Probing the quark-gluon plasma with jets and heavy flavor

Raymond Ehlers[1] for the ALICE, ATLAS, and CMS Collaborations

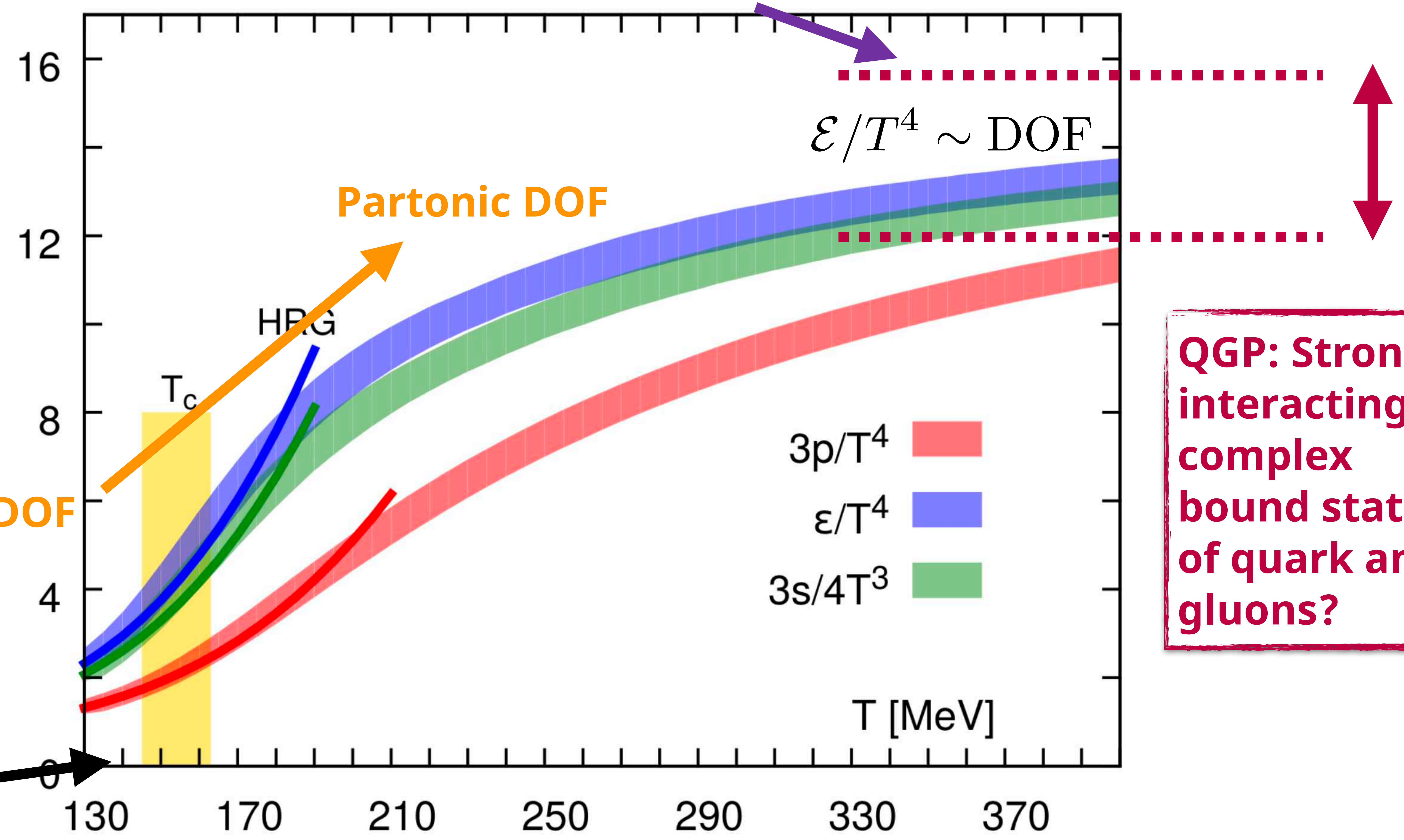
LHCP 2024, 06 June 2024
Boston, MA, USA

[1]Lawrence Berkeley National Lab/UC Berkeley
raymond.ehlers@cern.ch

Lattice QCD and the quark-gluon plasma

Lattice QCD calculations at μ_B = 0

Non-interacting limit (Stefan-Boltzmann)



QGP: Strongly interacting, complex bound states of quark and gluons?

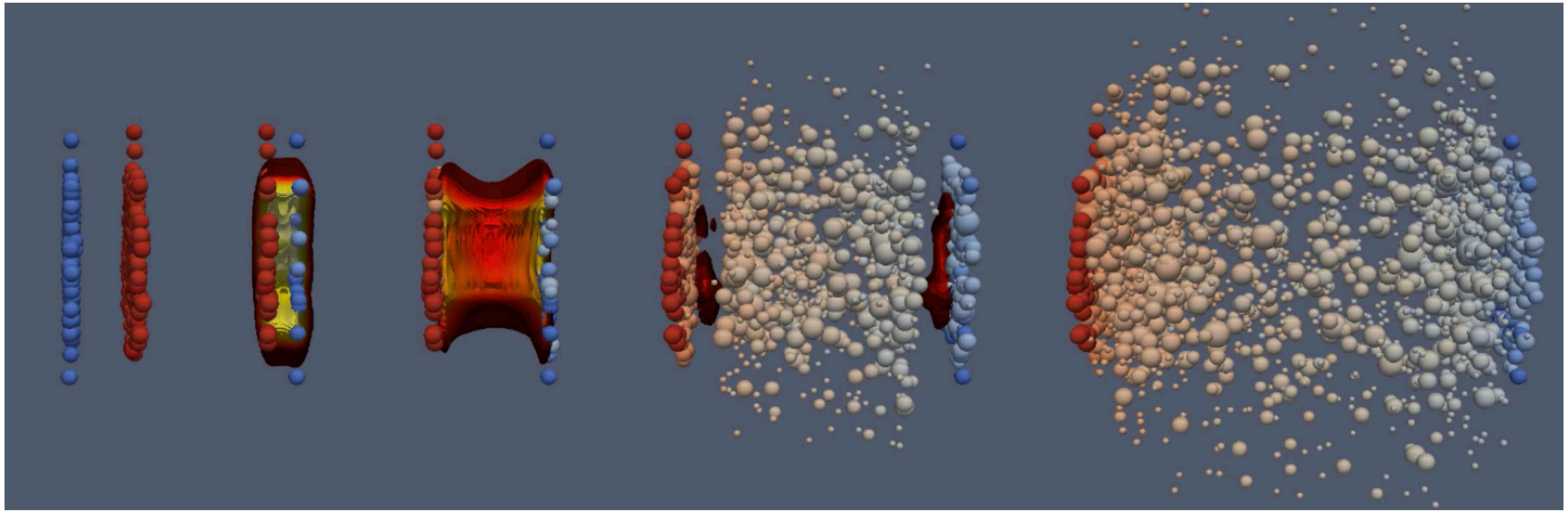
Predict **phase transition** at $T_C \sim$ **155 MeV**

Confined → **Non-perturbative deconfined**

Hot QCD collaboration, Phys.Rev.D 90 (2014) 094503

Experimental tool #1: heavy-ion collisions

What can we learn about **many-body QCD from this complex quantum fluid?**



Initial state

Hydrodynamic evolution
Medium response

Hadronization
Rescattering

How does a beam of partons **thermalize into the QGP**?

Is there **emergent behavior: collective motion, quasi-particles DOF, …?**

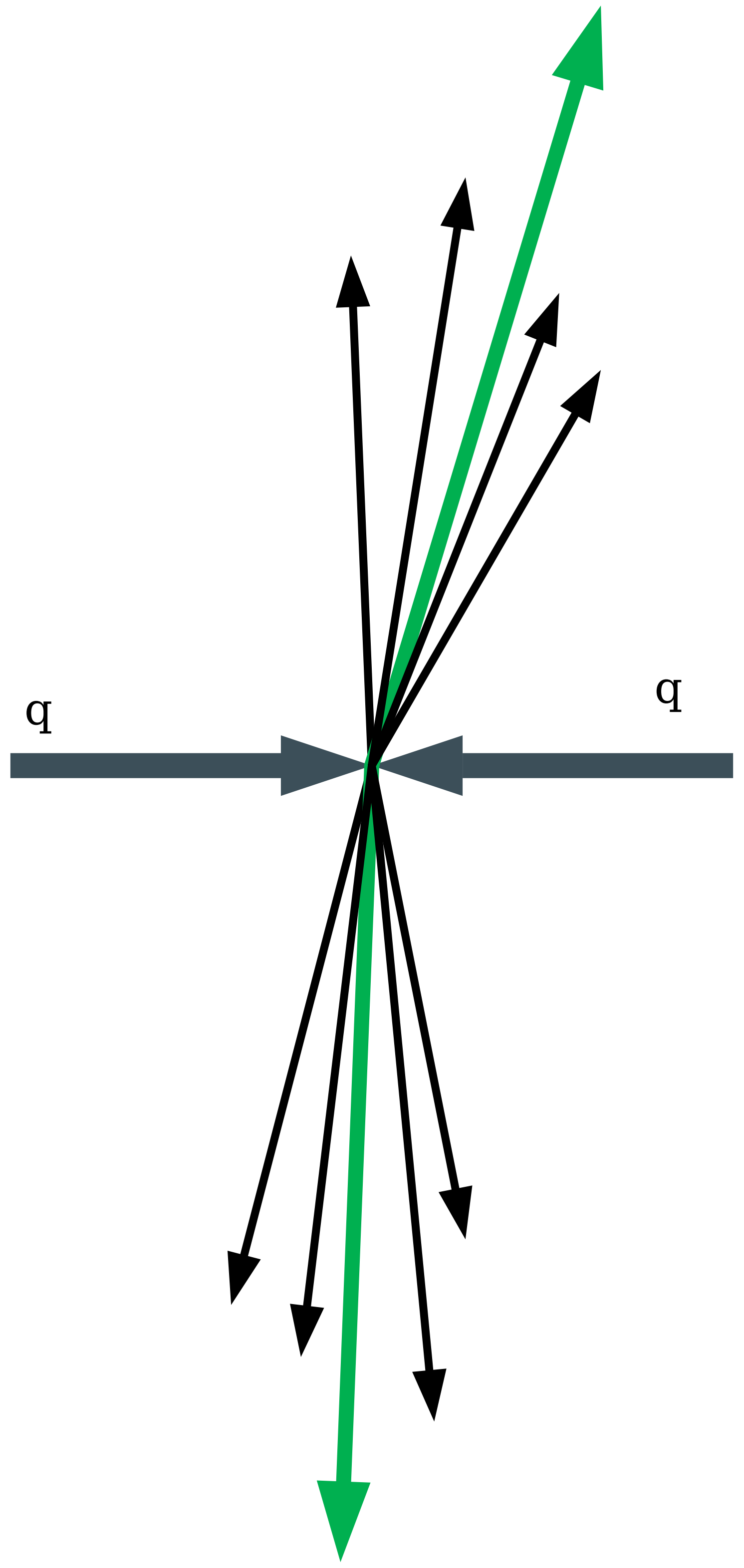
What are the **relevant length scales**?

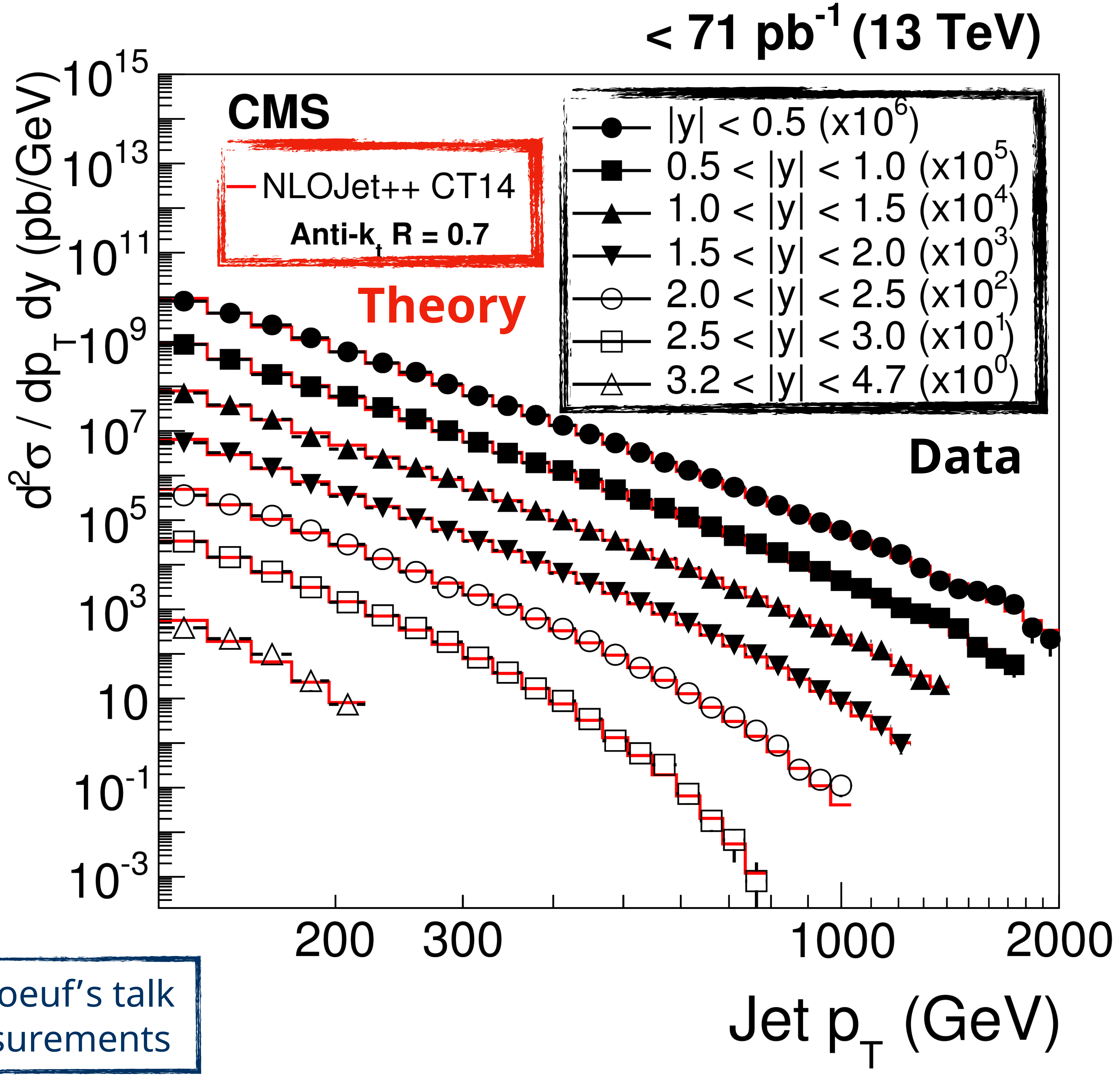
See C. Andres' talk on recent HI developments

Illustration: MADAI

Experimental tool #2: jets

- Jets: **collimated sprays of particles** approximating a **hard-scattered parton**.
- **pp collisions: extensively measured to high precision**
- **Well described by perturbative calculations**



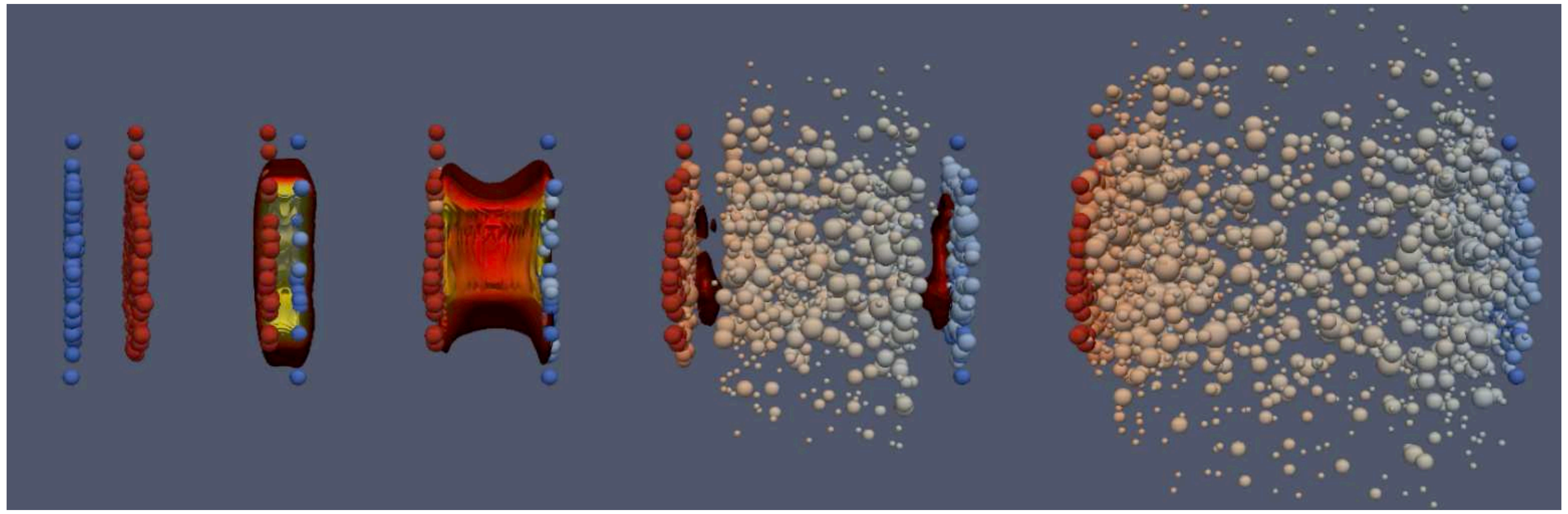


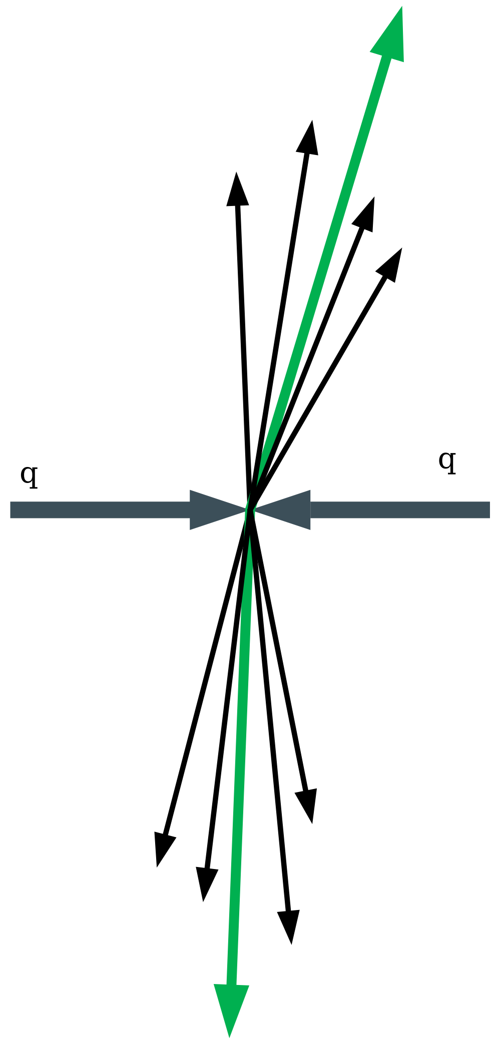
See S. Porteboeuf's talk on QCD measurements

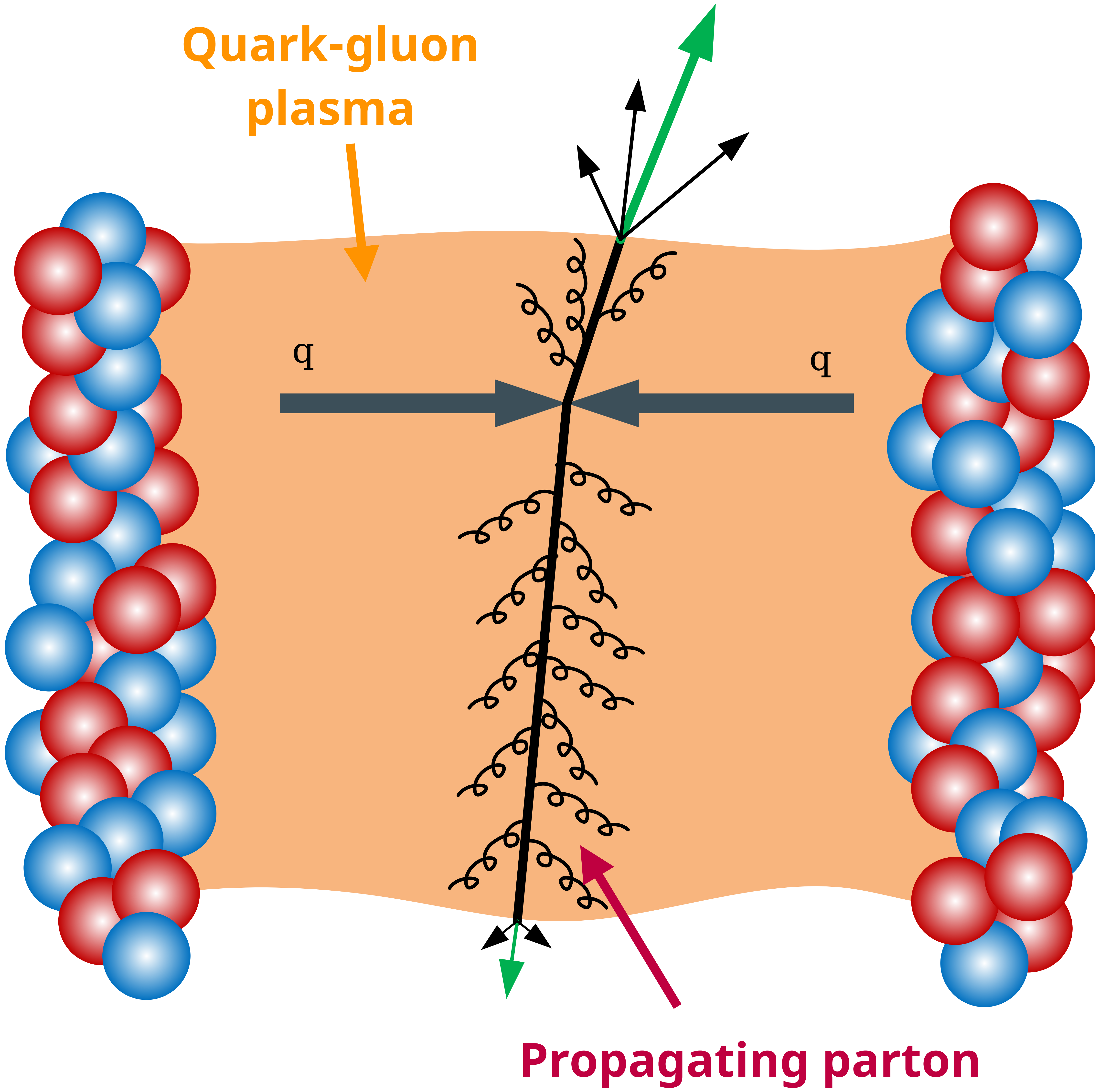
Cartoon: Martin Rybar

CMS, Eur.Phys.J.C 76 (2016) 8, 451

Jets in the quark-gluon plasma



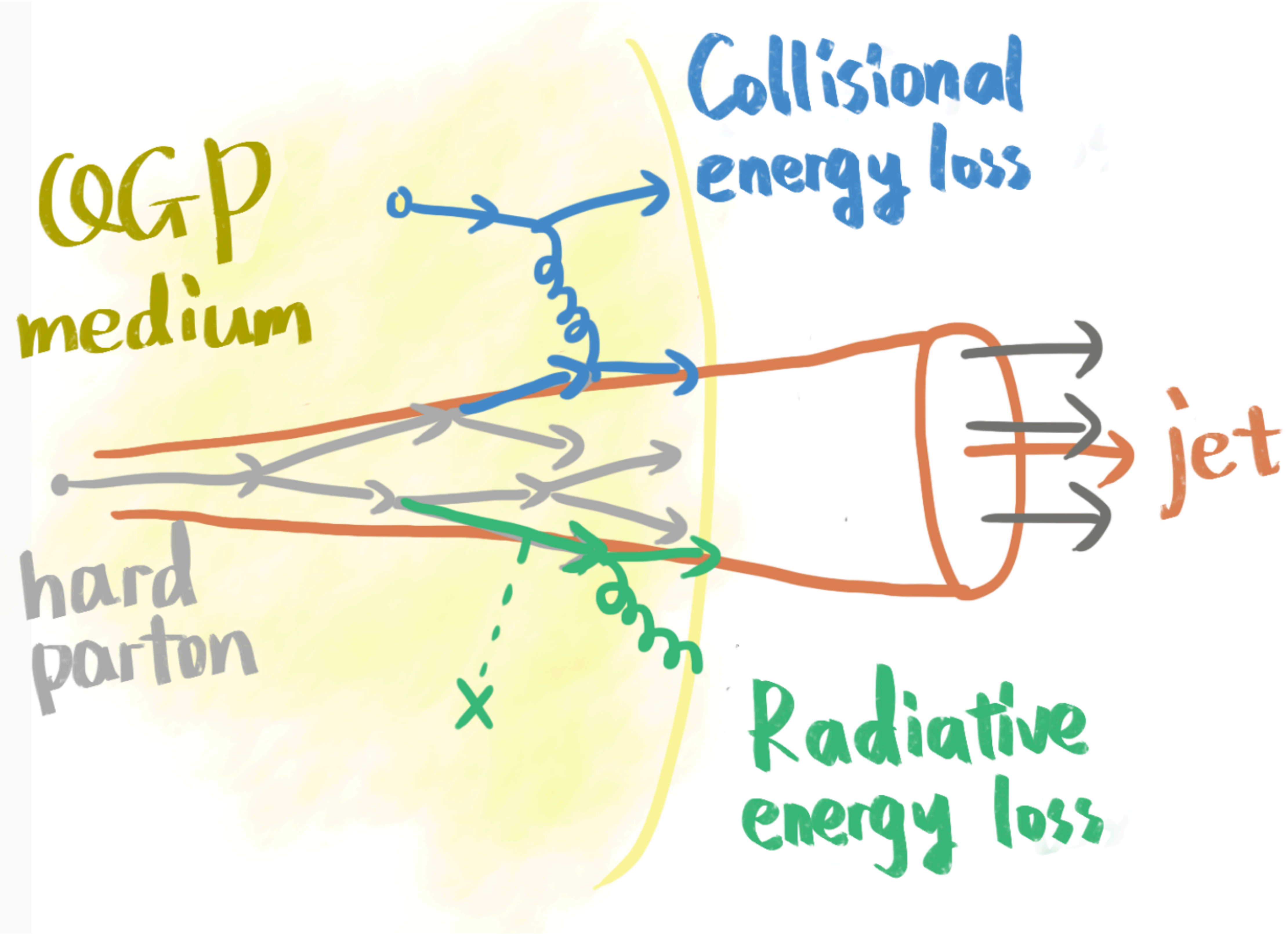




Cartoon: Martin Rybar

Probing the physics of the quark-gluon plasma

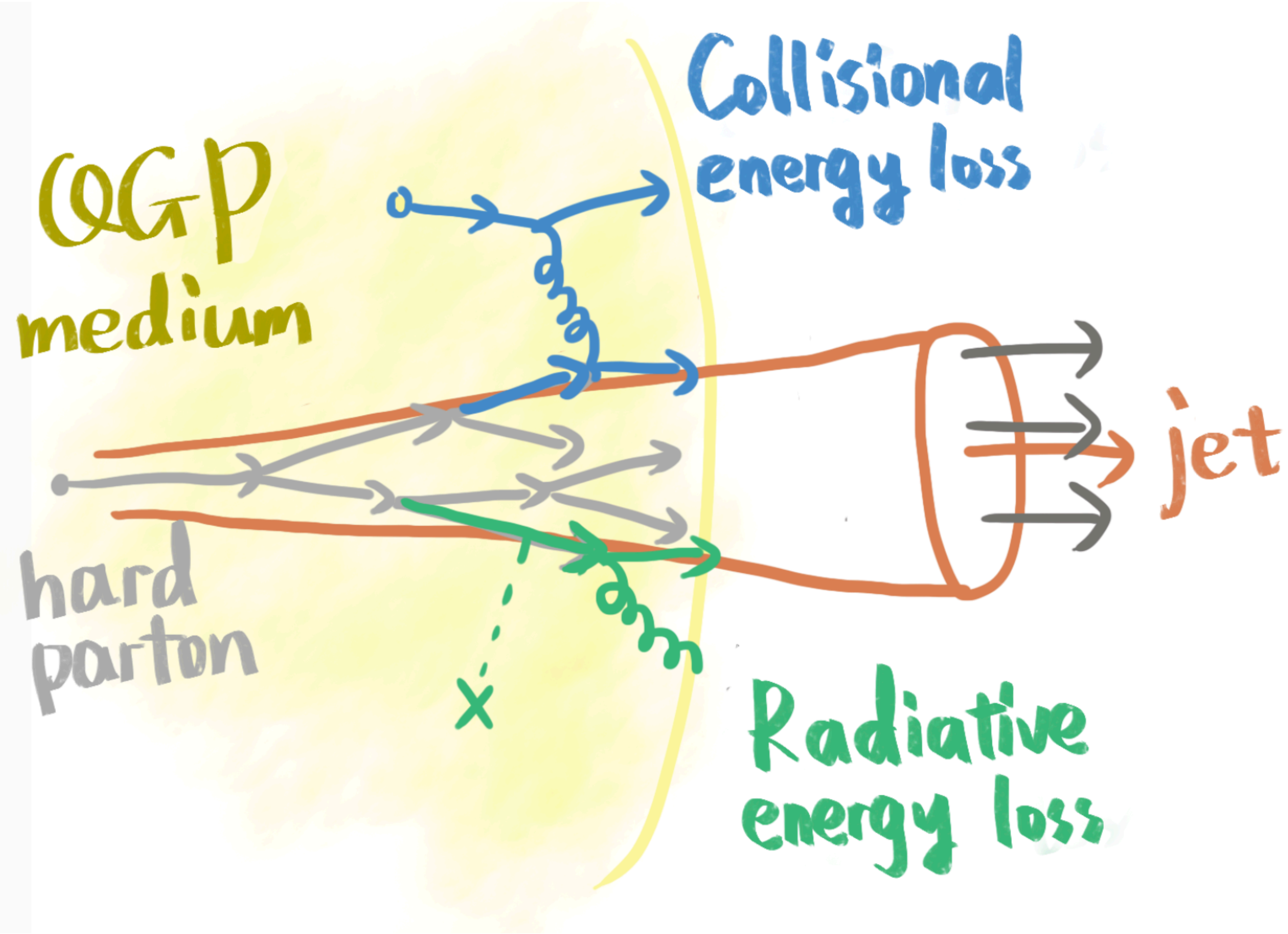
A probe parton traverses the quark-gluon plasma…



Cartoon: Jing Wang

Probing the physics of the quark-gluon plasma

A probe parton traverses the quark-gluon plasma…

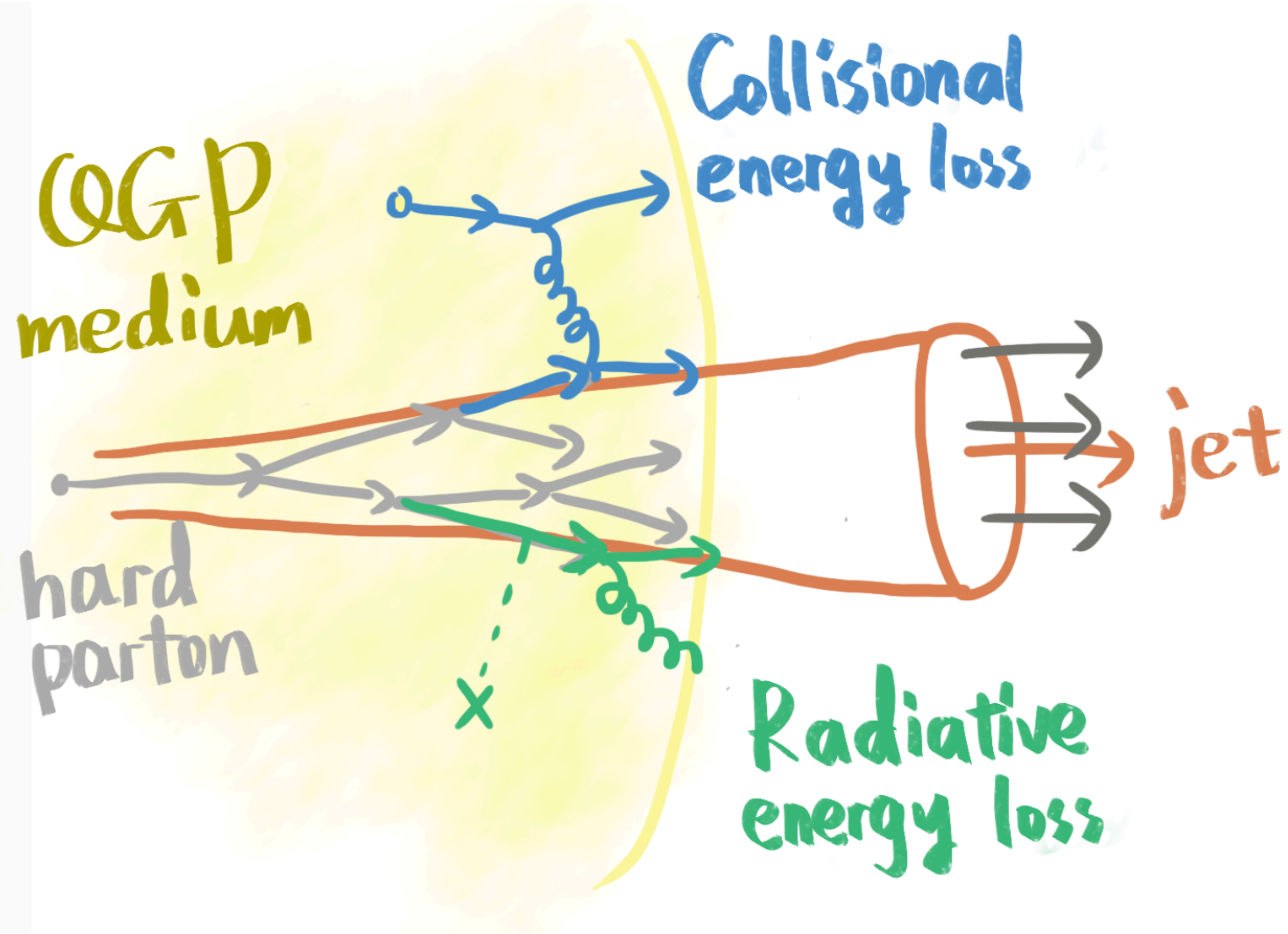


1. What does the **parton** resolve?
   - QGP microstructure?

Cartoon: Jing Wang

Probing the physics of the quark-gluon plasma

A probe parton traverses the quark-gluon plasma…



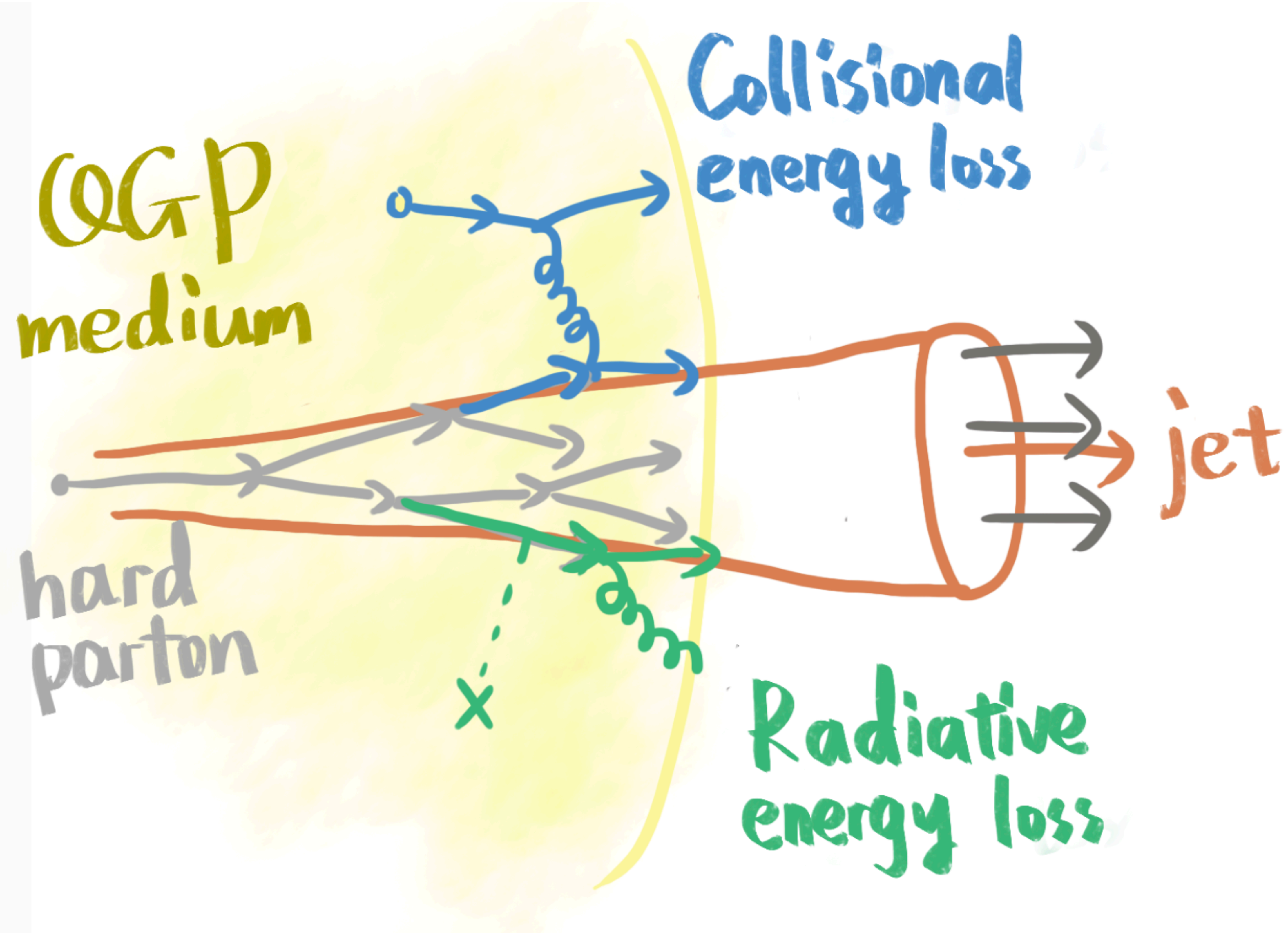
1. What does the **parton** resolve?
   - QGP microstructure?

2. What does the **medium** resolve?
   - Jet shower: one charge or many?

Cartoon: Jing Wang

Probing the physics of the quark-gluon plasma

A probe parton traverses the quark-gluon plasma…

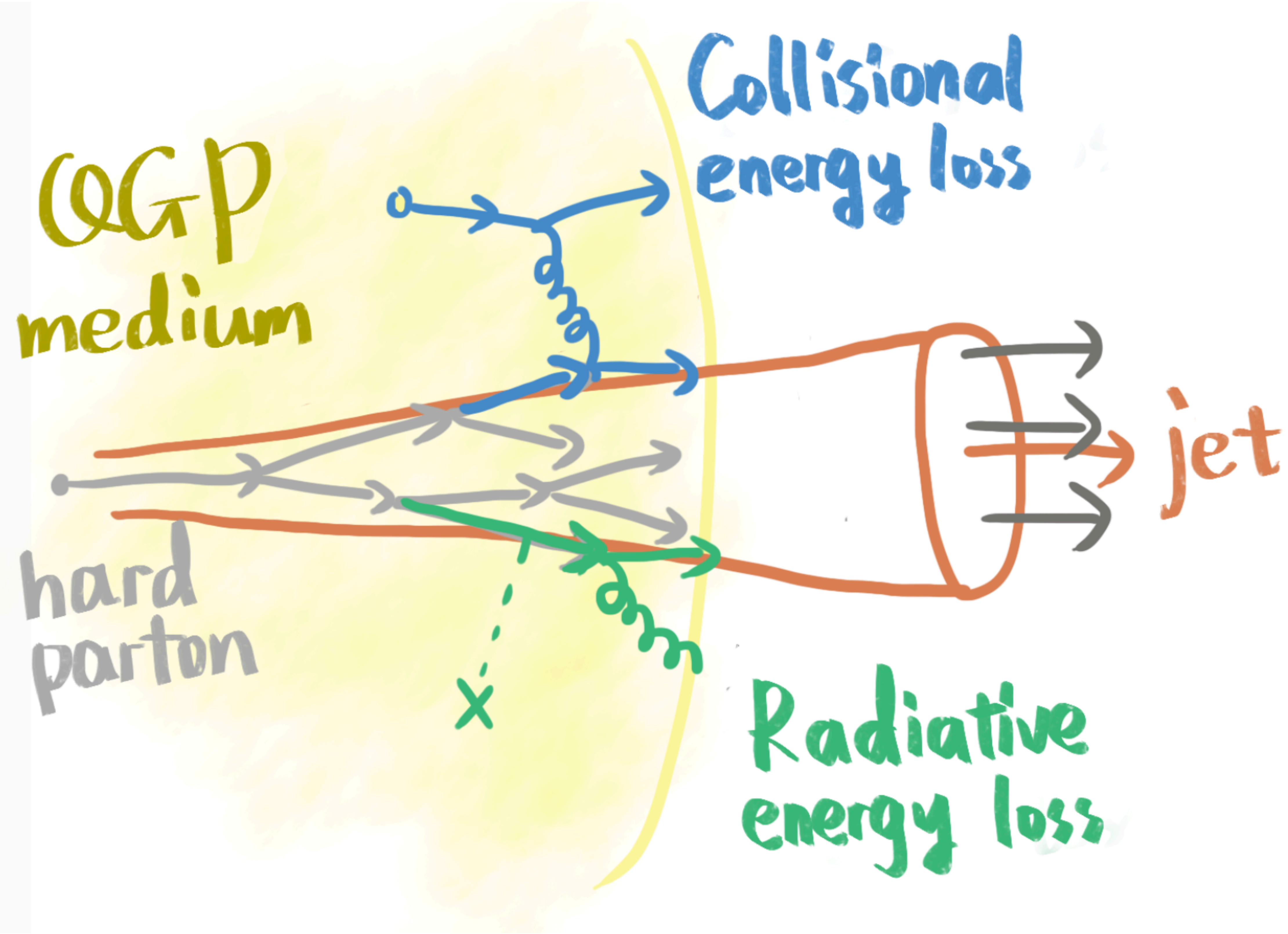


1. What does the **parton** resolve?
   - QGP microstructure?
2. What does the **medium** resolve?
   - Jet shower: one charge or many?
3. How does the **presence** of the **medium** change the **probe**?
   - Mass and color charge dependence?
   - Dissipation?

Cartoon: Jing Wang

Probing the physics of the quark-gluon plasma

A probe parton traverses the quark-gluon plasma…



1. What does the **parton** resolve?
   - QGP microstructure?
2. What does the **medium** resolve?
   - Jet shower: one charge or many?
3. How does the **presence** of the **medium** change the **probe**?
   - Mass and color charge dependence?
   - Dissipation?
4. How does the **presence** of the **probe** change the **medium**?
   - Is there a wake?

Cartoon: Jing Wang

Characterizing (radiative) energy loss in QCD matter

See A. Takacs' talk on jet and substructure mod.

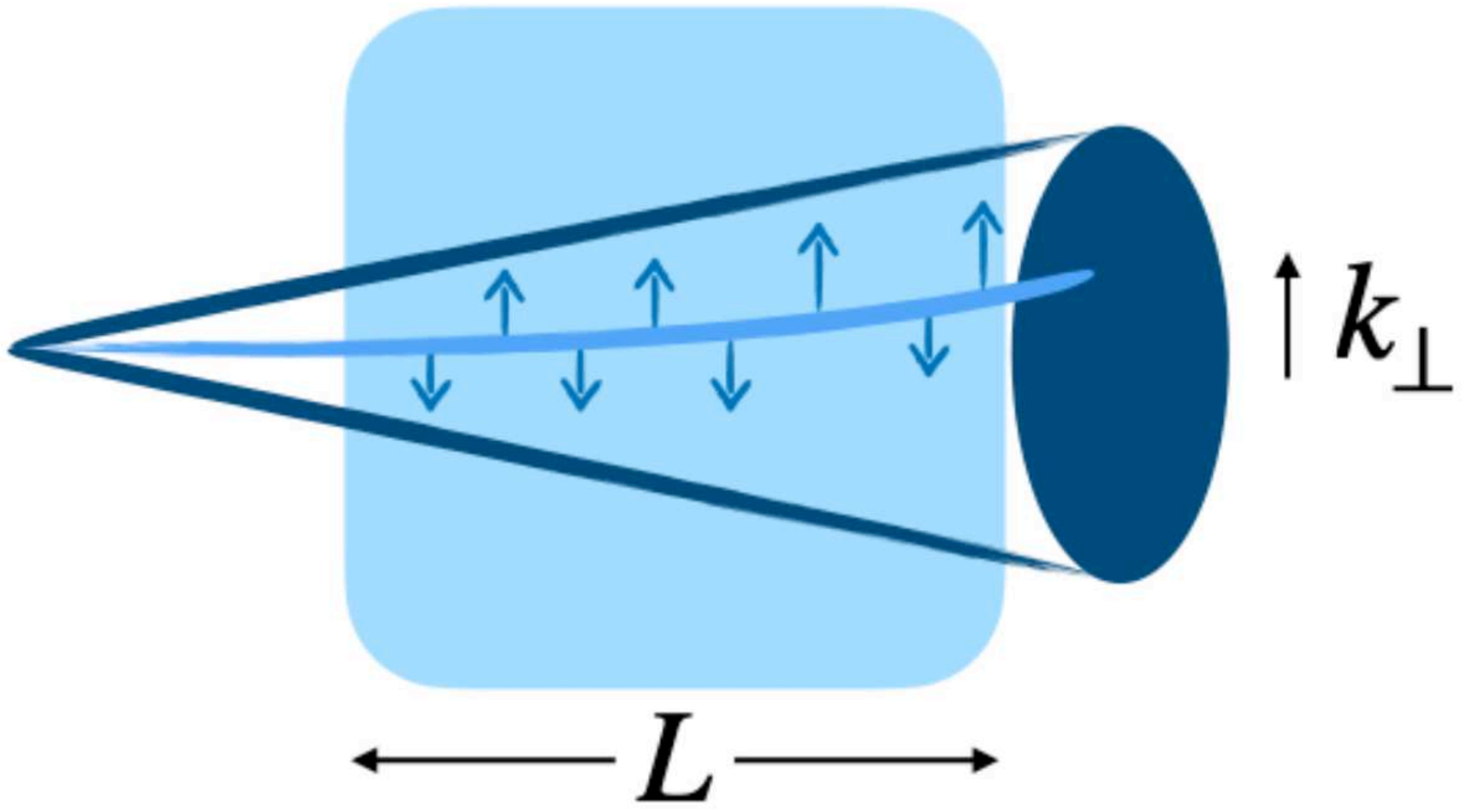
See J. Barata' talk on energy correlators

See F. Krizek's talk on quenching in small systems

- **Energy loss in QCD** matter characterized by **jet transport coefficient $\hat{q}$**

$$\hat{q} \equiv \frac{\langle k_{\mathrm{T}}^2 \rangle}{L} \sim \int k^2 C(k) \mathrm{d}^2 k$$

- Path length L, momentum transfer k
- Derived from **thermal field theory**
- Details of **model descriptions heavily vary**



Scattering depends on QGP properties

$$C(k) = \frac{g_{\mathrm{s}}^2 m_{\mathrm{D}}^2 T}{k^2(k^2 + m_{\mathrm{D}}^2)}$$

Dependence:
Medium temperature T
Debye mass m_{D}

Cartoon: James Mulligan

Experimental tool #3: heavy flavor

- **Heavy Quarks (HQ) produced early, before medium**
- $m_Q \gg T, \Lambda_{QCD} \rightarrow$ **perturbative even as $p_T \rightarrow 0$**

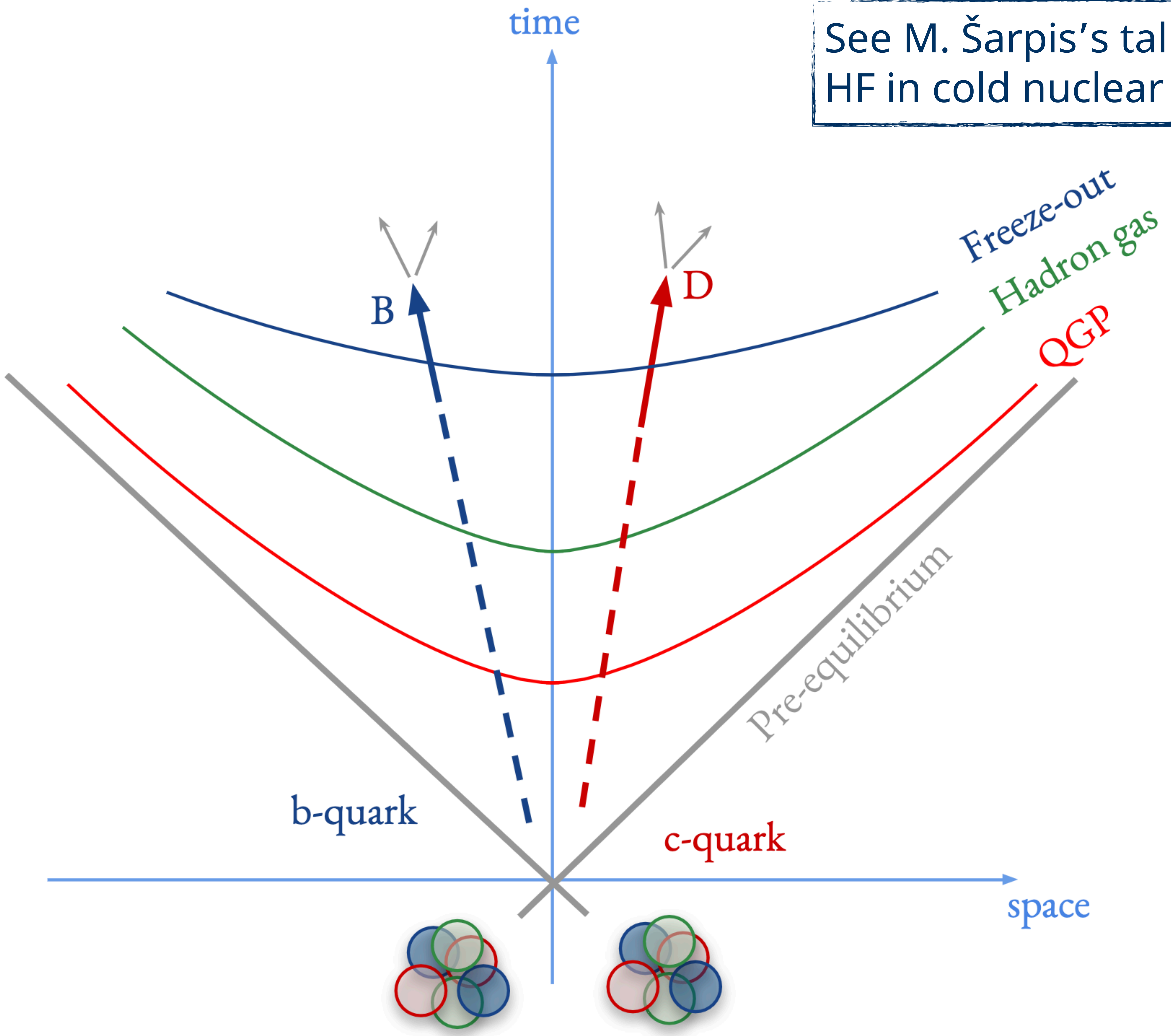
Low p_T

- Dominated by **elastic collisions**
  - **Heavy quarks diffuse** in medium
  - **Partial thermalization?**
- **Spatial diffusion coefficient:** $D_S \propto \frac{T}{m_Q \gamma}$
  HQ thermalization time

High p_T

- Dominated by **radiative energy loss**
- **Quark mass dependence**
- **Dead cone: $\theta \leq m_Q/E$**

See M. Šarpis's talk on HF in cold nuclear matter



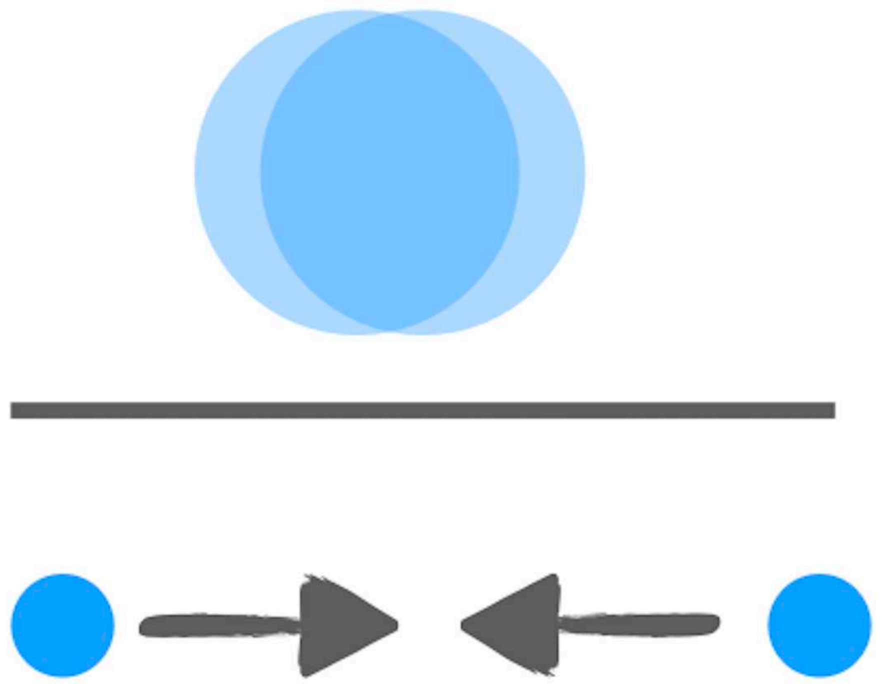
Calibrated probe: energy loss, diffusion, thermalization

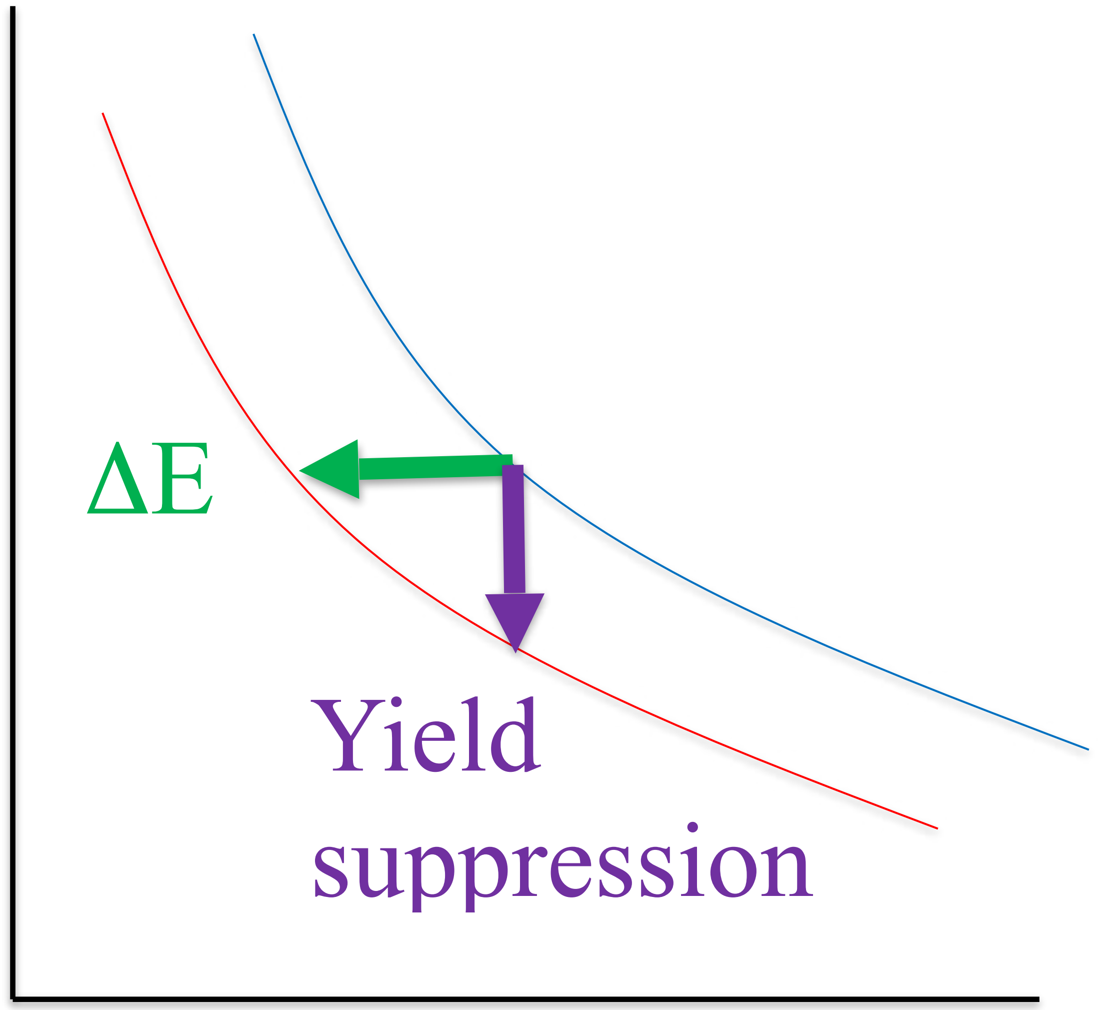
Cartoon: Fabrizio Grosa, Stefano Politanò

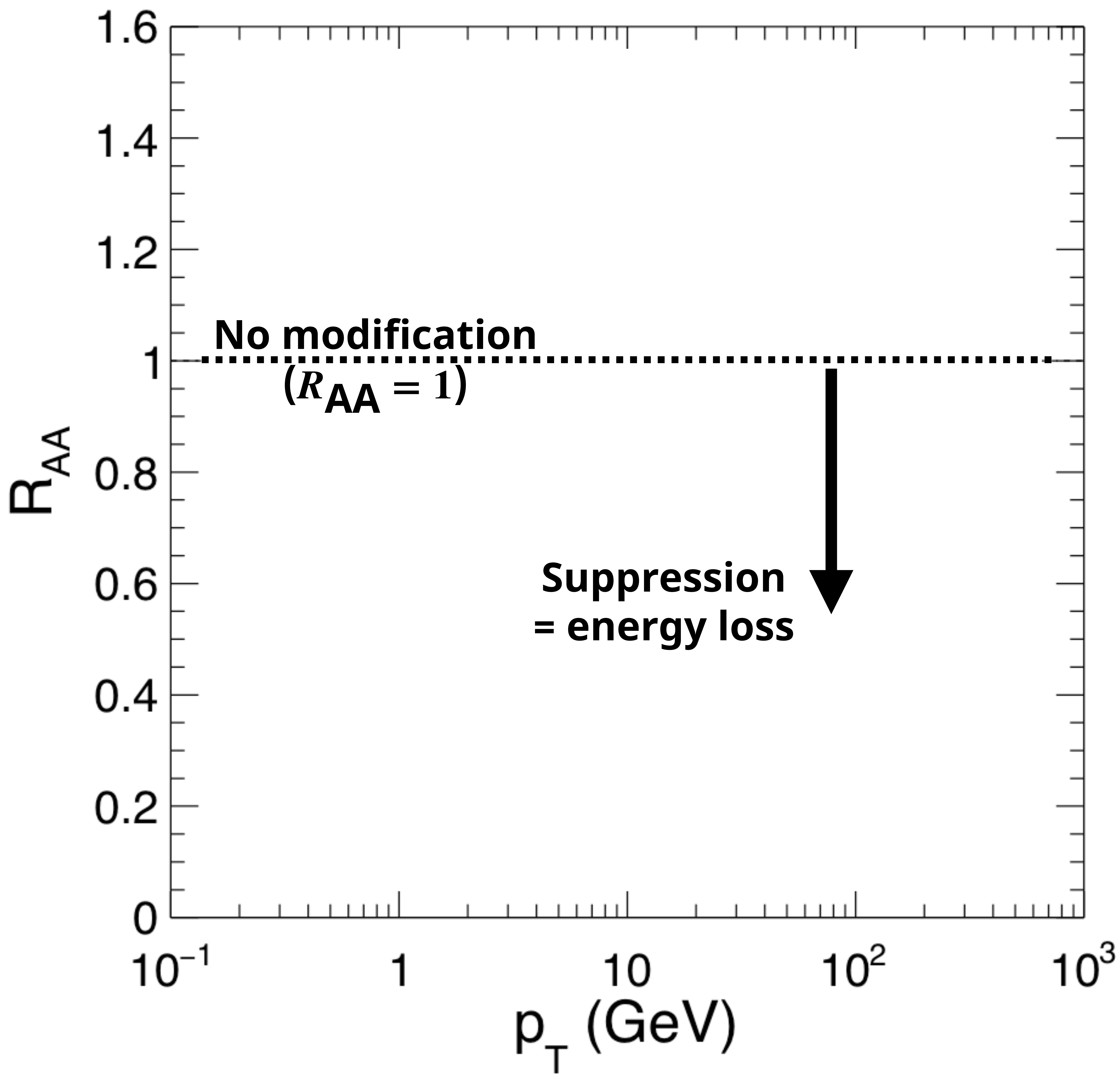
Single inclusive hadrons

Inclusive hadron yield modification

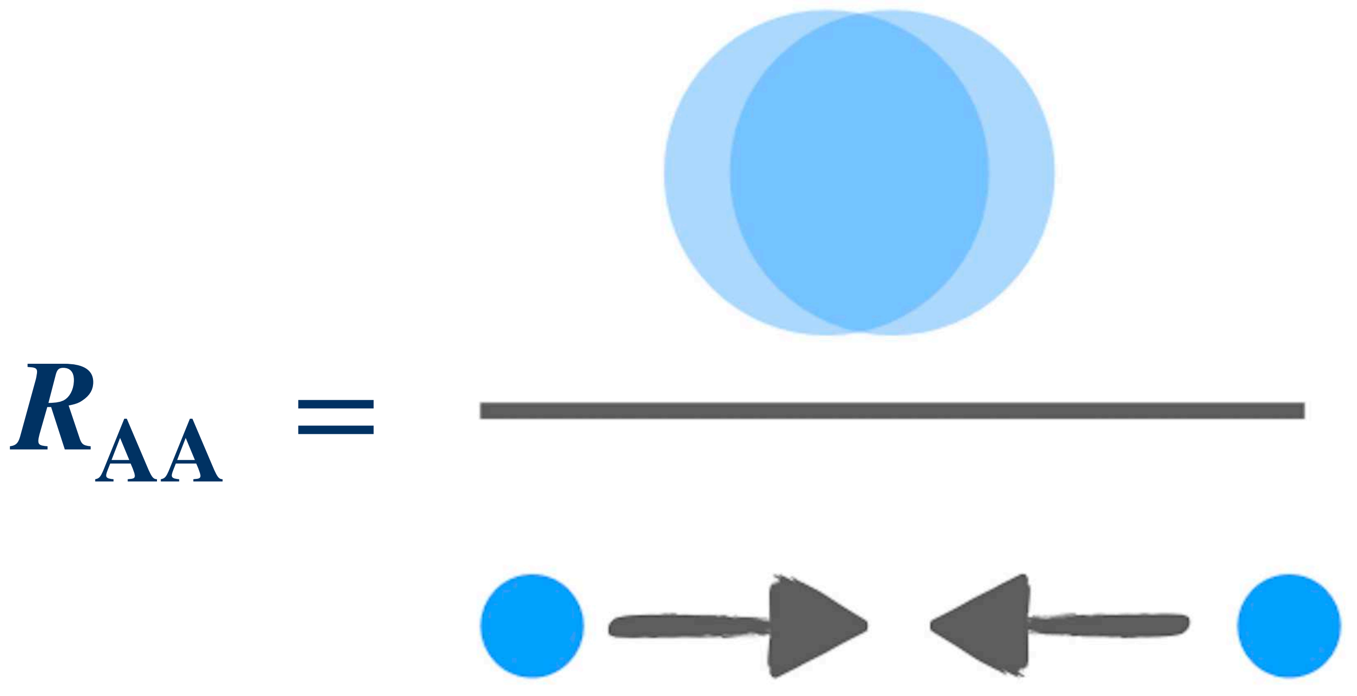
R_{AA} =



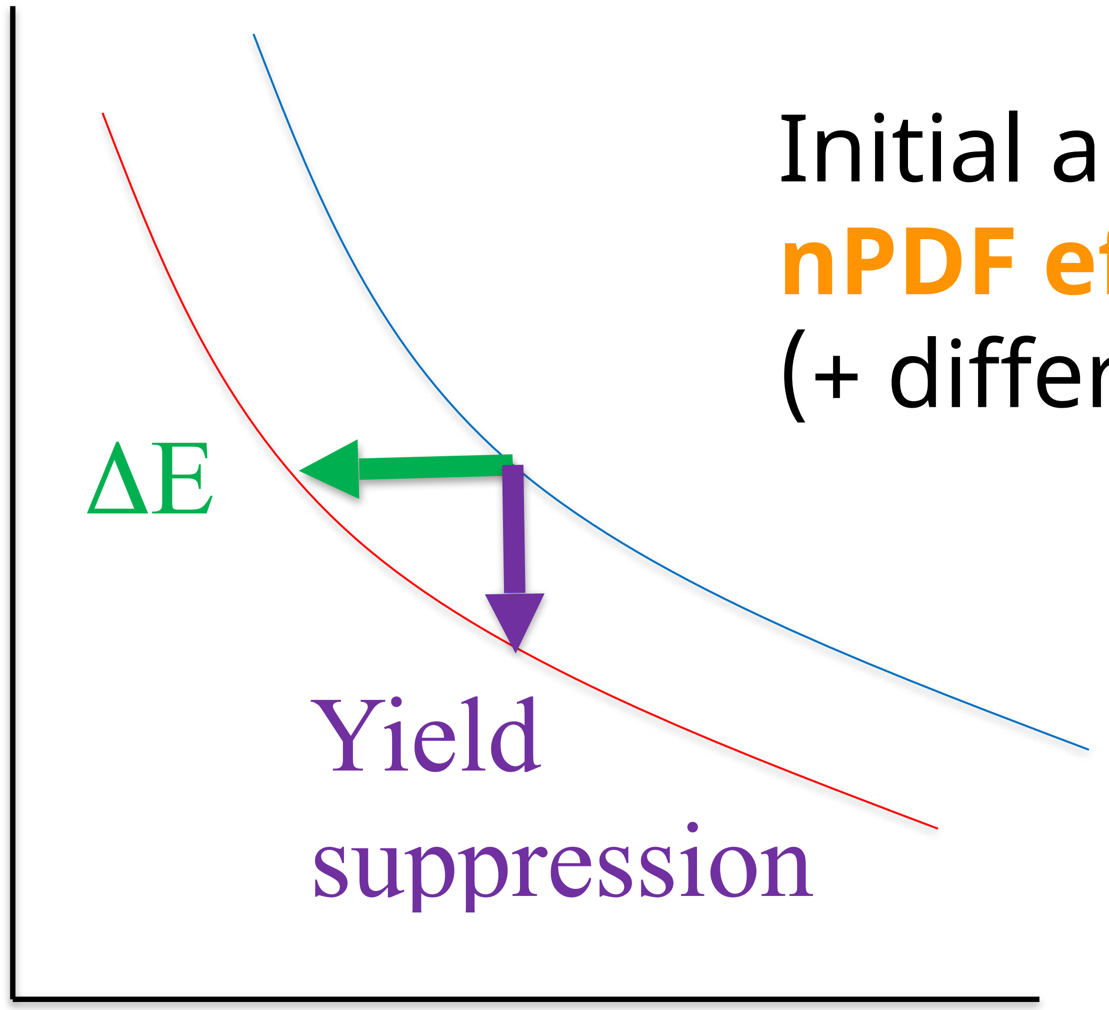




Inclusive hadron yield modification

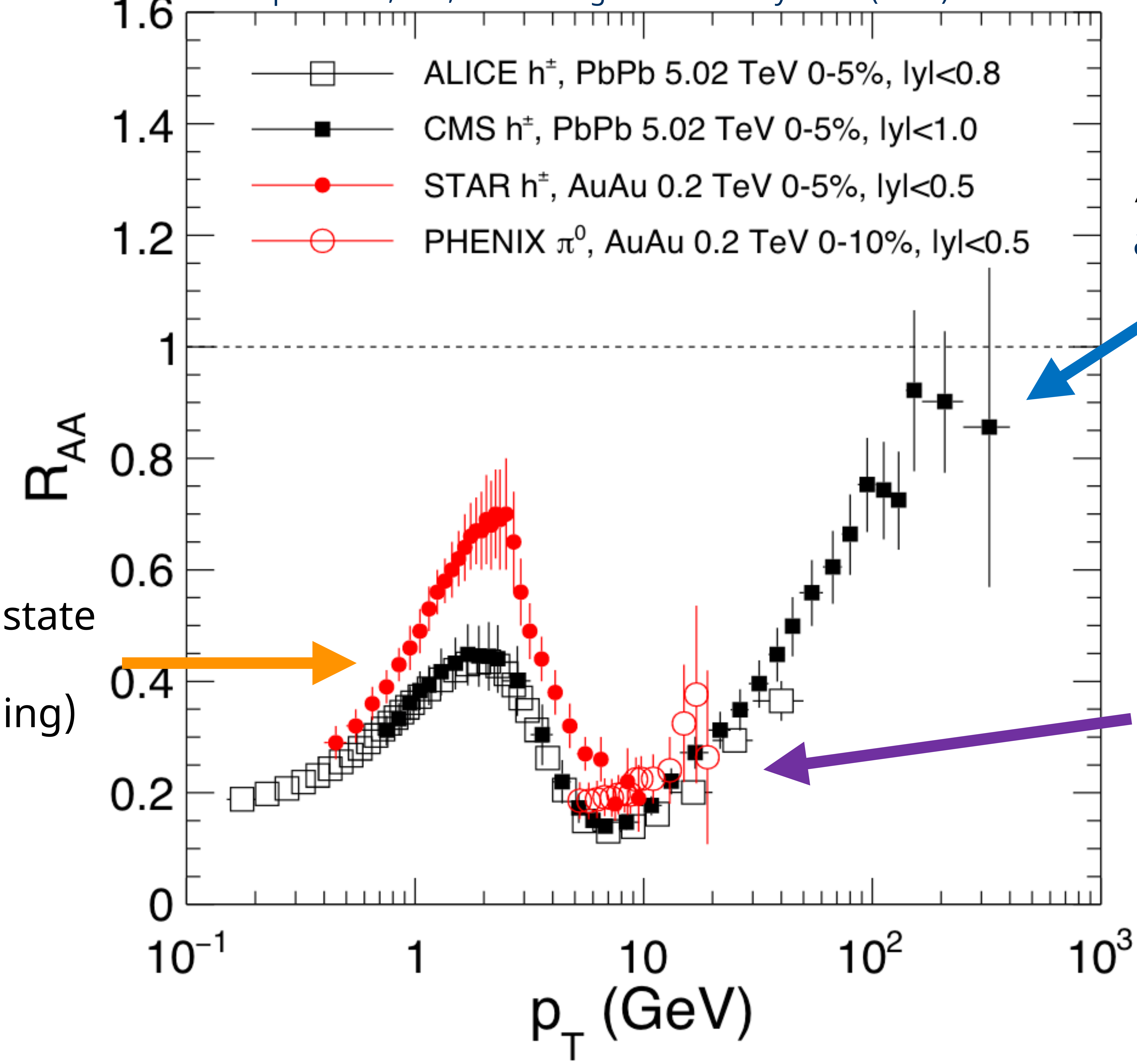


- Inclusive hadron yield: track **energy loss**
- **Probe modified by presence of medium**



Initial and final state **nPDF effects** (+ different scaling)

Apolinário, Lee, Winn: Prog.Part.Nucl.Phys. 127 (2022) 103990



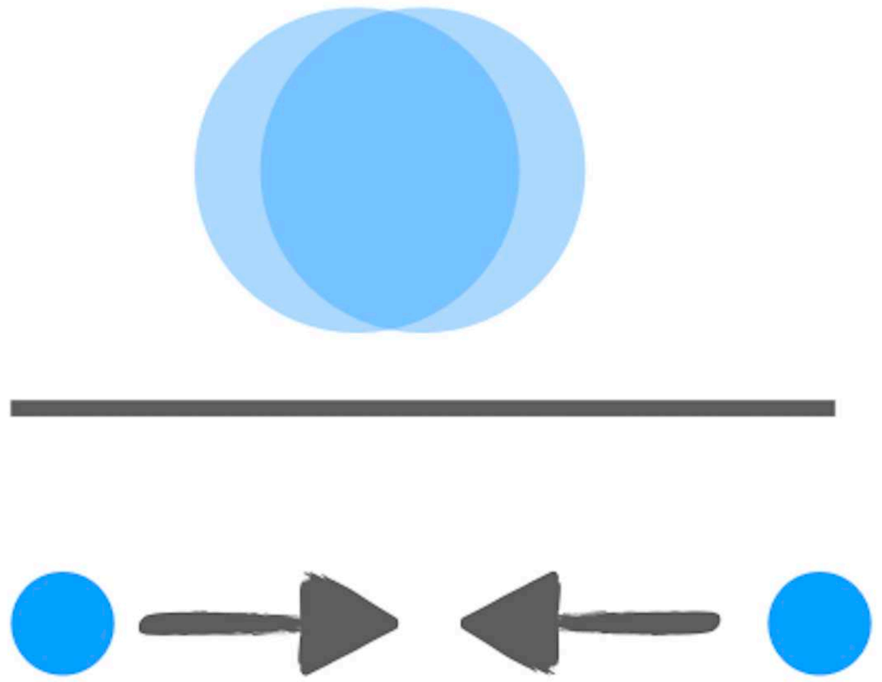
$\Delta E_{\text{loss}} \ll p_T$: **Small absolute E-loss**

Significant yield suppression

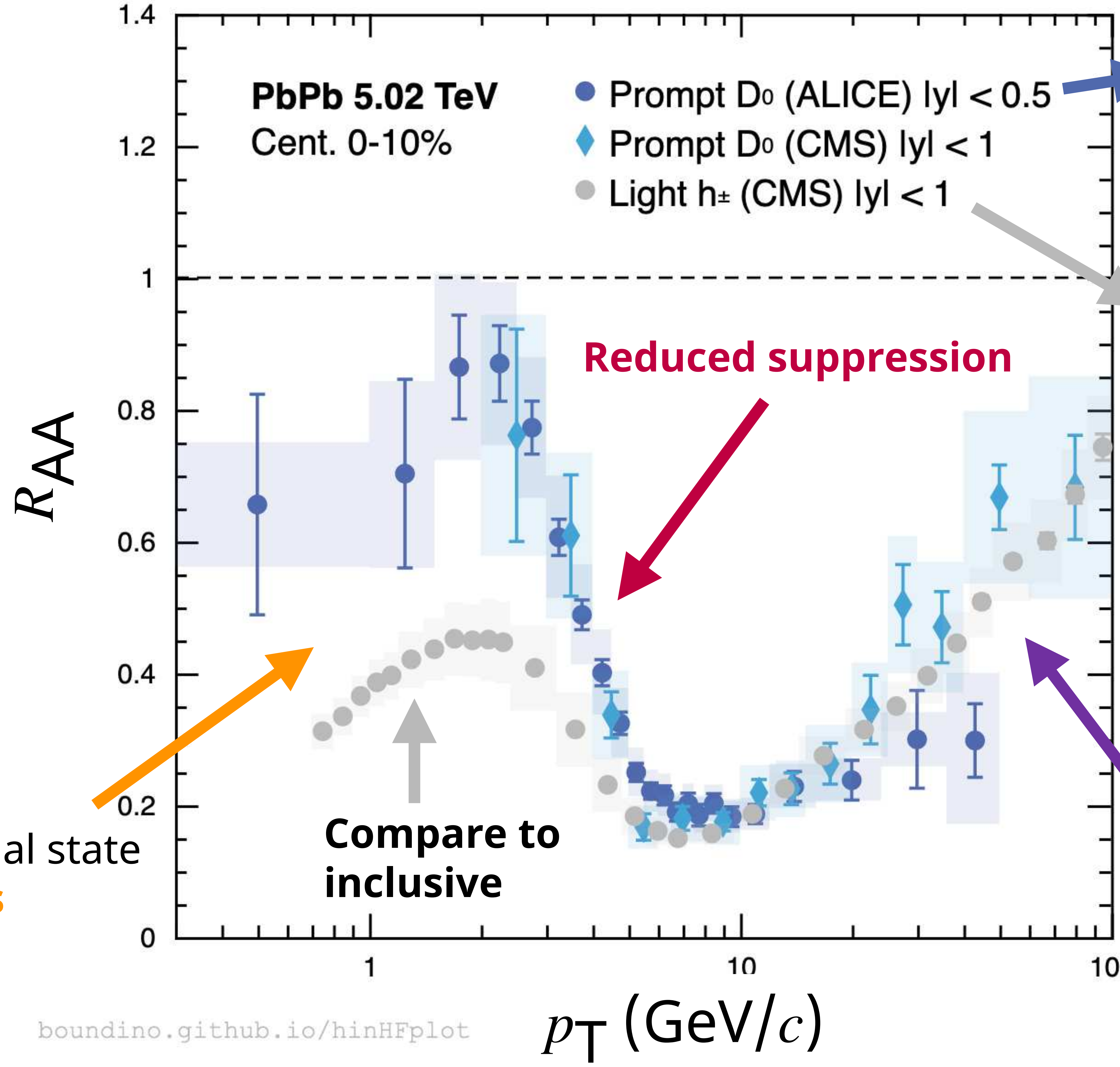
ALICE, JHEP 11 (2018) 013
CMS, JHEP 04 (2017) 039
PHENIX, PRC 87 (2013) 3, 034911
STAR, PRL 91 (2003) 172302

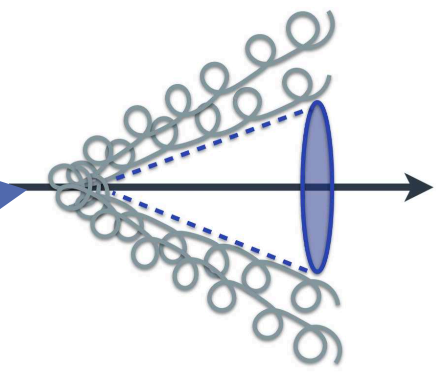
Open charm yield modification

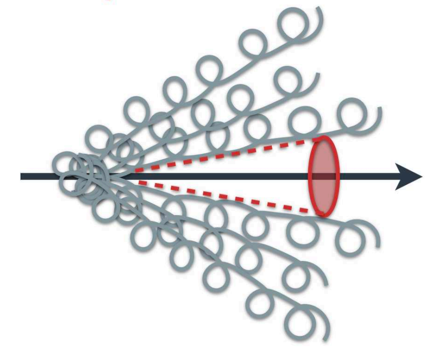
R_{AA} =



- **Charmed hadron yield:** **energy redistribution**, **mass effects**
- **High p_T: mass effects small**
  - **HF consistent with q/g**
- Consistent with **mass dependent hierarchy**







ALICE, JHEP 01 (2022) 174

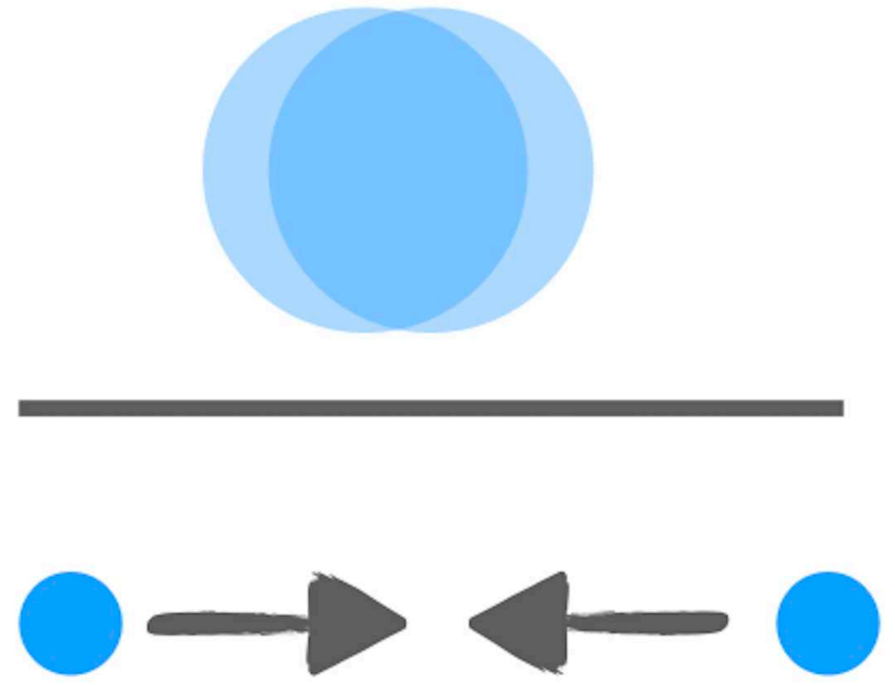
CMS, PLB 782 (2018) 474-496

CMS inclusive, JHEP 04 (2017) 039

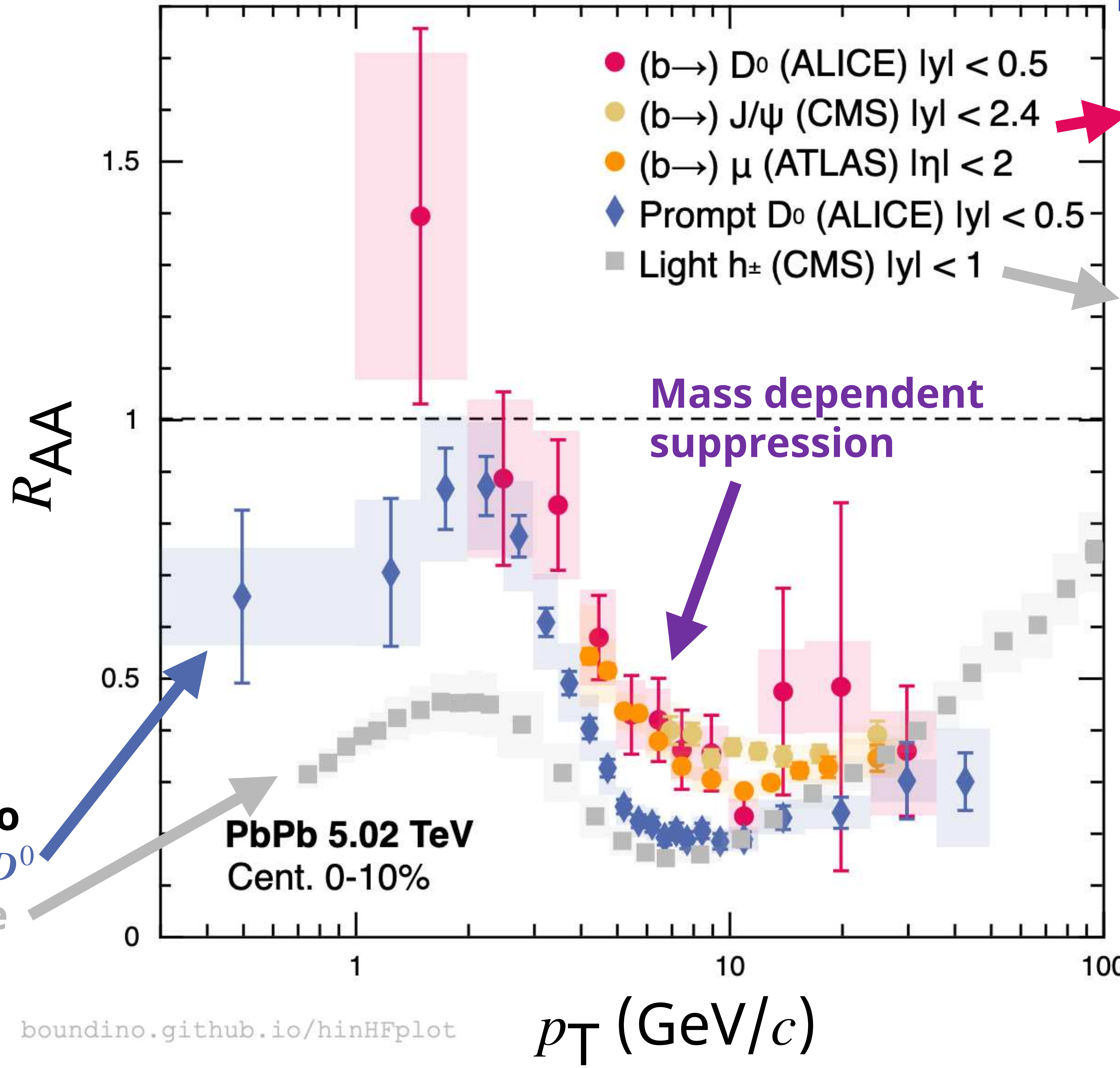
Open beauty yield modification

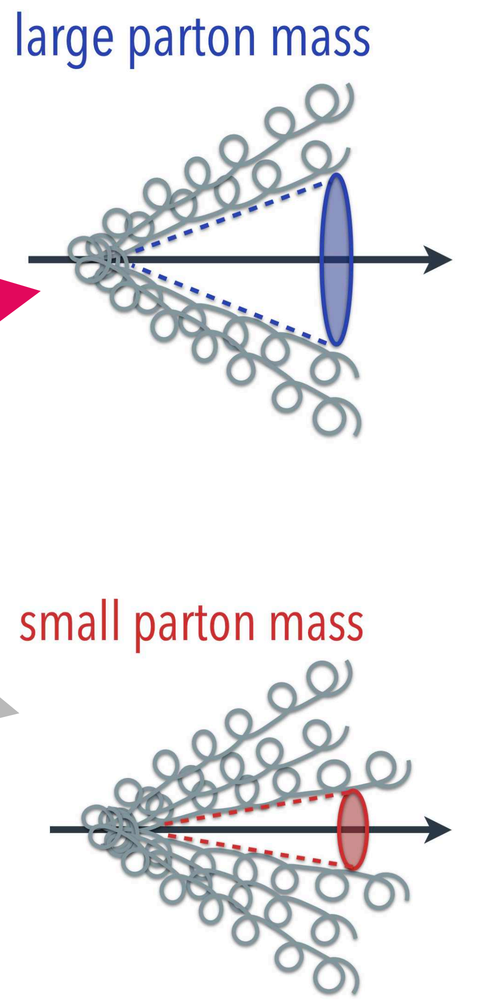
LHCb reconstructing to 30% central in Run 3

R_{AA} =



- Next step: **beauty hadron, μ yield**
- Isolate **energy redistribution**, **mass effects**
- $R_{AA}(q/g) < R_{AA}(c) < R_{AA}(b)$
- Consistent with **mass dependent hierarchy**





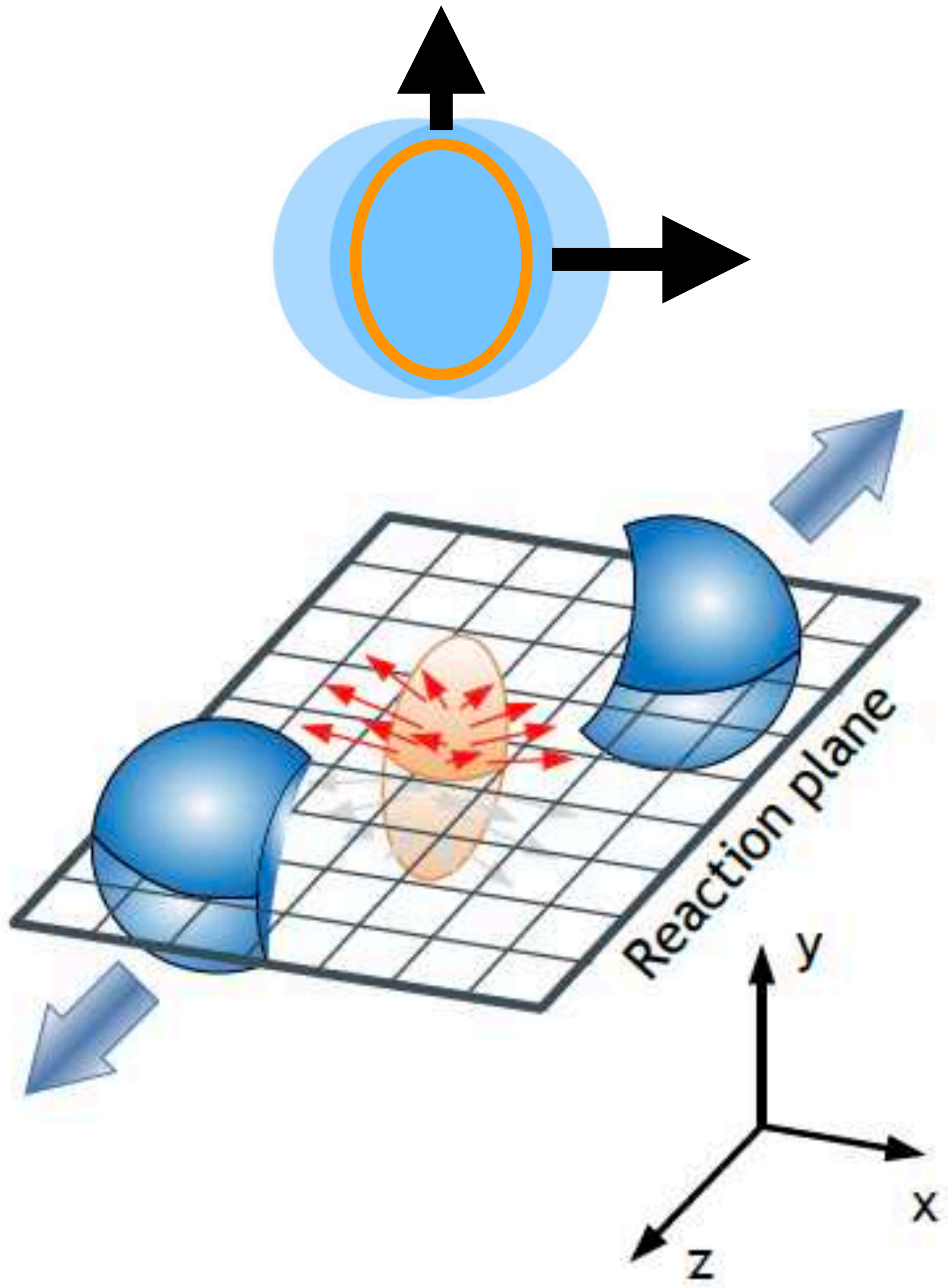
Compare to
Prompt D^0
Inclusive

ALICE, JHEP 12 (2022) 126
ATLAS, PLB 829 (2022) 137077
CMS, EPJC 78 (2018) 509
ALICE Prompt D, JHEP 01 (2022) 174
CMS inclusive, JHEP 04 (2017) 039

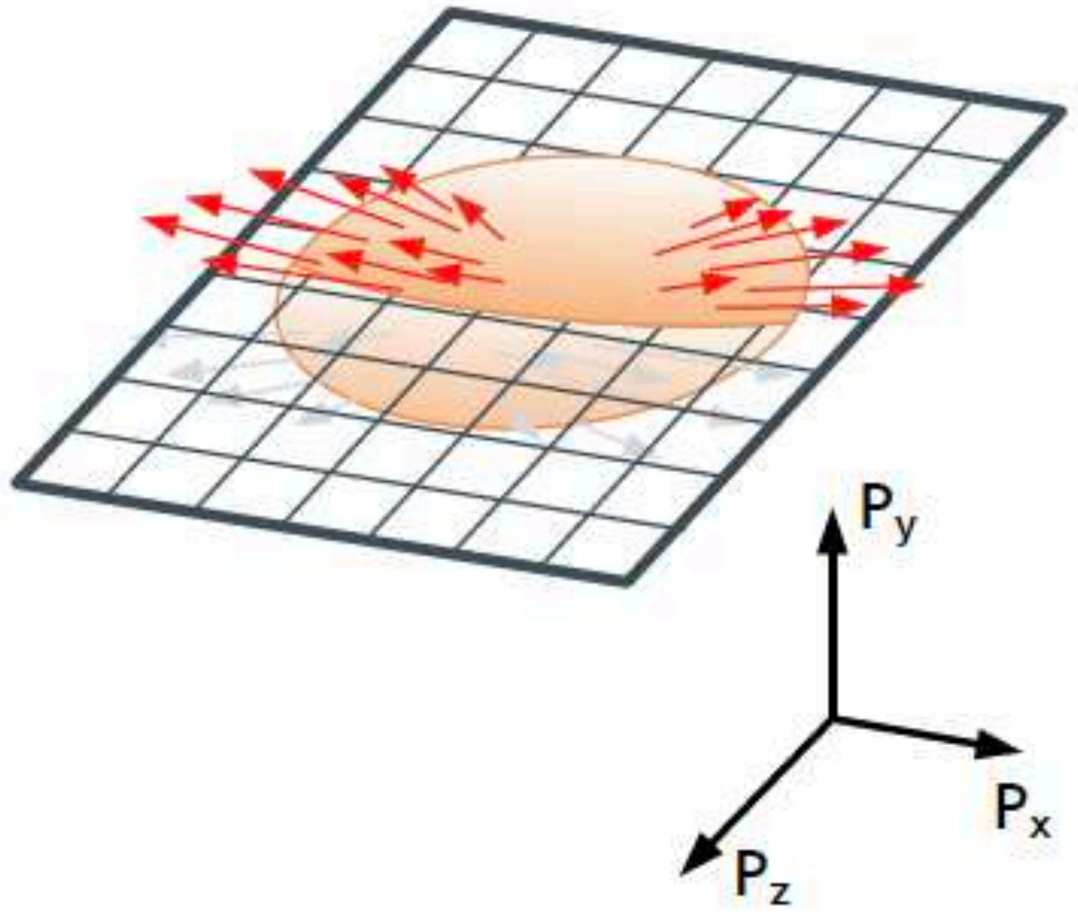
Collective flow

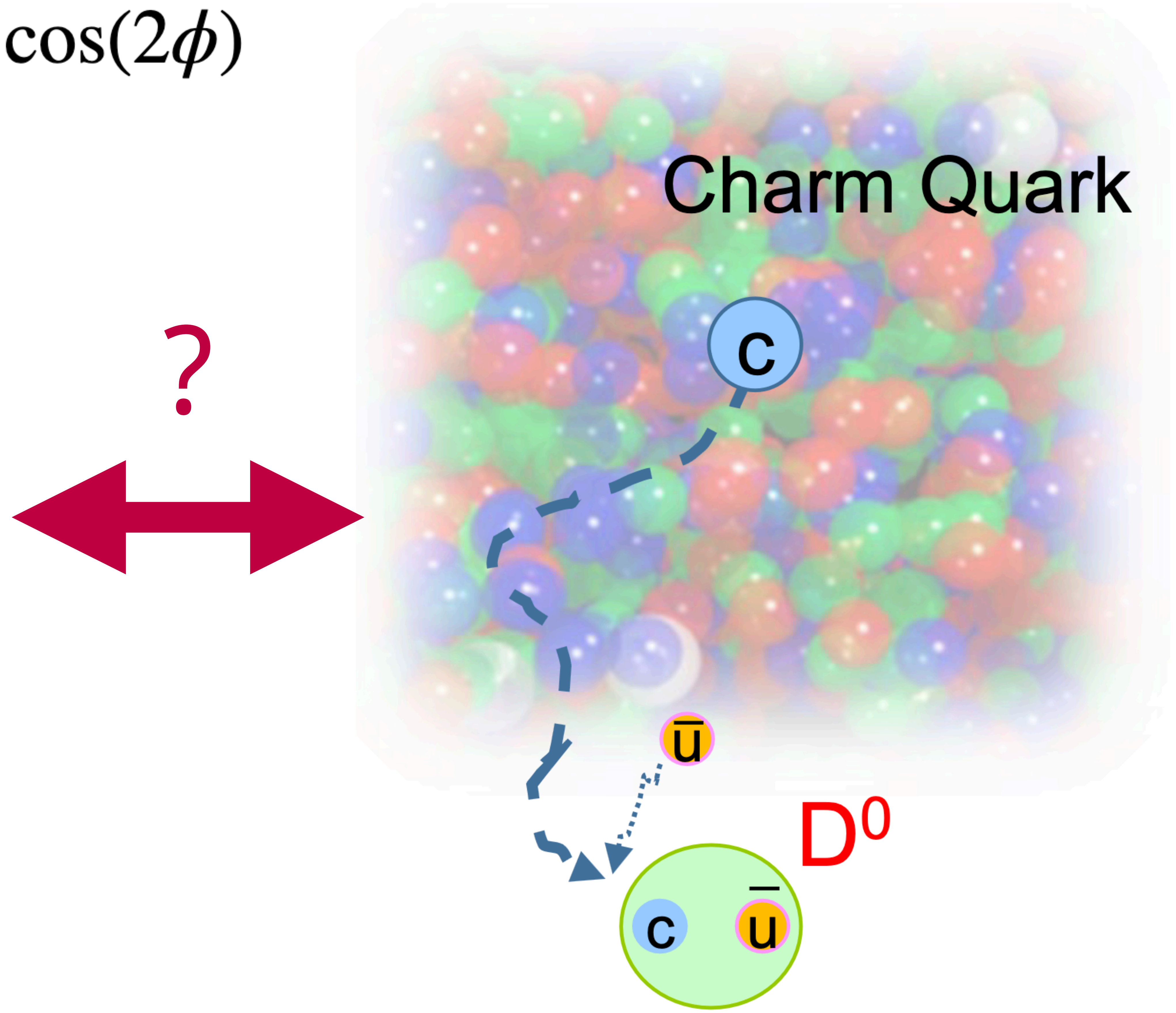
Heavy quark diffusion and medium expansion

Non-central collisions



$$\frac{dN}{d\phi} \sim 1 + v_2(p_T)\cos(2\phi)$$





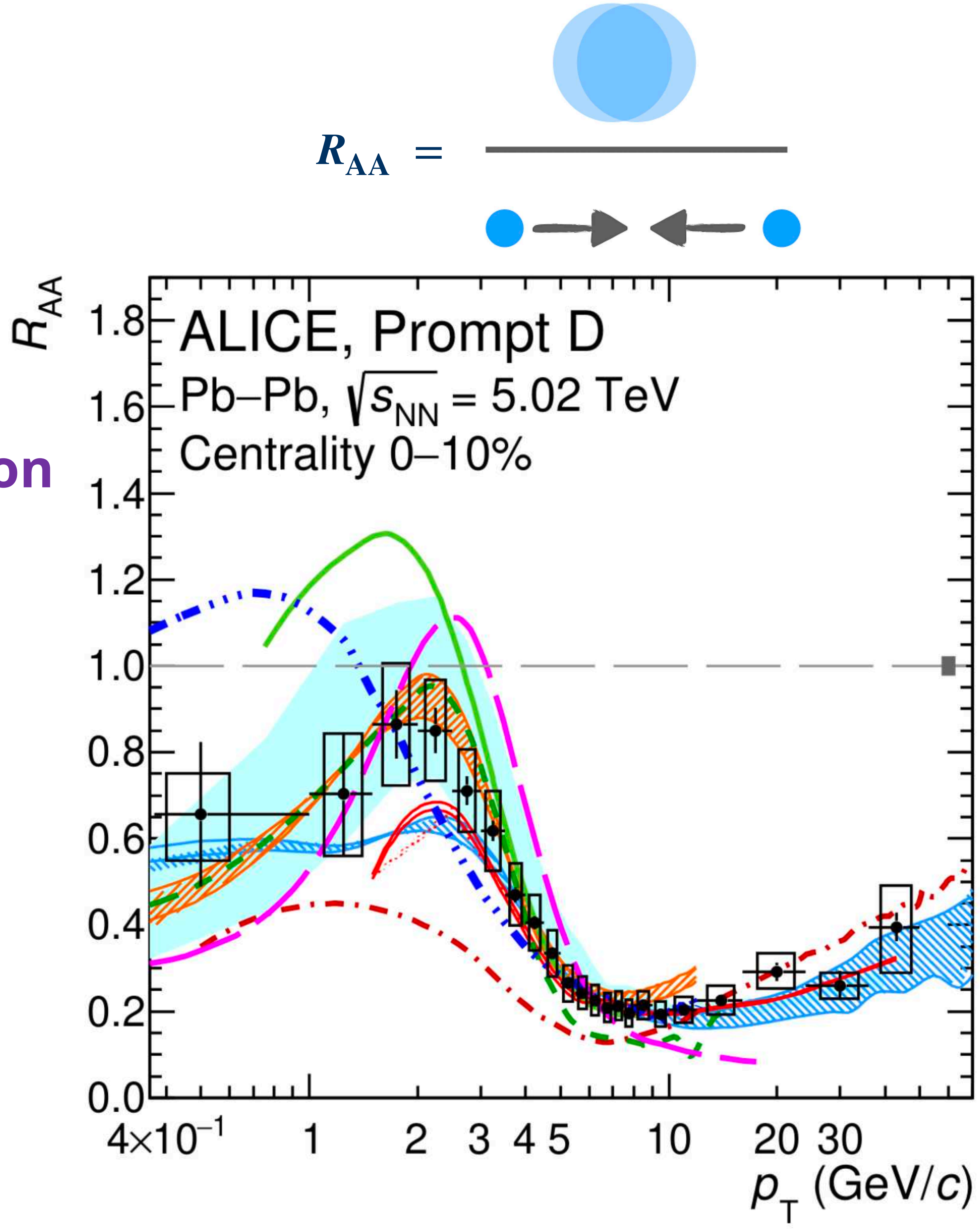
Spatial → momentum anisotropy

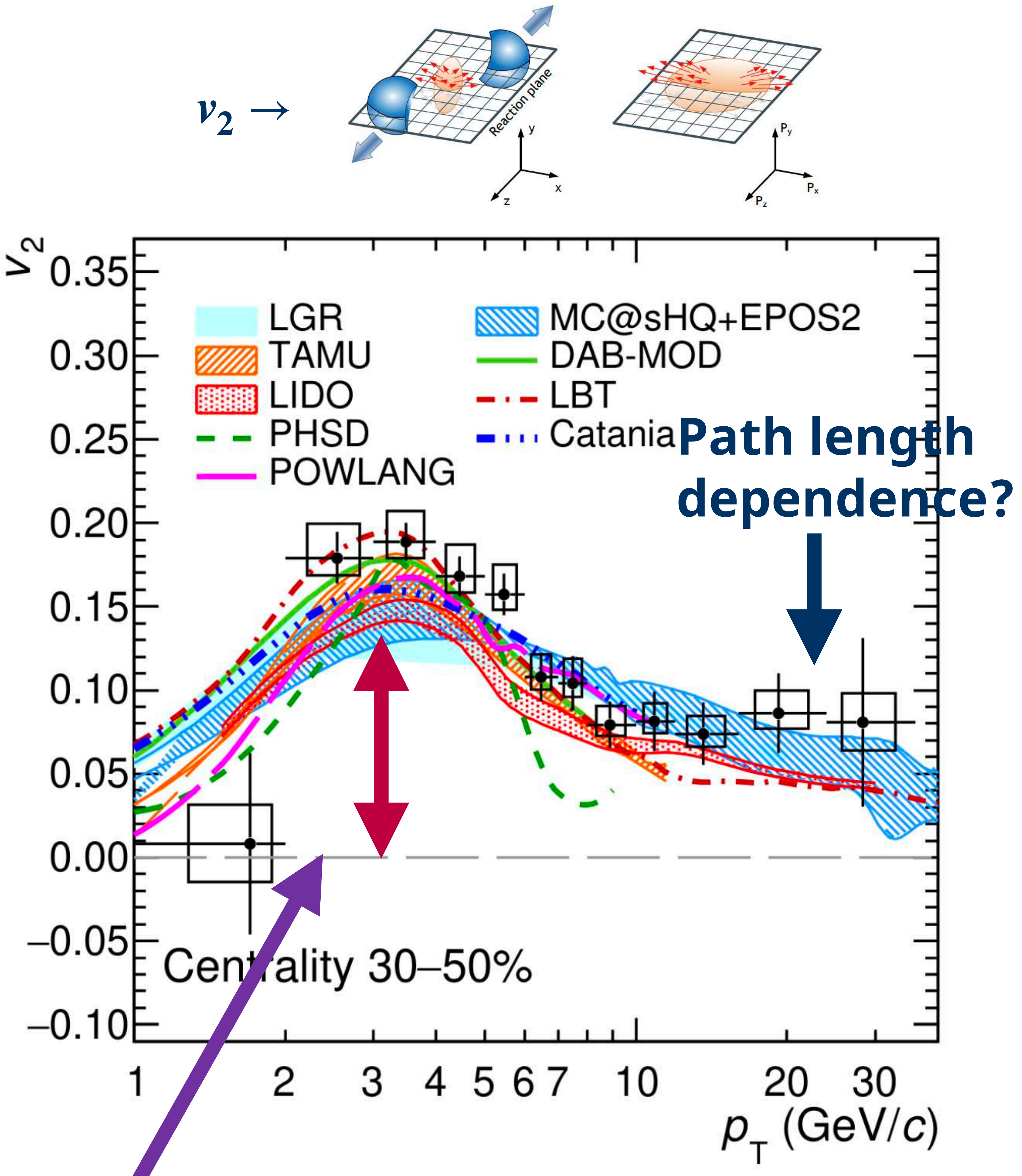
Do heavy quarks flow? Diffuse?

Cartoons: Martin Rybar, Yen-Jie Lee

Charm hadron diffusion and expansion

- Correlate v_2 and R_{AA}: probe **collective expansion** and **thermalization**
  - **Azimuthal anisotropy “elliptic flow”**
- Diffusing charm quark **moves with expanding medium**





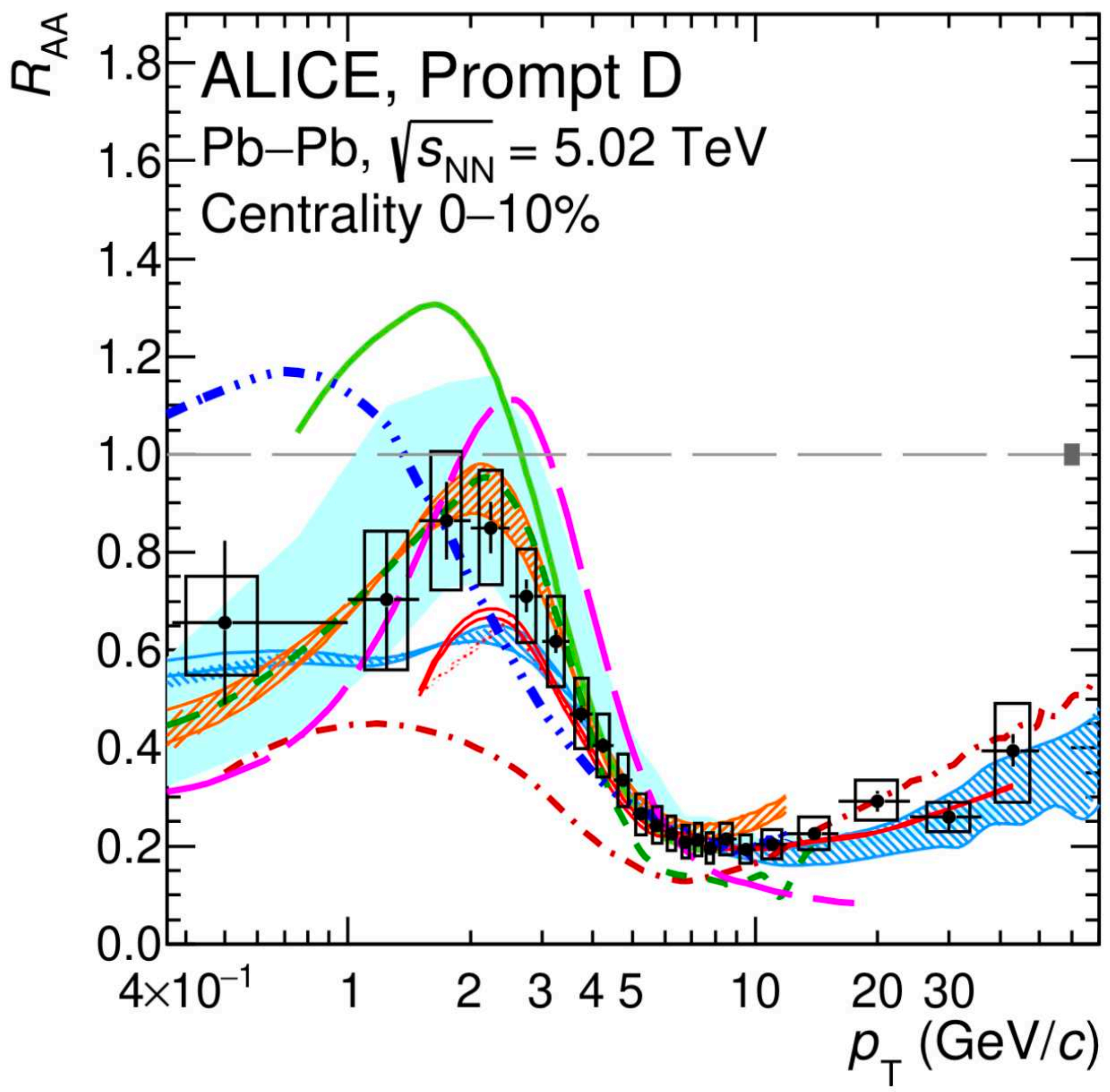
Models with **different HQ transport, hydro, and hadronization describe data**

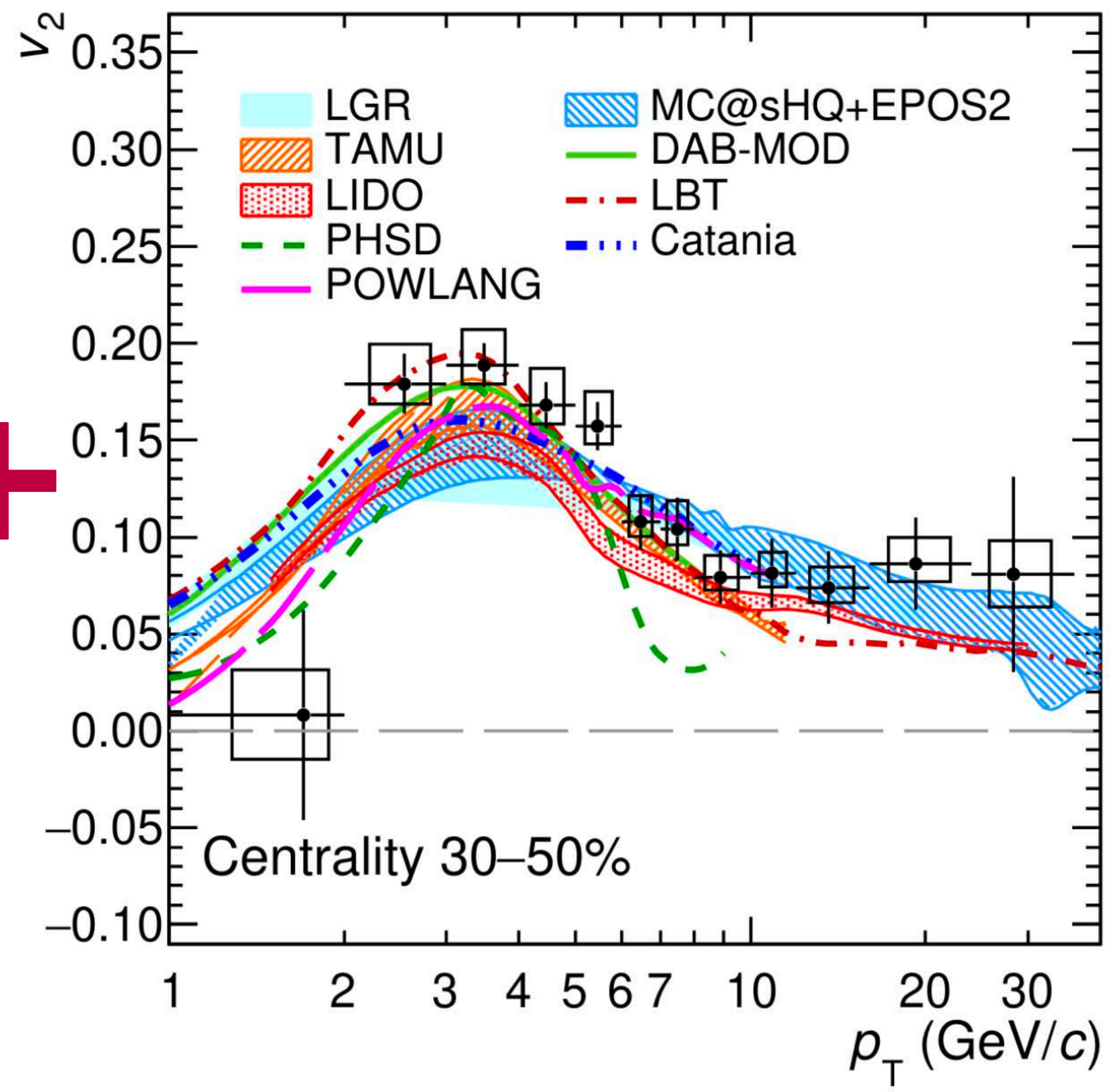
Charm flows collectively with medium

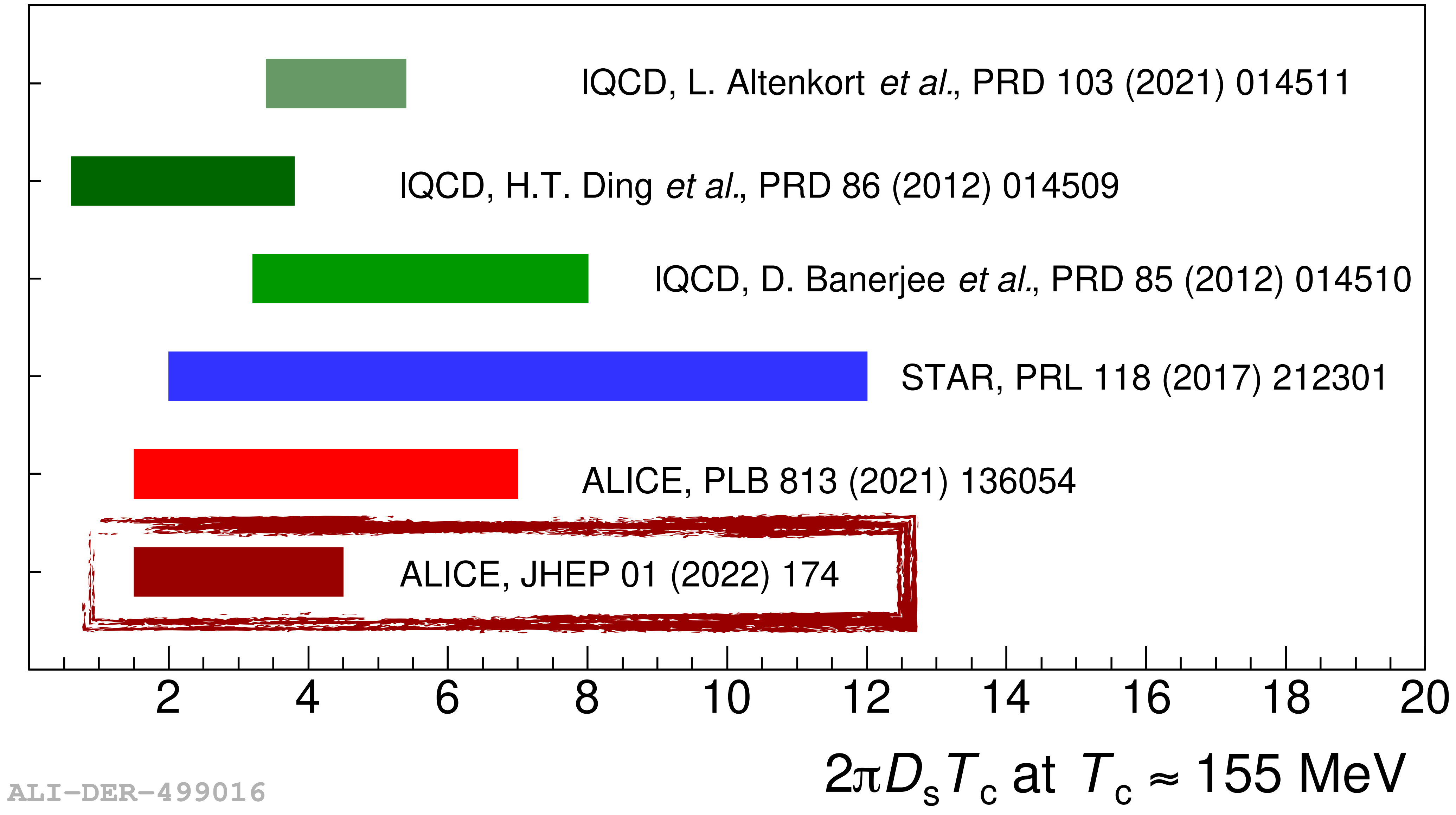
ALICE, JHEP 01 (2022) 174

Charm hadron diffusion and expansion

Simultaneously fit models to extract D_S







$$1.5 < 2\pi D_S T_C < 4.5 \rightarrow \tau_{charm} = 3\text{–}8 \text{ fm}/c$$

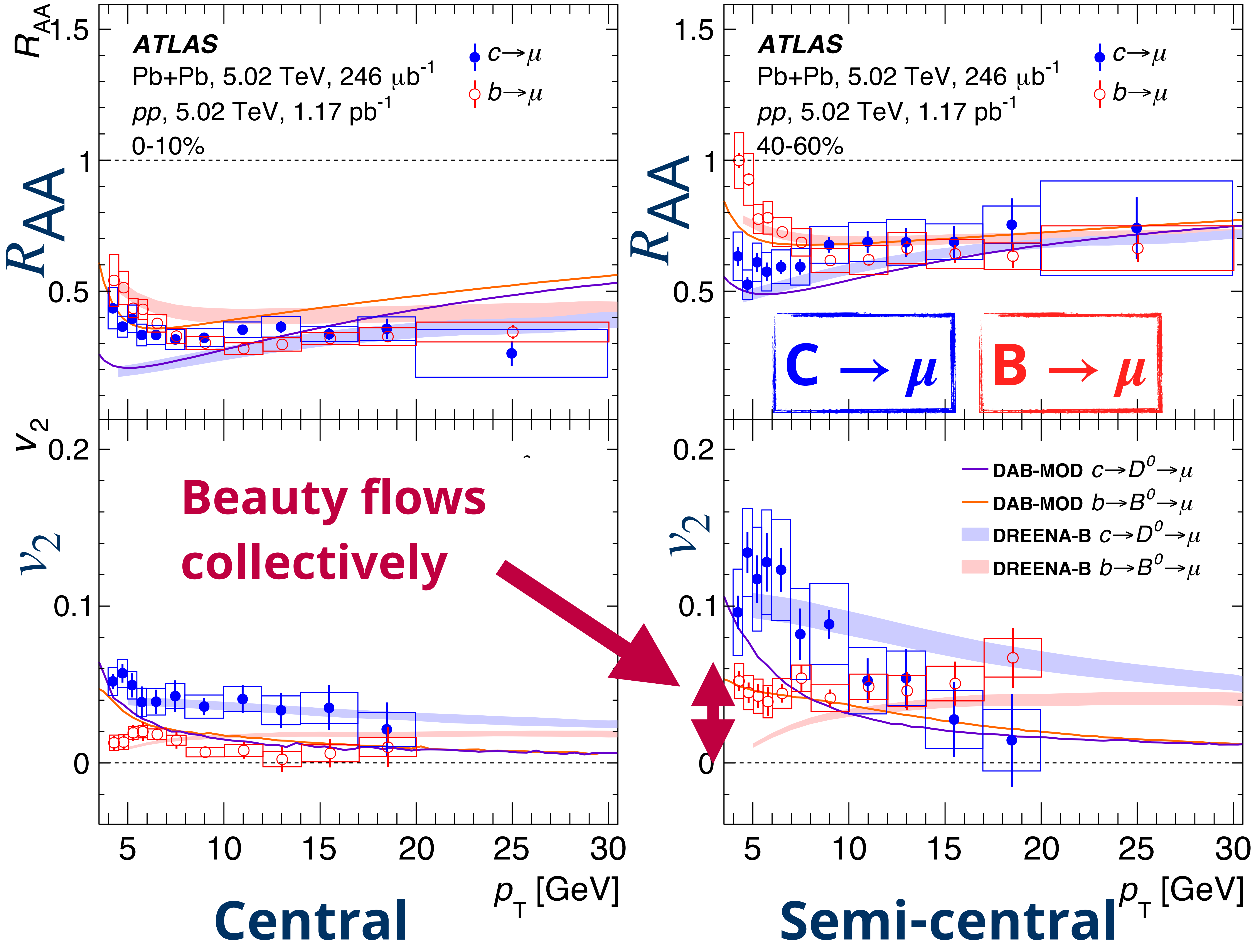
Charm diffuses, partially thermalizes

ALICE, JHEP 01 (2022) 174 ALICE, arXiv:2211.04384

Beauty hadron diffusion and expansion

Simultaneously fit models to extract D_S

See S. Politanò's talk on HF in the QGP



ATLAS:

Charm: $2\pi D_S T_C = 2.23$

Beauty: $2\pi D_S T_C = 2.79$

ALICE

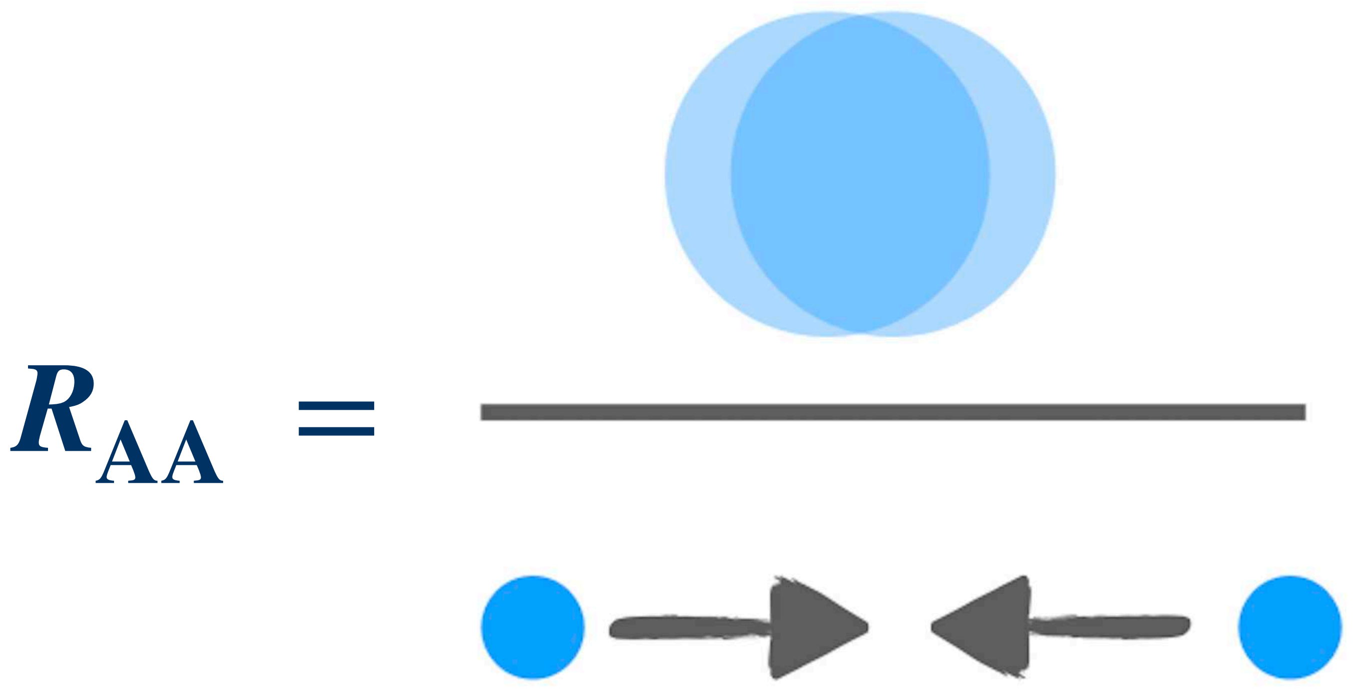
Charm: $1.5 < 2\pi D_S T_C < 4.5$

Beauty partially thermalizes
Consistent values of D_S

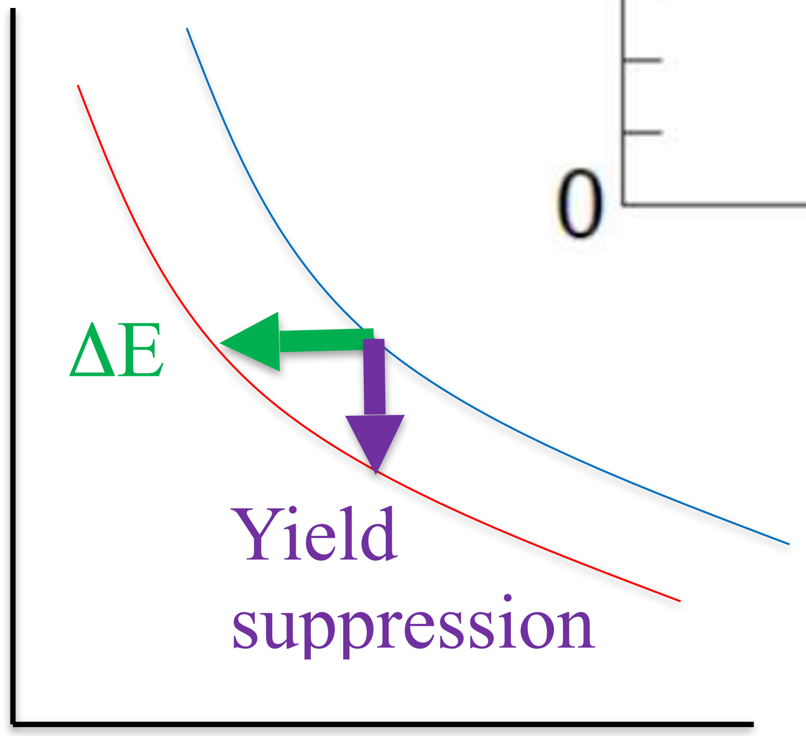
ATLAS, PLB 829 (2022) 137077

Inclusive jet modification

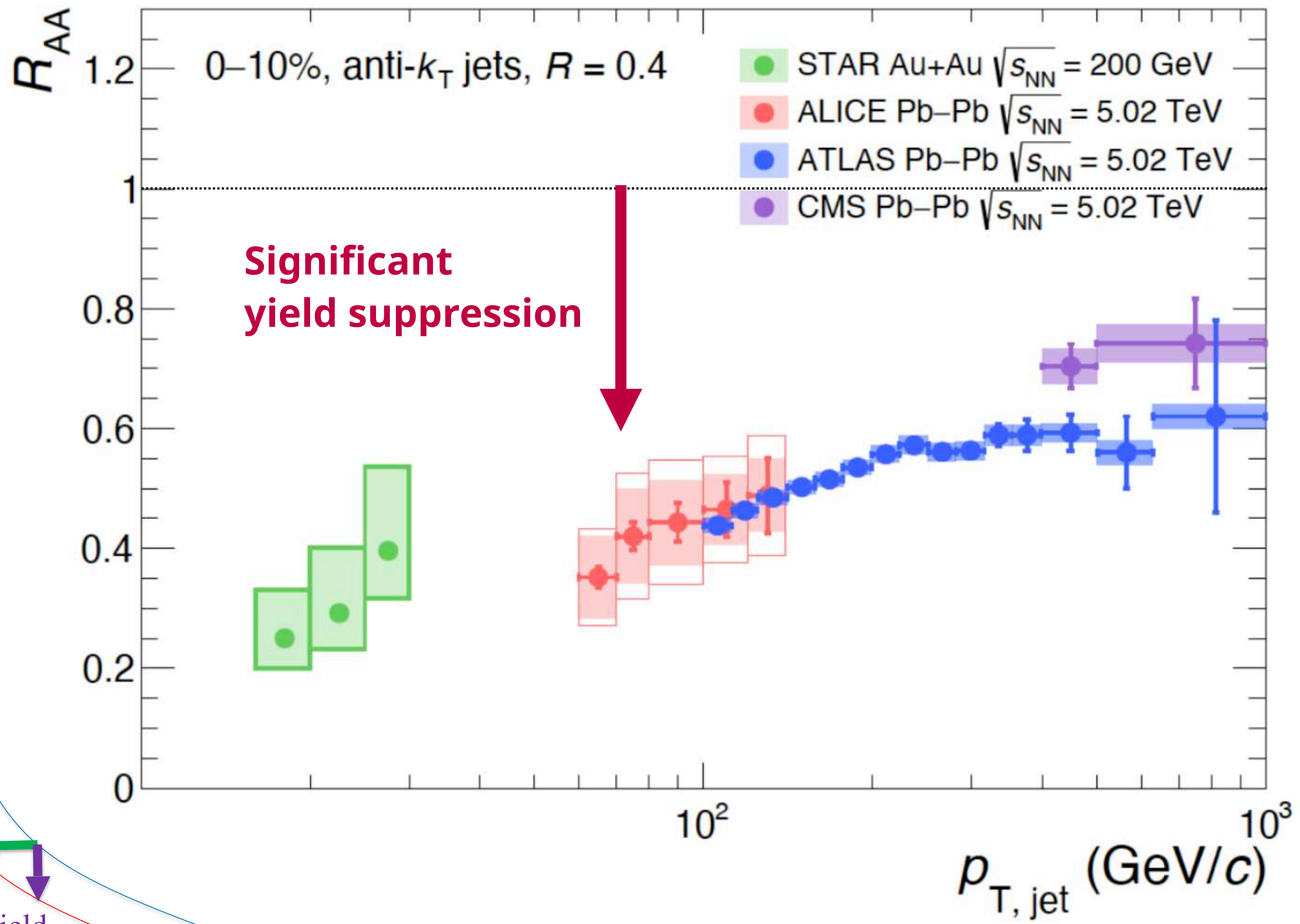
Inclusive jet yield modification



- **Expand aperture with jets from single particle** to **characterize energy loss**
- **Energy redistribution:** lost energy **transported to larger angles**
- Recent years: expanding phase space to **larger R, lower p_T**
  - **New background subtraction techniques**

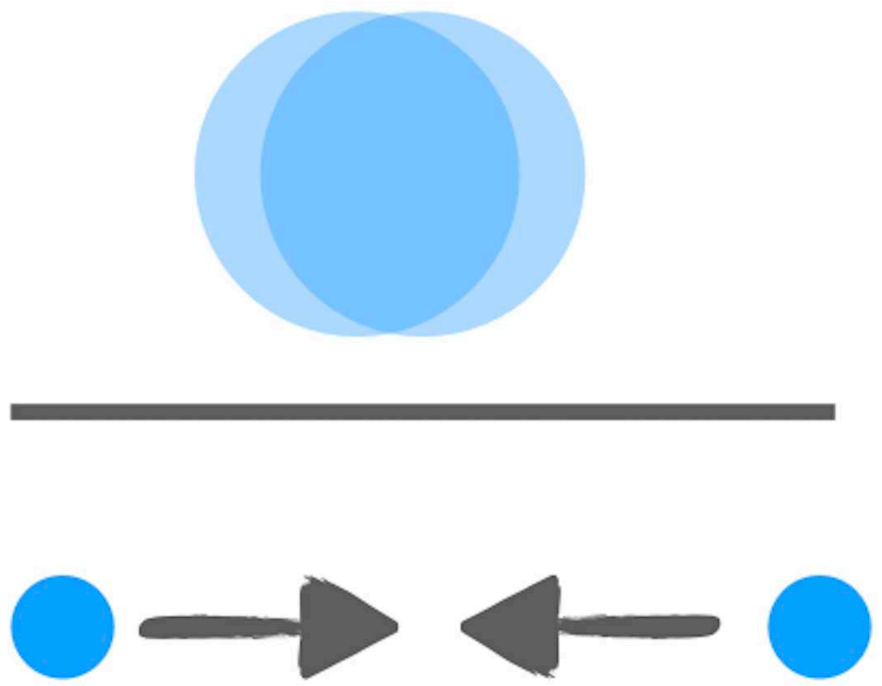


Harris, Müller, EPJC 84, 247 (2024)

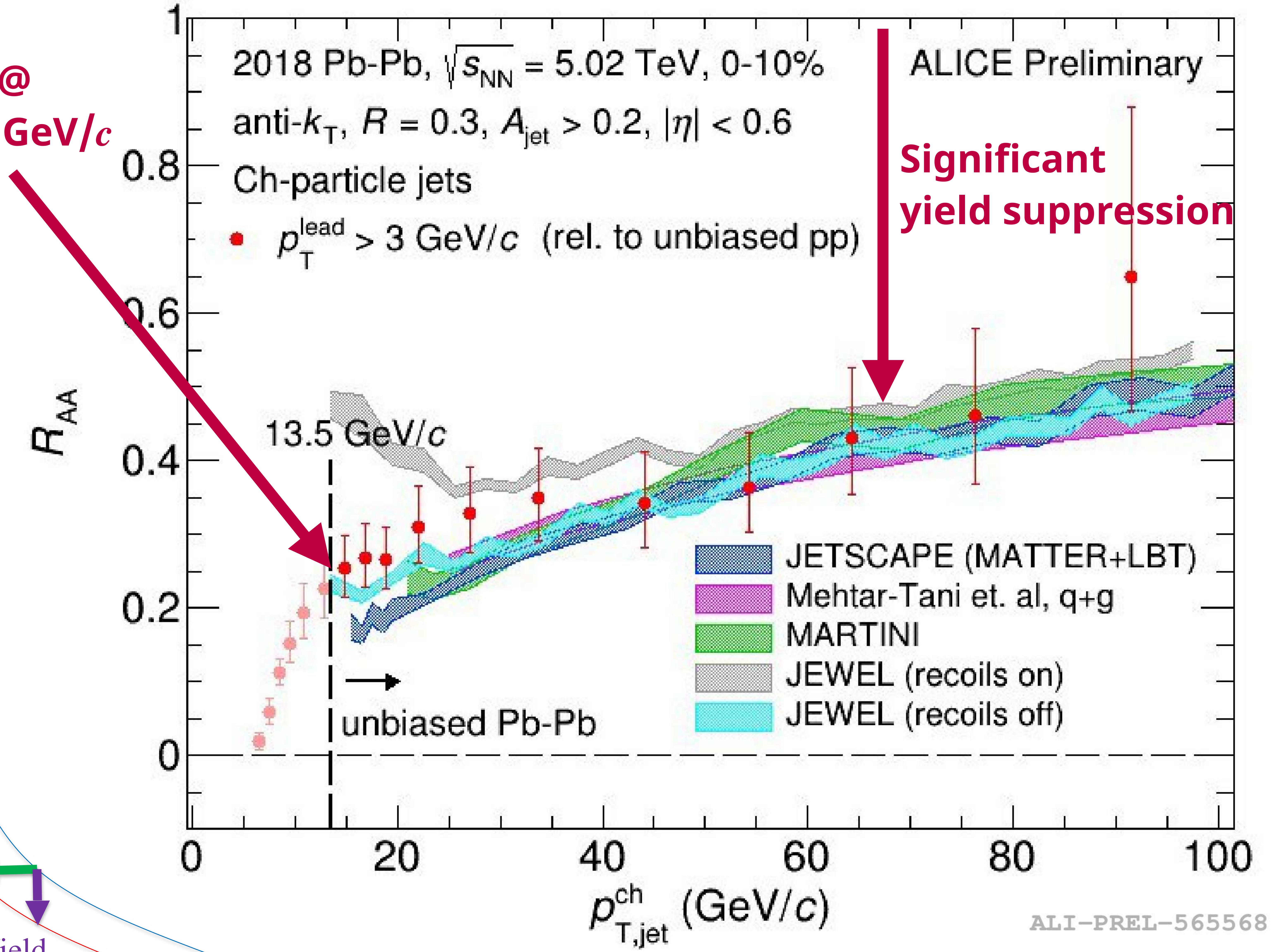


ALICE, PRC 101 (2020) 3, 034911 ATLAS, PLB 790 (2019) 108-128
CMS, JHEP 05 (2021) 284 STAR, PRC 102 (2020) 5, 054913

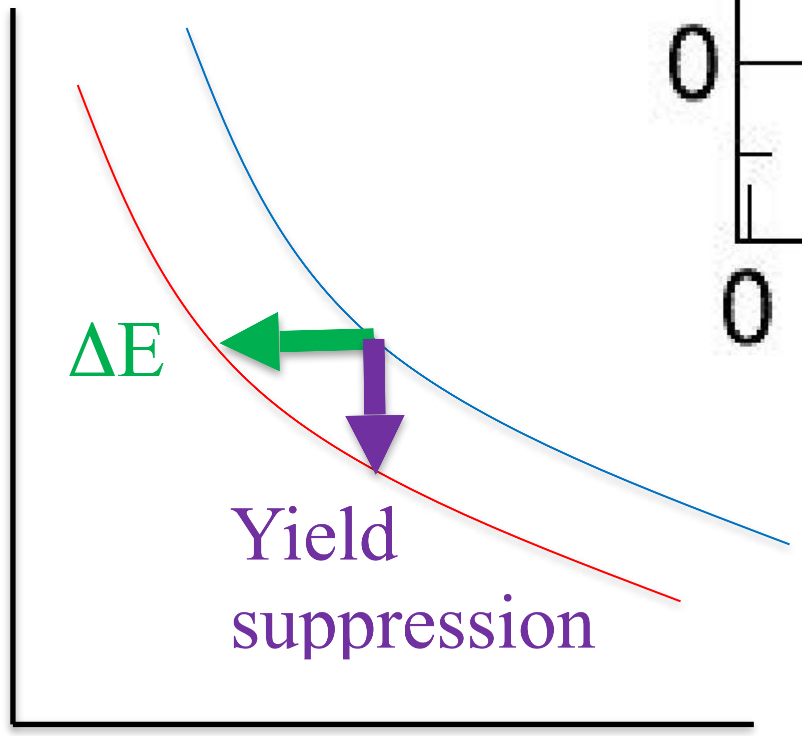
Inclusive jet yield modification

$R_{AA} =$ 

R = 0.3 @ p_T = 15 GeV/c

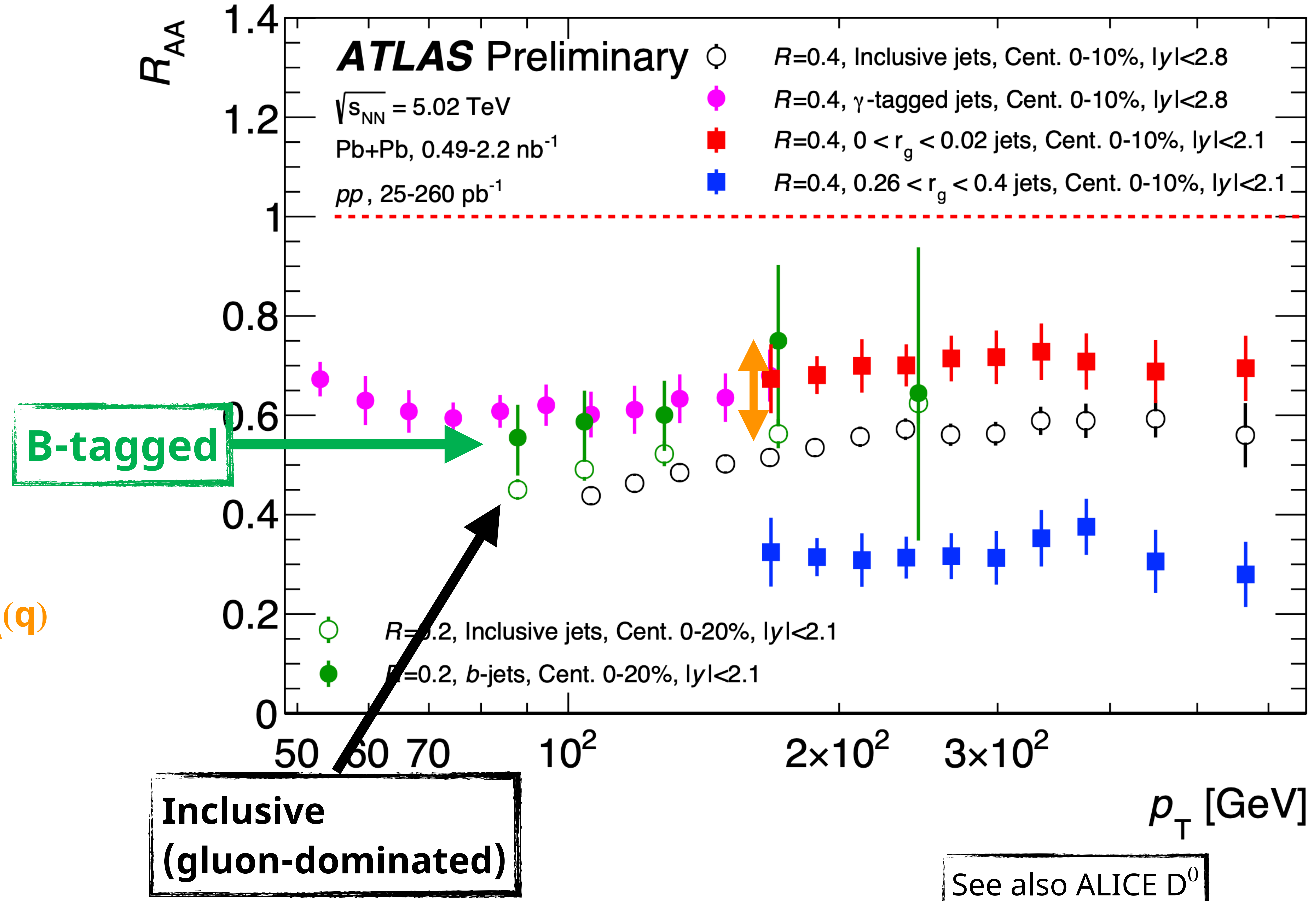


- **Expand aperture with jets from single particle** to **characterize energy loss**
- **Energy redistribution:** lost energy **transported to larger angles**
- Recent years: expanding phase space to **larger R, lower p_T**
  - **New background subtraction techniques**



Exploring mass and color charge dependence

- **Tag populations (b-jet and γ tagged jet)** to isolate **mass dependence, color charge dependence**
  - Compare to **inclusive**
- Hint of **reduced suppression for b-tagged jets**
- **Reduced suppression for quark dominated** samples
- $R_{AA}(g) < R_{AA}(b)$, $R_{AA}(g) < R_{AA}(q)$



ATLAS b-jet, EPJC 83 (2023) 5, 438
ATLAS gamma-tagged, PLB 846 (2023) 138154
ATLAS summary figure

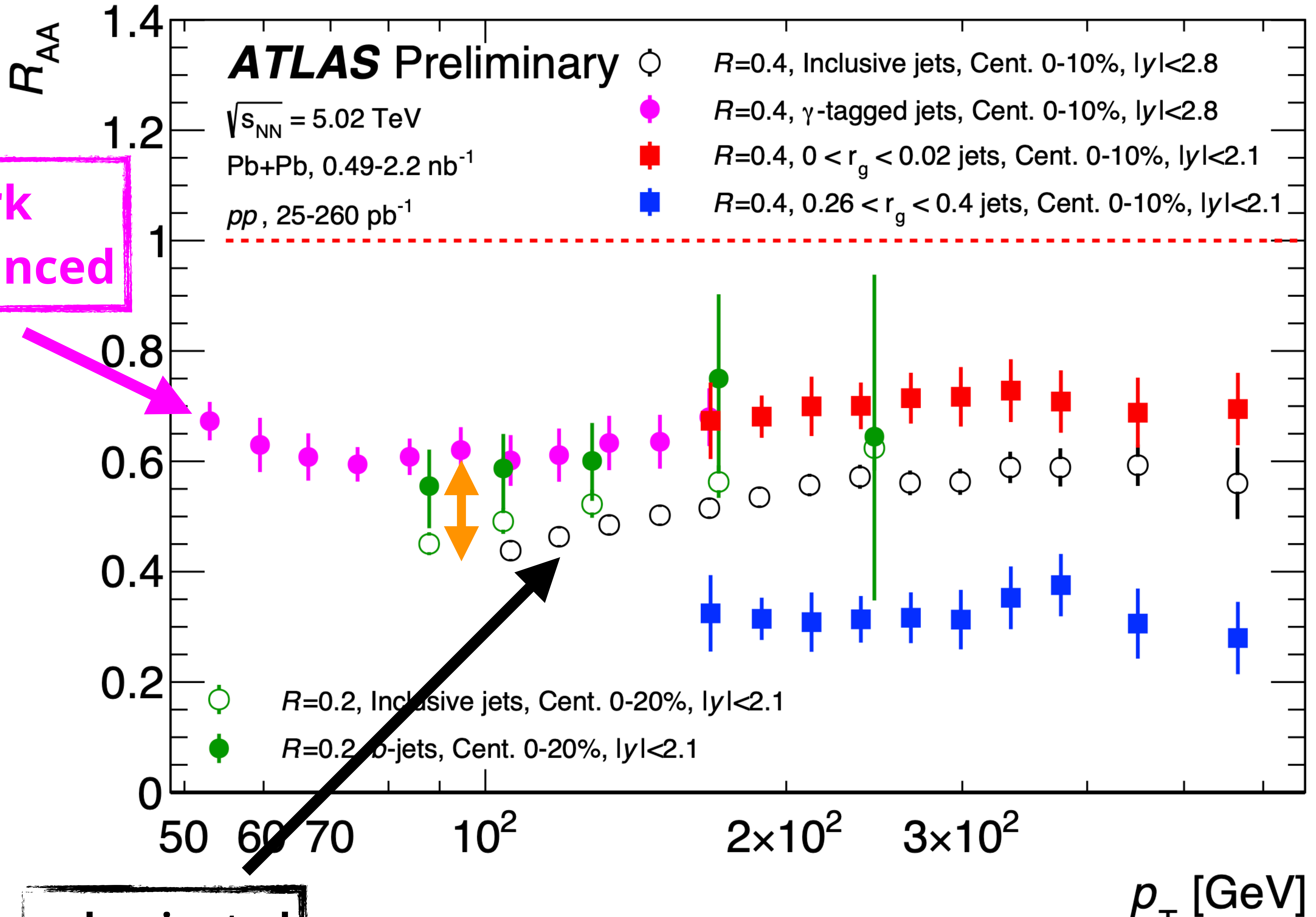
See also ALICE D^0 (figure group)

Exploring mass and color charge dependence

- **Tag populations (b-jet and γ tagged jet)** to isolate **mass dependence**, **color charge dependence**
  - Compare to **inclusive**
- Hint of **reduced suppression for b-tagged jets**
- **Reduced suppression for quark dominated** samples
- $R_{AA}(g) < R_{AA}(b)$, $R_{AA}(g) < R_{AA}(q)$

$C_A/C_F = 9/4$

Quark enhanced



g dominated

[ATLAS b-jet, EPJC 83 (2023) 5, 438](#)
[ATLAS gamma-tagged, PLB 846 (2023) 138154](#)
[ATLAS summary figure](#)

See also ALICE D^0 (figure group)

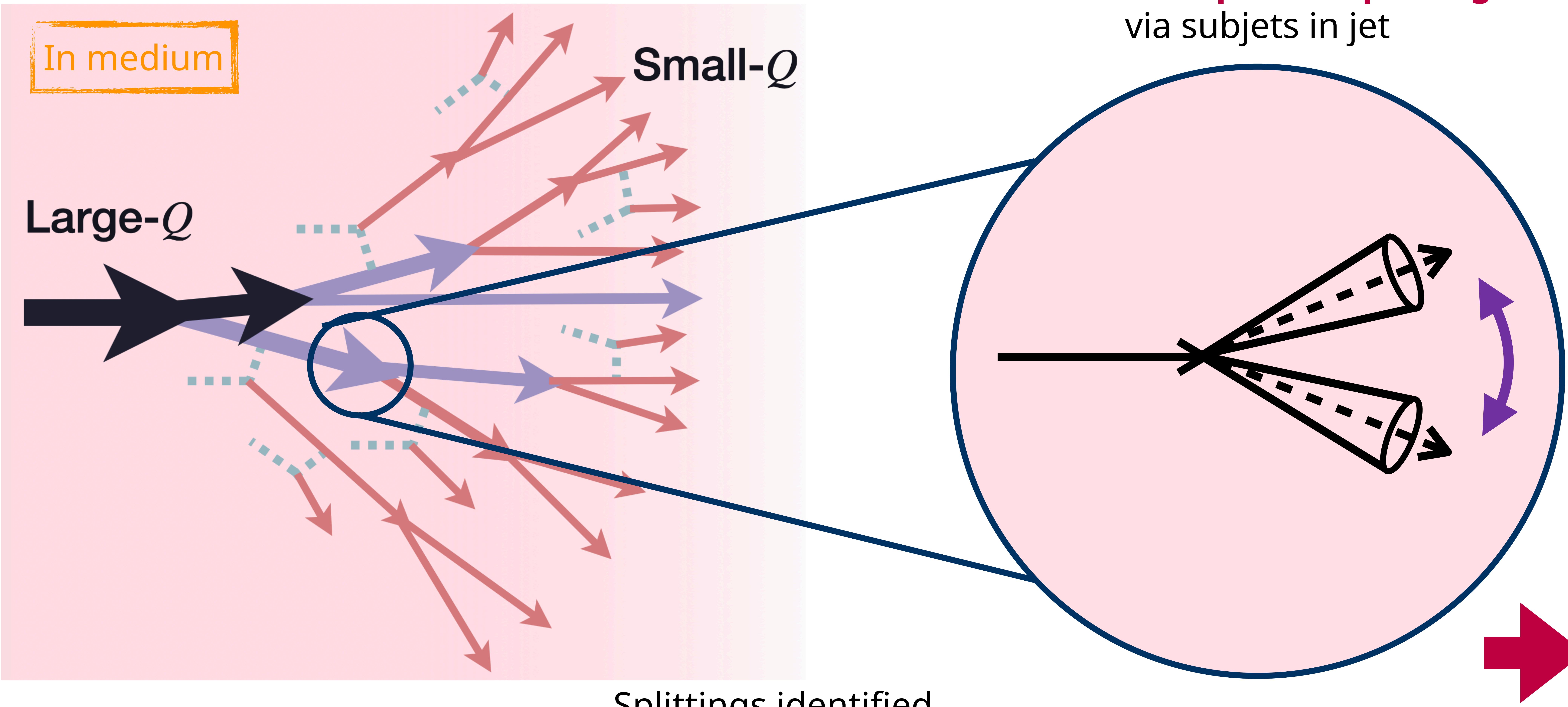
Jet substructure

Probing microscopic structure with jet substructure

See P. Das' talk on jet frag. and hadrochemistry

Impact of **presence of medium** on **parton shower**

Access **hard parton splittings** via subjets in jet



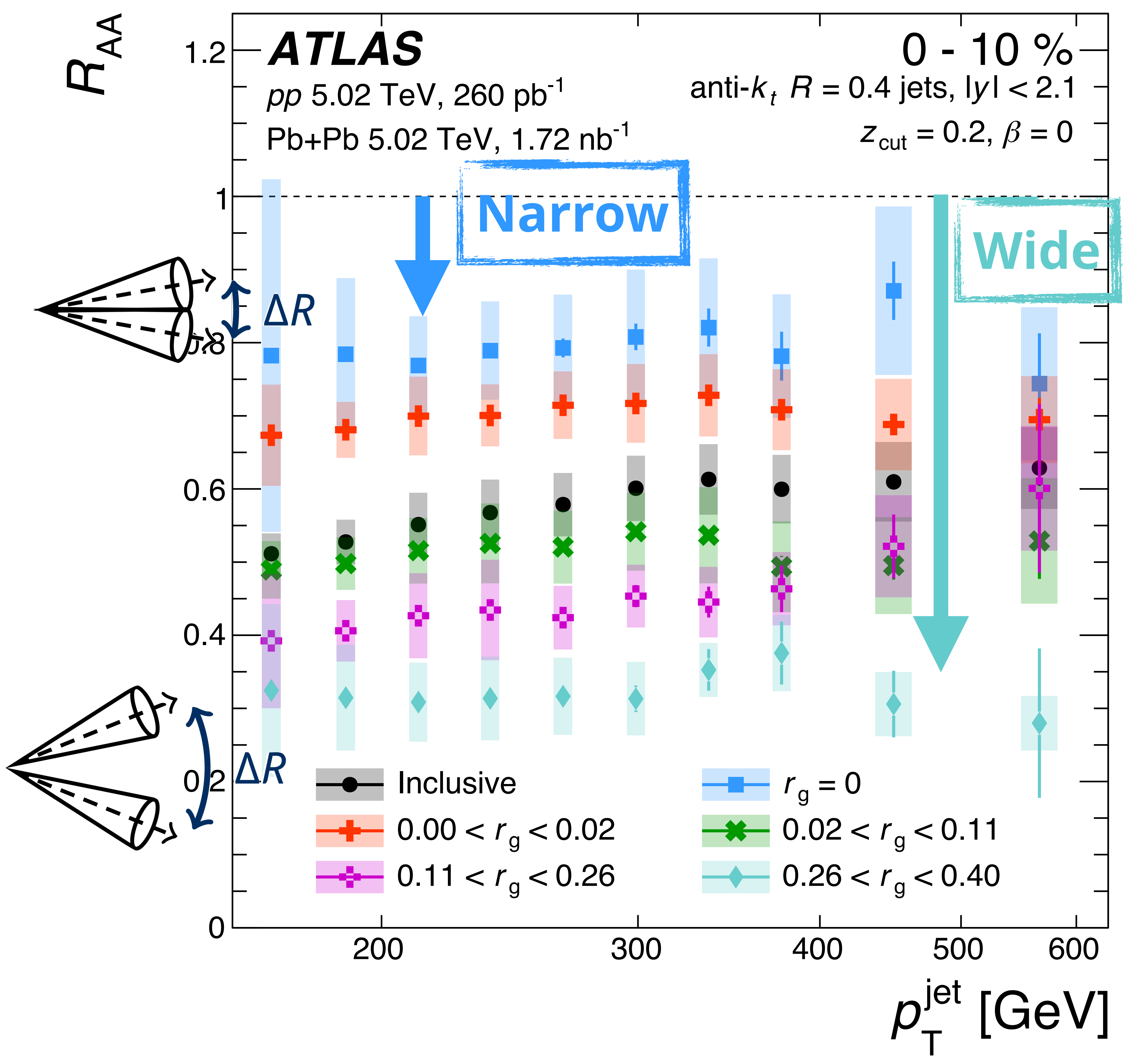
Compare medium vs vacuum splittings

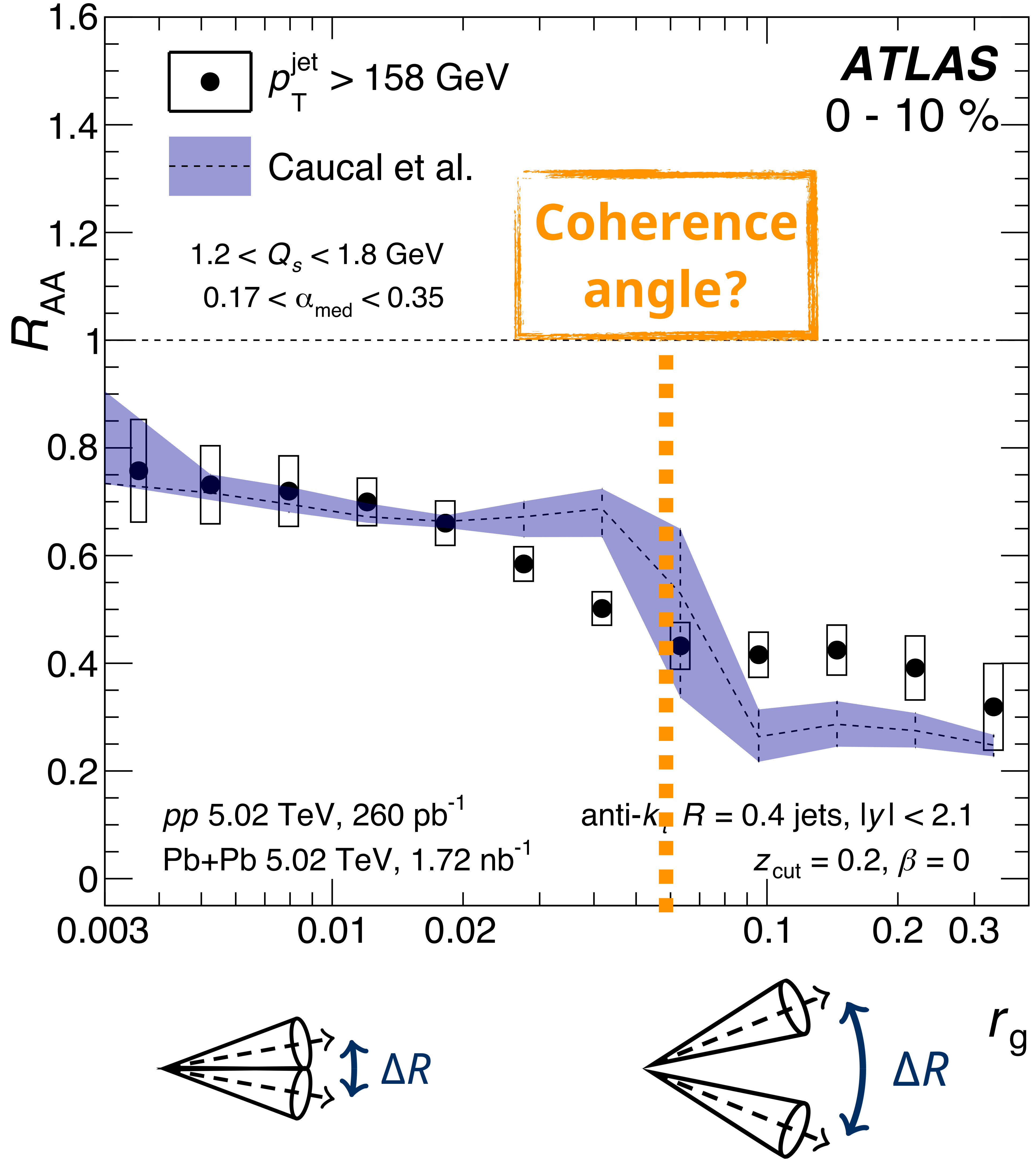
Splittings identified **via grooming methods**

Cartoon derived from: Yasuki Tachibana

Probing microscopic structure with jet substructure

- **Opening angle of hard splitting:** isolate **presence of medium** on **parton shower**
- **Sensitive to QGP resolution scale: color coherence**



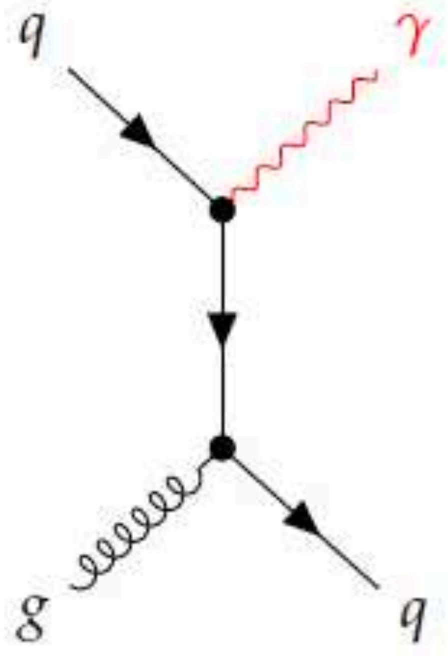


Survival bias: narrow jets more likely to survive
Medium may resolve splittings

ATLAS, PRC 107 (2023) 054909

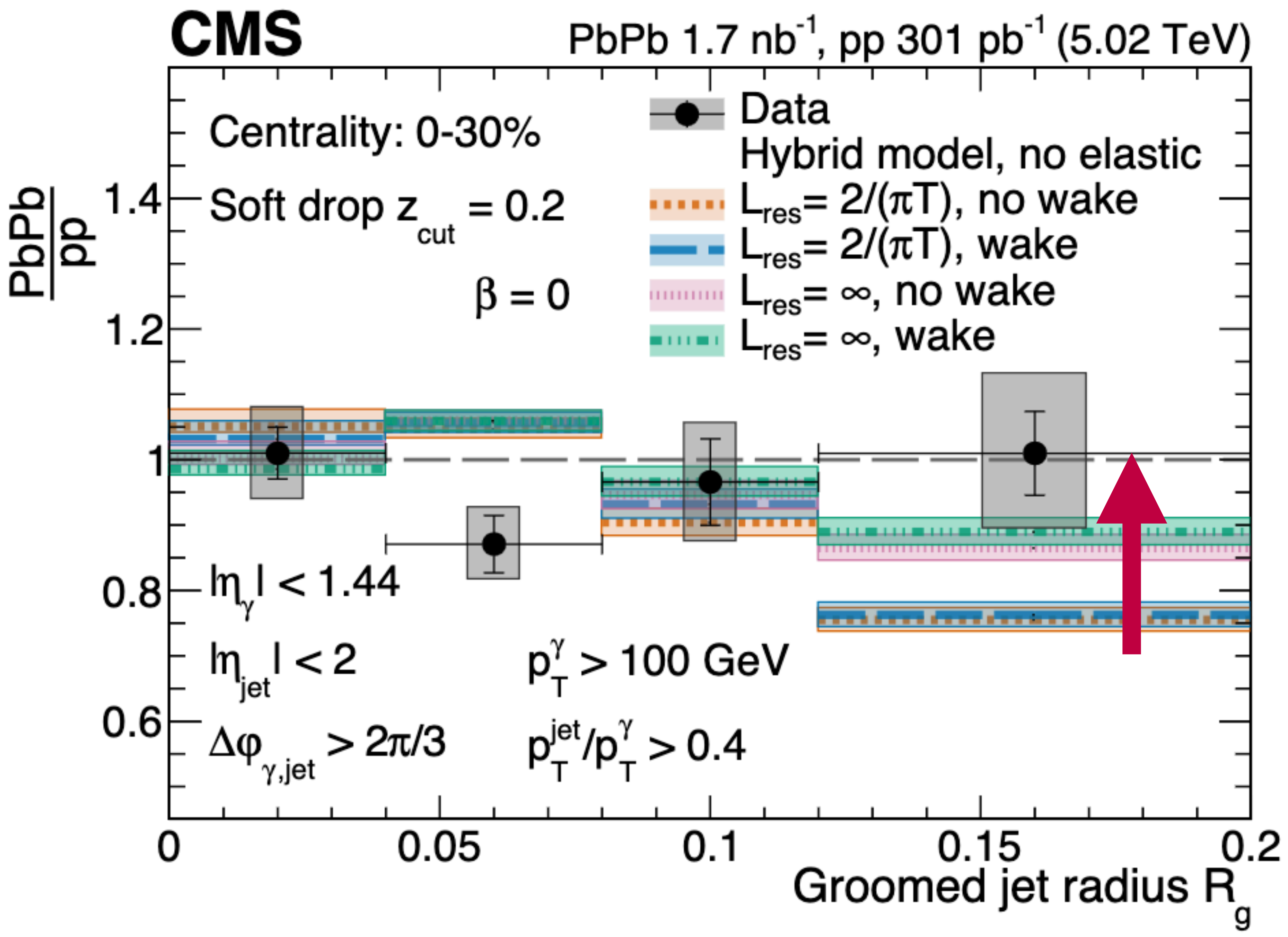
See also ALICE R_g
PRL 128 (2022) 10, 102001

Probing microscopic structure with jet substructure

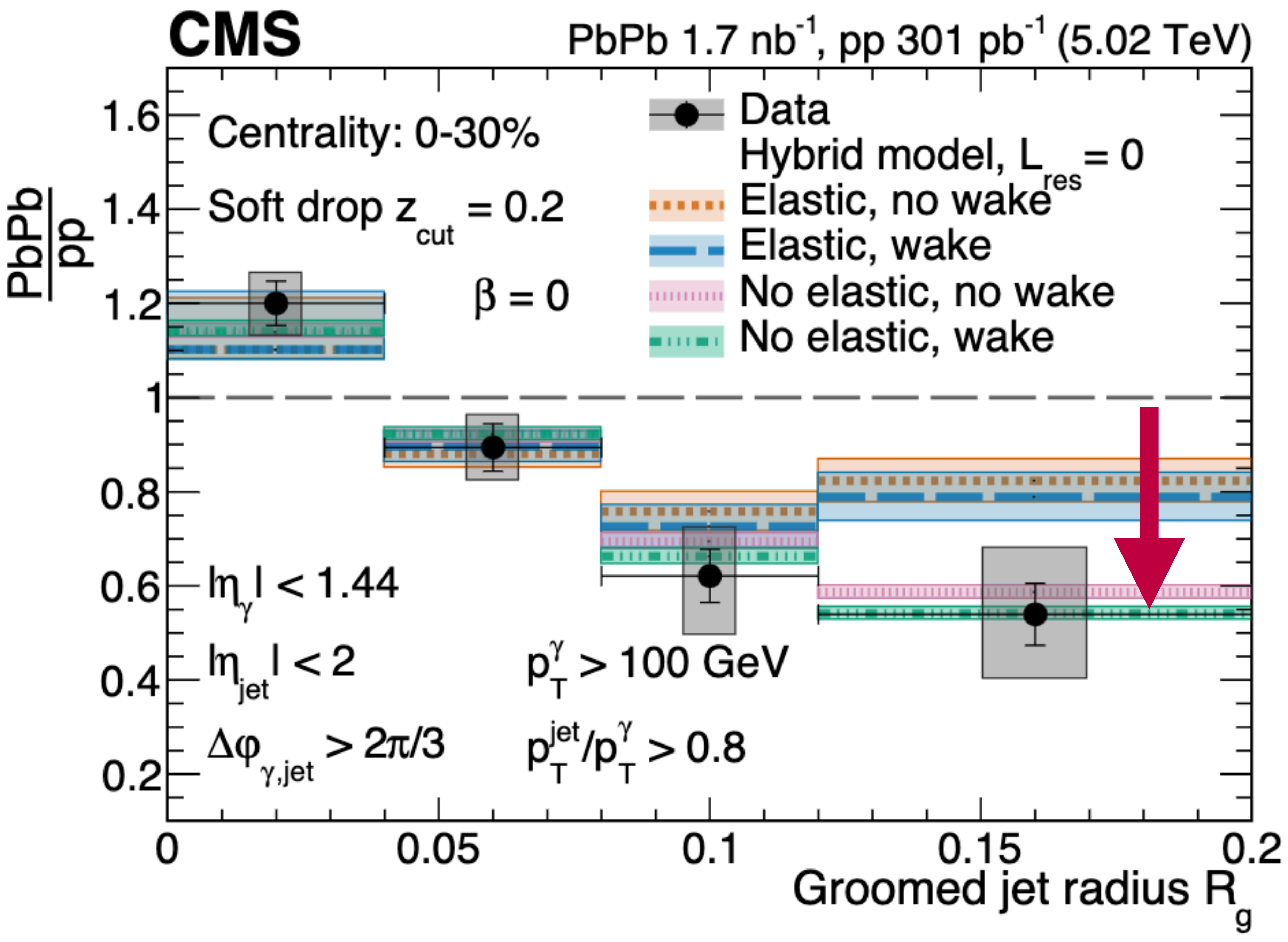


- γ-tagged substructure **reduces bias vs inclusive**
- Sensitivity:
  - **Color coherence**
  - **Point-like (Moliere) scattering**
- **No single set** of preferred model parameters

More quenched: $p_{\mathrm{T}}^{\mathrm{jet}}/p_{\mathrm{T}}^{\gamma} > 0.4$



Less quenched: $p_{\mathrm{T}}^{\mathrm{jet}}/p_{\mathrm{T}}^{\gamma} > 0.8$

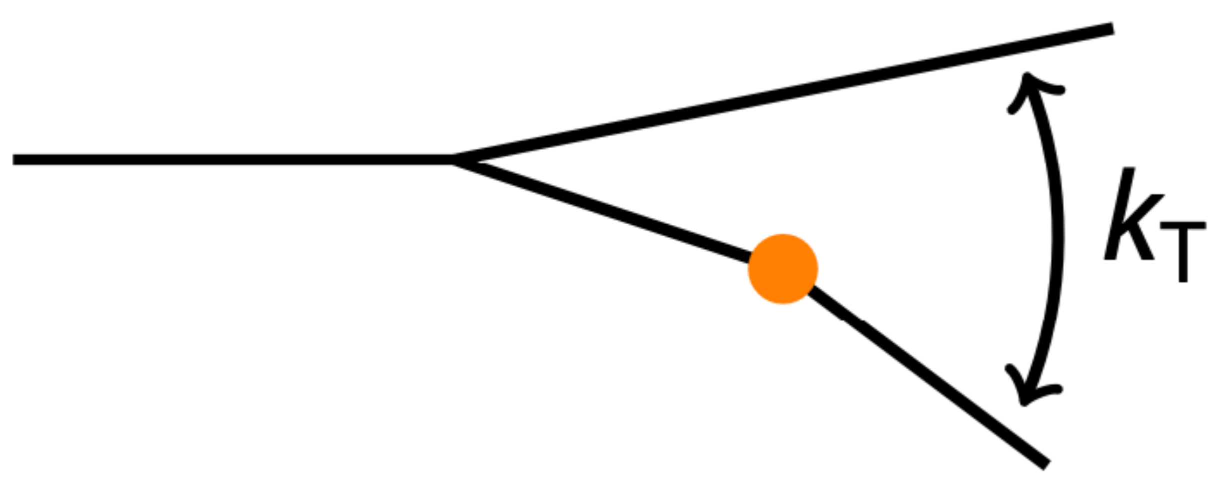


Balanced requirement induces narrowing: selection bias

CMS, arXiv:2405.02737

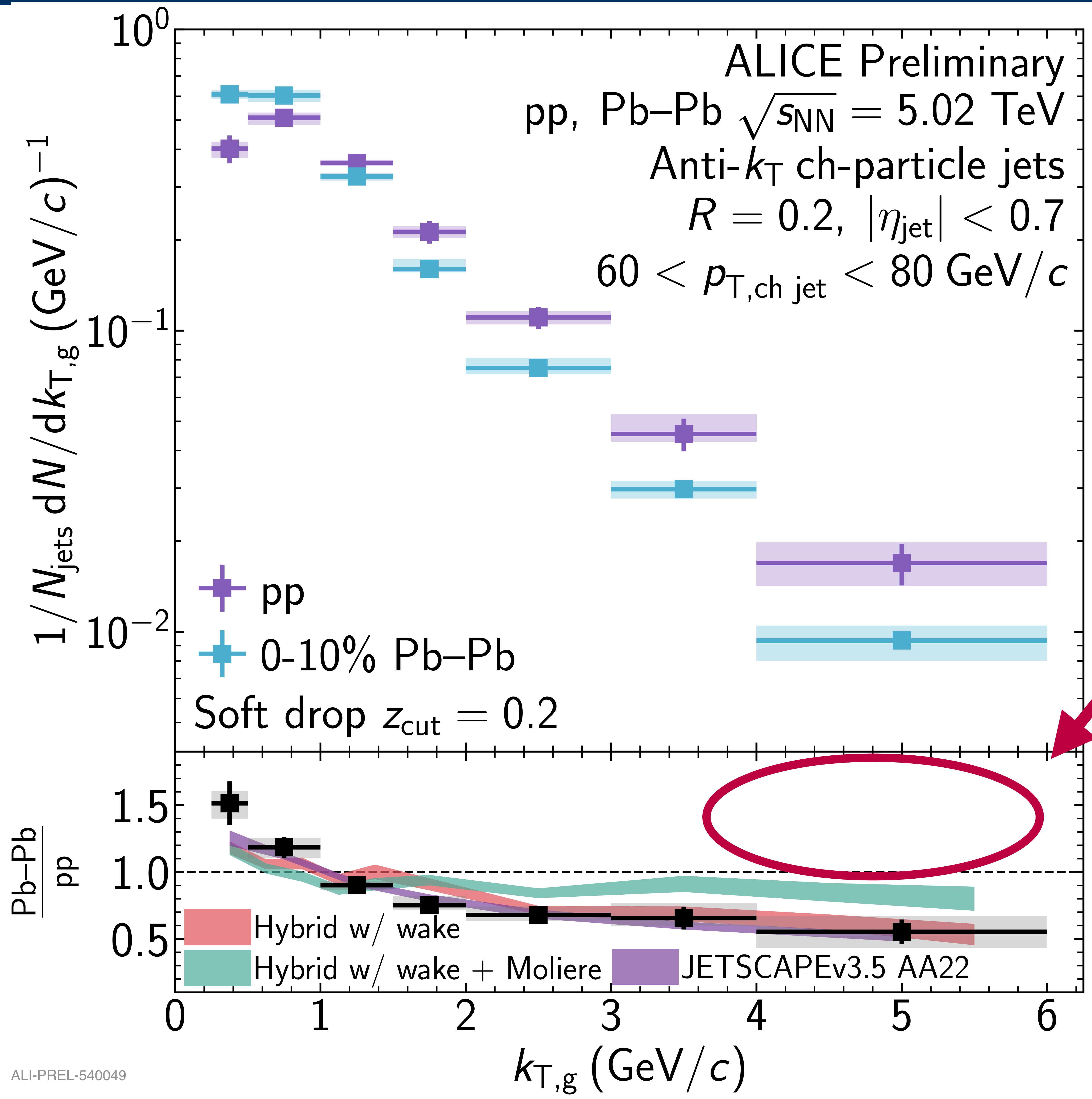
Probing microscopic structure with jet substructure

- Search for high k_T emissions **as signature of point-like (Moliere) scattering**
  - Probe **quasi-particle nature of the medium**



- **Consistent with narrowing picture** seen in inclusive substructure analyses

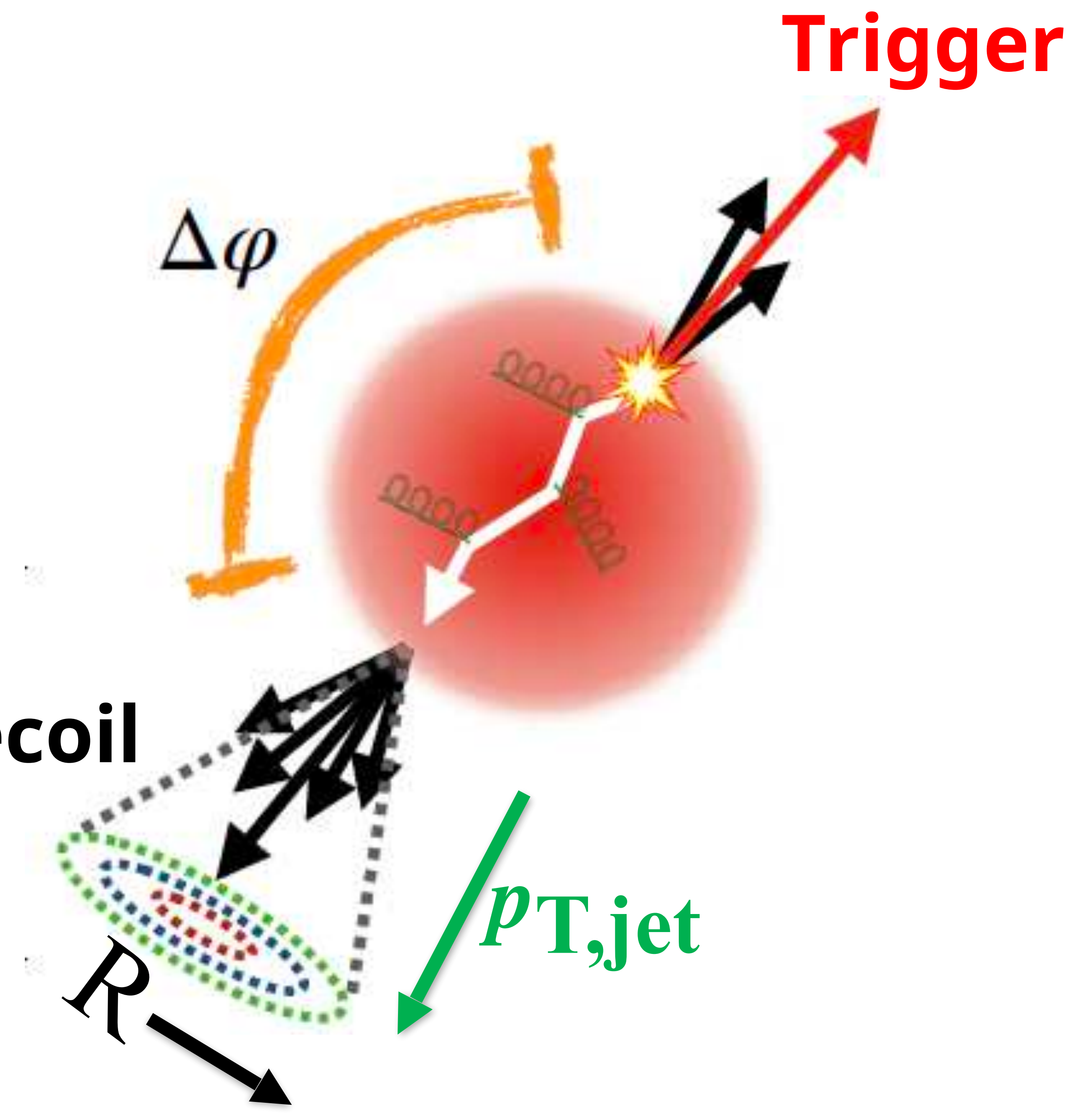
→ **No clear evidence for point-like scattering**



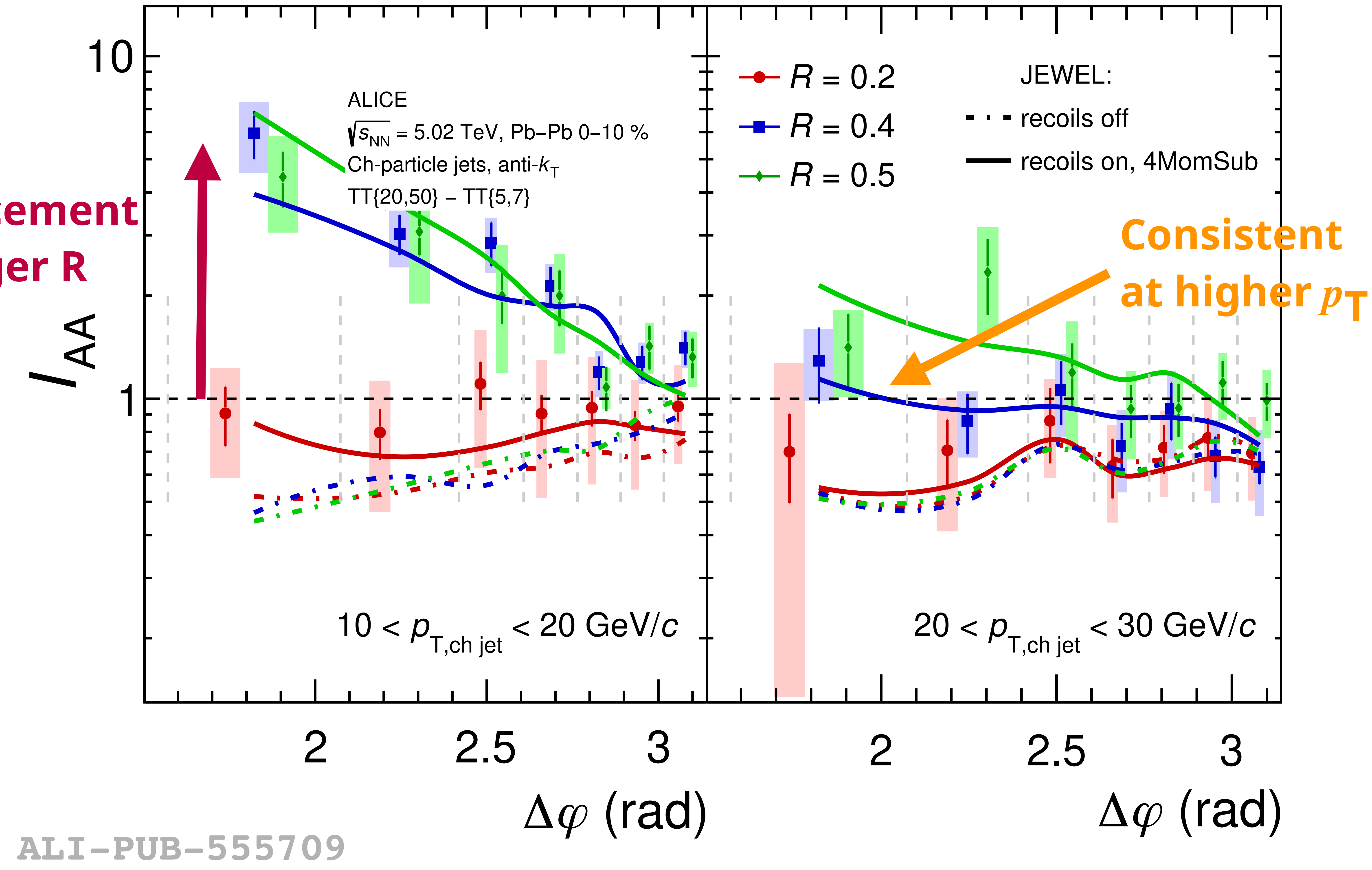
Expectation for Moliere scattering

Medium response

Semi-inclusive yield modification



- Statistical background subtraction:
  ***R* dependence at low p_T**
- Sensitive to:
  medium response?
  point-like scattering?

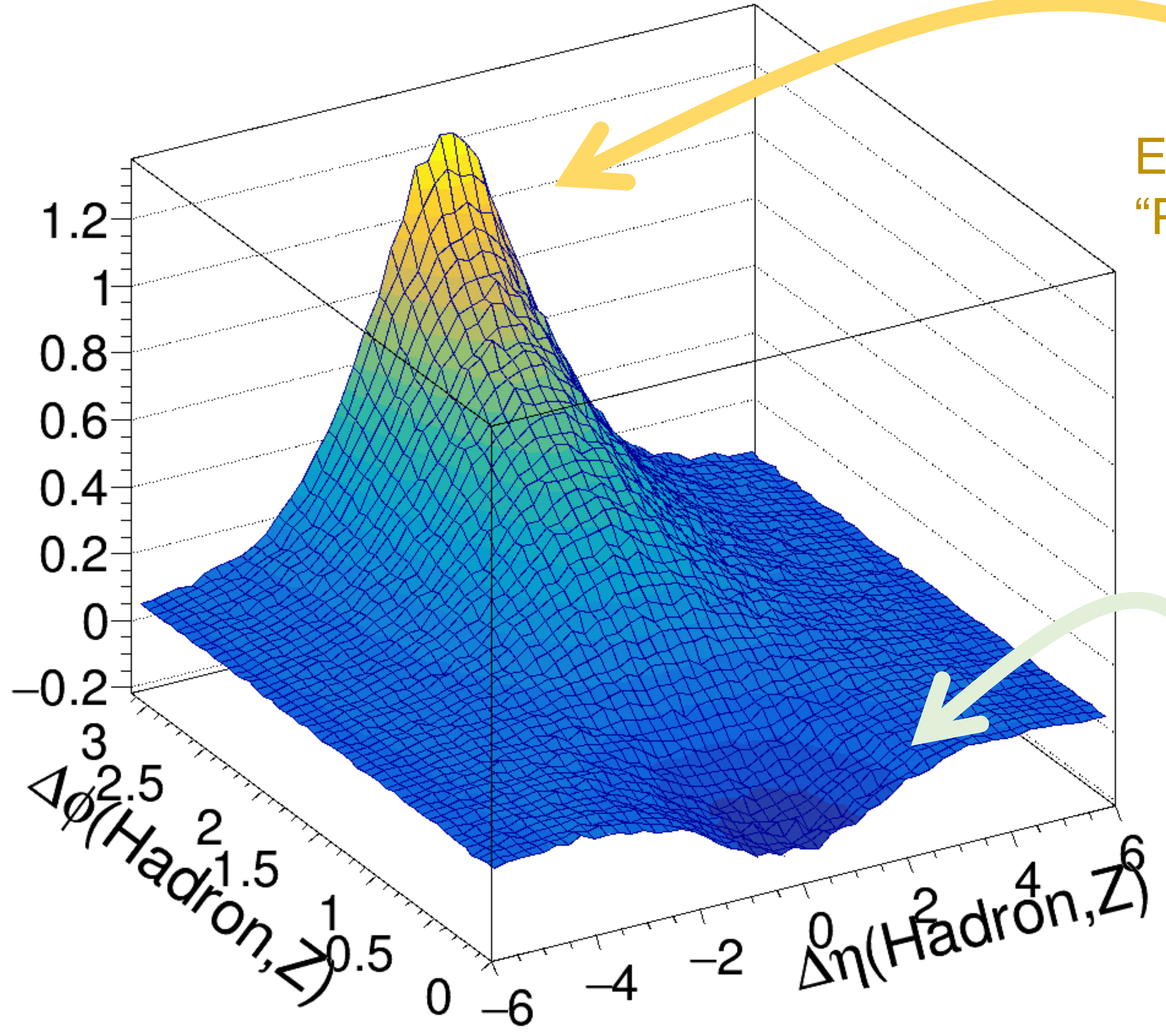


Consistent with medium response rather than Moliere scattering

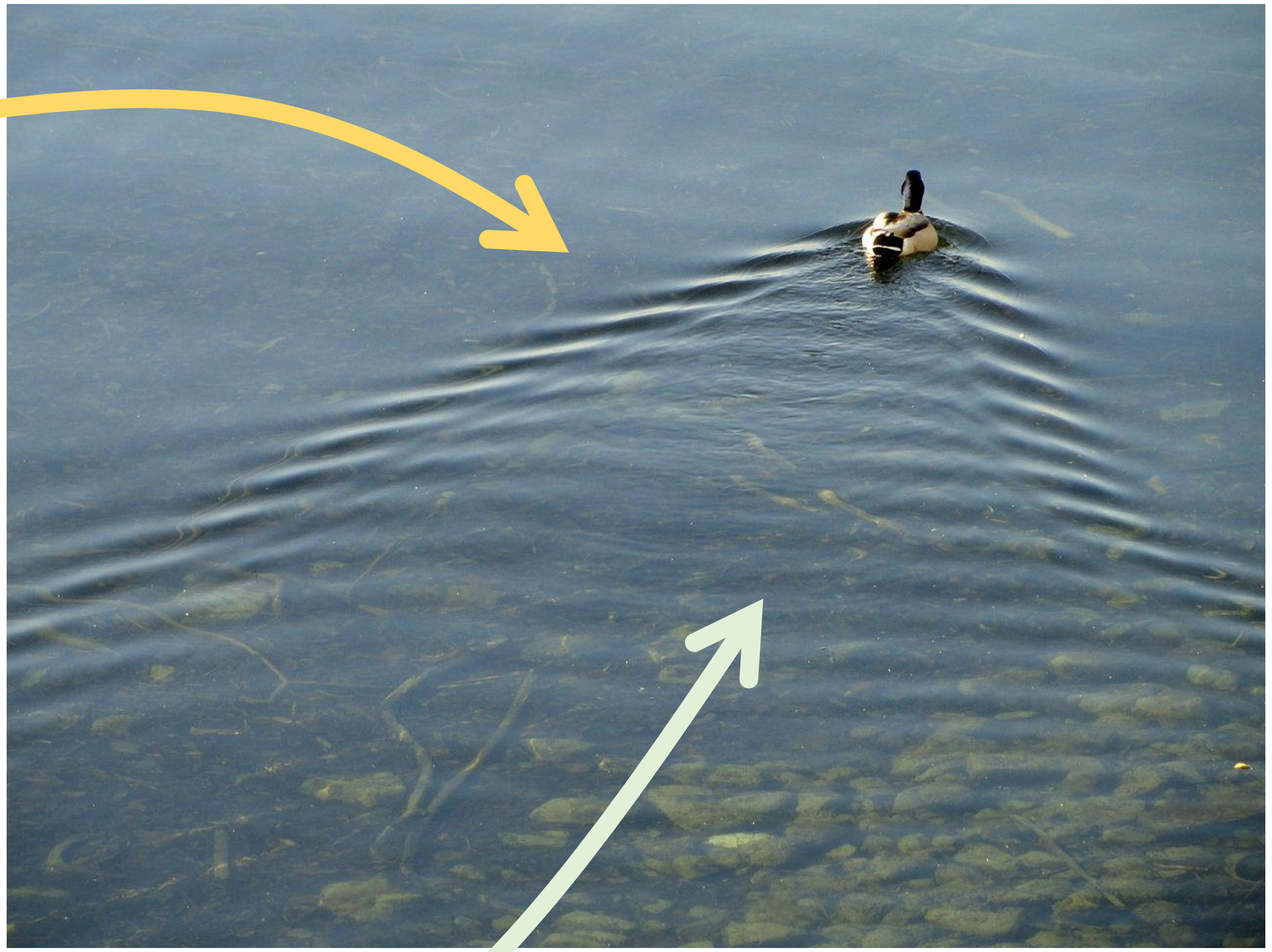
See P. Jacobs' talk on jet modification

ALICE, PRL in press, arXiv:2308.16131
PRC in press, arXiv:2308.16128

Diffusion wake via jet-hadron correlations



Enhancement of particle
"Positive wake"



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

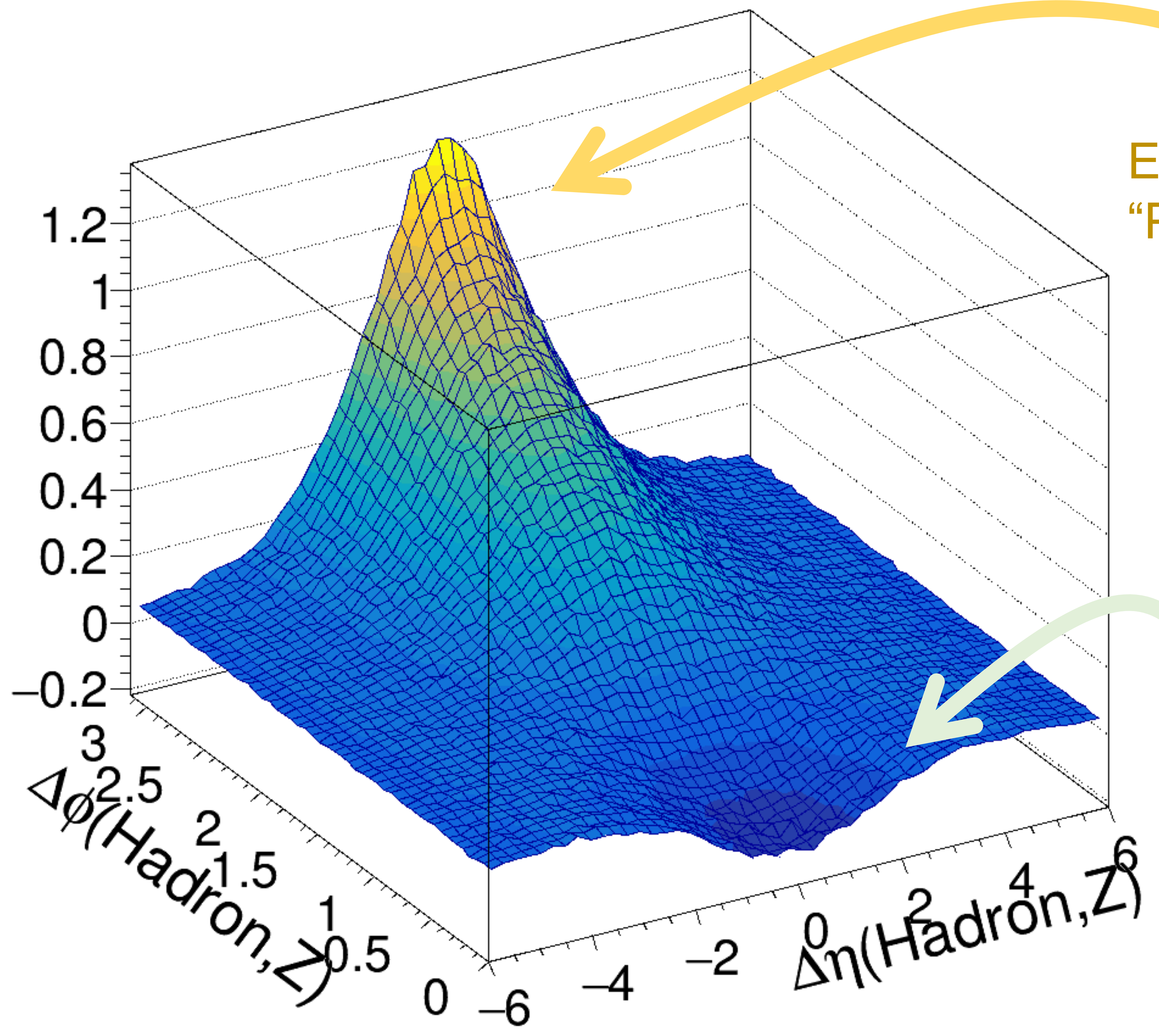
Position space

Z^0 and **wake hadron** correlation in Hybrid model

Daniel Pablo, Krishna Rajagopal, YJL

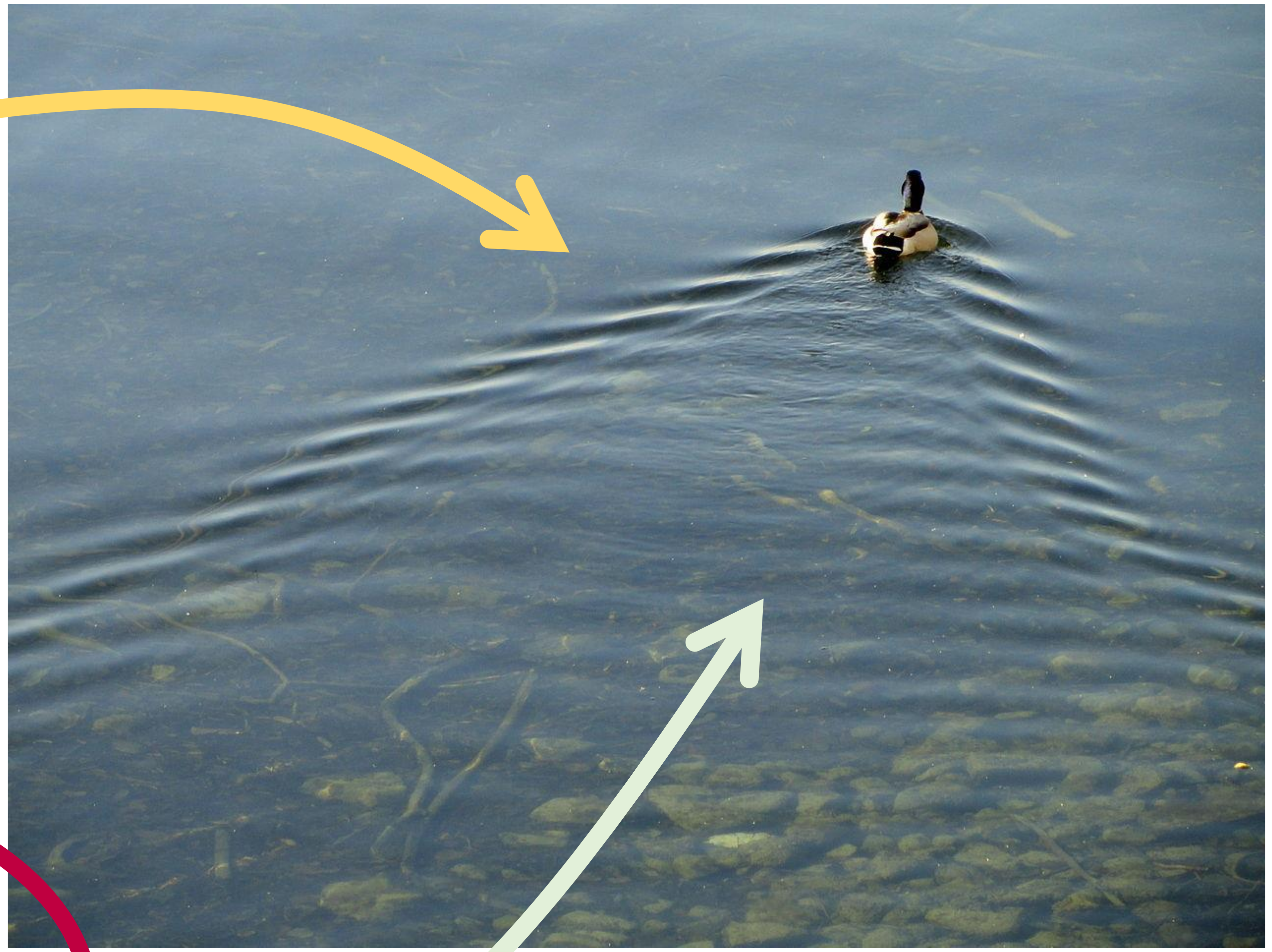
Momentum space

Diffusion wake via jet-hadron correlations



Enhancement of particle
"Positive wake"

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



Position space

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

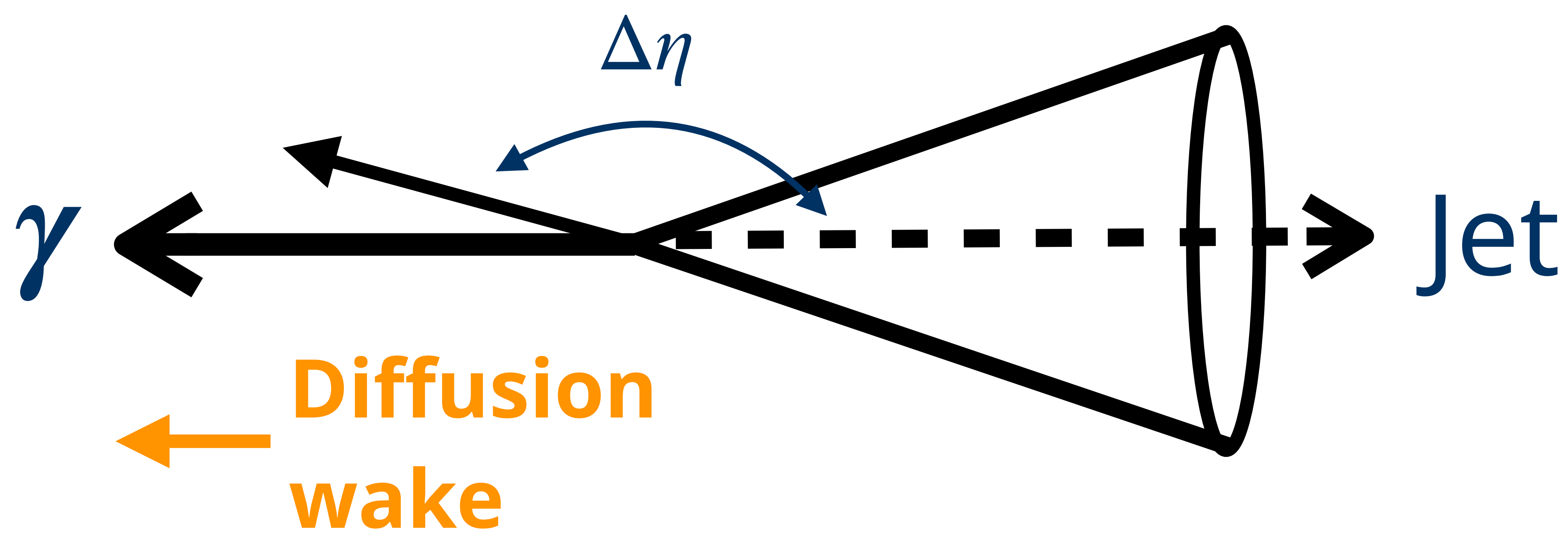
Daniel Pablo, Krishna Rajagopal, YJL

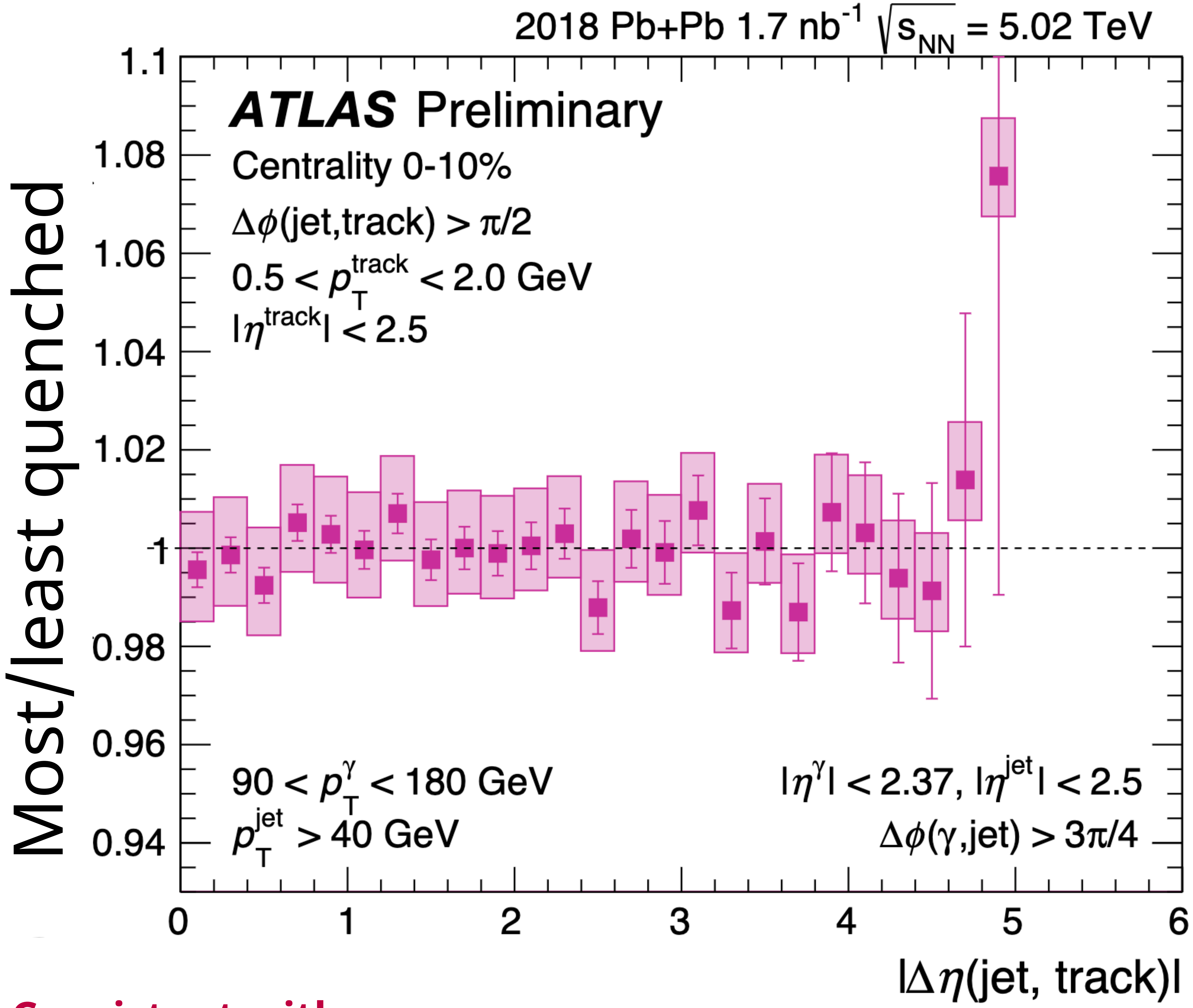
Momentum space

Diagram: Yen-Jie Lee

Diffusion wake via jet-hadron correlations

- Disentangle **energy redistribution** and **medium response**?
- **γ-tagged angular correlations:** **Access to diffusion ("negative") wake in γ direction**
  - **γ doesn't interact with medium**





See Y. Go's talk on medium response

Consistent with no significant diffusion wake

What have we learned?

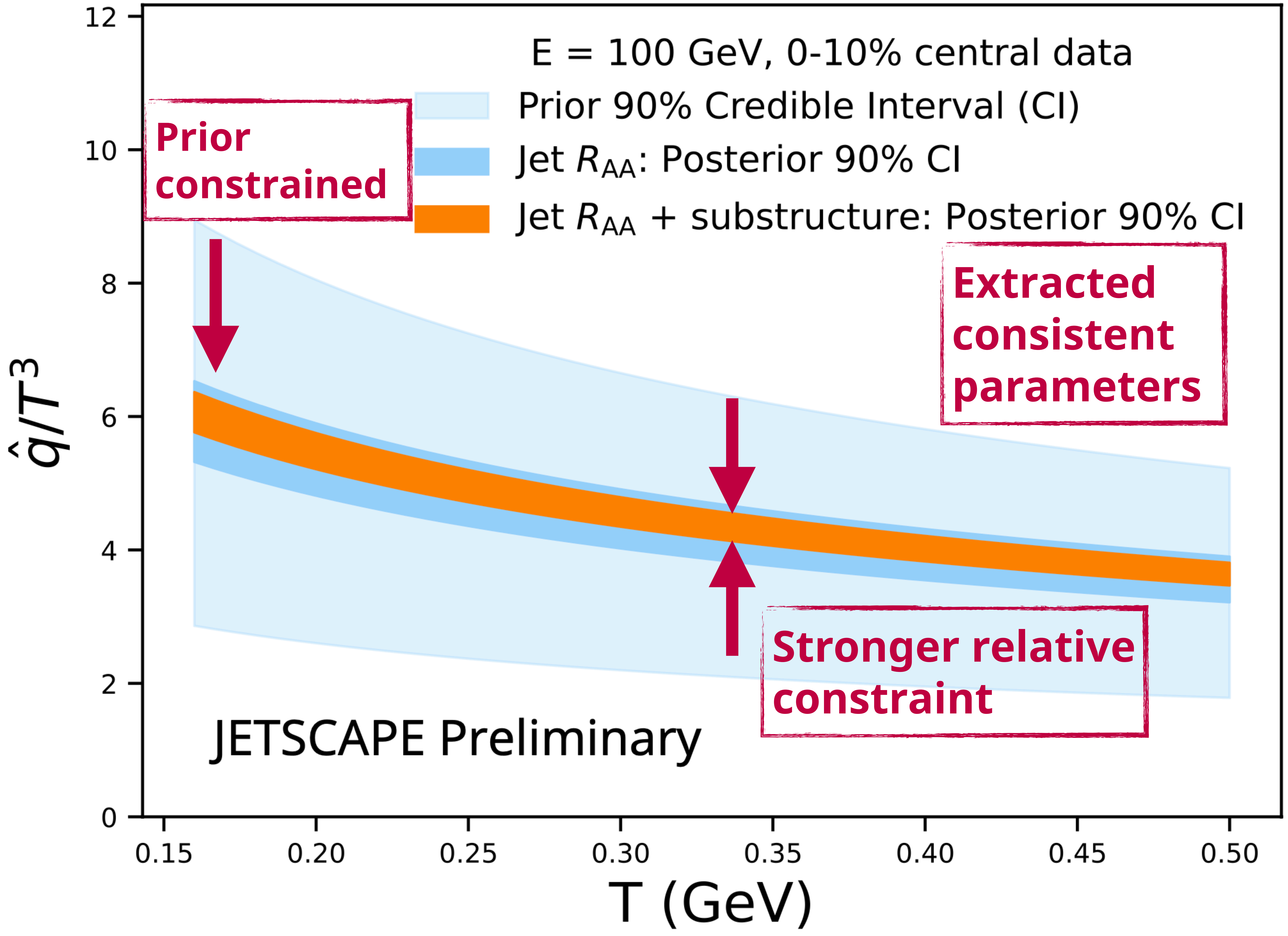
Extracting medium properties from measurements

Bayesian inference

- **Data-model comparisons**: learn from data
- Bayesian inference provides a **rigorous tool for comparison of theory and experiment**
- **Connects data to underlying parameters**

One application

- **Jet suppression** vs **jet suppression + substructure**
- **Additional information in substructure observables**

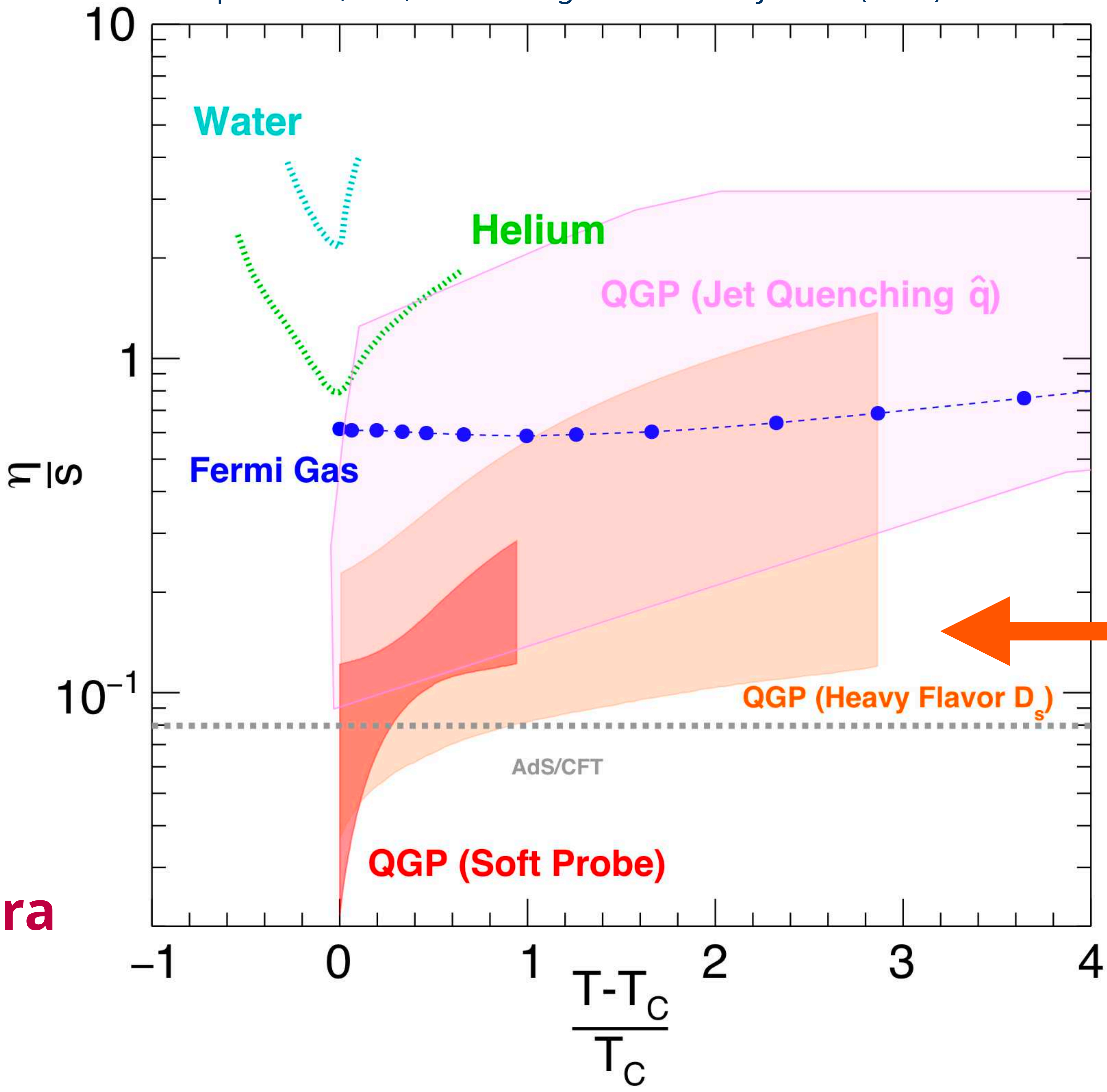


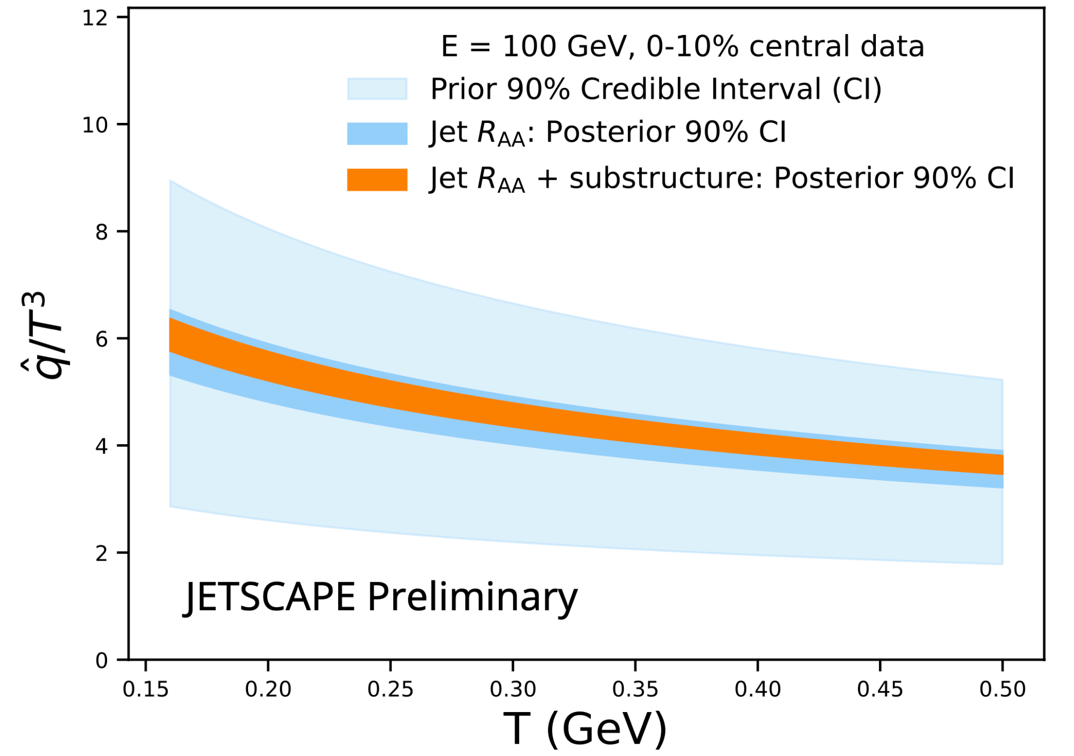
Inferring medium properties

- Under **specific assumptions**, **can relate $\hat{q}$ and D_s to η/s**
- With large uncertainties, **both are consistent with soft sector Bayesian analysis**

Entering precision era

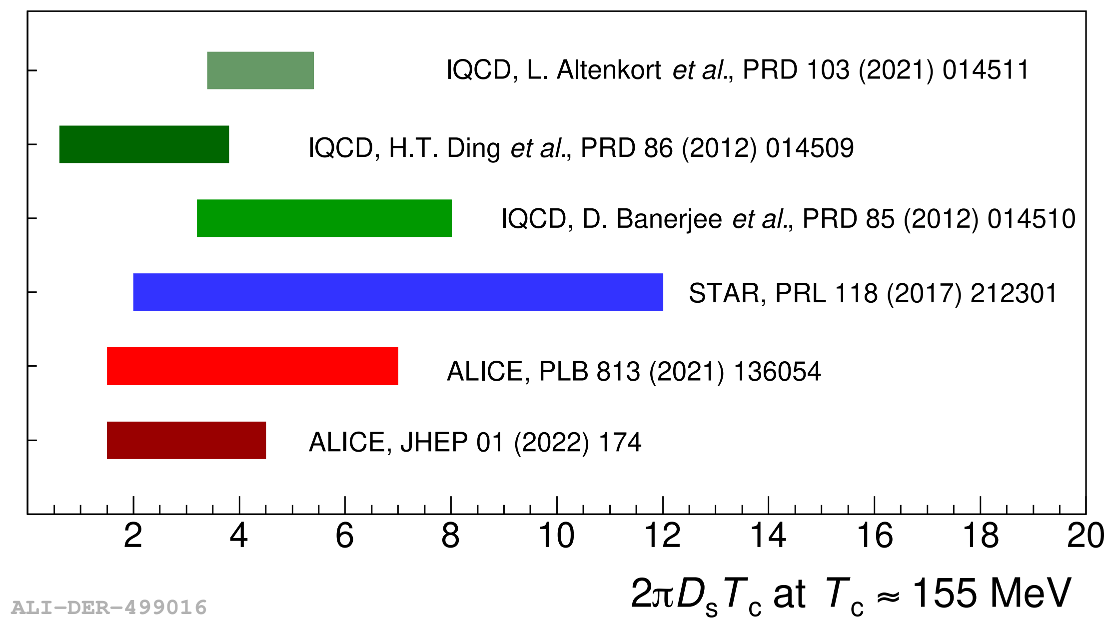
Apolinário, Lee, Winn: Prog.Part.Nucl.Phys. 127 (2022) 103990





$\hat{q}$

D_s



Summary + Outlook

Only small selection of results shown today

1. Parton probe and medium modified due to presence of each other

- Evidence for **energy redistribution**, **mass and charge dependence**
- Hints towards details of **medium structure + response**, **resolution scales**, **thermalization**

2. Data-model comparison: extract medium parameters

3. Much more to come from Run 2 + Run 3

- **Observables:**
  Energy correlators
  More differential HF-tagged substructure
  ...
- **Upgrades:**
  ALICE continuous readout
  LHCb → more central PbPb

Entering the precision era for rare probes (HF + jet + γ/Z)

Thanks to Helen Caines, Fabio Colamaria, Fabrizio Grosa, Laura Havener, Peter Jacobs, Florian Jonas, Mateusz Ploskon, Deepa Thomas, Nima Zardoshti for useful discussions, figures and edits

Thanks to LBL group members, ALICE members, and conveners of the other LHC experiments for valuable input

Backup

Transport models for charm quarks (F. Grosa, QM 2023)

- Models based on the charm-quark transport on a hydrodynamically expanding QGP
  - ➡ Typical momentum transfers in scatterings between charm quarks and medium constituents (heat bath) are small
  - ➡ Charm quarks undergo soft and incoherent collisions → Brownian motion
  - ➡ Boltzmann equation can be reduced to a Langevin or Fokker-Plank equation

$$\frac{\partial}{\partial t} f_Q(t, \mathbf{p}) = \frac{\partial}{\partial p^i} \left\{ A^i(\mathbf{p}) \cdot f_Q(t, \mathbf{p}) + \frac{\partial}{\partial p^j} \left[B^{ij}(\mathbf{p}) \cdot f_Q(t, \mathbf{p}) \right] \right\}$$

- In case of a medium in thermal equilibrium
  - ➡ $A^i(\mathbf{p}) = A(\mathbf{p}) p_i$ friction
  - ➡ $B^{ij}(\mathbf{p}) = B_0(p) \cdot P_{ij}^{\perp}(\mathbf{p}) + B_1(p) \cdot P_{ij}^{\parallel}(\mathbf{p})$ momentum broadening

- Brownian motion of heavy quarks in QGP governed by the coupling of heavy quarks to the medium
  - ➡ Spatial diffusion coefficient

$$D_s = \frac{T}{m_{\text{charm}} A(p=0)}$$

→ Related to the thermalisation time of the charm quark

Approximately $A(p=0) \propto 1/m_{\text{charm}}$

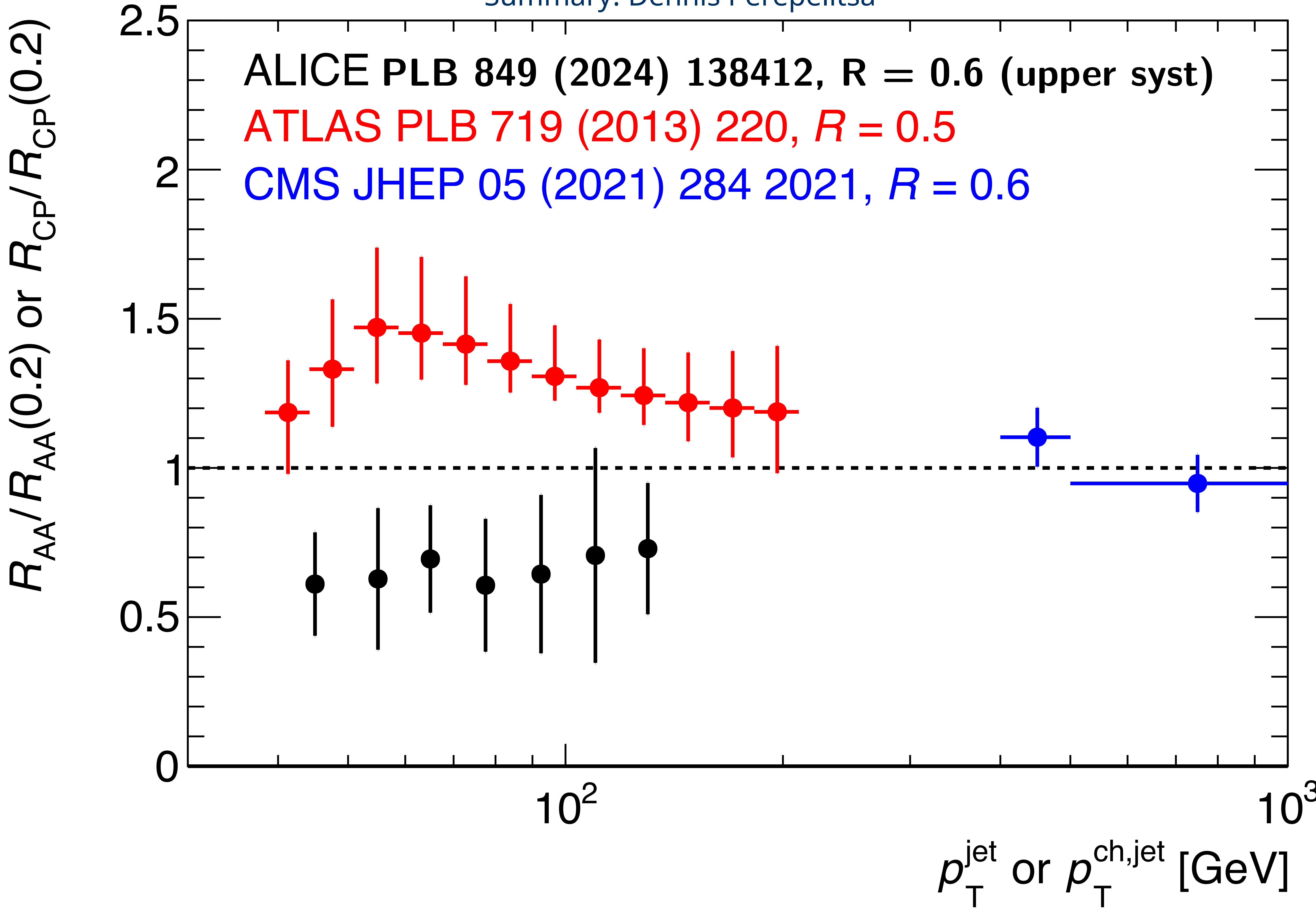
$$\tau_{\text{charm}} = (m_{\text{charm}}/T) \cdot D_s$$

Scanning aperture size via inclusive jet R_{AA} yield ratios

$$\frac{R_{AA}(R)}{R_{AA}(R = 0.2)}$$

- Study radial dependence **medium response (due to presence of probe)** and **energy redistribution (due to presence of medium)** via increasing aperture size
  - May evolve with different dependence on aperture
- **Apparent tension*** between ALICE and ATLAS measurements at low p_T
- **Weak-to-no energy recovery** with increasing R at high p_T
- Opportunity to **disentangling sources on a global basis**?

Summary: Dennis Perepelitsa



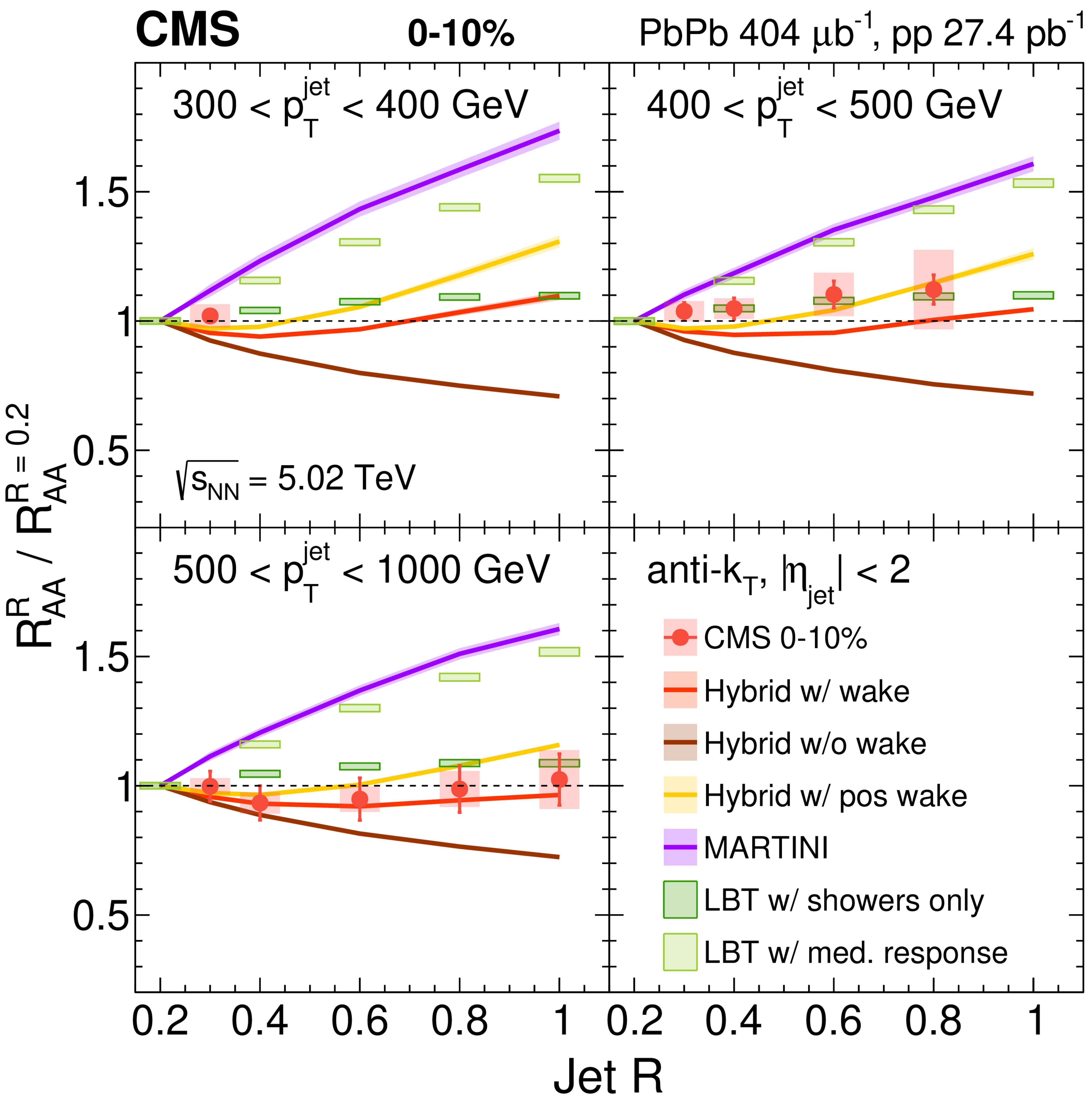
*: Measurement techniques are not identical

Scanning aperture size via inclusive jet R_{AA} yield ratios

$$\frac{R_{AA}(R)}{R_{AA}(R=0.2)}$$

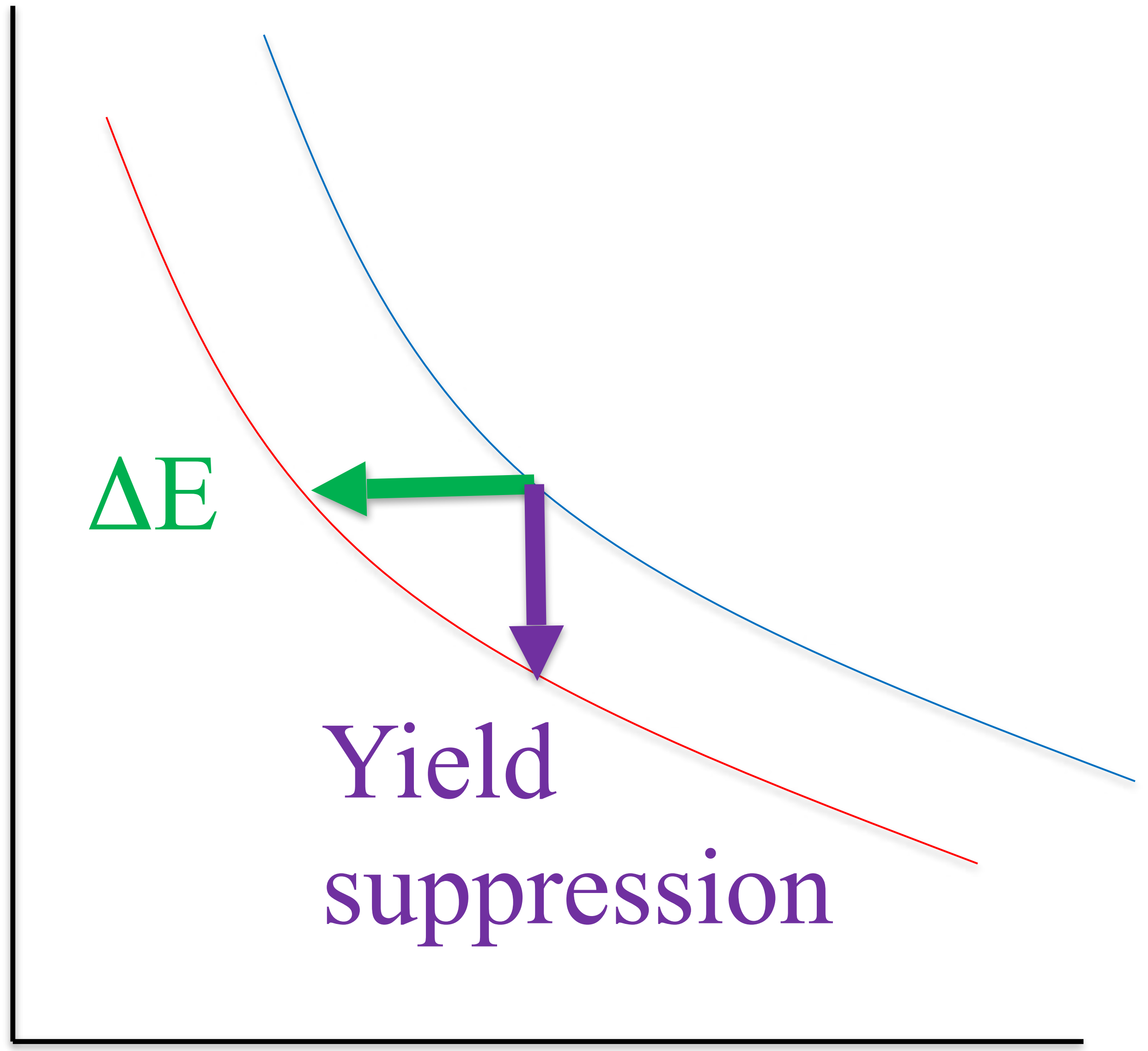
- Study radial dependence **medium response (due to presence of probe)** and **energy redistribution (due to presence of medium)** via increasing aperture size
  - May evolve with different dependence on aperture
- **Weak-to-no energy recovery** with increasing R at high p_T
- Opportunity to **disentangling sources on a global basis**?
  - **Difficult for models to describe dependence**

CMS, JHEP 05 (2021) 284



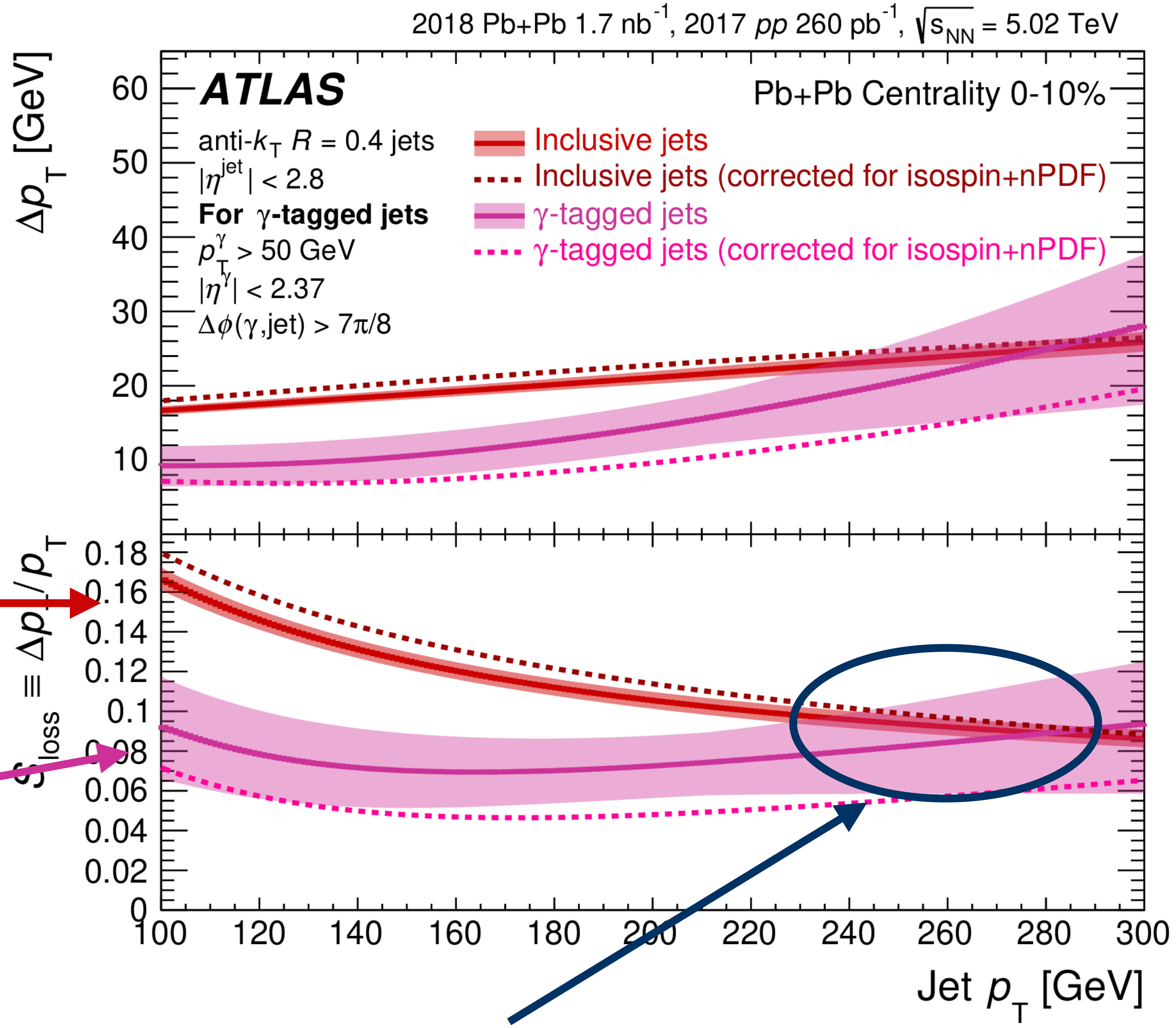
Extracting energy loss

- Extract measure of energy loss to **isolate impact of medium on probe**
- S_{loss} ~ fractional average energy loss at fixed p_T^{pp}
- **Increased E-loss for gluon enhanced**
- **Consistent with Casimir factor**



Gluon enhanced

Quark Enhanced

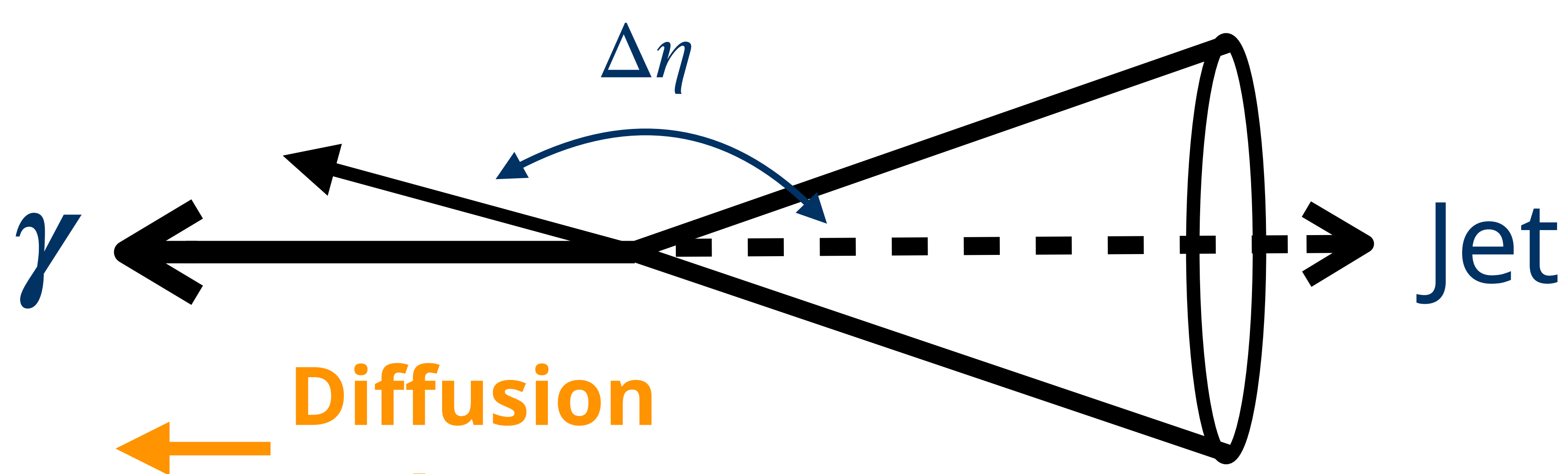


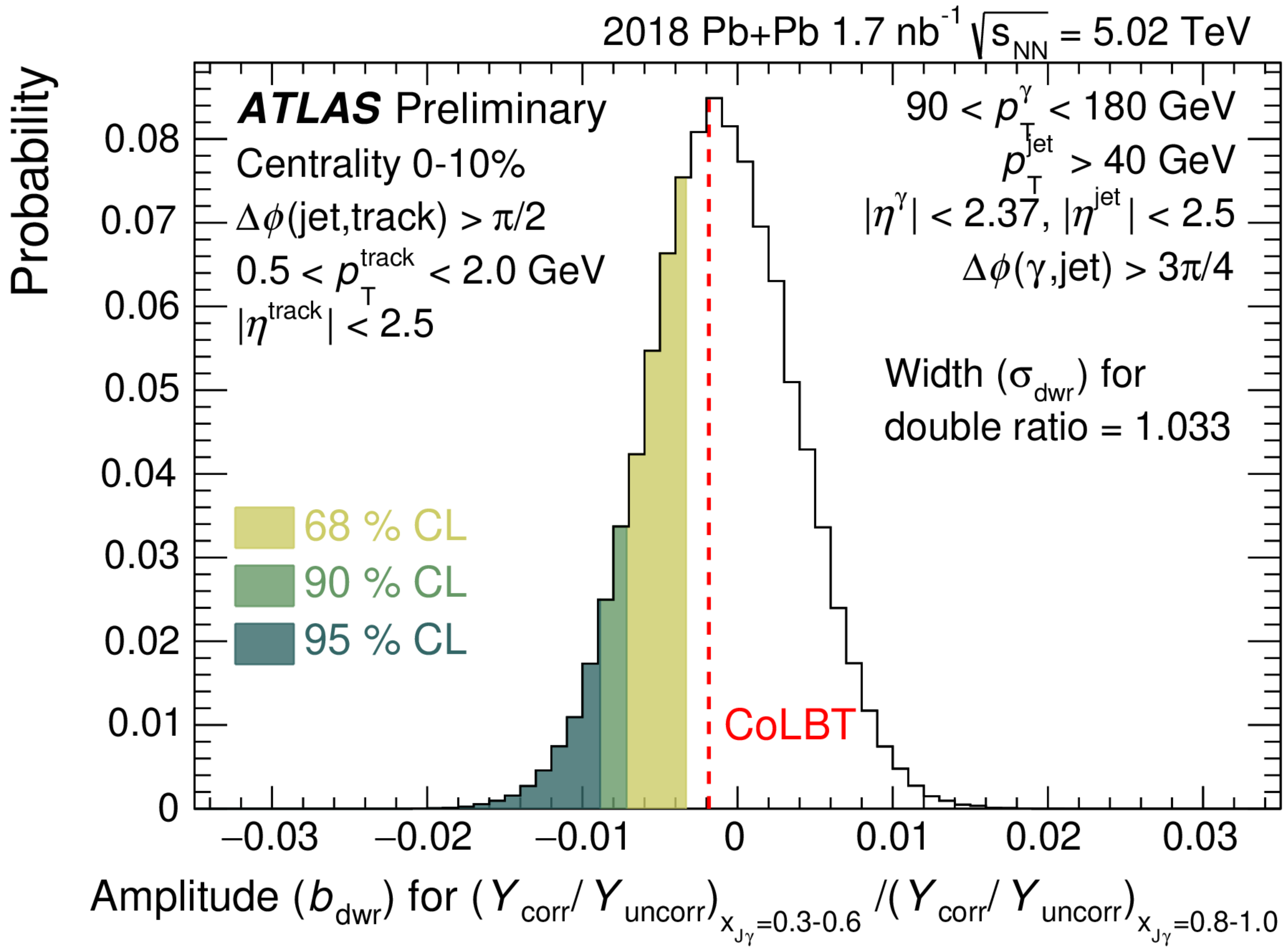
Inclusive becomes more quark-like

Phys. Lett. B 846 (2023) 138154
DOI: 10.1016/j.physletb.2023.138154

Diffusion wake via jet-hadron correlations

- Disentangle **energy redistribution** and **medium response**?
- **γ-tagged angular correlations:** **Access to diffusion ("negative") wake in γ direction**
  - **γ doesn't interact with medium**



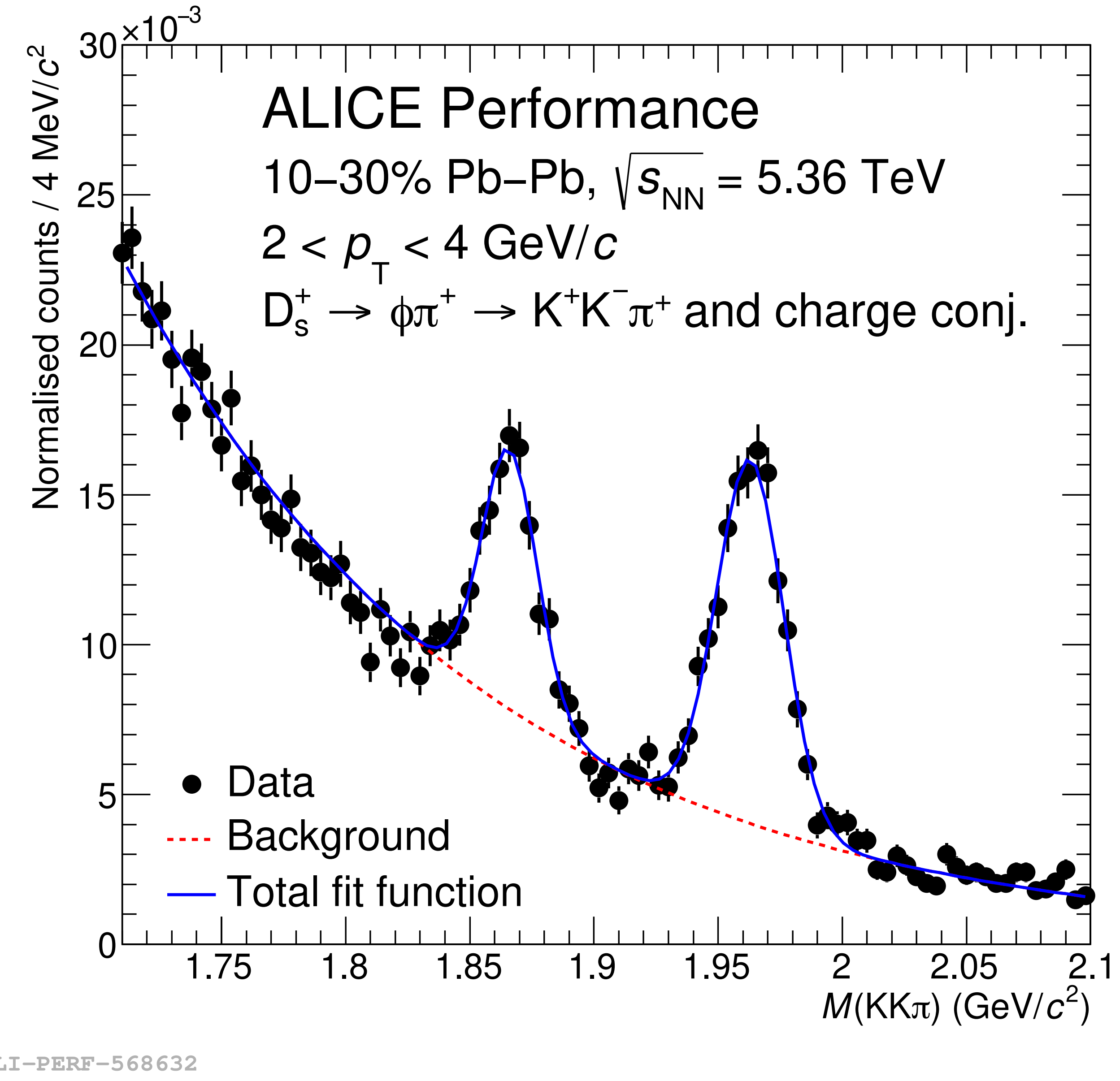


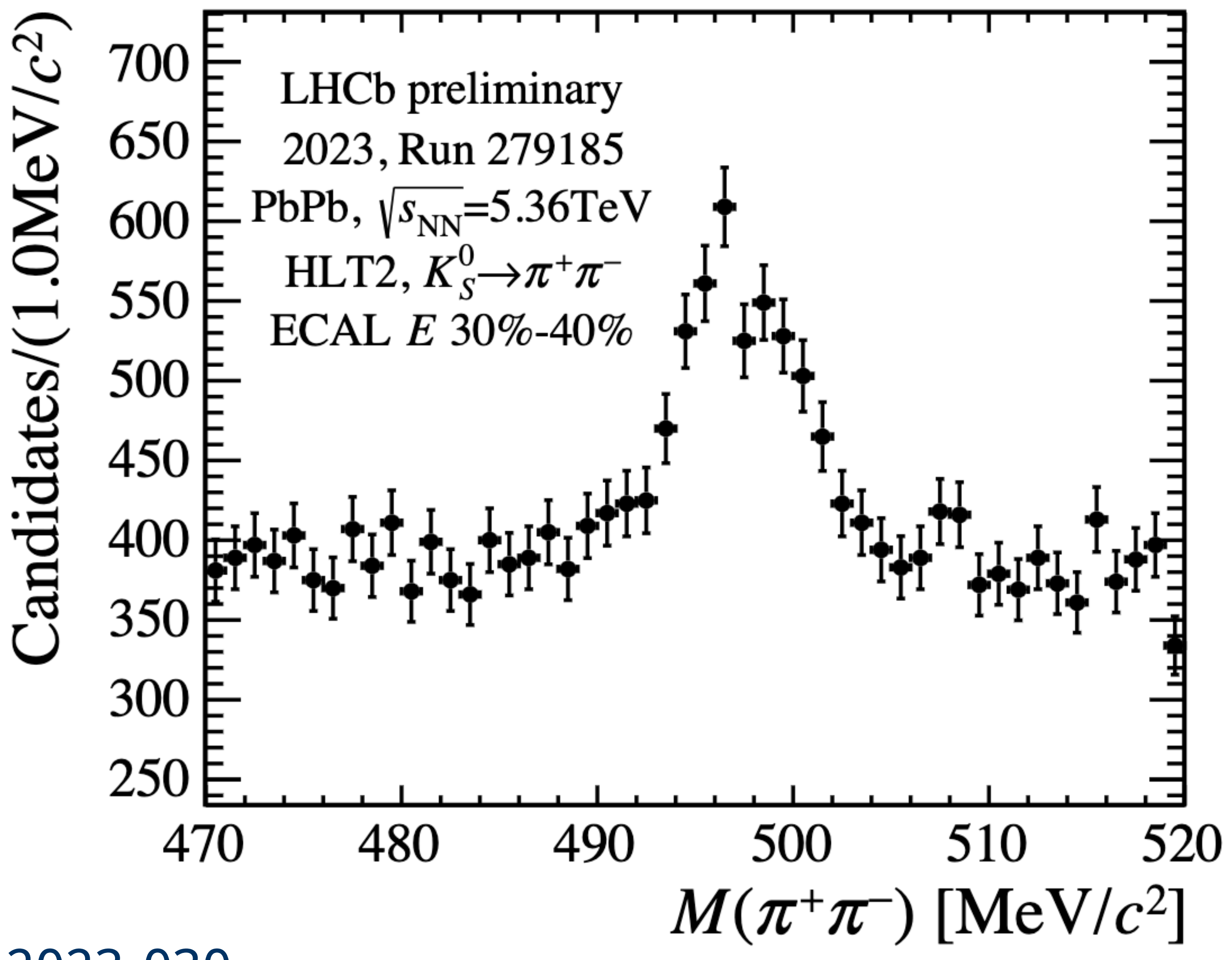
See Y. Go's talk on medium response

Consistent with no significant diffusion wake

What's up next?

- Substantial **detector upgrades for ALICE and LHCb** in Run 3
  - **Significant increase** in ALICE readout rate
  - LHCb **reconstructing Pb-Pb data to 30%** centrality
- **Significant promise for HF and jet observables in coming years**
  - New observables**:** e.g. **energy-energy correlators**
  - New techniques: e.g. **substructure of a HF tagged jet**
- Run 3 Pb-Pb measurements **in progress**





LHCb-FIG-2023-030

Yield suppression via R_{AA}

- Ratio of pp and AA yields
- Modification of yield at fixed p_T
- Scaled such that:
  No modification → ratio at unity

$$R_{AA} = \frac{\frac{1}{N_{\mathrm{event}}} \left.\frac{d^2 N^{\mathrm{PbPb}}_{\mathrm{jet}}}{dp_T dy}\right|_{\mathrm{cent}}}{\langle T_{AA} \rangle \frac{d^2 \sigma^{\mathrm{pp}}_{\mathrm{jet}}}{dp_T dy}} =$$