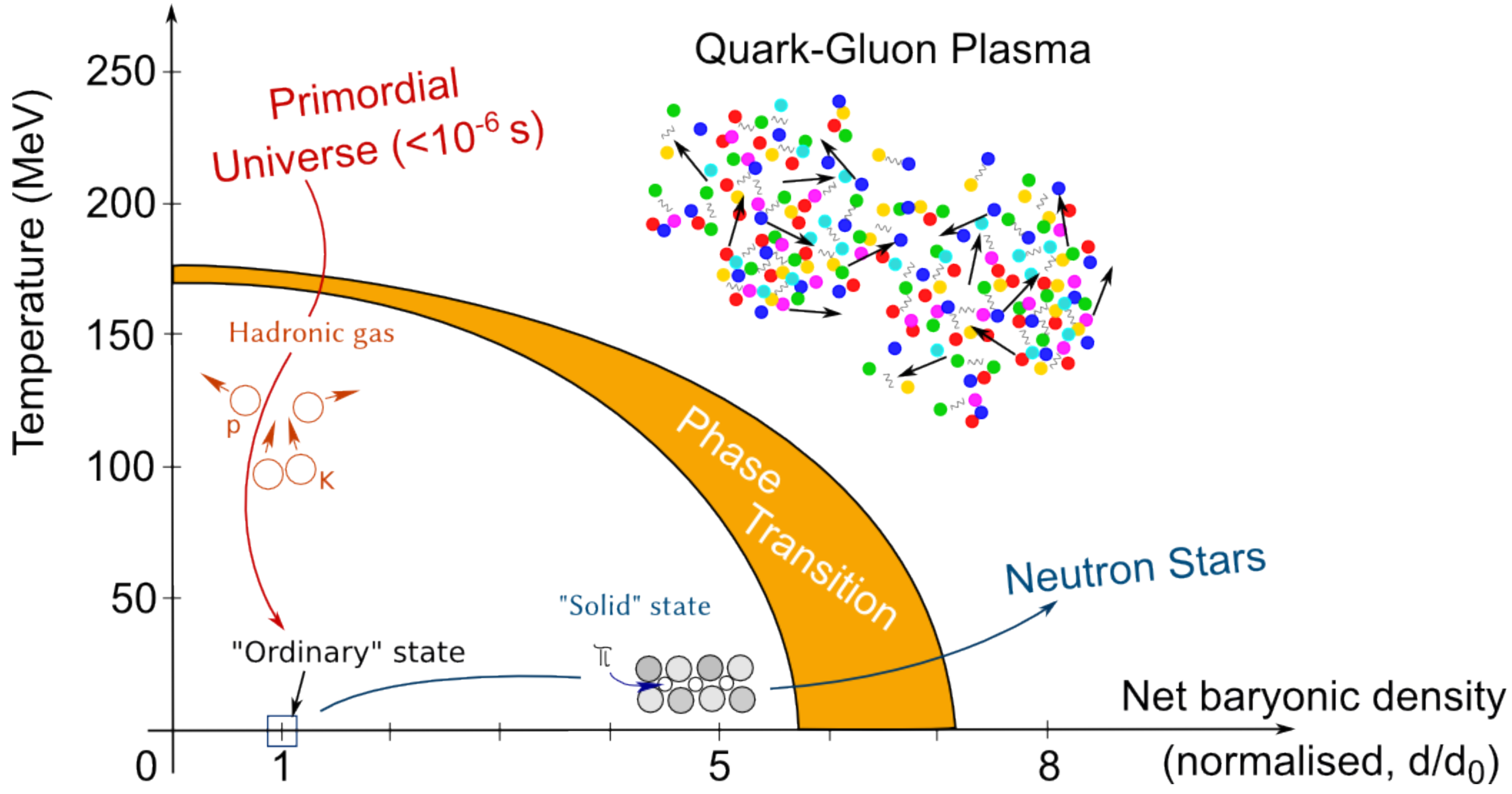
Recent ATLAS EXPERIMENT measurements in heavy-ion collisions

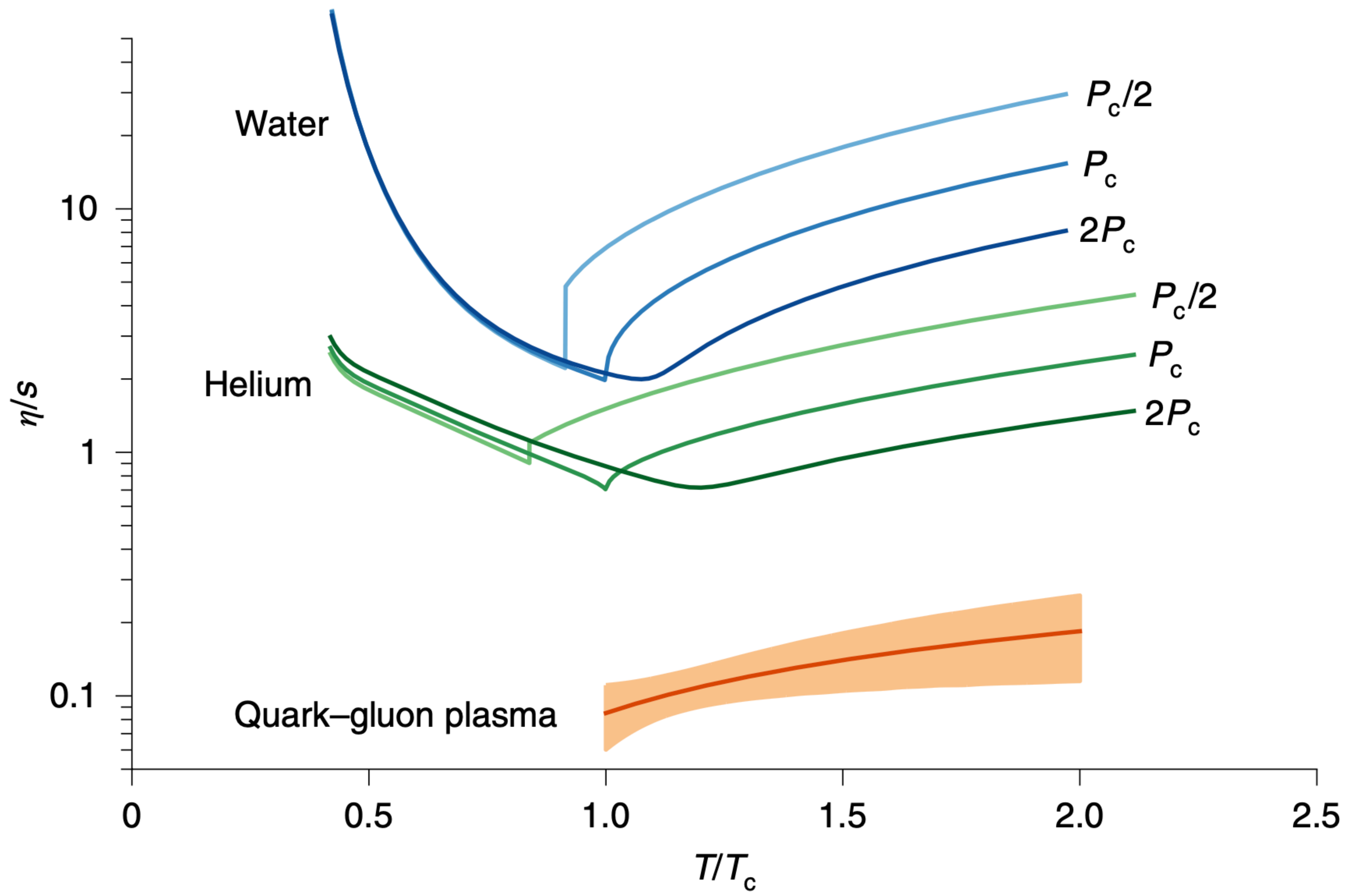
MPI@LHC 2022 - 13th International workshop on
Multiple Partonic Interactions at the LHC
14-18 November 2022, Madrid, Spain

University of Colorado **Boulder**

Yeonju Go
University of Colorado Boulder
on behalf of the *ATLAS* collaboration

Quark Gluon Plasma and Heavy-ion Collisions

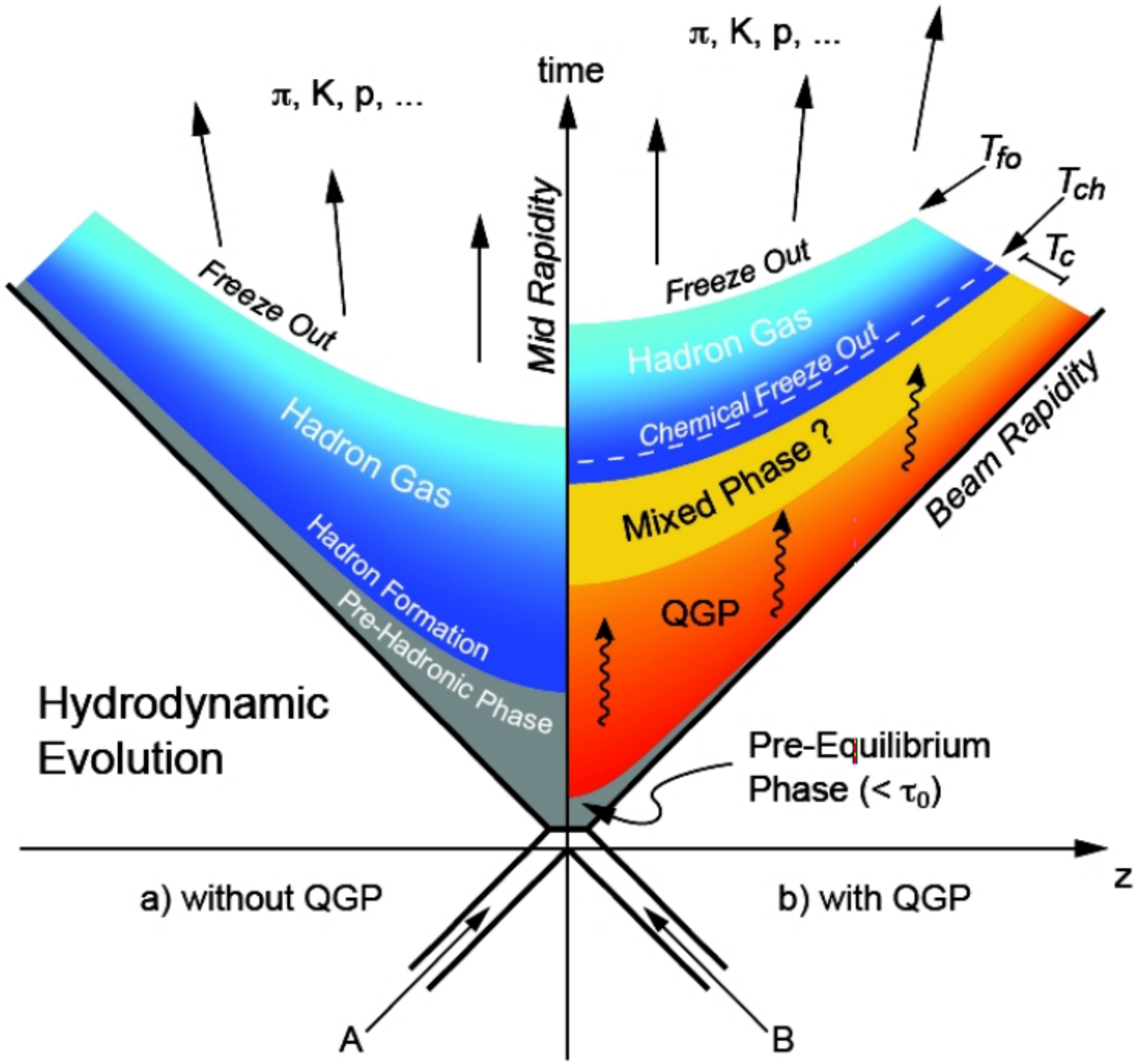


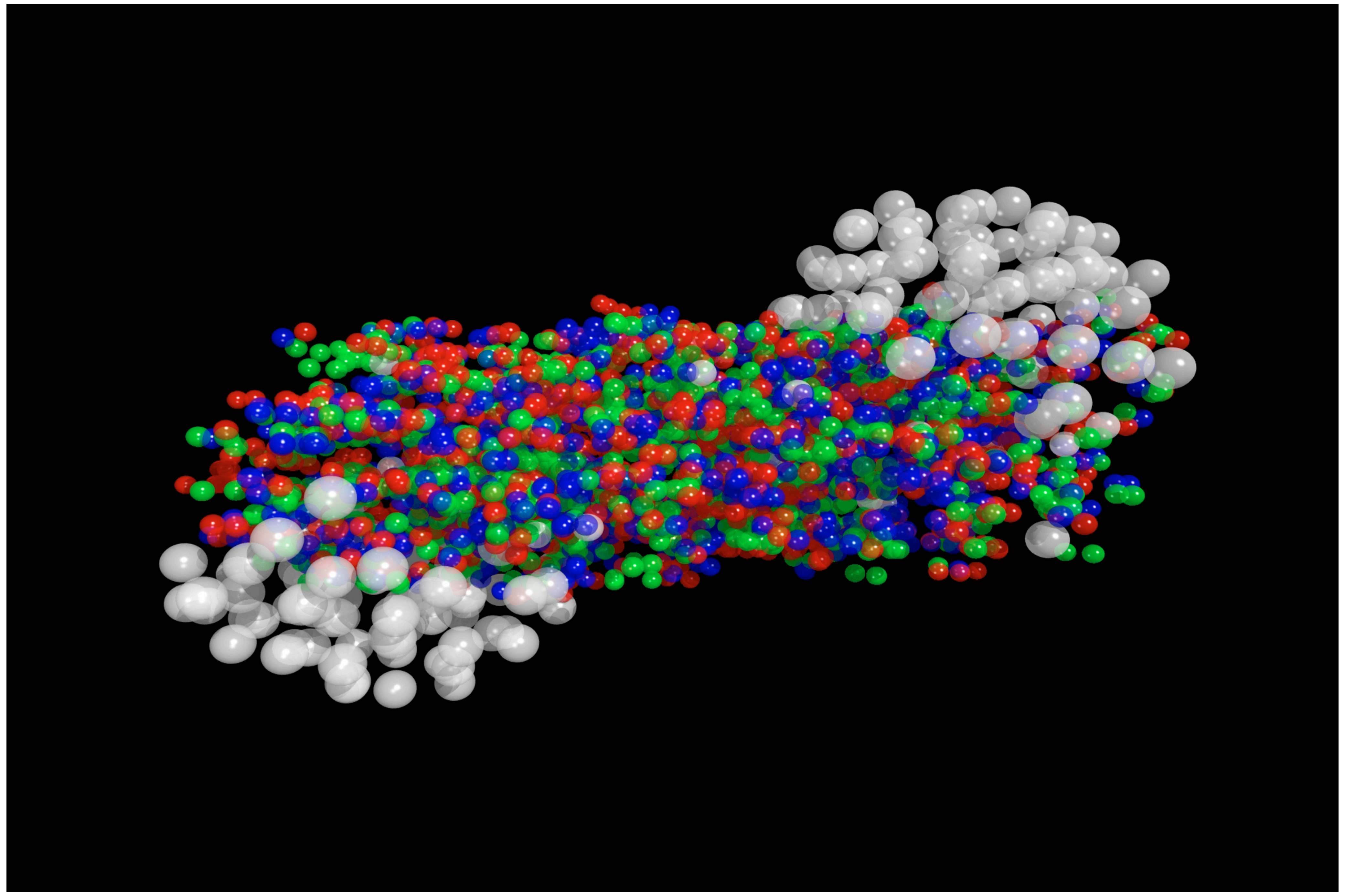


Nature Physics 15 (2019) 1113

- **Quark Gluon Plasma (QGP)**: extremely hot and dense phase of matter in which quarks and gluons are no more confined into hadrons
  - ➡ properties known as an almost perfect fluid
  - ➡ lowest specific sheer viscosity (η/s) of any known substance

Quark Gluon Plasma and Heavy-ion Collisions





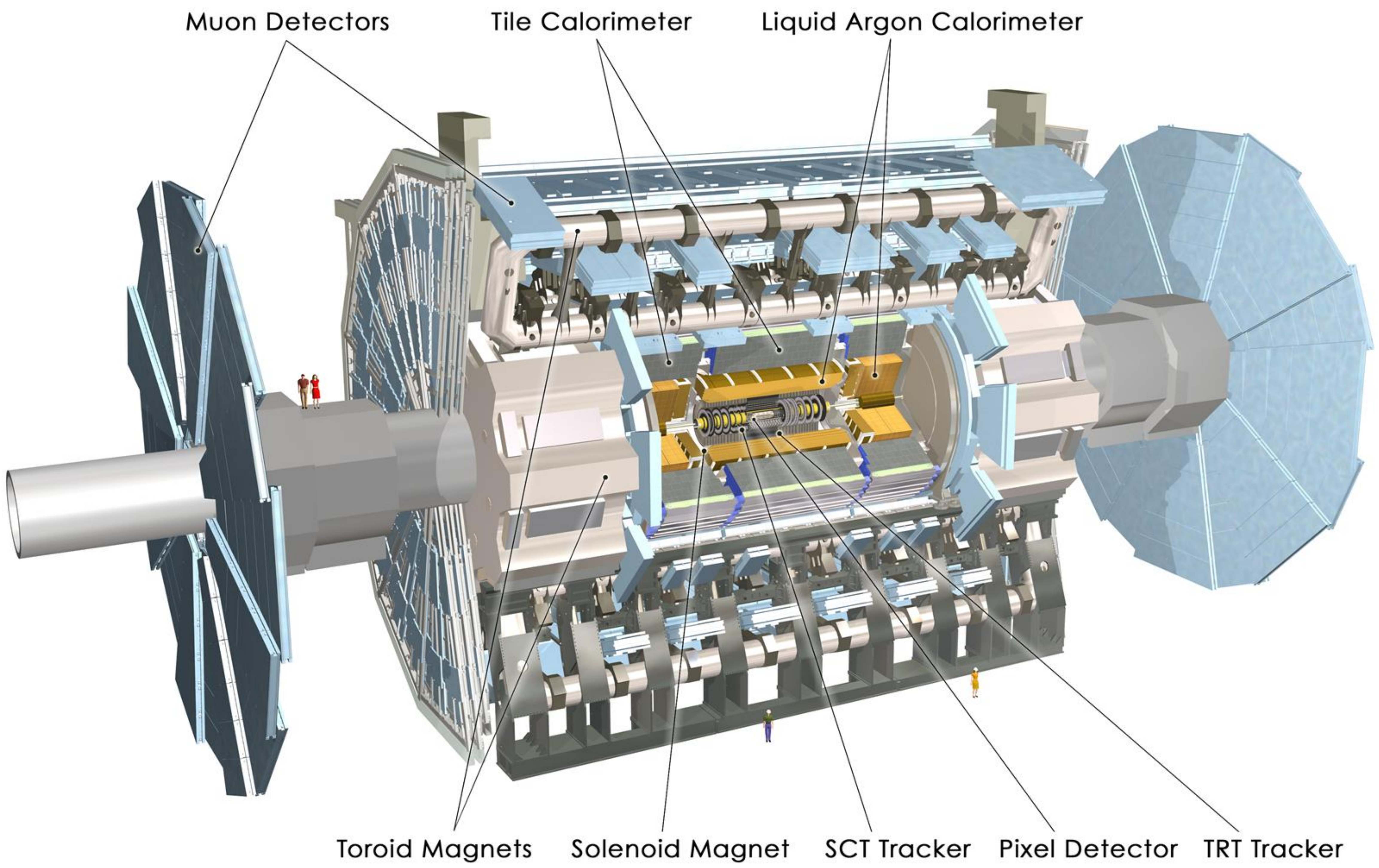
- **Hard Probes**: produced in the early phase of the collision and experience the evolution of QGP
  ➡ jets, heavy flavour, quarkonia, …

Recent ATLAS Results in Heavy-ion Collisions...

Jets
- photon-tagged jets
- b-jets
- reclustered large R jets
- dijet momentum imbalance
- jet substructure

Heavy flavor
- charm and bottom muon R_{AA} and v_2
- upsilon production

Photo-nuclear collisions
- dijet production

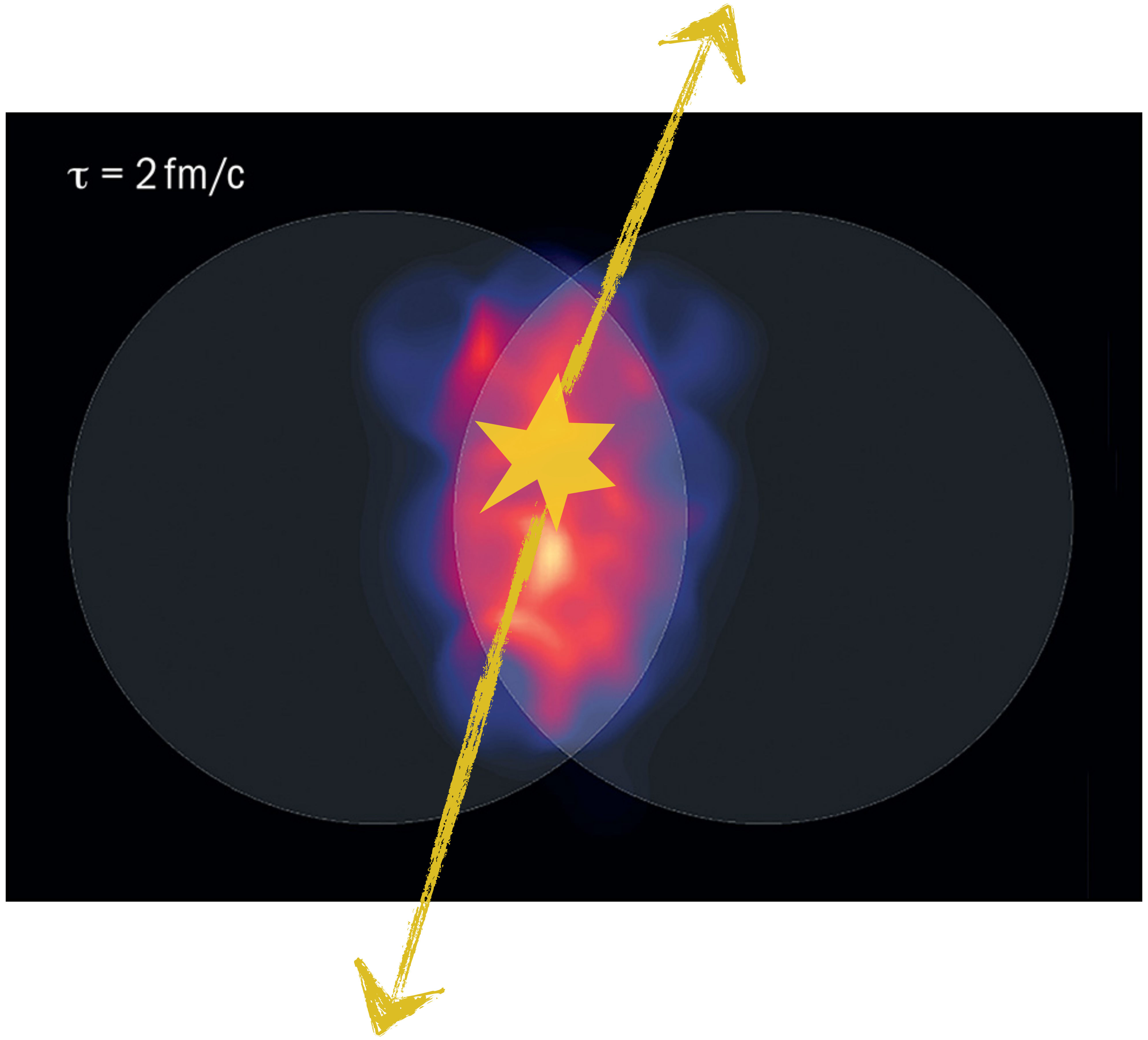


+ Many more!

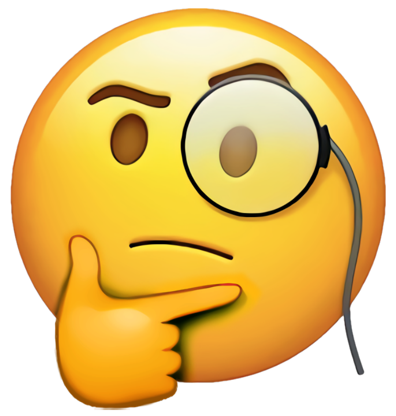
Only selected hard probe measurements will be shown due to the time limit

Probes of Bulk QGP

Hard Probes



Jets

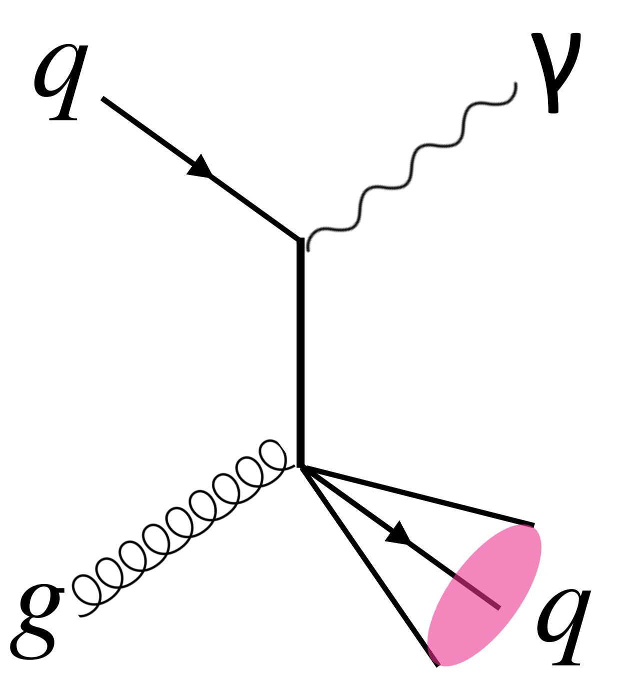


How does the color charge interact with and lose energy in the medium? Can we utilize quark versus gluon probes?

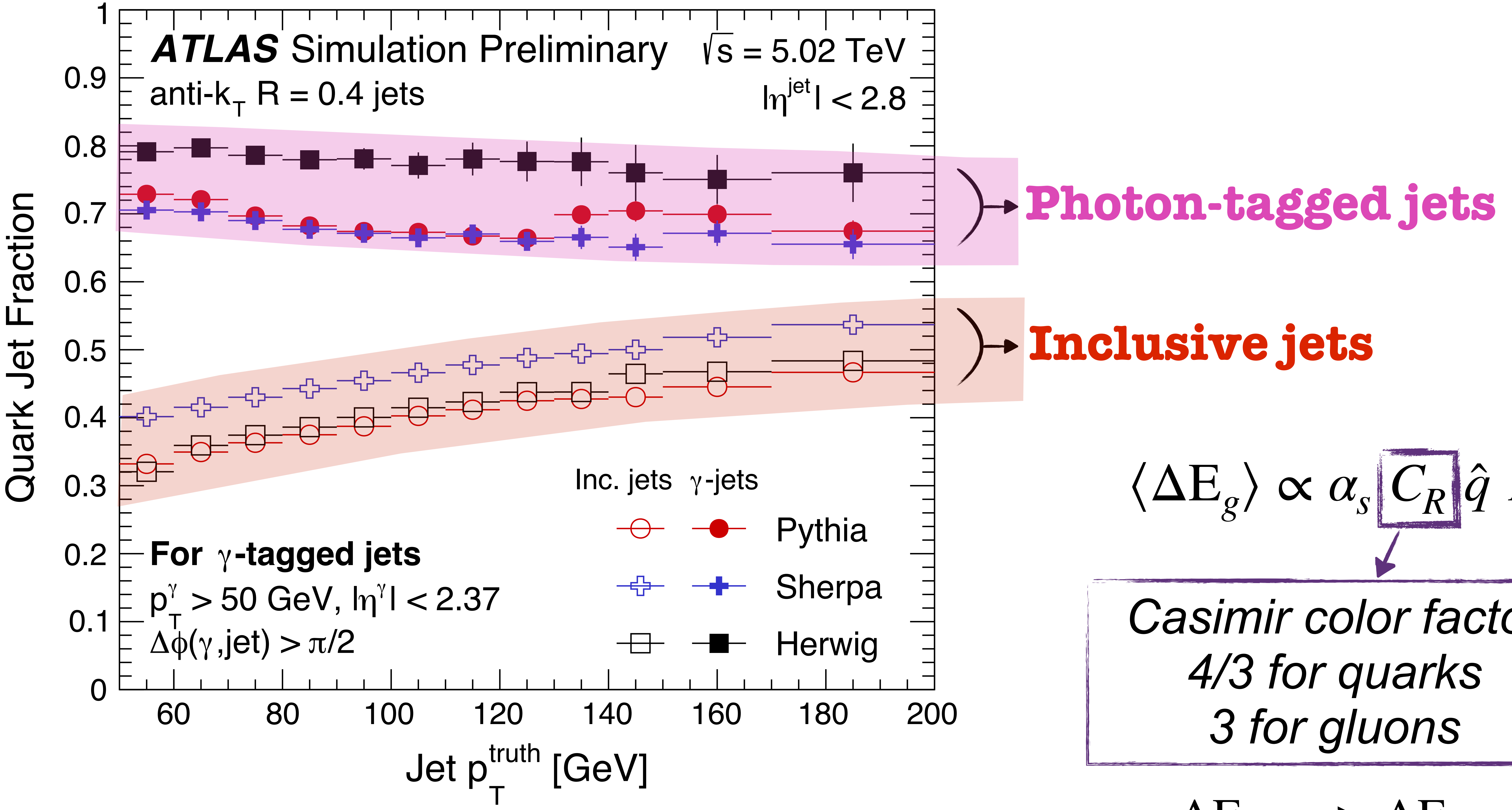
Photon-tagged Jet R_{AA}

- **Color-charge dependence** of energy loss

ATLAS-CONF-2022-019



q-g
Compton scattering



$$\langle \Delta E_g \rangle \propto \alpha_s \boxed{C_R} \hat{q} L^2$$

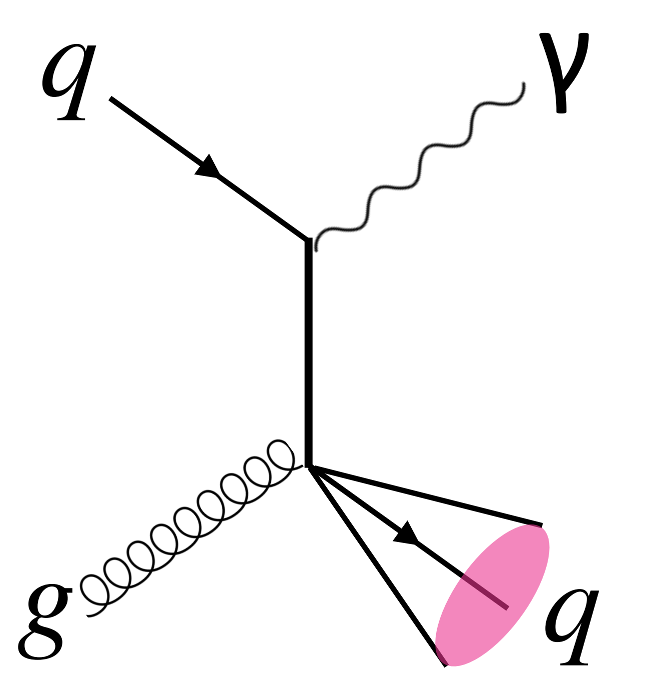
Casimir color factor
4/3 for quarks
3 for gluons

$$\Delta E_{\mathrm{gluon}} > \Delta E_{\mathrm{quark}}$$

Photon-tagged Jet R_{AA}

- **Color-charge dependence** of energy loss

ATLAS-CONF-2022-019



q-g
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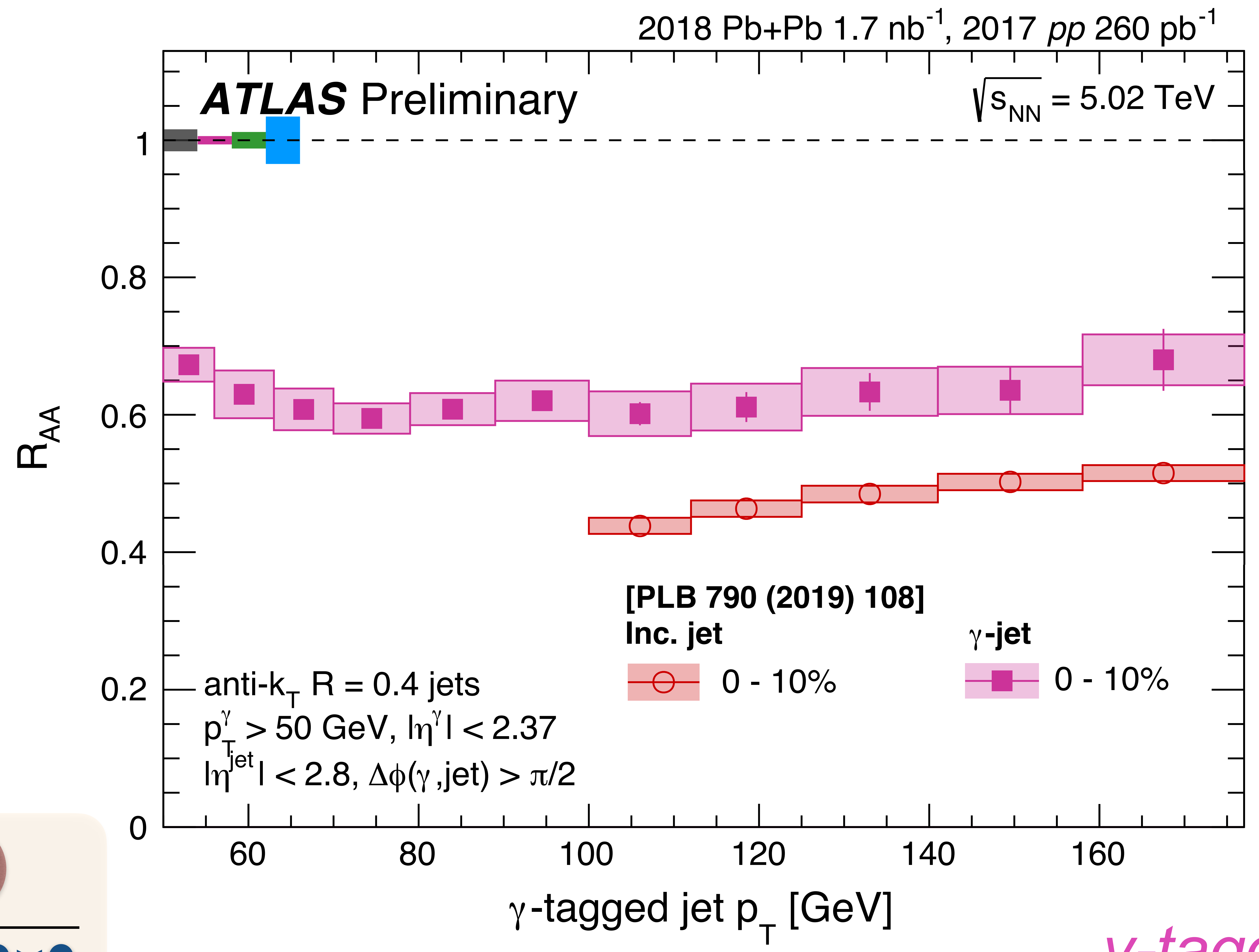
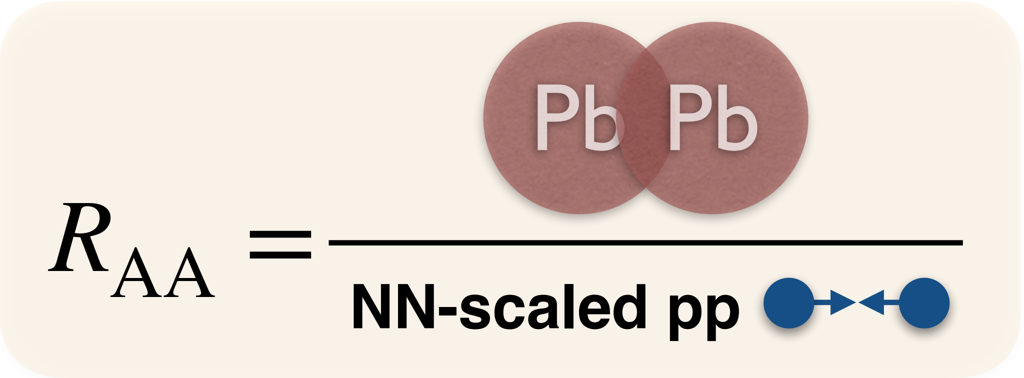


quark-initiated jet dominant

Photon-tagged jet R_{AA}

Inclusive jet R_{AA}

gluon-initiated jet dominant



less suppression of
γ-tagged jets than inclusive jets

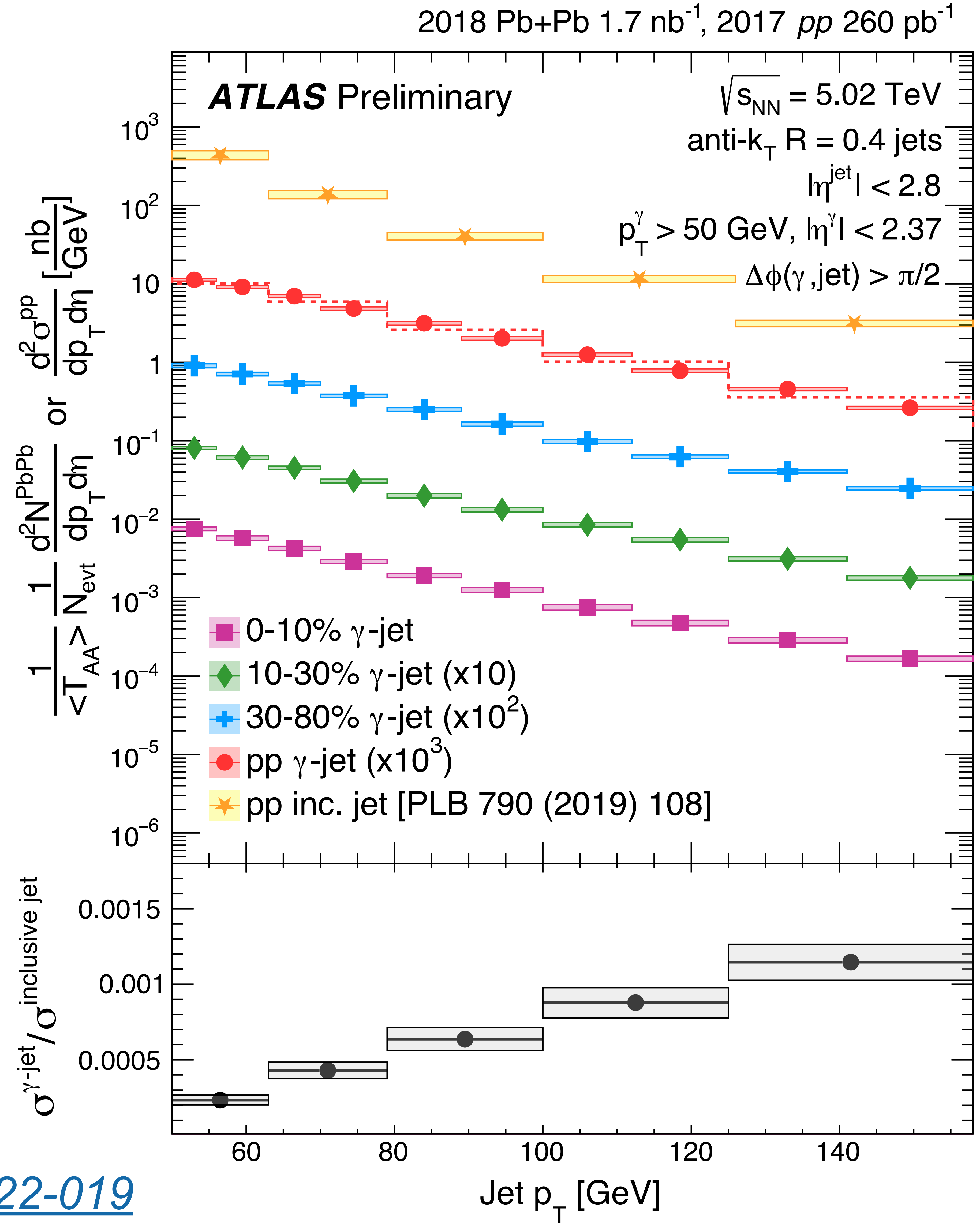
Photon-tagged Jet R_{AA}

***Two factors** to consider*
besides the different quark/gluon fraction
between the γ-tagged jets
and inclusive jets…

1) p_T^{jet} distribution difference
→ *makes R_{AA} ↑ by 0.05~0.08*

2) Isospin and nuclear PDF effect
→ *makes R_{AA} ↓ by 0.05~0.1*

These two effects are expected to have **opposite sign** and **similar magnitude**



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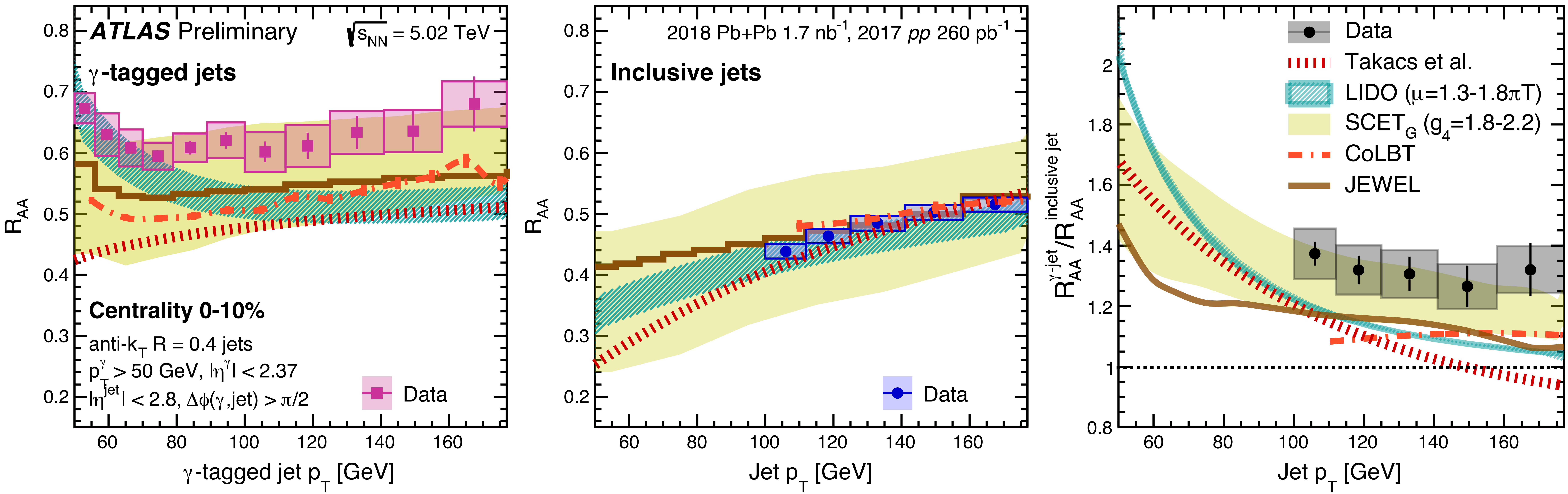
Photon-tagged Jet R_{AA}

- **Color-charge dependence** of energy loss

ATLAS-CONF-2022-019



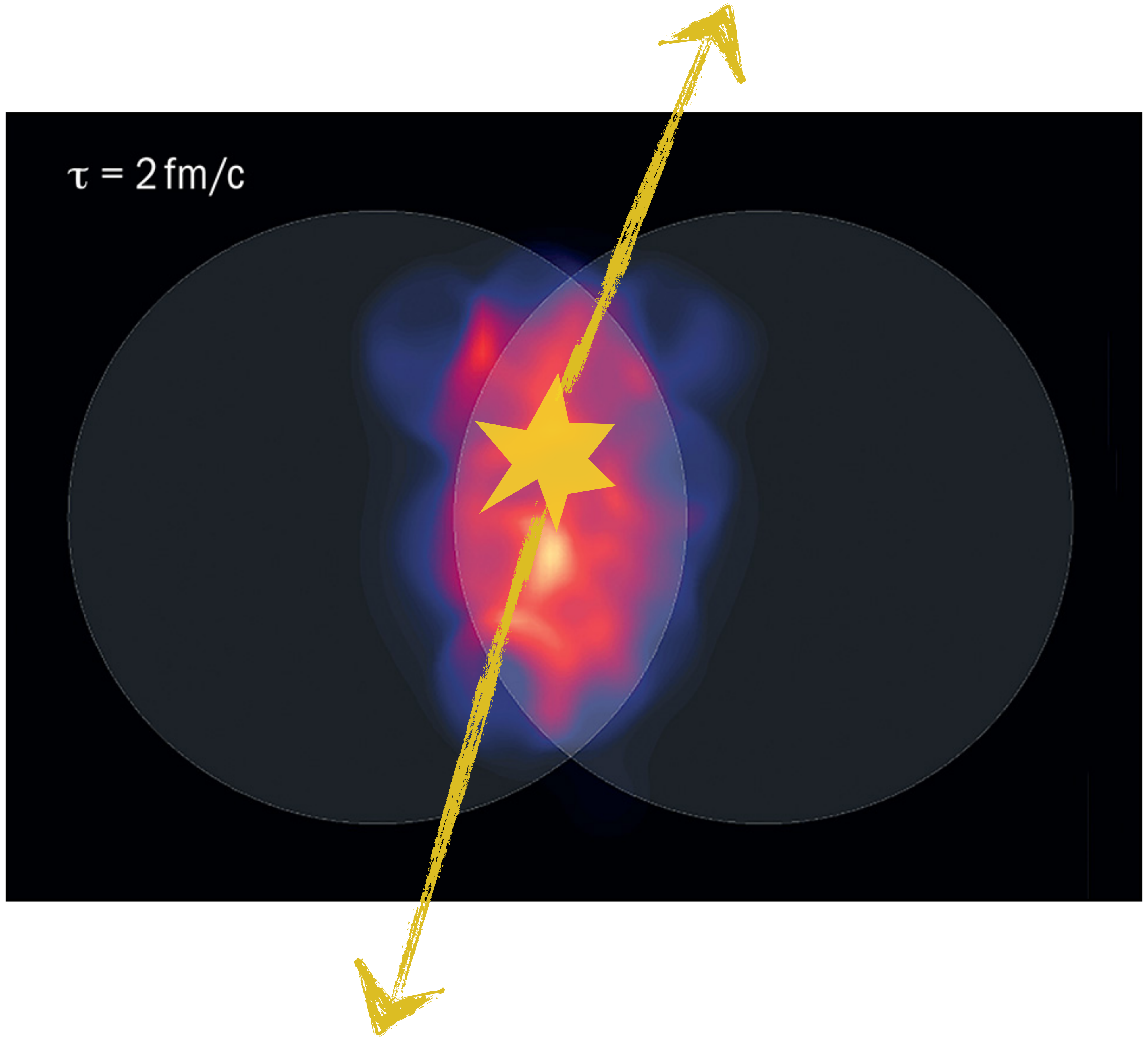
***Photon-tagged jets**: overall, higher R_{AA} for data than the one for predictions*

***Inclusive jets**: qualitative agreement between various models and the data*

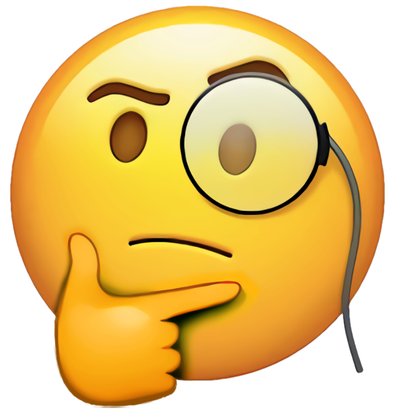
***R_{AA} (γ-jet) / R_{AA} (inc. jet)**: higher than unity; test of color-charge dependence*

Probes of Bulk QGP

Hard Probes



Jets



What is parton mass dependence energy loss mechanism in the medium?

b-Jet R_{AA}

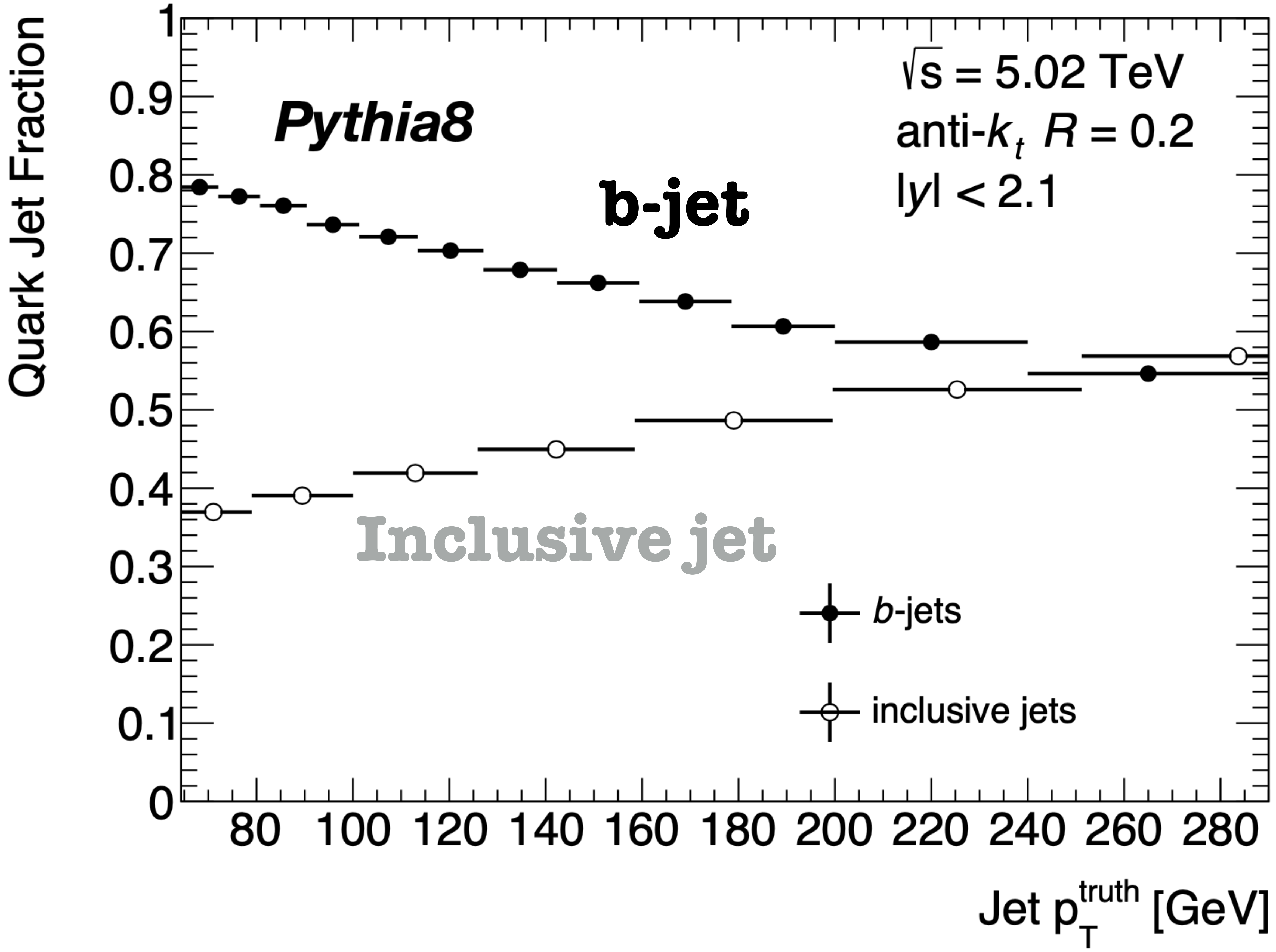
- **Color-charge** and **parton mass dependence** of energy loss

Casimir color factor

$$\langle \Delta E_g \rangle \propto \alpha_s \boxed{C_R} \hat{q} L^2$$

*4/3 for **quarks***
*3 for **gluons***

$$\Delta E_{gluon} > \Delta E_{quark}$$



b-Jet R_{AA}

- **Color-charge** and **parton mass dependence** of energy loss

arXiv:2204.13530
submitted to EPJC

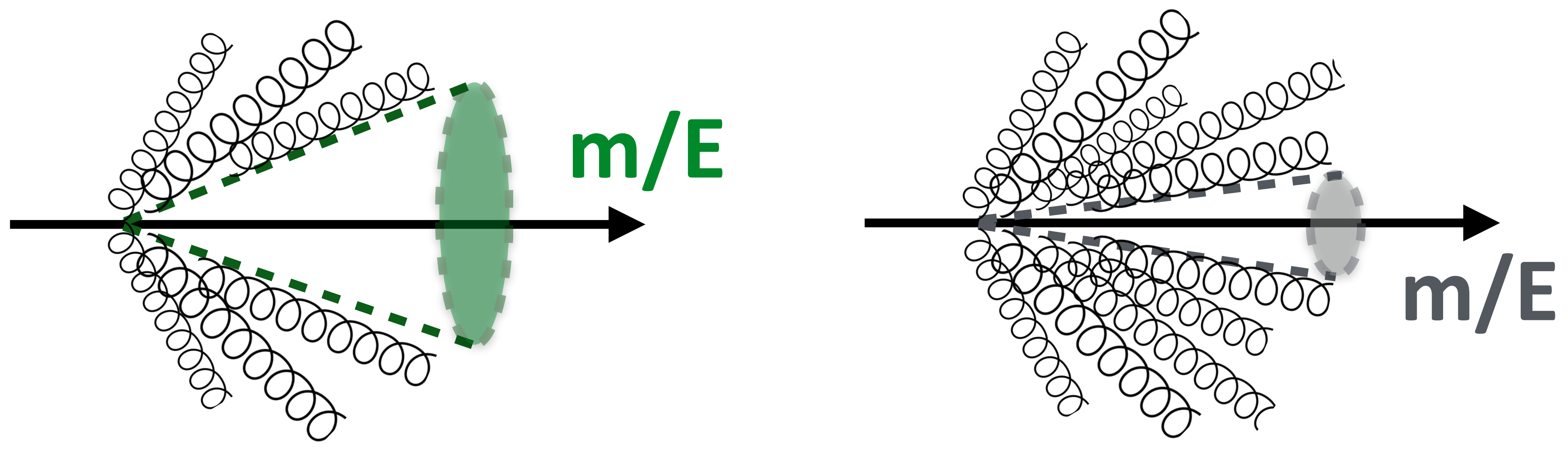
Casimir color factor

$$\langle \Delta E_g \rangle \propto \alpha_s \boxed{C_R}\, \hat{q}\, L^2$$

*4/3 for **quarks***
*3 for **gluons***

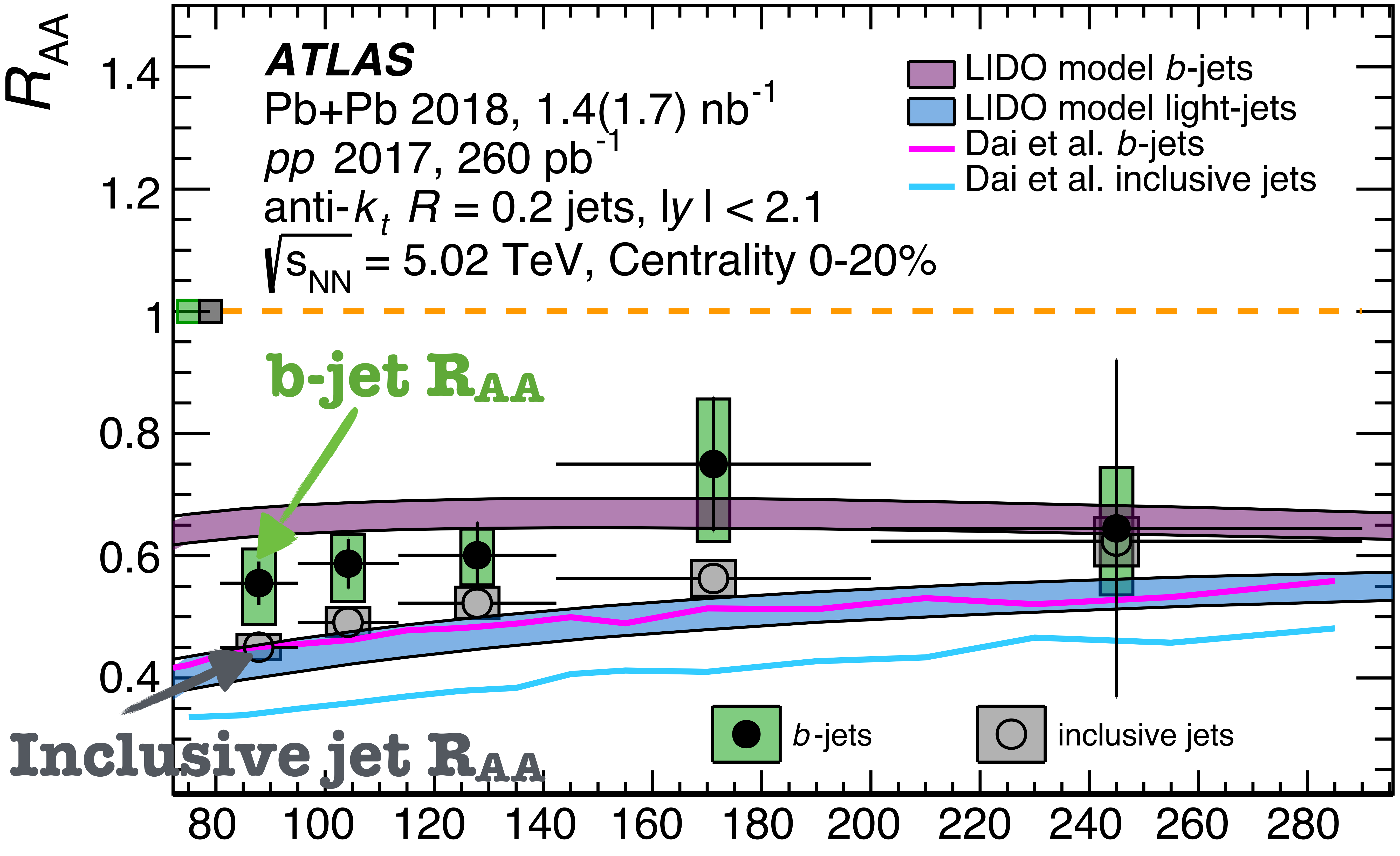
$$\Delta E_{\text{gluon}} > \Delta E_{\text{quark}}$$

Dead cone effect



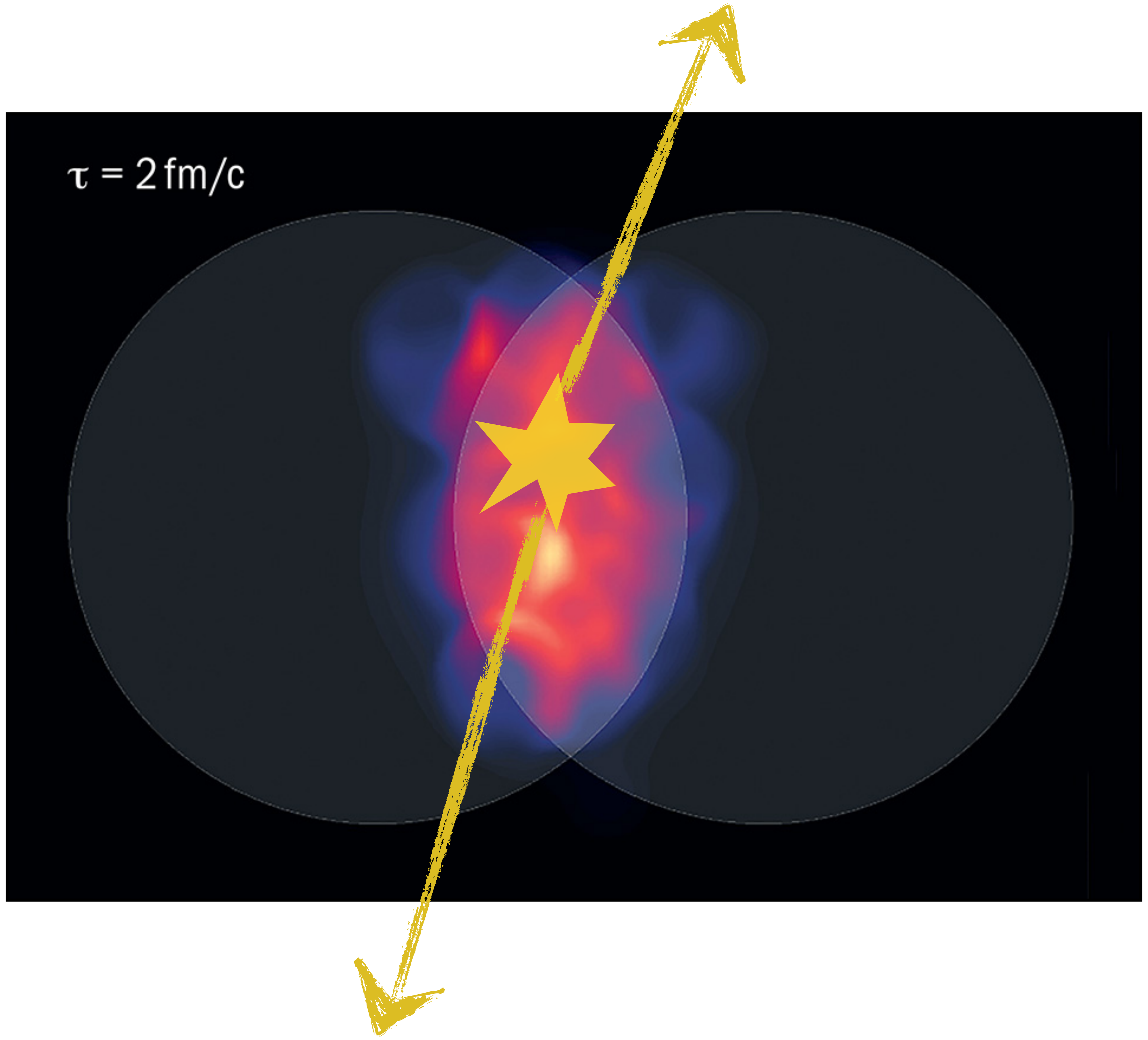
heavy mass parton   **light** mass parton

$$\Delta E_g > \Delta E_{u,d,s} > \Delta E_c > \Delta E_b$$



*less suppression of **b-jets** than **inclusive jets***

Probes of Bulk QGP



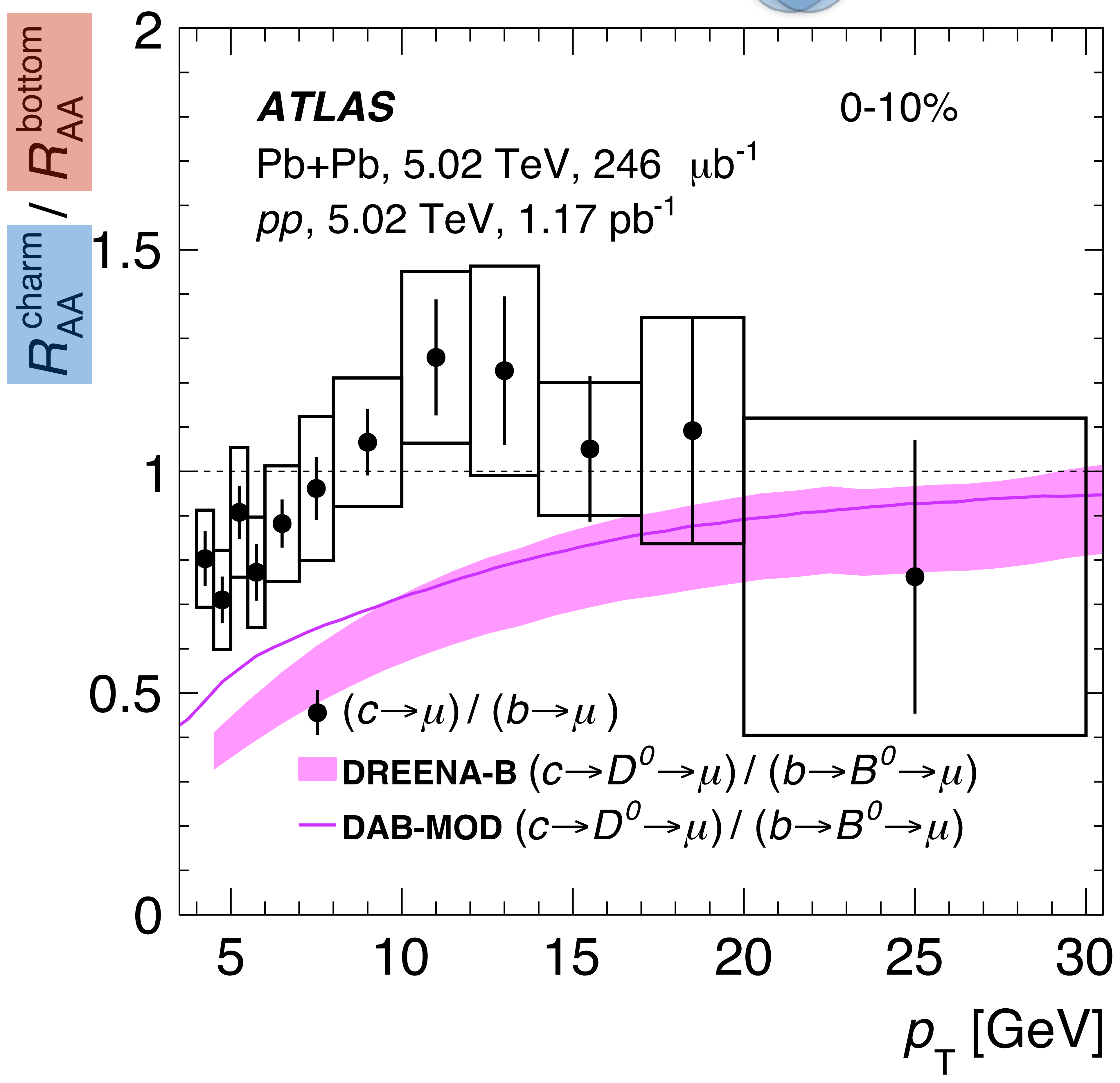
Hard Probes

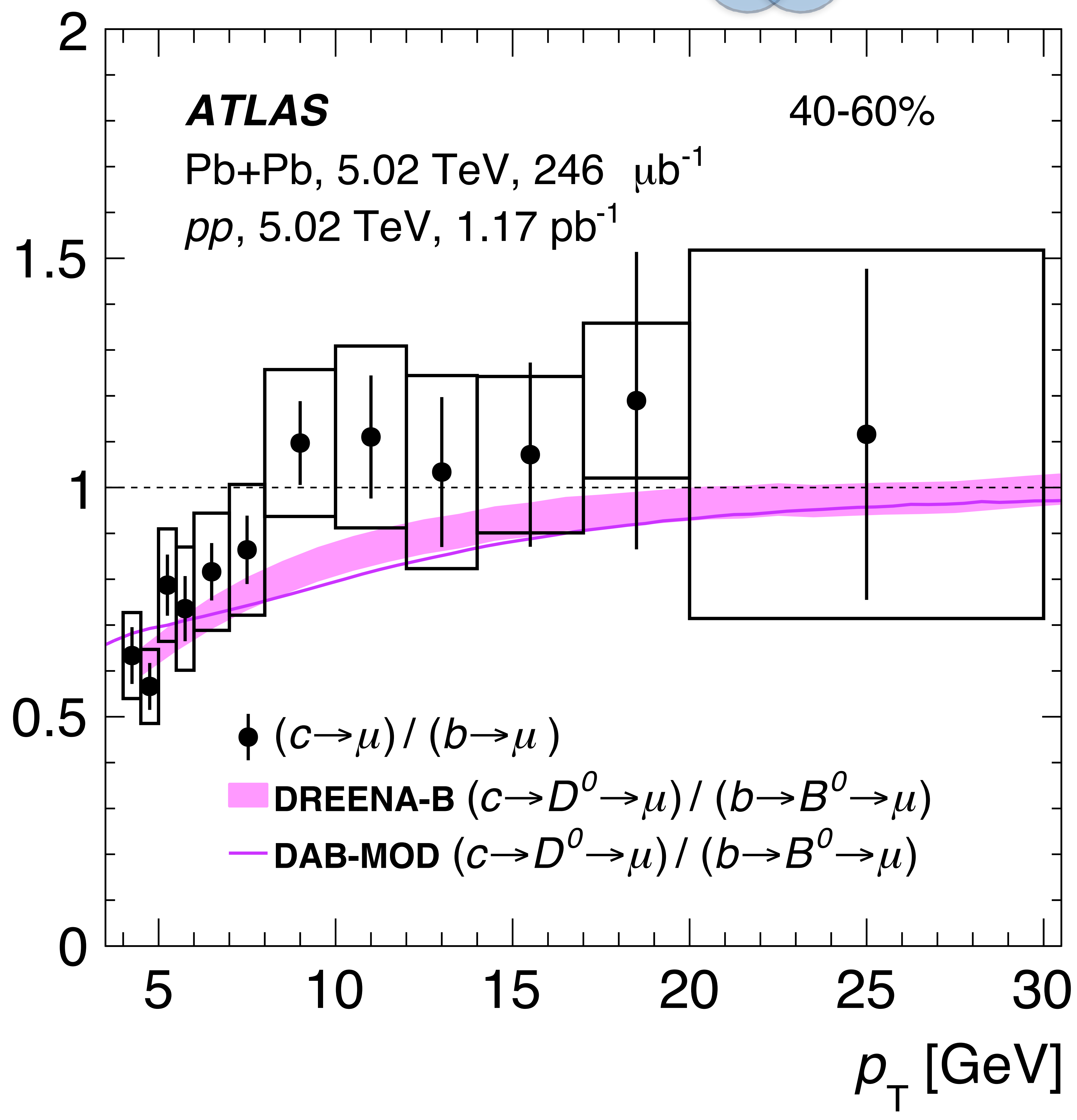
Heavy Flavor
Quarkonia

What is the production mechanism of open heavy flavor and quarkonia?

Heavy Flavour R_{AA}

0-10% **40-60%**





[Phys. Lett. B 829 (2022) 137077]

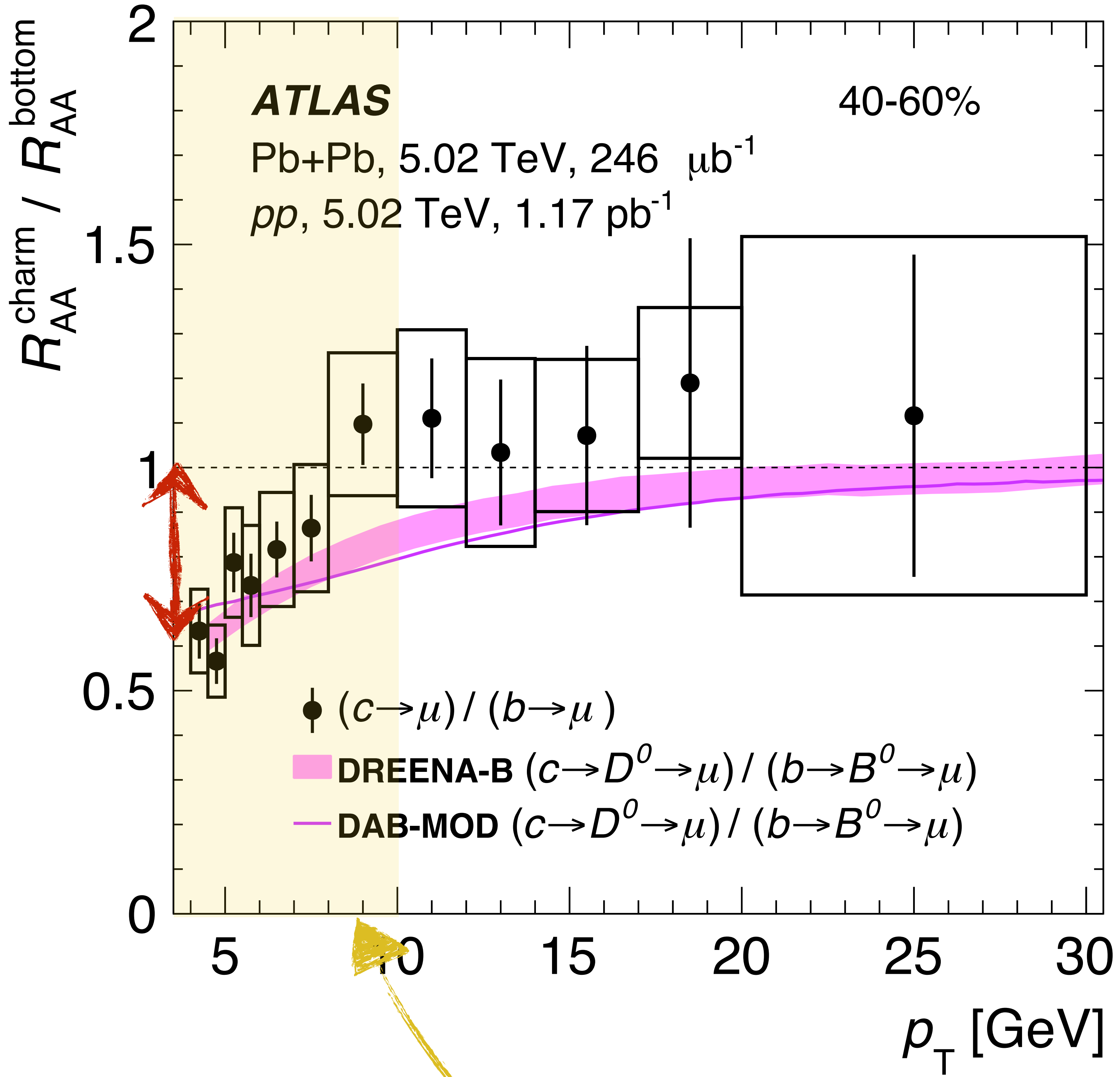
R_{AA} (charm) / R_{AA} (bottom)

*At low p_T, separation between **charm** and **bottom** muons*

Some discrepancy between the data and models

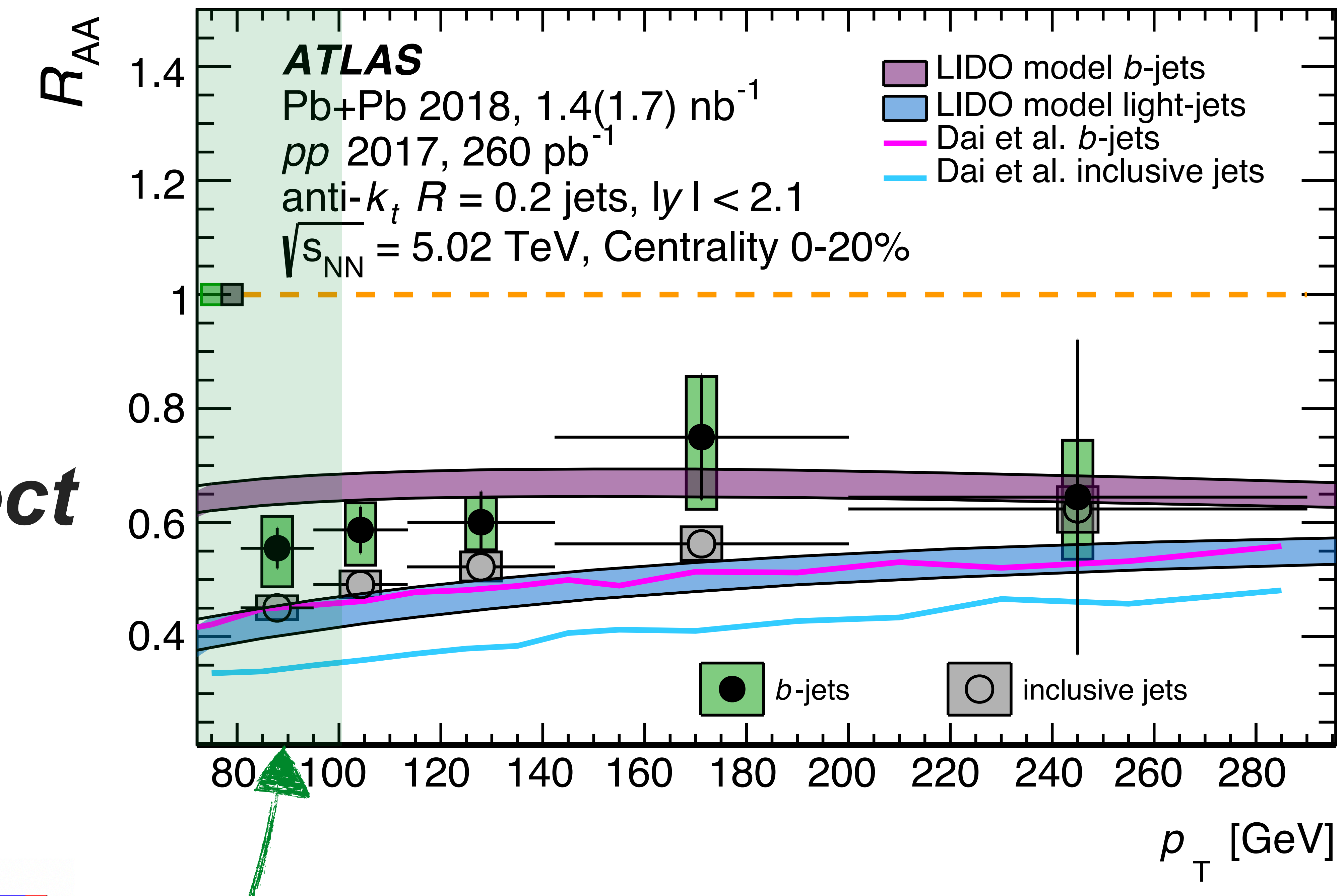
***Mass hierarchy** for both the data and models*

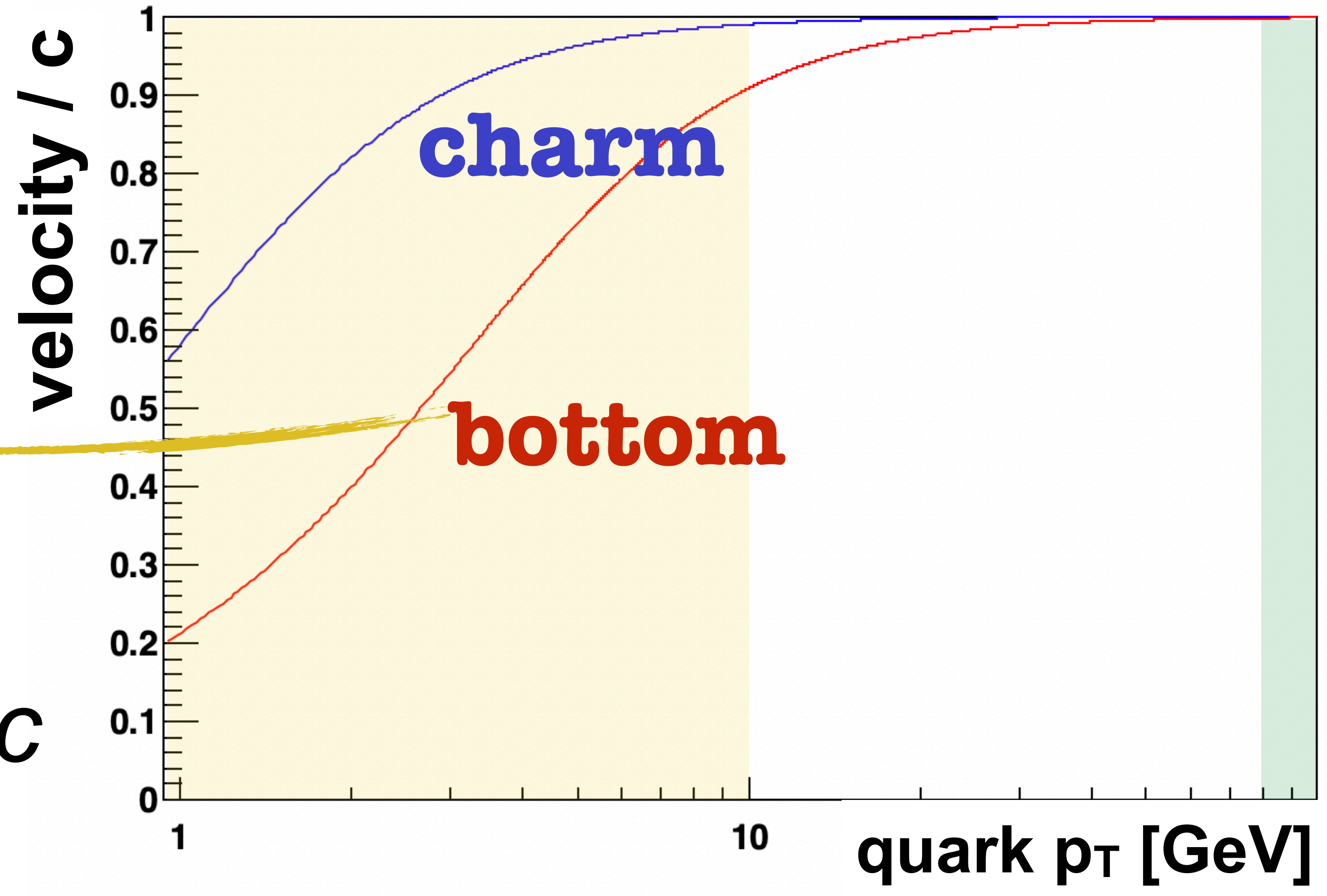
Heavy Flavour Muons and Jets



charm *vs.* ***bottom****:*

difference at low p_T
from the ***dead cone effect***
+ ***radiative processes***



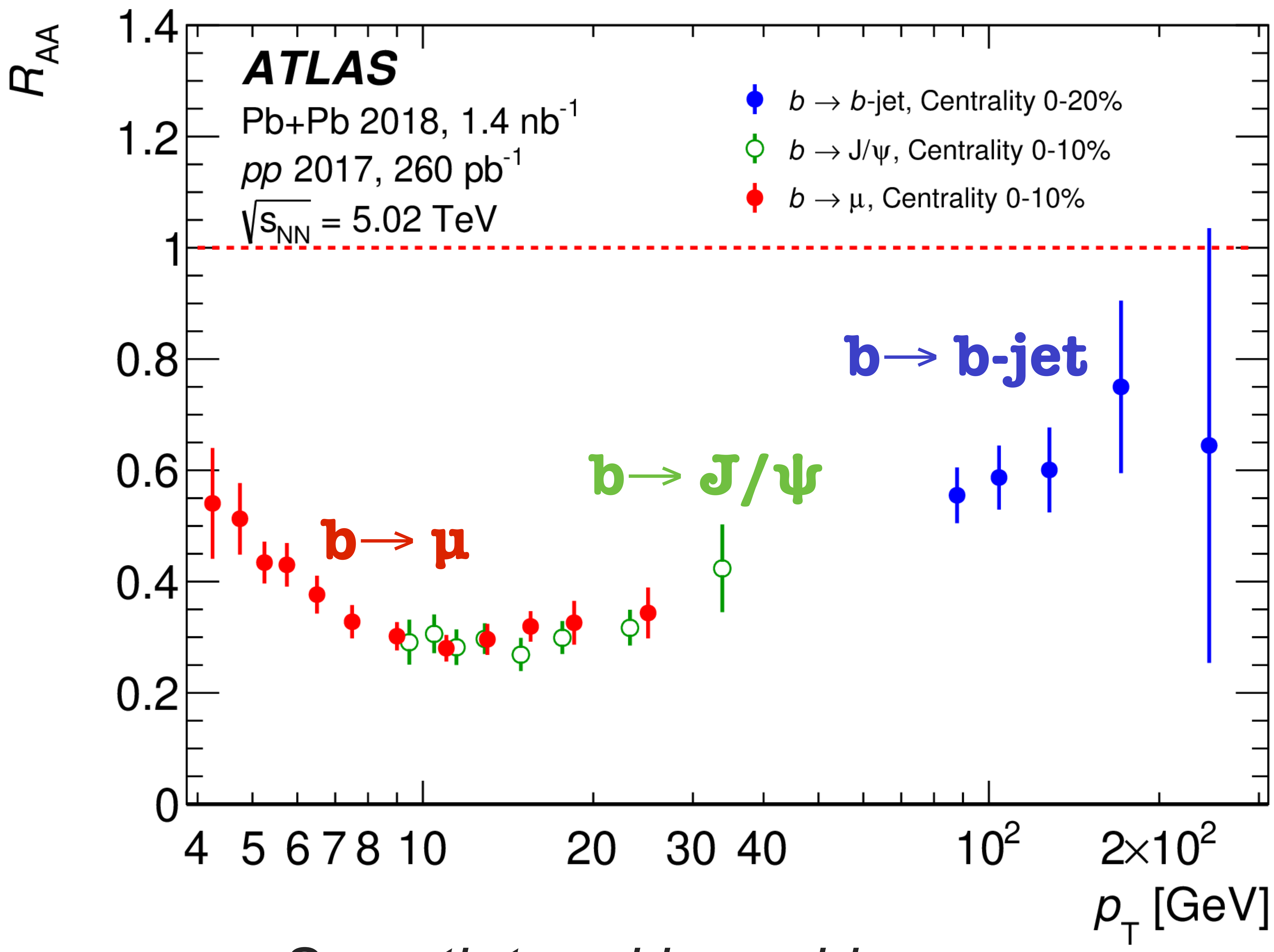


In general,
the dead cone effect is
more important when $v \ll c$

b-jet *vs.* ***inclusive jet****:*

difference potentially more from
quark *vs.* ***gluon***
(Casimir color factor)
than the dead cone effect

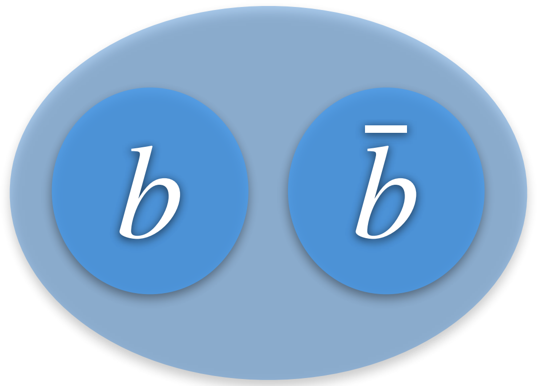
Heavy Flavour R_{AA}



Smooth trend in a wide p_T range
from B-decay to b-jets

Upsilon R_{AA}

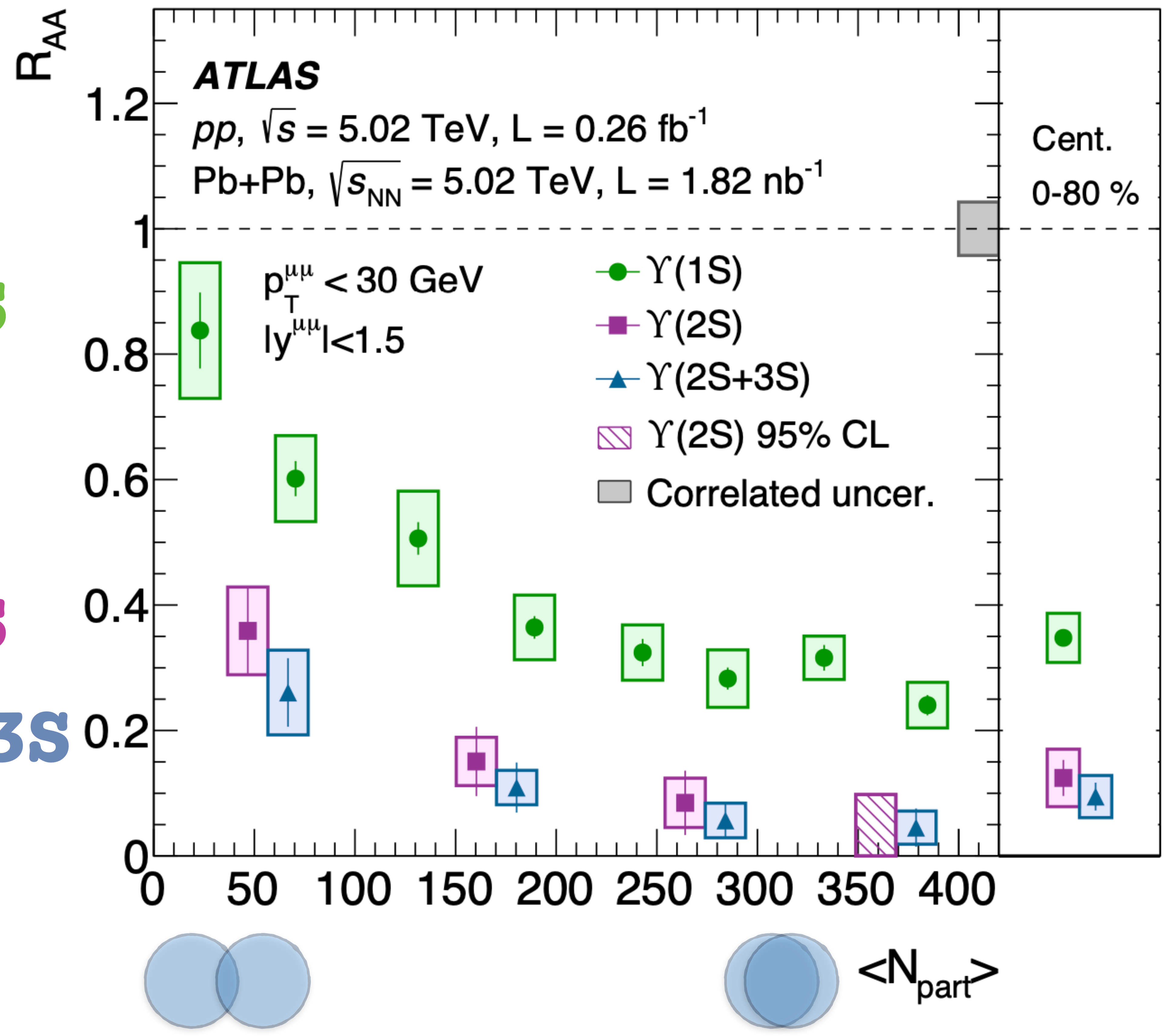
- Suppression of the $b\bar{b}$ bound states



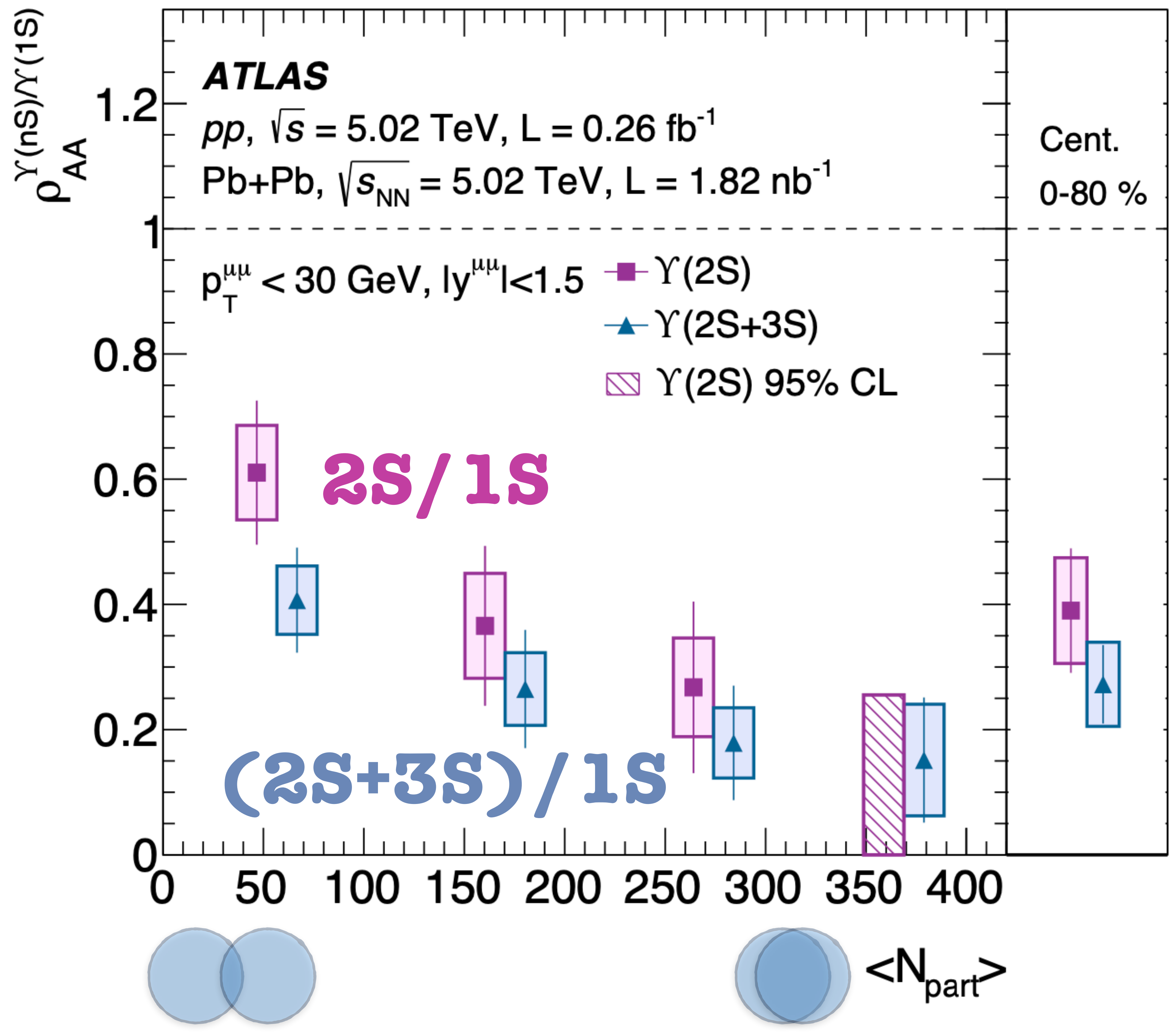
arXiv:2205.03042
submitted to PRC

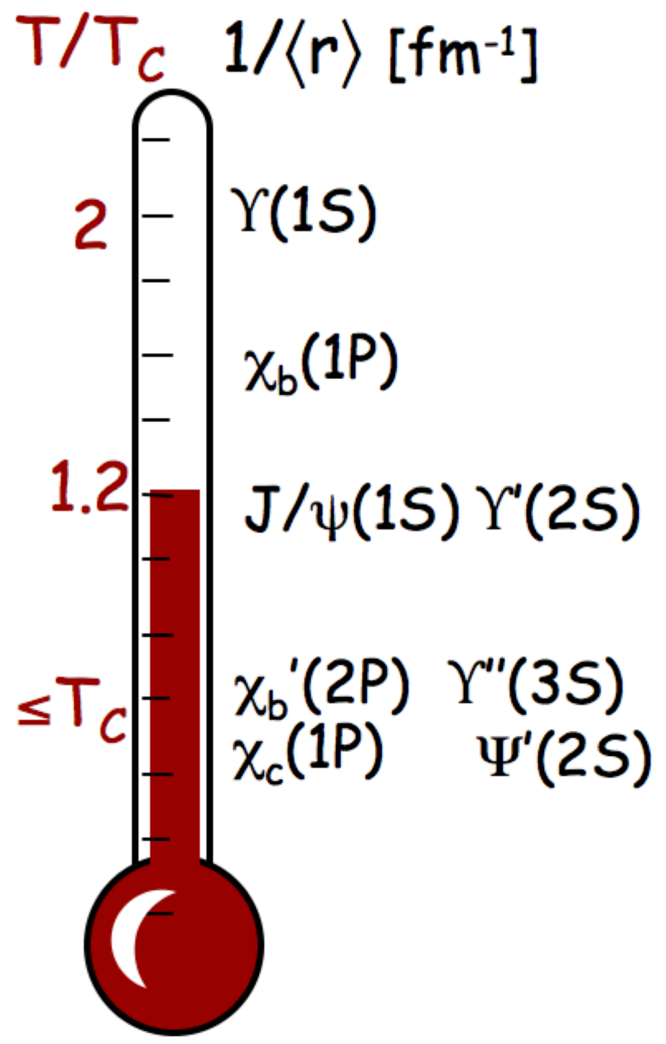
R_{AA}

1S
2S
2S+3S



$R_{AA}(\Upsilon(ns)) / R_{AA}(\Upsilon(1s))$

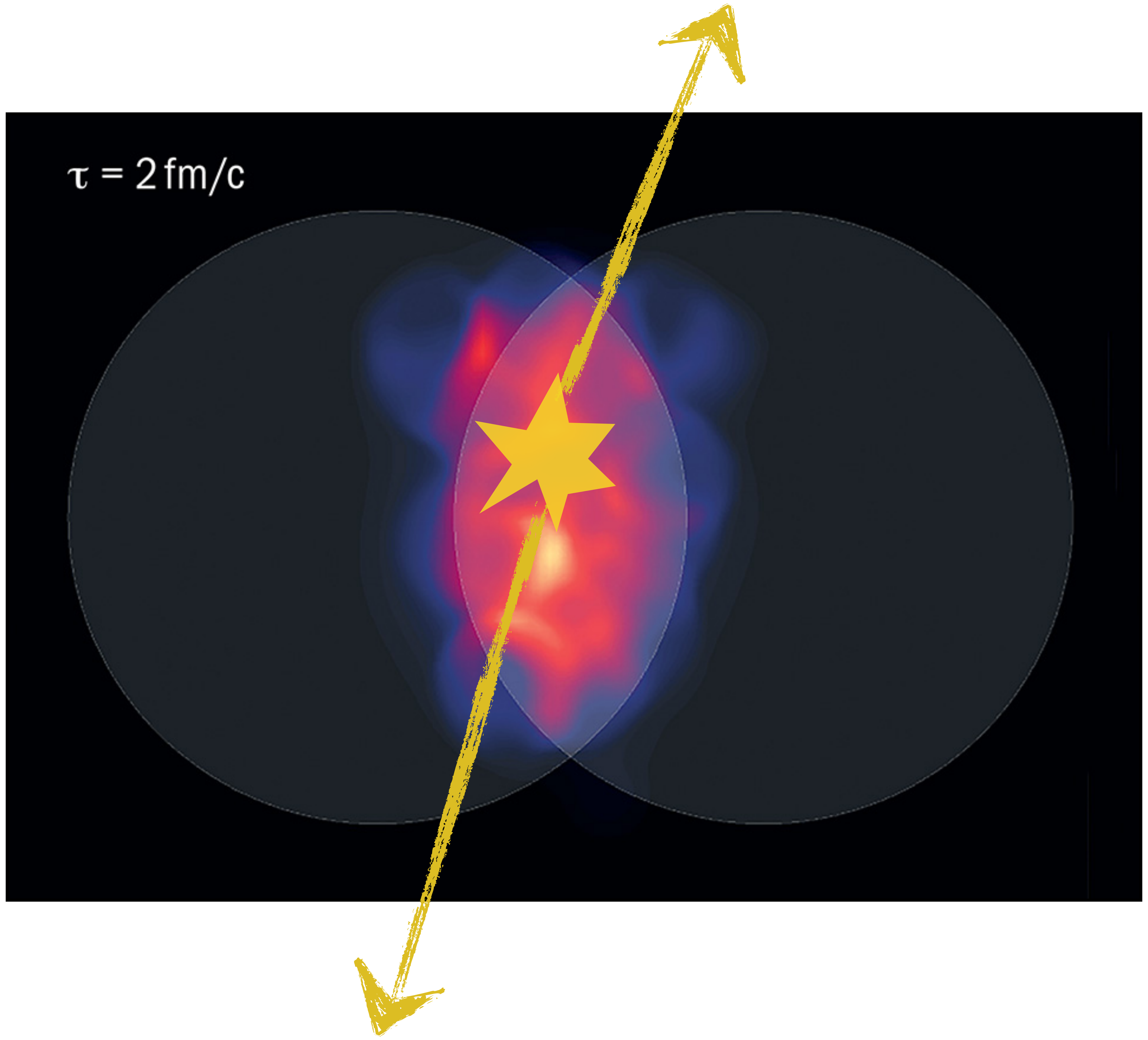




Sequential suppression!

Probes of Bulk QGP

Hard Probes



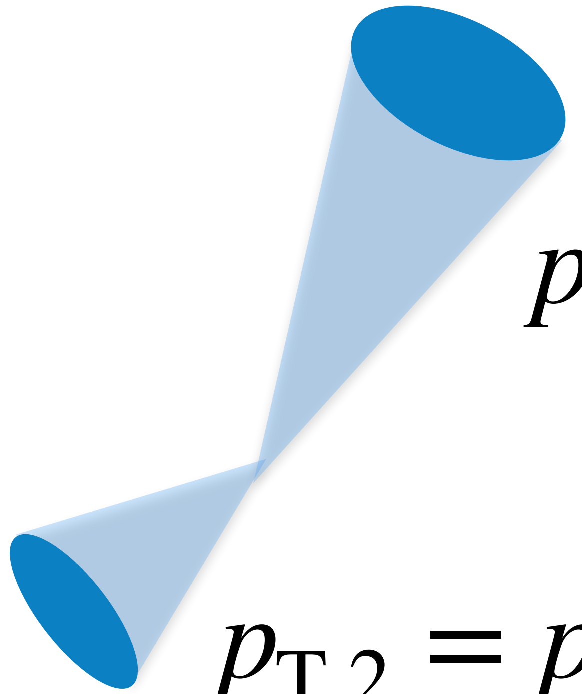
Jets

Do jets experience different energy loss due to unequal path lengths?

Dijet momentum imbalance

[arXiv:2205.00682](https://arxiv.org/abs/2205.00682)
submitted to PRC

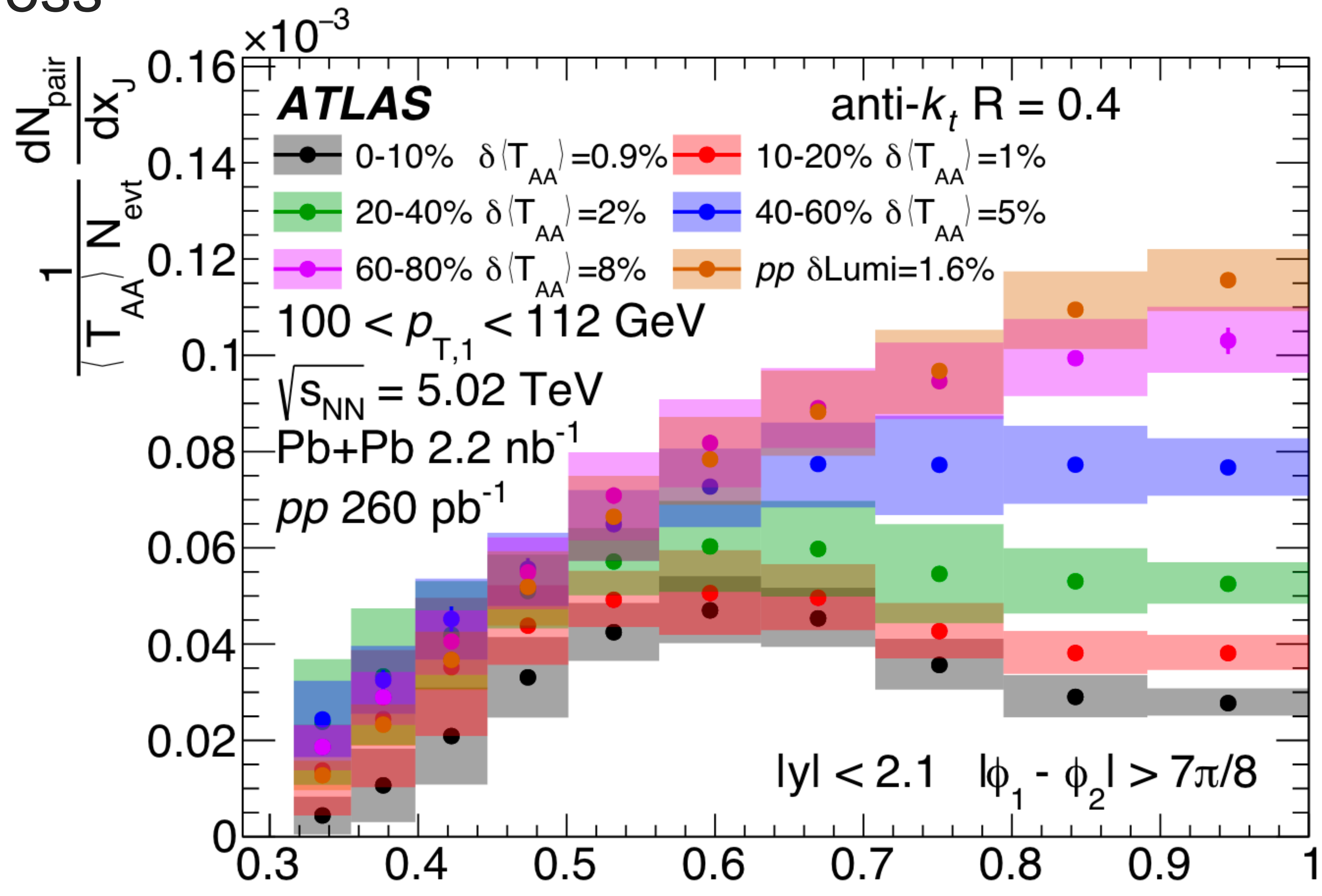
- Path length dependent energy loss



$$p_{\mathrm{T},1} = p_{\mathrm{T}}^{\text{leading jet}}$$

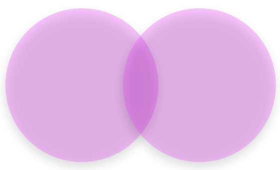
$$p_{\mathrm{T},2} = p_{\mathrm{T}}^{\text{subleading jet}}$$

$$x_{\mathrm{J}} \equiv \frac{p_{\mathrm{T},1}}{p_{\mathrm{T},2}}$$

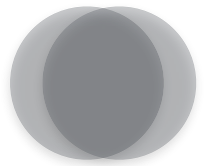


pp

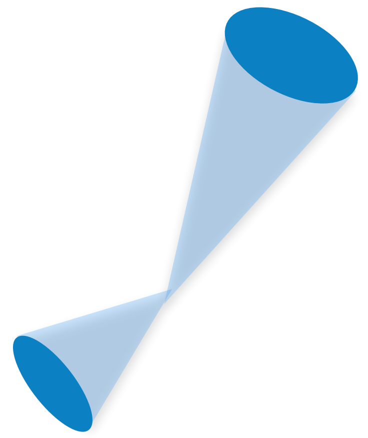
60-80% Pb+Pb

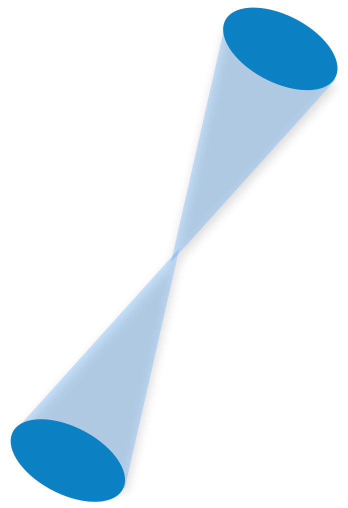


0-10% Pb+Pb



Suppression of balanced dijets (high ***x_J****) in Pb+Pb collisions with centrality ordering*





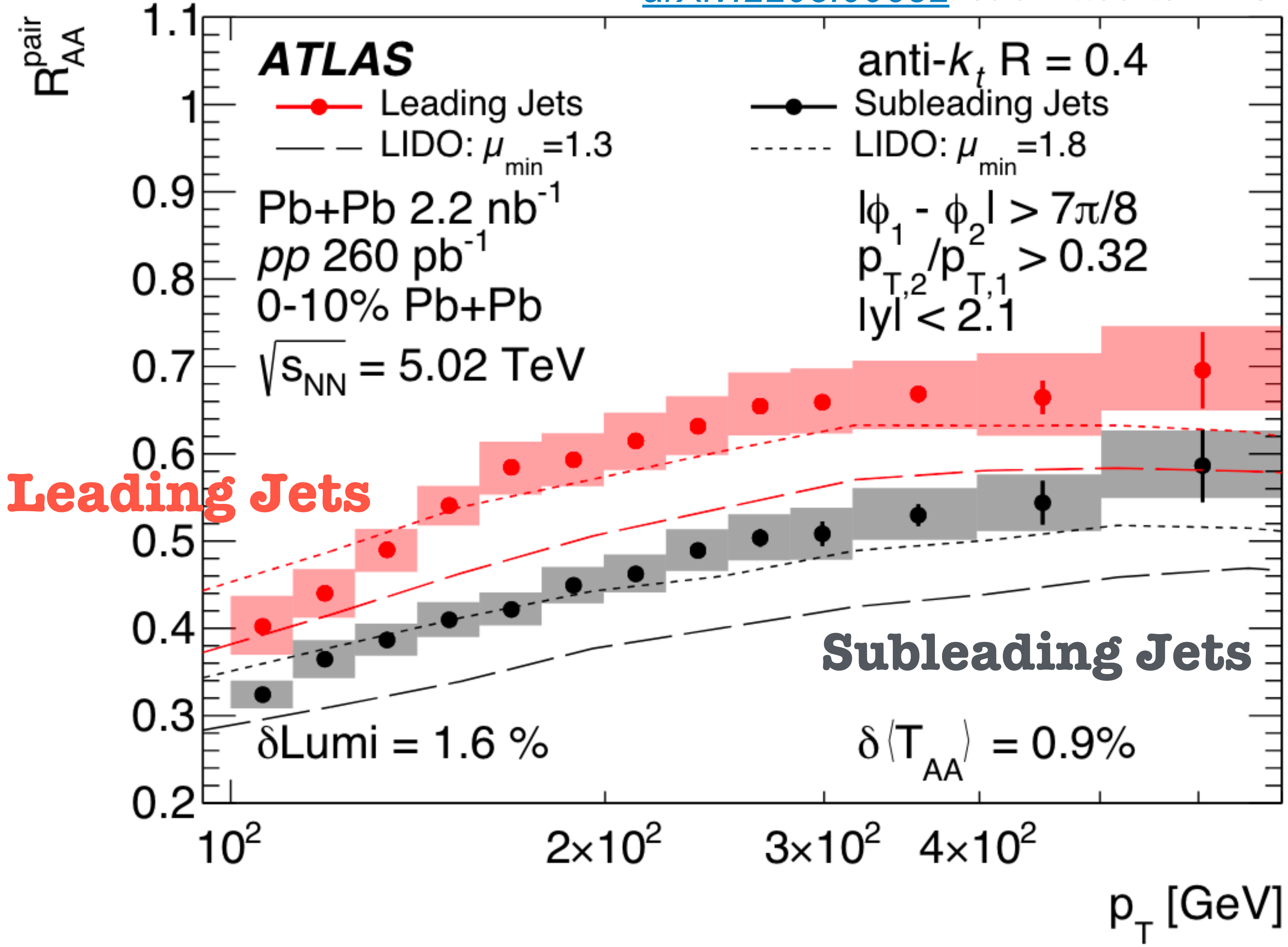
Dijet momentum imbalance

- Path length dependent energy loss

subleading jets** are more suppressed than **leading jets

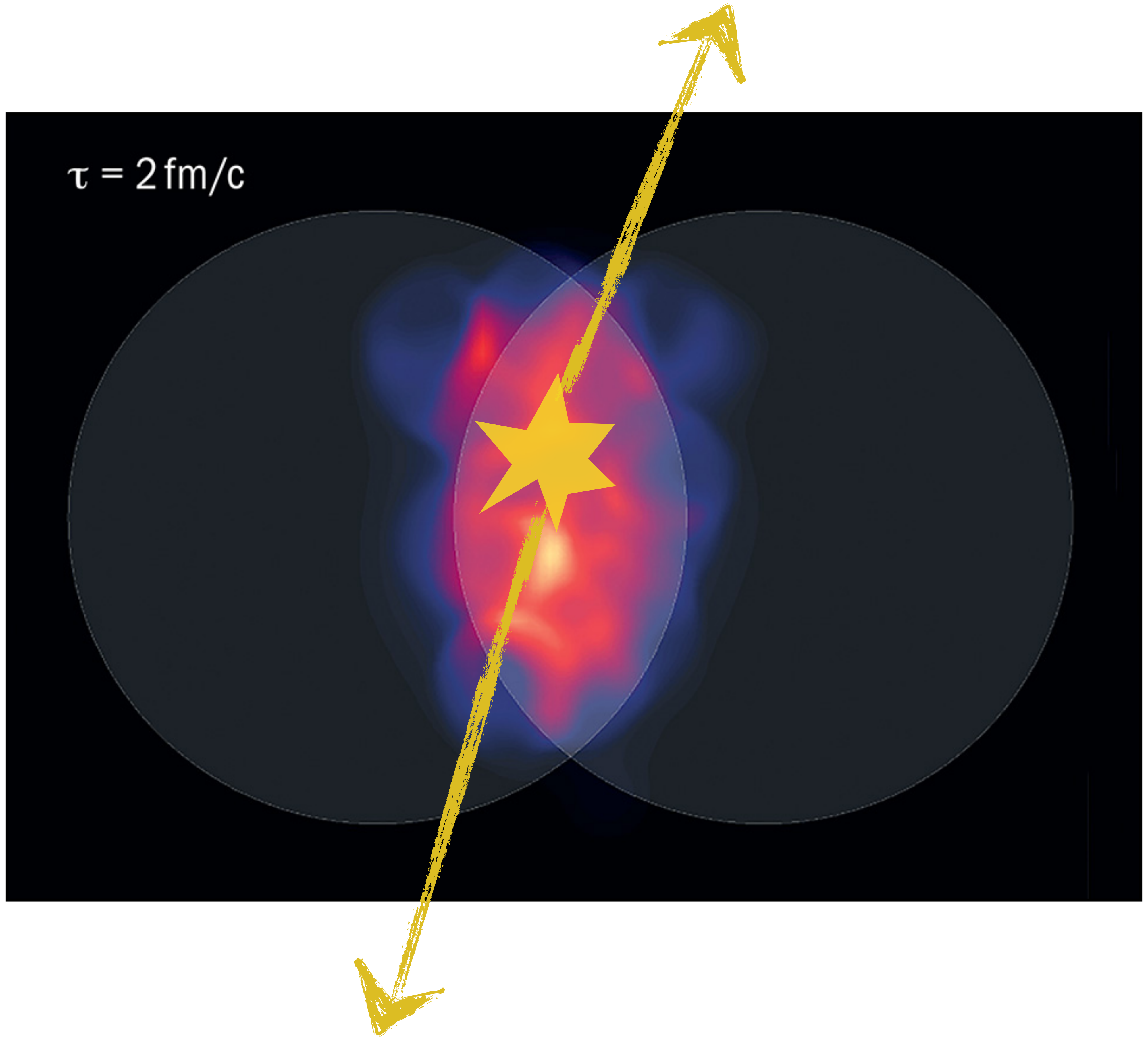
$$R_{AA} = \frac{\text{Pb Pb}}{\textbf{NN-scaled pp}}$$

arXiv:2205.00682 *submitted to PRC*

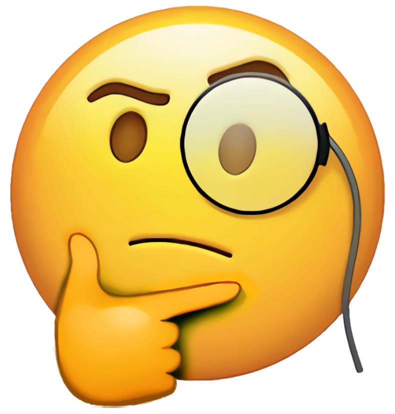


Probes of Bulk QGP

Hard Probes



Jets



Can we study color (de)coherence using jet substructure measurements?

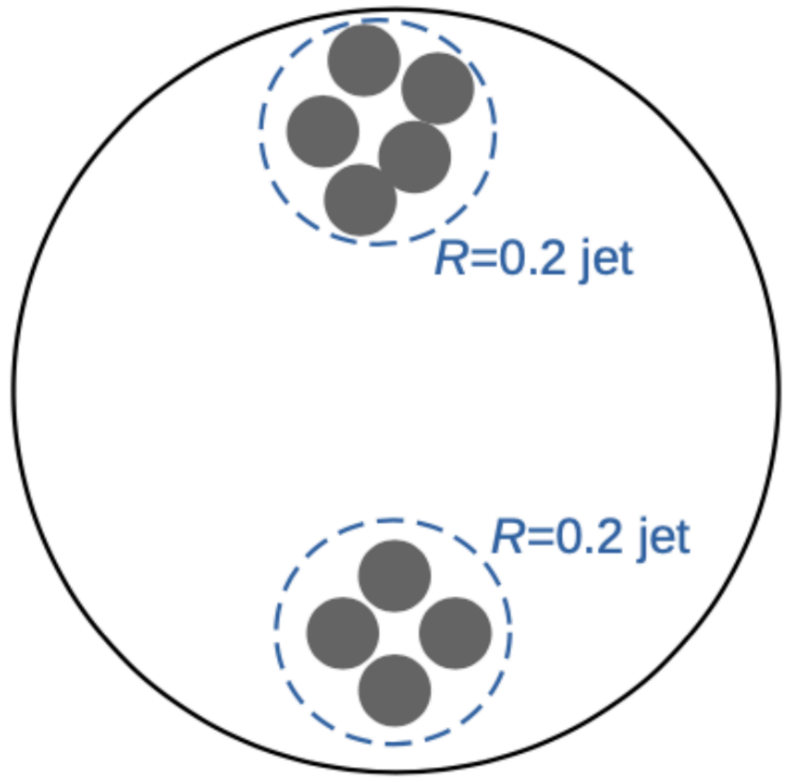
Re-clustered Large-radius jets

ATLAS-CONF-2019-056

- **Hard parton splitting** using re-clustered R=1.0 jets

➡ ***re-clustered R=1.0 jets***;
by using anti-k_T R=0.2 jets
with p_T>35 GeV as inputs
to anti-k_T algorithm with R=1.0

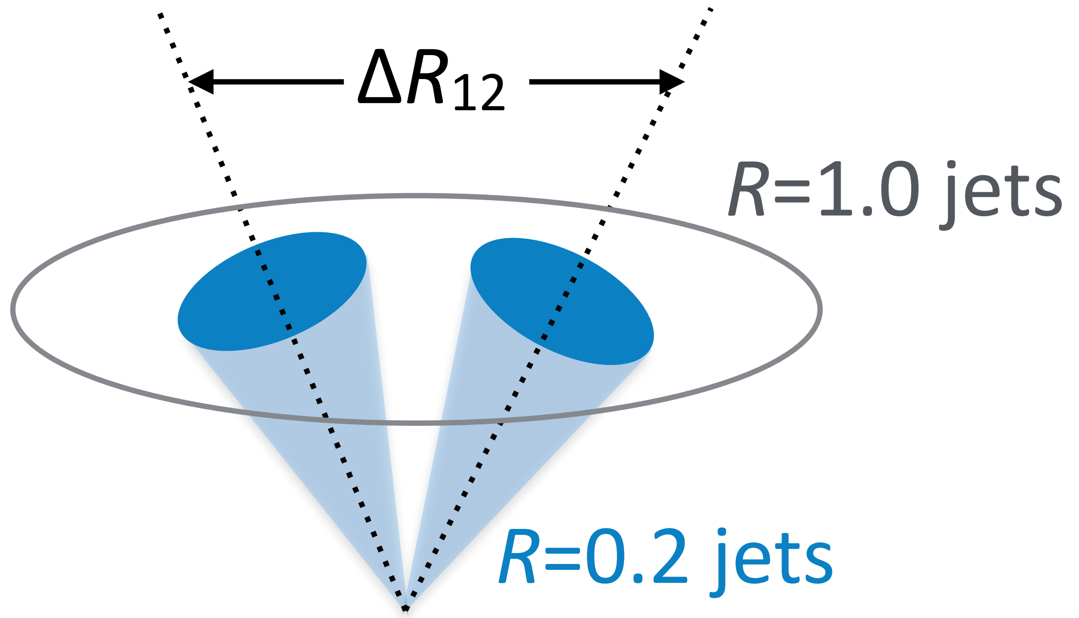
- soft contributions removed
- no recovering energy outside R=0.2 sub-jets



Re-clustered
R=1.0 jet

➡ two sub-jets at the final clustering step from k_T algorithm used to define **k_T splitting scale** ($\sqrt{d_{12}}$)

$$\sqrt{d_{12}} = \min(p_{\mathrm{T},1}, p_{\mathrm{T},2}) \cdot \Delta R_{12}$$

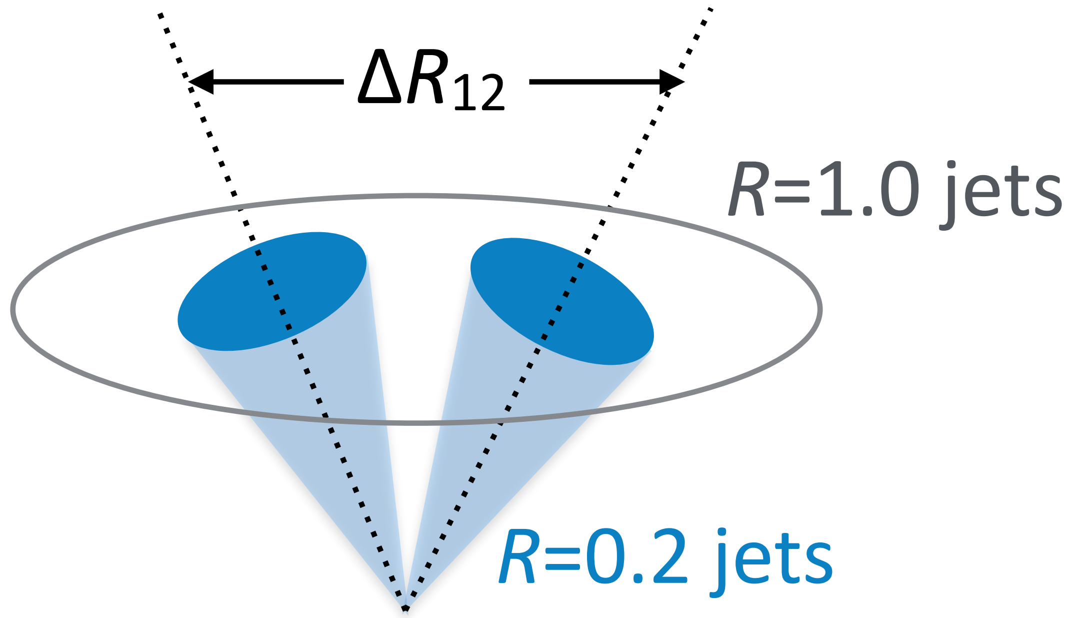


Re-clustered Large-radius jets

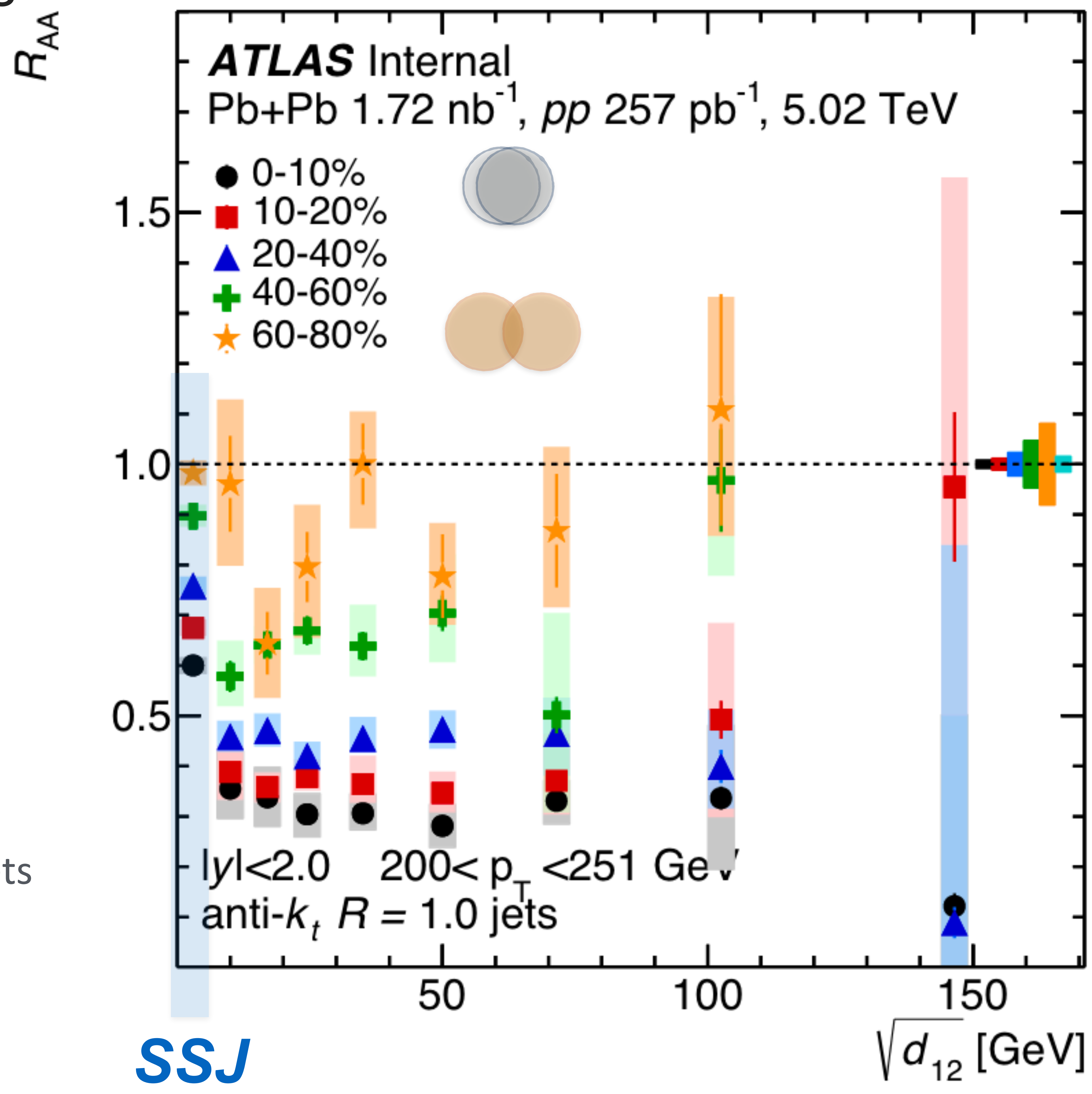
- **Hard parton splitting** using re-clustered R=1.0 jets

*A significant difference between single sub-jet (**SSJ**) and those with more complex substructure*

$$\sqrt{d_{12}} = \min(p_{\mathrm{T},1}, p_{\mathrm{T},2}) \cdot \Delta R_{12}$$



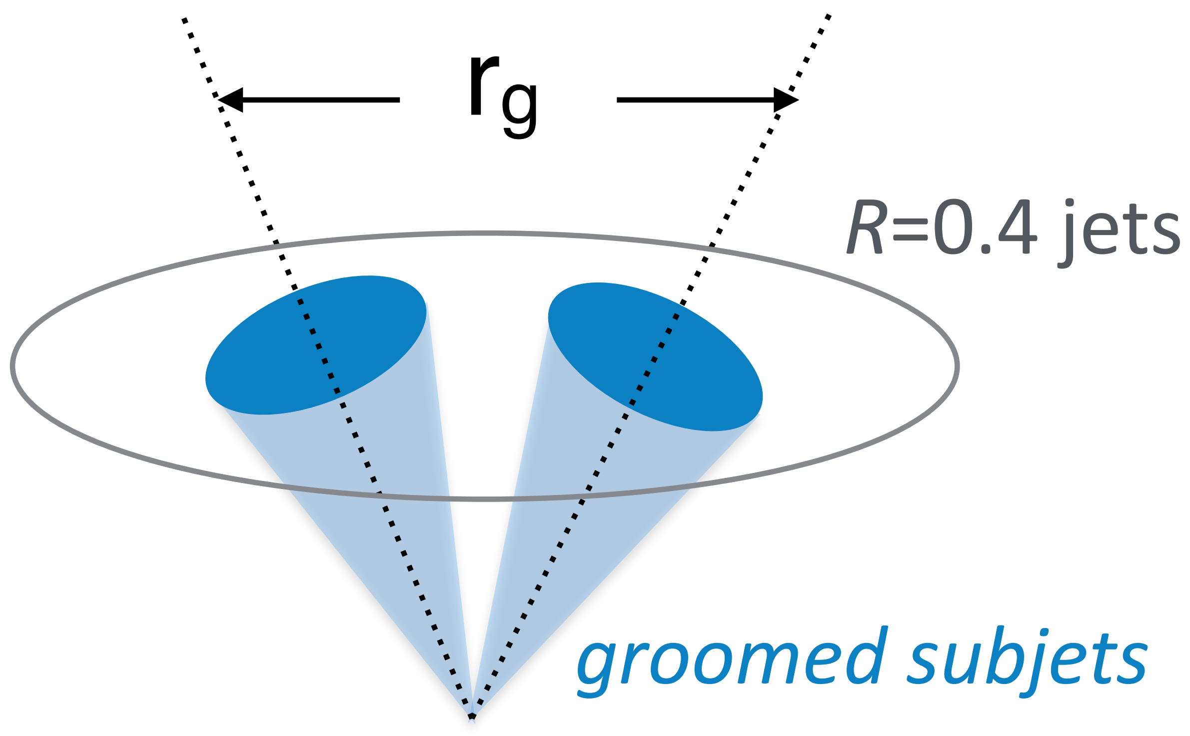
ATLAS-CONF-2019-056



Jet Substructure

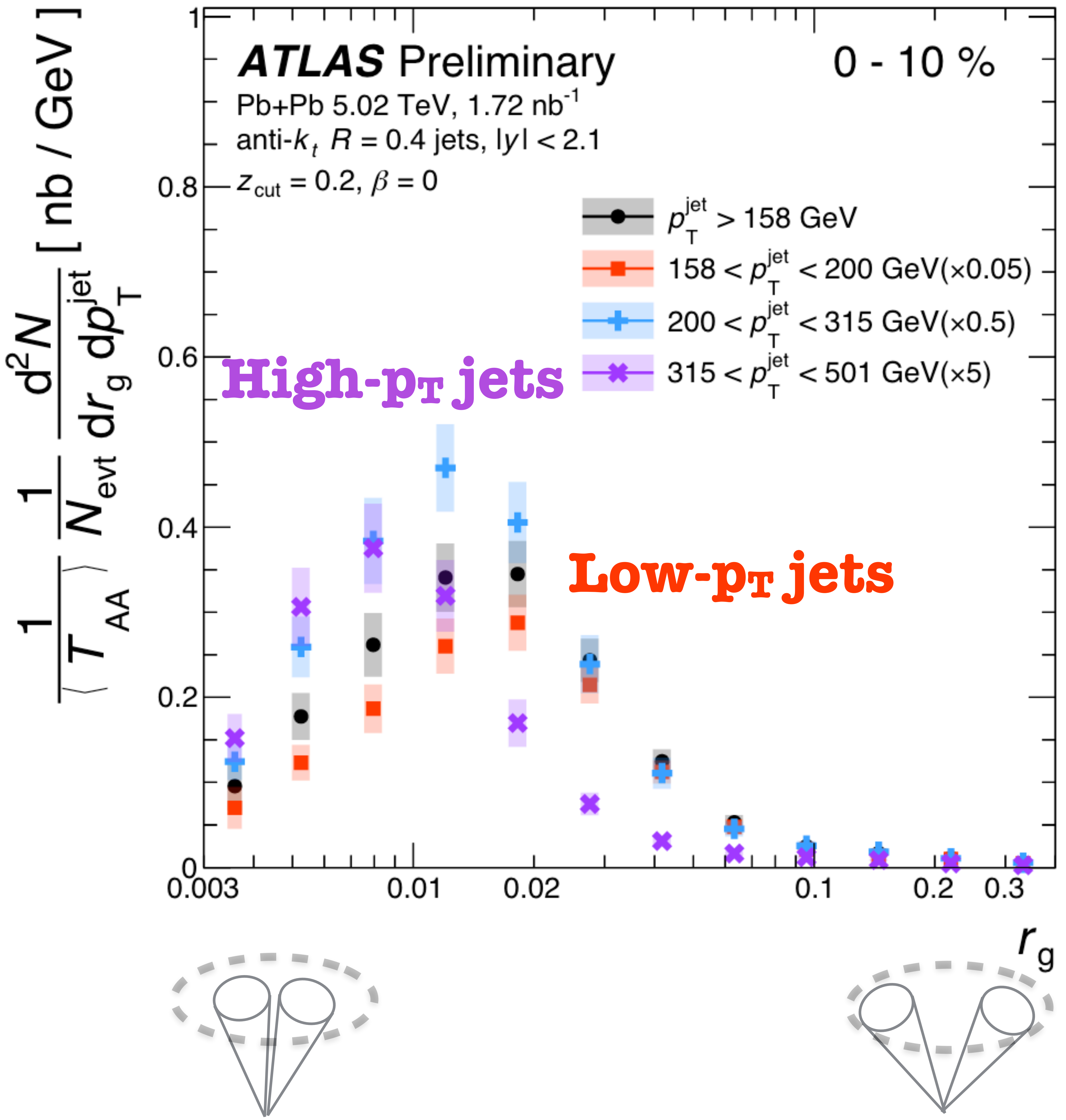
- Study **color (de)coherence** using jet splitting angle
  - ➡ soft drop grooming procedure to determine **opening angle of the hardest splitting ($\mathbf{r_g}$)**

$$\frac{\min(p_{T,1}, p_{T,2})}{p_{T,1} + p_{T,2}} > z_{cut}(=0.2)$$



Lower $\mathbf{r_g}$ with increasing jet p_T
*→ **high-p_T jets** are more collimated*

ATLAS-CONF-2022-026



Jet Substructure

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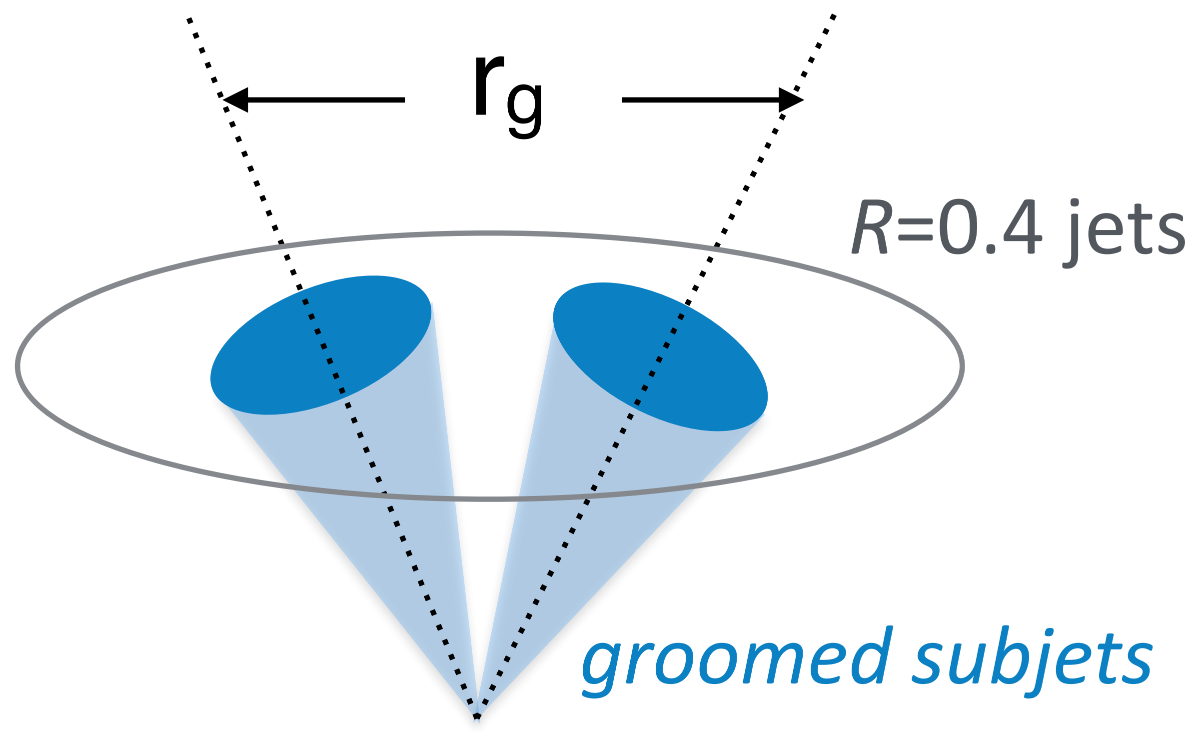
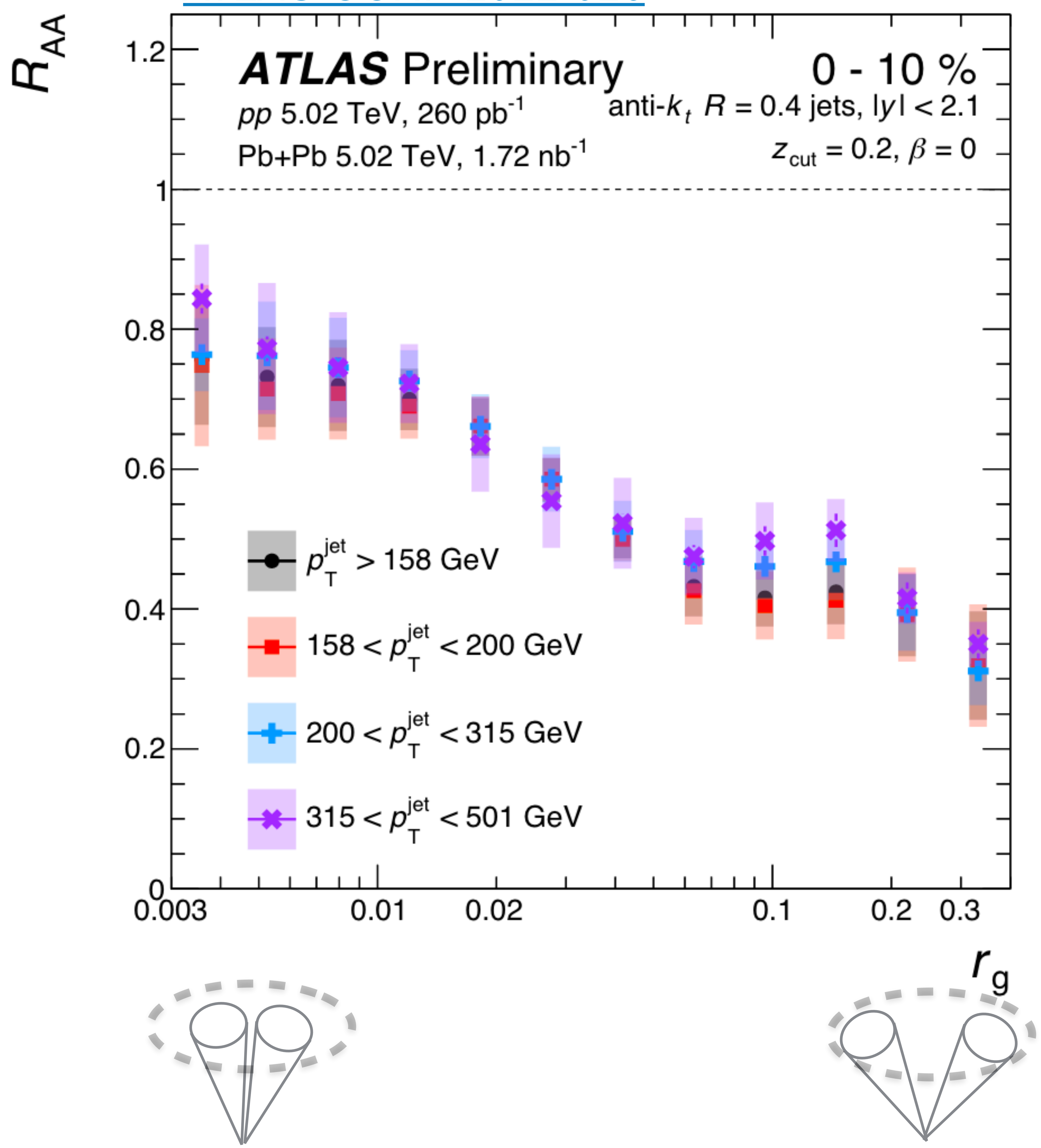


Jets with larger opening angles (large $\mathbf{r_g}$) lose more energy

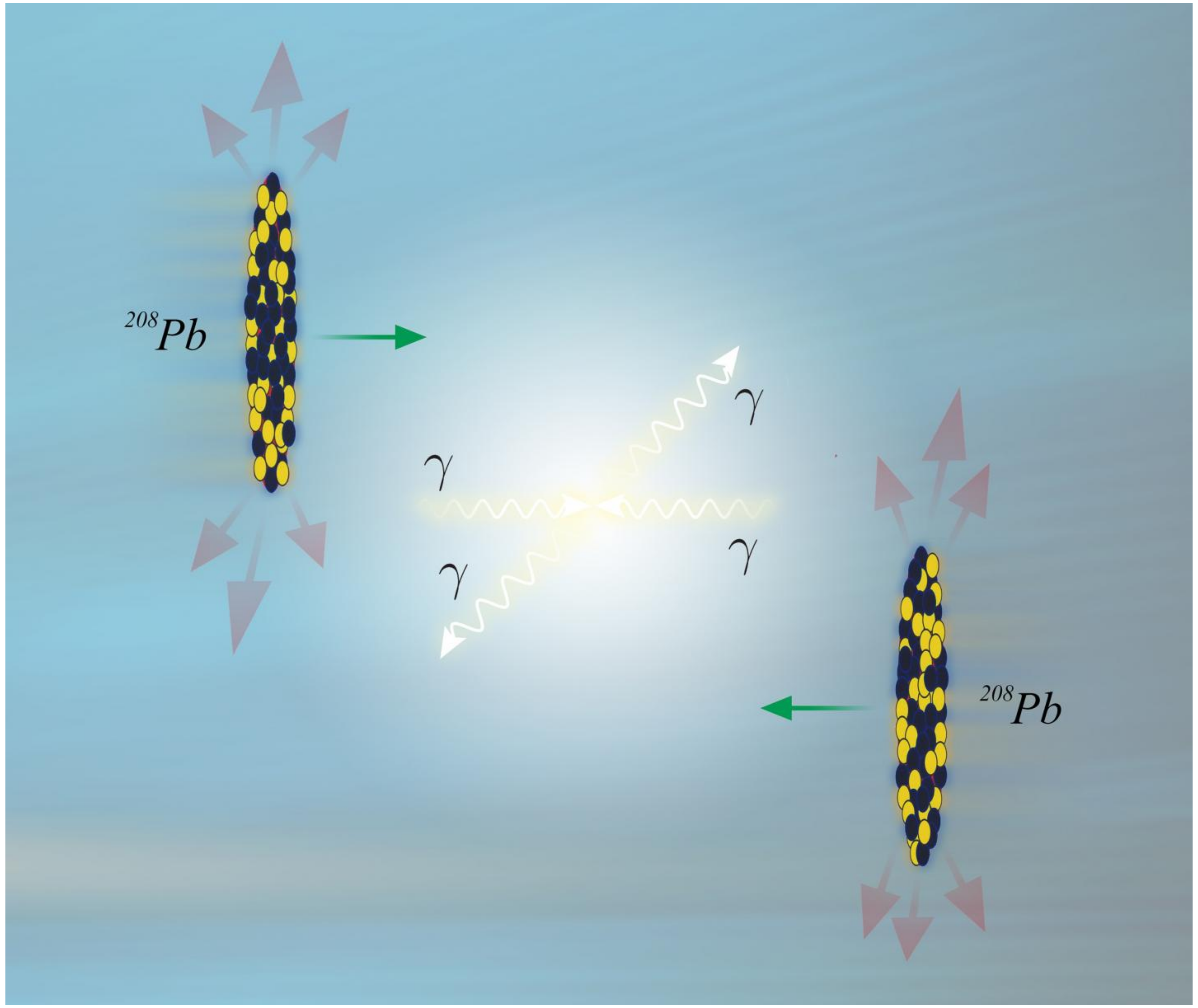
No strong jet p_T dependence in R_{AA} at a given r_g

ATLAS-CONF-2022-026

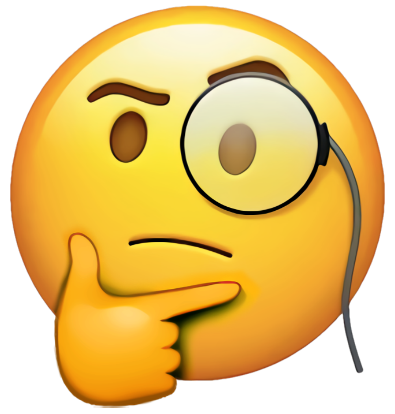


Probes of nuclear parton distribution function (nPDF)

Hard Probes



Jets



Can we also study the initial state of the collisions?
.. how about using ultra-peripheral collisions (UPC)?

Photo-nuclear Dijet Production

- Constrain **nPDFs** with di-jets produced in **UPC** collisions

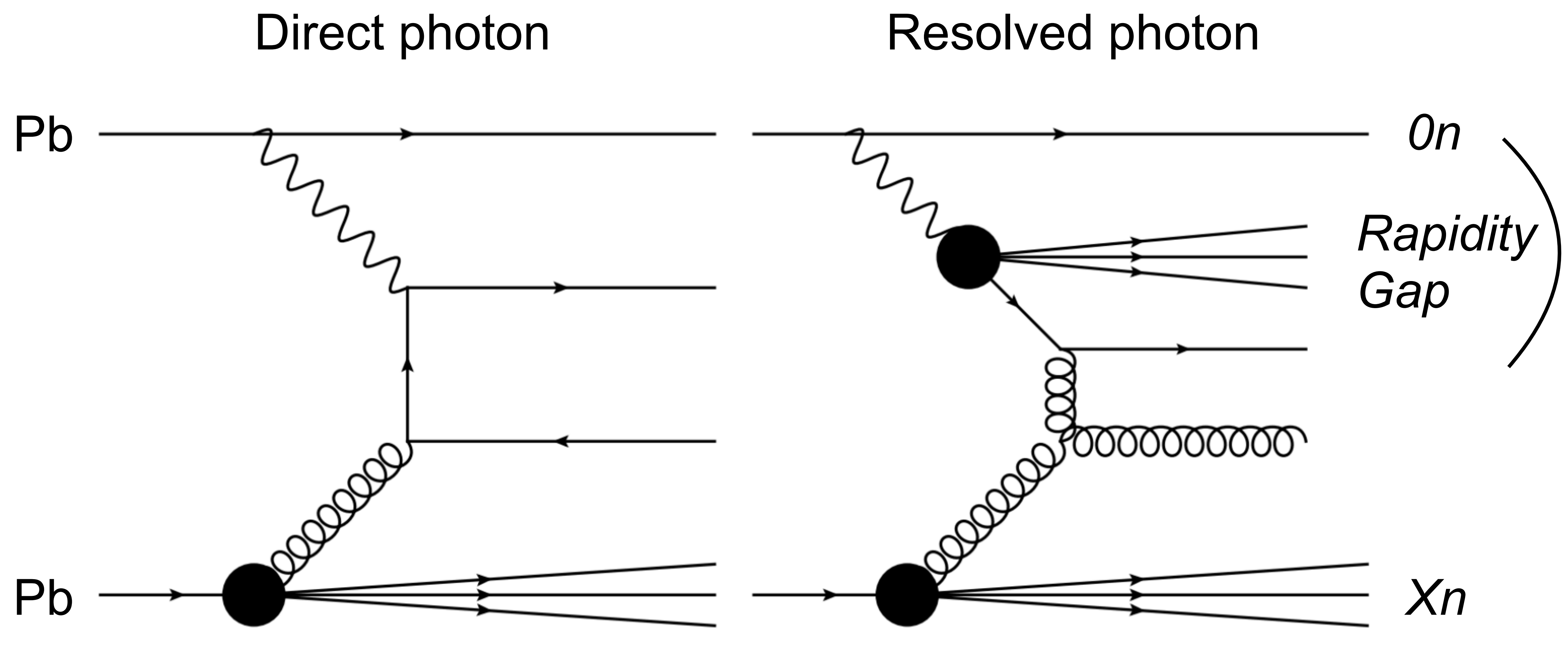
  ➡ triple-differential cross sections measured

ATLAS-CONF-2022-021

Nuclear momentum fraction $x_A \equiv \frac{M_{\text{jets}}}{\sqrt{s}} e^{-y_{\text{jets}}}$

Photon parton momentum fractions $z_\gamma \equiv \frac{M_{\text{jets}}}{\sqrt{s}} e^{+y_{\text{jets}}}$

Total transverse momenta of the jets $H_T \equiv \sum_i p_{T,i}$



Jet kinematics correspond to hard scattering kinematics

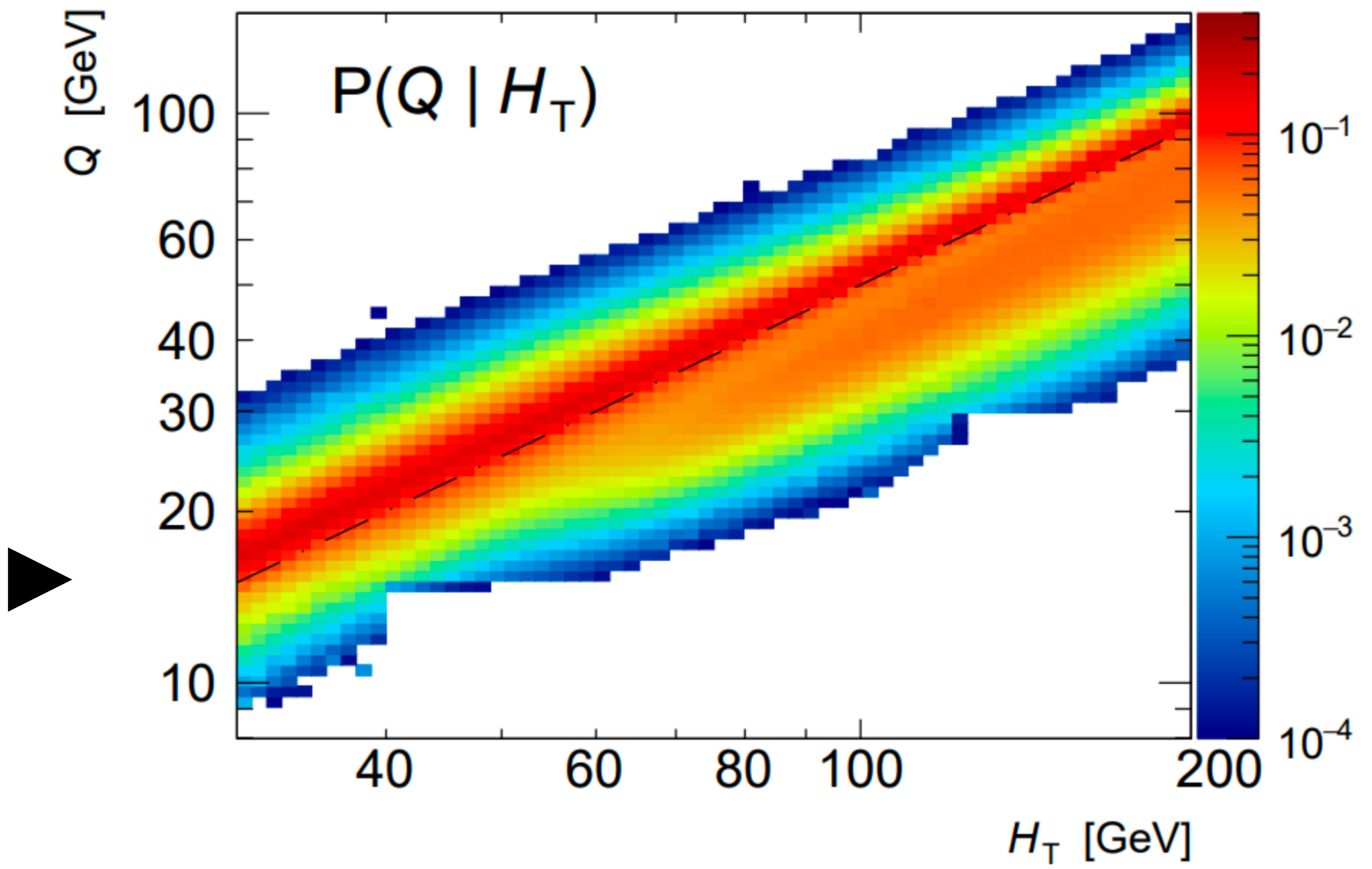
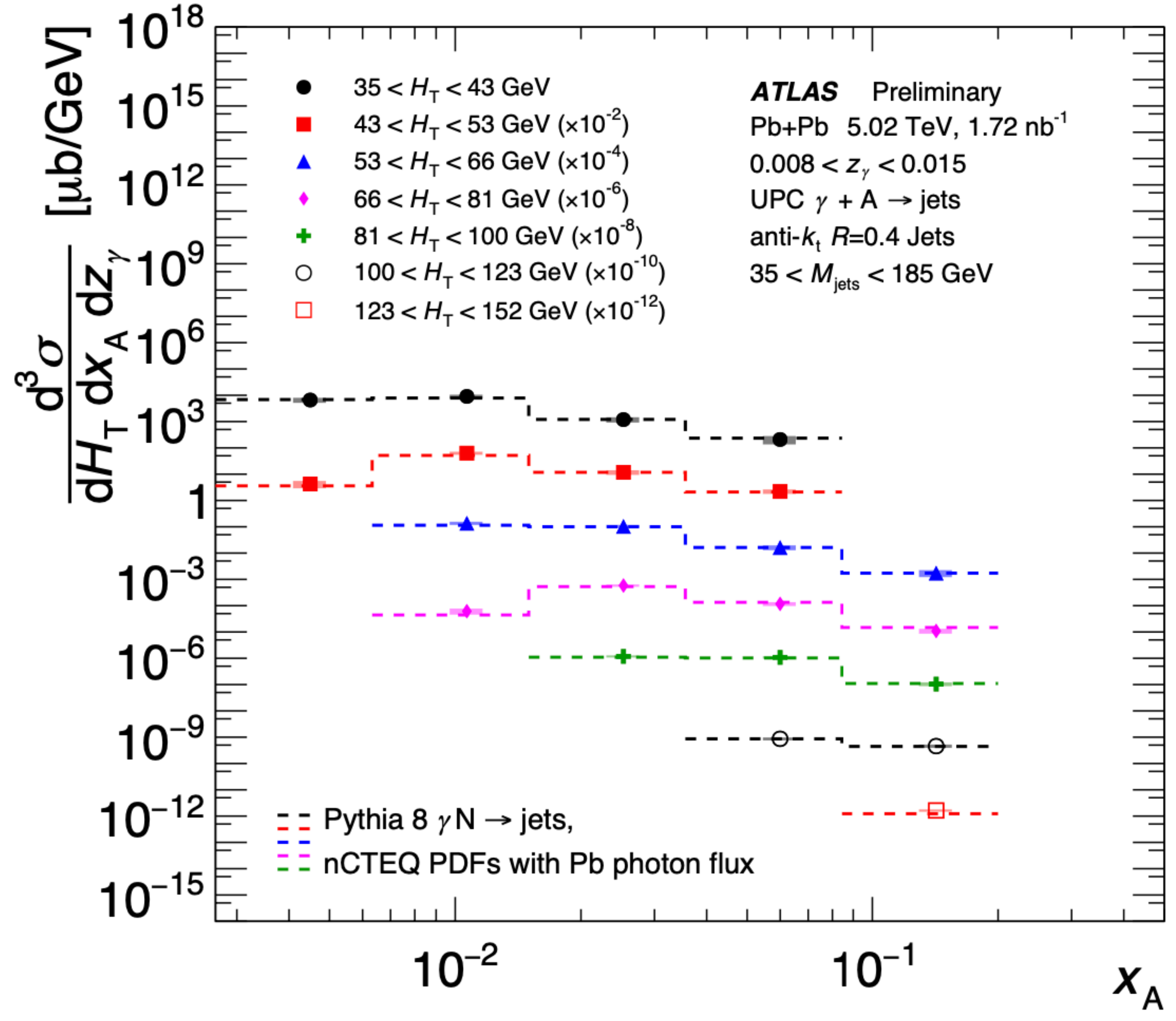
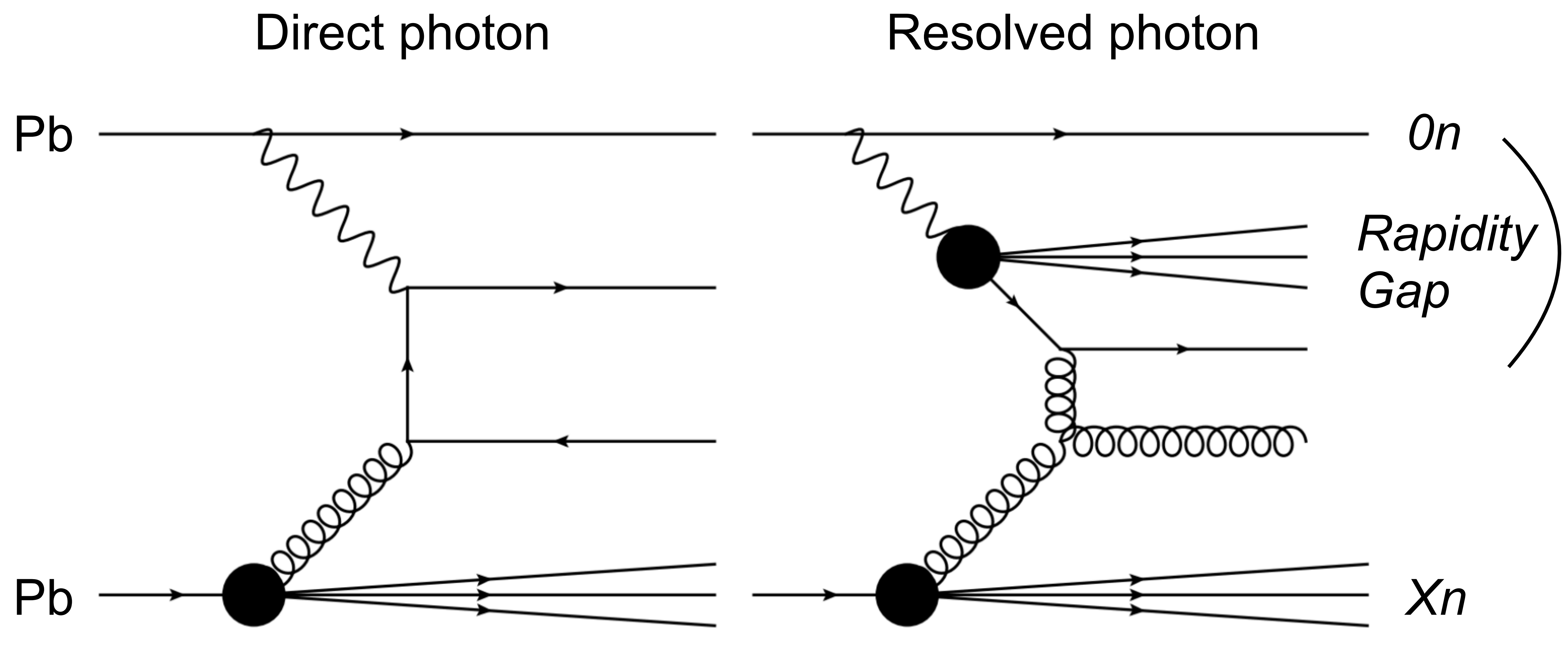


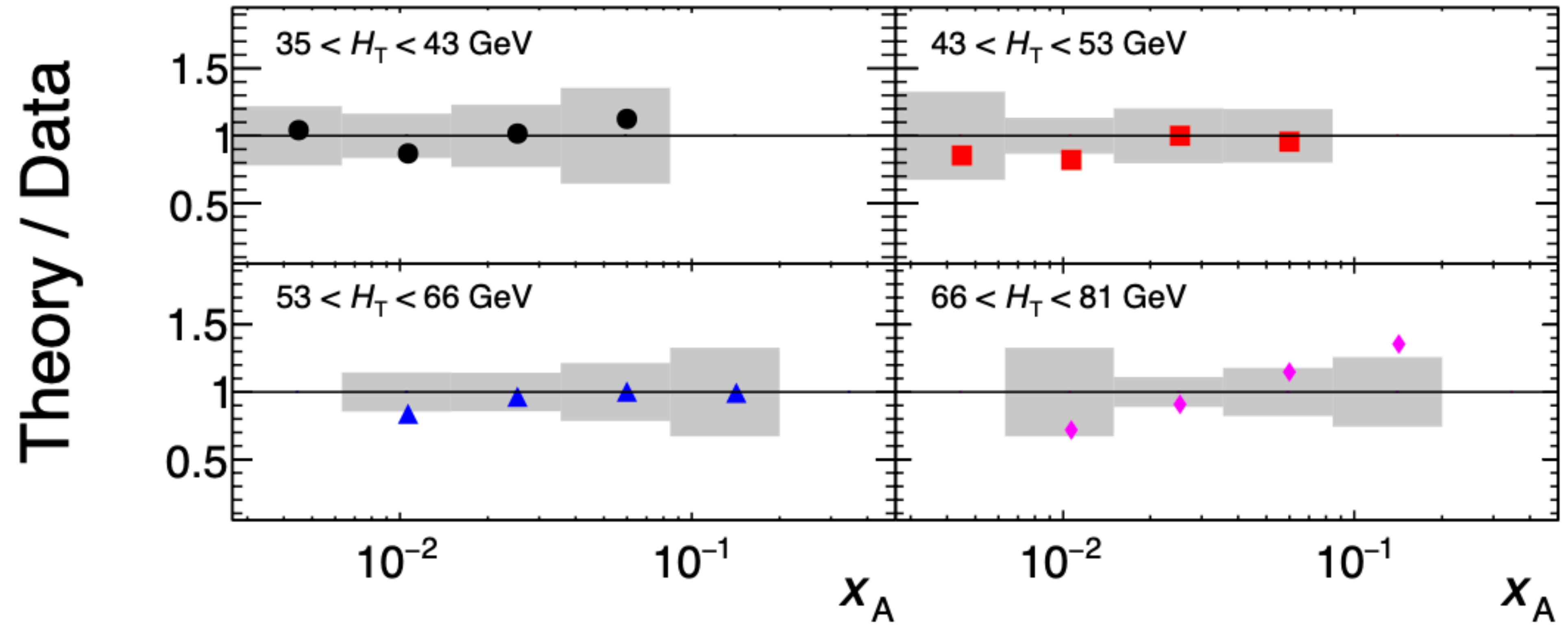
Photo-nuclear Dijet Production

- Constrain **nPDFs** with di-jets produced in **UPC** collisions [*ATLAS-CONF-2022-021*]
  - ➡ triple-differential cross sections measured





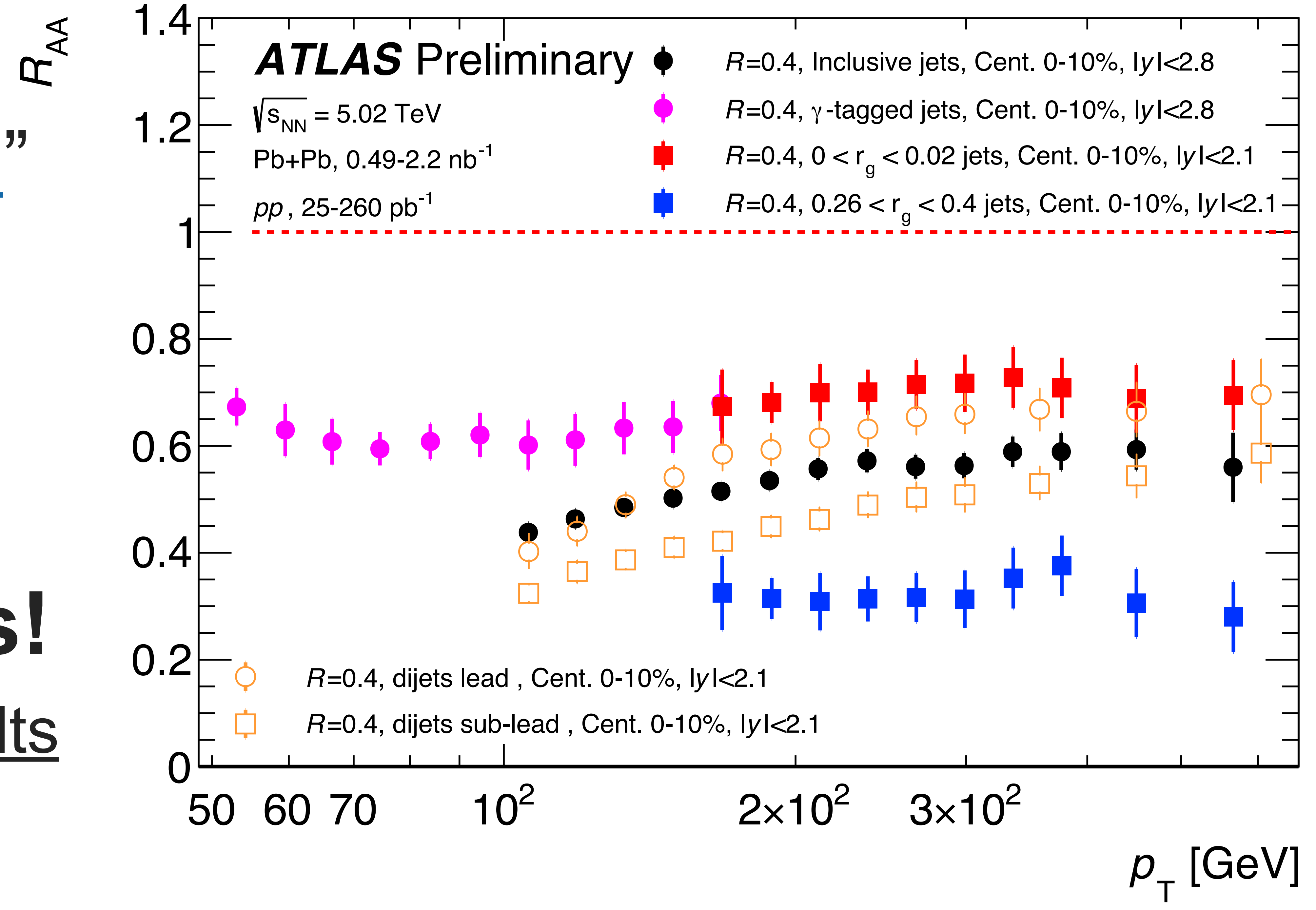
Provide limits on nPDFs



Summary

- Various ***ATLAS*** measurements in heavy ion collisions to study *quark gluon plasma* and *nuclear modifications*
  - ➡ different partonic energy loss between quarks vs. gluons ← ***photon-tagged jets, b-jets***
  - ➡ parton mass hierarchy and sequential suppression ← ***heavy flavor muons, Upslions***
  - ➡ color (de)coherence and jet hard splittings ← ***jet substructure***
  - ➡ constraining nPDF at small x ← ***di-jets in UPC collisions***

ATL-PHYS-PUB-2022-020



- "Recent ATLAS measurements in small collision systems" presented by Sruthy Das on Tue. at 10:50am

Find other interesting ATLAS EXPERIMENT *heavy ion* results!

https://twiki.cern.ch/twiki/bin/view/AtlasPublic/HeavyIonsPublicResults

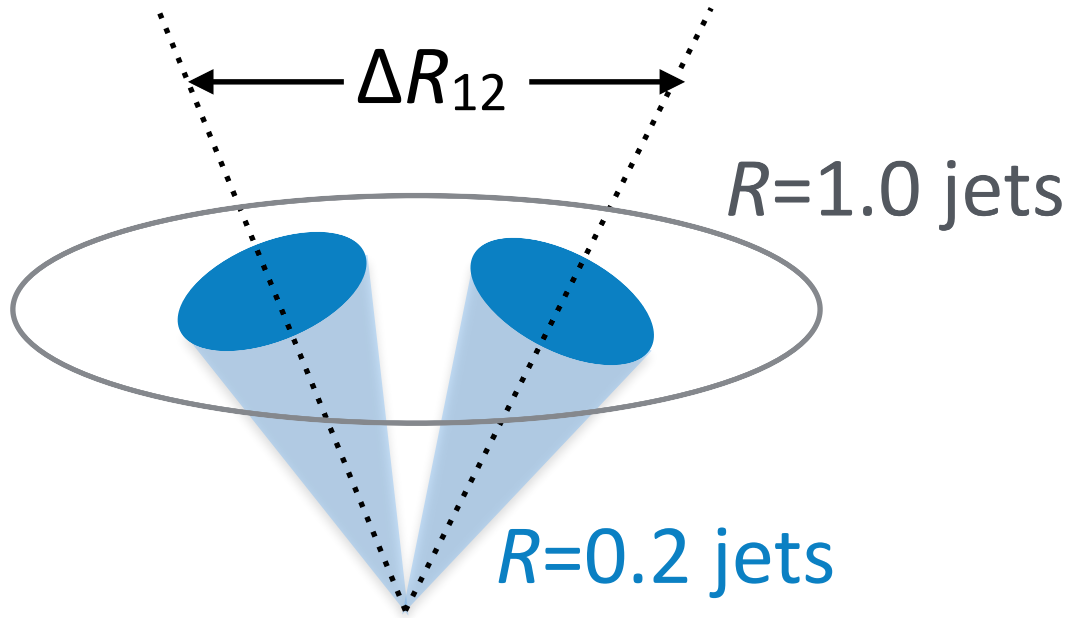
BACK UP

Re-clustered Large-radius jets

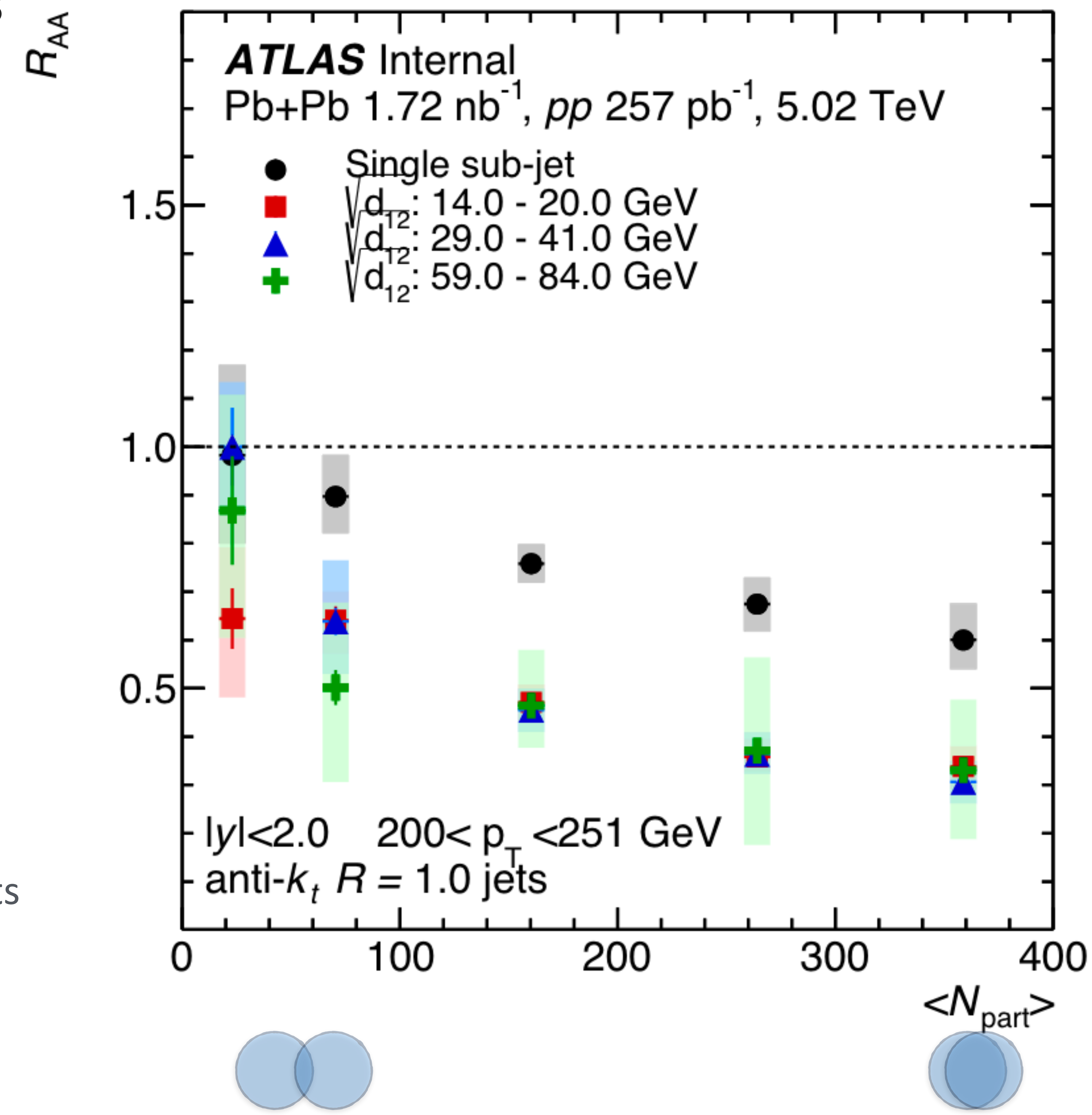
- **Hard parton splitting** using re-clustered R=1.0 jets

*A **continuous increase** of the suppression with increasing centrality*

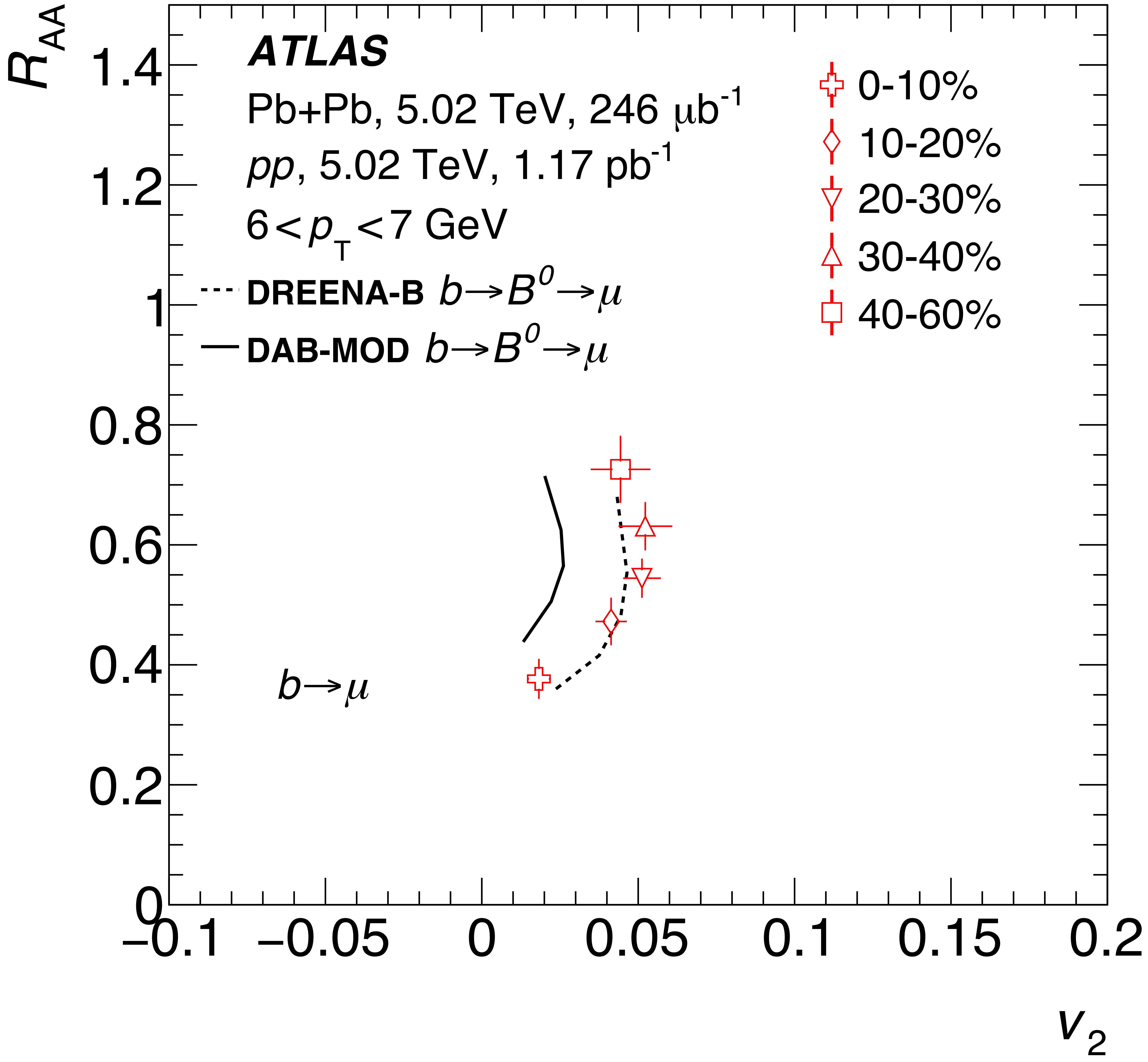
$$\sqrt{d_{12}} = \min(p_{\mathrm{T},1}, p_{\mathrm{T},2}) \cdot \Delta R_{12}$$



ATLAS-CONF-2019-056



Heavy Flavour



[Phys. Lett. B 829 (2022) 137077](#)

[Phys. Lett. B 807 (2020) 135595](#)

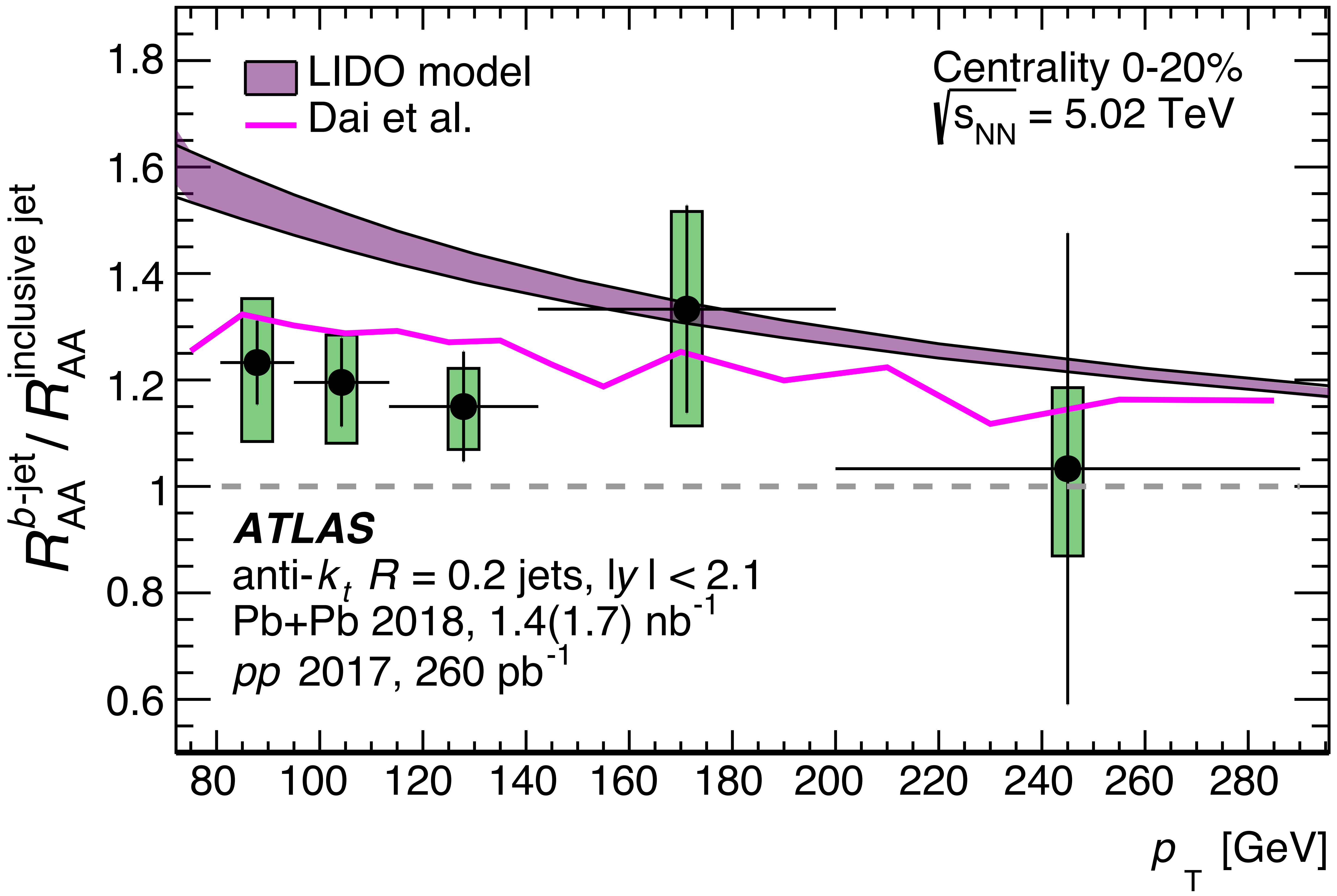
R_{AA} vs v_2

simultaneous description of R_{AA} and v_2 can constraint models!

b-Jet R_{AA}

- **Color-charge** and **parton mass dependence** of energy loss

arXiv:2204.13530



RAA (b-jet) / RAA (inc. jet)

~20% above unity

for both the data and calculations