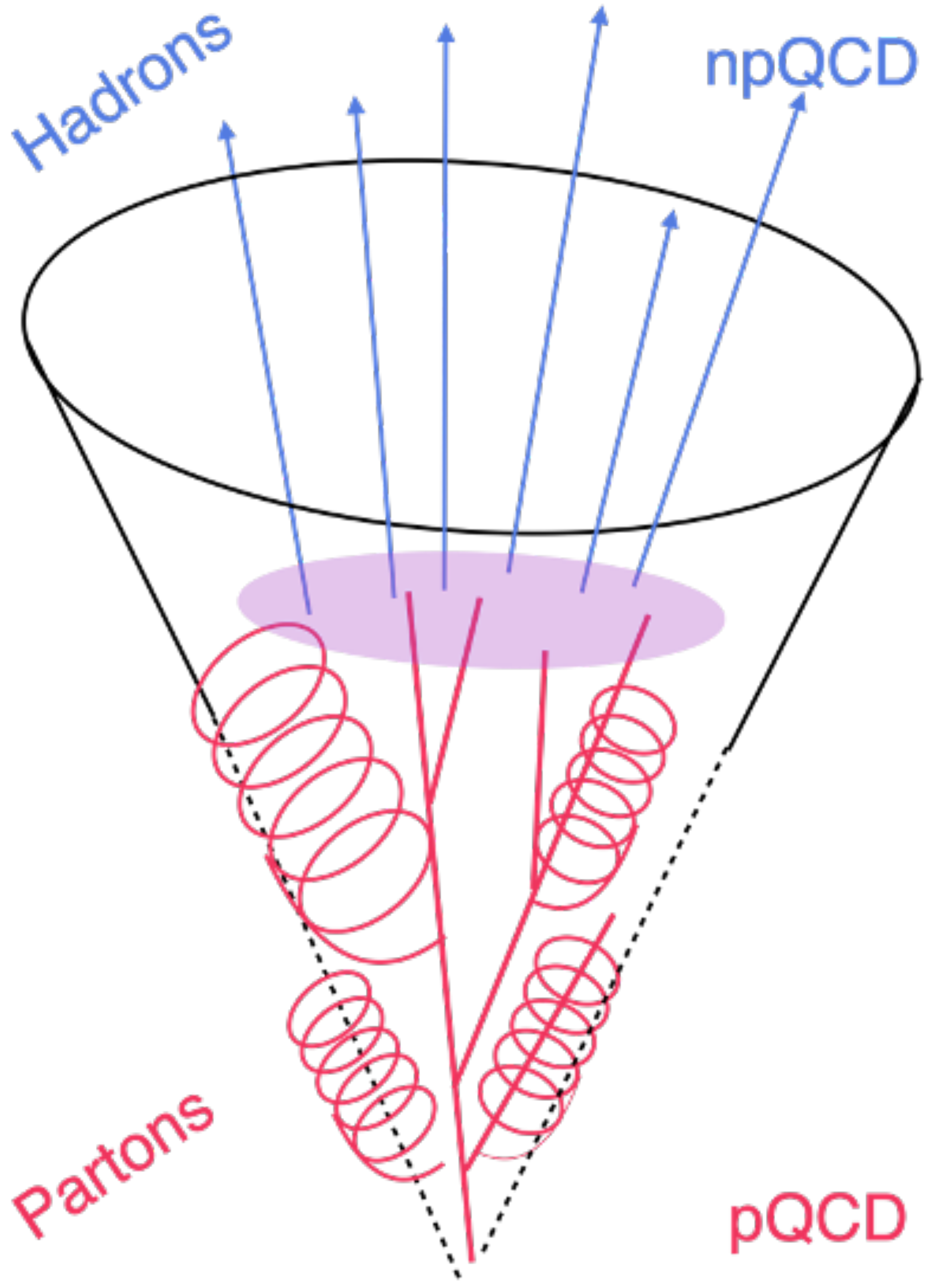
Wright Laboratory

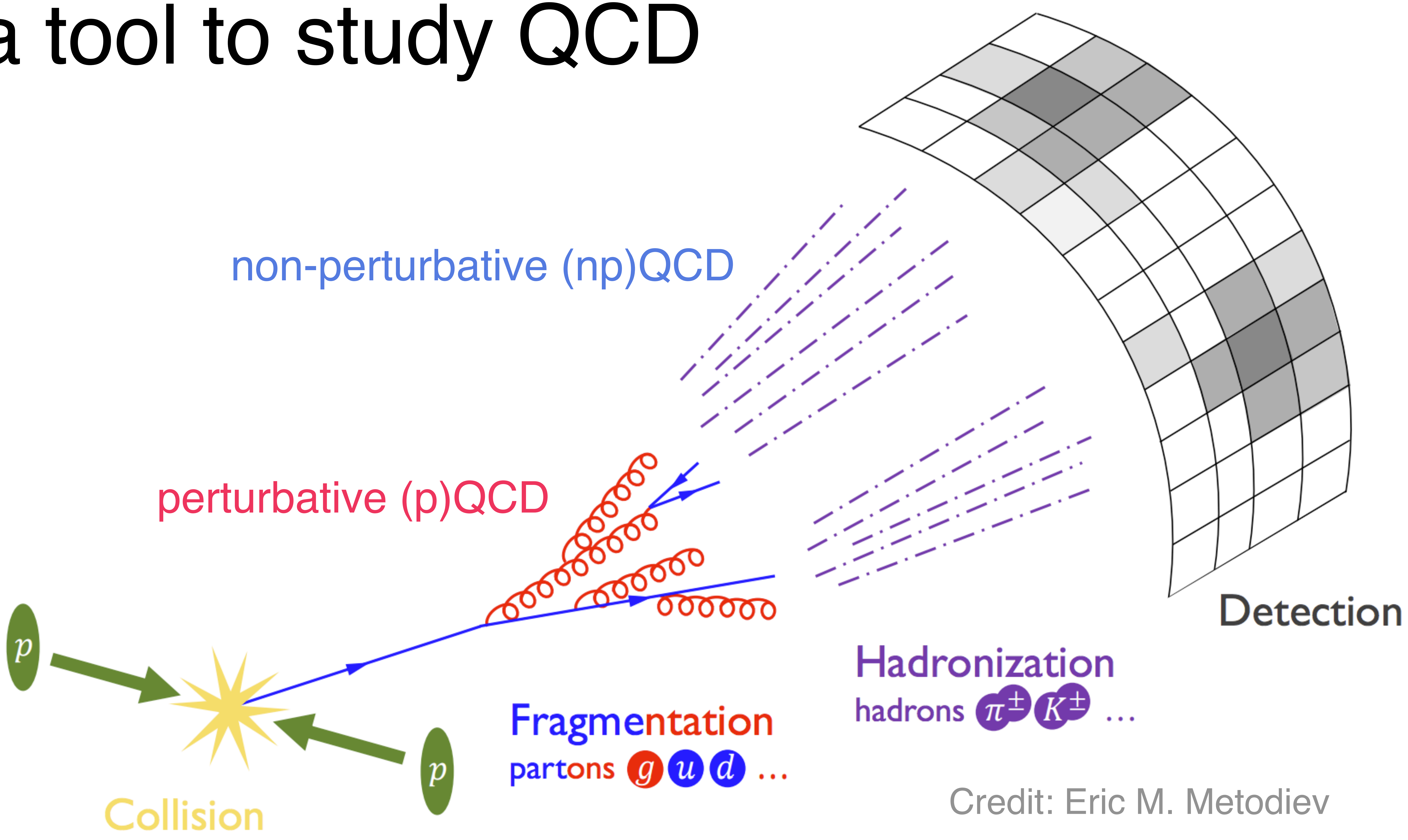
Yale

Jet experiment overview

Laura Havener, Yale University
RHIG/AGS Users Meeting 2024, BNL
Wednesday, June 12th, 2024



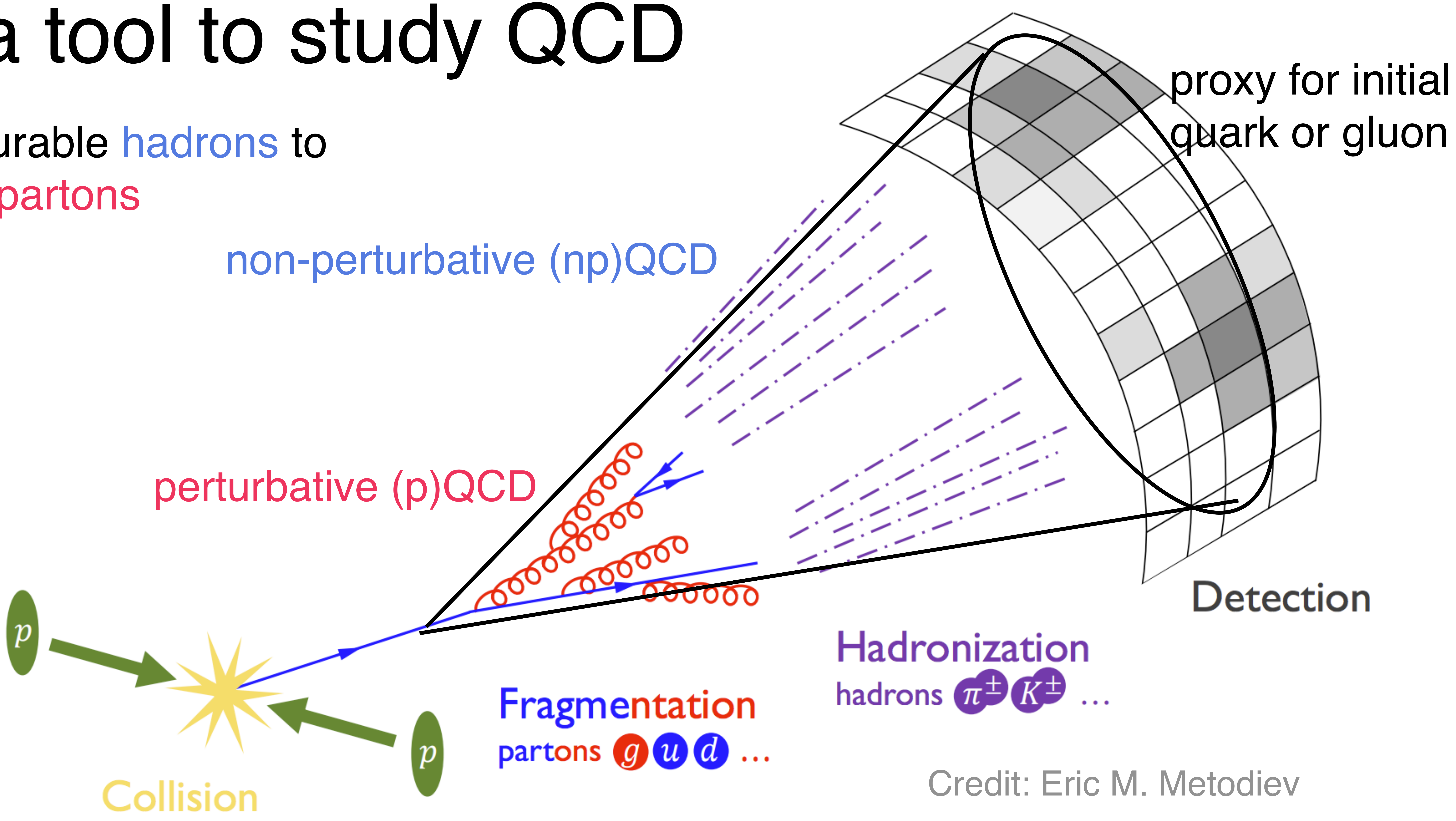
Jets as a tool to study QCD



Credit: Eric M. Metodiev

Jets as a tool to study QCD

Connect measurable hadrons to unmeasurable partons

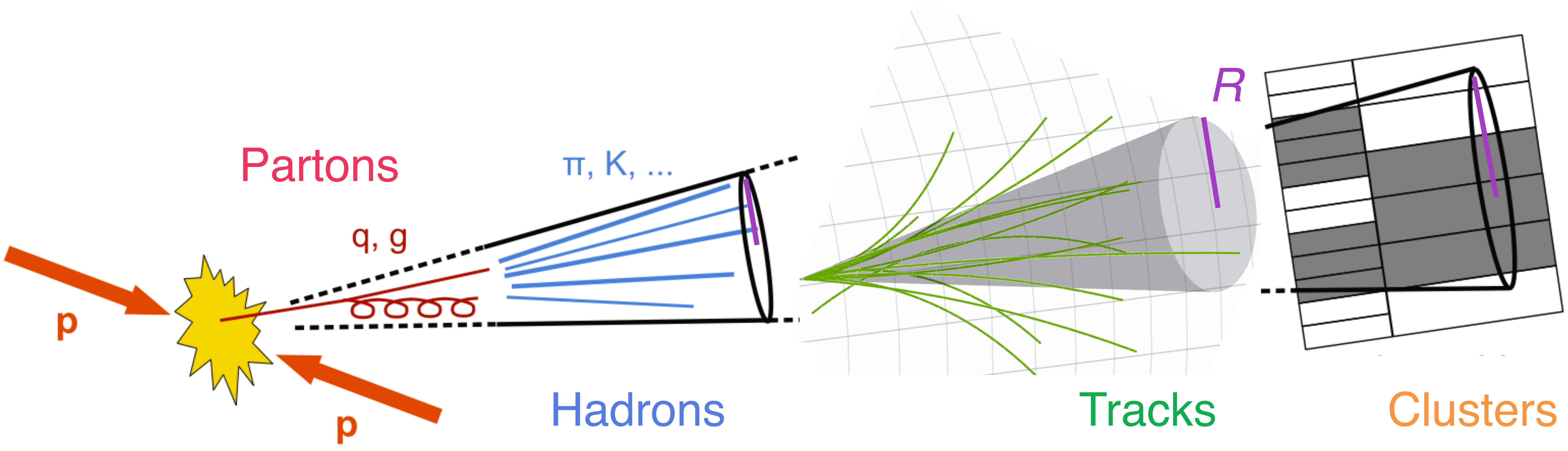


Credit: Eric M. Metodiev

Multi-scale dynamic objects whose complex structure contains QCD information

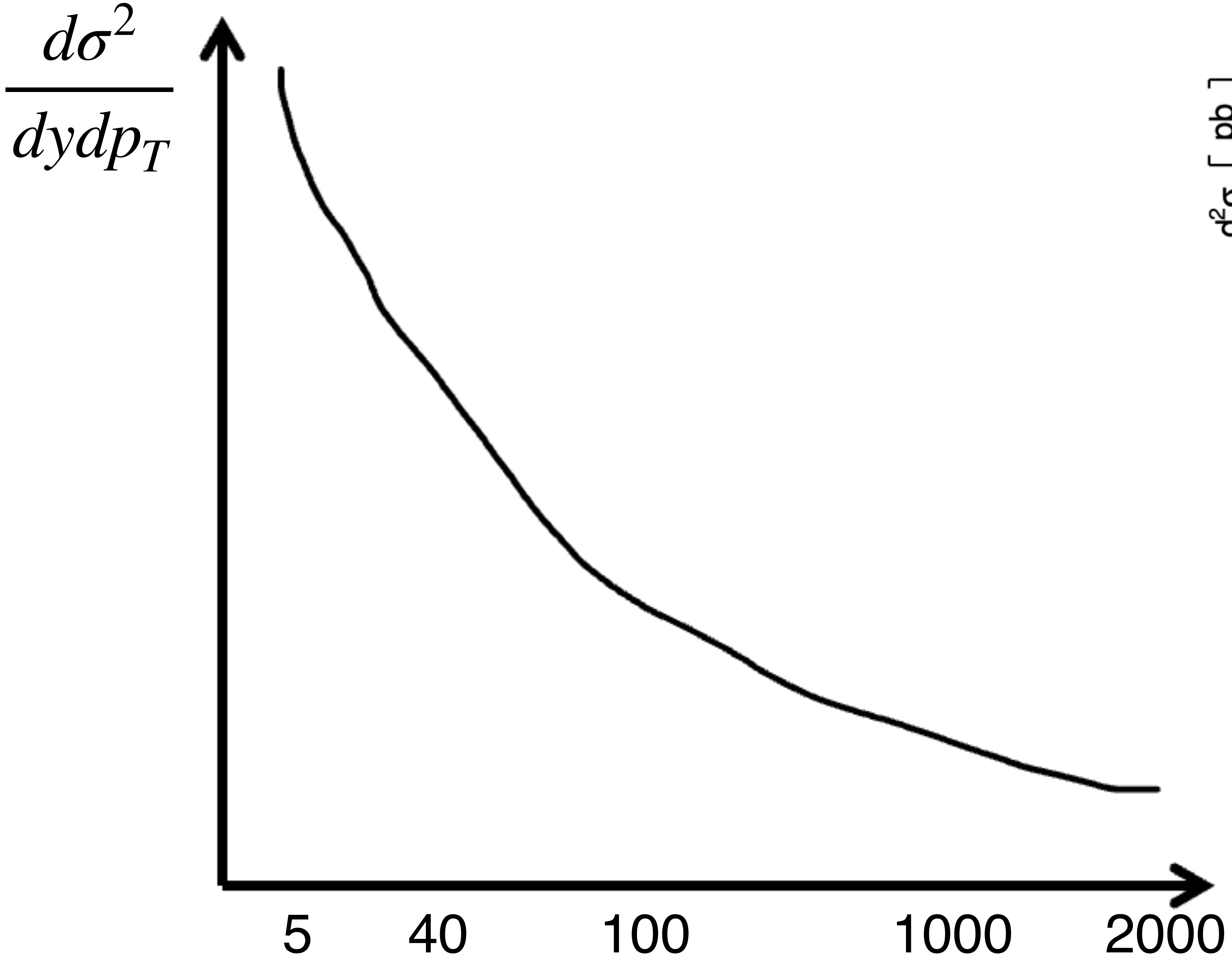
Measuring jets in a detector

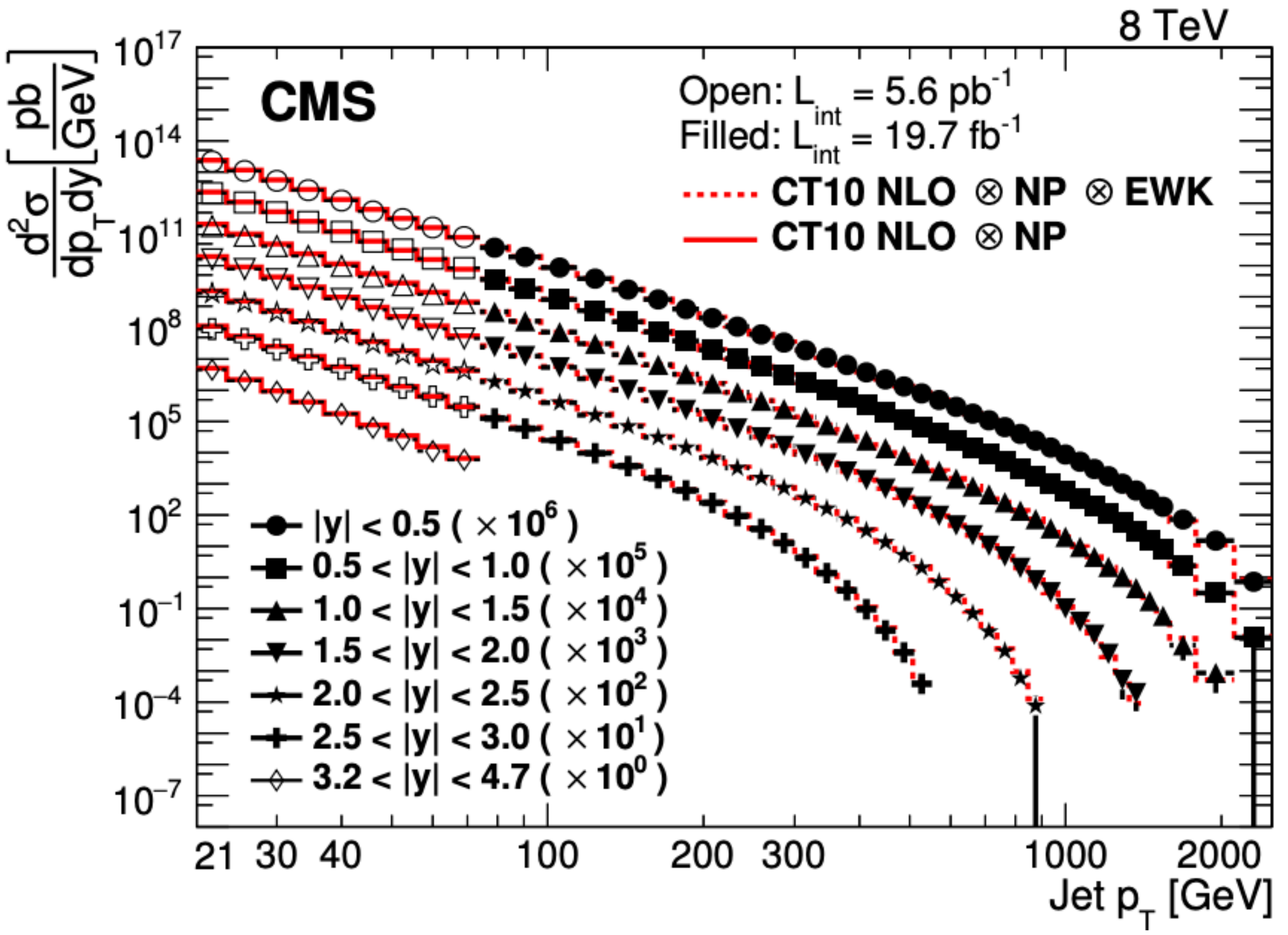
Hadronized particles from the parton shower form tracks in a tracking detector or clusters of energy in a calorimeter



Grouped together using *jet clustering algorithms* to form **experimental jets** with a p_T and resolution parameter R

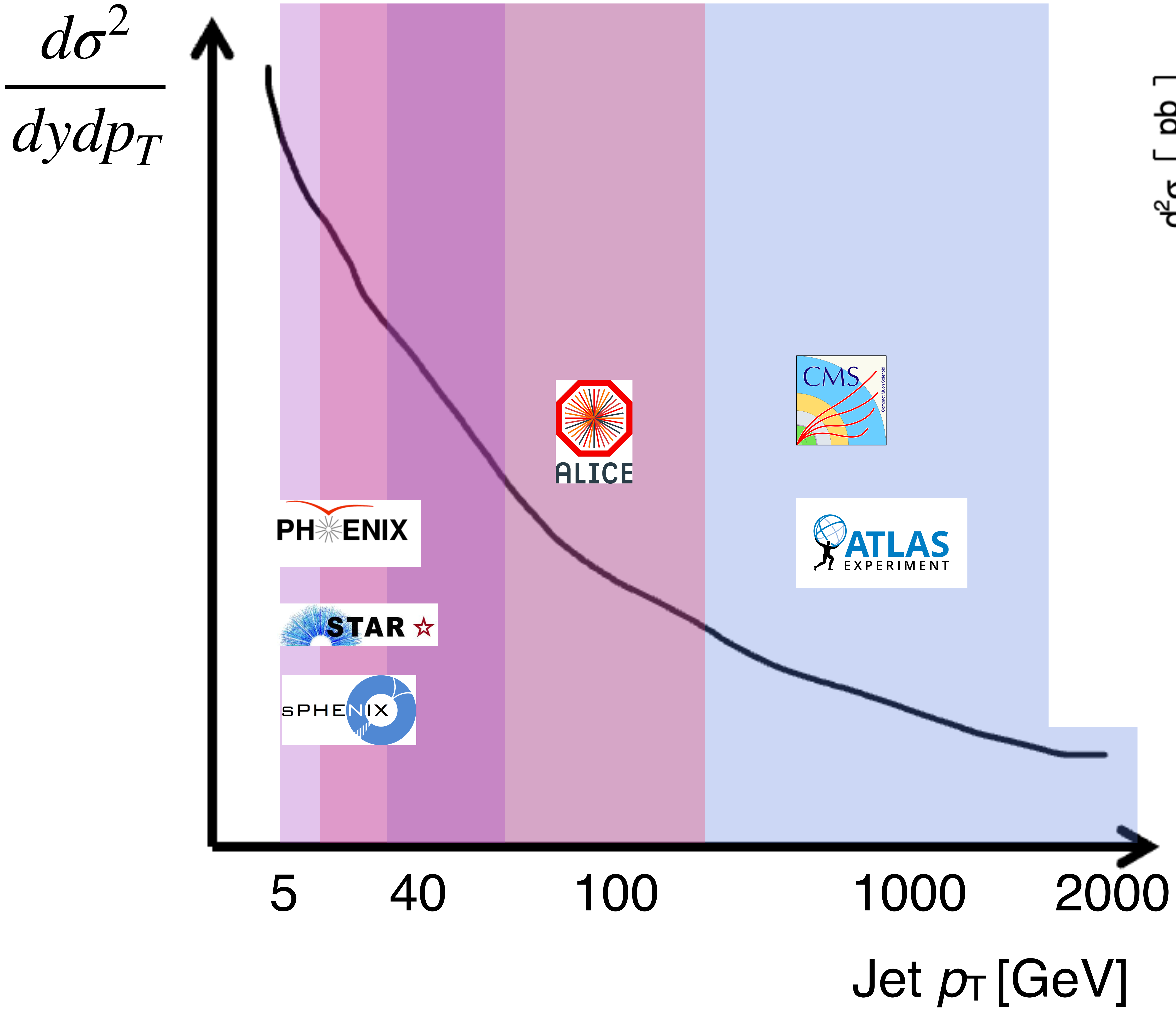
Jet kinematics: QCD knob

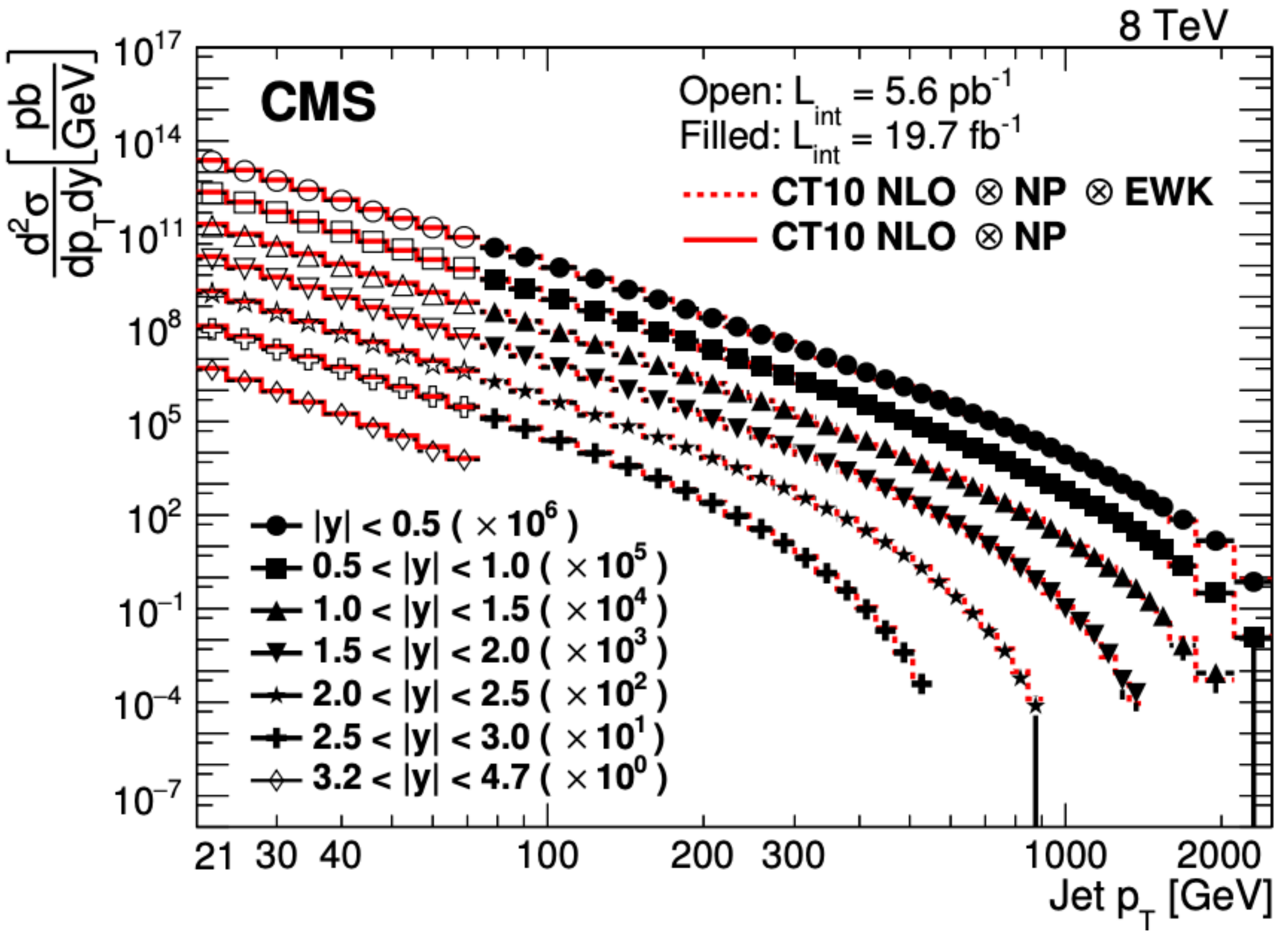




CMS JHEP 03 (2017) 156

Jet kinematics: QCD knob

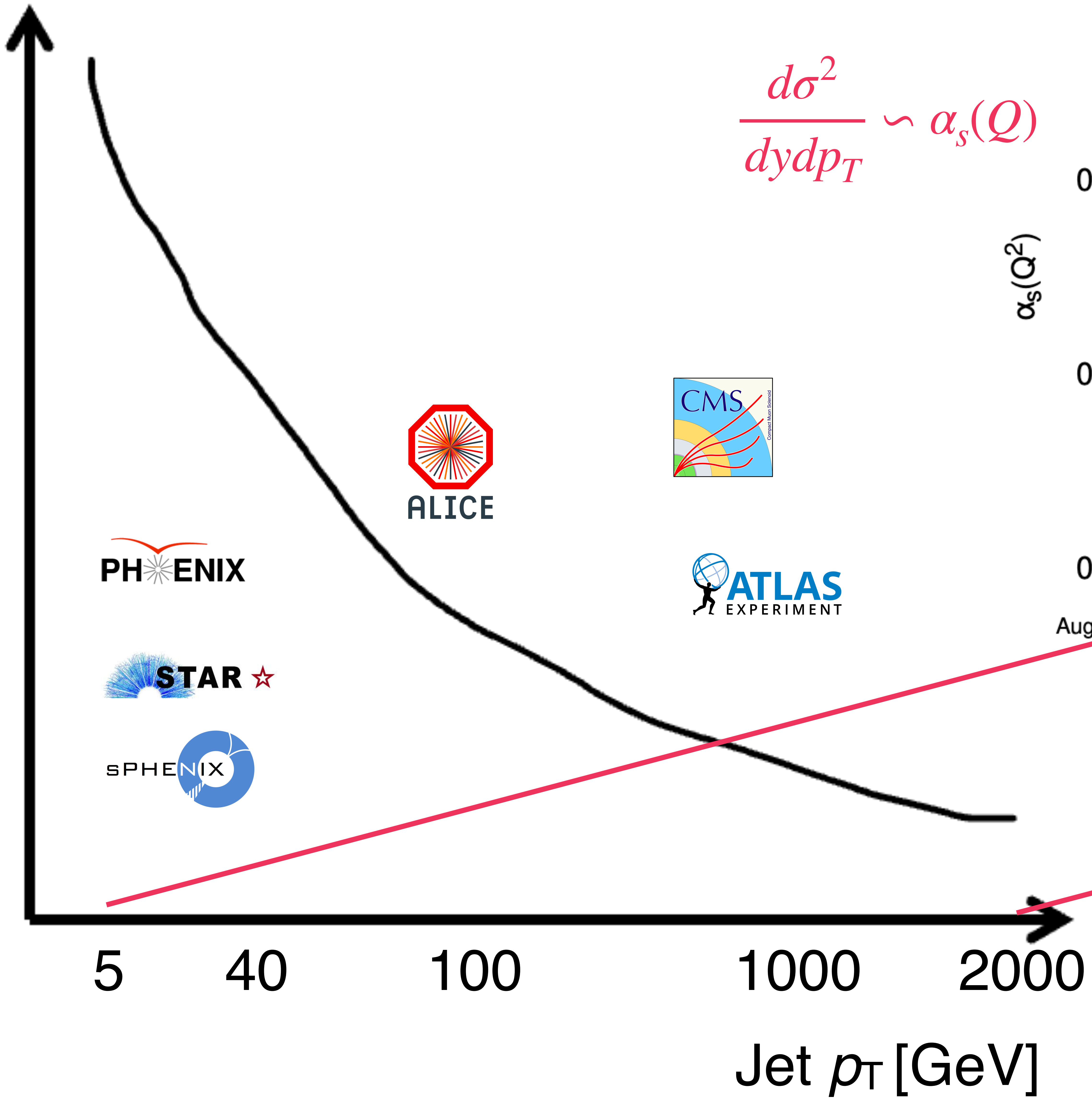




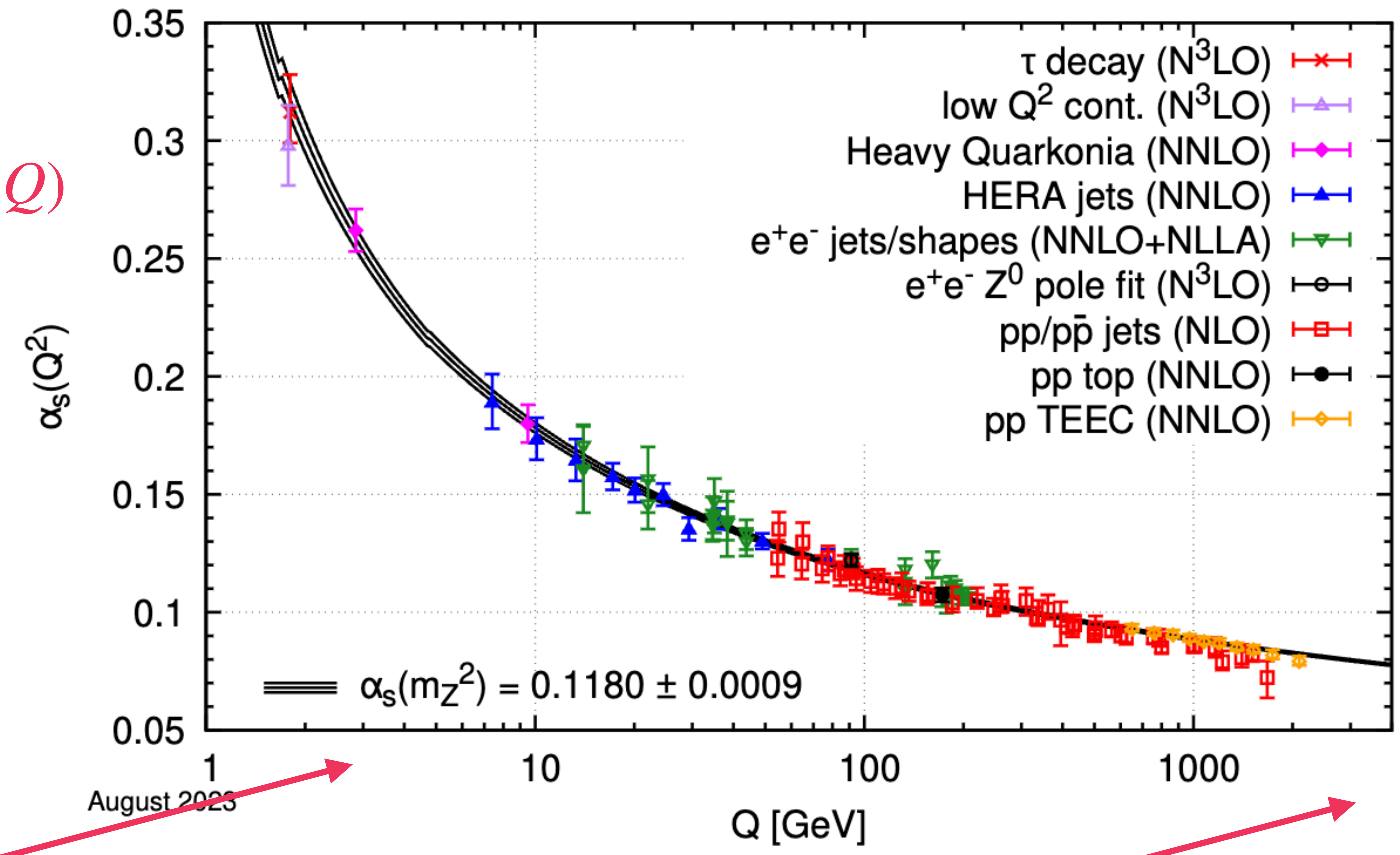
CMS JHEP 03 (2017) 156

**Caveat: approximate ranges!

Jet kinematics: QCD knob



$$\frac{d\sigma^2}{dydp_T} \backsim \alpha_s(Q)$$



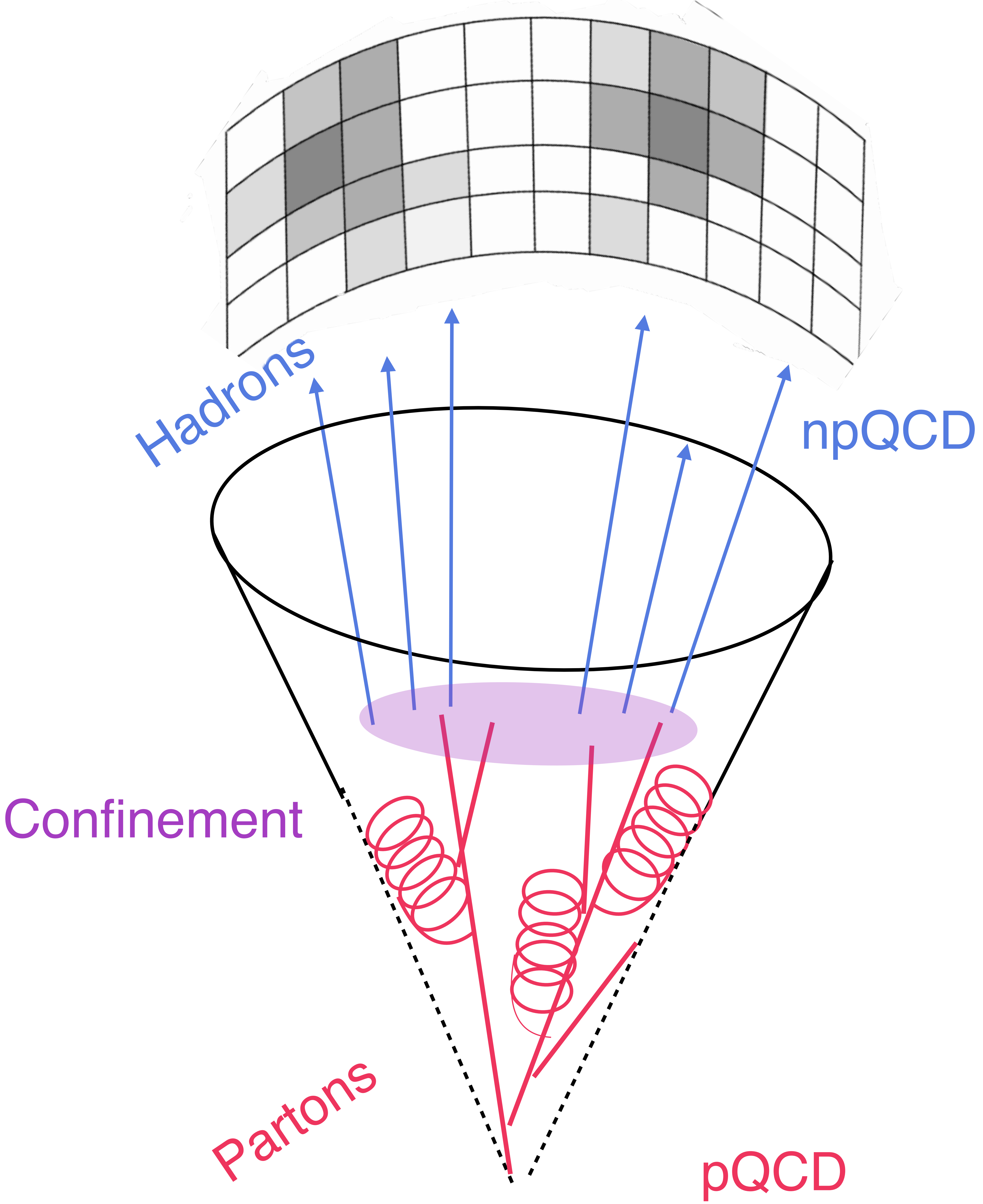
Jet $p_T \sim Q^2$

**Caveat: approximate ranges!

Jet substructure

High energy physics community designed jet substructure tools for particle physics searches and to study fundamental QCD

Complex patterns contain information about original parton shower and confinement transition



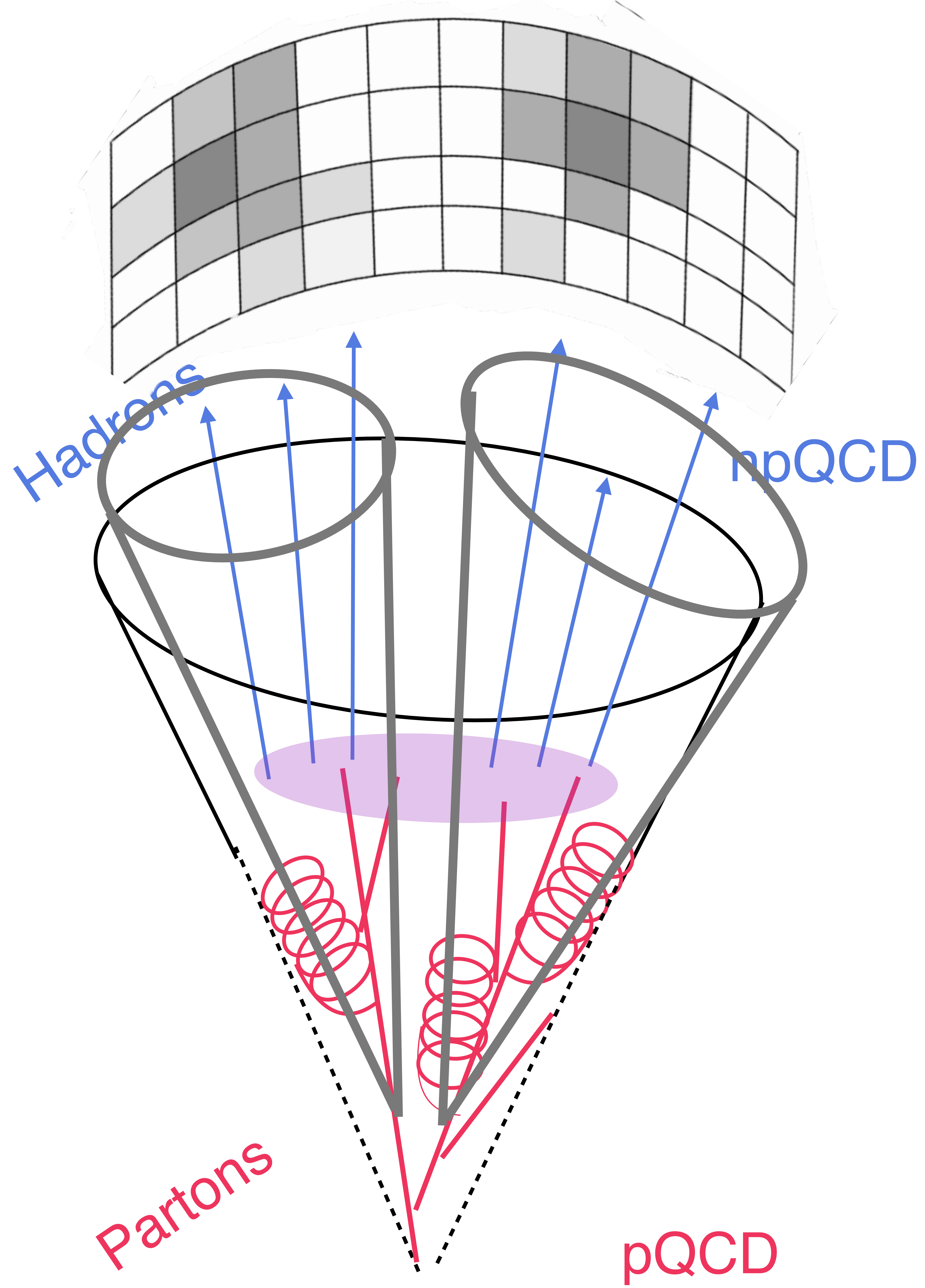
Jet substructure

High energy physics community designed jet substructure tools for particle physics searches and to study fundamental QCD

Complex patterns contain information about original parton shower and confinement transition

Measure subjets within jet: proxy for the hard parton splittings

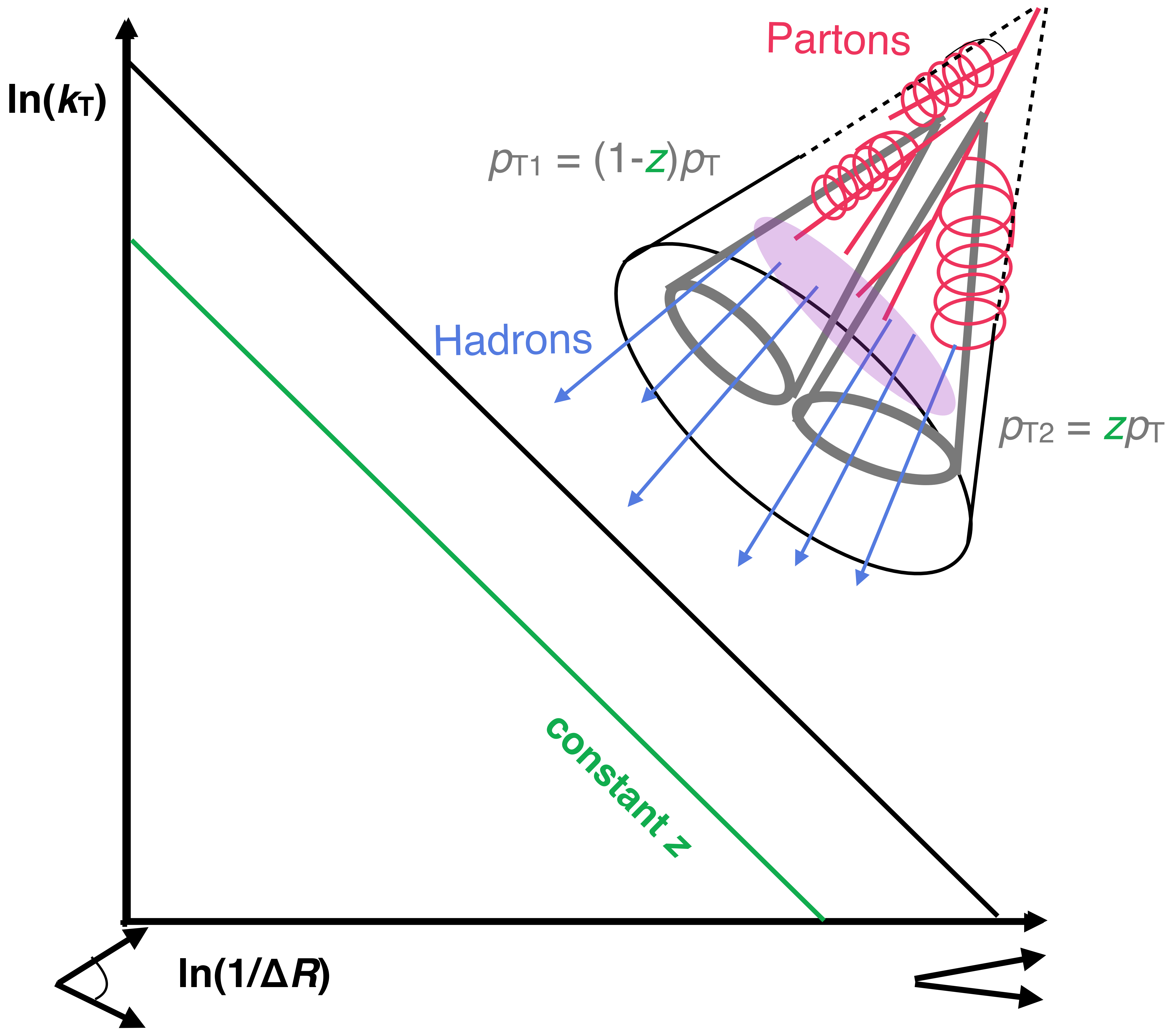
Dreyer et al JHEP 12 (2018)



Lund plane: visualize patterns inside of jets

Phase space of jet splittings

Andersson et al ZPC43 (1989) Dreyer et al JHEP 12 (2018)

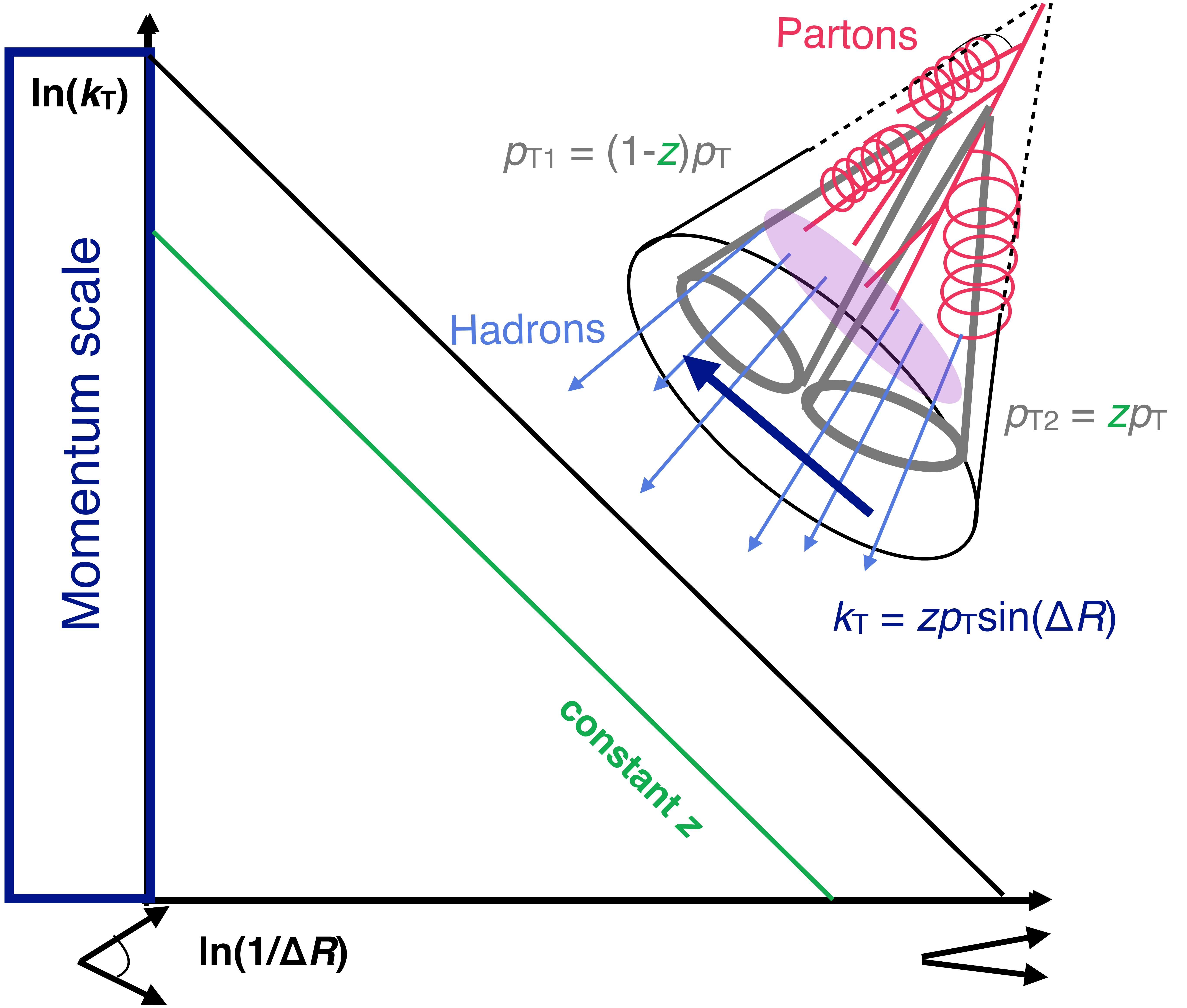


Lund plane: visualize patterns inside of jets

Phase space of jet splittings

Andersson et al ZPC43 (1989) Dreyer et al JHEP 12 (2018)

k_T: relative transverse momentum



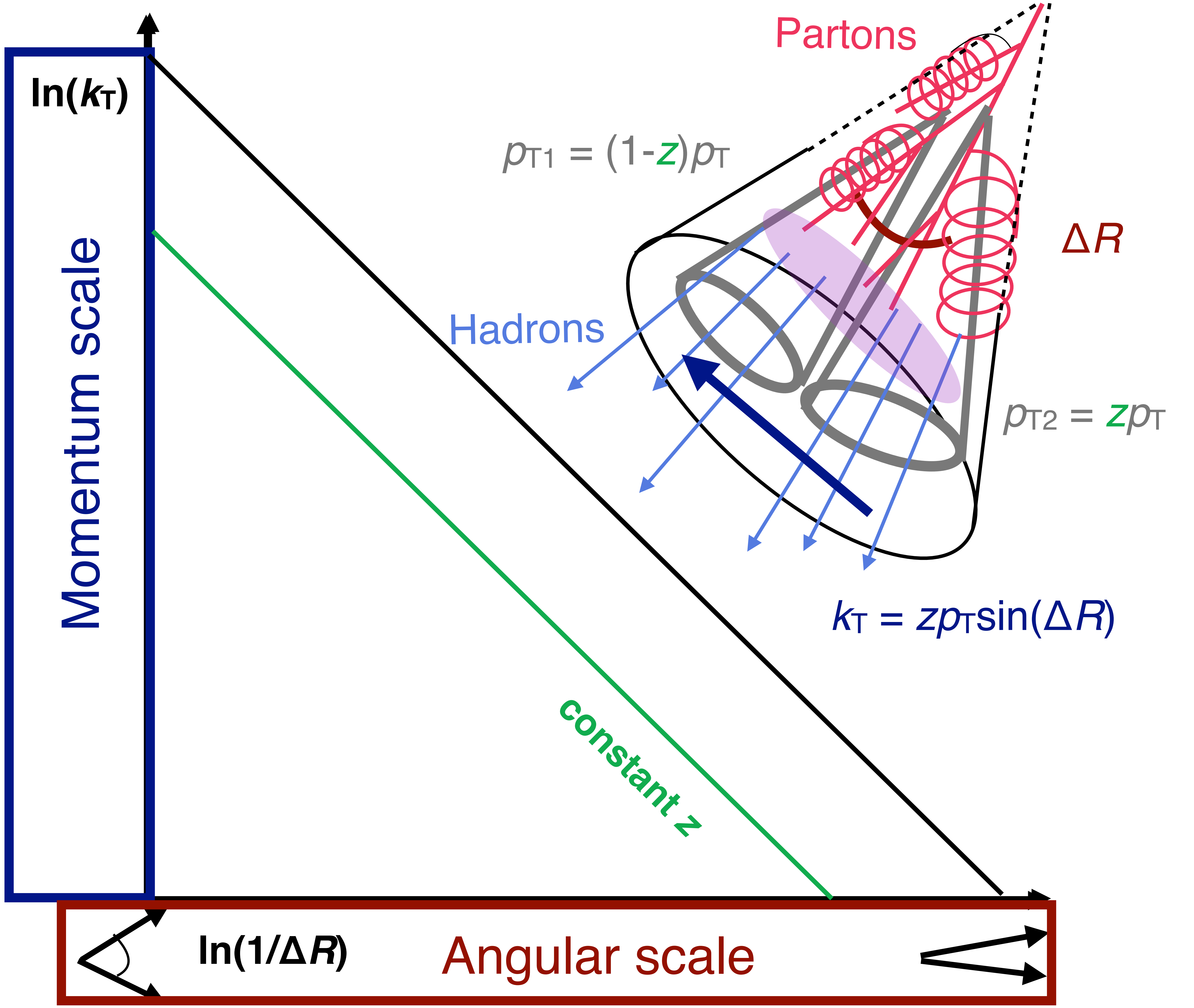
Lund plane: visualize patterns inside of jets

Phase space of jet splittings

Andersson et al ZPC43 (1989) Dreyer et al JHEP 12 (2018)

k_T: relative transverse momentum

ΔR: opening angle



Lund plane: visualize patterns inside of jets

Phase space of jet splittings

Andersson et al ZPC43 (1989) Dreyer et al JHEP 12 (2018)

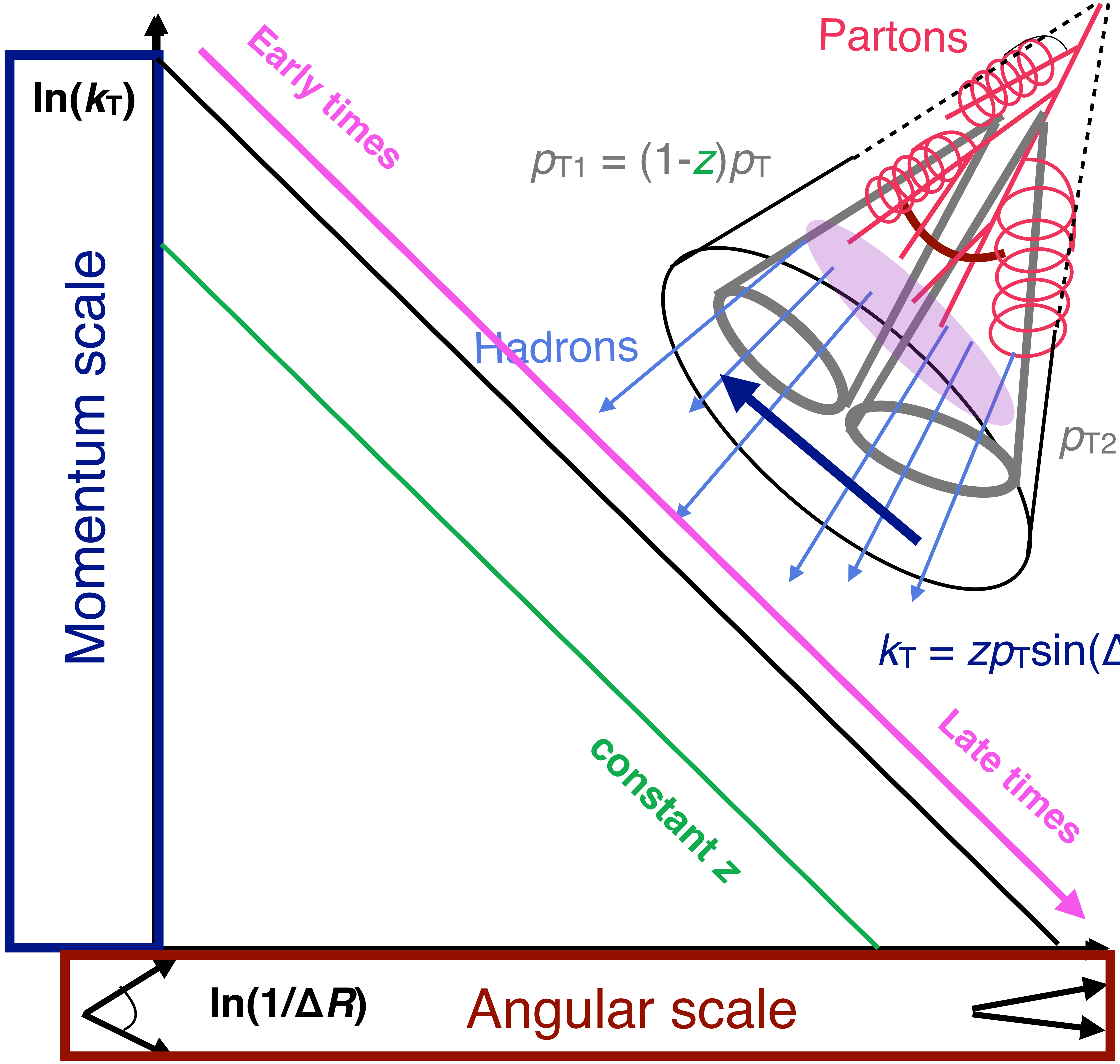
k_T: relative transverse momentum

ΔR: opening angle

Formation time: how long until the splitting occurred

Y. L. Dokshitzer, et.al.

$$t_f \approx \frac{1}{k_T \Delta R^2}$$

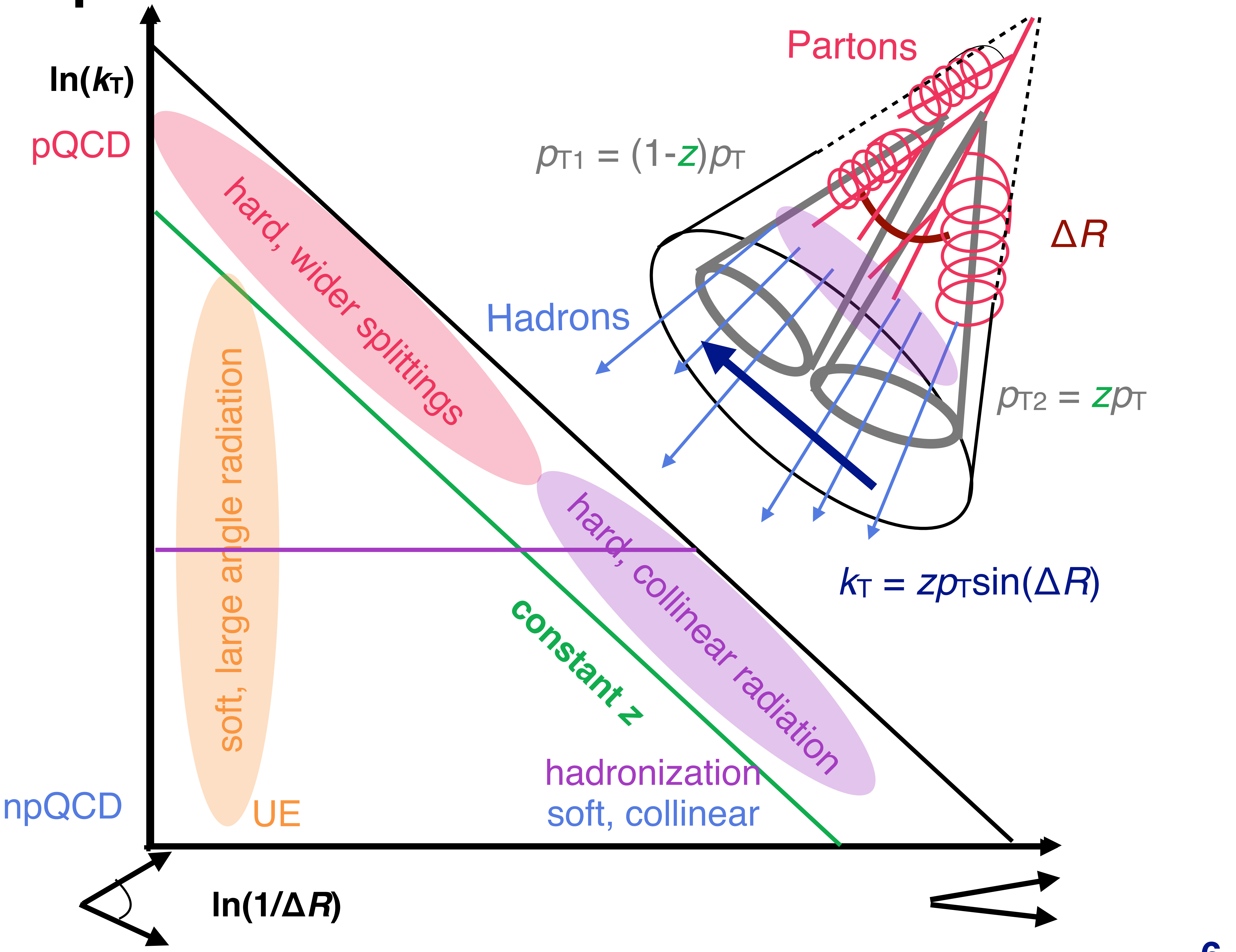


Lund plane: phase space of QCD

$k_T \sim \Lambda_{QCD}$ accesses confinement transition

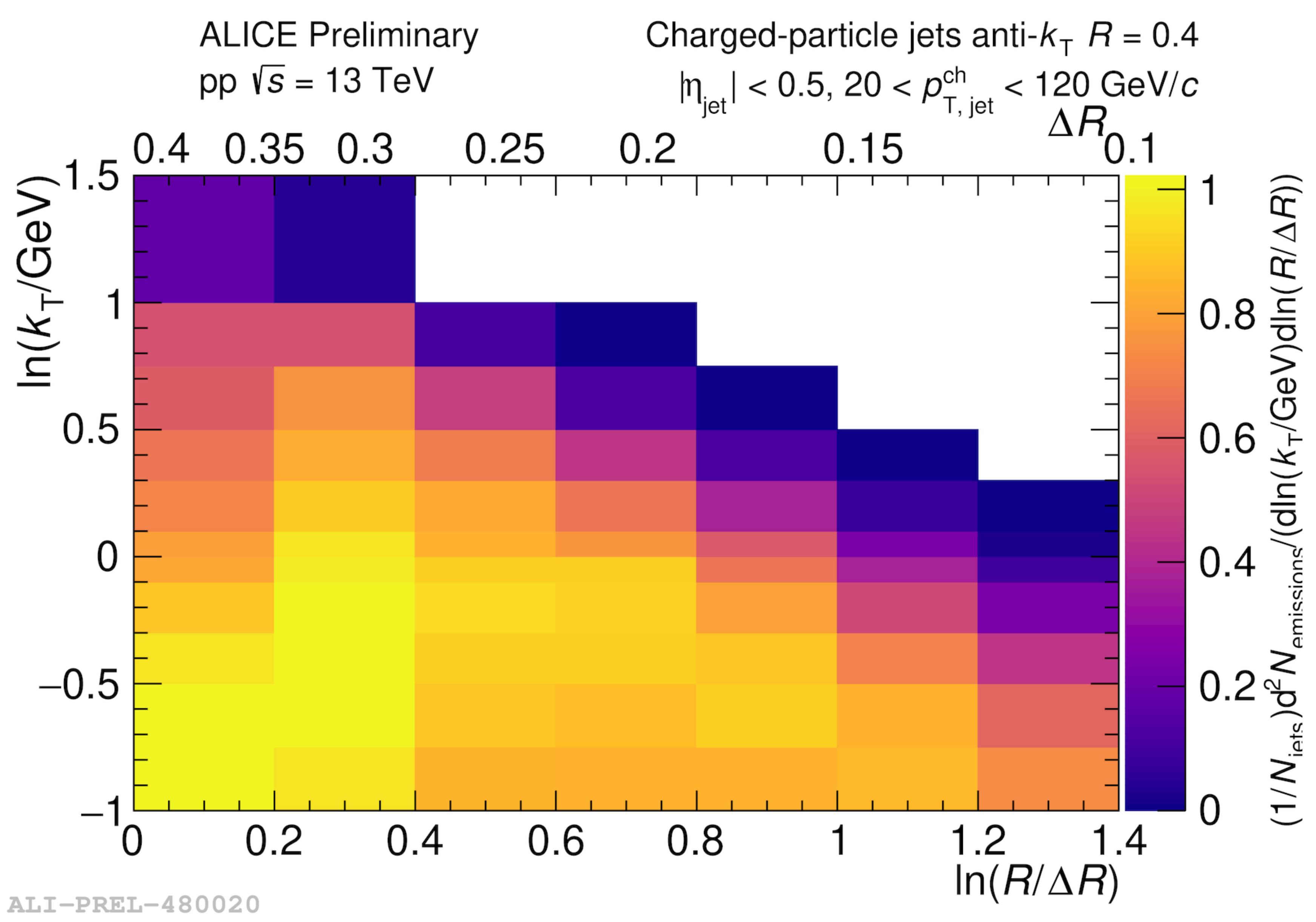
Running of the QCD coupling constant sculpts the shape of the plane

Isolate different QCD effects and inform simulations

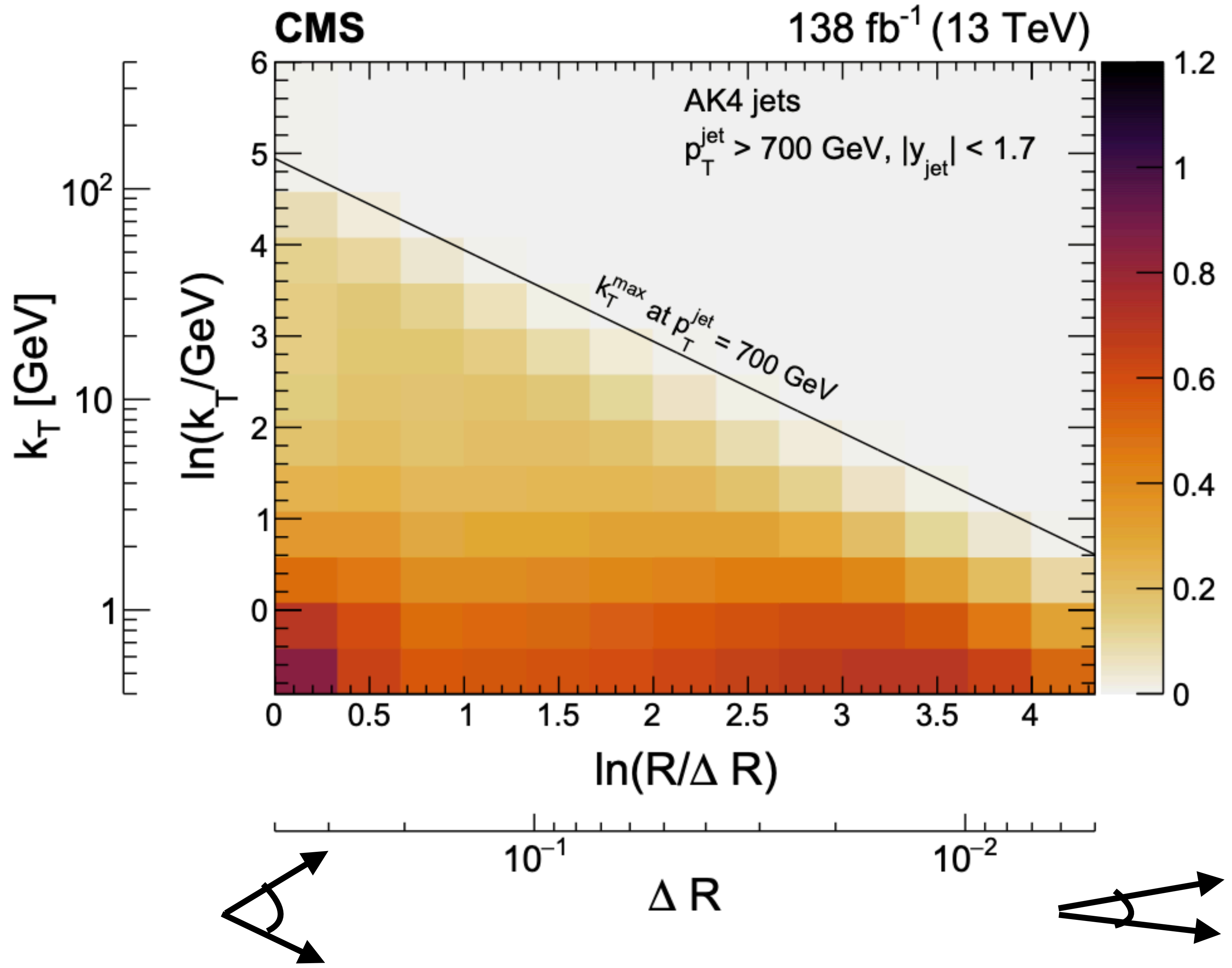


Measured Lund plane

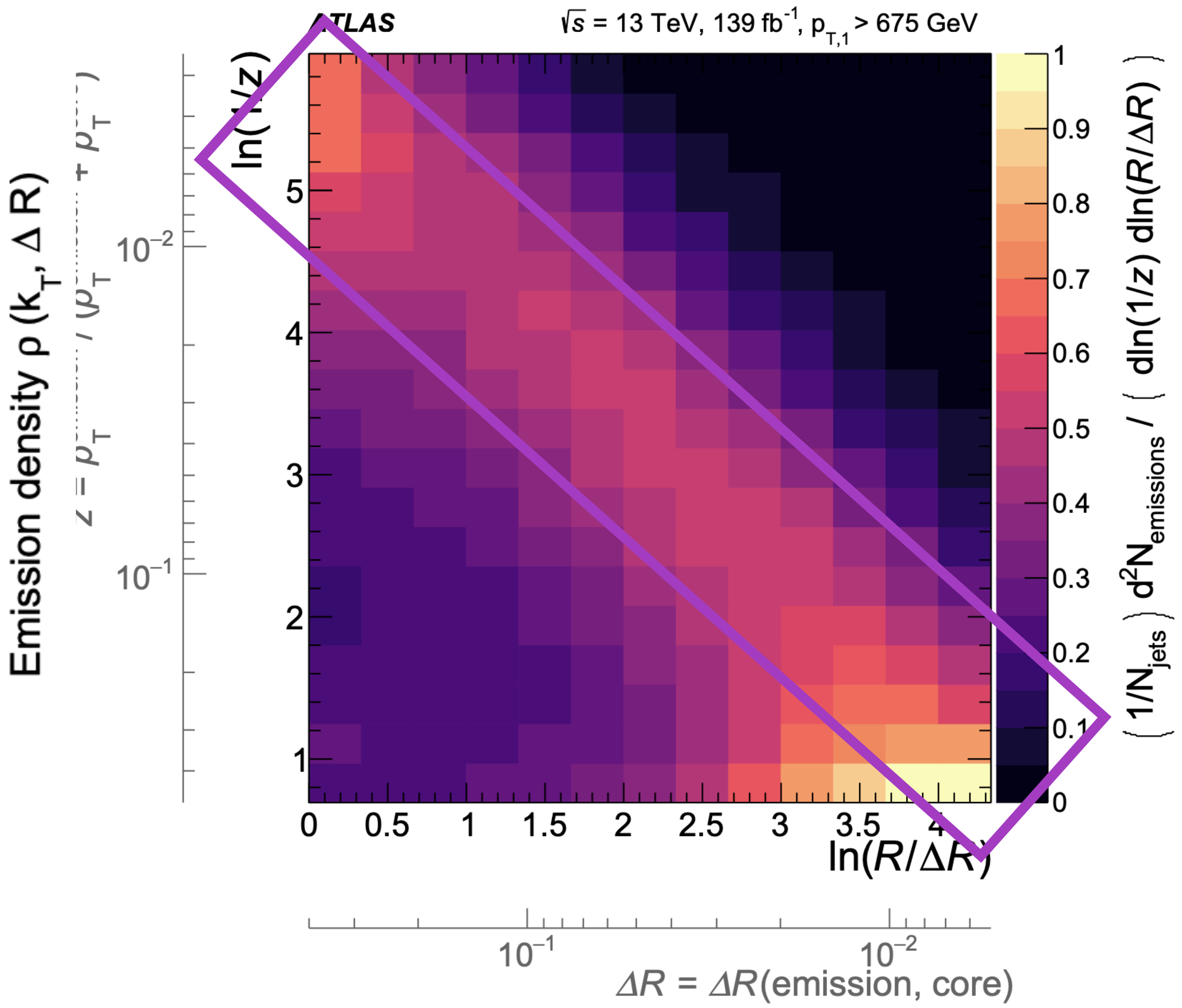
ALICE-PUBLIC-2021-002



arXiv:2312.16343



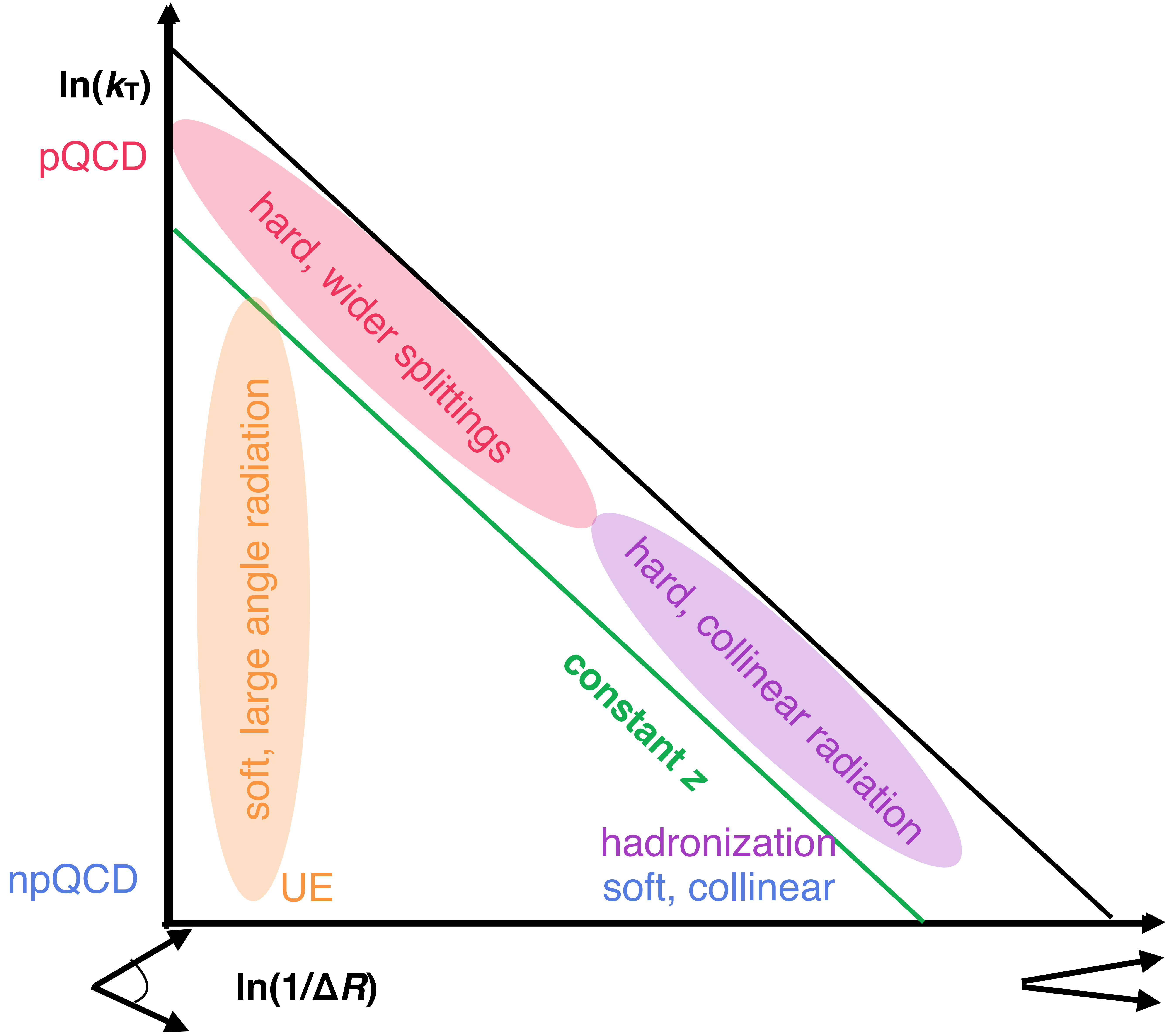
ATLAS PRL 124 (2020)



Make projections to isolate regions of phase space
and make detailed comparisons to generators

Visual features emerge

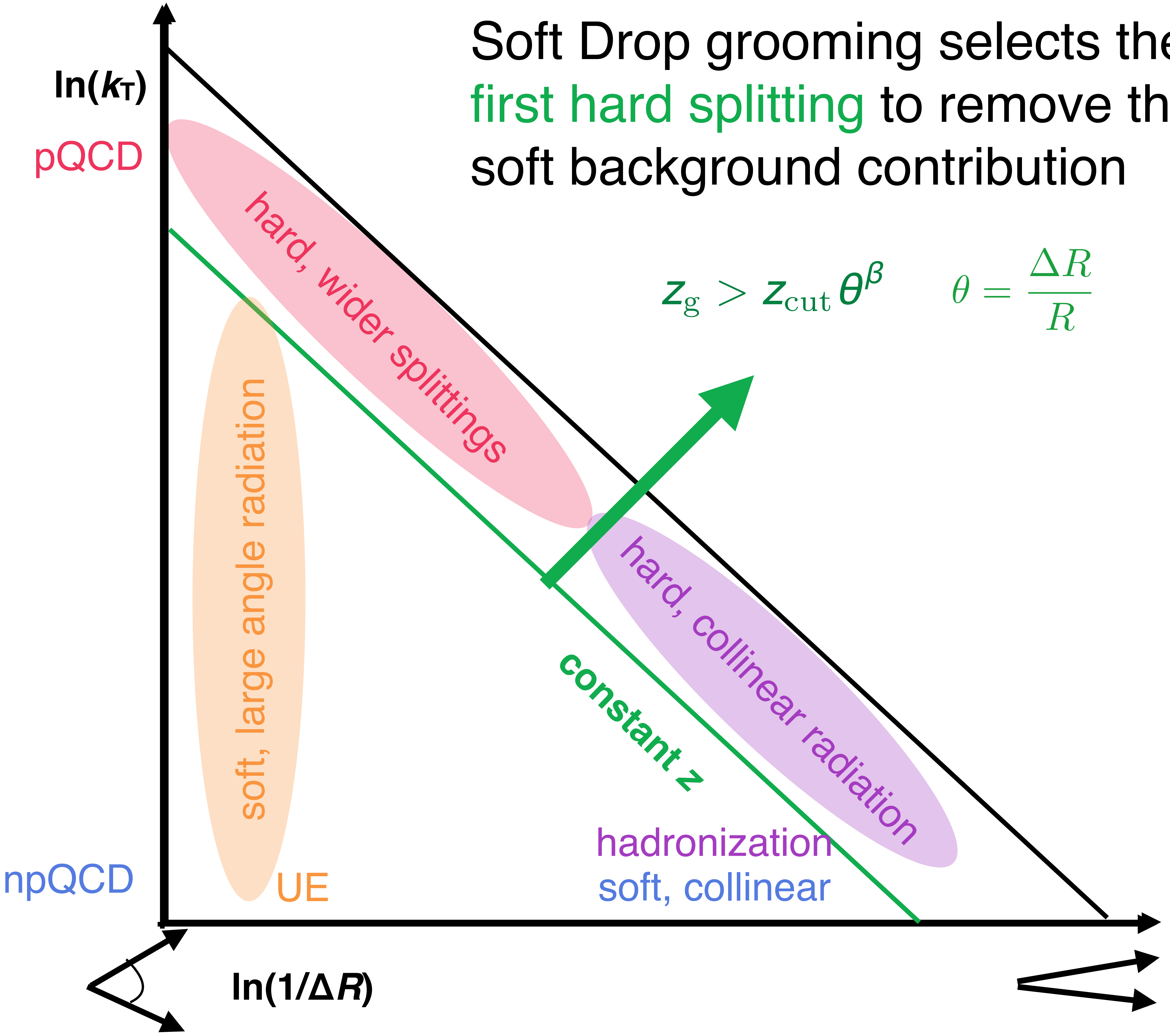
Grooming away soft radiation



Grooming away soft radiation

$$z_g = \frac{\min(p_{Ti}, p_{Tj})}{p_{Ti} + p_{Tj}}$$

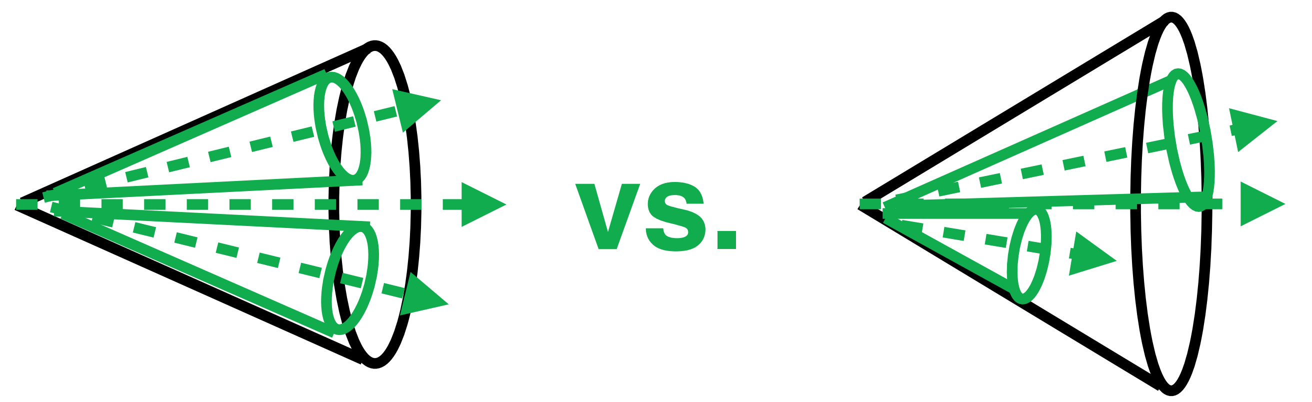
Soft Drop grooming selects the first hard splitting to remove the soft background contribution



Grooming away soft radiation

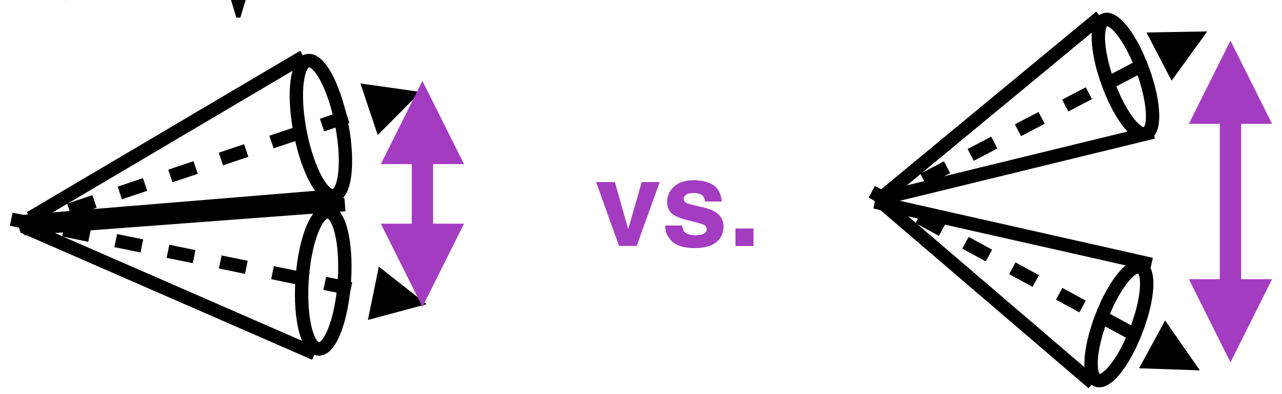
Shared momentum fraction

$$z_{\rm g} = \frac{\min(p_{\rm Ti}, p_{\rm Tj})}{p_{\rm Ti} + p_{\rm Tj}}$$



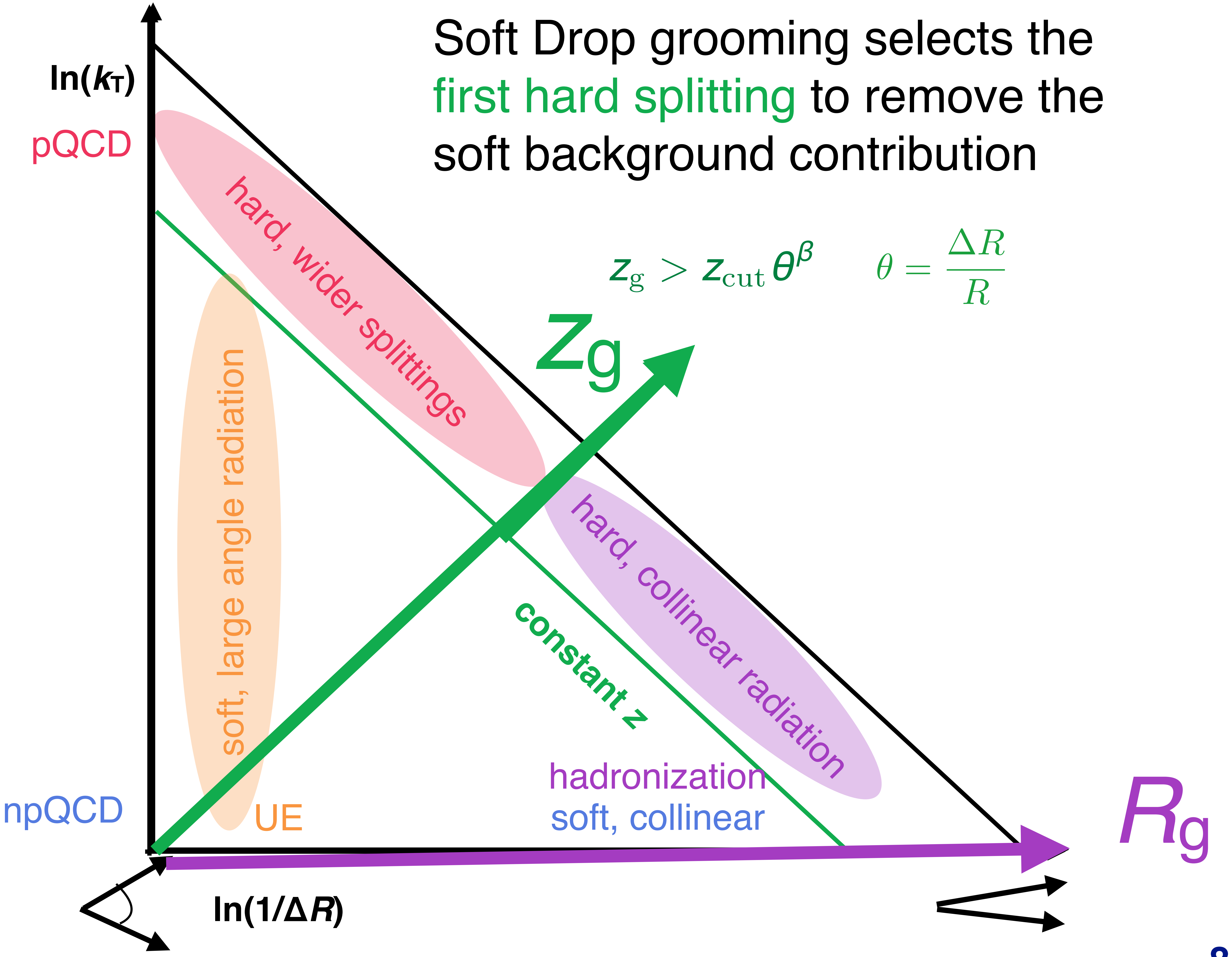
Distance between subjets

$$R_{\rm g} = \sqrt{\Delta\eta^2 + \Delta\phi^2}$$



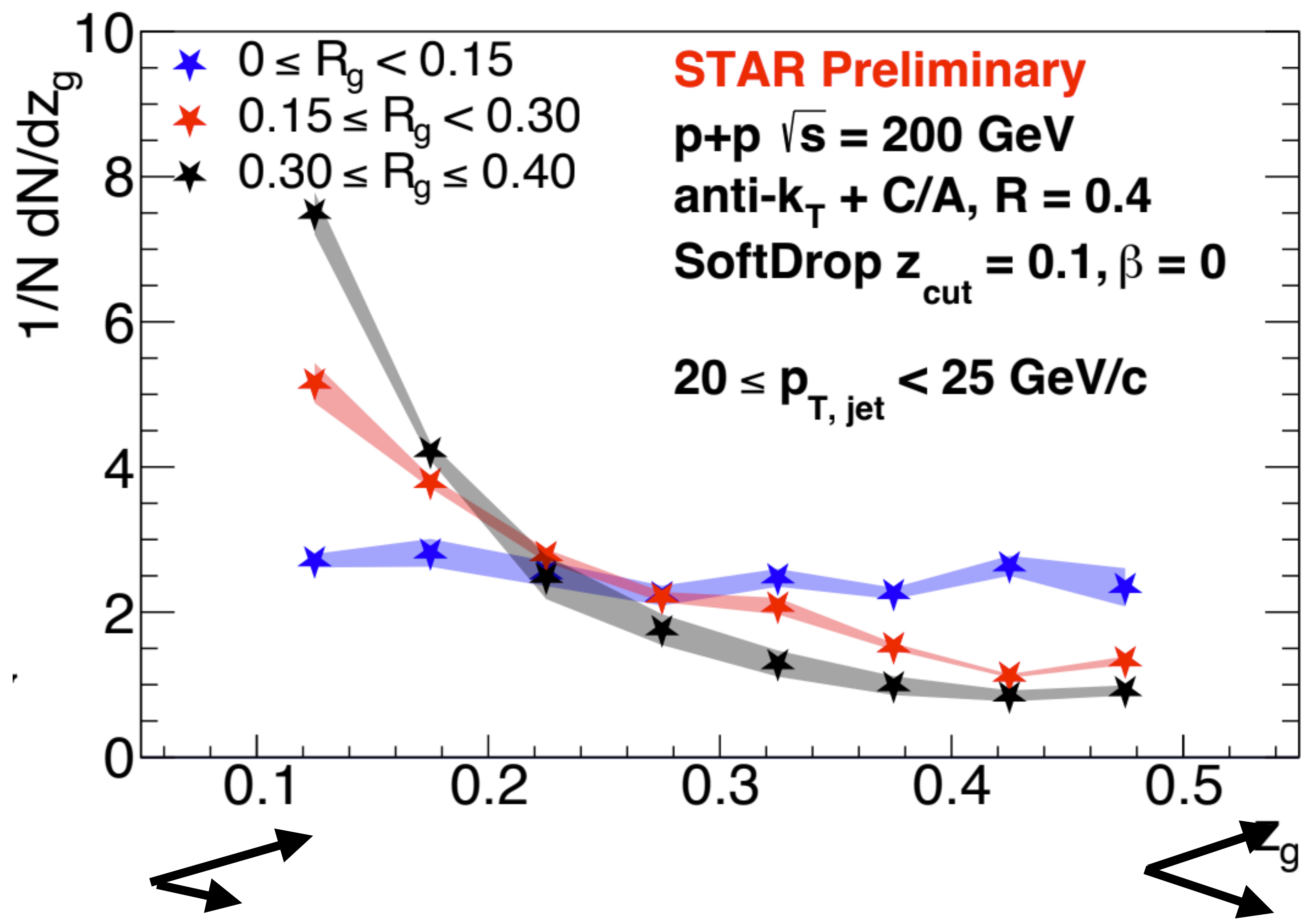
Soft Drop grooming selects the first hard splitting to remove the soft background contribution

$$z_{\rm g} > z_{\rm cut}\,\theta^{\beta} \qquad \theta = \frac{\Delta R}{R}$$



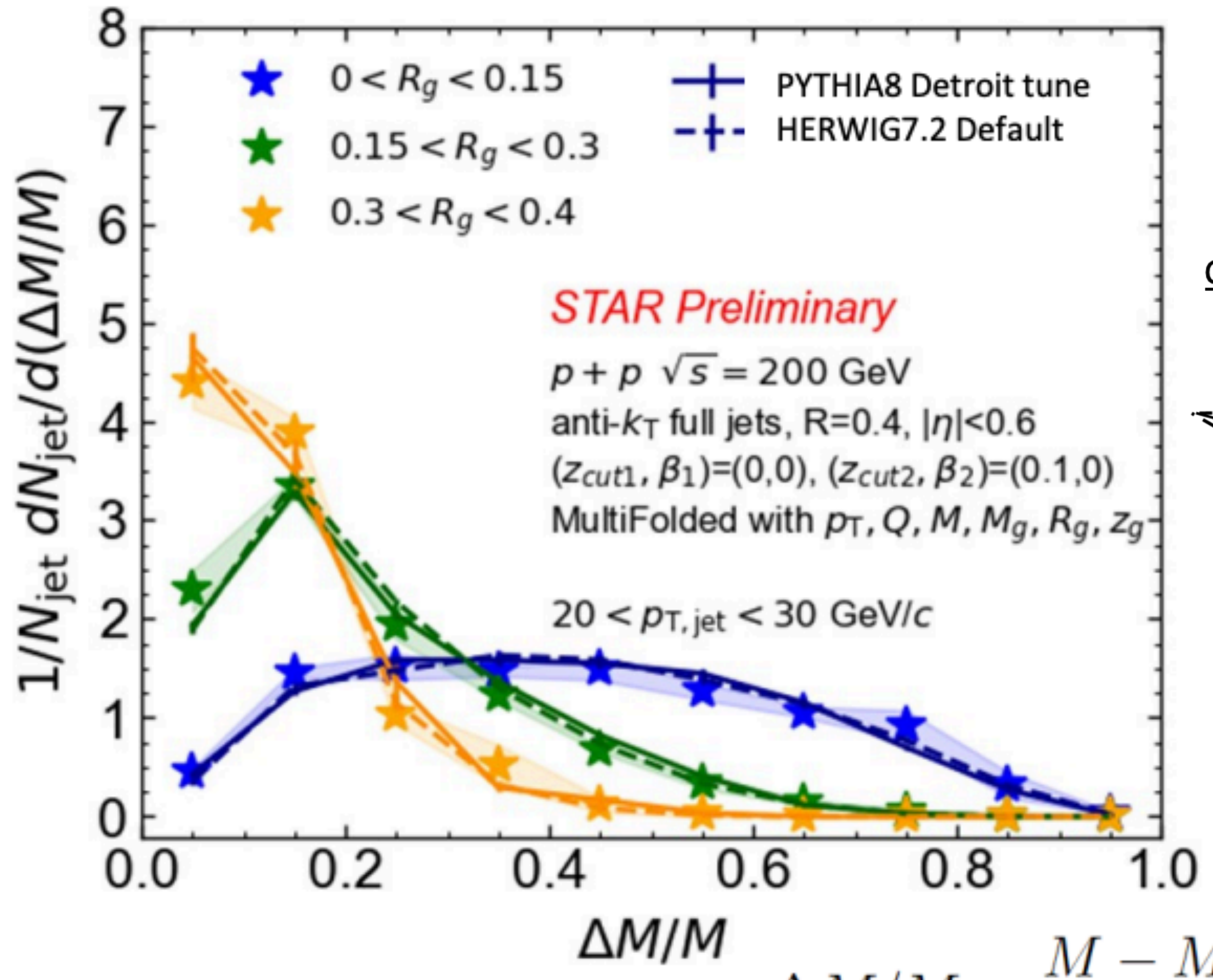
Multi-dimensional jet substructure

Groomed Lund plane: R_g vs. z_g



Evolves from soft large-angle to collinear hard splittings

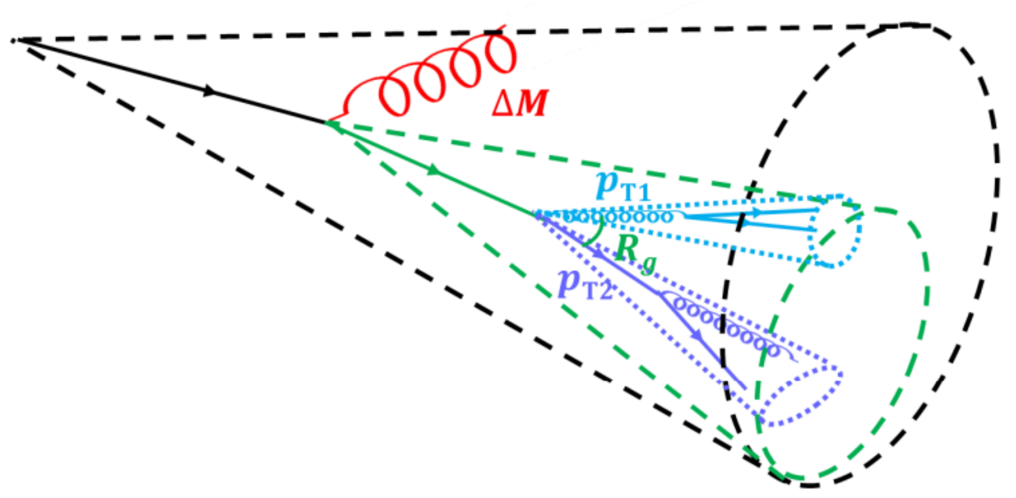
Multifold: **6D correlation** between substructure observables measured!



Collinear Drop:

probes the soft component

Chien and Stewart JHEP 2020, 64 (2020).



$$\Delta M/M = \frac{M - M_g}{M}$$

Less groomed soft component for wider splittings

See Y. Song talk yesterday

New jet substructure tool: energy correlators

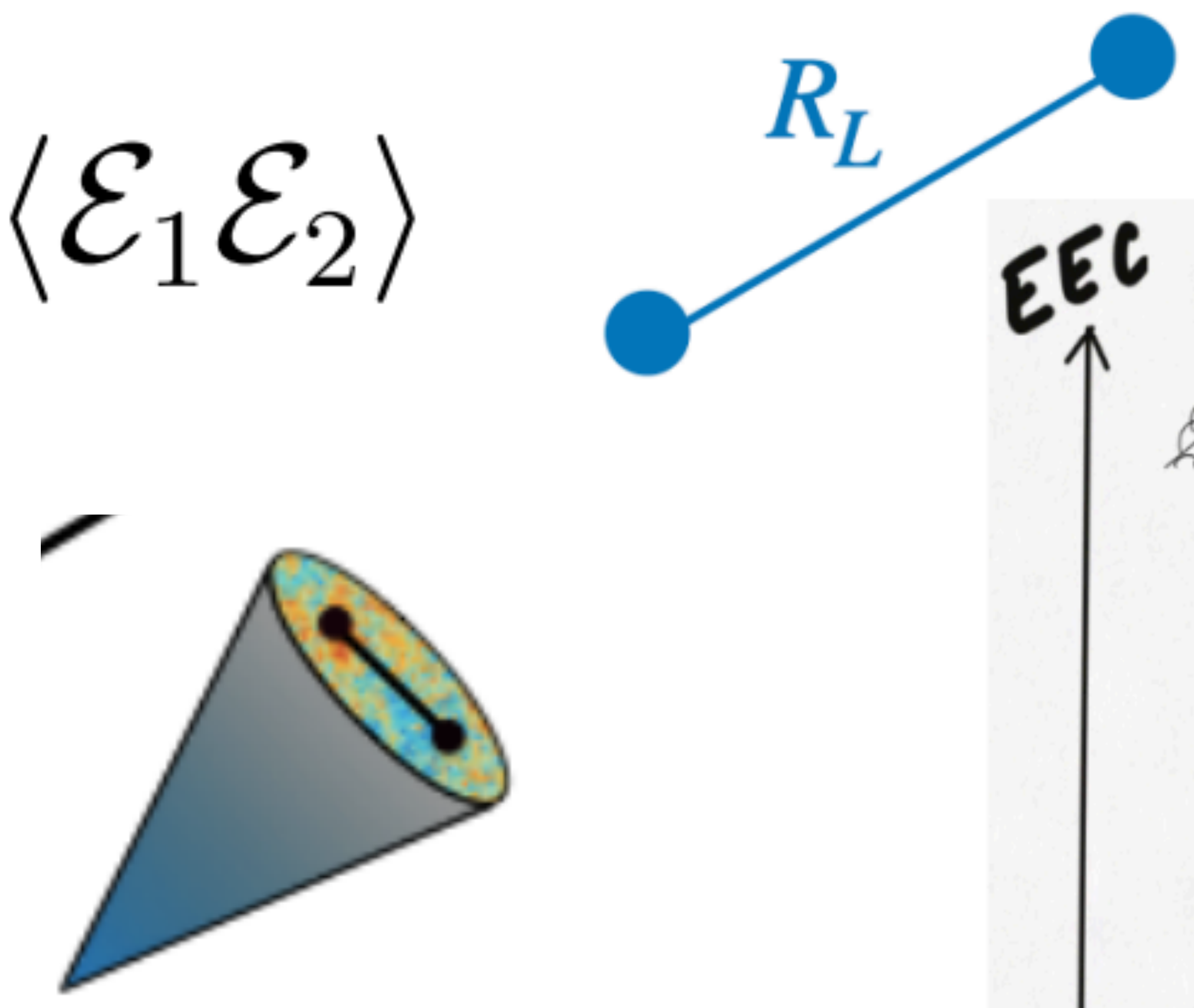
Komiske et al arxiv:2201.07800

Lee, Mecaj, Moult arxiv:2205.0314

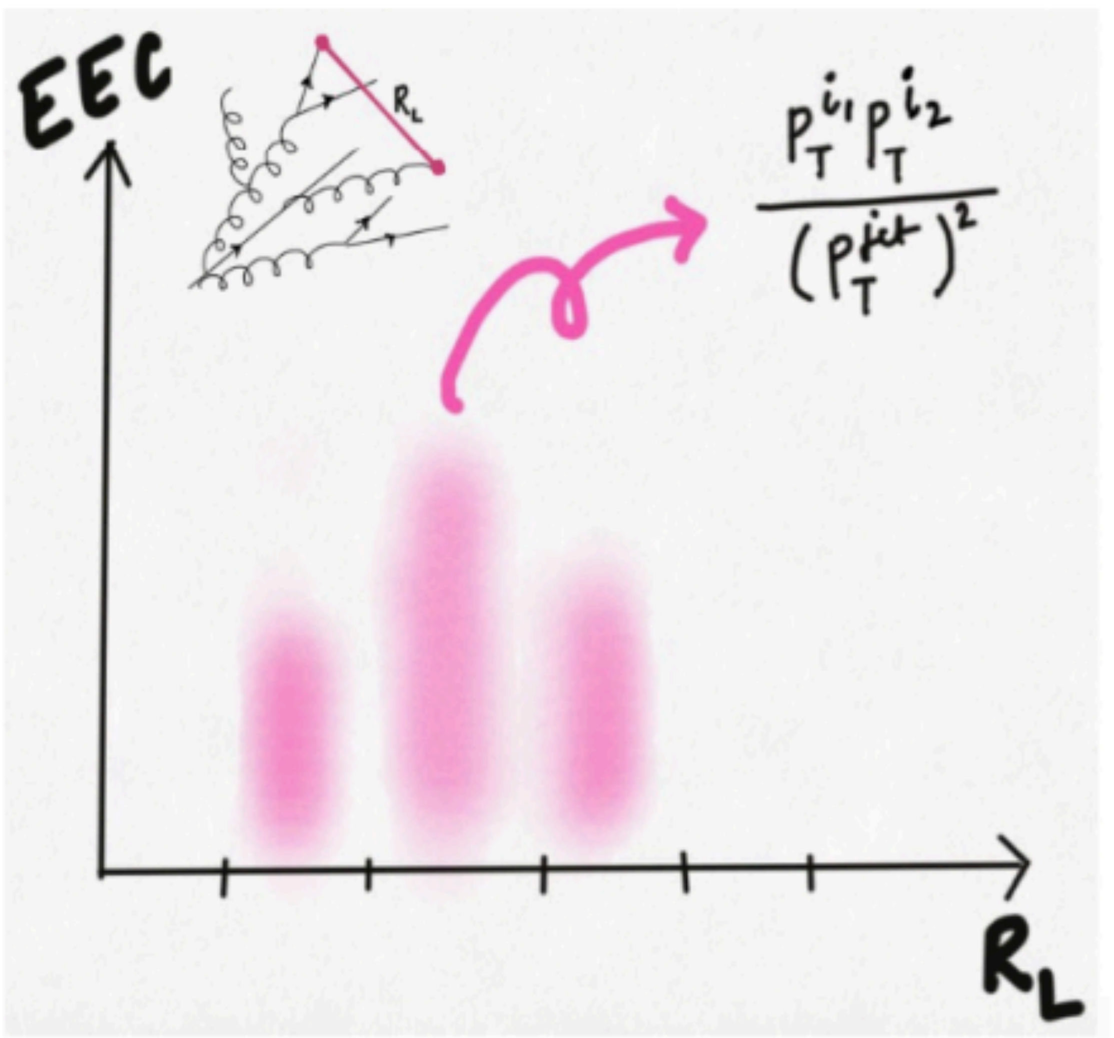
Measure the angular correlation between hadron pairs inside a jet

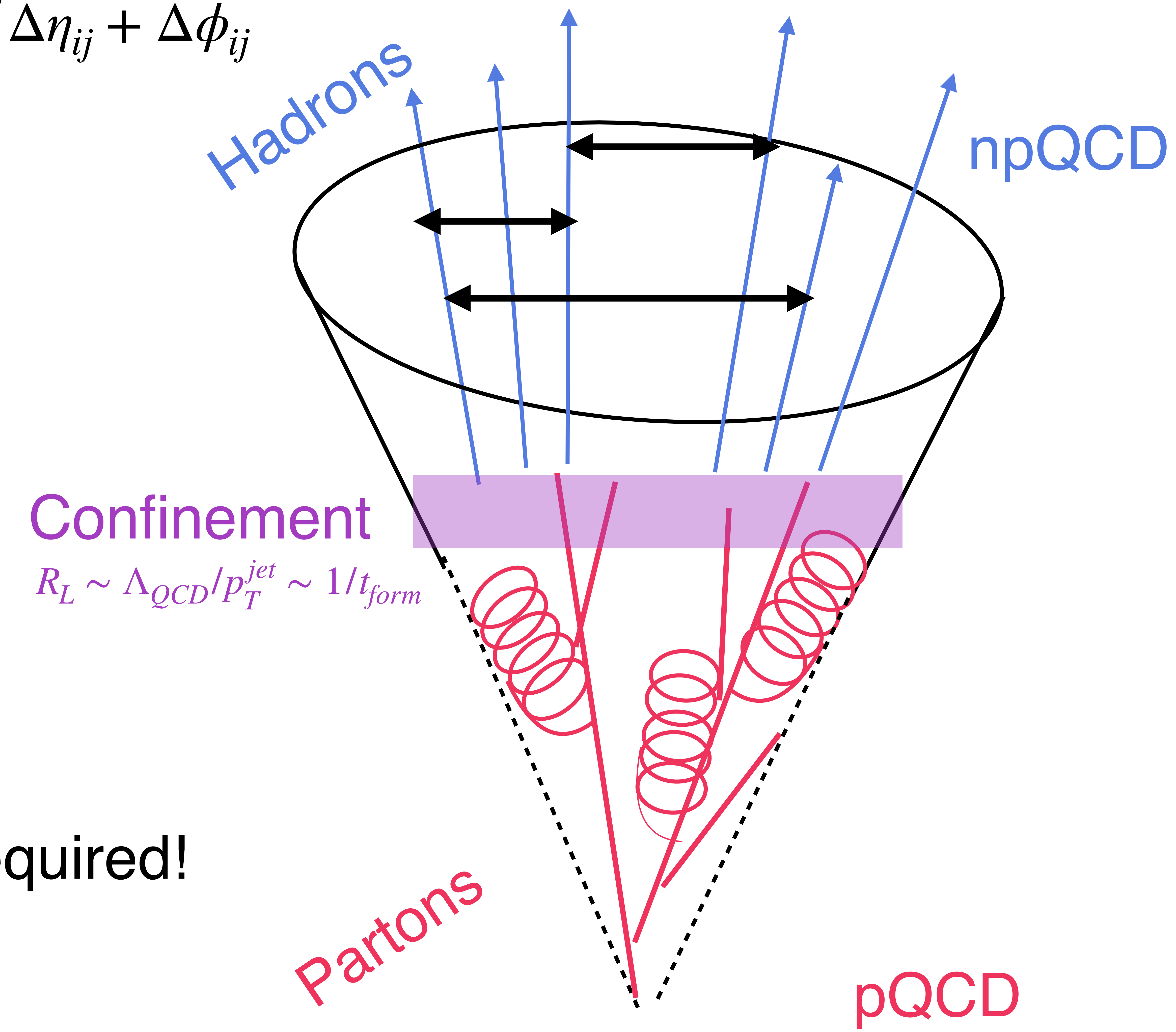
$$R_L = \sqrt{\Delta\eta_{ij} + \Delta\phi_{ij}}$$

$\langle \mathcal{E}_1 \mathcal{E}_2 \rangle$



Credit: A. Rai

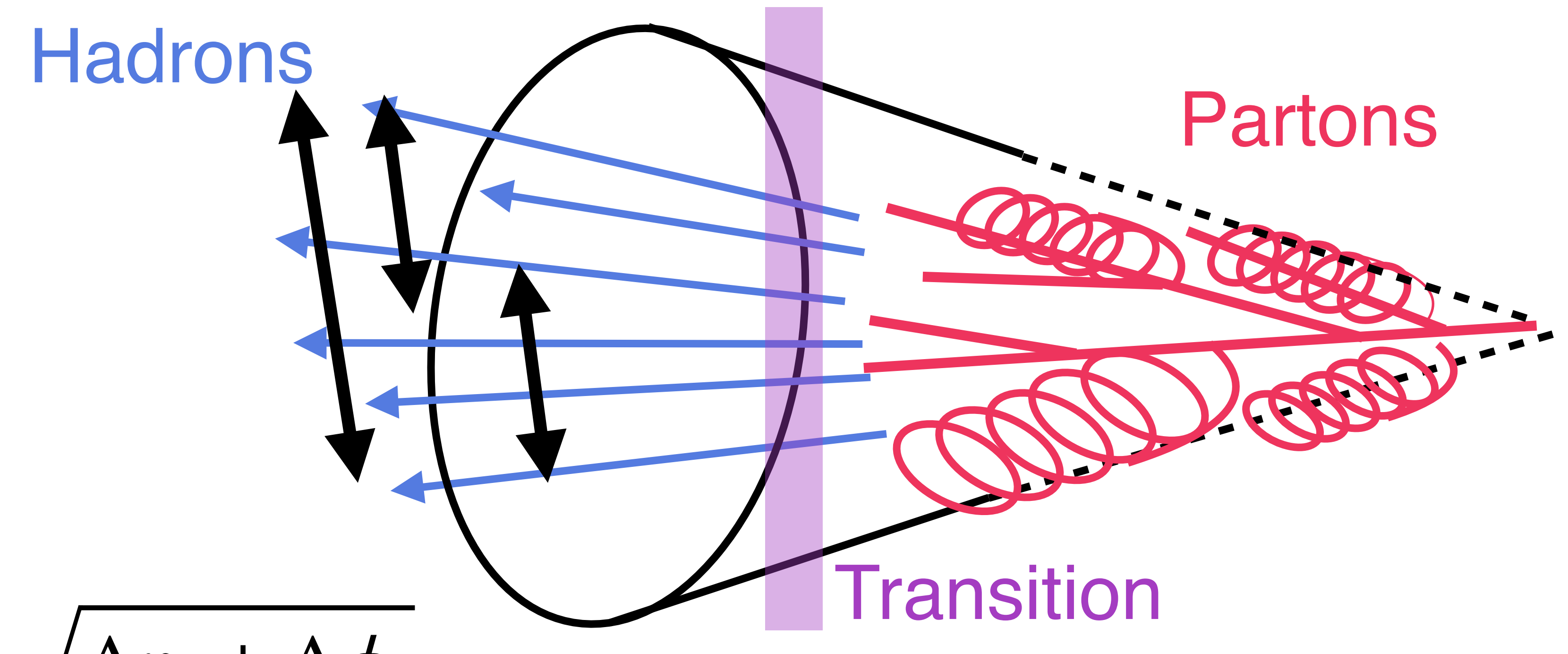




Defined from first principles QFT, no grooming required!

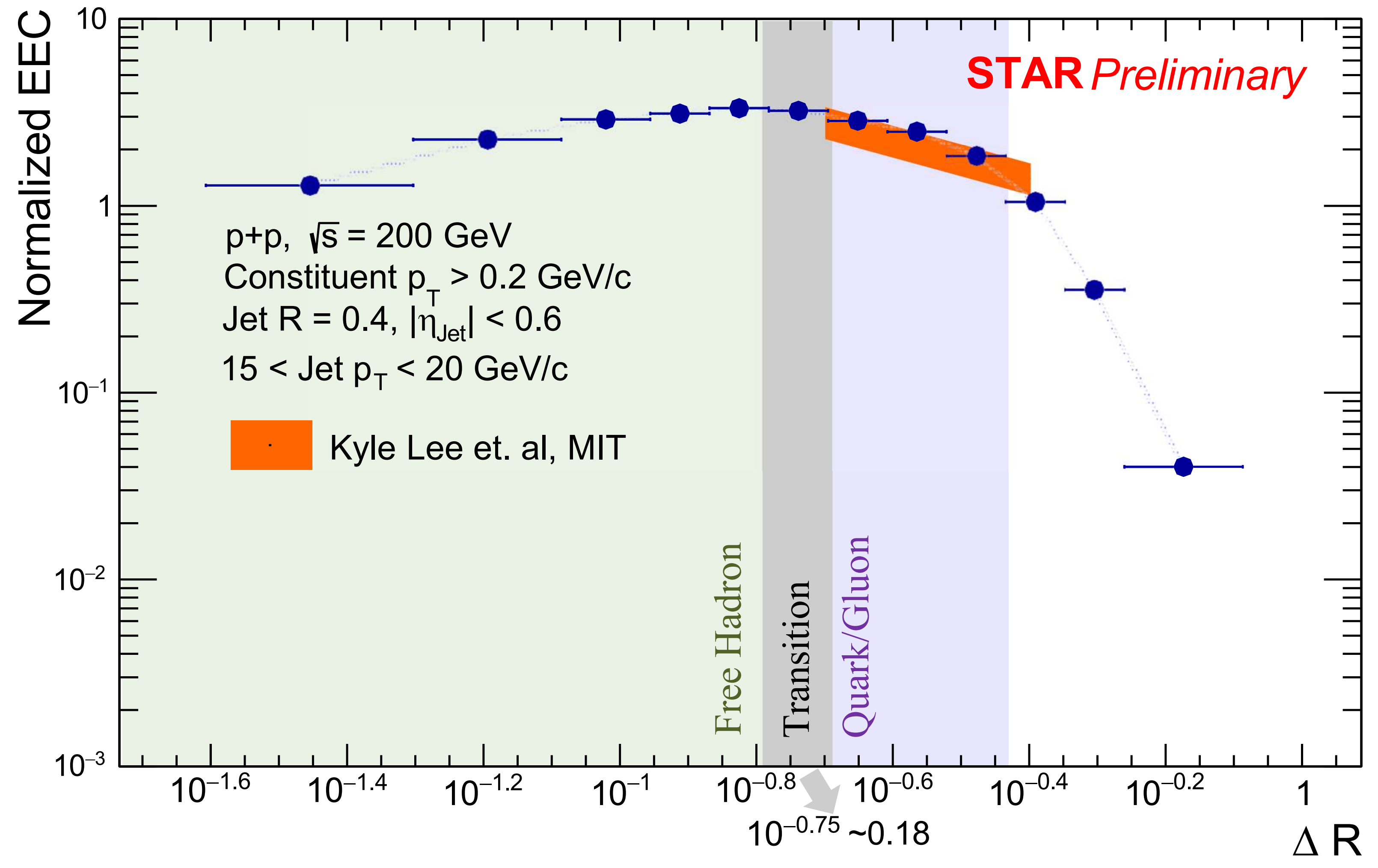
Separate the pQCD and npQCD scales

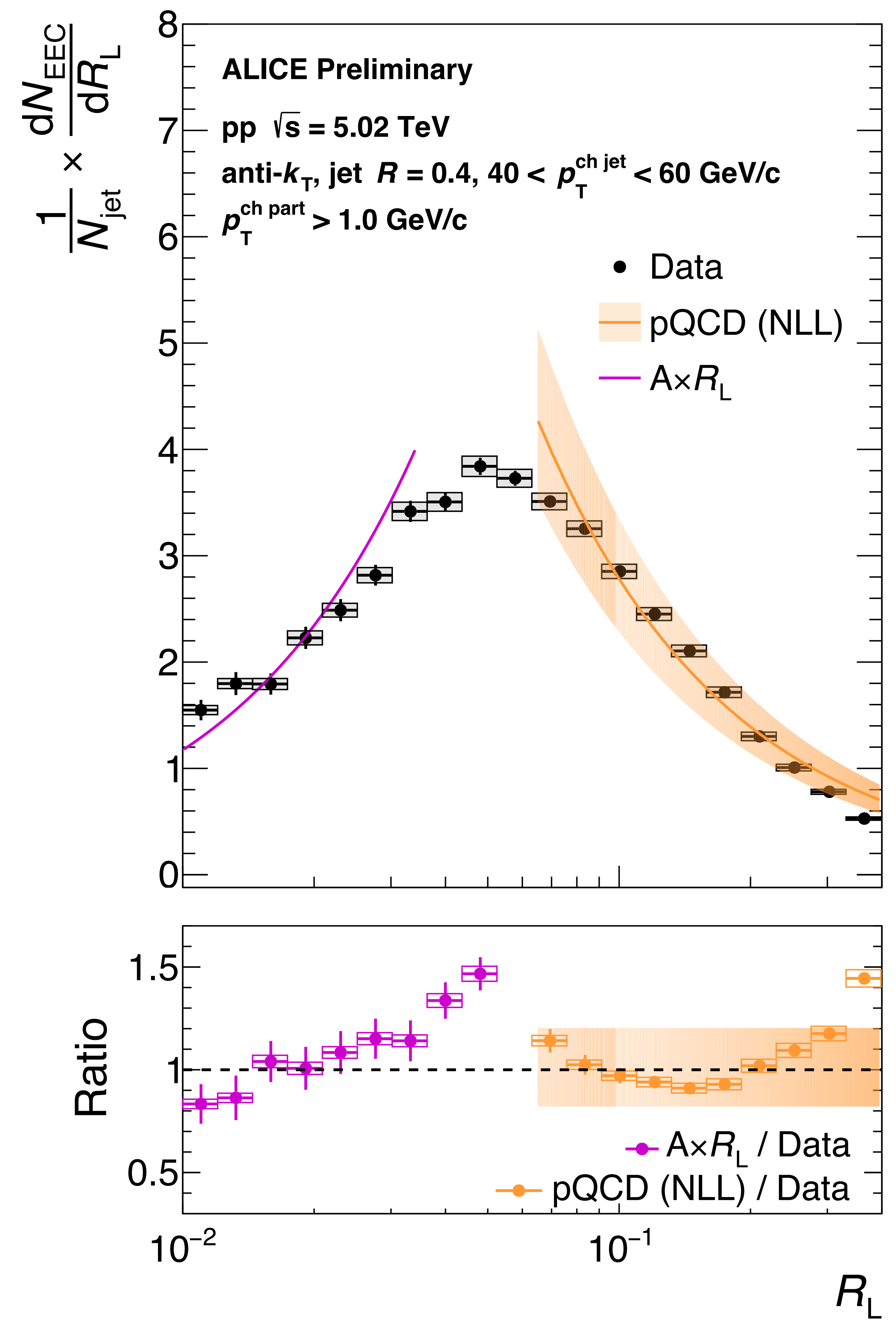
Energy correlators as a separation of scales

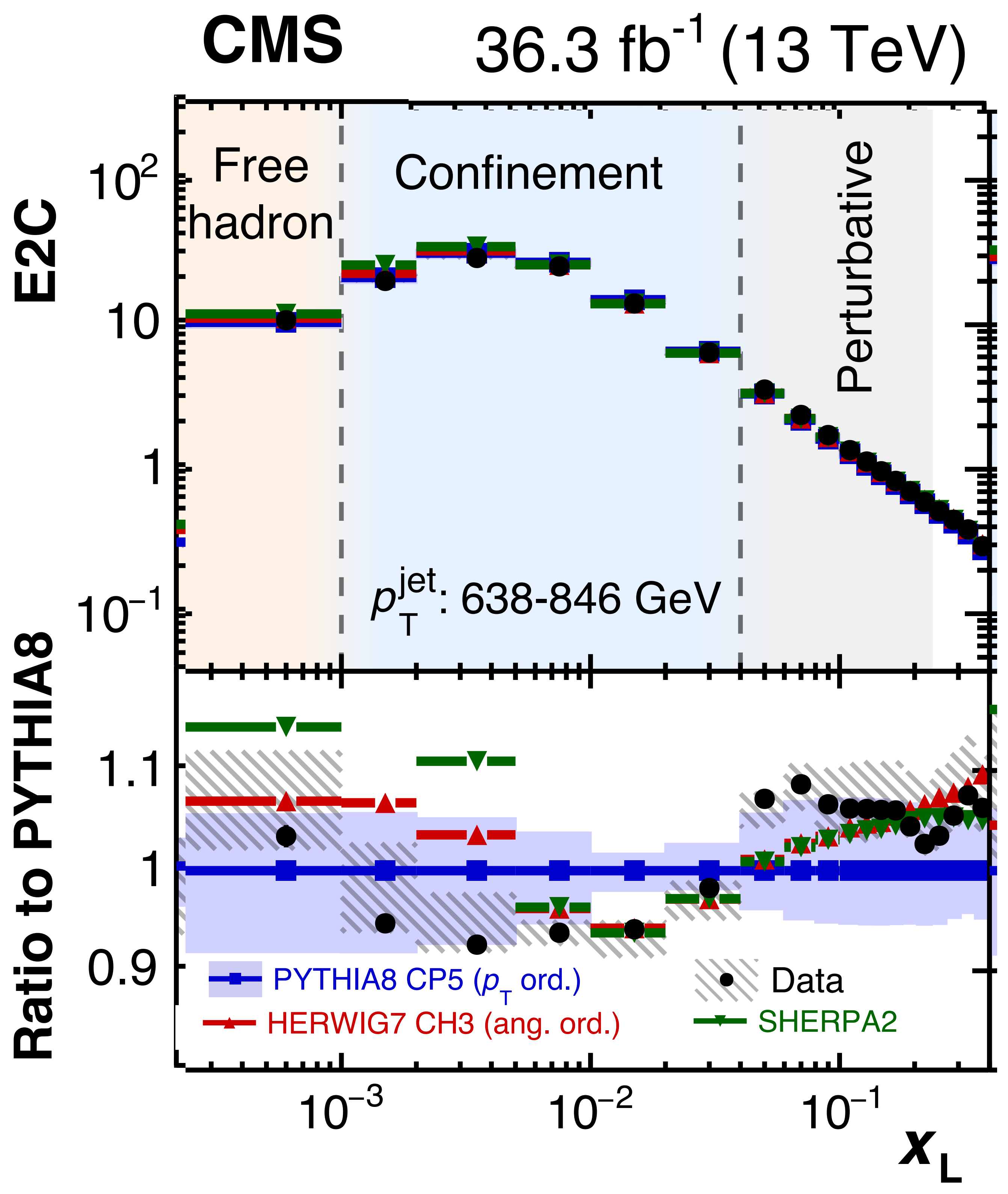


$$R_L = \sqrt{\Delta\eta_{ij} + \Delta\phi_{ij}}$$

$$R_L p_T^{jet} \sim \Lambda_{QCD}$$







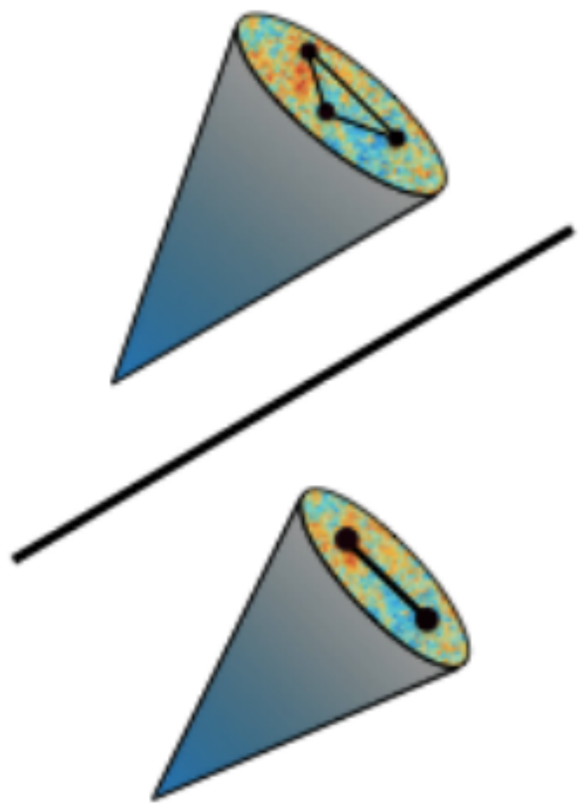
Small R_L: free hadrons (npQCD)

Confinement transition between two regions

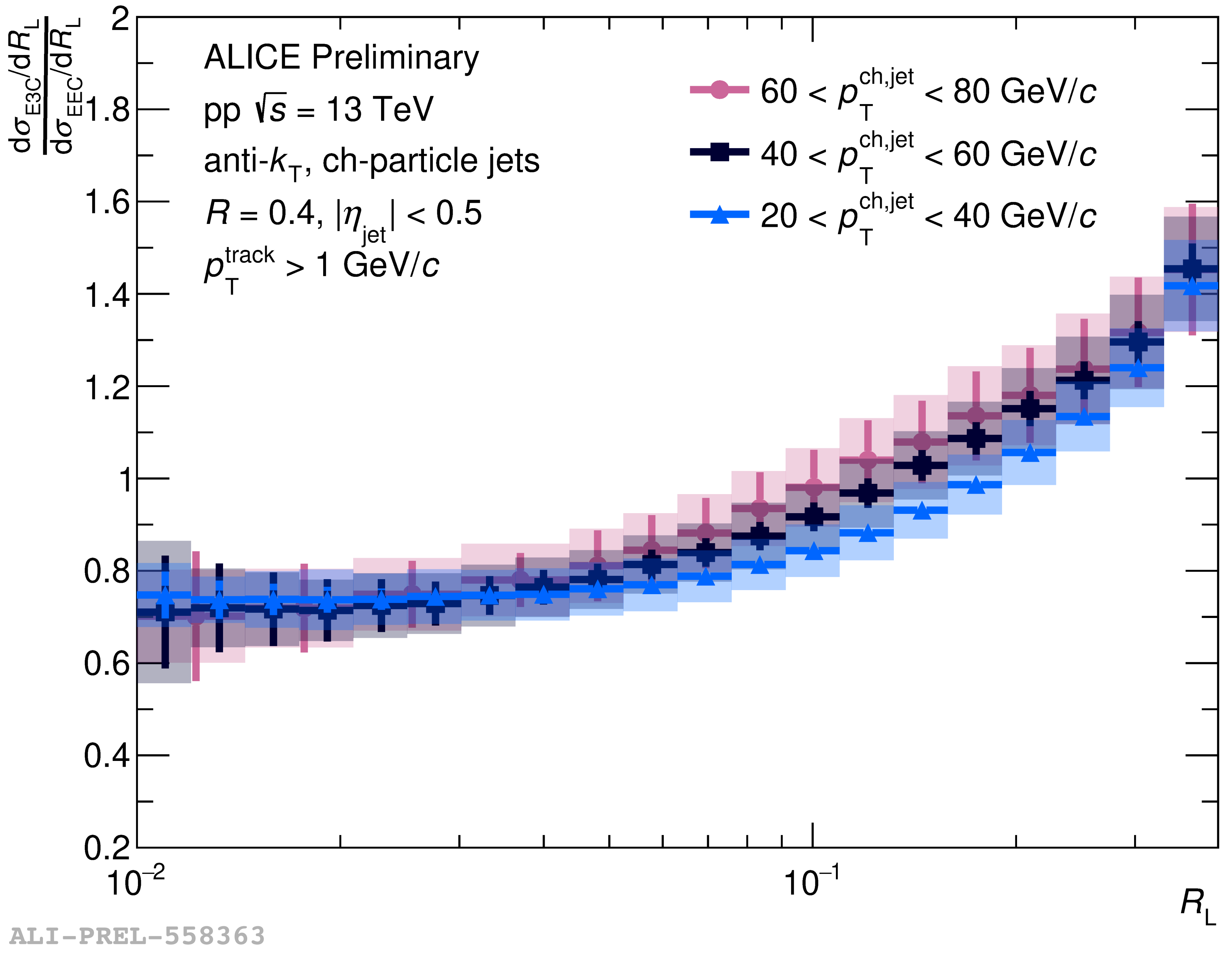
Large R_L: partons (mostly pQCD)

Strong coupling from 3 to 2 point correlators

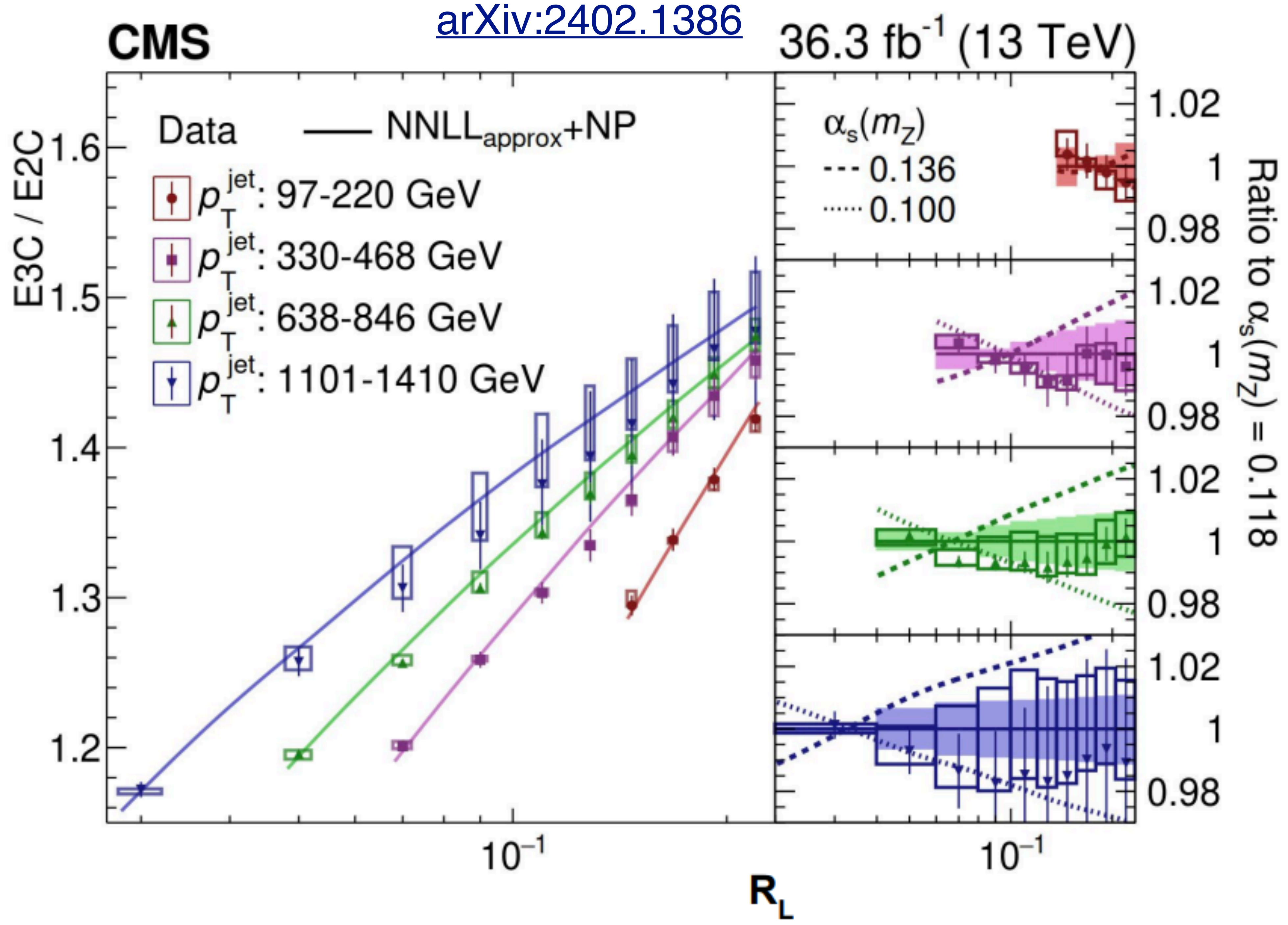
E3C/E2C $\propto \alpha_s ln(R_L)$ Ratio cancels some npQCD effects



Credit: B. Mecaj



arXiv:2402.1386



Small R_L: flat with jet p_T

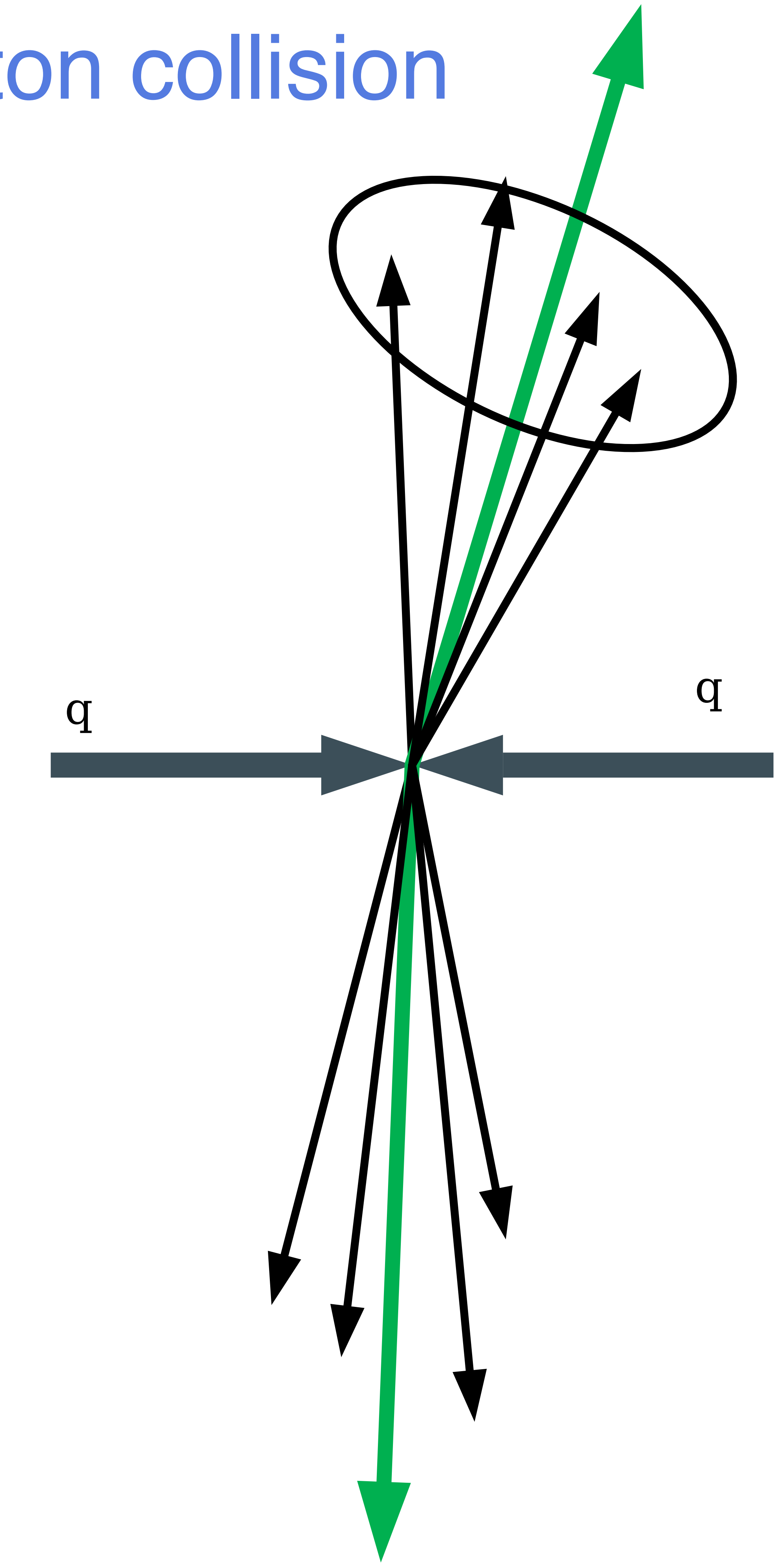
Large R_L: scales with jet p_T (running coupling)

Extract $\alpha_s(m_z)$ from slope -> most precise extraction from jet substructure!

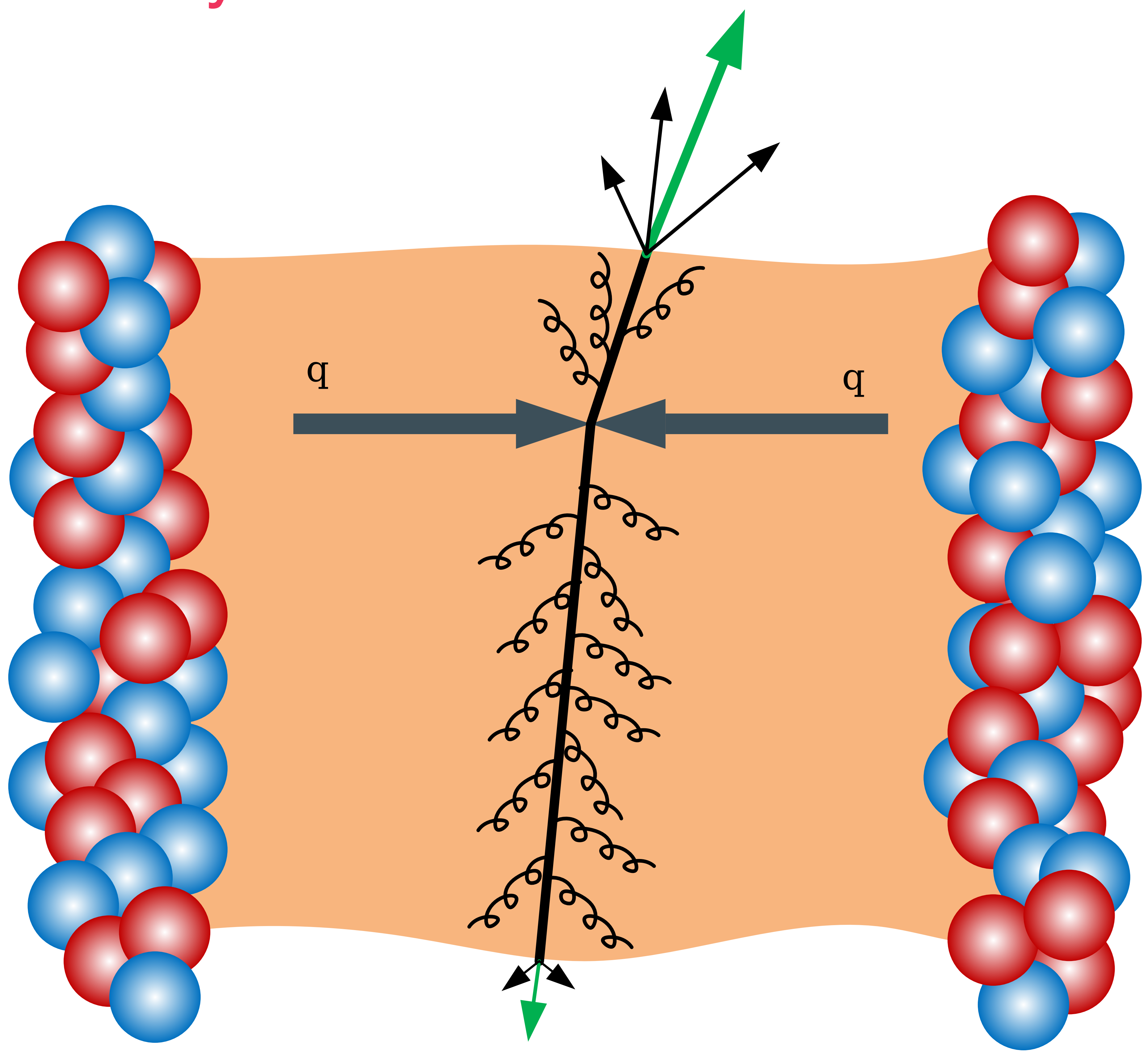
$$\alpha_S = 0.1229^{+0.0014(stat.)+0.0030(theo.)+0.0023(exp.)}_{-0.0012(stat.)-0.0033(theo.)-0.0036(exp.)}$$

Jet quenching in the quark-gluon plasma

Proton-proton collision



Heavy-ion collision



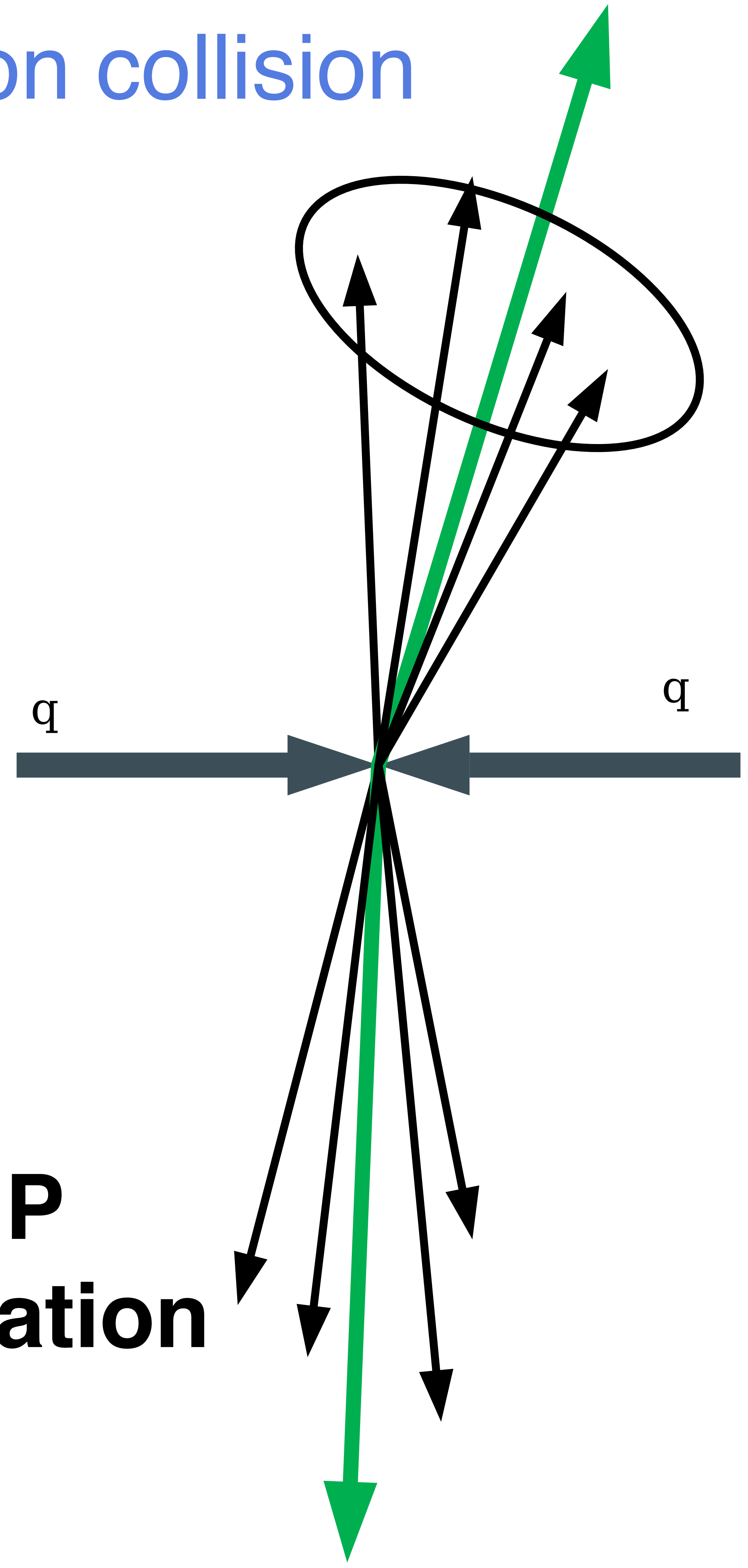
Jet quenching in the quark-gluon plasma

Jet quenching: partons strongly interact with the QGP medium

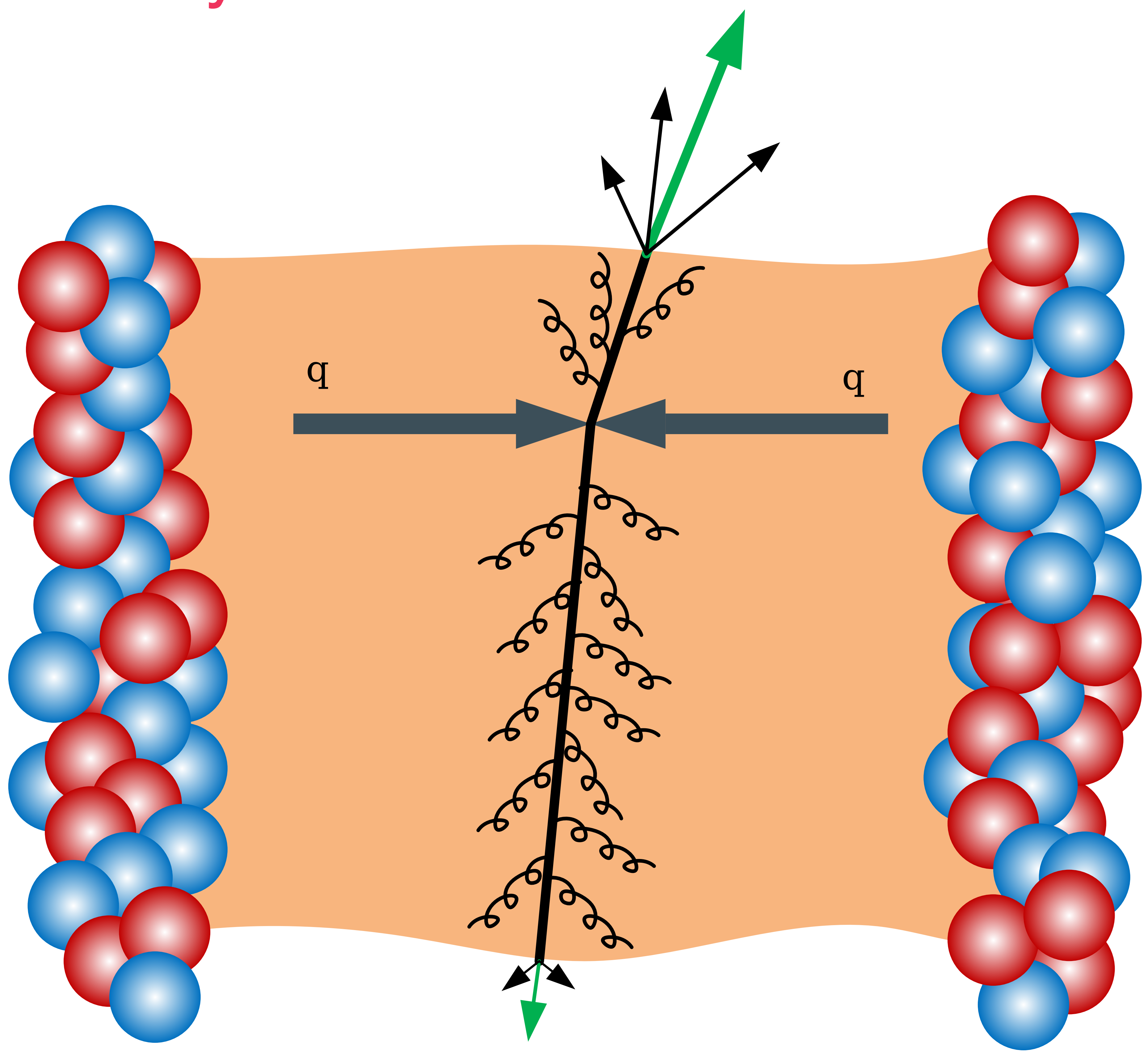
Energy loss and complex structure modified

Evolves through entire QGP evolution encoding information about its properties

Proton-proton collision



Heavy-ion collision



Different jet-medium interactions

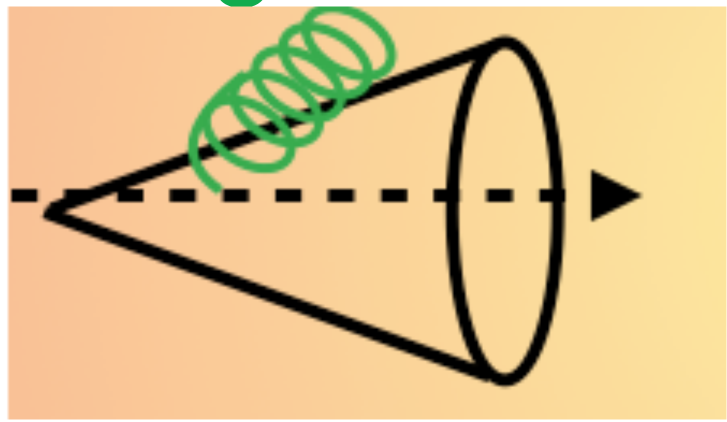
Inelastic collisions (radiative)

Elastic collisions (collisional)

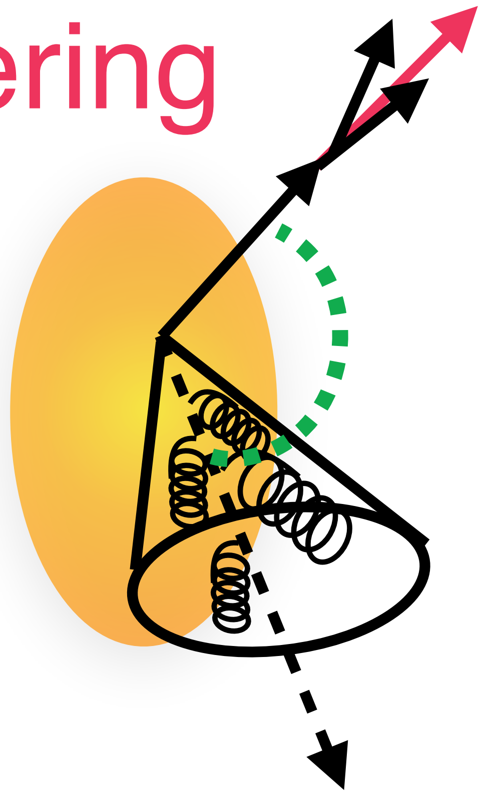
Credit: C. Beattie

Different jet-medium interactions

Medium-induced splittings



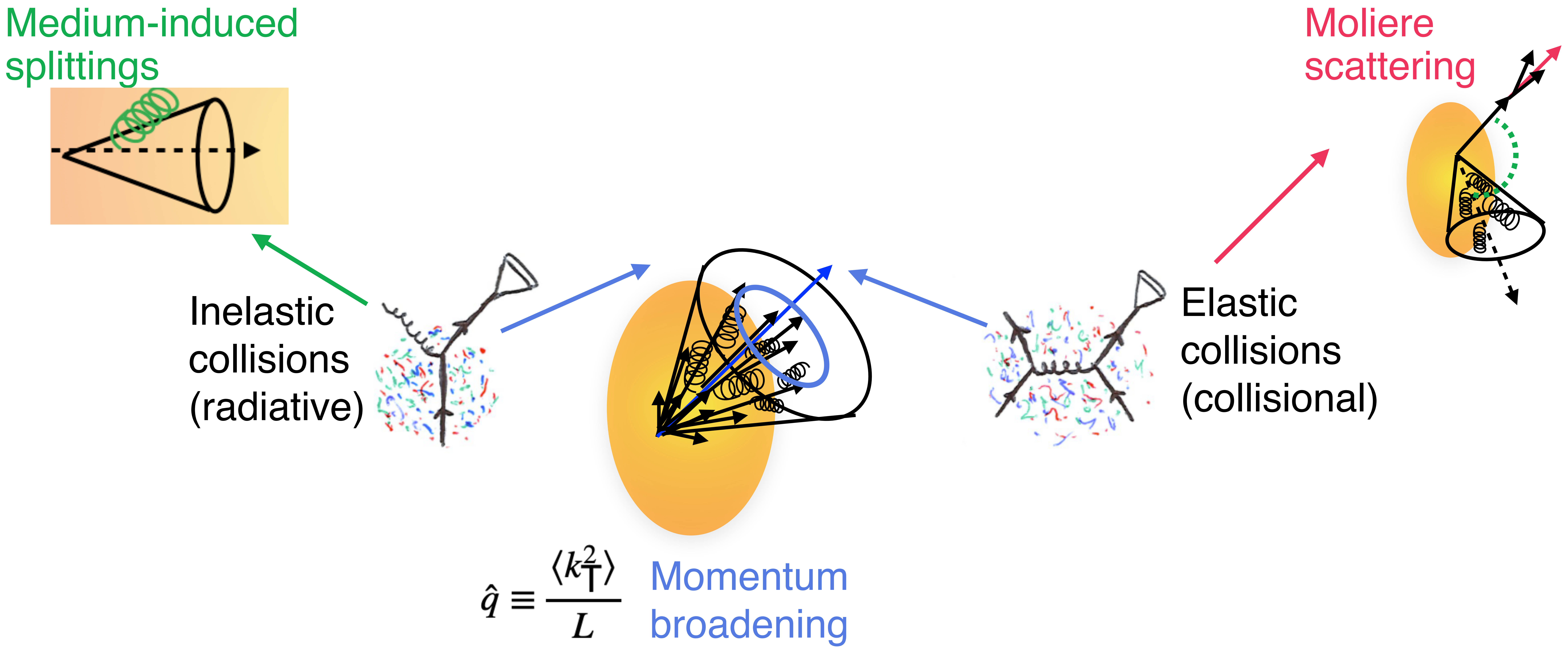
Moliere scattering



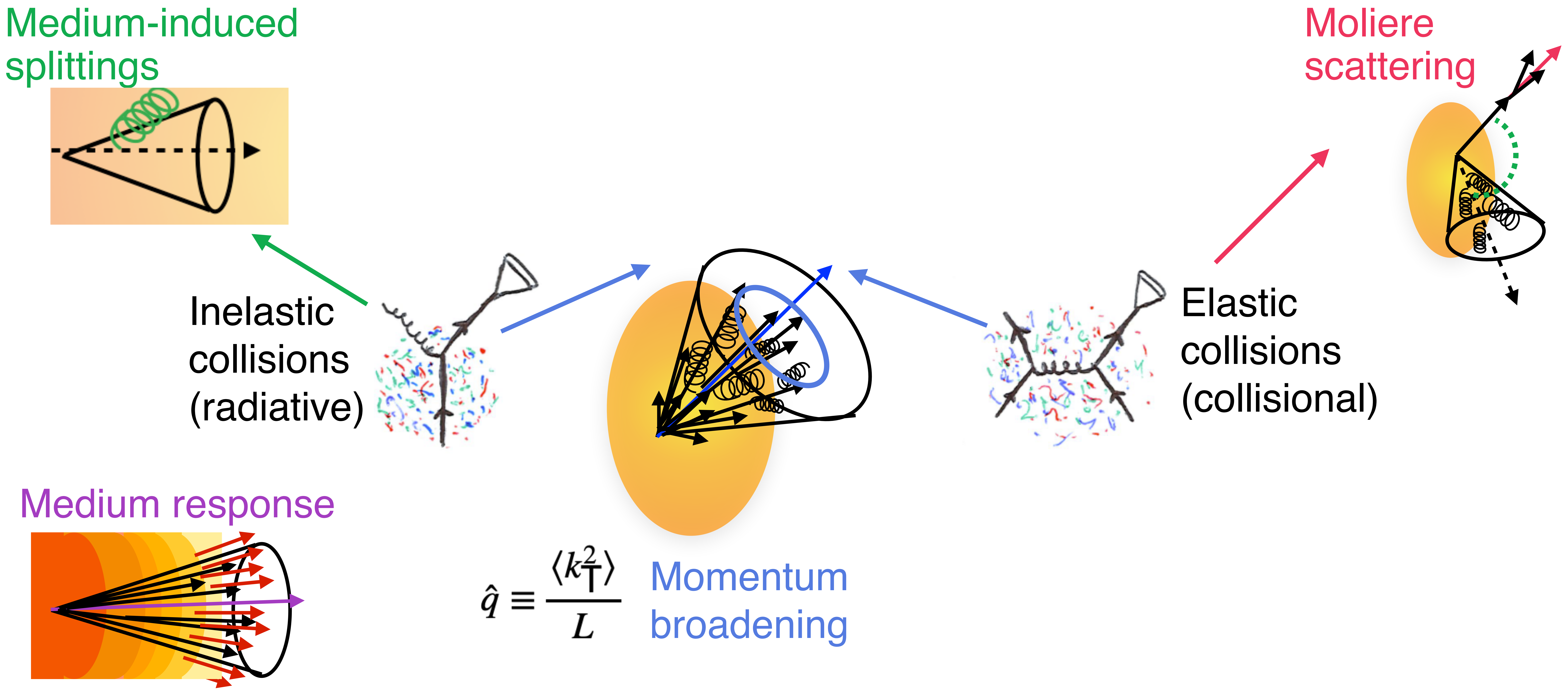
Inelastic collisions (radiative)

Elastic collisions (collisional)

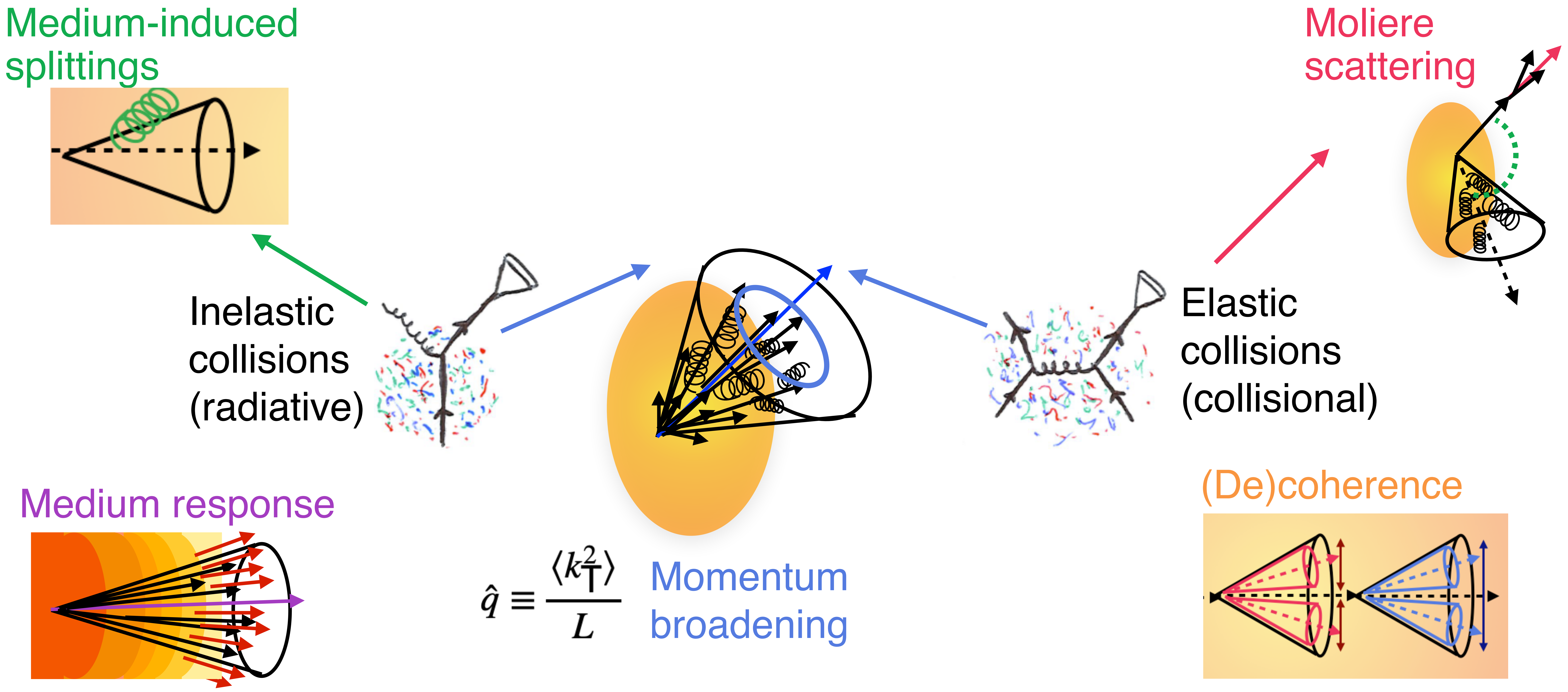
Different jet-medium interactions



Different jet-medium interactions

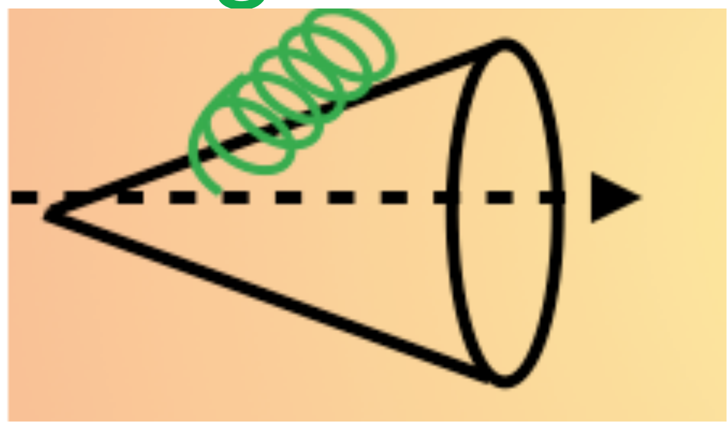


Different jet-medium interactions



Different jet-medium interactions

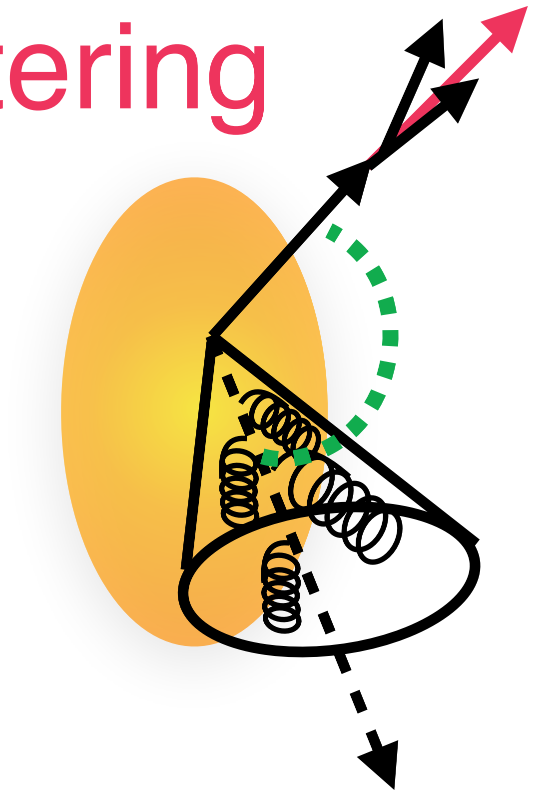
Medium-induced splittings



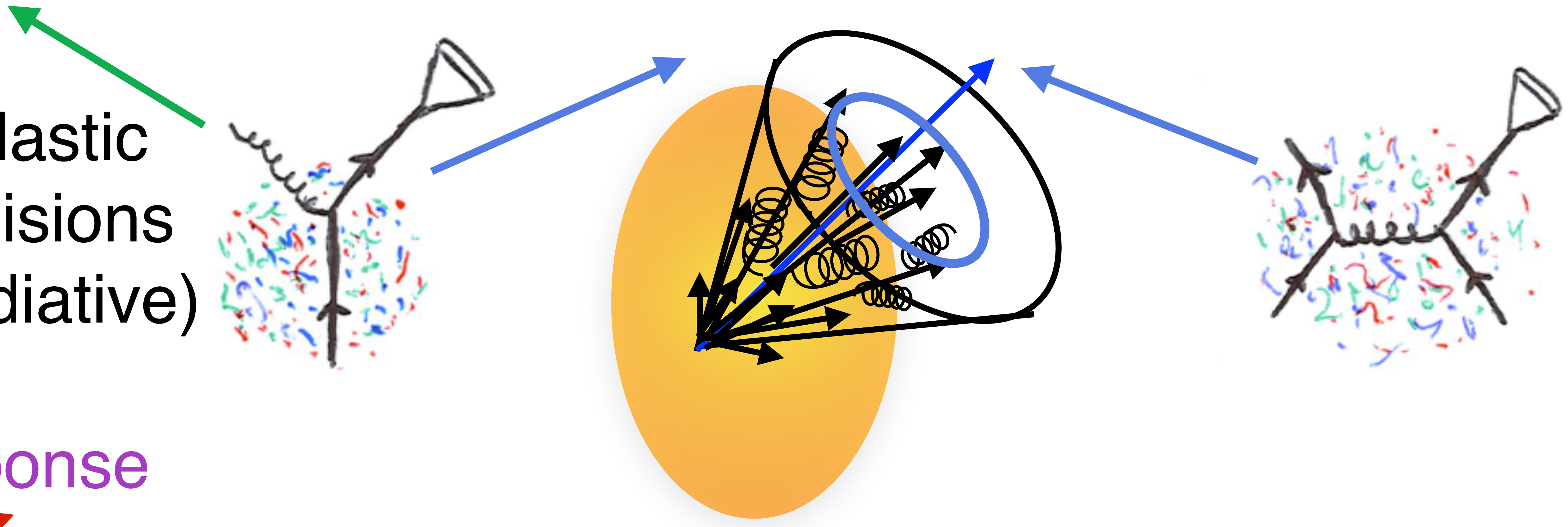
Jet responds to medium?

Jet resolves quasi-particles in medium?

Moliere scattering

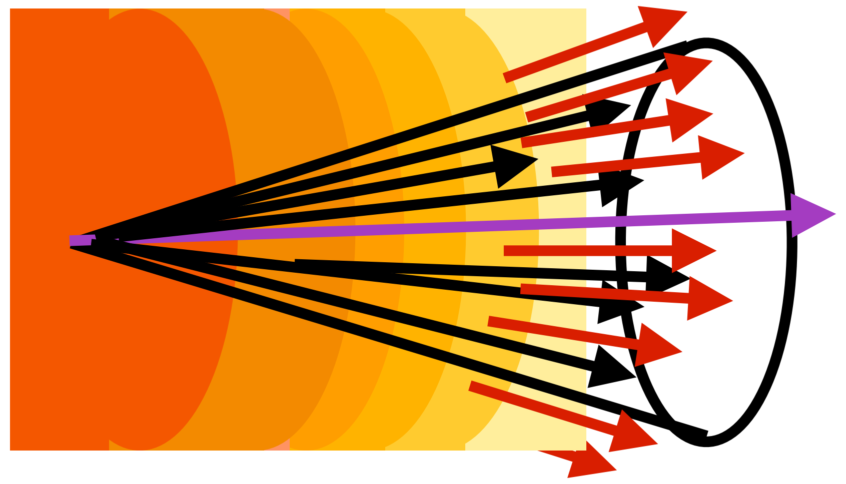


Inelastic collisions (radiative)



Elastic collisions (collisional)

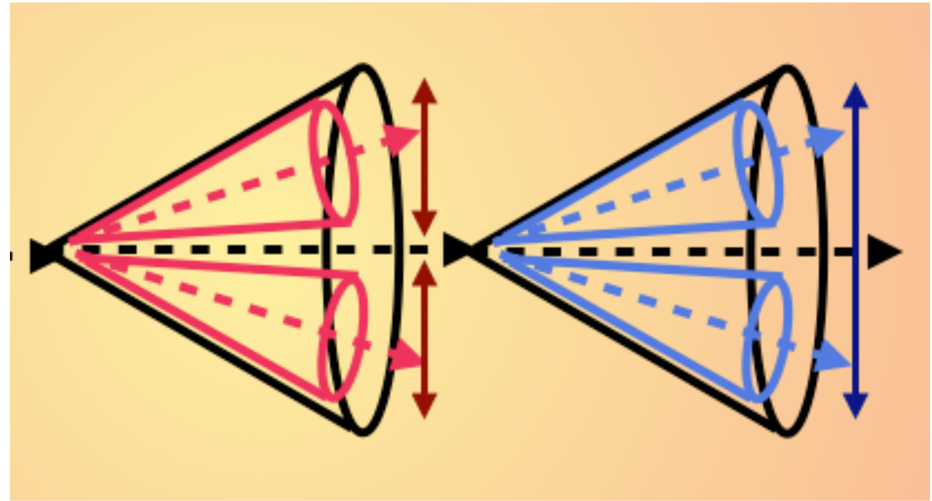
Medium response



$$\hat{q} \equiv \frac{\langle k_T^2 \rangle}{L}$$

Momentum broadening

(De)coherence

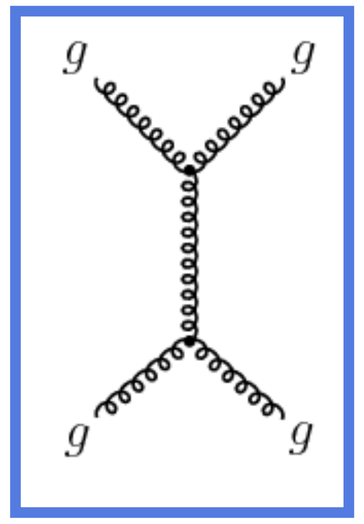


Medium responds to jet?

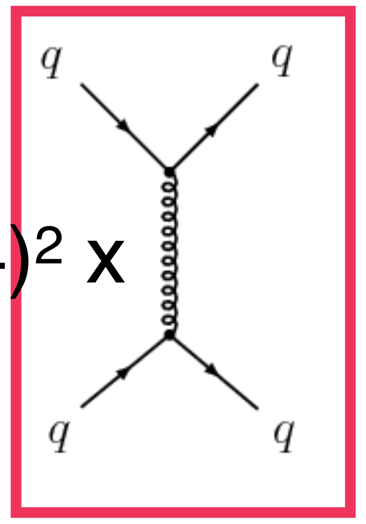
Medium resolves color charges in jet?

Different probes, different mediums

Flavor and mass dependence



~$(9/4)^2$ x

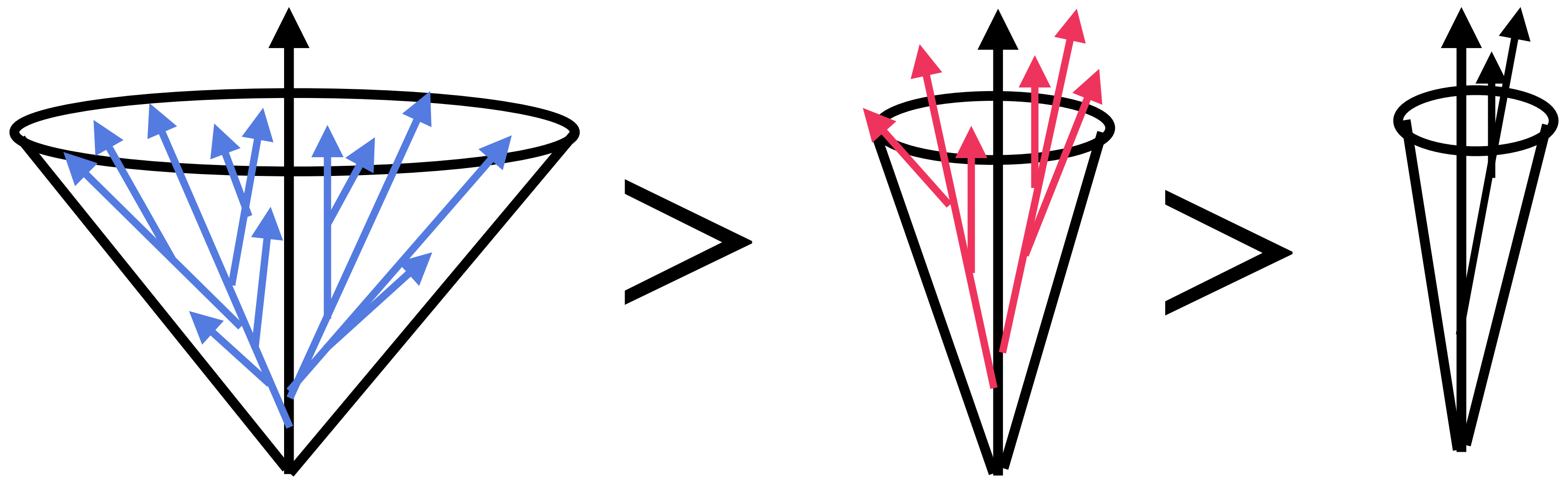


E_{loss} > E_{loss} > E_{loss}^{HQ}

Gluon | Light quark | Heavy quark

Charm | Beauty

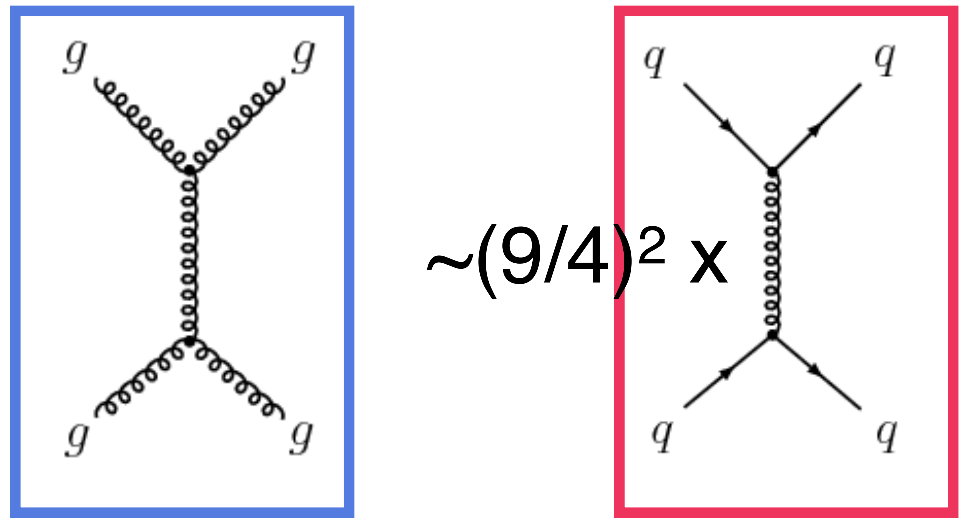
More complex structure -> more opportunities for interactions

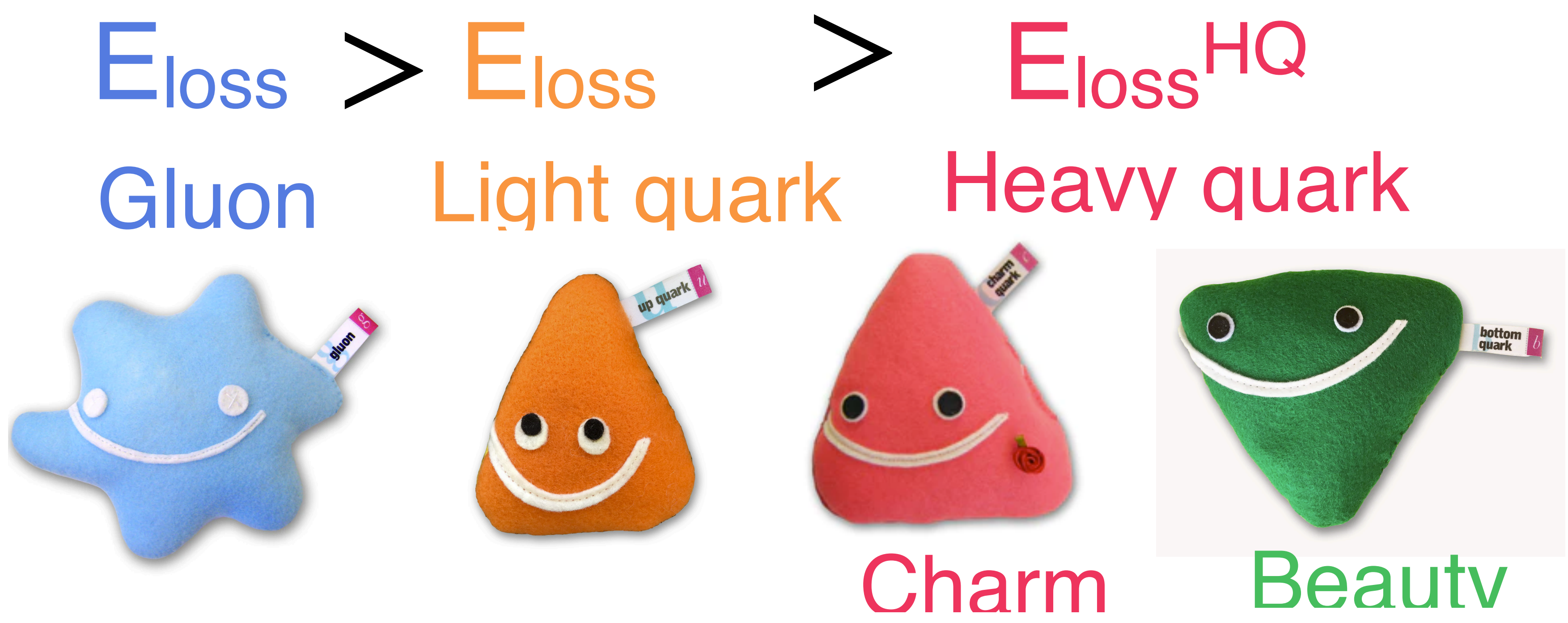


Quark jets narrower than gluon jets

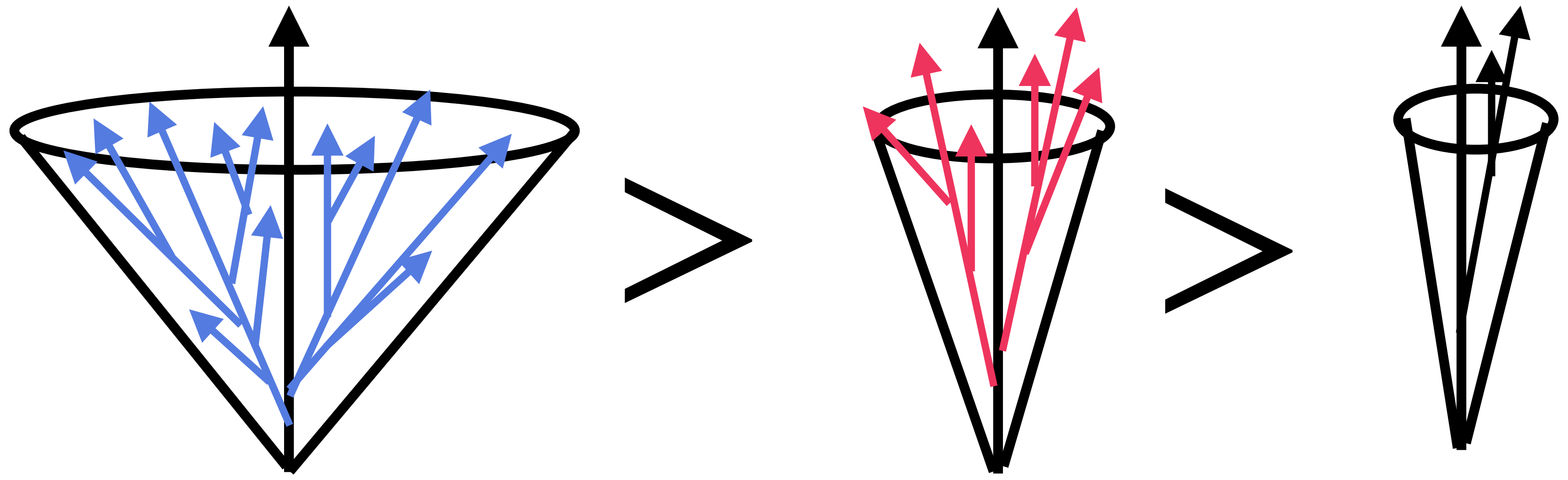
Different probes, different mediums

Flavor and mass dependence





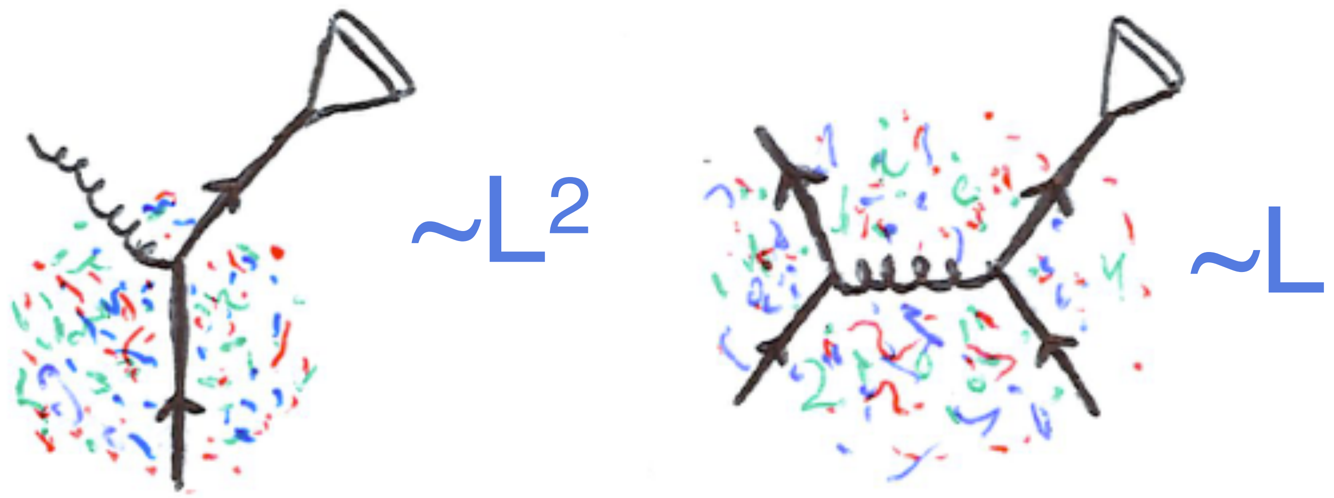
More complex structure -> more opportunities for interactions



Quark jets narrower than gluon jets

Path length dependence

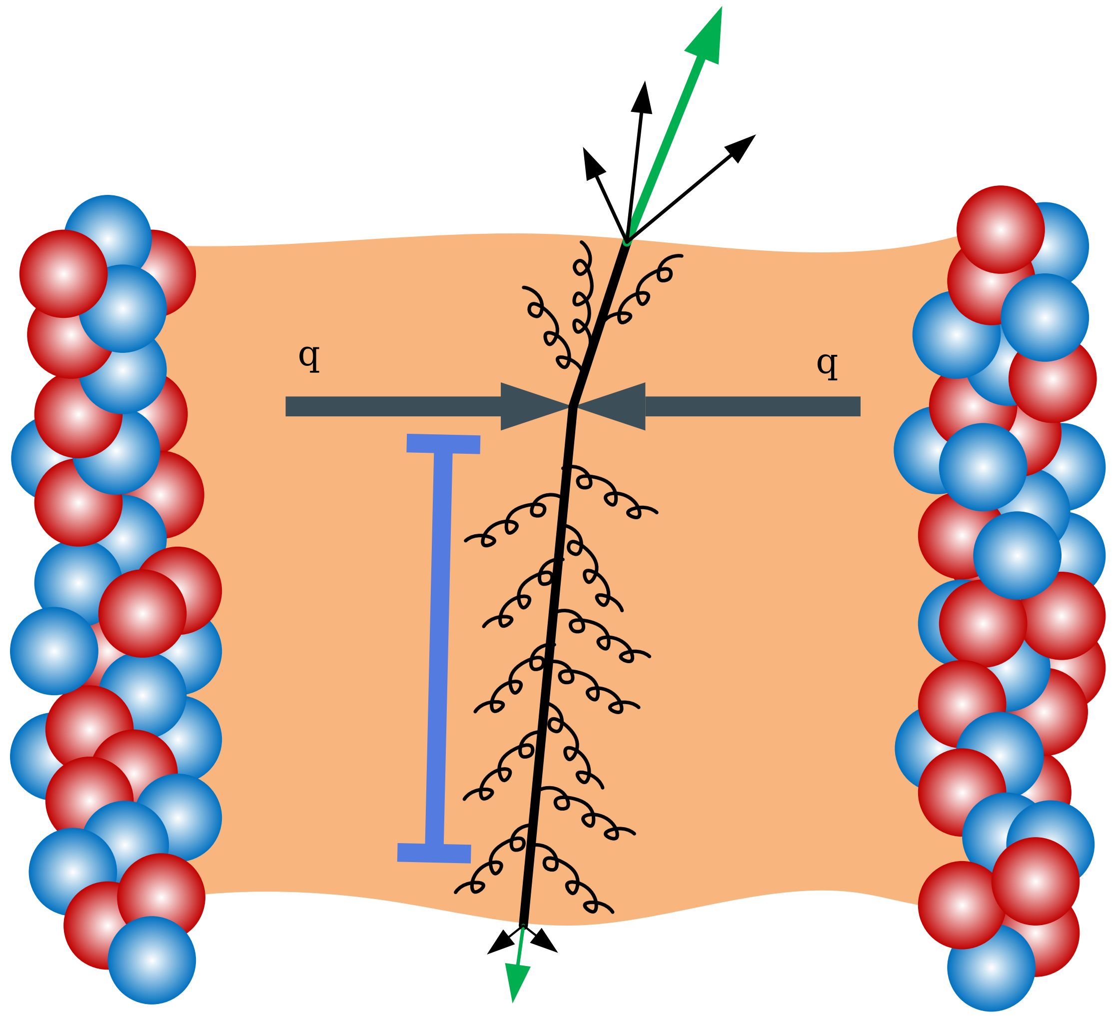
See M. Conner's talk



System size (p, O, Cu, Zr, Ru, Xe, Au, Pb)

See V. Bailey's talk

QGP at LHC hotter, denser, and longer lived than RHIC!



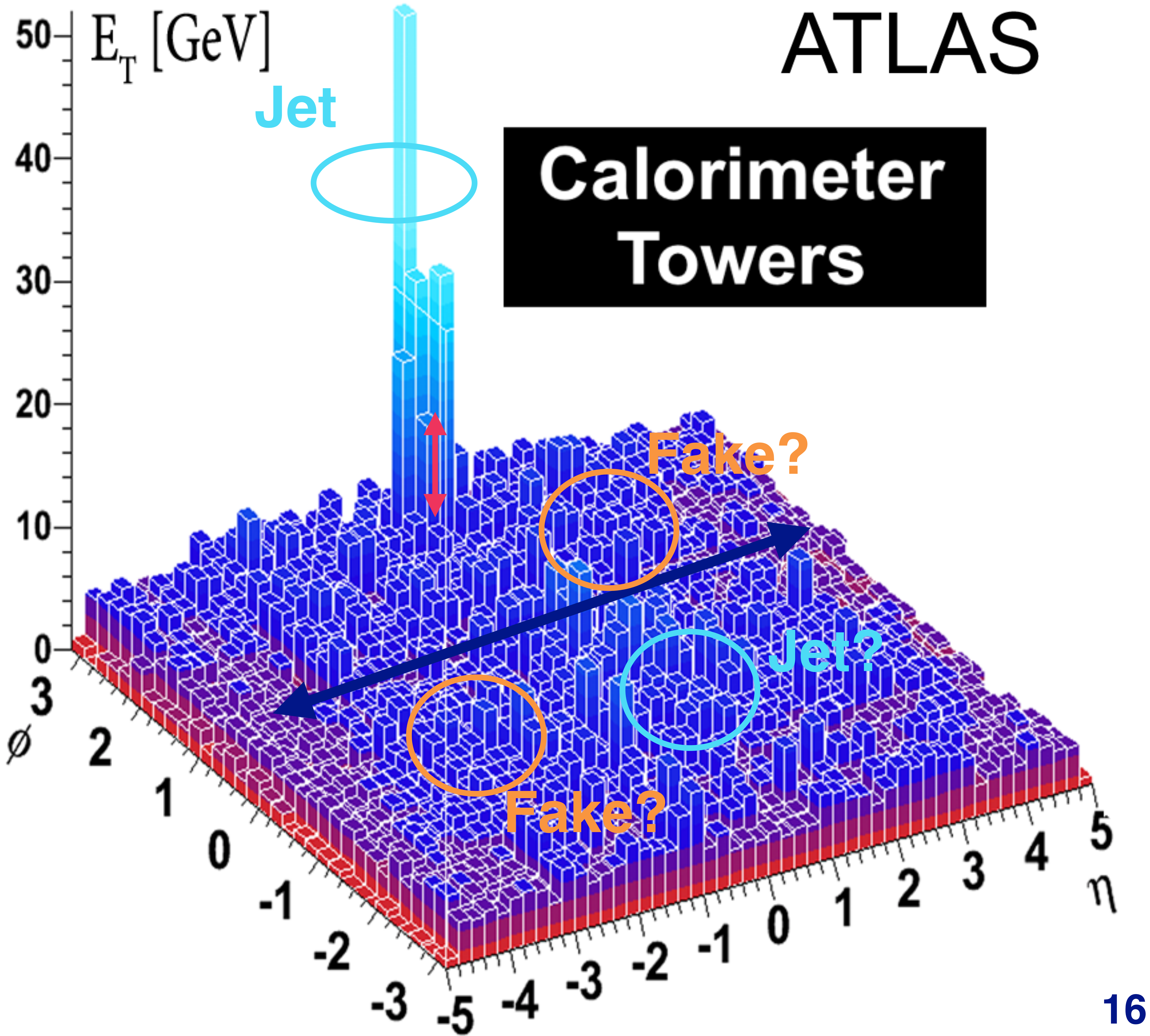
Measuring jets in a heavy-ion collision

Large background due to the underlying event (UE) that contributes background energy inside the jet cone

Fake jets due to upward fluctuations

Challenging to remove, obscures physics and restricts where jets can be measured

Different techniques for each obervable and experiment!



Jets lose energy in the medium

Before and after energy loss at fixed value of jet p_T

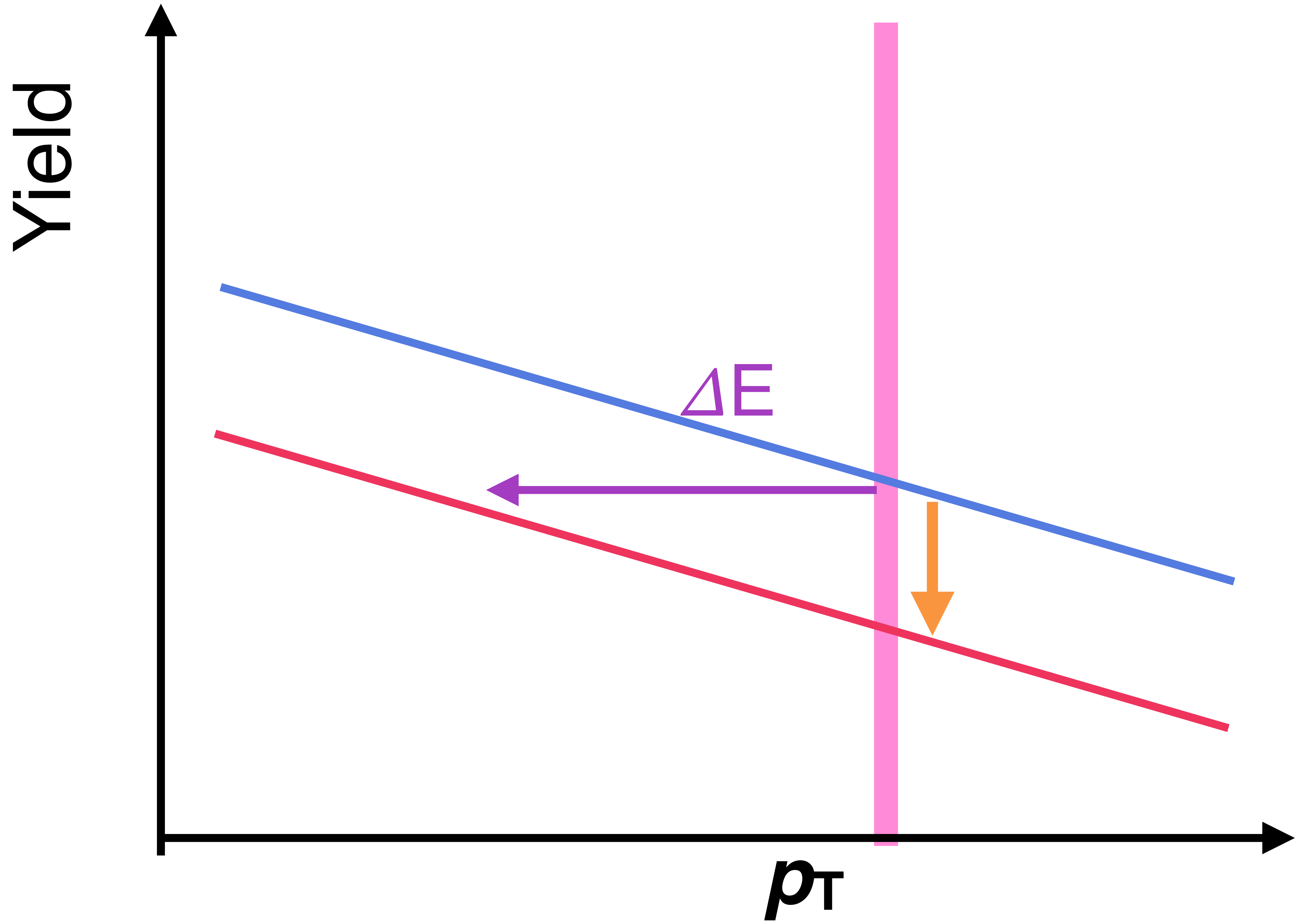
$$R_{AA} = \frac{\frac{1}{N_{evnt}} \frac{d^2 N_{jet}^{PbPb}}{dp_T dy}\Big|_{cent}}{\langle T_{AA} \rangle_{cent} \times \frac{d^2 \sigma_{jet}^{pp}}{dp_T dy}}$$

$$R_{AA} = \frac{\text{Pb-Pb}}{\text{scaled} \otimes \text{pp}}$$

< 1 is suppression

= 1 no suppression

> 1 enhancement



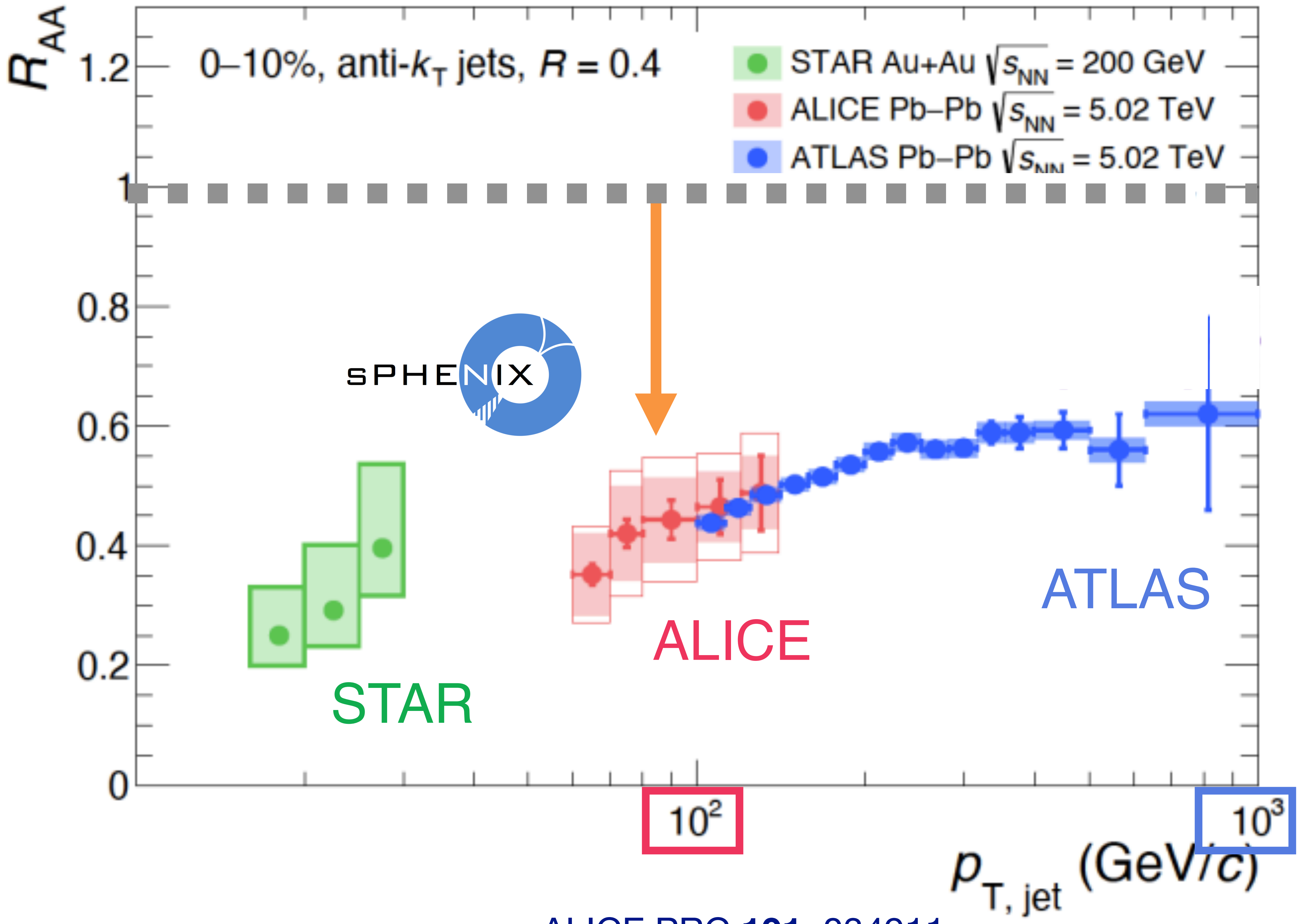
Jets lose energy in the medium

$$R_{\mathrm{AA}} = \frac{\frac{1}{N_{\mathrm{evnt}}} \frac{\mathrm{d}^2 N_{\mathrm{jet}}^{PbPb}}{\mathrm{d}p_{\mathrm{T}}\mathrm{d}y}\Big|_{\mathrm{cent}}}{\langle T_{\mathrm{AA}} \rangle_{\mathrm{cent}} \times \frac{\mathrm{d}^2 \sigma_{\mathrm{jet}}^{pp}}{\mathrm{d}p_{\mathrm{T}}\mathrm{d}y}}$$

Muller, Harris arixiv:2308.05743

$$R_{\mathrm{AA}} = \frac{\text{Pb-Pb}}{\text{scaled}\otimes\text{pp}}$$

< 1 is suppression



ALICE PRC **101**, 034911

STAR PRC 102 (2020) 054913

ATLAS PLB 790 (2019) 108

Jet production is suppressed in the QGP over two orders of magnitude in jet momentum!

Energy loss dependence on parton flavor

Flavor and mass dependence

E_{loss} > E_{loss} > E_{loss}^{HQ}

Gluon — Light quark — Heavy quark

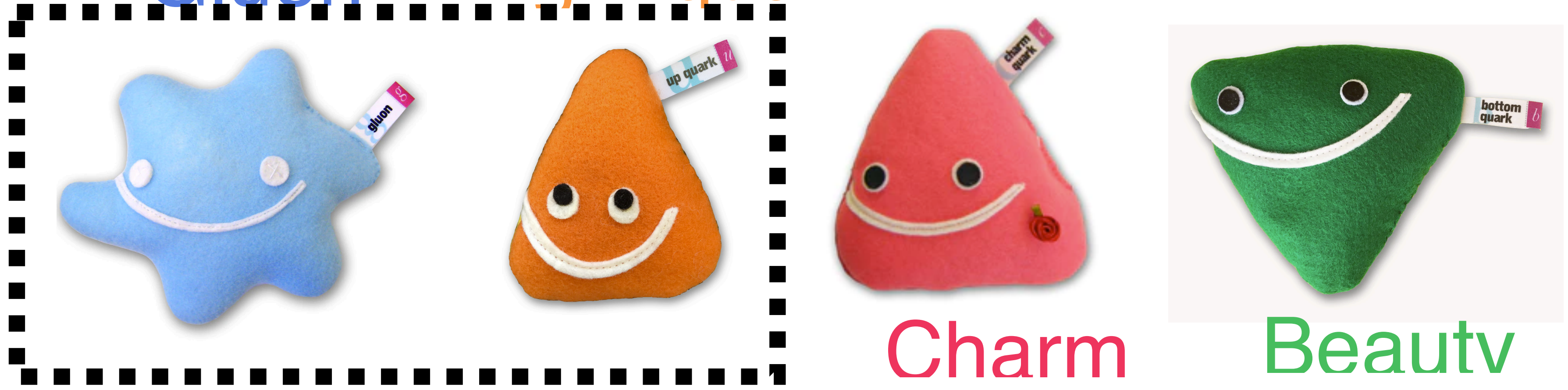
Charm — Beauty

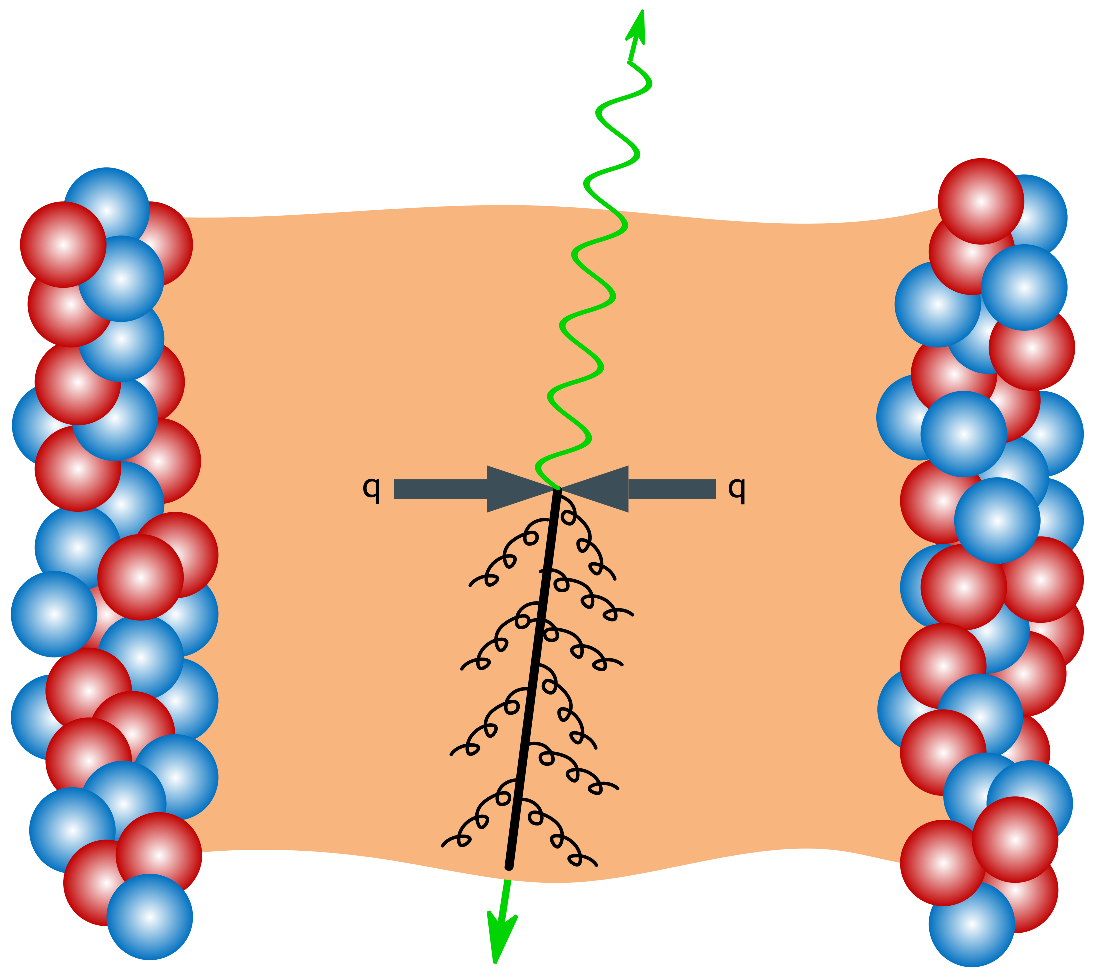
Energy loss dependence on parton flavor

Flavor and mass dependence

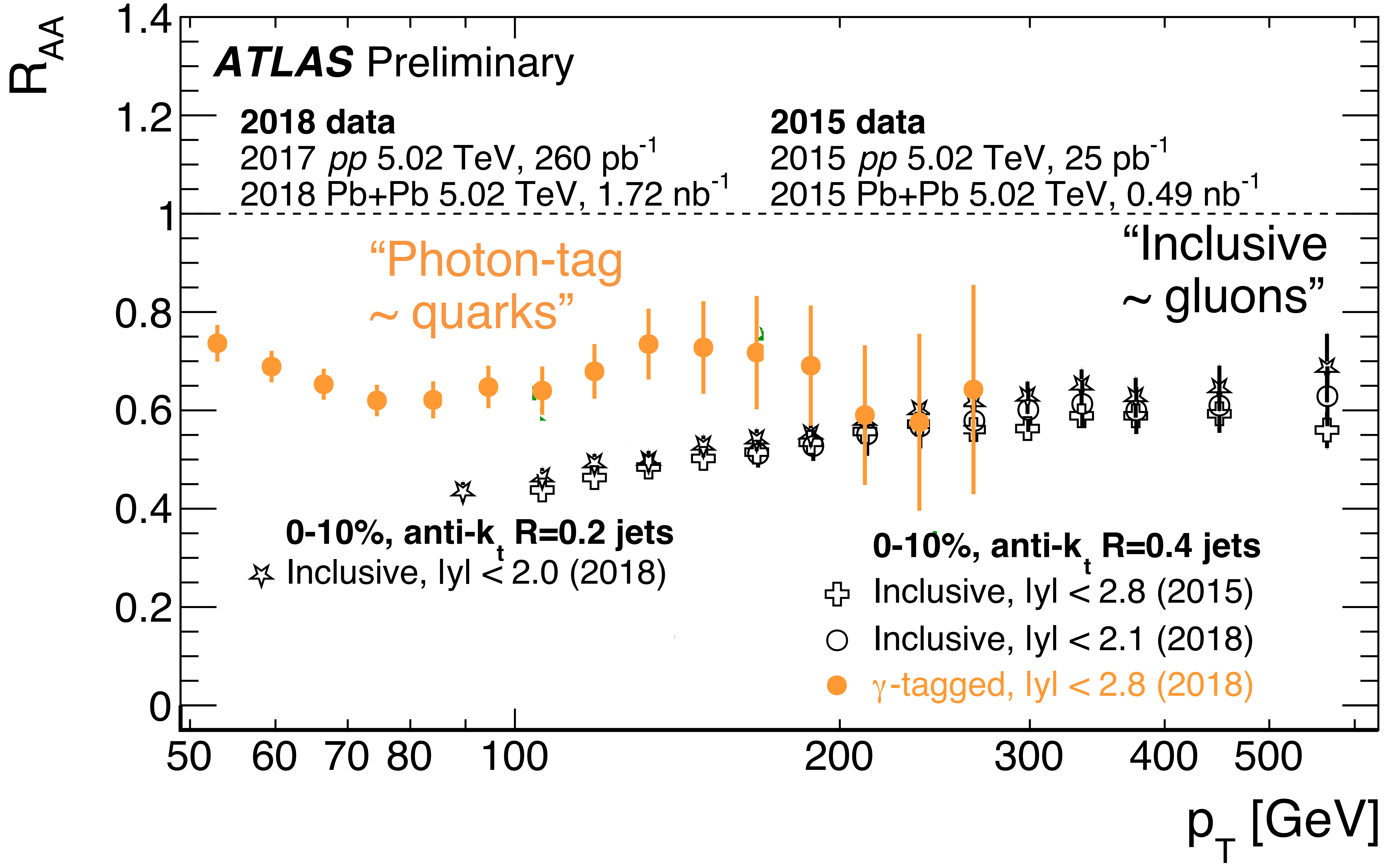
E_{loss} > E_{loss} > E_{loss}^{HQ}

Gluon Light quark Heavy quark





Caveat: "spectra steepness" plays a role!



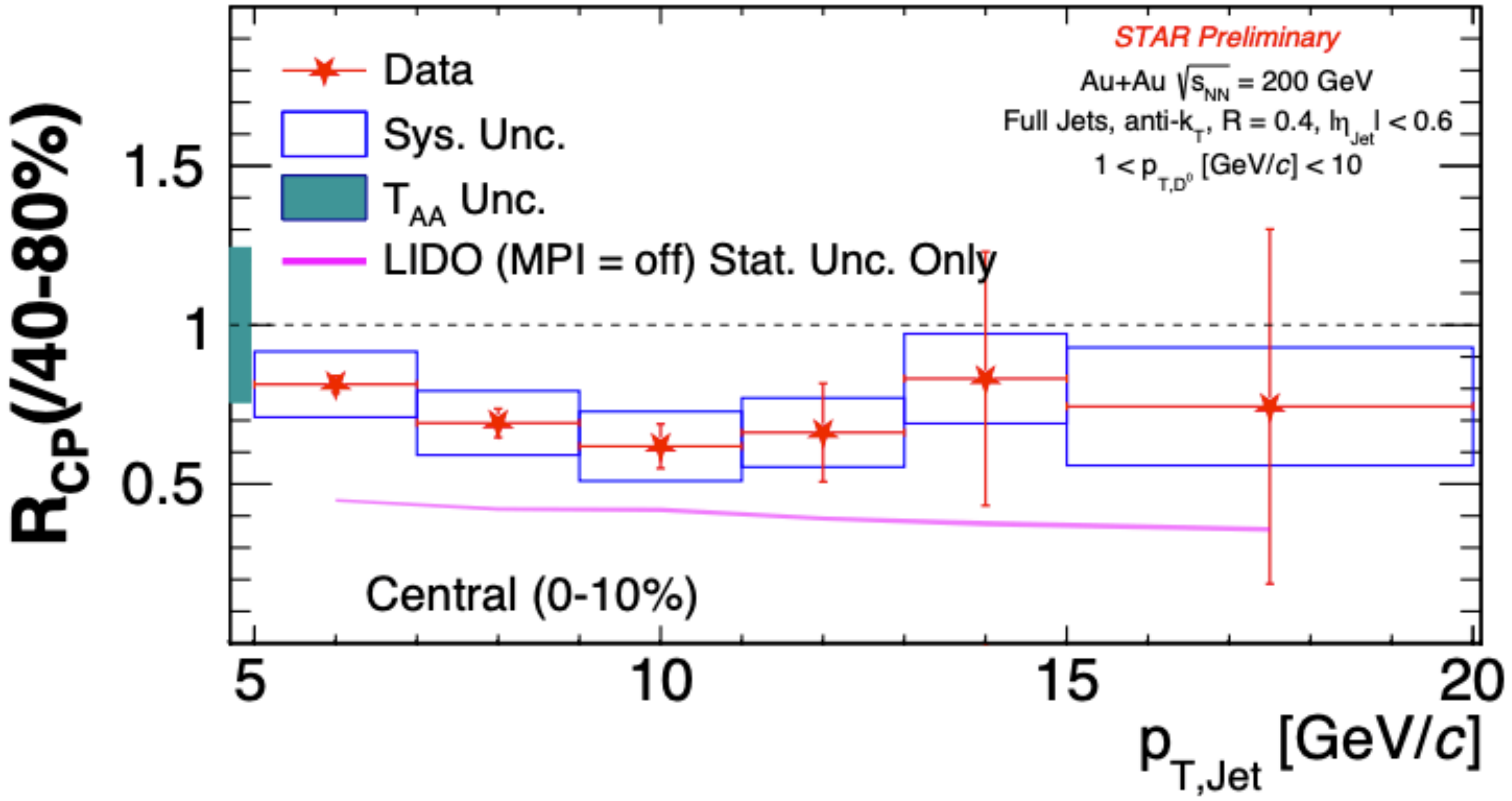
Energy loss depends on color charge

Energy loss dependence on parton flavor

Flavor and mass dependence

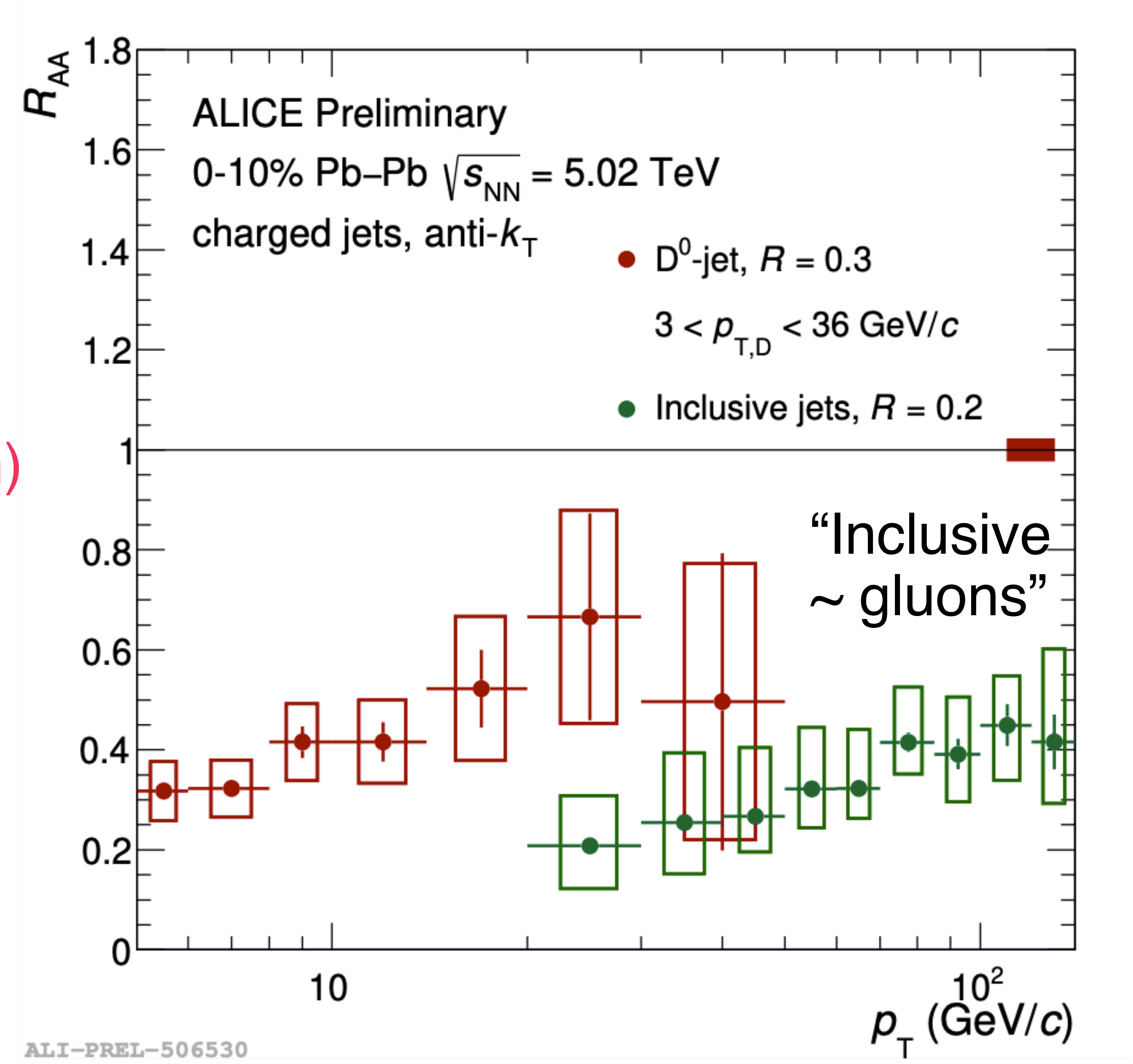
E_{loss} > E_{loss} > E_{loss}^{HQ}

Gluon Light quark Heavy quark



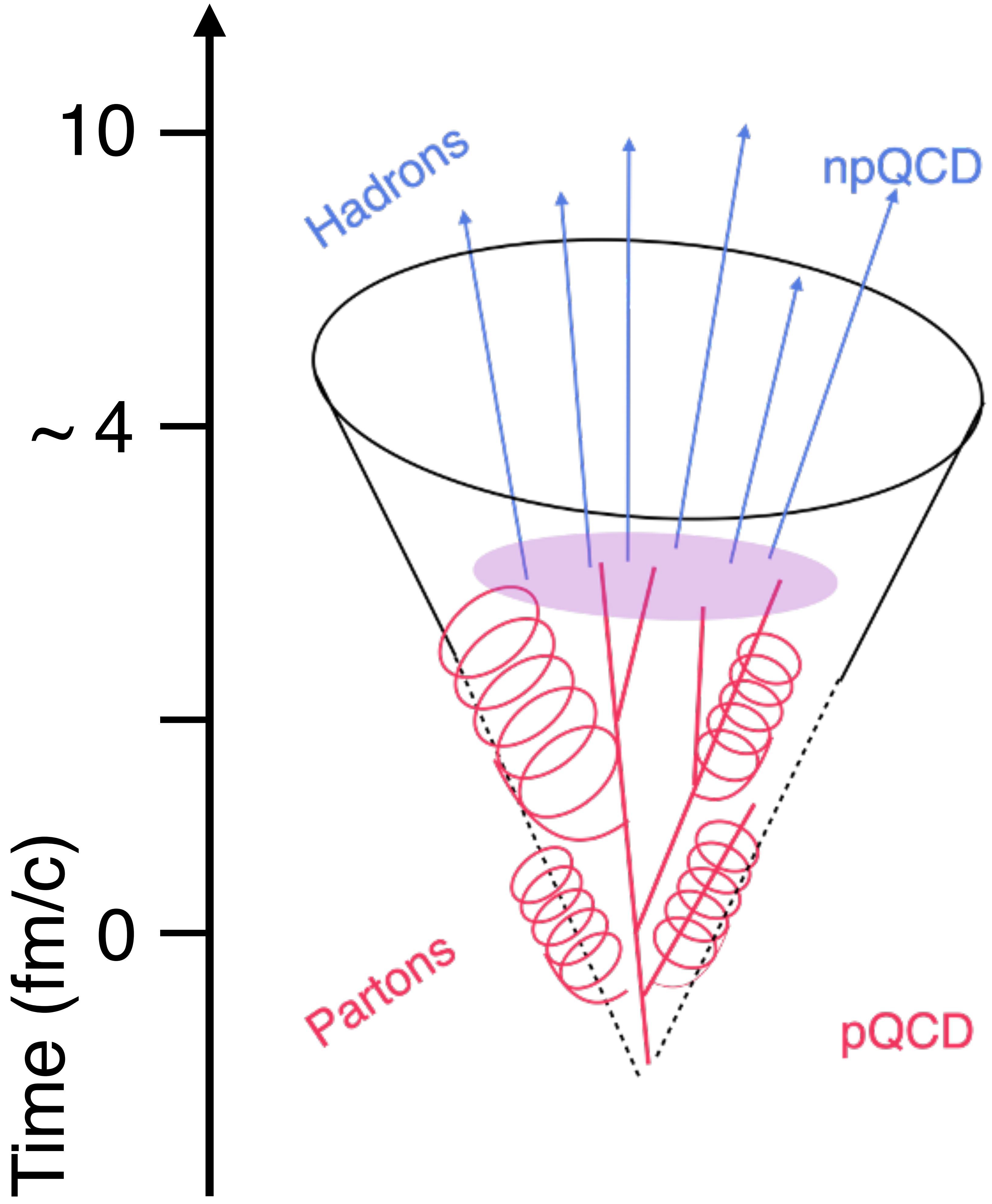
Caveat: "spectra steepness" plays a role!

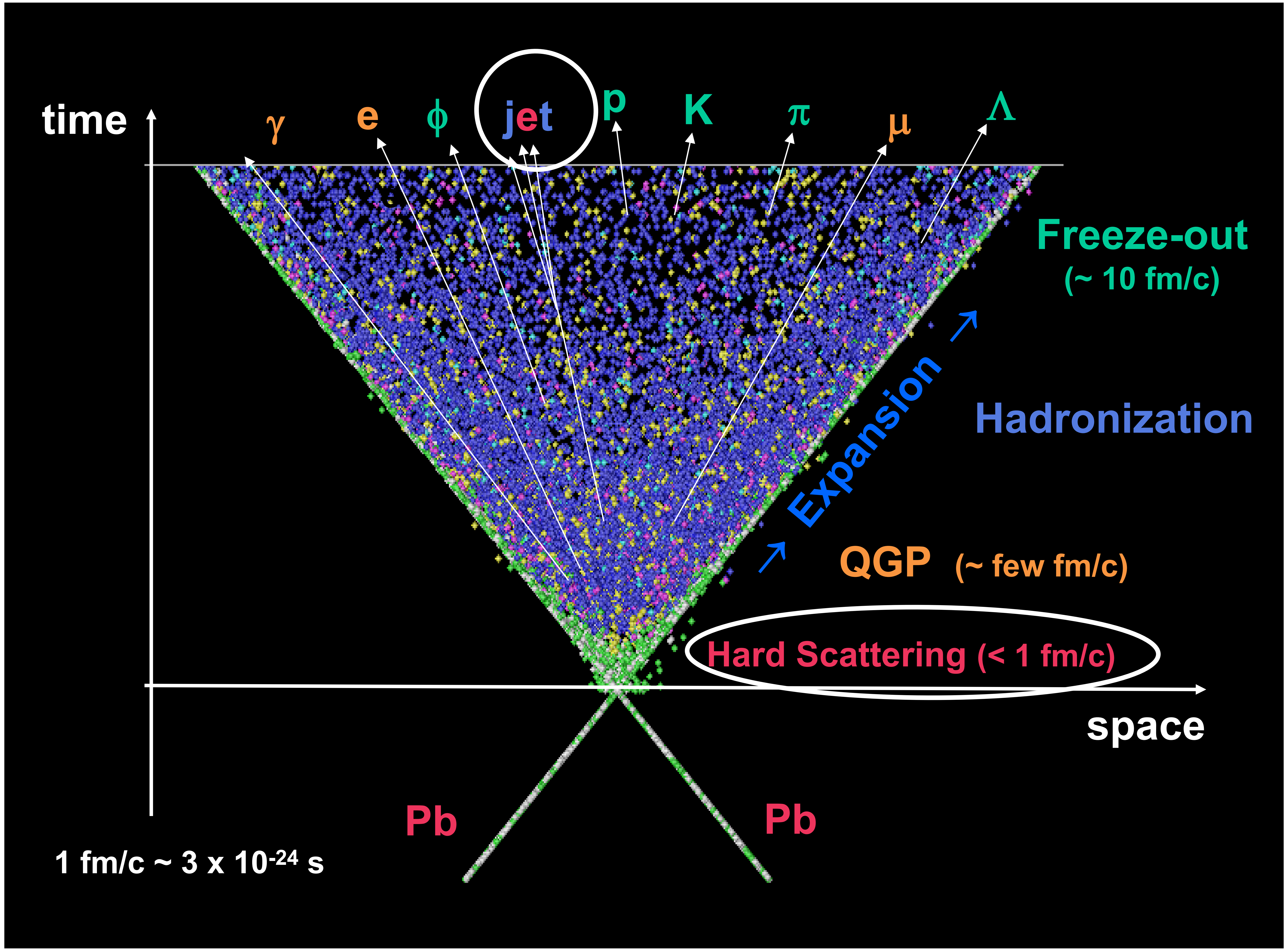
D0-tagged jets (charm)



Energy loss depends on color charge (and mass of parton?)

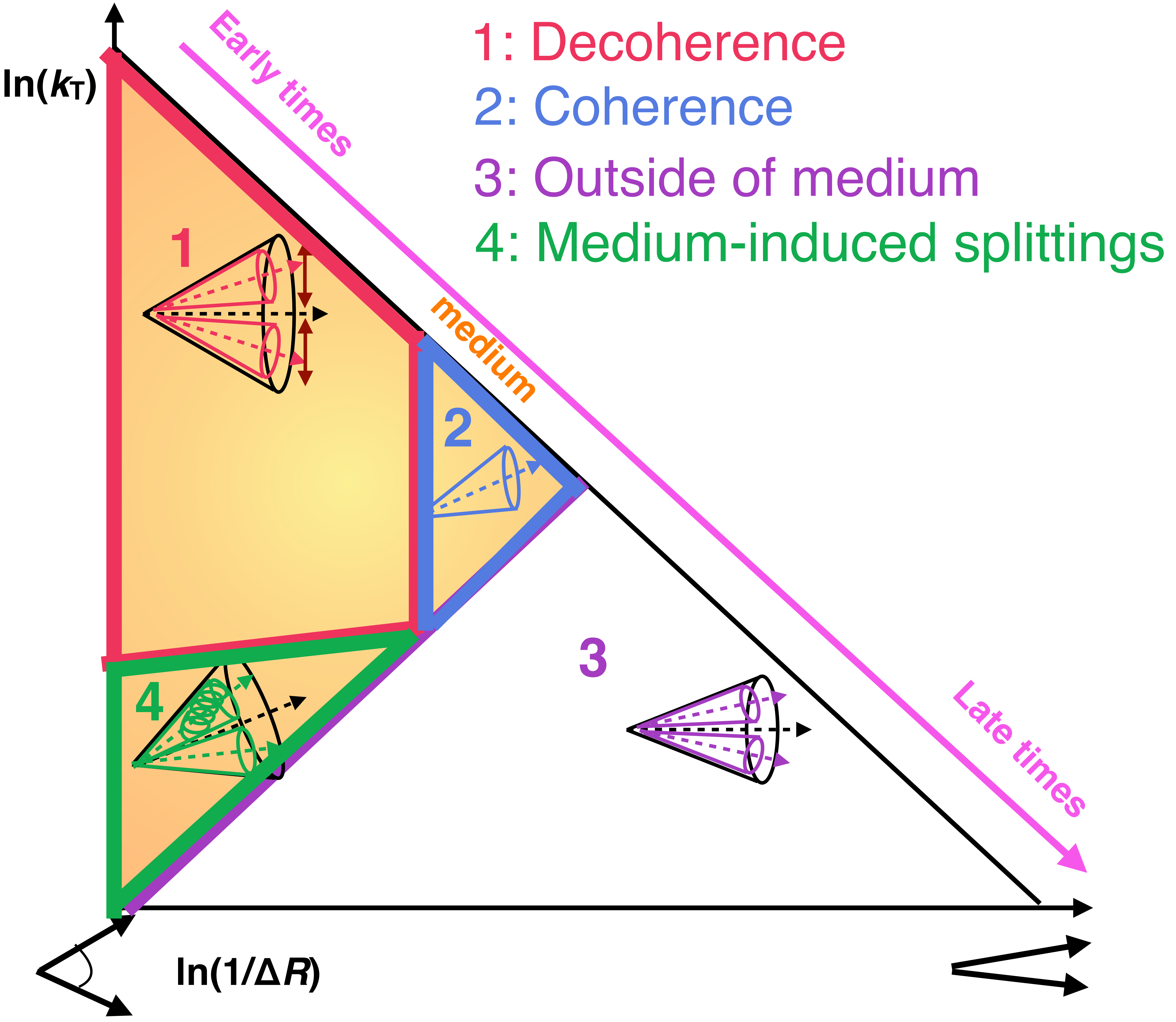
Jet and medium evolving in space and time

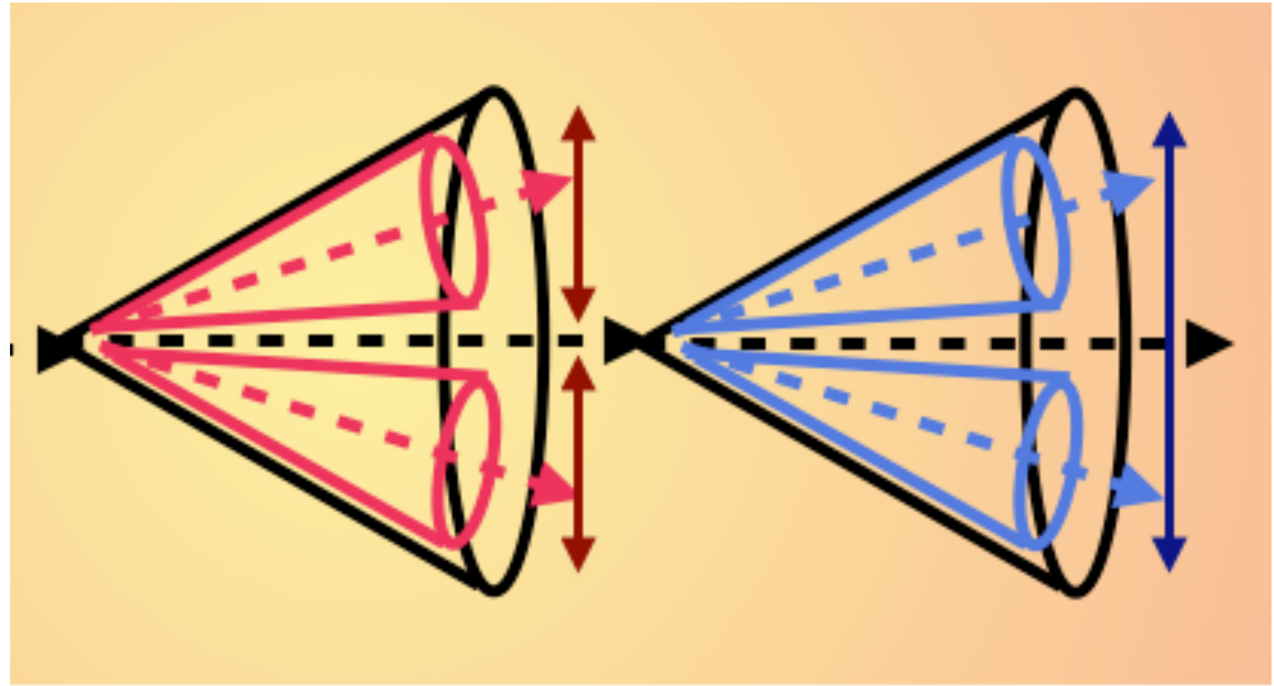


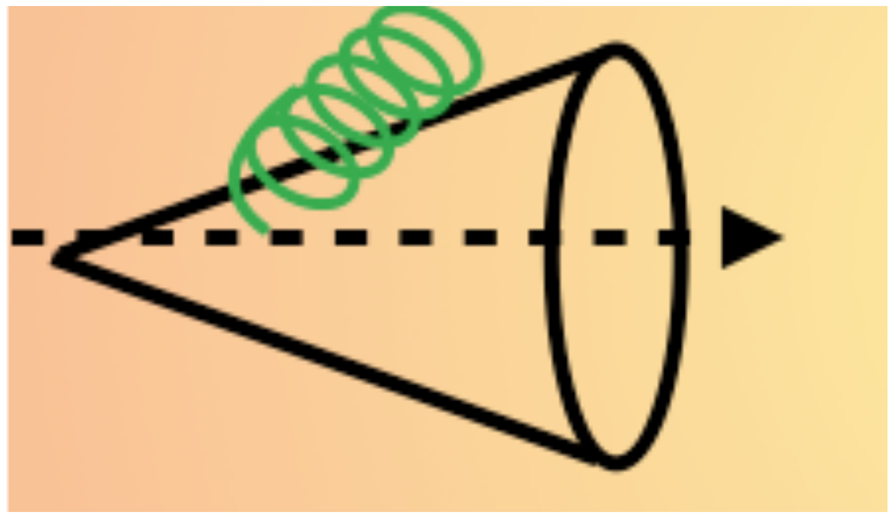


Complex, dynamic structure accesses a more detailed picture

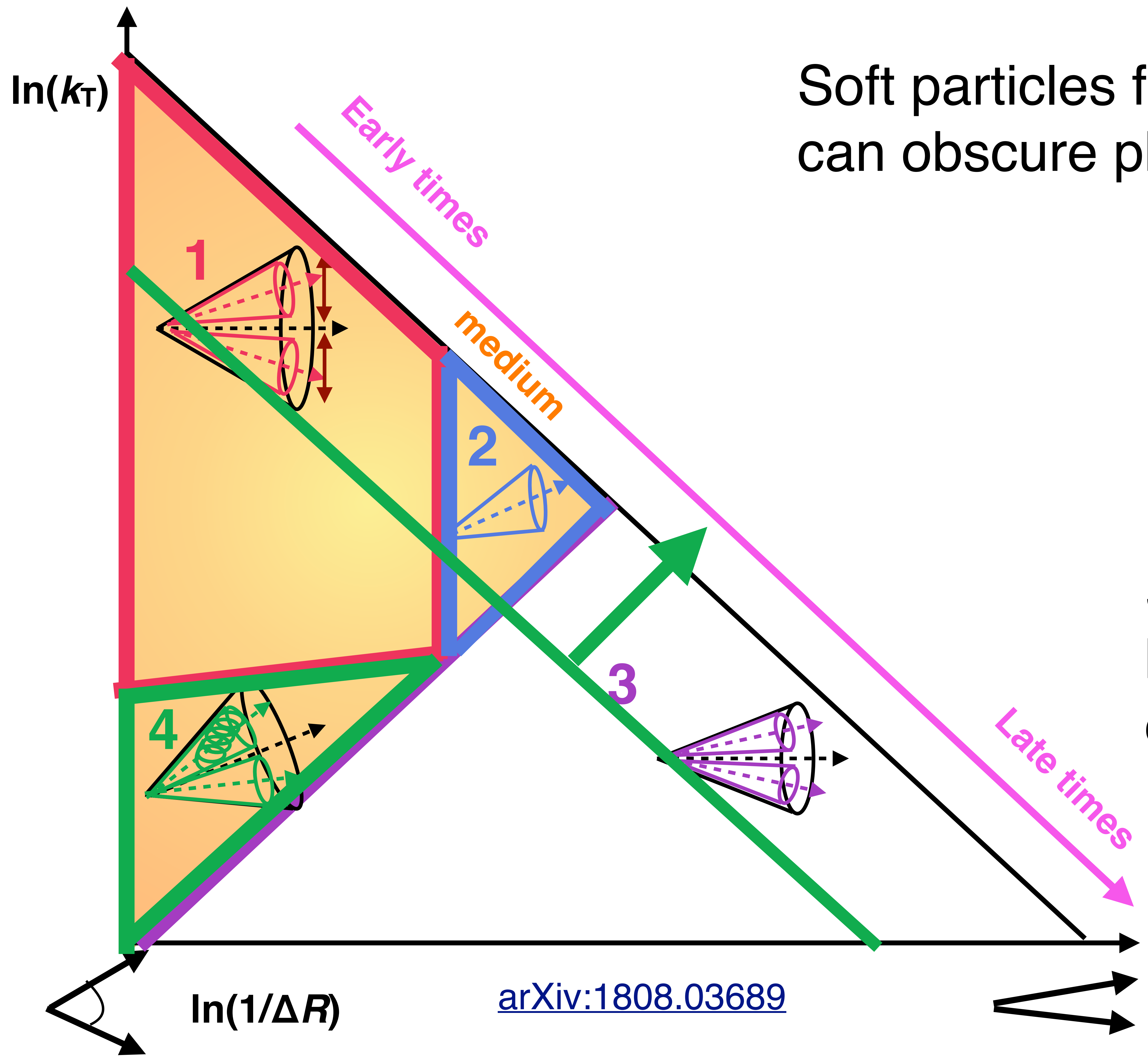
Lund plane: space-time structure of QGP





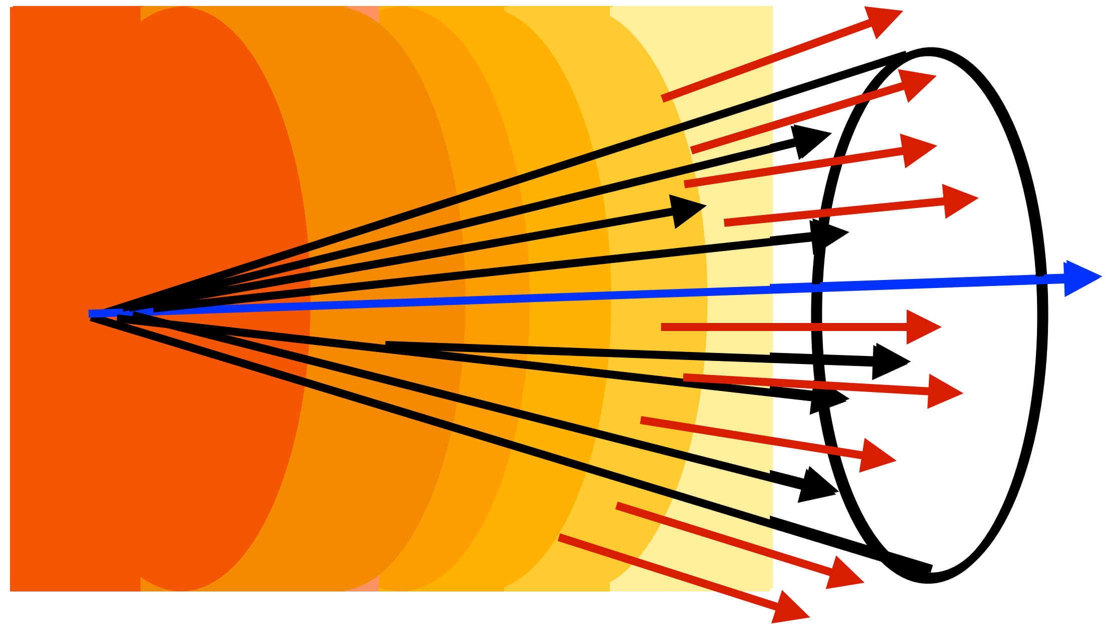


Focus on modification of jet core



arXiv:1808.03689

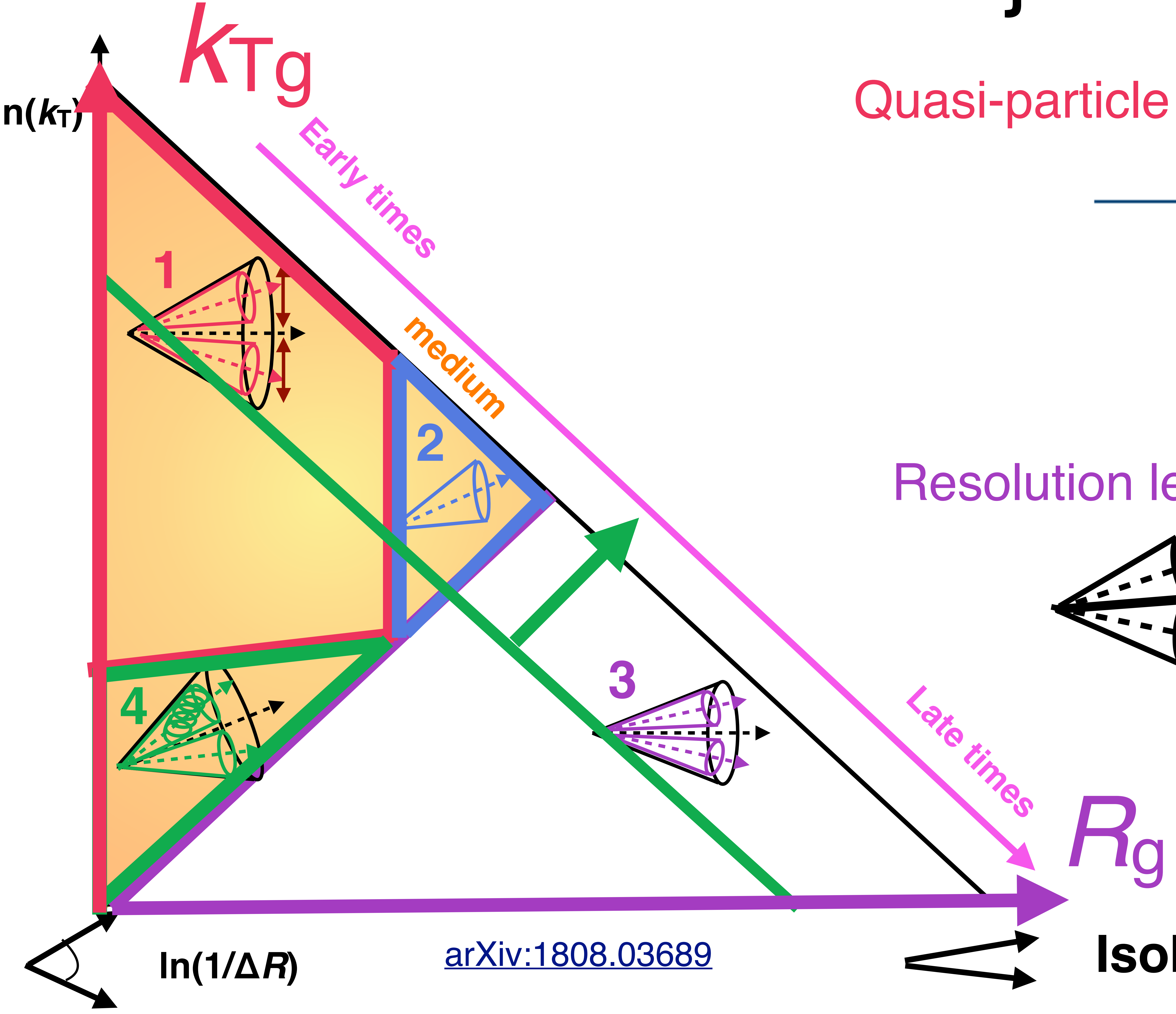
Soft particles from background and medium response can obscure physics message



Solution: Apply grooming to suppress background and remove softer components to focus on hard splittings

Caveat: may remove physics

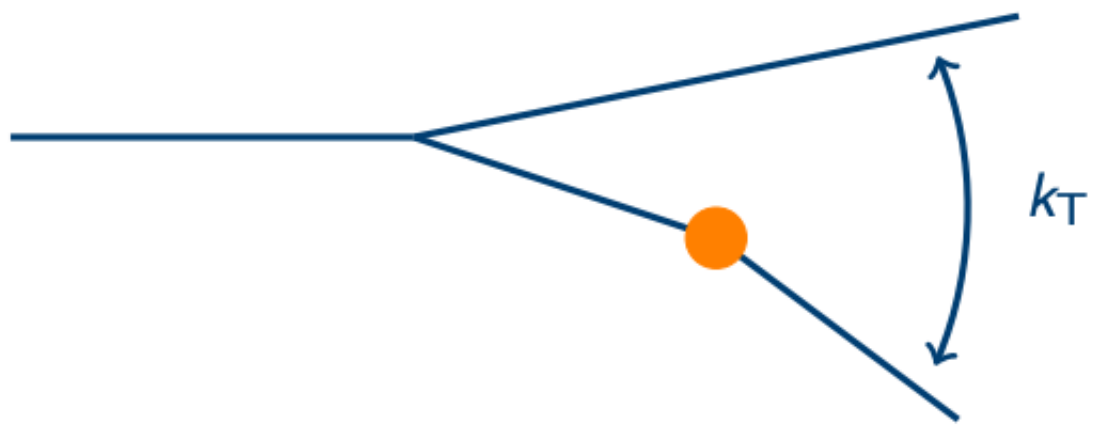
Focus on modification of jet core



arXiv:1808.03689

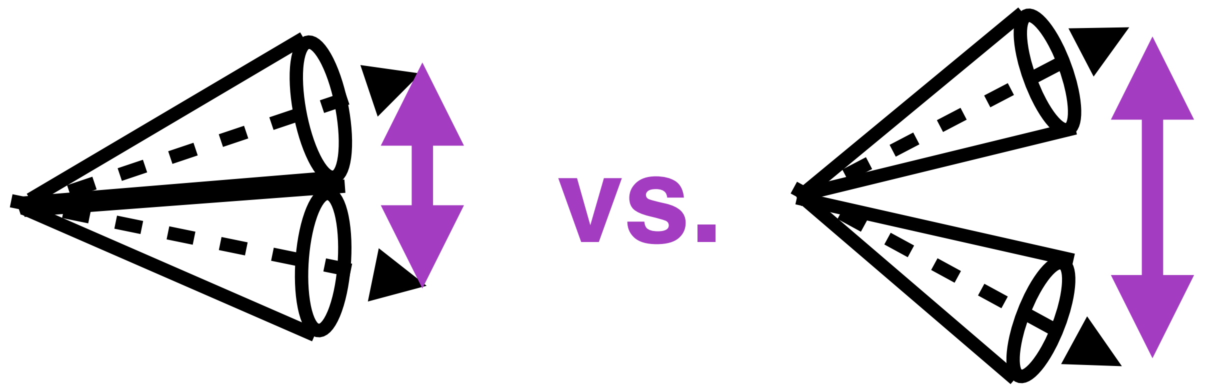
Quasi-particle structure?

$k_{Tg} \sim z_g p_T R_g$



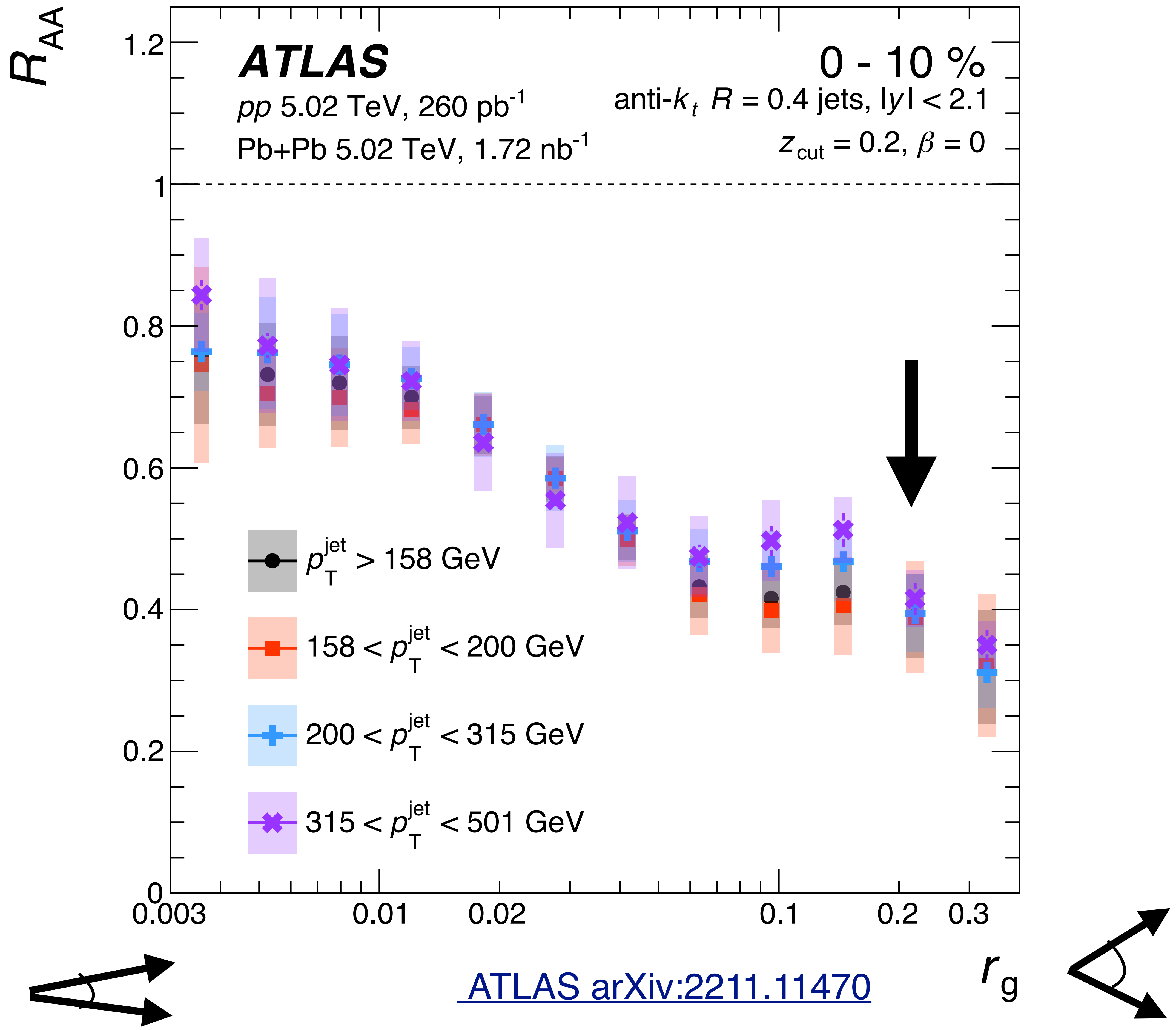
Resolution length?

$$R_g = \sqrt{\Delta\eta^2 + \Delta\phi^2}$$

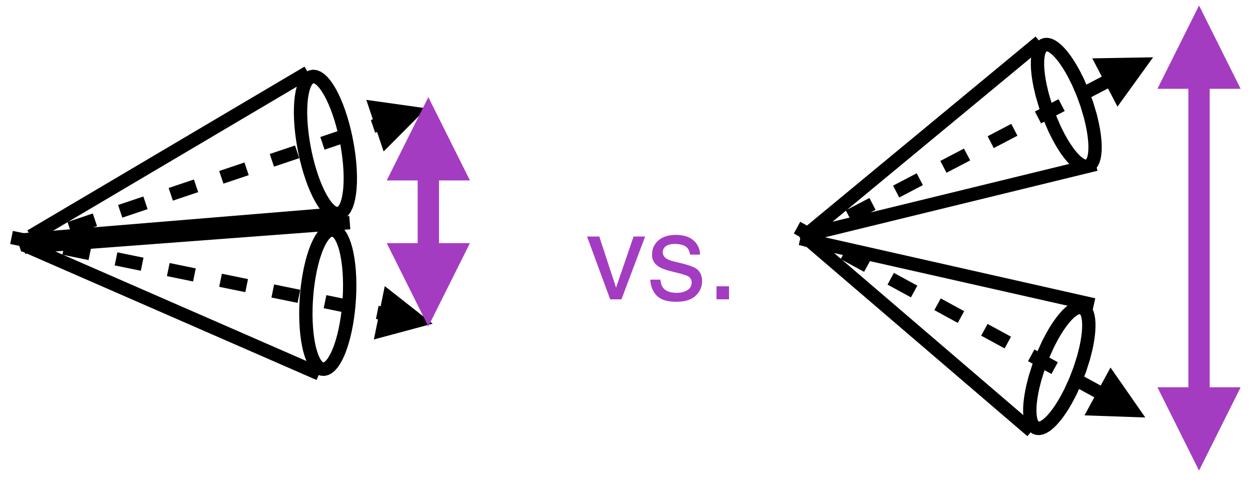


Isolate different jet-medium effects

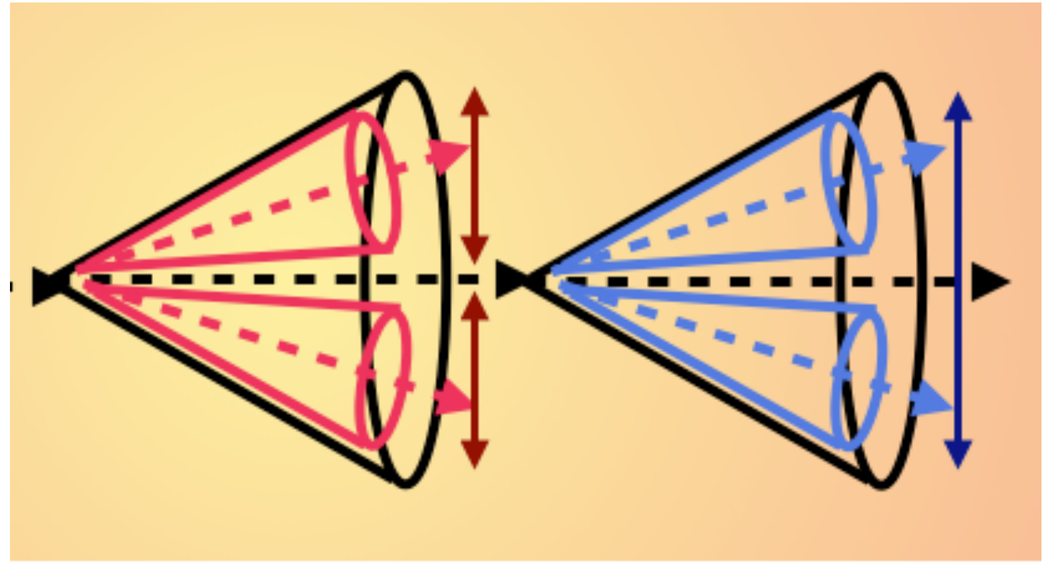
Splitting angular scale probes color coherence



ATLAS arXiv:2211.11470

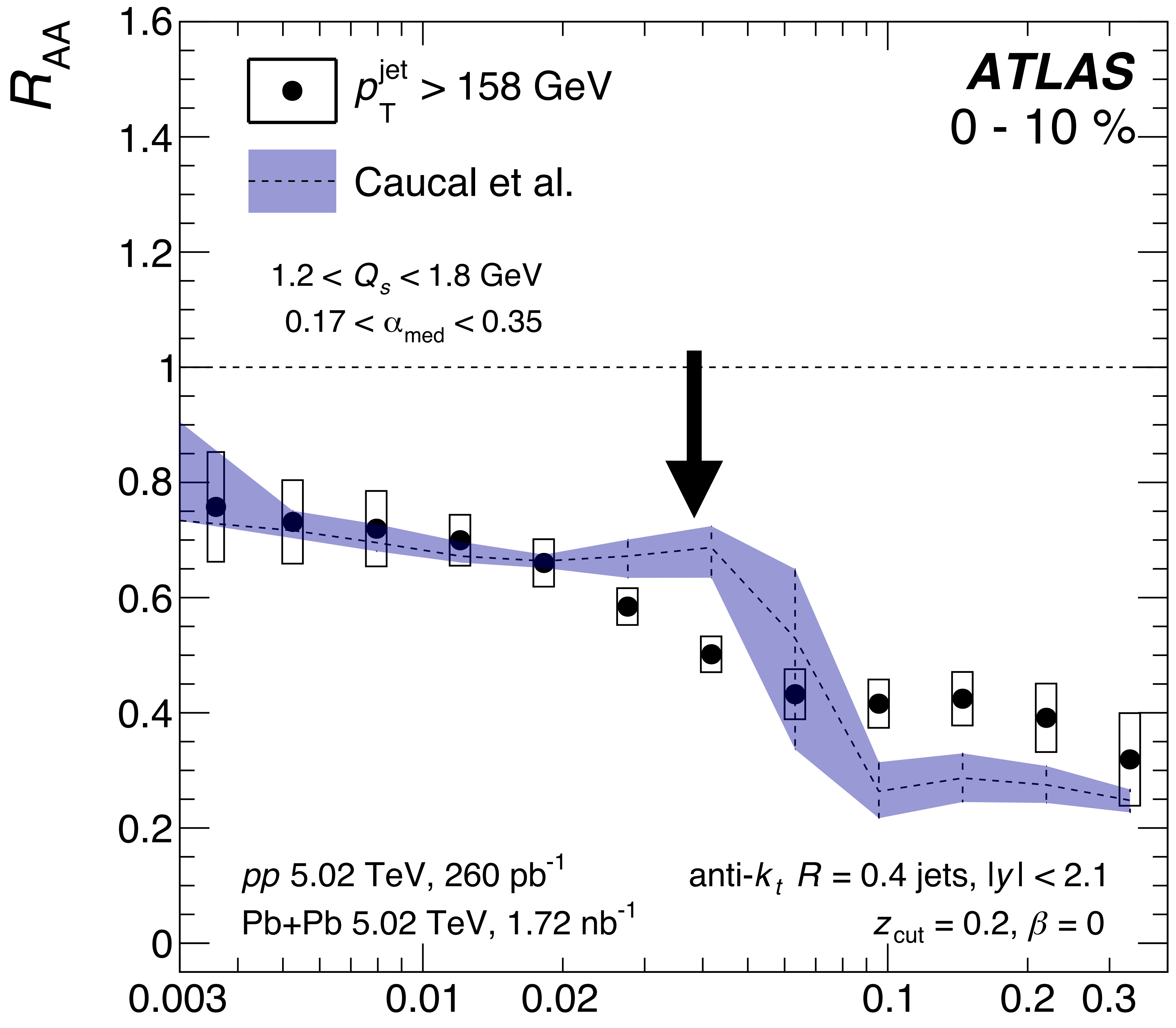


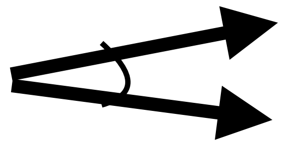
Resolution length of QGP?



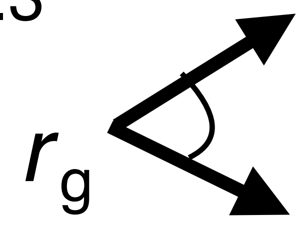
Narrowing feature observed that is consistent across jet p_T

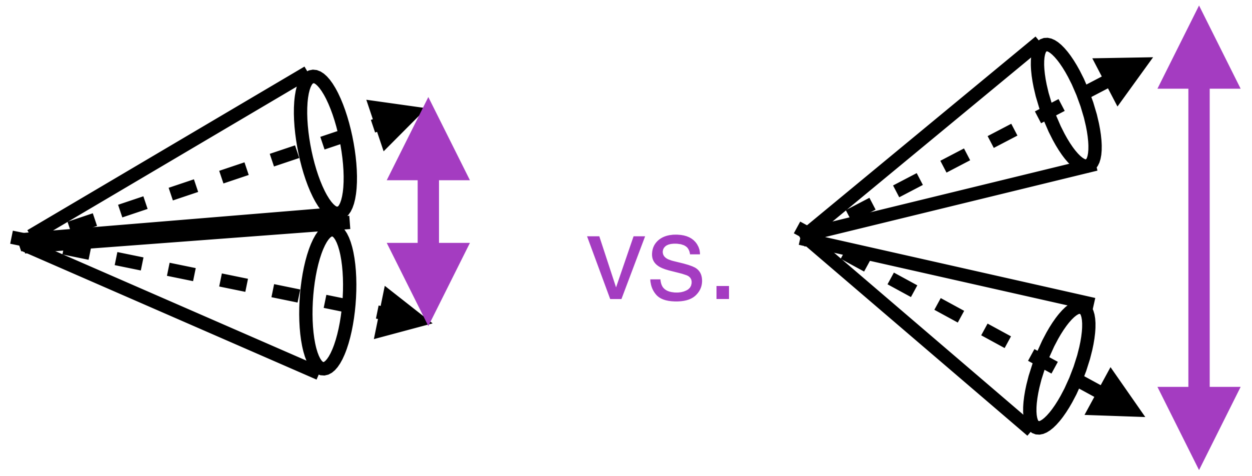
Splitting angular scale probes color coherence



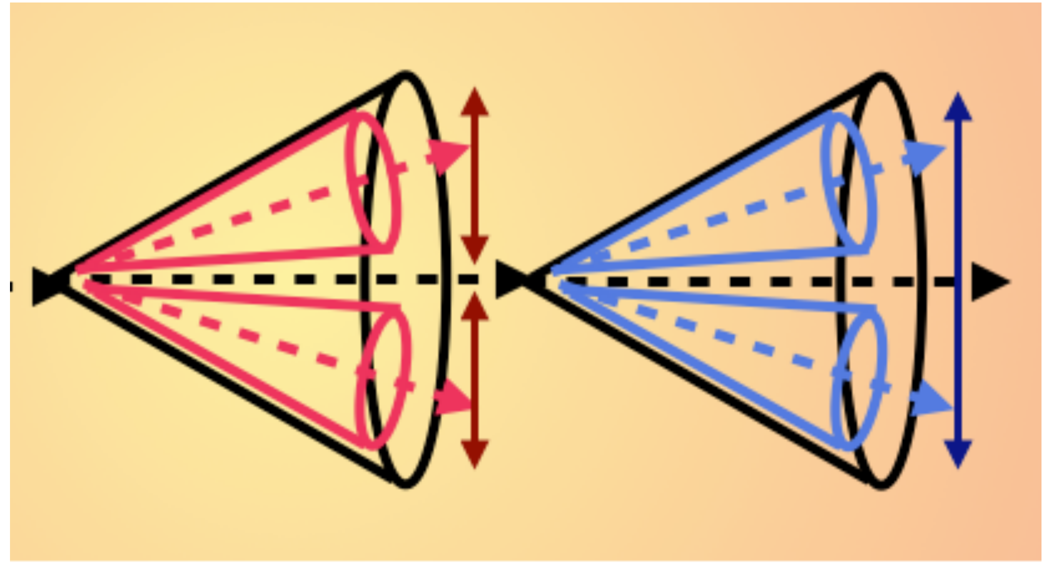


ATLAS arXiv:2211.11470



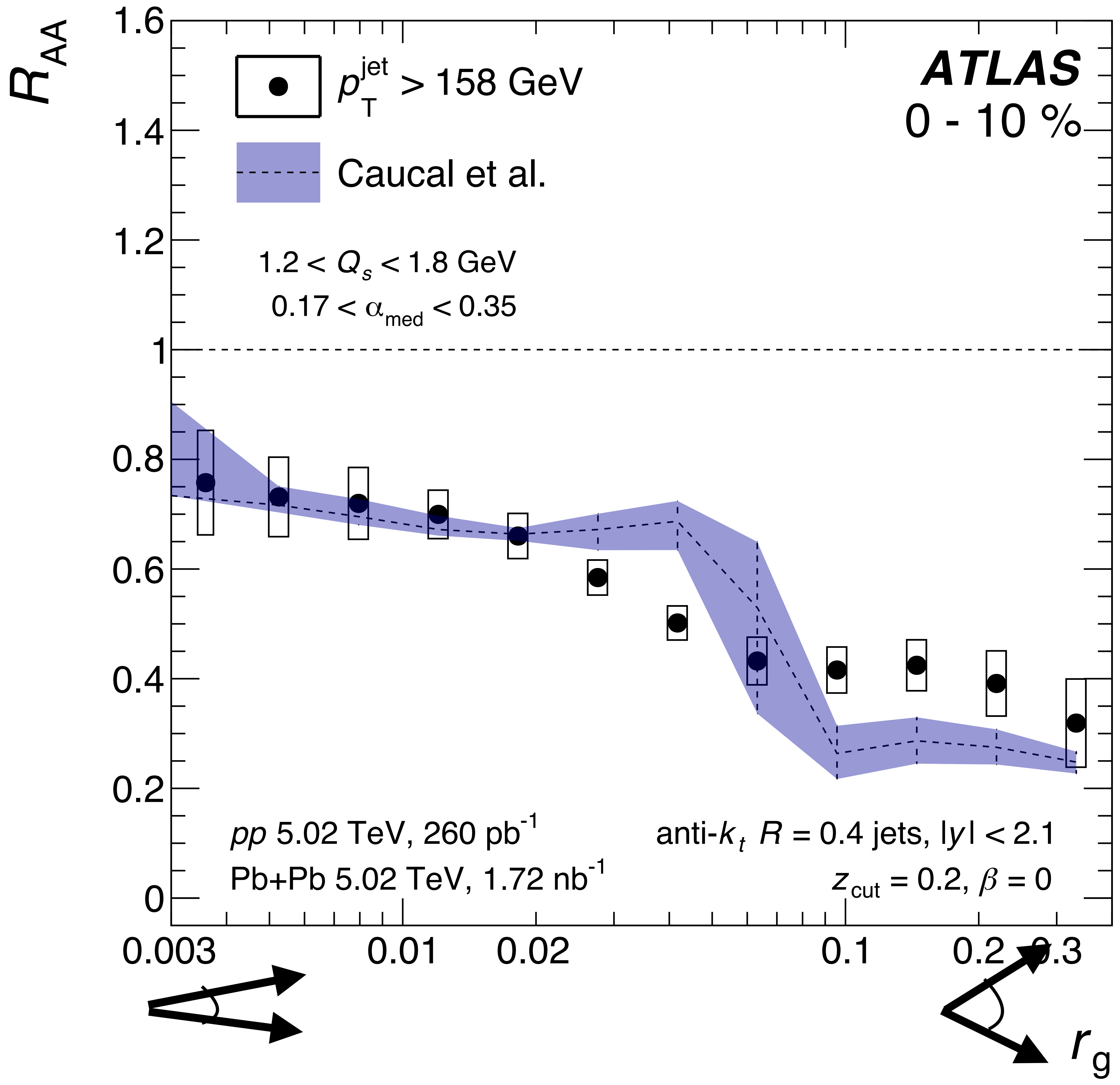


Resolution length of QGP?

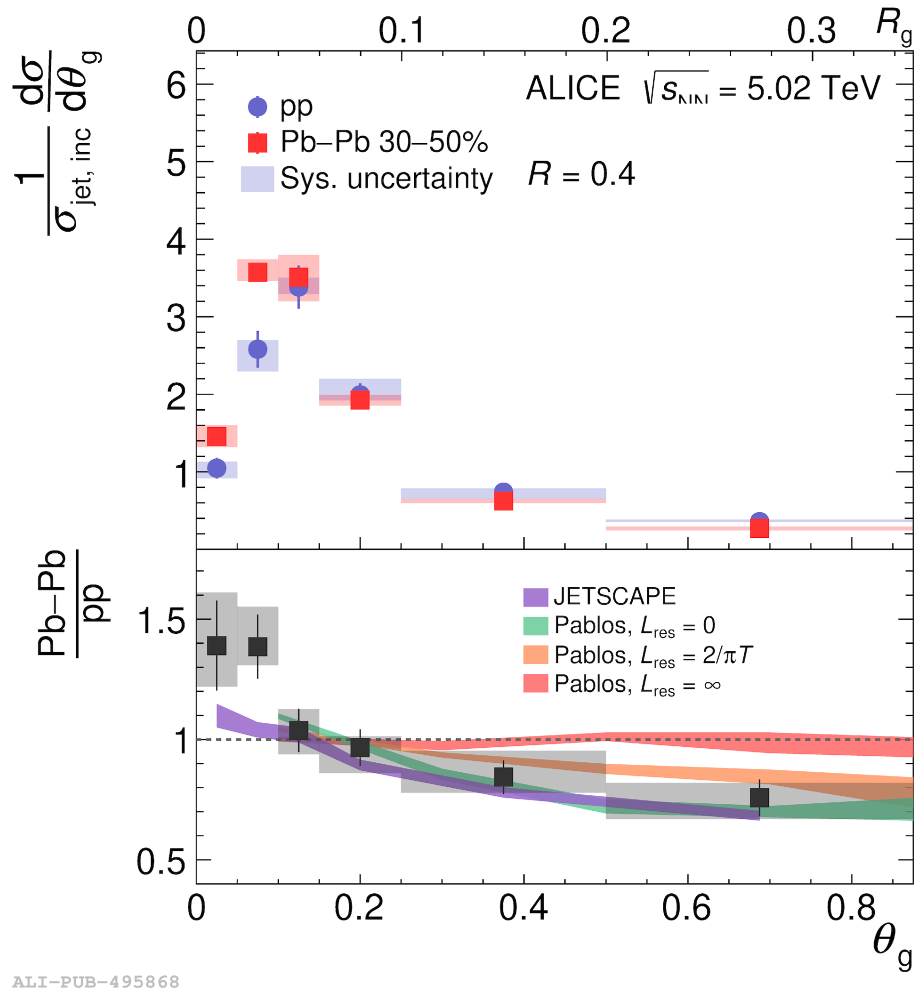


Narrowing is consistent with color decoherence models but is also described by quarks vs. gluons

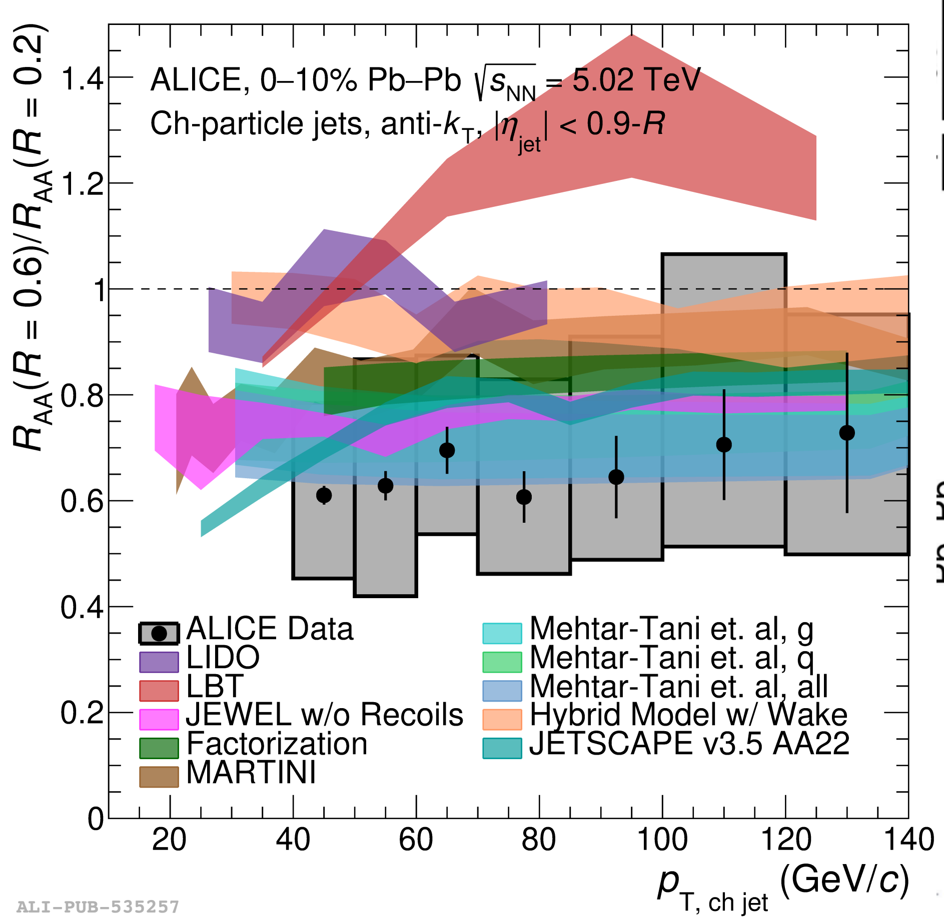
Narrowing picture is persistent



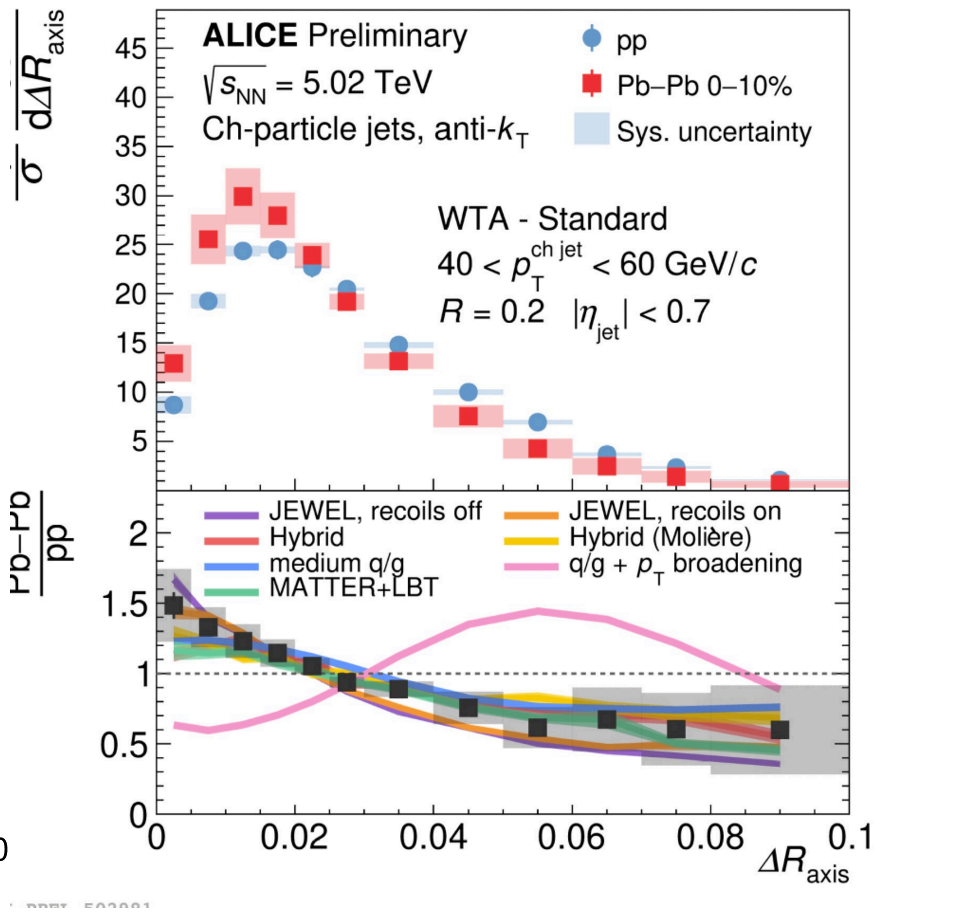
ATLAS arXiv:2211.11470

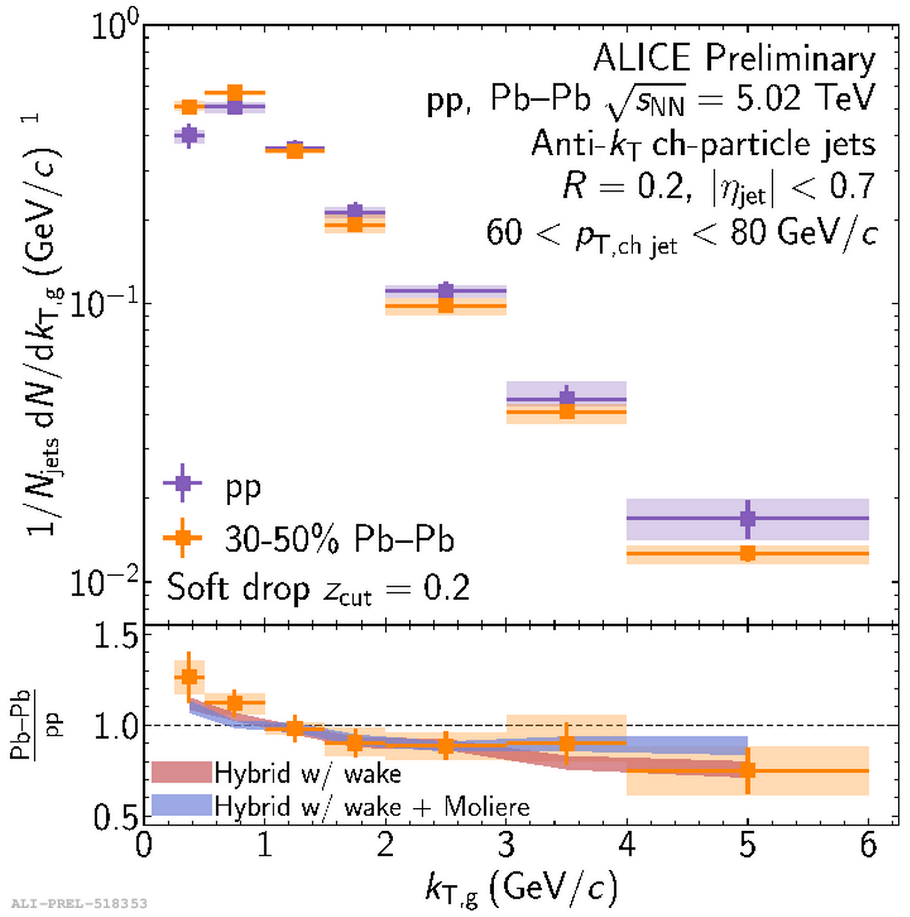


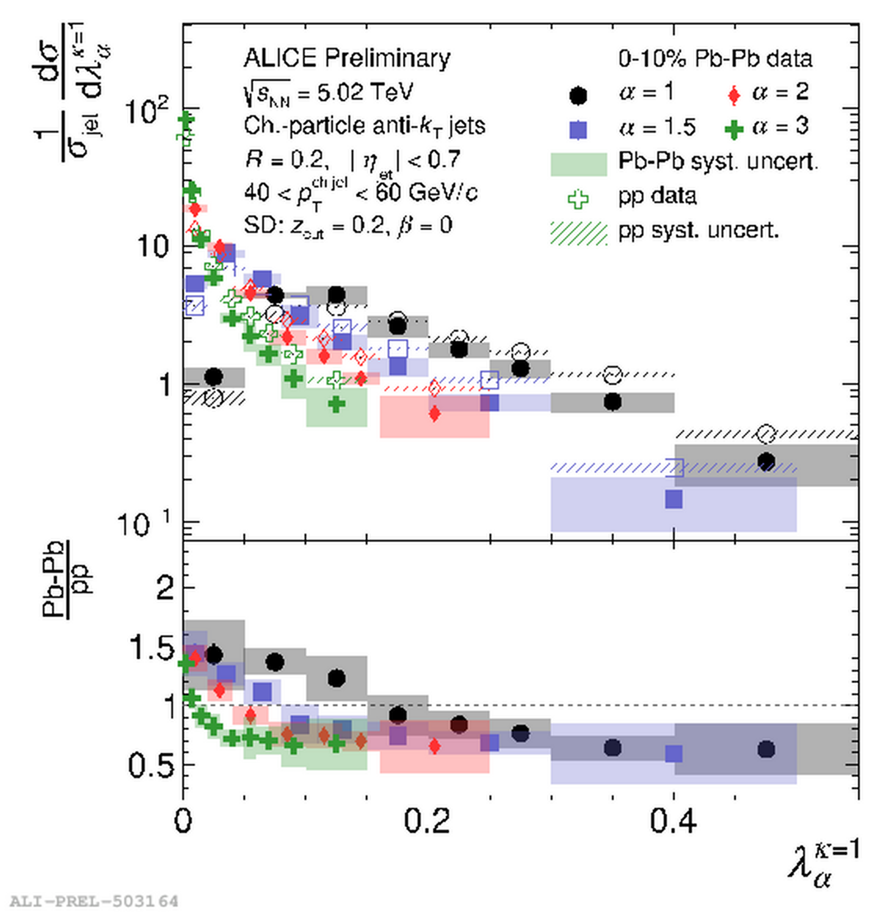
ALICE, PRL 128 (**2022**)

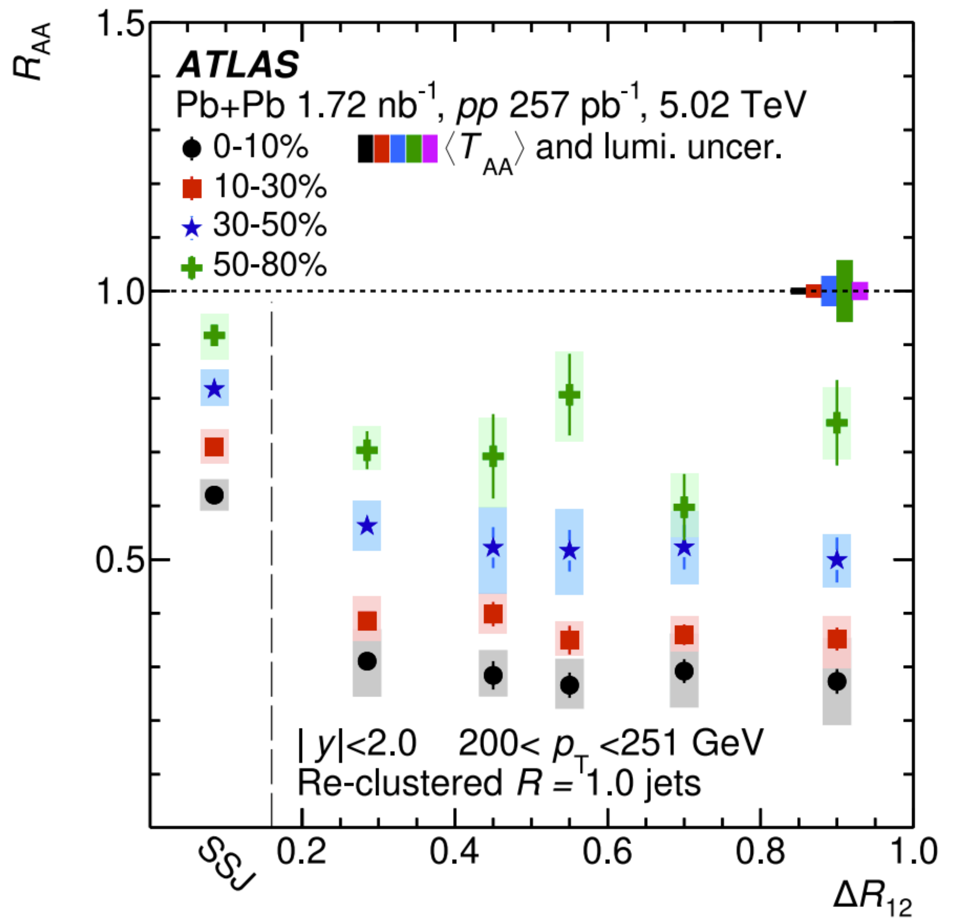


ALICE arXiv:2303.00592









ATLAS arXiv:2301.25606

Many substructure measurements show narrowing in QGP

Narrowing?

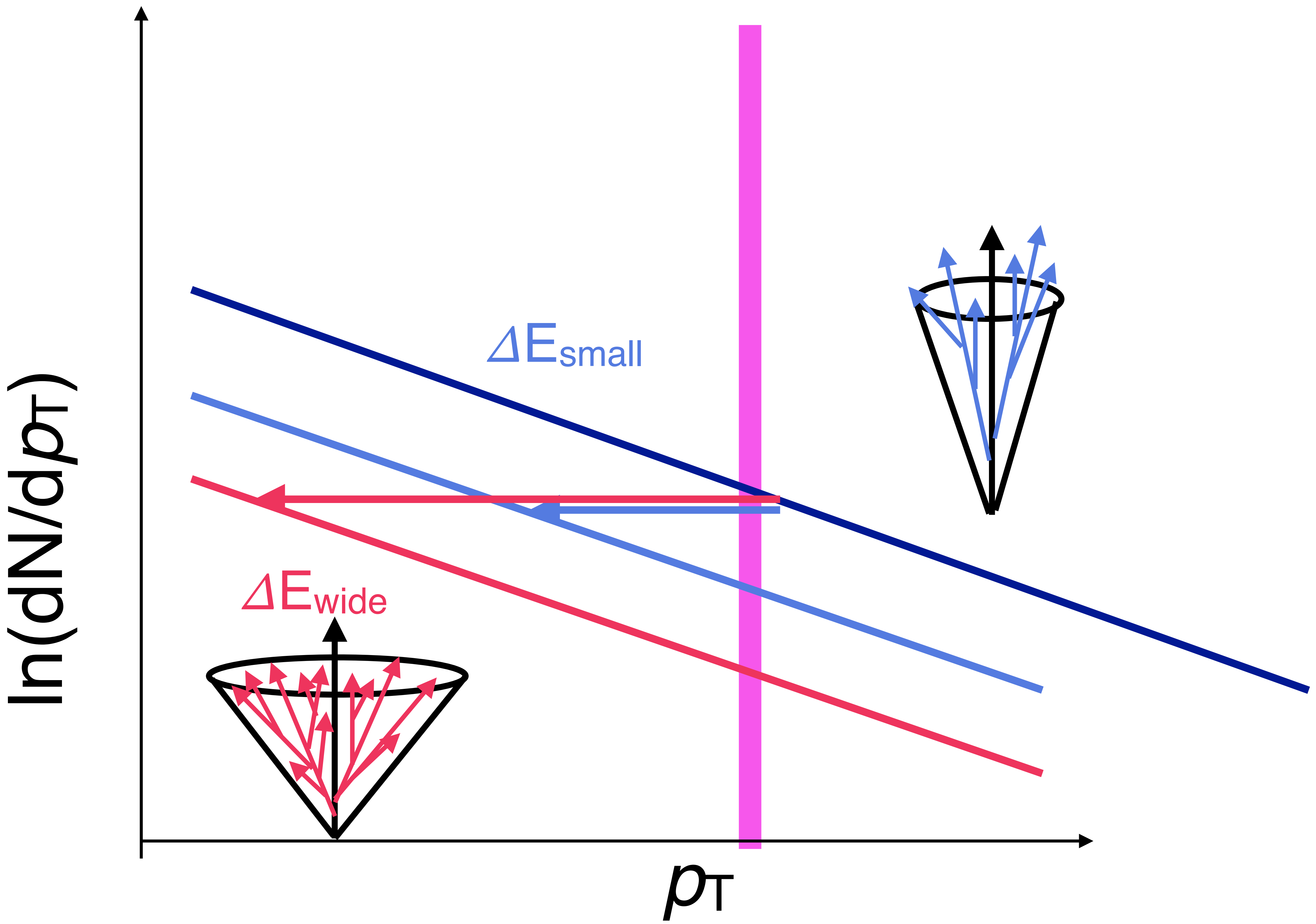
Always measuring less quenched jets that have survived the QGP -> **selection bias**

Comparing modified Pb-Pb vs. unmodified pp jet populations -> less quenched narrower jets remain

Du, Pablos, Tywoniuk, JHEP 21 (2020), 206

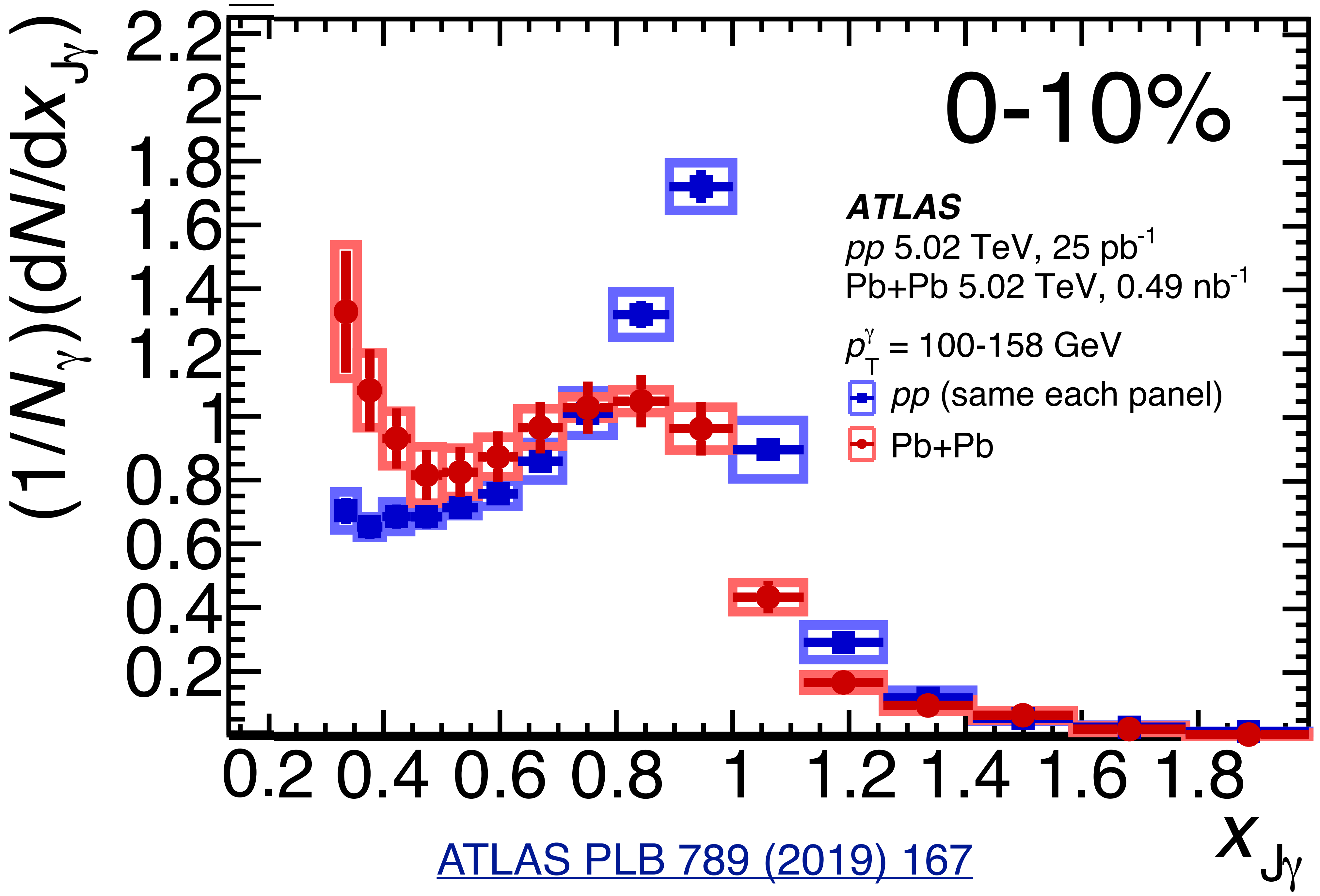
Brewer, et al PRL **122**, 222301

Brodsky et al arXiv:2009.03316

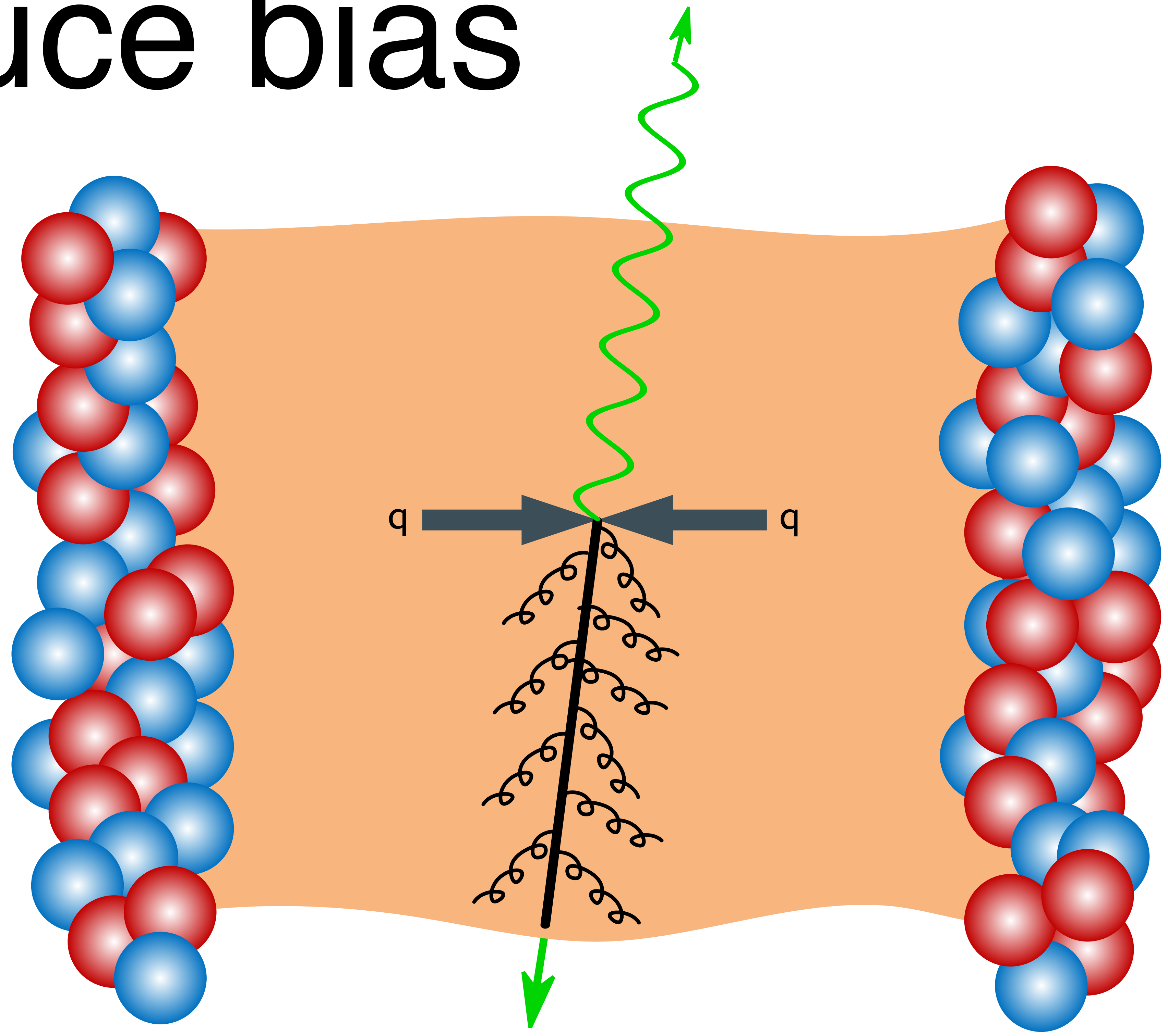


Photon+jet substructure to reduce bias

- Photon-jets dominated by quark jets
- Photon tag provides approximate initial momentum of jet (no energy loss)



ATLAS PLB 789 (2019) 167



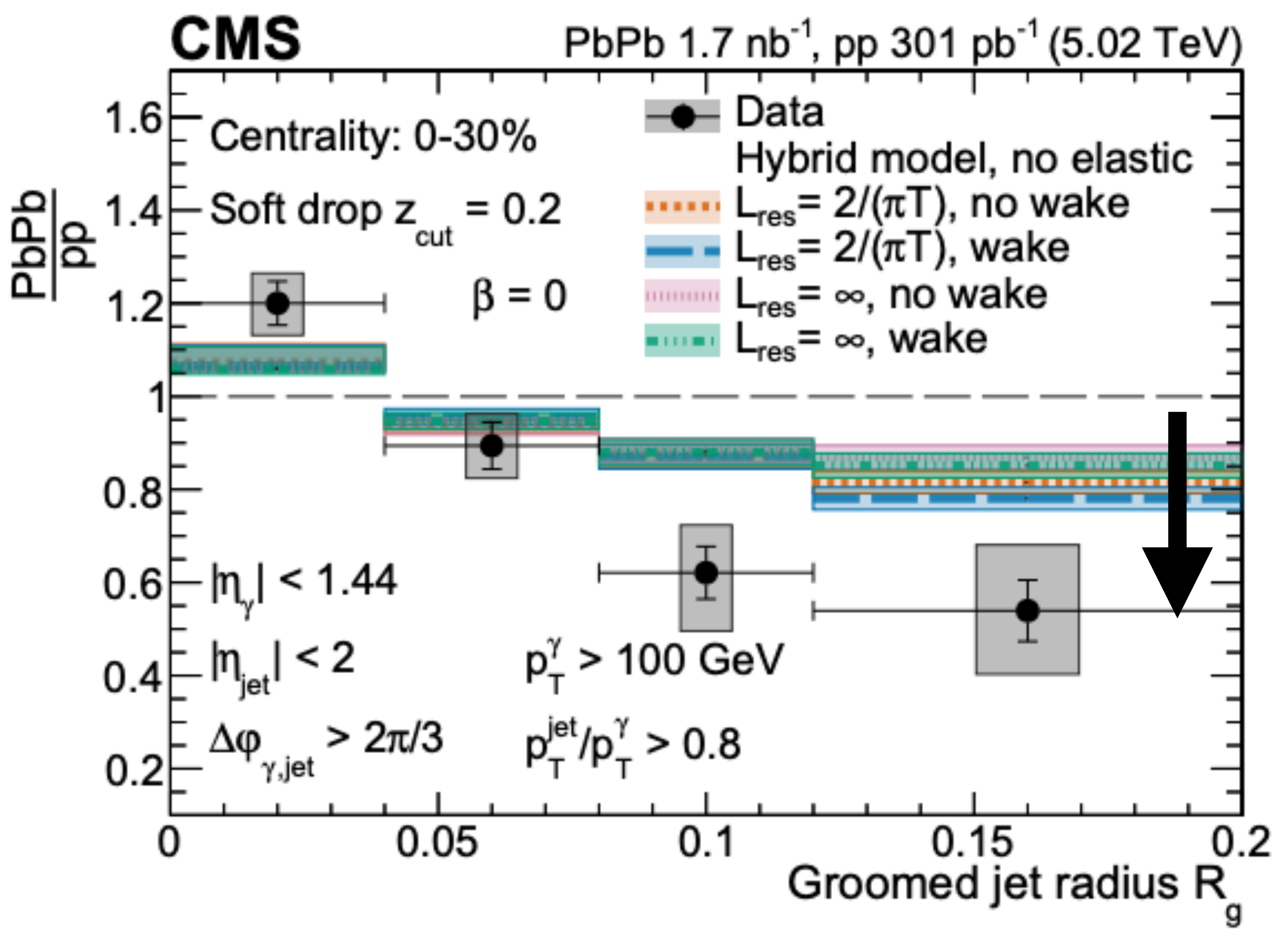
$$x_{J\gamma} = \frac{p_{\mathrm{T,jet}}}{p_{\mathrm{T}\gamma}}$$

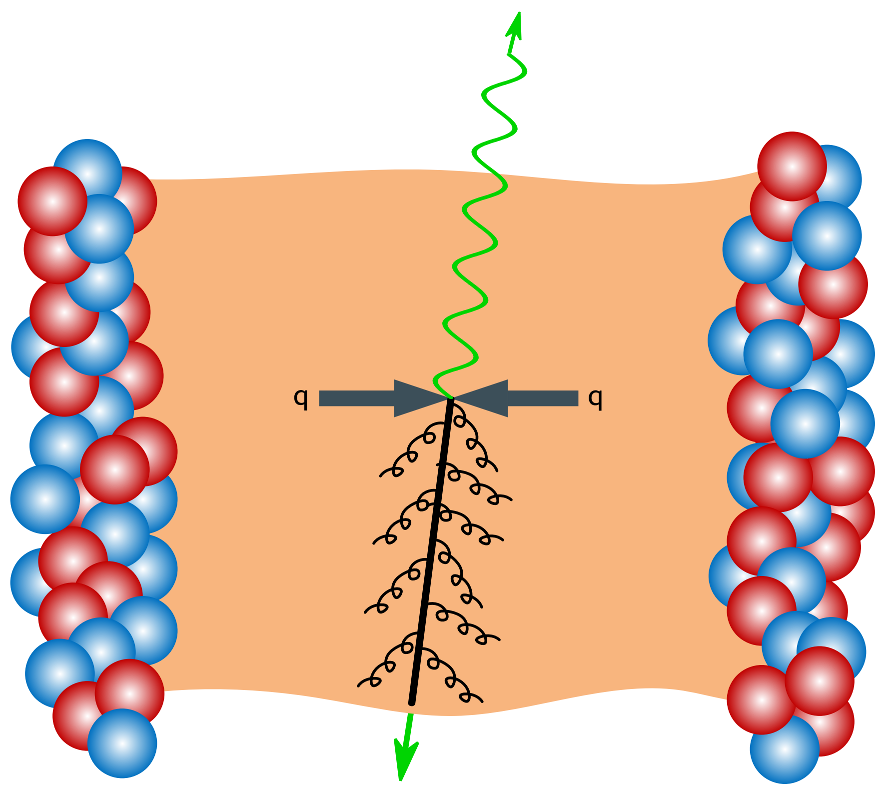
Photon+jet substructure to reduce bias

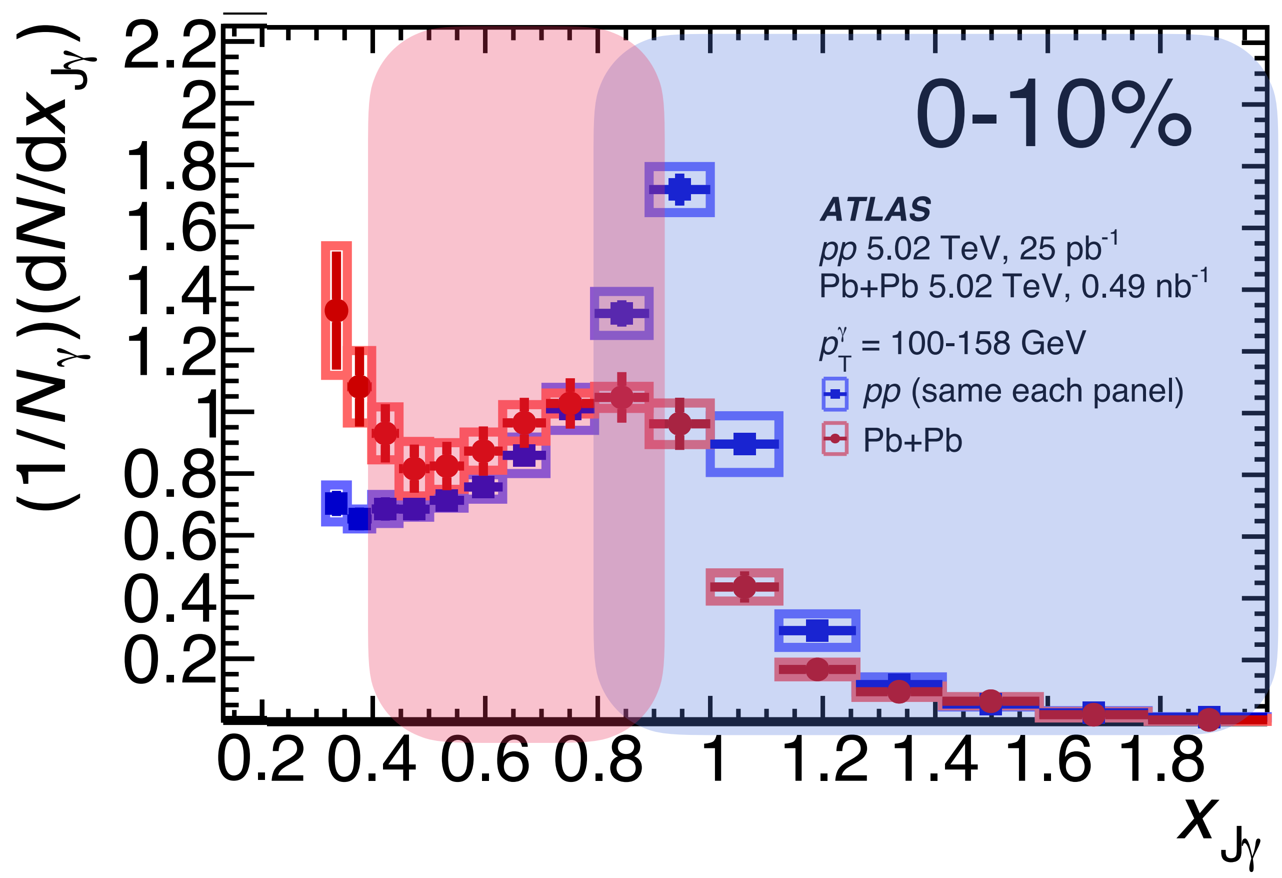
arXiv:2405.02737

Select balanced configurations

$$x_{J\gamma} > 0.8$$

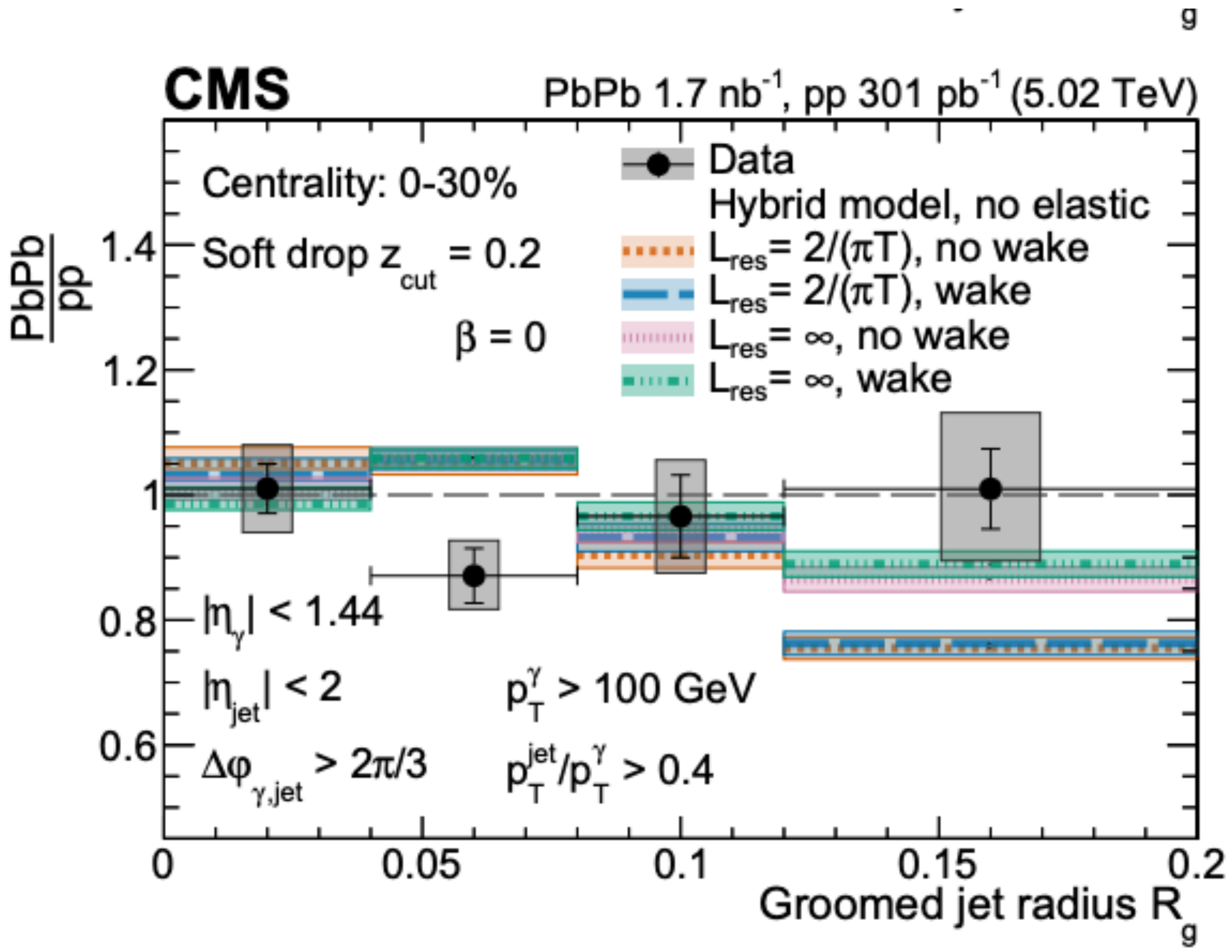






Include unbalanced configurations

$$x_{J\gamma} > 0.4$$



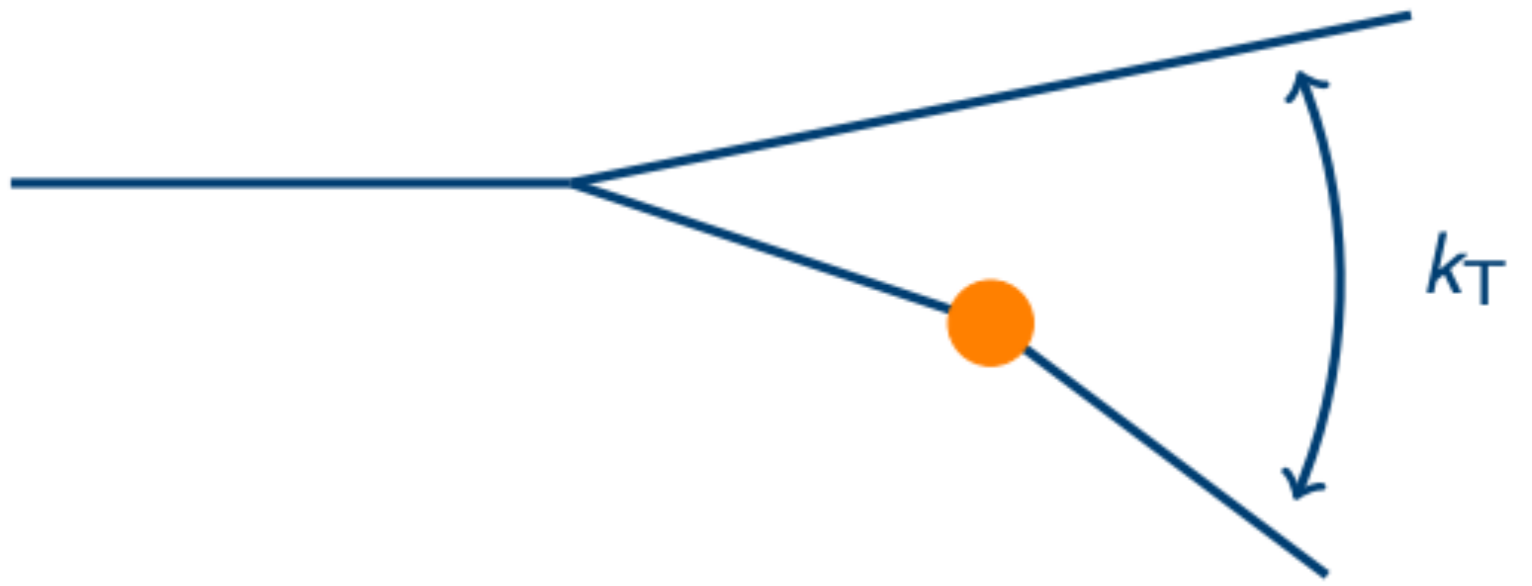
Less quenched jets: narrowing still observed

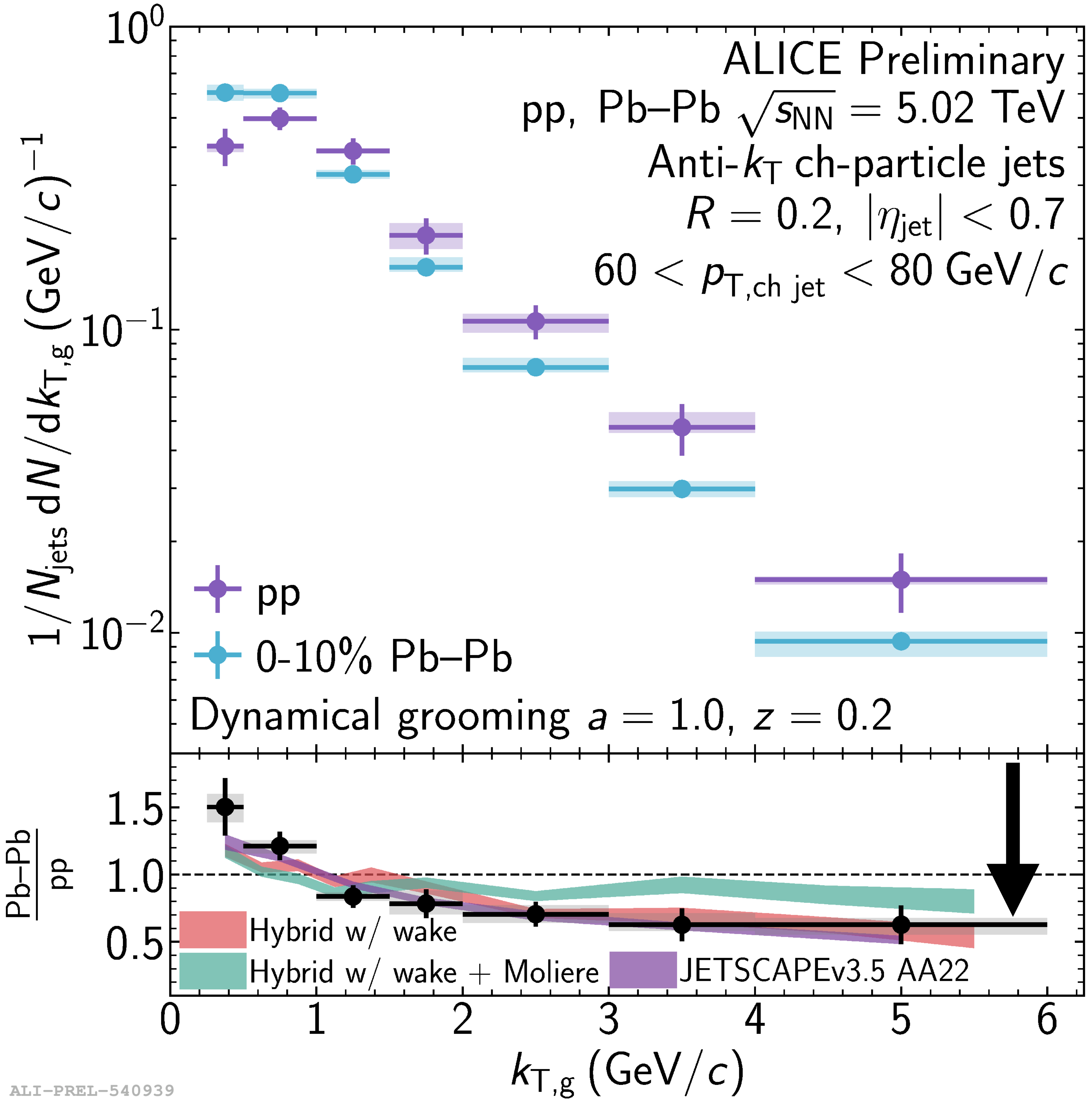
More quenched + unquenched jets: no modification

Search for quasi-particle structure of QGP

Search for Moilere scattering off quasi-particles in the medium $k_{Tg} \sim z_g p_T R_g$

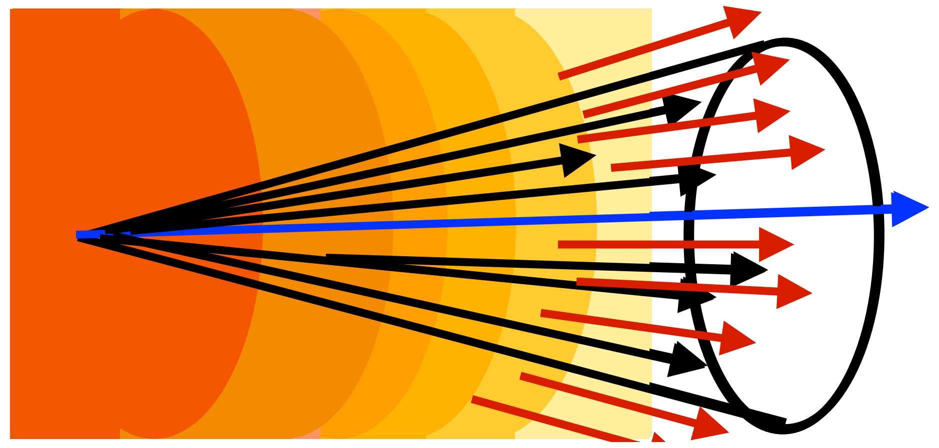
Hardest k_T kicks: looked at groomed k_{Tg} for a hard kick at high k_T

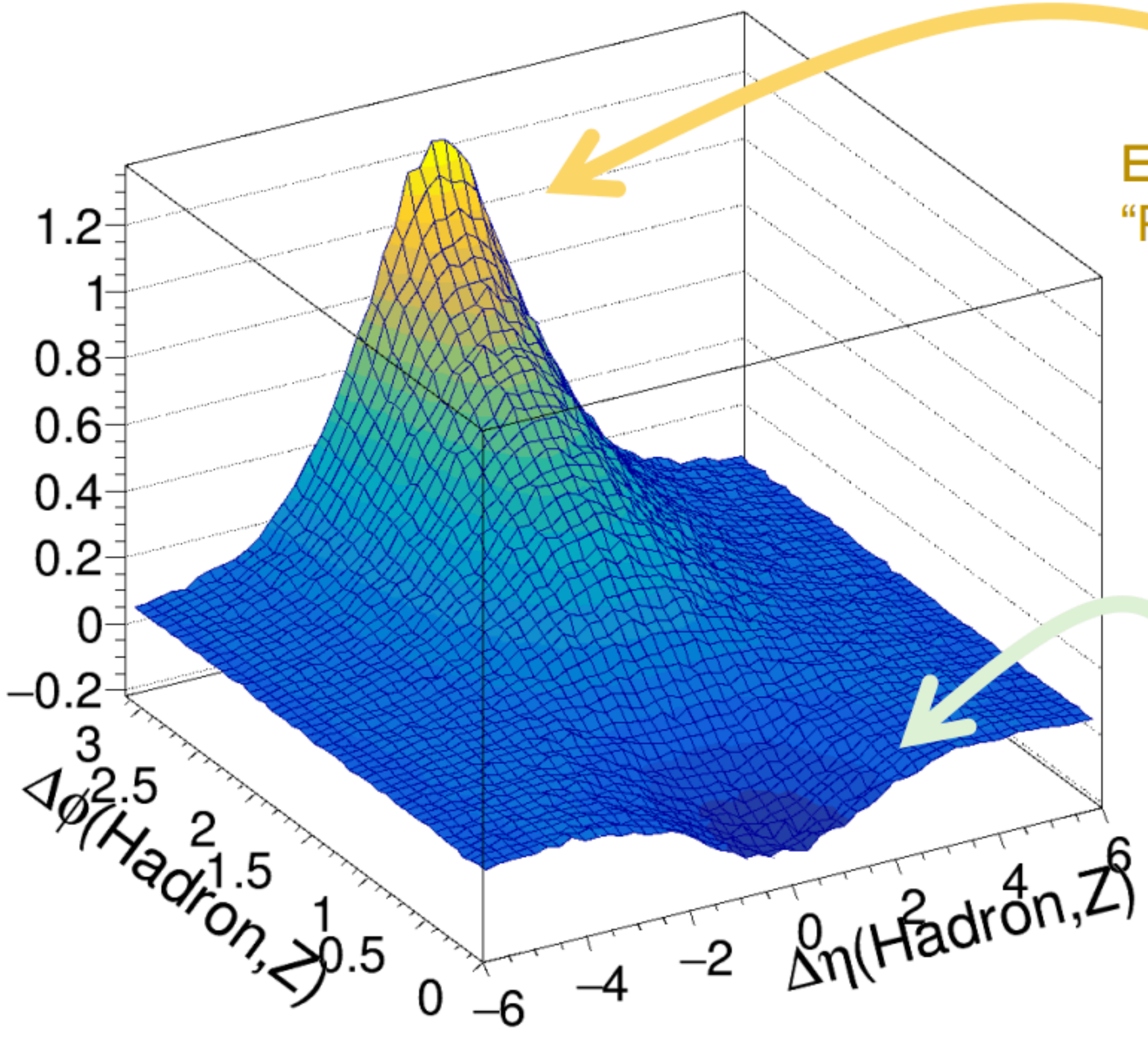




Narrowing observed, no clear evidence but sensitive to differences in models

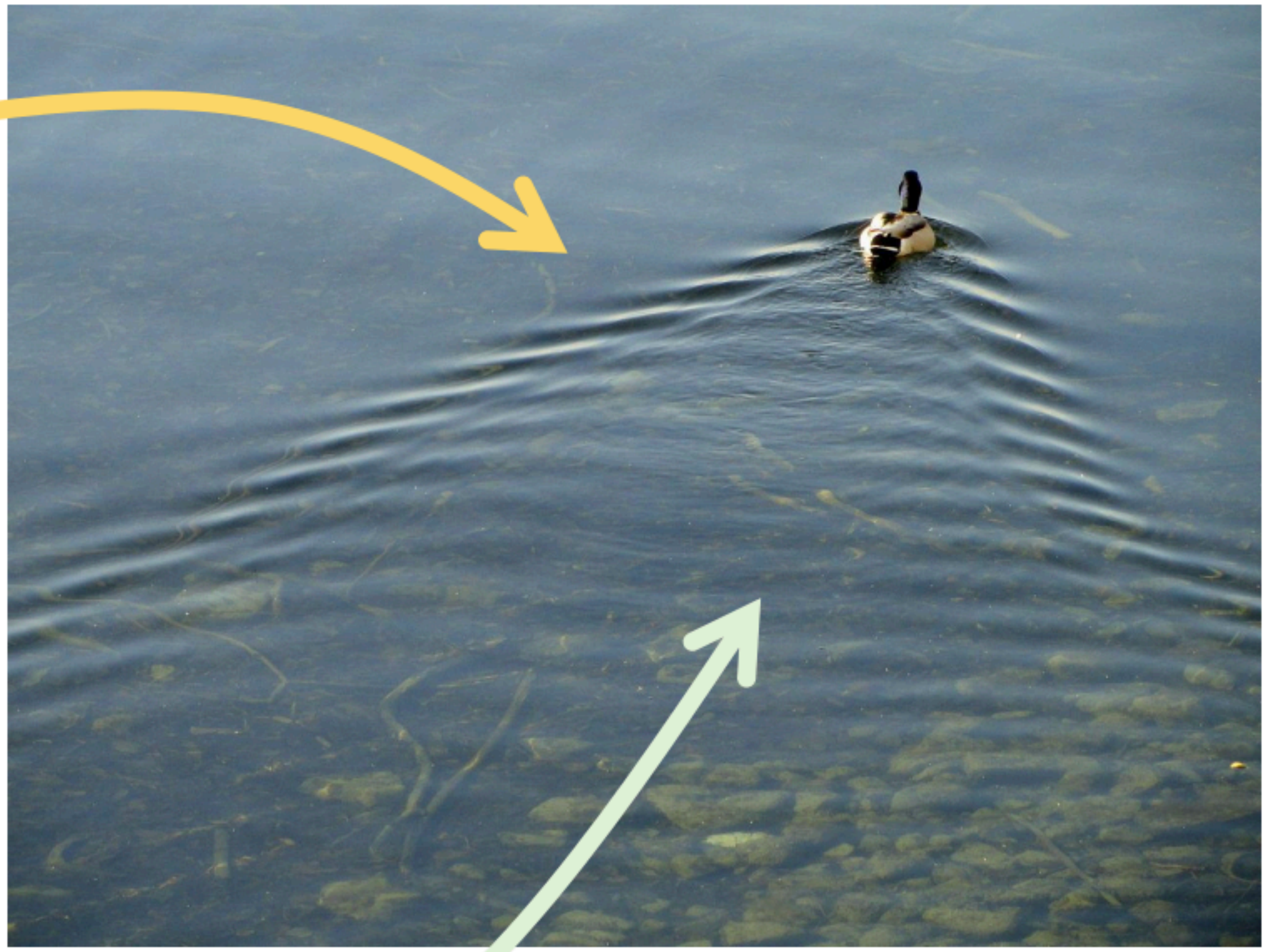
Searching for the medium response





Enhancement of particle
"Positive wake"

Depletion of particle
"Recoil"
"QGP hole"
"Negative wake"



Position space

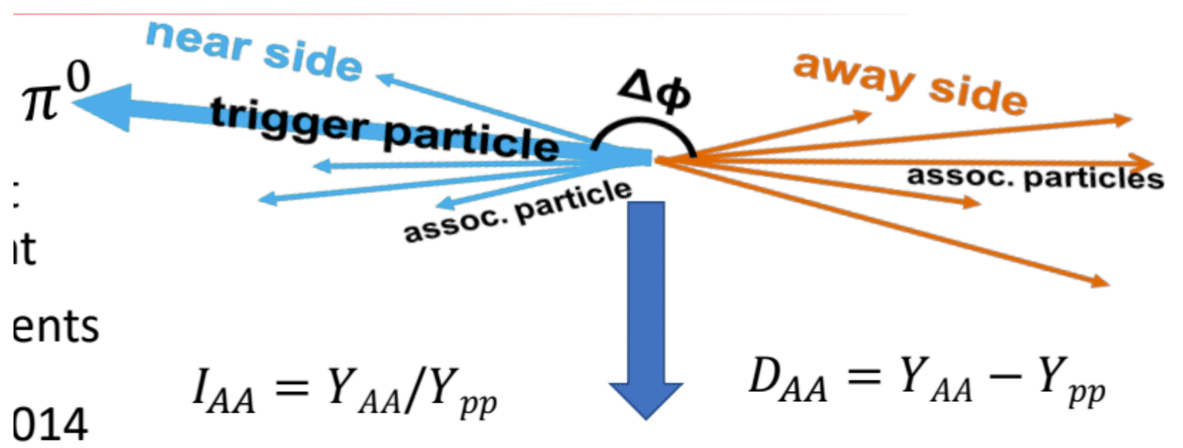
Credit: Yen-Jie Lee

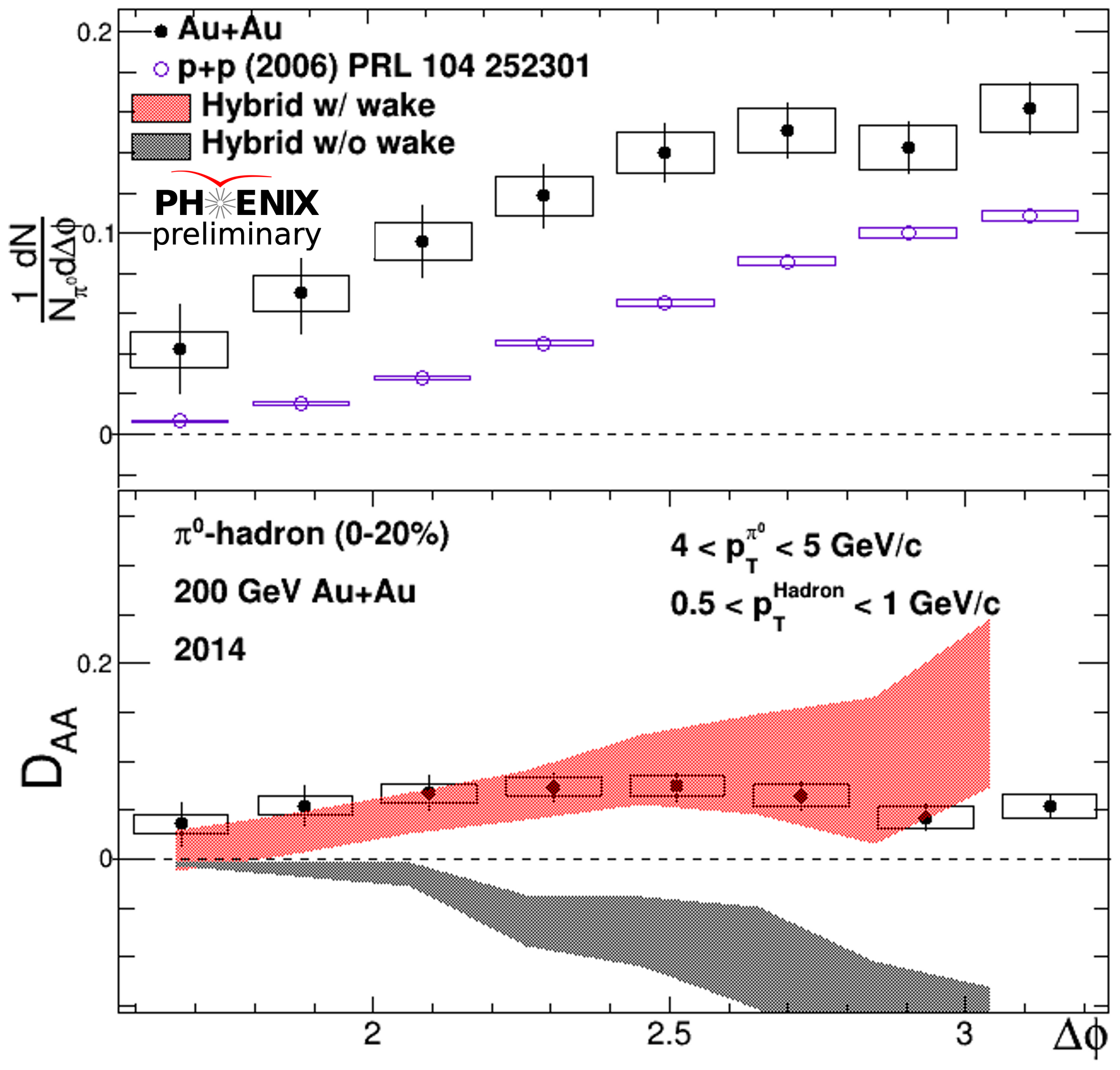
Z⁰ and **wake hadron** correlation in Hybrid model

Daniel Pablo, Krishna Rajagopal, YJL

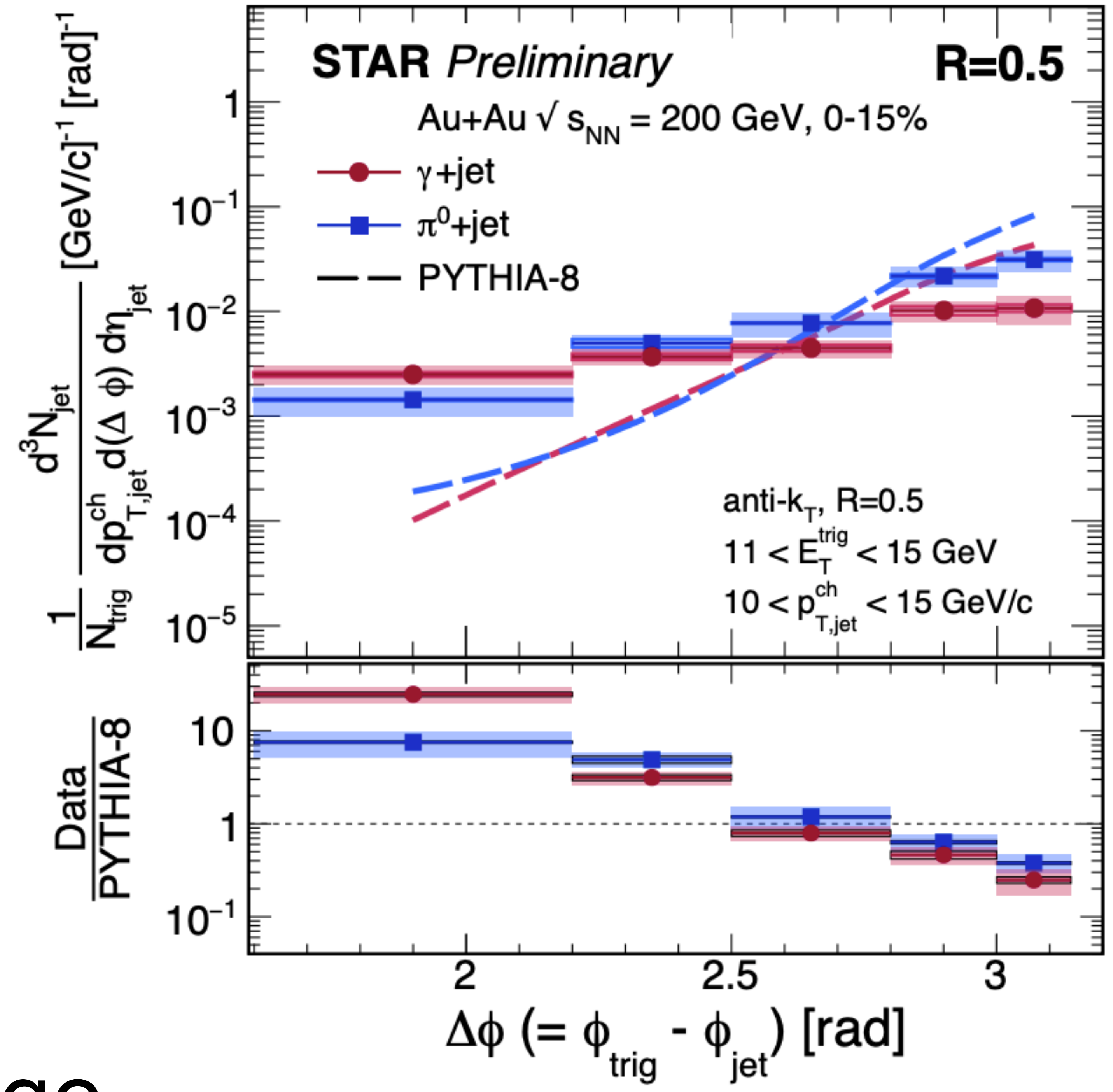
Momentum space

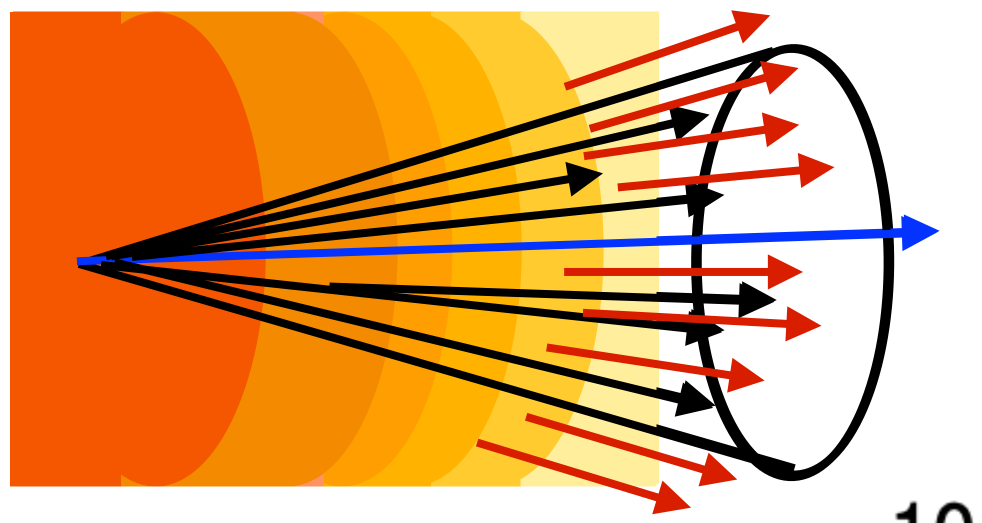
Positive wake impact in hadron+jet correlations

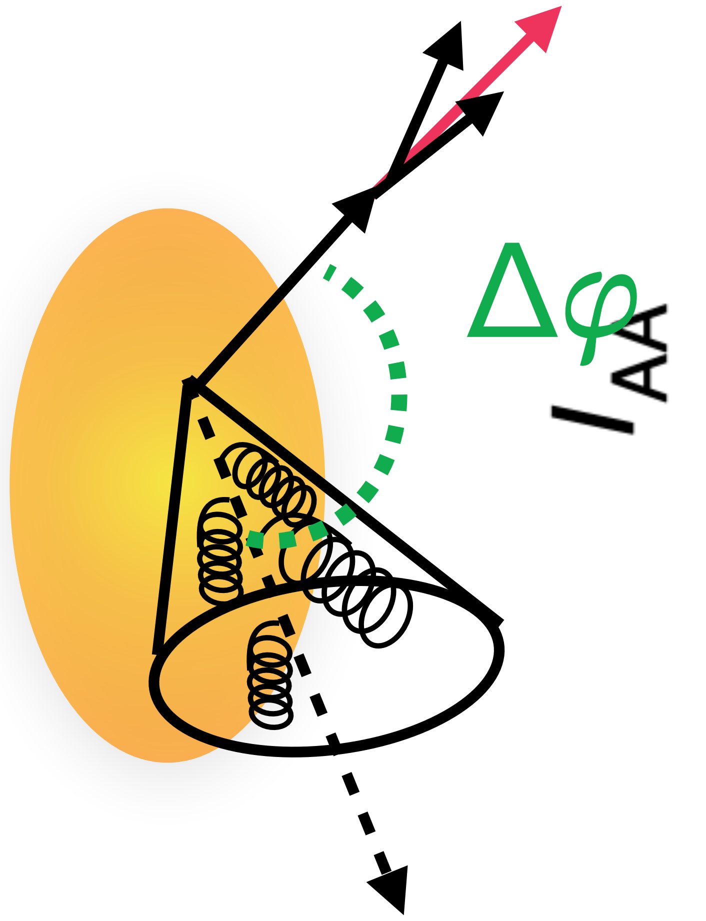




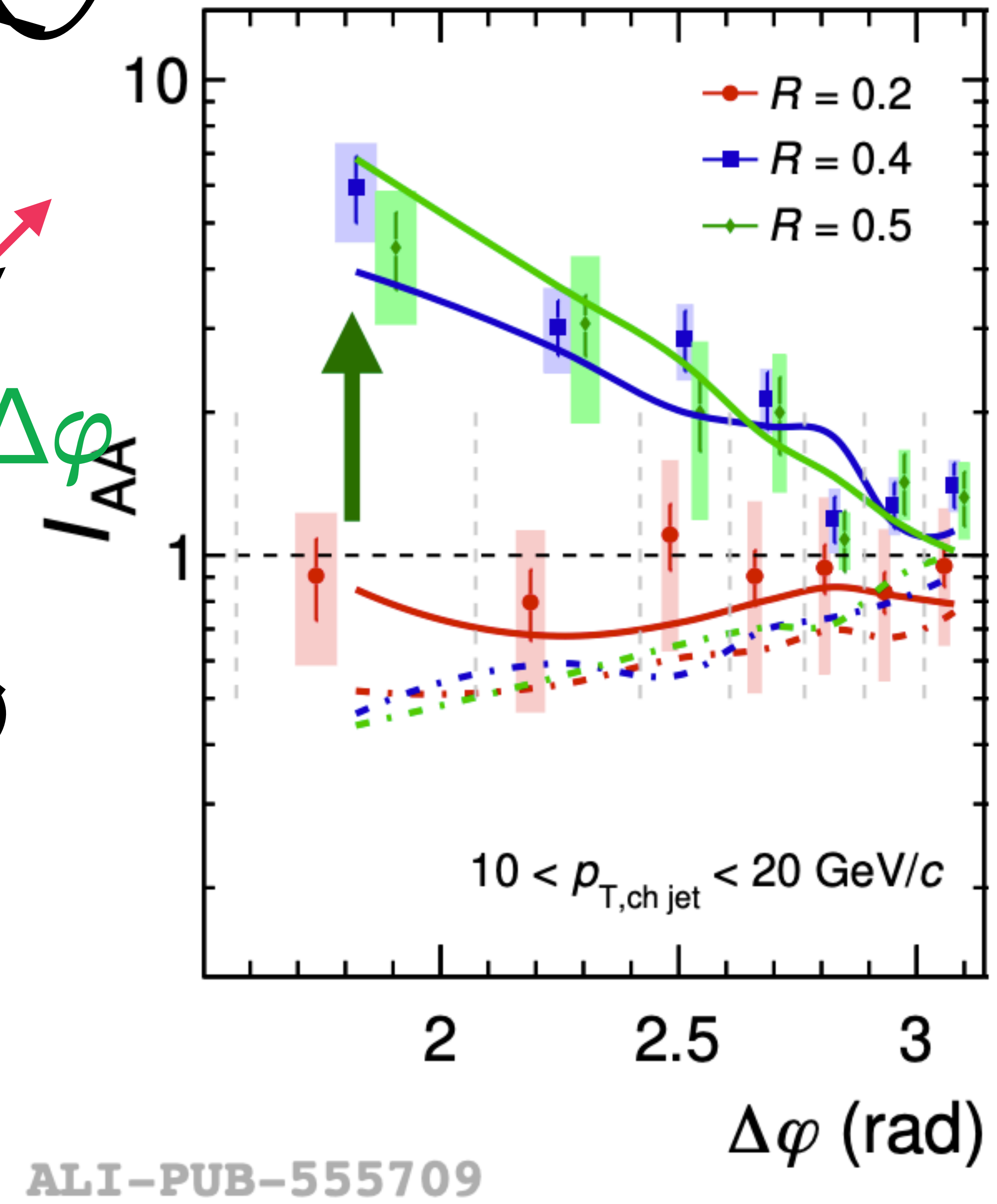
STAR arxiv:2309.00156
STAR arxiv:2309.00145







ALICE arxiv:2308.16131
ALICE arxiv:2308.16128



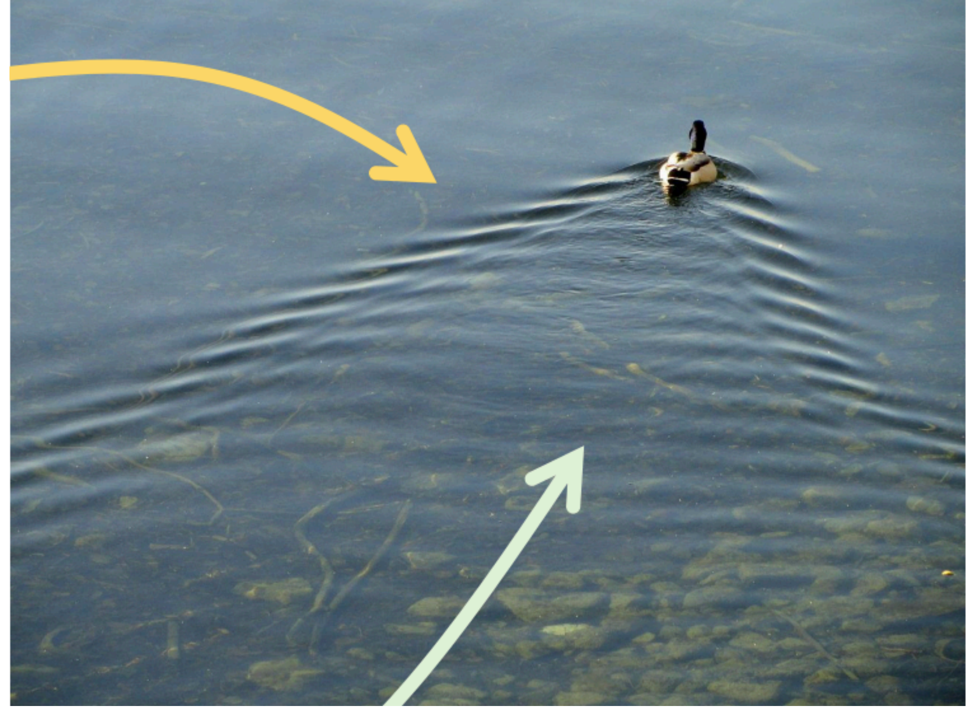
Energy is transferred to large angles for every track p_T

And at larger R and low p_T

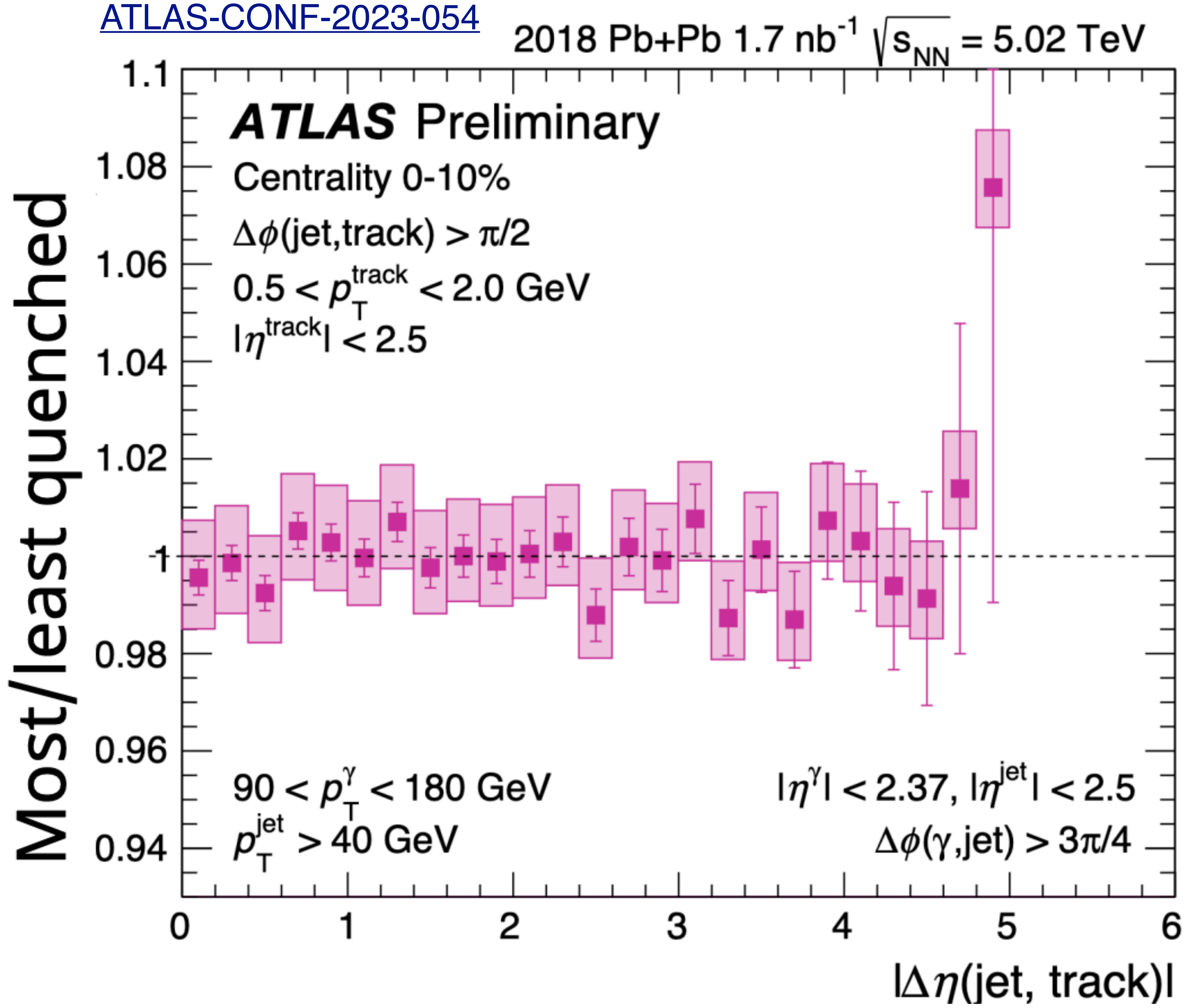
Consistent with medium response

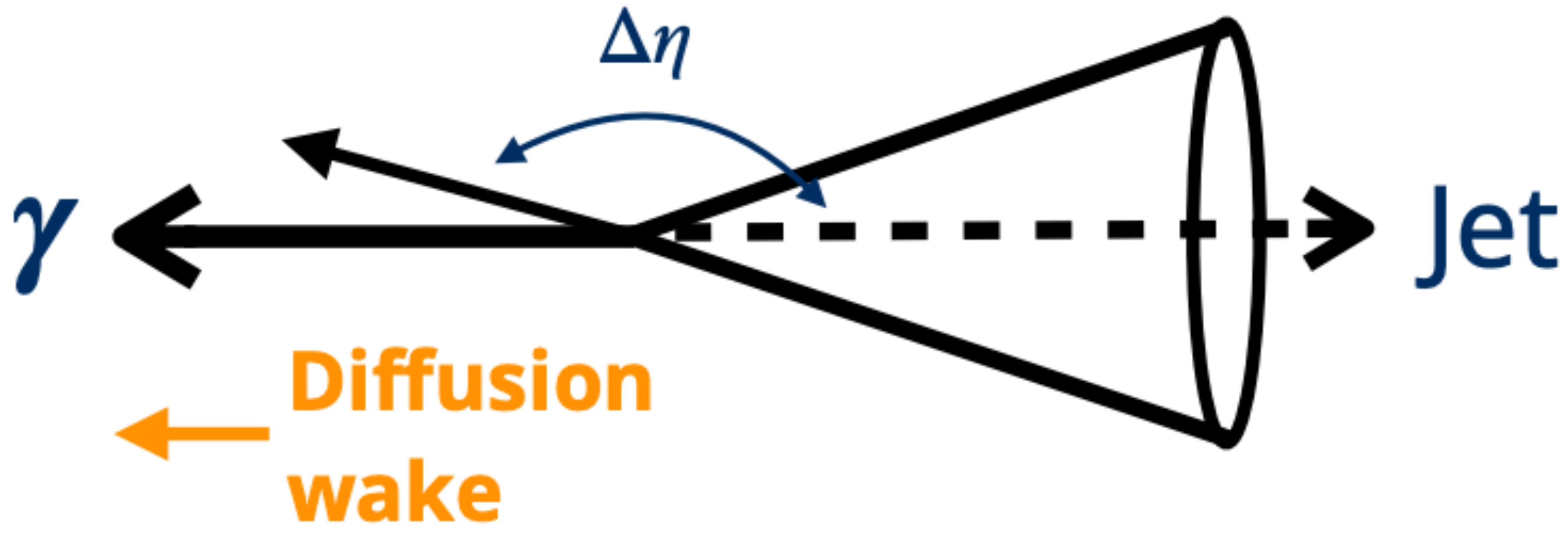
Isolate the diffusion wake

Credit: Yen-Jie Lee



ATLAS-CONF-2023-054



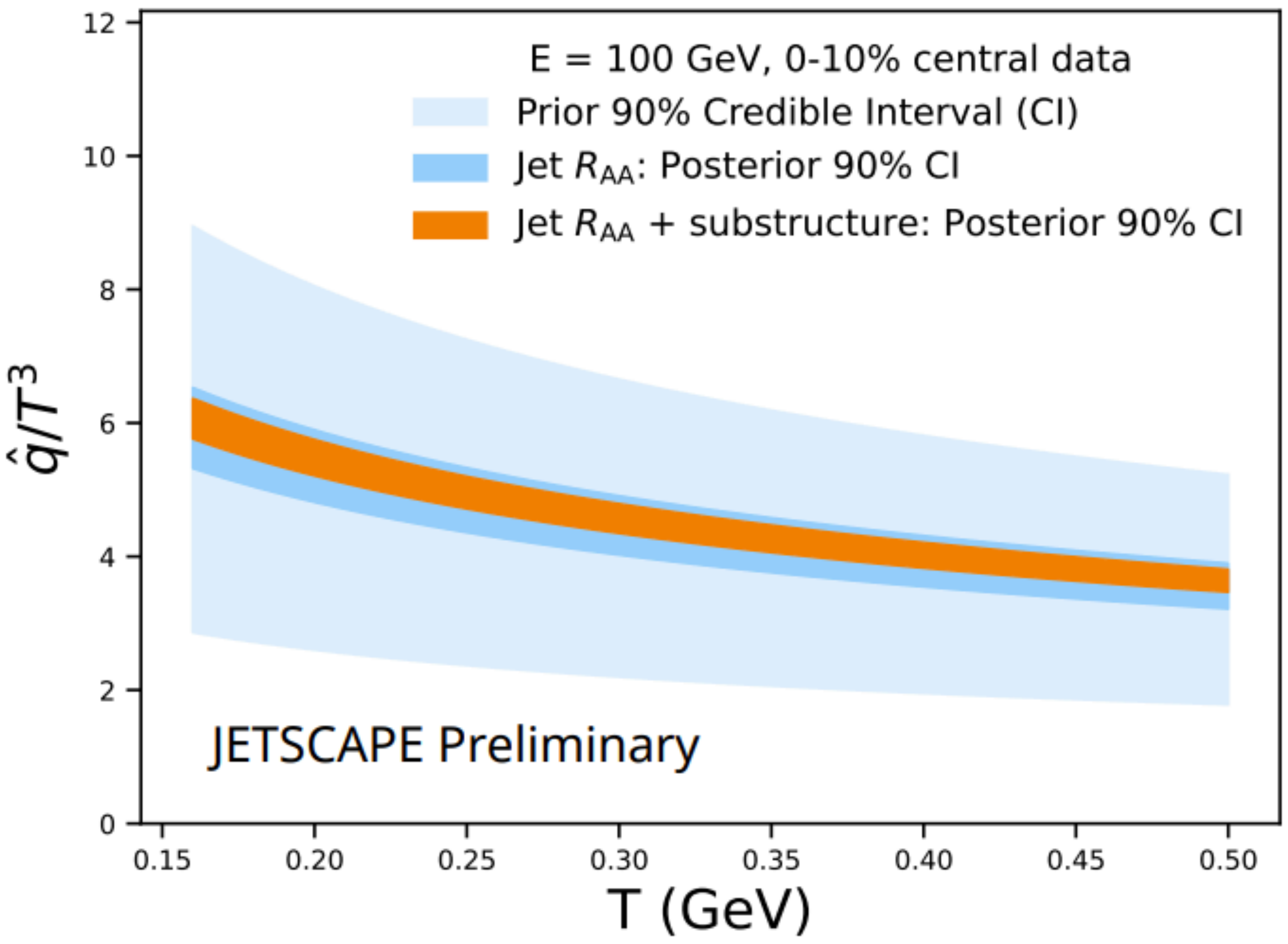


Credit: R. Ehlers

Consistent with no significant diffusion wake

Extracting QGP medium properties from jets

Bayesian analyses of LHC and RHIC data using **jet p_T and substructure** to extract the QGP jet transport coefficient qhat using JETSCAPE framework



learning which observables carry complementary information

caveat: exploratory study with only 0-10%, simplified error treatment

Using experimental data to learn about the medium!

Summary and Outlook

Jets in vacuum isolate QCD effects and constrain MC generators

Correlations between observables gives the full picture of jet evolution

Jets provide a multi-scale probe of QGP medium

See signifiant *jet suppression* over multiple scales, including flavor dependence

Narrowing of jets in the QGP, consistent with color decoherence picture

Progress made towards understanding selection biases with photon+jets

No direct evidence for quasi-particle structure yet

Evidence of impact of medium response but no significant diffusion wake

Future: wealth of Run 3 data at LHC and sPHENIX results coming at RHIC

Differential, precise measurments from high statistics data -> apply differential tools from pp to HIs like EECs and multi-dimensional Lund plane

Rare probes: photons and HF

Backup

Primary jet Lund plane density

- Primary Lund jet plane is filled with splittings from the hardest prong

Andersson et al ZPC43 (1989)

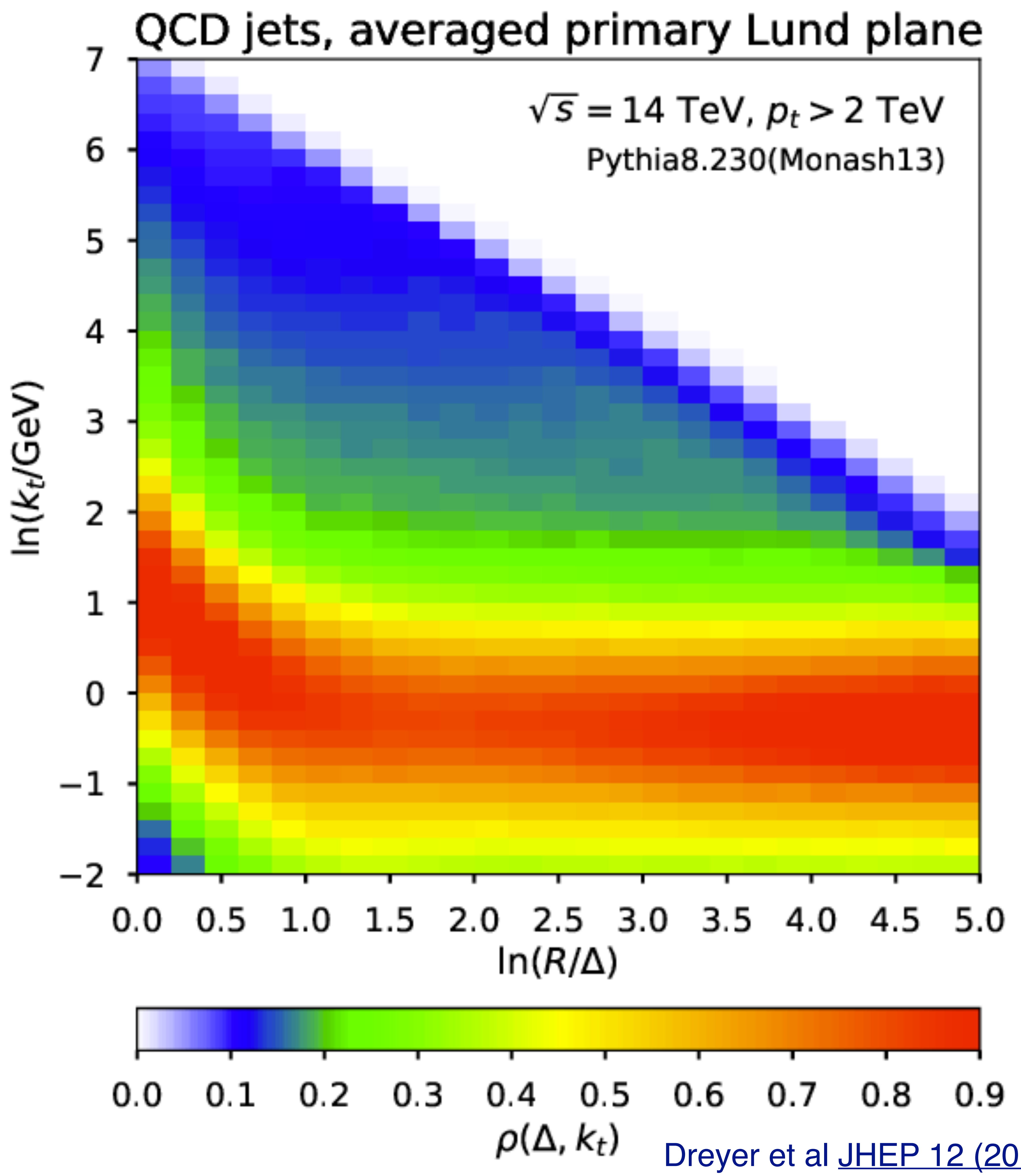
- At leading order the emissions populate the plane uniformly

- Running of the coupling constant sculpts the plane!

Coupling constant

$$d^2P = 2\frac{\alpha_s(k_\perp) C_R}{\pi} d\ln(z\theta) d\ln(\frac{1}{\theta})$$

Color factor



Dreyer et al JHEP 12 (2018)

Jet Lund plane density

- Lund Diagram: phase space of jet splitting

Andersson et al ZPC43 (1989)
Dreyer et al JHEP 12 (2018)

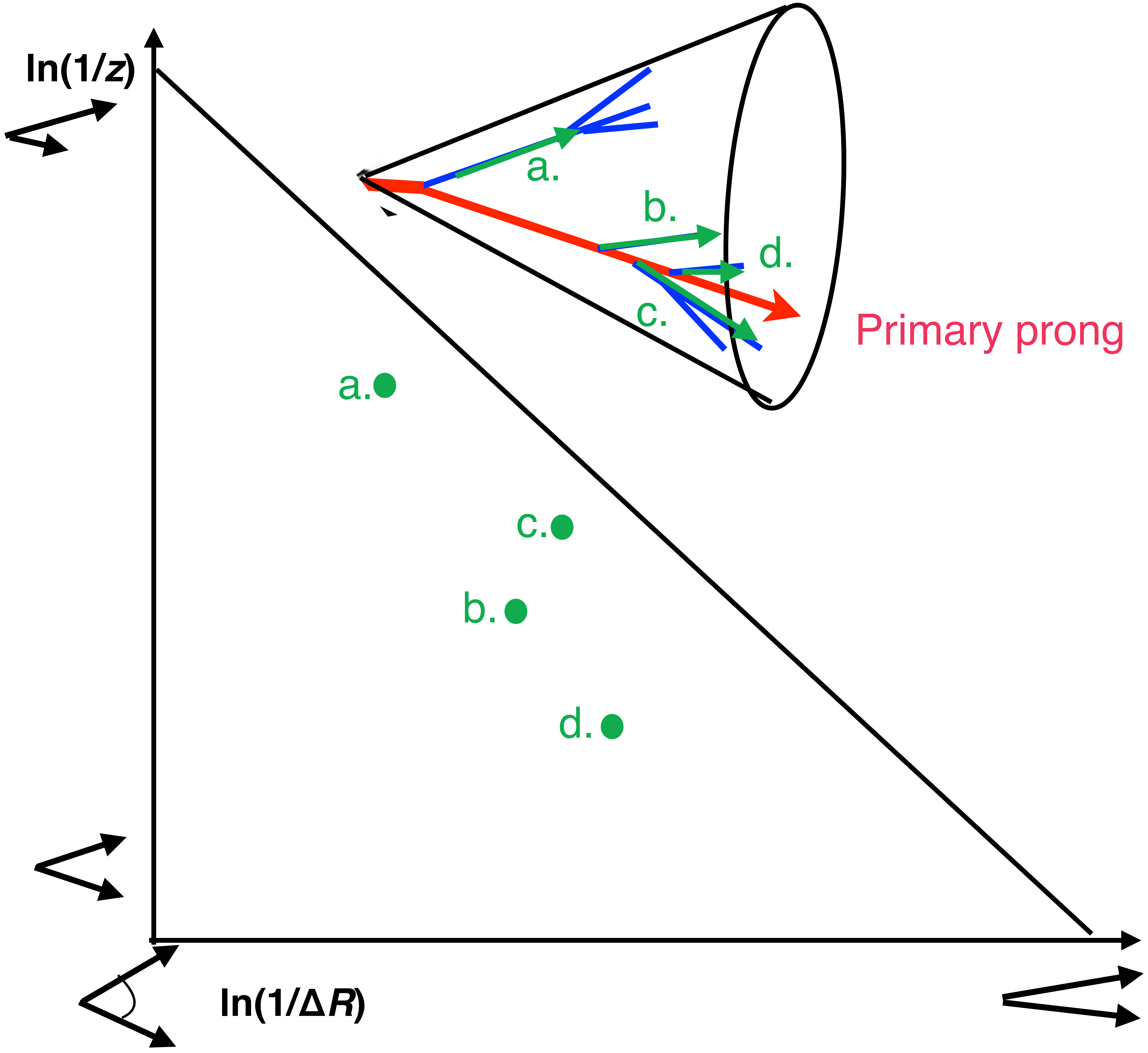
$$d^2P = 2\frac{\alpha_s(k_\perp) C_R}{\pi} d\ln(z\theta) d\ln(\frac{1}{\theta})$$

Color factor

Coupling constant

- k_T: relative transverse momentum

- Primary Lund jet plane filled with splittings from the hardest prong



Lund plane measurement

- Recluster anti-k_T $R = 0.4$ jets with C/A algorithm and follow primary splittings from the leading prong

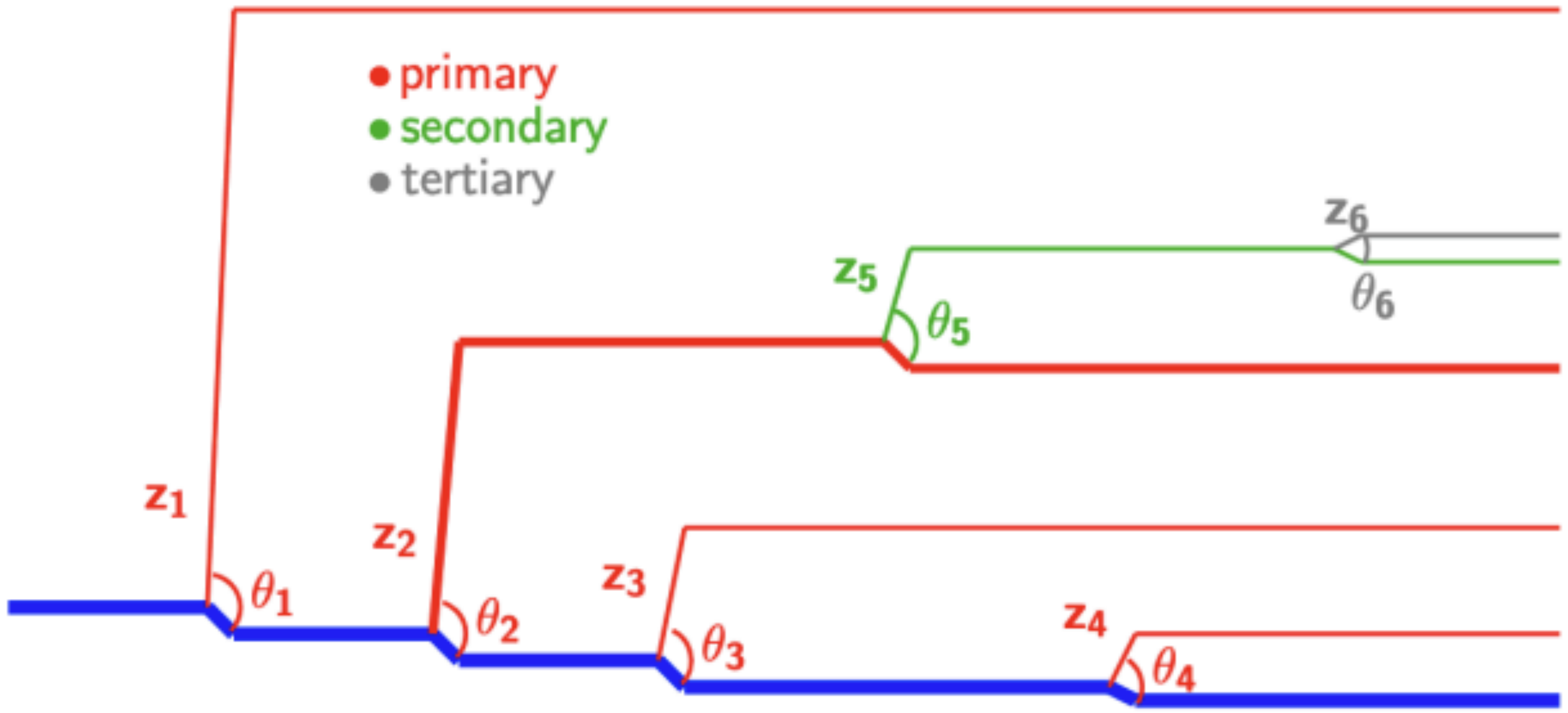


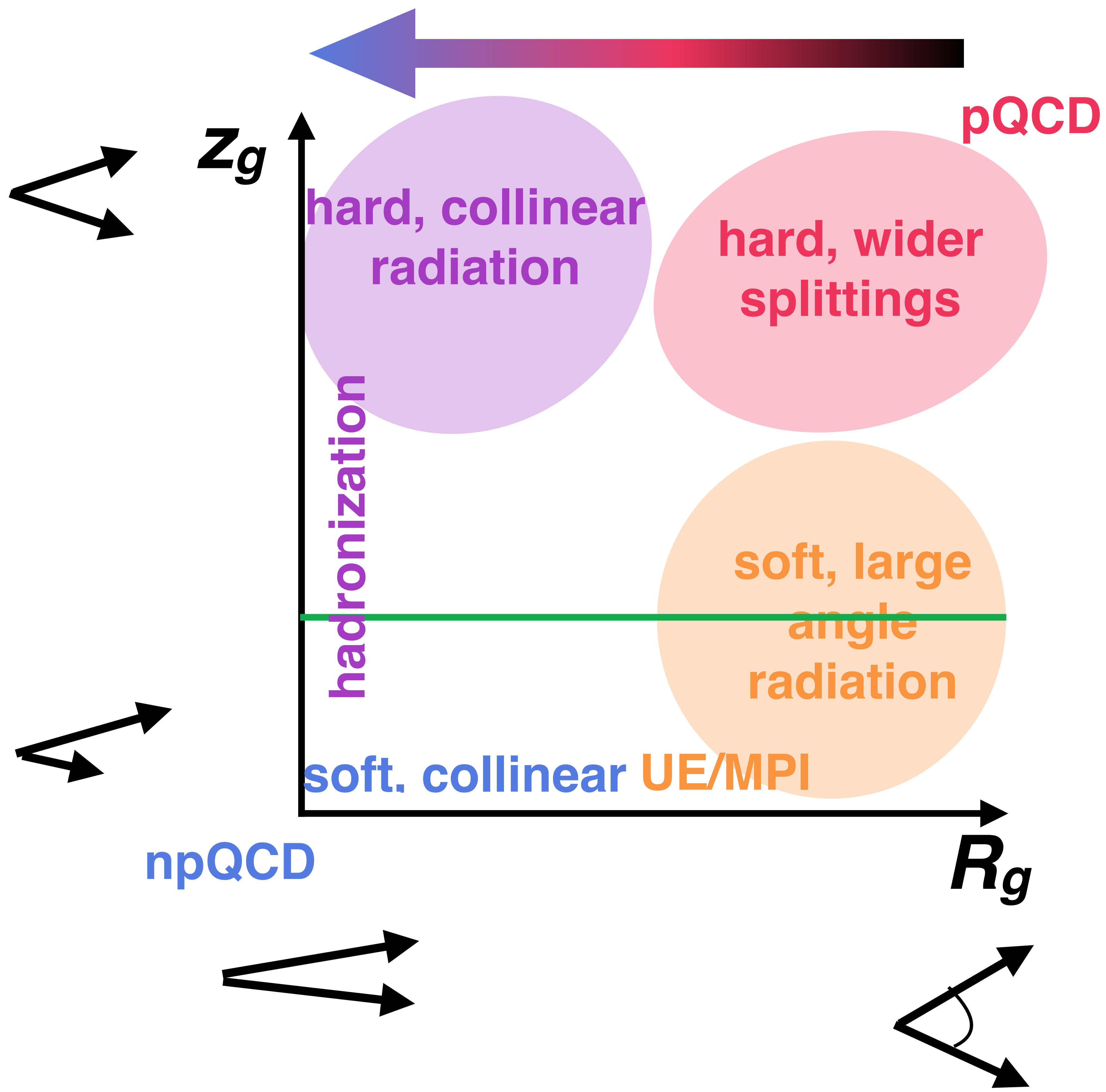
Image from Gregory Soyez

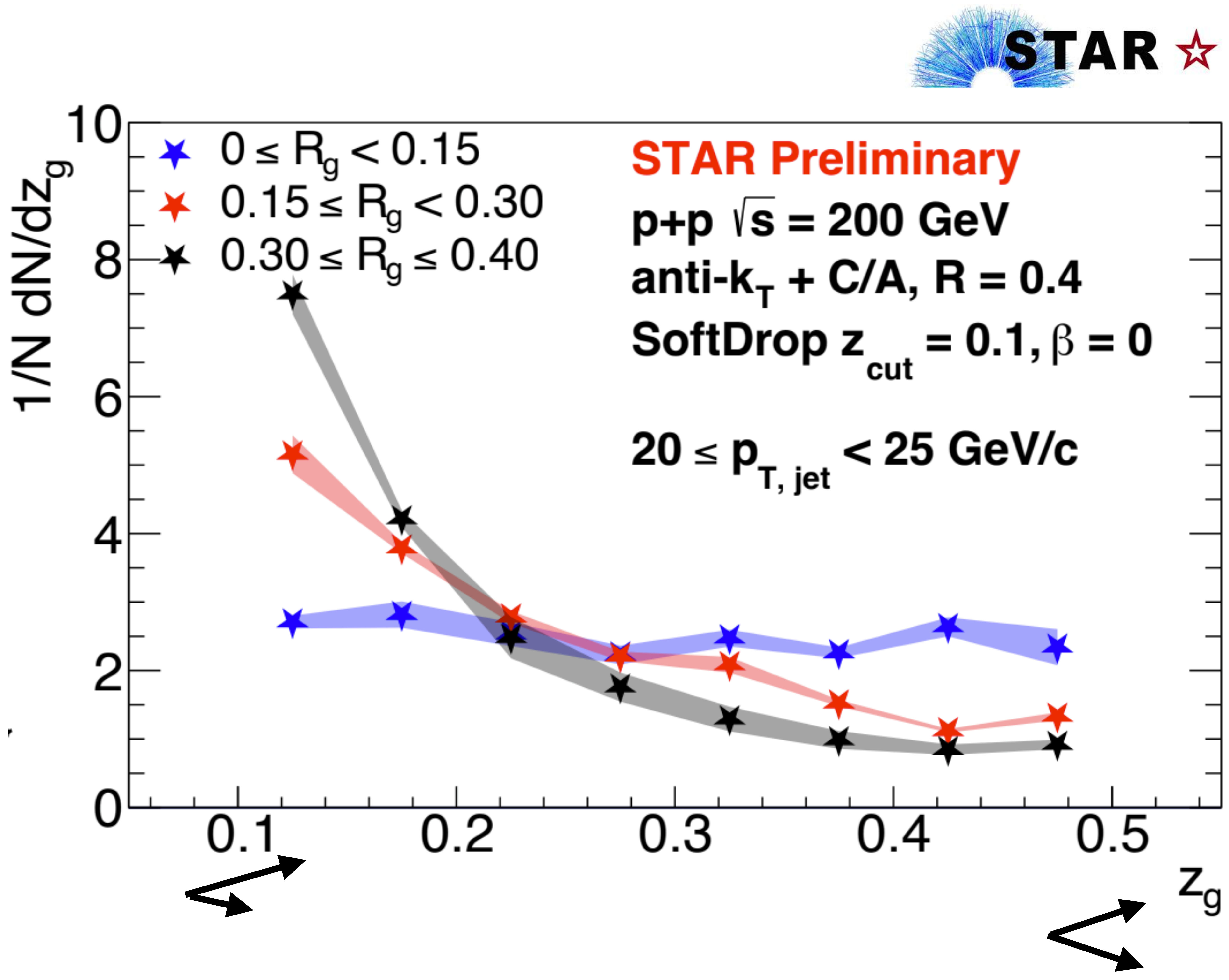
$\sqrt{s}$ = 13 TeV	ALICE	ATLAS
Jet p_T (GeV/c)	20-120*	> 675
Max k_T(GeV/c)	5	> 135
ΔR	0.1 - R	0.005 - R

*charged-particle jets

- Fully corrected with 3D unfolding in axes of Lund plane and jet p_T

R_g vs. z_g





Evolves from soft large-angle to collinear hard splittings

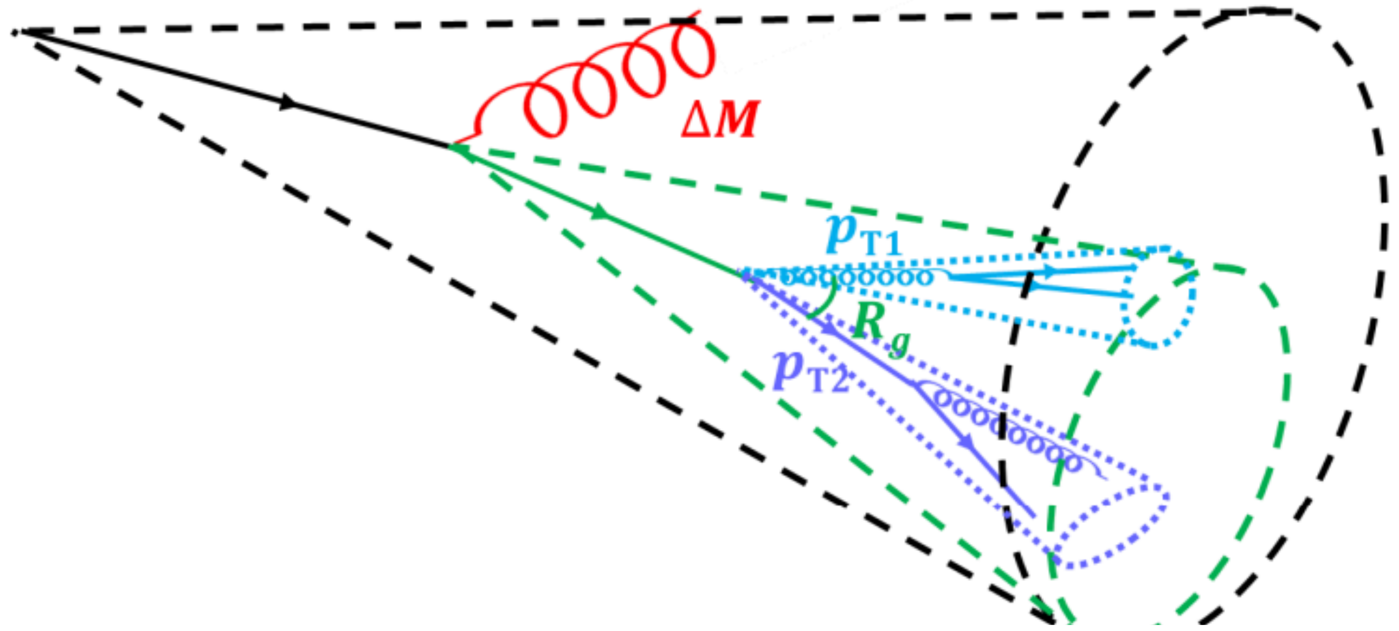
Multi-dimensional jet substructure

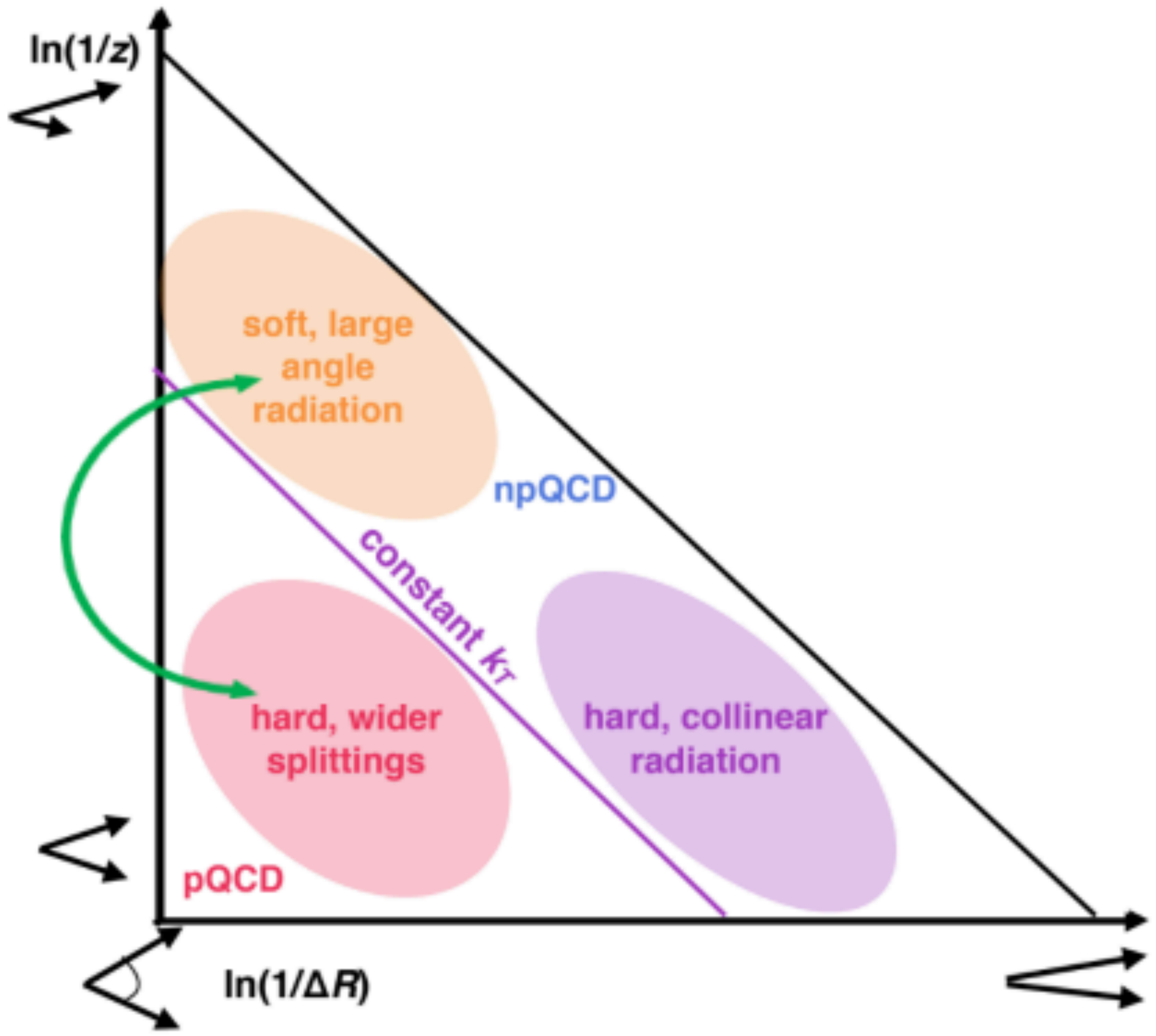
With Multifold obtain **6D correlation** between substructure observables measured!

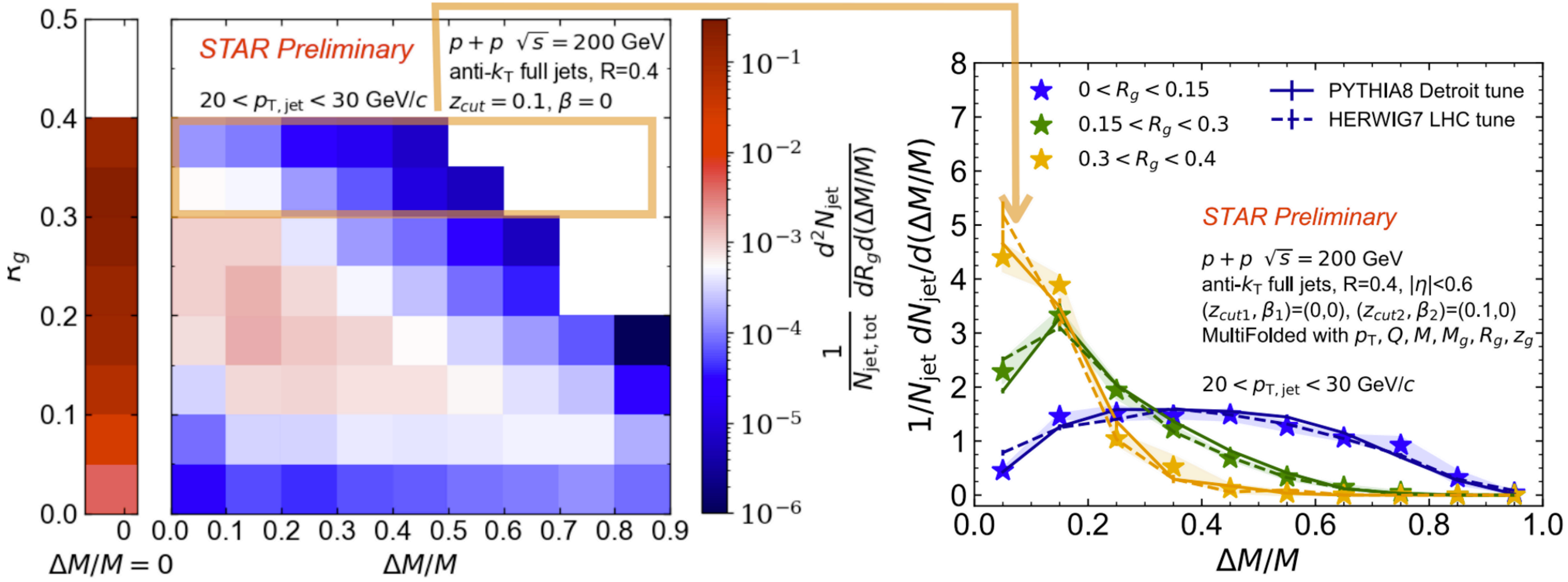
Collinear Drop: probes the soft component

Chien and Stewart JHEP 2020, 64 (2020).

$$\Delta M/M = \frac{M - M_g}{M}$$







Connect the npQCD and pQCD parts of the shower

Energy loss dependence on parton flavor

Flavor and mass dependence

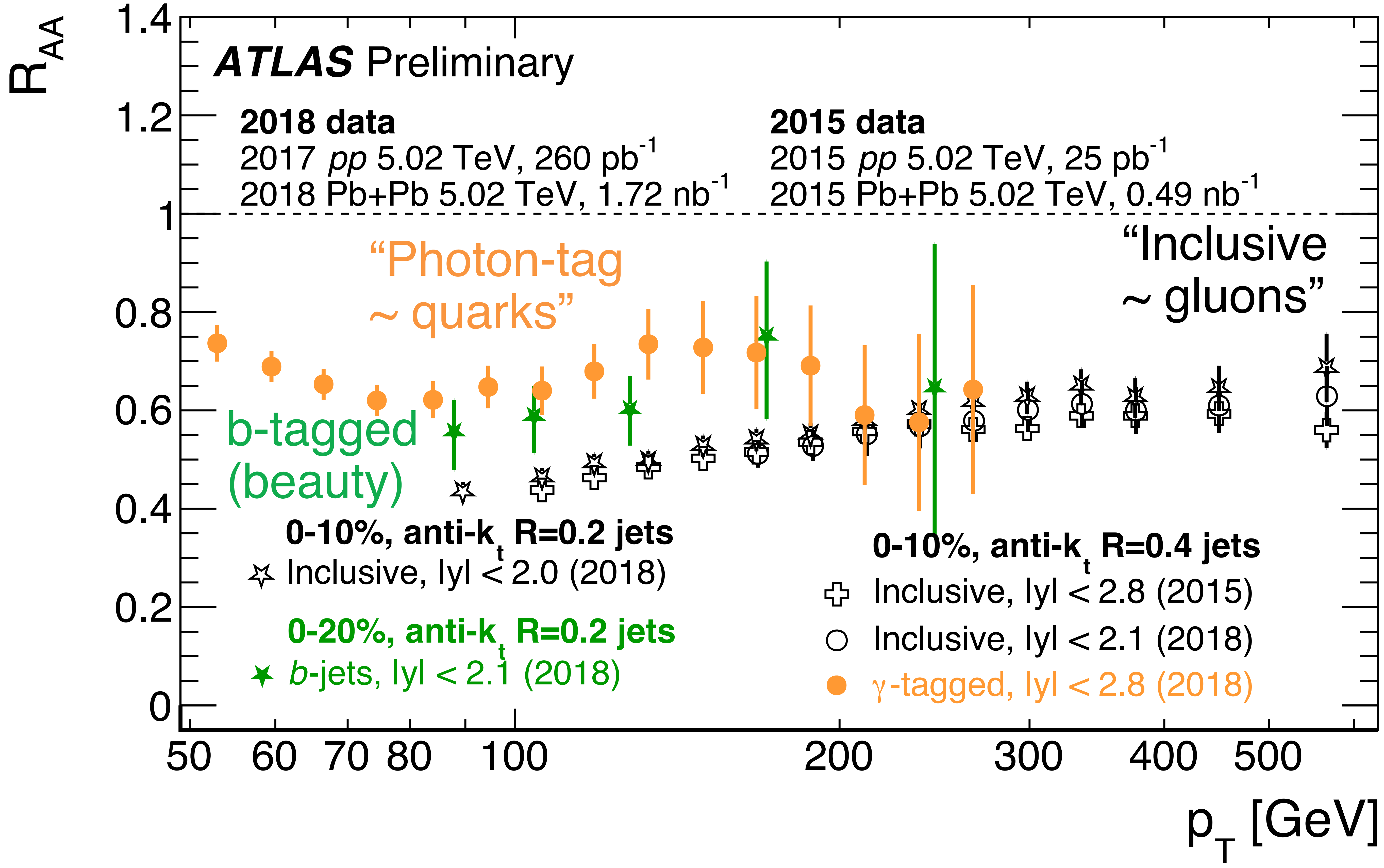
$E_{loss} > E_{loss} > E_{loss}^{HQ}$

Gluon Light quark Heavy quark

Dead-cone effect

Large parton mass Small parton mass

Caveat: "spectra steepness" plays a role!

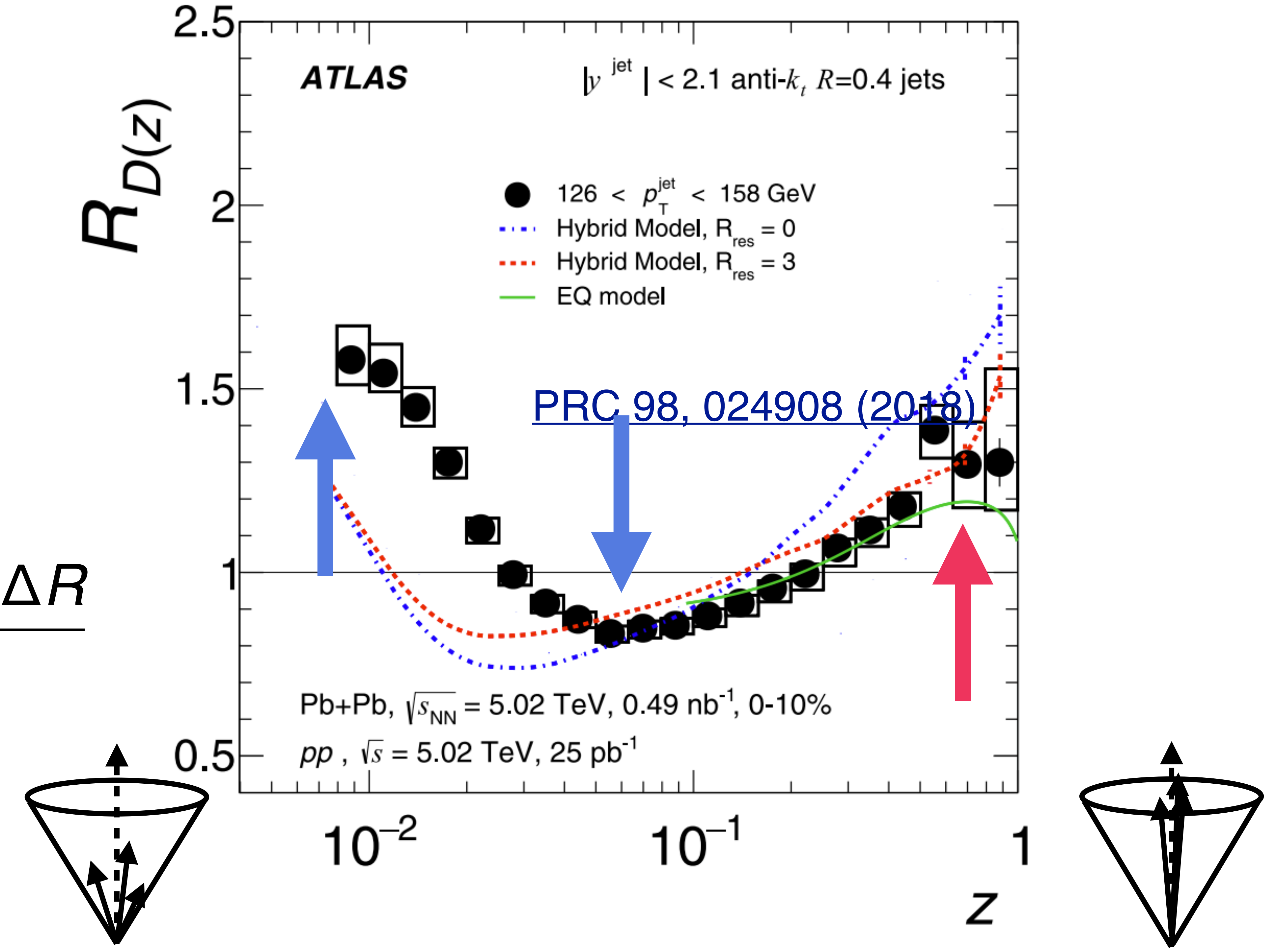


Energy loss depends on color charge (and mass of parton?)

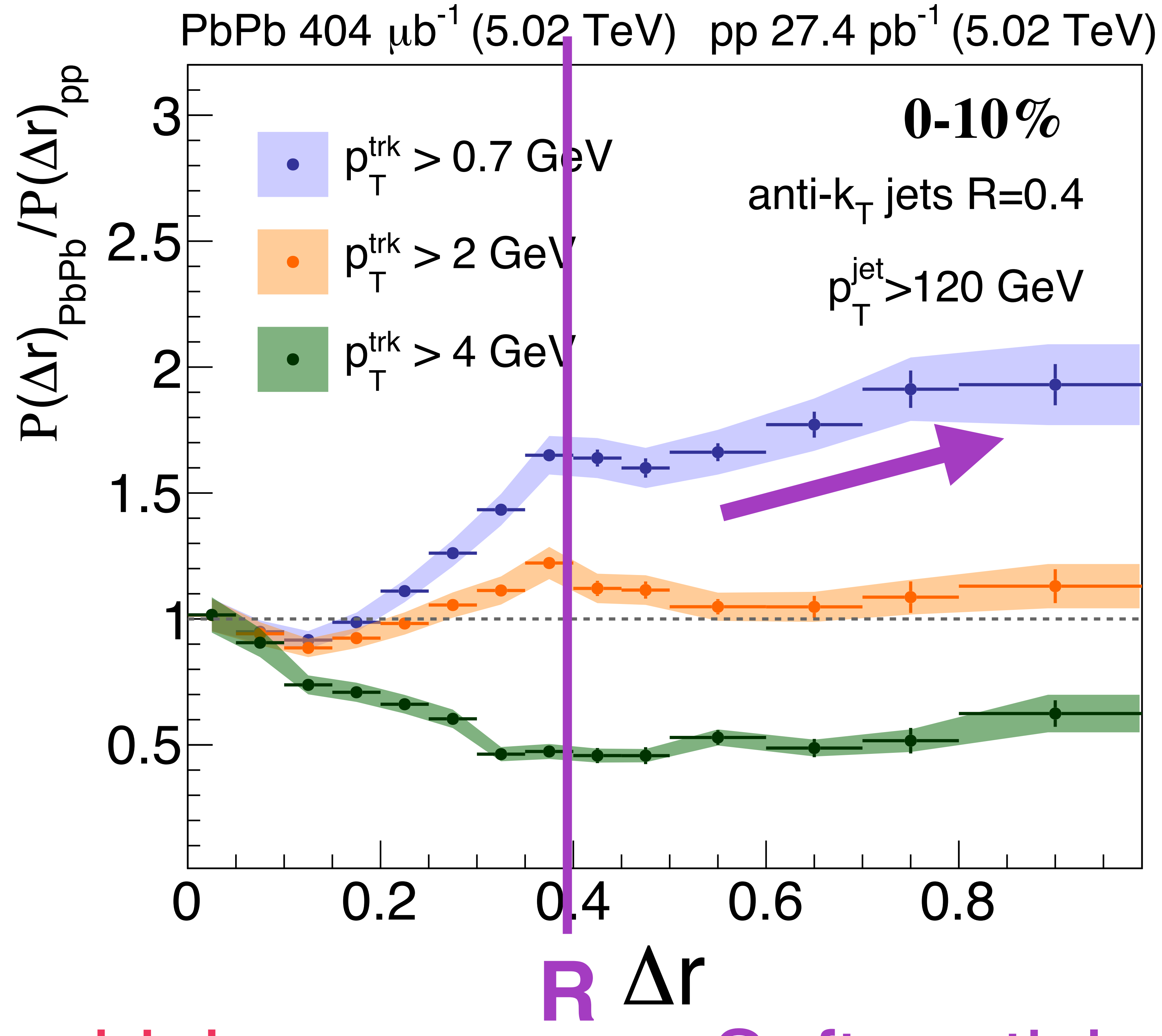
Jet structure is softened and broadened

Jet fragmentation: longitudinal profile of charged particles in a jet

Jet shape: radial profile of charged particles in a jet



$$z = \frac{p_T \cos \Delta R}{p_T^{jet}}$$



Energy transferred to soft particles inside the jet

Hardening of core: high z enhancement from quark vs. gluons?

Soft particles are at large angles from jet axis

Energy correlators: new HI observable?

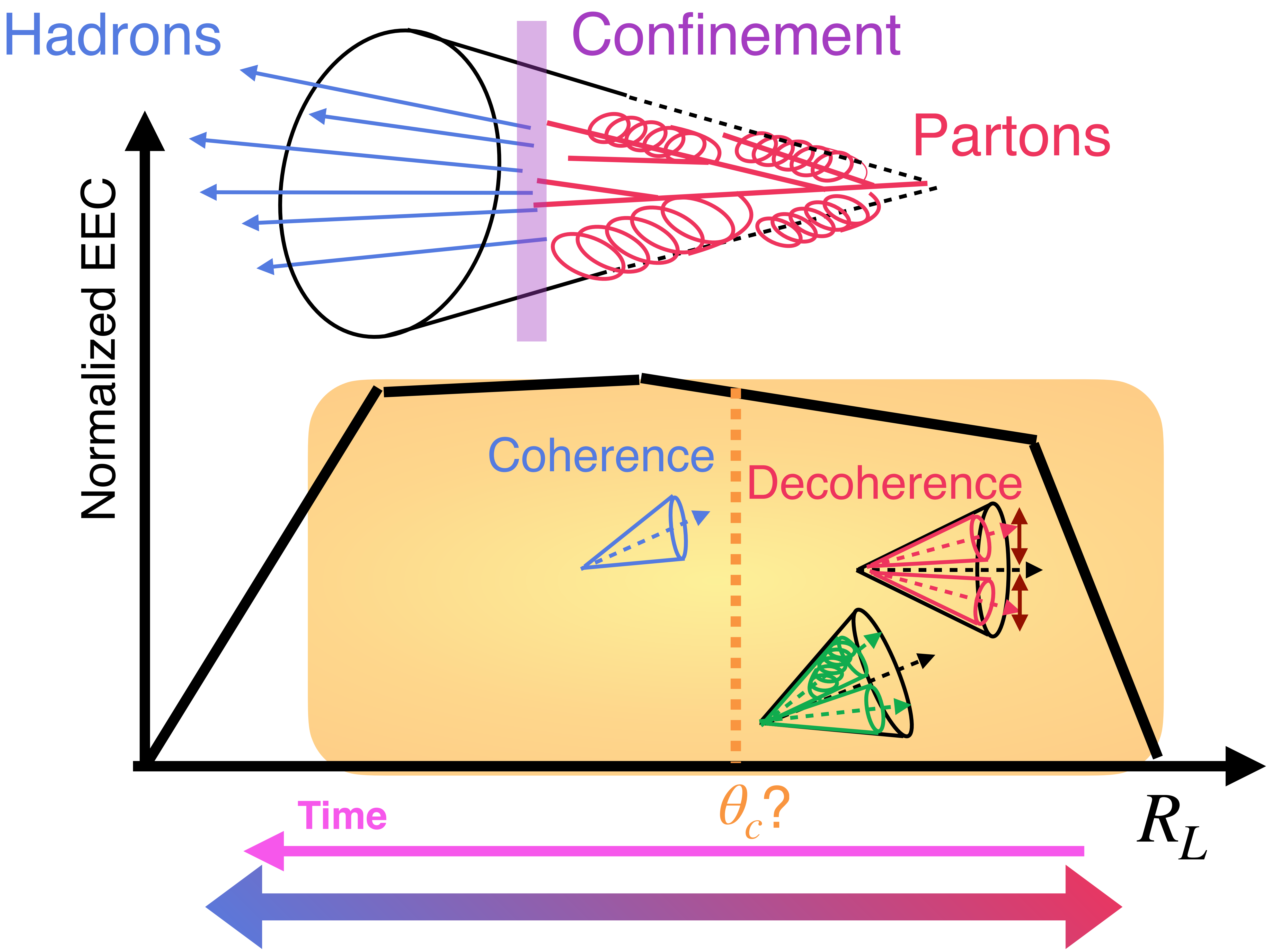
Clear distinction between perturbative and npQCD regions

Less sensitive to soft physics, may be more resilient to background?

No soft drop required: access all aspects of the jet evolution in medium including in-medium splittings?

See Carlota Andres BOOST talk for first look

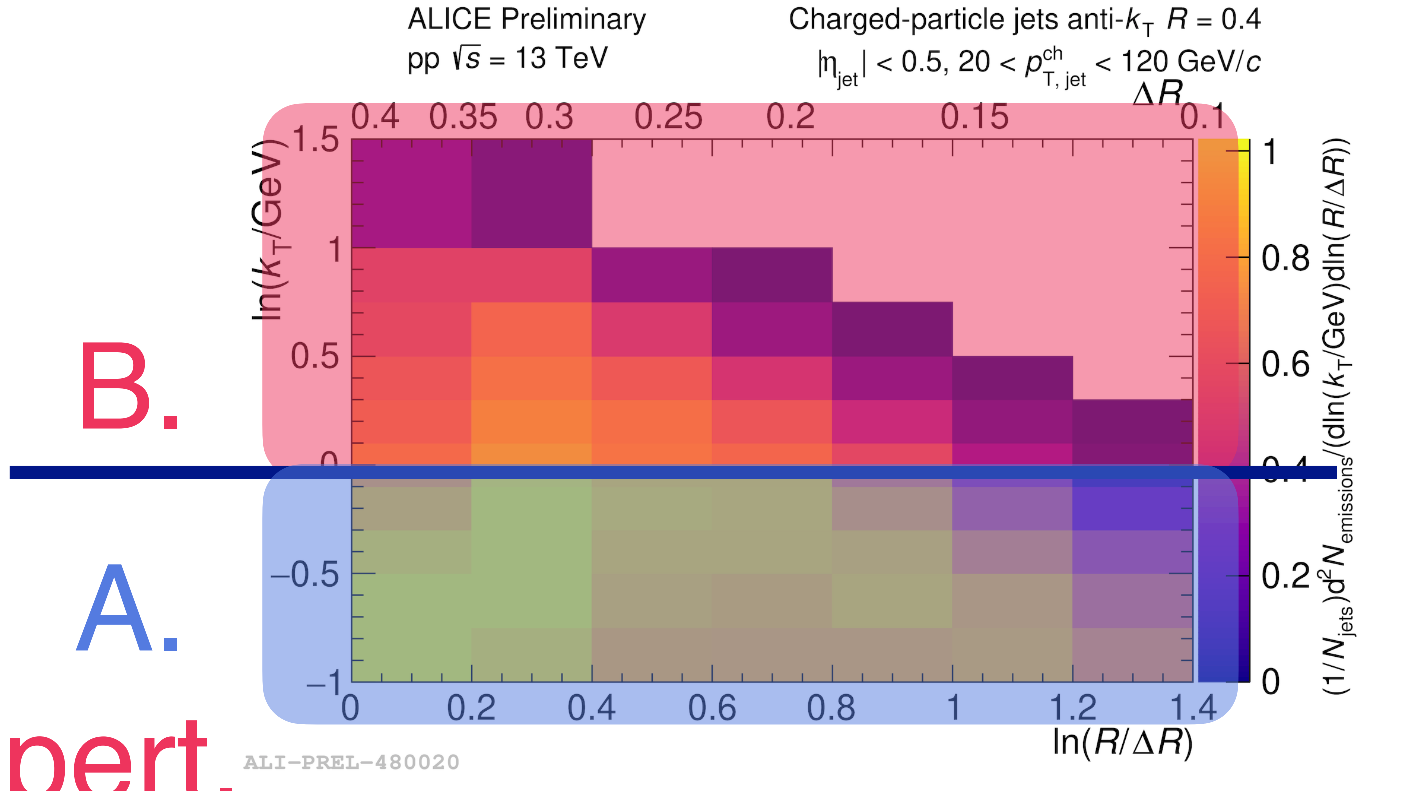
Direct access to resolution length?



Regions of the Lund plane

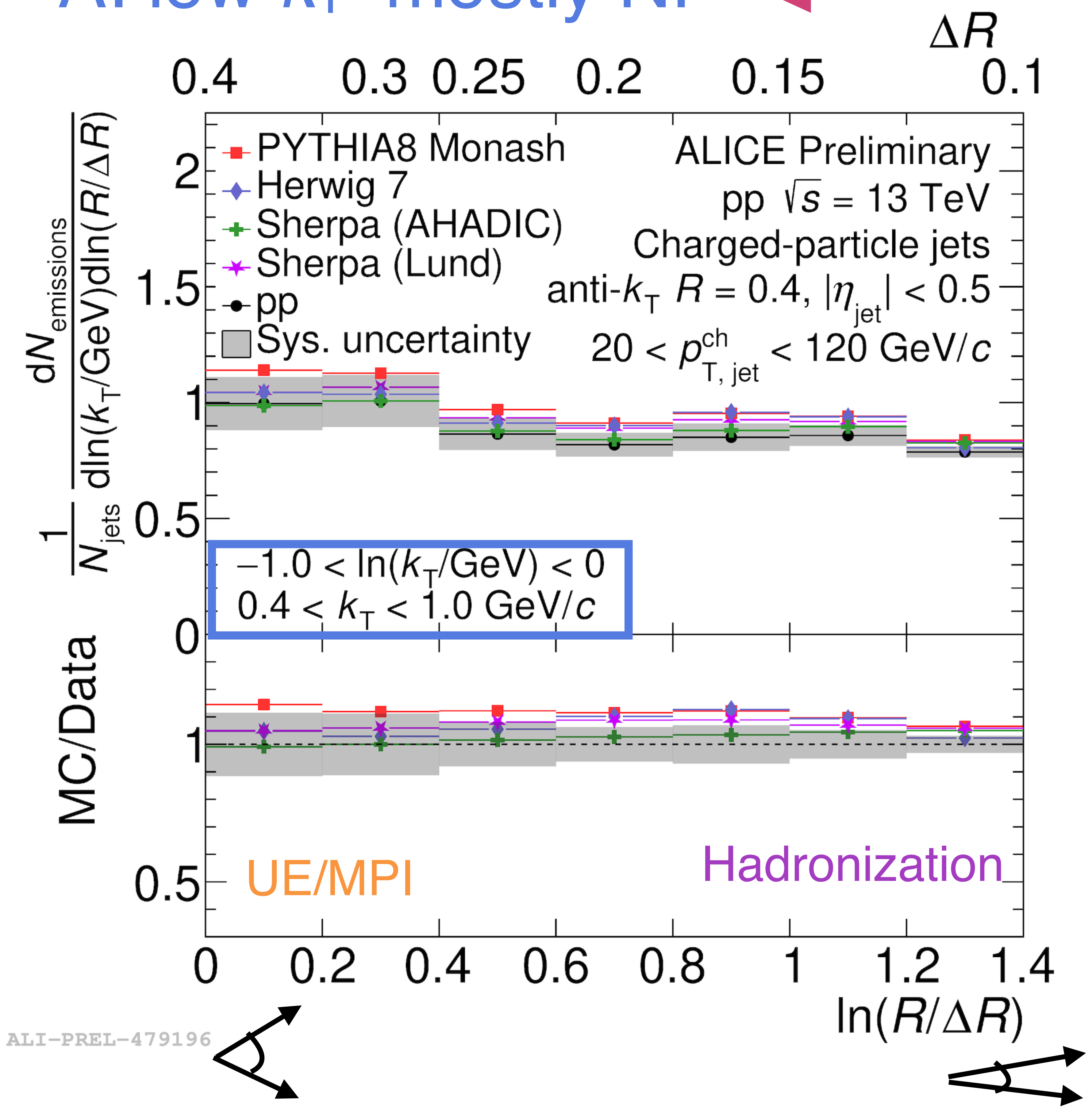
Agreement with MC ~10% in most cases

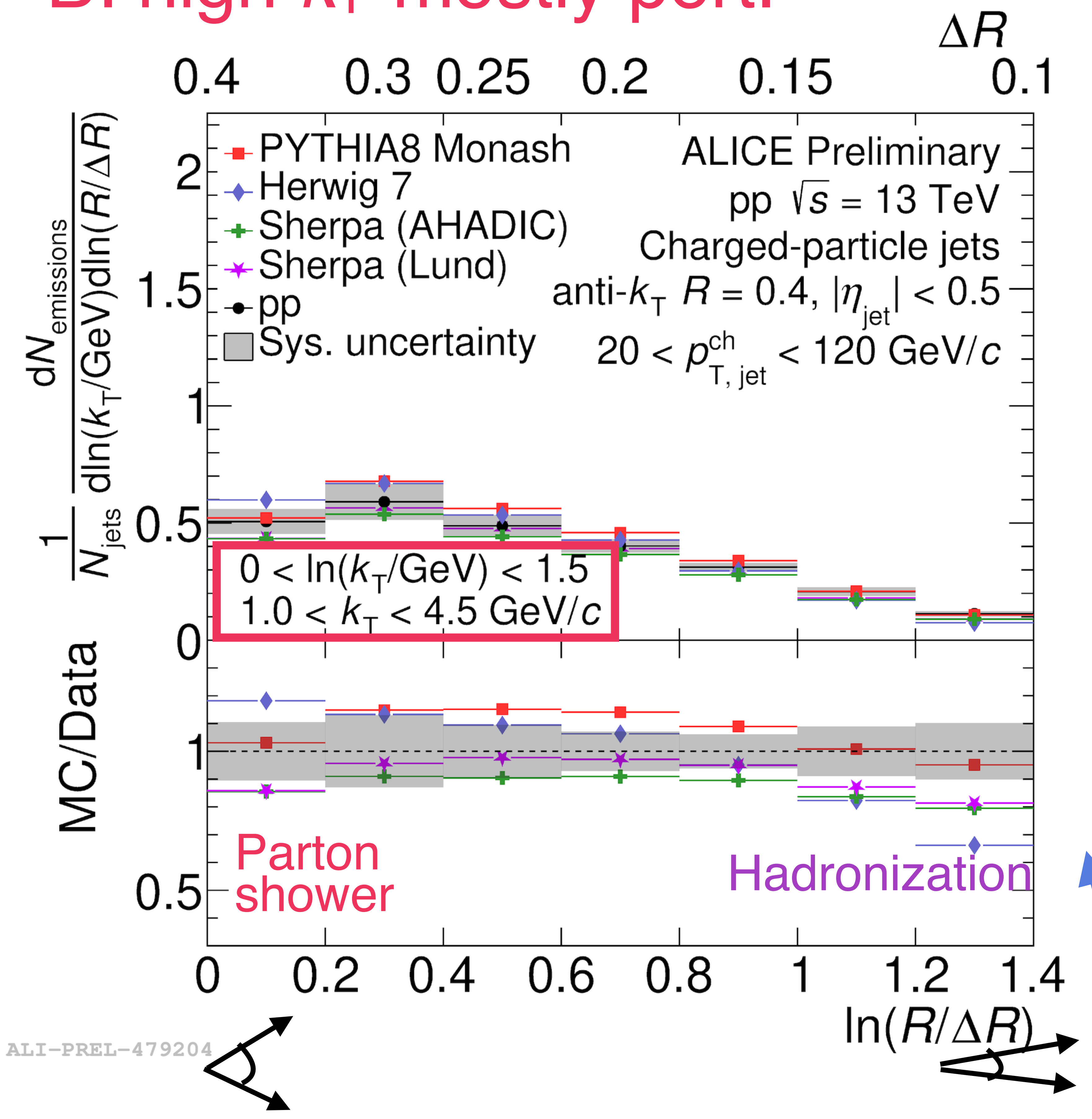
ALICE-PUBLIC-2021-002



A: low k_T mostly NP

B: high k_T mostly pert.

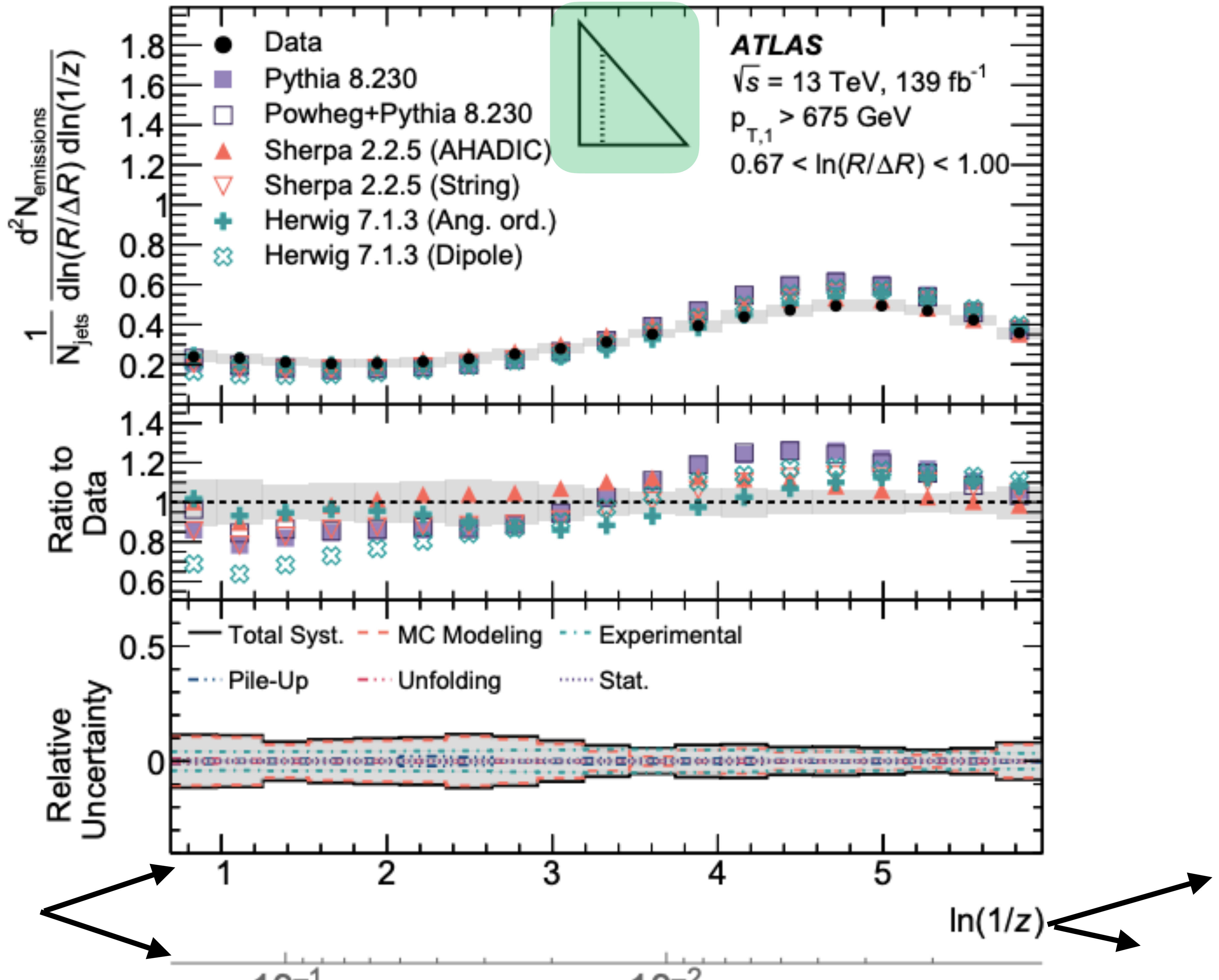


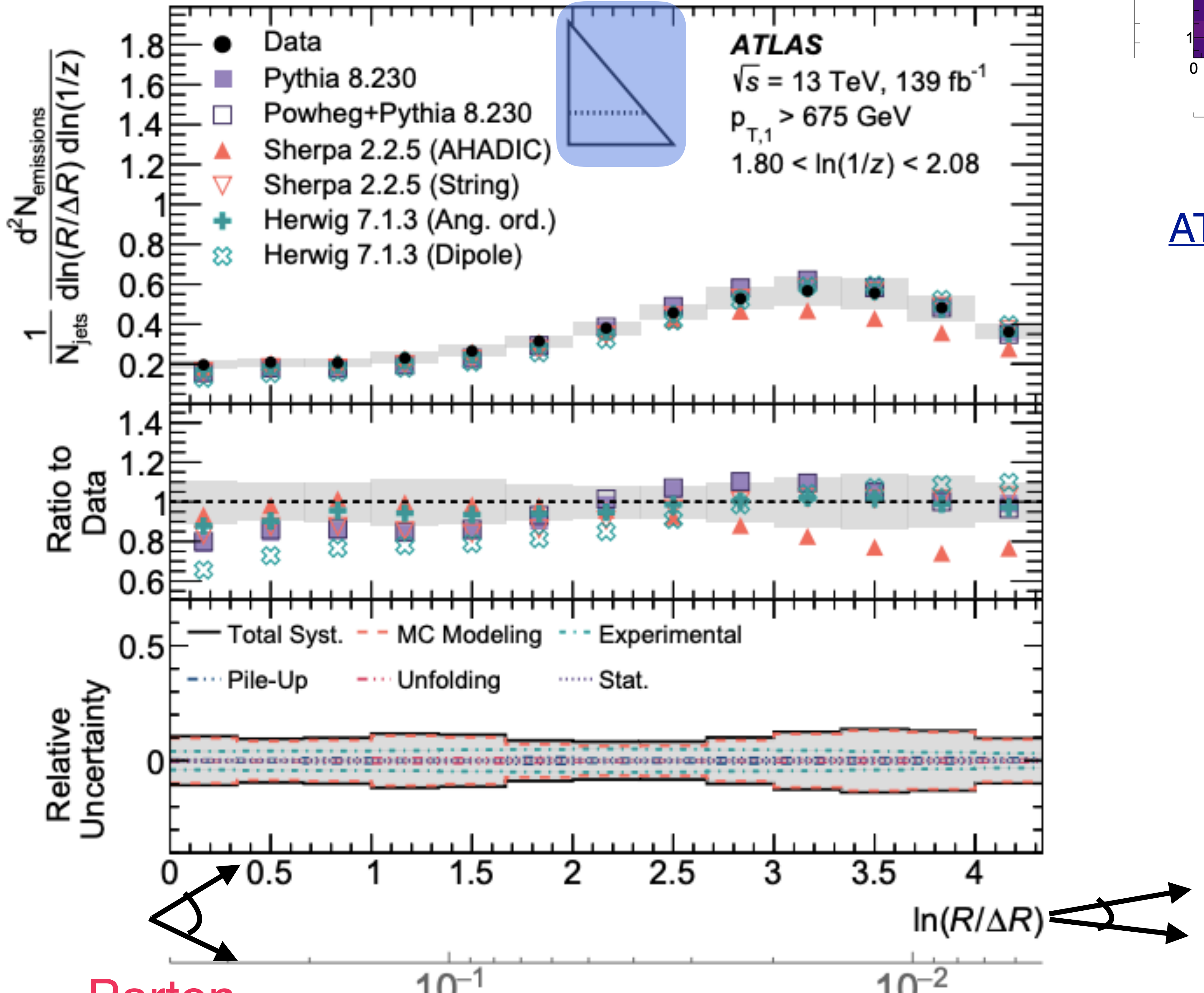


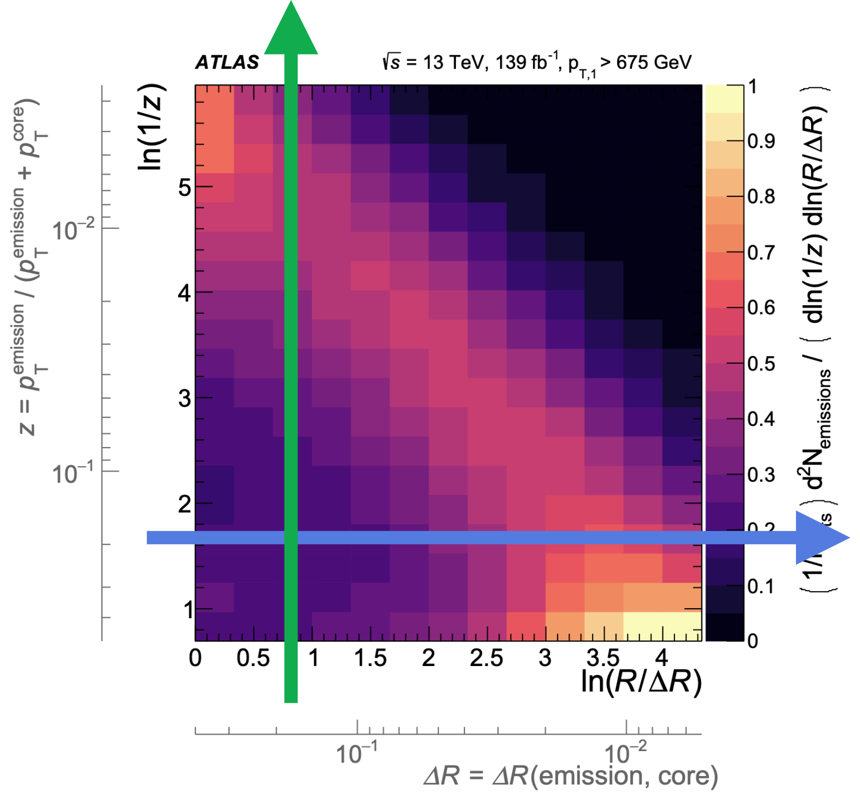
Herwig suppressed relative to data for hard collinear splitting

Regions of the Lund plane

Good agreement with MC in most cases







ATLAS PRL 124 (2020)

Parton shower

UE/MPI

Parton shower

Hadronization

Differences seen for Herwig PS implementation

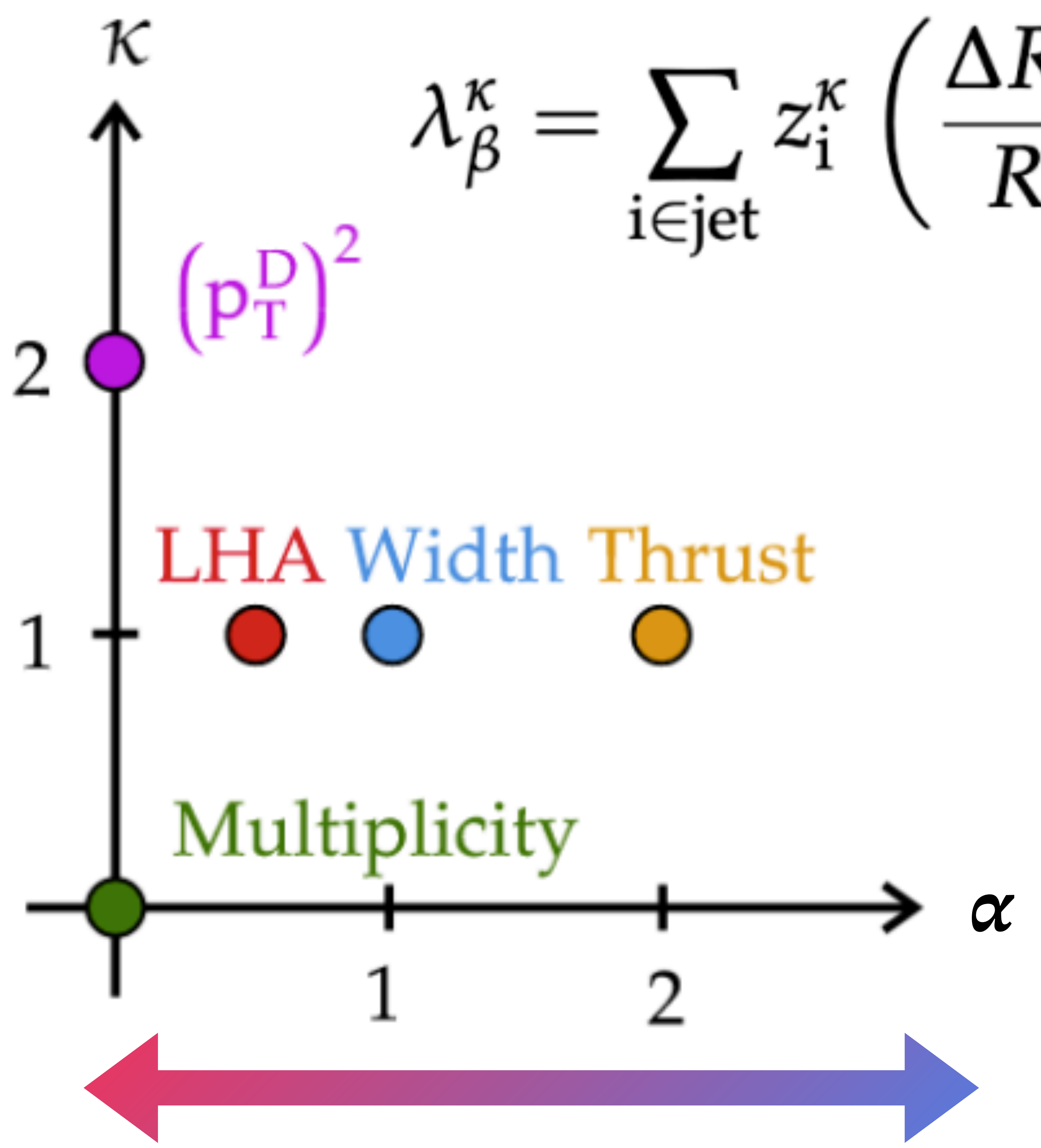
Differences seen for Sherpa hadronization implementation

Generalize angularities

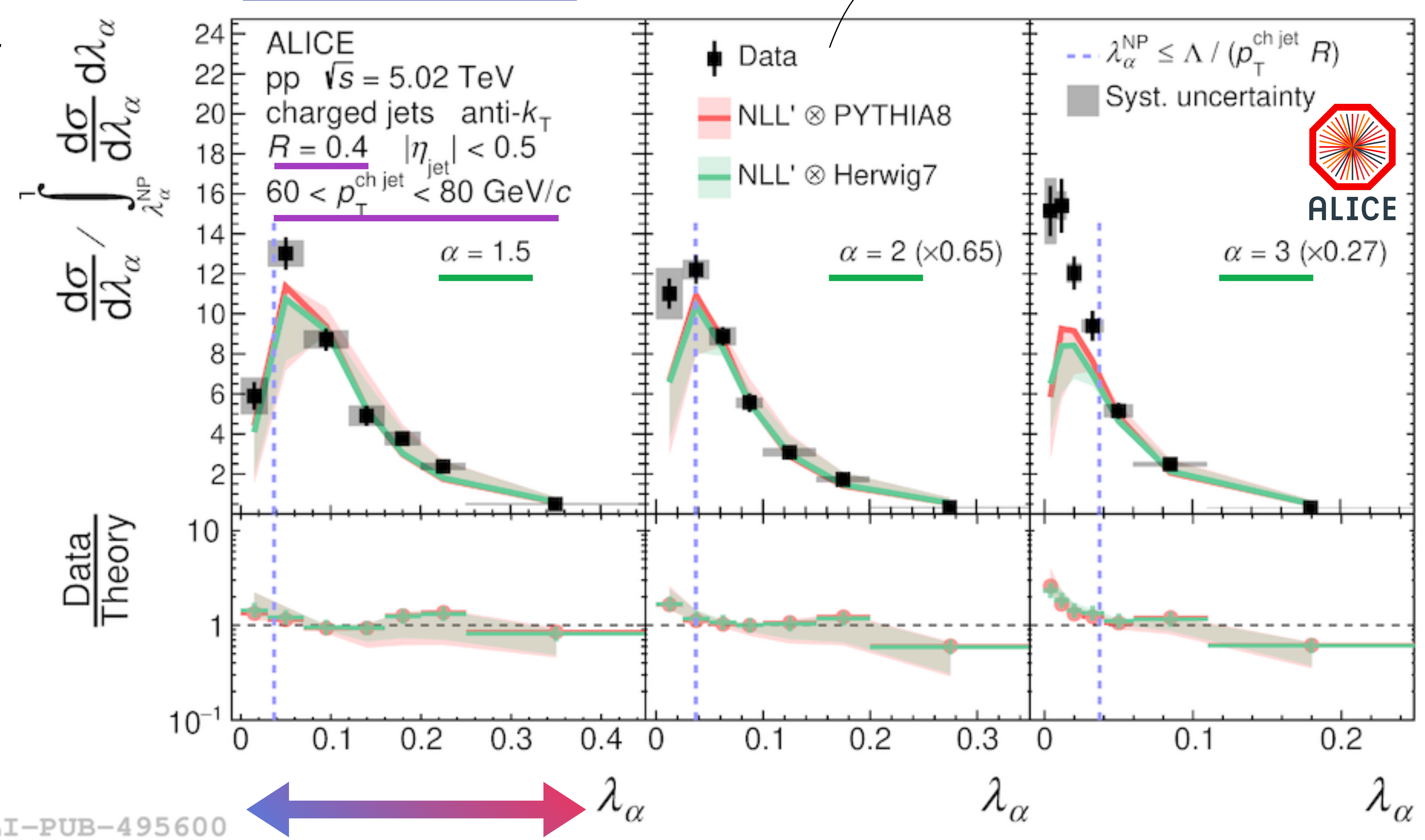
α scales from pert. to np

Exponents vary aspects of QCD

$$\lambda_\beta^\kappa = \sum_{i \in \text{jet}} z_i^\kappa \left(\frac{\Delta R_i}{R}\right)^\alpha$$



ALICE arXiv:2107.11303



λ scales from np to pert.

NNL' pQCD calculations describe data fairly well in perturbative regions

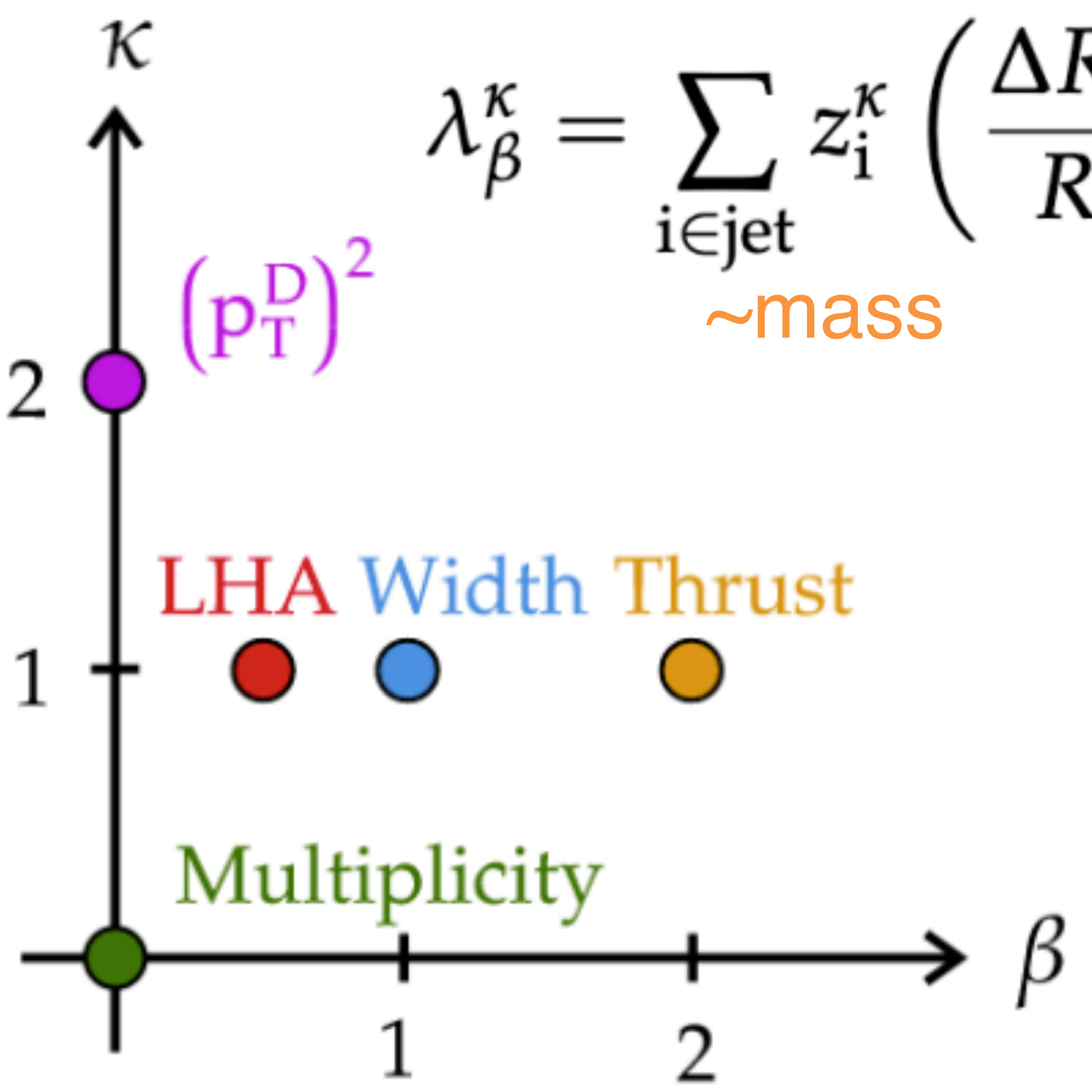
Generalized angularities

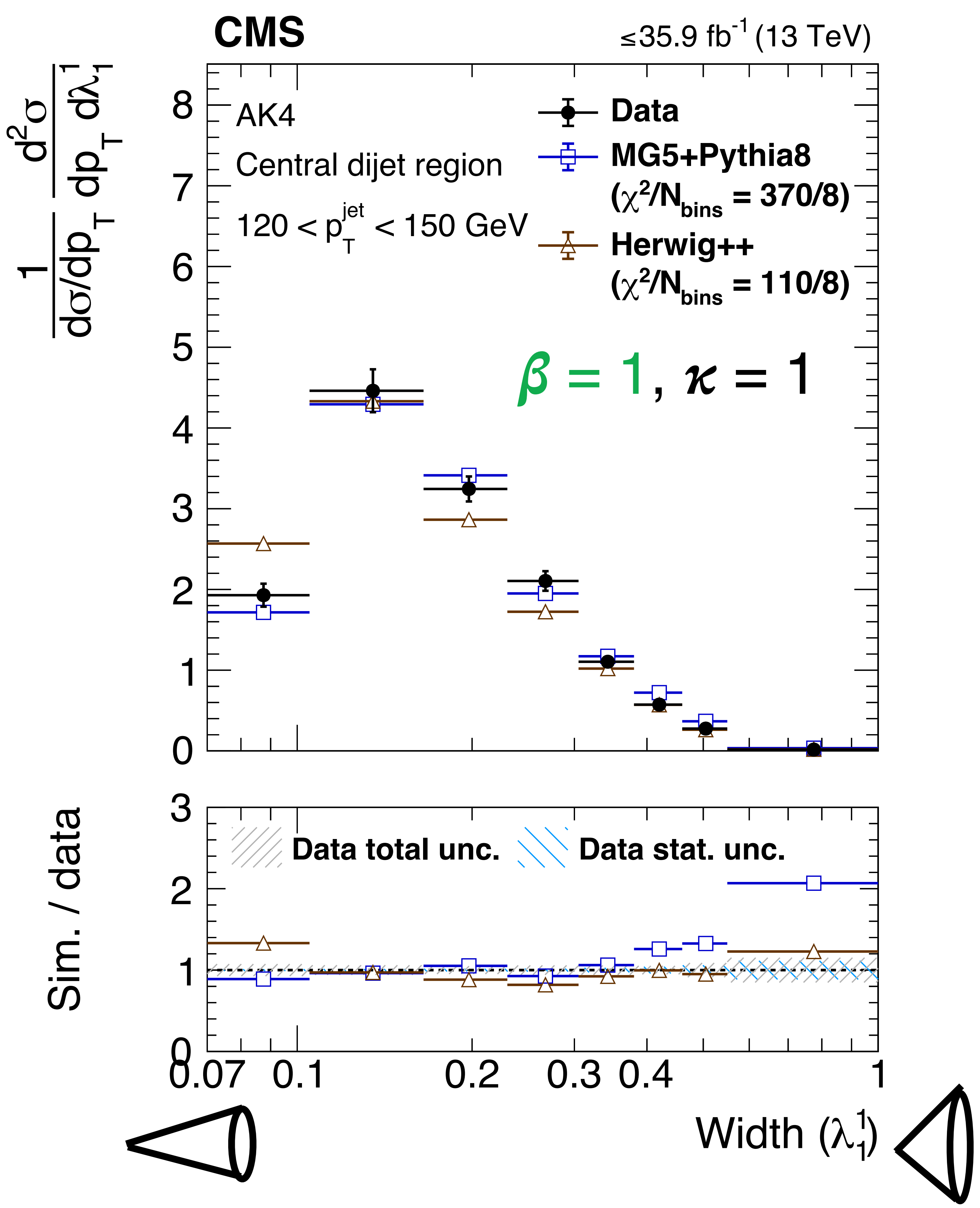
CMS JHEP 01 (2022) 188
ALICE arXiv:2107.11303

Vary R, jet p_T, λ, β, κ all changes the pert. to np scale!

$$\lambda_\beta^\kappa = \sum_{i \in \text{jet}} z_i^\kappa \left(\frac{\Delta R_i}{R} \right)^\beta$$

~mass





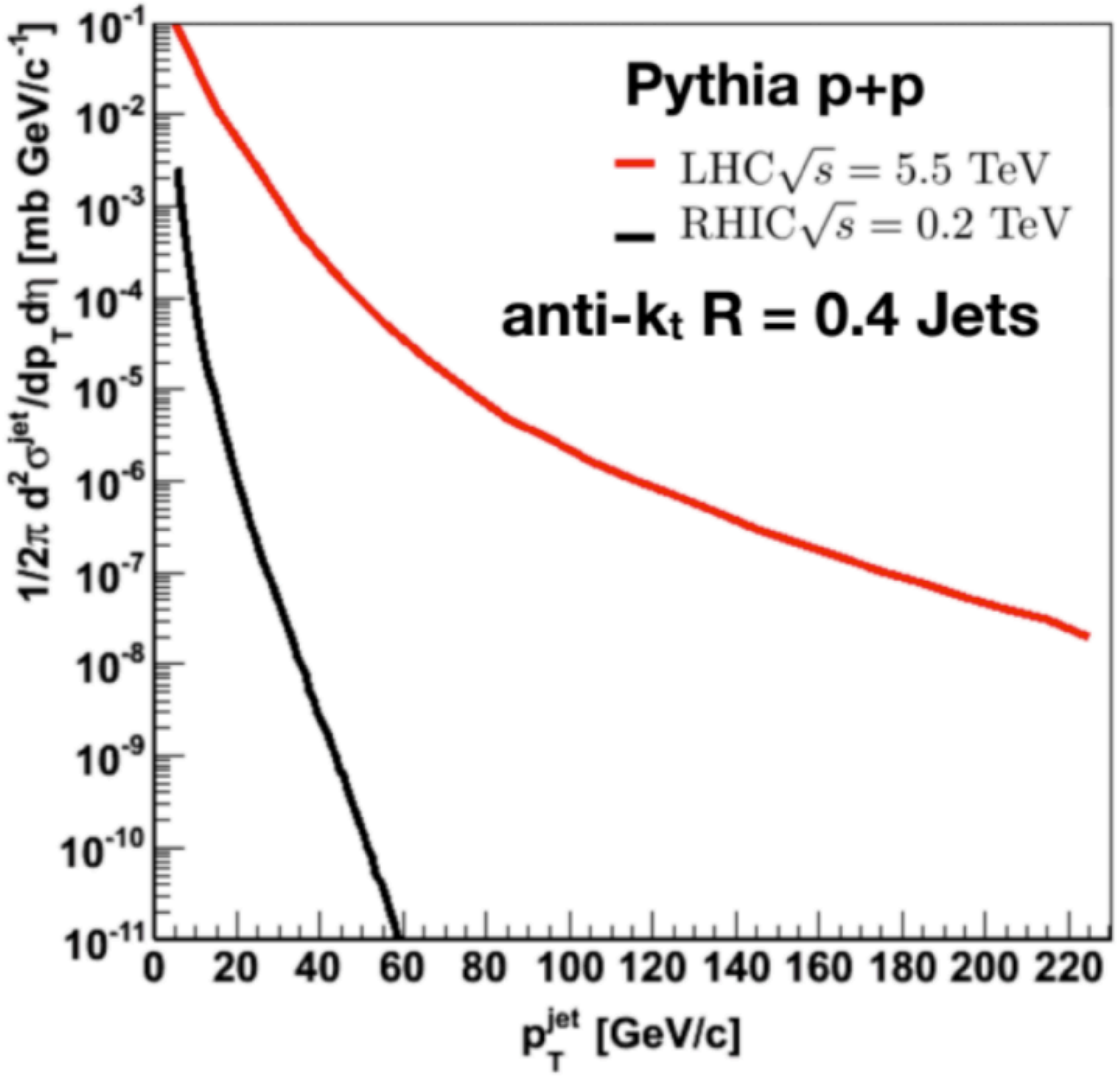
Exponents vary aspects of QCD

Shape and structure of jet varies significantly

Jets at RHIC vs. LHC

- Keep in mind: not a direct comparison, kinematics and QGP medium different!

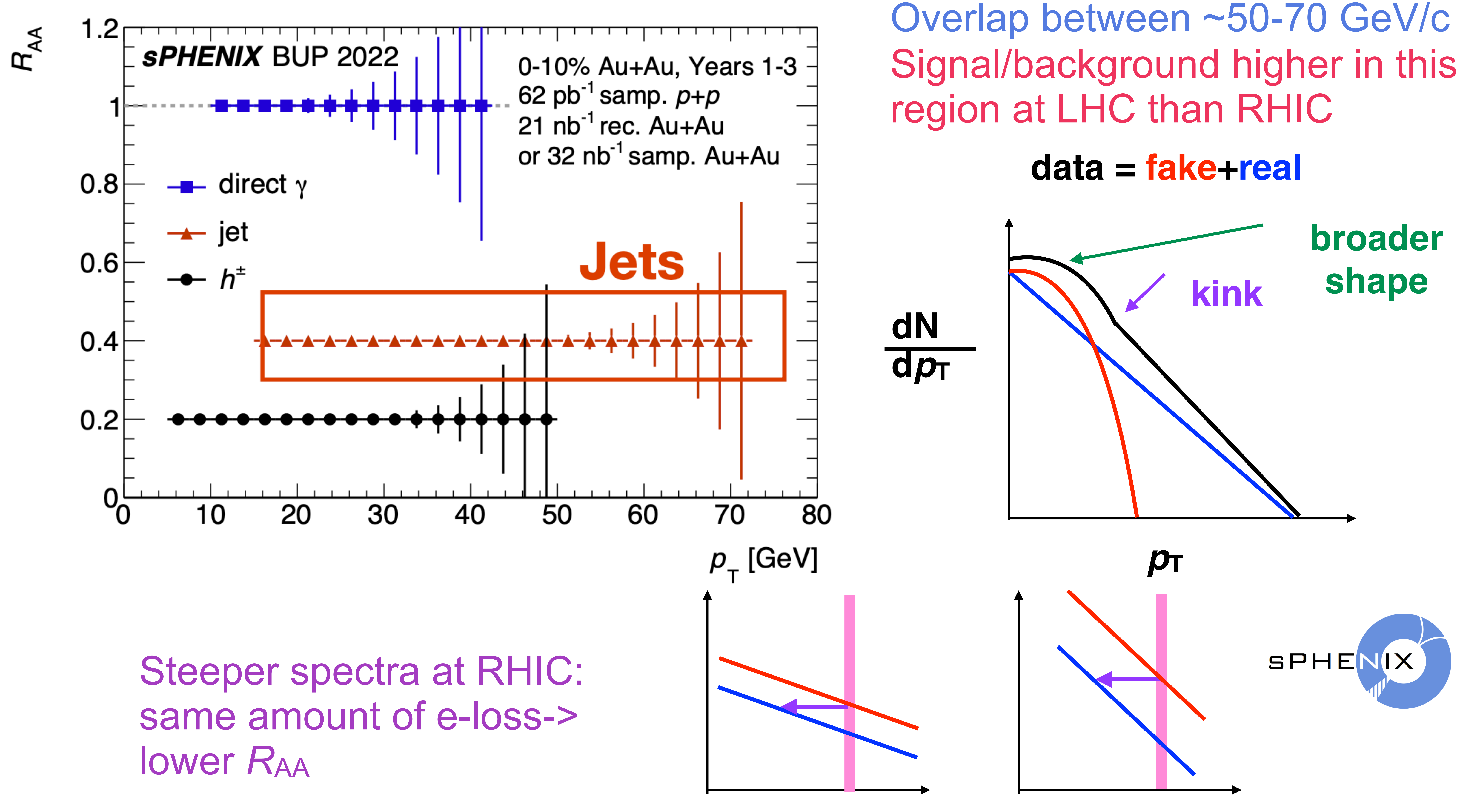
QGP at LHC hotter, denser, and longer lived than RHIC!



	RHIC	**LHC**
Center-of-Mass ($\sqrt{s}$)	3-510 GeV	2.76-5.02 TeV
Collision systems	Many species	Pb, Xe, p
Effective temperature	~220 MeV PHENIX: PRL 104 (2010) 132301	~300 MeV ALICE: PLB 754 (2016) 235-248
Detectors	STAR, PHENIX, sPHENIX	ALICE, ATLAS, CMS, LHCb

Jet spectra at RHIC is steeper and contains a higher quark fraction at the same p_T.

Inclusive jet suppression



Overlap between ~50-70 GeV/c

Signal/background higher in this region at LHC than RHIC

Steeper spectra at RHIC: same amount of e-loss-> lower R_{AA}

PRC 102 (2020) 5, 054913 PRC **101**, 034911 PLB 790 (2019) 108