Latest techniques for studying perturbative and non-perturbative physics with jets at colliders

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CFNS Workshop - Advancing the Understanding of Non-Perturbative QCD using Energy Flows, BNL

Monday, September 19th 2022

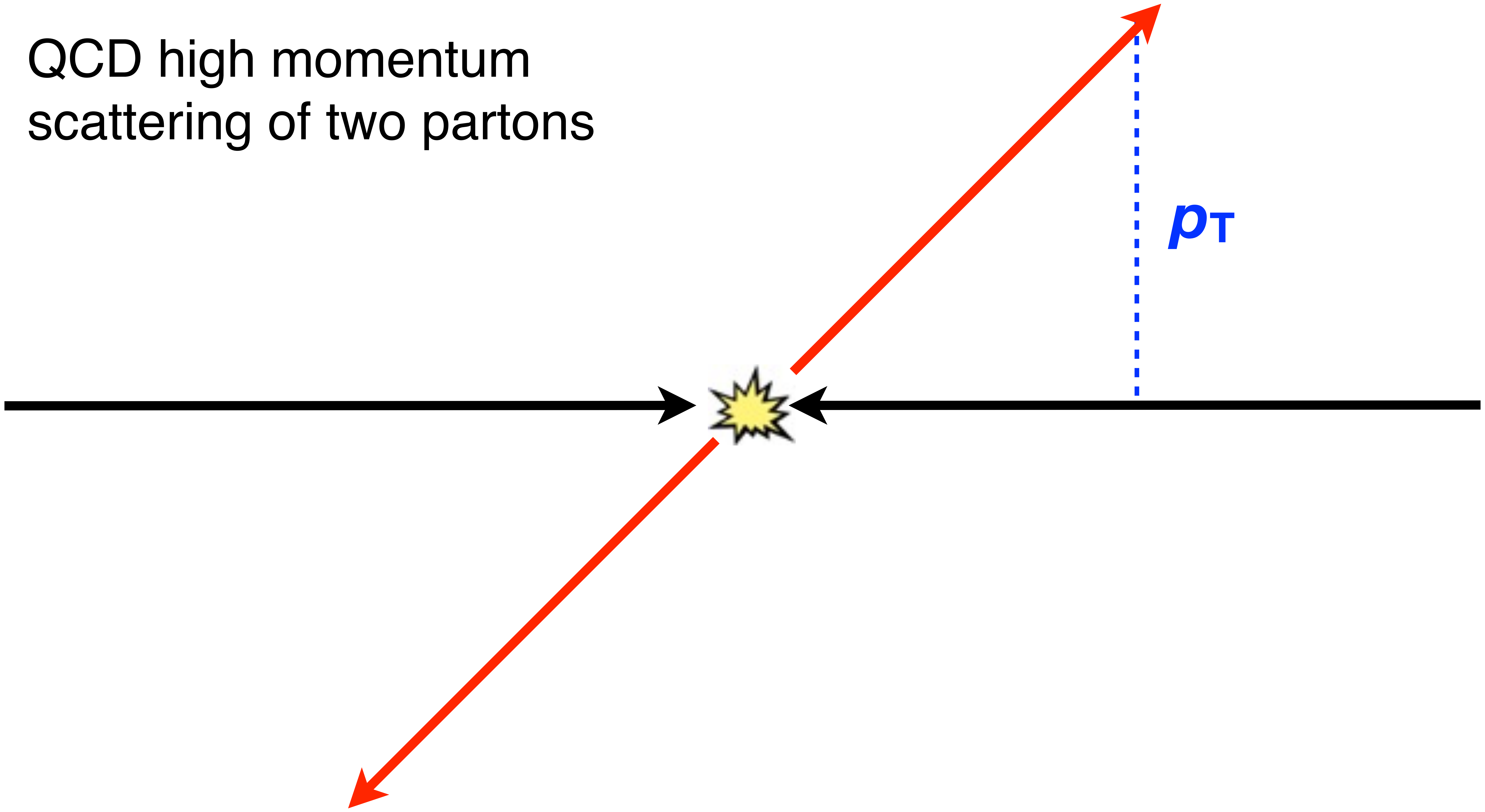
Wright Laboratory

Yale

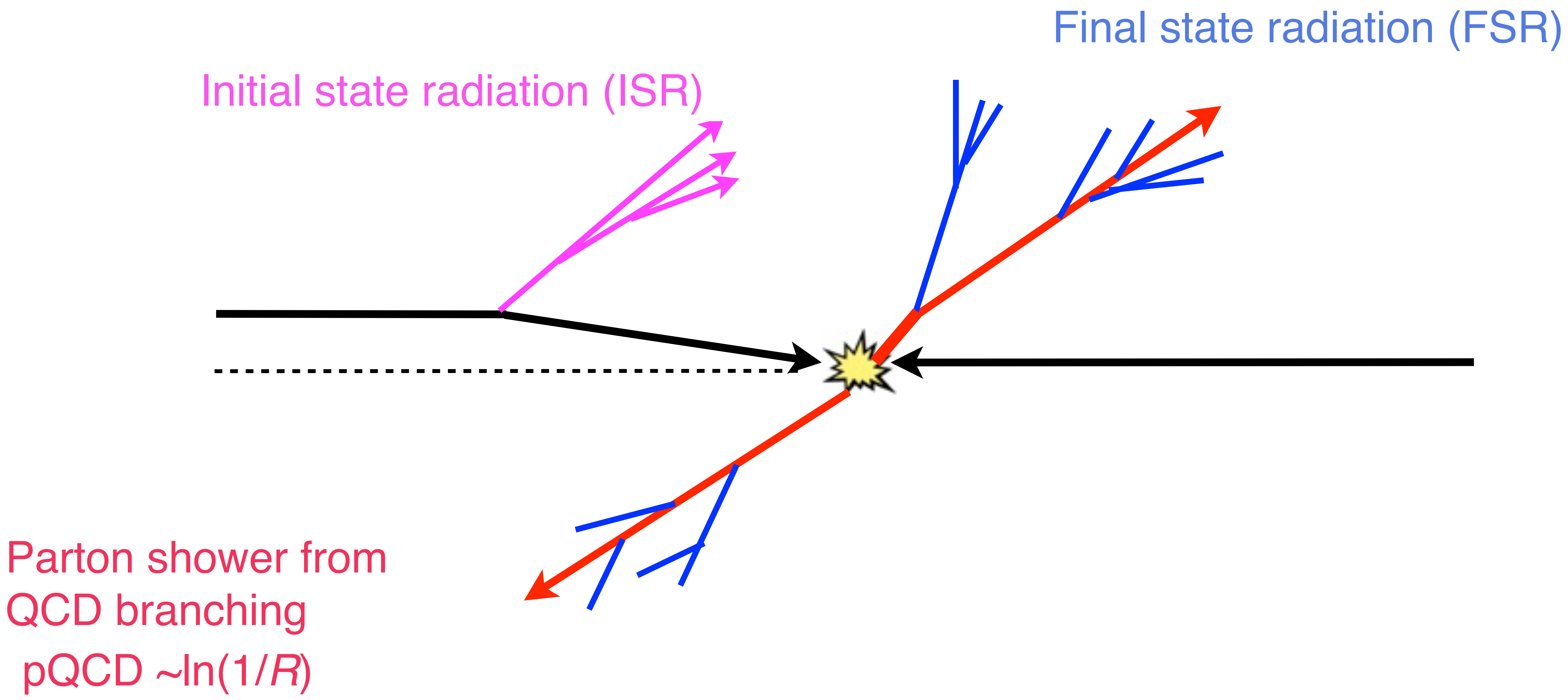
Why jets?

Why jets?

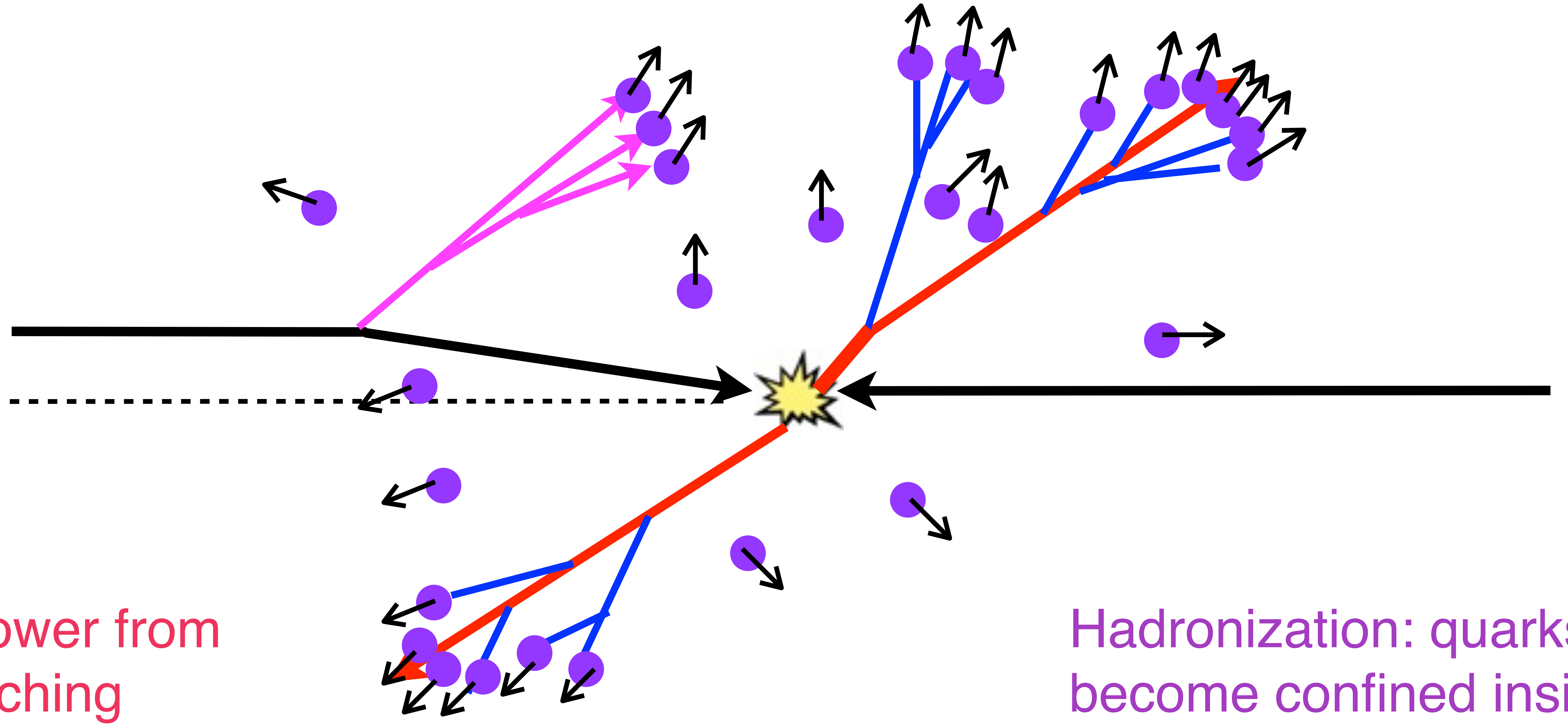
QCD high momentum
scattering of two partons



Why jets?


Final state radiation (FSR)
Initial state radiation (ISR)
Parton shower from
QCD branching
pQCD ~ln(1/*R*)

Why jets?



Parton shower from QCD branching

pQCD ~ln(1/*R*)

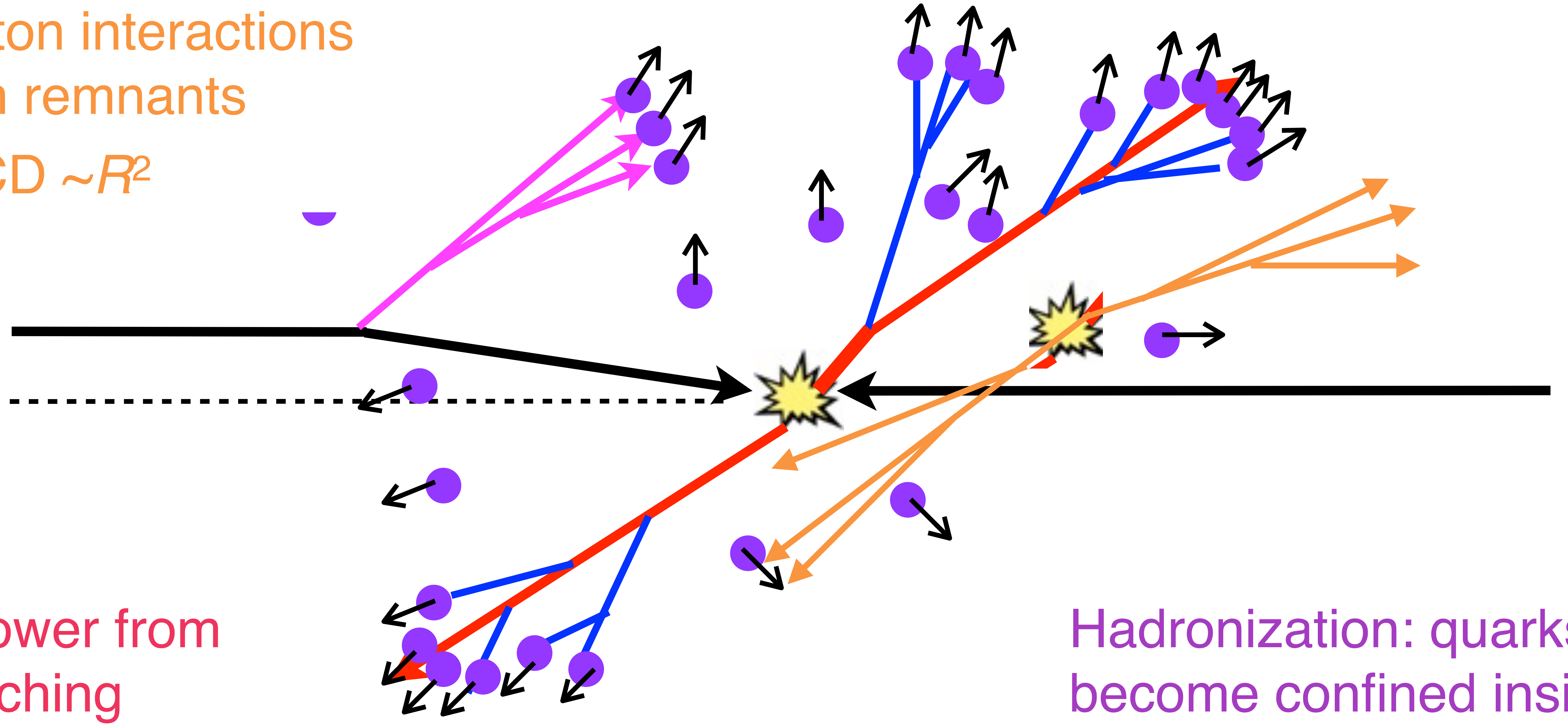
Hadronization: quarks and gluons become confined inside hadrons

npQCD ~1/*R*

Why jets?

Underlying Event (UE): multiple parton interactions (MPI), beam remnants

npQCD ~R^2



Parton shower from QCD branching

pQCD ~ln(1/R)

Hadronization: quarks and gluons become confined inside hadrons

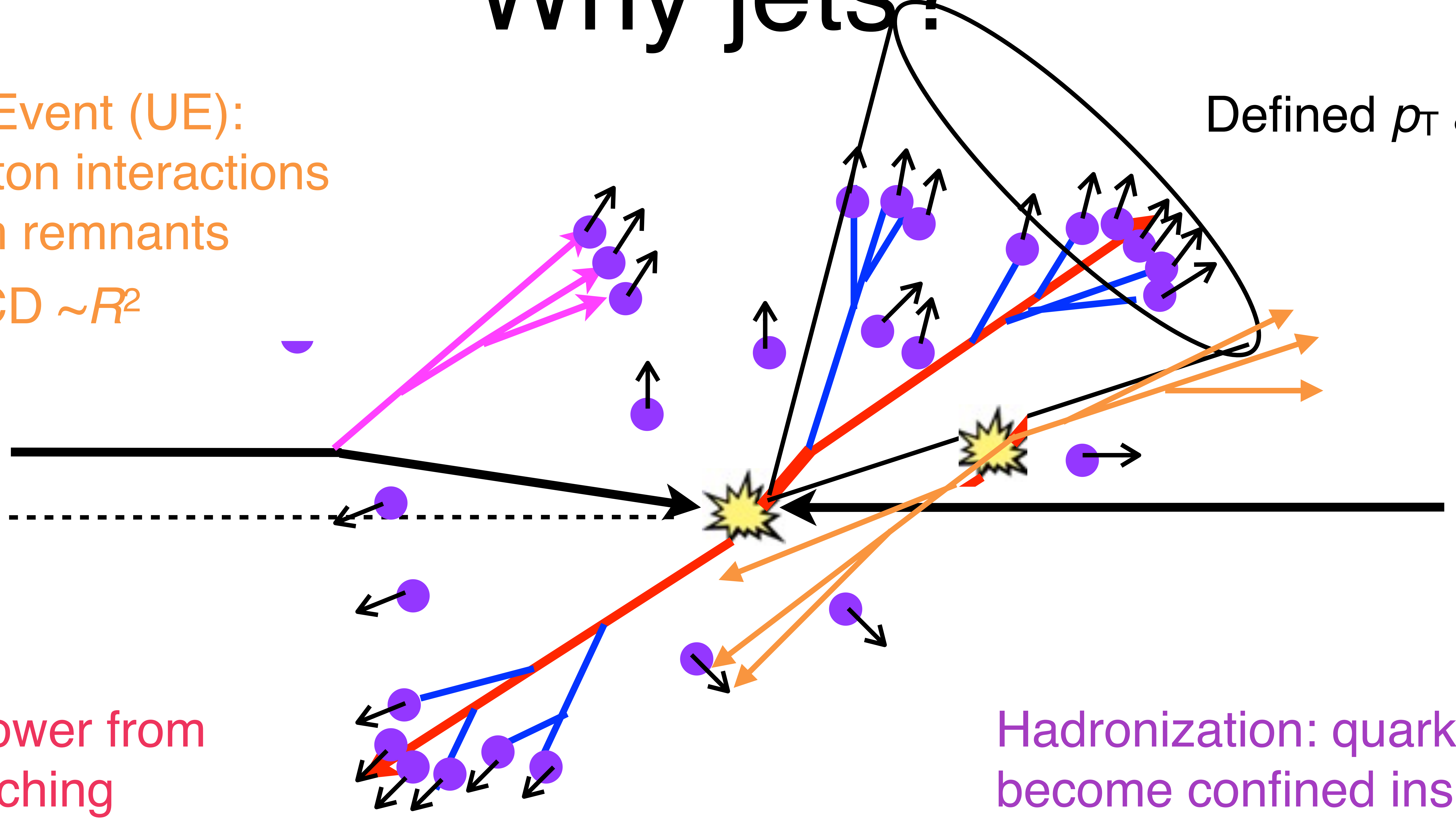
npQCD ~1/R

Why jets?

Defined p_T and R

Underlying Event (UE): multiple parton interactions (MPI), beam remnants

npQCD $\sim R^2$



Parton shower from QCD branching

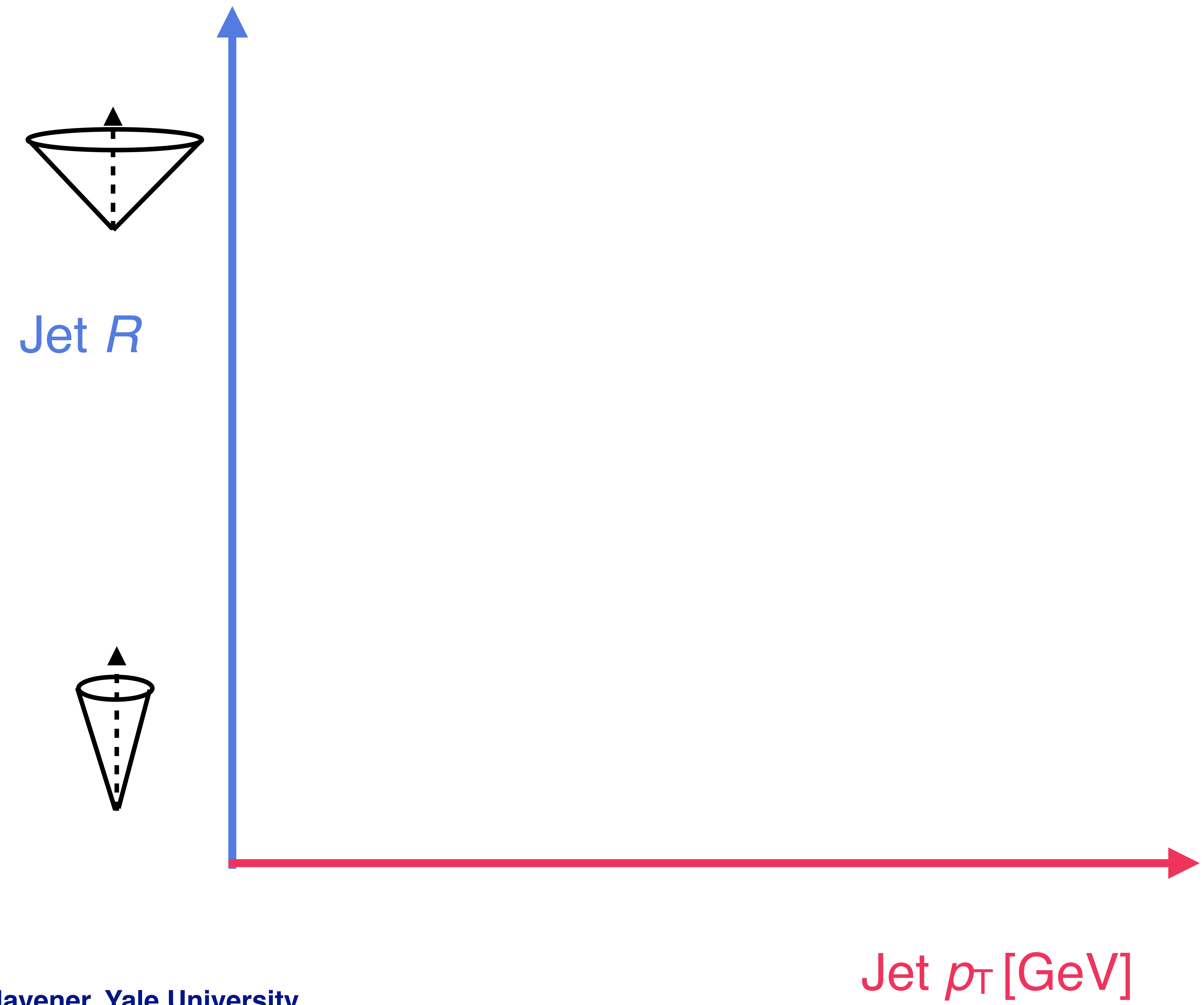
pQCD $\sim \ln(1/R)$

Hadronization: quarks and gluons become confined inside hadrons

npQCD $\sim 1/R$

Jets connect the pQCD and npQCD scales!

Jet kinematics: QCD knob



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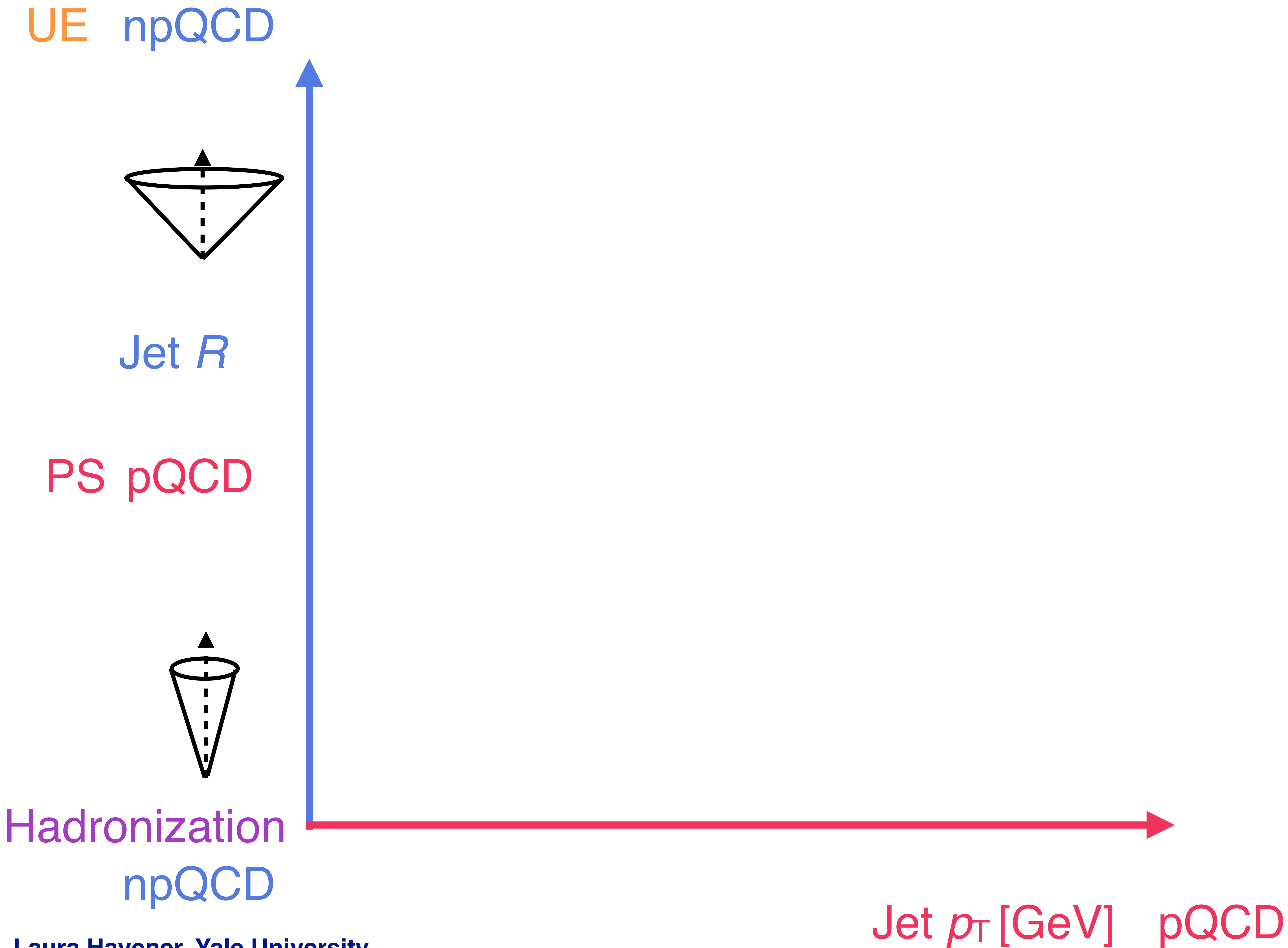
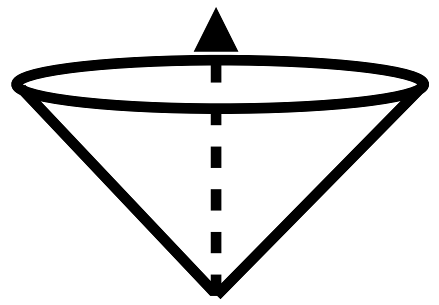
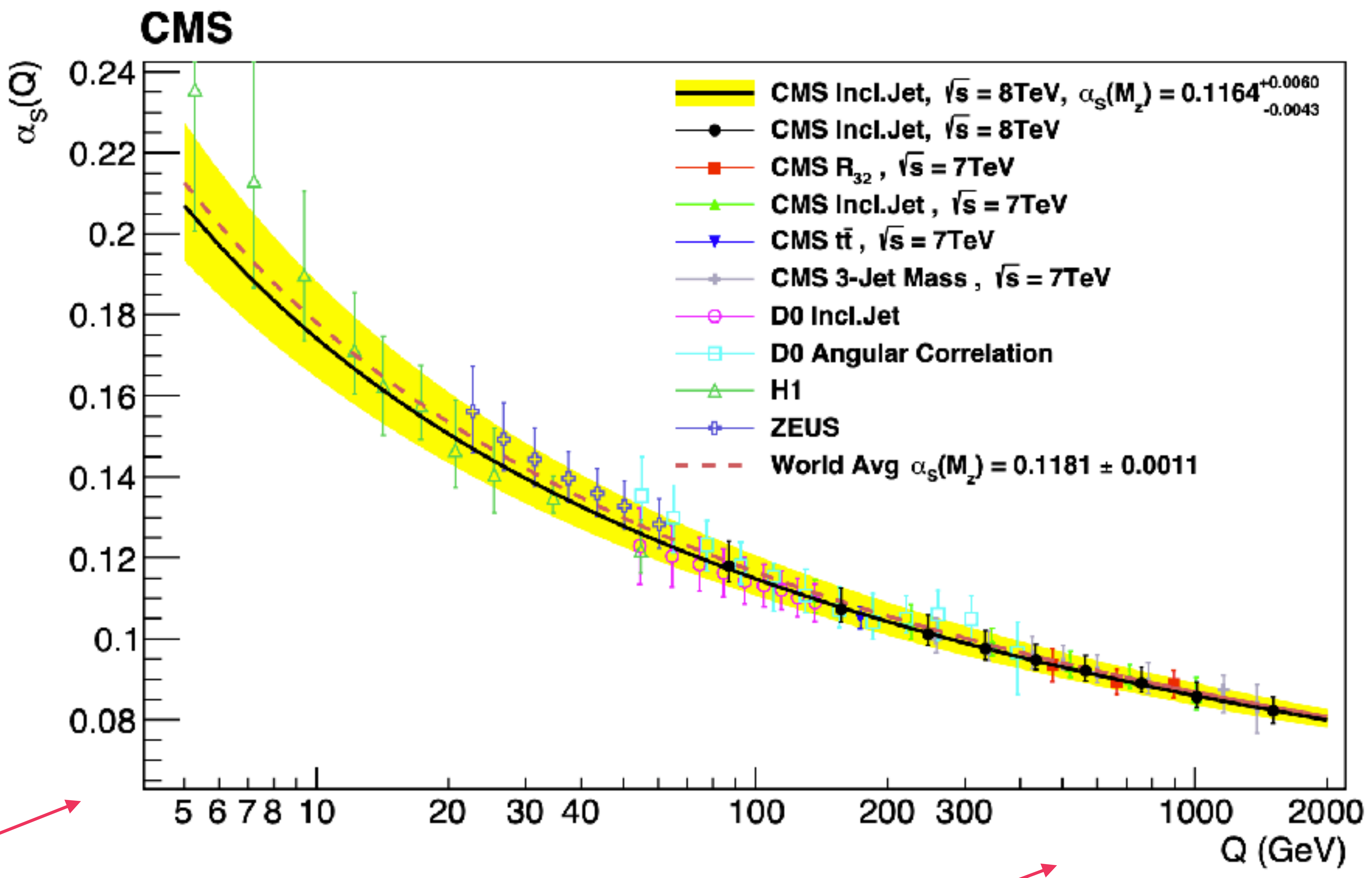


Jet kinematics: QCD knob

UE npQCD



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

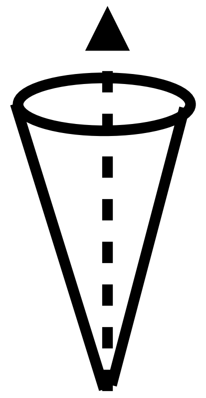


CMS JHEP 03 (2017) 156

Jet R

PS pQCD

Jet $p_T \sim Q^2$



Hadronization npQCD

Jet p_T [GeV] pQCD

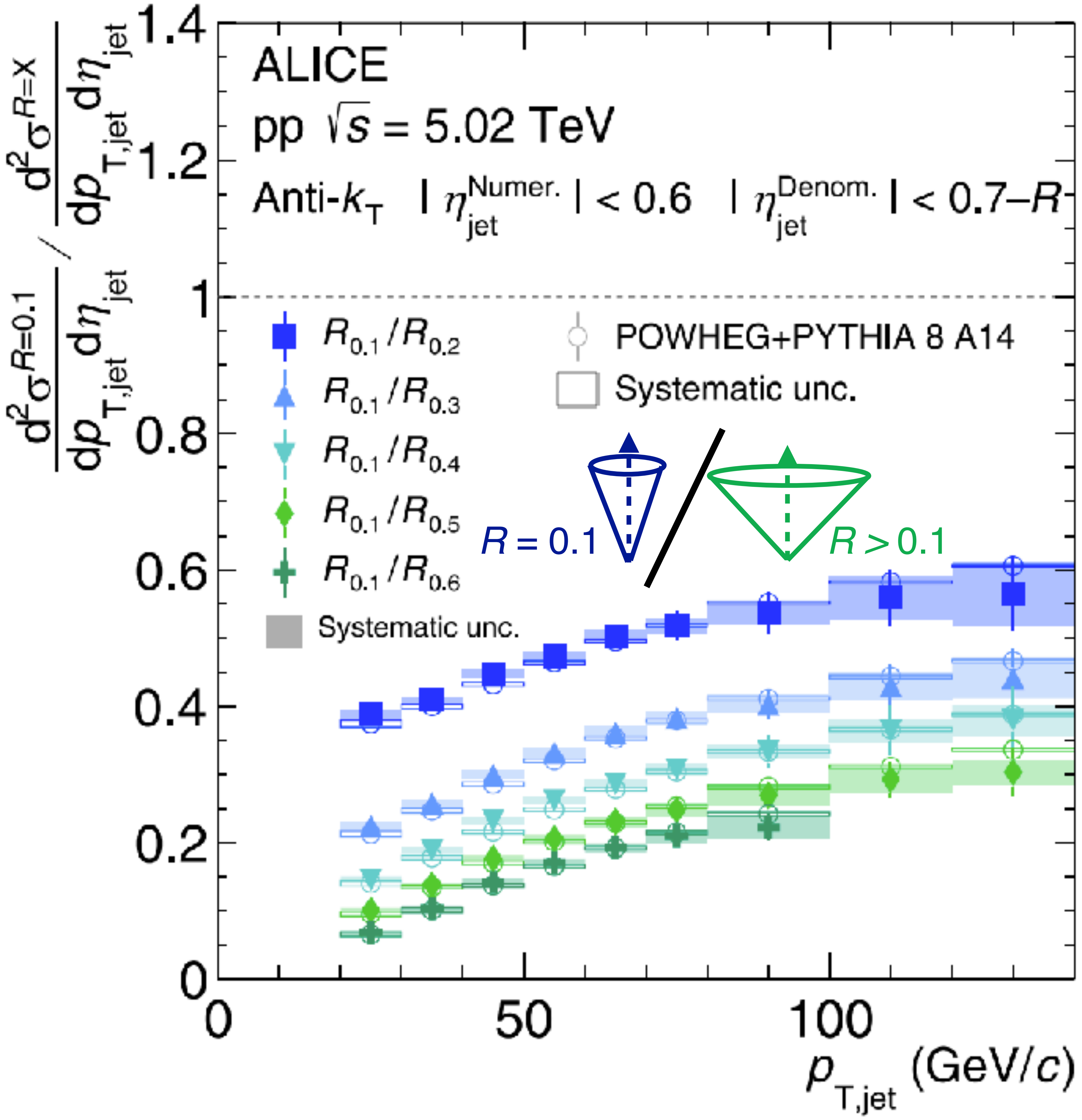
Jet kinematics: QCD knob

**Caveat: approximate ranges!

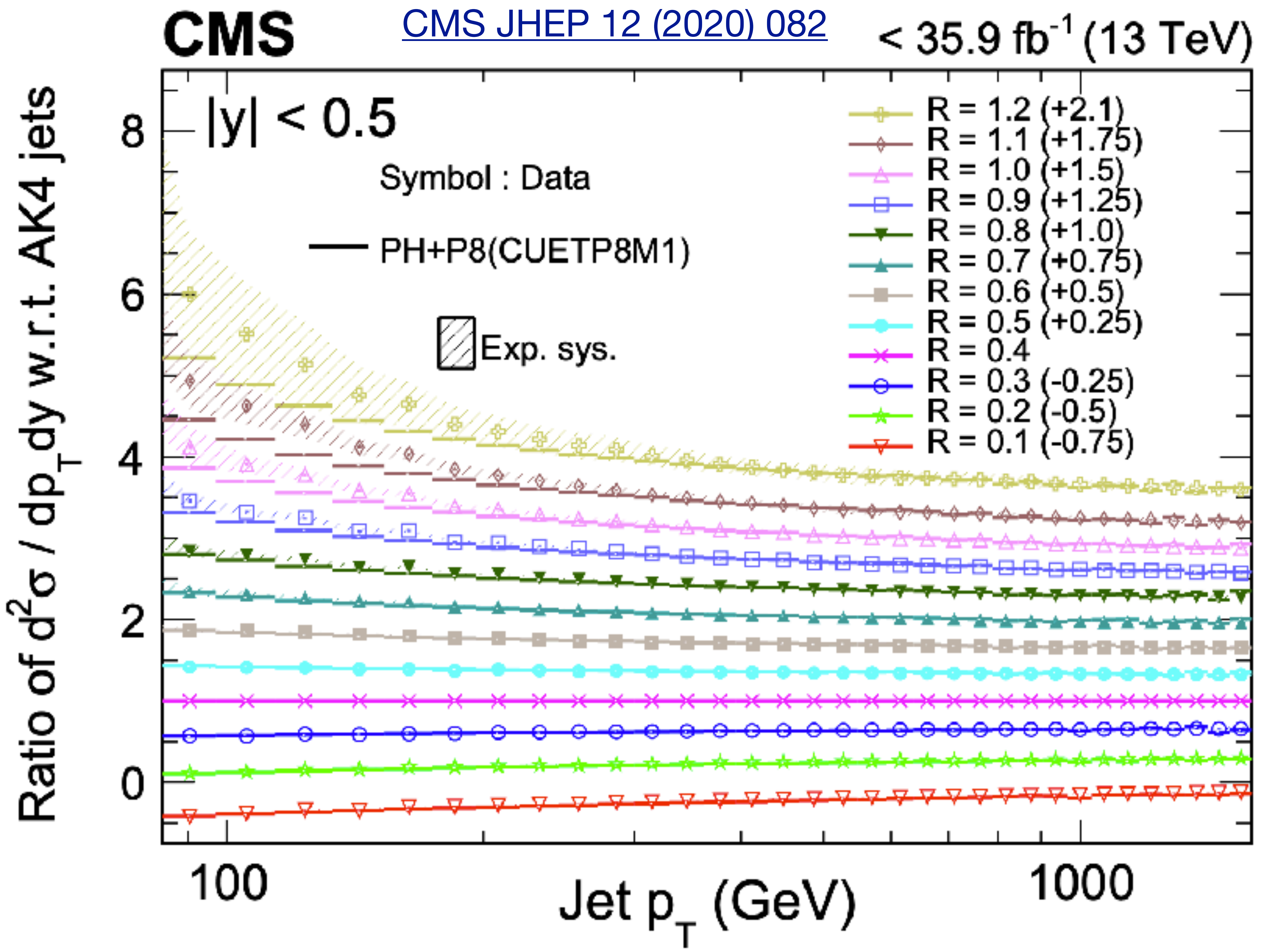
Radial scan: varying perturbative scale

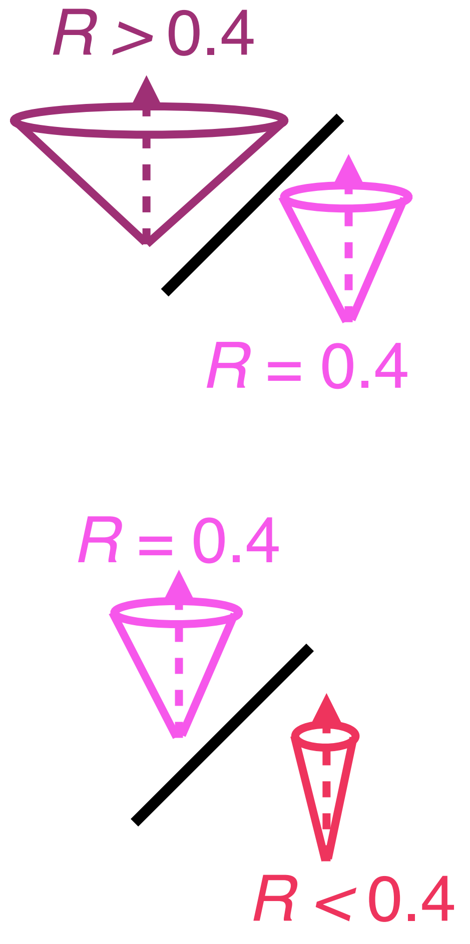
ALICE PRC **101**, 034911

Input to constrain MC generators



CMS JHEP 12 (2020) 082





Jet population evolves with R and p_T

Jet p_T [GeV]

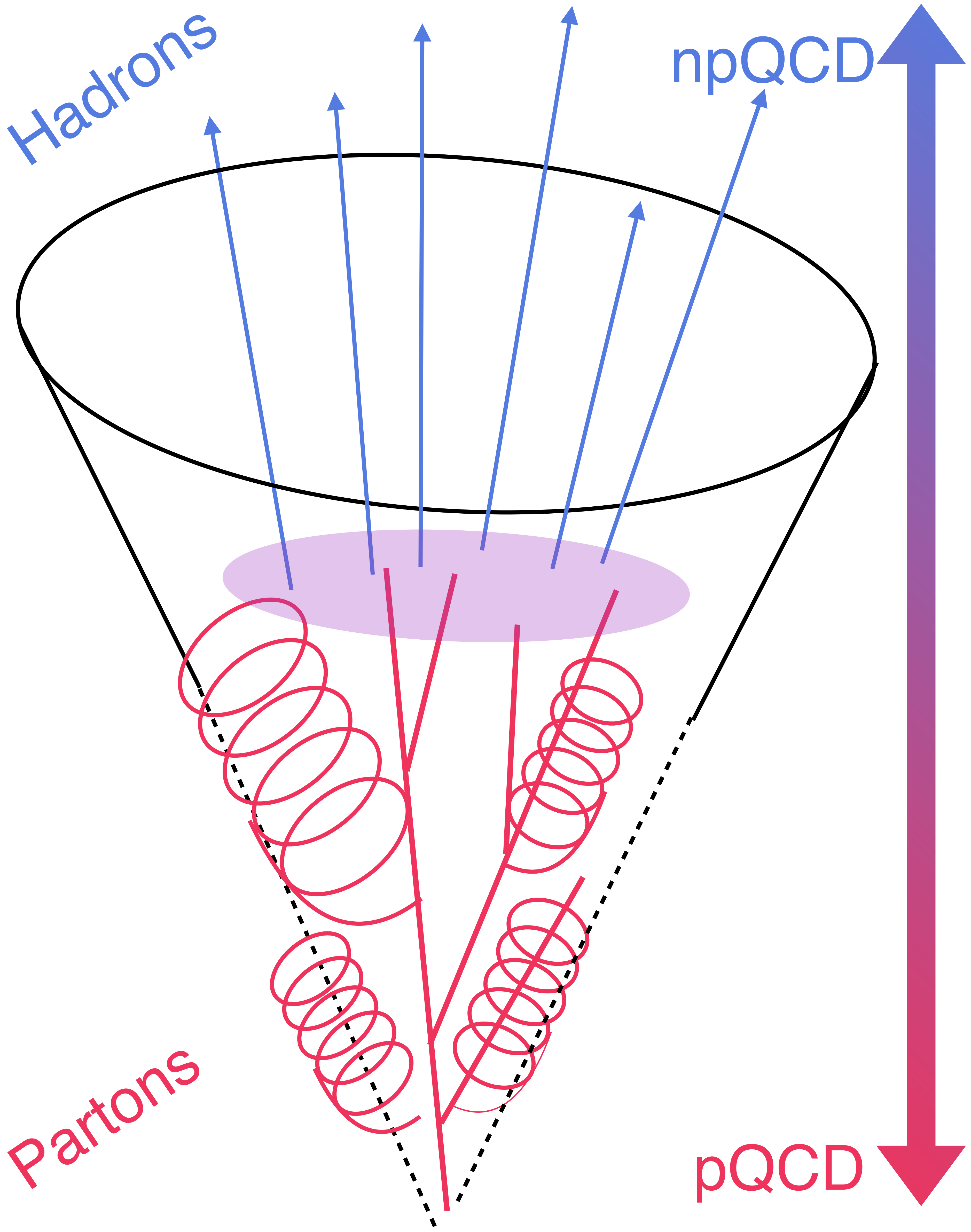
Jet internal structure

- Different variables probe different scales

➡ Distribution of charged hadrons inside the jet

Sensitive to hadronization

➡ Subjets from hard parton splittings



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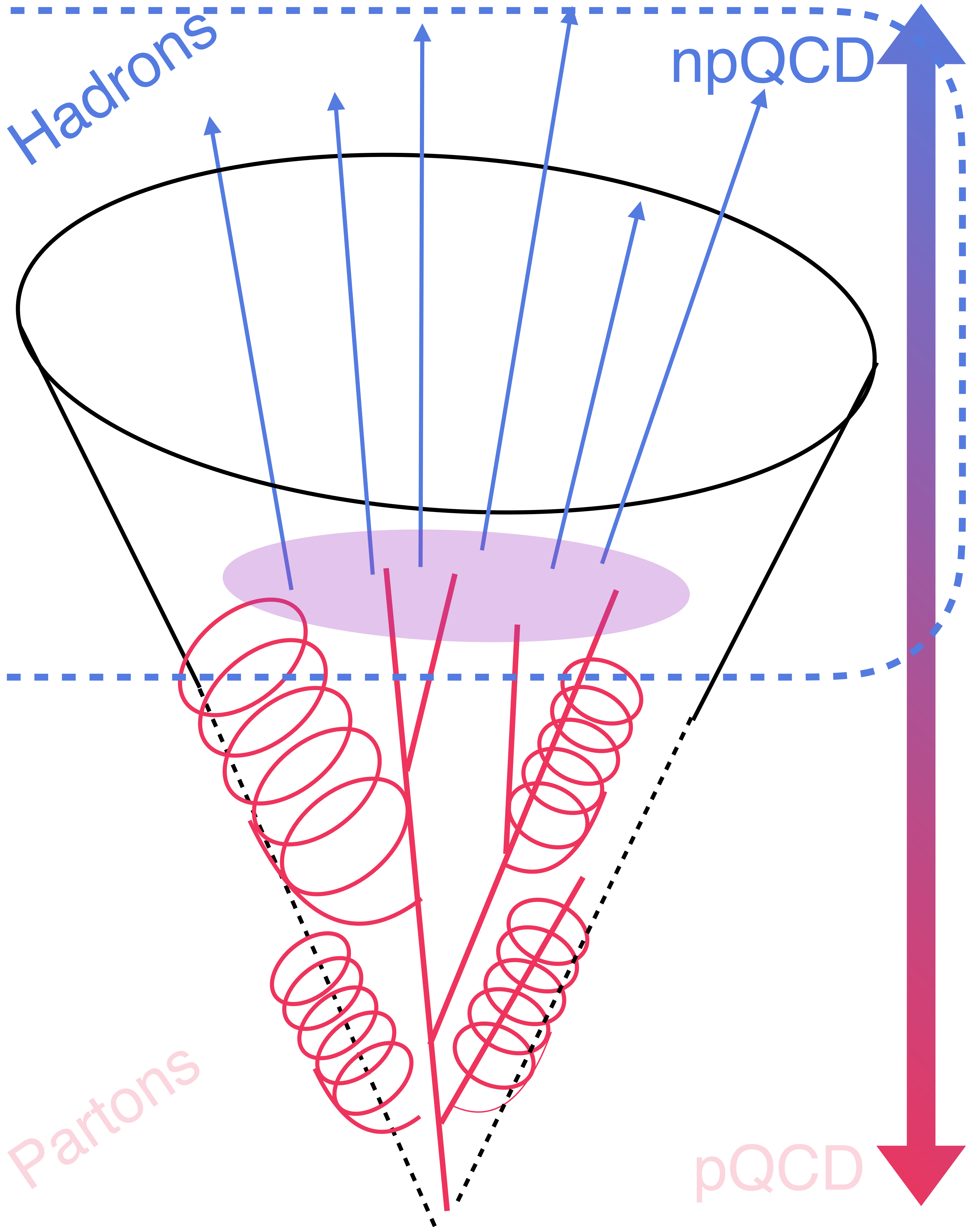
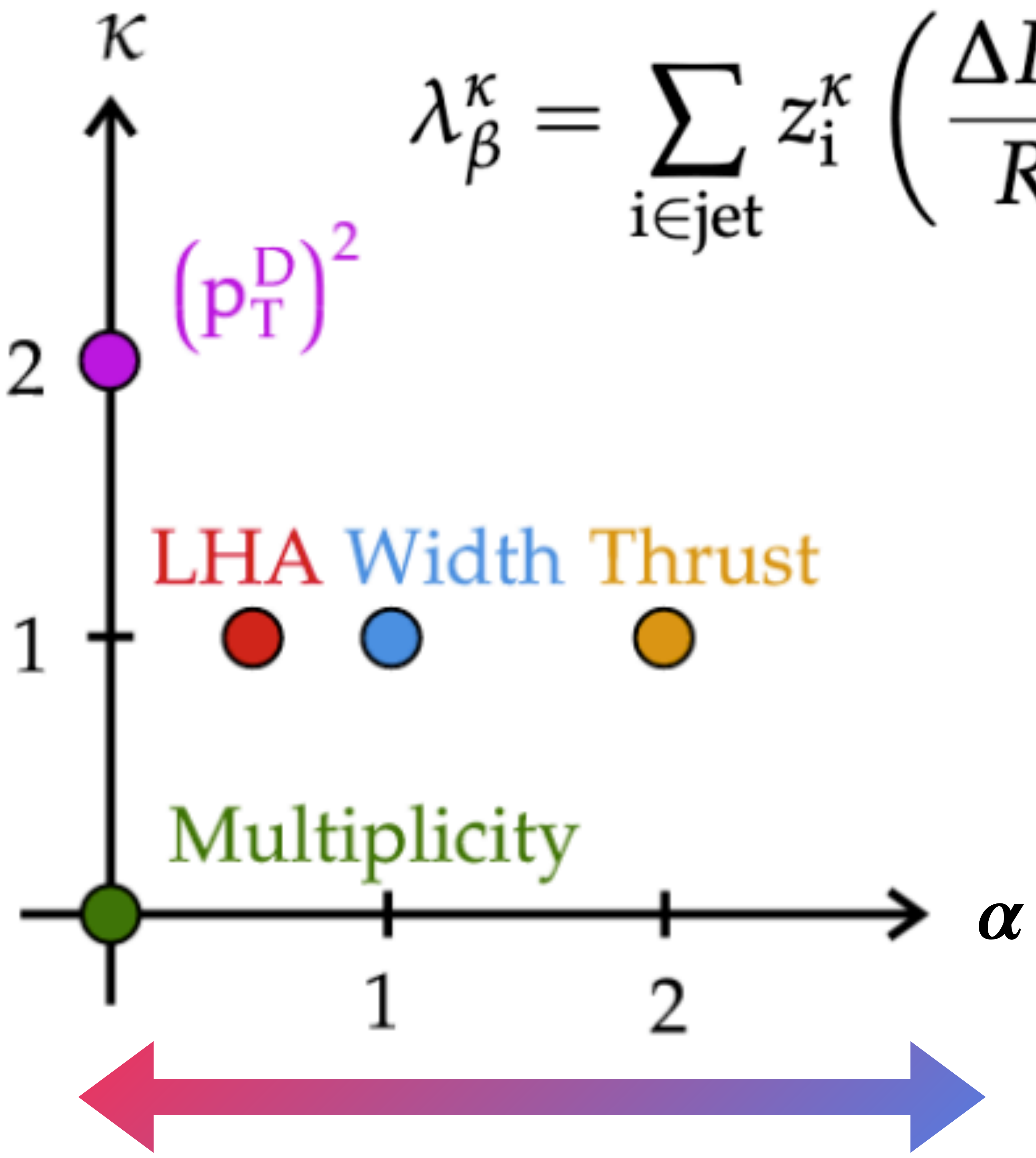


Generalize angularities

Exponents vary aspects of QCD

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



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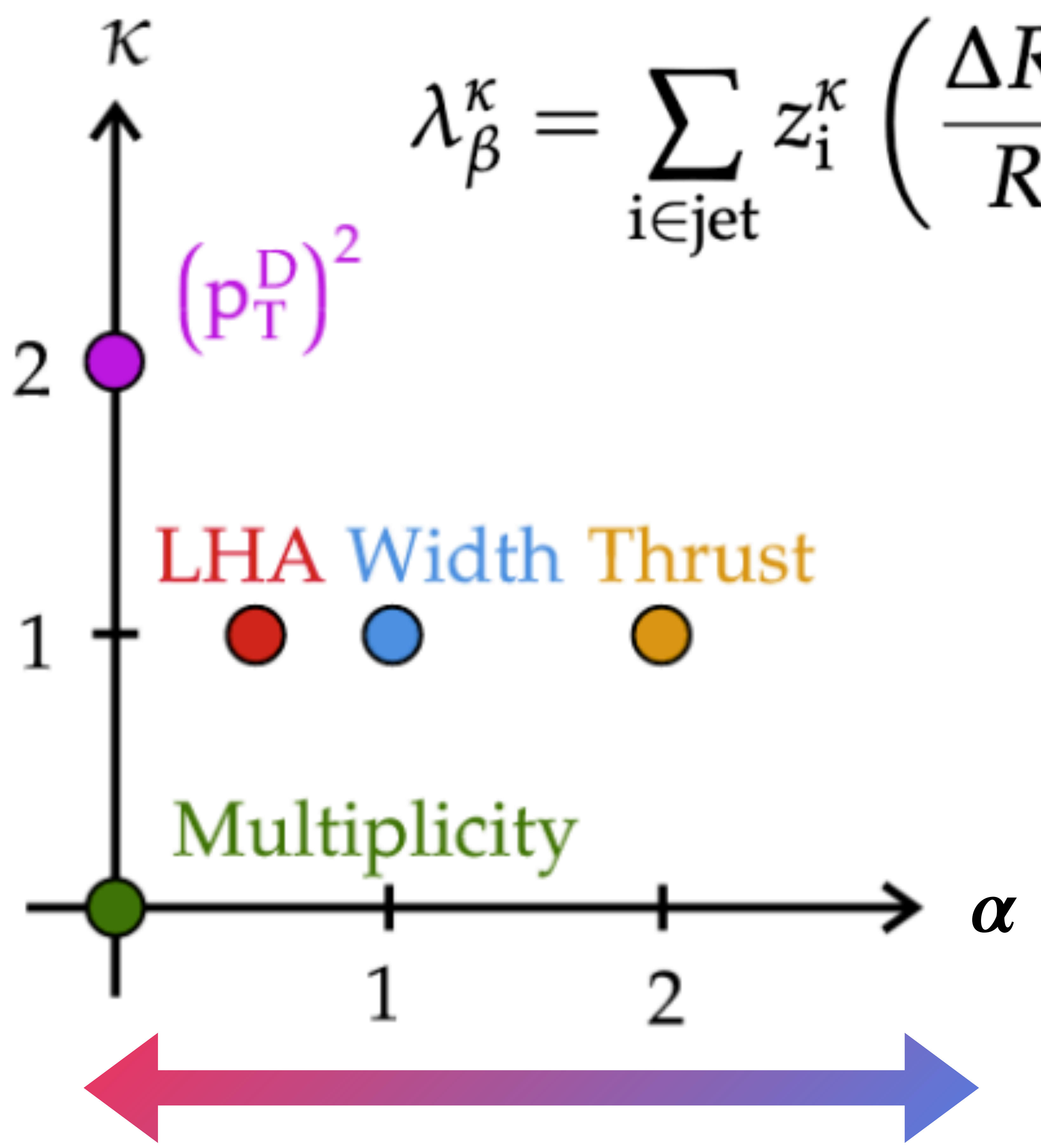
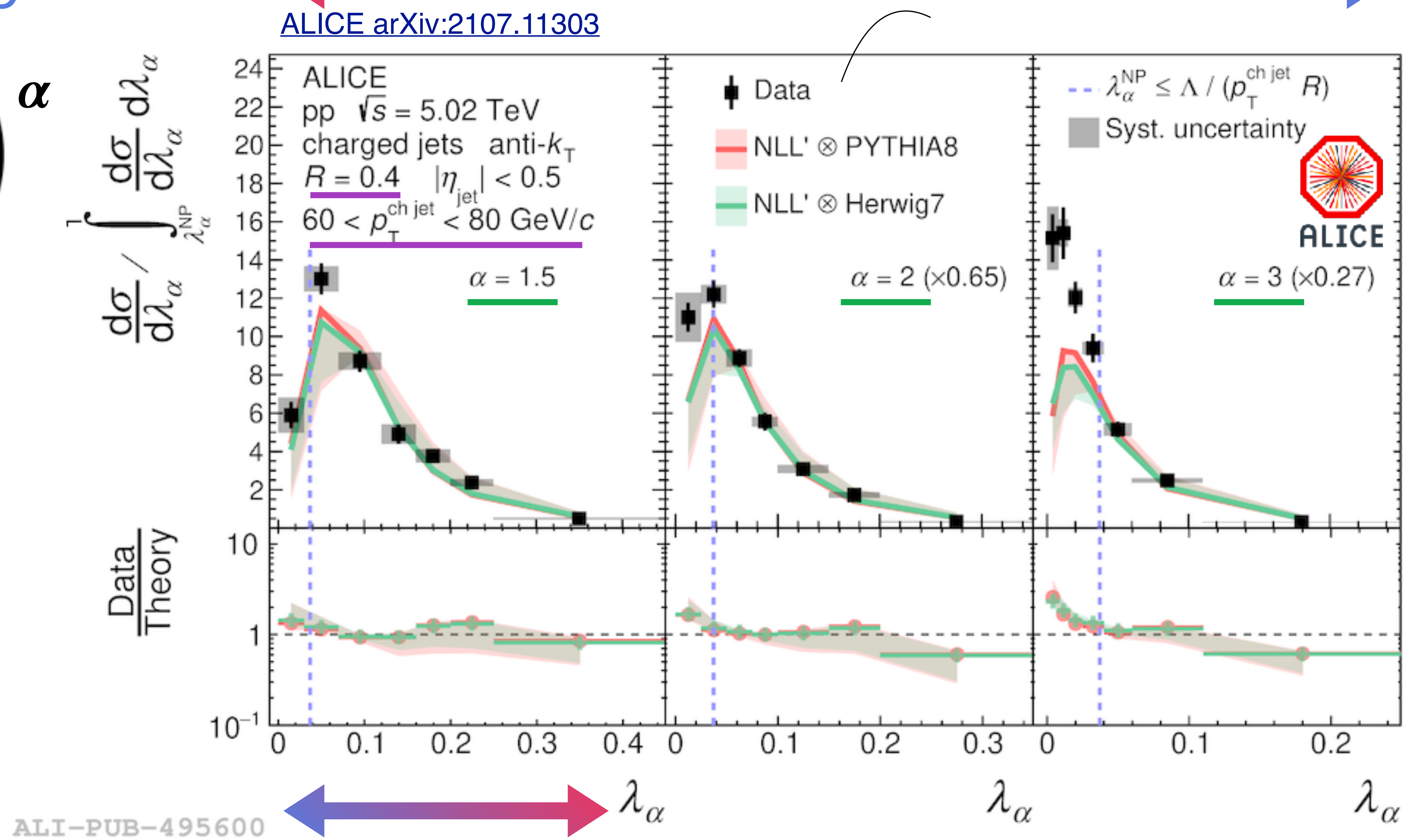


α scales from pert. to np

ALICE arXiv:2107.11303



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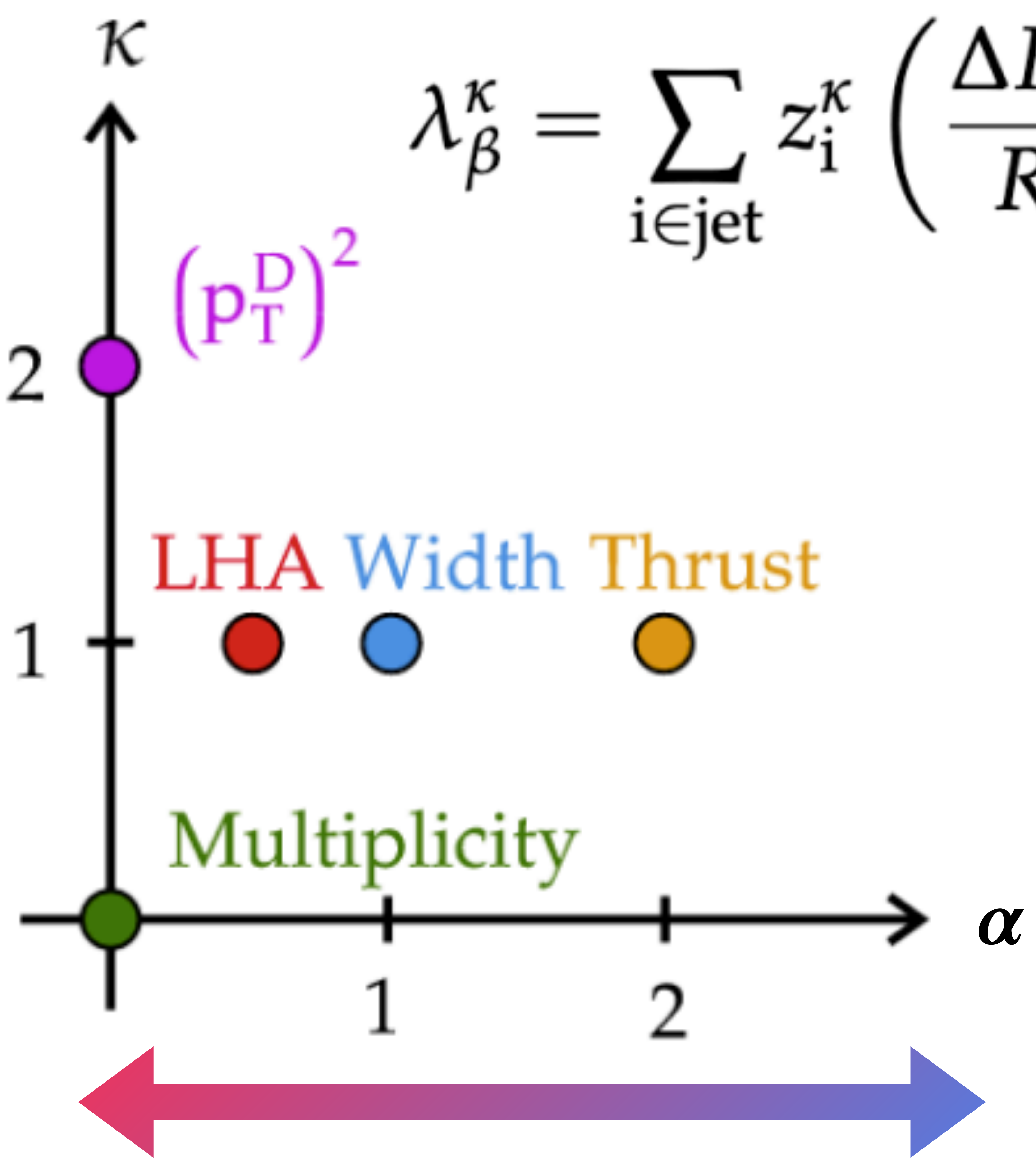

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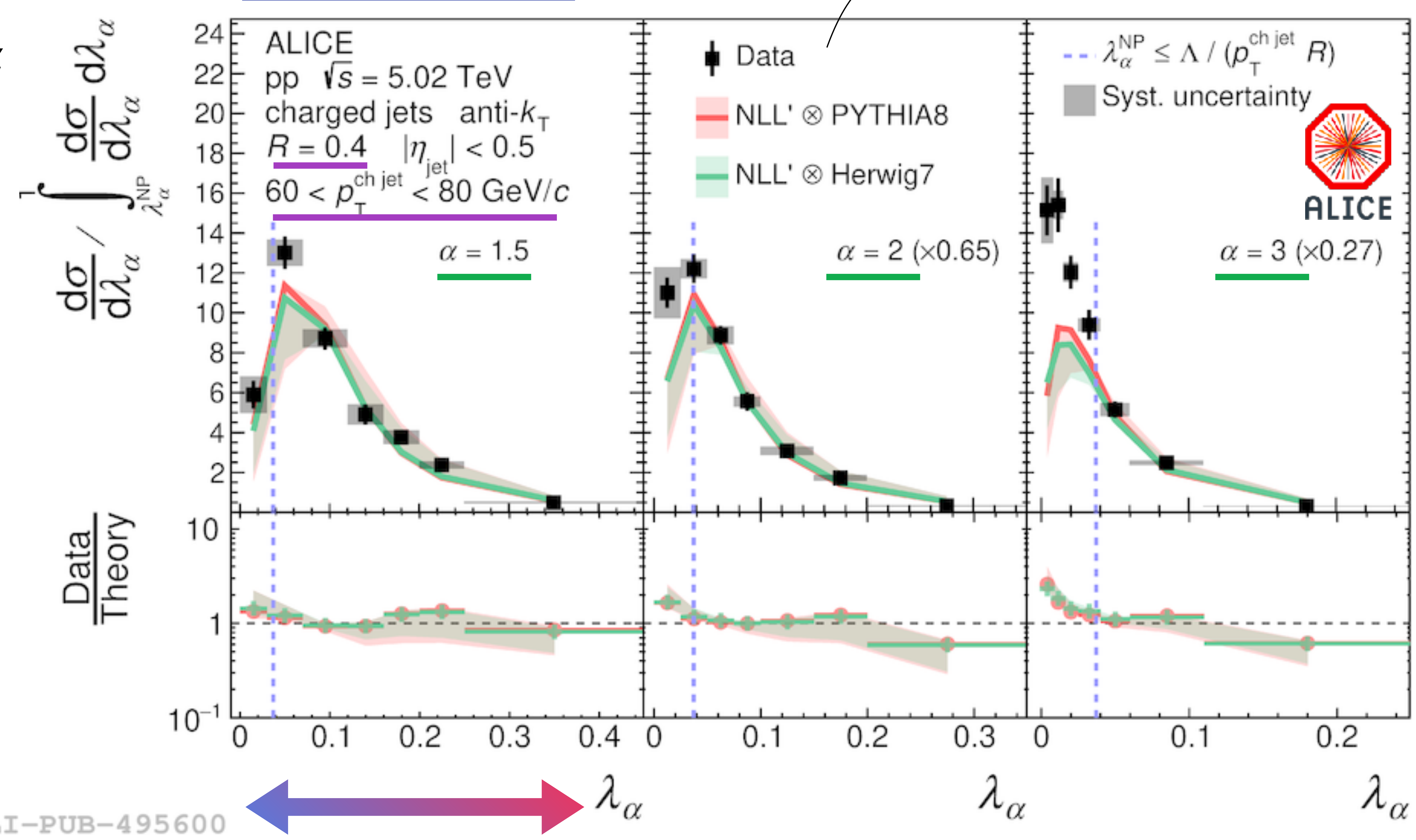


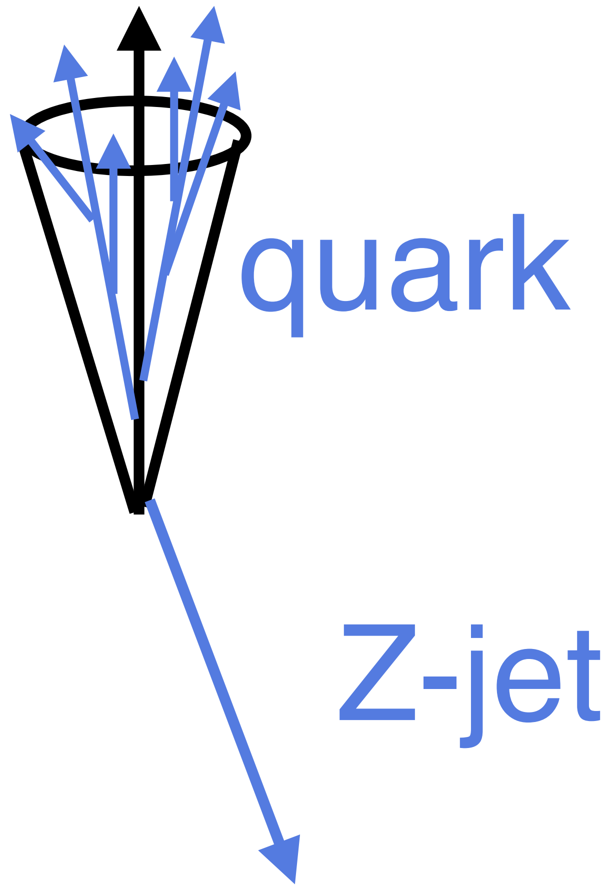
λ scales from np to pert.

NNL' pQCD calculations describe data fairly well in perturbative regions

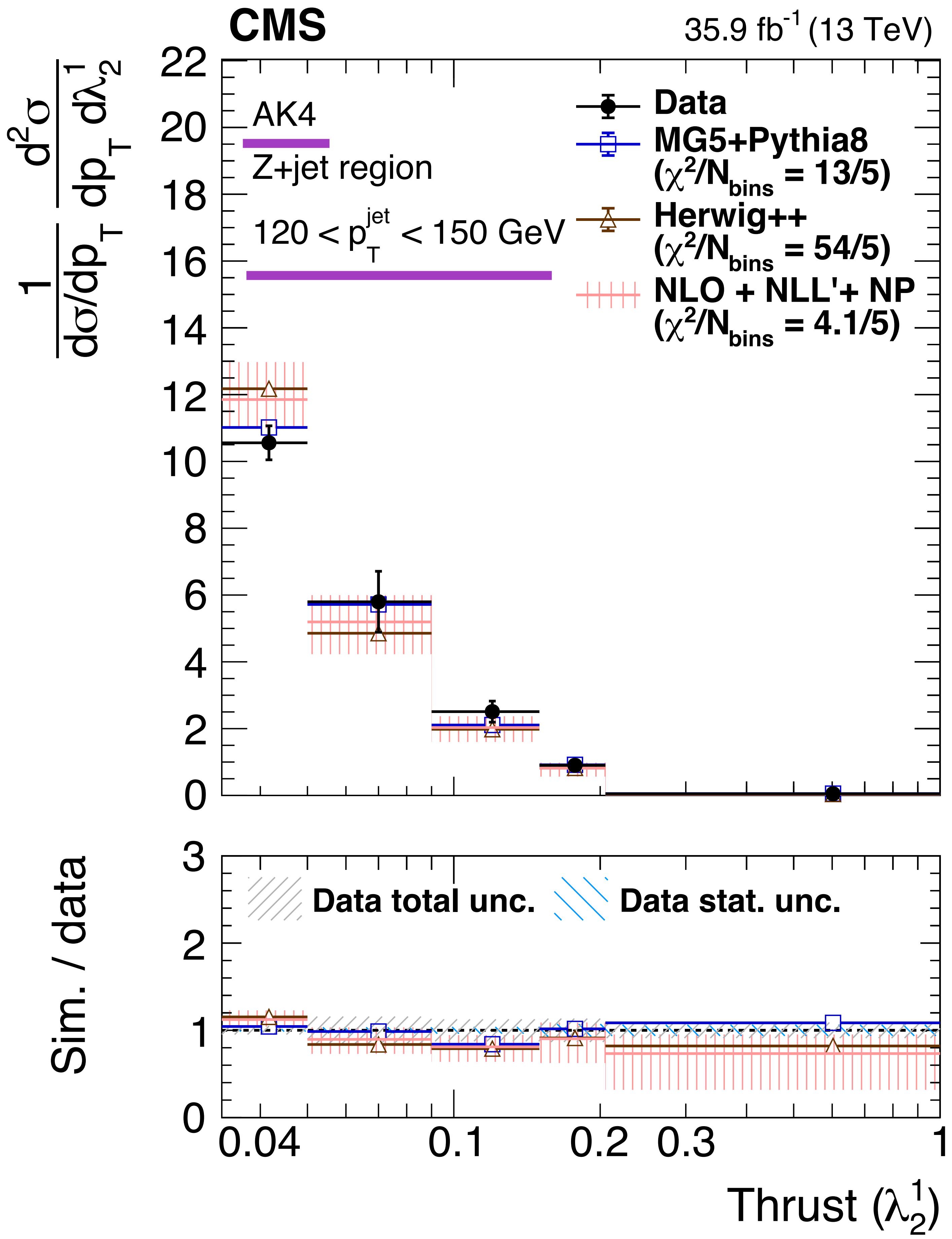
Generalize angularities: q/g seperation

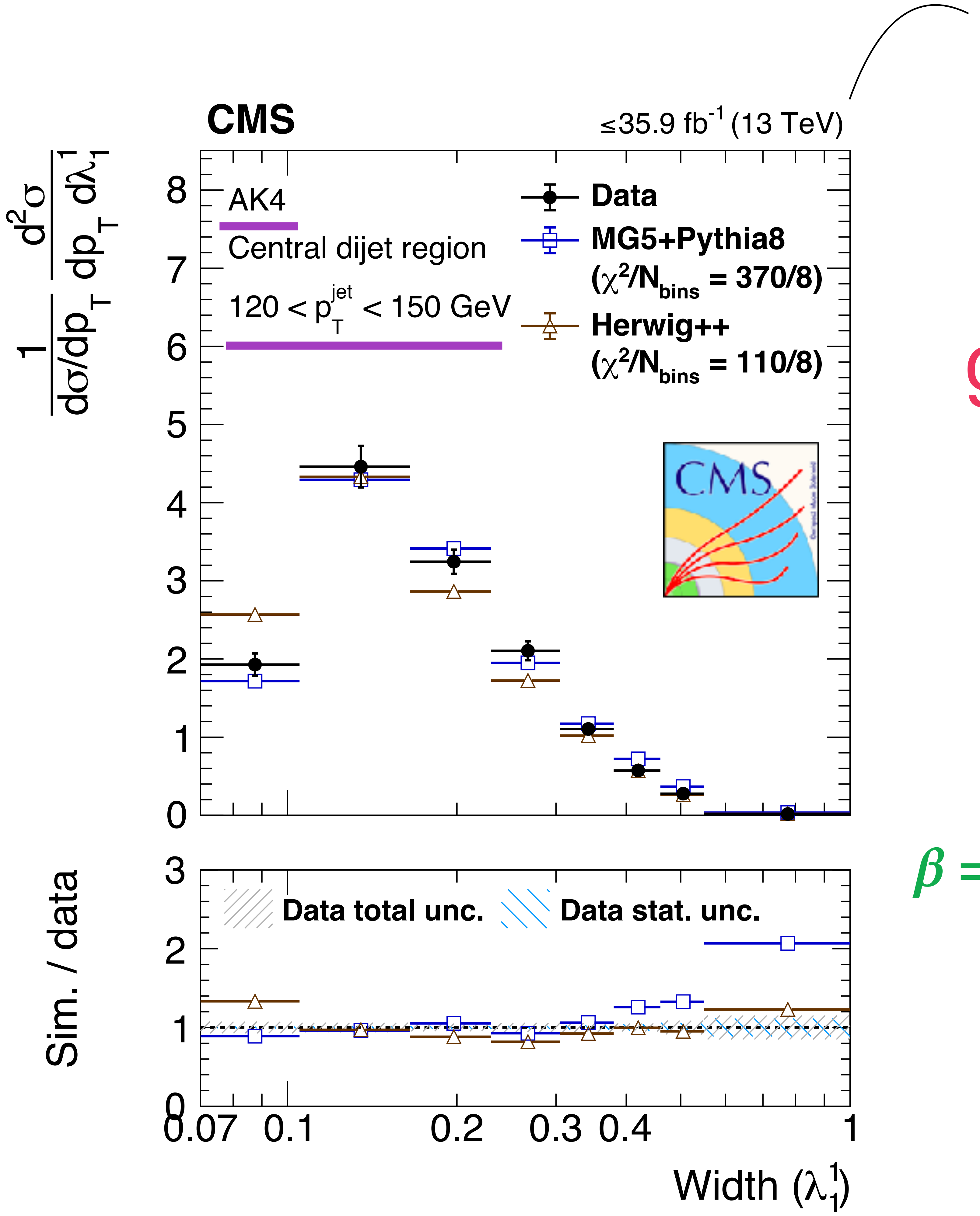
Vary R, jet p_T, λ, β, κ all changes the pert. to np scale!

CMS JHEP 01 (2022) 188



$\beta = 2$, $\kappa = 1$





$\beta = 1$, $\kappa = 1$

Exposes regions where models are (more) less constrained

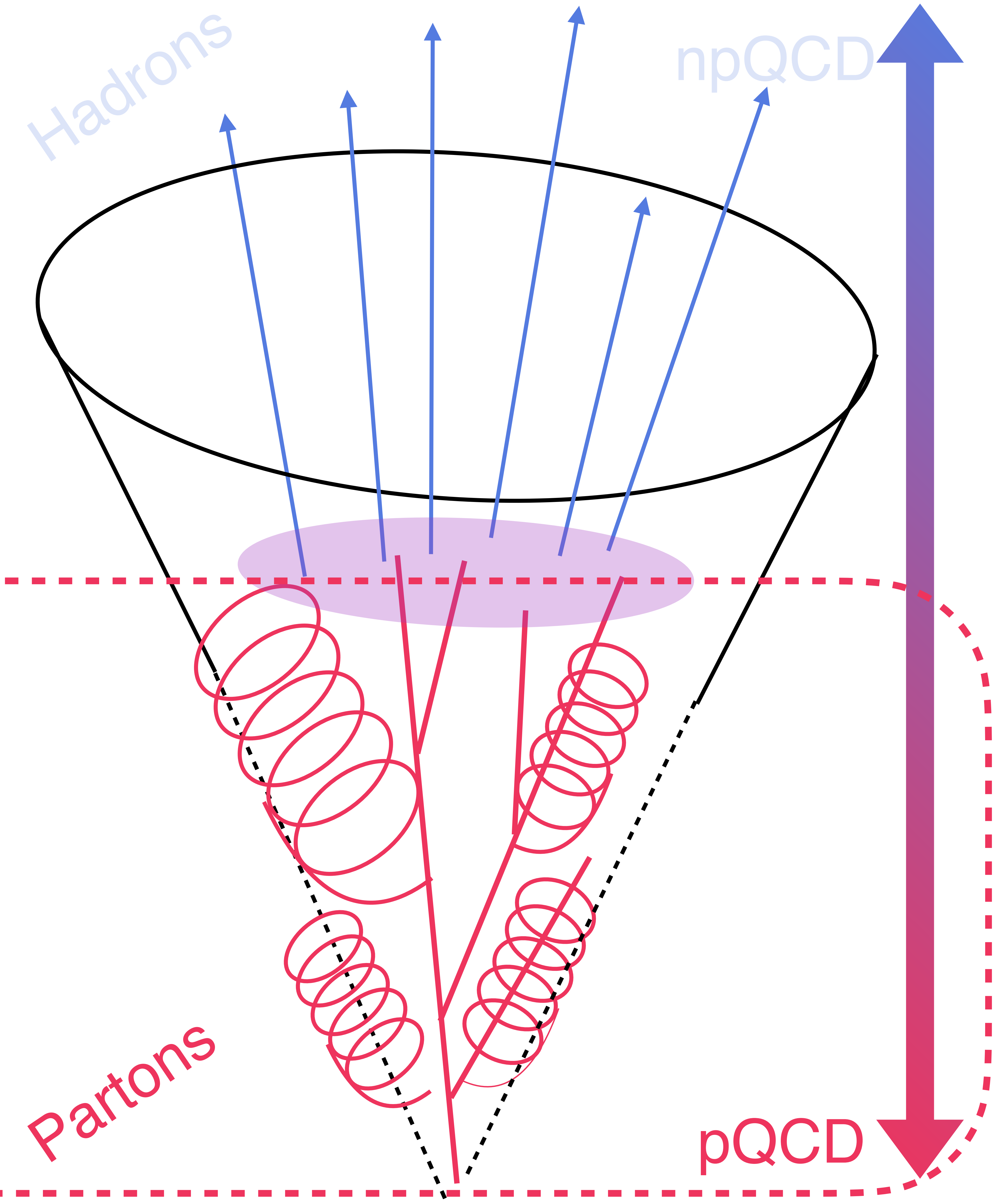
Jet internal structure

- Different variables probe different scales

➡ Distribution of charged hadrons inside the jet

Sensitive to hadronization

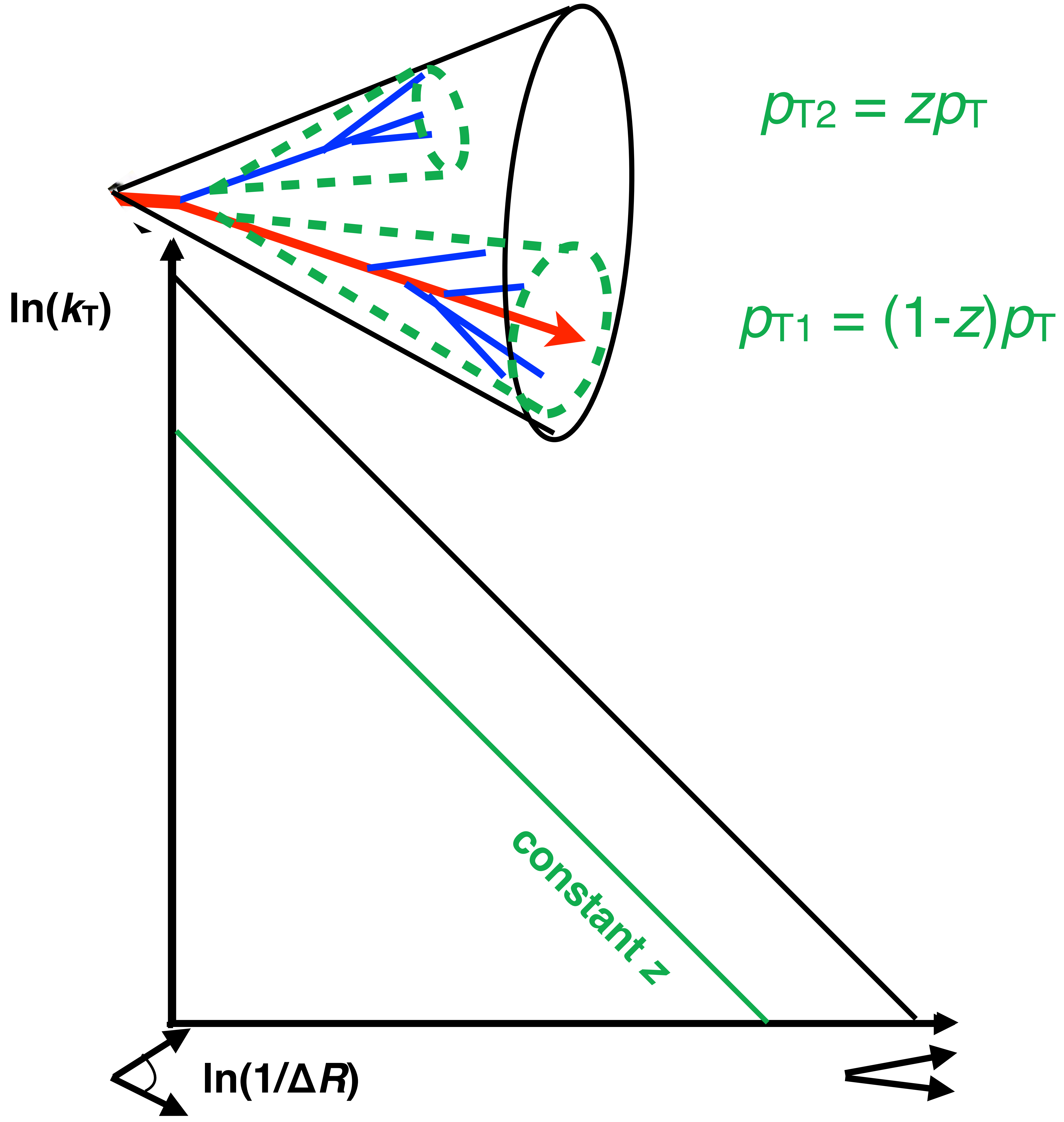
➡ Subjets from hard parton splittings



Jet Lund plane density

- Lund Diagram: phase space of jet splitting

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



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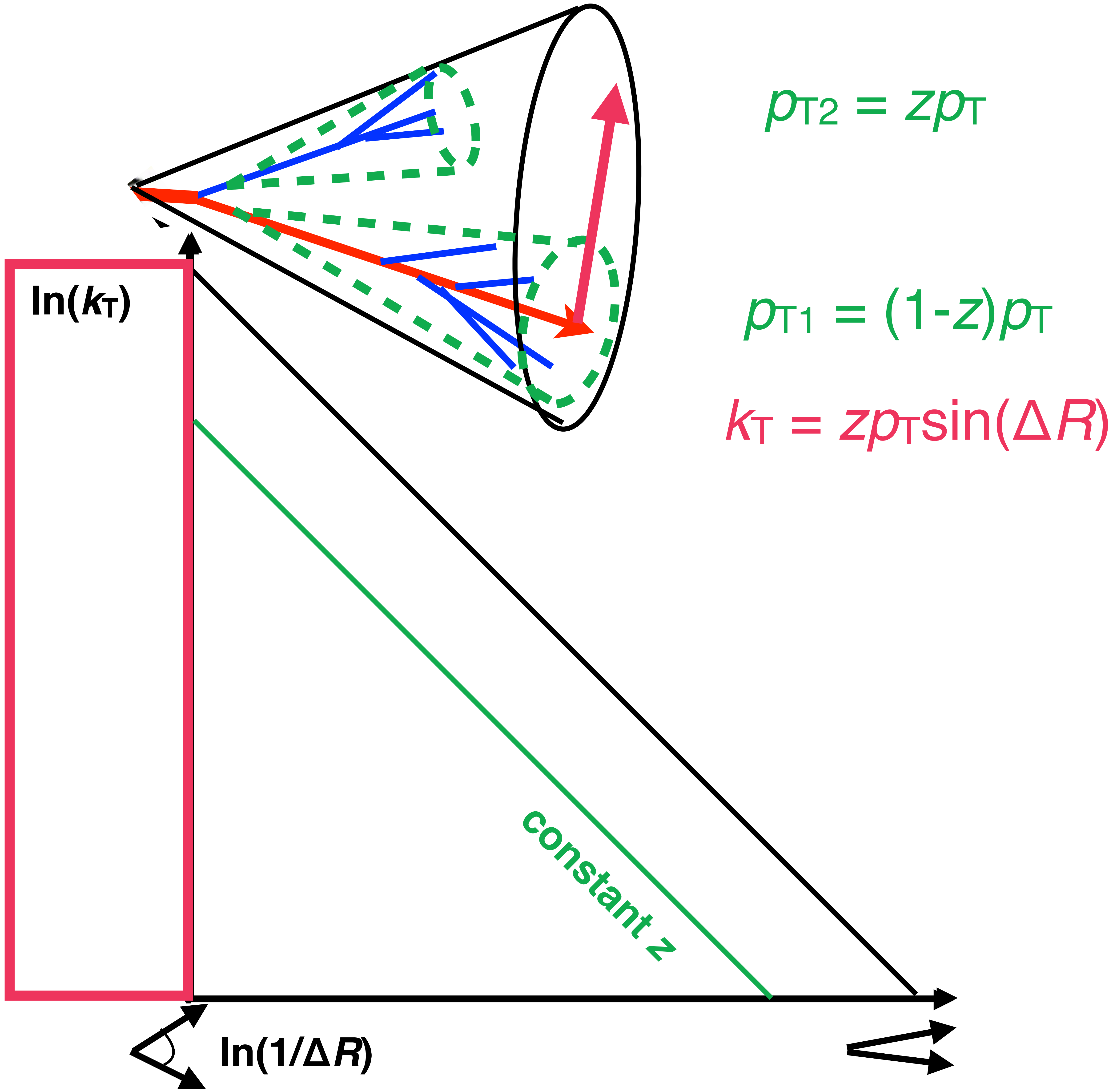
- k_T: relative transverse momentum



Jet Lund plane density

- Lund Diagram: phase space of jet splitting

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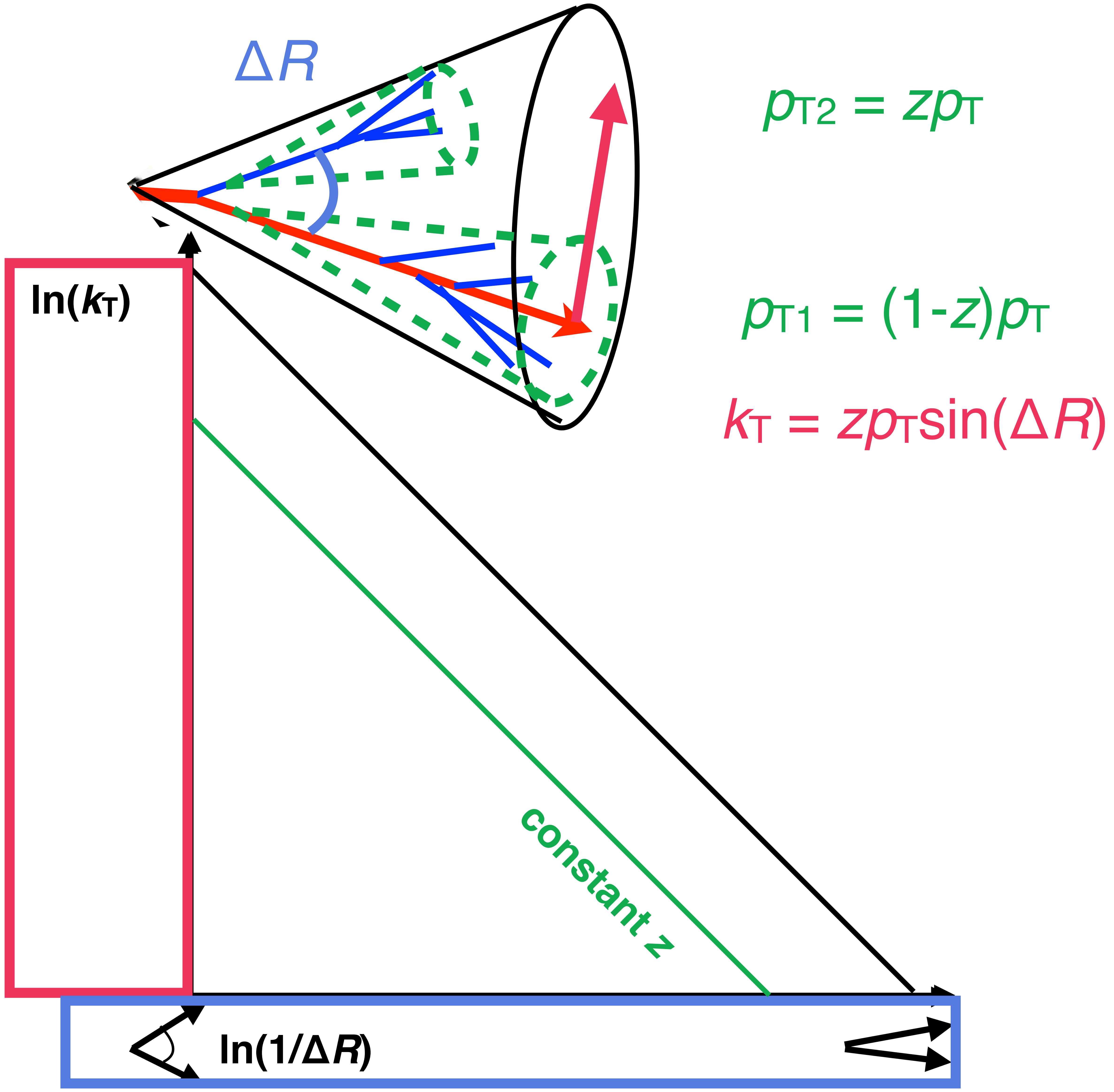
- k_T: relative transverse momentum

- ΔR: opening angle



Jet Lund plane density

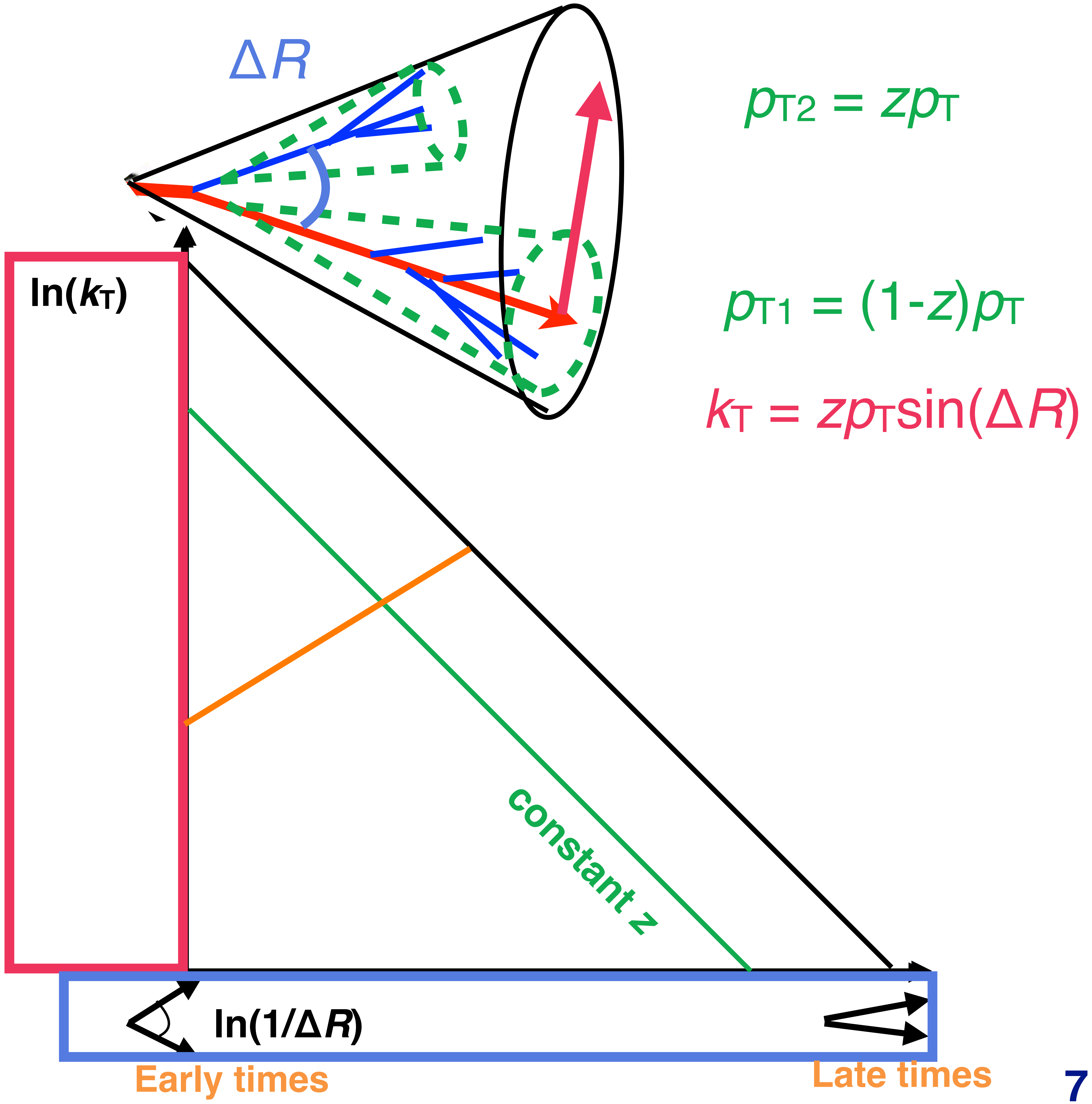
- Lund Diagram: phase space of jet splitting

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.

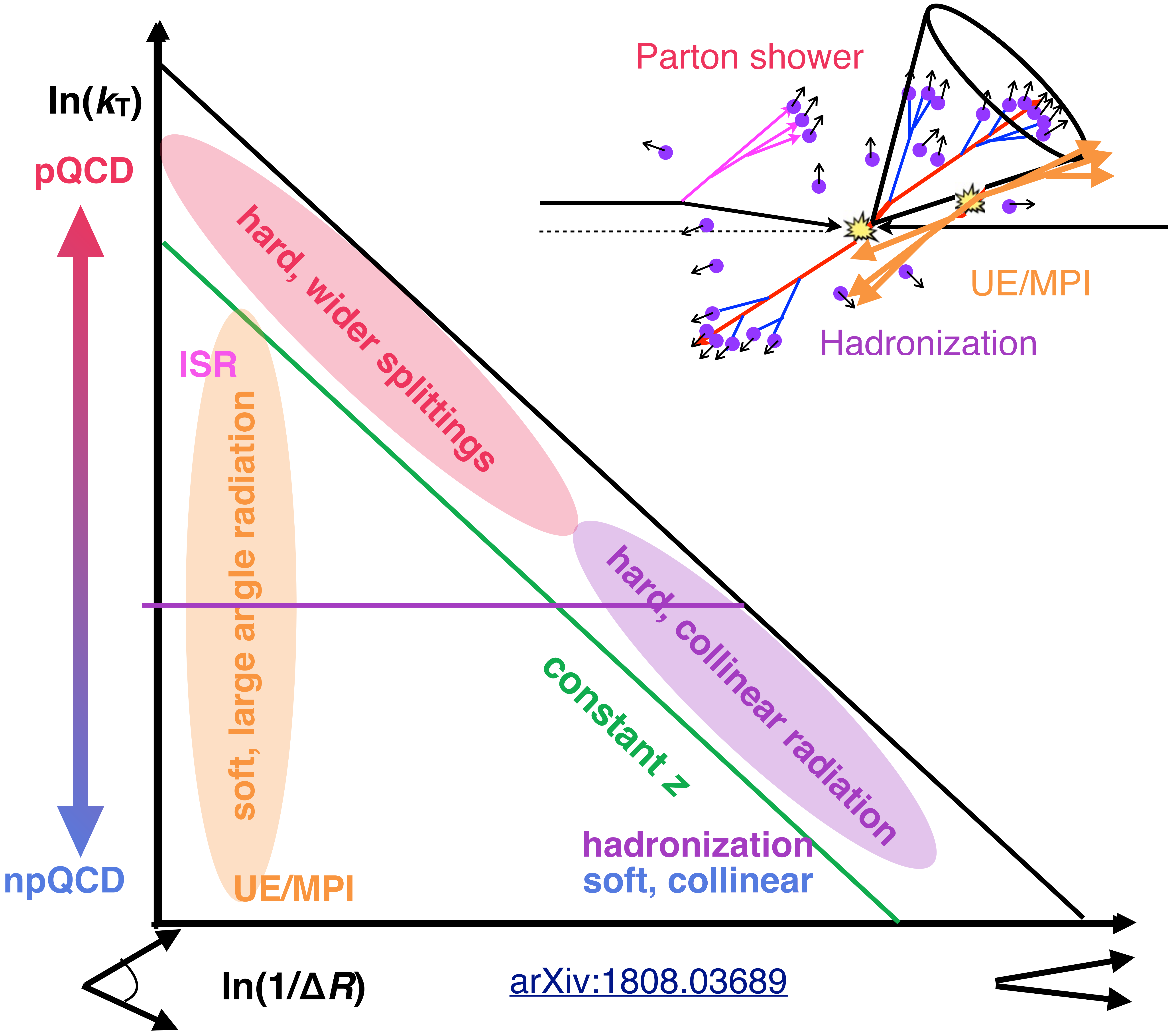
$$t_f \approx \frac{1}{(1-z)k_T\Delta R}$$



Exploring phase space of QCD

- Isolate different QCD effects like ISR, UE, MPI, hadronization, perturbative vs. non-perturbative emissions, etc. and tune MC models

- $k_T \sim \Lambda_{QCD}$ separates perturbative from non-perturbative regime

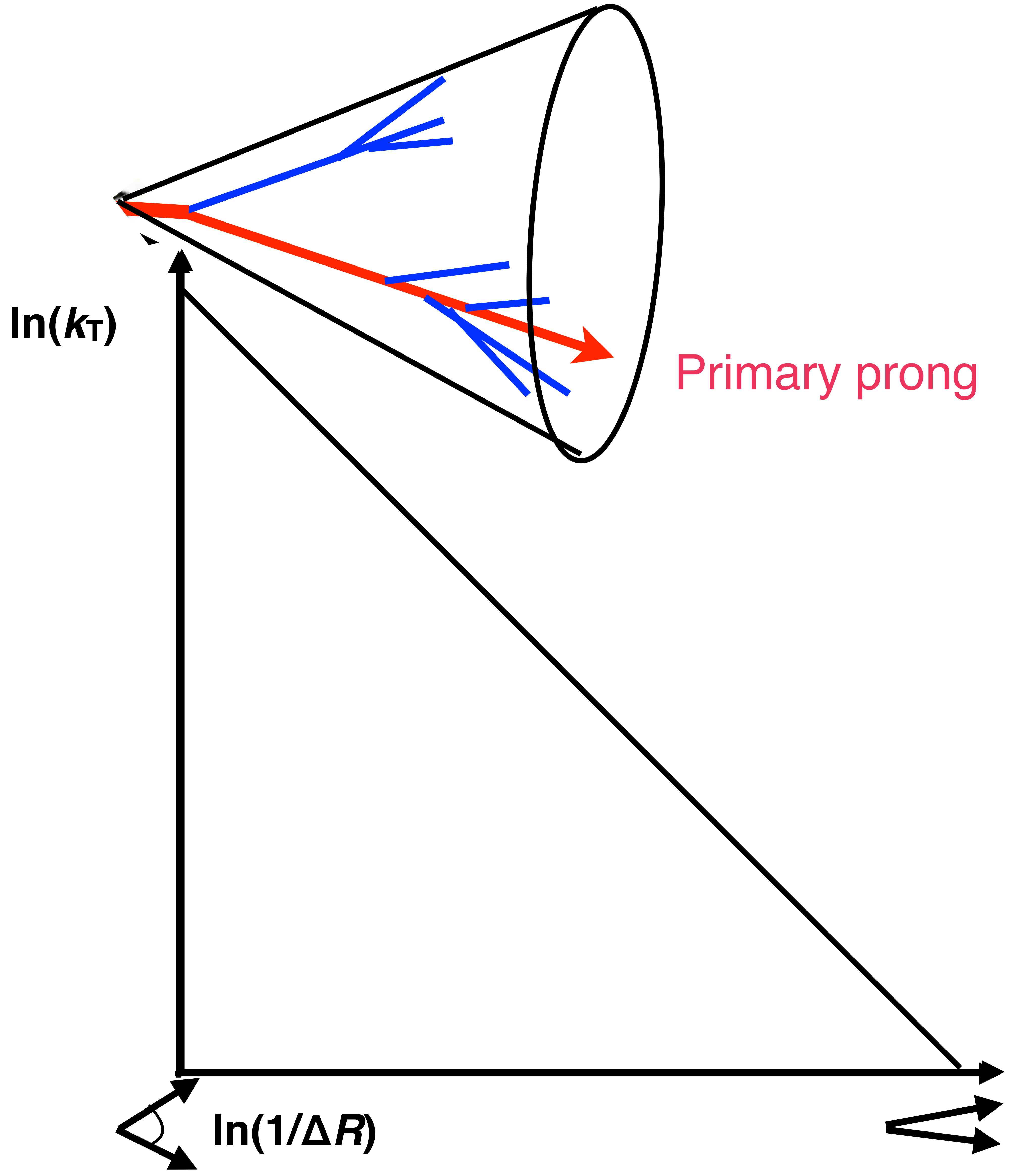


arXiv:1808.03689

Primary jet Lund plane density

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

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



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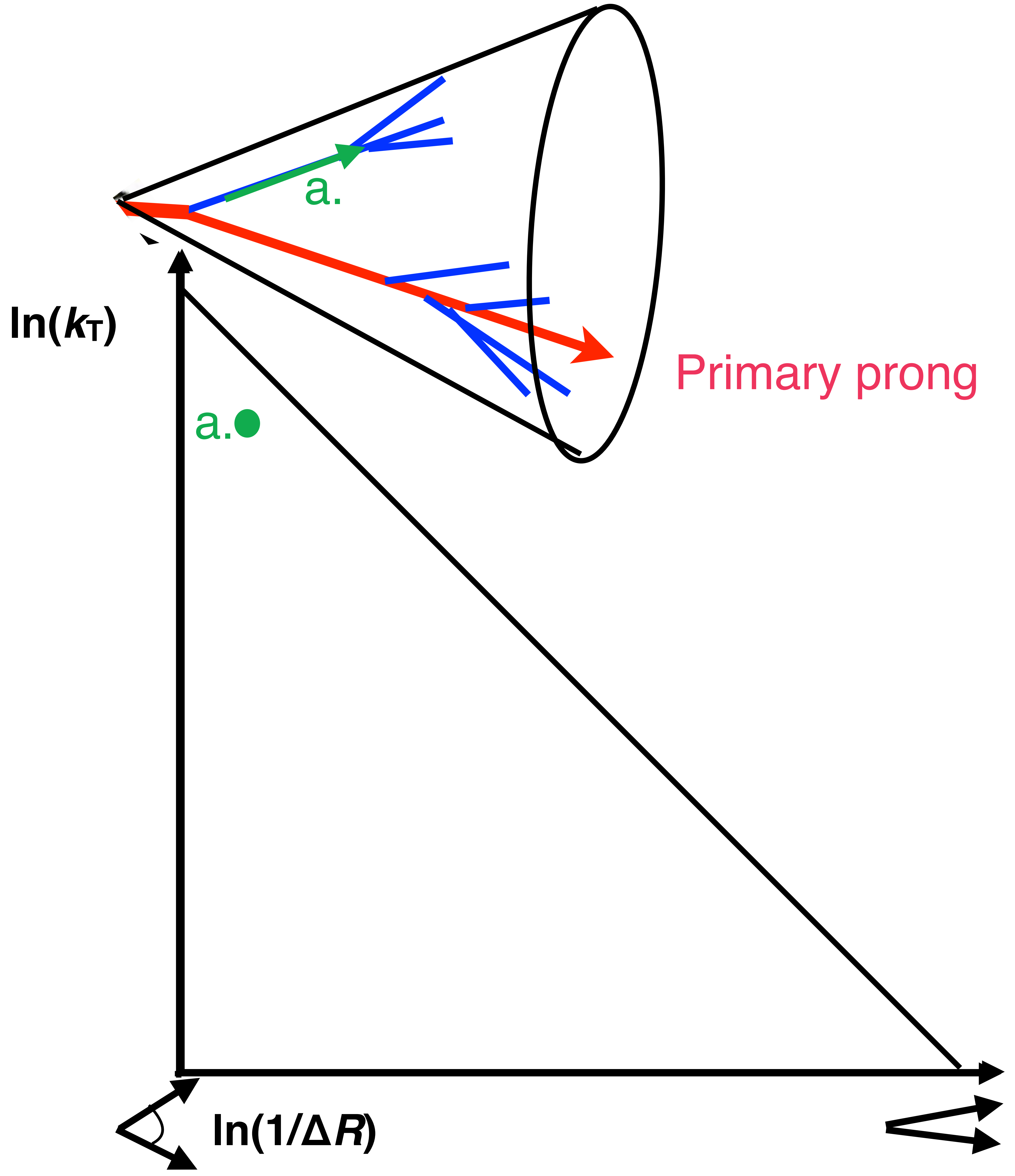

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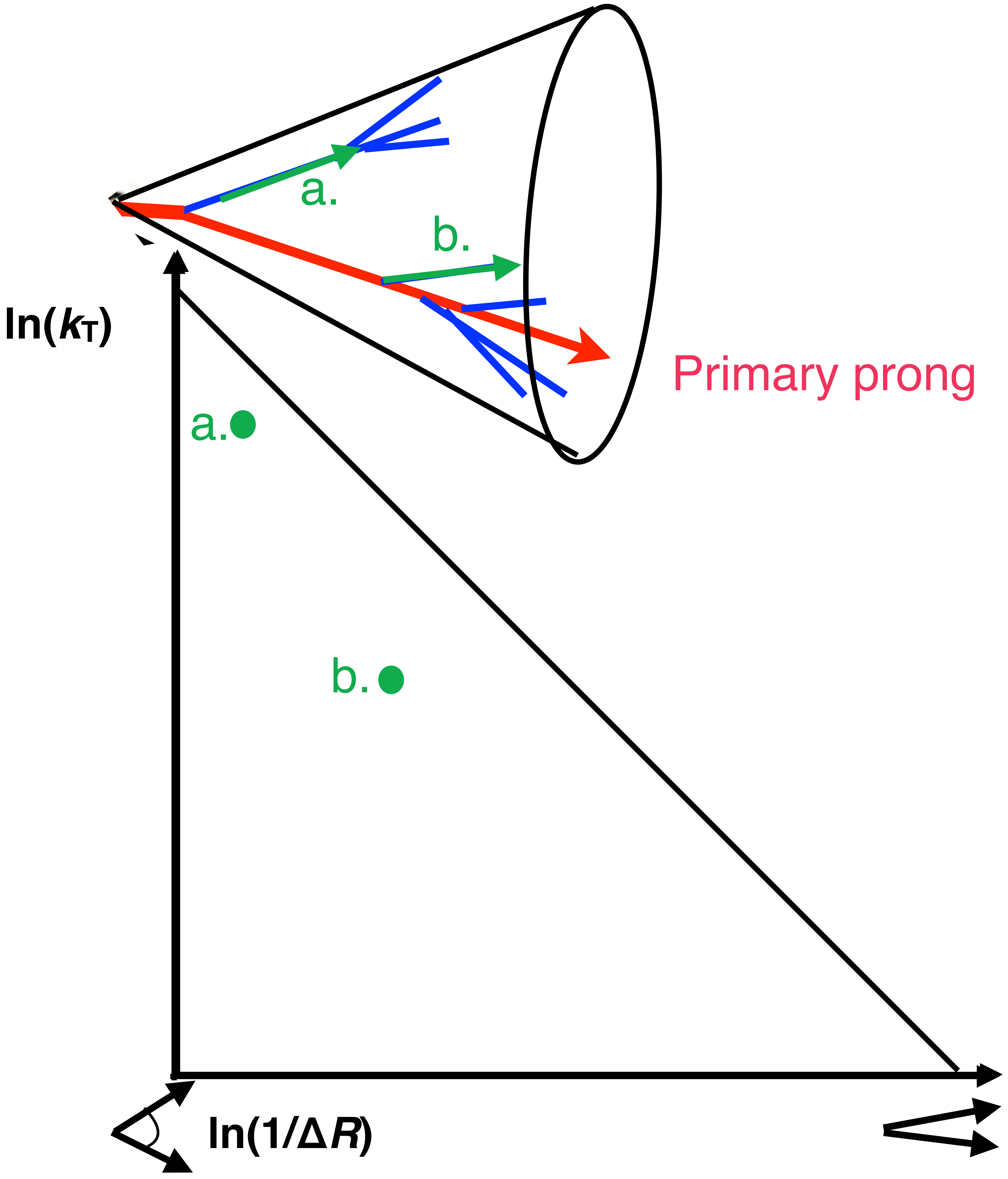

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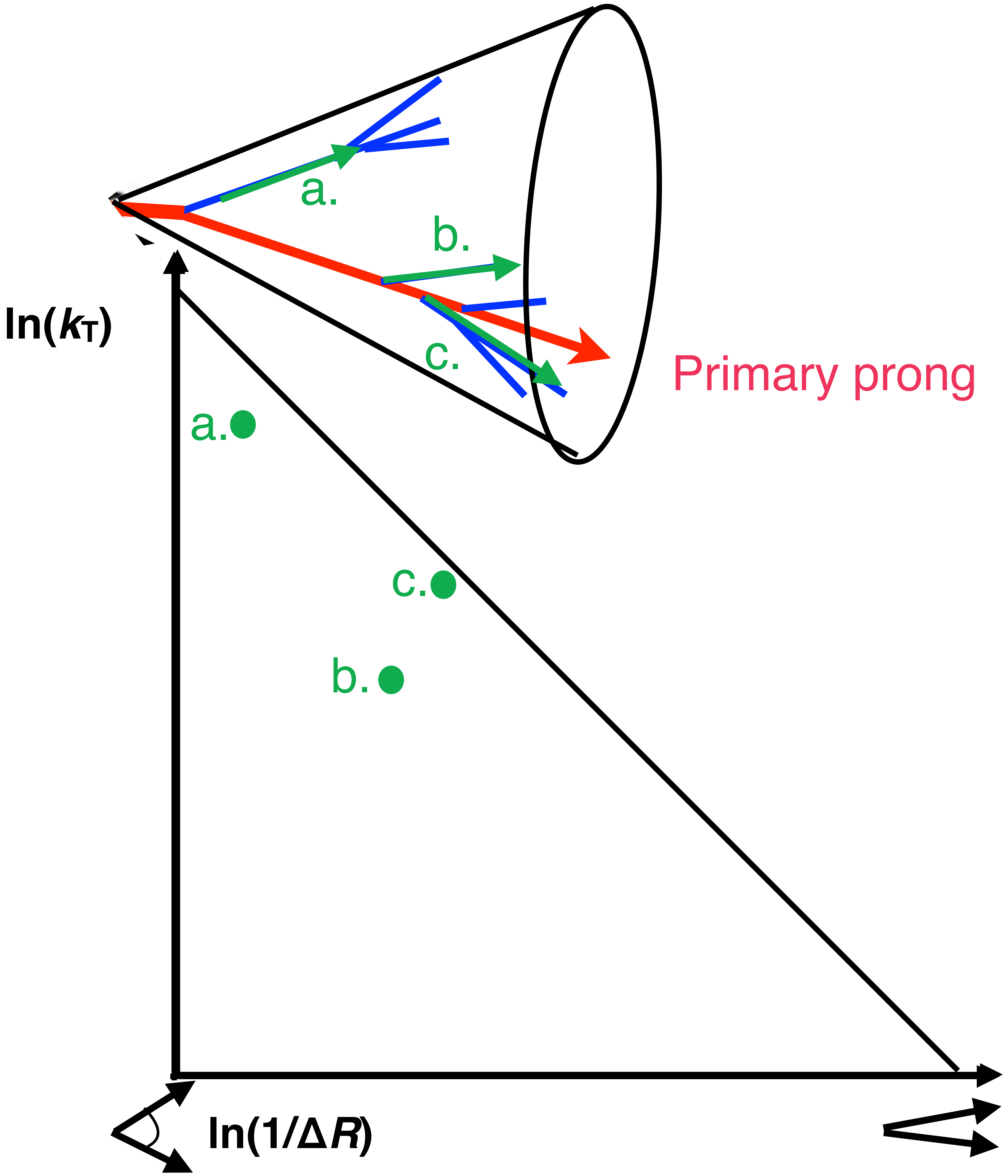

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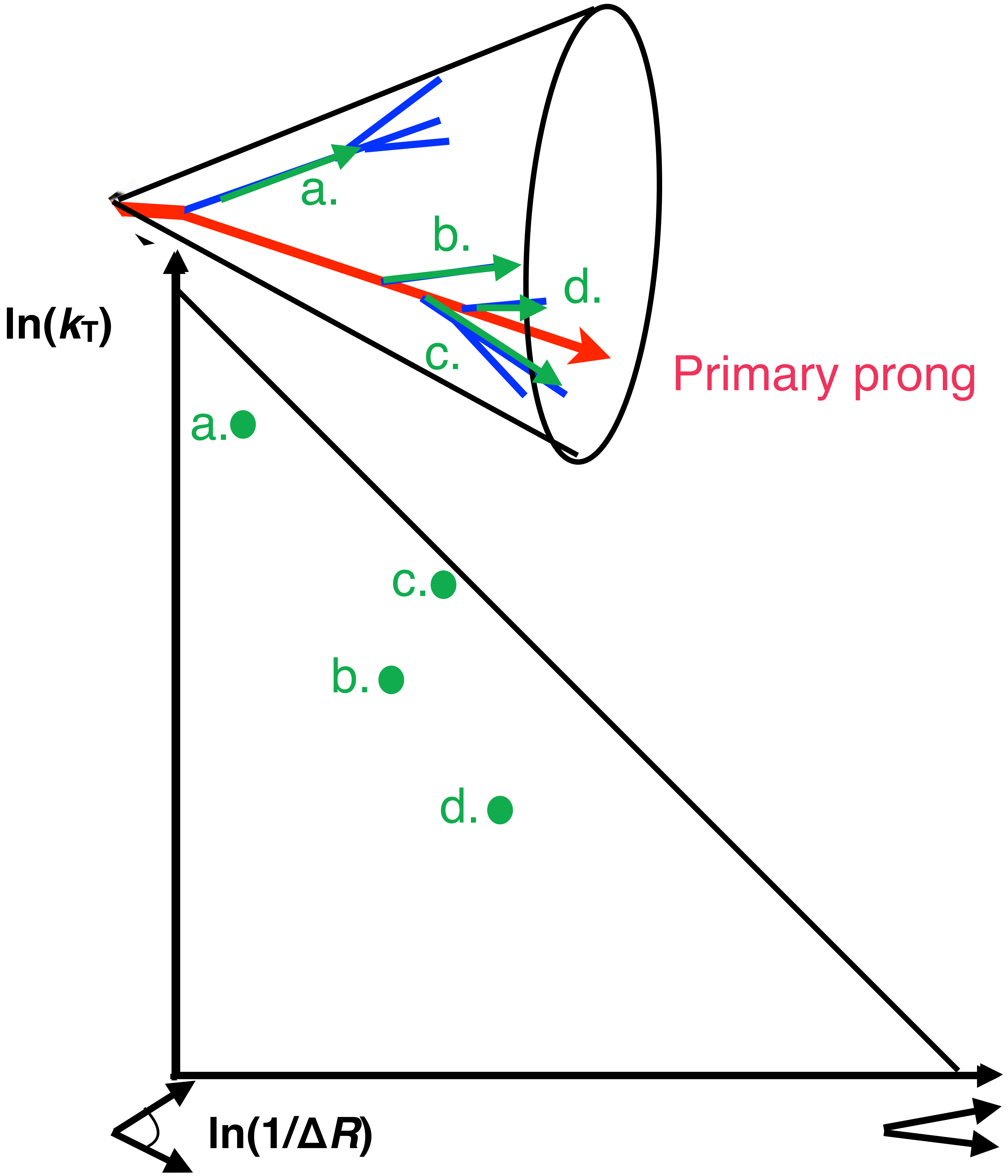


Primary jet Lund plane density

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

Andersson et al ZPC43 (1989)

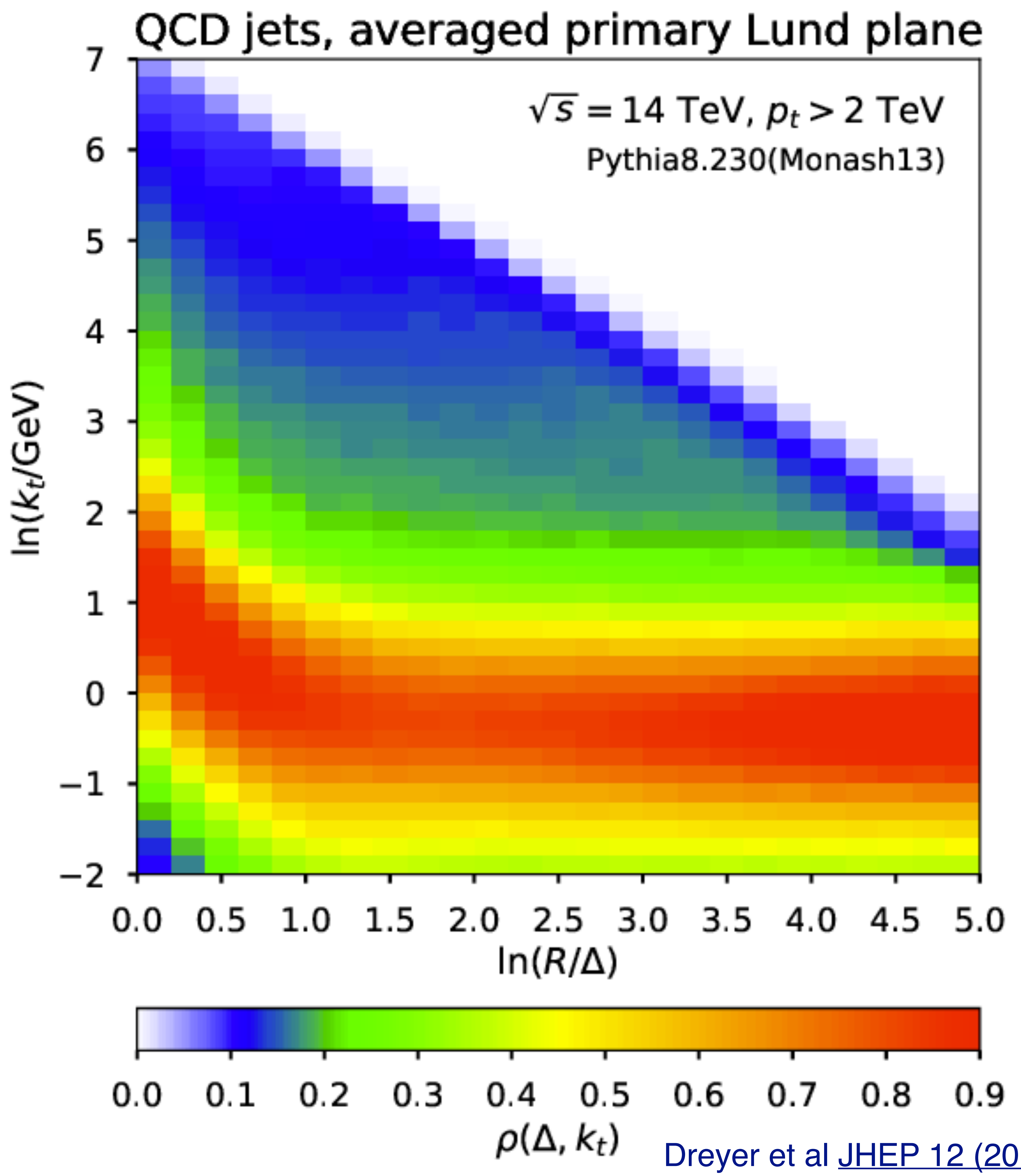
- At leading order the emissions populate the plane uniformly

- 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)

Lund plane measurement

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

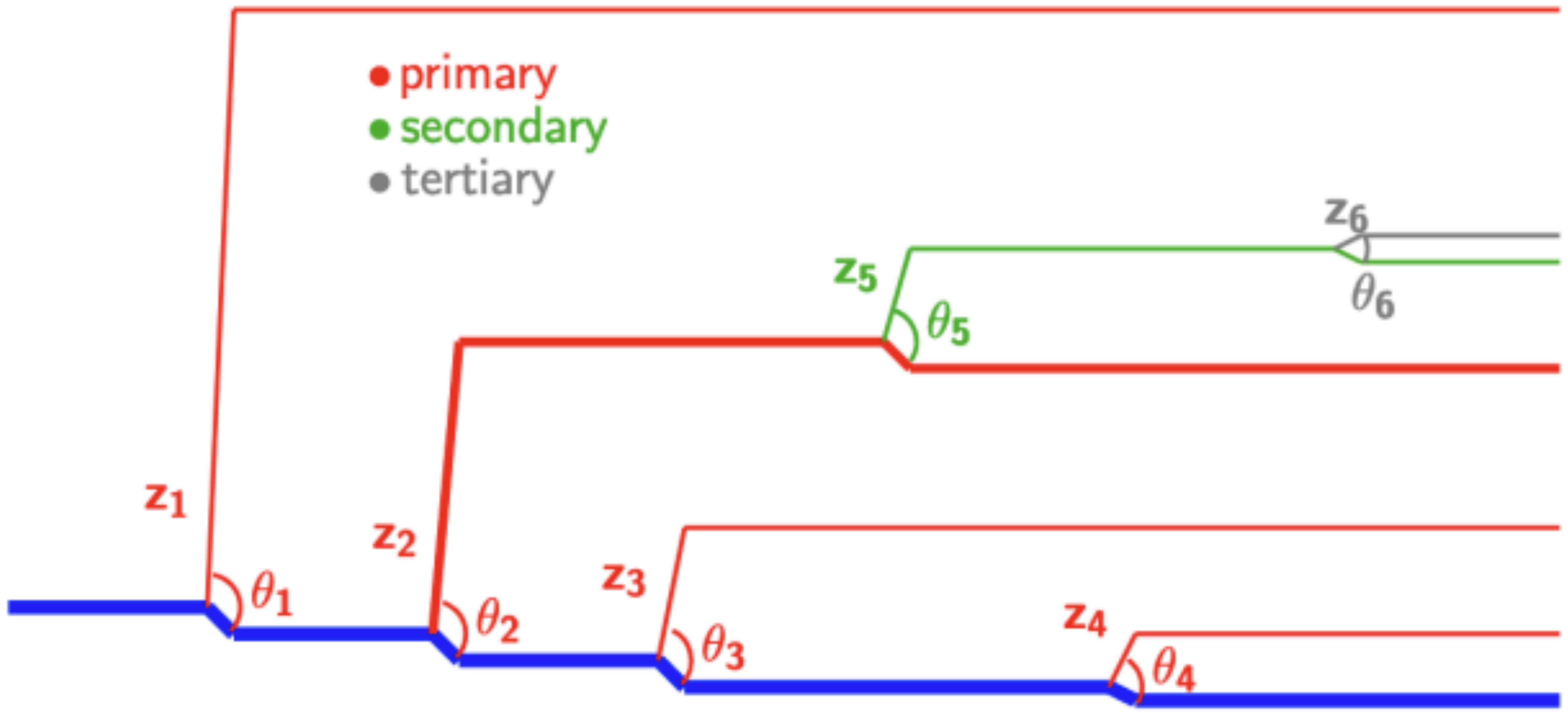


Image from Gregory Soyez

$\sqrt{s}$ = 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

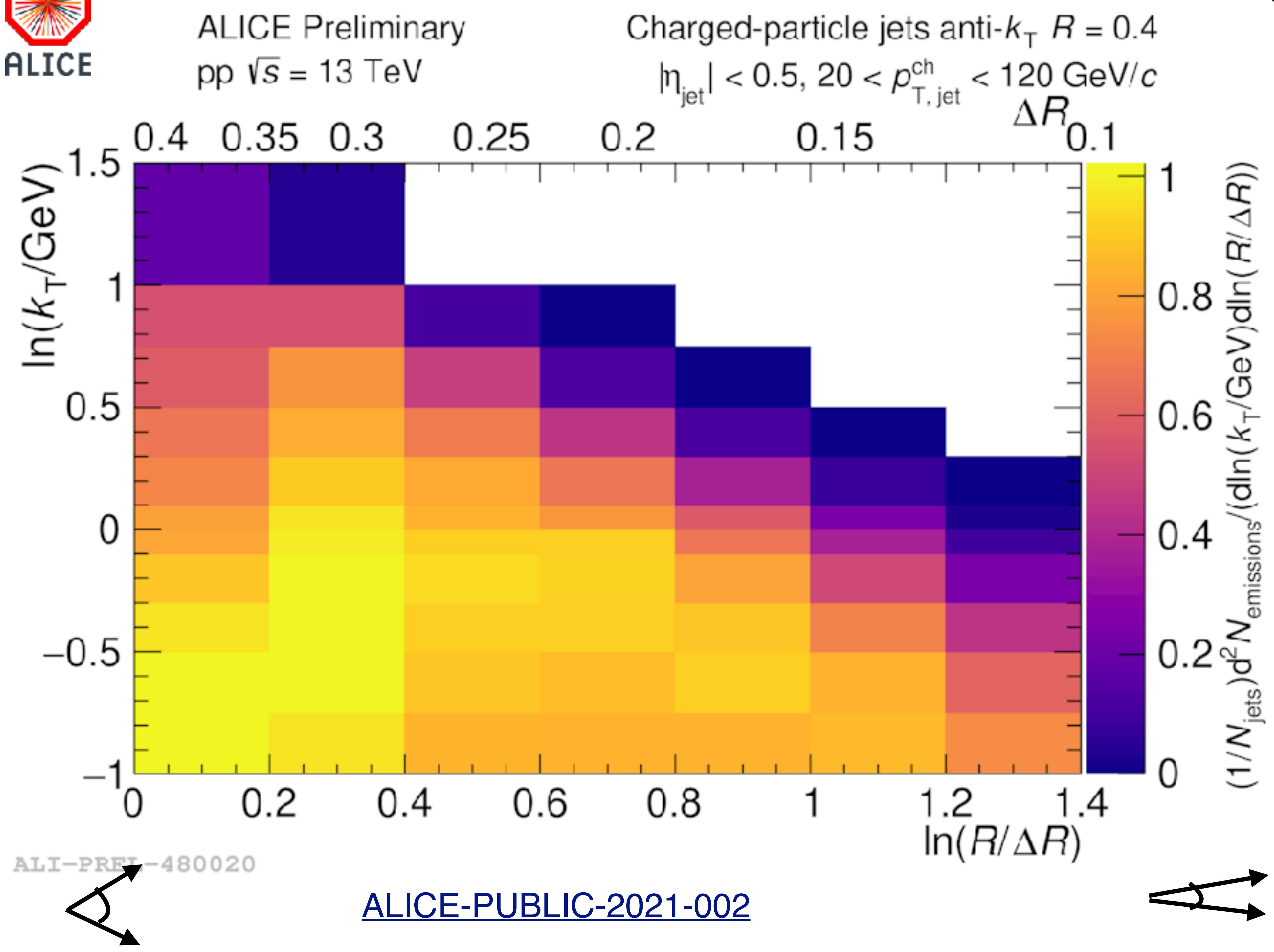
*charged-particle jets

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

Unfolded Lund plane density

	ALICE	ATLAS
Jet p_T (GeV/c)	20-120*	> 675

*charged-particle jets



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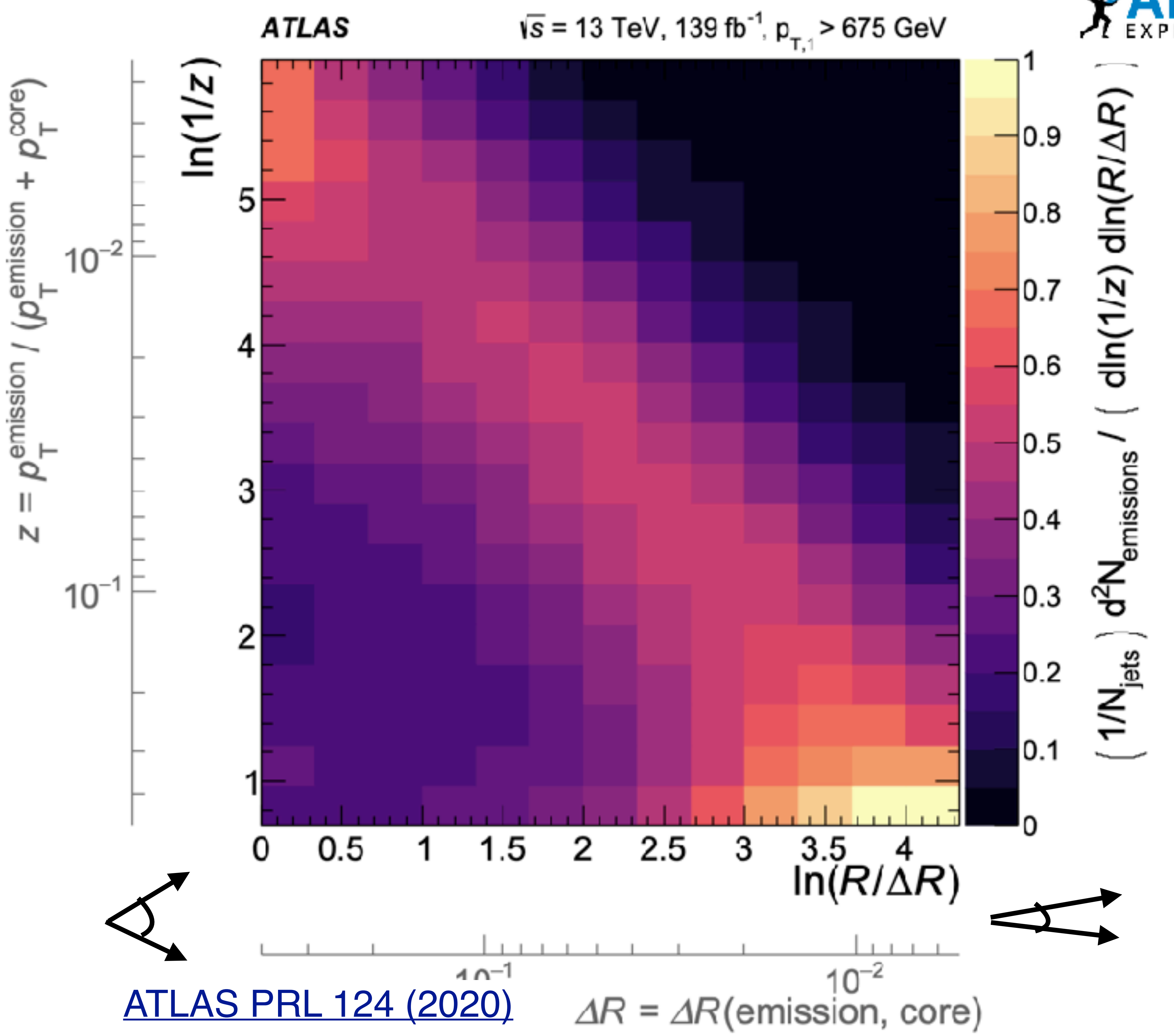

ATLAS PRL 124 (2020)

Unfolded Lund plane density

	ALICE	ATLAS
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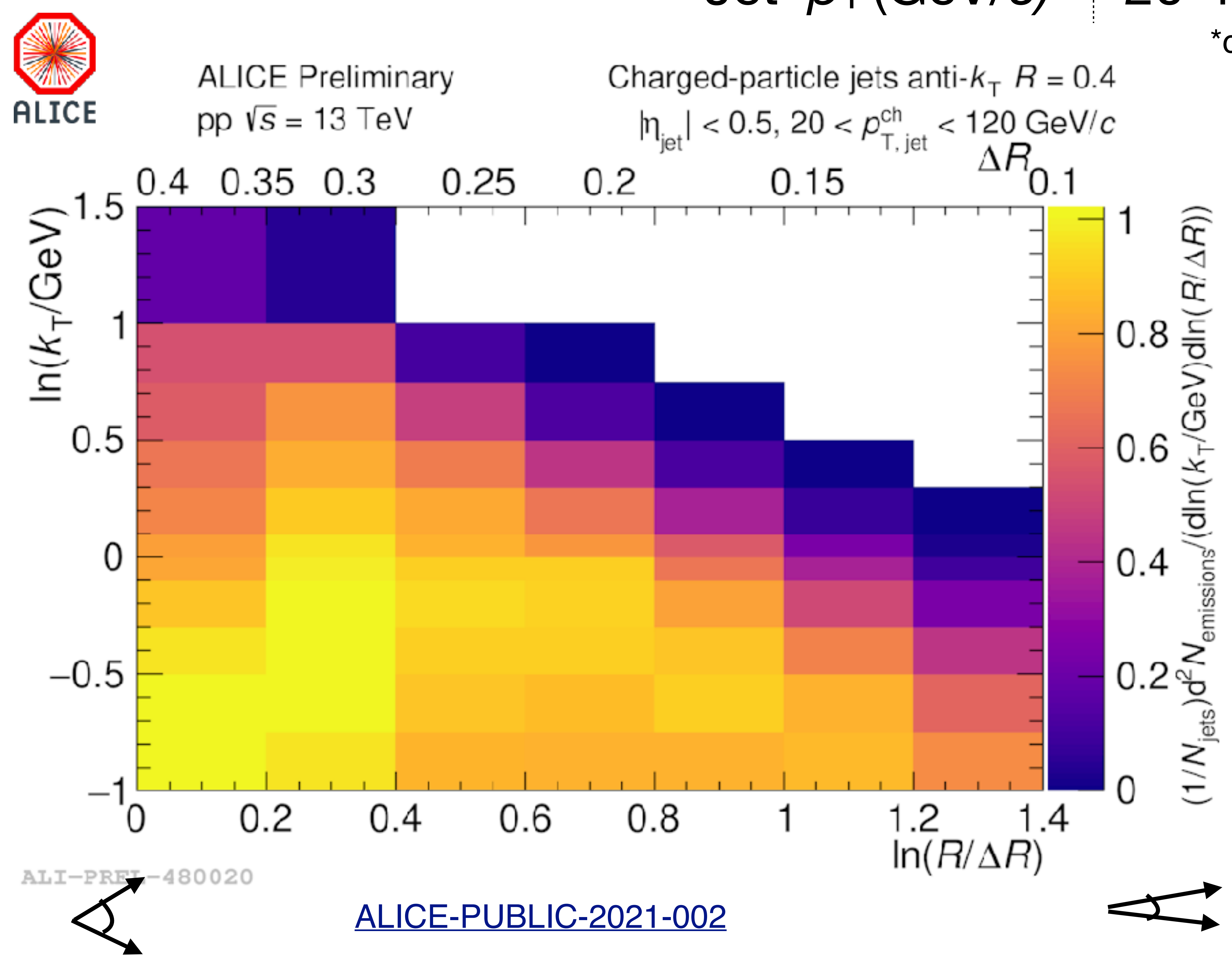
*charged-particle jets

Emissions enhanced for np to pQCD transition at $k_T \sim \Lambda_{QCD}$



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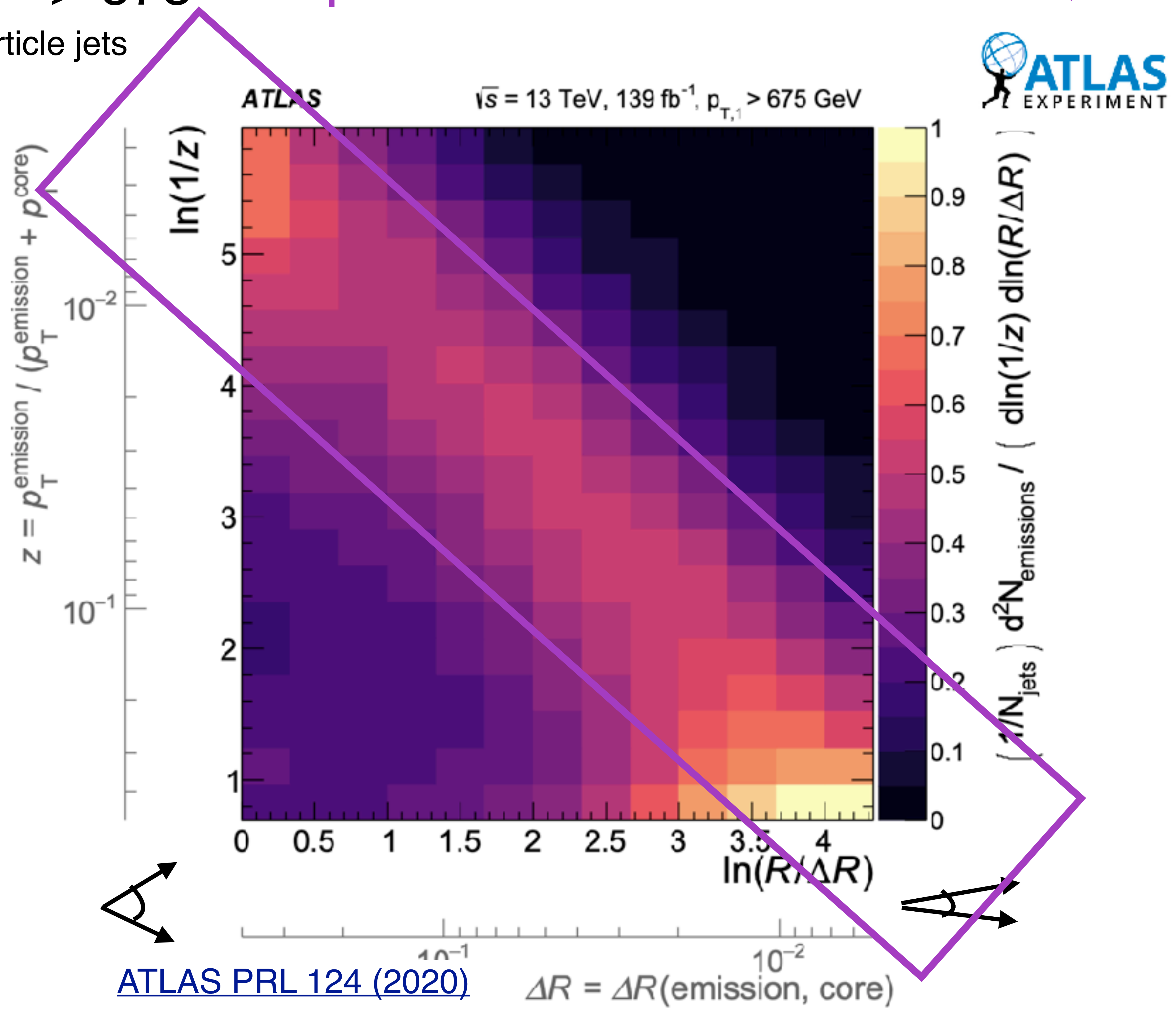

ATLAS PRL 124 (2020)

Projections isolate regions of QCD phase space to compare to generators

Regions of the Lund plane

Agreement with MC ~10% in most cases

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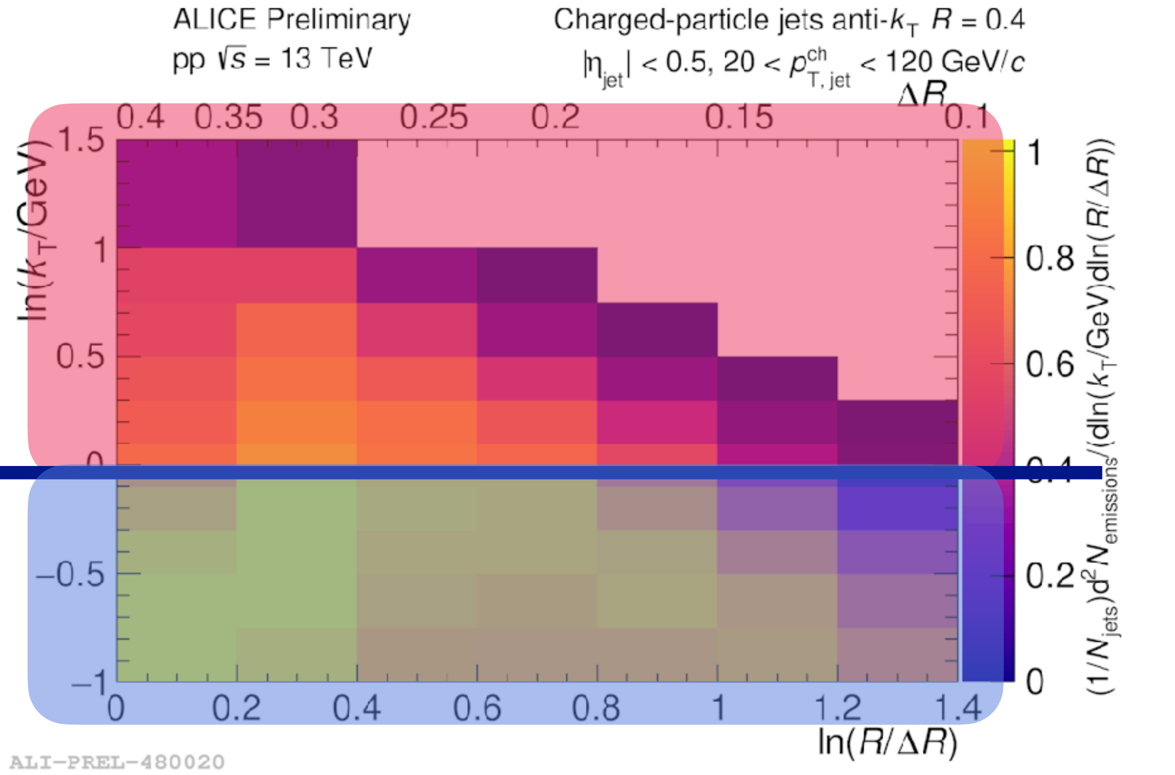
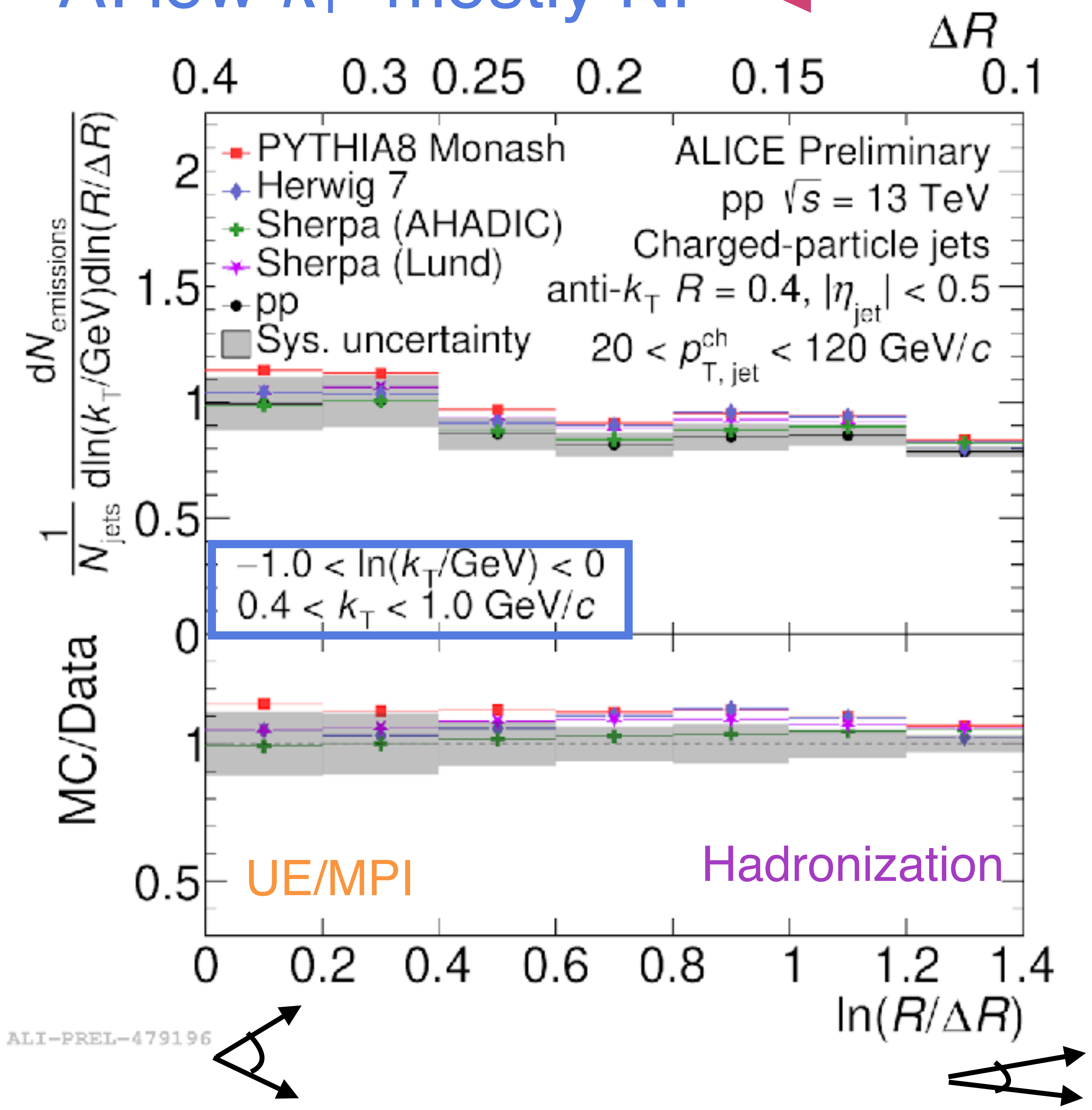
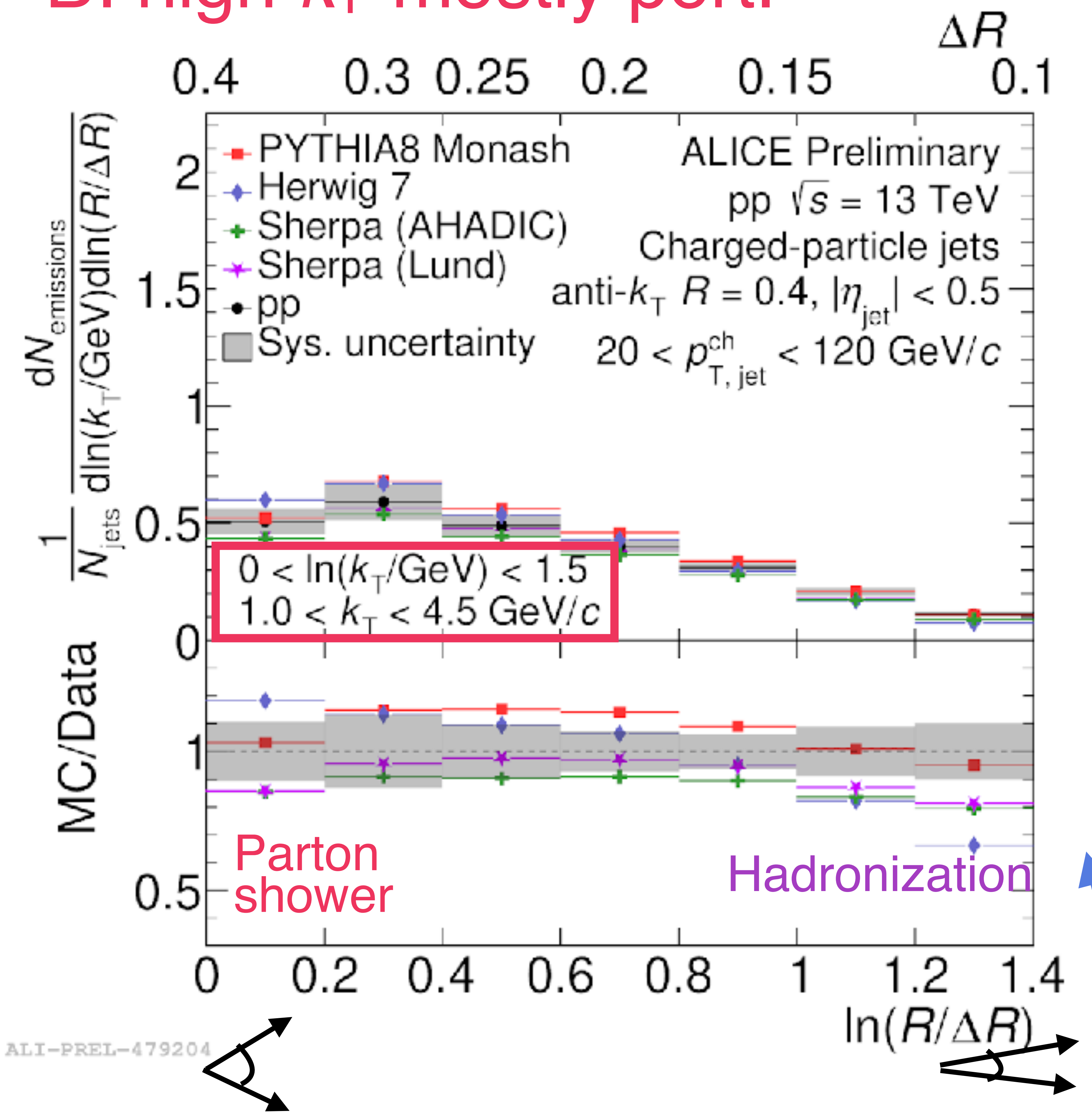


A: low k_T mostly NP ⟷ B: high k_T mostly pert.

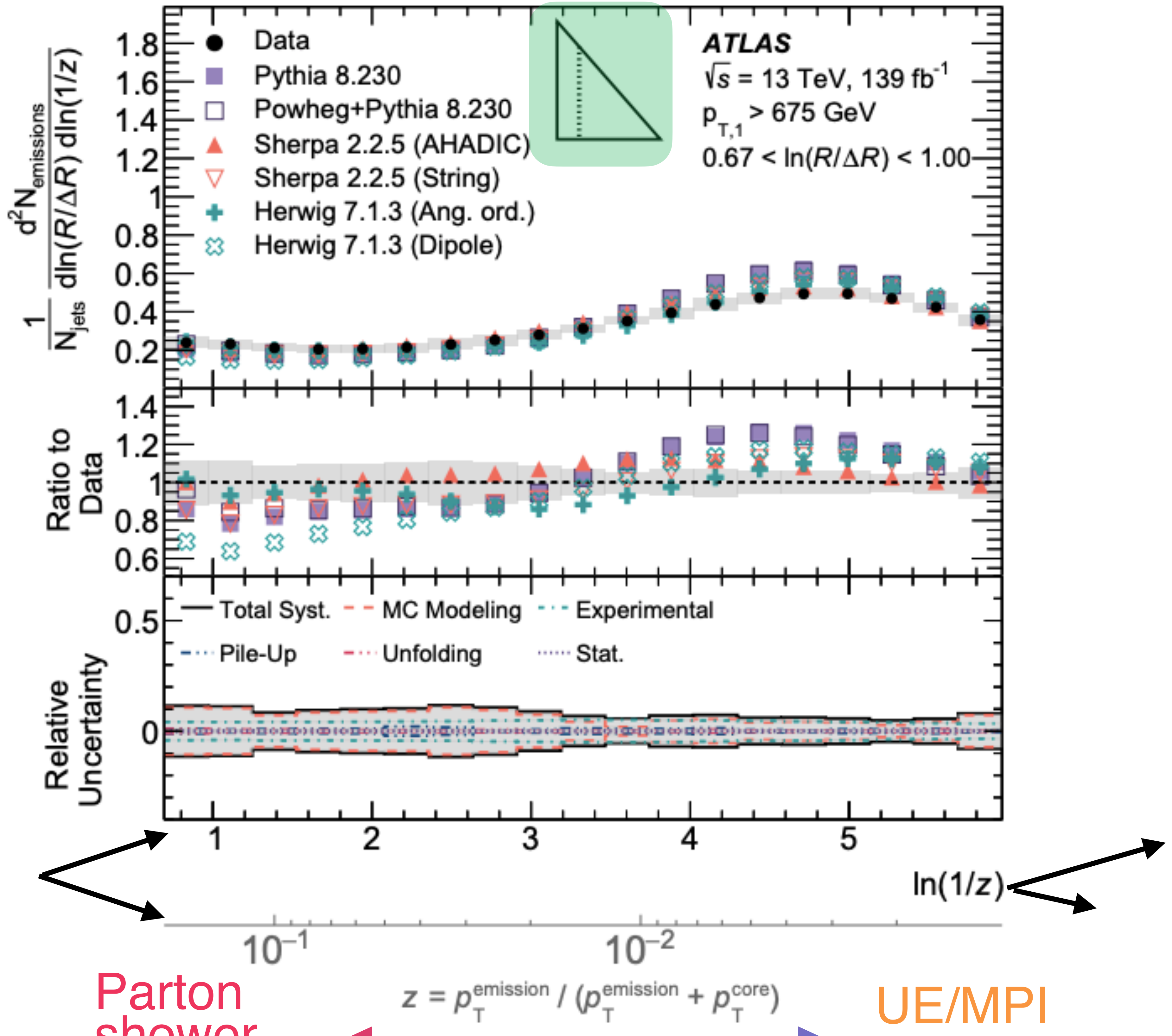


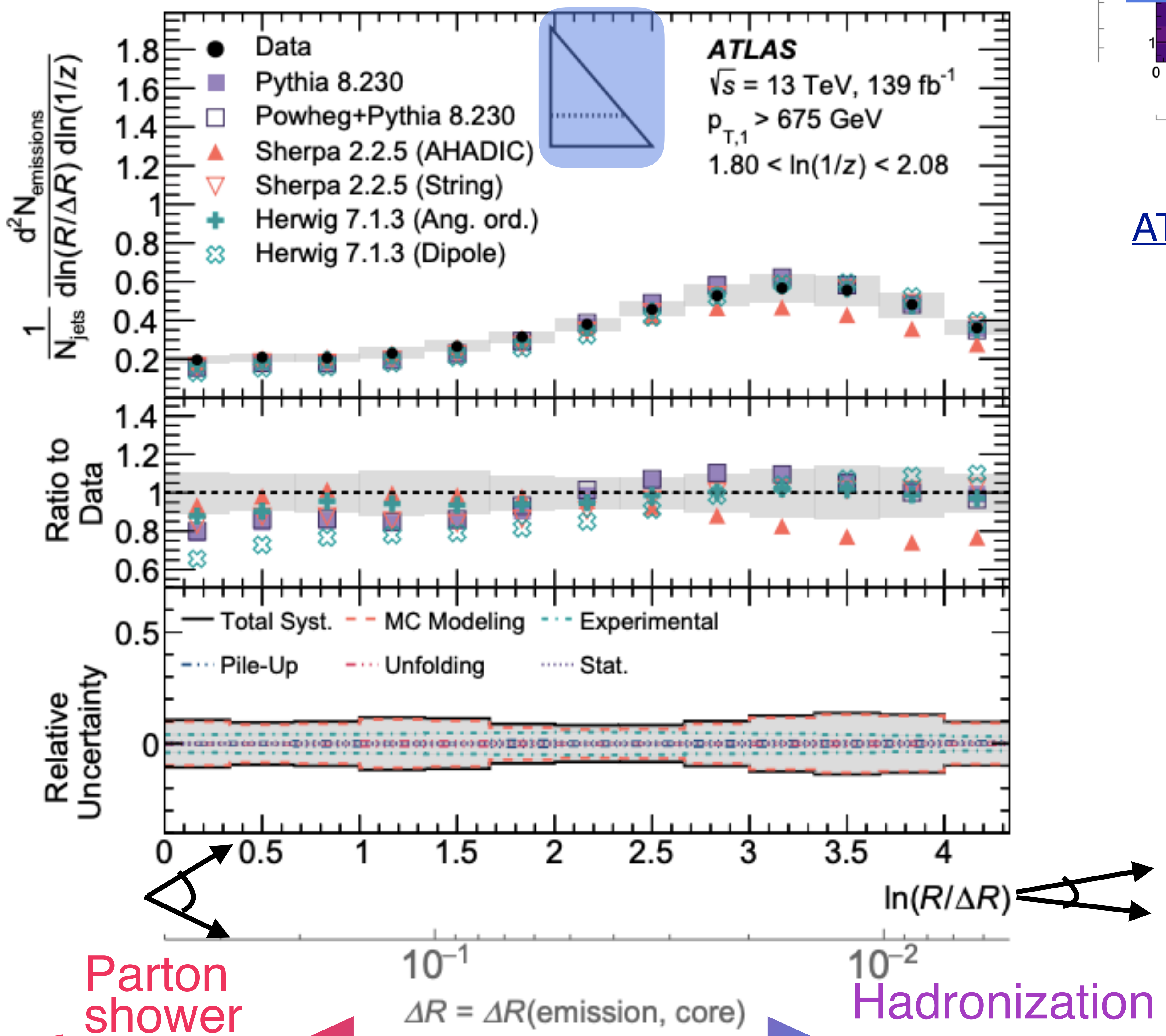


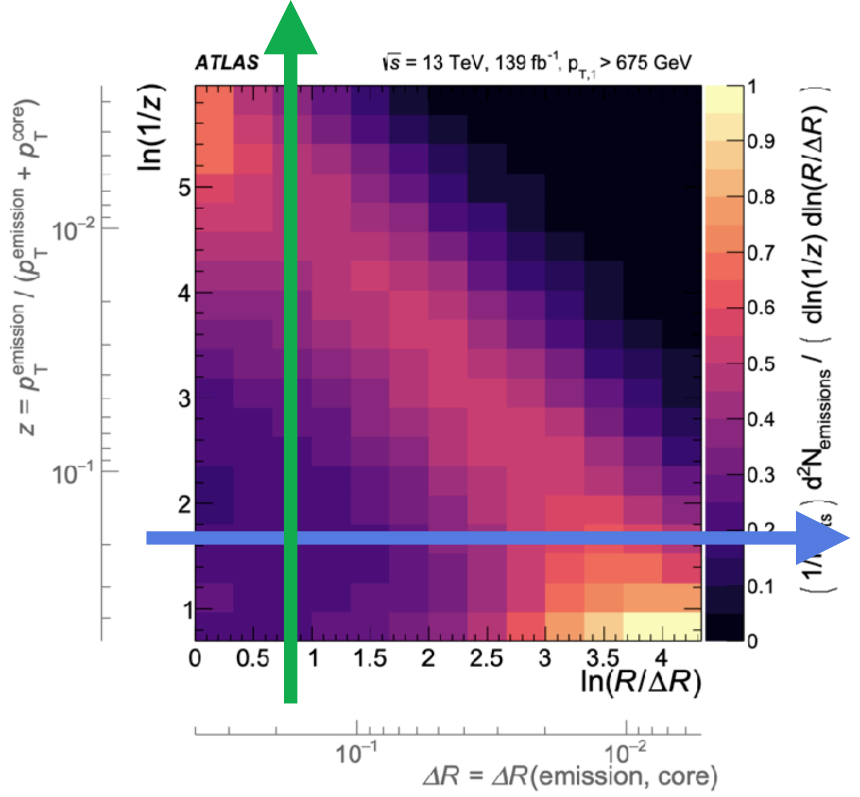
Herwig suppressed relative to data for hard collinear splitting

Regions of the Lund plane

Good agreement with MC in most cases







ATLAS PRL 124 (2020)

Parton shower

UE/MPI

Parton shower

Hadronization

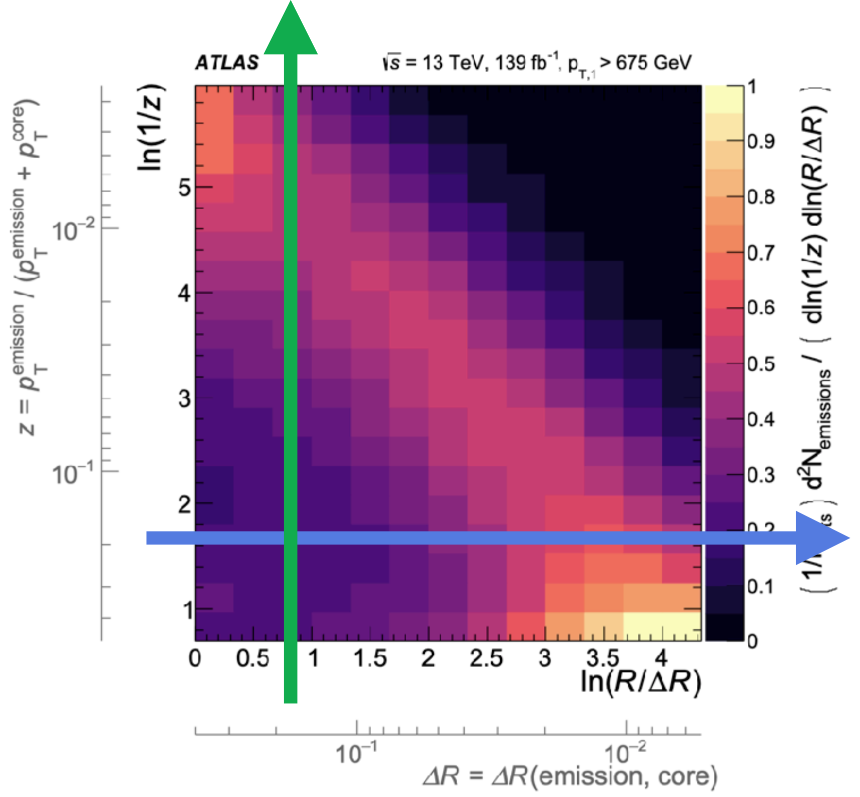
Differences seen for Herwig PS implementation

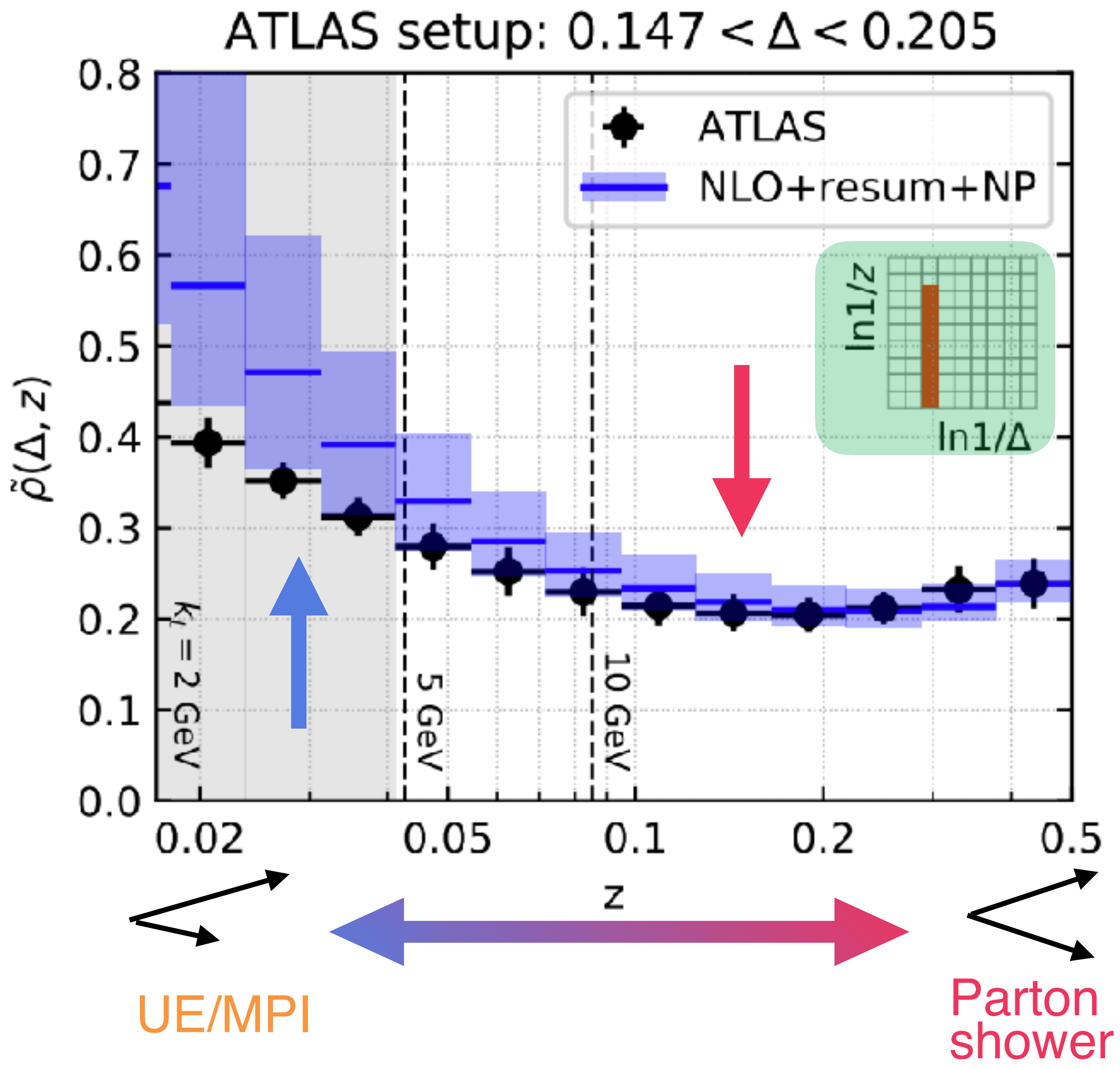
Differences seen for Sherpa hadronization implementation

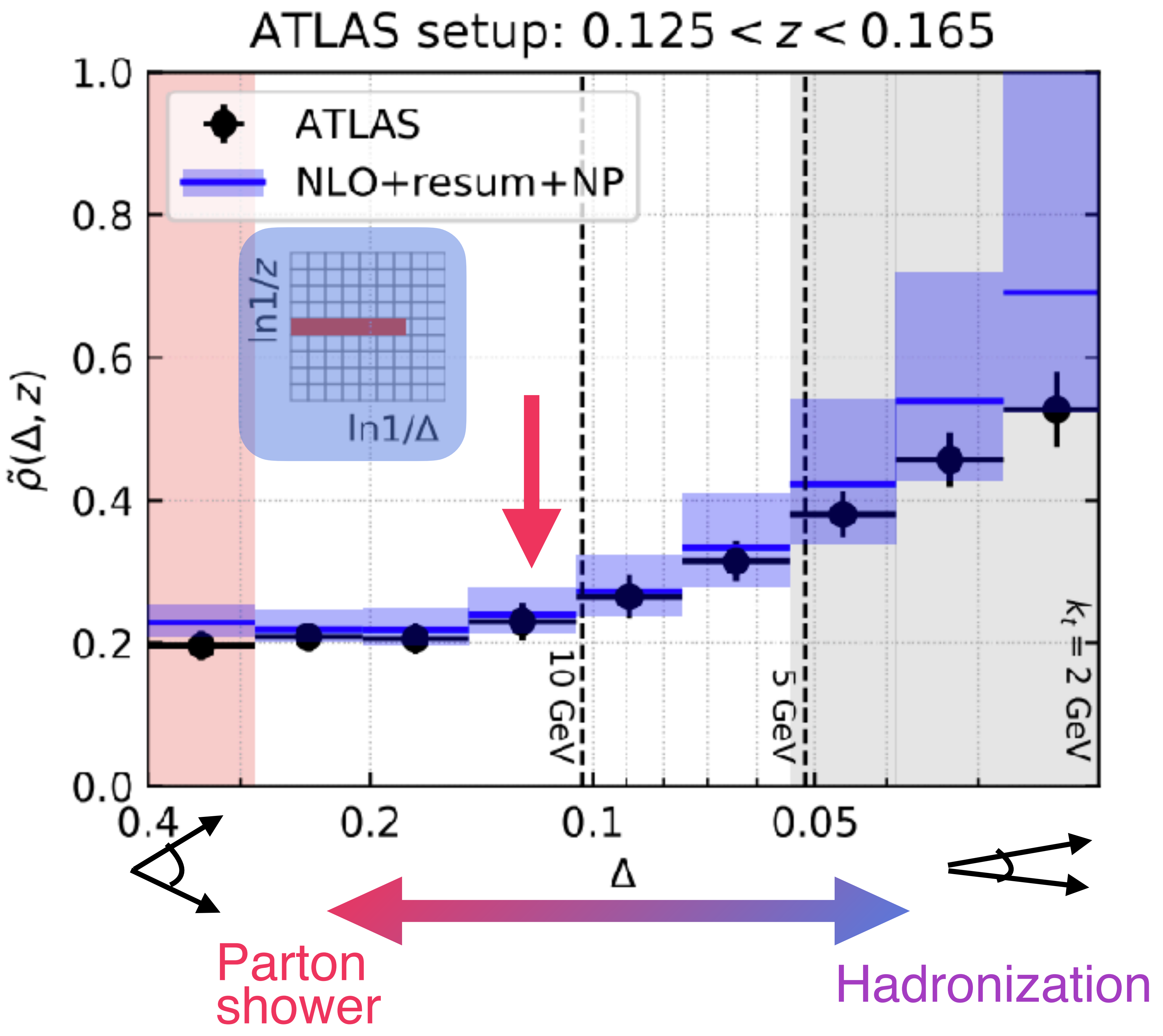
Analytical calculations

Compare to analytical all-order single log+NP calculations

Lifson et al, JHEP 10 (2020) 170



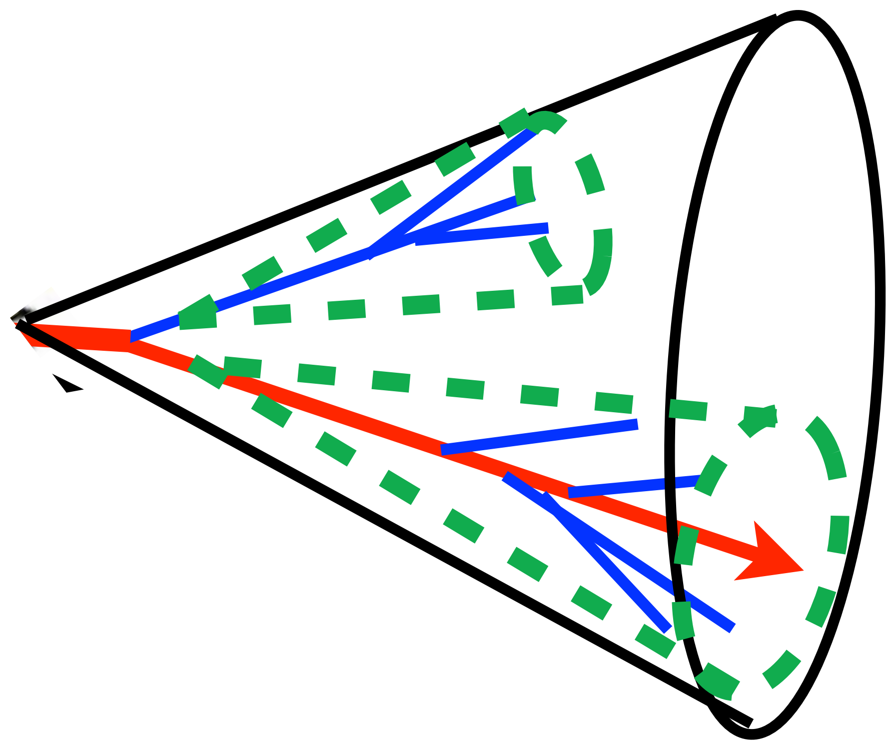




Good agreement seen in perturbative regions

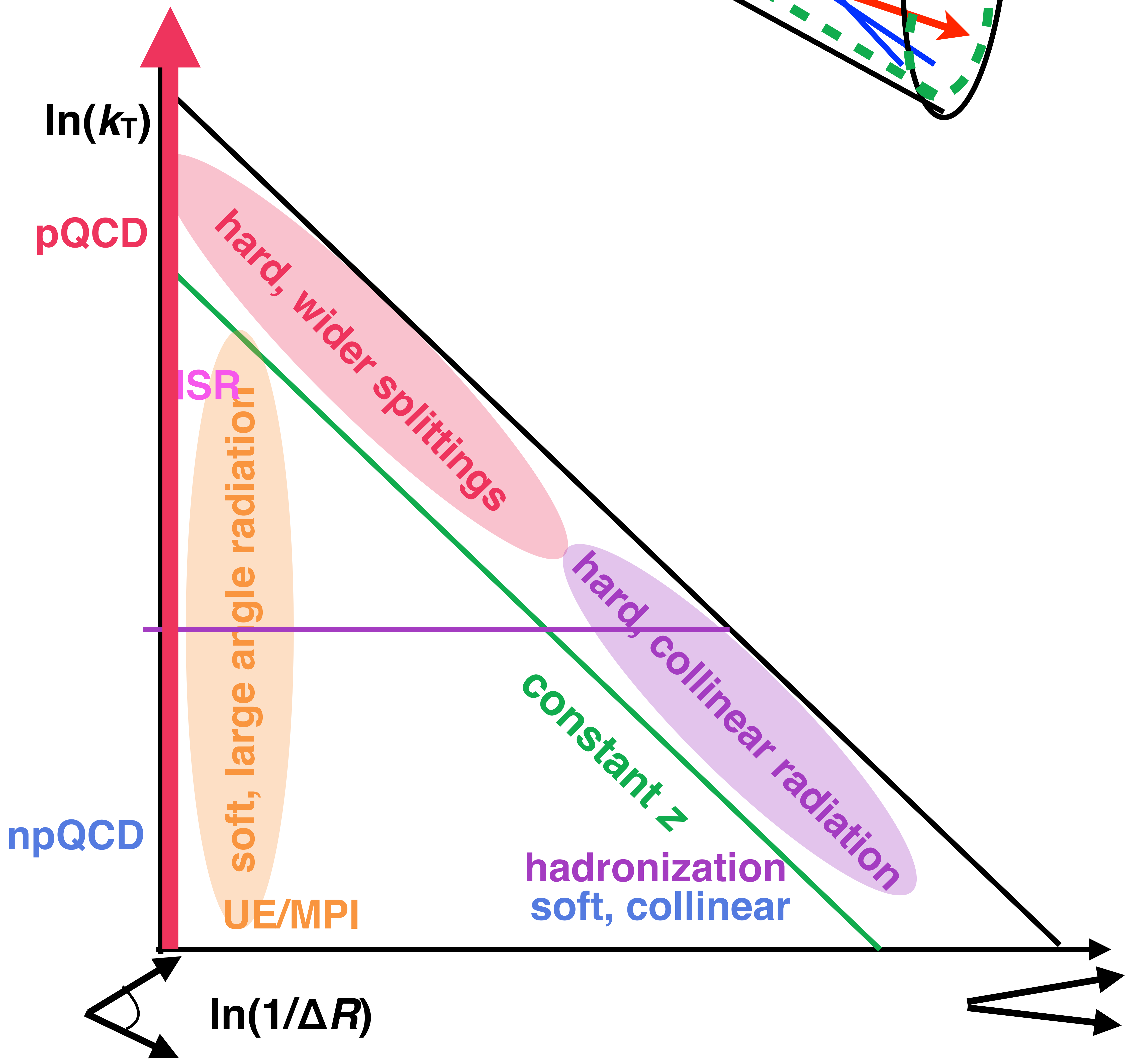
Tension in NP region

Soft drop grooming

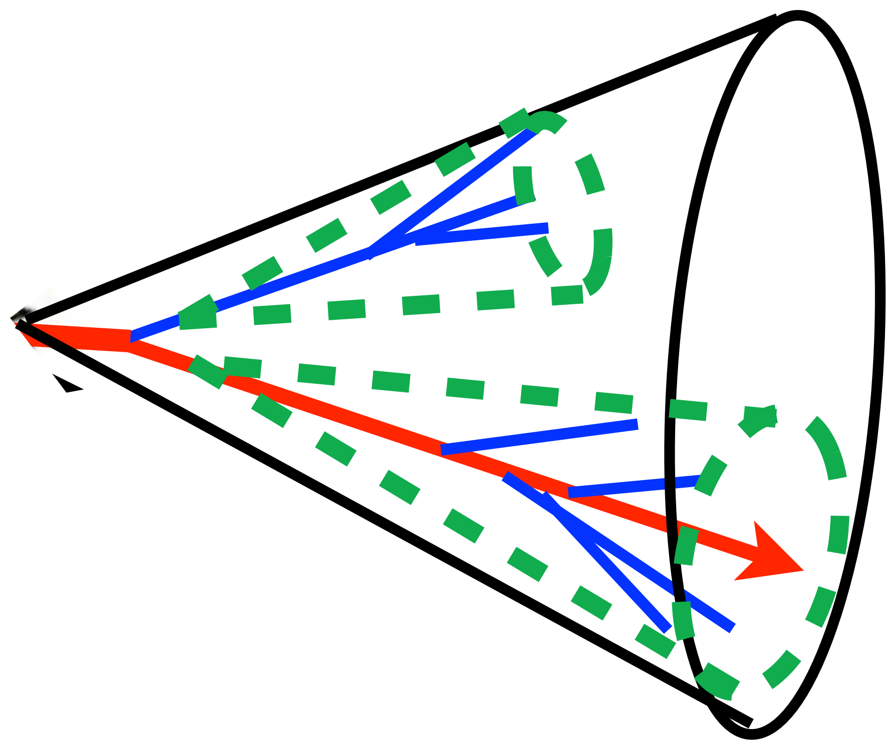


- Soft drop grooming method select on harder splittings inside the jet to remove the soft background contribution

  ➡Directly calculable in pQCD



Soft drop grooming



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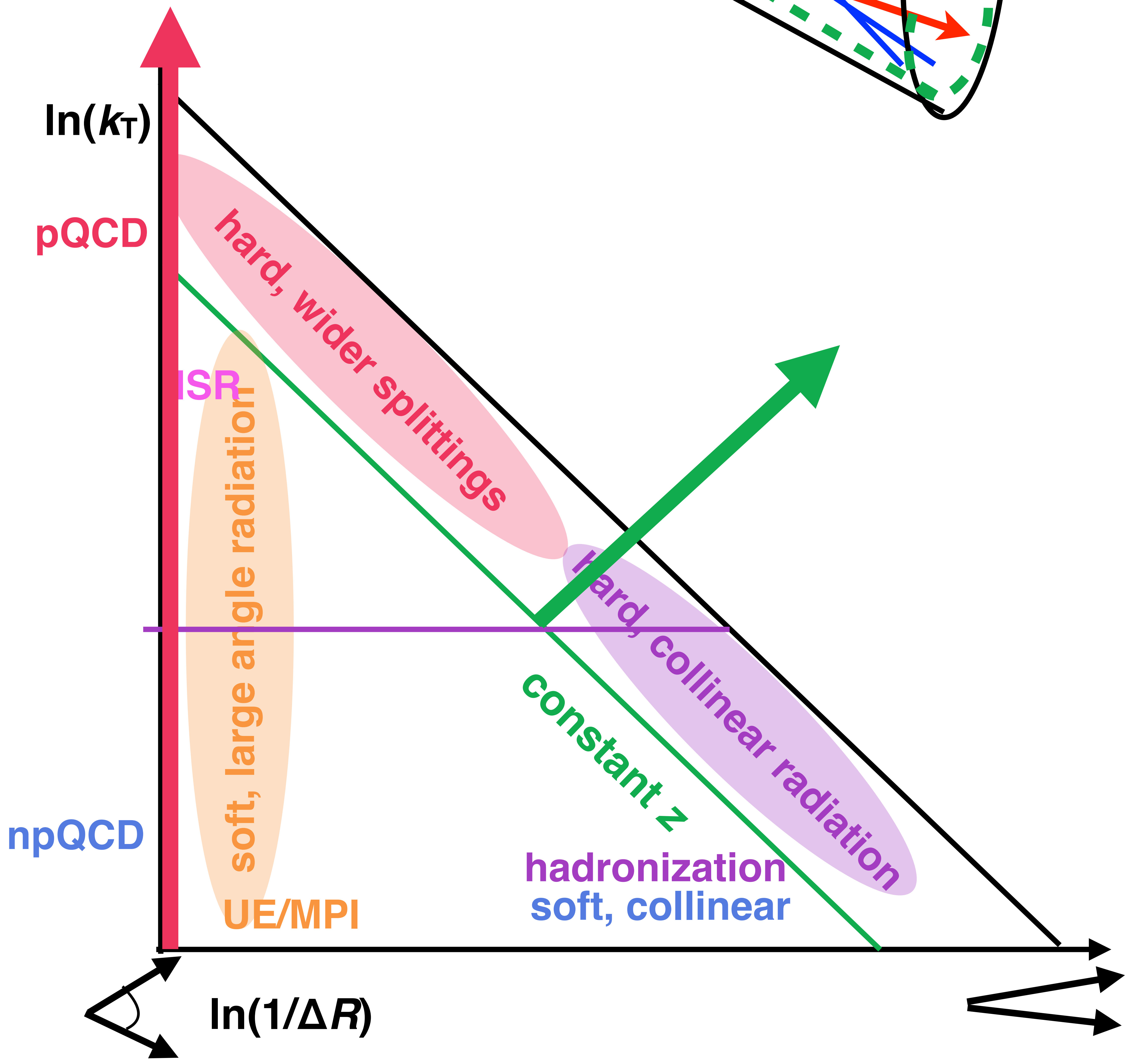
- First hard splitting:

$$z_g = \frac{\min(p_{Ti}, p_{Tj})}{p_{Ti} + p_{Tj}} \qquad z_g > z_{cut}\,\theta^{\beta} \qquad \theta = \frac{\Delta R}{R}$$



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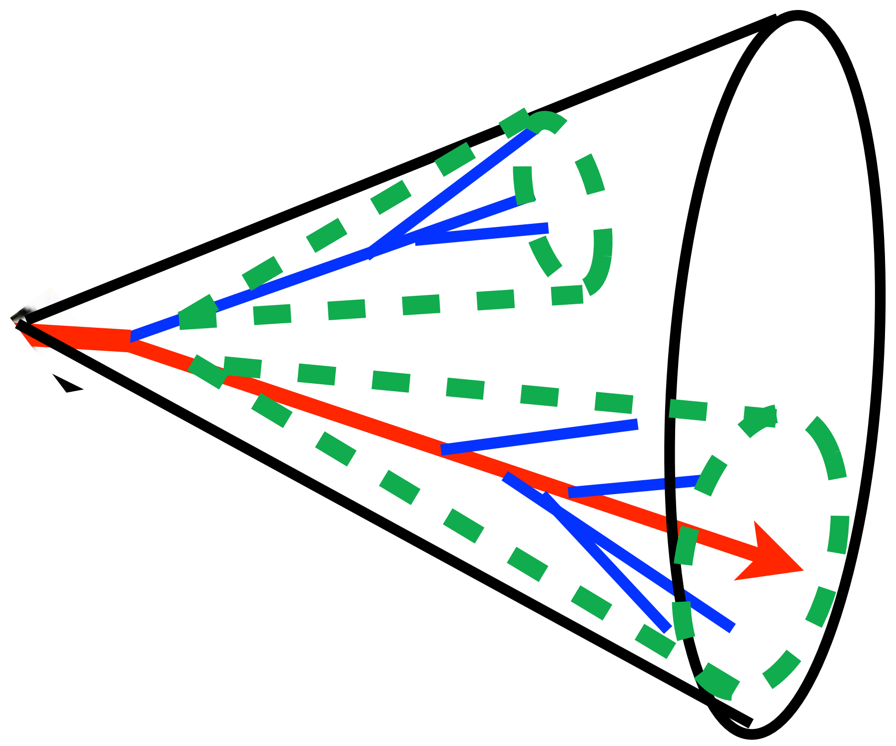

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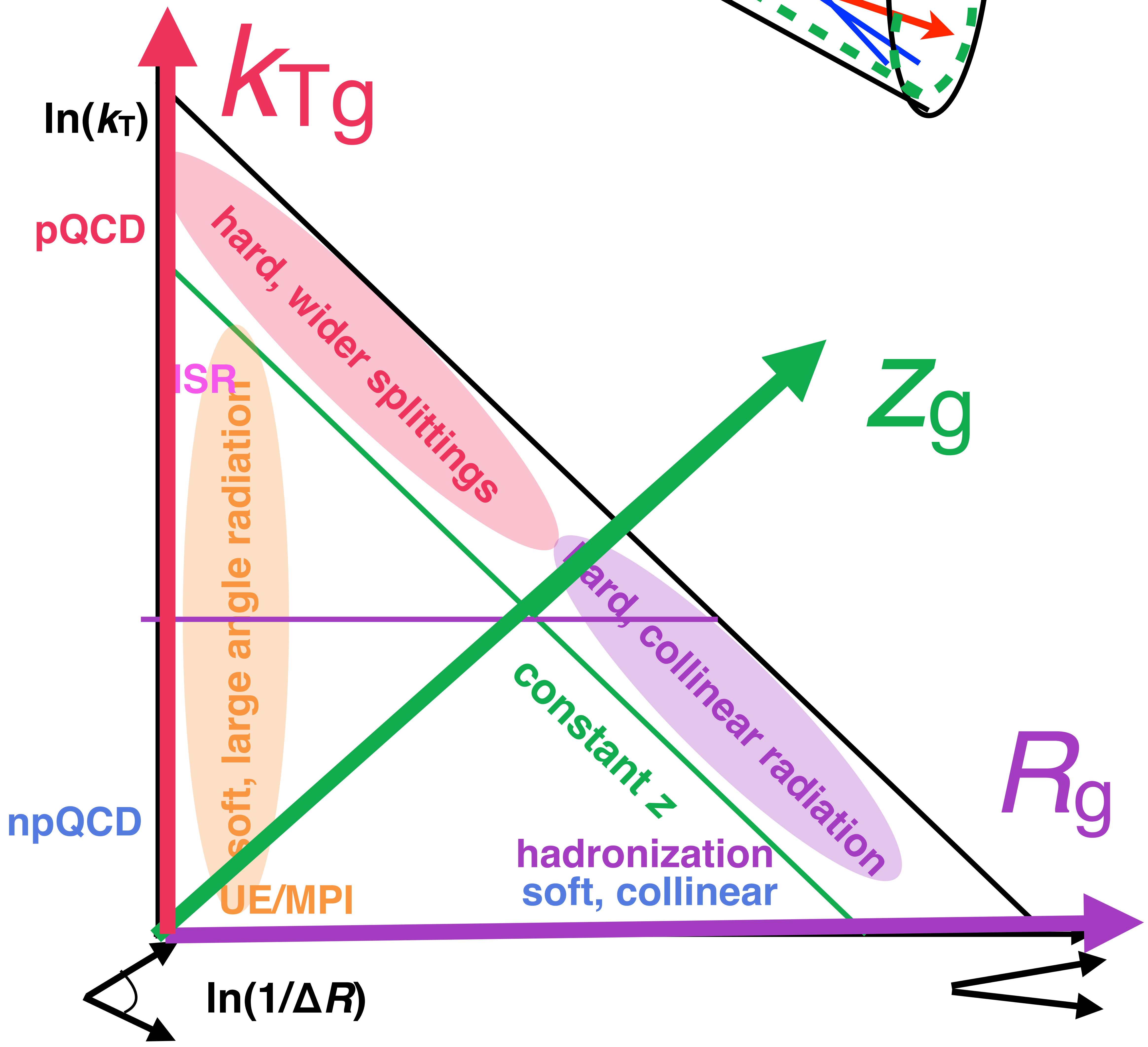
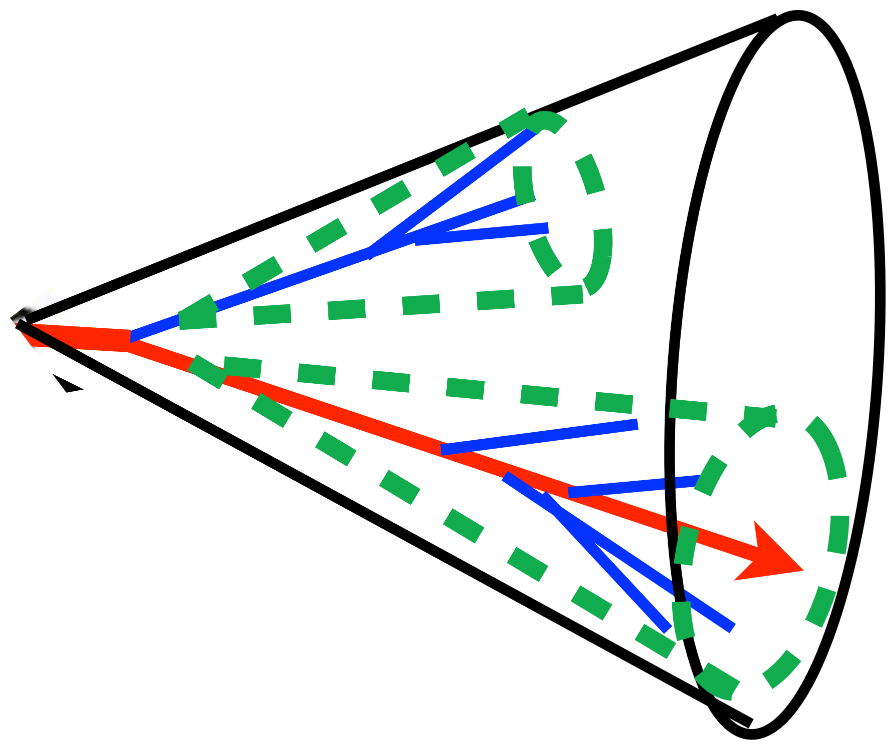
$$z_g = \frac{\min(p_{Ti}, p_{Tj})}{p_{Ti} + p_{Tj}} \quad z_g > z_{cut}\,\theta^{\beta} \quad \theta = \frac{\Delta R}{R}$$

- Make projections to access different substructure variables



Soft drop grooming



- Soft drop grooming method select on harder splittings inside the jet to remove the soft background contribution

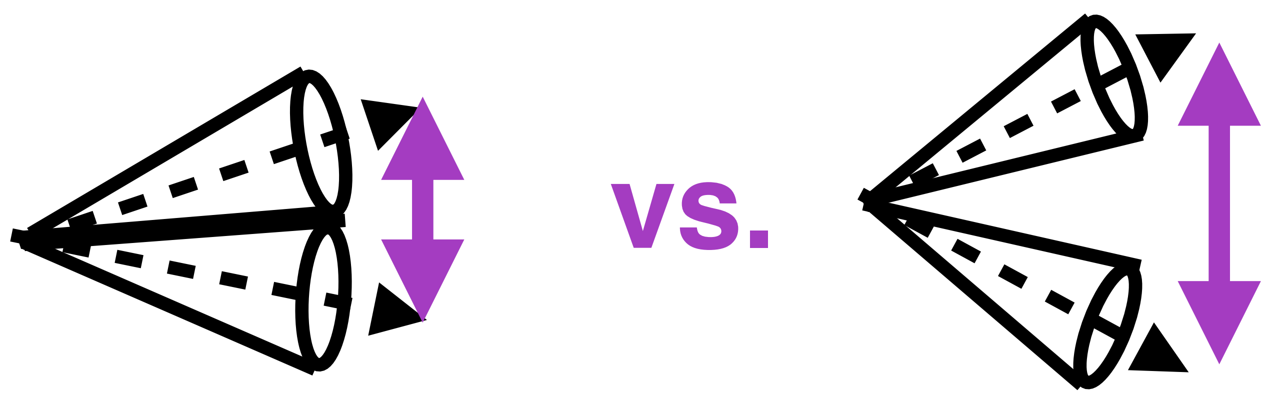
  ➡ Directly calculable in pQCD

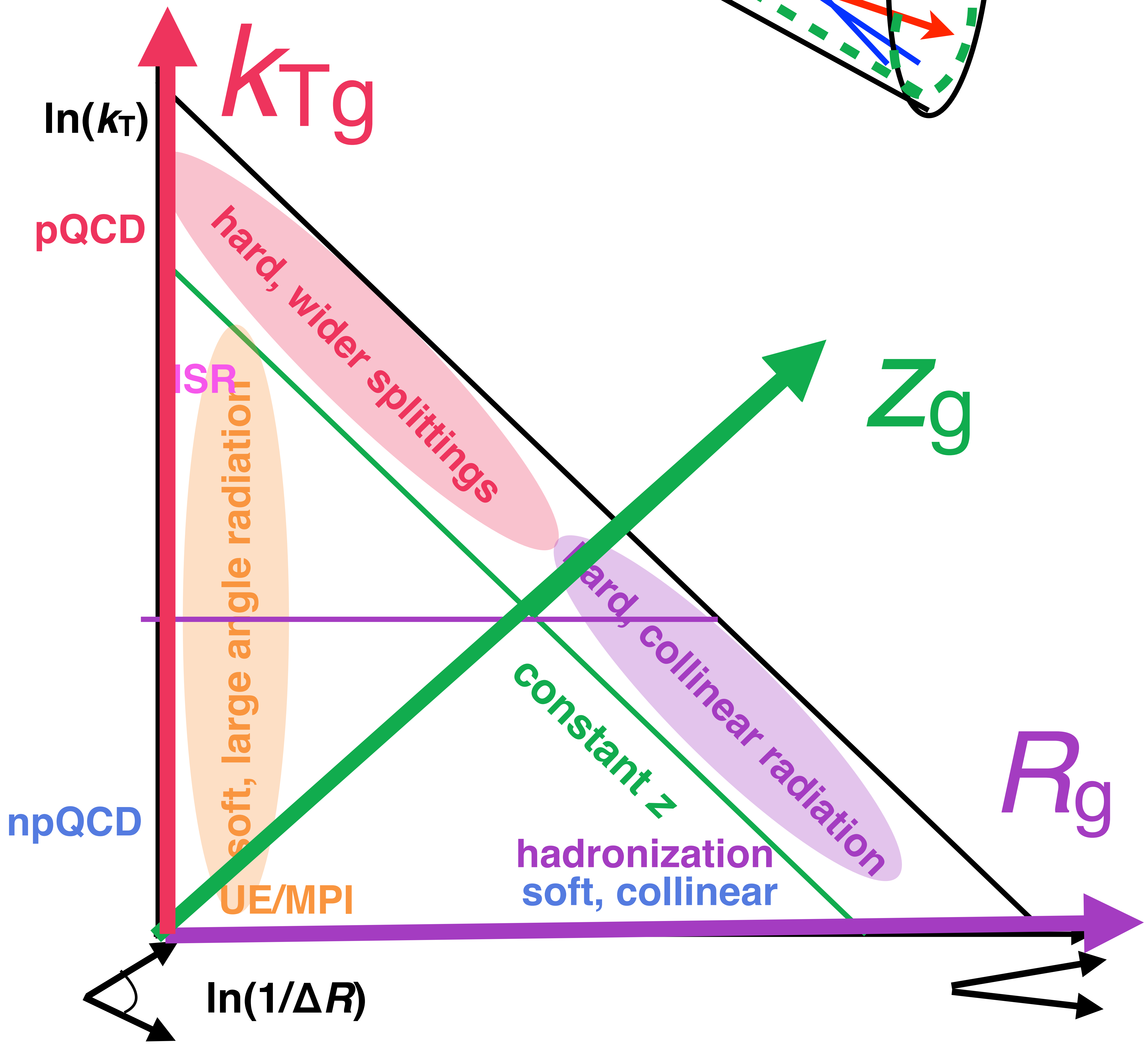
- First hard splitting:

$$z_g = \frac{\min(p_{Ti}, p_{Tj})}{p_{Ti} + p_{Tj}} \qquad z_g > z_{cut}\,\theta^{\beta} \qquad \theta = \frac{\Delta R}{R}$$

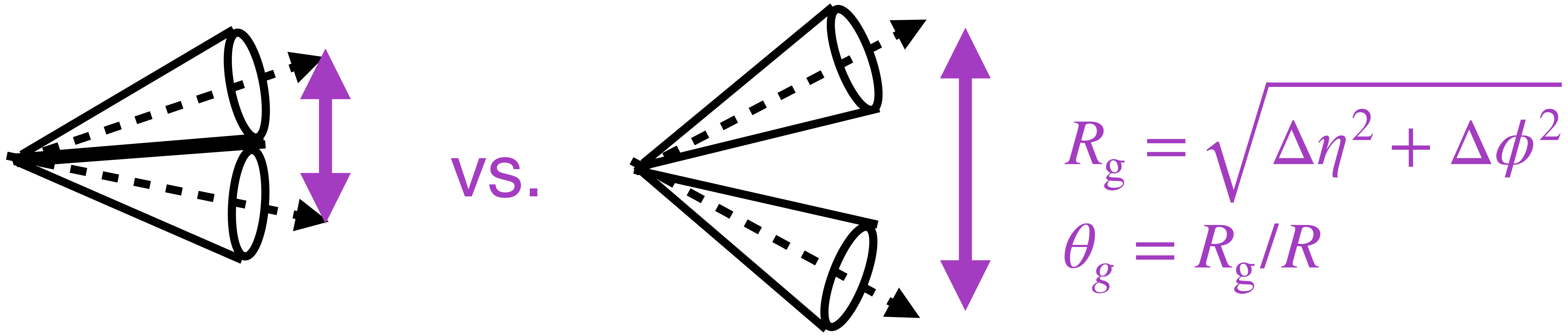
- Make projections to access different substructure variables

- Distance between subjets $R_g = \sqrt{\Delta\eta^2 + \Delta\phi^2}$





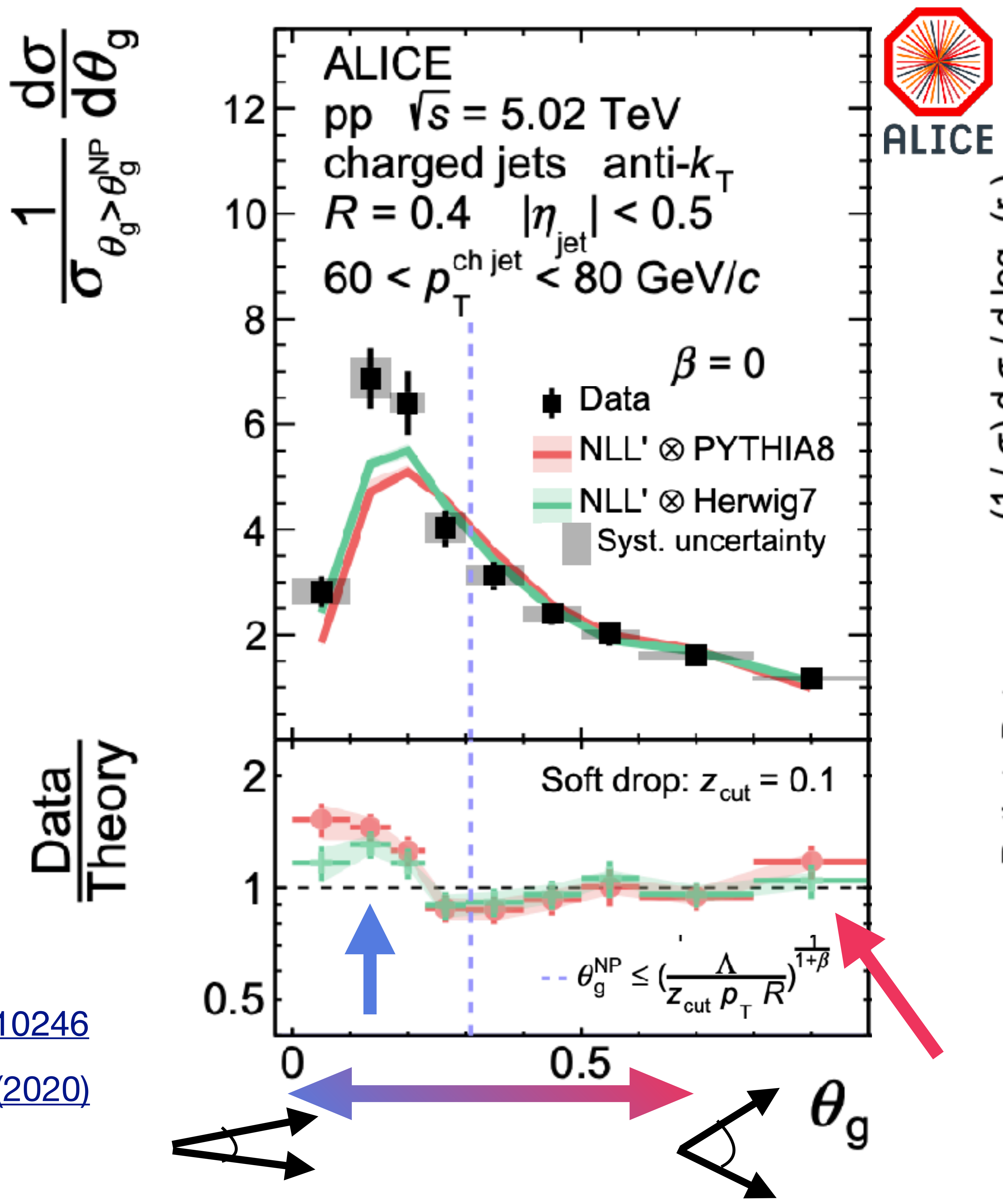
SD grooming: R_g



Compare to NLL' pQCD calculations

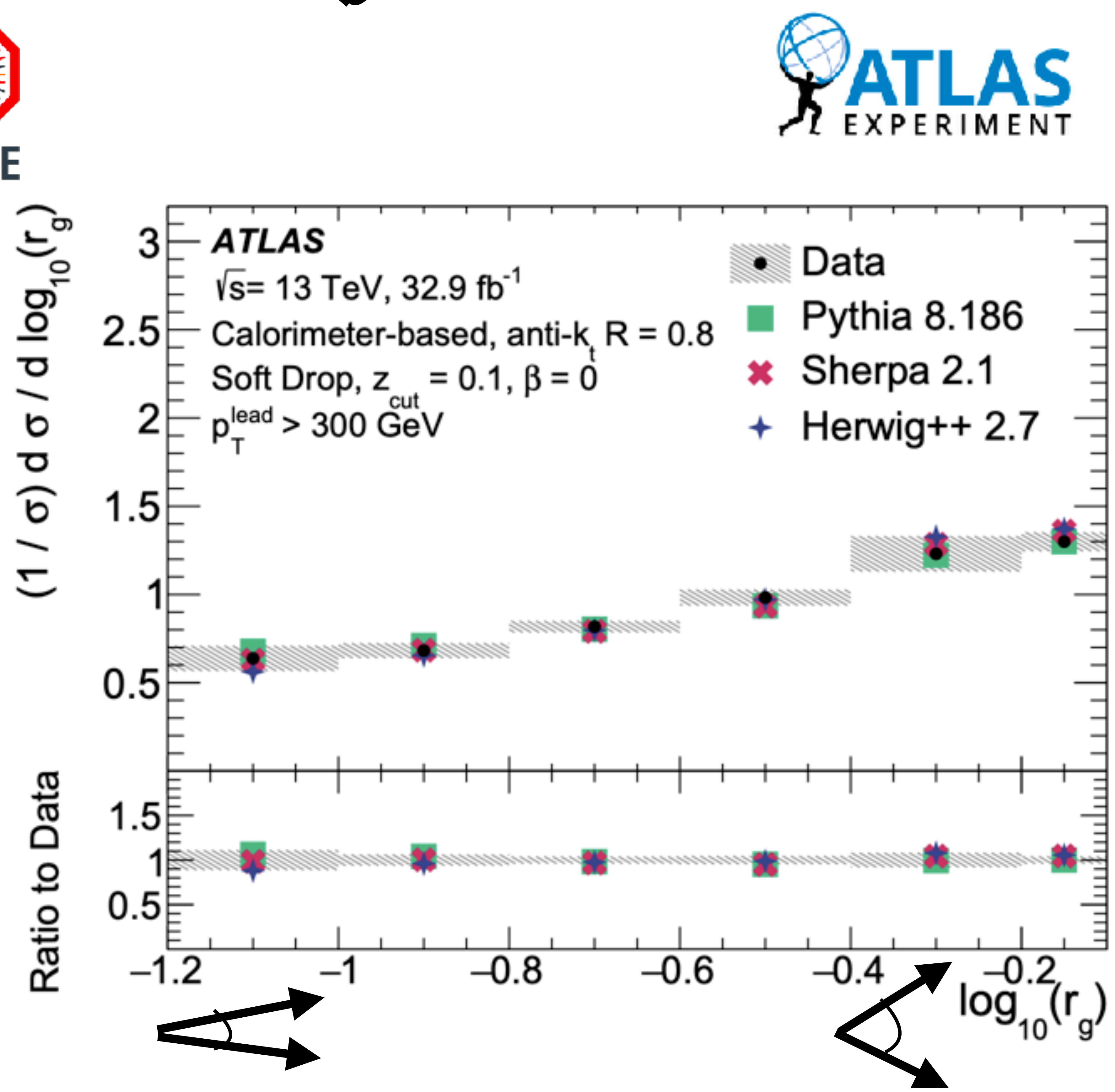
Good agreement in perturbative region

Underestimate in NP region



ALICE arXiv:2204.10246

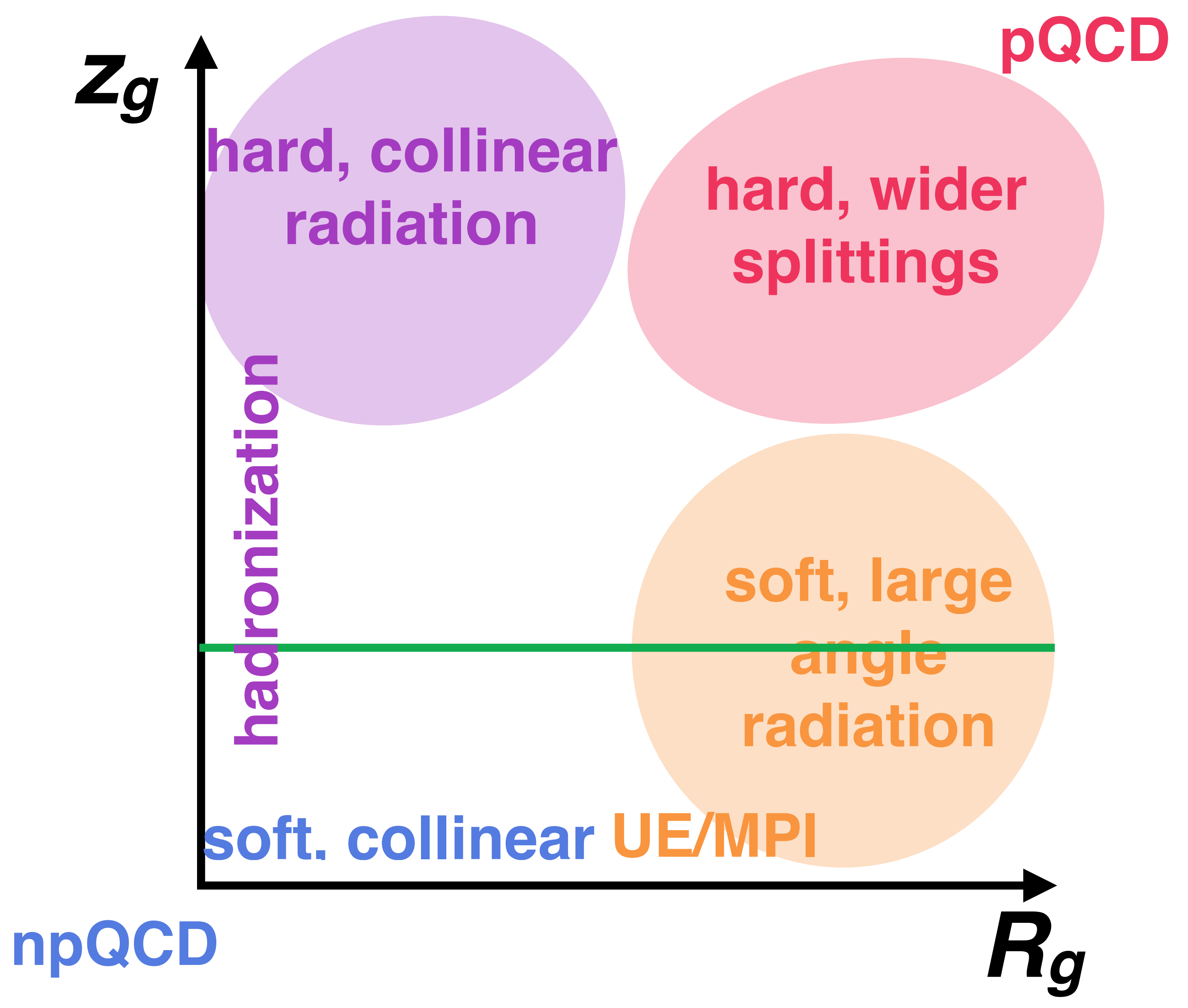
Kang et al, JHEP 02, 054 (2020)



ATLAS PRD 101, 052007 (2020)

CMS PRD 98, 092014 (2018)

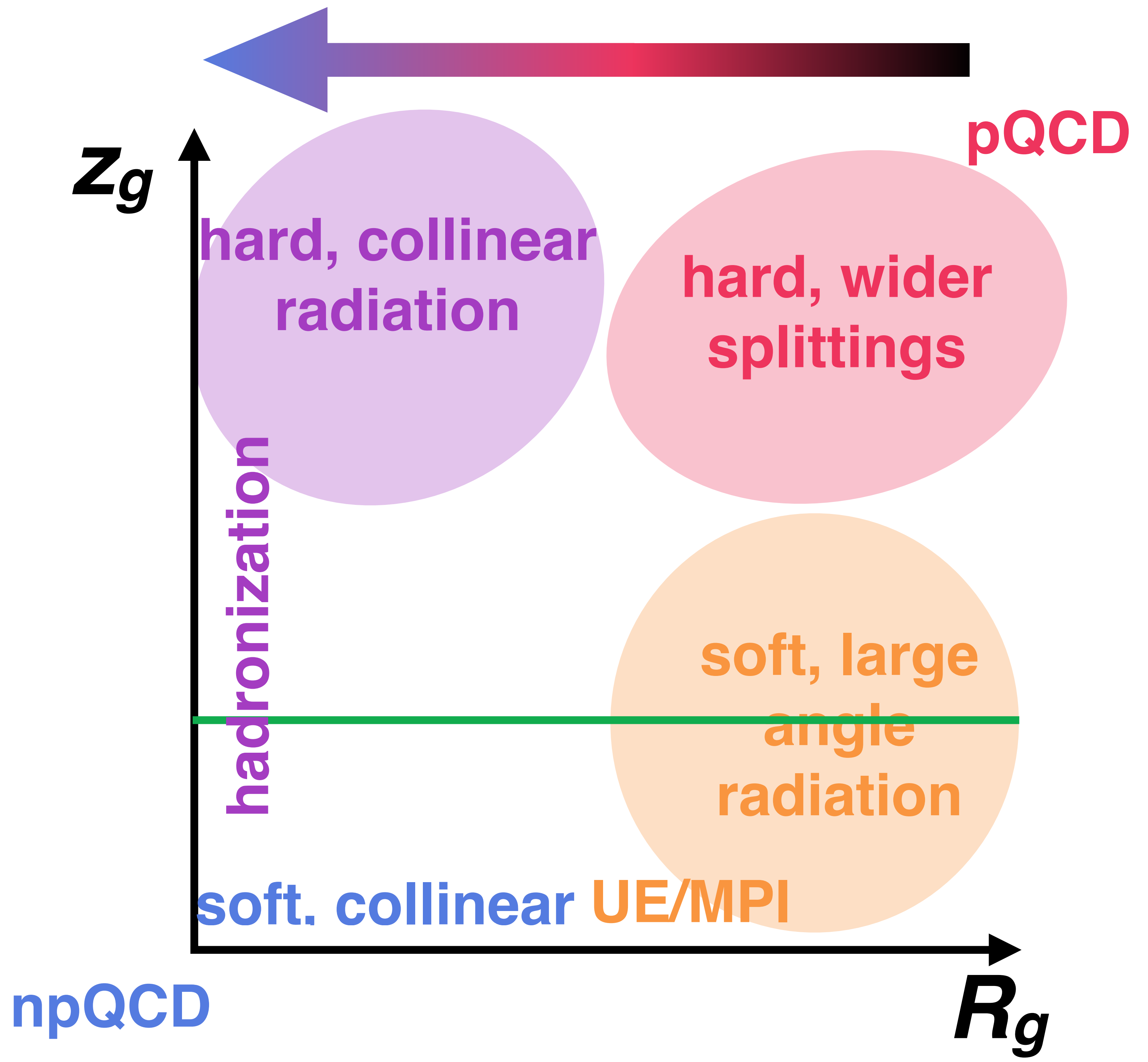
R_g vs. z_g

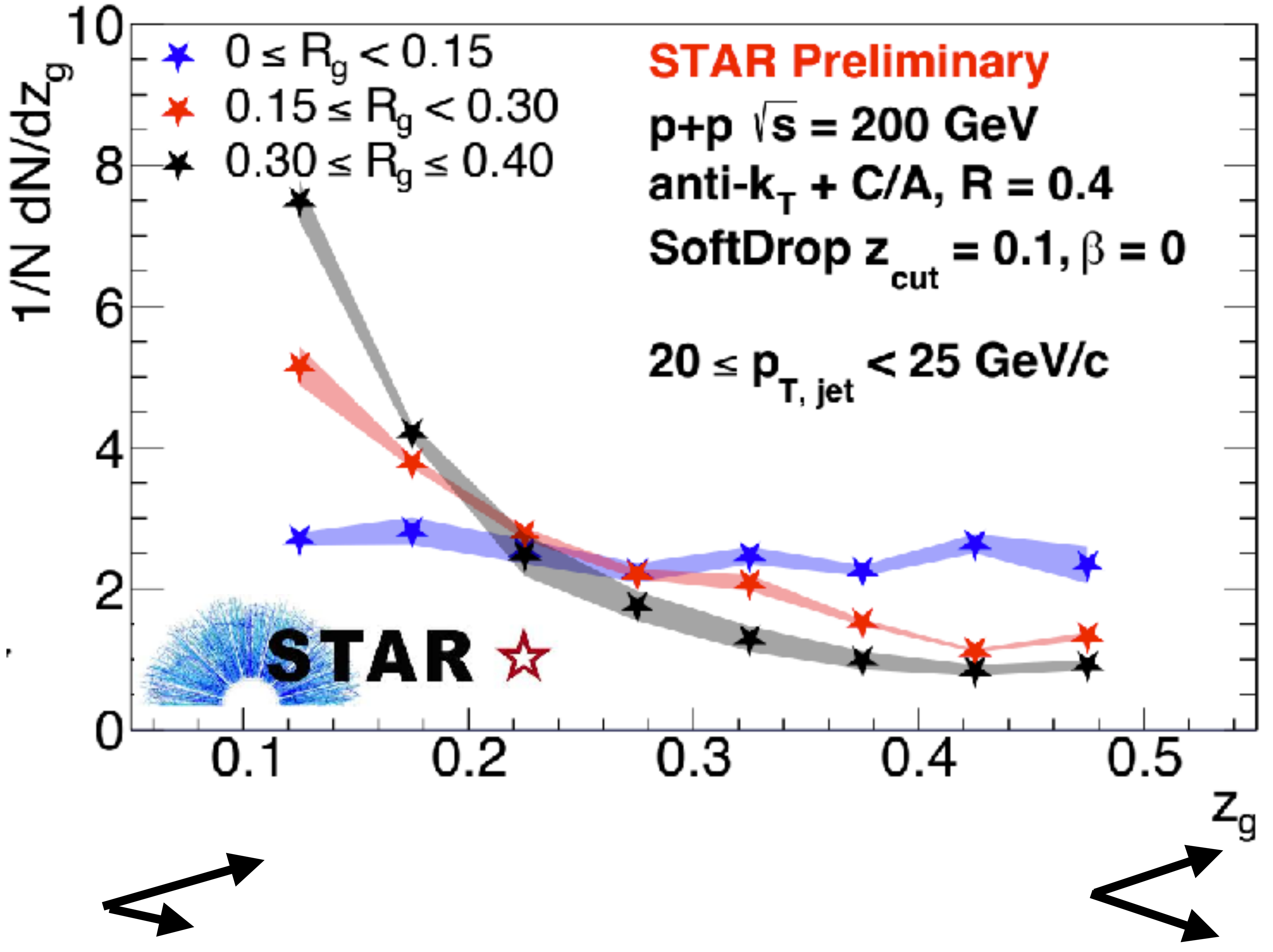


z_g
hard, collinear radiation
pQCD
hard, wider splittings
hadronization
soft, large angle radiation
soft, collinear
UE/MPI
npQCD
R_g

R_g vs. z_g

See Isaac's talk today!





Evolves from soft large-angle to collinear hard splittings

R_g vs. z_g vs. splitting

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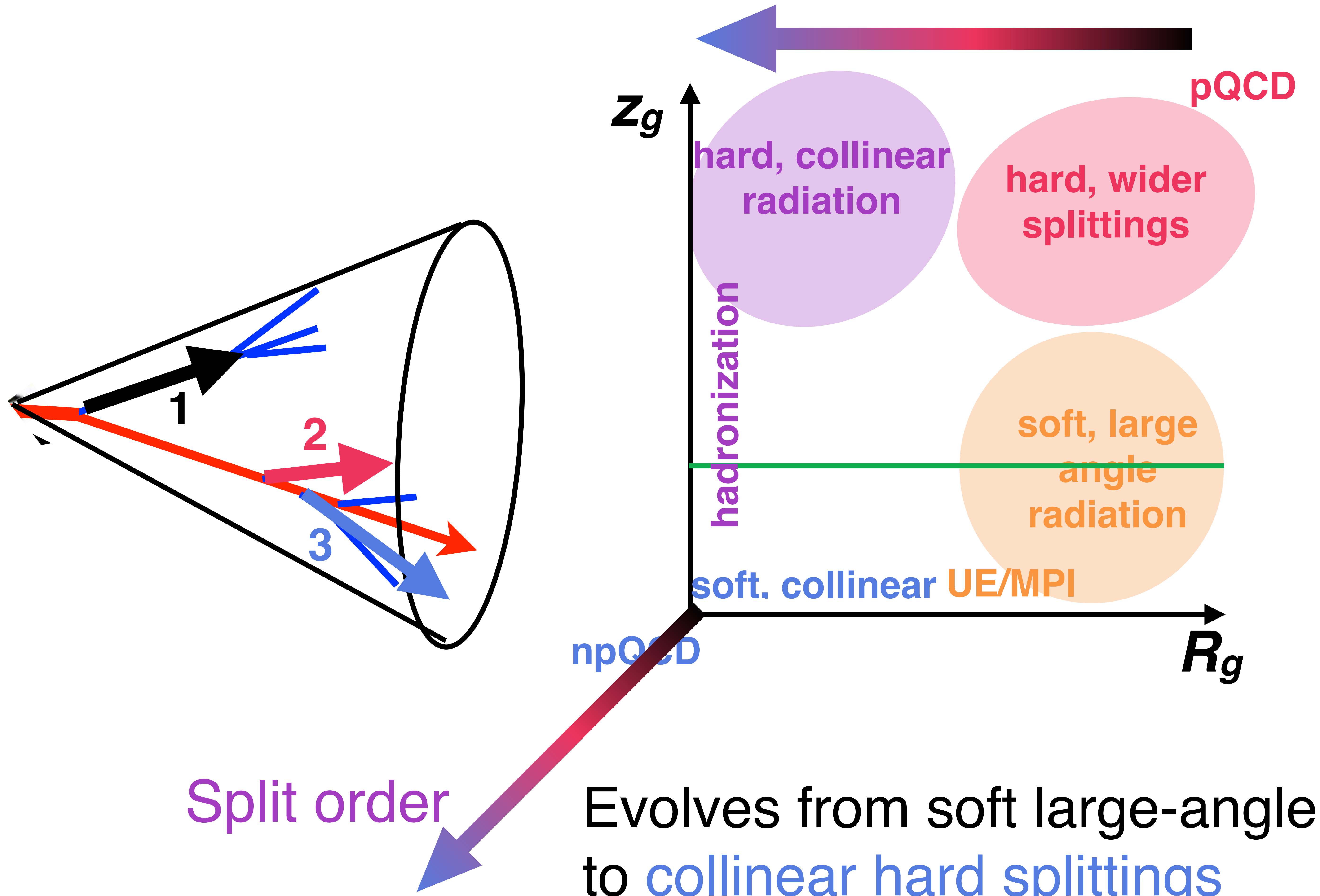

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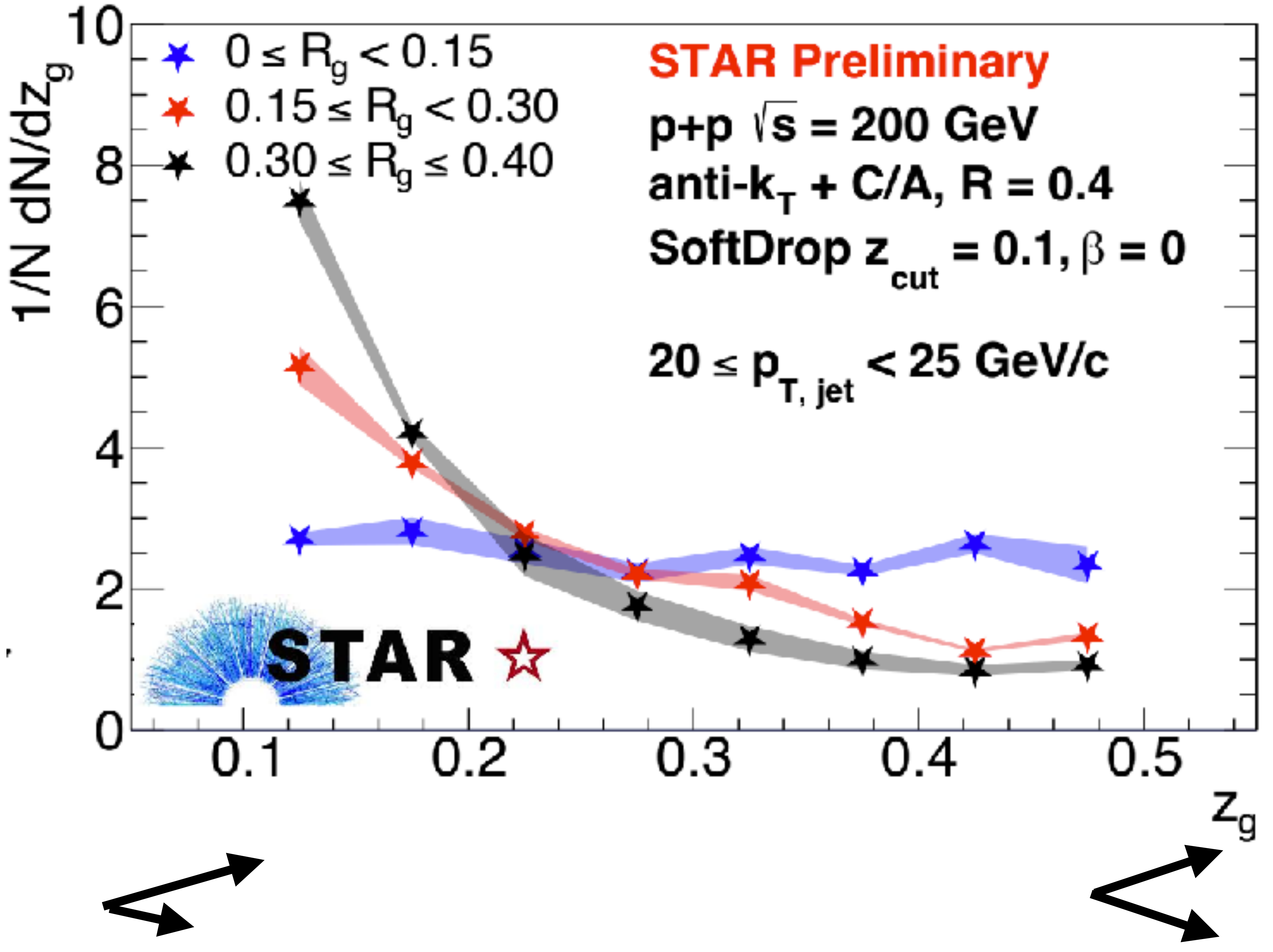

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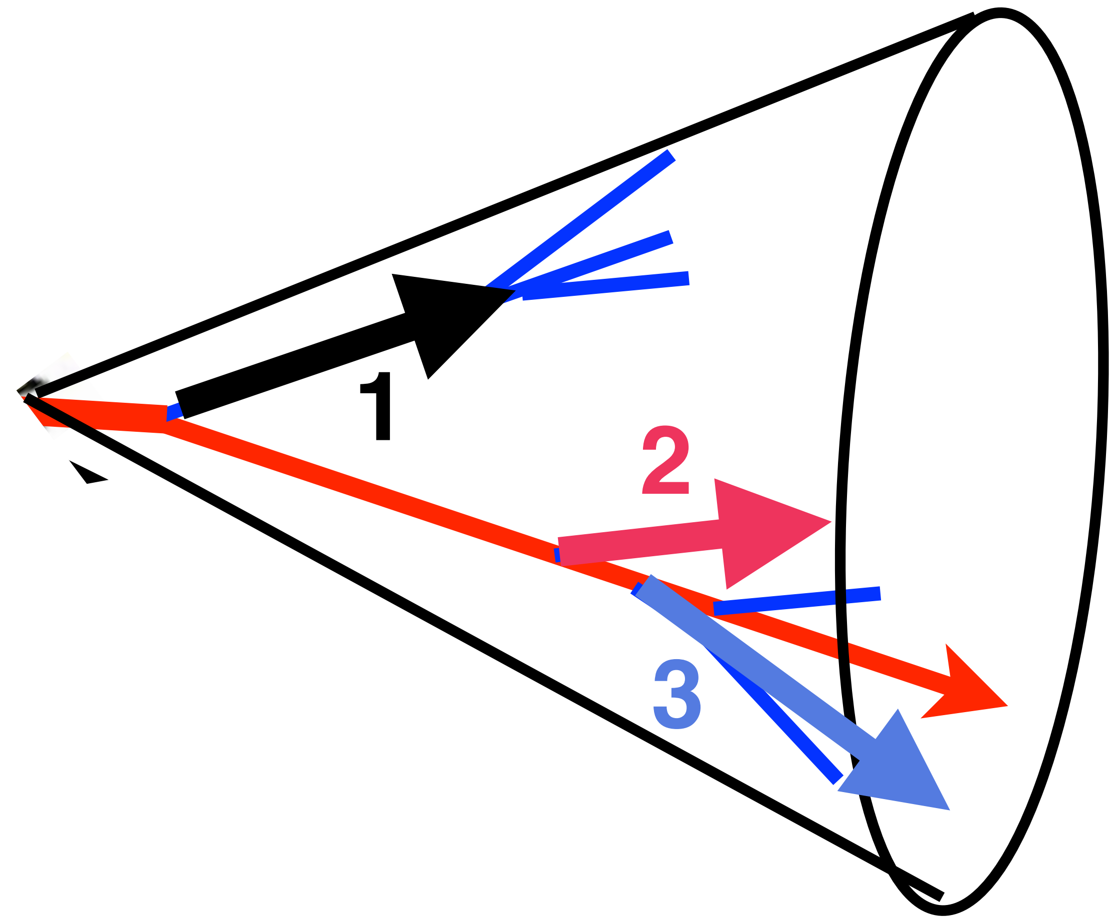
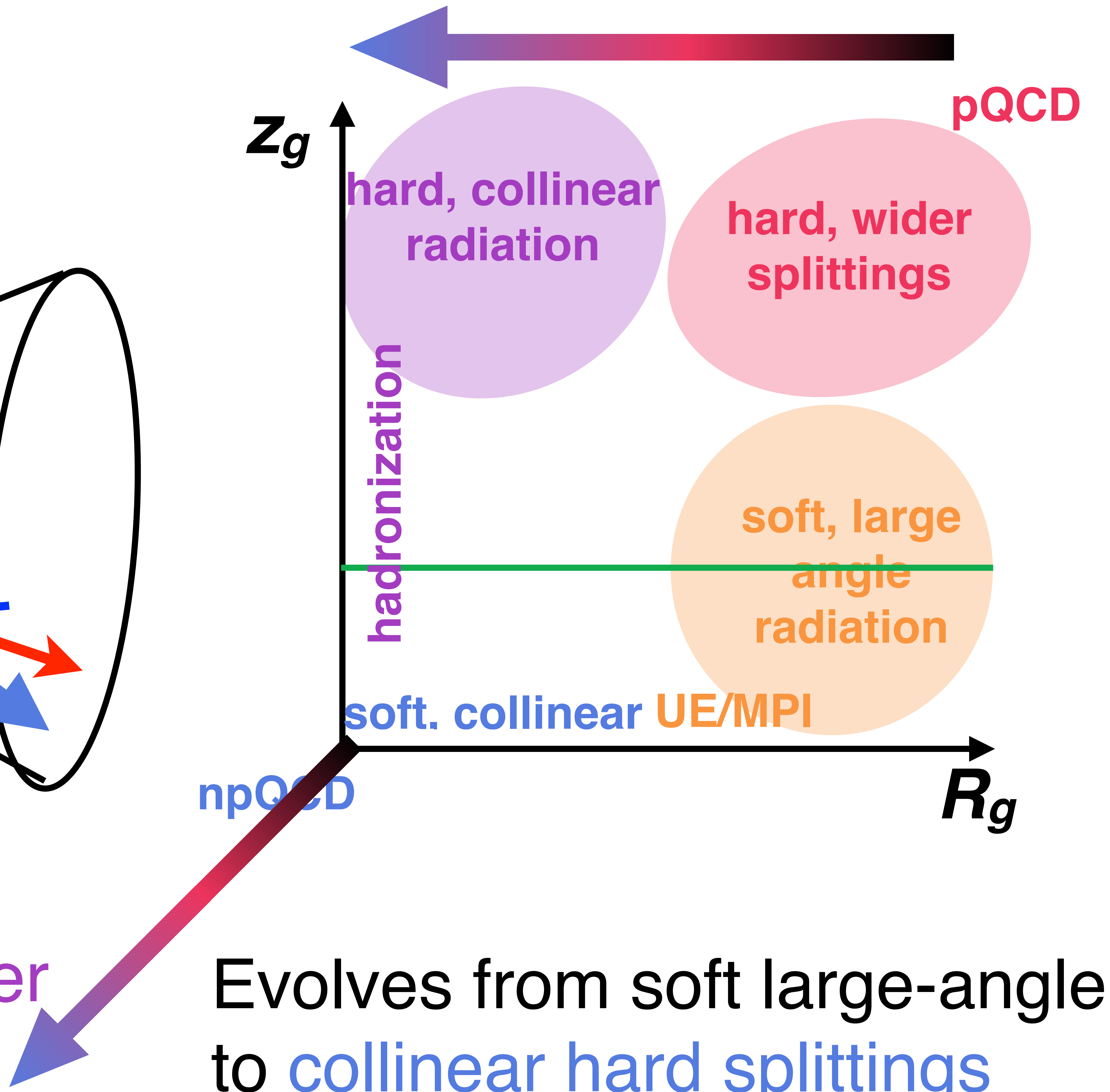
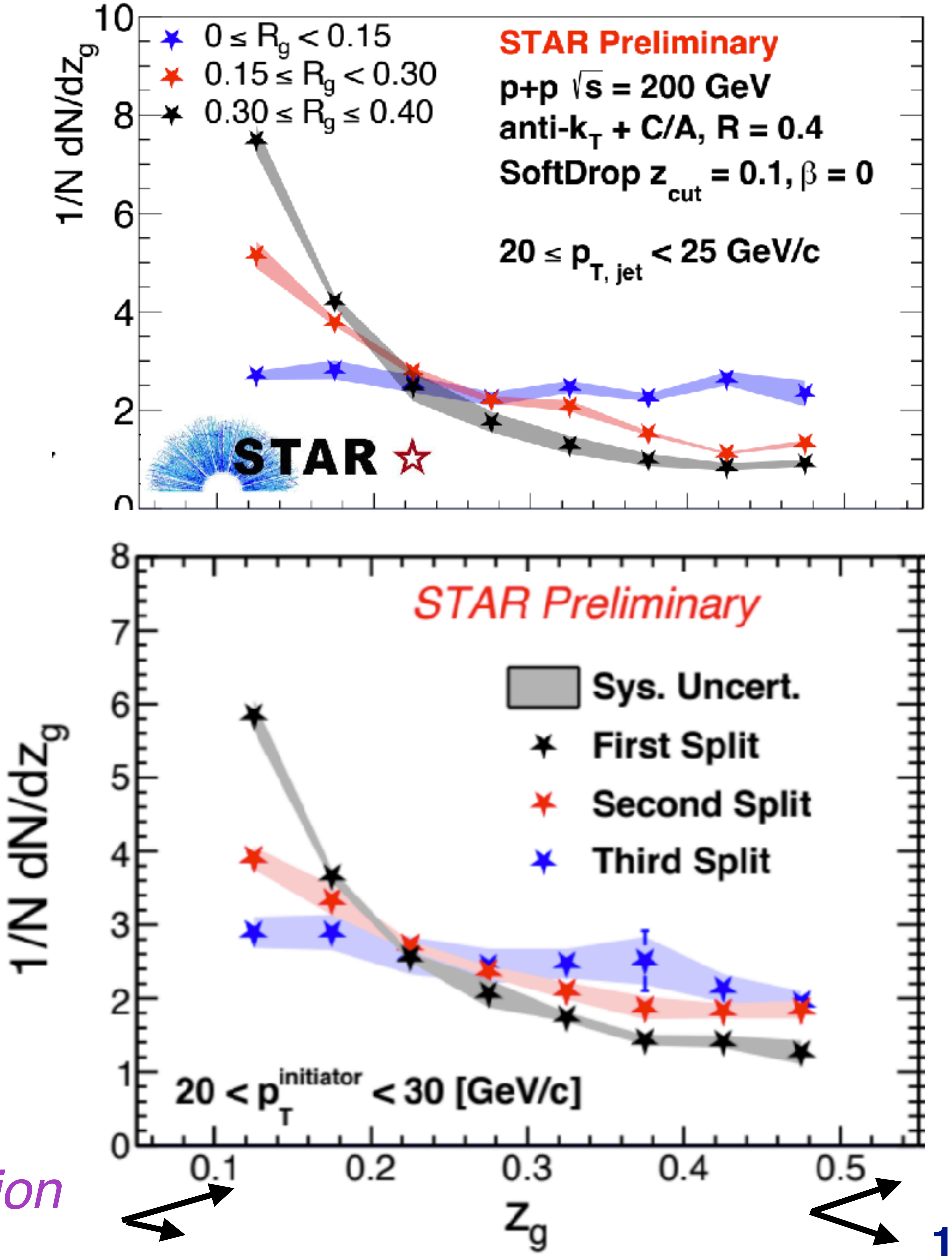




Evolves from soft large-angle to collinear hard splittings

…and follows split order evolution



Measure splitting formation time

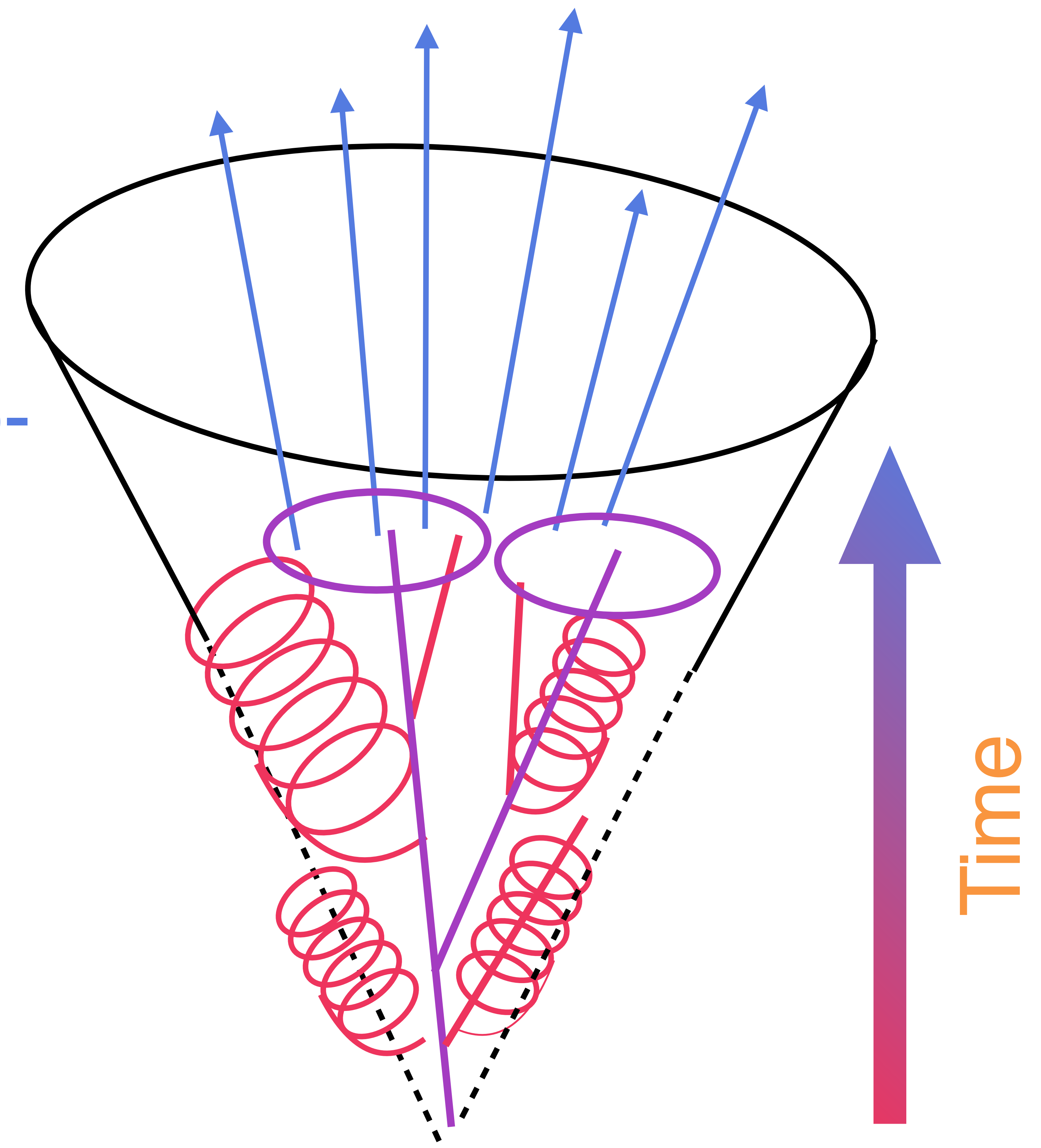
Apolinario et al *EPJC* **81**, 561 (2021)
Chien et al arXiv:2109.15318

Measure different formation time definitions

$$t_{\mathrm{f}} \approx \frac{1}{(1-z)k_{\mathrm{T}}\Delta R}$$

Final state leading and sub-leading charged particles: later and NP?

SD splitting formation time: earlier and pert?



See Mriganka's and Isaac's talk today!

Measure splitting formation time

Measure different formation time definitions

[Apolinario et al *EPJC* **81**, 561 (2021)](#)
[Chien et al arXiv:2109.15318](#)

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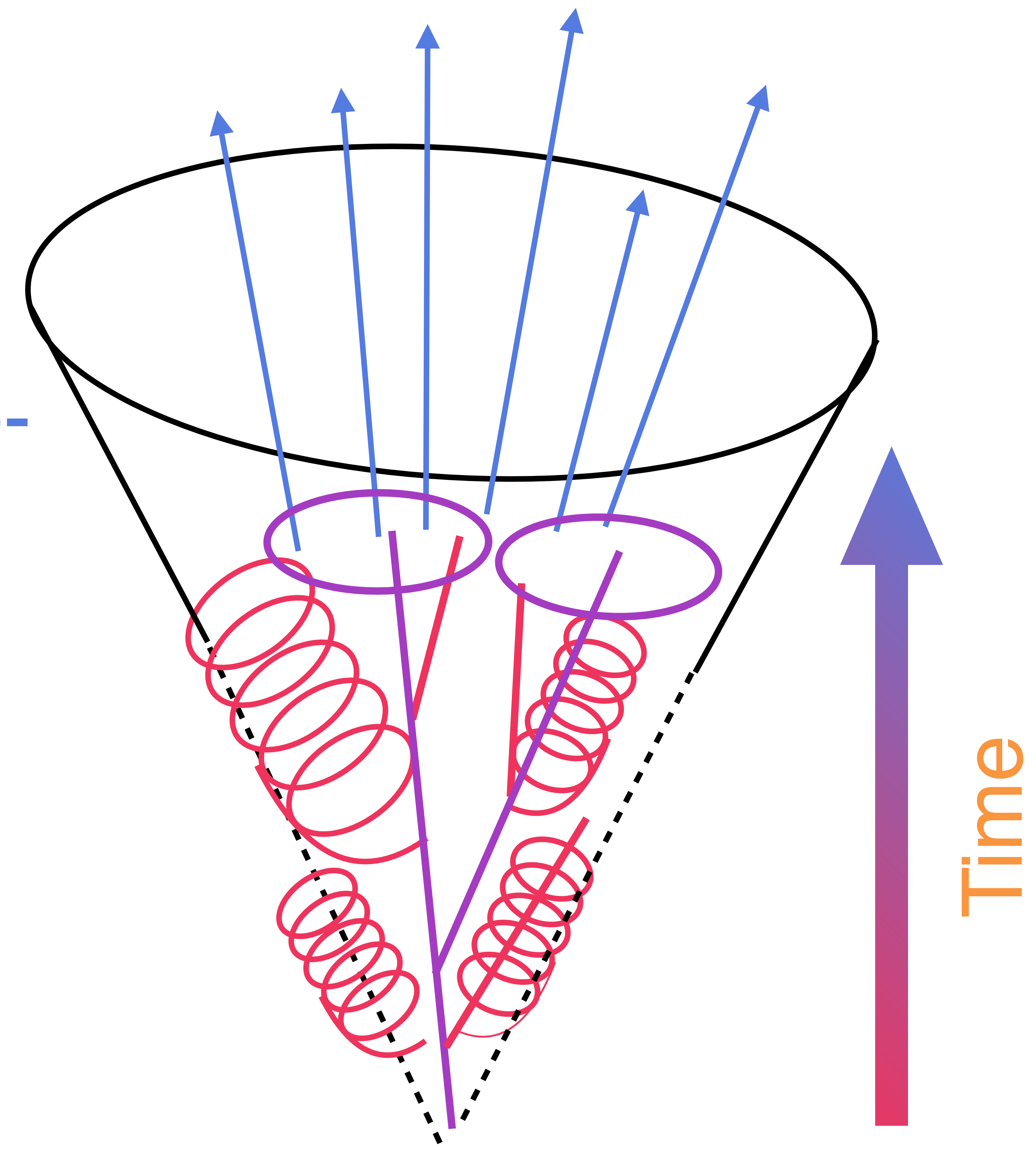
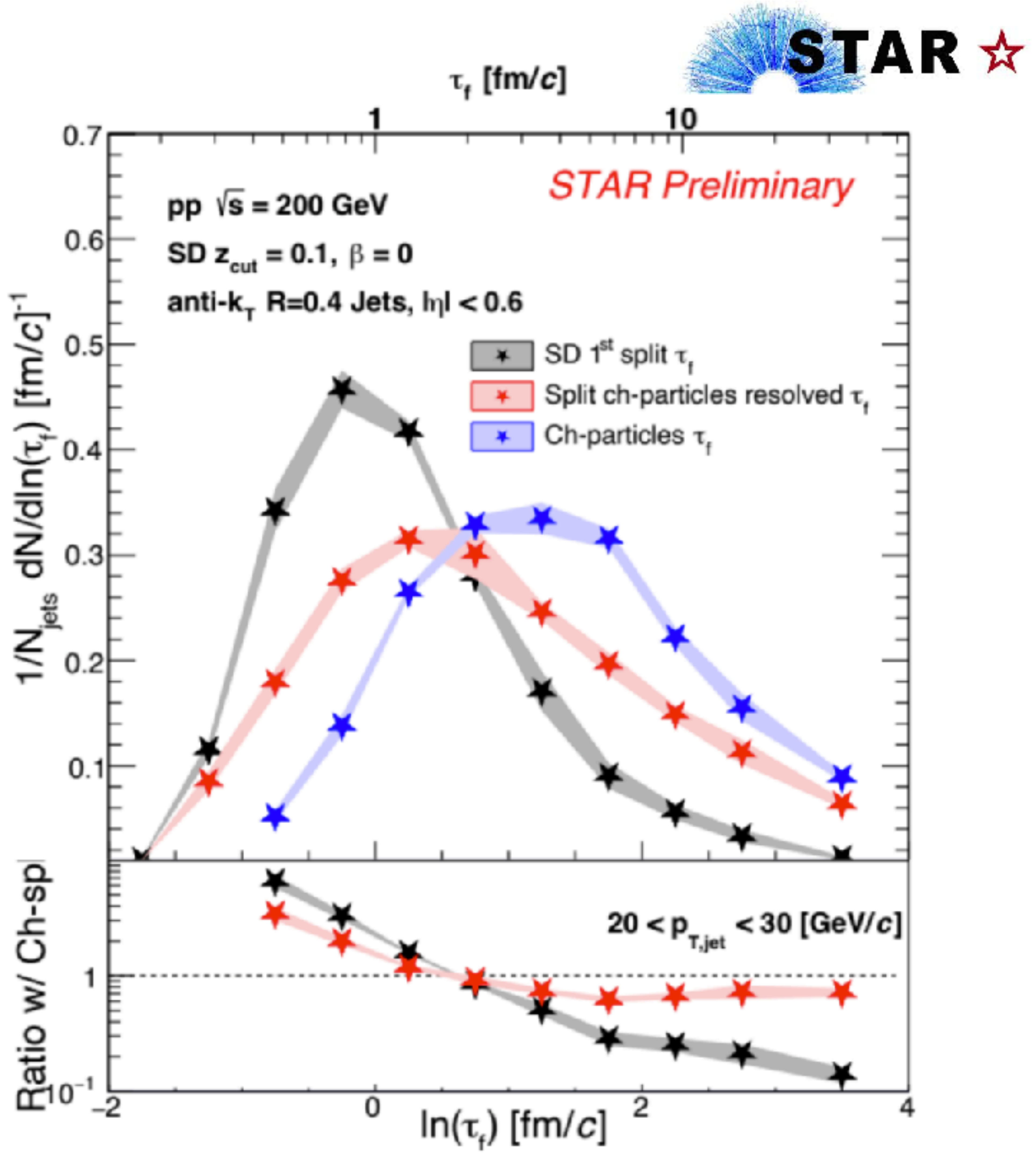


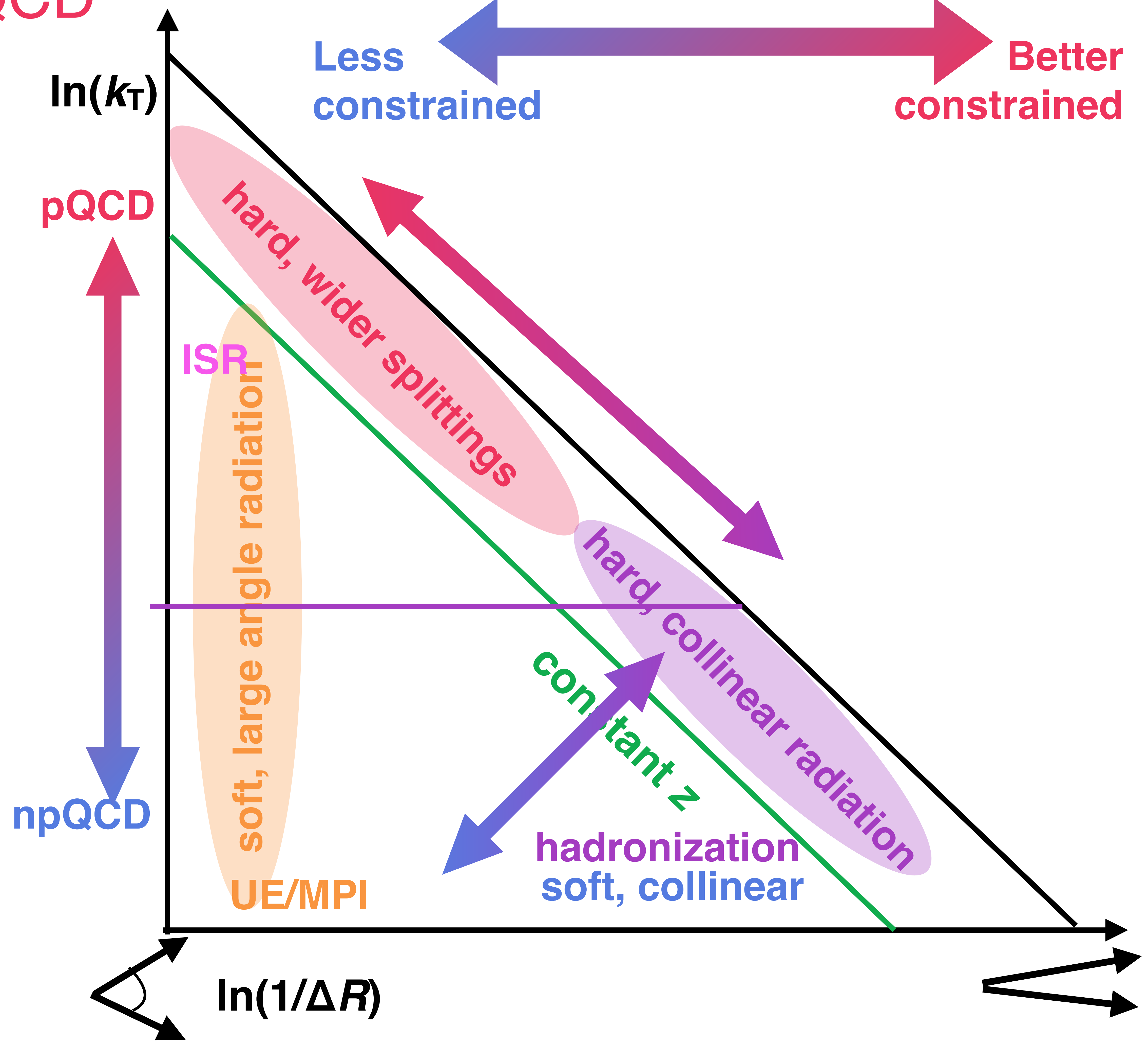


Highlight perturbative to NP transition!

See Mriganka's and Isaac's talk today!

Summary of pp measurements

- Jets are a powerful tool for study both np and pQCD
- Precise comparisons to generators/calculations useful to tune and provide theoretical constraints
  - MC generators analytical calculations describe pert. better than NP regions, still some PS and hadronization implementation differences
    - Grooming/higher p_T better described by MC
- QCD effects still convoluted in observables



What's next?

Energy correlators: confinement transition

Defined from first principles QFT, no grooming required!

Komiske et al arxiv:2201.07800

Lee, Mecaj, Moult arxiv:2205.0314

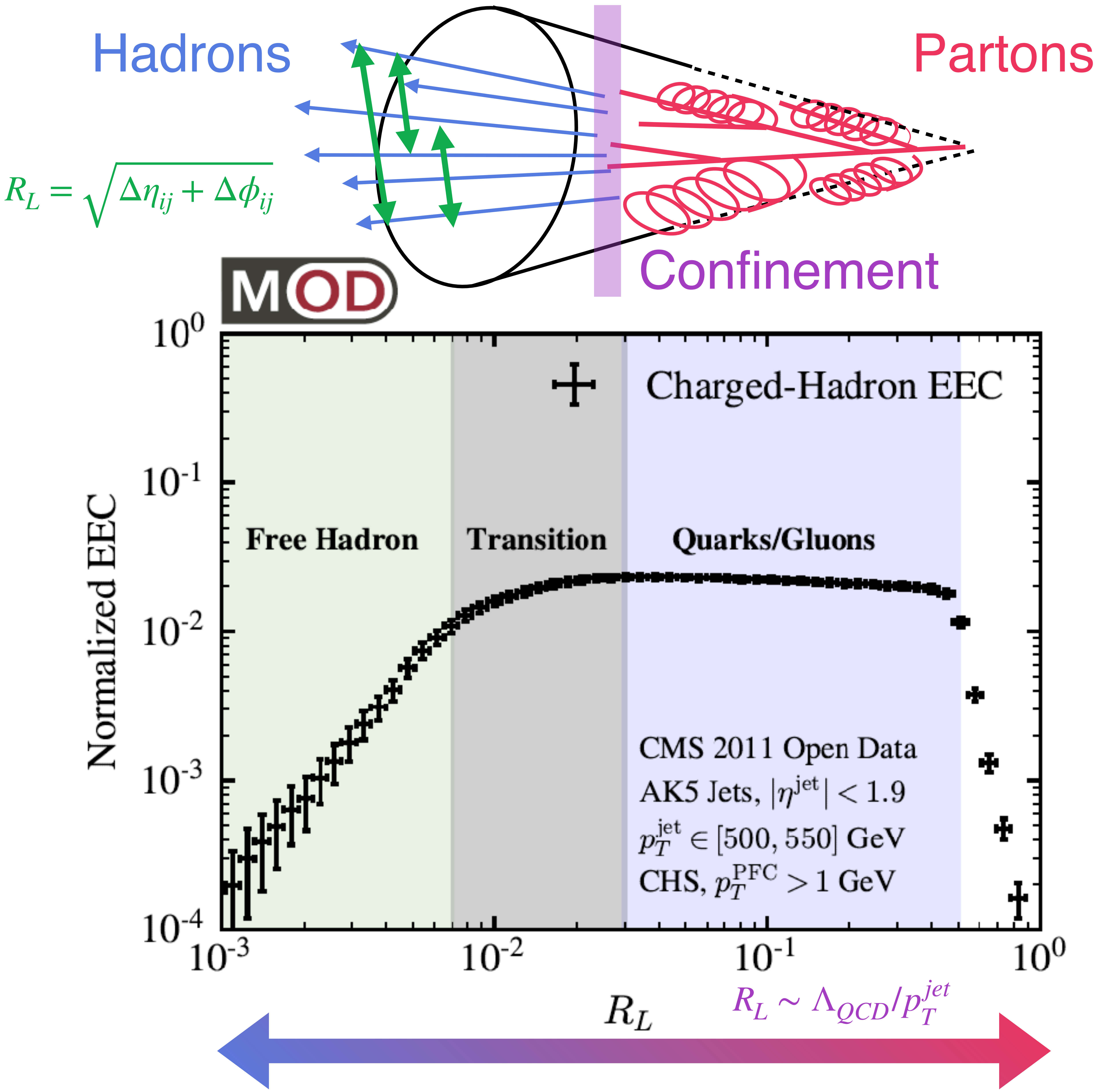
Clear distinction between pQCD and npQCD regions

Access hadronization transition!

See Bianka's talk today for more, including in HF!

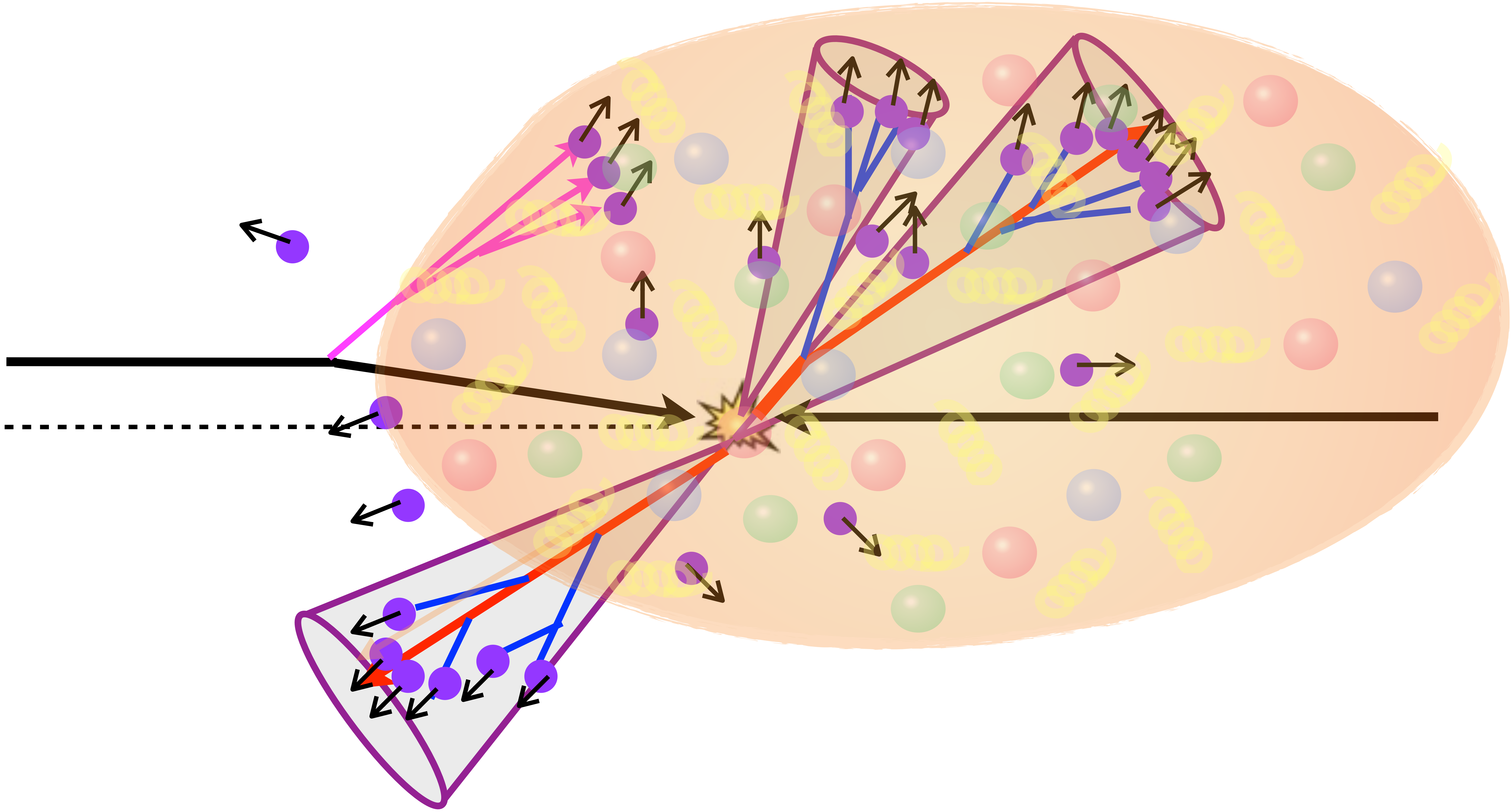
CMS open data: not unfolded for detector effects, experimental challenge!

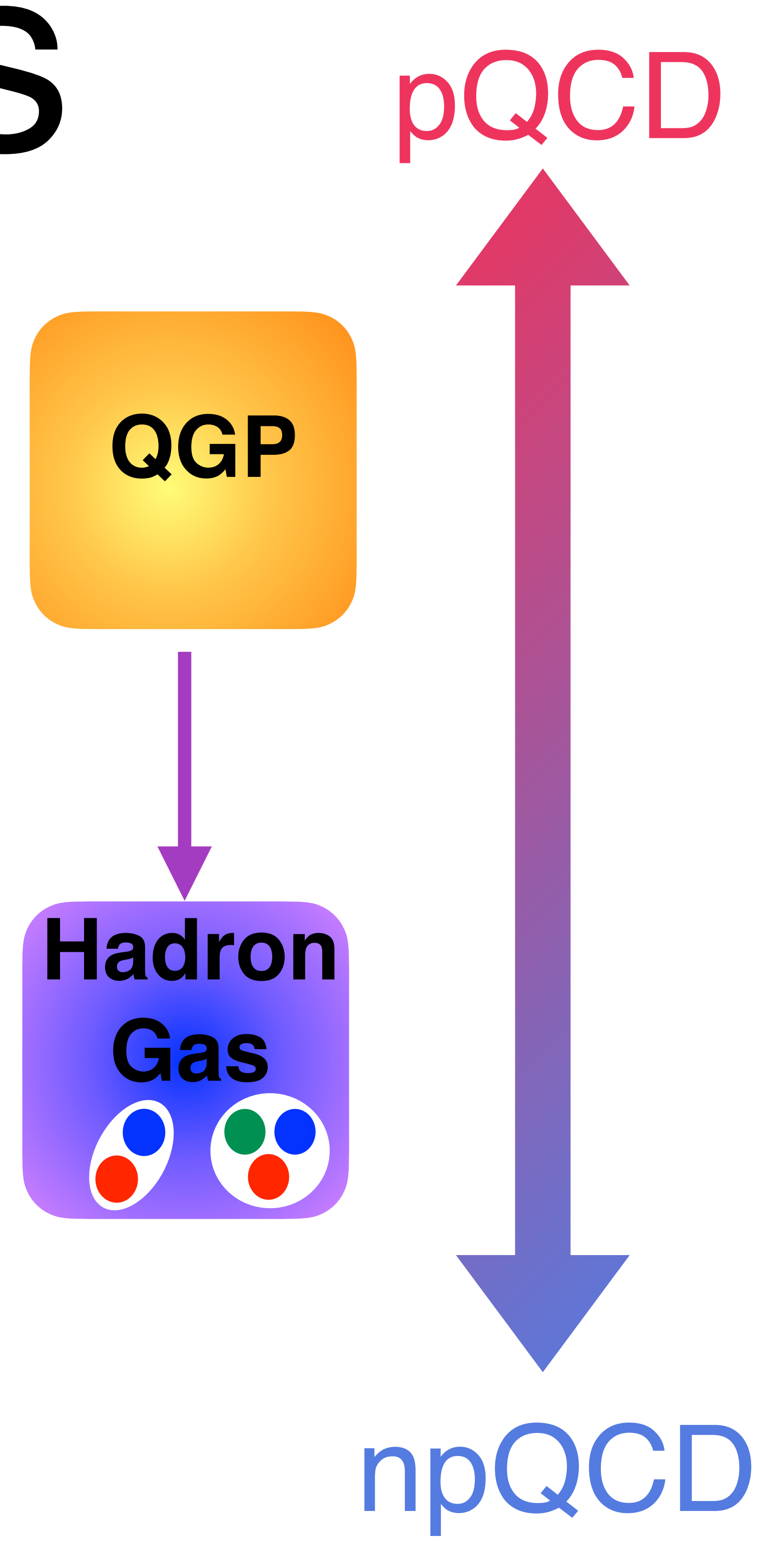
See Andrew's talk today for a look at pp simulations for RHIC



Jets in QGP: multi-scale probes

QGP: deconfined state of QCD matter at high temperatures

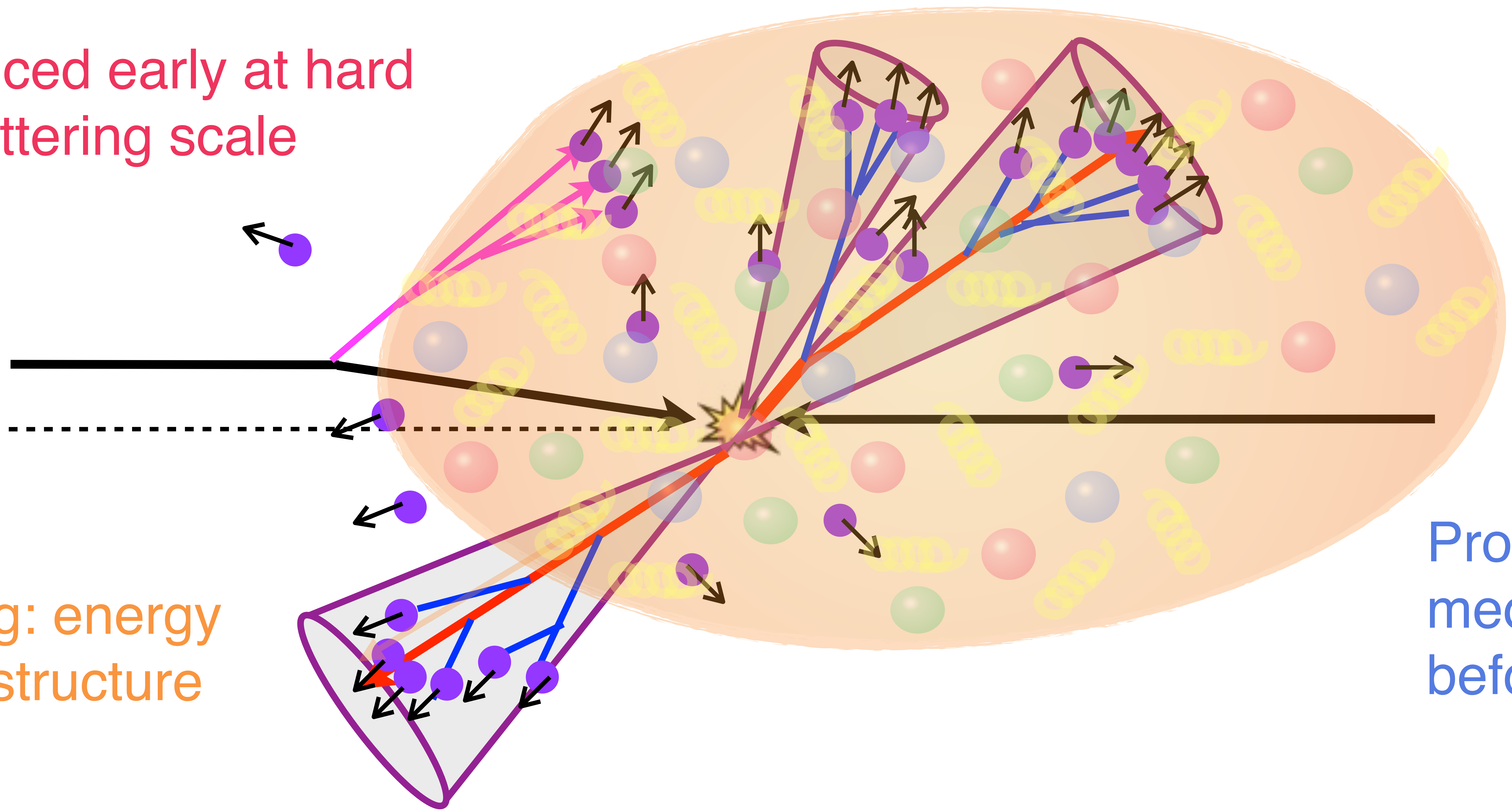




Jets in QGP: multi-scale probes

QGP: deconfined state of QCD matter at high temperatures

Jets produced early at hard pQCD scattering scale



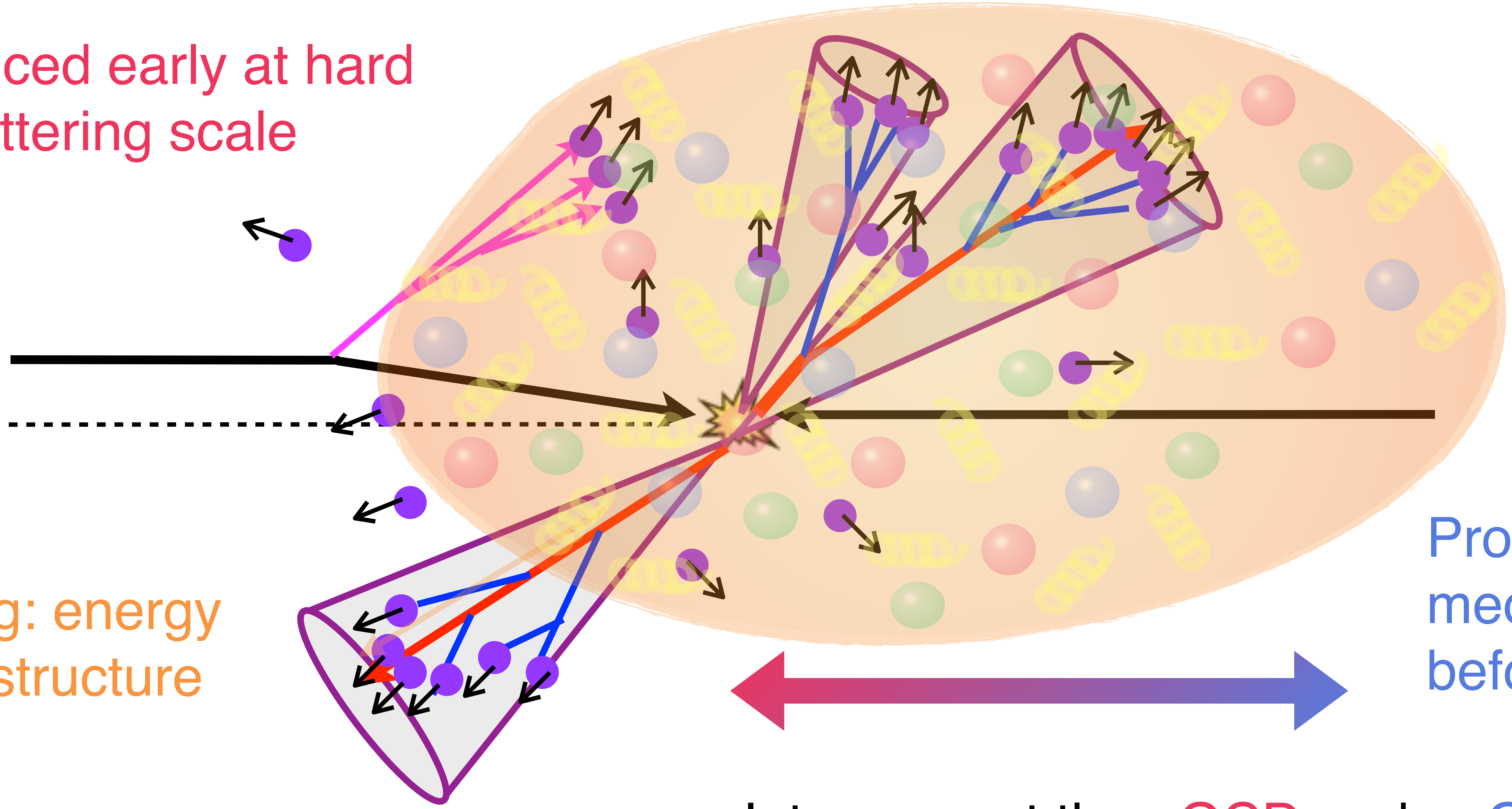
Jet quenching: energy loss and substructure modification

Propagate through medium and interact before hadronizing

Jets in QGP: multi-scale probes

QGP: deconfined state of QCD matter at high temperatures

Jets produced early at hard pQCD scattering scale



Jet quenching: energy loss and substructure modification

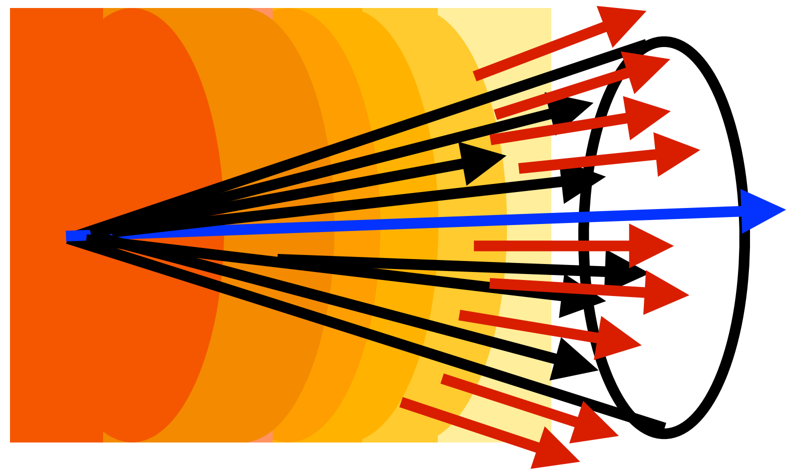
Propagate through medium and interact before hadronizing

Jets connect the pQCD and npQCD scales

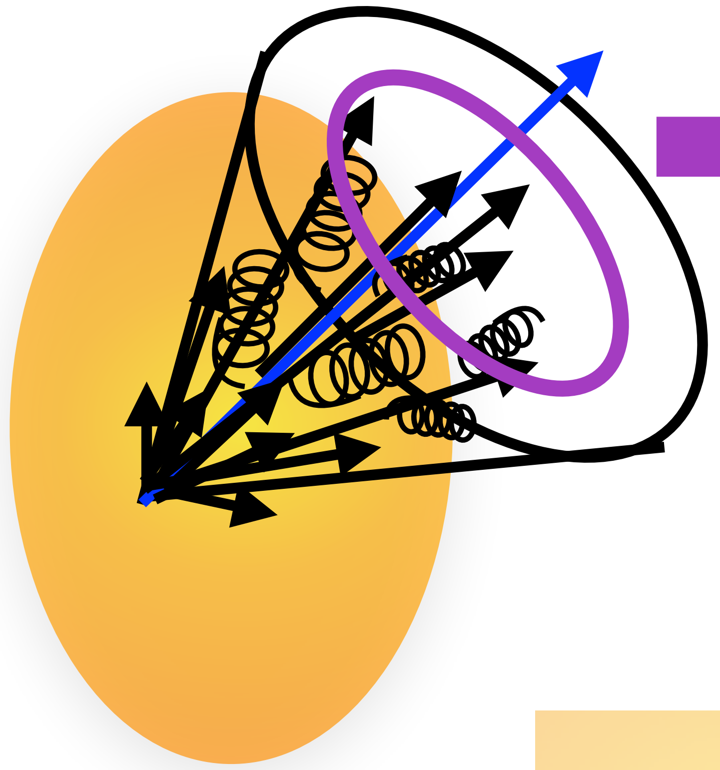
Space-time structure of the evolving medium

Jet quenching expectations

- Jet-medium interactions:

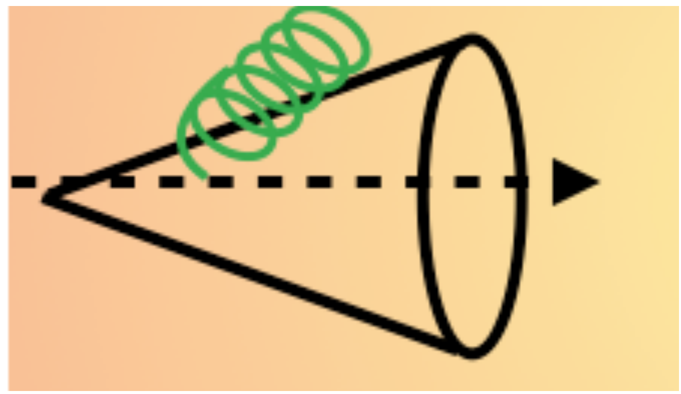


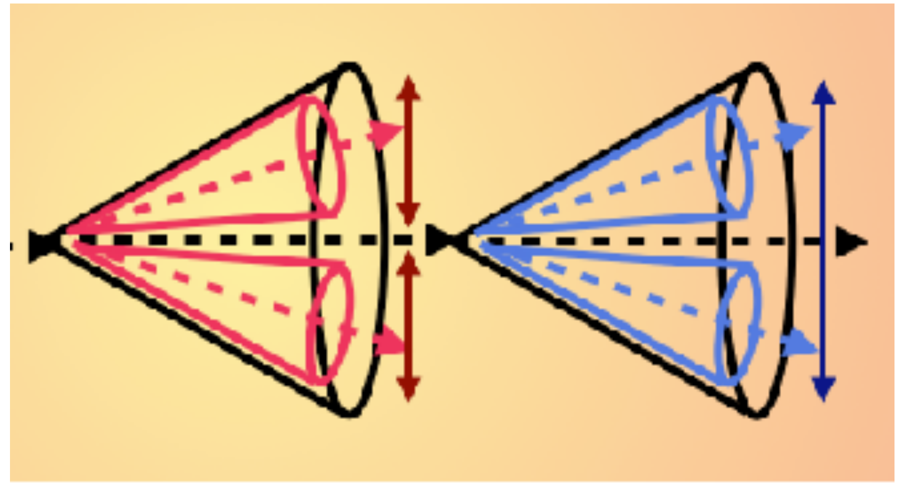
➡ Medium response



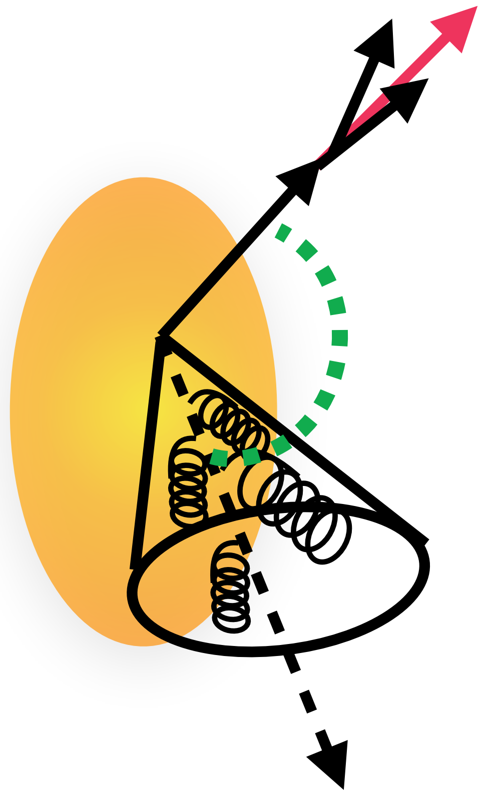
➡ Momentum broadening

➡ Medium-induced splittings

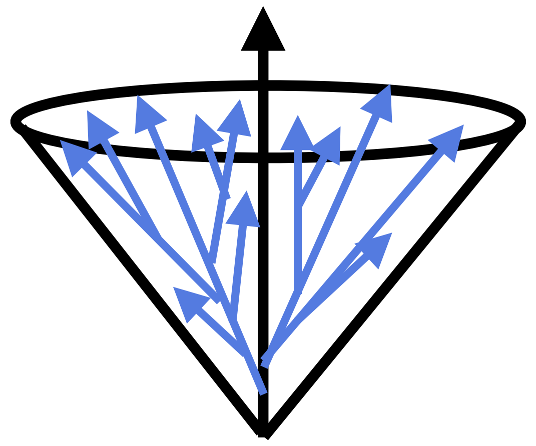




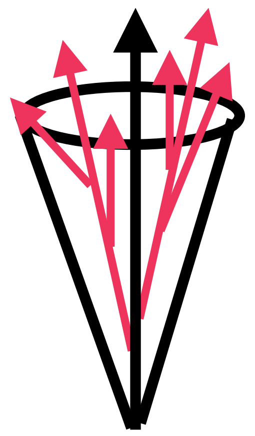
➡ Coherence/decoherence



➡ Wide-angle deflection



$E_{loss}^{g} > E_{loss}^{q}$

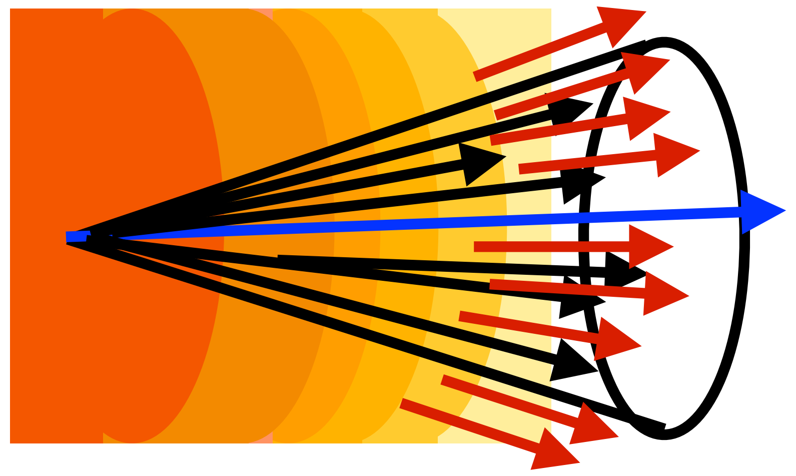


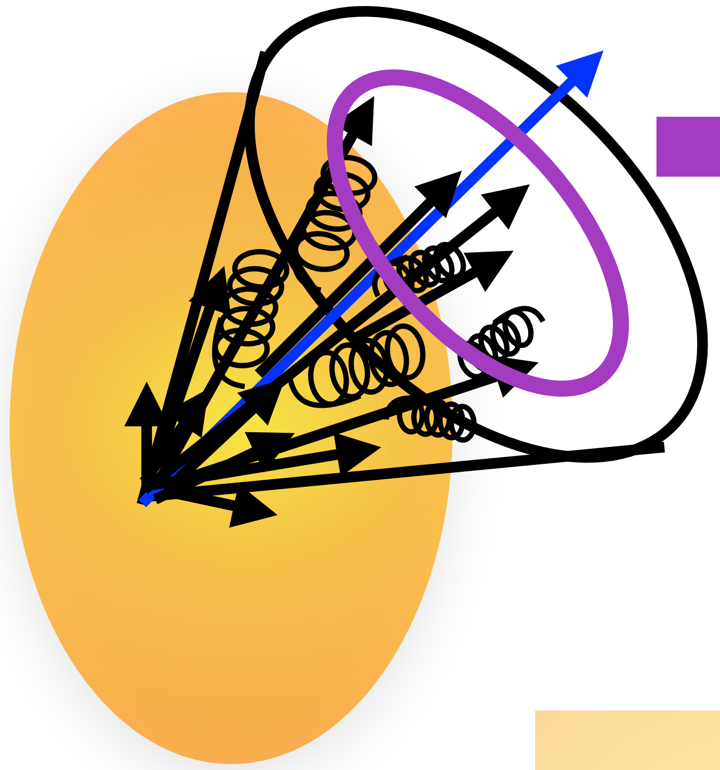
➡ Flavor dependence

Jet quenching expectations

- Jet-medium interactions:

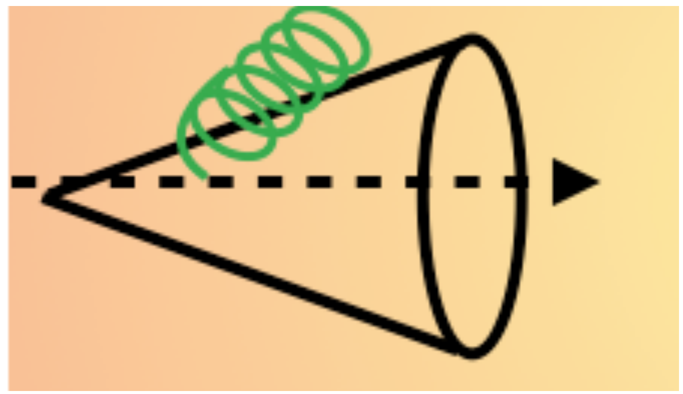
➡ Medium response

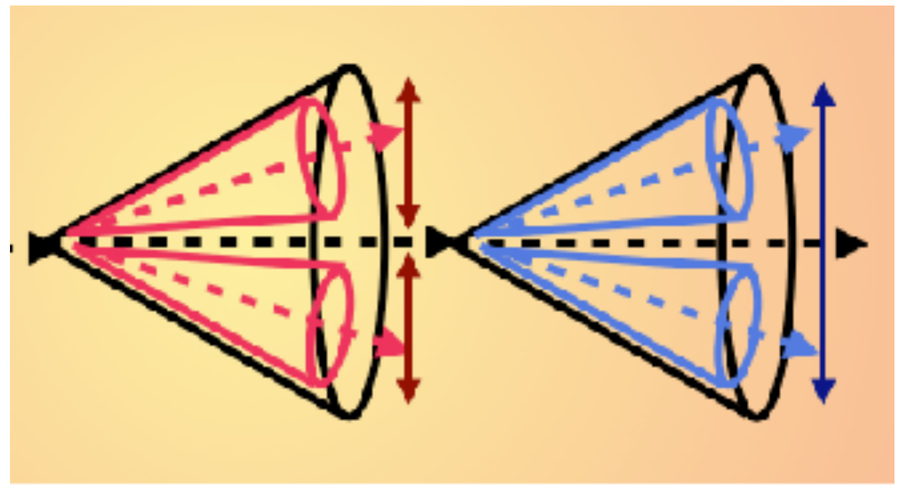




➡ Momentum broadening

➡ Medium-induced splittings





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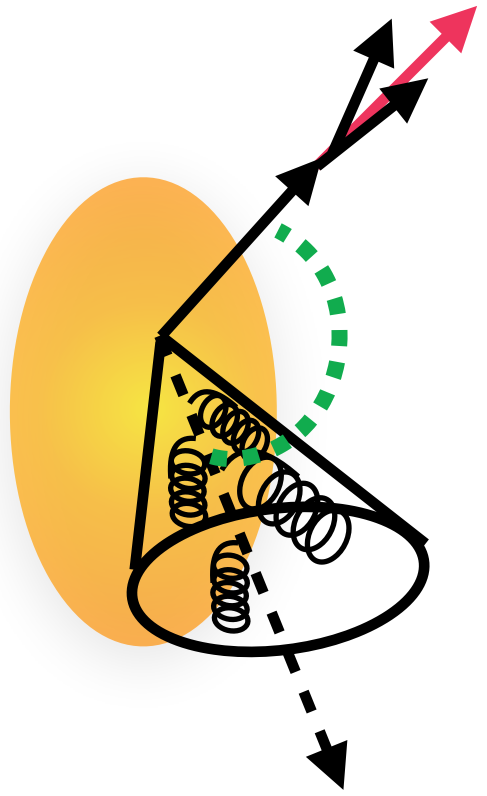
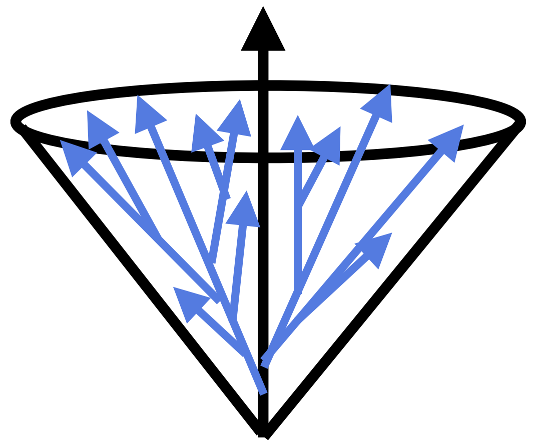
➡ Wide-angle deflection





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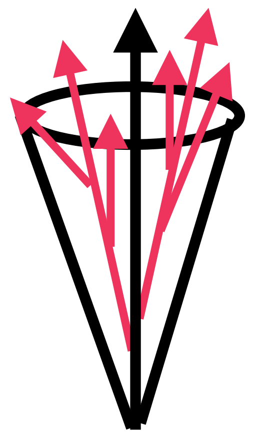


➡ Flavor dependence

npQCD

More pQCD

Jet quenching expectations

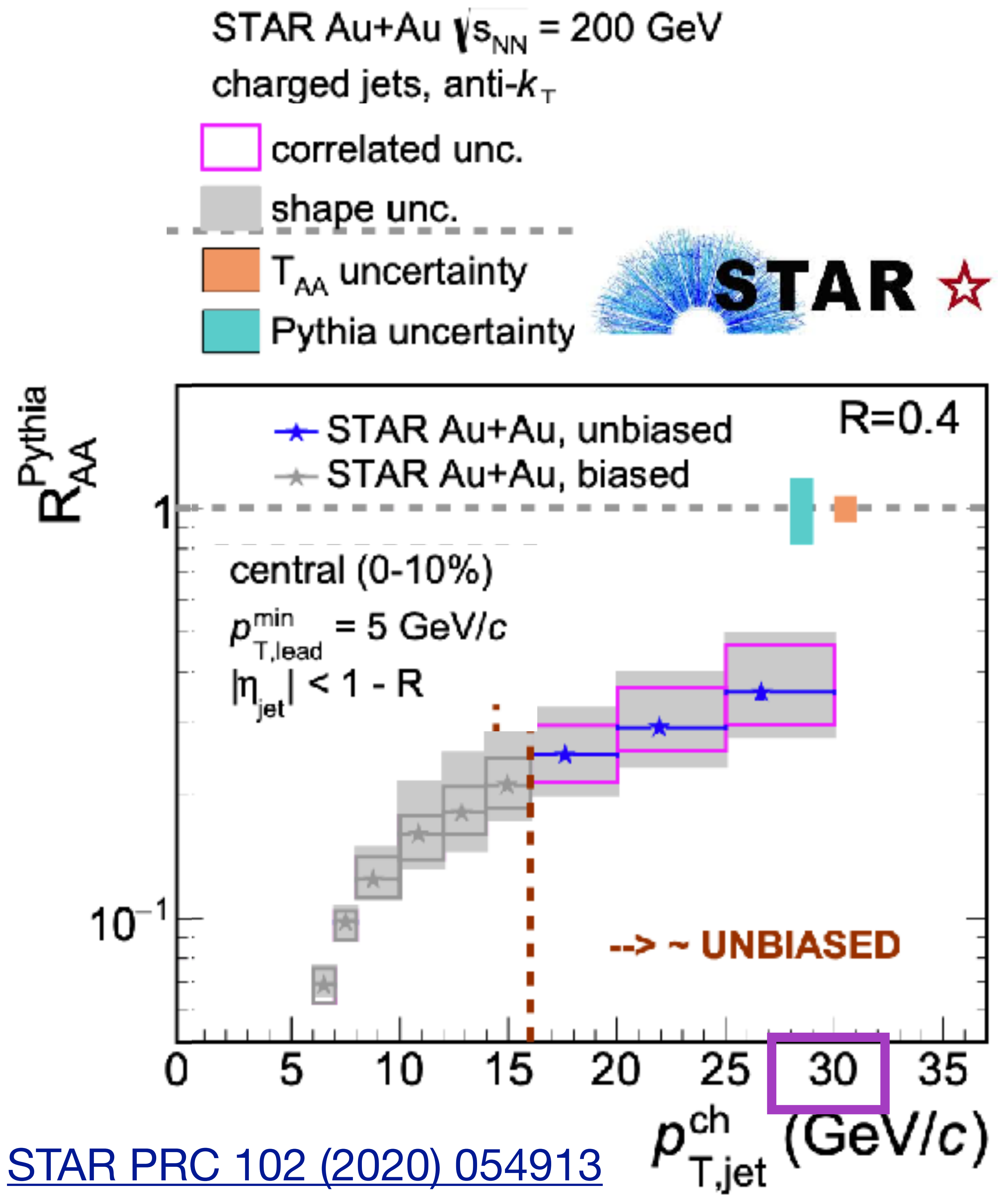
- Jet-medium interactions:

Inclusive jet suppression

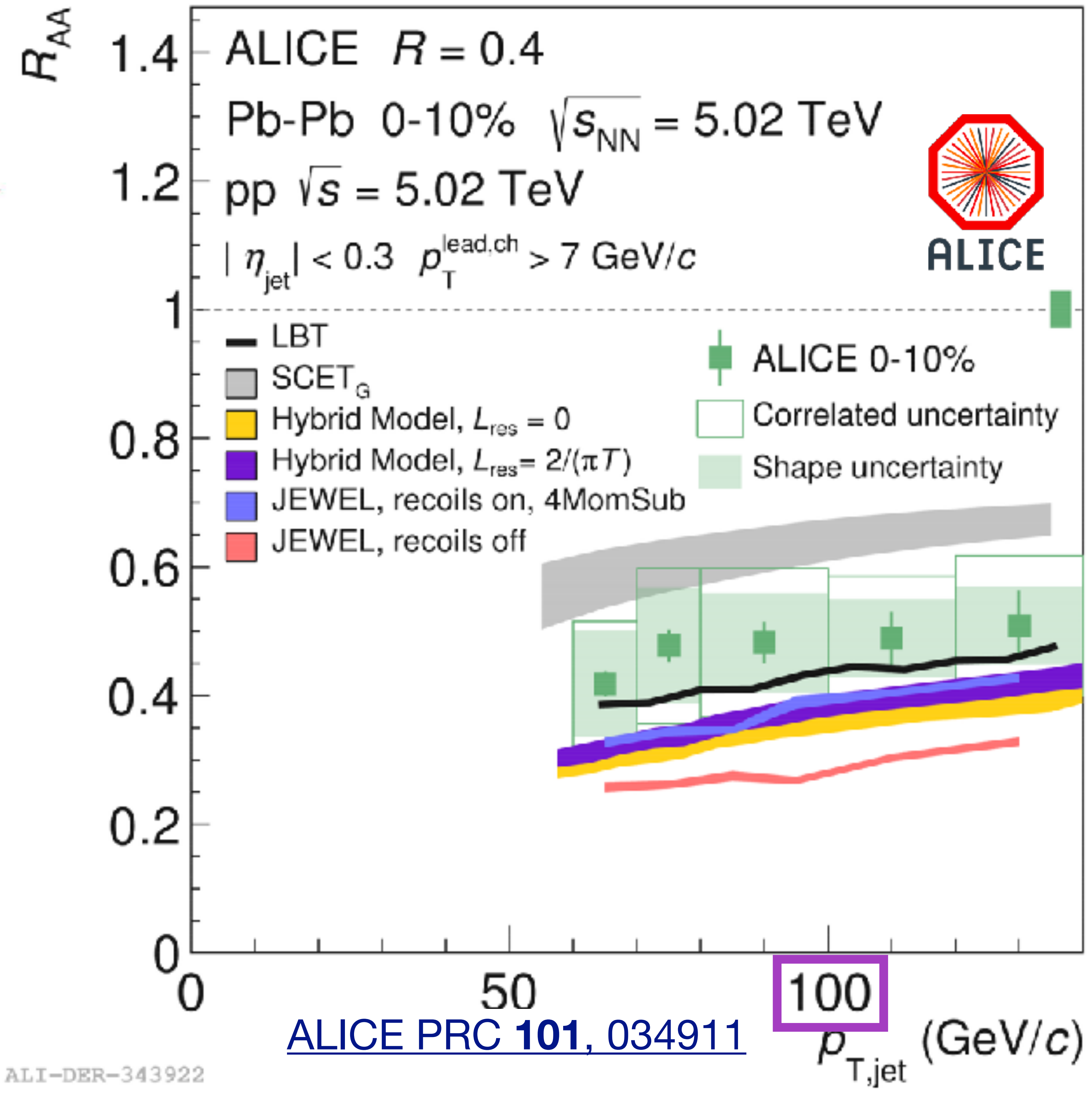
- Inclusive jet suppression over a large jet p_T range

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

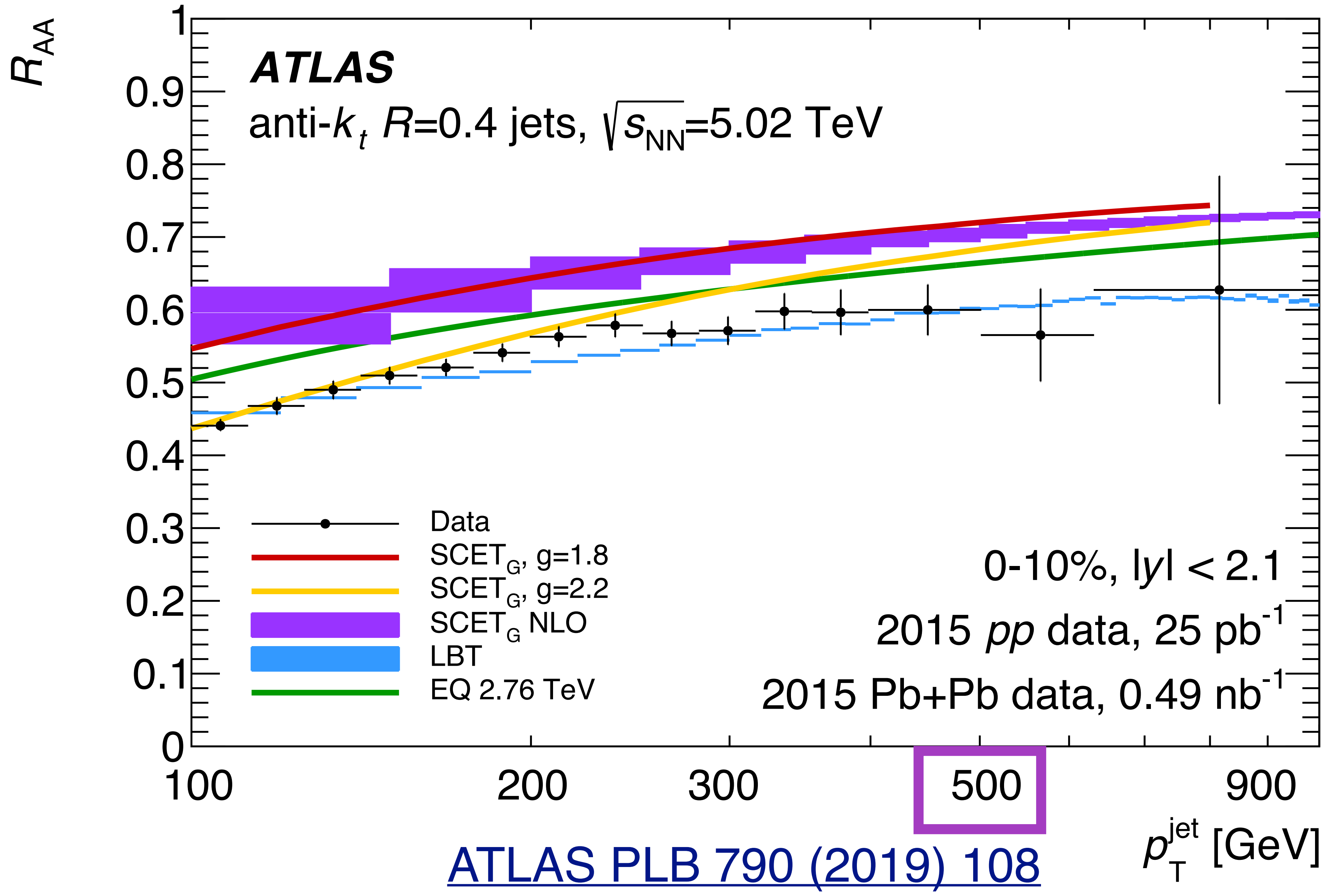
Larger R: use higher p_T



STAR PRC 102 (2020) 054913



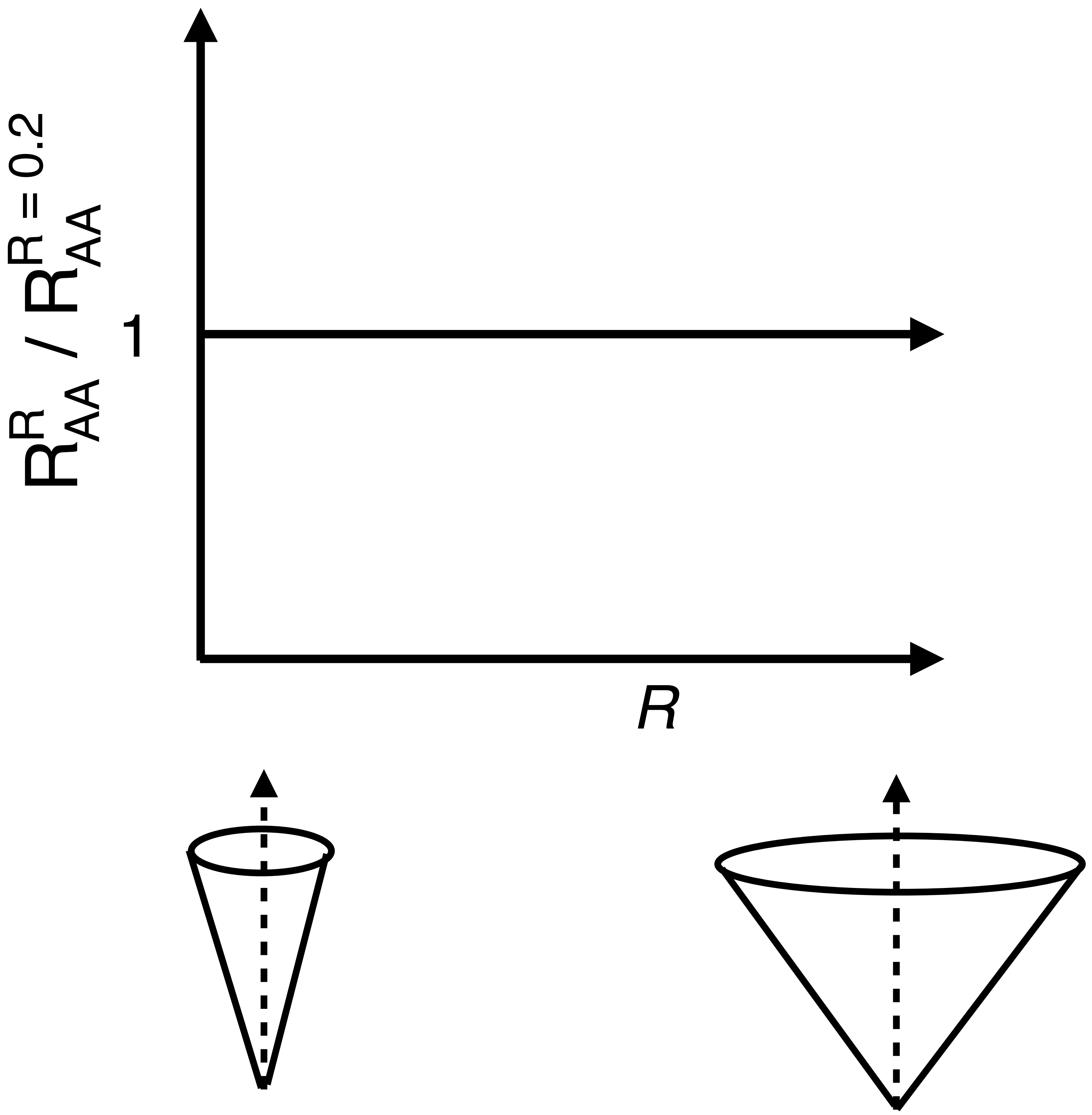
ALICE PRC **101**, 034911



ATLAS PLB 790 (2019) 108

R-dependence of jet suppression

- Compare R_{AA} at larger R to R_{AA} at R=0.2



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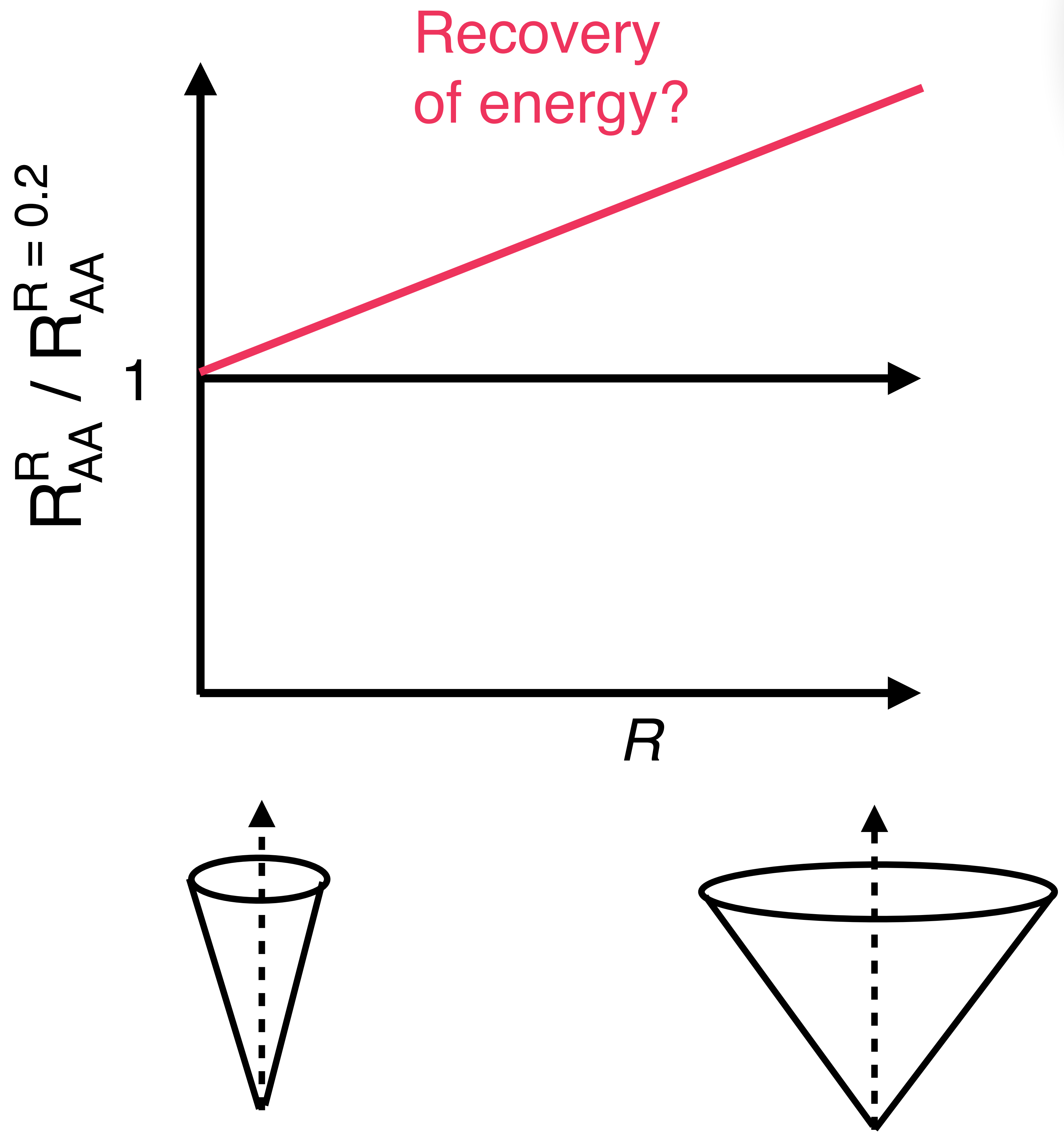

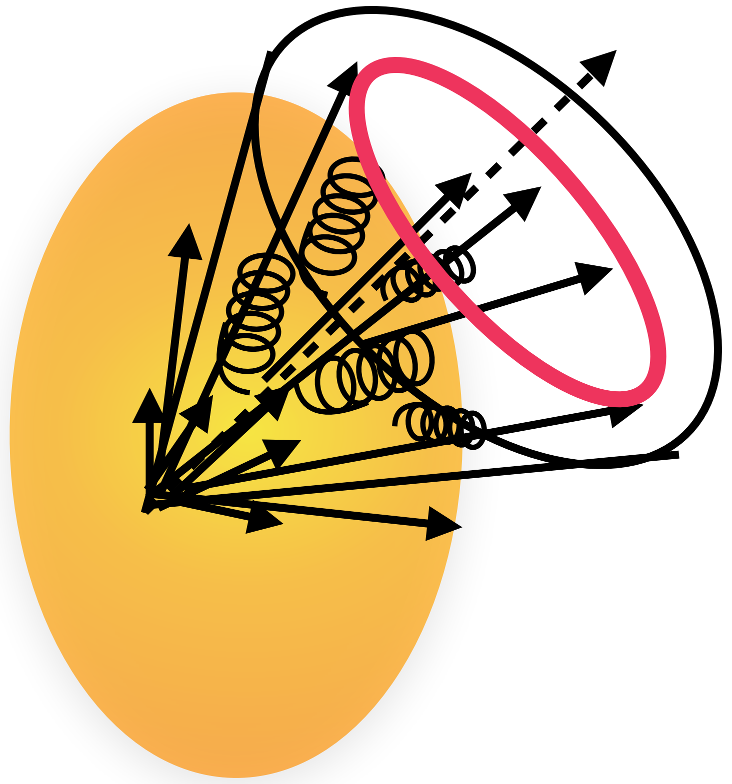

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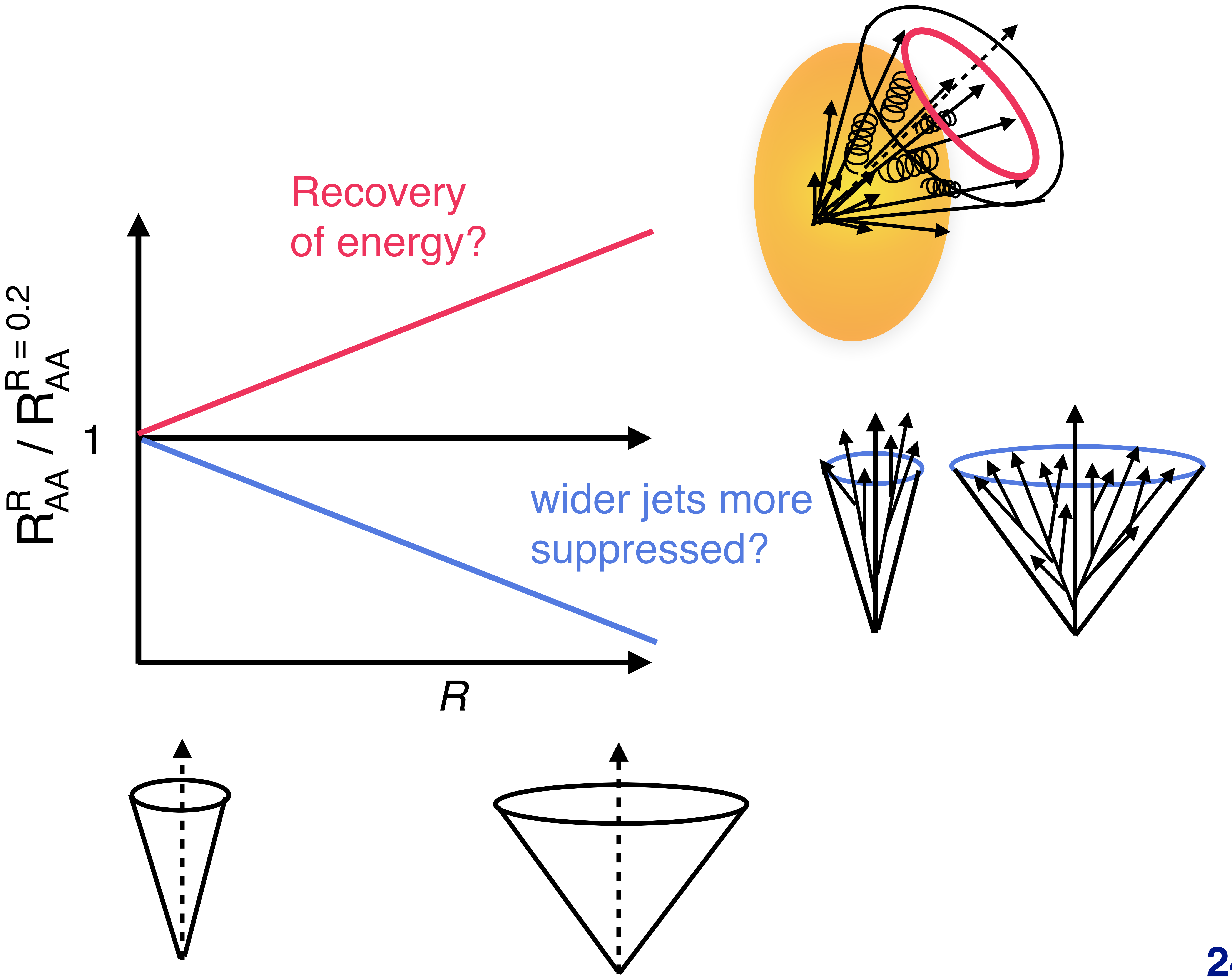
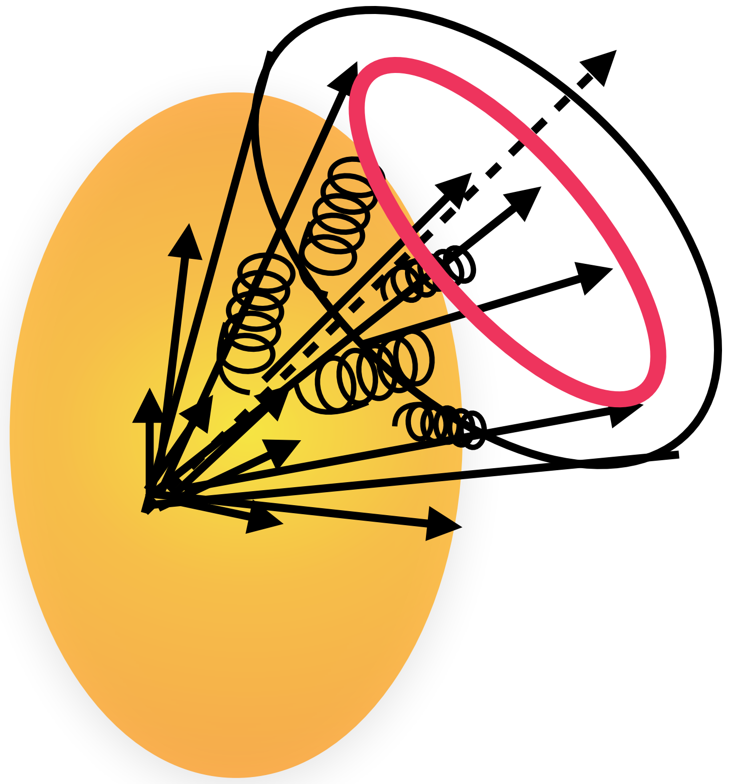
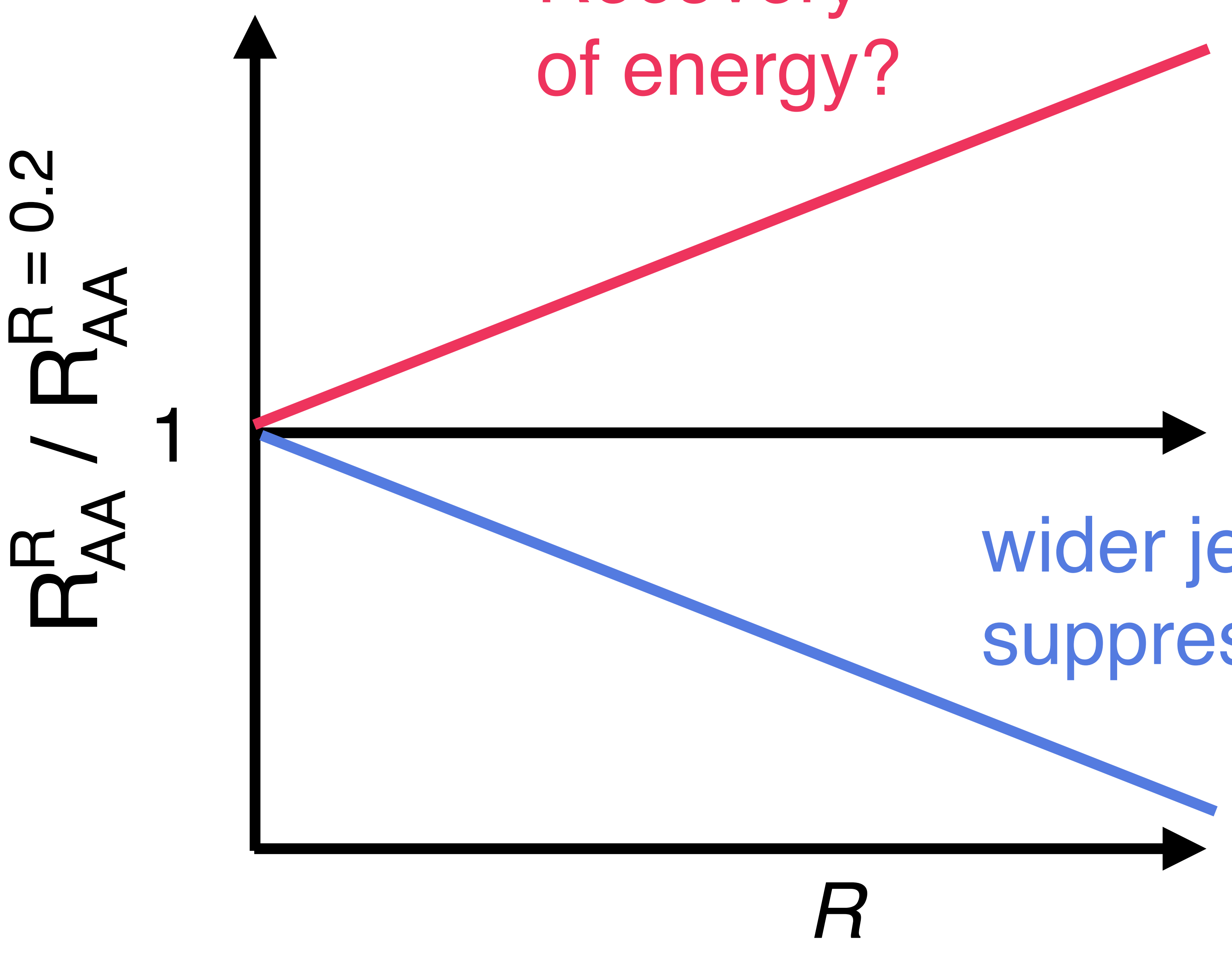


R-dependence of jet suppression

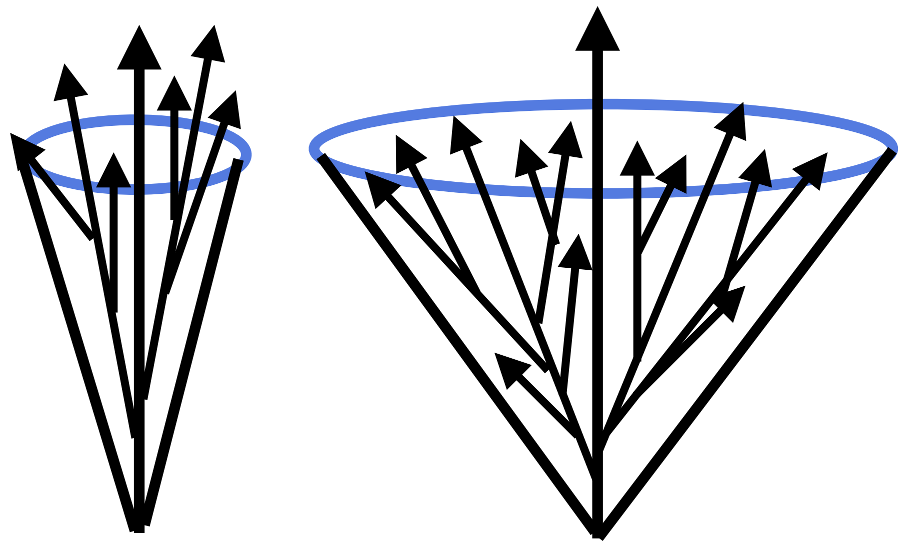
- Compare R_{AA} at larger R to R_{AA} at R=0.2

Recovery of energy?



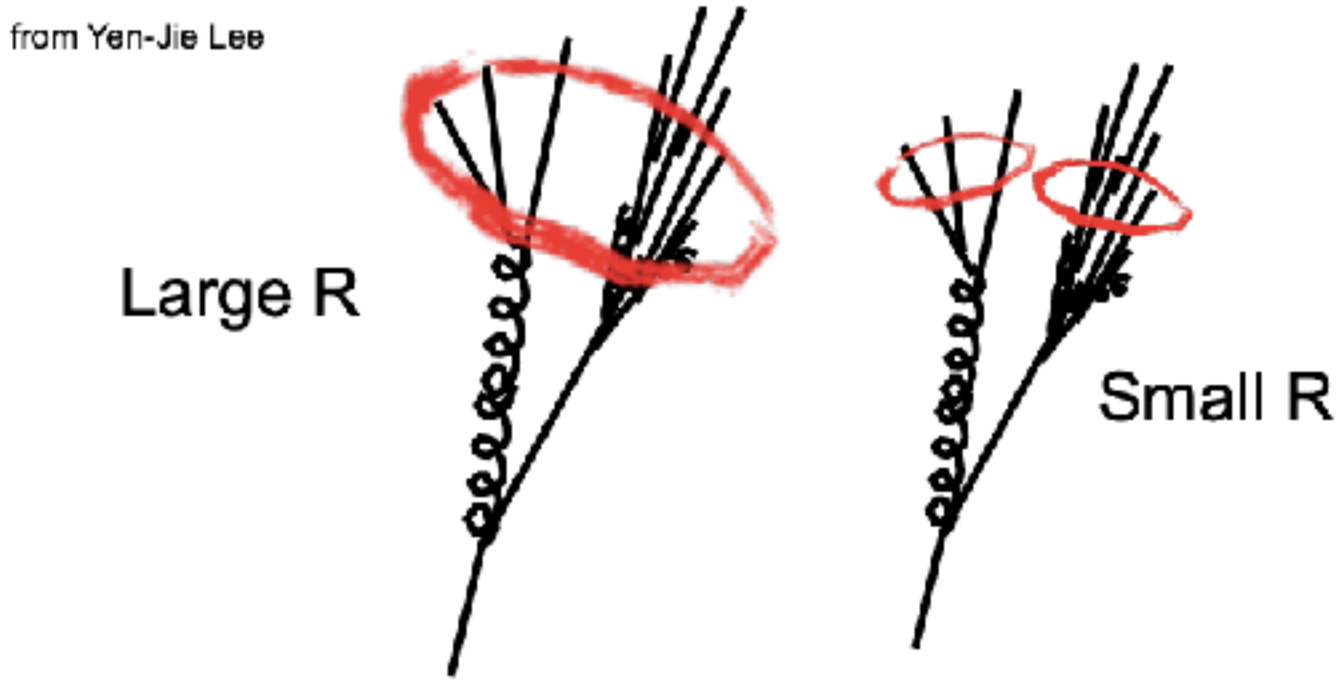


wider jets more suppressed?

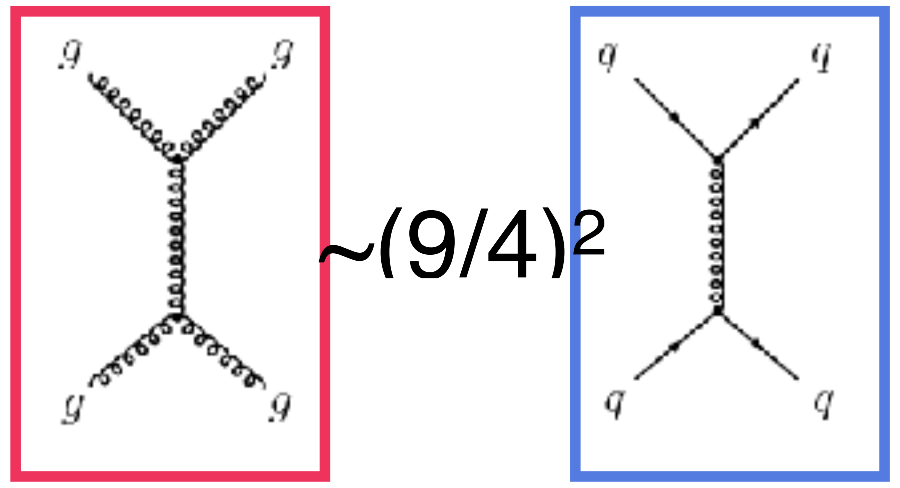


CMS JHEP 12 (2020) 082
ALICE PRC **101**, 034911

Different jet populations in pp collisions?

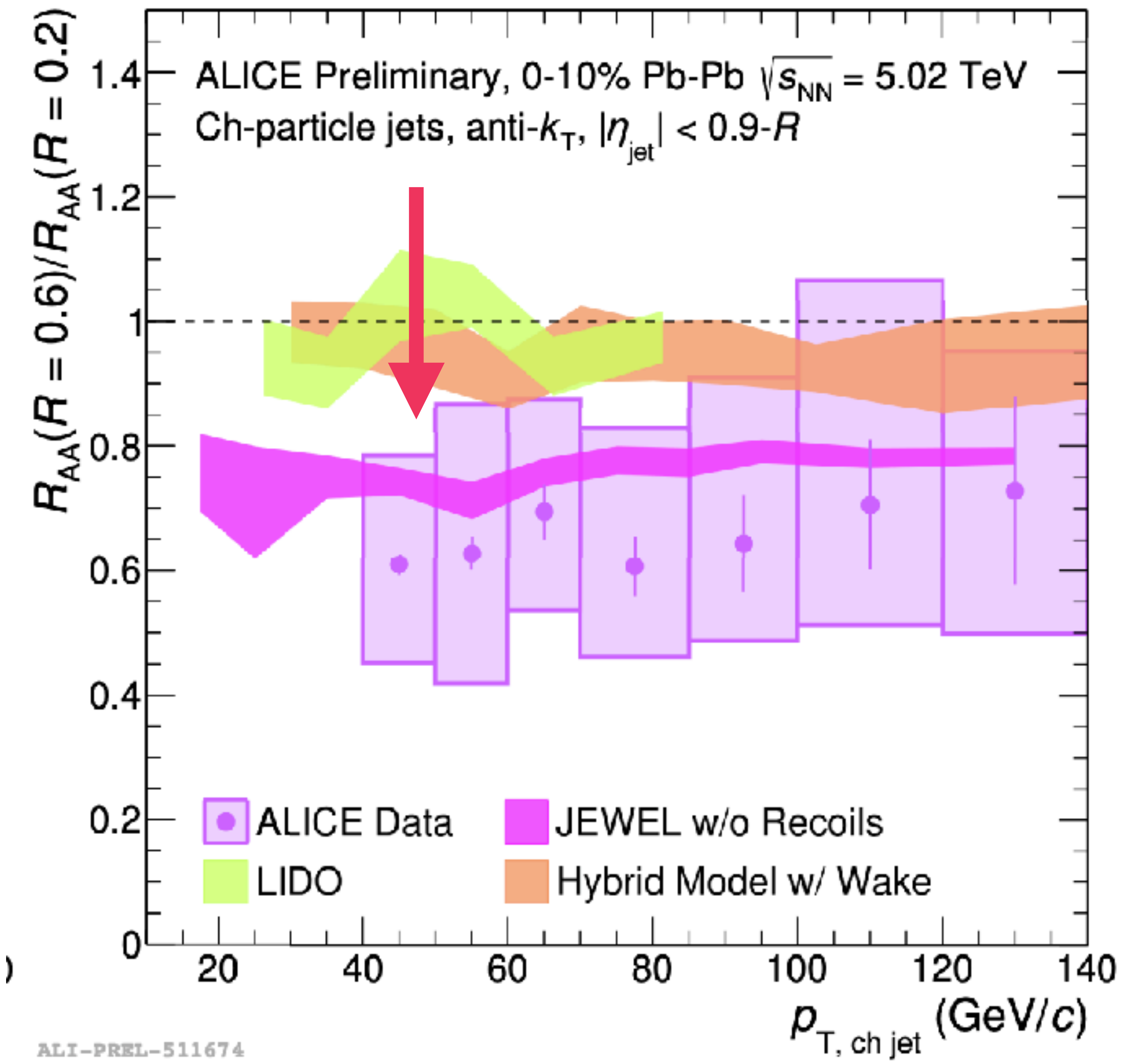


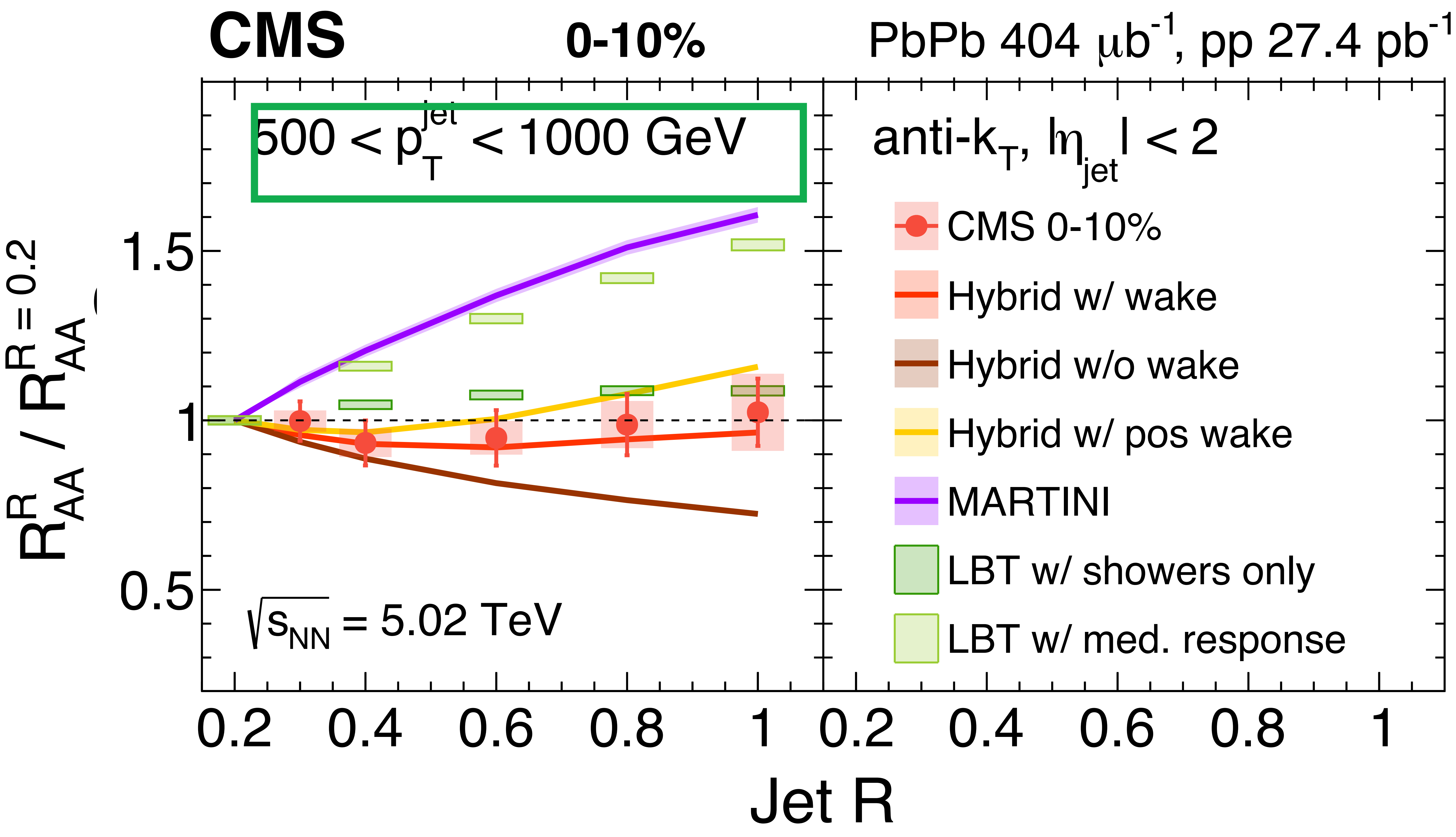
Increase in gluon fraction at larger R?



R-dependence of jet suppression

Varying R and p_T has a high discrimination power for models





Lower p_T wider jets more suppressed*: perturbative effects dominate?

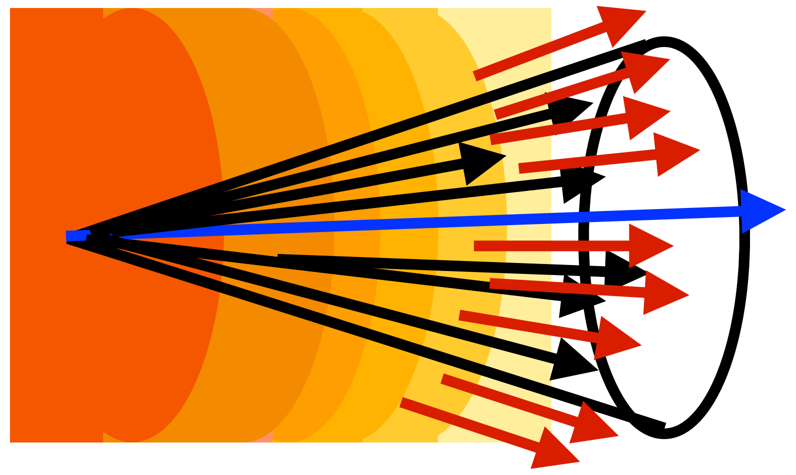
Higher p_T no R dependence: convolution of effects?

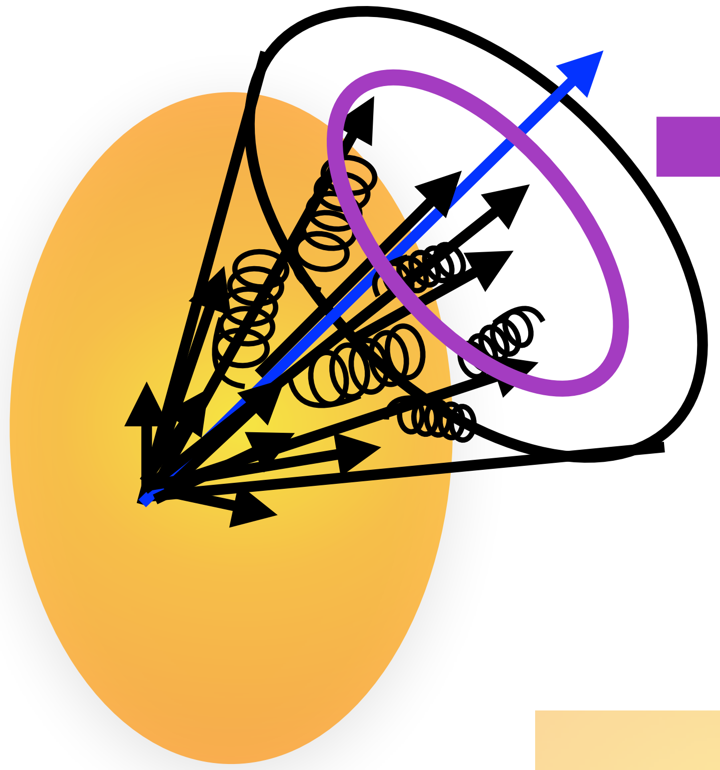
*Caveat: tension at low p_T with ATLAS result at 2.76 TeV Phys. Lett. B 719 (2013) 220-241

Jet quenching expectations

- Jet-medium interactions:

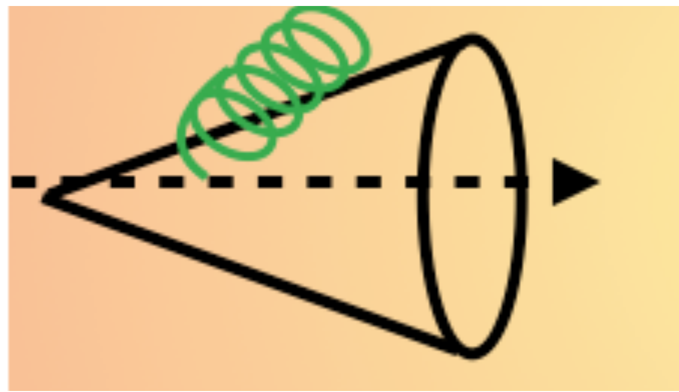
➡ Medium response

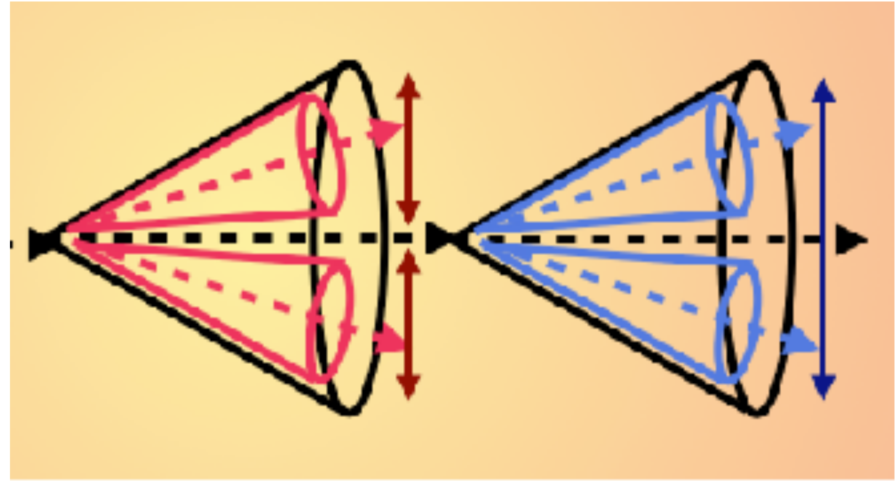




➡ Momentum broadening

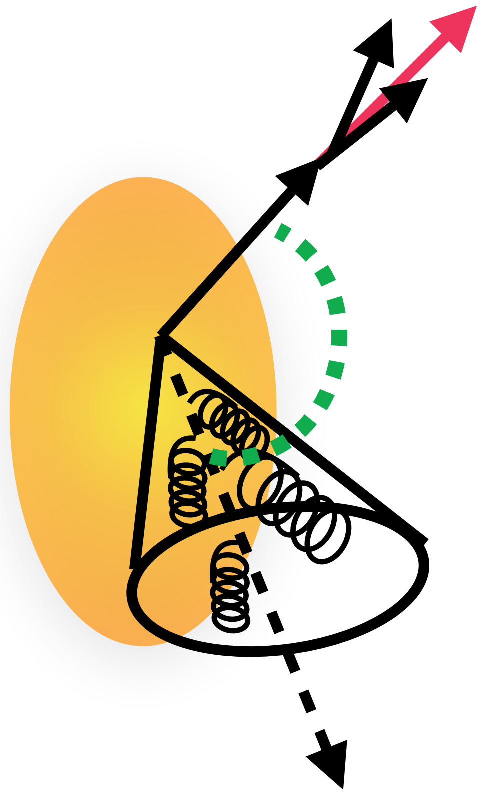
➡ Medium-induced splittings

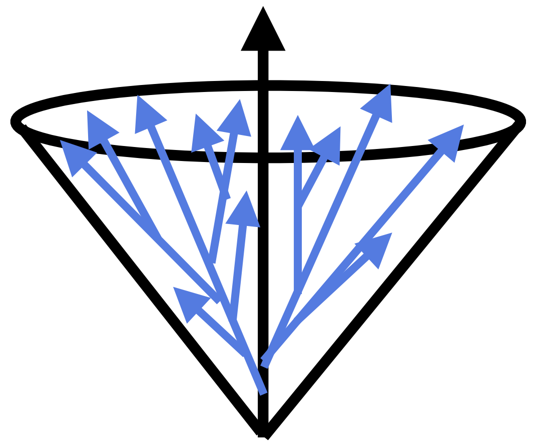




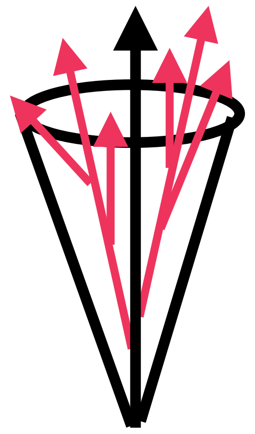
➡ Coherence/decoherence

➡ Wide-angle deflection



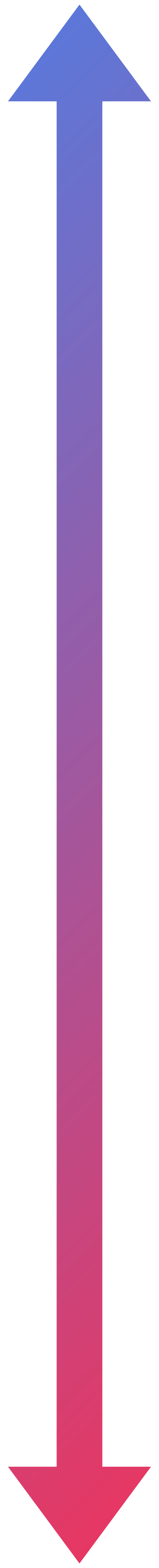


$E_{loss}^{g} > E_{loss}^{q}$



➡ Flavor dependence

npQCD

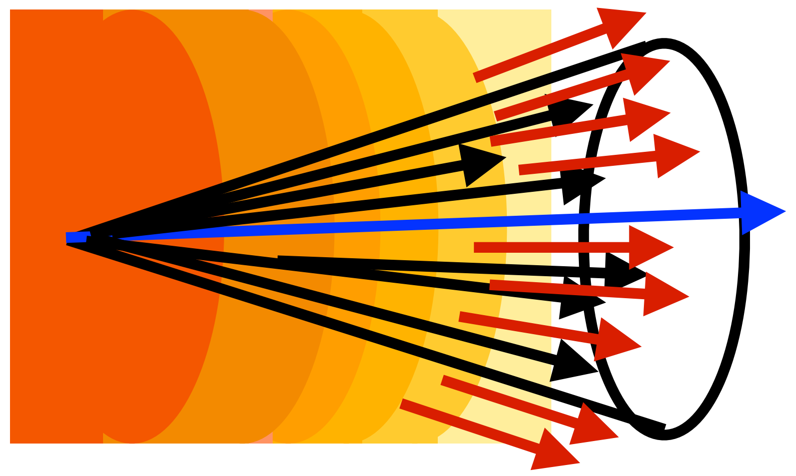


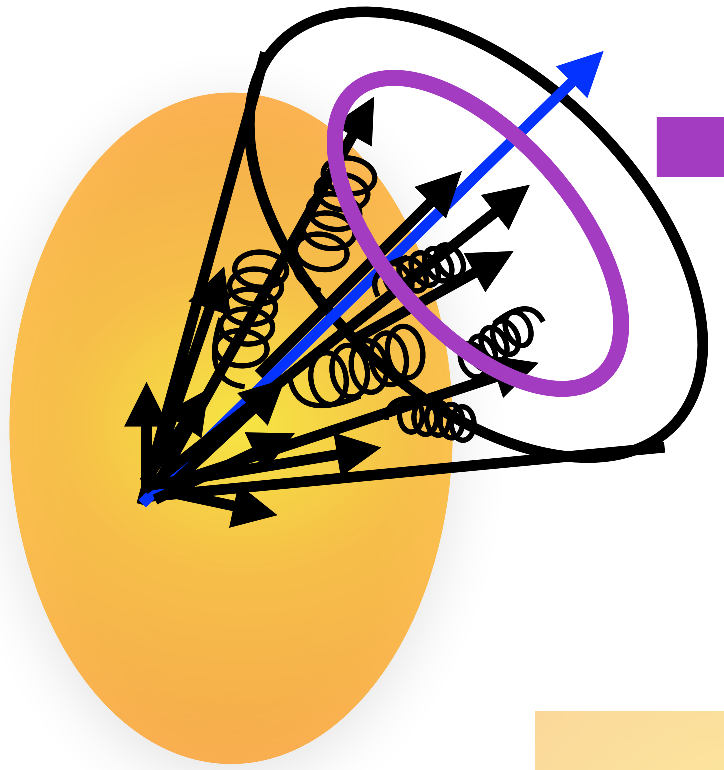
More pQCD

Jet quenching expectations

- Jet-medium interactions:

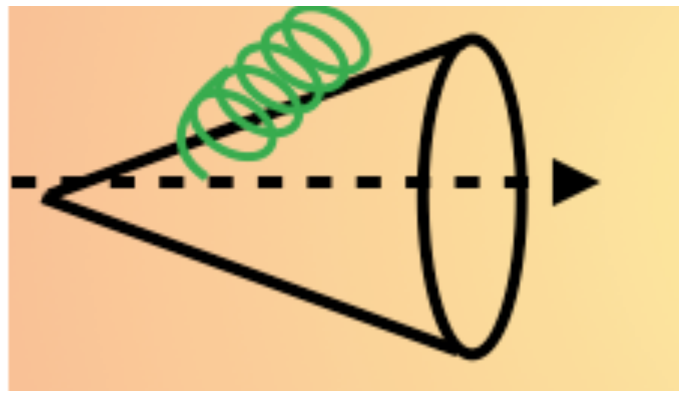
Medium response

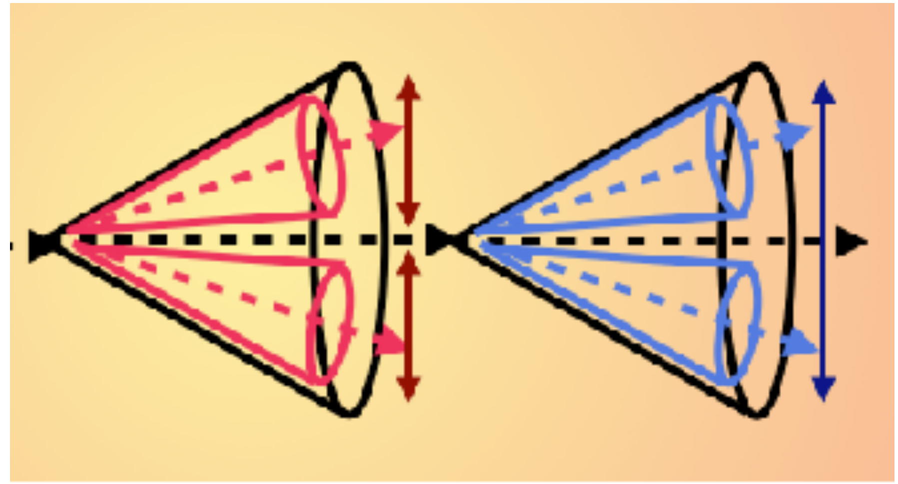




Momentum broadening

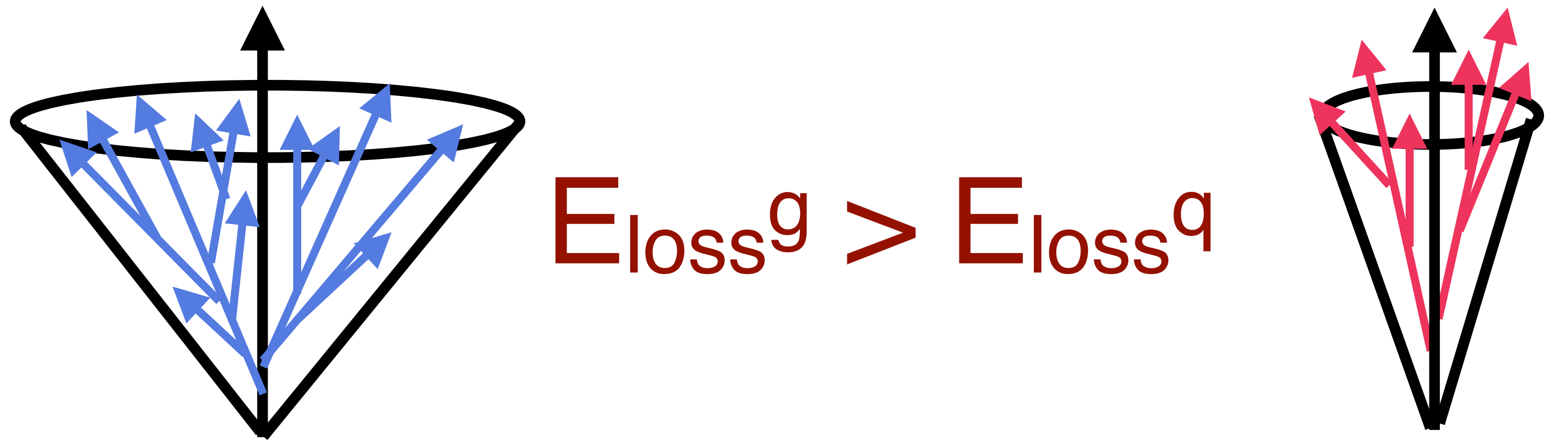
Medium-induced splittings





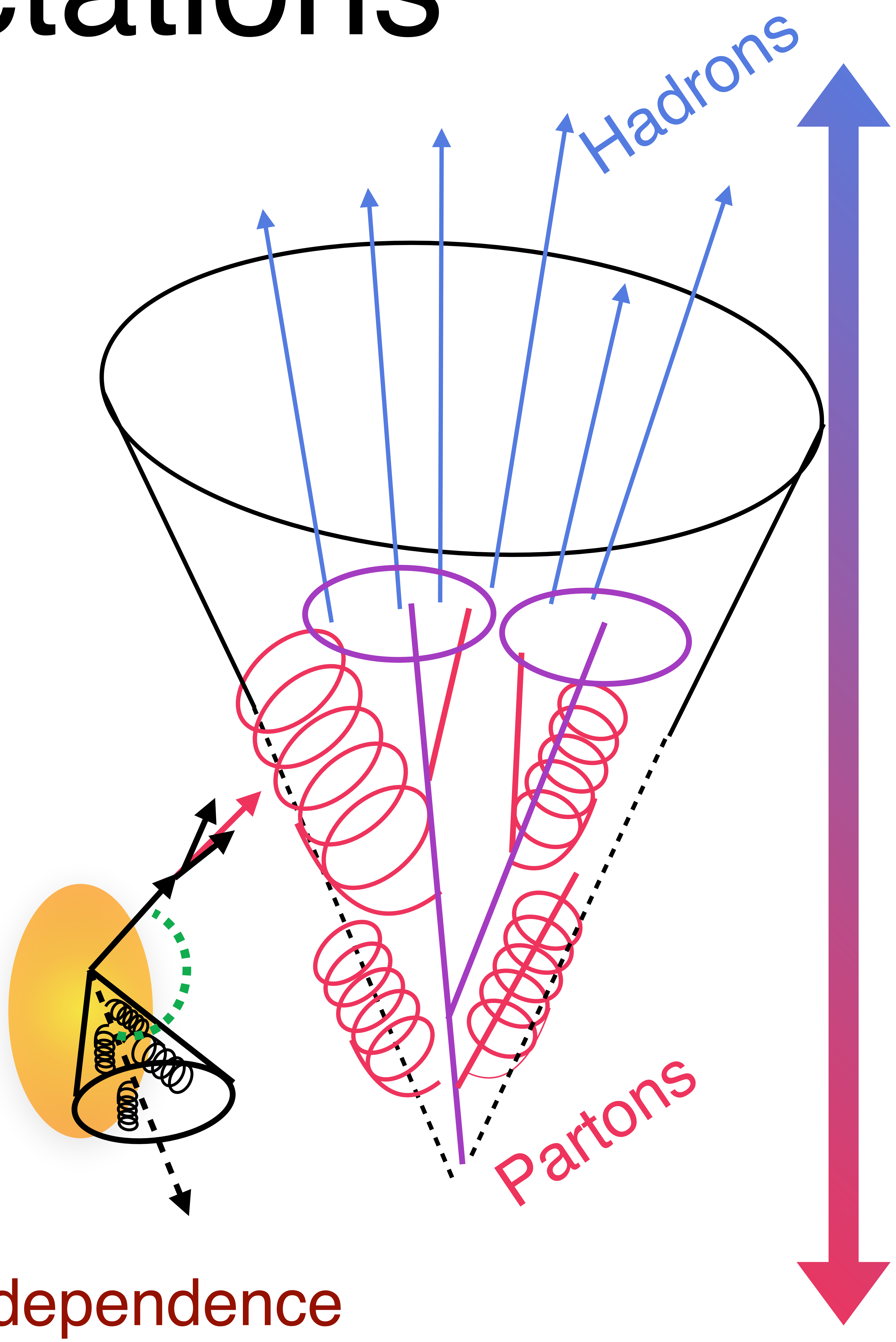
Coherence/decoherence

Wide-angle deflection



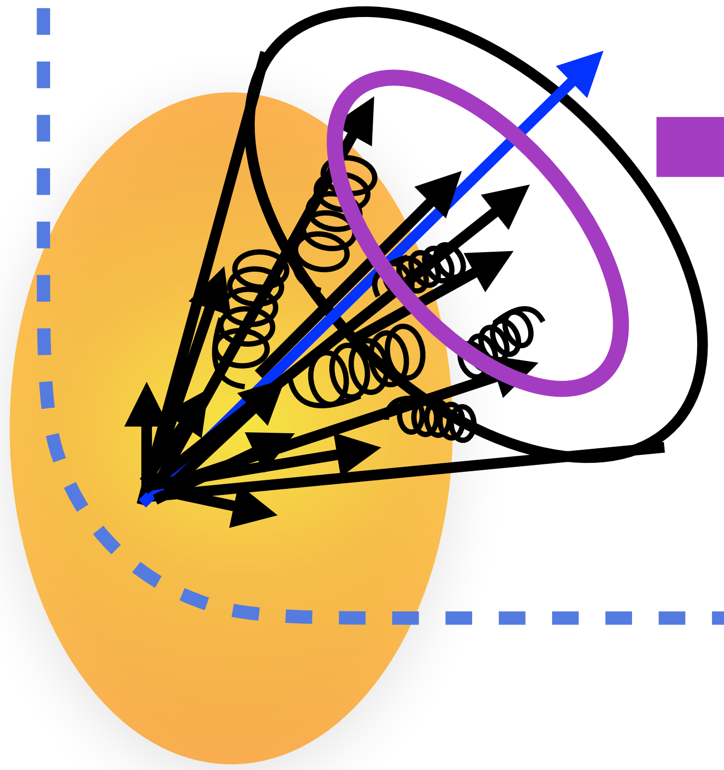
$E_{loss}^{g} > E_{loss}^{q}$

Flavor dependence

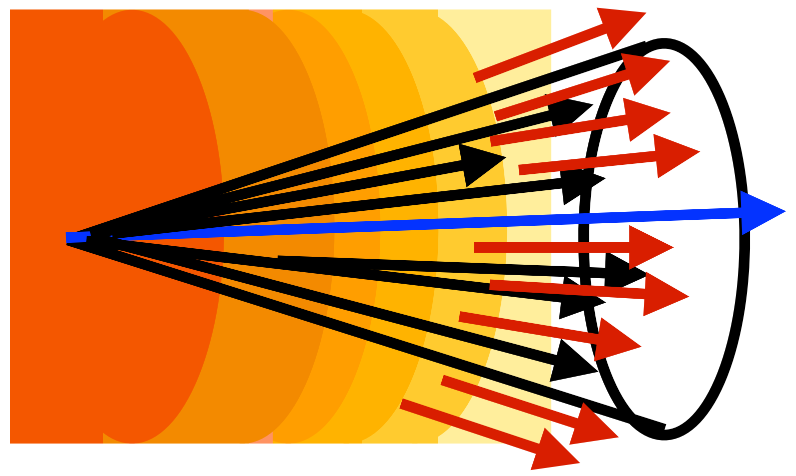


Jet quenching expectations

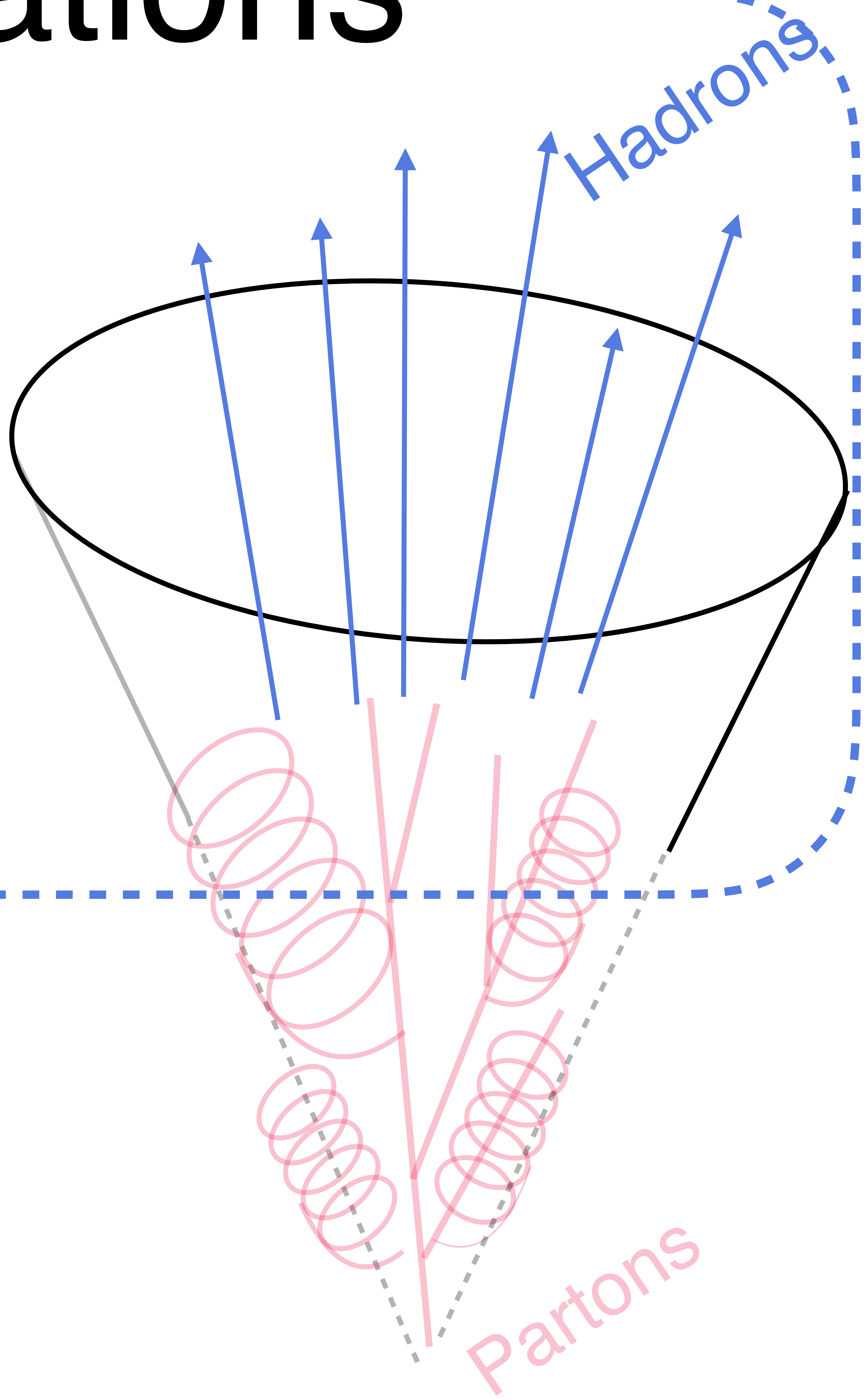
- Jet-medium interactions:



➡ Medium response



Distribution of charged hadrons inside the jet



➡ Momentum broadening

➡ Medium-induced splittings

➡ Coherence/decoherence

➡ Wide-angle deflection

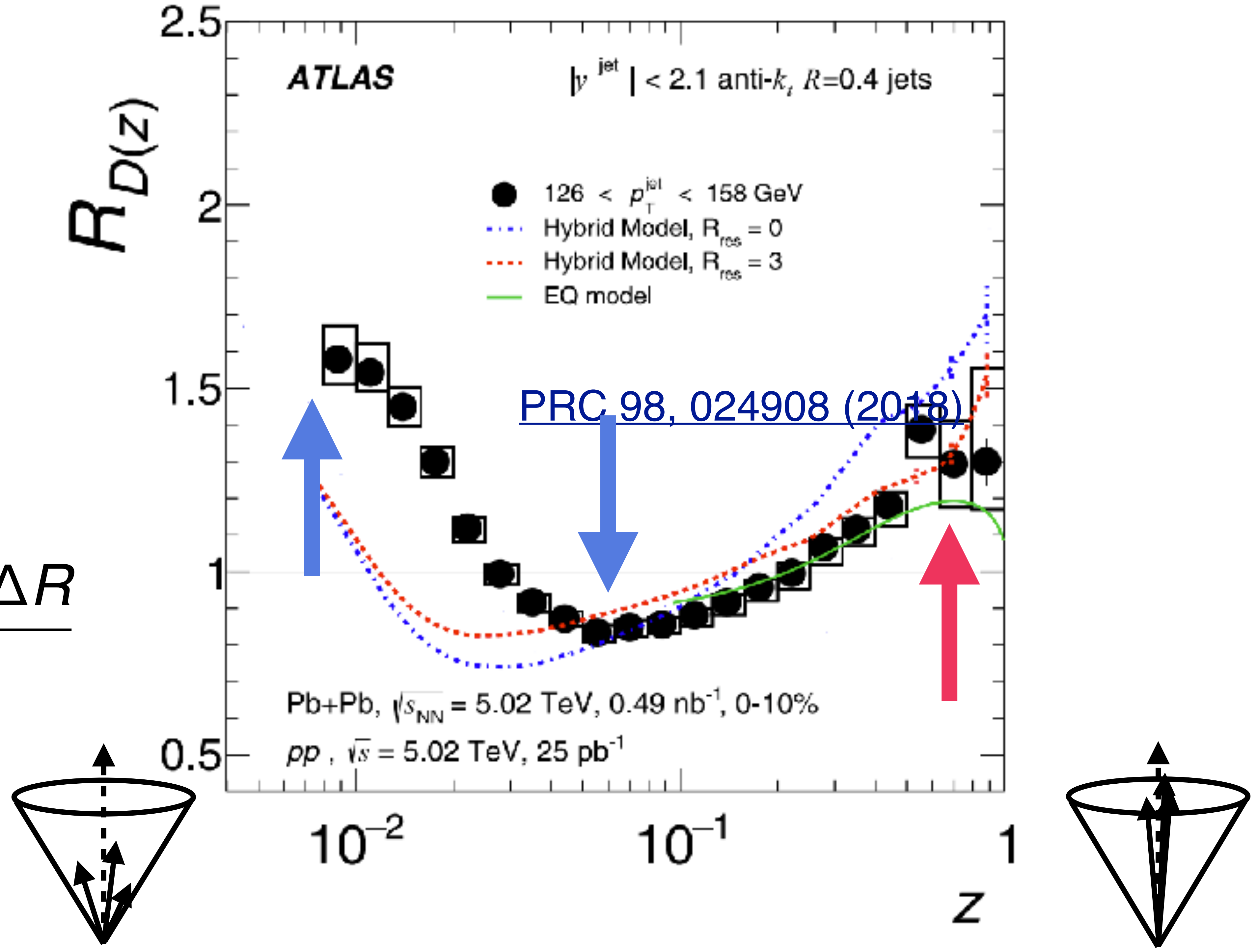
➡ Flavor dependence

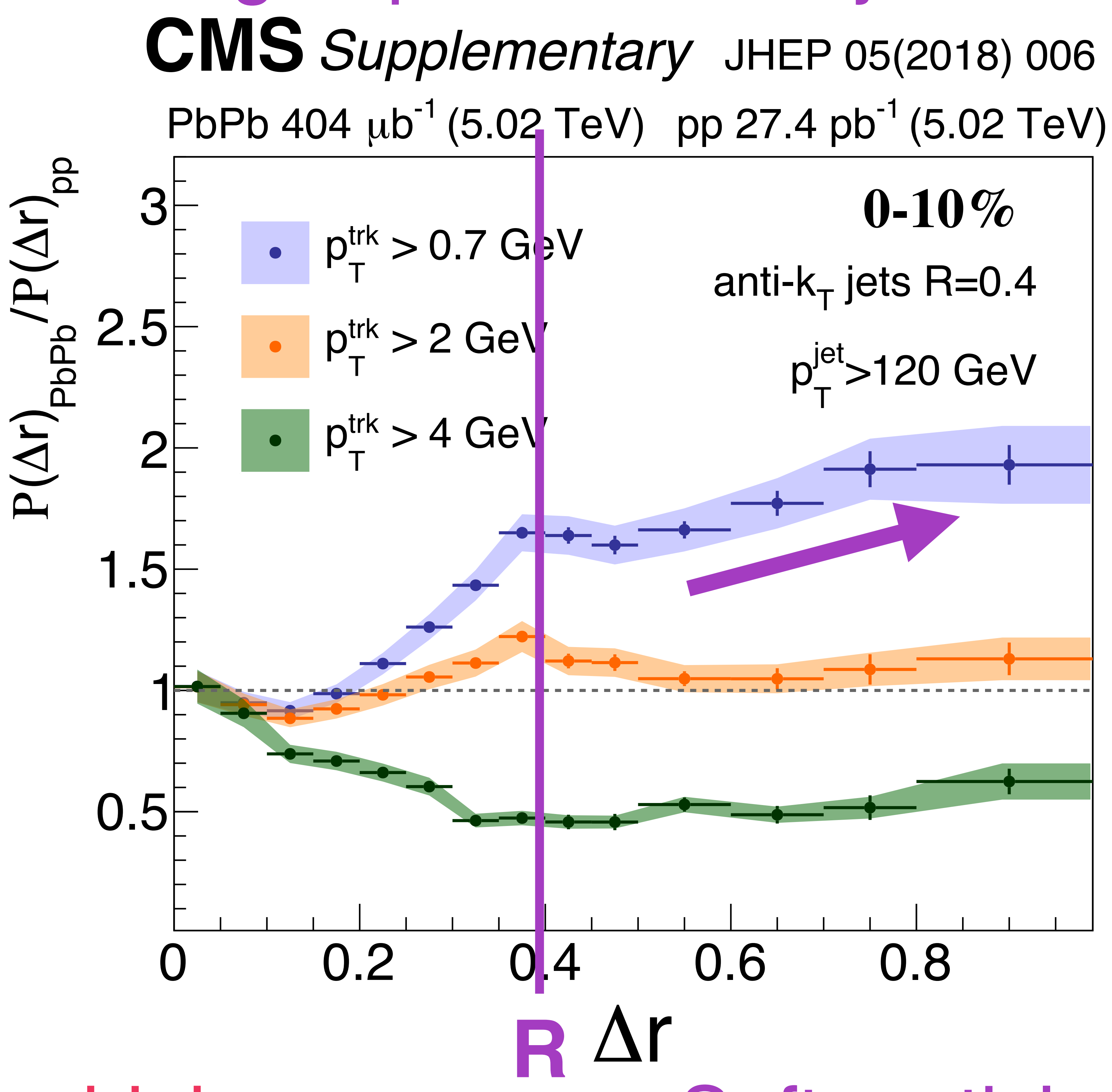
Jet shapes and fragmentation

Jet fragmentation: longitudinal profile of charged particles in a jet

Jet shape: radial profile of charged particles in a jet

$$z = \frac{p_{\mathrm{T}} \cos \Delta R}{p_{\mathrm{T}}^{\mathrm{jet}}}$$





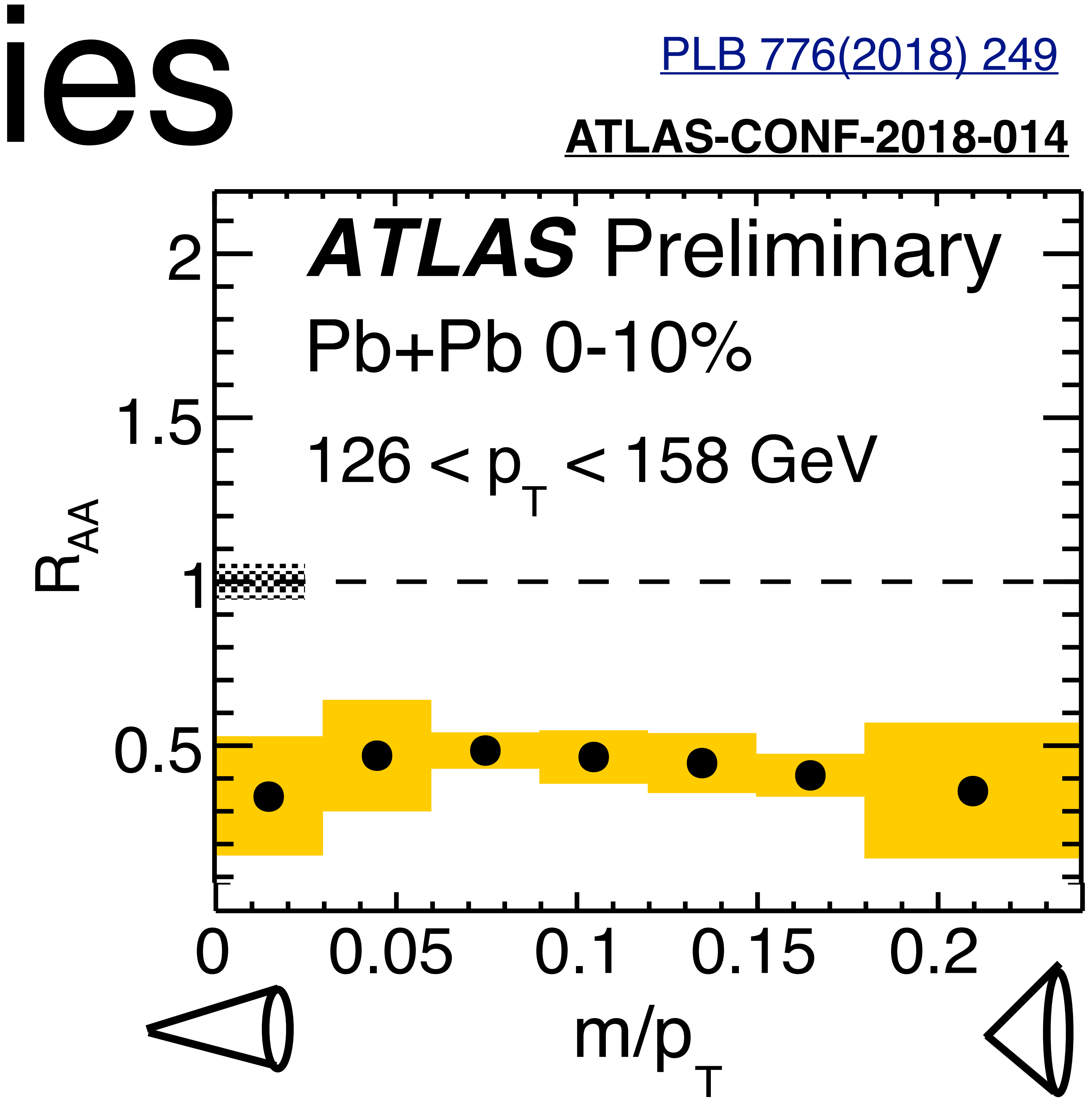
Energy transferred to soft particles inside the jet

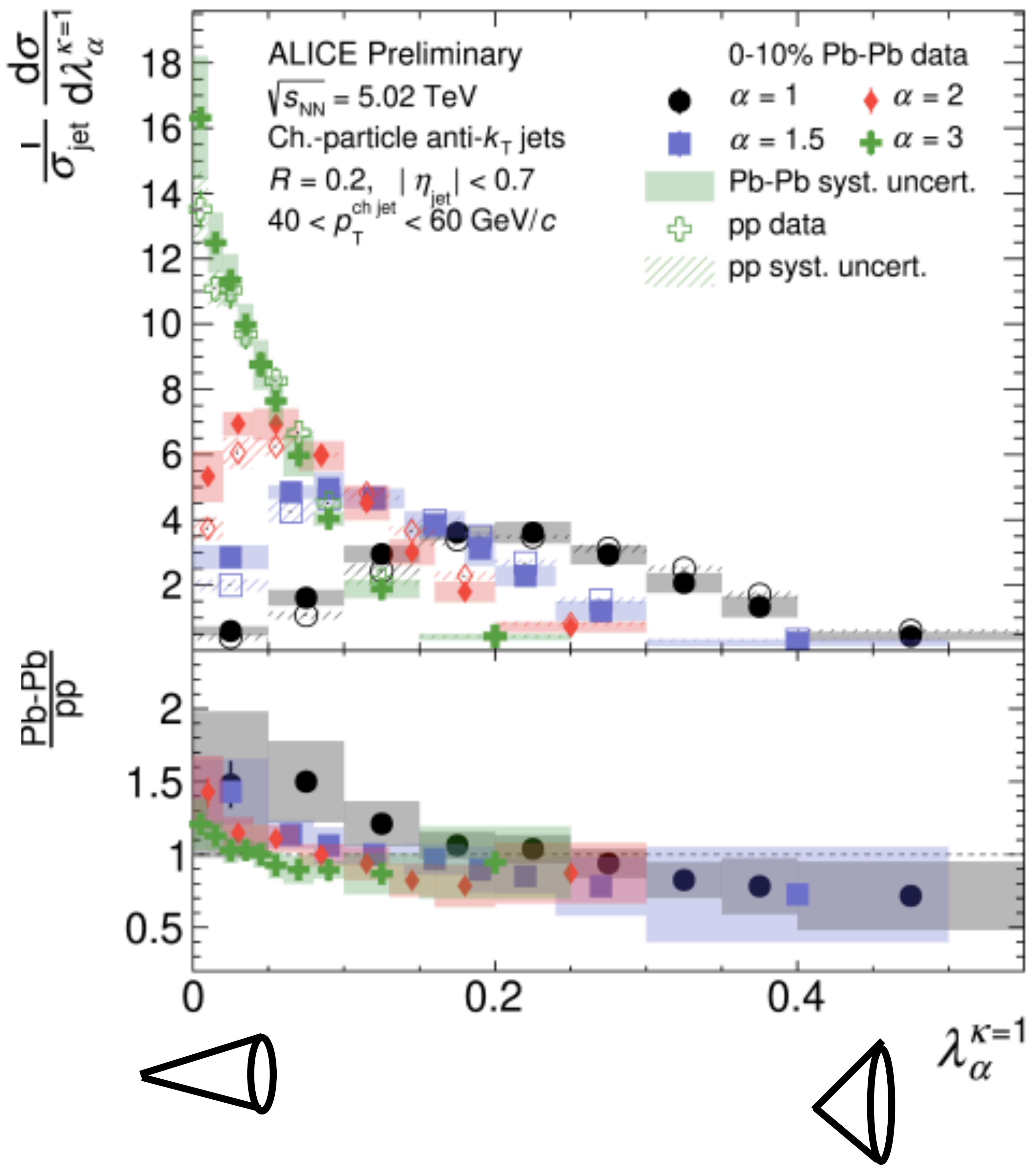
Hardening of core: high z enhancement from quark vs. gluons?

Soft particles are at large angles from jet axis

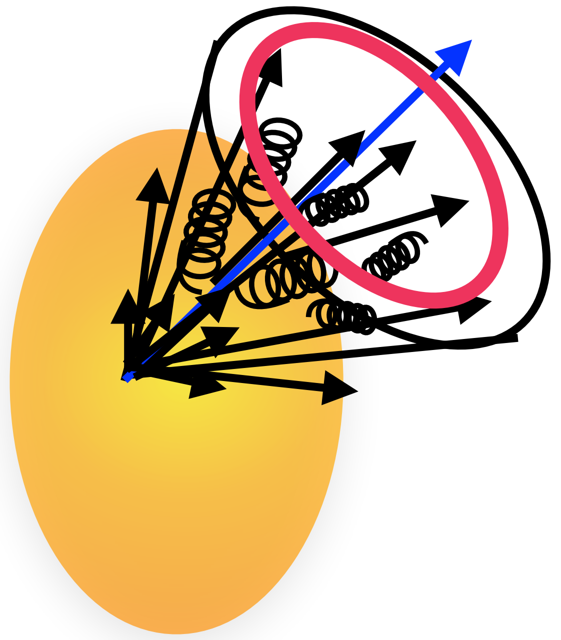
Jet angularities

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

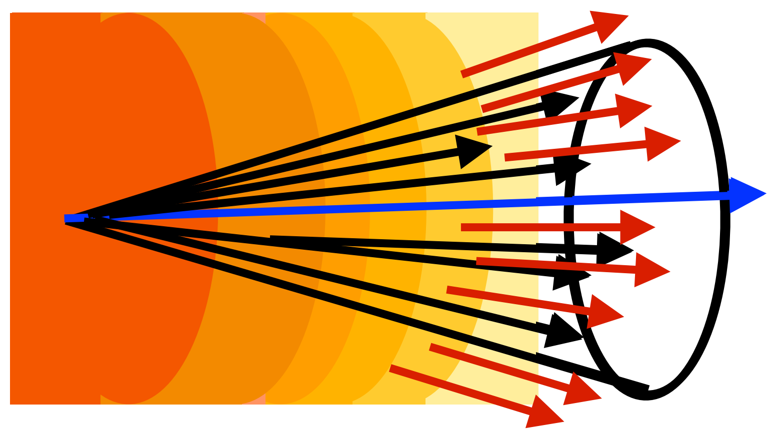




- Little to no modification of jet *mass (~α =2)*
- Insensitive to medium effects or cancellation of effects?
- Momentum broadening:
  - Inside cone->larger mass
  - Outside cone->smaller mass



- Medium recoil->larger mass
- Larger jets more modified-> smaller mass



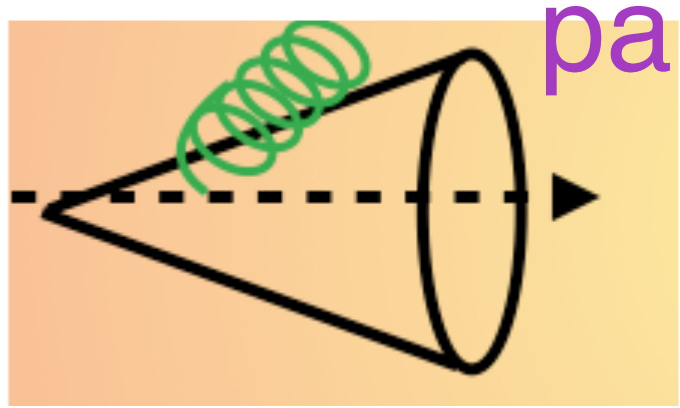
Jet quenching expectations

- Jet-medium interactions:

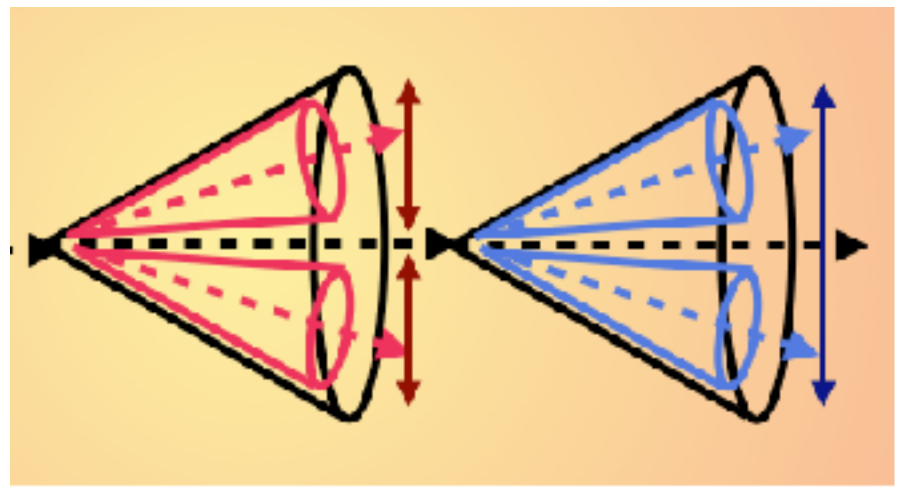
➡ Medium response

➡ Momentum broadening

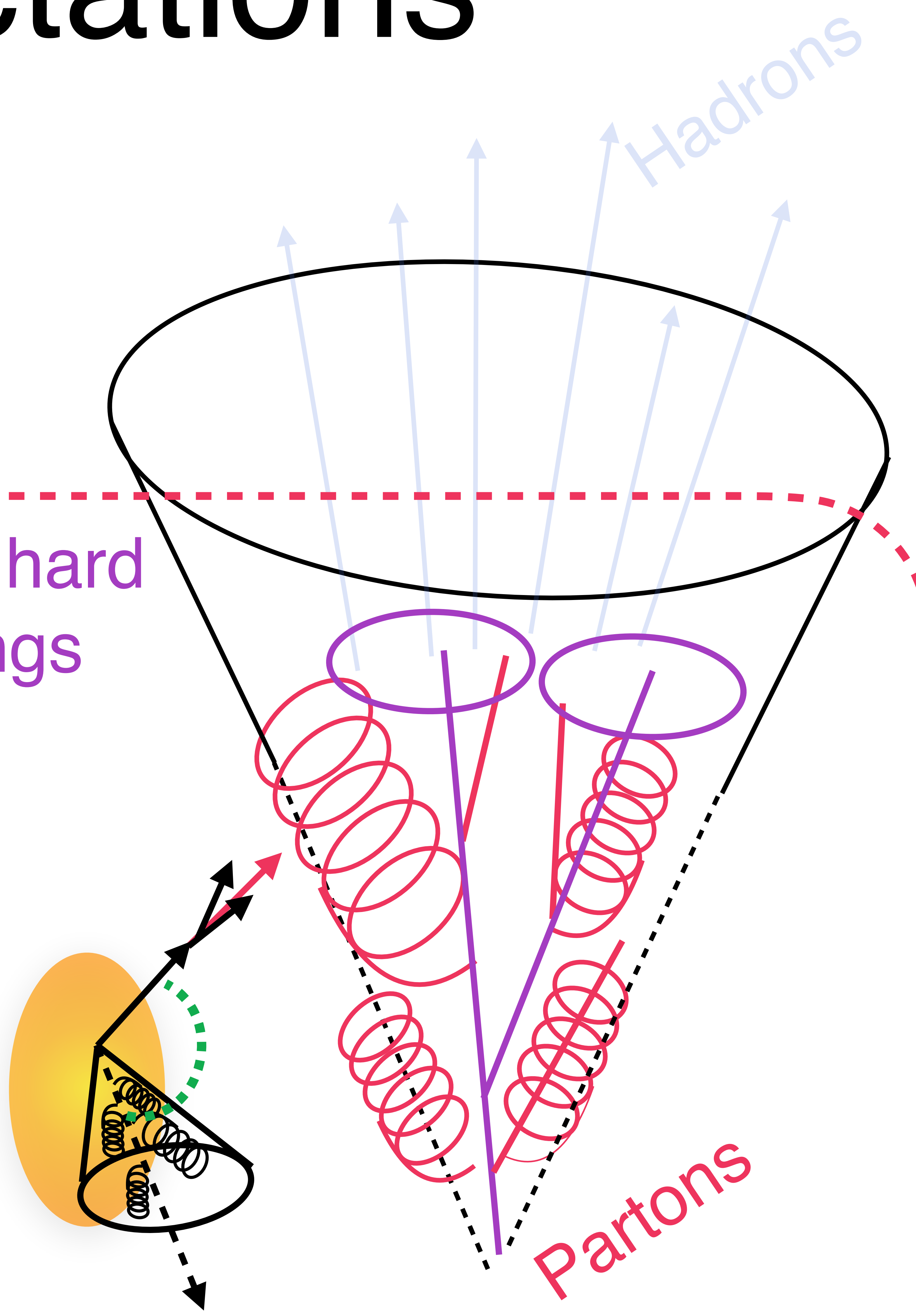
➡ Medium-induced splittings



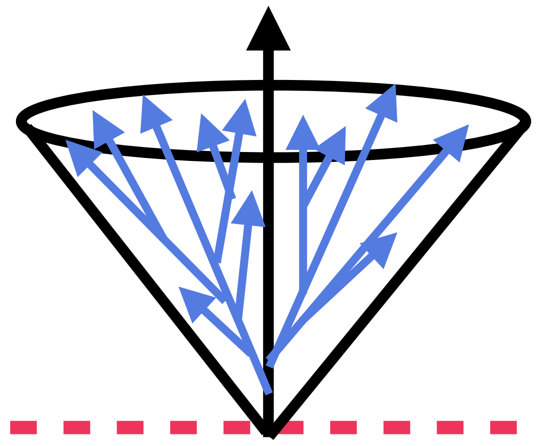
Subjets from hard parton splittings



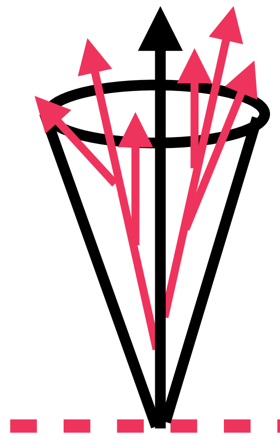
➡ Coherence/decoherence



➡ Wide-angle deflection

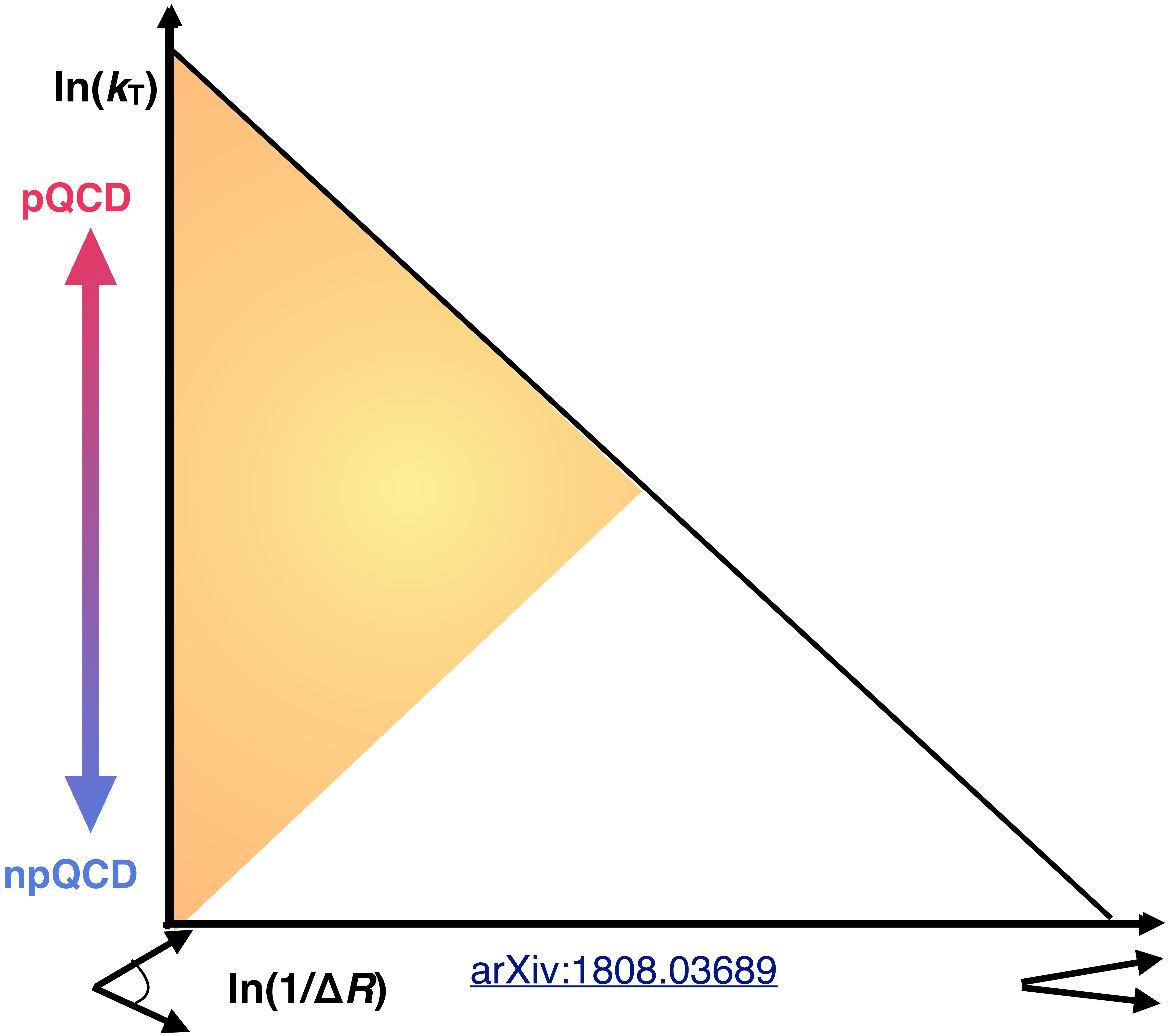


$E_{loss}^{g} > E_{loss}^{q}$



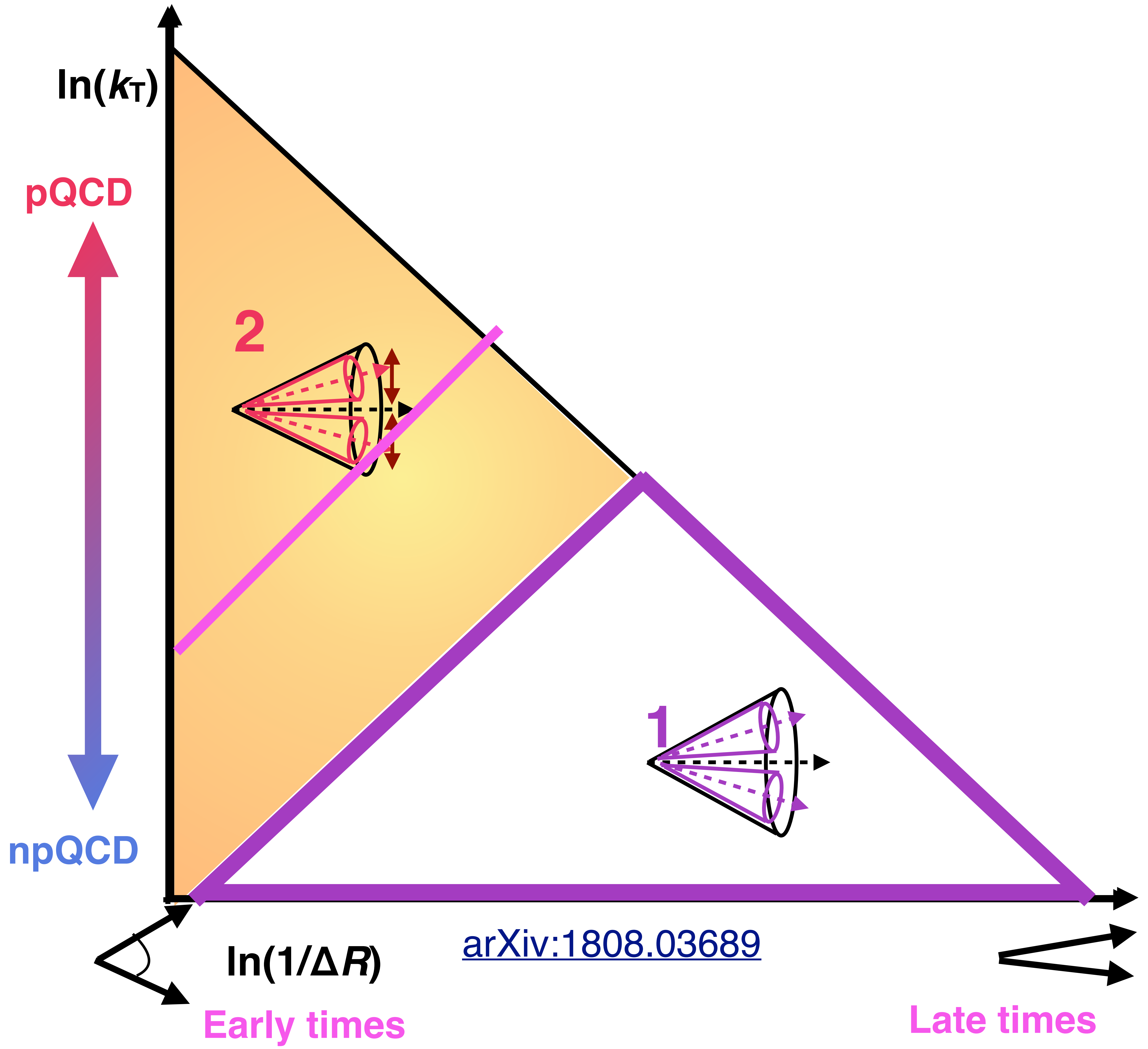
➡ Flavor dependence

Lund Plane: space-time structure of QGP



Lund Plane: space-time structure of QGP

1: Outside of medium



- Formation time: wider jets formed earlier experience more medium

$$t_f \approx \frac{1}{(1-z)k_T \Delta R}$$

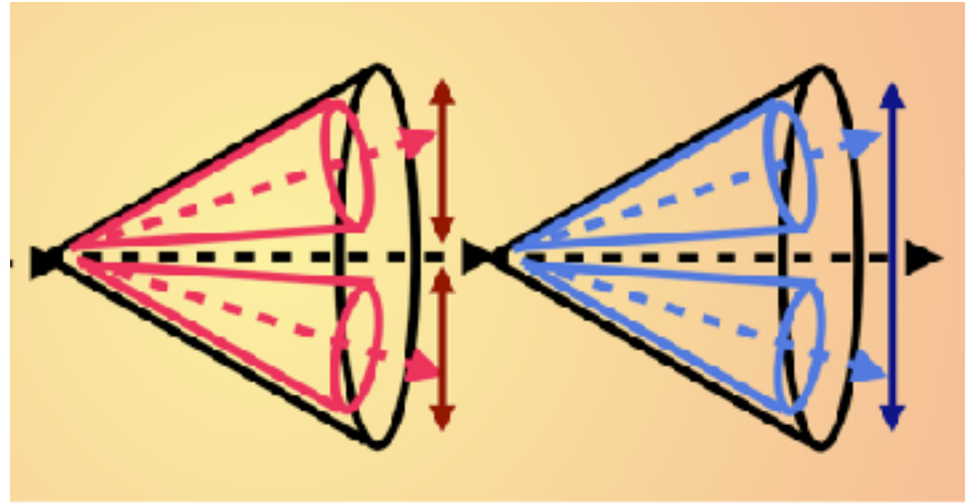
Y. L. Dokshitzer, et.al.

Lund Plane: space-time structure of QGP

1: Outside of medium

2: Decoherence

3: Coherence



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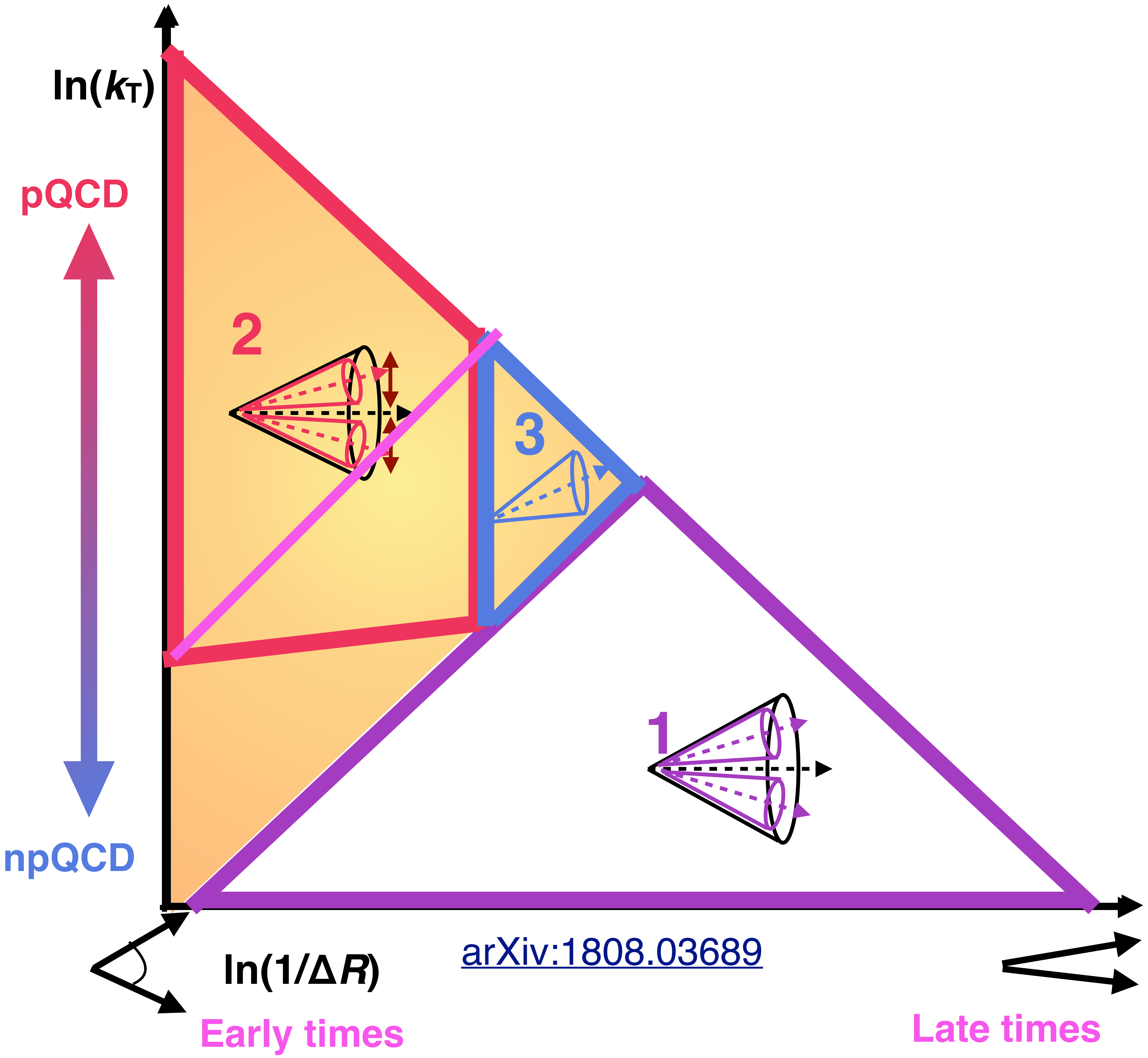
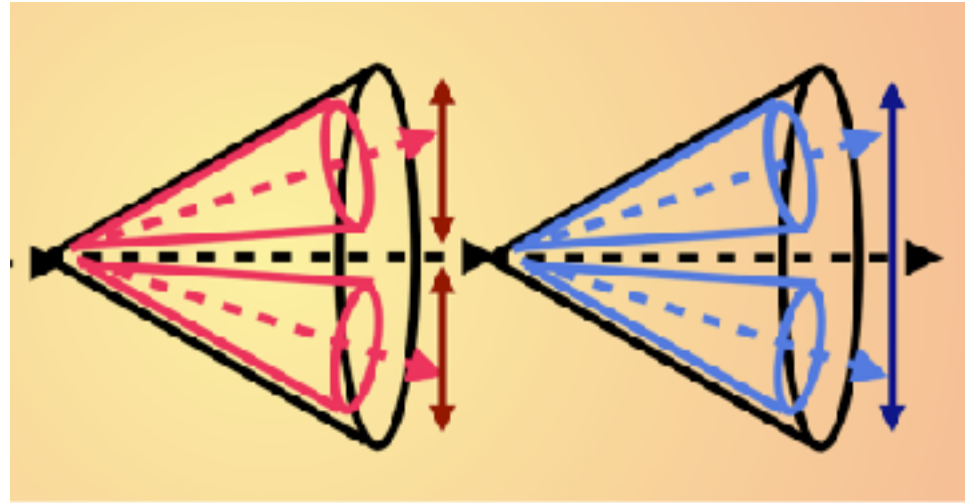
Y. L. Dokshitzer, et.al.



Lund Plane: space-time structure of QGP

1: Outside of medium

2: Decoherence



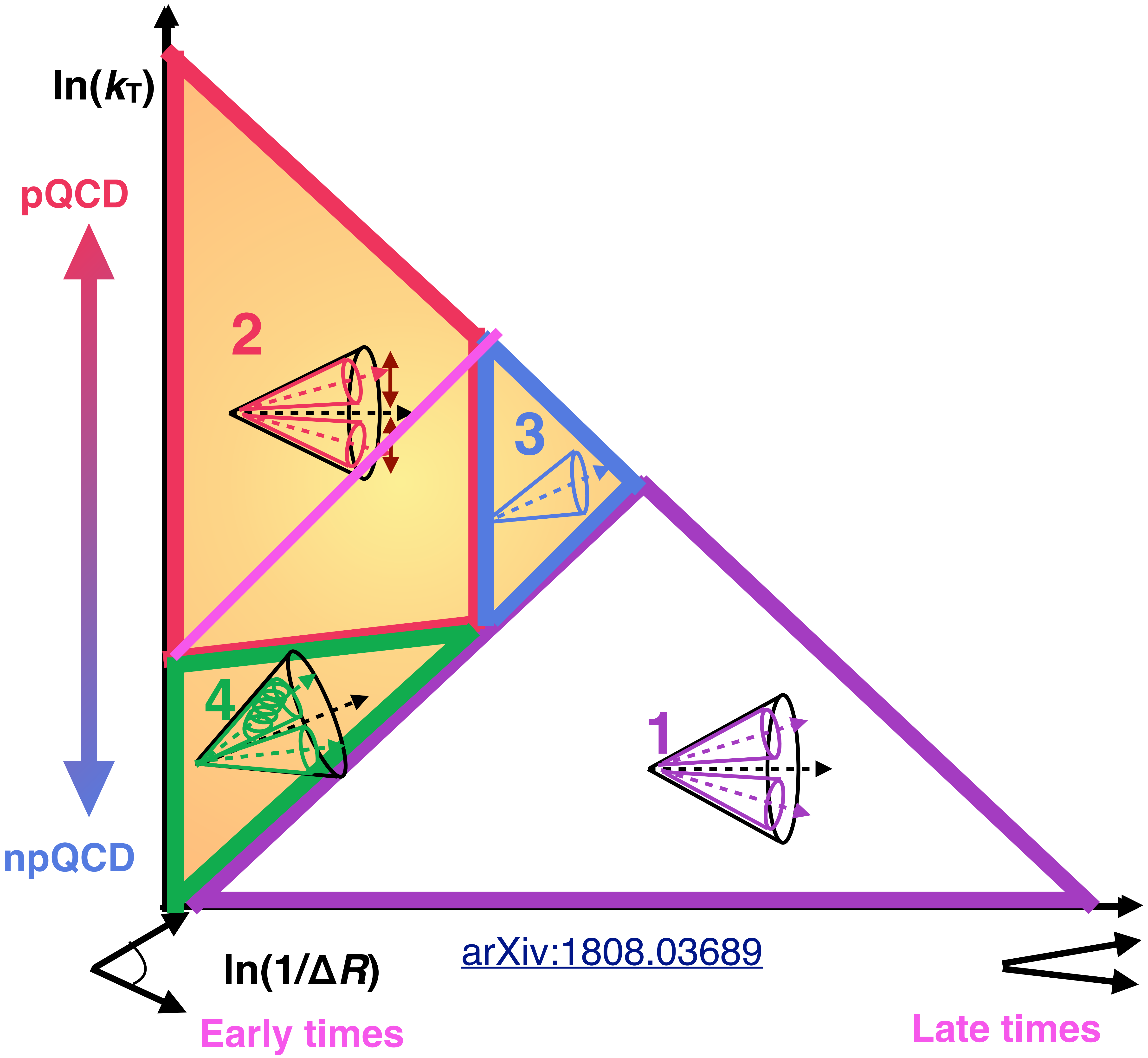
3: Coherence

4: Medium-induced splittings

- Formation time: wider jets formed earlier experience more medium

$$t_{\mathrm{f}} = \frac{1}{(1-z)k_{\mathrm{T}}\Delta R}$$

Y. L. Dokshitzer, et.al.

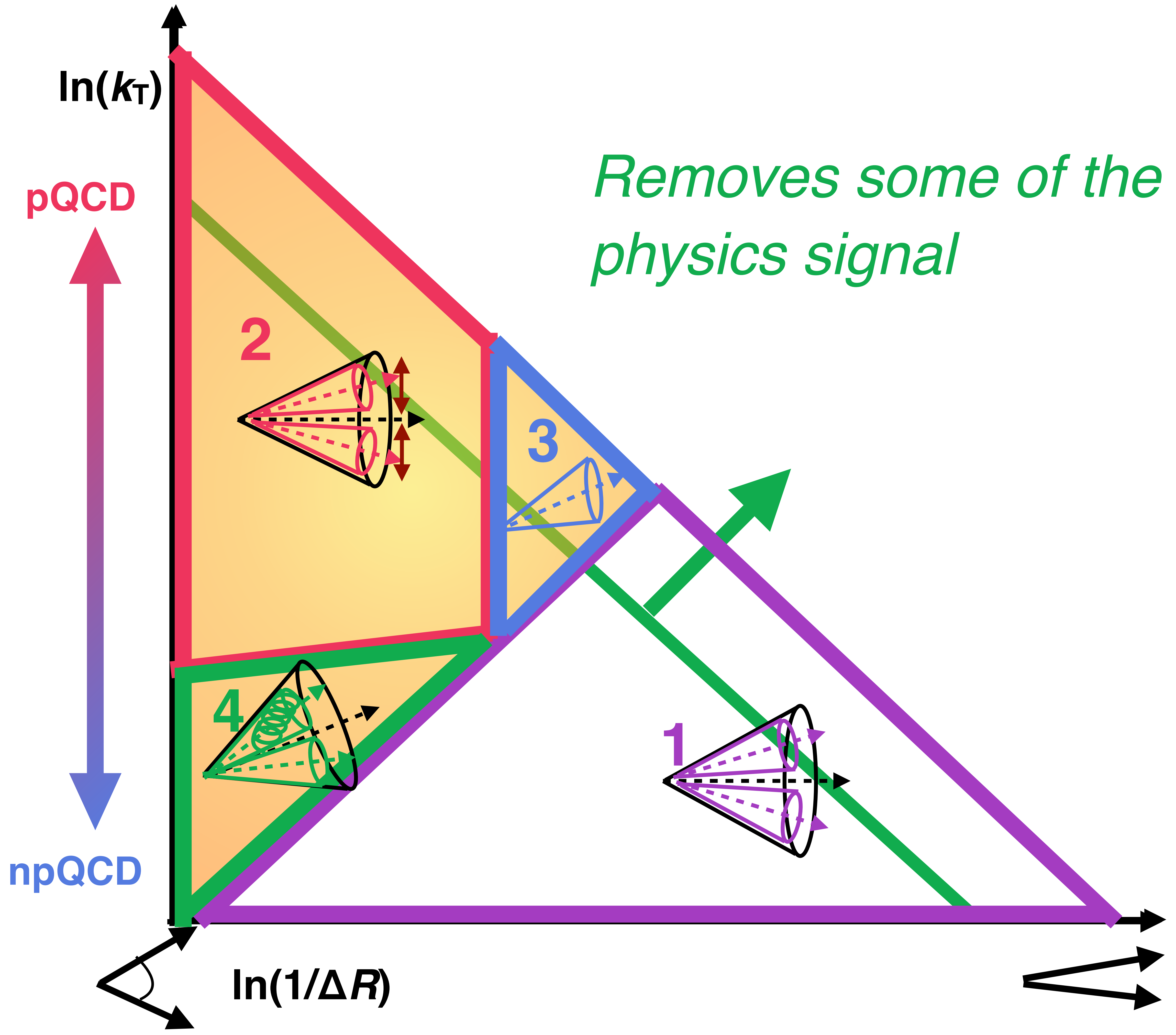


Soft drop grooming: in-medium

Removes NP effects to focus on hard structure modification

Perturbative regime under better theoretical control

Advantage: less sensitive to HI background



Soft drop grooming: in-medium

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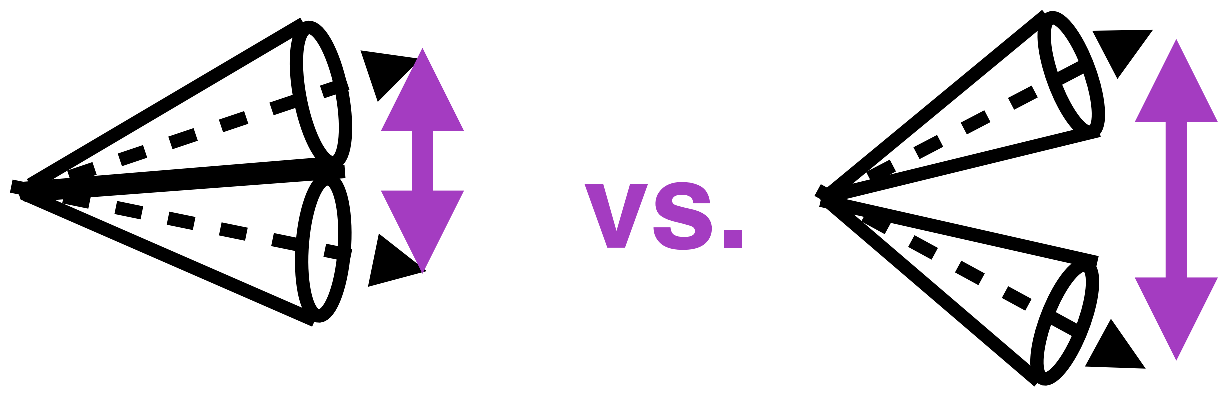
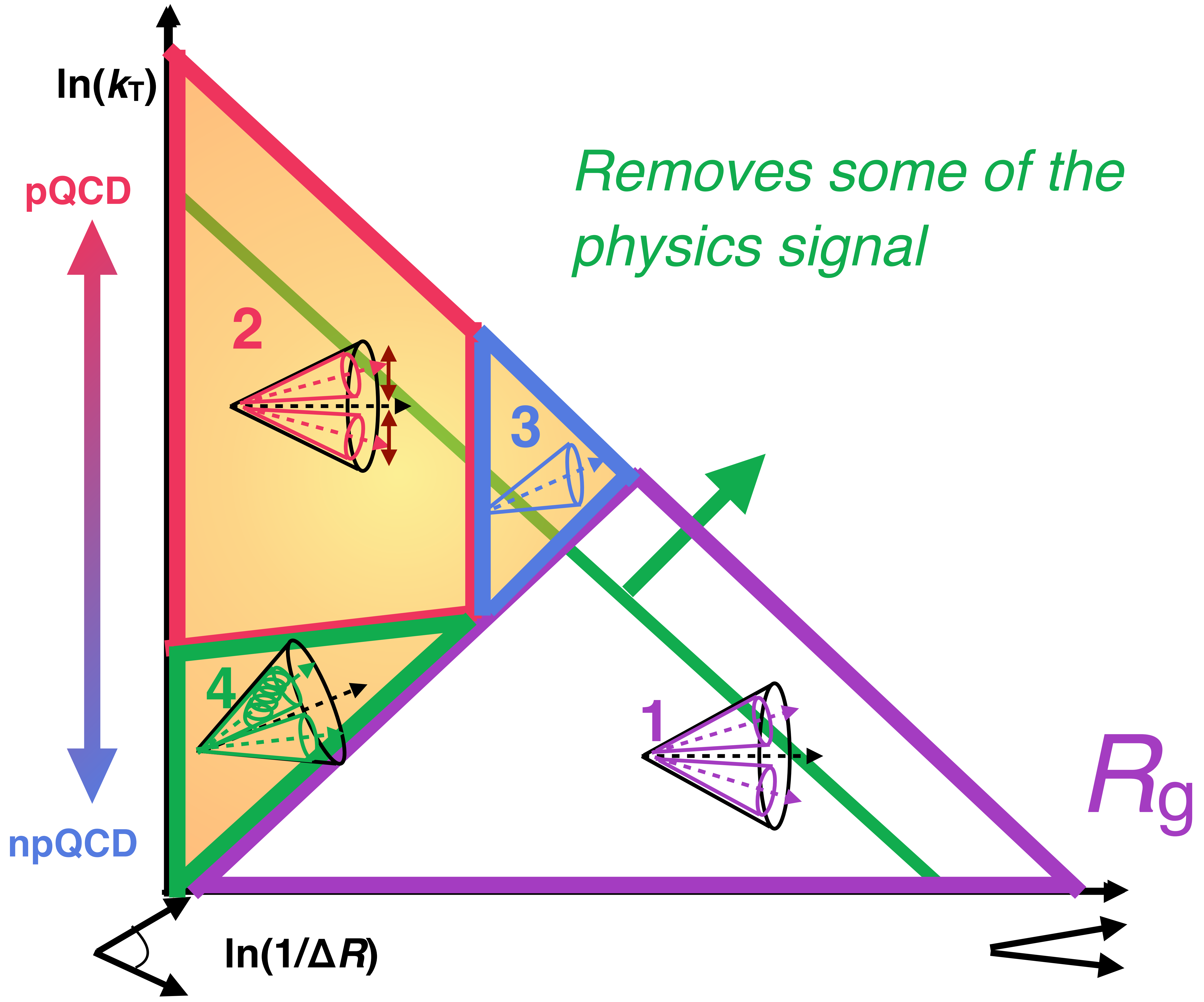
Perturbative regime under better theoretical control

Advantage: less sensitive to HI background

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

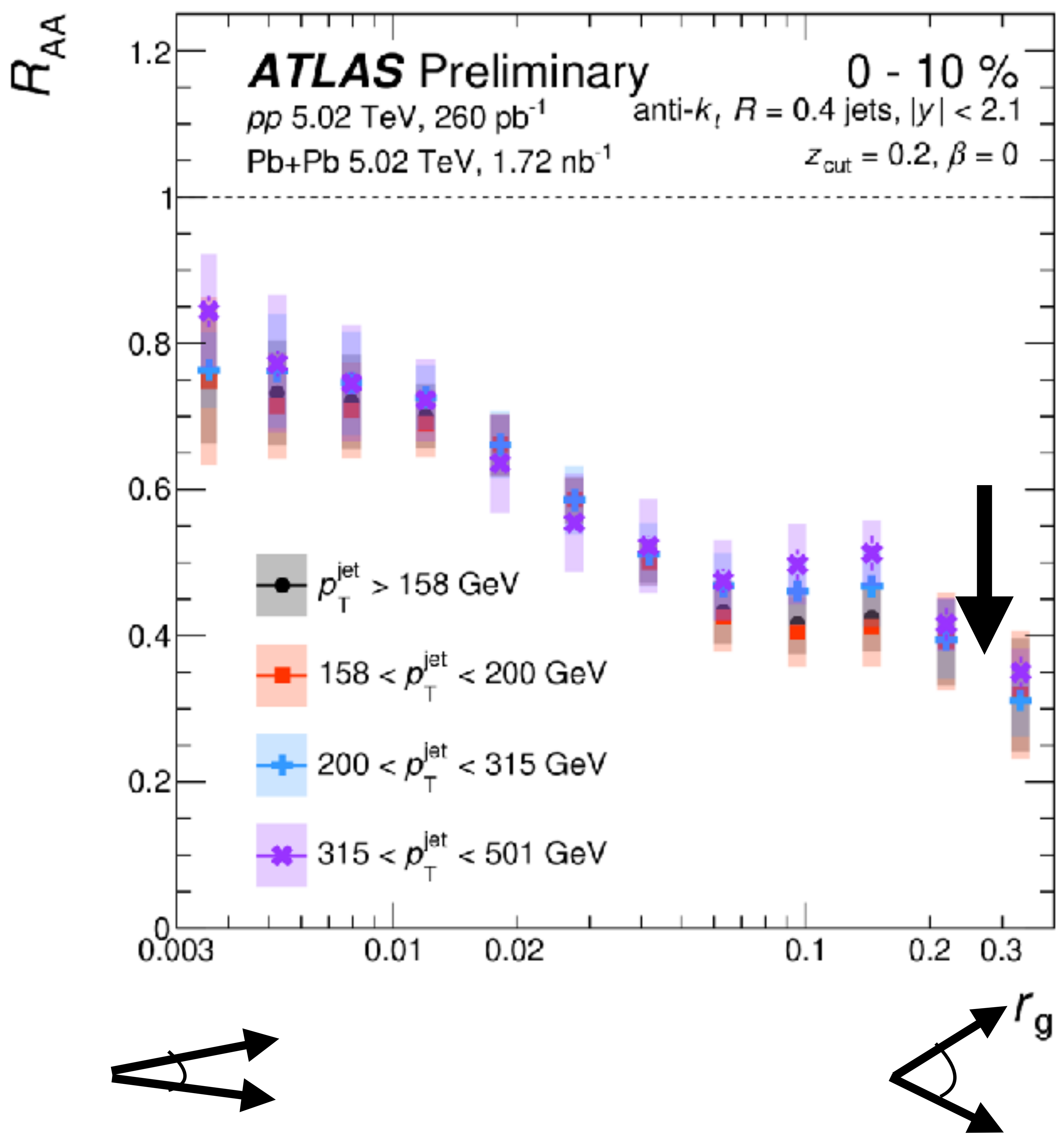


Resolution length of the QGP?



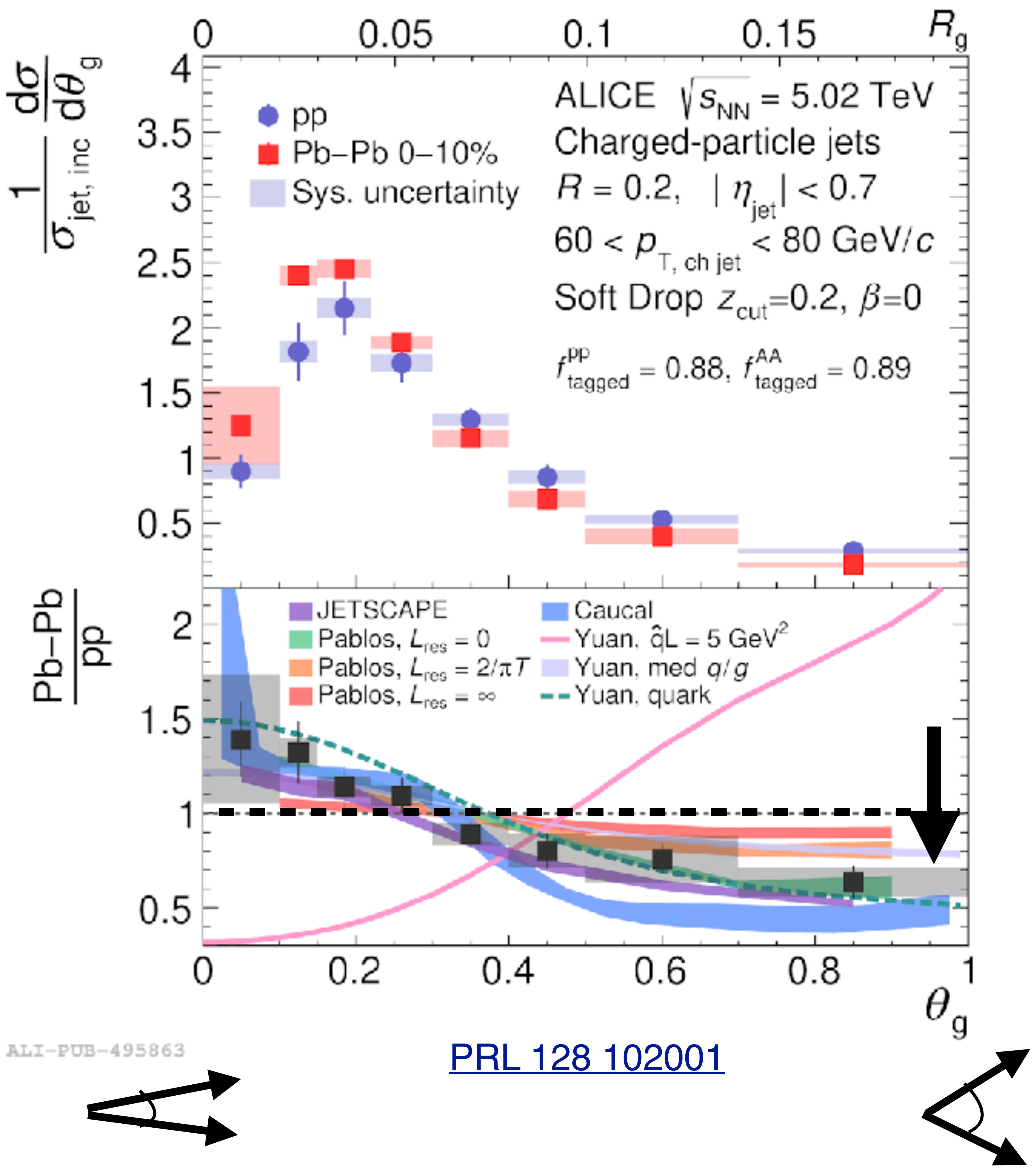
Jet splittings: R_g

Resolution length of QGP?

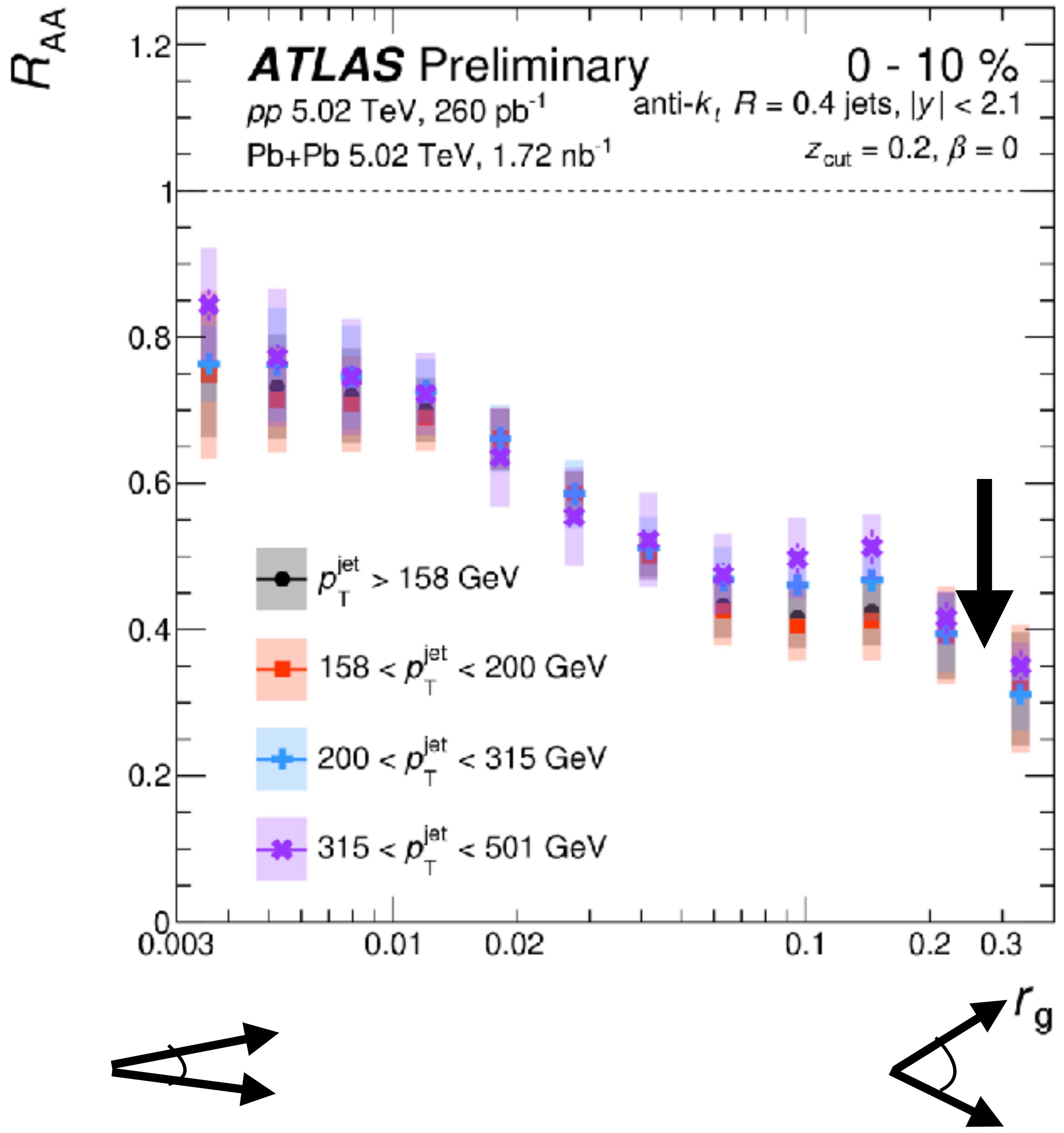


Jet splittings: R_g

Resolution length of QGP?

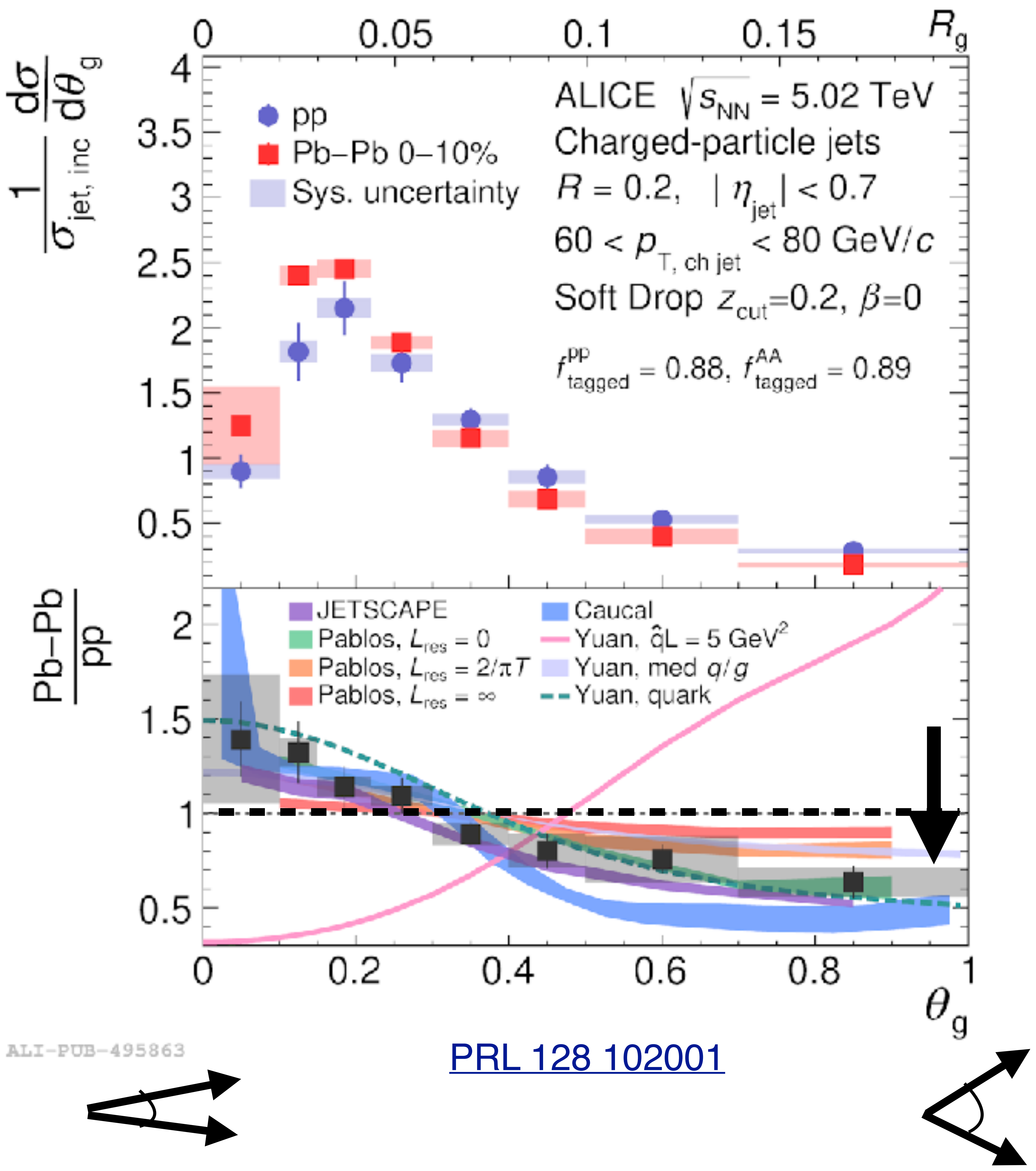


PRL 128 102001

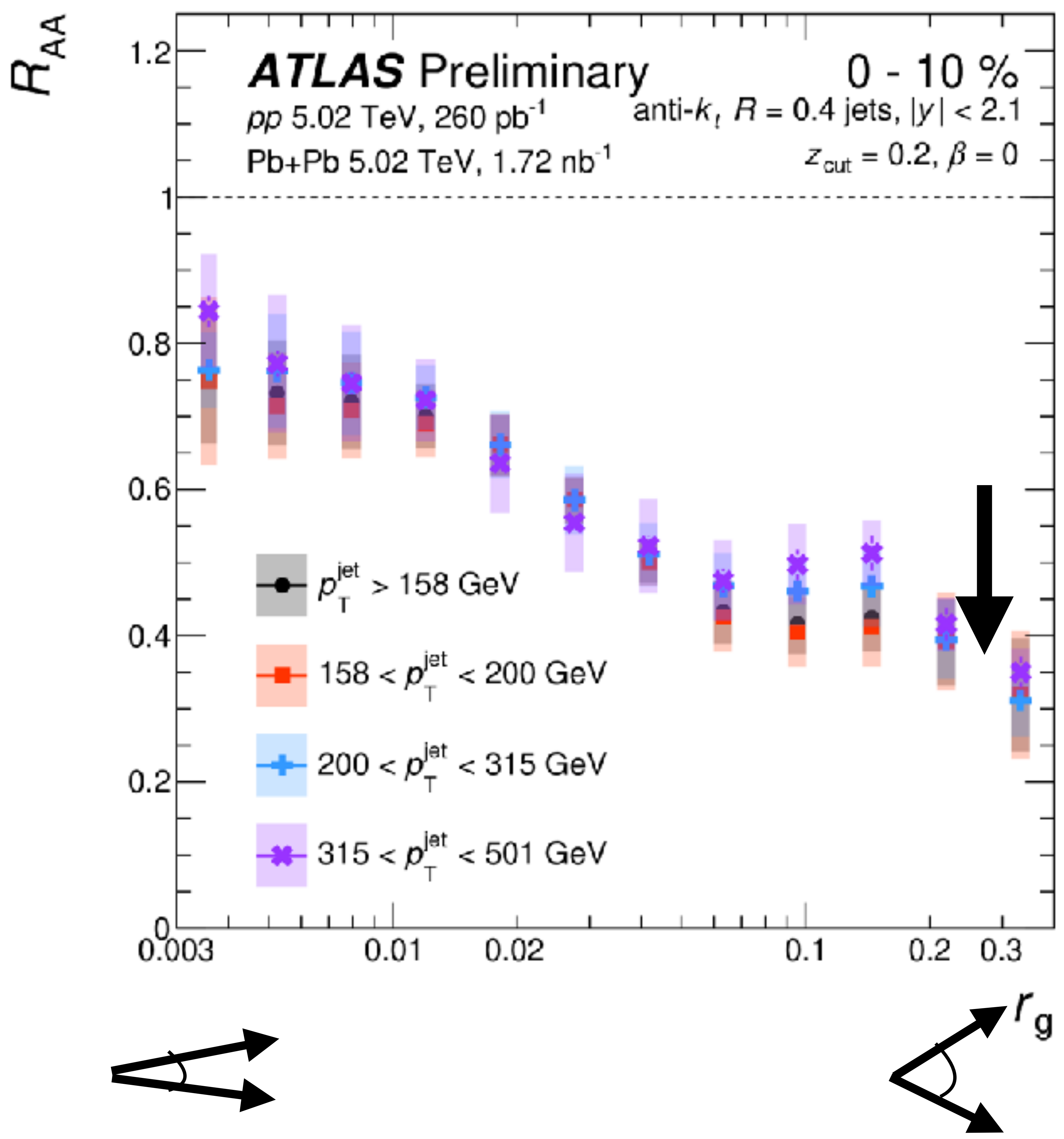


Jet splittings: R_g

Resolution length of QGP?



PRL 128 102001

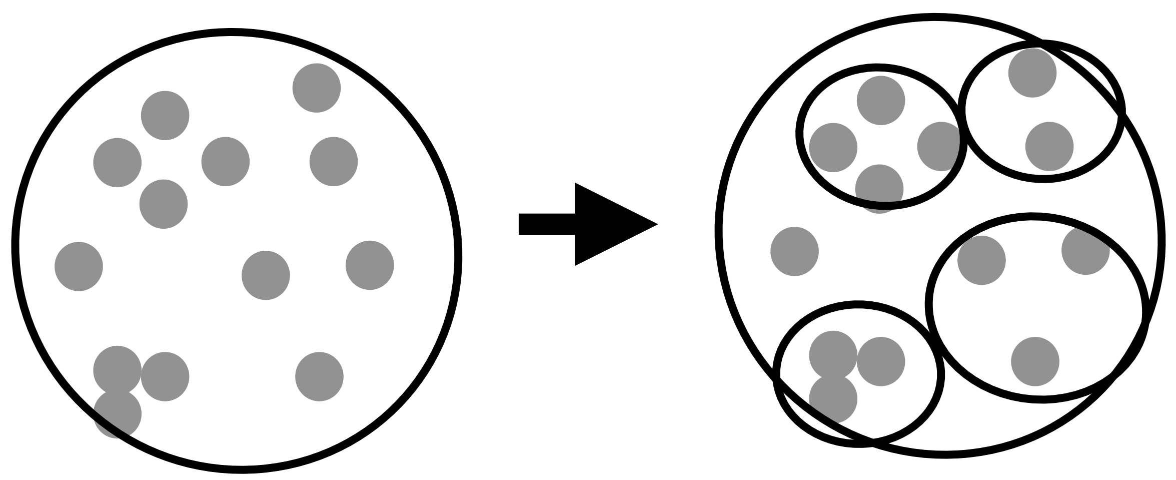


- *Modification with large angle suppression (narrowing core)*

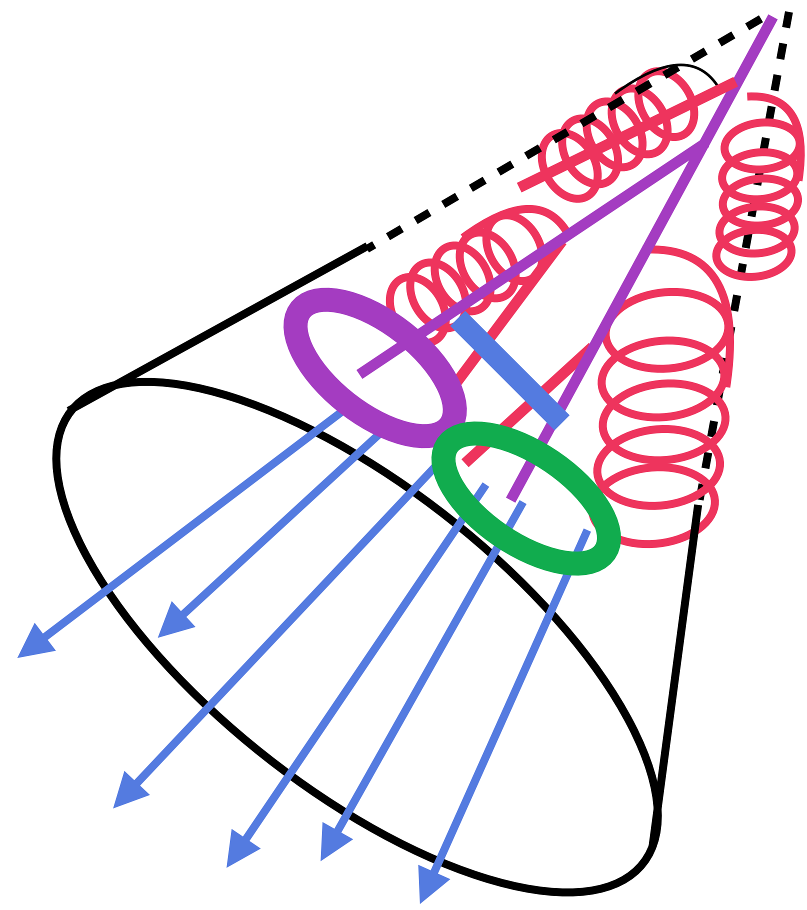
Substructure with subjets

See Isaac's talk today!

- Recluster constituents of R=0.4 jets into r=0.1 jets



$$\theta_{\mathrm{SJ}} = \Delta R_{1,2}$$

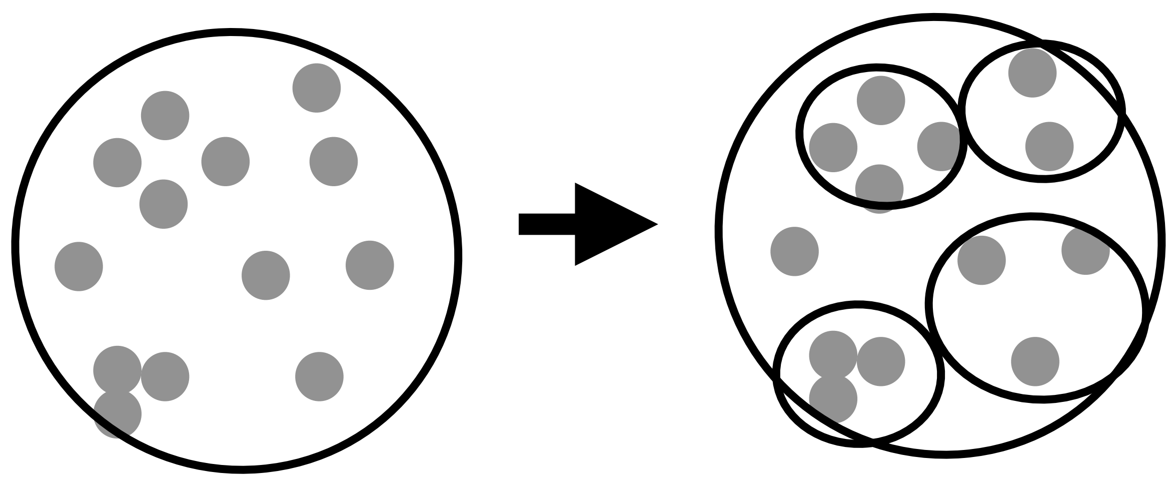


- Find the leading (1) and subleading (2) jet

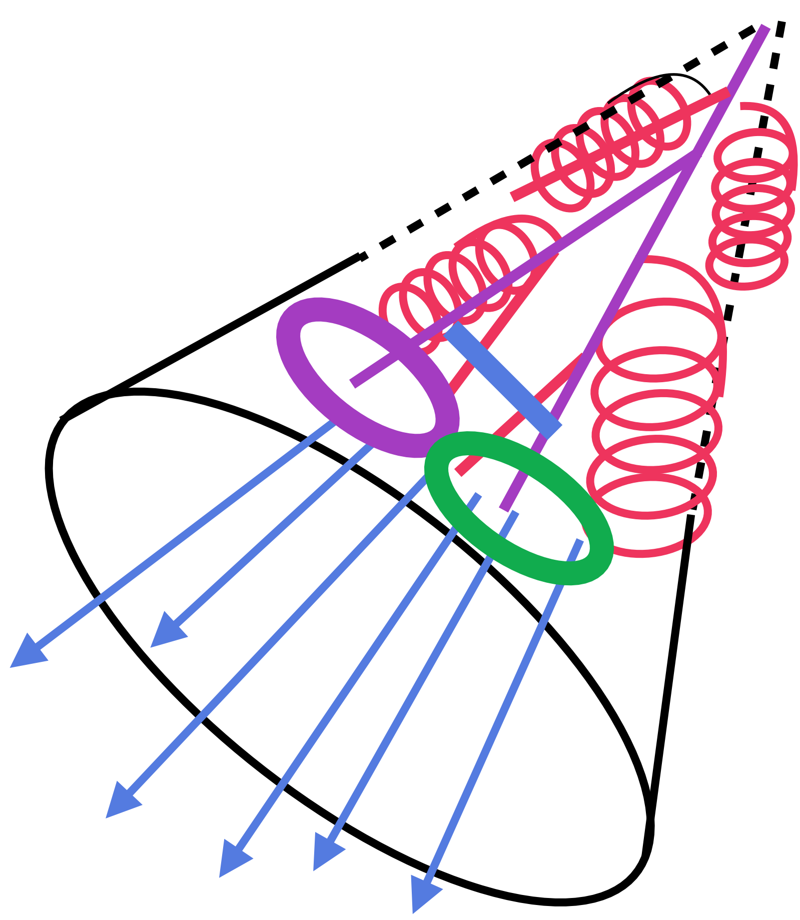
Substructure with subjets

See Isaac's talk today!

- Recluster constituents of R=0.4 jets into r=0.1 jets



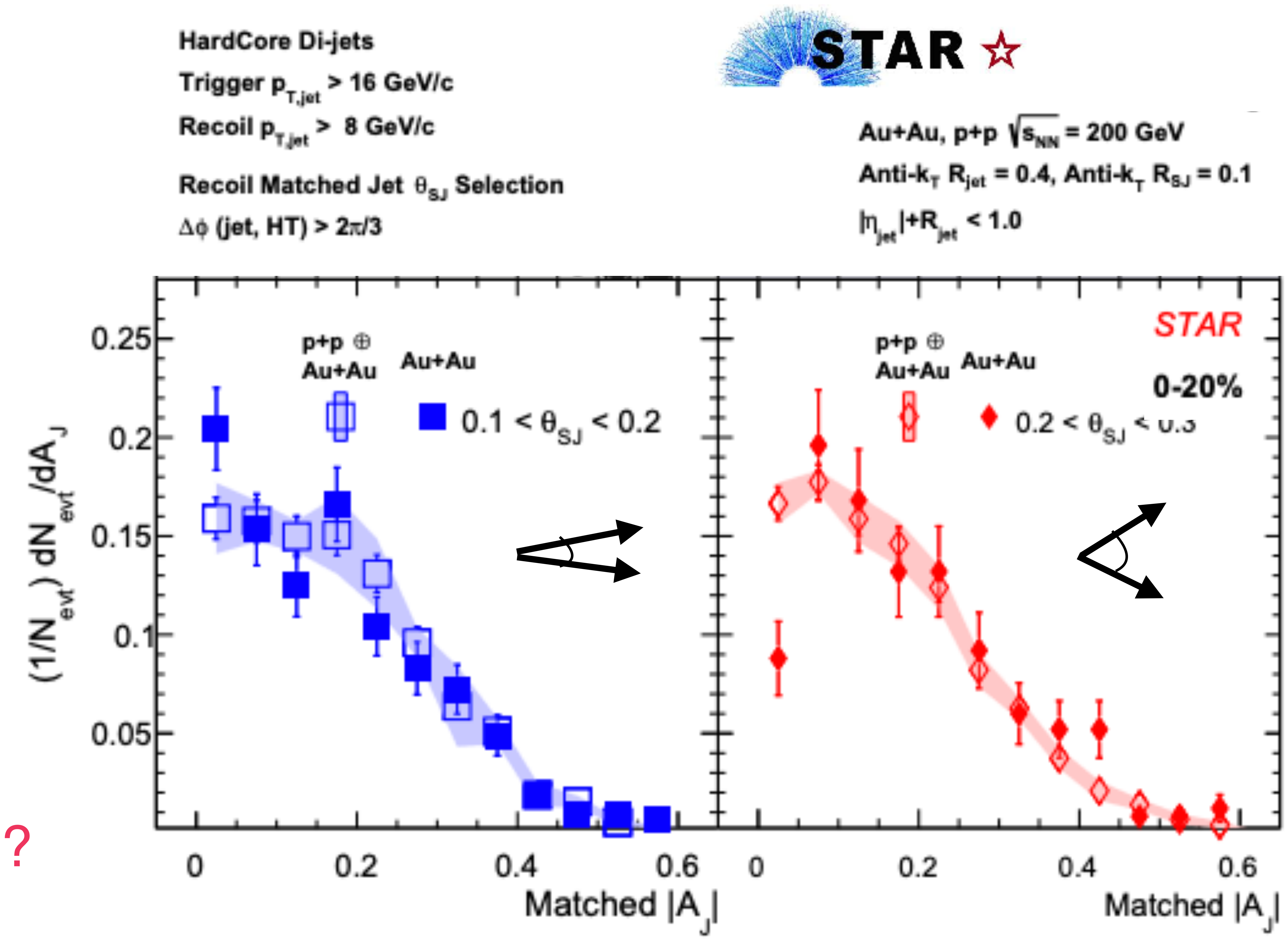
$$\theta_{SJ} = \Delta R_{1,2}$$

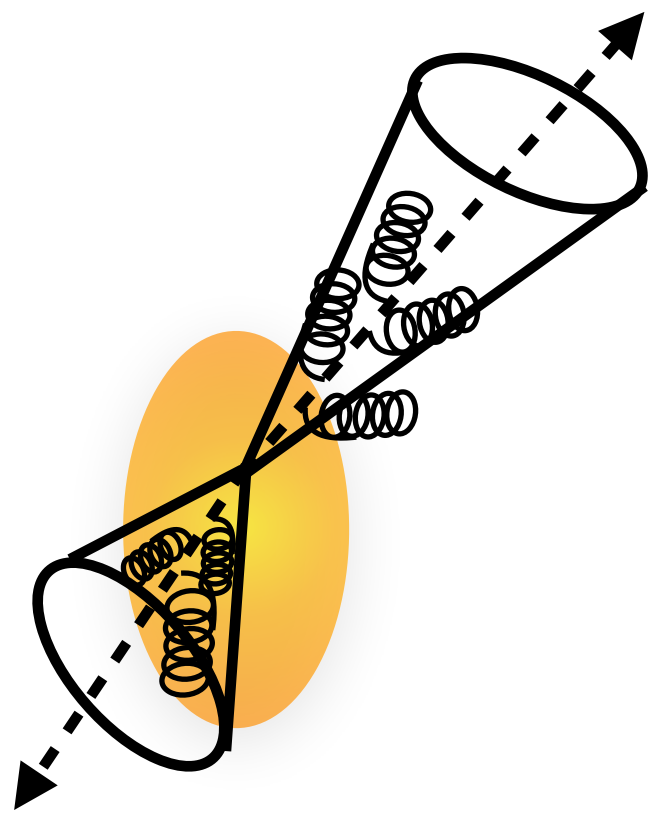


- Find the leading (1) and subleading (2) jet

No modification with angle

- Contradiction with LHC? RHIC later formation times?

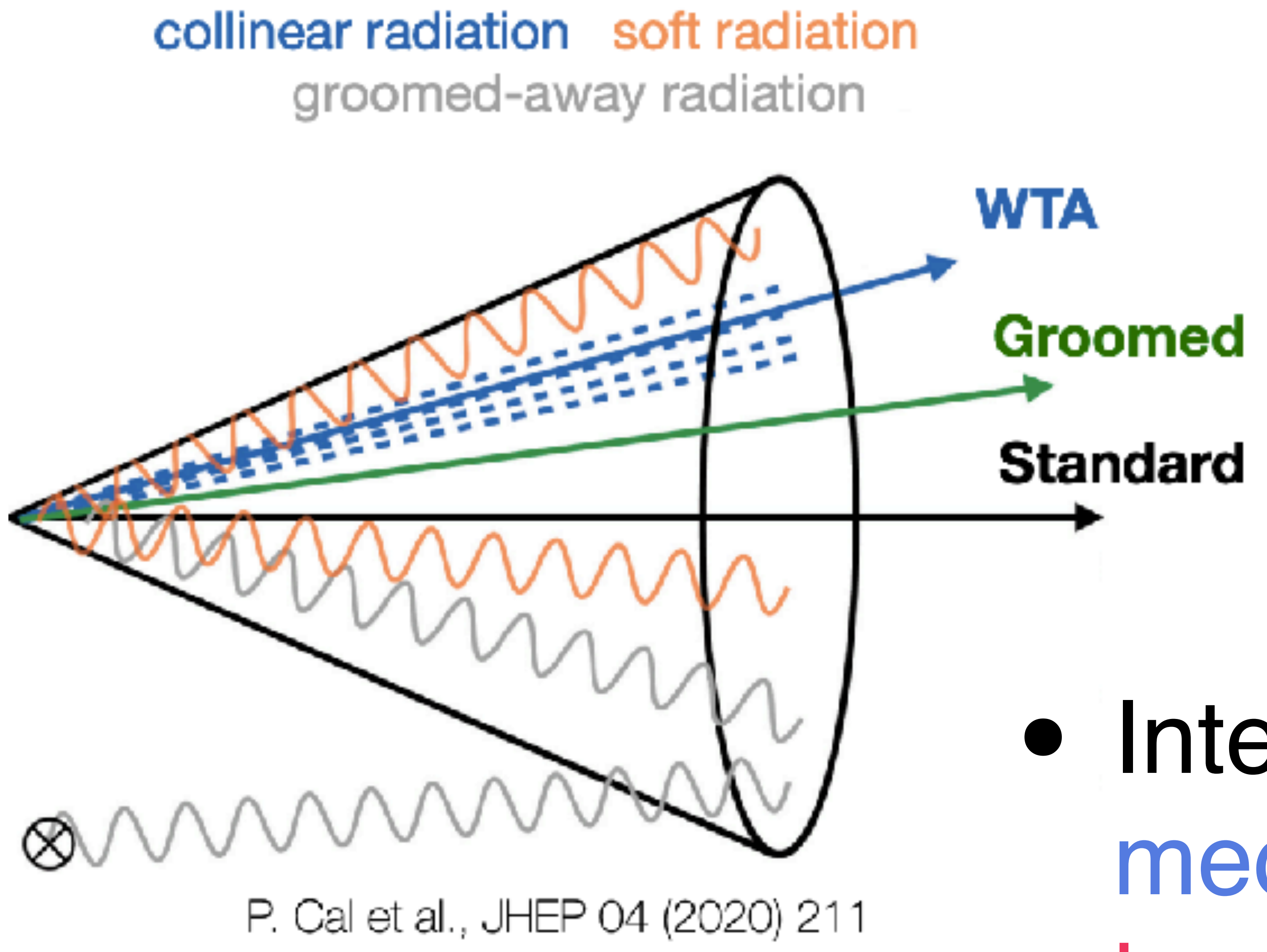




$$A_J = \frac{p_{T1} - p_{T2}}{p_{T1} + p_{T2}}$$

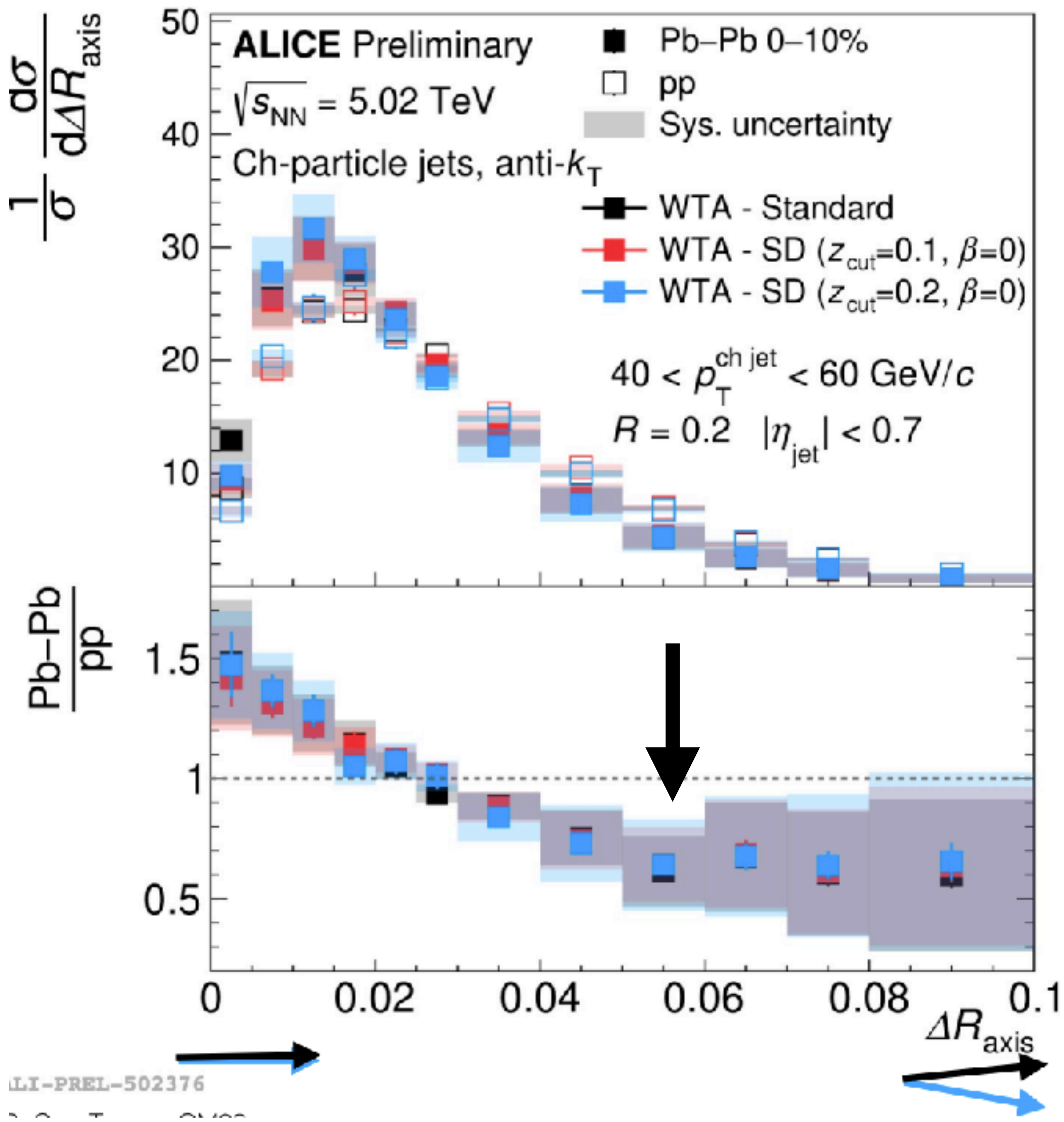
STAR PRC 105, 044906 (2022)

Jet axis



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

- Interplay between np medium response and hard core modification

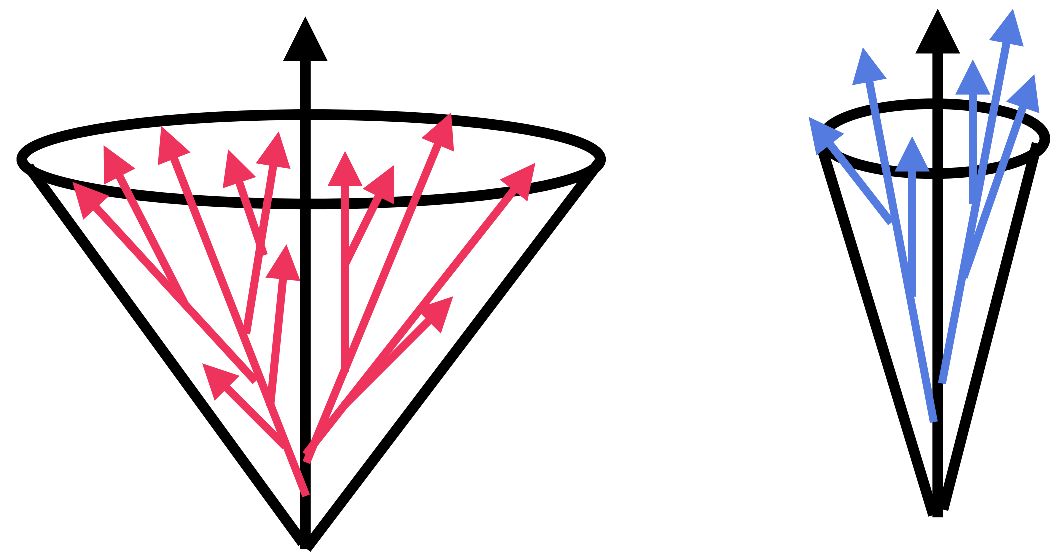


- Not sensitive to grooming: does not change jet direction

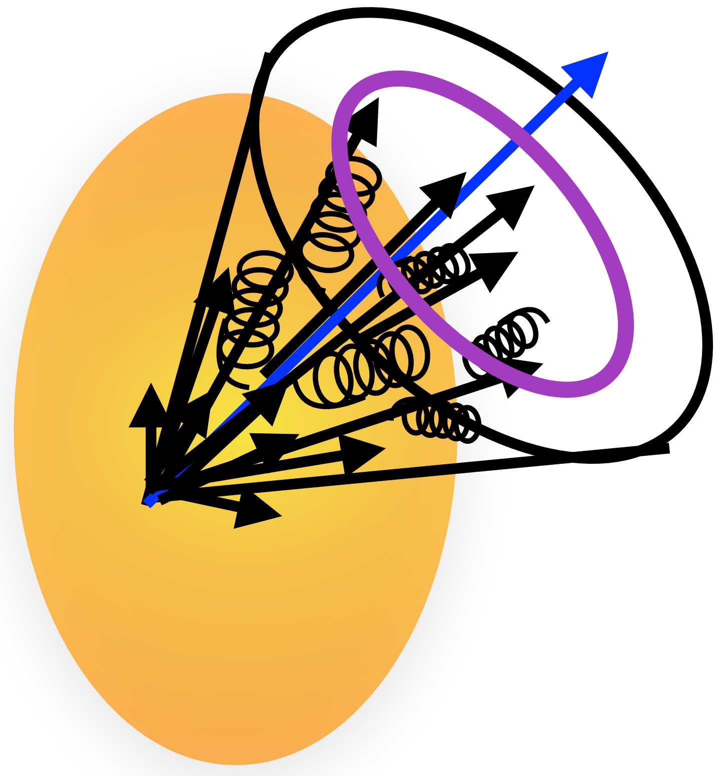
- *See narrowing effect unaffected by soft contribution*

Summary of HI measurements

1. Narrowing of hard core observed for pQCD sensitive observables



2. Softening and broadening observed for more npQCD sensitive observables



3. Some observables show a cancellation of effects

All observables have a “survivor bias” where we are looking at less quenched, more perturbative jets

Are in-medium splittings groomed away?

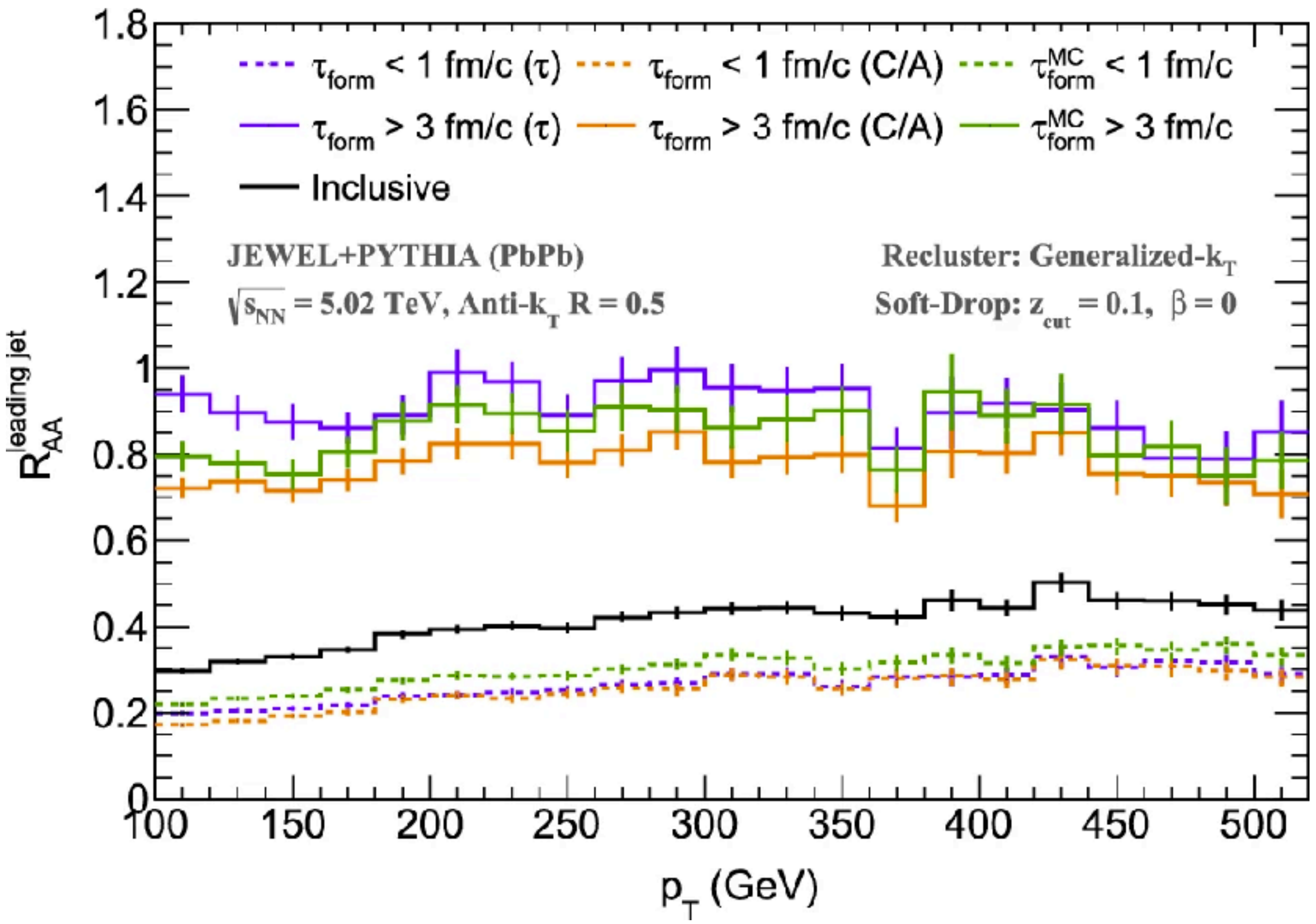
Whats next? need observables that are sensitive to both np and pQCD effects BUT have a clear separation of scales

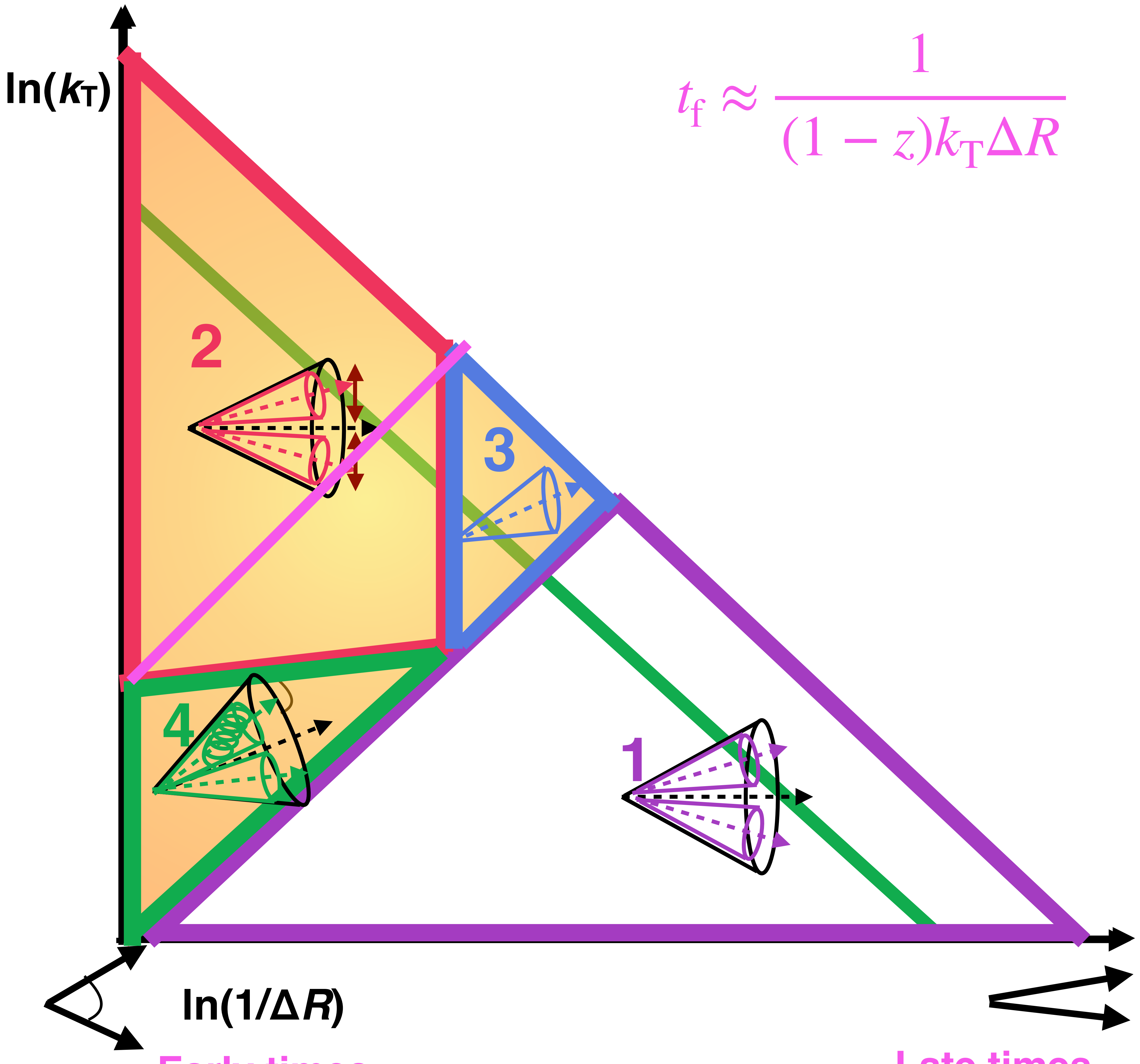
Accessing formation time in HIs

Apolinario et al *EPJC* **81**, 561 (2021)

Instead of C/A (p=0) reclustering,
use τ algorithm (p= 0.5)

$$d_{ij} \approx p_{Ti}\theta^2 \sim \frac{1}{\tau_{form}}$$





$$t_f \approx \frac{1}{(1-z)k_T\Delta R}$$

Directly access time-ordered information may better separate medium interactions

Energy correlators: new HI observable?

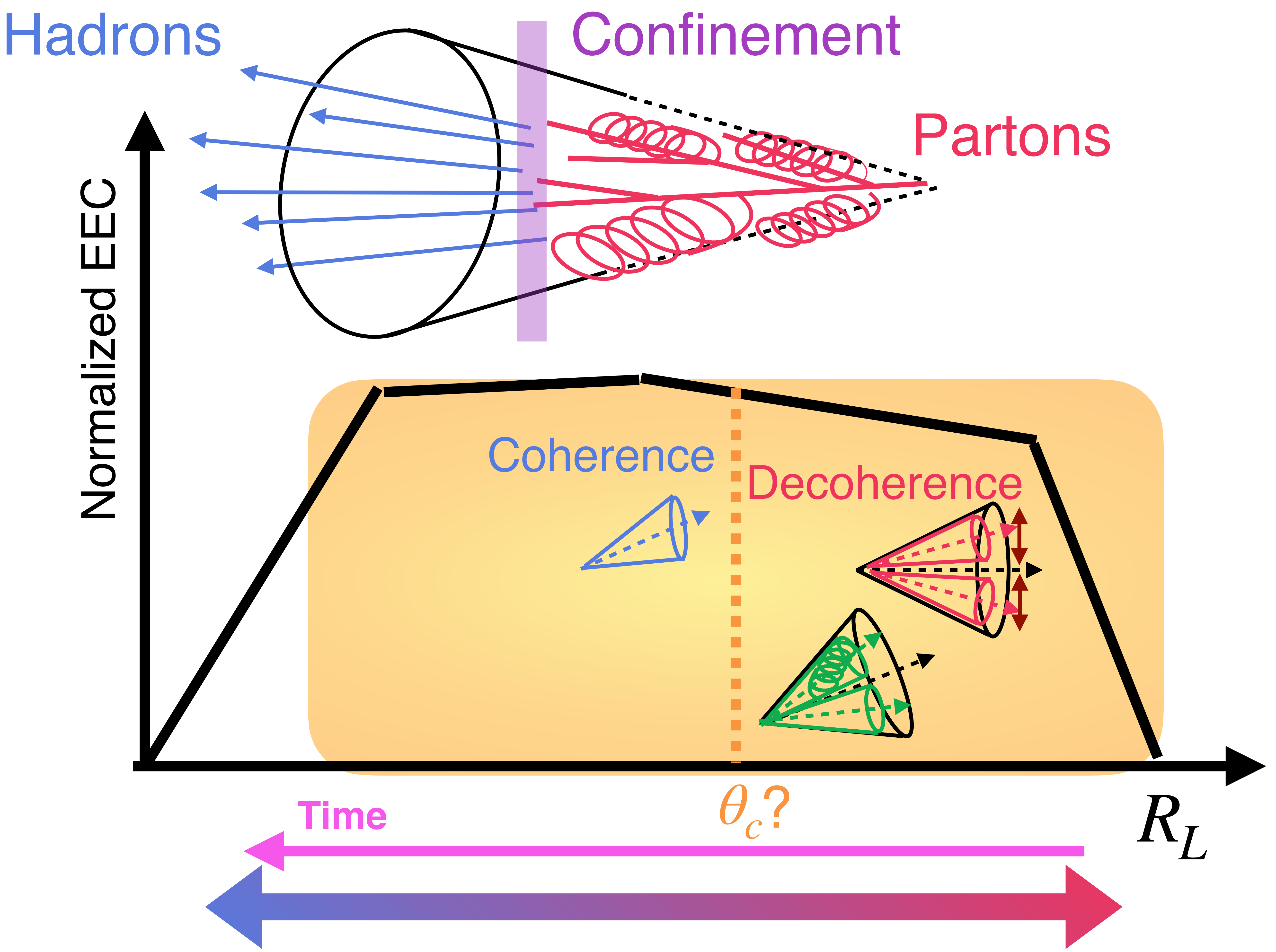
Clear distinction between perturbative and npQCD regions

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?



Conclusion/Outlook

- Vast array of results in pp and HIs that access both npQCD and pQCD
  - Only scratched the surface: see recent BOOST conference for more!
  - Many observables for HF jets as well, dedicated HF day tomorrow!
  - Open questions to understand and constrain models in pp and HI
- Future: Complementary, parallel programs at RHIC and LHC will access uncharted regions of the QCD phase space

Brookhaven National Laboratory

sPHENIX turns on!
STAR upgrades

sPHENIX

STAR

EIC: precision QCD measurements in a cleaner environment

Today

2023———2025

2022——————— 2025

2030s

Time

CERN

LHC Run 3 started!
pp and HI data

HL-LHC: continued HI and QCD program, ALICE3 and other detector upgrades

Thank you!

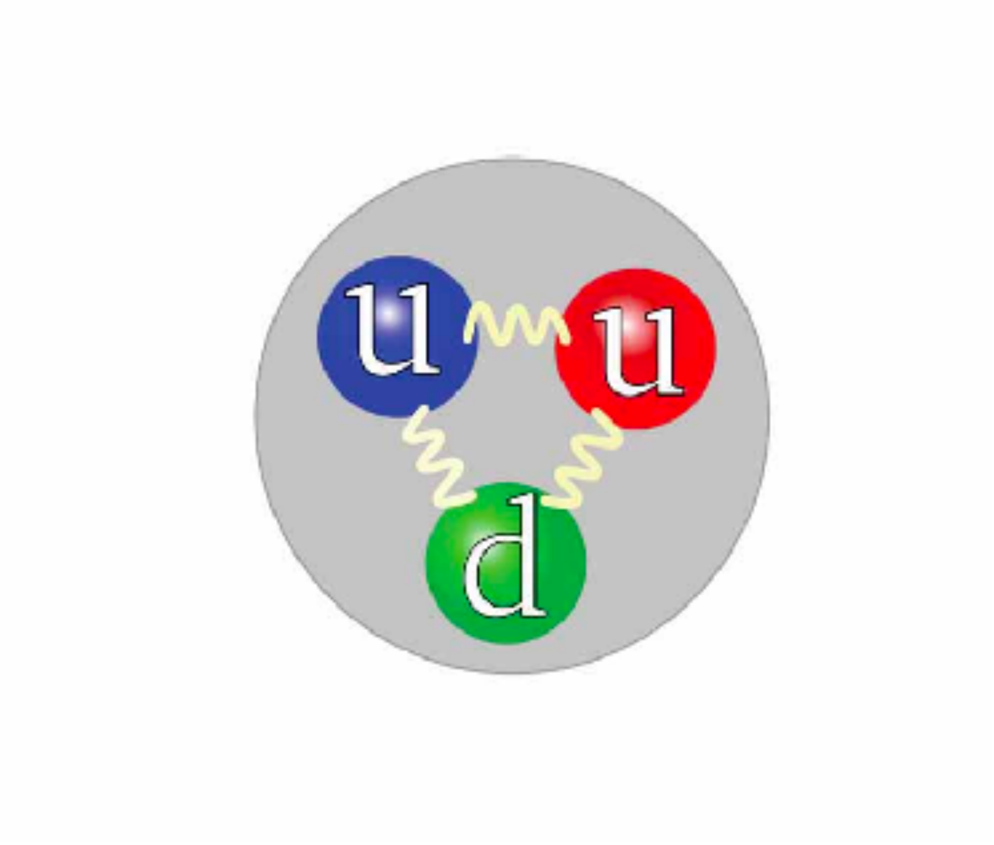
Backup

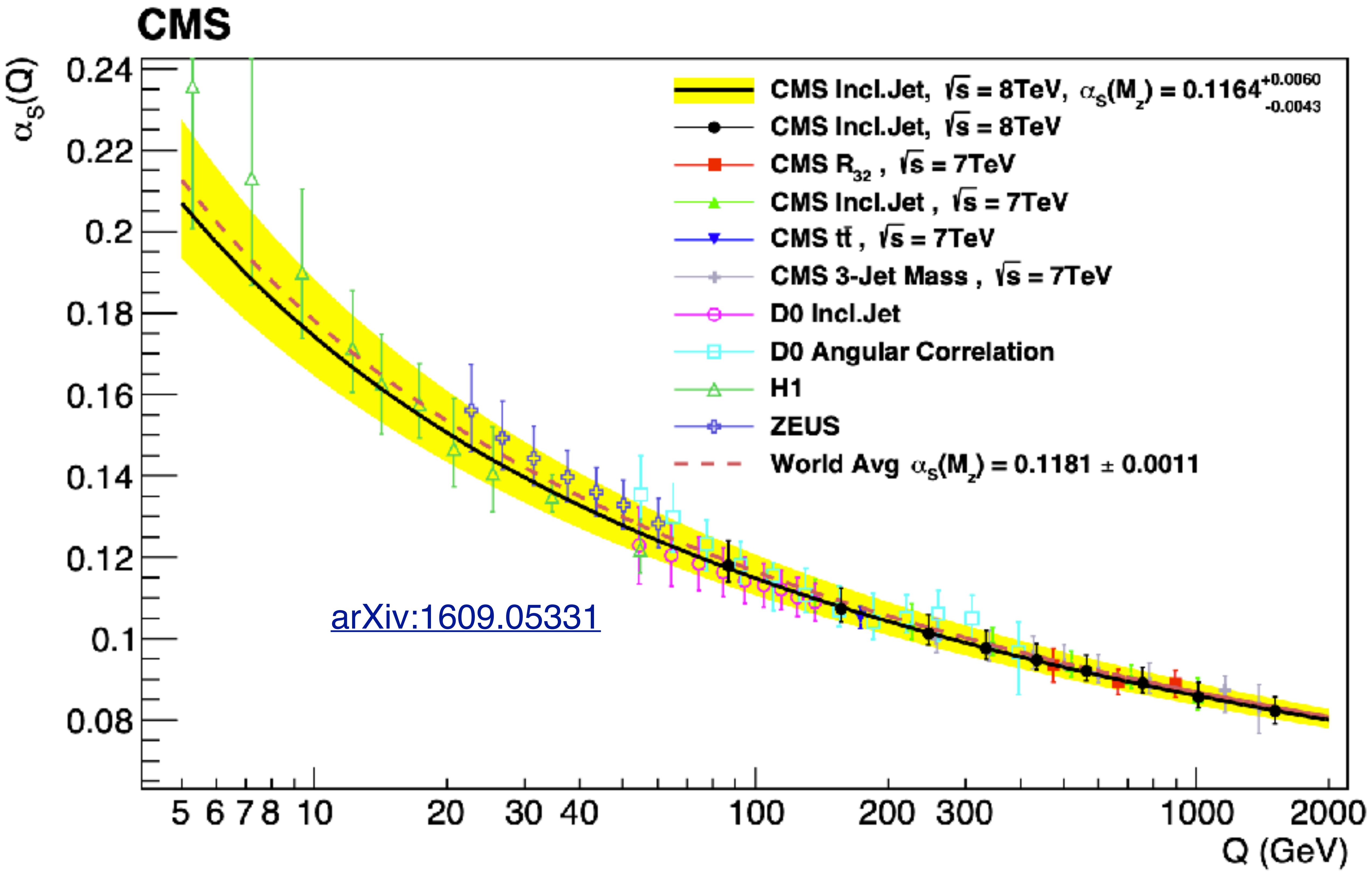
Perturbative and non-perturbative QCD

- Quantum Chromodynamics (QCD): theory of the *strong* interaction

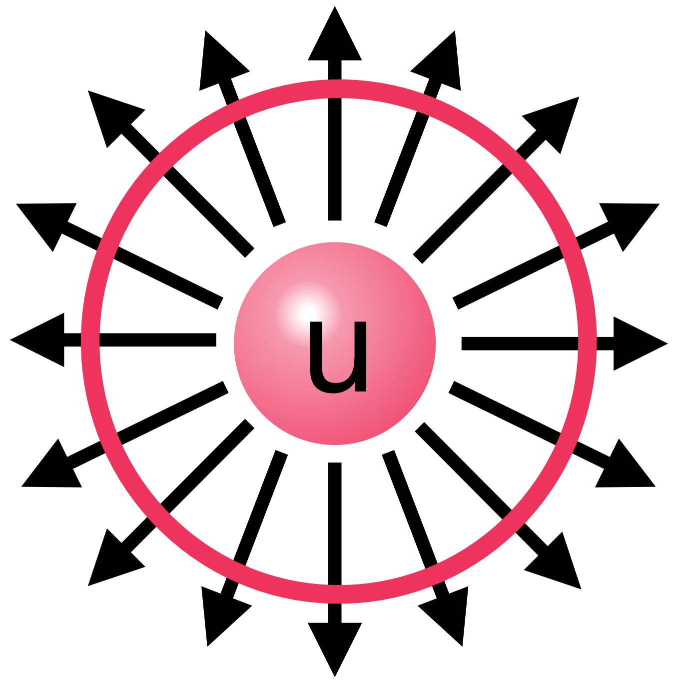
Quarks and gluons typically *confined*
Non-perturbative QCD (npQCD): low energies

Asymptotically free (*deconfined*) at high energies!
Perturbative QCD (pQCD)





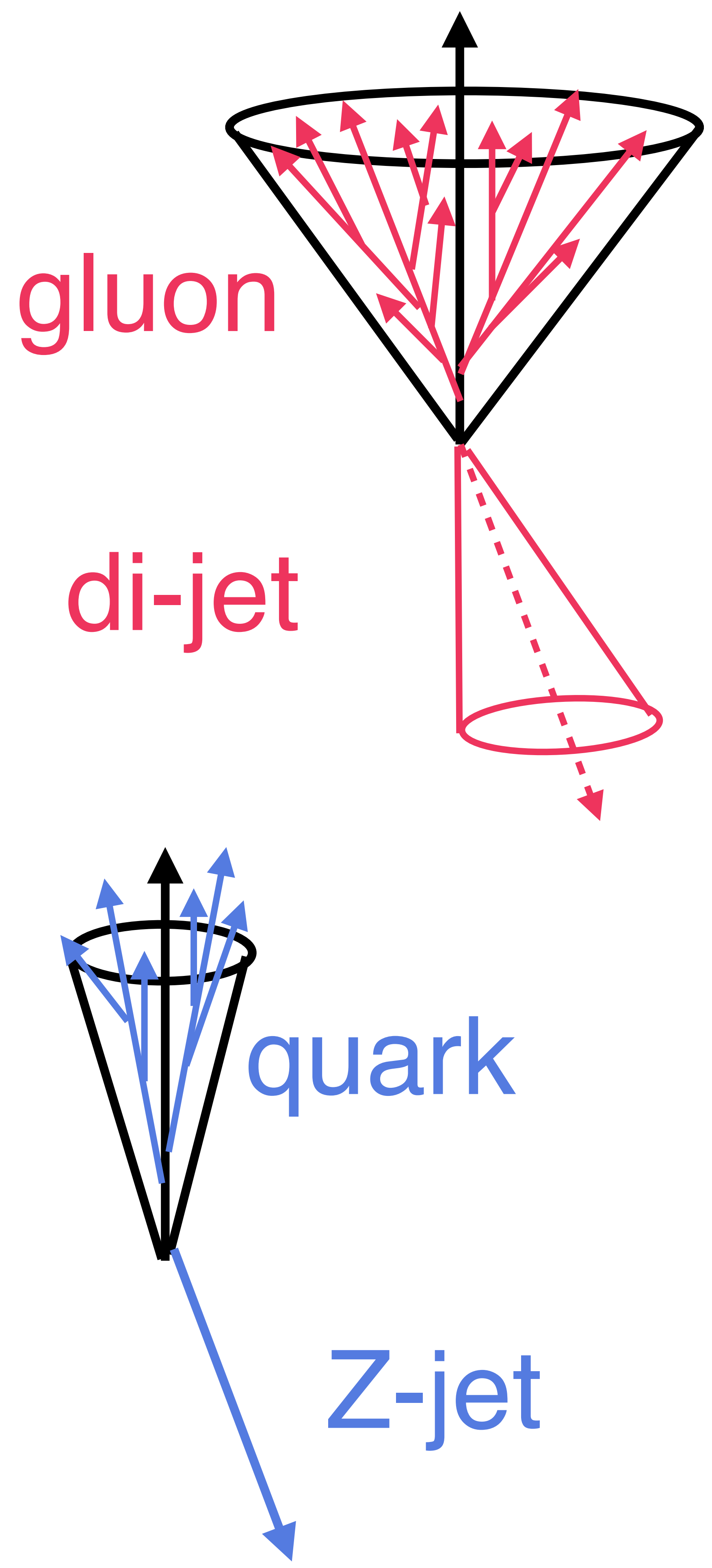
arXiv:1609.05331



Not analytical, needs lattice QCD

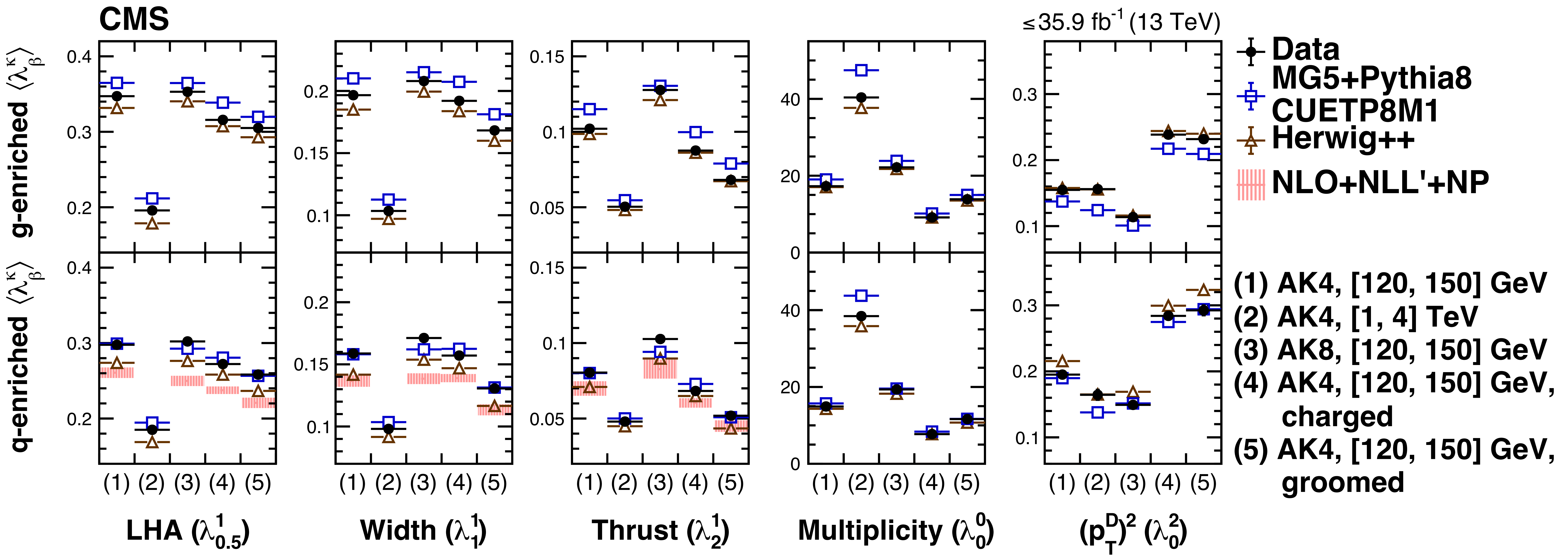
Calculable using perturbation theory

Generalize angularities: q/g seperation



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

CMS JHEP 01 (2022) 188



Exposes regions where models are more and less constrained

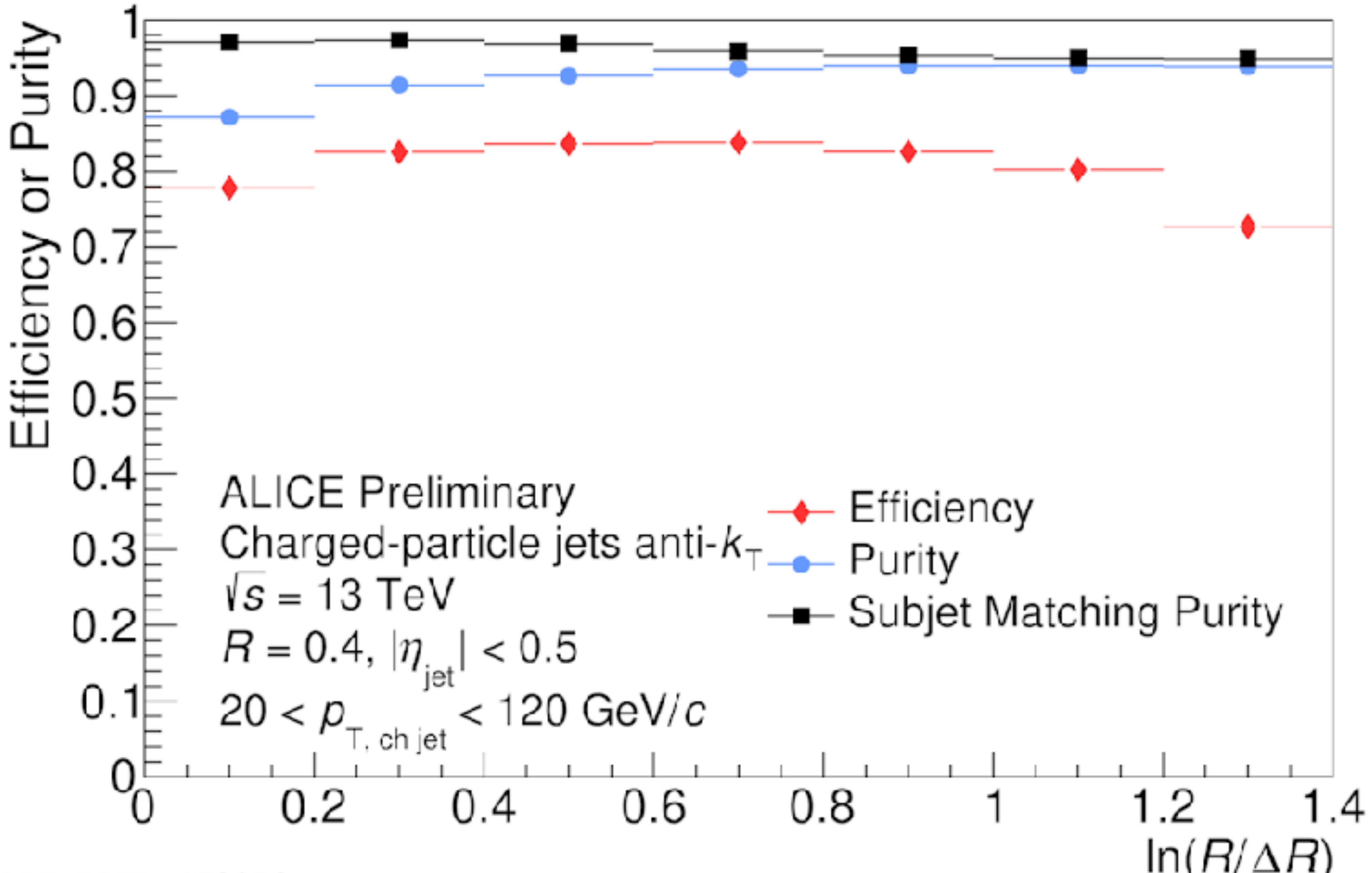
Analysis procedure

- Calculate the efficiency and purity:

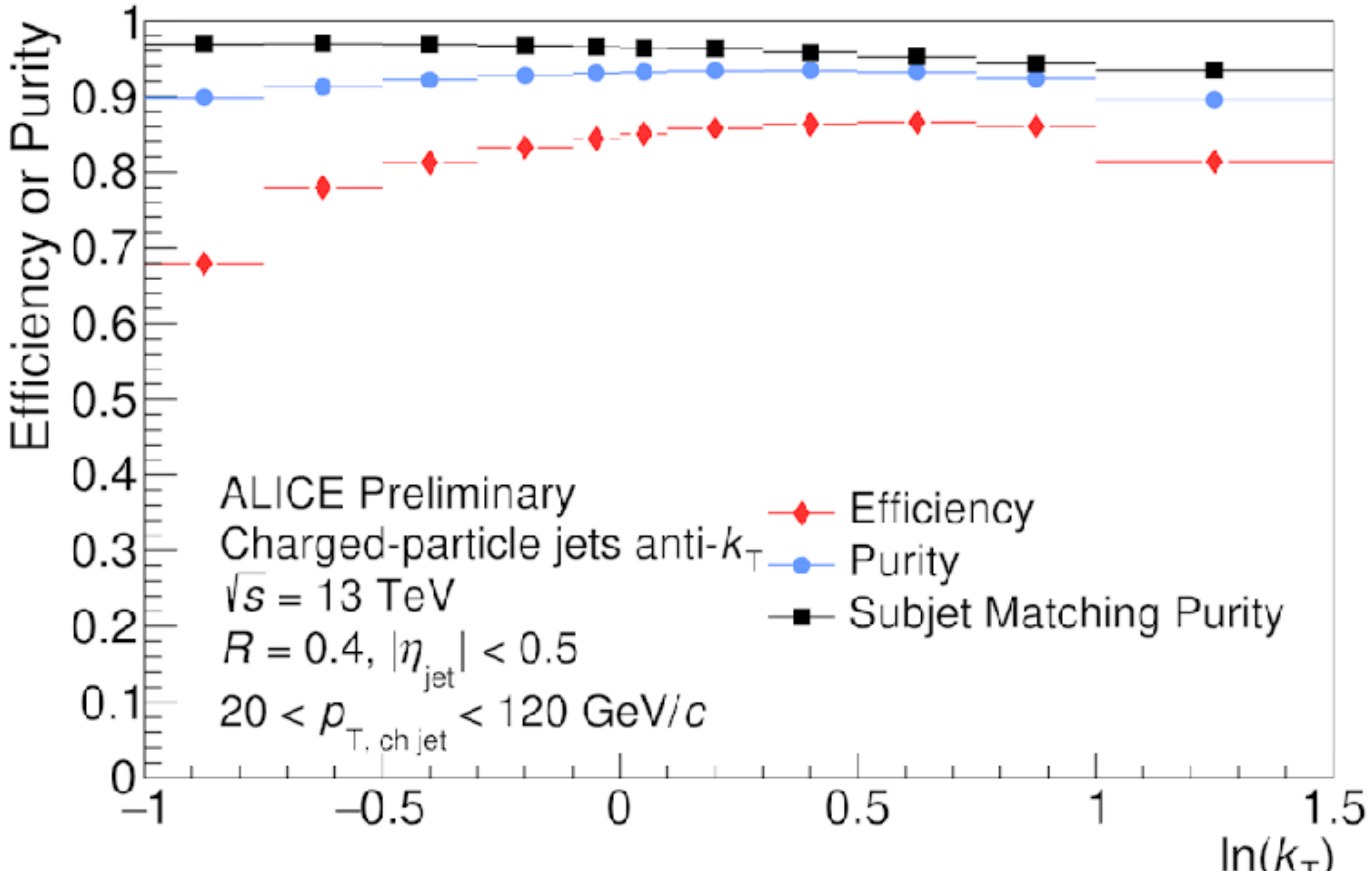
$$e = \frac{N_{\mathrm{true}}^{\mathrm{match}}}{N_{\mathrm{true}}} \qquad p = \frac{N_{\mathrm{reco}}^{\mathrm{match}}}{N_{\mathrm{reco}}}$$

- Correct the raw data for the purity $N_{\mathrm{raw,corr}} = p * N_{\mathrm{raw}}$
- Unfold using response and correct unfolded result for the efficiency $N_{\mathrm{tot}} = (1/e) * N_{\mathrm{unf}}$
- Normalize with 1D unfolded spectra
- Subjet matching purity: did the true splittings end up in the correct reconstructed splittings?

Subjet matching purity is very high!



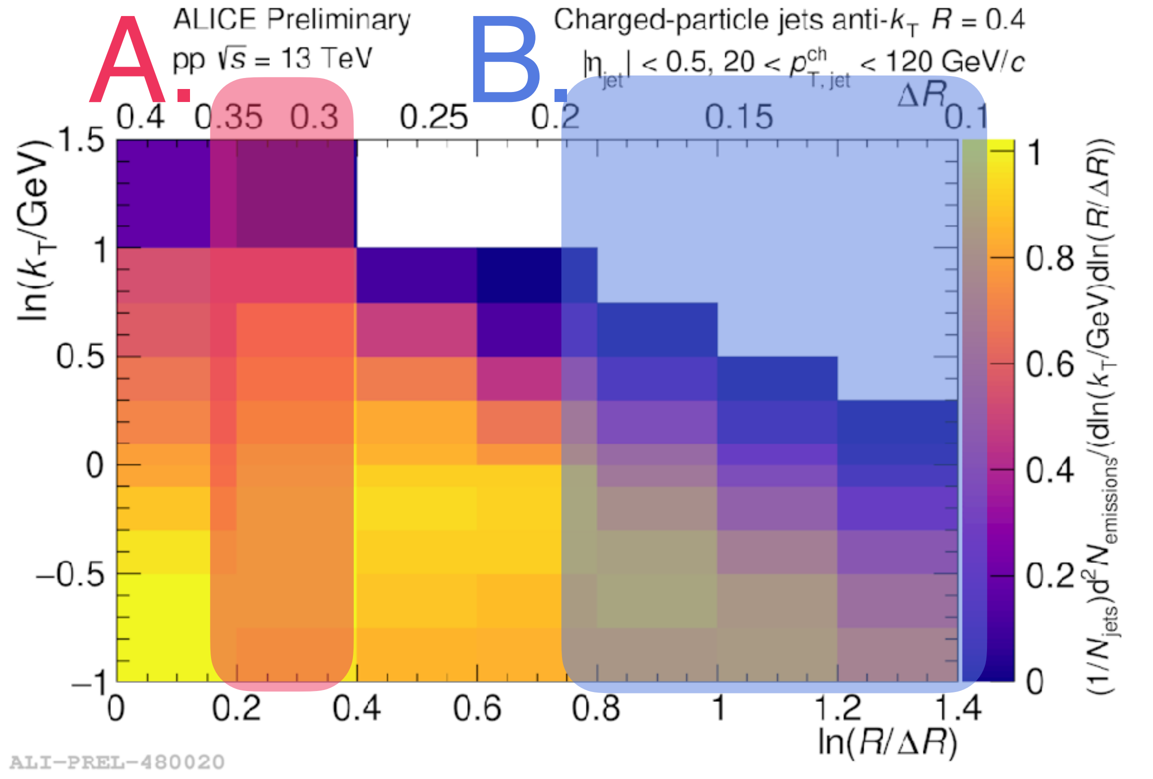
ALI-PREL-479059



ALI-PREL-479067

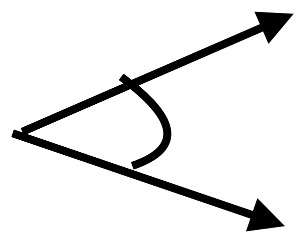
Laura Havener, Yale University

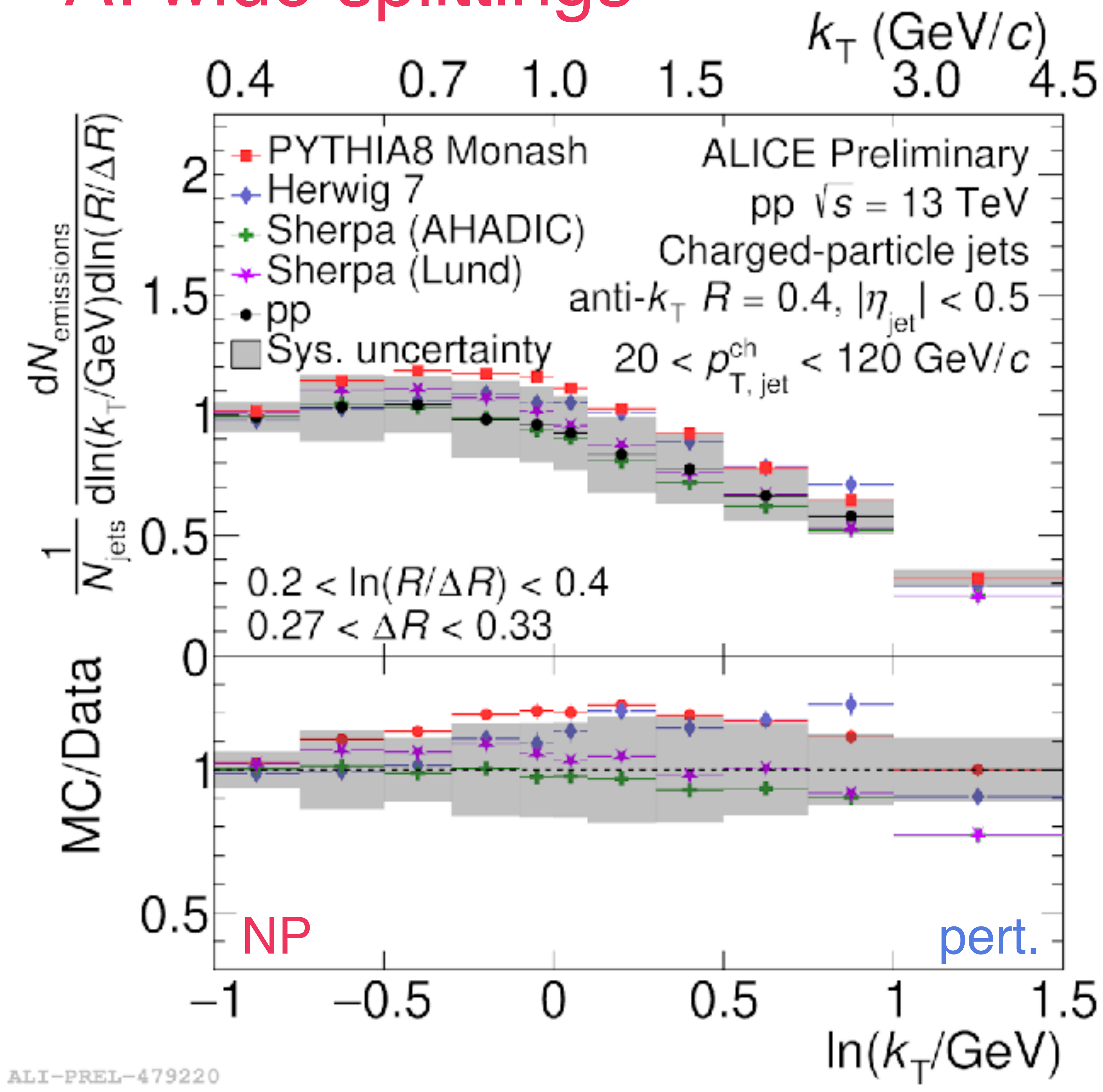
Regions of the Lund plane



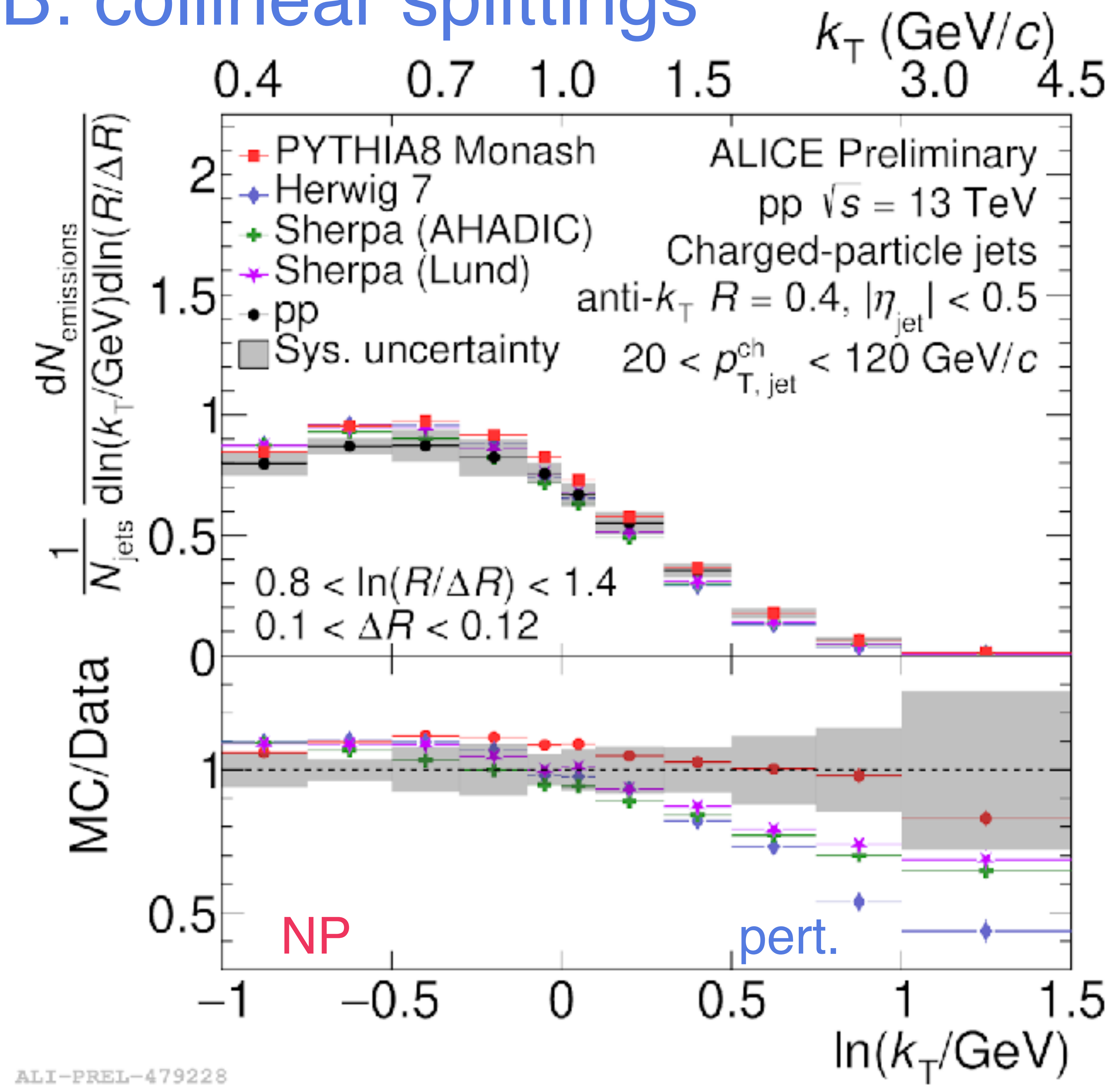
Agreement with MC ~10% in most cases

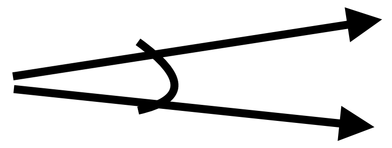
A: wide splittings





B: collinear splittings





Significant suppression of MC compared to data for hard collinear splitting

Laura Havener, Yale University

ATLAS EXPERIMENT

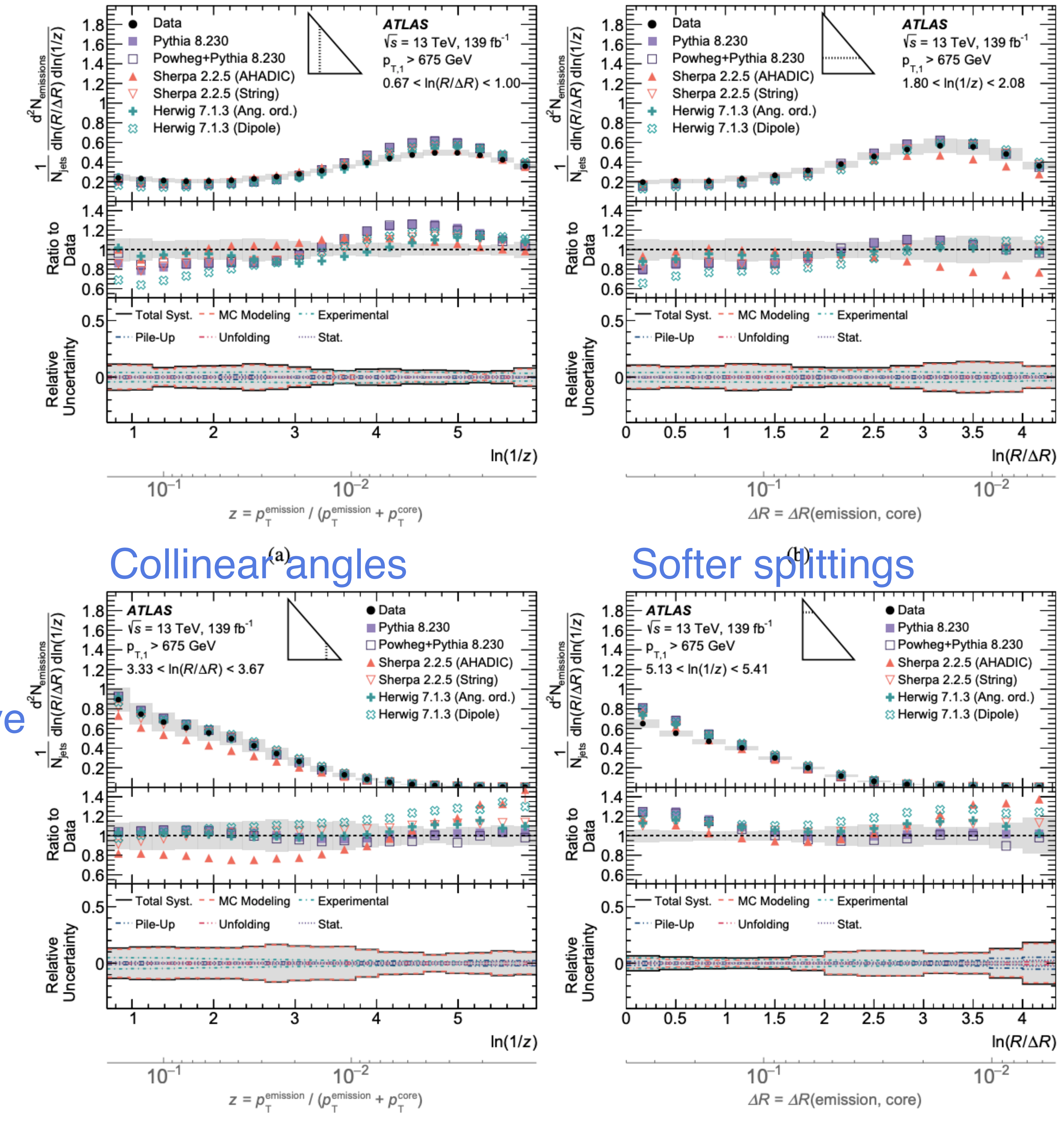
Wider angles

Harder splittings

Non-perturbative

Collinear angles

Softer splittings



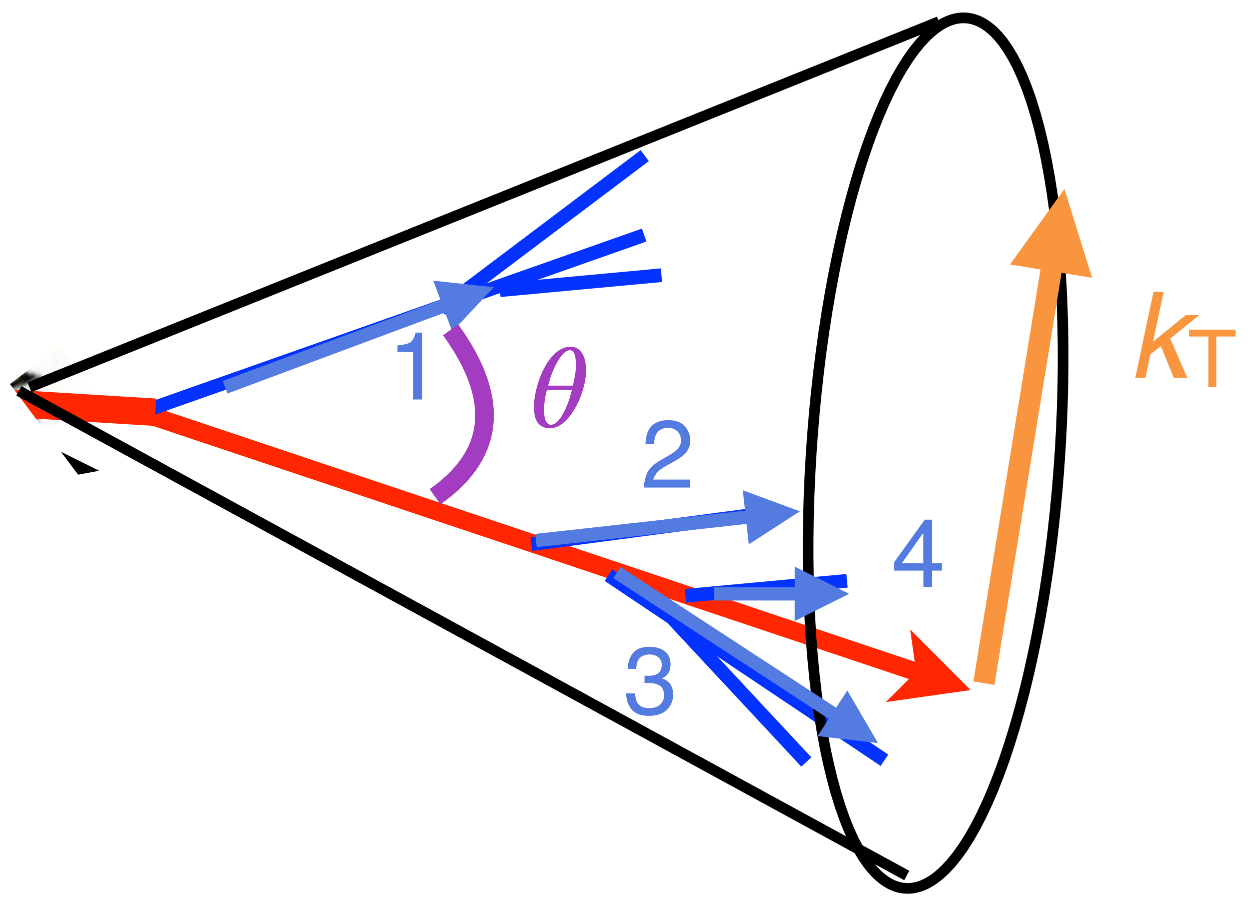
(a) (b) (c) (d)

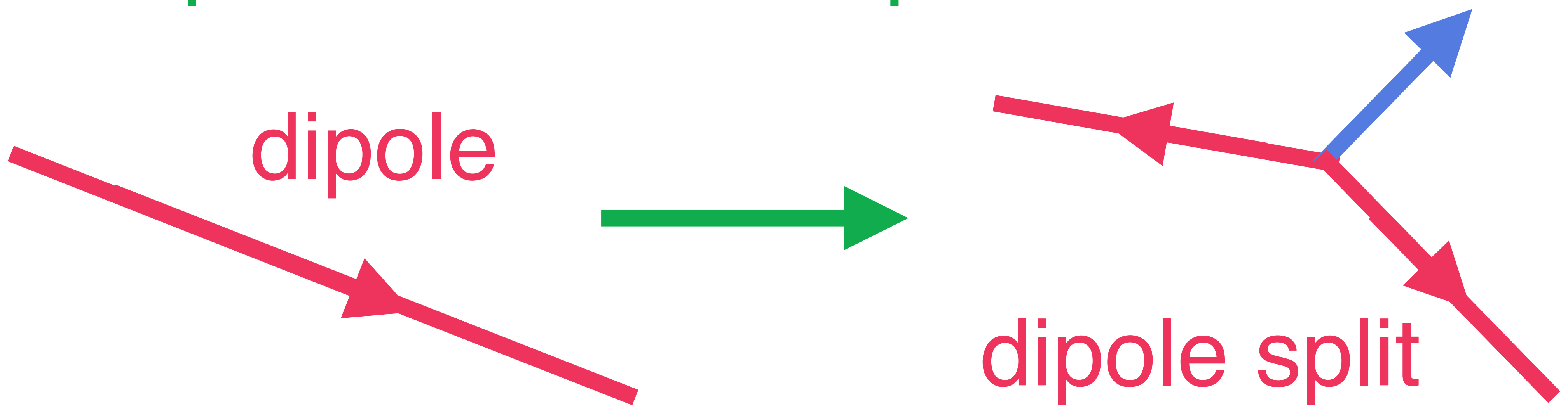
ATLAS PRL 124 (2020) 222002

MC generator comparisons

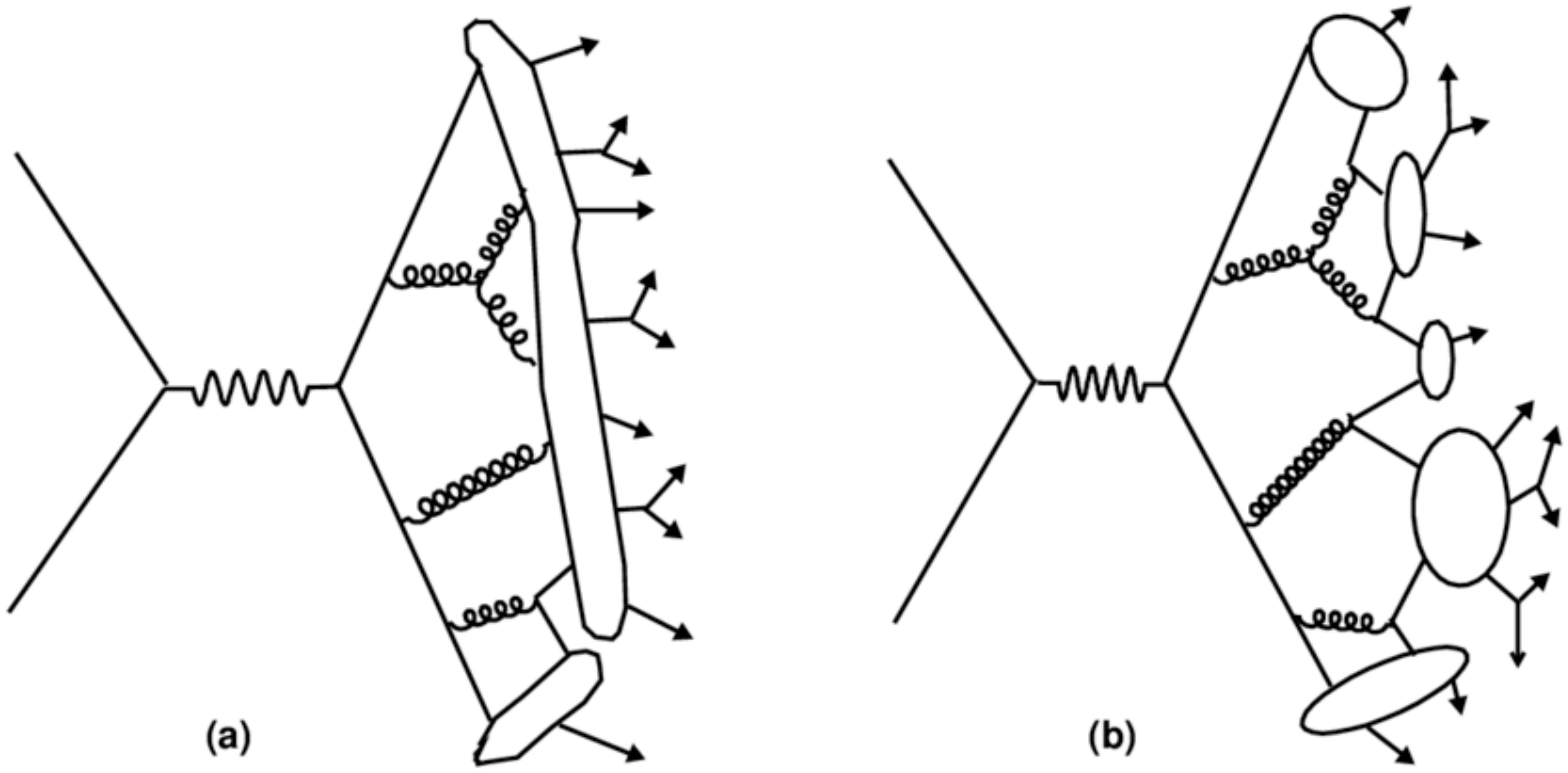
- Different MC generators have different implementations of the parton shower and hadronization

	Parton Shower	
PYTHIA8 Monash *CPC* 178 (2008) 852-867	k_T ordered	$k_{T1} > k_{T2} > k_{T3} > k_{T4}$
Herwig 7 *EPJC* 76 (2016) 4, 196	Angular ordered	$\theta_1 > \theta_2 > \theta_3 > \theta_4$
Sherpa (AHADIC) *JHEP* 02 (2009) 007	Dipole shower	1 parton -> 2 vs. 2 partons -> 3
Sherpa (Lund)	Dipole shower	





Hadronization models



Lund string: long distance limit of npQCD where partons are connected by QCD flux tubes, or strings (lattice QCD)

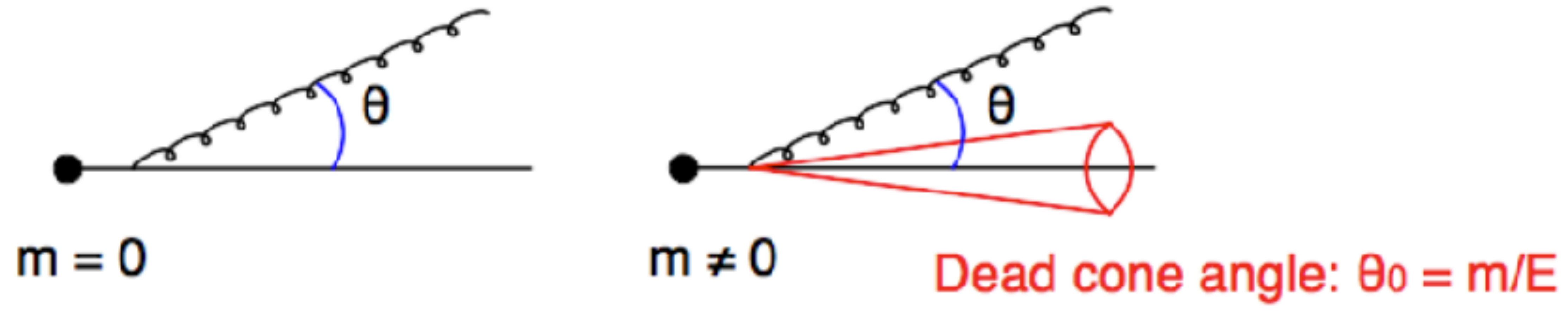
Cluster: perturbative limit where partons that are at energies above hadronization scale are grouped together like in a parton shower in color-neural clusters (pre-confinement)

Heavy-flavor jet tagged Lund plane

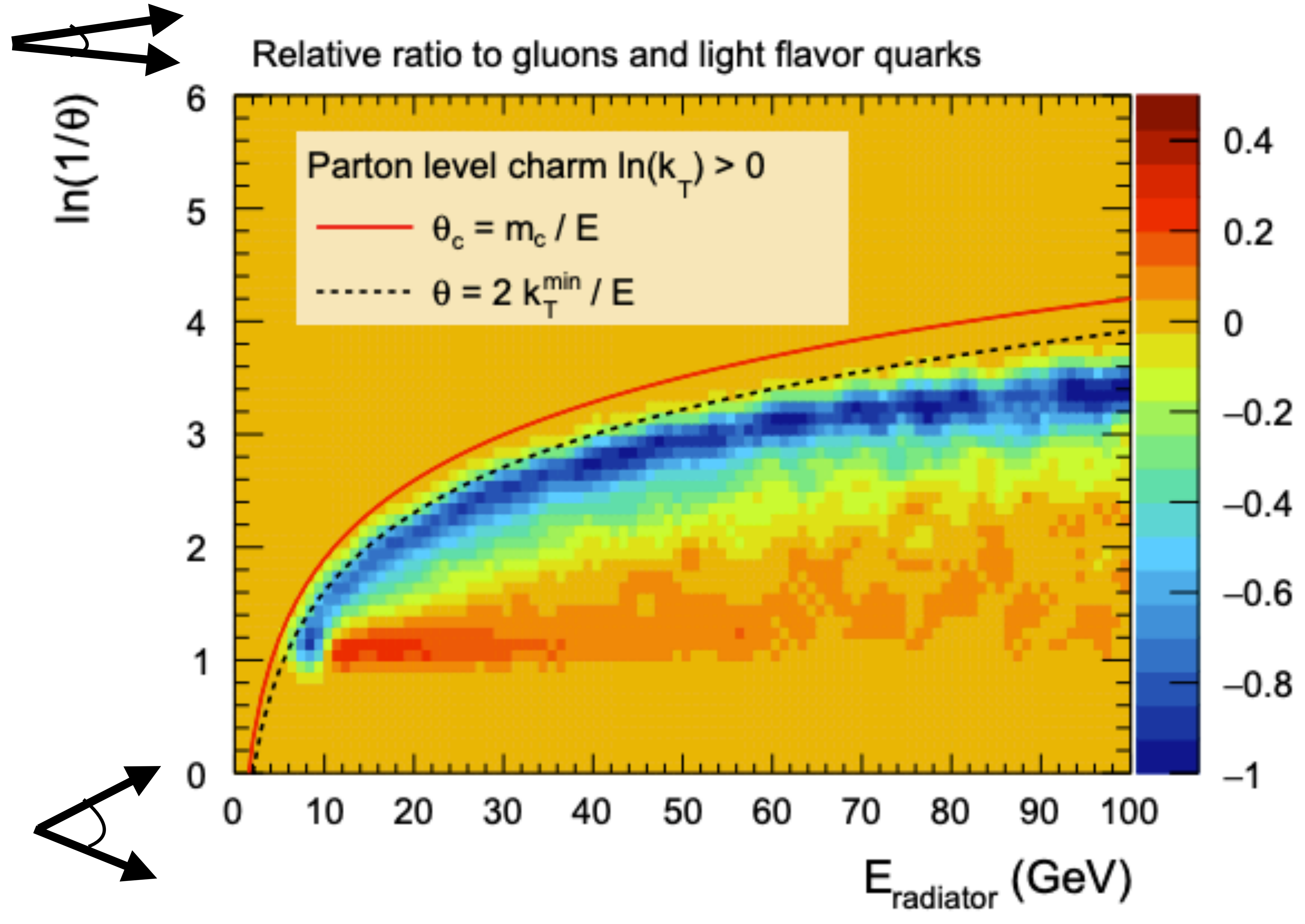
- Lund plane for D⁰-tagged (charm) jets compared to inclusive jets

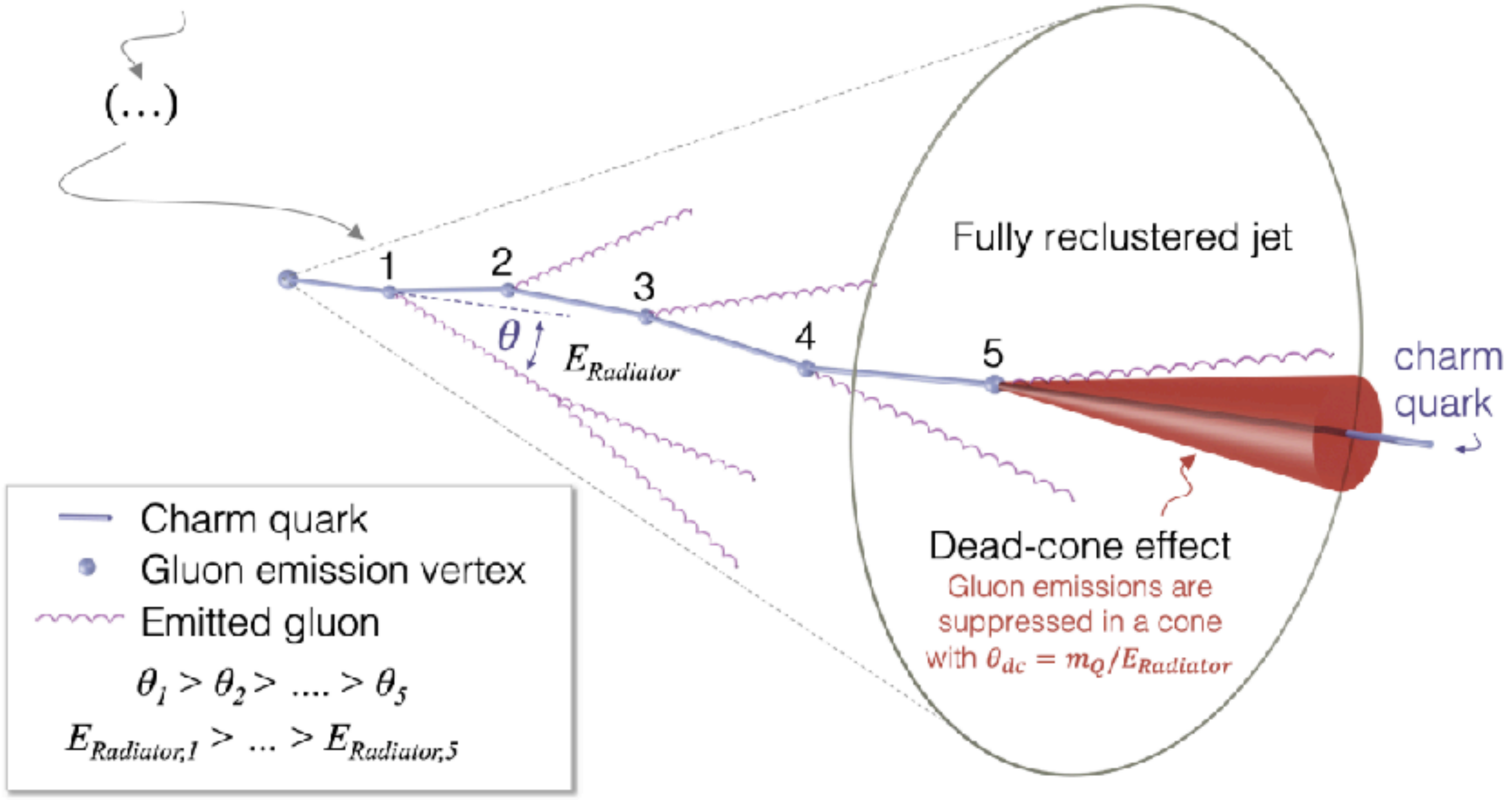
- Dead cone effect: suppression of emissions from a radiator (quark) with,

$$\theta < \frac{m_q}{E_q}$$



Cunqueiro, Ploskon PRD 99, 074027

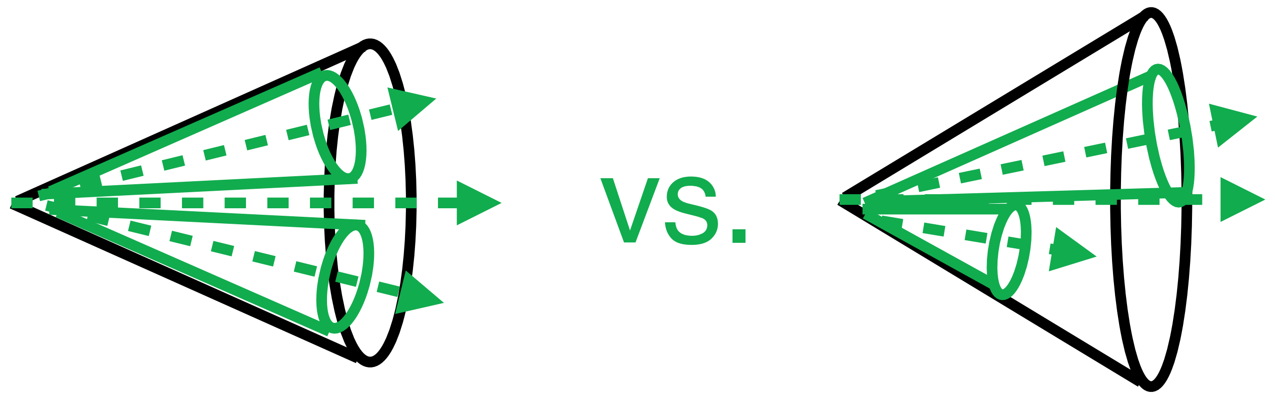




- Expect a suppression at small angles for heavy quarks

SD grooming variables

Modifications to splitting function?

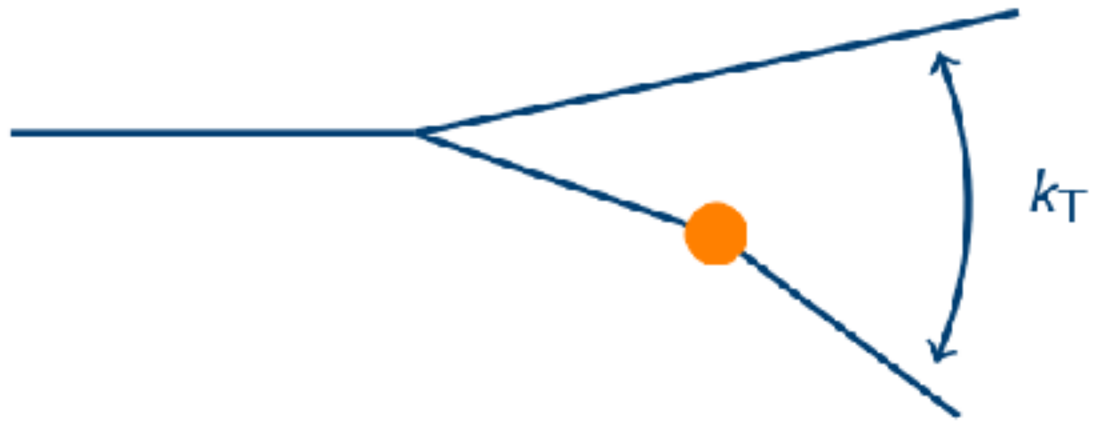


$$z_g = \frac{\min(p_{T1}, p_{T2})}{p_{T1} + p_{T2}}$$

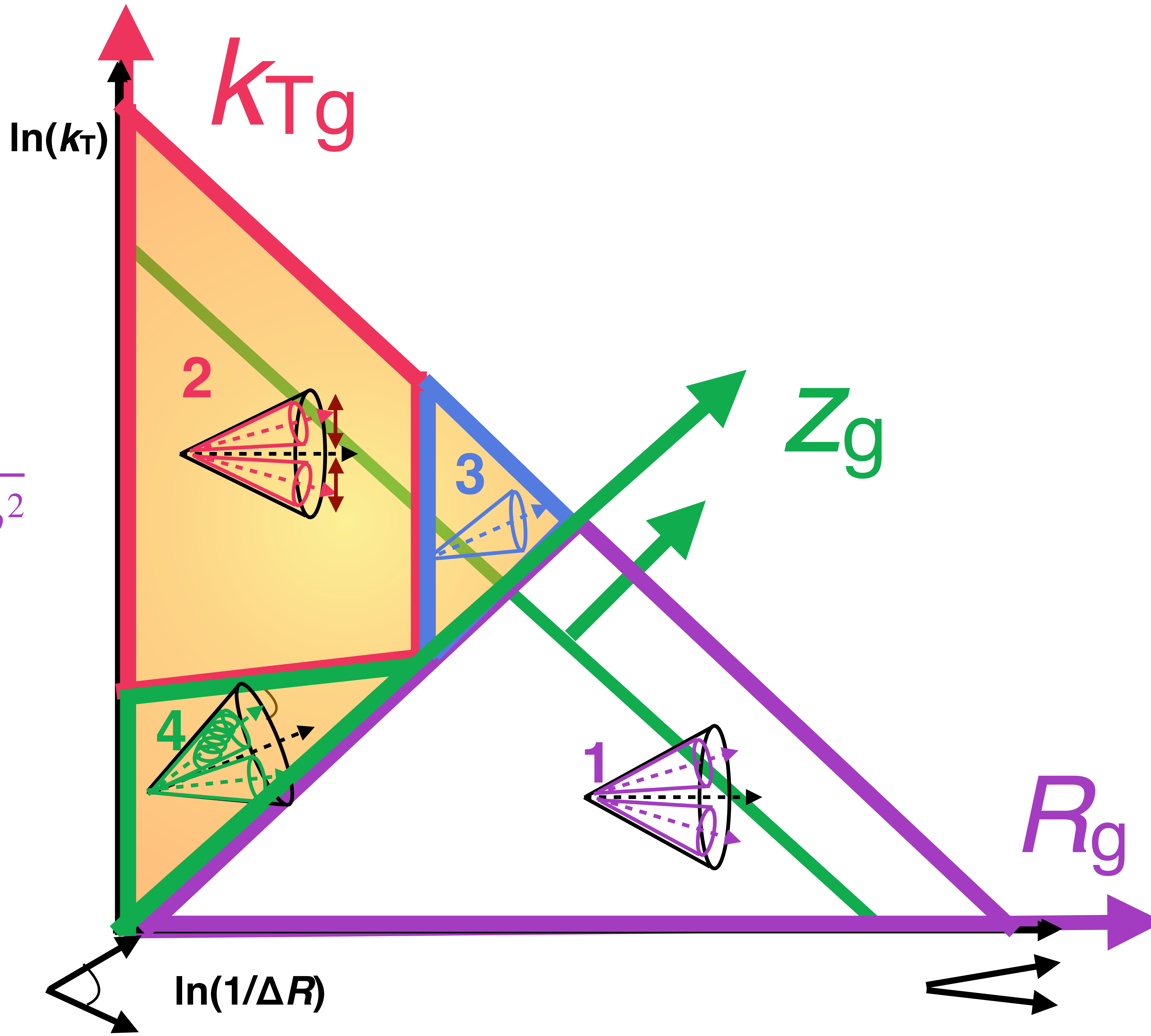
Resolution length of the QGP?

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

In-medium Moliere scattering?



$k_{Tg} \sim z_g p_T R_g$



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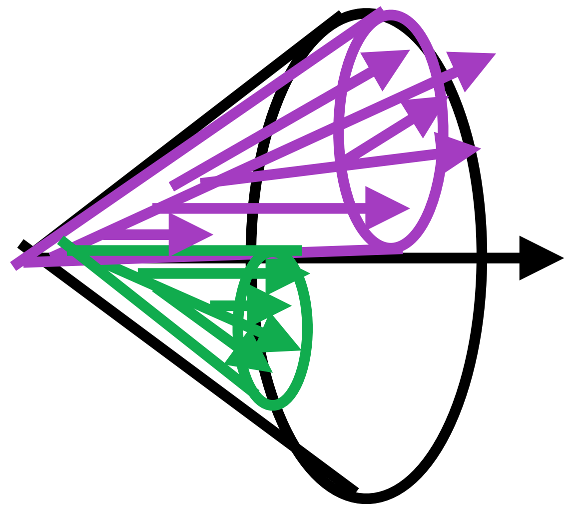
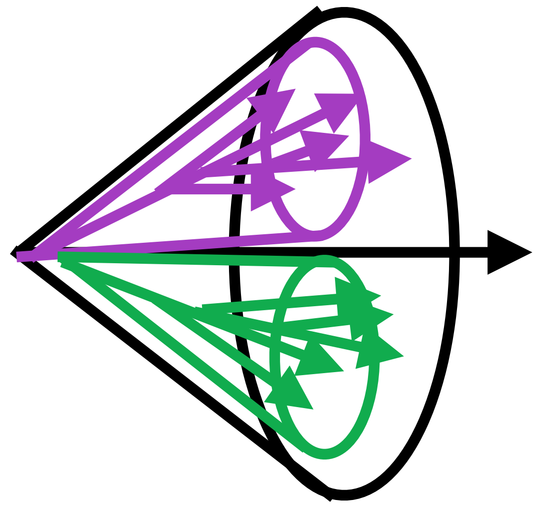
SD grooming: z_g

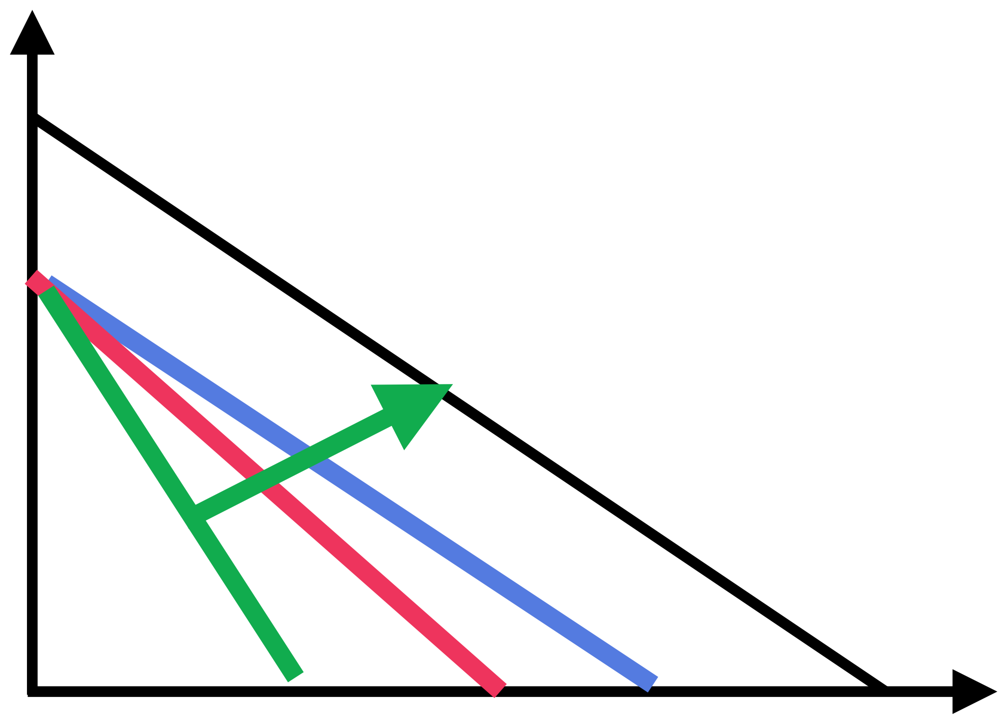


vs.

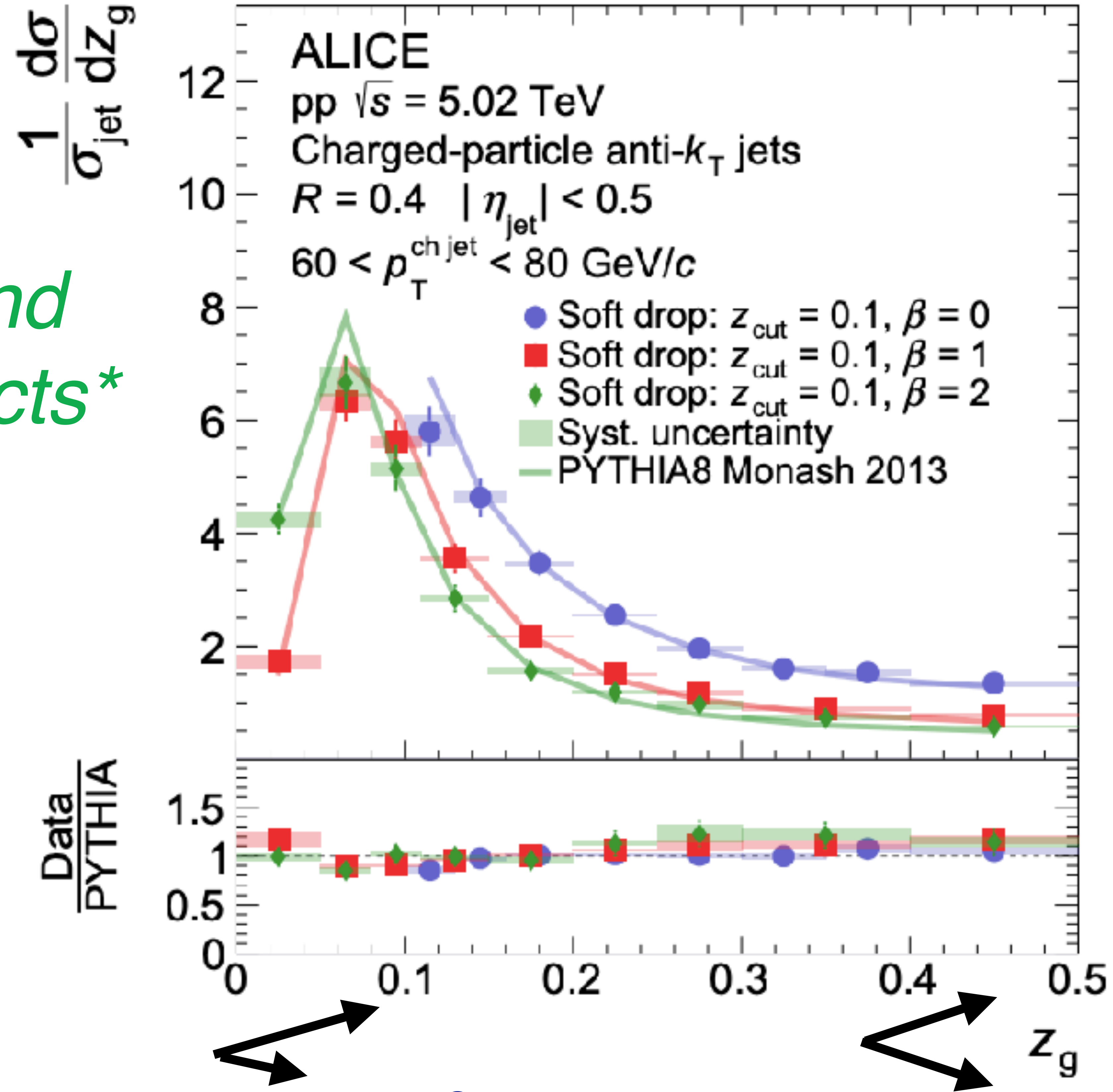


$$z_g = \frac{\min(p_{Ti}, p_{Tj})}{p_{Ti} + p_{Tj}}$$

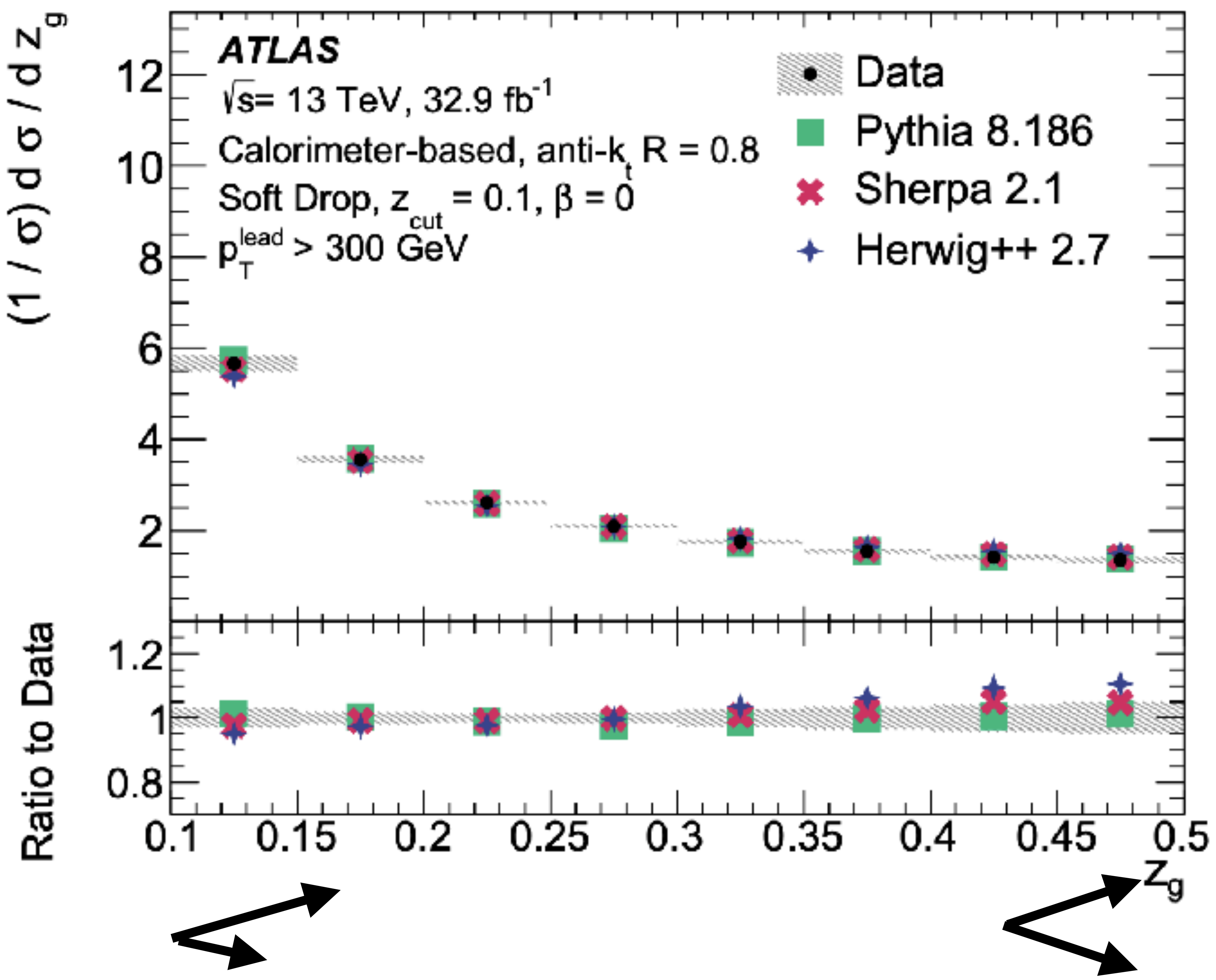
- Dependence on grooming (β) measured:
  - *Useful to constrain pQCD calculations and non-perturbative effects**



[*arXiv:1908.01783v1](#)



[ALICE arXiv:2204.10246](#)



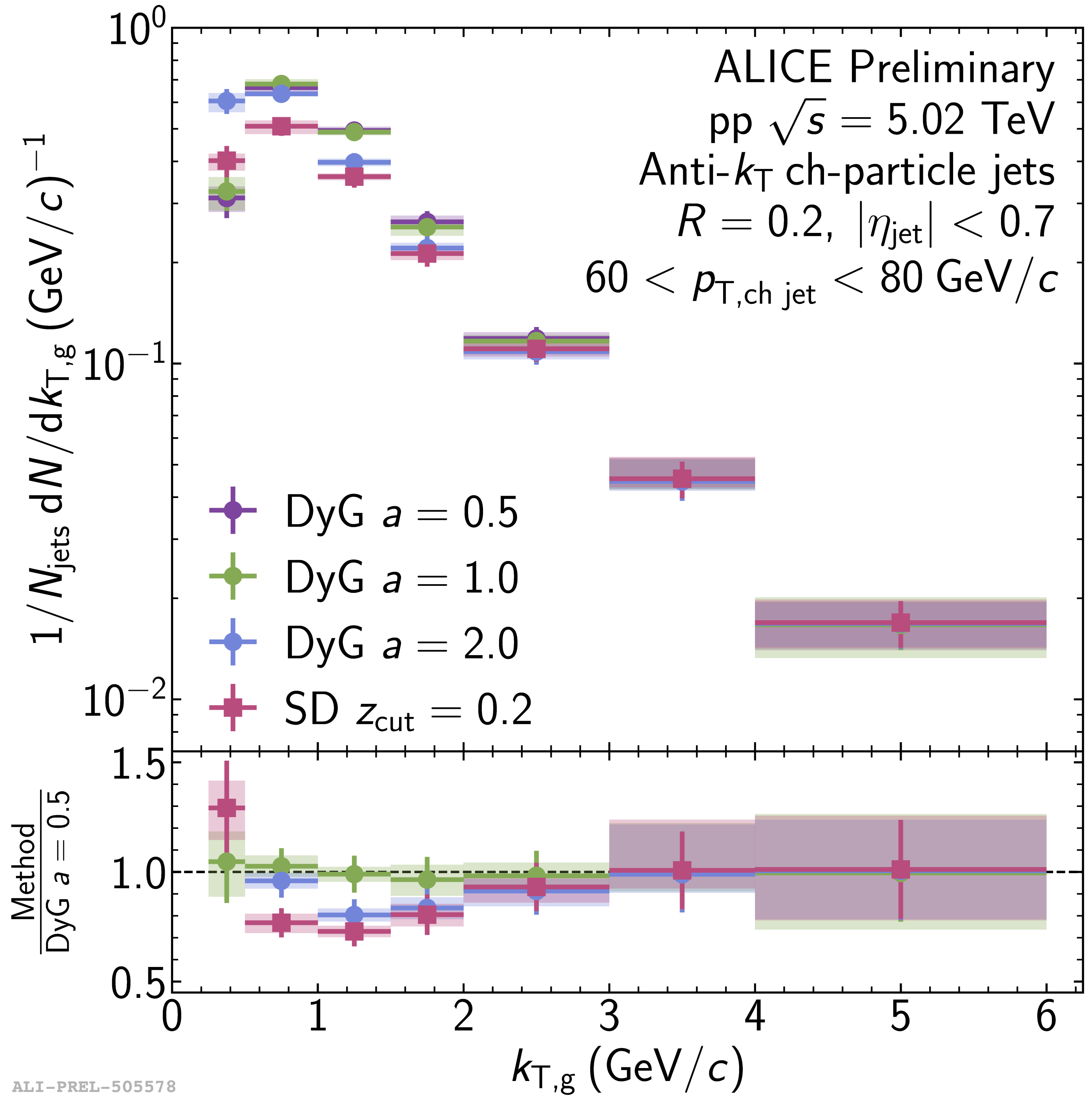
[ATLAS PRD 101, 052007 (2020)](#)

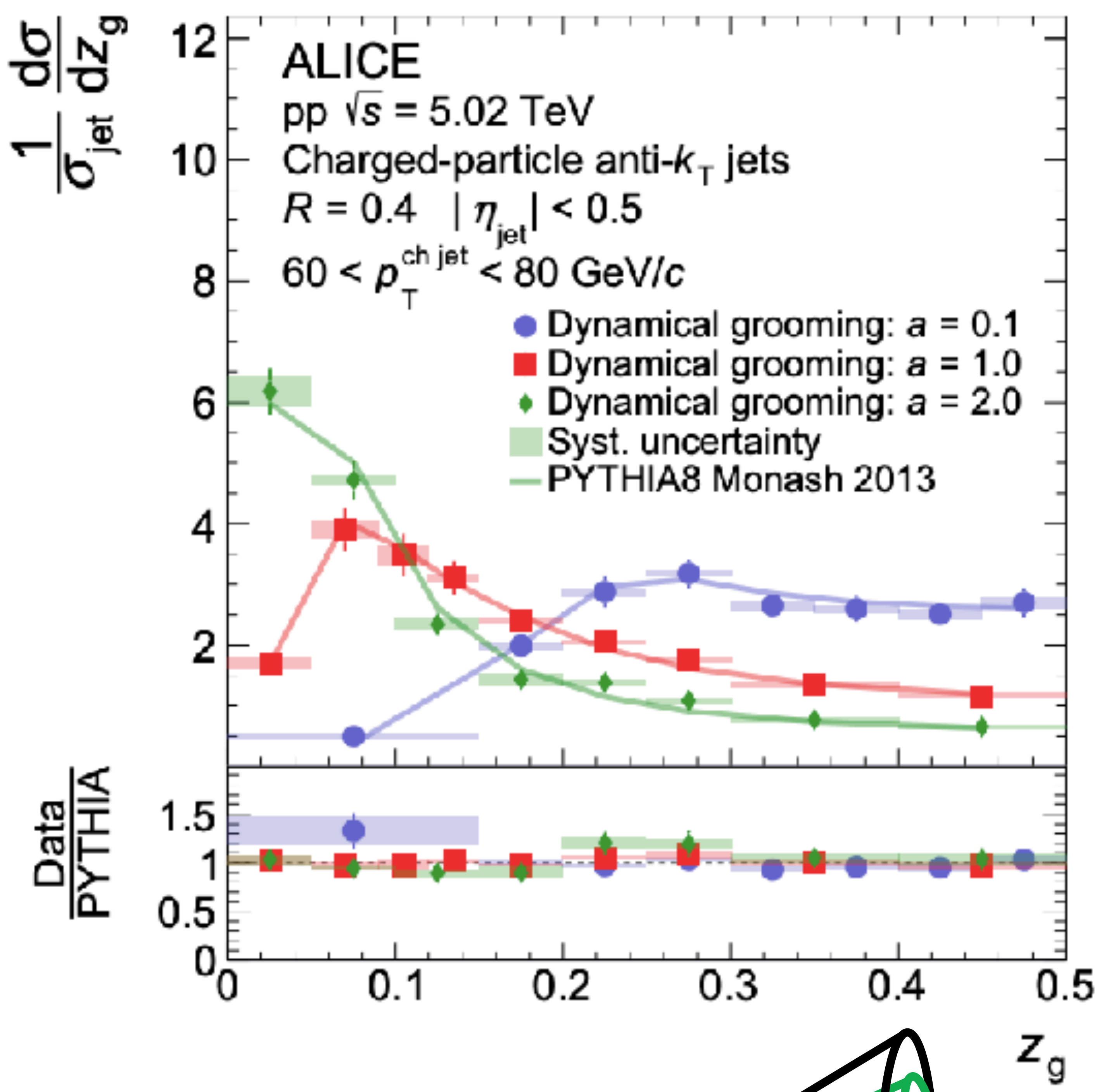
Dynamical grooming

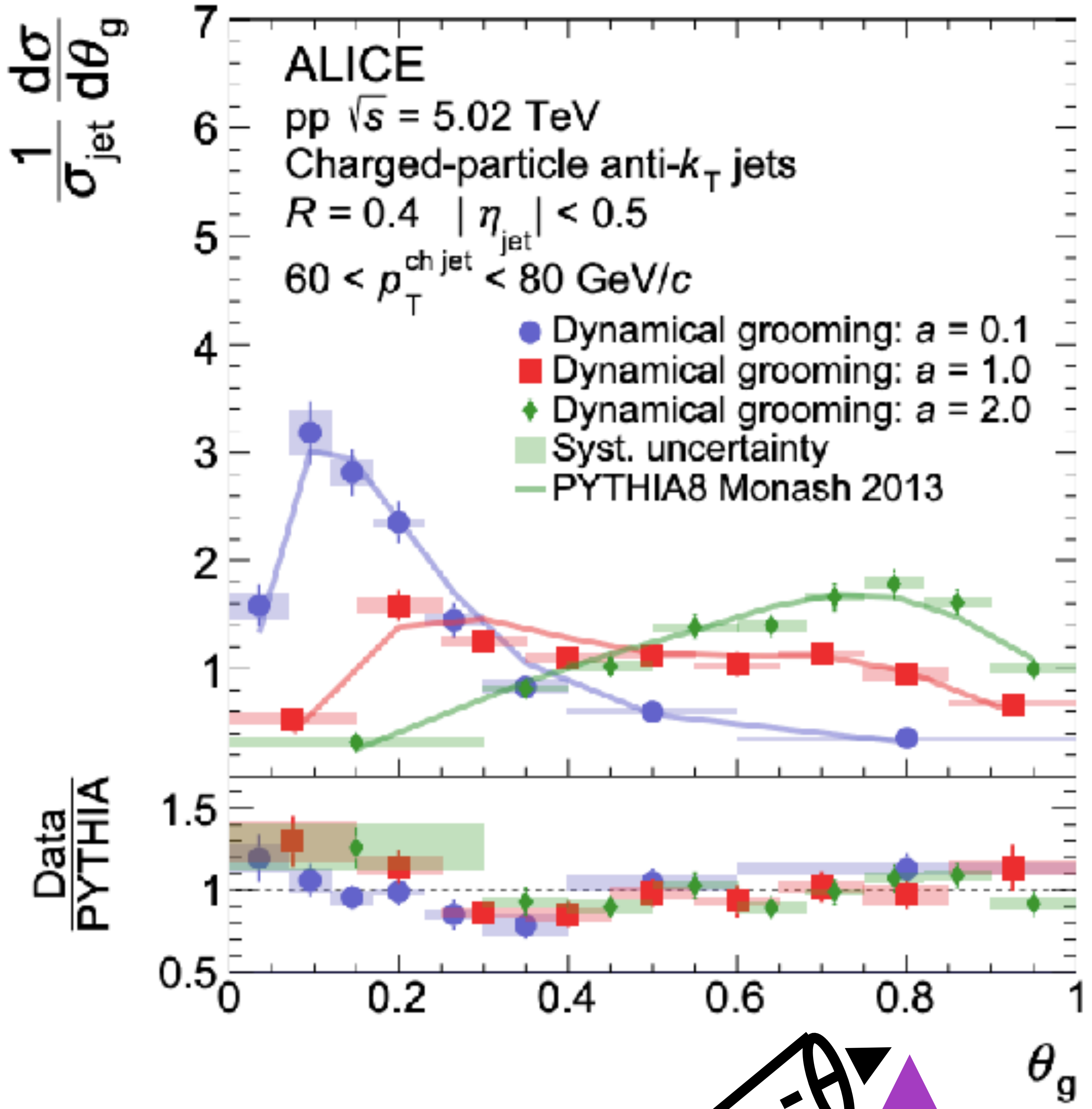
- First measurements using dynamical grooming in pp collisions

a~0: zDrop a=1: k_TDrop a=2: TimeDrop

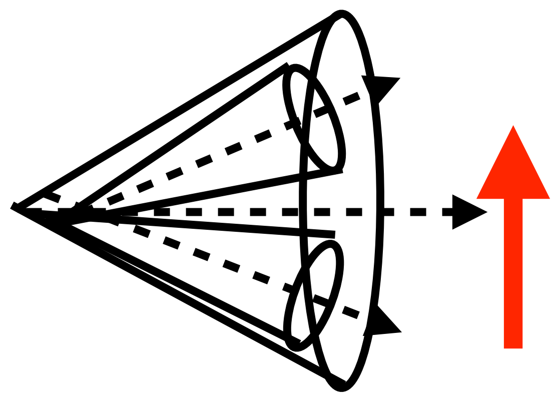
ALICE arXiv:2204.10246

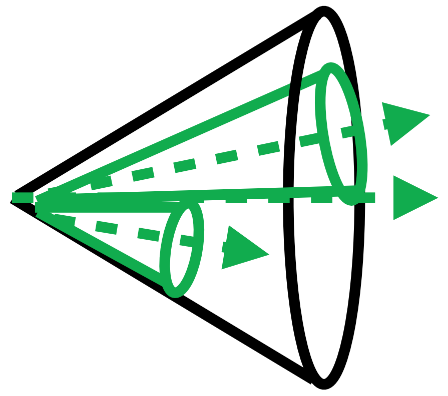


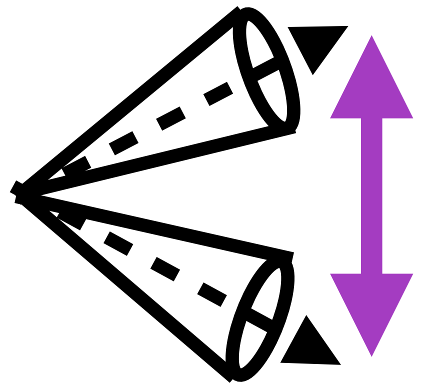




- Grooming methods converge at high k_T







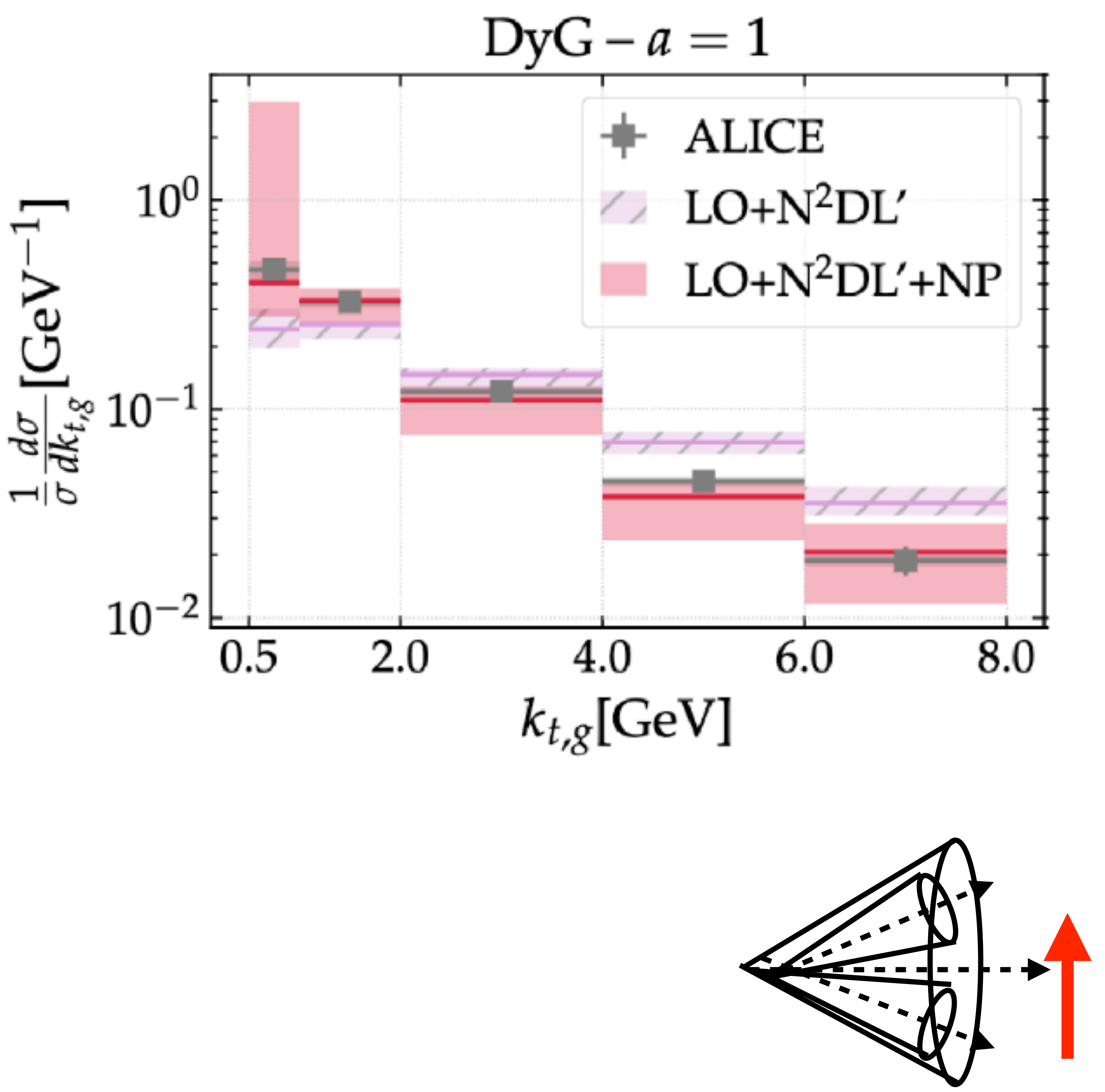
- Data well described by Pythia in pert. region

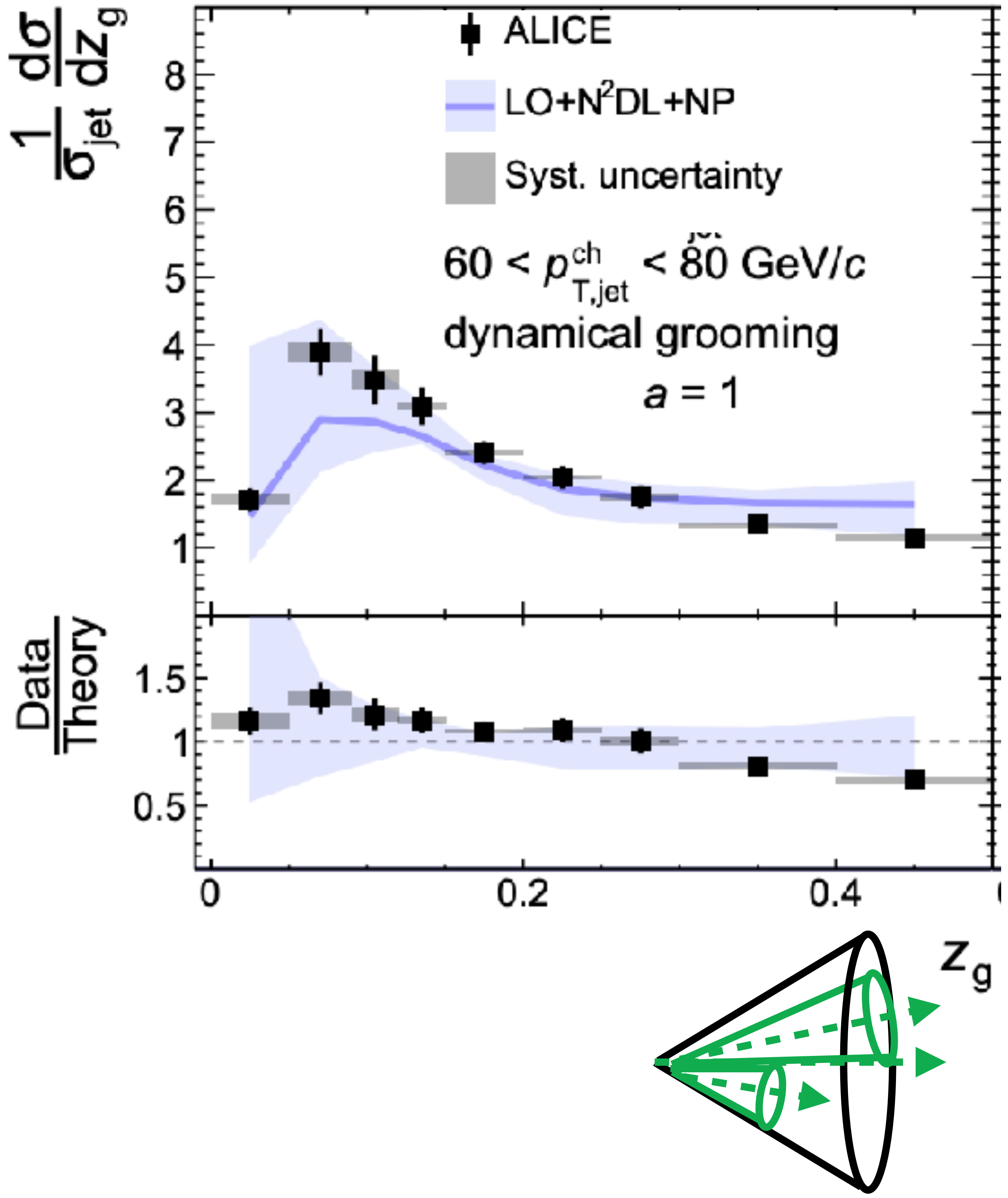
Laura Havener, Yale University

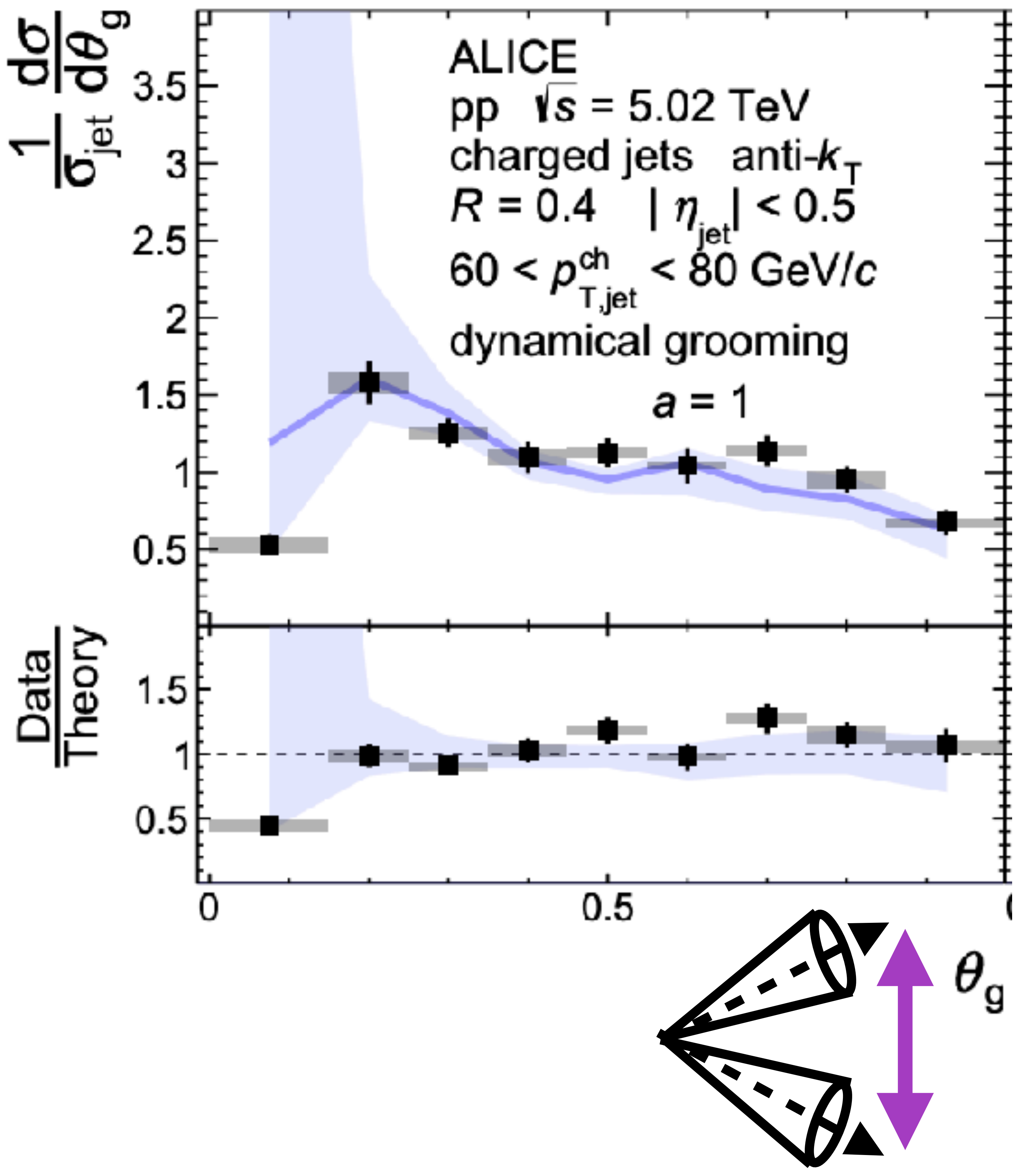
Compare to analytical calculation

- First comparisons to analytical calculations at LO+N^{2}DL+NP accuracy

[Caucal, Soto-Ontoso, Takas, arXiv:2103.06566]() [ALICE arXiv:2204.10246]()





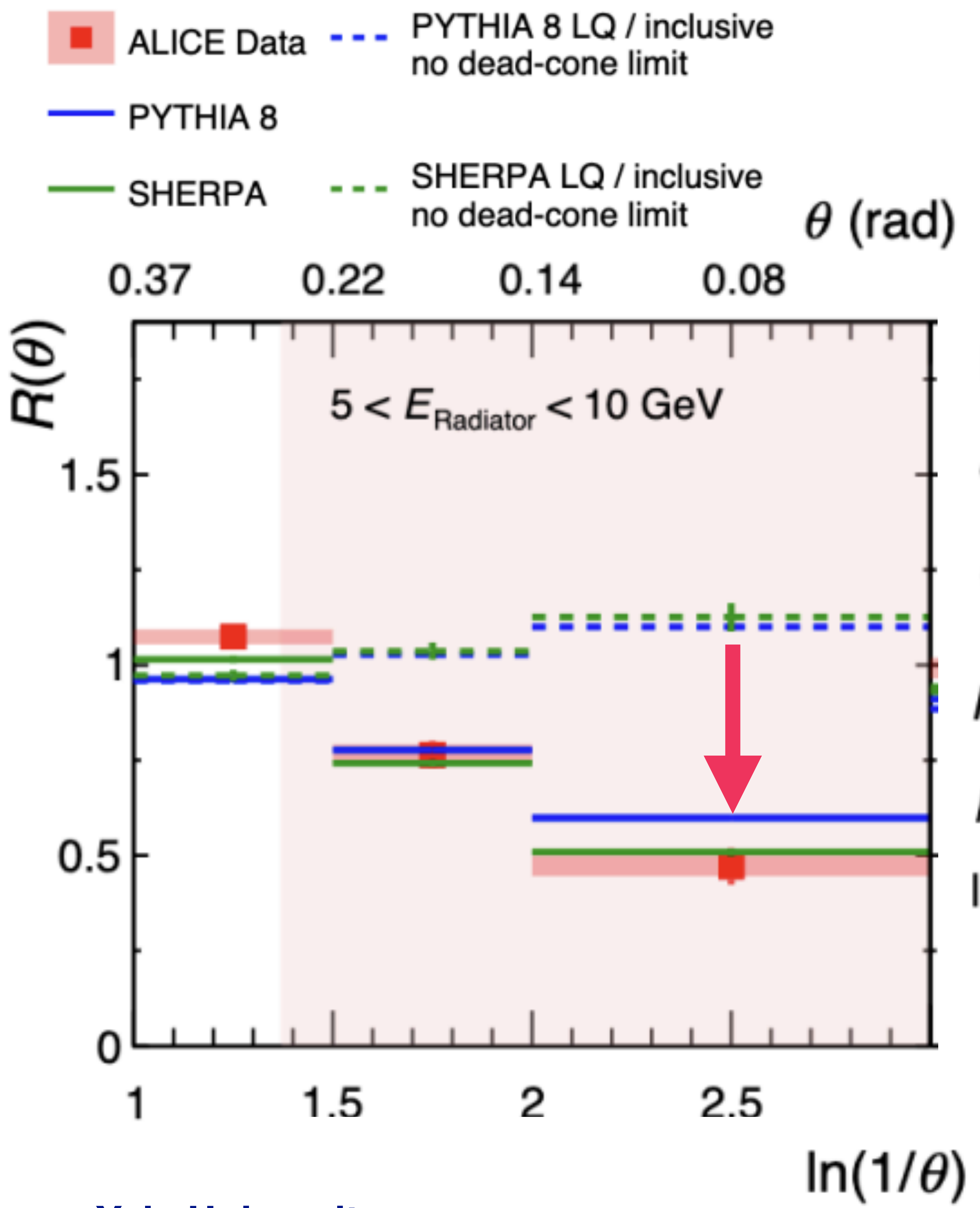


- ▸ Once the analytic result was corrected by a phenomenologically determined non-perturbative factor, good agreement with the data is found

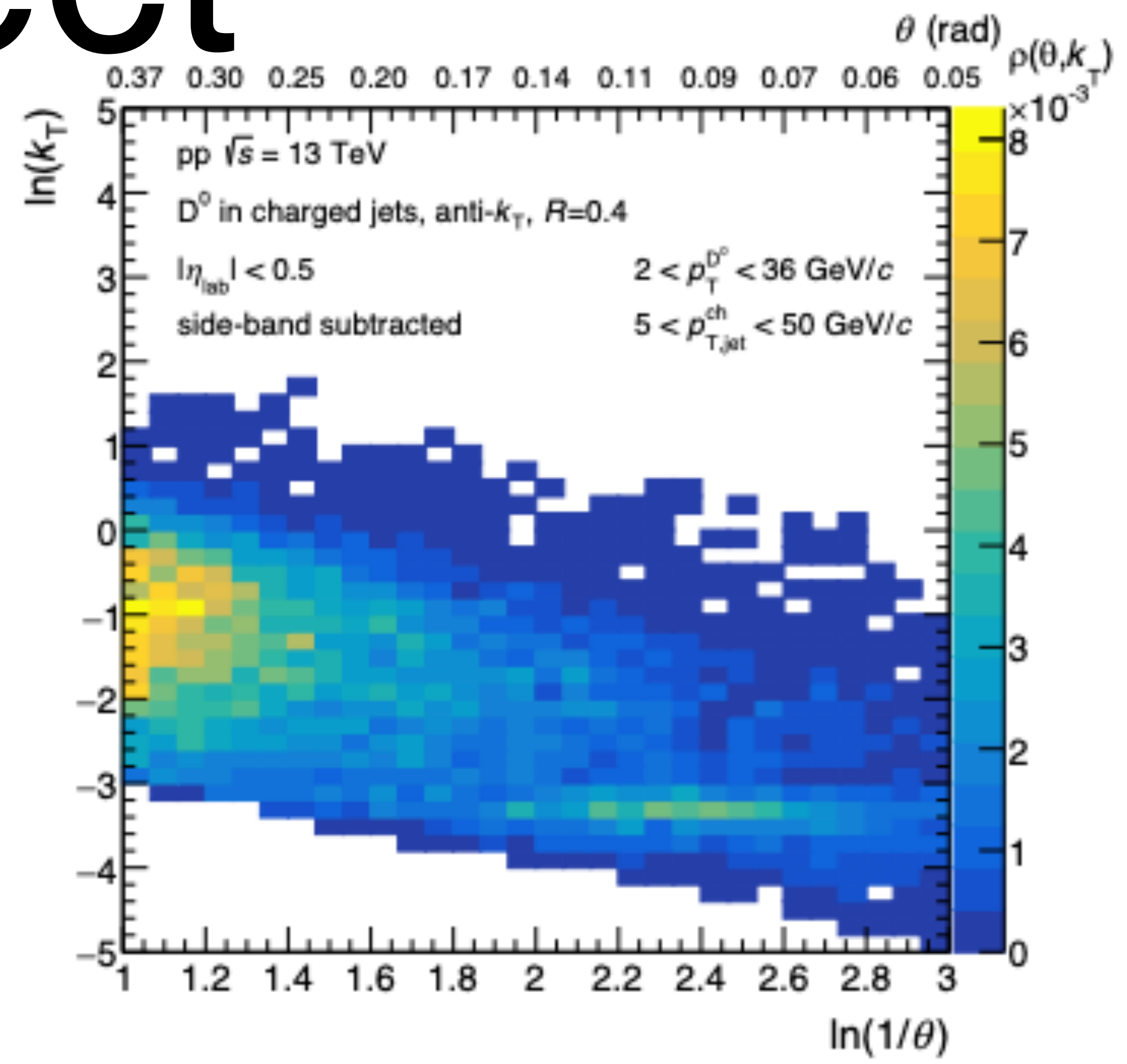
Lund plane: dead cone effect

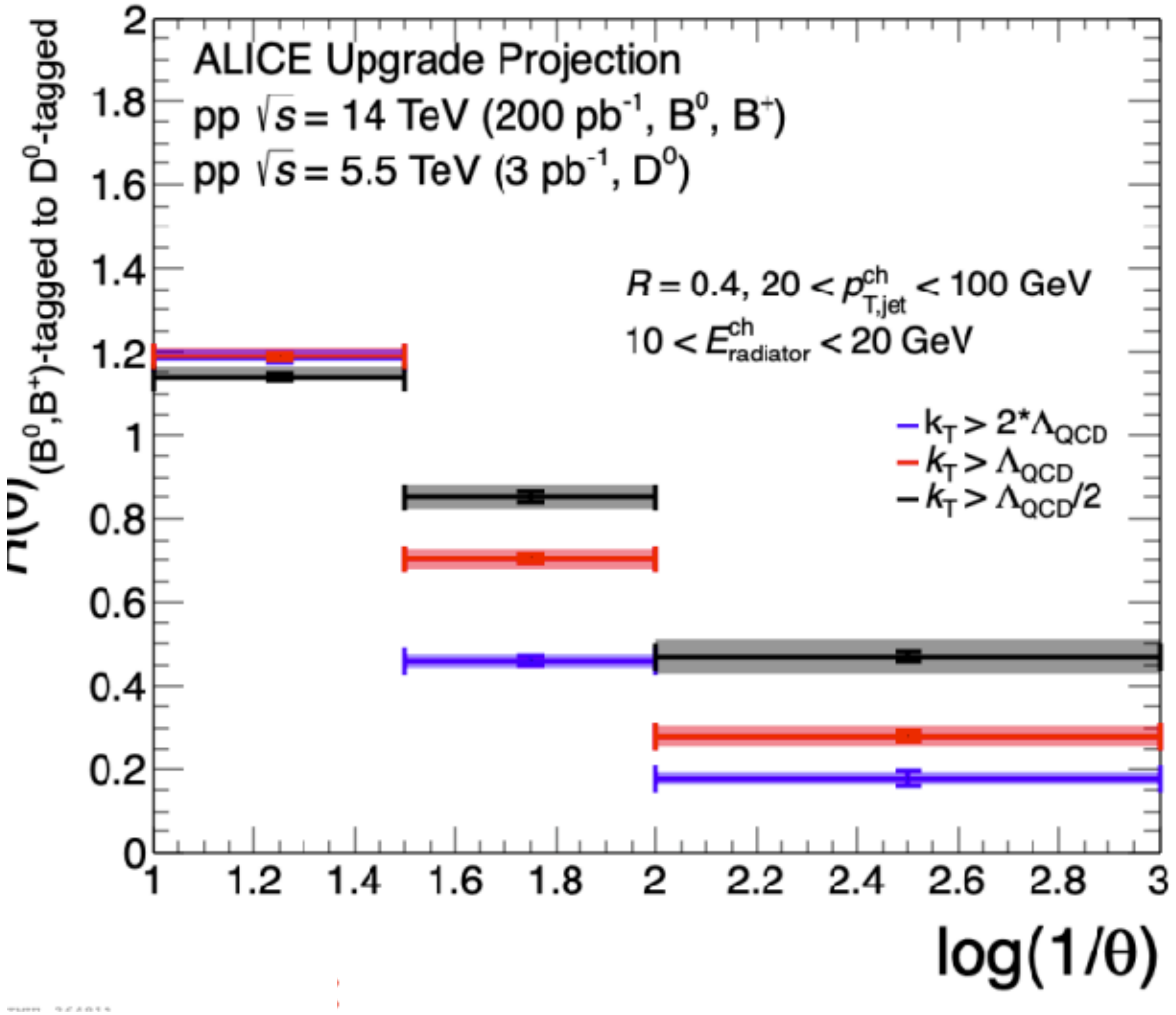
- Lund plane for D⁰-tagged (charm) jets compared to inclusive jets

[ALICE arXiv:2106.05713](https://arxiv.org/abs/2106.05713)



- Significant suppression at small angles!

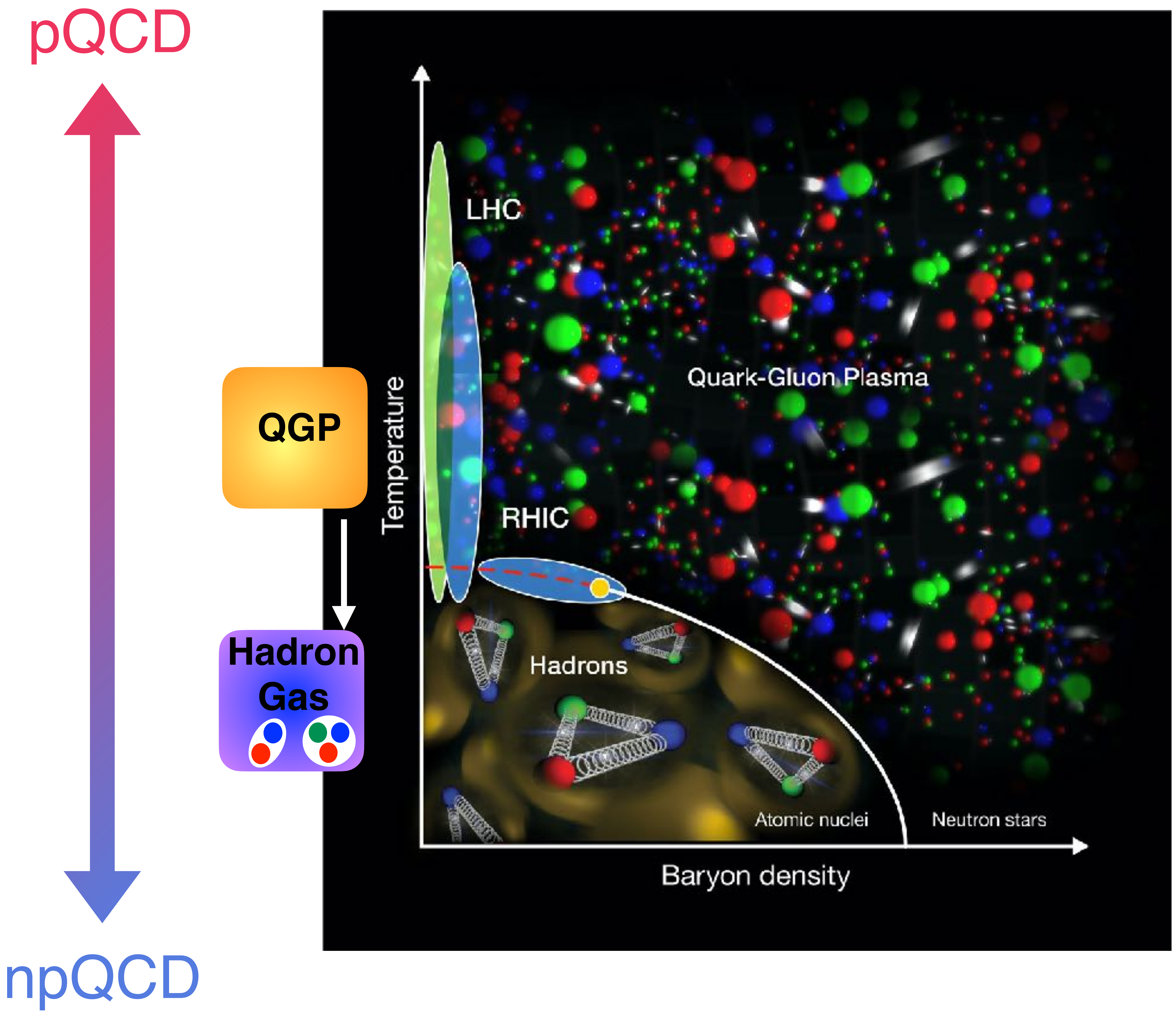




High temperature QCD

- Deconfined state of quarks and gluons: quark-gluon plasma at high temperatures

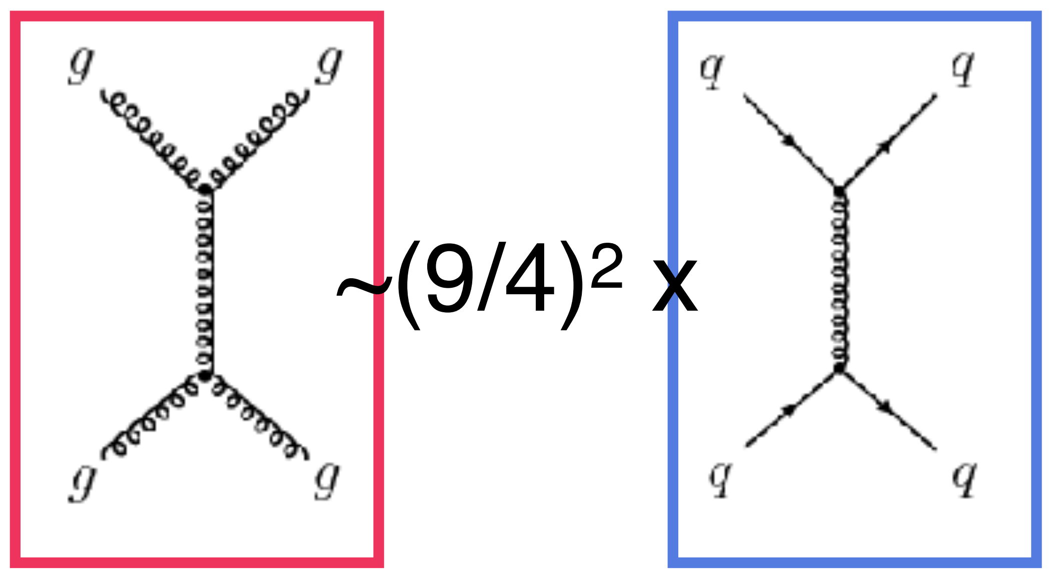
- Study dynamics of phase and confinement transition with heavy-ion collisions at colliders



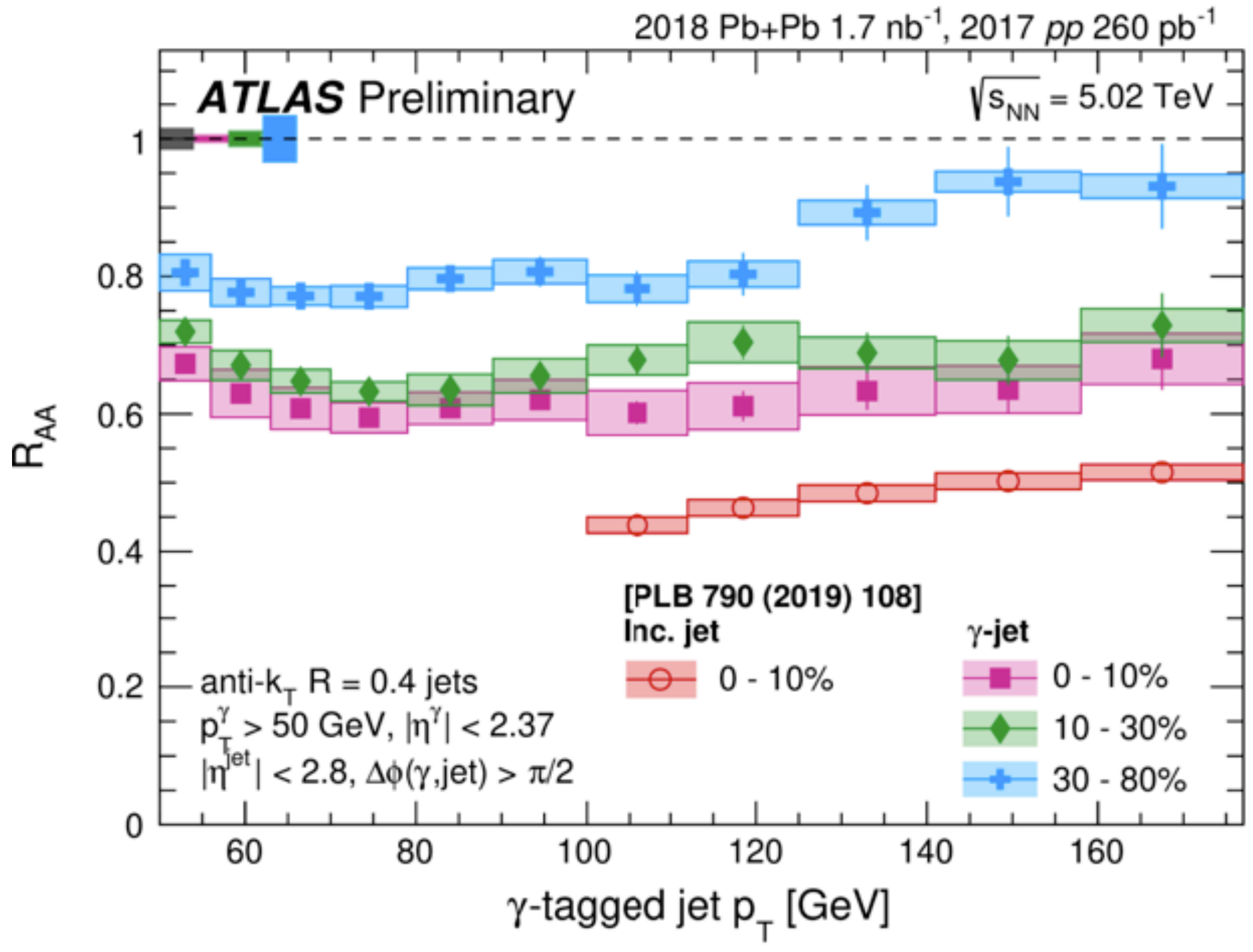
Laura Havener, Yale University

Flavor dependence

- The energy loss by quarks is predicted to be less than the energy loss by gluons

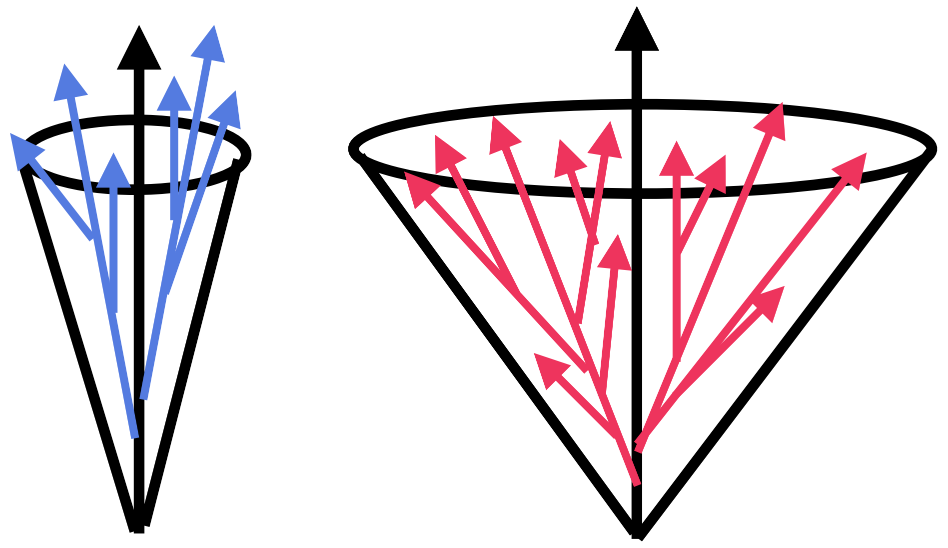


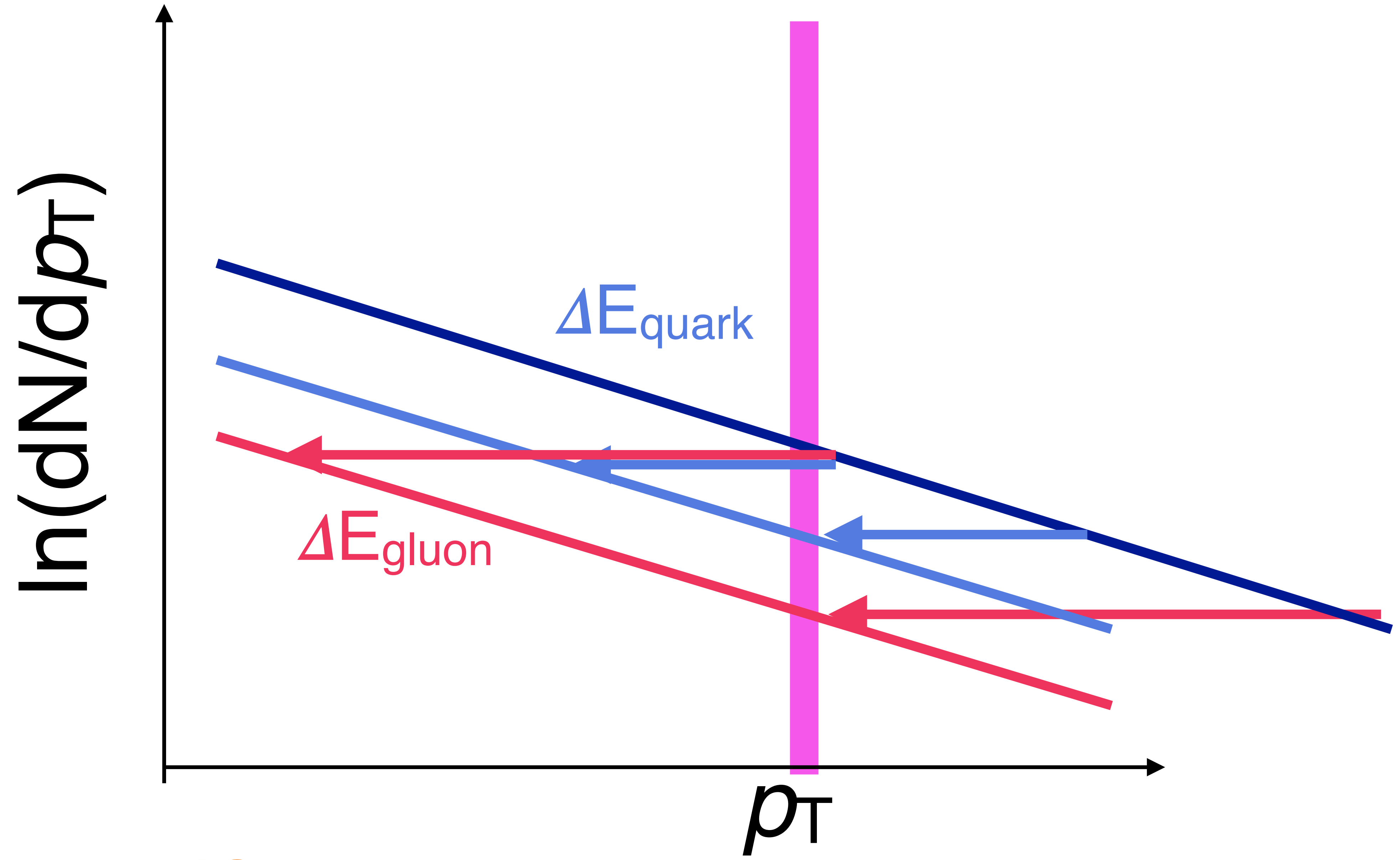
See talk by Sebastian Tapia Araya



ATLAS-CONF-2022-019

- Quark jets are narrower and have less structure than gluon jets





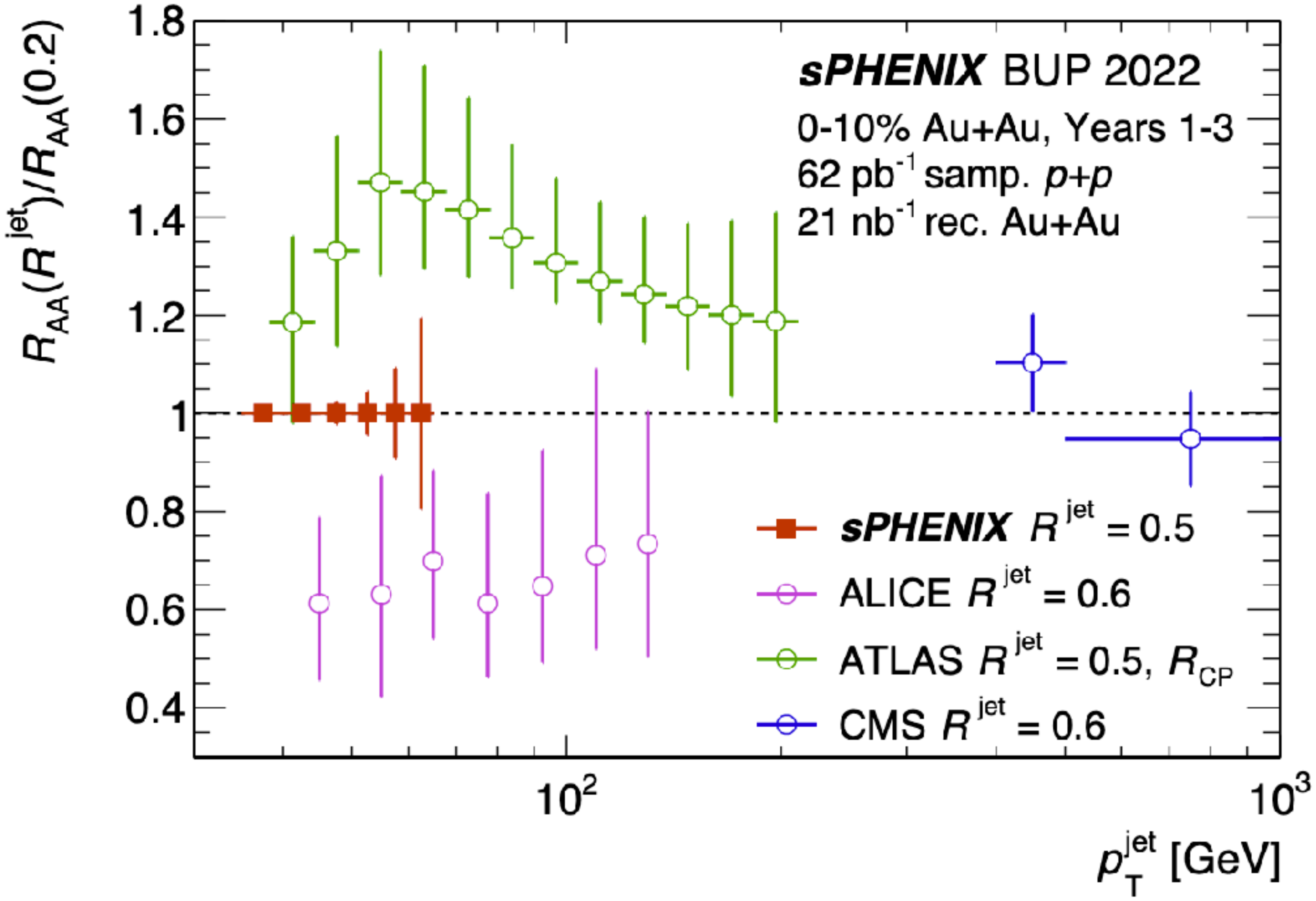
Will wider gluon jets be suppressed?

Laura Havener, Yale University

R-dependence of jet suppression

- Tension at low p_T with ATLAS result at 2.76 TeV   Phys. Lett. B 719 (2013) 220-241
  - Converge to CMS result at high p_T CMS arXiv:2102.13080
- Differences:
  - R_{CP} vs. R_{AA} Center-of-mass, rapidity, charged vs. full jet
  - ALICE track p_T above 150 GeV, ATLAS calorimeter towers from tracks about ~700 GeV
  - Background subtraction: region with large HI background is challenging!

From G. Roland ECT* slides



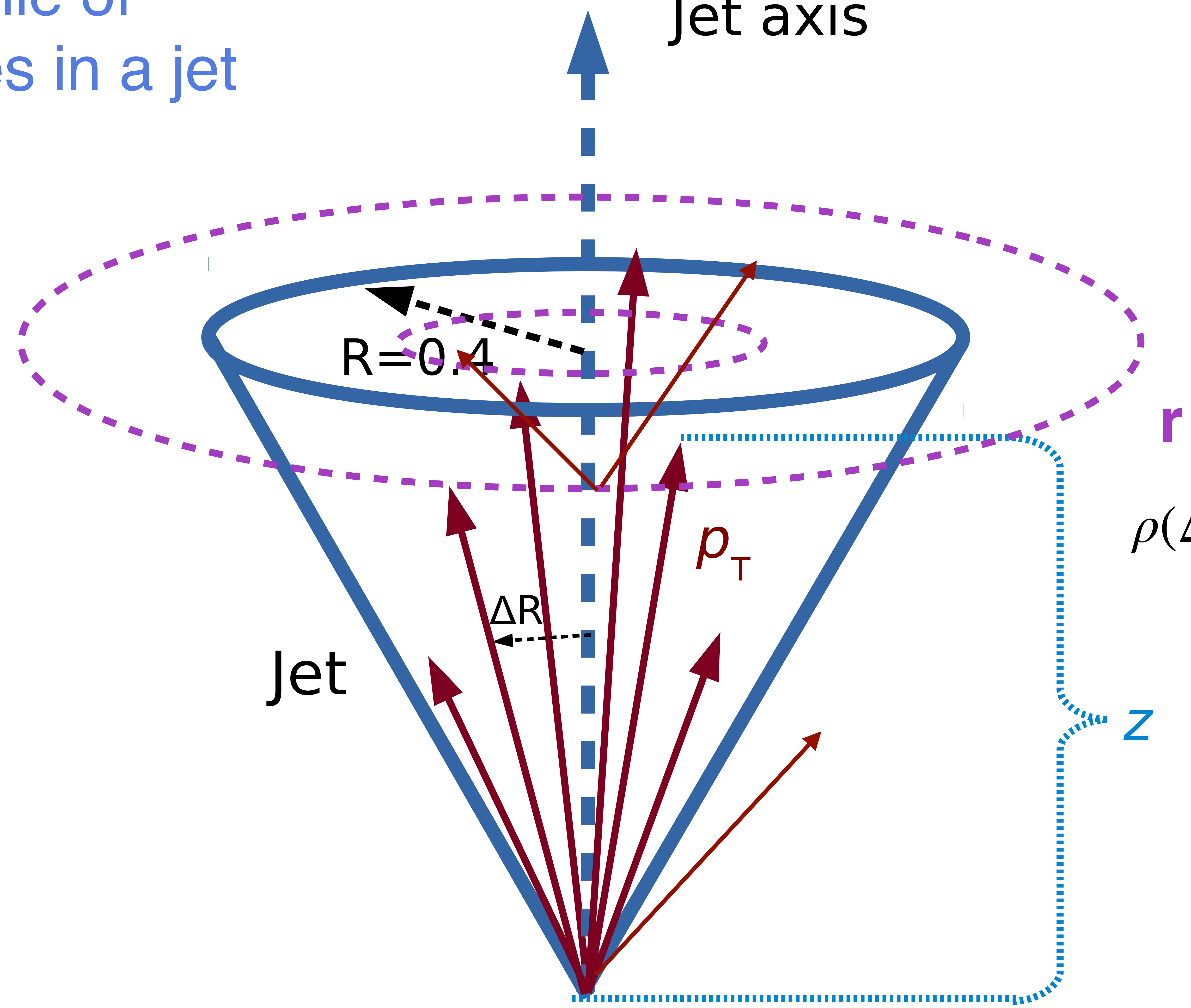
- sPhenix will measure this region and be less background dominated

Jet shapes and fragmentation

- Jet fragmentation: longitudinal profile of charged particles in a jet

$$D(z) = \frac{1}{N_{\text{jet}}}\frac{dN_{ch}}{dz}$$

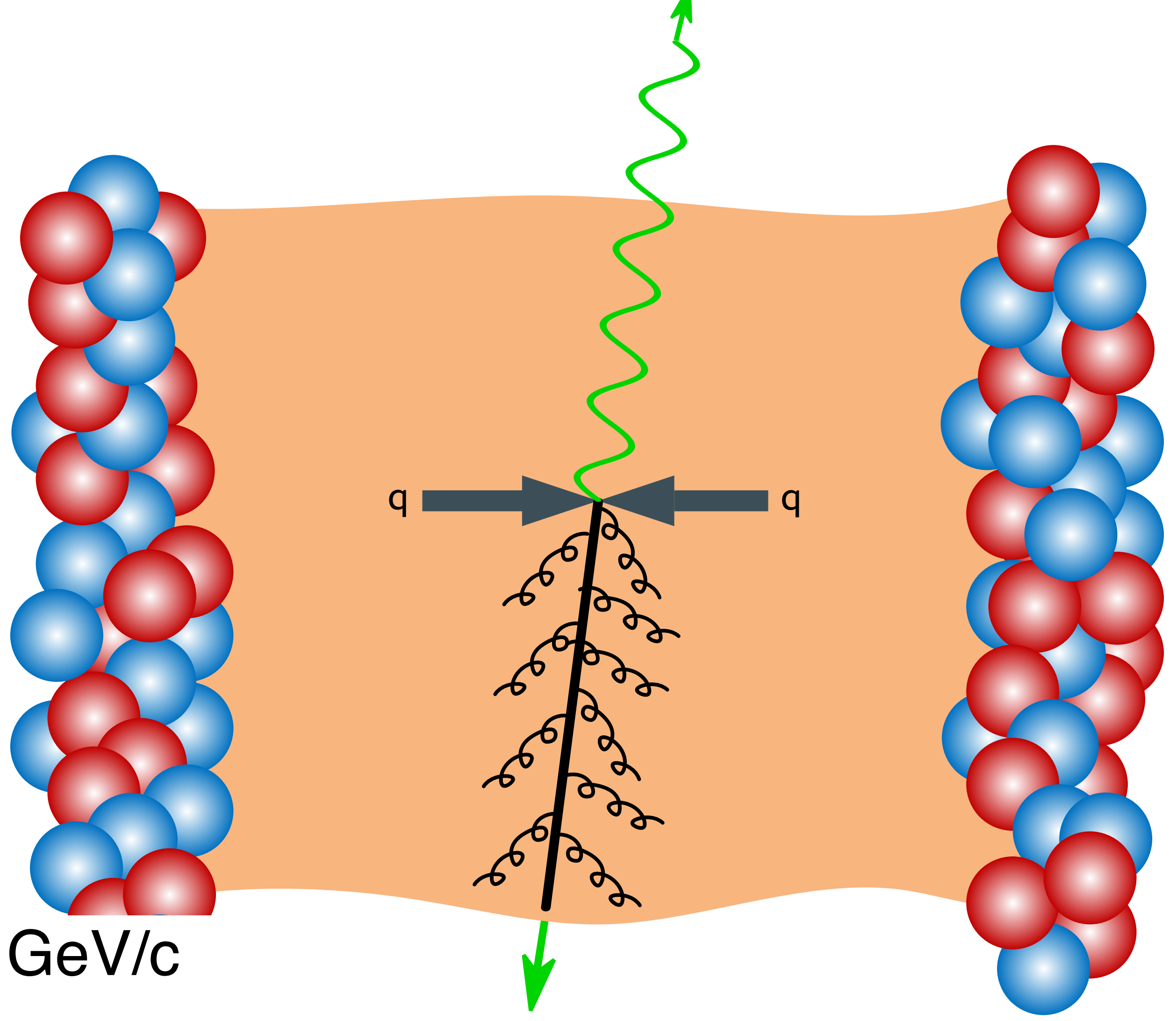
$$z = \frac{p_{\text{T}} \cos \Delta R}{p_{\text{T}}^{\text{jet}}}$$



- Jet shape: radial profile of charged particles in a jet

$$\rho(\Delta r) = \frac{1}{\delta r}\frac{1}{N_{\text{jets}}}\frac{\sum_{\text{jets}}\sum_{\text{tracks}\in(\Delta r_a,\Delta r_b)} p_{\text{T}}^{\text{ch}}}{\sum_{\text{jets}}\sum_{\text{tracks}\in\Delta r\leq 1} p_{\text{T}}^{\text{ch}}}$$

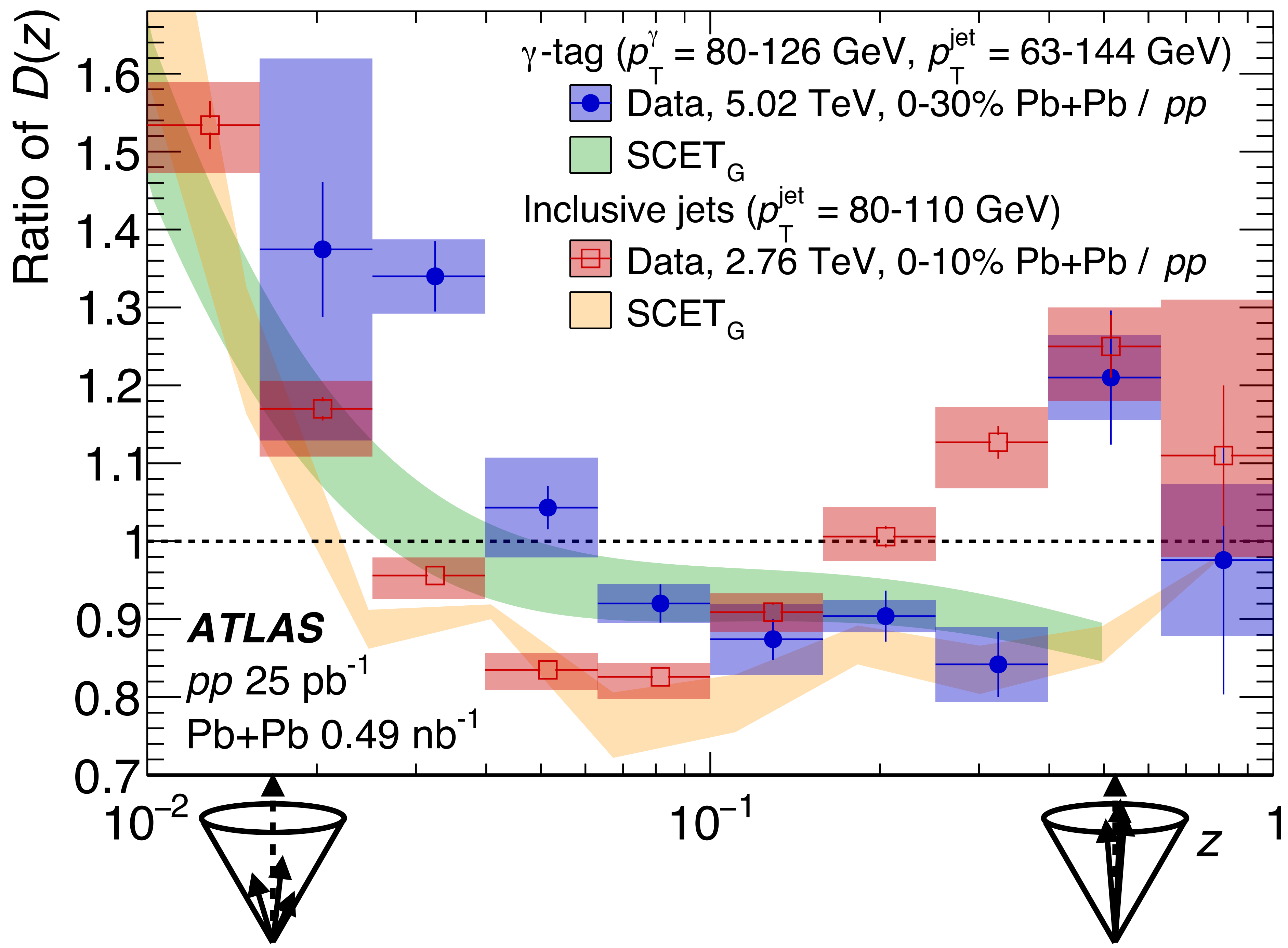
Boson-tagged jet structure



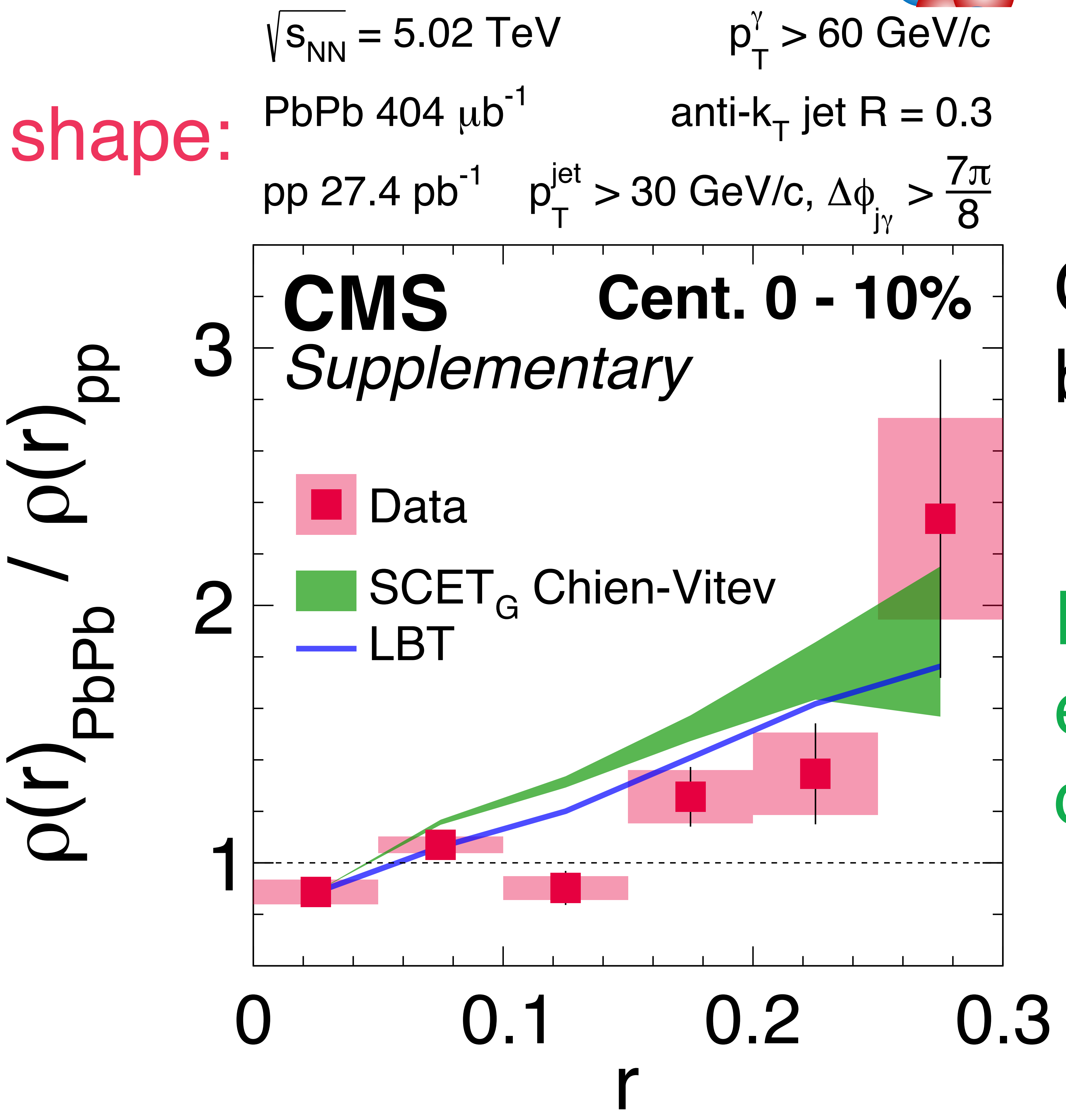
- Boson-jets dominated by quark jets
- Boson tag provides approximate initial momentum of jet (no energy loss)

- Photon-jet fragmentation

PRL 123 (2019) 042001



- Photon-jet shape:



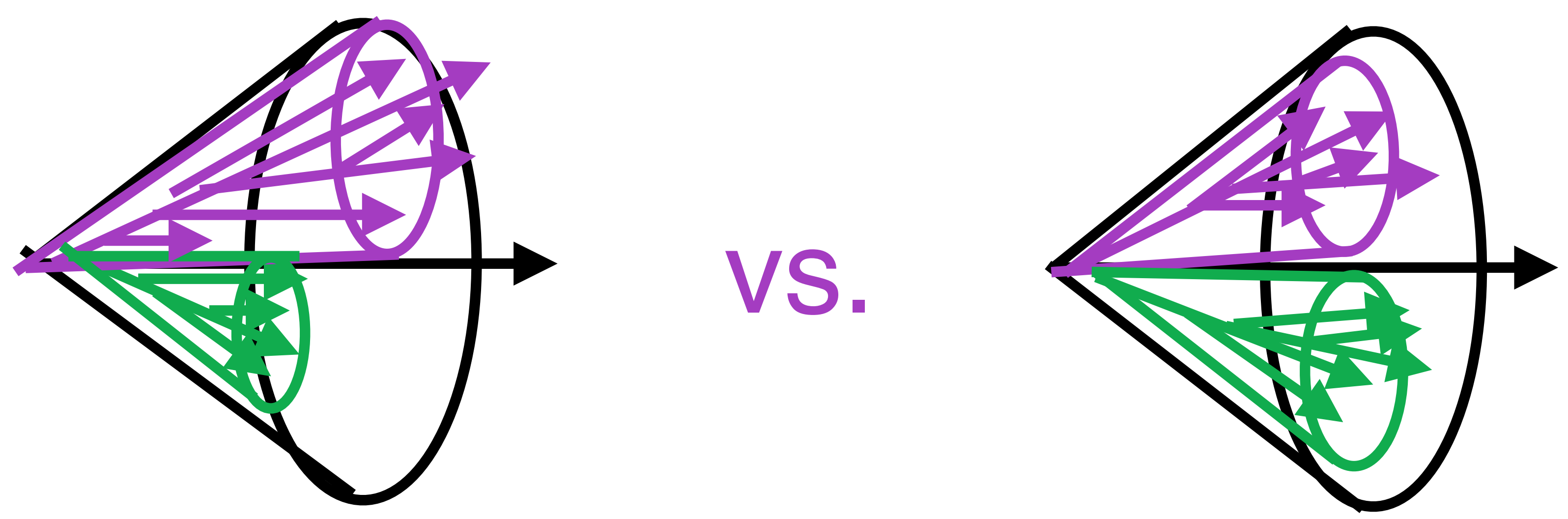
Qualitatively similar behavior to inclusive

Except high z enhancement disappears?

PRL 122 (2019) 1520

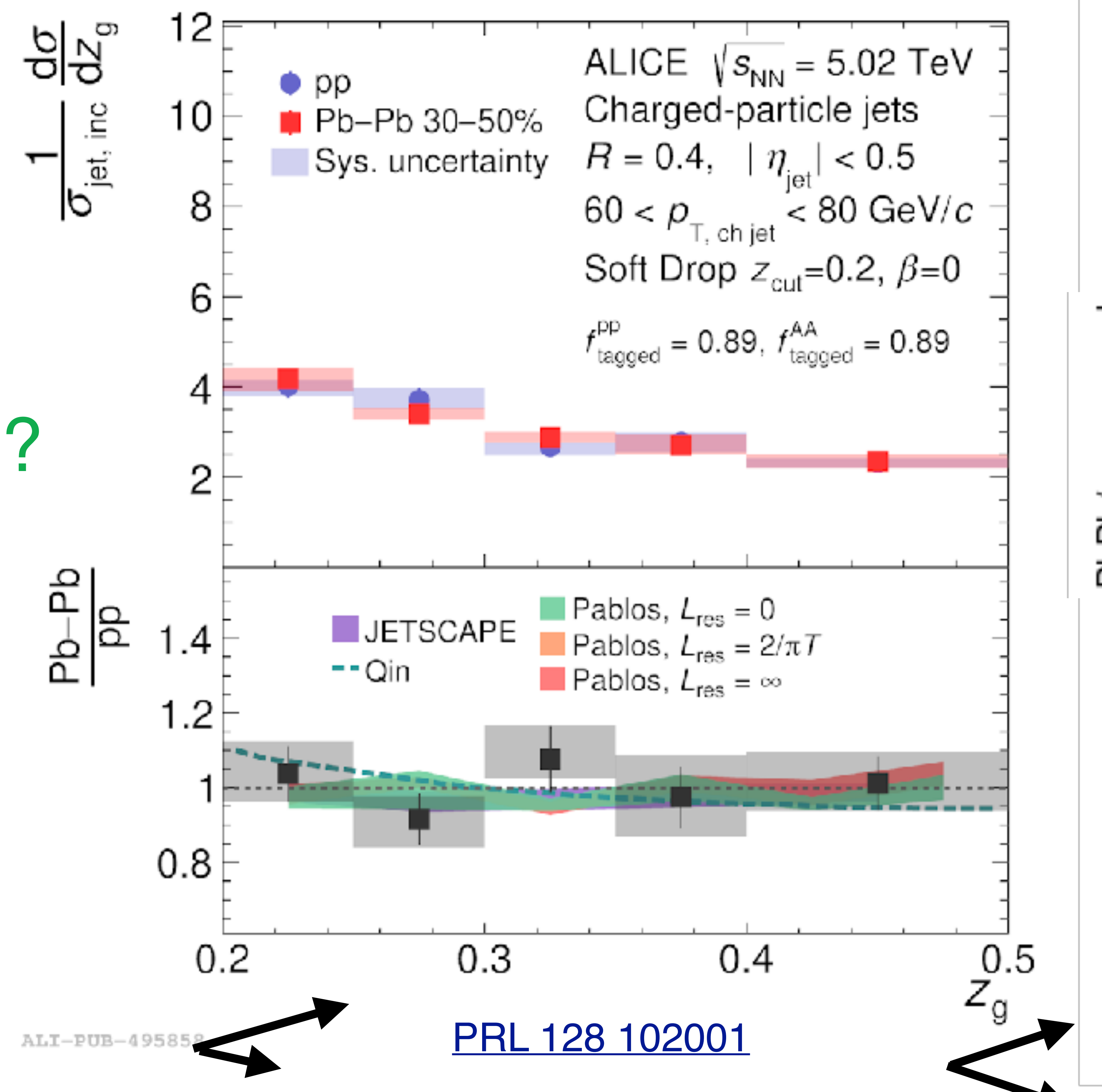
Jet splittings: z_g

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

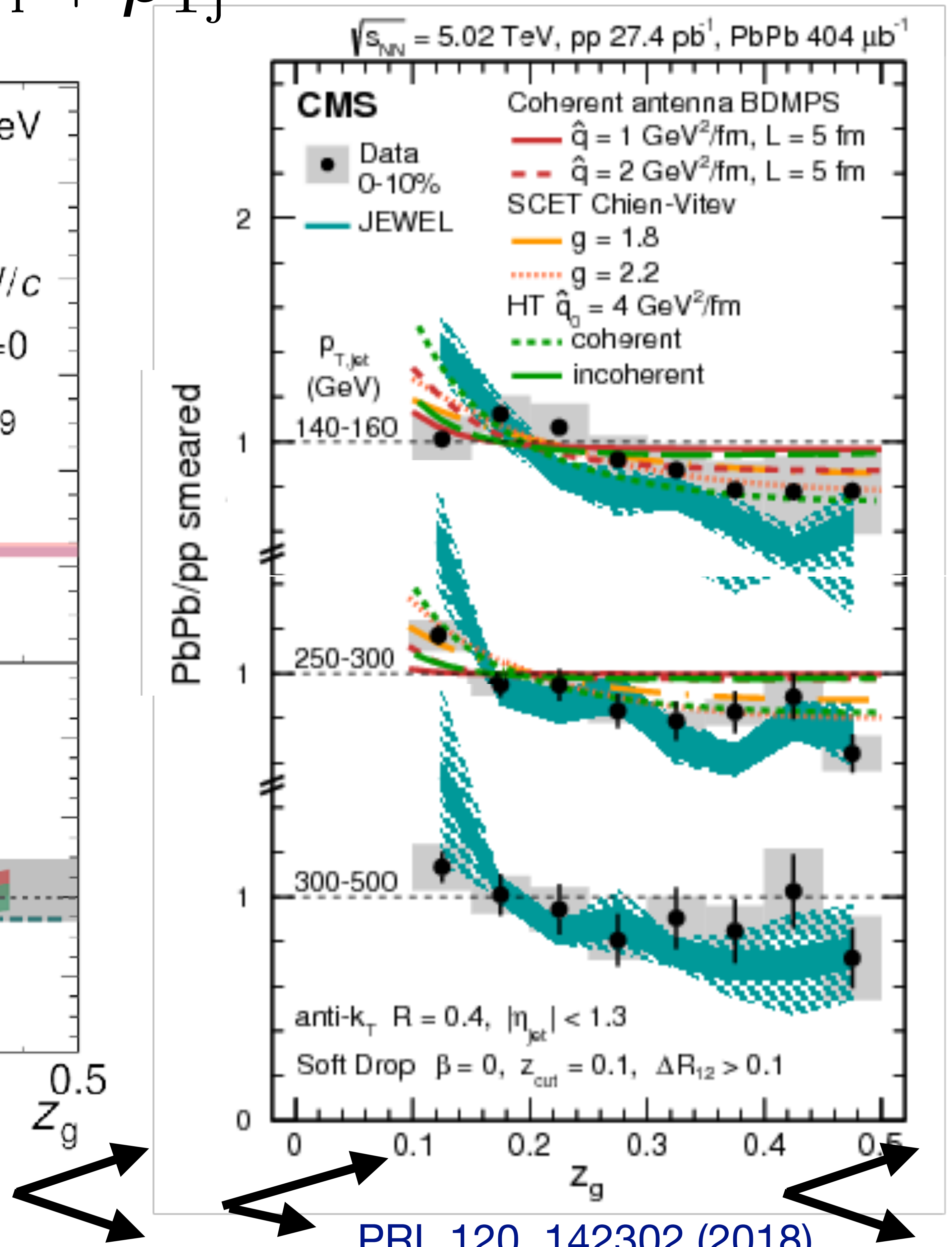


Modification of splitting function?

- *Low p_T: no significant modification, mostly consistent with models*
- *High p_T: hint of suppression at high z_g*



PRL 128 102001



PRL 120, 142302 (2018)

ALICE: low p_T, z_{cut}=0.2, unfolded

CMS: high p_T, z_{cut}=0.1, smeared

Jet splittings: narrowing?

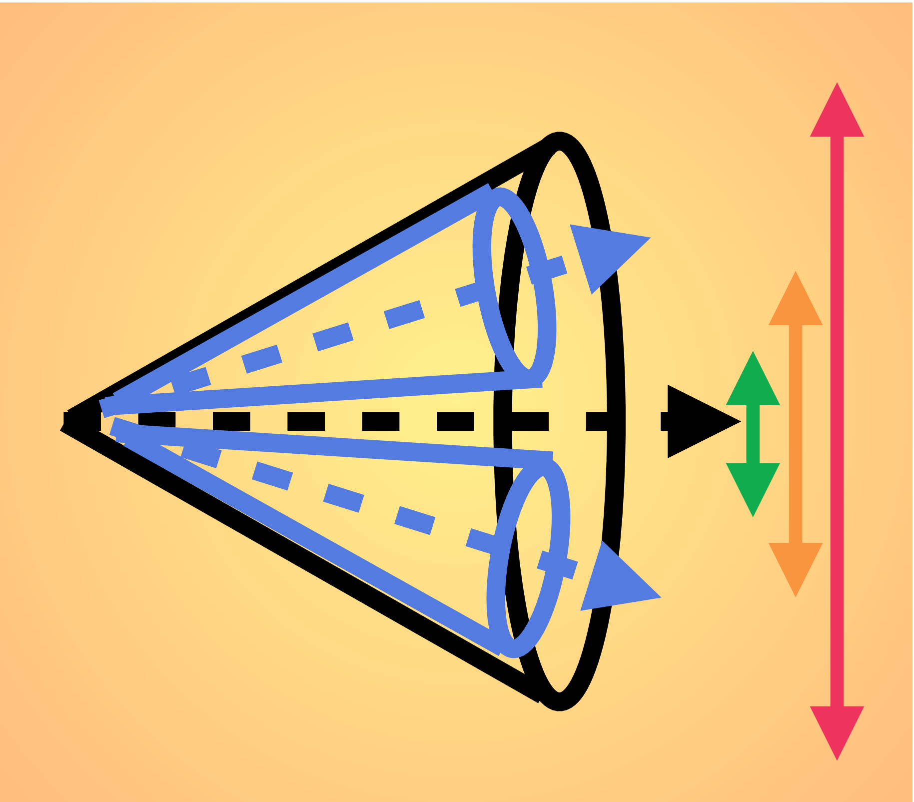
- *Narrowing reproduced by models with different implementations of jet-medium interactions*

- Model 1: role of color coherence? Pablos et al JHEP (2020) 044

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

  -$L_{res} = \infty$, coherence

  -$L_{res} = 0$, decoherence

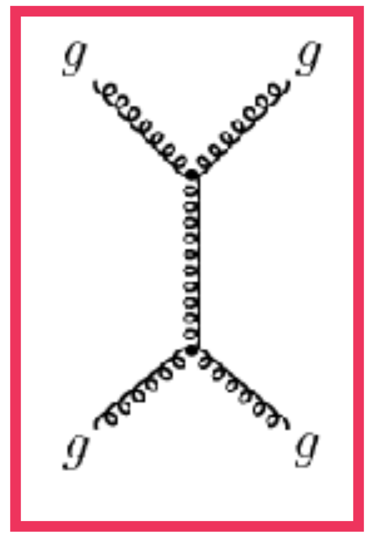


- Model 2: coherence with changing q/g fractions?

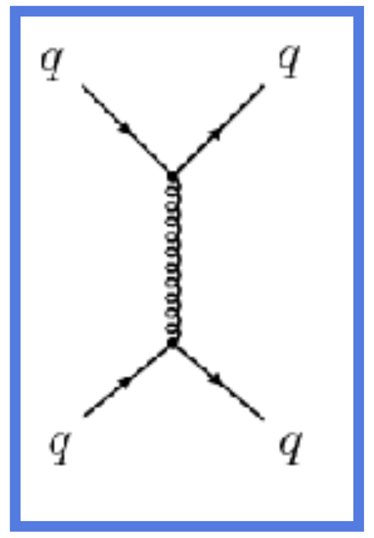
  -quark only

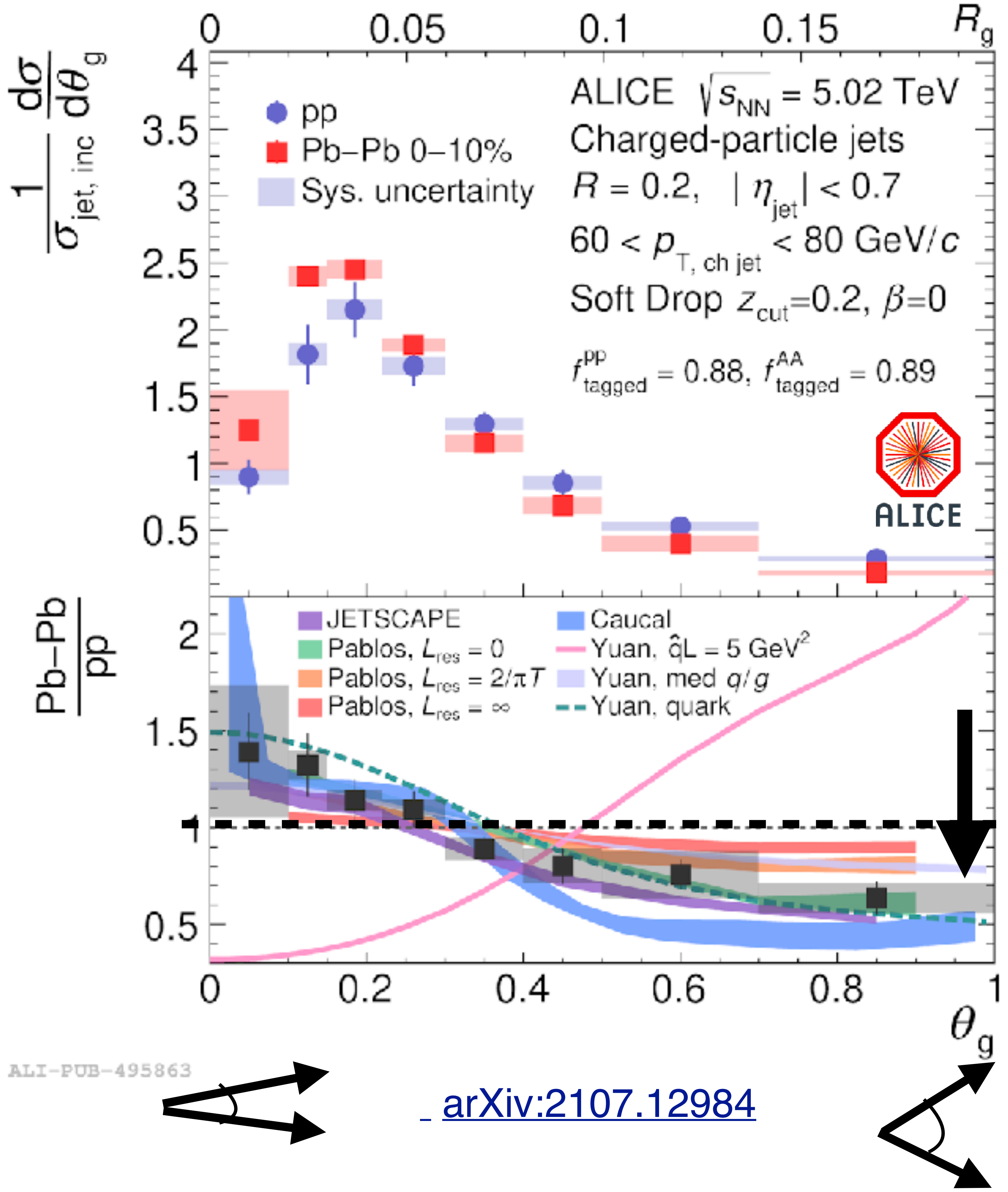
  -medium q/g

Yuan et al arXiv:1907.12541



~$(9/4)^2$ x

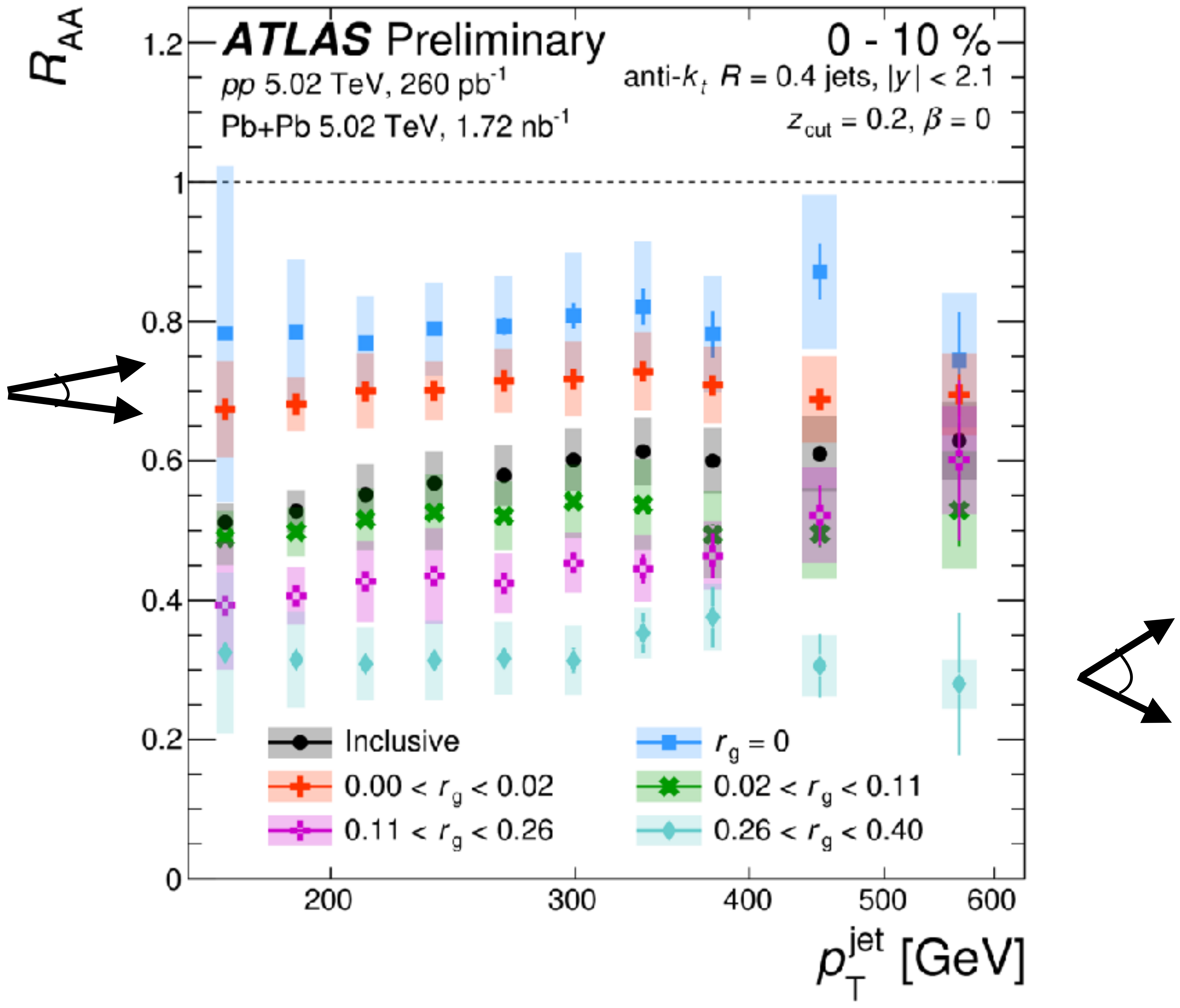




arXiv:2107.12984

Jet splittings: R_g suppression

Resolution length of QGP?



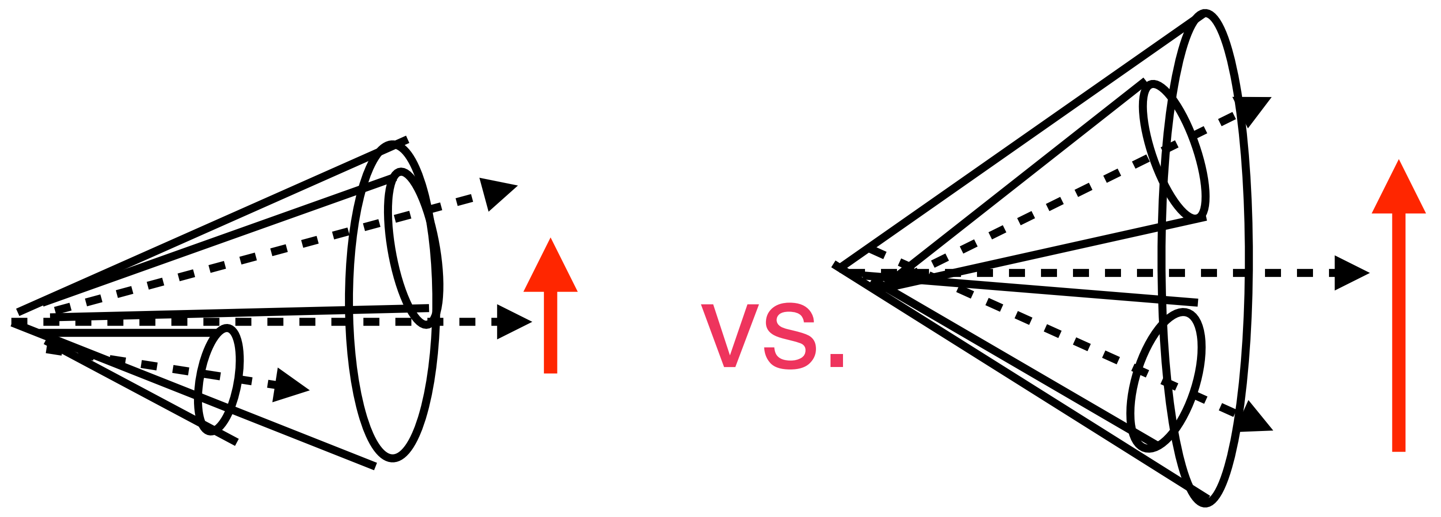
- ATLAS measurement at higher p_T
- Absolute suppression with RAA instead of per-jet, differential in p_T

▸ *Larger jets are more suppressed*

ATLAS-CONF-2022-026

Laura Havener, Yale University

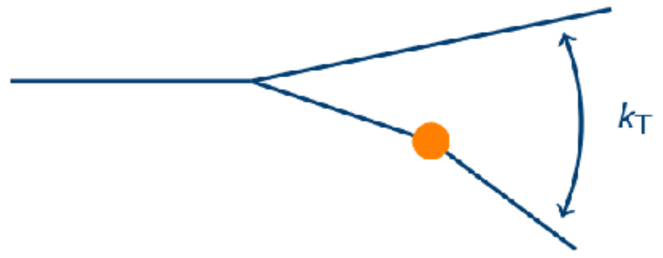
Jet splittings: hardest k_{Tg}



- Hybrid model: role of Moliere scattering?

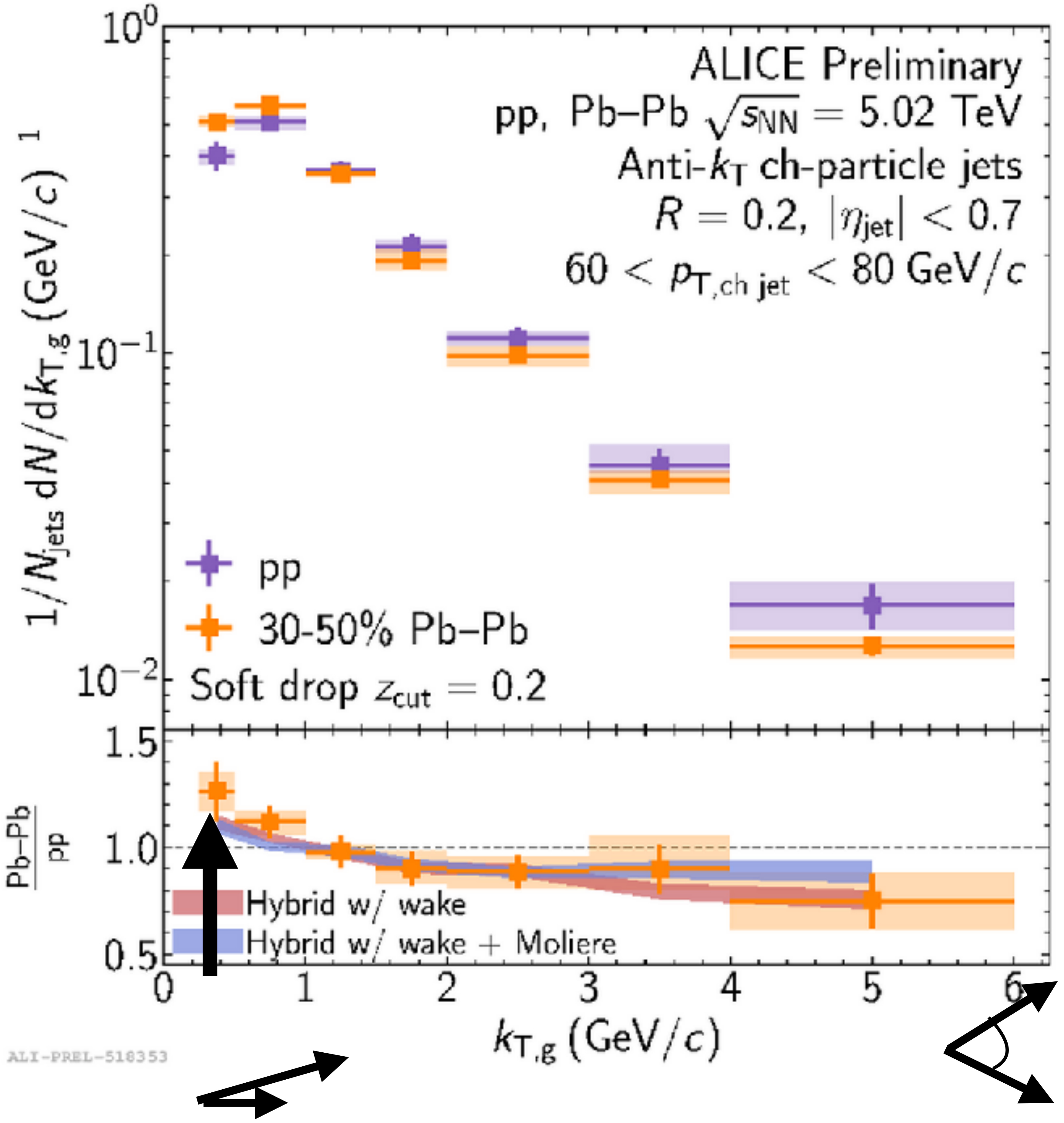
  -without Moliere

  -with Moliere



Pablos et al JHEP (2020) 044

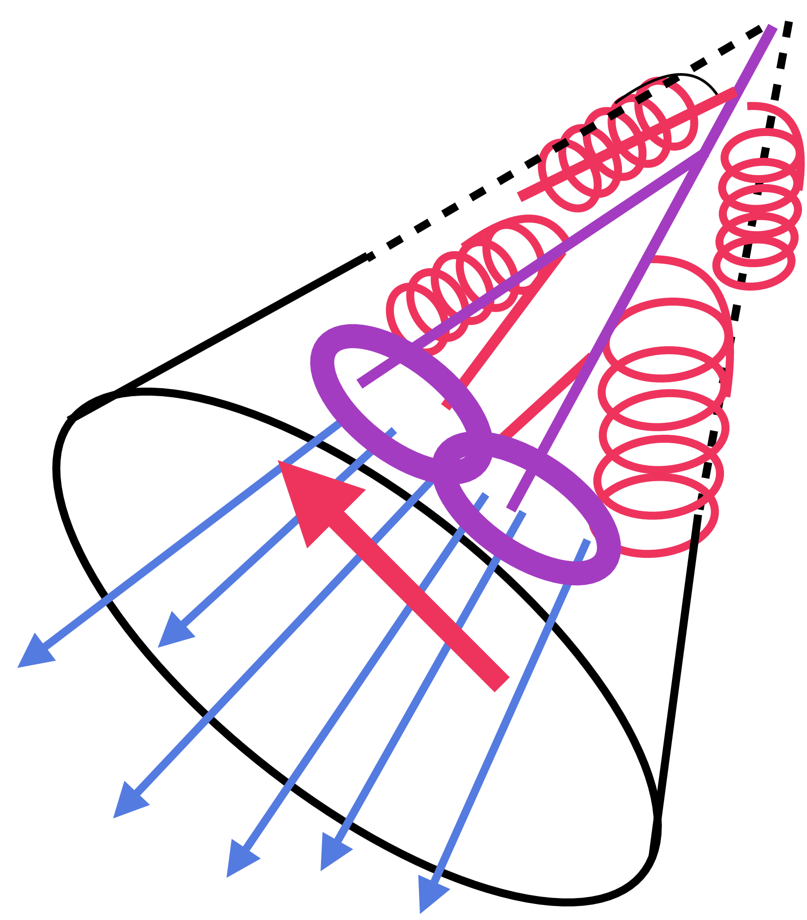
Quasi-particle nature of QGP?



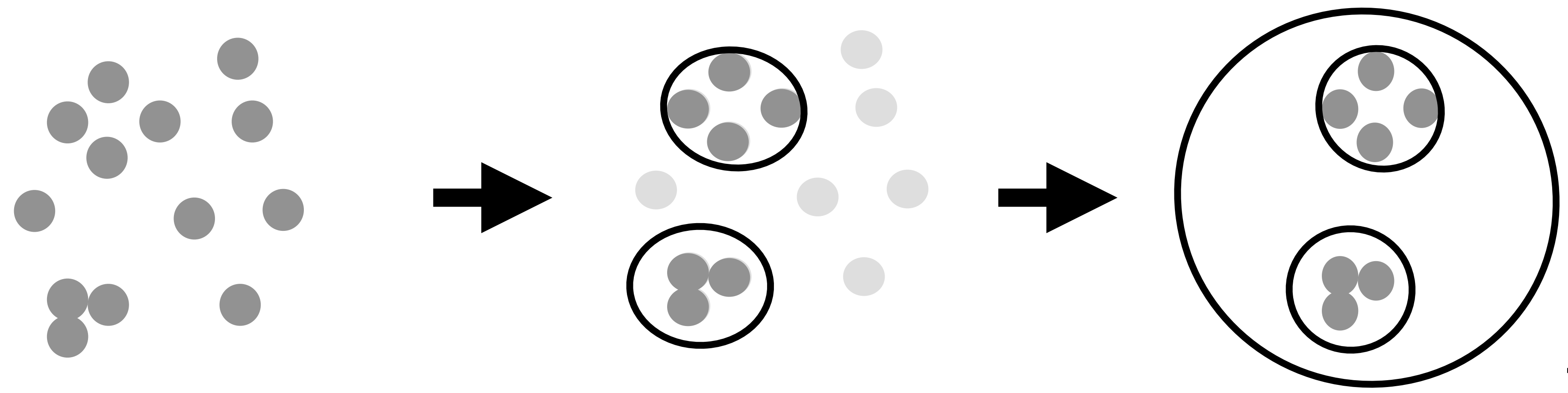
- *Not sensitive enough to distinguish models yet*

- *Hint of enhancement at small k_{Tg}-> consistent with narrowing picture?*

Jet splittings: large R trimming

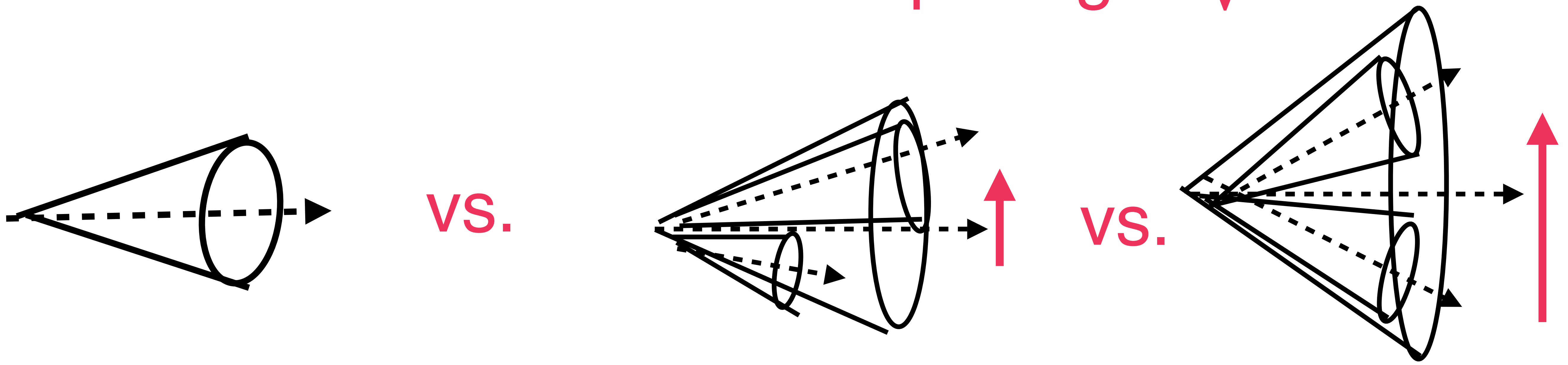


- Combining R=0.2 into R=1.0 jets removes energy radiated between subjets



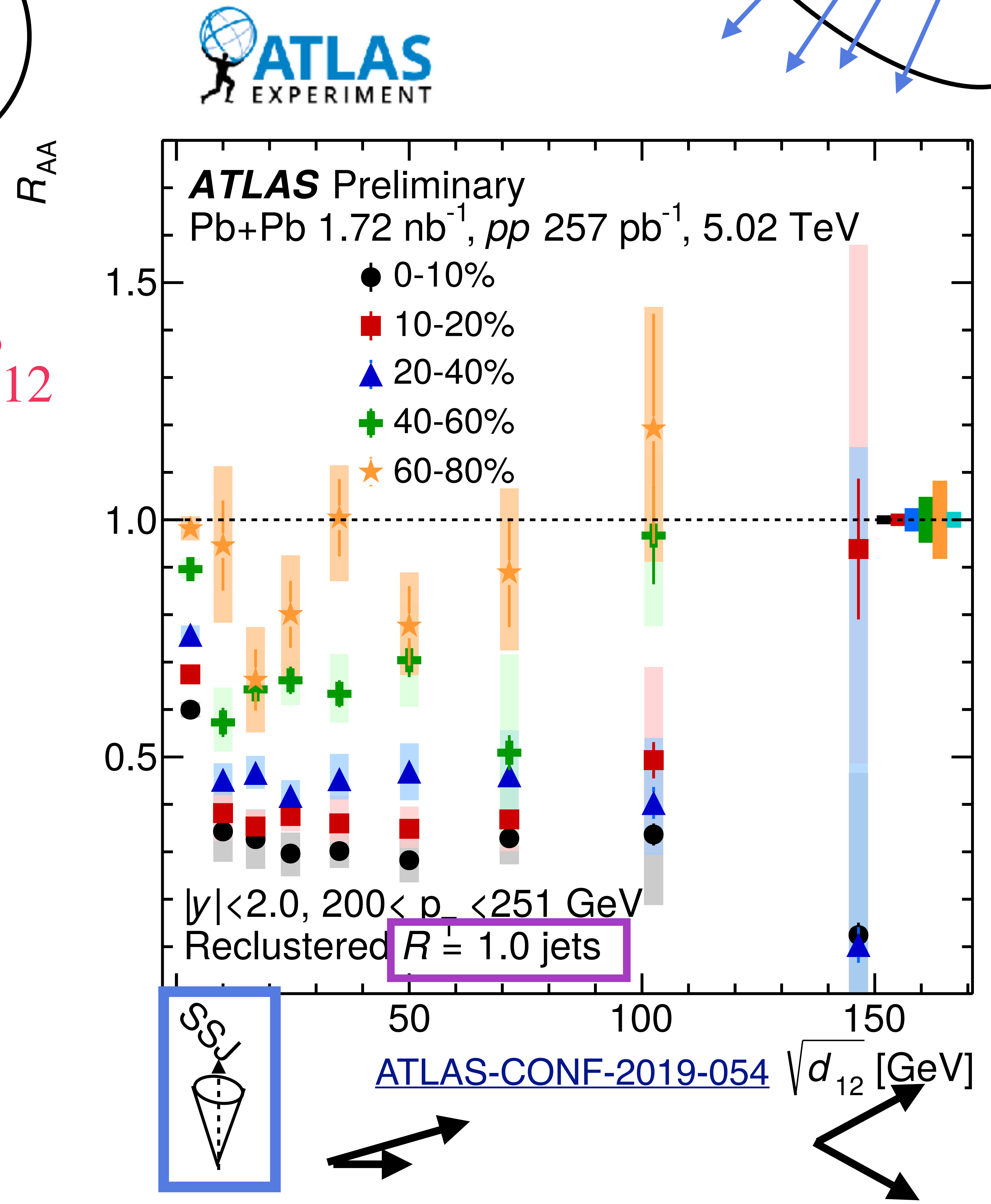
Recluster with k_T algorithm to access k_T

How hard is the resolved splitting? $\sqrt{d_{12}} = p_{T2}\Delta R_{12}$



- Jets with a substructure more suppressed than jets without (single subjets SSJ)

Is the medium resolving the splittings?

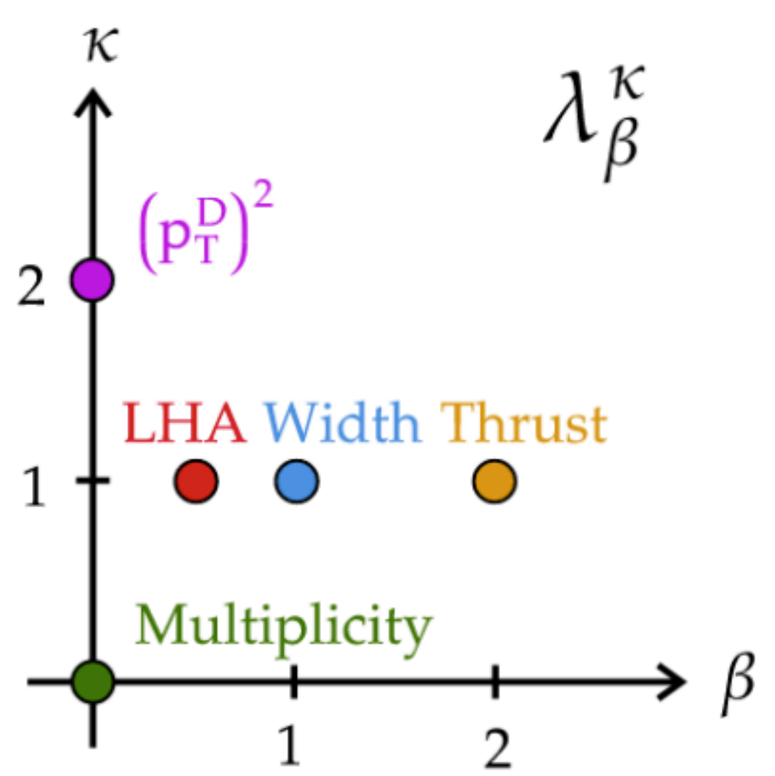


ATLAS-CONF-2019-054

Laura Havener, Yale University

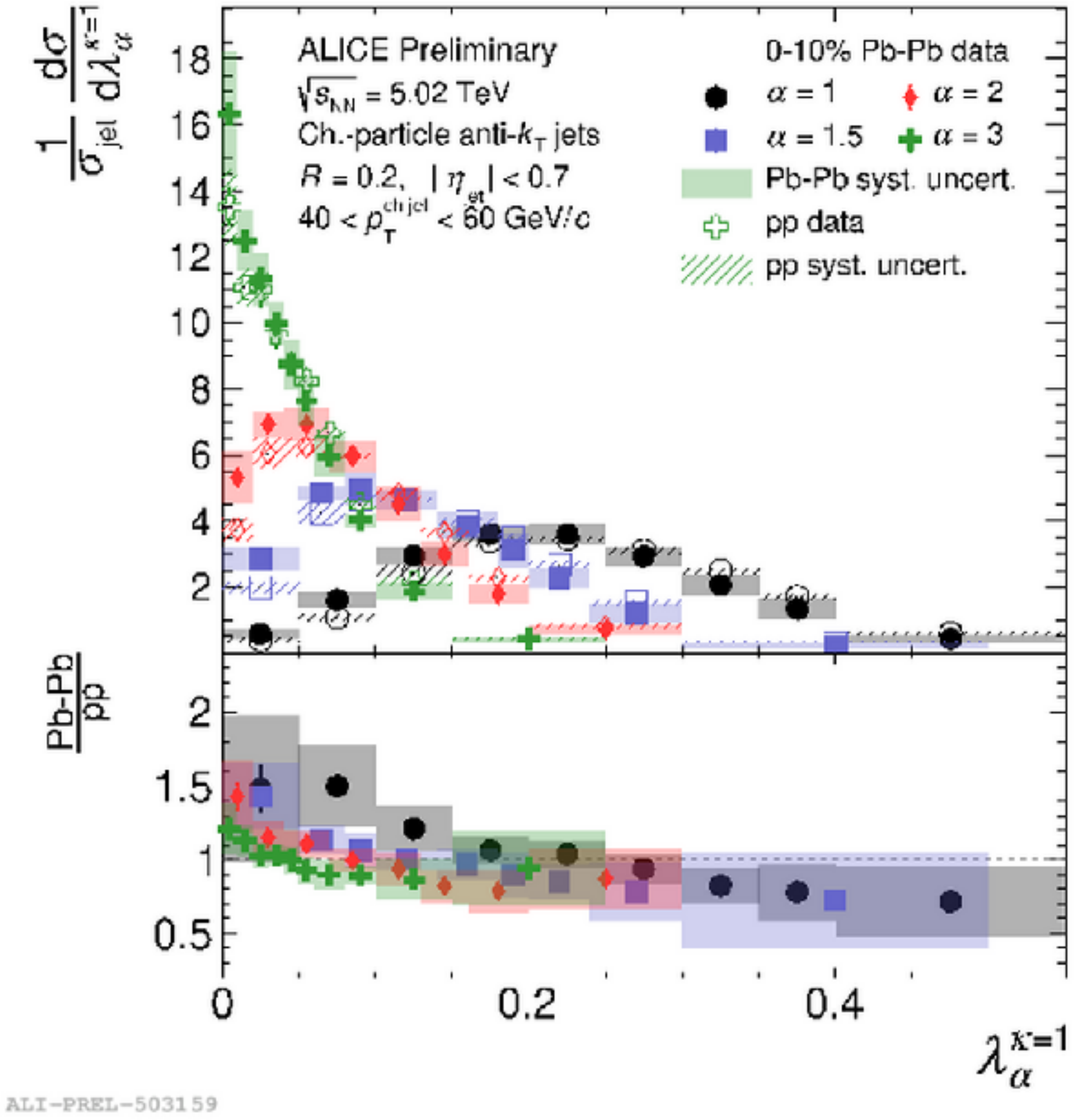
Groomed jet angularities

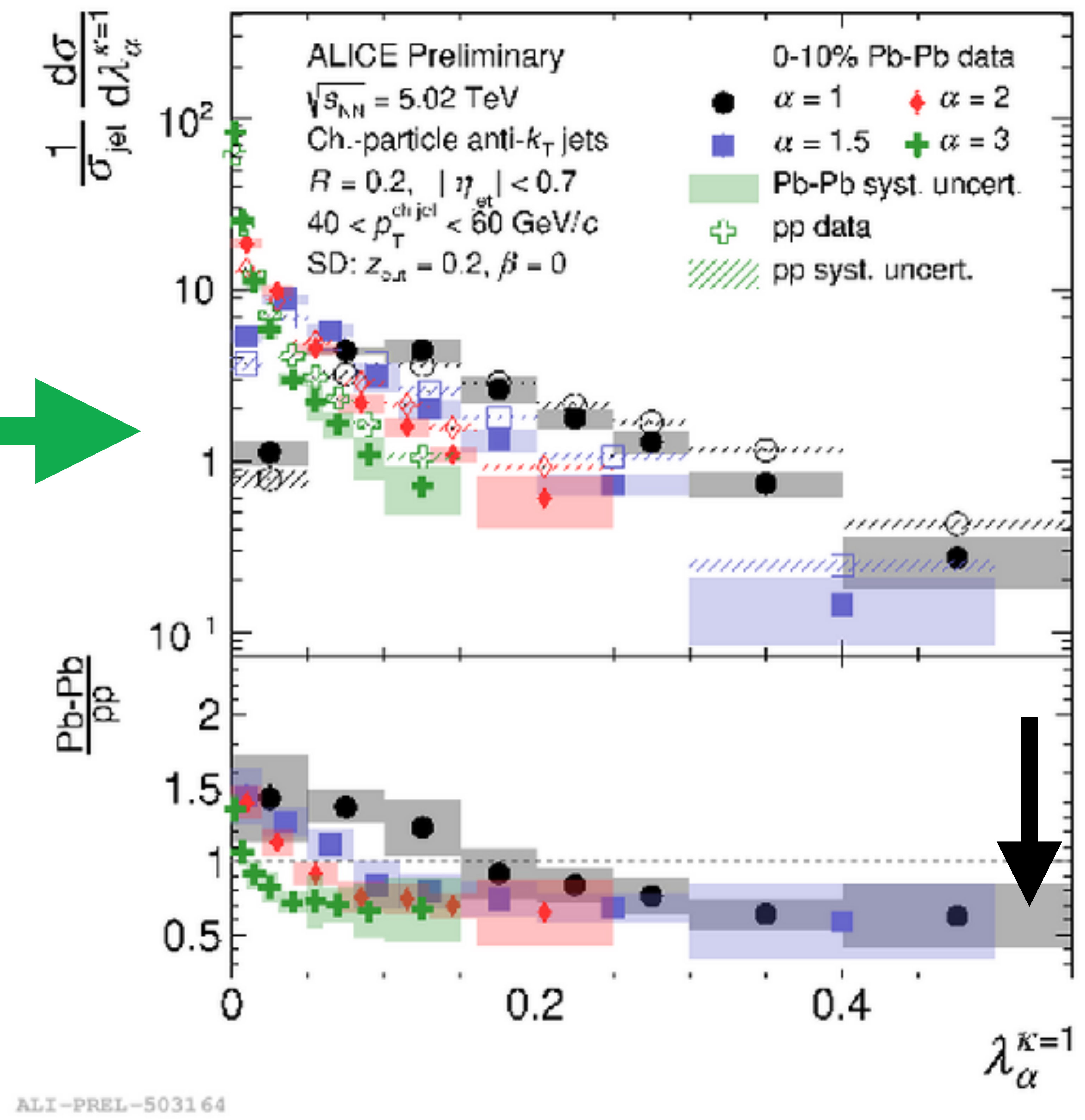
- Class of IRC-safe observables to summarize all substructure



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

Related to jet shapes:
Angularity (girth) g α=1
~Mass α=2



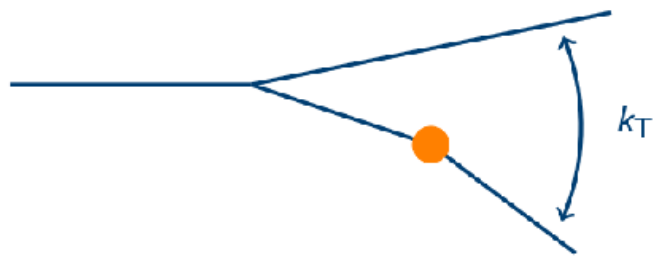


- Grooming reduces systematics and reveals narrowing feature
  - *Grooming reduces intra-jet broadening and recoil effects*

Jet axis: model comparisons

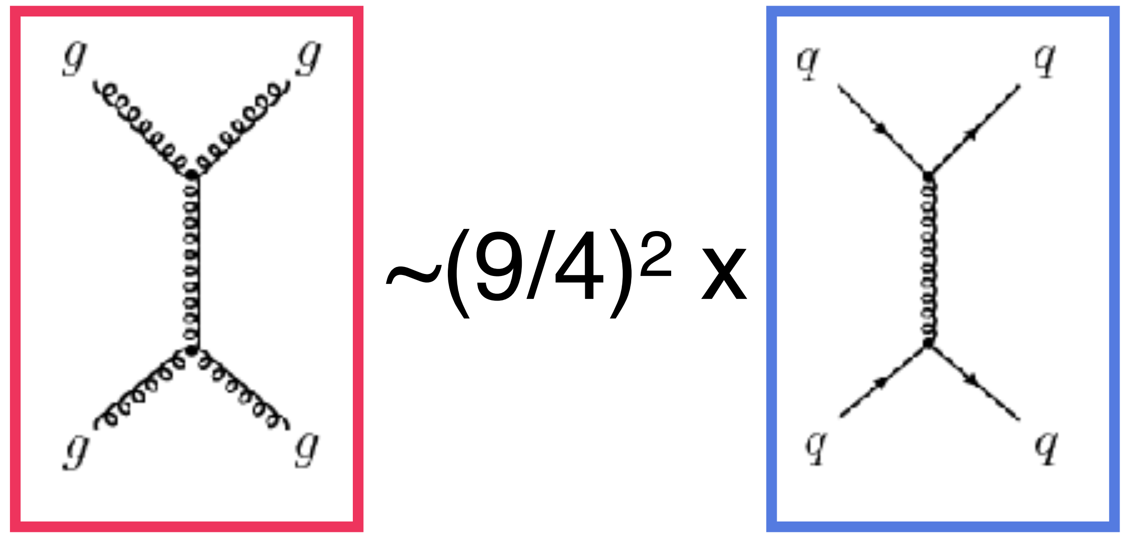
- Hybrid model: role of Moliere scattering?
  - -without Moliere
  - -with Moliere

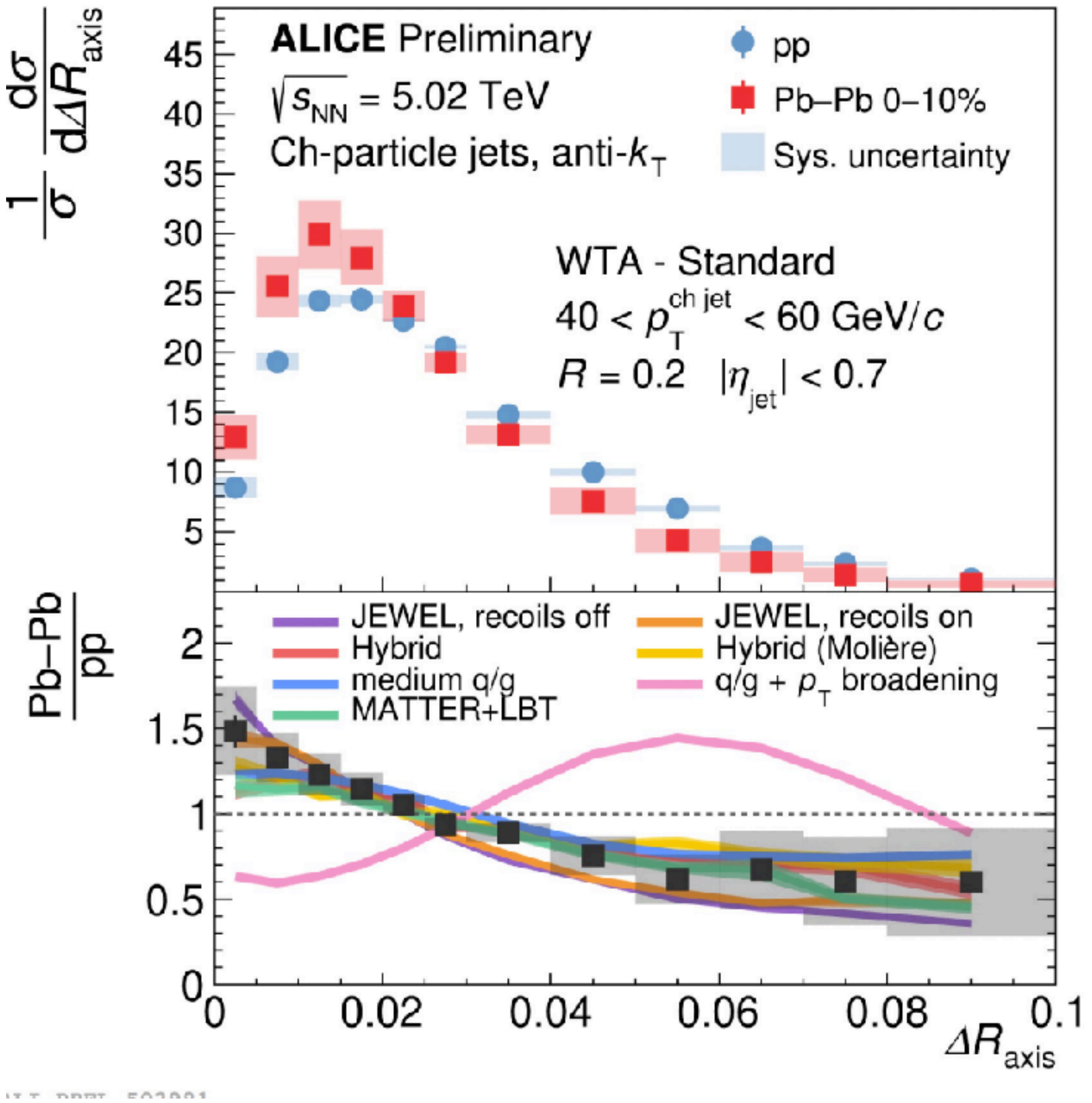
Pablos et al JHEP (2020) 044



- Model: coherence with changing q/g fractions?
  - -medium q/g

Yuan et al arXiv:1907.12541

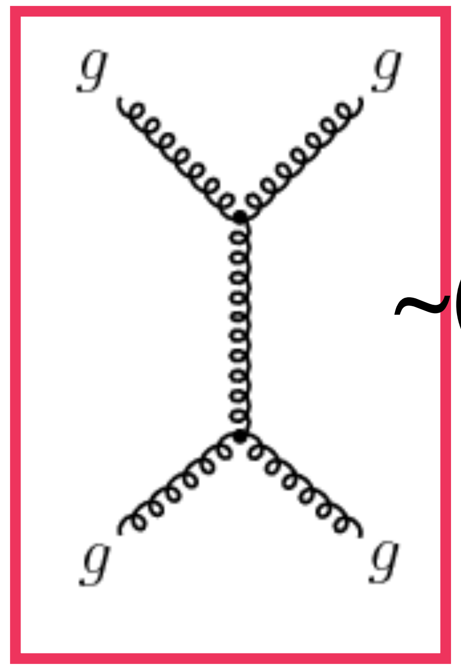




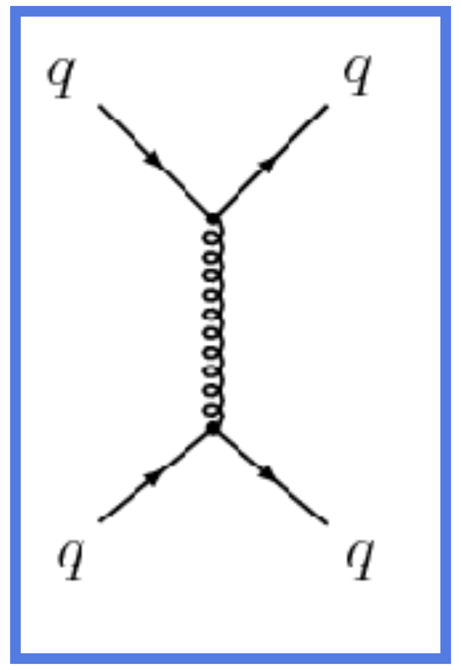
Jet charge: q/g fraction modification?

- Jet charge sensitive to electric charge of initial parton

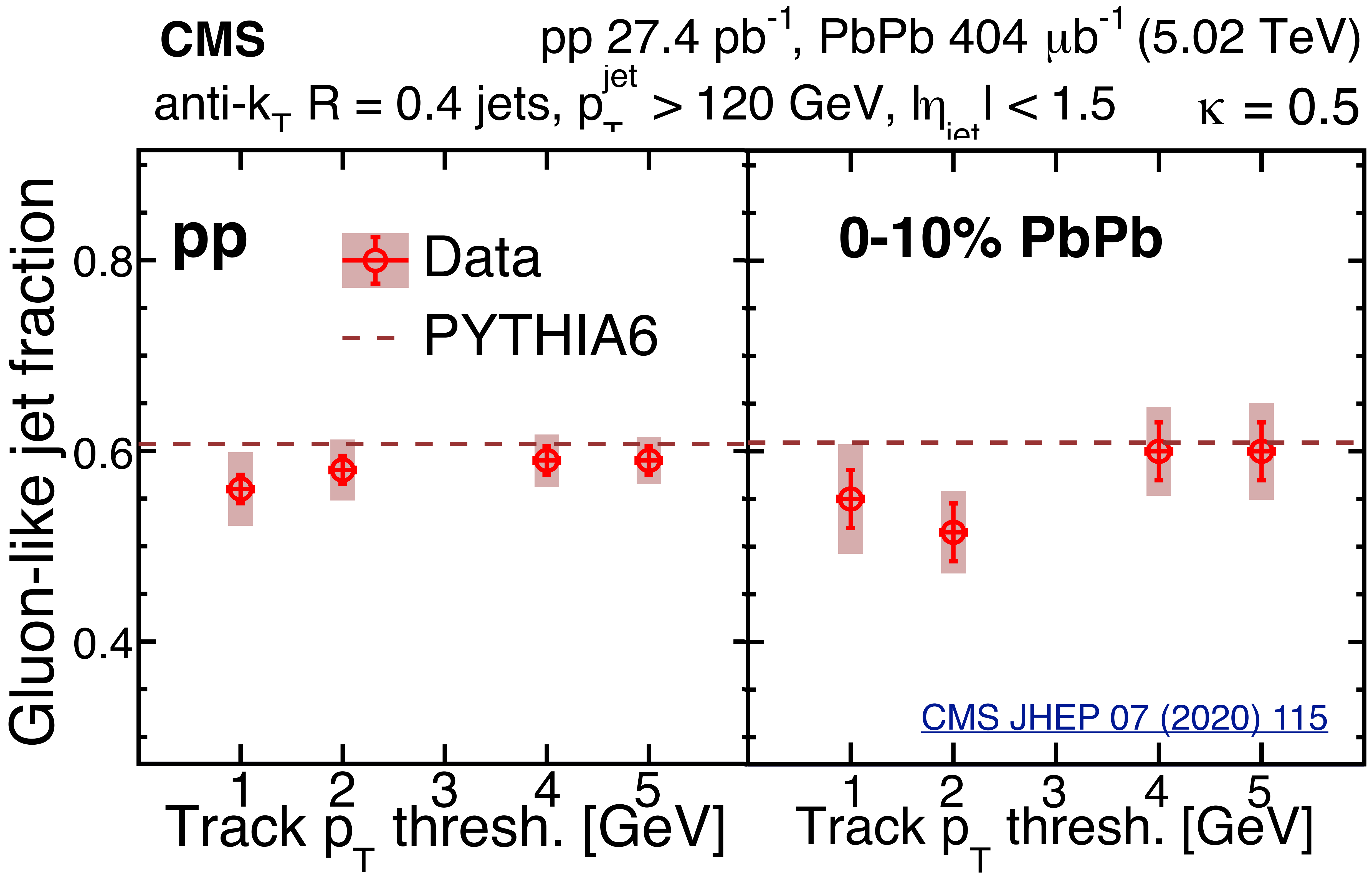
$$Q^k = \frac{1}{p_T^{jet}} \sum_{i \in jet} q_i p_{T,i}^k$$



~(9/4)² x



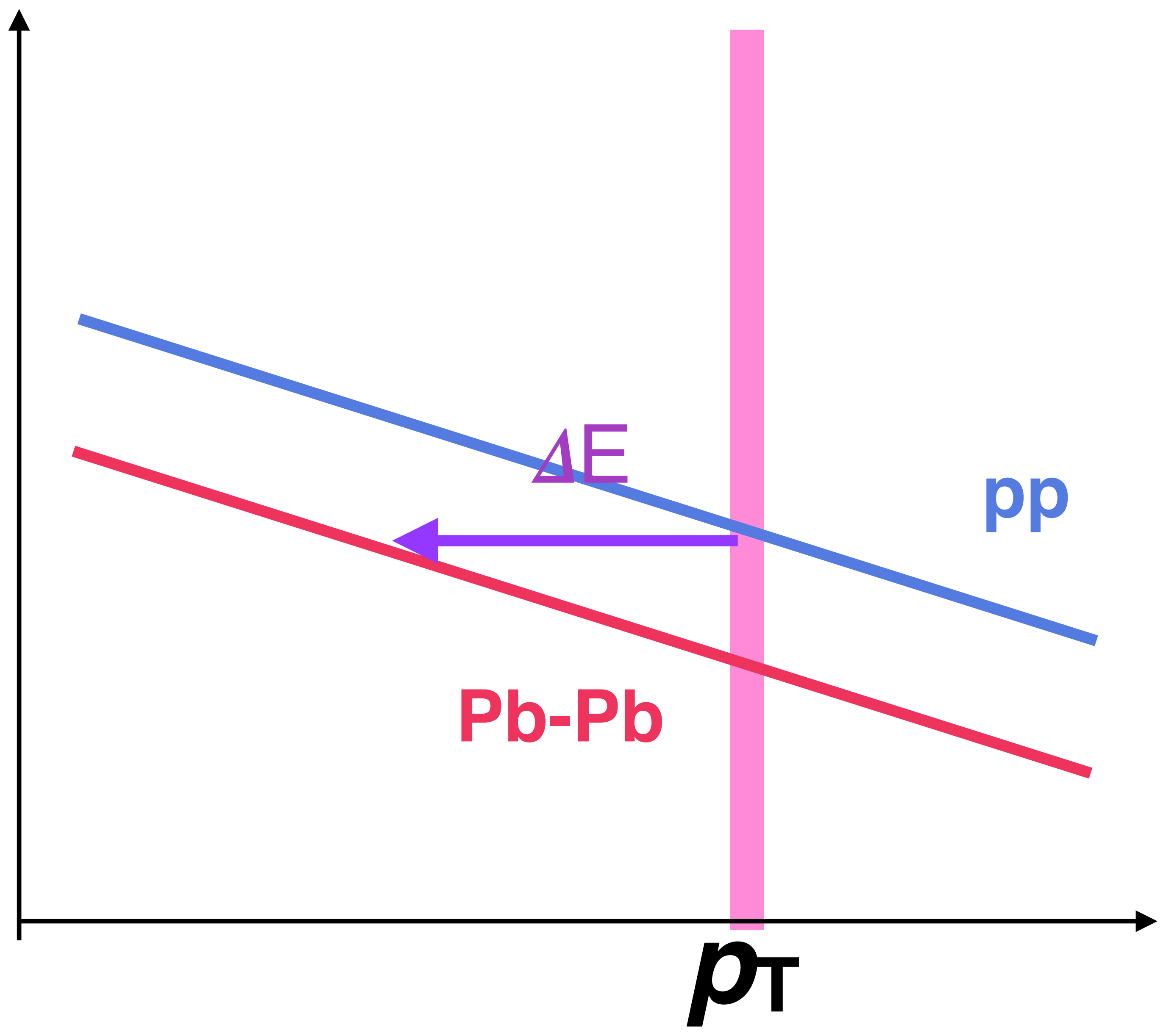
- Fractions in pp and Pb-Pb similar -> no modification of gluon fraction?



- *Possibly indicates that narrowing is due to decoherence effects!*
- Is this measurement sensitive to same effects as jet mass?

“Survivor Bias”

C. Nattrass recent talk at INT

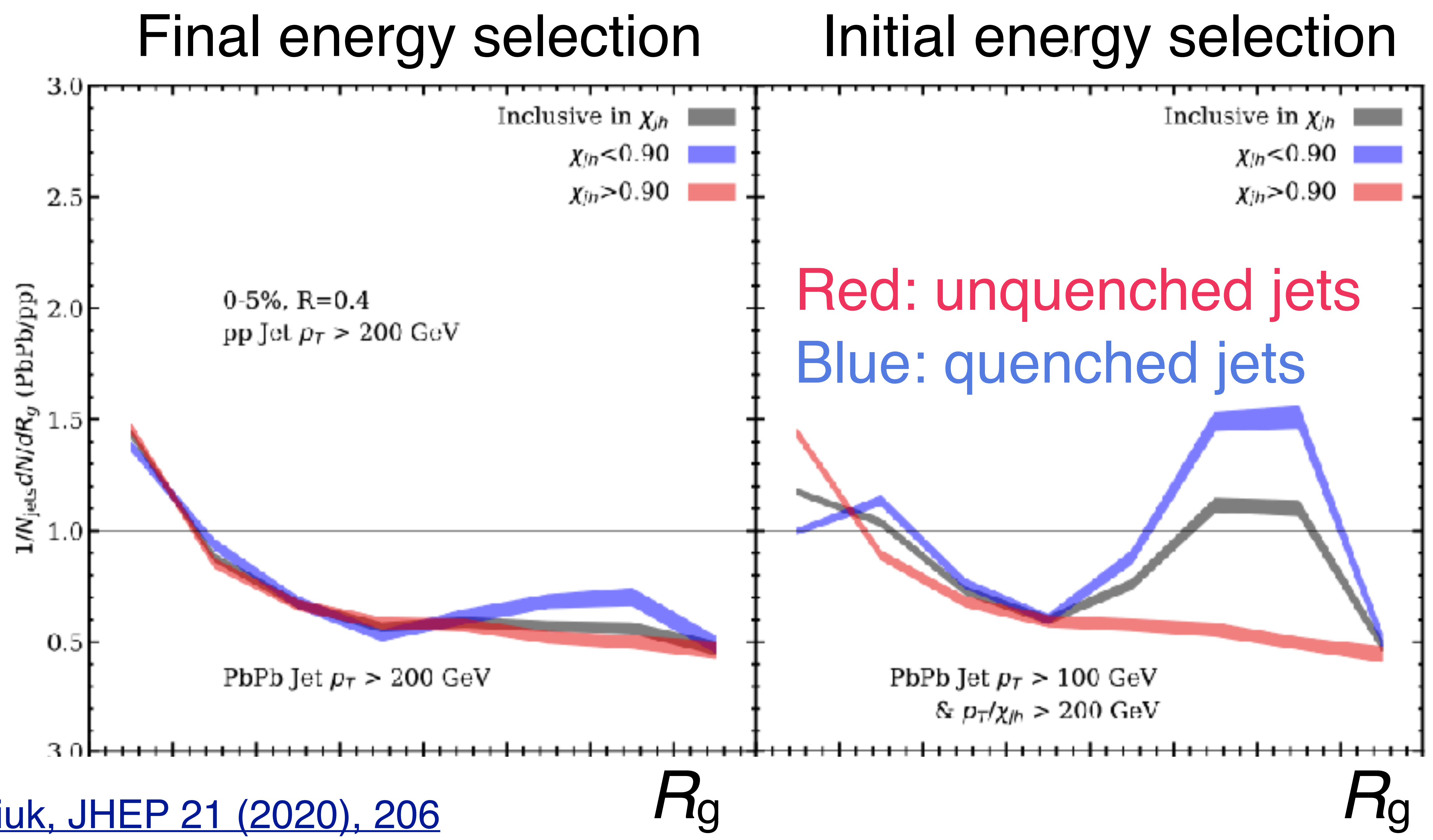


Comparing final modified Pb-Pb jet to unmodified pp jets instead of comparing the initial unmodified jets

“Survivor bias” where at a fixed p_T bin we are left with less quenched narrower jets

Cole, Spousta EPJ C76 (2016) 50
Caucal et al *JHEP* **2020,** 204 (2020)
Brewer, et al PRL **122**, 222301
Brodsky et al arXiv:2009.03316

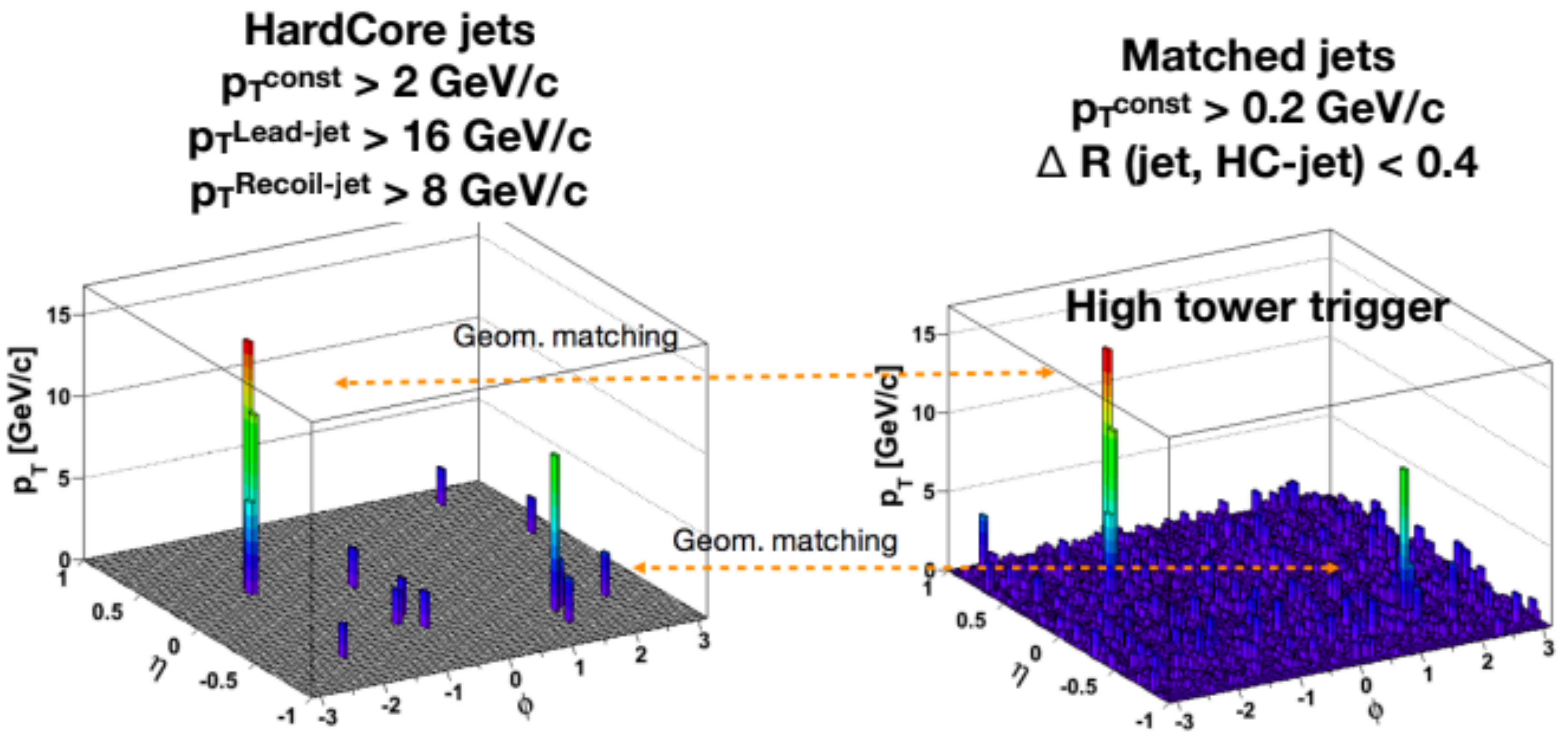
- Selection on the initial instead of final energy removes narrowing effect for more quenched jets in hybrid model

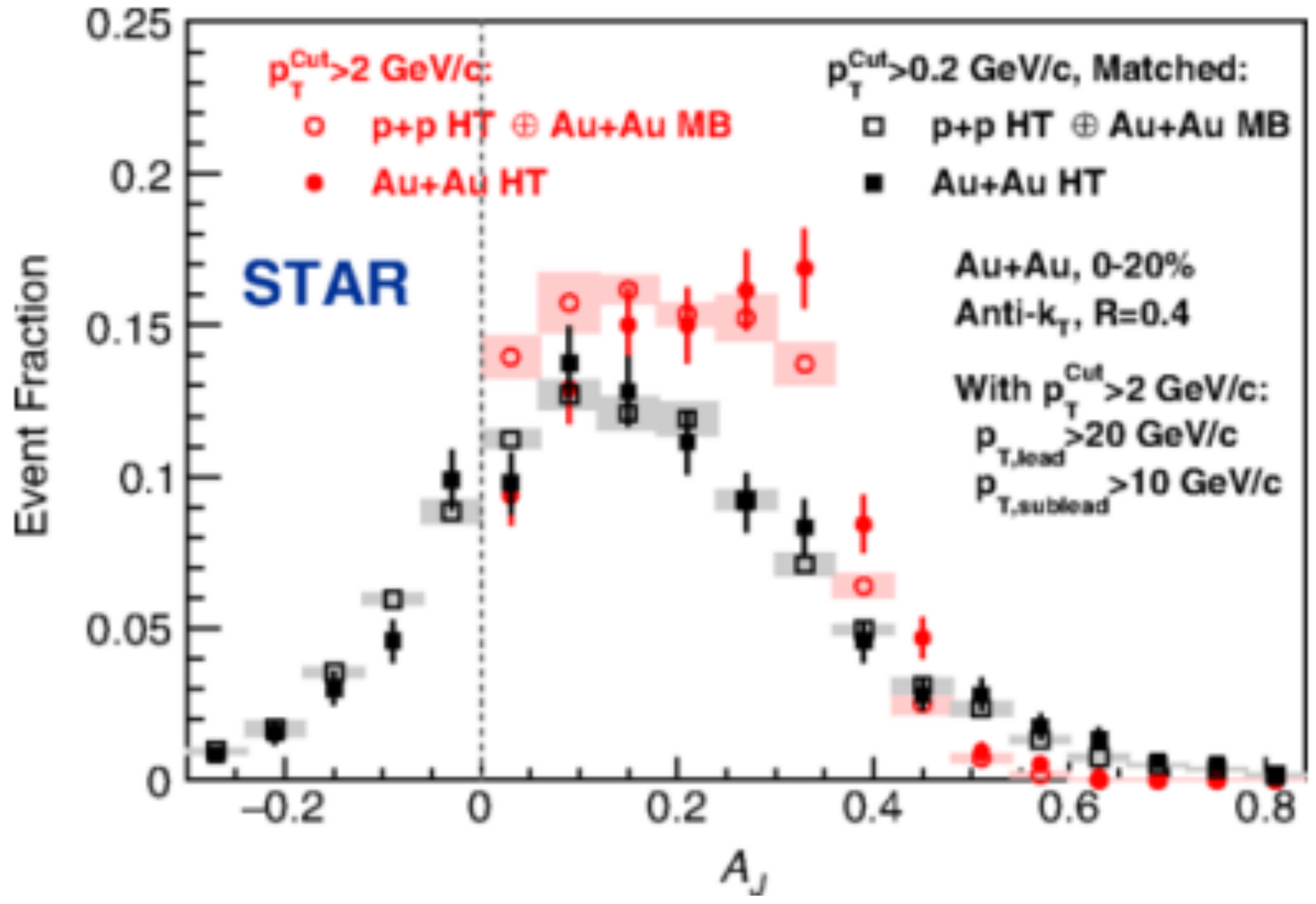


Du, Pablos, Tywoniuk, JHEP 21 (2020), 206

Jet substructure at RHIC

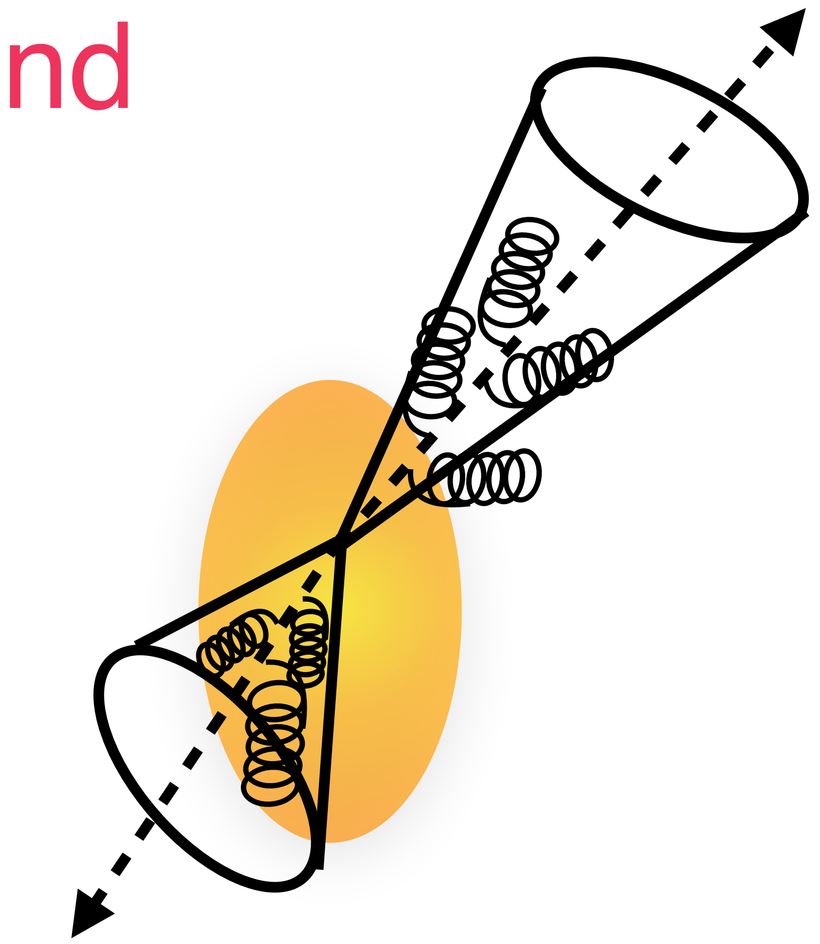
- STAR uses a HardCore selection to suppress the background
- Then matches to original jet to recover constituents





- HardCore jets are imbalanced and matched jets are balanced

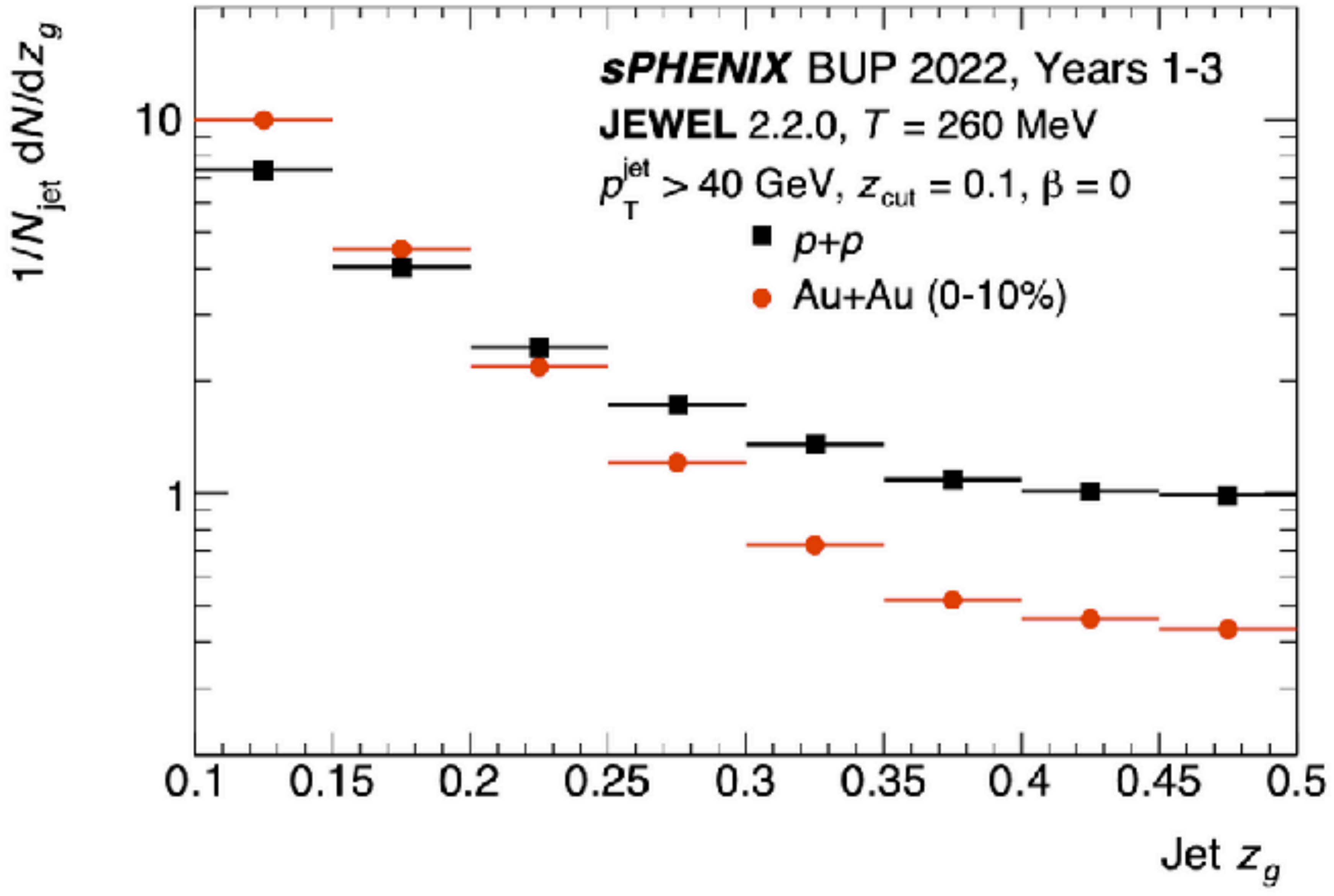
$$A_J = \frac{p_{T1} - p_{T2}}{p_{T1} + p_{T2}}$$

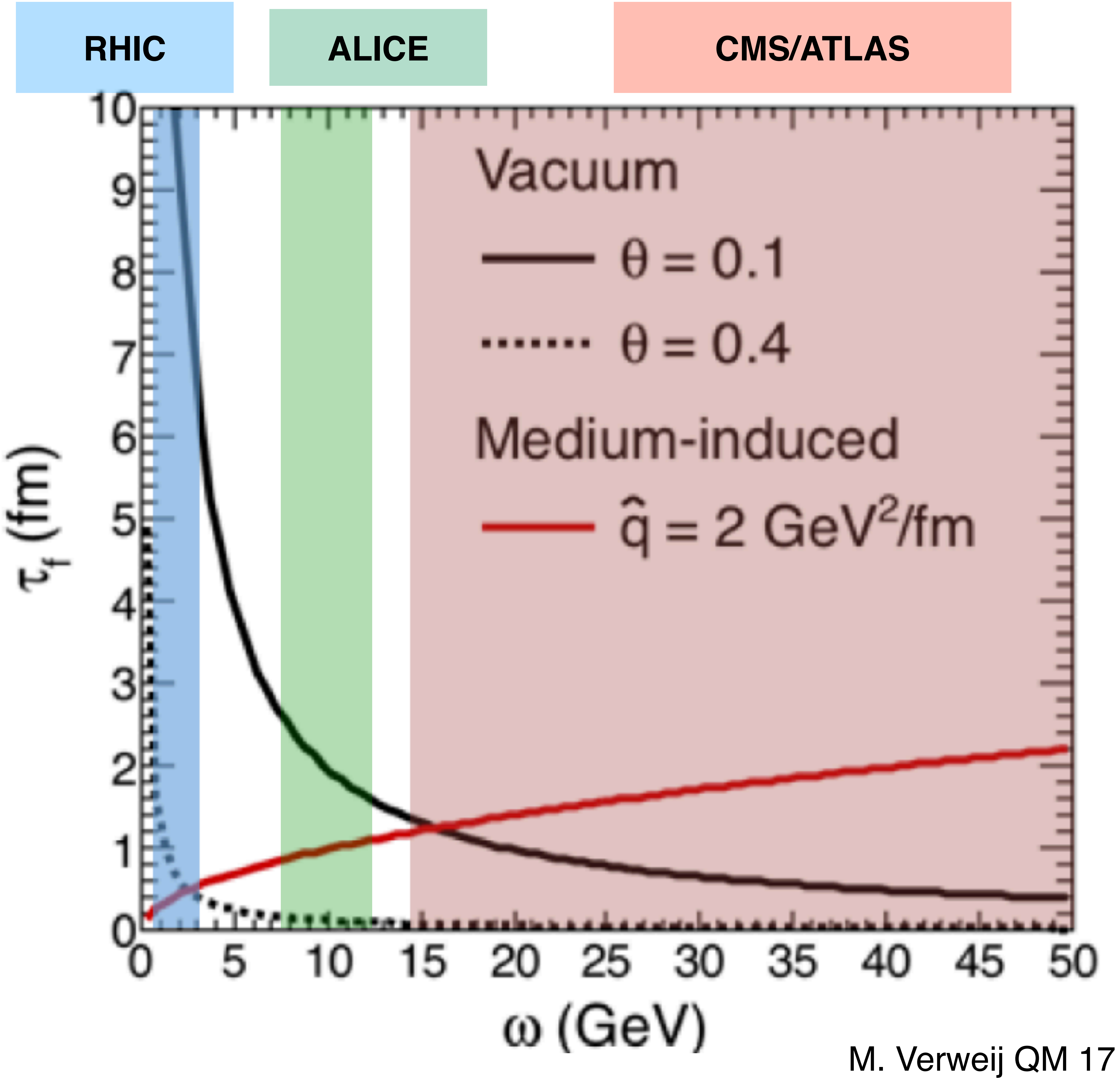


STAR, PRL 119 062301 (2017)

Jet splittings at RHIC

- Higher quark fraction could help resolve question about the selection bias and gluon suppression
- Lower jet pT will allow us to study different phase space
- Caveat: RHIC later formation times outside of medium?





M. Verweij QM 17