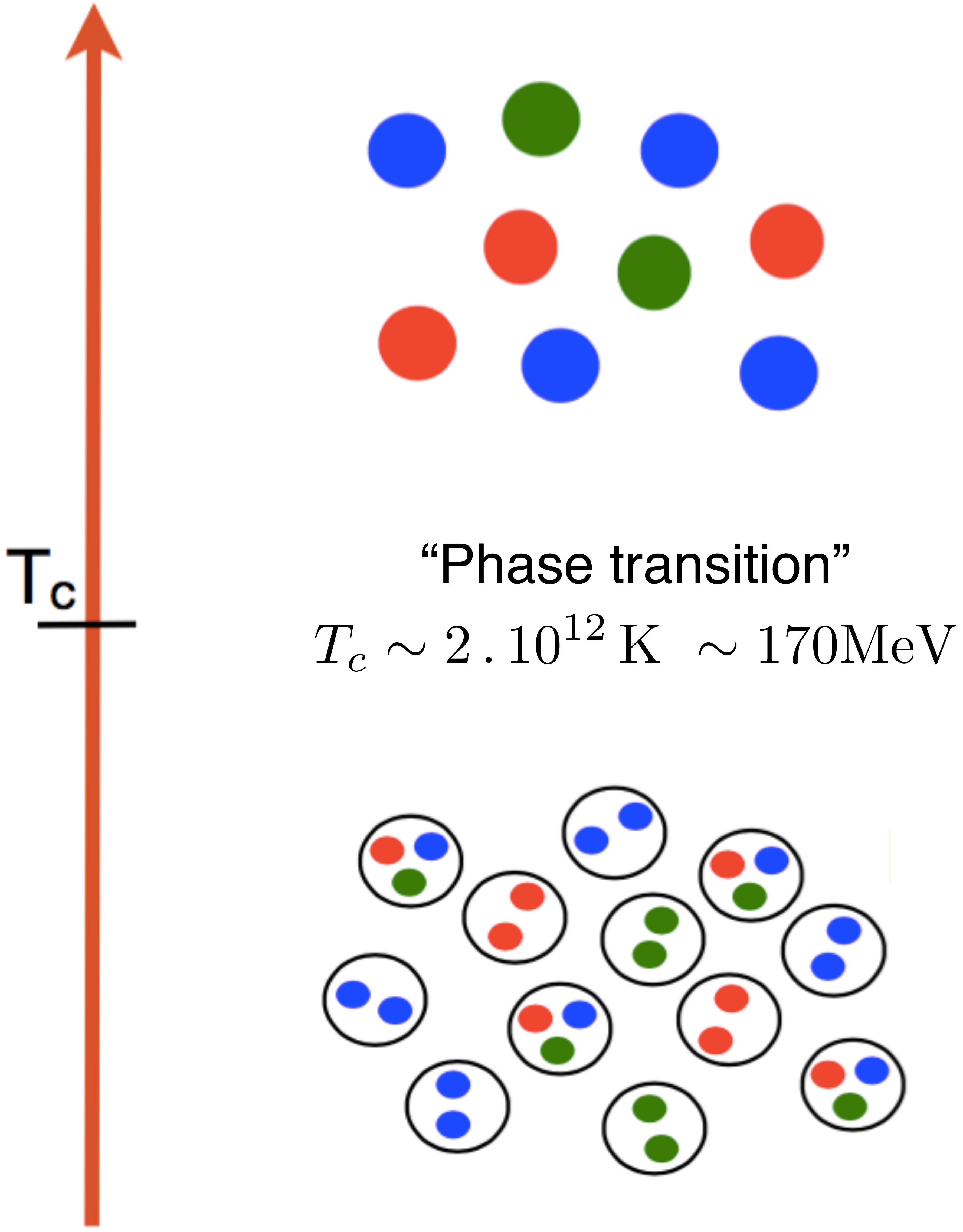
Jet substructure in heavy ion collisions

Daniel Pablos

Free Meson Seminar
TIFR

15th October 2020

QCD Matter



“Phase transition”

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

A New Phase: Quark-Gluon Plasma

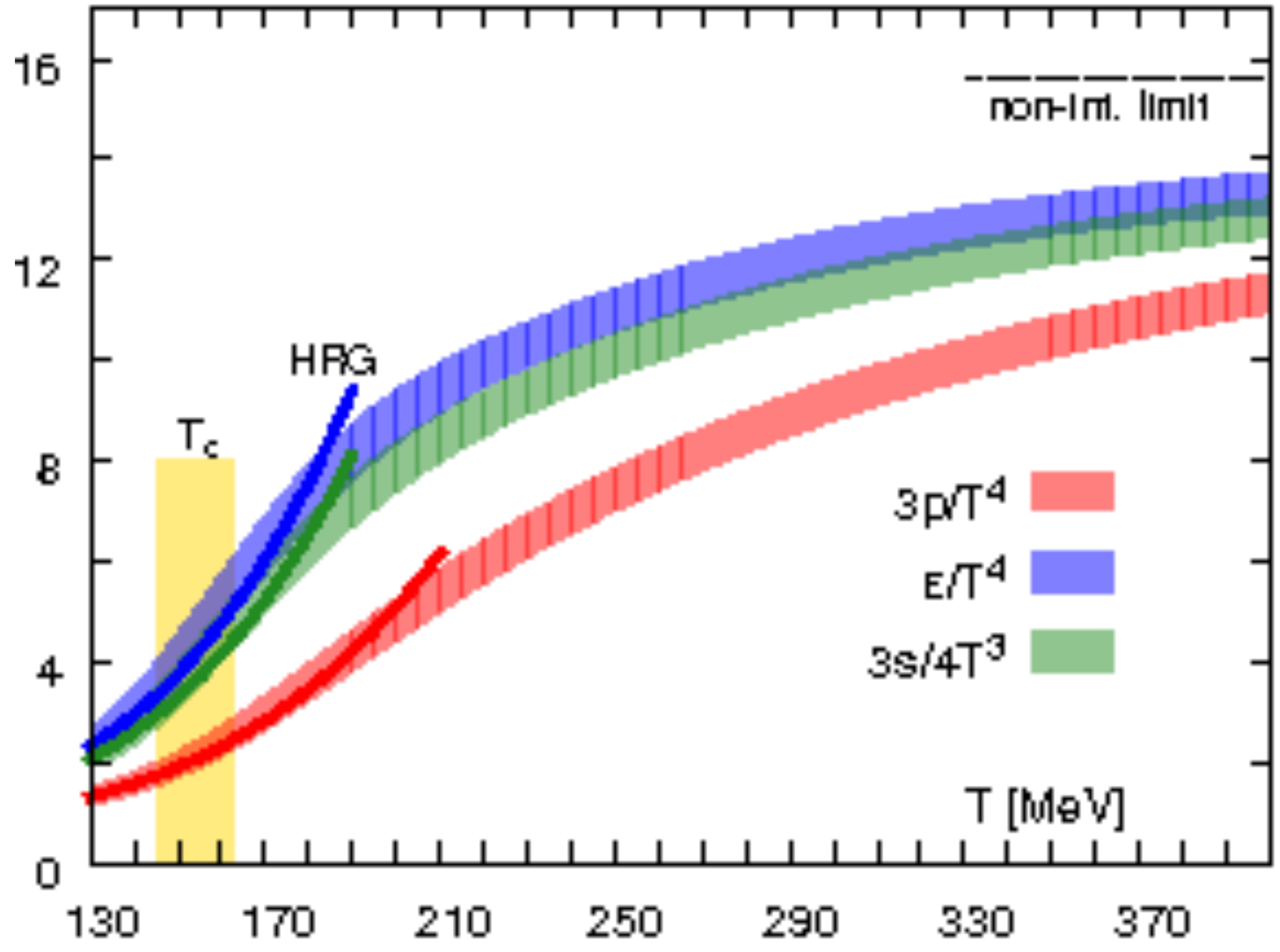
- Filled the universe μs after Big Bang
- Colour is liberated
- A gas of quarks and gluons

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

Hadron Gas

- Color is confined
- Hadrons re-scatter

Equation of State



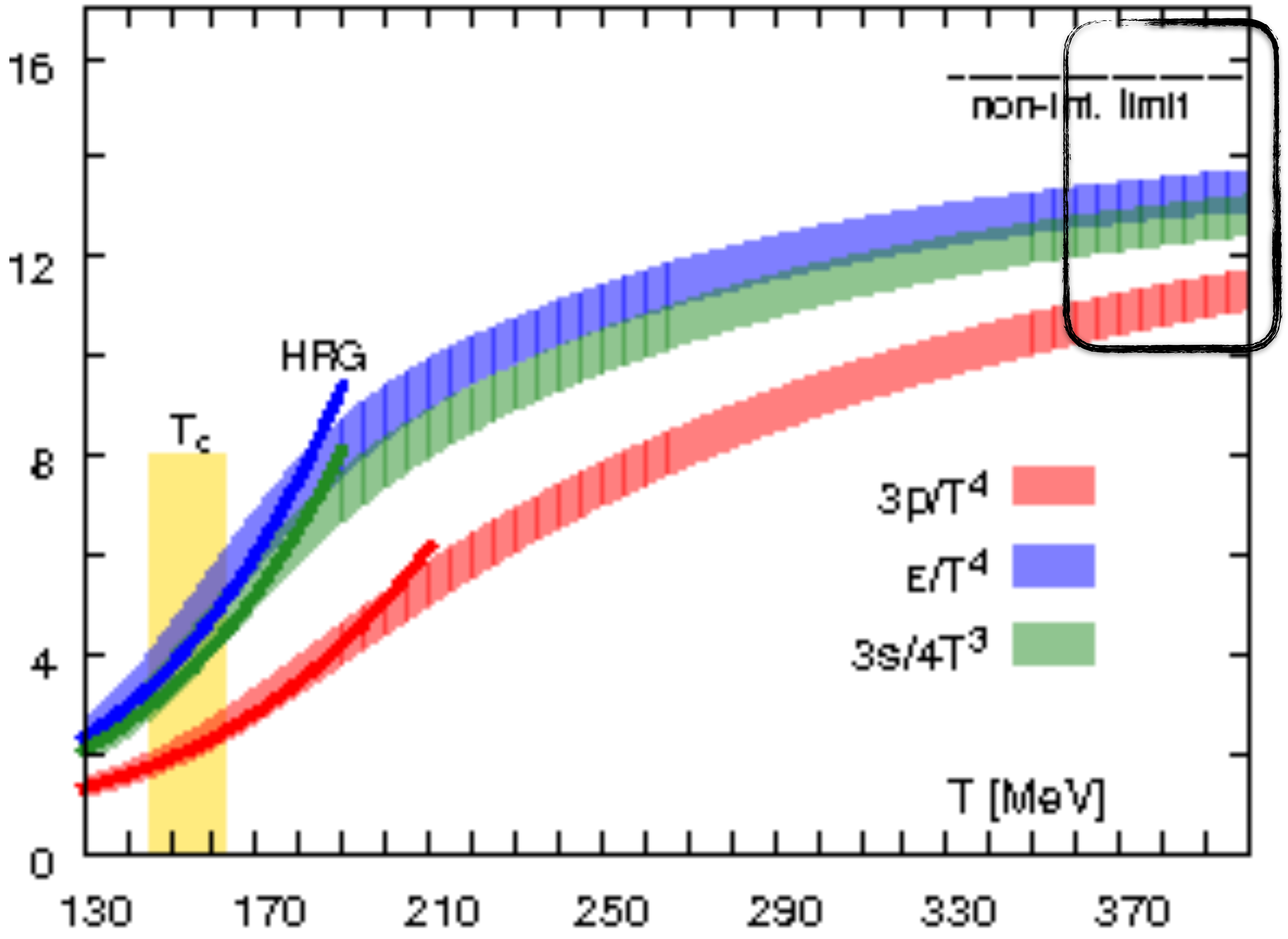
HotQCD Collaboration - PRD ‘14

- Rapid crossover transition

- Deconfined matter: large increase in # d.o.f. above Tc

- Asymptotically approaches non-int. limit

Equation of State



HotQCD Collaboration - PRD '14

Weakly coupled?

$$\frac{s_{\lambda=\infty}}{s_{\lambda=0}} = \frac{P_{\lambda=\infty}}{P_{\lambda=0}}$$

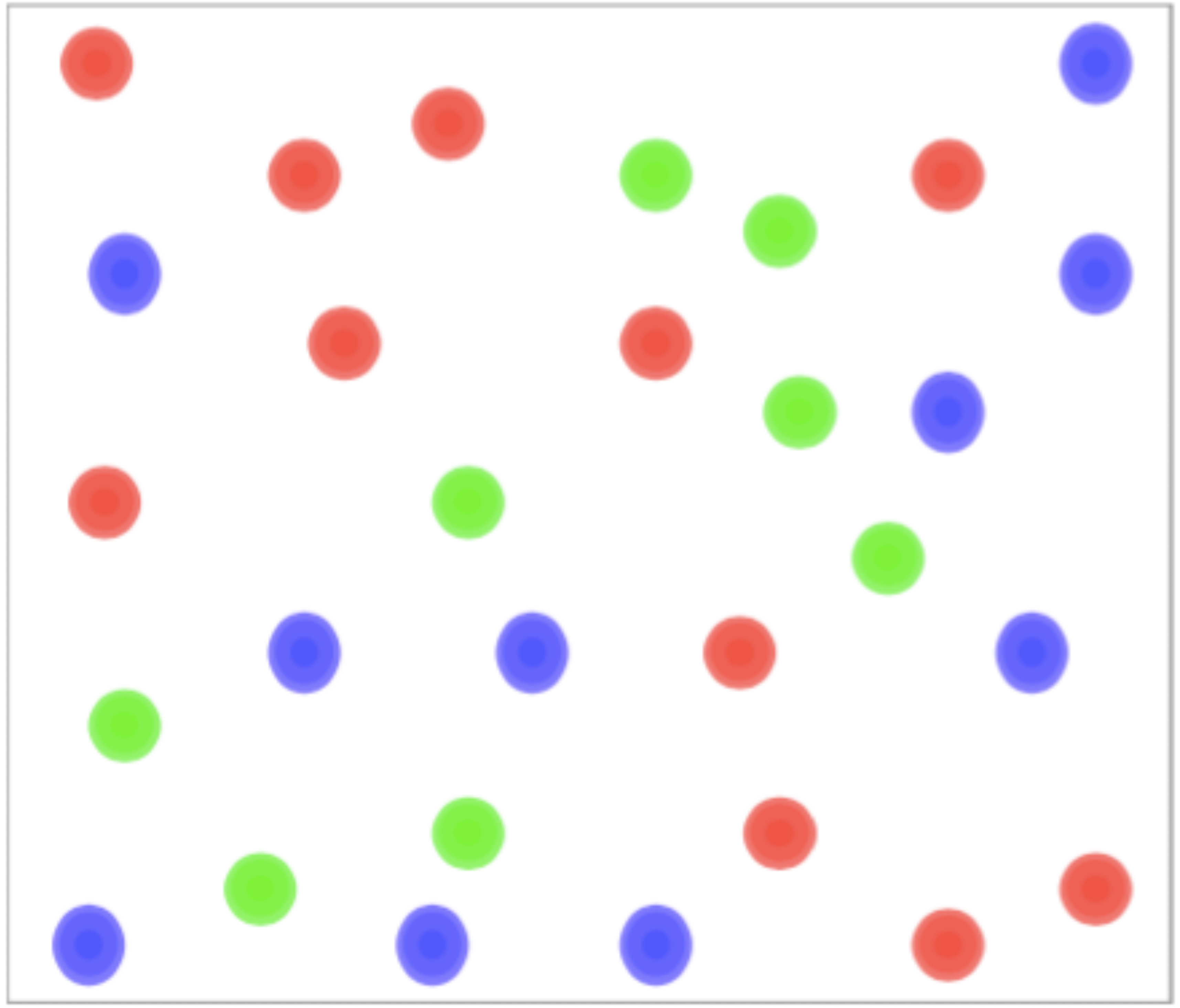
$$= \frac{\epsilon_{\lambda=\infty}}{\epsilon_{\lambda=0}} = \frac{3}{4}$$

Poor indicator!

- Rapid crossover transition
- Deconfined matter: large increase in # d.o.f. above T_c
- Asymptotically approaches non-int. limit

A Gas of Quarks and Gluons

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

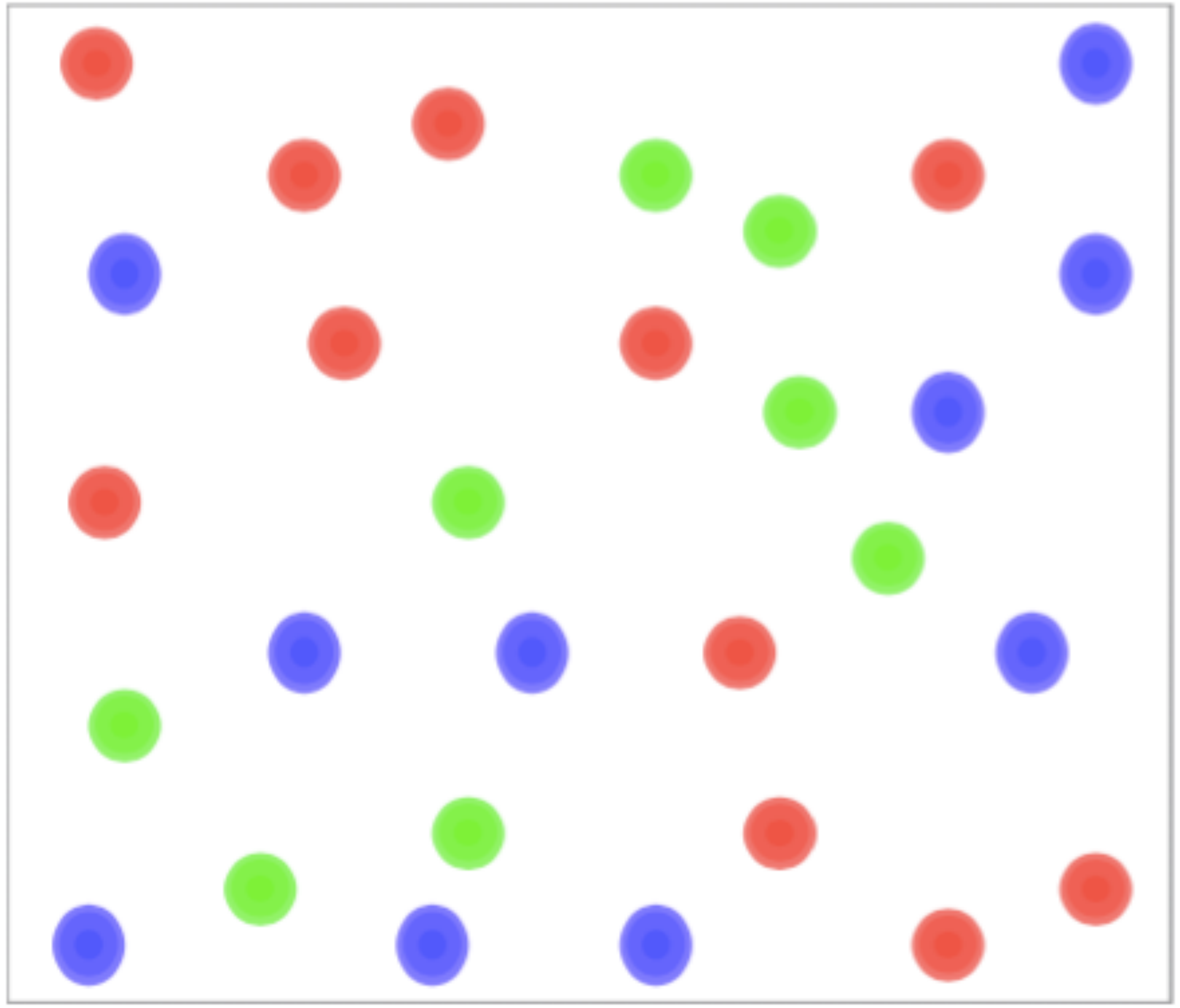


$$\frac{1}{T} \ll \frac{1}{gT} \ll \frac{1}{g^2T}$$

Inter-particle spacing	Interaction range	Mean free path

A Gas of Quarks and Gluons

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



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

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

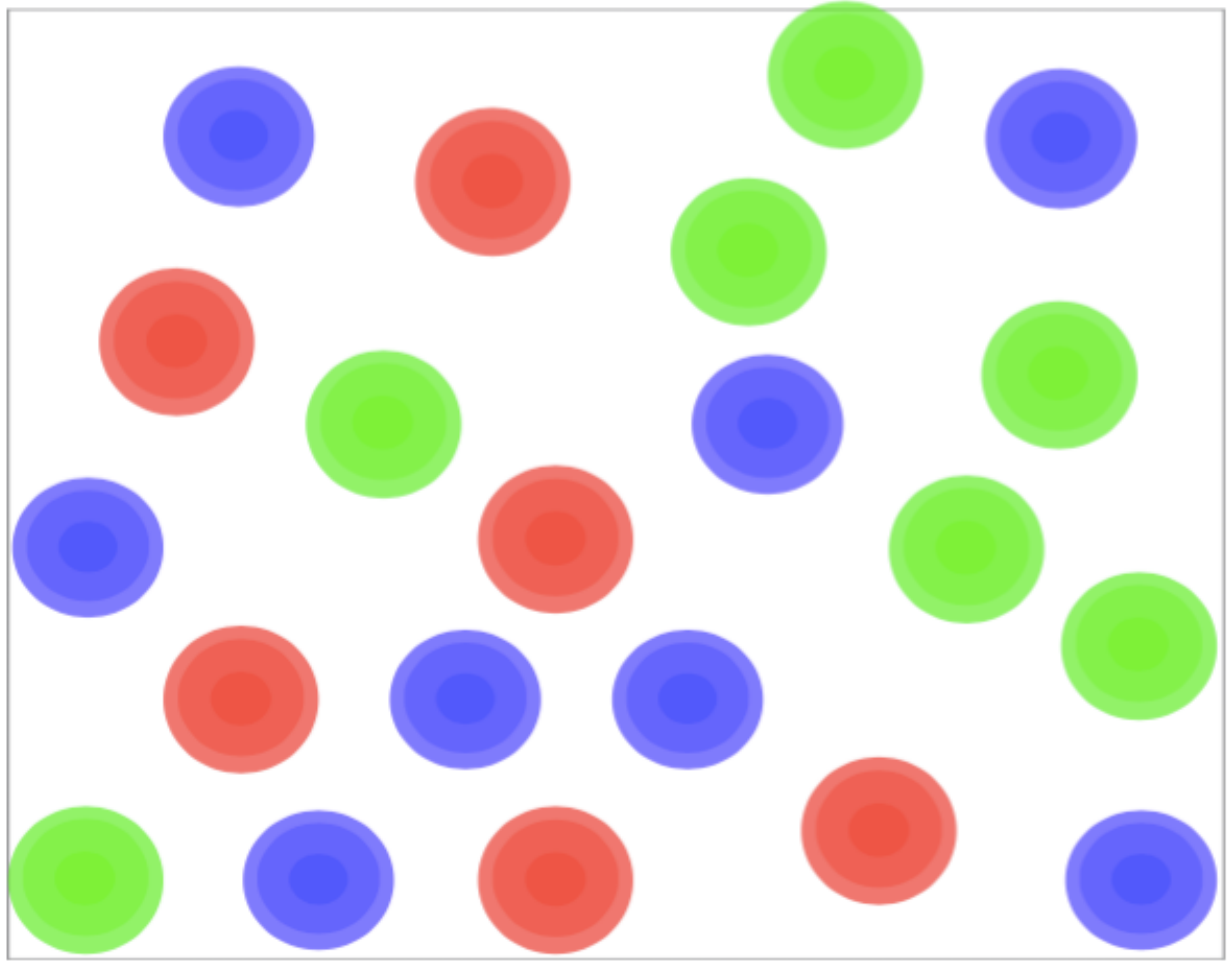
Inter-particle spacing

Interaction range

Mean free path

Which is the correct picture of the plasma?

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



Is it a gas of quarks and gluons?

Which is the correct picture of the plasma?

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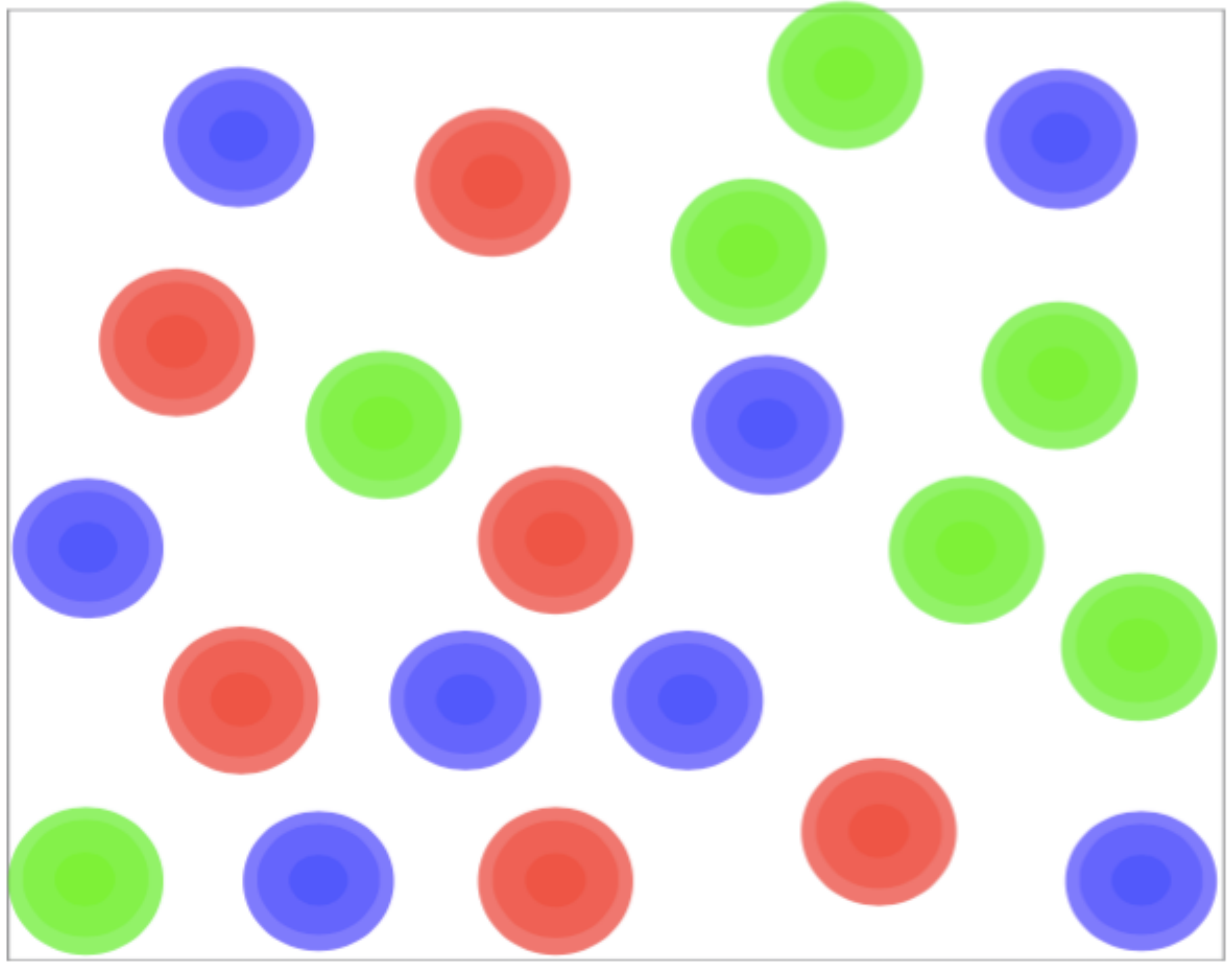

Is it a gas of quarks and gluons?

$$\alpha_s = 0.3 \to g = 2$$

Which is the correct picture of the plasma?

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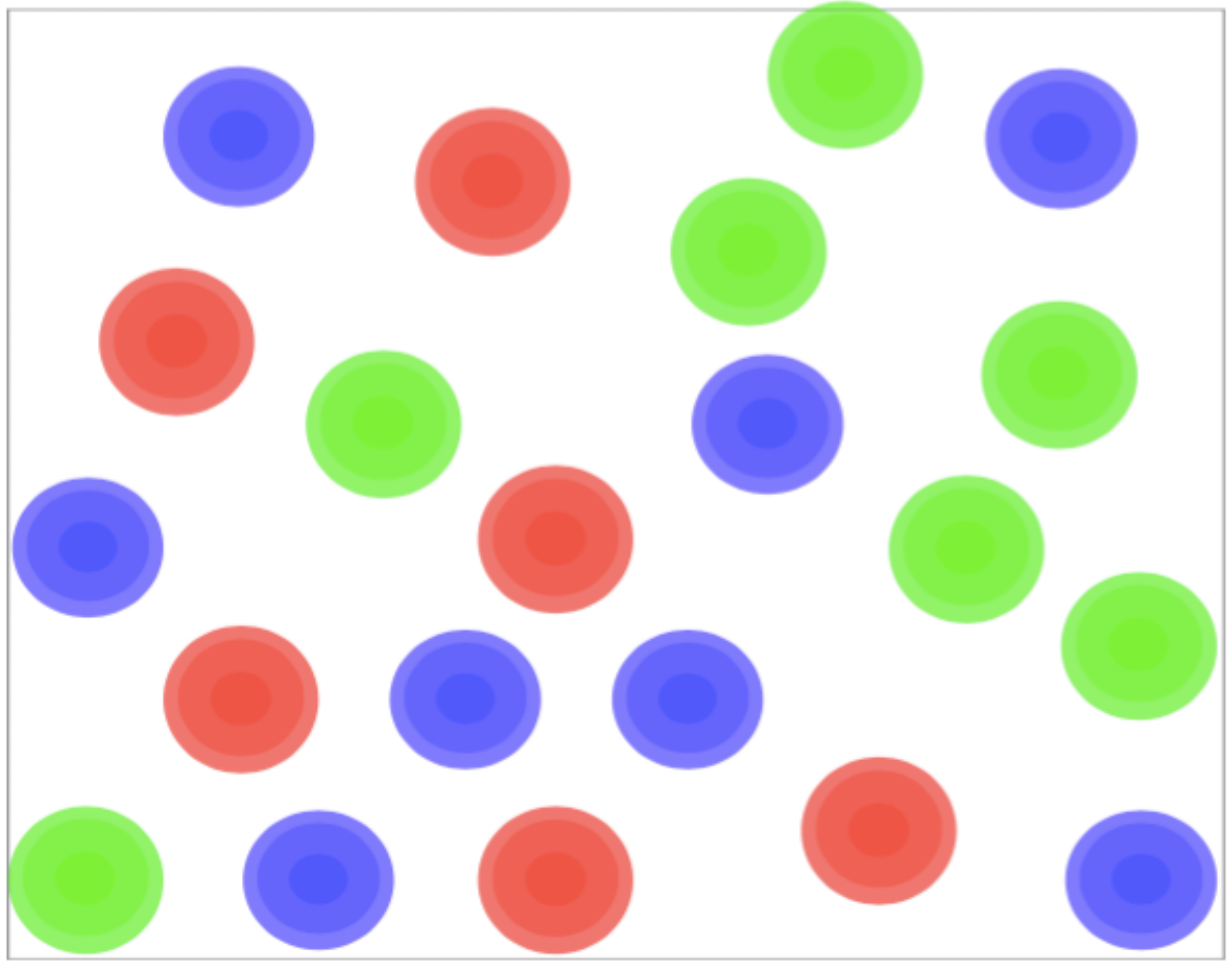

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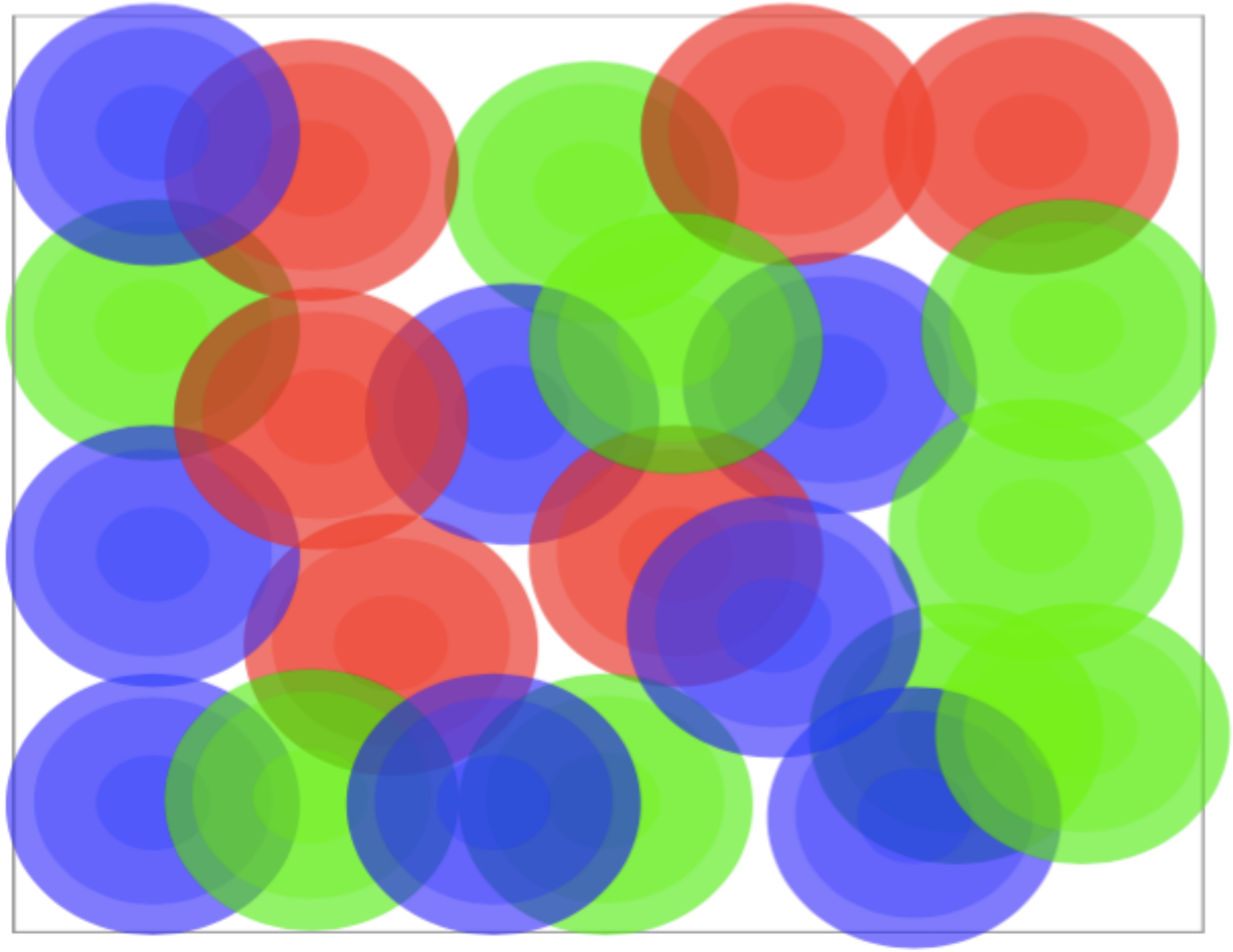


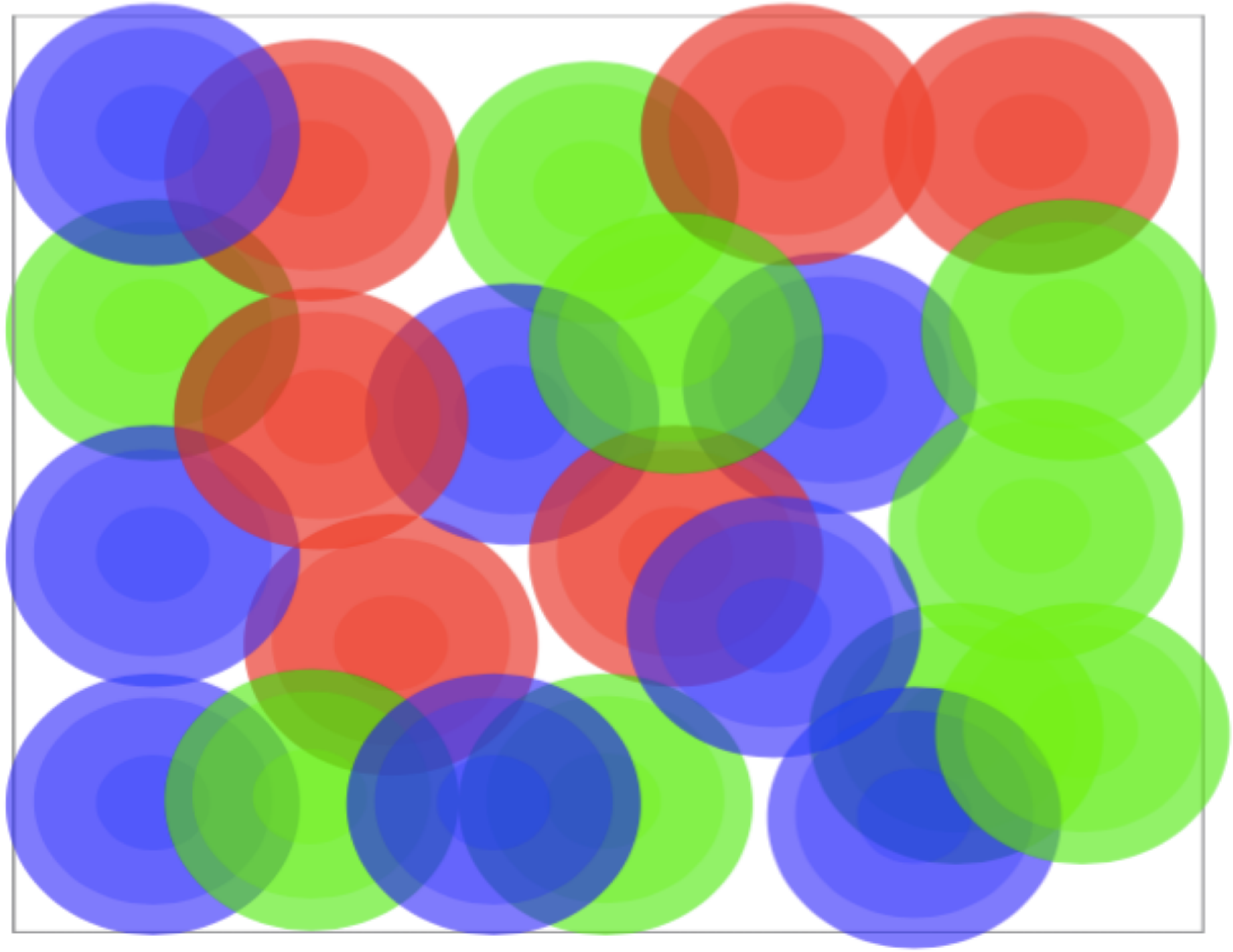
Is it a system with no long lived excitations?

$$\alpha_s = 0.3 \to g = 2$$

$$T \sim gT \sim g^2T$$

Which is the correct picture of the plasma?

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

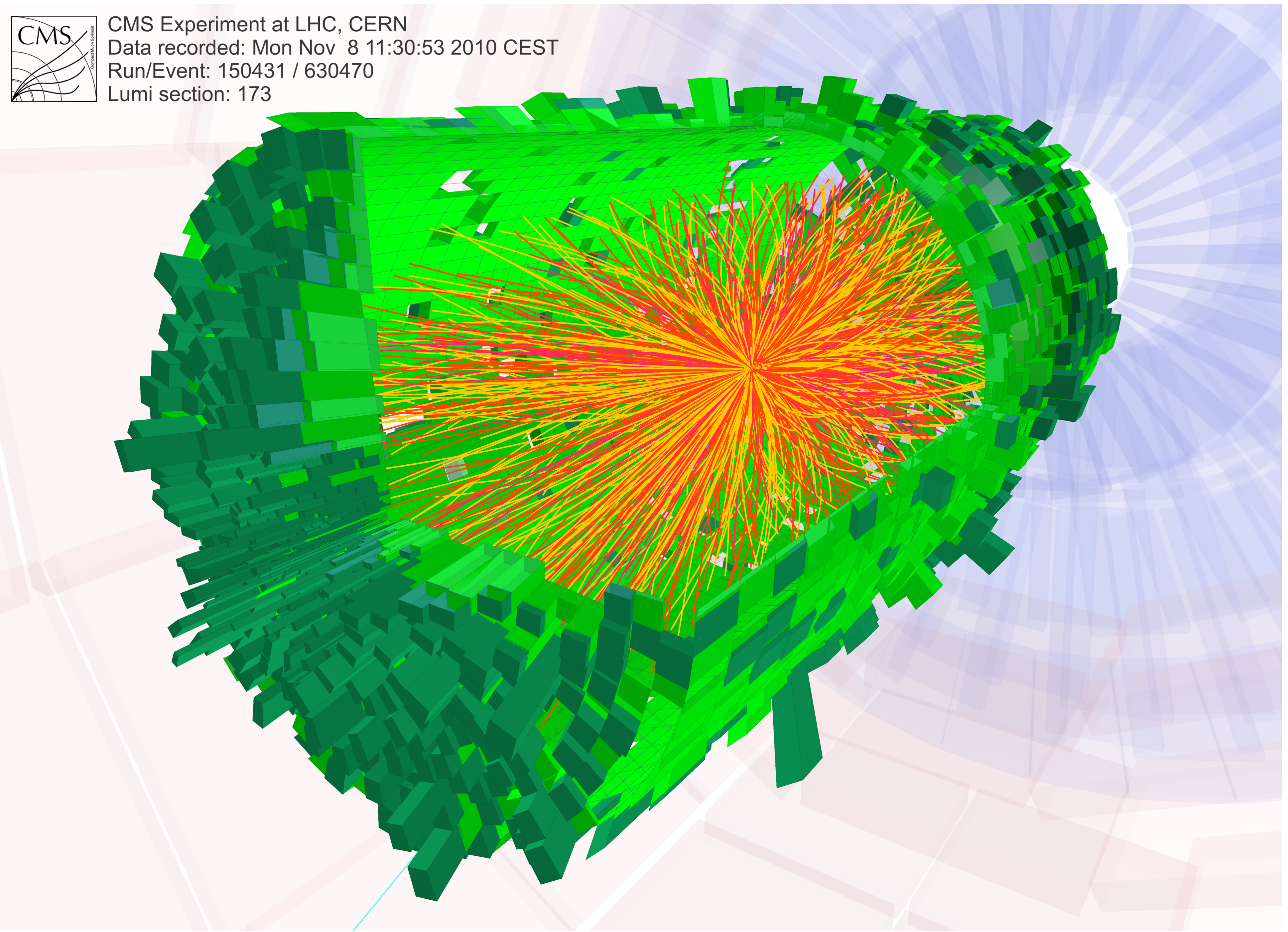


Is it a system with no quasiparticles?

$$\alpha_s = 0.3 \to g = 2$$

$$T \sim gT \sim g^2 T$$

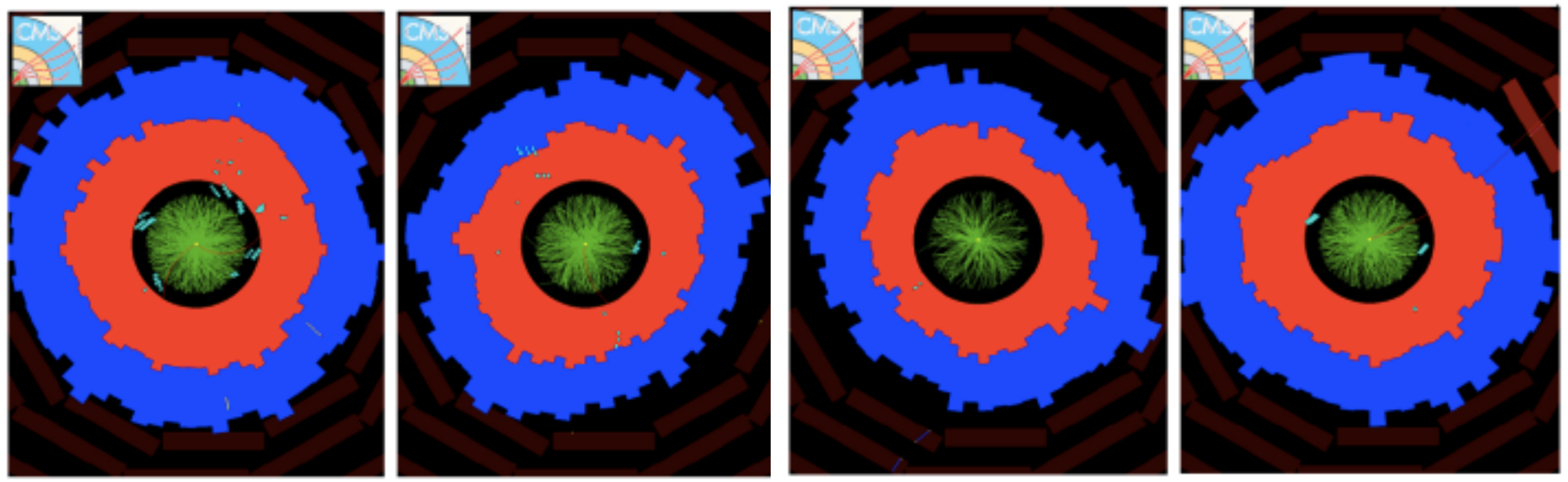
Heavy Ion Collisions: the Little Bang

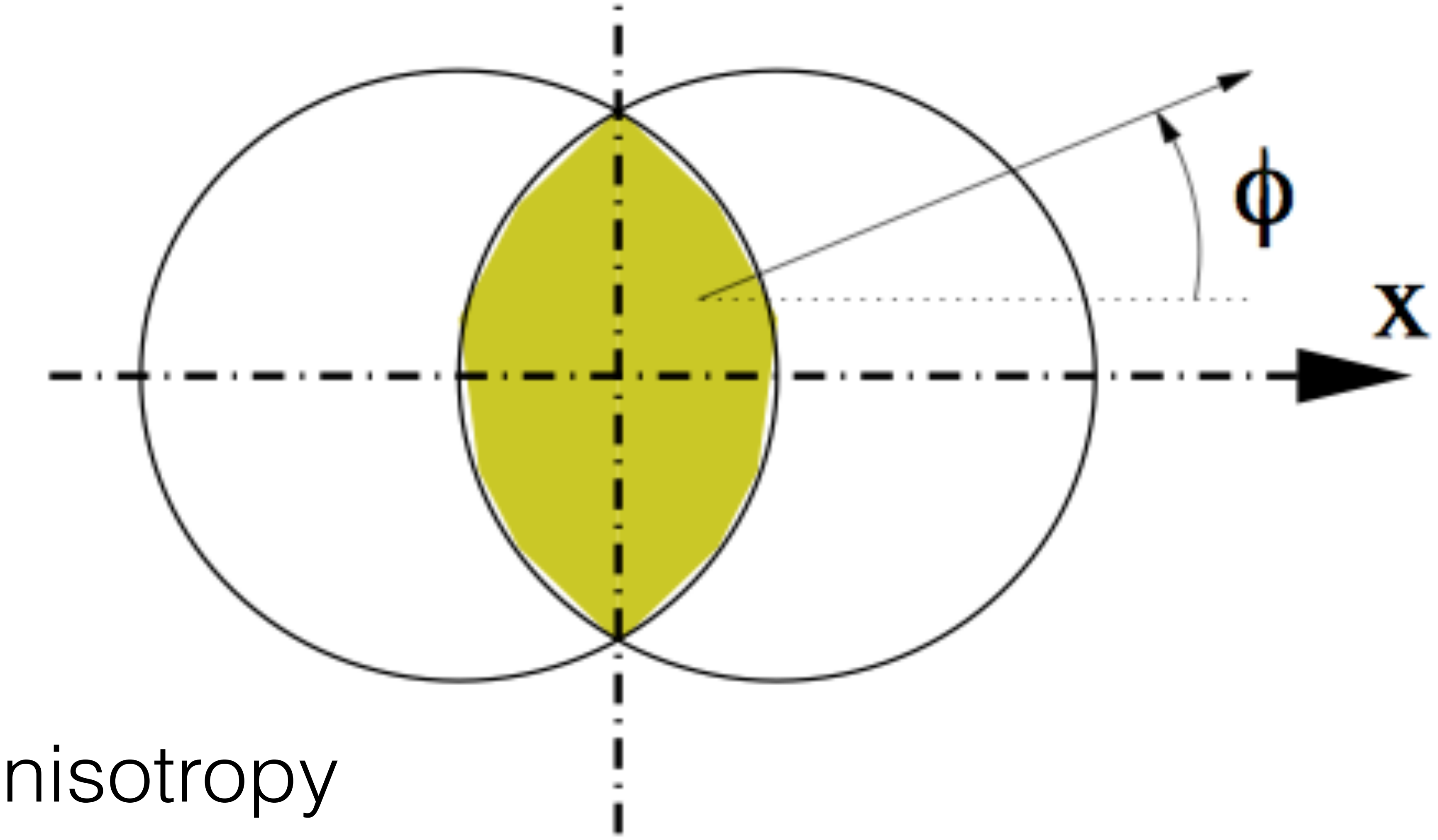


- Very strong collective effects
- 20.000 particles correlated according to collision geometry
- Hydrodynamic explosion

The QGP is a very good fluid!

The QGP: Strongly Coupled Liquid





- Spatial anisotropy translates into momentum anisotropy

$$\frac{dN}{d^2\mathbf{p}_t\, dy} = \frac{1}{2\pi p_T} \frac{dN}{dp_T\, dy} \left[1 + 2v_1 \cos(\phi - \Phi_R) + 2v_2 \cos 2(\phi - \Phi_R) + \cdots\right]$$

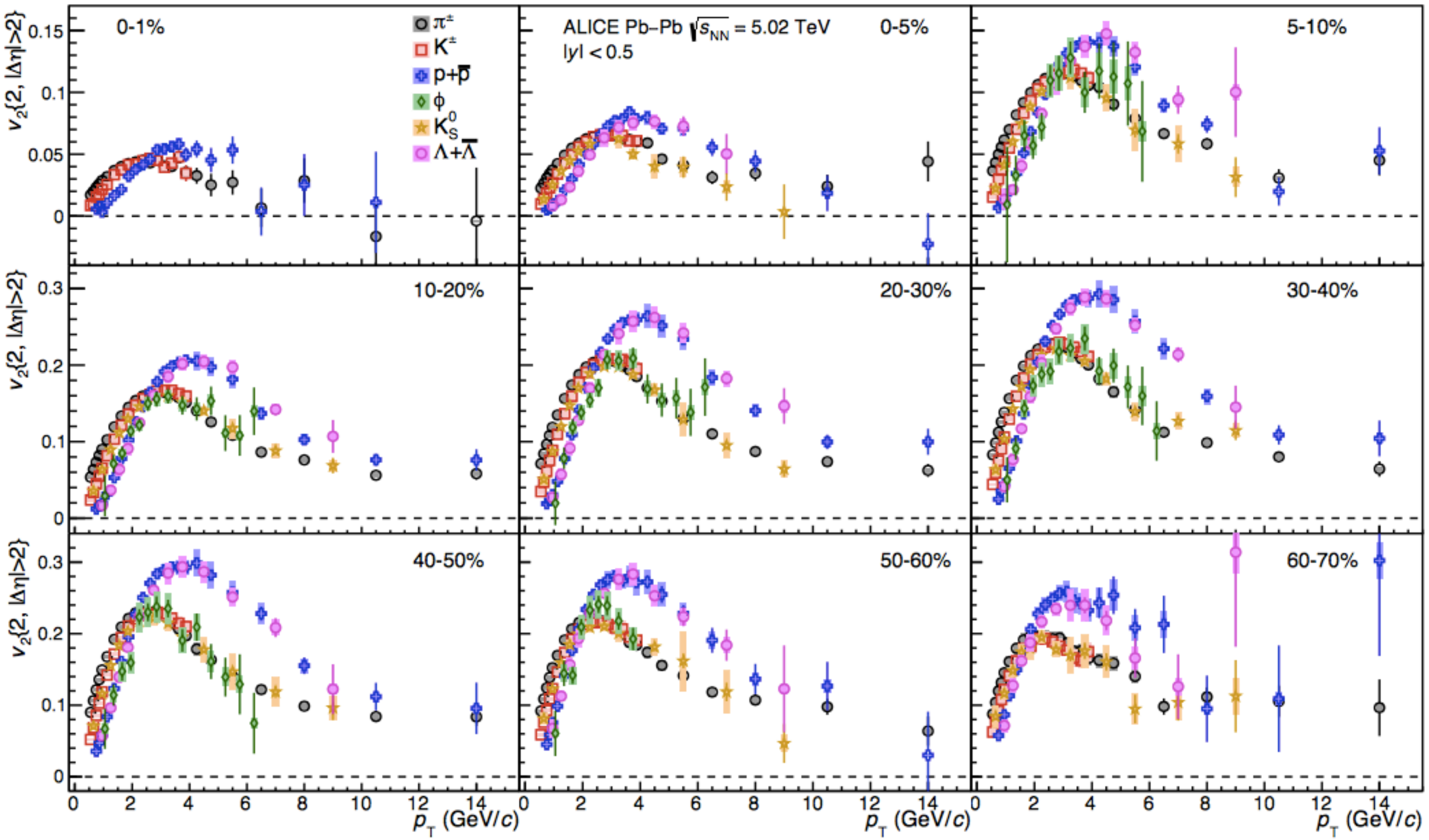
$$\left(\frac{\eta}{s}\right)_{T_c} = 0.08 \pm 0.05$$

Bernhard et al. - PRC '16

- Data strongly favors very low shear viscosity over entropy density ratio. Characteristic of strongly coupled system (absence of weakly interacting quasiparticles)

$$\frac{\eta_{\lambda=\infty}}{s_{\lambda=\infty}} = \frac{1}{4\pi} \simeq 0.08 \qquad \frac{\eta_{\lambda\to 0}}{s_{\lambda\to 0}} = \frac{A}{\lambda^2 \log\left(B/\sqrt{\lambda}\right)}$$

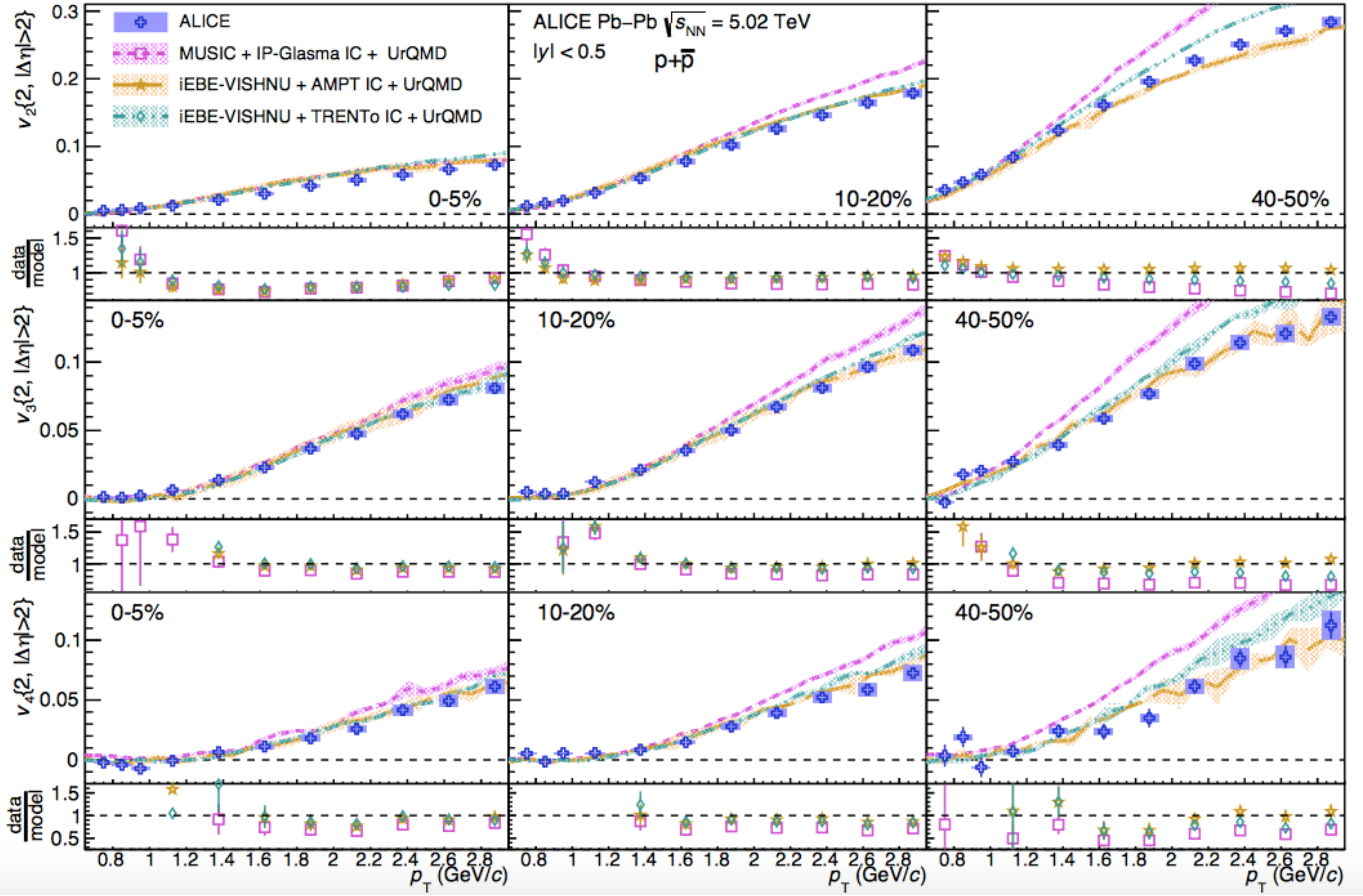
Mass ordering of flow



$$E\frac{d^3N}{dp^3} = \frac{1}{2\pi}\frac{d^2N}{p_T dp_T dy}\left(1+2\sum_{n=1}^{\infty} v_n\cos[n(\varphi-\Psi_n)]\right)$$

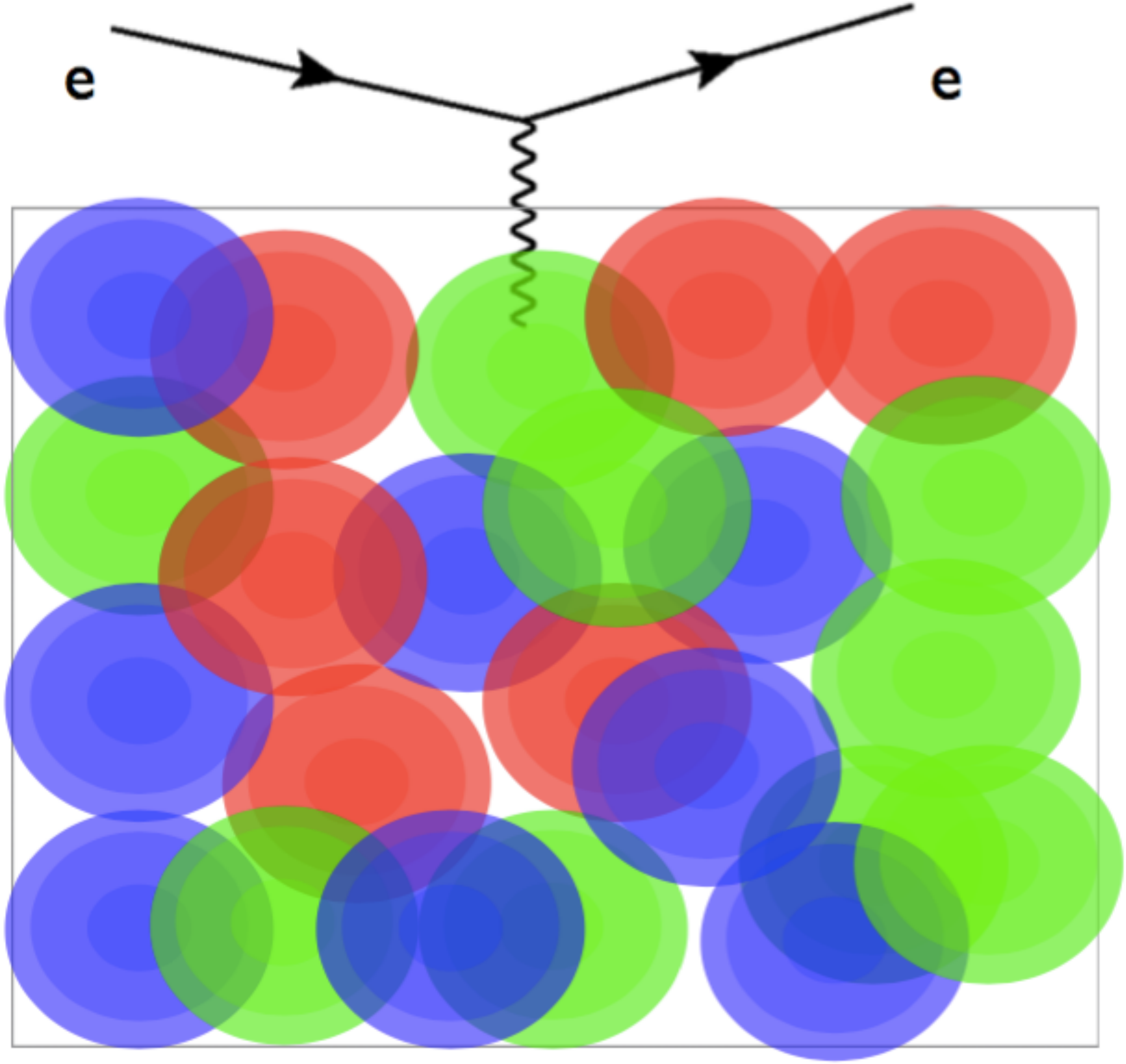
ALICE - JHEP ‘18

Hydrodynamics Simulations

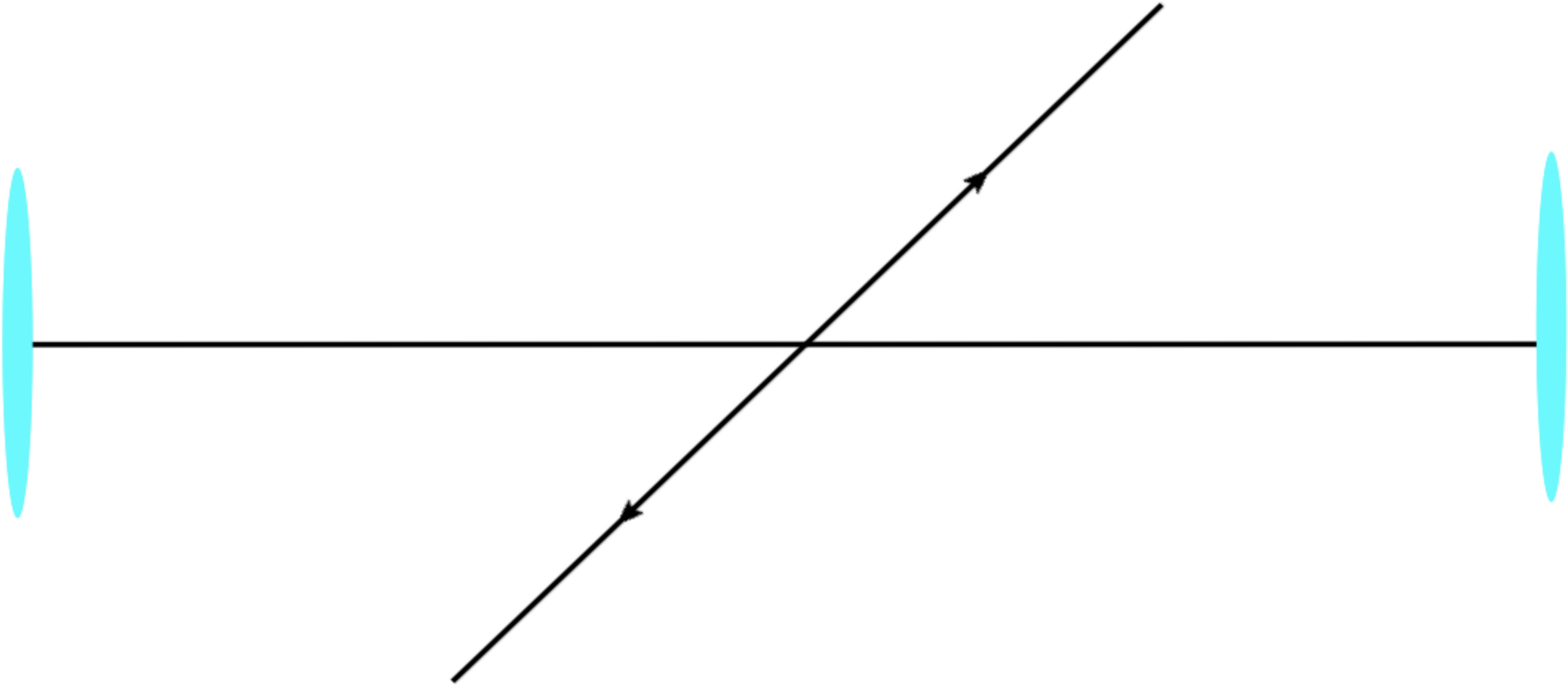


ALICE - JHEP ‘18

How can we probe the QGP?



Jets



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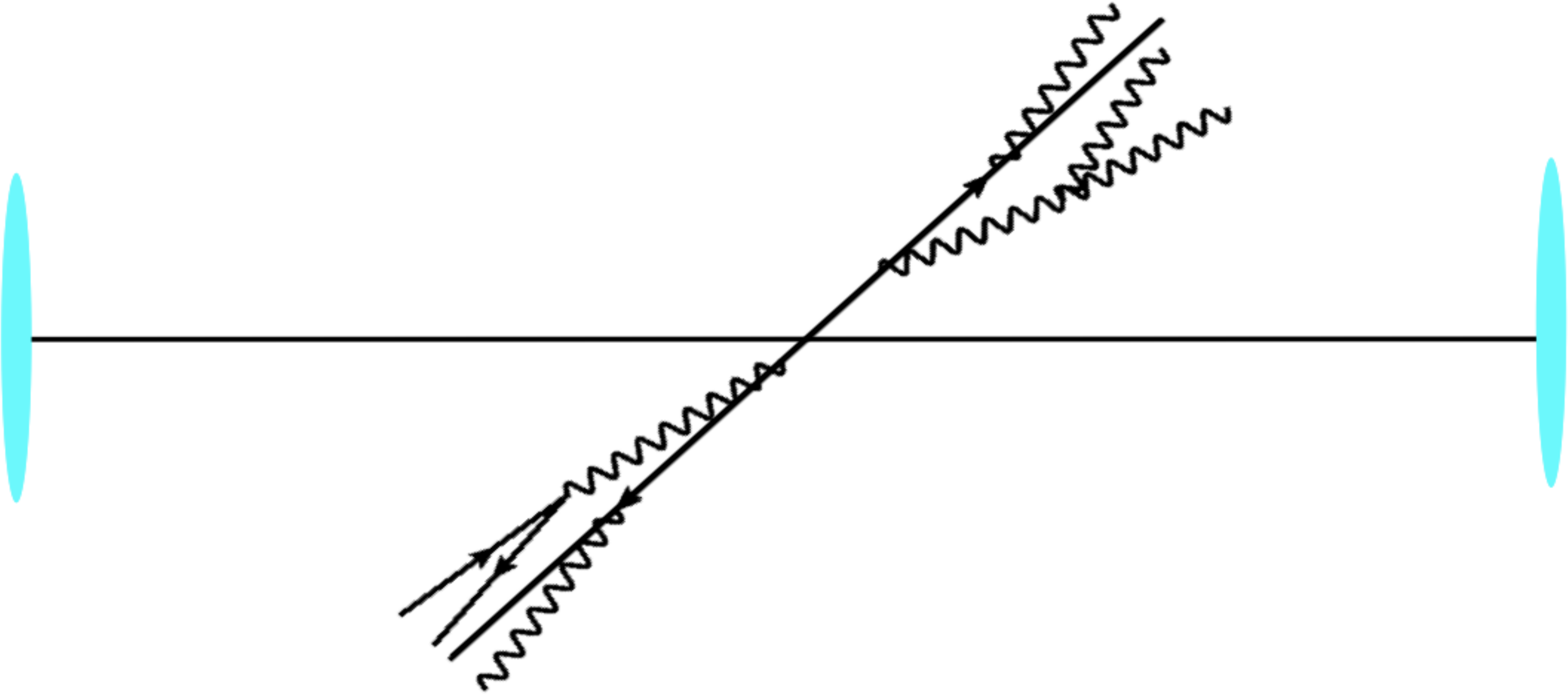

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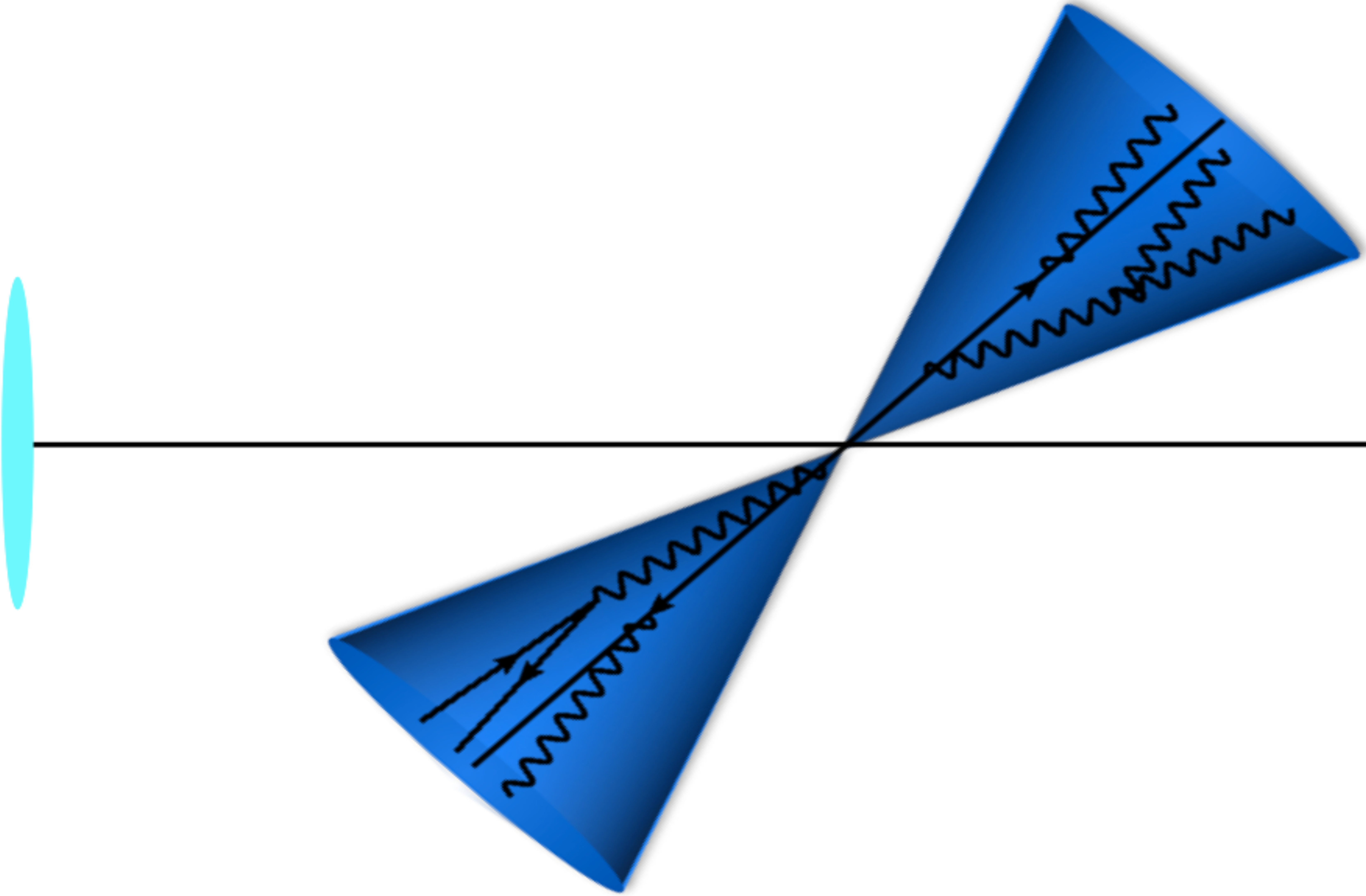
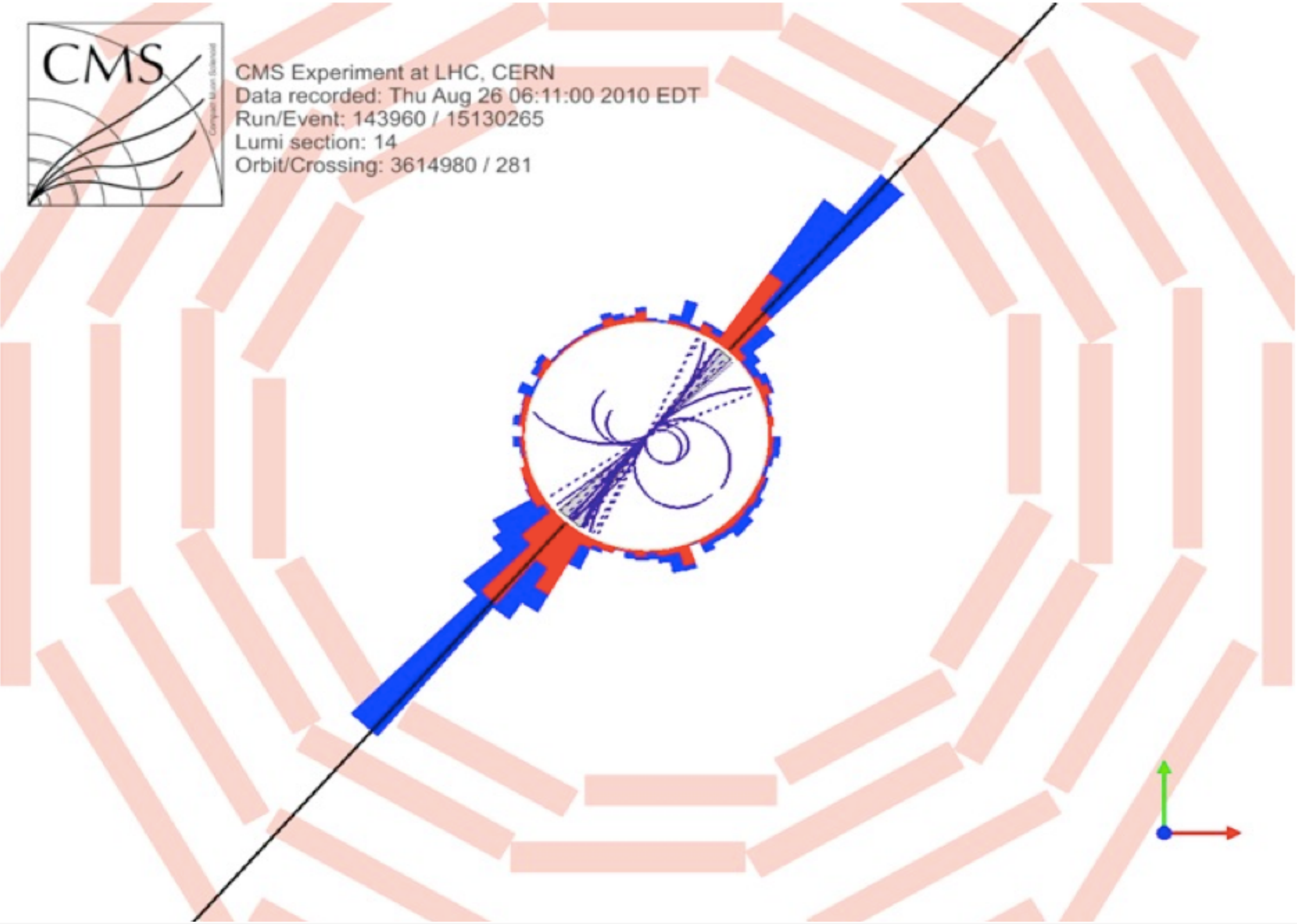
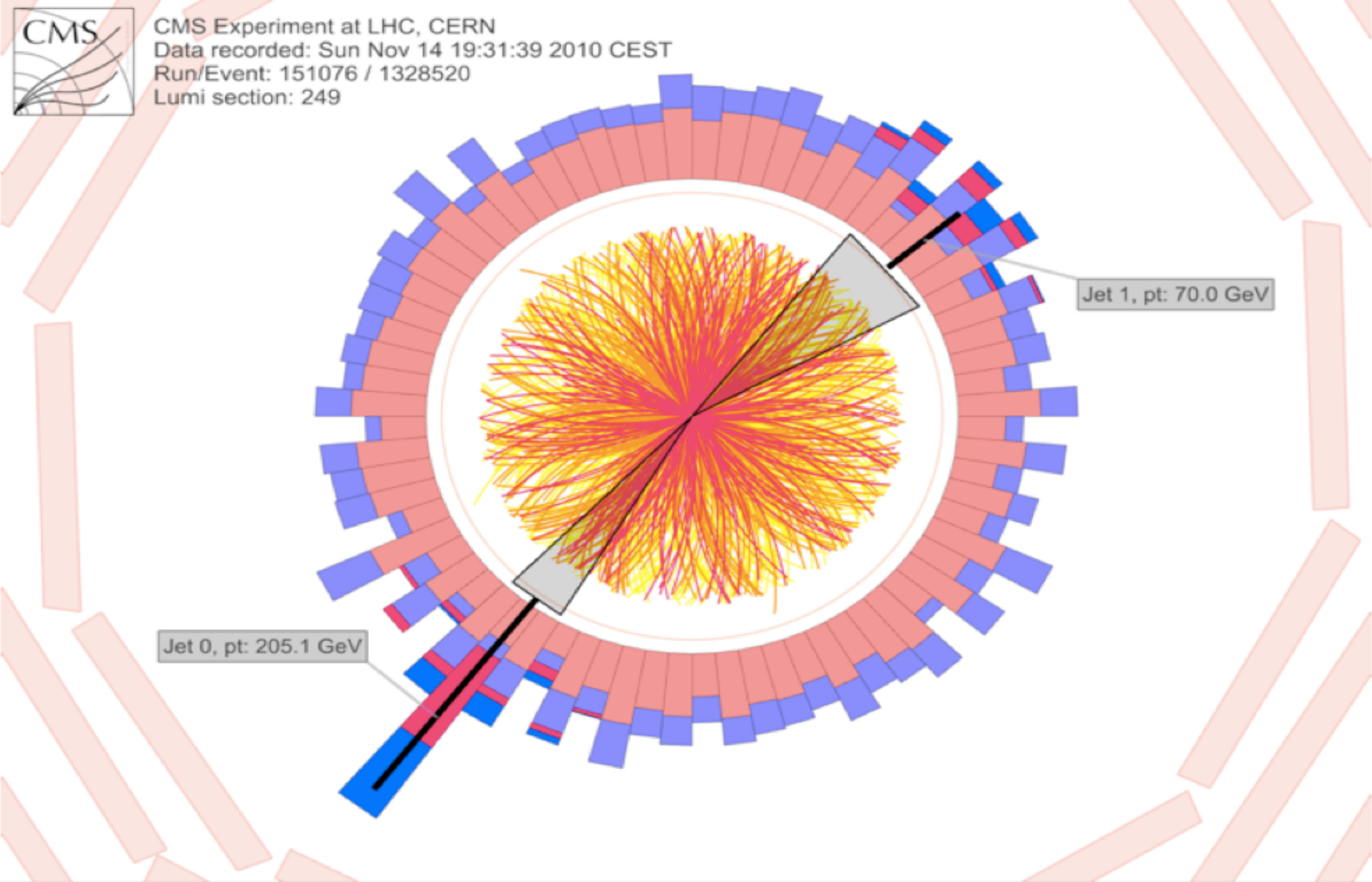


Jets

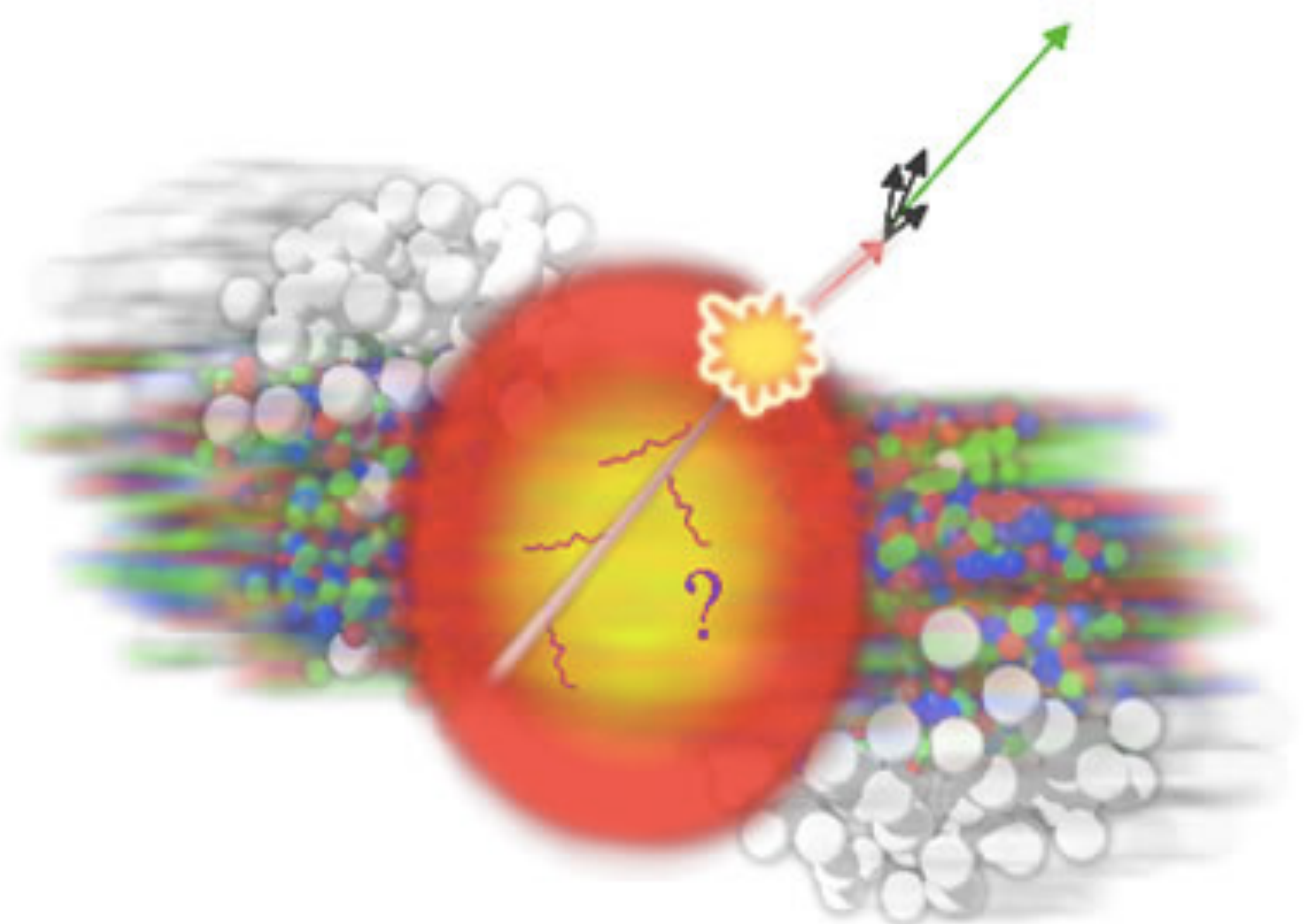


CMS Experiment at LHC, CERN
Data recorded: Thu Aug 26 06:11:00 2010 EDT
Run/Event: 143960 / 15130265
Lumi section: 14
Orbit/Crossing: 3614980 / 281

Jets in HIC

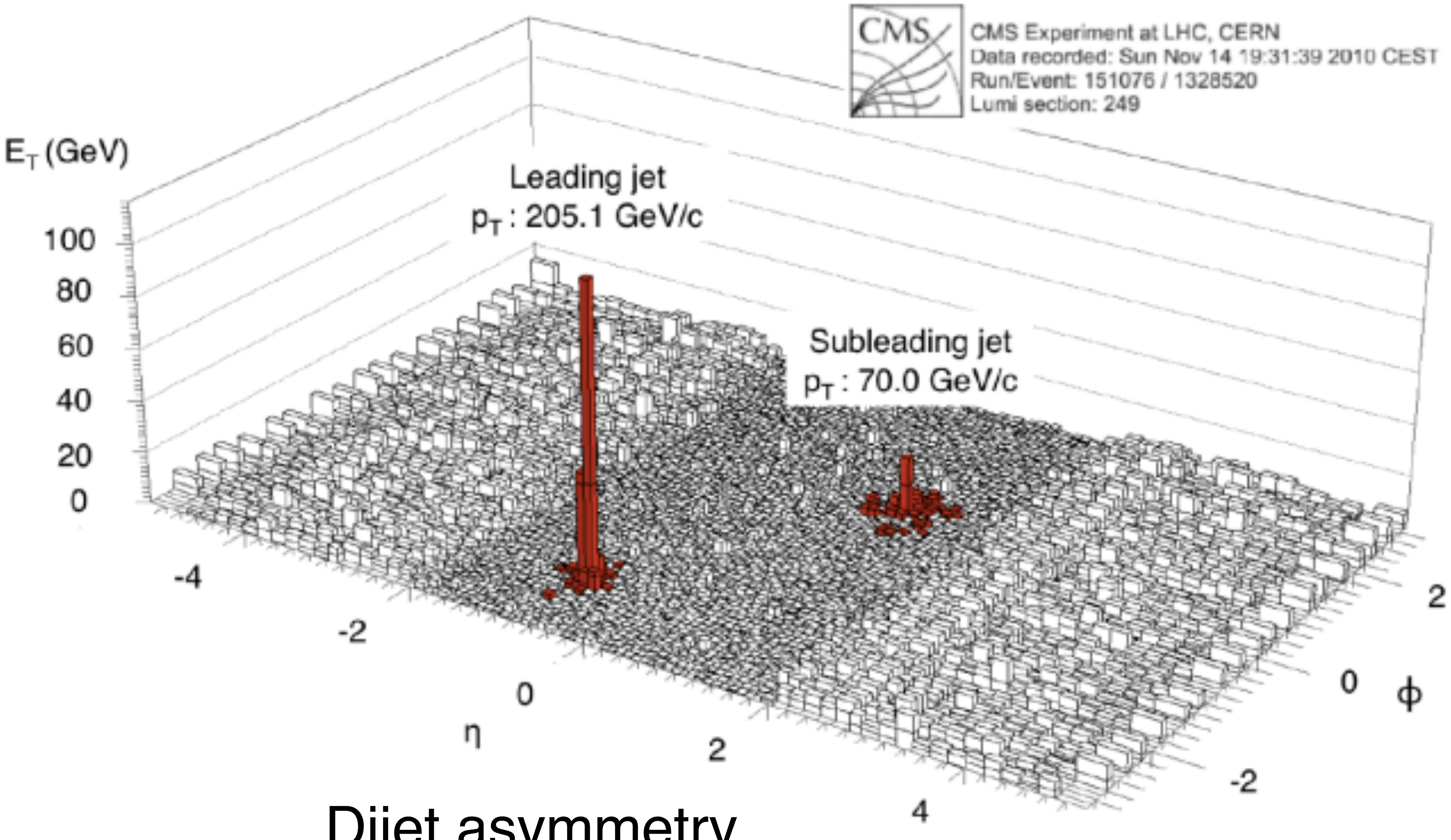

CMS
CMS Experiment at LHC, CERN
Data recorded: Sun Nov 14 19:31:39 2010 CEST
Run/Event: 151076 / 1328520
Lumi section: 249
Jet 1, pt: 70.0 GeV
Jet 0, pt: 205.1 GeV

Dijet Asymmetry



Traditional interpretation:

→ Path length difference within QGP.



Dijet asymmetry

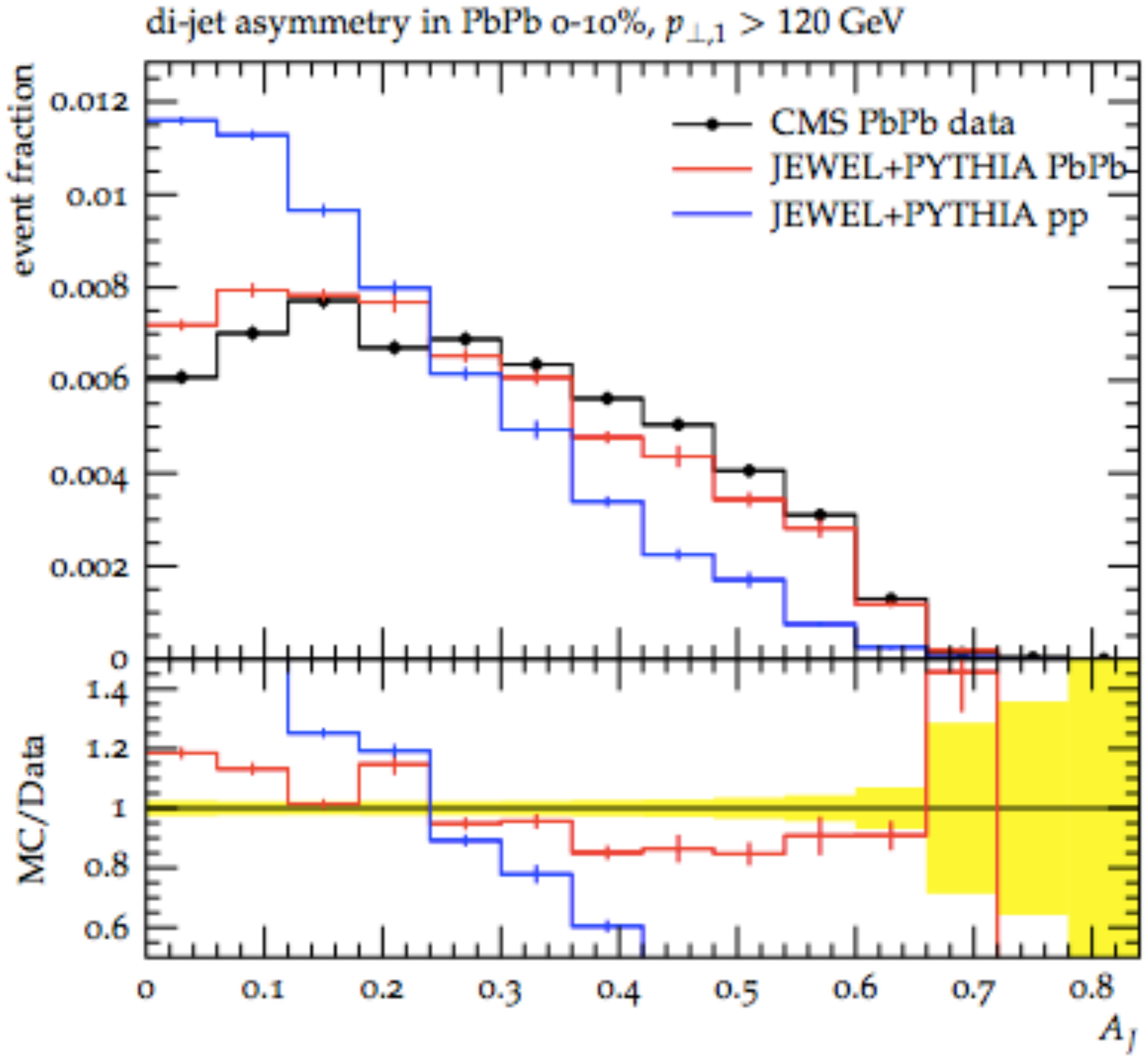
Based on single parton energy loss processes:

- Medium induced radiation
- Elastic collisions

} Controlled by transport parameter $\hat{q}\ [\mathrm{GeV}^2/\mathrm{fm}]$

GW '94
BDMPS-Z '97
AMY '02

Dijet Asymmetry



$$A_J = \frac{p_{\perp,1} - p_{\perp,2}}{p_{\perp,1} + p_{\perp,2}}$$

JEWEL jet energy loss Monte Carlo model:

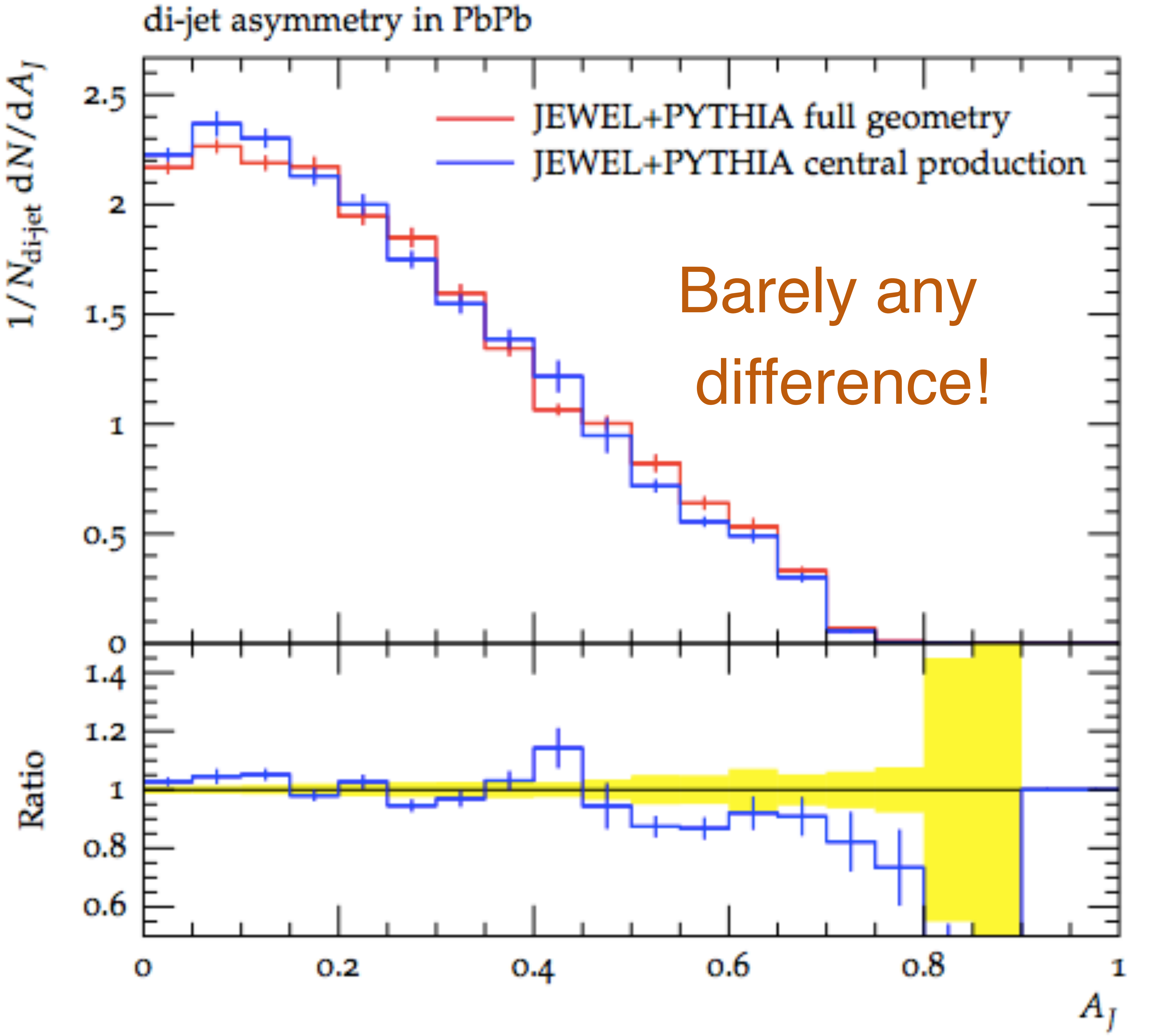
- Partons can collide with the medium scatterers.
- After-collision kinematics can alter the radiation pattern.
- Actual radiation pattern based on shortest formation time.

Good description of dijet asymmetry data.

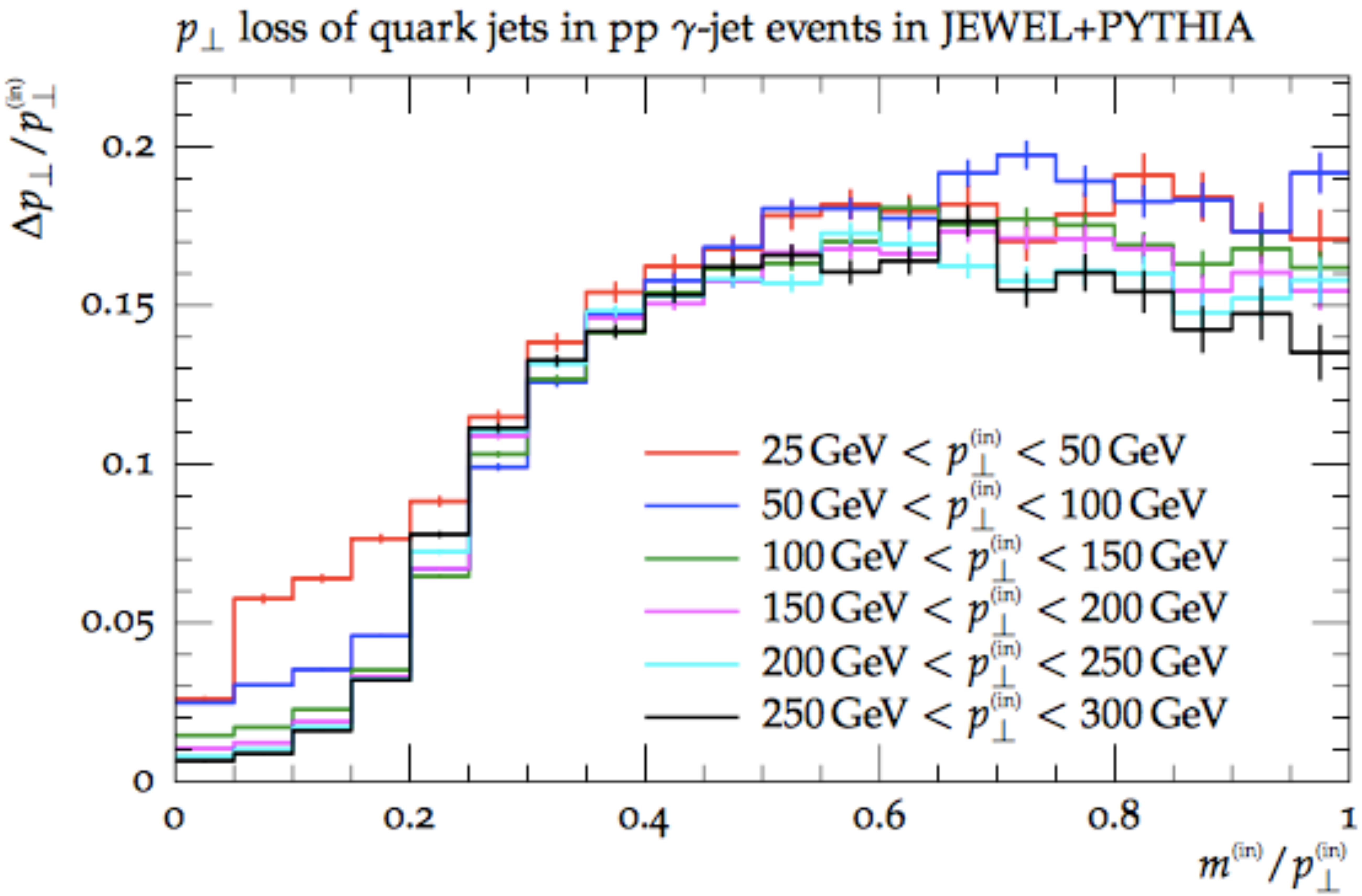
Look under the hood…

Milhano & Zapp - EPJ '16

Dijet Asymmetry



Barely any difference!



Full geometry

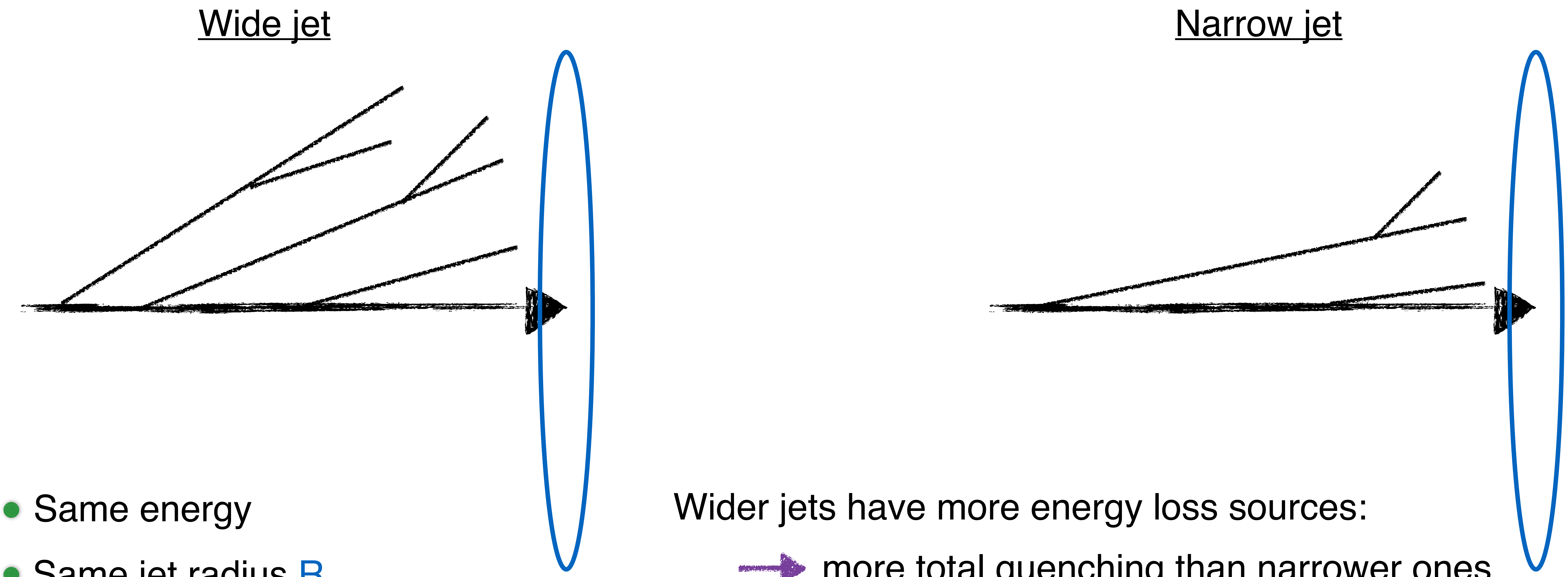
vs

Central production

Milhano & Zapp - EPJ '16

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

Jets and Jets



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

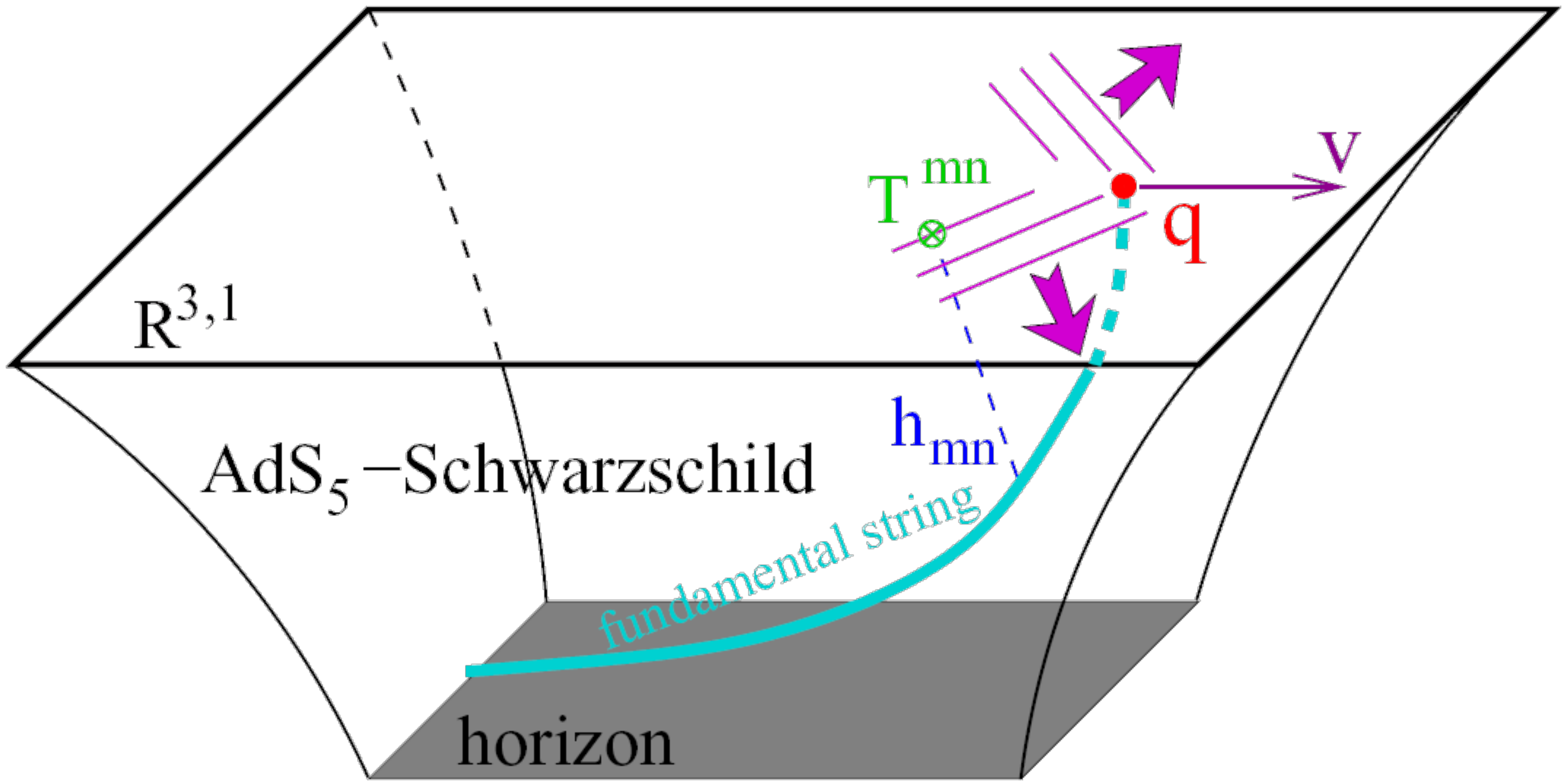
Wider jets have more energy loss sources:

→ more total quenching than narrower ones

Assuming:

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

Holography



J Friess, et al., PRD75 (2007)

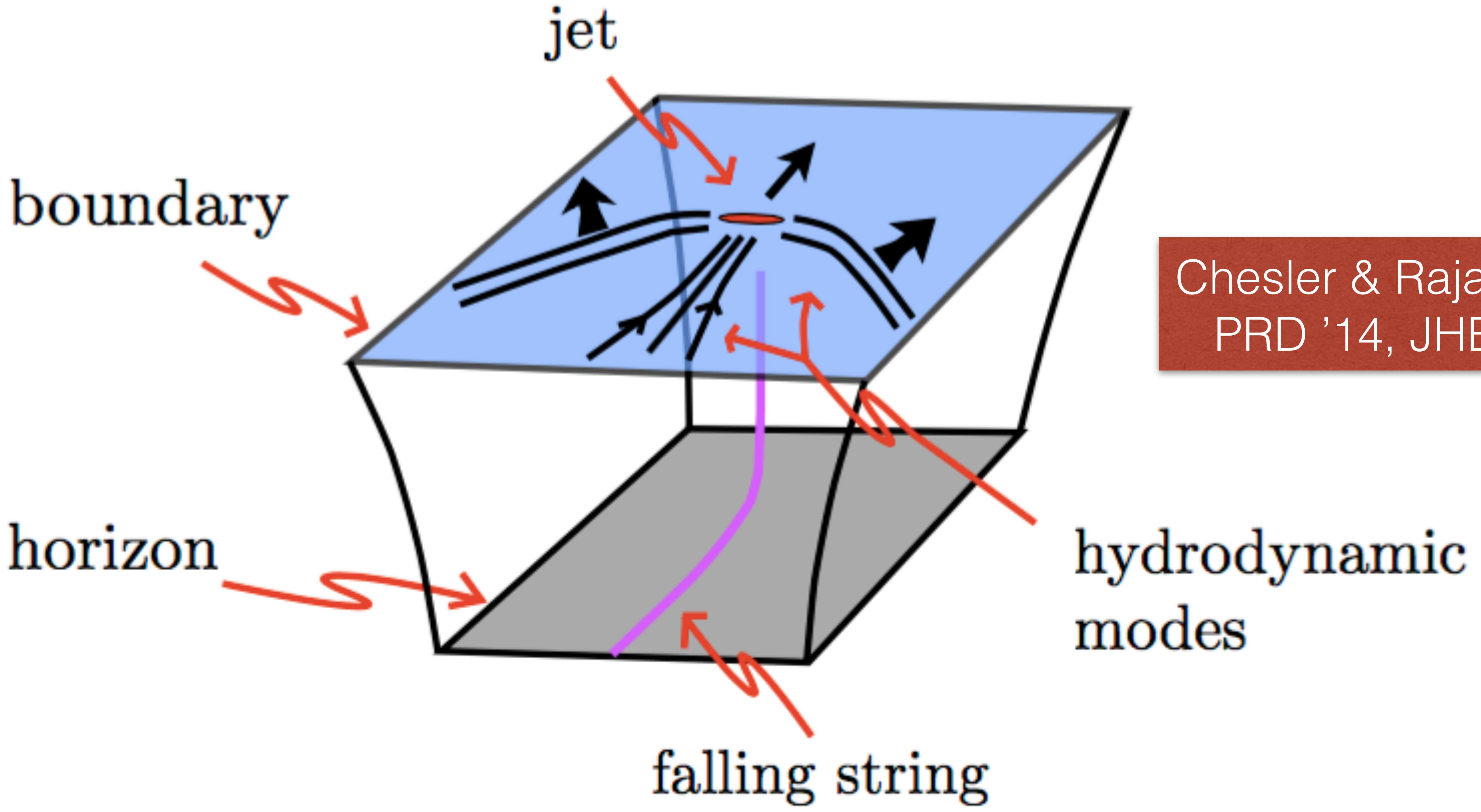
- quarks are dual to open strings attached to probe flavour branes
- having a plasma in the gauge theory is equivalent to a black hole in the bulk
- bulk metric perturbations encode boundary stress energy variations

! $\mathcal{N}=4$ SYM and QCD have very different vacuums

but

? $\mathcal{N}=4$ $T\neq 0$ and QCD $T>T_c$ share similarities

Null falling strings

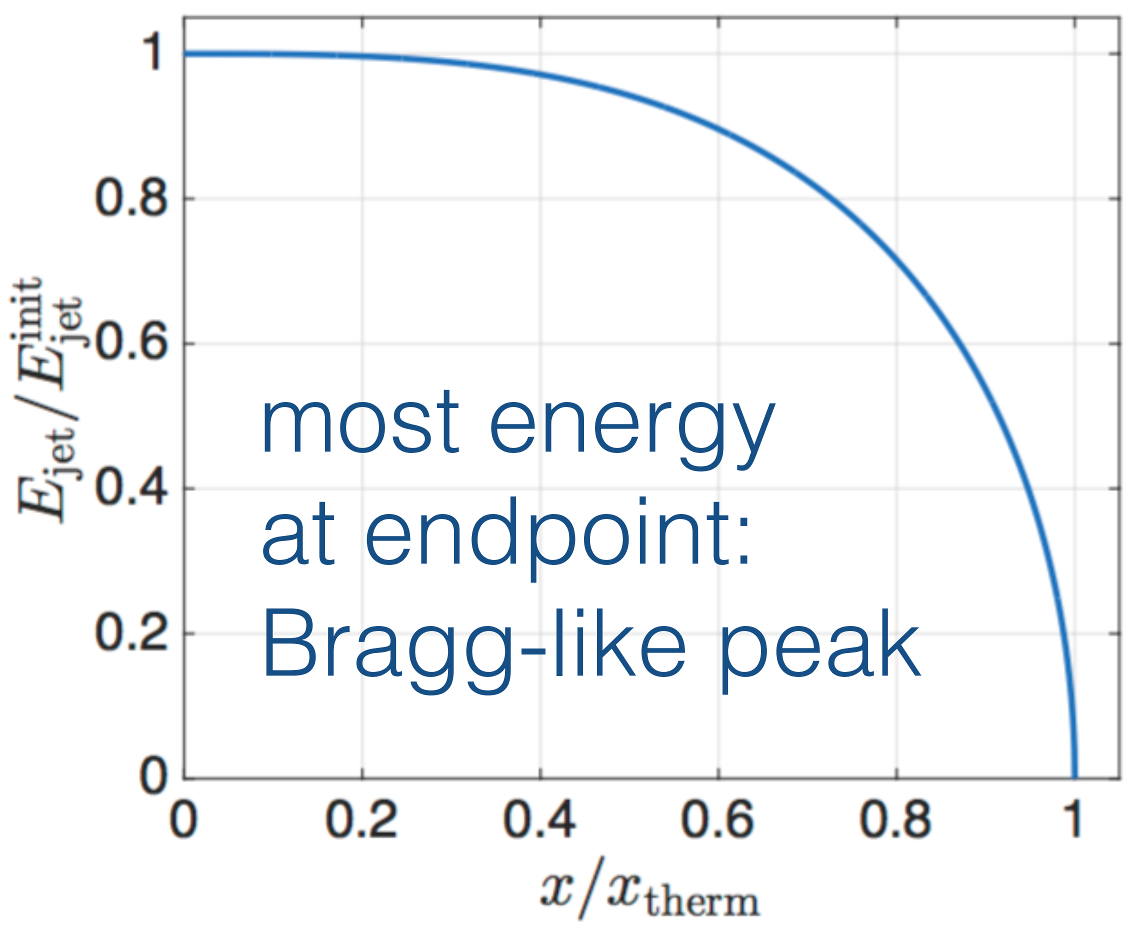


Chesler & Rajagopal - PRD '14, JHEP '16

- unambiguous determination of boundary jet properties
- the rate at which energy flows into hydrodynamic modes:

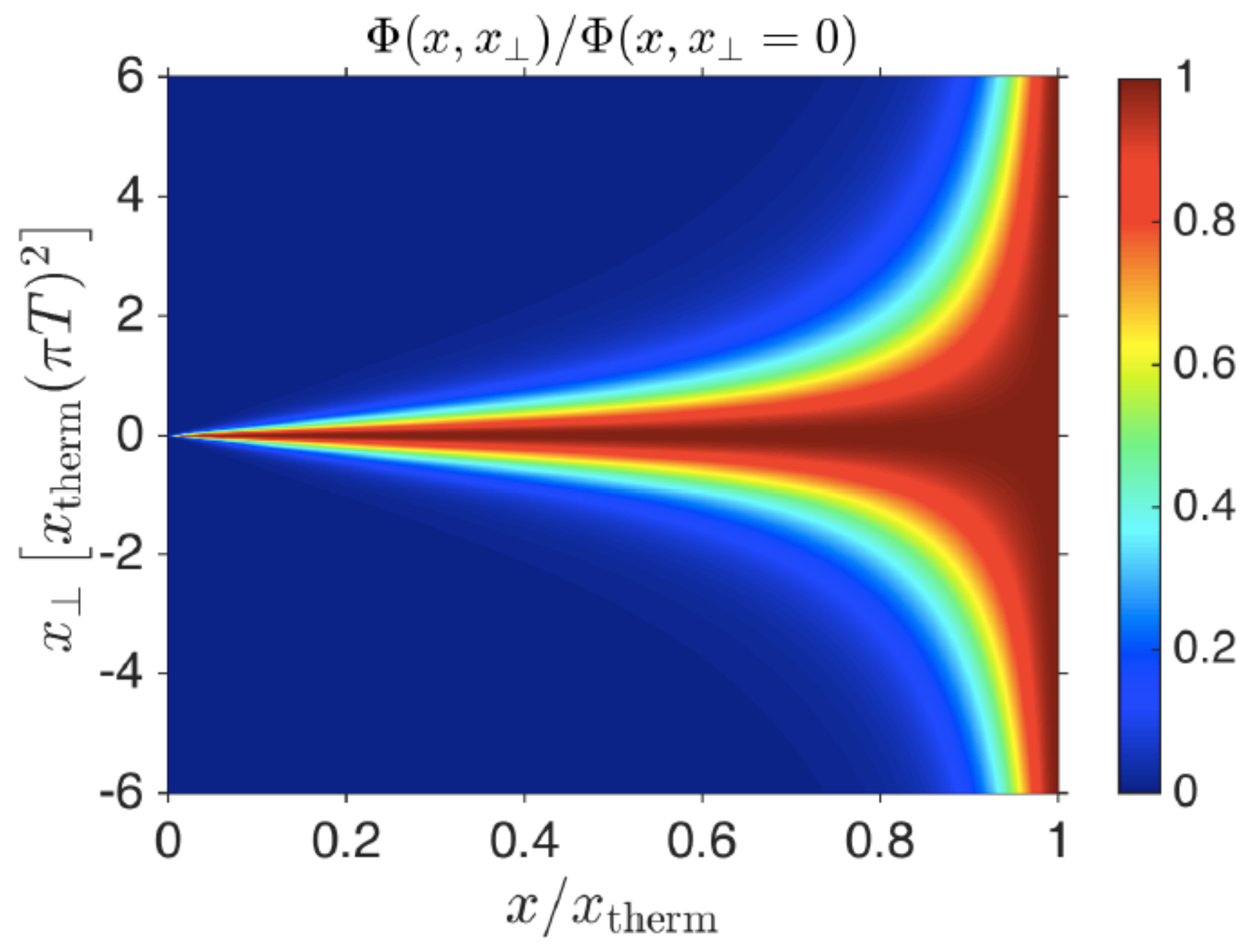
$$\frac{1}{E_{\rm init}}\frac{dE_{\rm jet}}{dx} = -\frac{4x^2}{\pi x_{\rm therm}^2\sqrt{x_{\rm therm}^2 - x^2}}$$

as the jet loses energy



most energy at endpoint: Bragg-like peak

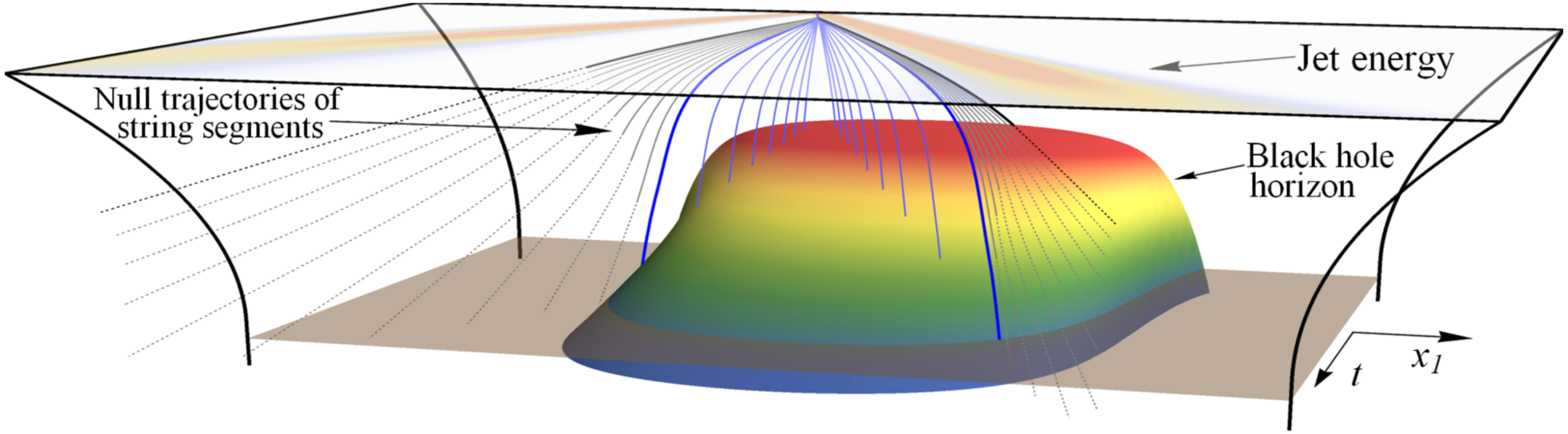
… it gets wider



Fractional energy loss only depends on initial jet opening angle

$$x_{\rm therm} = \frac{1}{T}\sqrt{\frac{\kappa}{\theta_{\rm jet}^{\rm init}}}$$

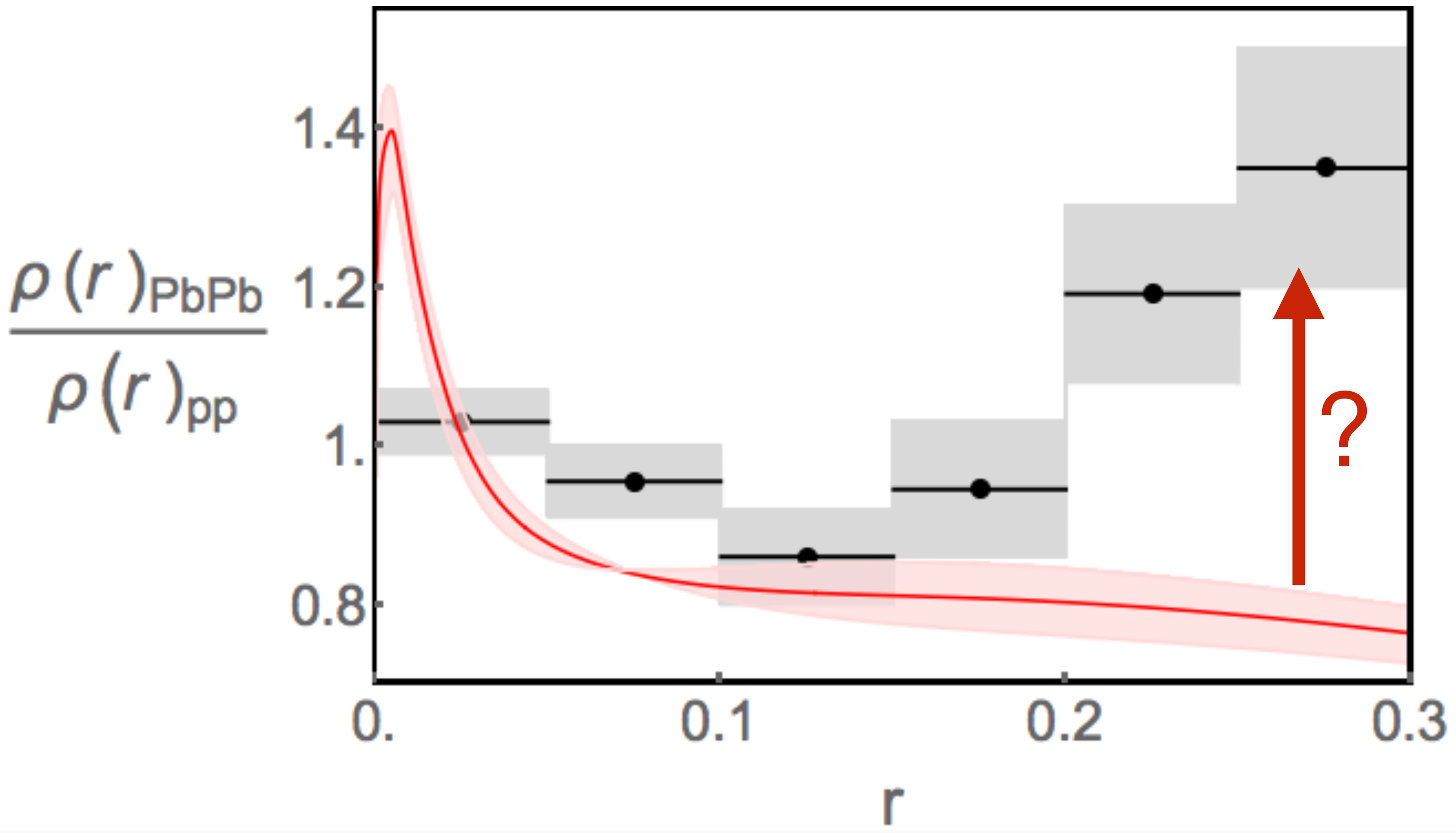
Holographic quenching with pure strings



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

Rajagopal et al. - PRL '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



Jet shapes:
transverse jet energy distribution vs radial distance

Jet narrowing due to selection bias!

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

measures jet angle in pQCD

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

The hybrid strong/weak coupling model

- Evolution of high virtuality energetic jets dominated by DGLAP evolution;

- Interaction of partons with QGP of T~Λ_{QCD} is strongly coupled;

- Energy and momentum deposited in the QGP hydrodynamize quickly;

The hybrid strong/weak coupling model

→ Evolution of high virtuality energetic jets dominated by DGLAP evolution;

- Parton shower generated with PYTHIA8.
- Formation time argument for space-time picture.

Pablos et al. - JHEP '14, '16, '17

→ Interaction of partons with QGP of T~ Λ_{QCD} is strongly coupled;

- Energy loss rate from holography:

Chesler & Rajagopal - PRD '14, JHEP '16

$$\frac{1}{E_{\text{in}}}\frac{dE}{dx} = -\frac{4}{\pi}\frac{x^2}{x^2_{\text{stop}}}\frac{1}{\sqrt{x^2_{\text{stop}} - x^2}}$$

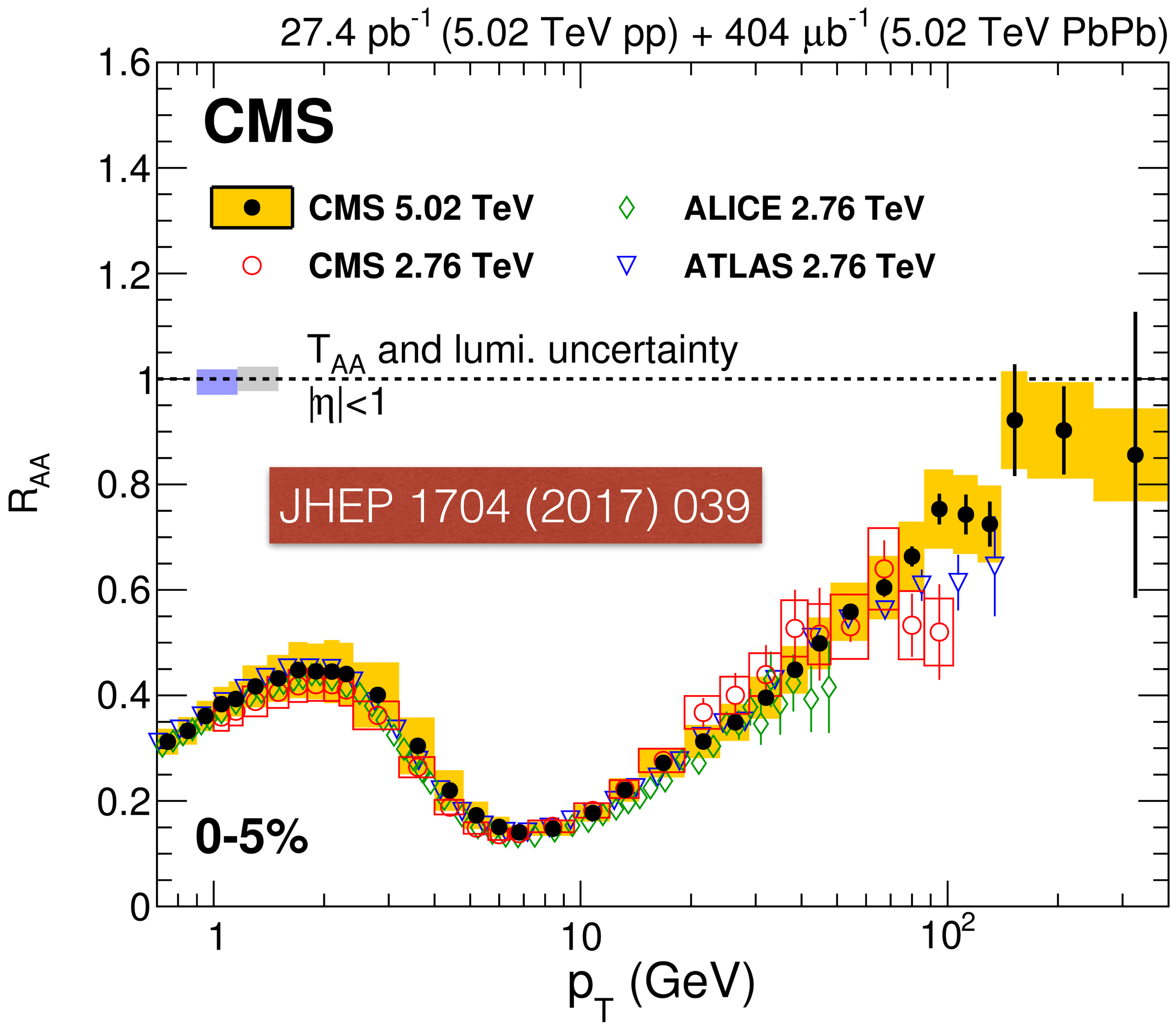
$$x_{\text{stop}} = \frac{1}{2\kappa_{\text{sc}}}\frac{E_{\text{in}}^{1/3}}{T^{4/3}}$$

$\mathcal{O}(1)$ free parameter

→ Energy and momentum deposited in the QGP hydrodynamize quickly;

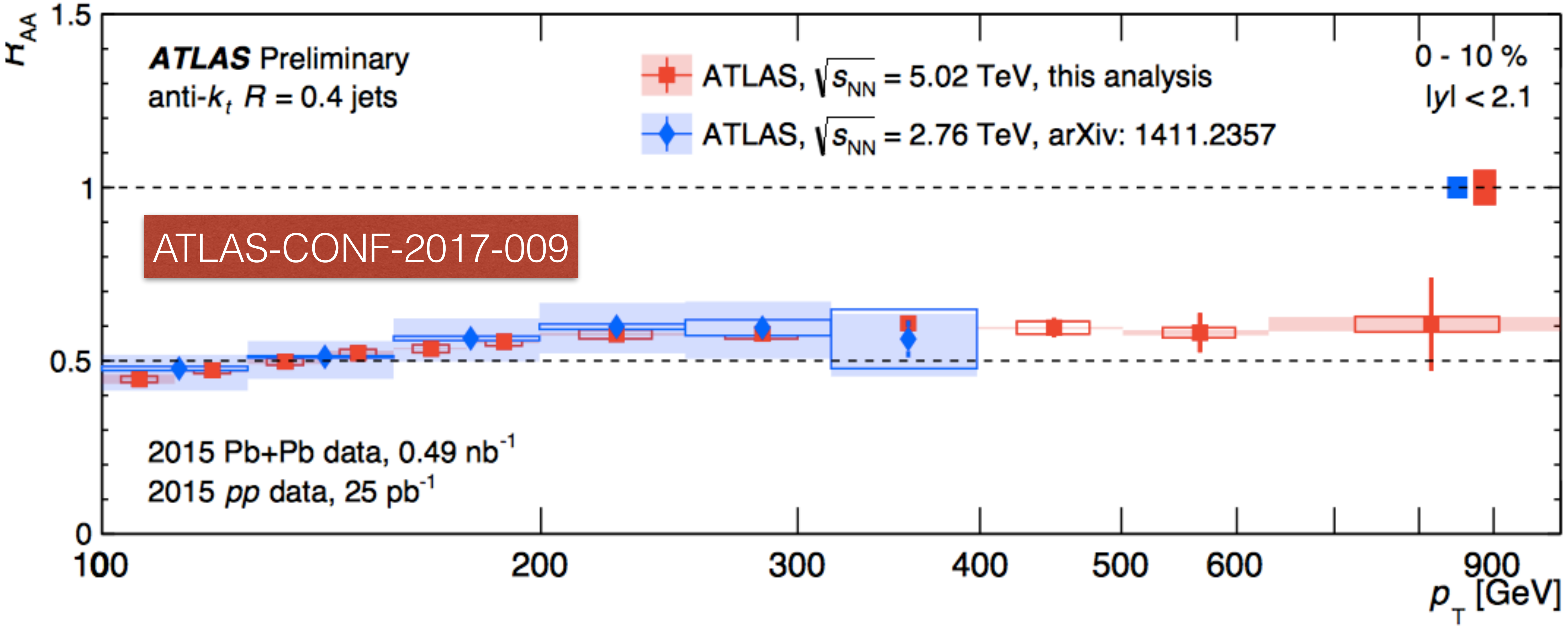
- Compute modified hadron spectrum from perturbed freeze-out hyper-surface.
- Produce soft, thermal particles correlated with jet direction.

Jet vs Hadron Suppression



JHEP 1704 (2017) 039

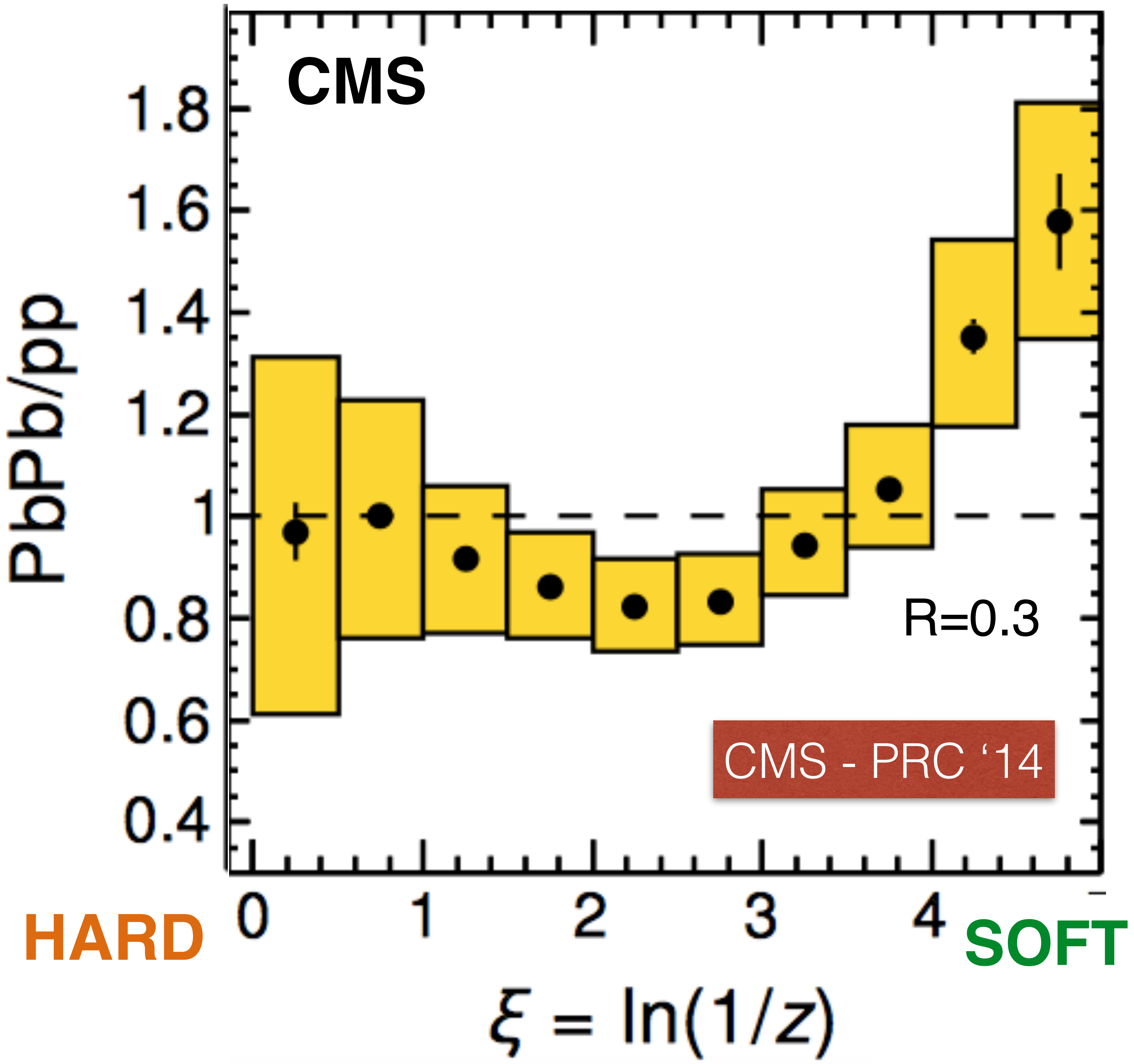
Precise data available up to very high momentum



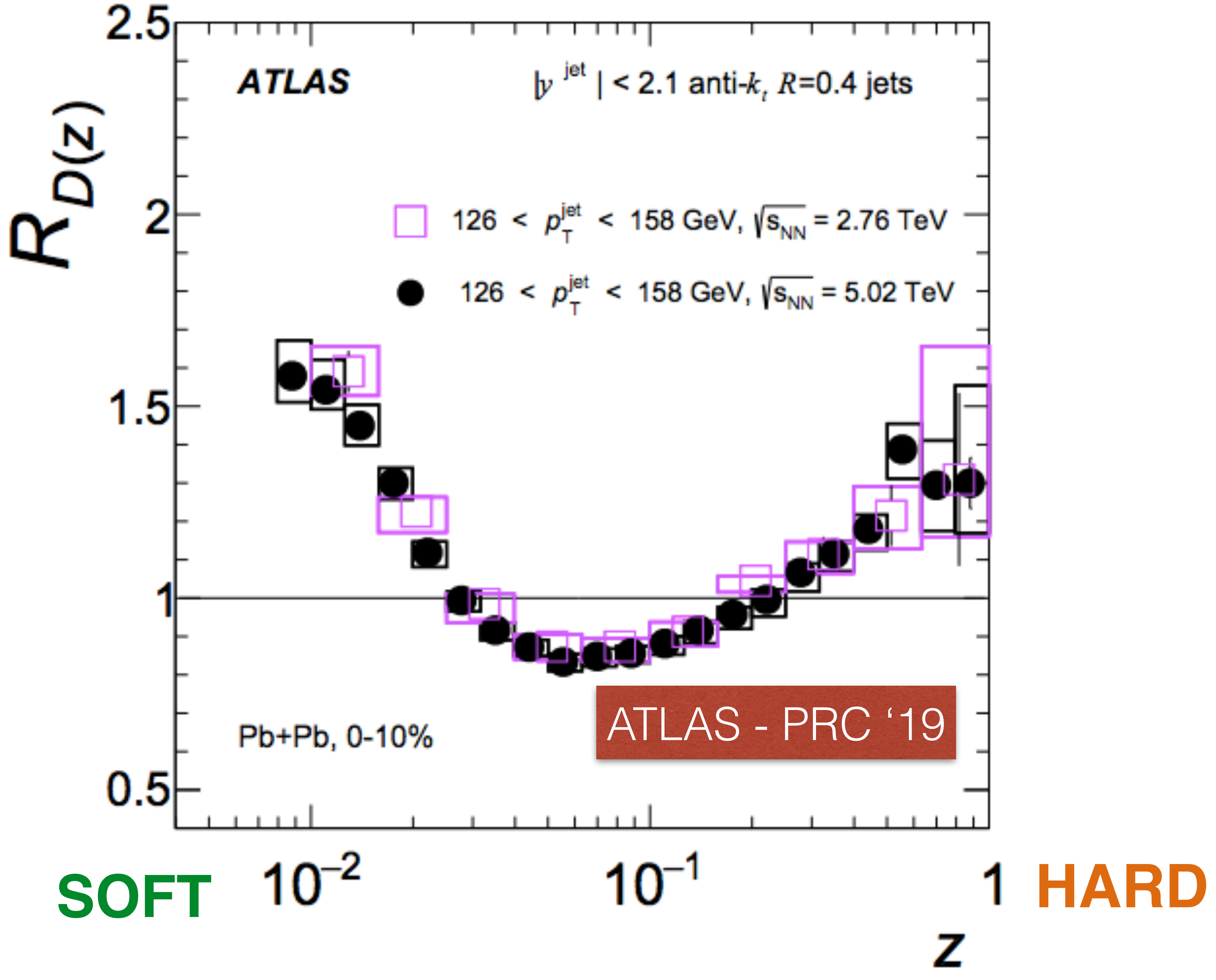
ATLAS-CONF-2017-009

- How to understand high momentum behaviour?
- Different asymptotic trend for jets than for hadrons?

Jet Fragmentation Functions (FFs)



CMS - PRC ‘14



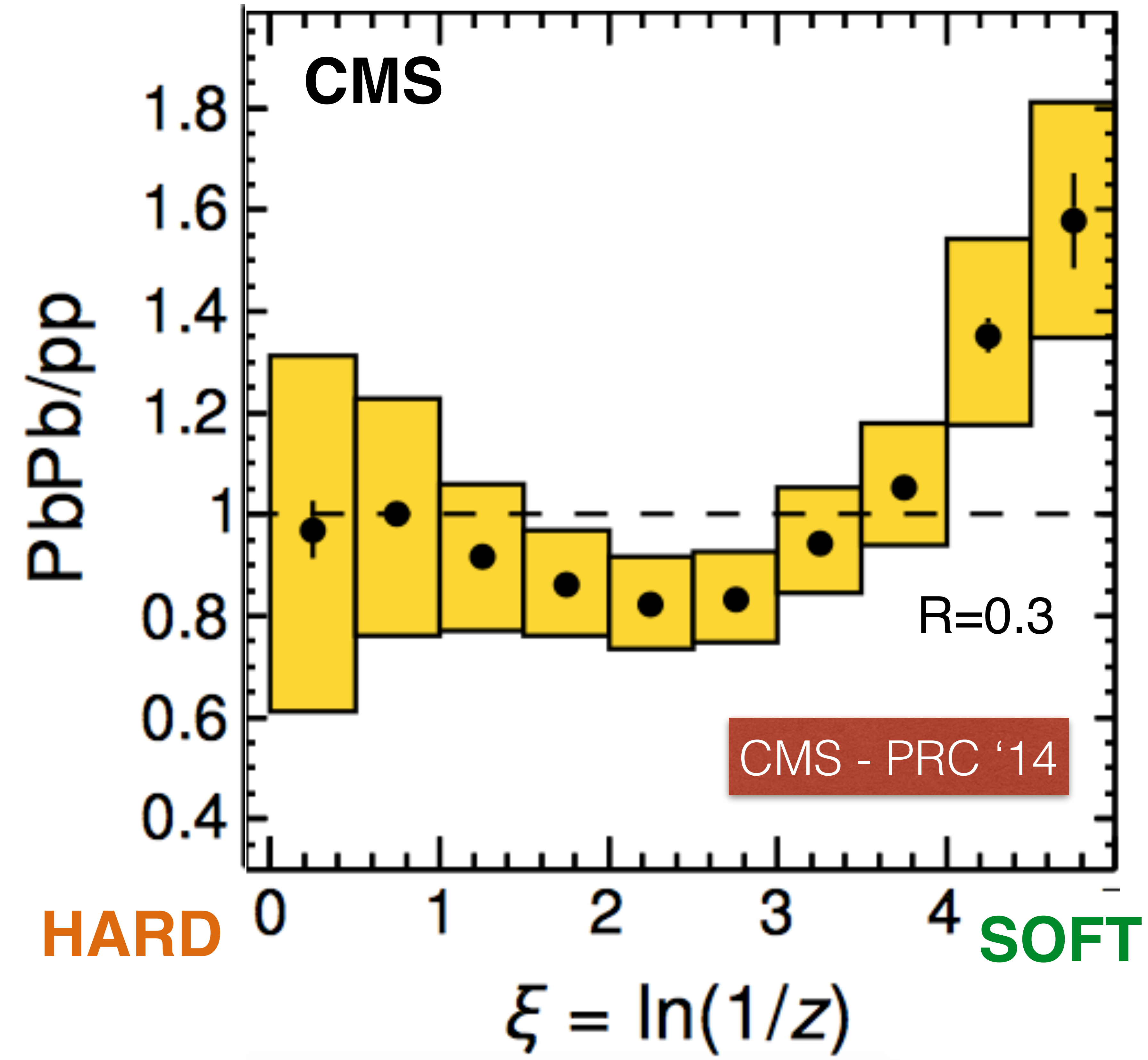
ATLAS - PRC ‘19

Jet FFs count the number of hadrons, per jet, with an energy fraction *z*

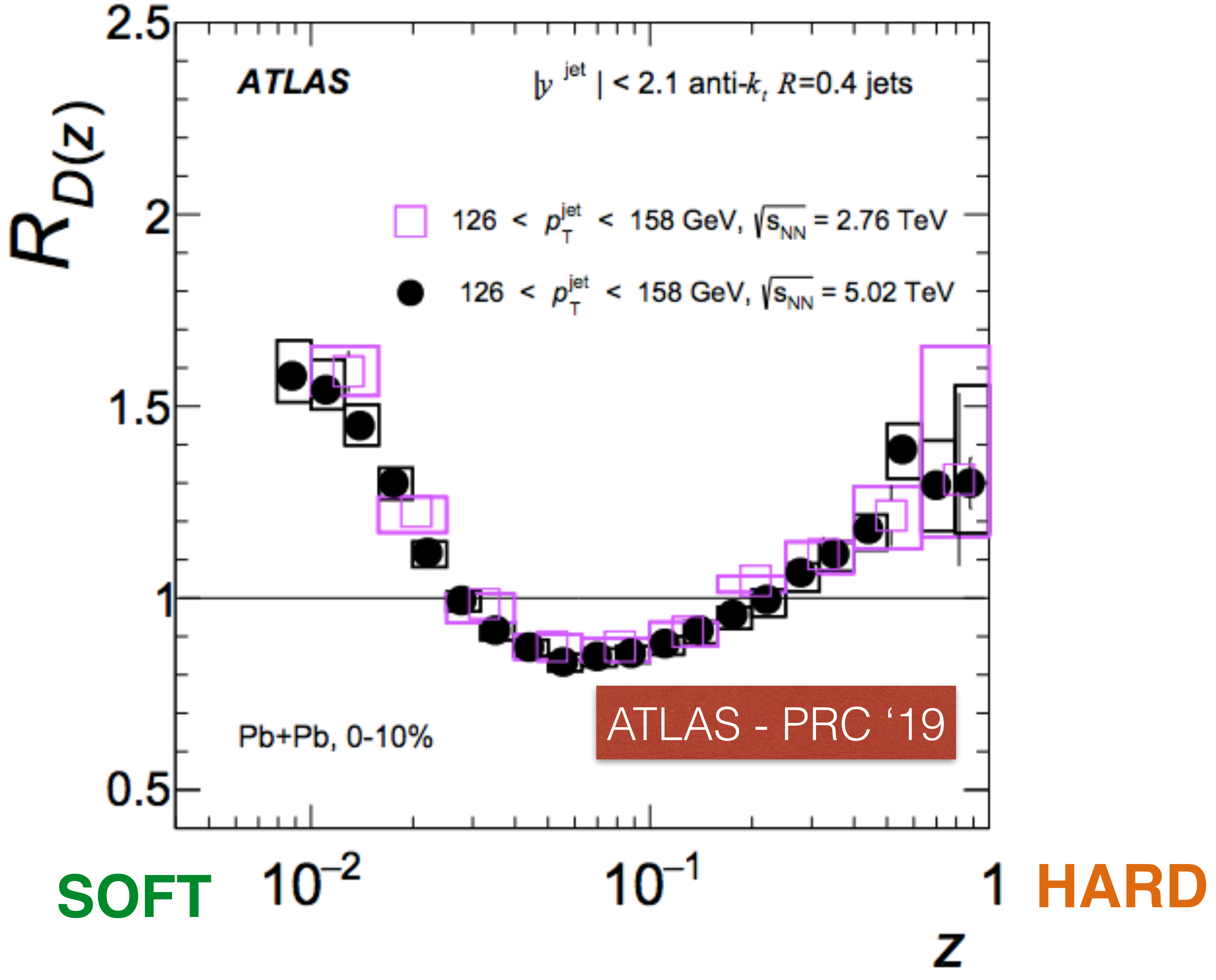
Soft particle enhancement w.r.t. pp jets

- Medium back-reaction to deposited energy & momentum — Pablos et al. - JHEP ‘17 — He et al. - PRC ‘15
- Antenna decoherence breaks angular ordering — Mehtar-Tani et al. - PLB ‘12 — Caucal et al. - 2005.05852

Jet Fragmentation Functions (FFs)



CMS - PRC '14



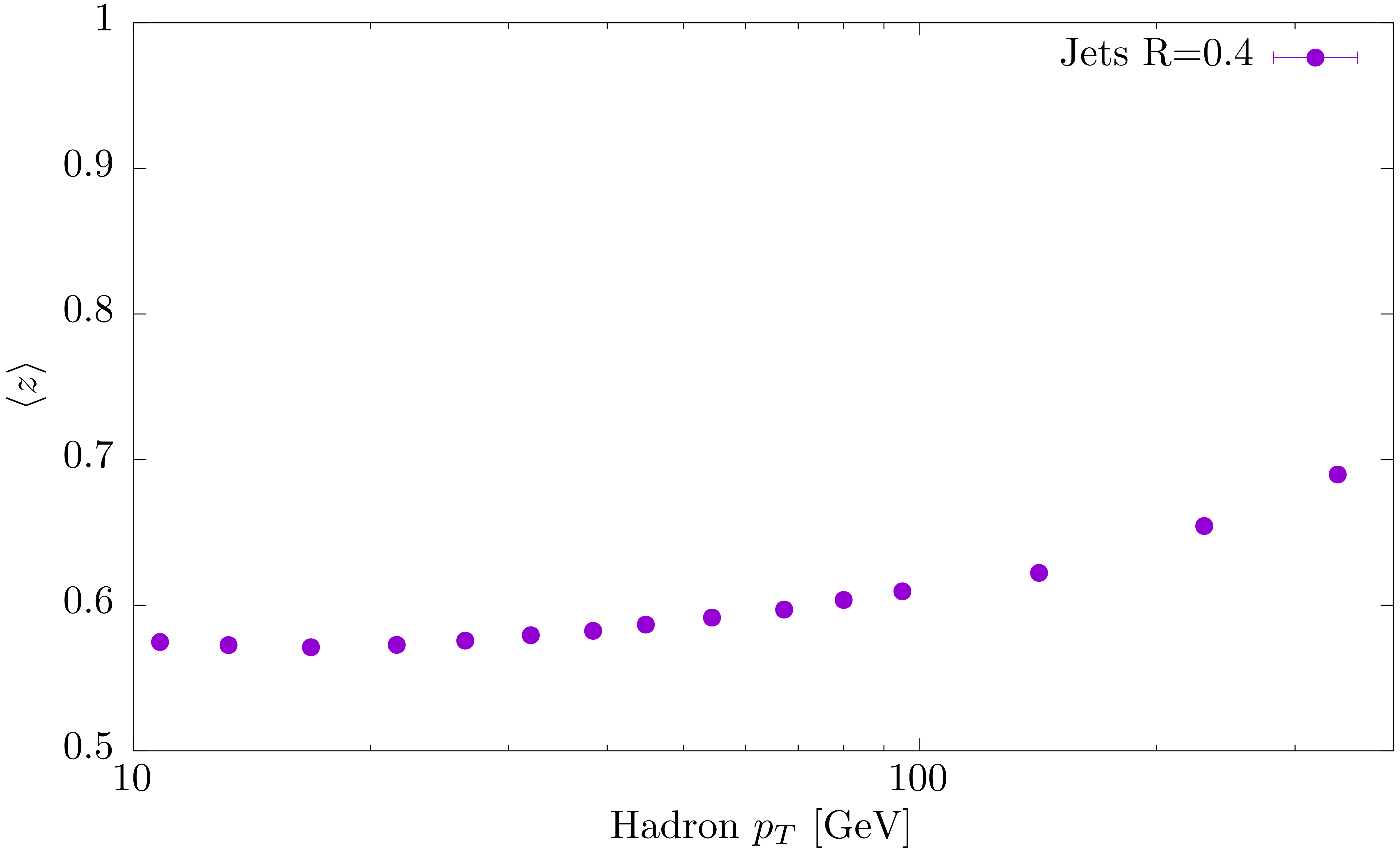
ATLAS - PRC '19

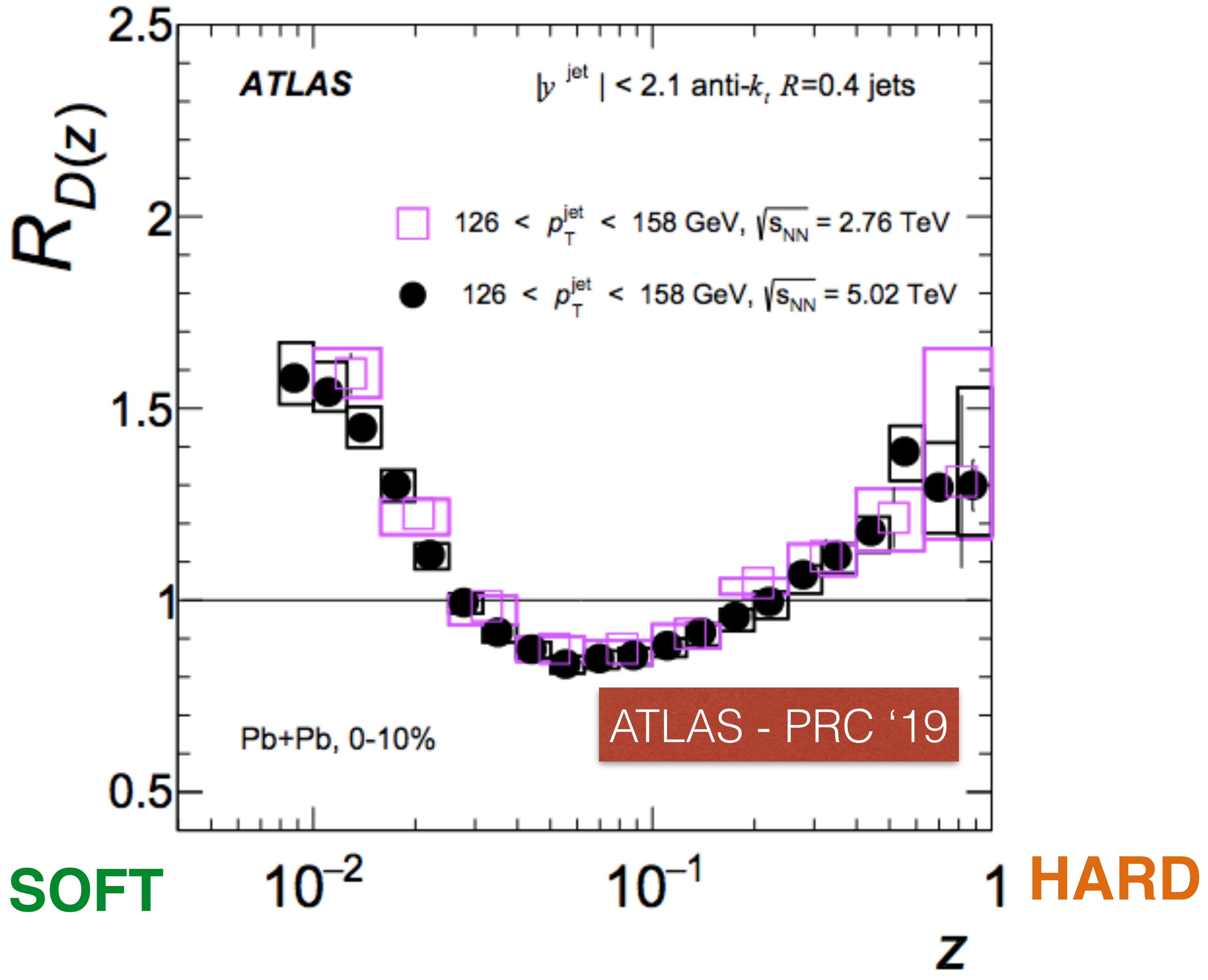
Jet FFs count the number of hadrons, per jet, with an energy fraction *z*

Hard particle enhancement w.r.t. pp jets

Steeply falling jet spectrum → High p_T hadron spectrum dominated by leading tracks (from hard fragmenting jets)

Jet Fragmentation Functions (FFs)





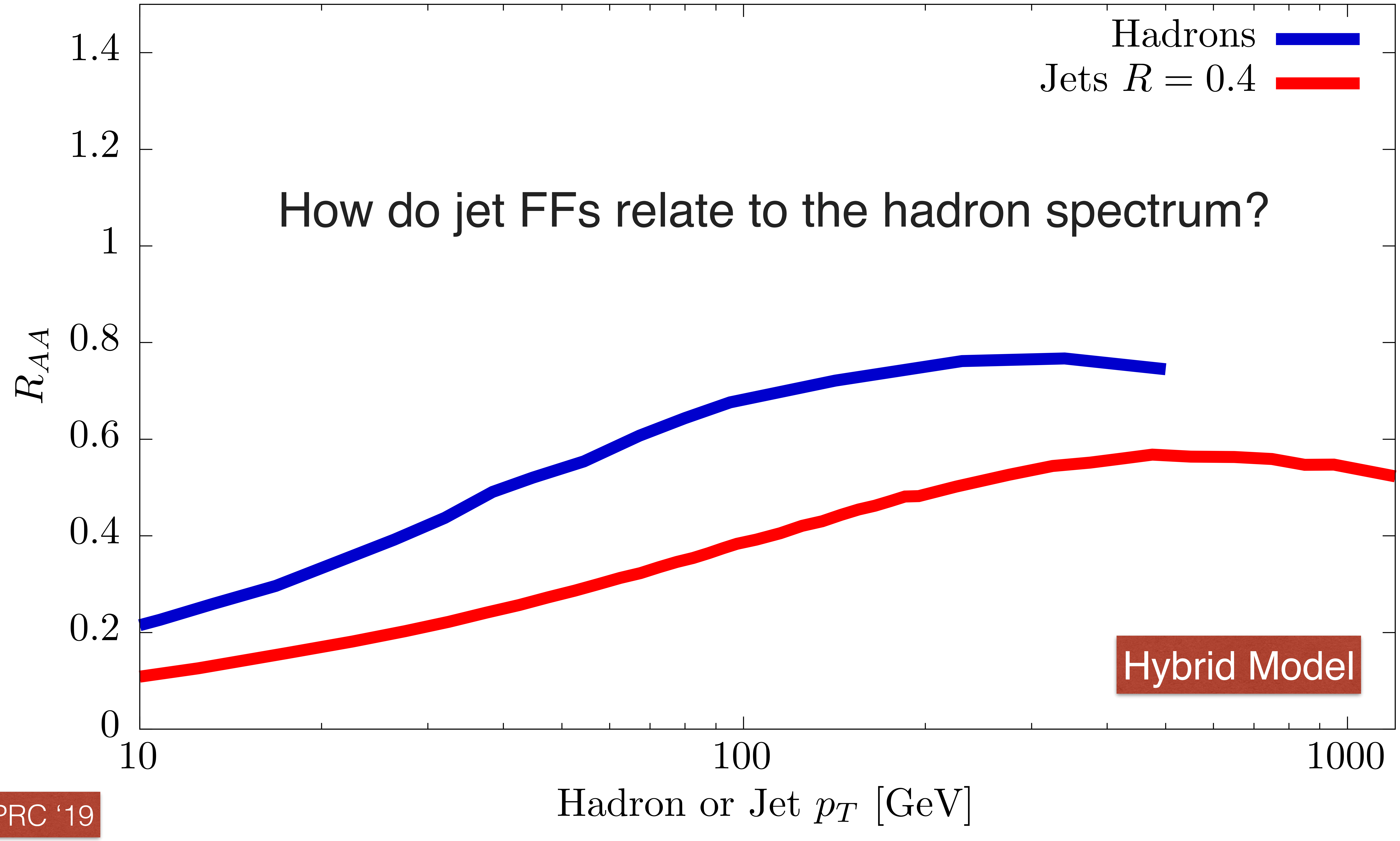
ATLAS - PRC ‘19

Jet FFs count the number of hadrons, per jet, with an energy fraction *z*

Hard particle enhancement w.r.t. pp jets

High z region of jet FFs closely related to hadronic spectrum

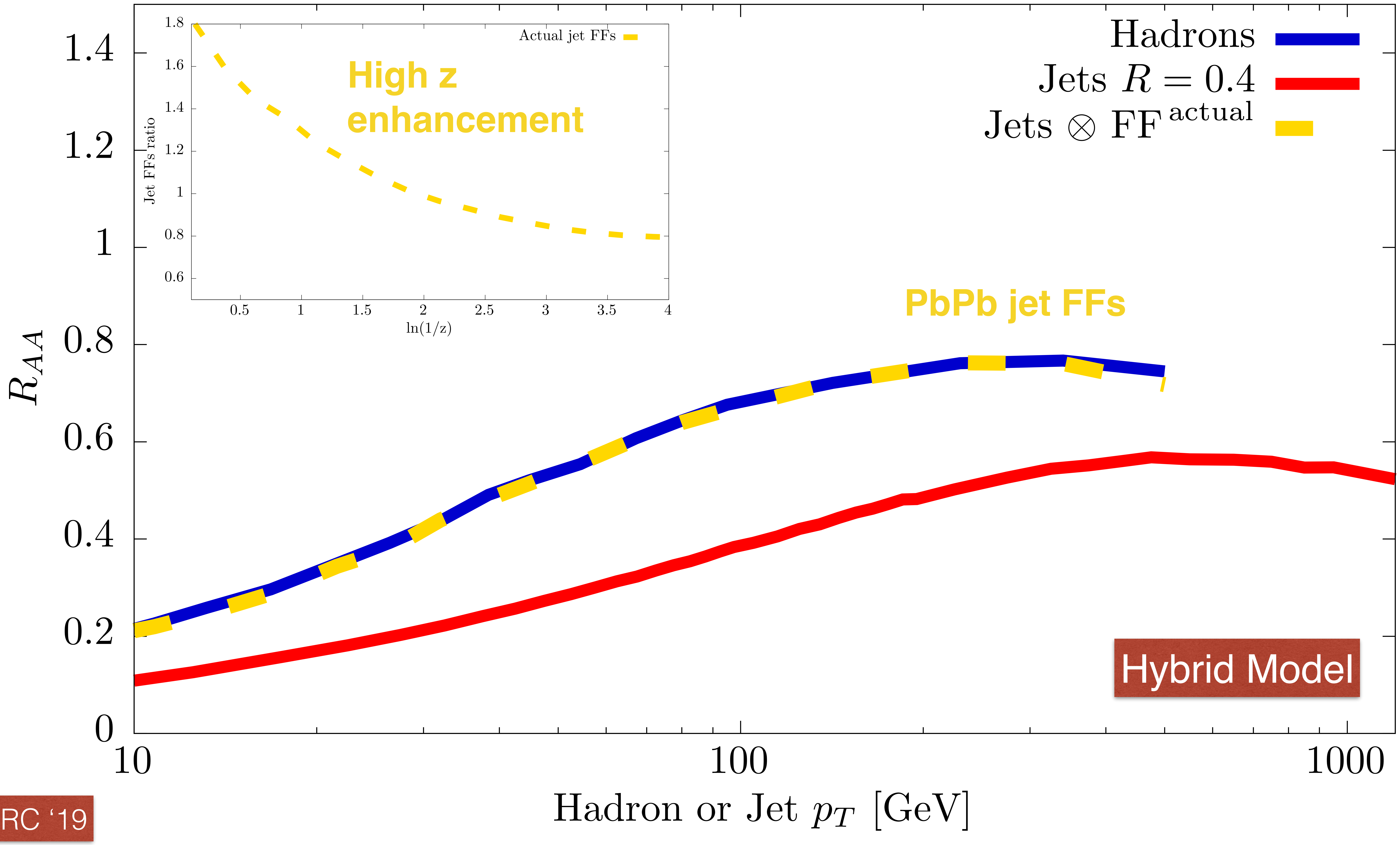
Jets, their FFs, and hadrons



How do jet FFs relate to the hadron spectrum?

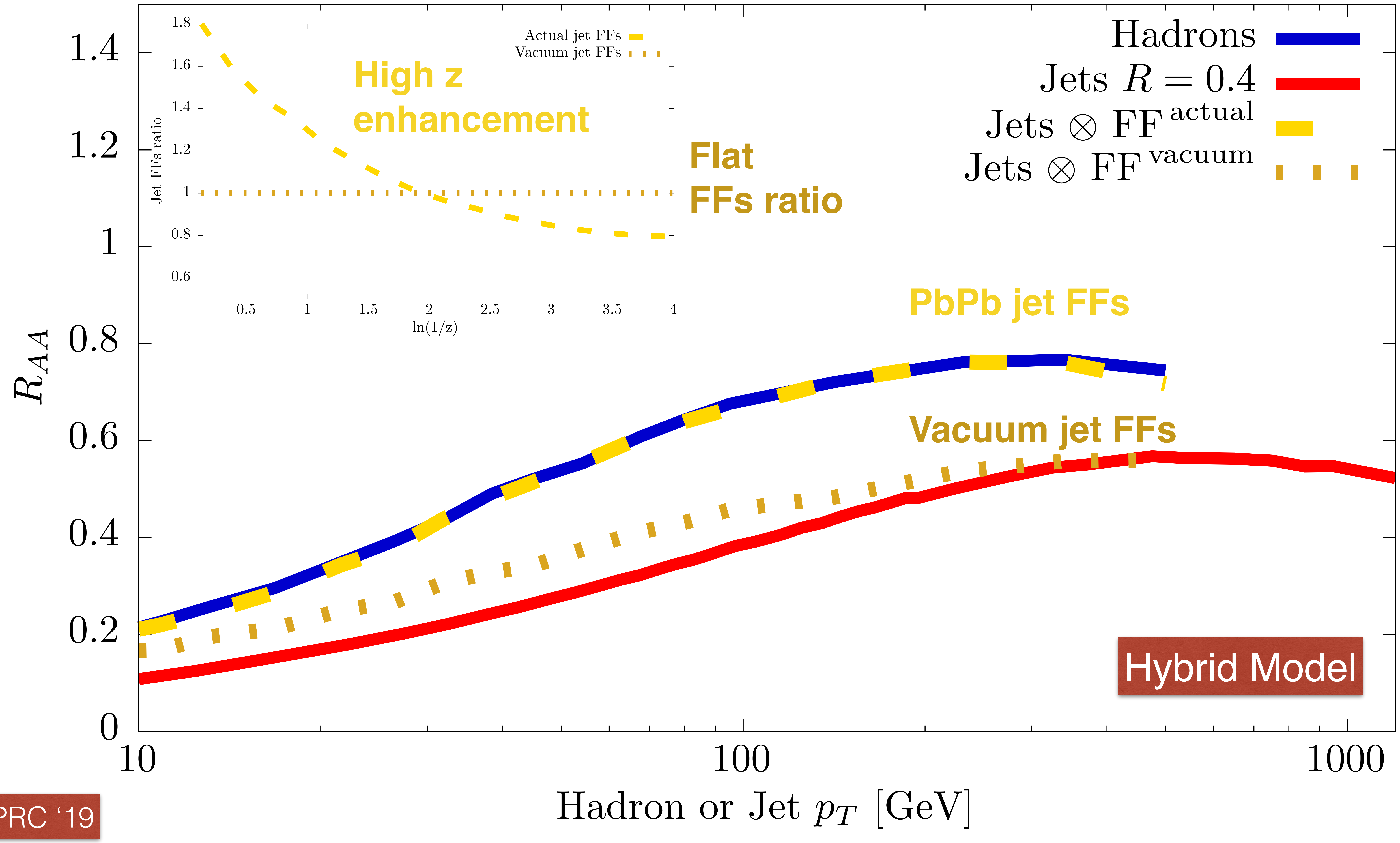
Pablos et al. - PRC ‘19

Jets, their FFs, and hadrons



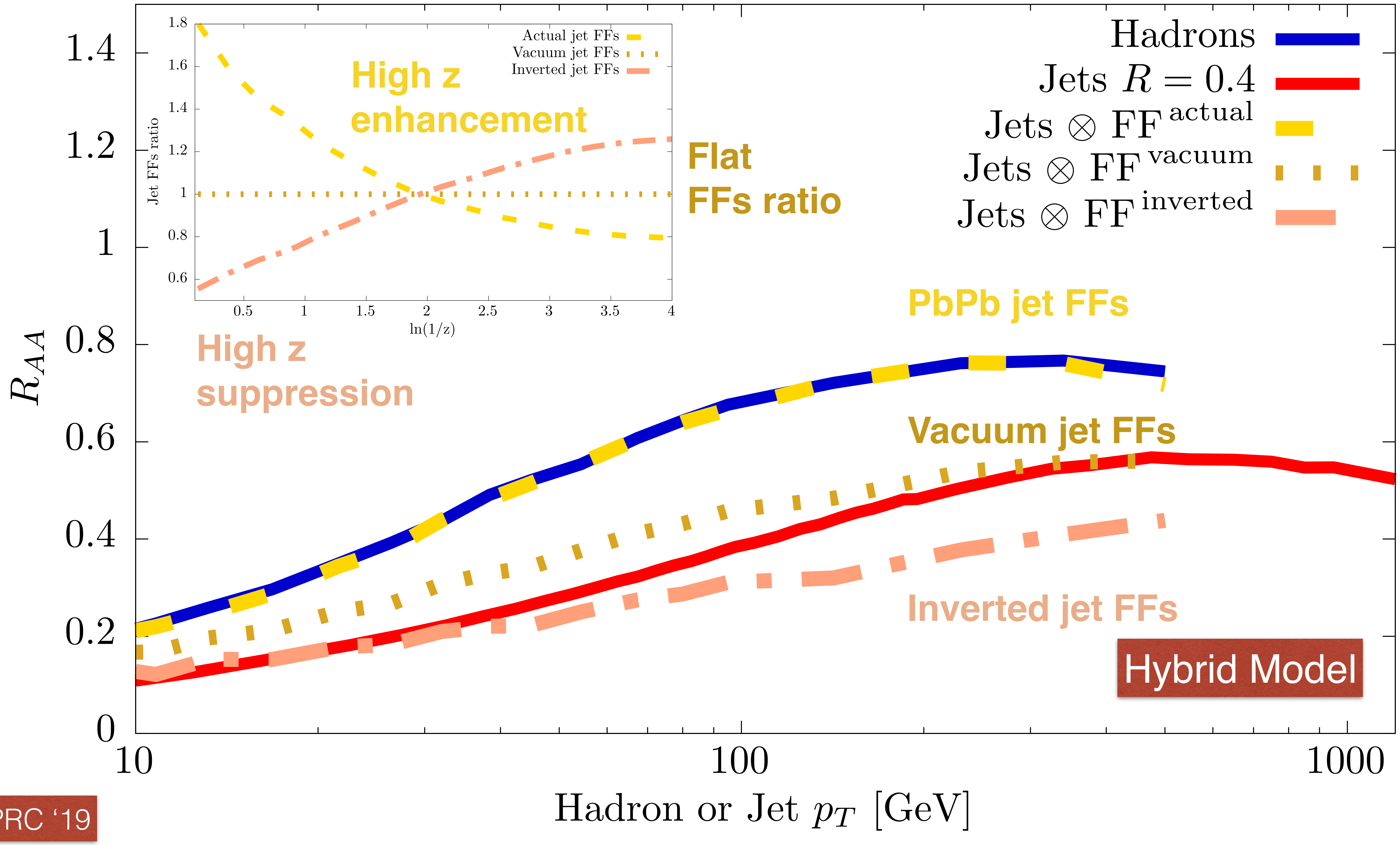
Pablos et al. - PRC '19

Jets, their FFs, and hadrons



Pablos et al. - PRC '19

Jets, their FFs, and hadrons



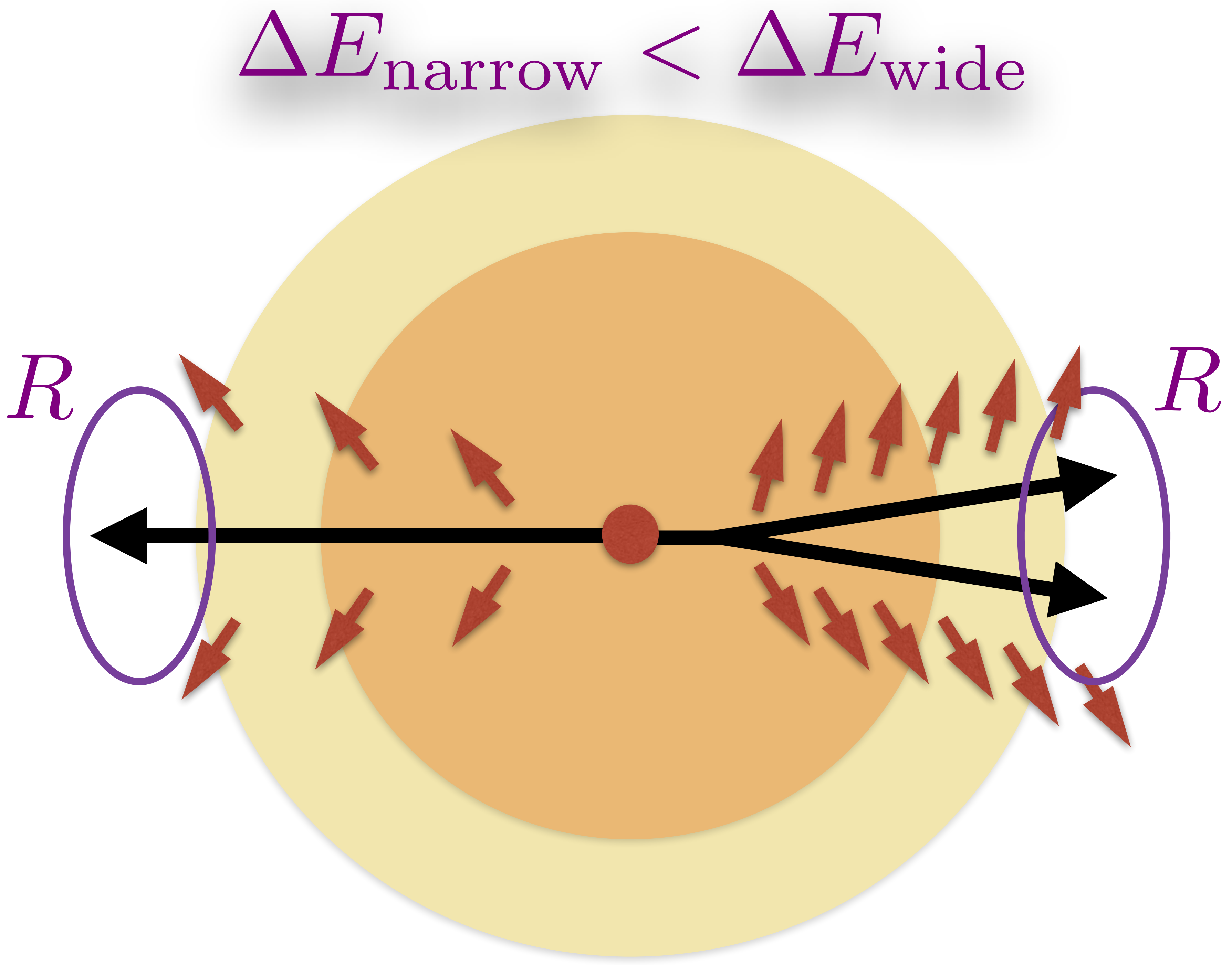
Pablos et al. - PRC '19

Jet narrowing: a selection bias

Wider, more active jets lose more energy than narrower, hard fragmenting ones

Steeply falling jet spectrum → bias inclusive jet sample to narrower ones, explains high z enhancement

High p



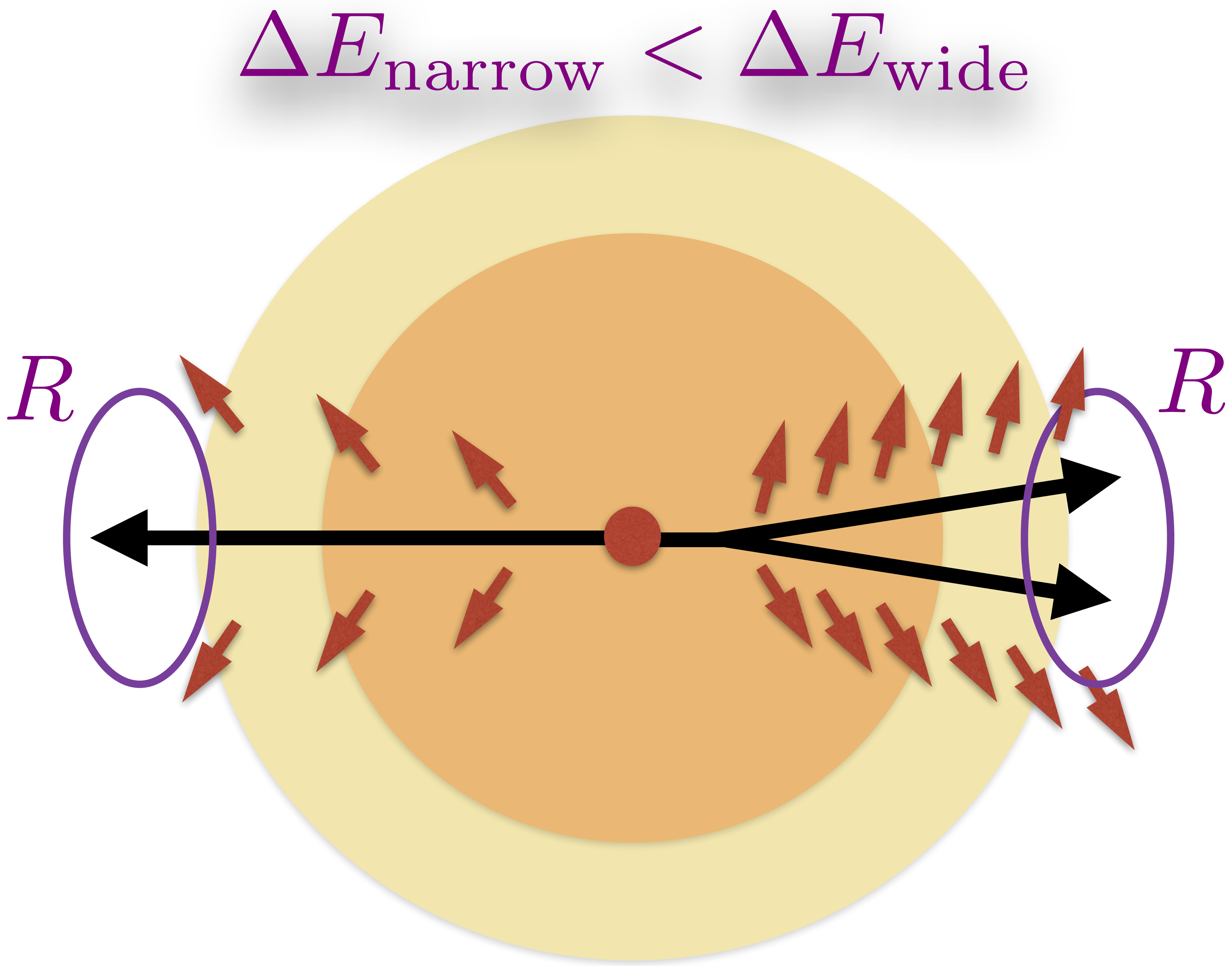
Jet narrowing: a selection bias

<u>Wider, more active jets lose more energy than narrower, hard fragmenting ones</u>

Steeply falling jet spectrum → bias inclusive jet sample to narrower ones, explains high z enhancement

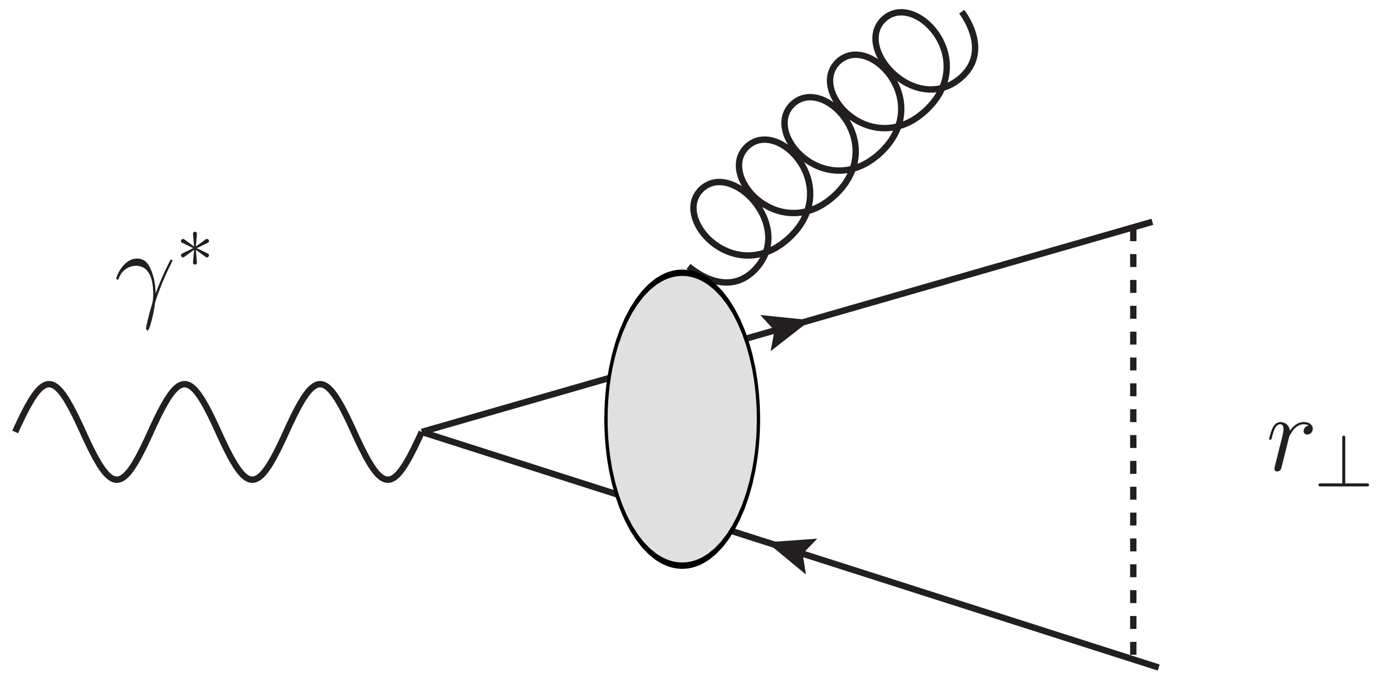
High p_T hadrons belong to such subsample of narrow jets, which get less quenched, and so $R_{AA}^{had} > R_{AA}^{jet}$

But, how well does the QGP resolve the internal structure of the jet?



Coherence in Vacuum: Heuristic Interpretation

Need to think in terms
of the *formation time*



Time at which the gluon decorrelates from the quark:

$$\tau_f = \frac{w}{k_\perp^2} = \frac{1}{w\theta^2}$$

- Transverse size of the gluon is $\lambda_\perp \sim \frac{1}{k_\perp} = \frac{1}{w\theta}$
- Size of the antenna when the gluon is being emitted $r_\perp = \theta_{q\bar{q}}\tau_f = \frac{\theta_{q\bar{q}}}{w\theta^2}$

Compare the two:

→ If $r_\perp < \lambda_\perp$ the gluon cannot resolve the pair: coherent
No emission (color singlet) $\frac{r_\perp}{\lambda_\perp} < 1 \rightarrow \theta_{q\bar{q}} < \theta_q$

→ If $r_\perp > \lambda_\perp$ independent emission by quark and antiquark $\frac{r_\perp}{\lambda_\perp} > 1 \rightarrow \theta_{q\bar{q}} > \theta_q$

Coherence in Vacuum: Heuristic Interpretation

Need to think in terms

Time at which the gluon decorrelates from the quark:

For medium induced emissions:

- Typical wavelength determined by interaction potential:

→ Dilute medium: Debye mass

→ Dense medium: Accumulated momentum $\hat{q}L$

- Color correlation can be lost through multiple scatterings.

→ If $r_\perp > \lambda_\perp$ independent emission by quark and antiquark $\frac{}{\lambda_\perp} > 1 \rightarrow \theta_{q\bar{q}} > \theta_q$

The QGP Resolution Length

QGP resolution length:

minimal distance between two coloured charges such that they engage with the plasma independently. → The medium perceives a parton shower as a collection of effective probes.

The QGP Resolution Length

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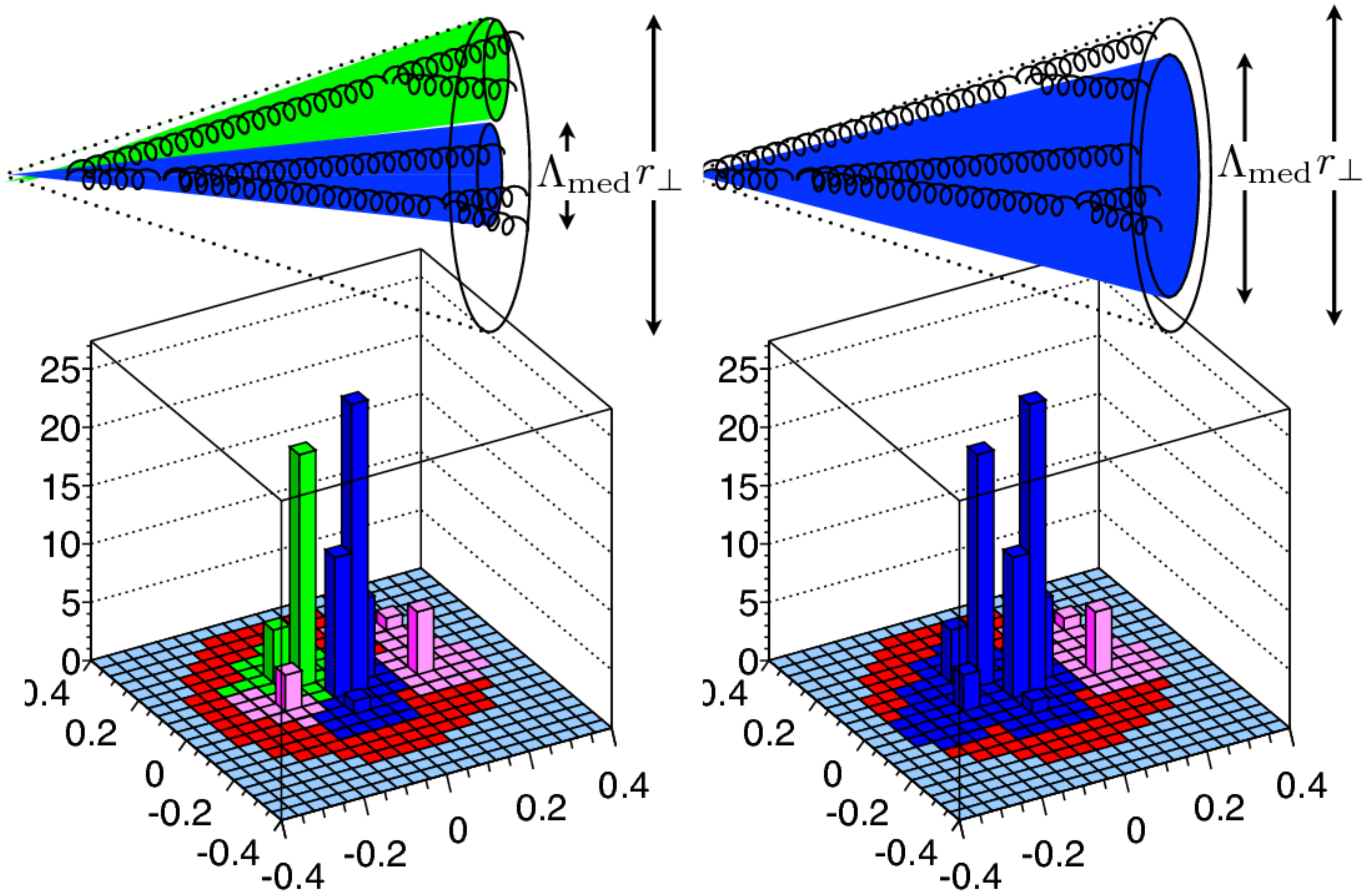
minimal distance between two coloured charges such that they engage with the plasma independently.

The medium perceives a parton shower as a collection of effective probes.

At weak coupling:
connection between resolution length and energy loss.



J. Casalderrey et al. - PLB '13

At strong coupling:
no such connection (yet).

In the hybrid model:
resolution length proportional to the Debye screening length of QGP.

$$L_{\rm res} \sim \lambda_D$$

Hulcher et al. - JHEP '18

Two extreme scenarios

Look for sensitivity of observables to L_{res} :

Take two extreme values for L_{res}

(explore realistic values later on)

- $L_{\text{res}} = 0$ fully resolved case
- $L_{\text{res}} = \infty$ fully unresolved case

)

Two extreme scenarios

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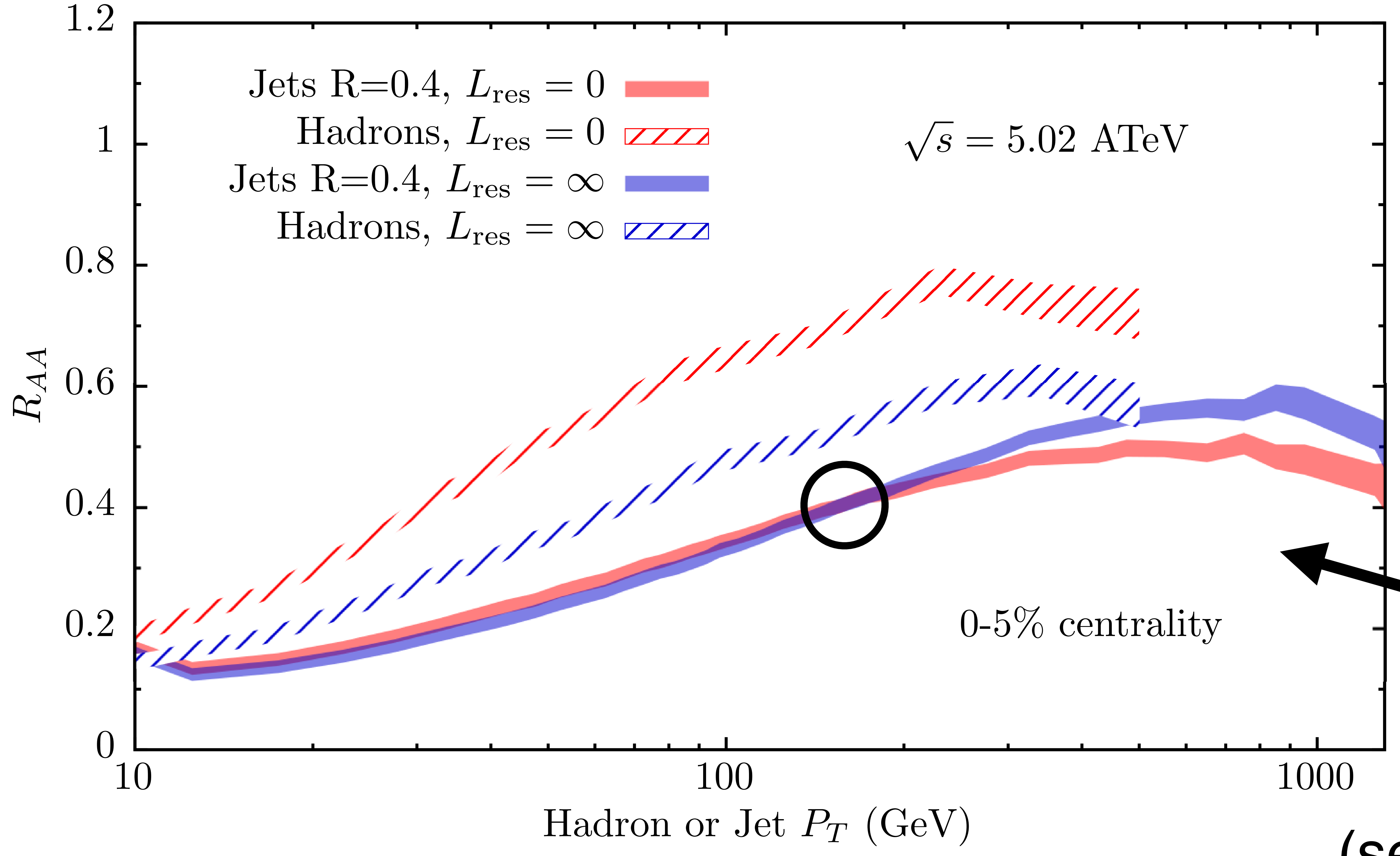


Amount of *jet* quenching depends on L_{res}

→ Adjust value of κ_{sc} to compare results at the same value of jet RAA

$L_{\text{res}} = 0$ (global fit)

$0.404 < \kappa_{\text{sc}} < 0.423$

$L_{\text{res}} = \infty$ (adjusted)

$0.5 < \kappa_{\text{sc}} < 0.52$

Relative suppression of hadrons vs jets strongly depends on QGP resolution length.

(see Pablos et al. - PRC '19 and Mehtar-Tani & Tywoniuk - PRD '18)

Soft Drop

Soft Drop (SD) procedure in a nutshell:

1. Reconstruct jet with anti-k_T.
2. Recluster jet with Cambridge-Aachen.
3. Go back clustering history, store **z** and **ΔR** of each pair of branches.

Soft Drop

Soft Drop (SD) procedure in a nutshell:

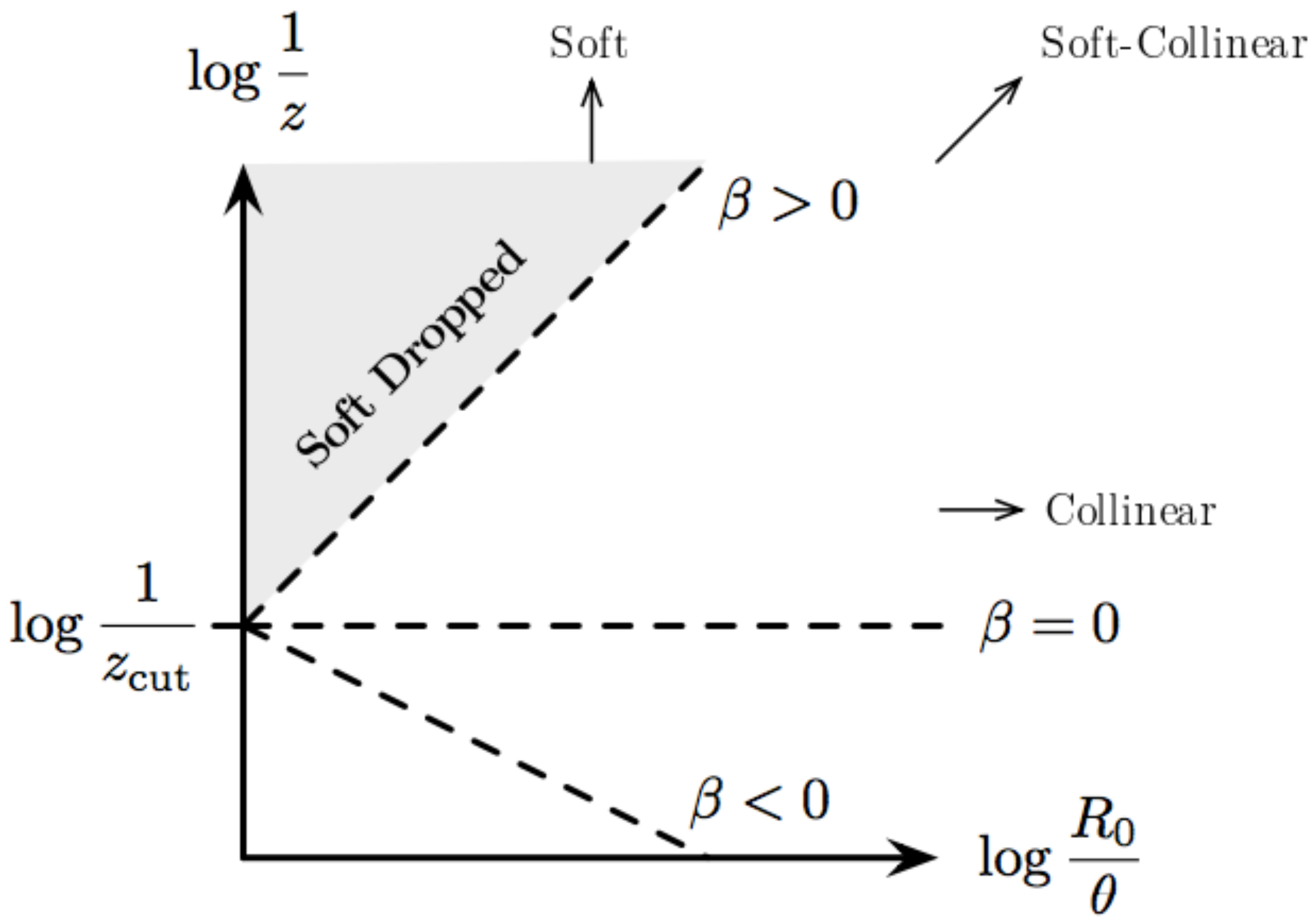
Larkoski et al. - JHEP ‘14, PRD ‘15

1. Reconstruct jet with anti-k$_T$.
2. Recluster jet with Cambridge-Aachen.
3. Go back clustering history, store **z** and **ΔR** of each pair of branches.

→ If stop at first step that satisfies SD condition:

1st SD “splitting”

- study such 1st “splitting”
- study groomed jet properties



Soft Drop condition:

$$\frac{\min\left(p_{T1}, p_{T2}\right)}{p_{T1} + p_{T2}} > z_{\rm cut} \left(\frac{R_{12}}{R_0}\right)^{\beta}$$

Soft Drop

Soft Drop (SD) procedure in a nutshell:

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→ If stop at first step that satisfies SD condition:

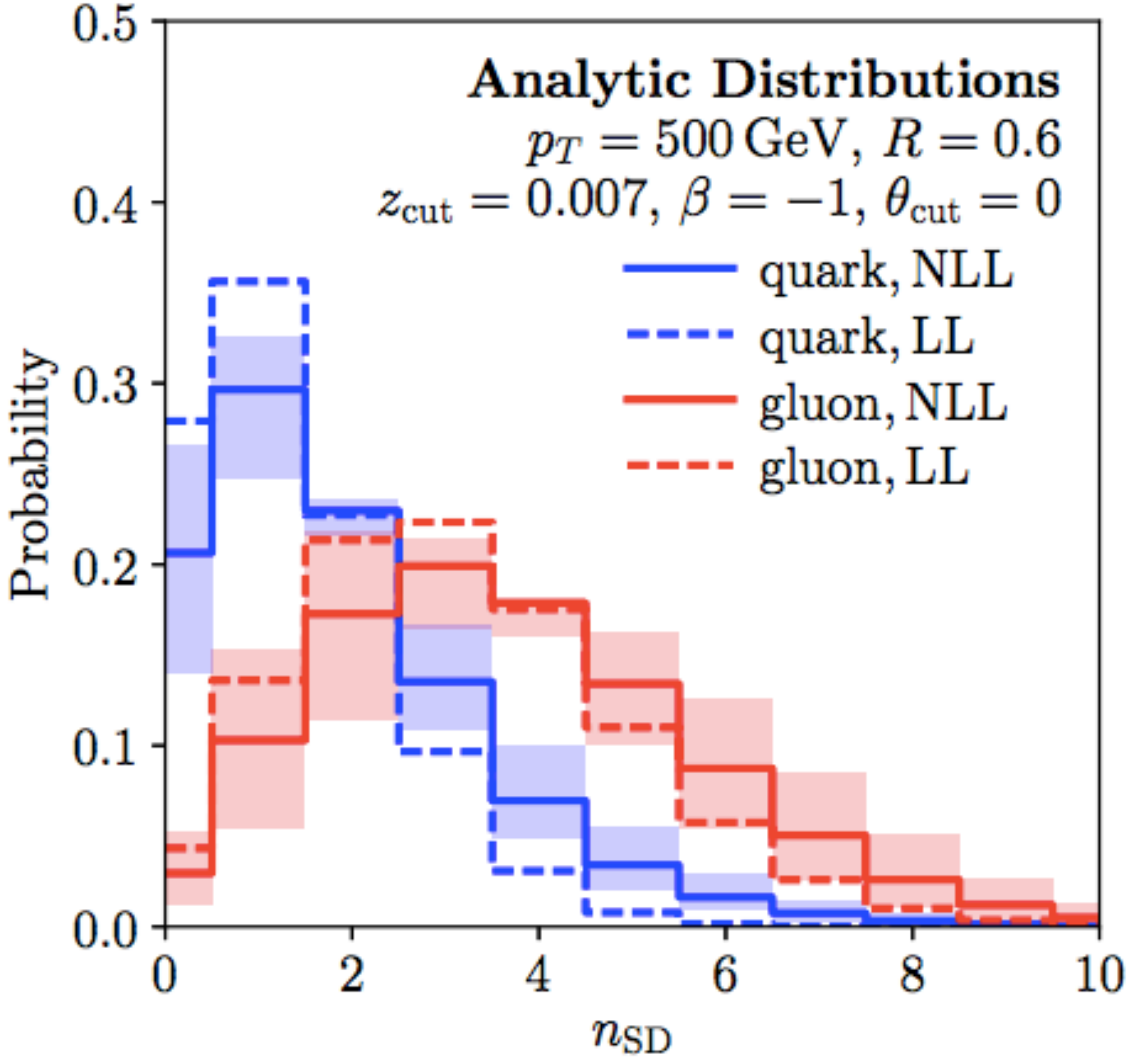
1st SD "splitting"

- study such 1st "splitting"
- study groomed jet properties

→ If count all "splittings" that satisfy SD condition: (following the hardest branch, i.e. Iterative SD)

 # SD "splittings", n_{SD}

Frye et al. - JHEP '17



SD Splittings

Flat grooming setup:

$z_{\text{cut}} = 0.1 \quad \beta = 0$

Remove soft & soft-collinear

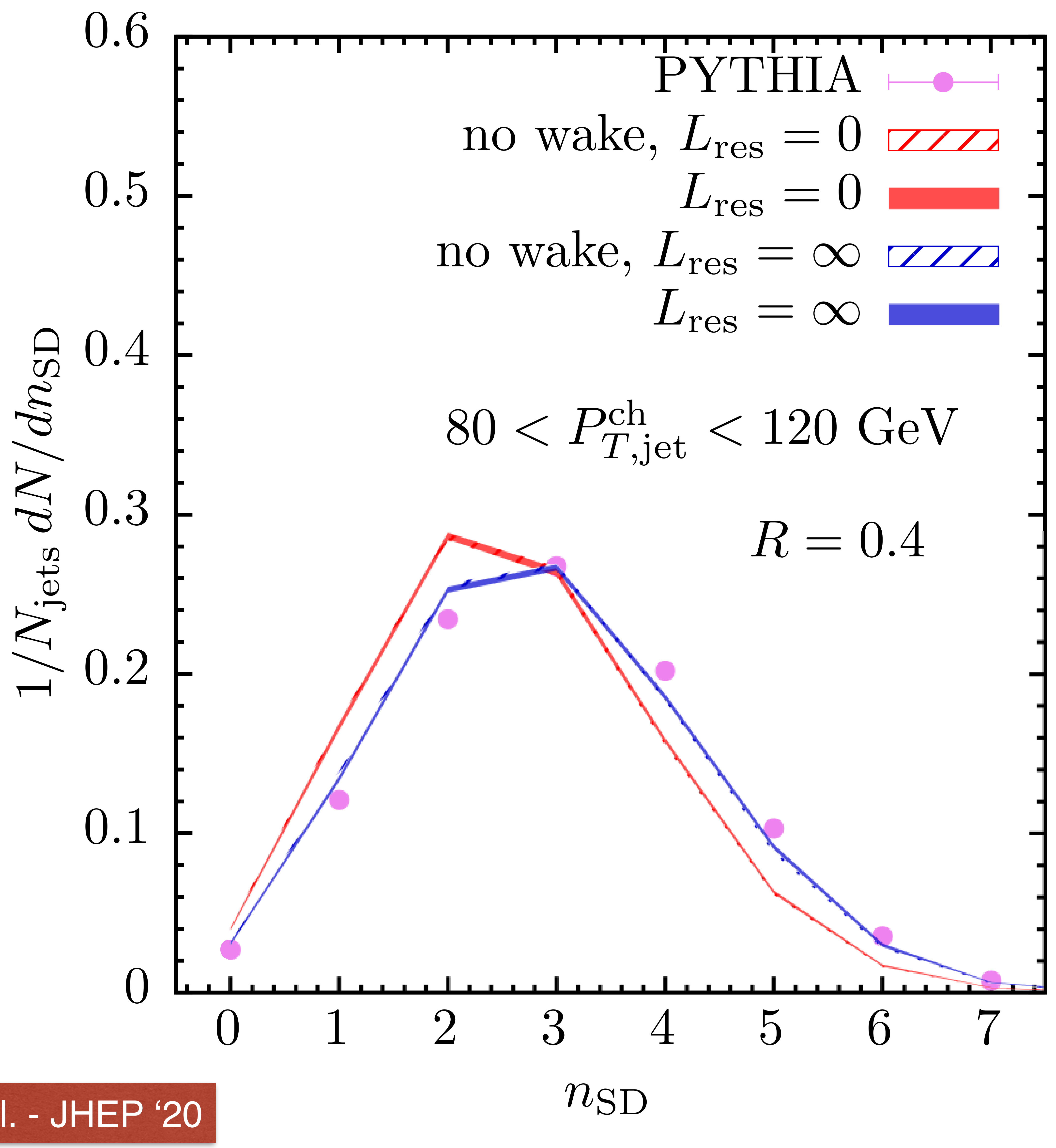
$L_{\text{res}} = 0$

reduction of n_{SD}

Wake negligible.

$L_{\text{res}} = \infty$

barely any modification



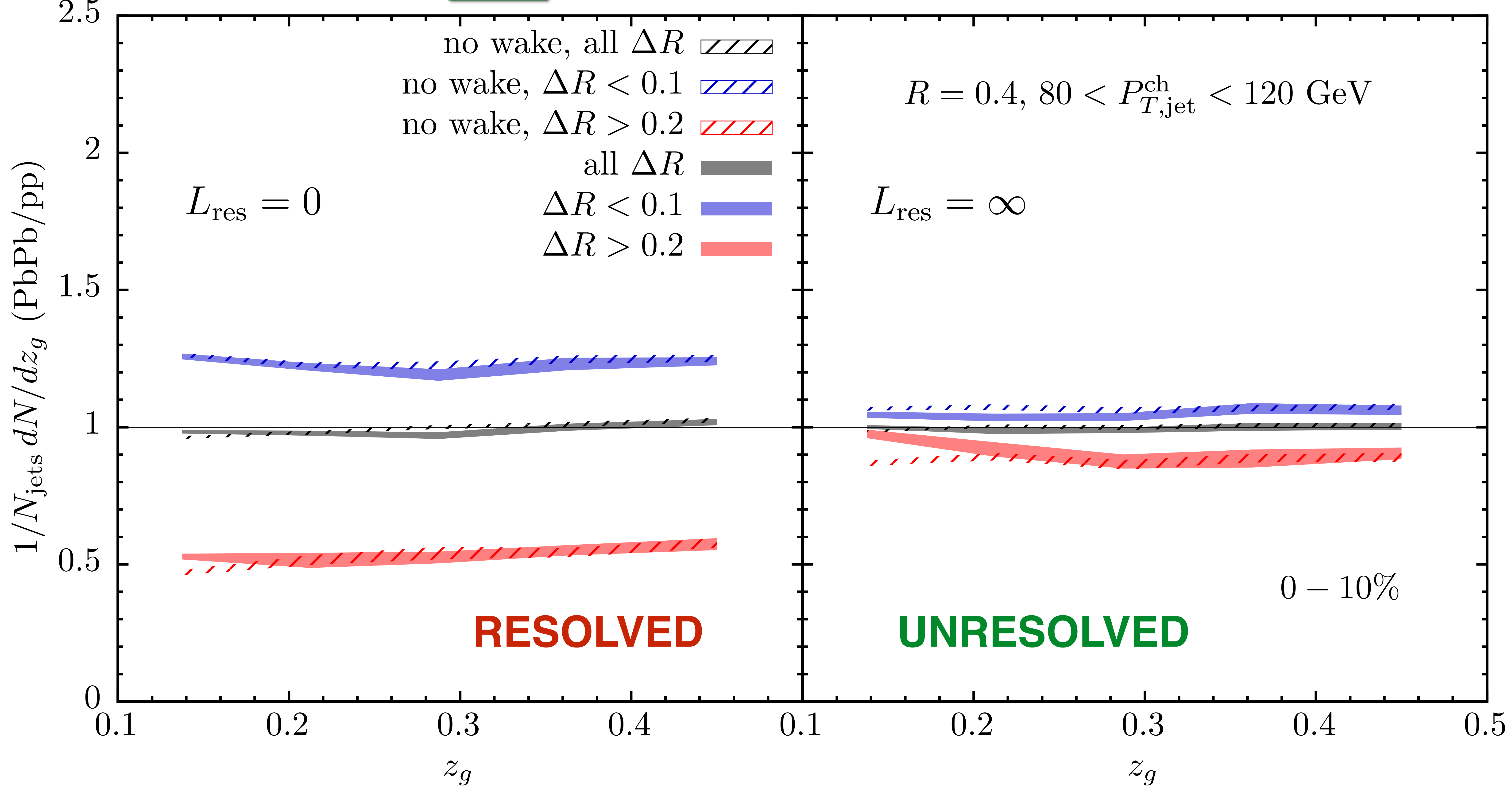
Jets with higher multiplicity are more suppressed, ensemble biased towards less active ones if substructure is resolved.

(also a subleading effect from “per jet” energy loss, see back-up)

Pablos et al. - JHEP ‘20

1st SD splitting z_g vs ΔR

Flat $z_{\mathrm{cut}} = 0.1 \quad \beta = 0$



normalised to N_{jets}

Strong ordering in ΔR
(if parton shower resolved).

Larger ΔR;

↓

Larger phase-space for emissions;

↓

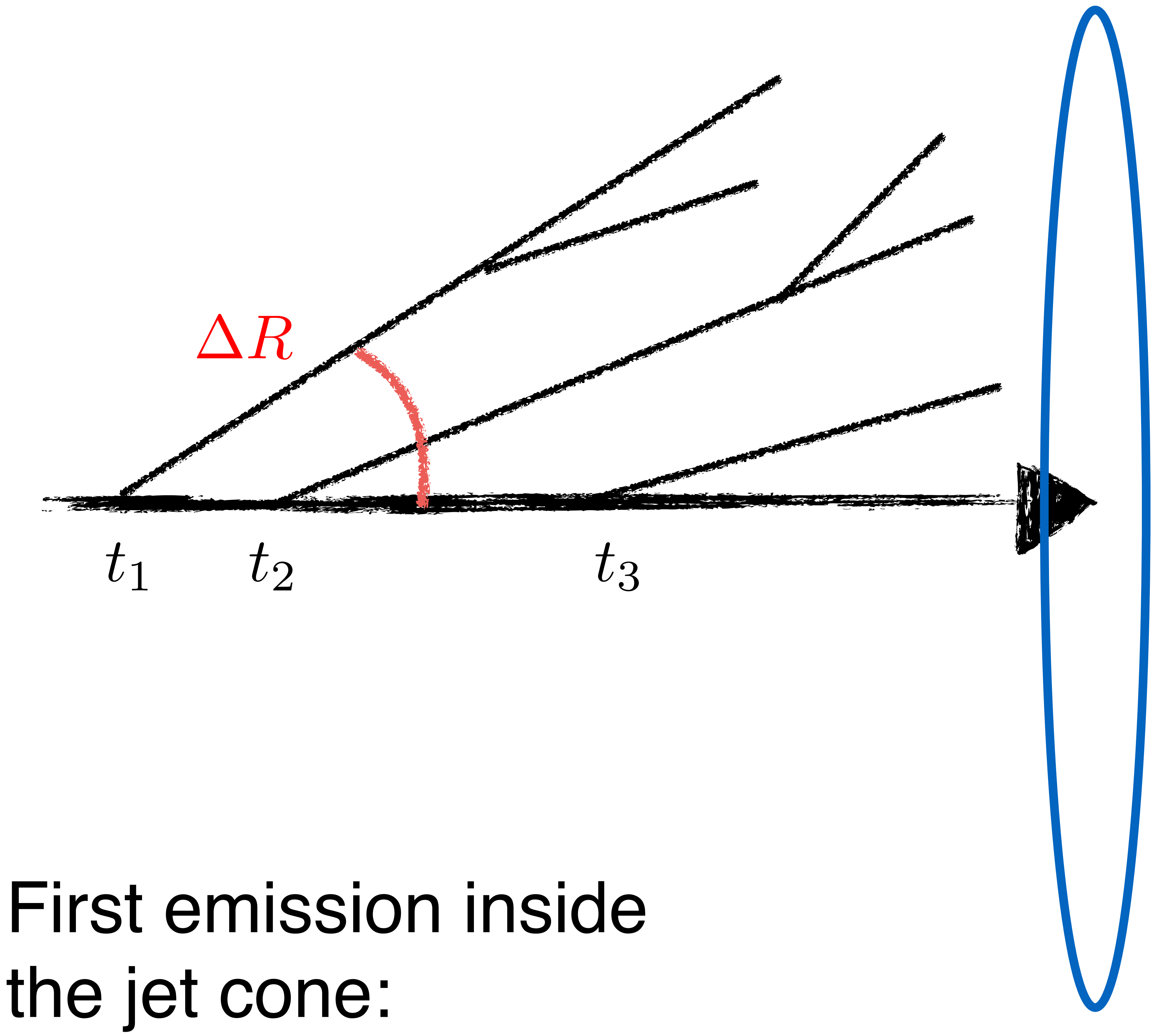
Larger quenching, smaller survival rate;

(almost NO effect from "per jet" energy loss, see back-up)

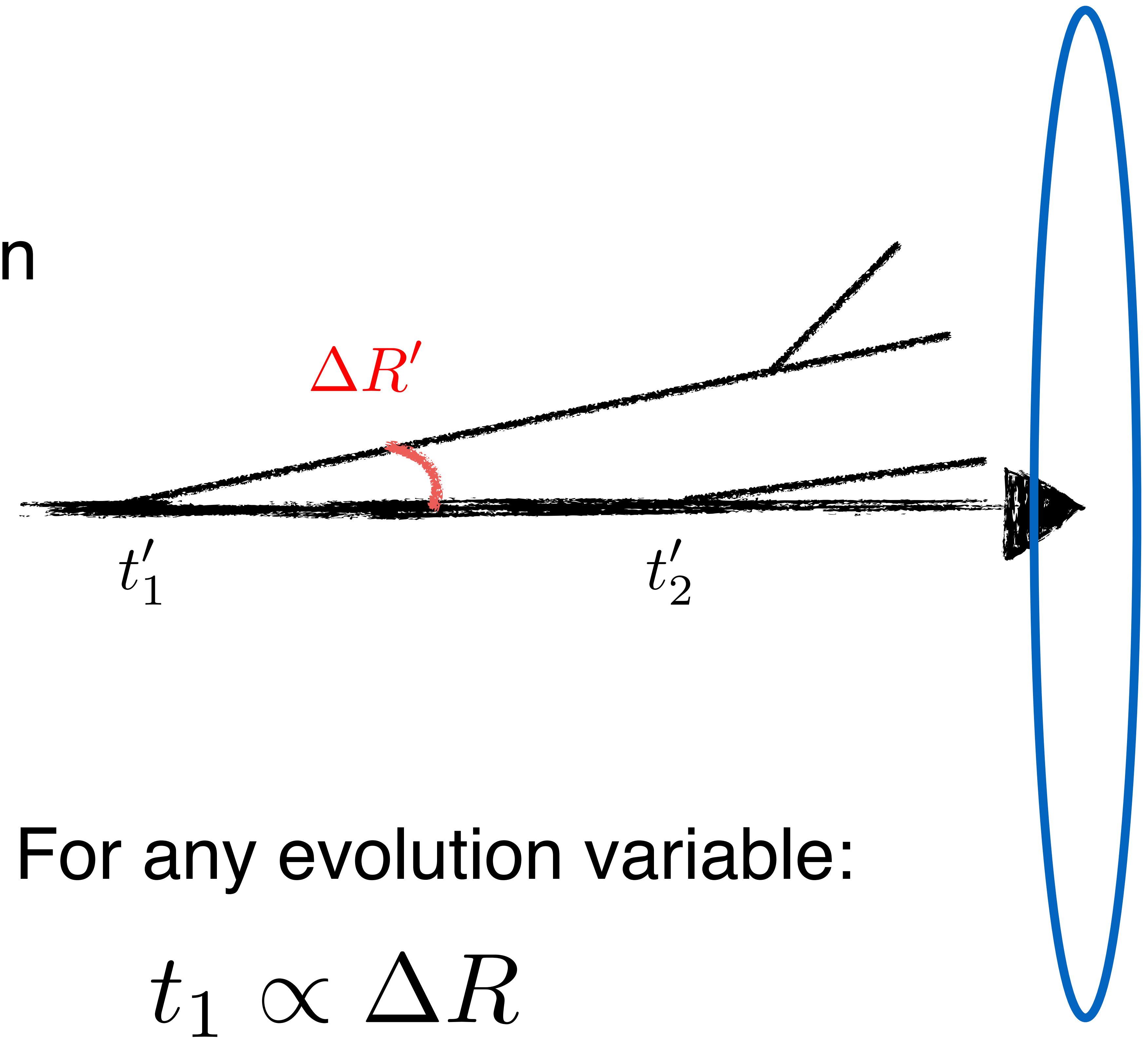
Pablos et al. - JHEP '20

Jets and Jets (again)

Wide jet



Narrow jet



Scale of emission *t* sampled from Sudakov distribution

$$t_1 > t'_1$$

First emission inside the jet cone:

- If high, increased probability for further emissions
- If low, decreased probability for further emissions

For any evolution variable:

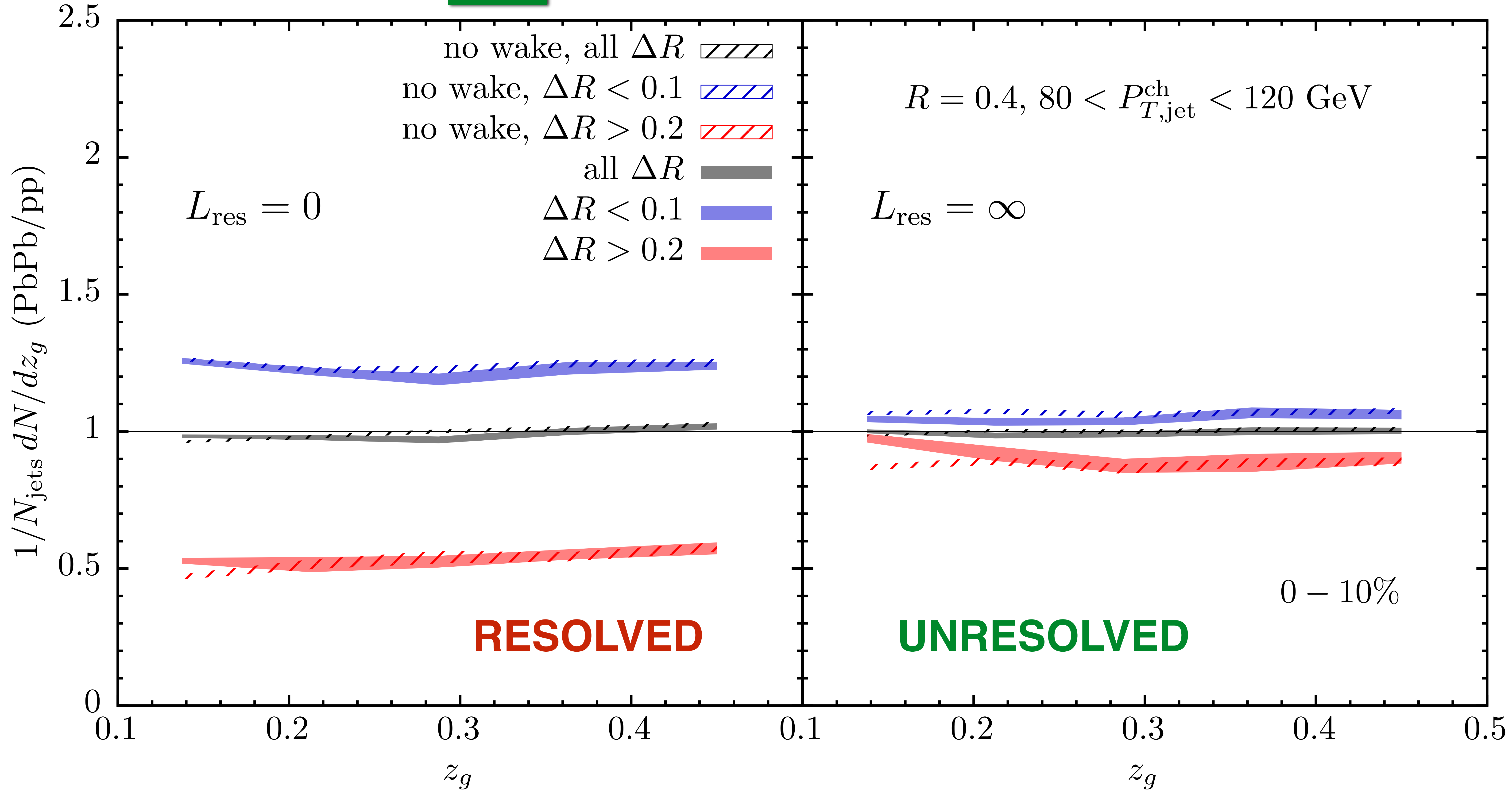
$$t_1 \propto \Delta R$$

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

Groomed angle is proxy for jet activity

1st SD splitting z_g vs ΔR

Flat $z_{\mathrm{cut}} = 0.1 \quad \beta = 0$



Strong ordering in ΔR
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Larger ΔR;

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↓

Larger quenching, smaller survival rate;

(almost NO effect from "per jet" energy loss, see back-up)

normalised to N_{jets}

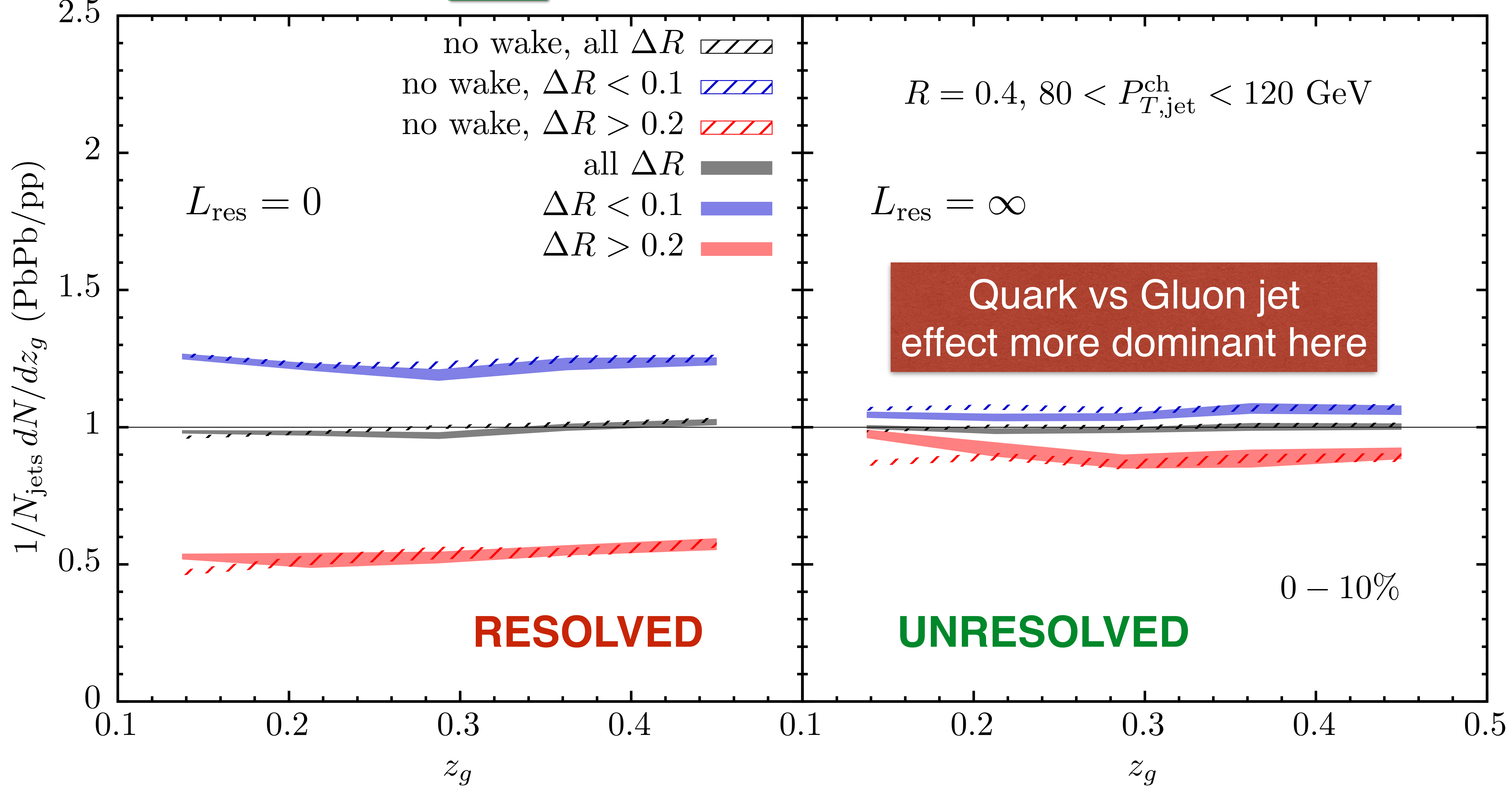
- Wake almost no effect.
- Negligible modification z_g shape.

(small incoherent energy loss effect visible at partonic level, see back-up)

Pablos et al. - JHEP '20

1st SD splitting z_g vs ΔR

Flat $z_{\mathrm{cut}} = 0.1 \quad \beta = 0$



Quark vs Gluon jet
effect more dominant here

normalised to N_{jets}

Strong ordering in ΔR
(if parton shower resolved).

Larger ΔR;

↓

Larger phase-space
for emissions;

↓

Larger quenching,
smaller survival rate;

(almost NO effect from "per jet"
energy loss, see back-up)

- Wake almost no effect.
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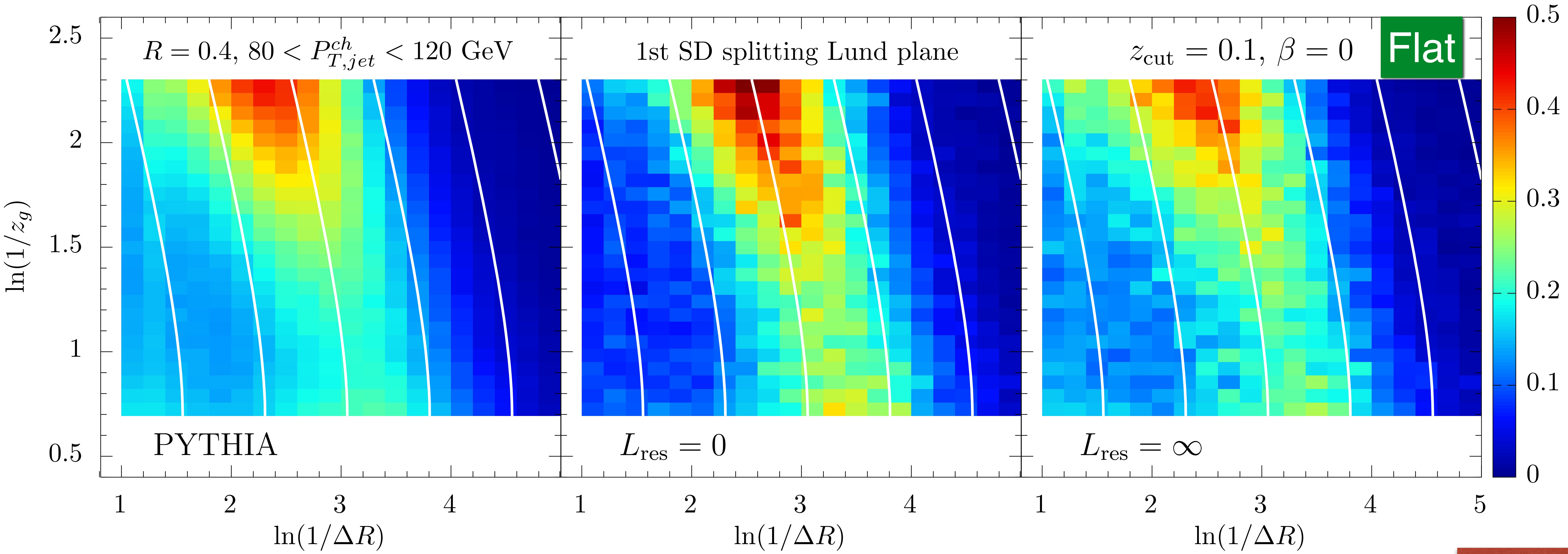
effect visible at partonic level, see back-up)

Pablos et al. - JHEP '20

1st SD splitting Lund Plane



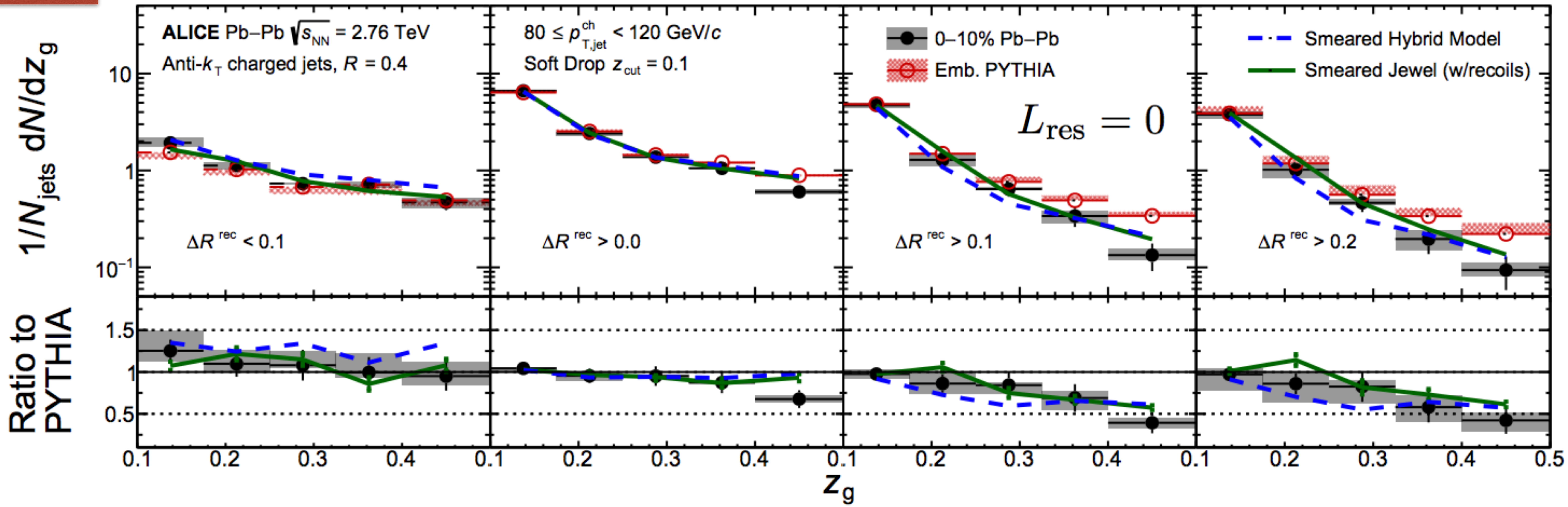
Pablos et al. - JHEP '20

If shower resolved → increased weight of jets with smaller (groomed) mass.

White curves: lines of constant $\log(1/(M_g/p_{T,g}))$, where $\frac{M_g^2}{p_{T,g}^2} \simeq z_g(1 - z_g)\Delta R^2$

Comparison with (not unfolded) data

ALICE - PLB ‘20



$L_{\rm res} = 0$

Low z_g enhancement arises in our model from smearing effects.

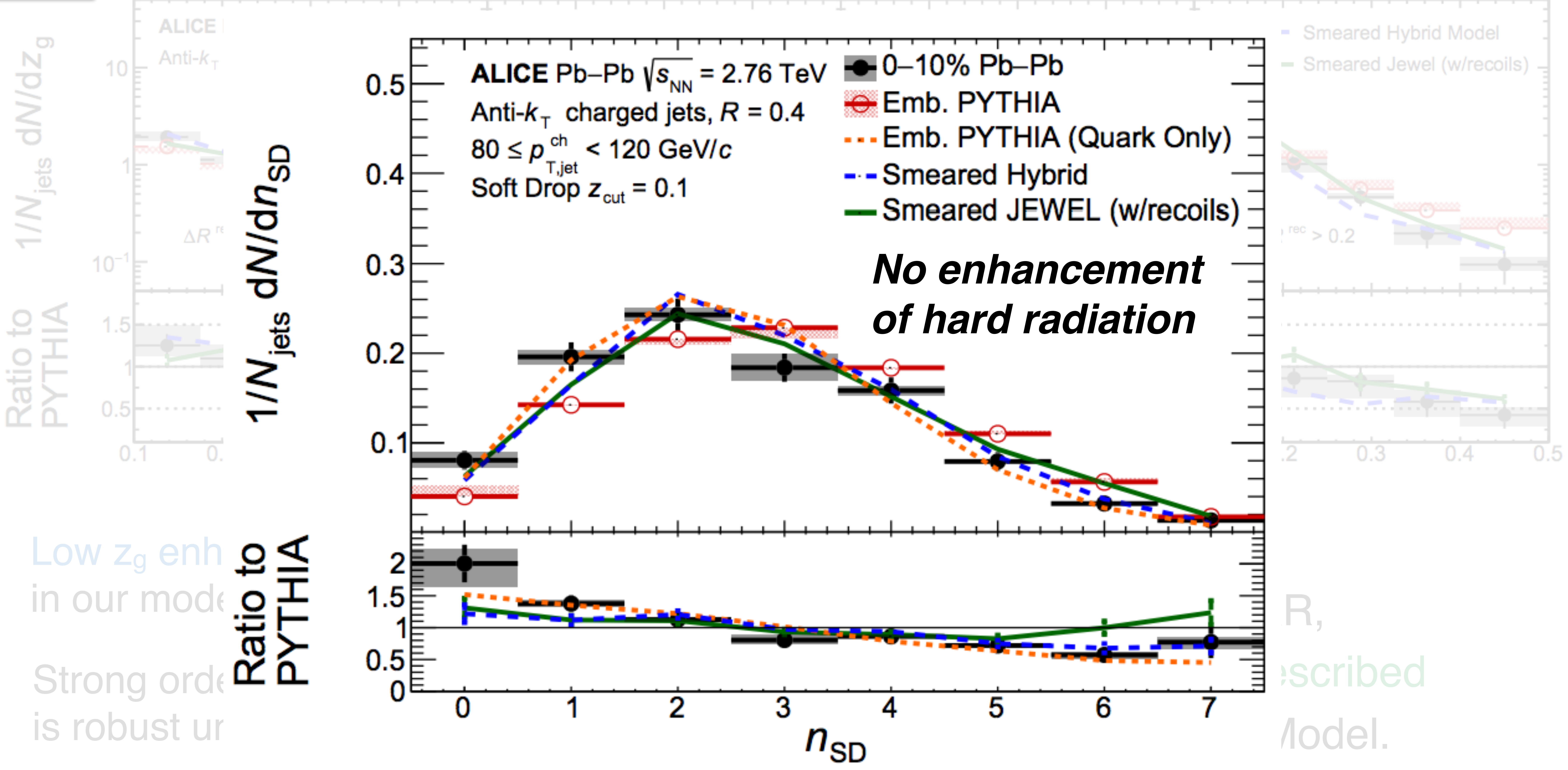
Strong ordering in ΔR is robust under smearing effects.

$L_{\rm res} = \infty$ is disfavoured by data.

z_g distribution, differential in ΔR, successfully described by the Hybrid Model.

Comparison with (not unfolded) data

ALICE - PLB ‘20



No enhancement of hard radiation

Low z_g enh

in our mode

Strong orde

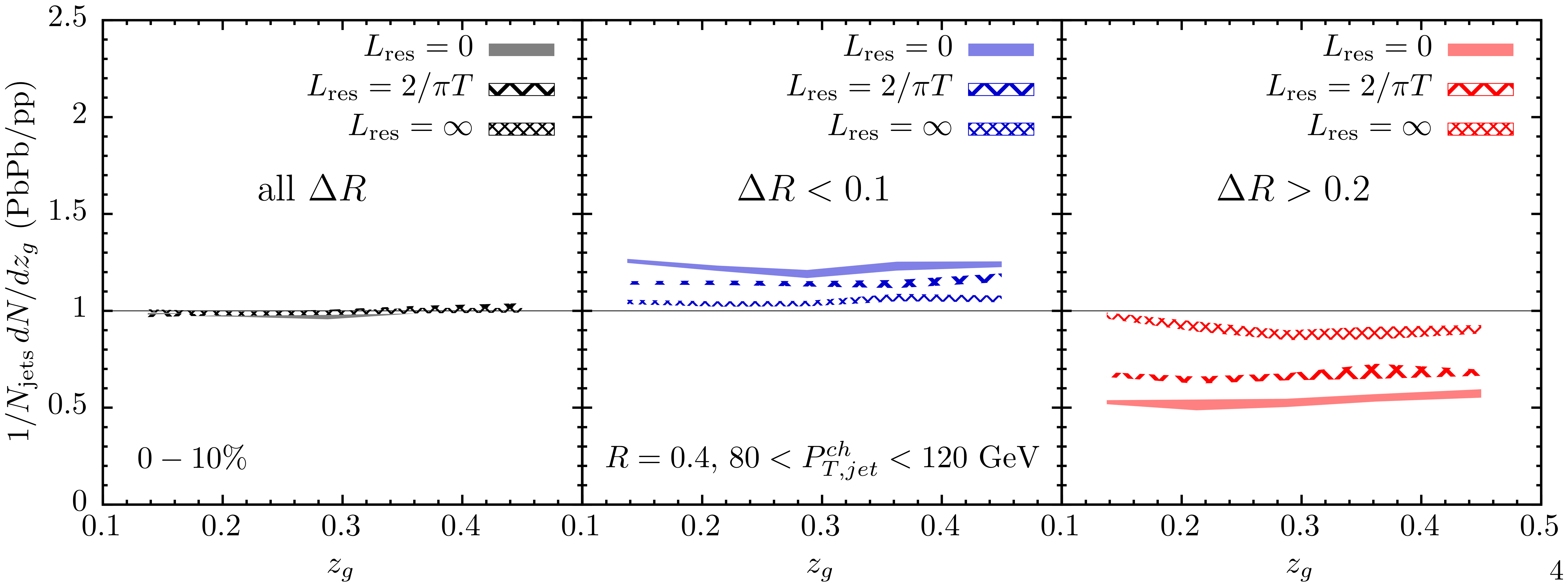
is robust ur

R,

scribed

odel.

Sensitivity to L_{res}

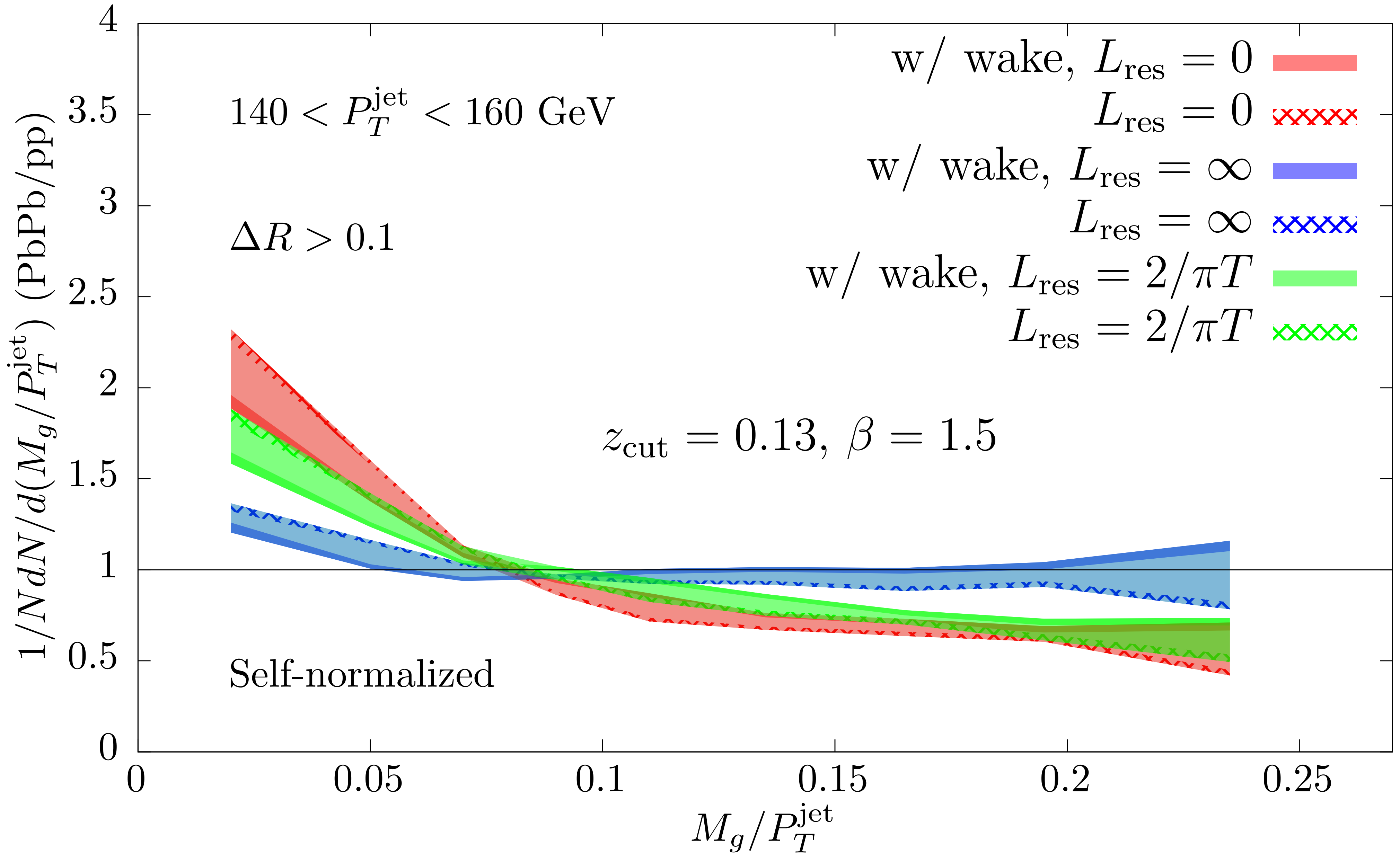


ΔR ordering of z_g dist. closely correlated with value of QGP resolution length.

Results for $L_{res} = 2/\pi T$ closer to $L_{res} = 0$ than to $L_{res} = \infty$

Tagged rate (# selected jets)

	$\Delta R > 0.0$	$\Delta R < 0.1$	$\Delta R > 0.2$
PYTHIA	0.9729(2)	0.5757(7)	0.1730(4)
$L_{res} = 0$	0.9599(8)	0.710(4)	0.092(2)
$L_{res} = 2/\pi T$	0.9633(8)	0.660(3)	0.115(2)
$L_{res} = \infty$	0.969(1)	0.603(3)	0.161(2)



Pablos et al. - JHEP ‘20

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:

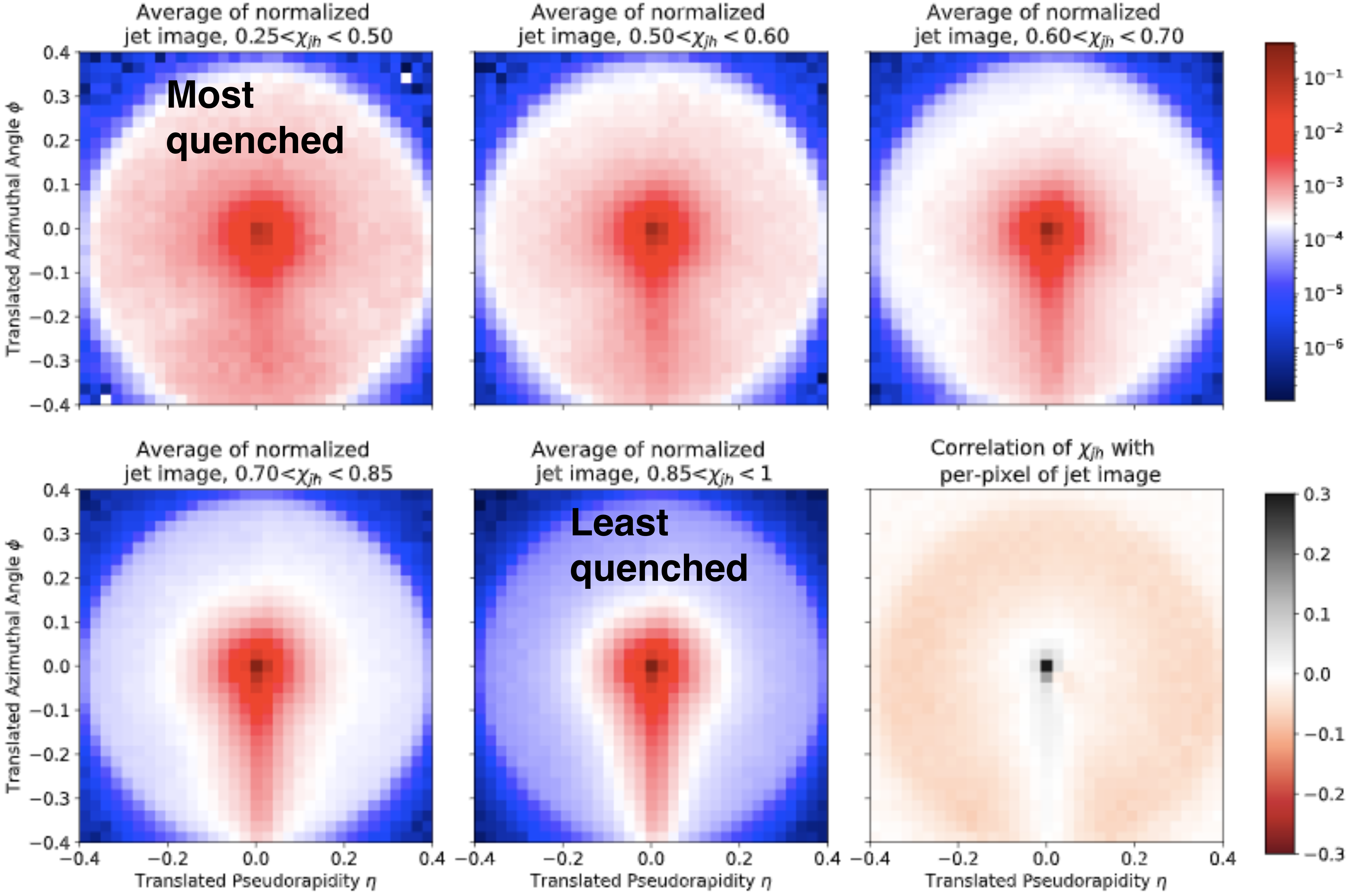
$$\chi_{jh} \equiv \frac{E_f}{E_i}$$

E_f ← Final, measurable jet energy

E_i ← Vacuum energy (had there been no medium)

Du et al. - 2010.XXXX

Jet Images



- Image rotated jet-by-jet to have subleading branch at -π/2
- Quenching increases # of soft particles, specially at the periphery

→ Use images as input for CNN

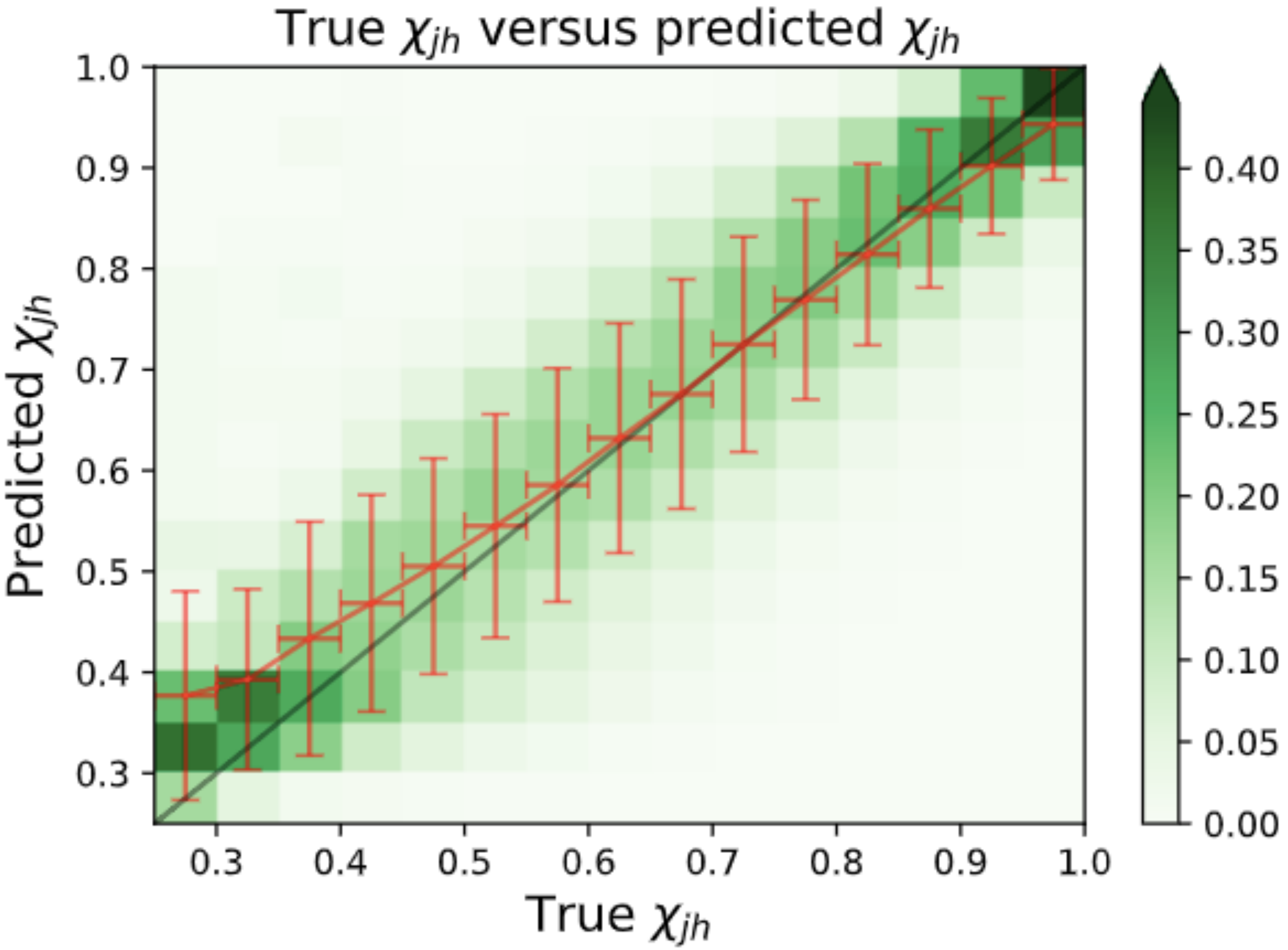
Du et al. - 2010.XXXX

Performance of neural network

- Good performance across a wide range in χ_{jh}

- Consistency check: pp jets get $\chi_{jh} \simeq 1$
  (after training on medium jets only)

- Interpretability: jet shape (lower dimensional projection of jet image) contains greatest discriminating power



Du et al. - 2010.XXXX

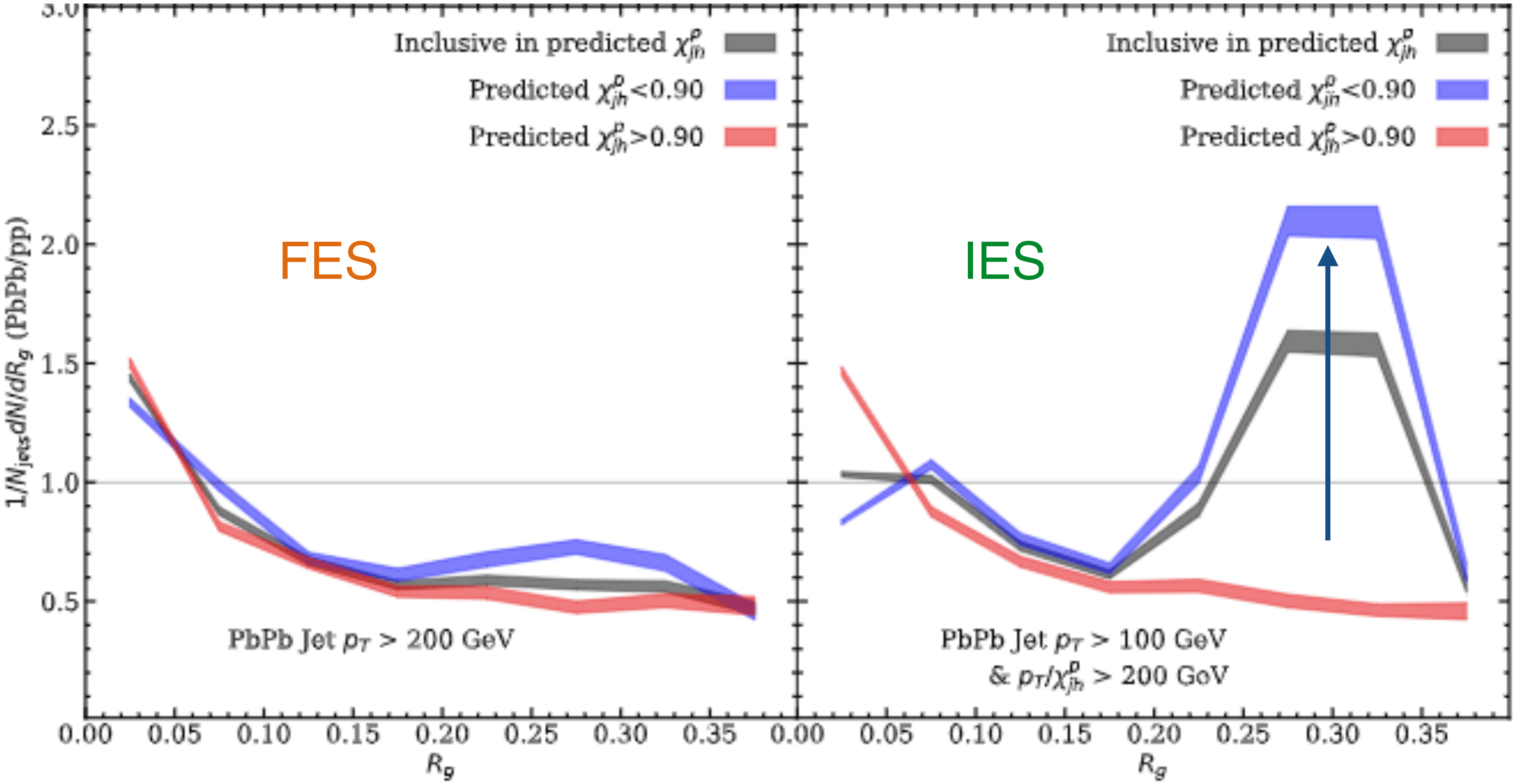
Applications to jet observables

- FES (Final Energy Selection): select jets according to measured energy (usual)

  → Mostly unquenched jets due to selection bias

- IES (Initial Energy Selection): select jets according to initial energy (new)

  → Observe true effects of energy loss!



Modification of groomed radius

Du et al. - 2010.XXXX , see also Brodsky et al. - 2009.03316

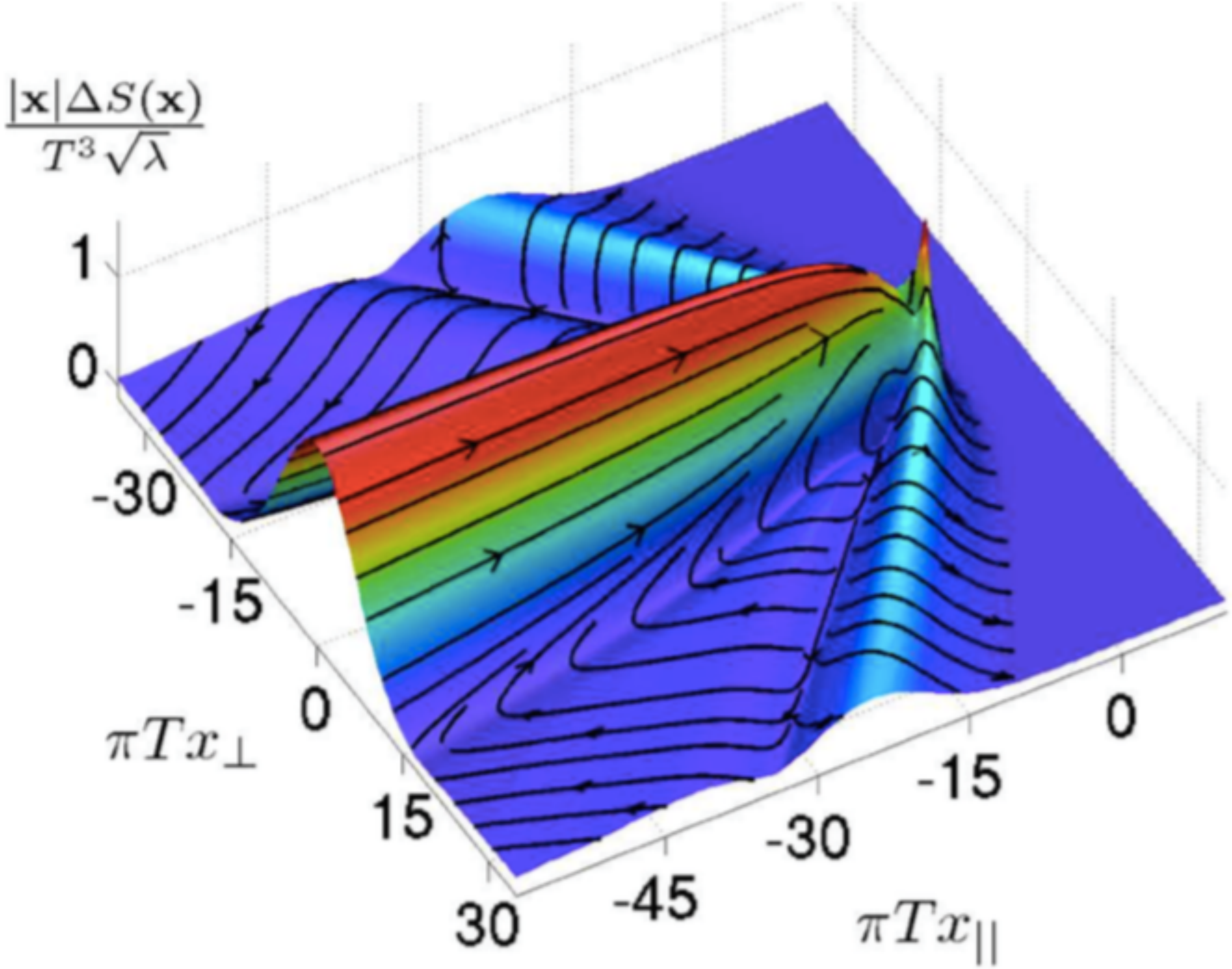
The Wake of the Jet

Chesler & Yaffe - PRL '07

At strong coupling:

- String acts as a perturbation in the large N_c limit.
- Agreement between hydrodynamics & wake of a quark in gauge/gravity duality.

energy-momentum conservation in the jet+plasma interplay



The hadrons from the wake

Pablos et al. - JHEP '17

- Assuming small perturbations on top of Bjorken flow:

→ Expand Cooper-Frye spectrum to first order in perturbations:

Fully constrained by energy-momentum conservation.

$$E\frac{d\Delta N}{d^3p} = \frac{1}{32\pi}\frac{m_T}{T^5}\cosh(y-y_j)\exp\left[-\frac{m_T}{T}\cosh(y-y_j)\right]$$

$$\left\{p_T\Delta P_T\cos(\phi-\phi_j)+\frac{1}{3}m_T\,\Delta M_T\,\cosh(y-y_j)\right\}$$

$$\Delta P^i_\perp = w\,\tau\int d^2x_\perp\,d\eta\,\delta u^i_\perp \qquad\qquad \Delta S = \frac{s\,\tau}{c_s^2}\int d\eta\,d^2x_\perp\,\frac{\delta T}{T}$$

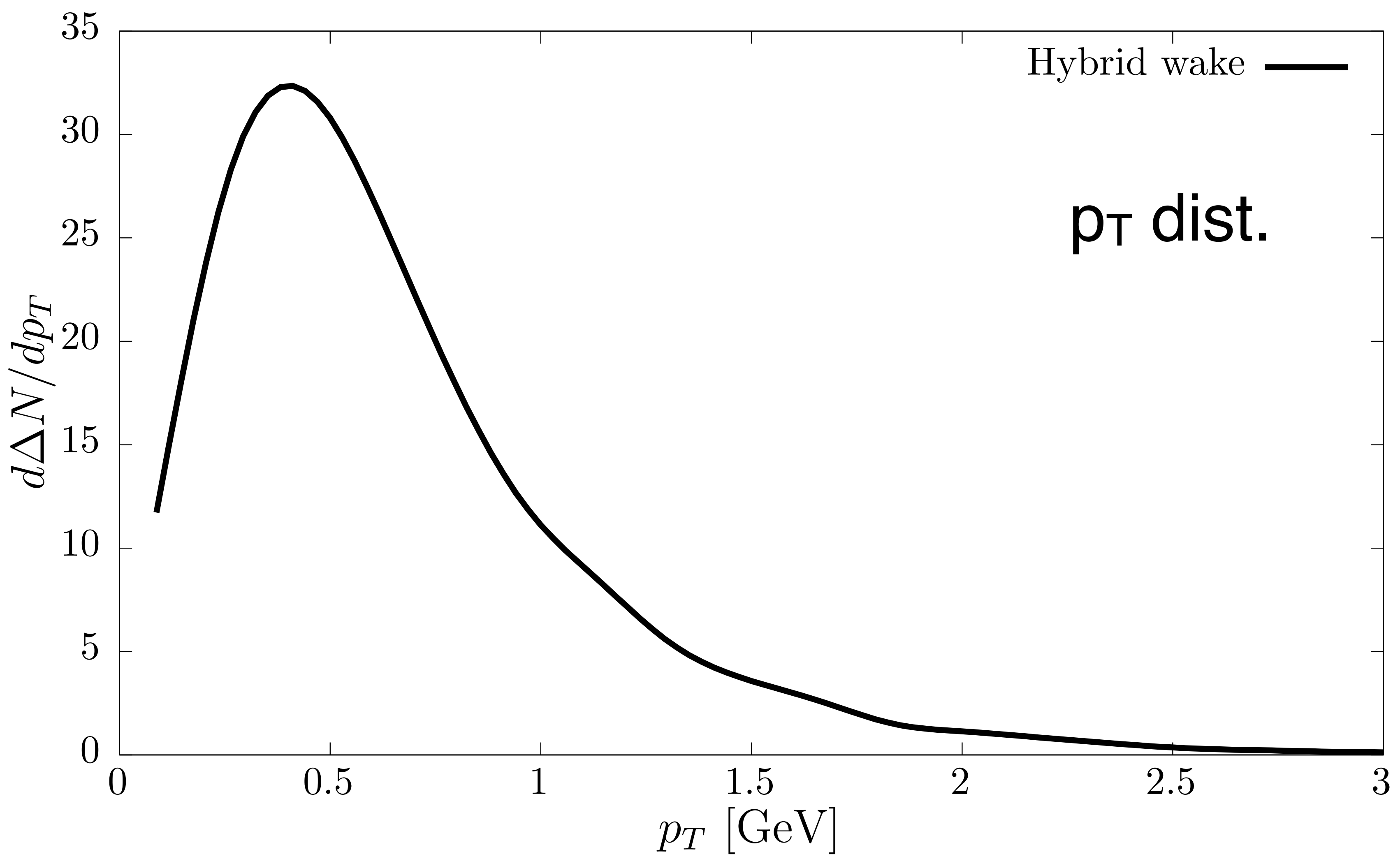
velocity pert.

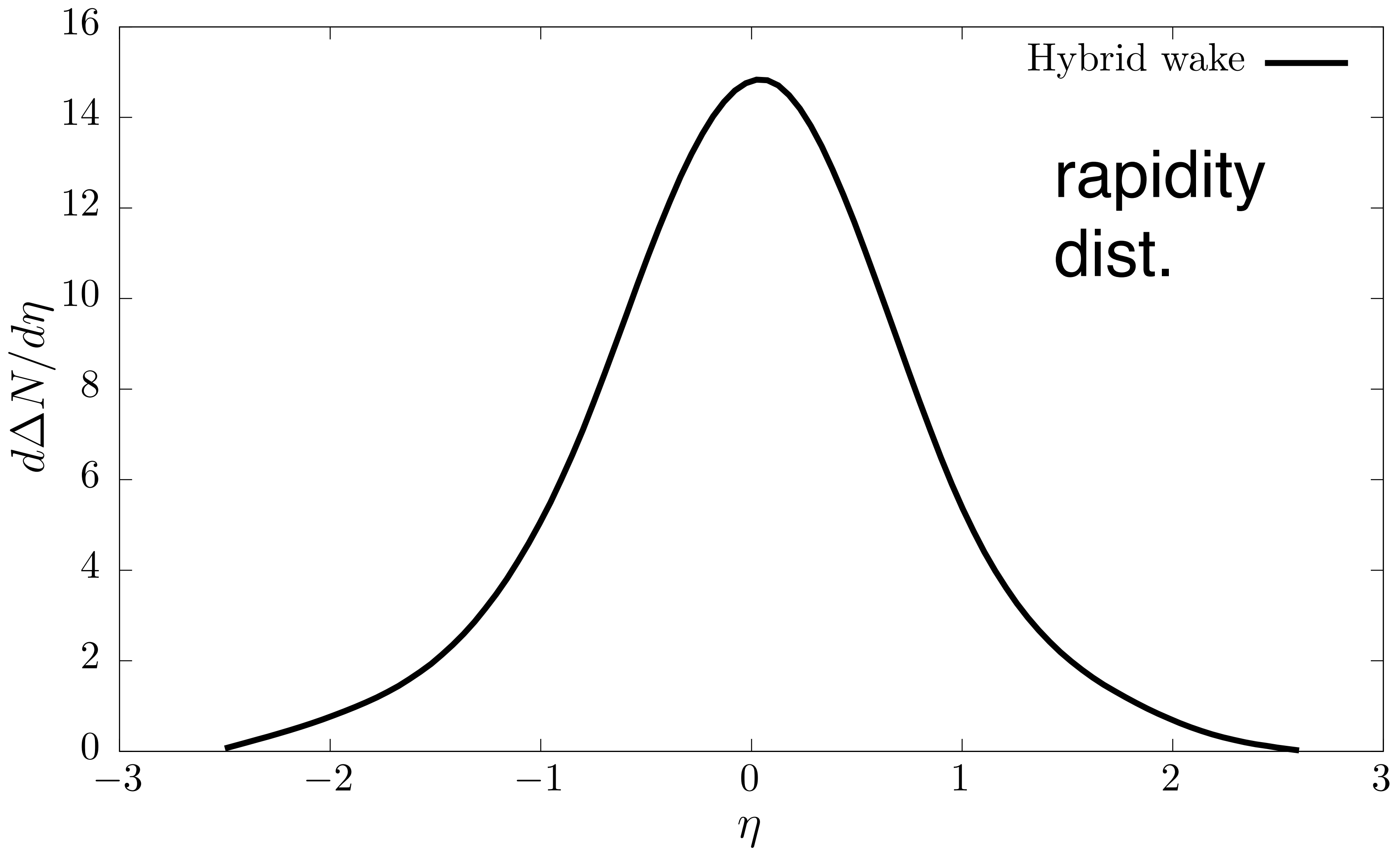
temperature pert.

! Only valid for soft particles.

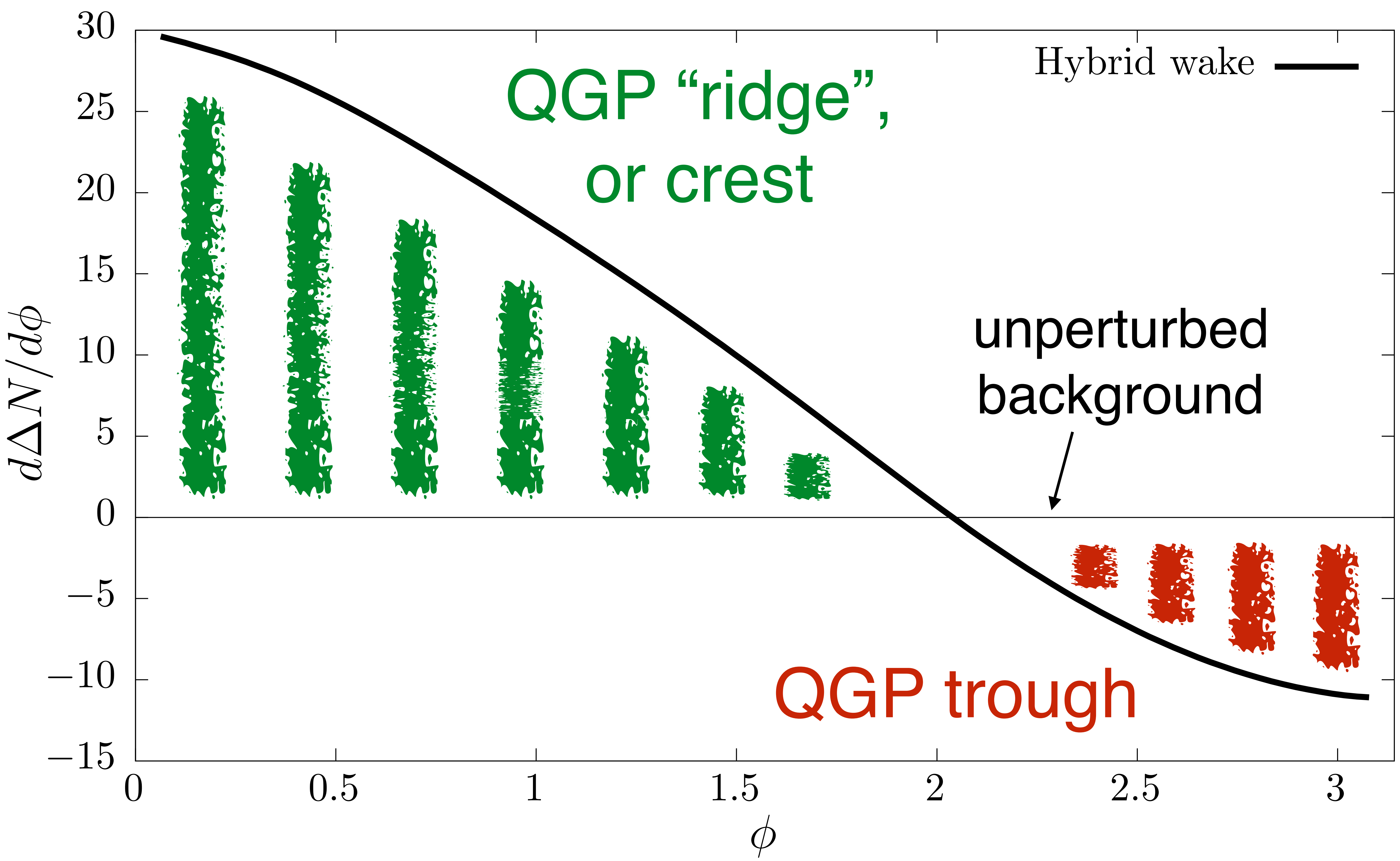
! Effect from background flow not included.

The hadrons from the wake





- Sample hadrons from one body dist.
- Energy-momentum cons. through Metropolis.



Jet R_{AA} at LHC

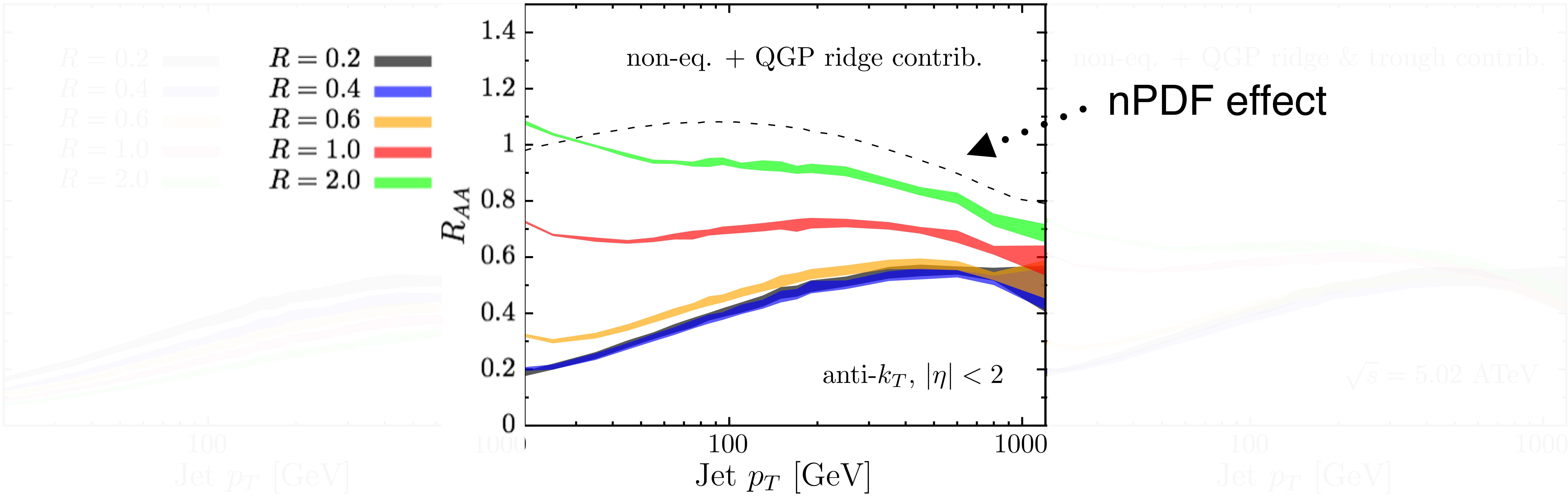
Include non-eq. contribution only, i.e. jet particles that did not hydrodynamize:

- Jet suppression increases with increasing R.

→ Wider jets “lose” more energy, more energy loss sources.

Pablos - PRL ‘20

Jet R_{AA} at LHC



nPDF effect

Include both non-eq. and QGP “ridge” contributions:

- Energy is progressively recovered with increasing R.

! nPDF effect sets an upper limit on R_{AA} at very high p_T.

Pablos - PRL ‘20

Jet R_{AA} at LHC

Include non-eq., QGP “ridge” and QGP trough contribution:

- QGP trough amounts to jet suppression; over-subtraction effect.
- Effect increases with increasing R.

Pablos - PRL ‘20

Jet R_{AA} at LHC

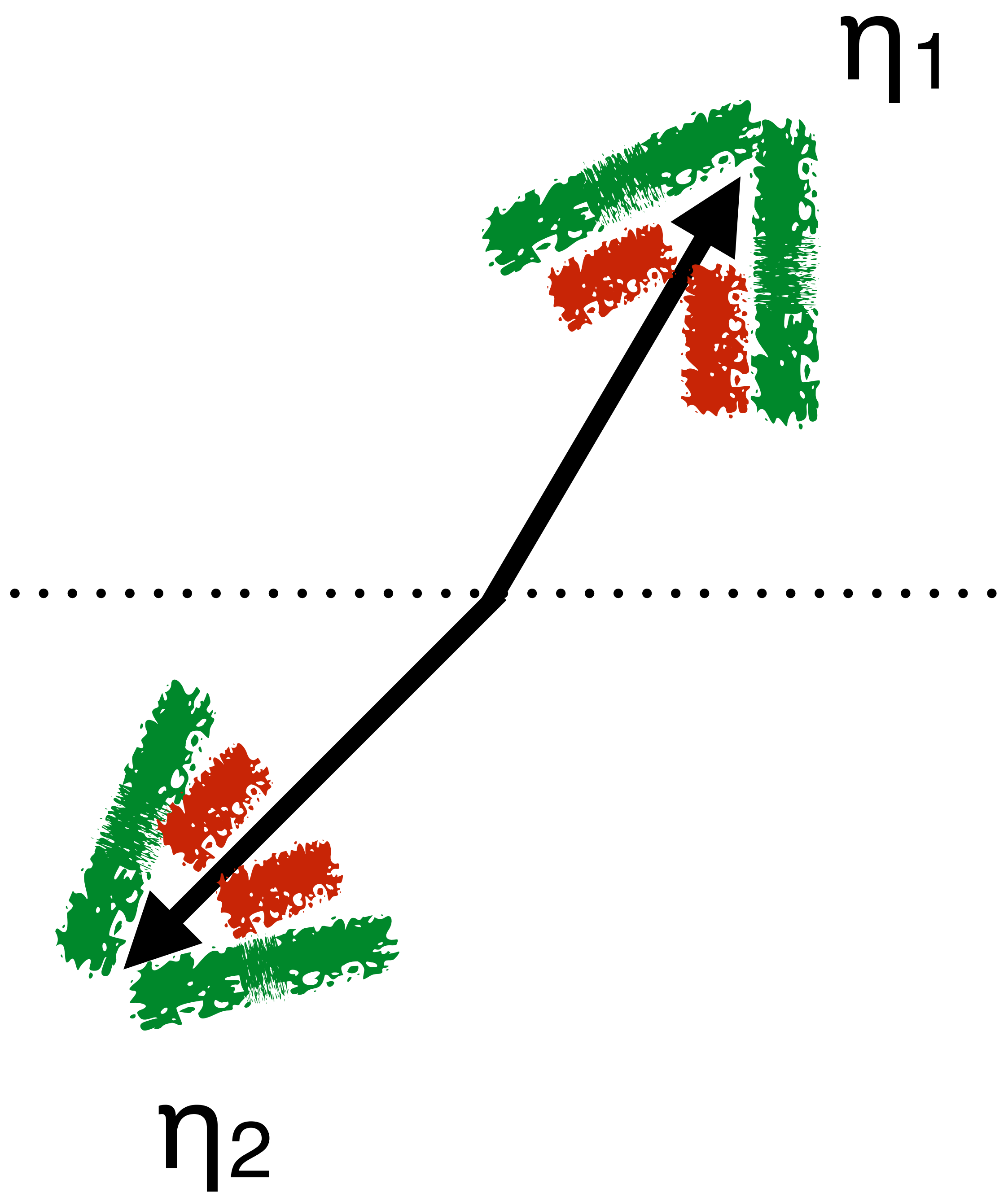
Competition of effects that yield, overall,
a very mild evolution from small to large R.

Pablos - PRL '20

The effect of the recoiling jet

Jet suppression due to QGP trough comes from the wake of the *recoiling* jet.

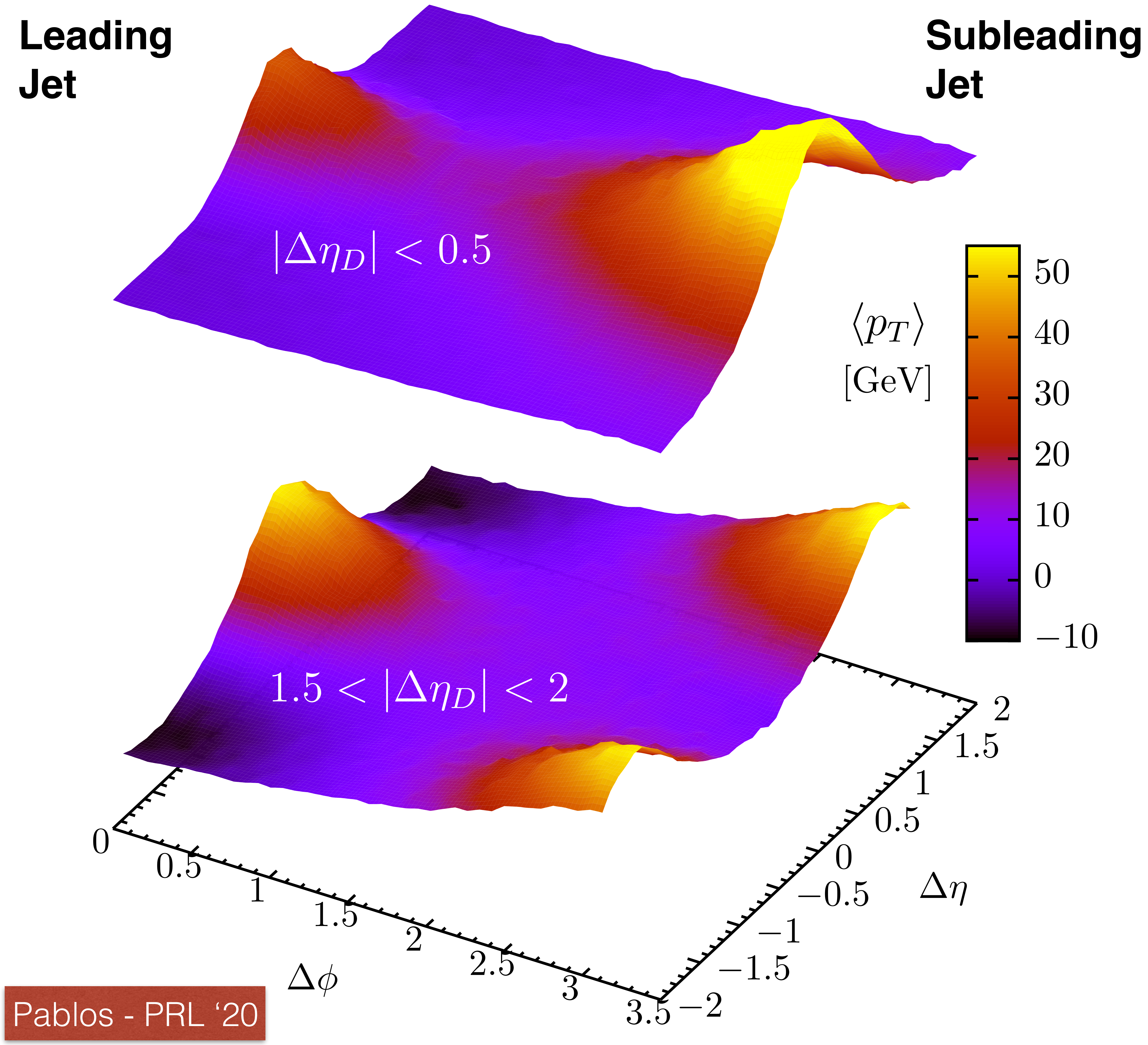
- Rapidity dist. from the wake hadrons relatively **narrow**.
- Rapidity gap dist. between dijet system relatively **wide**.



Study dijet systems with different rapidity gaps.

Pablos - PRL '20

The effect of the recoiling jet



Pablos - PRL ‘20

⟨p_T⟩ 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.

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

differential in

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

Leading jet suppression vs. |ηD|

Pablos - PRL '20

A new observable

R=0.4

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

R=1.0

strong dependence on |ηD|;
knee visible when |ηD|~R.

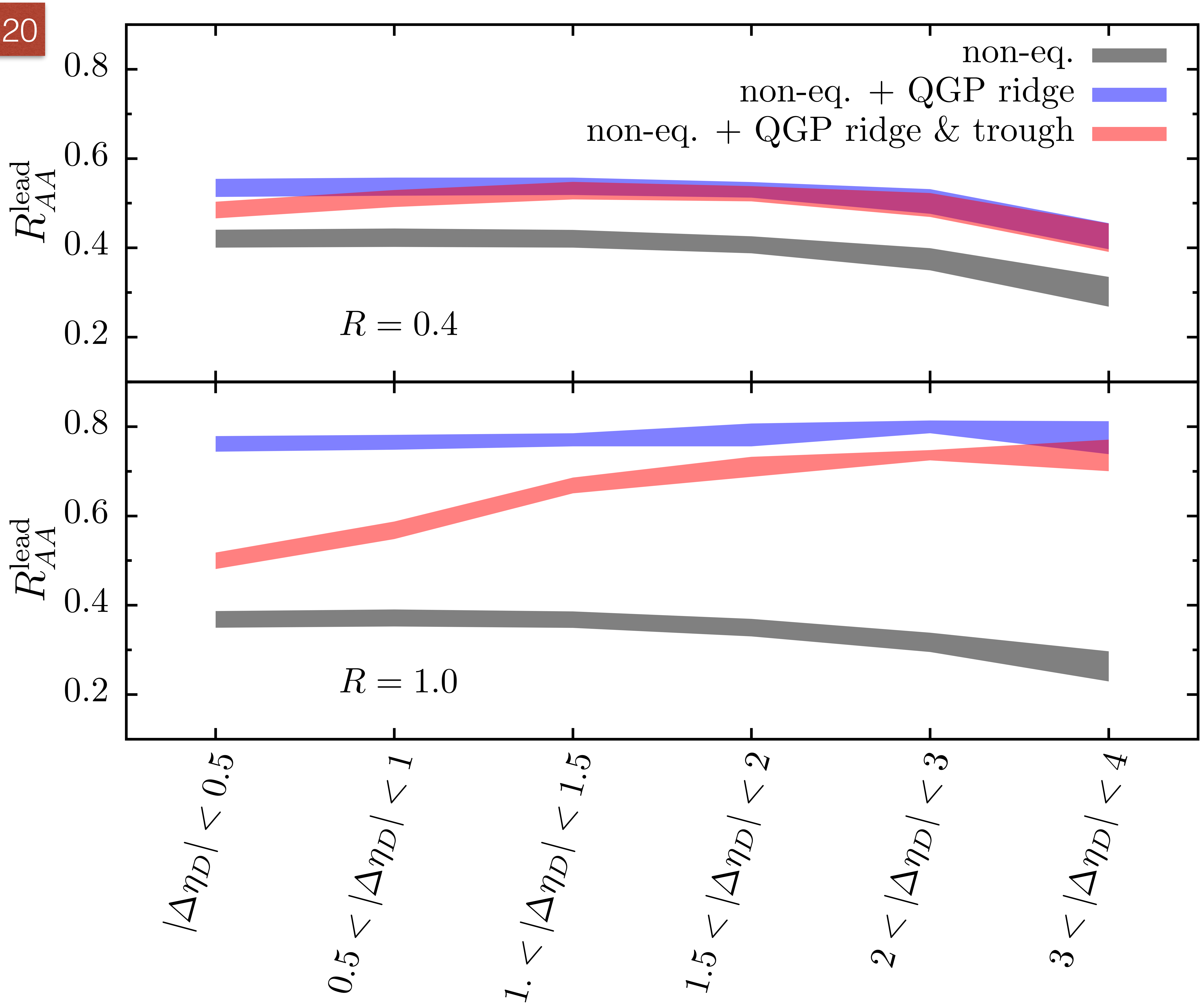
$p_T^L > 250$ GeV

$p_T^S > 80$ GeV

$\Delta\phi_D > 2\pi/3$

differential in

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



Improving the wake description

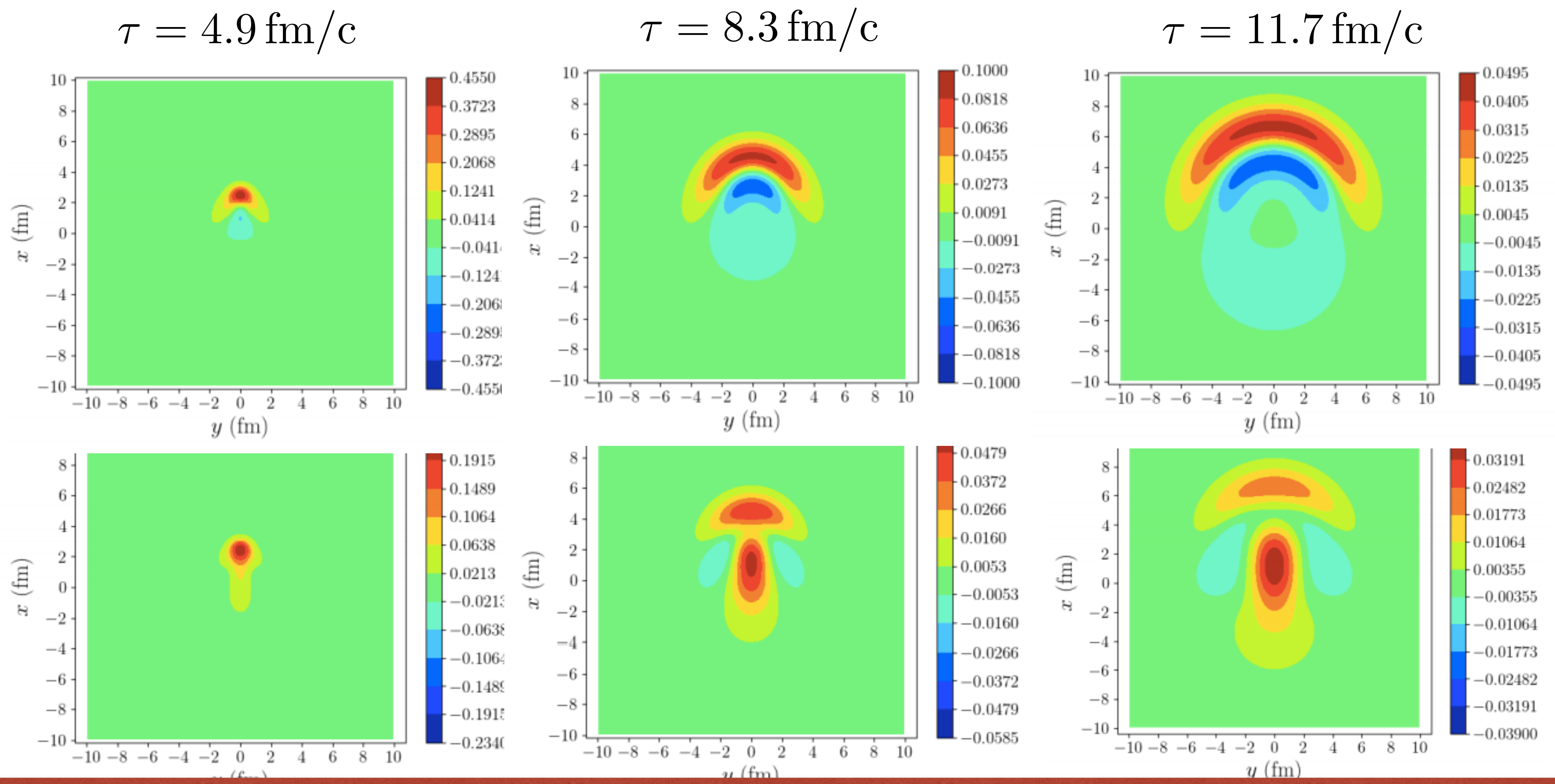
Efficient, but over-simplified medium response needs to be improved:

- Extend kinematical validity: requires knowledge of spacetime evolution of hydro perturbations.

→ Linearised hydro eqs. for perturbations on top of viscous Bjorken flow:

$$\nabla_\mu T^{\mu\nu}_{(0)} = 0$$

$$\nabla_\mu \delta T^{\mu\nu} = J^\nu$$



$$\frac{\delta\varepsilon}{\varepsilon_0}(\eta_s = 0)$$

energy perturbation

$$\delta u^x(\eta_s = 0)$$

velocity perturbation

Yao et al. - 2010.01140

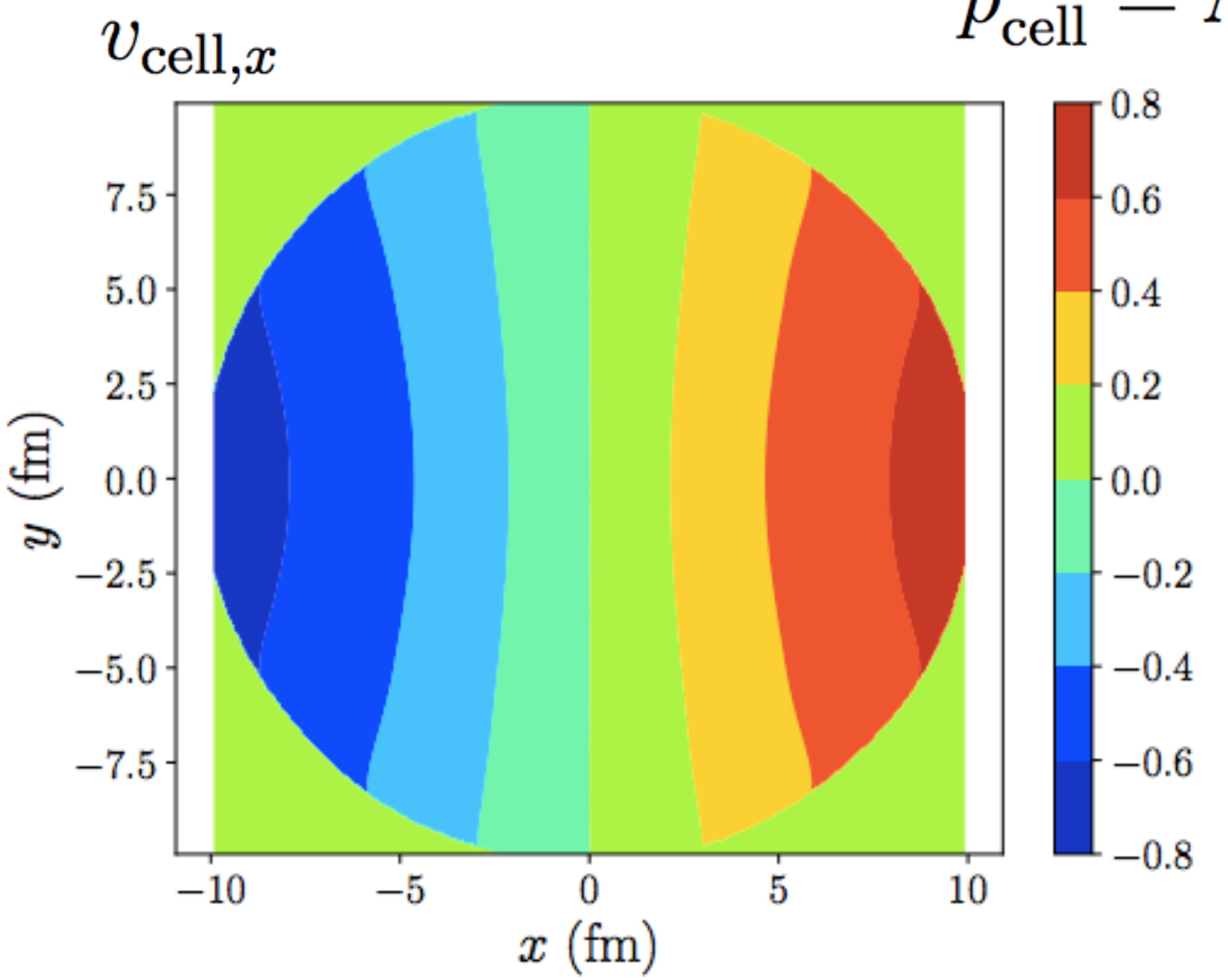
Improving the wake description

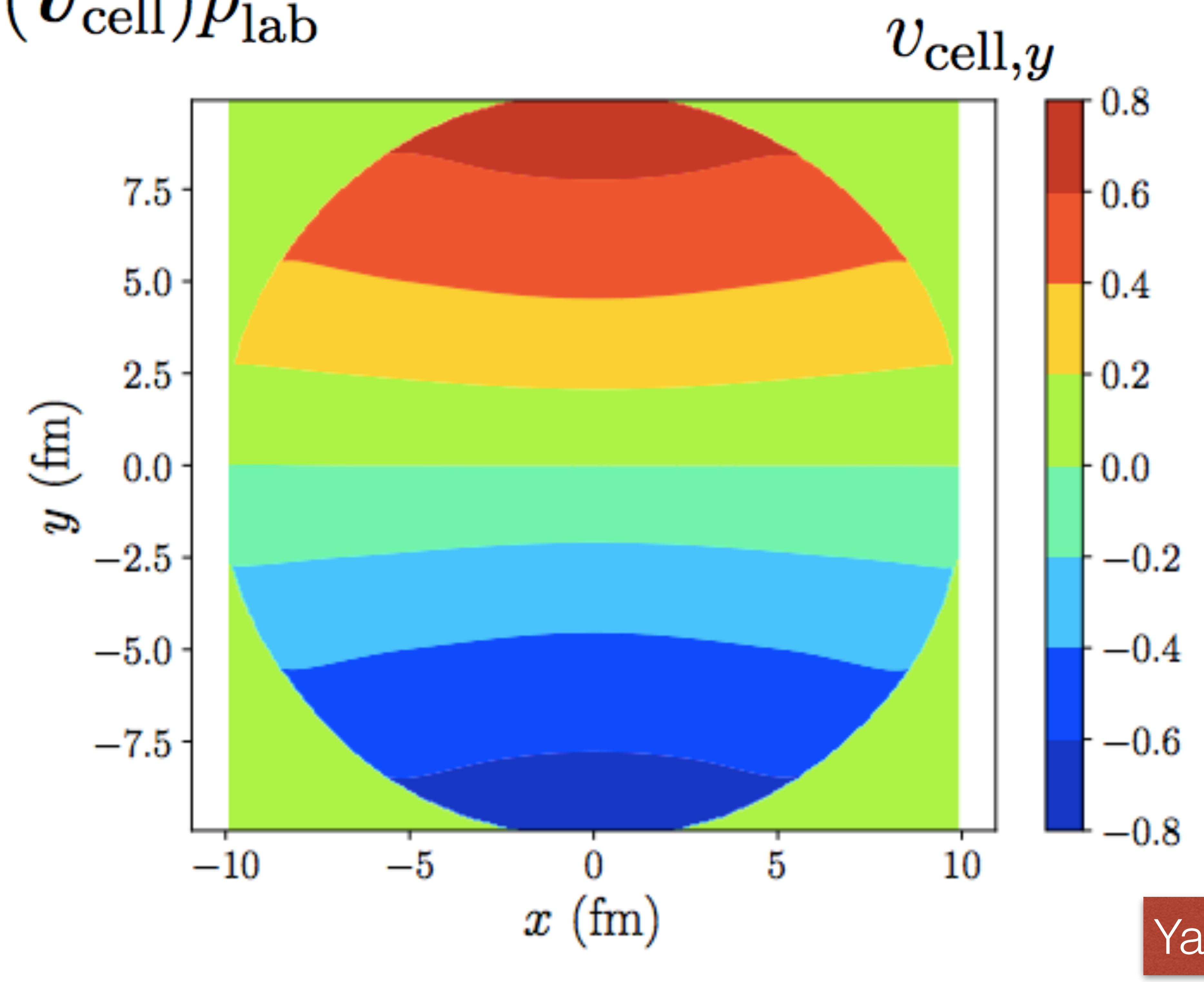
Efficient, but over-simplified medium response needs to be improved:

- Include the effects of realistic background flow.

→ Boost fluid cell of the perturbation according to local radial flow at freeze-out hyper surface:

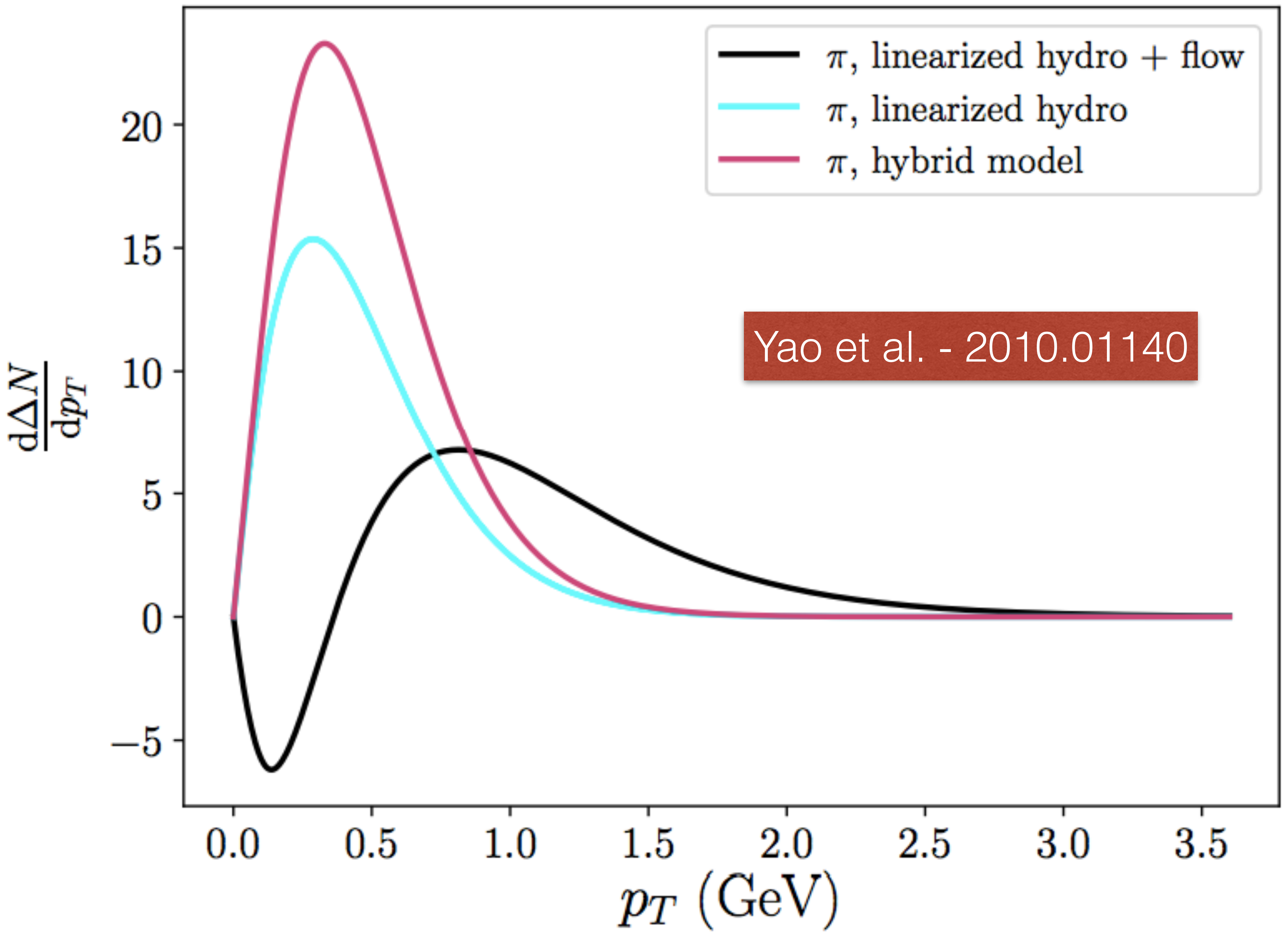
$$p^{\mu}_{\text{cell}} = \Lambda^{\mu}{}_{\nu}(\boldsymbol{v}_{\text{cell}})p^{\nu}_{\text{lab}}$$

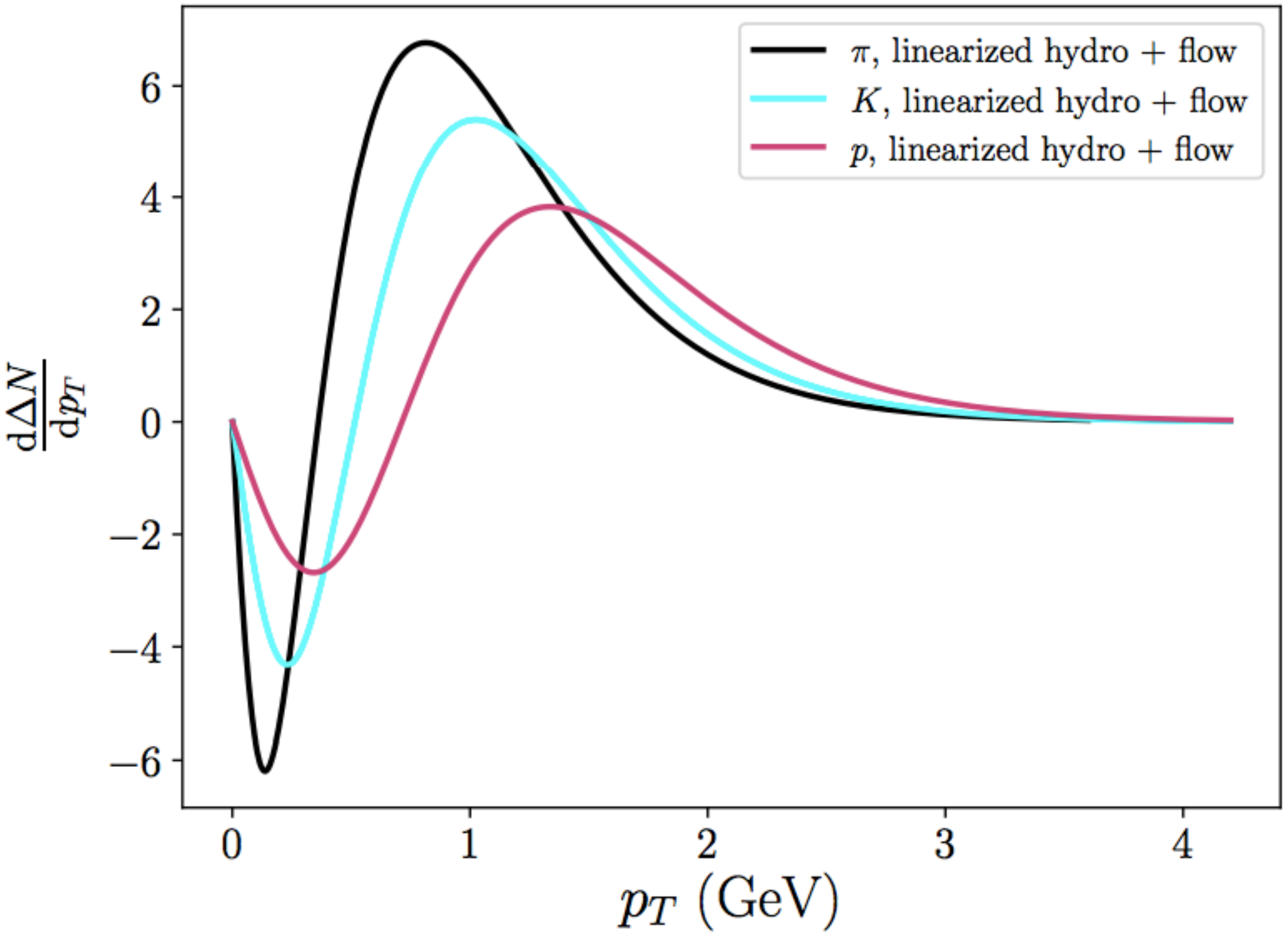




Yao et al. - 2010.01140

Linearised Wake: effects on observables





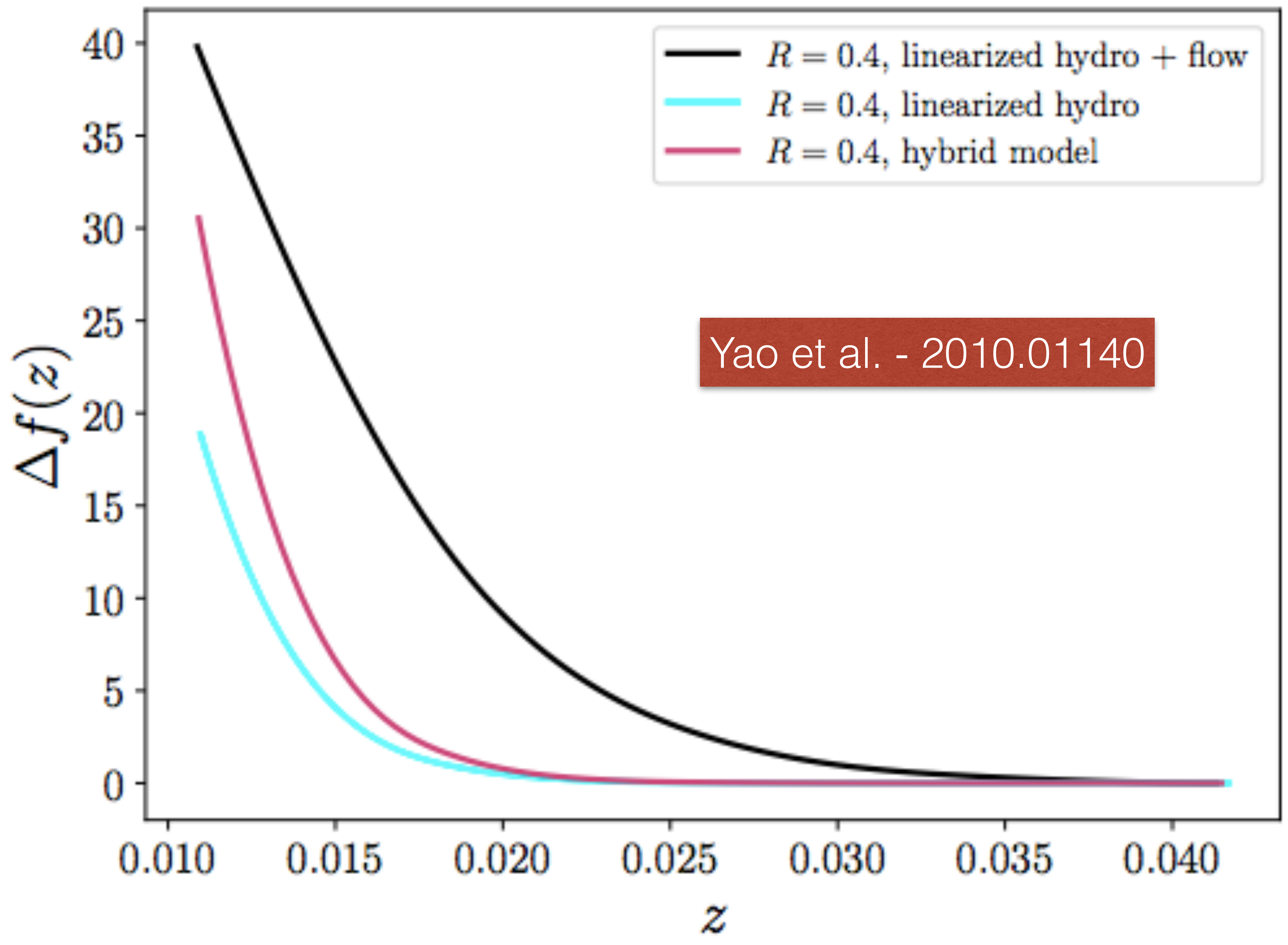
Strongest new effect comes from radial flow:

- Important hardening of hadrons p_T spectrum.

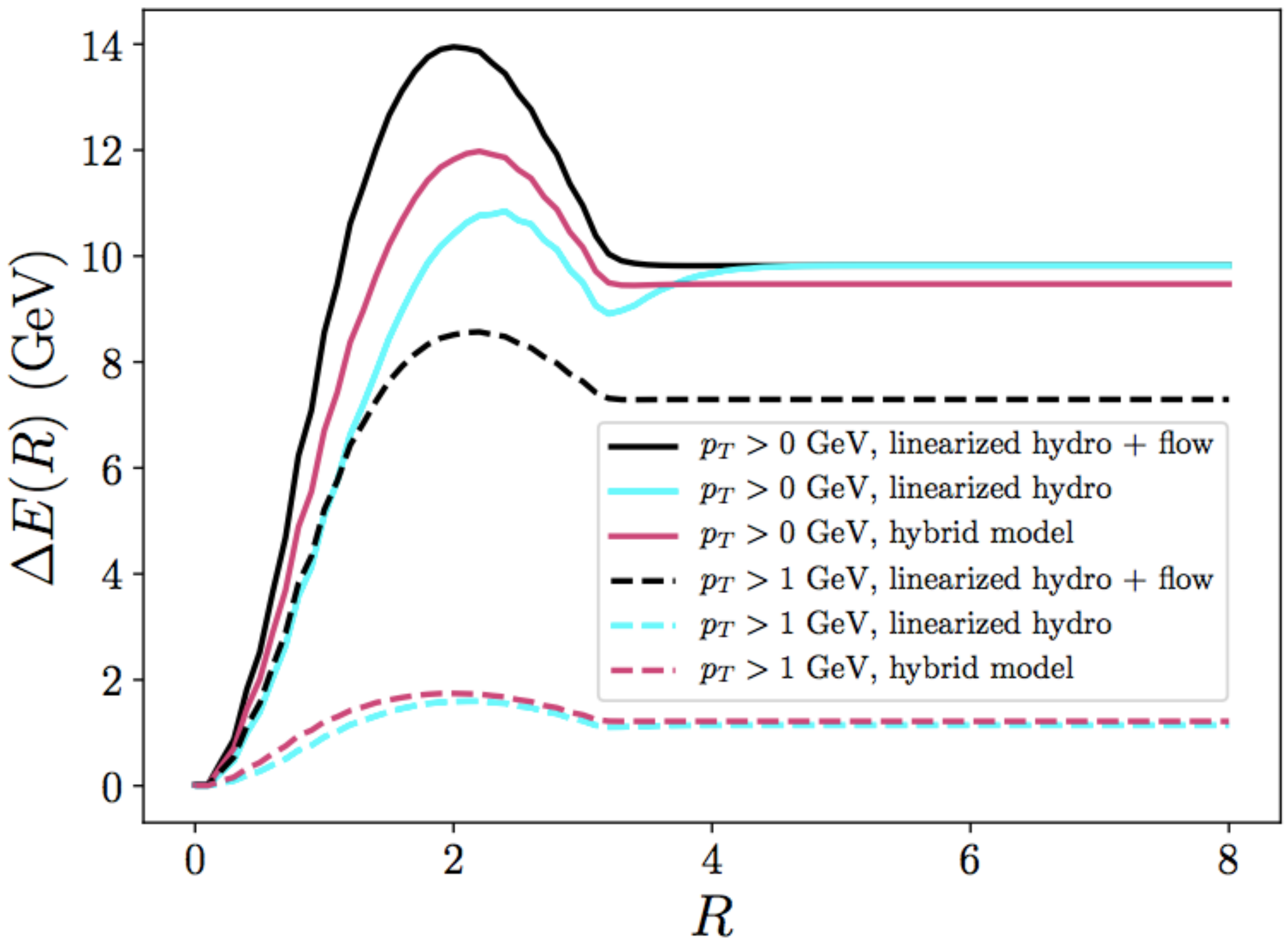
As expected from hydrodynamics:

- Hadrons from the wake display mass ordering.

Linearised Wake: effects on observables



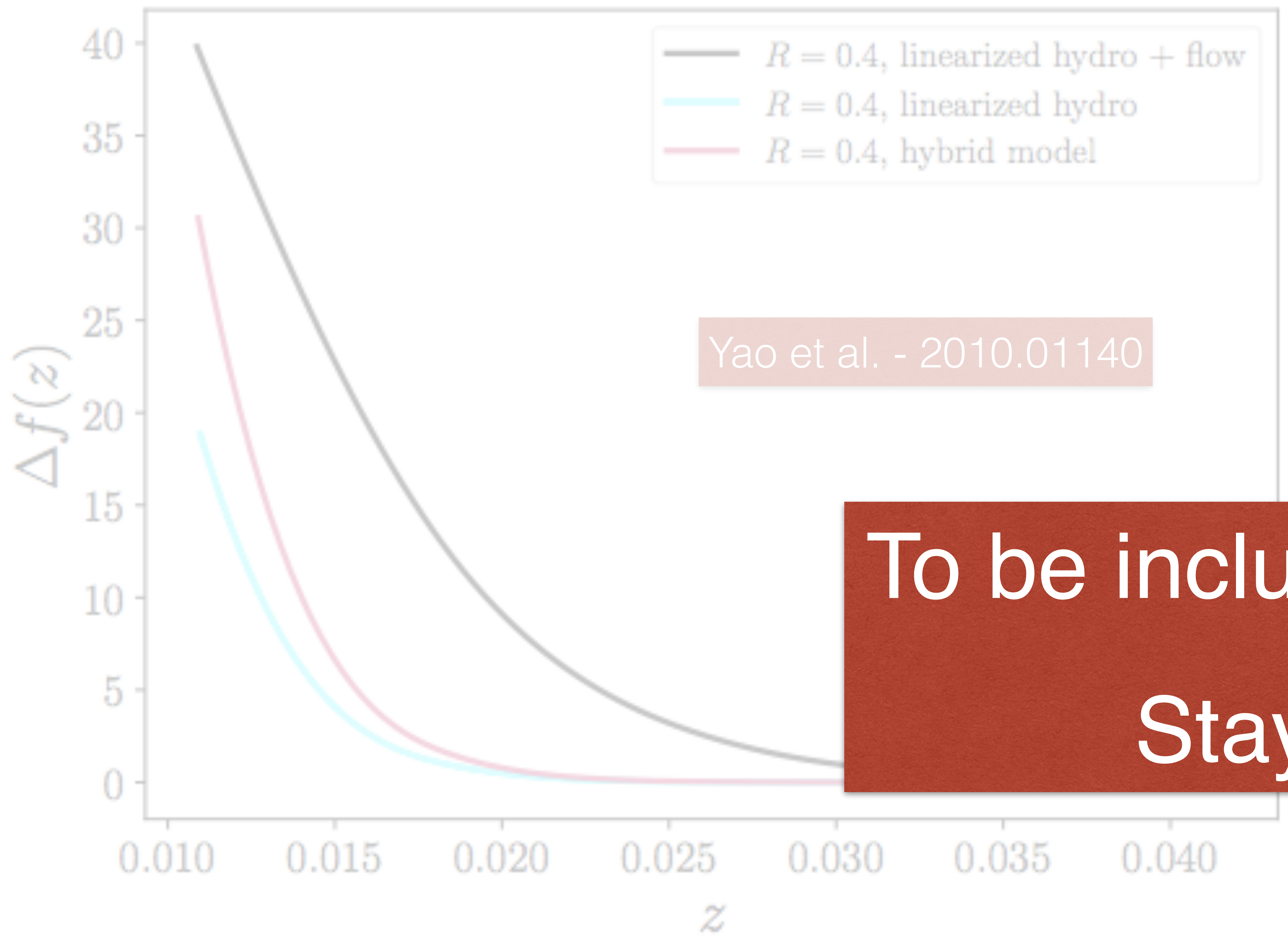
Yao et al. - 2010.01140



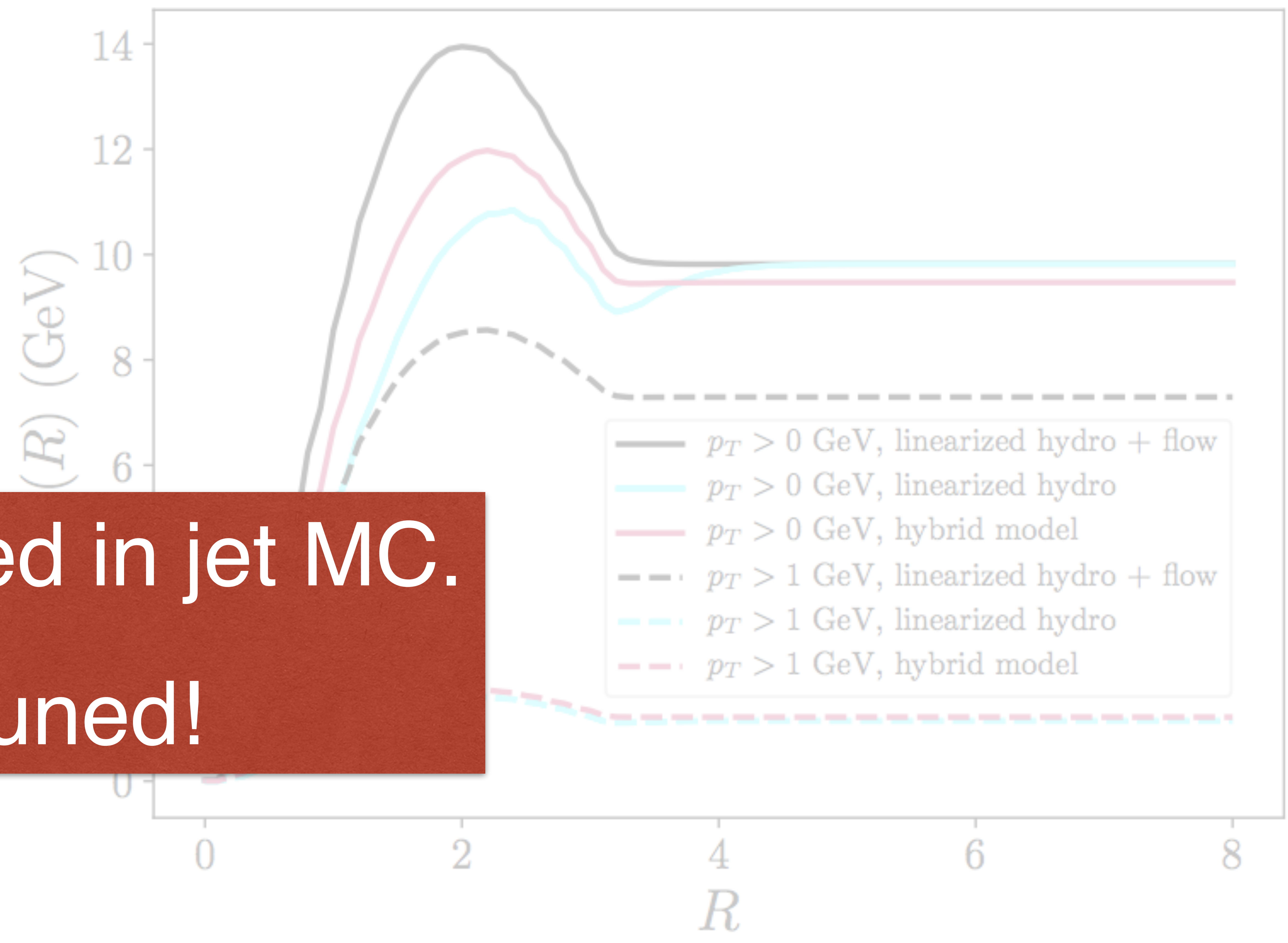
- Increase in # fragments with higher z inside the jet (jet FFs)

- Modified recovery of energy as a function of radial distance (jet shapes, R_{AA} vs R)

Linearised Wake: effects on observables



Yao et al. - 2010.01140



To be included in jet MC.

Stay tuned!

Increase in # fragments
with higher z inside the jet
(jet FFs)

Modified recovery of energy as a
function of radial distance
(jet shapes, R_{AA} vs R)

Jet Suppression: Analytics

- Great deal of jet observables are understood through consideration of jet substructure fluctuations within the medium:

  → Jet MC quenching models naturally include these effects, although with many uncontrolled modelling assumptions.

- Want to extend these concepts to phenomenologically relevant perturbative, analytic calculations in QCD. We need to:

  → Resum quenching effects from multi-prong nature of jets.

  → Take into account color coherence effects.

  → Gauge uncertainties on non-perturbative components (e.g. the wake).

  → Embed into realistic heavy ion environment to account for in-medium path flucs.

Jet Suppression: Analytics

- Cross-section of jet with radius R in the medium:

$$\sigma_{AA}(p_T, R) = f^{(n-1)}_{\mathrm{jet}/k}(R|p_T, R_0)\,\hat{\sigma}_k(p_T, R_0)$$

$$f^{(n-1)}_{\mathrm{jet}/k} = \sum_{i=q,g} Q_i(p_T, R)\, f^{(n-1)}_{i/k}$$

quenching factor

moment of jet frag. function

Dasgupta et al. - JHEP ‘15

- Resummation of bare quenching factor through DGLAP:

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

Mehtar-Tani & Tywoniuk - PRD ‘18

with quenched phase space: $\Theta_{\mathrm{in}}(p,R) = \Theta(t_{\mathrm{f}} < t_{\mathrm{d}} < L)$

Quench resolved emission inside the medium only

with initial condition: $Q_i(p,0) = Q^{(0)}_{\mathrm{rad},i}(\nu)\,Q^{(0)}_{\mathrm{el},i}(\nu)$

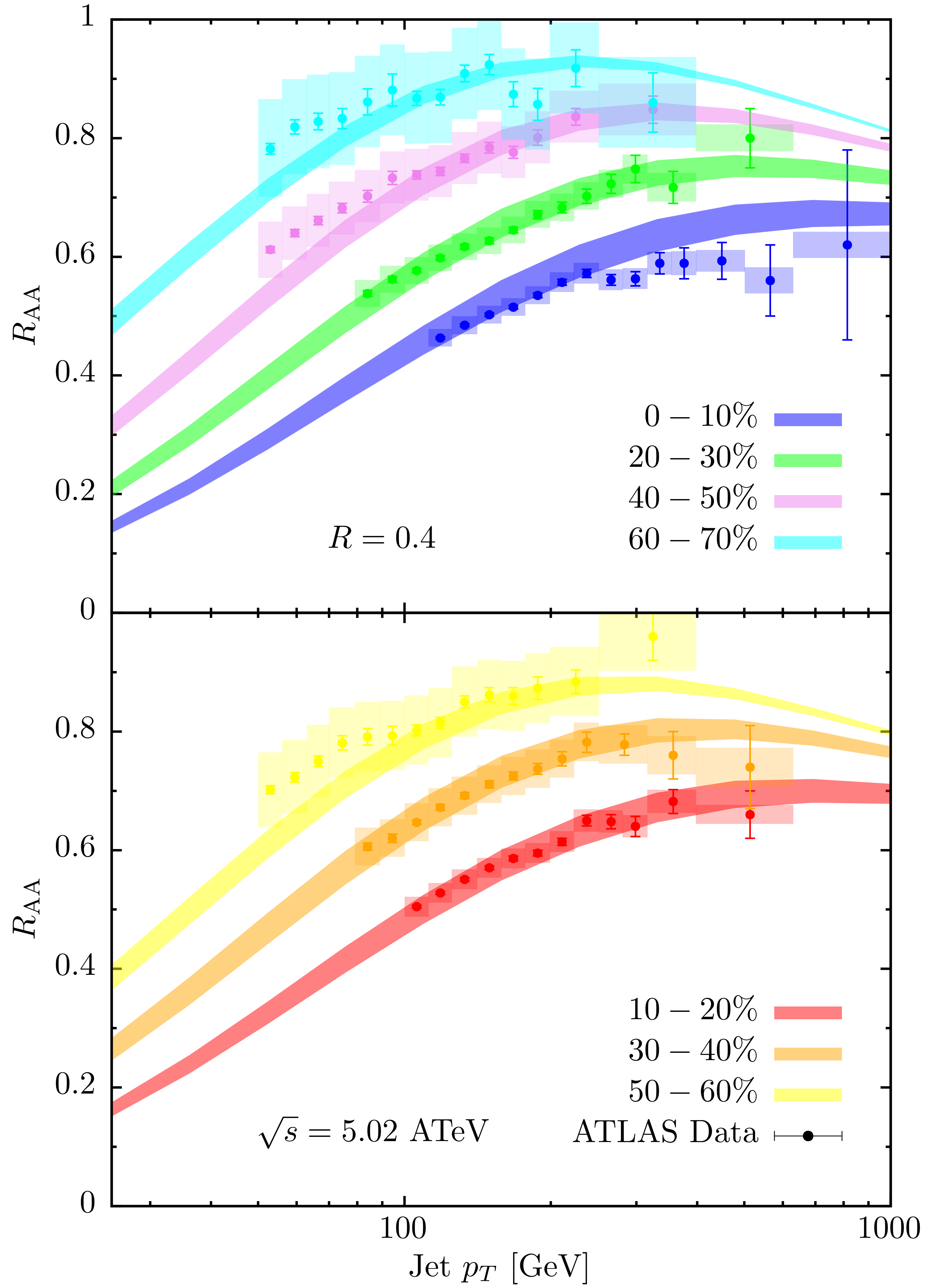
Radiative component at NLO in improved opacity expansion

Barata & Mehtar-Tani - 2004.02323

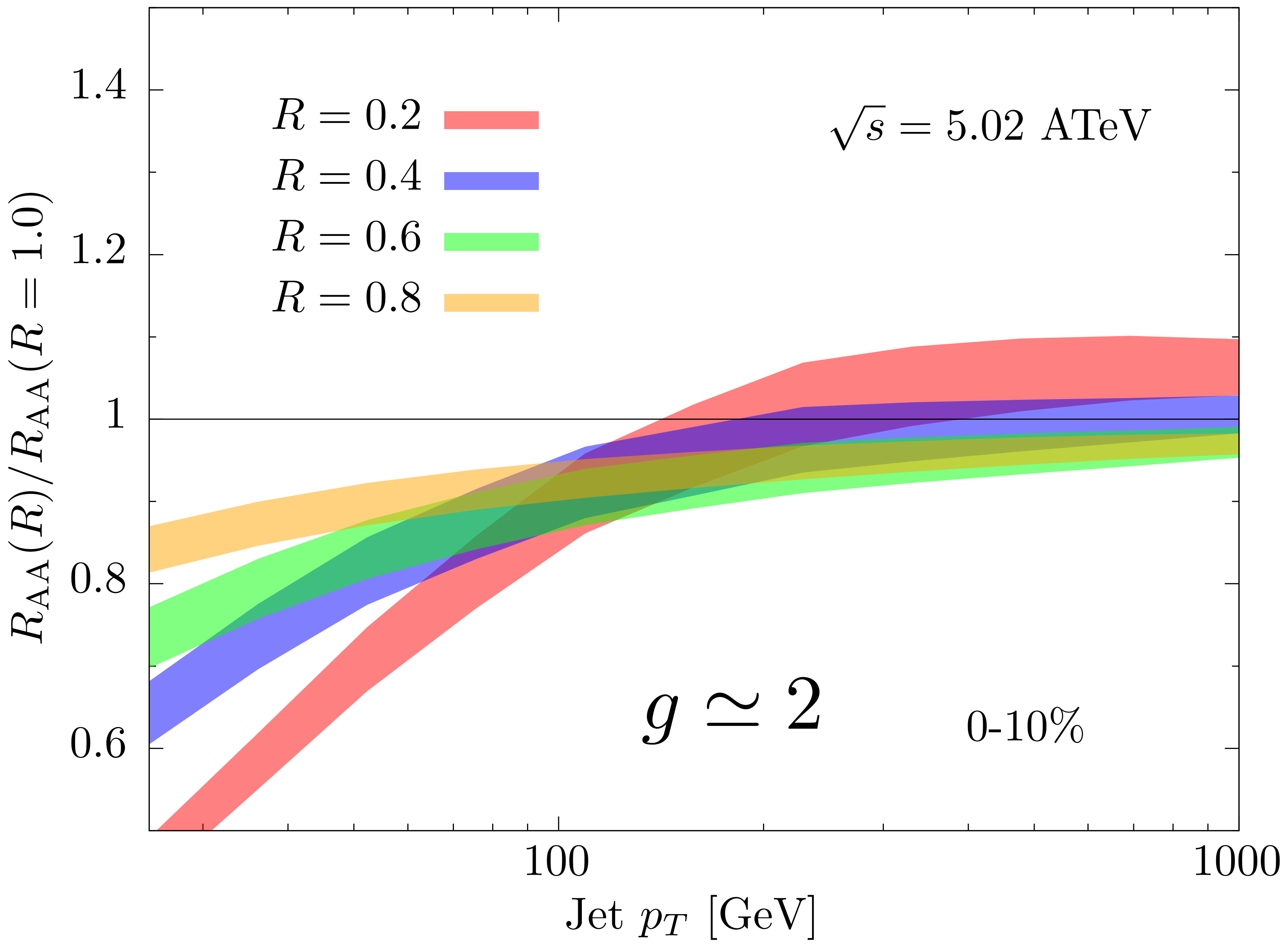
Include R_{rec} parameter for energy recovery vs R

Mehtar-Tani et al. - 2010.XXXX

Jet Suppression: Analytics



Mehtar-Tani et al. - 2010.XXXX

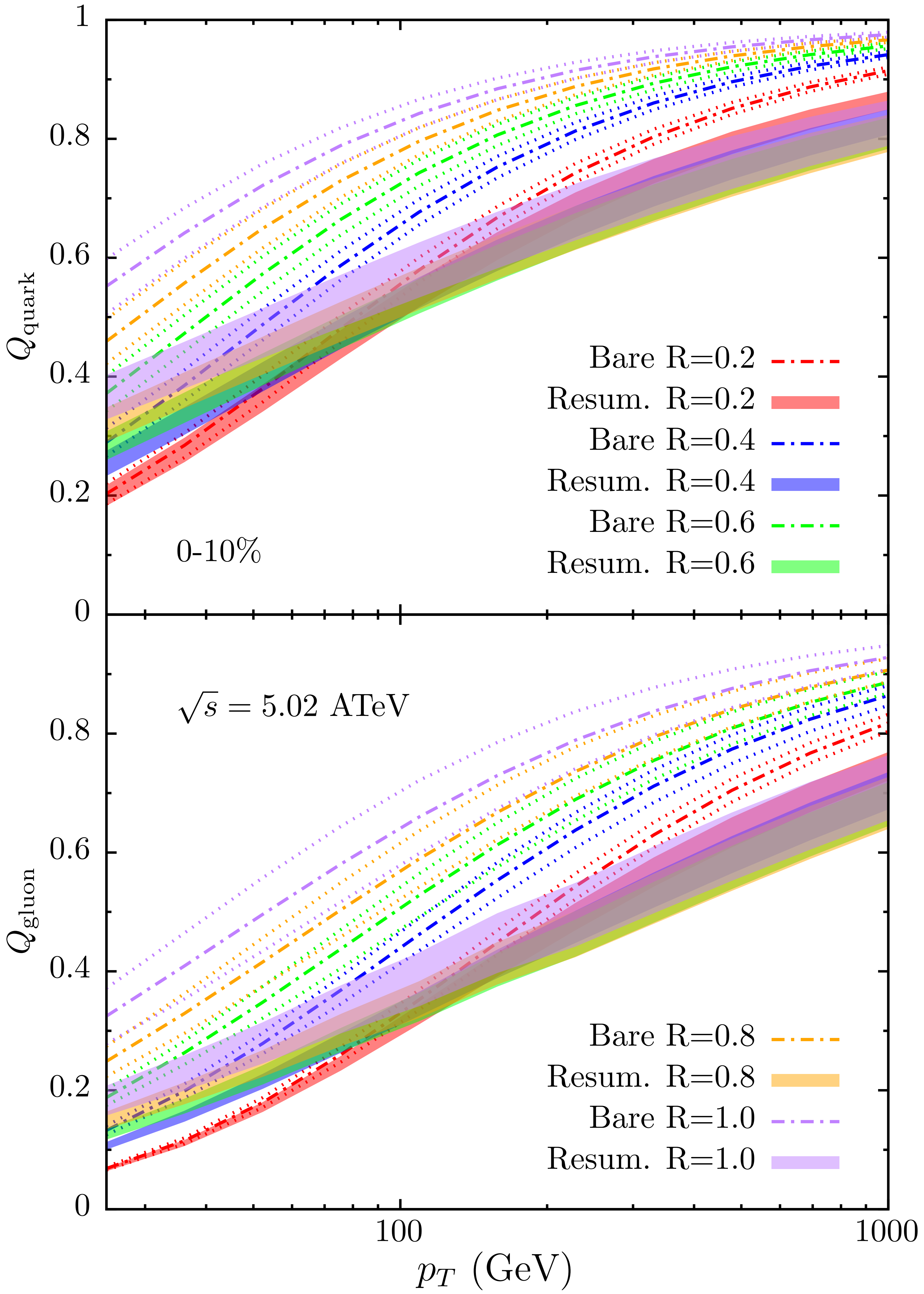


- Excellent description of p_T and centrality evolution

ATLAS - PLB '18

- Mild R dependence of jet suppression in agreement with recent CMS data

CMS-PAS-HIN-18-014



Summary

- Jet substructure fluctuations are key to our understanding of jet quenching phenomenology.

  Early fragmentation pattern of the jet (mostly dominated by vacuum physics)
  controls amount of quenching:

  → Selection bias towards narrower jets due to steeply falling spectrum,
  provided that the medium resolves the internal structure of the jet.

  → Can use machine learning to select jets with a certain amount of energy loss,
  study observables based on initial jet energy, getting rid of the selection bias.

- Hydrodynamization of jet energy can be studied through jet substructure observables.

  Soft particles from the wake enter the jet cone:

  → Sensitive to background flow, display mass ordering.
  → Long range correlations between dijet system vs R.

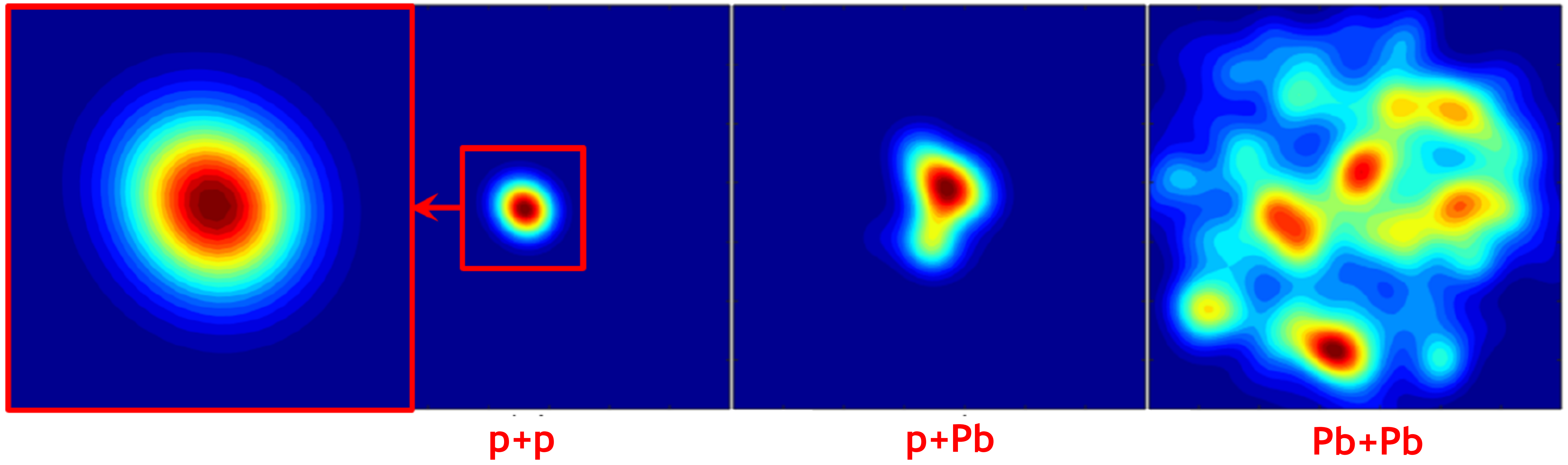
  } Crucial elements of fluid QGP paradigm!

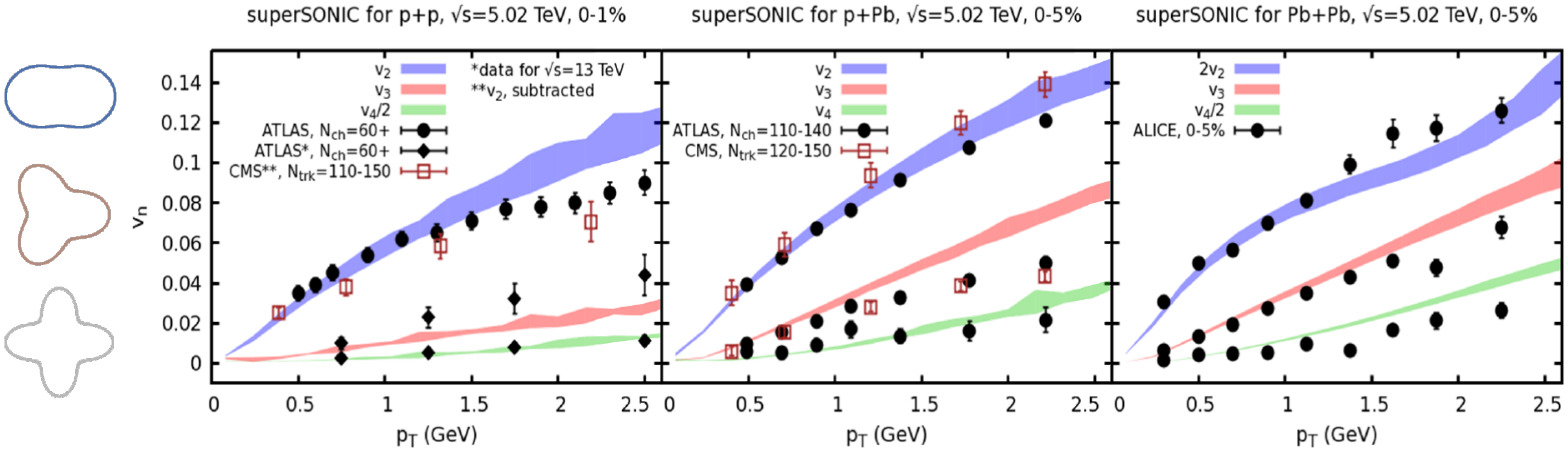
Backup Slides

Hydro in Small Systems

“One fluid to rule them all”

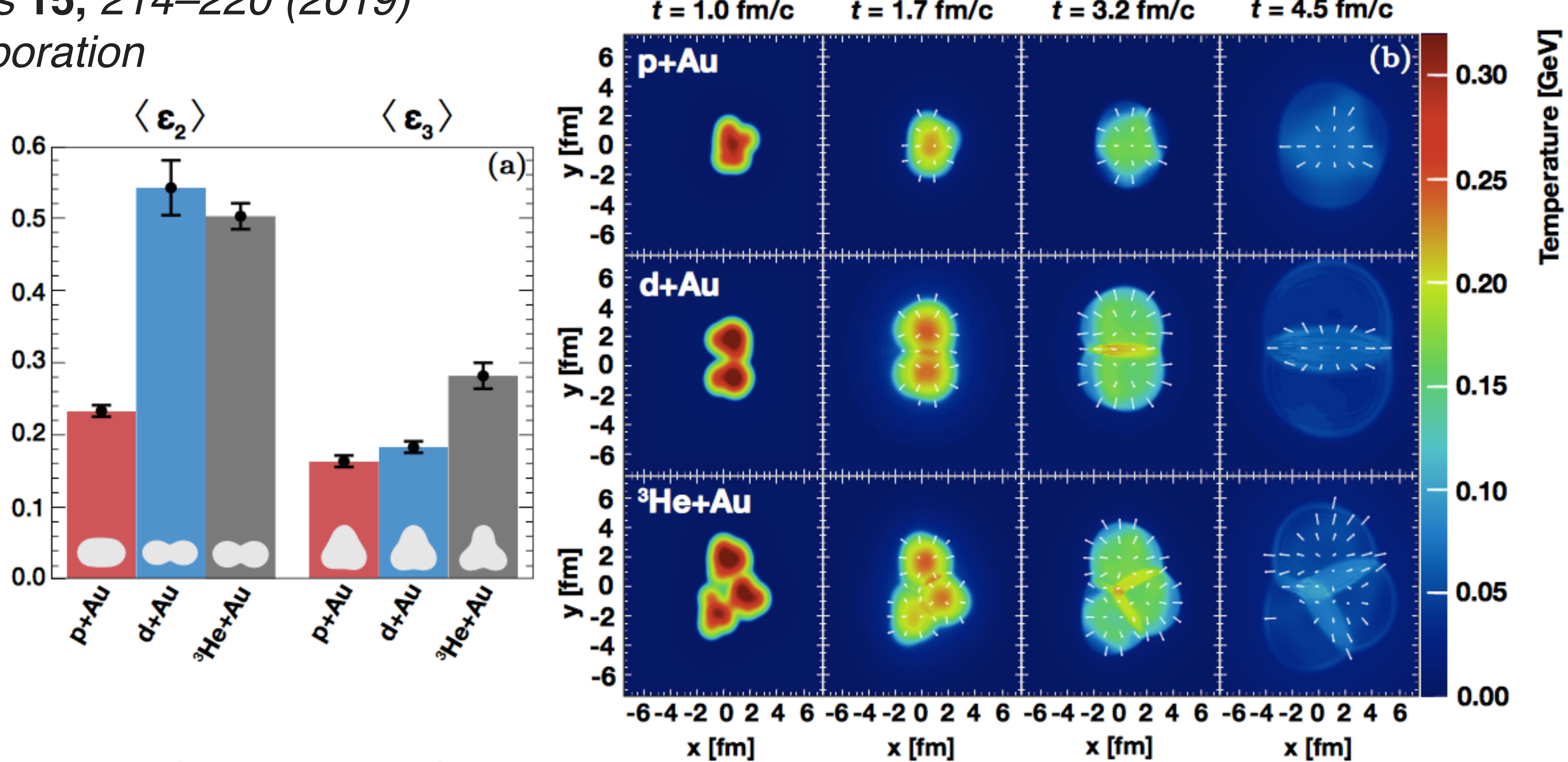
Weller & Romatschke - PLB ‘17





Hydro in Small Systems

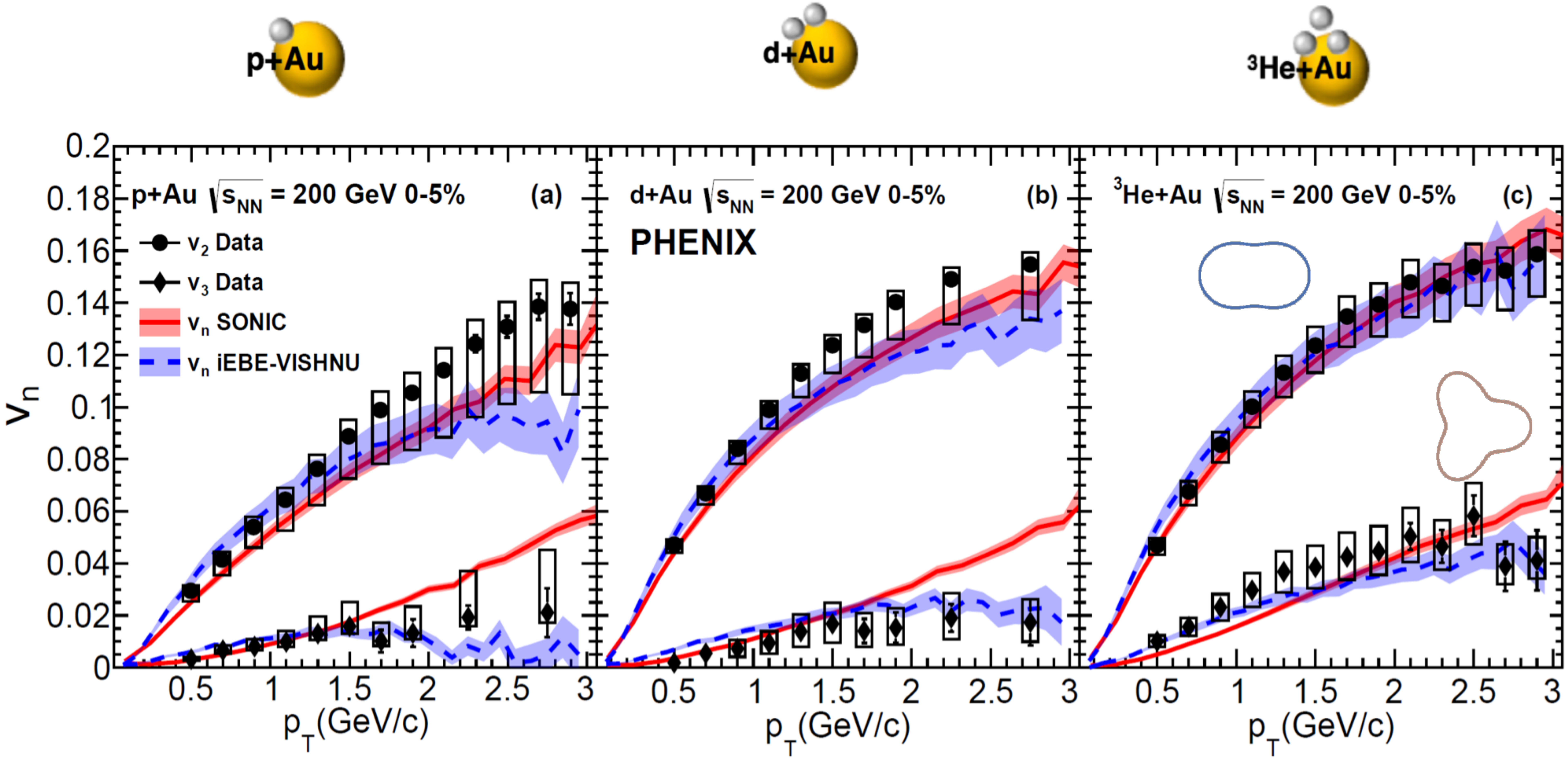
Nature Physics **15,** *214–220 (2019)*
PHENIX collaboration



Expectation from hydro arguments:

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

Hydro in Small Systems



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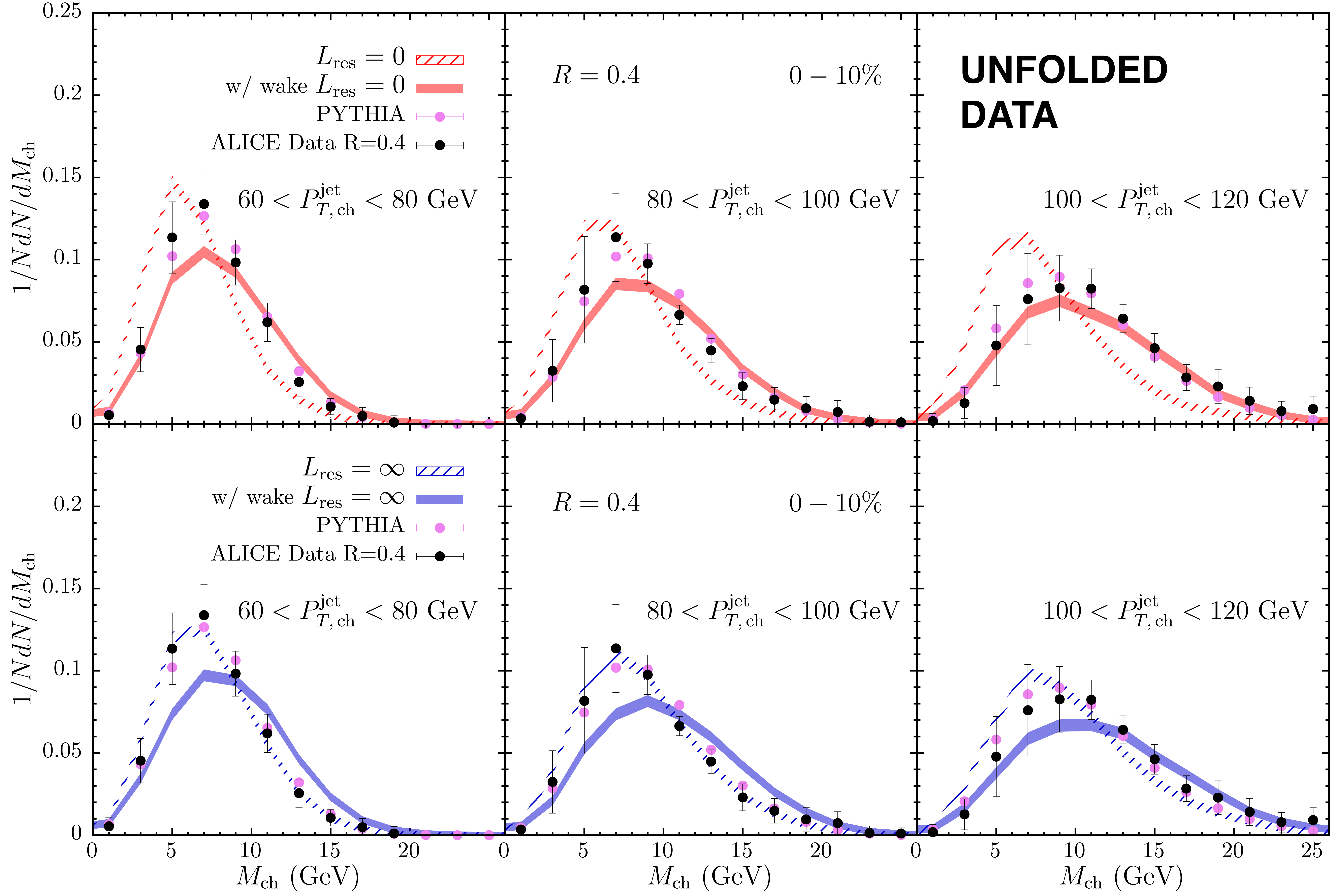
Nature Physics **15,** *214–220 (2019)*
PHENIX collaboration

A *frustrating* observable: charged jet mass



Without wake:

$L_{\rm res} = 0$

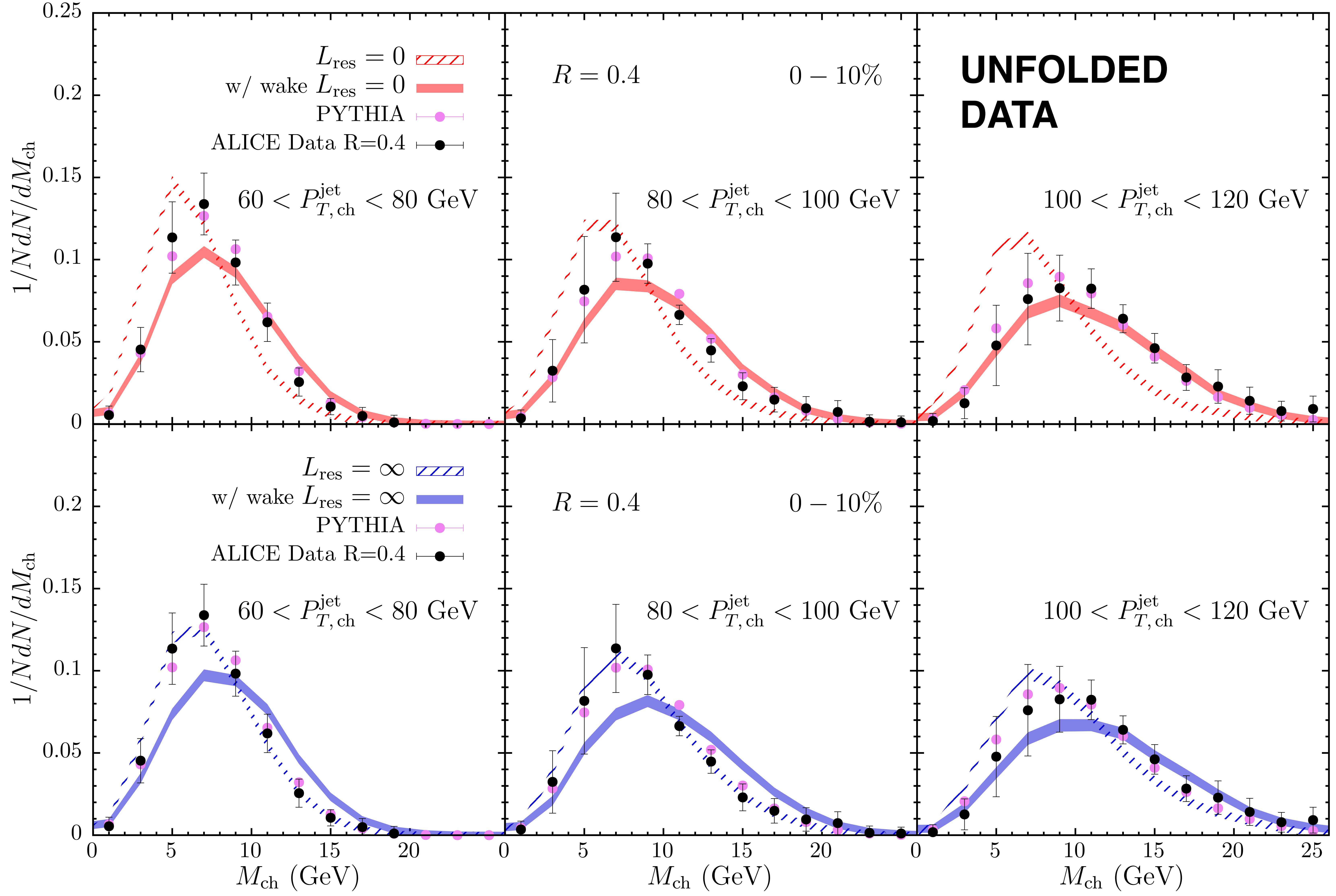
shift towards smaller masses

$L_{\rm res} = \infty$

barely any modification

Larger mass jets
are more active;
more suppressed if
substructure resolved.

A *frustrating* observable: charged jet mass



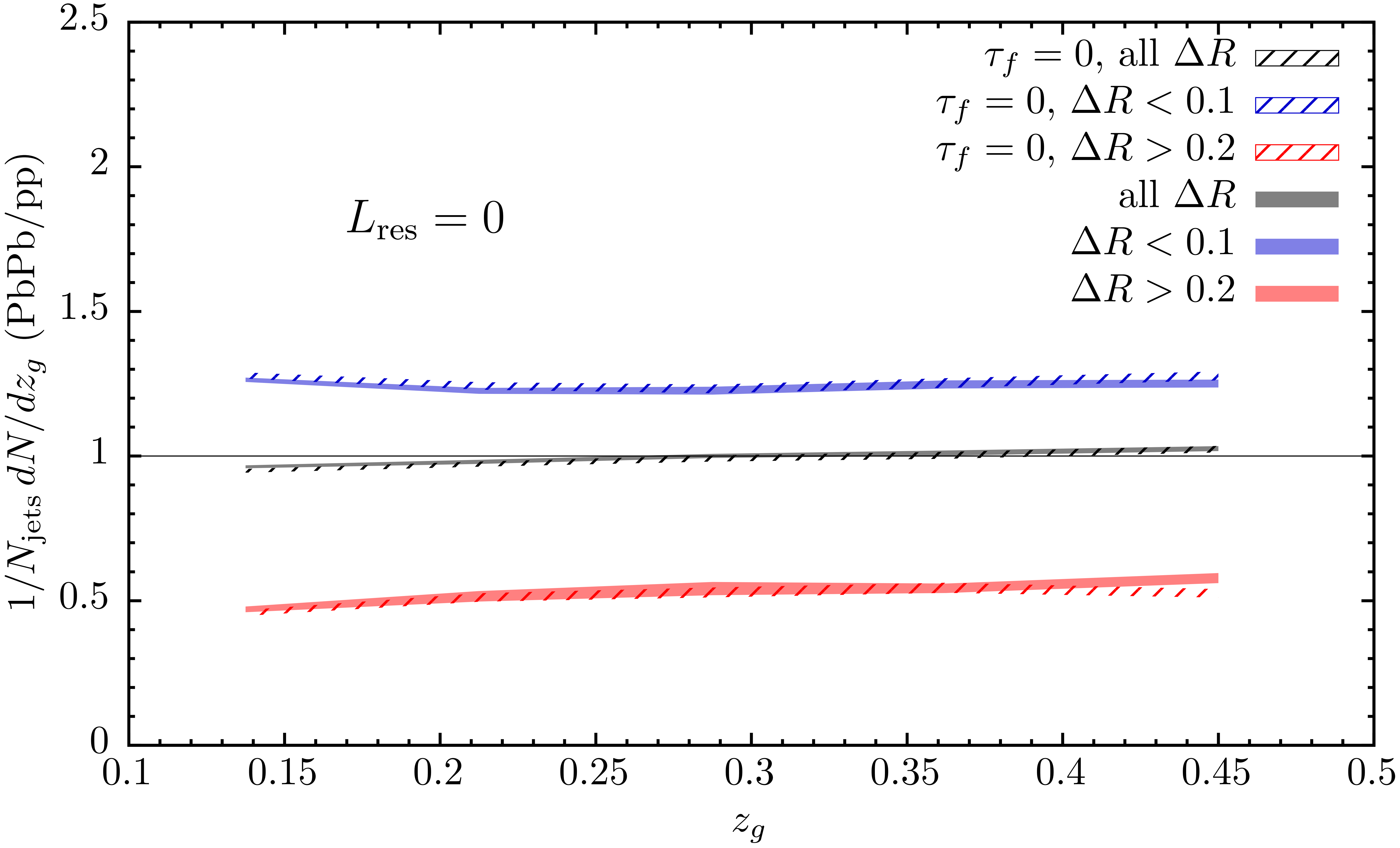
With wake:

Soft particles from the wake increase the mass, compensating quenching.

$L_{\rm res} = 0$ and $L_{\rm res} = \infty$ barely distinguishable!

Surprisingly good description of data across three p$_T$ ranges, after cancellation of effects…

The role of formation time



Is wide configuration suppressed because formed early?

Radical test:
Assume all formation times are zero.

- Small adjustment of kappa.
- Almost no change in ΔR ordering.

Observable dominated by correlation between ΔR and multiplicity.

Cutting the Lund Plane

Difference PbPb-pp
of 1st SD splitting Lund plane

Flat

Removes soft & soft-collinear

Core

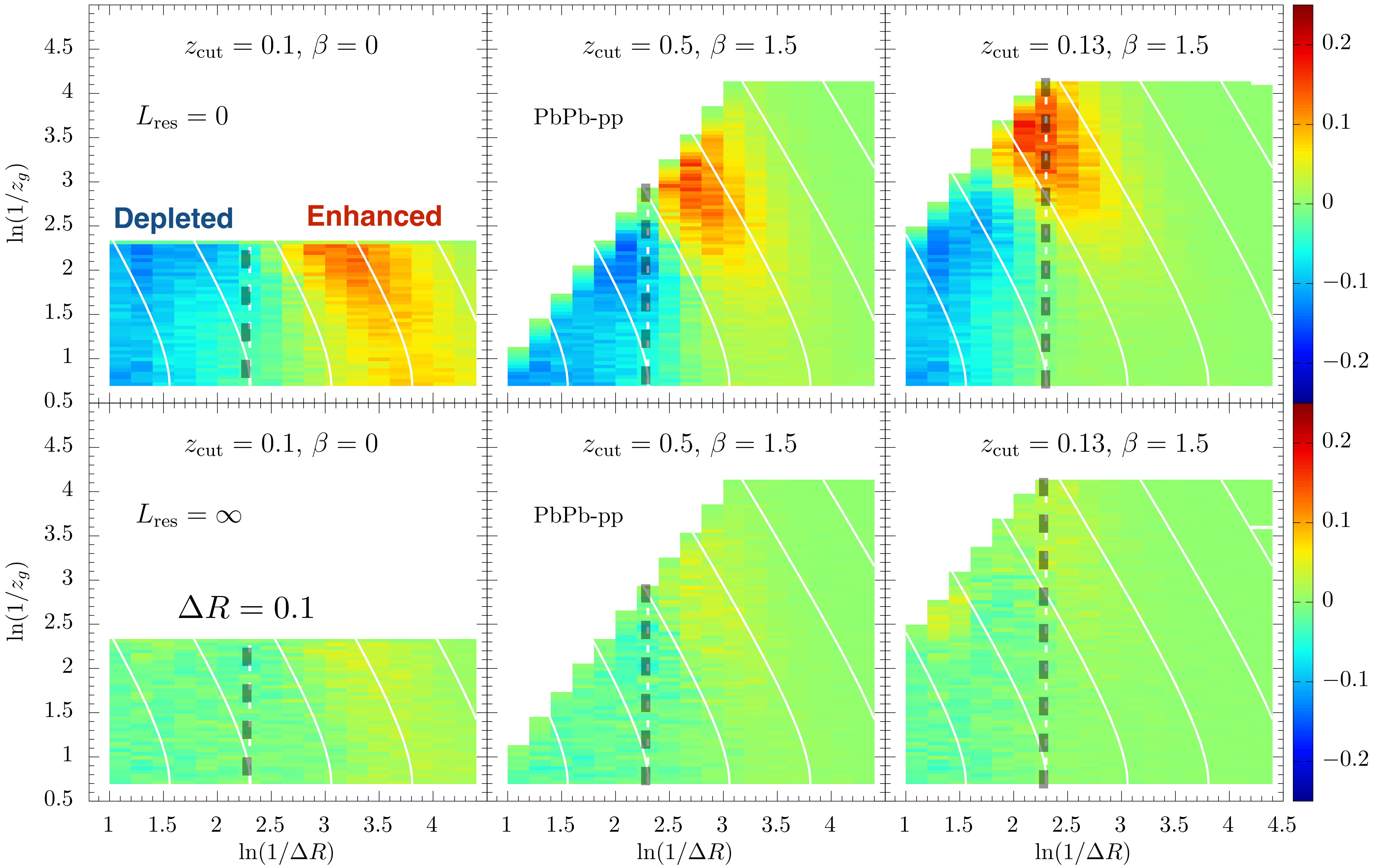
Removes soft-wide

Soft-core

Extends soft-collinear region

CMS angularity limit: $\Delta R > 0.1$

Flat **Core** **Soft-core**



Cutting the Lund Plane

Difference PbPb-pp
of 1st SD splitting Lund plane

Flat

Removes soft & soft-collinear

Core

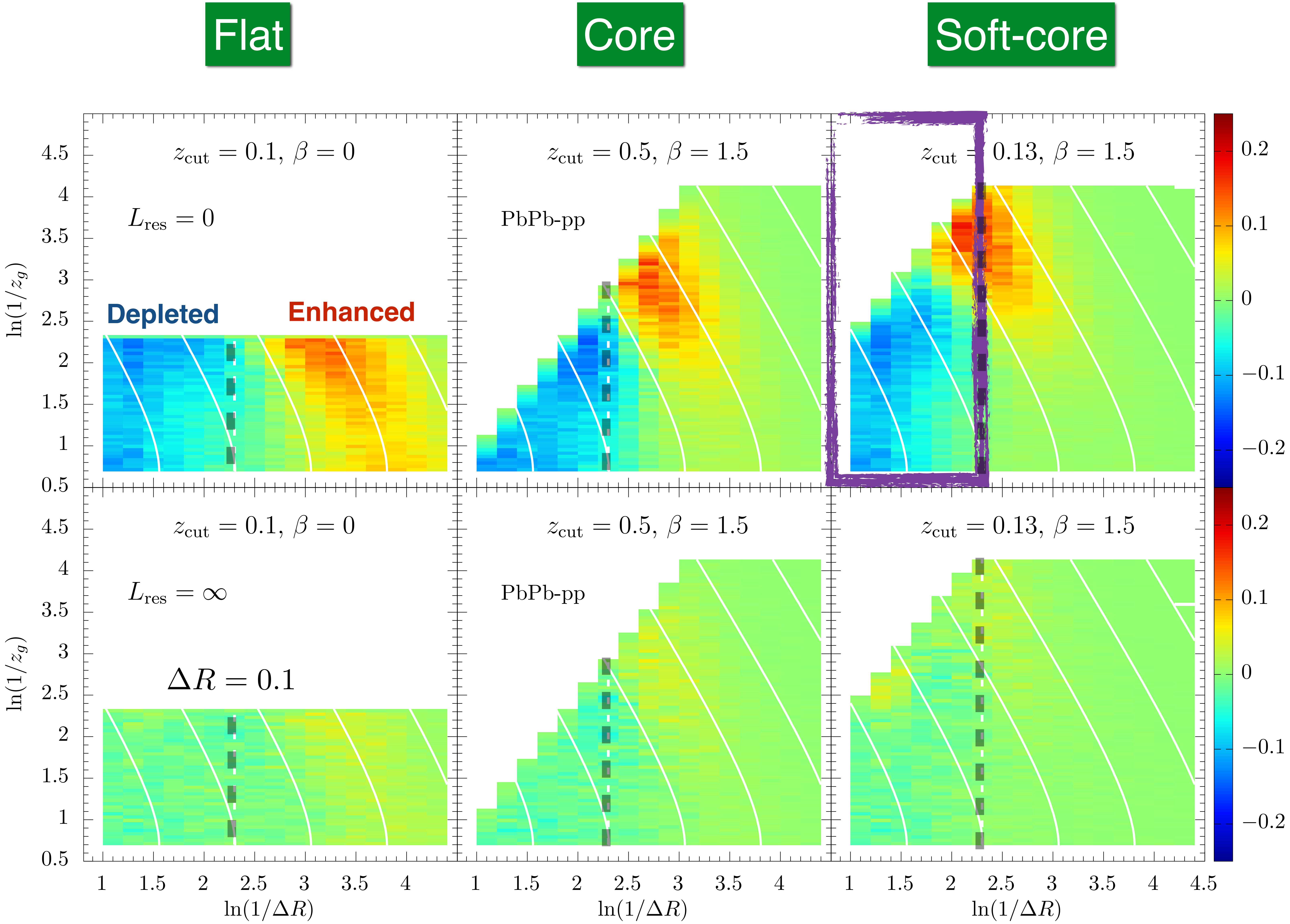
Removes soft-wide

Soft-core

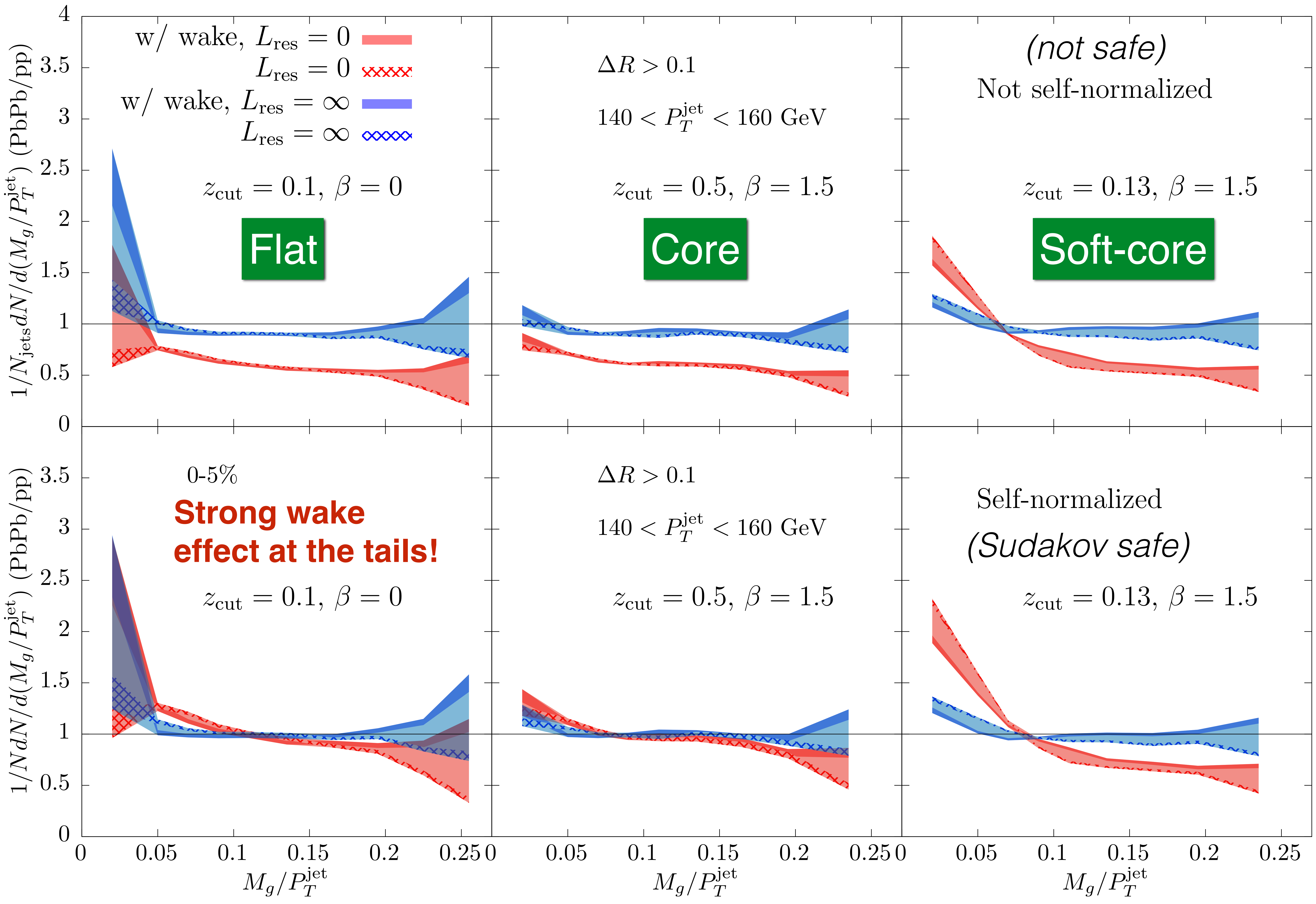
Extends soft-collinear region

Enhances Lund plane structure above $\Delta R > 0.1$

CMS angularity limit: $\Delta R > 0.1$



Groomed jet mass



Flat

Core

Soft-core

(not safe)

Strong wake effect at the tails!

(Sudakov safe)

Flat **Core**

Not self-normalized:

merely reflect absence of wide angle configurations

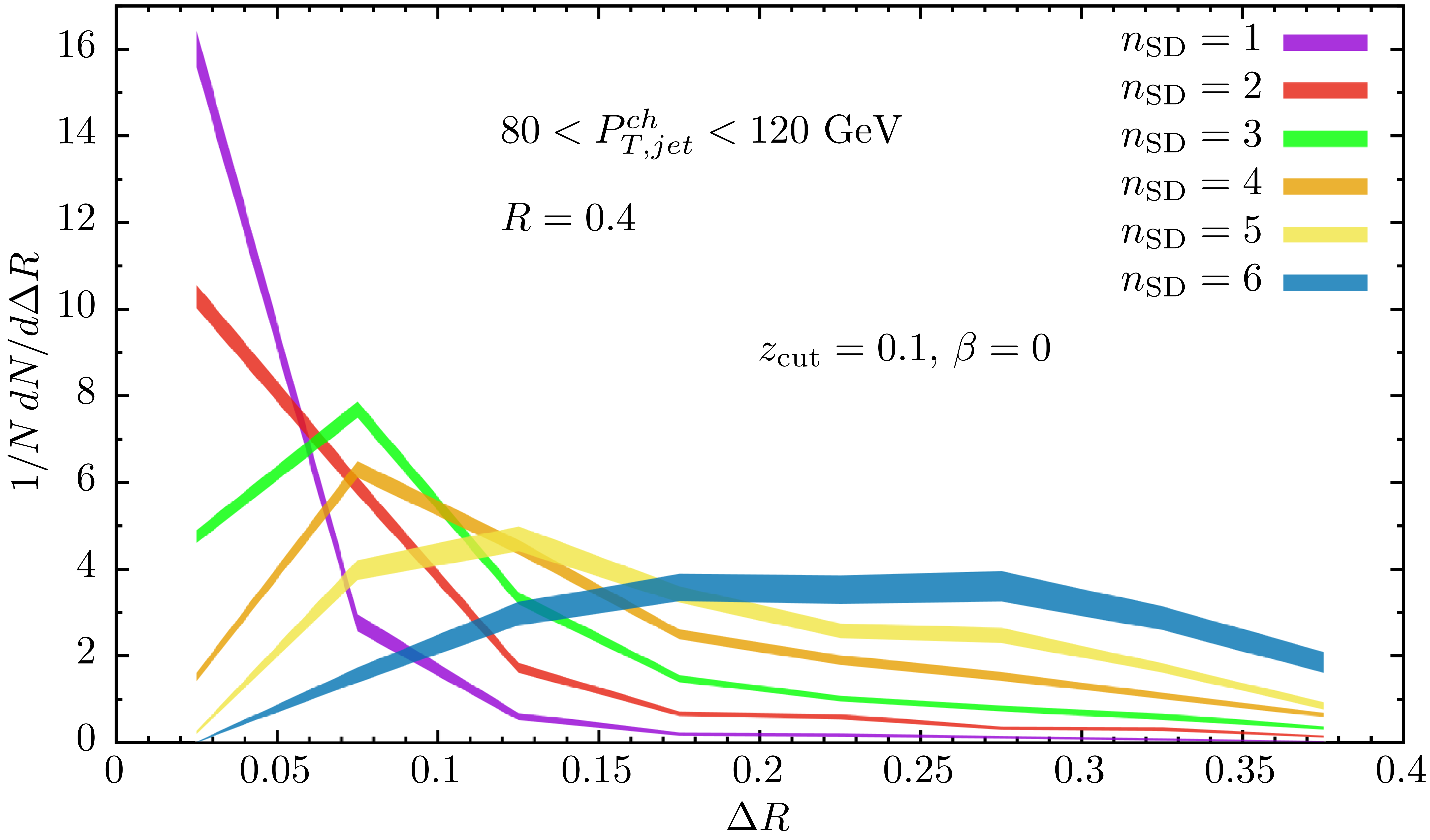
Self-normalized:

differences due to $L_{\rm res}$ of the size of the wake effect

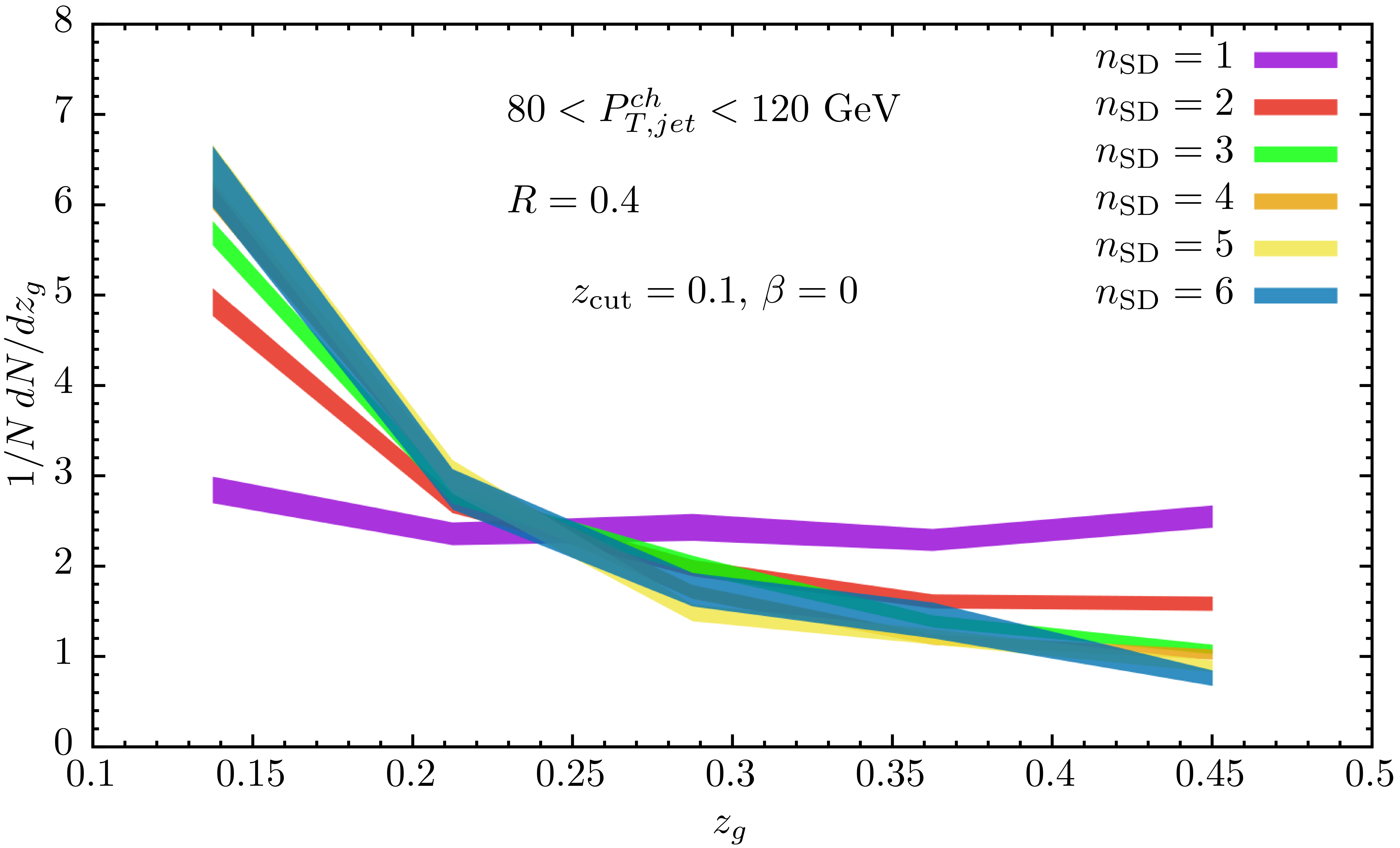
Soft-core

Strong discriminating power, not relying on the norm.

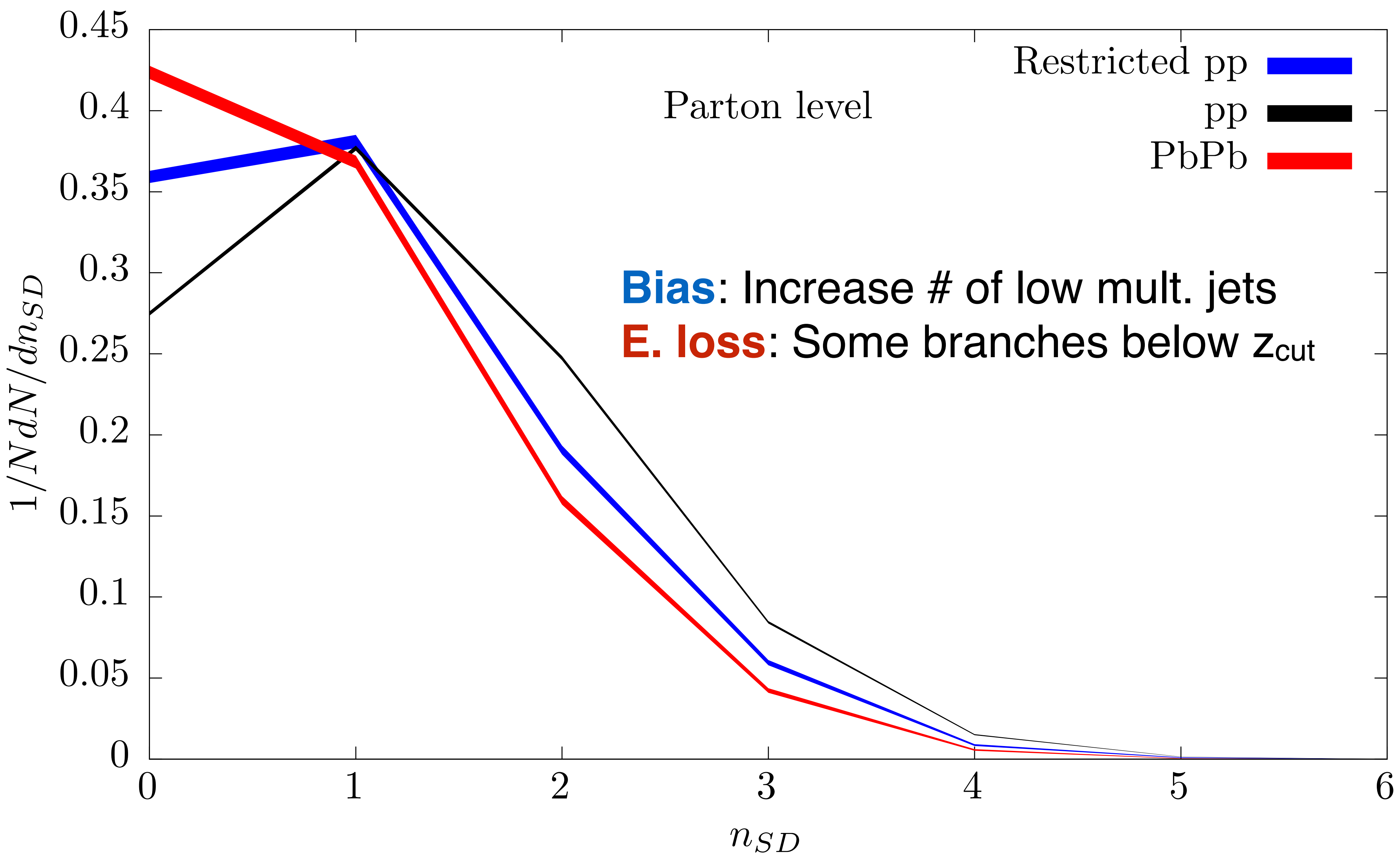
Correlation between n_{SD} and ΔR



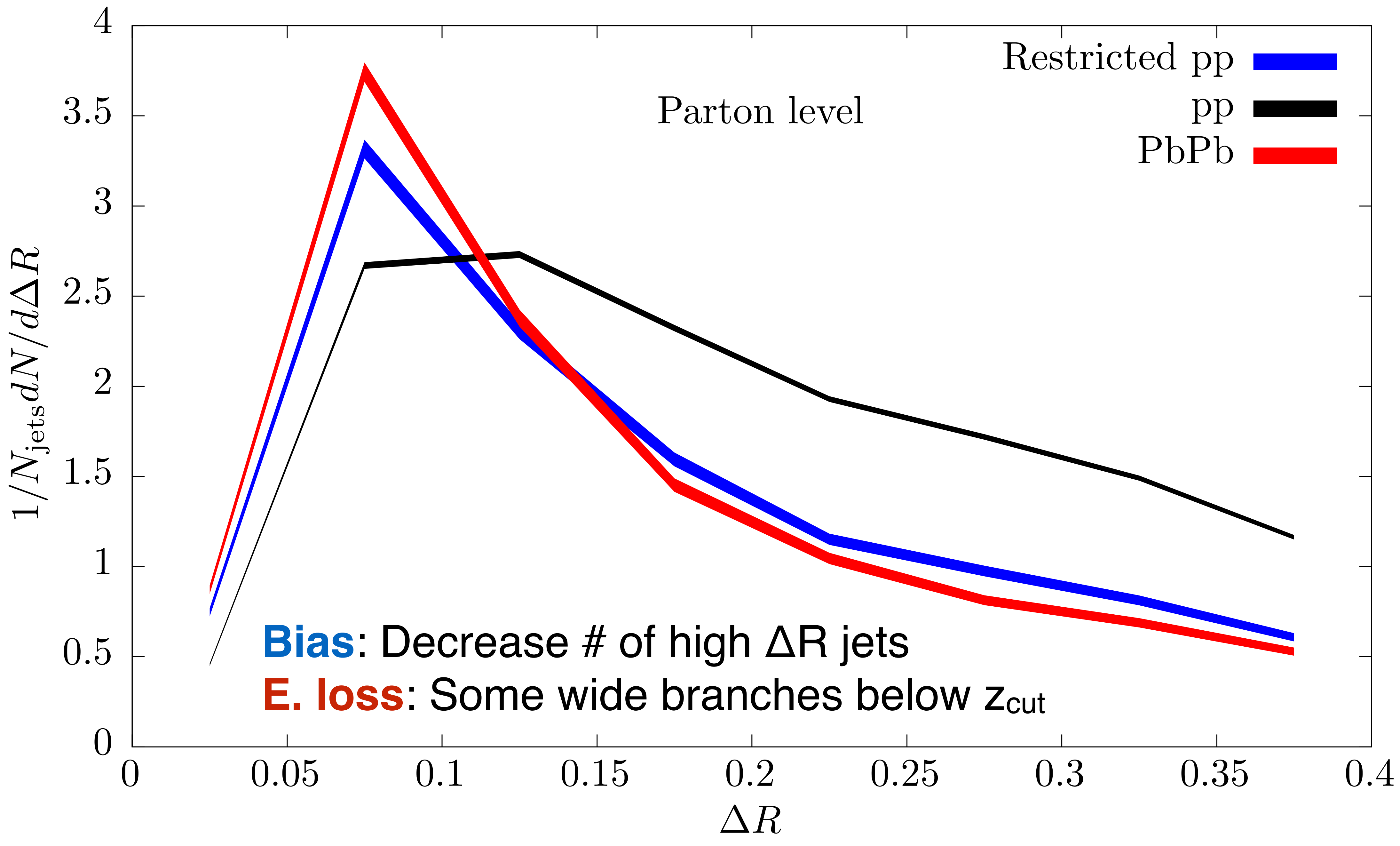
Correlation between n_{SD} and z_g



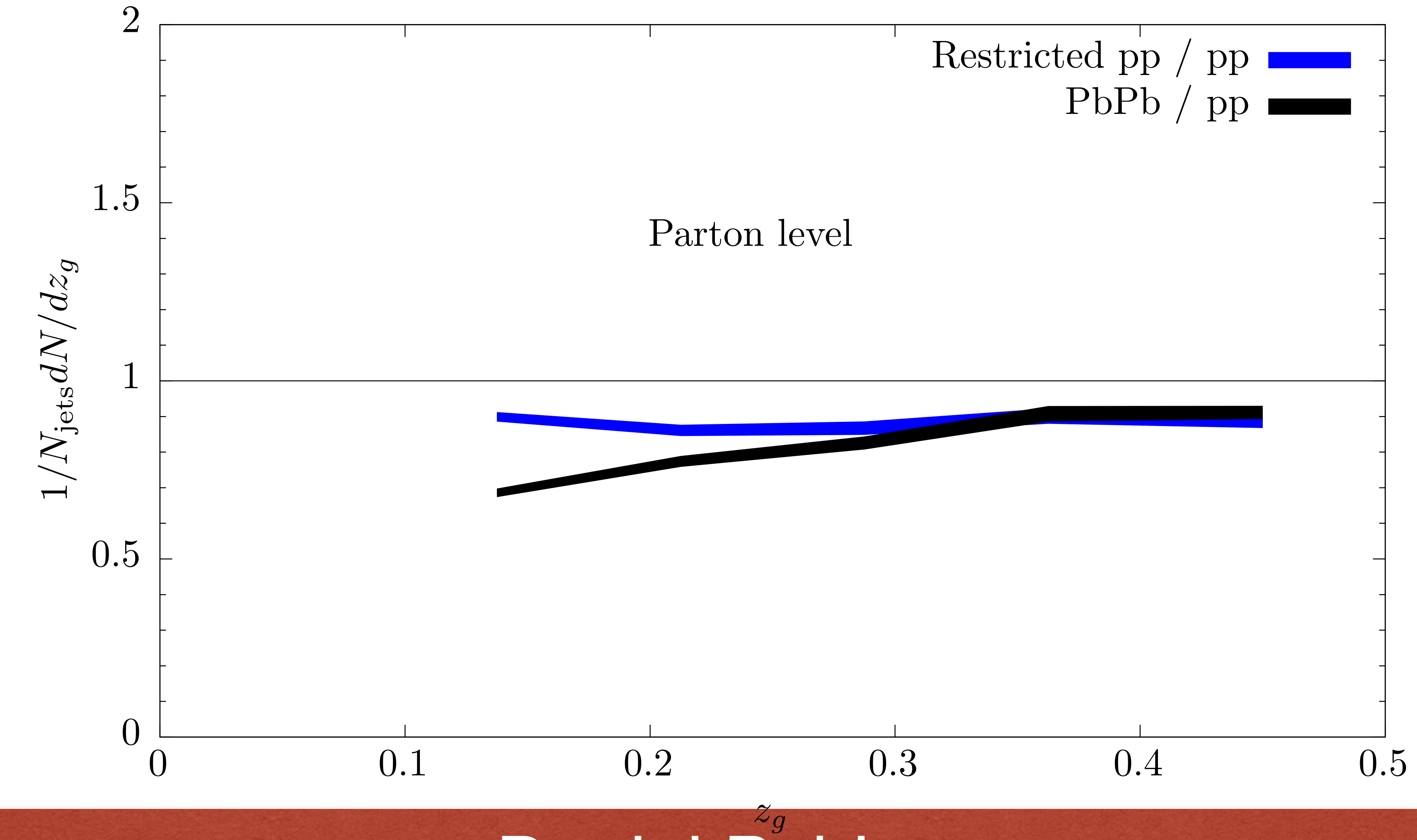
A careful look into the selection bias



Bias: Increase # of low mult. jets
E. loss: Some branches below z_{cut}



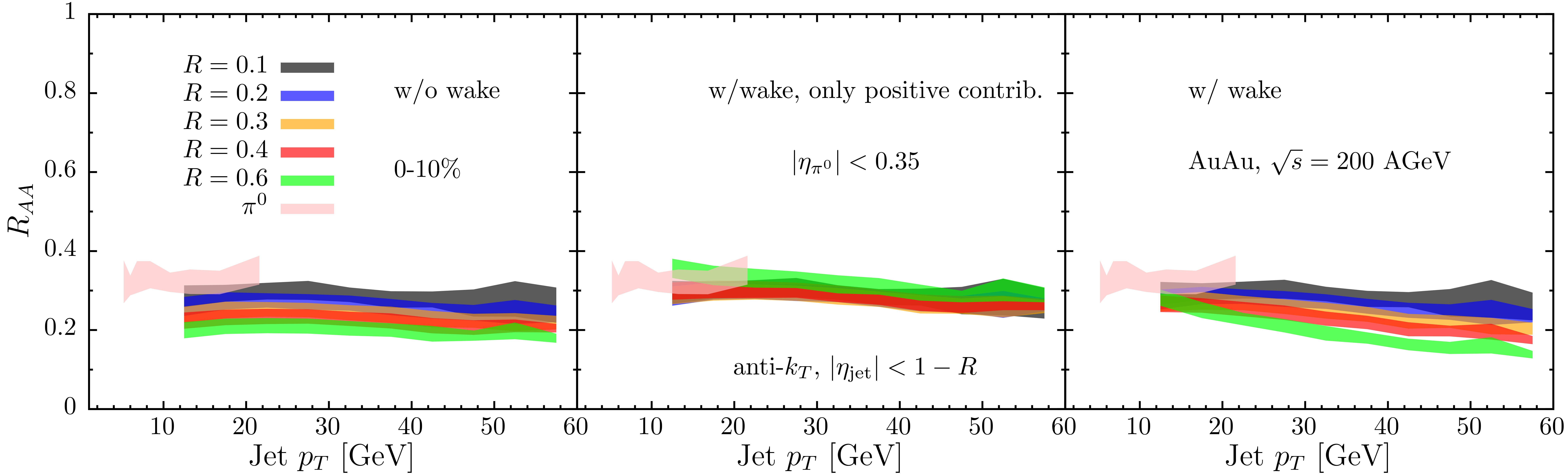
Bias: Decrease # of high ΔR jets
E. loss: Some wide branches below z_{cut}



Restricted pp: sample of pp jets from which the "surviving" sample of PbPb jets come from

Bias: Increase # of one-pronged jets
E. loss: Incoherent energy loss shift of z_g (see Mehtar-Tani & Tywoniuk - JHEP '17)

Jet suppression vs. R at RHIC



- QGP trough effect more pronounced at RHIC than at LHC; effect increases with jet p_T.

→ steeper spectrum

reduced dijet rapidity gap.

R_{AA} more sensitive to ΔE.