

Highlights, open questions and perspectives: Jets and high p_T



Laura Havener, Yale University
Hard Probes 2023, Aschaffenburg, Germany
Friday, March 31st 2023



Wright
Laboratory

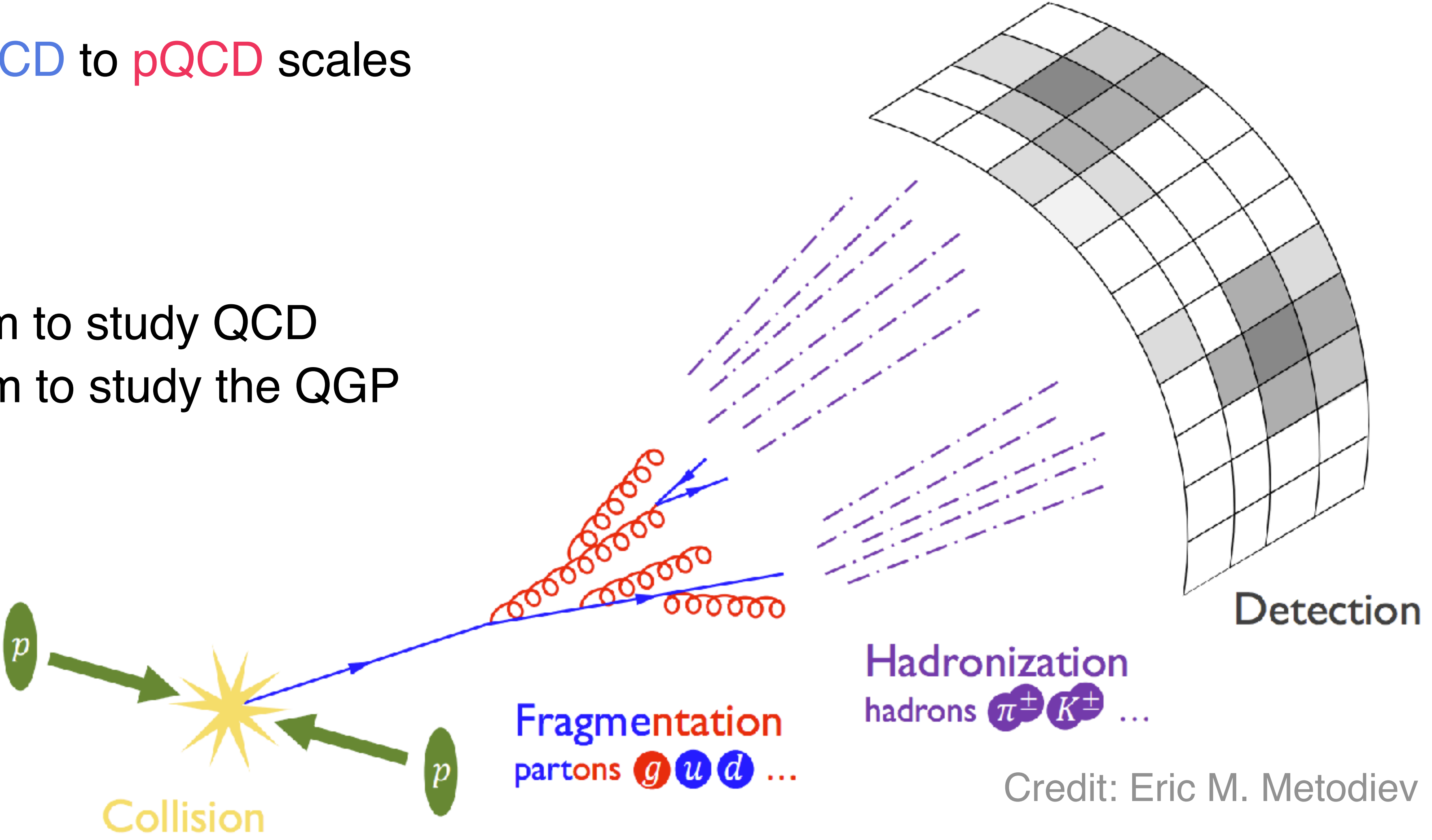
Yale

Jets and high p_T hadrons are QCD probes

Jets connect **npQCD** to **pQCD** scales

Outline

- 1. Jets in vacuum to study QCD
- 2. Jets in medium to study the QGP



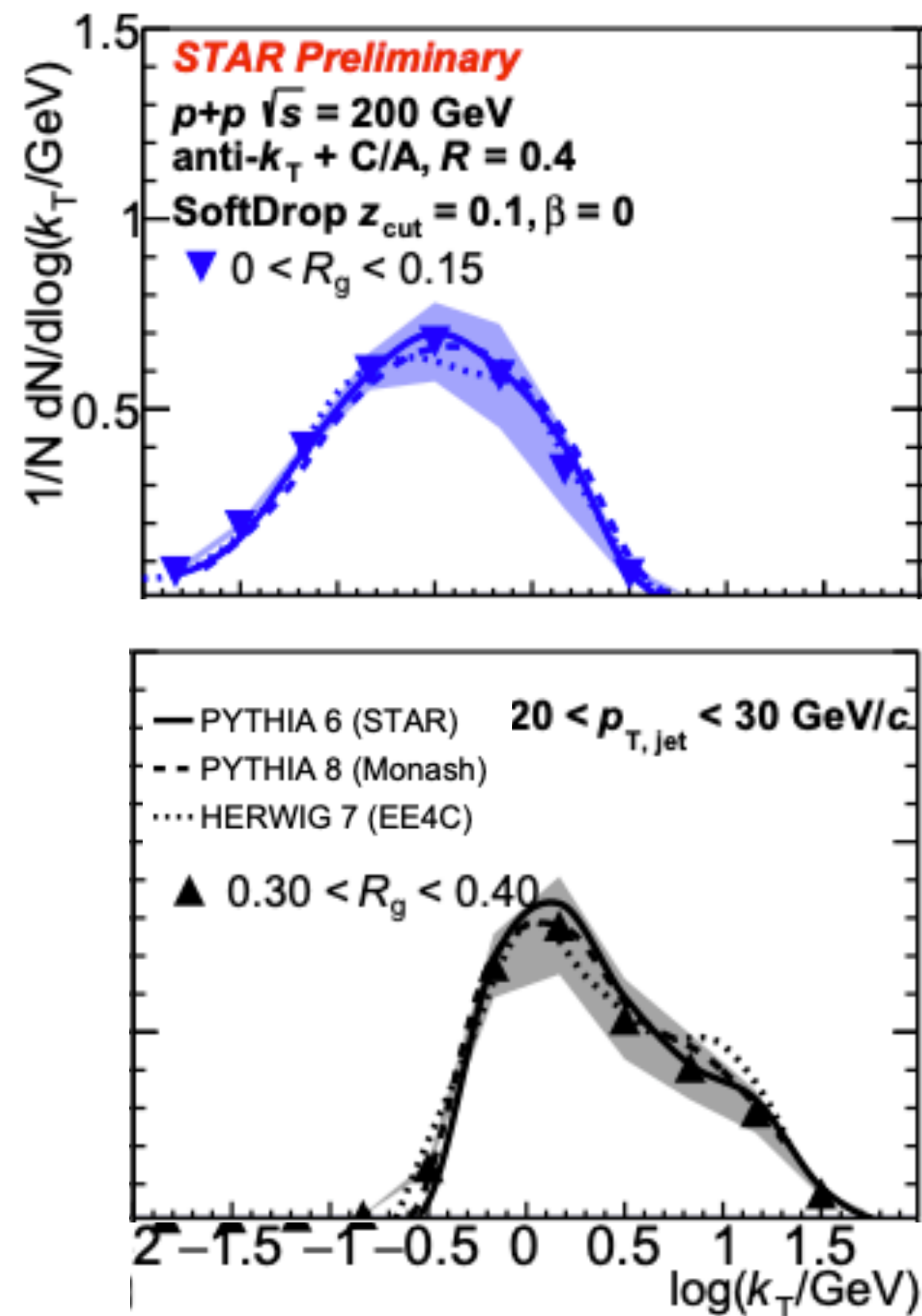
Credit: Eric M. Metodiev

Multi-scale dynamic objects whose complex structure contains QCD information

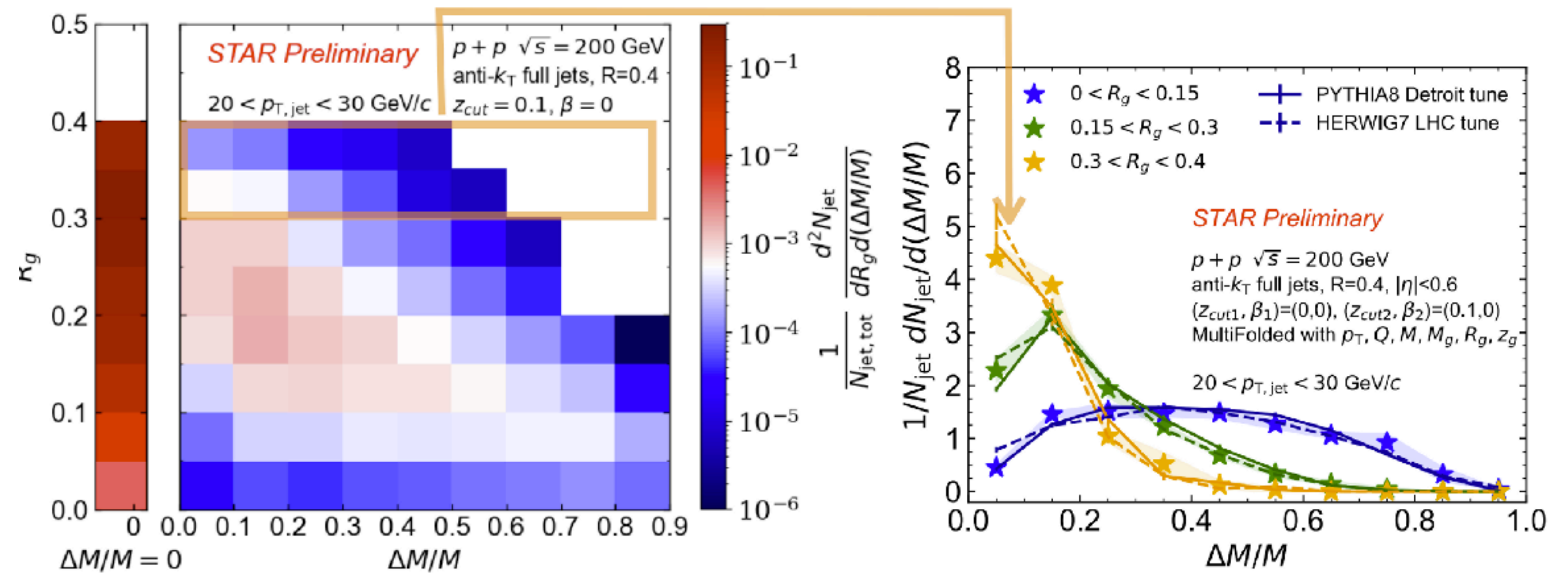
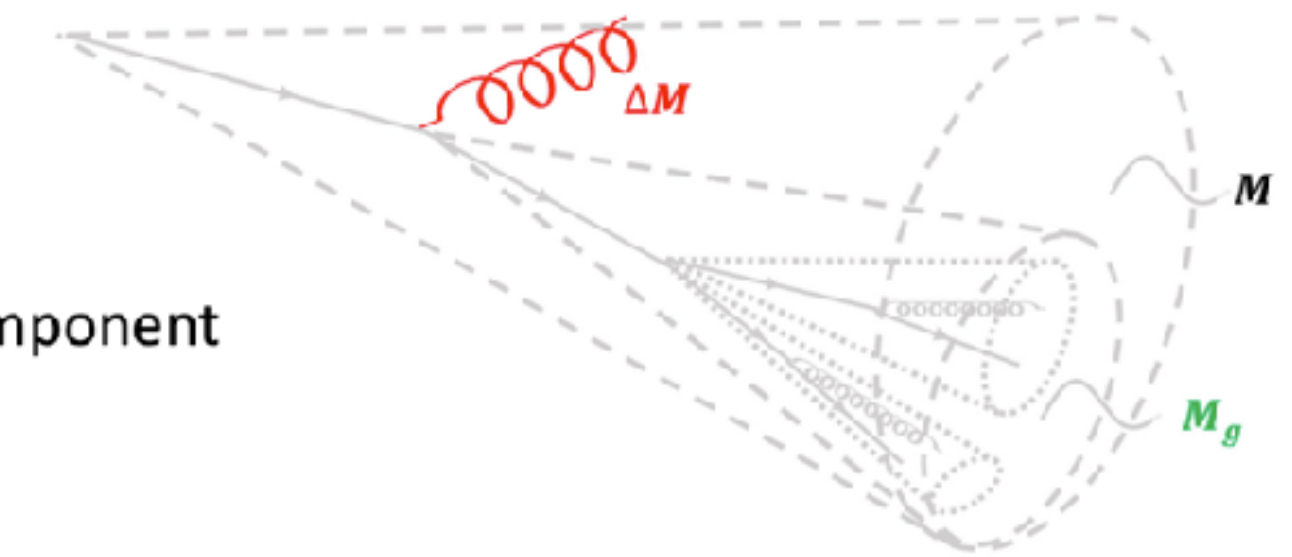
Multi-dimensional jet substructure

Relate splitting observables through 2D correlations in the Lund plane

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

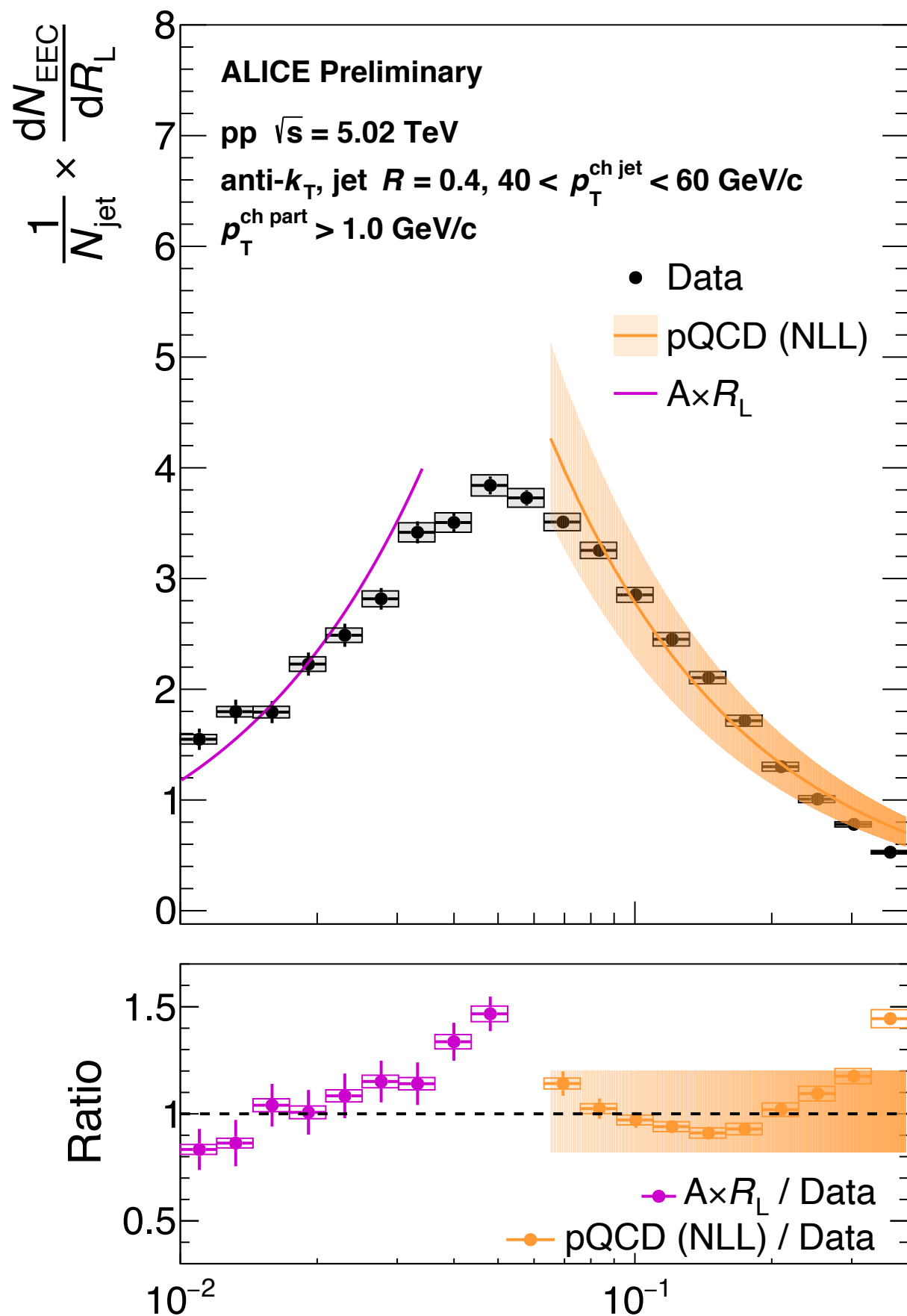


Collinear Drop: probes the soft component
 Chien and Stewart JHEP 2020, 64 (2020).

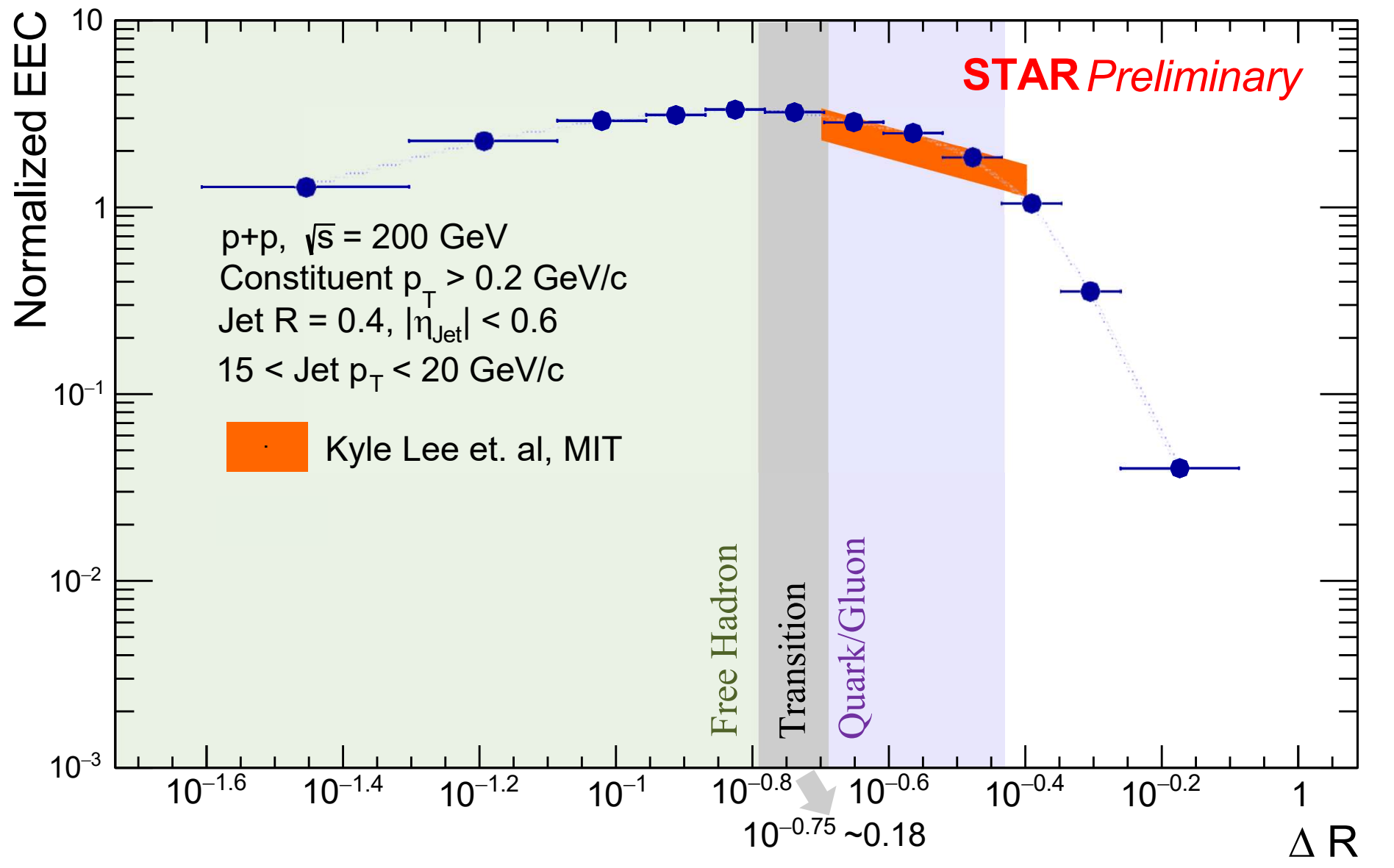
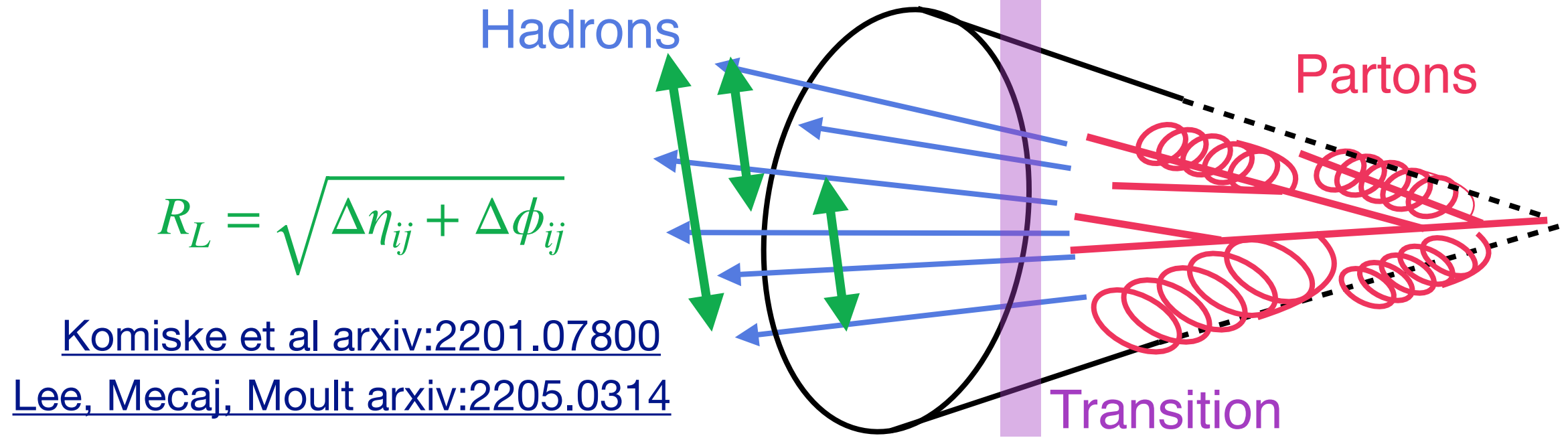


Connect the npQCD and pQCD parts of the shower

Energy correlators as a separation of scales



$R_L \sim R_{LP_T}^{\text{jet}} \sim \Lambda_{\text{QCD}}$

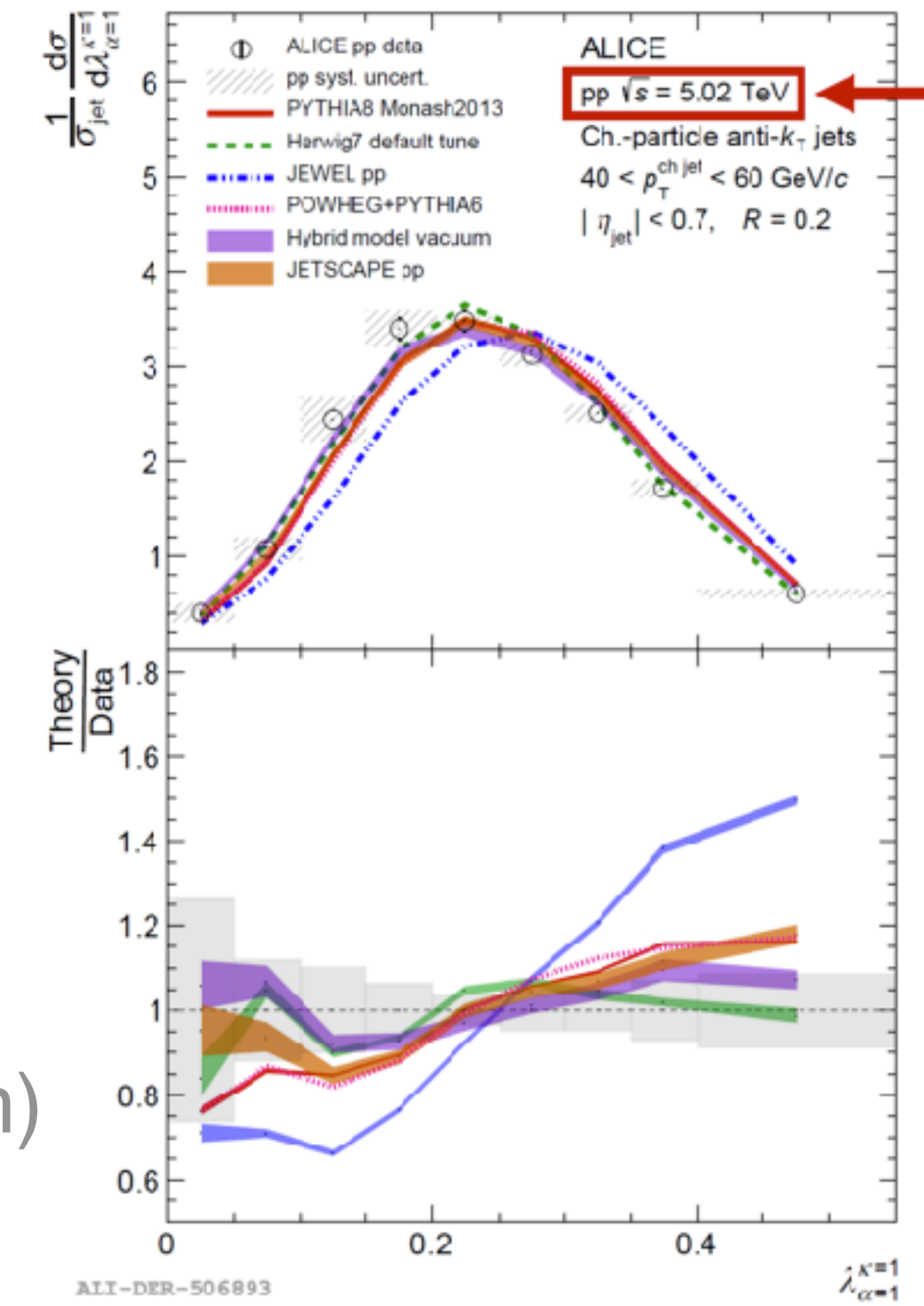


Clear distinction between pQCD and npQCD region around 2-3 GeV at RHIC and LHC: universal scaling

Lessons from pp data and model comparisons

- Measurements provide constraints to models in pp and HIs
- Not all models describe the pp baseline well

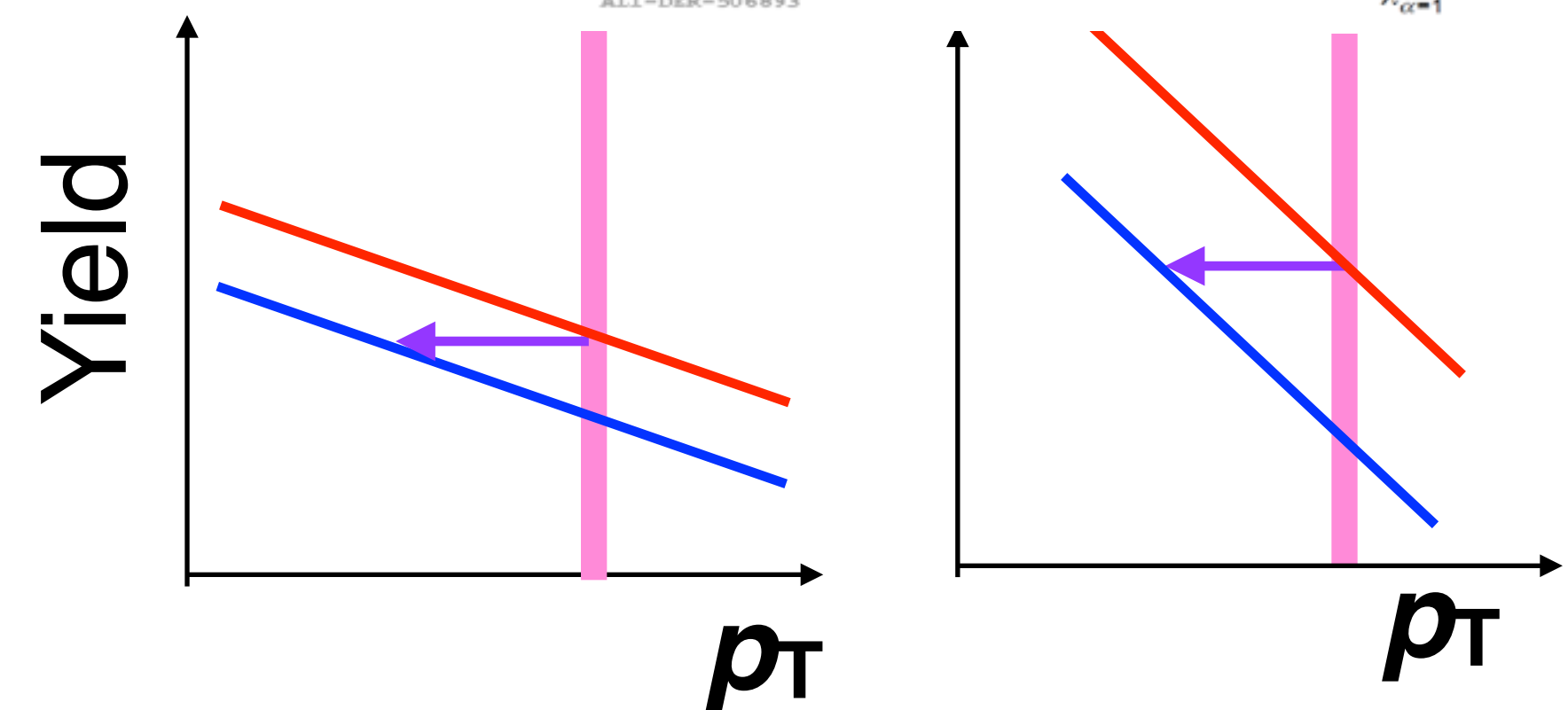
A. Soto-Ontoso (Mon. 5:05pm)



E. Lesser (Tues. 4:50pm)

- Differences in underlying pp distribution affect interpretation of HI measurements
- Ex: steepness of spectra, quark vs. gluon structure

L. Apolinário (Mon. 5:55 pm)

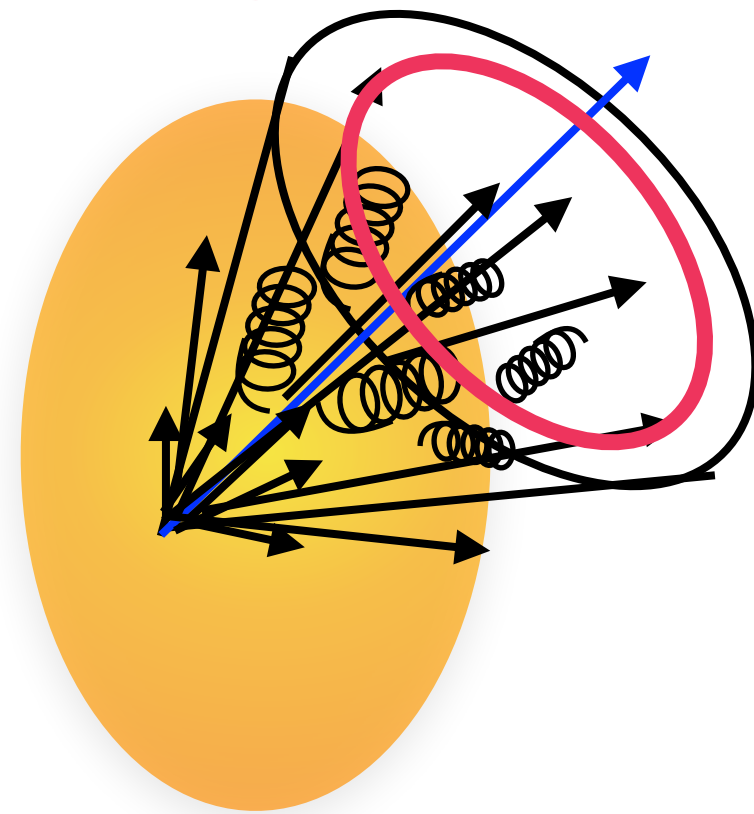


Jets as a probe of the quark-gluon plasma

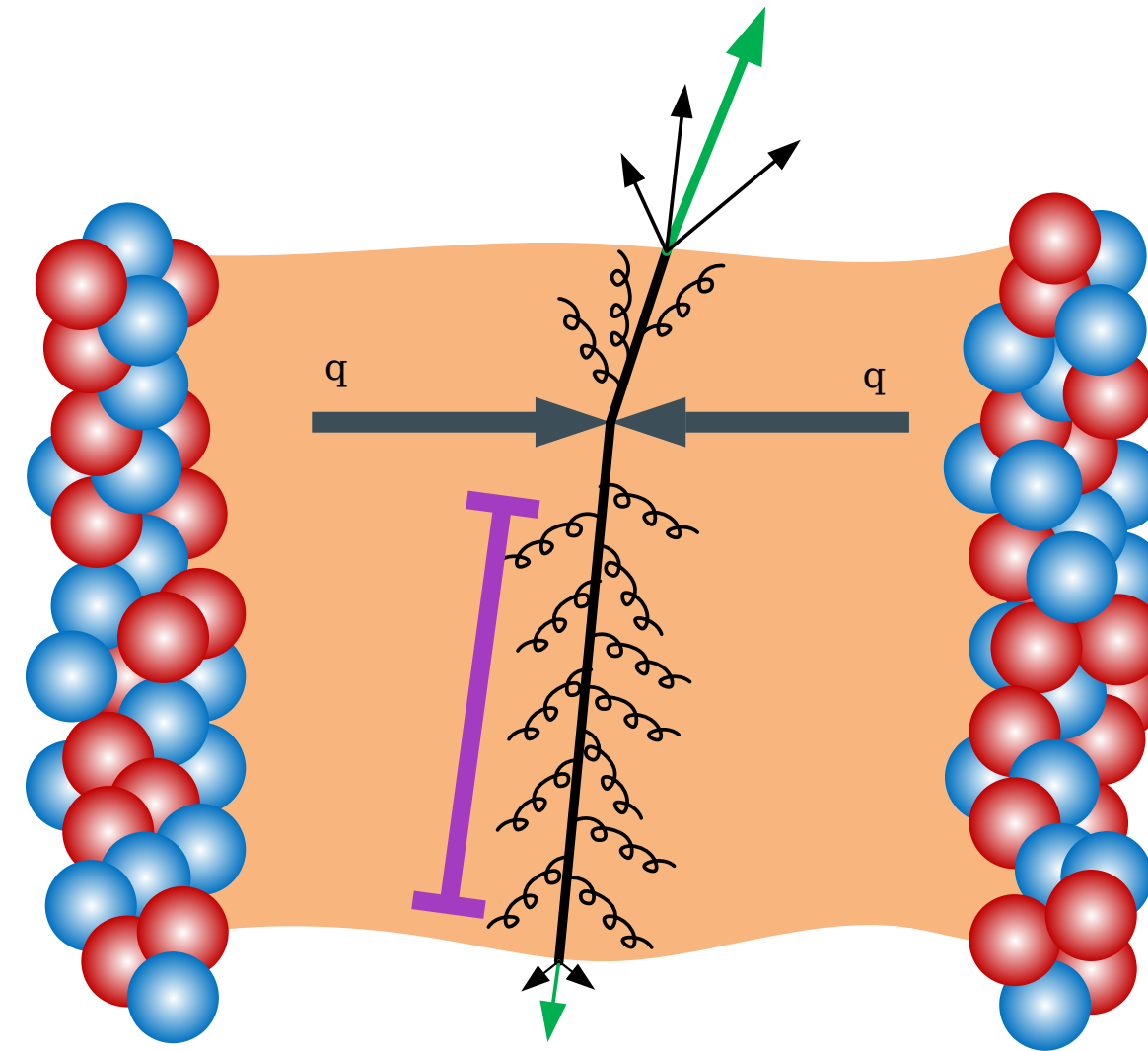
Jet quenching: jet energy loss and substructure modification

Depends on the **path** traveled in the medium

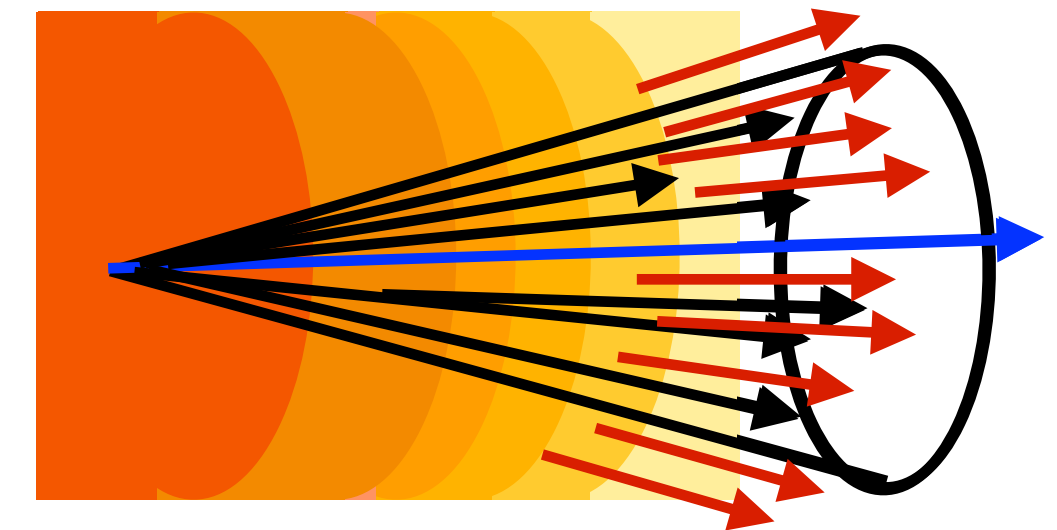
Soft gluon emissions cause **momentum broadening**, widening the jet



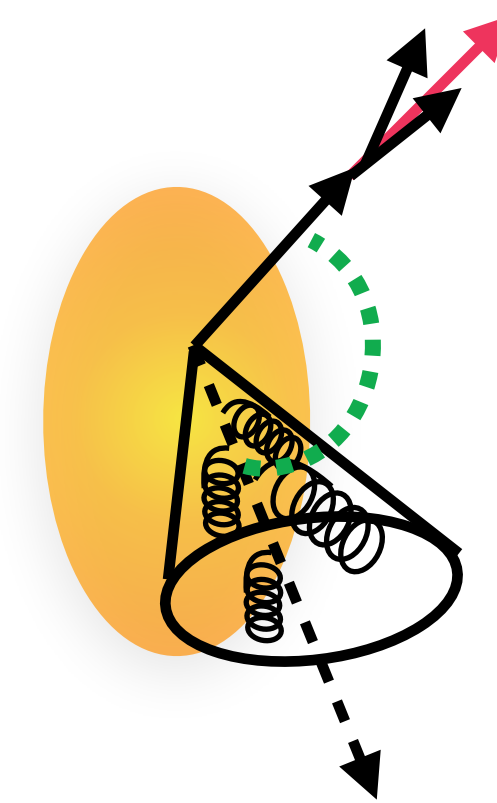
Flavor dependence



Medium response, causing a wake of soft particles



Moliere scattering causes **wide-angle deflection**



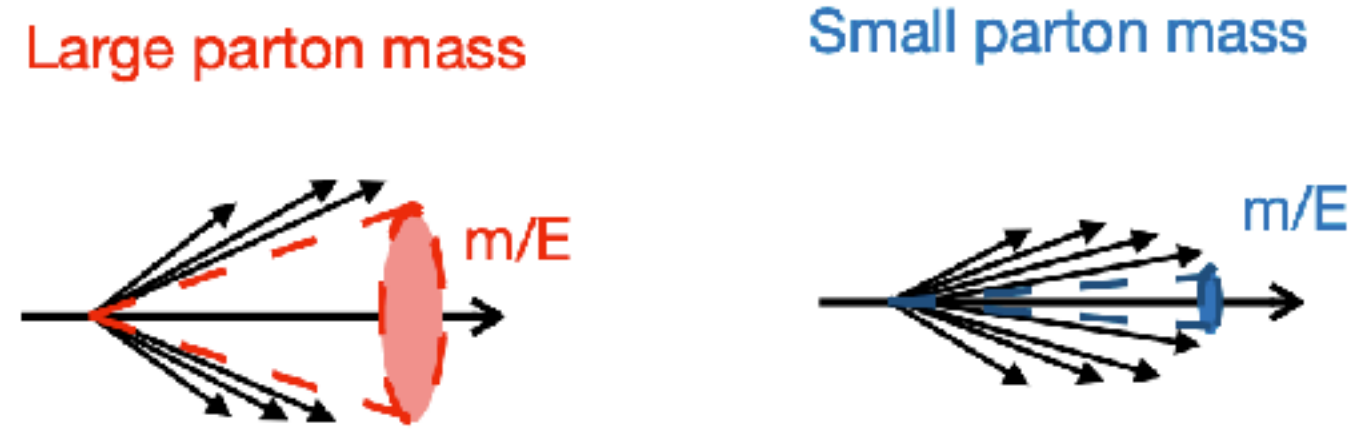
Goal: design observables to disentangle effects and extract properties of the QGP

Energy loss dependence on parton flavor

Flavor and mass dependence

$$E_{\text{loss}}^g > E_{\text{loss}}^q > E_{\text{loss}}^{\text{HQ}}$$

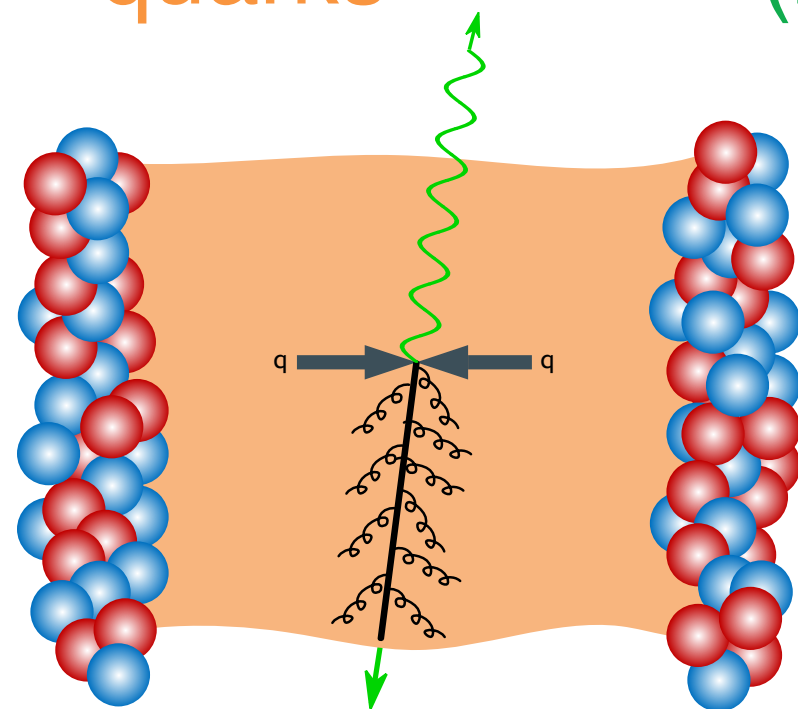
Dead-cone effect



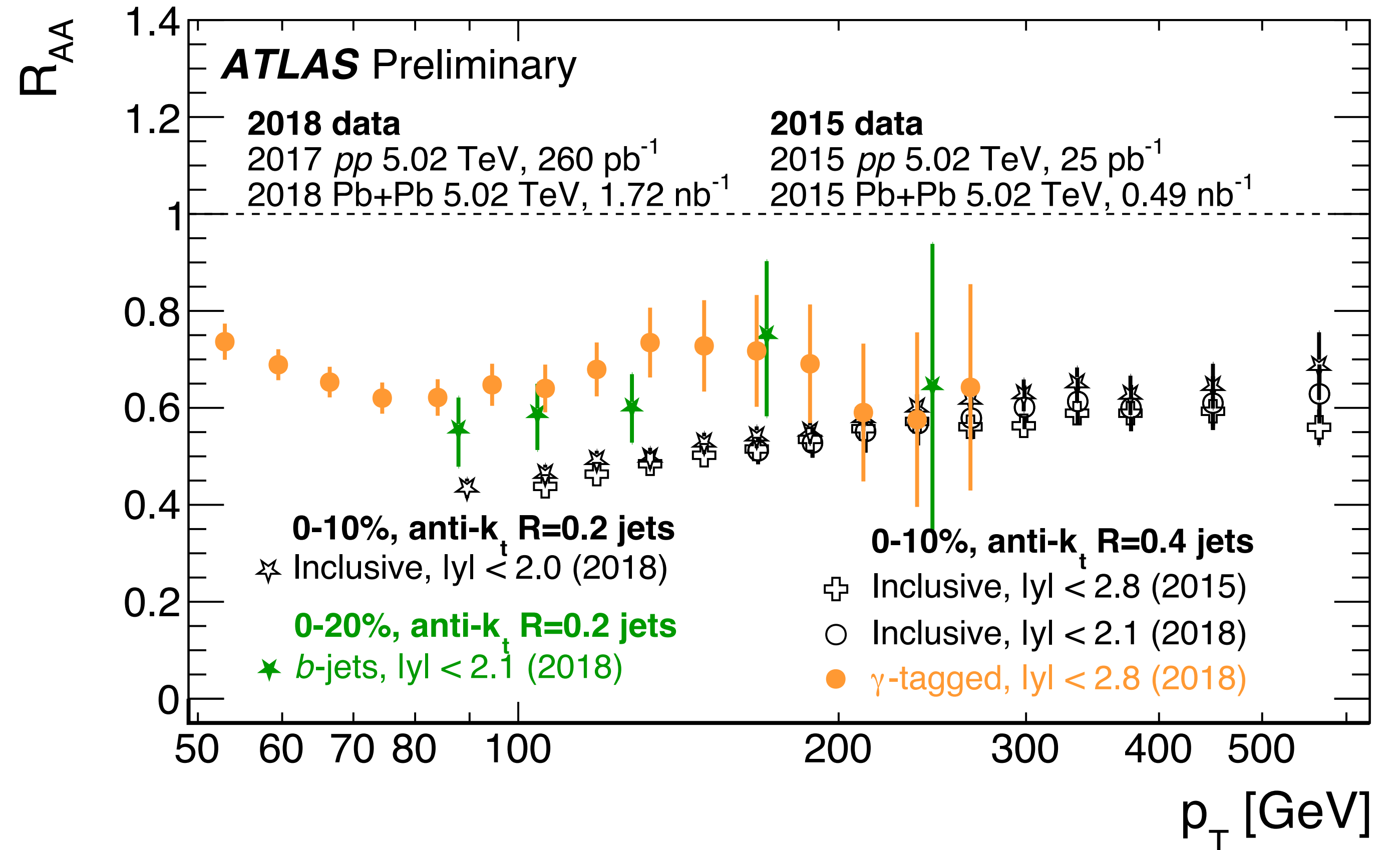
“Inclusive
~ gluons”

“Photon-tag
~ quarks”

b-tagged jets
(beauty)



Caveat: “spectra steepness” plays a role!

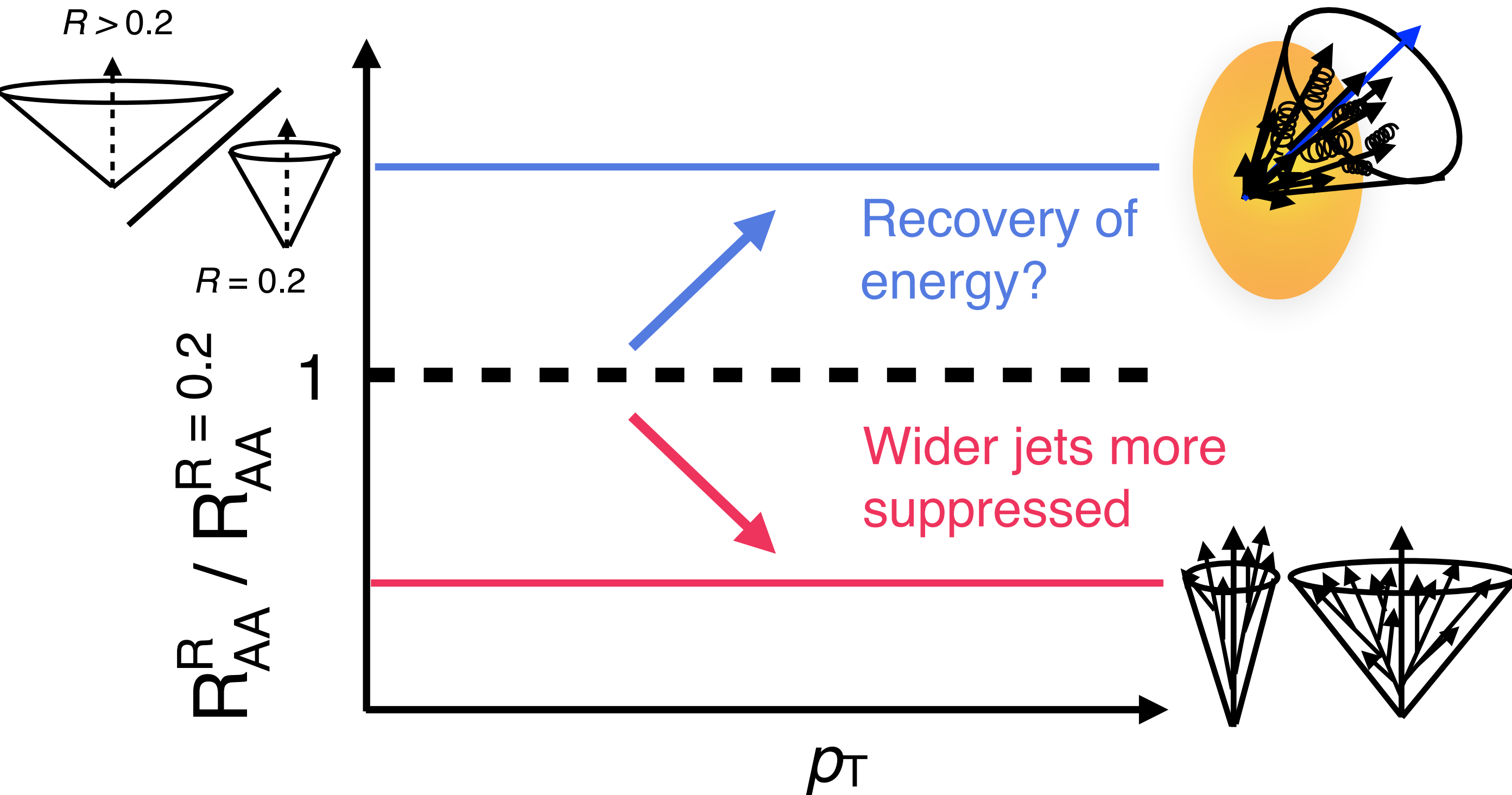


Energy loss depends on color charge
(and mass of parton?)

Vary jet R to disentangle medium effects

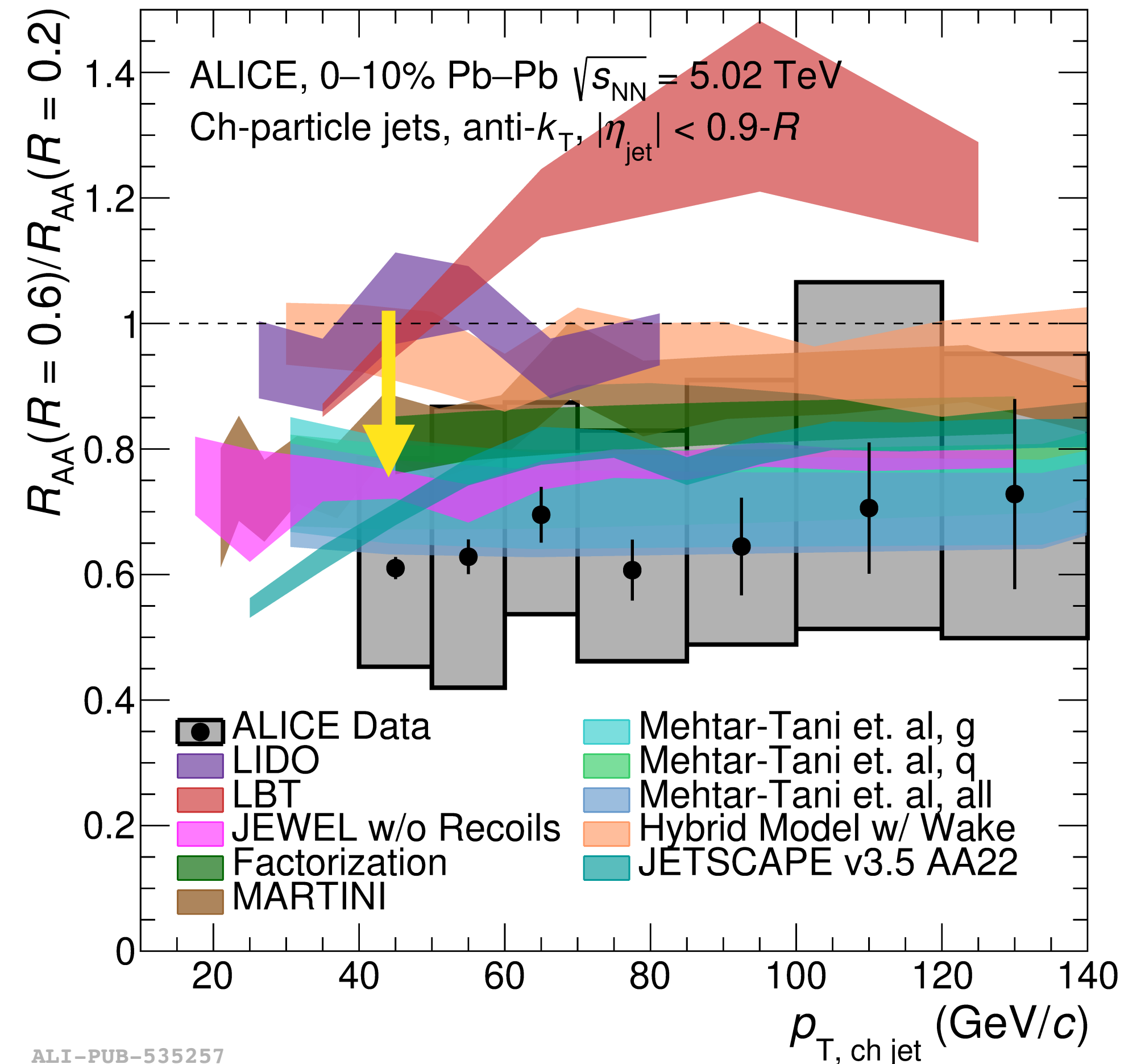
ML-based correction for background [Haake, Loizides PRC 99, 064904 \(2019\)](#)

[ALICE arXiv:2303.00592](#)



Larger jets more suppressed: **jets are narrowed in the QGP**

Discriminating power for models



ALI-PUB-535257

Caveat: tension at low p_T with **ATLAS result**

[Phys. Lett. B 719 \(2013\) 220-241](#)

Path length dependence of energy loss

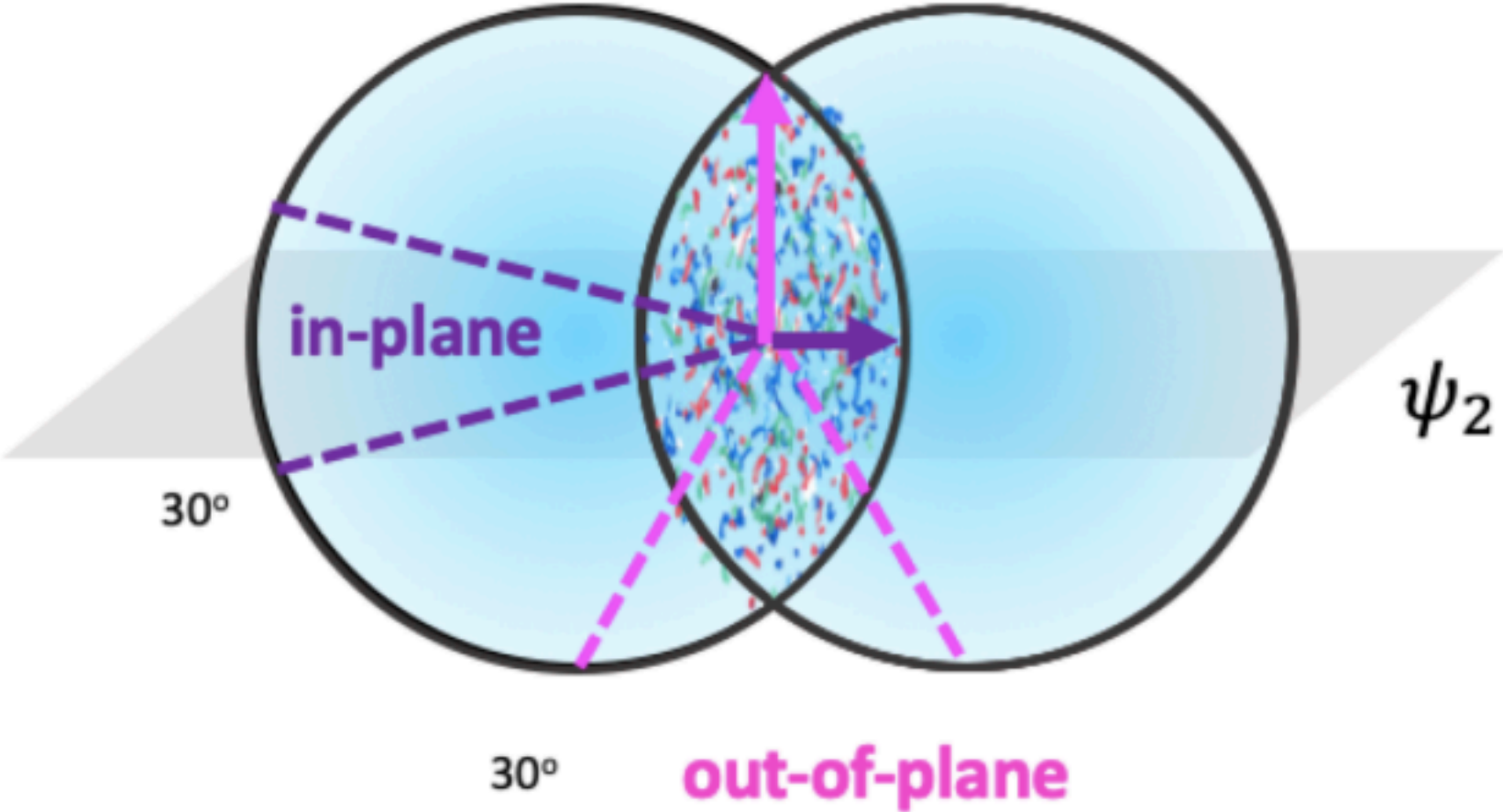
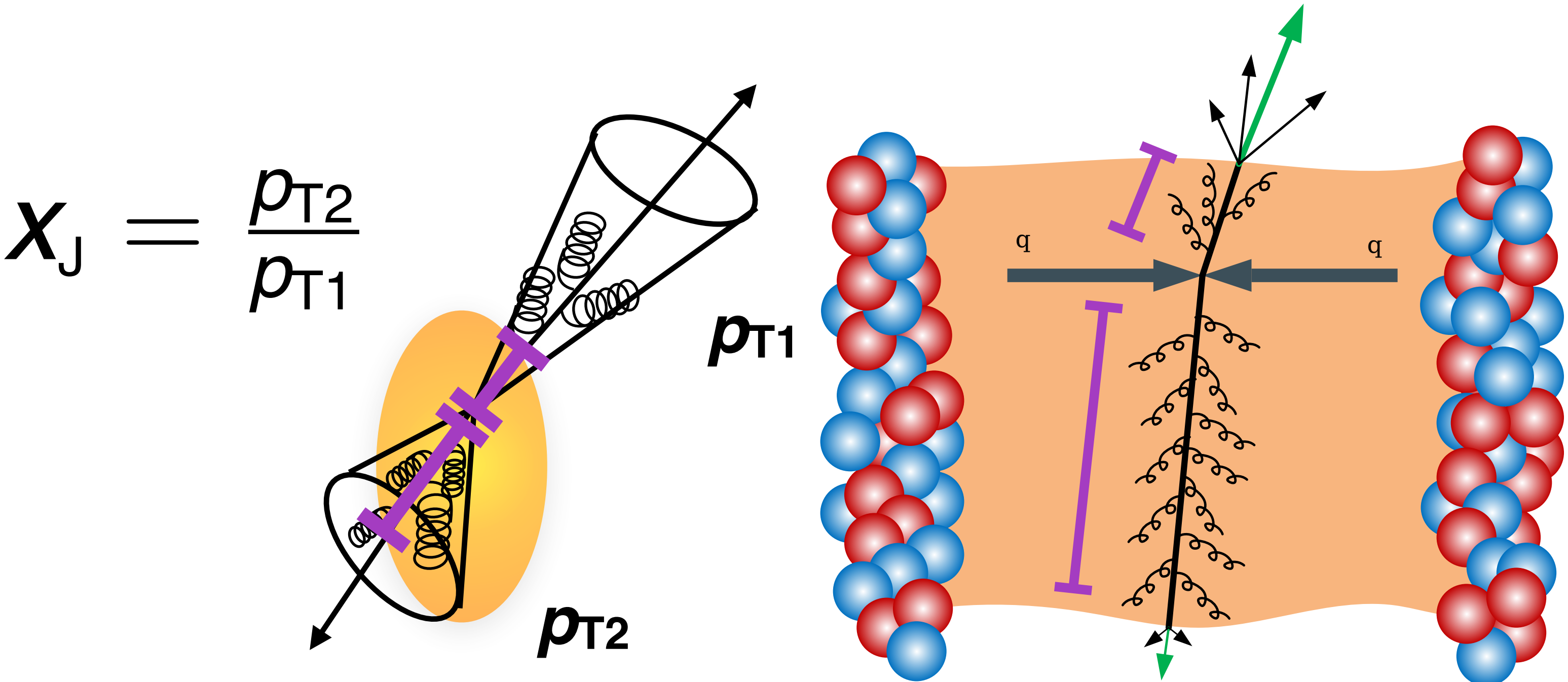
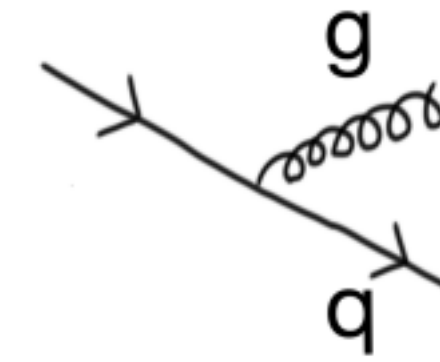


Image credit: Caitie Beattie

Dijet asymmetry: expected **imbalance** due to different paths and fluctuations in jet and energy loss

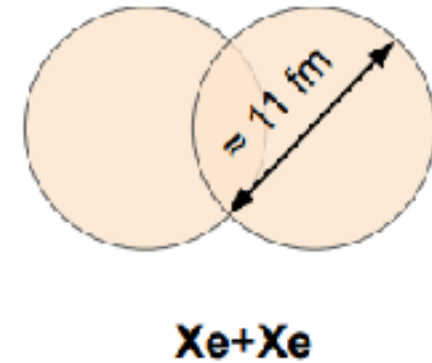
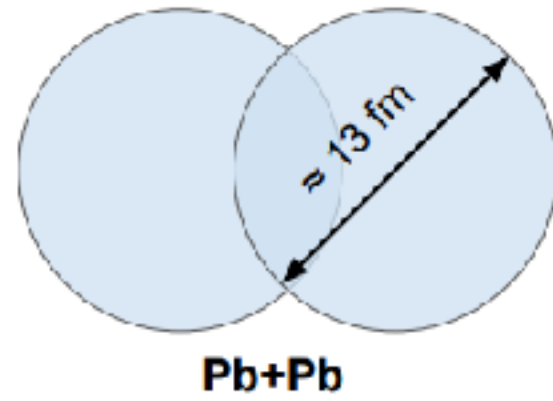
Event plane dependence: expect **reduced yield out-of-plane**

Momentum imbalance

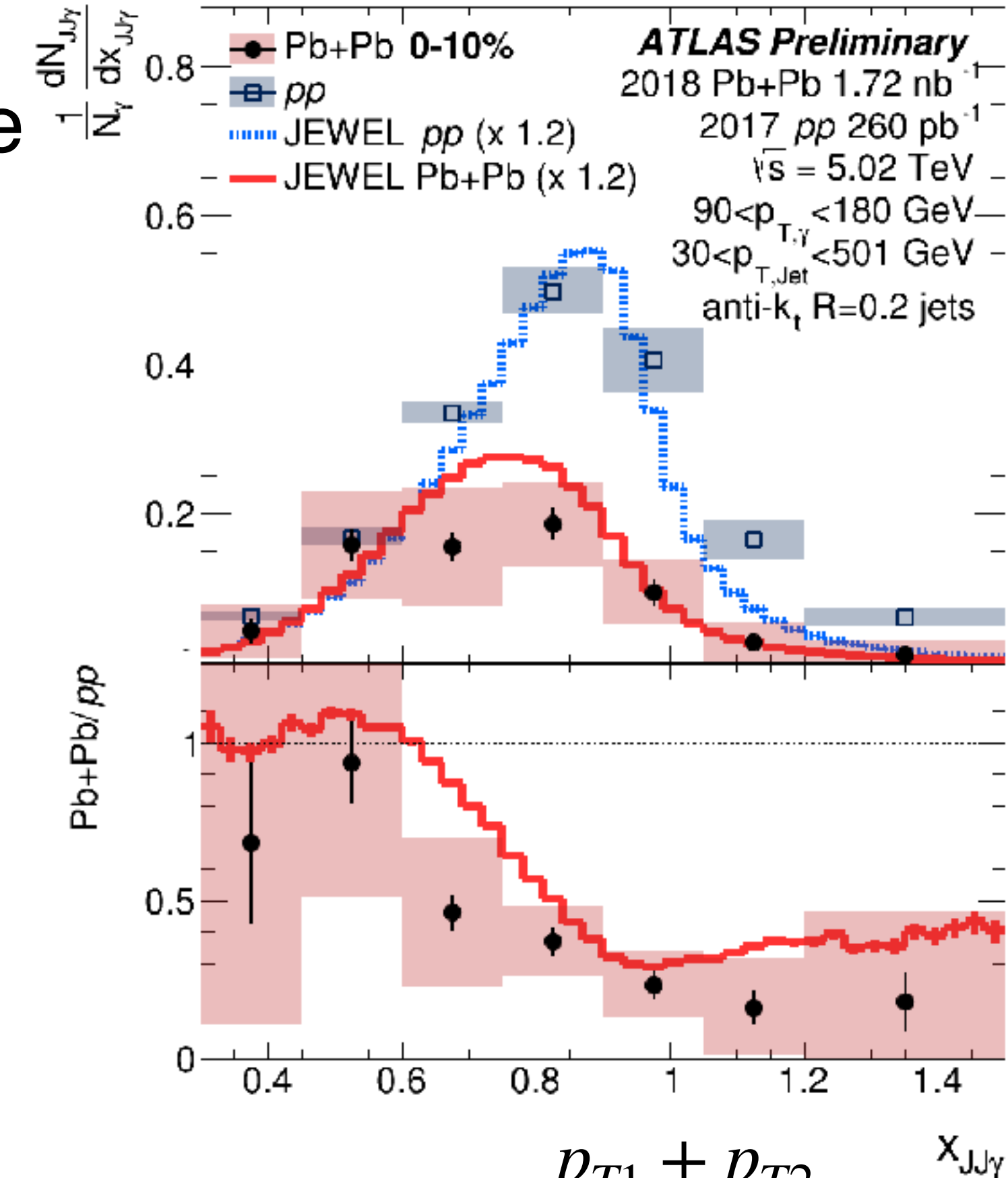
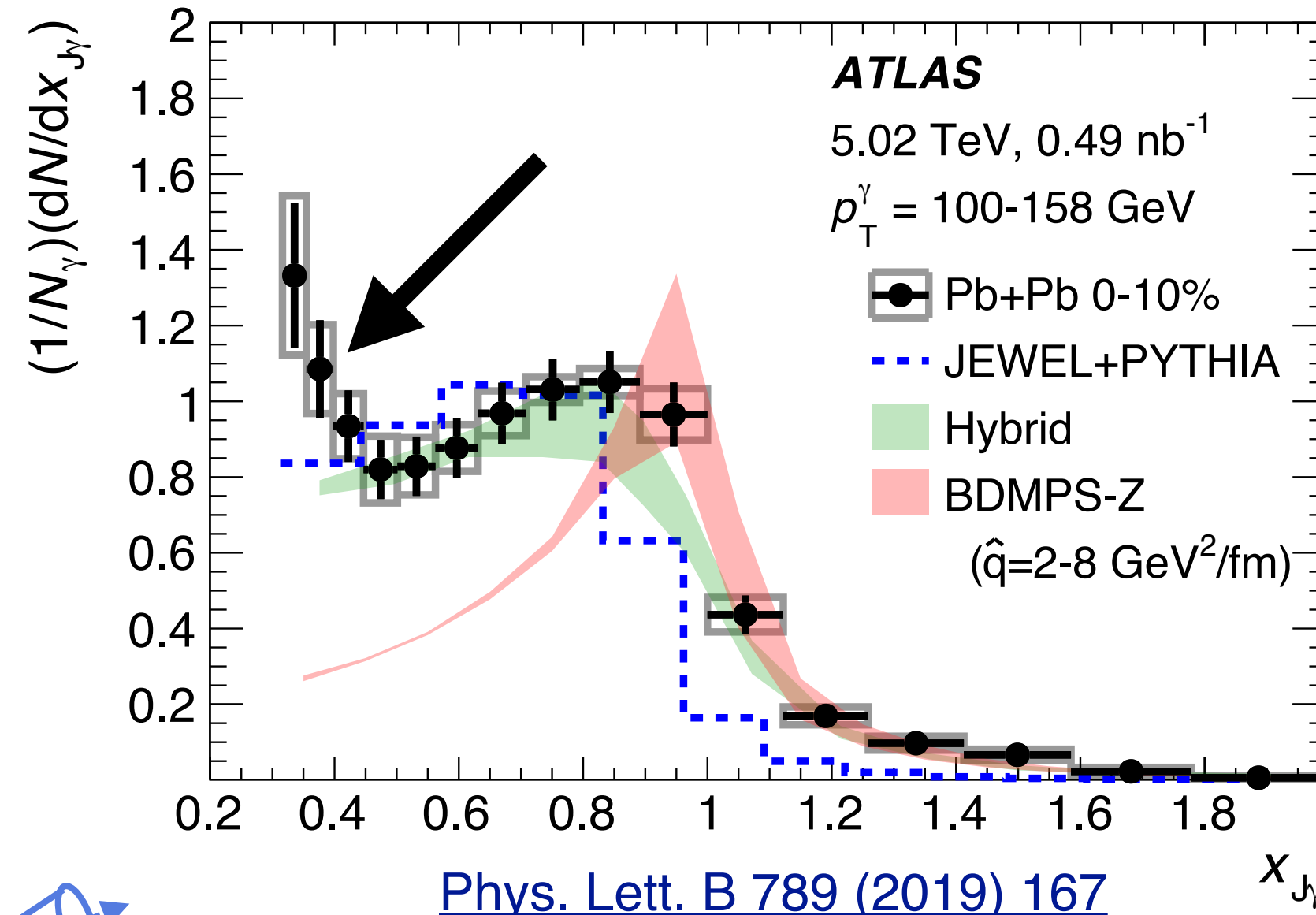
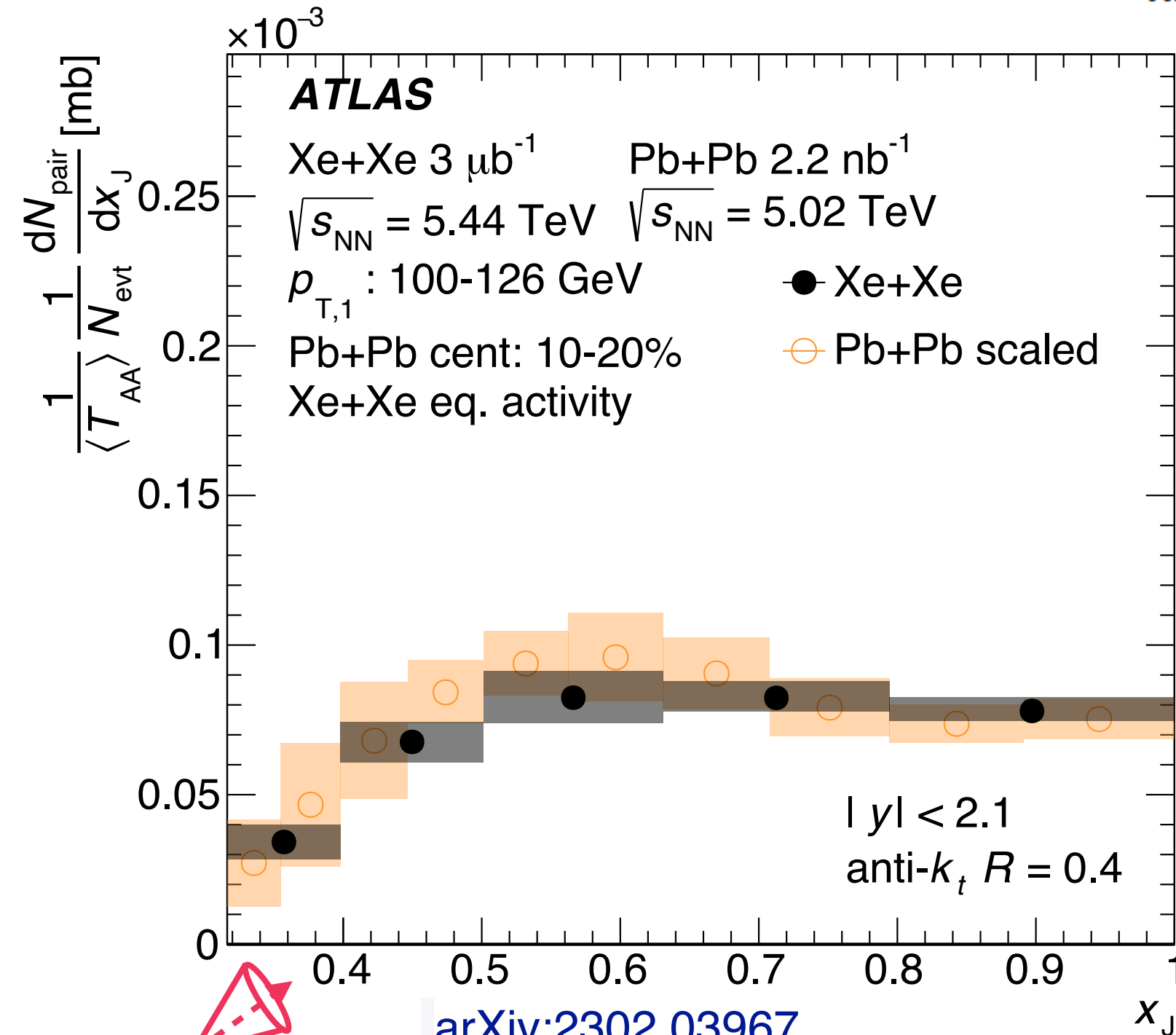


ATLAS-CONF-2023-008

$$X_J = \frac{p_{T2}}{p_{T1}}$$



Photon+jet shows increased asymmetry in medium but is the structure from photon+2 jets?



$$x_{JJ\gamma} = \frac{p_{T1} + p_{T2}}{p_{T\gamma}}$$

Same asymmetry in Xe+Xe and Pb+Pb at fixed geometry and event activity

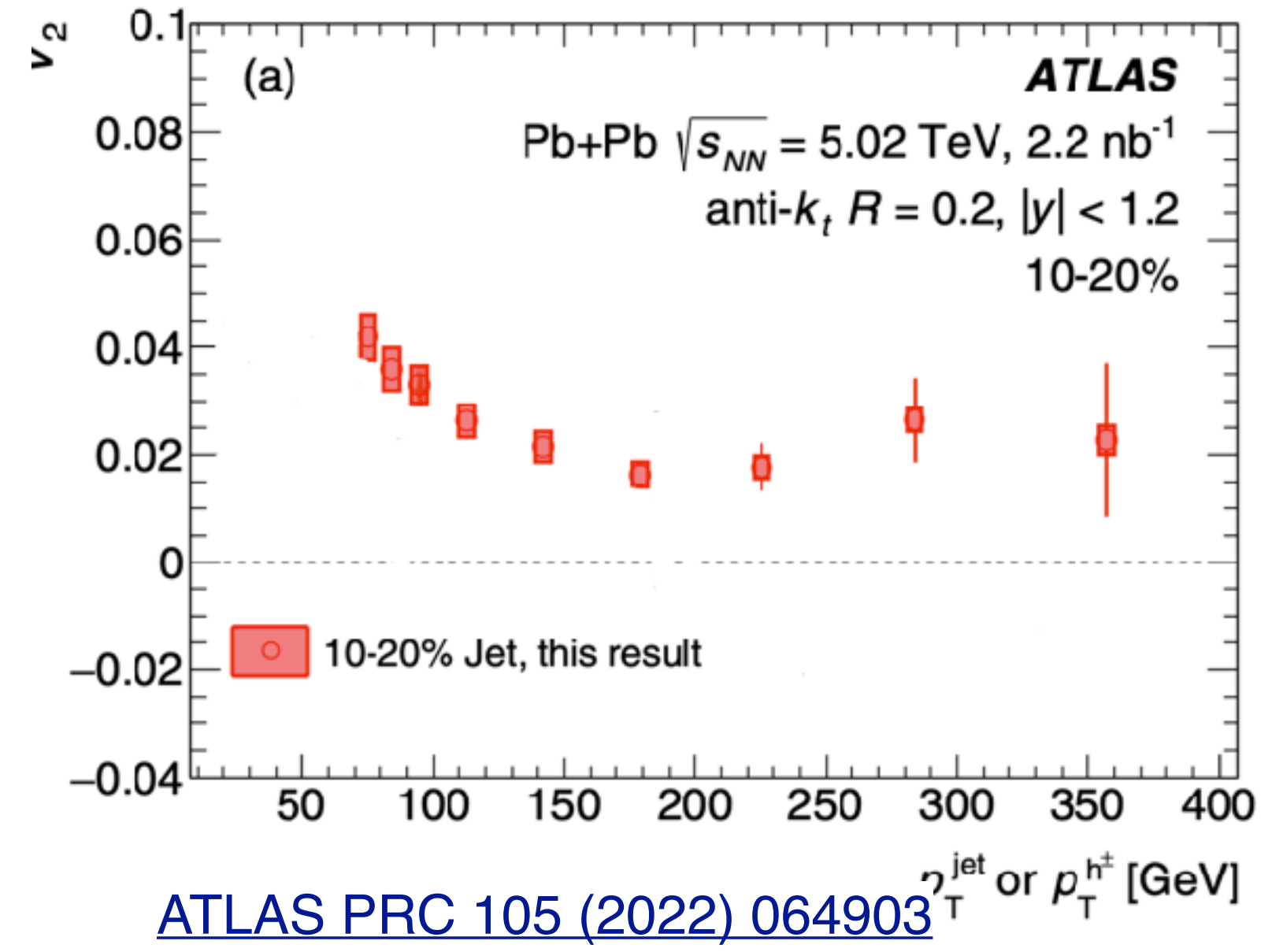
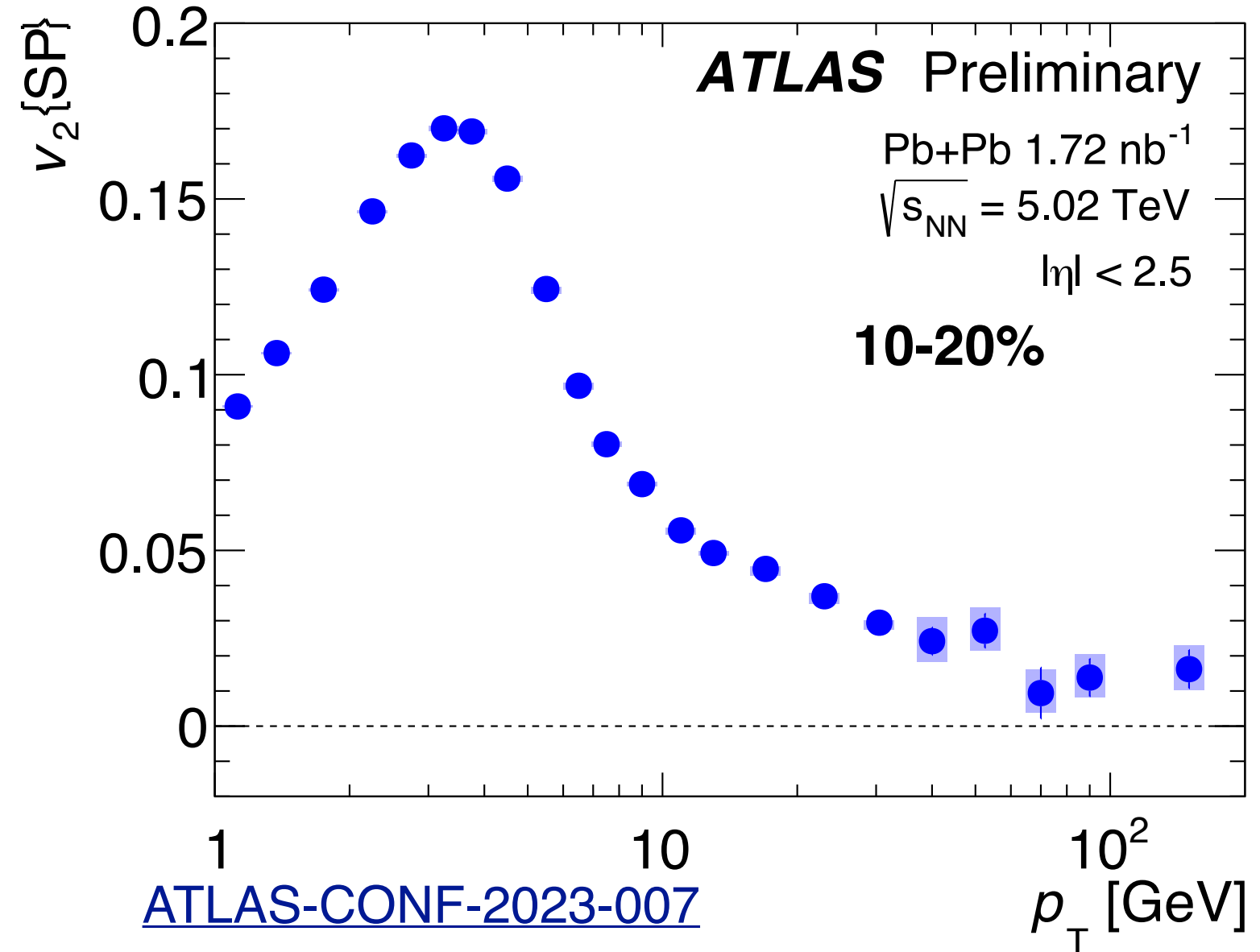
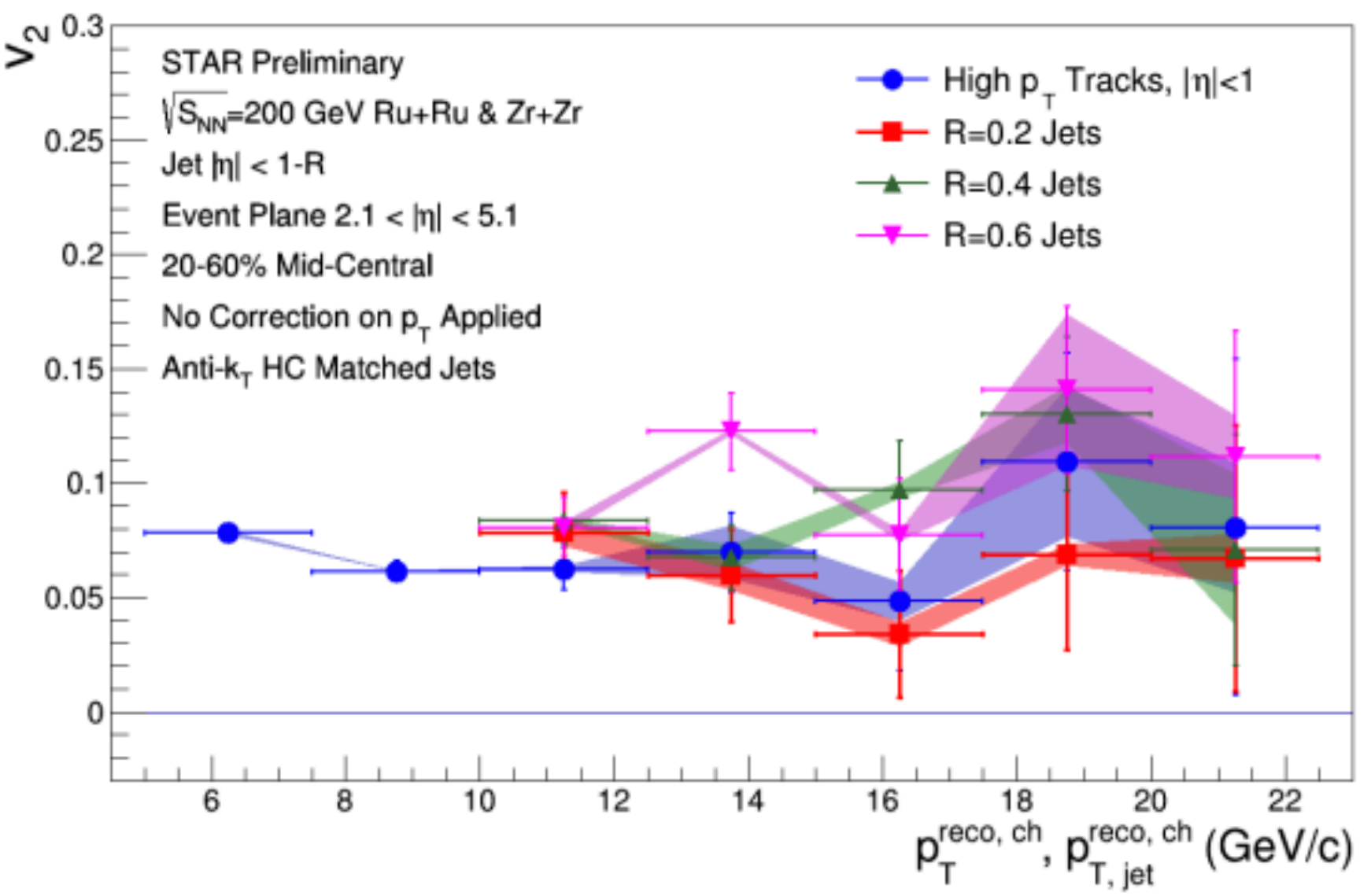
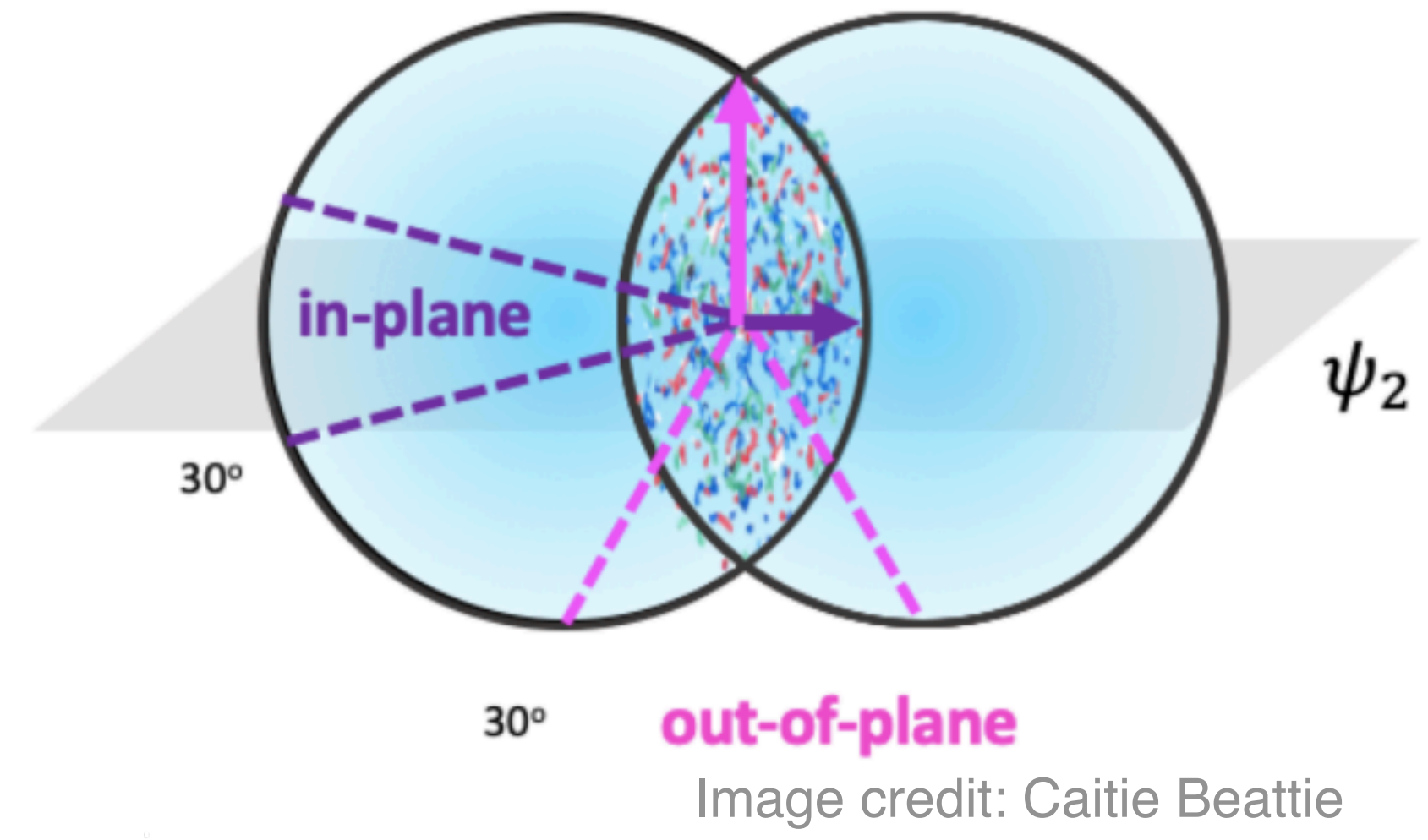
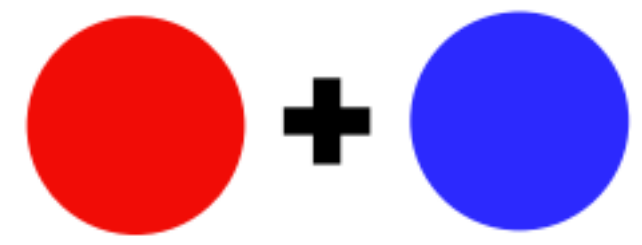
Balanced configurations more suppressed
 Informs interpretation of photon+jet configurations

Event azimuthal anisotropies fix path length

Ru+Ru & Zr+Zr



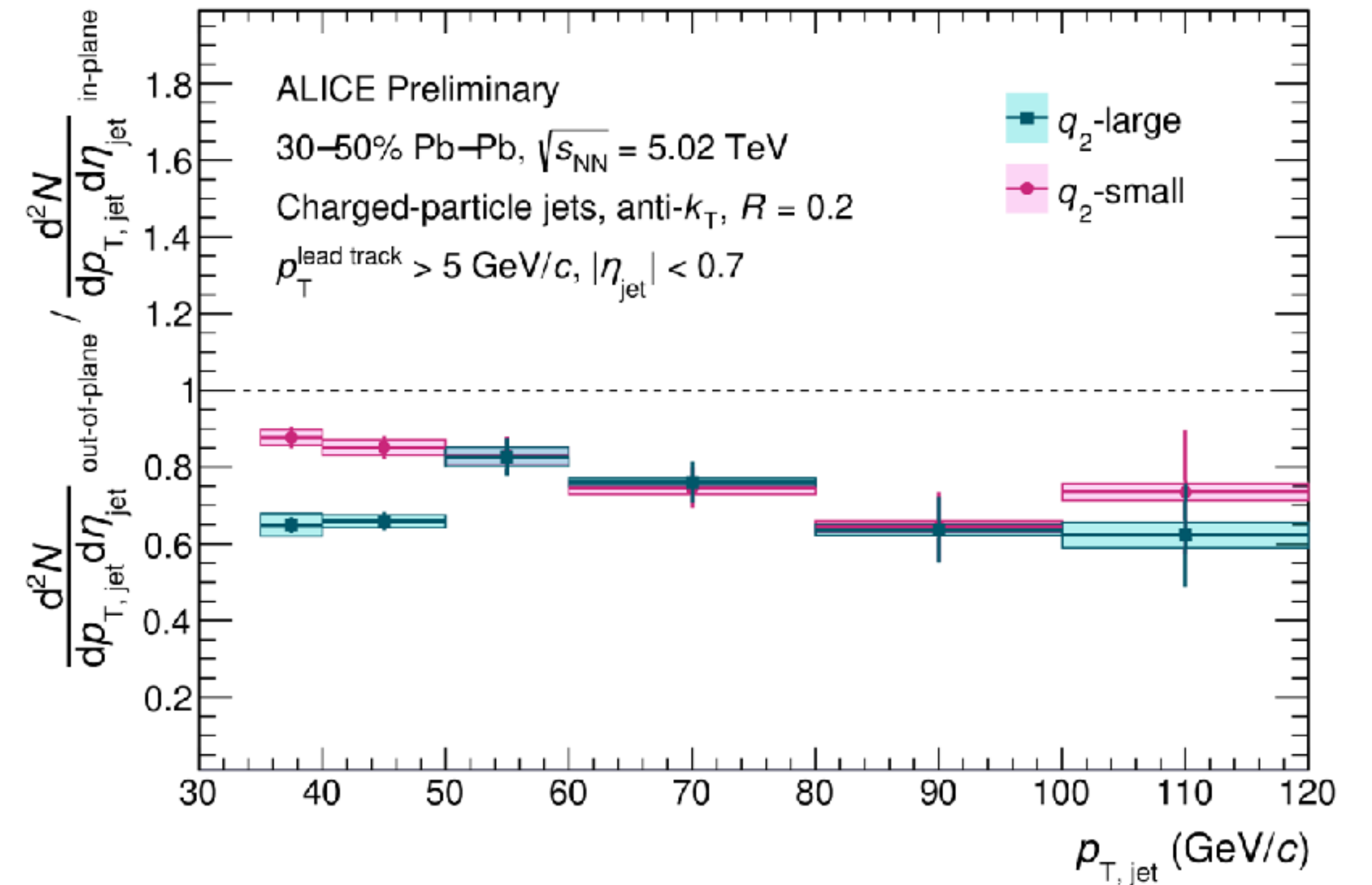
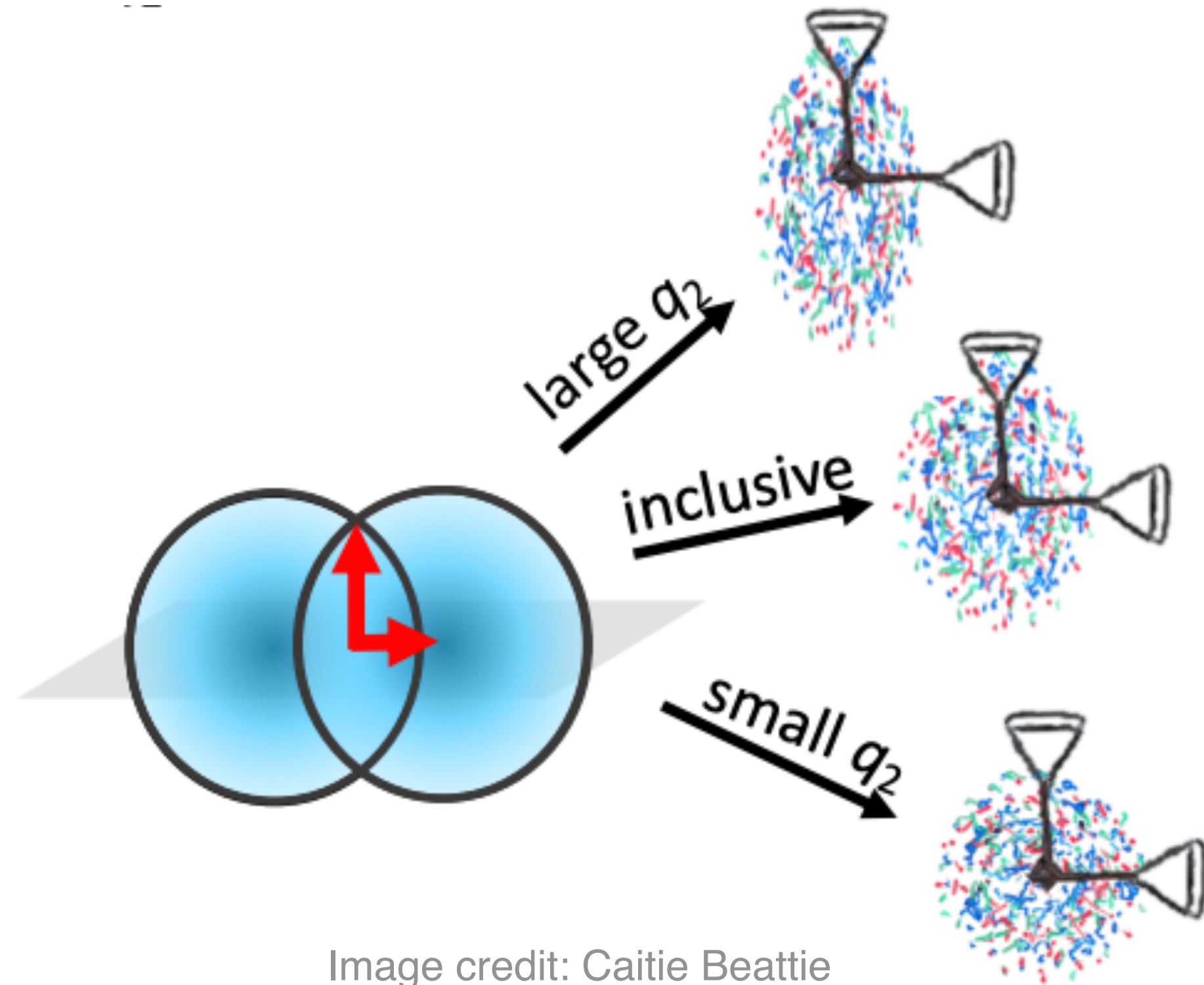
Pb+Pb



Persistent jet and high $p_T v_2$ over large kinematic range at RHIC and LHC

Event-shape engineering in jets

Classify events based on their anisotropy within a centrality class to maximize differences in path lengths



ALI-PREL-537622

Increase suppression in high q_2 events consistent with path length dependence

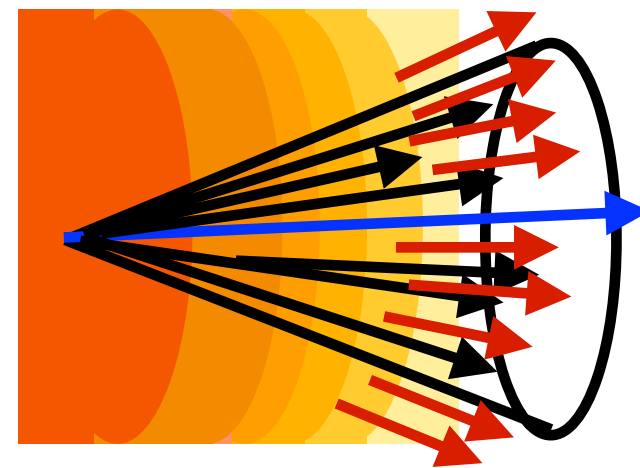
Substructure modification in the QGP

- Different variables probe a different aspect of jet structure modification

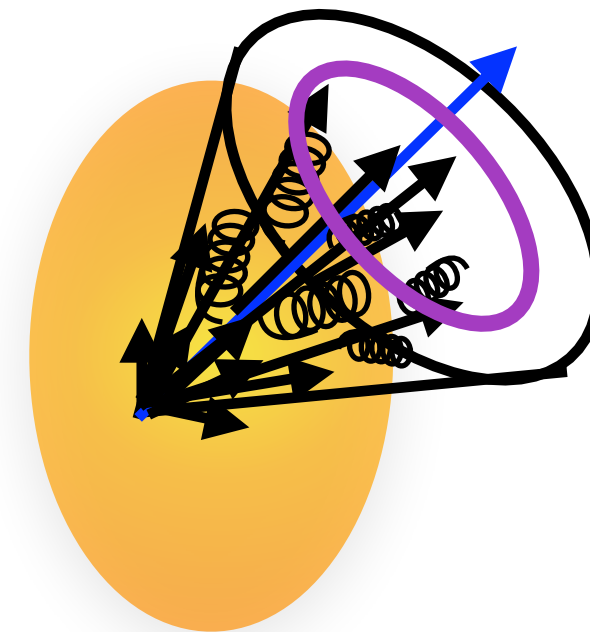
➡ Distribution of charged hadrons

➡ Properties (mass, width)

Medium response

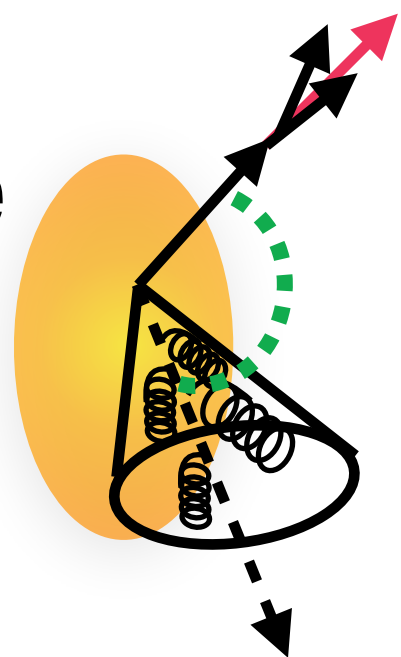


Momentum broadening

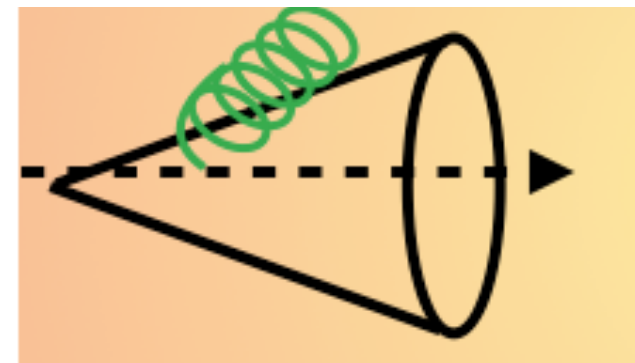


➡ Subjets from hard parton splittings

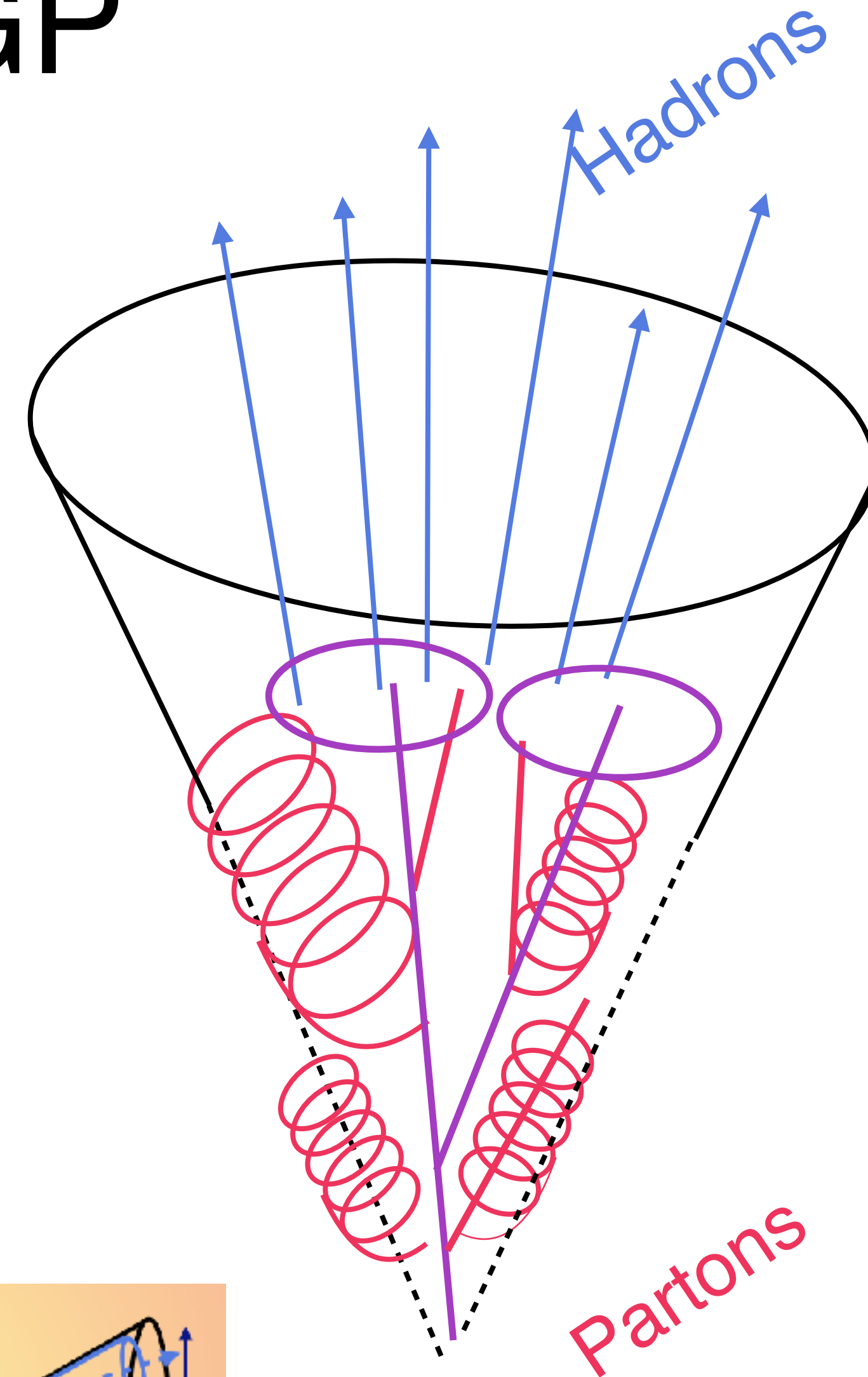
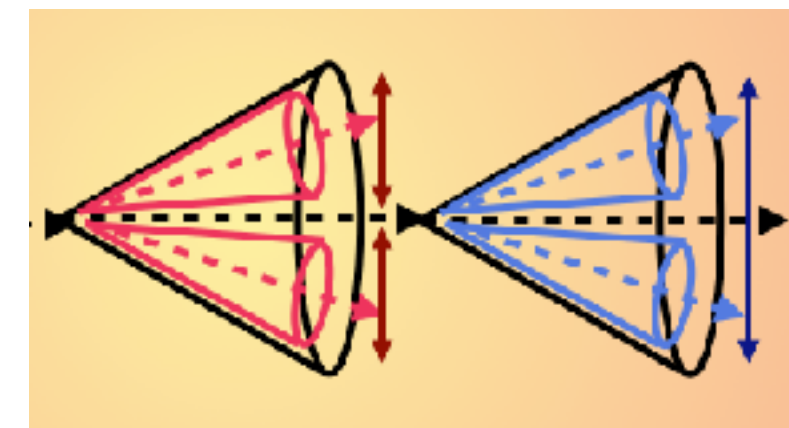
Moilere



Medium-induced splittings



Coherence/ decoherence



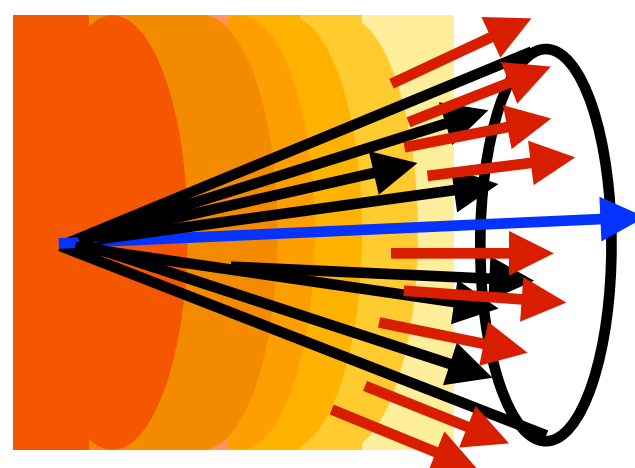
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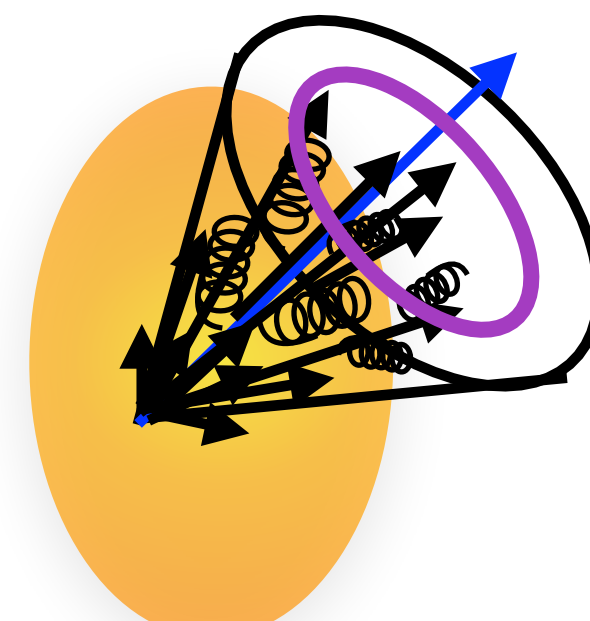
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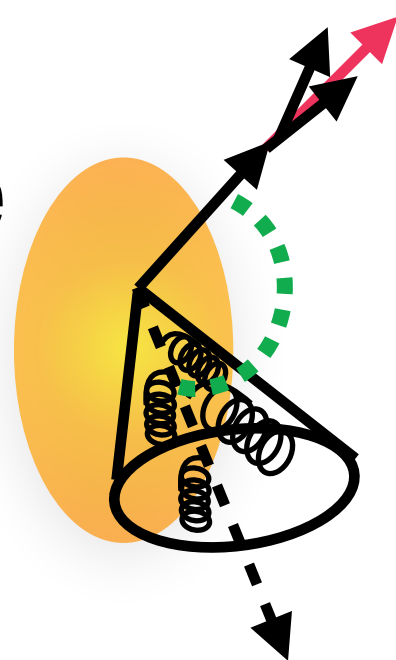


Momentum broadening

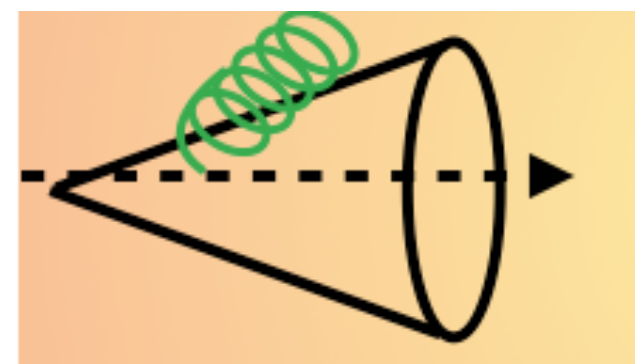


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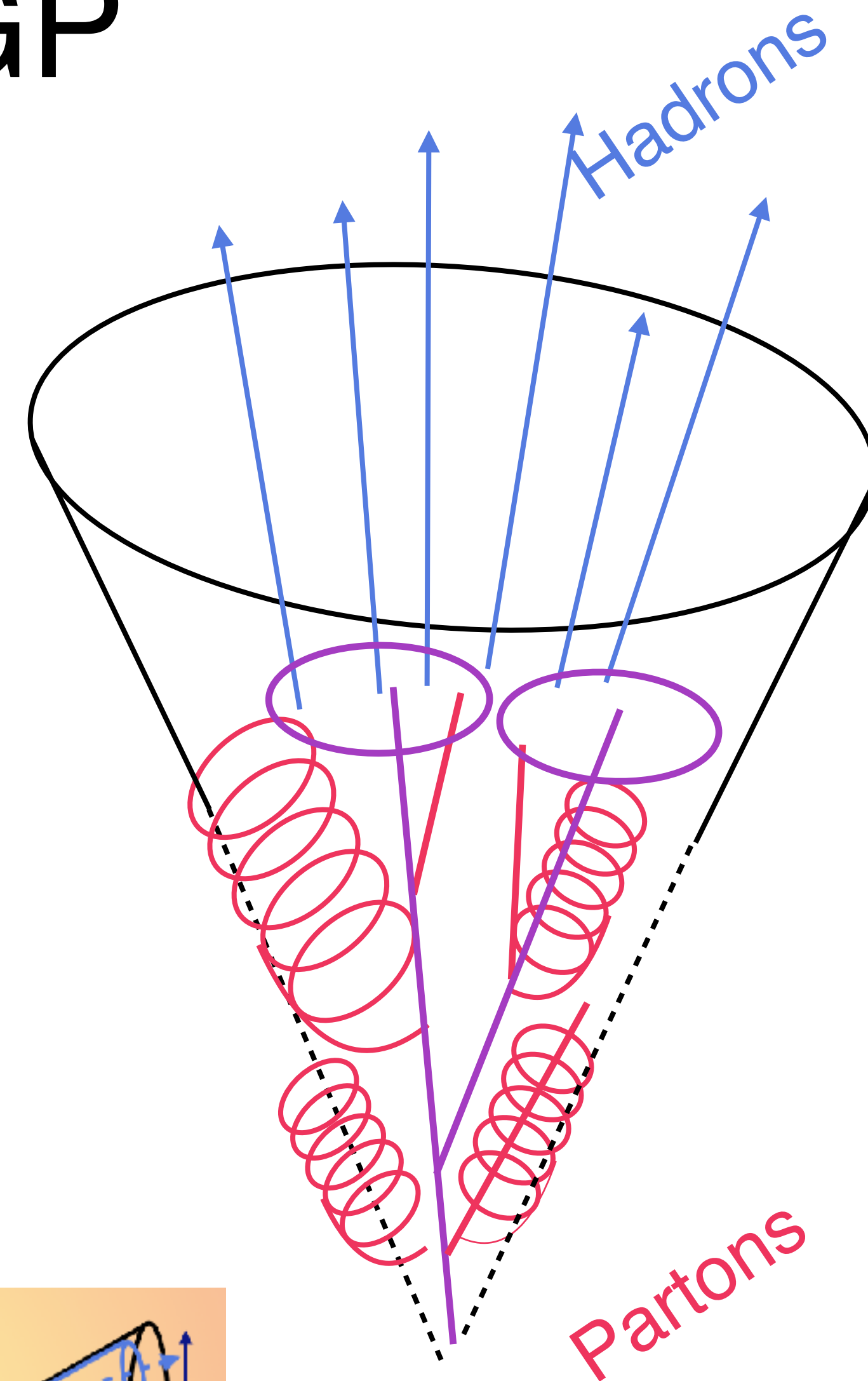
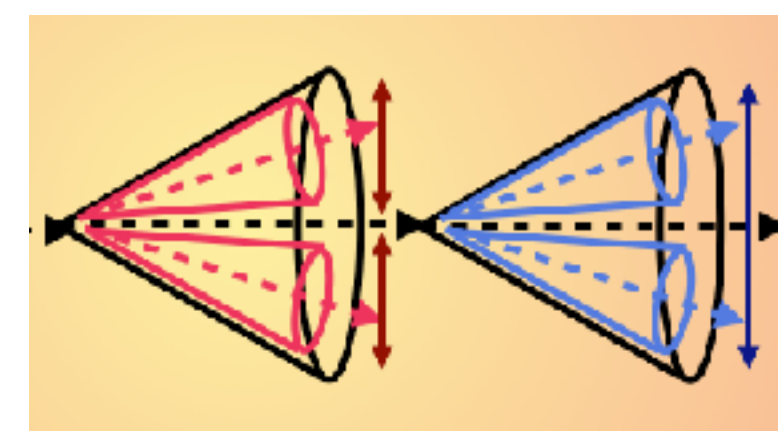
Moliere



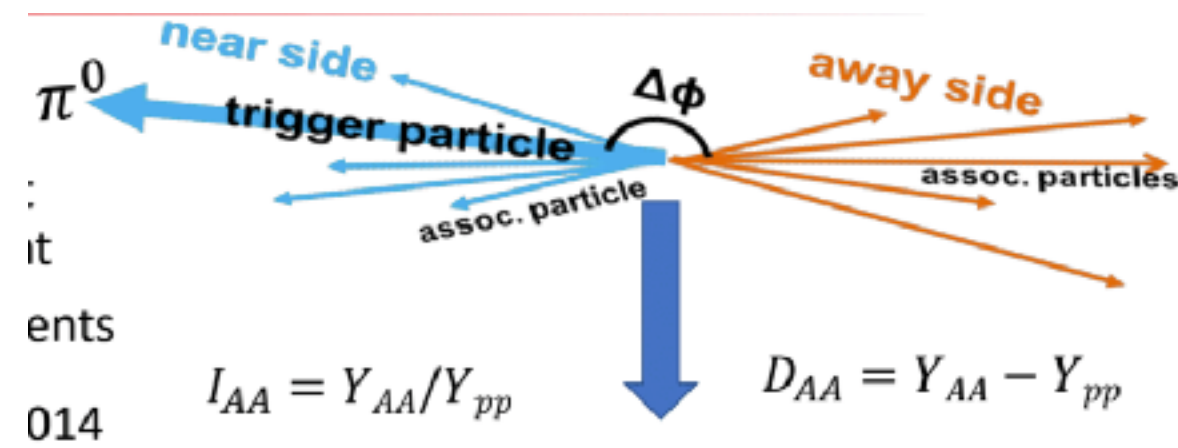
Medium-induced splittings



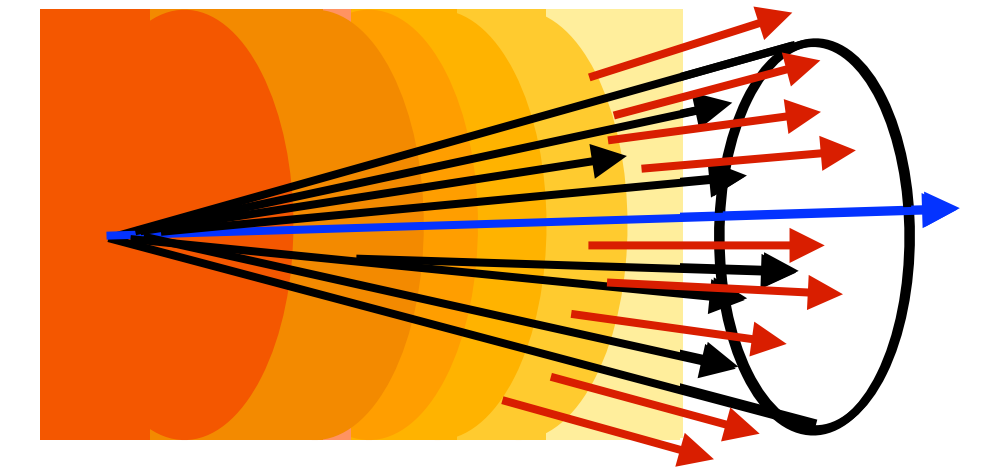
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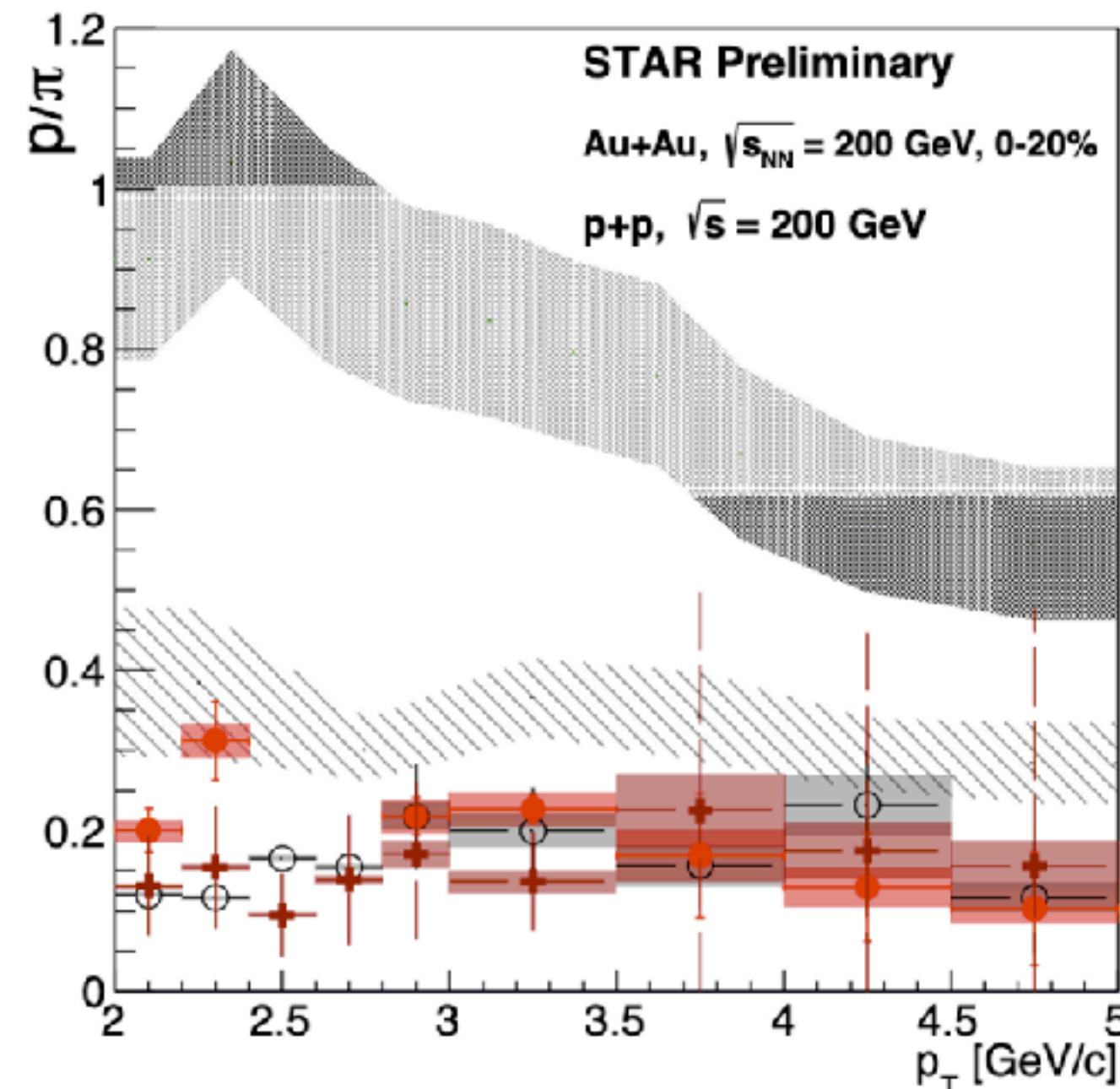
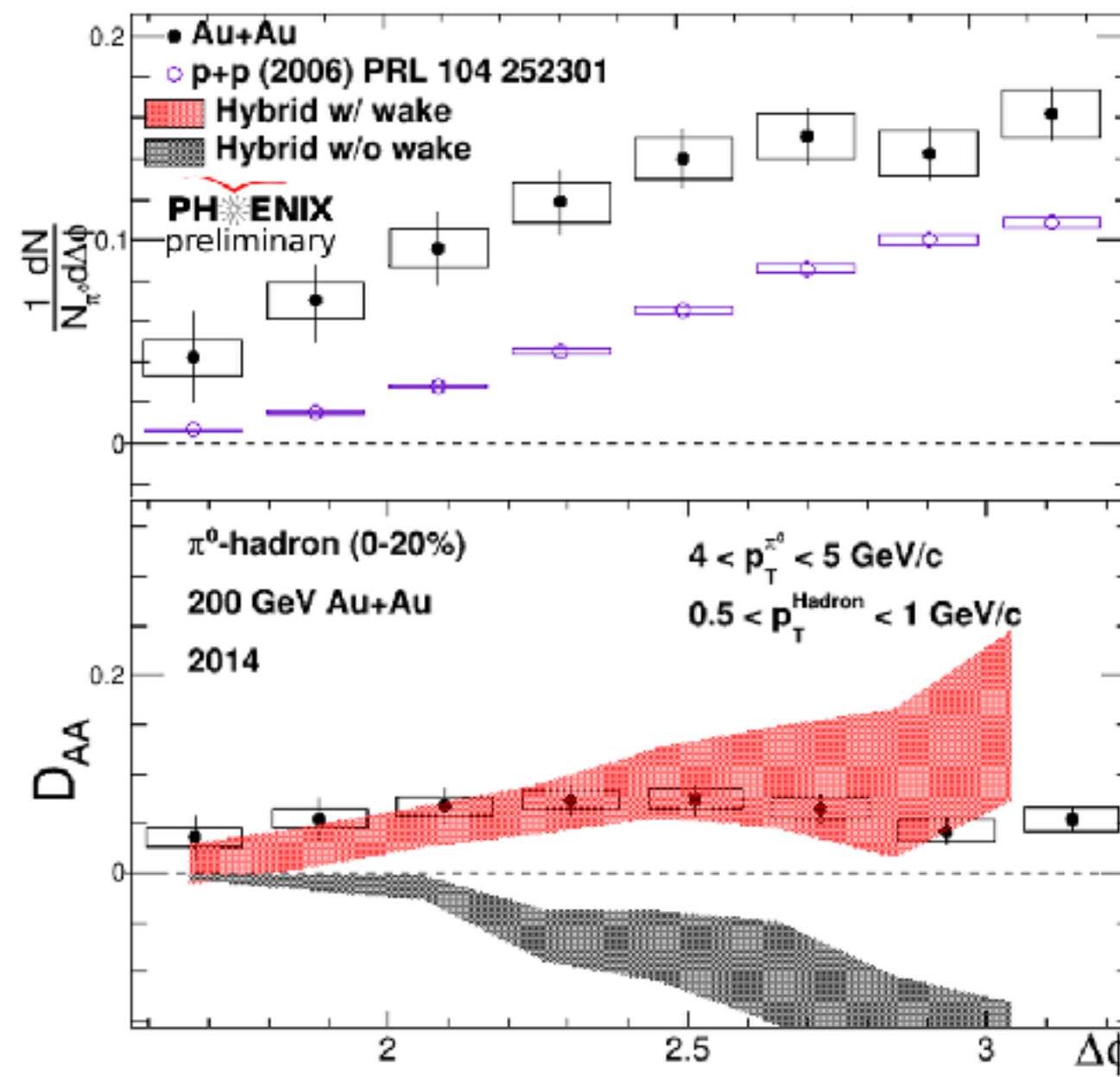
Searching for the medium response



Models implement medium recoils (weak coupling) or wake (strong coupling)

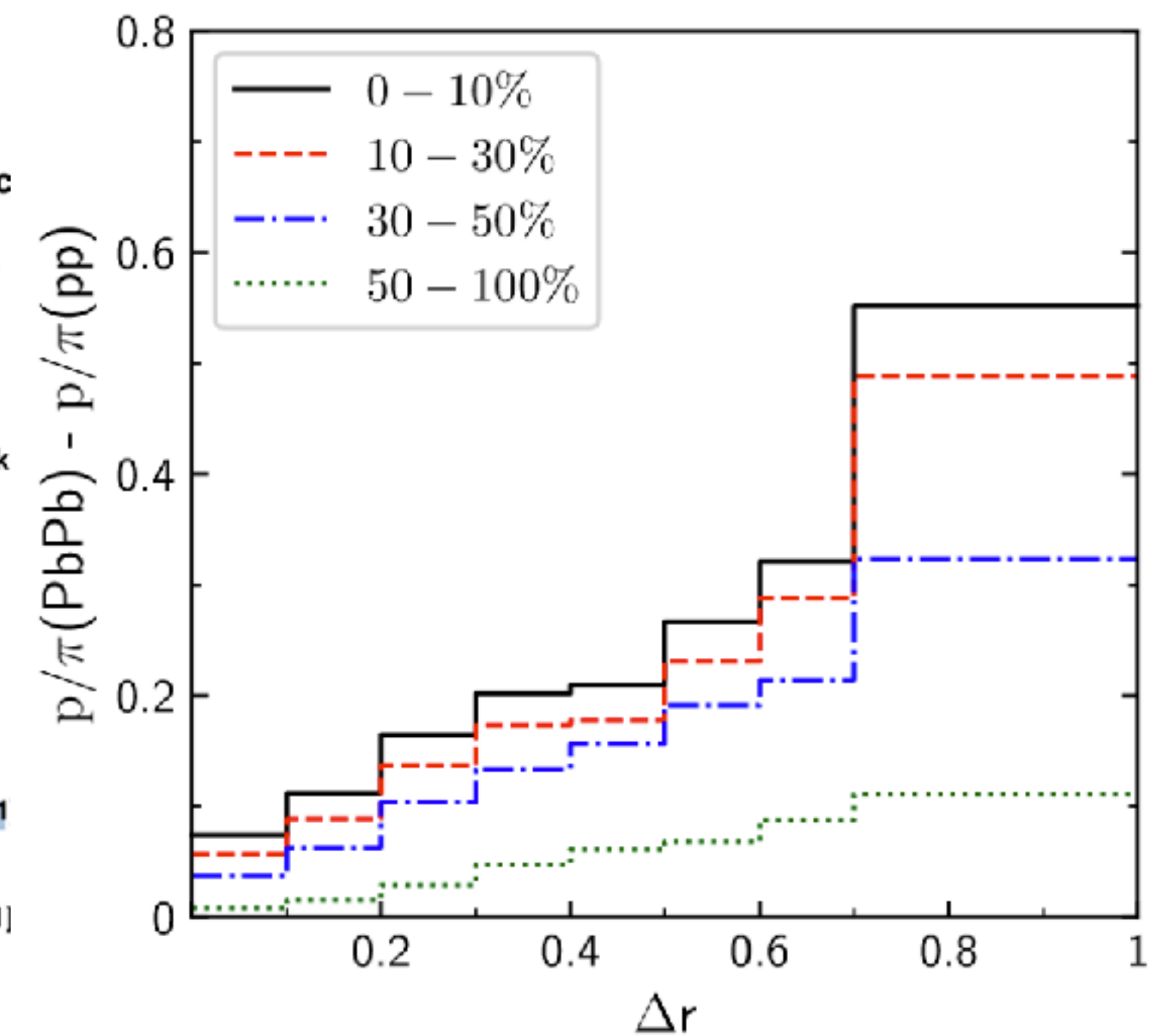


Baryon/meson in jets



Anti-k_T
 Jet $p_T^{\text{raw}} > 10 \text{ GeV}/c$
 $p_T^{\text{const}} > 3.0 \text{ GeV}/c$

Inclusive
 Au+Au, 0-20%
 [PRL97(2006)152301]
 p+p
 [PRLB637(2006)161]



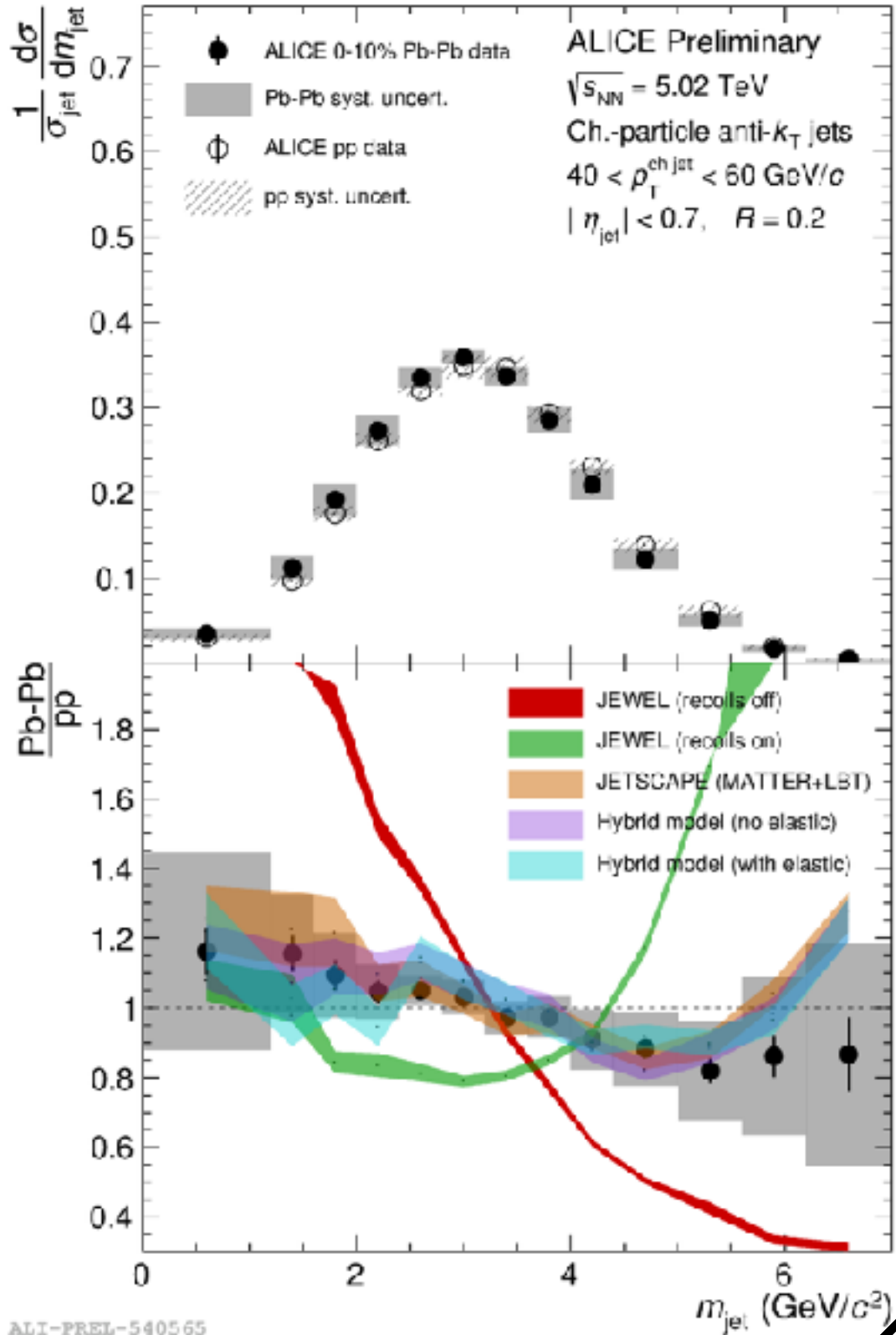
Energy transferred to large angles for every track p_T ; consistent with medium response

No significant difference from pp: effects outside of the cone?

Complementary jet substructure observables

Jet mass

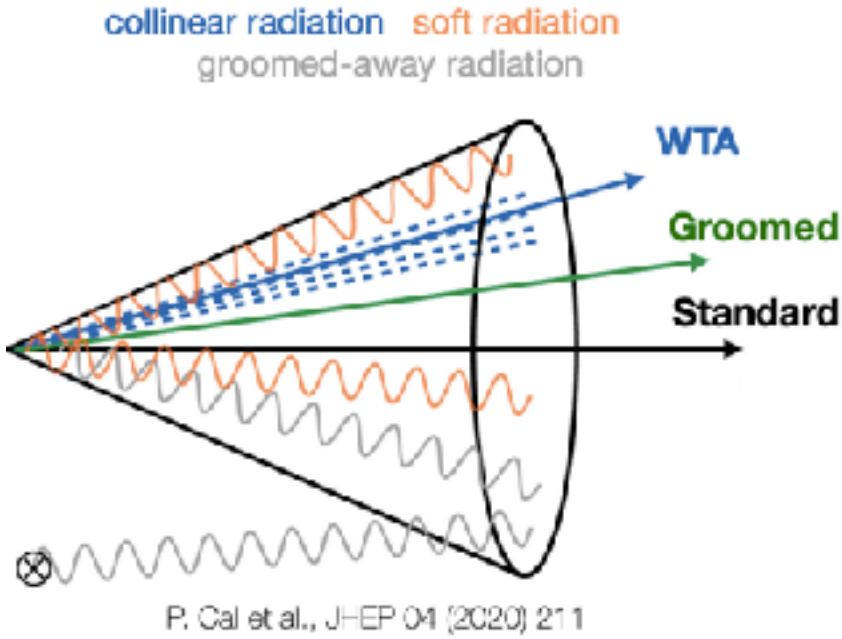
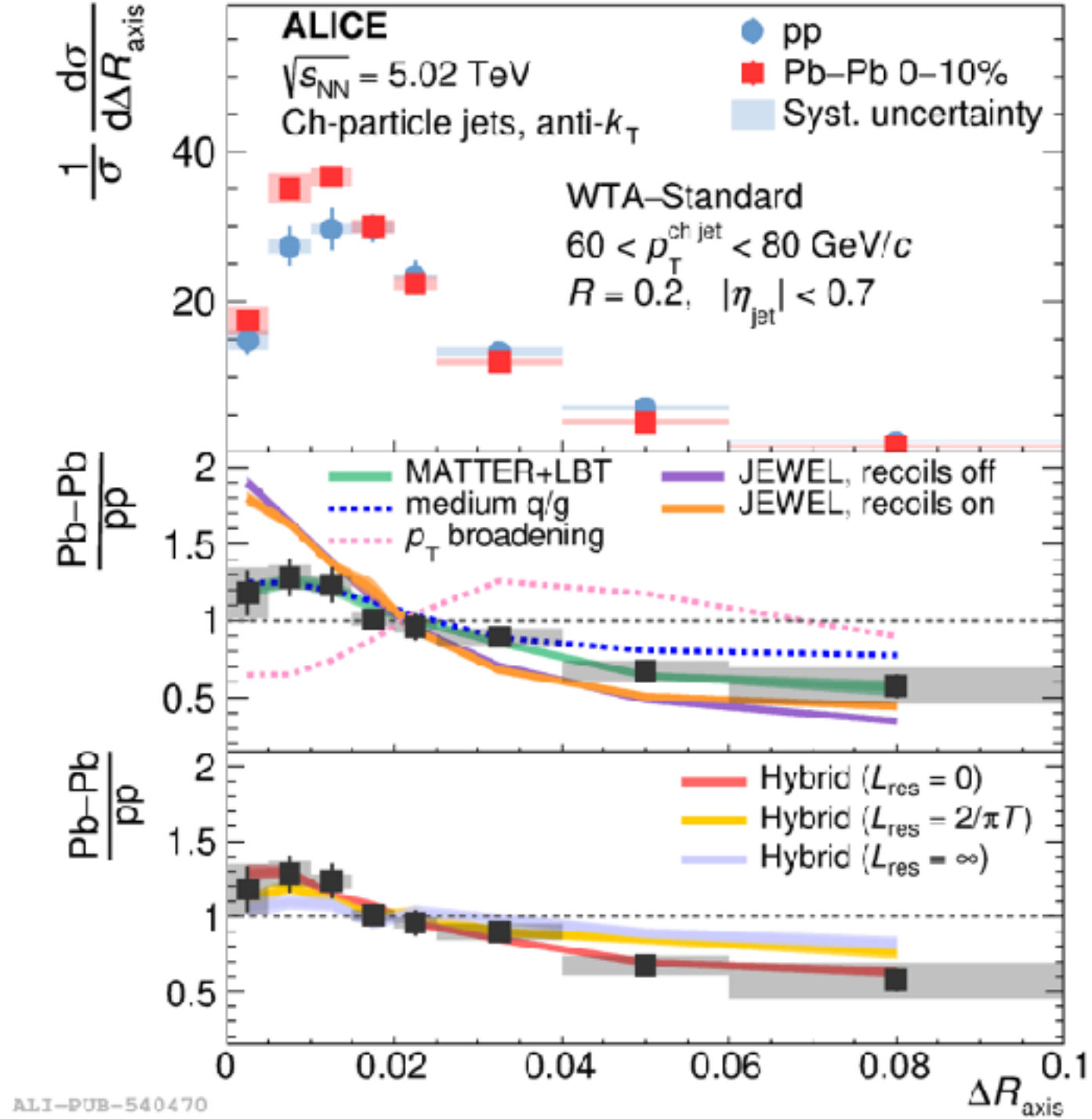
E. Lesser (Tues. 4:50pm)



mass sensitive to models;
 hint of narrowing

Jet axis differences

R. Cruz Torres



Jet axis shows narrowing that
 is sensitive to decoherence

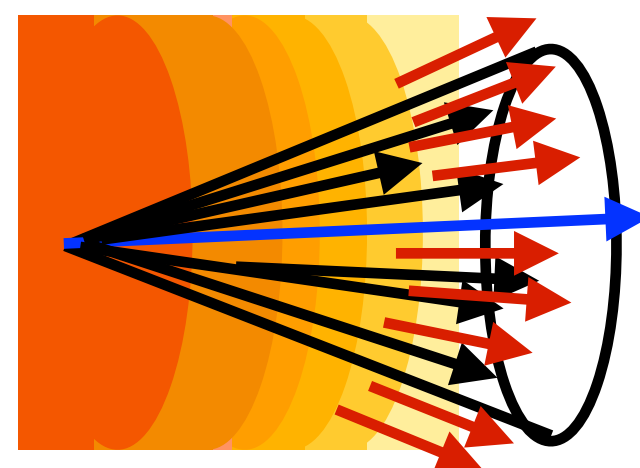
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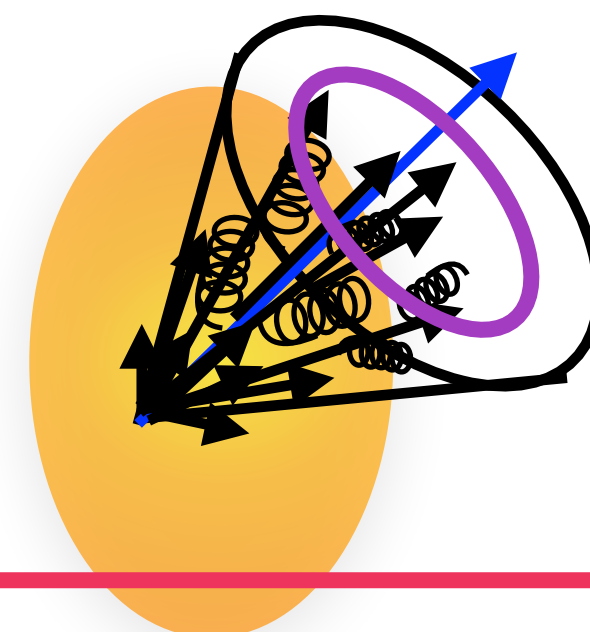
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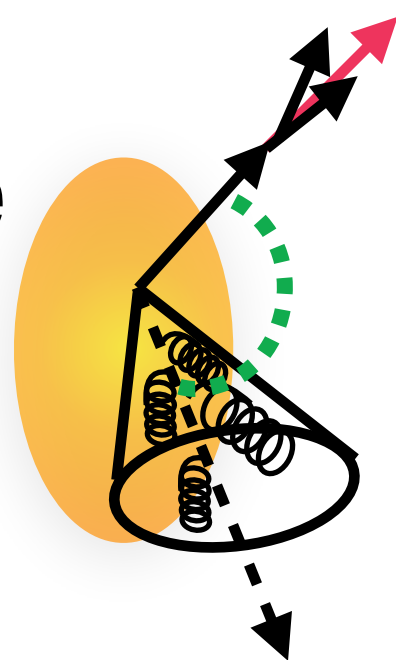


Momentum broadening

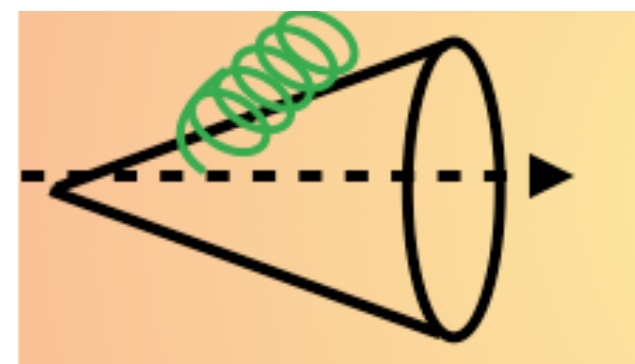


➡ Subjets from hard parton splittings

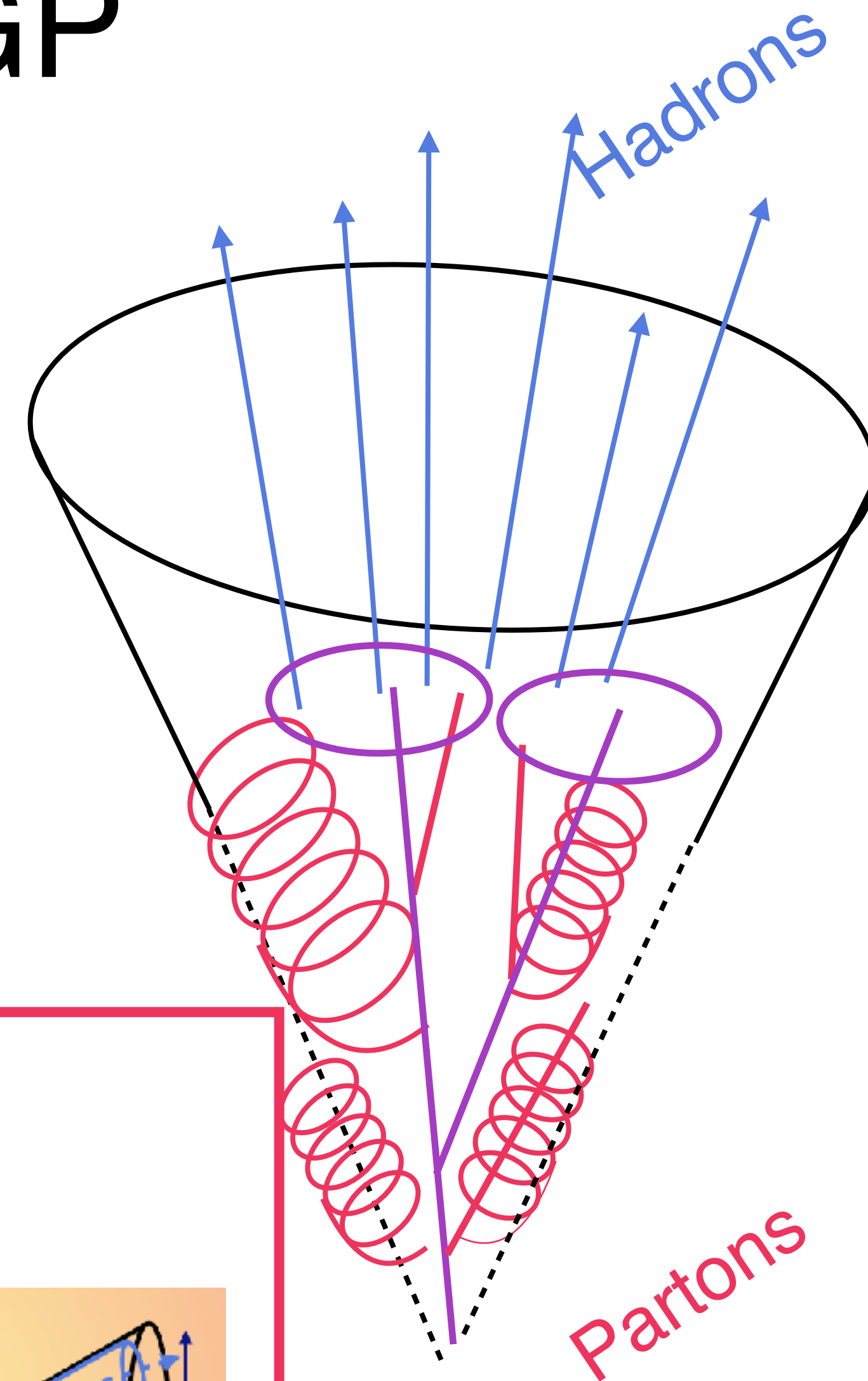
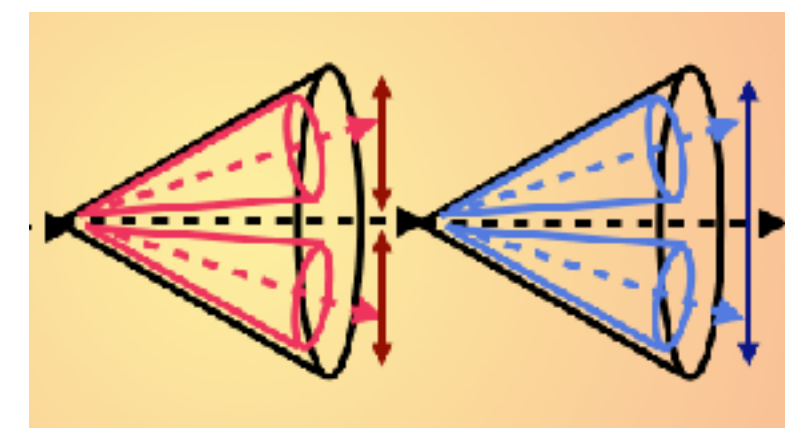
Moliere



Medium-induced splittings

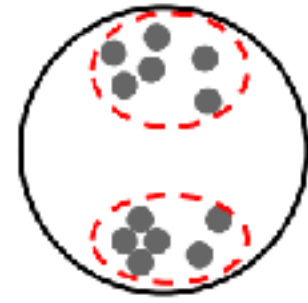


Coherence/ decoherence

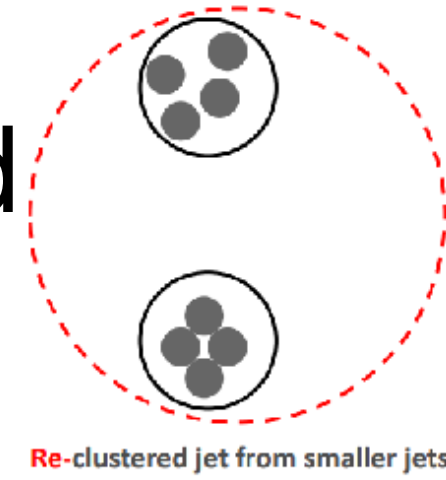


Splitting angular scale probes color coherence

Groomed jet

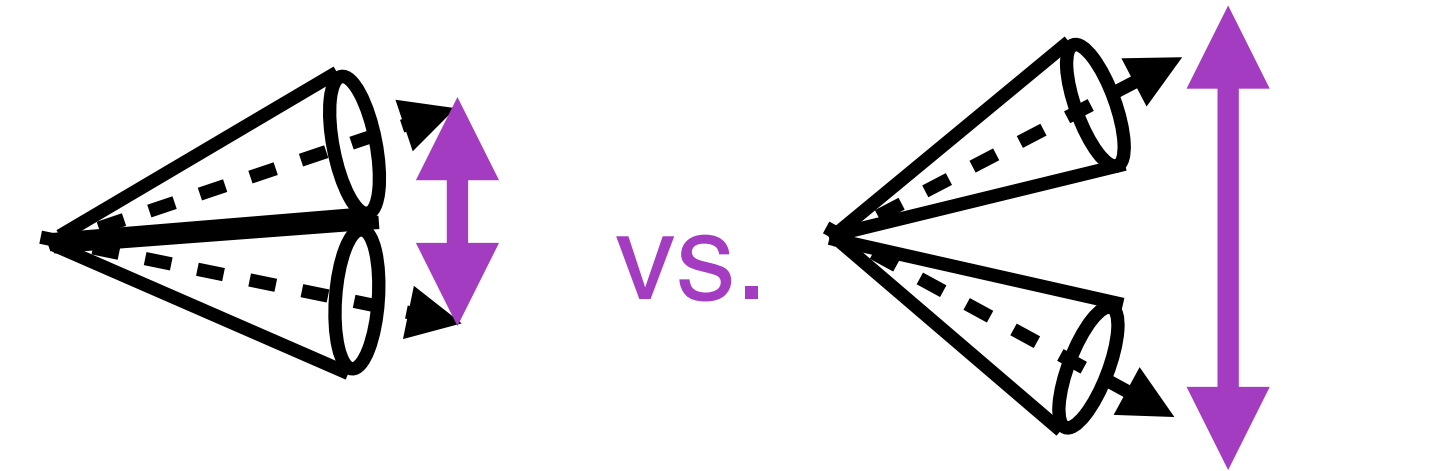
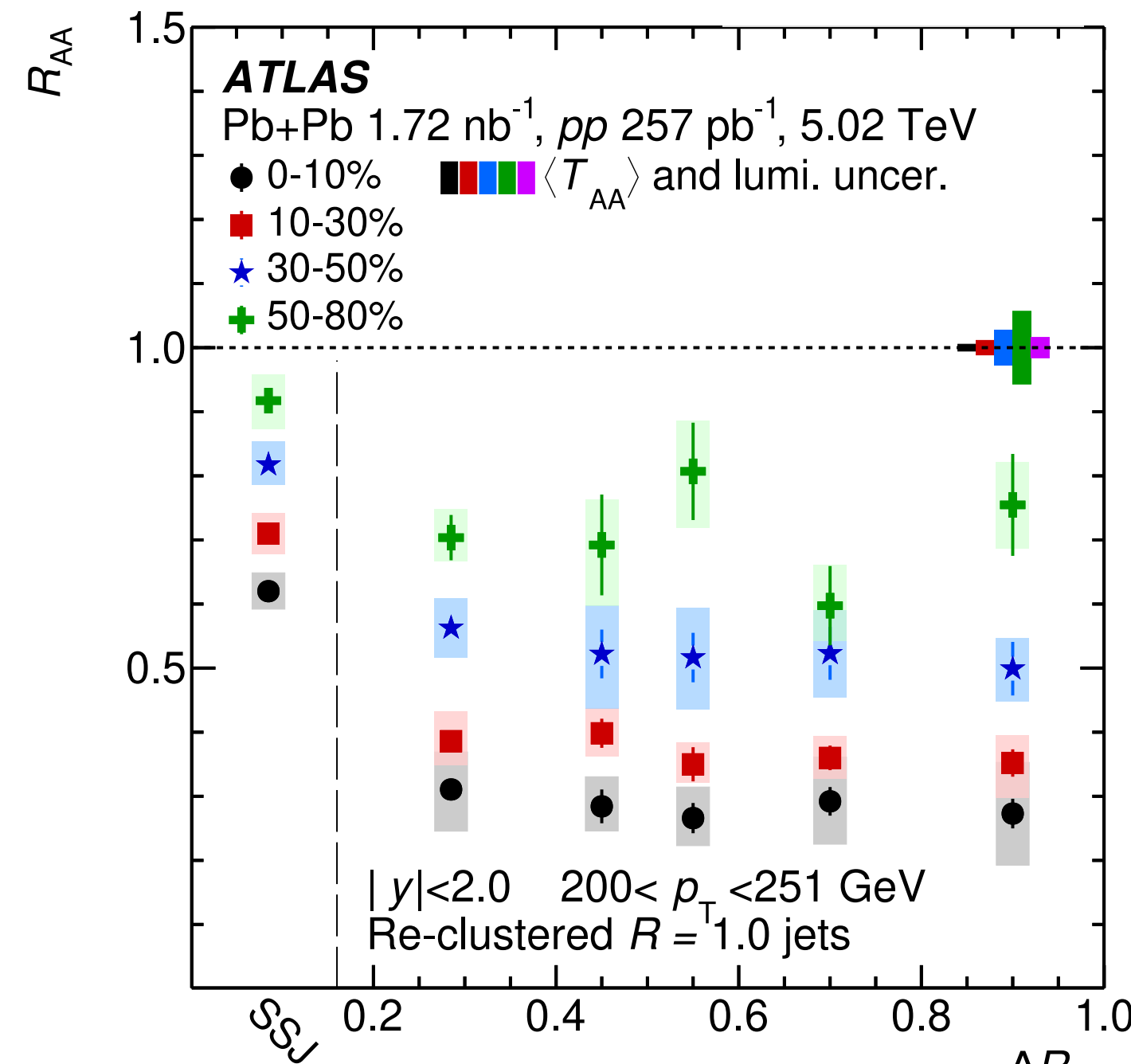
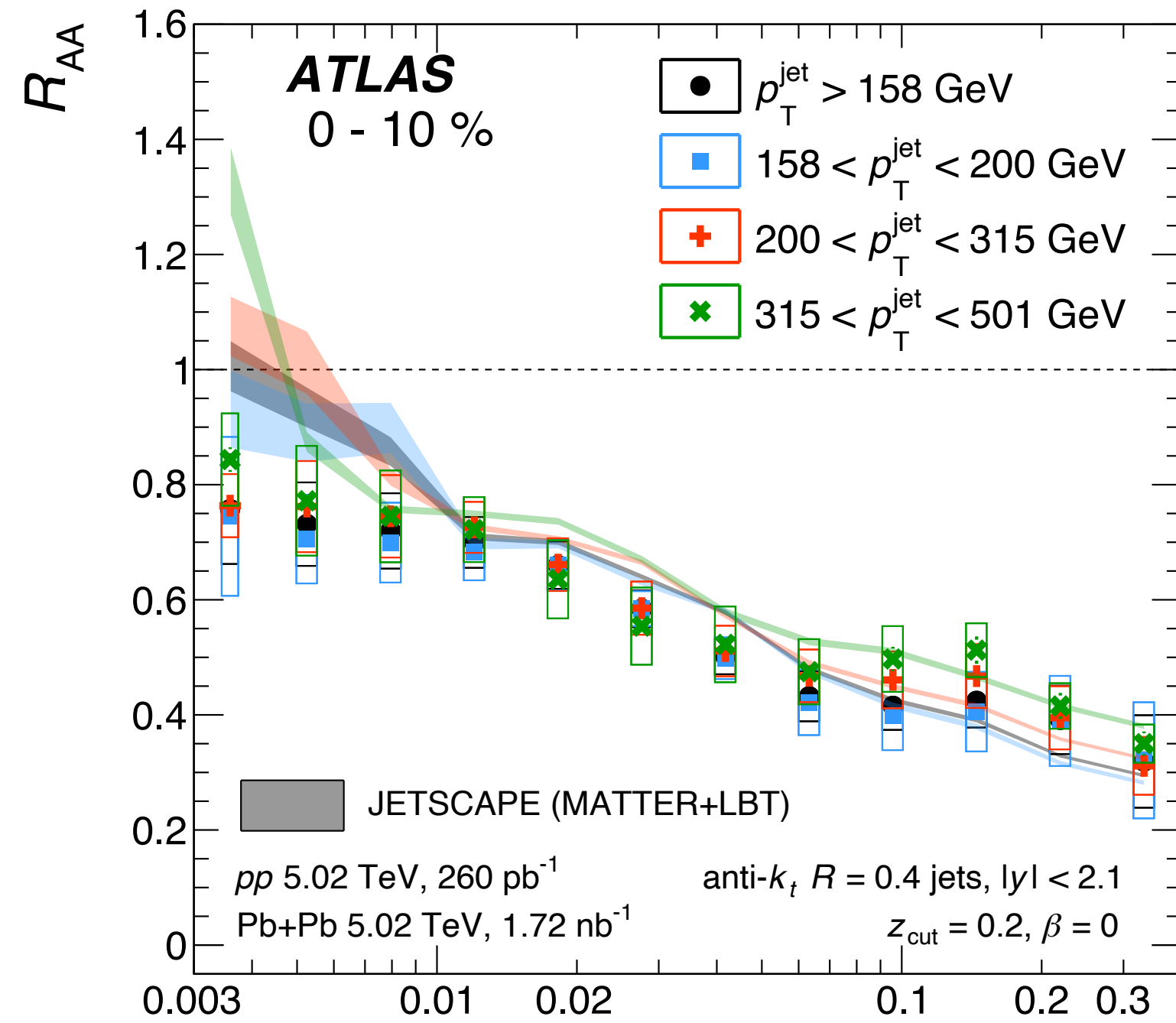


Reclustered Large-R



Re-clustered jet from smaller jets

M. Rybar



Resolution length of QGP?

Consistent with color decoherence but also describe by quarks vs. gluons

Narrowing?

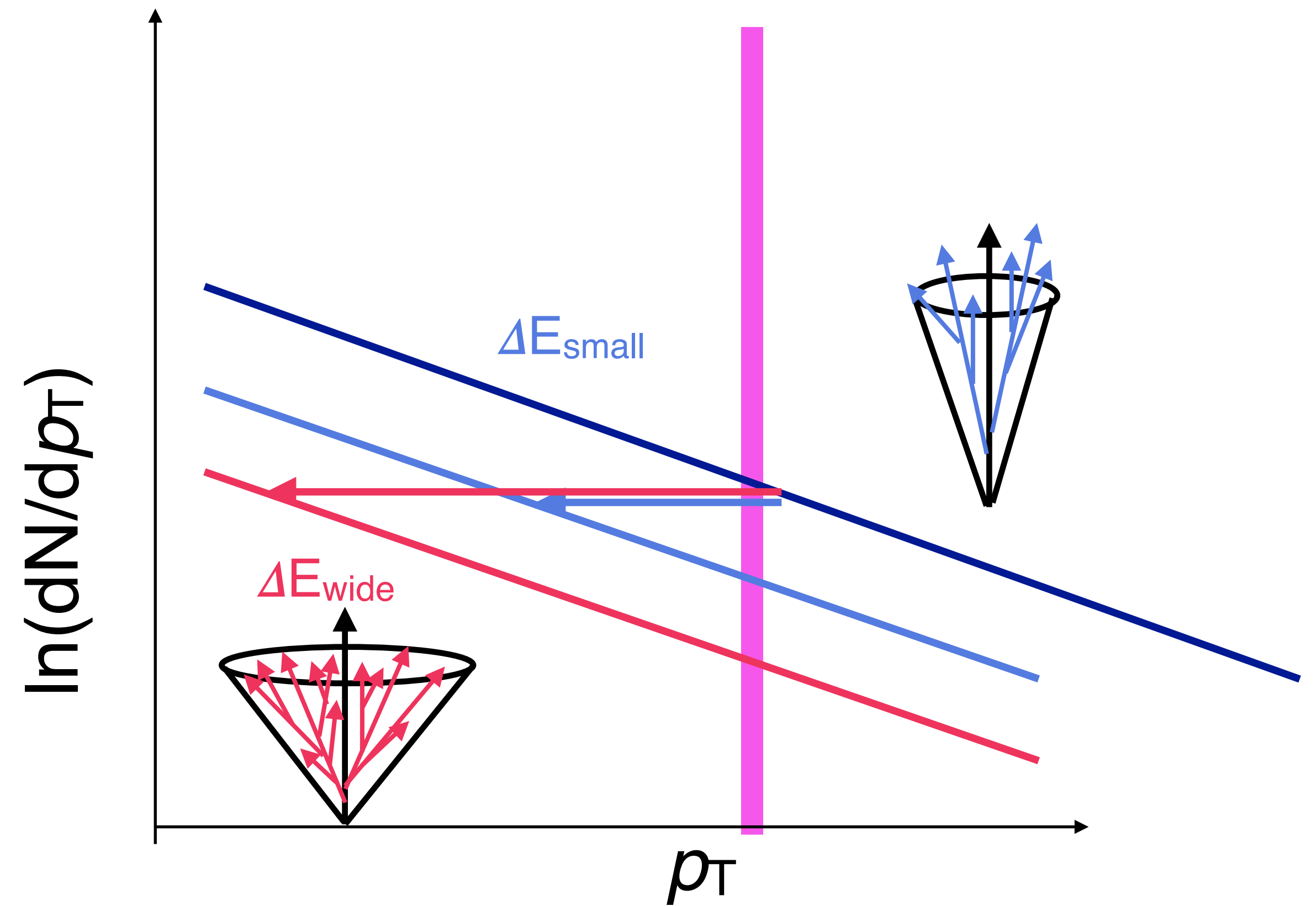
Always measuring less quenched jets that have survived the QGP -> **selection bias**

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

[Du, Pablos, Tywoniuk, JHEP 21 \(2020\), 206](#)

[Brewer, et al PRL **122**, 222301](#)

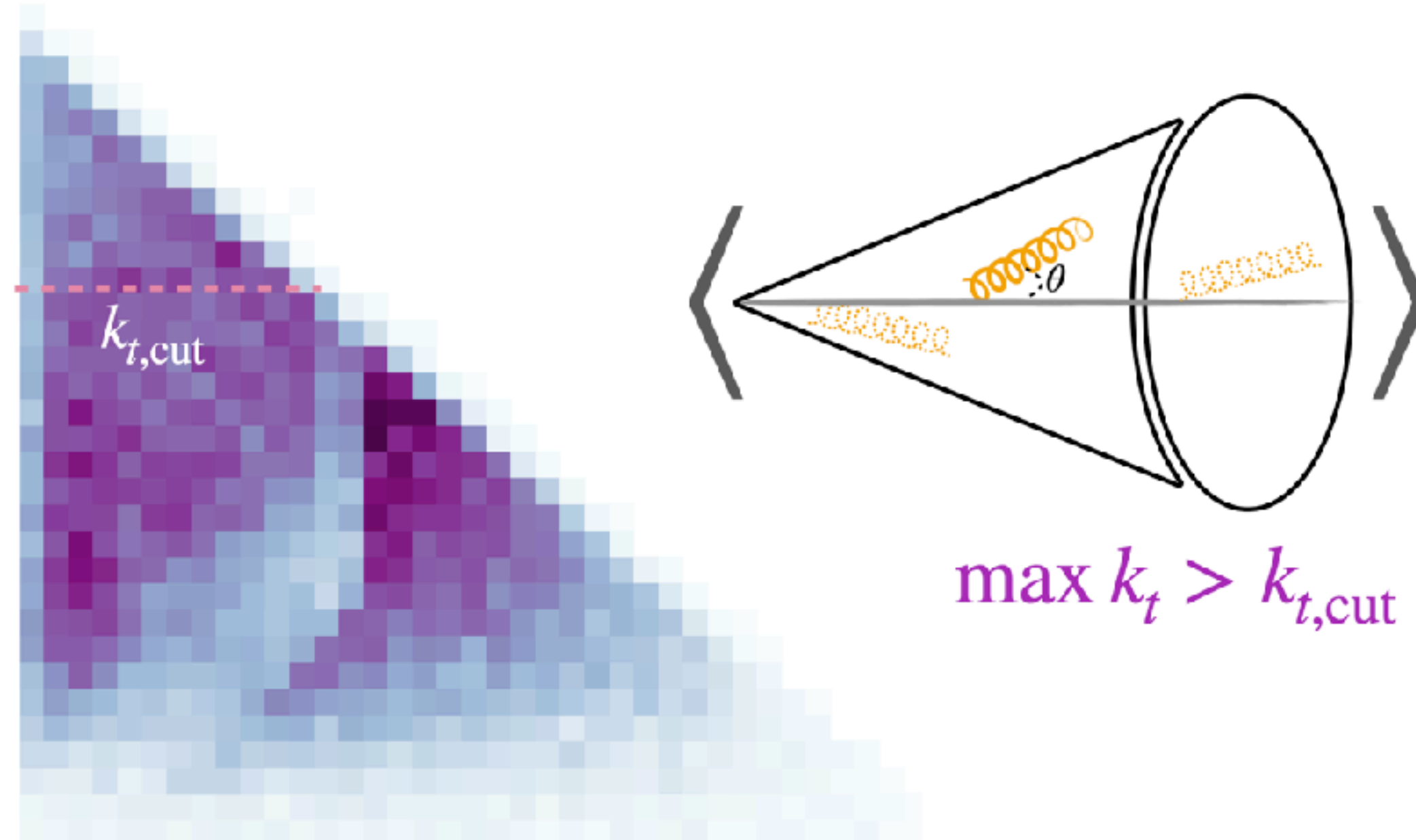
[Brodsky et al arXiv:2009.03316](#)



Access the resolution length of the medium

A. Soto-Ontoso (Mon. 5:05pm)

[Work in progress with L.Cunqueiro, J.Holguin, D.Pablos, M.Spousta, A.Takacs and M.Verweij]



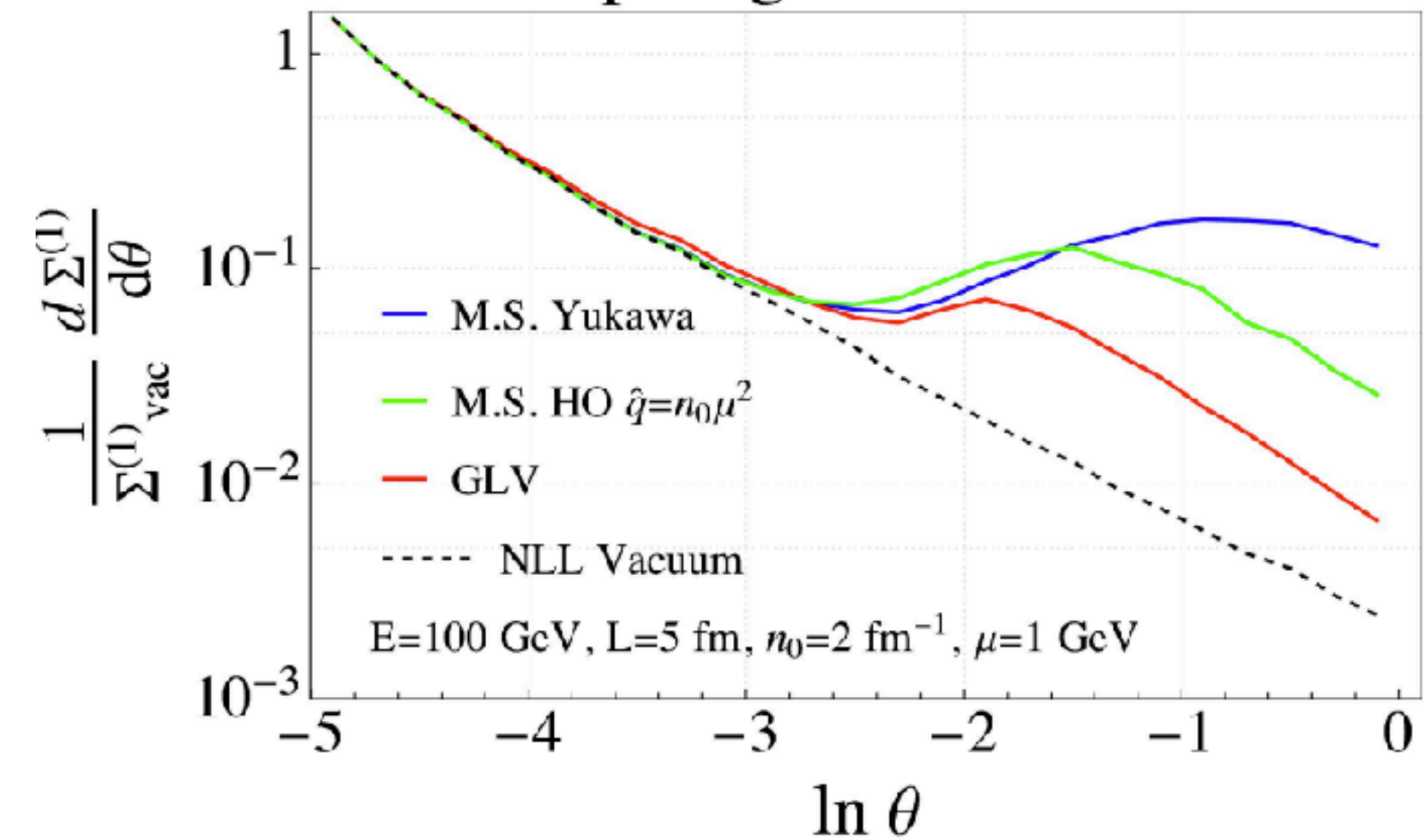
High k_T cut reduces sensitivity to non-perturbative region

F. Dominguez (Wed. 3:20pm)

C. Anders (Mon. 4:40pm)

J. Barata (Tue. 12:10pm)

Two-Point Energy Correlator
Comparing Medium Models



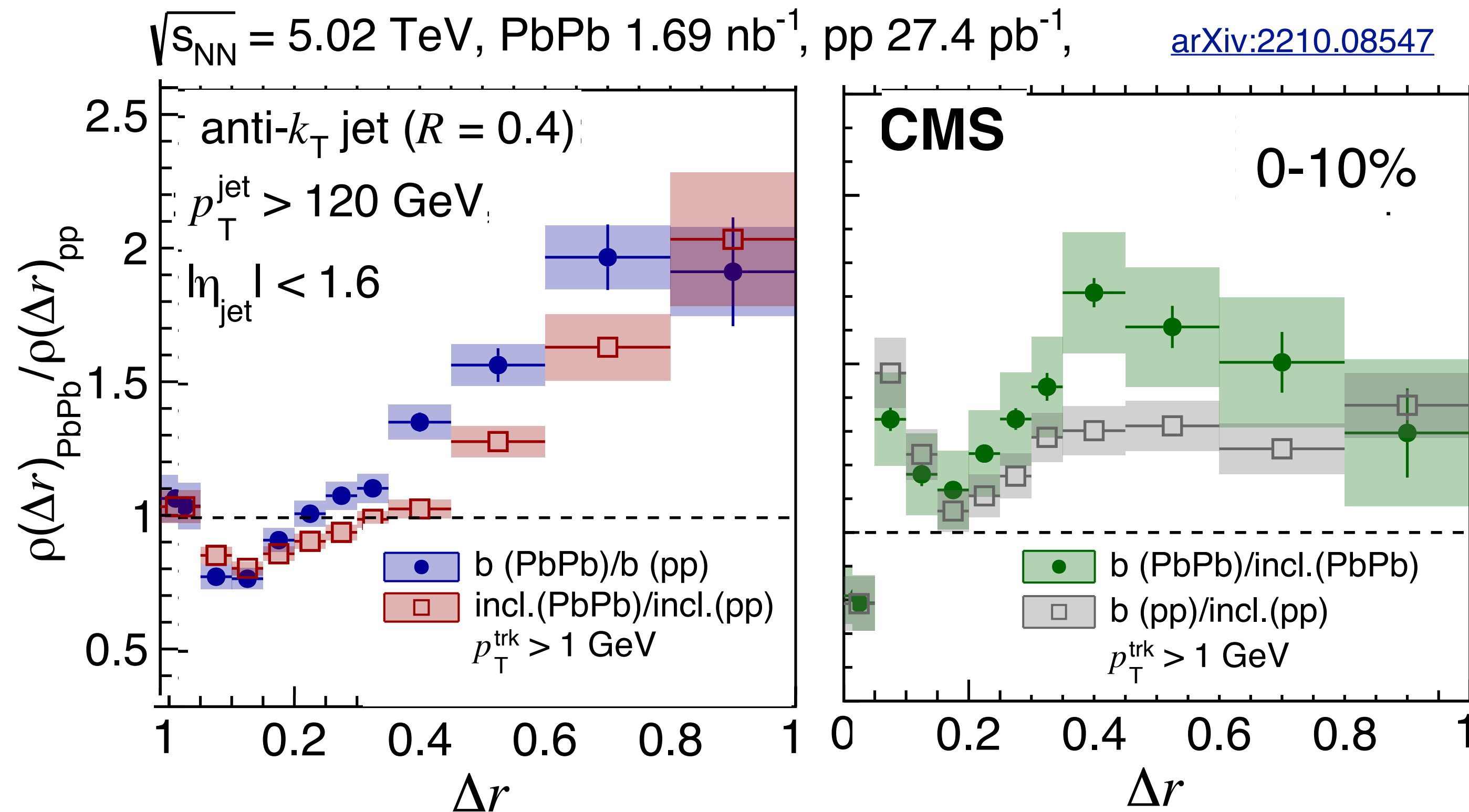
EECs provide a better separation of **medium scales**

[Anders, Dominguez, Holguin, Marquet, Mout, 2303.03413](#)

[Anders, Dominguez, Elayavalli, Holguin, Marquet, Mout, 2209.11236](#)

Beauty jet radial distribution in QGP

Radial profiles: **energy redistribution to large angles**



Vacuum: b-tagged to inclusive shows large angle enhancement (gluon splitting) and small angle suppression (dead cone?)

Medium: increased enhancement

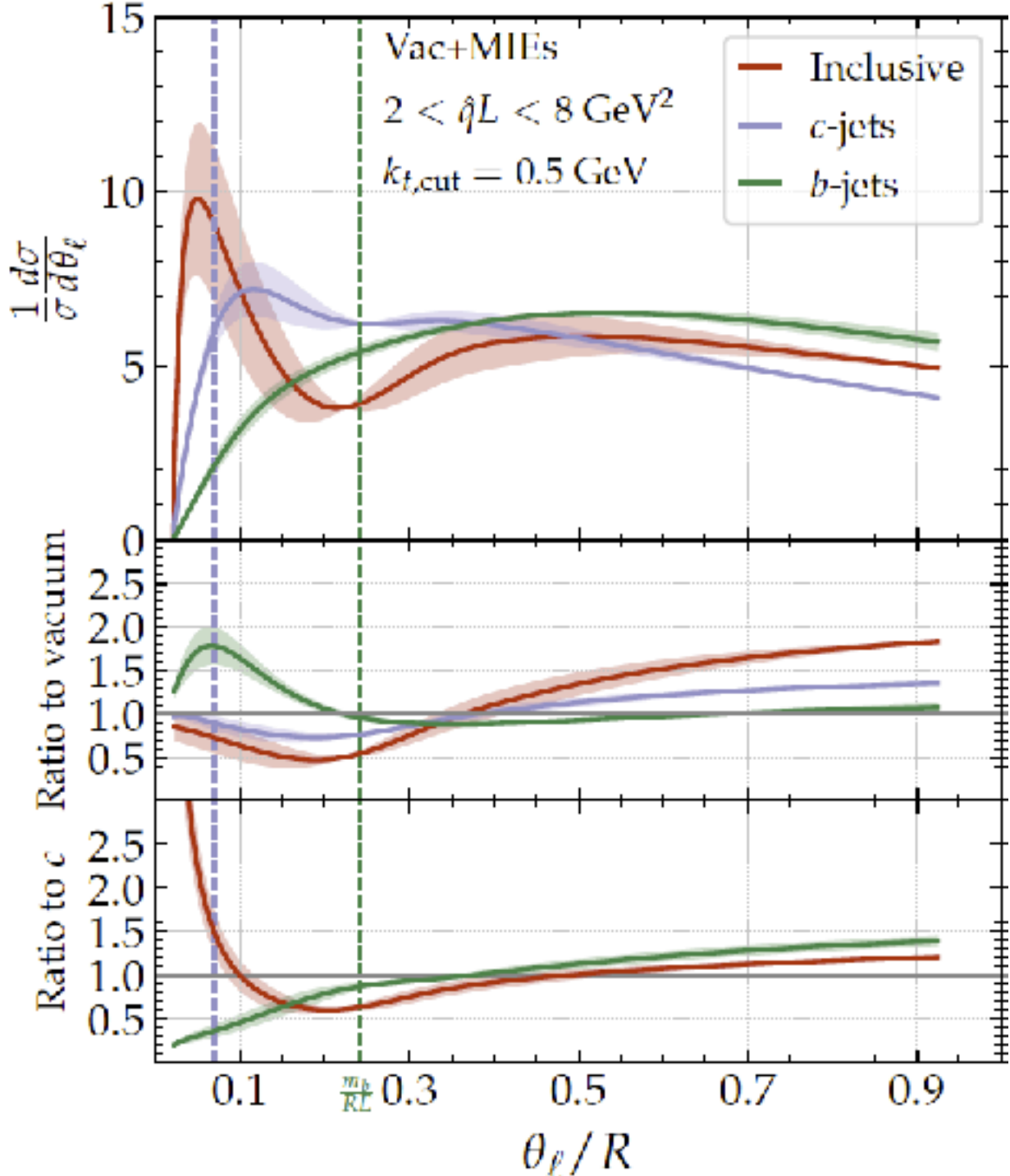
The b jets are more significantly modified

Direct modifications of dead cone in the QGP

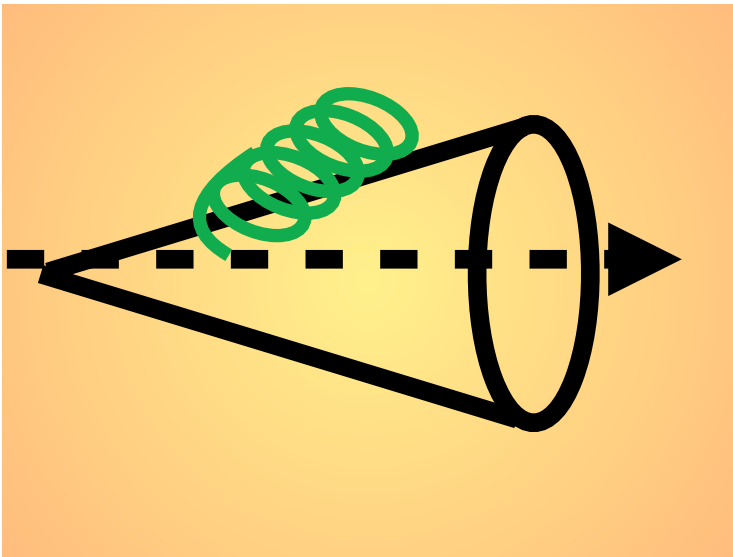
Late- k_T grooming: designed to be naturally sensitive to **small-angle radiation**

L. Cunqueiro (Wed. 11:30am)

[arXiv:2211.11789](https://arxiv.org/abs/2211.11789)

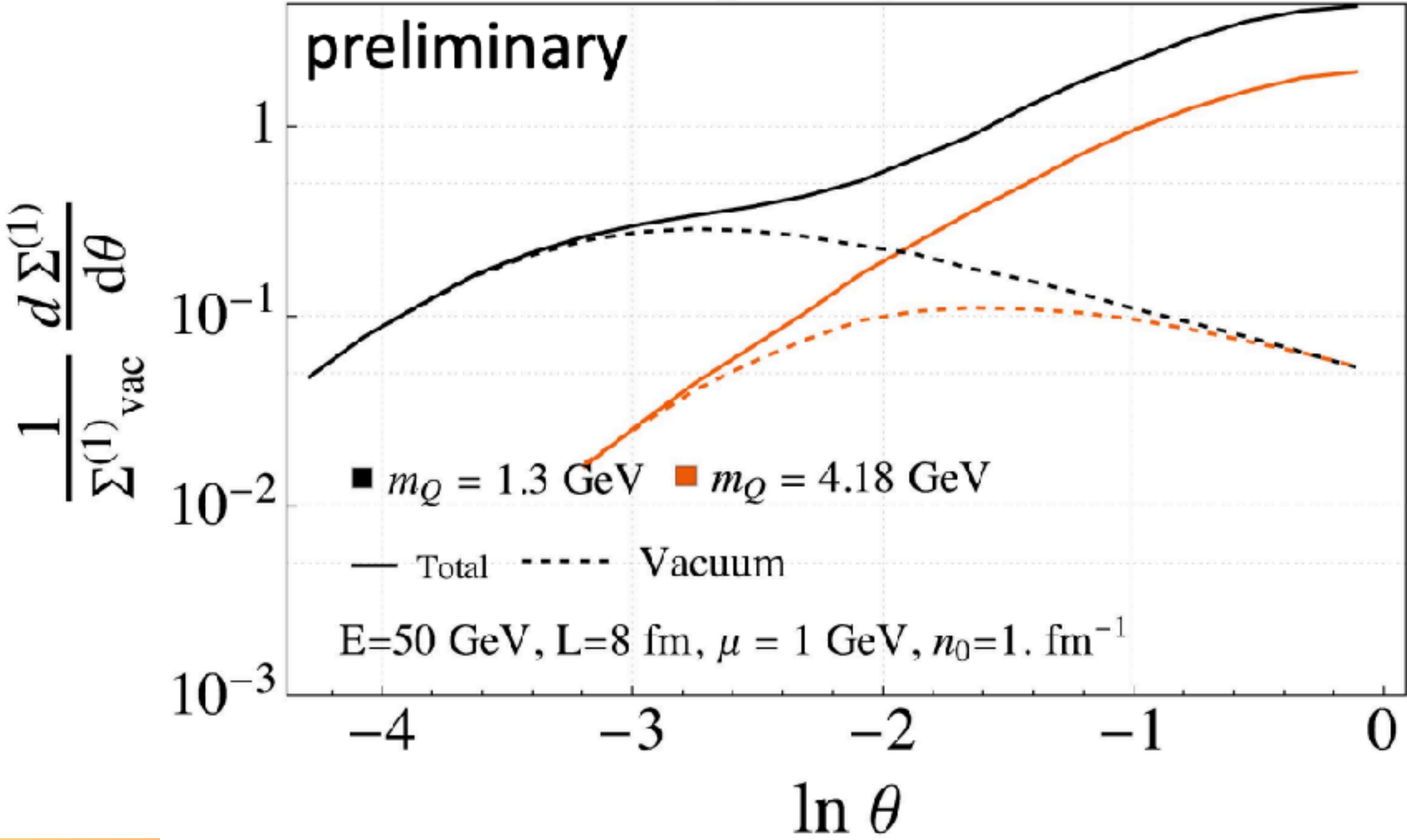


Use **empty dead cone** to cleanly reveal **medium-induced splittings in the Lund plane**



J. Holguin (Wed. 11:30am)

Two-Point Energy Correlator Comparing Masses

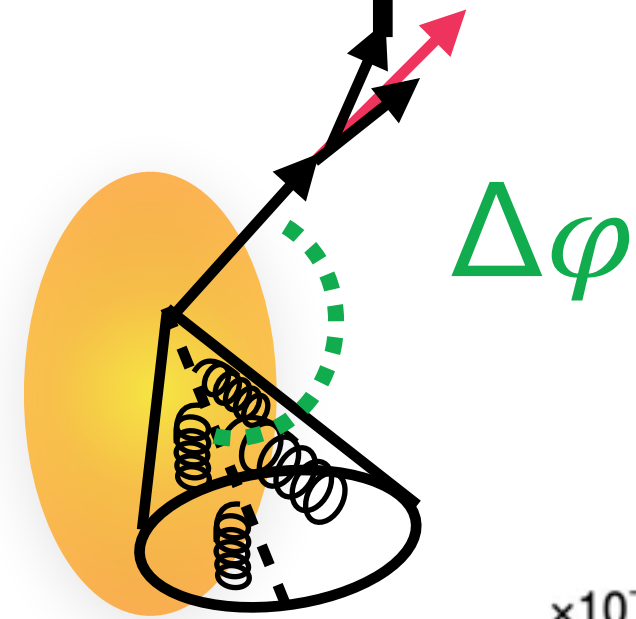


EECs sensitive to **dead cone** and medium modifications to the **dead cone**

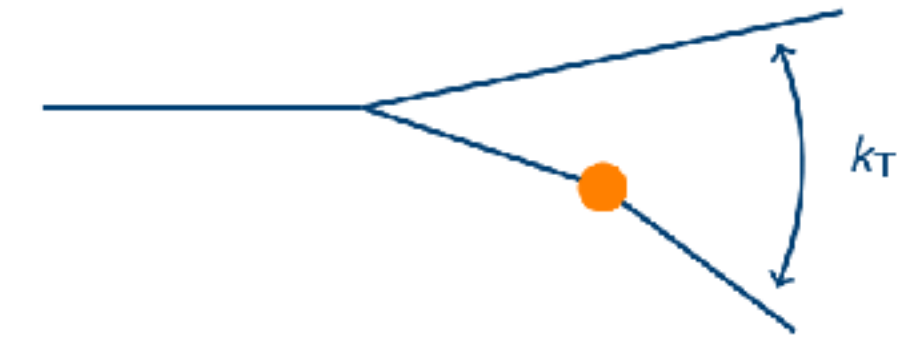
W. Dai (Wed. 11:50am)

Search for quasi-particle structure of QGP

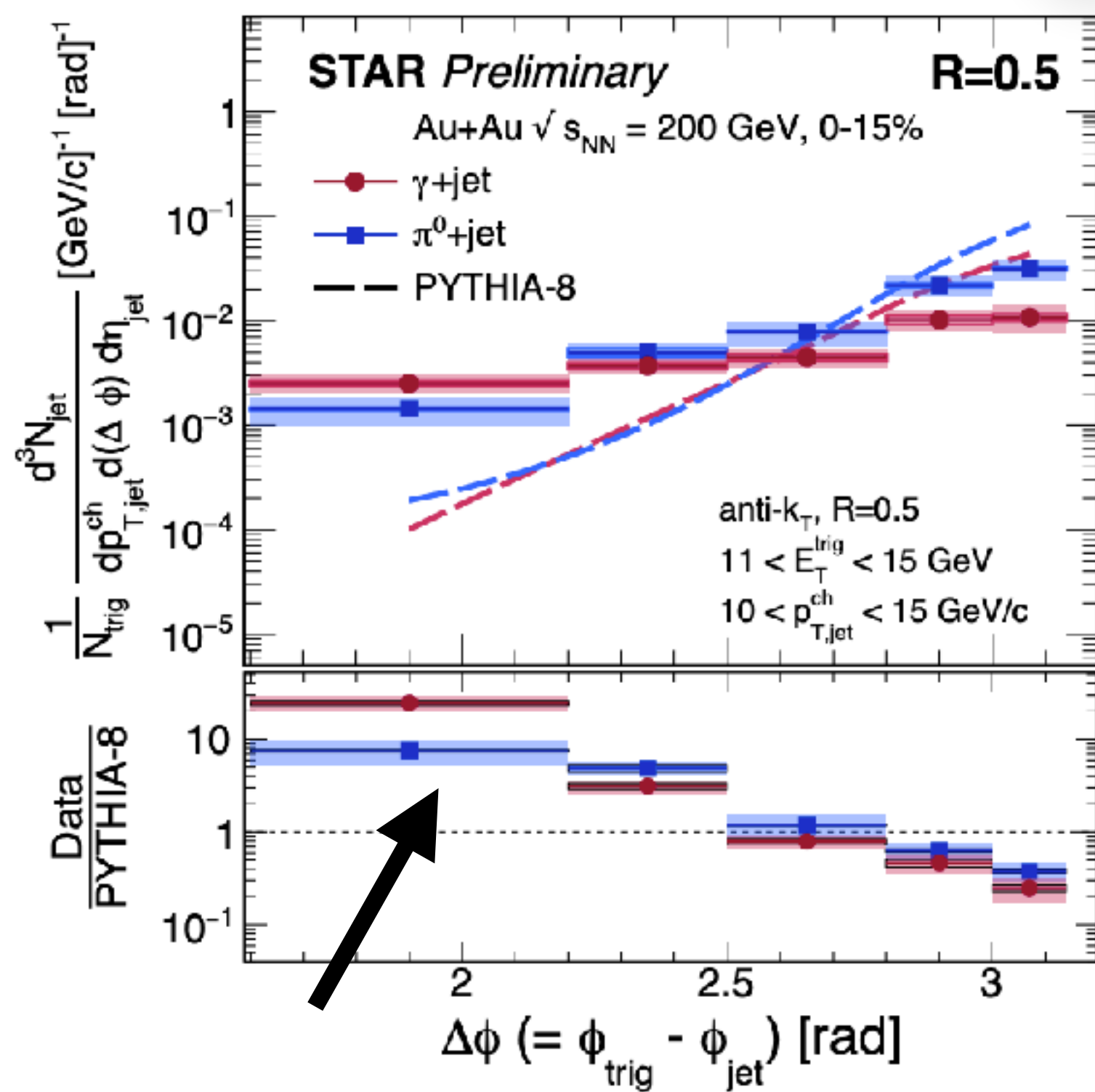
Jet acoplanarity



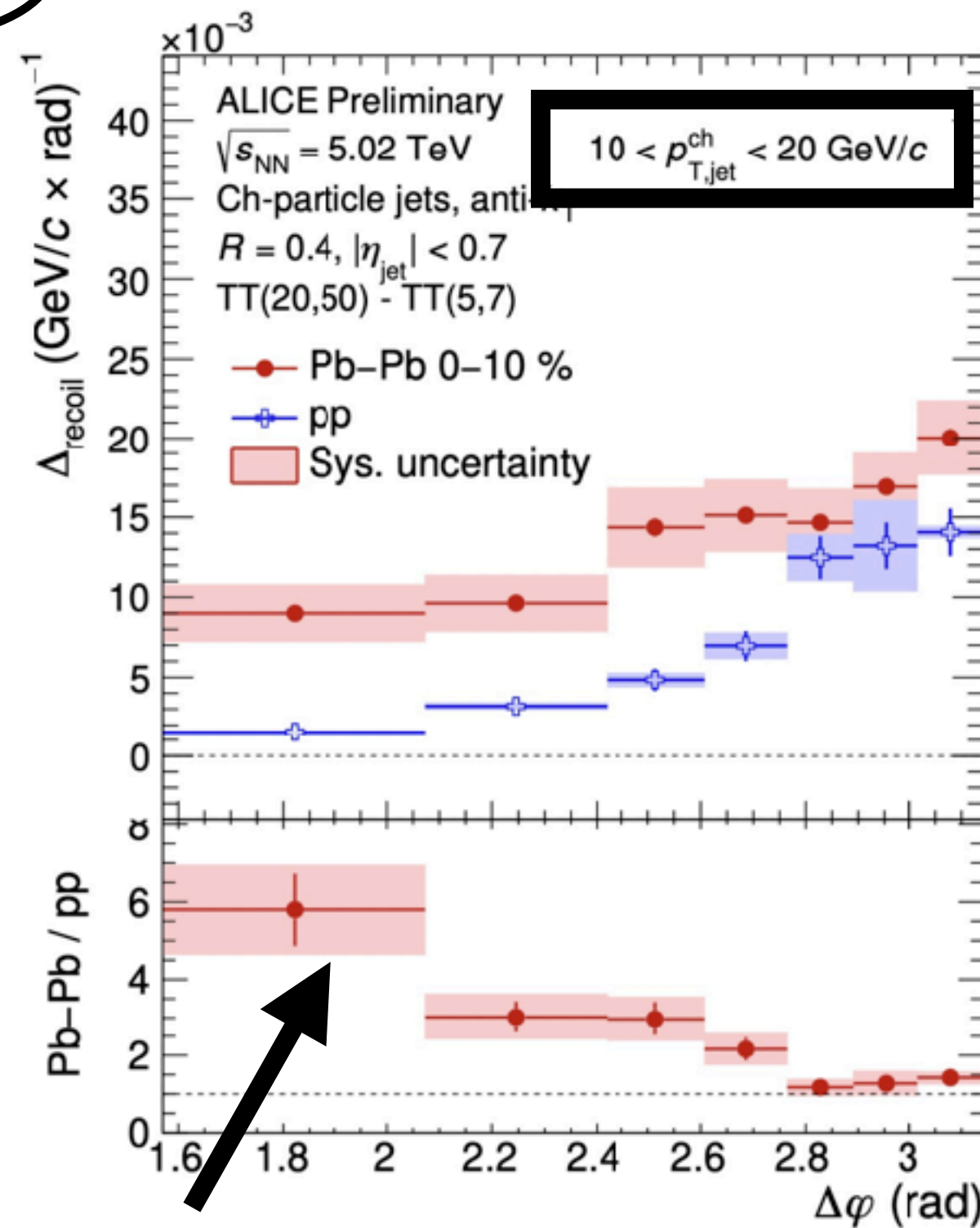
Hardest k_T kicks



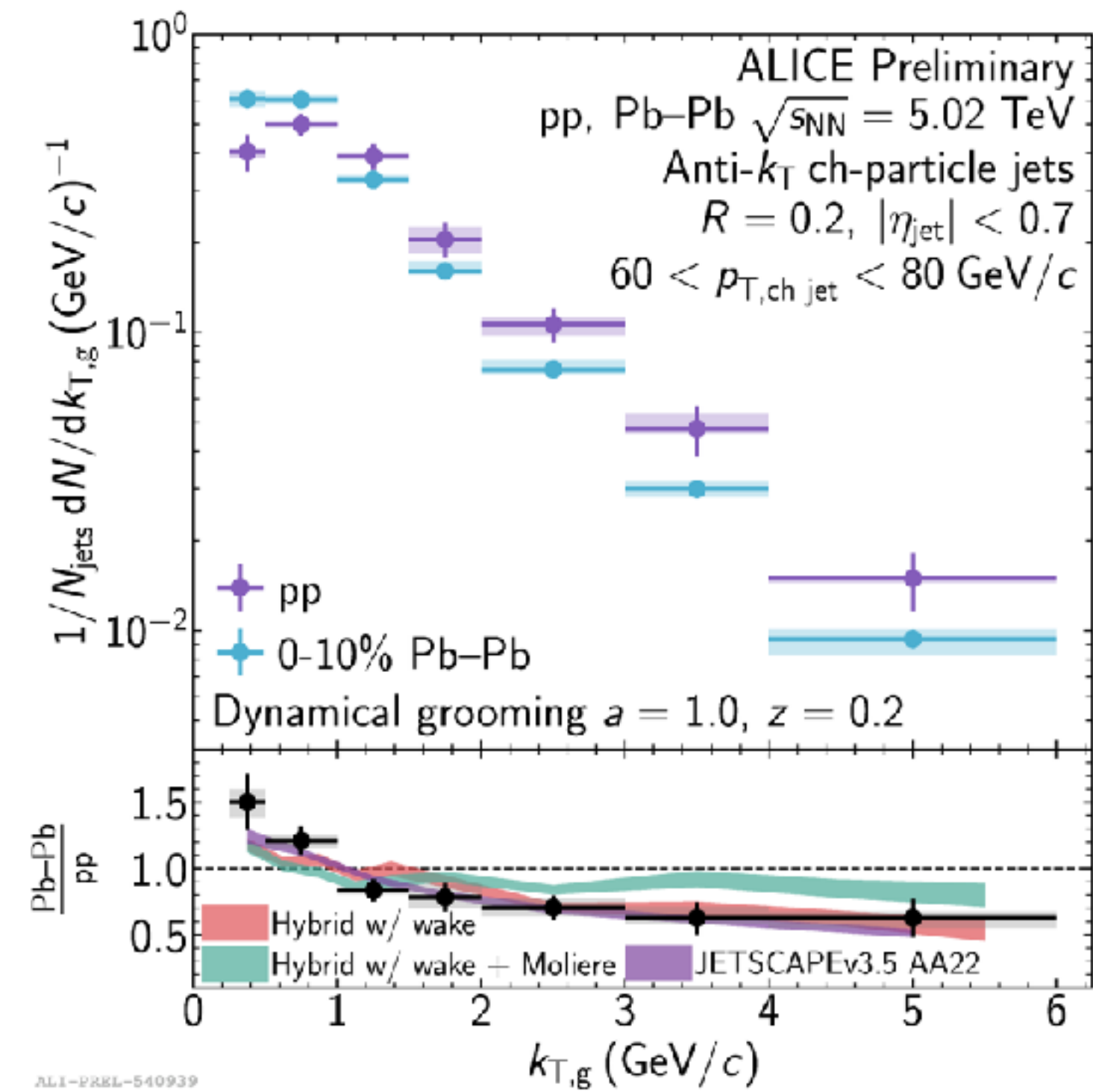
R. Ehlers



Signature of jet azimuthal broadening but may be dominated by wake effects

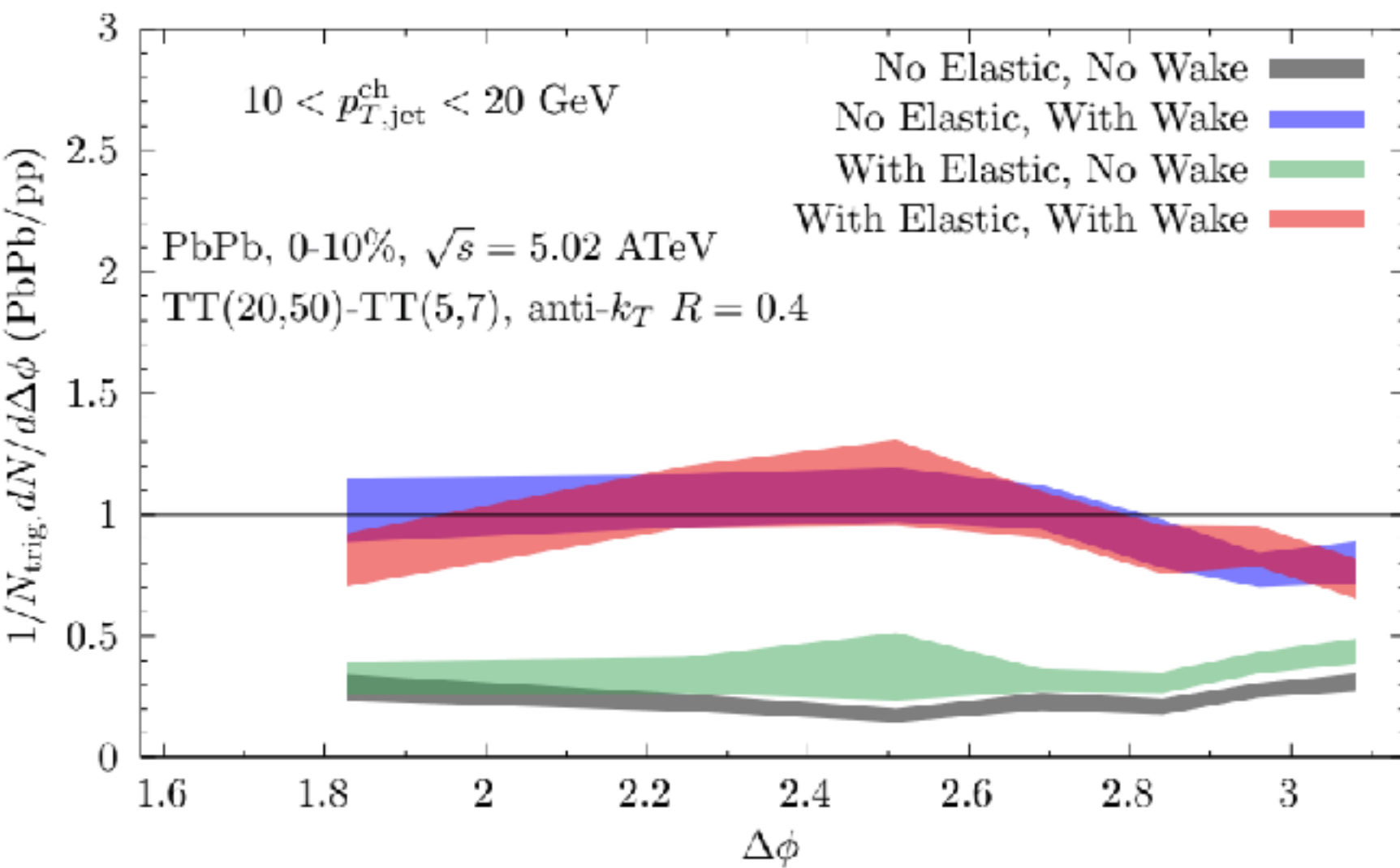


Narrowing observed, no clear evidence but sensitive to differences in models

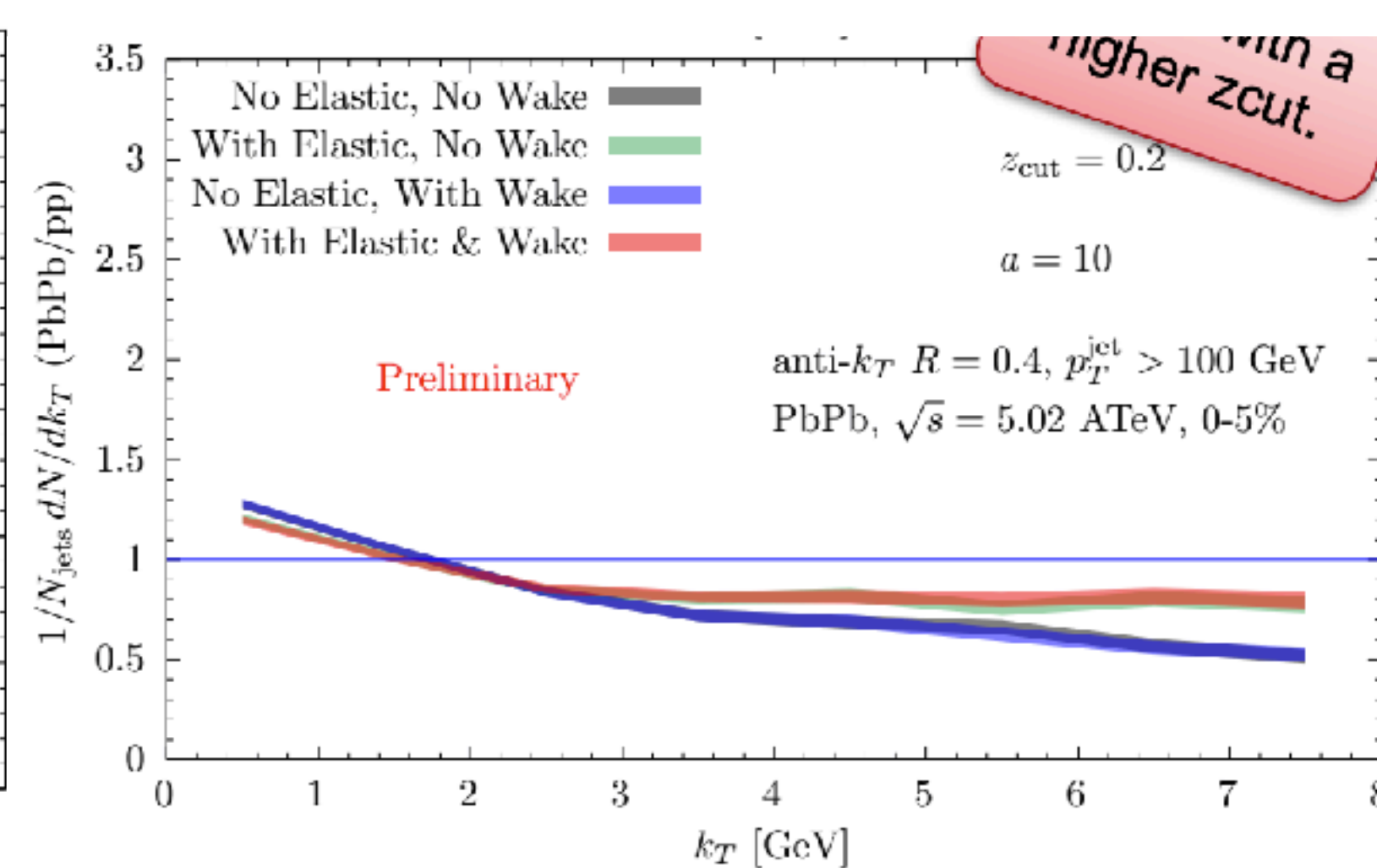


Theoretical insight: where to find Moilere?

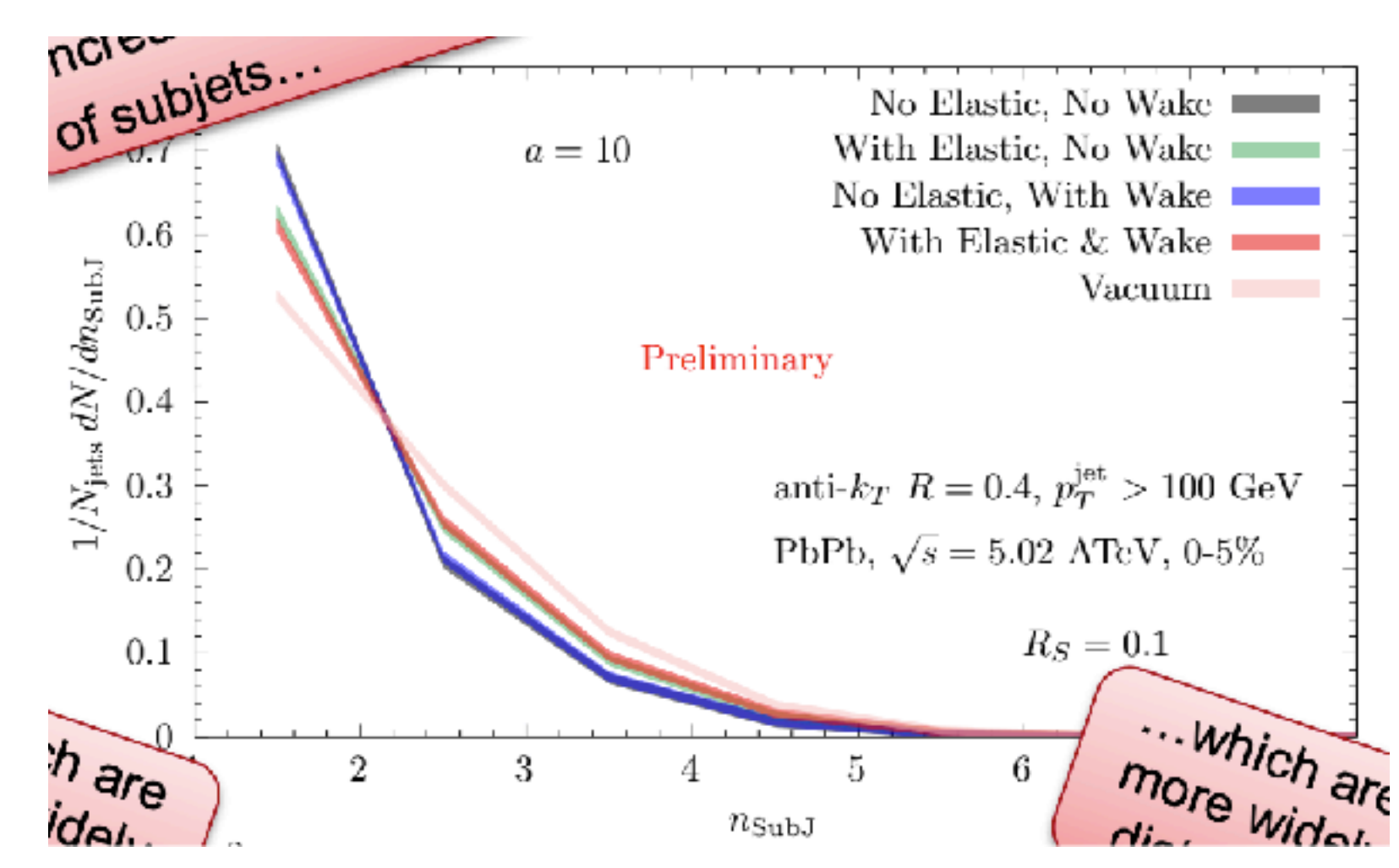
No clear evidence in experimental data yet, hybrid model explores sensitivity of different observables to **Moliere** and **wake** effects K. Rajagopal



Acoplanarity more sensitive to **wake** effects



Hardest k_T more sensitive to **Moliere** effects

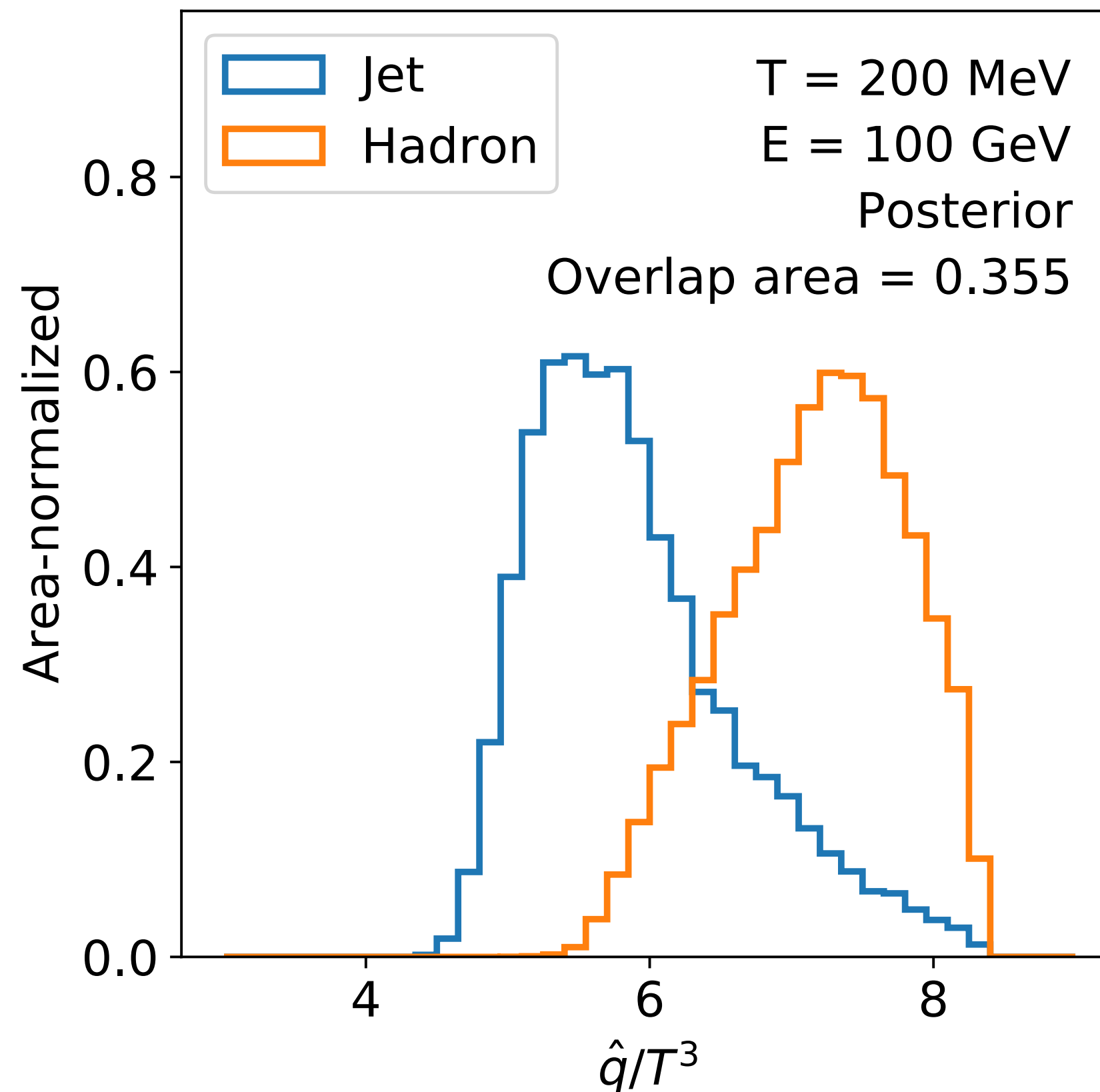
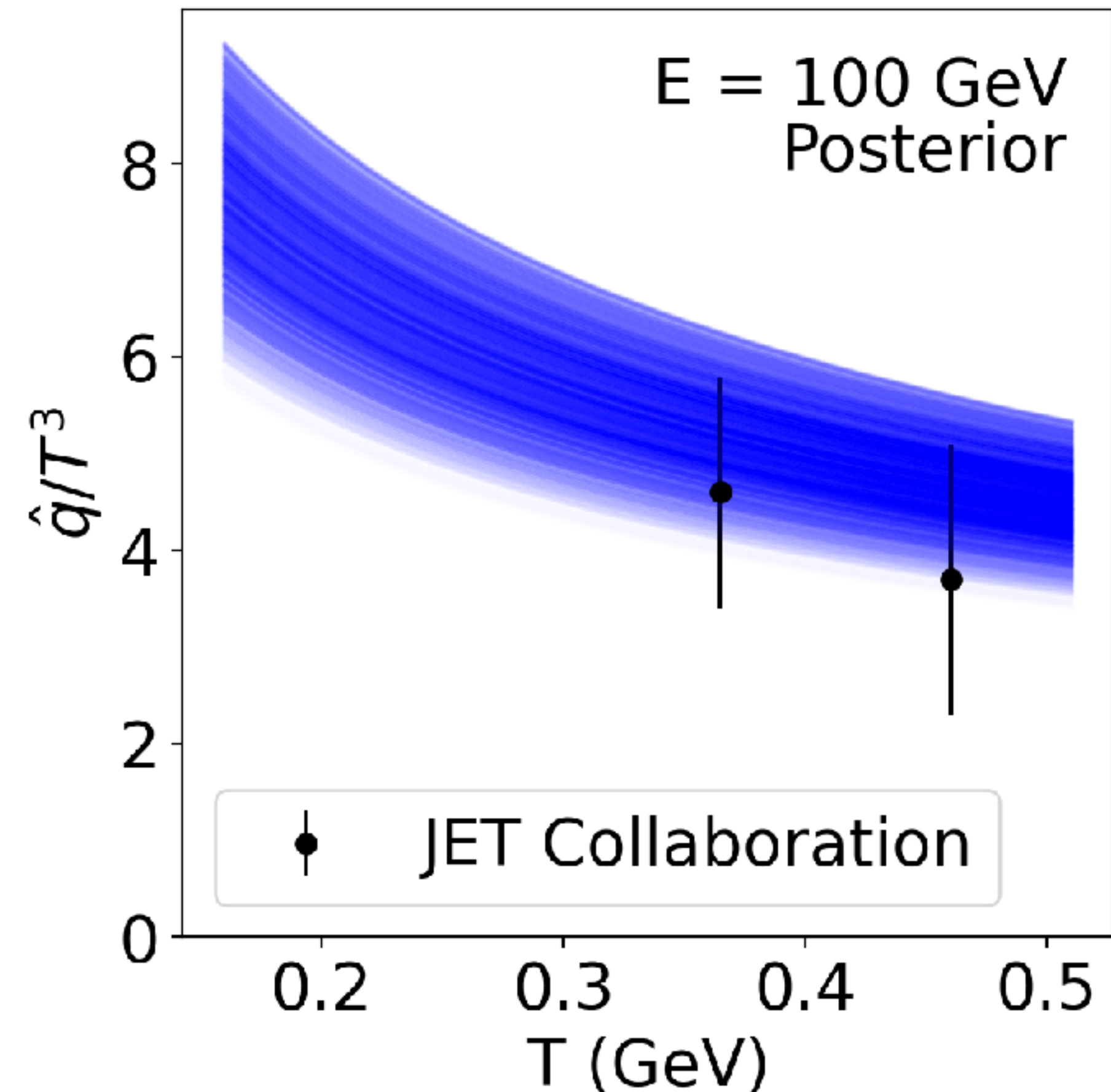


Number of subjects inside a jet very sensitive to Moilere

Extracting QGP medium properties from jets

Bayesian analyses of LHC and RHIC data using hadron p_T and jet p_T to extract the QGP jet transport coefficient \hat{q} using JETSCAPE framework

Y. Chen (Tues. 4:30 pm)



See differences between jet and hadron extraction

S. Bass (Wed. 9:40 am)

Using experimental data to learn about the medium!

Searching for jet quenching in small systems

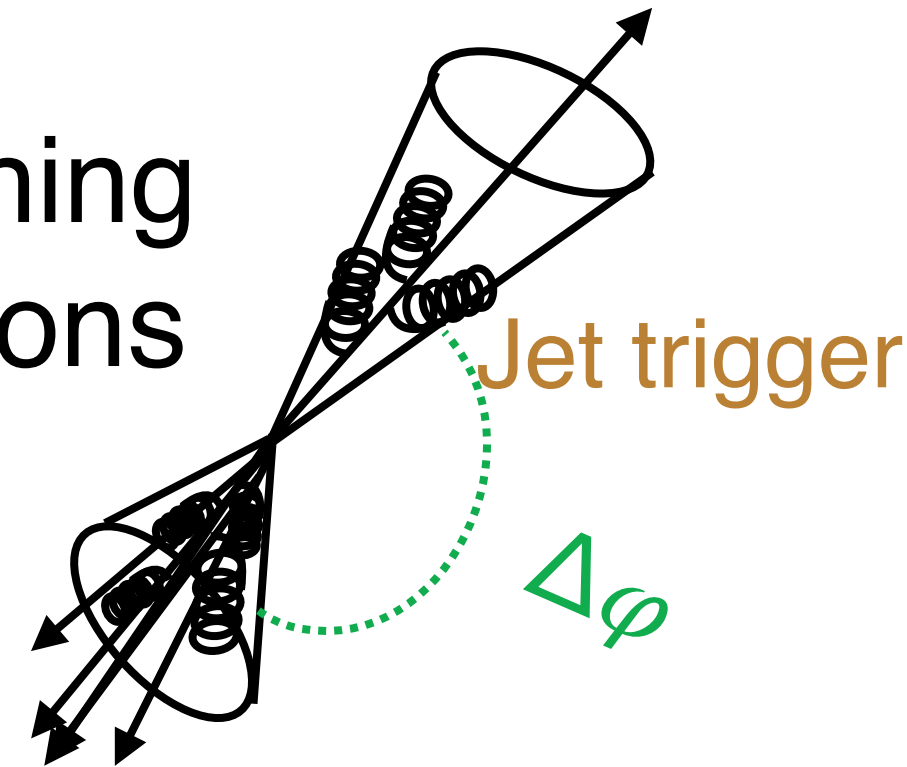
Non-zero jet v_2 at high p_T in p-Pb

[ALICE arXiv:2212.12609](#)

[ATLAS EPJC 80 \(2020\) 73](#)

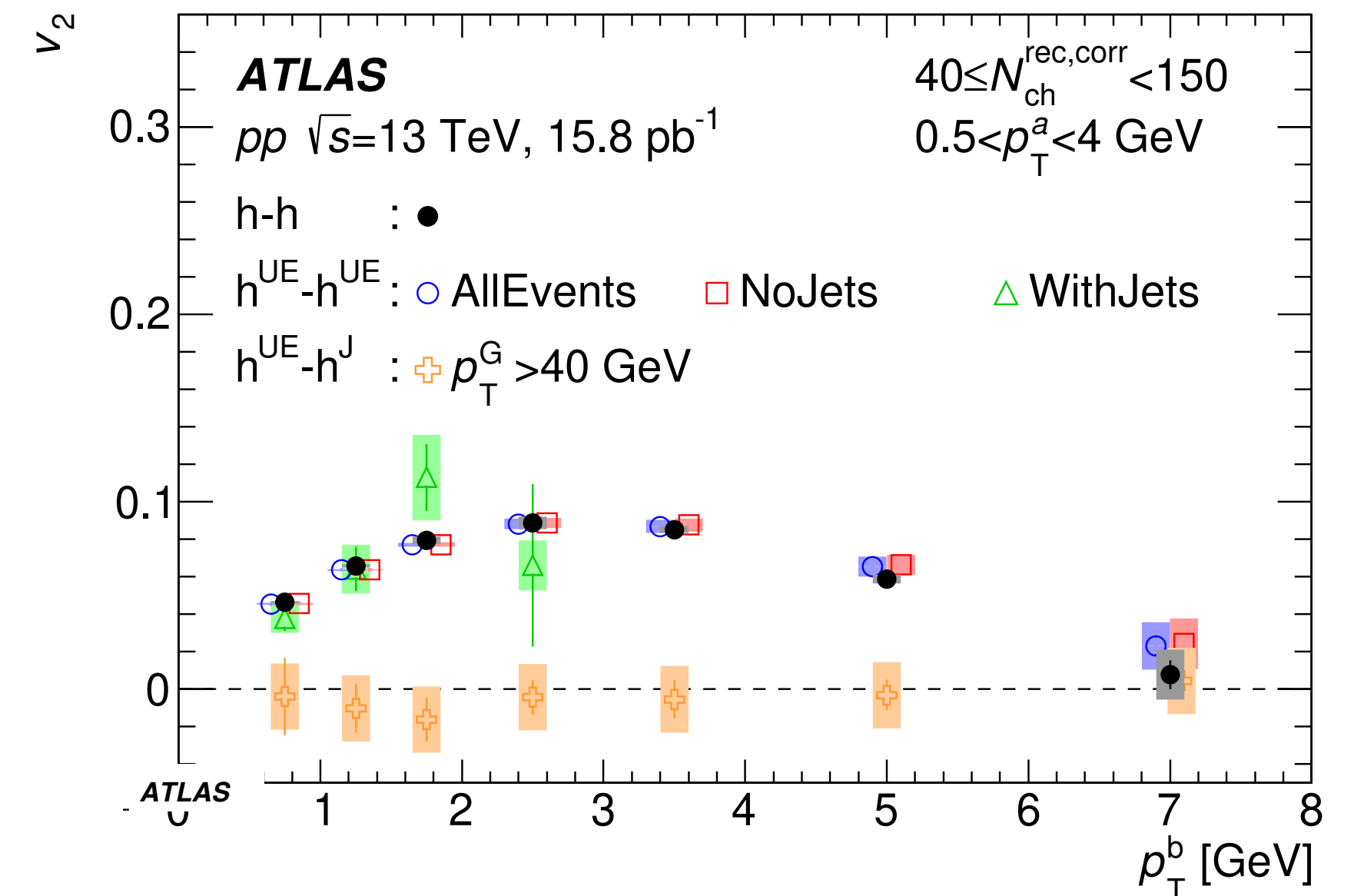
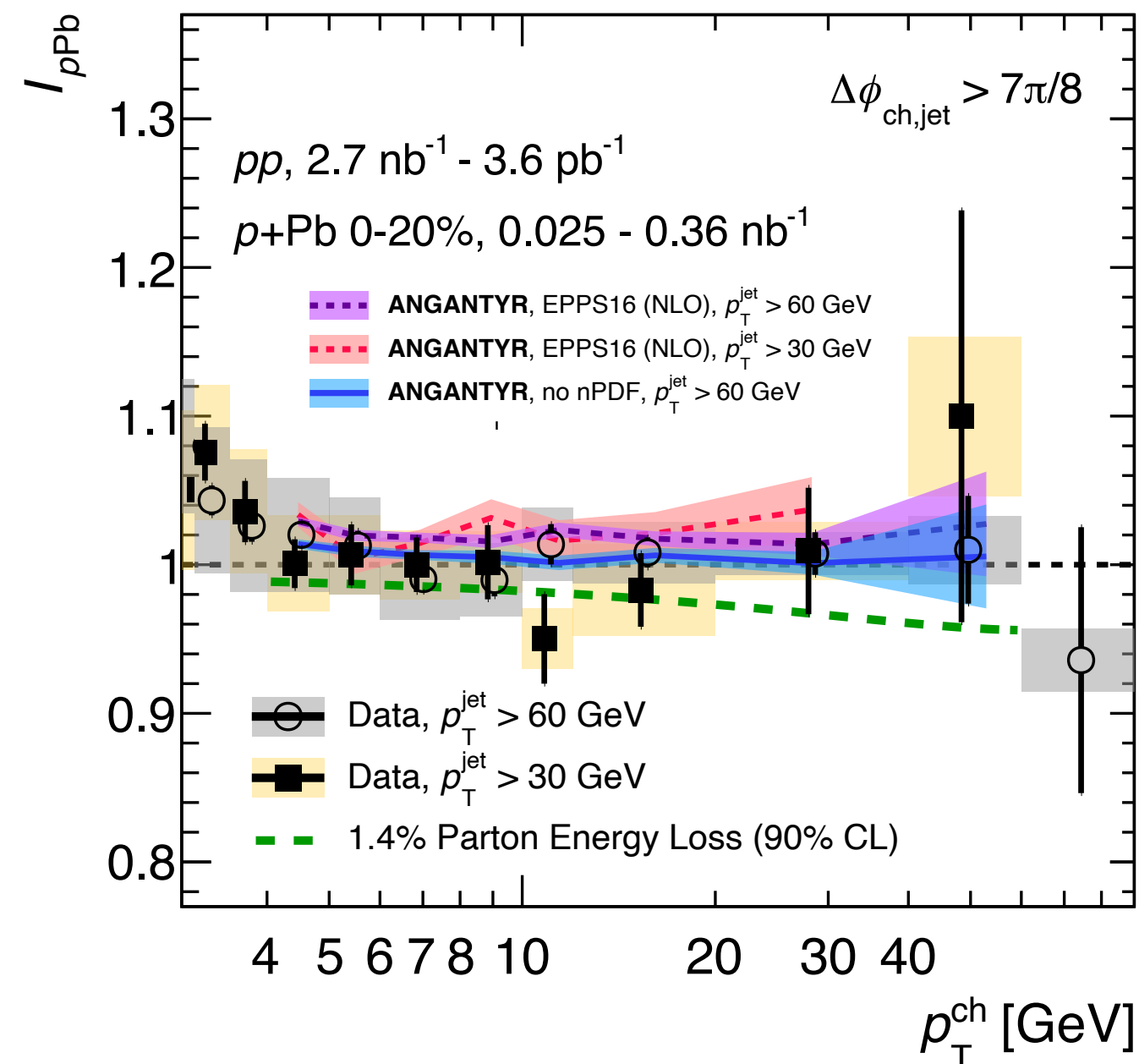
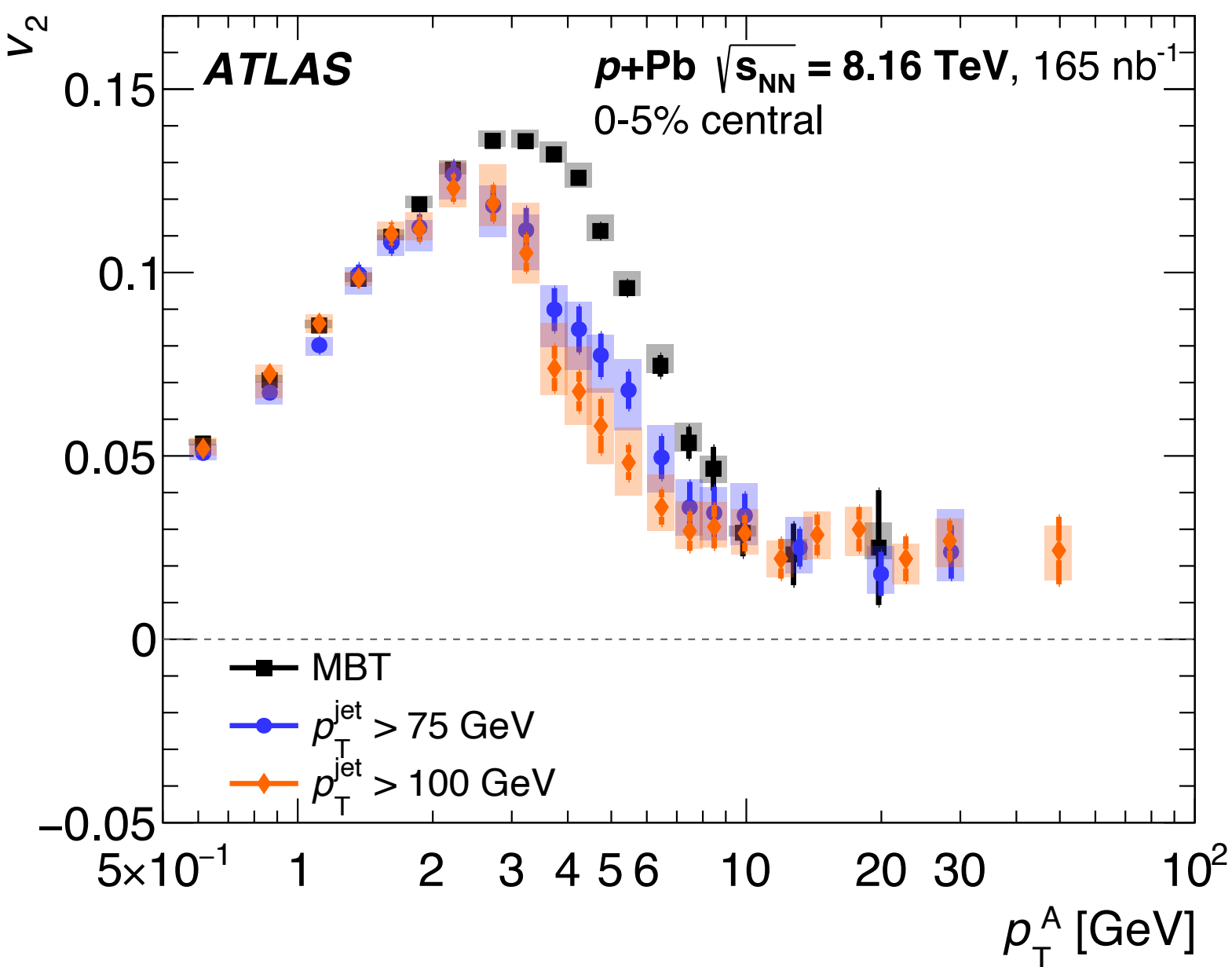
Search for jet quenching in p-Pb with jet+hadrons

J. Nagle (Tues. 10:00 am)



Is hard process decoupled from soft underlying event in pp? B. Cole (Tues. 10:00 am)

Correlate jet-UE particles



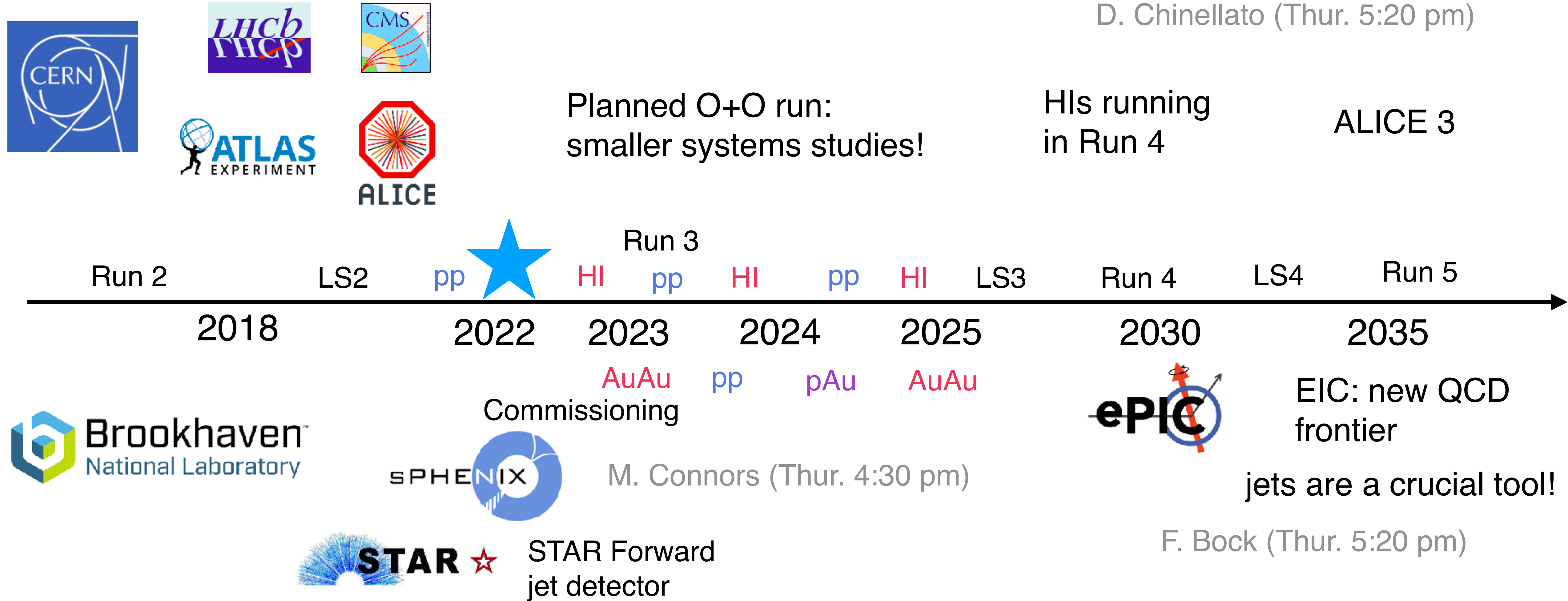
No parton energy loss found, limit set

[ATLAS arXiv:2206.01138](#)

jet-UE $v_2 \sim 0$, soft and hard physics decoupled? [ATLAS arXiv:XXXX](#)

Looking towards the future with jets

D. Chinellato (Thur. 5:20 pm)



Significant statistics for jets, HF jets and photon jets!

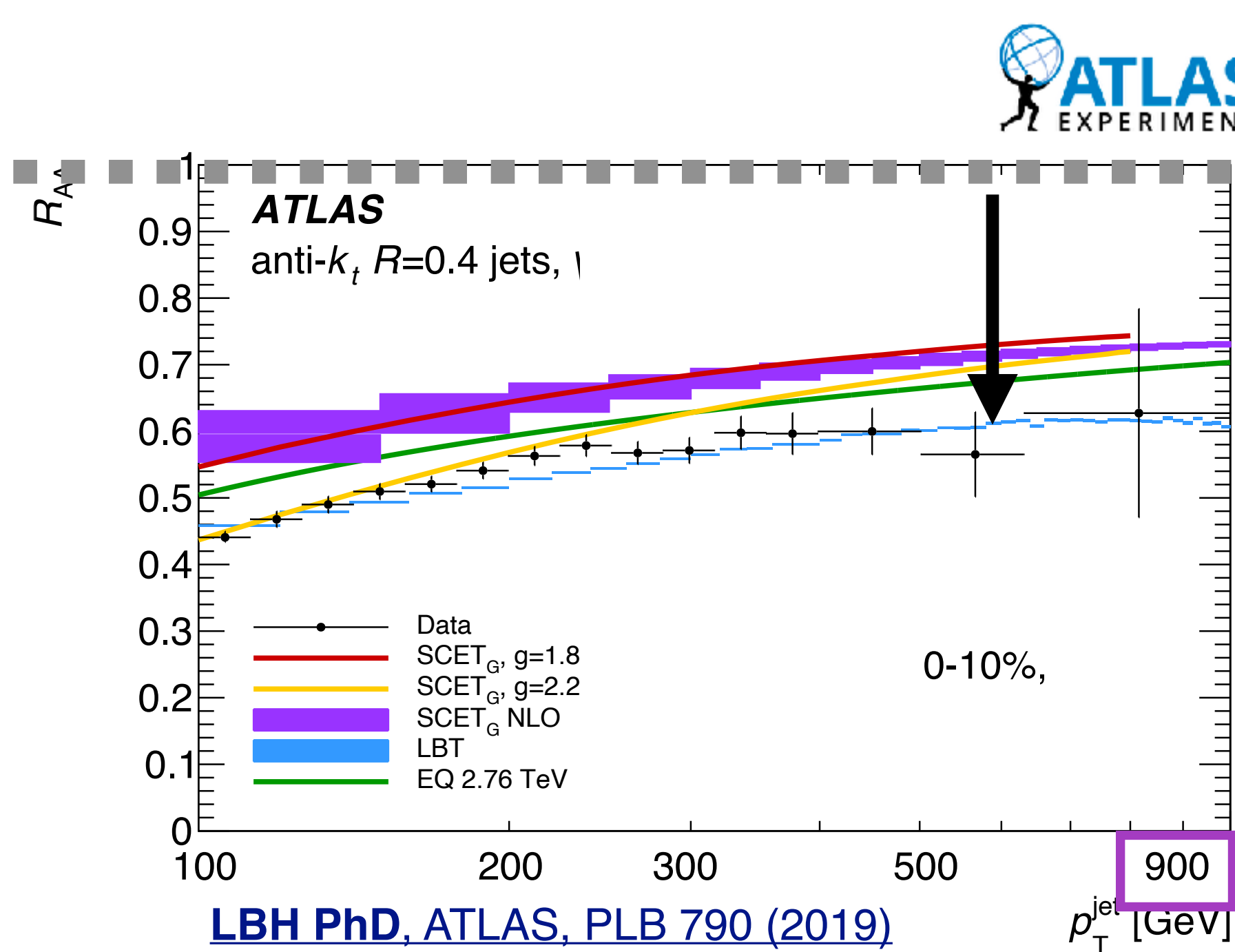
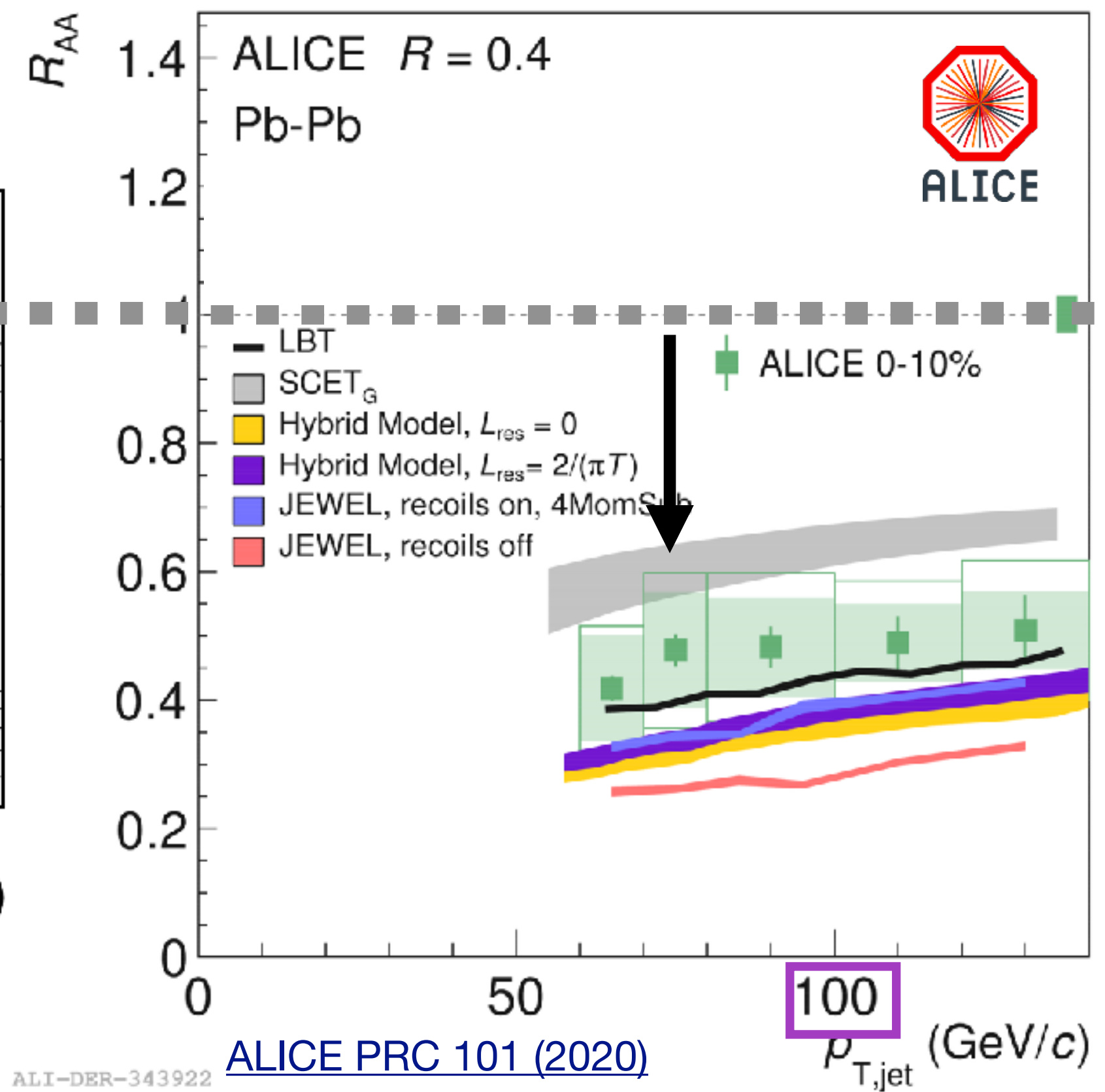
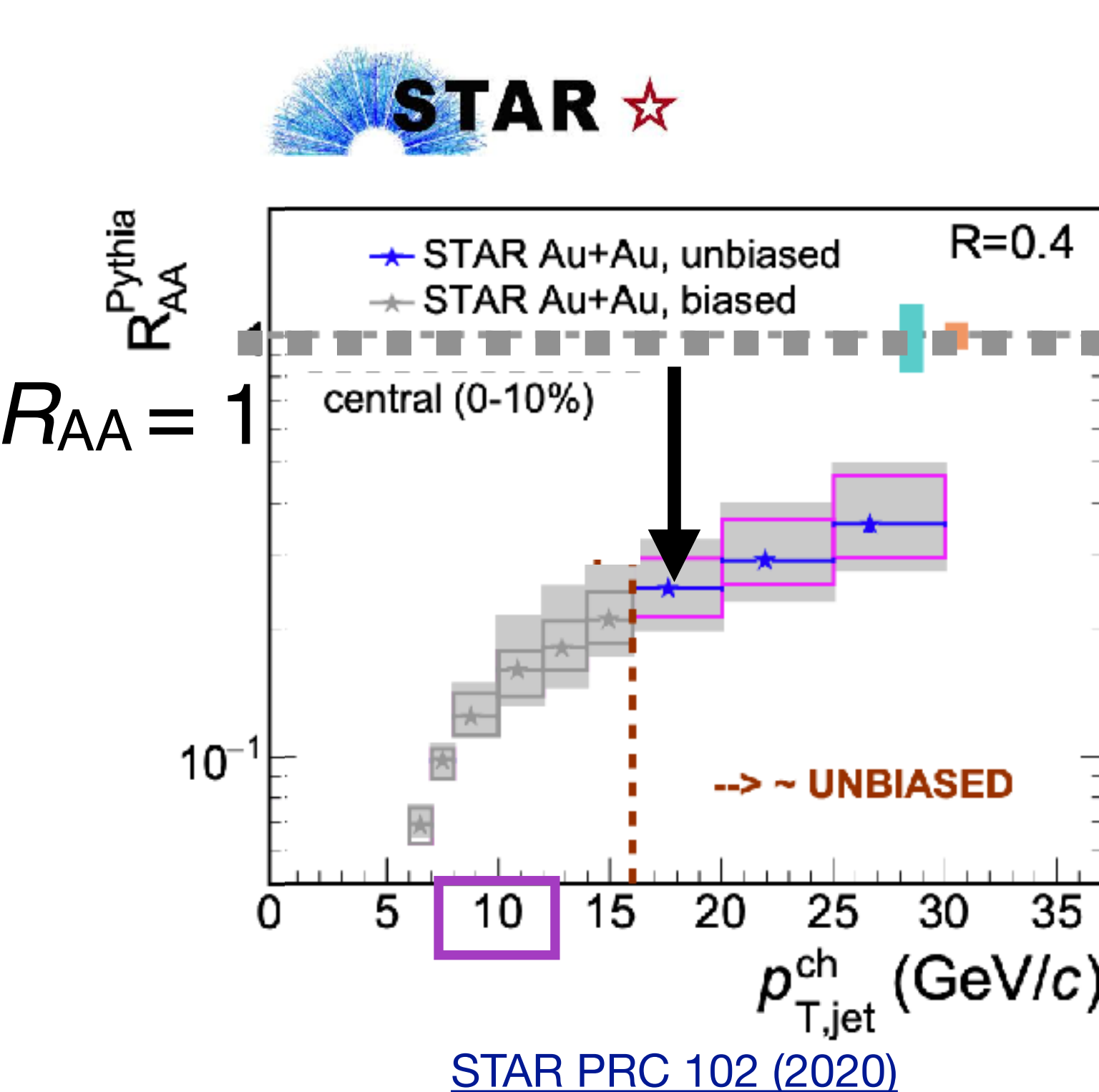
Thank you!

Thank you to Hannah Bossi, Raymond Ehlers, Caitie Beattie, Andrew Tamis, Mike Sas, Isaac Mooney, Yi Chen, Martin Rybar for useful discussions, figures, and/or edits!

Backup

Jet suppression observed over a large p_T range

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

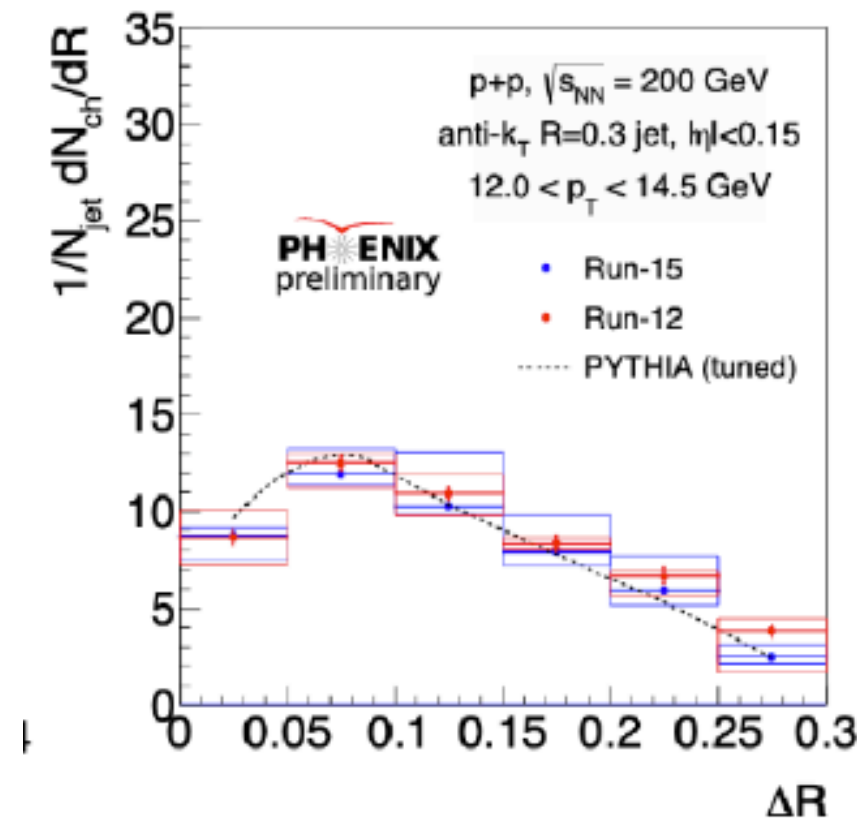


Jet quenching models describe data fairly well but what do we learn?

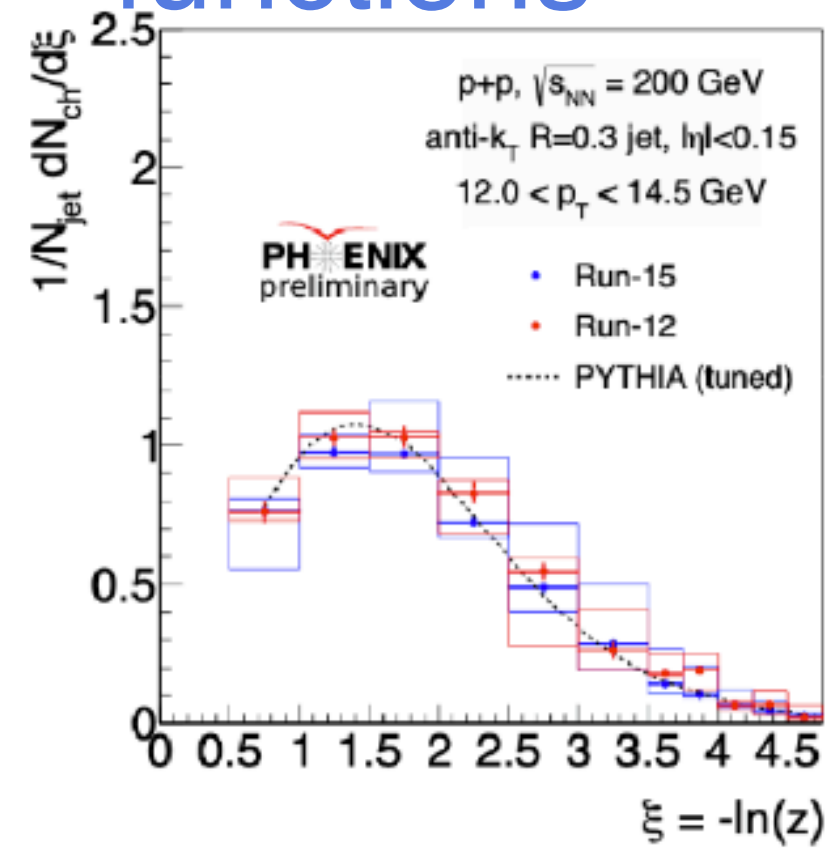
Jets as a tool to study QCD

- Different variables probe different scales

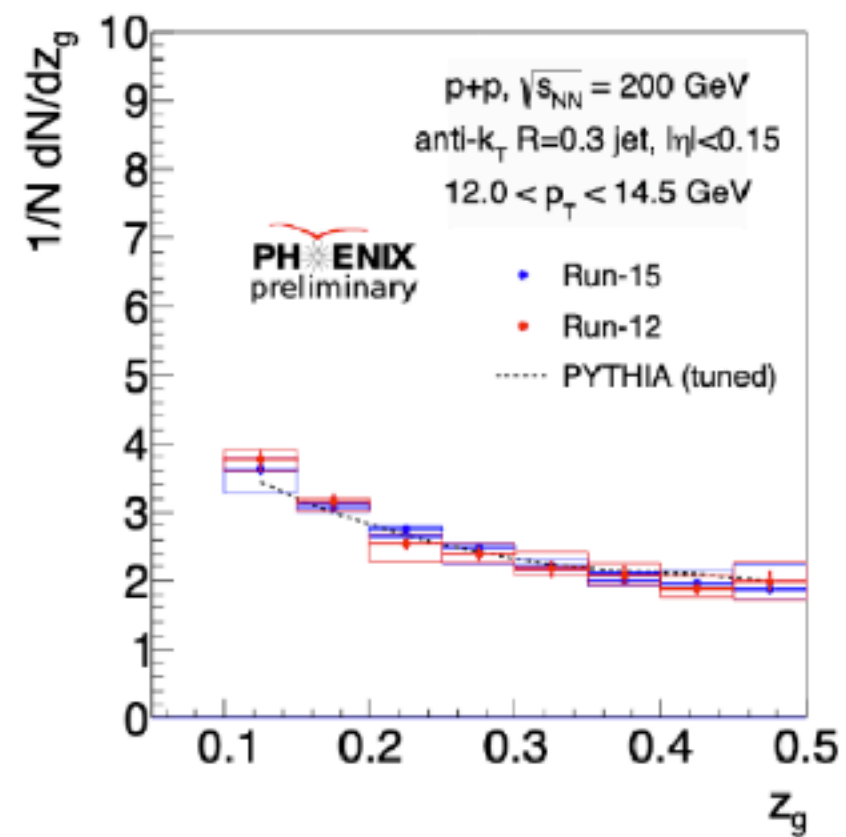
→ Distribution of charged radial profiles hadrons inside the jet



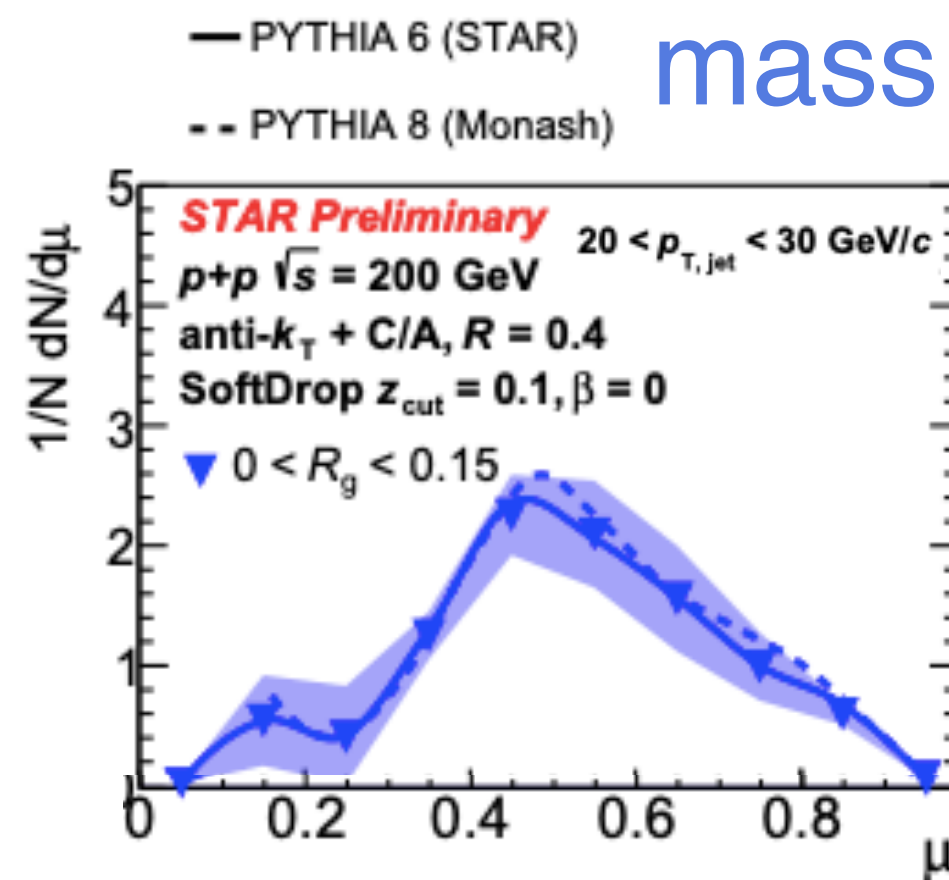
fragmentation functions



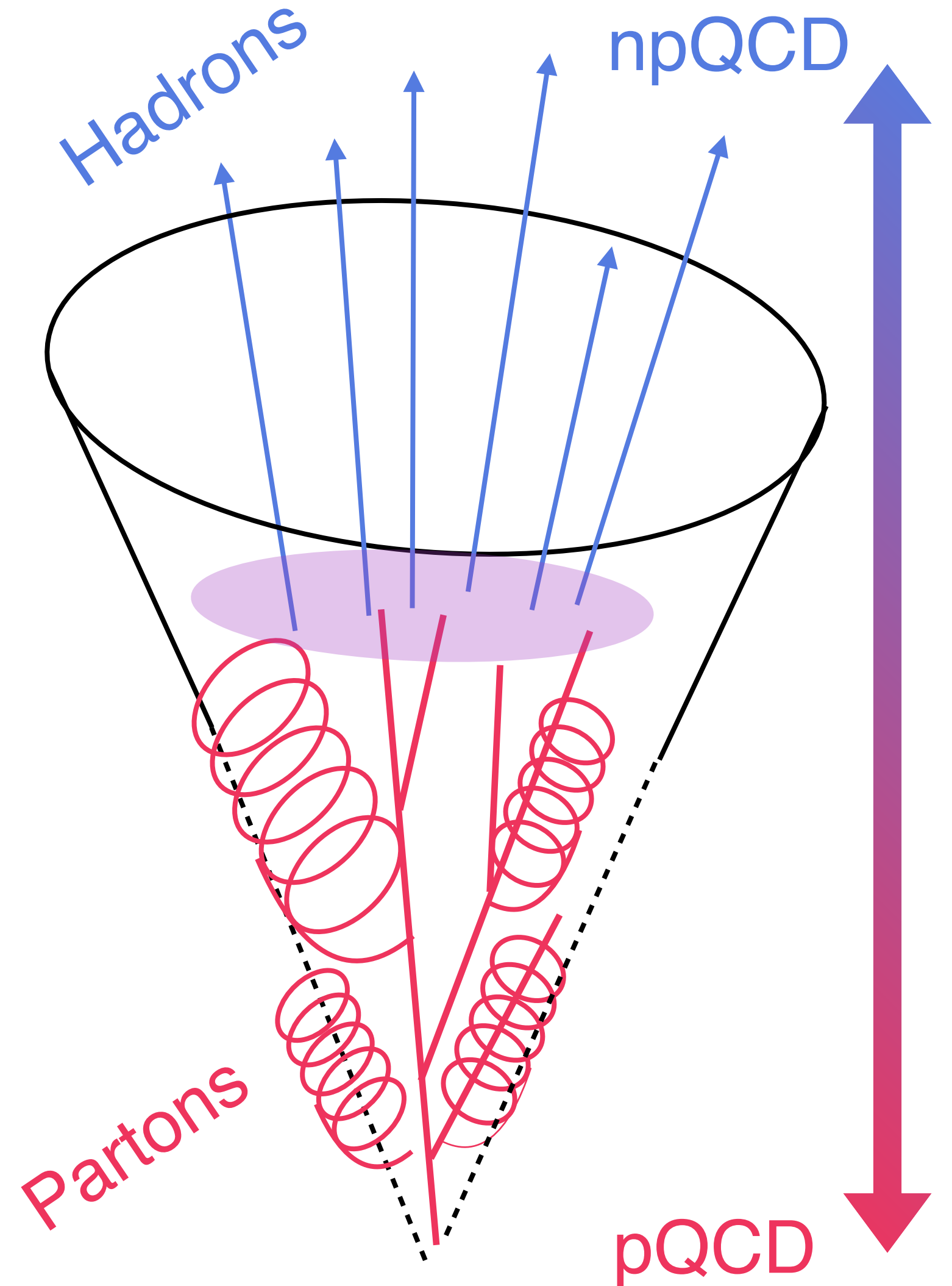
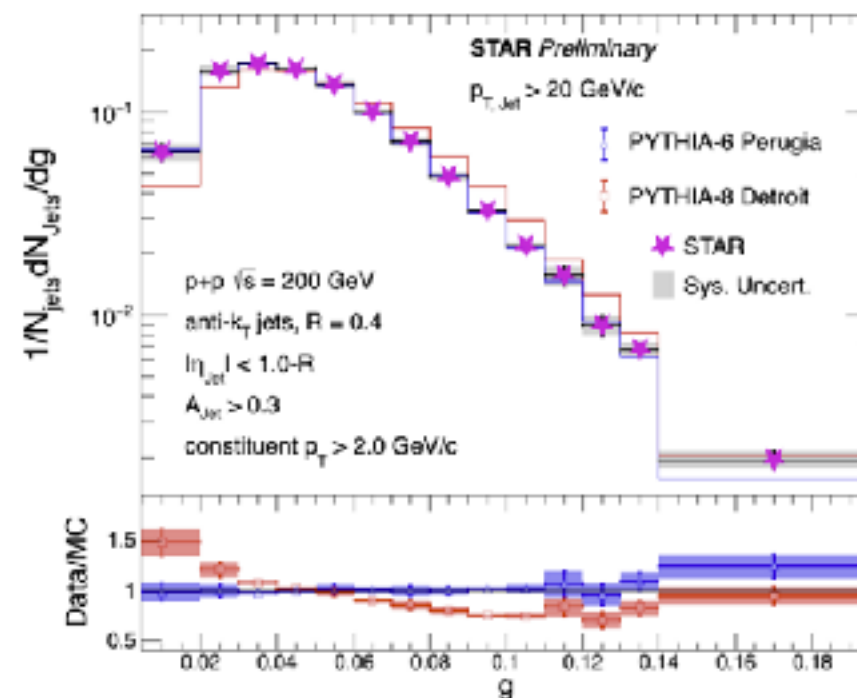
→ Subjets from hard parton splittings



Z_g



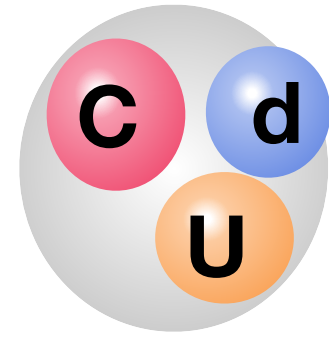
angularities



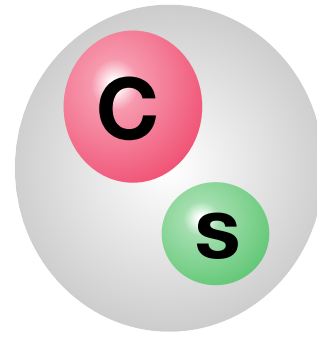
Wealth of new pp data to inform and constrain models

Charm hadrons inside jets

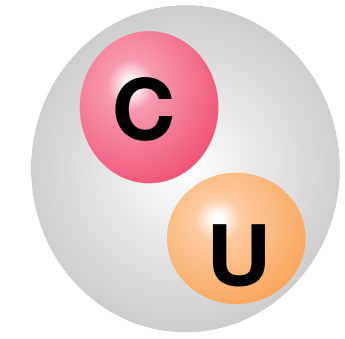
Λ_c^+/D^0



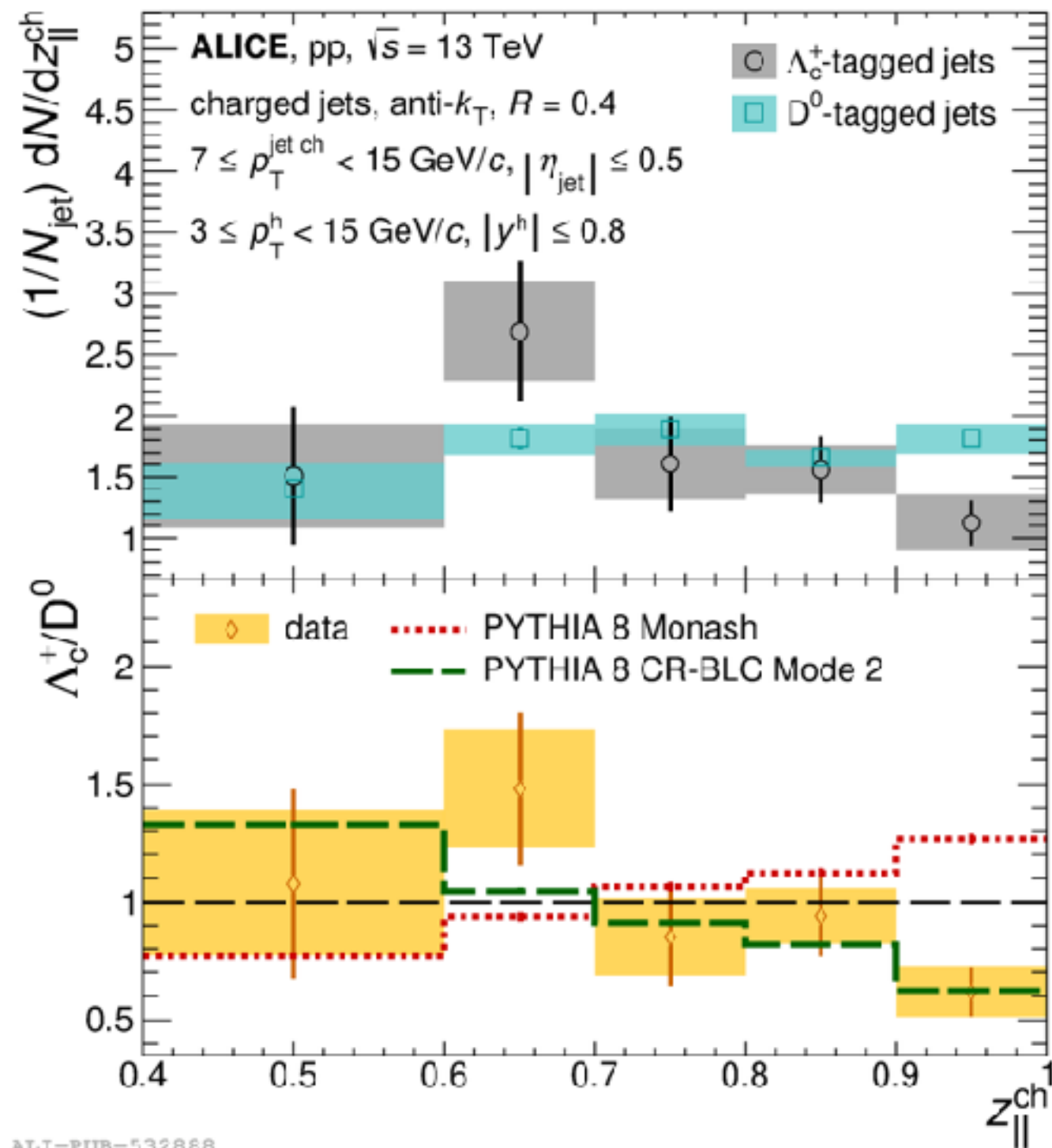
D_S^*/D^0



$D^0/\text{inclusive}$

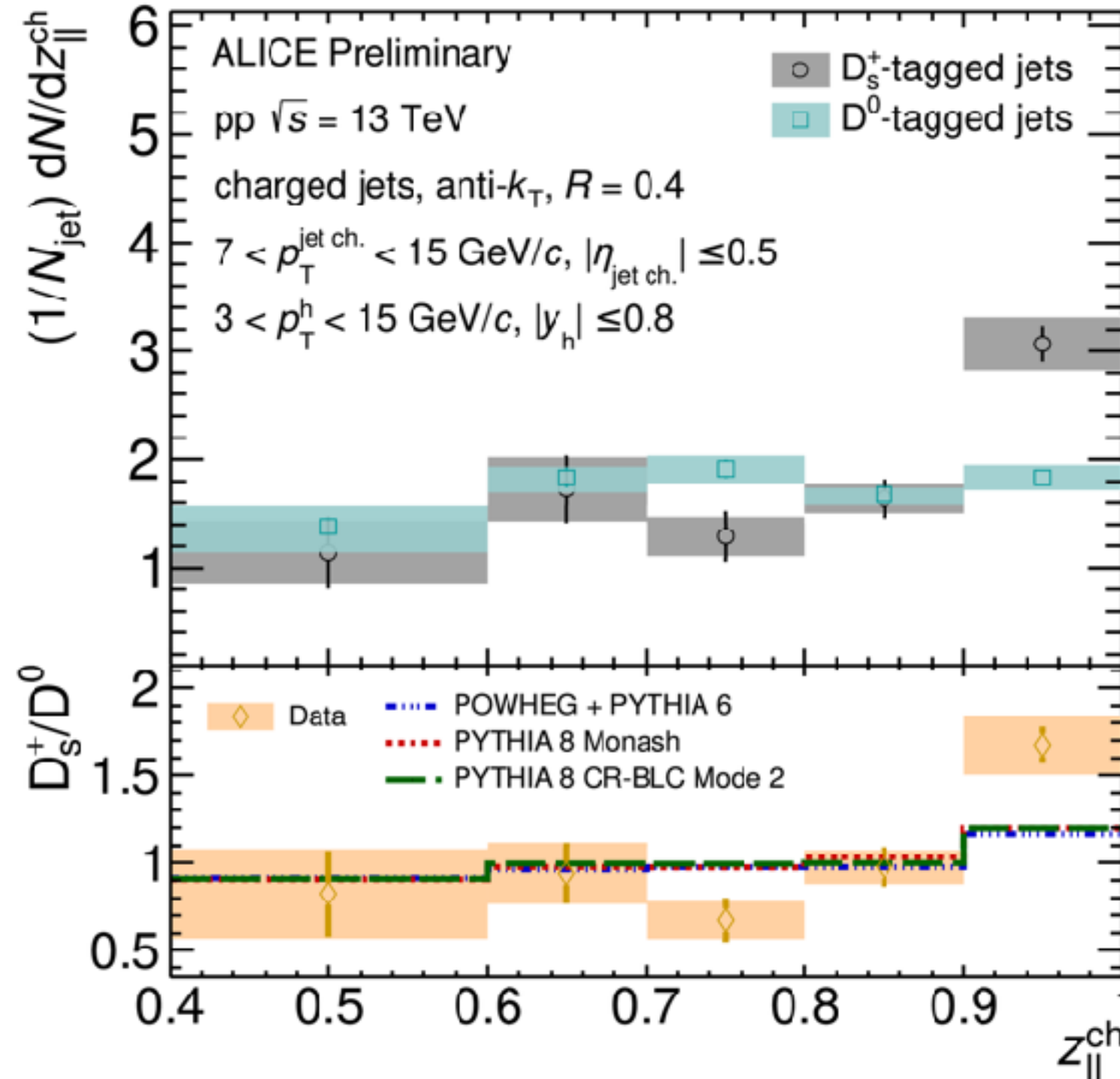


[arXiv:2301.13798](https://arxiv.org/abs/2301.13798)



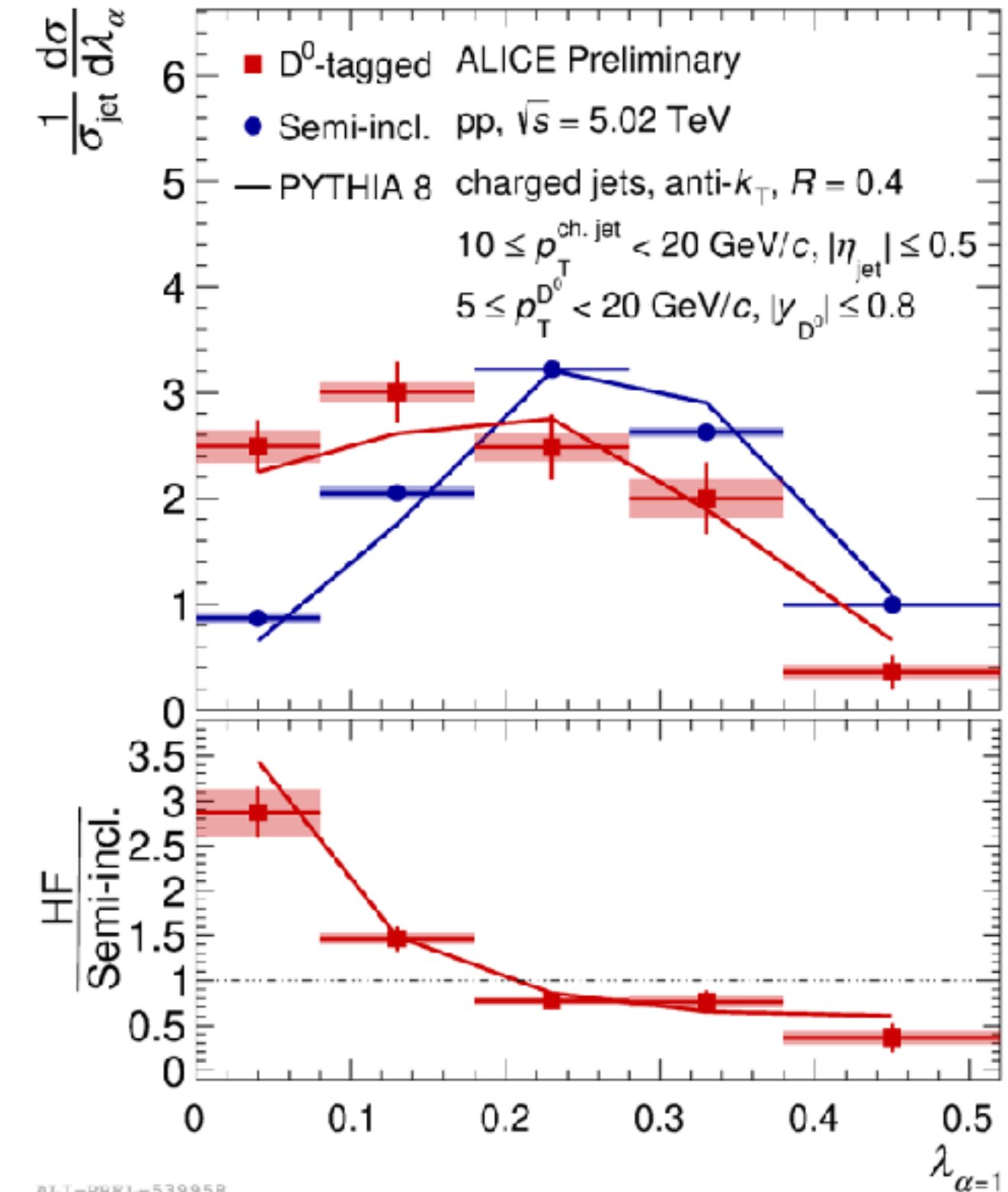
ALI-PUB-532868

Differences in charm baryon and meson fragmentation

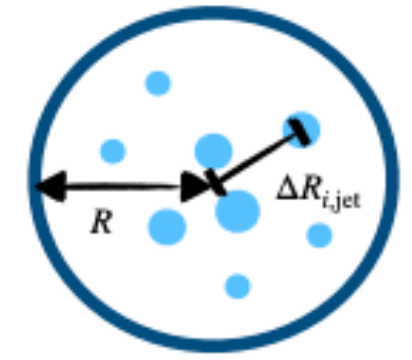


ALI-PREL-539362

Strangeness in charm



Mass and flavor dependence of fragmentation patterns



$$\lambda_\alpha = \sum_i z_i \theta_i^\alpha$$

Constraints on charm fragmentation and hadronization; paves path for HIs

Theoretical challenges and advances

- Week began with excellent overview of jet quenching effects and theory
- Challenging to describe everything so each model has different assumptions and implementations of jet quenching effects

Improved numerical and analytical calculations

C. Andres (Mon. 4:40 pm)

Jet substructure observables under better theoretical control

A. Soto-Ontoso (Mon. 5:05 pm)

Medium response is important when interpreting results and models: significant discussion this week

Y. Go (Mon. 5:30 pm)

Pros and cons of analytical calculations and MCs

L. Apolinário (Mon. 5:55 pm)

- Increased communication between theory and experiment has provided theoretically motivated observables that are experimentally measurable (challenging!)

Vary jet R to disentangle medium effects

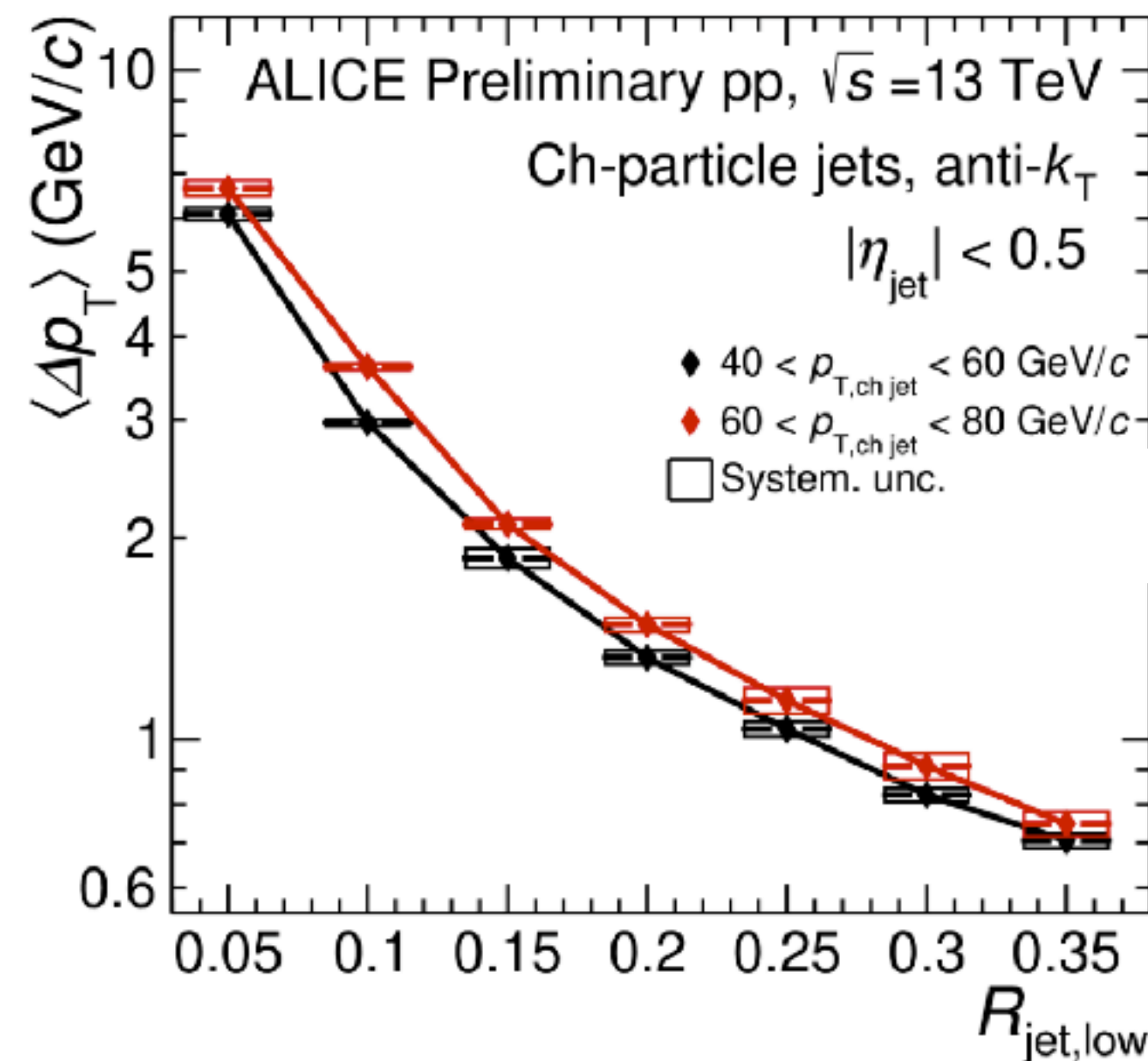
Tension at low p_T with **ATLAS result**

Converge to **CMS result** at high p_T

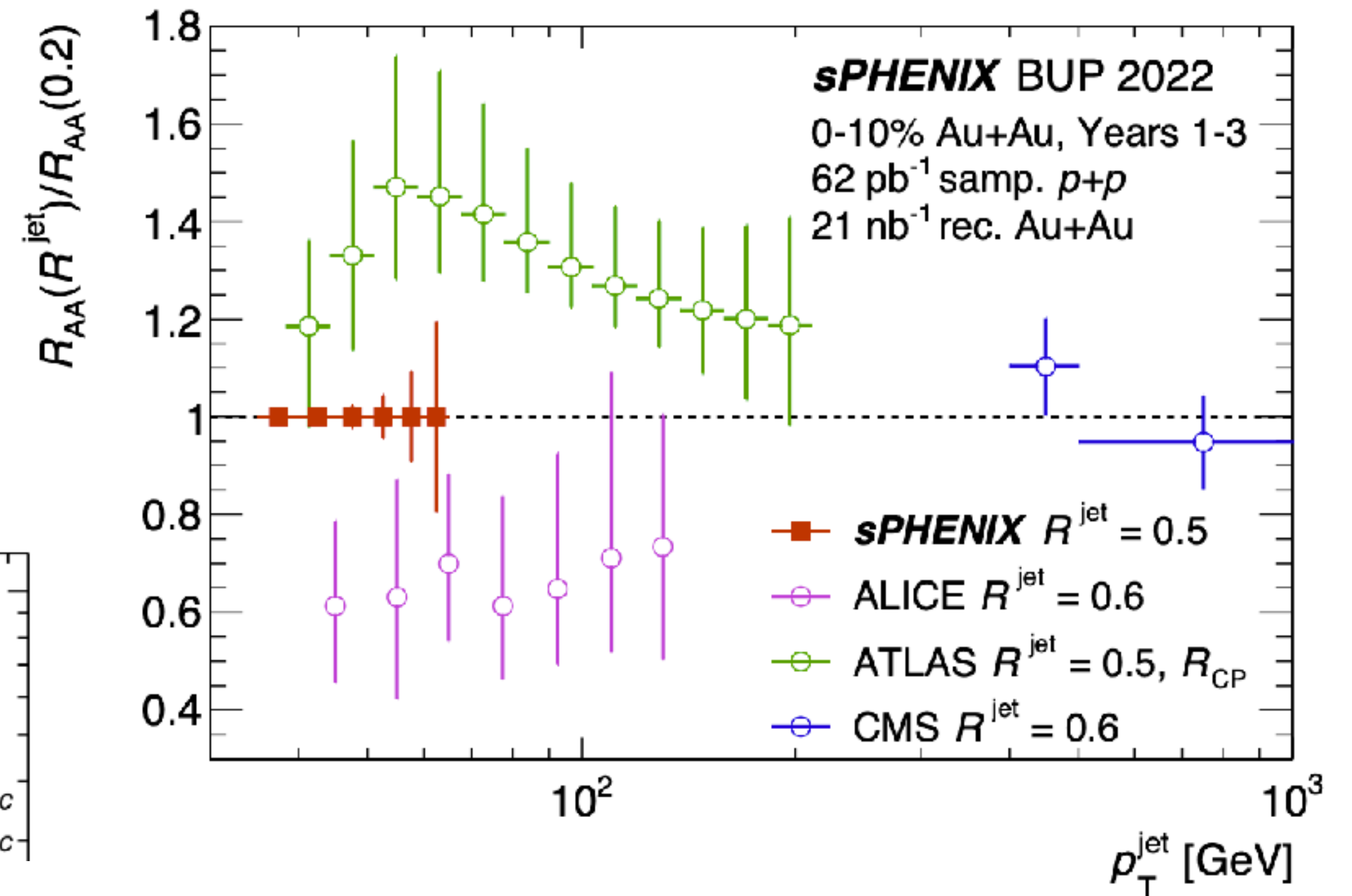
Differences: R_{CP} vs. R_{AA} , c-o-m, rapidity, charged vs. full jet, min. p_{Tconst} , background subtraction: region with large HI background is challenging!

Christos Tues. :
Jet energy flow
between jet radii

photon+jet R -
dependence



ALICE arXiv:2303.00592
Phys. Lett. B 719 (2013) 220-241 CMS arXiv:2102.13080

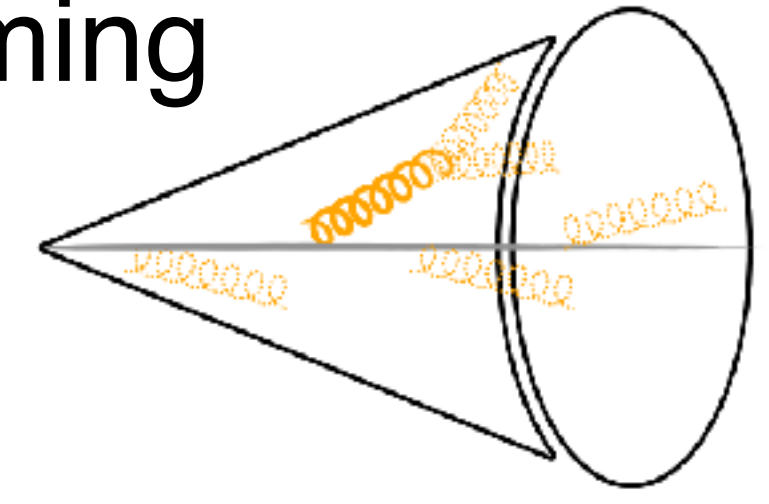


sPhenix will measure this
region and be less
background dominated

Subjets access hard parton splittings

R. Ehlers (Tues. 11:10am)

Grooming



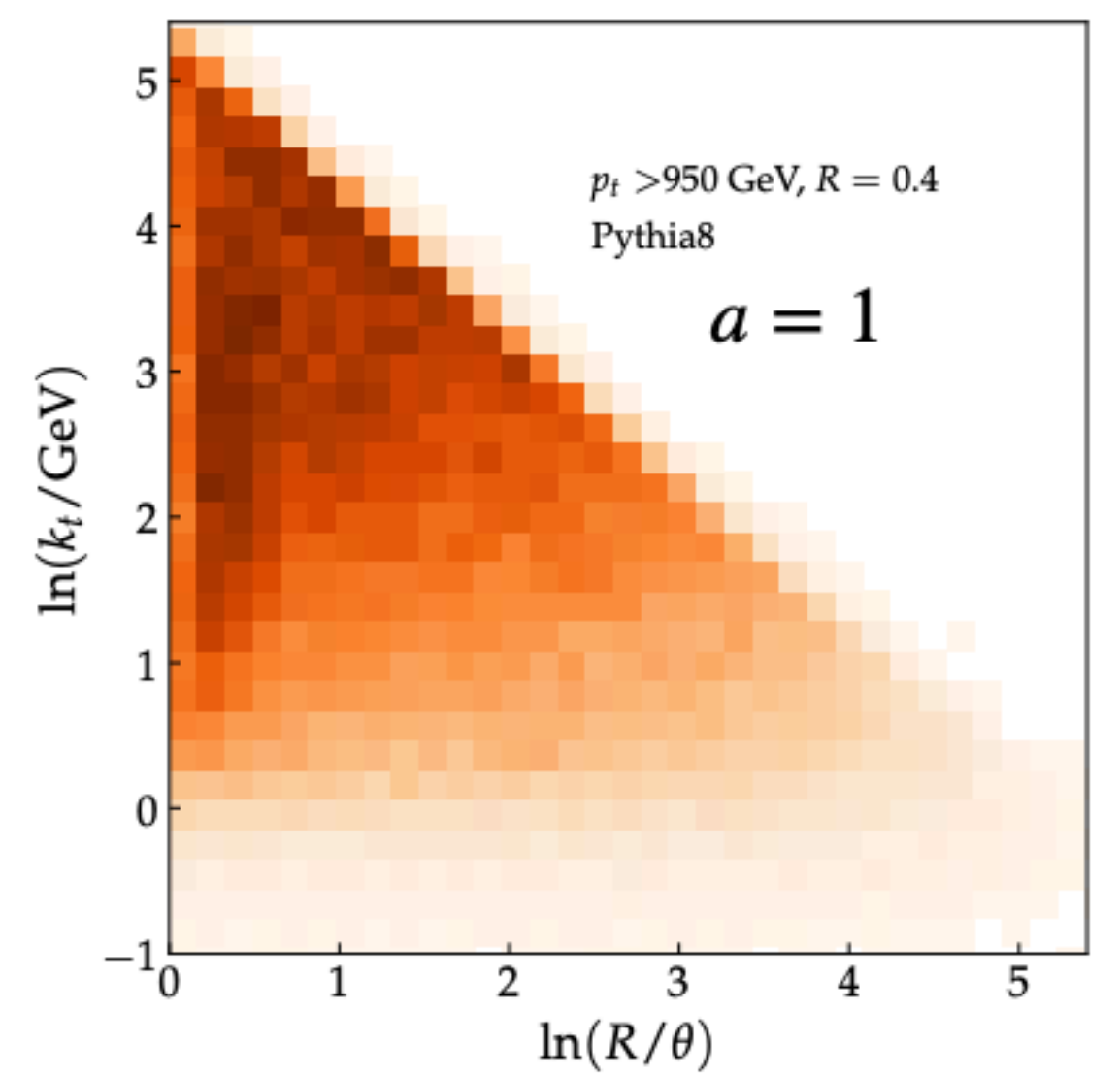
$$\frac{d\sigma}{d\mathcal{O}} = f(E_i, \theta_i) \Theta(\Omega_i - \Omega)$$

phase-space cut

Dynamical grooming

[PRD 101 (2020) 3, 034004]

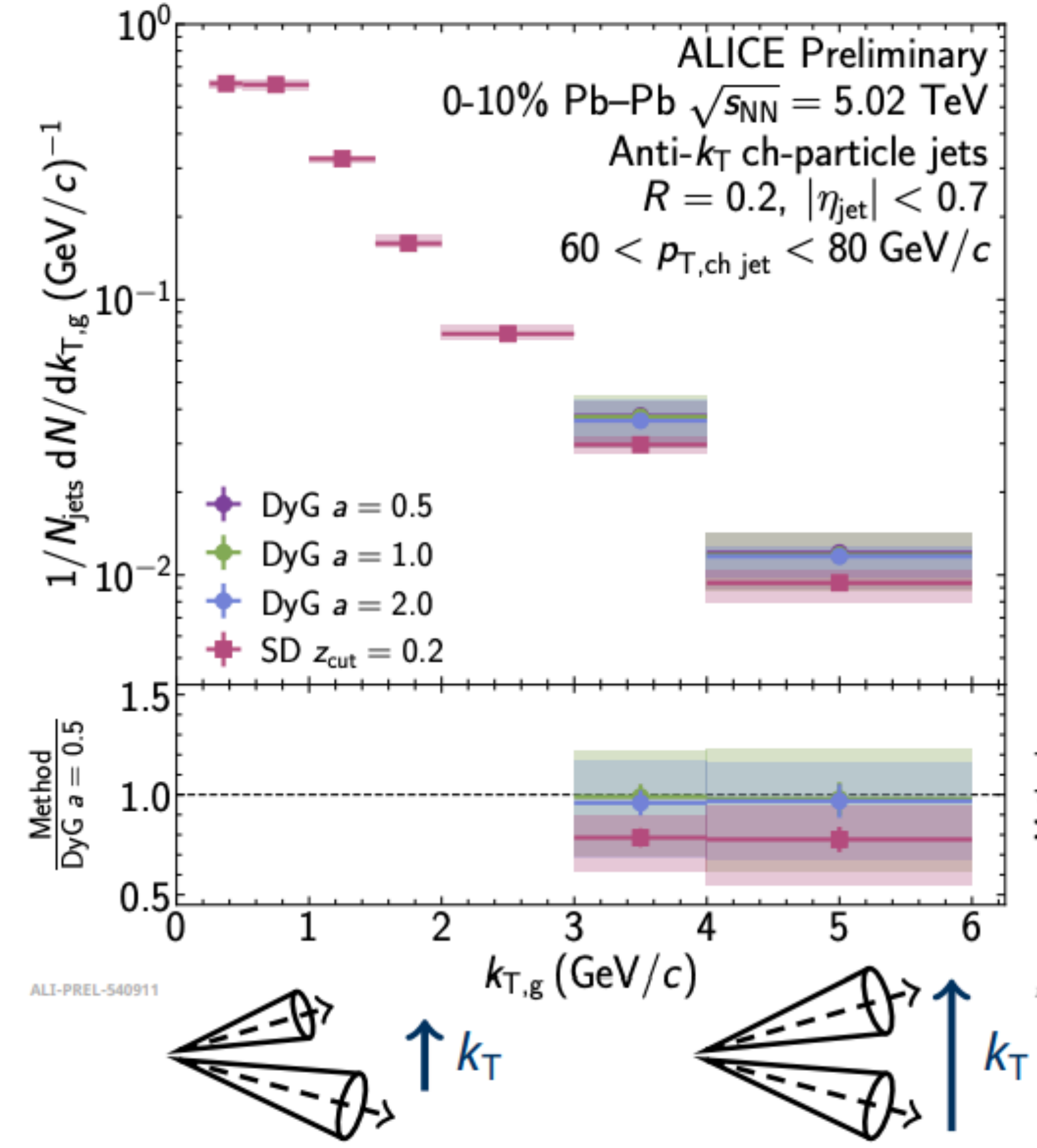
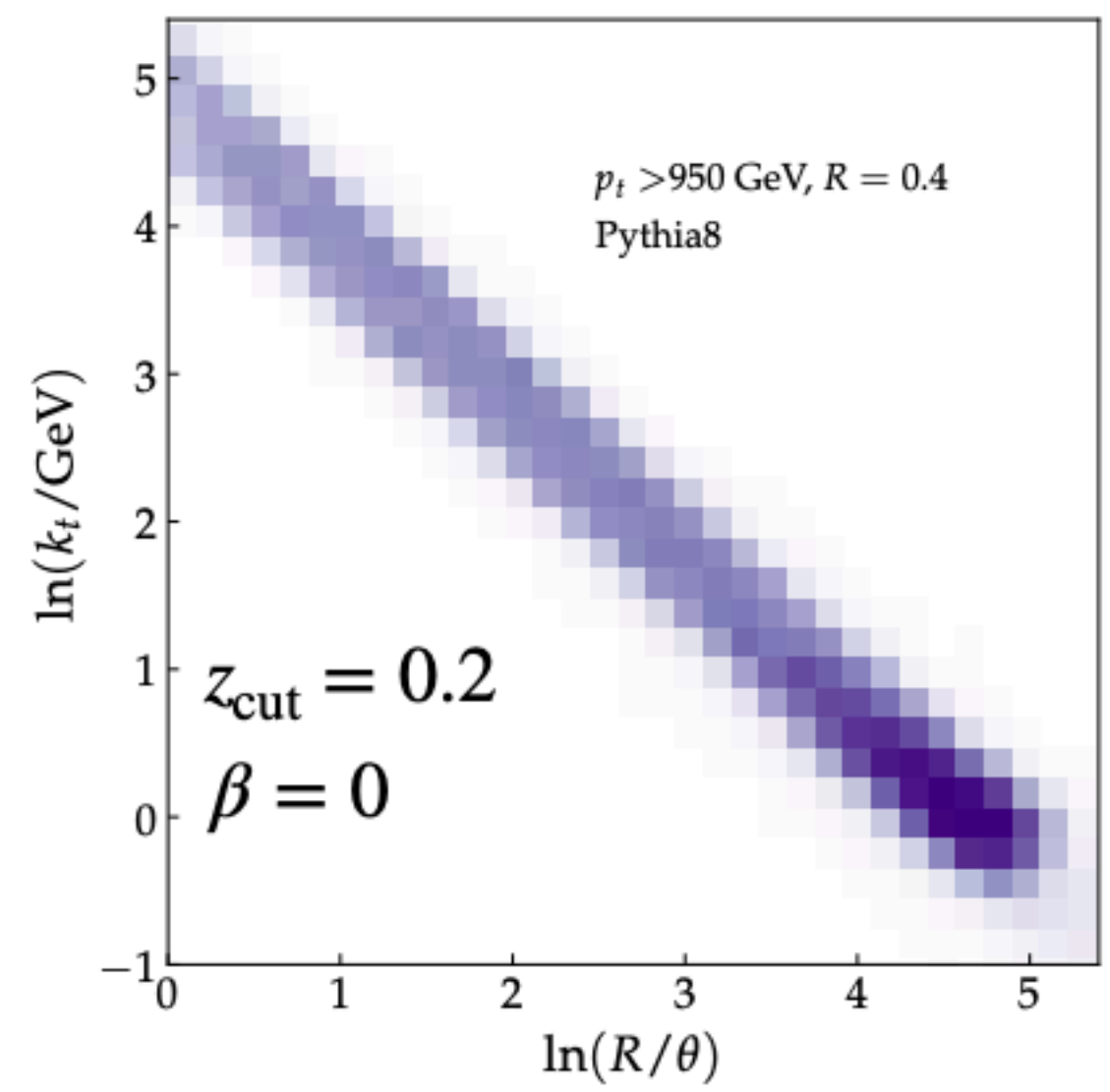
$$\max(z\theta^a)$$



SoftDrop

[JHEP 09 (2013) 029, JHEP 05 (2014) 146]

$$\Theta(z > z_{\text{cut}} \theta^\beta)$$



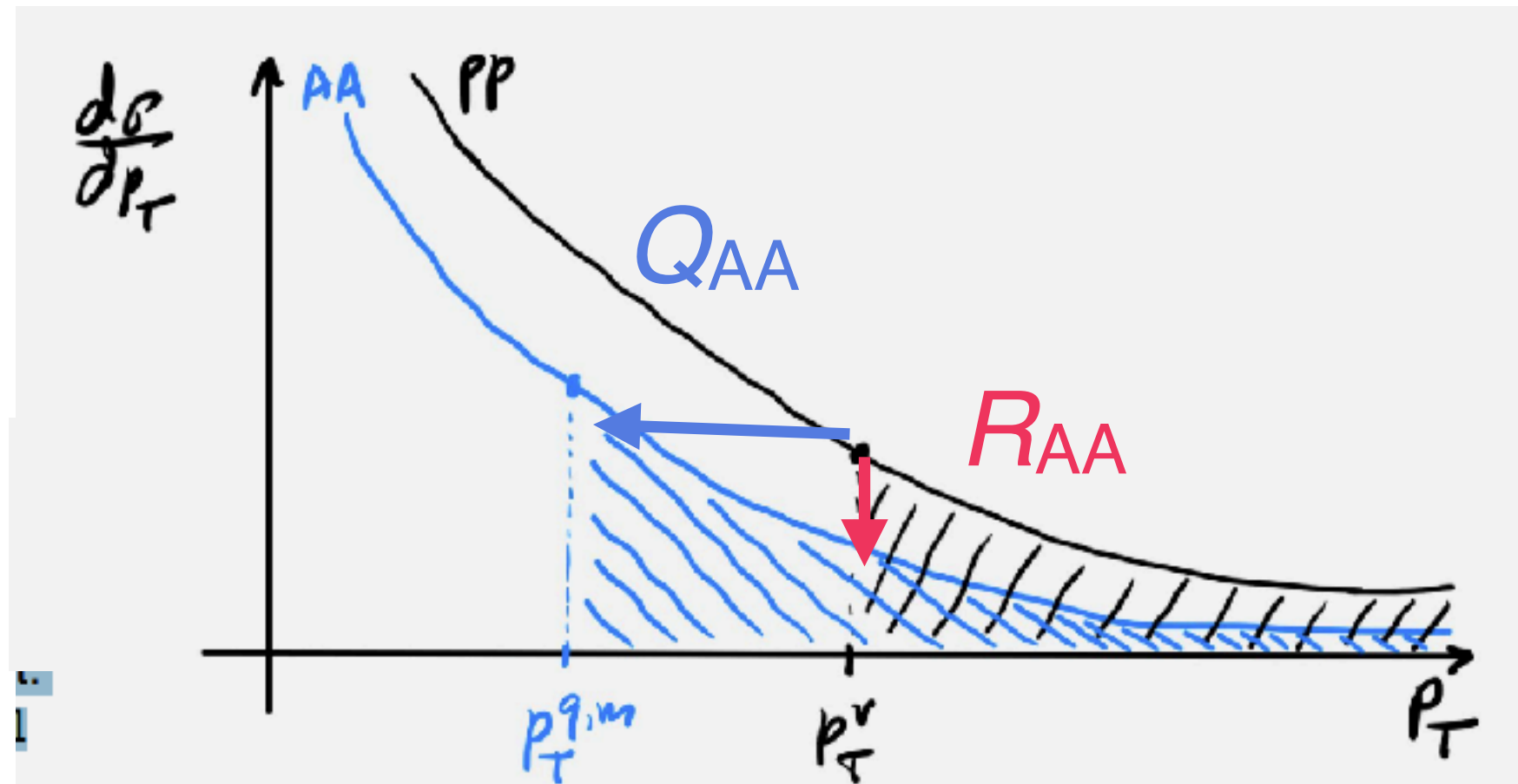
A. Soto-Ontoso (Mon. 5:05pm)

Comprehensive set of grooming studies in Pb-Pb: grooming methods converge at high k_T

Solutions to survival bias?

Match quantiles of spectra to remove bias

J. Silvia (Wed. 2:00pm) [Brewer et. al. PRL, 122\(22\), 222301](#)



Instead of C/A (p=0) reclustering, use τ algorithm (p= 0.5) [Apolinario et al EPJC 81, 561 \(2021\)](#)

P. Guerrero-Rodríguez (Thur. 9:20am)

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

Less biased spectra and better access medium scales

Bias free observables

B. Wu (Wed. 2:00pm)

Heavy flavor tagged jet accesses quark sample

Photon and Z tag jets unmodified by medium so provide initial momentum

Forward rapidity for more quarks

