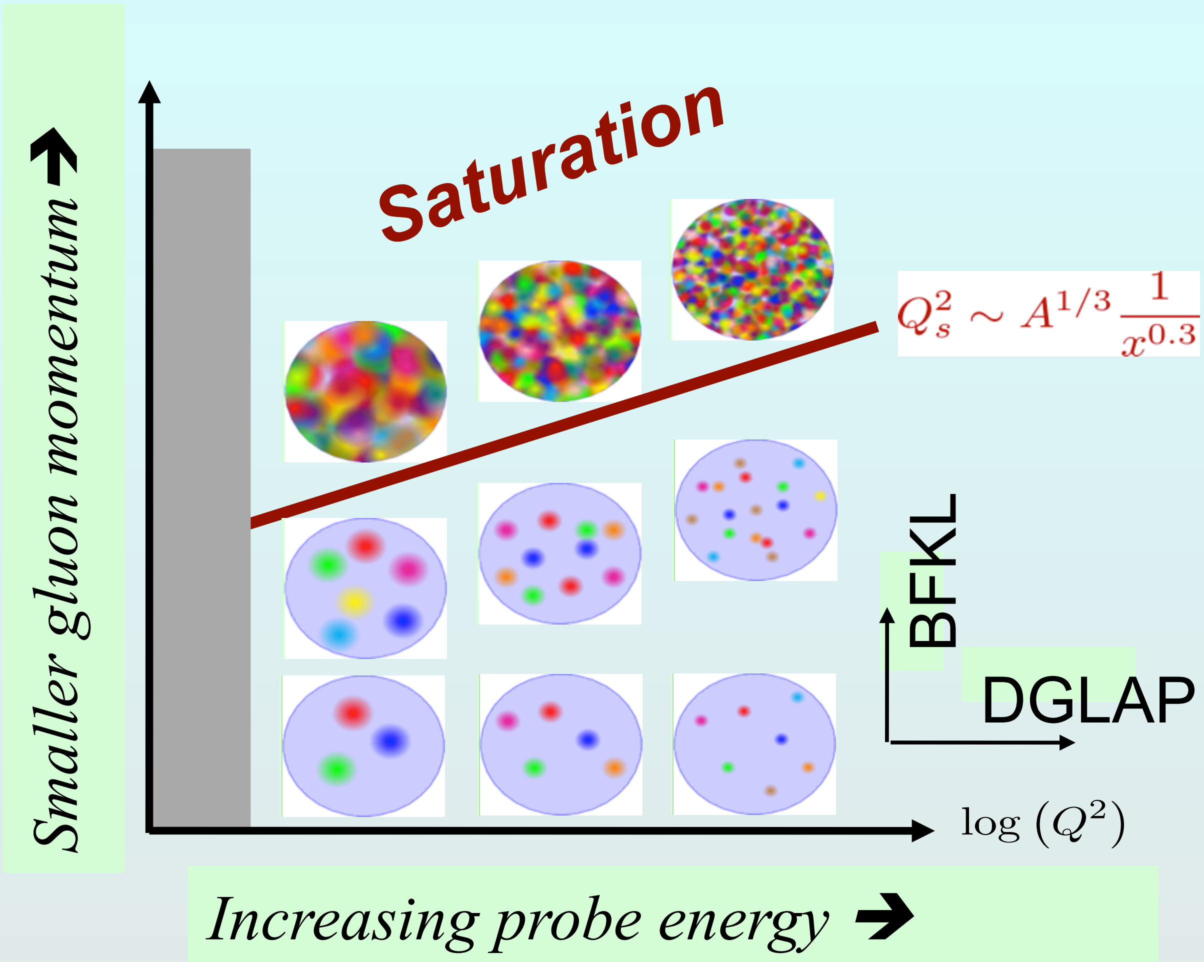
PRL 120, 142302 (2018)



Modification observed!

Experiment + Theory: *constrain E, p transport.*

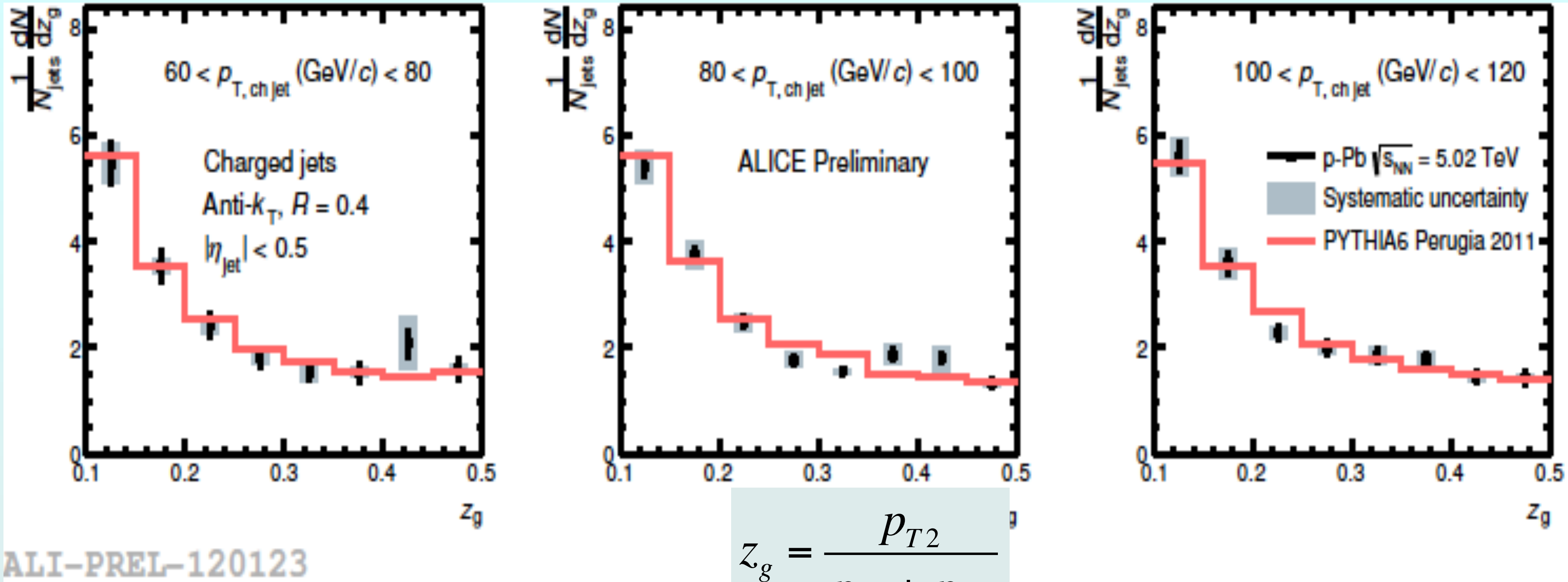
Gluon density increases at small x



Probe with jet & di-jet production

Energy loss will affect lepton-jet opening angle

Jets in cold nuclear matter: p+Pb

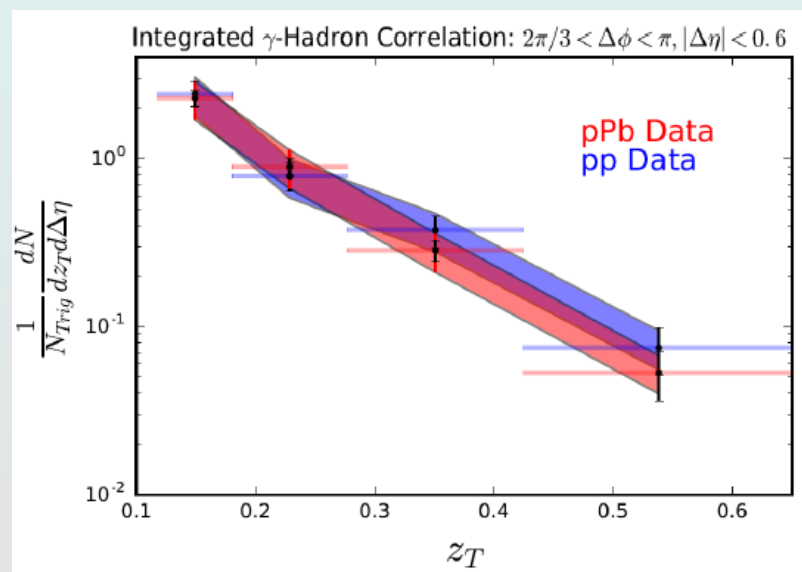


$$z_g = \frac{p_{T2}}{p_{T1} + p_{T2}}$$

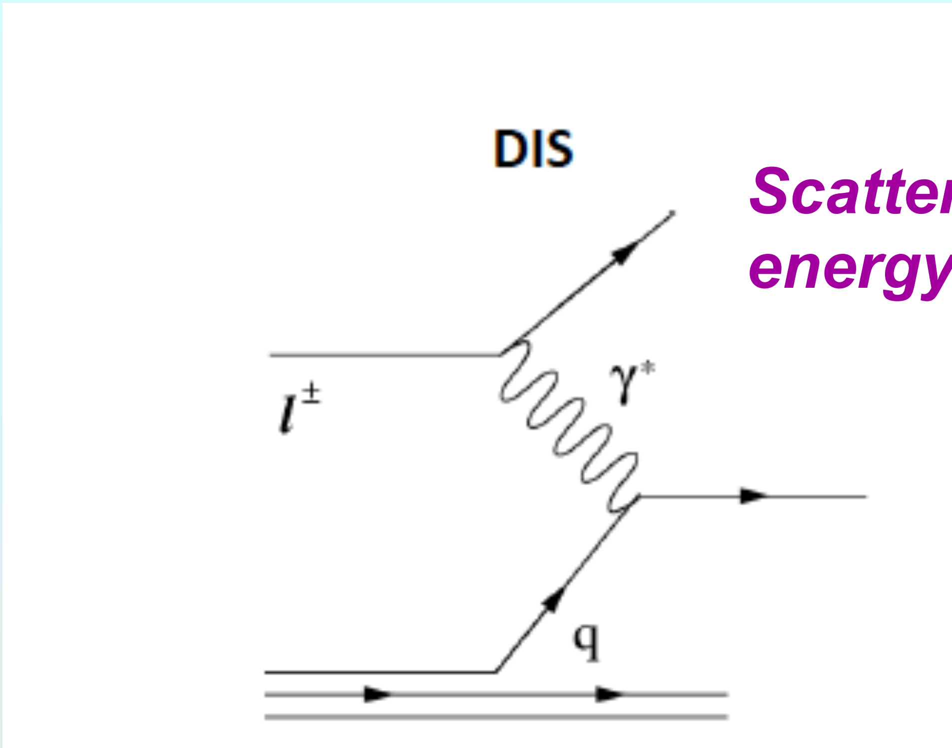
p+Pb ~p+p, at ~20% level

Need precision for $\hat{q}$ ~ 0.02

Both on measurement and on the kinematics to understand hydro onset



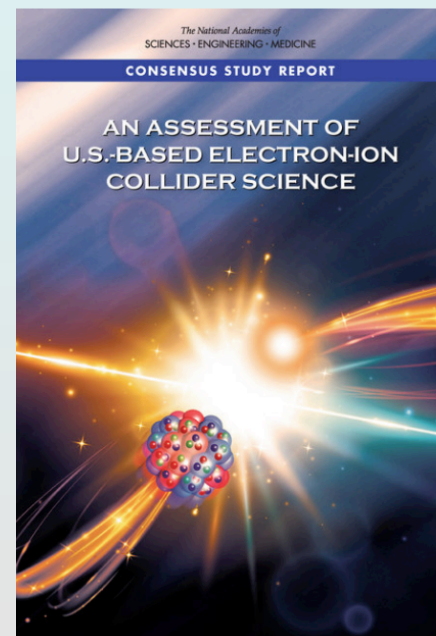
Parton - cold matter interaction: use DIS instead of γ – jet



Scattered electron: energy & angle → x, Q^2

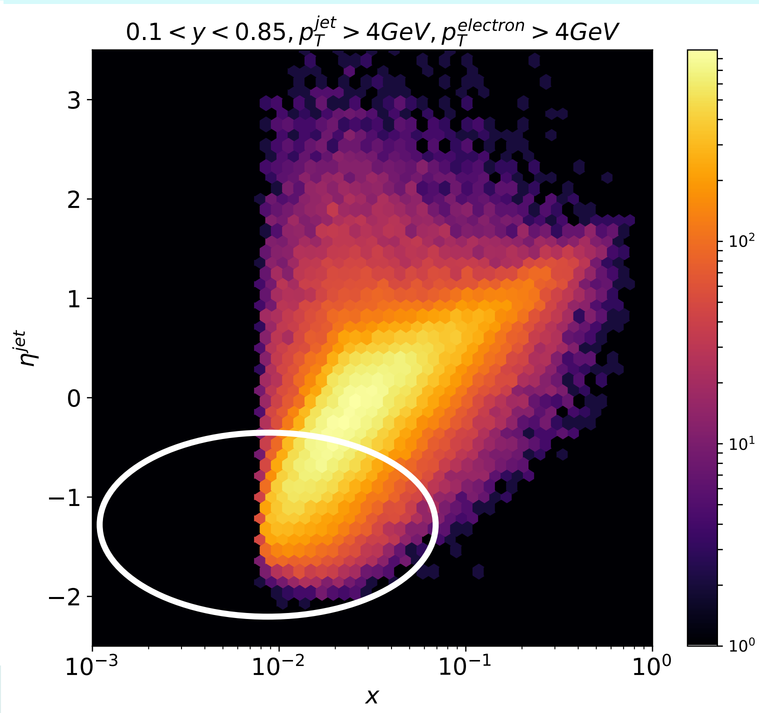
jets!

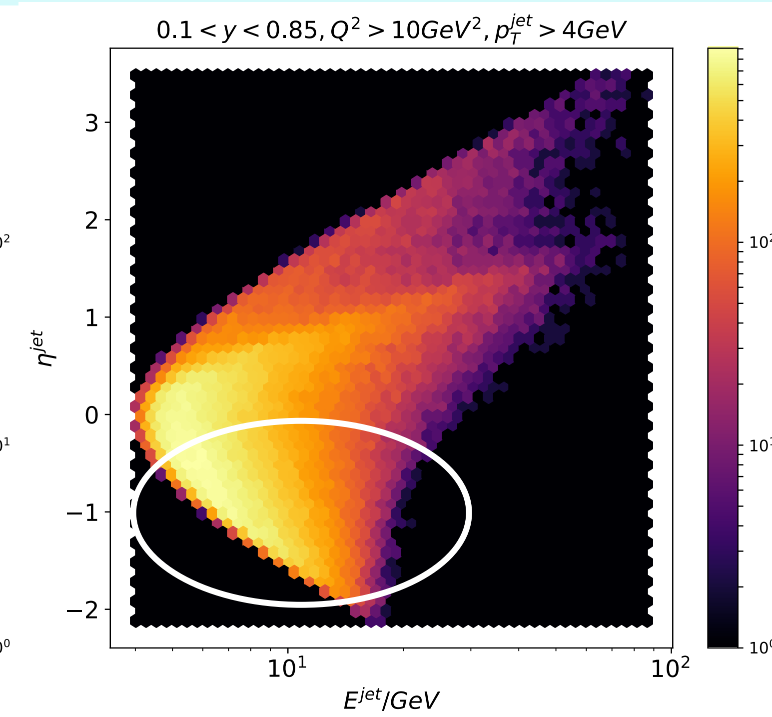
Can do this at the EIC!



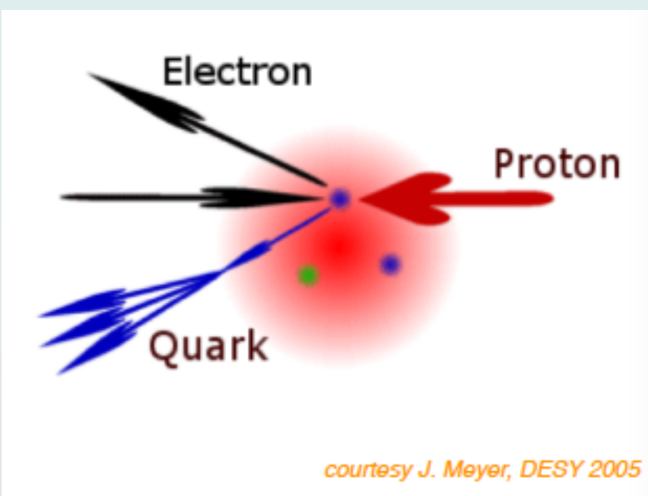
Studying the low-x region with DIS jets

Semi-Inclusive Deep Inelastic Scattering





Y. Song, M. Arratia



For struck quark at x ~ 10^{-3} - 10^{-2}

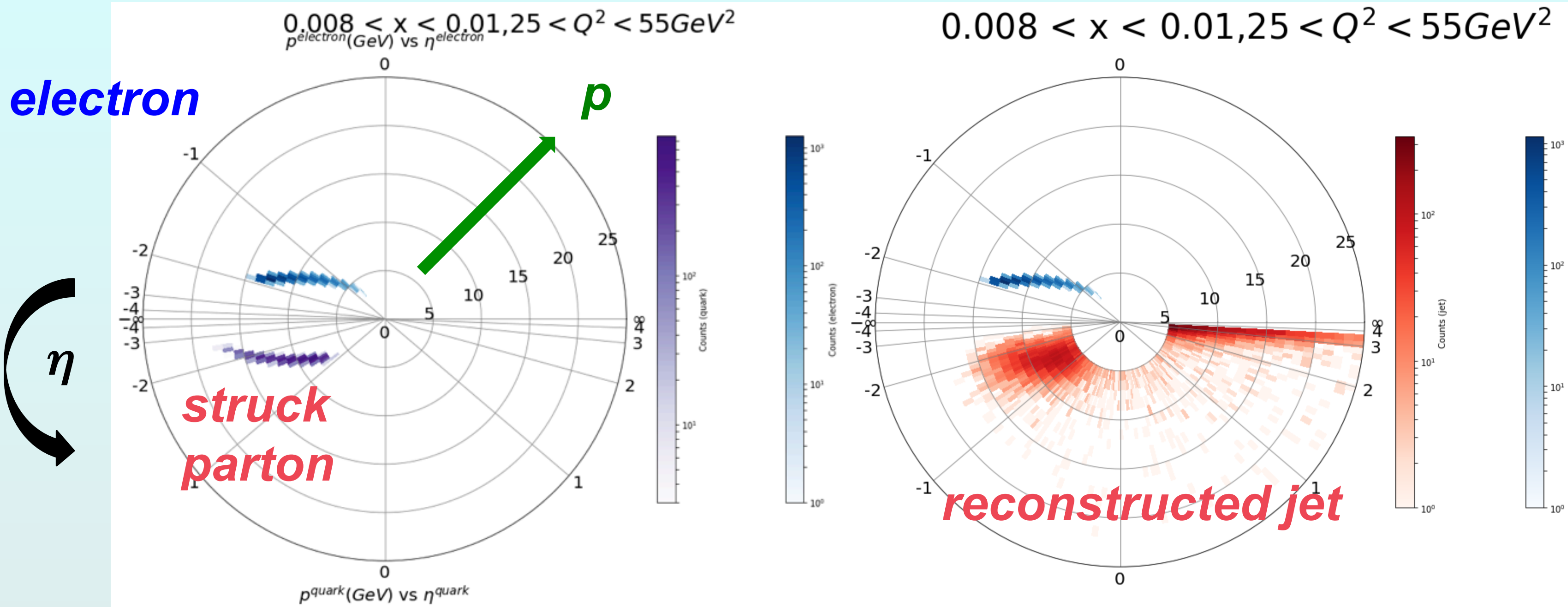
P_{quark} ~ 100 MeV – 1 GeV

Lowest x is like fixed target!

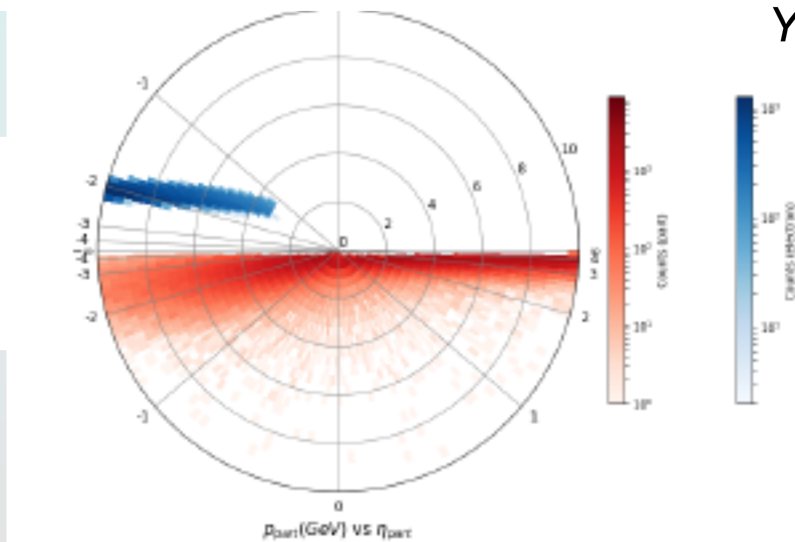
Jet goes into electron direction

Using tagged jet probe

e+p, DIS; Pythia 8. Require $W^2 > 4$ GeV^2, $Q^2 = 25 - 55$ GeV^2

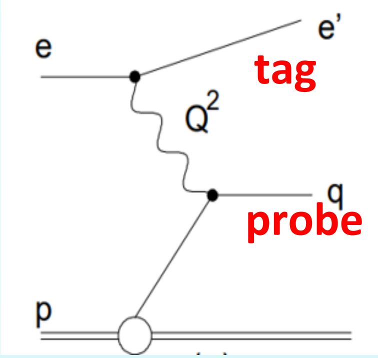


Youqi Song, M. Arratia

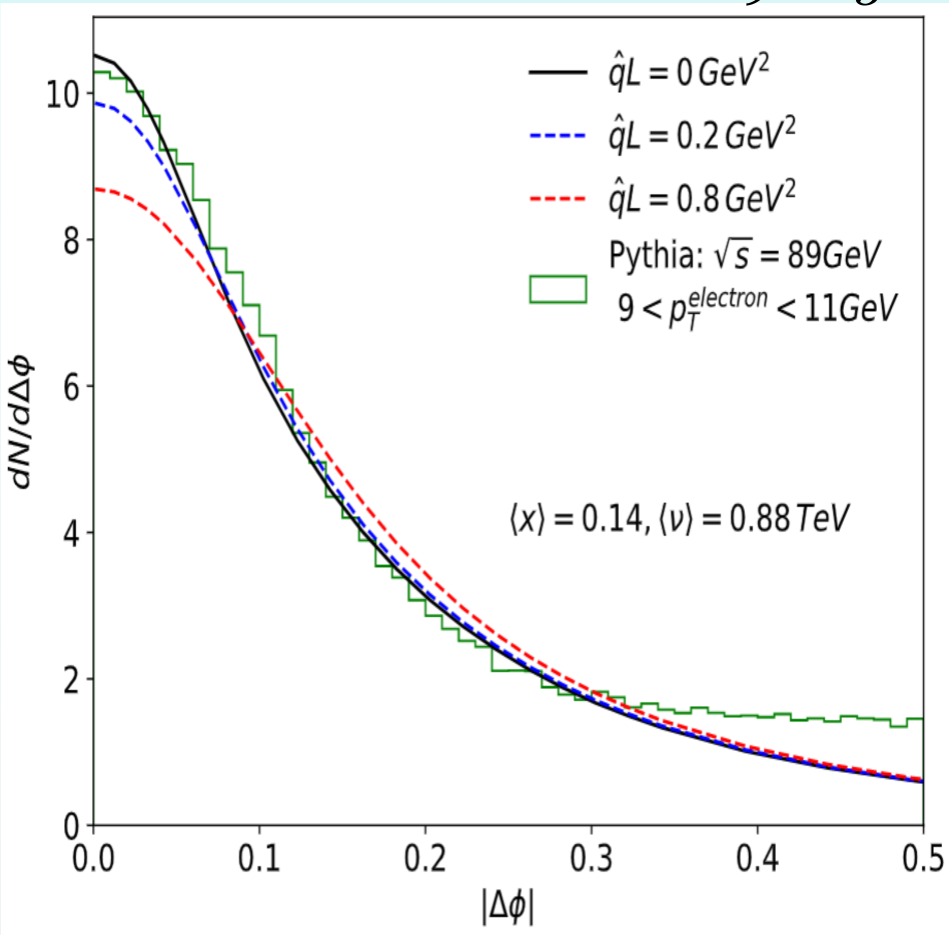


Smearing is larger for single hadrons; more so for low Q^2

Lepton-jet azimuthal correlation



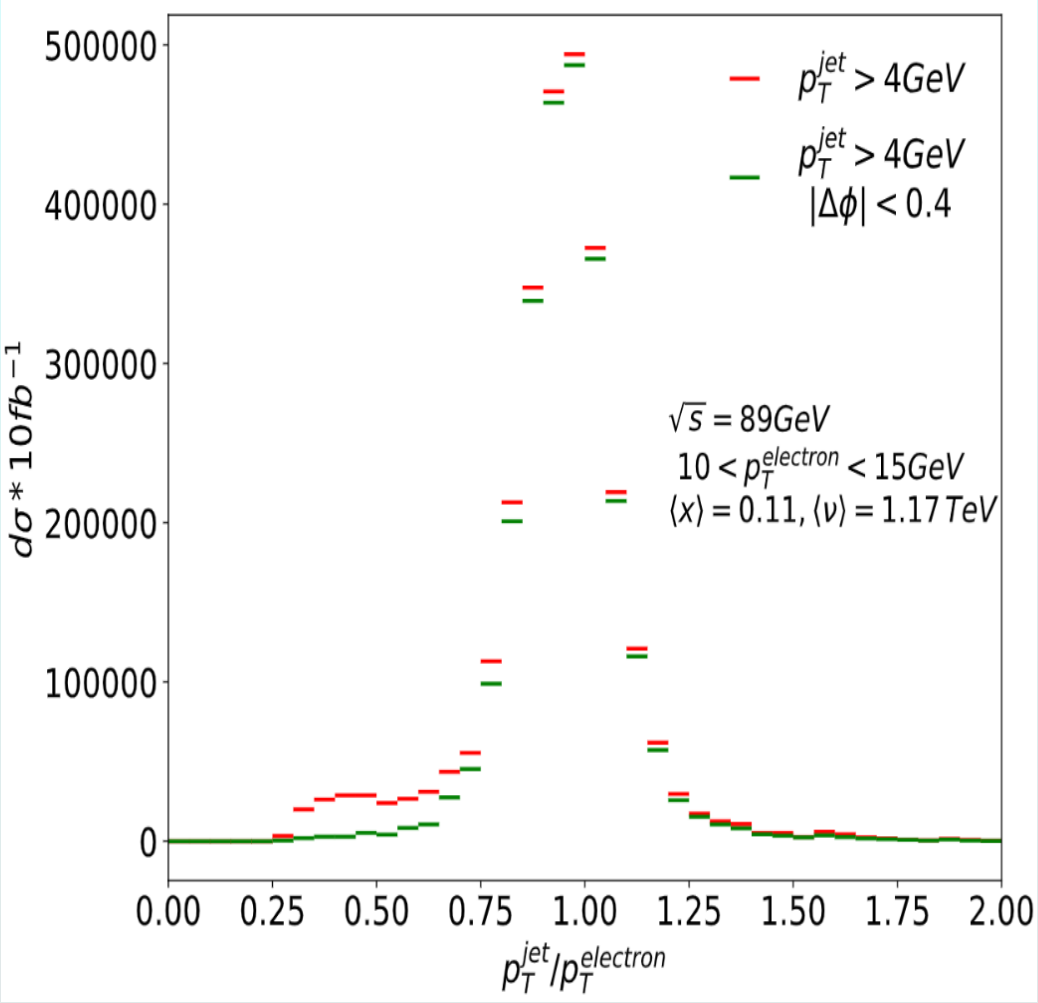
PRL 122 192003



- Imbalance due to intrinsic quark k_T and soft radiation.
- Channel to measure jet transport parameter qhat
- in e-p also quark TMD PDF, quark Sivers function

Liu et al. PRL 122 192003

Lepton-jet p_T balance



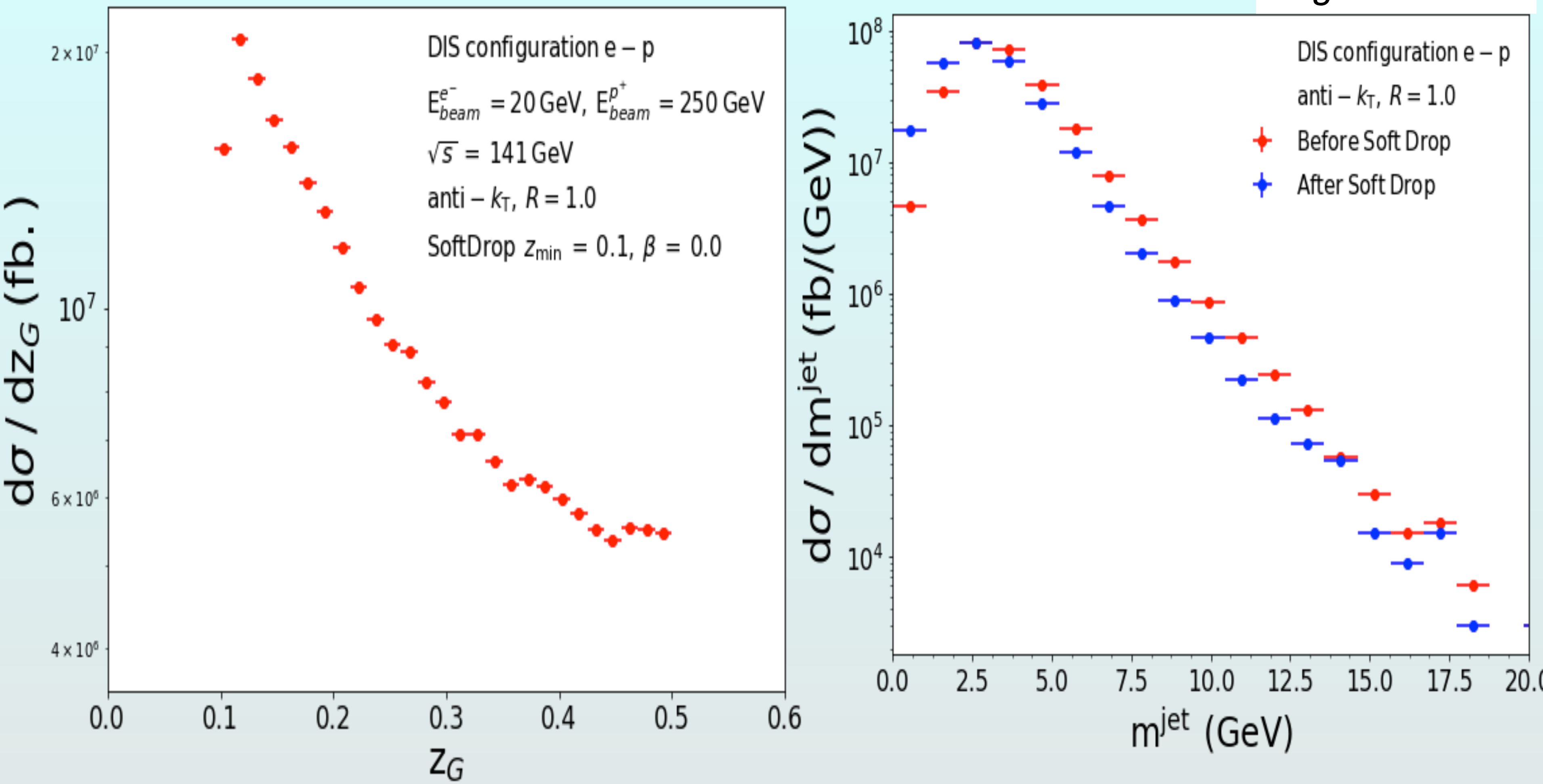
Lab frame

- eA/ep comparison for E-loss studies:
  - event-by-event tagging
    - ~ static medium.
    - ~ pure quark fraction.
    - ~ background free.
  - Ultra-precise data!

- ***"How does the nucleus react to a fast color charge?"***

Jet substructure in e + p

Miguel Arratia



Sensitive to interactions with matter; hadronization…

Next steps: simulate e+A, detector response effects

Conclusions

- Jets offer precision probe of QCD matter!
  - quantify parton - matter interactions
  - Groomed substructure observables <-> QCD
- Jets at the EIC will open a new window
  - Precise nucleon & nuclear pdf's
  - Gluon contribution to proton spin
  - Possible saturation effects
  - Sensitive to hadronization pro

- Congratulations Wick!
  You've had tremendous
  influence in many areas!

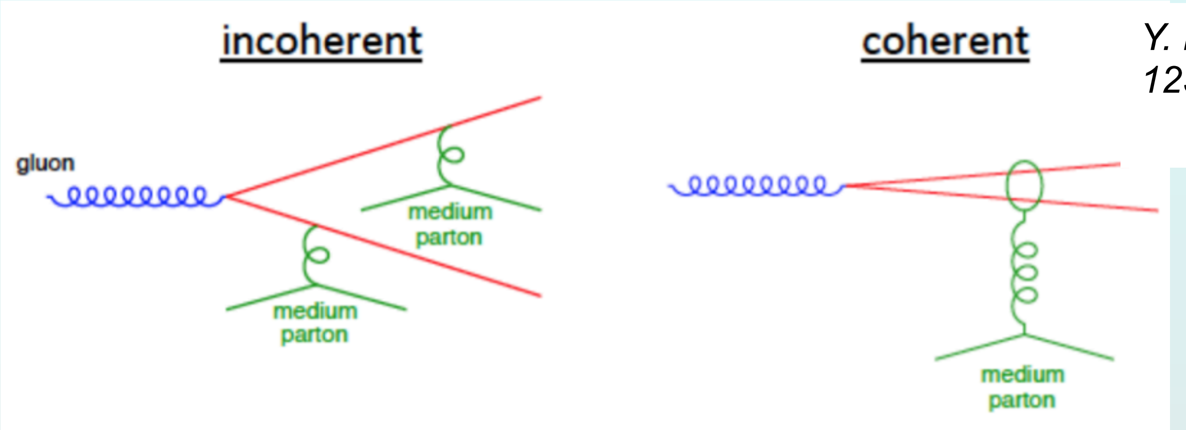
- **Backup**

Fast QCD matter isotropization*

- **Very hard to measure directly!**

  Depends on transport in (cold) QCD matter

- **Is coherent scattering the reason?**
  - ***Parton interactions in hot, dense QCD and cold, dense QCD should be similar***



Y. Mehtar Tani: JHEP04, 125 (2017) 2017

picture: M. Arratia

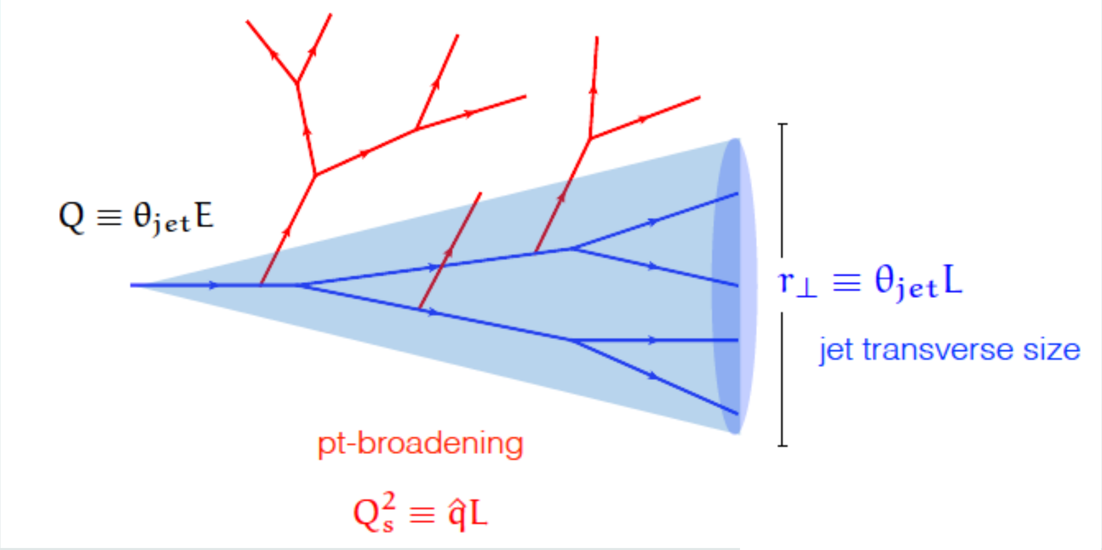
- **Or, might the system already have many-body interactions that change the distributions from a sum of pp collisions?**
  - ***g+g ➔ g large if approaching saturation…***

*** Full thermalization not required for hydrodynamics**

maybe not even isotropization… but why is not known!

How to make progress?

- What *are* the pre-equilibrium dynamics?
- Need to better understand parton transport!
  - In matter at small x in nucleon/nucleus
  - In hot, dense quark gluon plasma
- Need QCD transport in medium(s) & medium response
  - Have a nice tool to use!



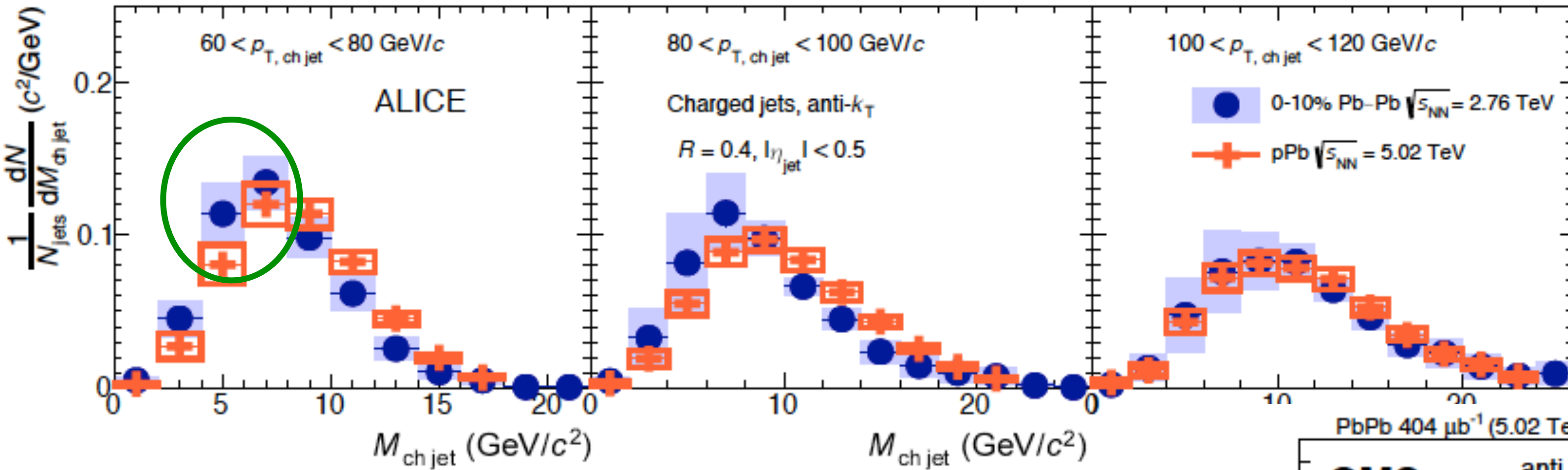
Y. Mehtar-Tani

Jets:
Parton energy loss
Quark mass
Dependence
Jet structure modifications from parton-plasma interactions

Groomed jet mass

$M_{Jet} \sim z\theta^2$

PLB 776 ,249 (2018)

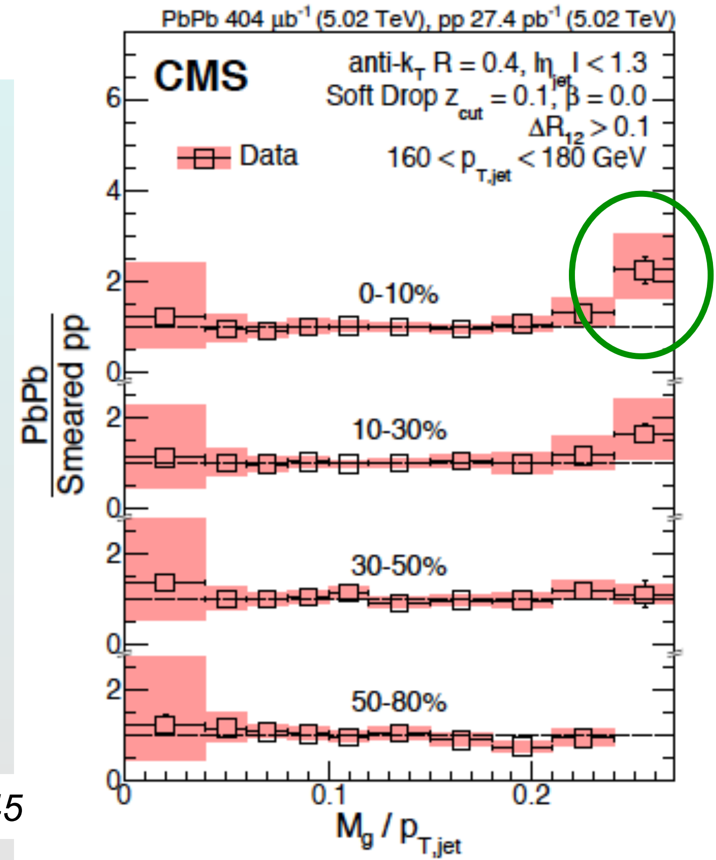


Grooming allows comparison to QCD calculations (< hadronization effects)

So, is the mass modified?

Perhaps a bit for lower p_T jets?

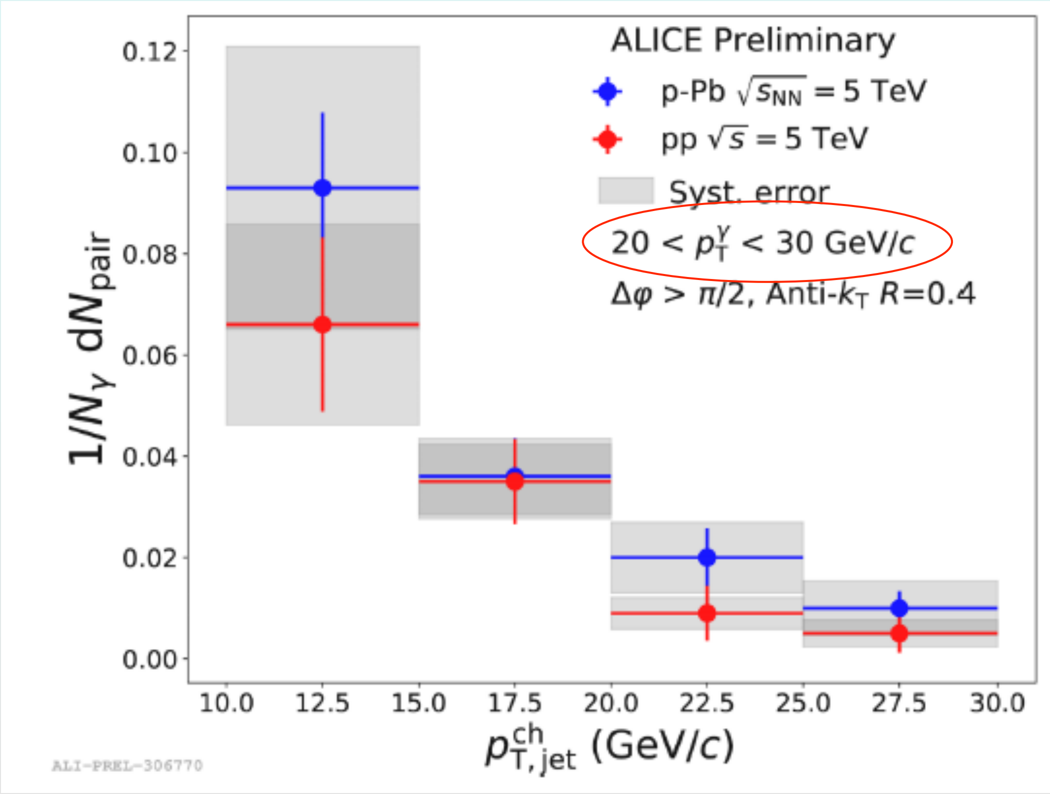
But, the mass is controlled by the groomer!



arXiv: 1805.05145

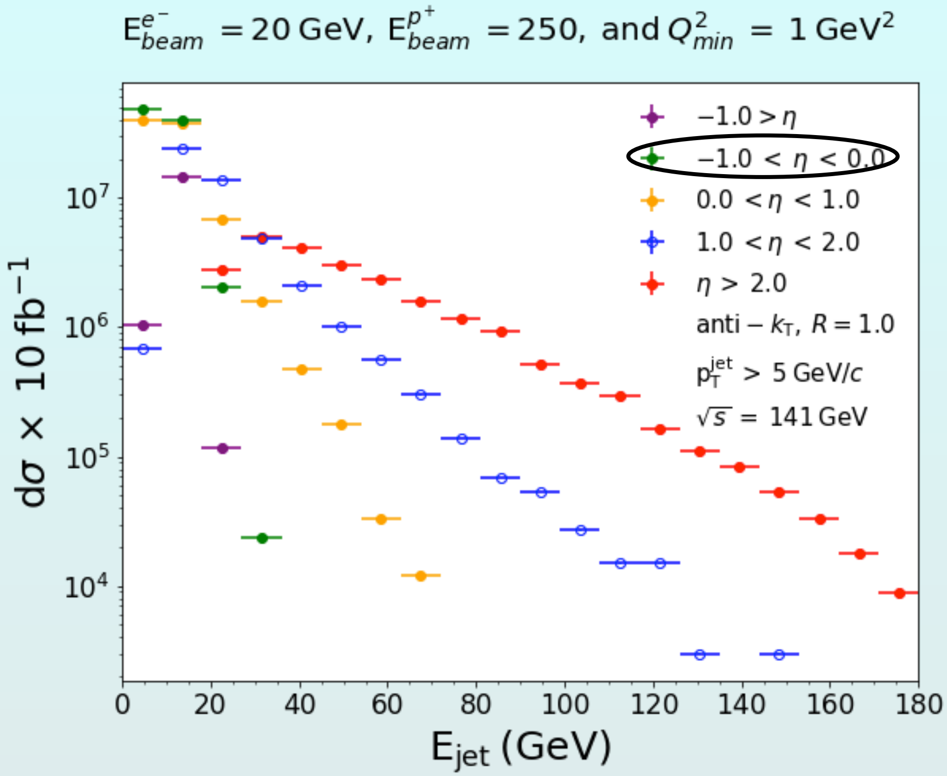
How about in cold matter?

- Look at cold matter using p + nucleus collisions
  Low x is where the gluon density is high
- Use γ-jet correlations from QCD Compton scattering
  γ energy tags the energy of the scattered parton

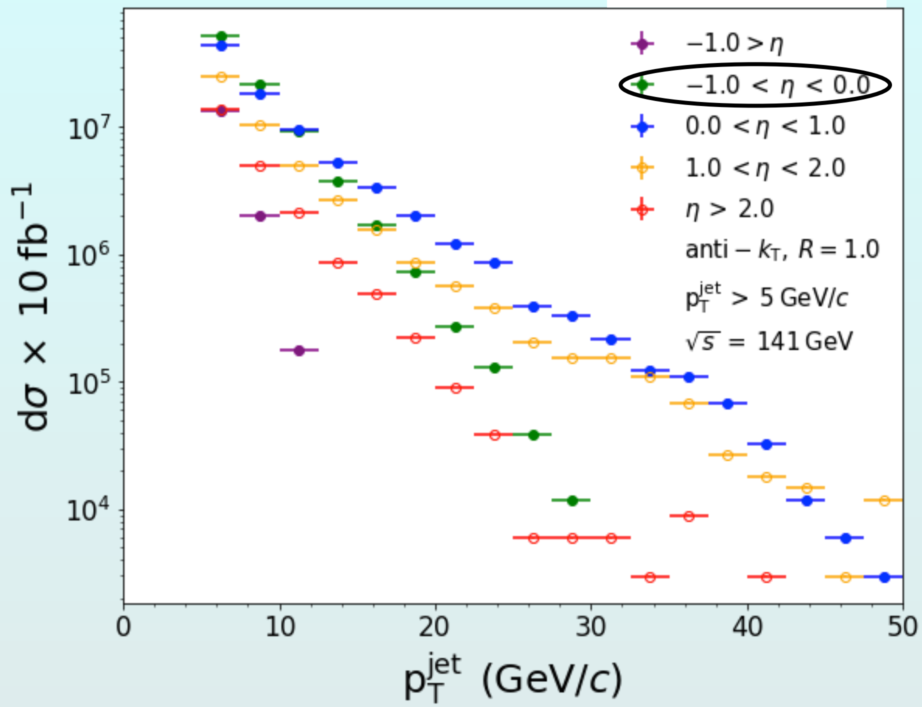


Jet spectra in p+Pb same as that in p+p, within ~20%

Kinematic reach for DIS jets



Jose Soria



bins	SD of x	Mean of x
-1 > eta	0.005	0.0035
-1 < eta < 0	0.008	0.0063
0 < eta < 1	0.021	0.016
1 < eta < 2	0.047	0.041
eta > 2	0.11	0.10

Low-x reach is limited by kinematics

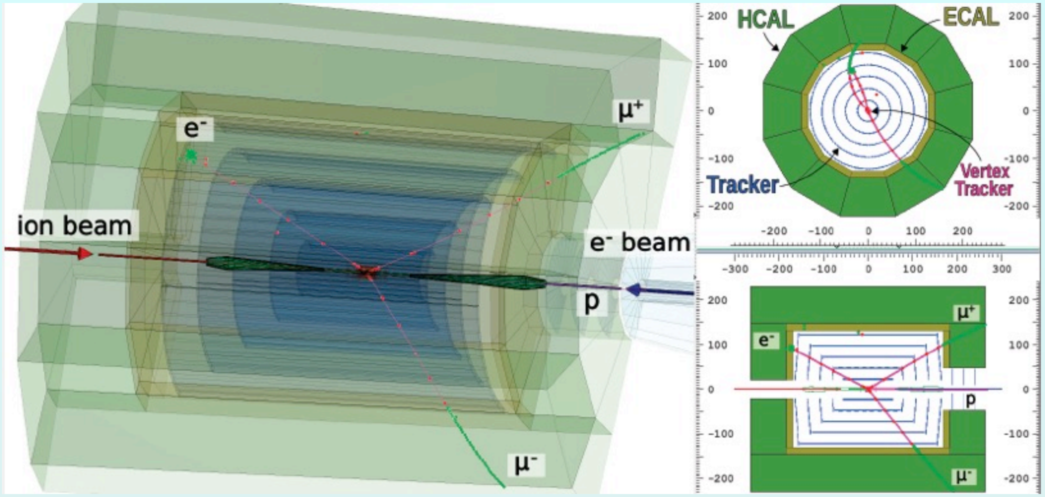
Reasonable jet p_T at $-1 < \eta < 0$

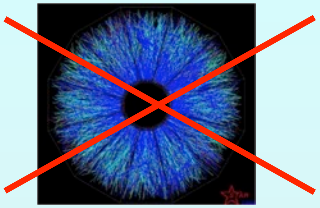
Scatter off q at $x \sim 8 \times 10^{-3}$

(for $\sqrt{s} = 89$ GeV)

These jets go thru lower x matter

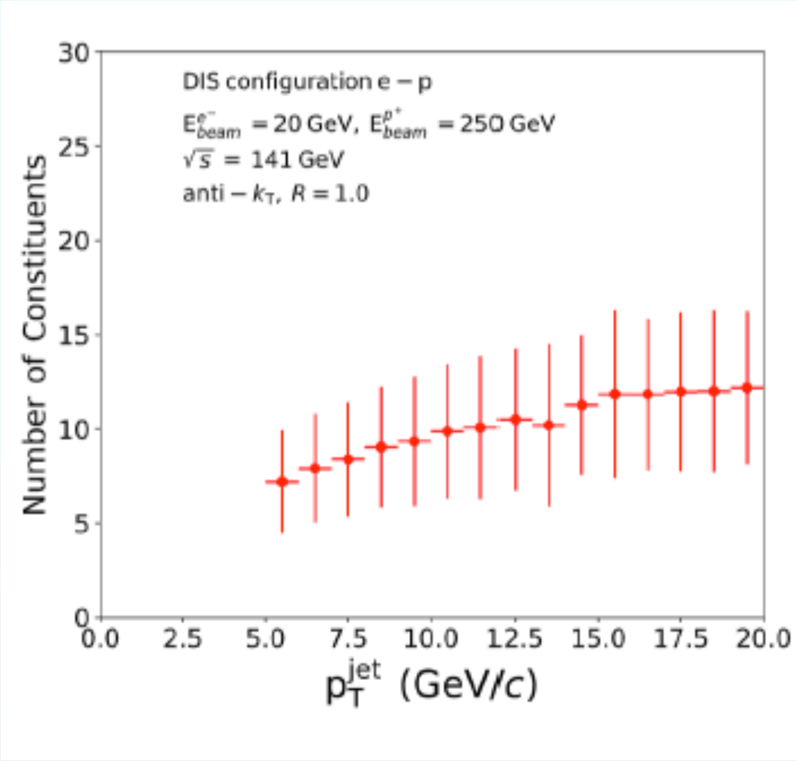
Cleaner events -> easier reconstruction





- Can reconstruct with R=1.0
  No underlying event!

- Can study substructure
  Jet grooming effects should be less important



Other QCD topics with jets at the EIC

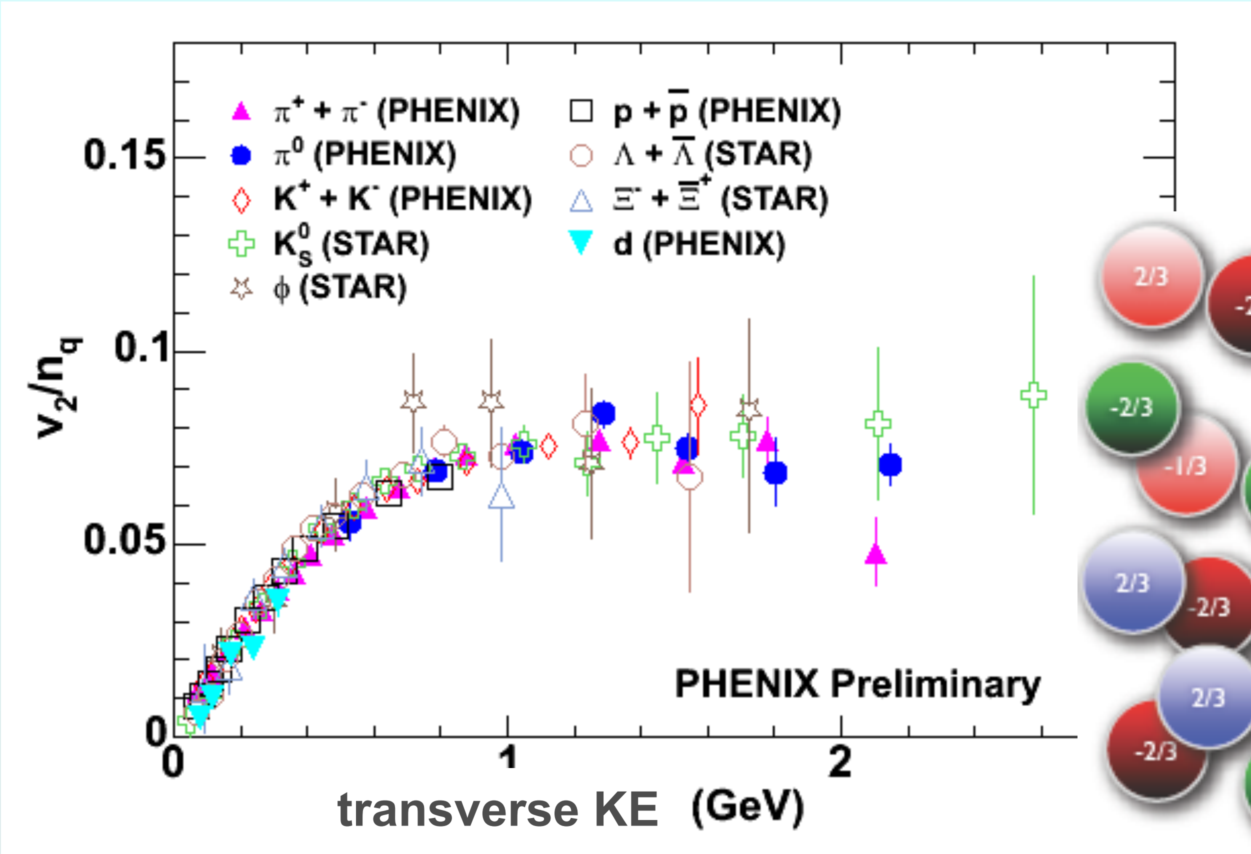
- pdf's
  In nucleons (evolution in x and Q^2)
  In nuclei
    modification from that in protons
    especially at low x, where nucleons overlap

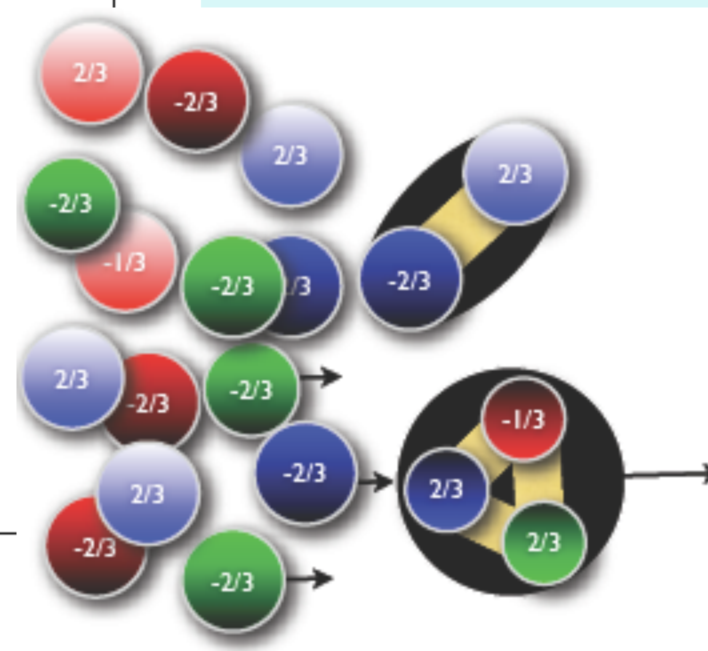
- Photon pdf

- Spin in the gluons
  Δg via scaling violations in $g_1(x,Q^2)$

How about hadronization?

Hadronization of quark gluon plasma





All particles flow
as if frozen out from
a flowing soup of
constituent quarks

implication: valence quarks, not hadrons

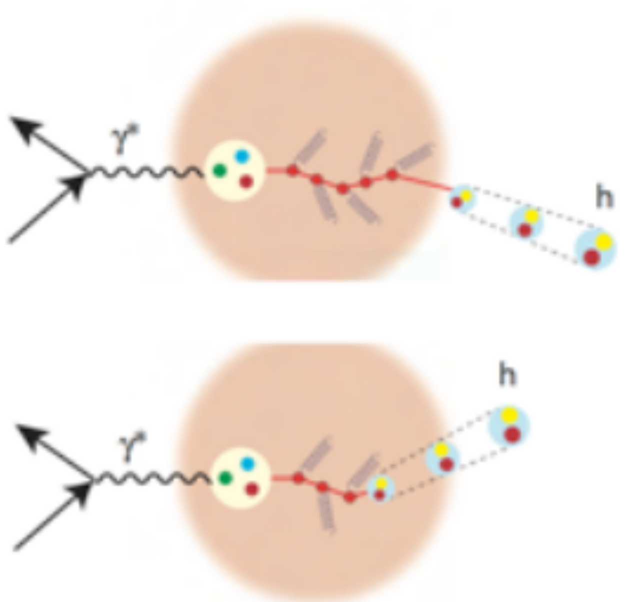
pressure builds early, dressed quarks are

hadronize by (simple) coalescence of co

Is coalescence the right picture?

EIC - SIDIS to study Emergence of Hadrons

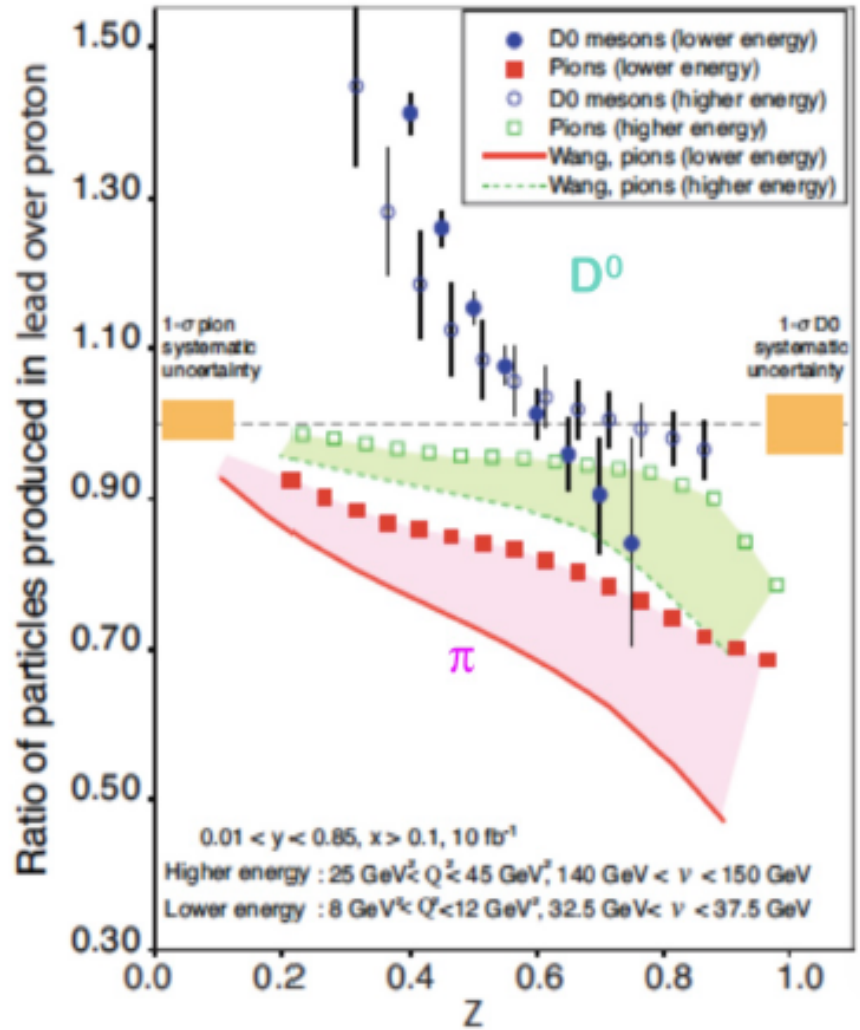
E. Sichtermann



Control of $\nu = \dfrac{Q^2}{2mx}$ and

medium length

Study mass-dependence via charmed hadrons.

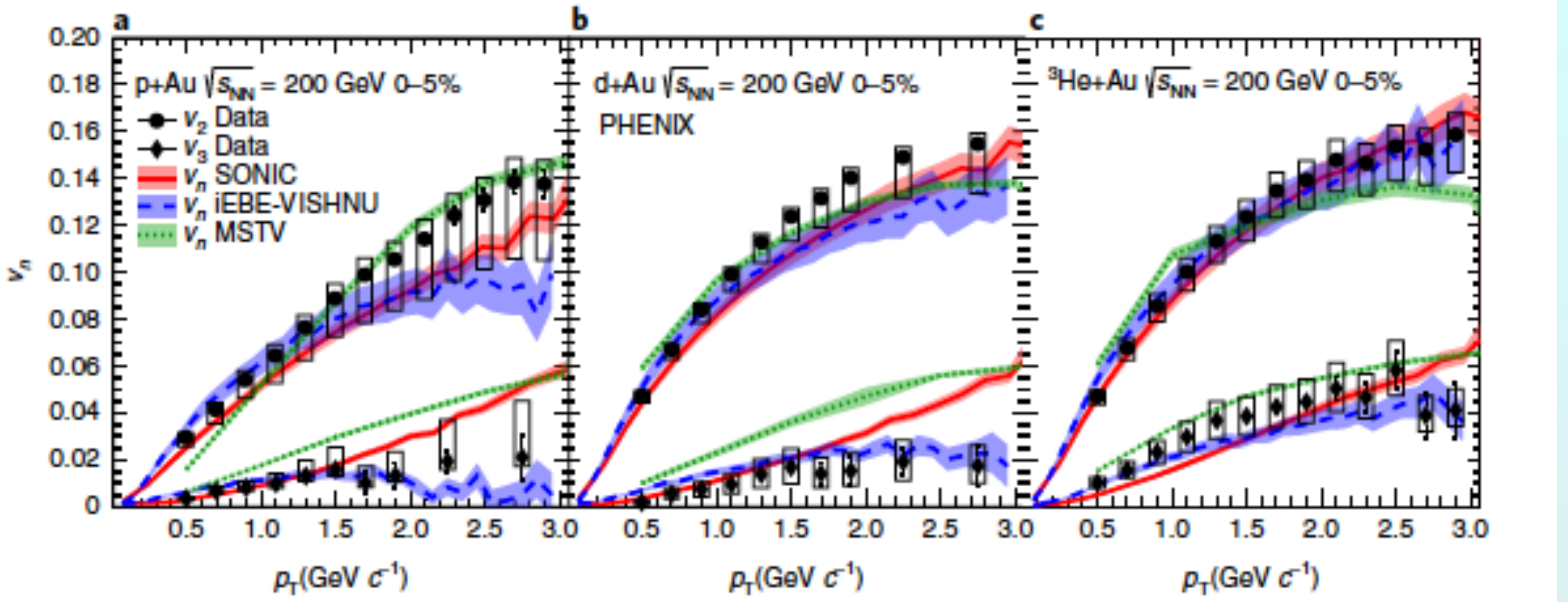


+ nucleus-filtered jet constituents & substructure

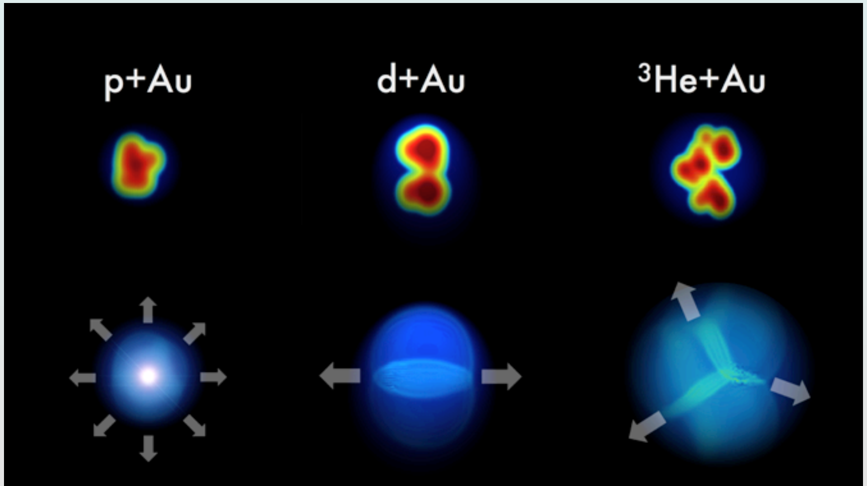
Hydrodynamics works in small systems!

PHENIX Collaboration

Nature Physics 15, 214 (2019)



Collective flow! Seeded by initial geometry



Why/how can the pressure build up before this tiny system evaporates??

Heavy quarks

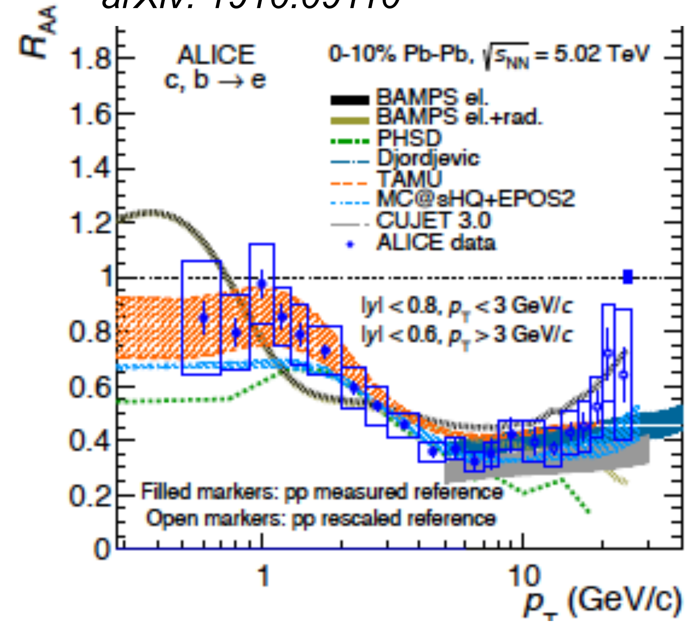
Lose energy too!

Dominated by collisions at low p_T

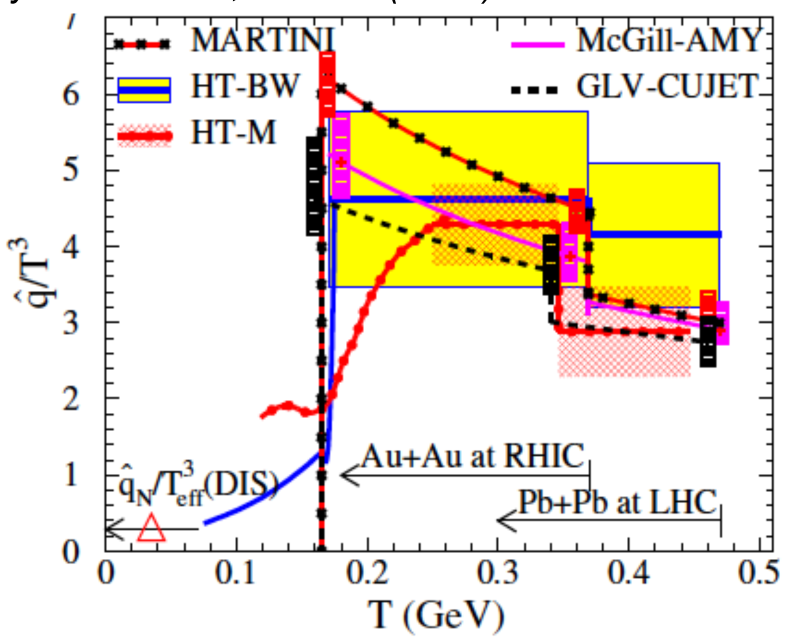
Radiation at high p_T

$$\hat{q} = \sqrt{\mu^2/\lambda}$$

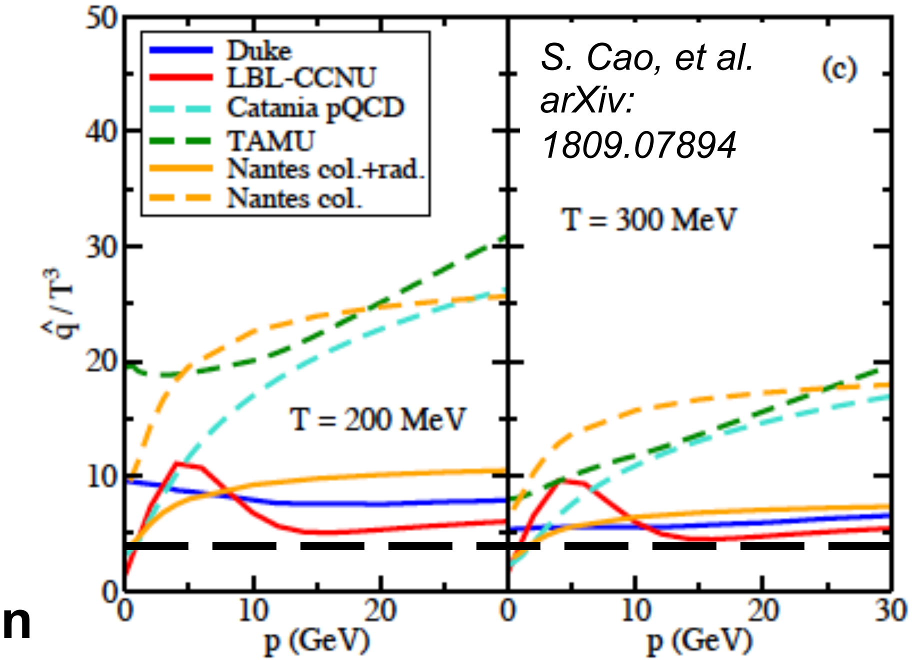
arXiv: 1910.09110



Phys. Rev. C 90, 014909 (2014)



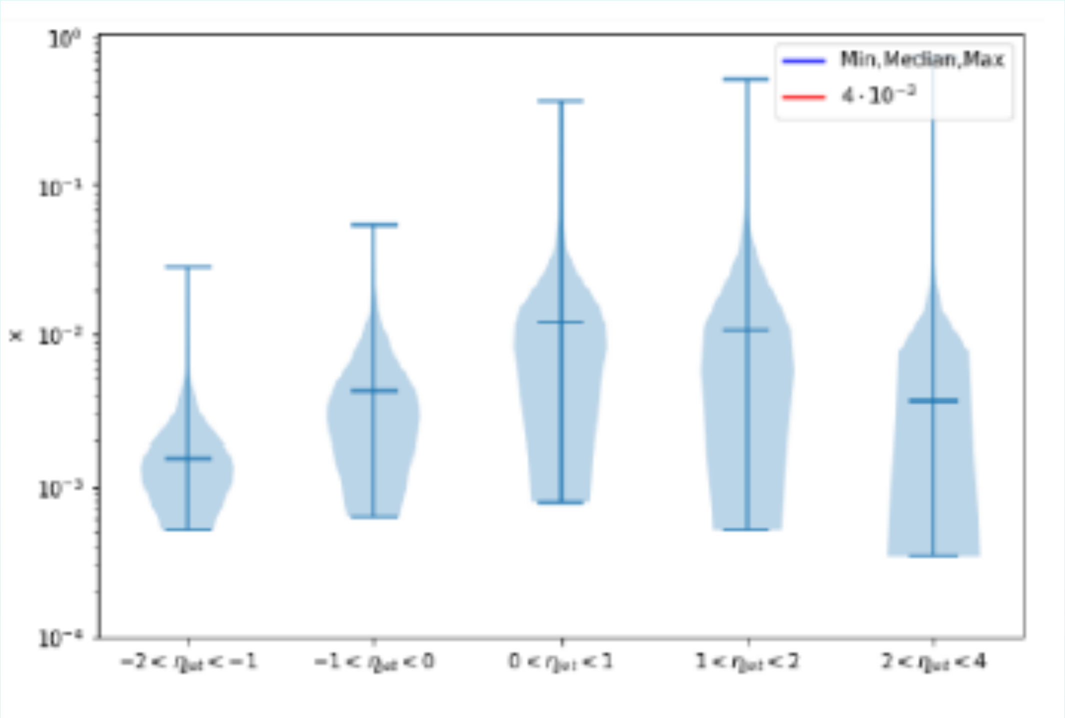
Light quark R_{AA} fits: JET collaboration



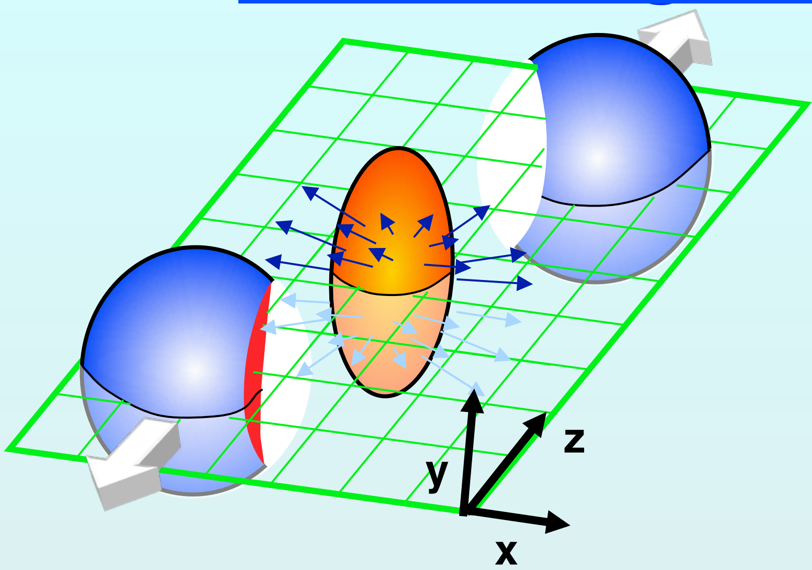
Heavy quark R_{AA} fits

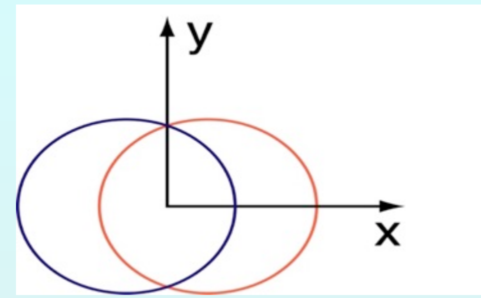
Range in x

$$Q^2 > 1\,GeV^2,\, p_{jet} > 5\,GeV,\, 0.01 < y < 0.85,\, W^2 > 4\,GeV^2$$



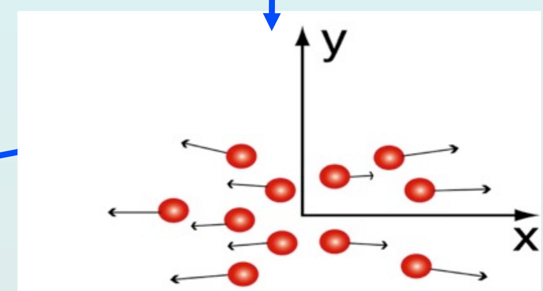
Measuring collective flow in QGP

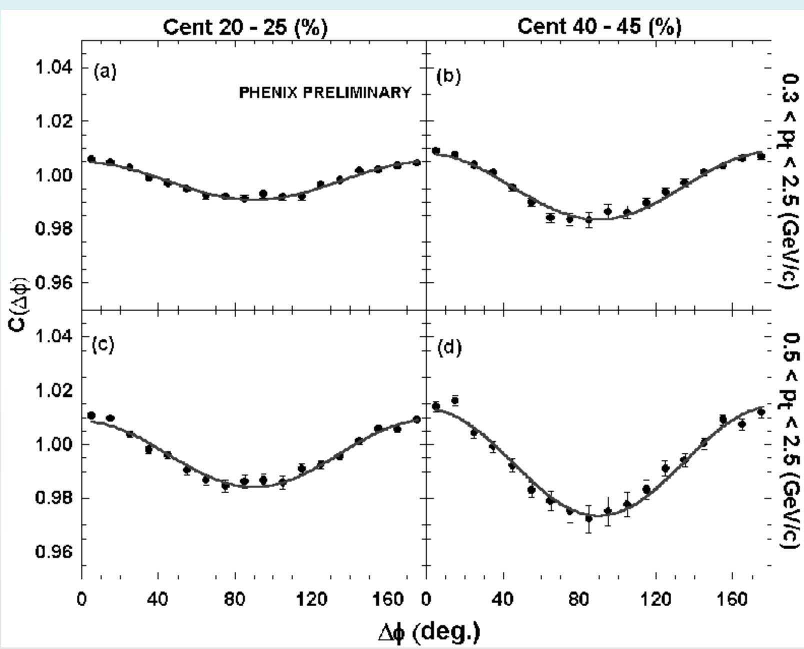




Almond shape overlap region in coordinate space

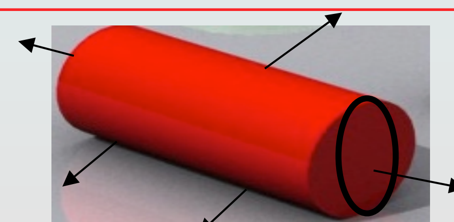
momentum space





$dN/d\phi \sim 1 + 2\, v_2(p_T) \cos(2\phi) + \ldots$

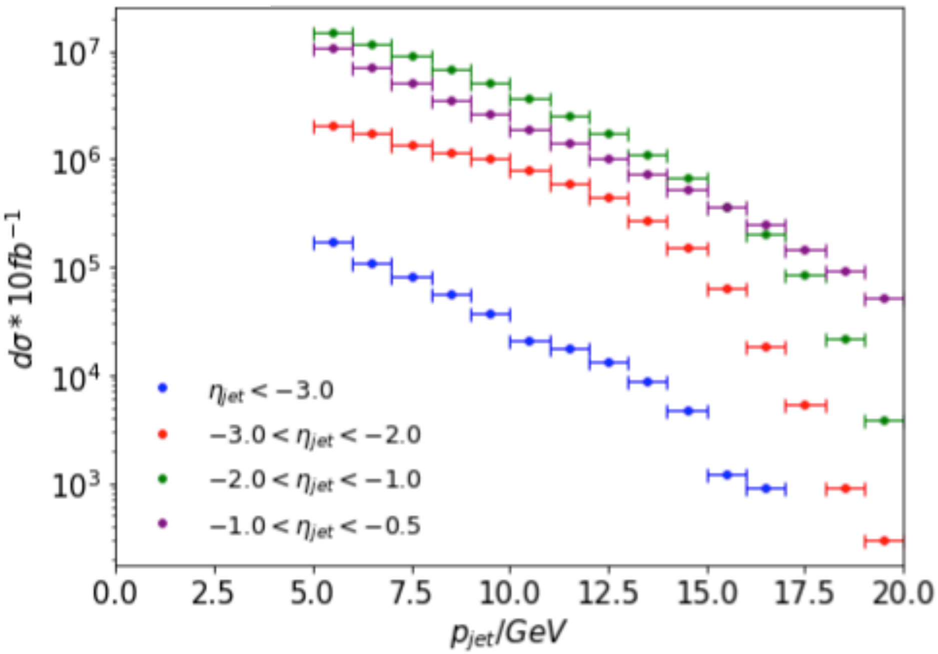
"elliptic flow"

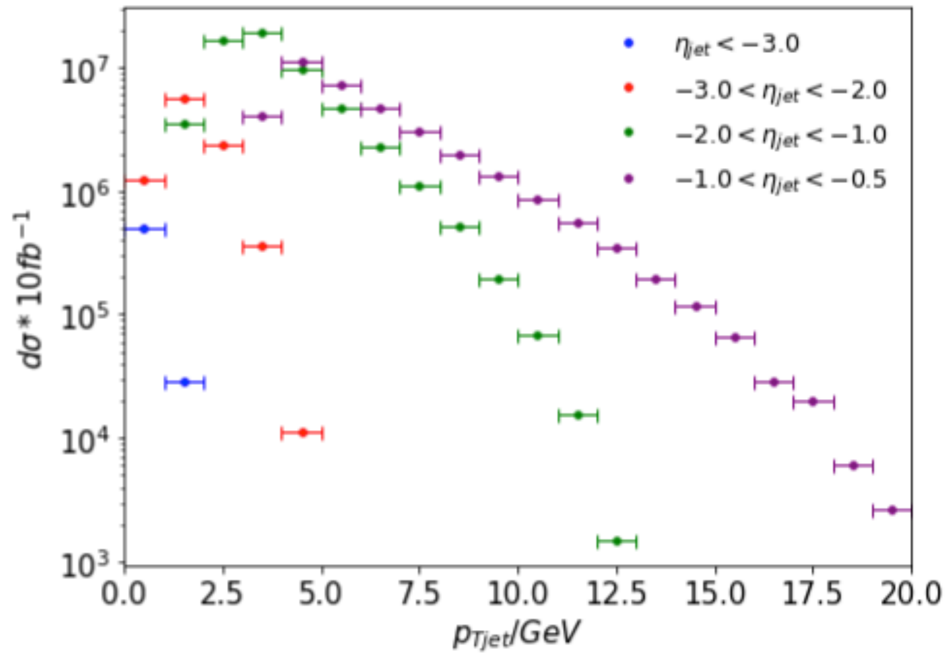


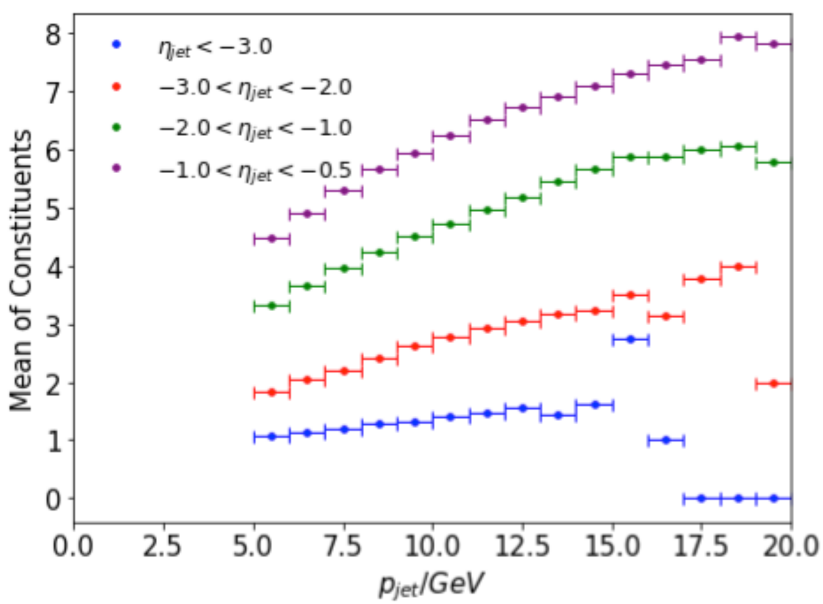
Youqi Song

At η < -1: $p_T \neq p$

$x = 1 - 4 \times 10^{-3}$







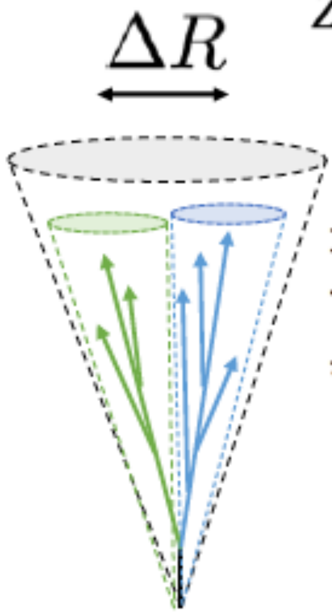
Look at jet p > 5 GeV/c

- **Kinematic cut-off visible**
- **For η < -2, dihadrons rather than jets**

Groomed Jet Substructure with Soft Drop

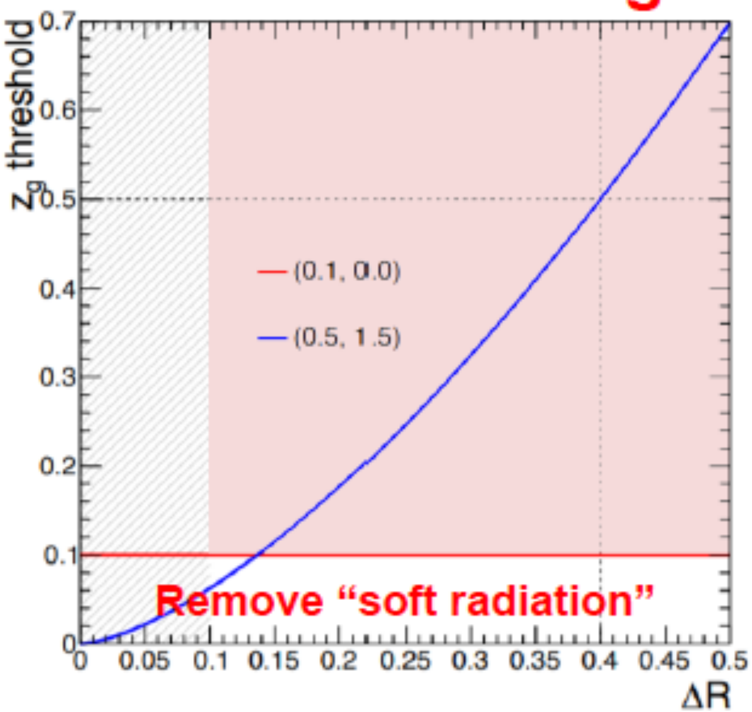
- Jet grooming: design observables **sensitive to different phase space**
- Two soft drop settings with ΔR>0.1 cut

$$z_g = \frac{p_{T,2}}{p_{T,1} + p_{T,2}} > \boxed{z_{\mathrm{cut}}} \left(\frac{\Delta R}{R_0}\right)^{\boxed{\beta}}$$

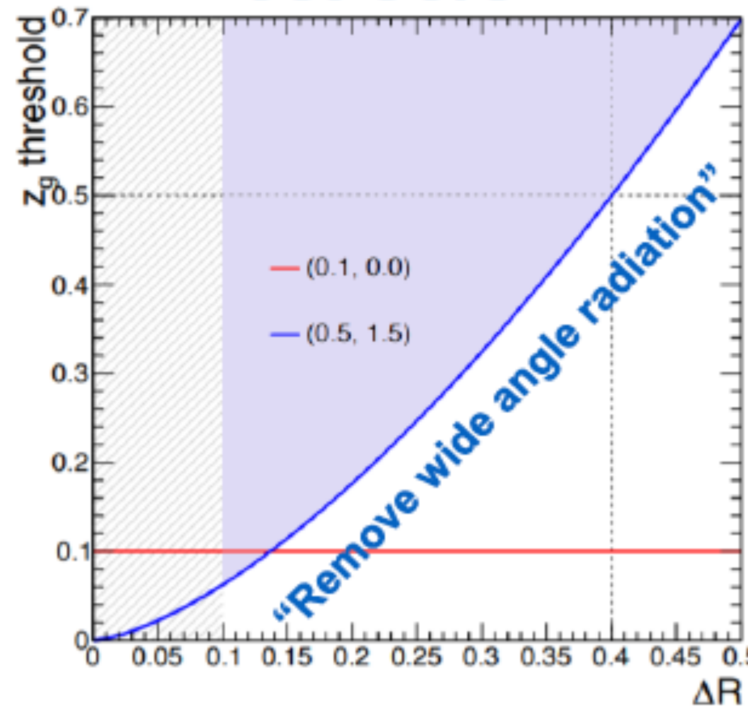


Soft Drop:
JHEP 1405 (2014) 146

"Flat Grooming"



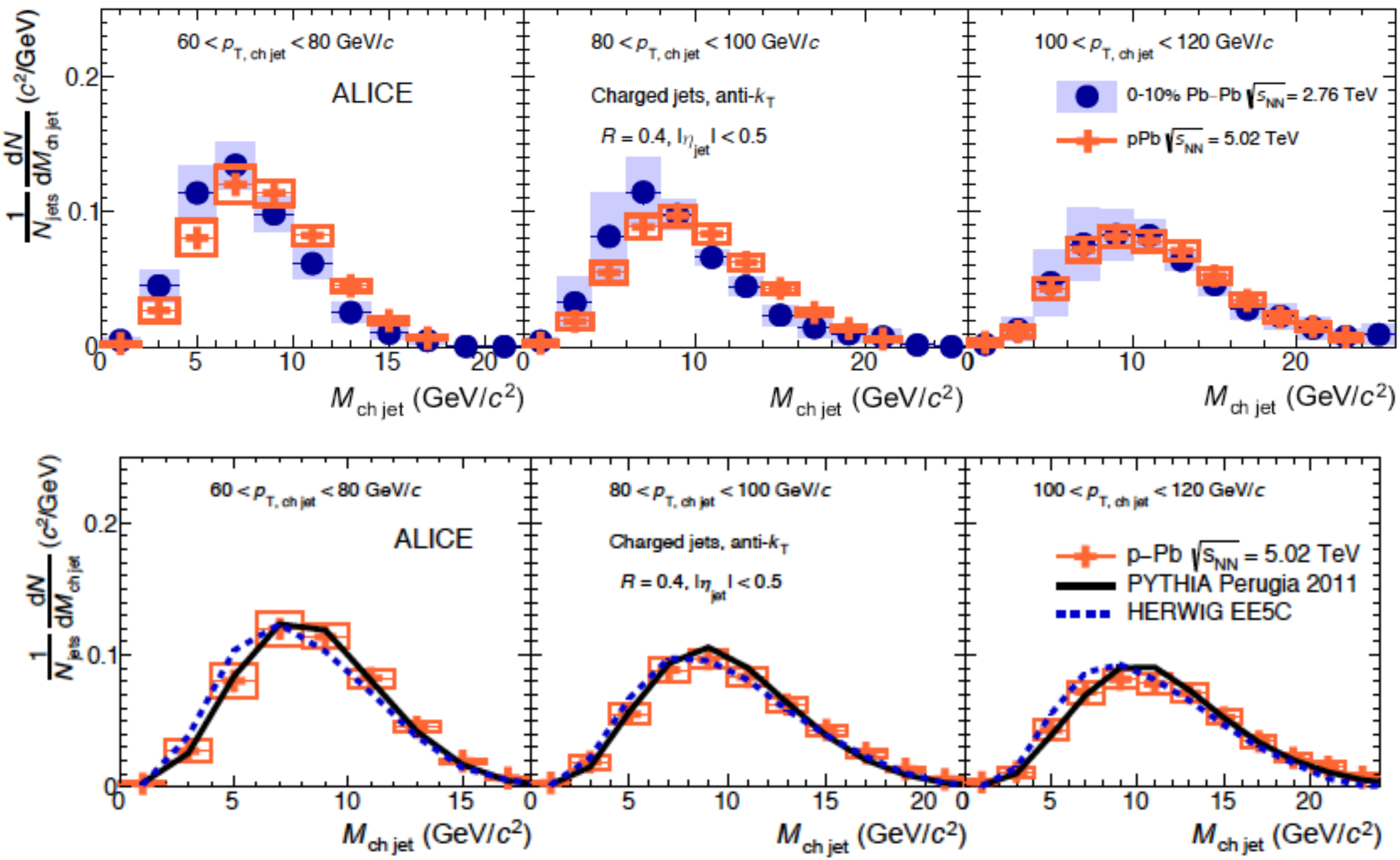
"Jet Core"



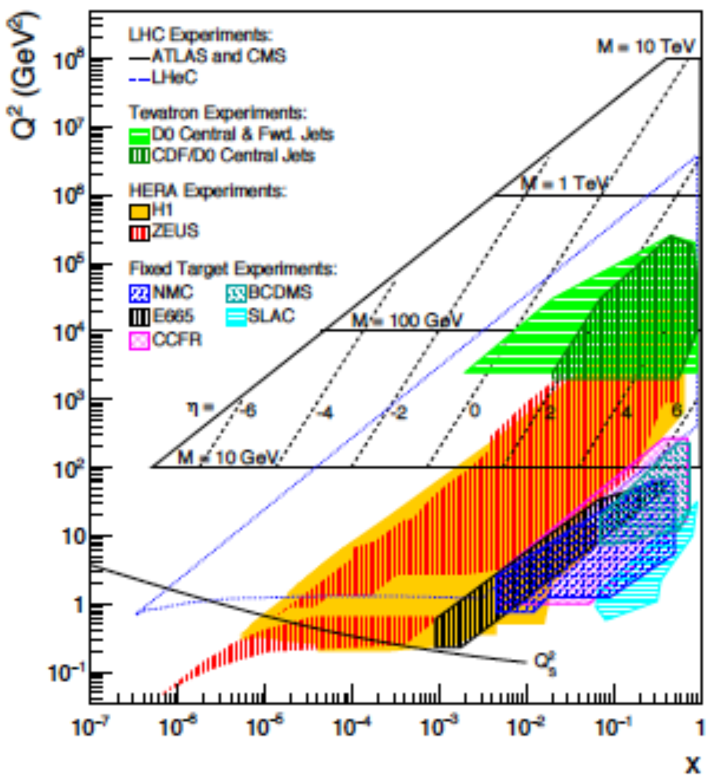
Jet mass

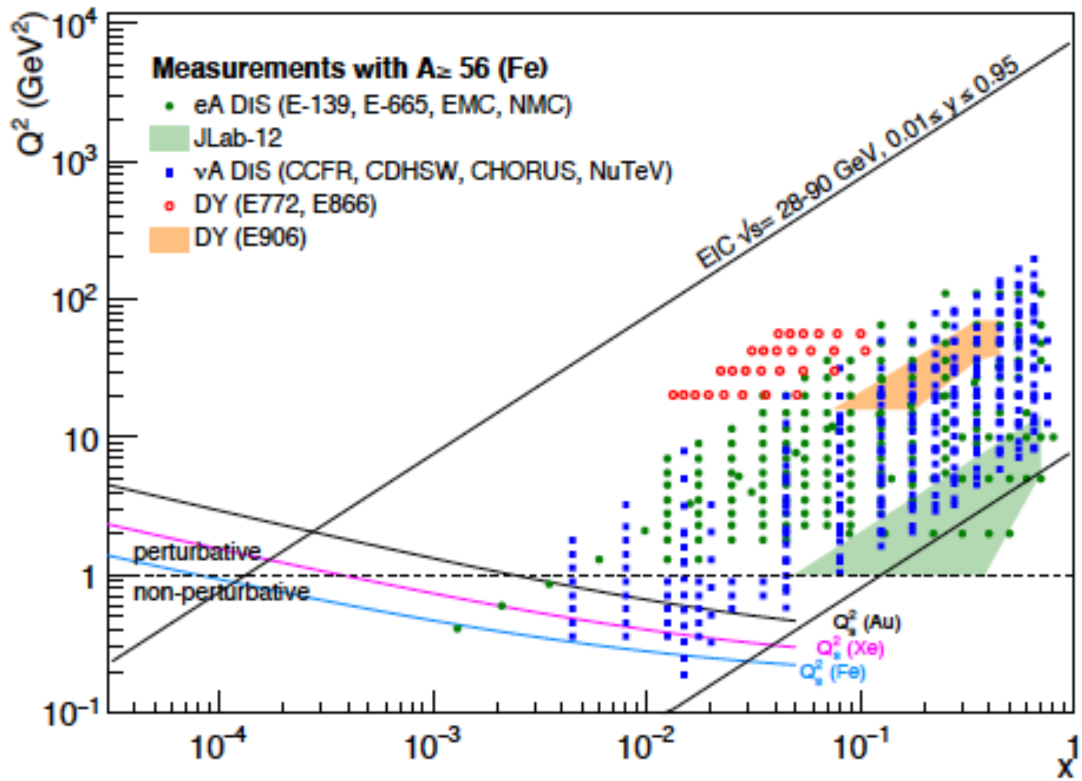
$$M_{Jet} = \sqrt{E_{Jet}^2 - p_{Jet}^2} \propto Virtuality$$

$$M_{Jet} \sim z\theta^2$$



Gluon Saturation: Past Experimental Reach





HERA (ep)

- Marginal reach of Q_S
- Only at low Q^2 making comparison with perturbative QCD impossible

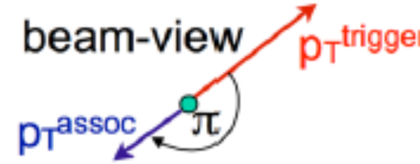
Fixed Target DIS Experiment

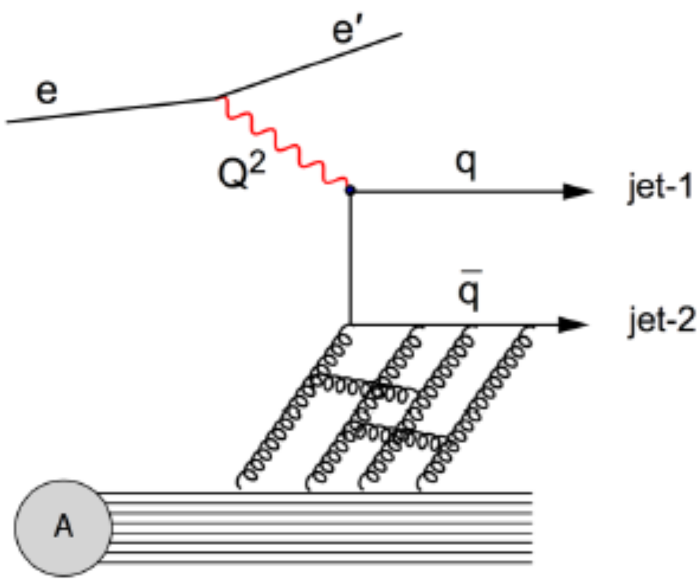
- eA, μA, νA
- Same marginal reach
- Only at low Q^2 ($Q^2 < 1$ GeV^2)

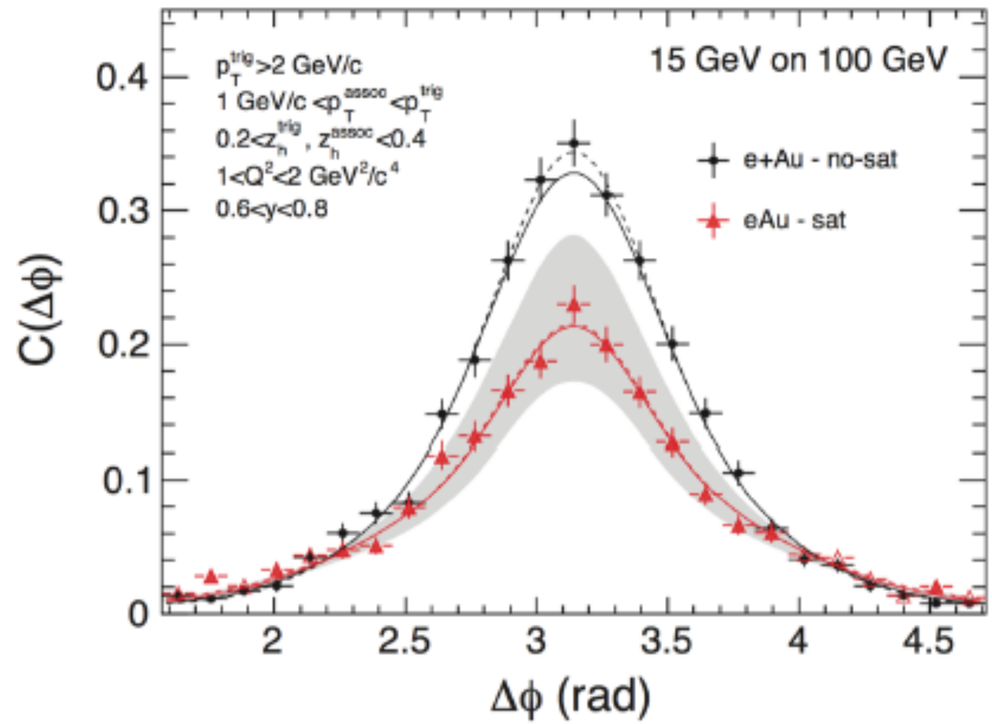
T. Ullrich

EIC - Dihadrons to probe Saturation

E. Sichtermann







Zheng et al (2014)

Dominguez, Xiao, Yuan (2011)

Suppression of back-to-back hadron or jet correlation directly probes the (un-)saturated gluon distributions in nuclei,

We tickled the nucleus with a proton

In p+A probe cold nuclear matter with a parton, not a photon.

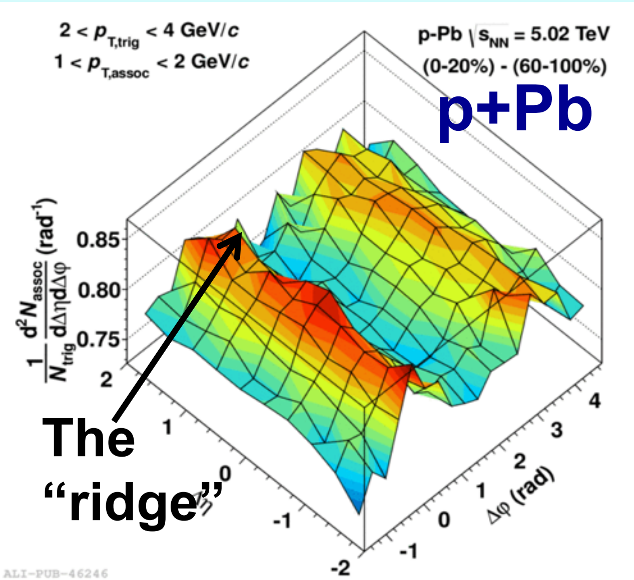
- **Partons can lose energy before the hard scattering**
  Photons do not
- **Parton can lose energy after the hard scattering**
- **Parton experiences multiple scattering**
- **These may be not be independent!**

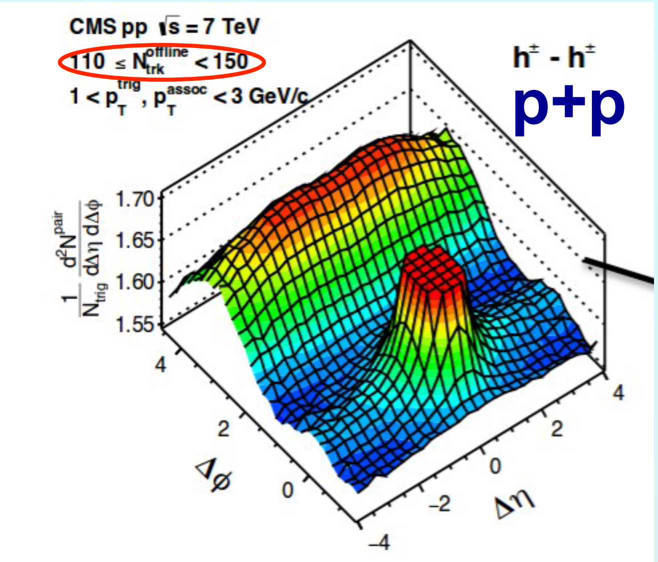
Many-body QCD suggests coherent interactions!

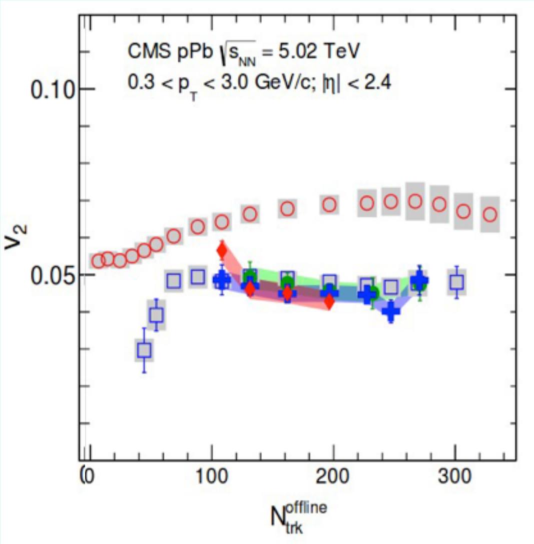
same as in parton-plasma interactions…

Goal: turn off the interactions before the hard scattering!

Collective flow causes particle correlations







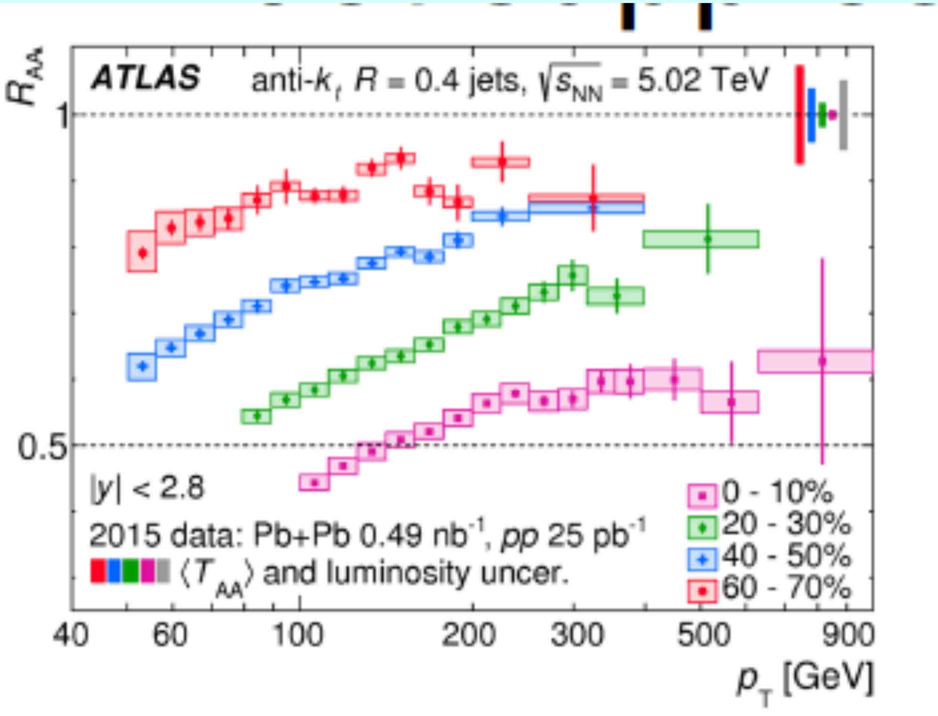
See Fourier components v_N (n=2 to 5) as in Au+Au and Pb+Pb

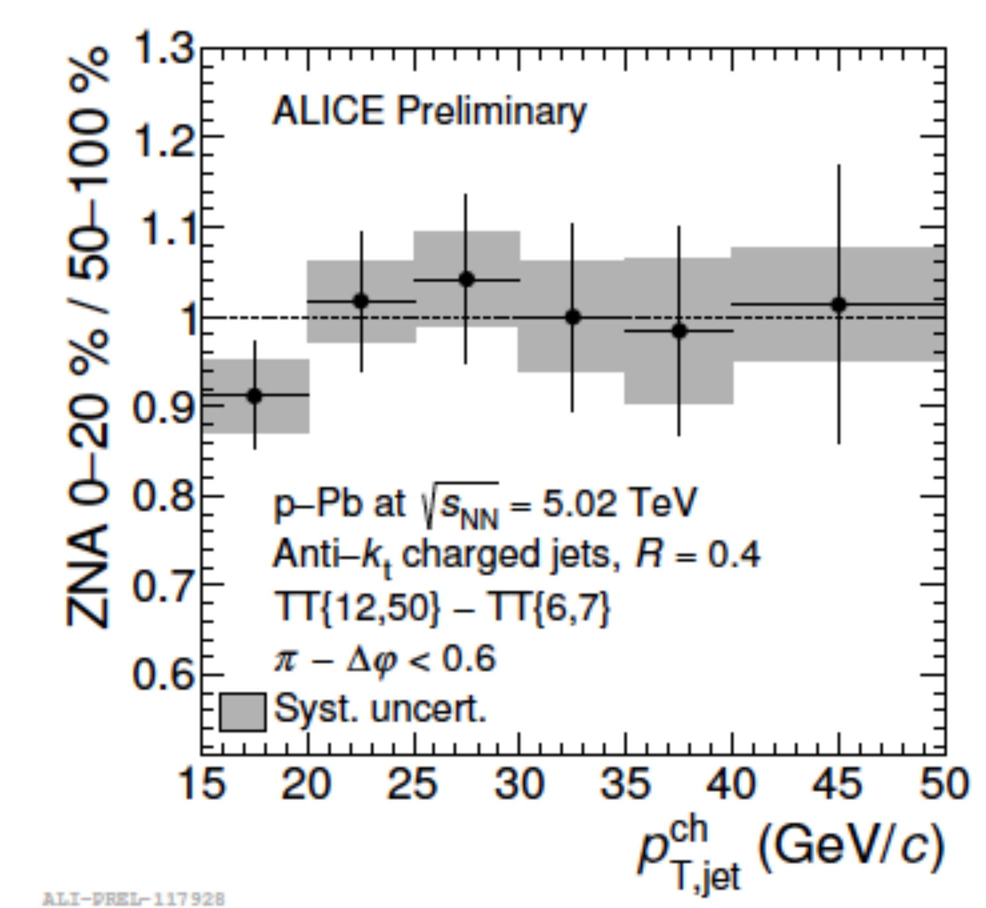
Multi-particle correlations (v2{4}≈v2{6}≈v2{8}≈v2{LYZ})

- Collective system once there are > 100 particles?
- Early time particle correlations mock up flow signal?
- Artefact of particle freeze-out surface?
- NB: no significant energy loss seen in pp and pA

  But hot spot is pretty small here…

Jet R_{AA}





- Consistent picture with single hadrons: jets are suppressed in Pb+Pb
- Nuclear effects are small in p+Pb