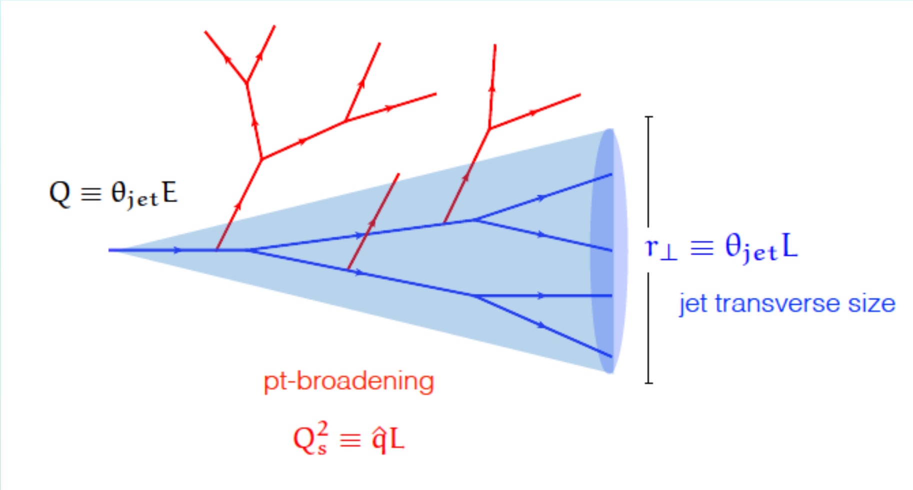
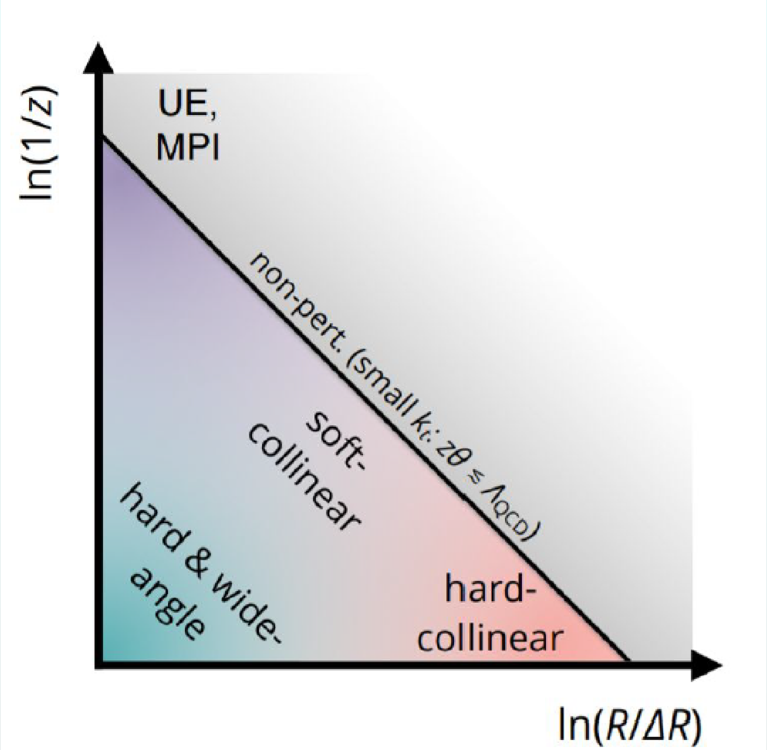
Lecture 3 & 4
QCD Many-body interactions, screening, initial stage of the collisions





Barbara Jacak

UC Berkeley & LBNL

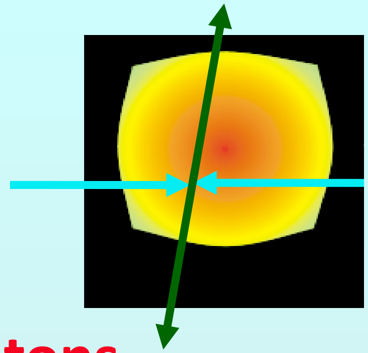
June 16, 2023

outline

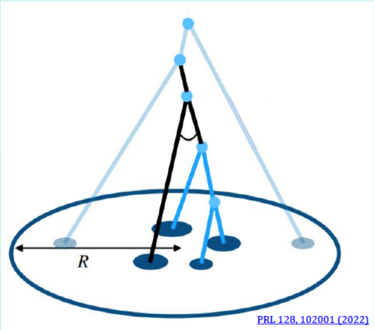
- What is a jet?
  - Jet "fragmentation" process
  - Jet finder
- Looking under the hood
  - Parton splitting & rearrangement by the QGP
- Correlations among jet fragments
  - Energy-energy correlators and hadronization
- Color screening in quark gluon plasma
- Vorticity
- Initial stage of the collision

Many thanks to Ezra Lesser, Rey Cruz Torres, Preeti Dhankher, Wenqing Fan

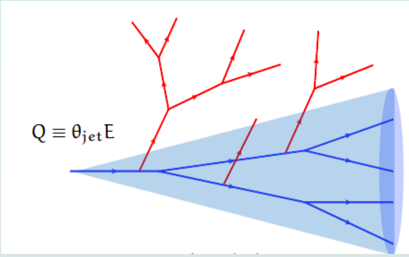
Quark & gluon probes



- Produced by hard scattering among incoming q, g
  - Scatter out of the beam direction
- The partons produce a "shower" of secondary photons
  - Radiate gluons (just as in bremsstrahlung)
  - Gluons can split into two
  - Partons can collide with q, g in any medium they encounter (e.g. underlying event in pp, or QGP)



- Shower particles also evolve, creating a cascade
  - Especially in the presence of large, dense medium

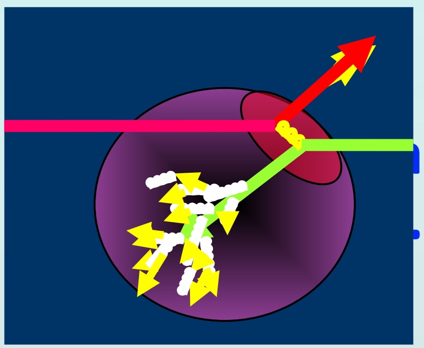


- At the end, hadrons form from all of the produced partons

Where does the lost energy go?

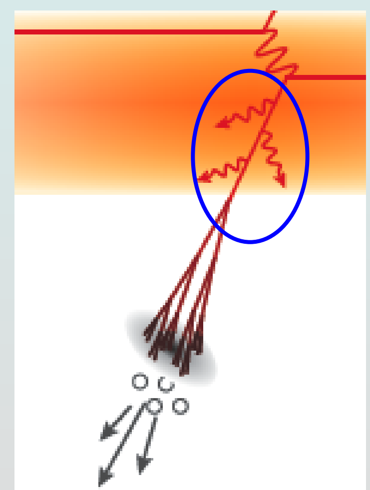
- **Several possibilities**

extra gluons at small angles (in/near jet cone)



diated gluons thermalize in
. they're gone!)

remain correlated with leading parton, but broaden/change jet



Look inside and around the jet

- Precise measurement of energy loss by tagging with a photon or vector boson (which do not interact with the plasma)

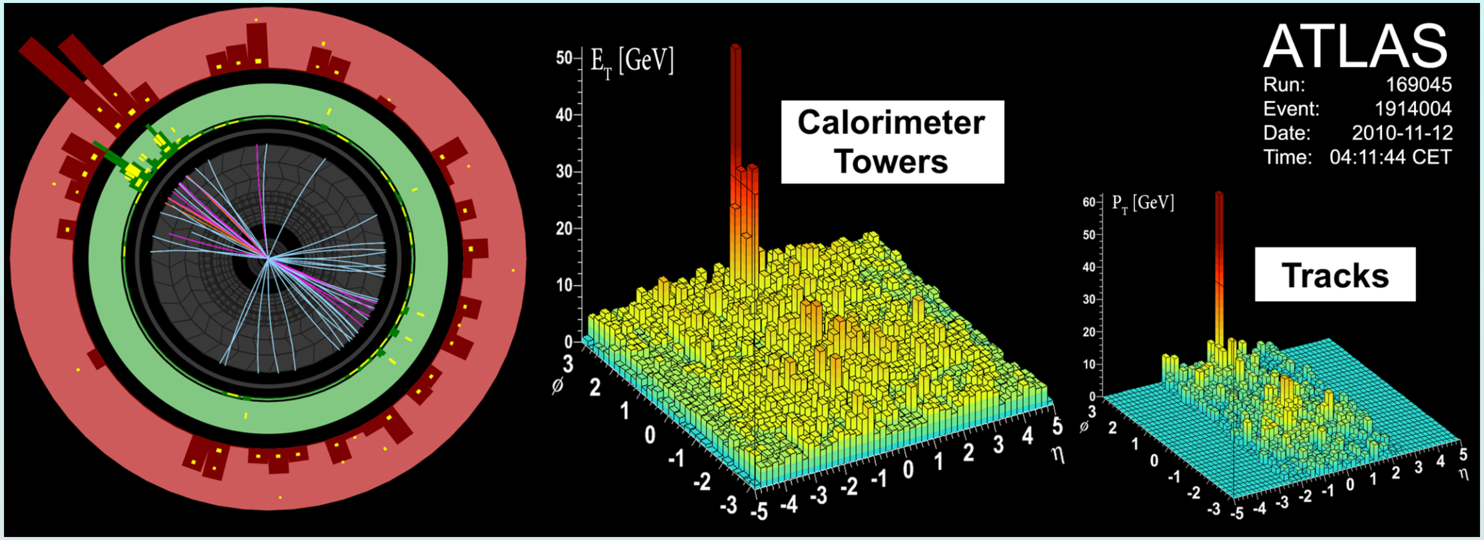
- Longitudinally: jet fragmentation function

- Also transverse to the jet axis: jet substructure observables

What, actually, IS a jet??

- No such object! (despite the cartoons)
- We define a "jet"

  by choosing algorithm and size scale



- *Which hadrons belong to the same jet?*

  In Pb+Pb: many particles from other than the hard parton

  In p+p the underlying event is smaller, but not zero

- Reconstruct jets from all hadrons, or charged ones only

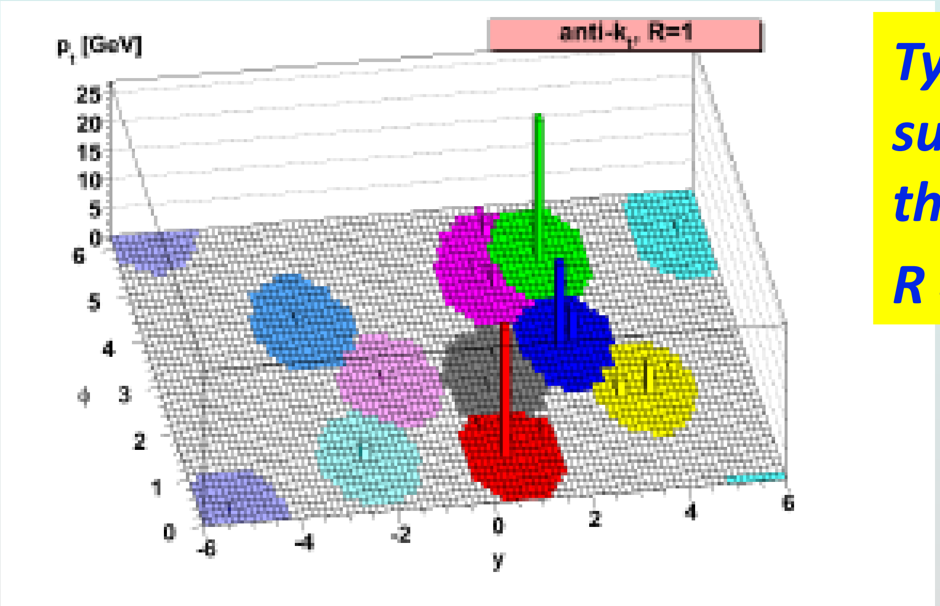
Jet algorithm of choice: "anti-k_T"

arXiv:1802.1189

- Seed is hardest hadron or calorimeter tower
- Calculate distance to other particles:

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

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



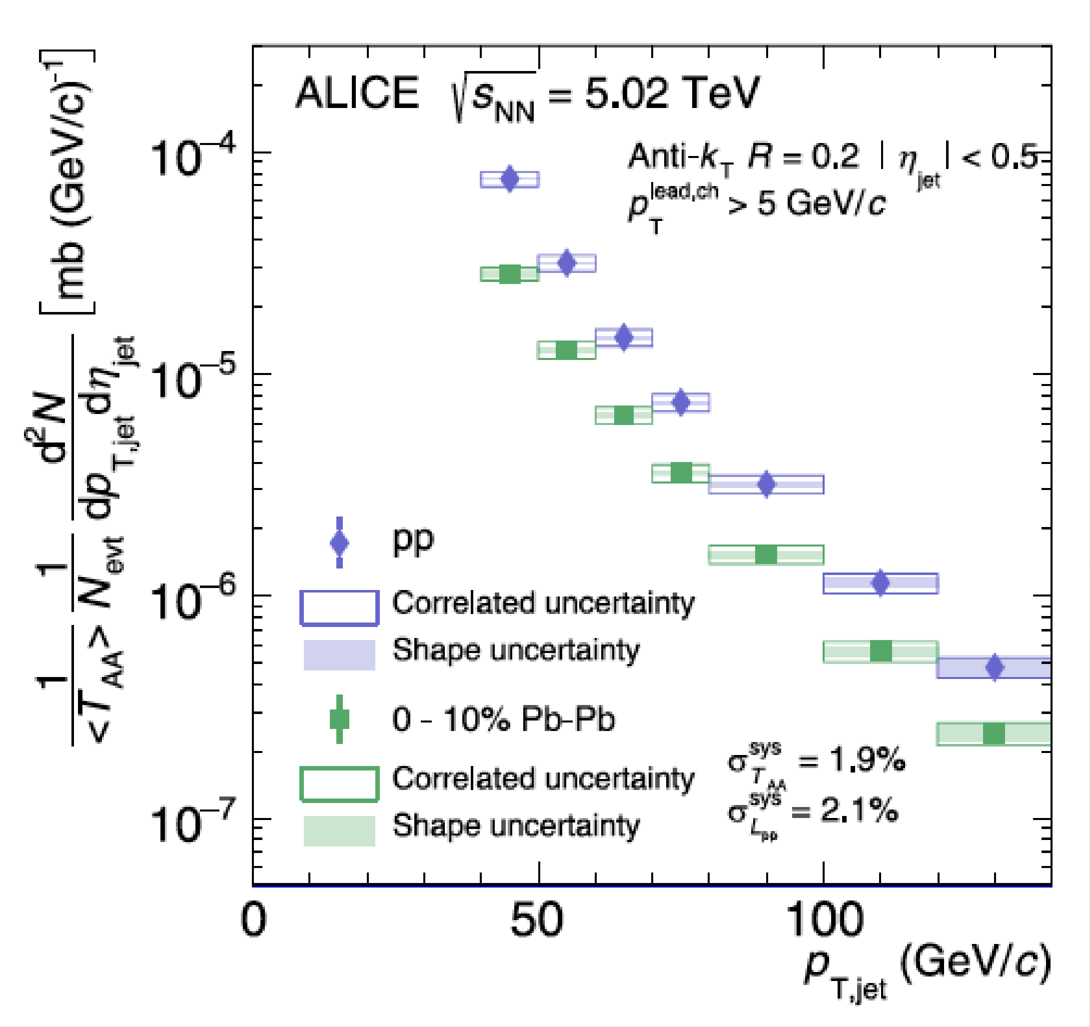
Typically, use R ~ 0.4 to allow statistical subtraction of the underlying event. But this misses some of the parton's energy.

R = 1.0 is better. Feasible in e+A

Theorists can do this at the parton level, so jets are calculable with perturbation theory

Jet spectrum

PRC101, 034911 (2020)



Power law shape:

Due to distribution of partons inside nucleons f_a and f_b

+ combinatorics of finding partons of similar momentum fraction x_a~x_b

We will come back to the fragmentation function D

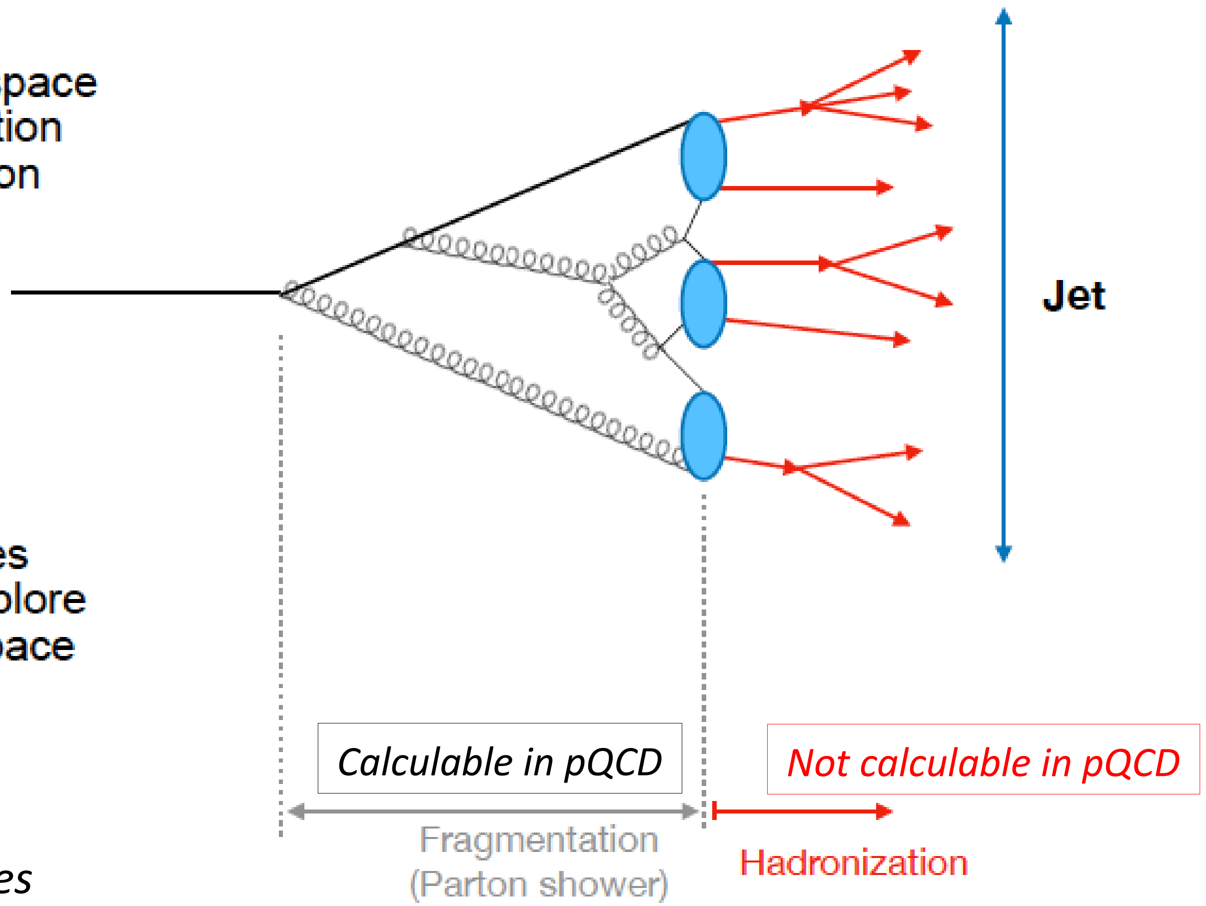
$$\frac{d\sigma}{dX} = \sum_{a,b} \sum_{f} \int_{\hat{X}_f} f_a(x_a, Q_i^2) f_b(x_b, Q_i^2) \frac{d\hat{\sigma}_{ab\to f}(x_a, x_b, f, Q_i^2, Q_f^2)}{d\hat{X}_f} D(\hat{X}_f \to X, Q_i^2, Q_f^2)$$

Under the hood: parton shower evolution

Significant scale difference between parton from hard-scattering and hadrons measured in detector

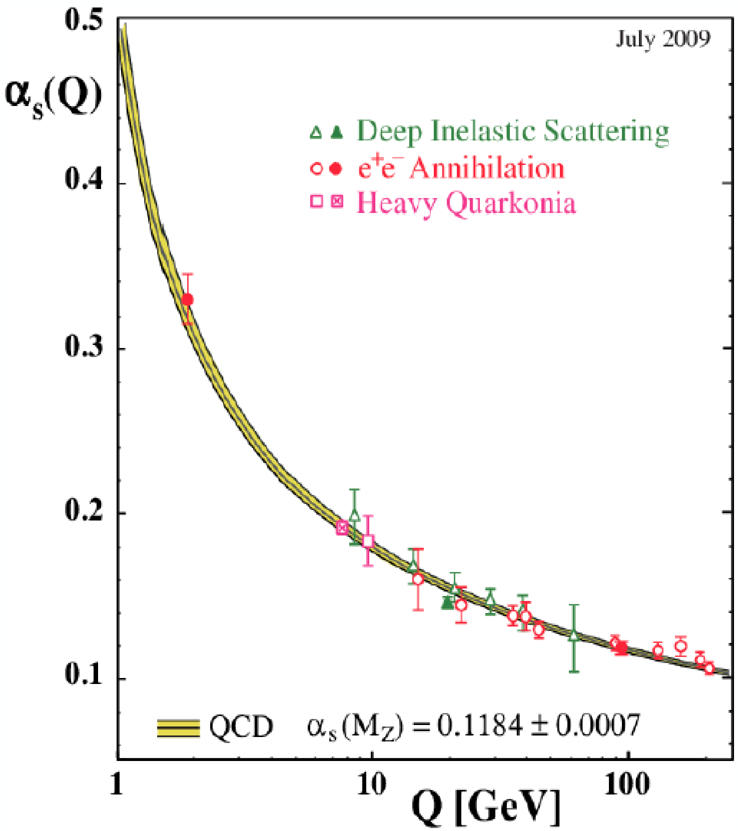
Large phase space for jet formation and evolution

Suite of observables needed to explore this phase space



Rey Cruz Torres

Perturbative QCD calculation



$$\sigma(\tau) = \sigma_0 + \alpha_s\sigma_1 + \alpha_s^2\sigma_2 + \alpha_s^3\sigma_3 + \mathcal{O}(\alpha_s^4)$$

LO or Born

NLO

N²LO

$\tau \equiv$ generic observable

Infrared and Collinear (IRC) safety

For complete cancellation of IRC singularities, observables must satisfy:

Collinear safety: $1/\theta$ ✗

Infrared safety: $1/E$ ✗

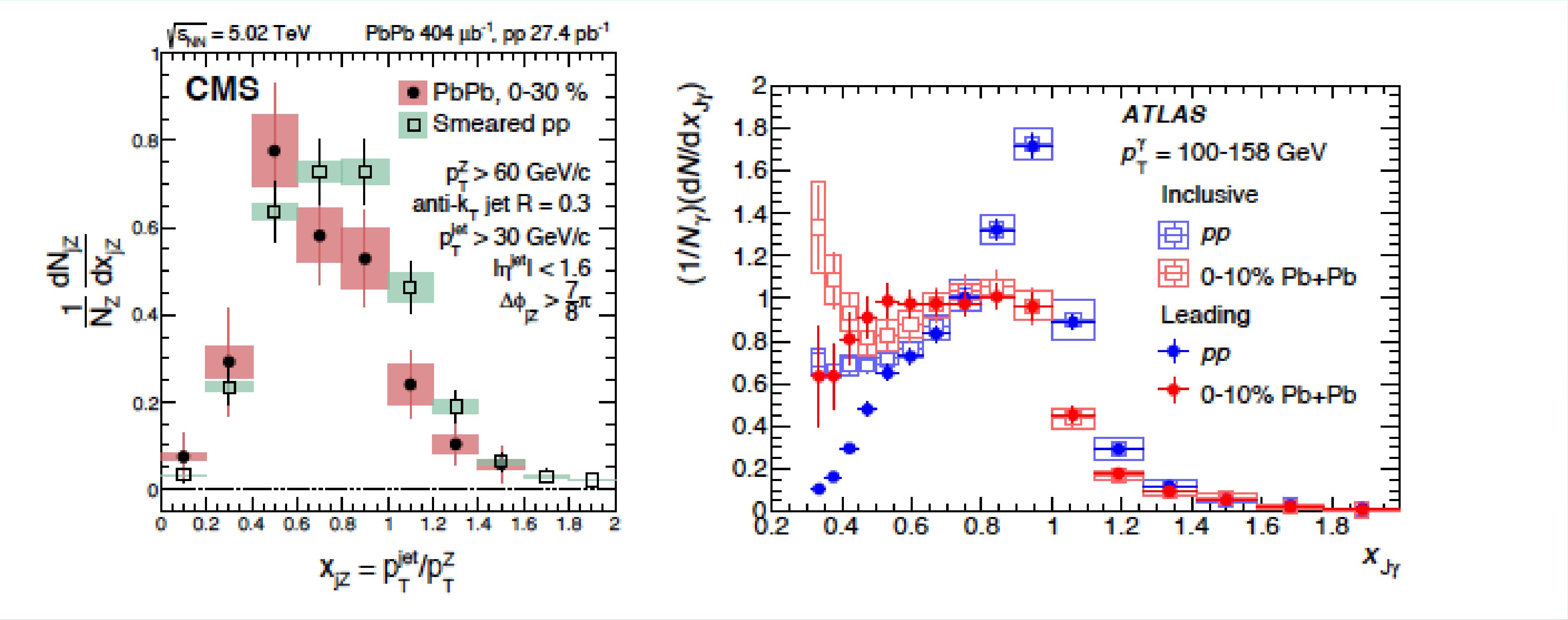
Coupling constant runs with momentum transfer, becomes small

Expand interaction cross section in powers of α_s

Jet energy and shape modification

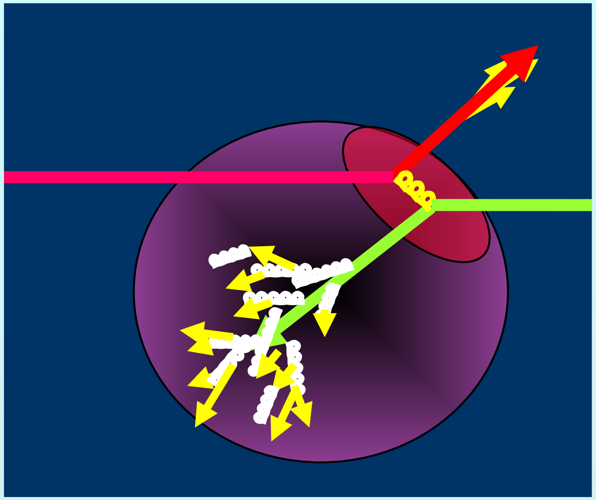
Energy unbalanced in g, Z – tagged jets

- **With photon or Z, you know the initial energy**



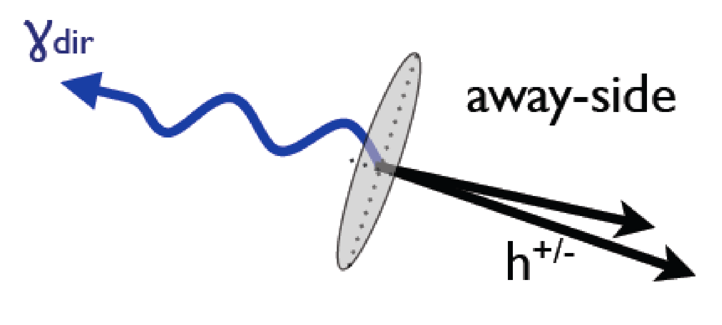
- **Plasma reduces the jet's energy. Jet and boson p_T no longer balance**

Look inside: Jet Fragmentation function



$D(z) = 1/N_{jet}\, dN(z)/dz;\ z = p_{had}/p_{jet}$

Count jet fragments as fraction of the jet's momentum



$z_T = p_{Ta}/p_{T\gamma} \sim z$ **for γ trigger**

$\xi = \ln(1/z_T)$

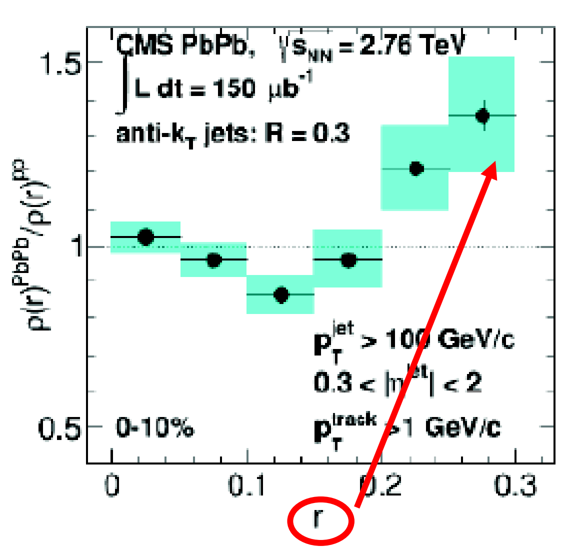
Modification factor similar to R_{AA}:

$$I_{AA} \equiv \frac{(1/N_{trig}\, dN/d\xi)_{AA}}{(1/N_{trig}\, dN/d\xi)_{pp}}$$

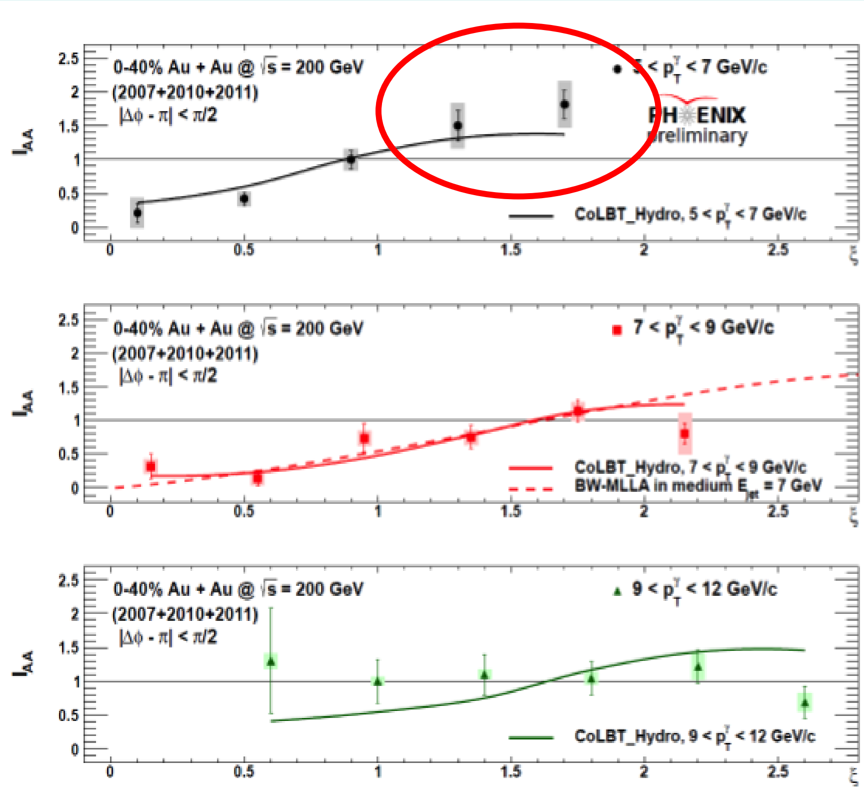
γ-jet data: jets get wider & softer in plasma

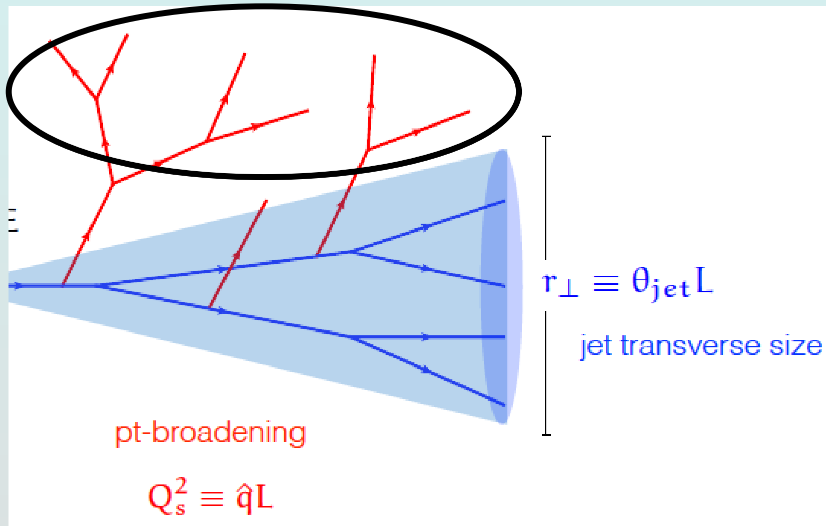
Pb+Pb/p+p:

Extra low momentum particles; high momenta suppressed



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





Medium induced radiation!

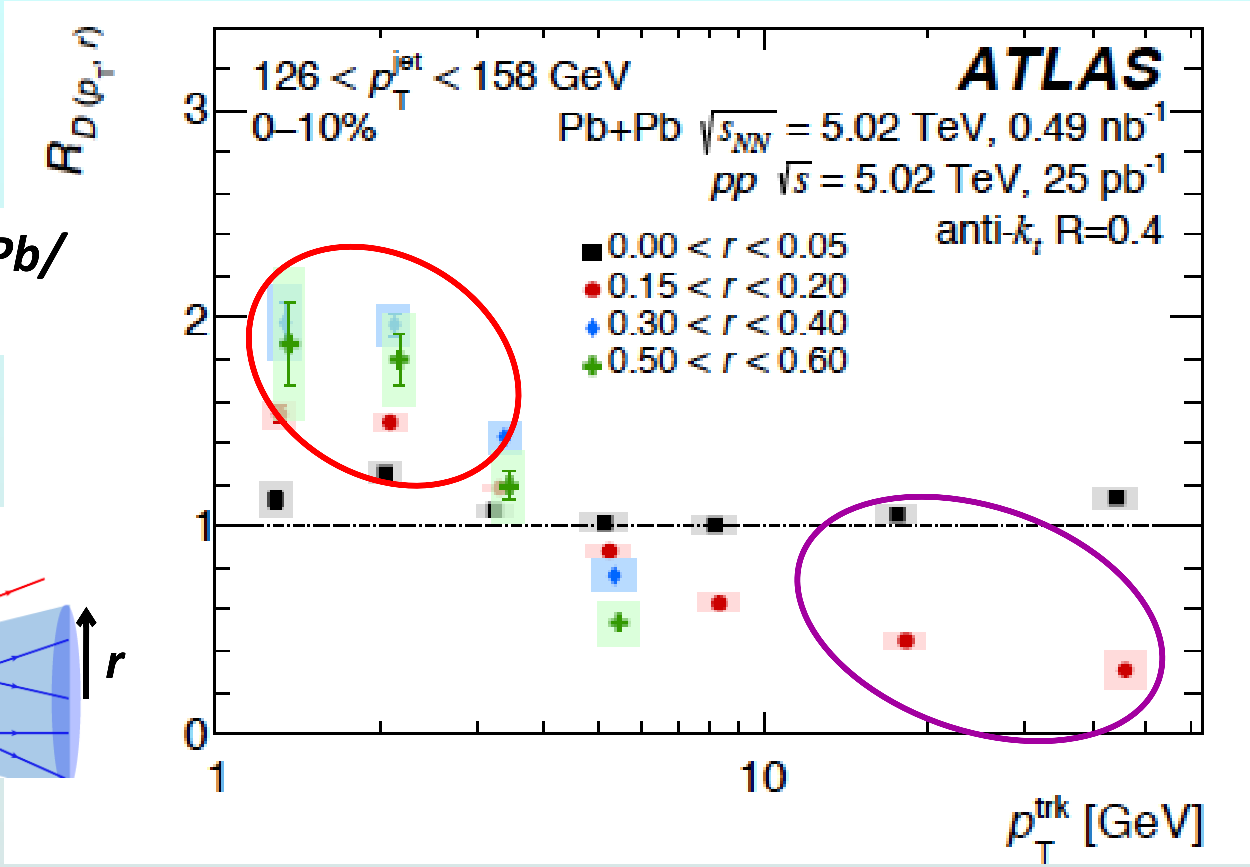
Jet structure more differentially

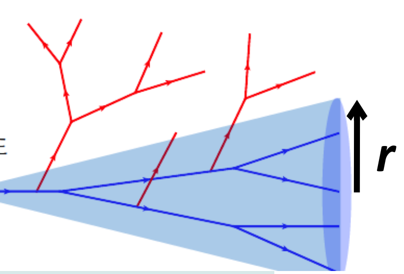
p_T vs. r of jet fragments

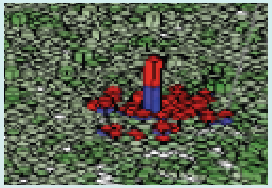
arXiv: 1908.05264

See also: CMS arXiv: 1803.00042

Pb+Pb/ p+p



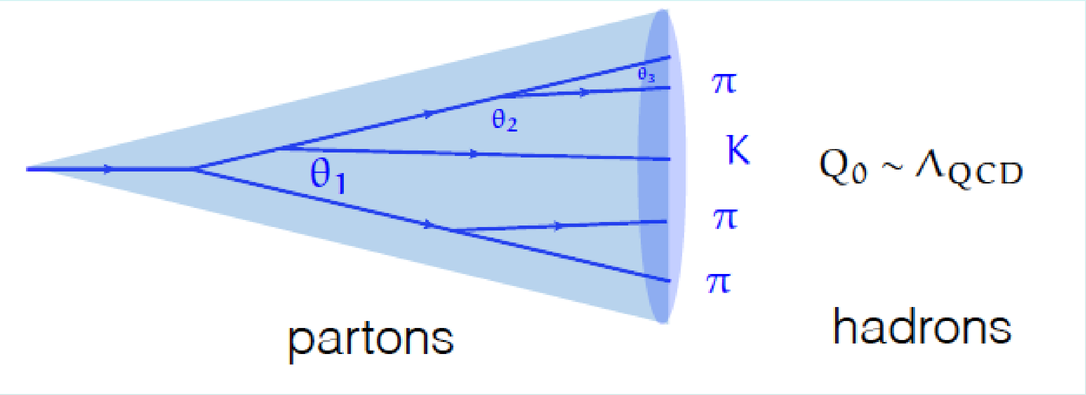




- Excess soft hadrons at large jet radius
- Narrowing of high p_T particle distribution
- Energy loss (and medium response?)

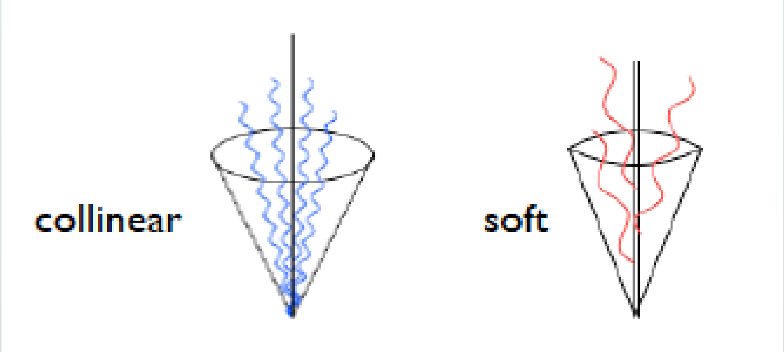
Connect to QCD

- 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



High energy q, g fragment mostly outside the plasma

Collide in the plasma & radiate extra gluons. These produce secondary showers

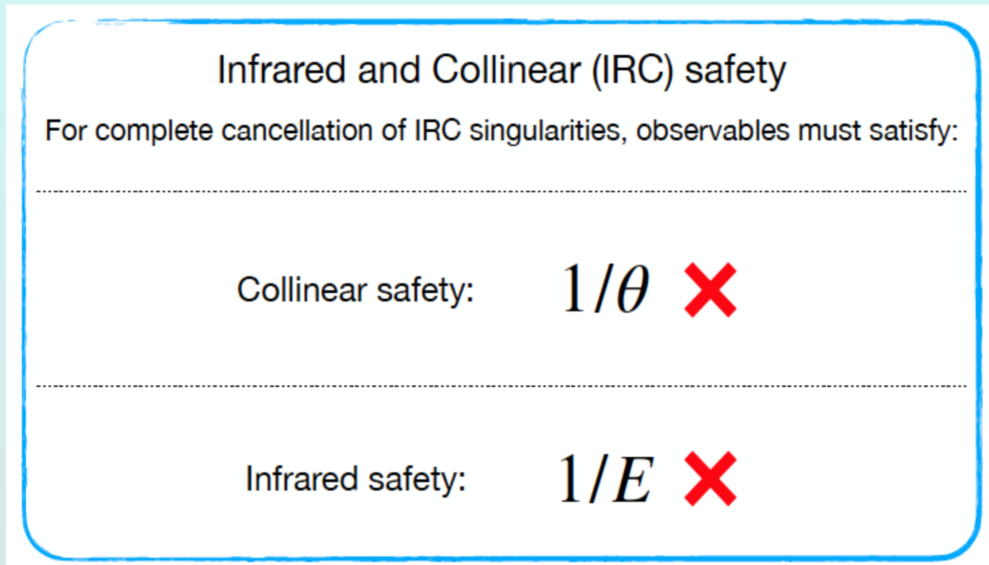


Lower energy jets start to fragment in medium – can rearrange particles or add stuff from medium

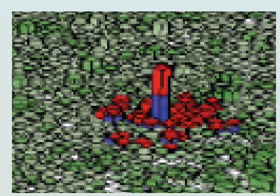
But – 3 problems in connecting data & QCD

1. Measure *hadrons* but QCD calculates *quarks and gluons*
   Hadronization is non-perturbative and so intractable

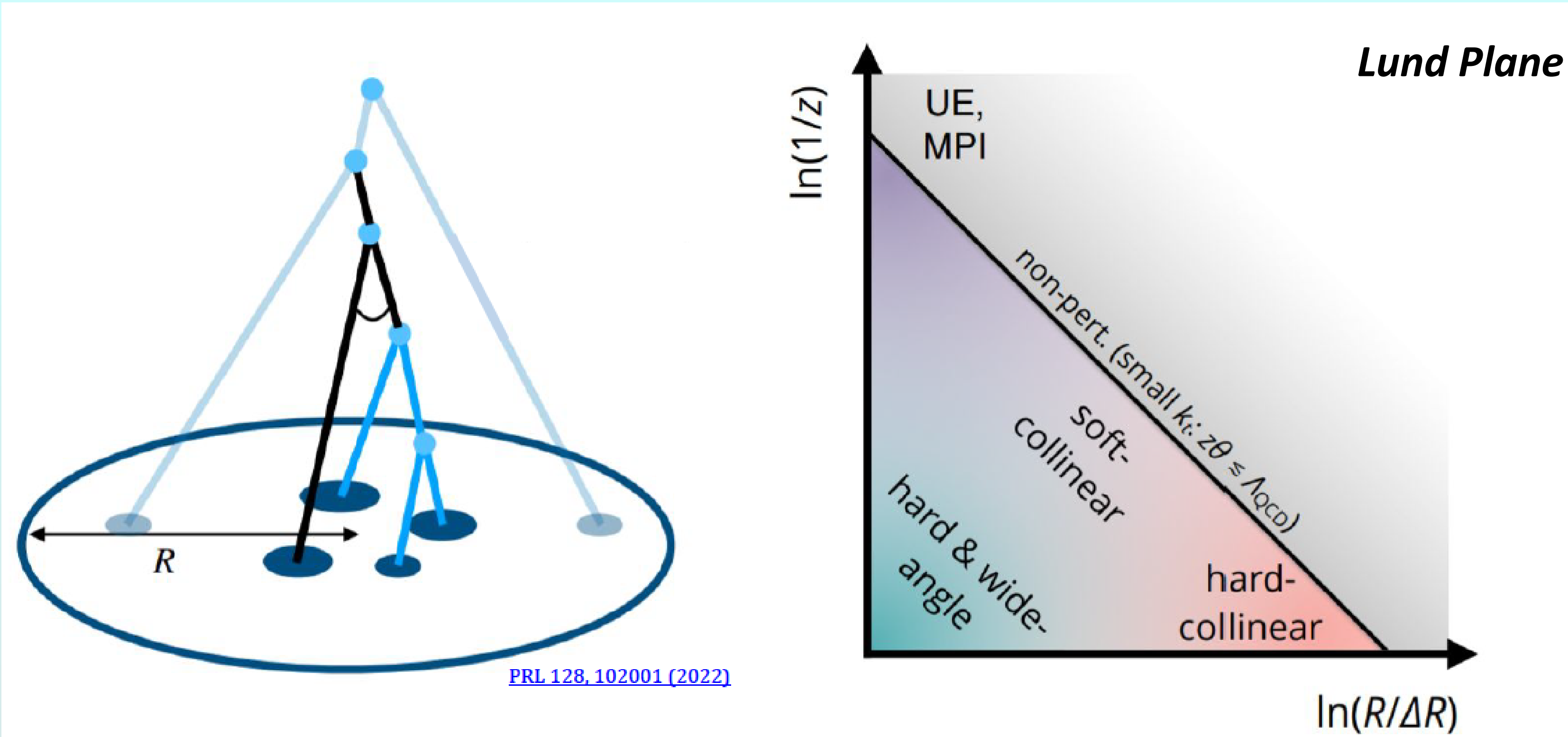
2. Singularities



3. Particles from underlying event



Look at (calculable) parton splittings

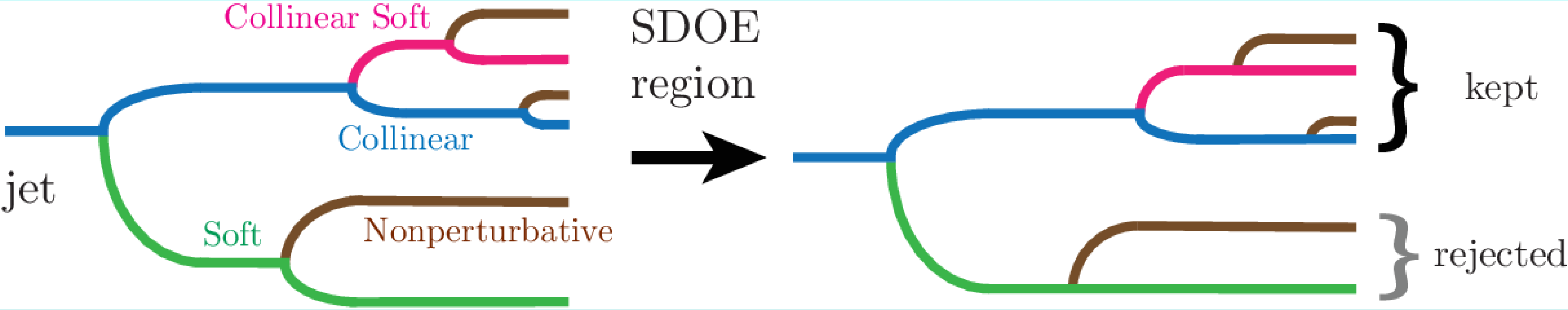


- **Find observables that avoid singularities**

  e.g. jet axis, z_g, □$_g$, jet mass, angularities, n-sub jettiness, energy-energy correlators, etc.

- **Groom away softest particles to remove underlying event and minimize hadronization effects, using combination of momentum & angle**

Grooming jets



- **Collect particles into subjets**
- **Use "soft drop" algorithm to remove soft subjets**

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

$z < z_{cut}\theta^{\beta}$: drop the softer branch

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

typically, z_{cut} ~ 0.1-0.2 , β=0 or 1

- **Removes soft radiation & non perturbative effects**

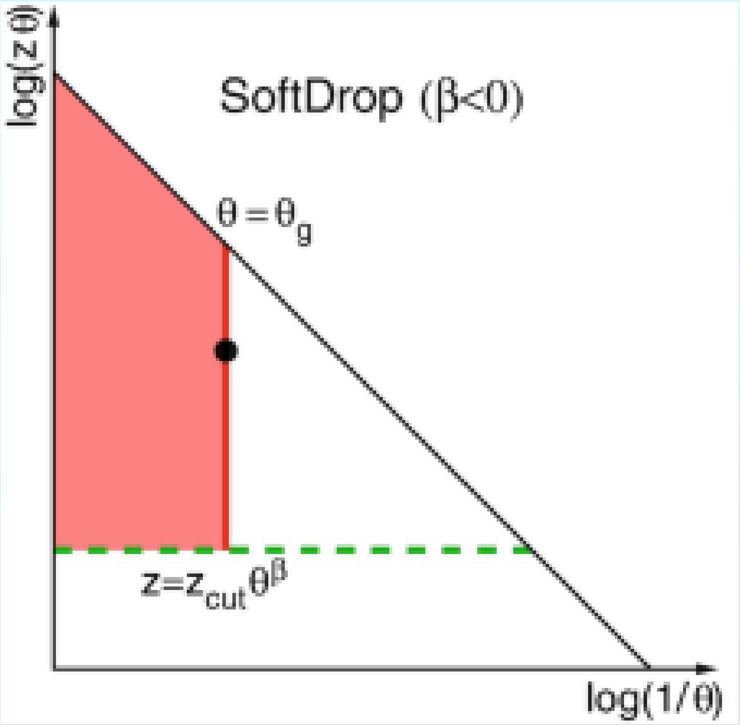
  Allow access to perturbative splittings

  Also grooms away remaining underlying event

Grooming effect on Lund Plane

Cutting away low z and low ΔR particles makes holes in the Lund Plane

Allows looking at jet splittings in IR safe region and comparing to pQCD calculations

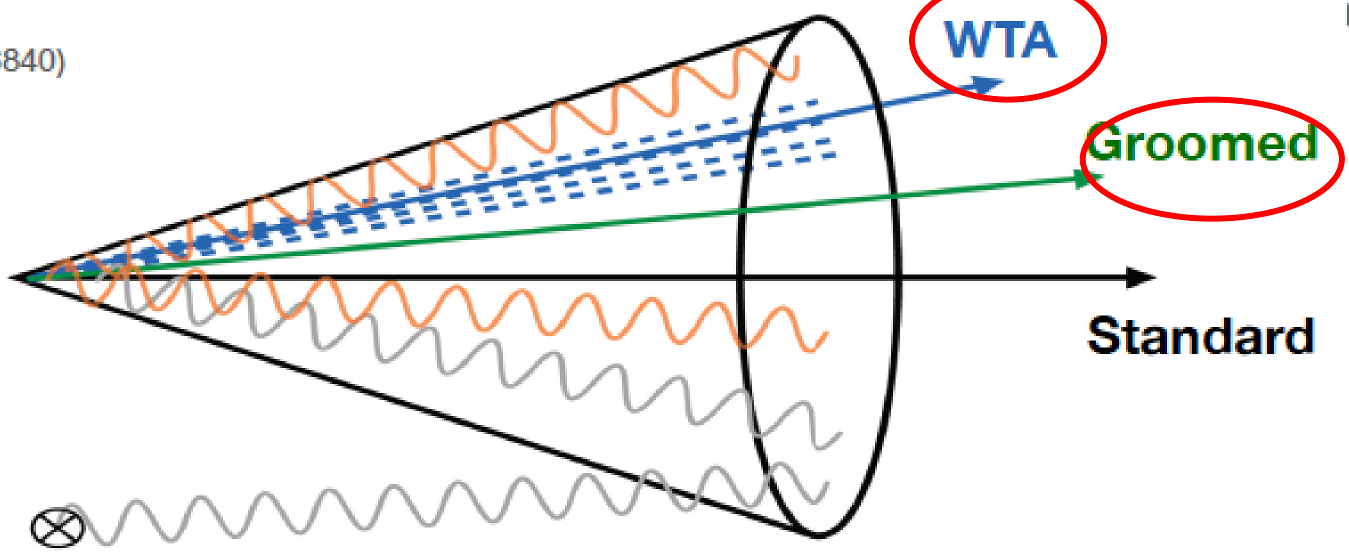


Jet axis

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?

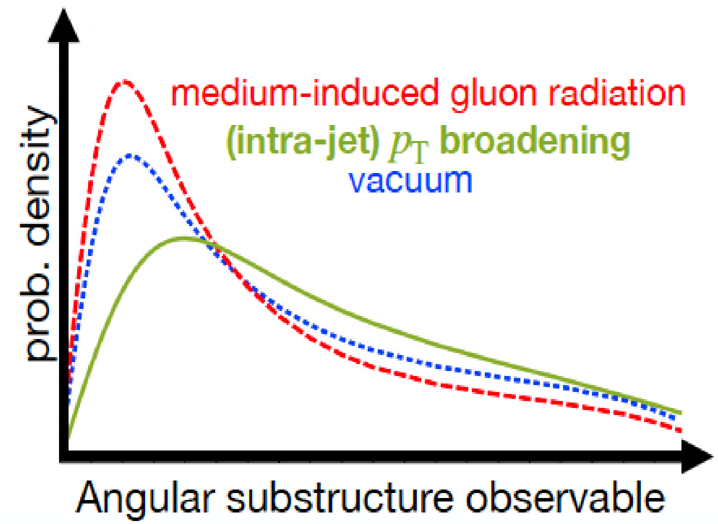
- Substructure observable: angular difference:

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

between two definitions of the jet axis

Why measure this observable?

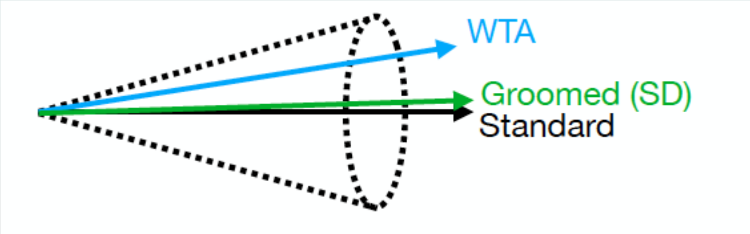
- Study properties of the QGP via modification of angular (TMD-sensitive) jet substructure
- Contrast substructure modification with(out) grooming
- Understand interplay between QGP competing effects
  - e.g. **medium-induced gluon radiation** vs. **multiple-scattering-like (intra-jet) p_T broadening**



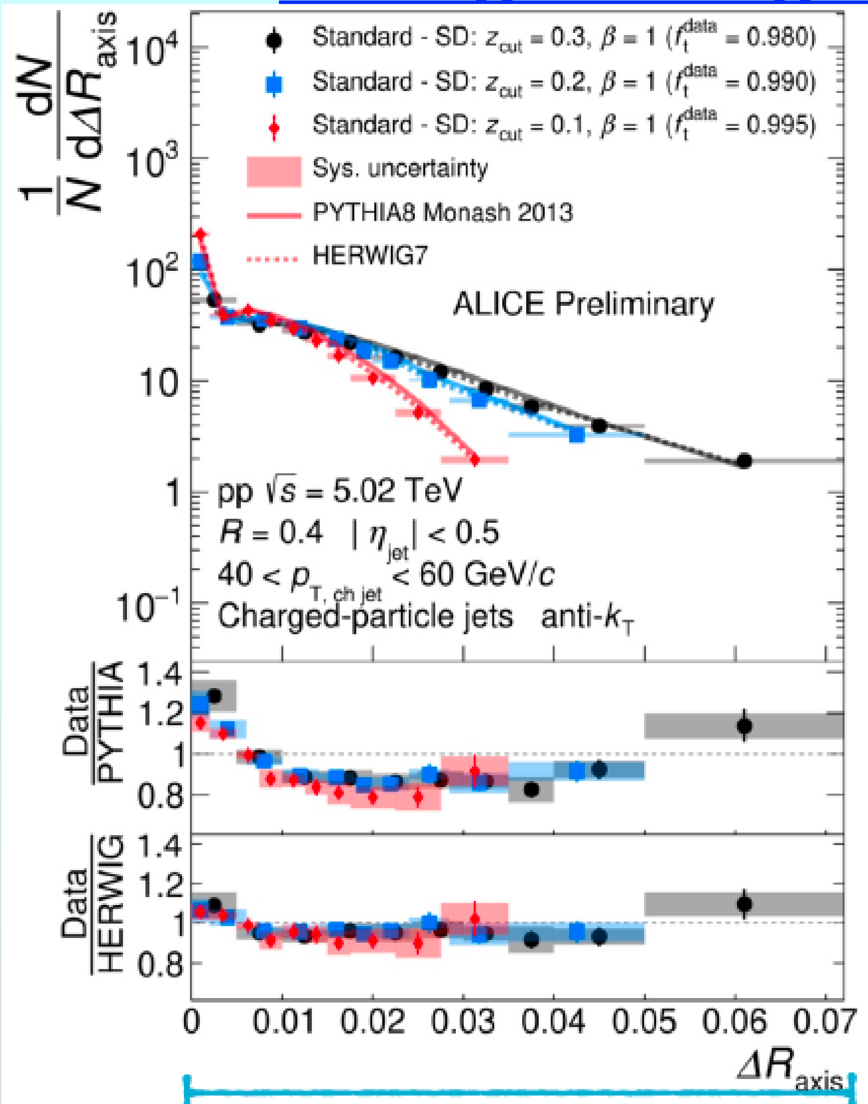
Ringer et al., PLB 808 (2020) 135634

Axis difference can be calculated perturbatively

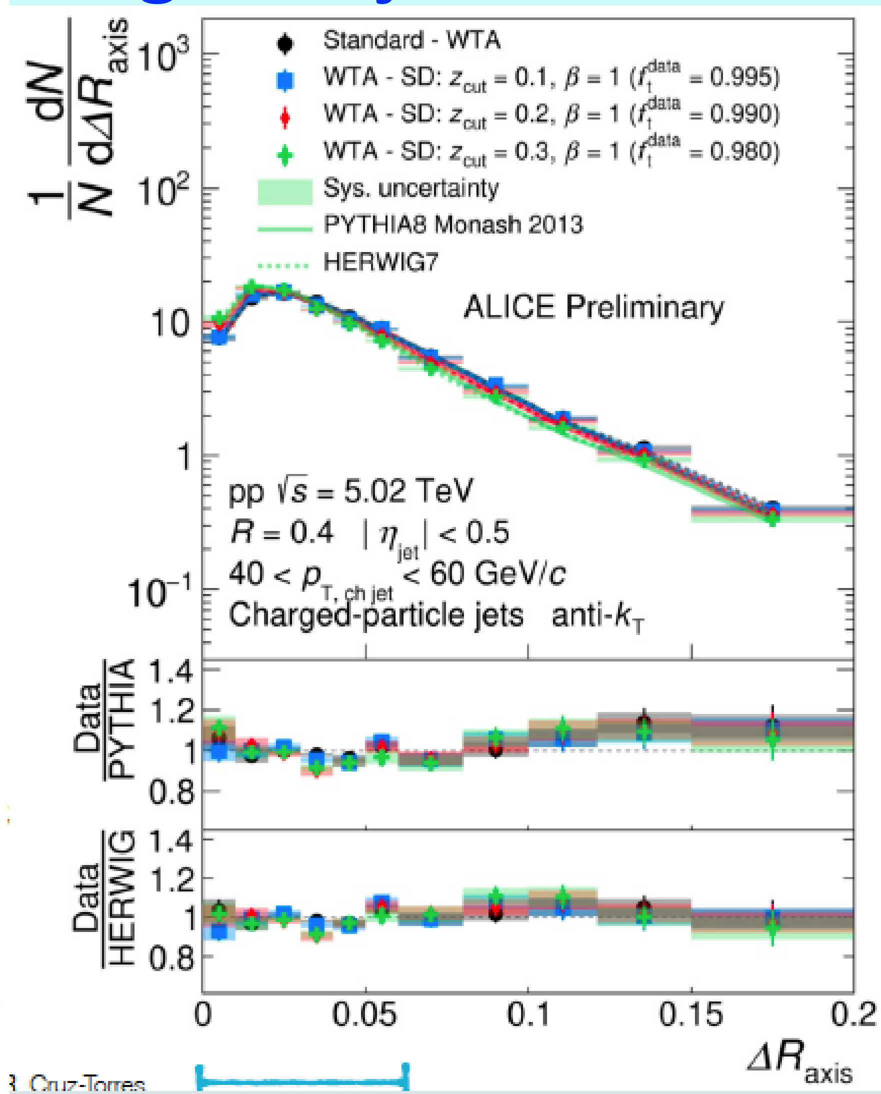
Especially if jets are groomed to remove the soft particles at large angles.



Does grooming change the jet axis?



arXiv:2211.08928

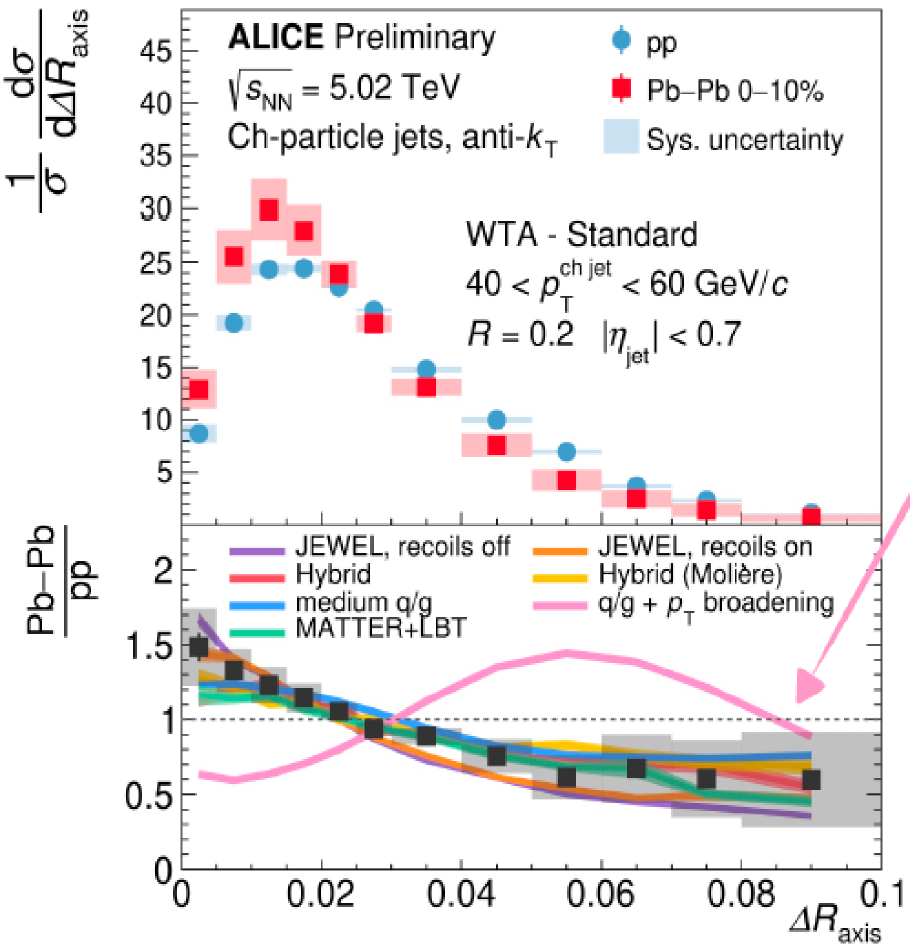


arXiv:2303.13347

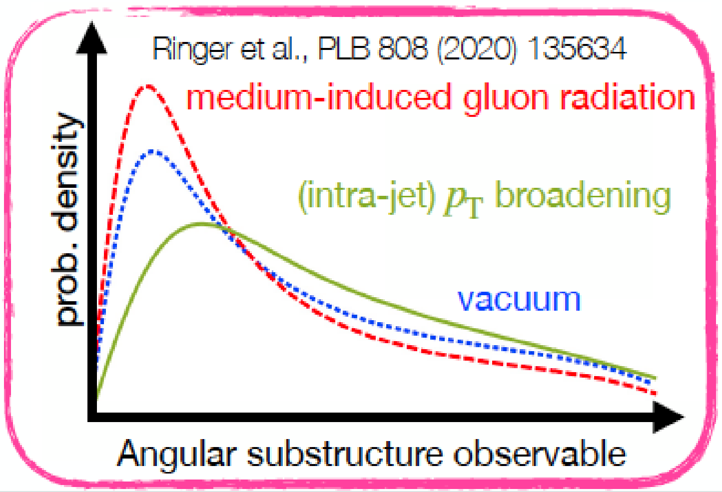
Not much!

Results in pp are well reproduced by Pythia & Herwig

In Pb+Pb

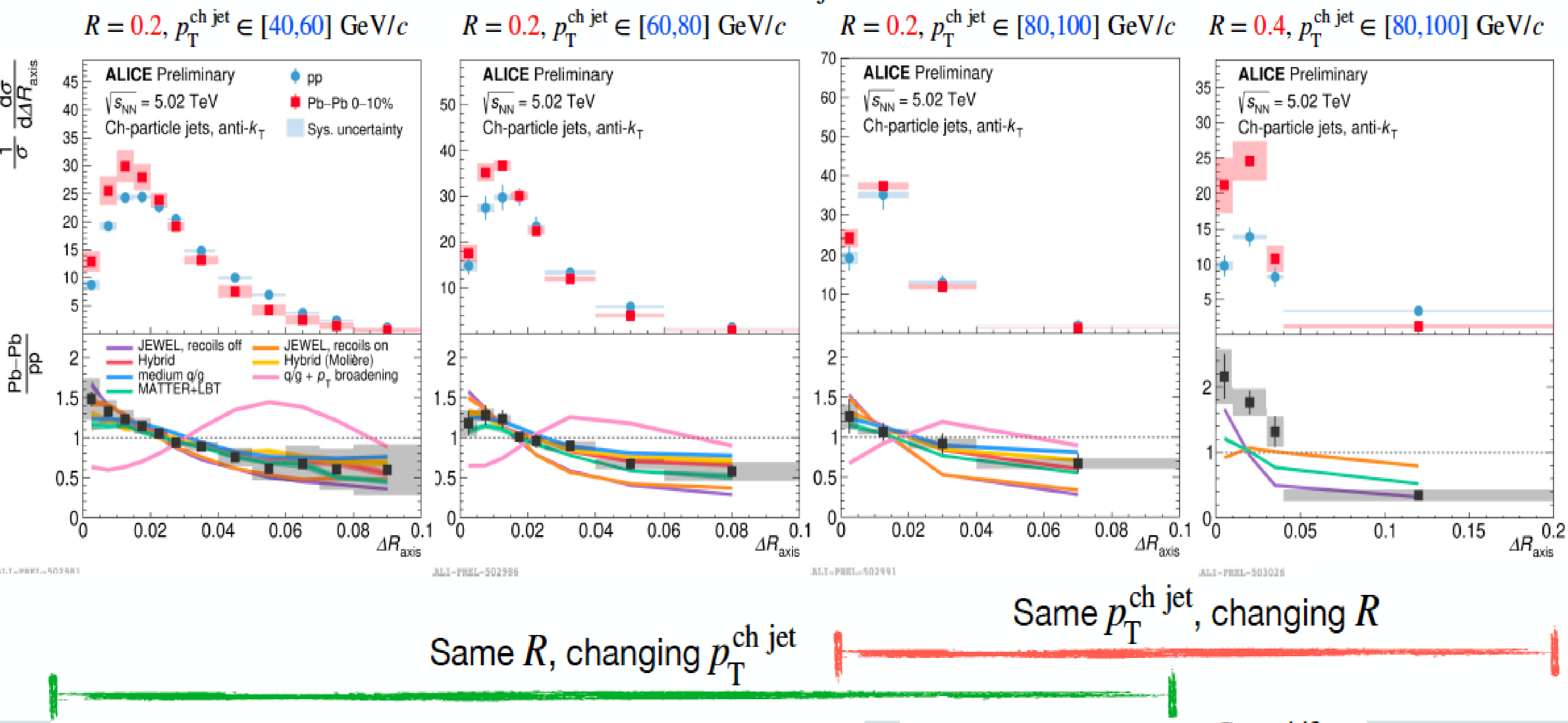


Data rejects intra-jet p_T broadening described by BDMPS formalism as the main mechanism of energy loss in the QGP



Evolution of jet axis difference

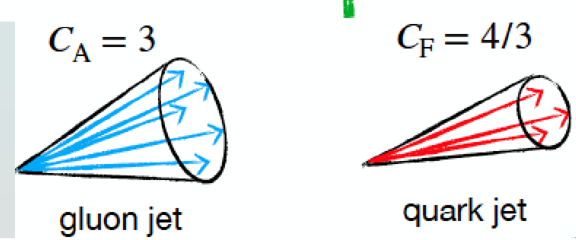
WTA - Standard, $|\eta_{jet}| < 0.9 - R$



Jets narrow in PbPb

Larger effect in softer jets

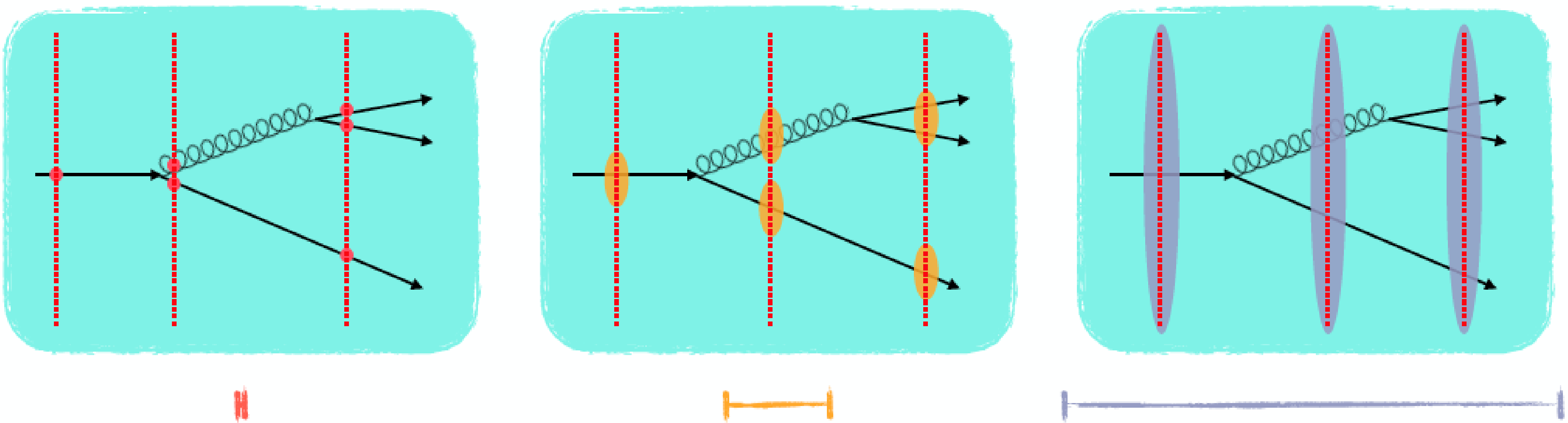
Quark jets start out narrower. Are the gluon jets more modified?



C: relative probability to emit a gluon

Medium resolution length

Characteristic scale of the medium at which a splitting can be resolved



$L_{res} = 0$

medium resolves splitting immediately after parton fragments.

Fully-incoherent energy loss

$L_{res} = 2/\pi T$

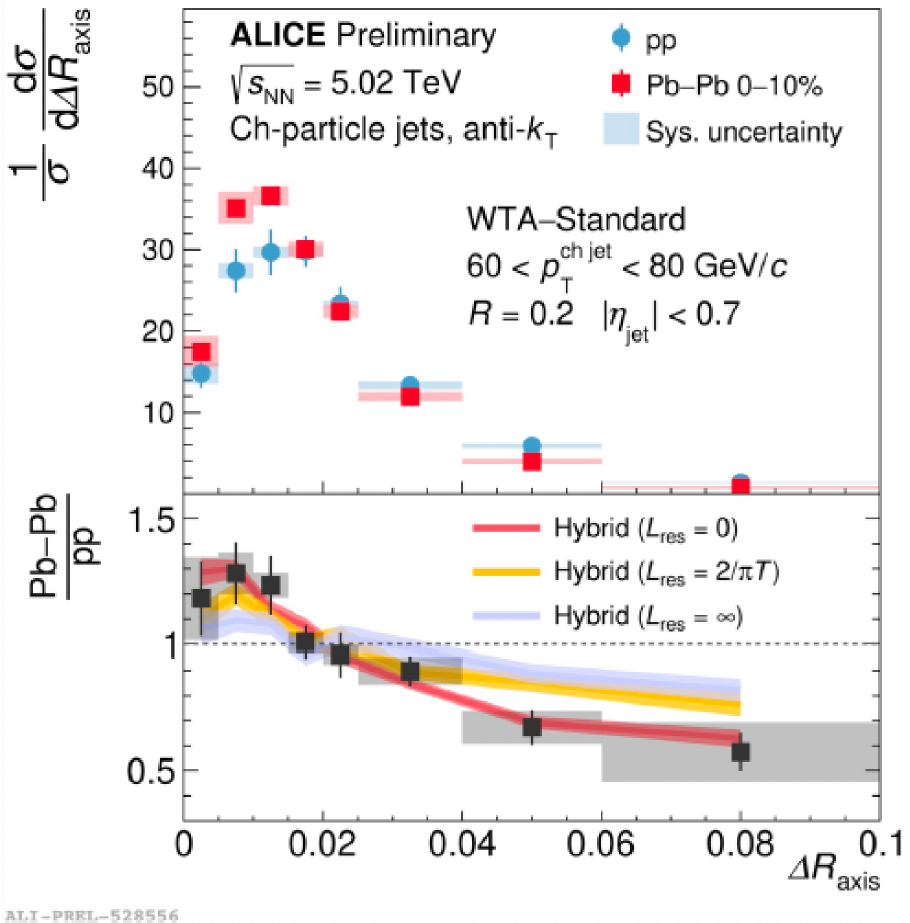
Intermediate case

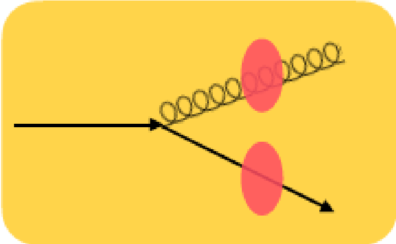
$L_{res} = \infty$

medium does not resolve splitting.

Fully-coherent energy loss

Interactions appear to be incoherent





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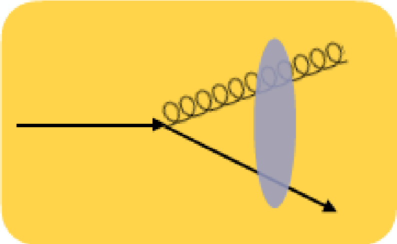
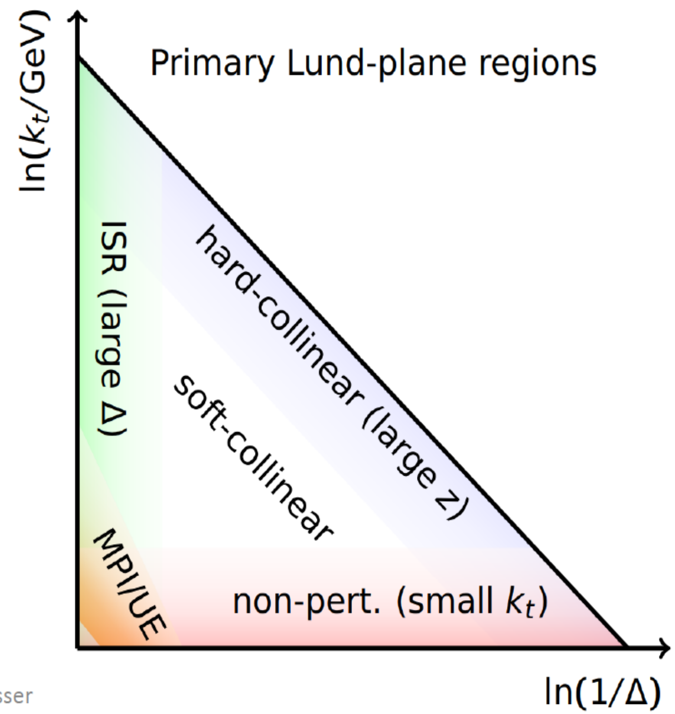


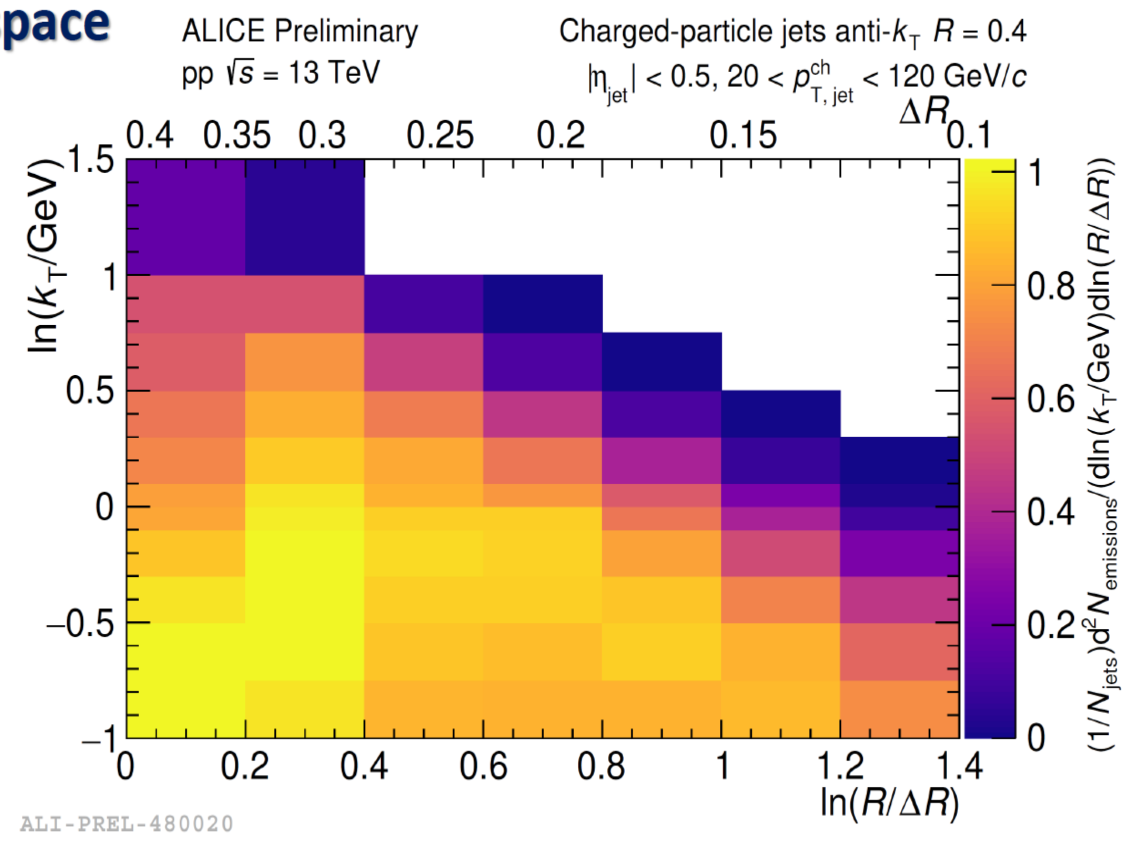
Data favors mechanisms of incoherent energy loss in the QGP

Look at the parton splittings

Lund Plane in pp data

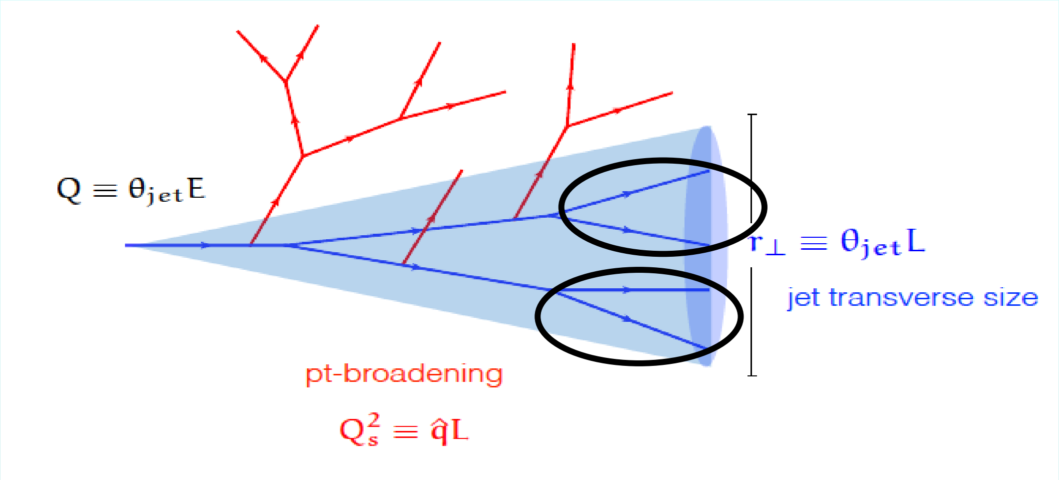
- Illustrates **branching phase space**
- Has been also measured by ATLAS [8] at higher jet p_T





[8] Phys. Rev. Lett. 124, 222002 (2020)

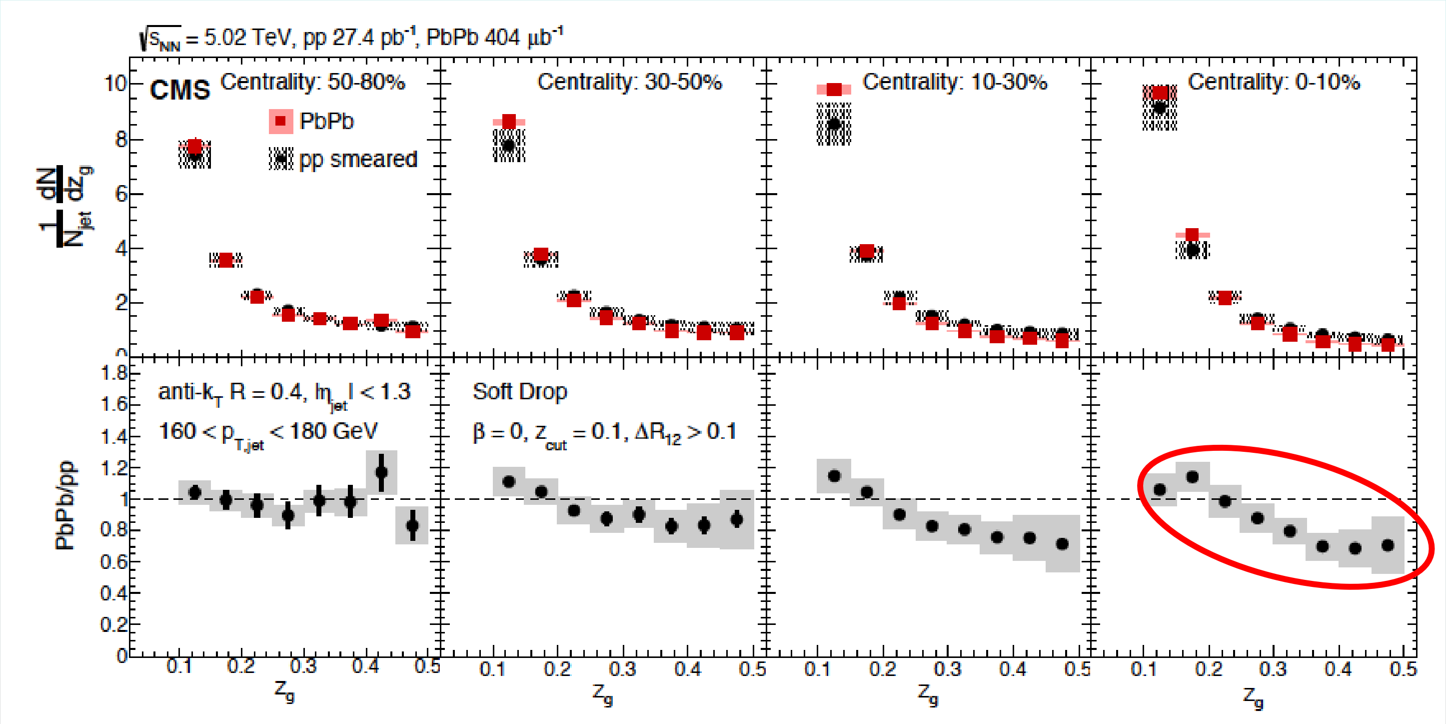
Early gluon splitting



Recluster & groom jet

Use 2 leading clusters

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



Useful to quantify energy, p_T transport.

See significant dependence on jet E, grooming.

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)

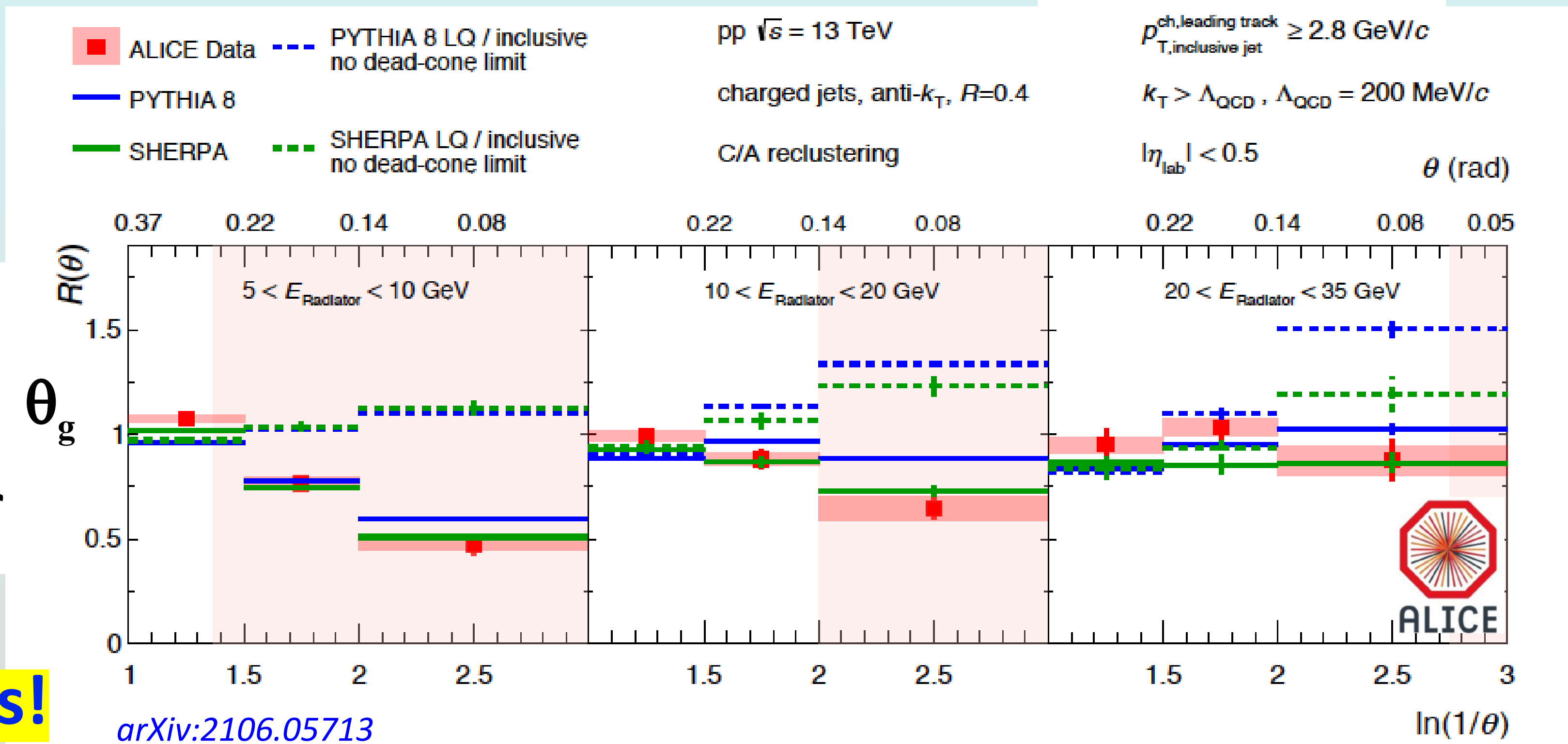
Large M suppresses small angle radiation (phase space effect)

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

Combine p_T & θ: Angularity

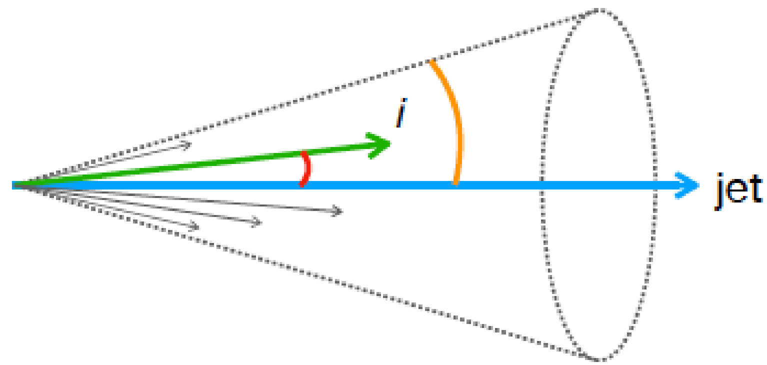
Ezra Lesser, Preeti Dhankher

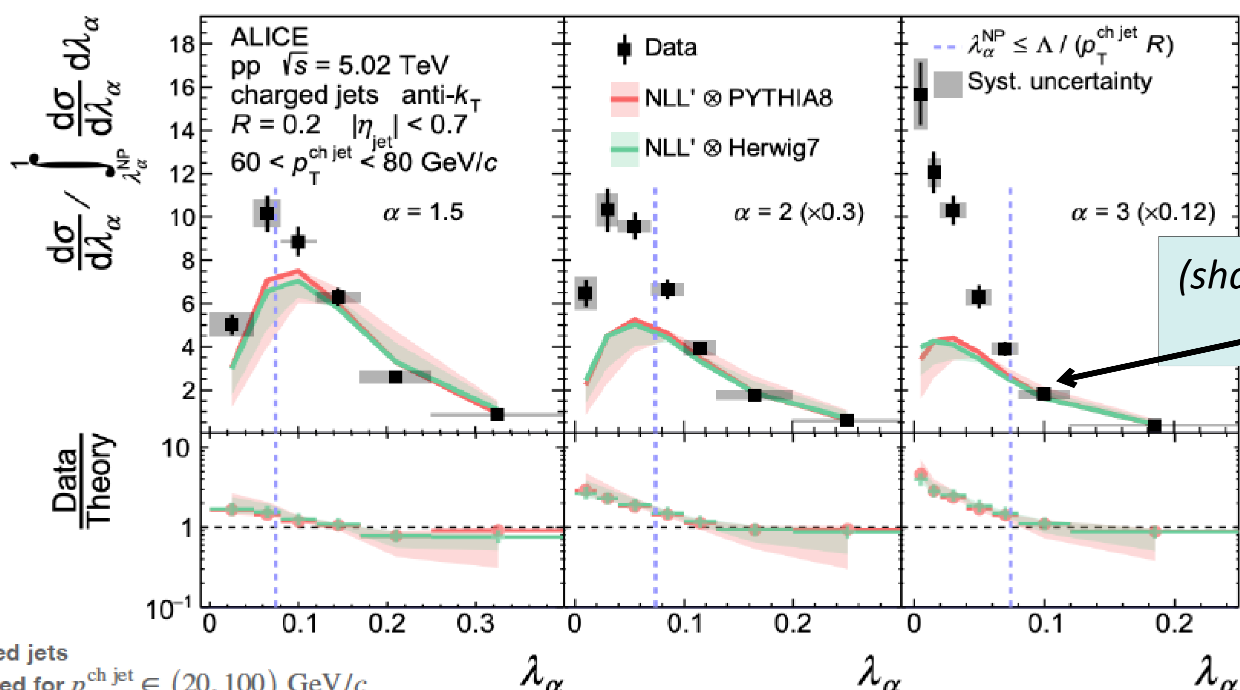
arXiv:2107.11303

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

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

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





Charged jets measured for $p_T^{\text{ch jet}} \in (20, 100)$ GeV/c

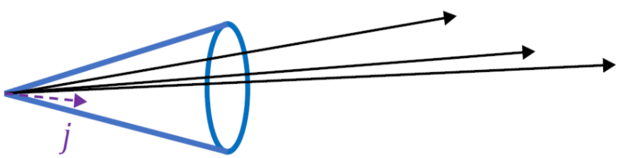
(shape) Calculable in pQCD
data, model agree

Let's groom away the soft stuff

Why is angularity safe for pQCD?

Ezra Lesser

Infra-Red safety: the observable should not change if an infinitely-low-momentum particle is added to the event/jet



$$\lambda^{\kappa}_{\alpha,\text{new}} = \sum_{i \in \text{jet}} z_i^{\kappa}\theta_i^{\alpha} + z_j^{\kappa}\theta_j^{\alpha}$$

$$z_j = 0 \rightarrow z_j^{\kappa}\theta_j^{\alpha} = 0 \quad (\kappa > 0)$$

$$\lambda^{\kappa}_{\alpha,\text{new}} = \lambda^{\kappa}_{\alpha,\text{old}}$$

Collinear safety: the observable should not change if one particle splits into two collinear particles

$$\lambda^{\kappa}_{\alpha,\text{new}} = \sum_{(i \neq j) \in \text{jet}} z_i^{\kappa}\theta_i^{\alpha} + \left(\lambda z_j\right)^{\kappa}\theta_j^{\alpha} + \left[(1-\lambda) z_j\right]^{\kappa}\theta_j^{\alpha}$$

Need $\lambda^{\kappa} + (1-\lambda)^{\kappa} = 1 \quad \forall\{\lambda \in [0,1]\} \;\rightarrow\; \kappa = 1$

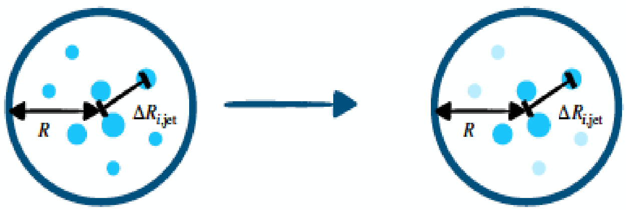
Consider 1-particle jet: $\lambda^{\kappa}_{\alpha,\text{new}} = \left(\lambda z_j\right)^{\kappa}\theta_j^{\alpha} + \left[(1-\lambda) z_j\right]^{\kappa}\theta_j^{\alpha}$

$$\theta_j = 0 \rightarrow z_j^{\kappa}\theta_j^{\alpha} = 0 \quad (\alpha > 0)$$

Groomed jets well described by NLL QCD

Ezra Lesser

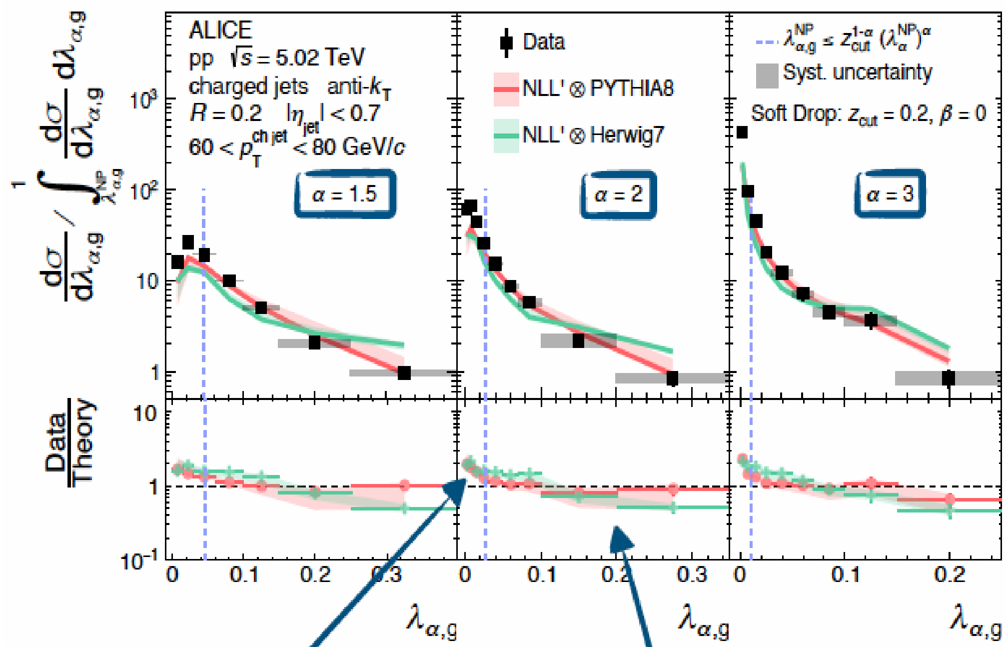
Apply grooming procedure to remove low-energy, wide-angle radiation



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

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

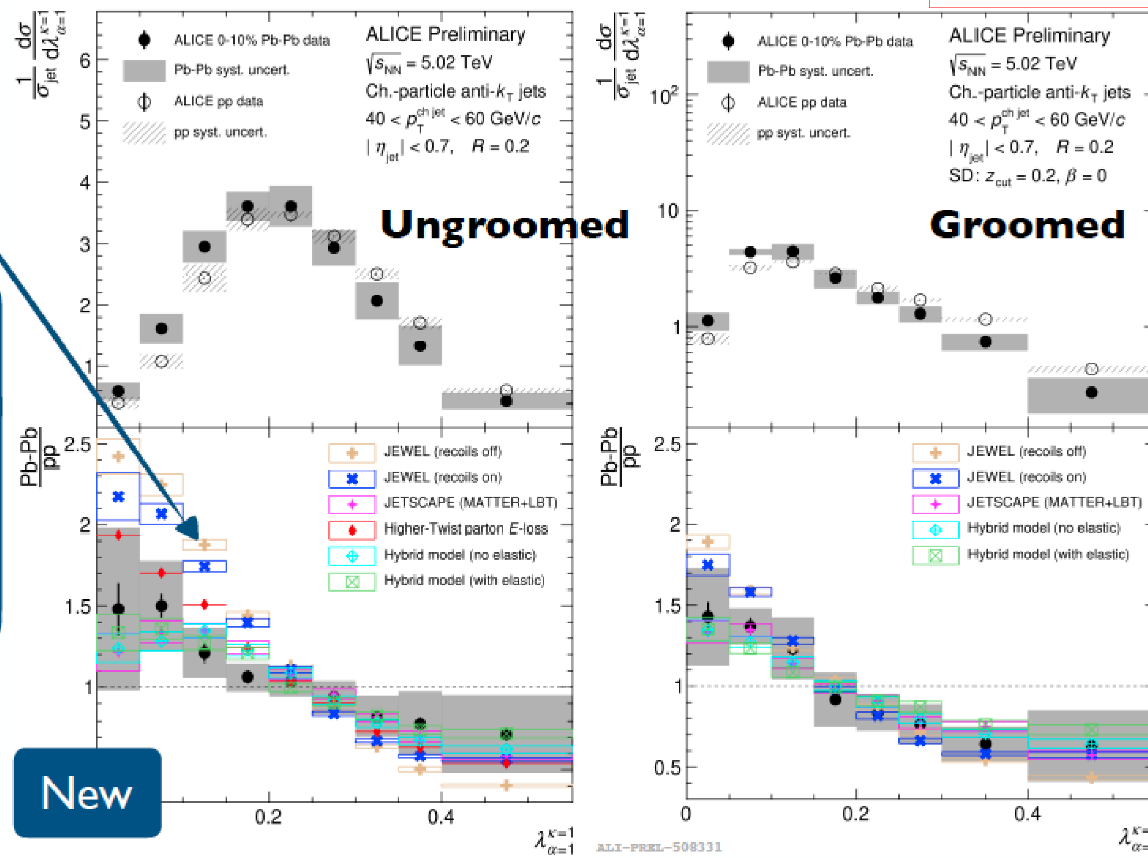
$$\lambda_\alpha \equiv \sum_{i\in\text{jet}} \left(\frac{p_{\text{T},i}}{p_{\text{T,jet}}}\right)\left(\frac{\Delta R_{\text{jet},i}}{R}\right)$$

In Pb+Pb

Ezra Lesser

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



New

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!

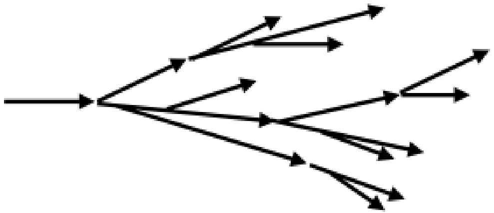
Angularity in groomed Pb+Pb jets:
large λ depleted, small λ enhanced.
Expect this if jets narrow in QGP

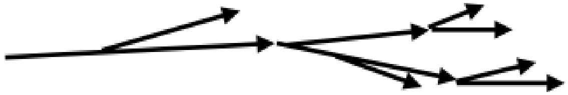
Jets initiated by a charm quark

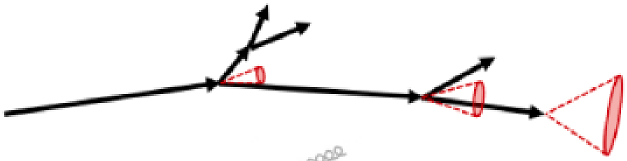
Preeti Dhankher

Flavour dependence in the QCD shower

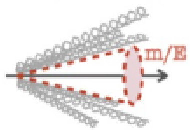
Gluon-initiated shower | **Quark-initiated shower** | **Heavy-quark-initiated shower**







$$\frac{C_A}{C_F} = \frac{9}{4}$$



Casimir color factors

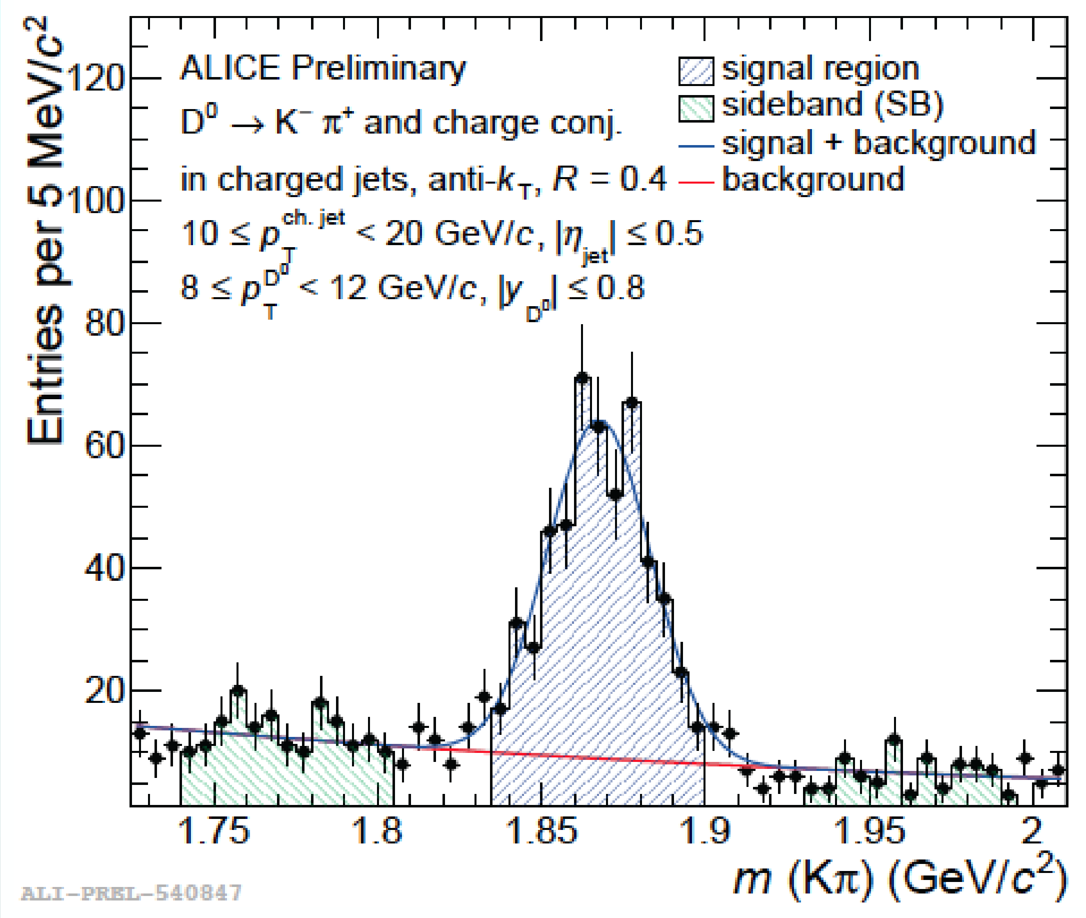
Gluon-initiated showers are expected to have a broader and softer fragmentation profile than quark-initiated showers

Mass effects

A harder fragmentation is expected in low energy heavy-quark initiated showers due to the presence of a dead cone which suppresses radiation close to the heavy-quark

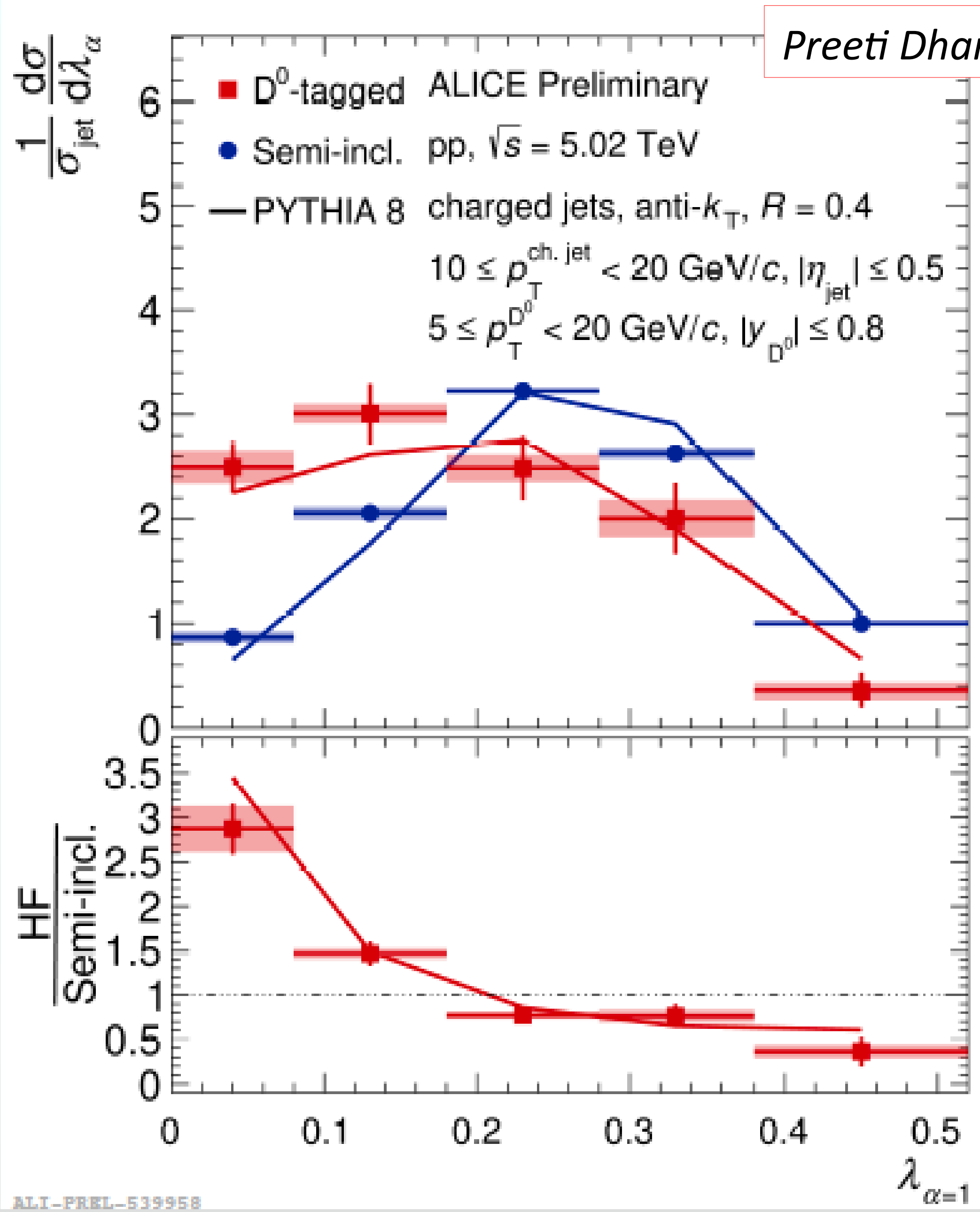
Reconstructing D jets

Preeti Dhankher



- **Reconstruct D^0 meson from K & π**
- **Find charged jet around the D**
- **Calculate angularity**
- **Correct for D efficiency & background**
- **Unfold for energy resolution and missing neutral particles**

Compare D jet with light parton jets



Preeti Dhankher

- D jets are narrower (smaller angularity)
- Increasing α (weight of angular term) decreases the difference
- Comparison dominated by jet core
- Observation is exactly what we would expect from dead cone:
  Fewer & harder jet fragments

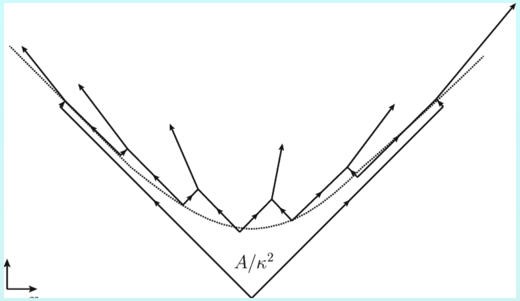
Fly in the ointment: hadronization

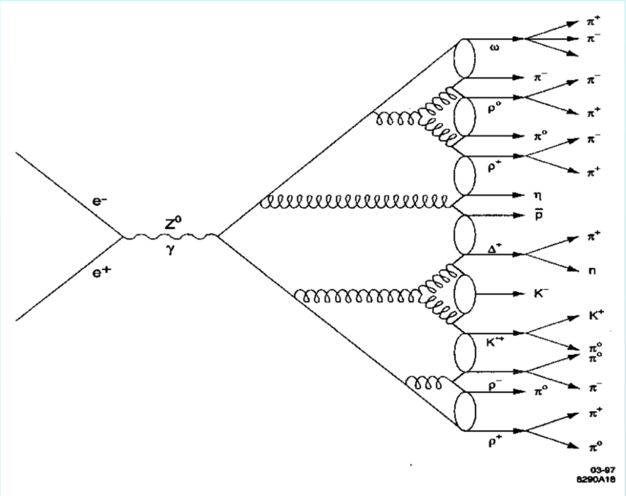
How do the partons become hadrons?

- **String breaking (e.g. Pythia)**

String carries flavor correlations

Partons tunnel out of the string





- **Cluster hadronization (e.g. Herwig)**

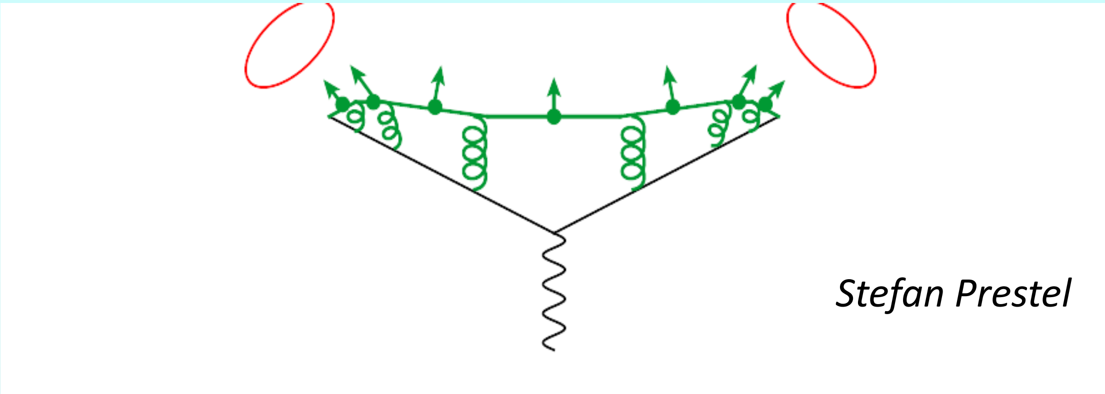
Cluster locally connected partons

After the shower is finished

- **Coalescence or Statistical Hadronization?**

Connect partons which end up close by in phase space

String breaking



Based on ideas of linear confinement

@ end of shower, color-connected partons form string pieces w/ quark endpoints; gluons = transverse kinks

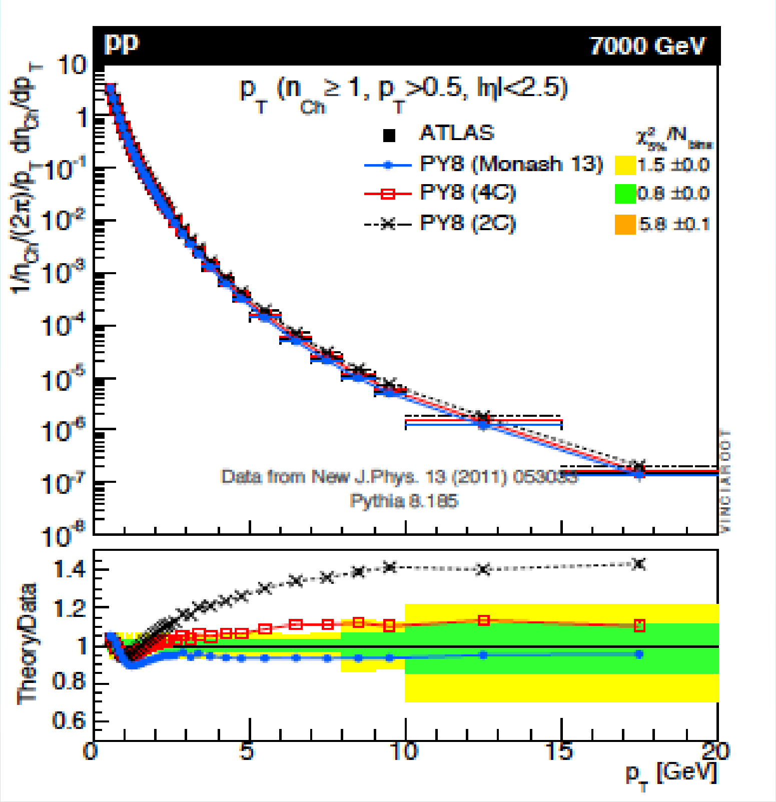
String junctions are asymmetric color tensor carrying baryon number

Strings break by tunneling;

"string tension" = energy

Pythia Monash tune for LHC

arXiv: 1404.5630



Cluster hadronization

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

  heavy clusters fission

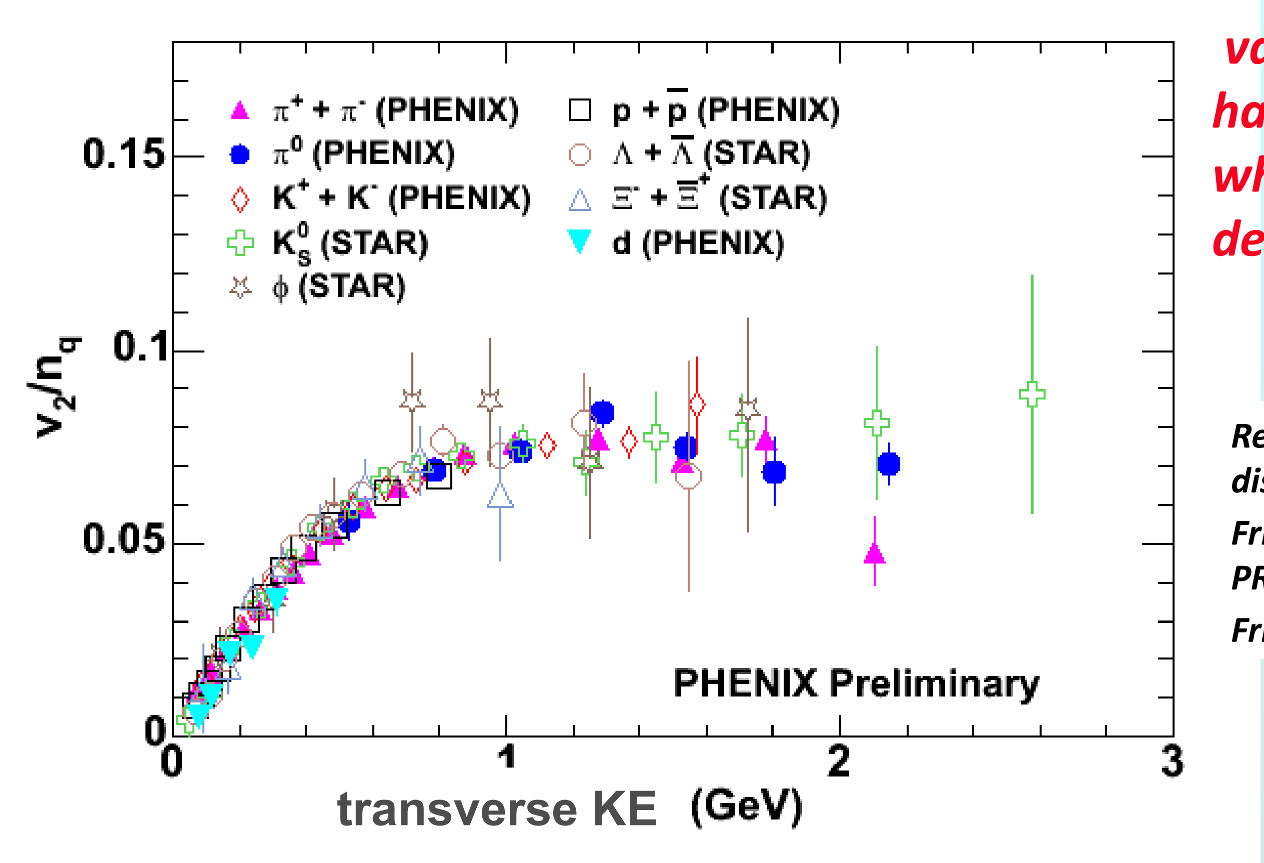
  randomly fill shower & beam remnant mass distribution

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

  ensure sufficient cluster mass for hadron masses

  draw flavor k from vacuum

Coalescence in quark gluon plasma



valence quarks, not hadrons, are present when collective flow develops

Recombination from thermal distribution:

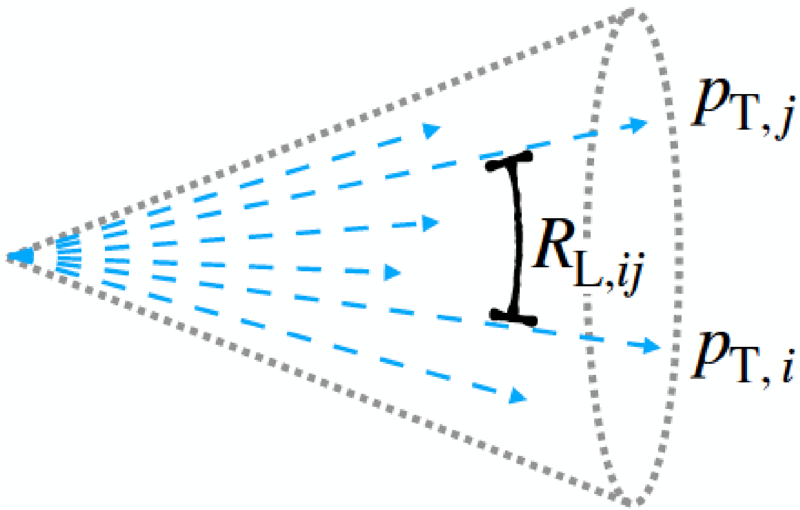
Fries, Mueller, Nonaka & Bass, PRC68, 044902 (2003)

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

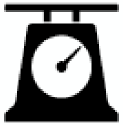
- ***dressed quarks are born of flowing field***
- ***hadronize by (simple) coalescence of co-moving quarks***
- ***quarks (miraculously?) dressed by gluons***

Explore with jet energy-energy correlators

$$R_L = \sqrt{\Delta\varphi_{ij}^2 + \Delta\eta_{ij}^2}$$



$$\frac{p_{T,i}\, p_{T,j}}{p_{T,\text{jet}}^2}$$



$$\frac{d\sigma_{EEC}}{dR_L} = \sum_{i,j} \int d\sigma(R'_L)\, \frac{p_{T,i}\, p_{T,j}}{p_{T,\text{jet}}^2}\, \delta(R'_L - R_{L,ij})$$

Komiske et al., PRL 130 (2023) 051901

Lee et al., arXiv:2205.03414

- Reduced sensitivity to soft radiation
  - related to p_T weighting
  - No need for grooming

Energy-energy correlator definition

$$< \varepsilon(\vec{n}_1)\, \varepsilon(\vec{n}_2) >$$

Where $\varepsilon(\vec{n}) =$

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

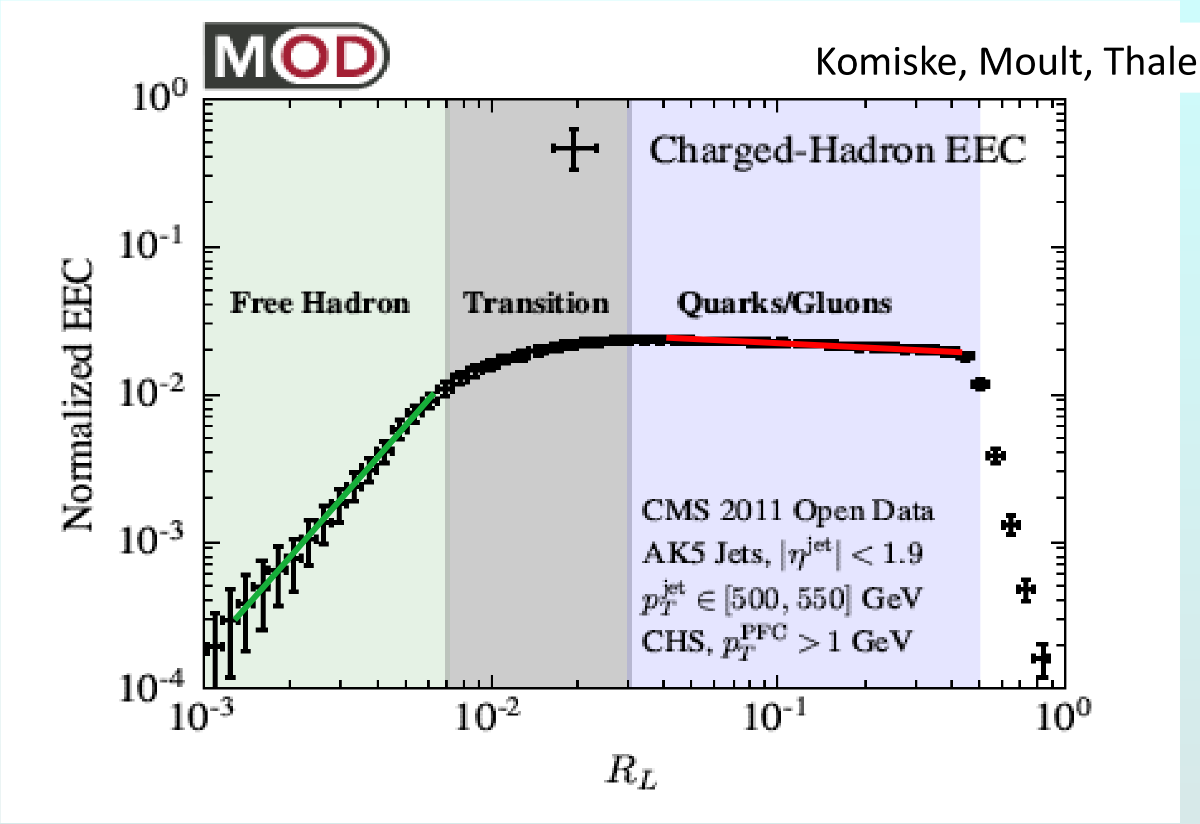
ε is the asymptotic energy flow operator

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

=

- This is a weighted two-particle correlation; plot vs. R_L

Separates pQCD & non-perturbative regions



Komiske, Moult, Thaler, Zhu. arXiv:2201.07800

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

=

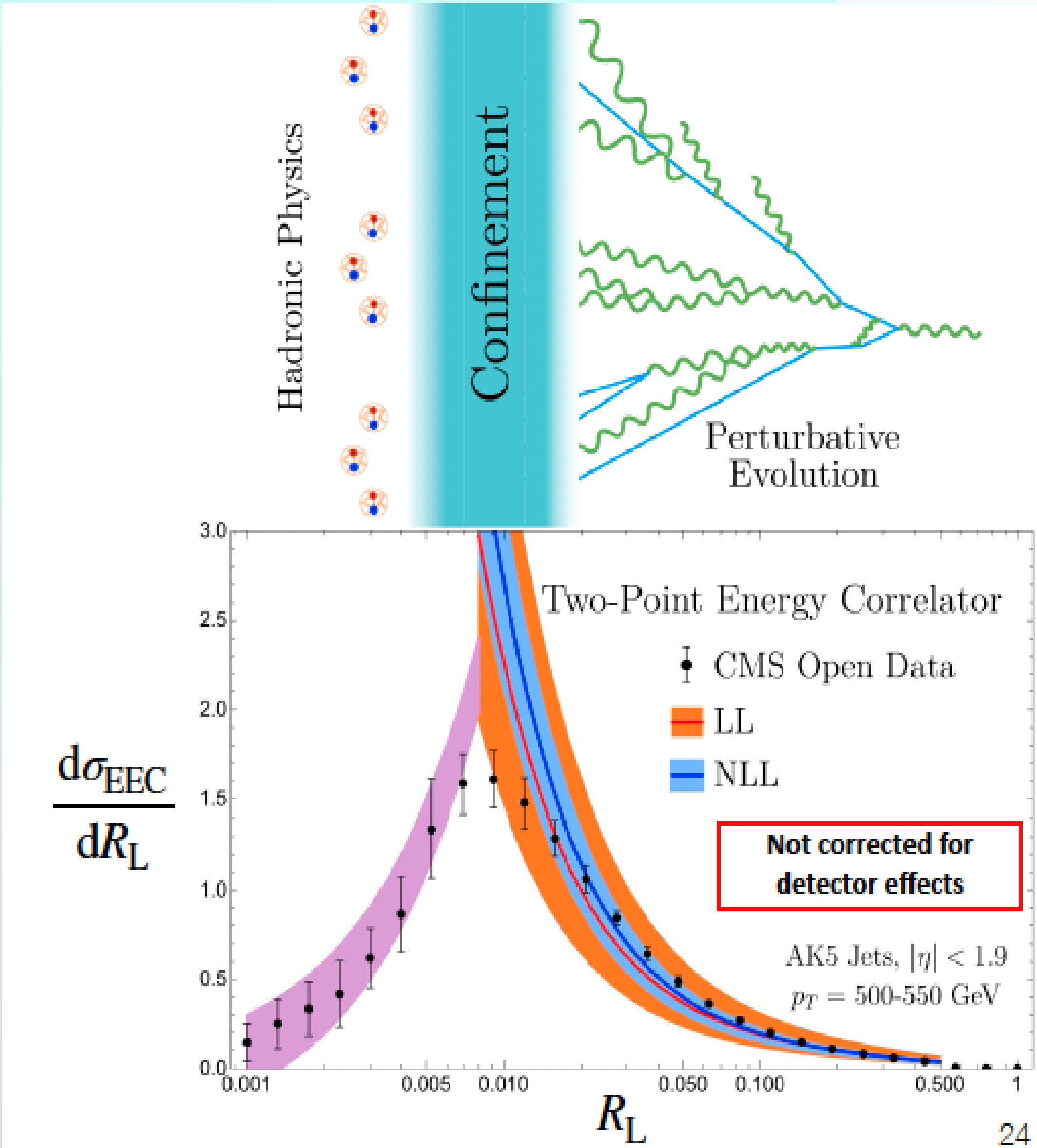
500 GeV jets

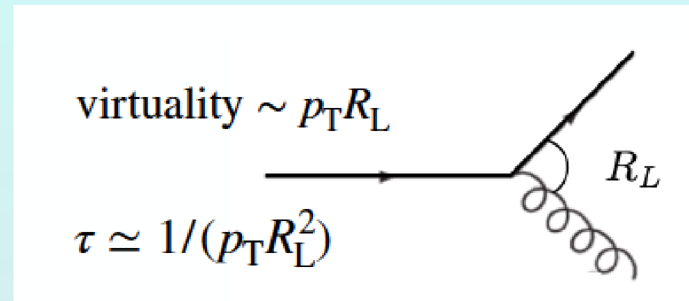
- **At large R_L: universal scaling w/ perturbative quark and gluon interactions**
- **At small R_L: for uniformly distributed hadrons**

  $R_L\, d\sigma/dR_L \sim R_L^2$
- **Transition region = correlator at hadronization**

Quark-gluon region calculable

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

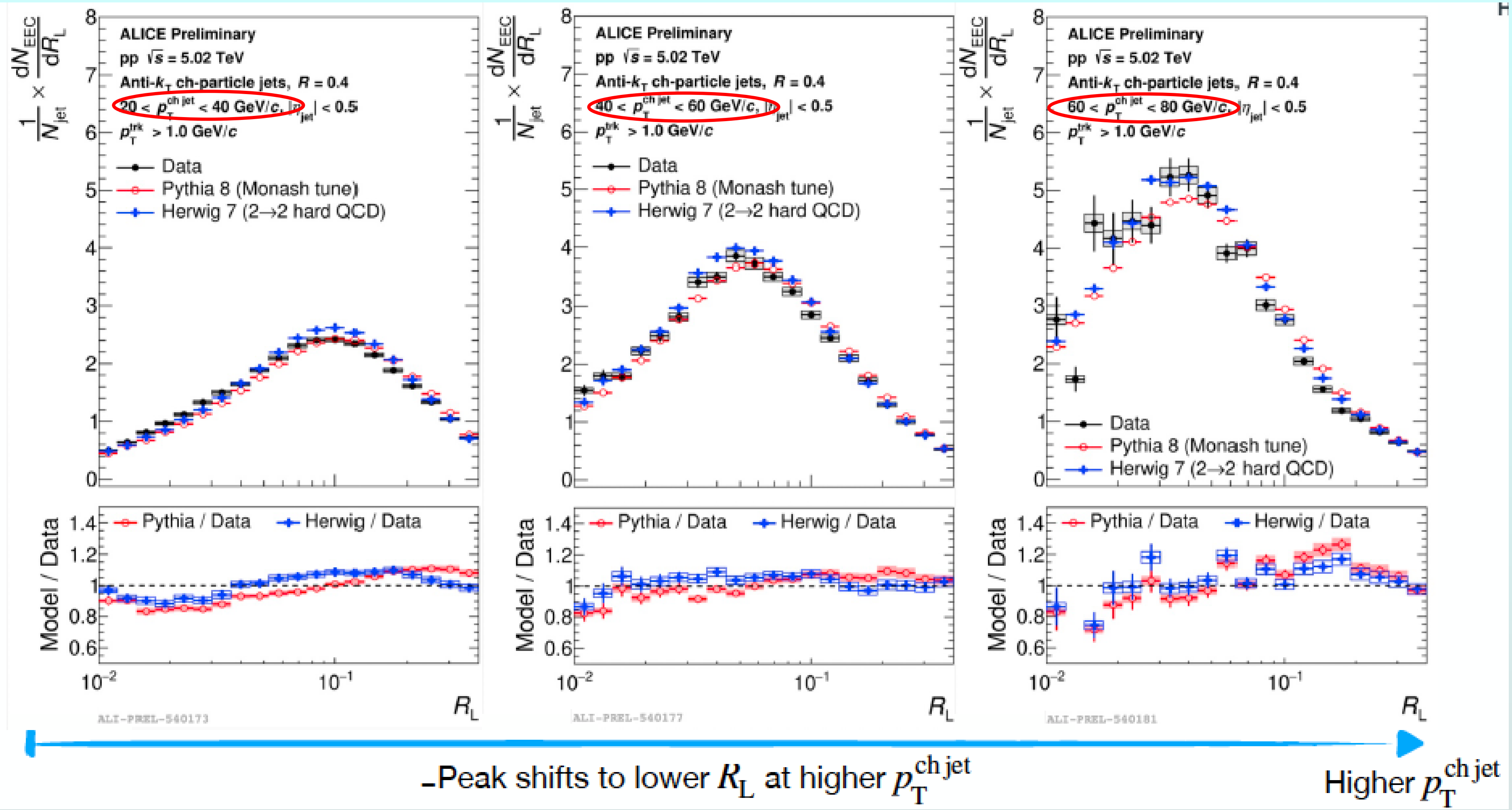




When the virtuality approaches $\mathcal{O}(\Lambda_{QCD})$, EEC undergo transition into confinement region

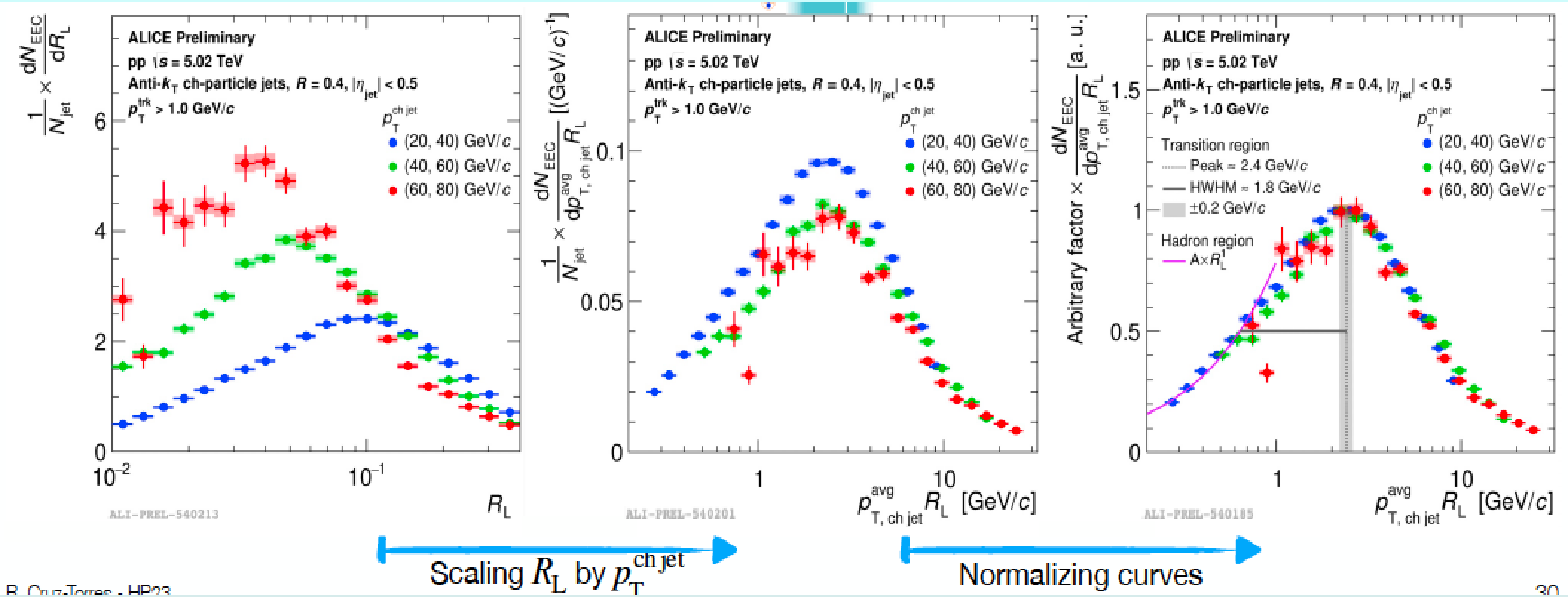
$_L \sim \left(\Lambda_{QCD}\right)/$ 49 $, jet$

Compare data to models Pythia & Herwig



- **Herwig (hadronization via clusters) agrees better with the data**
- **But data are somewhat broader than Herwig. Longer time needed to form hadrons?**

Check for scaling

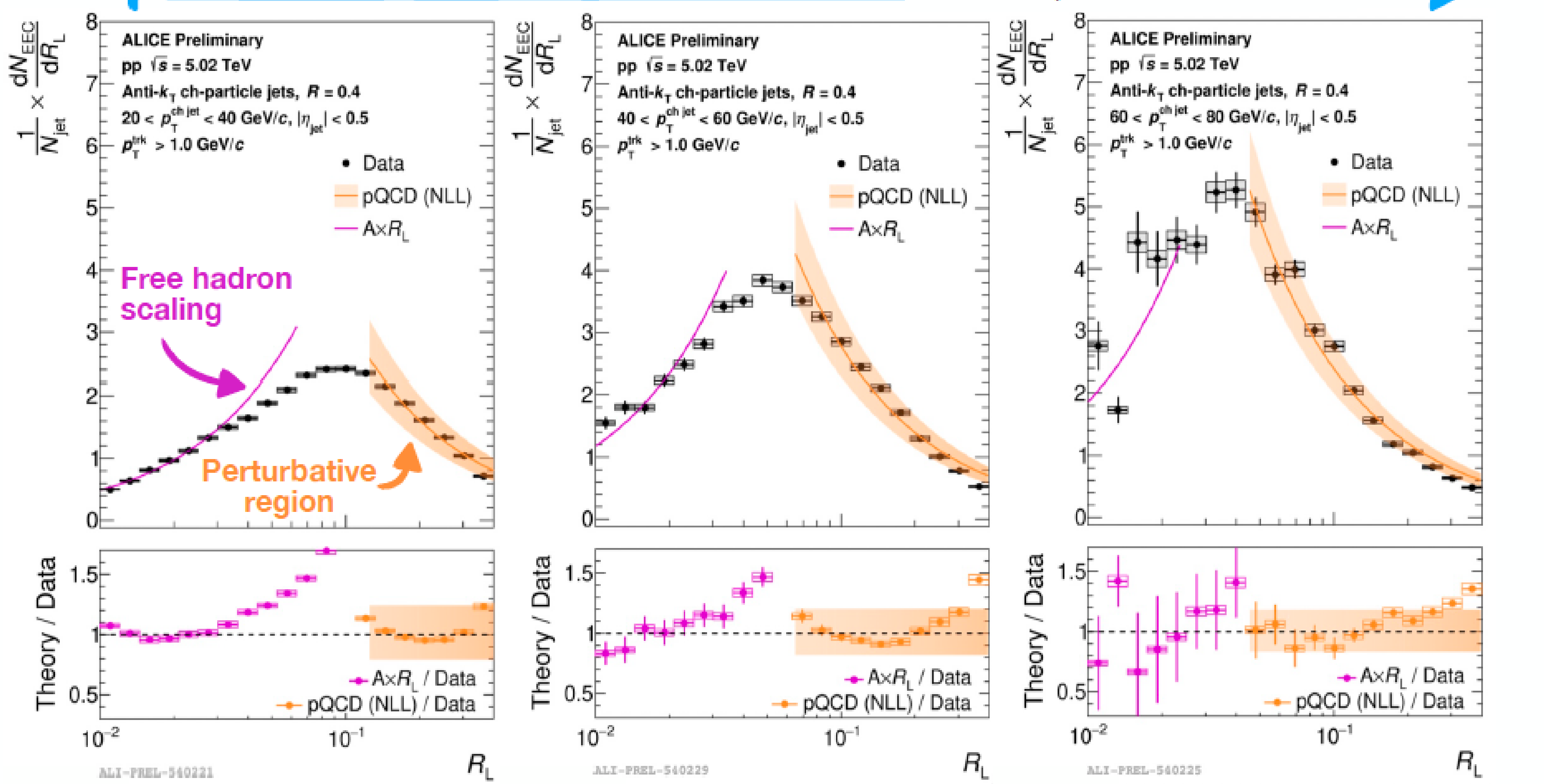


- Recall p_T*R_L is order of Λ_{QCD}
- Common shape for all jet energies – transition region is universal
- HWHM = 1.8 ± 0.2 GeV/c

Separate pQCD, hadronization & hadron gas

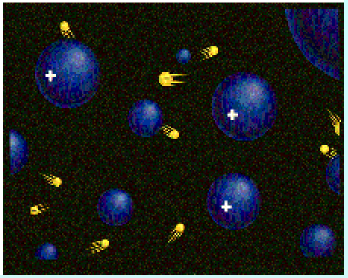
Higher $p_T^{\text{ch jet}}$

Lee et al., arXiv:2205.03414



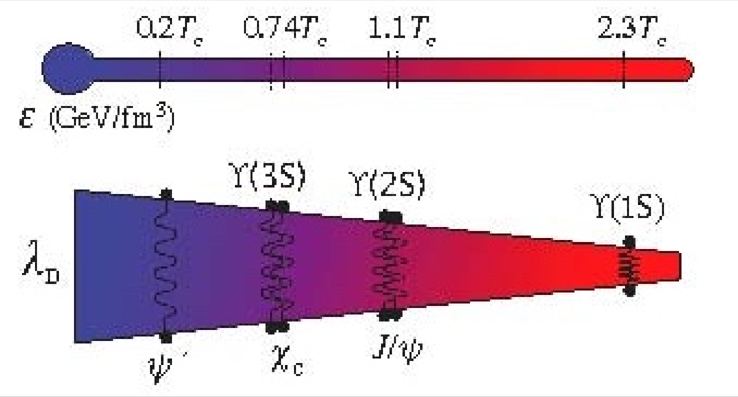
NLL calculations correspond to full (charged+neutral) jets and are normalized to data in perturbative region

- **Deviation between data and NLL: non-perturbative onset**
- **Agreement between data and free hadron scaling: hadron gas phase**
- **Transition region physics – stay tuned!**

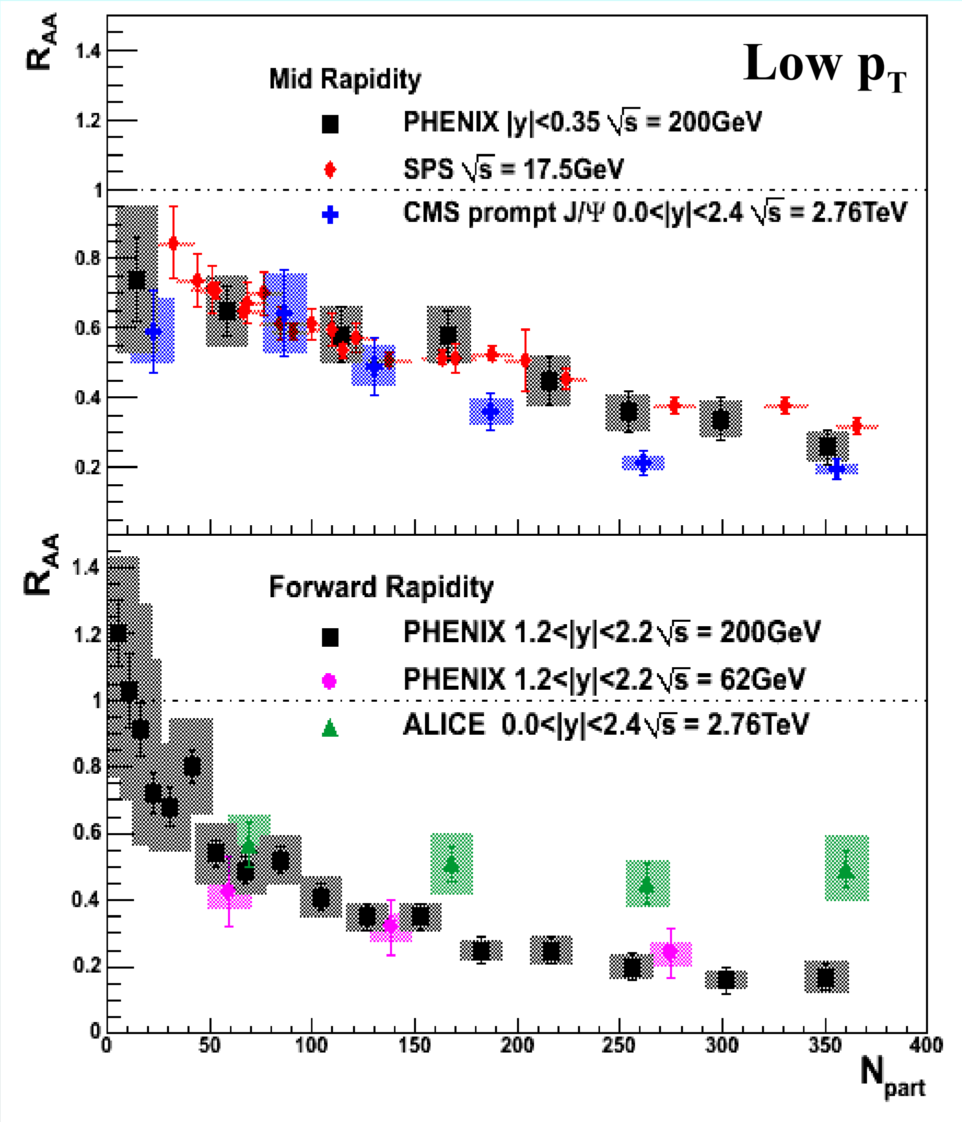


Is there a relevant screening length?

- Plasma: interactions among charges of multiple particles
  spreads charge into characteristic (Debye) length, λ_D
  particles inside Debye sphere screen each other
- Strongly coupled plasmas: few (~1-2) particles in Debye sphere
  Partial screening -> liquid-like properties
  sometimes even crystals!
- *Test* QGP *screening with heavy quark bound states*
  Do they survive?
  All? None? Some? Which size?
- Are residual correlations important?



J/ψ vs. system size, √s



To quantify color screening in quark gluon plasma: study as function of √s, y, p_T, **r**$_{onium}$

More suppression at y=2

Breakup in hadron gas?

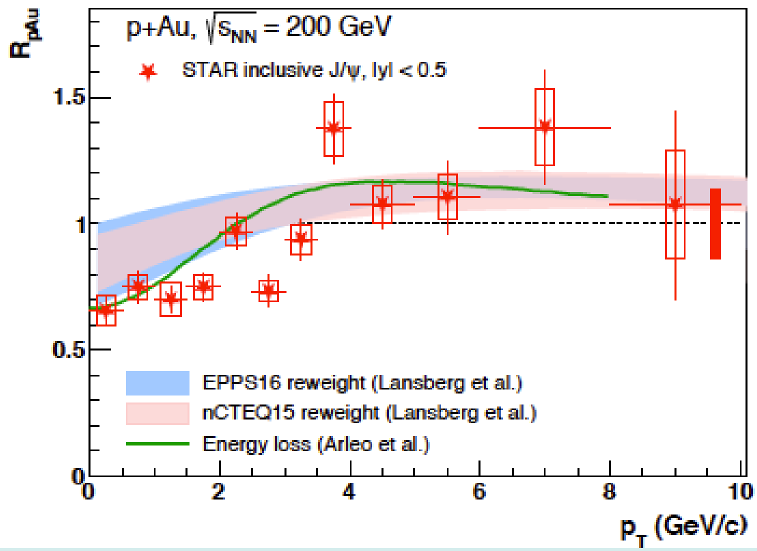
Final state coalescence of $q\bar{q}$!

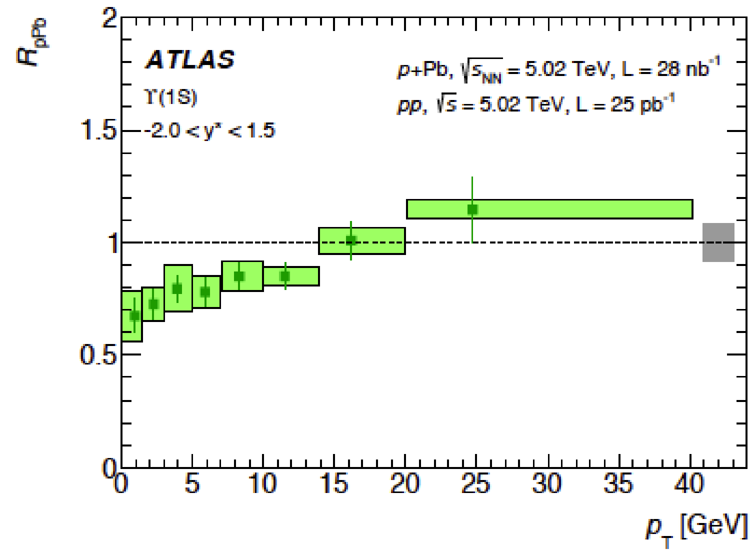
Make many c-cbar pairs at LHC

Measure J/ψ in p+A to account for cold matter effects: gluon shadowing, energy loss

@ 2.76 TeV direct J/ψ lower at mid-y, above at forward y

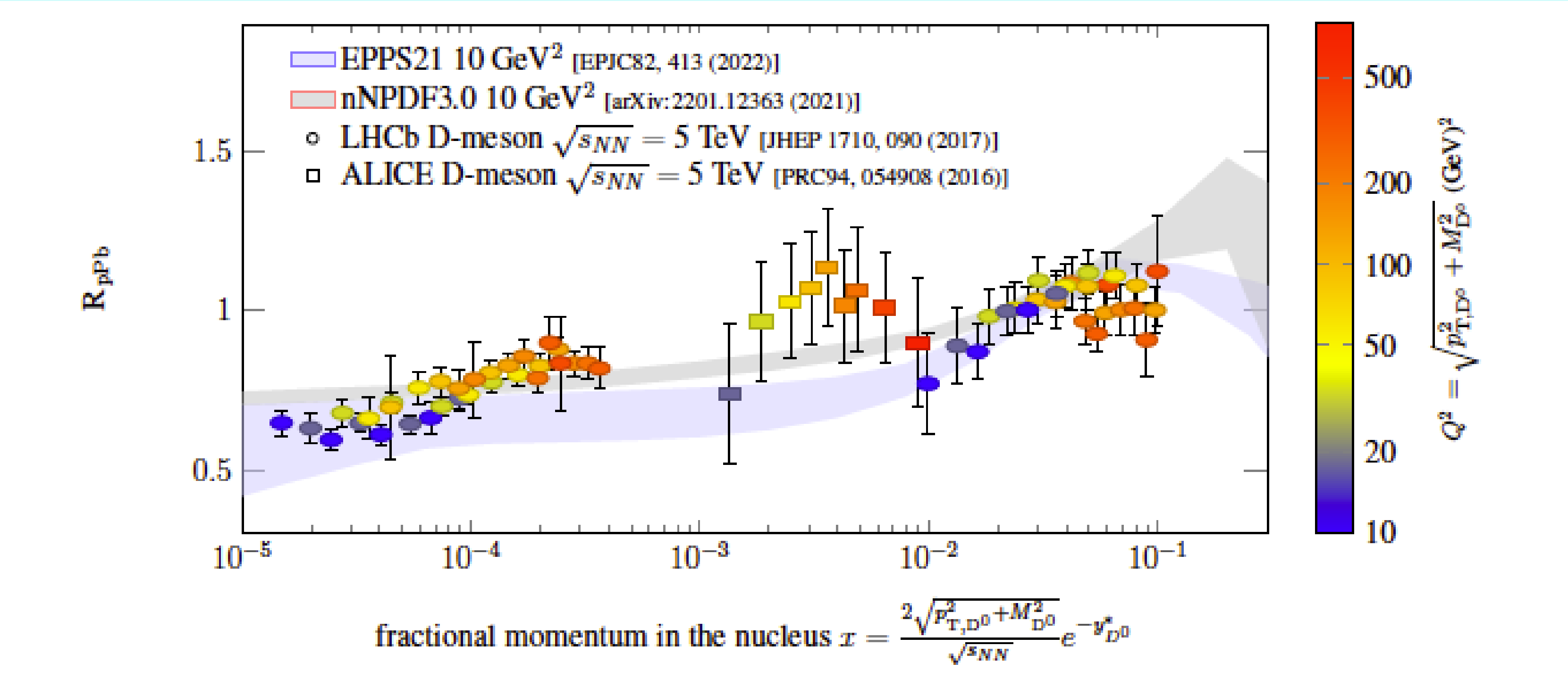
Cold nuclear matter also affects J/ψ





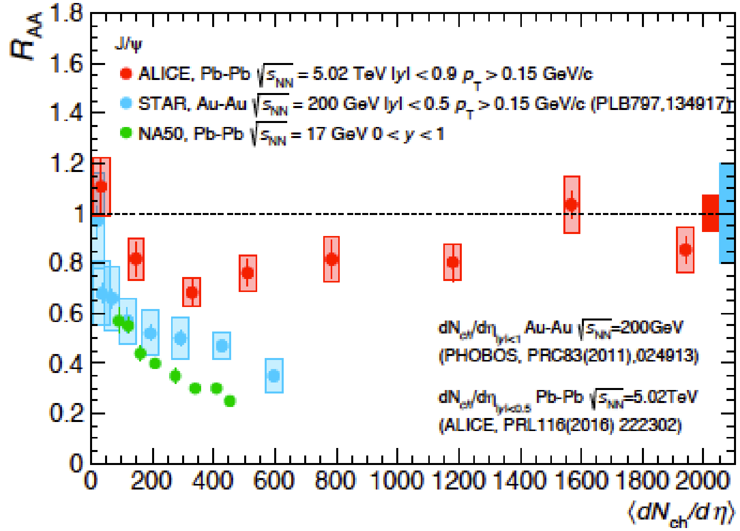
- J/ψ suppressed at low p_T in a nucleus (at midrapidity)
- Can reproduce this with realistic PDFs and some energy loss in cold nuclear matter

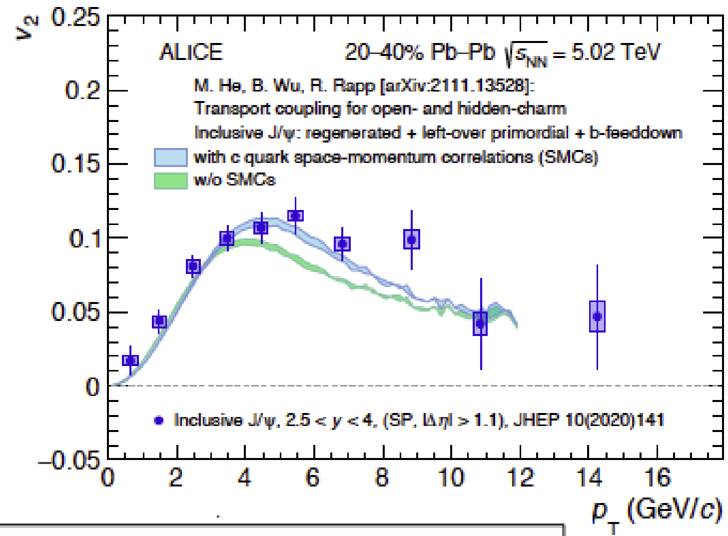
Initial or final state effect in p+A?

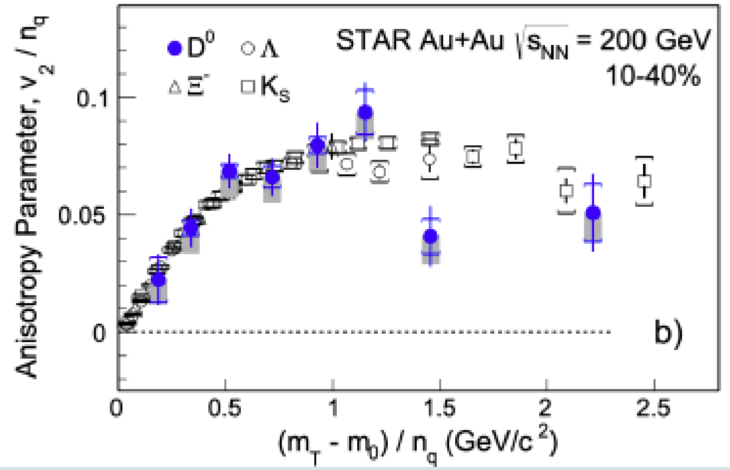


- **p+Pb D meson data reproduced with known parton distribution functions**
- **Gluon shadowing -> lower gluon density -> less gluon fusion -> fewer charm – anti-charm quark pairs**
- **+ small (but not zero) energy loss**
- ***p+Pb suppression is an initial state effect***

J/ψ added by coalescence and removed by QGP

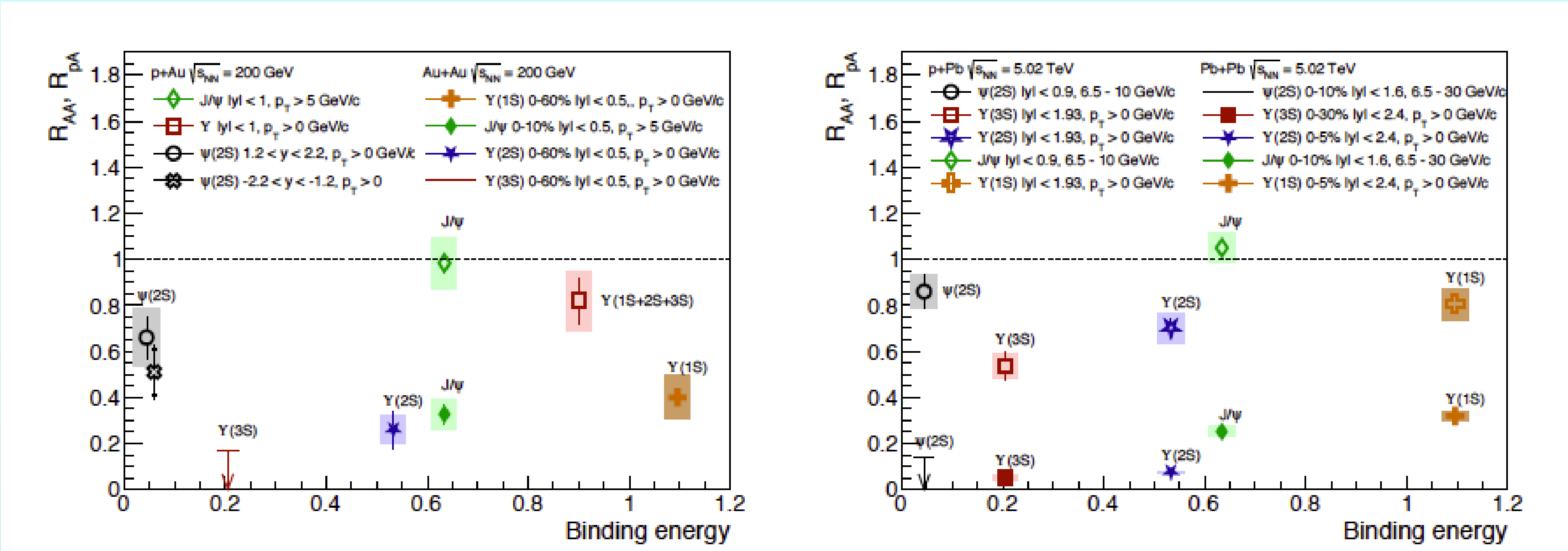






- Suppression decreases with increasing √s
- Flow magnitude is substantial
- Expect both effects from final state c-cbar recombination

Suppression vs. binding energy

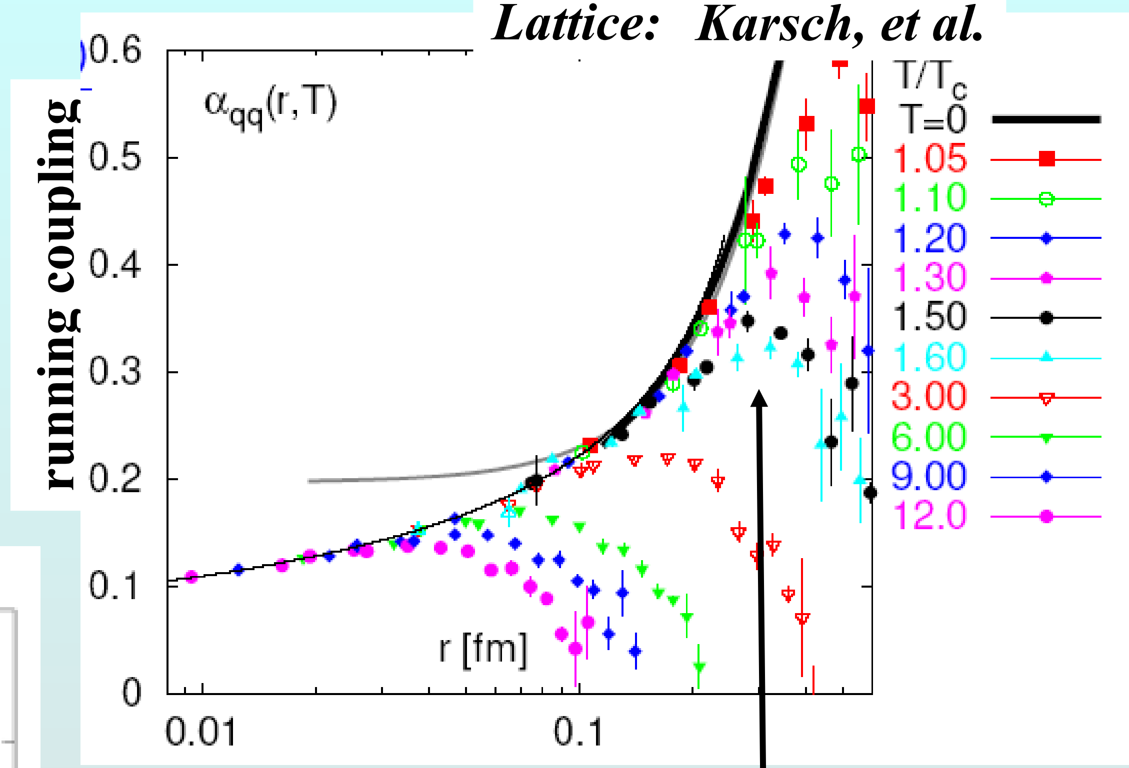


- A+A J/ψ more suppressed than in p+A
- Trend: less suppression for more tightly bound species

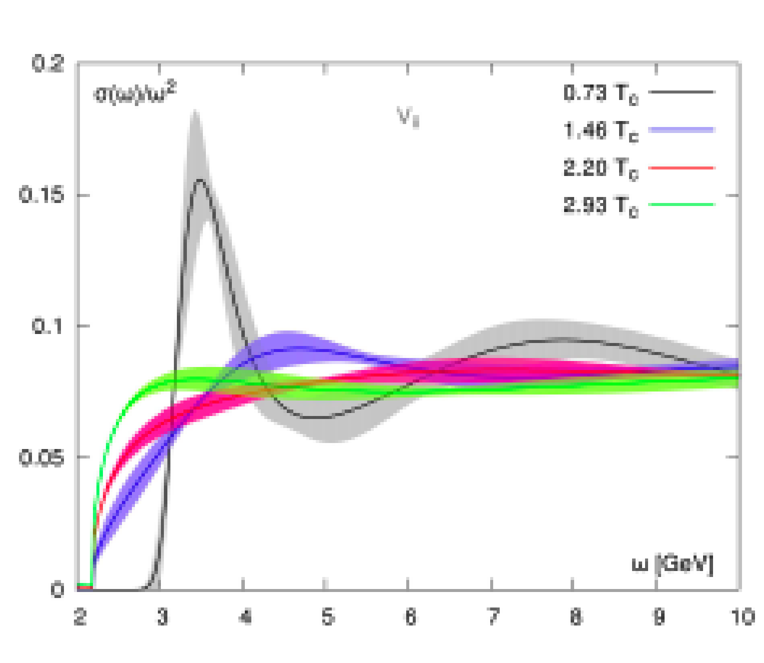
Is there a relevant screening length?

- Strongly coupled matter: few particles in Debye sphere - decreases screening!

Lattice: Karsch, et al.

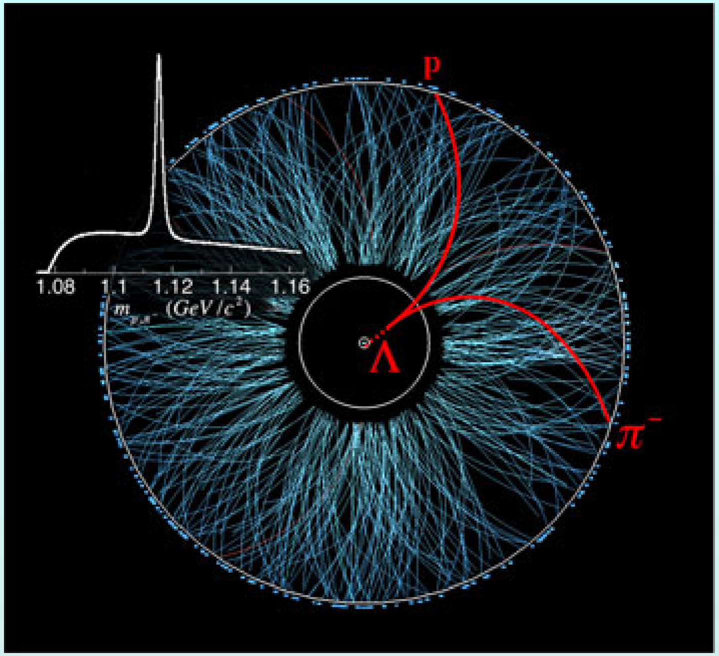


coupling drops off for r > 0.3 fm



Ding, et al. arXiV: 1107.0311

LQCD spectral functions show correlation remaining at $T>T_c$
Partial screening?



Vorticity in QGP?

Vortex aligns spins of emitted particles

So, reconstruct Λ & anti-Λ

Observe global polarization via proton angle vs. reaction plane

$$\overline{P}_\Lambda \equiv \left\langle \vec{P}_\Lambda \cdot \hat{J} \right\rangle = \frac{8}{\pi \alpha_\Lambda} \frac{1}{R_{\mathrm{EP}}^{(1)}} \left\langle \sin\left(\Psi_1 - \phi_p^*\right)\right\rangle^{\mathrm{sig}}$$

α_Λ = 0.732 ± 0.014; Λ decay constant

L ~ 10^5 $$P \approx \frac{(s+1)}{3} \frac{(\omega + \mu B/s)}{T},$$

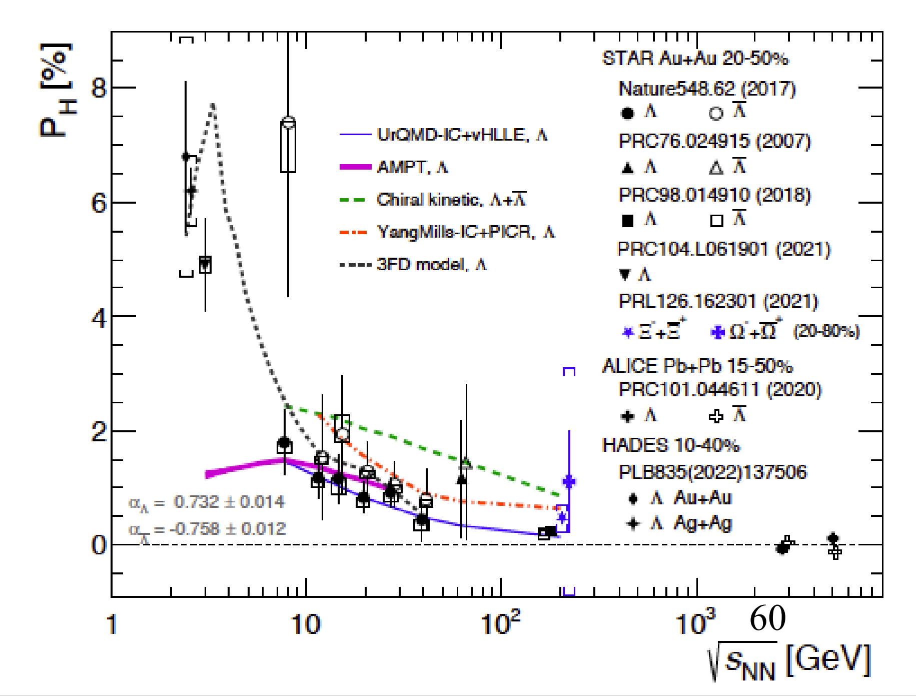
Extract ω ~ 10^{21}

Largest at Λ threshold (hadron gas phase); hydro agrees 😱

Longer life (η damped) at high E?

Background effects?

Stay tuned!!



Impact of the initial state

Inside nucleons and nuclei

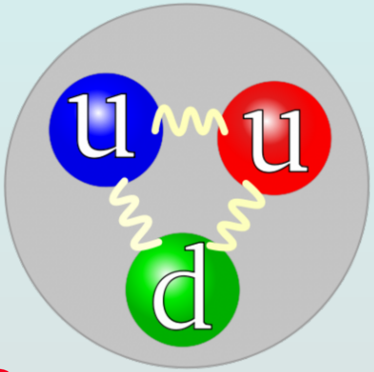
- **Discovery at RHIC:**

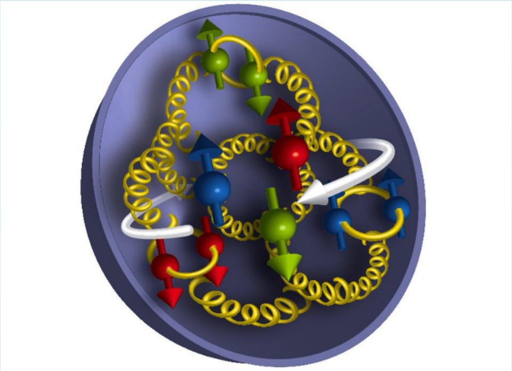
  Spin of the nucleon is spread out among the quarks and gluons!

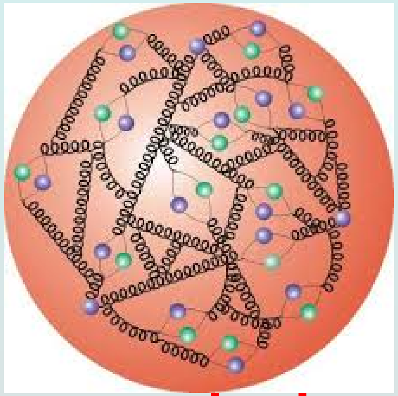
  quarks & gluons in polarized proton also polarized

- **Implications:**

  Cold nuclear matter also strongly interacting when density of quarks and gluons is large



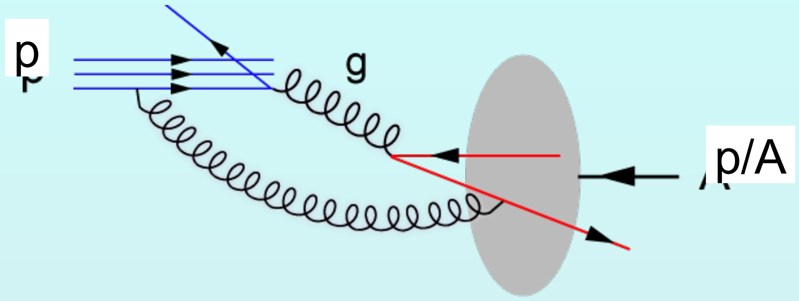




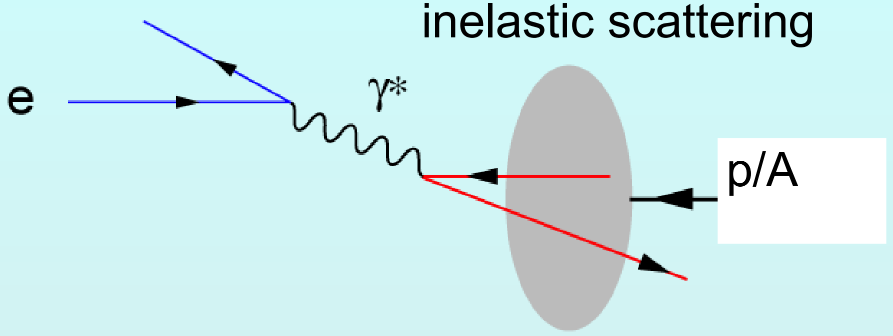
- **Initial state of colliding Pb nuclei already has many-body interactions**

Probe cold, dense matter: Collide e + A

Hadron-Hadron



Electron beam: deep inelastic scattering

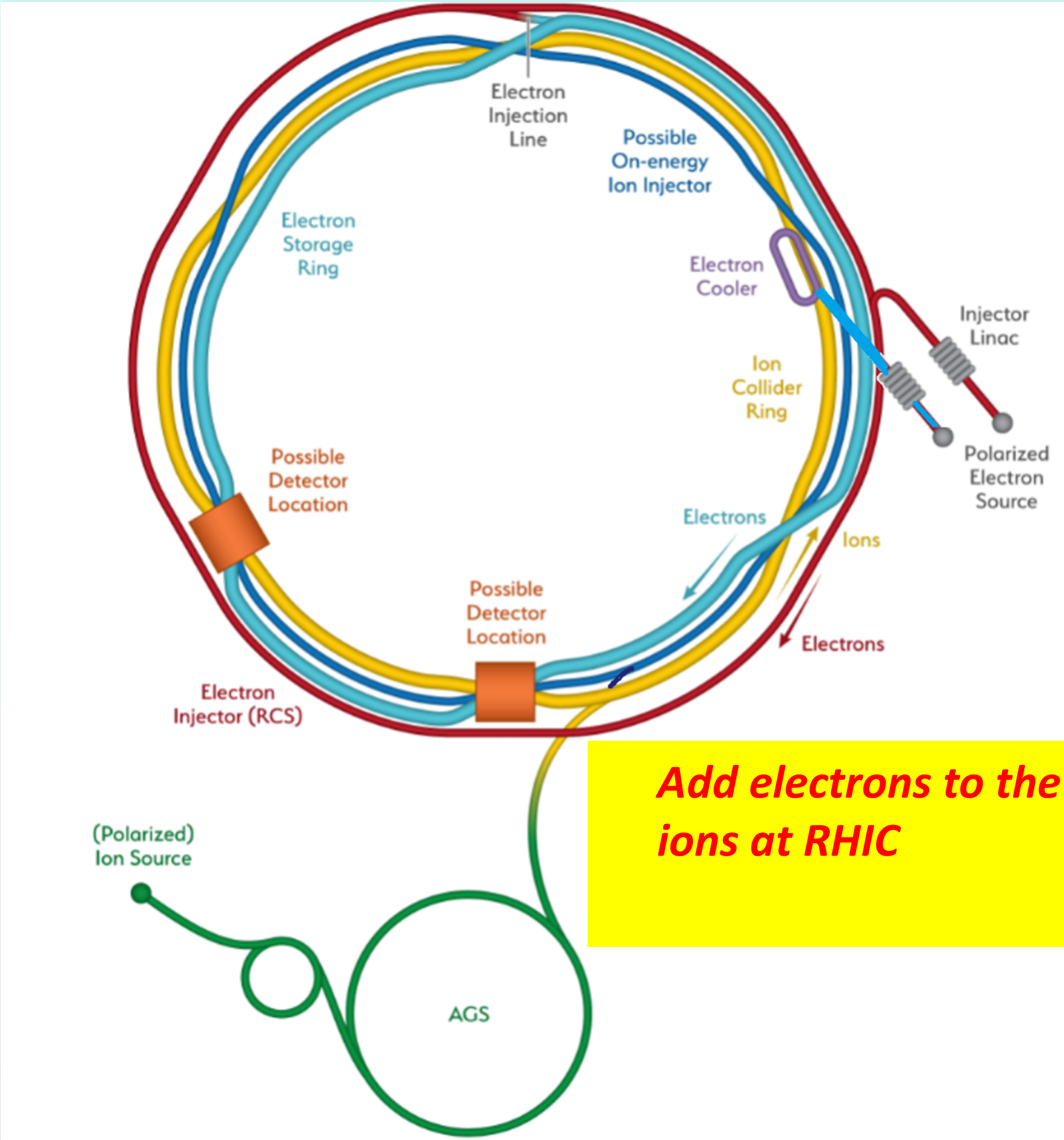


- Probe is a gluon
- Probe has structure!
- Dynamics of the probe mixed up with structure of the nucleus
- RHIC & LHC

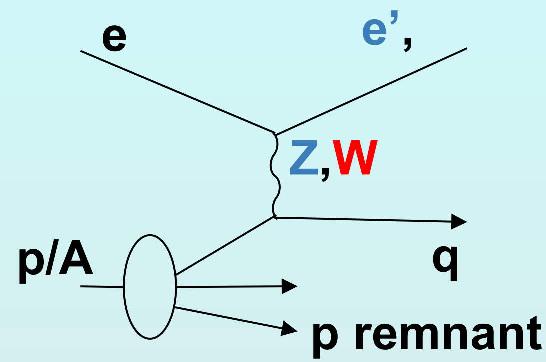
- Point-like probe
- No strong interaction before high momentum transfer process
- Control probe kinematics by measuring scattered electron
- Electron-Ion Collider

We'll also find out: will there be hydrodynamic flow if we excite a hot spot with a point particle??!

Electron-ion collider at Brookhaven



Scatter electrons from nuclei!

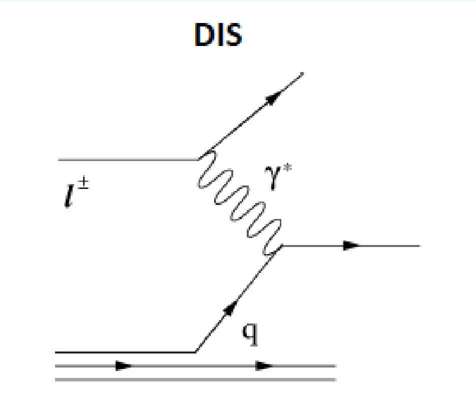


- √s = 30 to 140 GeV

Add electrons to the ions at RHIC

Hadron Storage Ring
Electron Storage Ring
Electron Injector Synchrotron
Possible on-energy Hadron injector ring
Hadron injector complex

See quarks & gluons with electron beam?

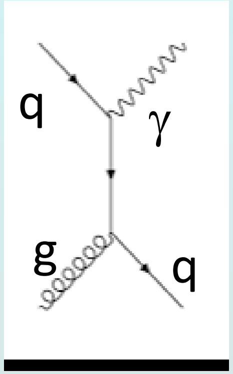


- **Deep inelastic scattering**

  scatter virtual γ off the q charge
- **"See" gluons when quark distributions don't scale with energy transfer from the electron**

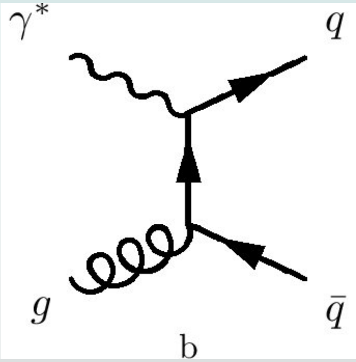
- **Seeing gluons more directly:**

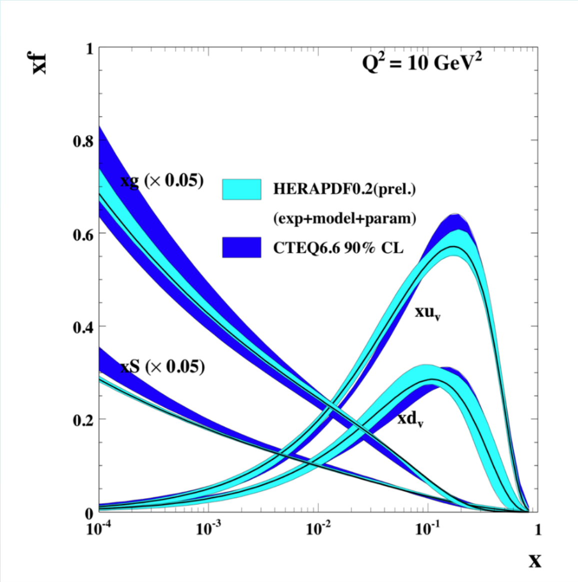
  in p+p: QCD Compton scattering



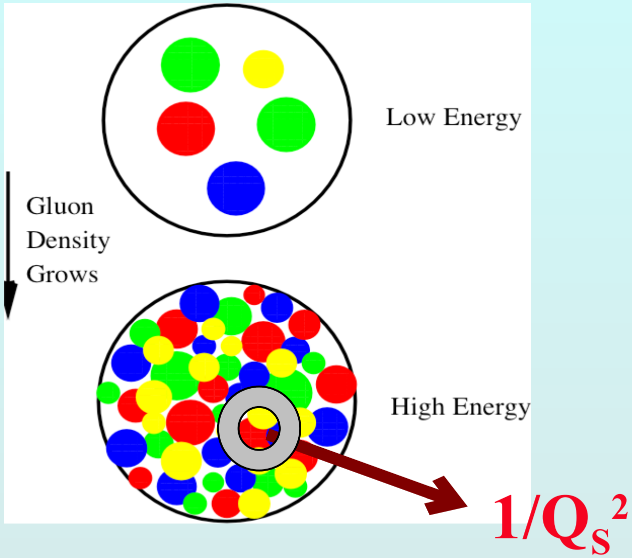
in e+p: γ + g -> c$\bar{c}$

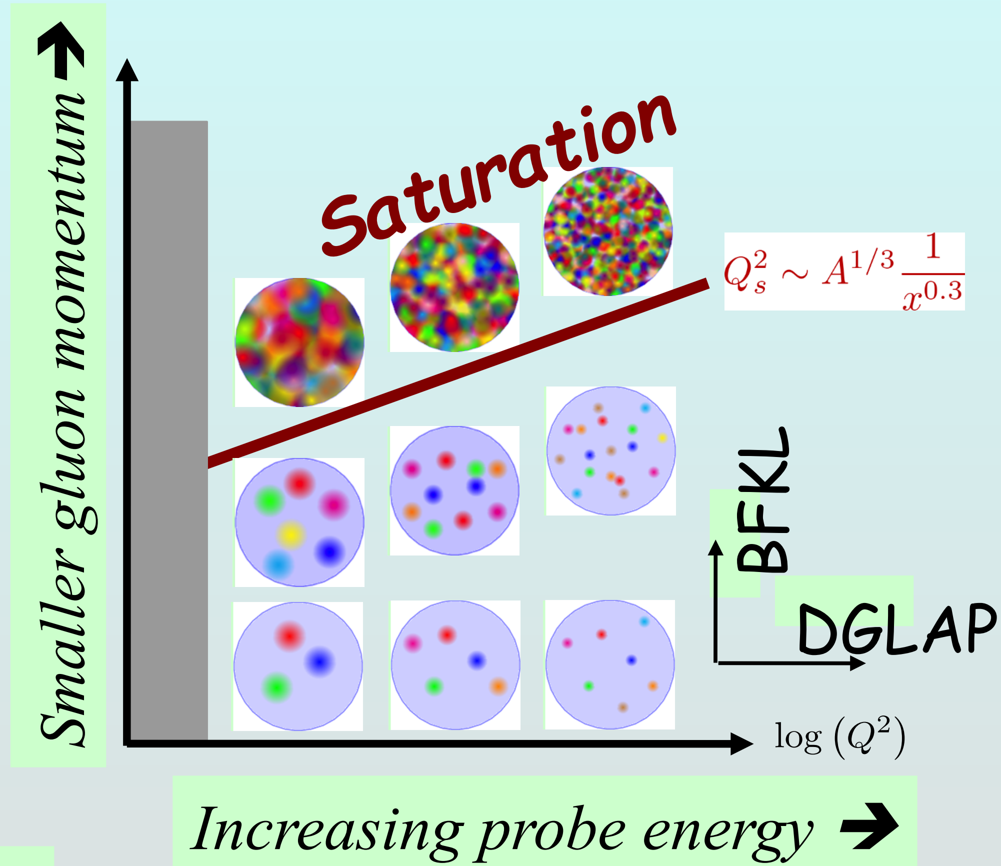
photon-gluon fusion



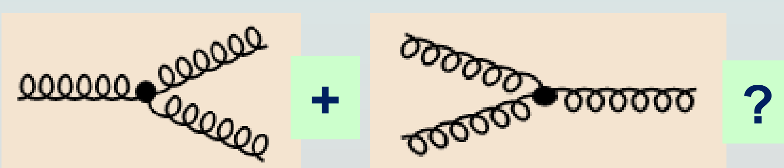


Deep in a nucleus: gluons are numerous



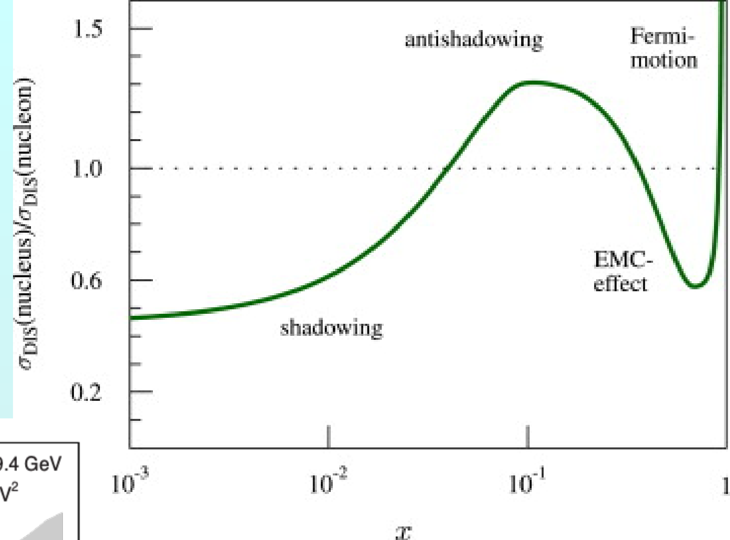


- *At high density, what? gluon # saturates?*

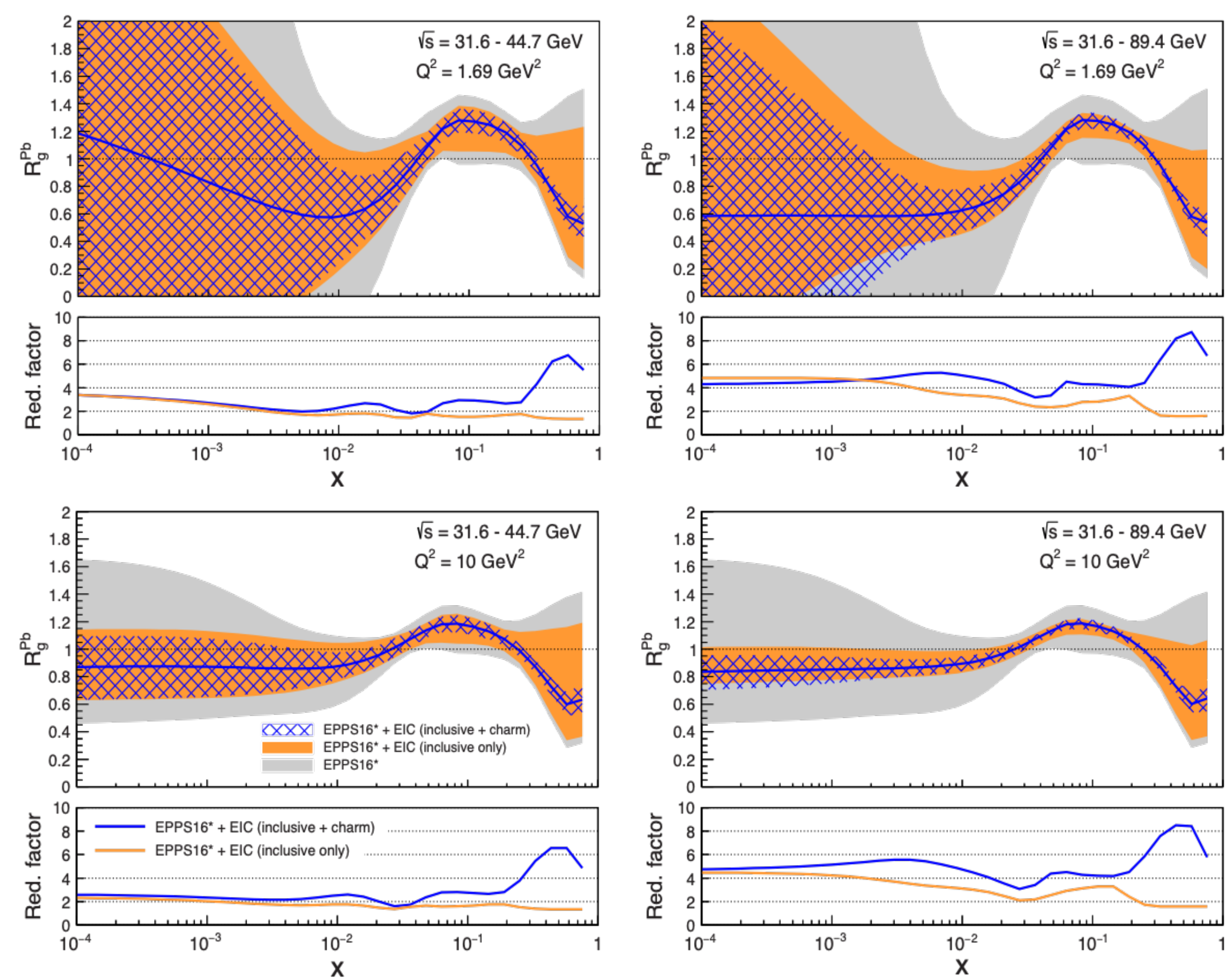


Nuclear PDF's

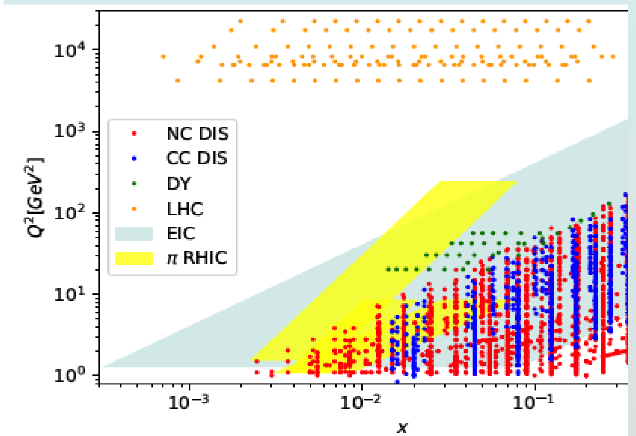
- **Inside nucleus: densities modified**
  q, g from different nucleons interact



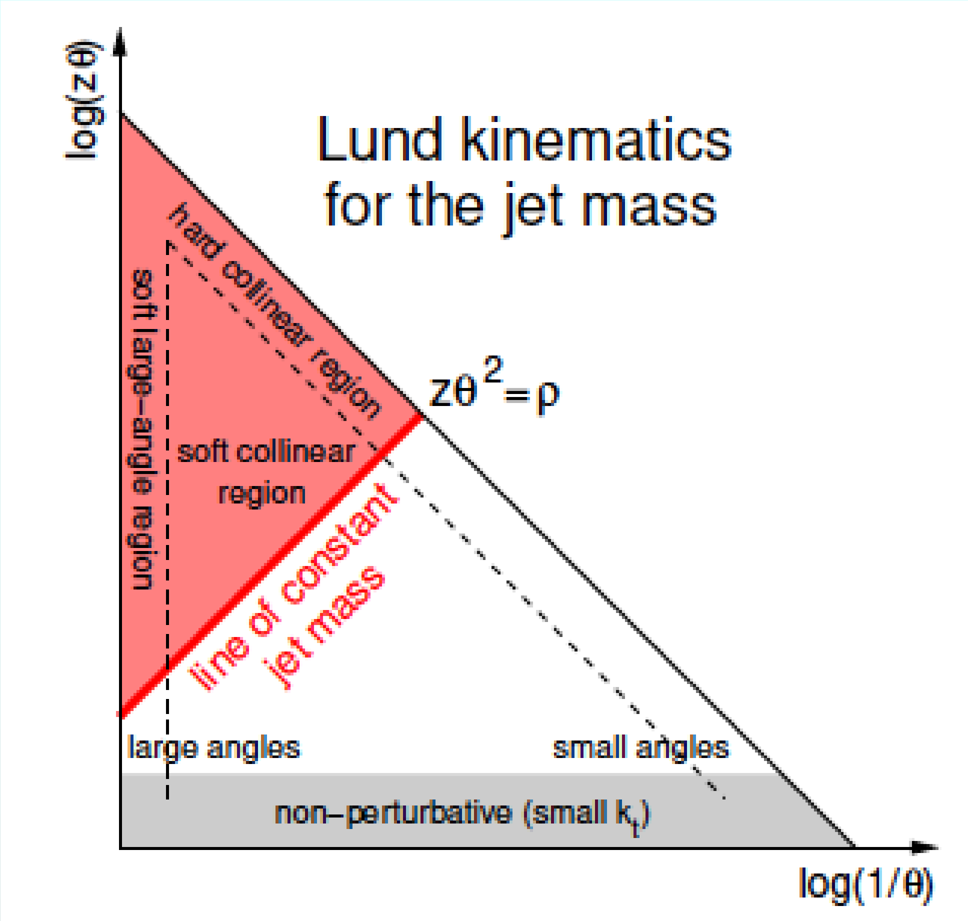
arXiv:1708.01527



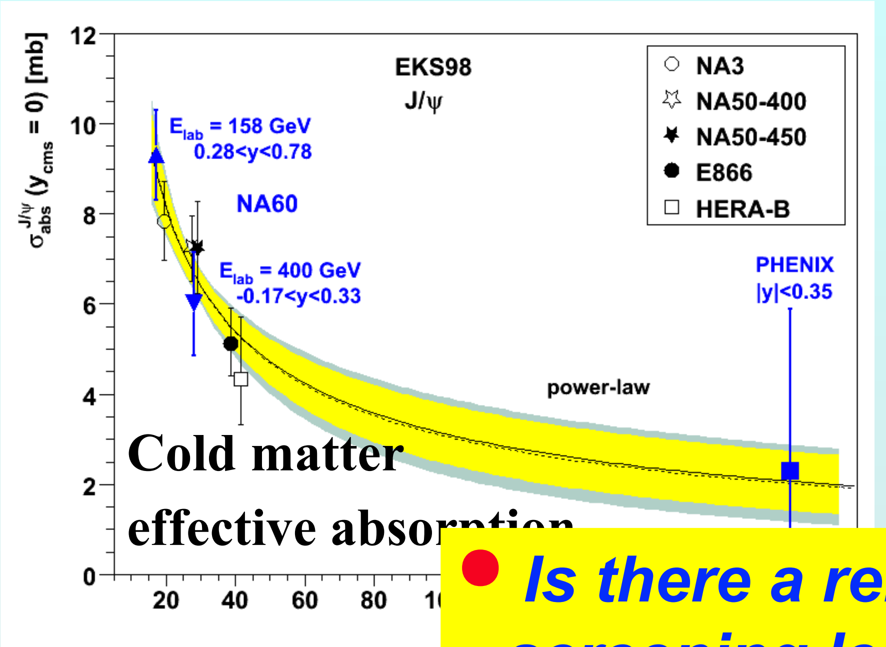
Inclusive DIS off nuclear beams

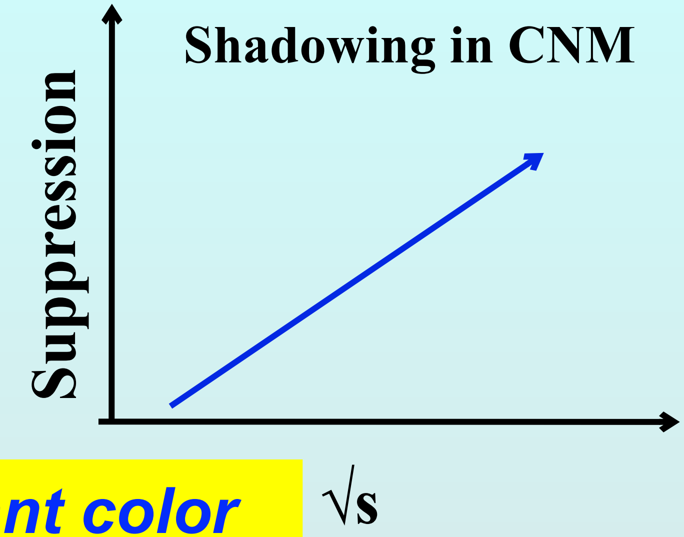


- **backup slides**

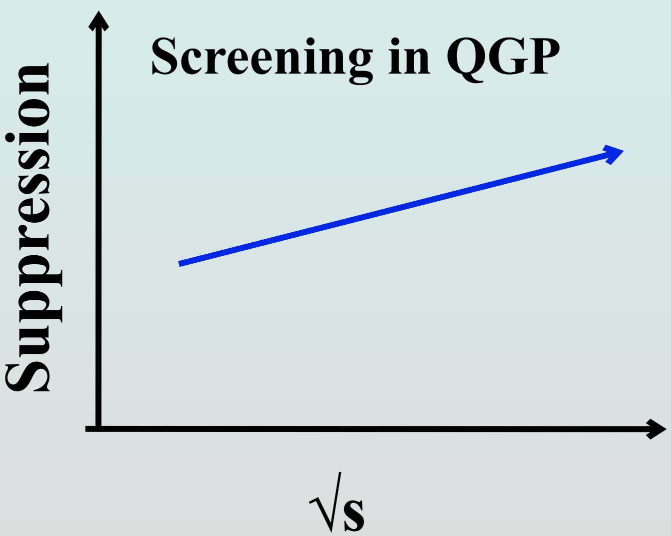

Lund kinematics
for the jet mass
log(zθ)
log(1/θ)
hard collinear region
soft large−angle region
soft collinear
region
zθ^2=ρ
line of constant
jet mass
large angles
small angles
non−perturbative (small k$_t$)

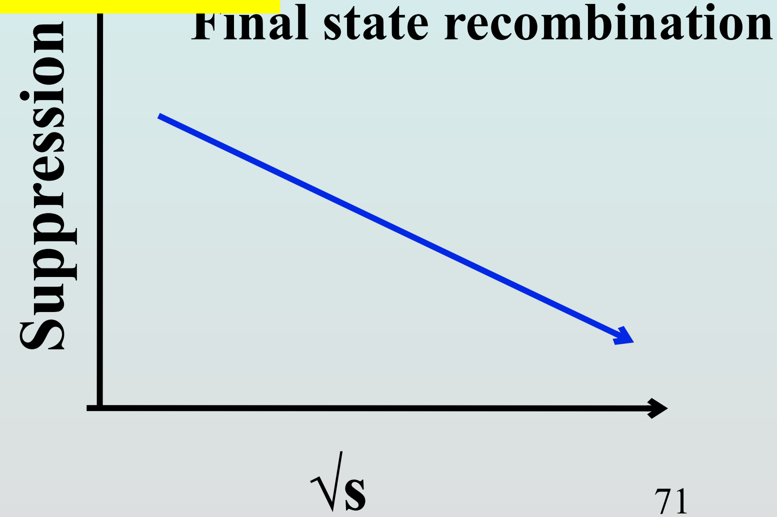
√s dependence of suppression effects



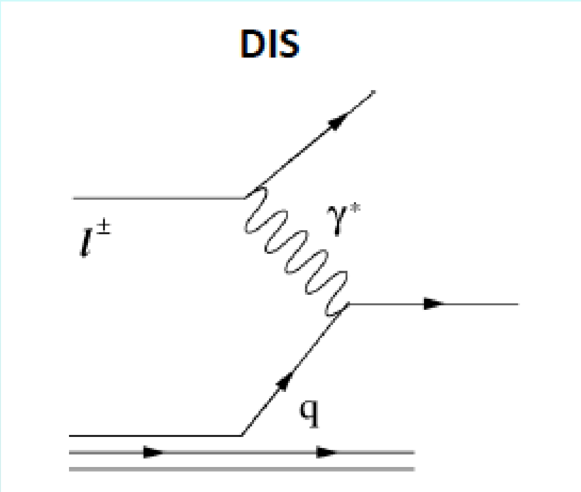


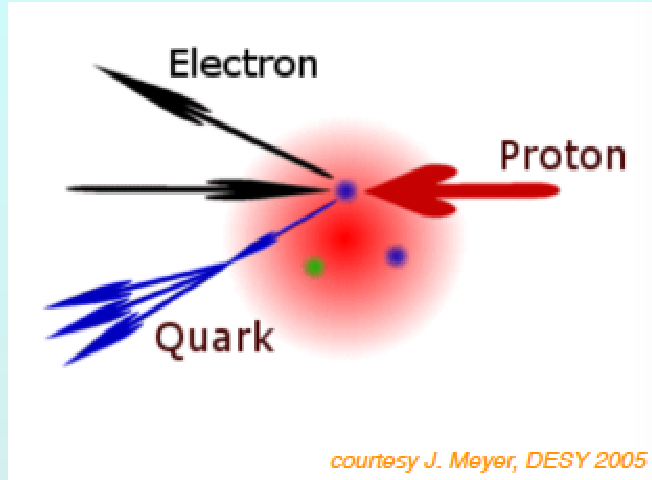
- *Is there a relevant color screening length?*





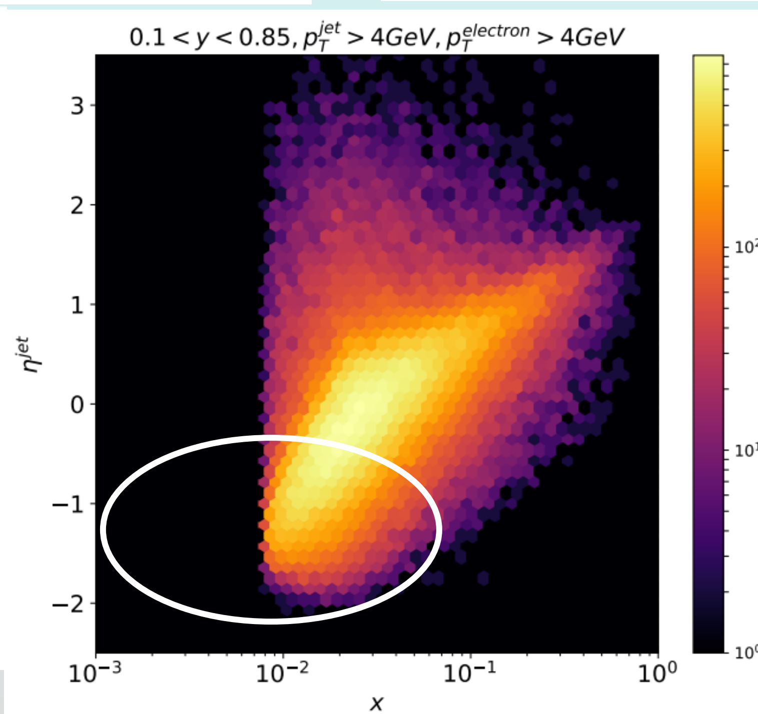
Deep inelastic scattering off dense QCD matter at low-x

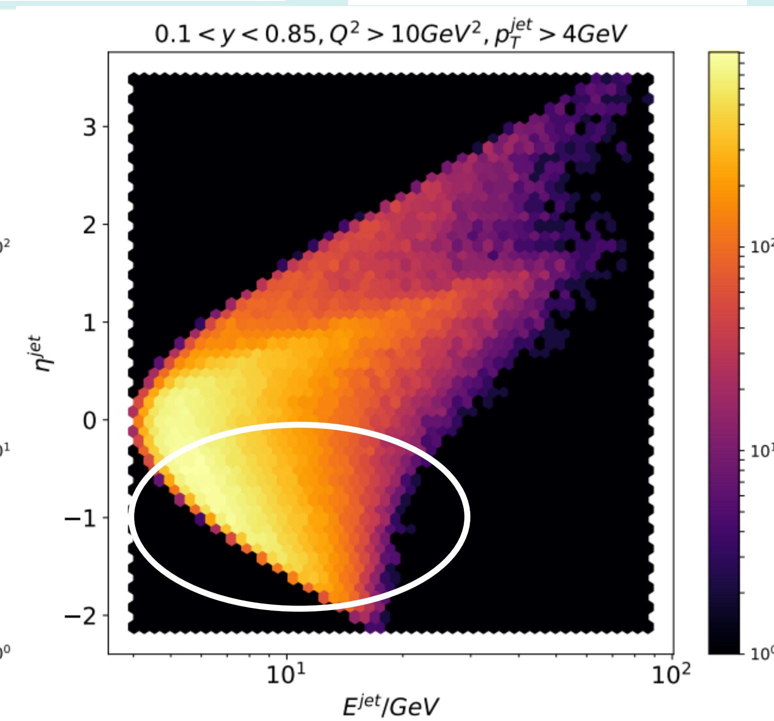




Probe nucleon or nucleus at $x=10^{-2}$ with 5-15 GeV jets

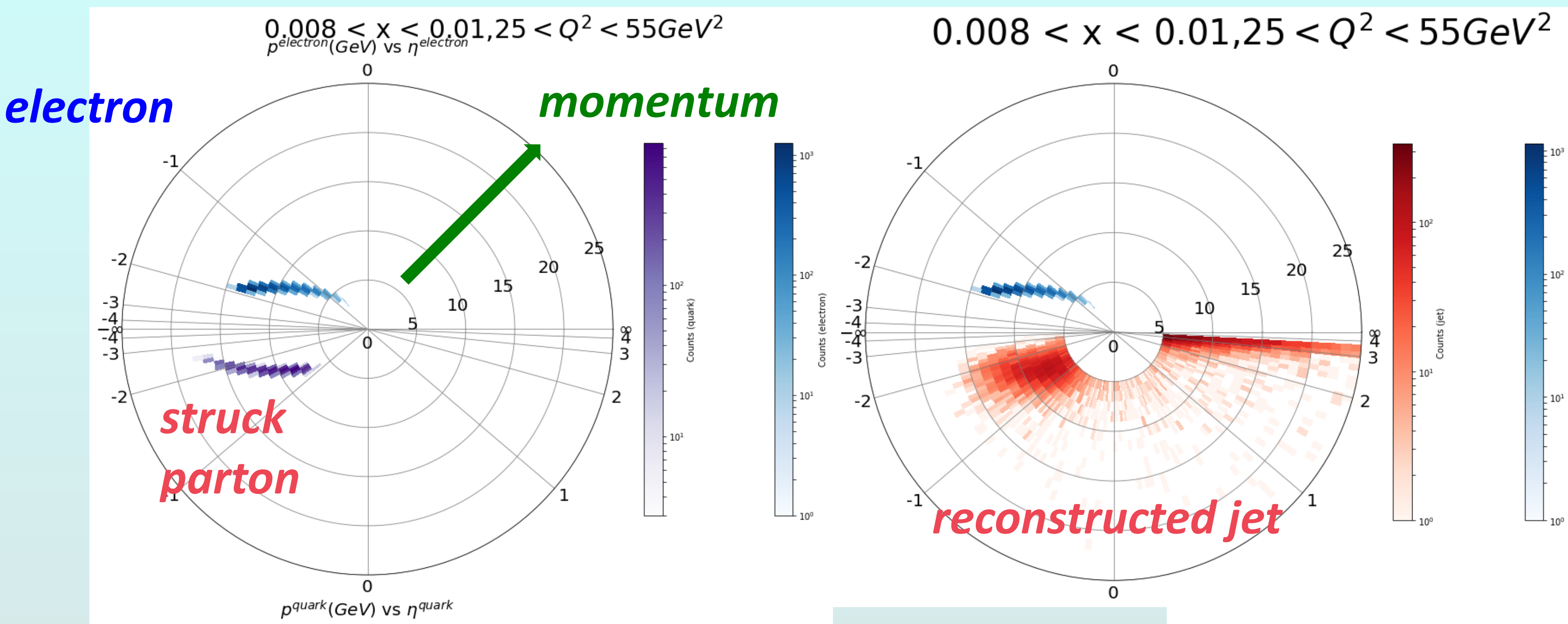
Y. Song, M. Arratia





Electron tags original jet energy, angle

e+p, DIS; Pythia 8. Require $W^2 > 4$ GeV^2,



Youqi Song, M. Arratia

← electron direction

proton/ion → direction

Rest of the event is very clean (we can find these jets!)

How much energy is lost to the cold, dense matter?

Jet's fate in cold, dense QCD matter

- Energy & angle balance
  via lepton-jet correlations
  compare energy loss to
  hot, denser QCD matter

- Jet broadening?

- Jet substructure
  Energy flow/shower development
  Quantum # correlation in jets
  Hadron formation in jets
  Jet angularities

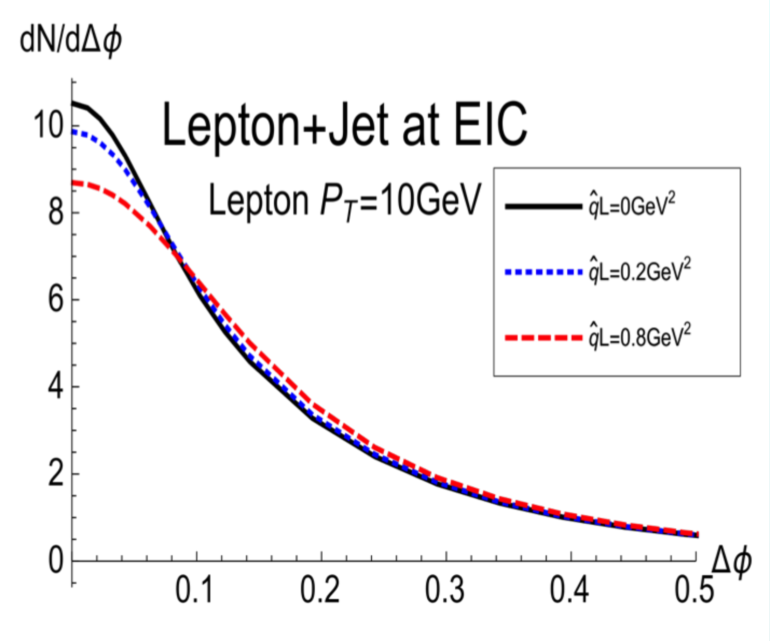
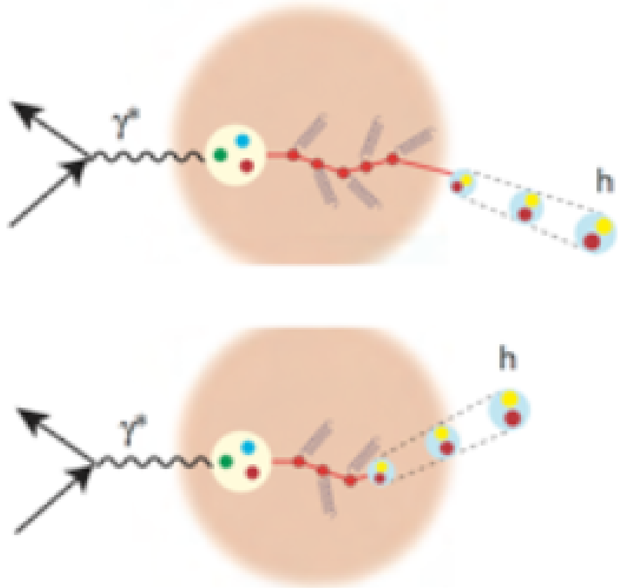


Figure it out at EIC

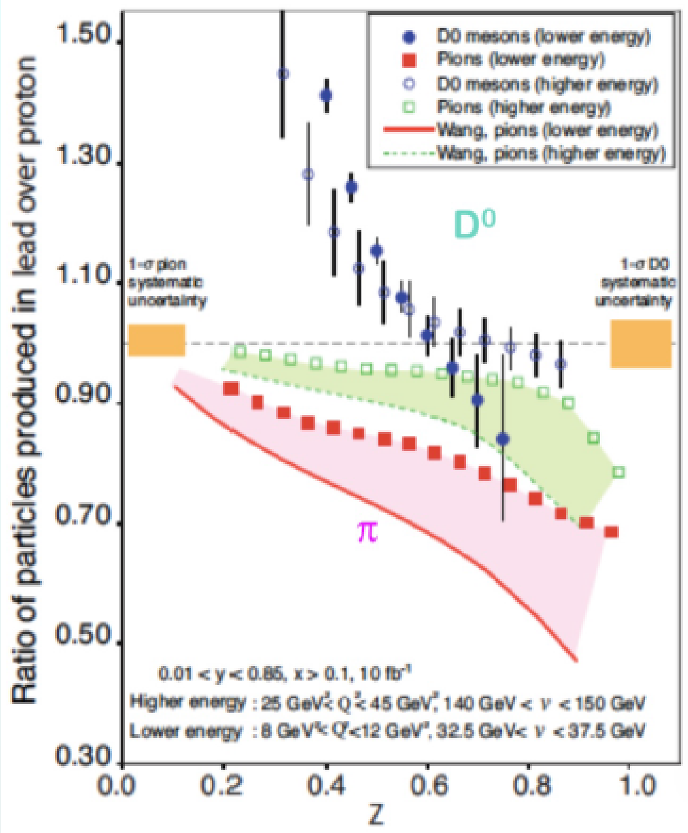


Control of $\nu = \frac{Q^2}{2mx}$ and

medium length

Study mass-dependence via charmed hadrons.

Hadron yields

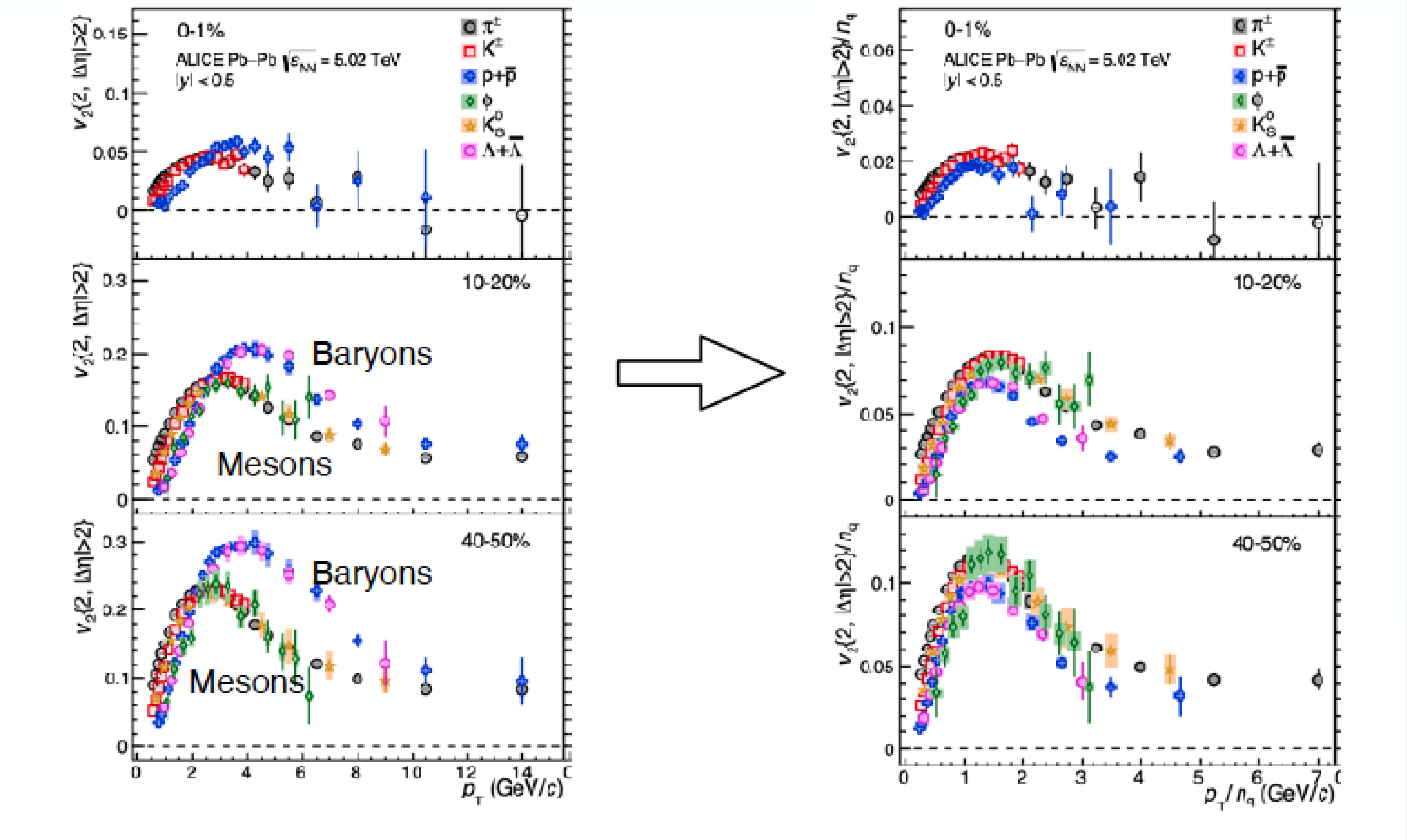


And correlations

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

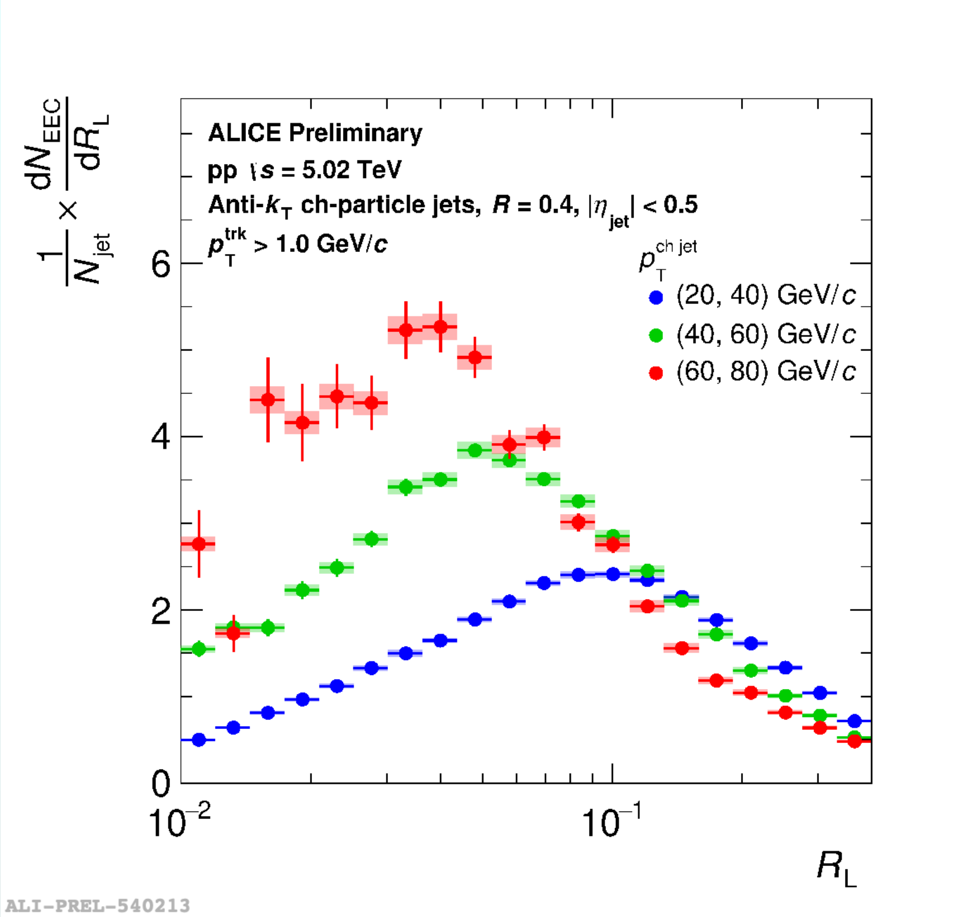
Same message from LHC



Is coalescence in phase space the whole story?

Results from ALICE

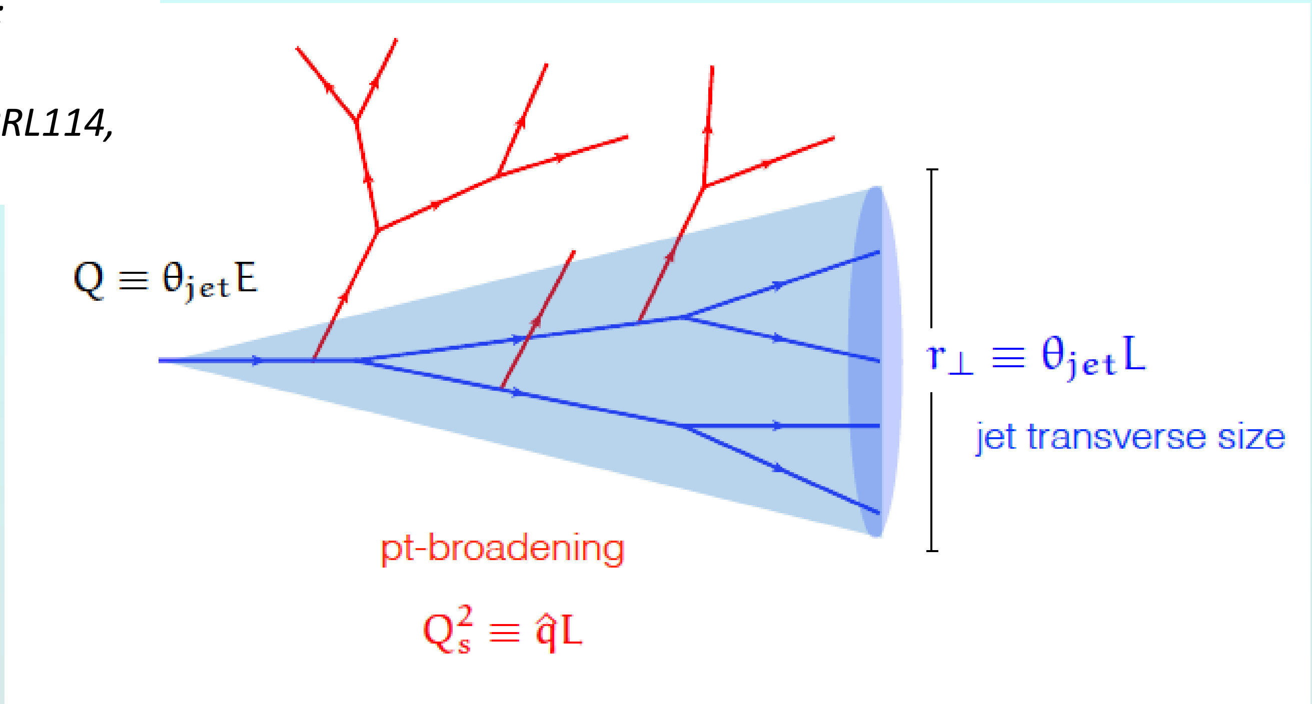
- Correct for detector and reconstruction effects
- Peak shifts to lower R_L for higher p_T jets
- Width is related to the time required for hadrons to form

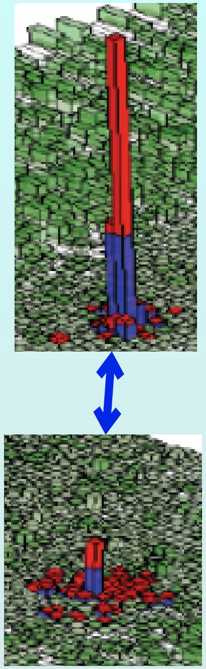


Connect observations to QCD

Y. Mehtar-Tani: 1602.01047

Blaizot, et al, PRL114, 222002 (2015)





Can't see a single quark or gluon in the detector

Partons radiate gluons, which collect into final state hadrons (which we call "fragmentation")

The hadrons are co-moving and boosted by quark's momentum

We detect them as jets of hadrons