Jet Evolution within Deconfined QCD Matter

Daniel Pablos - INFN Torino

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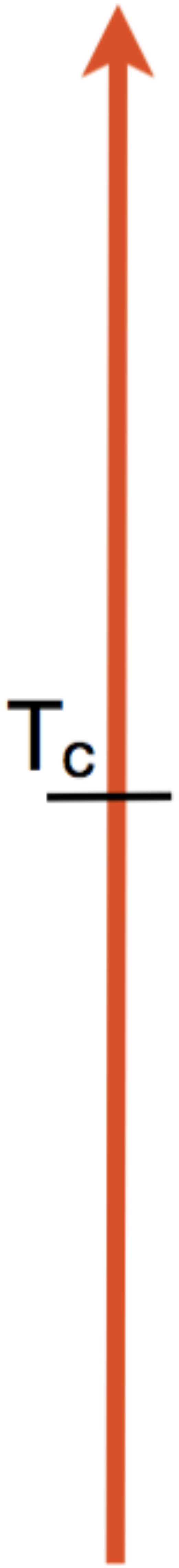
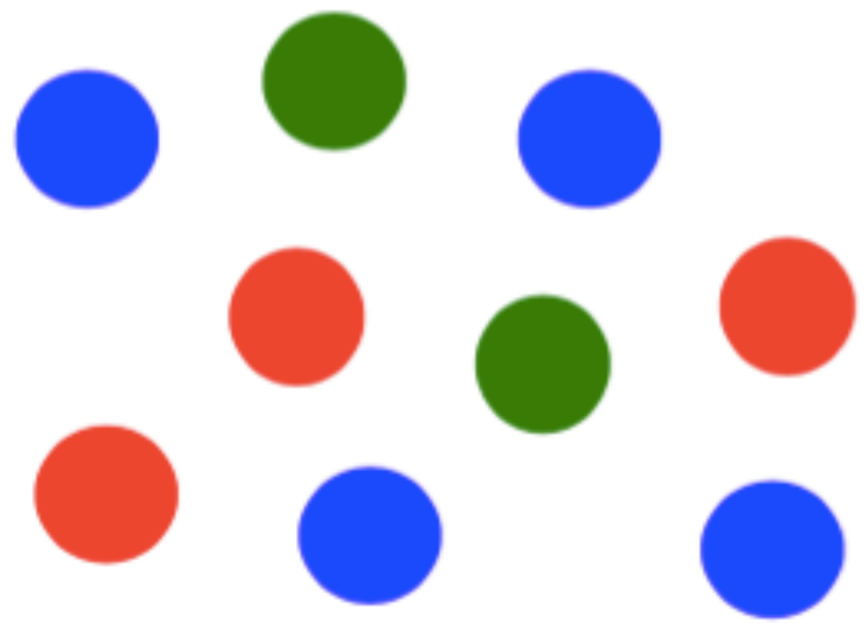
Fellini Seminar

1st Dec. 2023

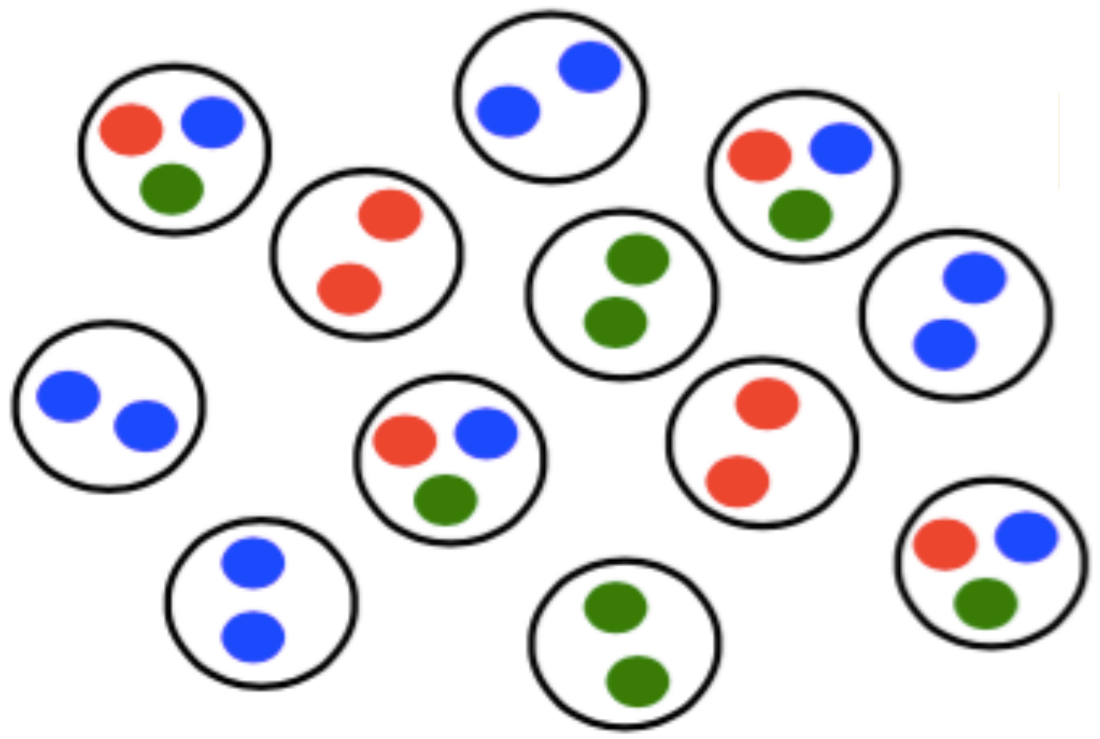
QCD Matter





“Phase transition”

$T_c \sim 2 \, . \, 10^{12} \, \mathrm{K} \quad \sim 170 \mathrm{MeV}$



A New Phase: *Quark-Gluon Plasma (QGP)*:

- Filled the universe µs after Big Bang.
- Colour is liberated.
- A gas of quarks and gluons.

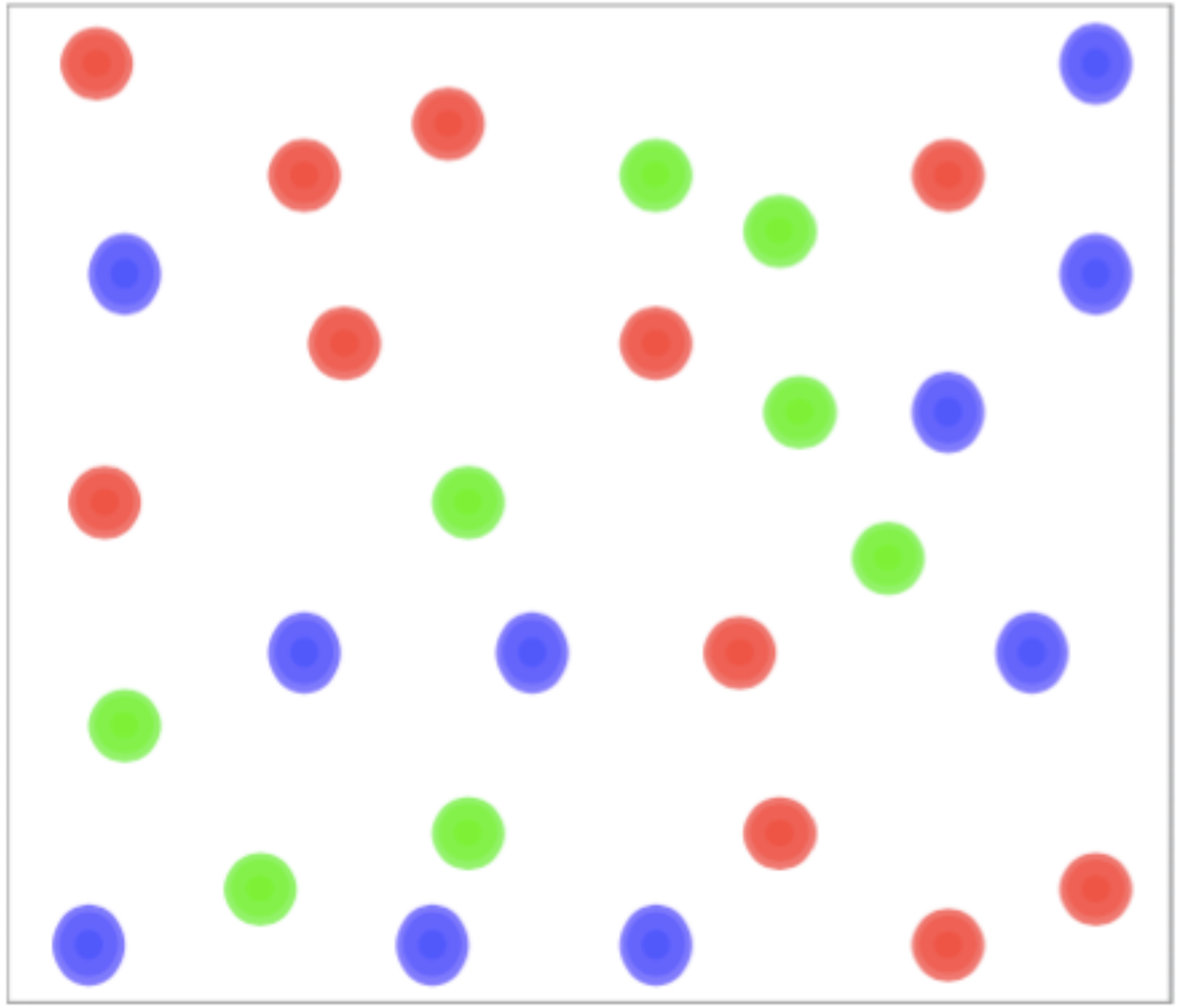
What are the properties of the plasma close to the transition?

Hadron Gas:

- Color is confined.
- Hadrons re-scatter.

A Gas of Quarks and Gluons

$T > 10^4\ \mathrm{GeV}$



Resummation techniques can bring the validity of perturbative methods to much lower temperatures

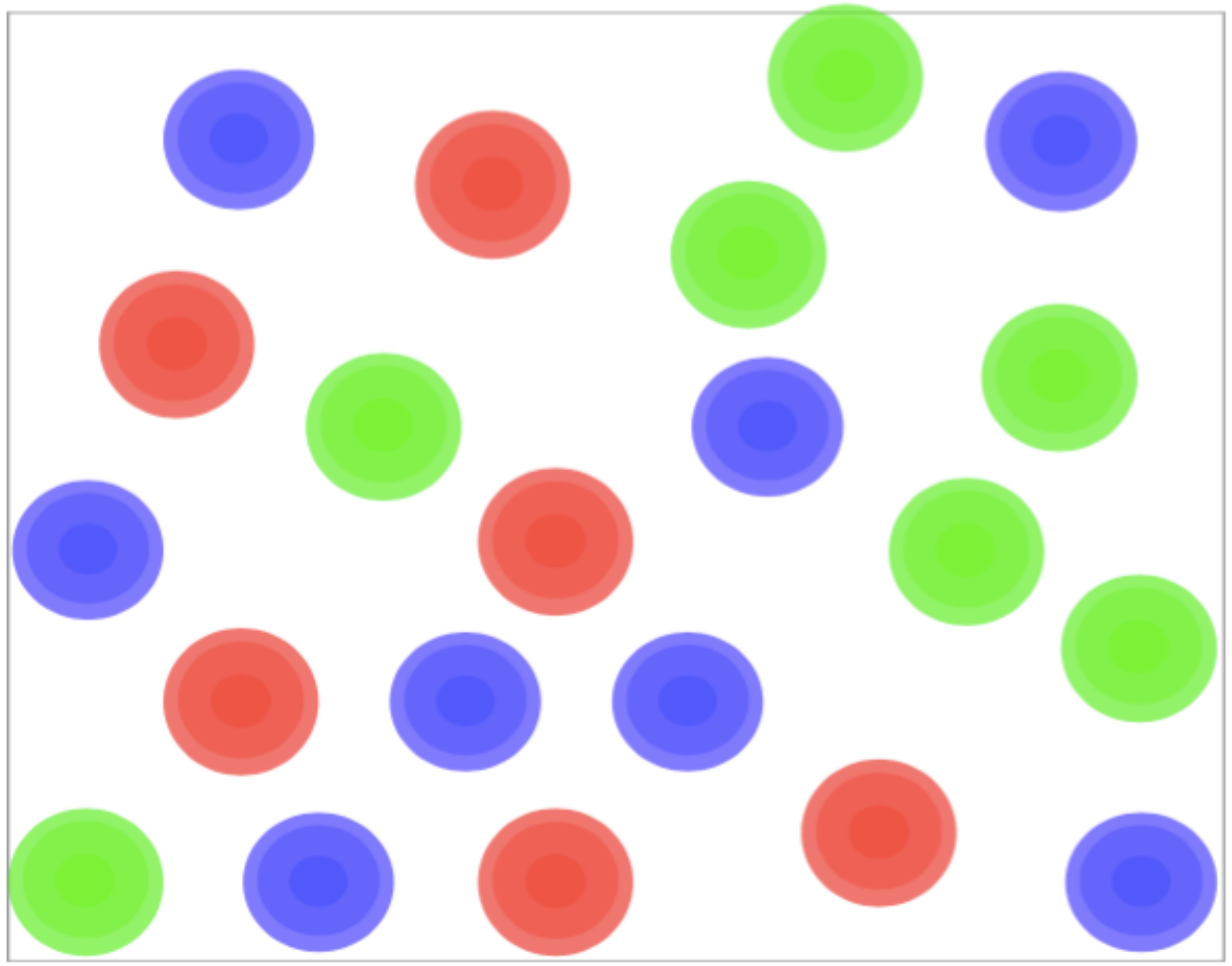
(e.g. Hard Thermal Loop)

$$\frac{1}{T} \ll \frac{1}{gT} \ll \frac{1}{g^2T}$$

Inter-particle spacing | Interaction range | Mean free path

Which is the Correct Picture of the Plasma?

$T \sim 0.2\,\mathrm{GeV}$



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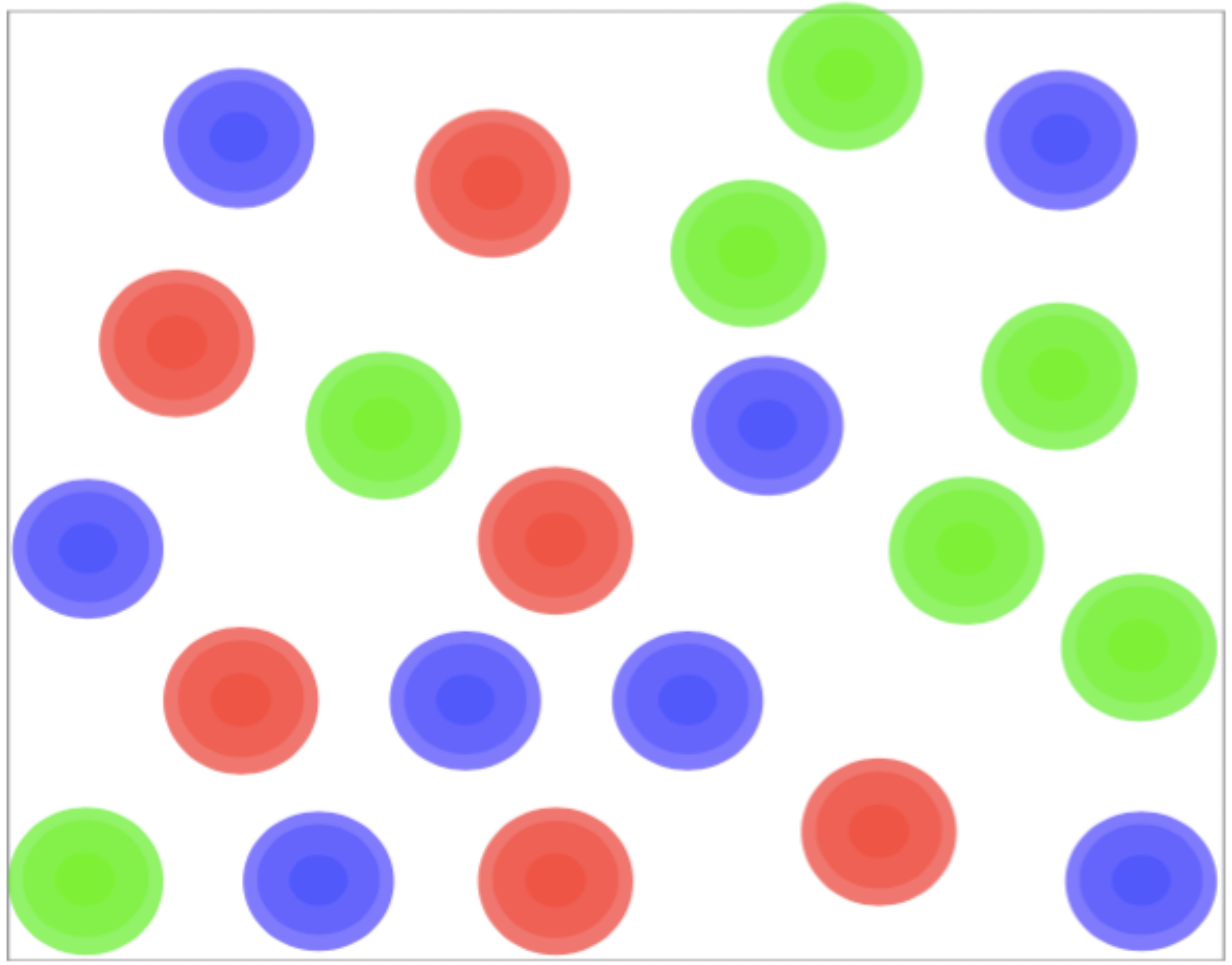

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$$\alpha_s = 0.3 \rightarrow g = 2$$

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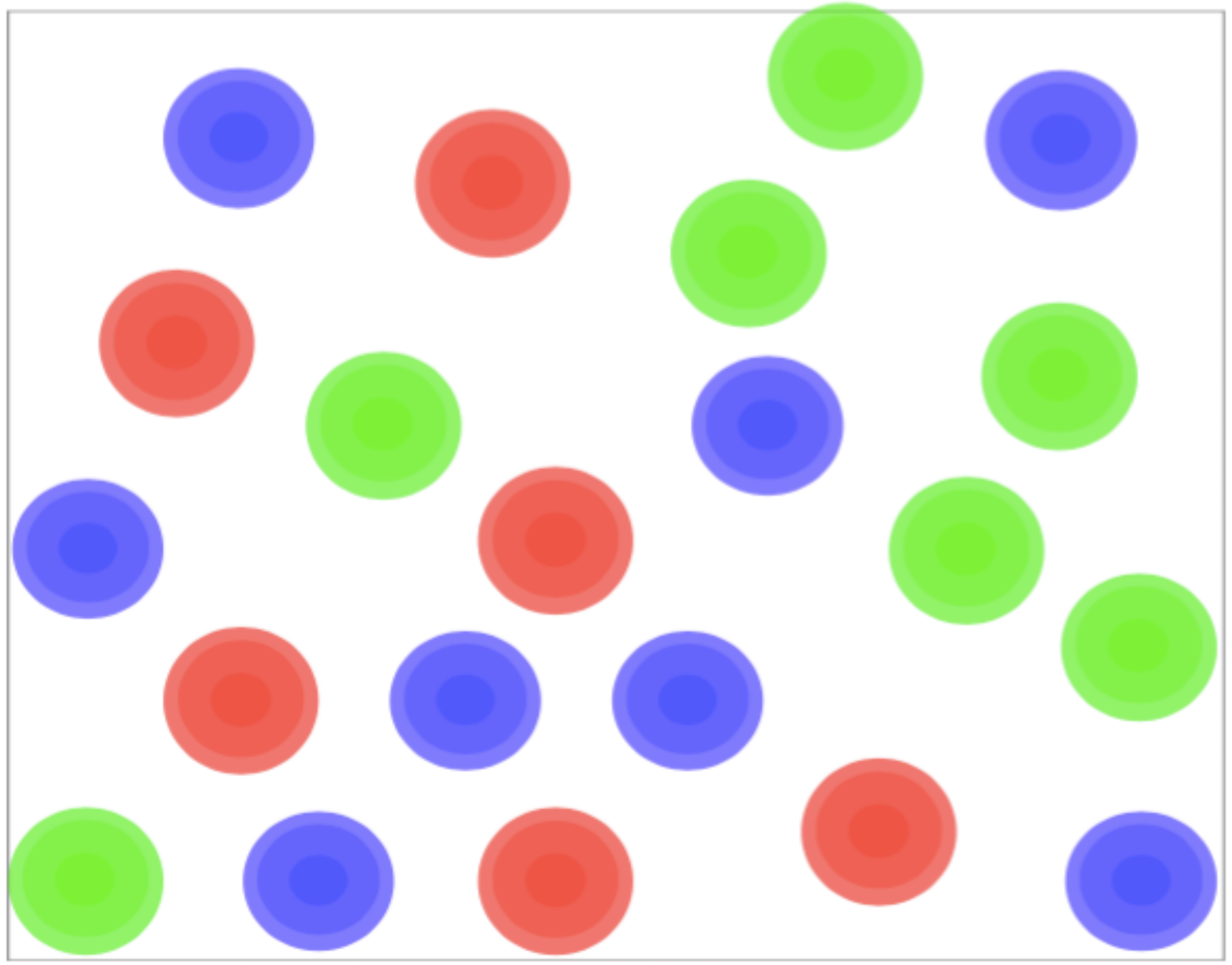

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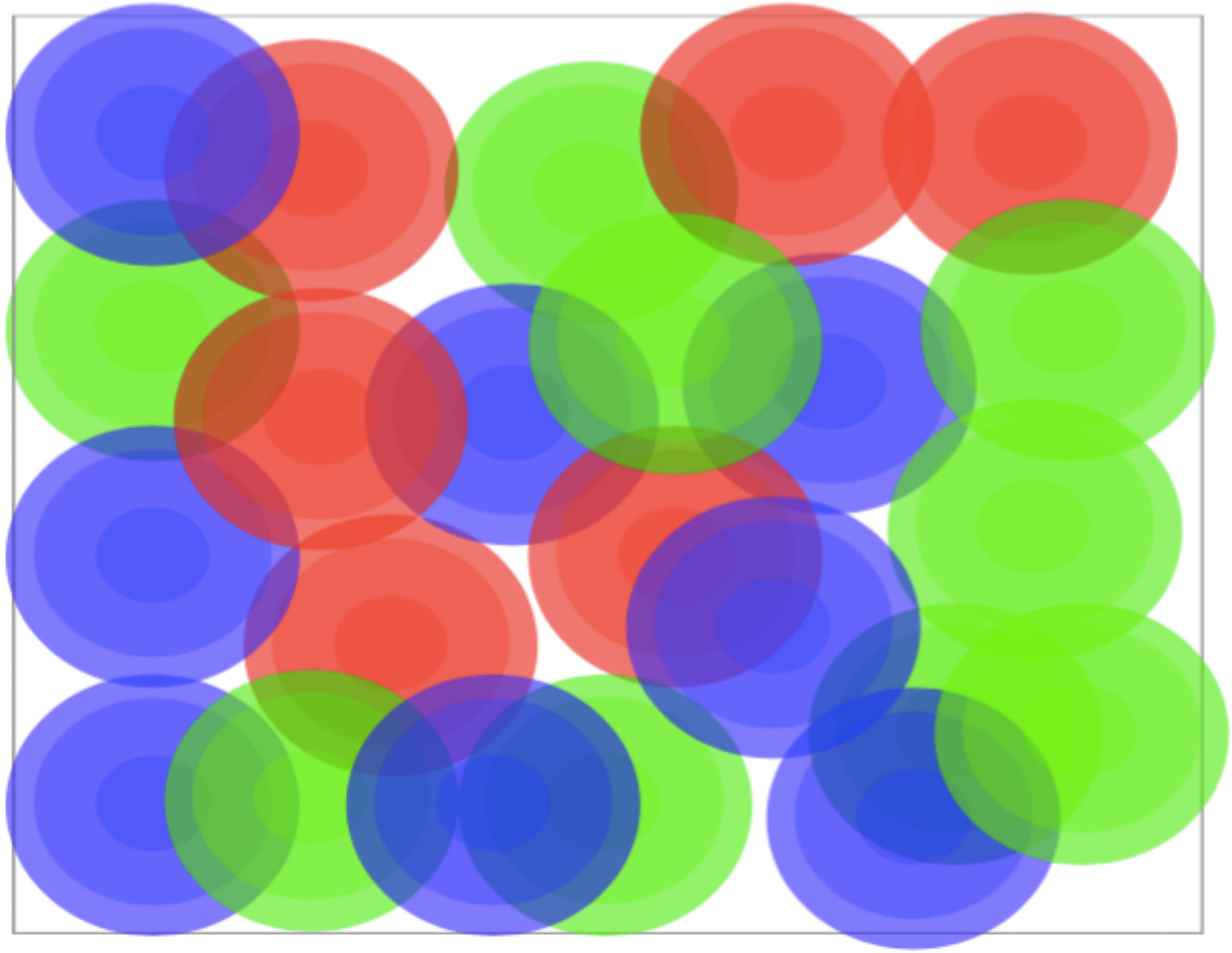

Is it a system with no long lived excitations?

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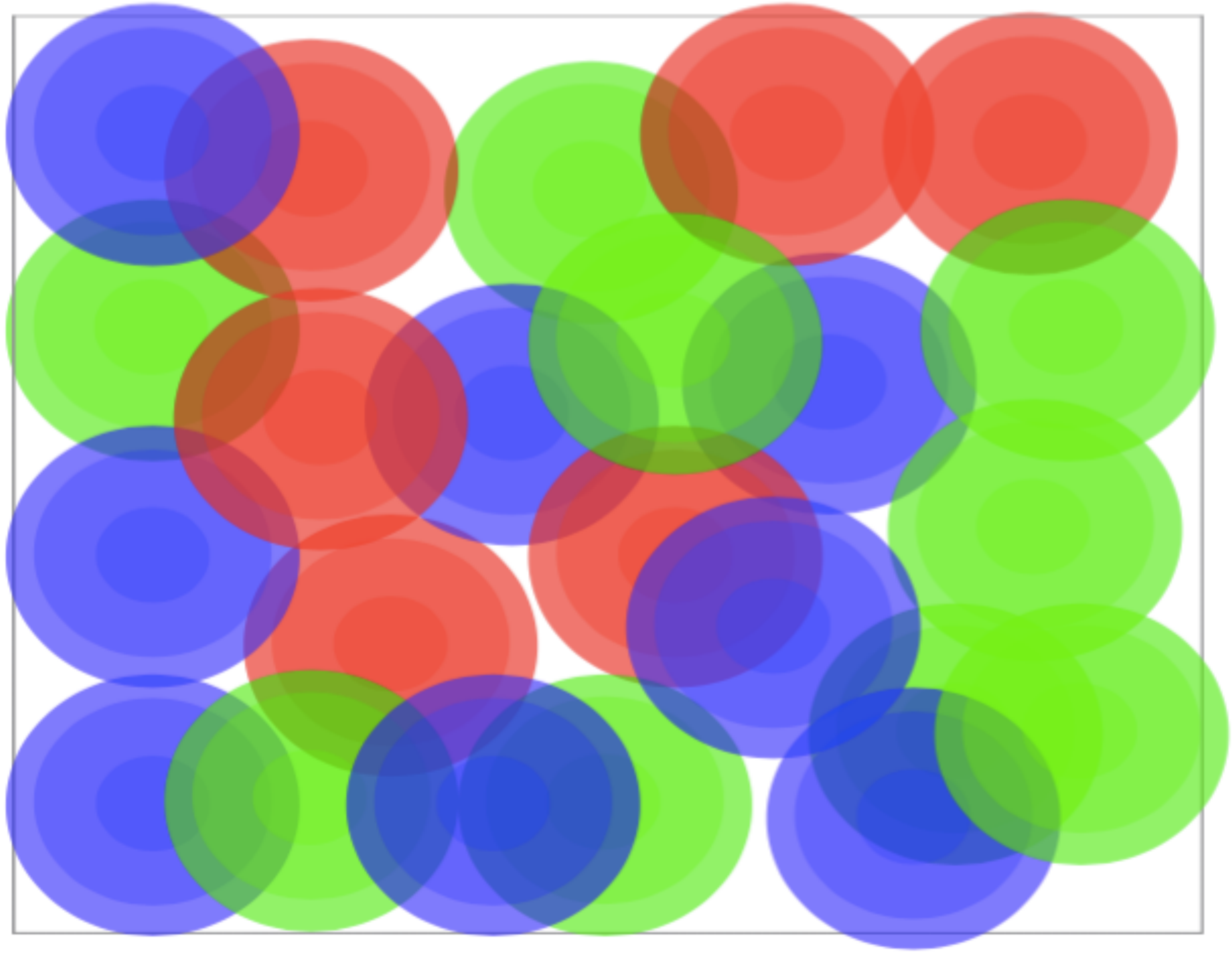

Is it a system with no quasiparticles?

$$\alpha_s = 0.3 \rightarrow g = 2$$

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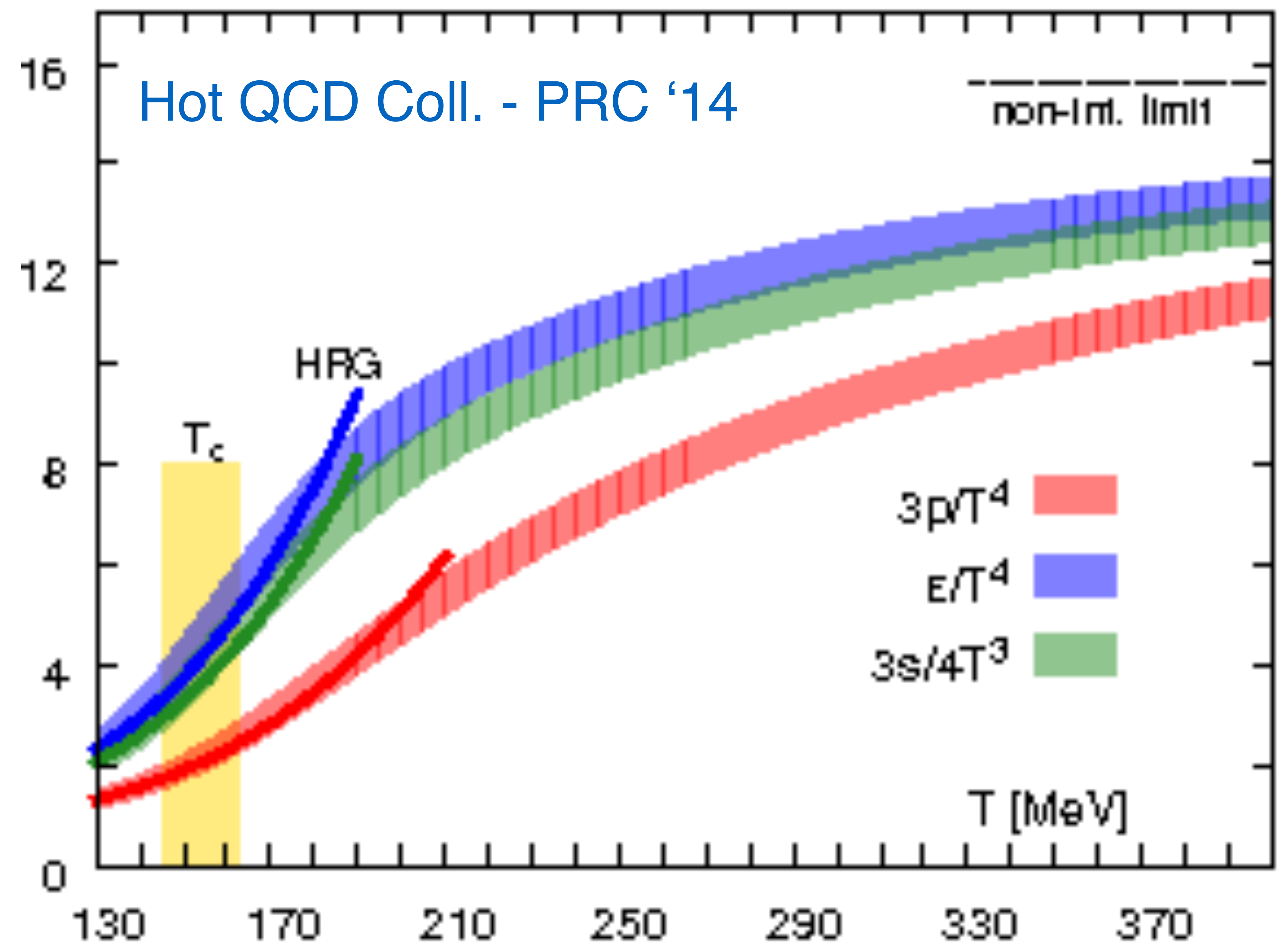
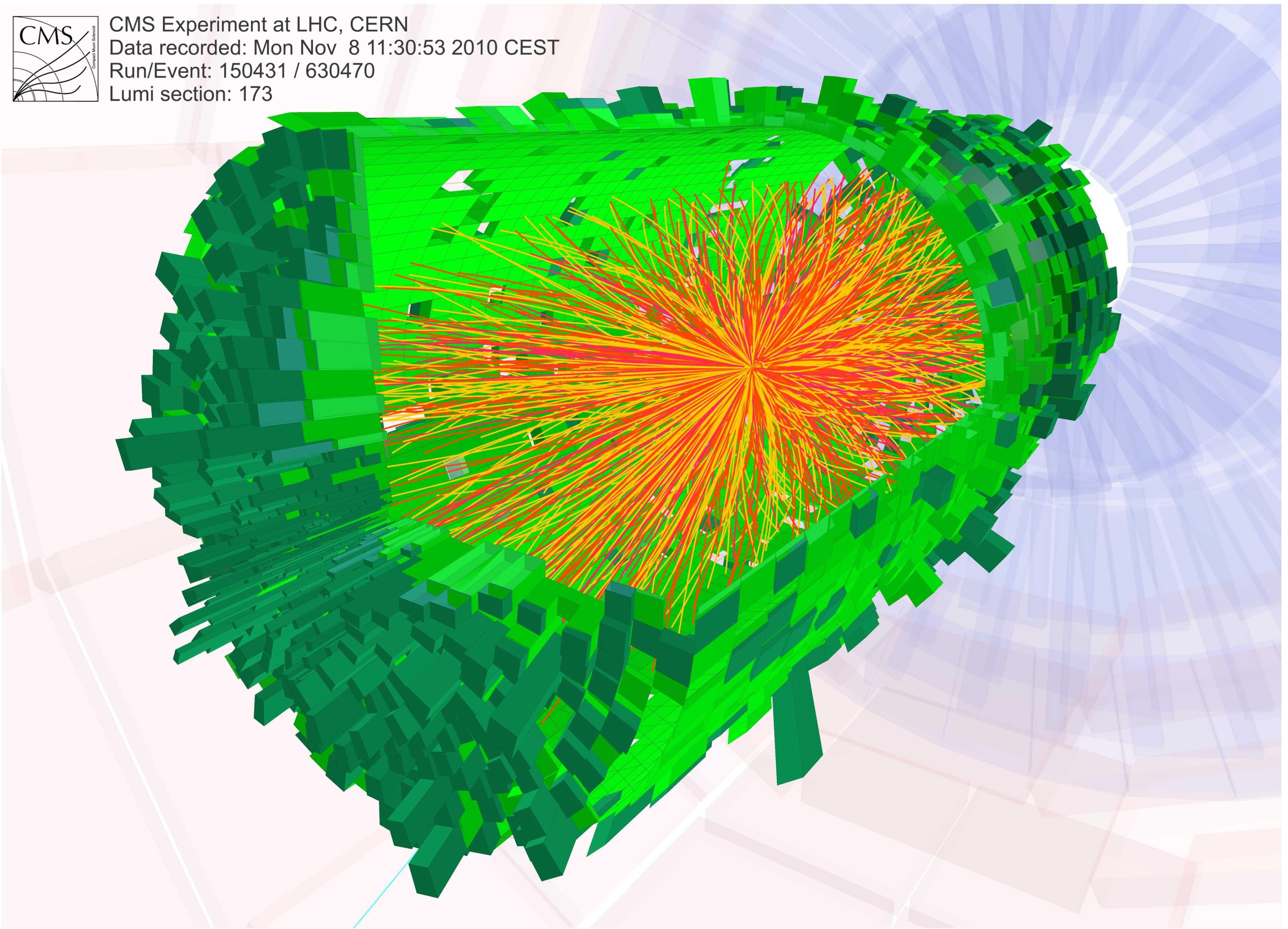
Heavy-Ion Collisions (HIC): The Little Bangs





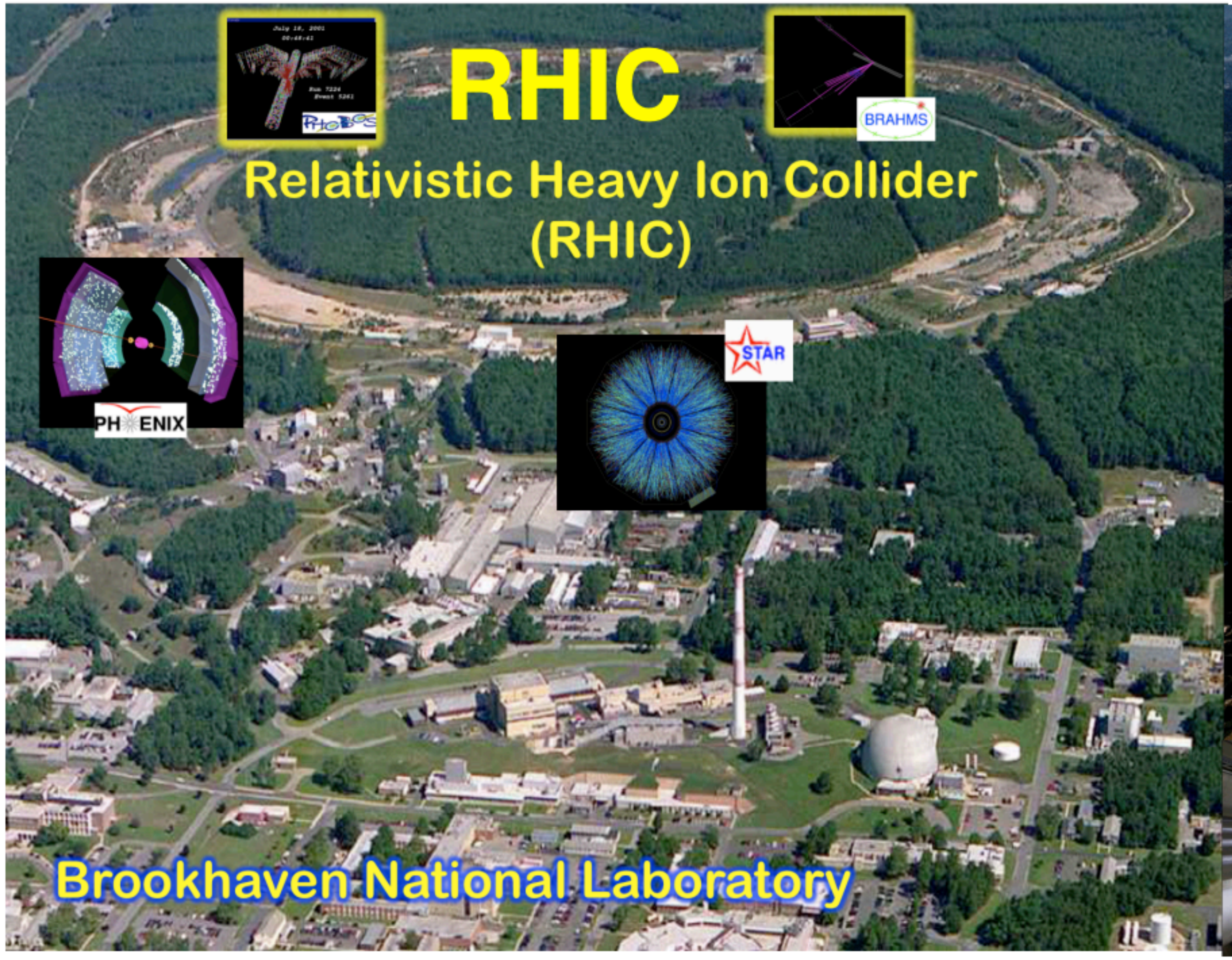
RHIC $\sqrt{s} \sim 0.2\,\mathrm{ATeV}$

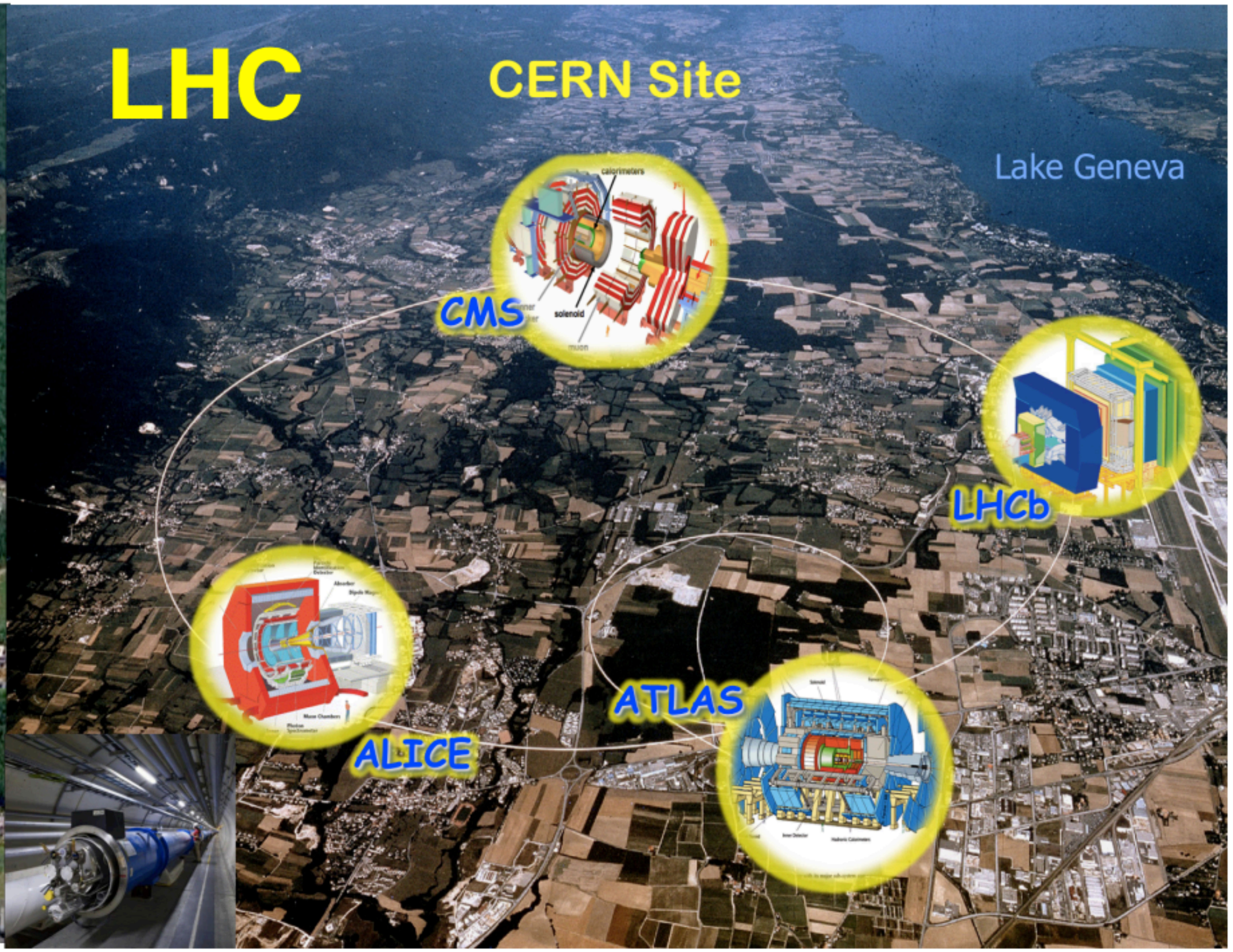
LHC $\sqrt{s} \sim 4\,\mathrm{ATeV}$

- Deconfined matter in experiments:
  - Very strong collective effects.
  - Thousands of particles correlated according to initial geometry.
  - Hydrodynamic explosion!

Heavy-Ion Collisions (HIC): The Little Bangs

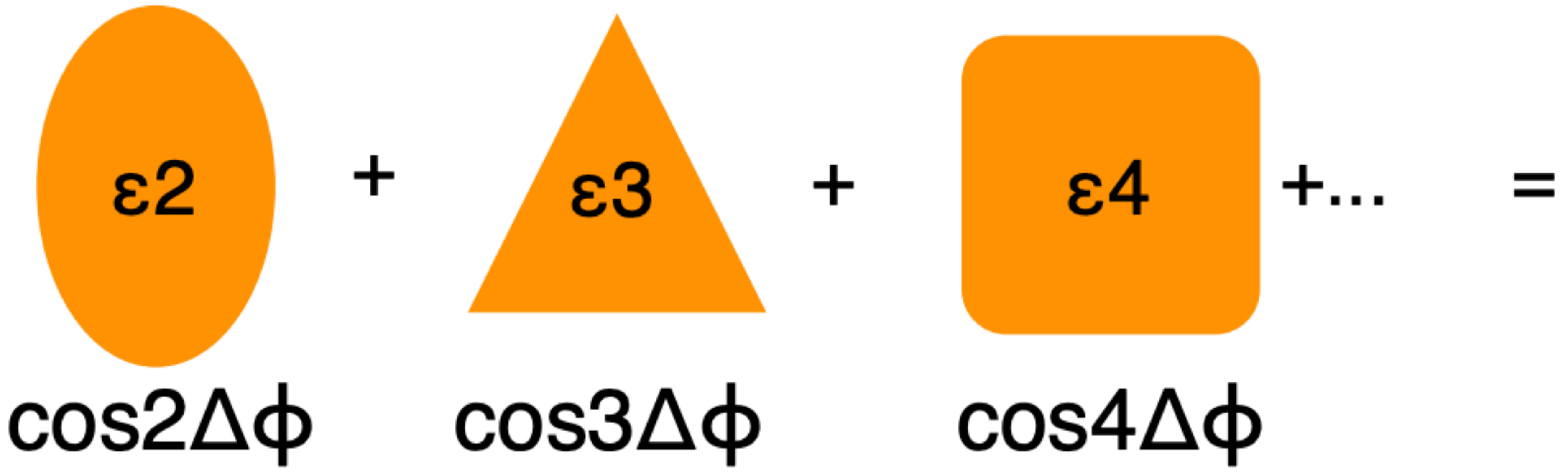
slide adapted from Z. Chen



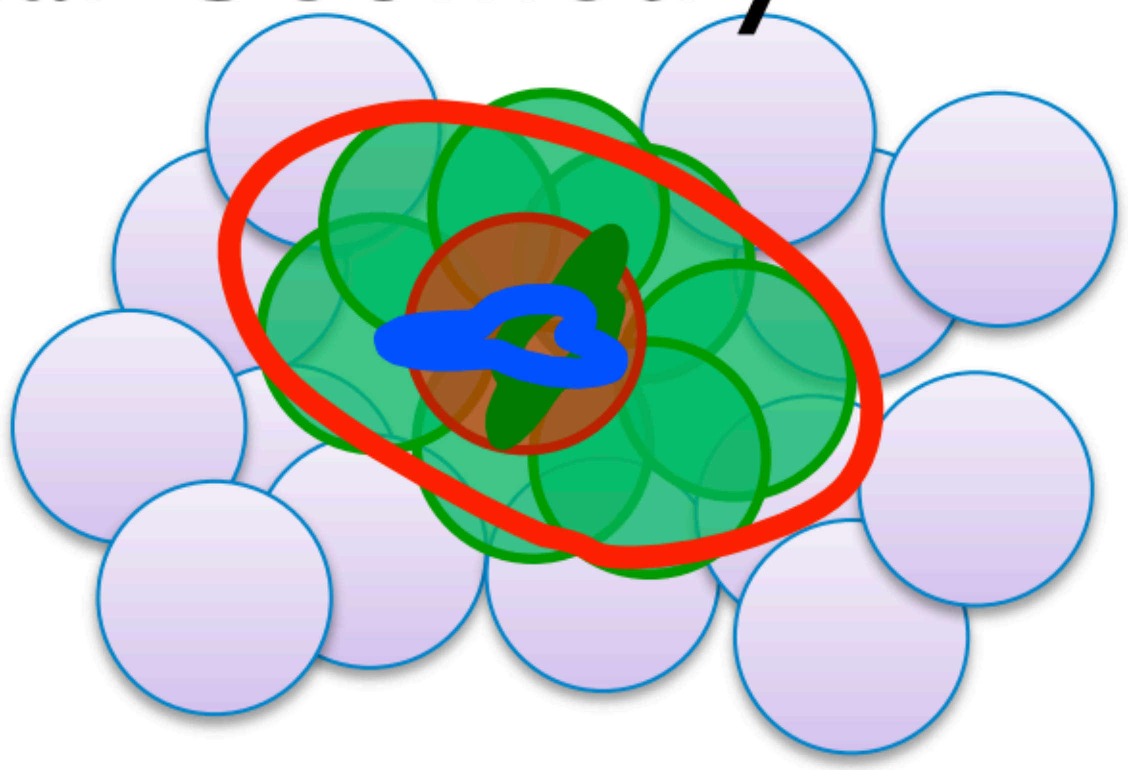


Evidence of Fluidity

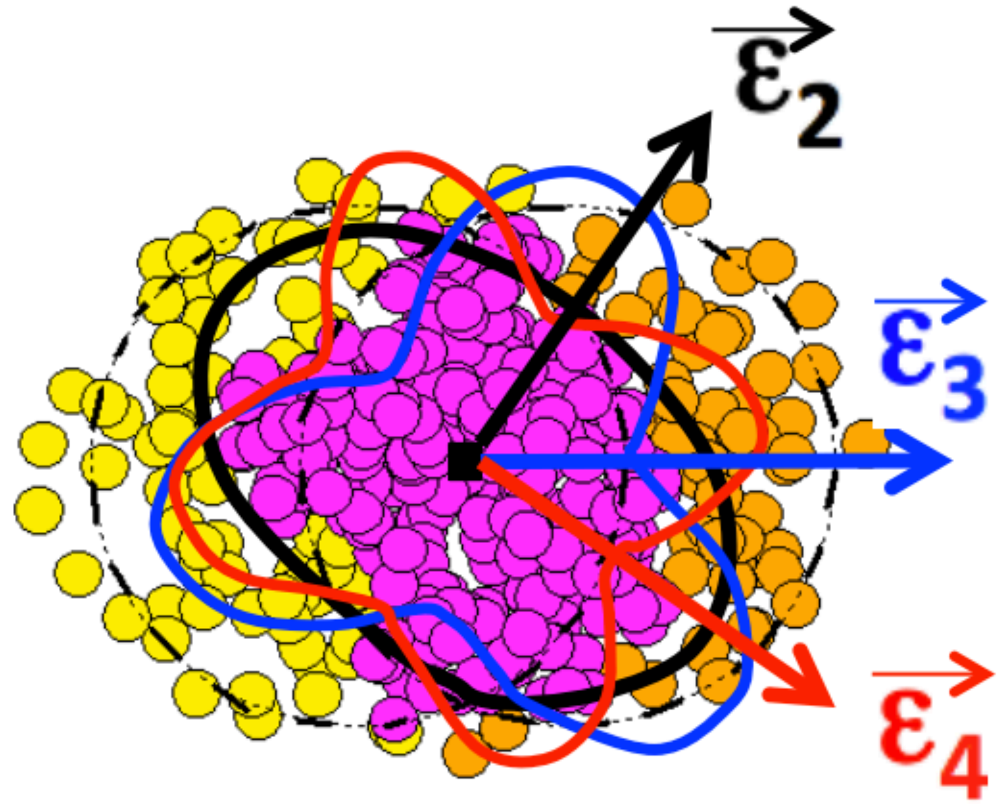
slide adapted from Z. Chen



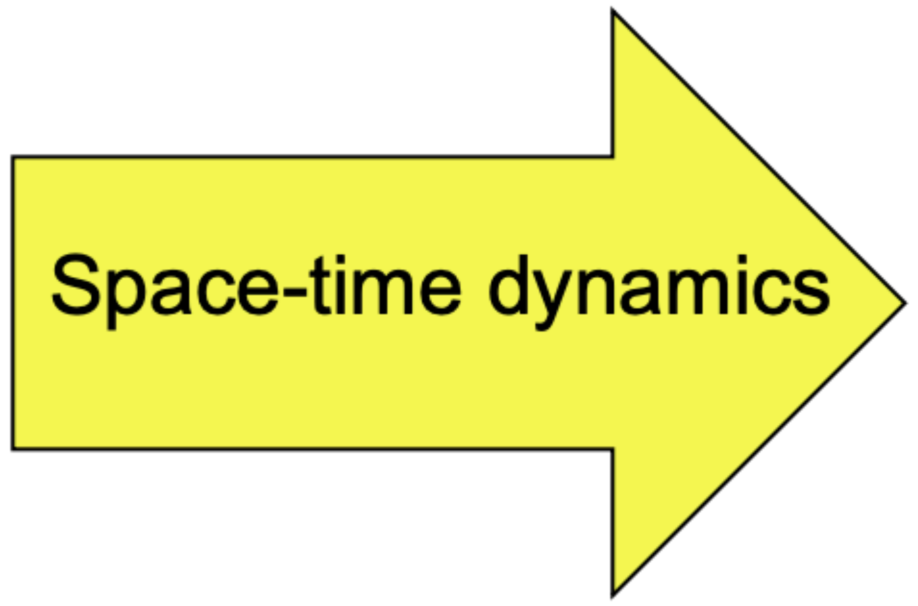
Initial Geometry



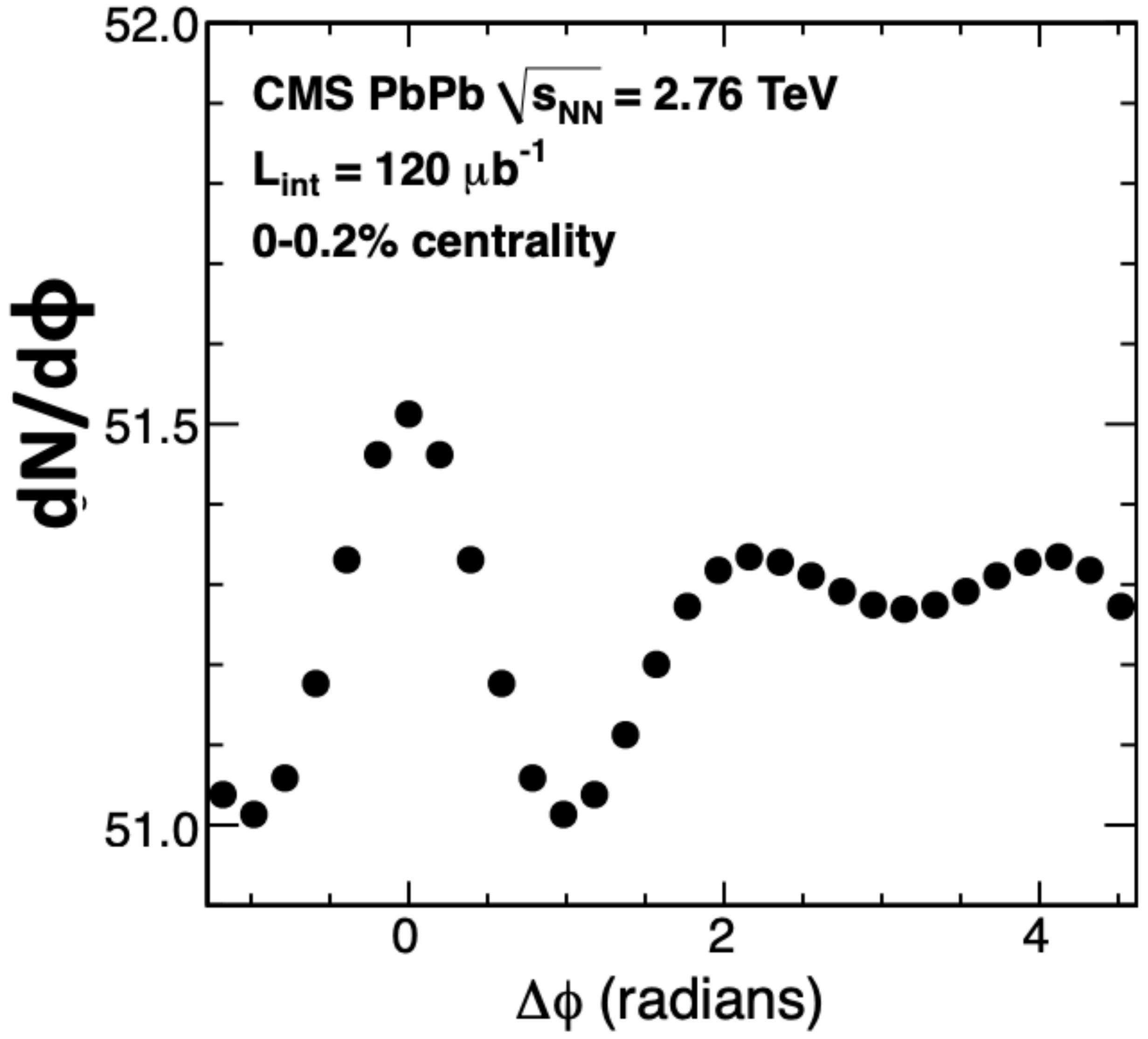
Initial state



Hydro-response



Particle distribution



$$\vec{\epsilon}_n \equiv \epsilon_n e^{in\Phi_n^*} \equiv -\frac{\langle r^n e^{in\phi} \rangle}{\langle r^n \rangle}$$

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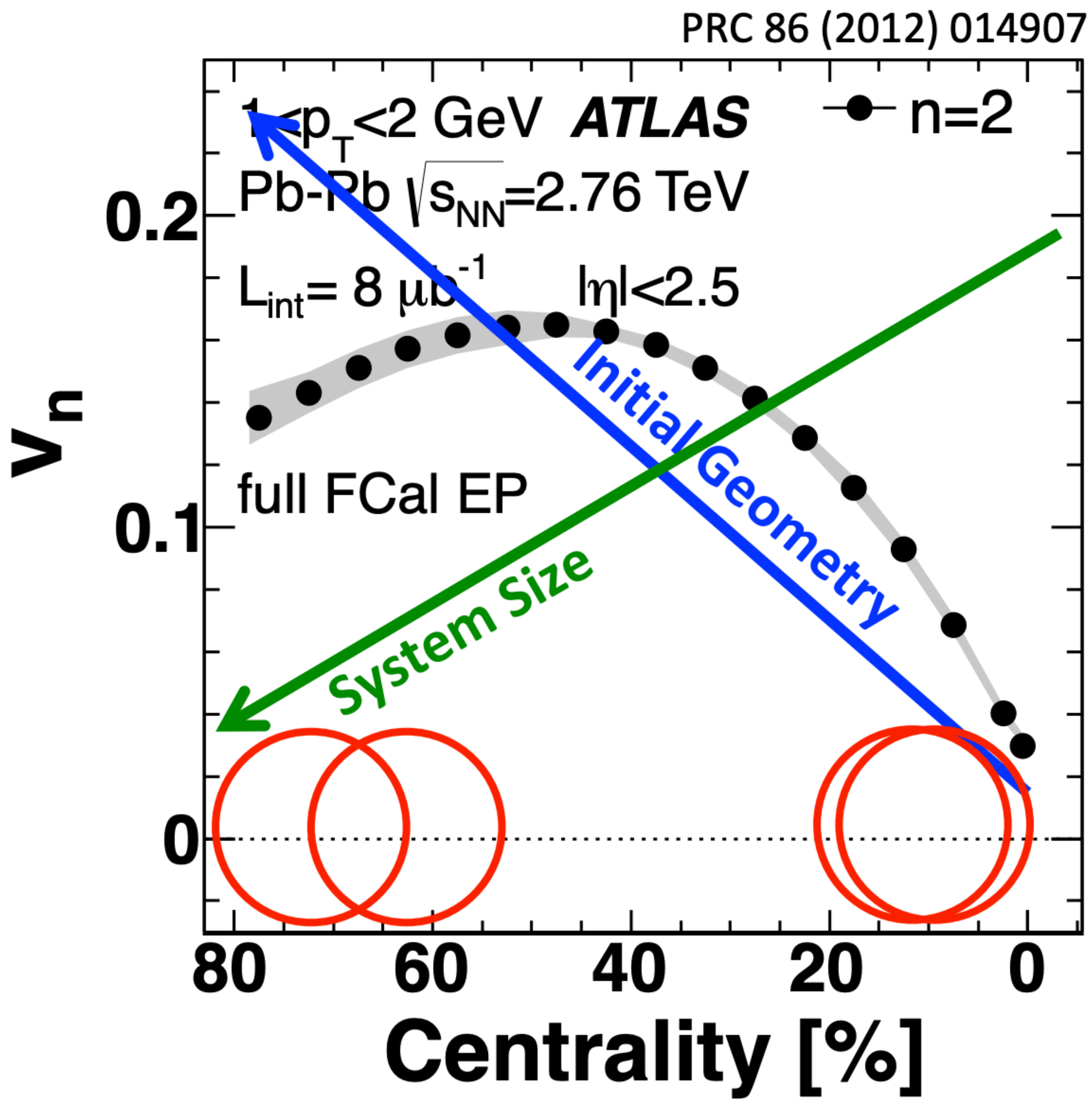
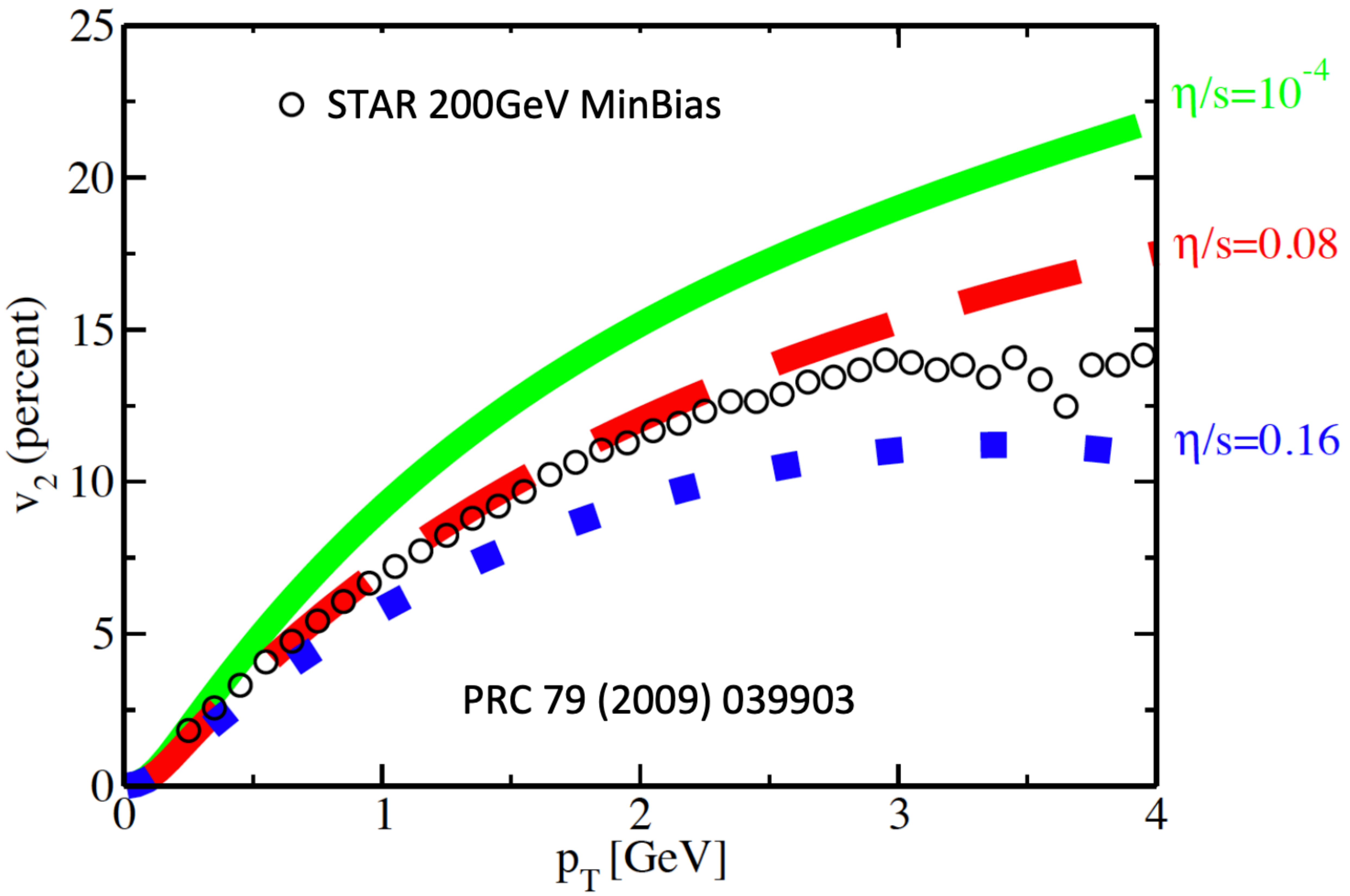
Elliptic Flow vs Centrality

slide adapted from Z. Chen

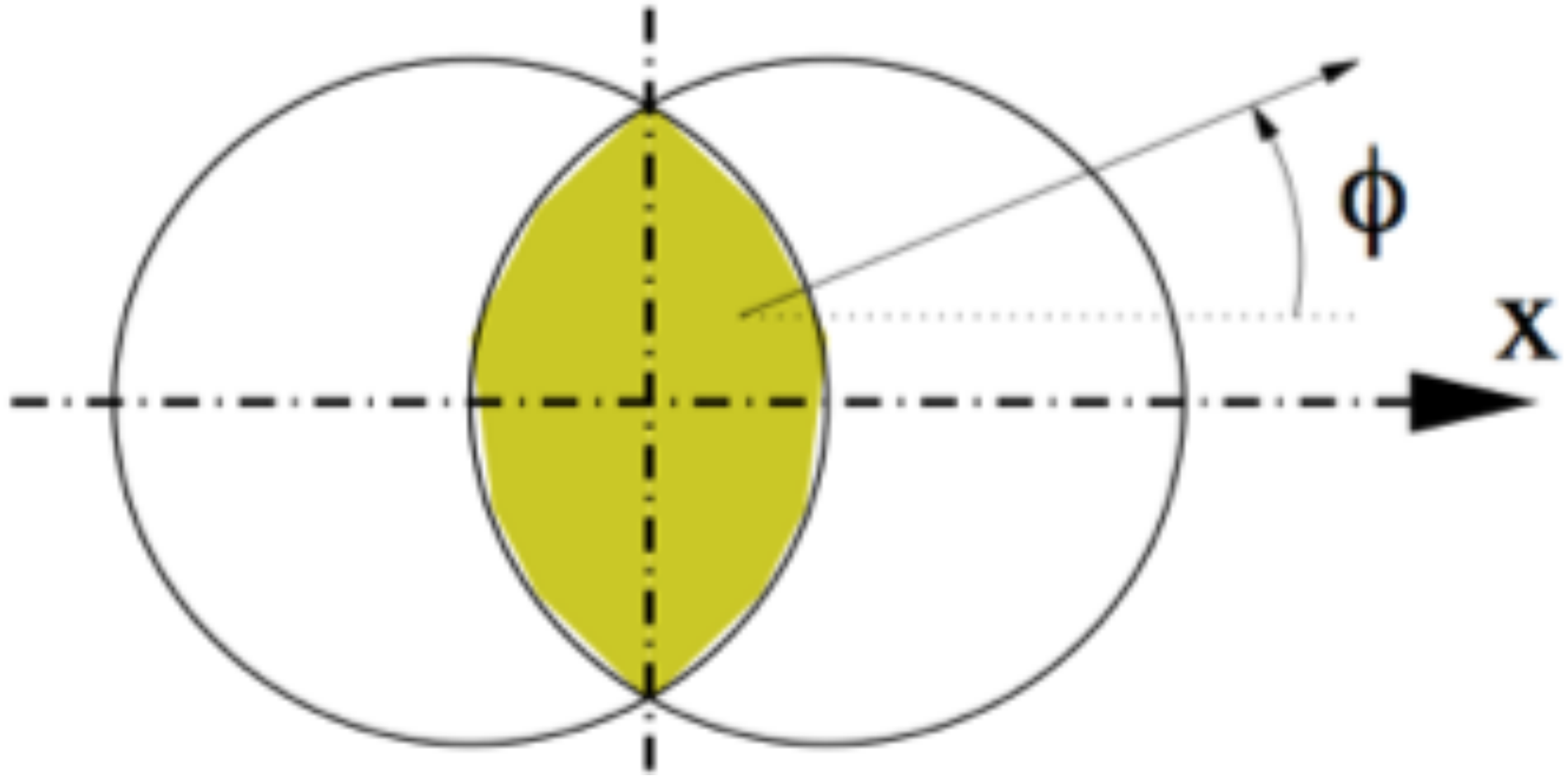


- "Pancake" overlap determines initial eccentricities. Also determines multiplicity.
- To leading order $v_n \propto A\varepsilon_n$.
- As system size decreased, less flow.

Elliptic Flow and Viscosity



- Strong sensitivity of elliptic flow to the value of viscosity (microscopic details).

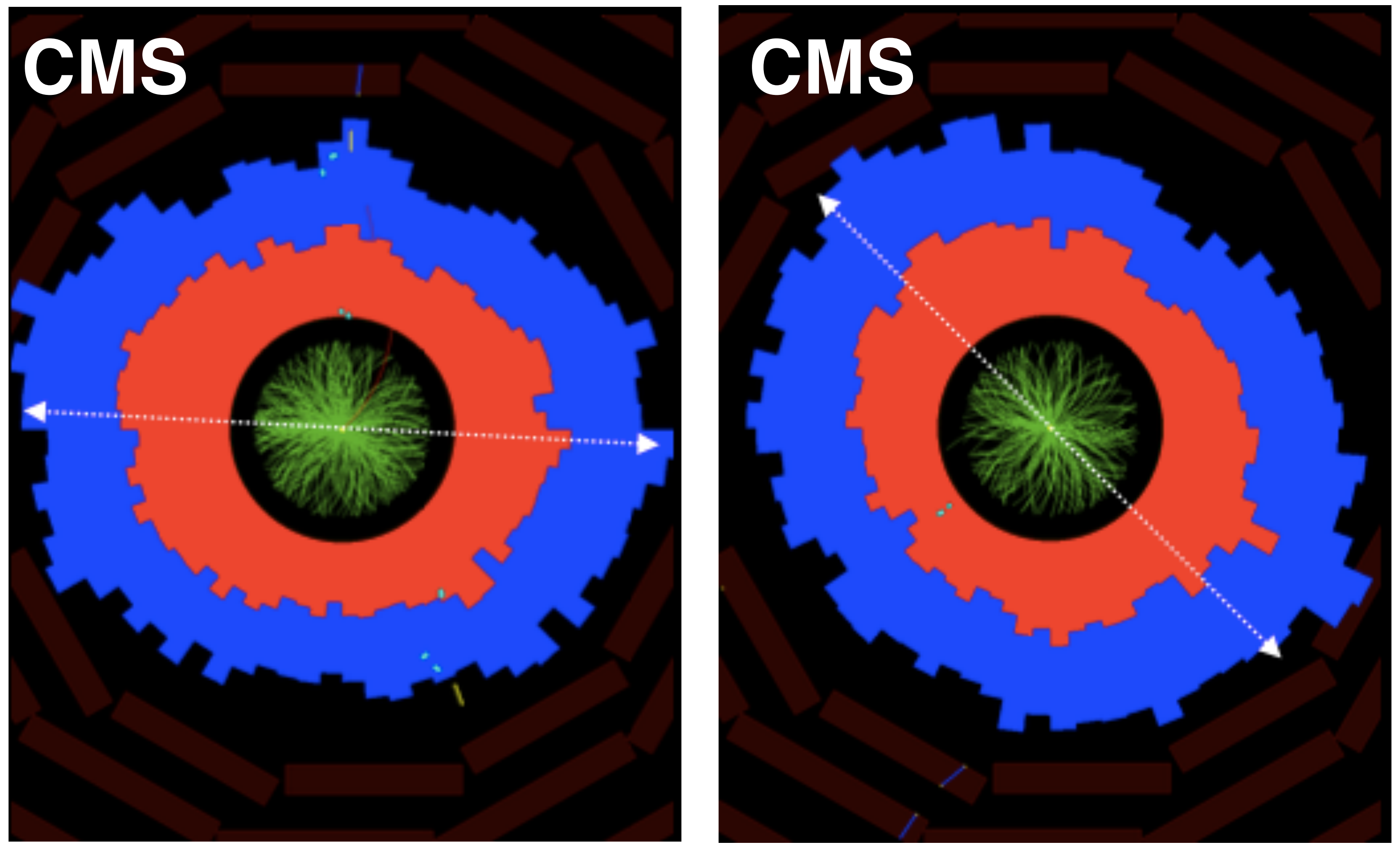


Hydrodynamics:

Spatial anisotropies.

↓

Pressure gradients.



- Correlations quantified in the experiments through so-called flow coefficients:

$$E\frac{d^3N}{d^3p}=\frac{1}{2\pi}\frac{d^2N}{p_t dp_t dy}\left(1+\sum_{n=1}^{\infty}2v_n\cos[n(\phi-\Psi_R)]\right)$$

Ψ_R is event plane angle.

v_2

v_3

v_4

etc…

- Hydrodynamic simulations point to almost ideal fluid:

$$\left(\frac{\eta}{s}\right)_{T_c}\simeq 0.08$$

Bernhard et al. - PRC '16

$$\frac{\eta_{\lambda\to 0}}{s_{\lambda\to 0}}=\frac{A}{\lambda^2\log\left(B/\sqrt{\lambda}\right)}$$

N=4 SYM @ weak coupling

$$\frac{\eta_{\lambda=\infty}}{s_{\lambda=\infty}}=\frac{1}{4\pi}$$

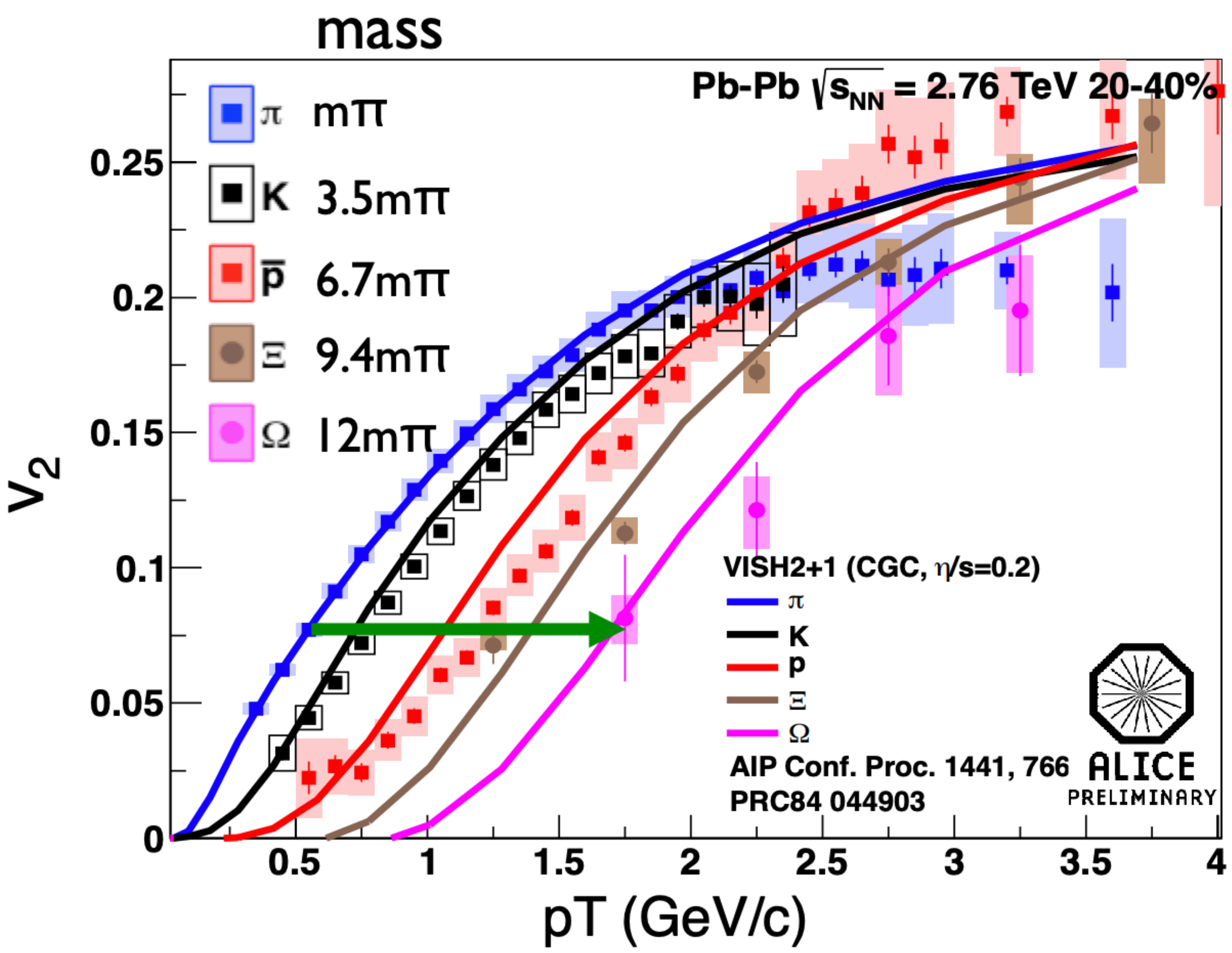
Preferred by data

N=4 SYM @ strong coupling

Gauge/String Duality, Hot QCD and Heavy Ion Collisions - Cambridge University Press '14

Mass Ordering of Flow

slide adapted from Z. Chen



Boost:
$\Delta p_T \sim m\beta_T$

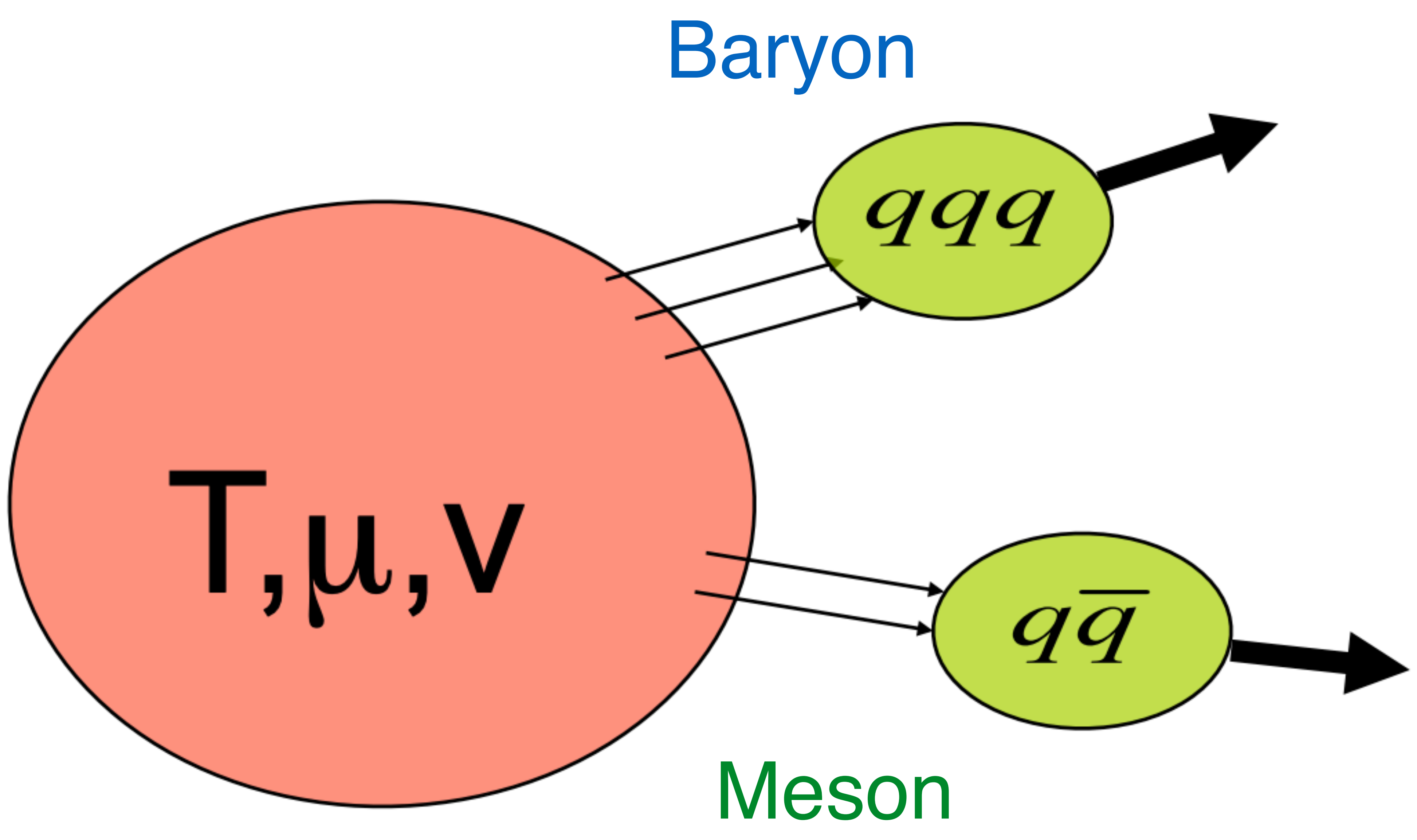
- Heavier particle has smaller v_2 for same p_T.
  - Predicted by hydro: common boost at partonic level.

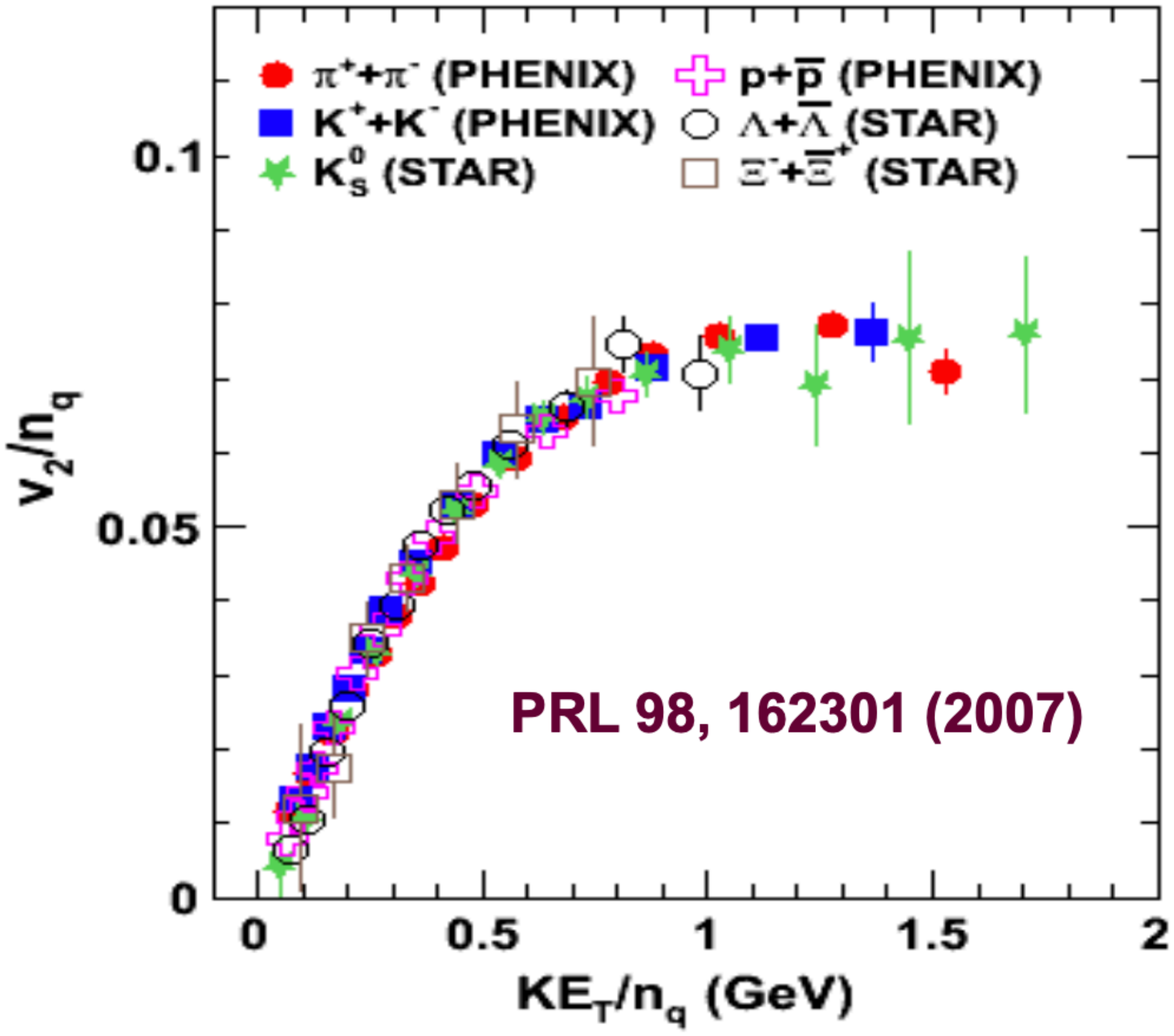
Quark Coalescence

slide adapted from B. Mueller

$$v_2^{\mathrm{M}}(p_{\mathrm{T}}) = 2\ v_2^{\mathrm{q}}(p_{\mathrm{T}}/2)$$

$$v_2^{\mathrm{B}}(p_{\mathrm{T}}) = 3\ v_2^{\mathrm{q}}(p_{\mathrm{T}}/3)$$



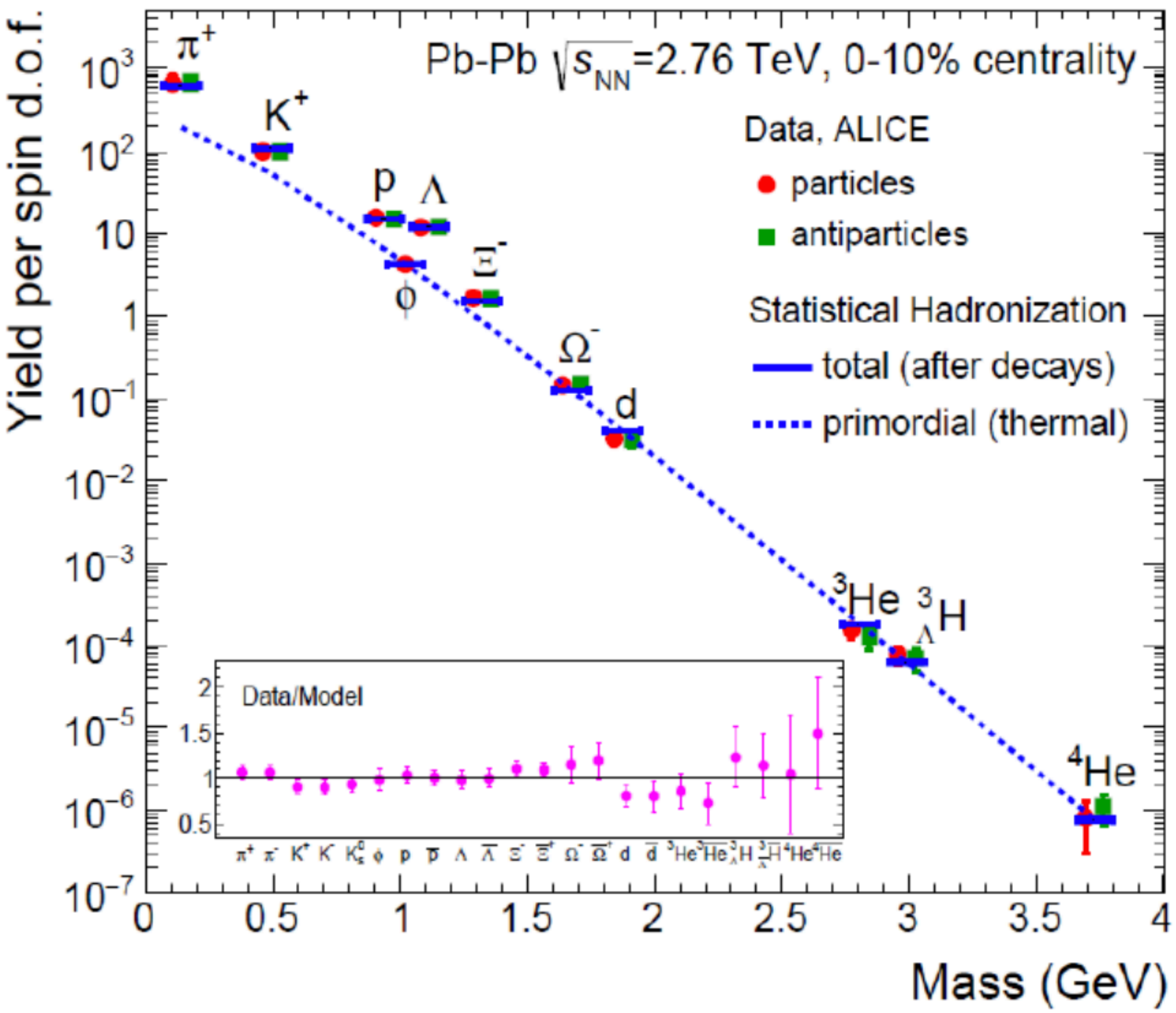


- Scaling of elliptic flow with number of quarks.
  - ➔ Driven by flowing partonic d.o.f.

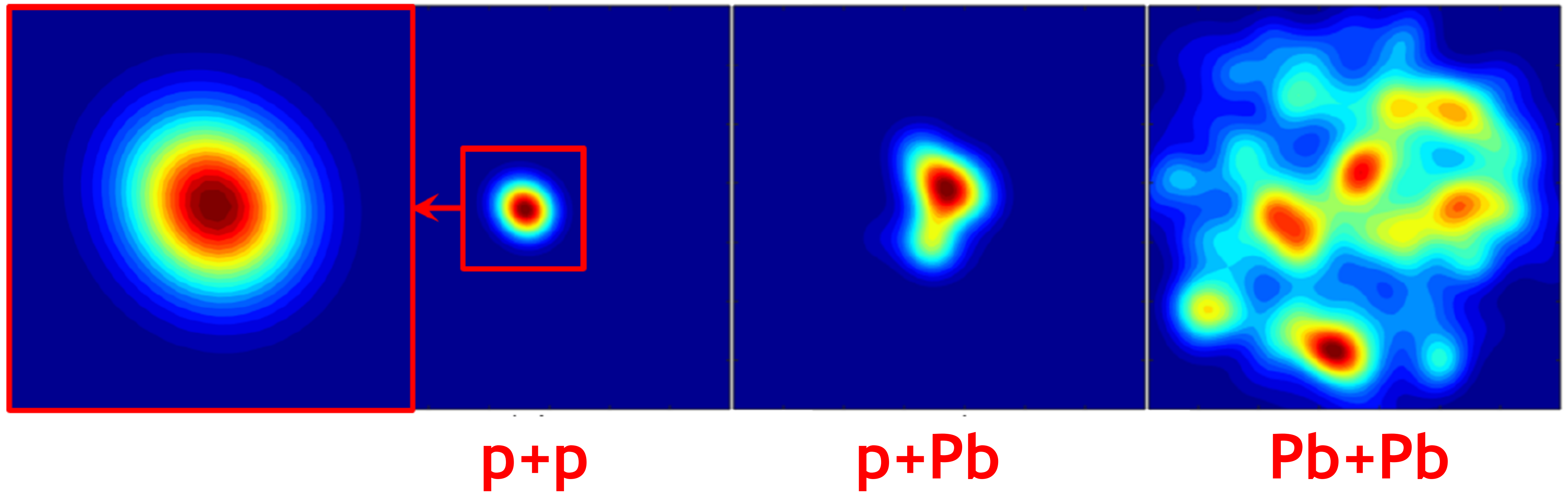
Statistical Hadronization Model

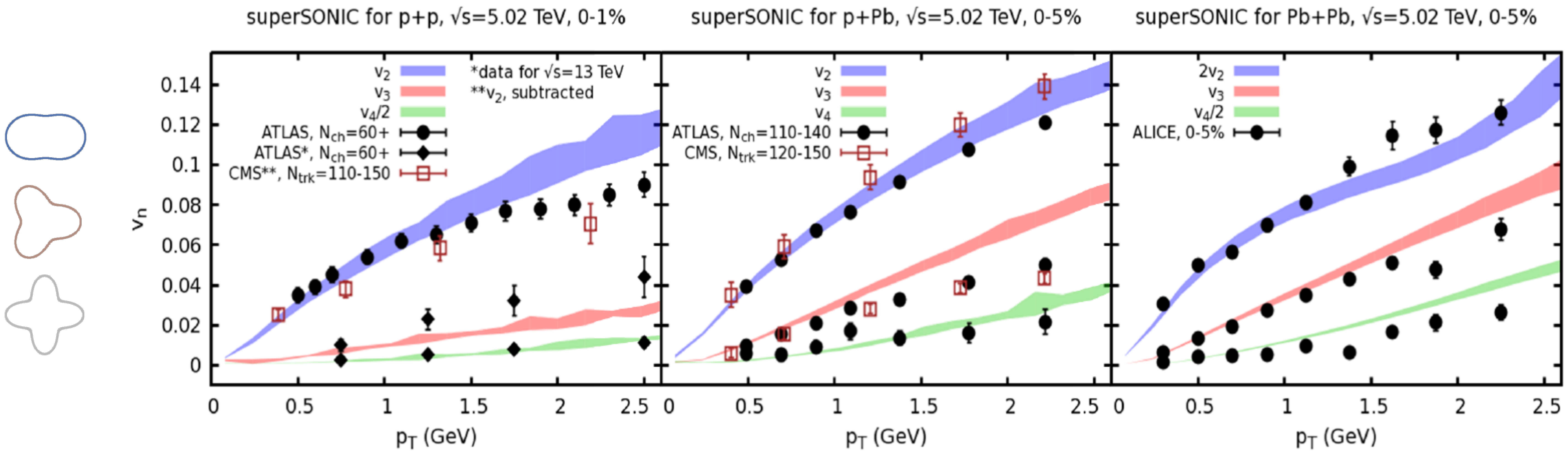
- Thermal production of hadrons using canonical or grand-canonical ensembles.
  - ➔ 1 free parameter: T ~ 156.5(1.5) MeV
- Describes yields accurately in *all collision systems.*
  - ➔ How is thermalization achieved!?
- Some ideas: analogy between confinement and black hole physics.
  - ➔ Event horizon for colored signals, causally disconnected region. (Hawking-Unruh hadronization).

A. Andronic, P. Braun-Munzinger, K. Redlich, J. Stachel, Nature 561 (2018) 321



"One fluid to rule them all"

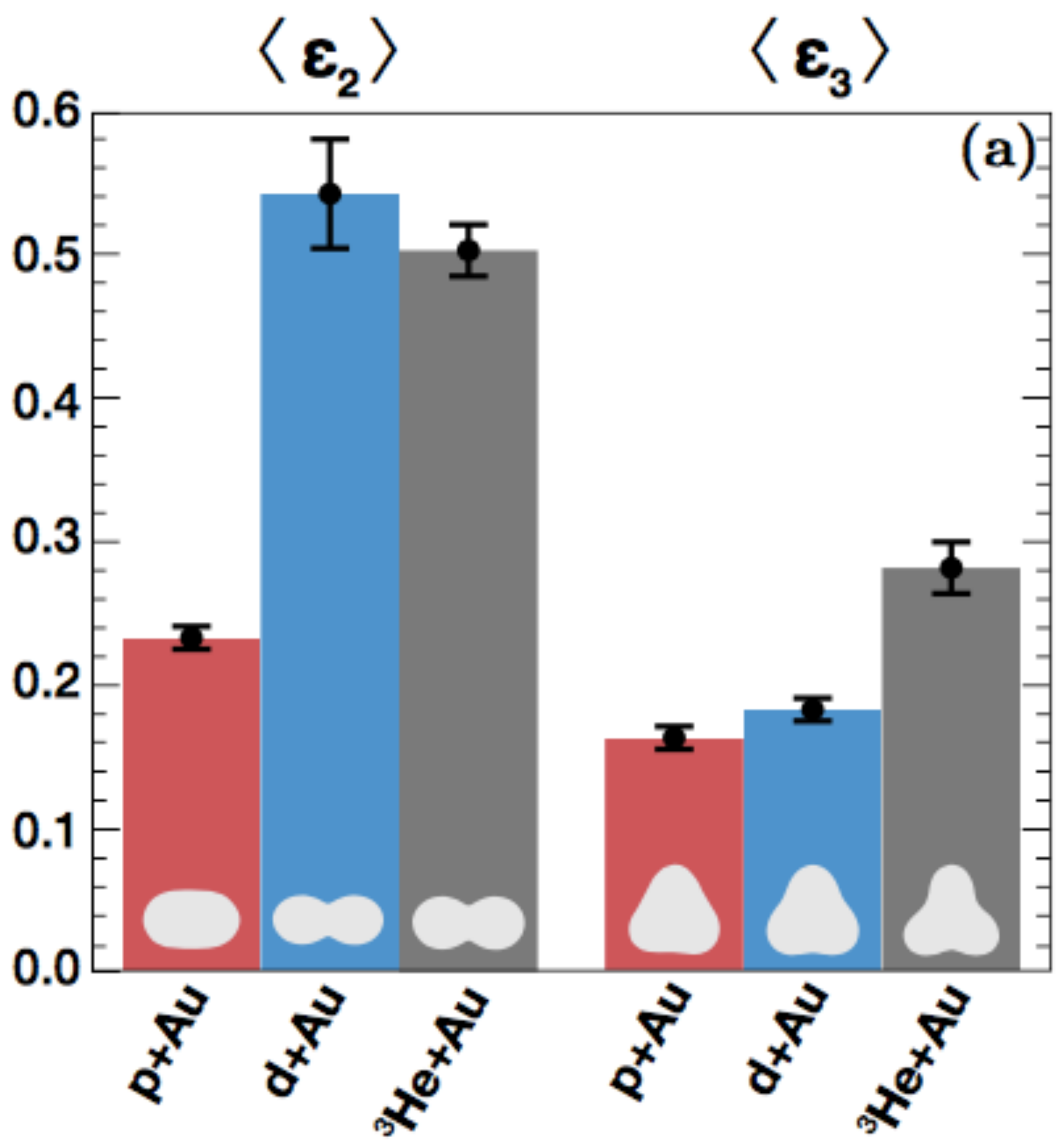


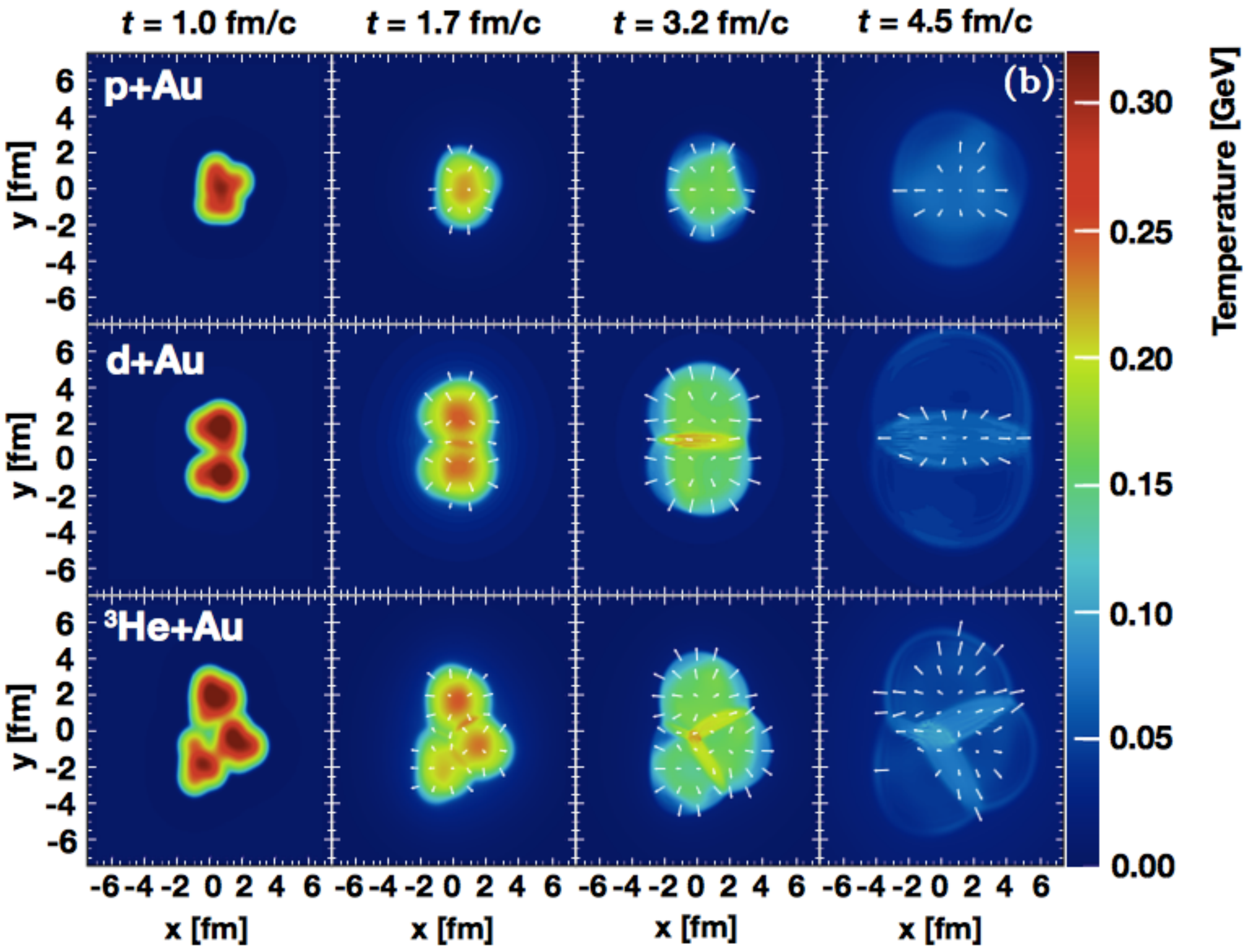


Weller and Romatschke, 1701.07145

Tuning Eccentricities in Small Systems

Nature Physics **15,** *214–220 (2019)*
PHENIX collaboration

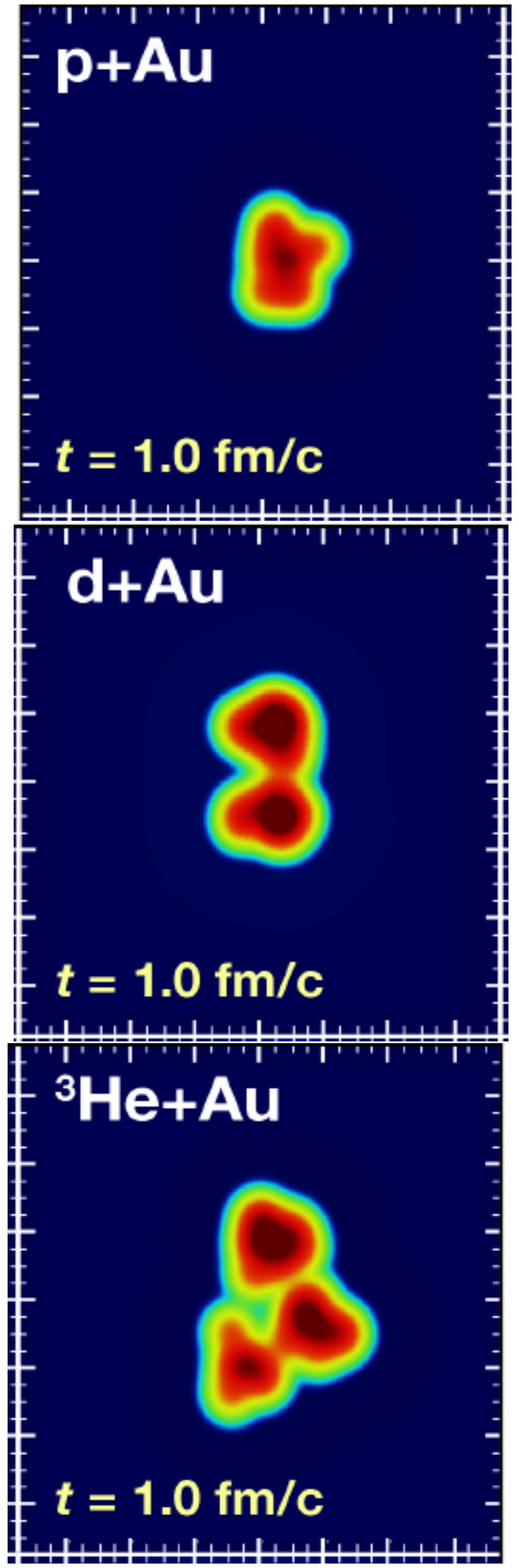


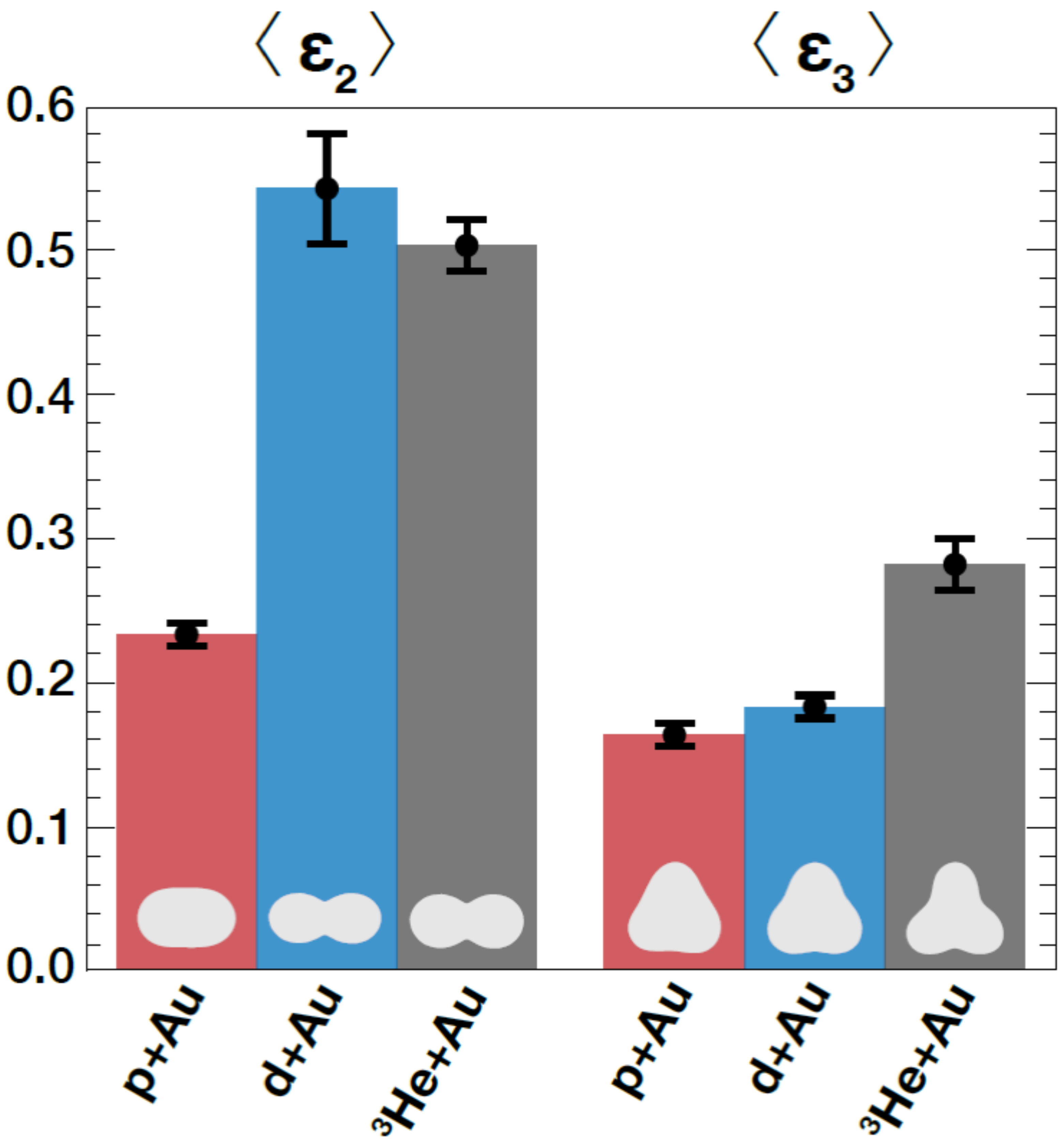


→ Expectation from hydro arguments:

$$v_2^{p+\mathrm{Au}} < v_2^{d+\mathrm{Au}} \approx v_2^{^3\mathrm{He+Au}},$$
$$v_3^{p+\mathrm{Au}} \approx v_3^{d+\mathrm{Au}} < v_3^{^3\mathrm{He+Au}}.$$

Tuning Eccentricities in Small Systems





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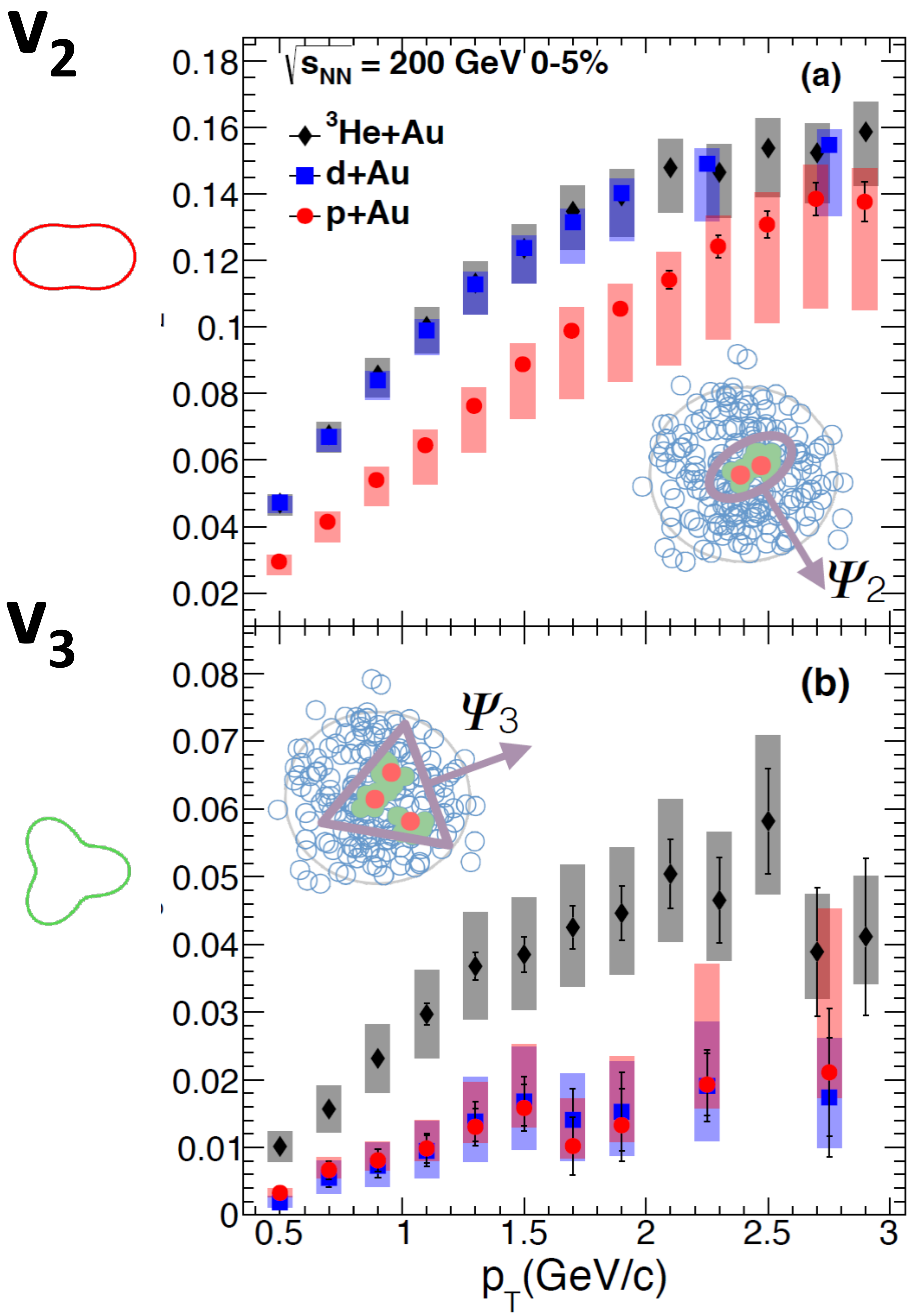
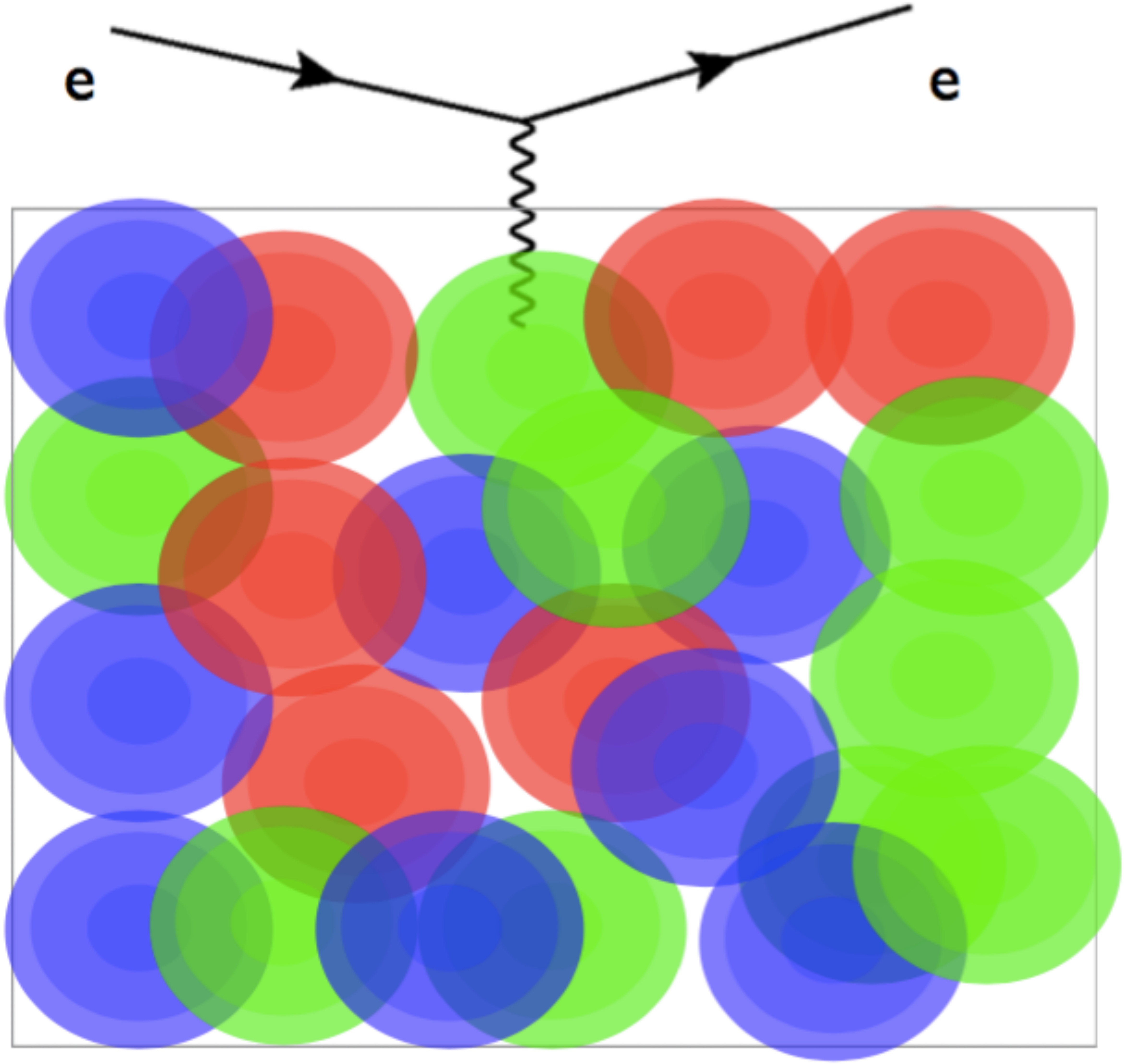
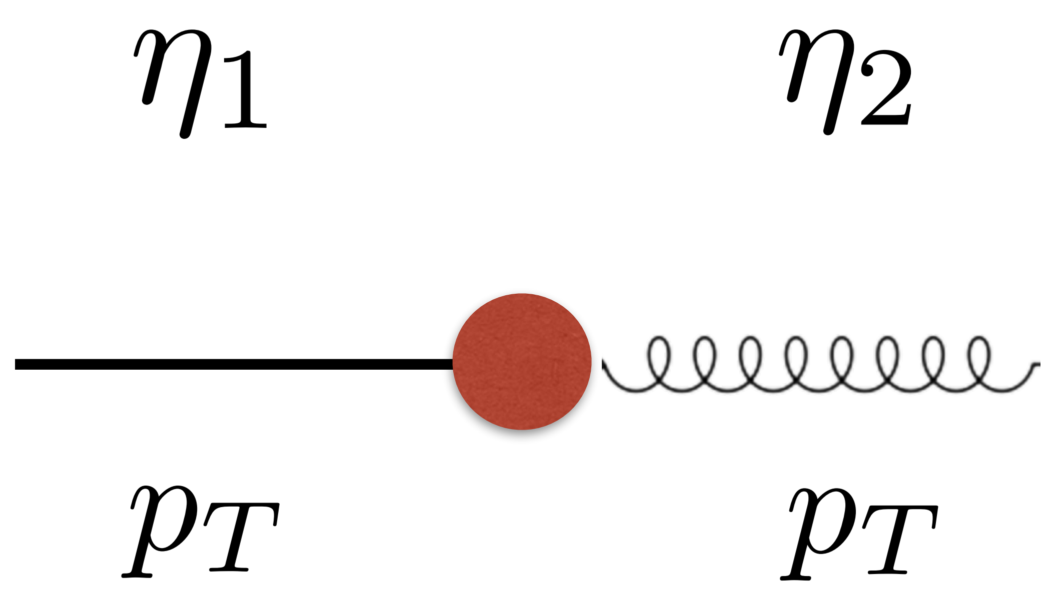


How Can We Probe the QGP?



Jets in pp

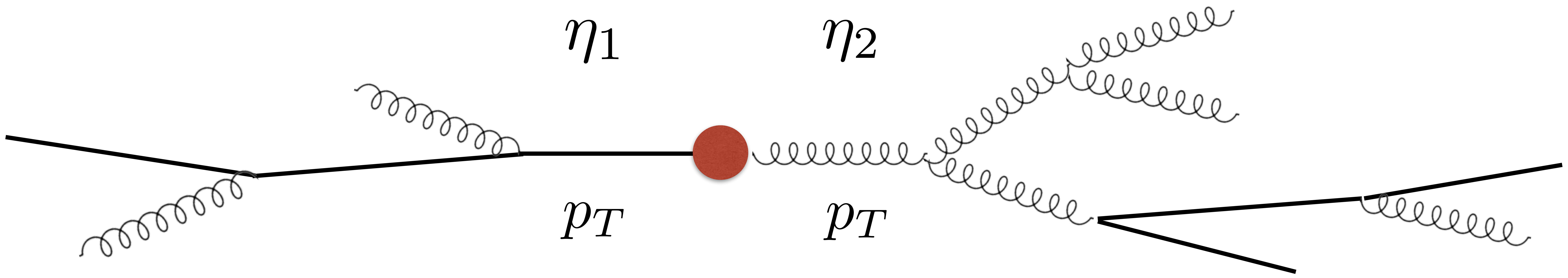
- Hard parton pairs produced back-to-back in transverse plane, misaligned in rapidity.



Jets in pp

- Hard parton pairs produced back-to-back in transverse plane, misaligned in rapidity.
- Parton density evolution described via DGLAP:

$$t\frac{\partial}{\partial t}f(x,t) \;=\; \int \frac{dz}{z}\,\frac{\alpha_s}{2\pi}P_+(z)\,f\left(\frac{x}{z},t\right)$$



- Collimated structure enforced through collinear divergences & color coherence.

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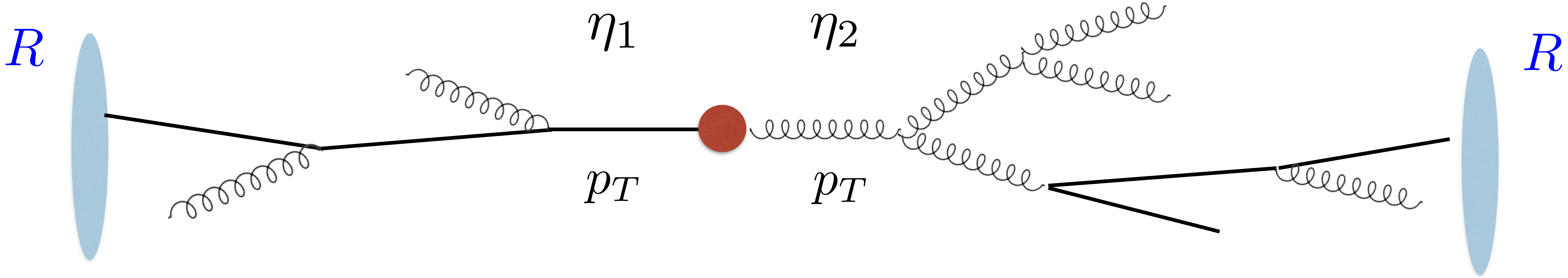

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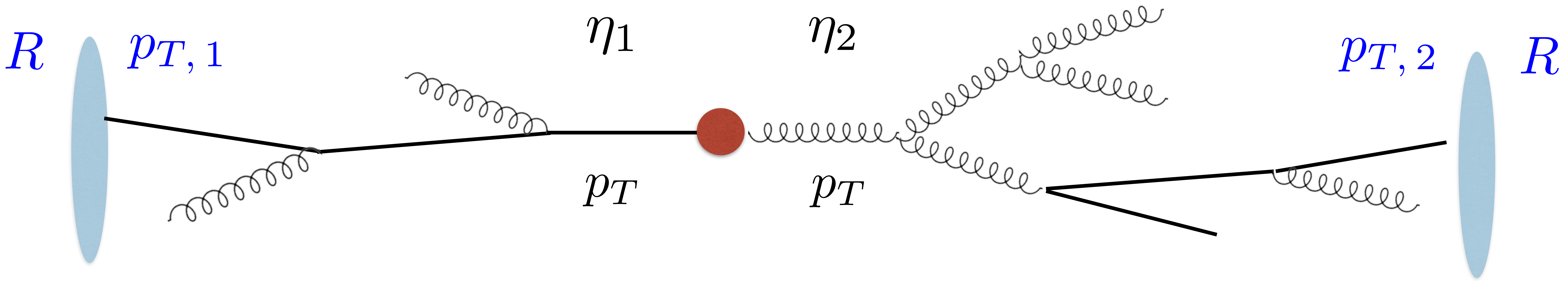
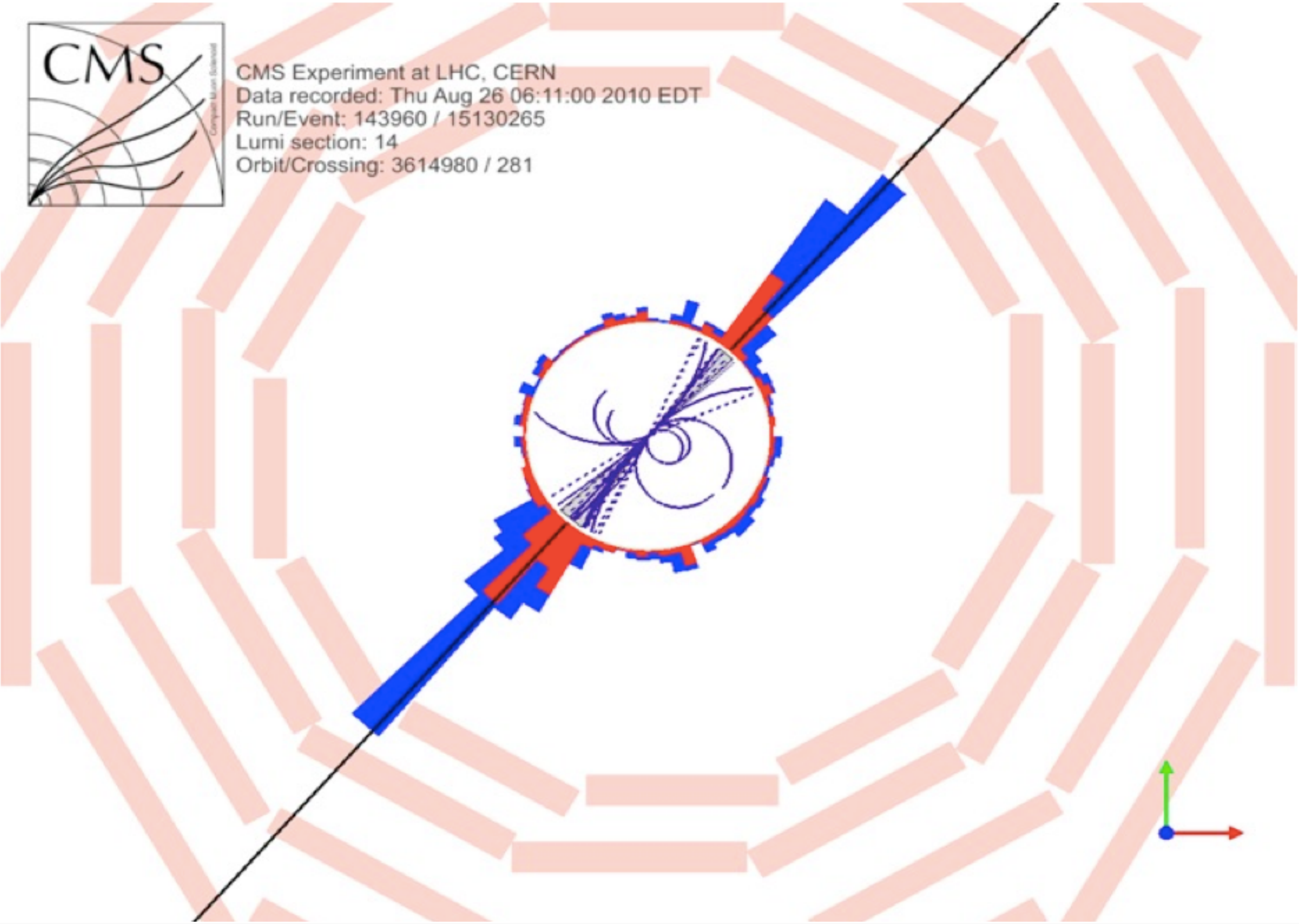


- Collimated structure enforced through collinear divergences & color coherence.
- Jets are defined with clustering algorithm, reconstruction radius R.

➜ Degree of jet activity determines, e.g., out-of-cone radiation (causes dijet asymmetry in pp).

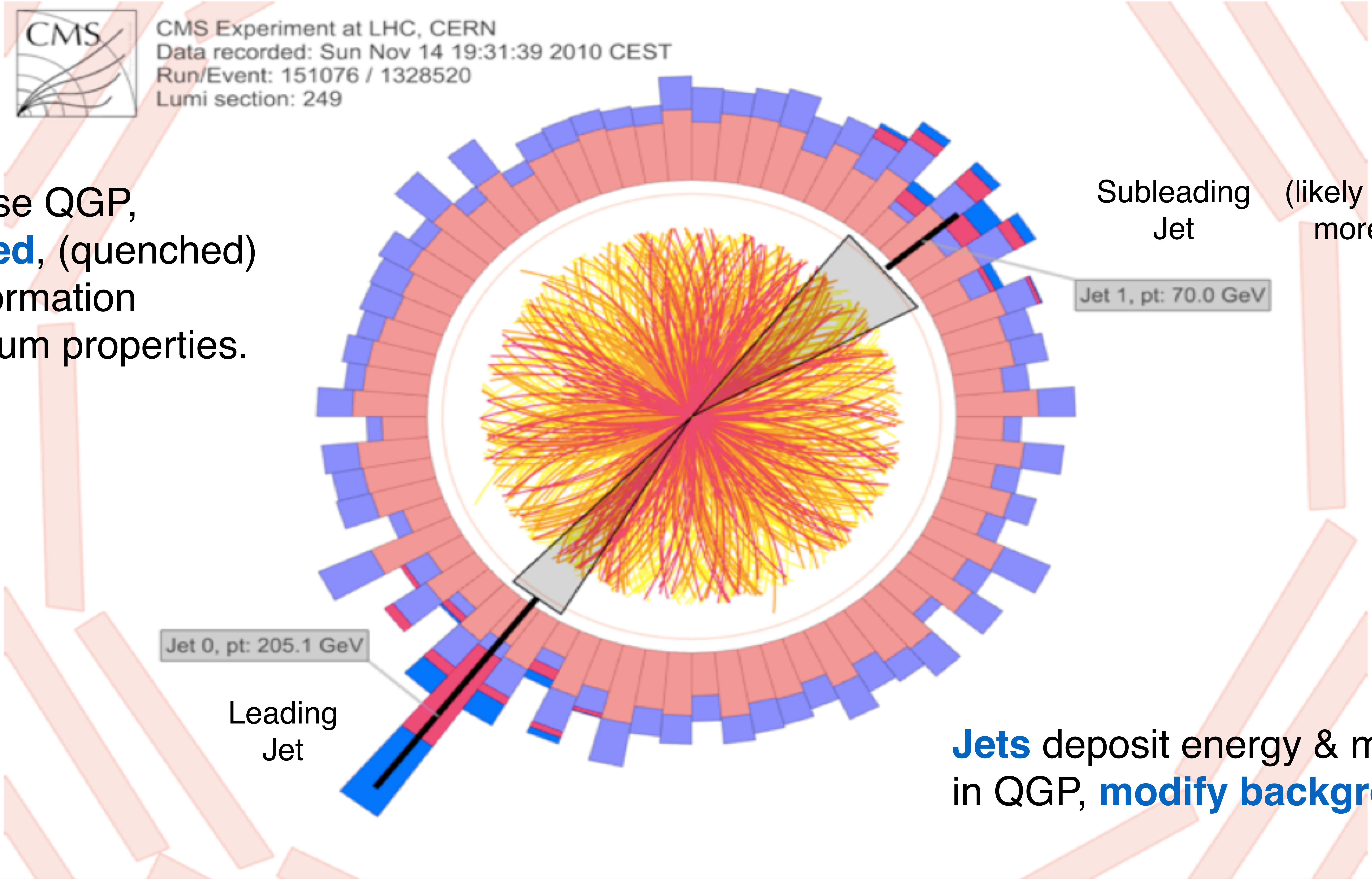
$$p_{T,1} > p_{T,2}$$

Jets in Proton-Proton Collisions



Jets in HIC

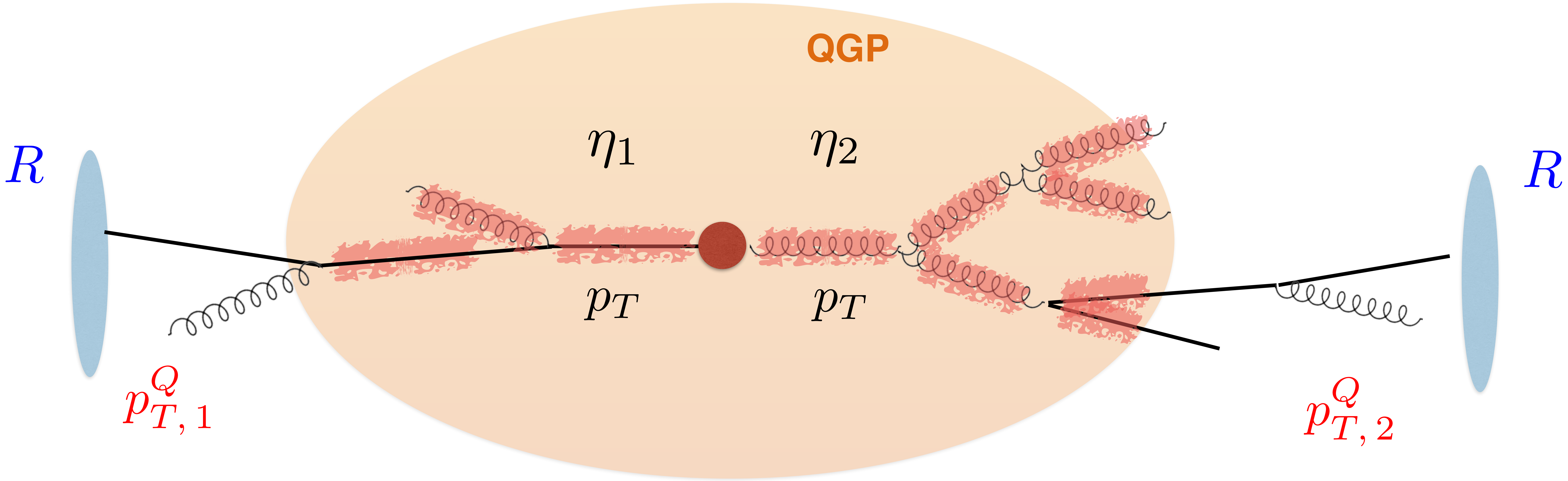
Jets traverse QGP,
get modified, (quenched)
provide information
about medium properties.



Jets deposit energy & momentum in QGP, **modify background**.

Outline

- Jet partons interact with QGP and experience energy loss.



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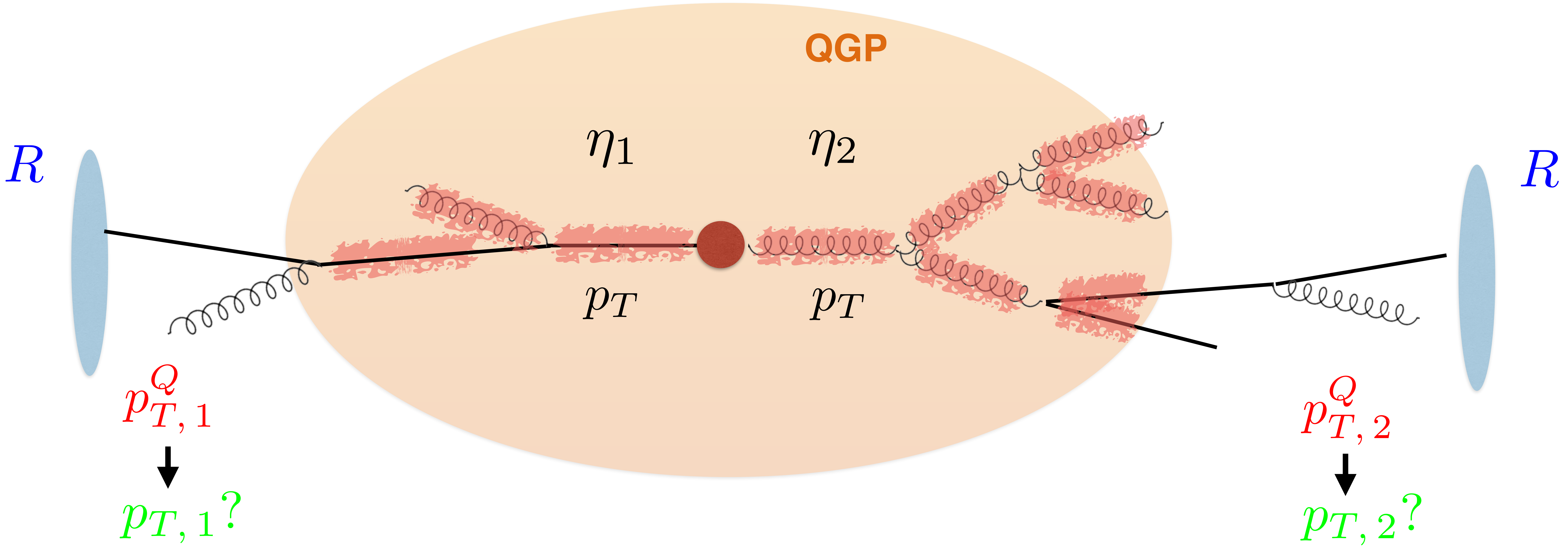

- What can we learn by knowing how much energy a given jet has lost?

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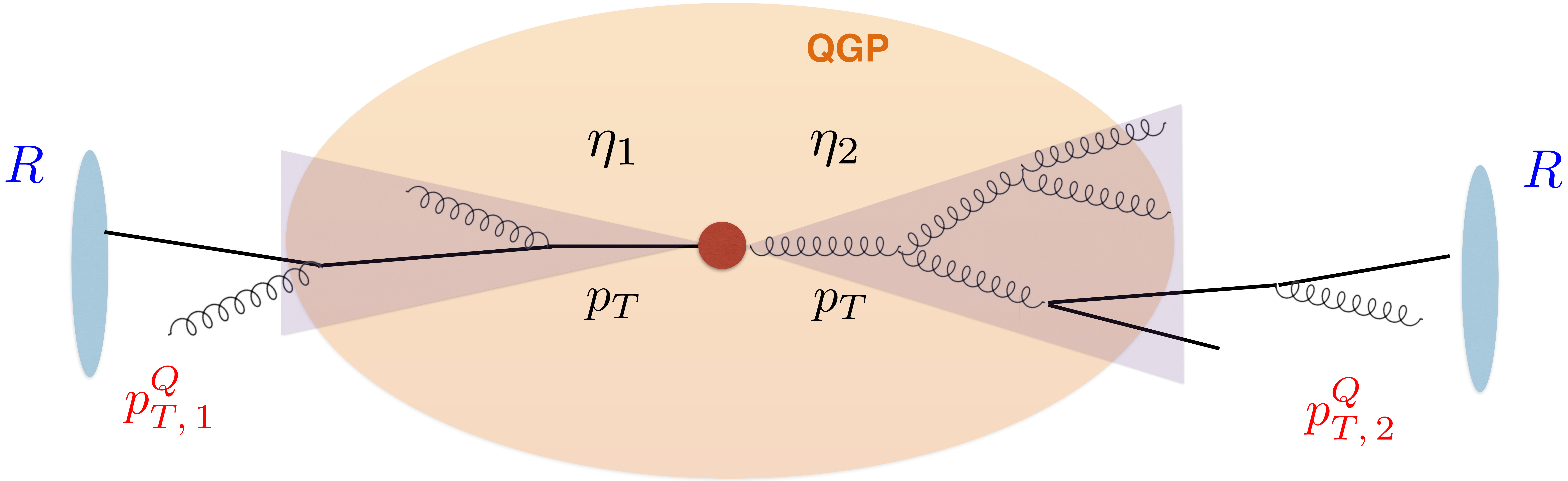
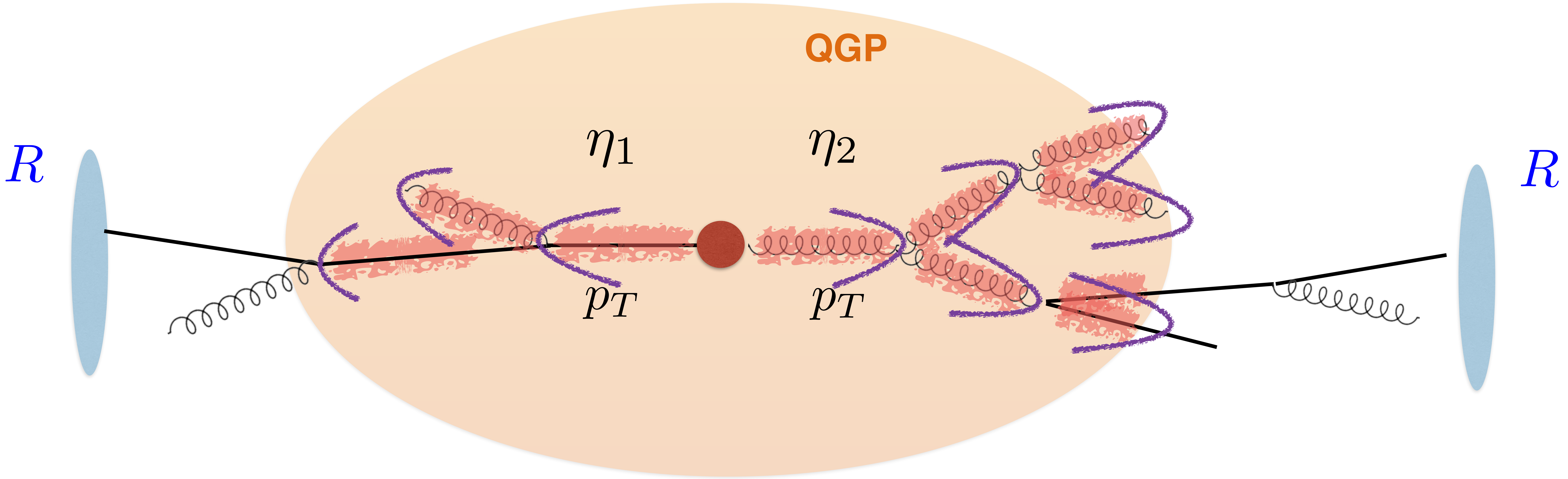


- How sensitive is the medium to jet substructure fluctuations?

  Does it resolve anything beyond total charge?

Outline

- Jet partons interact with QGP and experience energy loss.



- Non-perturbative modelling of long wavelength jet modes:

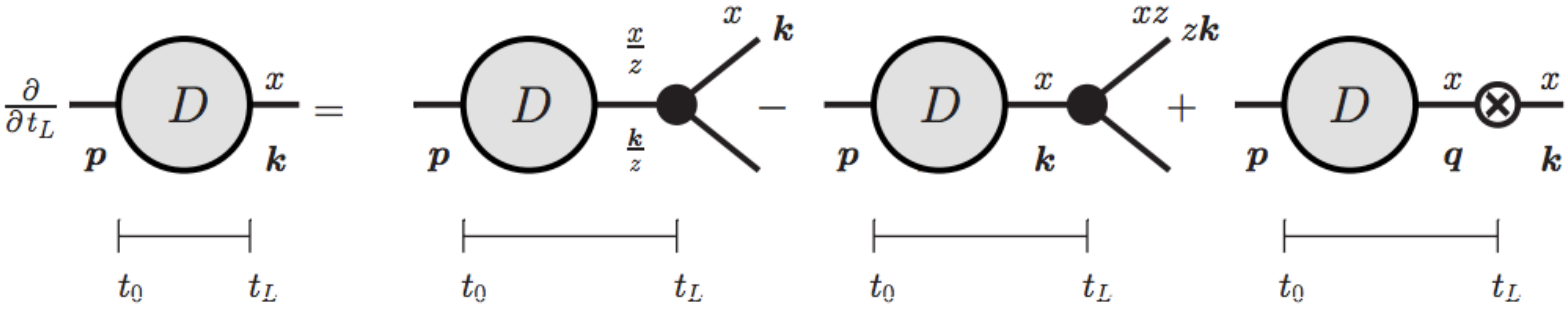
  Where does “lost” energy go to?

Parton Energy Loss

pQCD

High energy partons in the QGP:

- emit quanta, which in turn emit more quanta, and should (eventually) hydrodynamize.



$D(x, \boldsymbol{k}, t)$ is one-gluon distribution.

Blaizot et al. - JHEP ‘13 & ‘14, PRL ‘13

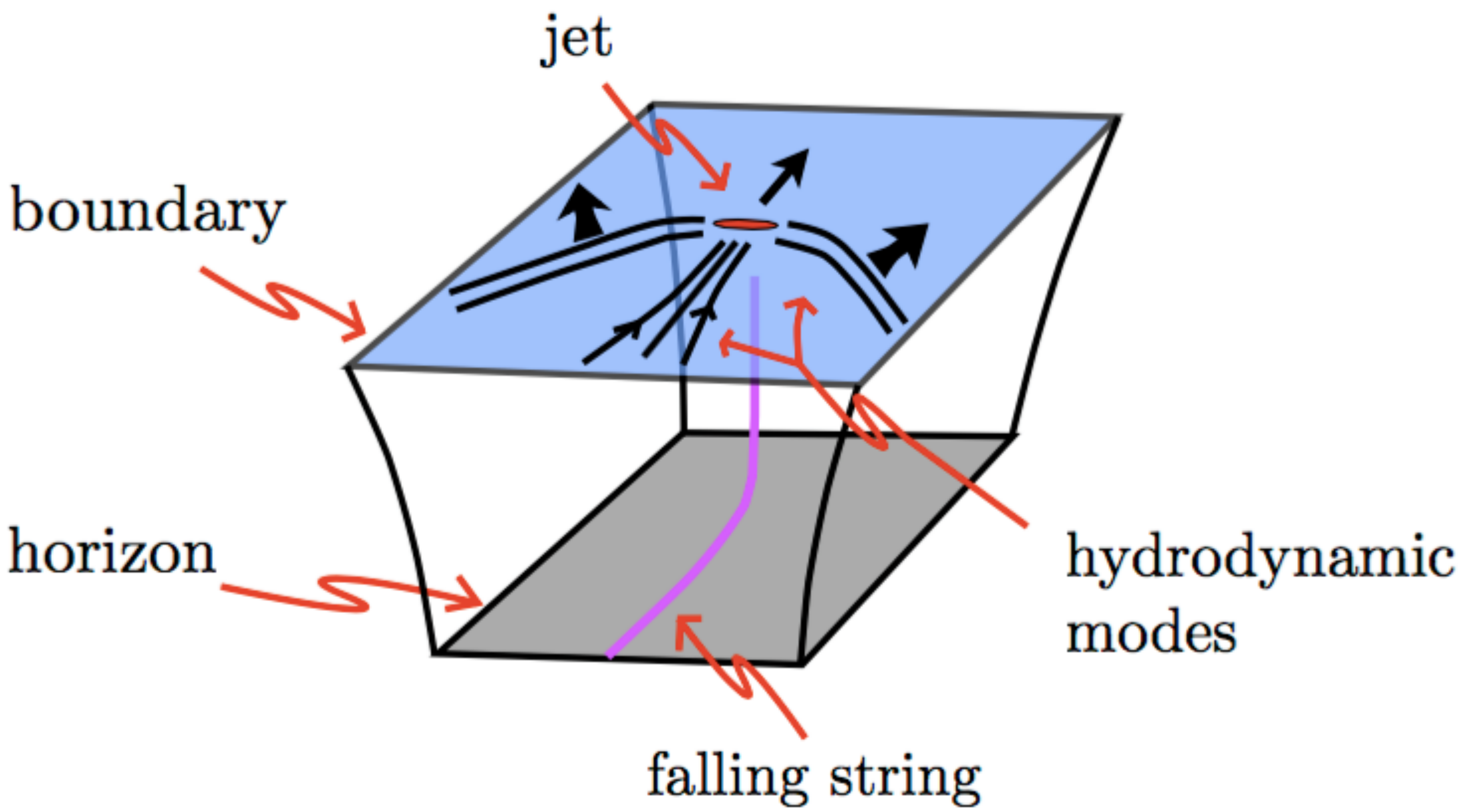
- Turbulent cascade develops, with a sink at E ~ T.
- Necessary length to reach the turbulent regime?

Parton Energy Loss

npSYM

High energy partons in the QGP:

→ are dual to strings falling into a black hole, hydrodynamizing.



Chesler & Rajagopal - PRD ‘14, JHEP ‘16

$$\langle \Delta T^{\mu\nu}(t,\boldsymbol{x})\rangle = \frac{L^3}{4\pi G_{\text{Newton}}} H^{(4)}_{\mu\nu}(t,\boldsymbol{x})$$

“Jet” induced EM tensor: hard + soft modes.

Perturbed metric @ boundary.

Long wavelength limit (hydrodynamization rate):

$$\frac{1}{E_{\text{init}}}\frac{dE_{\text{jet}}}{dx} = -\frac{4x^2}{\pi x^2_{\text{therm}}\sqrt{x^2_{\text{therm}} - x^2}}$$

Interpretation of Observables

Jet observables in heavy ion collisions:

→ usually look at differences, ratios, between medium and vacuum
jet ensembles selected with a given $p_T > p_T^{cut}$

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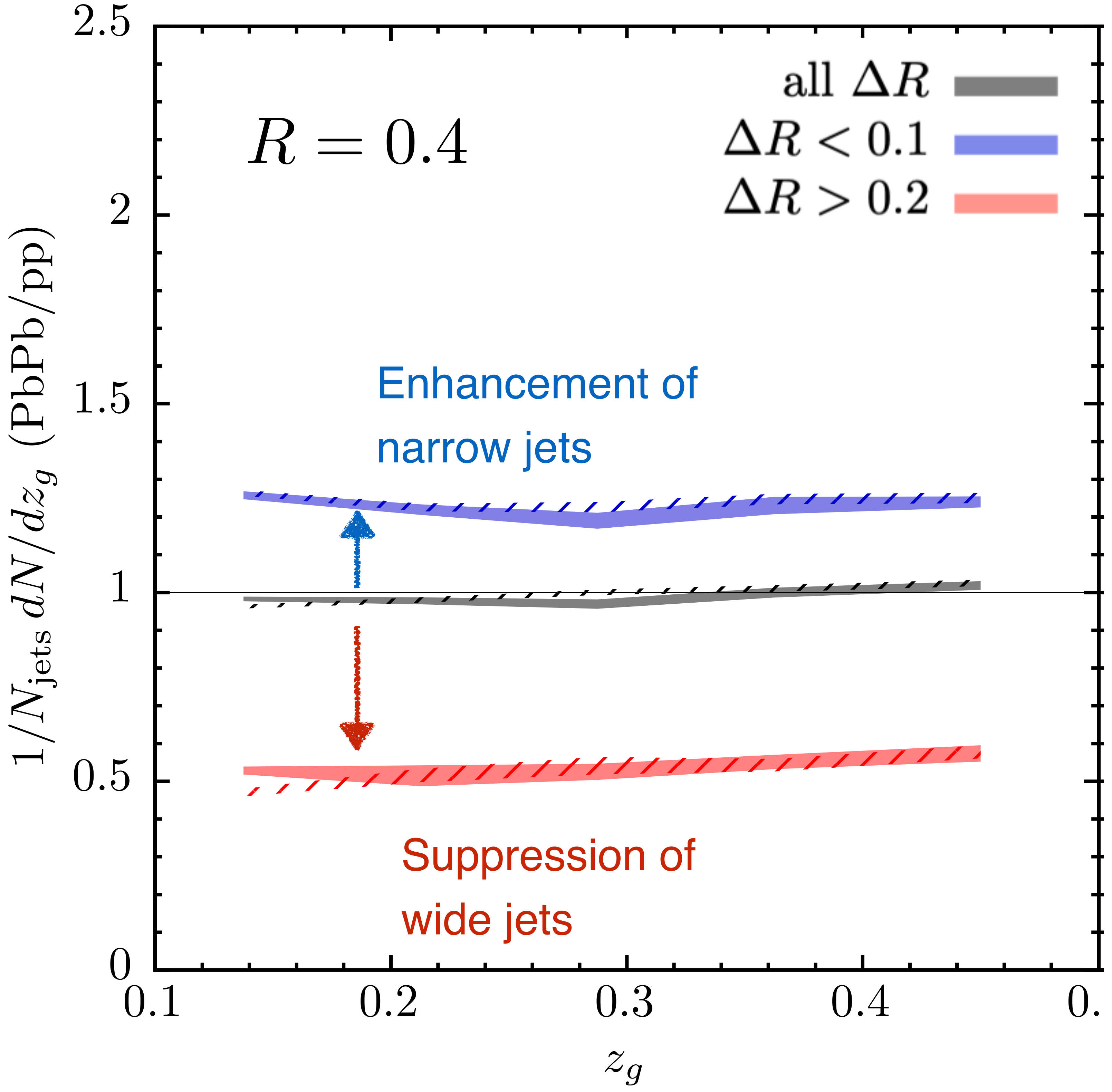
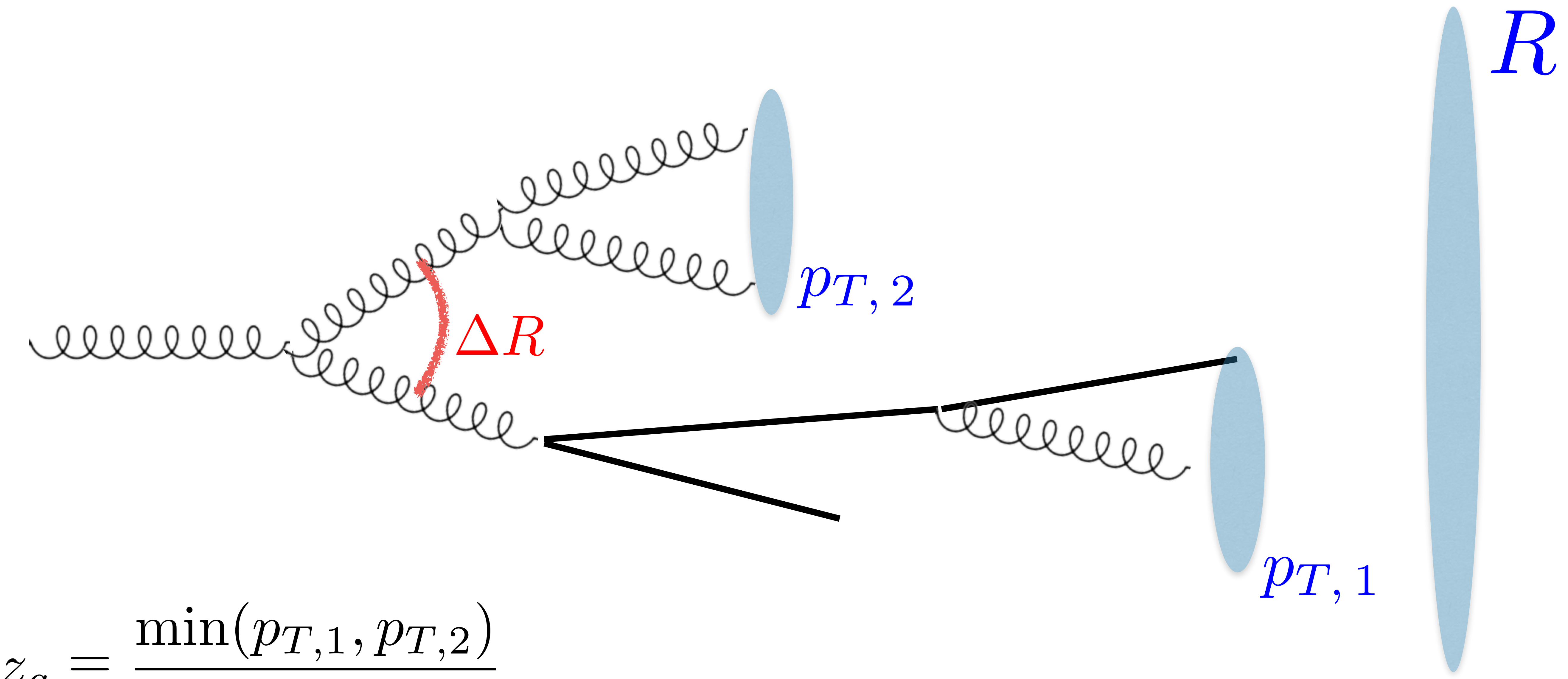


Casalderrey-Solana, Milhano, DP, Rajagopal, JHEP '20

Test case: ΔR (or R_g)

ΔR is groomed angle of 1st SoftDrop (SD) with z_{cut}=0.1 and β=0.



$$z_g \equiv \frac{\min(p_{T,1}, p_{T,2})}{p_{T,1} + p_{T,2}}$$

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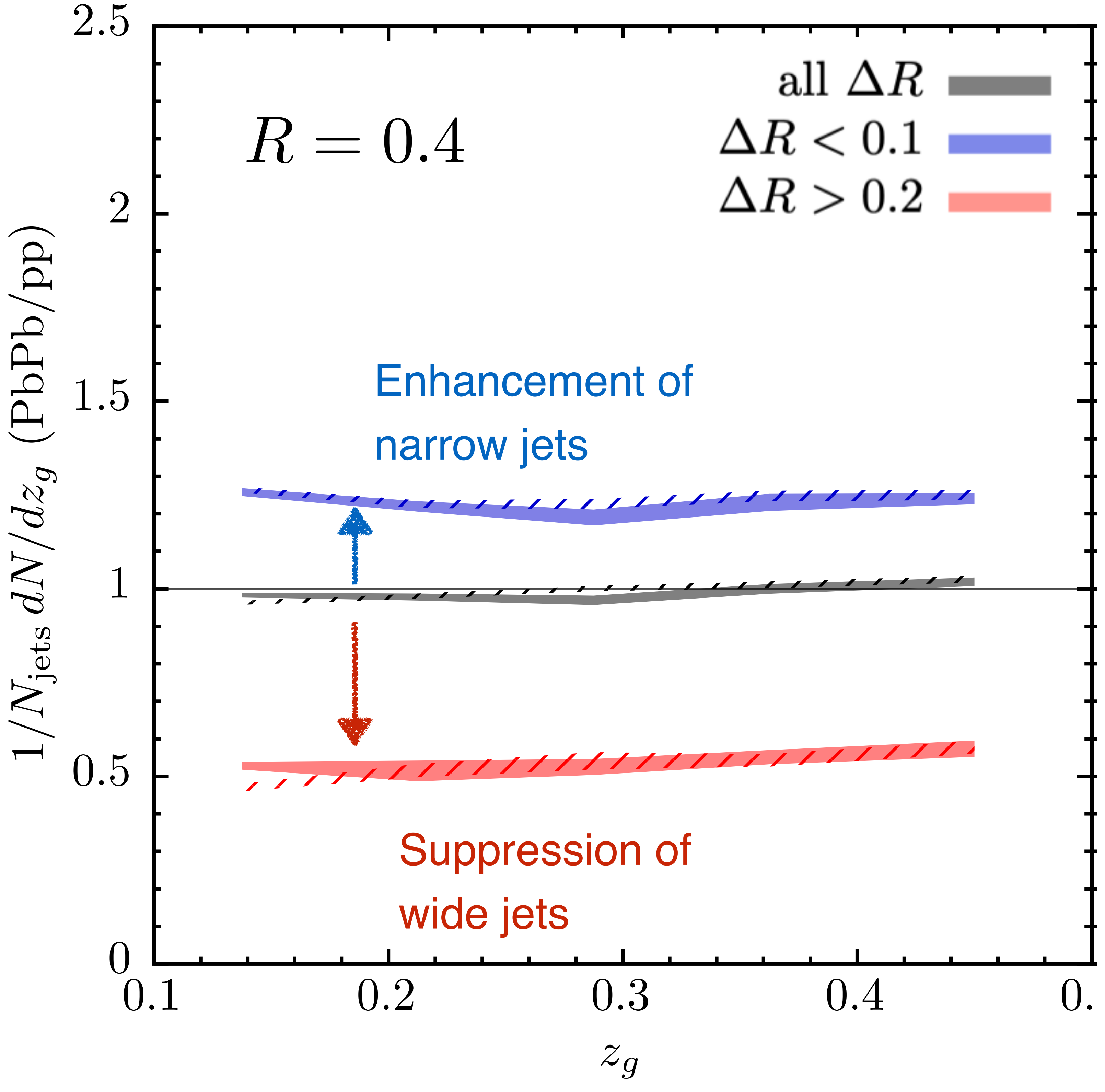


Casalderrey-Solana, Milhano, DP, Rajagopal, JHEP '20

Test case: ΔR (or R_g)

ΔR is groomed angle of 1st SoftDrop (SD) with z_{cut}=0.1 and β=0.

Some possible interpretations:

- Jets in medium produce emissions with smaller ΔR than in vacuum.

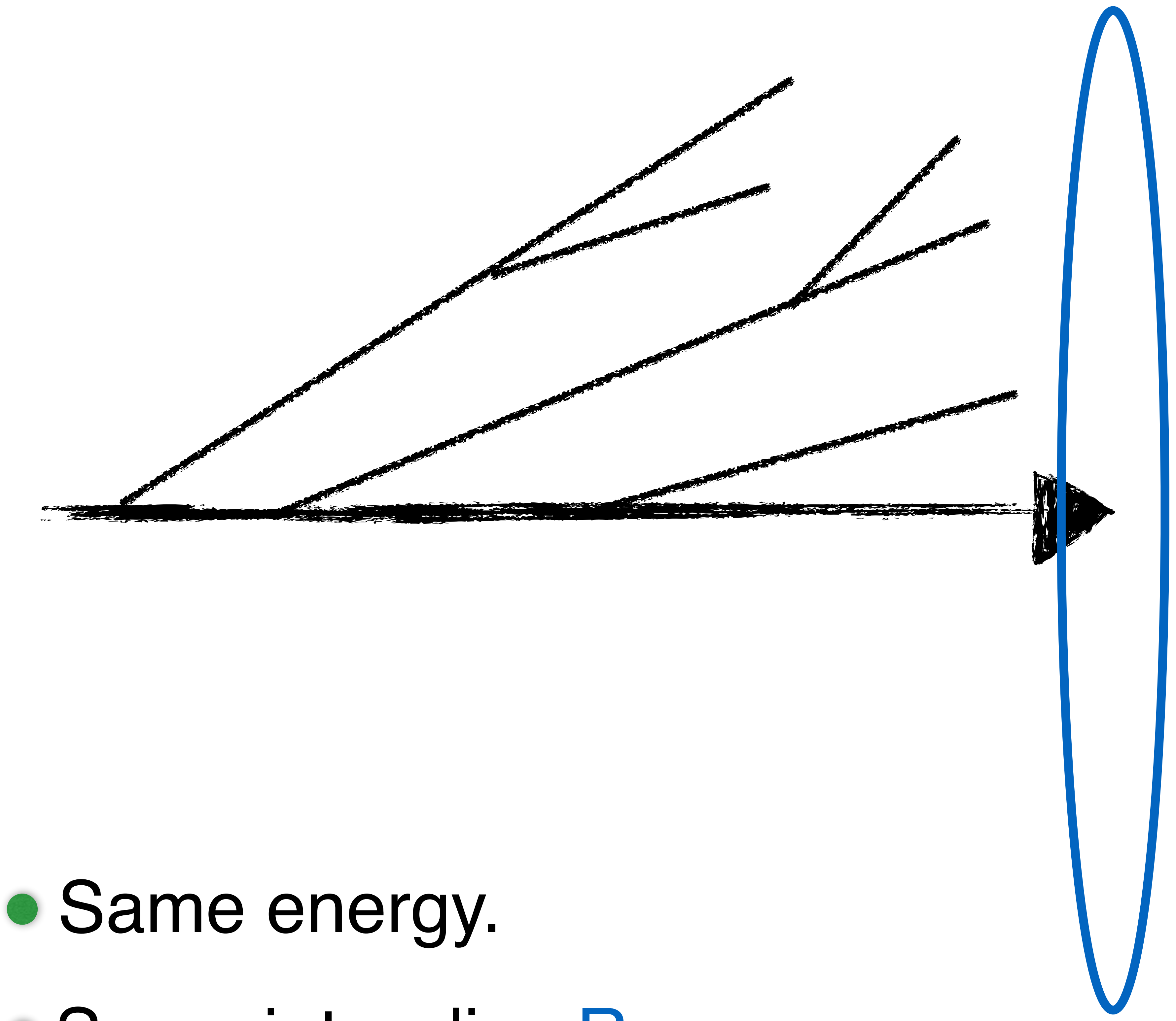
  Presumes such physics dominated by medium scale.

- Jets with larger ΔR are more suppressed and don't pass the pt cut of the distribution.

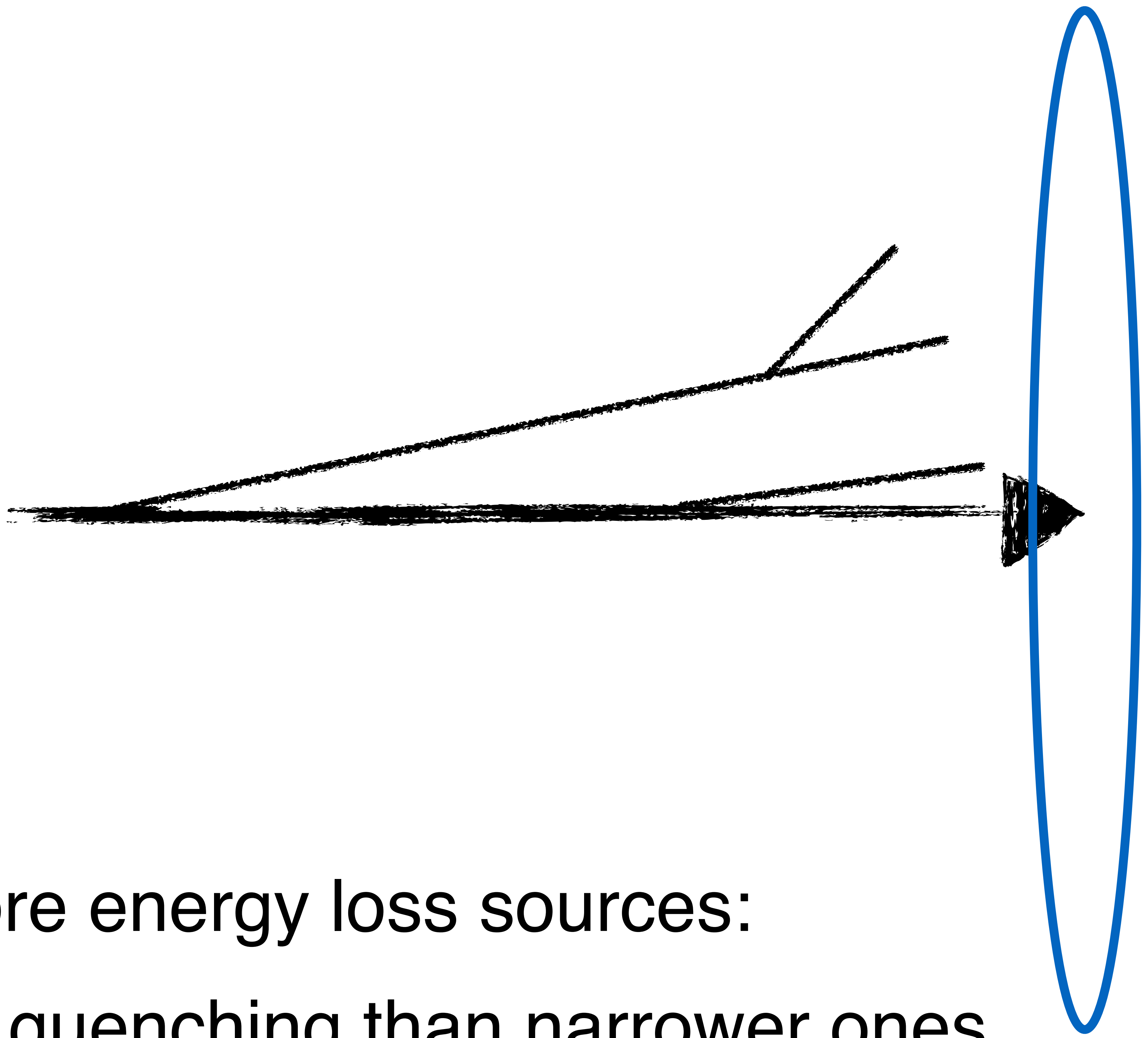
  Presumes such physics dominated by vacuum scale.

Jets and Jets

Wide jet



Narrow jet



Vacuum-like emission

- Same energy.
- Same jet radius R.
- Different fragmentation pattern.

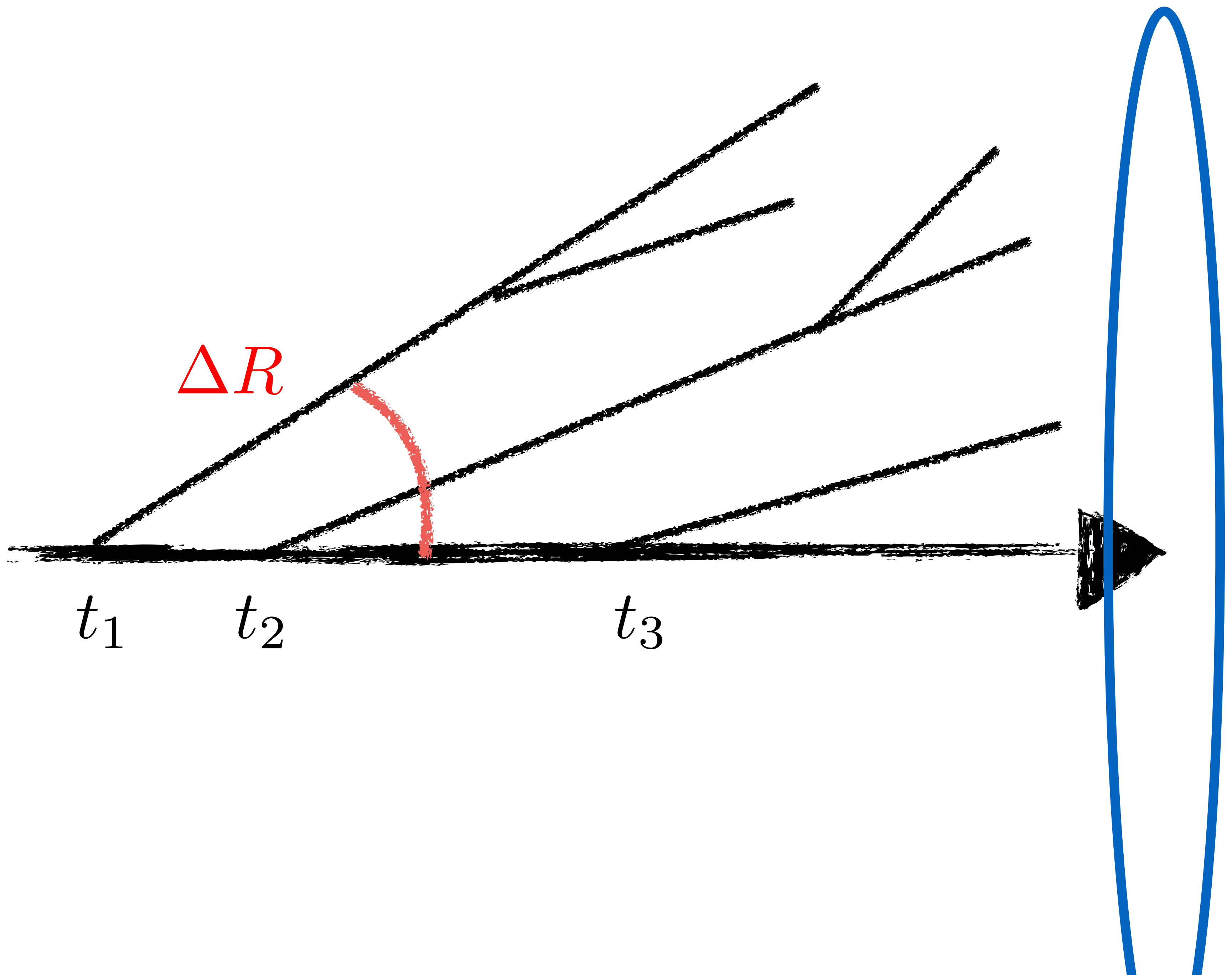
Wider jets have more energy loss sources:

→ more total quenching than narrower ones.

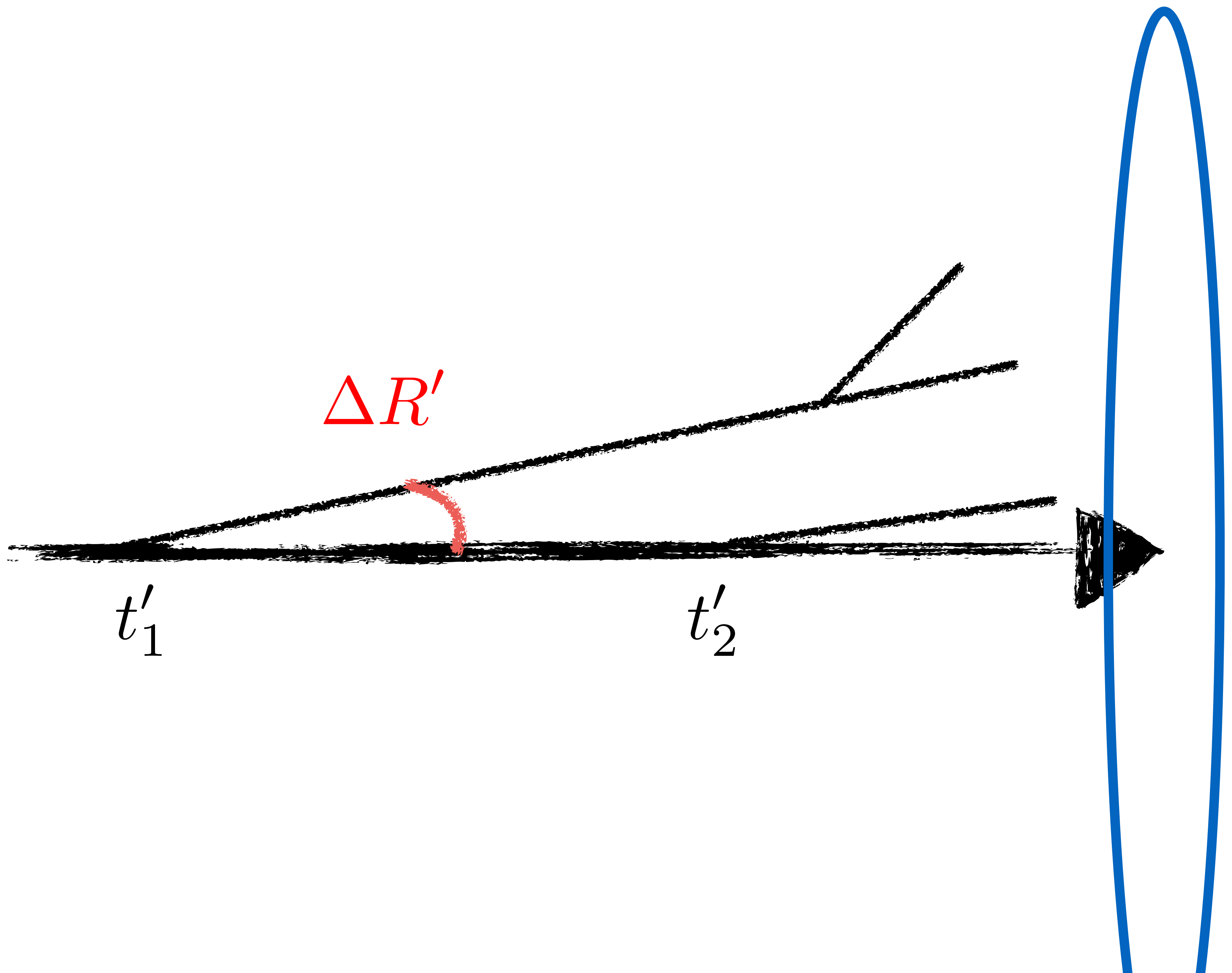
Assuming:

- most of the energy goes out of the cone.
- internal structure resolved by QGP.

Wide jet



Narrow jet



$$t_1 > t'_1$$

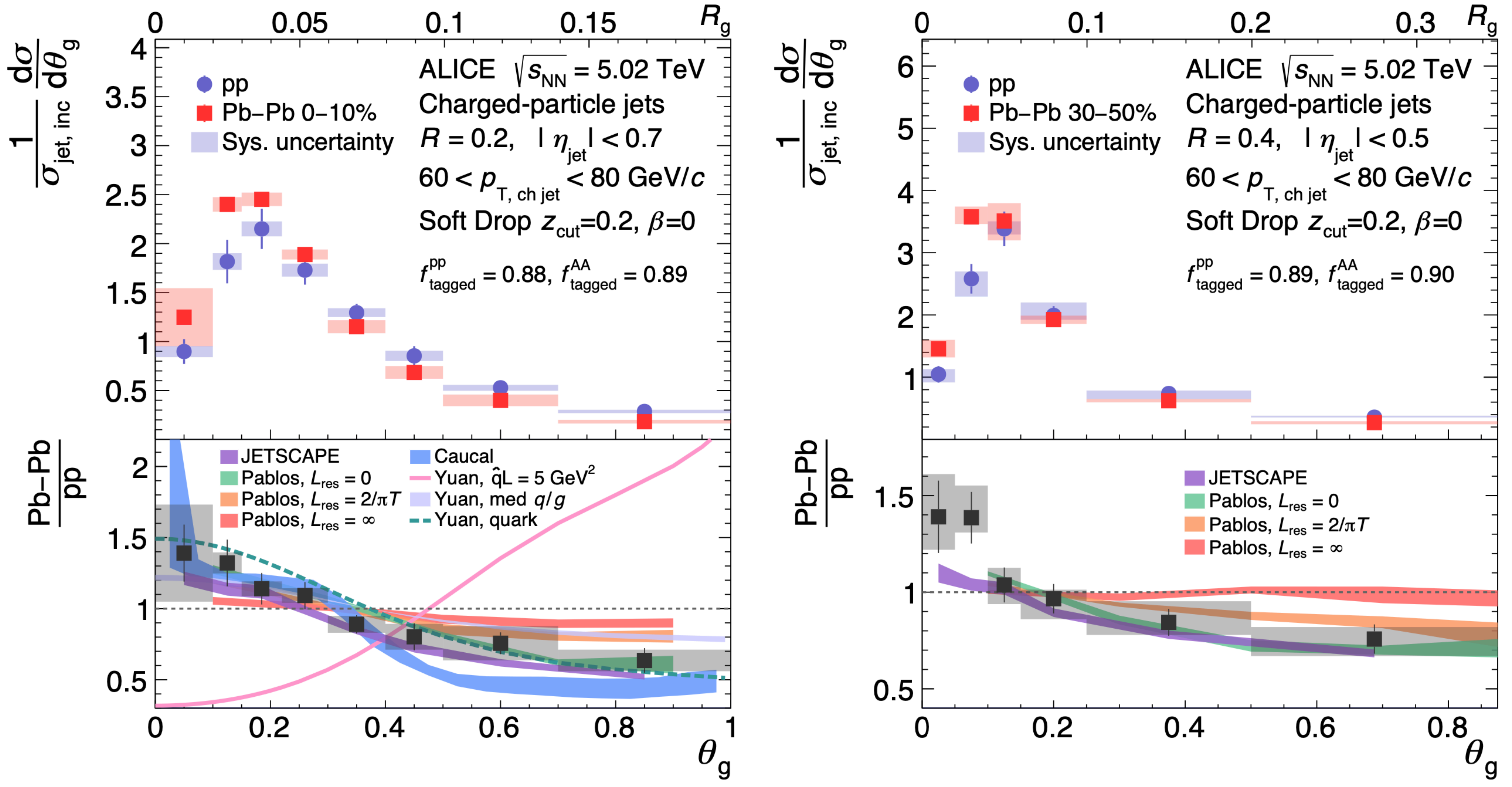
“First” emission inside the jet cone determines available phase space for further in-cone emissions.

Groomed angle is proxy for jet activity.

For any evolution variable:

$$t_1 \propto \Delta R$$
$$t'_1 \propto \Delta R'$$

Common feature among MC models



ALICE - PRL '22

ΔR narrowing observed in data, well reproduced by variety of models.

We observe the absence of wide jets because of p_T cut, selection bias.

Most relevant common feature between MCs:

→ dominance of vacuum physics at early, high energy stages of the shower.

Vacuum-like Jets in the Medium

Jets experience part of their evolution as if they were in vacuum, *formation times arguments*.

Formation time τ_f : when wavelength of emitted gluon resolves transverse separation.

A given emission is vacuum-like (VLE) if:

$$\tau_f \ll \tau_{\text{med}}$$

Implies separation of momenta.

$k_\perp$
- med: From multiple soft scatterings. ($\hat{q}$)
- vac: From DGLAP evolution.

A given dipole is resolved (both legs lose energy) if:

$$\tau_{\text{coh}} < L \quad \longrightarrow \quad \theta > \theta_c \sim 1/\sqrt{\hat{q}L^3}$$

Time it takes a dipole to decohere via multiple color rotations.

All VLE are angular ordered, since $\tau_v < \tau_{\text{coh}}$. Caucal et al. - 1801.09703

VLEs included in MC, either full factorization, or allowing corrections from rare kicks (JEWEL, MATTER).

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VLEs included in MC, either full factorization, or allowing corrections from rare kicks (JEWEL, MATTER).

Interplay between Vacuum-like & Medium-induced emissions still not well understood!

Diagnosing jet energy loss with deep learning

Selection bias is a dominant effect for many jet observables:

- Common to all calculations, jet MCs, that include jet substructure fluctuations.
- Obscures the interpretation of data: how do quenched jets really look like?

→ Use deep learning techniques to determine amount of energy loss jet-by-jet:

Energy loss ratio: $$\chi_{jh} \equiv \frac{E_f}{E_i}$$

E_f ← Final, measurable jet energy.

E_i ← Vacuum energy (had there been no medium).

Want to:

- Understand true, most revealing features of energy loss.
- Extract amount of energy loss jet-by-jet in experimental data.

Du, DP, Tywoniuk - JHEP '21

Defining the Energy Loss Ratio

Jet Image

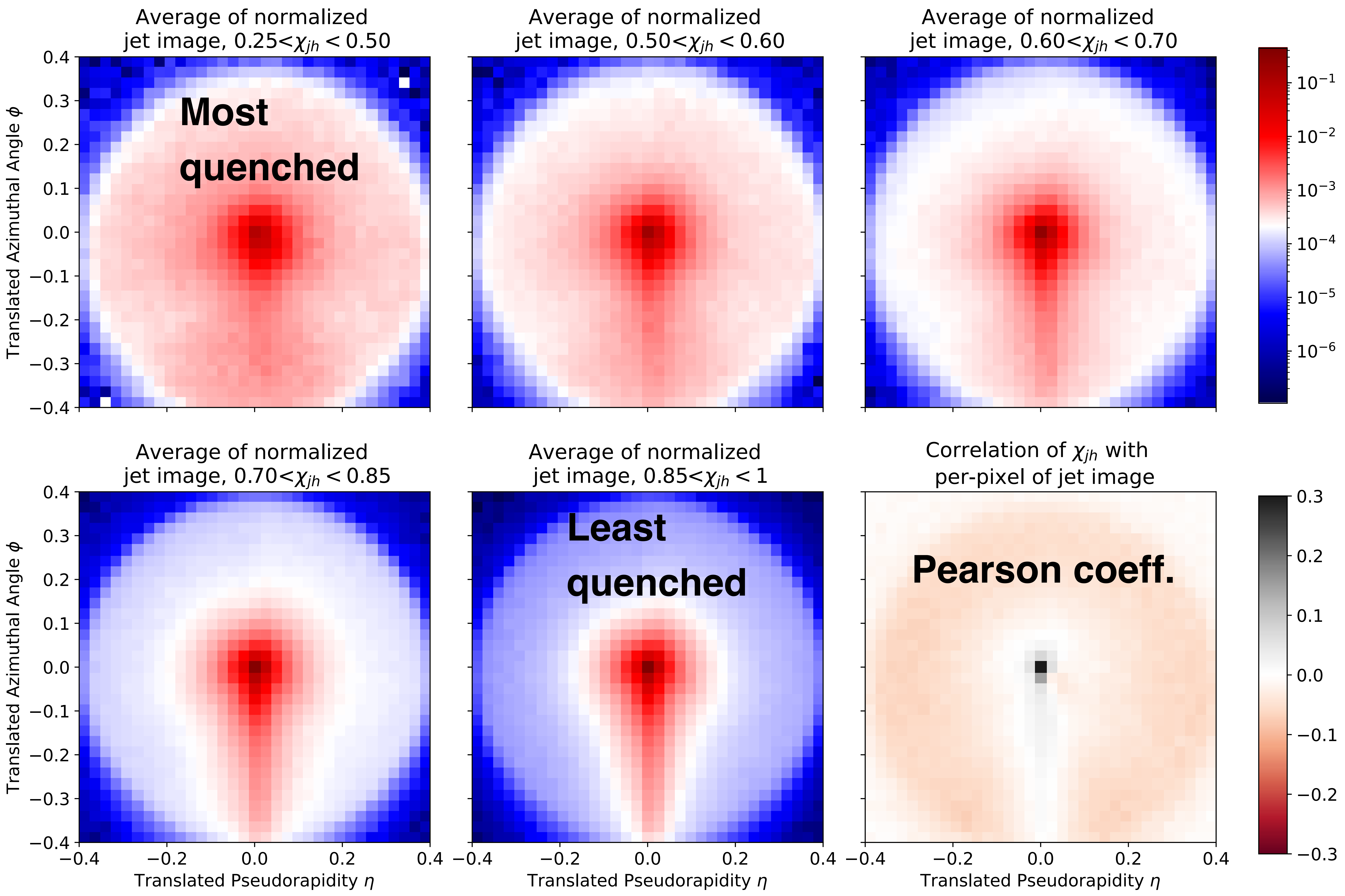


Image preprocessing:

- Φ and η coord. w.r.t. jet axis.
- Rotate image to have groomed subjet at Φ = - π/2.

Recognize basic features of jet quenching:

→ Energy loss increases number of soft particles at large angles.

Prediction Performance

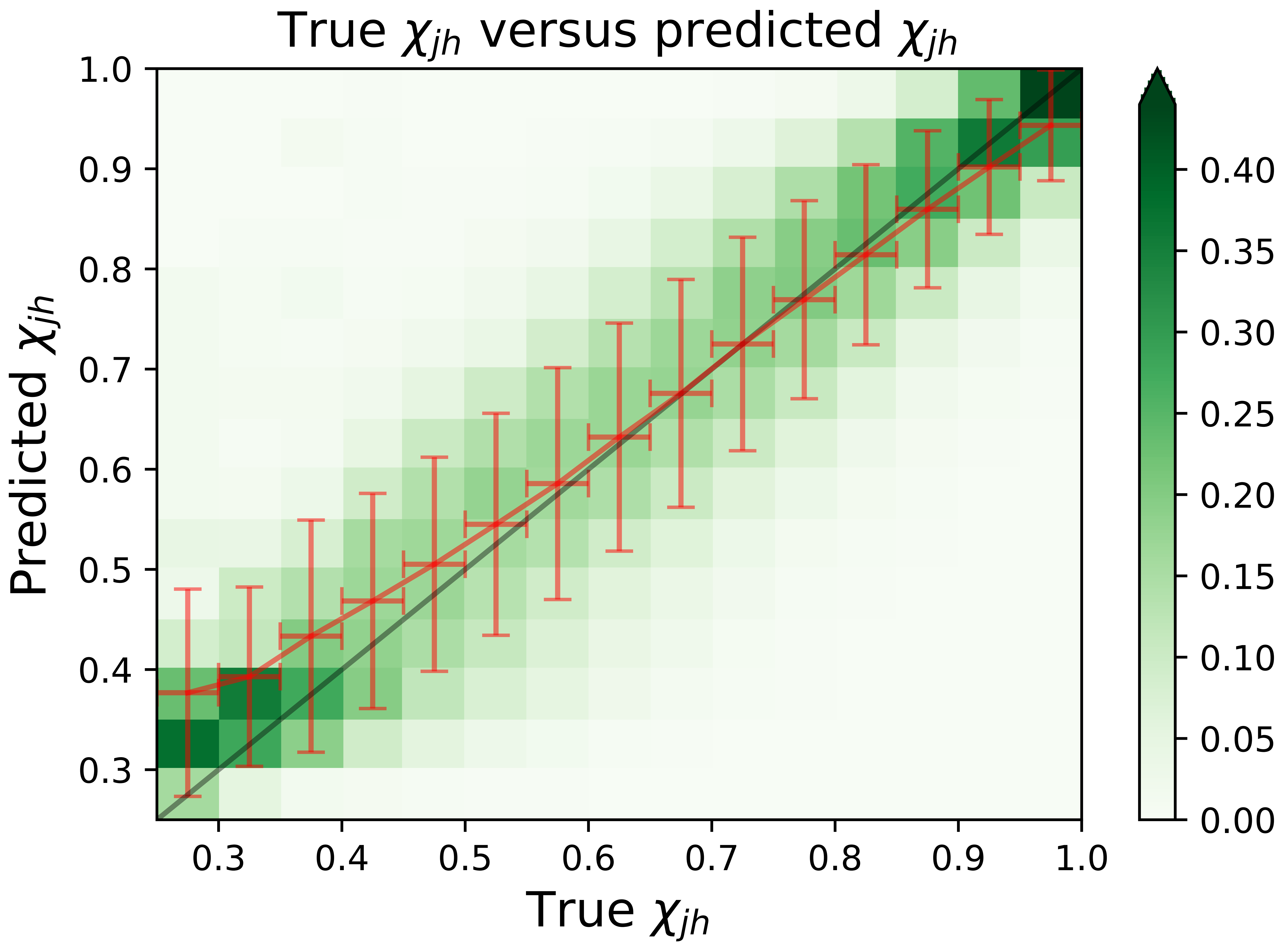
Good performance over wide range of χ.

Histo: Probability of predicted χ given true χ.

Bars: Average and standard deviation.

Sanity checks:

- Performance not species dependent (quark or gluon initiated jet).
- Network predicts χ = 0.98(3) for pp jets.



Applications: Groomed Observables

R_g ratio between PbPb and pp:

FES:

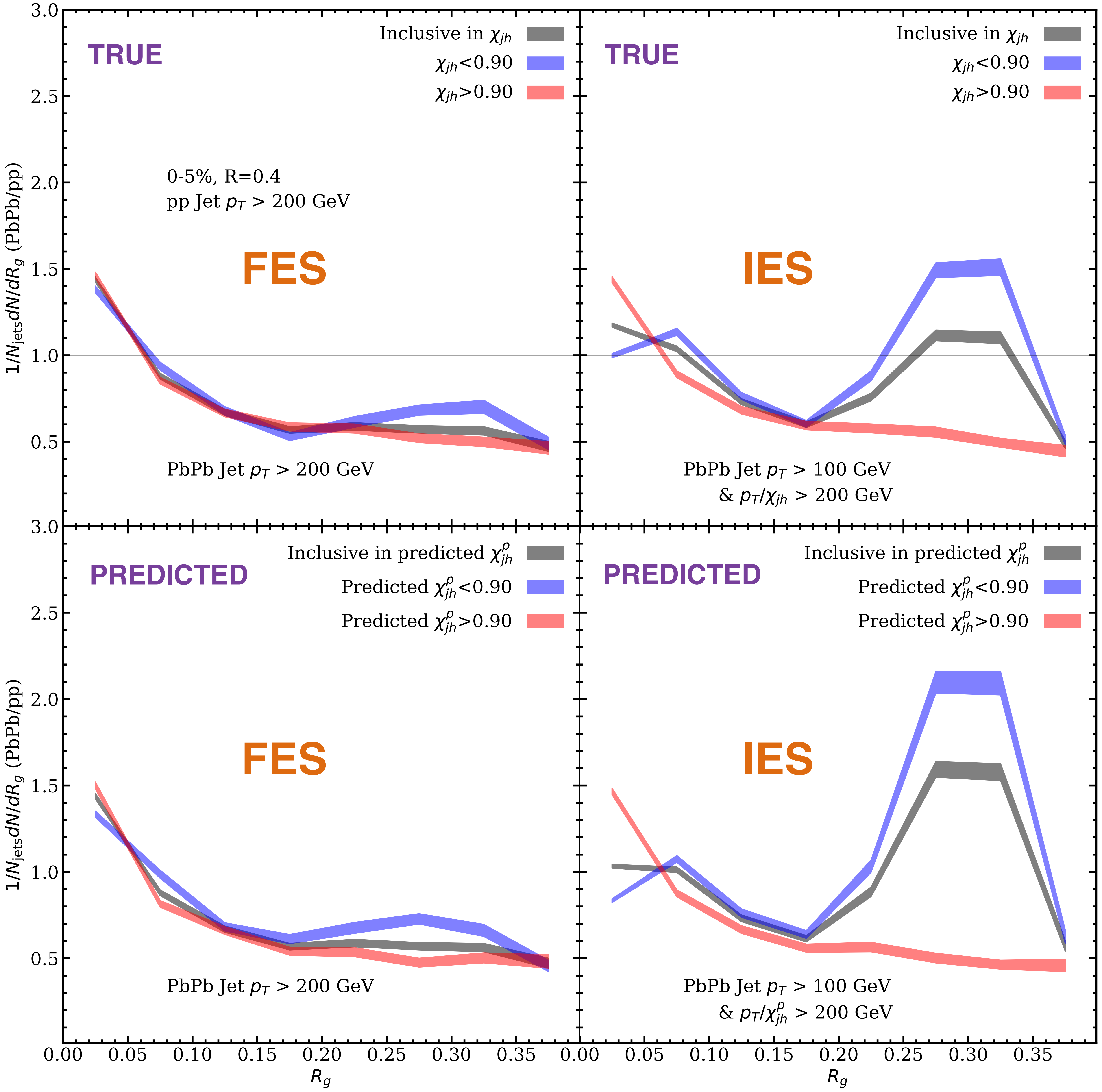
Observe selection bias towards jets with small R_g.

IES:

Quenched class presents features actually related to energy loss:

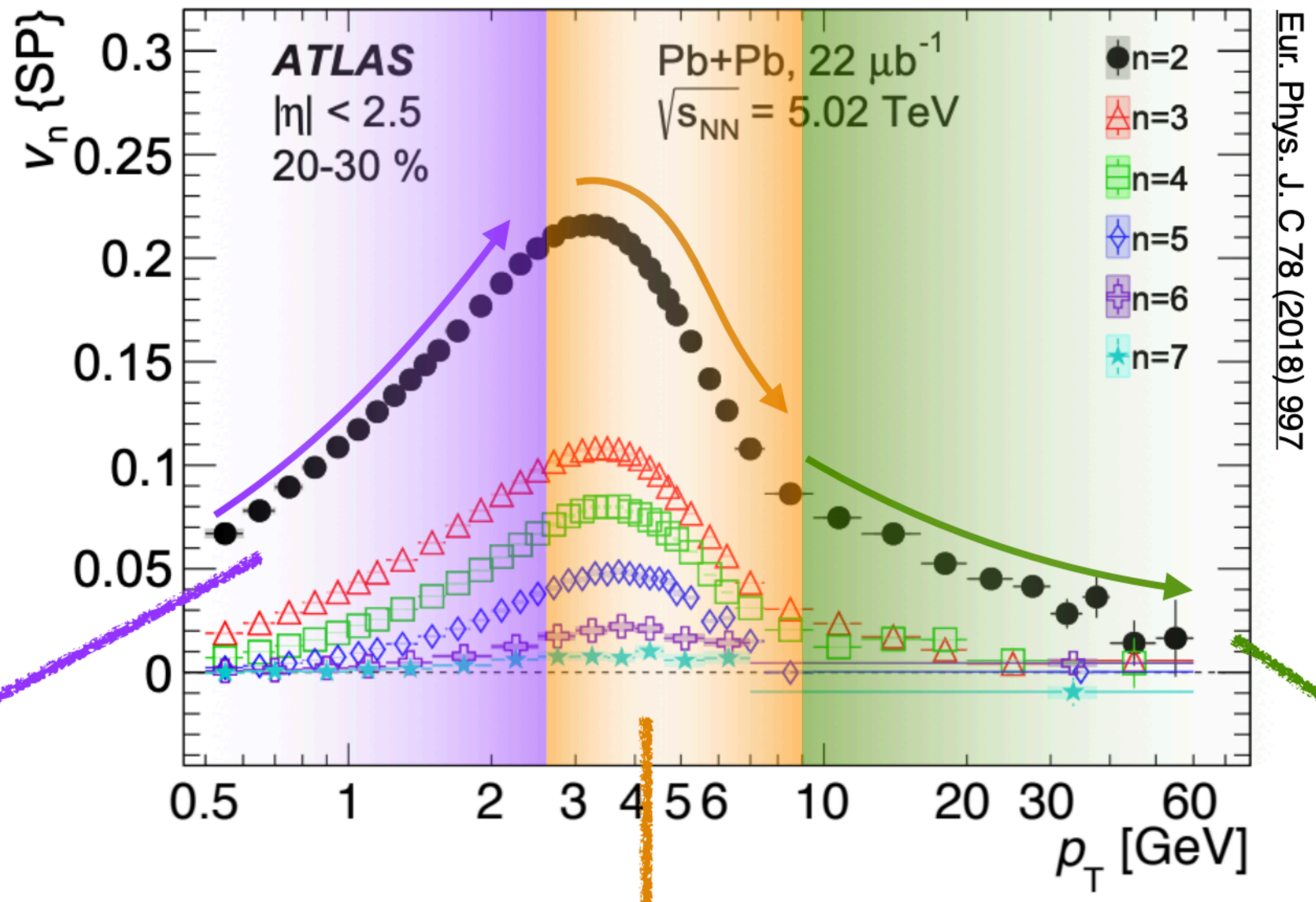
→ Enhancement at large R_g.

Unquenched class still biased (to belong to this class, a jet needs to be of a special kind).

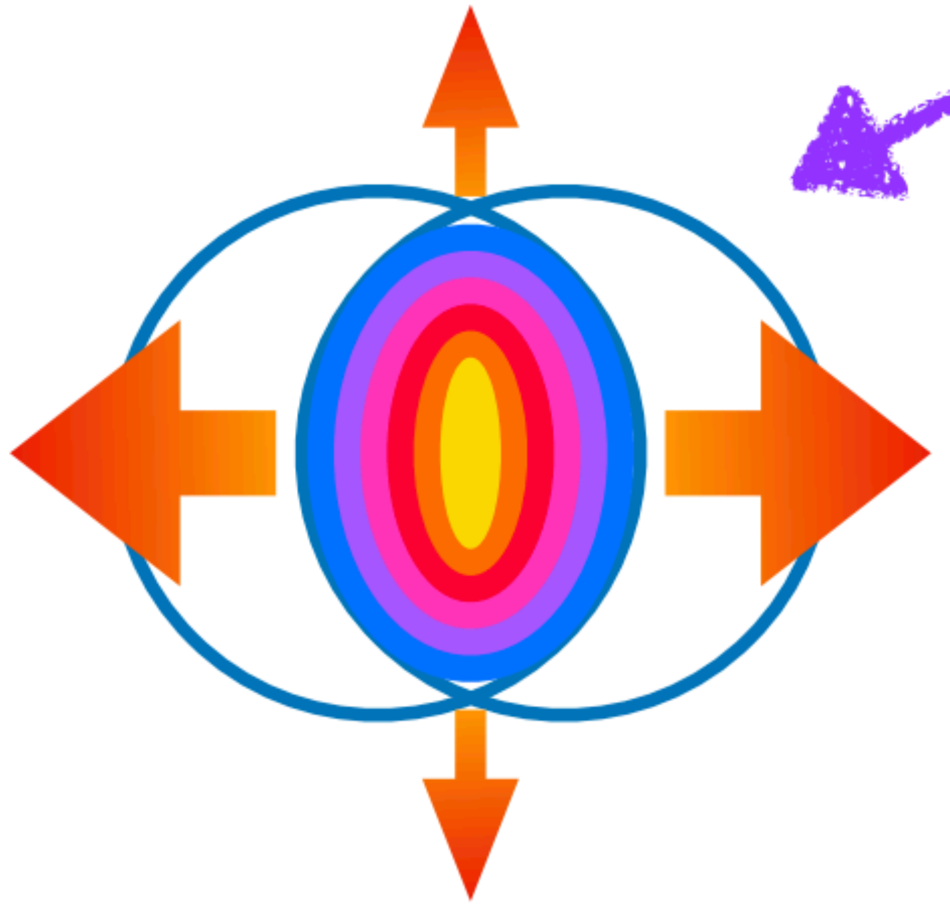


Jet Azimuthal Anisotropy

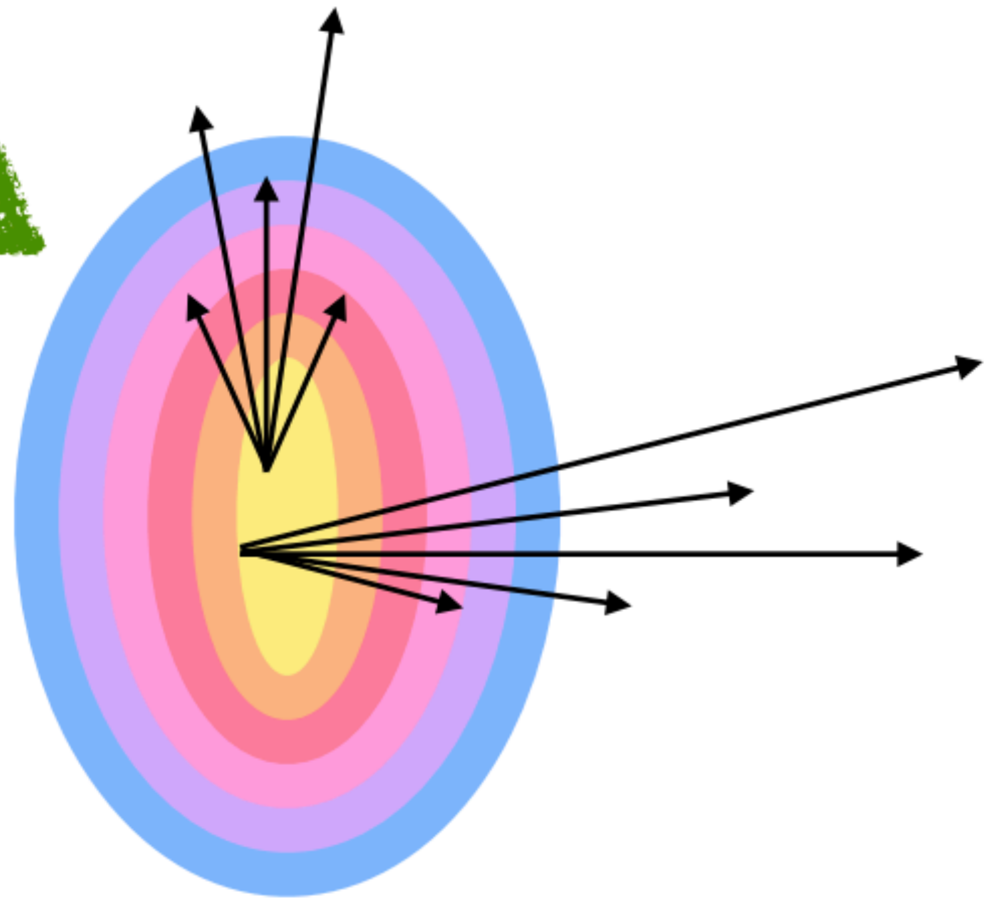
Slide from
K. Hill at QM‘19



Hydrodynamics



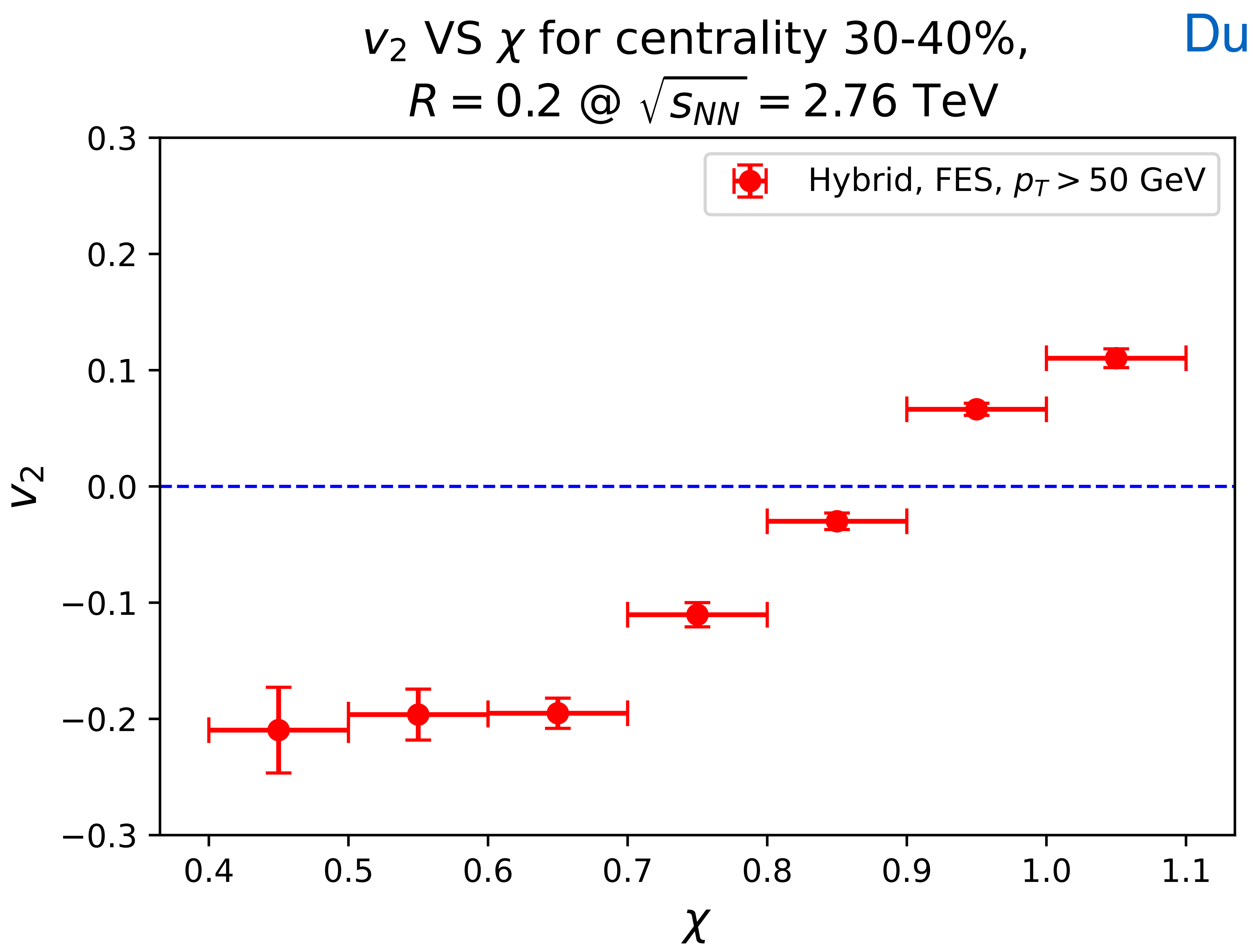
Differential energy loss

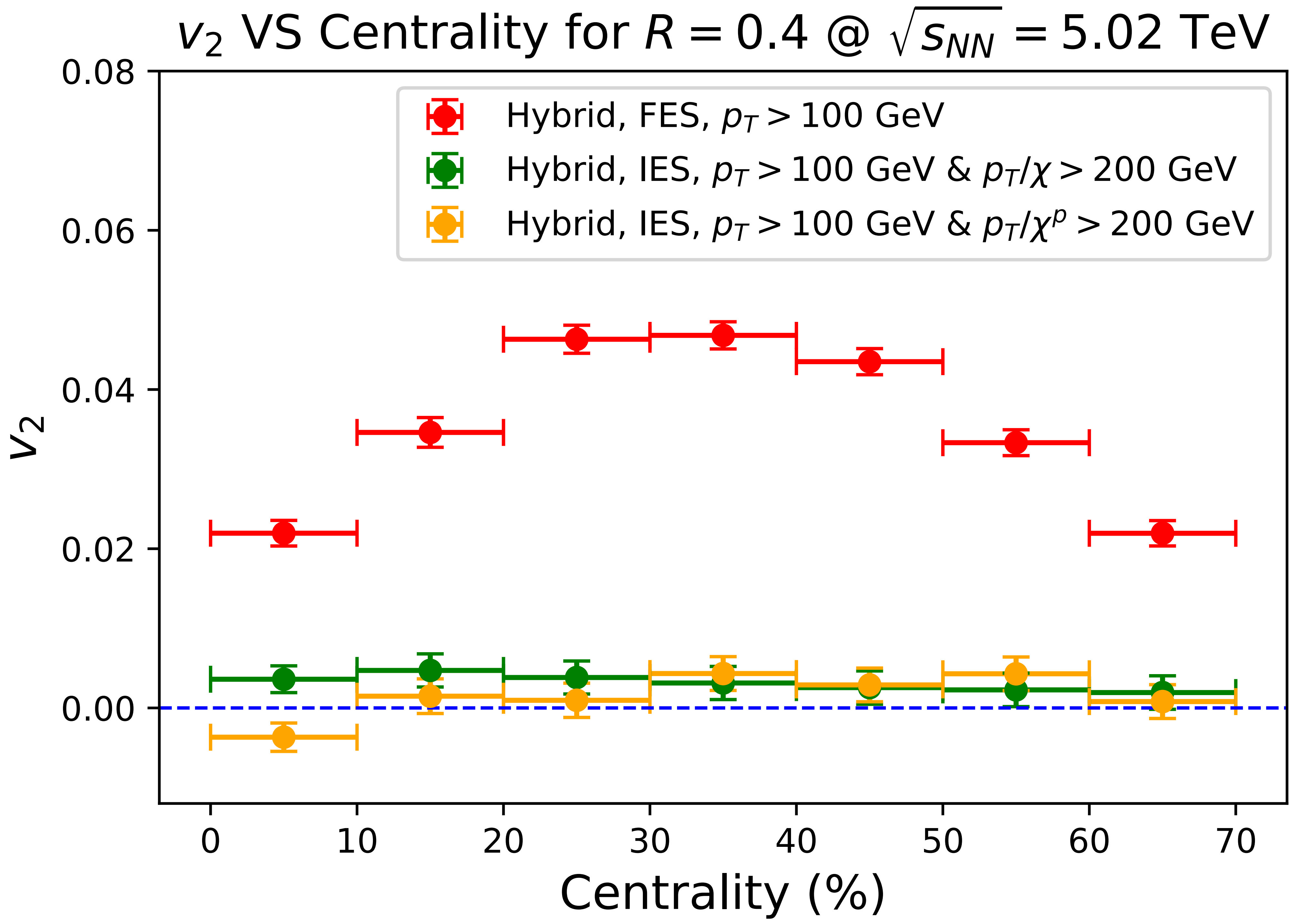


Transition region

Accessing Initial Jet Anisotropies

Du, DP, Tywoniuk - PRL '21





- Intuitive origin of high-p_T jet anisotropies:

  Small χ (large energy loss):

  → longer path length;

  → $v_2 < 0$.

  and viceversa for large χ.

- However, if use IES:

  Reveals initial azimuthal anisotropies.

  In this model: none → $v_2 \sim 0$.

  And in experiments?

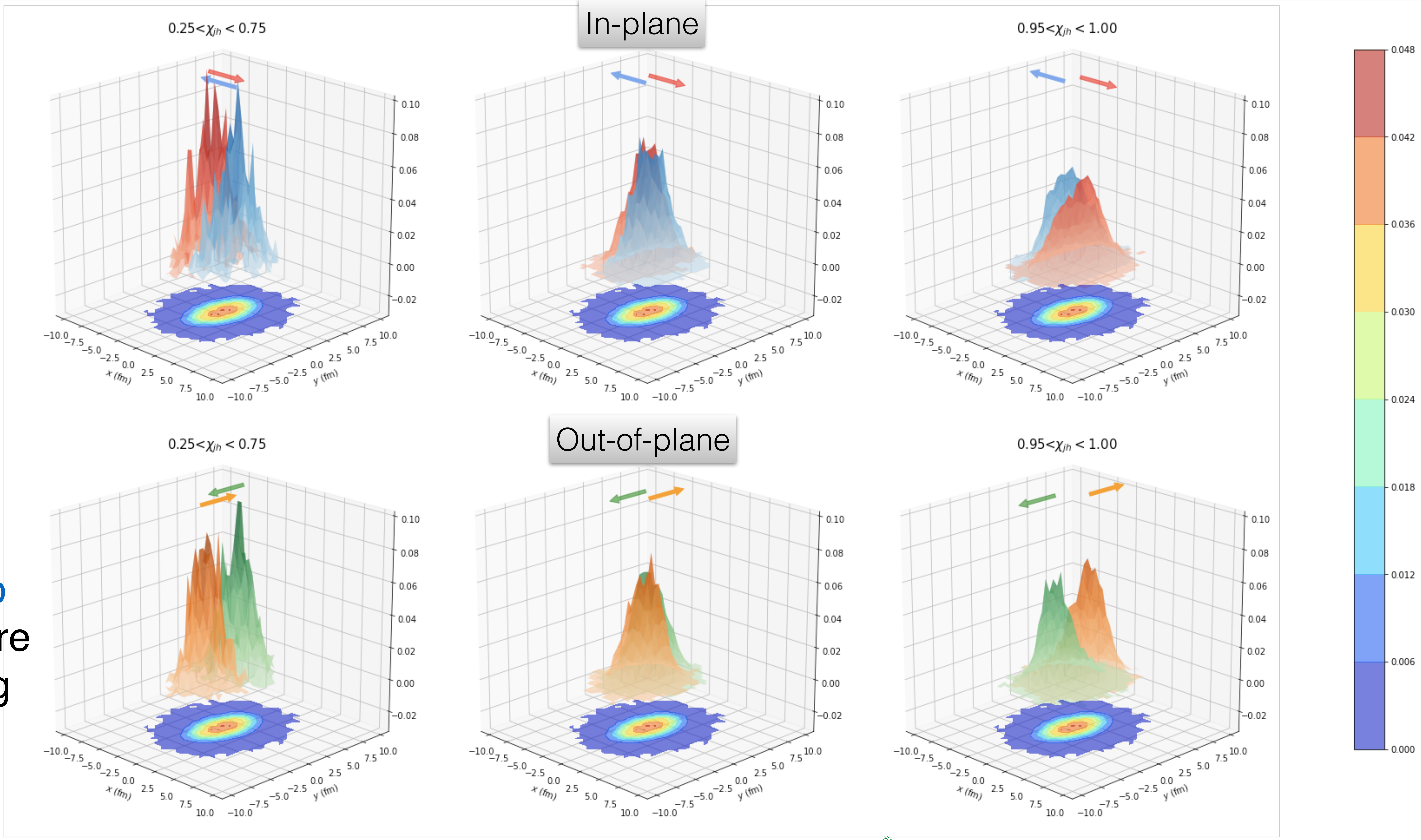
Tomography with Deep Learning

Determination of production point in transverse plane.

Differential in:

- Orientation w.r.t. event plane.
- Energy loss ratio χ .

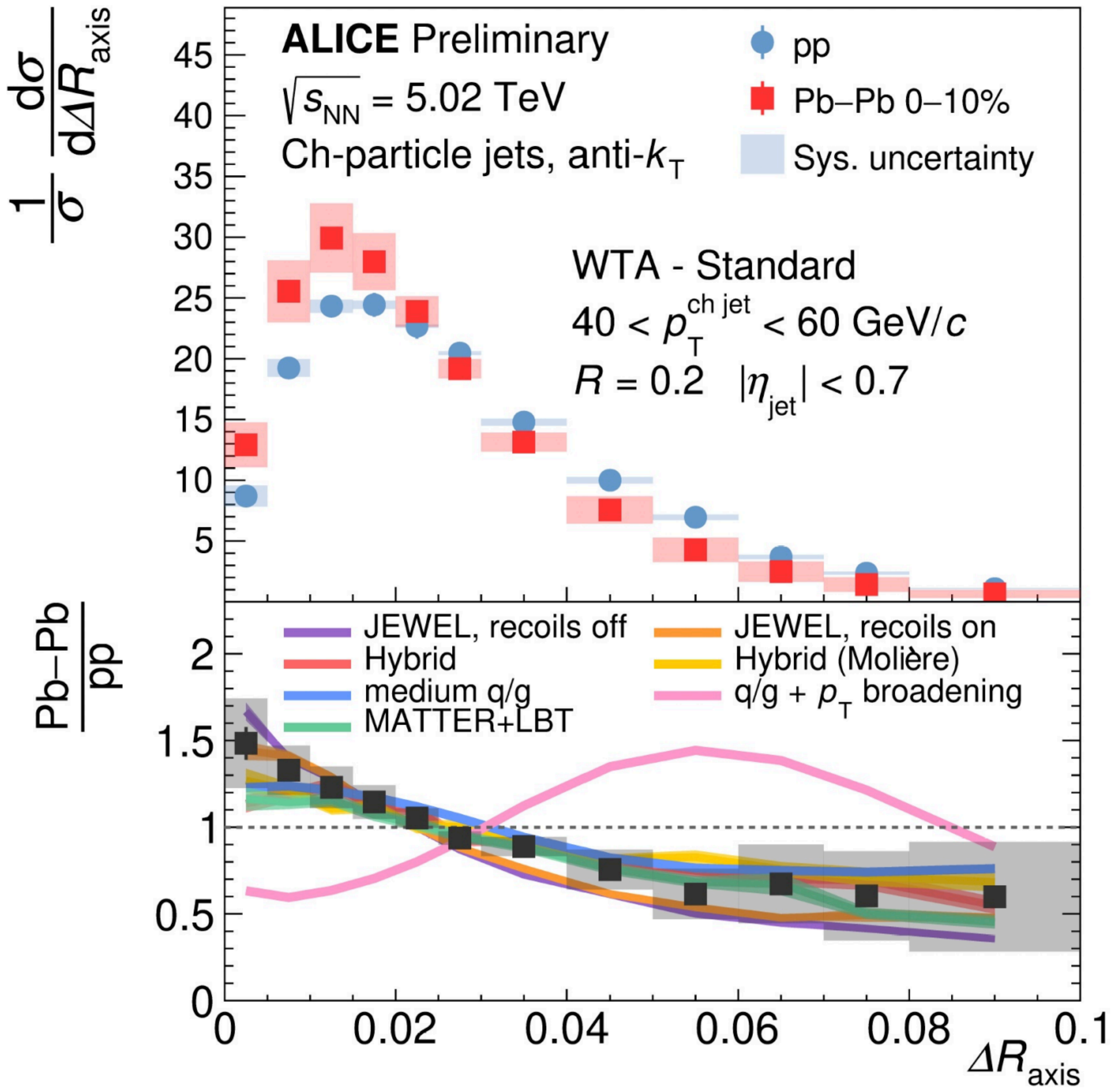
Production points swap in order to traverse more medium with increasing energy loss.



Du, DP, Tywoniuk - PRL ‘21

more quenched ← χ → less quenched

Narrowing of Jet Substructure



R. Cruz-Torres talk at QM22

Example: WTA axis distance w.r.t. anti-k_T axis

Many Monte Carlo models get similar results.

Bias towards narrower, less active jets.

Medium q/g can also account for the signal.

Strong suppression of gluon jets (factor 4 w.r.t. pp).

Qiu et al. - PRL ‘19

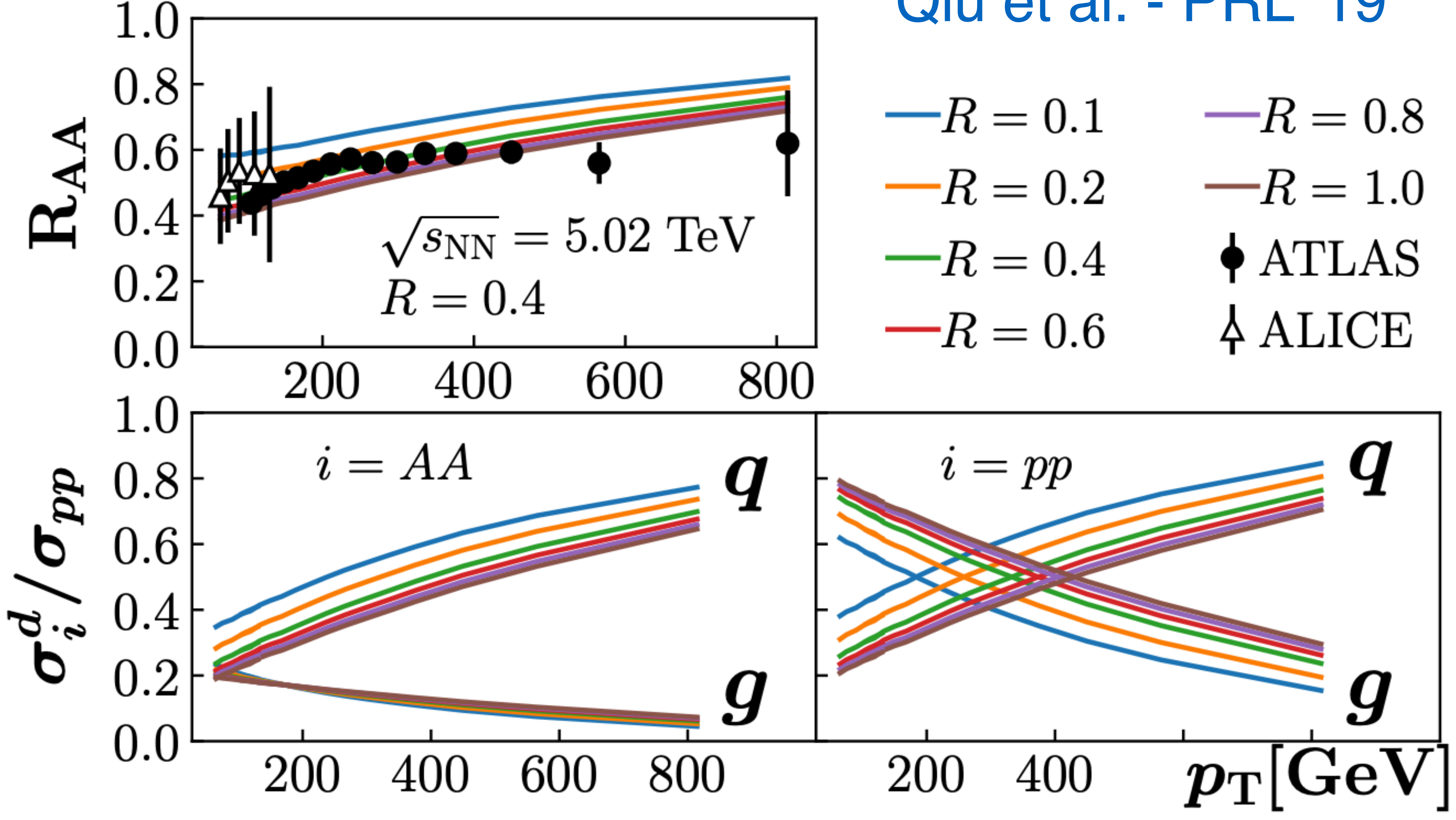
Medium q/g + p_T broadening fails.

Not accounting for selection bias, while broadening emissions, results in a broader jet ensemble.

Ringer et al. - PLB ‘19

Modified q/g Fraction

Qiu et al. - PRL '19



- Parametrization of modification of jet function (similar to nPDF).

$$\mu \frac{d}{d\mu} J_c(z, p_T R, \mu) = \sum_d P_{dc}(z) \otimes J_d(z, p_T R, \mu)$$

$$J_c^{\rm med}(z, p_T R, \mu_J) = W_c(z) \otimes J_c(z, p_T R, \mu_J)$$

$$W_c(z) = \epsilon_c \delta(1-z) + N_c\, z^{\alpha_c}(1-z)^{\beta_c}$$

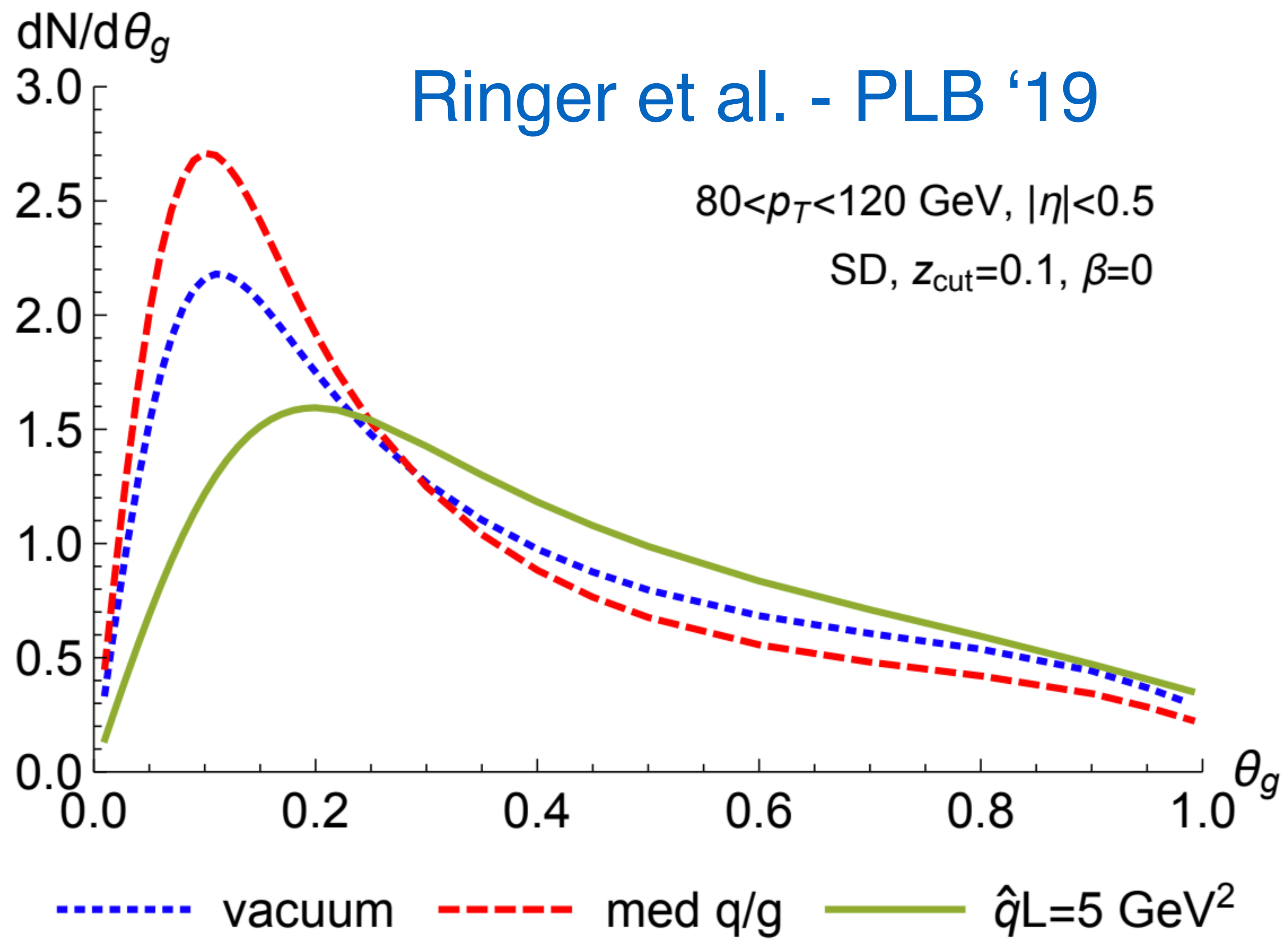
→ Best fit seems to leave quark jets untouched.

- Combination of quark and gluon contributions:

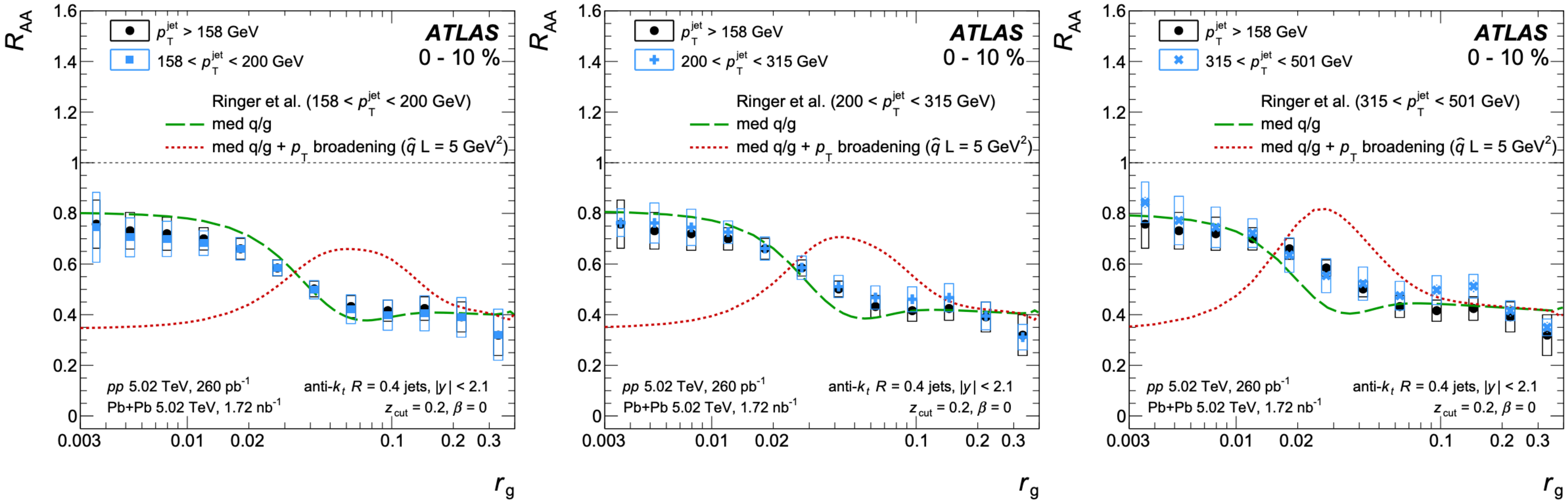
$$\frac{1}{\sigma_{\rm incl}} \frac{{\rm d}\Sigma(\theta_g)}{{\rm d}p_T\, {\rm d}\eta} = f_q\, \Sigma_q(\theta_g) + f_g\, \Sigma_g(\theta_g)$$

- Broadening added as non-perturbative kick.

Ringer et al. - PLB '19



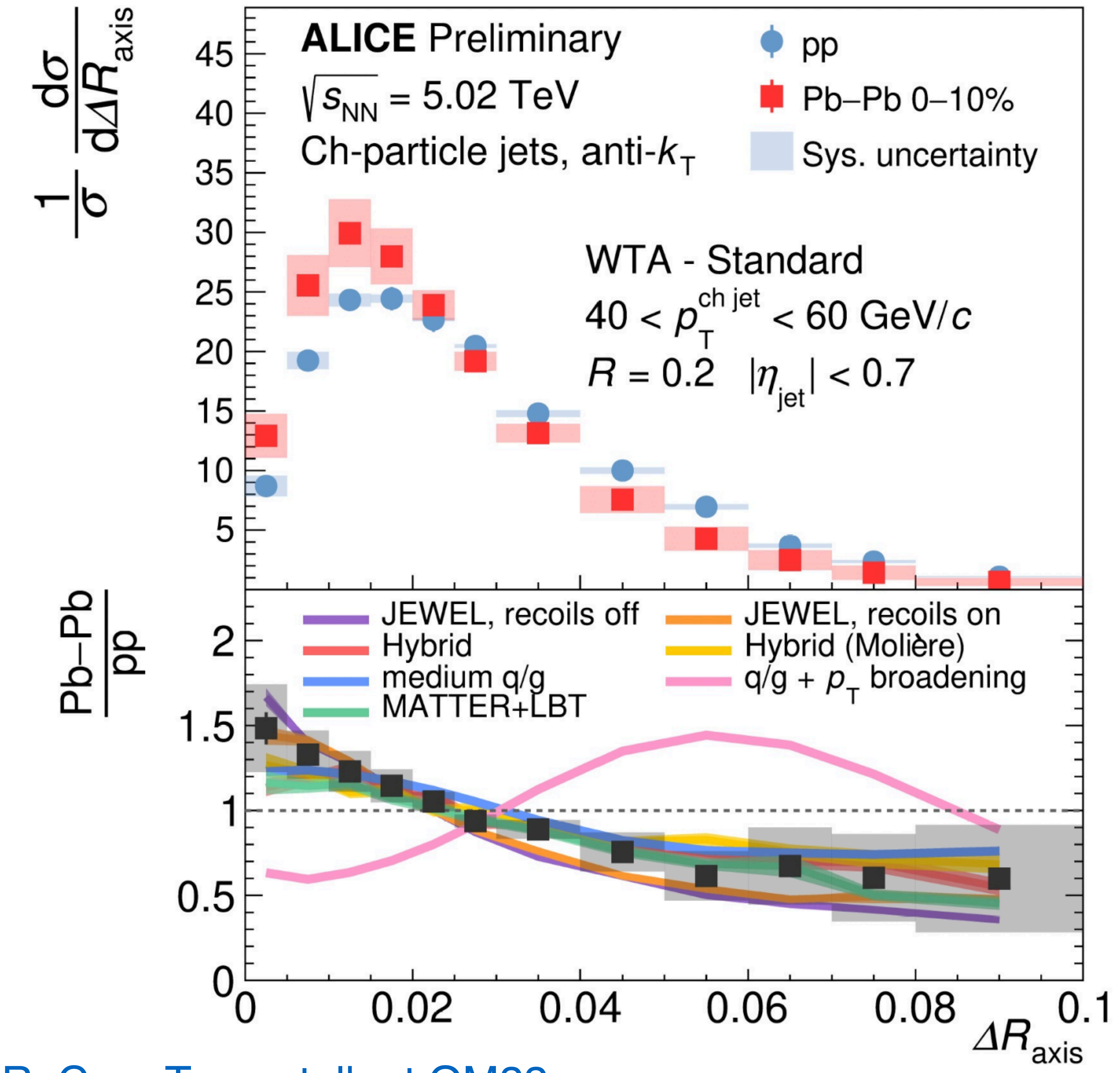
Substructure dependent jet suppression



ATLAS - 2211.11470

- Recent ATLAS results for R_{AA} vs r_g can also be explained by modified q/g fraction model.

Narrowing of Jet Substructure



R. Cruz-Torres talk at QM22

How can we discriminate between:

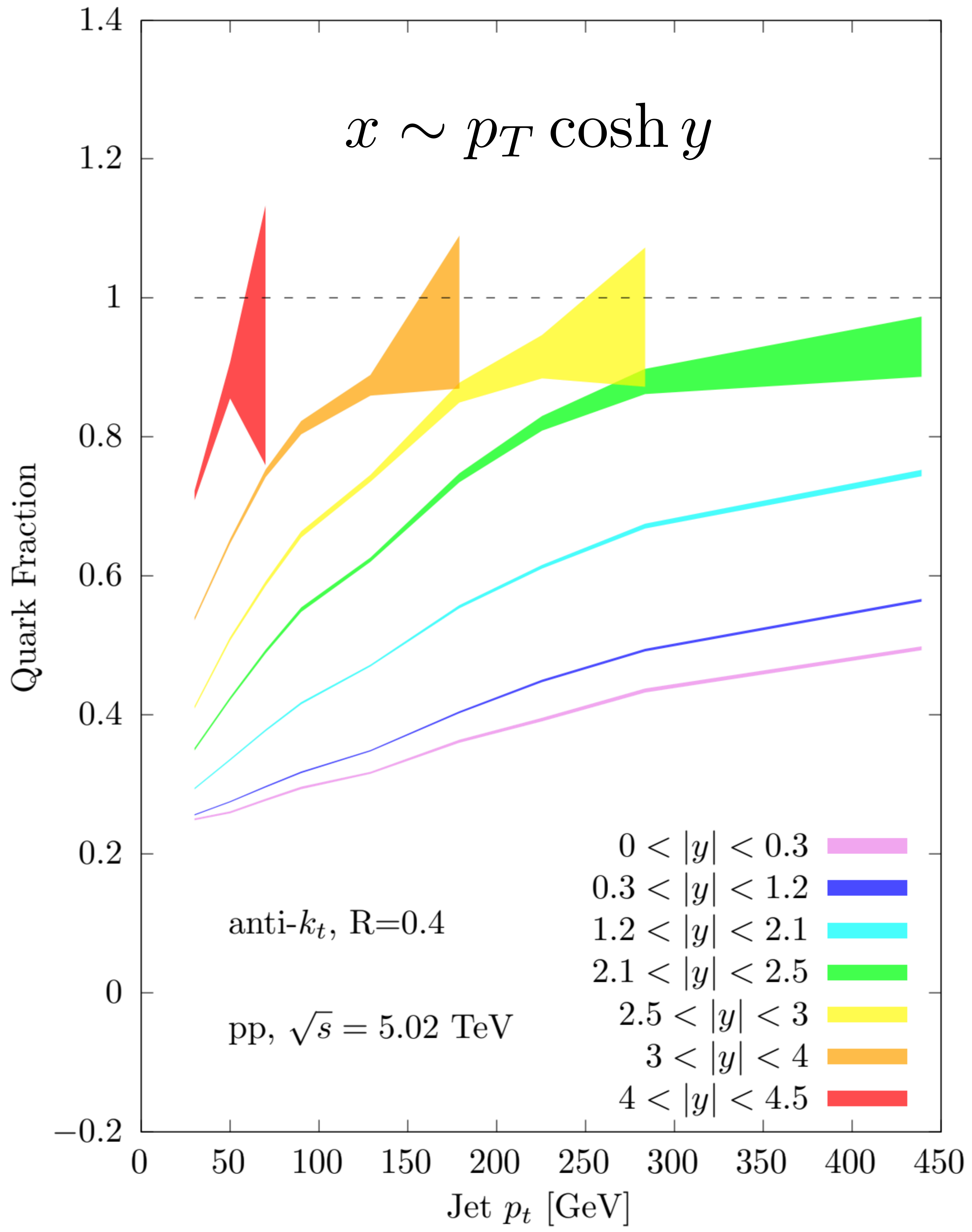
- Quenching of wider jets, either quark or gluon (medium sensitive to jet substructure fluctuations).
- Modification of q/g fraction (medium sensitive to total charge only).

Simple proposal:

→ Use an enriched quark sample, so that over-quenching of gluons has very little effect.

Rapidity Evolution of Quark Fraction

DP & A. Soto-Ontoso - PRD '23



- Quark enriched samples can be obtained from e.g. inclusive b-tagged jets, semi-inclusive boson-jets.
- In this work: exploit rapidity evolution of quark fraction to engineer quark enriched samples.

Extended rapidity coverages available in future detector upgrades.

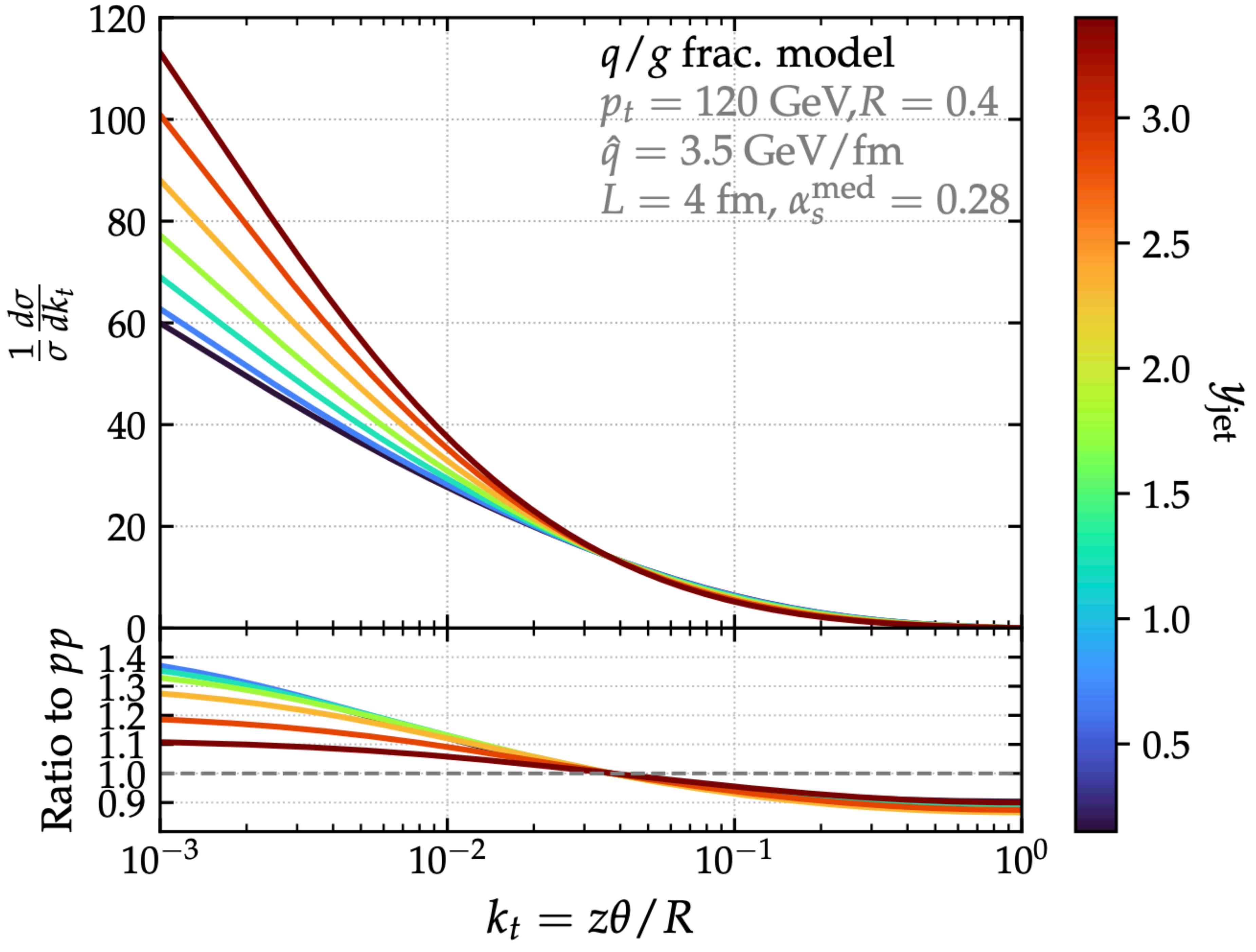
ALICE3

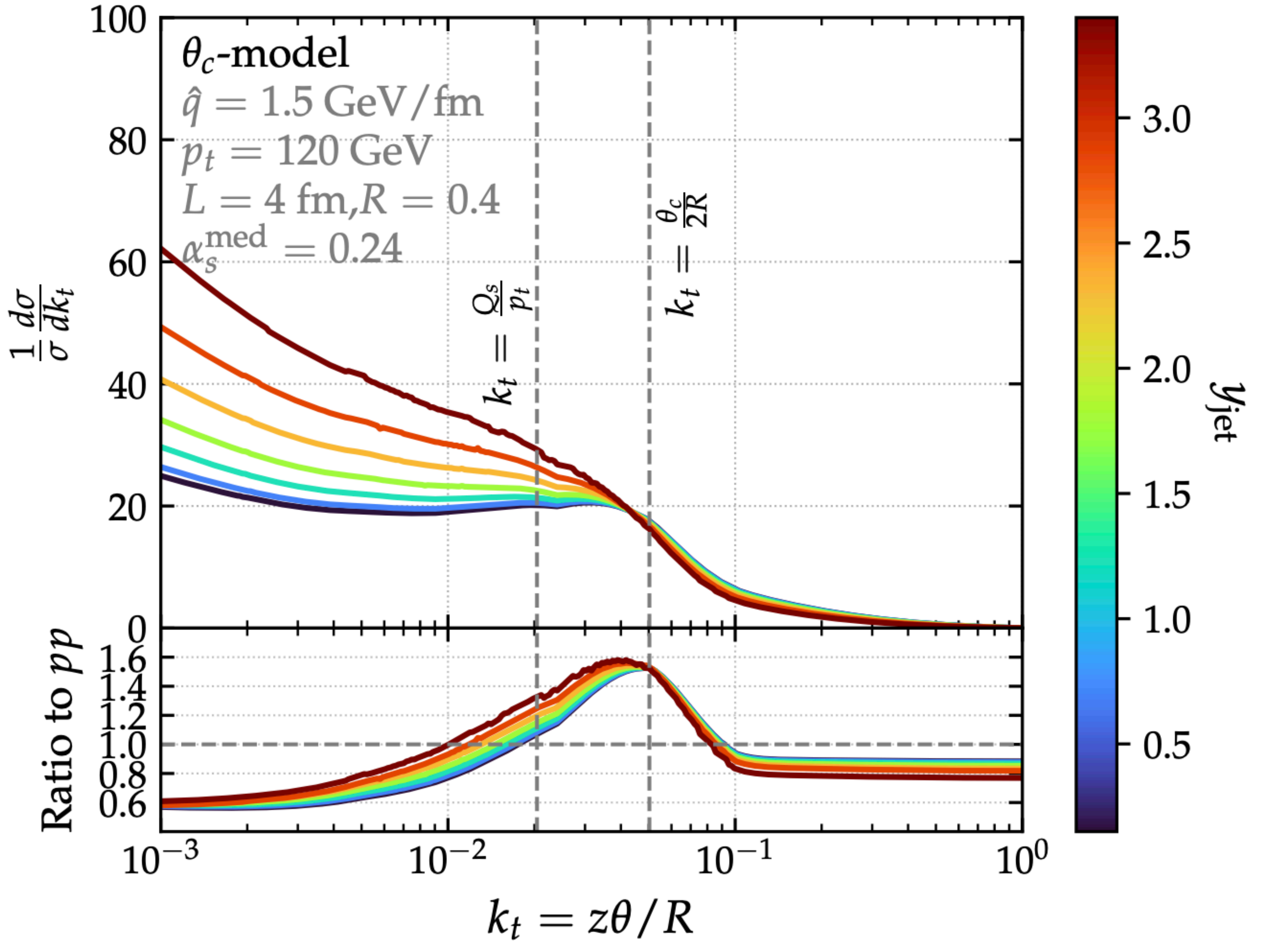
Run 6 with |η|<4
and great p_T resolution.

CERN-LHCC-2022-009

Also ATLAS and CMS!

Analytic Estimates at DLA - Summary





q/g frac model:

→ Quenching of leading charge only.

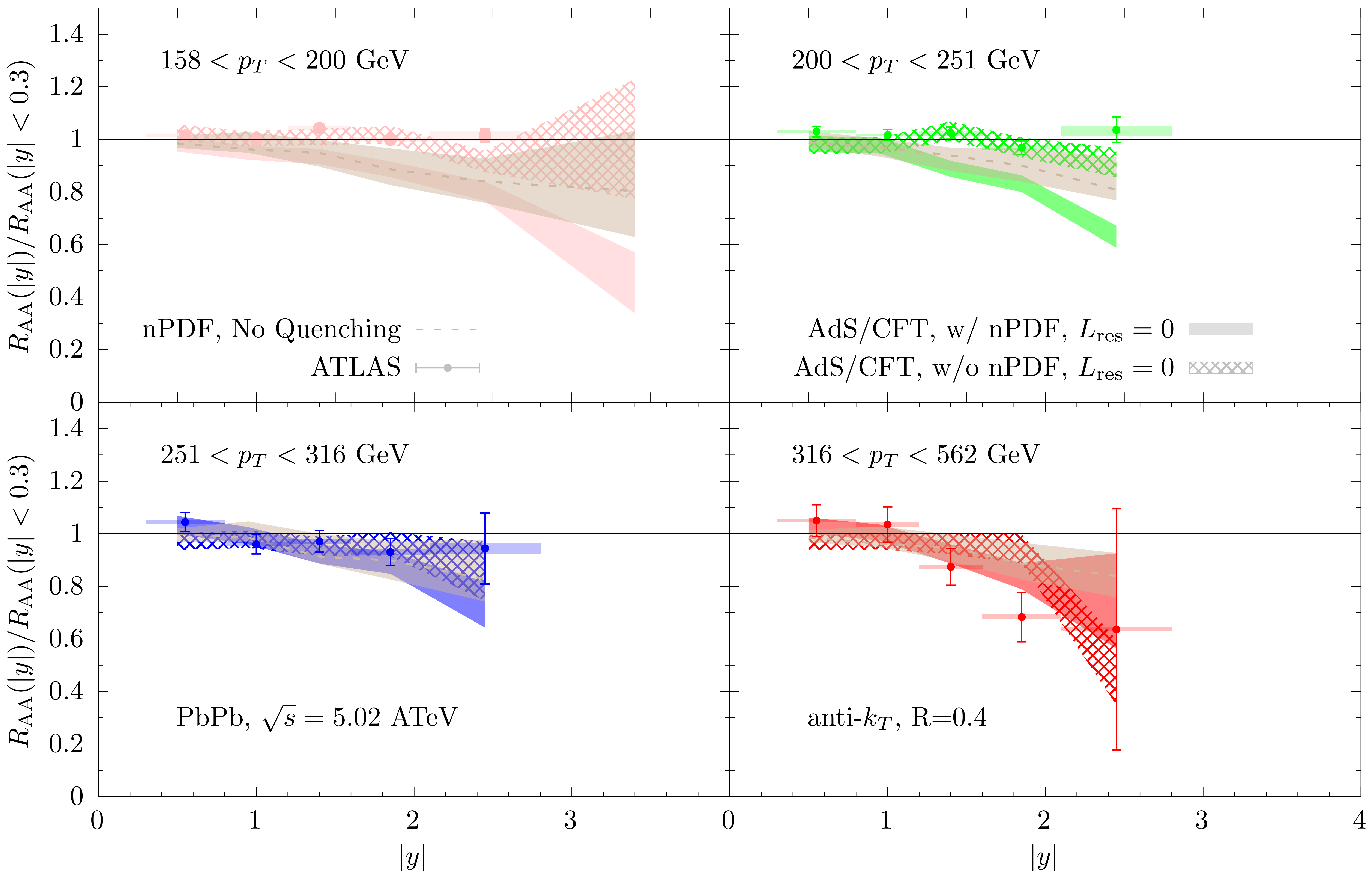
θ_c model:

→ Quenching of leading and tagged prongs if resolved (i.e. with $\theta > \theta_c$).

Less narrowing with increasing rapidity.

Narrowing persists also at forward rapidities.

Rapidity Dependence of R_{AA}



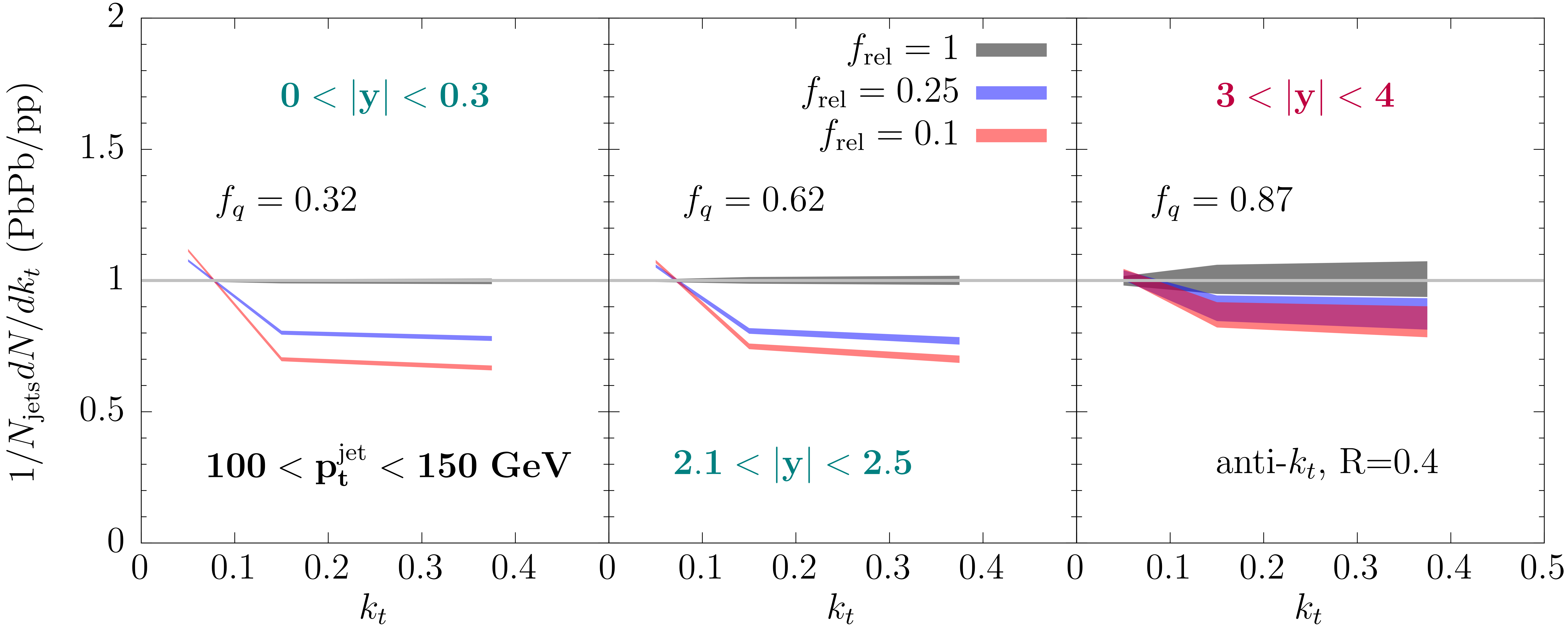
- Without nPDF, flatness of R_{AA} result of competing effects:
  Steepness of spectrum,
  change in q-fraction.

- Initial state effects affect R_{AA} vs rapidity.
  (Also observed in Adhya et al. - EPJC '22.)

- Need to check with updated sets EPPS21 and nNNPDF3.0.
  Differences among nPDF?
  Could we constrain nPDF?

Toy q/g Fraction Model

Using statistics projected for HL-LHC



BDMPS-Z:

$f_{rel} = \mathcal{Q}_q^{C_A/C_F - 1}$

$f_{rel} \approx 0.5$

for $\mathcal{Q}_q = 0.6$

$$\frac{1}{\sigma}\frac{d\sigma}{dk_t}\Big|_{AA} = \mathcal{N}^{-1}\left[f_q \frac{d\sigma_q}{dk_t}\Big|_{pp} + f_{rel}(1-f_q)\frac{d\sigma_g}{dk_t}\Big|_{pp}\right]$$

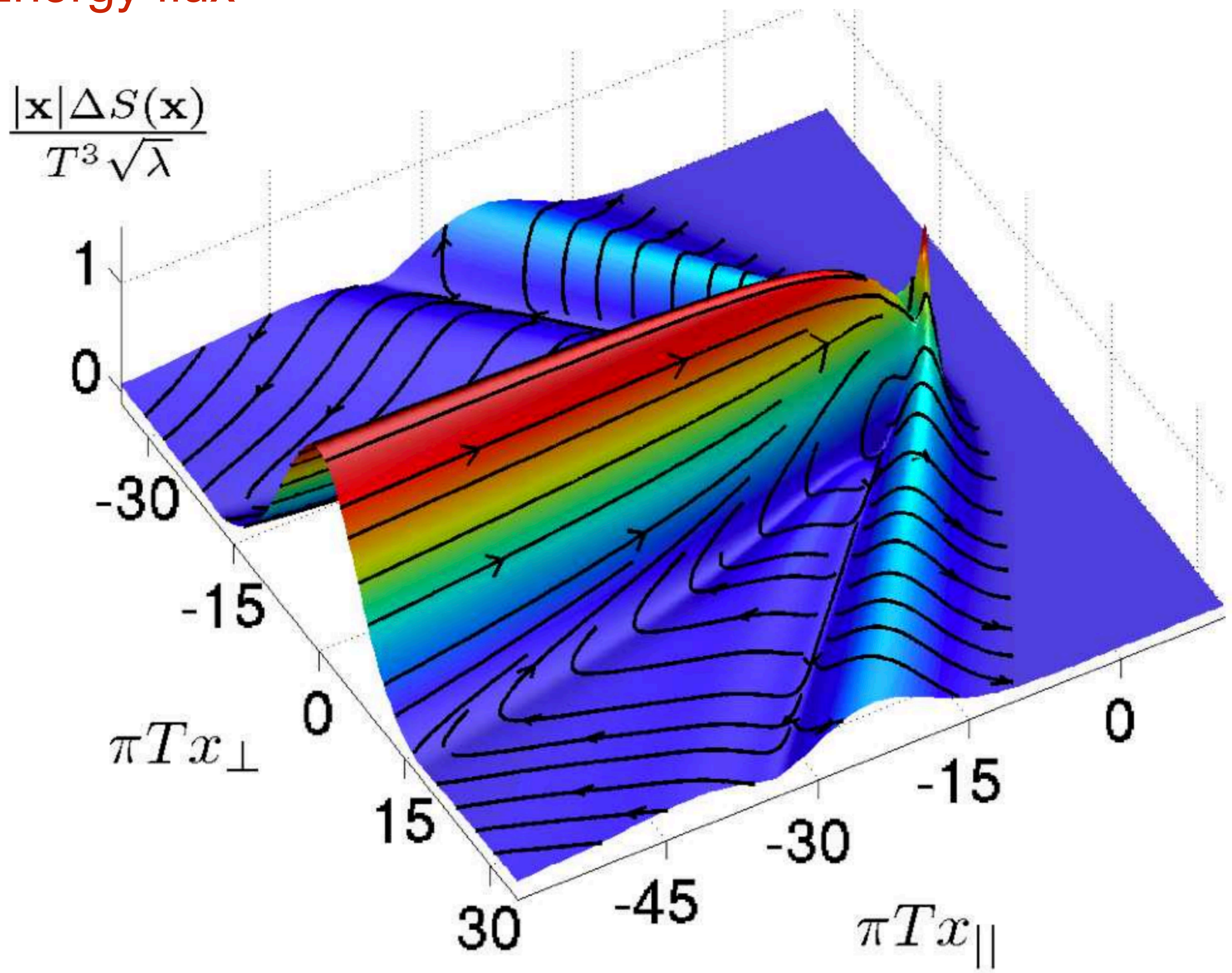
Combine quark and gluon pp templates with modified q/g fraction.

- Strong narrowing observed at mid-rapidity fades away toward forward rapidities.

The Wake of a Quark

- At strong coupling:
  - Modification of stress-energy tensor due to supersonic quark contains sound and diffusive modes.
  - Effective source for hydro corresponds to drag force on the quark.
  - Agreement between hydrodynamics & wake of a quark even for small distances ~ 1/T.

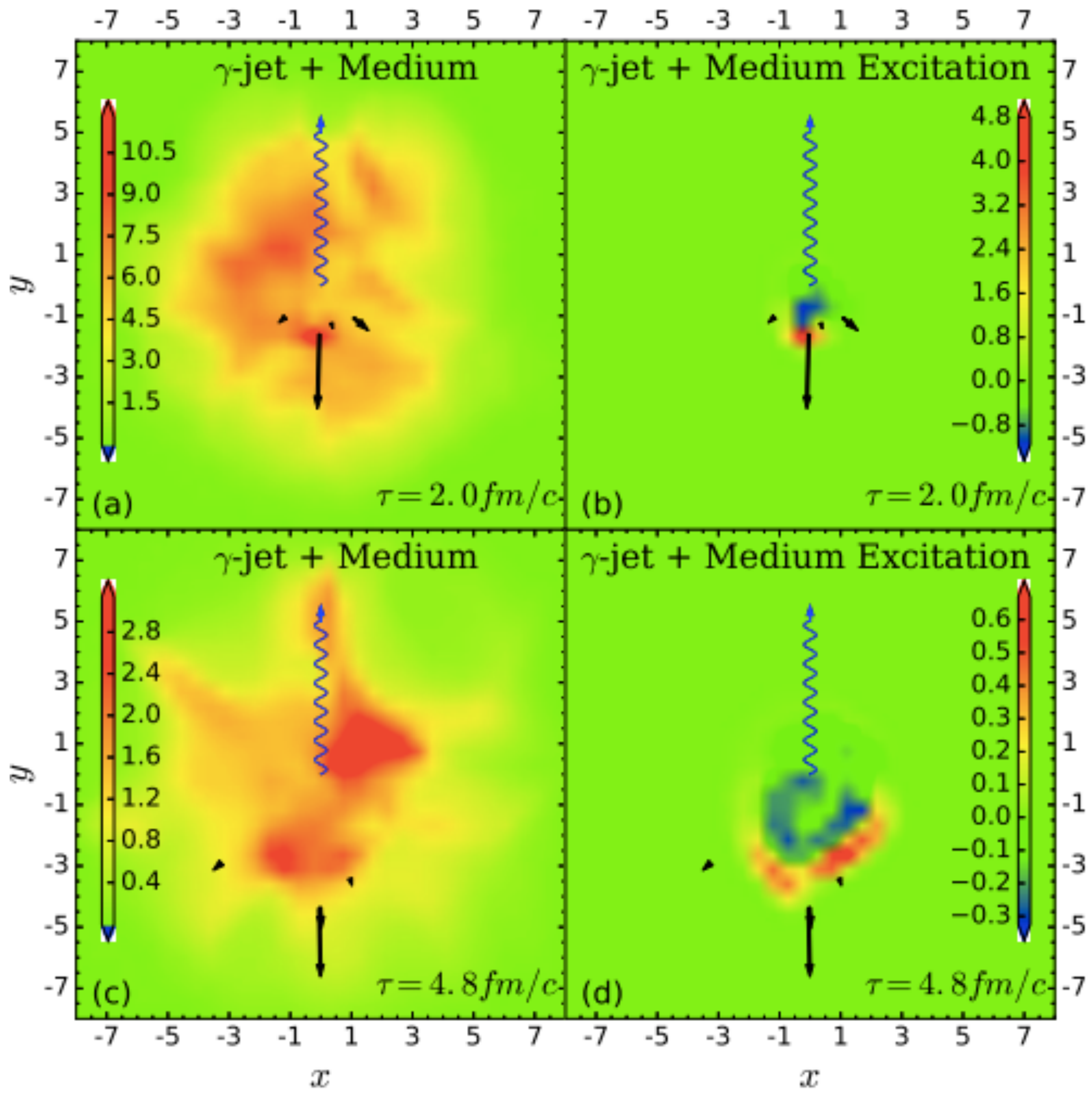
Energy flux



Fulfills Energy-Momentum Conservation in the Jet+Plasma Interplay.

Chesler & Yaffe - 0712.0050

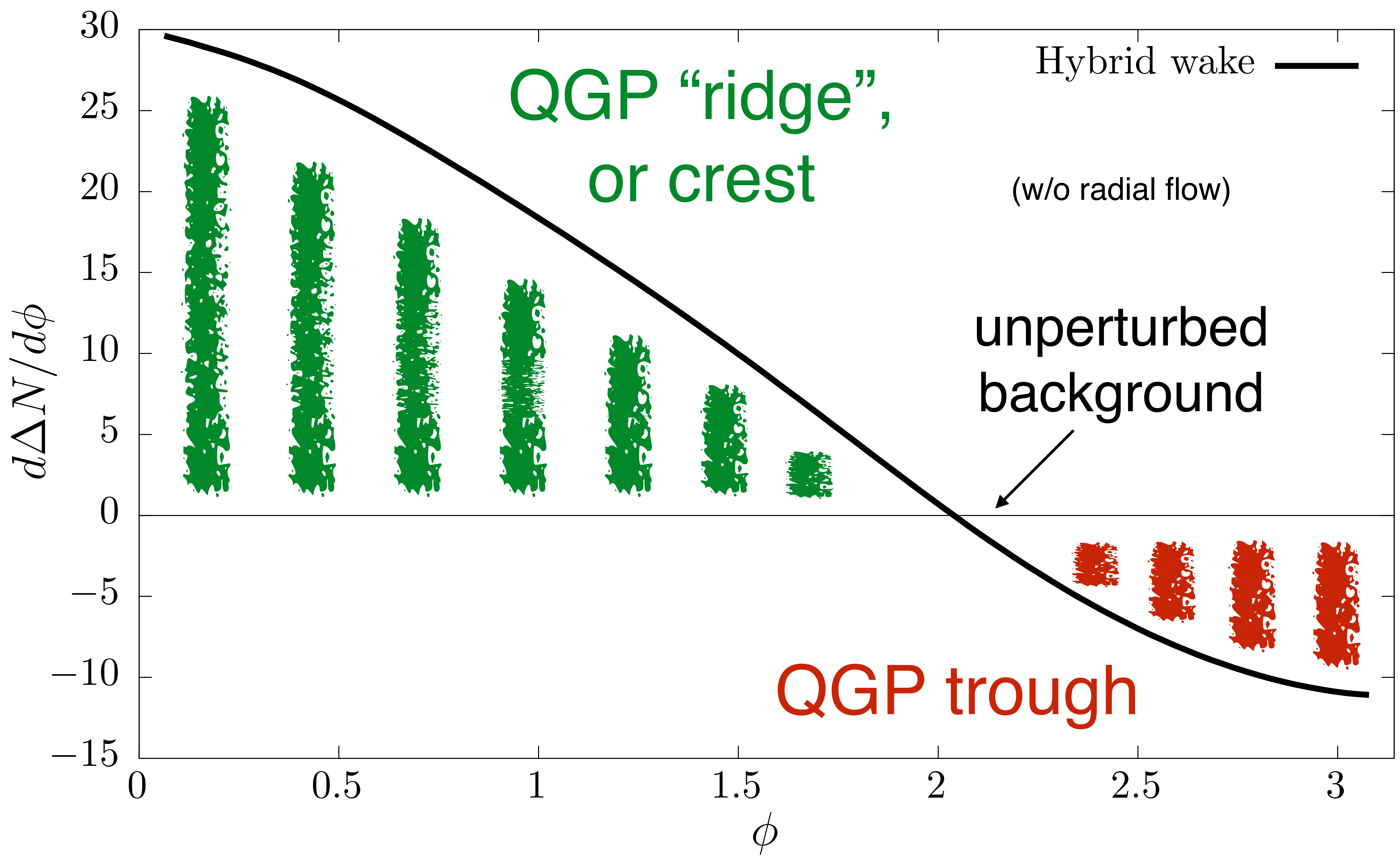
The Diffusion Wake



Chen et al. - [1704.03648](1704.03648)

QGP trough arises due to the diffusion wake:

- Depletion of energy density behind the jet (the jet drags the fluid along its direction of propagation, reduces yield of particles in the opposite direction).

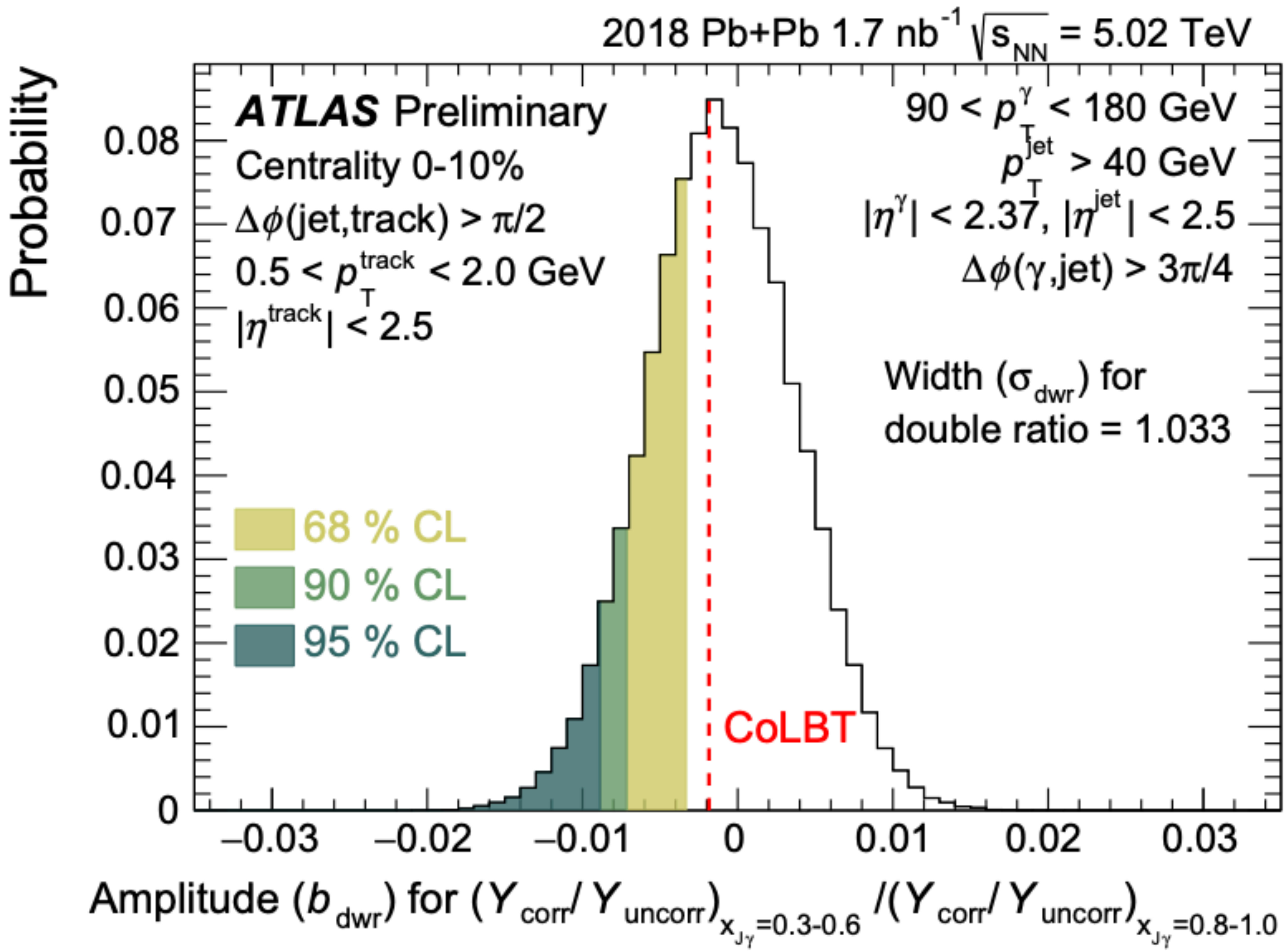


Ex: depletion in the away-side for boson-jet events with CoLBT model.

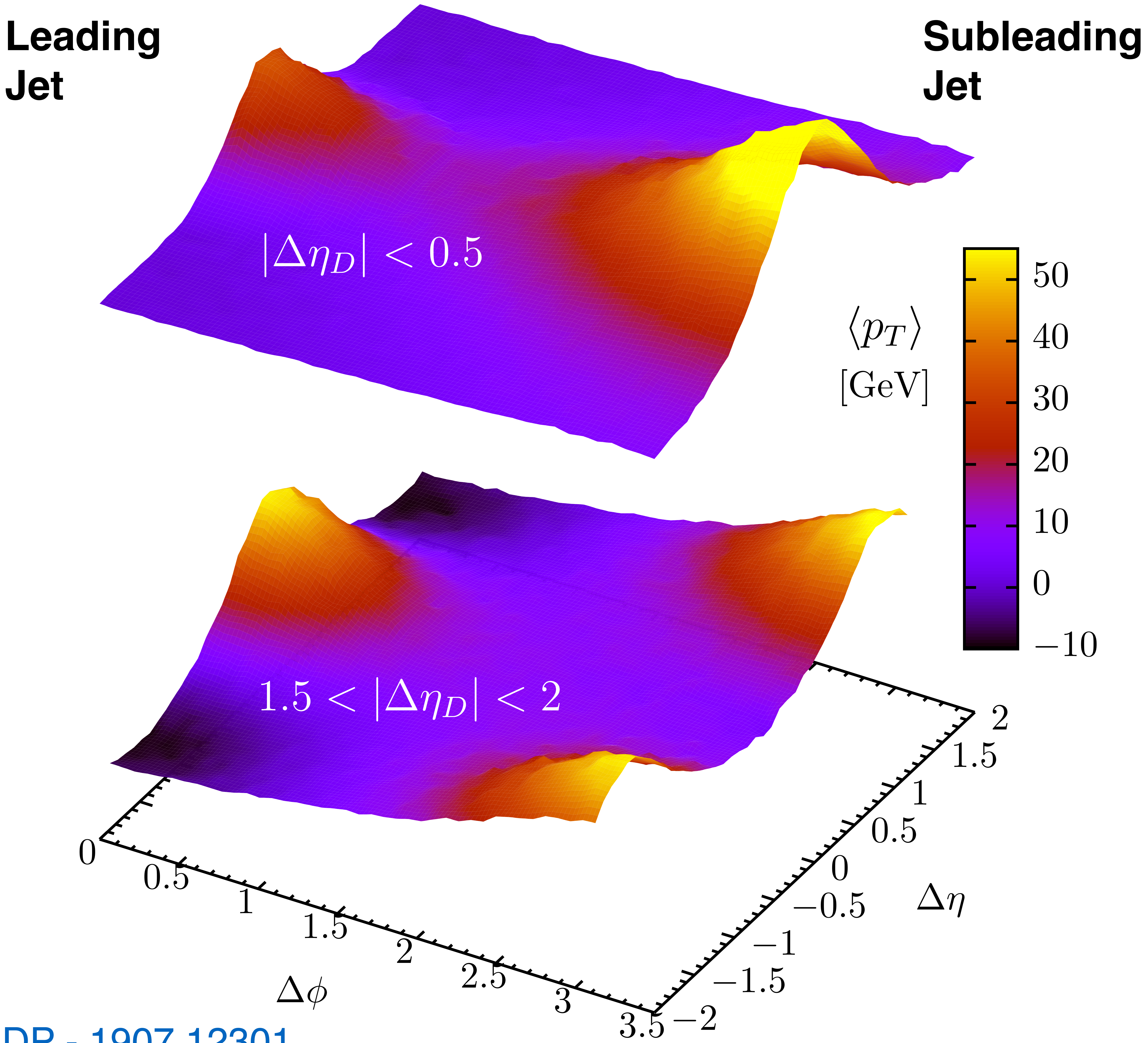
Looking For the Diffusion Wake

ATLAS-CONF-2023-054

- No evidence for diffusion wake in recent results from ATLAS.
- 95% CL at 0.8% perturbation on bulk, compatible with CoLBT 0.2% prediction.
- Statistics will be improved in Run 3.



The Effect of the Recoiling Jet



DP - [1907.12301]

$\langle p_T \rangle$ density of wake hadrons w.r.t leading jet axis.

Aligned in rapidity

Subleading jet's QGP trough hits leading jet.

Separated in rapidity

Subleading jet's QGP trough misses leading jet.

$p_T^L > 250$ GeV
$p_T^S > 80$ GeV
$\Delta\phi_D > 2\pi/3$

differential in

$|\eta_D| \equiv |\eta_L - \eta_S|$

Leading Jet Suppression vs. $|\eta_D|$

DP - 1907.12301

A new observable.

R = 0.4

leading jet area easy to miss;
small effect from QGP trough.

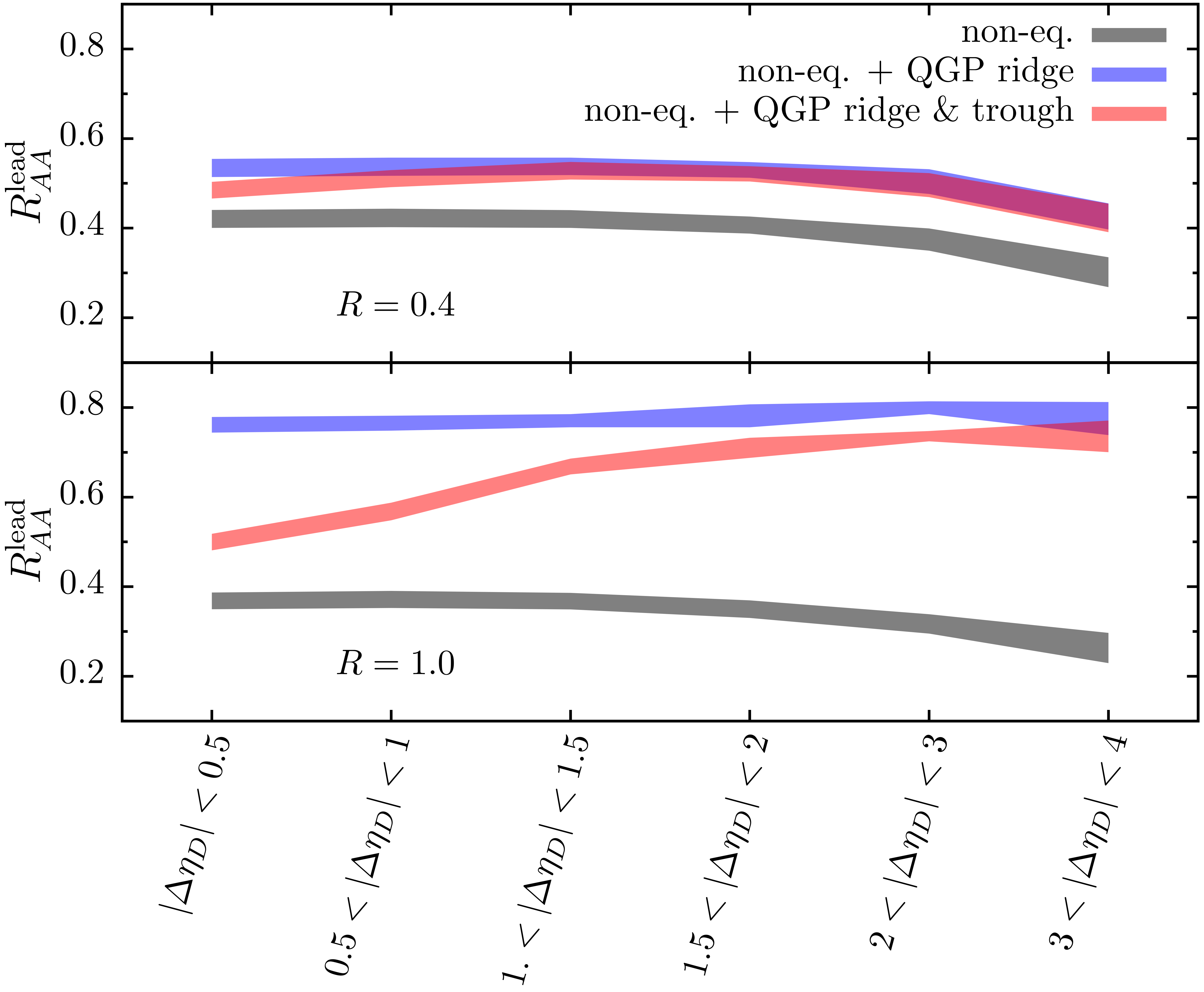
R = 1.0

strong dependence on $|\eta_D|$;
knee visible when $|\eta_D| \sim R$.

$$p_T^L > 250 \text{ GeV}$$
$$p_T^S > 80 \text{ GeV}$$
$$\Delta\phi_D > 2\pi/3$$

differential in

$$|\eta_D| \equiv |\eta_L - \eta_S|$$



Leading Jet Suppression vs. $|\eta_D|$

Benefits of the strategy:

- Much higher stats for inclusive jets compared to boson-jets.
- Can reach higher p_T, larger wake effects.
- Many systematics cancelled in ratios between different $|\eta_D|$.

Also: replace subleading jet by high-p_T hadron (just need an axis!).

Jet Suppression: Framework

- Use microjet distributions derived using Generating Functional (GF) framework:

Dasgupta et al. - JHEP ‘14

Vacuum evol. obeys DGLAP:

$$\frac{df^{\rm incl}_{j/i}(z,t)}{dt} = \sum_k \int_z^1 \frac{dz'}{z'} P_{jk}(z')\, f^{\rm incl}_{k/i}(z/z',t)$$

- Extend GF in the medium to resum energy loss effects due to multi-particle nature of jet:

PS$_{\rm in}$ constraint

$$\frac{\partial Q_i(p,\theta)}{\partial \ln\theta} = \int_0^1 {\rm d}z\, \frac{\alpha_s(k_\perp)}{2\pi} p^{(k)}_{ji}(z) \boxed{\Theta_{\rm res}(z,\theta)} \times \left[Q_j(zp,\theta)Q_k((1-z)p,\theta) - Q_i(p,\theta)\right]$$

Initial condition at zero angle is single charge quenching factor:

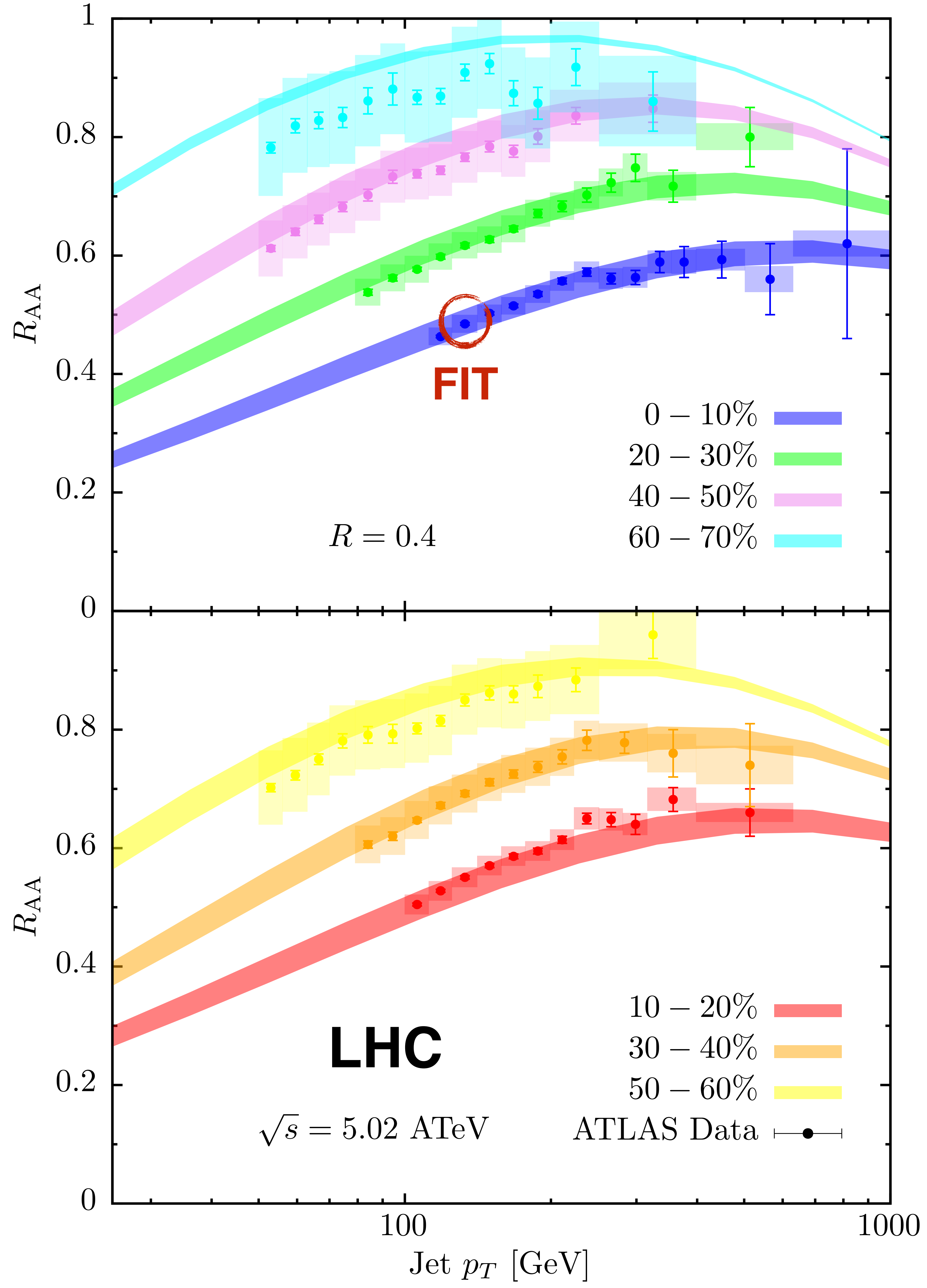
$$Q_i(p,0) = Q^{(0)}_{{\rm rad},i}(p_T)\,Q^{(0)}_{{\rm el},i}(p_T)$$

Radiative energy loss — Elastic energy loss

- Energy loss versus R displays non-monotonic behaviour. Competing effects:
  - → Increasing R means more likely to retain emitted (or thermalised) quanta: less quenching.
  - → Increasing R means larger quenched phase space: more quenching.

Mehtar-Tani, DP, Tywoniuk - PRL ‘21

Jet Suppression at LHC



Mehtar-Tani, DP, Tywoniuk - PRL '21

- Modelling sensitivity at p_T=110 GeV for **R** between **0.2 and 0.6**:

Parameter	Variation	Effect
θ_c	$[\theta_c/2,\ 2\theta_c]$	$\lesssim 20\%$
IOE	LO/NLO	$\sim 2\%$
n	± 1	$\sim 10\%$
$R_{\rm rec}$	$[1,\ \infty]$	$\lesssim 10\%$
ω_s	$[\omega_s/2,\ 2\omega_s]$	$\lesssim 8\%$

→ NLO contribution very small (hard emissions tend to be collinear).

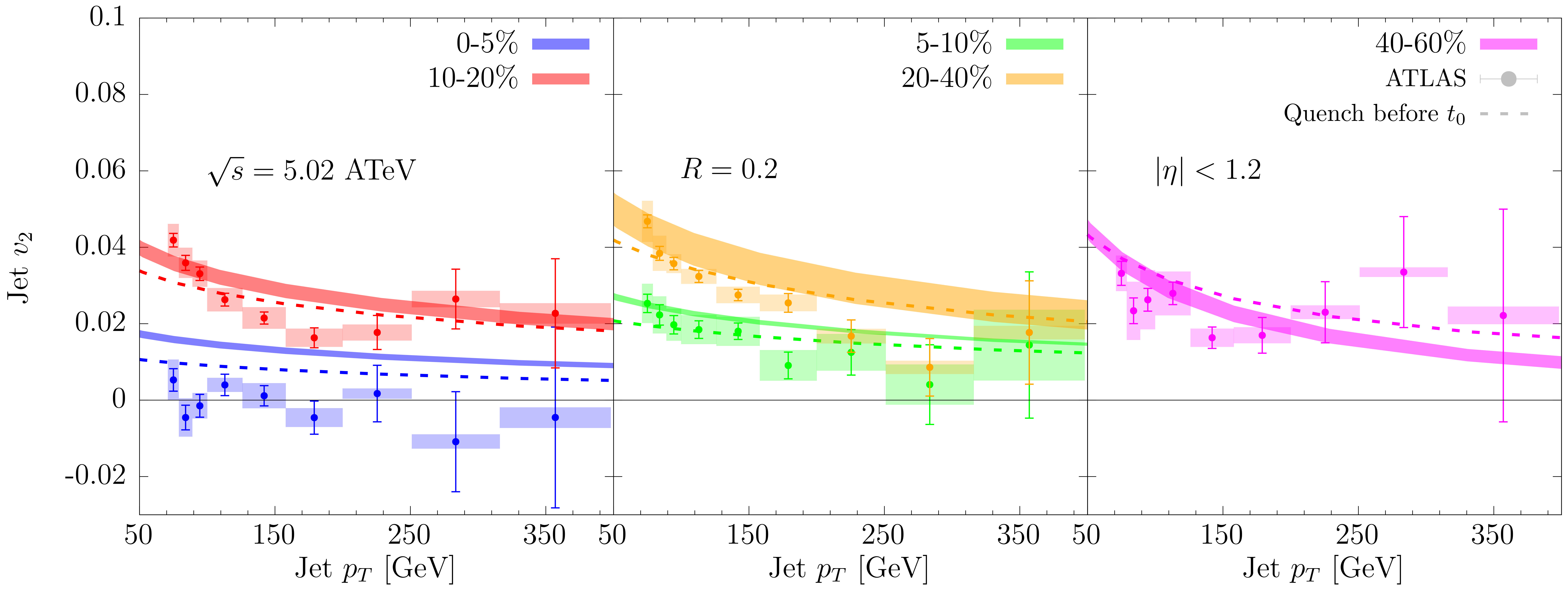
→ Modelling of fate of lost energy relatively small.

→ Determination of quenched phase space relatively large. Improvable in pQCD.

Need to improve perturbative sector before non-perturbative becomes relevant (for R<0.6!)

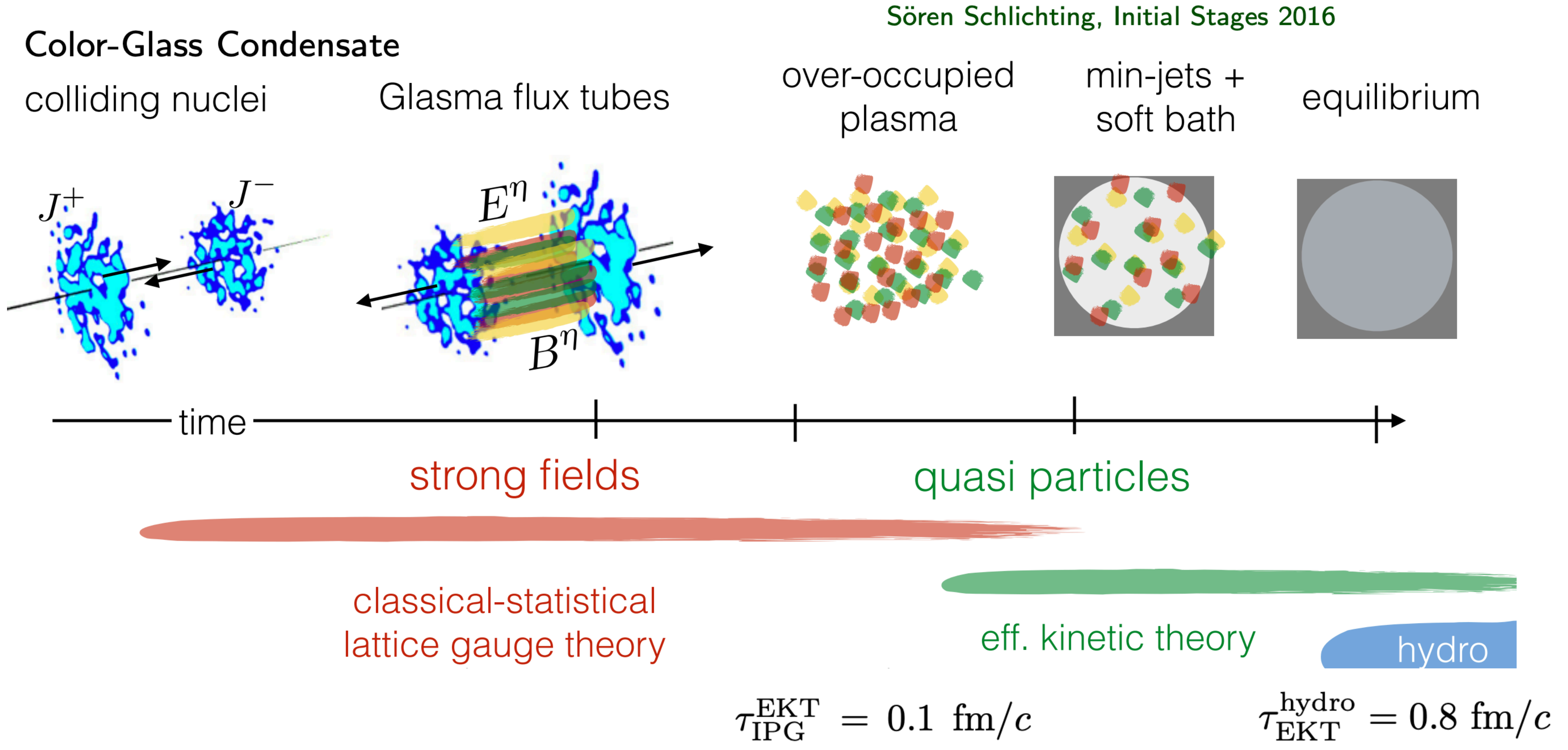
Jet Azimuthal Anisotropy at LHC

Mehtar-Tani, DP,
Tywoniuk - in preparation



- First analytical description of jet v_2.
- Sensitivity of jet v_2 to non-equilibrium stage.

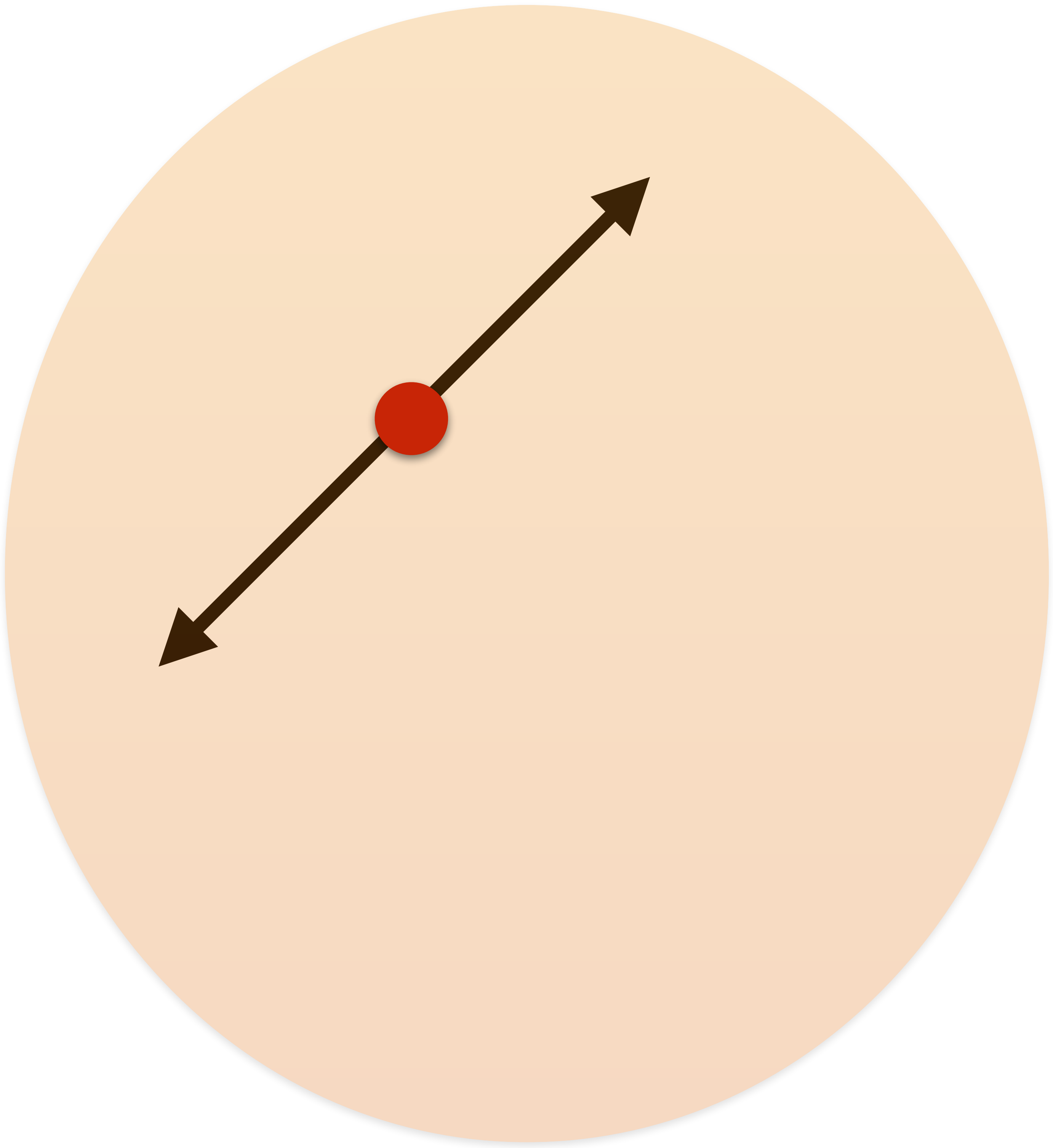
Current Perspective on Early Times



Gale, Paquet, Schenke, Shen - PRC '22

- Bulk of the system assumed to be produced with momenta $p \sim Q_s \sim 2\,\mathrm{GeV}$.
- Effective description switches at a fixed time.

Mini-Jets in Heavy-Ions

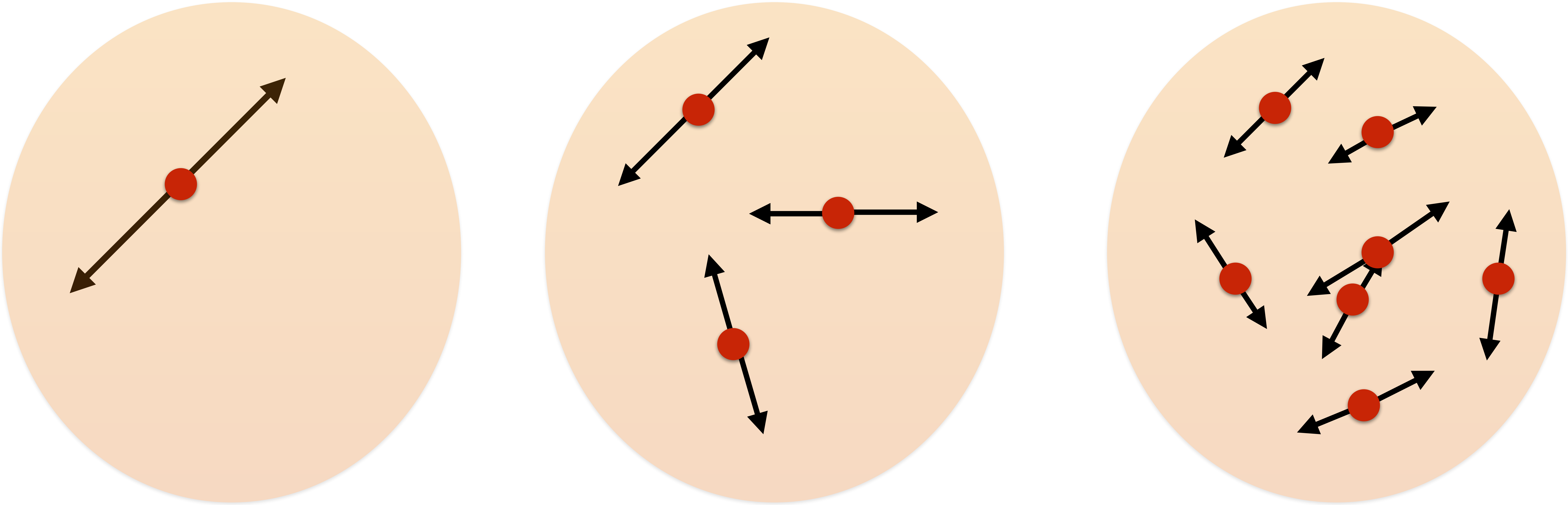


- Consider particle production with $p > Q_s$.
  - Perturbative process.
  - Production probability proportional to N_{coll}.
  - Can split and produce color coherent objects.
  - Random orientation in transverse plane and rapidity.

Mini-jets are an additional source of fluctuations.

For $p_T \sim 20$ GeV, one or zero dijet pair produced at central collisions at LHC…

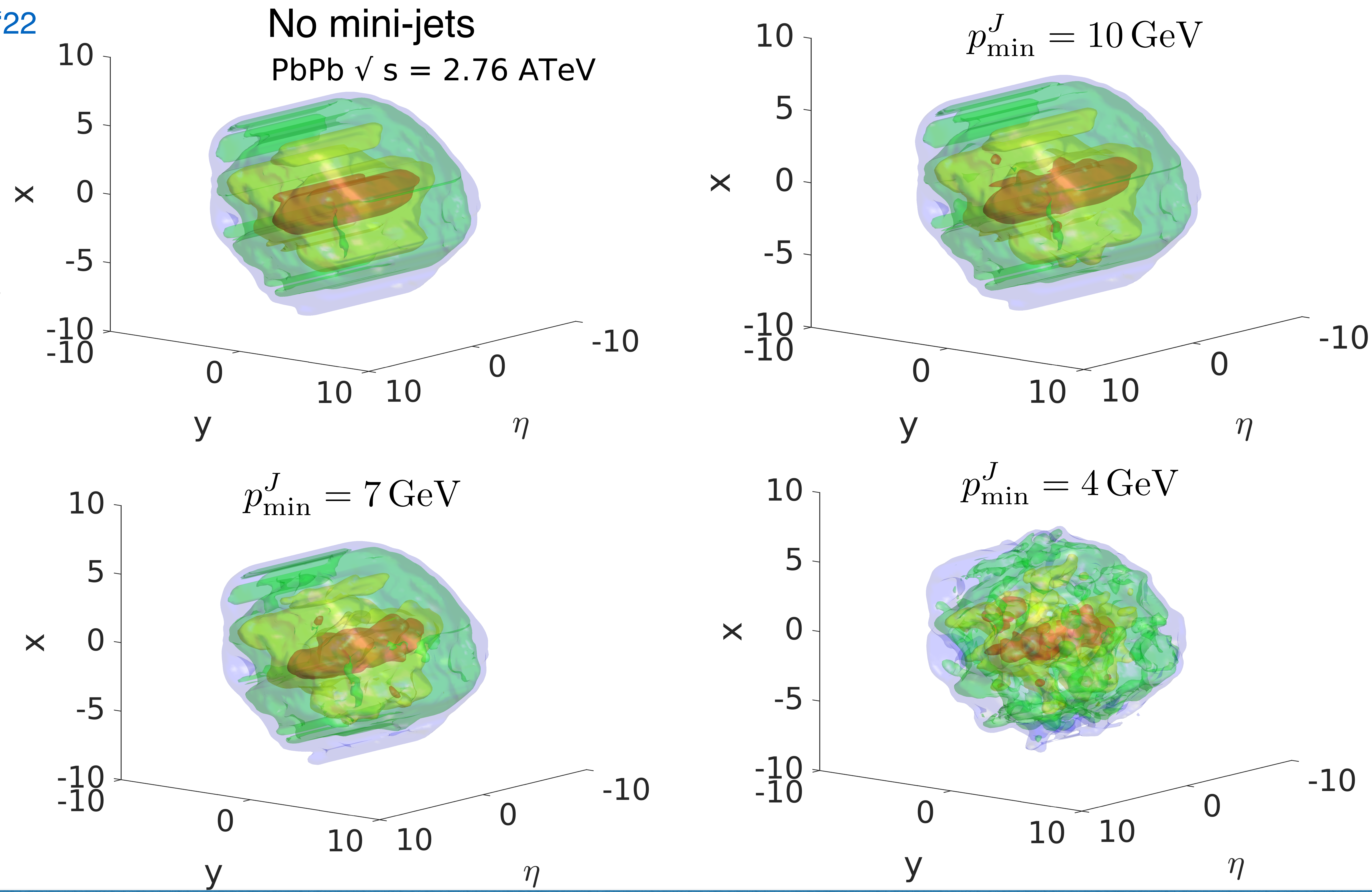
Mini-Jets in Heavy-Ions



As we consider lower p_T, mini-jet production becomes increasingly abundant.

A Spikier Evolution

DP, Singh, Gale, Jeon - PRC ‘22



3D isotherms at temperatures

220 MeV (red),

195 MeV (yellow),

170 MeV (green)

and 145 MeV (blue).

$\tau = 3.4\,{\rm fm/c}$

40-50% Centrality

Minimal Tuning

DP, Singh, Gale, Jeon - PRC '22

- To describe multiplicity, tune down amount of energy attributed to IP-Glasma ($s_{\rm factor}$), for each $p^J_{\rm min}$:

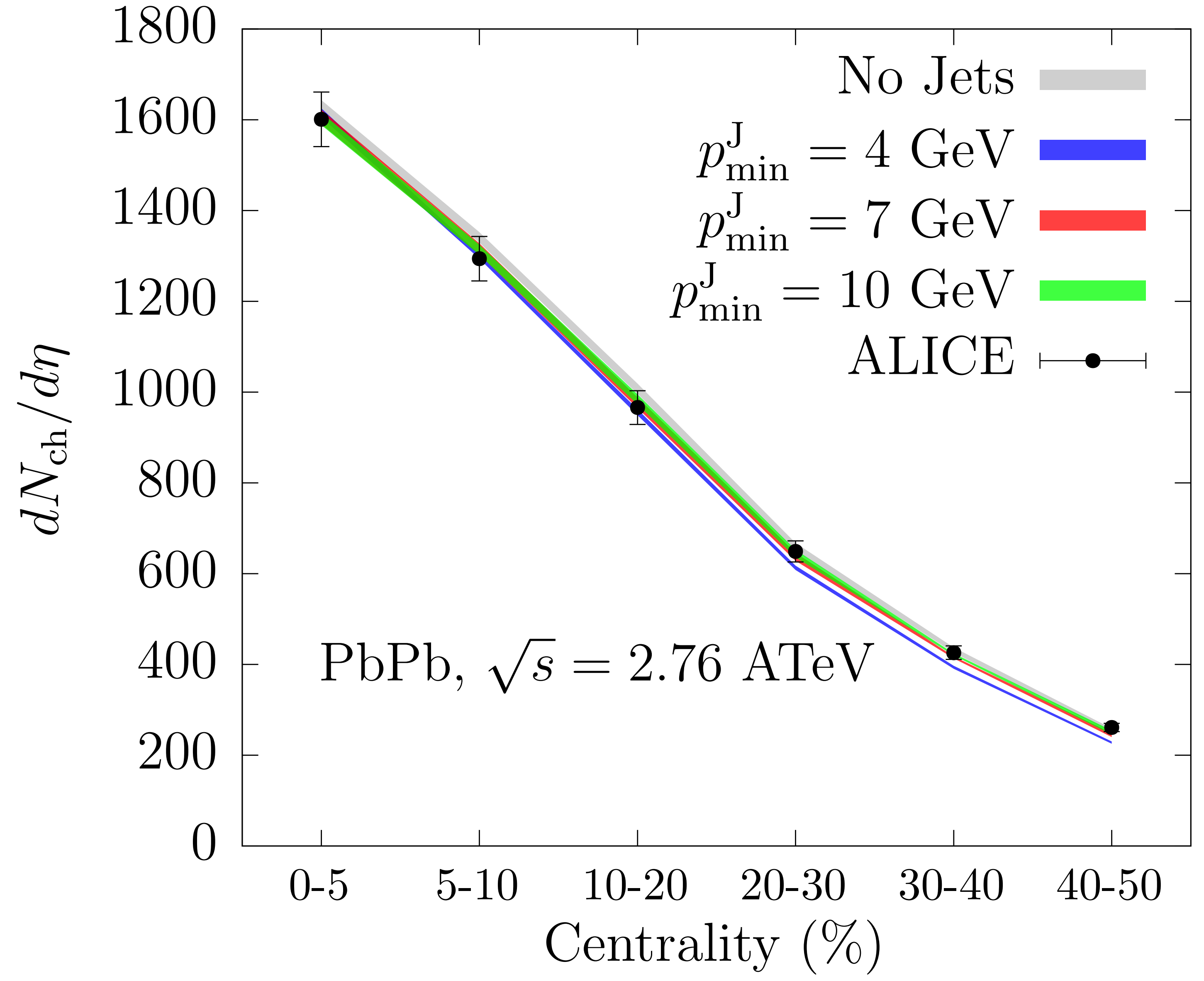
  → Single choice of $s_{\rm factor}$ works for all centralities.

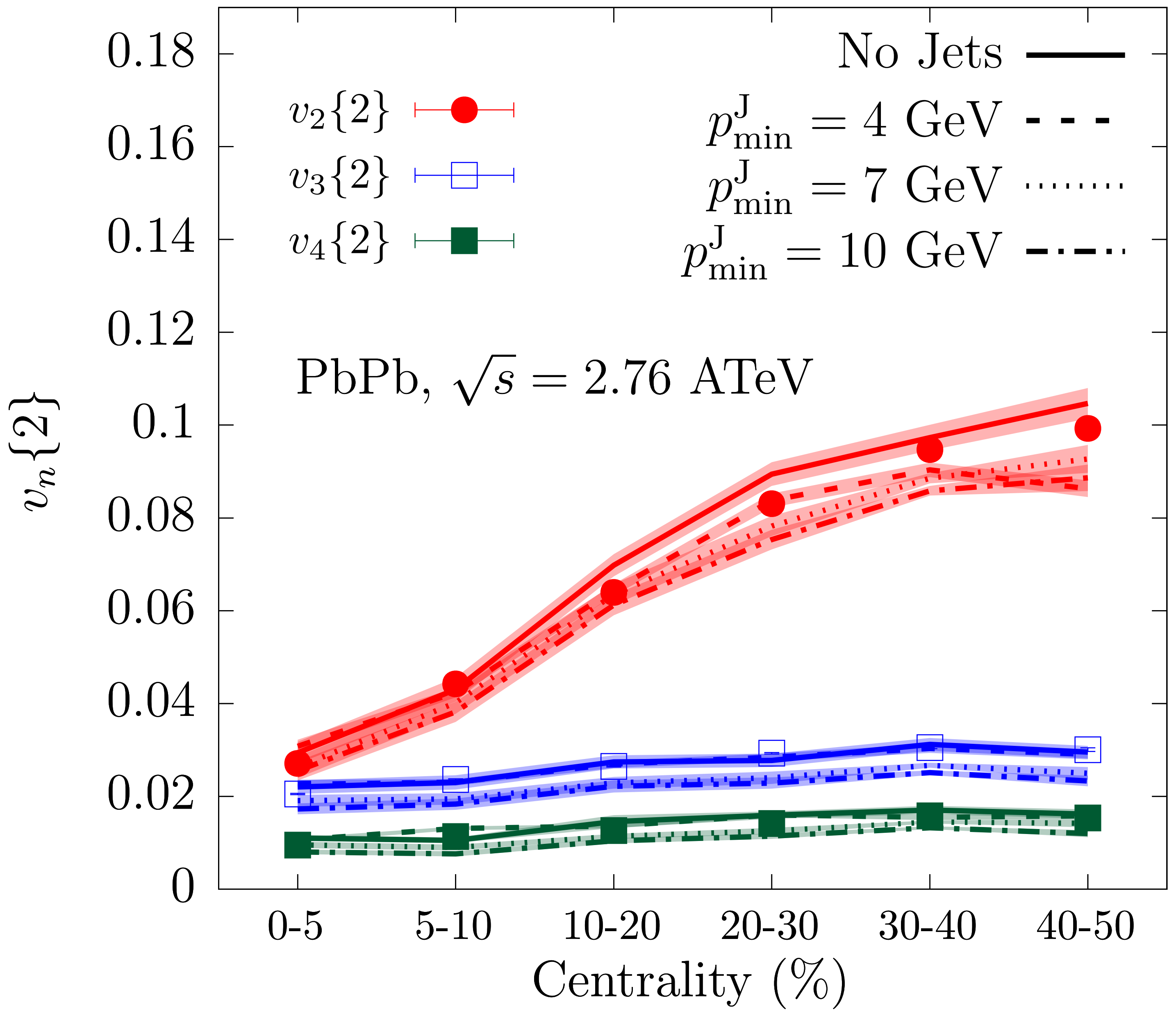
$p^{\rm J}_{\rm min}$	$s_{\rm factor}$	η/s
4 GeV	0.45	0.02
7 GeV	0.82	0.1
10 GeV	0.9	0.125
No Jets	0.915	0.13

- Mini-jet orientation is decorrelated with energy gradients at $\tau_{\rm hydro}$, reducing overall flow:

  → Need to recalibrate (constant) η/s to accommodate integrated and differential flow coeffs.

see also: Schulc &Tomasic - PRC '14
Okai et al. - PRC '17





My Fellini

- Have enjoyed complete independence

Mini-jets (McGill, Vanderbilt)

Linearized Hydro (MIT, UB, INT)

Analytical jet suppression (Bergen U., BNL)

Moliere scatterings in QGP (MIT, Stanford)

Rapidity dependence (CERN)

Heavy quarks in small syst. (INFN Torino)

Perturbative splittings in HI (CERN, Heidelberg)

- 7 talks at Hard Probes '23, 5 talks at Quark Matter '23, ***plenary*** at Quark Matter '23.

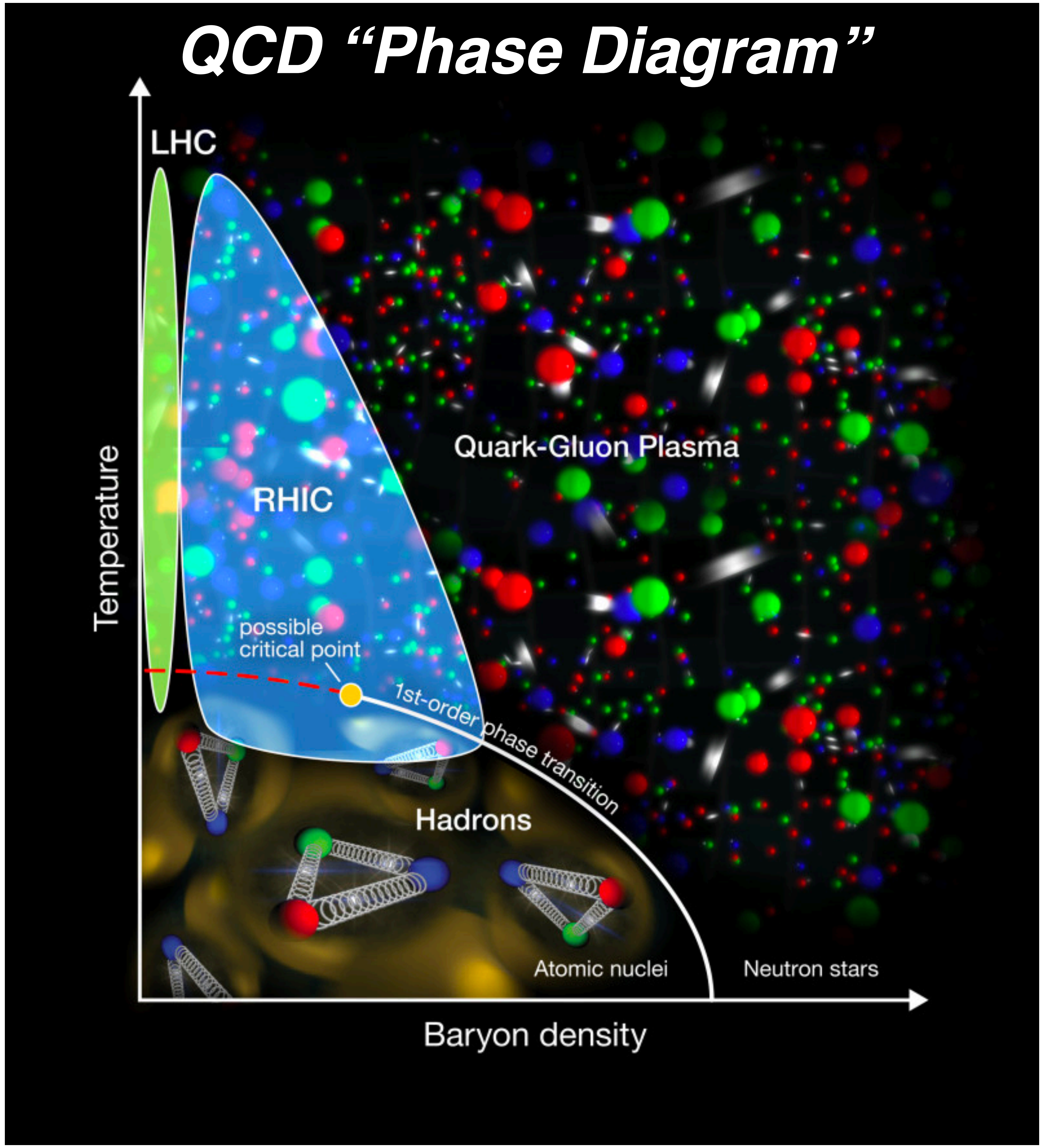
Invited by ALICE, PHENIX, STAR for jet theory talks several times.

- Secondment institution: Oviedo U.

Working with student on antenna scatterings.

Working with host supervisor on holographic energy loss.

- Now moving to Santiago for postdoc. Wish me luck.



Thanks for your attention!

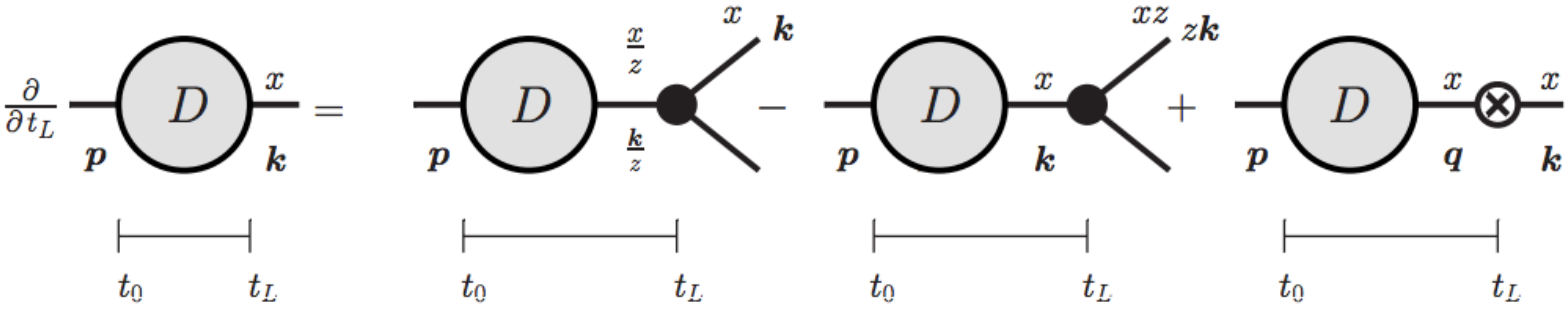
e Buon Natale!

Backup Slides

pQCD

High energy partons in the QGP:

→ emit quanta, which in turn emit more quanta, and should (eventually) hydrodynamize.



$D(x, \boldsymbol{k}, t)$ is one-gluon distribution.

Blaizot et al. - JHEP ‘13 & ‘14, PRL ‘13

- Turbulent cascade develops, with a sink at E ~ T.
- Necessary length to reach the turbulent regime?

Radiative Energy Loss

- Framework: Light-Cone Perturbation Theory.

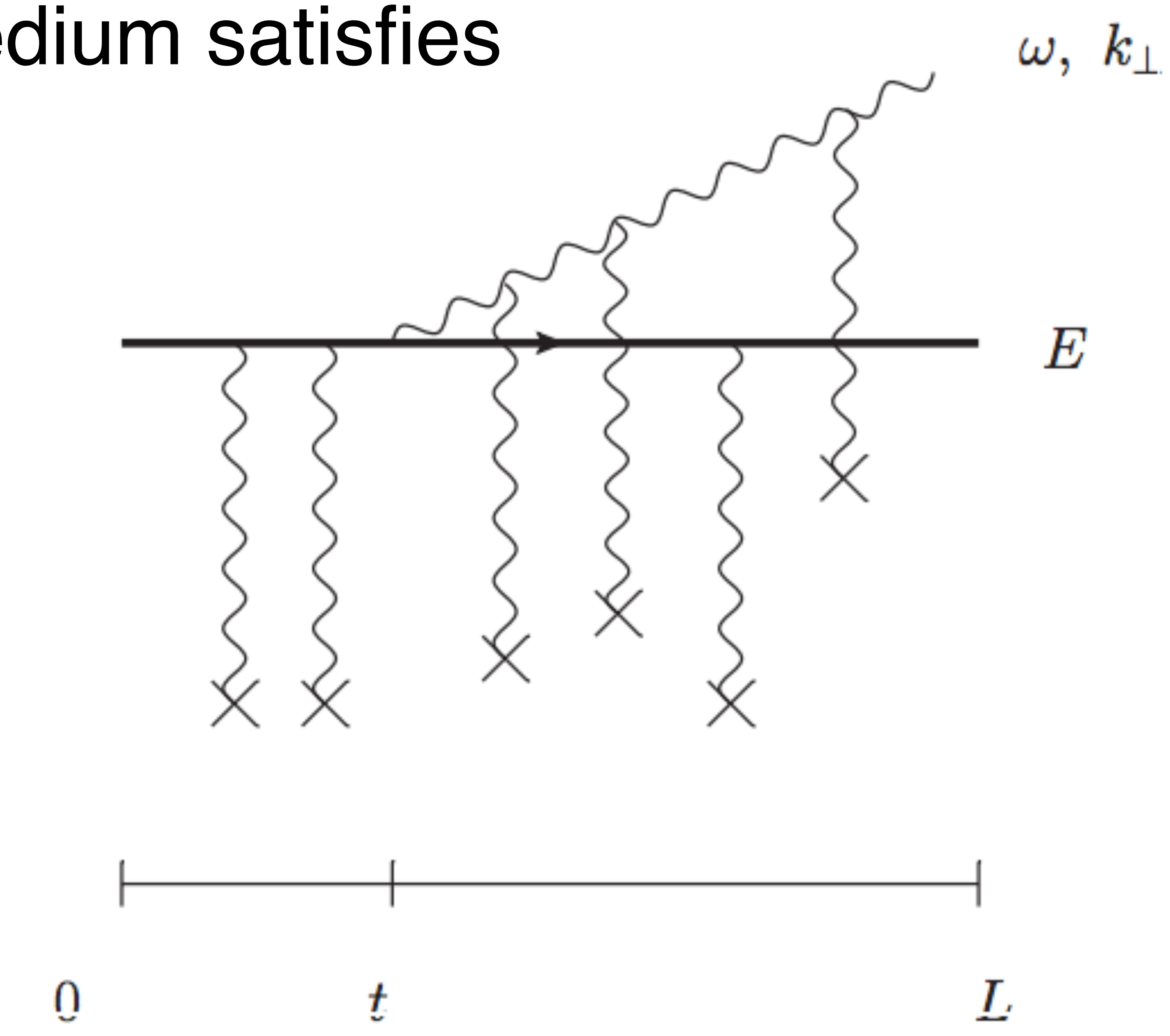
Baier, Dokshitzer, Mueller, Peigne, Schiff - NPB ‘97
Zakharov - JETP Lett. ‘96
Arnold, Moore, Yaffe - JHEP ‘03

  - Integrated medium induced spectrum:

$$\omega \frac{\mathrm{d}I}{\mathrm{d}\omega} = \frac{\alpha_s C_R}{\omega^2} \int_0^\infty dt_2 \int_0^{t_2} dt_1 \, \boldsymbol{\partial}_{\boldsymbol{x}} \cdot \boldsymbol{\partial}_{\boldsymbol{y}} \left[\mathcal{K}(\boldsymbol{x}, t_2 | \boldsymbol{y}, t_1) - \mathcal{K}_0(\boldsymbol{x}, t_2 | \boldsymbol{y}, t_1) \right]_{\boldsymbol{x}=\boldsymbol{y}=0}$$

  - Resummed propagator due to multiple interactions with the medium satisfies 2D Schrödinger-like equation:

$$\left[i\partial_t + \frac{\boldsymbol{\partial}^2}{2\omega^2} + iv(\boldsymbol{x}) \right] \mathcal{K}(\boldsymbol{x}, t_2 | \boldsymbol{y}, t_1) = i\delta(\boldsymbol{x} - \boldsymbol{y})\delta(t_2 - t_1)$$



  - With potential: $v(\boldsymbol{x}, t) = C_A \int_{\boldsymbol{k}} \frac{d^2\sigma}{d^2\boldsymbol{k}} (1 - e^{i\boldsymbol{k}\cdot\boldsymbol{x}})$

    and scattering cross-section:

Hard Thermal Loop:

$$\left(\frac{\mathrm{d}^2\sigma}{\mathrm{d}^2\boldsymbol{q}} \right)^{\mathrm{HTL}} = \frac{g^2 m_{\mathrm{D}}^2 T}{\boldsymbol{q}^2(\boldsymbol{q}^2 + m_{\mathrm{D}}^2)}$$

Gyulassy-Wang:

$$\left(\frac{\mathrm{d}^2\sigma}{\mathrm{d}^2\boldsymbol{q}} \right)^{\mathrm{GW}} = \frac{g^4 n(t)}{(\boldsymbol{q}^2 + \mu^2)^2}$$

Mehtar-Tani - JHEP ‘19

Usual Approximations of the Spectrum

- Dilute medium: expand to leading order in $v(\boldsymbol{x})$ (N=1 opacity expansion):

$$\omega \frac{\mathrm{d}I_{\mathrm{GLV}}}{\mathrm{d}\omega} = 32\pi\, \alpha_s\, C_R\, \hat{q}_0 \int_0^L \mathrm{d}s \int_{\boldsymbol{p},\boldsymbol{q}} \frac{\boldsymbol{p}\cdot\boldsymbol{q}}{\boldsymbol{p}^2(\boldsymbol{p}-\boldsymbol{q})^2(\boldsymbol{q}^2+\mu^2)^2} \left\{1-\cos\left[\frac{(\boldsymbol{p}-\boldsymbol{q})^2}{2\omega}s\right]\right\}$$

Gyulassy-Levai-Vitev spectrum

Single hard scattering, preserves full form of potential.

Wiedemann - NPB ‘00
Gyulassy, Levai, Vitev - NPB ‘00
Wang, Guo - NPA ‘01
Majumder - PRD ‘12
Sievert, Vitev, Yoon - PLB ‘19

- Harmonic oscillator (diffusion) approximation:

$$v(\boldsymbol{x},t) = C_A \int_{\boldsymbol{k}} \frac{d^2\sigma}{d^2\boldsymbol{k}}(1-e^{i\boldsymbol{k}\cdot\boldsymbol{x}}) \equiv \frac{1}{4}\hat{q}(\boldsymbol{x}^2,t)\boldsymbol{x}^2 = \frac{1}{4}\hat{q}_0\boldsymbol{x}^2 \log\left(\frac{1}{\mu^{\star 2}\boldsymbol{x}^2}\right)$$

neglect logarithmic dependence

$$\mu^{*2} \sim 1/\mathbf{x}^2$$

$$\omega \frac{\mathrm{d}I_{\mathrm{HO}}}{\mathrm{d}\omega} = 2\bar{\alpha}\ln|\cos(\Omega L)| \qquad \Omega(t) = \frac{1-i}{2}\sqrt{\frac{\hat{q}(t)}{\omega}}$$

BDMPS - ASW spectrum

Large medium, resums multiple soft interactions.

BDMPS-Z
Salgado, Wiedemann - PRD ‘03
Armesto, Salgado, Wiedemann - PRD ‘04

Improved Opacity Expansion (IOE)

- Perform "opacity" expansion on top of harmonic oscillator solution:

$$v(\boldsymbol{x},t) = \frac{1}{4}\boldsymbol{x}^2 \log\left(\frac{1}{\mu^{\star 2}\boldsymbol{x}^2}\right) = \frac{1}{4}\boldsymbol{x}^2\left(\log\left(\frac{Q^2}{\mu^{\star 2}}\right) + \log\left(\frac{1}{Q^2\boldsymbol{x}^2}\right)\right) \equiv v_{\rm HO}(\boldsymbol{x},t) + \delta v(\boldsymbol{x},t)$$

$$\mathcal{K}(\boldsymbol{x},t,\boldsymbol{y},s) = -\int_{\boldsymbol{z}}\int_s^t du\, \mathcal{K}_{\rm HO}(\boldsymbol{x},t|\boldsymbol{z},u)\delta v(\boldsymbol{z},u)\mathcal{K}(\boldsymbol{z},u|\boldsymbol{y},s)$$

Mehtar-Tani - JHEP '19
Mehtar-Tani, Tywoniuk - JHEP '19
Barata, Mehtar-Tani - JHEP '20

- Can systematically compute corrections up to arbitrary order in $\delta v(\boldsymbol{x},t)$:

$$\omega\frac{{\rm d}I}{{\rm d}\omega} = \omega\frac{{\rm d}I^{\rm HO=LO}}{{\rm d}\omega} + \omega\frac{{\rm d}I^{\rm NLO}}{{\rm d}\omega} + \cdots = \omega\frac{{\rm d}I^{\rm LO}}{{\rm d}\omega} + \sum_{m=1}^{\infty}\omega\frac{{\rm d}I^{{\rm N}^m{\rm LO}}}{{\rm d}\omega}$$

- Spectrum should be independent of Q^2 scale when all orders are included:

→ This leads to $Q^4 = \hat{q}_0\omega \,\ln Q^2/\mu_*^2$ (trans. mom. acquired by radiated gluon — natural scale)

Spectrum @ NLO in the soft limit in IOE:

$$\frac{{\rm d}I^{(0)}}{{\rm d}\omega} = \frac{2\alpha_s C_R}{\pi\omega}\ln|\cos\Omega L|\ ,$$

$$\frac{{\rm d}I^{(1)}}{{\rm d}\omega} = \frac{\alpha_s C_R \hat{q}_0}{2\pi}{\rm Re}\int_0^L {\rm d}s\,\frac{-1}{k^2(s)}\ln\frac{-k^2(s)}{Q^2\,{\rm e}^{-\gamma_E}}$$

$$\hat{q} = \hat{q}_0 \ln\frac{Q^2}{\mu_*^2}$$

$$\Omega = (1-i)\sqrt{\hat{q}/(4\omega)}$$

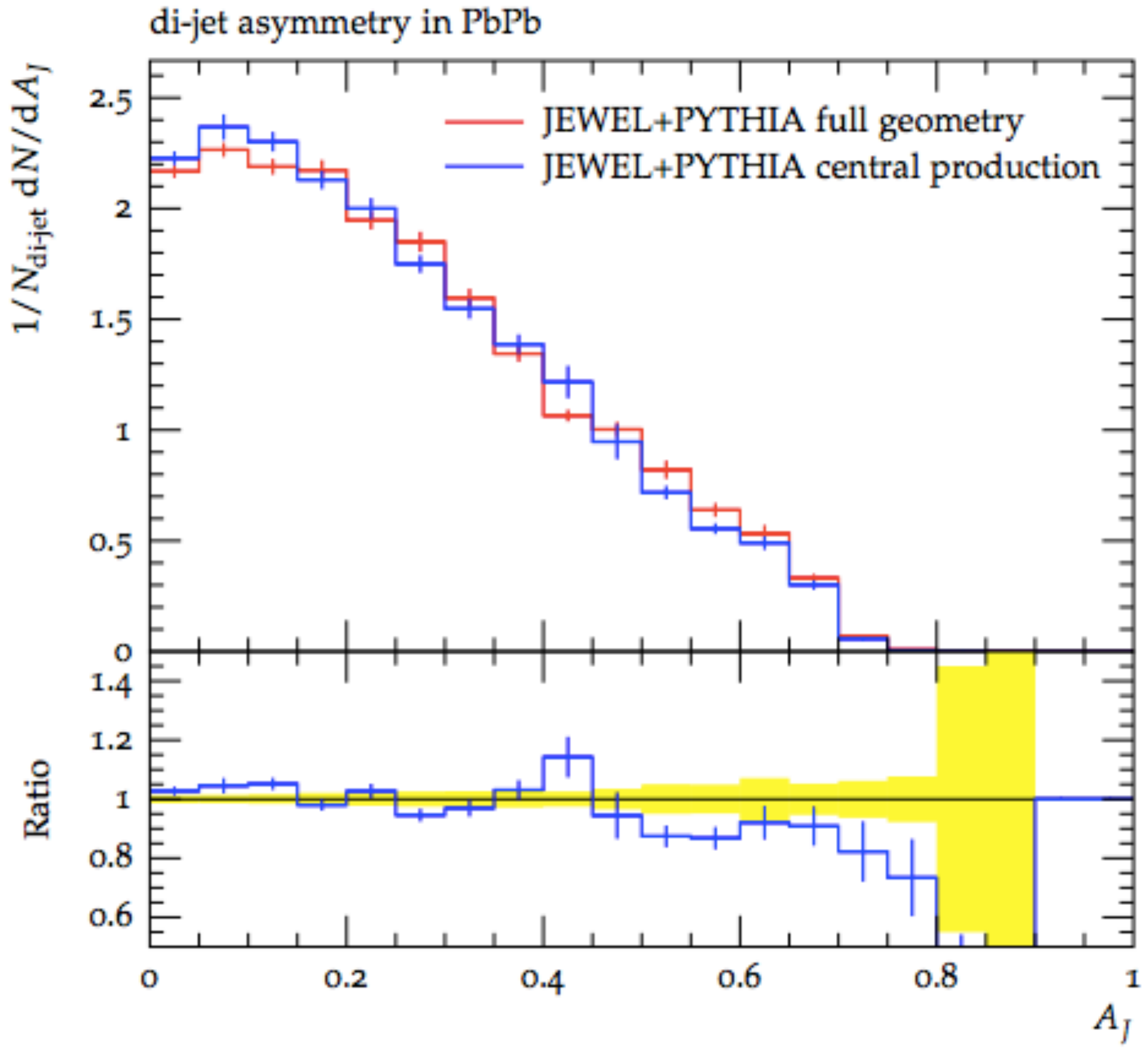
$$k^2(s) = i\frac{\omega\Omega}{2}[\cot\Omega s - \tan\Omega(L-s)]$$

Jet Substructure

- Monte Carlo jet quenching models have provided crucial insights:

→ Naturally include multi-particle nature of jets.

Essential in our current understanding of jet substructure in heavy-ion collisions:

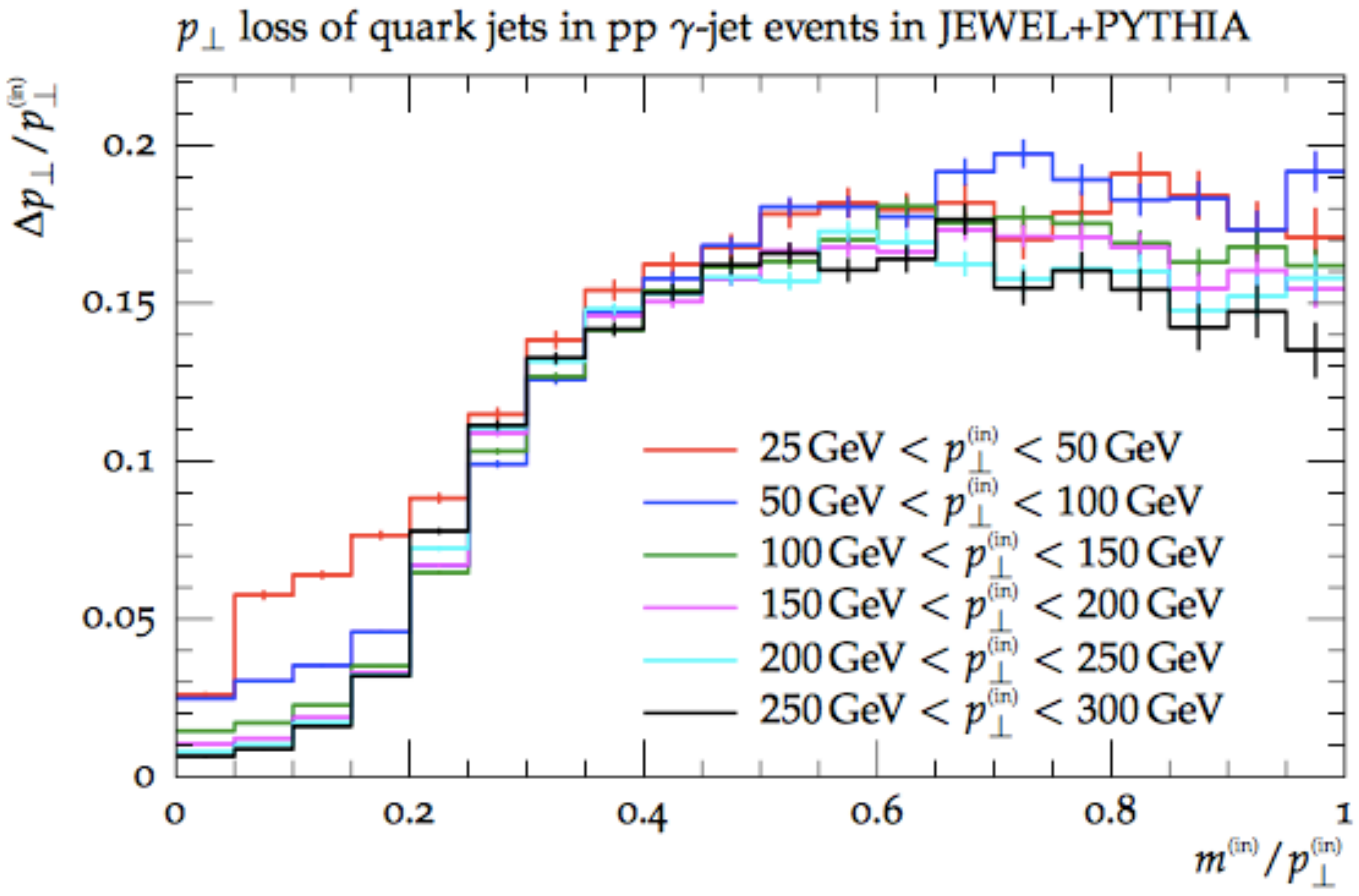


Full geometry

vs

Central production

JEWEL



Milhano & Zapp - EPJ ‘16

Dijet asymmetry dominated by mass to momentum ratio, proxy for # vacuum splittings.

Jet Substructure

- Monte Carlo jet quenching models have provided crucial insights:

  → Naturally include multi-particle nature of jets.

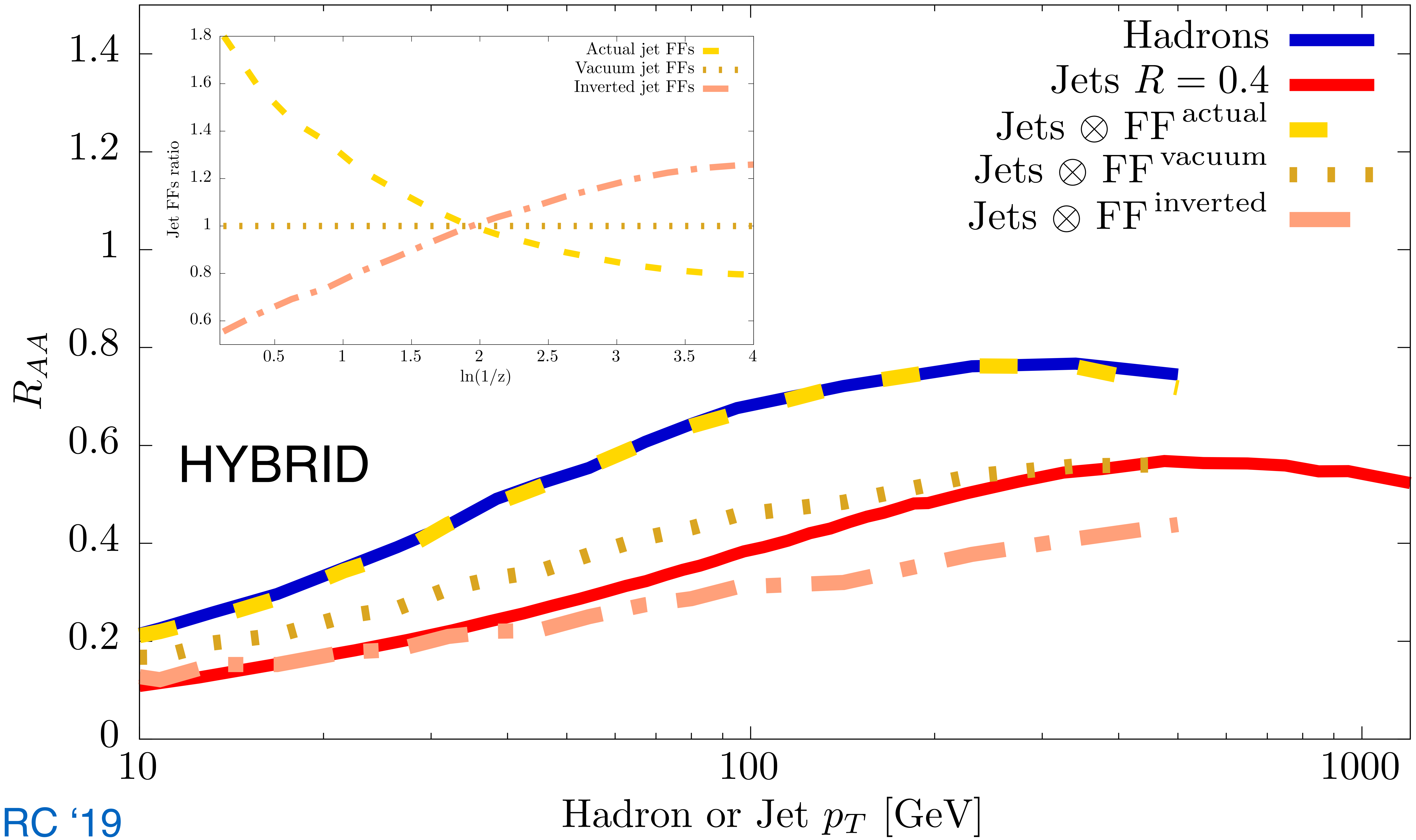
Essential in our current understanding of jet substructure in heavy-ion collisions:

Jet suppression

vs

Hadron suppression

Leading partons belong to narrower, less suppressed jets (high z enhancement).



Casalderrey, Hulcher, Milhano, DP, Rajagopal - PRC ‘19

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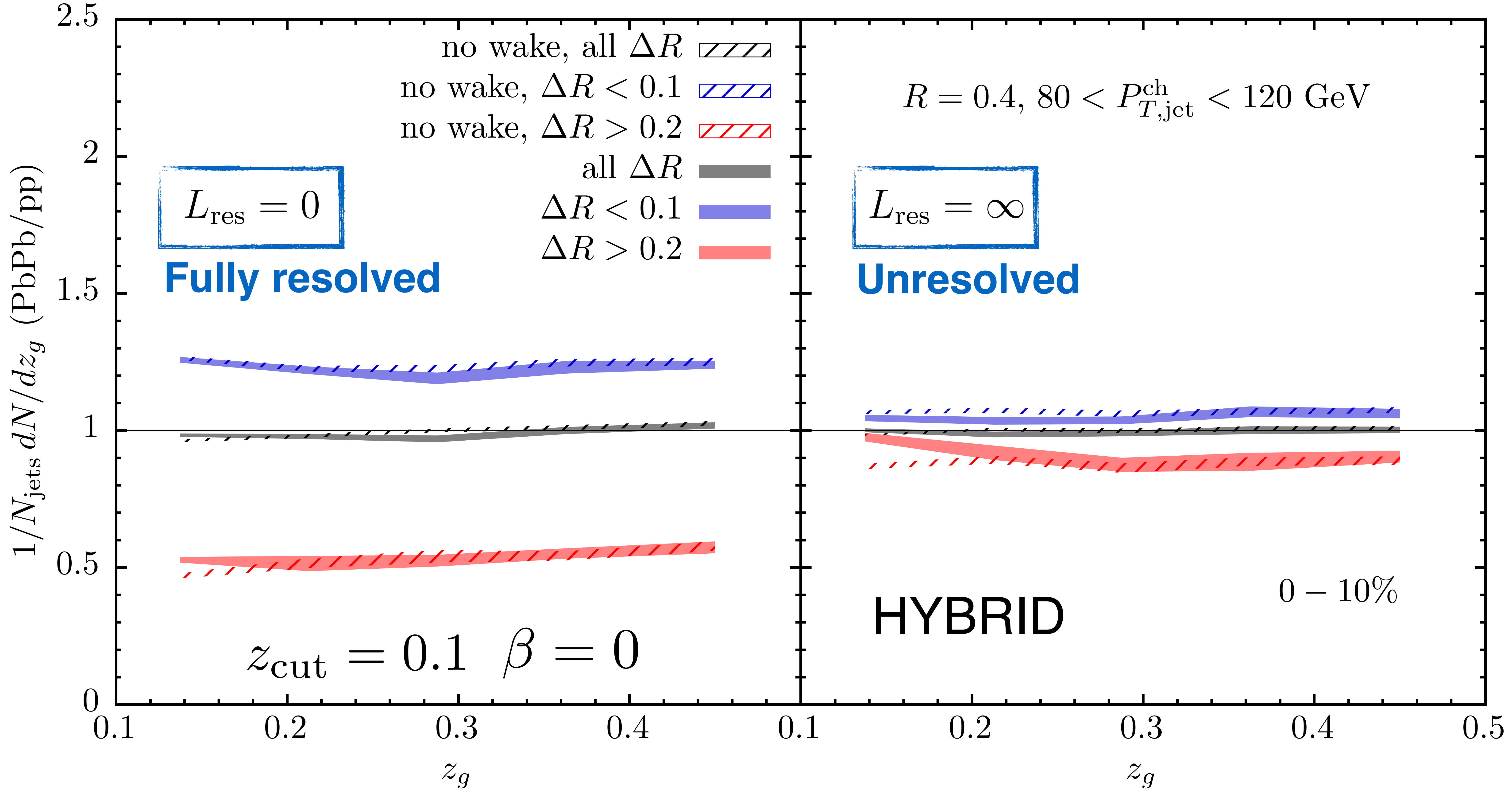


Strong ordering in ΔR (if parton shower resolved):

Larger ΔR;

↓

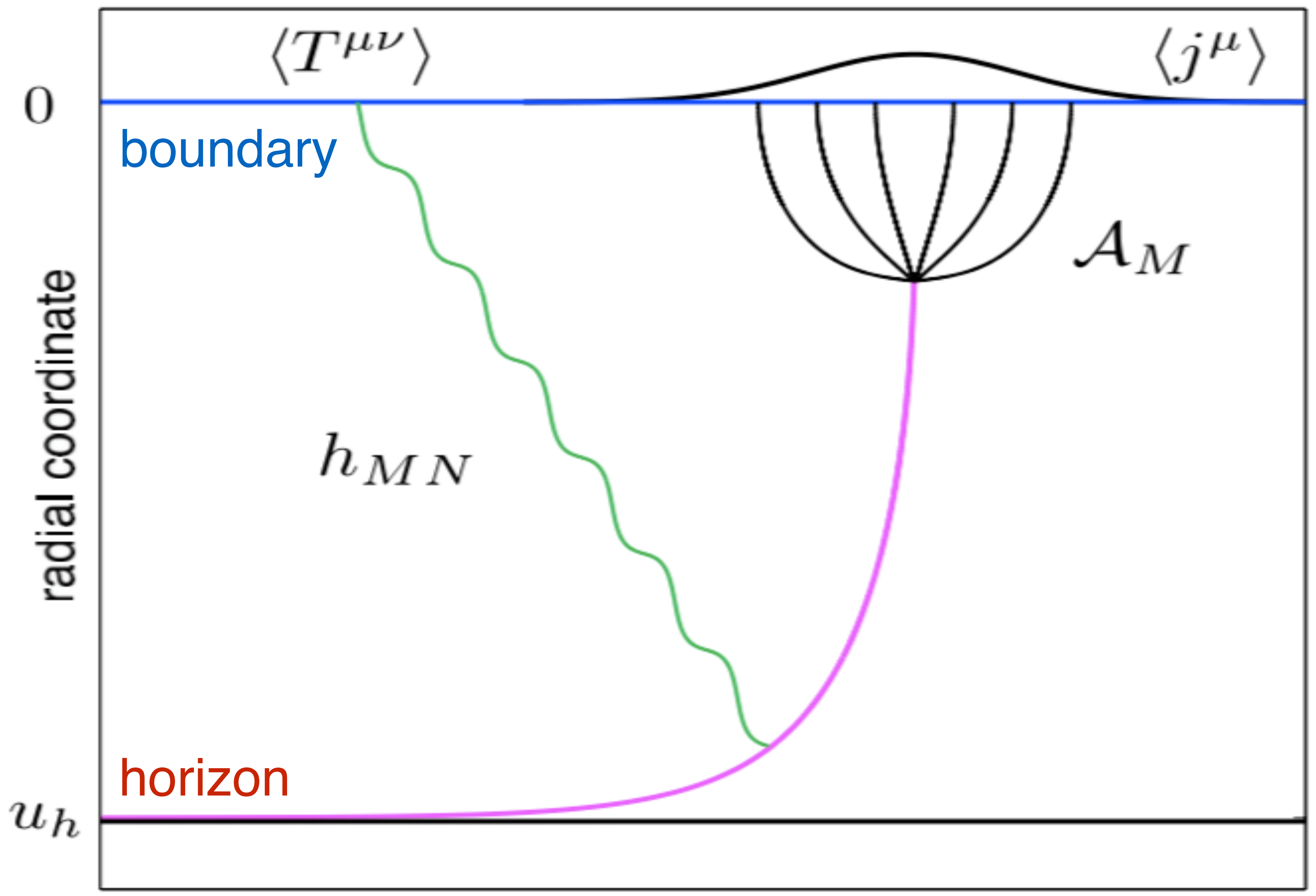
Larger phase-space for emissions;

↓

Larger quenching, smaller survival rate;

Casalderrey, Milhano, DP, Rajagopal - JHEP ‘20

Proxies for jets as falling strings



Chesler et al. - PRD '09

- dressed quarks are open strings attached to a D7 flavour brane
- charged under U(1) gauge field sourcing baryon current at boundary
- depth of string endpoint determines localisation of excitation at boundary

presence of string perturbs metric

$$G_{MN} = G^{(0)}_{MN} + \frac{L^2}{u^2} H_{MN}$$

satisfies linearised Einstein's equations

$$\mathcal{L}^{MN}_{AB} H_{MN} = 8\pi G_{\text{Newton}} \boxed{J_{AB}}$$

string sourced

near boundary expression of energy-momentum tensor

$$\langle \Delta T^{\mu\nu}(t,\boldsymbol{x})\rangle = \frac{L^3}{4\pi G_{\text{Newton}}} H^{(4)}_{\mu\nu}(t,\boldsymbol{x})$$

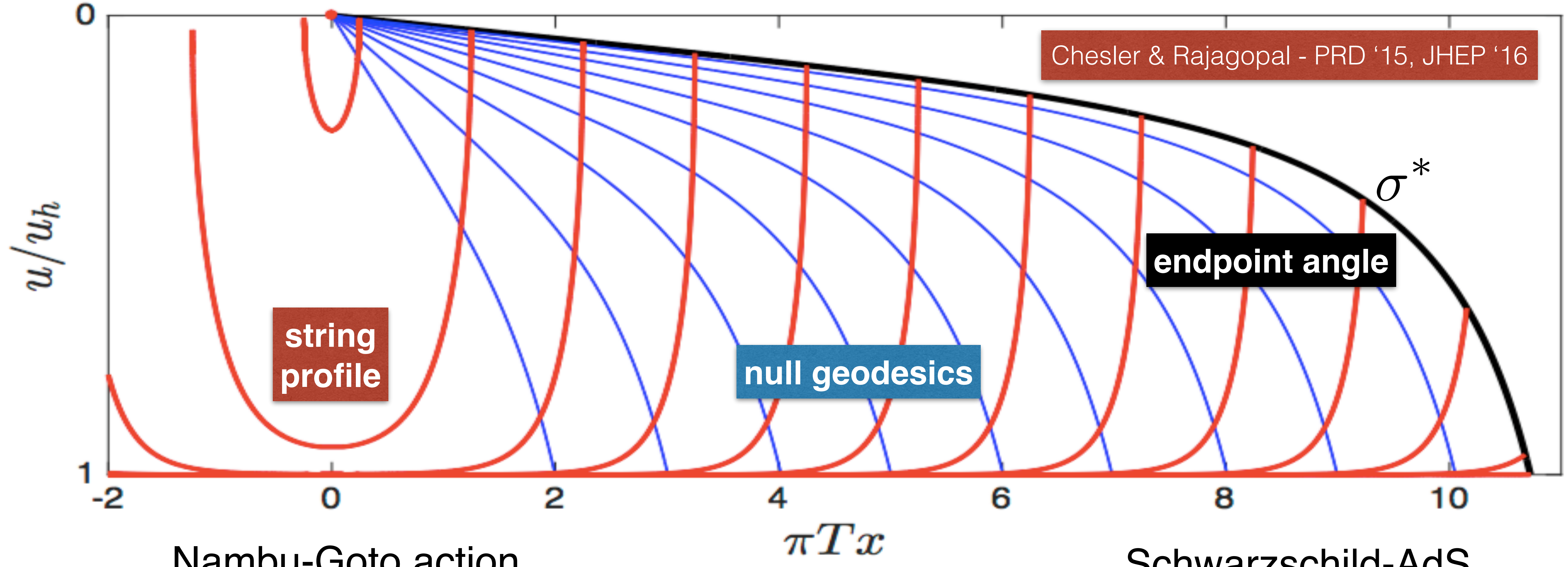
Chesler & Rajagopal, JHEP '16

hydro (long wavelength)

non-hydro (jet modes)

$$\langle \Delta T^{\mu\nu}\rangle \equiv \langle T^{\mu\nu}\rangle - \langle T^{\mu\nu}_{\text{eq}}\rangle$$

Null falling string approximation



<u>Nambu-Goto action</u>

$$S = -\frac{\sqrt{\lambda}}{2\pi L^2}\int d\tau d\sigma \sqrt{-g}$$

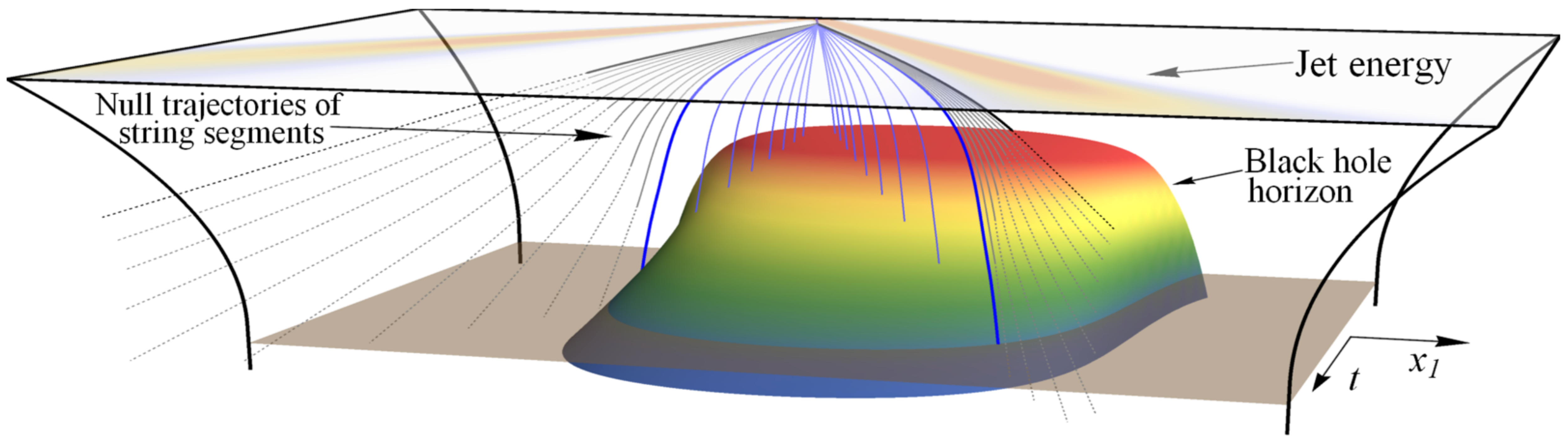
<u>Schwarzschild-AdS</u>

$$ds^2 = \frac{L^2}{u^2}\left[-f dt^2 + d\boldsymbol{x}^2 + \frac{du^2}{f}\right] \qquad f \equiv 1 - \frac{u^4}{u_h^4}$$

1. Solve E.O.M. by finding null geodesic profile: $x_{\rm geo}(t),\ u_{\rm geo}(t)$
2. Find energy carried by each geodesic: $\Pi_0^\tau(\sigma)$ (peaks at the endpoint)
3. Construct the string energy-momentum tensor:

$$J^{MN} = \int d\sigma J^{MN}_{\rm particle}(\sigma) \qquad J^{MN}_{\rm particle} = \frac{\Pi_0^\tau}{G_{00}}\frac{dX^M_{\rm geo}}{dt}\frac{dX^N_{\rm geo}}{dt}\frac{1}{\sqrt{-G}}\delta^3(\boldsymbol{x}-\boldsymbol{x}_{\rm geo})\delta(u-u_{\rm geo})$$

Holographic quenching with pure strings

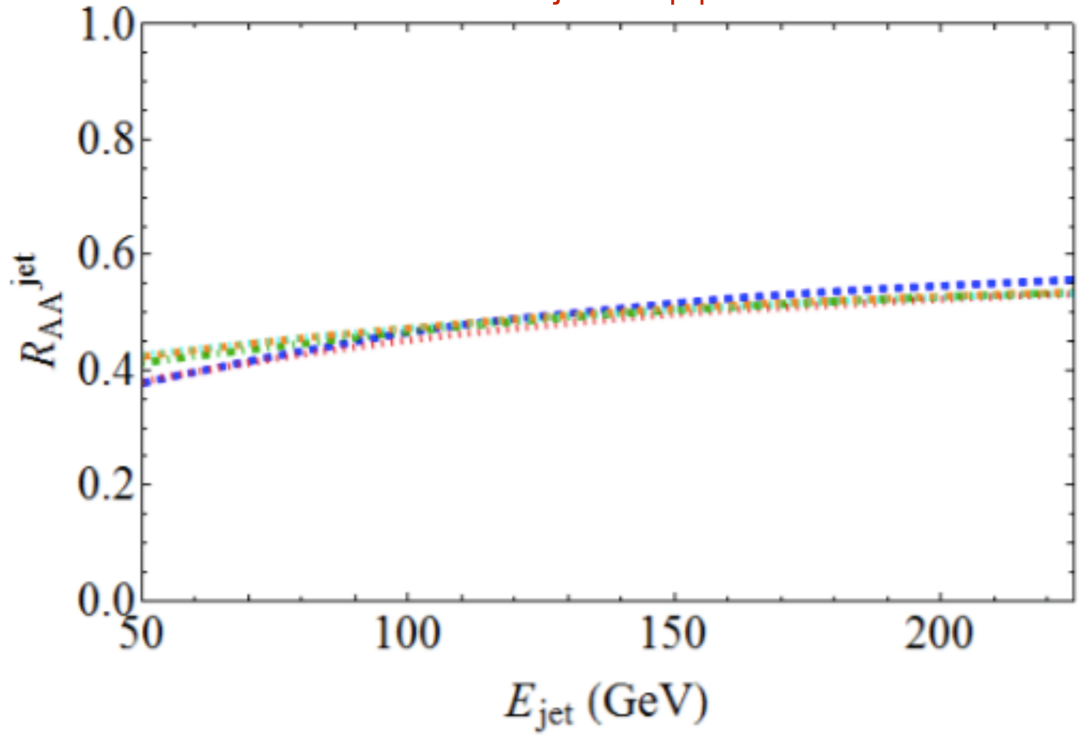


the *string* is treated as a model for the *jet as a whole*

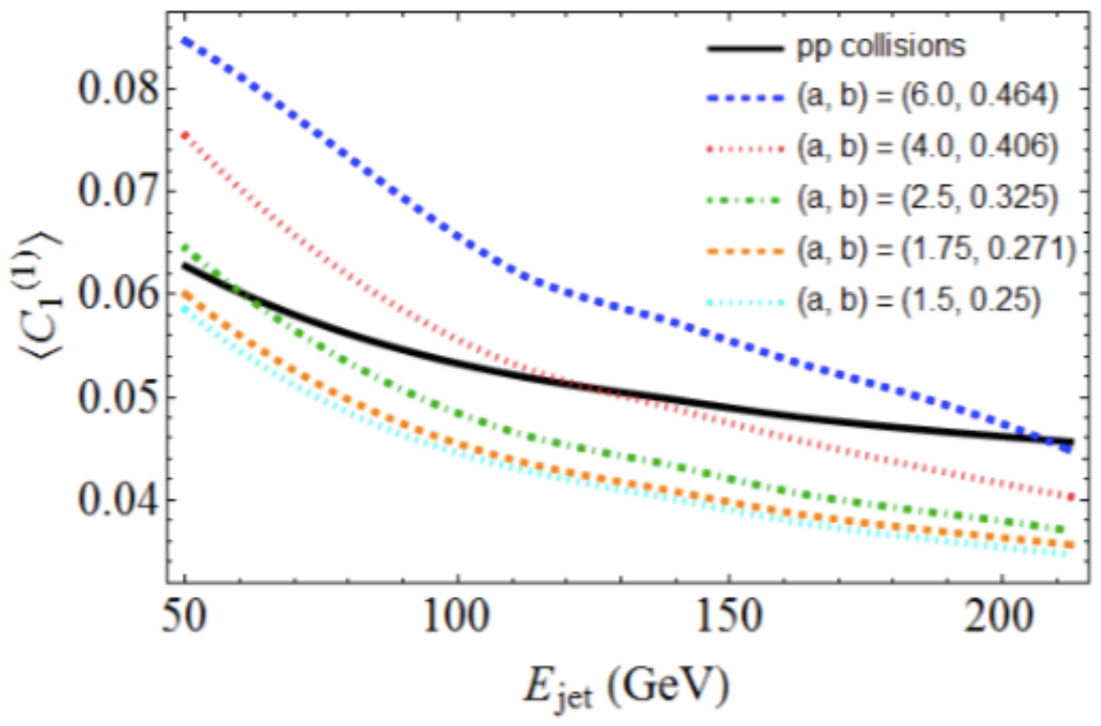
Rajagopal, Sadofyev, van der Schee '16

- consider an *ensemble* of such jets by choosing initial distributions of energy & angle from pQCD
- competing effects: each individual jet widens, while wider jets lose more energy

for the same jet suppression



different final angle dist.



$$C_1^{(\alpha)} \equiv \sum_{i,j} z_i z_j \left(\frac{|\theta_{ij}|}{R}\right)^\alpha$$

measures jet angle in pQCD

$$C_1^{(1)} = a\,\sigma_0$$
$$T_{\rm SYM} = b\,T_{\rm QCD}$$

also observed in pQCD

Milhano & Zapp '15

Diagnosing Jet Energy Loss

- Experimentally, so far is impossible to know how much energy a given jet has lost.
- Moreover, due to steep falling jet spectrum, what we observe is jets that lost the least energy. → Selection (or survival) bias.

→ Hinders our ability to analyse true effects of energy loss. E.g.:

- Measure jets above $p_T > 100$ GeV.
- Observe that they are narrower in PbPb than in pp:
  - ★ Energy loss makes jets narrower?
  - ★ Observe the surviving (less quenched) jets, which are narrow?

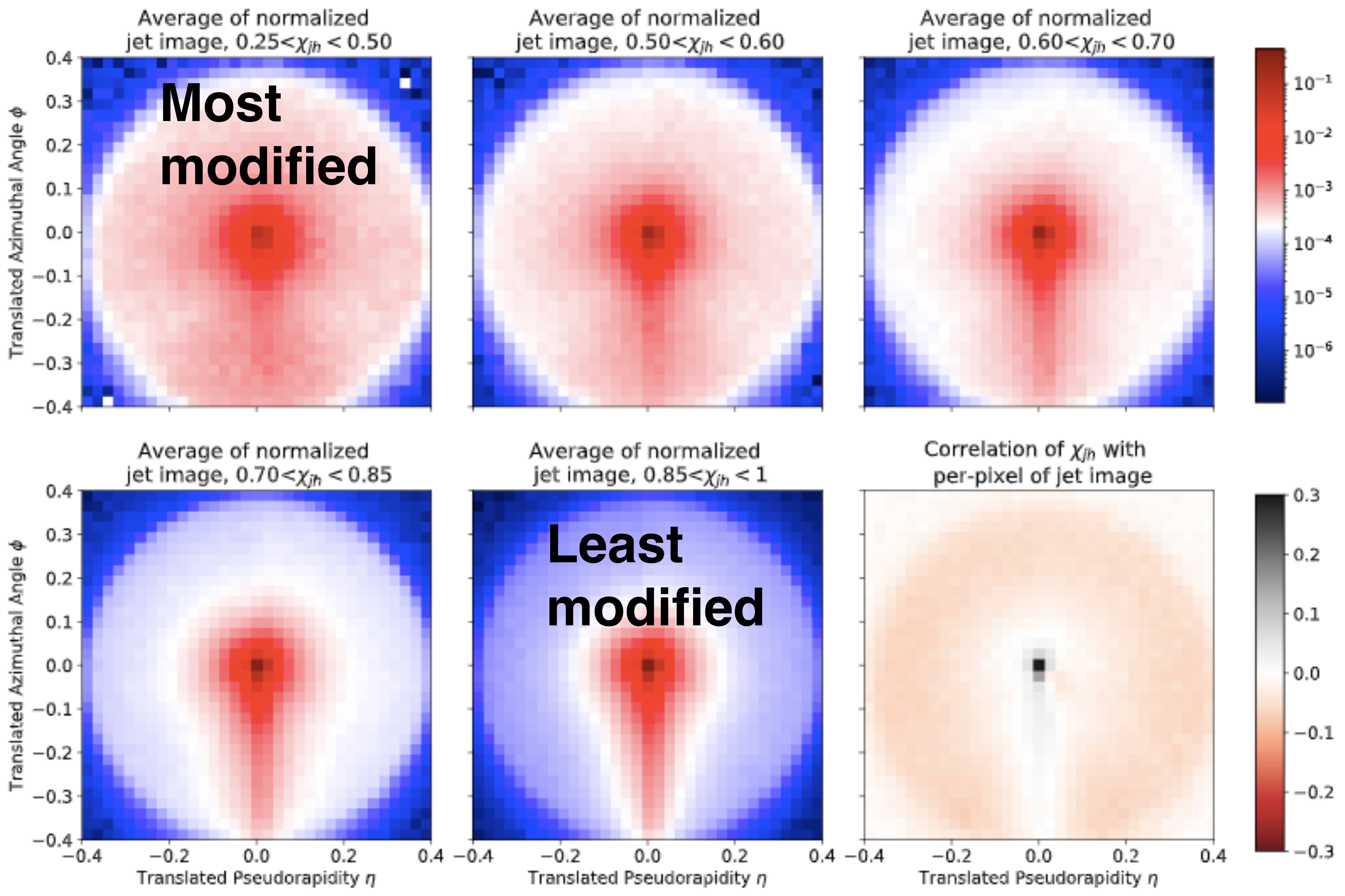
- Exploit deep learning techniques to extract energy loss jet-by-jet.

Energy loss ratio: $$\chi \equiv \frac{E_f}{E_i}$$

Final, measurable jet energy.

Vacuum energy (had there been no medium).

Deep Learning Jet Modifications

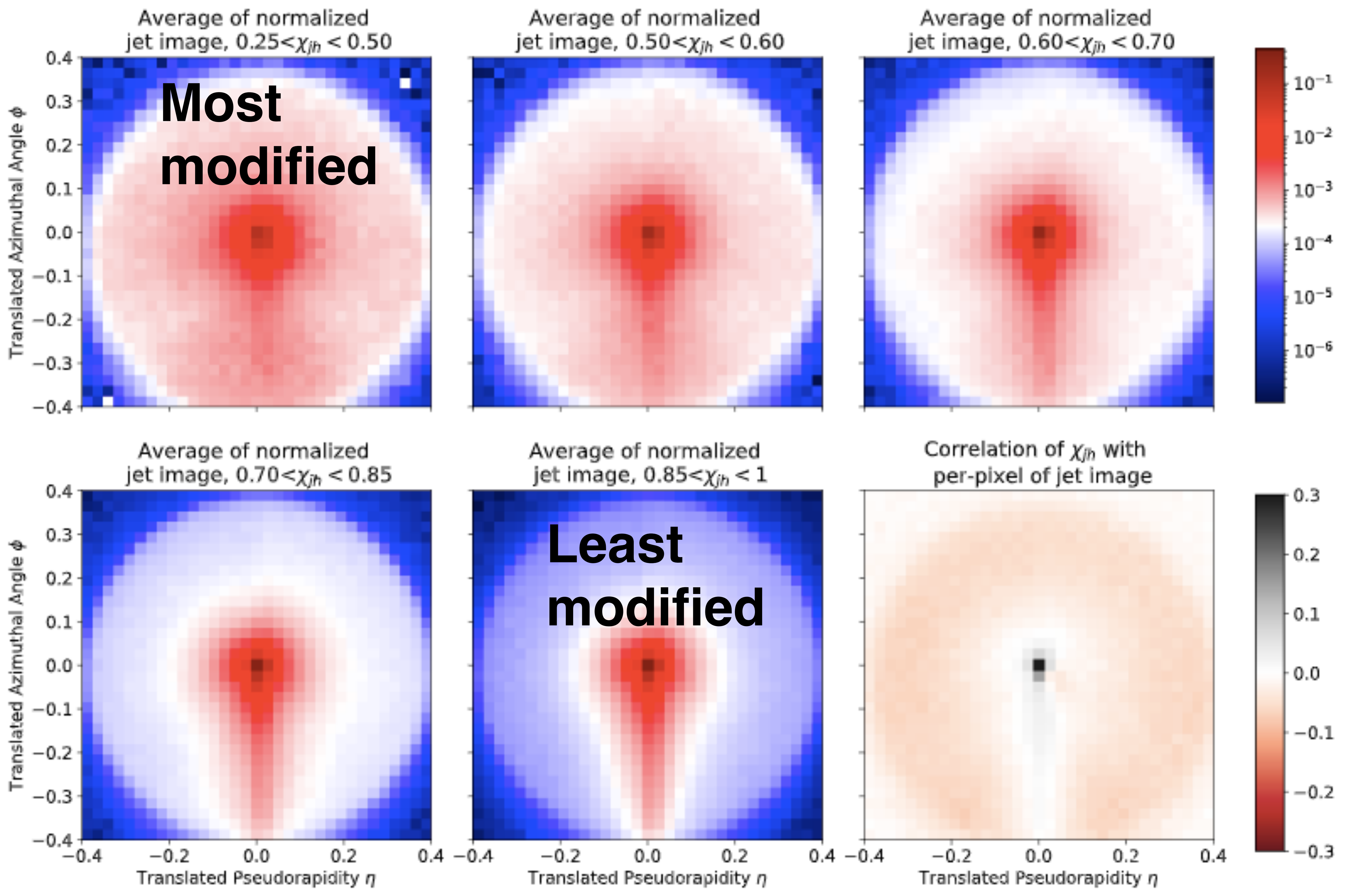


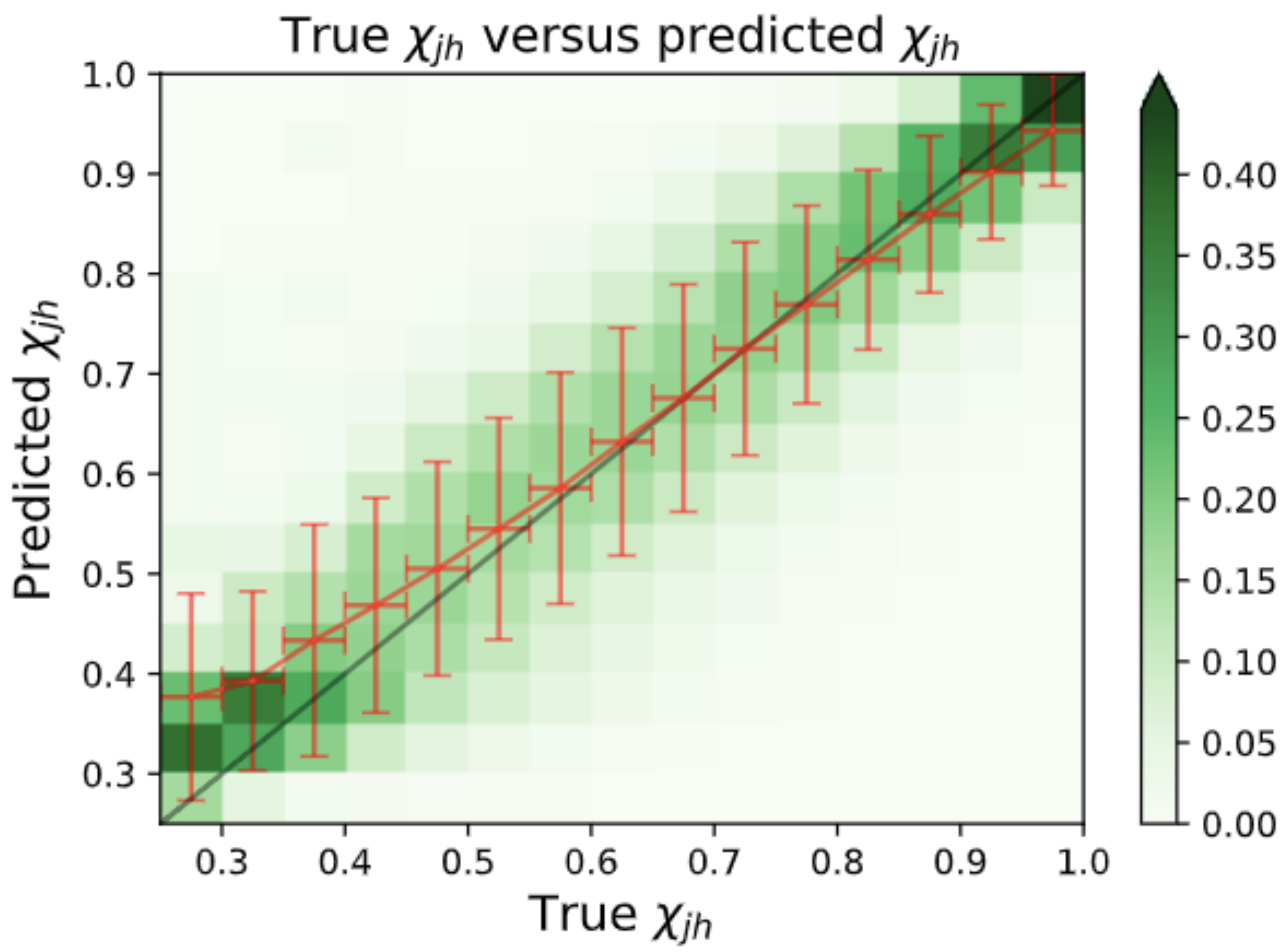
- Most models: Energy loss transfers jet energy to large angles in the form of soft particles.

- Use jet images as inputs for CNN. Main result.
- Use jet observables as inputs for FCNN. Mainly used for interpretability.

Du, DP, Tywoniuk - JHEP '21

Deep Learning Jet Modifications





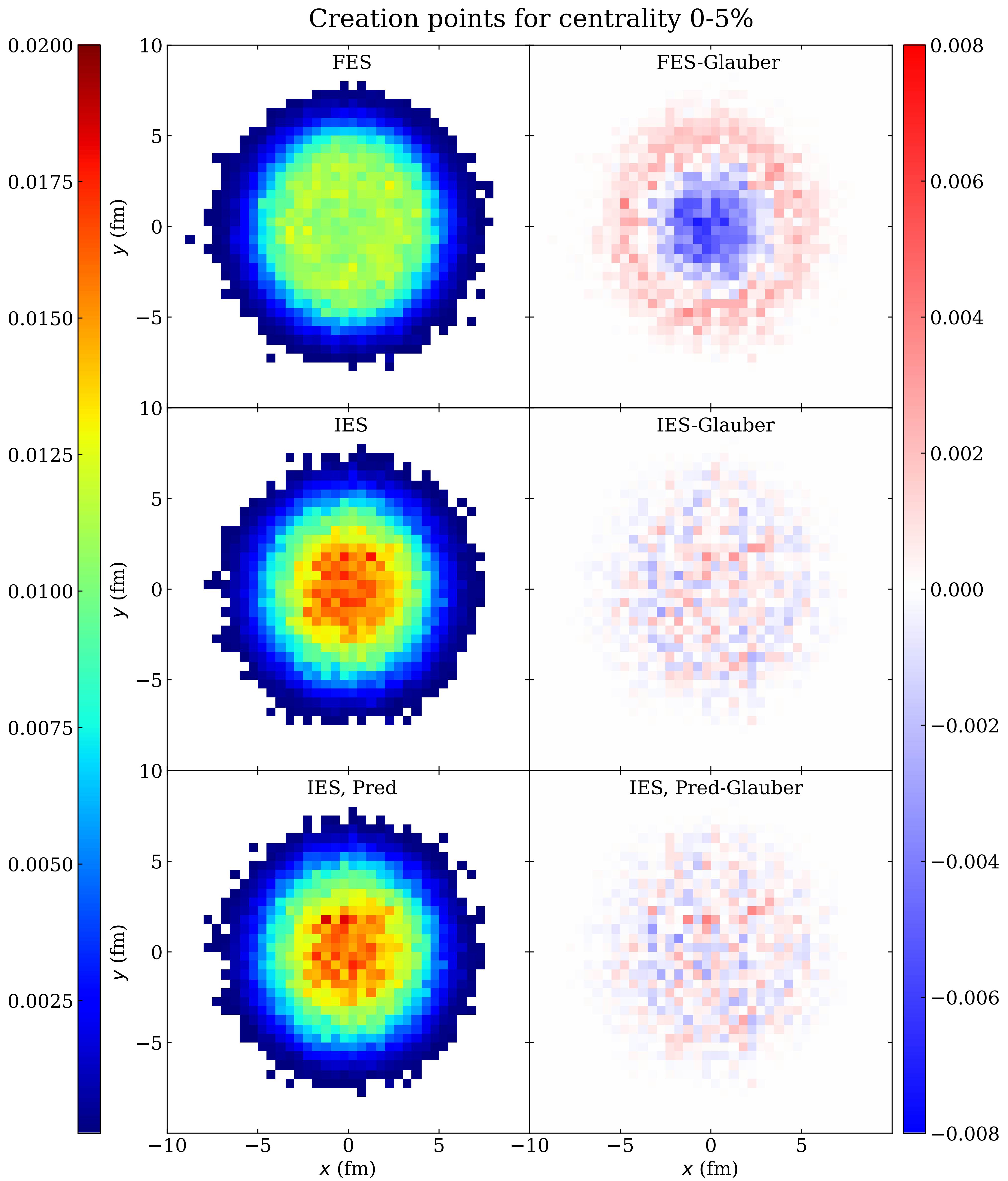
- Use jet images as inputs for CNN. Main result.
- Use jet observables as inputs for FCNN. Mainly used for interpretability.

Du, DP, Tywoniuk - JHEP '21

Good performance across a wide range in χ

- Consistency check: pp (vacuum) jets get $\chi \simeq 1$

Accessing True Path Length Distributions



True label

Predicted label

- FES: Select jets according to final energy.

$$E_f > E_{\text{cut}}$$

→ Surface bias compared to actual nuclear overlap density.

- IES: Select jets according to “initial” energy.

$$E_f/\chi > E_{\text{cut}}$$

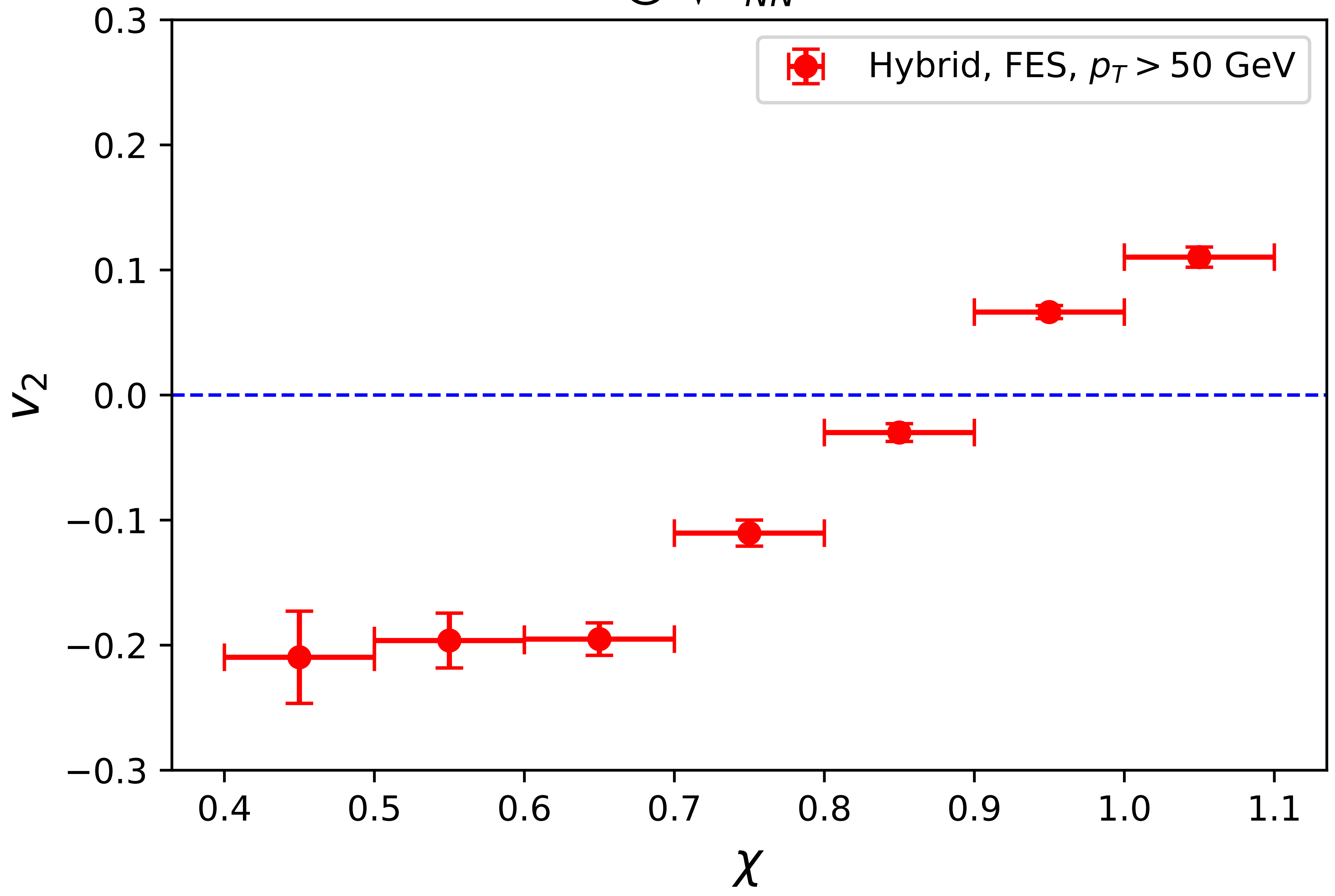
→ Production point density unbiased w.r.t. true underlying distribution.

Du, DP, Tywoniuk - in preparation

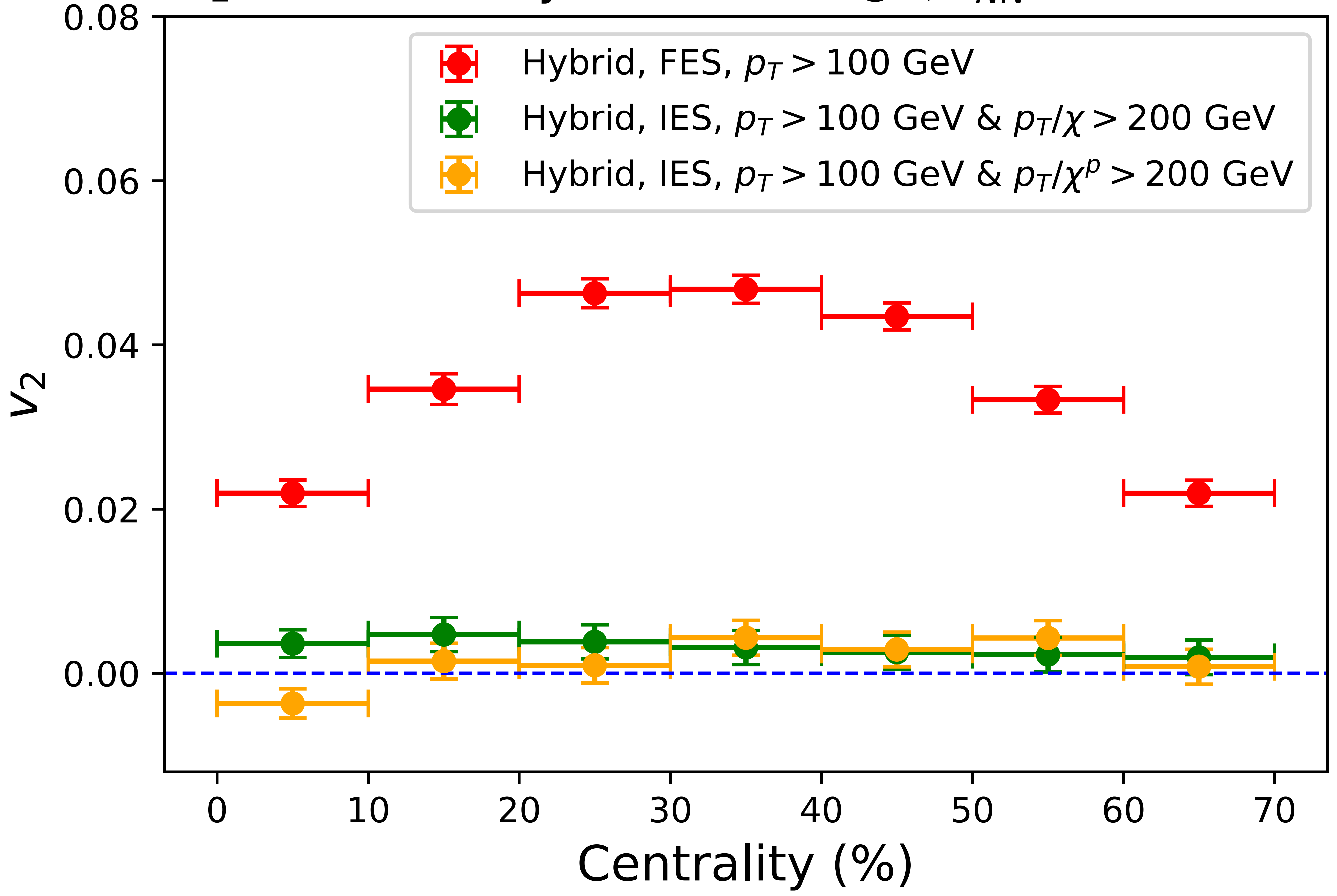
Accessing Initial Jet Anisotropies

Du, DP, Tywoniuk - in preparation

v_2 VS χ for centrality 30-40%, $R = 0.2$ @ $\sqrt{s_{NN}} = 2.76$ TeV



v_2 VS Centrality for $R = 0.4$ @ $\sqrt{s_{NN}} = 5.02$ TeV



- Intuitive origin of high-p_T jet anisotropies:

  Small χ (large energy loss):

  ➜ longer path length;

  ➜ $v_2 < 0$.

  and viceversa for large χ.

- However, if use IES:

  Reveals initial azimuthal anisotropies.

  In this model: none ➜ $v_2 \sim 0$.

  And in experiments?

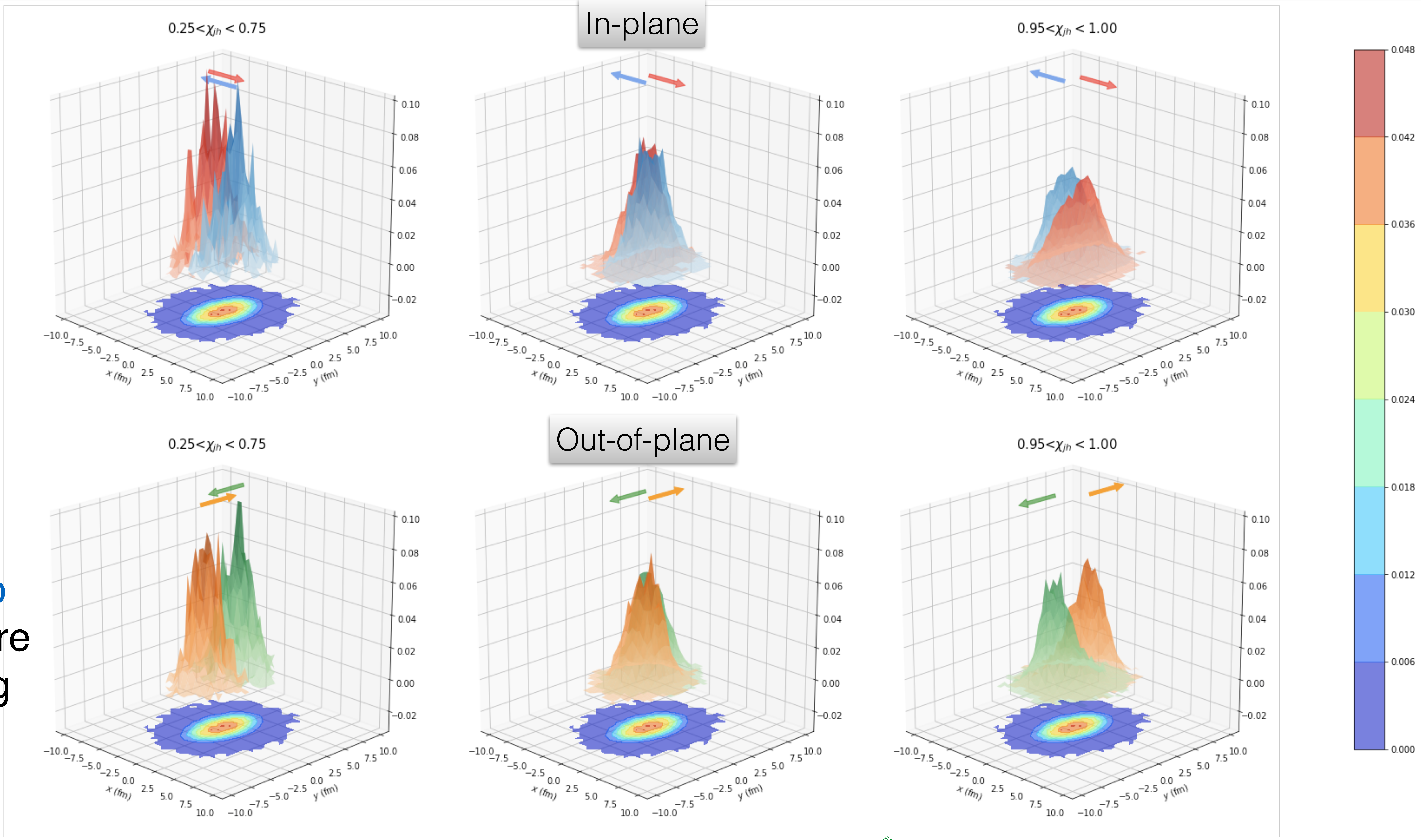
Tomography with Deep Learning

Determination of production point in transverse plane.

Differential in:

- Orientation w.r.t. event plane.
- Energy loss ratio χ .

Production points swap in order to traverse more medium with increasing energy loss.



Du, DP, Tywoniuk - in preparation

more quenched ⟵ χ ⟶ less quenched

Collectivity from interference

Motivation

Absence of jet quenching phenomena
(energy loss of high pt particles by traversing a medium)

in small systems (pA, pp)

calls to question the presence of deconfined medium (or hydro behaviour).

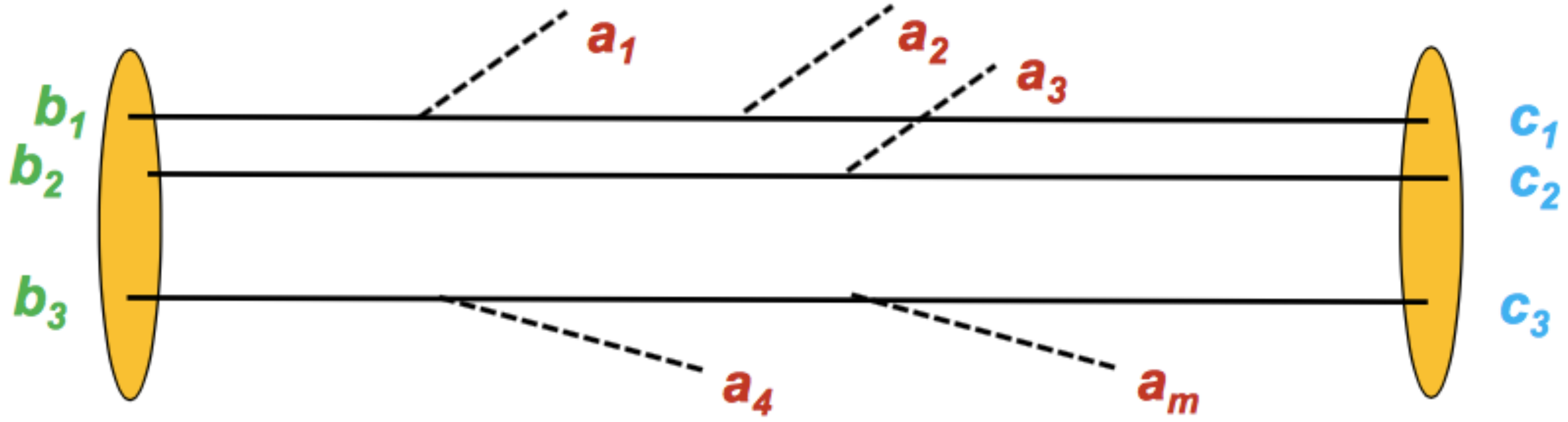
Are jet quenching effects too small to be observed (yet)?

Origin of **collectivity in small systems** is not final state interactions?
Can it be **quantum interference**?

B. Blok's talk at QM

A simple model

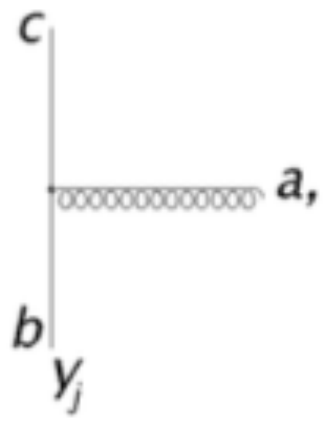
- *Schematic picture: pp collision = multiple parton-parton interactions at positions y_i.*



Source lines start (end) with colors b_i (c_j) at rapidity of 1st (2nd) hadron.

- *Diagrammatic rules: gluon emission keeps track of color and phases exactly.*

(basis for understanding QCD interference effects)



$$= T^a_{b_i c_i} \int d\mathbf{x}\, \vec{f}(\mathbf{x}-\mathbf{y})\, e^{i\,\mathbf{k}.\mathbf{x}} \equiv T^a_{b_i c_i} \vec{f}(\mathbf{k}) \exp\left[i\,\mathbf{y}.\mathbf{k}\right]$$

$$\rho(\mathbf{y}_1, \mathbf{y}_2) = \frac{1}{(2\pi B)^2} \exp\left[-\frac{\mathbf{y}_1^2}{2B} - \frac{\mathbf{y}_2^2}{2B}\right]$$

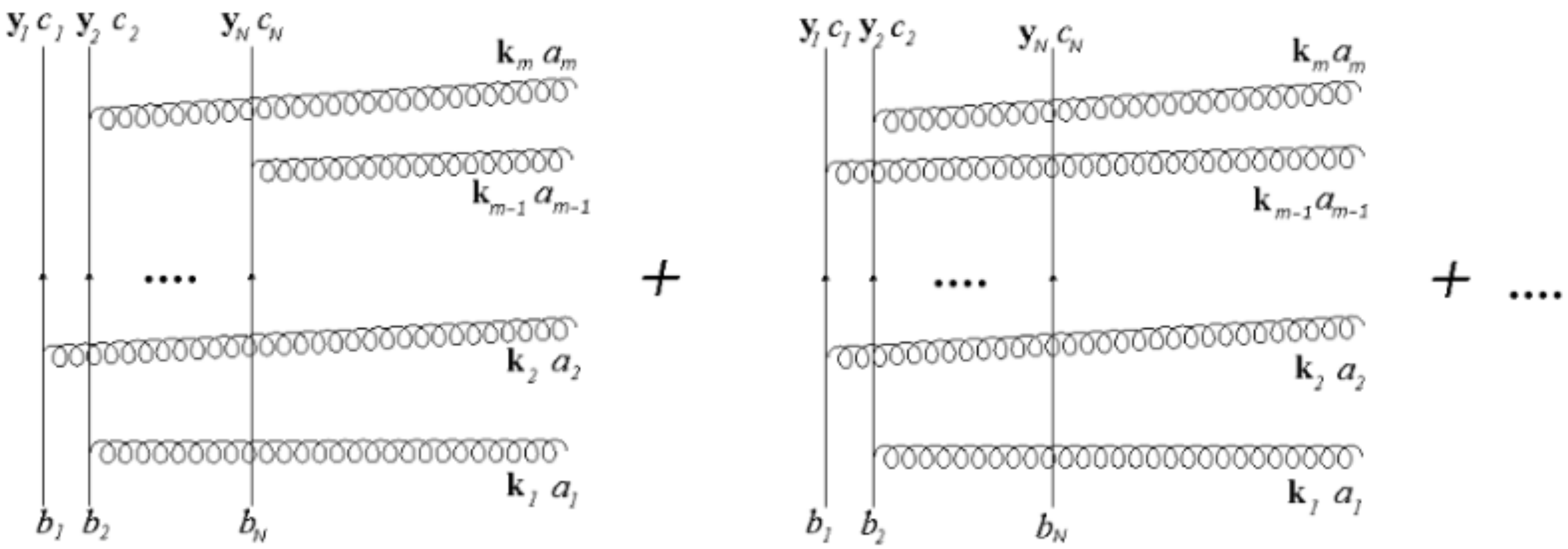
Simplifications:

- Don't specify the kinematics, flat rapidity dependence
- Assign a classical, gaussian weight to the distribution of sources in hadron (GPDs in mean field approximation). B scale from pp soft processes

B can be related to Qs, but note azimuthal isotropy!

m gluons from N sources

- *This model has N^m different m-particle emission amplitudes:*



- *Summing up and squaring these emission amplitudes returns a **gluon spectrum for a fixed set of transverse positions y_i.** Averaging over transverse positions with a **classical weight**, one finds the spectrum*

$$\frac{d\Sigma}{d\mathbf{k}_1 \ldots d\mathbf{k}_m} = \int \left(\prod_{i=1}^{N} d\mathbf{y}_i \right) \rho(\{y_i\}) \, \hat{\sigma}\left(\{\mathbf{k}_j\}, \{y_i\}\right)$$

We want to calculate this spectrum and its azimuthal anisotropies $v_n\{2k\}$ for arbitrary m and N.

B. Blok's talk at QM

Simplest case: emitting m=2 gluons from N=2 sources

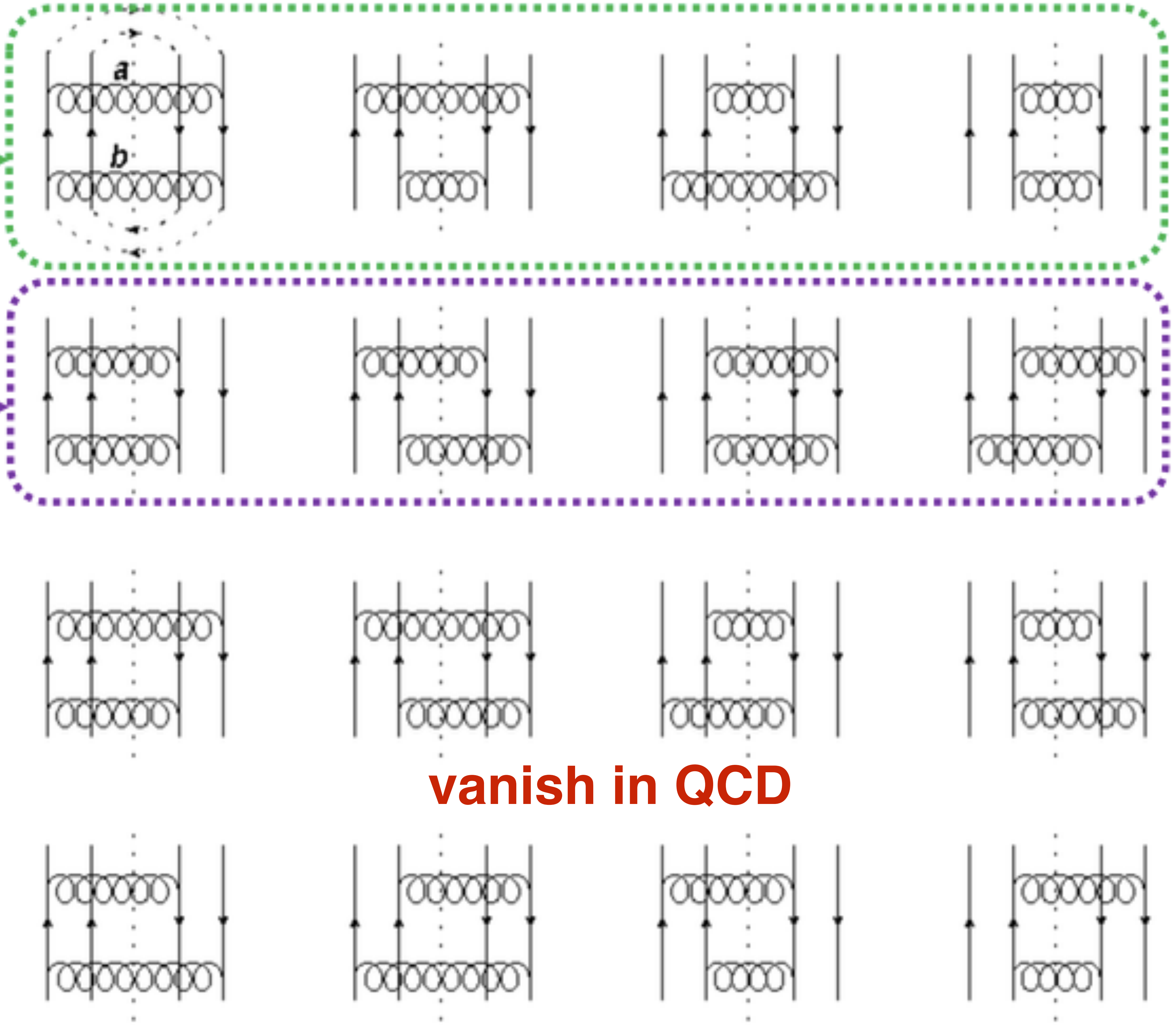
- *Color can be read easily from diagrams*

$$\mathrm{Tr}\left[T^aT^bT^bT^a\right]\,\mathrm{Tr}\left[\mathbb{1}\right] = N_c^2\,\left(N_c^2-1\right)^2$$

diagonal -> no interference

$$\mathrm{Tr}\left[T^aT^b\right]\,\mathrm{Tr}\left[T^bT^a\right] = N_c^2\,\left(N_c^2-1\right)$$

off-diagonal -> interference



correlation in azimuth arises from two gluons emitted from **same source pair**

$$\frac{d\Sigma}{d\mathbf{k}_1 d\mathbf{k}_2} \propto \left|\vec{f}(\mathbf{k}_1)\right|^2\,\left|\vec{f}(\mathbf{k}_2)\right|^2\left[1+\frac{\left(e^{-B(\mathbf{k}_1+\mathbf{k}_2)^2}+e^{-B(\mathbf{k}_1-\mathbf{k}_2)^2}\right)}{(N_c^2-1)}\right]$$

- *For $B = 1/Q_s^2$, this QCD agrees with CGC calculations,*

Altinoluk et al, PLB 751 (2015) 448; PLB 752 (2016) 113
Lappi, Schenke, Schlichting, Venugopalan JHEP 1601 (2016) 061

but it does not invoke saturation effects.

B. Blok's talk at QM

Odd harmonics

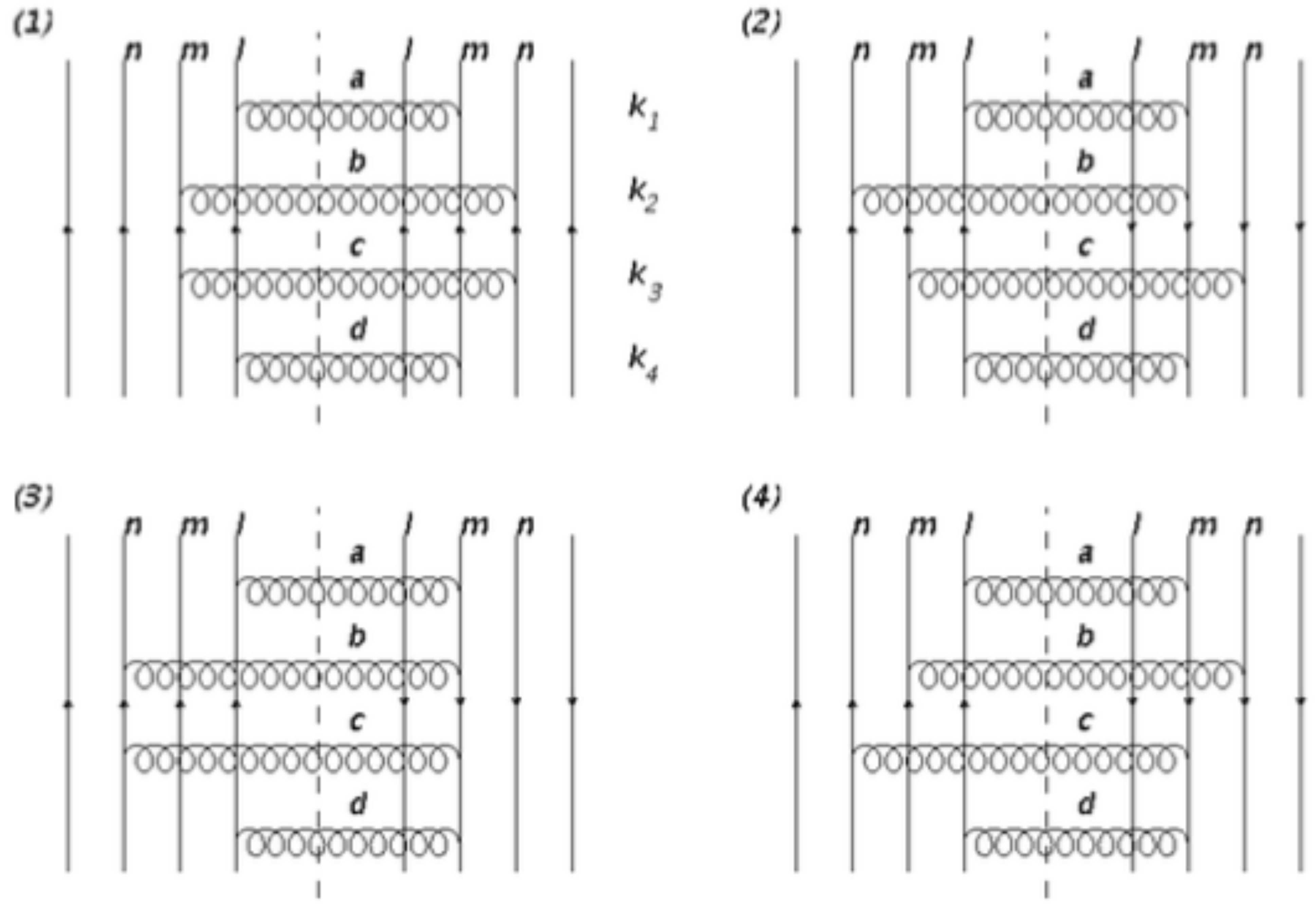
$$N = m = 4$$

$$\mathrm{Tr}\,[\mathbb{1}]\ \mathrm{Tr}\left[T^c T^b\right]\ \mathrm{Tr}\left[T^b T^c T^d T^a\right]\ \mathrm{Tr}\left[T^a T^d\right] = N_c^4\,(N_c^2-1)^2$$

$$\mathrm{Tr}\,[\mathbb{1}]\ \mathrm{Tr}\left[T^b T^c\right]\ \mathrm{Tr}\left[T^c T^d T^b T^a\right]\ \mathrm{Tr}\left[T^a T^d\right] = \frac{1}{2}N_c^4\,(N_c^2-1)^2$$

$$\mathrm{Tr}\,[\mathbb{1}]\ \mathrm{Tr}\left[T^b T^c\right]\ \mathrm{Tr}\left[T^d T^c T^b T^a\right]\ \mathrm{Tr}\left[T^a T^d\right] = N_c^4\,(N_c^2-1)^2$$

$$\mathrm{Tr}\,[\mathbb{1}]\ \mathrm{Tr}\left[T^c T^b\right]\ \mathrm{Tr}\left[T^b T^d T^c T^a\right]\ \mathrm{Tr}\left[T^a T^d\right] = \frac{1}{2}N_c^4\,(N_c^2-1)^2$$



To order 1/N, differences in color factors break the k to –k symmetry

$$e^{i\,\mathrm{k}_2.\Delta\mathrm{y}_{mn}}\left(e^{i\,\mathrm{k}_3.\Delta\mathrm{y}_{mn}}+\frac{1}{2}e^{-i\,\mathrm{k}_3.\Delta\mathrm{y}_{mn}}\right)+e^{-i\,\mathrm{k}_2.\Delta\mathrm{y}_{mn}}\left(\frac{1}{2}e^{i\,\mathrm{k}_3.\Delta\mathrm{y}_{mn}}+e^{-i\,\mathrm{k}_3.\Delta\mathrm{y}_{mn}}\right)$$
$$=3\cos\left(\mathrm{k}_2.\Delta\mathrm{y}_{mn}\right)\,\cos\left(\mathrm{k}_3.\Delta\mathrm{y}_{mn}\right)-\sin\left(\mathrm{k}_2.\Delta\mathrm{y}_{mn}\right)\,\sin\left(\mathrm{k}_3.\Delta\mathrm{y}_{mn}\right)\,. \qquad (5.$$

Odd harmonics arise due to non-abelian nature of QCD

B. Blok's talk at QM

Results for flow coefficients

- *Once spectrum is known, azimuthal phase space averages can be formed*

$$T_n(k_1,k_2) = \binom{m}{2}\int_\rho\int_0^{2\pi} d\phi_1\, d\phi_2 \exp\left[in(\phi_1-\phi_2)\right]\left(\int\prod_{b=3}^{m} k_b\, dk_b\, d\phi_b\right)\hat{\sigma}$$

- *Suitably normalized, these define v_n's (2nd order cumulants)*

$$\overline{T}(k_1,k_2) = \binom{m}{2}\int_\rho\int_0^{2\pi} d\phi_1\, d\phi_2 \left(\int\prod_{b=3}^{m} k_b\, dk_b\, d\phi_b\right)\hat{\sigma}$$

$$v_n^2\{2\}(k_1,k_2) \equiv \langle\langle e^{in(\phi_1-\phi_2)}\rangle\rangle(k_1,k_2) \equiv \frac{T_n(k_1,k_2)}{\overline{T}(k_1,k_2)}$$

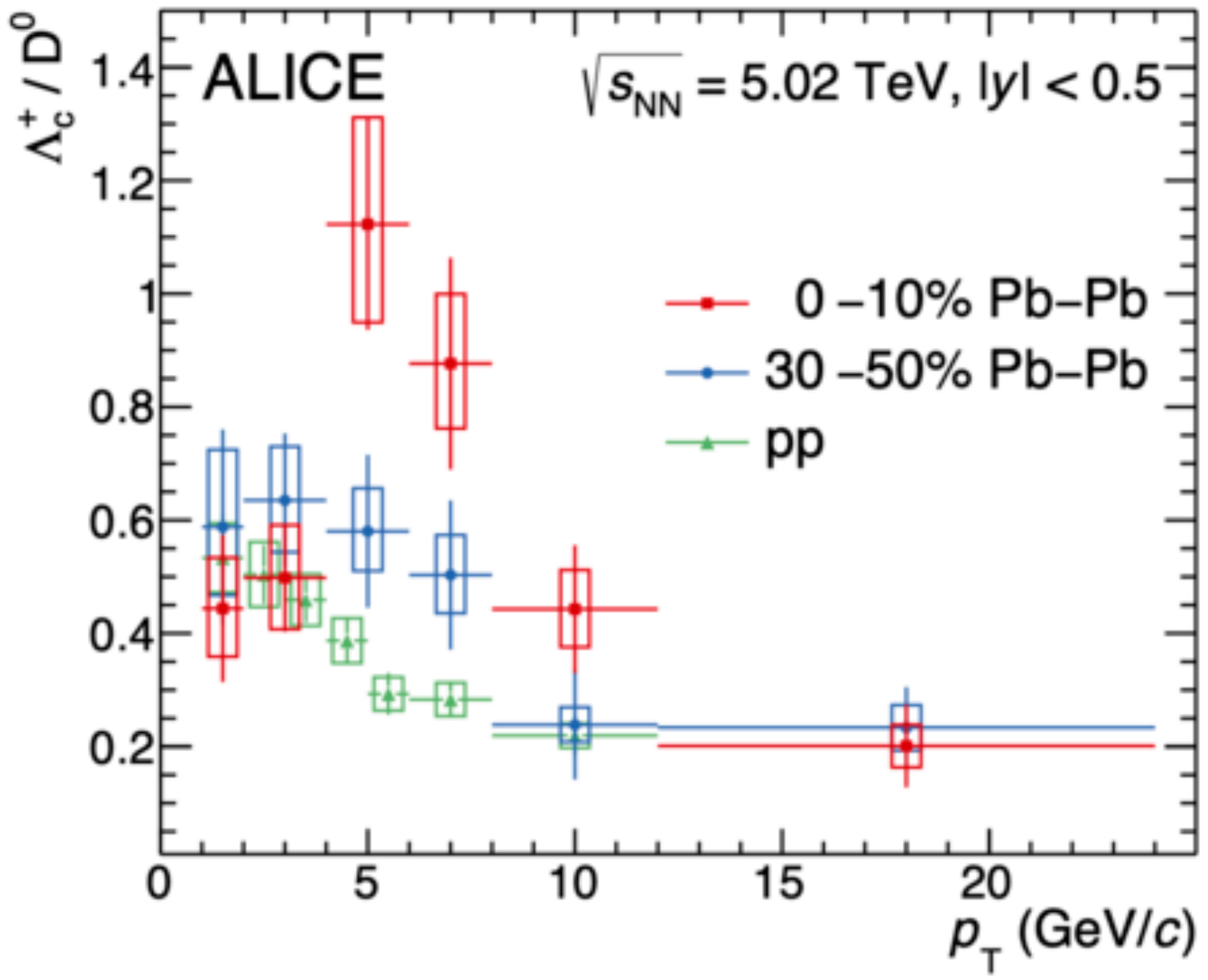
- *Higher order cumulants obtained in close similarity*

$$S(k_1,k_2,k_3,k_4) = \binom{m}{4}\int_\rho\int_0^{2\pi} d\phi_1\, d\phi_2\, d\phi_3\, d\phi_4\, e^{in(\phi_1+\phi_2-\phi_3-\phi_4)}\left(\int\prod_{b=5}^{m} k_b\, dk_b\, d\phi_b\right)\hat{\sigma}$$

$$\langle\langle e^{in(\phi_1+\phi_2-\phi_3-\phi_4)}\rangle\rangle_c = \langle\langle e^{in(\phi_1+\phi_2-\phi_3-\phi_4)}\rangle\rangle - \langle\langle e^{in(\phi_1-\phi_3)}\rangle\rangle\langle\langle e^{in(\phi_2-\phi_4)}\rangle\rangle - \langle\langle e^{in(\phi_1-\phi_4)}\rangle\rangle\langle\langle e^{in(\phi_2-\phi_3)}\rangle\rangle$$

associated to hydro behaviour

Collectivity in Small Systems



Baryon to meson enhancement observed also in pp collisions.

- Hadron spectra and yields can be described by thermal distribution… even in proton-proton!

→ Connection with microscopic description of hadronization? Colour-reconnection, entanglement…

- Improve understanding of hadronization, in large and small systems, using heavy quark probes.

  → Model proton-proton system as a droplet of liquid QGP.

  → Use novel hadronization mechanisms involving recombination.

Beraudo, De Pace, Nardi, Prino, DP - in preparation

Concurrent Mini-jet+Hydro Evolution

Elements of the framework:

- Initial state from IP-Glasma.
- Finite mini-jet production probability at each binary collision.

$$\tau = 0$$

- Hydro. energy-momentum from IP-Glasma.
- Mini-jets lose energy to the QGP (Hybrid Model) above T_c :
  - → Gaussian source into hydro. e.o.m.

$$\tau = 0.4\,\mathrm{fm/c}$$

- Cooper-Frye bulk.
- Hadronize non-stopped partons through Lund string model:
  - → If parton close to hypersurface, sample thermal partons to build colourless string.
  - → If not, construct single colourless string with all such "corona" partons.

$$\tau_{\text{freeze-out}}$$

- Everything evolves with UrQMD.

DP, Singh, Gale, Jeon - PRC '22

Further Improvements on Single Charge Energy Loss

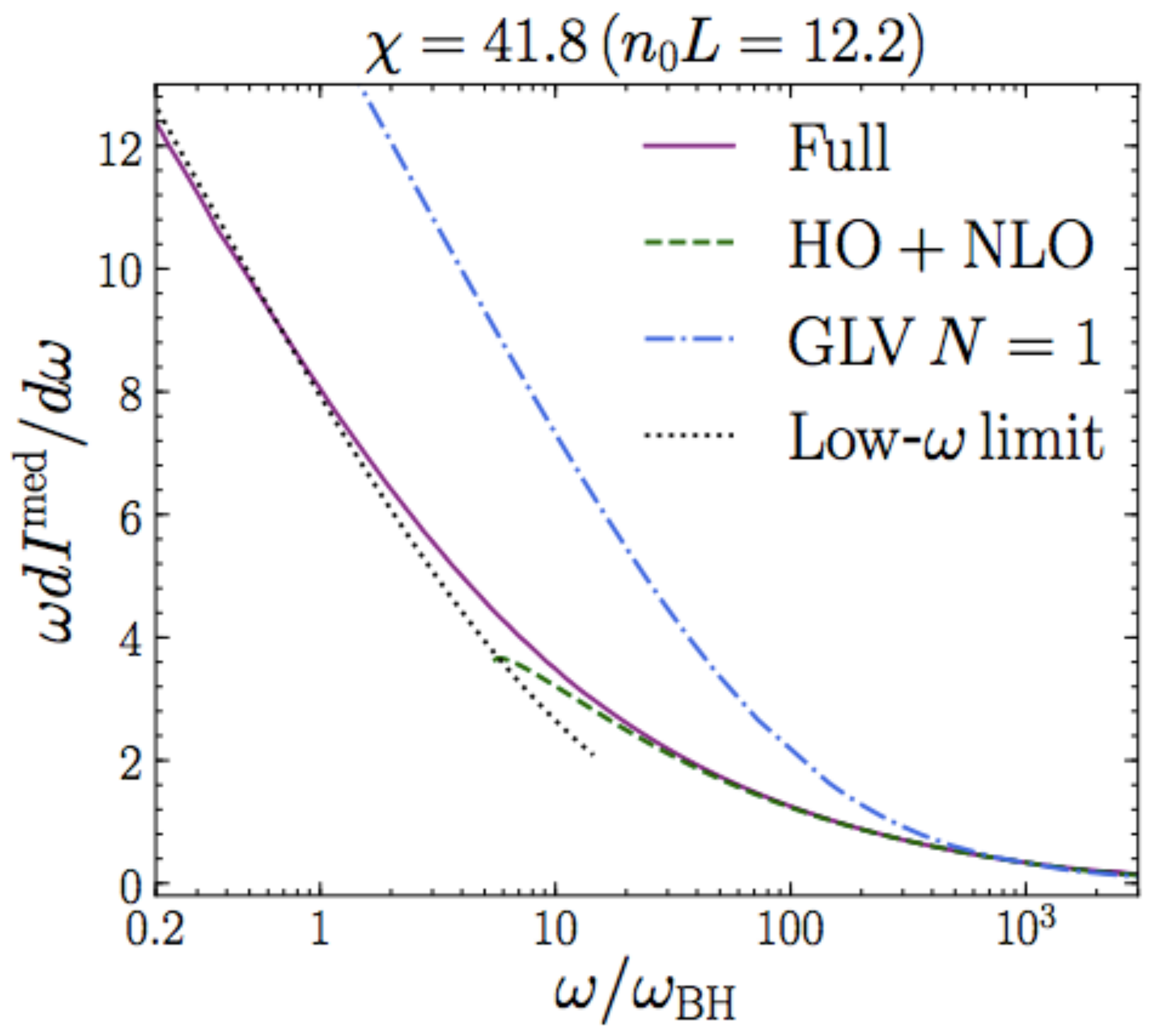
- All order resummation of medium induced radiation spectrum.

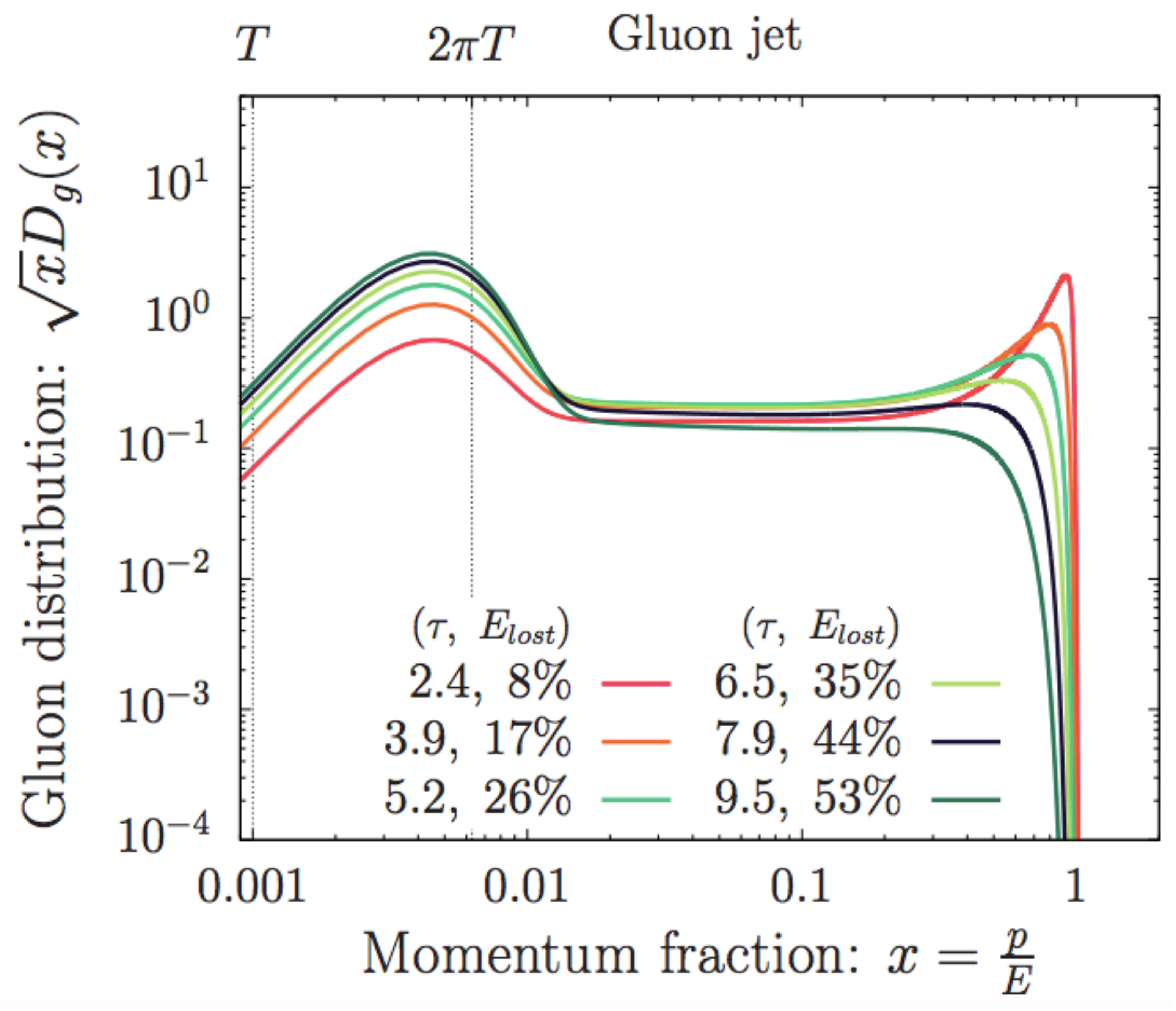
Feal et al. - PRD ‘18 & ‘19

Andrés et al. - JHEP ‘20 & ‘21

- Resummed Opacity Expansion (ROE) to cover Bethe-Heitler regime.

Isaksen et al. - arXiv:2206.02811



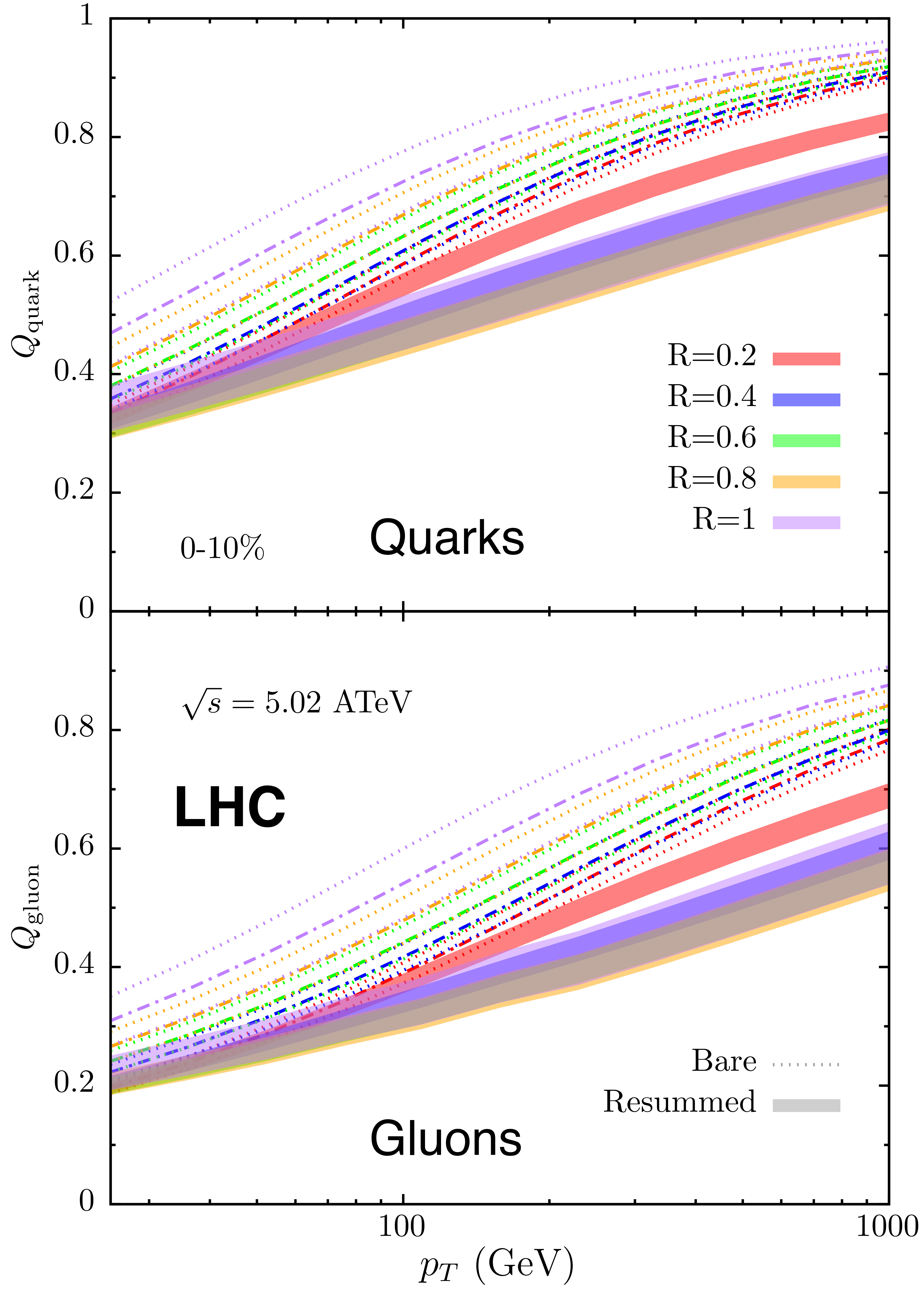


Schlichting & Soudi - JHEP ‘20

- In-medium fragmentation of hard parton in QGP through effective kinetic theory.
  - Includes 1⟷2 and 2⟷2 processes.
  - Features turbulent cascade, modified chemistry around the jet.

Detailed analysis of dynamics, can account for medium response.

Resummed Quenching Factor



- Bare quenching factors (dashed):
  - → less quenching for larger R.
    - → Easier to keep (recover) the emitted (thermalised) modes.
- Resummed quenching factors (solid):
  - → larger R can lead to more quenching.
    - → Interplay between energy recovery and size of quenched phase space.

Mehtar-Tani, DP, Tywoniuk - PRL '21