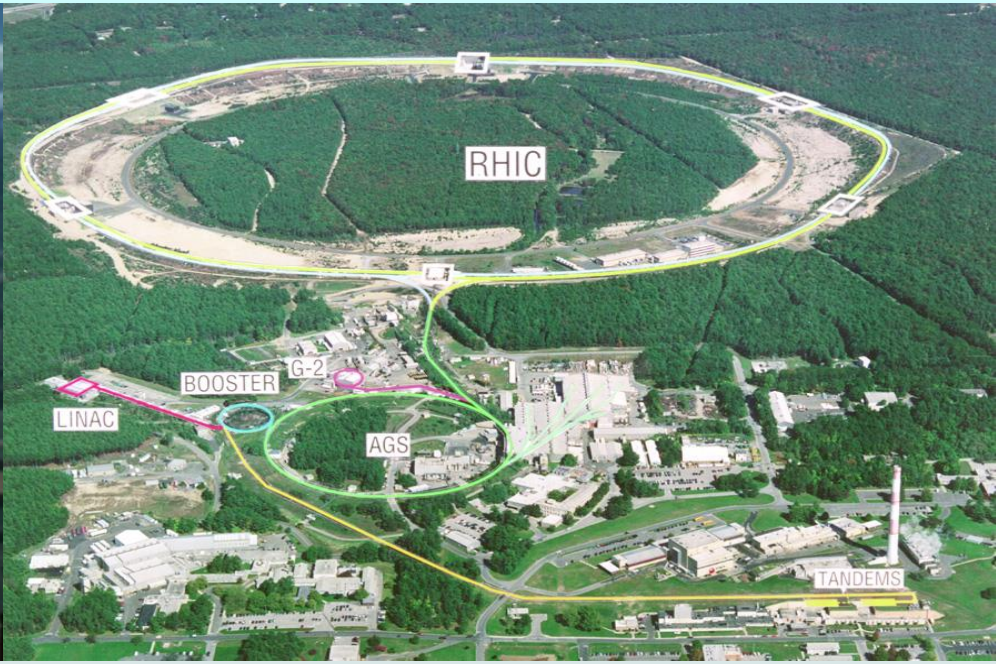
Experimental QCD



Barbara Jacak

UC Berkeley & LBNL

September 13, 2023

A journey from deconfinement to confinement

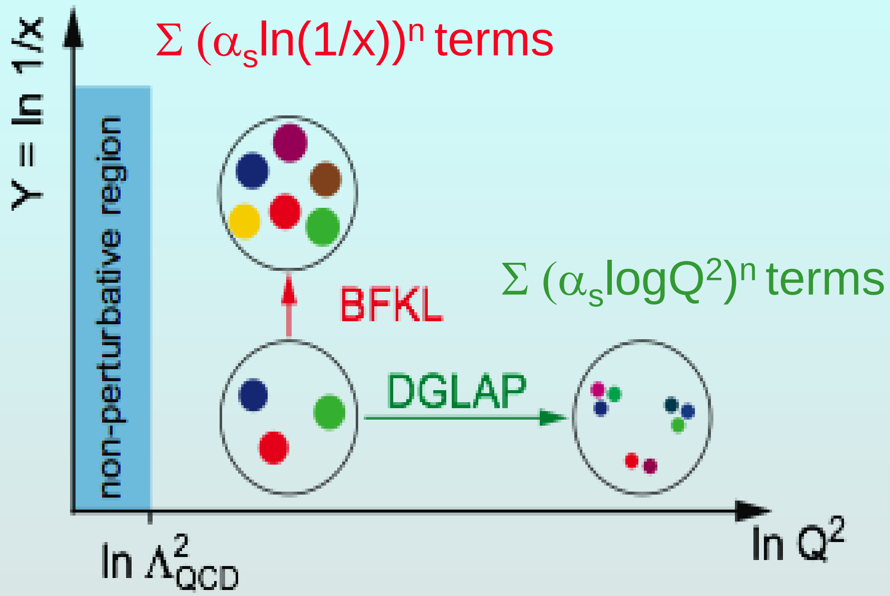
- Where do quarks live?
  - How does the strong force arrange quarks and gluons into a nucleon?
  - How does binding the nucleon into a nucleus rearrange the quarks and gluons?
- What is the many-body physics of QCD?
  - Quark gluon plasma and its properties
  - How do quarks and gluons interact in the plasma?
- QCD shower evolution
- How do hadrons emerge from quarks and gluons?

Starting point: inside a nucleon

Theorists' view

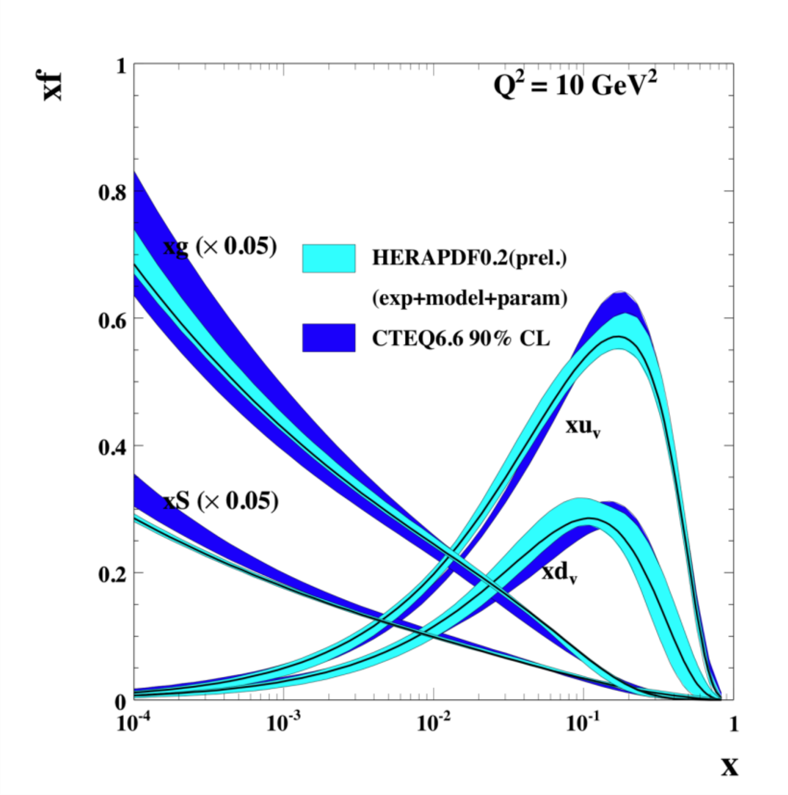
Experimenter's view

x: momentum fraction carried by parton



Q^2: momentum transfer in a collision

Scatter electrons off a p

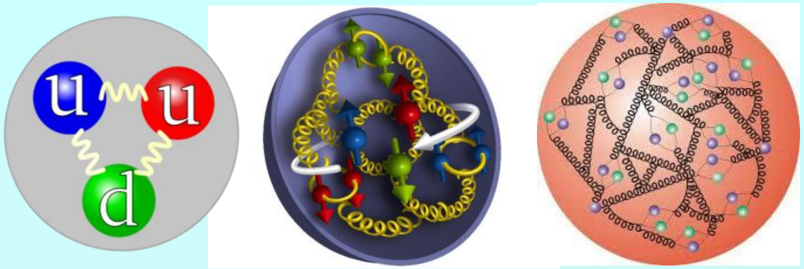


Valence quarks as expected

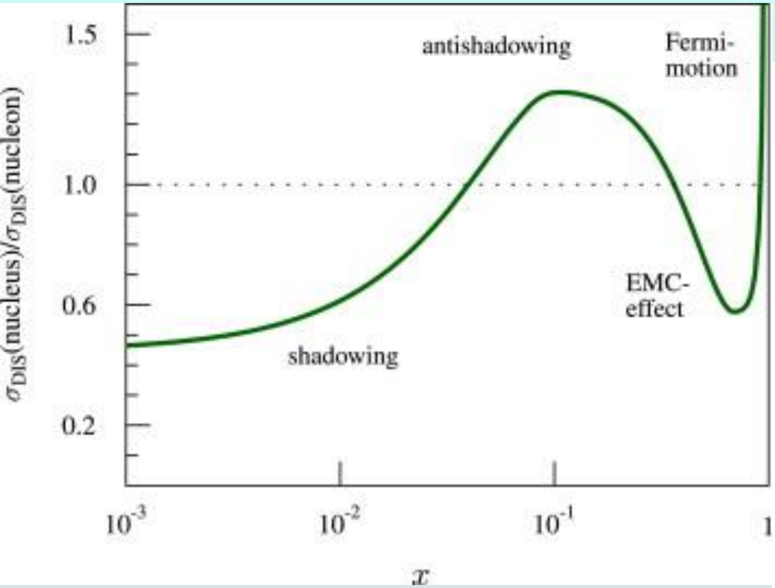
Huge rise in small x gluons

Virtual q-$\bar{q}$ pairs abundant

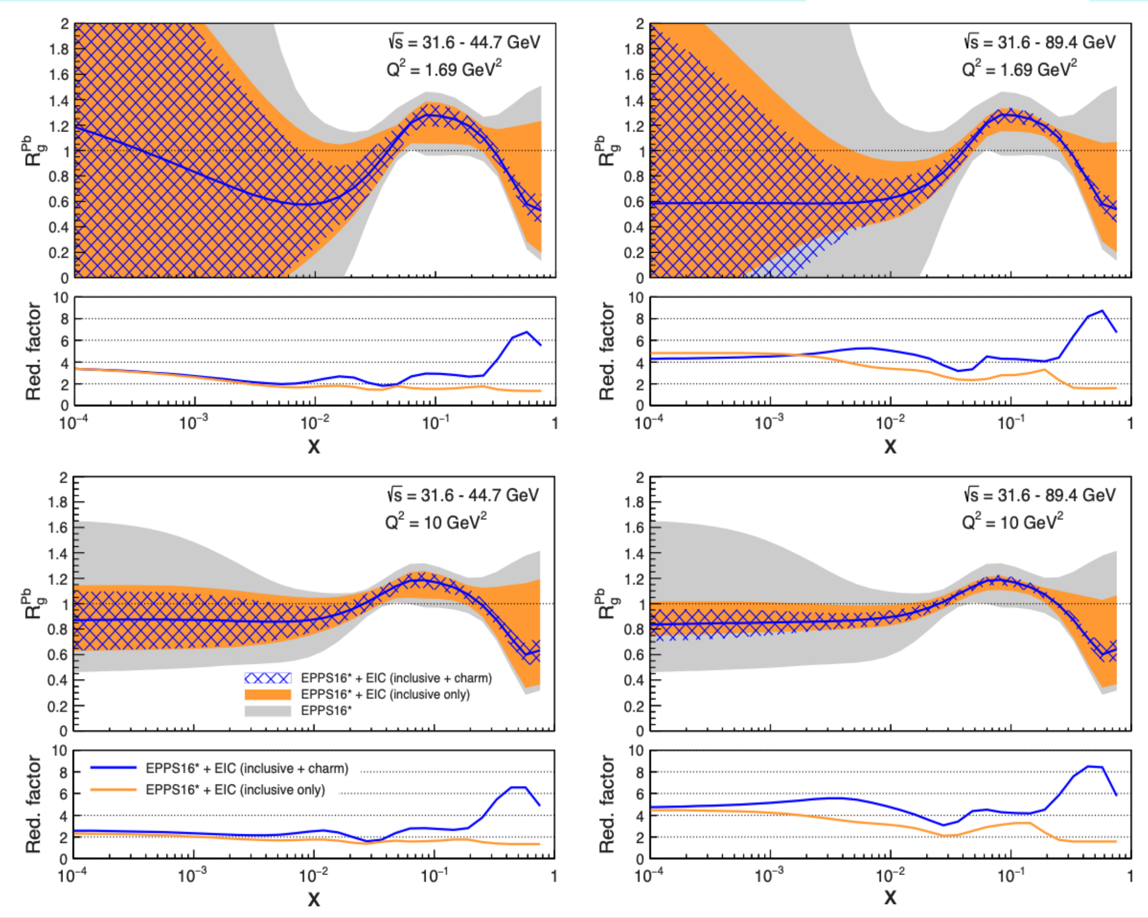
How about in a nucleus?



Gluon distributions from different nucleons overlap

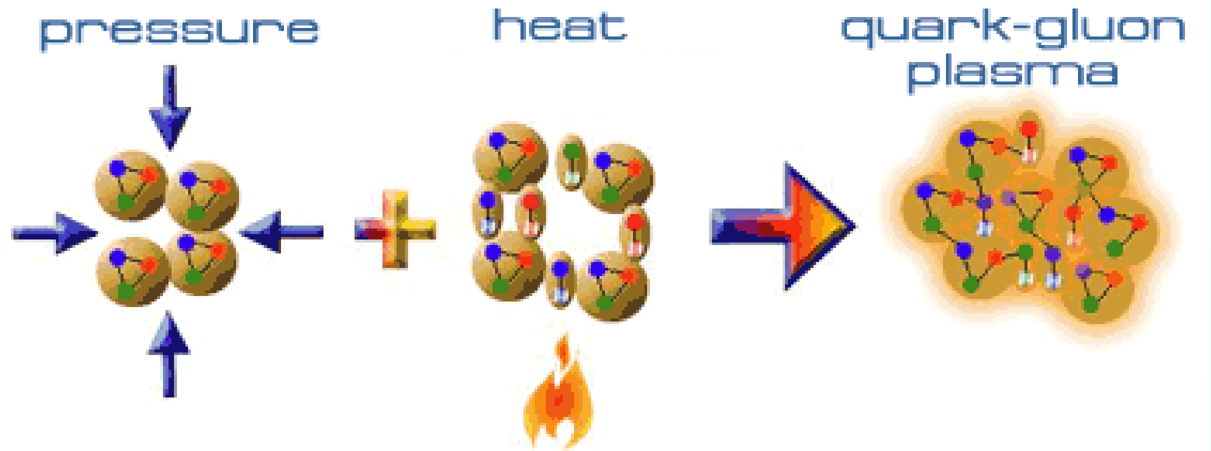


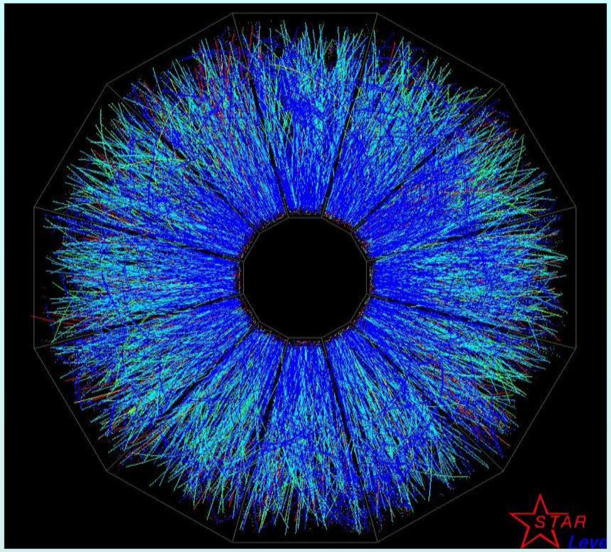
arXiv:1708.01527



Clear evidence of interactions among overlapping gluon distributions!

Next step: Make QCD Matter



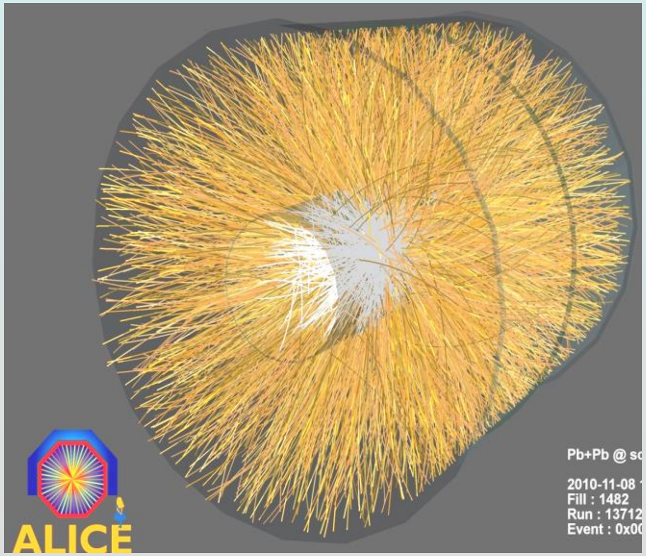


Collide Heavy Ions

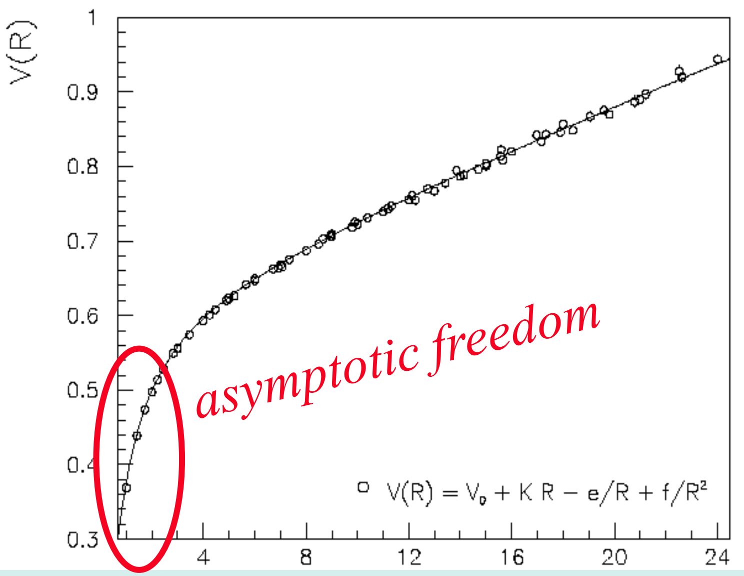
Au+Au at RHIC

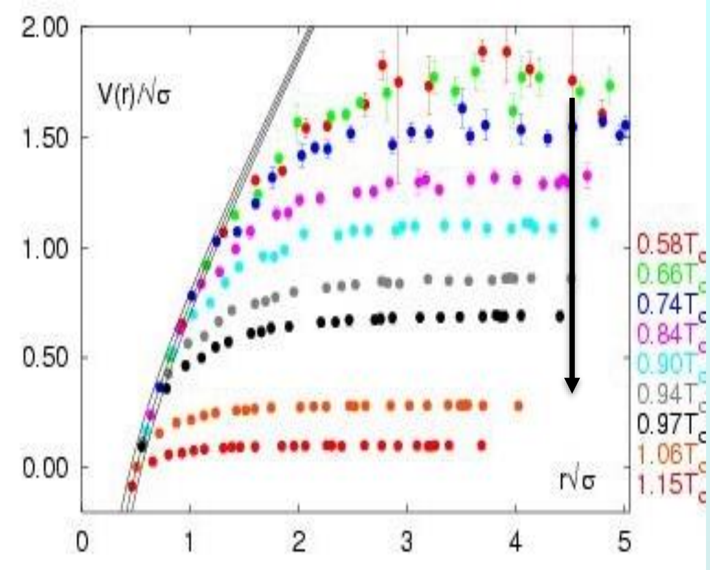
Pb+Pb at LHC

p-p and p+A for comparison



Why?





At high temperature/density

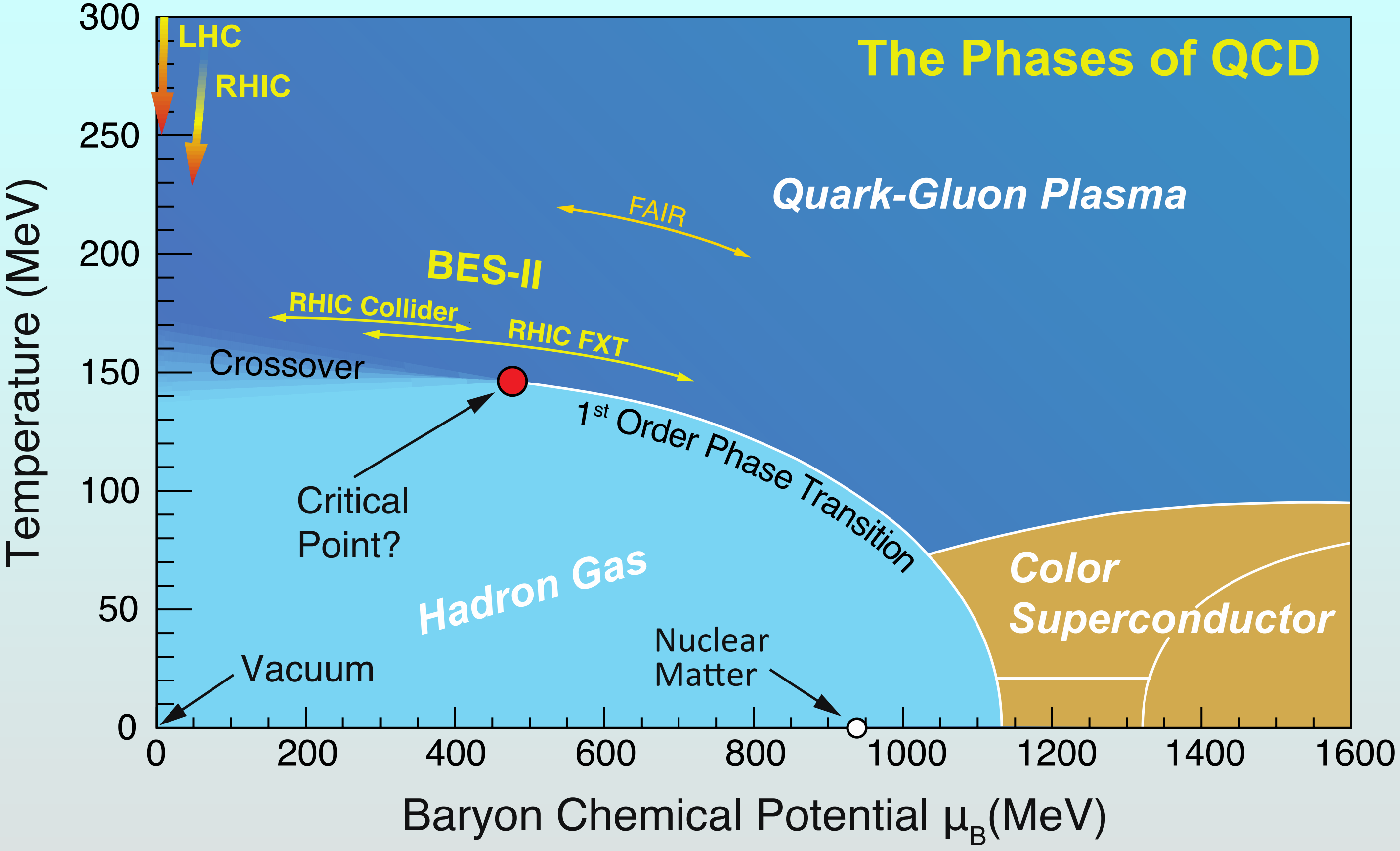
screening by produced colored particles

Expect a phase transition to deconfined

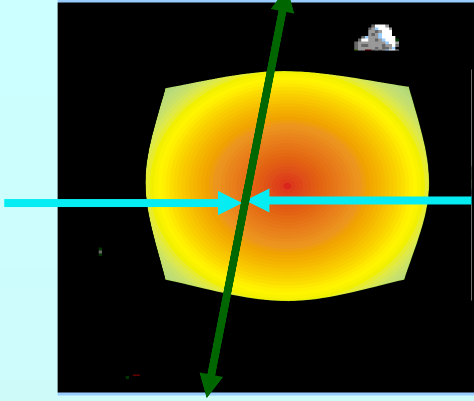
quark gluon plasma

Lattice QCD → T_c ~ 150 MeV

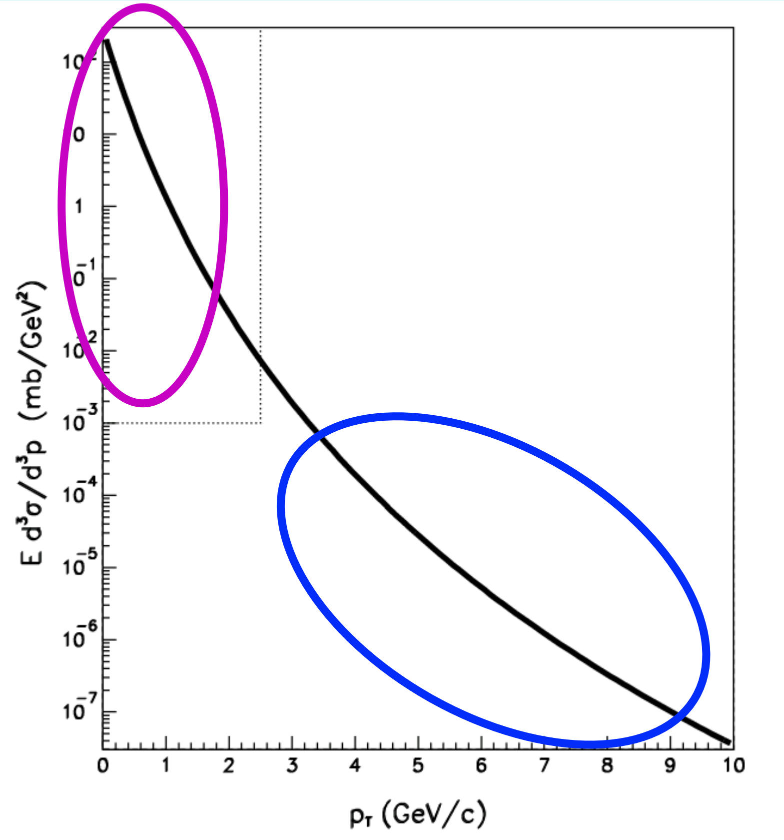
Phase diagram of QCD



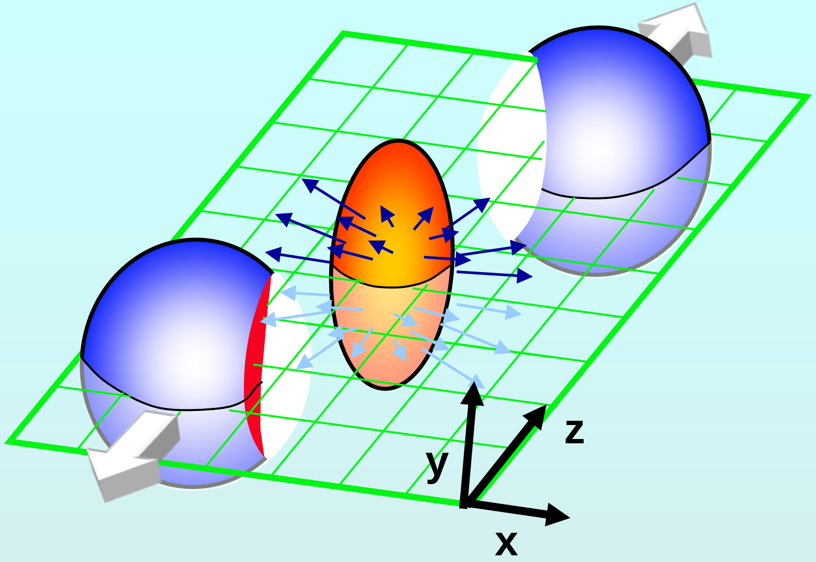
study plasma with radiated & "probe" particles

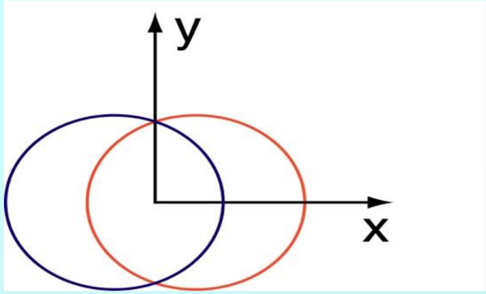


- as a function of transverse momentum
  90° is where the action is (max T, ρ)
  p_L between the two beams: midrapidity
- $p_T < 2$ GeV/c
  "thermal" particles
  radiated from bulk medium
  "internal" plasma probes
- $p_T > 3$ GeV/c
  large E_{tot} (high p_T or M)
  set scale other than T(plasma)
  autogenerated "external" probe
  describe by perturbative QCD
- control probe: photons
  EM, not strong interaction
  produced in Au+Au by QCD
  Compton scattering



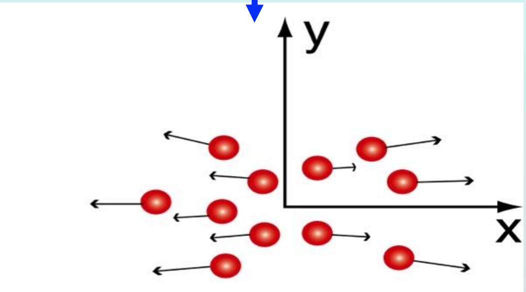
Measure collective behavior

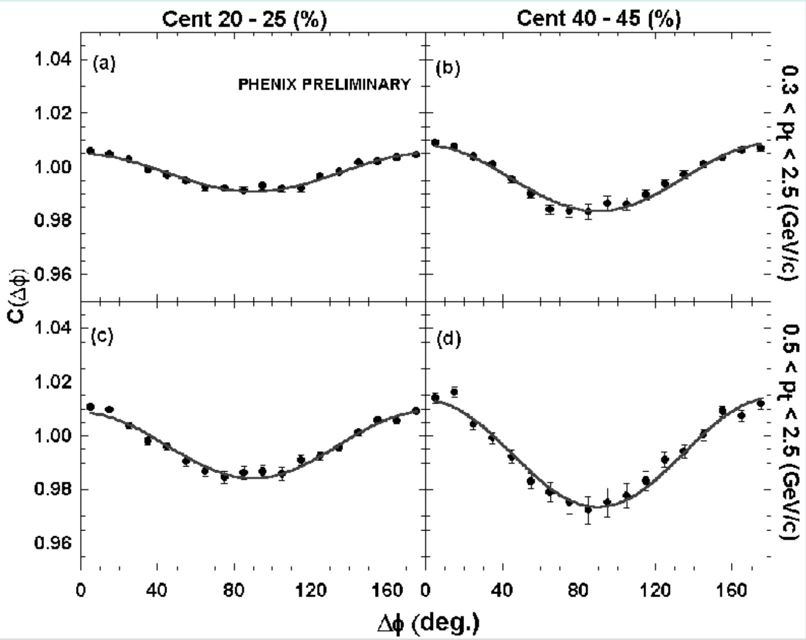




Almond shape overlap region in coordinate space

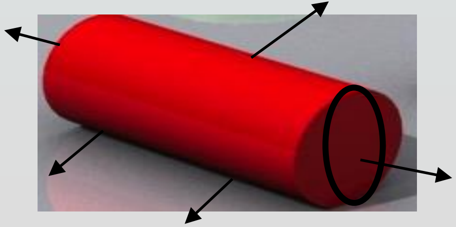
momentum space



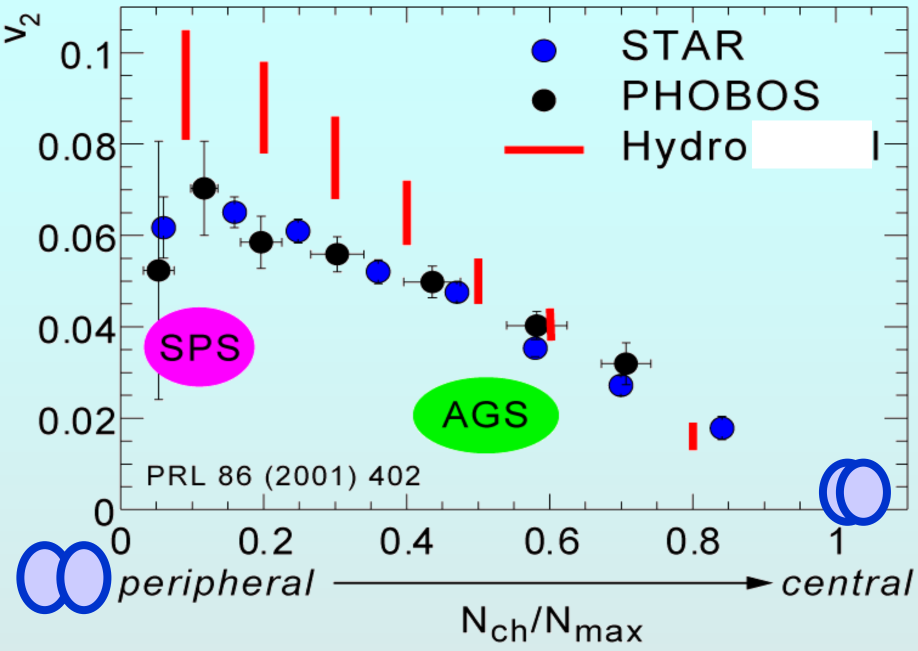


$$dN/d\phi \sim 1 + 2\, v_2(p_T) \cos(2\phi) + \dots$$

"elliptic flow"

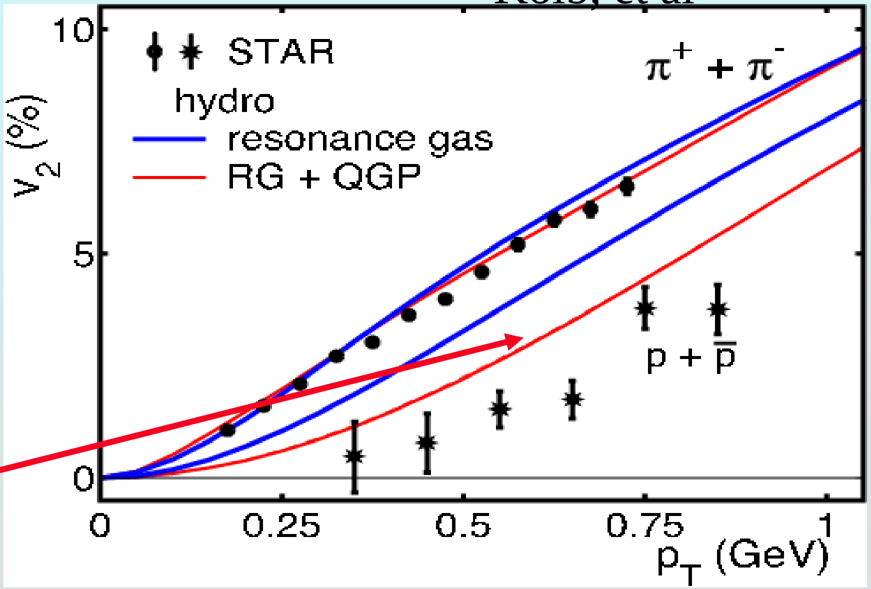


QGP flows , use hydrodynamics



- **large anisotropy!**
- **huge pressure buildup**
- **build up quickly, else hydro misses data**

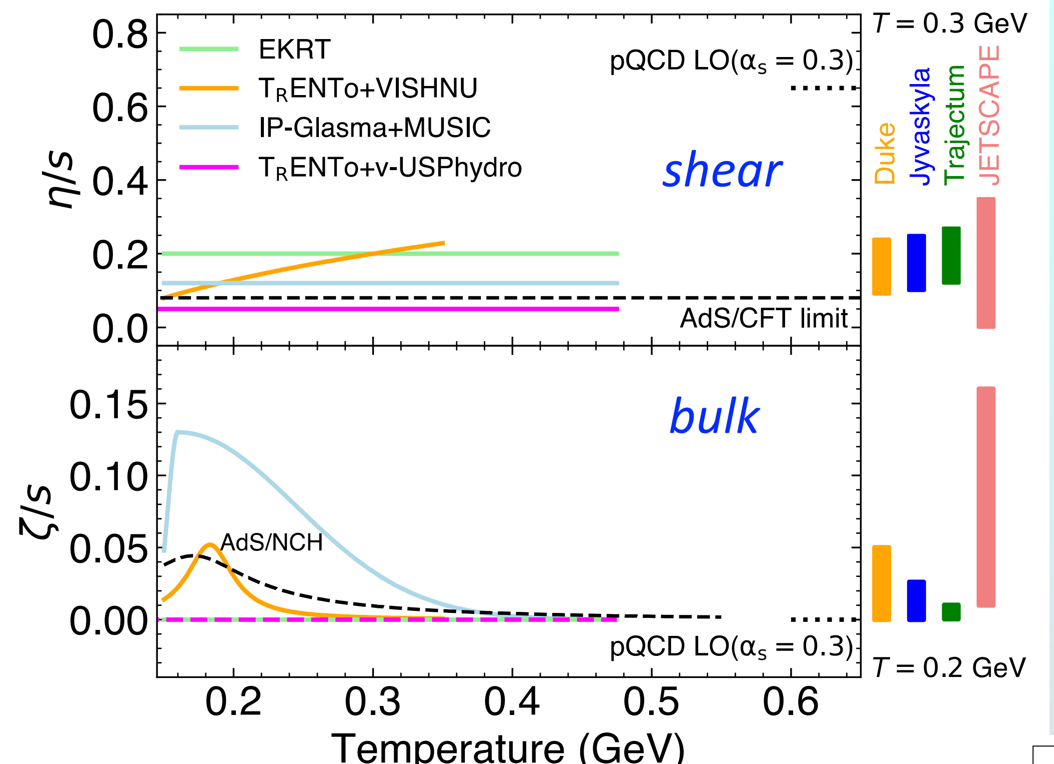
Kolb, et al

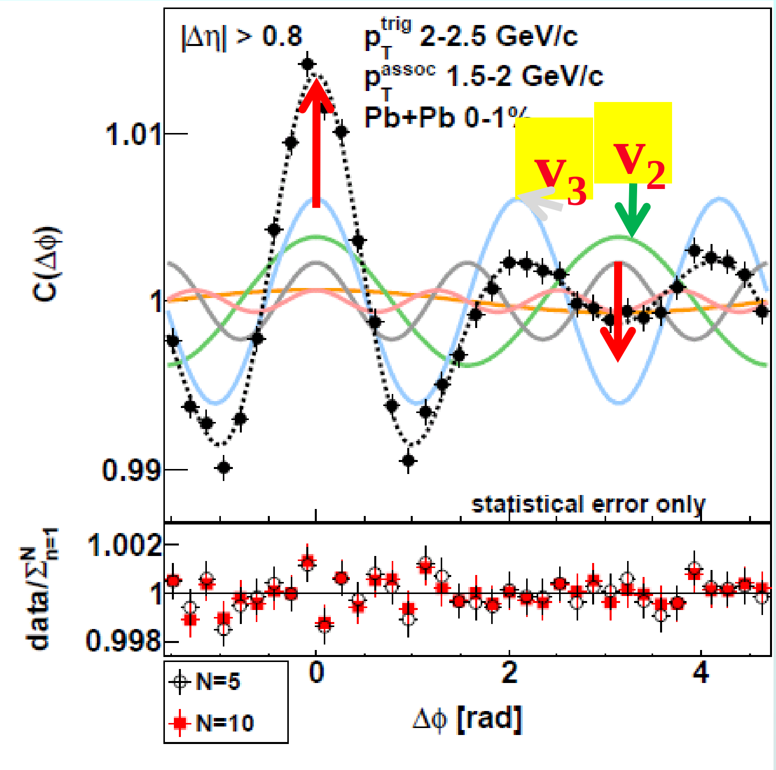


Hydrodynamics reproduces elliptic flow of q-$\bar{q}$ and 3q states
Mass dependence was first signal
QGP - NOT gas of hadrons

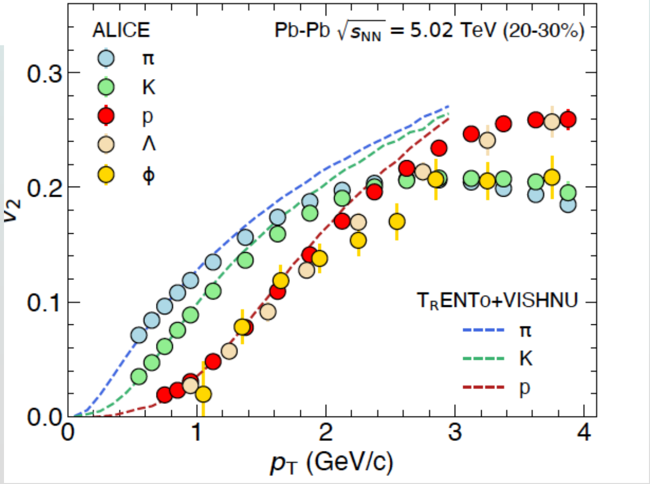
only works with very low viscosity/entropy
"perfect" liquid (D. Teaney, PRC68, 2003)
Many advances in relativistic viscous hydrodynamics in 20 years!

QGP property: viscosity per particle



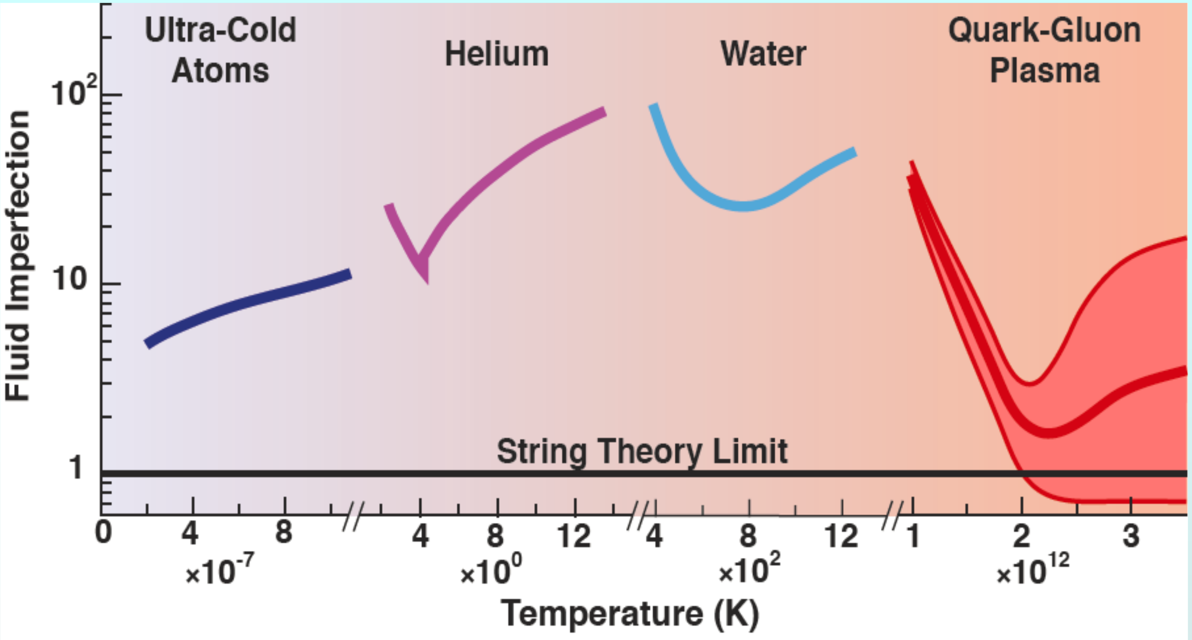


Bulk viscosity = resistance to volume growth



Compare to other fluids

$\eta/s * 2\pi$



hydrodynamic flow -> Nearly perfect liquid

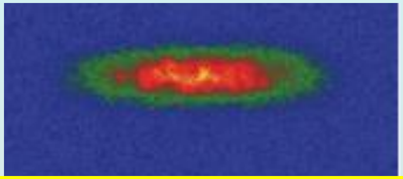
QGP is a strongly coupled QCD fluid!

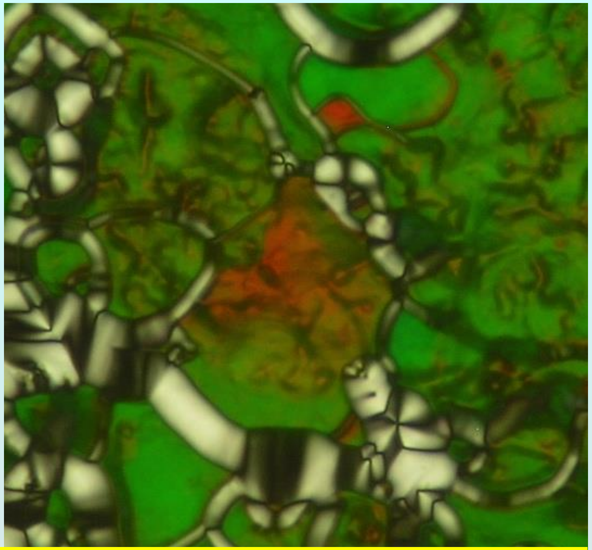
partons deconfined, but α_s is not so small

Many types of strongly coupled matter

Quark gluon plasma is like other systems with strong coupling
- all flow and exhibit phase transitions

Cold atoms: coldest & hottest matter on earth are alike!





Dusty plasmas &

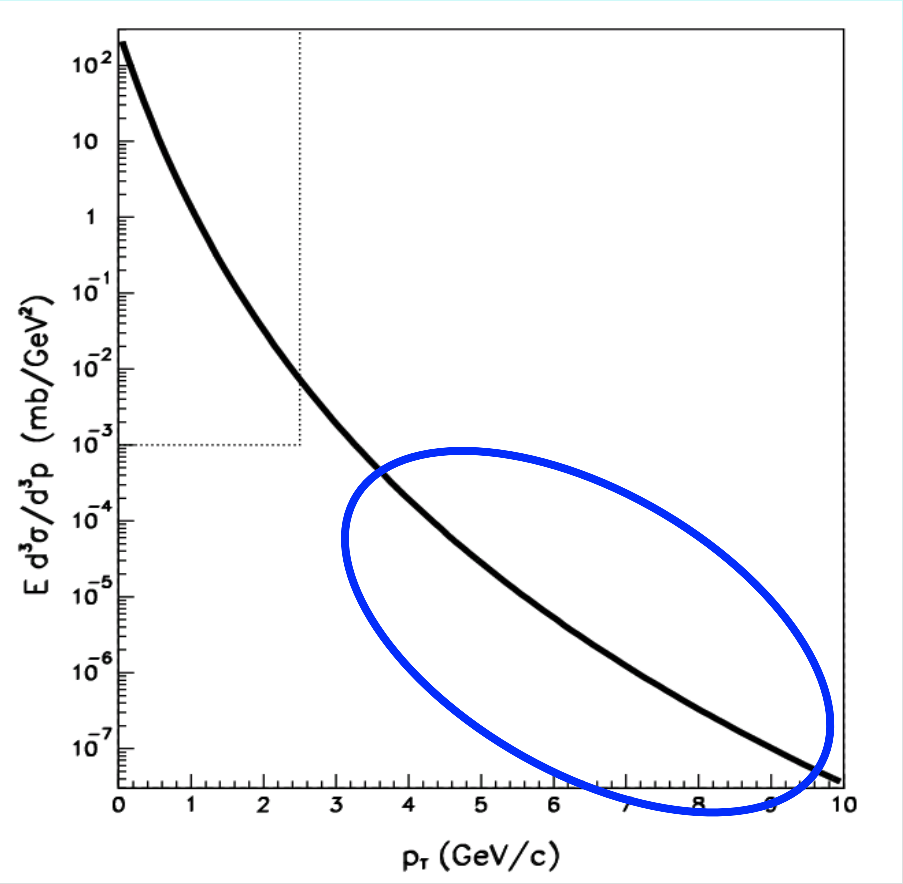
In all these cases have a competition:

Attractive forces ⇔ repulsive force or kinetic energy

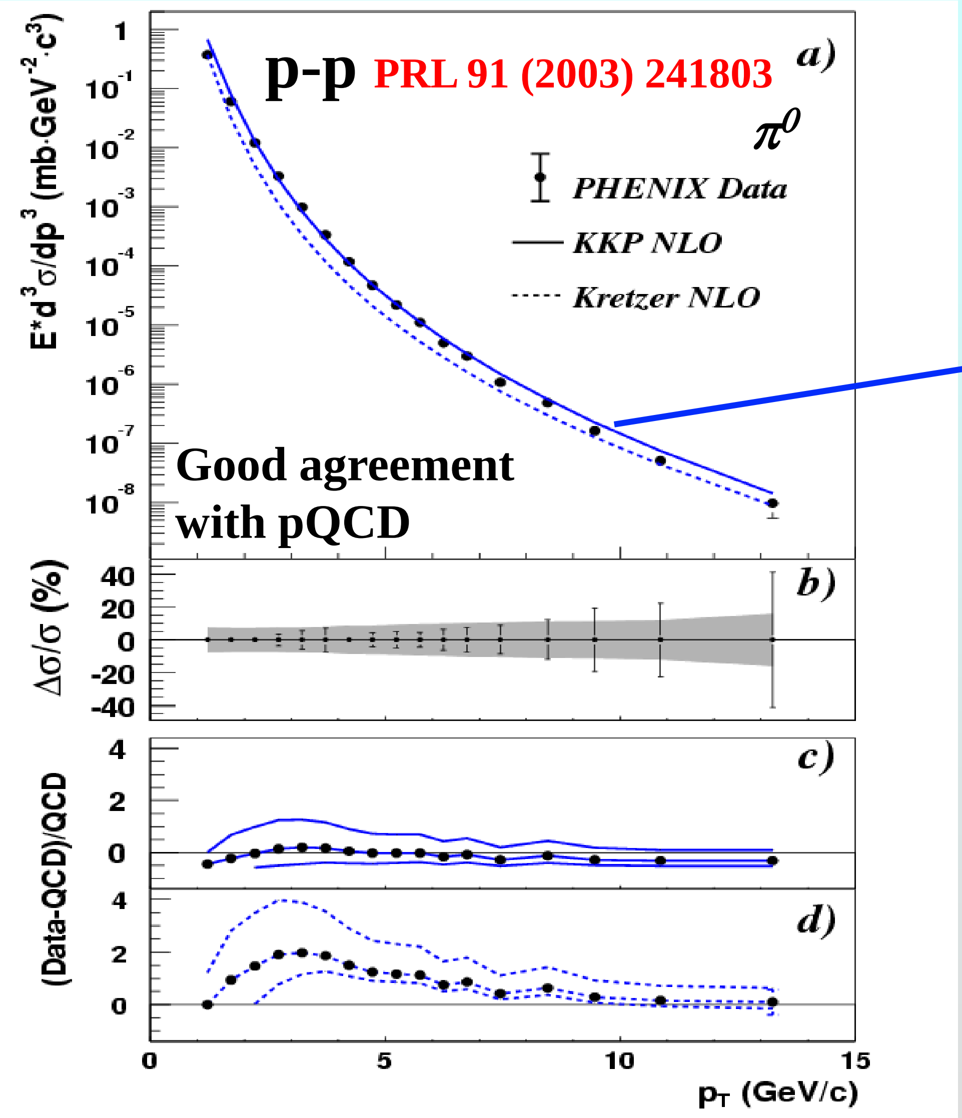
High T_c superconductors: magnetic vs. potential energy

Result: many-body interactions, not pairwise!

Interaction of quarks and gluons in plasma

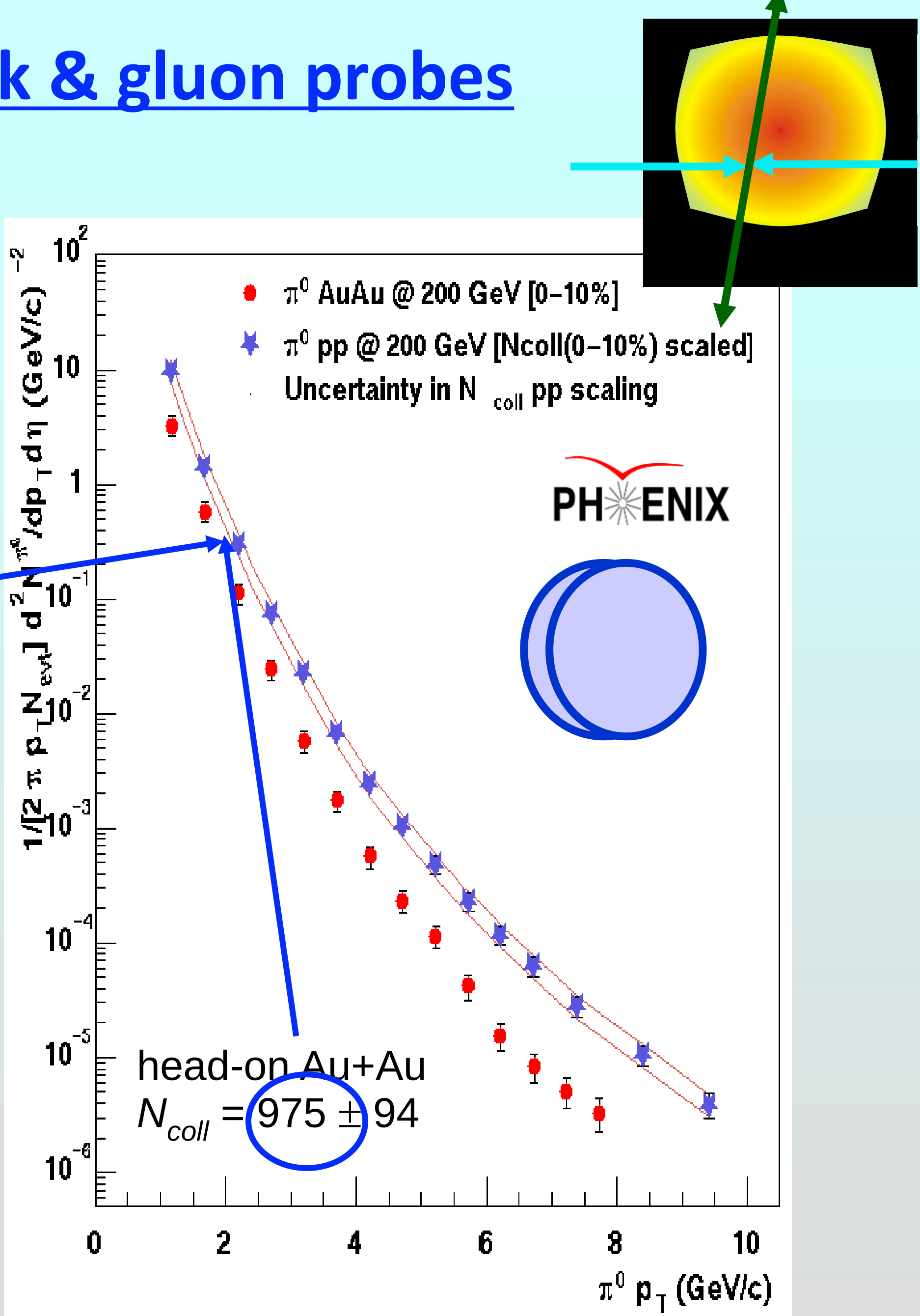


Opacity? Use quark & gluon probes



p-p PRL 91 (2003) 241803

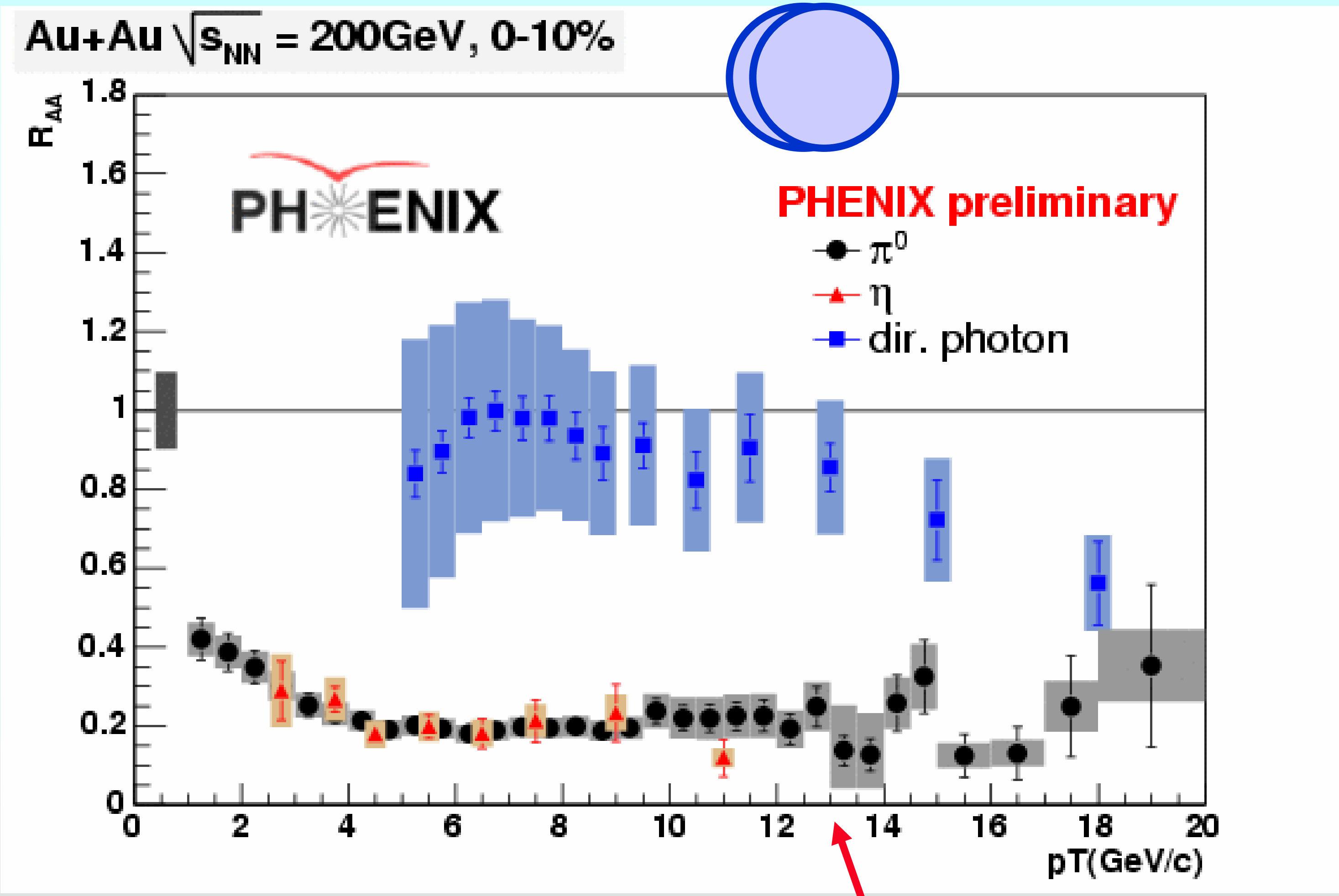
Good agreement with pQCD



head-on Au+Au

N_{coll} = 975 ± 94

Jets are quenched, photons are not

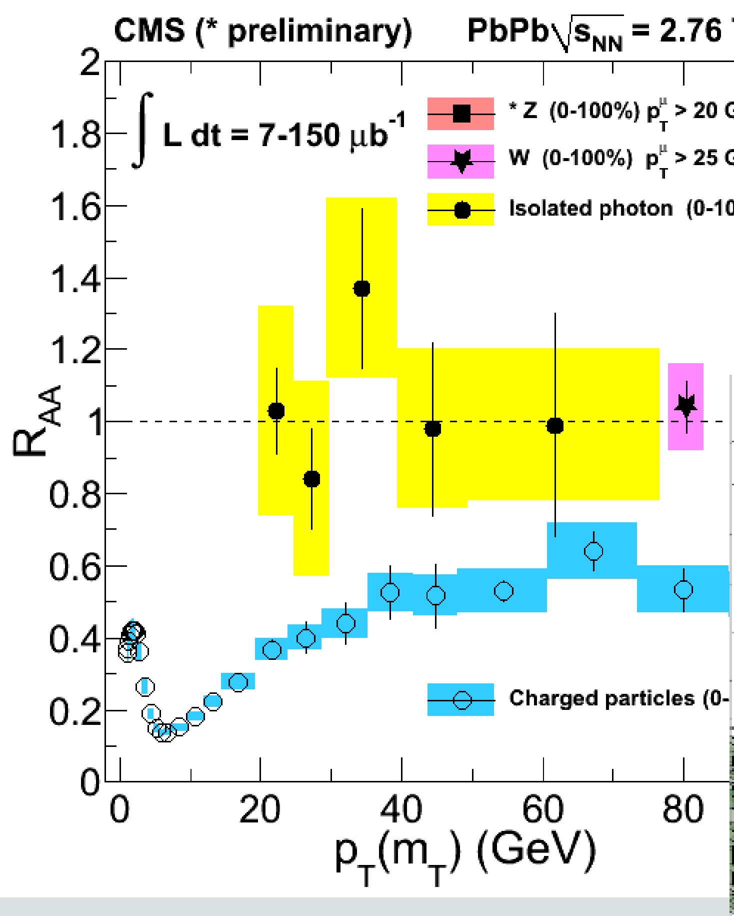


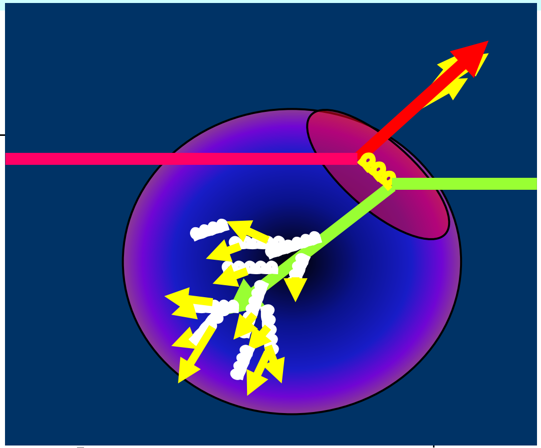
Nuclear modification factor:

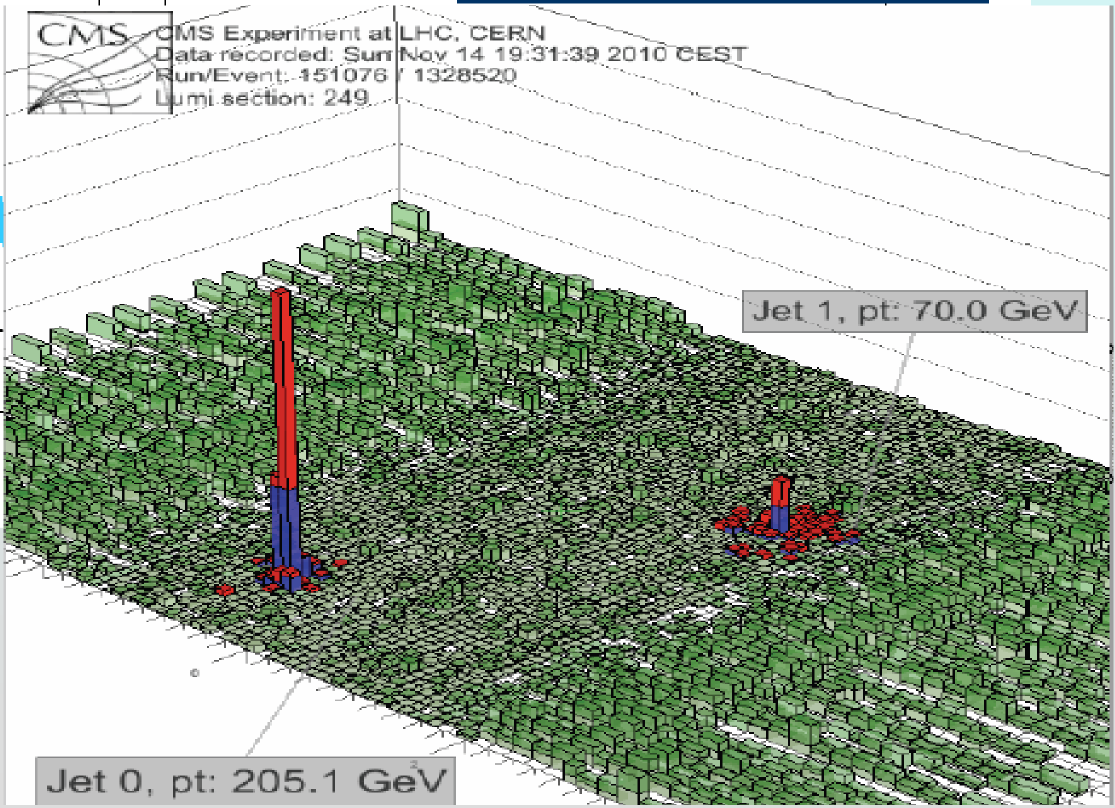
$$R_{AA}(p_T) = \frac{d^2N^{AA}/dp_T d\eta}{T_{AA} d^2\sigma^{NN}/dp_T d\eta}$$

VERY opaque! Gluon radiation (bremsstrahlung) induced

Energy loss even by very energetic q & g





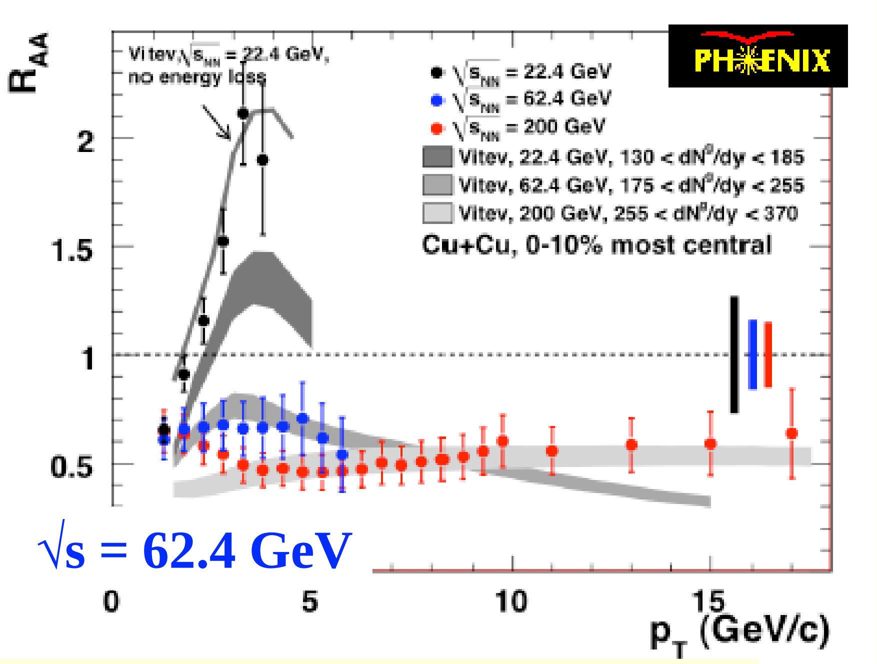


- LHC experiments reac

Suppression sets in between 27 & 39 GeV √s

Cu+Cu

√s = 20 GeV

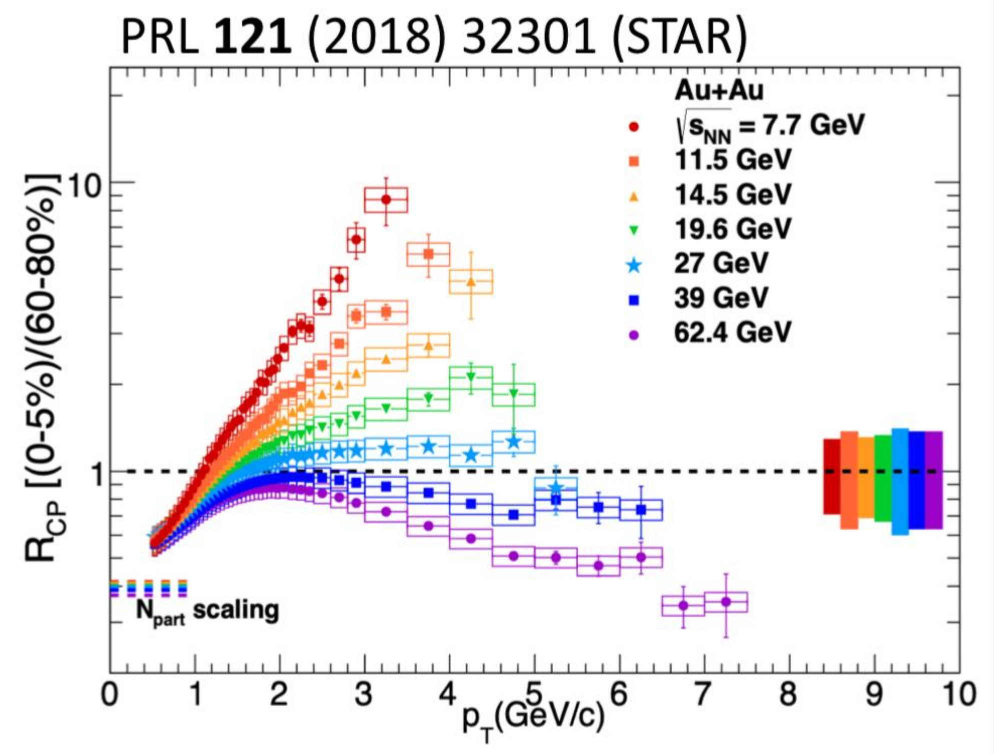


√s = 62.4 GeV

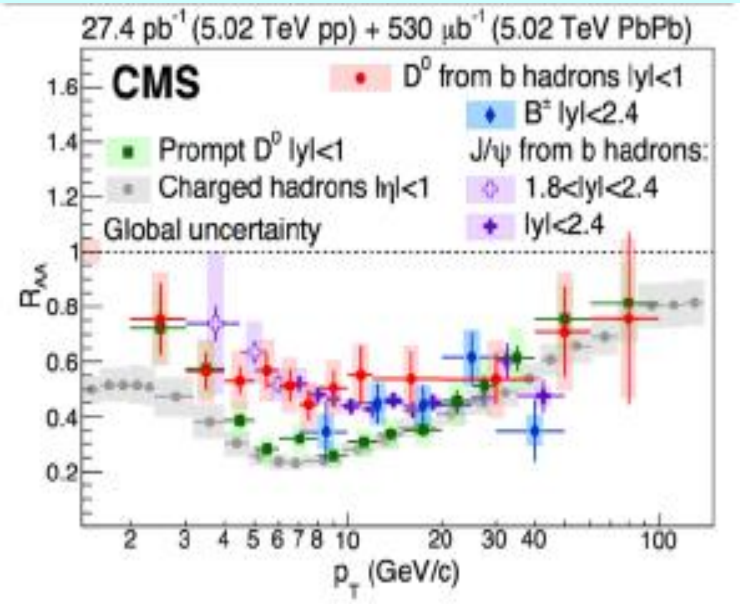
PRL 101, 162301 (2008)

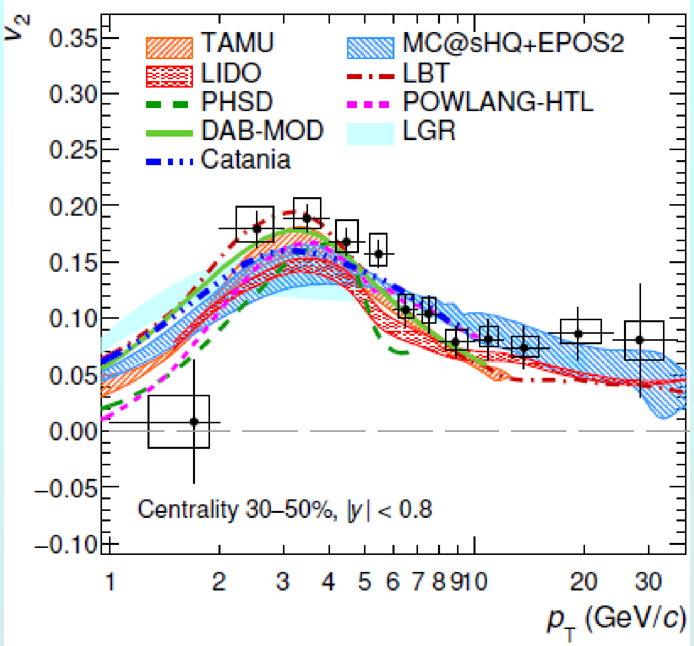
√s = 200 GeV

Au+Au


PRL **121** (2018) 32301 (STAR)

Surprise: heavy quarks lose energy & flow





Mix of radiation + collisions (diffusion)

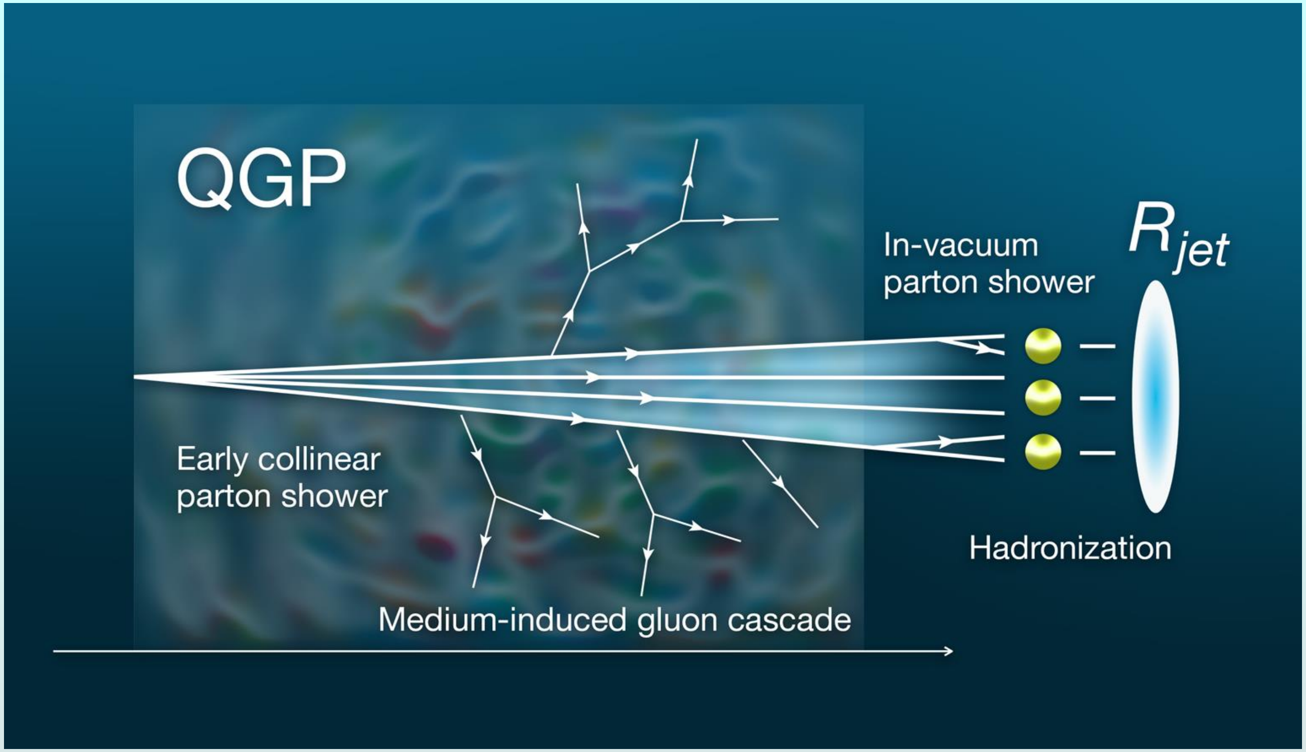
but collisions with what?

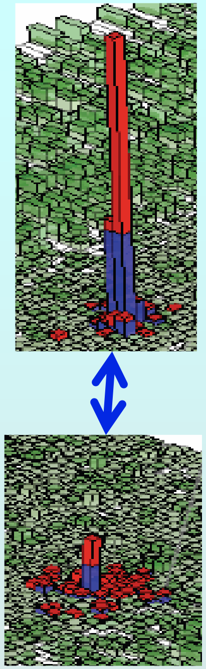
Drag force of strongly coupled plasma on moving quark?

Data vs. models including radiation, collisions, medium evolution

$D_s(2\pi T) = 1.5$ - 4.5 near T_c χ^2/DOF < 5 (2) for R_{AA} (v_2)

Connect observations to QCD





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

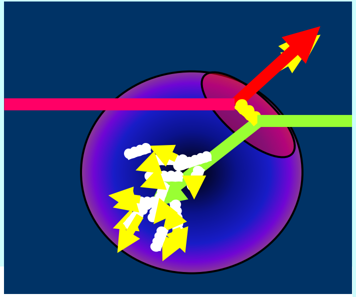
Partons radiate gluons, which collect into final state hadrons ("fragmentation")

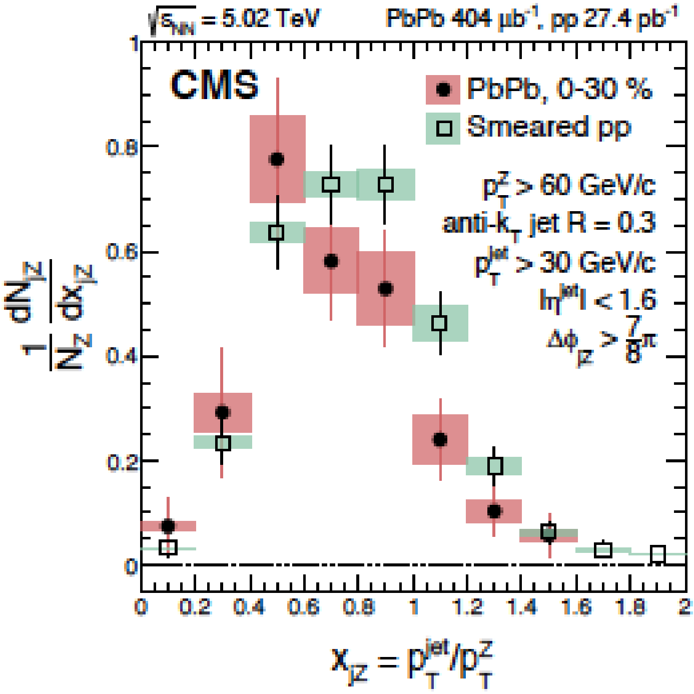
The hadrons are co-moving and boosted by quark's momentum

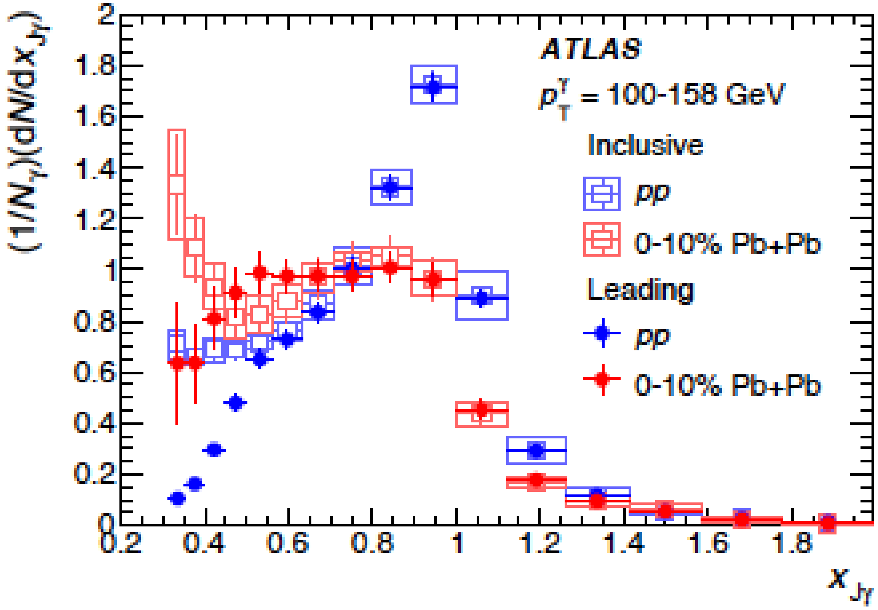
We detect them as jets of hadrons

Energy unbalanced in γ, Z – tagged jets

With photon or Z, you know the initial energy

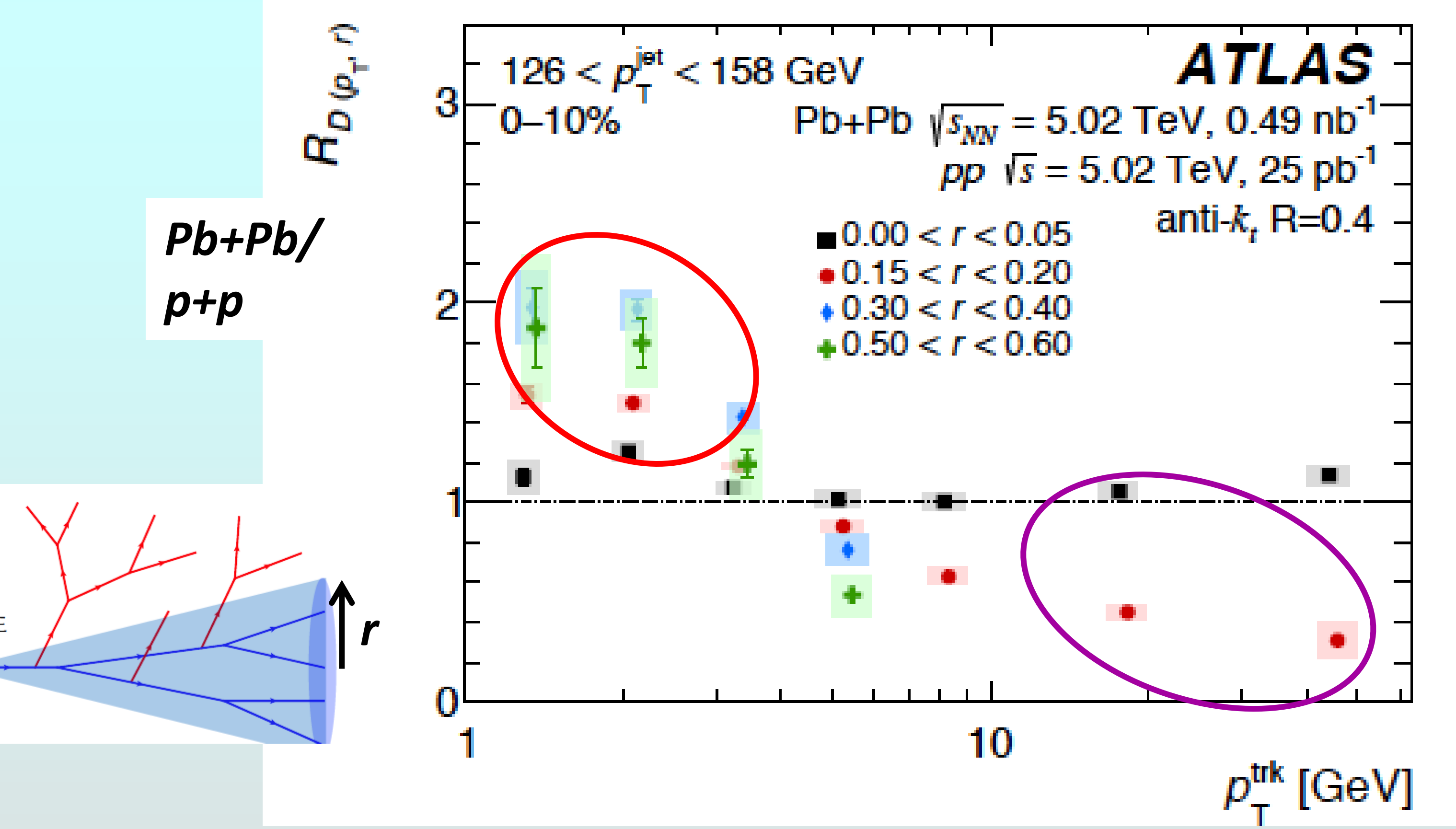






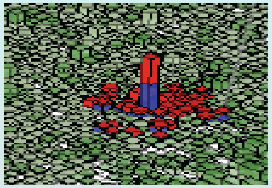
- Plasma reduces the jet's energy. Jet and boson p_T no longer balance

p_T vs. r of jet fragments



arXiv: 1908.05264

See also: CMS
arXiv: 1803.00042



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

Jet substructure

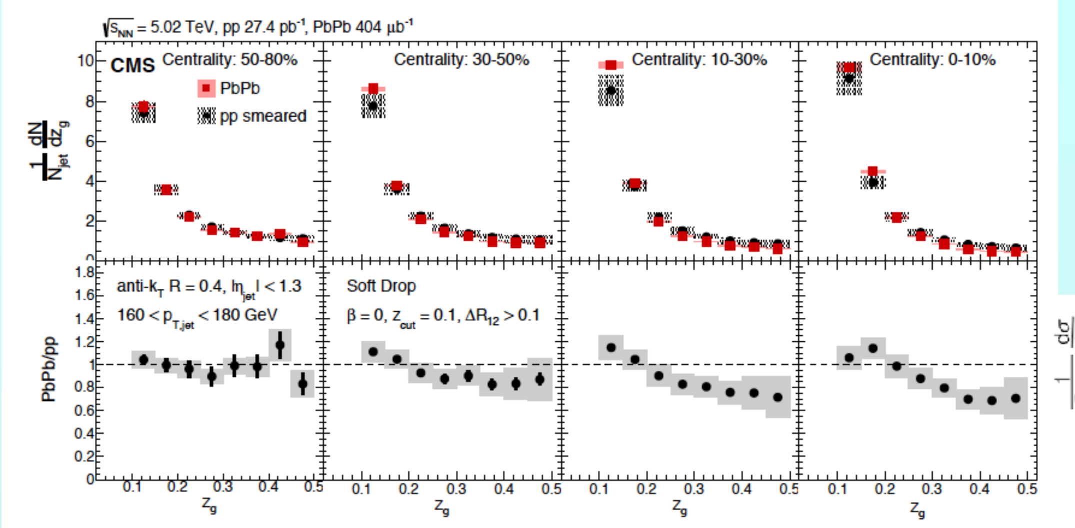
- Compare data to pQCD

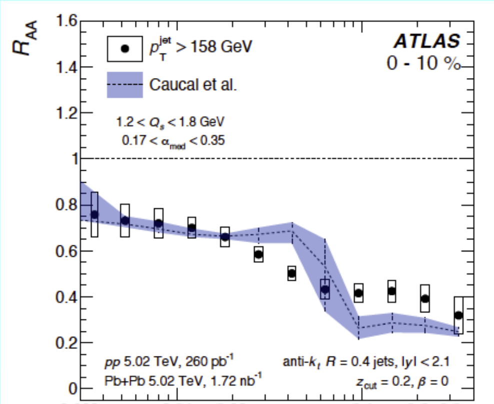
- Find observables that avoid singularities
  e.g. jet axis, z_g, θ_g, jet mass, angularities,
  n-sub jettiness, energy flow, etc.

- Groom jets to remove underlying event & minimize non-perturbative physics

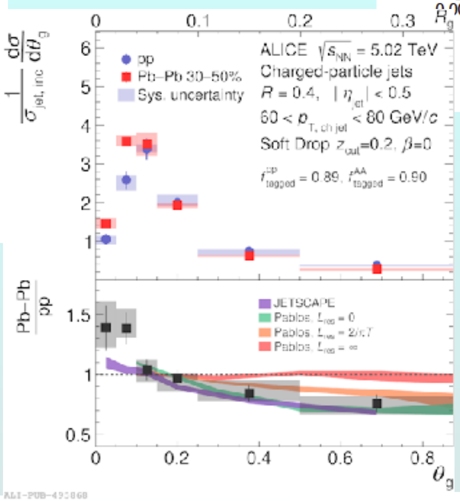
- Compare light and heavy quark jets
  And Pb+Pb to pp collisions

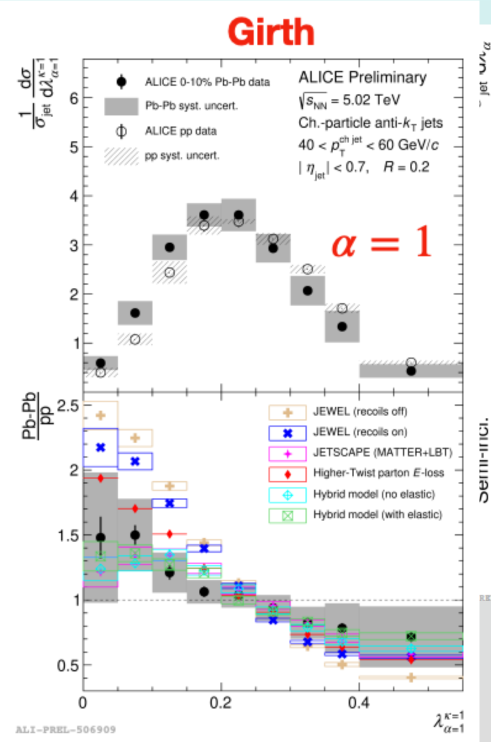
Much substructure data

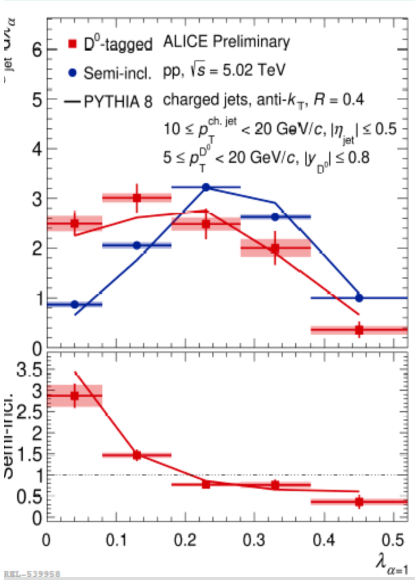


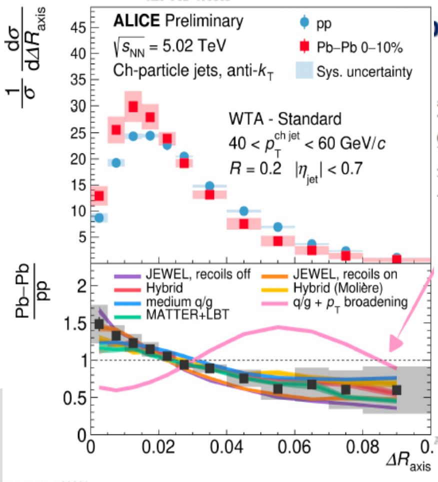


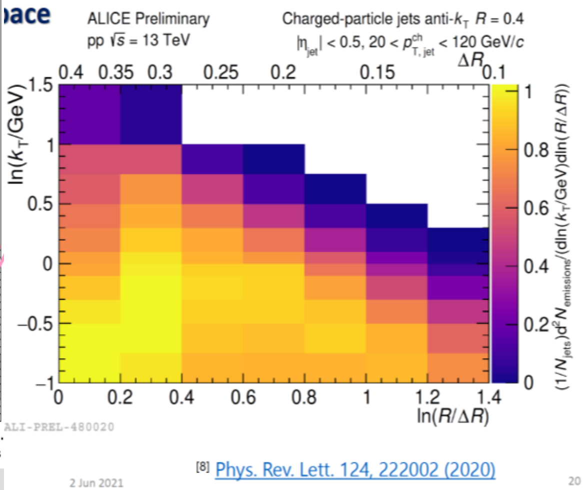
ATLAS arXiv:2211.11470





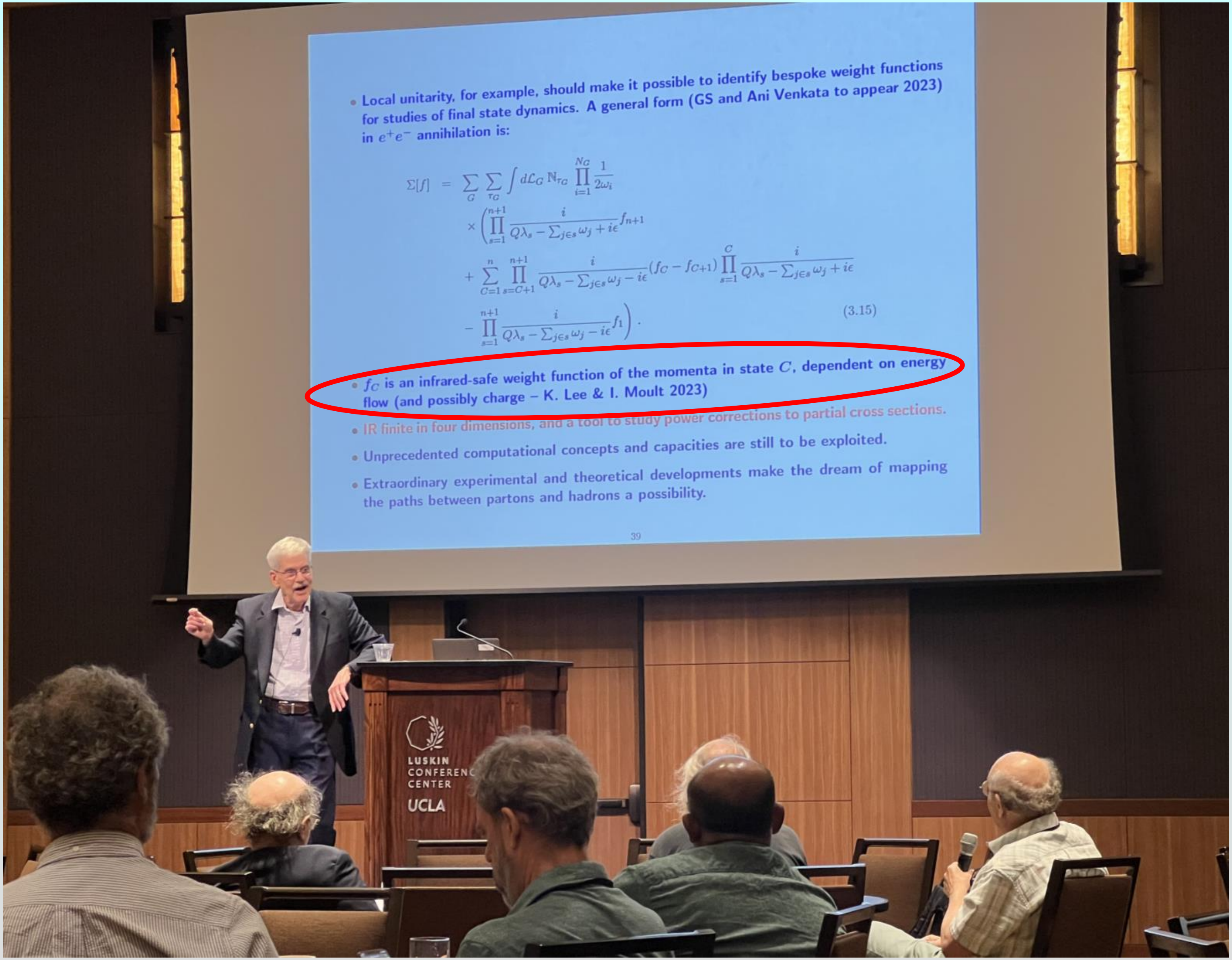






[8] Phys. Rev. Lett. 124, 222002 (2020)

Ask and you shall receive…



- Local unitarity, for example, should make it possible to identify bespoke weight functions for studies of final state dynamics. A general form (GS and Ani Venkata to appear 2023) in e^+e^- annihilation is:

$$\begin{aligned}\Sigma[f] \;=\; & \sum_G \sum_{\tau_G} \int d\mathcal{L}_G \, \mathbb{N}_{\tau_G} \prod_{i=1}^{N_G} \frac{1}{2\omega_i} \\ & \times \left(\prod_{s=1}^{n+1} \frac{i}{Q\lambda_s - \sum_{j\in s}\omega_j + i\epsilon} f_{n+1} \right. \\ & + \sum_{C=1}^{n} \prod_{s=C+1}^{n+1} \frac{i}{Q\lambda_s - \sum_{j\in s}\omega_j - i\epsilon} (f_C - f_{C+1}) \prod_{s=1}^{C} \frac{i}{Q\lambda_s - \sum_{j\in s}\omega_j + i\epsilon} \\ & \left. - \prod_{s=1}^{n+1} \frac{i}{Q\lambda_s - \sum_{j\in s}\omega_j - i\epsilon} f_1 \right) . \end{aligned} \tag{3.15}$$

- f_C is an infrared-safe weight function of the momenta in state C, dependent on energy flow (and possibly charge – K. Lee & I. Moult 2023)
- IR finite in four dimensions, and a tool to study power corrections to partial cross sections.
- Unprecedented computational concepts and capacities are still to be exploited.
- Extraordinary experimental and theoretical developments make the dream of mapping the paths between partons and hadrons a possibility.

Energy flow via energy-energy correlators

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

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

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

ε is the asymptotic energy flow operator

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

$$EEC(R_L) =$$

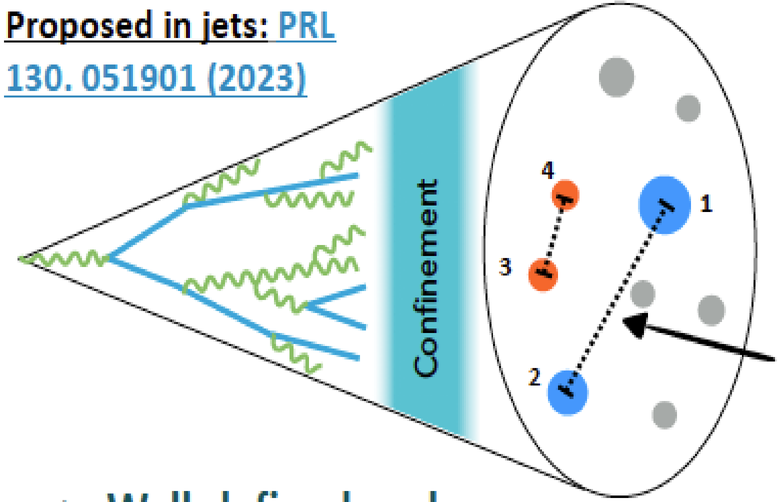
$$\sum_{pairs} \frac{p_{T1}\, p_{T2}}{p_{T,jet}^2} \text{ with } R_L = \sqrt[2]{\Delta\varphi^2 + \Delta\eta^2}$$

- **This is a weighted two-particle correlation function;**

  plot vs. R_L

energy-energy correlators inside jets

Proposed in jets: PRL 130. 051901 (2023)

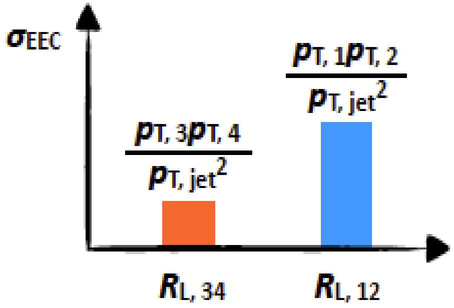


Count number of weighted pairs as function of R_L

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

Energy weight

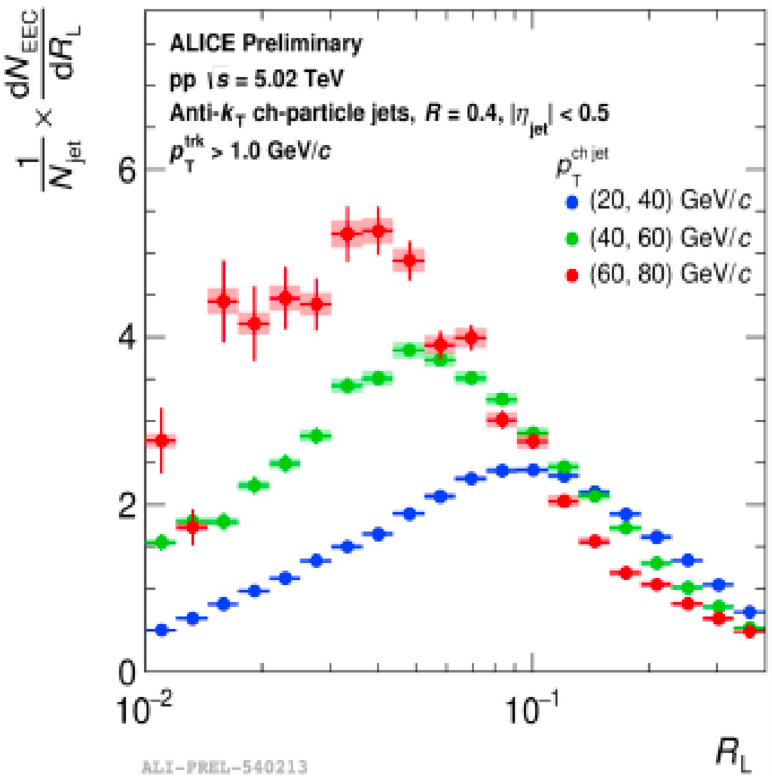
$$\frac{d\sigma_{EEC}}{dR_L} = \sum_{i,j}\int d\sigma(R'_L)\frac{p_{T,i}\,p_{T,j}}{p^2_{T,\mathrm{jet}}}\delta(R'_L - R_{L,ij})$$



- Well-defined probe
  - IRC safe + pQCD calculation available: K. Lee, B. Mecaj, I. Moult (arXiv:2205.03414)
  - Soft contribution (MPI, UE) power suppressed by energy weight: no need for grooming when comparing to pQCD calculation

EEC in 5 TeV pp colliisions

Wenqing Fan



ALI-PREL-540229

increasing time

Small angle ← Large angle

decreasing energy scale

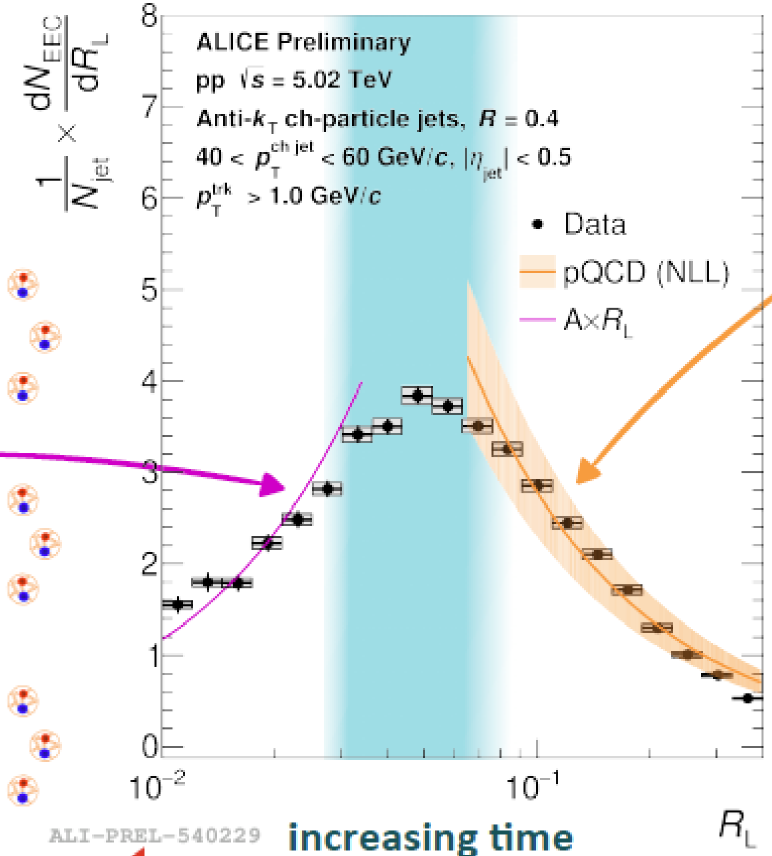
EEC in 5 TeV pp collisions

Confinement

$$\frac{d\sigma}{dR_L^2} = \text{constant}$$

$$\rightarrow \frac{d\sigma}{dR_L} \propto R_L$$

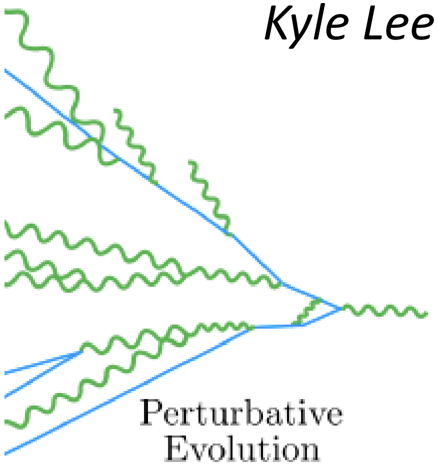
Free hadron scaling (hadronic degree of freedom)



pQCD scaling (partonic degree of freedom)

Calculation:

Kyle Lee



increasing time

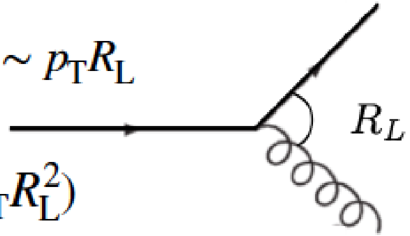
Small angle

Large angle

decreasing energy scale

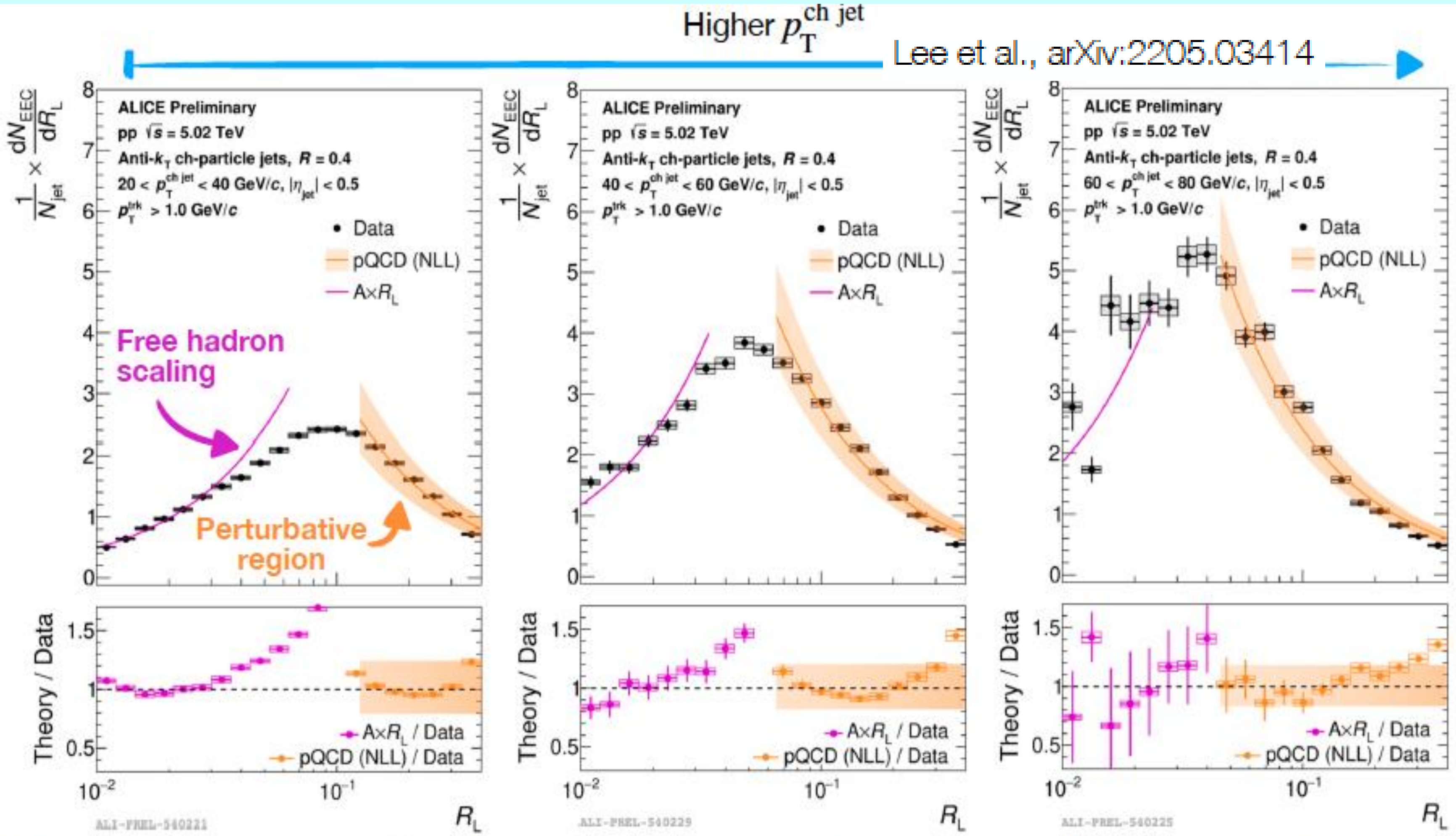
virtuality $\sim p_T R_L$

$\tau \simeq 1/(p_T R_L^2)$



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

Separate pQCD, hadronization & hadron gas



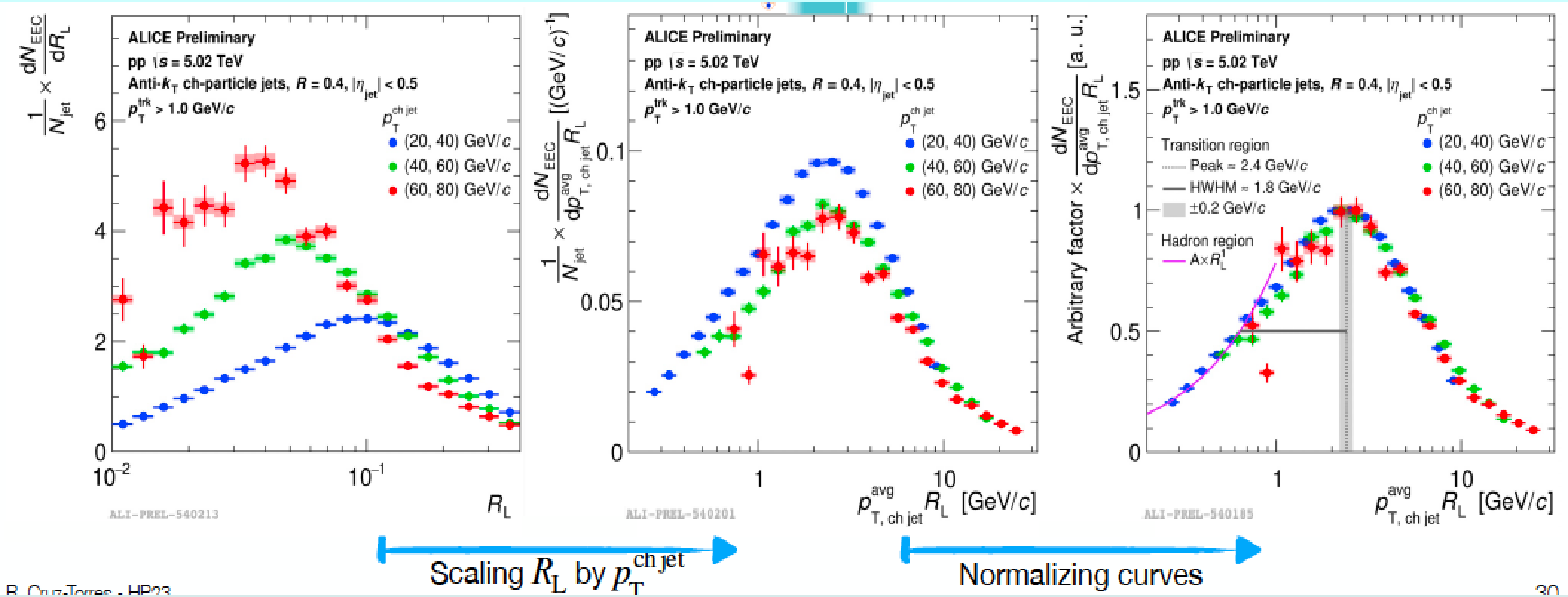
Lee et al., arXiv:2205.03414

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 = hadronization

Check for scaling

Wenqing Fan



Scaling R_L by $p_T^{ch\ jet}$

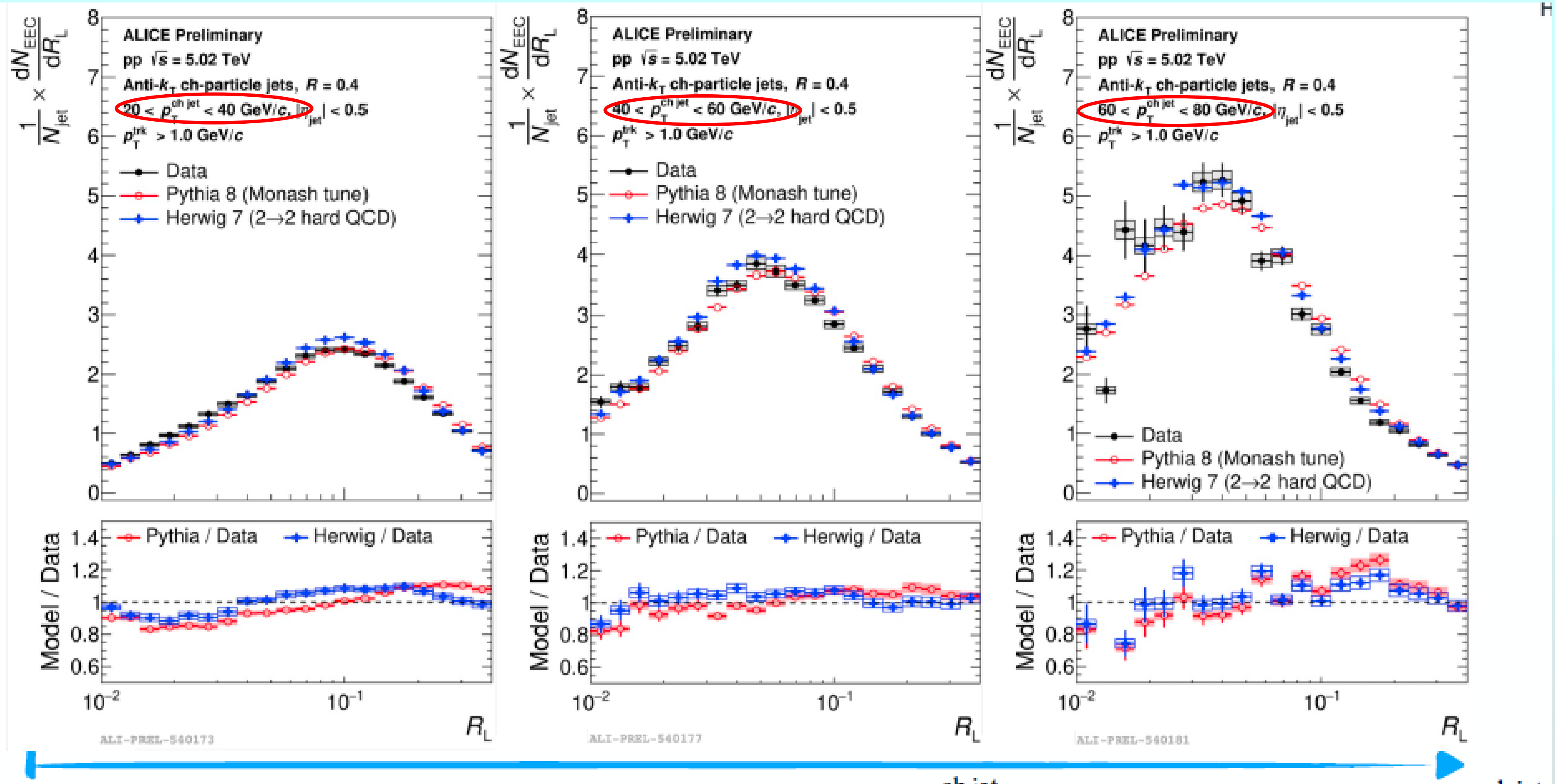
Normalizing curves

R. Cruz-Torres - HP23

30

- p_T*R_L ~ virtuality at which radiation stops
- Common shape for all jet energies – universal transition! HWHM = 1.8 ± 0.2 GeV/c
- Peak at 2.4 GeV. *What is magic about that?*

Compare data to models Pythia & Herwig

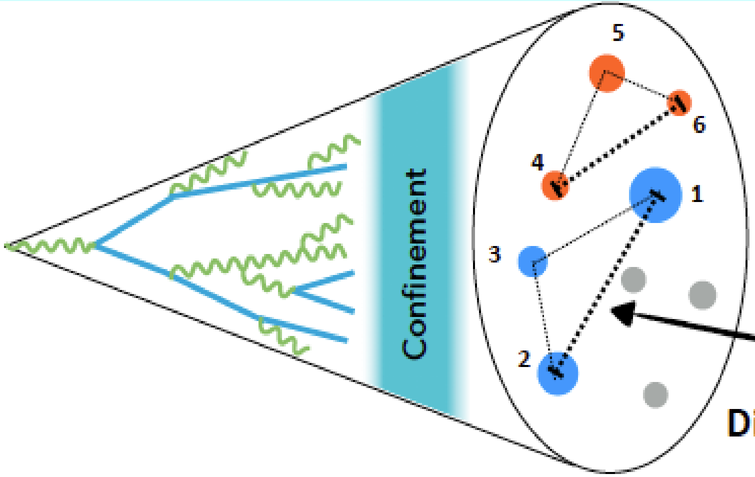


Peak shifts to lower R_L at higher $p_T^{\text{ch jet}}$

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

- **Herwig (hadronization via clusters) agrees better with the data**
- **But data are somewhat broader than Herwig.**

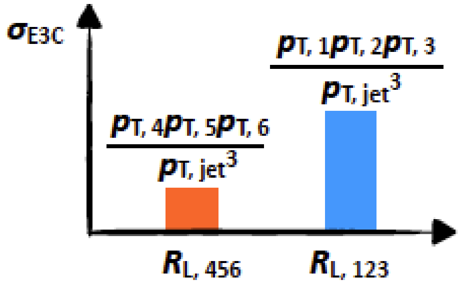
3-point energy correlators



Count number of weighted **triplets** as function of R_L

$$\frac{d\sigma_{E3C}}{dR_L} = \sum_{i,j,k}\int d\sigma(R'_L)\,\frac{p_{T,i}\,p_{T,j}\,p_{T,k}}{p_{T,\,jet}^3}\,\delta(R'_L - R_{L,ijk})$$

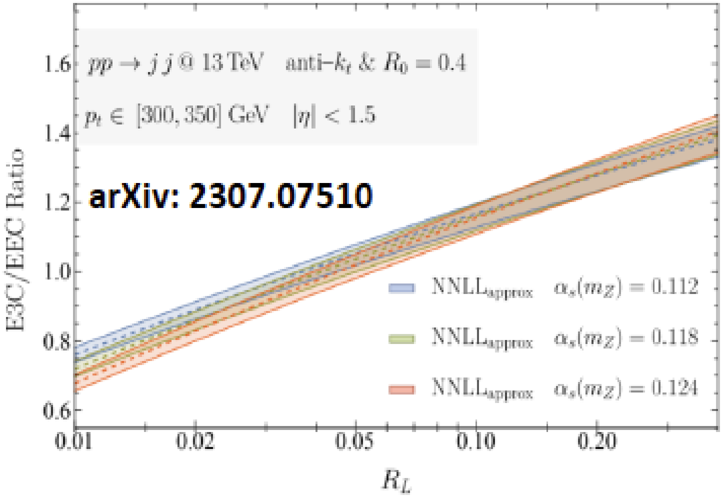
Energy weight



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

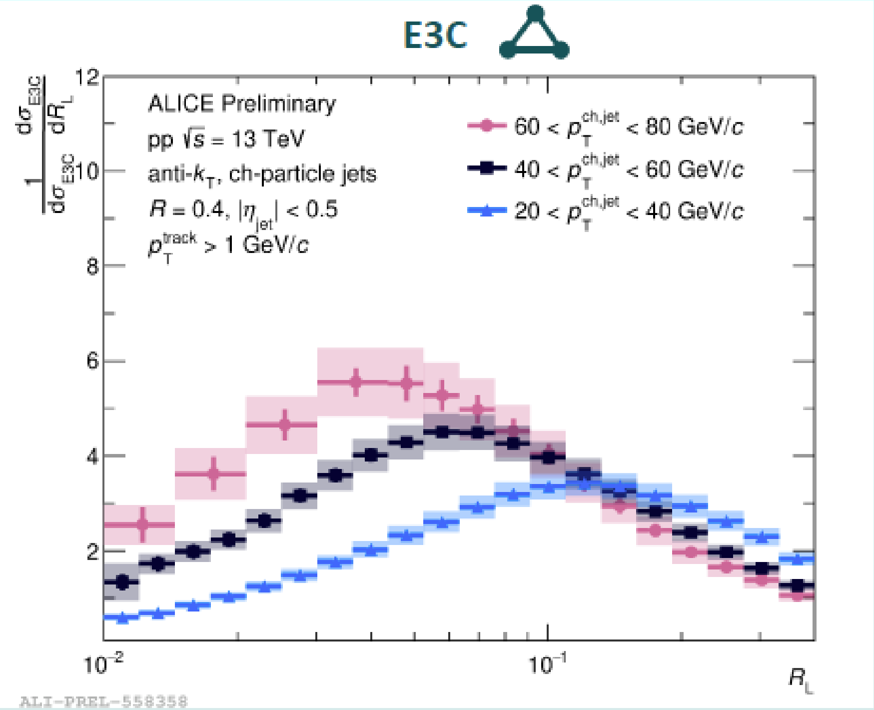
Distance along the longest side

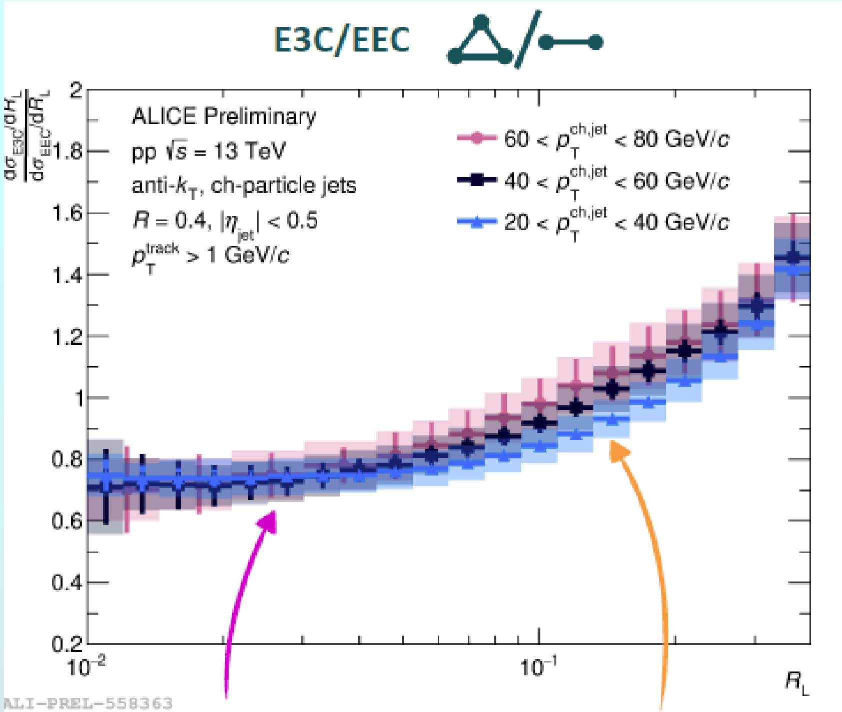
- Accessing higher order QCD dynamics: 1 ➡ 3 splitting
- More precision on the perturbative QCD studies
  - Cancellation of NP effects via E3C/EEC ratio



arXiv: 2307.07510

Results in 13 TeV p+p collisions





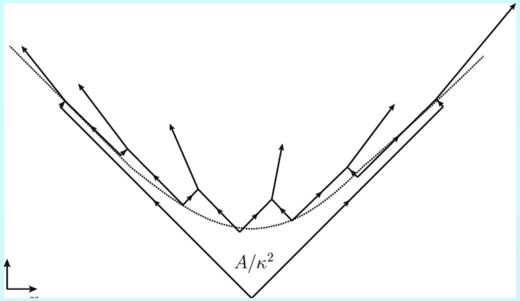
Free hadron scaling region

Perturbative scaling region

E3C/EEC ratio $\propto \alpha_s(Q) InR_L + \mathcal{O}(\alpha_s^2)$

- Ratio cancels NP effects & systematic uncertainties
- Universal curve in free hadron region
- Perturbative region sensitive to α_s
  Higher jet pT -> higher Q -> smaller α_s -> flatter slope

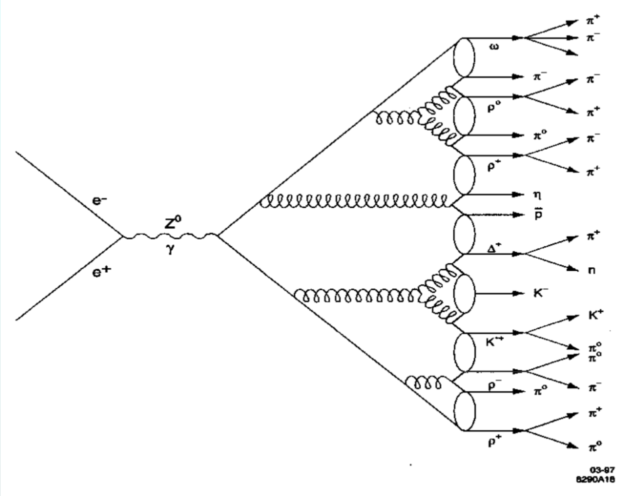
How do the partons become hadrons?



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

String carries flavor correlations

Partons tunnel out of the string



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

Cluster locally connected partons

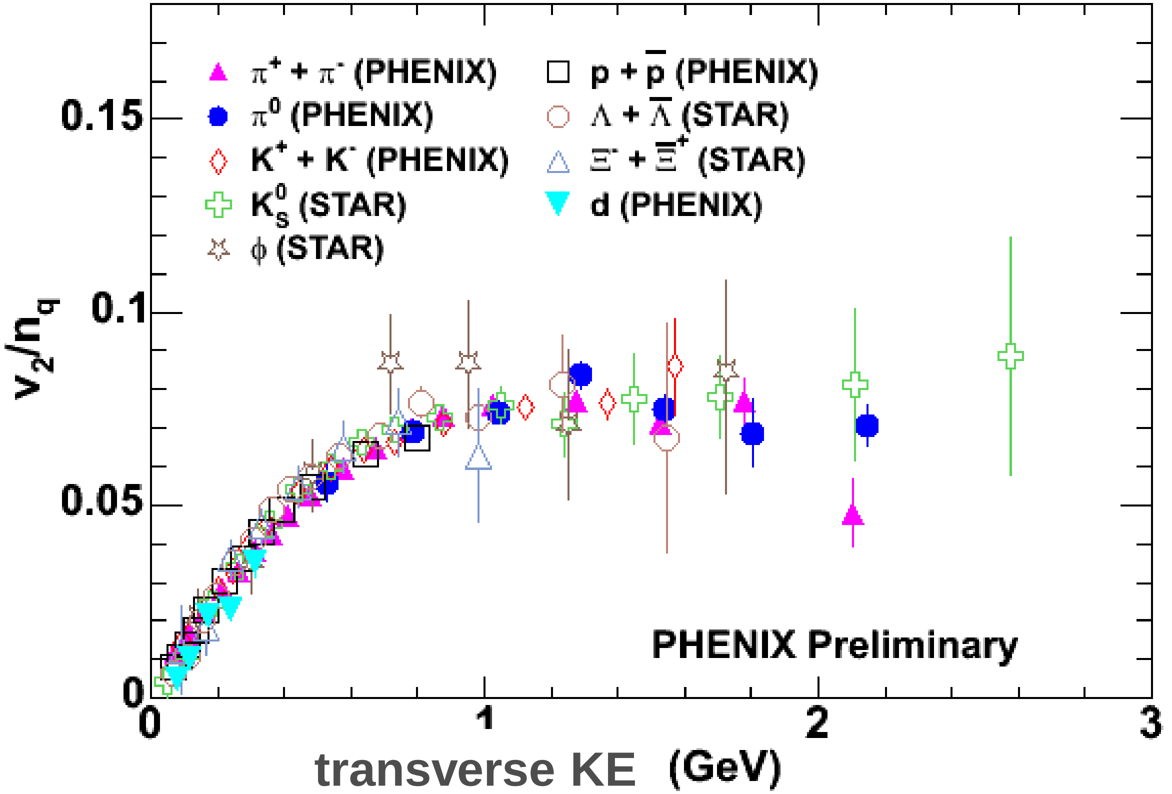
After the shower is finished

Additional step, takes longer

- **Coalescence or Statistical Hadronization?**

Connect partons which end up close by in phase space

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)

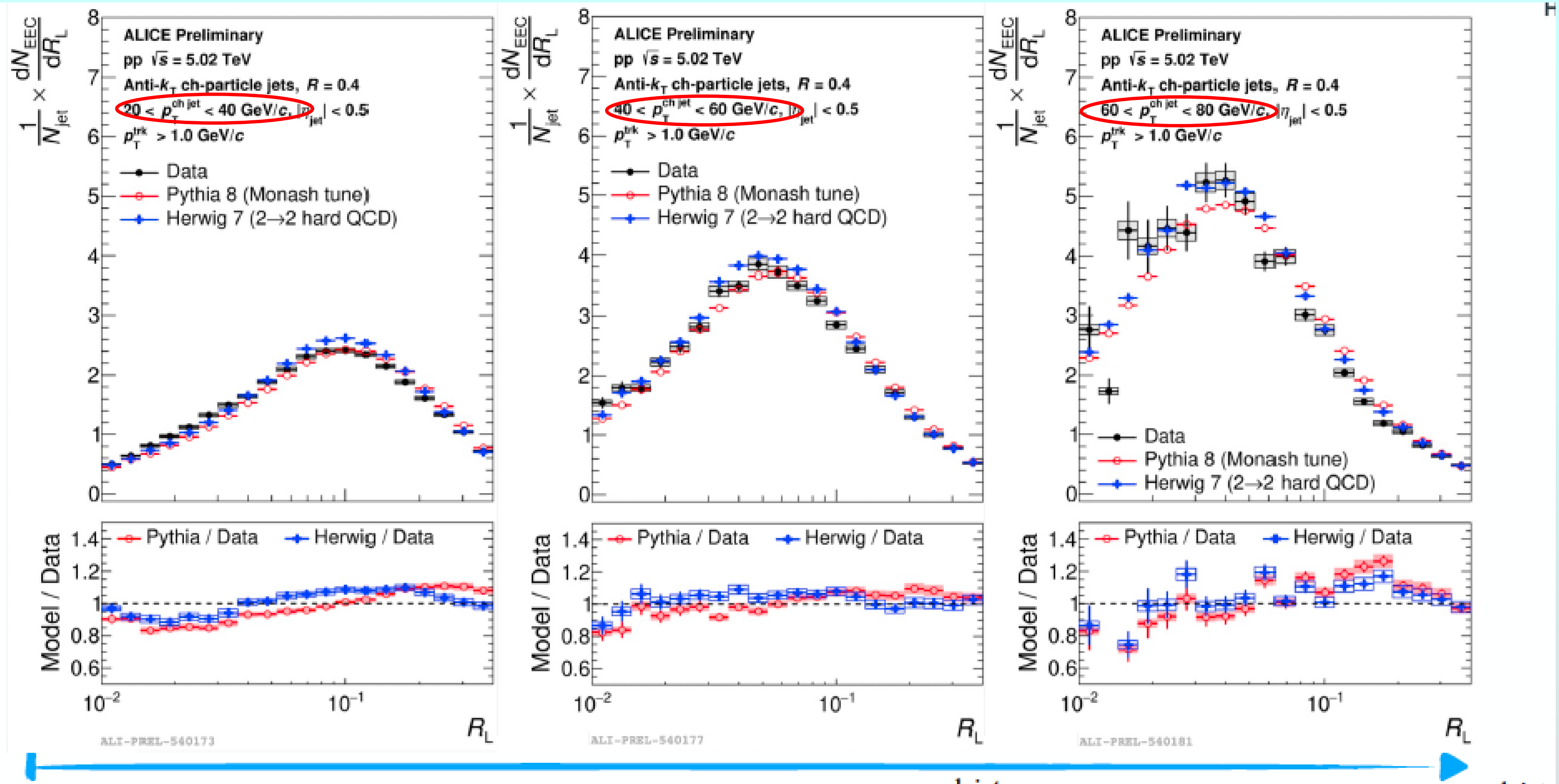
Fries, J. Phys. G32, S151 (2006)

◆ *dressed quarks are born of flowing field*

◆ *hadronize by (simple) coalescence of co-moving valence quarks*

◆ *quarks (miraculously?) dressed by gluons*

Compare data to models Pythia & Herwig

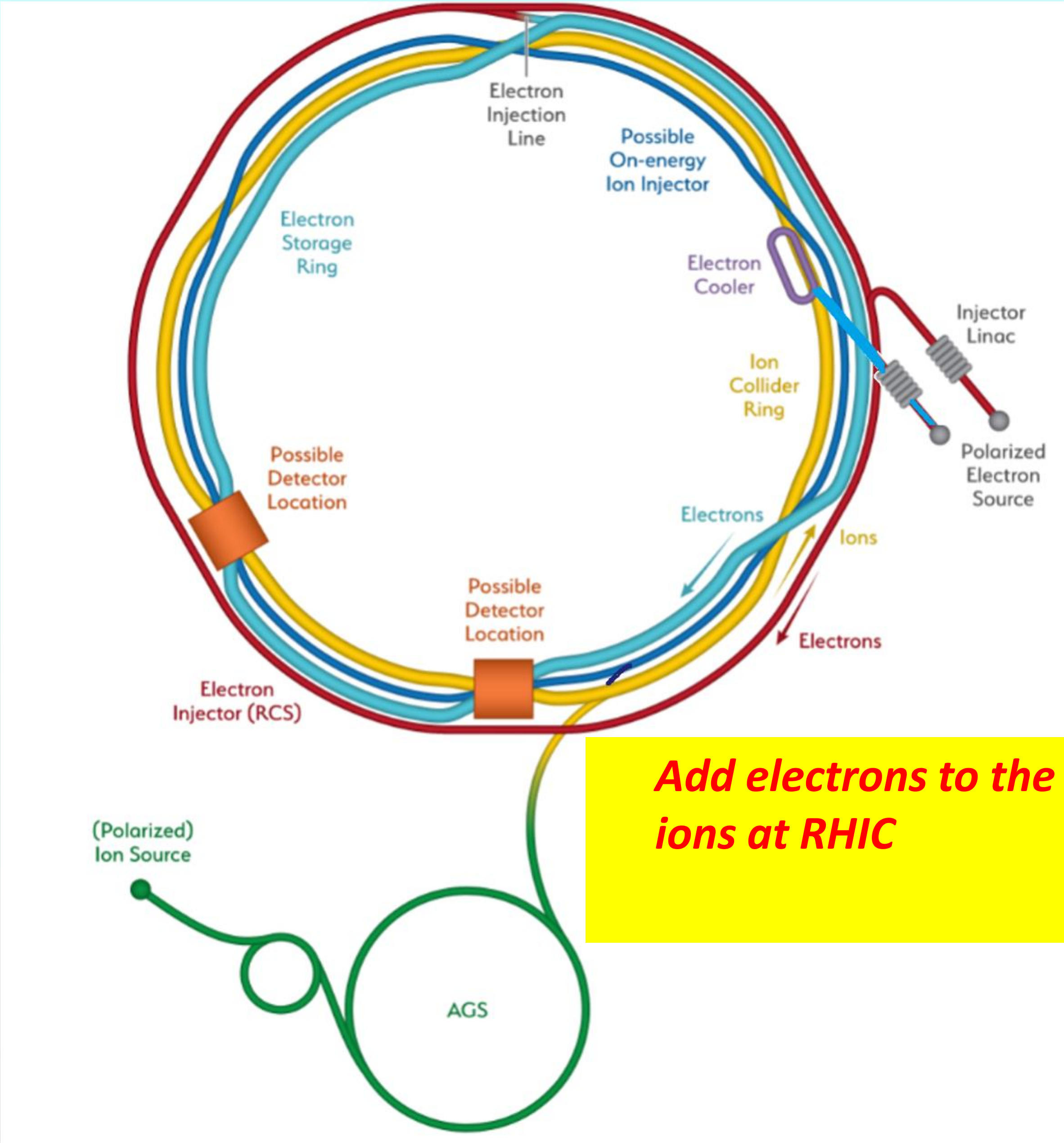


Peak shifts to lower R_L at higher $p_T^{\mathrm{ch\,jet}}$

Higher $p_T^{\mathrm{ch\,jet}}$

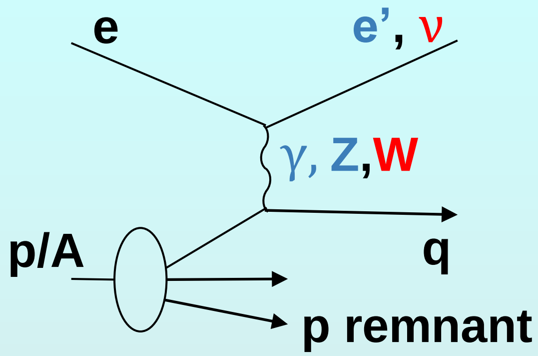
- **Herwig closer than Pythia**
- **Data are somewhat broader than Herwig. Longer time needed to form hadrons?!**

Electron-ion collider: new QCD machine



Add electrons to the ions at RHIC

Scatter (polarized) electrons from nuclei!



- **√s = 30 to 140 GeV**

🟨 **Hadron Storage Ring**

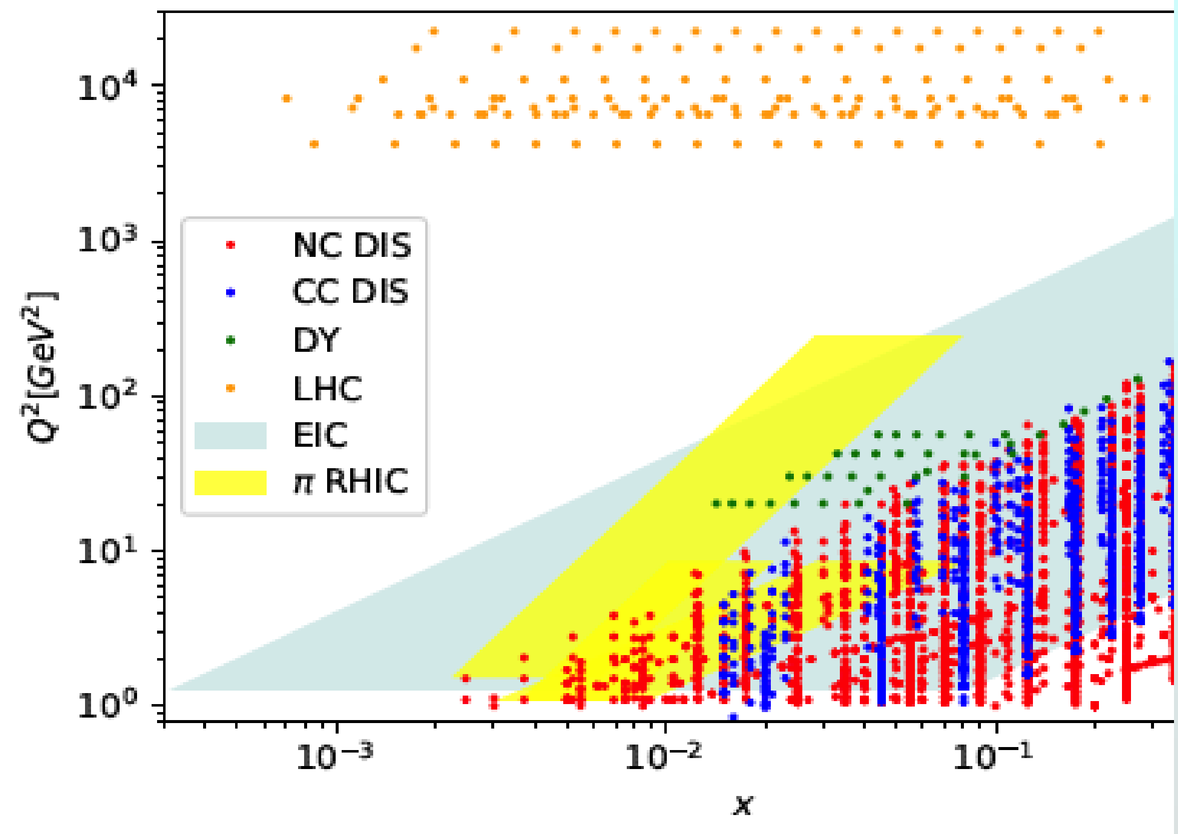
🟦 **Electron Storage Ring**

🟥 **Electron Injector Synchrotron**

🟦 **Possible on-energy Hadron injector ring**

🟩 **Hadron injector complex**

Kinematic range



Summary

- Experimental QCD is a thing!
- Binding rearranges partons inside nucleons
- Interesting many-body physics in QCD matter
  - Quark-gluon plasma exists & flows hydrodynamically
  - Extraordinarily low viscosity → QGP is strongly coupled
  - Jets are quenched in hot, dense matter
  - Even heavy quarks lose energy & flow along with plasma
- We can look inside jets and see QCD at work
  - Observe a "dead cone" for radiation off heavy quark
  - Jet energy loss shifts fragments to lower p_T & larger angle
- Energy correlators separate perturbative, hadronization and confined physics
  - Suggest longer hadronization time than Pythia's string breaking
  - Old tool with new job: pin down confinement!

backup slides

Observe mass effect on g radiation

- **Soft gluon radiation spectrum**

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

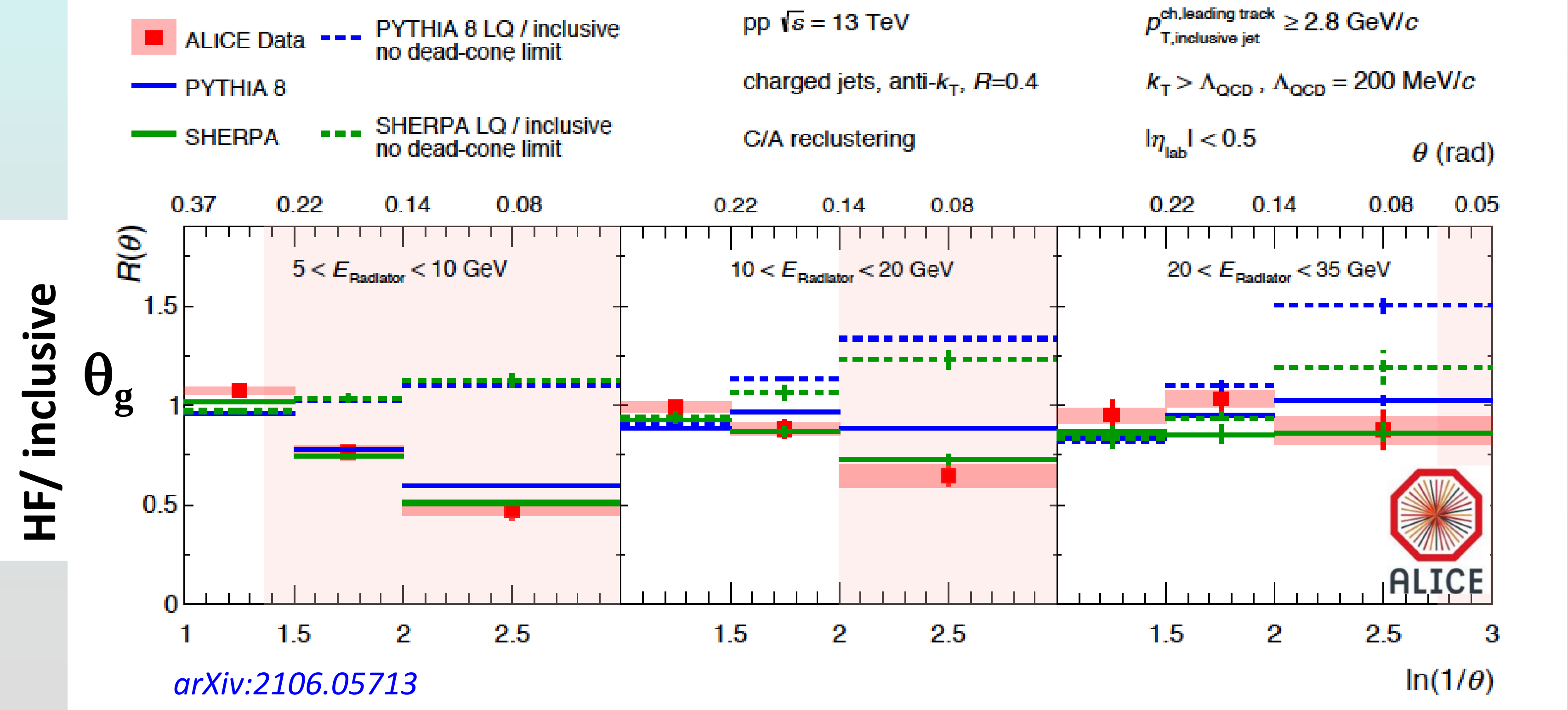
Dokshitzer, et al. J.Phys.G17,1602 (1991)
Dokshitzer & Kharzeev, PL B519, 199 (2001)

Large M suppresses small angle radiation (phase space effect)

Known as "dead cone effect"

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

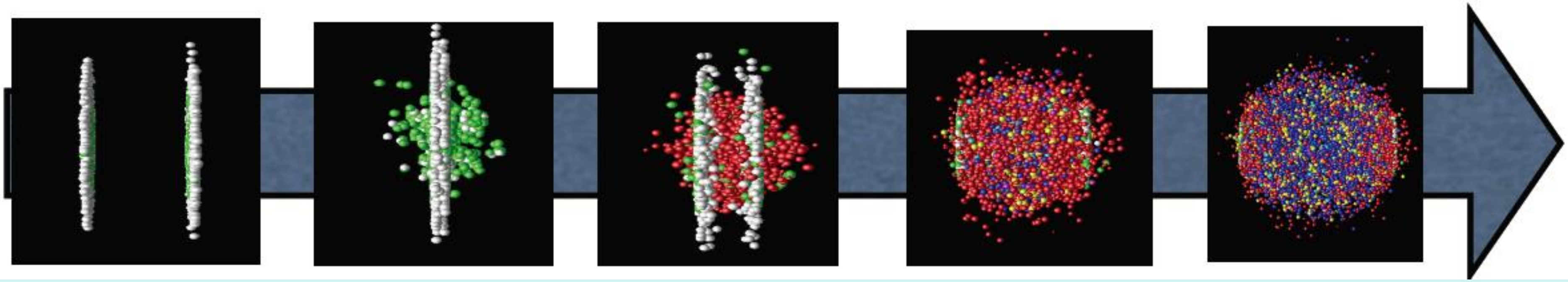
$$\theta_g \equiv \frac{R_g}{R} \equiv \frac{\sqrt{\Delta y^2 + \Delta\varphi^2}}{R}$$



arXiv:2106.05713

Nuclear collision timeline

plasma lives ~3×10^{-23} seconds, ~10^{-12} cm across



Lorentz contracted nuclei on their way in.

First scattering of q & g inside the nucleons. Some high momentum transfers.

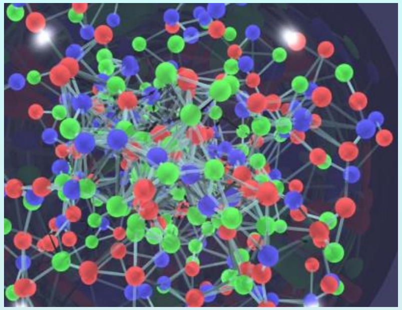
Secondary collisions, creating high density and temperature

Quark gluon plasma expands and cools, eventually condensing into hadrons.

Hadron gas interacts, expands and cools further. Eventually collisions stop & hadrons stream freely.

The medium density matters

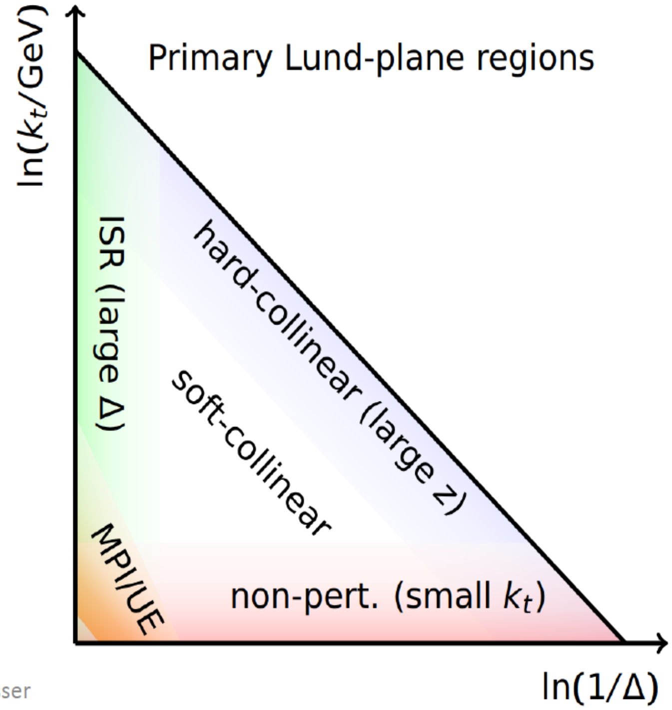
- In dilute medium:
  - Independent processes: bremsstrahlung & scattering
  - Calculate probabilities and add them up
  - Independent radiations follow Bethe-Heitler

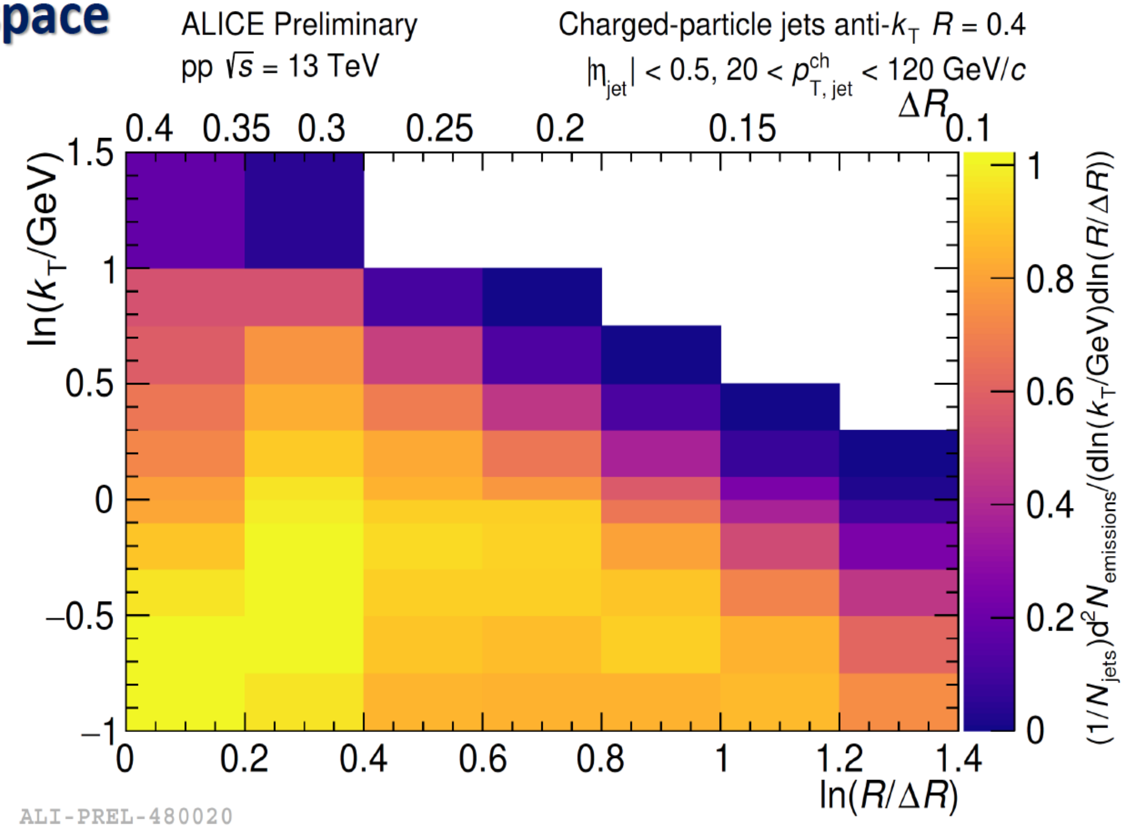


- In dense medium:
  - Mean free path is short: $\lambda = \sigma/\rho$
  - Formation time of radiated gluon: $\tau = \omega/k_T^2$
  - Transverse momentum of radiated gluon: $k_T^2 = n\mu^2$
    - # of collisions $n = L/\lambda$, μ=typical p_T transfer in 1 scattering
    - λ,μ are properties of the medium, combine to $\hat{q} = \sqrt{\mu^2/\lambda}$
- Coherence in the dense medium!
  - Next scattering takes place faster than gluon formation
  - Add amplitudes for all multiple scatterings
  - In QCD this increases the energy loss!

Lund Plane in pp data

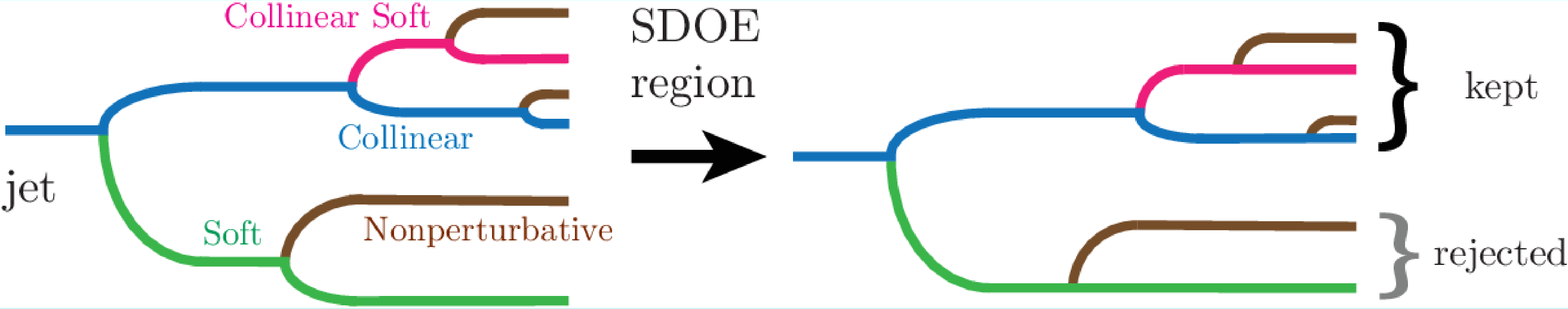
- Illustrates **branching phase space**
- Has been also measured by ATLAS [8] at higher jet p_{T}





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

Grooming jets



- Collect particles into subjets
- Use “soft drop” algorithm to remove soft subjets

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

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

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

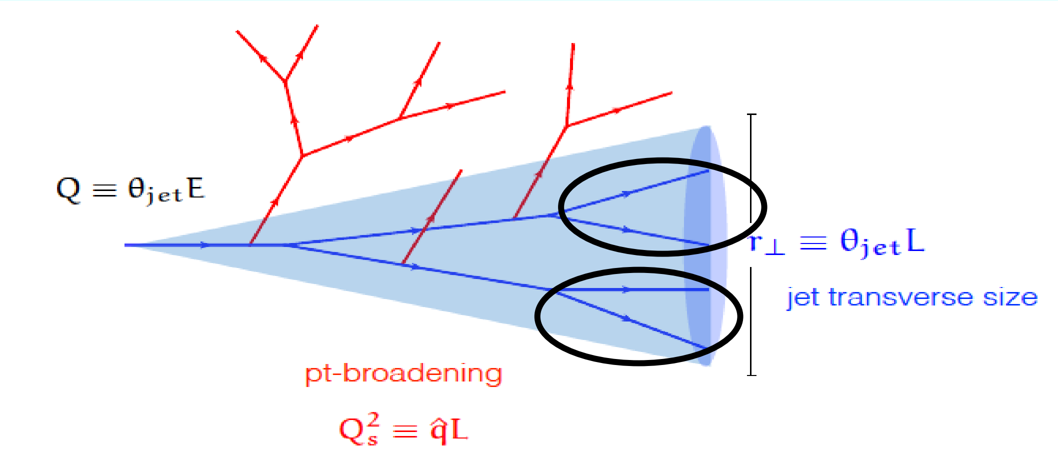
typically, z_{cut} ~ 0.1-0.2 , β=0 or 1

- Removes soft radiation & non perturbative effects

  Allow access to perturbative splittings

  Also grooms away remaining underlying event

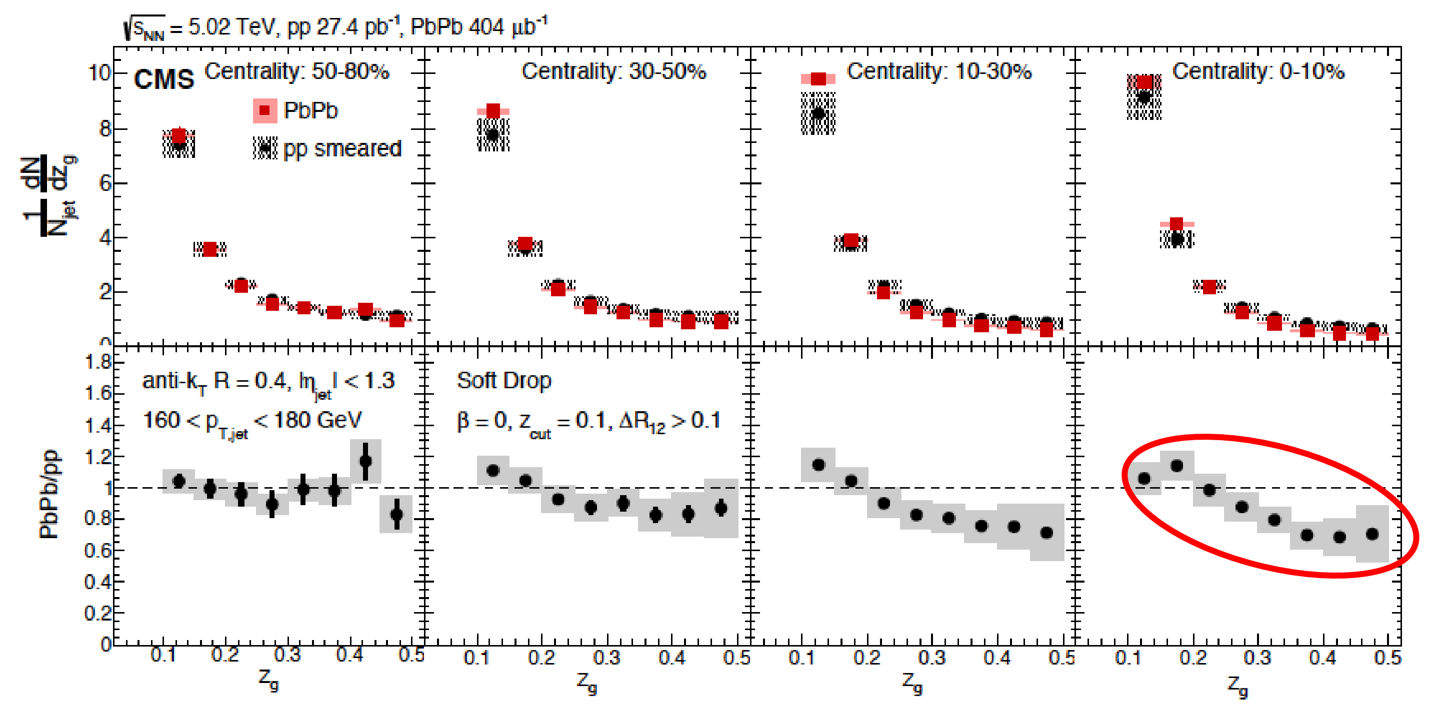
Early gluon splitting



Recluster & groom jet

Use 2 leading clusters

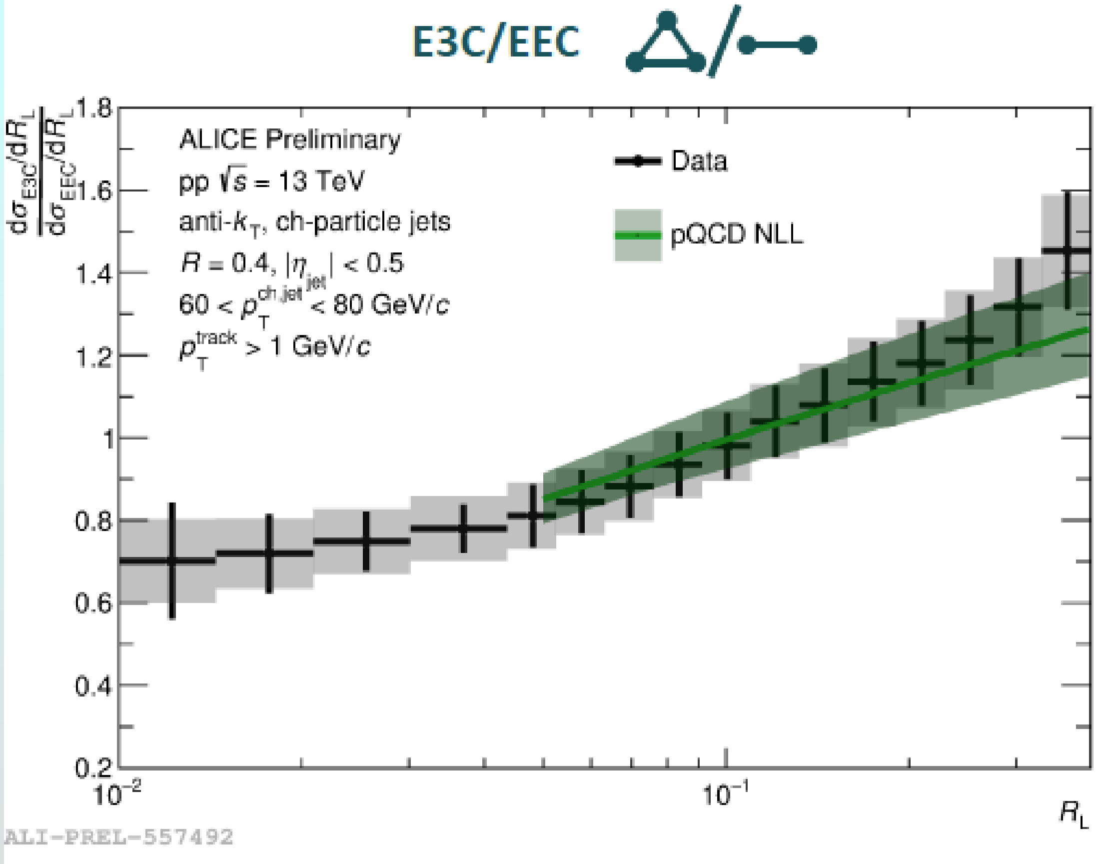
$$z_g = \frac{p_{T2}}{p_{T1} + p_{T2}}$$



Useful to quantify energy, p_T transport.

See significant dependence on jet E, grooming.

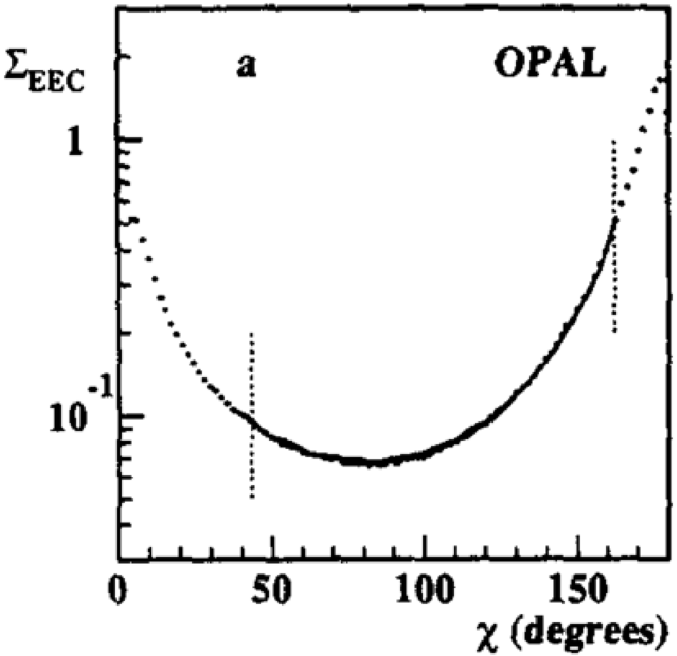
Agreement with pQCD prediction



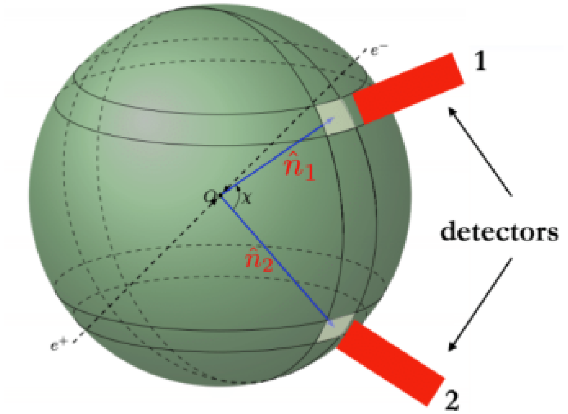
Energy-energy correlator at e^+e^- collider

- IRC safe, energy weighted cross section
  - Has been predicted and measured in e^+e^- collider
  - Used to constrain α_s

Phys. Lett. B 276, 547–564



Proposed in 1978: Phys. Rev. Lett. 41, 1585



$$\Sigma_{\mathrm{EEC}}(\chi)=\frac{1}{\Delta\chi\cdot N}\sum_{N}\int_{\chi-\frac{1}{2}\Delta\chi}^{\chi+\frac{1}{2}\Delta\chi}\sum_{i,j}\frac{E_iE_j}{E_{\mathrm{vis}}^2}\cdot\delta(\chi'-\chi_{ij})\,\mathrm{d}\chi', \qquad (4)$$

where E_i and E_j are the energies of particles i and j, E_{vis} is the sum over the energies of all particles in the event, $\Delta\chi$ is the angular bin width and N is the total number of events. The normalization ensures that the integral of $\Sigma_{\mathrm{EEC}}(\chi)$ from $\chi=0°$ to $180°$ is unity.

Combine p_T & θ: Angularity

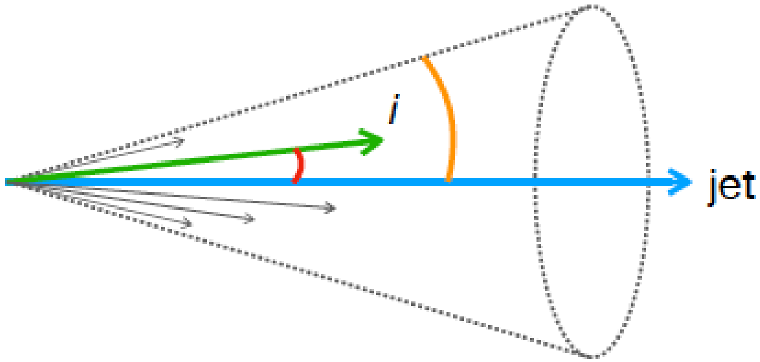
Ezra Lesser, Preeti Dhankher

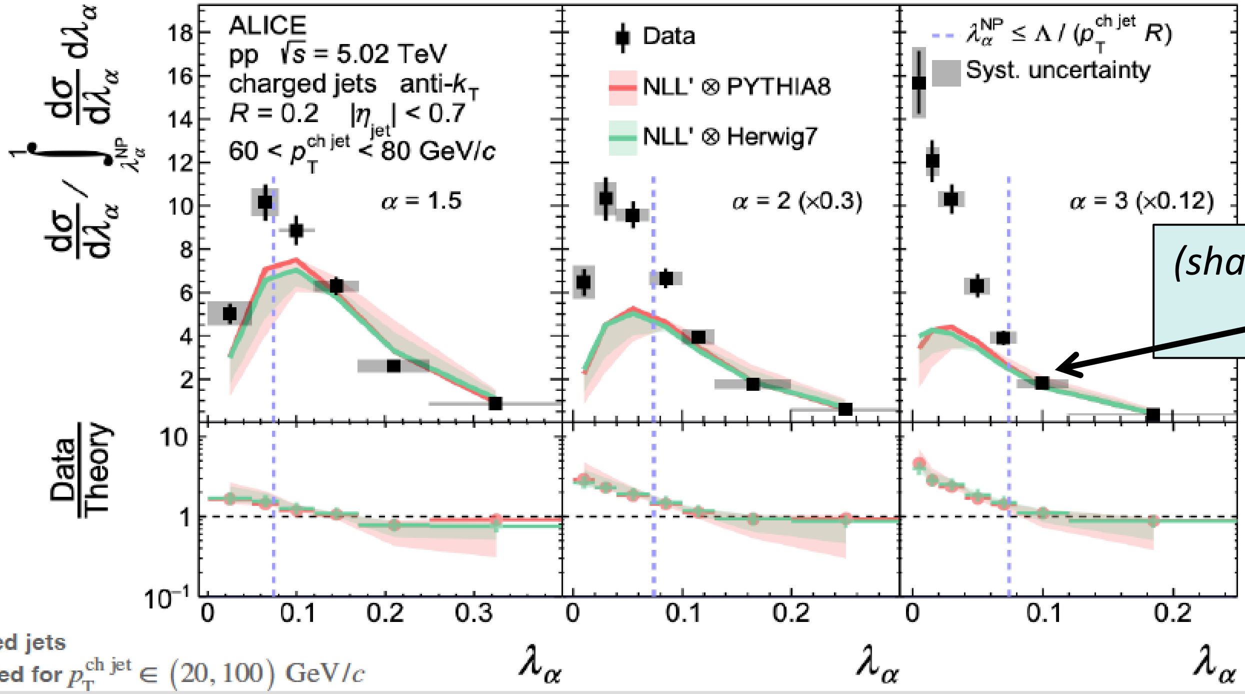
arXiv:2107.11303

$\alpha > 0$ → IRC-safe observable

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

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





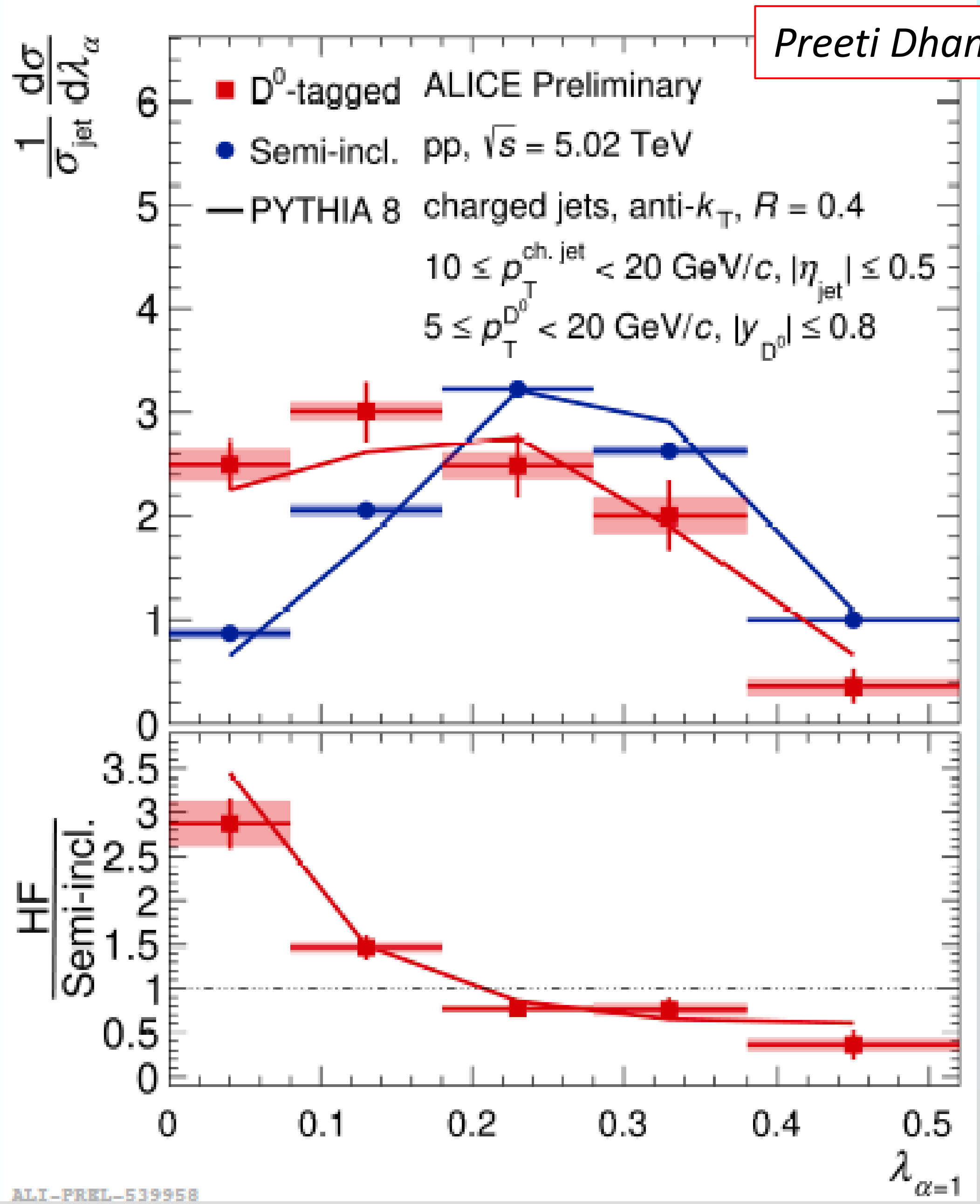
Charged jets measured for $p_T^{\text{ch jet}} \in (20, 100)$ GeV/c

(shape) Calculable in pQCD

data, model agree

Let's groom away the soft stuff

Compare D jet with light parton jets

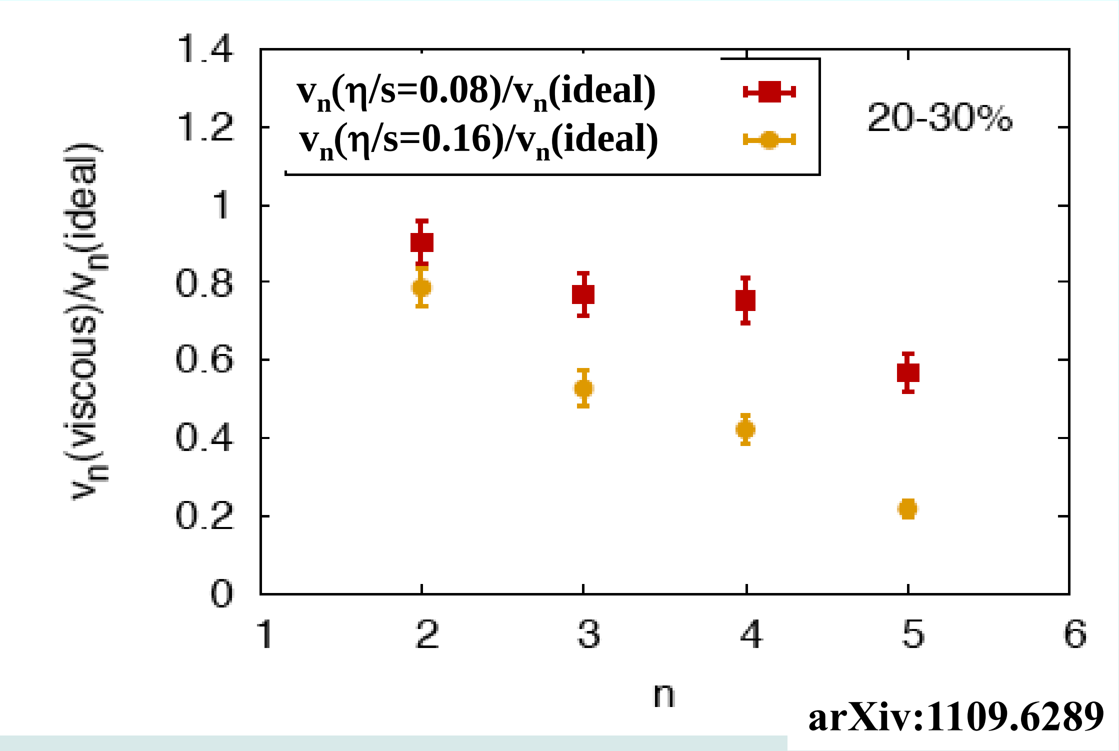


Preeti Dhankher

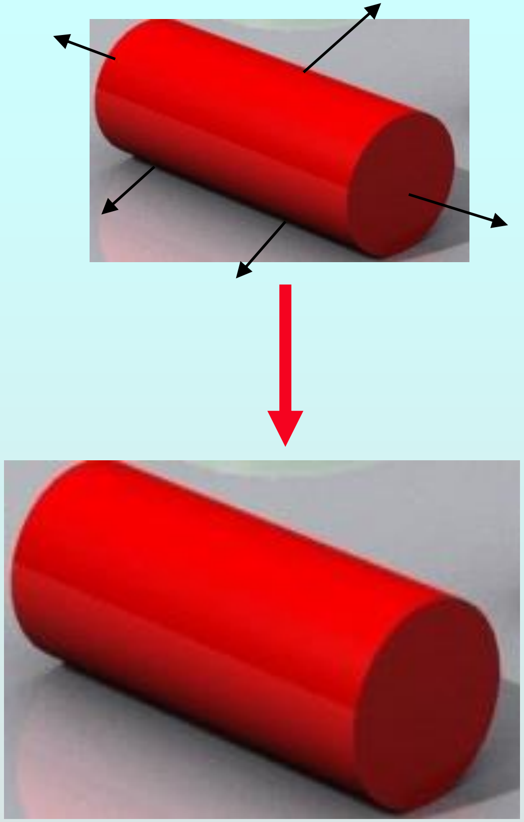
- D jets are narrower (smaller angularity)
- Increasing α (weight of angular term) decreases the difference
- Comparison dominated by jet core
- Observation is exactly what we would expect from dead cone:

  Fewer & harder jet fragments

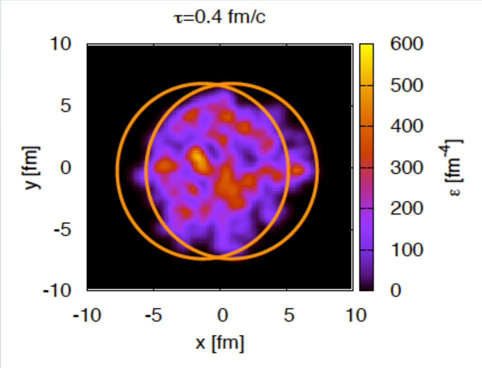
Higher moments more sensitive to viscosity



arXiv:1109.6289



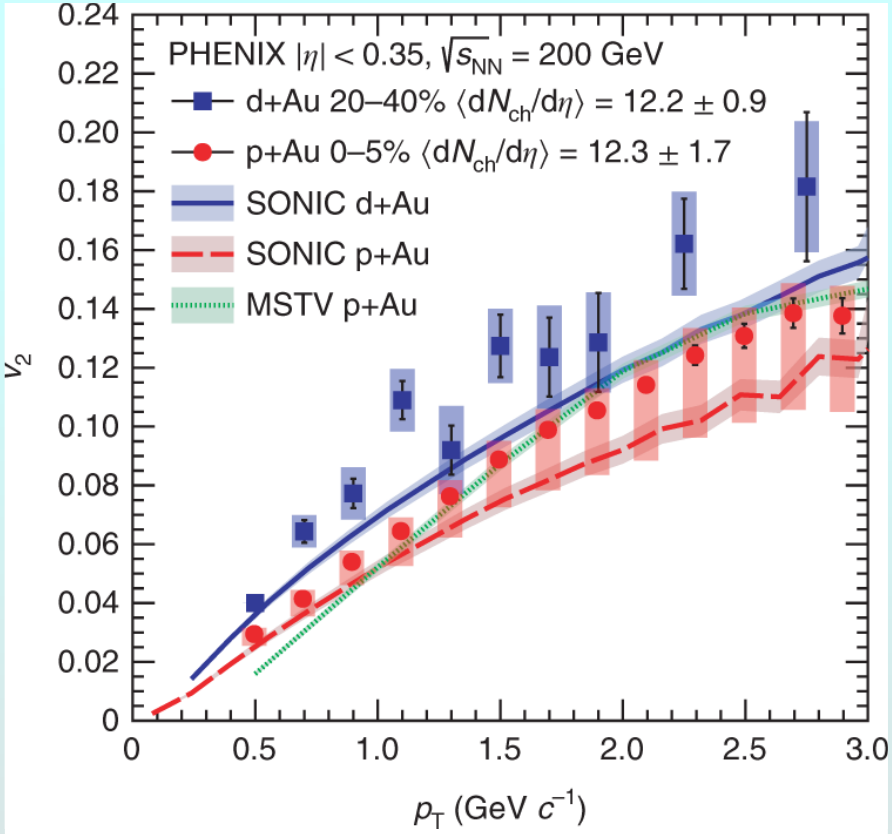
- Longitudinal expansion at v ~ c
- "freezes in" small shape perturbations
  e.g. triangular fluctuations (v_3)
- Viscosity (friction) opposes dissipation!



Hydrodynamic flow in small systems too

PHENIX Collaboration

Nature Physics (2018)

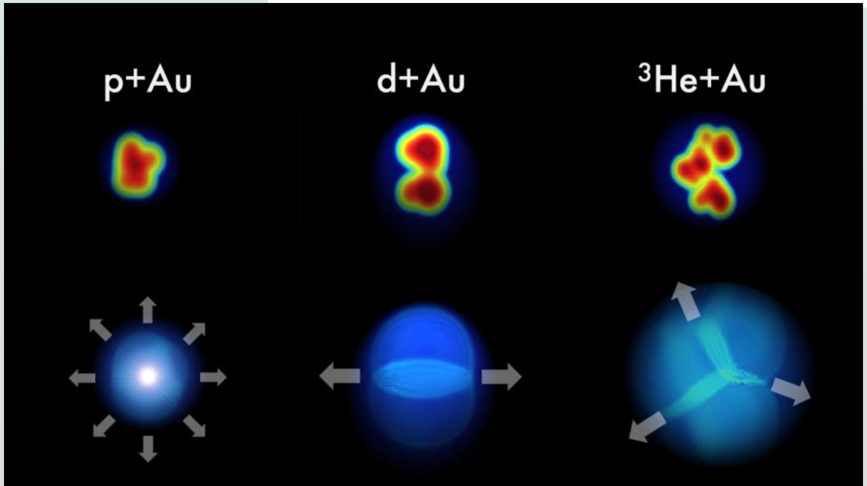


Not big & dense

But, we see collective flow!

Seeded by the initial geometry

A small droplet of QGP?!



Mechanism for fast thermalization?

- Must be thermalized in < 1 fm/c!

  Otherwise (viscous) hydro v_2 smaller than in data

- Can this be achieved with gg, qg, and qq binary scatterings?

  NO!

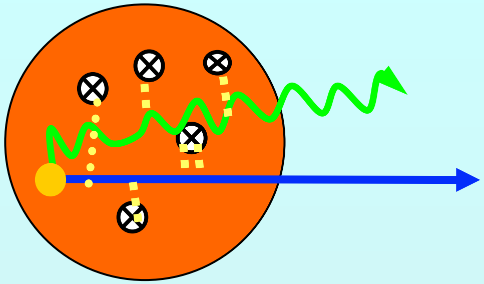
  Making this picture yield sufficient v_2, requires boosting the pQCD gg, qg,qq cross sections by a factor of ~50!

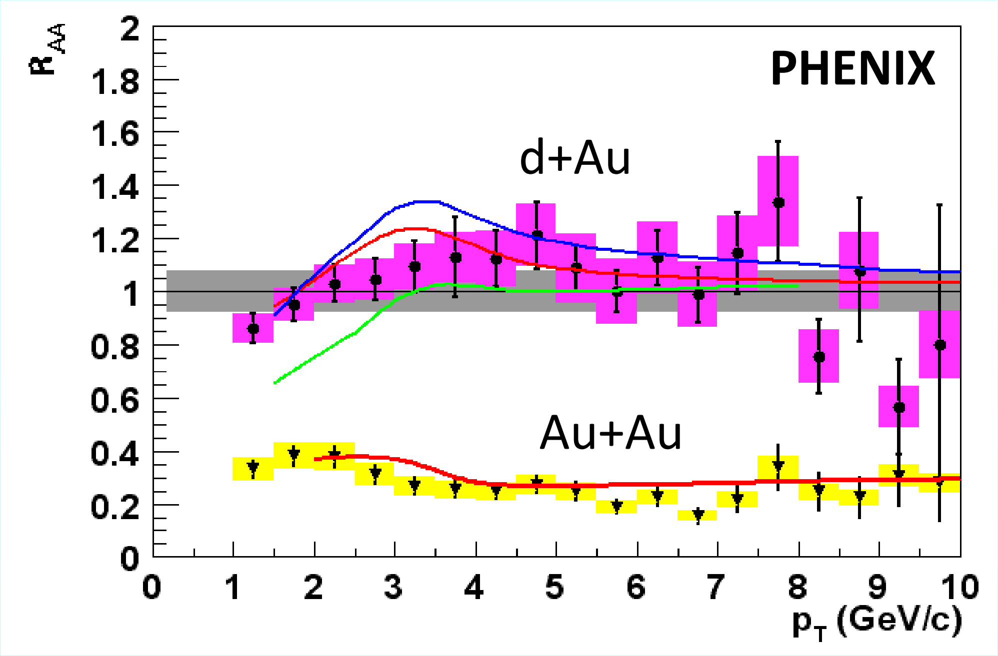
- Many-body interactions can do just that!

- But, can hydro set in before thermal equilibrium?

  Seems so, for longitudinal expansion v ~ c

Suppression seen in Au+Au but not d+Au





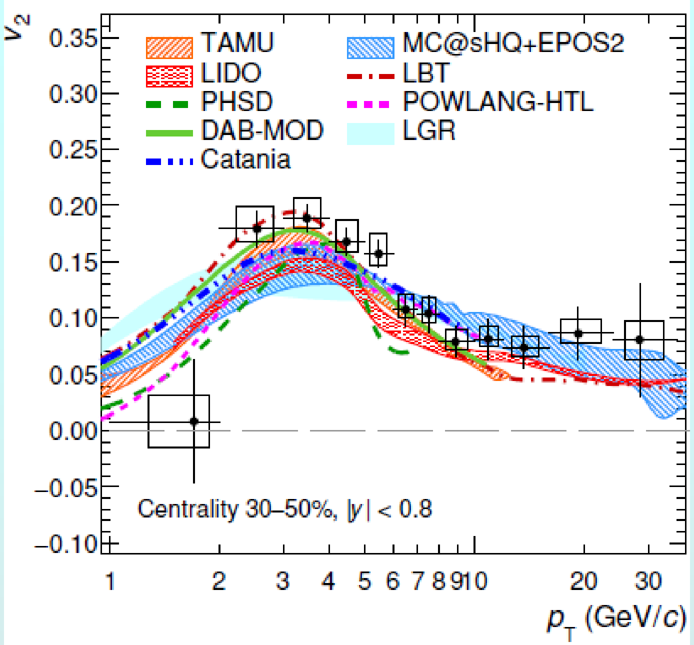
Calculations: I. Vitev

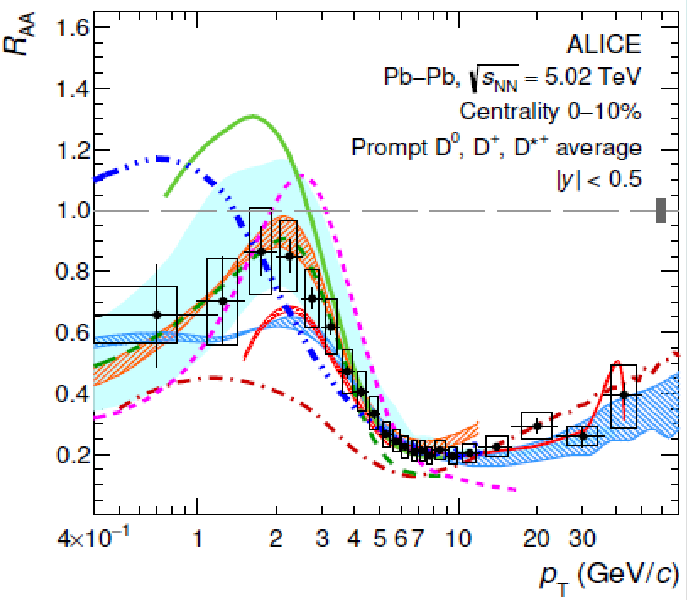
interaction of radiated gluons with gluons in the plasma greatly enhances the amount of radiation

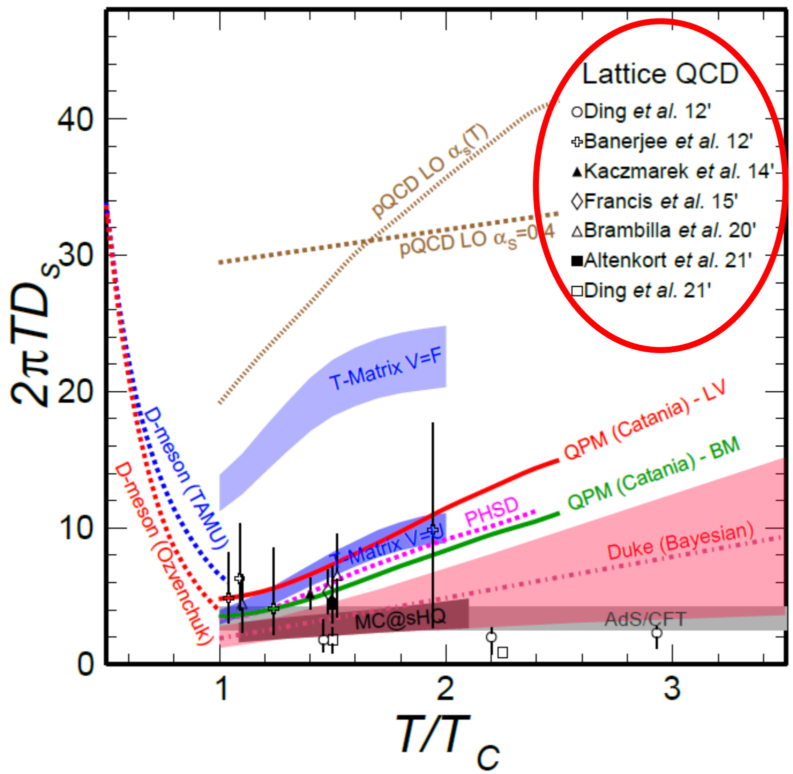
Radiation is coherent, rather than incoherent

Large energy loss should be absent if no large volume of plasma (and it is)

Heavy quark diffusion from D meson v_2 and R_{AA}







Again use data + models together:

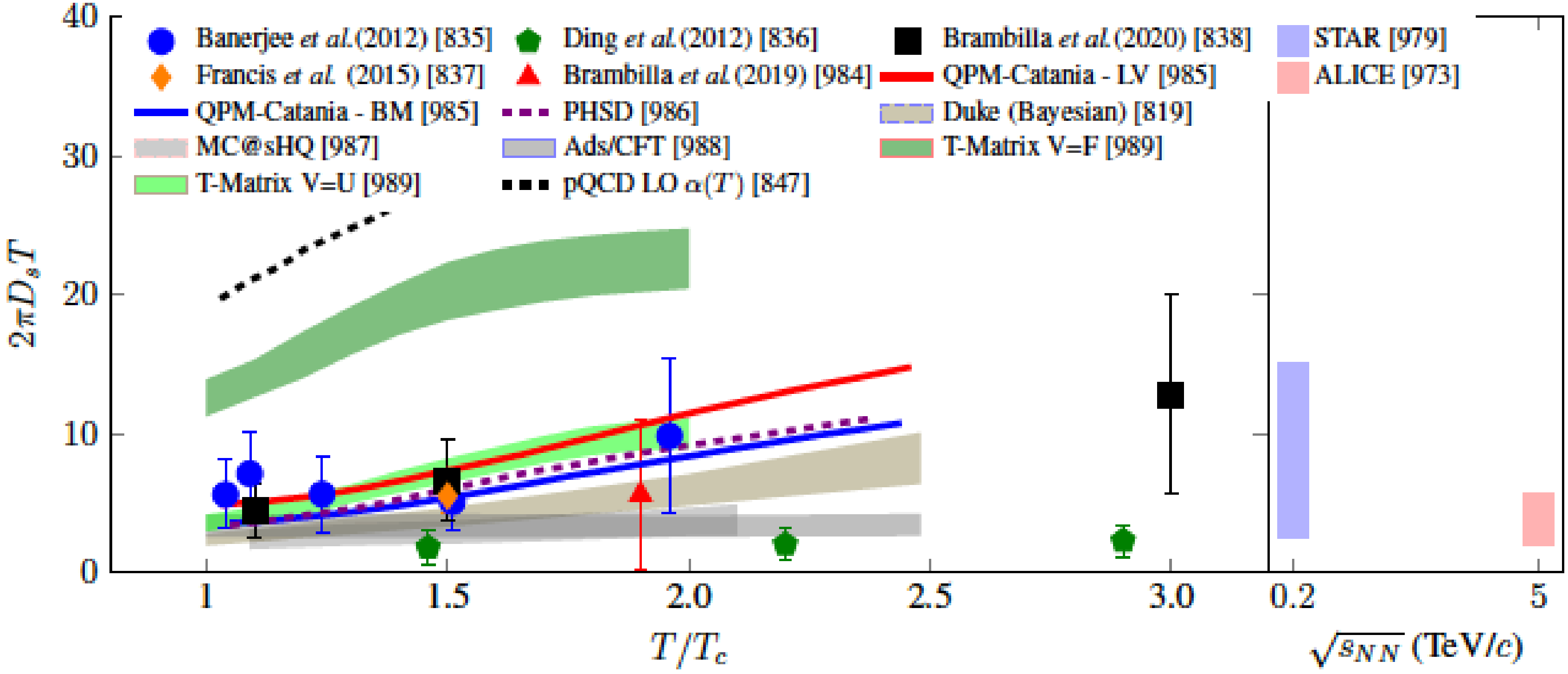
radiation, collisions, medium evolution

$D_s(2\pi T) = 1.5 - 4.5$ near T_c

per models with χ^2/DOF < 5 (2)

for R_{AA} (v_2)

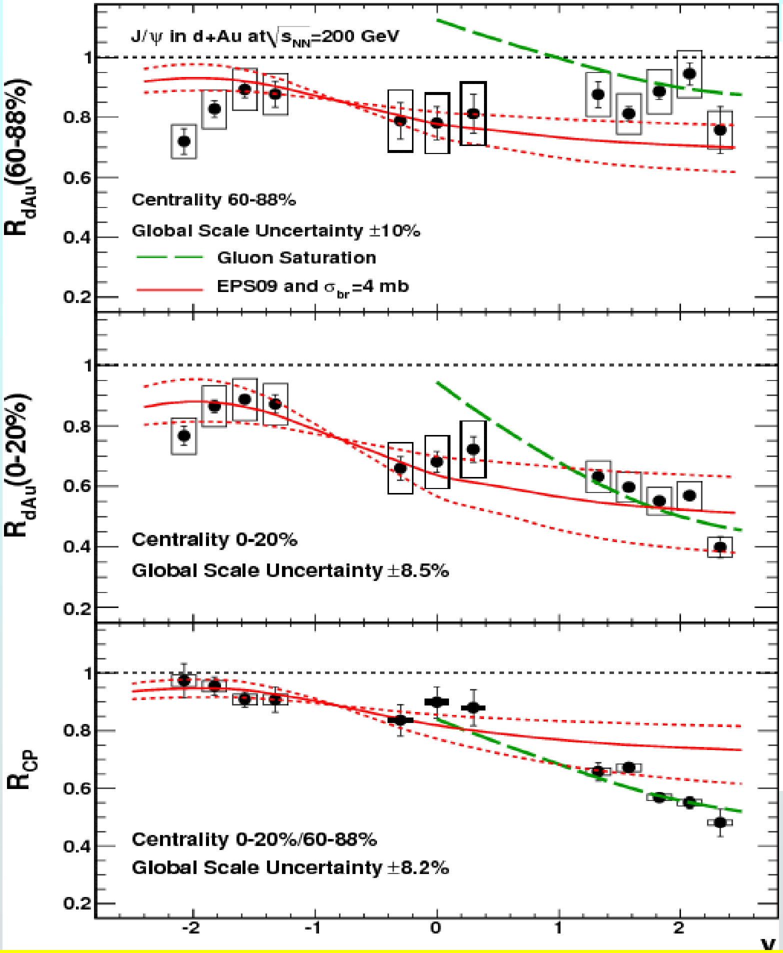
Compare diffusion models to data extraction

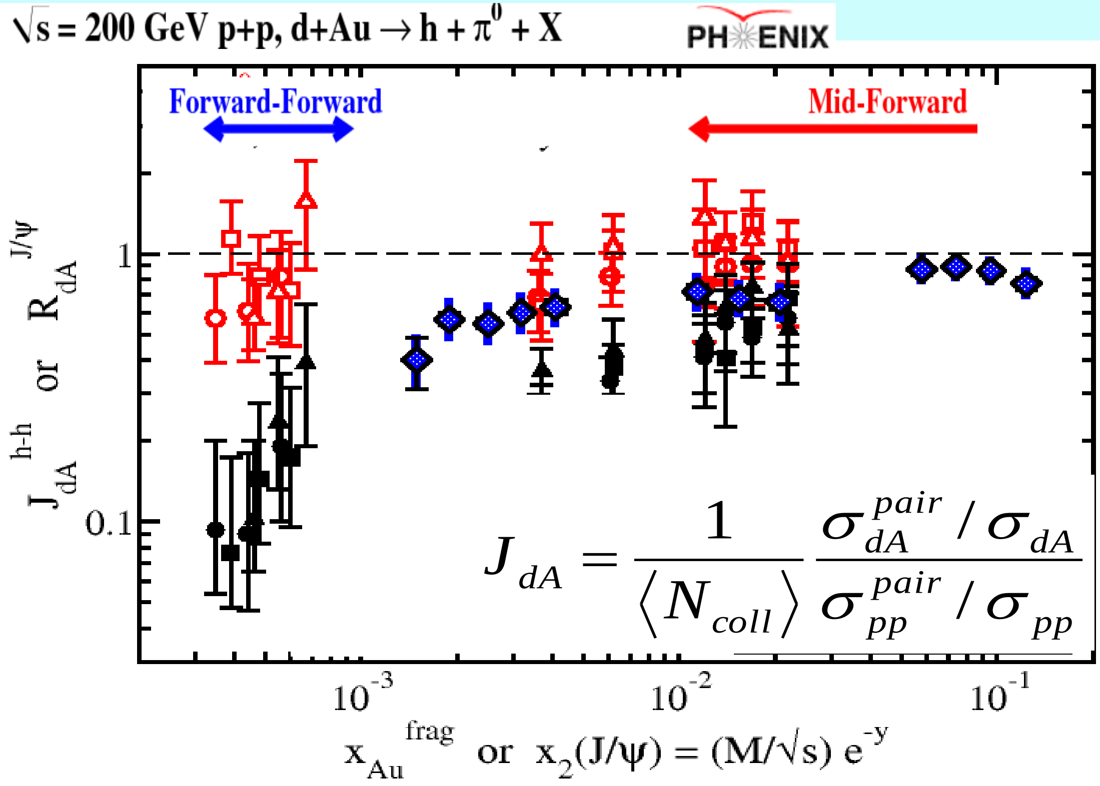


Dense gluonic matter (d+Au, forward y): large effects observed

arXiv:1010.1246

arXiv:1105.5112





$$J_{dA} = \frac{1}{\langle N_{coll} \rangle} \frac{\sigma_{dA}^{pair} / \sigma_{dA}}{\sigma_{pp}^{pair} / \sigma_{pp}}$$

Di-hadron suppression at low x

pocket formula (for 2➔2):

$$x_{Au}^{frag} = \frac{< p_{T1} > e^{-<\eta_1>} + < p_{T2} > e^{-<\eta_2>}}{\sqrt{s}}$$

Shadowing/absorption stronger than linear w/nuclear thickness

trend as, e.g. in CGC …