Hadronization and Jet Substructure

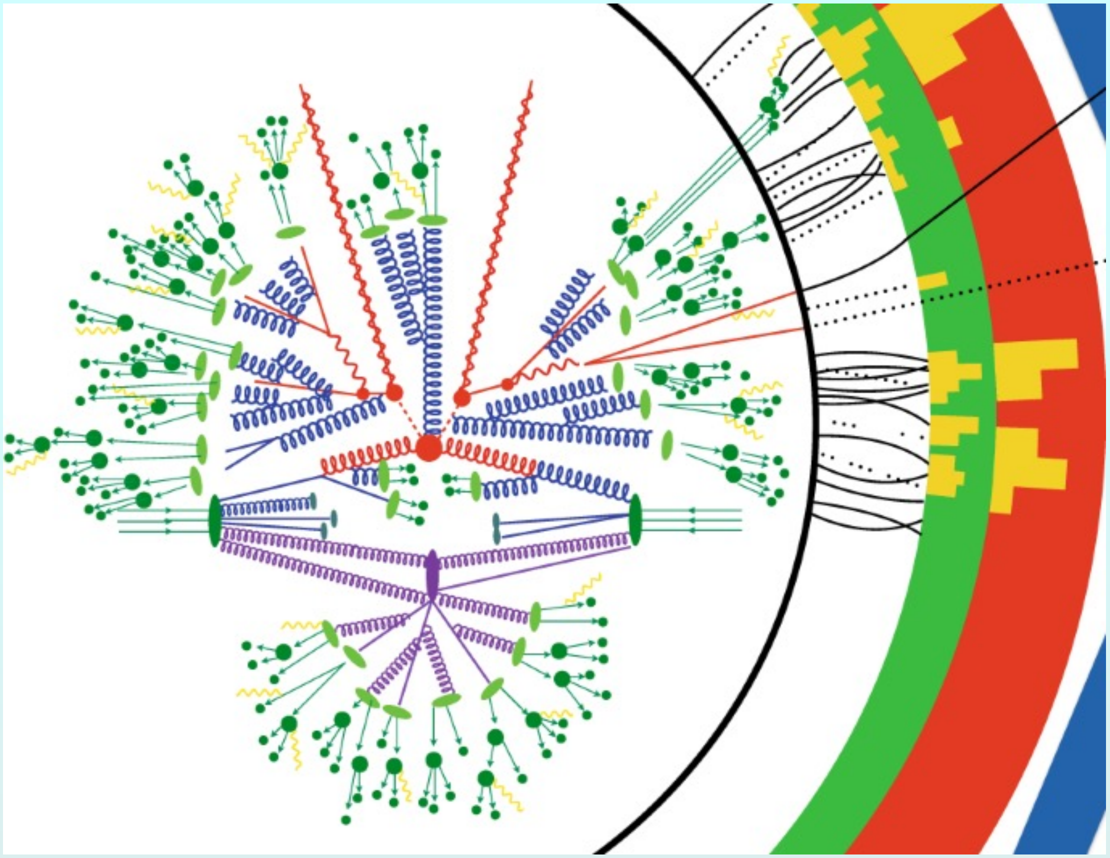


Figure from *Nature Reviews Physics* **3**, p. 73 (2021)

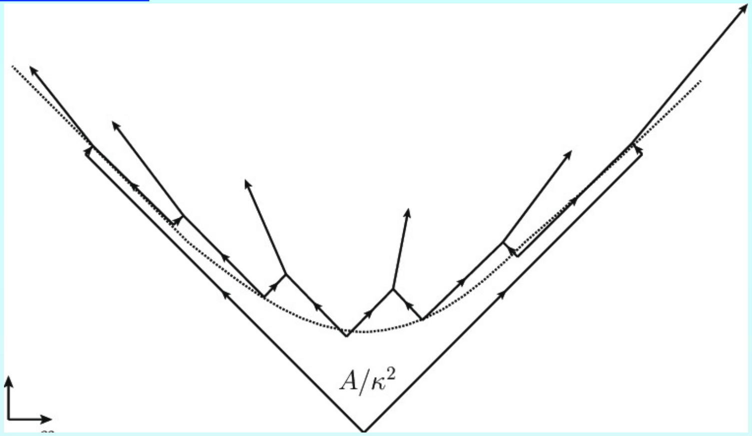
Barbara Jacak, UCB & LBNL

+ W. Fan, K. Lee, B. Mueller

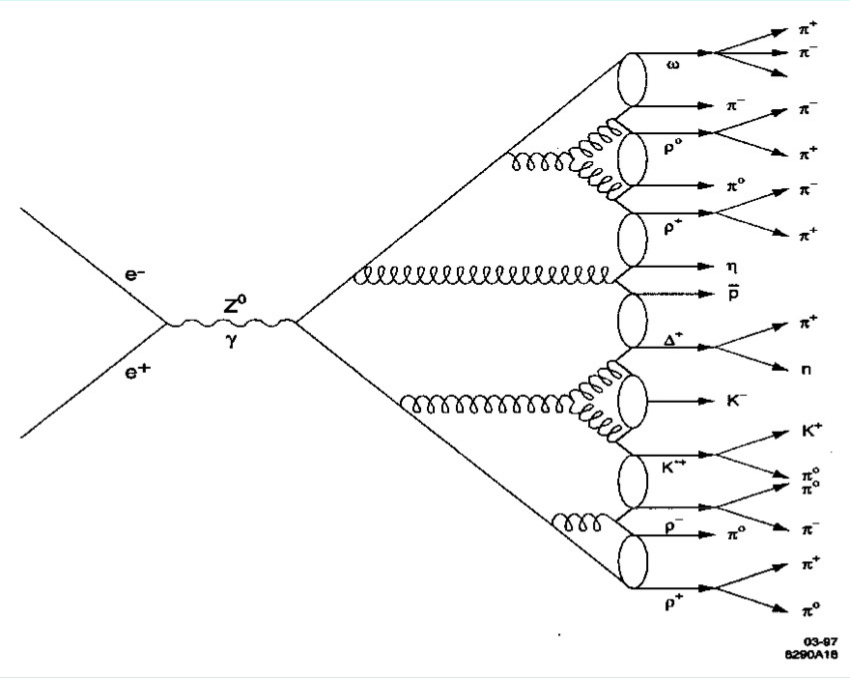
August 2, 2022

Hadronization

- String breaking (e.g. Pythia)



- Cluster hadronization (e.g. Herwig)

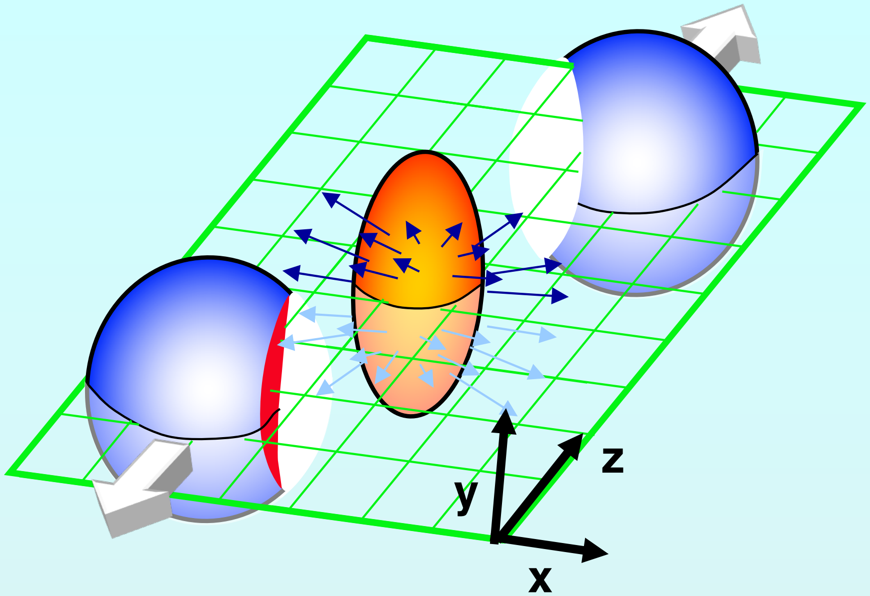


- Coalescence or Statistical Hadronization?

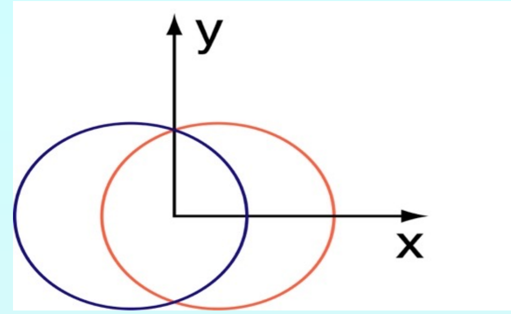
2 hadronization pictures

- **Cluster hadronization**
  - Based on idea of "pre-confinement"
  - @ end of shower, all gluons split into q-qbar pairs
  - Color-connected quark pairs form clusters
  - Large cluster fission into smaller clusters
  - Small clusters decay isotropically into 2 hadrons
- **String hadronization**
  - Based on ideas of linear confinement
  - @ end of shower, color-connected partons form string pieces w/ quark endpoints; gluons transverse kinks.
  - String junctions are asymmetric color tensor carrying baryon number
  - Strings break by tunneling; "tension" = energy
- **Small strings ⟷ clusters**
  - Both Pythia and Herwig tuned to reproduce data well

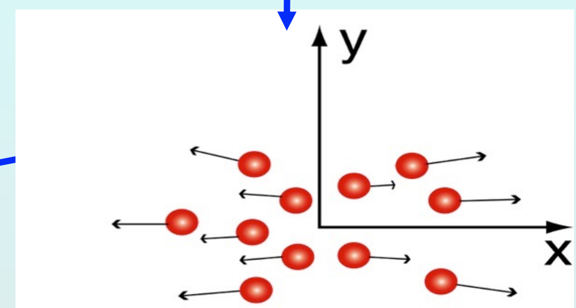
QGP collective flow & hadronization

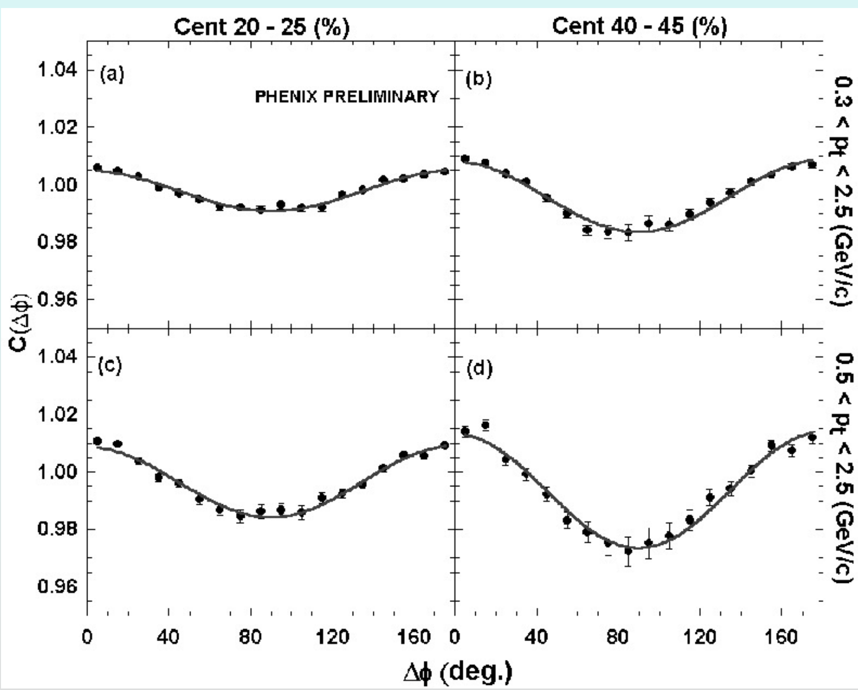


Almond shape overlap region in coordinate space



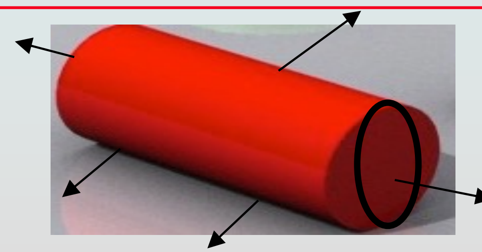
momentum space



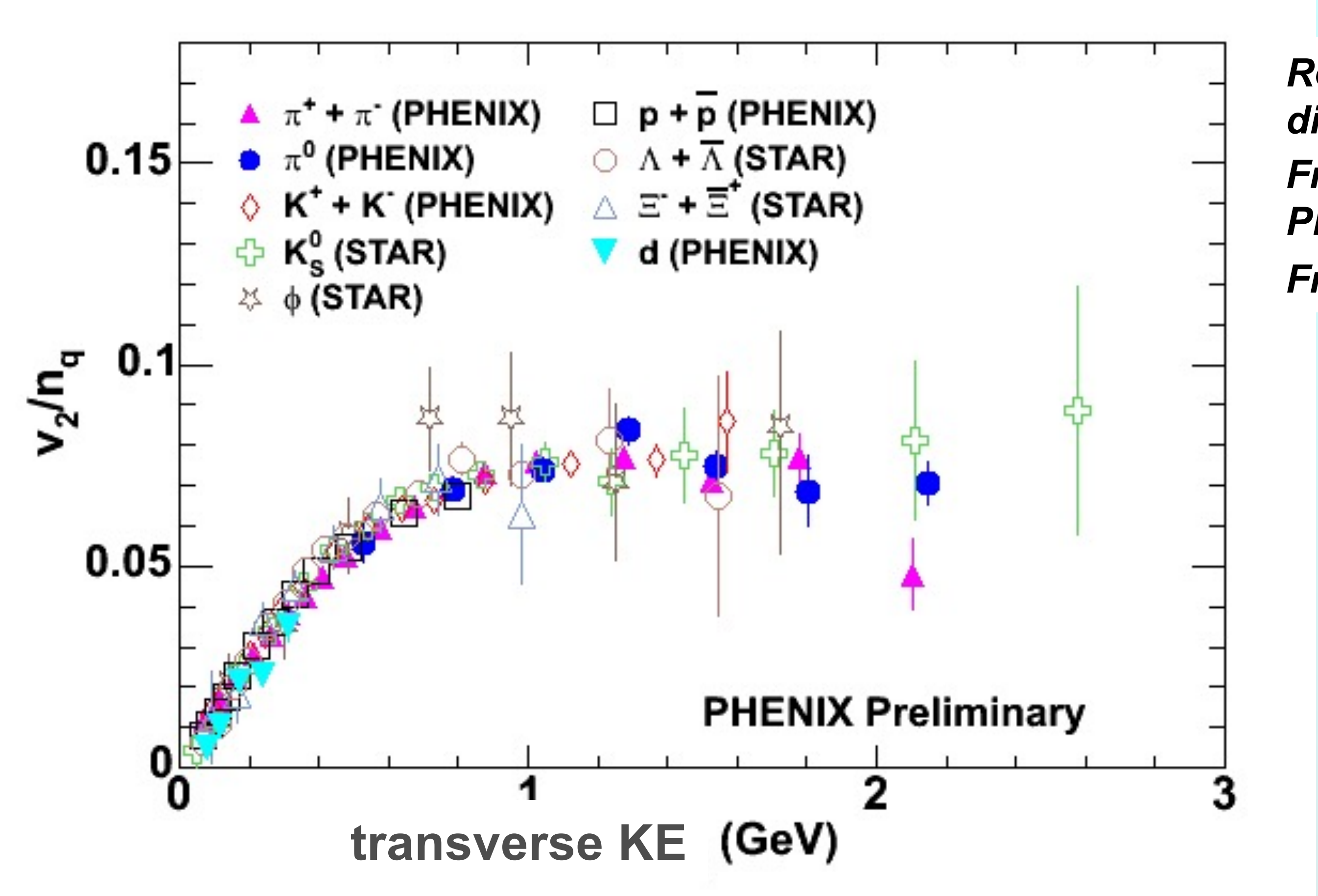


$dN/d\phi \sim 1 + 2\, v_2(p_T) \cos(2\phi) + \ldots$

"elliptic flow"



Hadronization of quark gluon plasma



Recombination from thermal distribution:

Fries, Mueller, Nonaka & Bass, PRC68, 044902 (2003)

Fries, J. Phys. G32, S151 (2006)

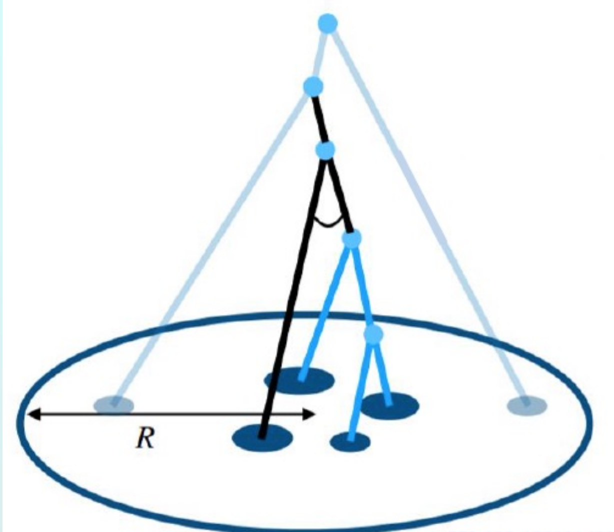
Quarks & gluons are present when collective flow develops

Thermalization erases all memory of initial state
Dressed quarks are born of flowing field
Hadronize by simple phase space coalescence

How to study hadronization dynamics?

- **We'd like to follow correlations of partons**
  Alas, we only measure the final state hadrons!
  How does matter filter parton correlations?
  Dependence on density, temperature?

- ***Jets = final state of parton showers***
  parton splitting calculable in pQCD
  many substructure variables to choose from

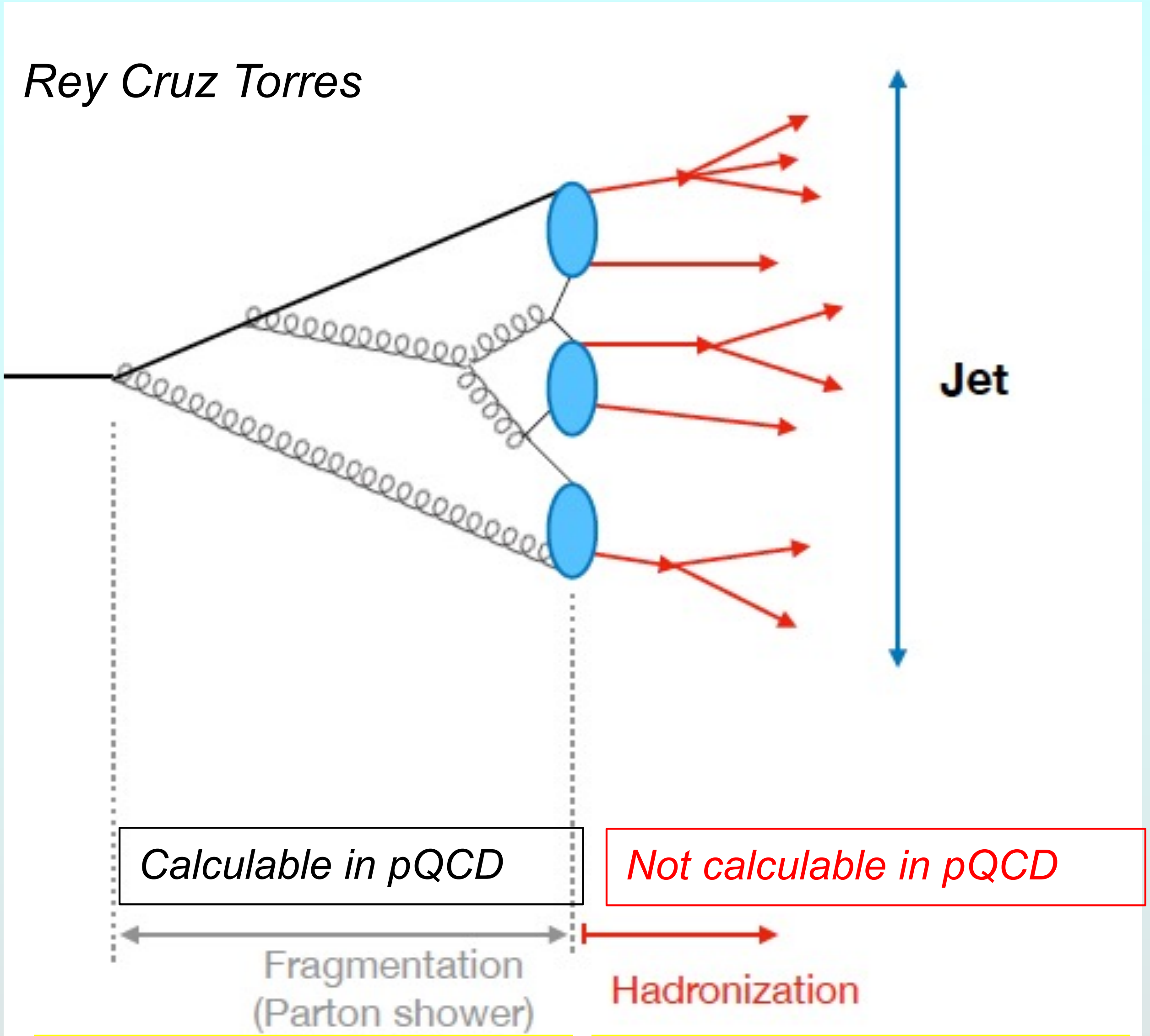


PRL 128, 102001 (2022)

- ***how do parton correlations from the shower (parton splitting) affect the hadron correlations inside a jet?***

- I will not discuss heavy flavor jets today, but these are also very promising

Transition to hadrons is non-perturbative



Scale of jet:

p_T ~ 20-500 GeV

Scale of transition:

Λ_{QCD} ~ 0.5 GeV

Relevant substructure observables

- **Overall jet shapes (integrated quantities)**
  e.g. thrust, sphericity
- **(re)cluster hadrons into subjets or "prongs"**
  Correspond to splitting history
  Can groom to remove non-jet background
  Theorists use "soft shape function" to correct pQCD for non-perturbative & hadronization effects
  e.g. N-subjettiness, z_g

talk by Rey Cruz Torres

- **Jet shapes or prongs without subjets**
  Can be IR and collinear safe, i.e. calculable
  e.g. jet mass, angularity

- **2 (or more) point correlators in energy or track momentum**

Energy-energy correlators

$$2 \text{ point } EEC = \int dN_{track} \frac{1}{E_{jet}^2} < \varepsilon(\vec{n}_1)\ \varepsilon(\vec{n}_2) >$$

Where $\varepsilon(\vec{n}) = \lim_{r \to \infty} \int_0^\infty dt\, r^2\, n^i\, T_{0i}\,(t, r\vec{n})$

$T_{\mu\nu}$ is the stress energy tensor

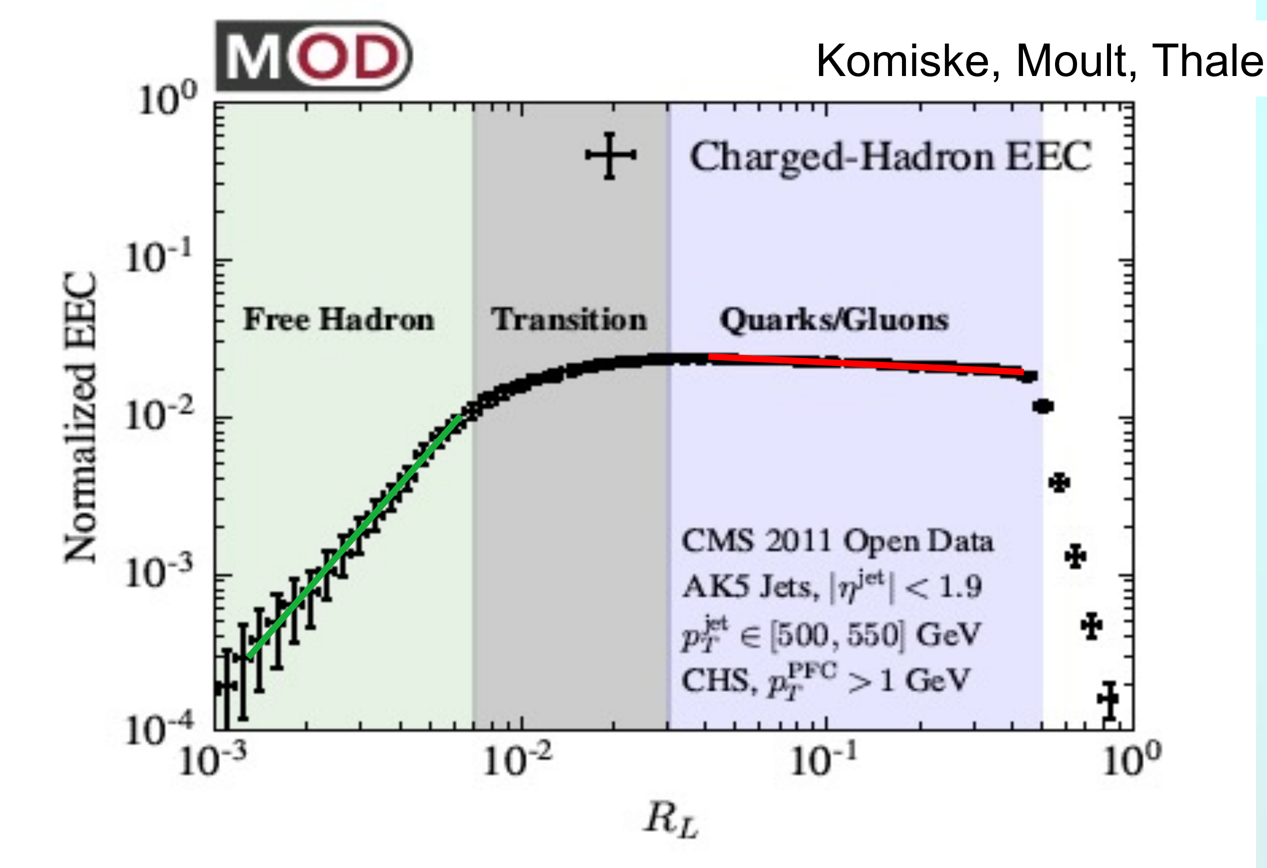
ε is the asymptotic energy flow operator

- **Experimentally, sum over all hadron pairs within the jet:**

$$EEC(R_L) =$$

$$\sum_{pairs} \frac{p_{T1}\, p_{T2}}{p_{T,jet}^2} \text{ with } R_L = \sqrt[2]{\Delta\varphi^2 + \Delta\eta^2}$$

Analysis of CMS Open Data



Komiske, Moult, Thaler, Zhu. arXiv:2201.07800

Exchanged p_T $\sim p_{Tjet} \times R_L$

$$R_L = \sqrt[2]{\Delta\varphi^2 + \Delta\eta^2}$$

500 GeV jets

- **At large R_L: universal scaling w/ perturbative quark and gluon interactions**
- **At small R_L: for uniformly distributed hadrons**

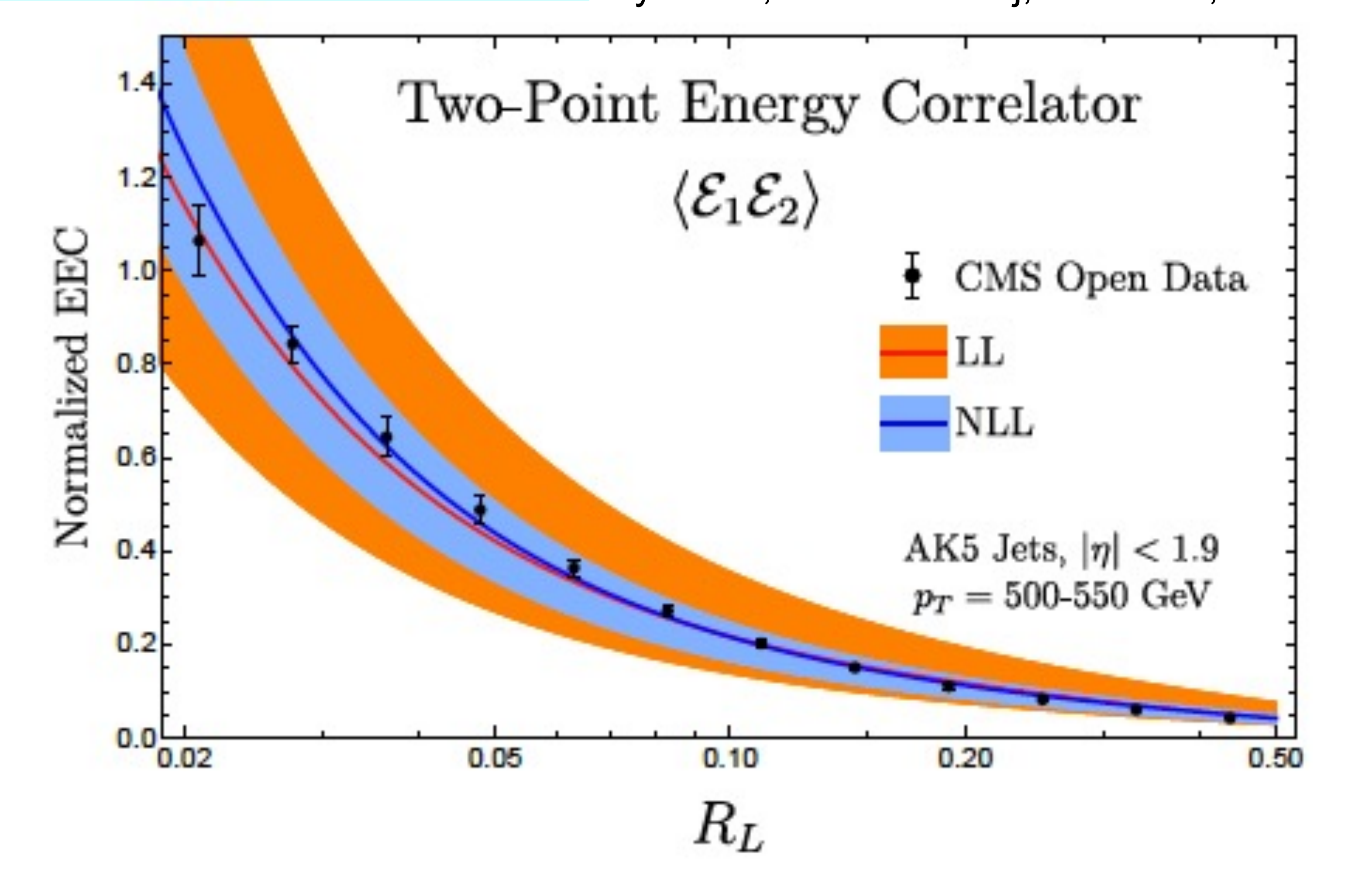
  $$R_L \, d\sigma/dR_L \sim R_L^2$$

- **Transition region = correlator at hadronization**

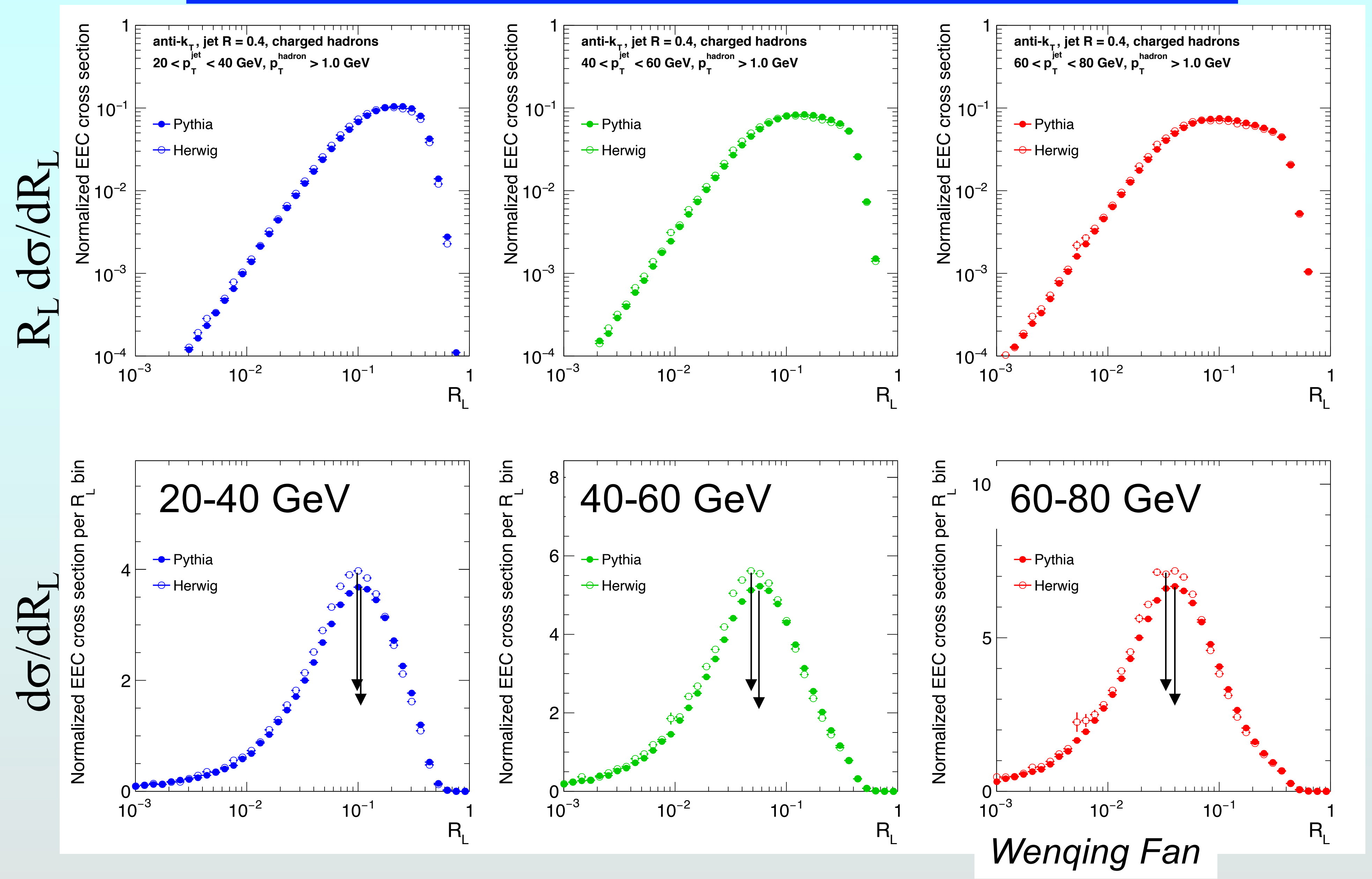
Quark-gluon region calculable

Kyle Lee, Bianca Mecaj, Ian Moult; arXiv:2205.03414

$d\sigma/dR_L$



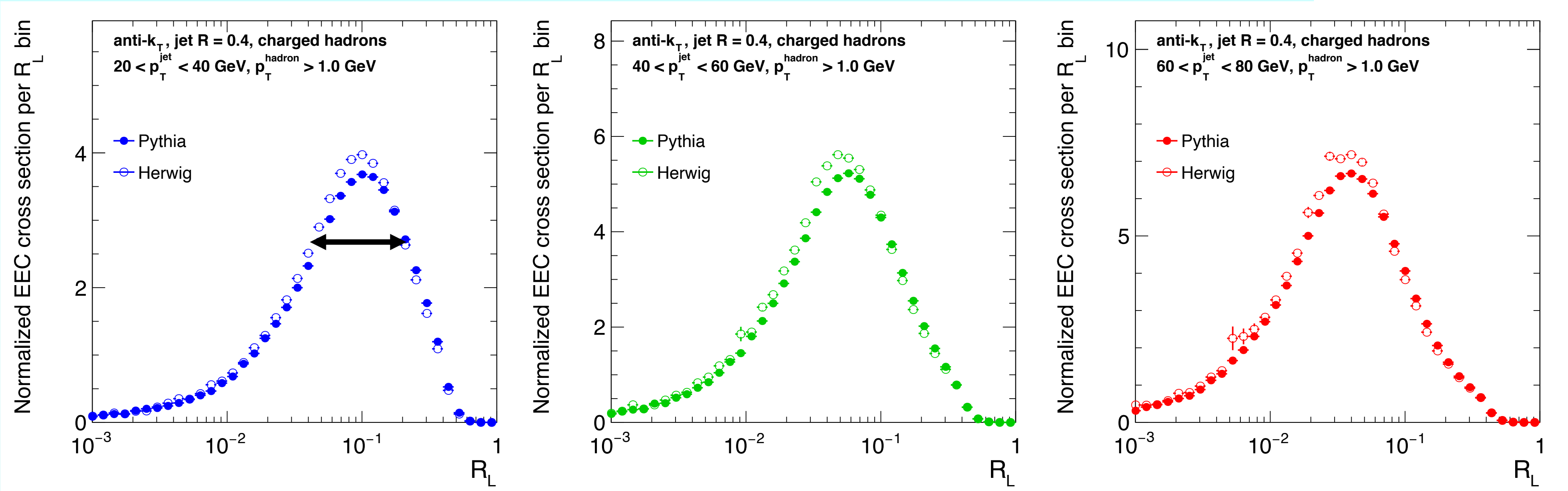
Pythia vs. Herwig in 20-80 GeV jets



Bottom: derivative to better locate transition region

Observations

Wenqing Fan



- **Transition region shifts to lower R_L at higher p_T**
  Transition $\propto \Lambda_{QCD}/p_{T,jet}$
  Parton virtuality scales as p_T x R_L
- ***Herwig transition at slightly lower R_L than Pythia***
- **Width of transition region ~ rate of transition between perturbative and non-perturbative**
- ***Herwig transition slightly wider than Pythia***

Questions

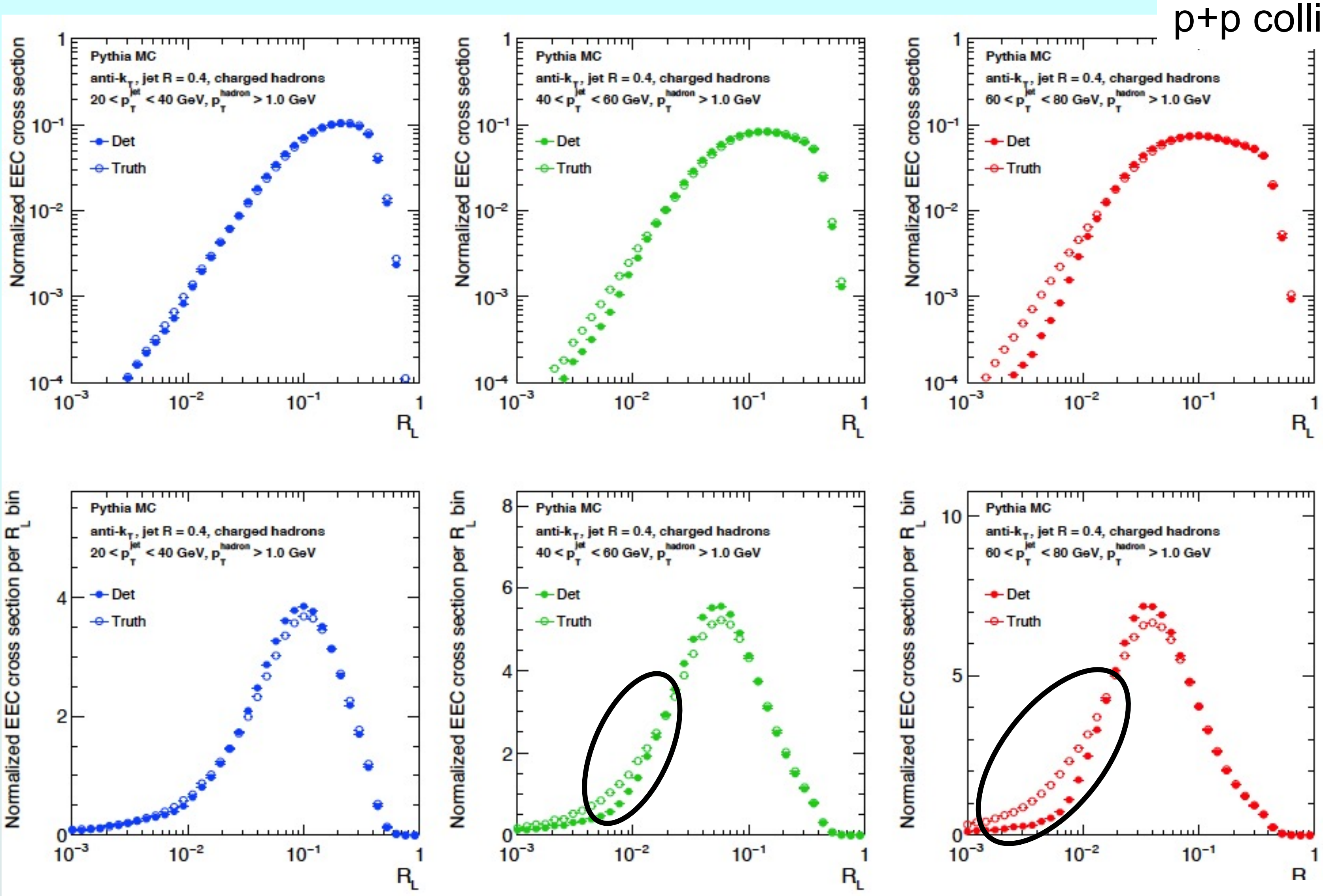
- Wider Herwig = slower transition to hadrons?
  - Cluster hadronization slower than string breaking as clusters are an additional stage?

- Transition onset R_L -> QCD coupling strengthens & interaction becomes non-perturbative
  - What does lattice QCD say about E-E correlator?
  - What does the peak R_L tell us?

- How do parton virtuality and the parton environment nearby interact to affect hadronization?
  - Vary the medium to explore this (pp, p+A, A+A)
  - Flavor correlations inside jets should reflect any remaining initial state correlations

Can we measure EEC for soft jets?

p+p collisions



Wenqing Fan

ALICE-like acceptance & efficiency effects

Will need unfolding to recover small R_L

Conclusions

- We don't yet know how hadronization works

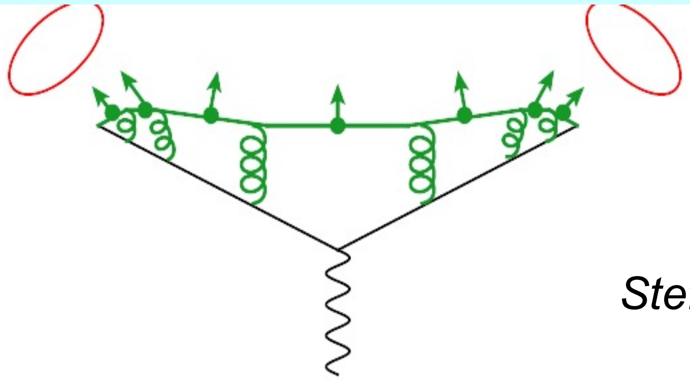
- Jet substructure a promising place to look for better understanding

- Energy-energy correlators offer a new tool
  - Can the correlator be calculated by lattice QCD?
  - How to interpret the features of the transition region between QCD and free hadrons?

- What happens when we add a nuclear medium?
  - Hot medium at LHC and RHIC (sPHENIX)
  - Cold medium at the EIC

- **Backup**

String breaking

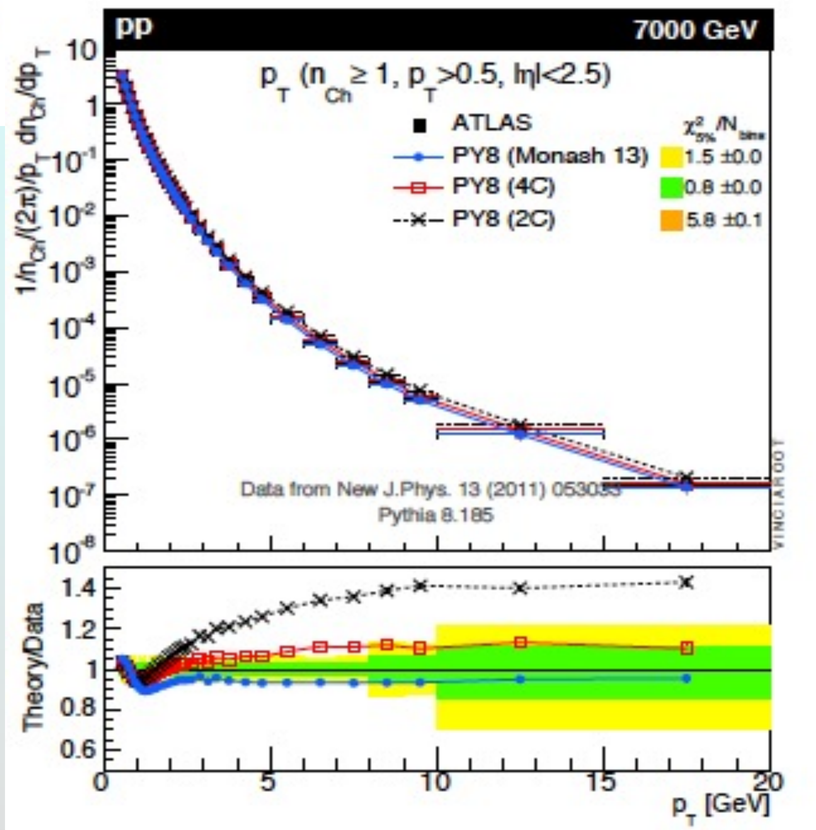


Stefan Prestel

Partons fragment together with their soft/collinear gluon field!
Gluons and soft/collinear partons from evolution make momentum flow small and allow non-perturbative parton-hadron vertices.

String carries flavor correlations

arXiv: 1404.5630



Pythia
Monash tune
for LHC

Cluster hadronization

- **Non-perturbative splitting follows pQCD shower**
- **Cluster color-connected partons together**

  heavy clusters fission

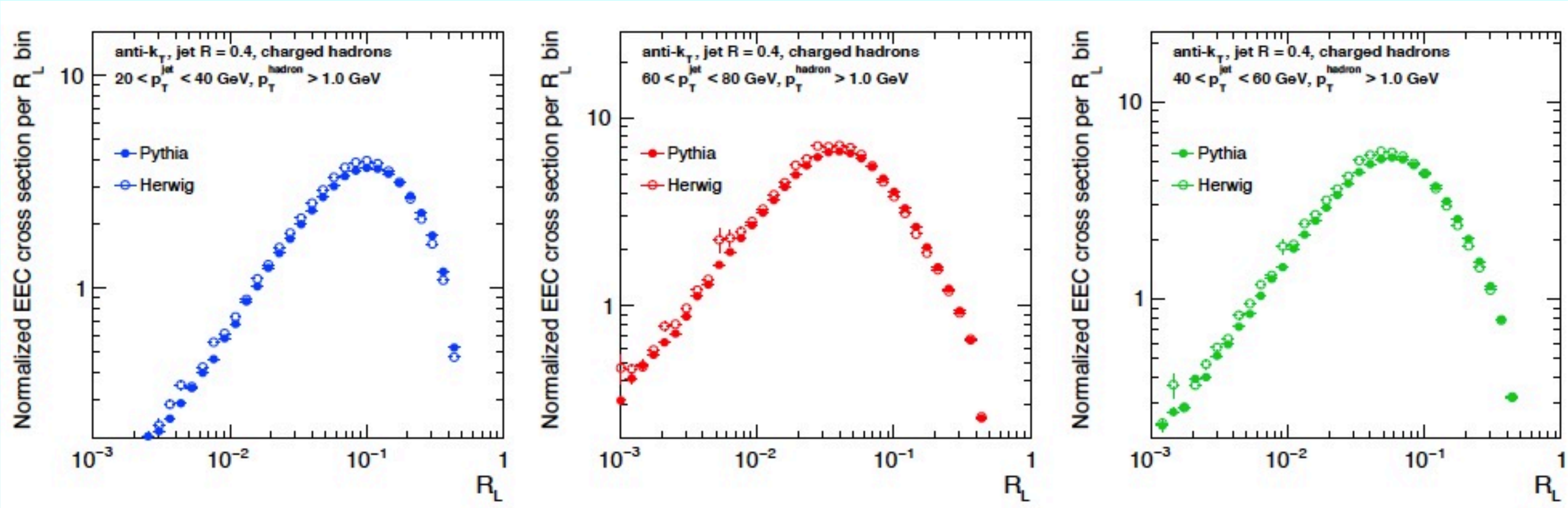
  randomly fill shower & beam remnant mass distrib.

  Color-connections more local than in Pythia
- **Clusters decay into hadrons**

  ensure sufficient cluster mass for hadron masses

  draw flavor k from vacuum

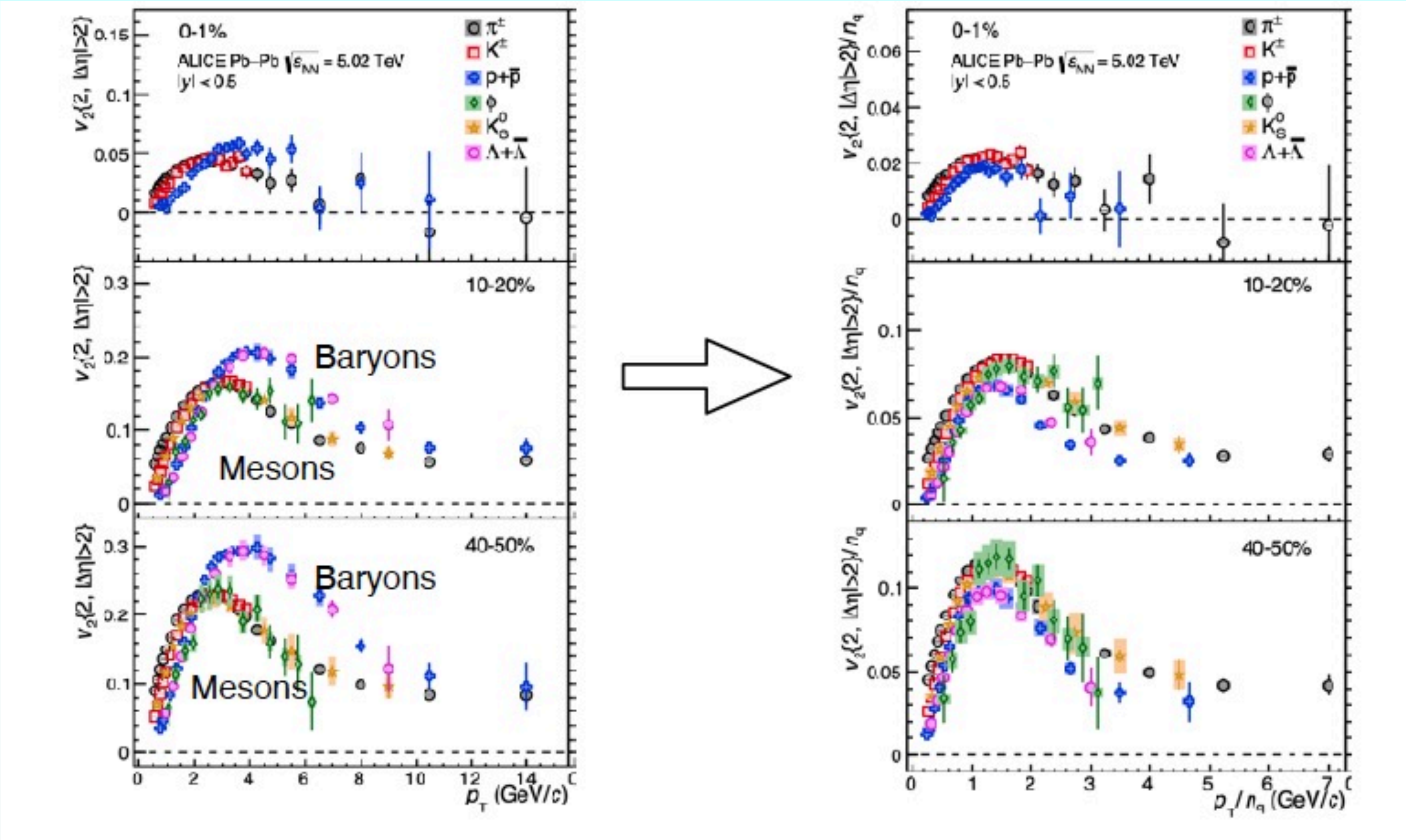
EEC Pythia vs. Herwig



Wenqing Fan

NB: Log y axis

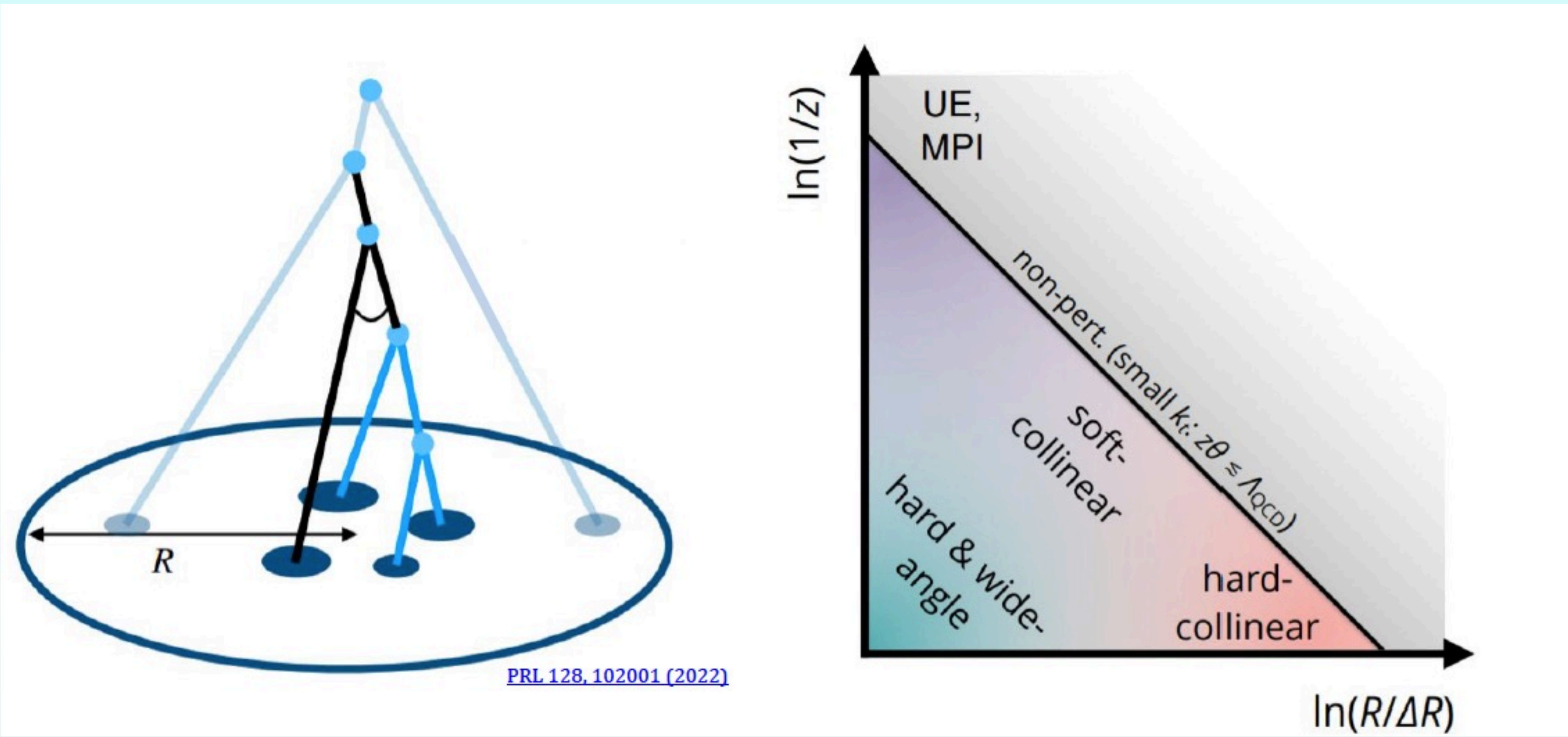
Same message from LHC



Is coalescence in phase space the whole story?

Measure parton splittings

- Modifications due to collisions in nuclear medium
- pQCD vs nonperturbative physics
- How do parton correlations affect hadrons?



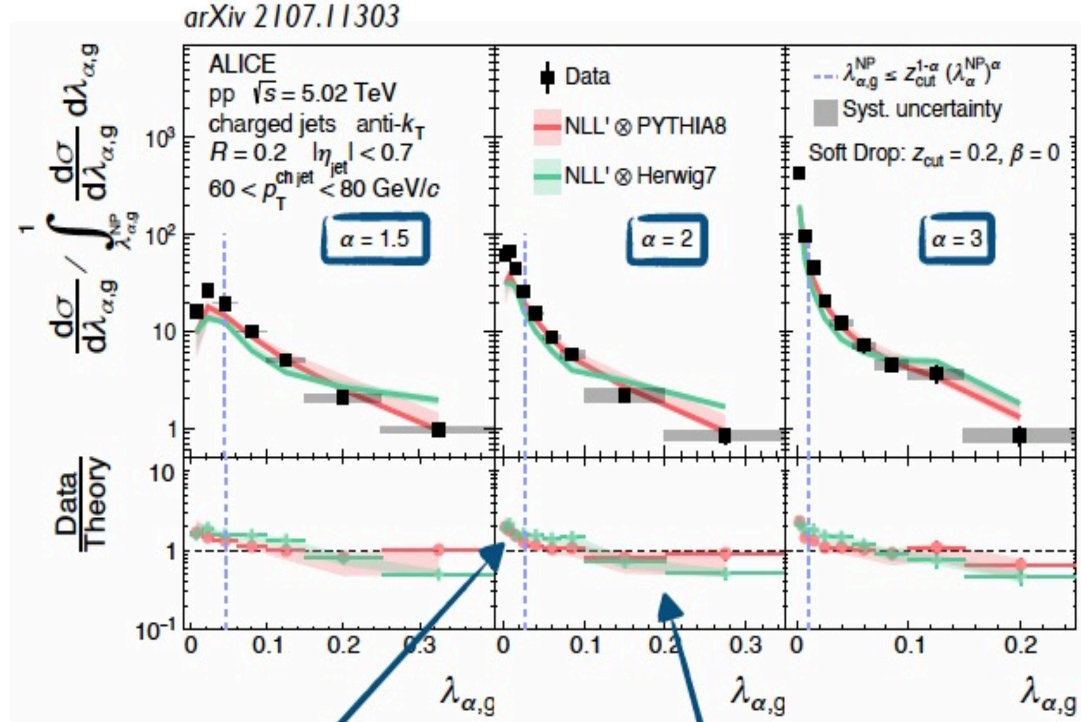
Groomed jets well described by NLL QCD

Apply grooming procedure to remove low-energy, wide-angle radiation

$$\lambda_{\alpha,\mathrm{g}} \equiv \sum_{i \in \text{groomed jet}} z_i \theta_i^\alpha$$

Jet grooming recovers larger region of successful perturbative description

arXiv 2107.11303



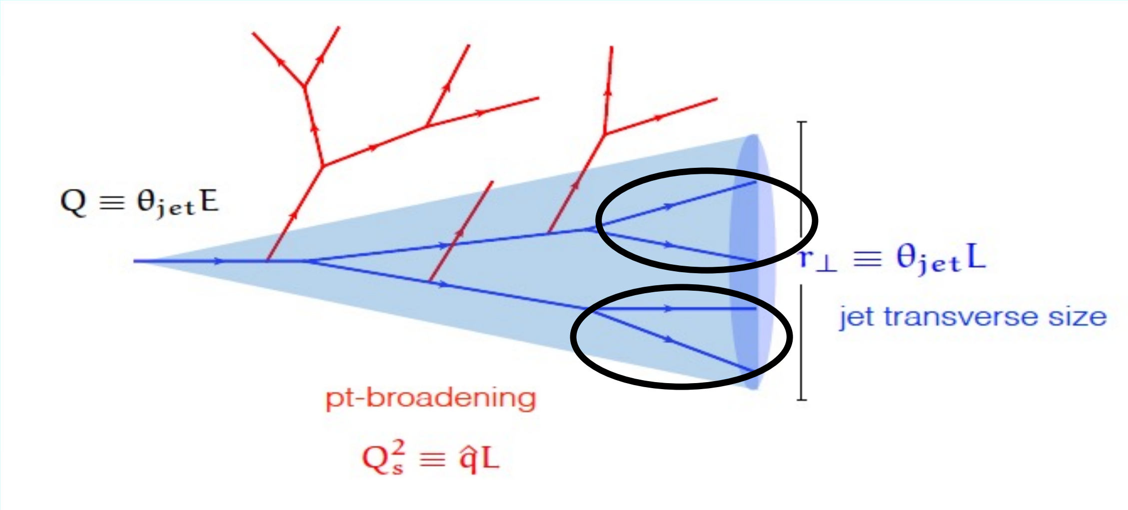
Small λ_α: Non-perturbative

Larger λ_α: Good agreement with pQCD calculations

Kang, Lee, Liu, Ringer PLB 793 (2019) 41

See also: CMS arXiv 2109.03340

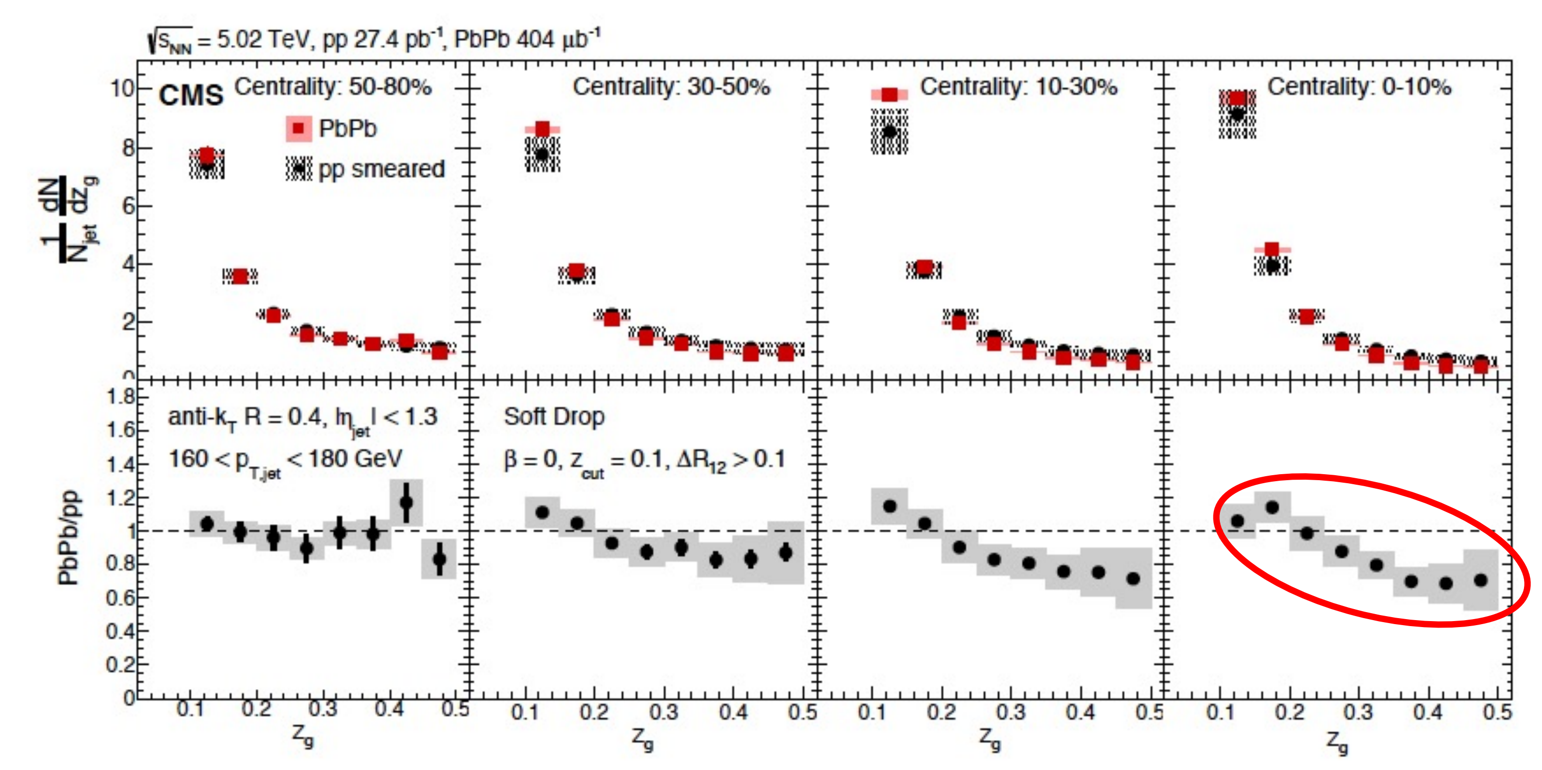
Probe early gluon splitting



Recluster & groom jet

Use 2 leading clusters

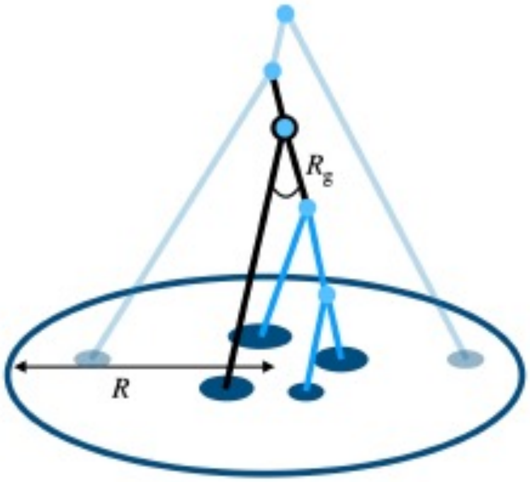
$$z_g = \frac{p_{T2}}{p_{T1} + p_{T2}}$$



Data to quantify energy, p_T transport.

See significant dependence on jet E, grooming.

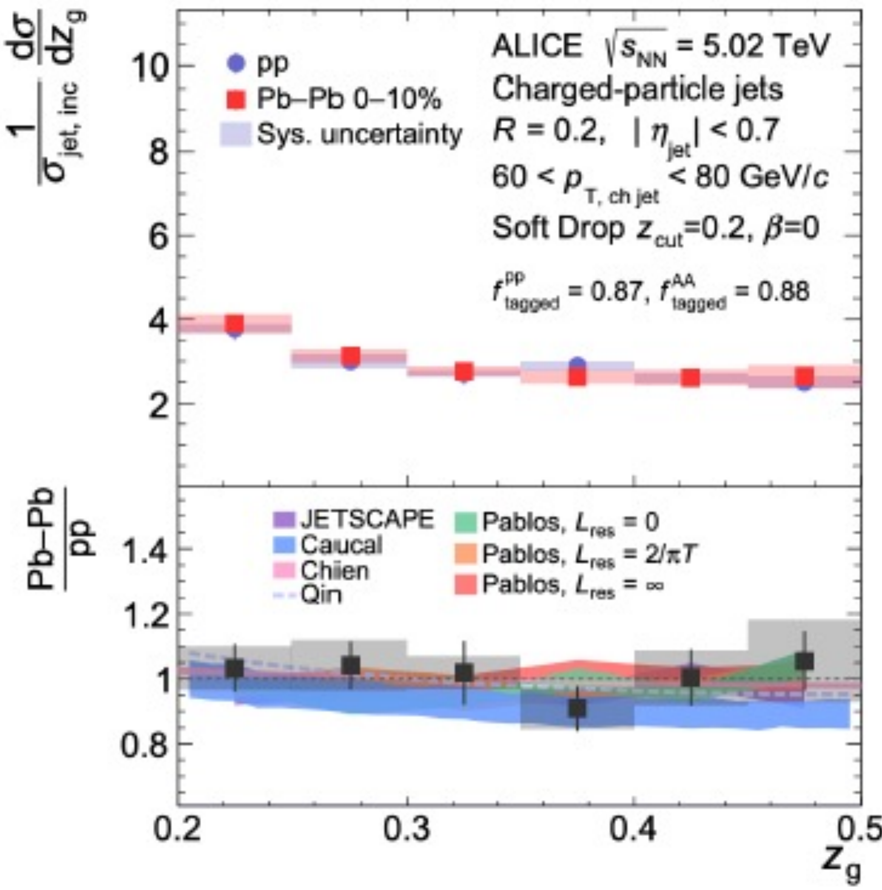
Groomed z_g and R_g

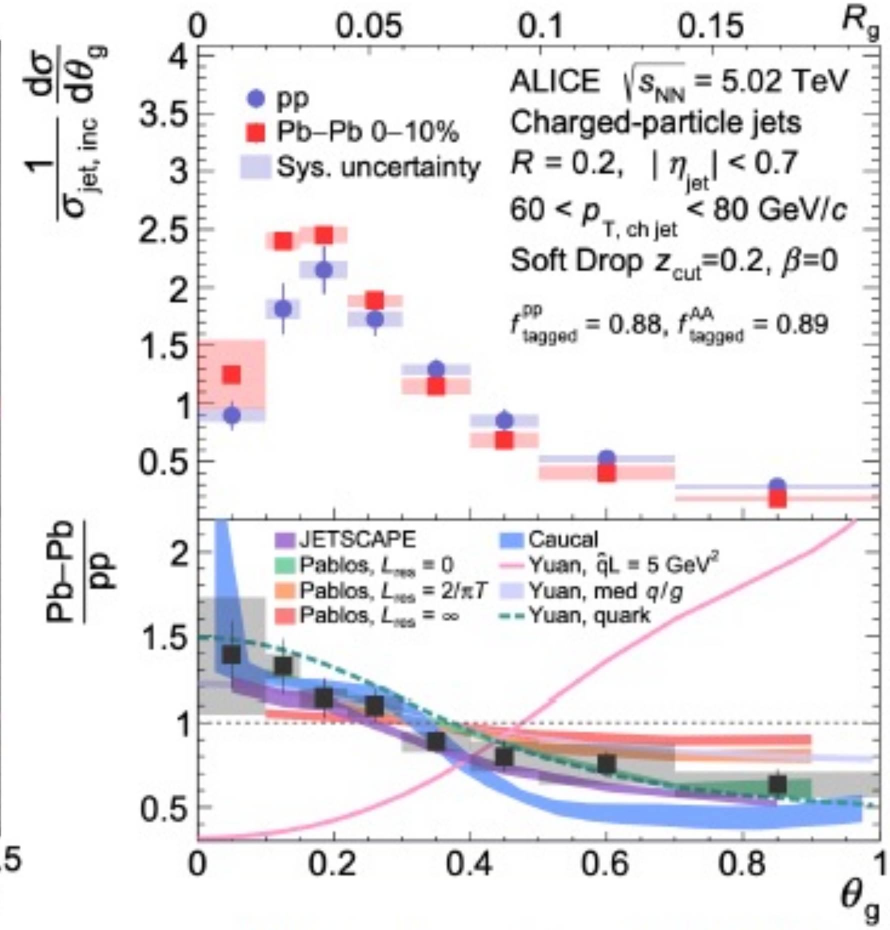


$$z_g \equiv \frac{p_{T,\text{subleading}}}{p_{T,\text{leading}} + p_{T,\text{subleading}}}$$

$$\theta_g \equiv \frac{R_g}{R} \equiv \frac{\sqrt{\Delta y^2 + \Delta\varphi^2}}{R}$$

Probe how hard-jet substructure is modified in heavy-ion collisions





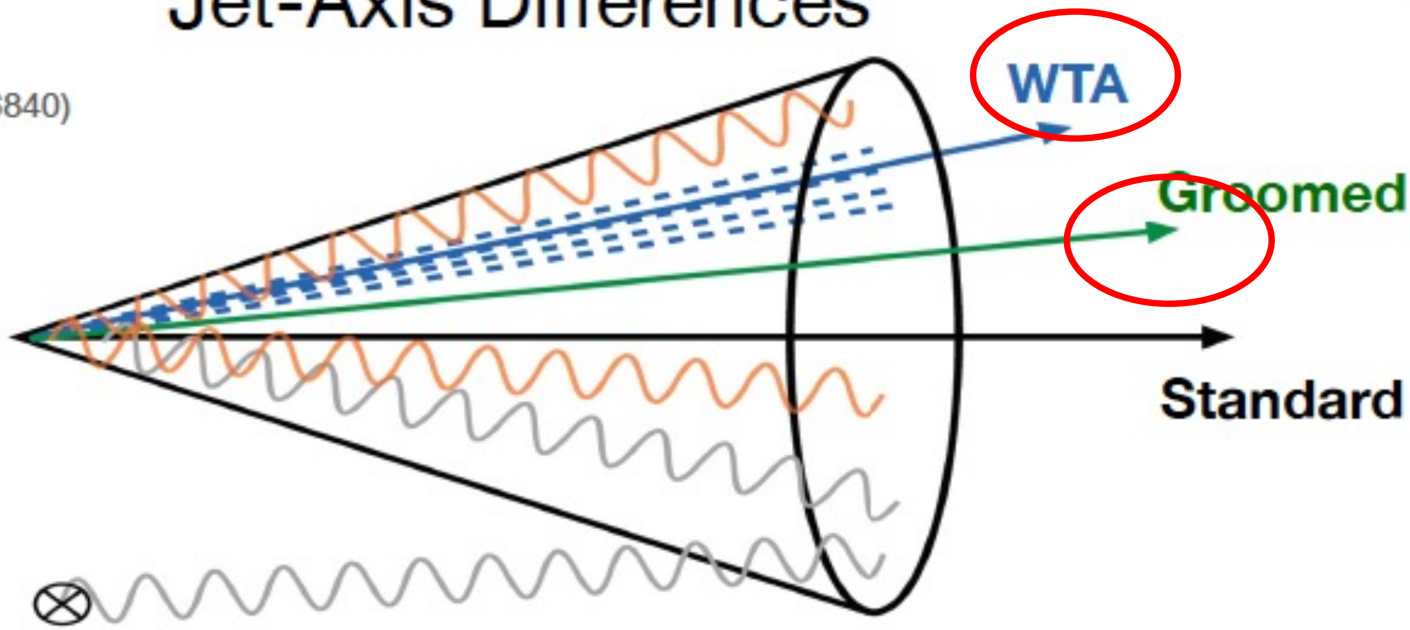
No significant modification

Jet core narrower in PbPb than in pp collisions

Rey Cruz Torres

Jet-Axis Differences

JHEP 04 (2020) 211 (1911.06840)



- Standard axis:
  coordinates in (y, φ) of jet clustered with anti-k_T algorithm and combined with E-Scheme

- Groomed axis:
  standard axis of groomed jet

- Winner-Takes-All (WTA) axis:
  - recluster jet with CA algorithm
  - $2 \rightarrow 1$ prong combination by taking direction of harder prong and $p_{\mathrm{T,\,tot}} = p_{\mathrm{T,\,1}} + p_{\mathrm{T,\,2}}$
  - Resulting axis insensitive to soft radiation at leading power

How aligned is hardest fragment with the jet axis?

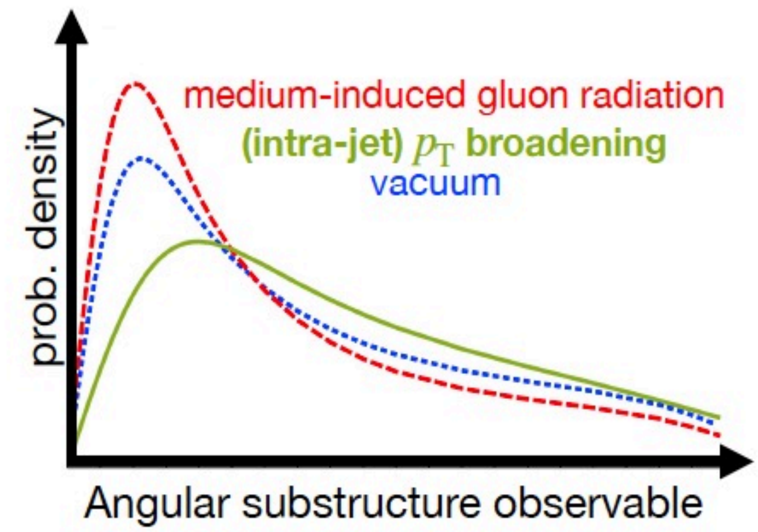
- Substructure observable: angular difference:

$$\Delta R_{\mathrm{axis}} = \sqrt{(y_2 - y_1)^2 + (\varphi_2 - \varphi_1)^2}$$

  between two definitions of the jet axis

Why measure this observable?

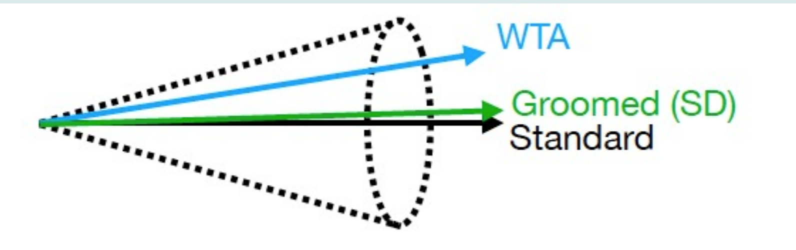
- Study properties of the QGP via modification of angular (TMD-sensitive) jet substructure
- Contrast substructure modification with(out) grooming
- Understand interplay between QGP competing effects
  - e.g. **medium-induced gluon radiation** vs. **multiple-scattering-like (intra-jet) p_T broadening**



Ringer et al., PLB 808 (2020) 135634

Axis difference can be calculated perturbatively

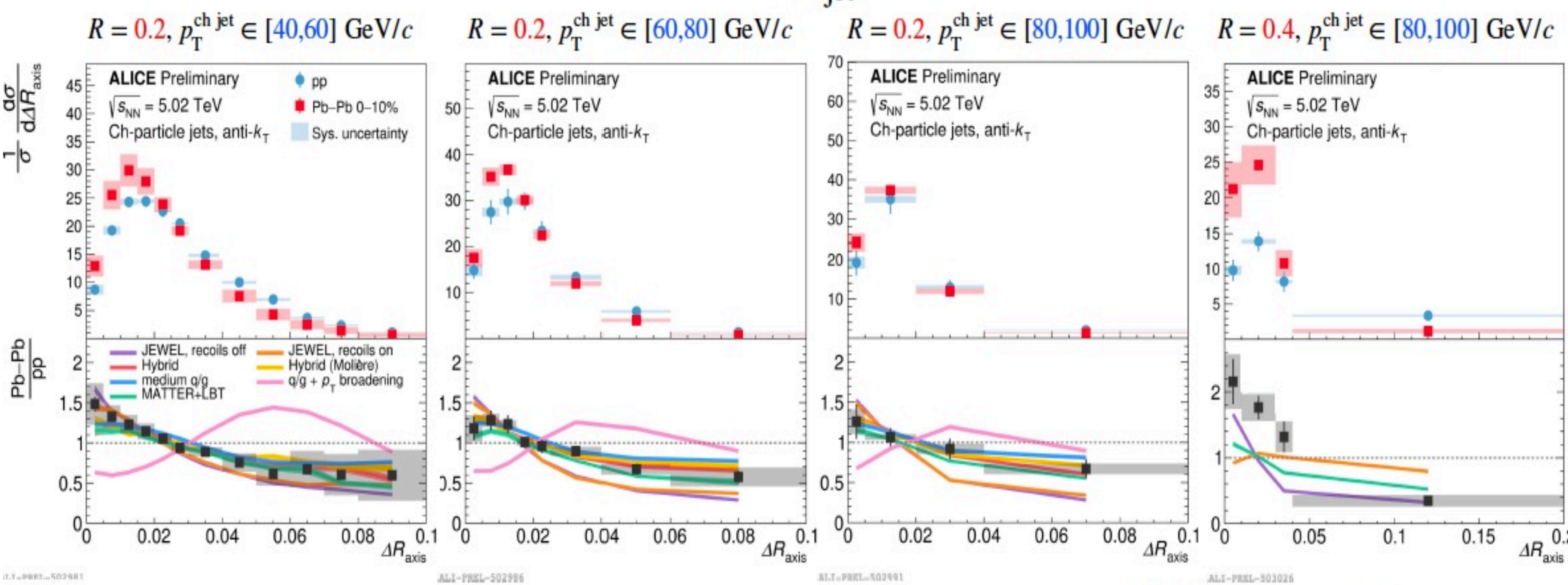
Especially if jets are groomed to remove the soft particles at large angles.



p_T and R evolution

Rey Cruz Torres

WTA - Standard, $|\eta_{jet}| < 0.9 - R$



Same R, changing $p_T^{ch\ jet}$

Same $p_T^{ch\ jet}$, changing R

Jets narrow in PbPb

Larger effect in softer jets

Quark jets are narrower. Are the gluon jets more modified?

- Modification is larger in R=0.4 than in R=0.2
- Larger disagreement with models for R=0.4

Will again use models vs. data to quantify the processes in jet evolution

Jet angularity:

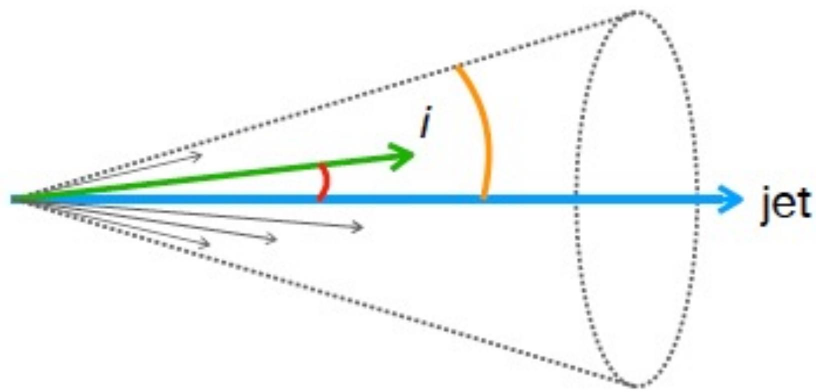
Ezra Lesser, Rey Cruz Torres

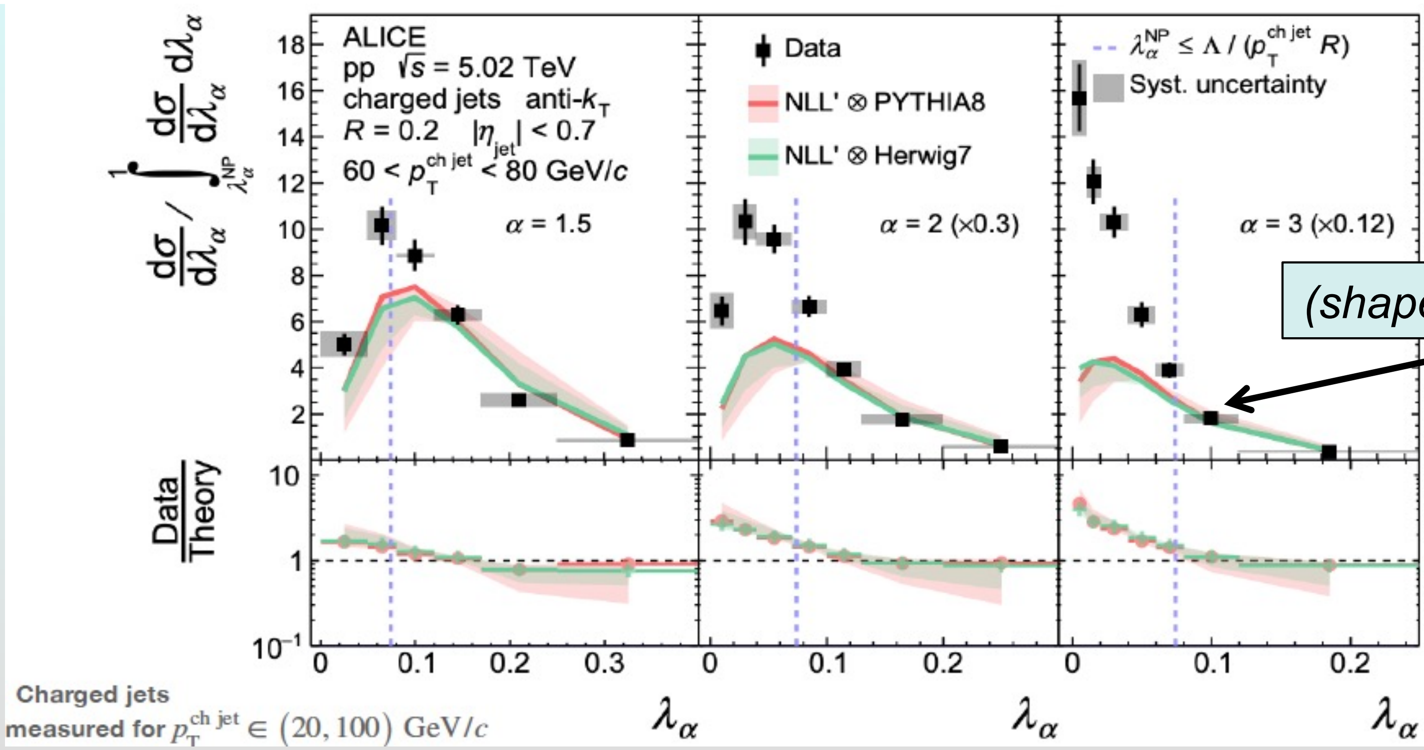
arXiv:2107.11303

$\alpha > 0 \ \rightarrow$ IRC-safe observable

Includes both transverse-momentum and angular components with relative weights given by continuous parameter α

$$\lambda_\alpha \equiv \sum_{i \in \text{jet}} \left(\frac{p_{\text{T},i}}{p_{\text{T,jet}}}\right)\left(\frac{\Delta R_{\text{jet},i}}{R}\right)^\alpha$$





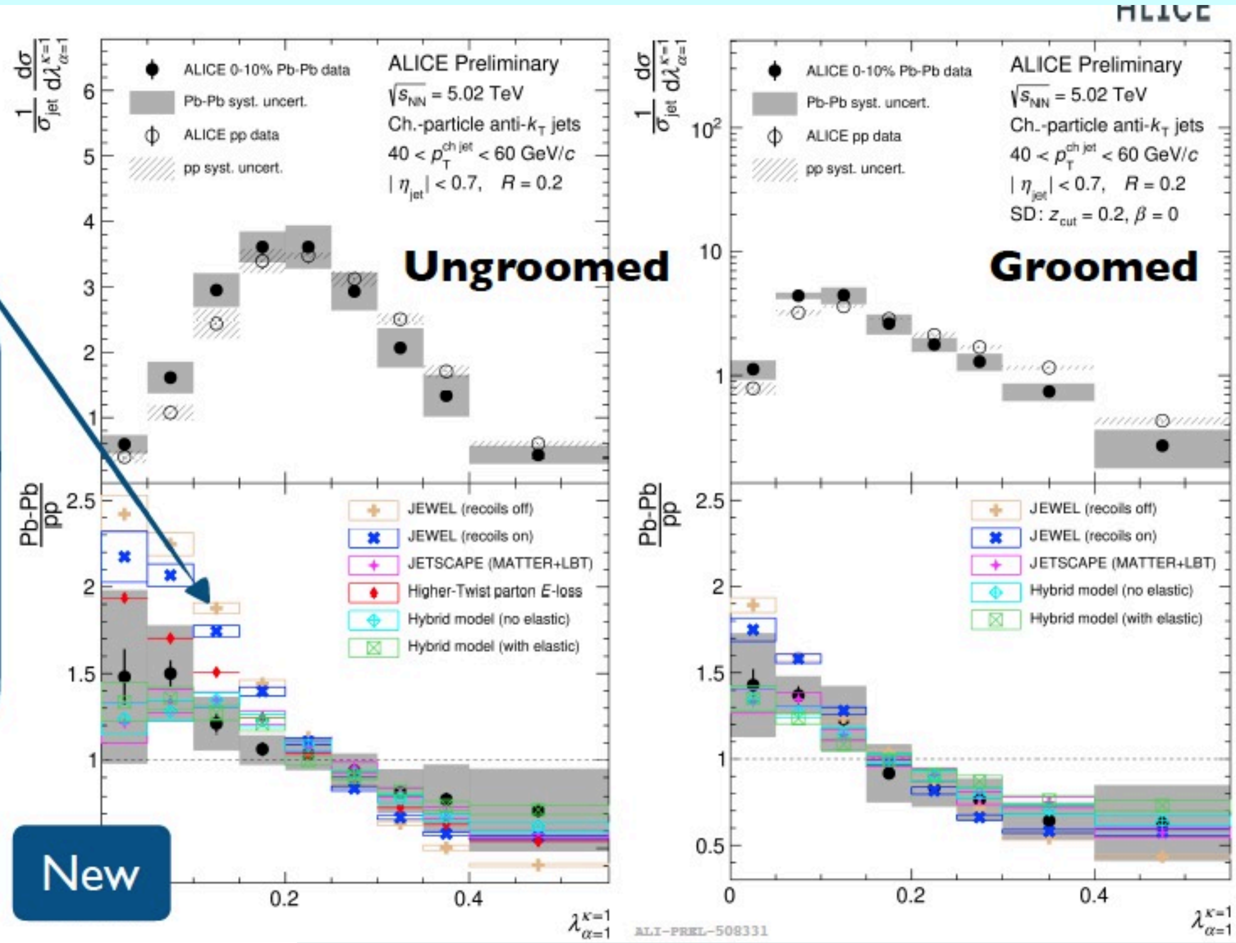
(shape) Calculable in pQCD

$$\lambda_\alpha \equiv \sum_{i \in \mathrm{jet}} \left(\frac{p_{\mathrm{T},i}}{p_{\mathrm{T,jet}}}\right)\left(\frac{\Delta R_{\mathrm{jet},i}}{R}\right)$$

In Pb+Pb

Models generally describe trends in data well, although some deviations

- JEWEL
  Zapp, EPJ C 74 2 (2014)
- JETSCAPE
  arXiv 2204.01163
- Higher Twist
  Chen, Zhang et al., CPC 45 (2021) 2, 024102
- Hybrid Model
  See Zach Hulcher, Tues 18:30



Additional α, p_T available:
https://alice-figure.web.cern.ch/node/21570

Recall:

Jets narrow in PbPb

Quark jets are narrower. Are the gluon jets more modified?

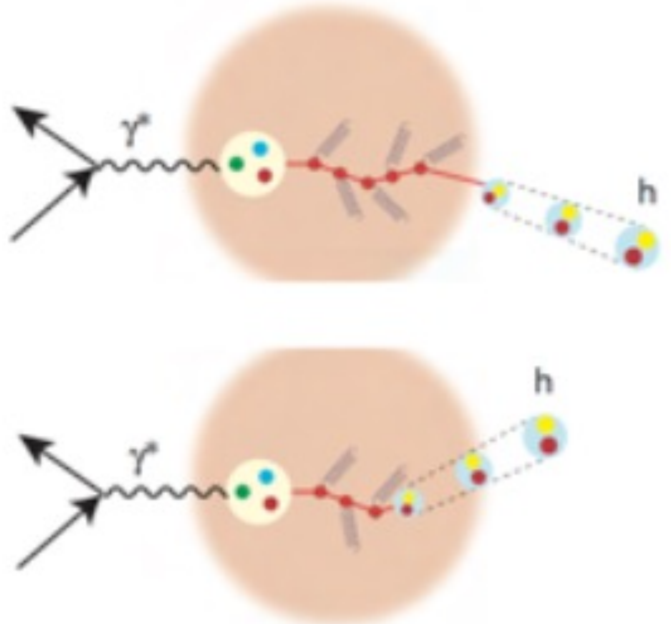
Models depend on QGP evolution too!

Angularity in groomed Pb+Pb jets: large λ depleted, small λ enhanced.

Expect this if jets narrow in QGP

Insensitive to medium

Figure it out at EIC

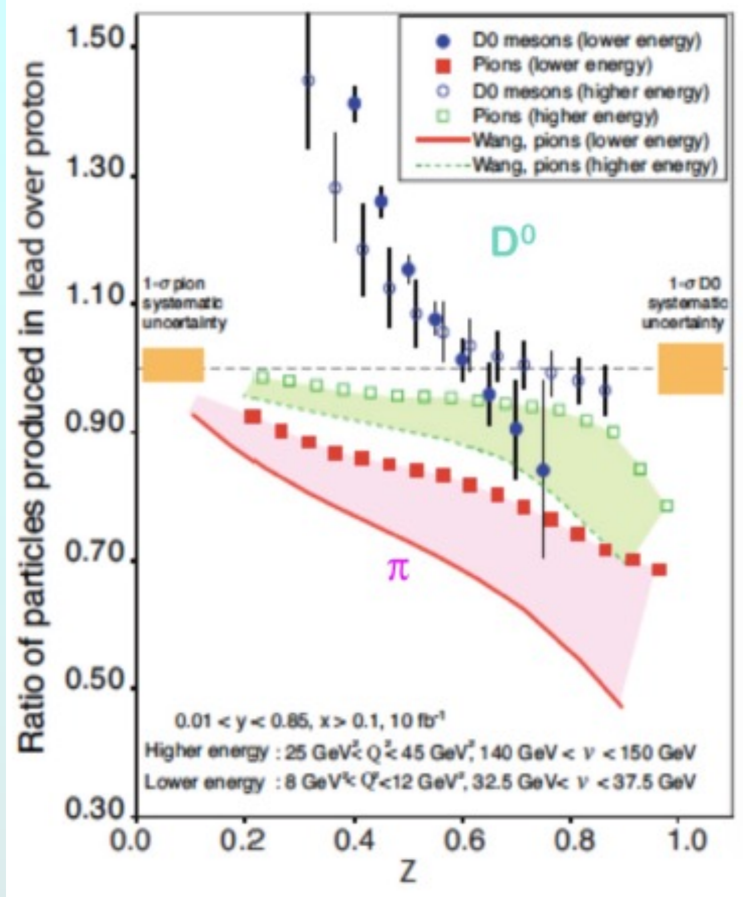


Control of $\nu = \dfrac{Q^2}{2mx}$ and

medium length

Study mass-dependence via charmed hadrons.

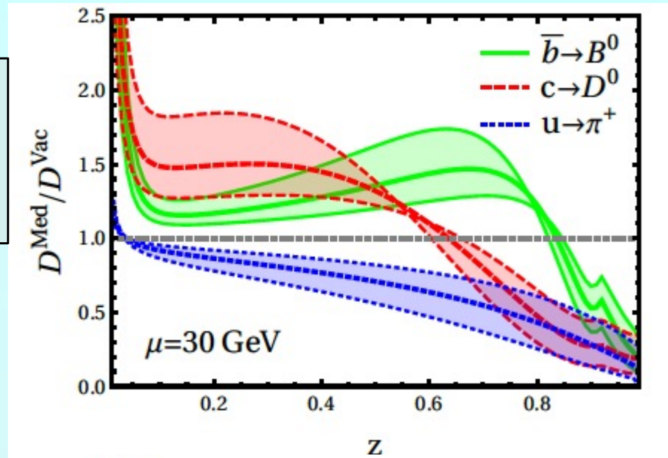
Hadron yields

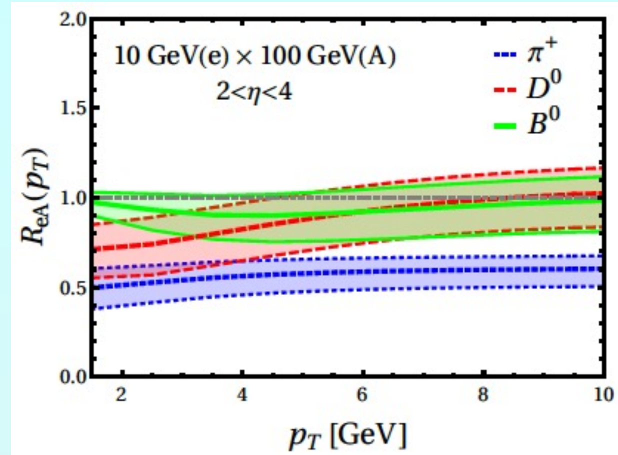


And correlations

Heavy Flavor at EIC

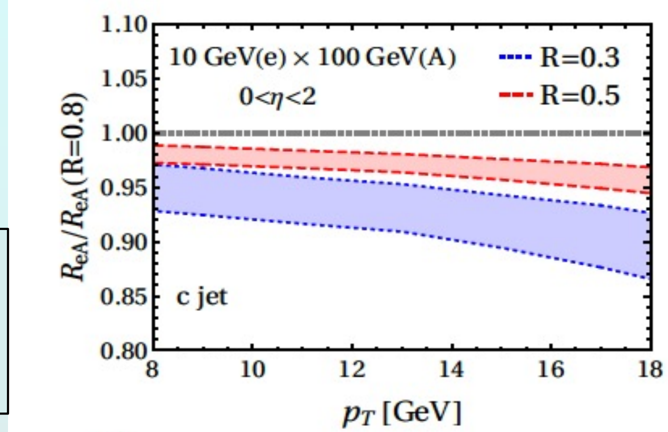
Open HF
Vitev, et al.
arXiv:2007.10994

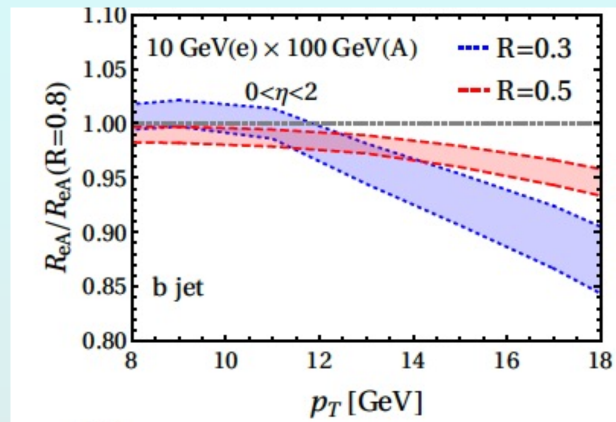




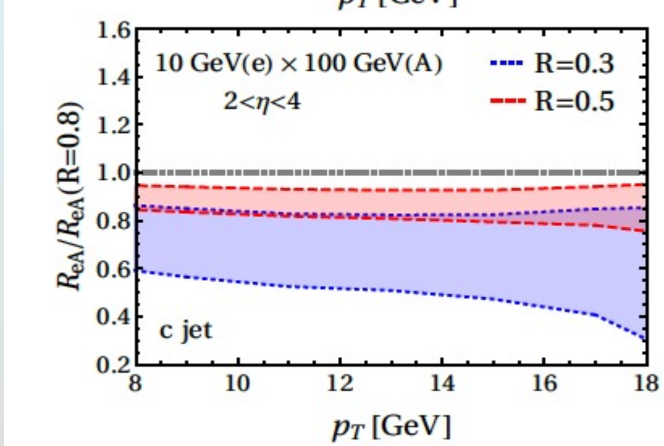
Frag. Function modification measurable in forward eta

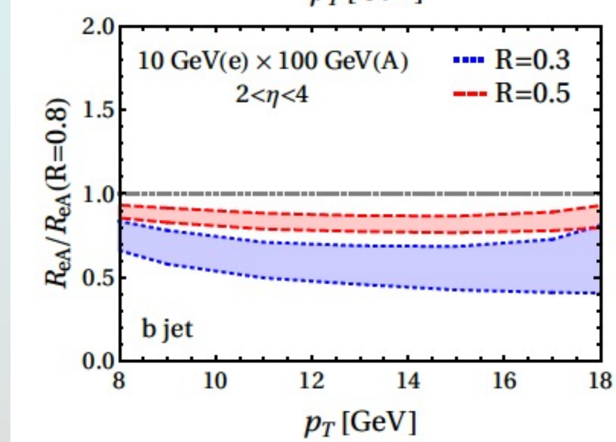
HF jets
Vitev, et al.
arXiv:2108.07809





Clever ratio of jet sizes reduces systematics for heavy flavor jets





Not such small x, but very sensitive to the medium!

Is there a mass effect on g radiation?

- **Soft gluon radiation spectrum**

$$dP = \frac{\alpha_s C_F}{\pi}\frac{d\omega}{\omega}\frac{k_\perp^2\, dk_\perp^2}{(k_\perp^2+\omega^2\theta_0^2)^2}, \quad \theta_0 \equiv \frac{M}{E},$$

Dokshitzer, et al. J.Phys.G17,1602 (1991)
Dokshitzer & Kharzeev, PL B519, 199 (2001)

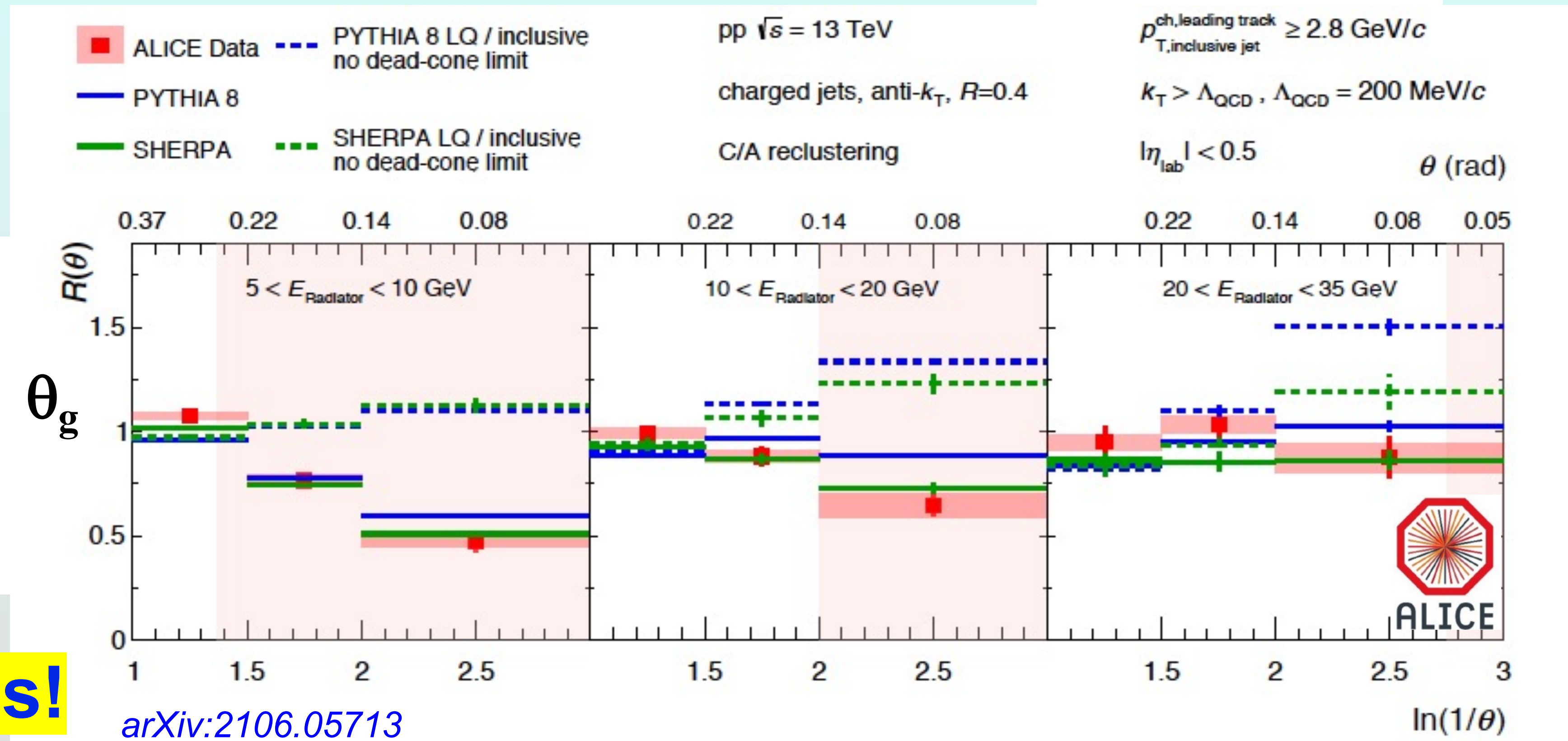
Large M suppresses small angle radiation (phase space effect)

Known as "dead cone effect"

ALICE D-tagged vs. inclusive jets in p+p

$$\theta_g \equiv \frac{R_g}{R} \equiv \frac{\sqrt{\Delta y^2 + \Delta\varphi^2}}{R}$$

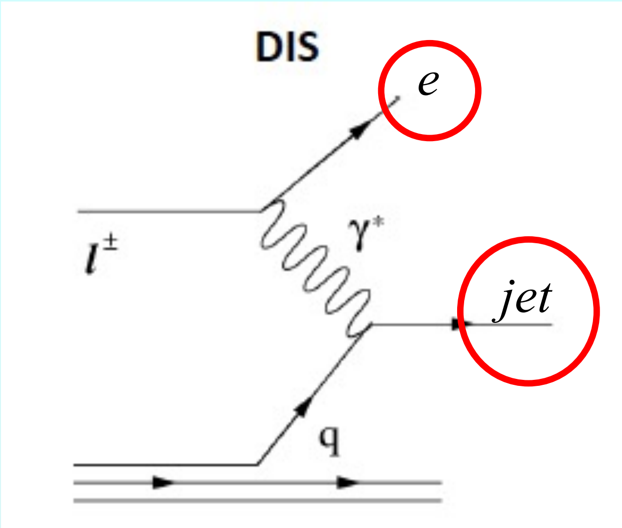
HF/ inclusive θ_g

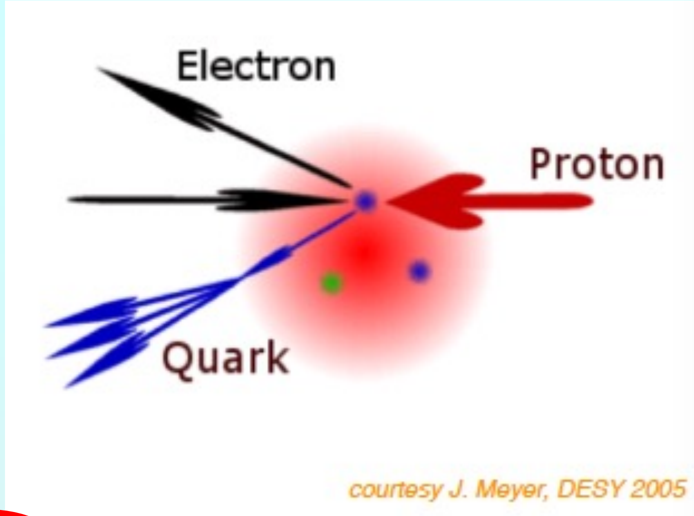


Yes!

arXiv:2106.05713

Deep Inelastic Scatter off low-x partons

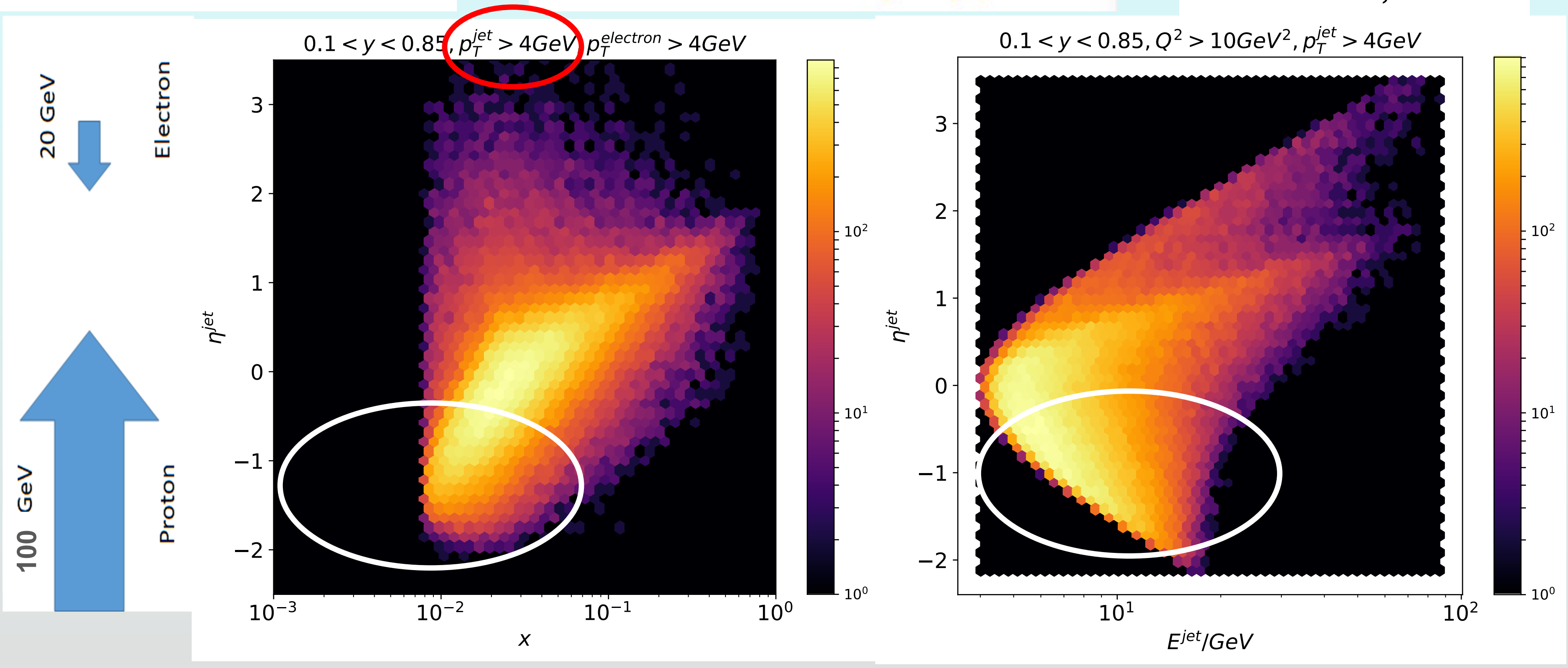




Probe parton at $x=10^{-2}$ (almost a fixed target)

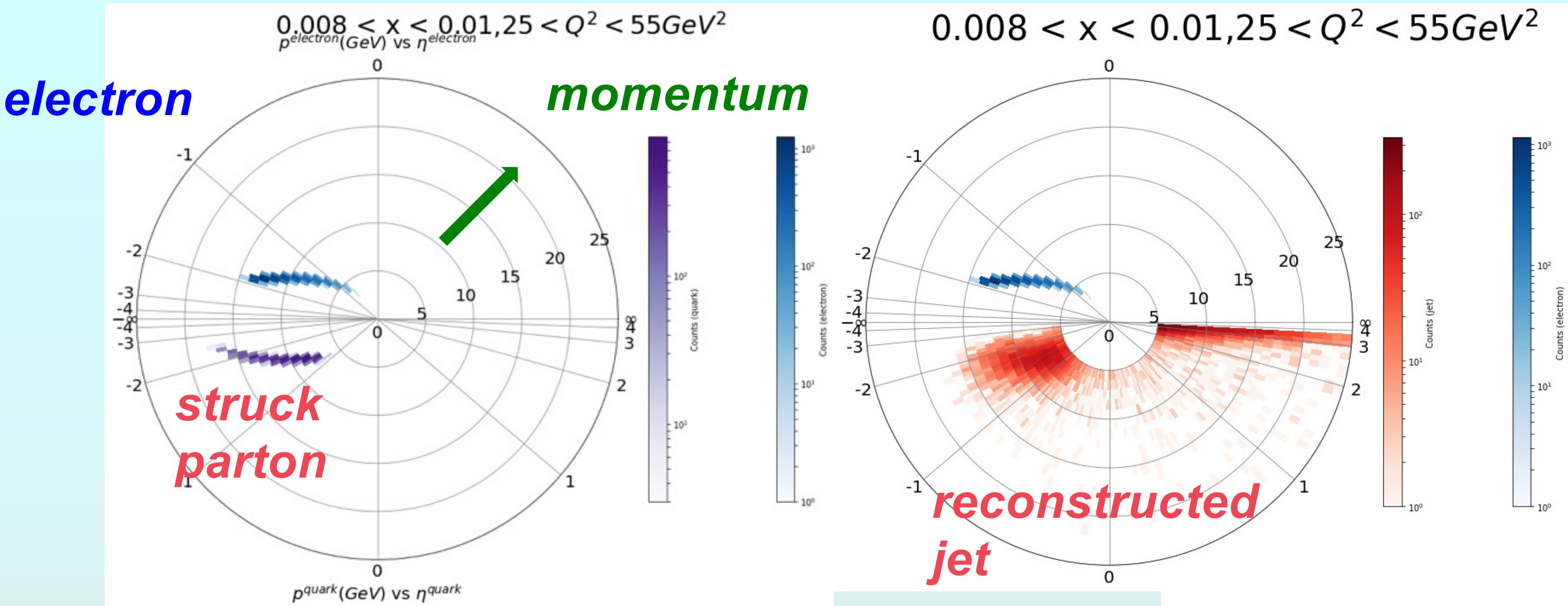
-> 5-15 GeV jets

M. Arratia, et al.



Electron tags original jet energy, angle

e+p, DIS; Pythia 8. Require W^2 > 4 GeV^2, jet R=1.0



Youqi Song, M. Arratia

← electron direction

proton/ion → direction

In R=1 jets hadronization uncertainties are small

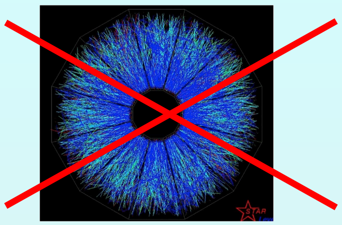
jet approximates the parton well; calculable with pQCD

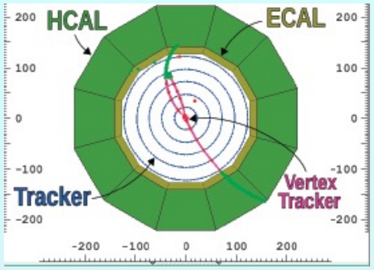
Directly measure energy lost to dense matter at small x

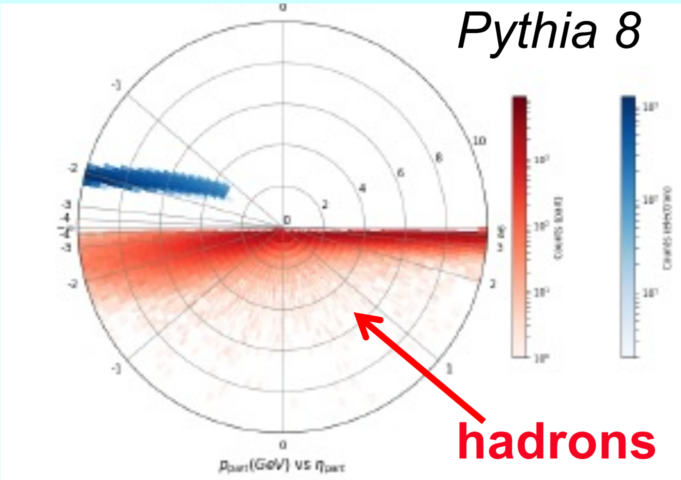
Use substructure observables!   *NB: Q^2 >25 GeV^2*

Measuring these jets

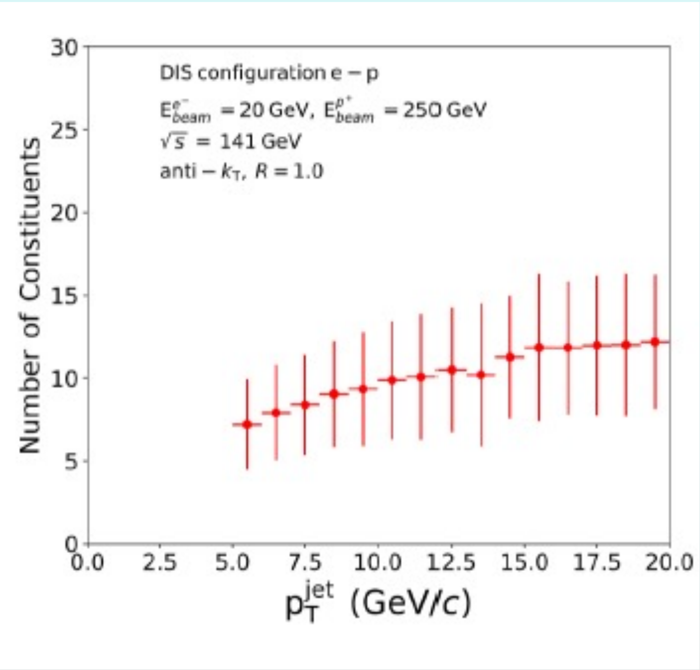
- **Is easy!**
  Underlying event is small
  MPI effects smaller than pp and pA





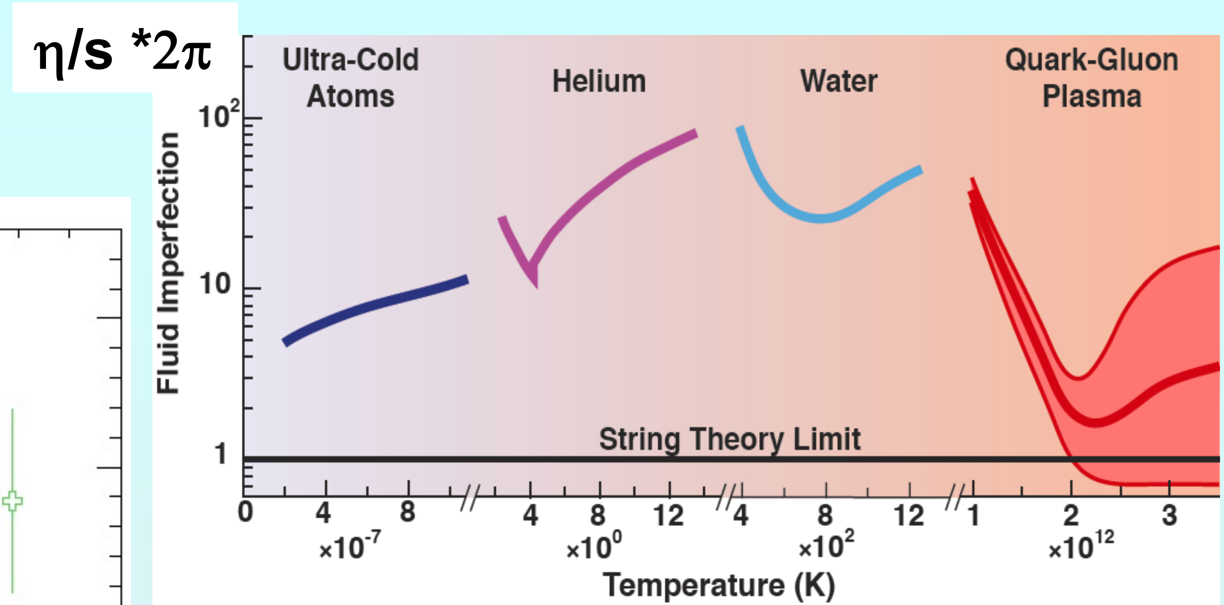


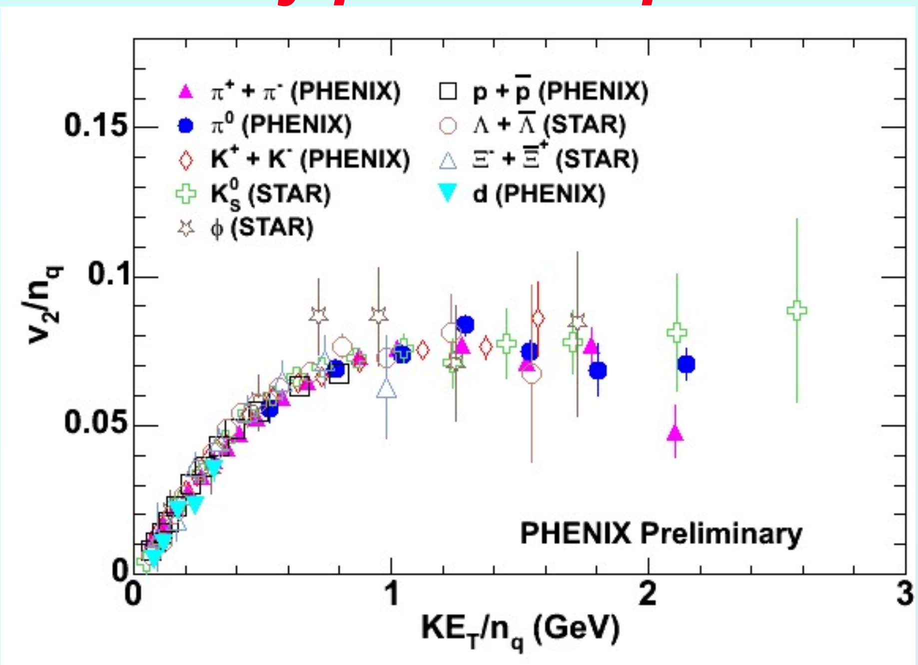
- **Is hard!**
  The jets are very soft
  Small number of constituents
  But we have practice at RHIC
  - under tougher conditions!
  Look at charged & full jets



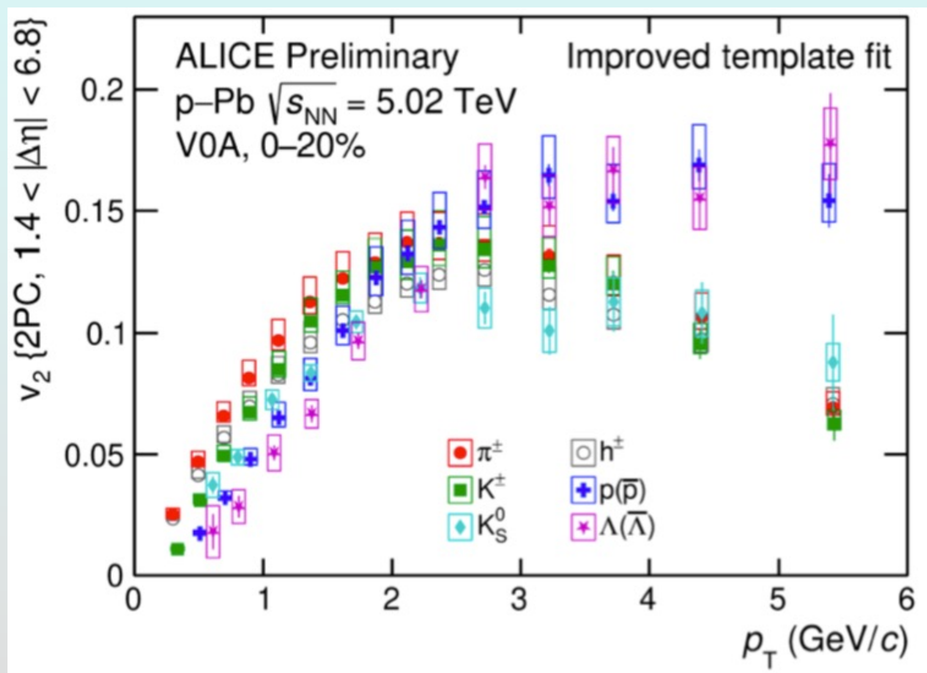
QGP flows with little friction

Hydrodynamic flow:
a nearly perfect liquid





Even in small droplets!



From data + hydrodynamics:

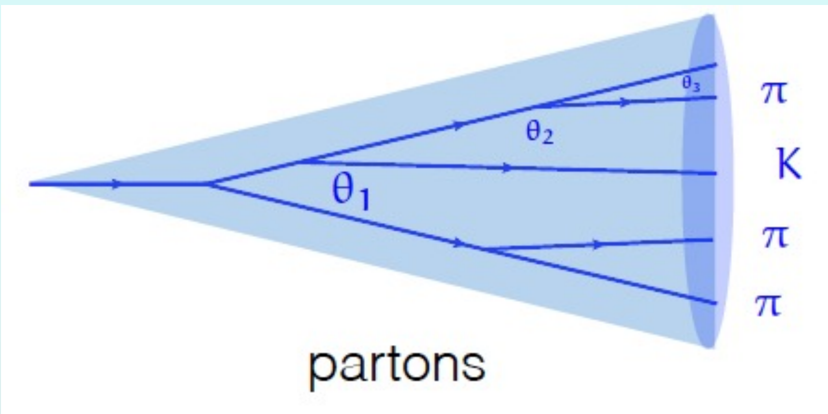
η/s near $1/(2\pi)$, near AdS/CFT limit

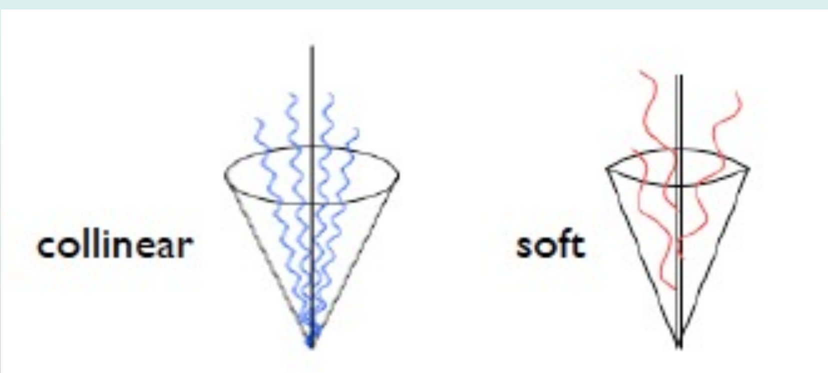
Not an ideal gas!! σ is larger

What's in a jet?

- 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

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





Modified by color exchange with QGP