Systematic studies of parton-Quark Gluon Plasma interactions with ATLAS

Qipeng Hu, LLNL

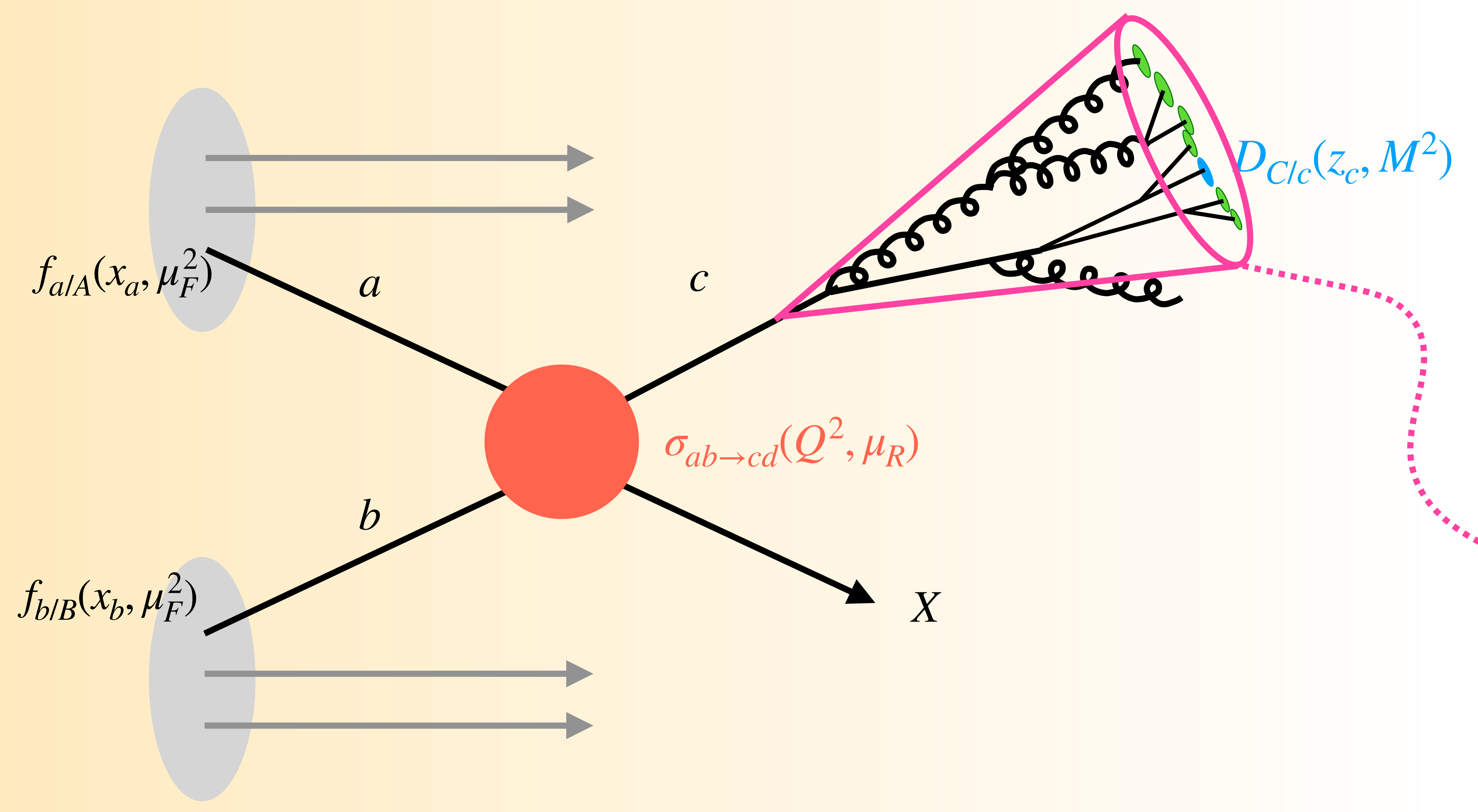
For the ATLAS Collaboration

LHC Seminar

May 10, 2022

QCD matter — Quark-gluon plasma (QGP)

QCD Parton model in vacuum



QCD factorization theorem (leading twist):

$$\mathrm{d}\sigma(A + B \to C + X) = f_{a/A}(x_a, \mu_F^2) \otimes f_{b/B}(x_b, \mu_F^2) \otimes \mathrm{d}\sigma_{ab\to cd}(Q^2 . \mu_R) \otimes D_{C/c}(z_c, M^2)$$

Perturbative QCD (pQCD) is used to calculate

- Partonic cross section

Non-perturbative, universal

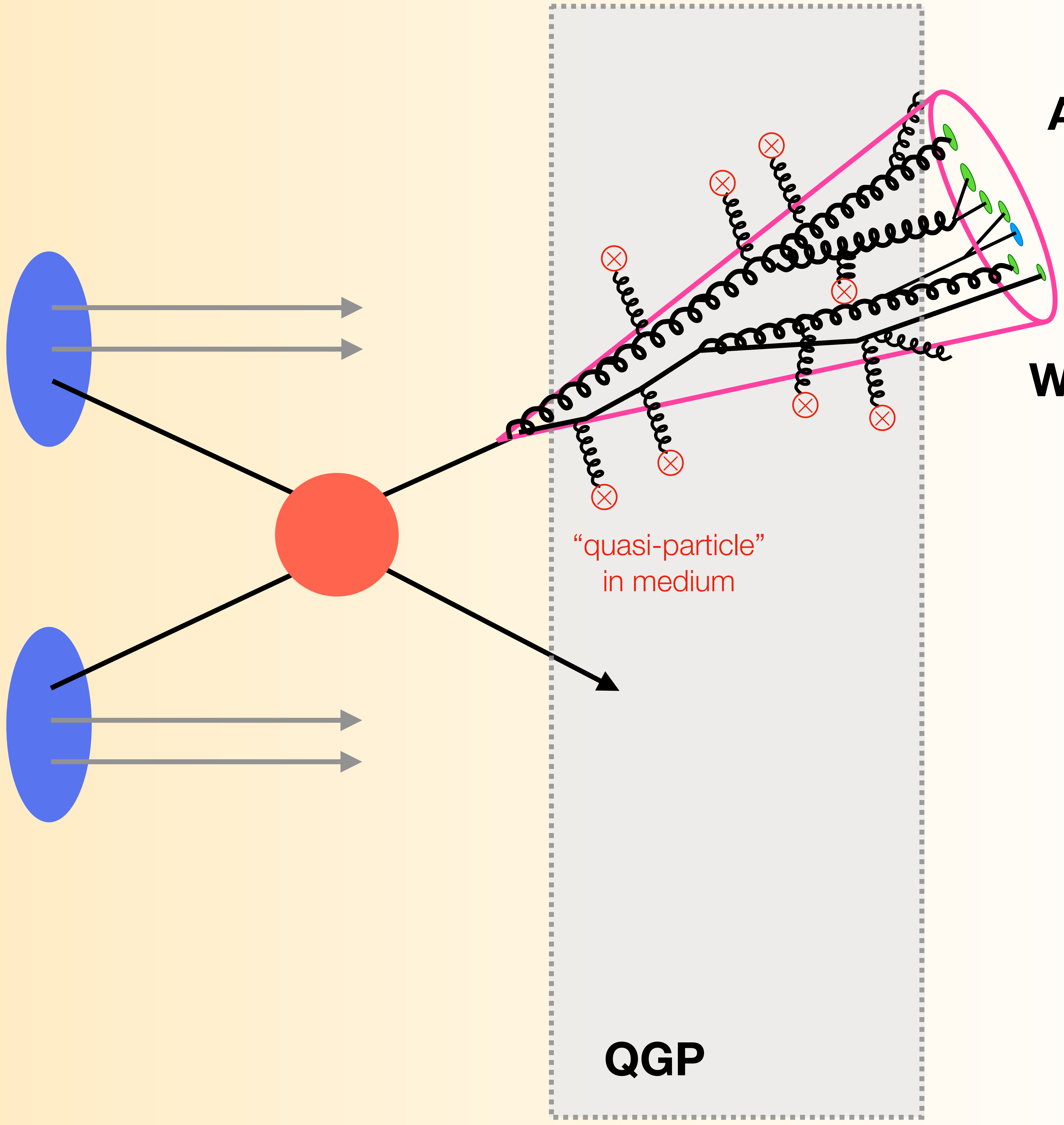
- Parton distribution functions (PDF)
- Fragmentation function (FF)

Factorization scale μ_F

Renormalization scale μ_R

Jet: access the whole shower of initial parton

QCD factorization in medium



QCD factorization in vacuum:

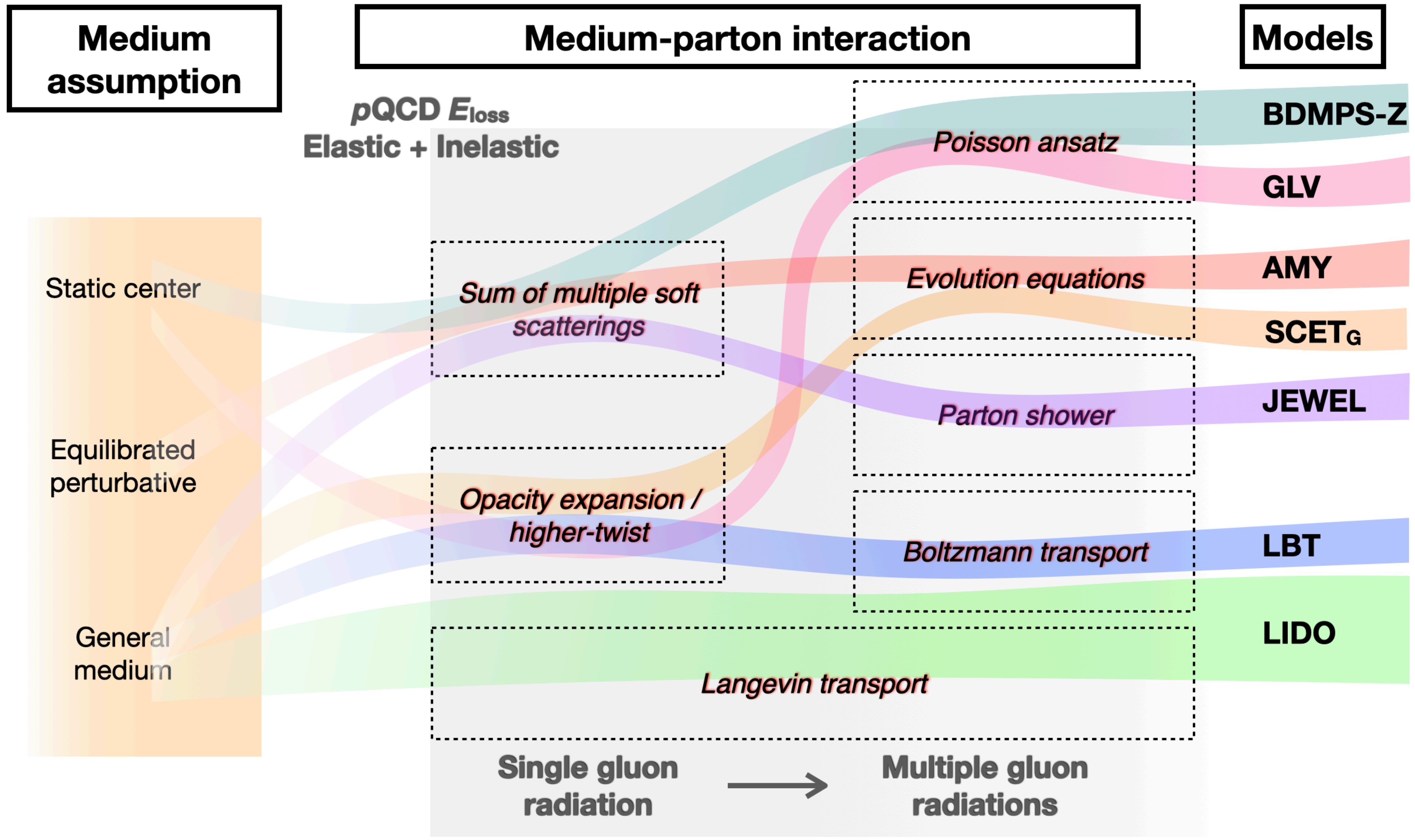
$$d\sigma(A+B\to C+X) = f_{a/A}(x_a,\mu_F^2)\otimes f_{b/B}(x_b,\mu_F^2)\otimes d\sigma_{ab\to cd}(Q^2\,.\,\mu_R)\otimes D_{C/c}(z_c,M^2)$$

Parton-medium interaction

Assumed QCD factorization in QGP:

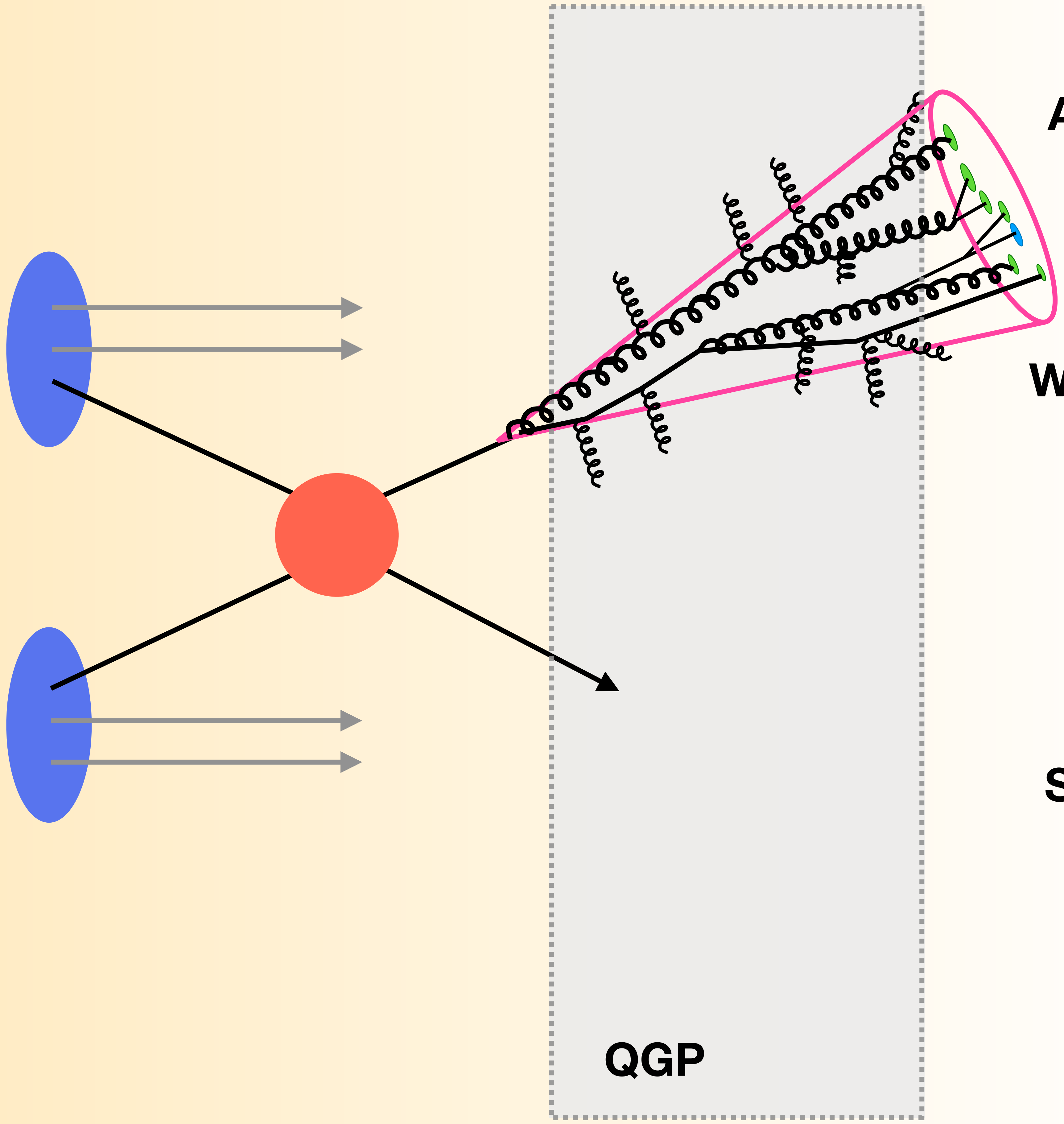
$$d\sigma(A+B\to C+X)\big|_{\rm geometry} = f^{A,Z}_{a/A}(x_a,\mu_F^2)\otimes f^{A,Z}_{b/B}(x_b,\mu_F^2)\otimes d\sigma_{ab\to cd}(Q^2\,.\,\mu_R)\otimes P_{c\to c'}(T_{QGP})\otimes D_{C/c'}(z_{c'},M^2)$$

Weakly coupled approach



*** Many models are more advanced than shown here

QCD factorization in medium — Cont.



QCD factorization in vacuum:

$$d\sigma(A+B\to C+X) = f_{a/A}(x_a,\mu_F^2)\otimes f_{b/B}(x_b,\mu_F^2)\otimes d\sigma_{ab\to cd}(Q^2\,.\,\mu_R)\otimes D_{C/c}(z_c,M^2)$$

Assumed QCD factorization in QGP:

Parton-medium interaction

$$d\sigma(A+B\to C+X)\big|_{\text{geometry}} = f^{A,Z}_{a/A}(x_a,\mu_F^2)\otimes f^{A,Z}_{b/B}(x_b,\mu_F^2)\otimes d\sigma_{ab\to cd}(Q^2\,.\,\mu_R)\otimes P_{c\to c'}(T_{QGP})\otimes D_{C/c'}(z_{c'},M^2)$$

Multiple scales involved:

- Vacuum QCD scales: μ_F, μ_R
- Medium scales: T, Λ_{med}, L_{path}, etc.
- Leading parton: m^2, $r_\perp$, etc

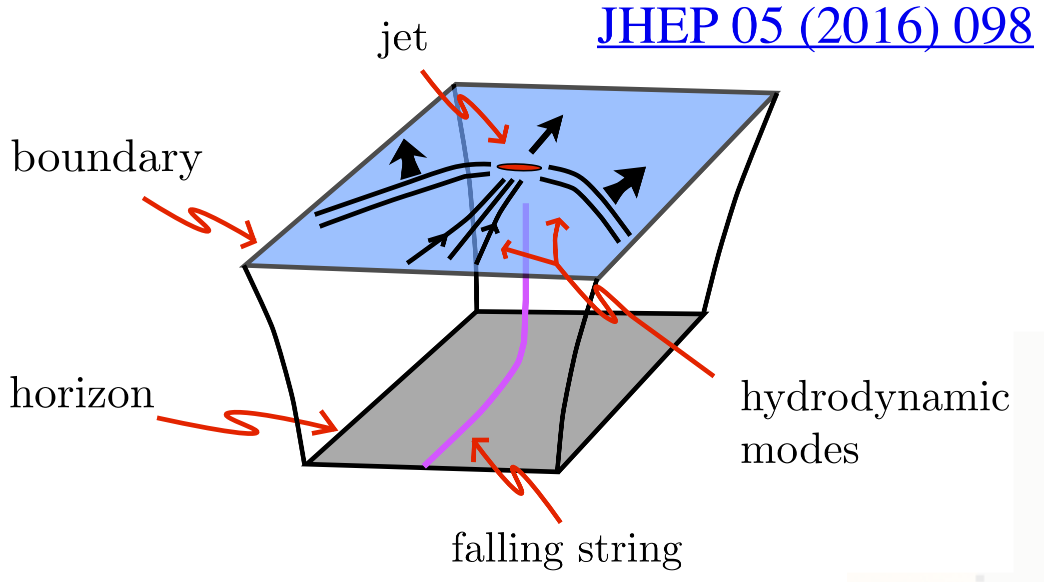
Weakly coupled approach

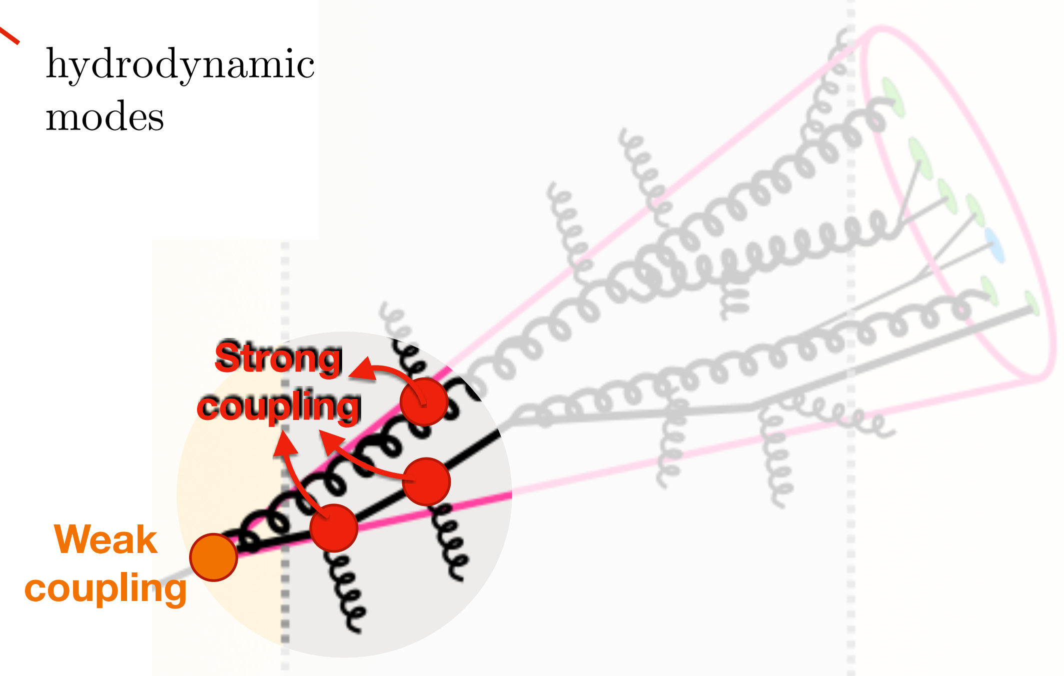
- Quenching formalism: BDMPS-Z, GLV, AMY, SCET$_G$ etc.
- Transport: LBT, LIDO etc.

Strongly coupled approach

- Holographic "jet"
- Strong/weak coupling hybrid

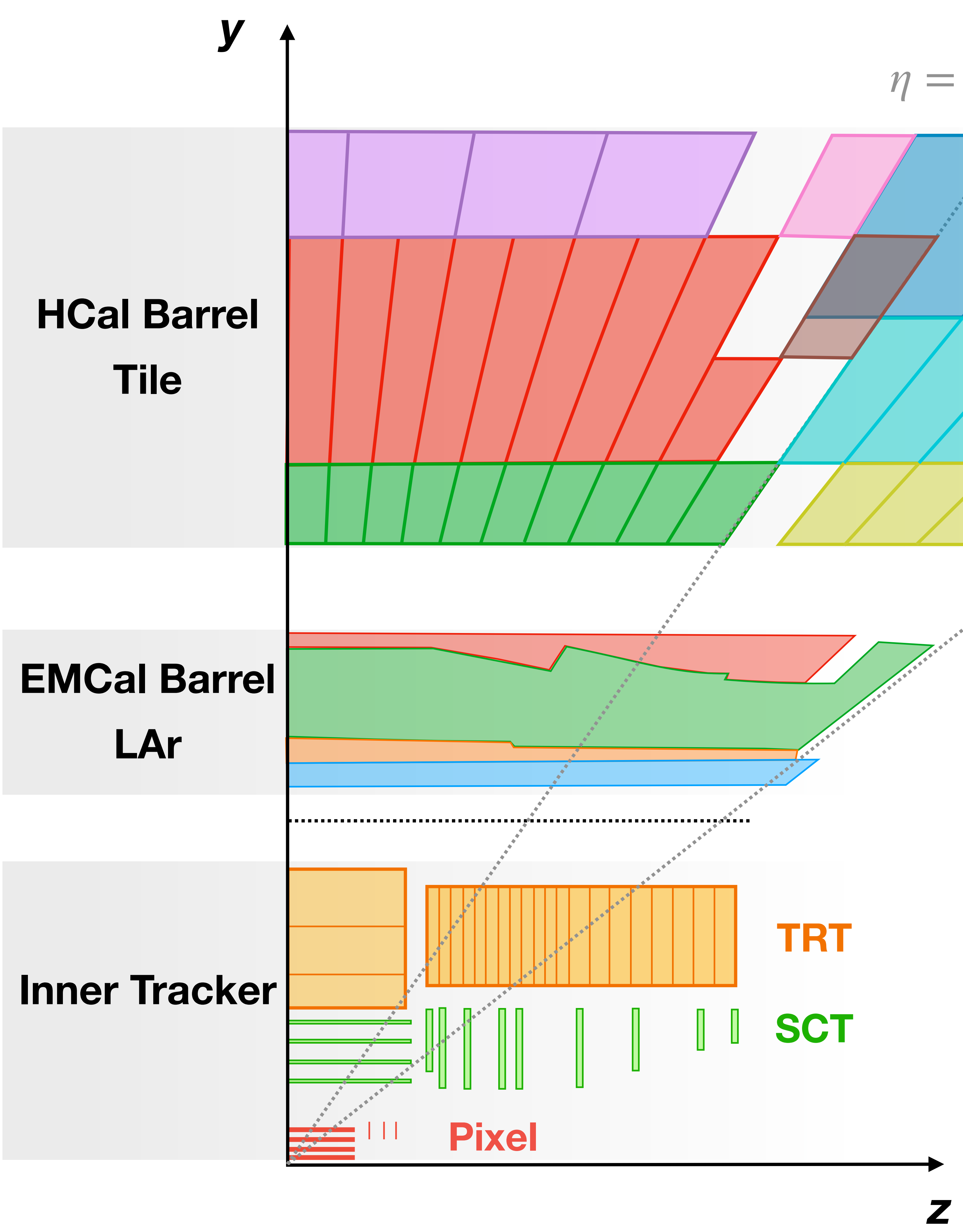
JHEP 05 (2016) 098

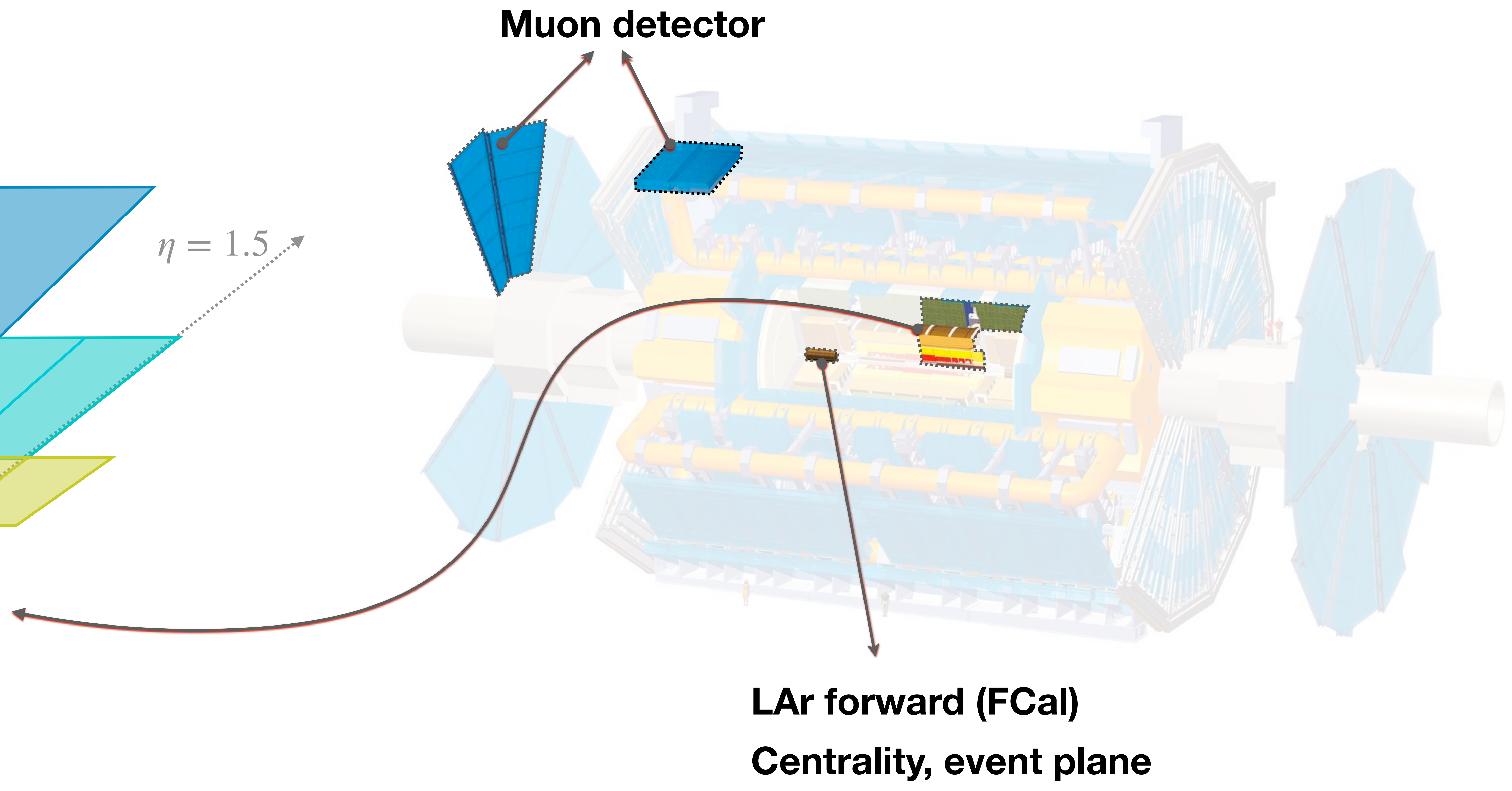




ATLAS detector

Simplified ATLAS detector geometry





2017 *pp* collisions, 5.02 TeV, $\int L\,\mathrm{d}t = 272\ \mathrm{pb}^{-1}$

2018 Pb+Pb collisions, 5.02 TeV, $\int L\,\mathrm{d}t = 1.76\ \mathrm{nb}^{-1}$

Centrality

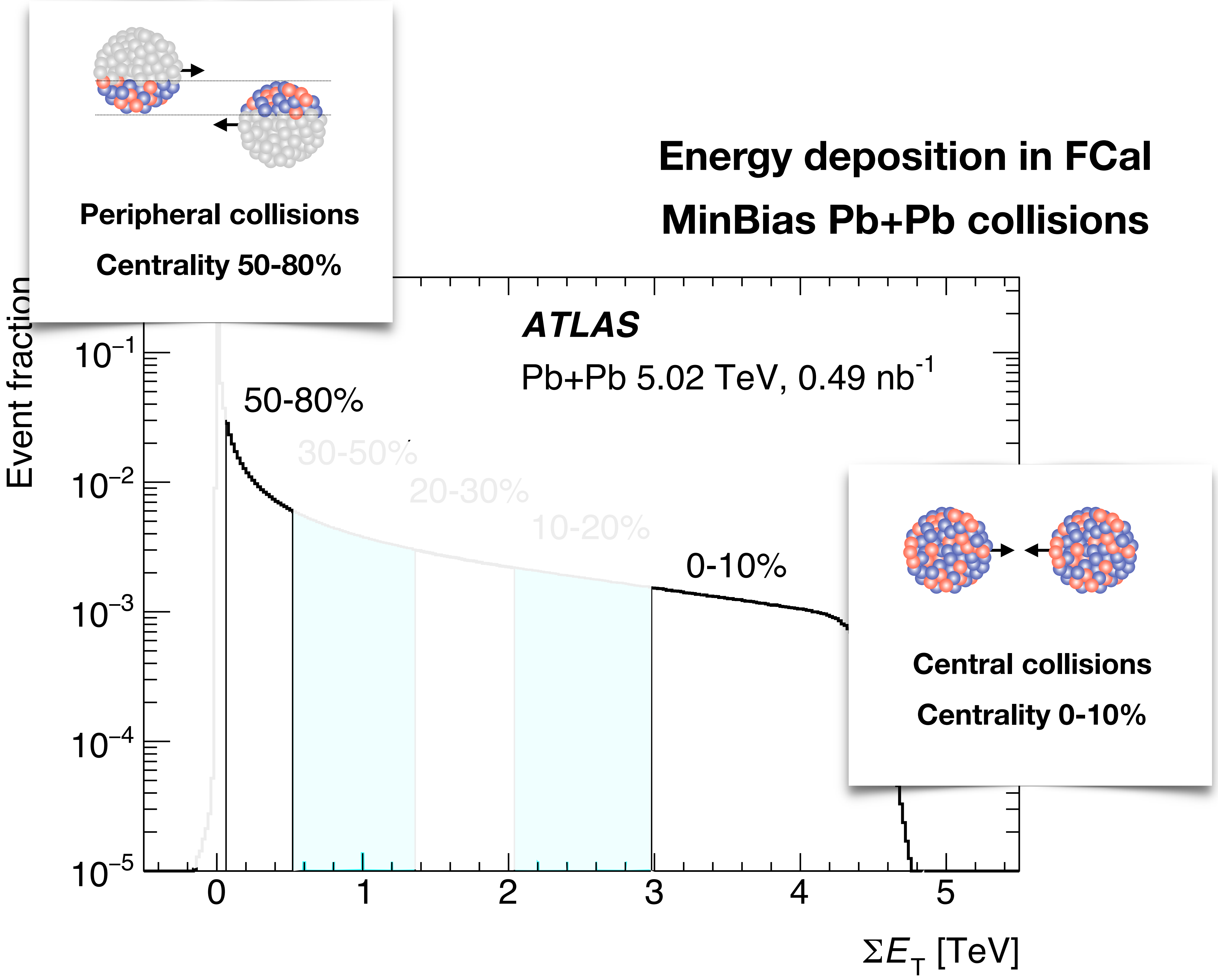
Phys. Lett. B 789 (2019) 167

Low activity

Low Number of binary ~ 50

Energy deposition in FCal

MinBias Pb+Pb collisions

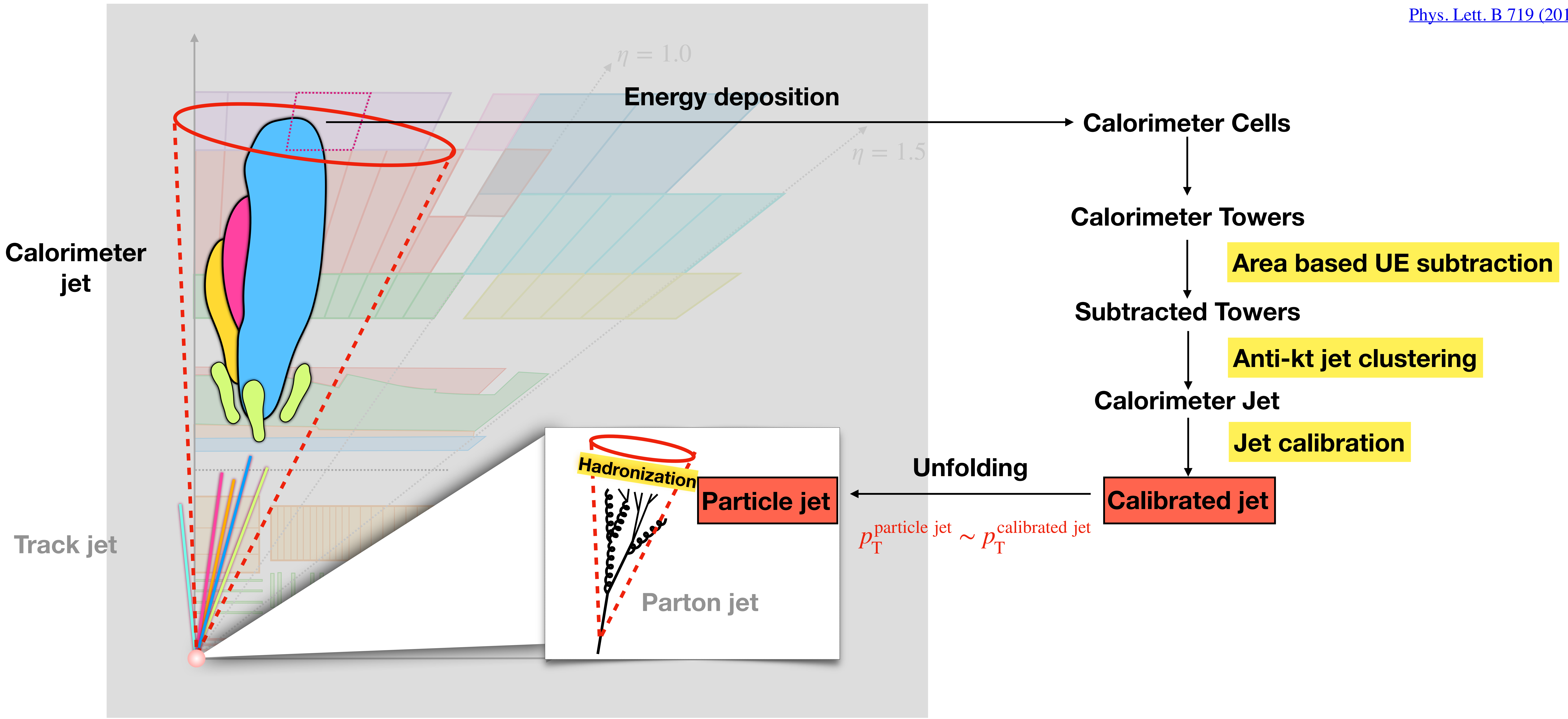


10% events with highest activities

High Number of binary collisions ~ 1600

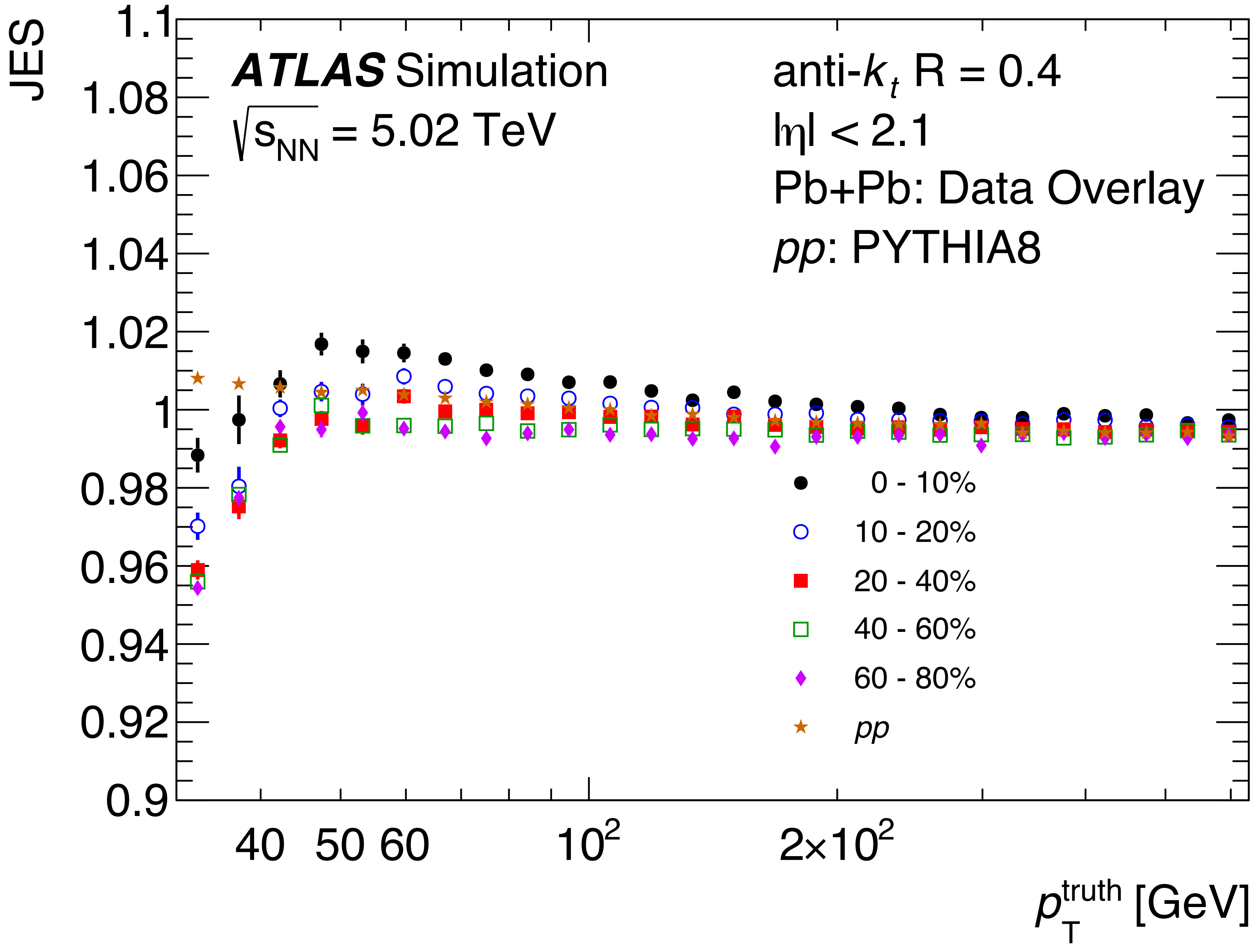
Jet reconstruction — Heavy ion version

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

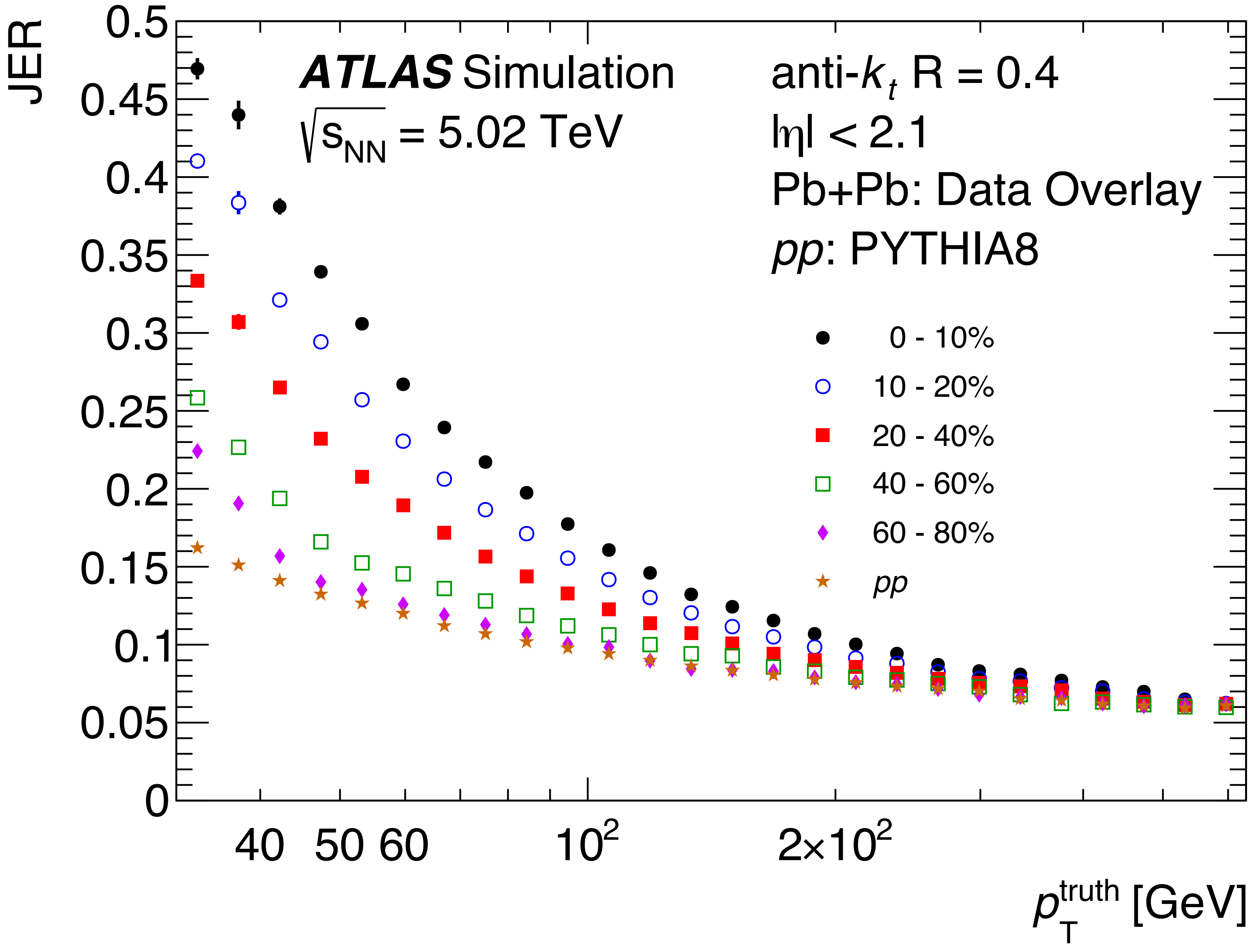


Jet performance in heavy ion collisions

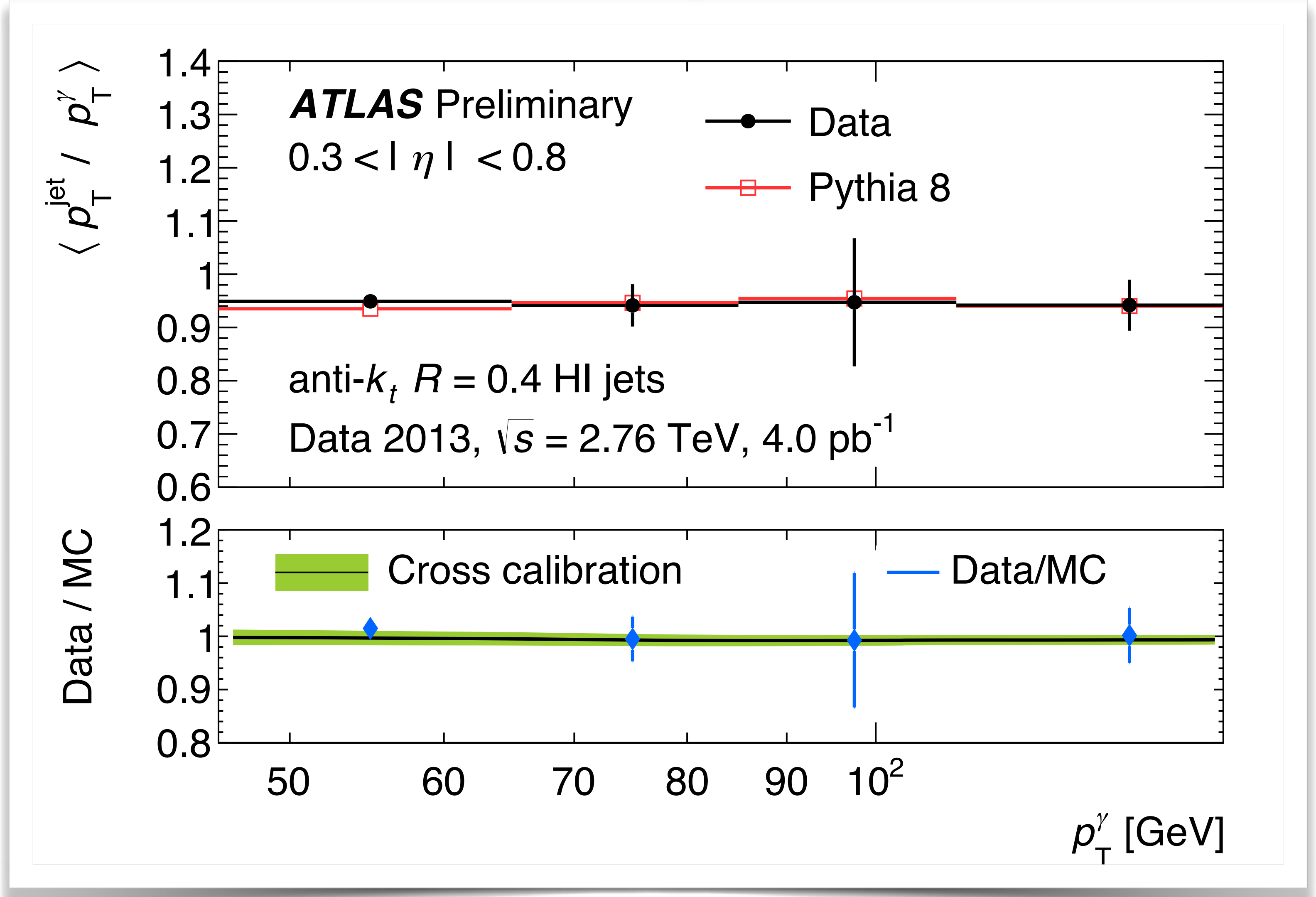
arXiv:2205.00682
ATLAS-CONF-2015-016/



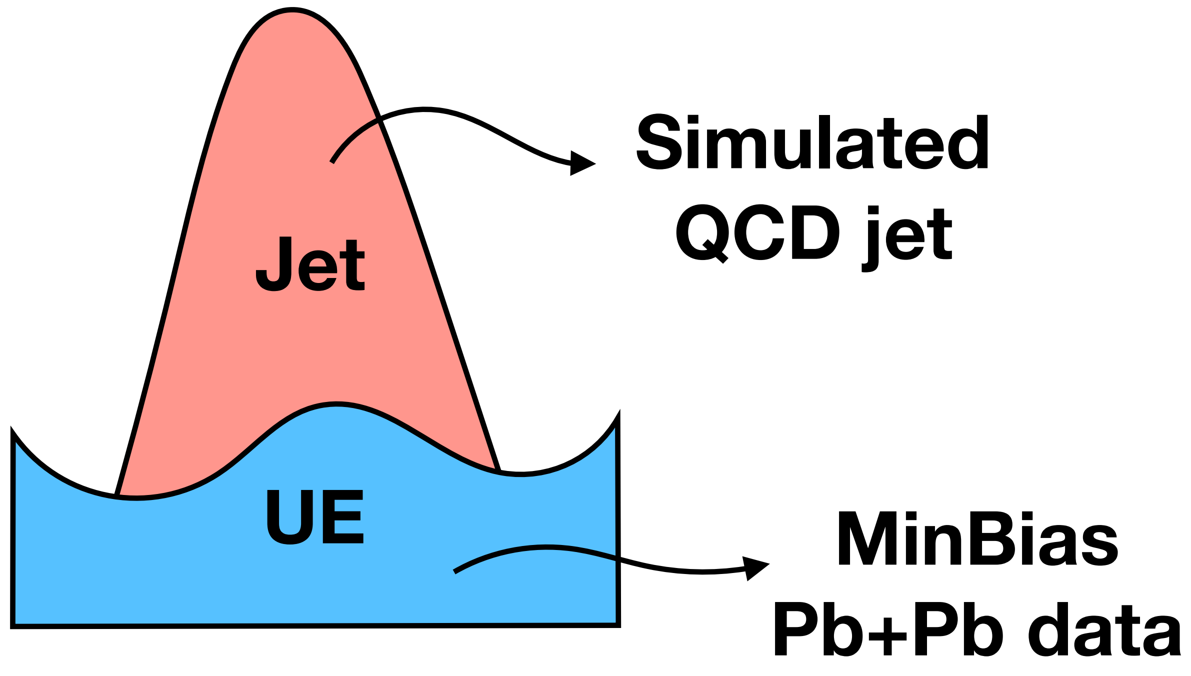
Jet Energy Scale (JES)



Jet Energy Resolution (JER)

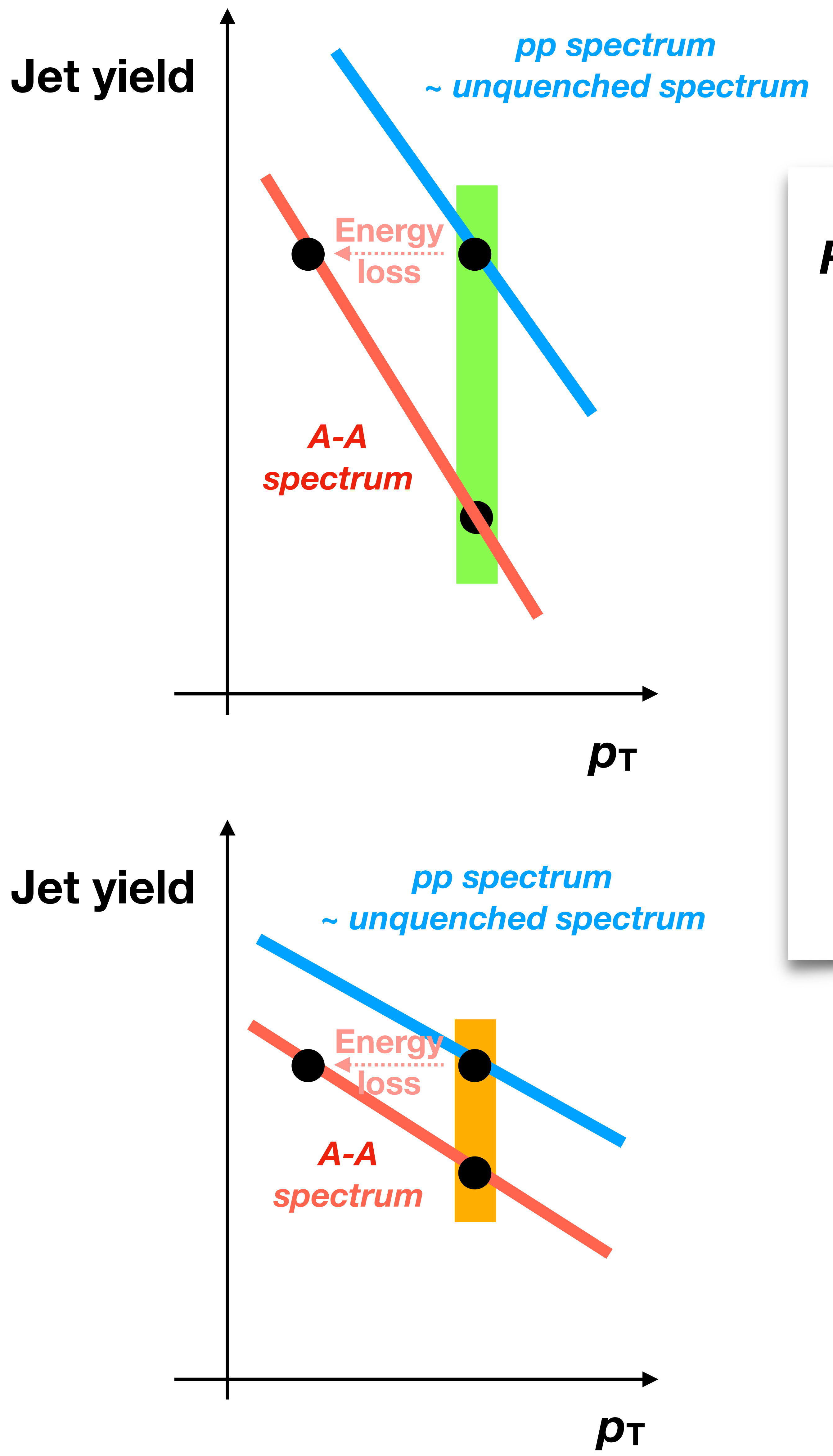


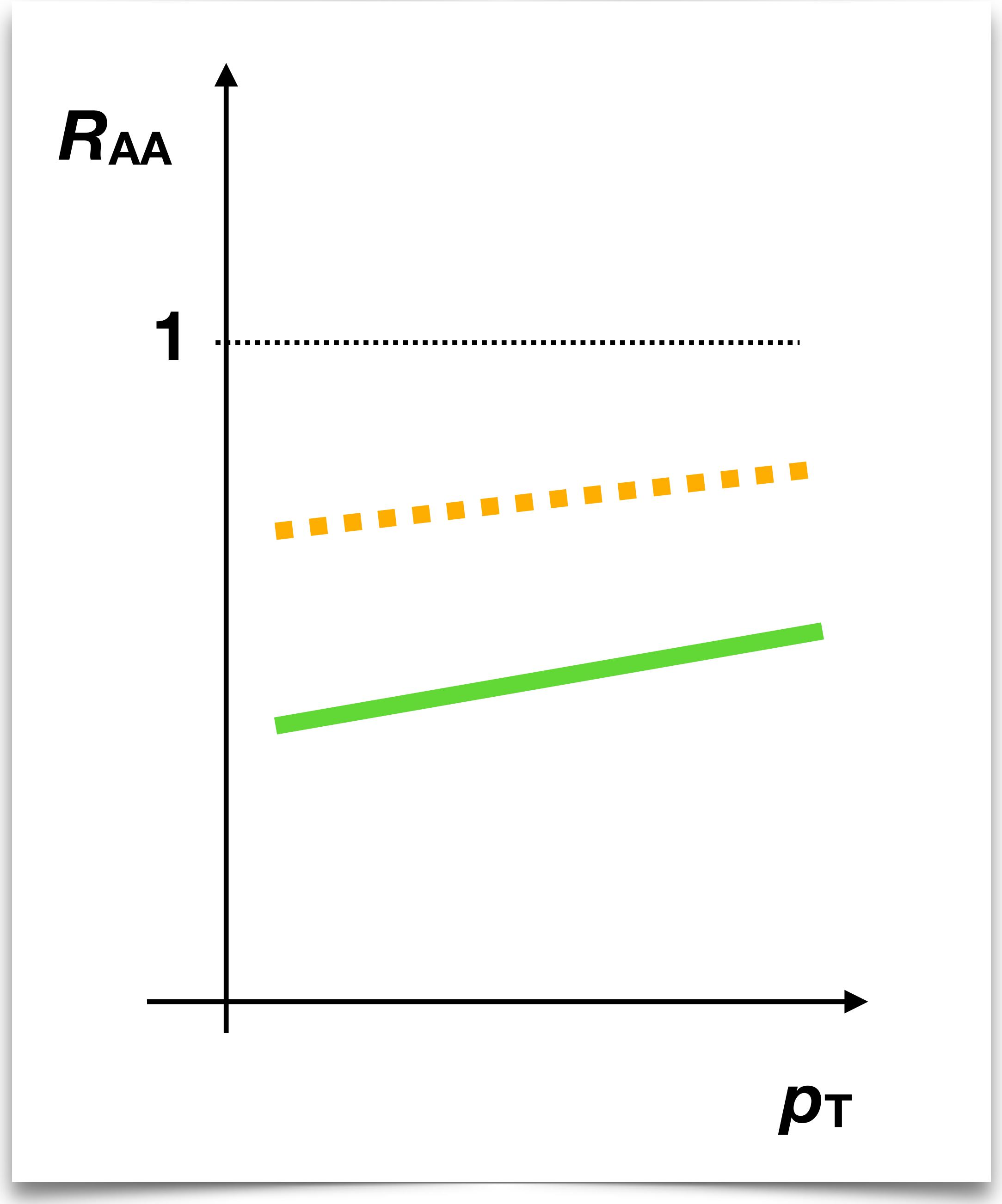
Good Data/MC agreement



Measuring jet quenching

PLB 790 (2019) 108





Jet production: heavy ion (**A-A**) collisions vs. ***pp*** collisions

Nuclear modification factor $R_{\rm AA} = \frac{\text{per-NN yields in A-A}}{\text{yields in } pp}$

$R_{\rm AA} < 1$ due to jet-QGP interaction: jets in A-A collisions are suppressed / **quenched**

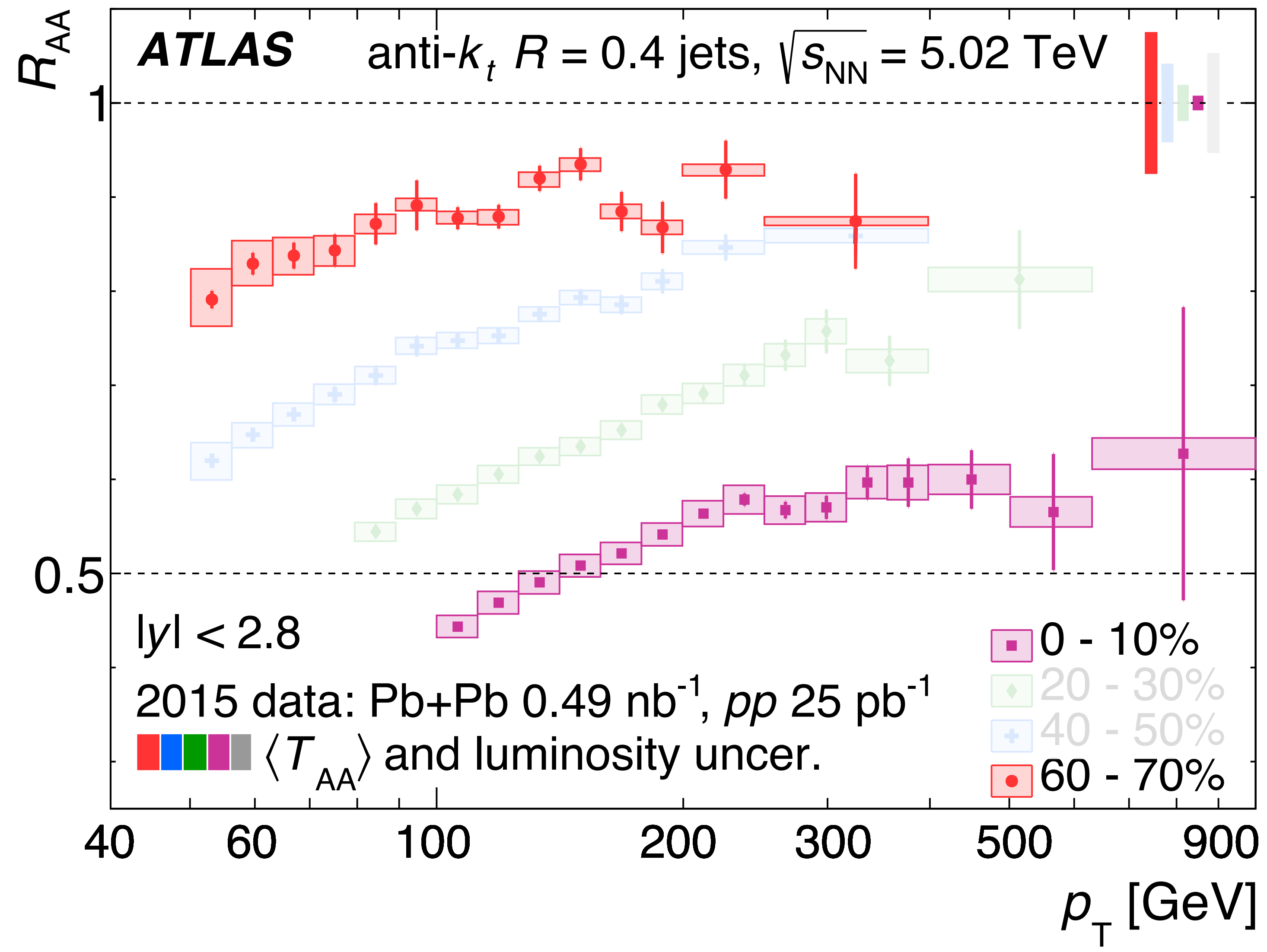
$R_{\rm AA}$ depends on:

- Energy loss
- Jet spectrum before quenching

What we learnt from inclusive jet quenching

PLB 790 (2019) 108
Phys. Rev. C 98 (2018) 024908
Phys. Rev. C 100 (2019) 064901

Modifications in Spectrum

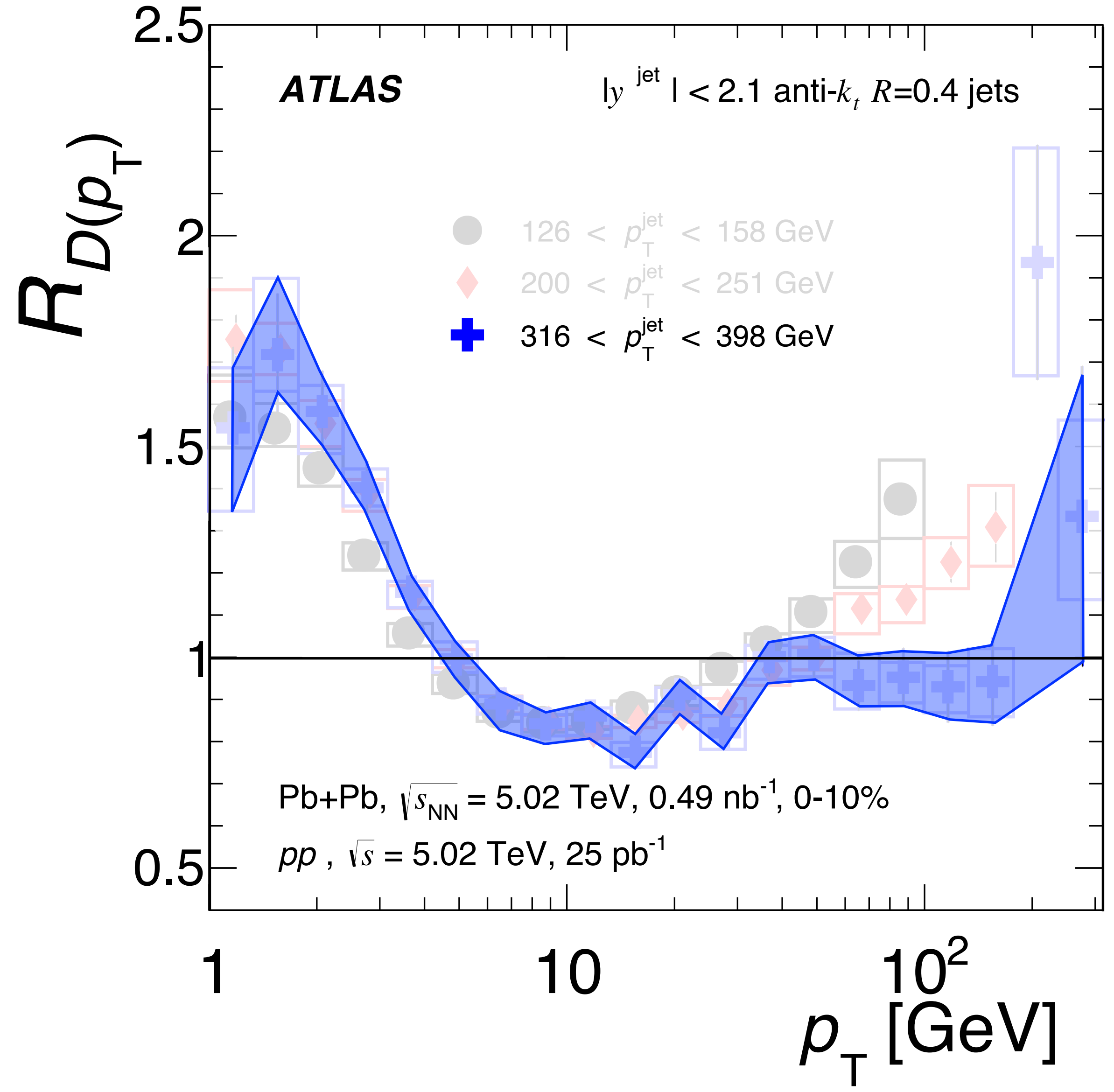


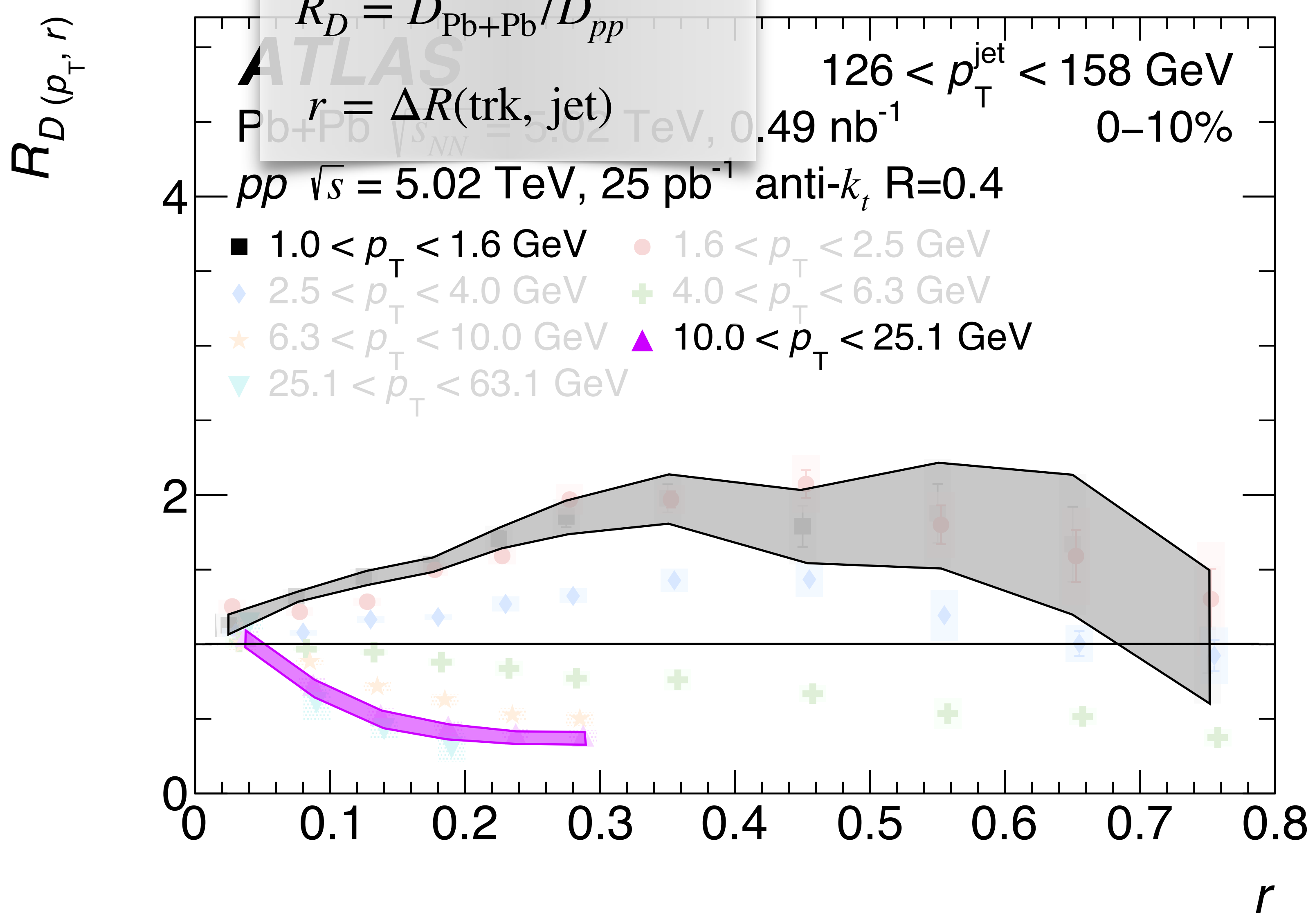
Modifications in jet fragmentation

$$D(p_T, r) \propto \frac{1}{N_{jet}} \frac{d^2 n_{trk}}{dp_T^{trk}\, dr}$$

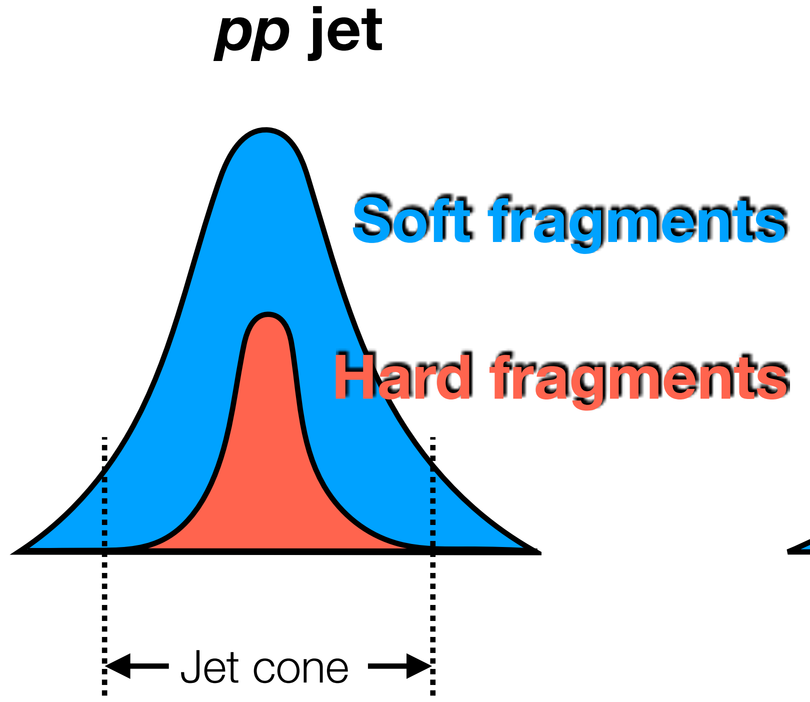
$$R_D = D_{Pb+Pb}/D_{pp}$$

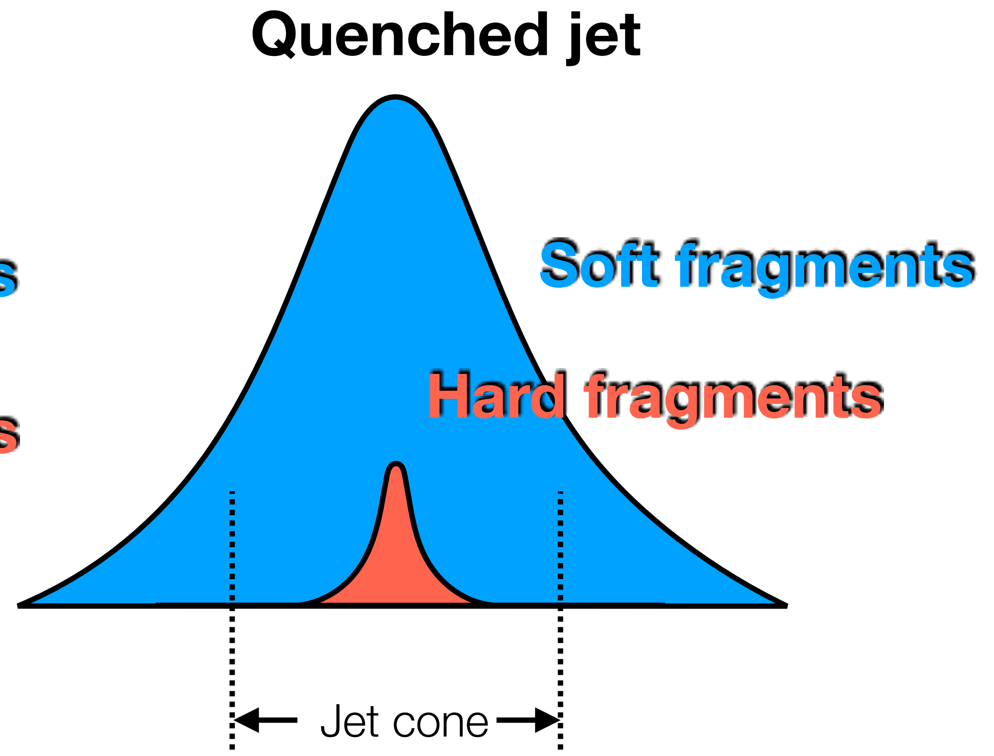
$$r = \Delta R(\text{trk, jet})$$





Jets are quenched in Pb+Pb, suppressed by a factor of 2 in central collisions





Quenched jet:

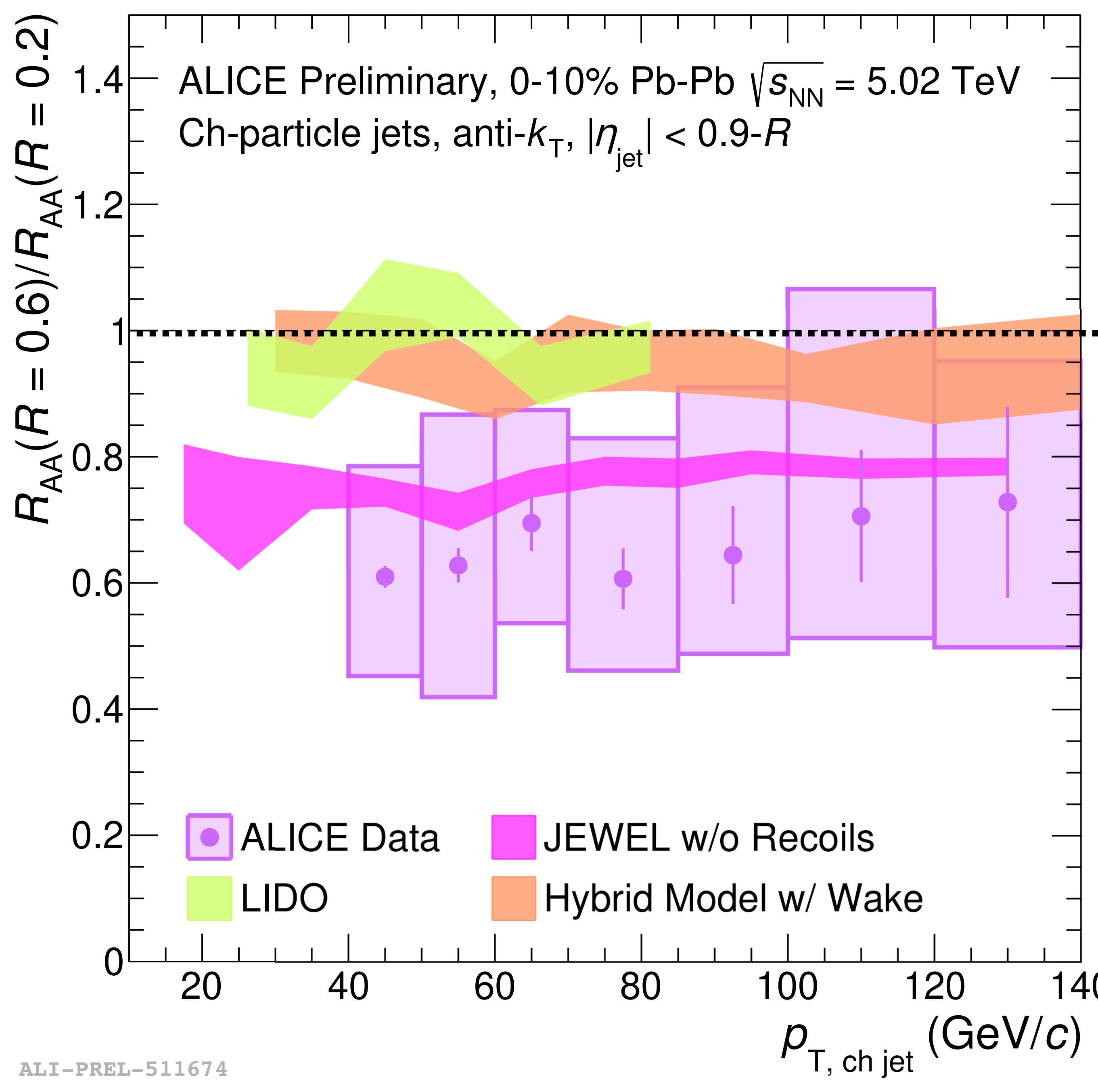
- Suppressed and narrowed hard fragments
- Enhanced and broadened soft fragments

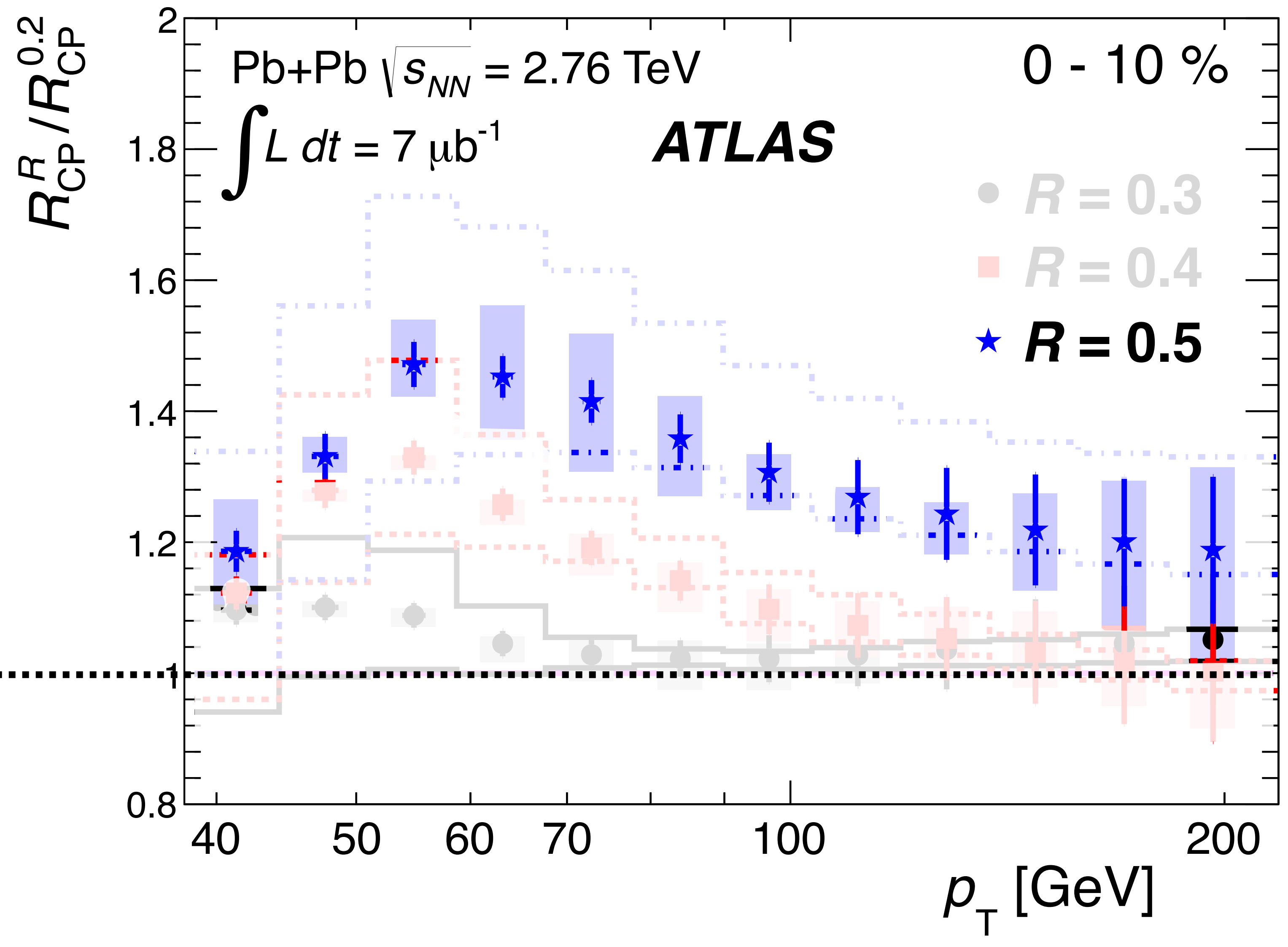
Next generation jet quenching measurements to directly probe different scales: Λ_{med}, m^2, L_{path}, etc.

R dependence of jet quenching

Phys. Lett. B 719 (2013) 220-241

R = 0.6 / R = 0.2





R = 0.5 / R = 0.2

Different UE estimations: ML based (ALICE) vs. Area based (ATLAS)

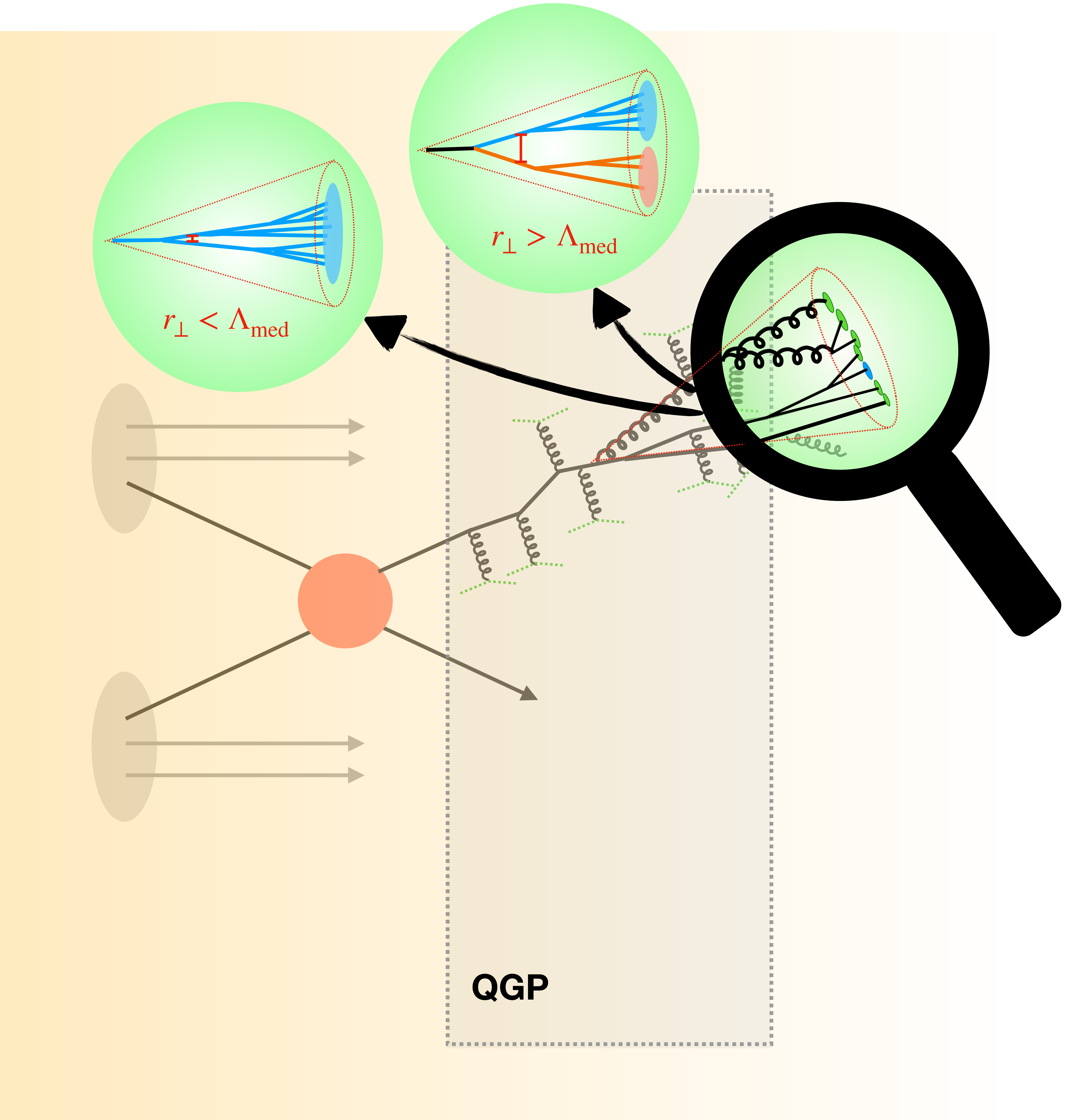
Different Jets: track jet (ALICE) vs. calorimeter jet (ATLAS)

Lager jet radius:

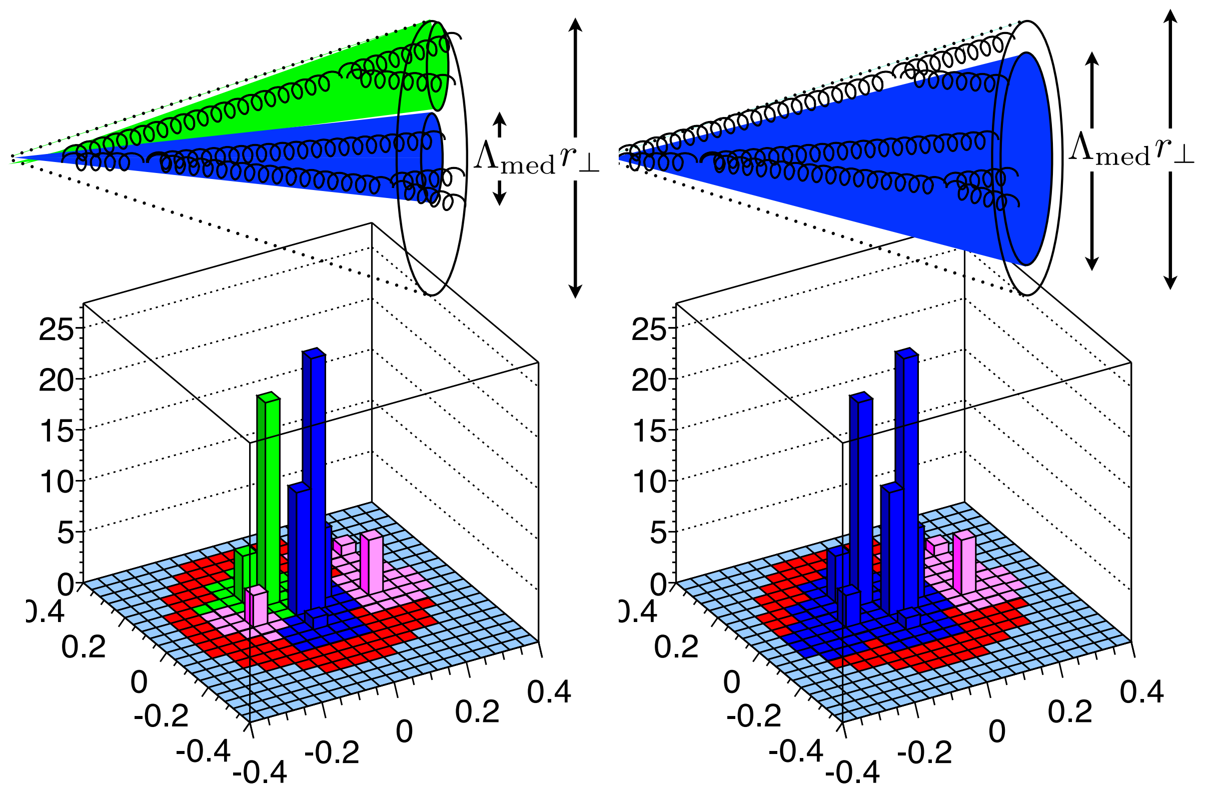
- Wider area to recover lost energy
- Open phase space to jets with wide splittings

Jet quenching — substructure dependence

Phys.Lett.B 725 (2013) 357-360



Jet quenching dictated by color coherence



Medium color coherence scale Λ_{med}

- Partons with separations below the scale → radiate as a single parton

Medium color coherence → Jet quenching depends on hard splitting of leading parton

Control jet substructure:

- Trimming of ***R=1.0*** jet
- Soft drop grooming of ***R=0.4*** jet

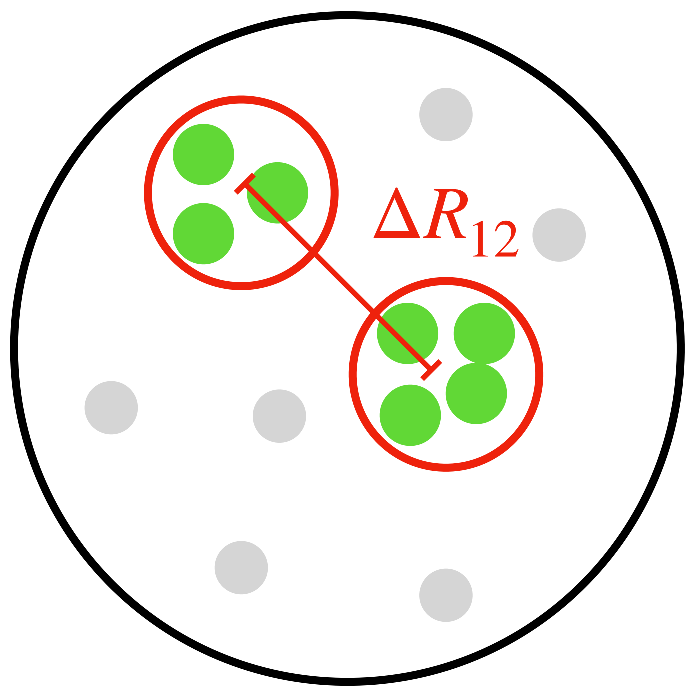
R_{AA} of trimmed large-R jet

ATLAS-CONF-2019-056

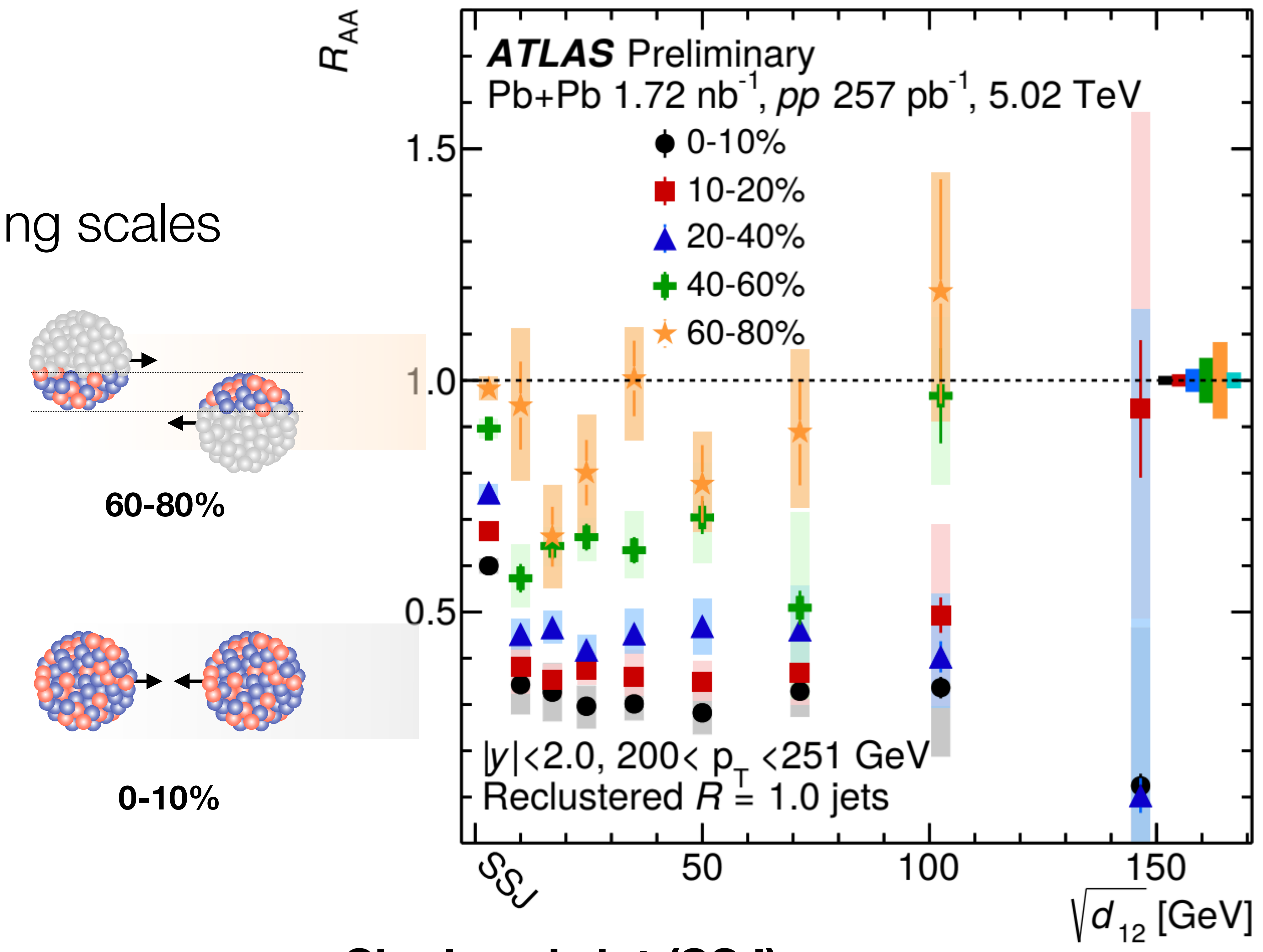
Trimming procedure

1. Cluster Anti-k_T $R=0.2$ jets to form Anti-k_T $R=1.0$ jet
2. Recluster $R=0.2$ jets in $R=1.0$ with algorithm to get k_T splitting scales

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



UE contribution suppressed by using R=0.2 jet as constituents



Single sub-jet (SSJ):

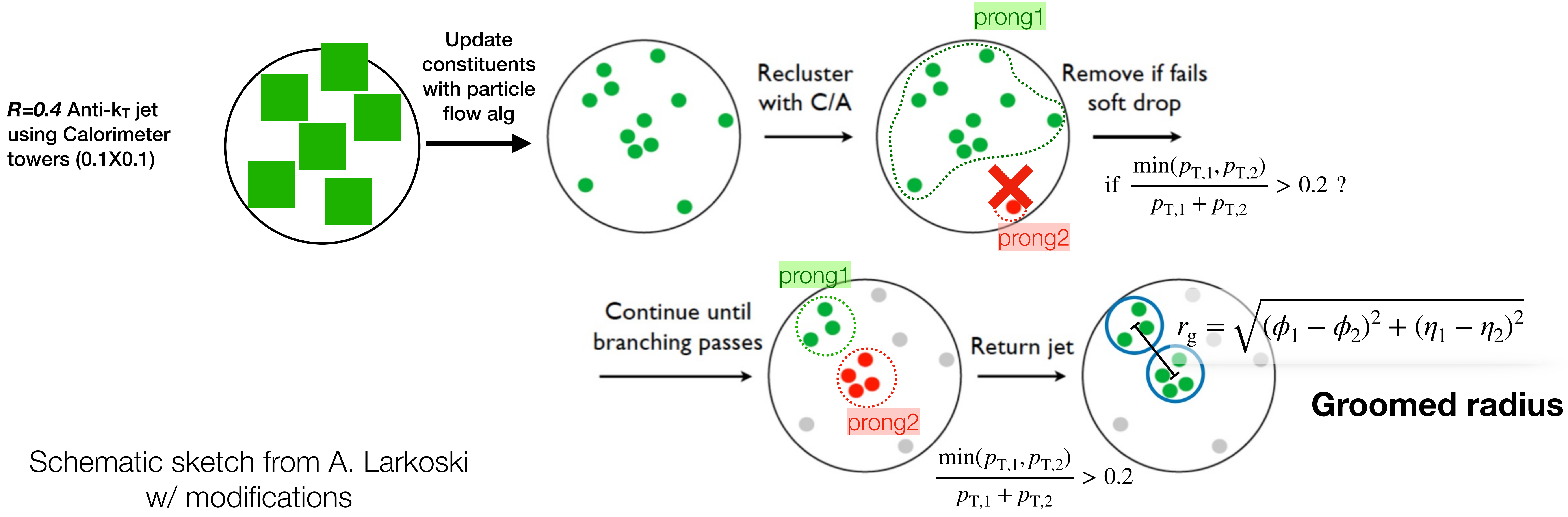
Two distinguished classes of jets:

- $\sqrt{d_{12}} > 0$, more suppressed, weakly depend on $\sqrt{d_{12}}$ value, $r_\perp > \Lambda_{\rm med}$
- $\sqrt{d_{12}} = 0$, significant less suppressed, $r_\perp > \Lambda_{\rm med} + r_\perp < \Lambda_{\rm med}$

Jet grooming procedure

To further access $\Delta R_{12} < 0.2$, jet grooming is used:

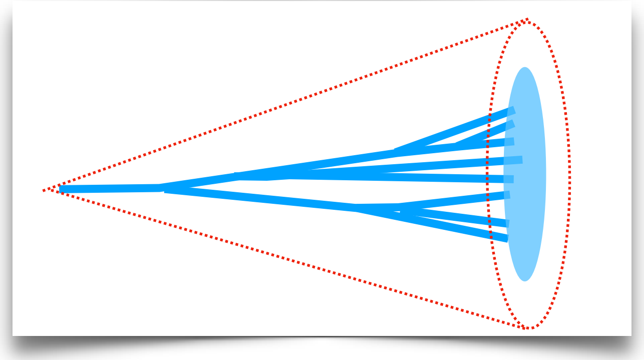
1. **Jet finding**: *R=0.4* Anti-k_T jet
2. **Reclustering**: C/A cluster sequence
3. **Declustering**: Soft drop grooming with $z_{\mathrm{cut}} = 0.2, \ \ \beta = 0$

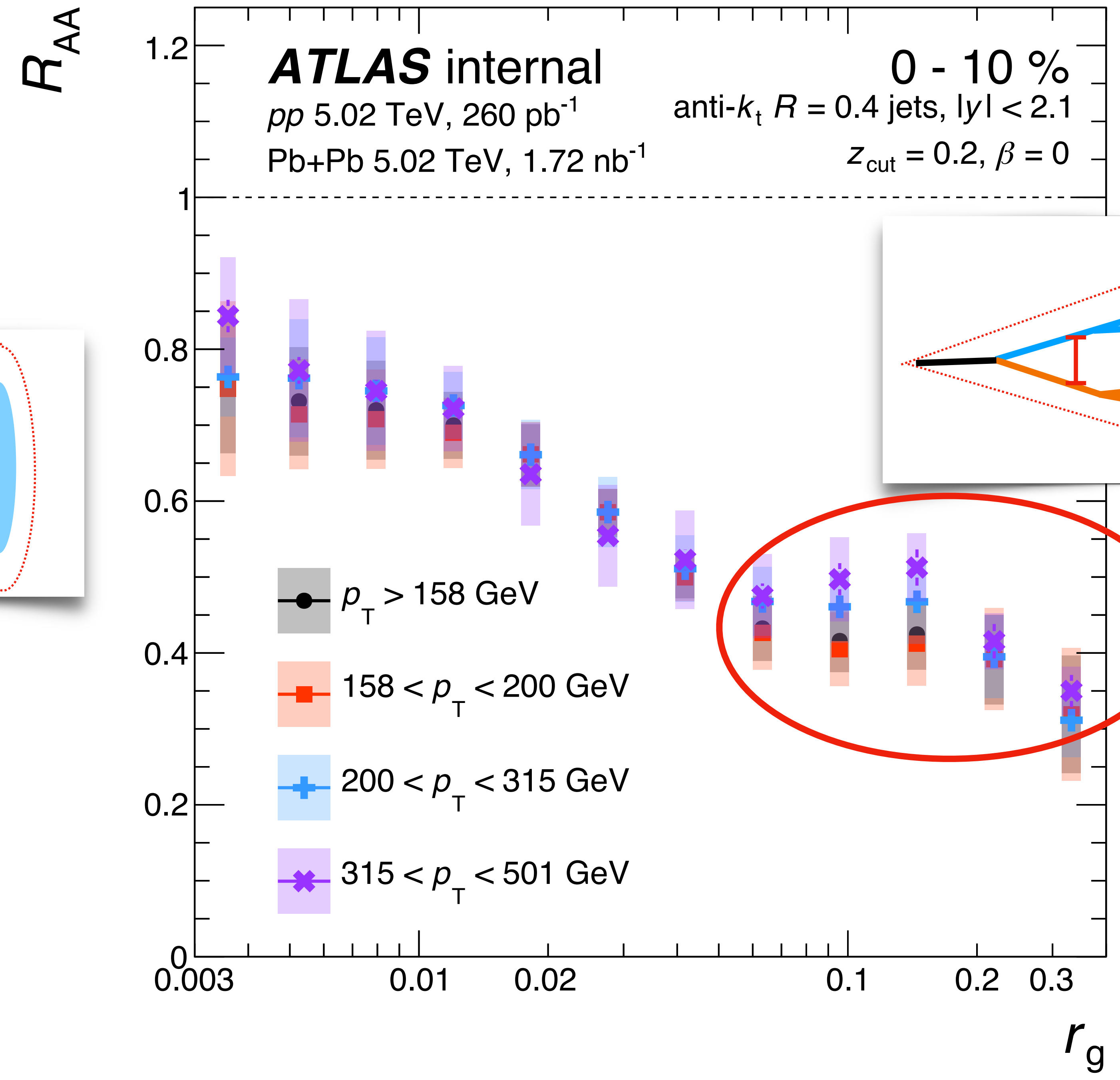


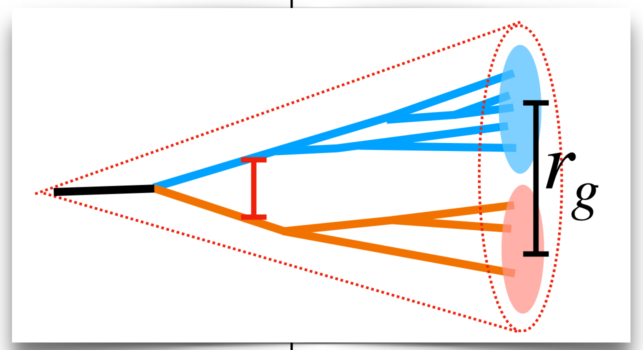
Schematic sketch from A. Larkoski
w/ modifications

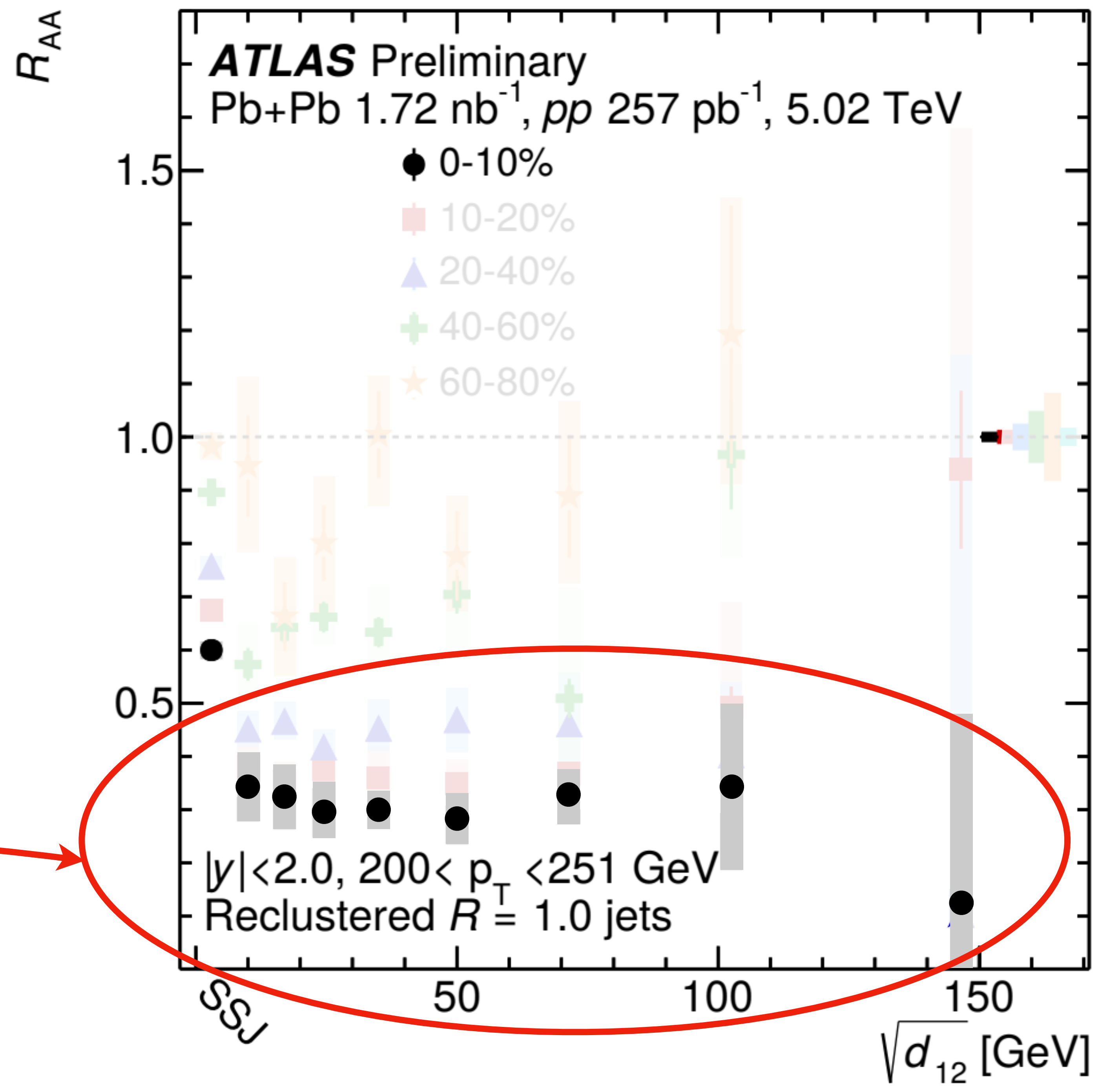
R_{AA} of groomed jets

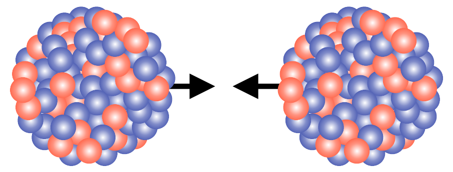
ATLAS-CONF-2022-026







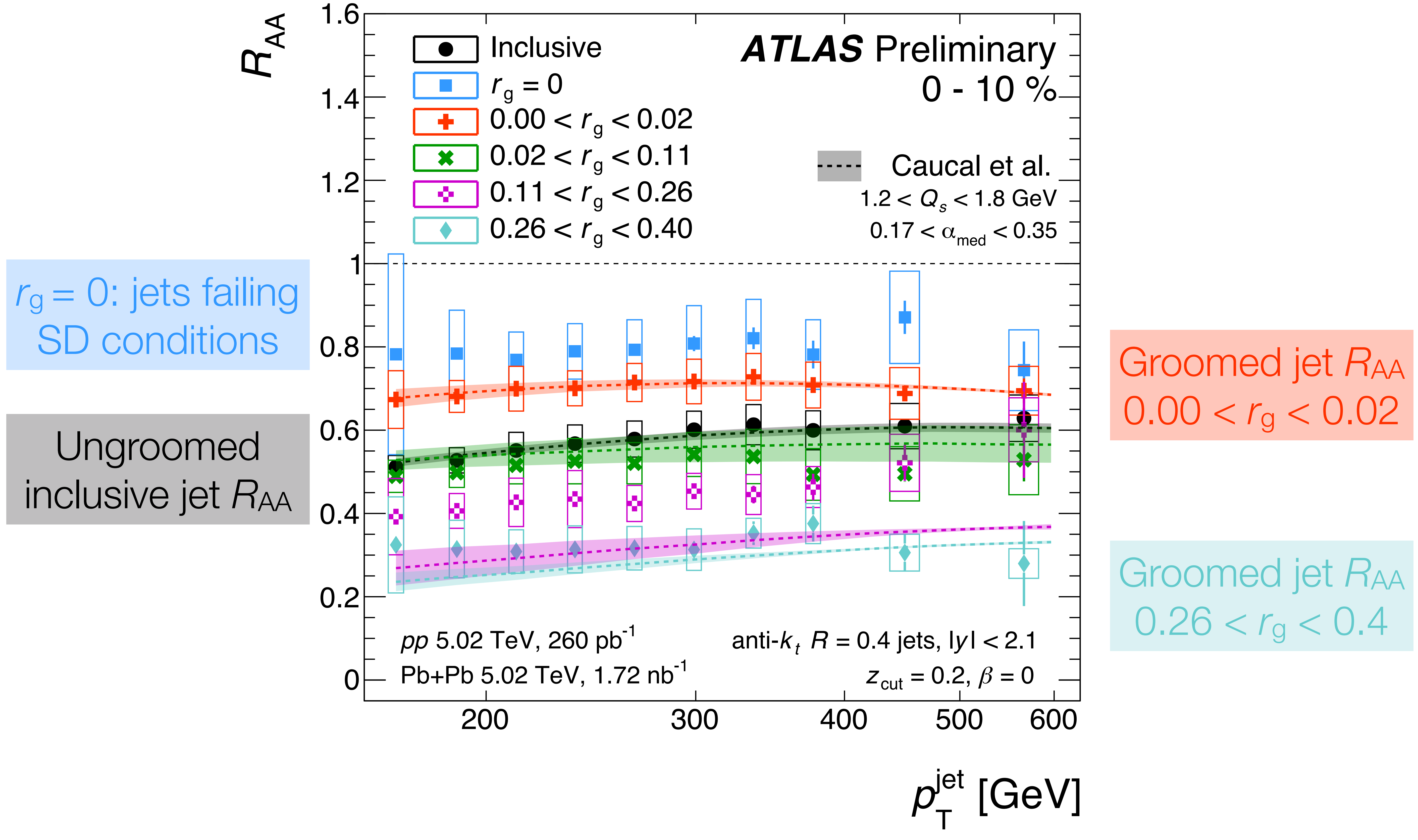


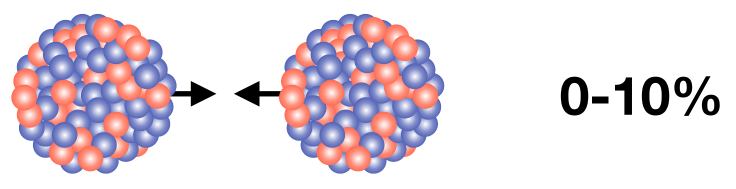


0-10%

R_{AA} of groomed jets — model comparison

ATLAS-CONF-2022-026

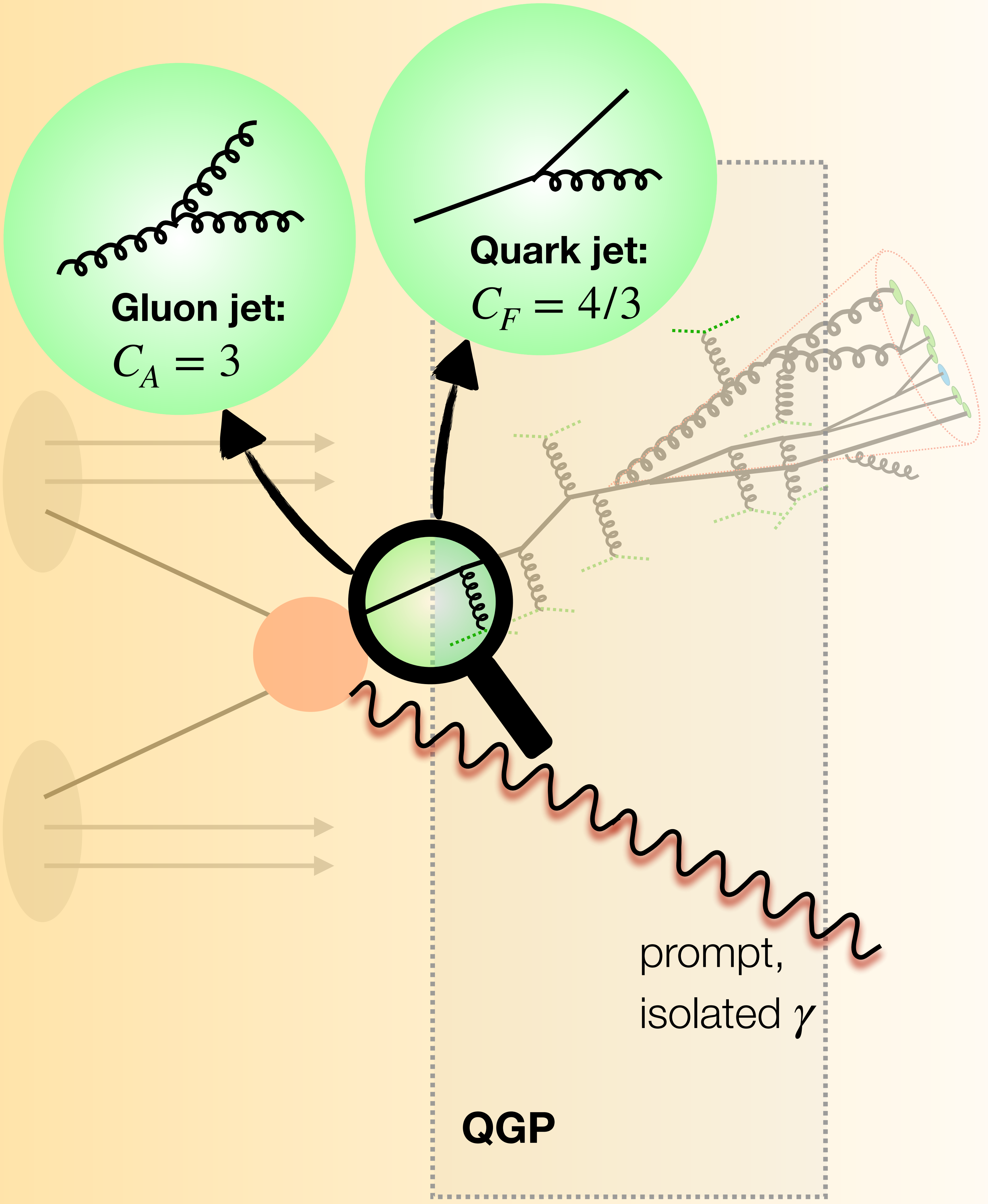




- Caucal et al.※, MC generator with pQCD in-medium parton shower
- Very good agreement at small and large r_g
- Discrepancies in $0.11 < r_g < 0.26$

Jet quenching — color charge dependence

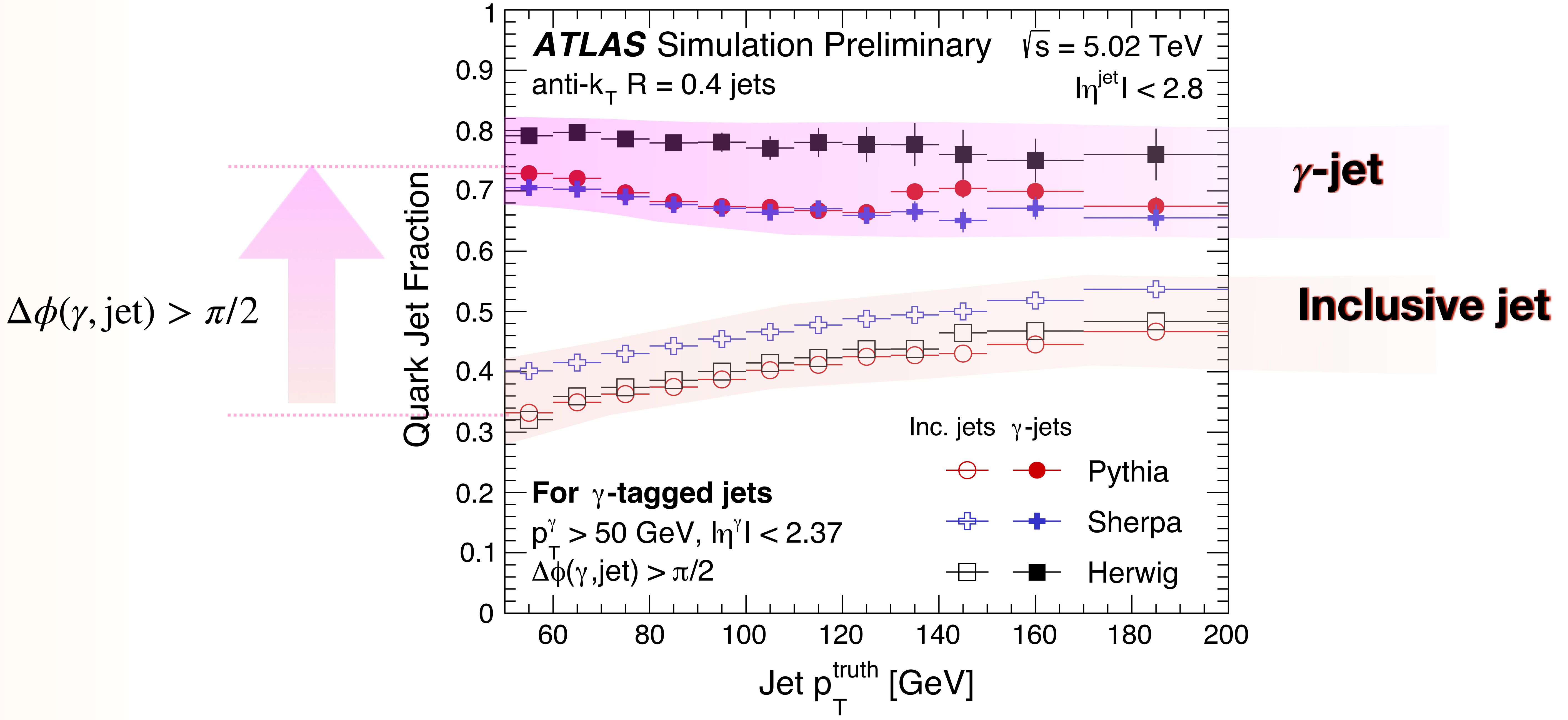
ATLAS-CONF-2022-019



Gluon jets vs. quark jets:

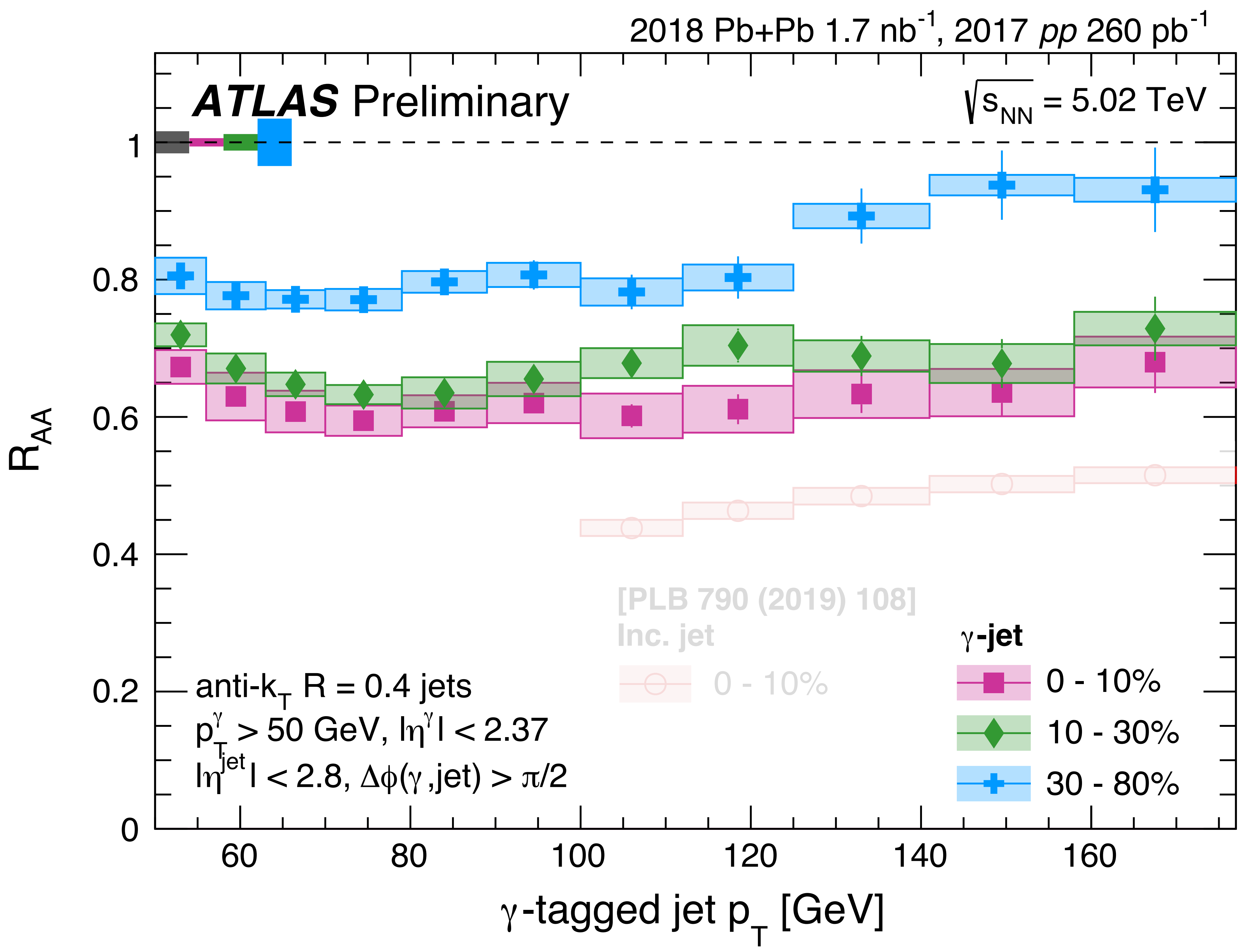
- Gluon jets are more active: fatter and produce more particles

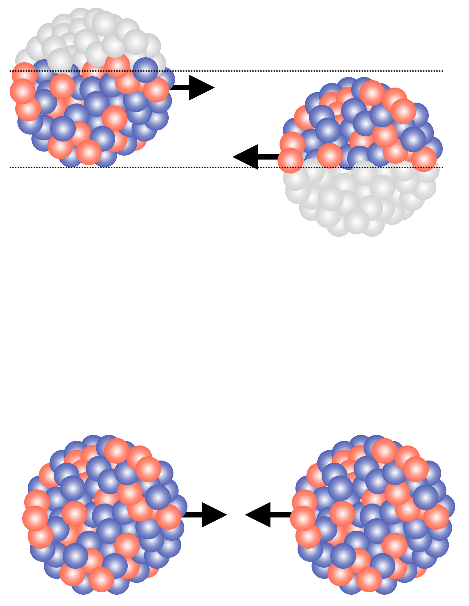
→ Jet quenching depends on color charge



γ-tagged jet R_{AA}

ATLAS-CONF-2022-019

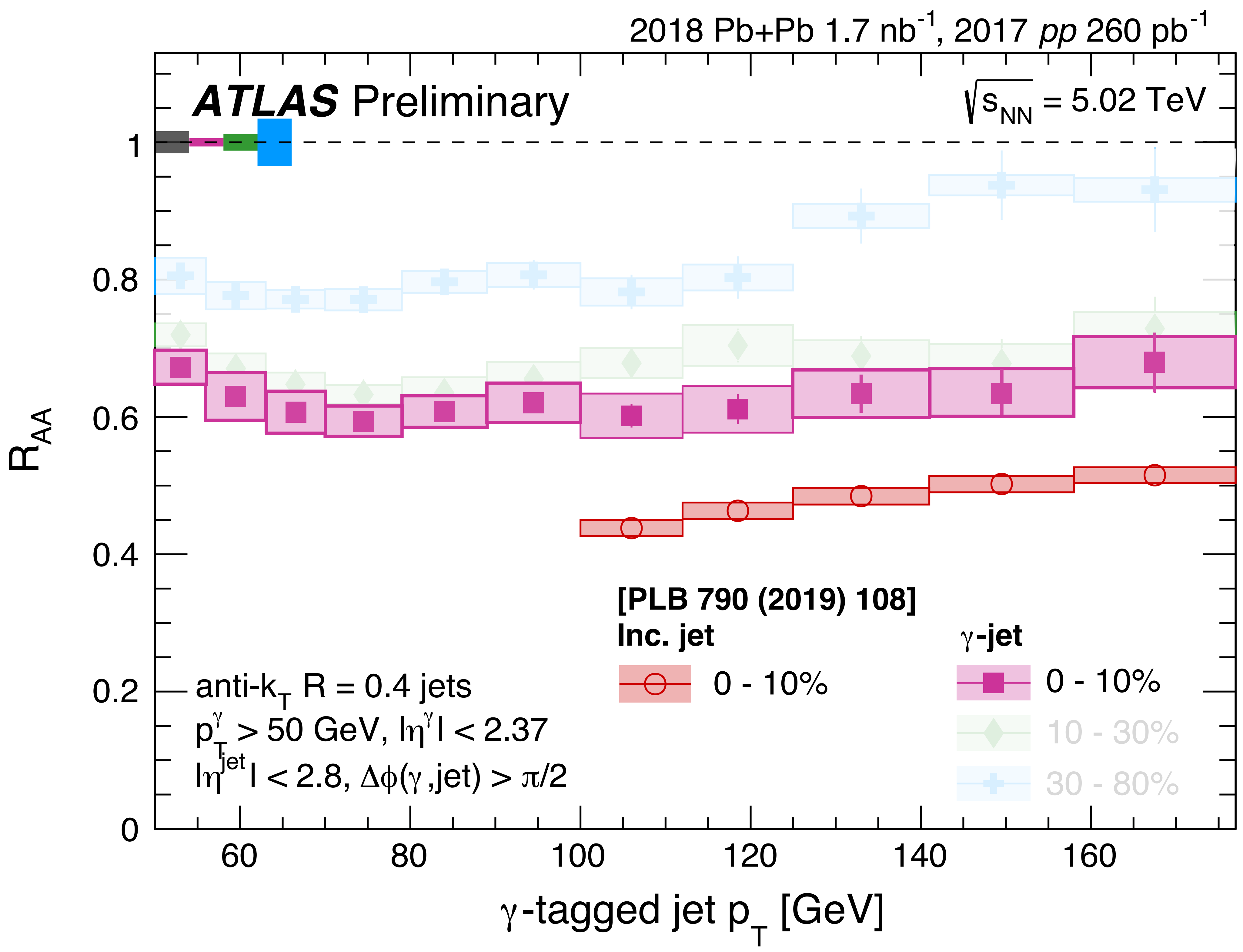


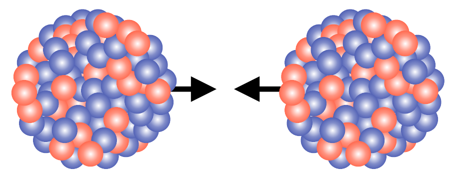


- Strong centrality dependence
- Weak dependence on jet p_T in central collisions

γ-tagged jets vs. inclusive jets

ATLAS-CONF-2022-019





0-10%

γ-tagged jet **~80% quark jets**

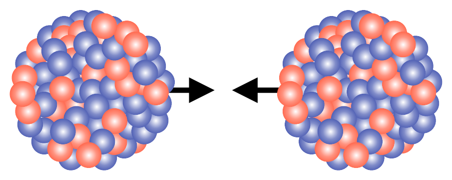
Inclusive jet **~40% quark jets**

γ-tagged jets are less suppressed than inclusive jets

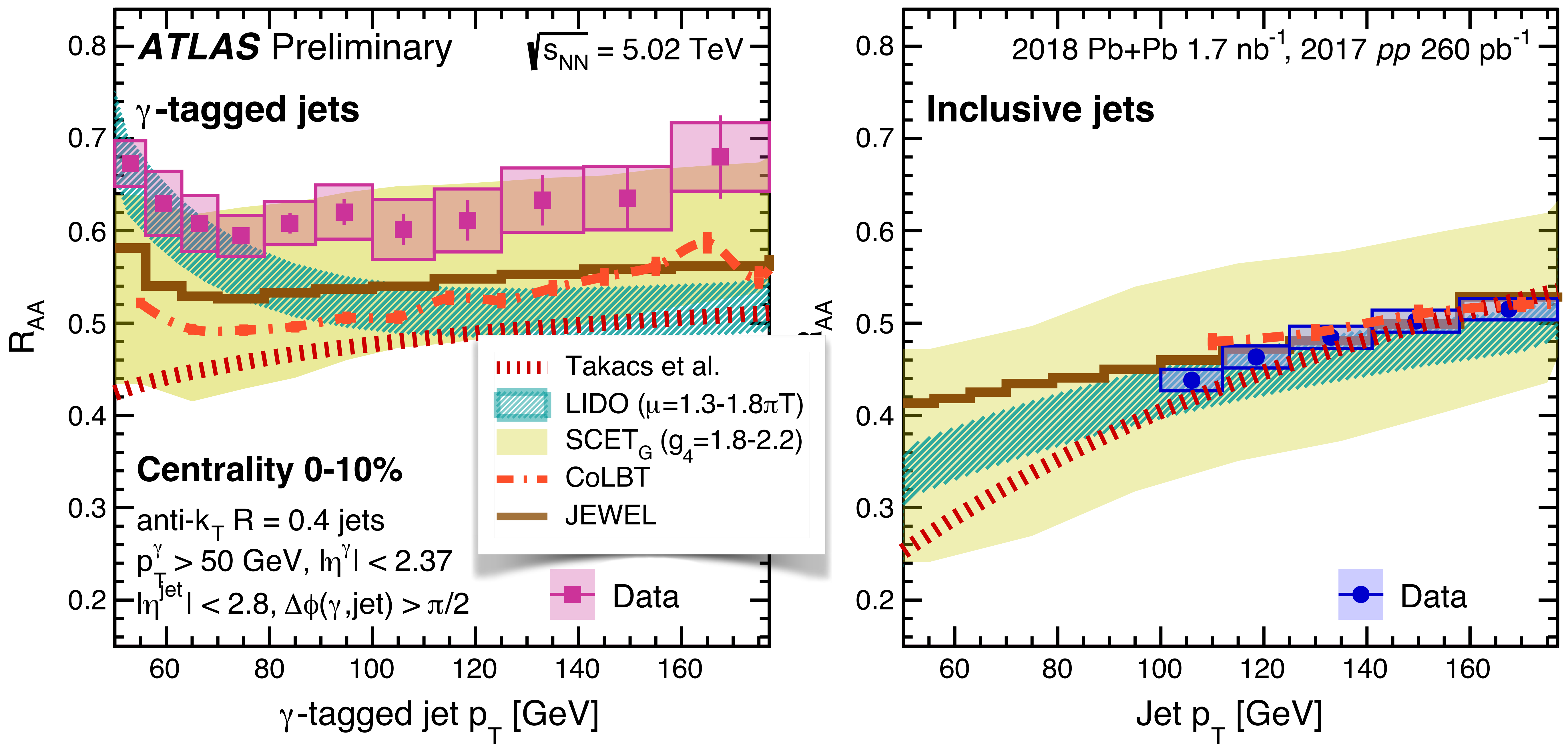
- Different virtuality / substructures
- Different jet spectra

γ-tagged jet R_{AA} — model comparisons

ATLAS-CONF-2022-019



0-10%

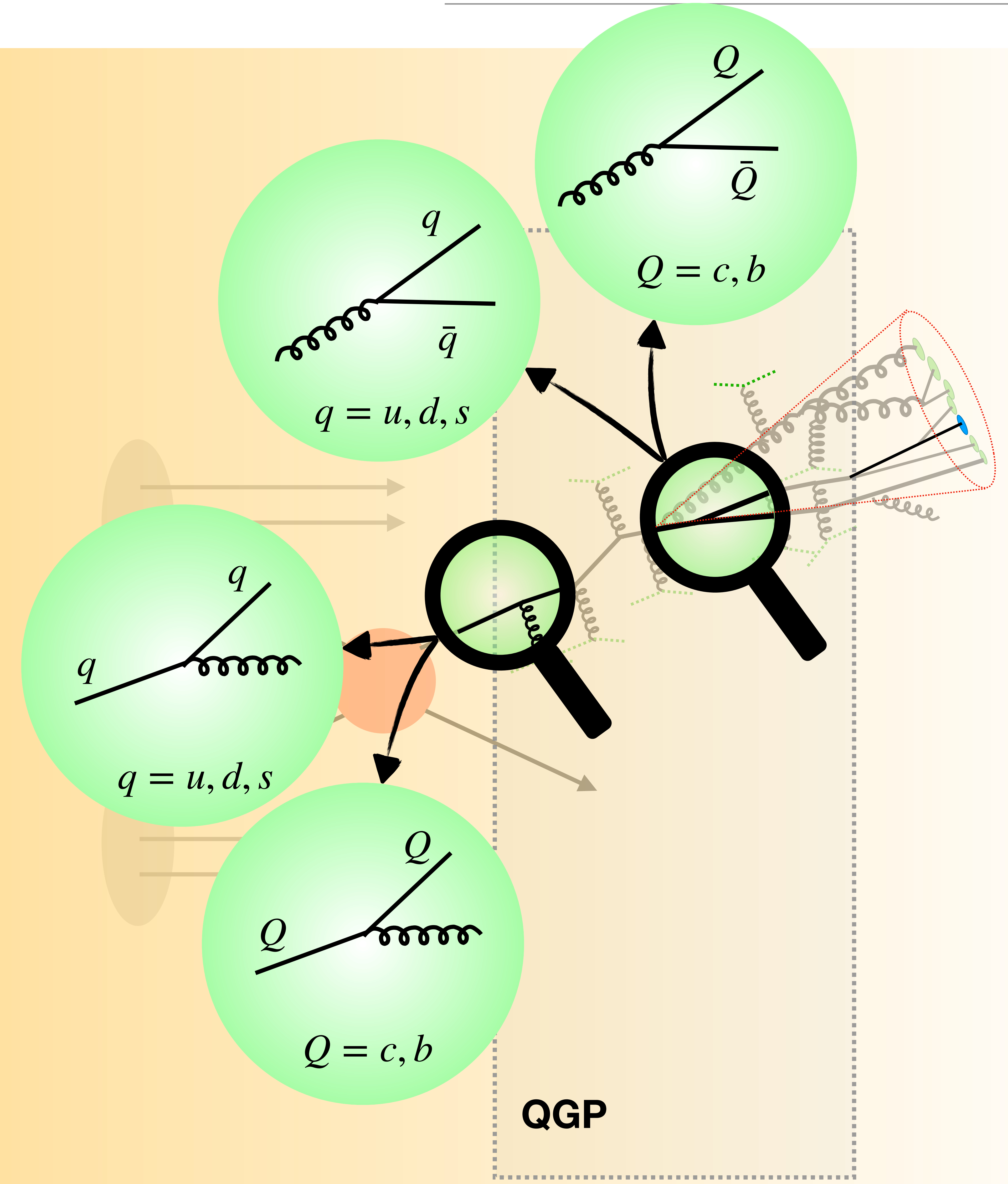


Models	Details	Uncetaitnty
LIDO※	Pythia8 + Boltzmann-Langevin transport	Medium-jet coupling
CoLBT※	Pythia8 + Higher-twist + Boltzmann transport	N/A
SCETG※	EFTs w/ medium modified splitting + Evolution equations	Medium-jet coupling
Takacs et al.※	Pythia8 + BDMPS-Z + GLV + Poisson ansatz	N/A
JEWEL※	Pythia6.4 + BDMPS + parton shower	N/A

Models describe inclusive jet R_{AA} well while under-predict γ-tagged jet at high p_T

Jet quenching — parton mass dependence

arXiv:2204.13530



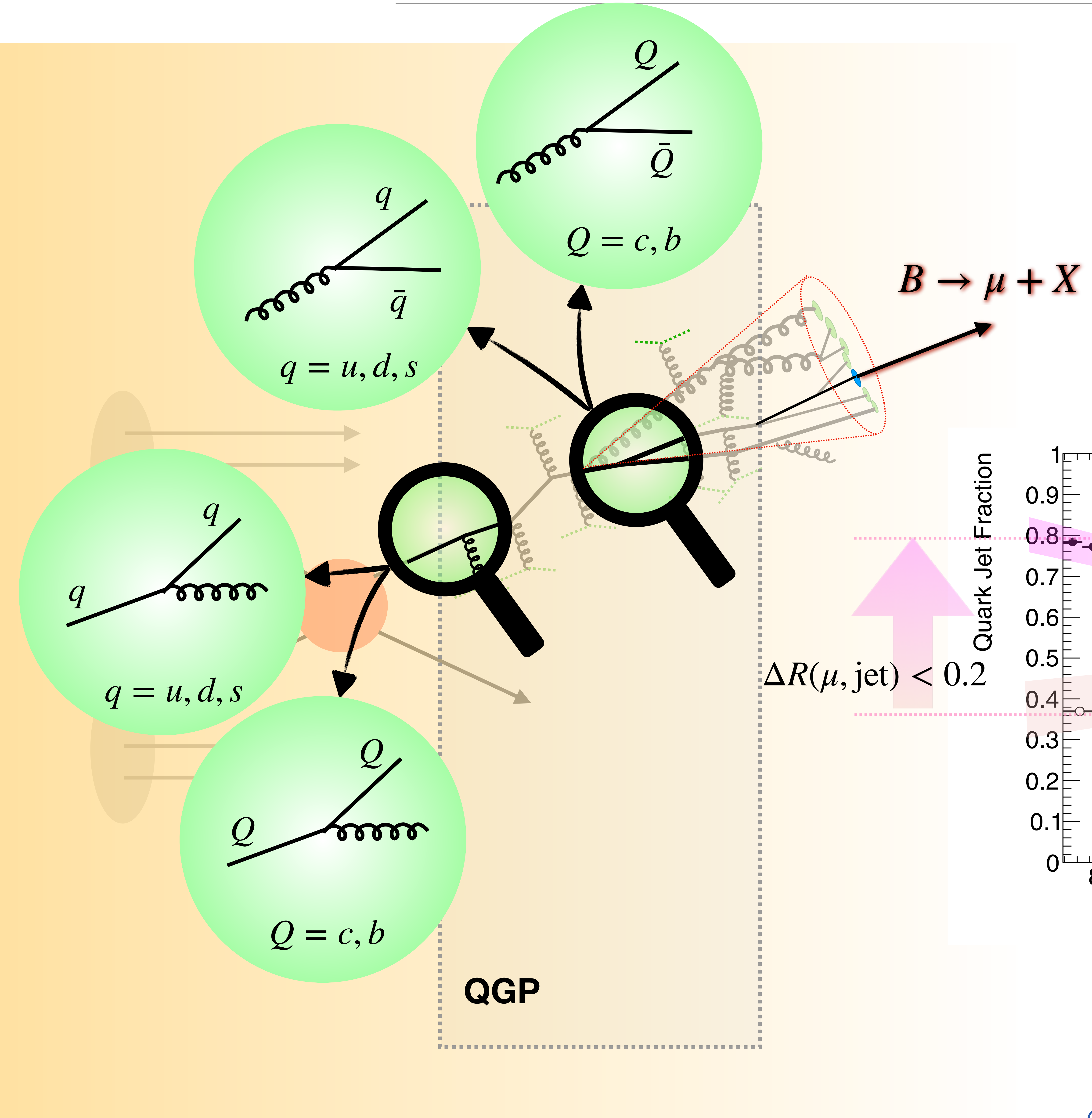
Heavy flavor jet: Particle jet contains **heavy flavor** hadrons

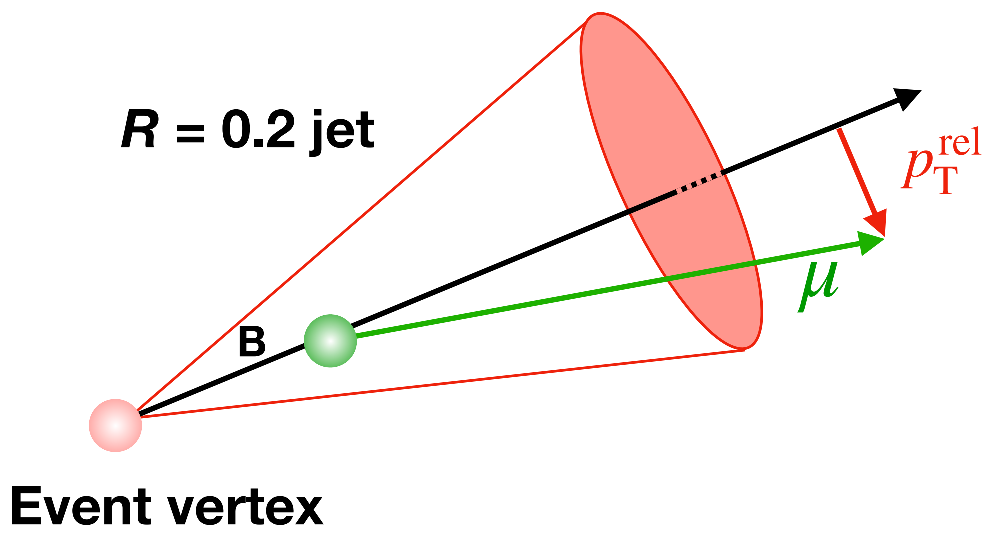
Heavy flavor quark created earlier in the heavy ion collisions, introduce variations on parton mass — dead cone effect

$$\mathrm{d}P_{\mathrm{Rad;Q}}(\theta) \propto \left(1 + \left(\frac{M_{\mathrm{Q}}}{E_{\mathrm{Q}}}\right)^2 \frac{1}{\theta^2}\right)^{-2}$$

Heavy flavor quark selection also introduces variations on initial parton color charge

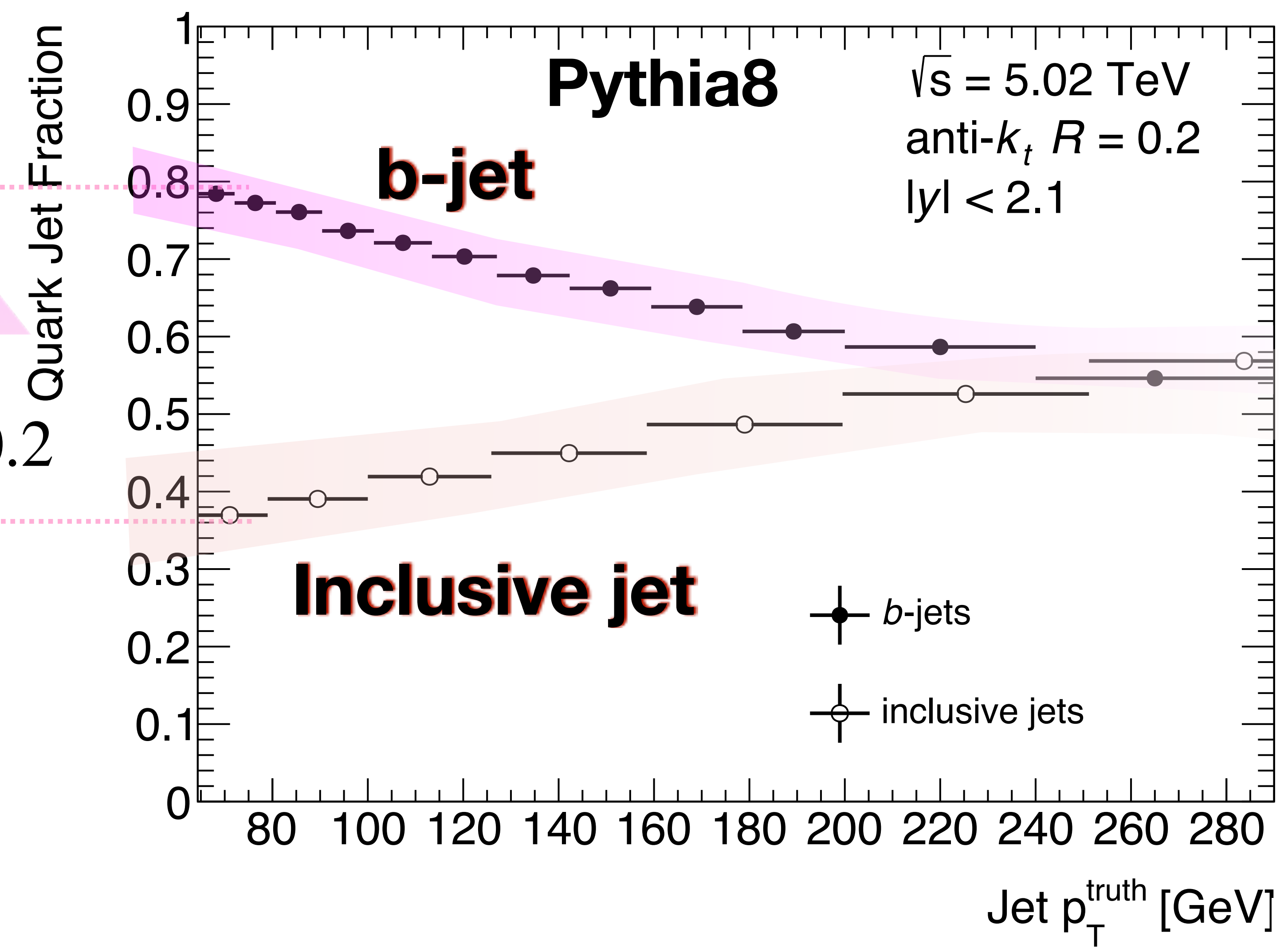
Jet quenching — parton mass dependence

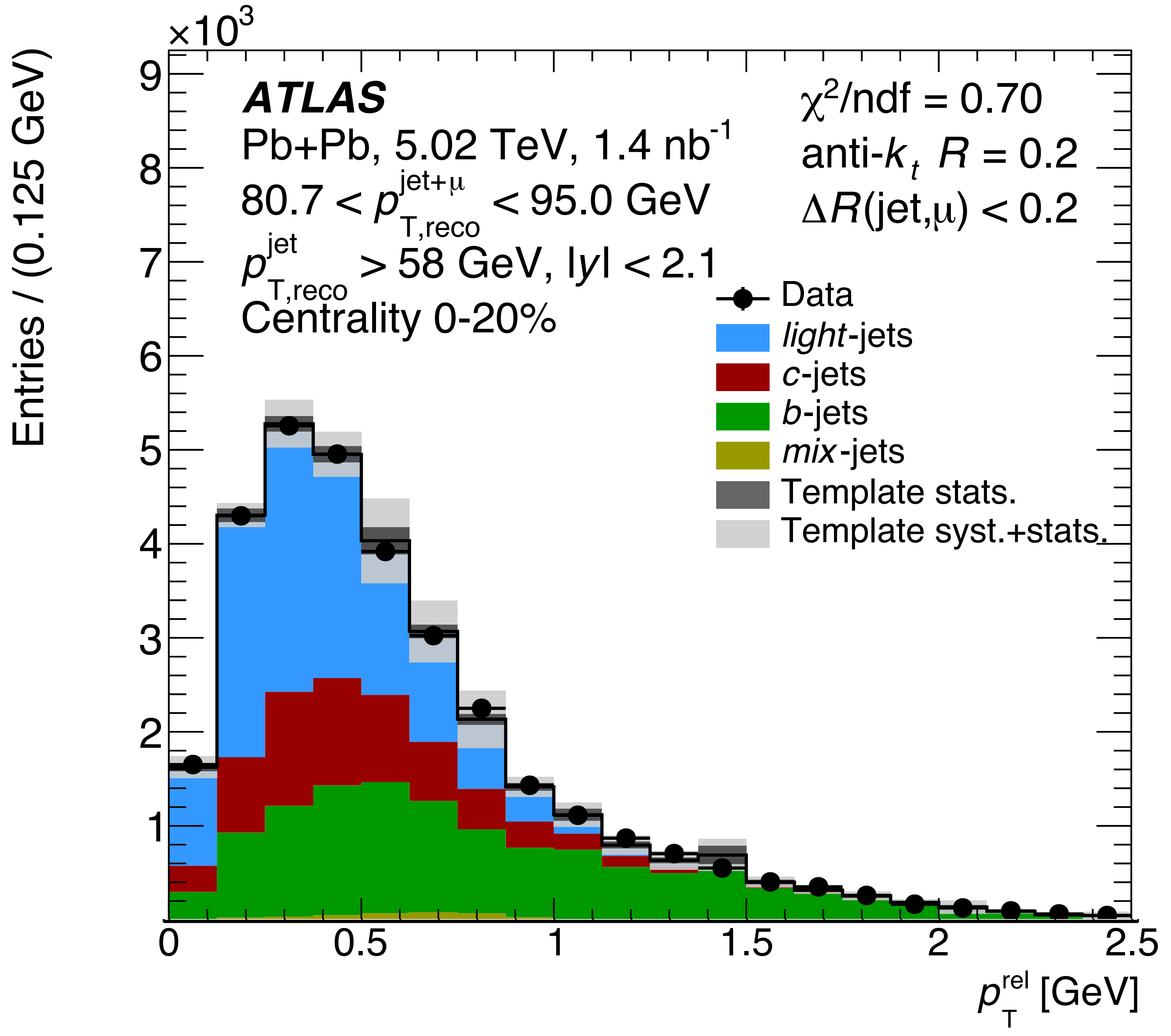




Muon in jets: $\Delta R(\mu, \text{jet}) < 0.2$

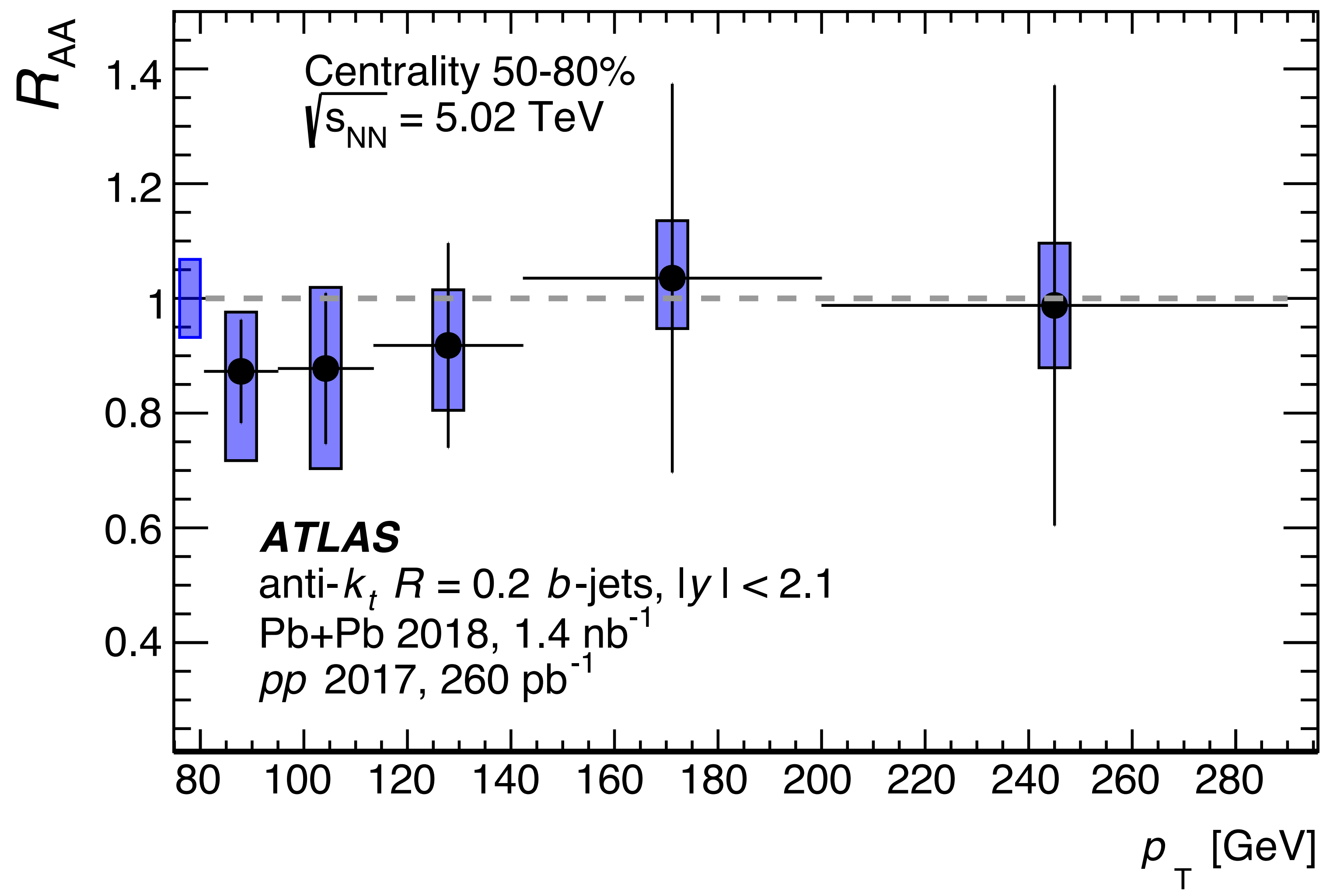
b-jet yields are measured from fitting p_T^{rel}

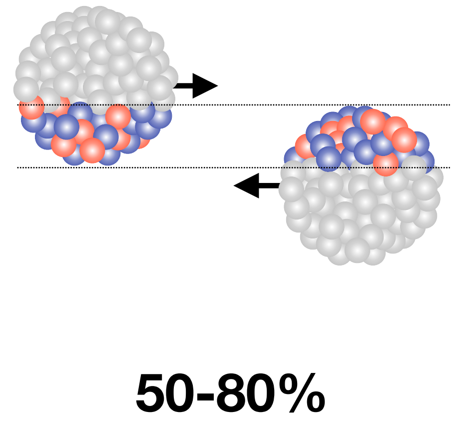


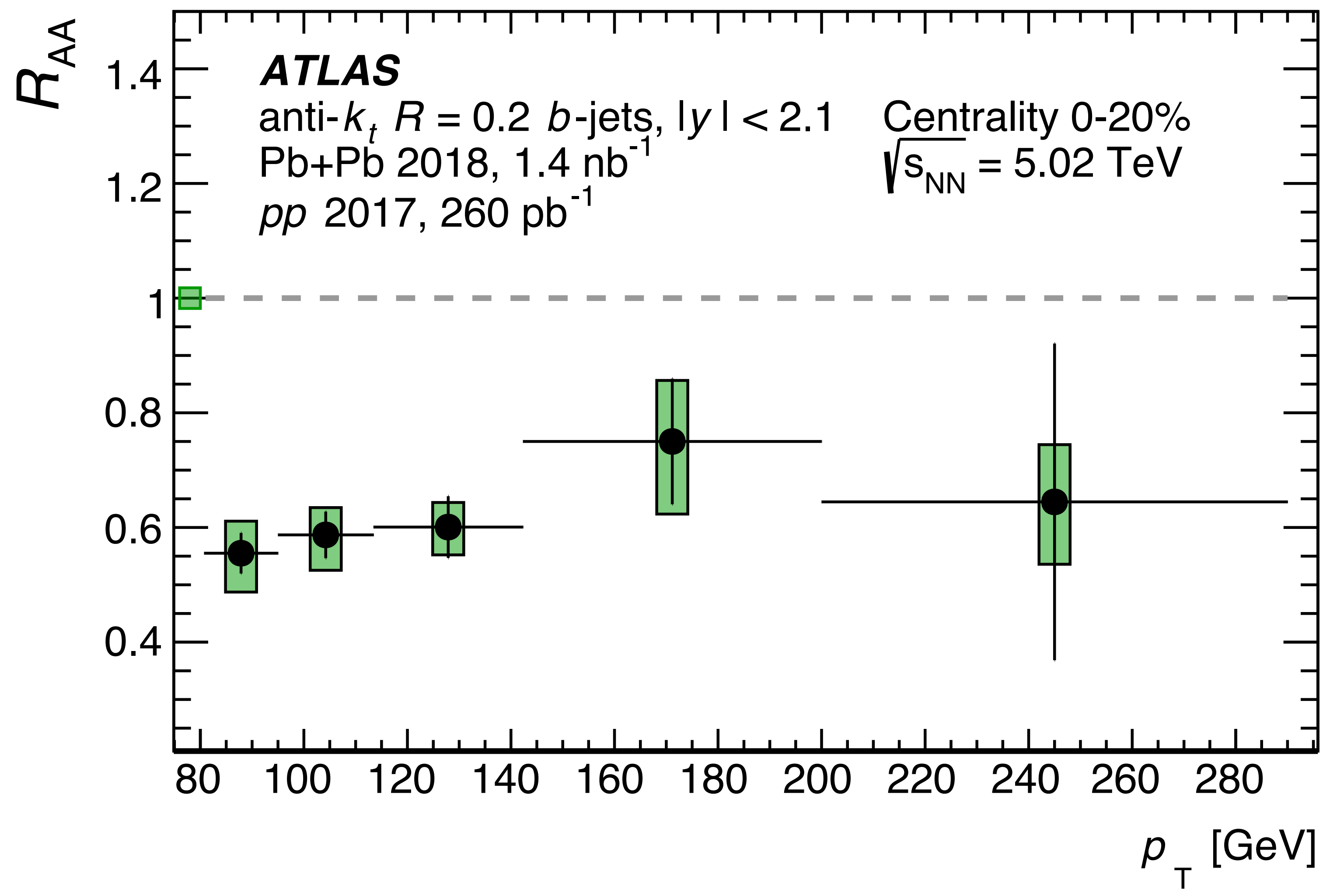


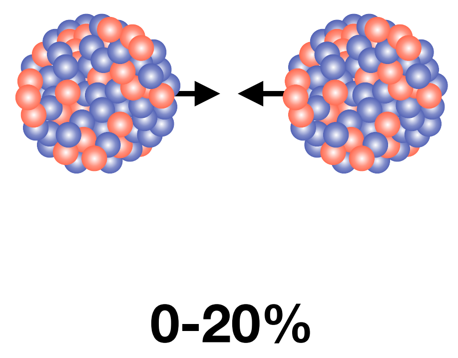
b-jet R_{AA}

arXiv:2204.13530





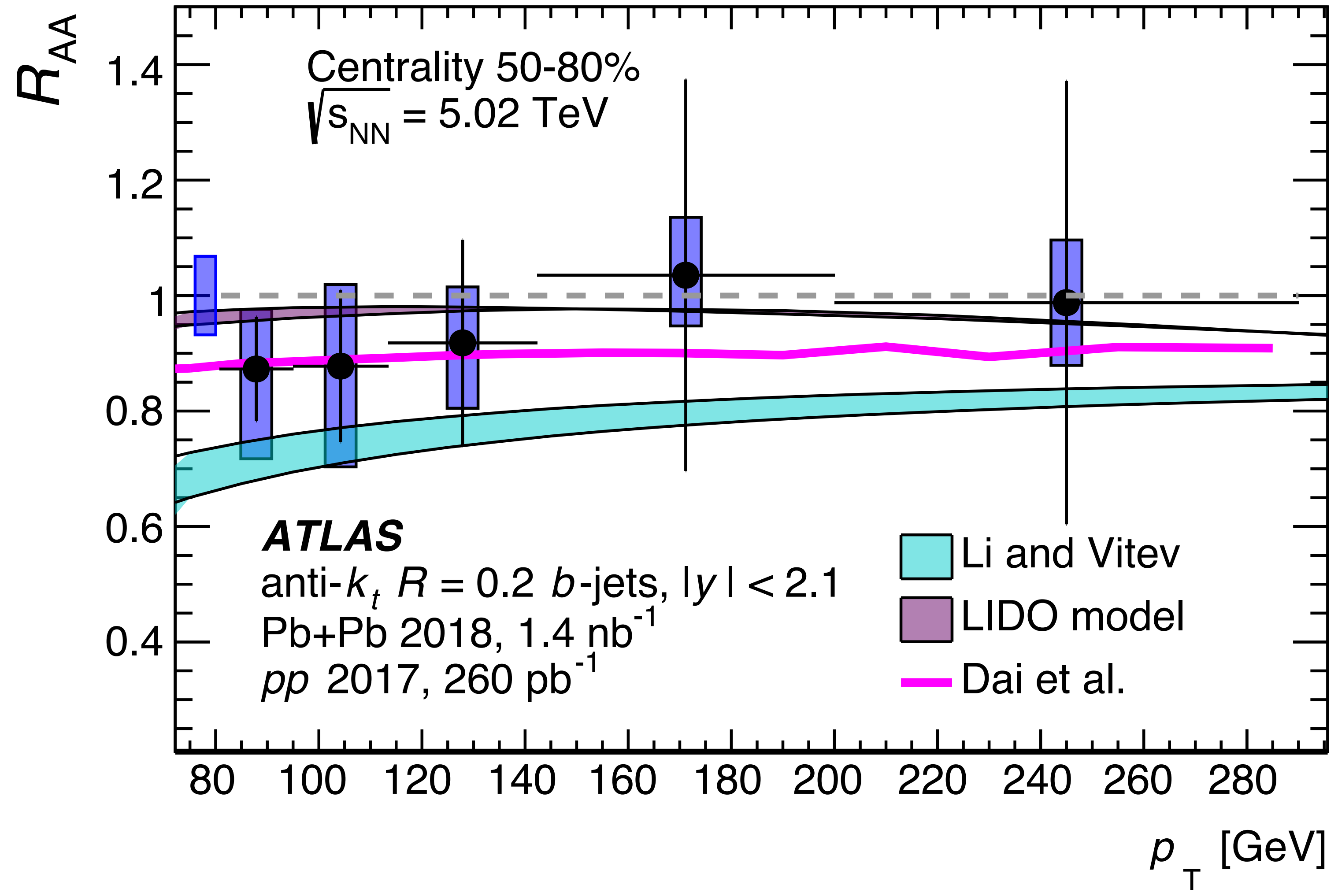


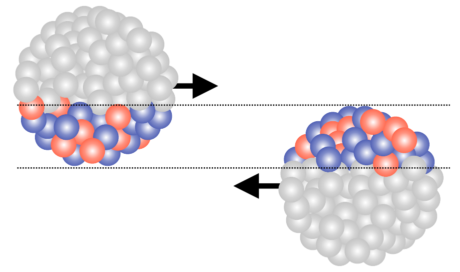


- Significantly more suppressed in 0-20% compare to 50-80%
- Weak dependence on b-jet p_T

b-jet R_{AA} — model comparison

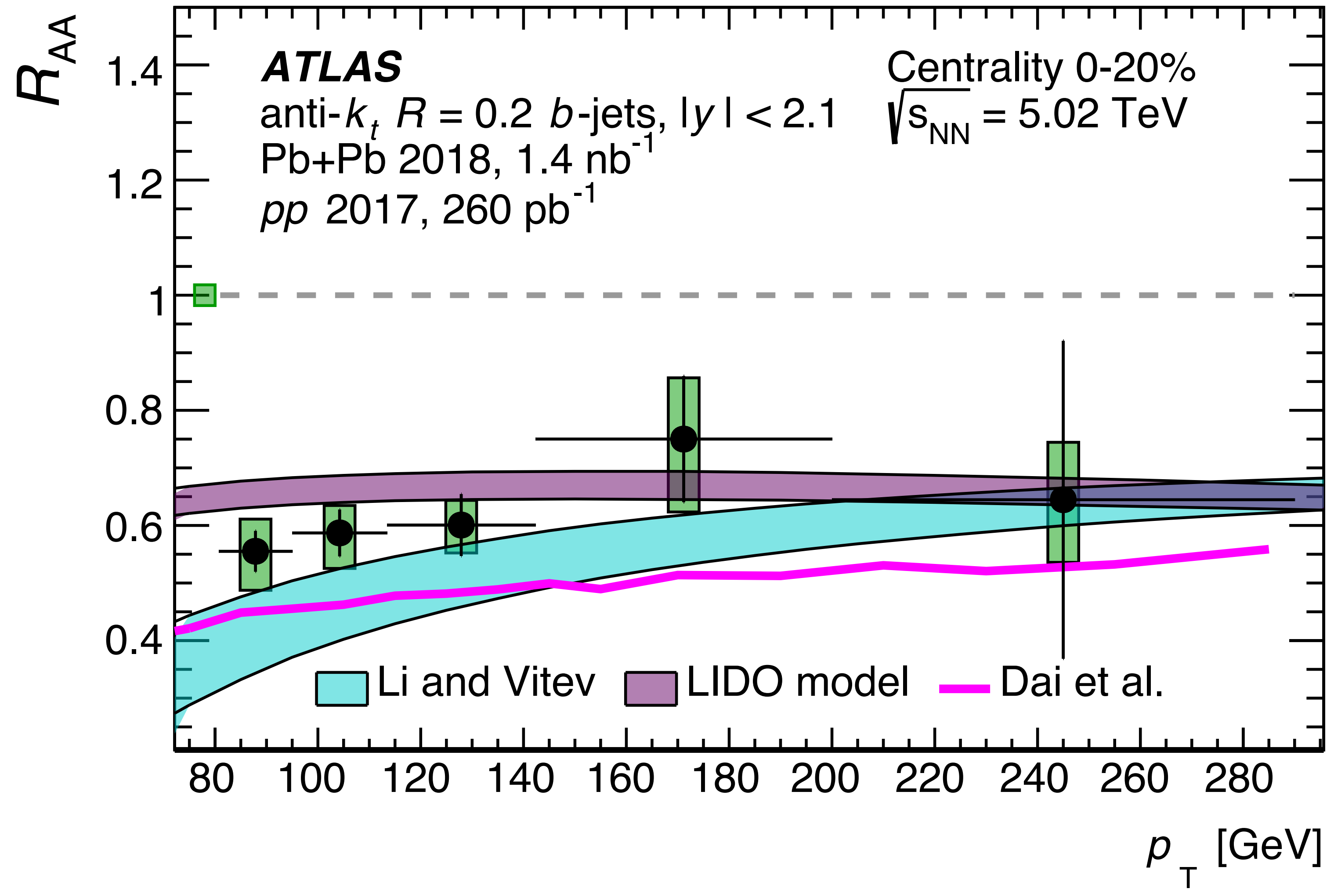
arXiv:2204.13530

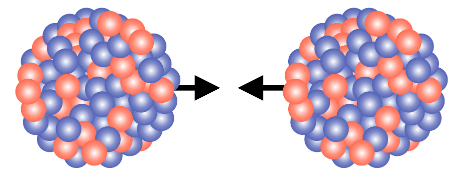




50-80%

Models	Details	Uncetaitnty
LIDO※	FONLL + Boltzmann-Langevin transport	Medium-jet coupling
Dai et al.※	Sherpa + Langevin transport w/ radiation	N/A
Li and Vitev※	EFTs w/ medium modified splitting + Evolution equations	Medium-jet coupling



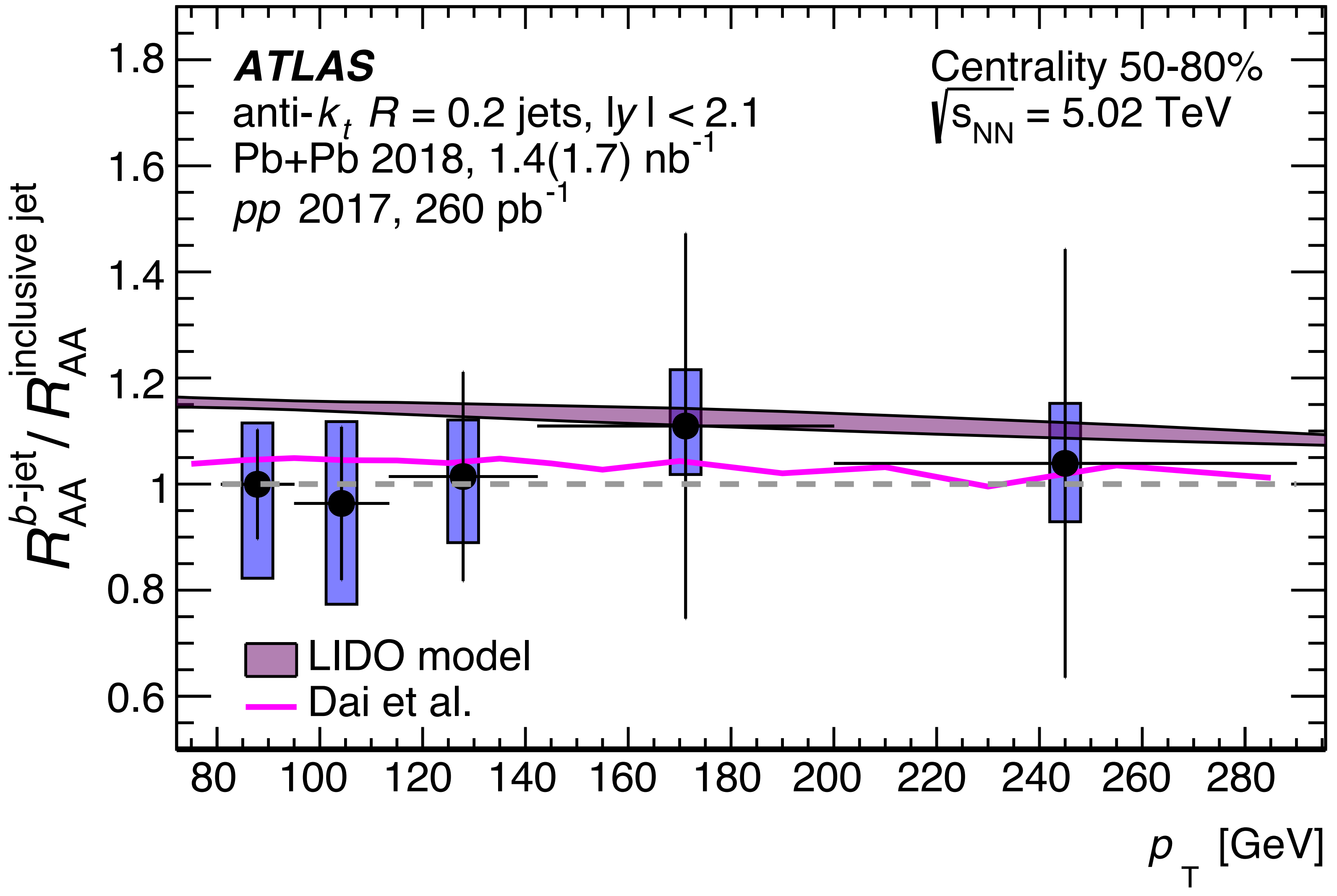


0-20%

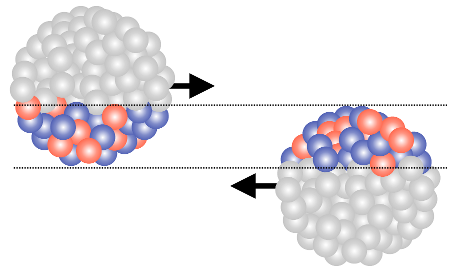
- LIDO (Boltzmann + Langevin) in good agreement with data
- Dai (modified Langevin) underpredicts b-jet R_{AA} in central collisions
- Li and Vitev (SCET) central values underpredict b-jet R_{AA} at low p_T

b-jet vs. inclusive jet

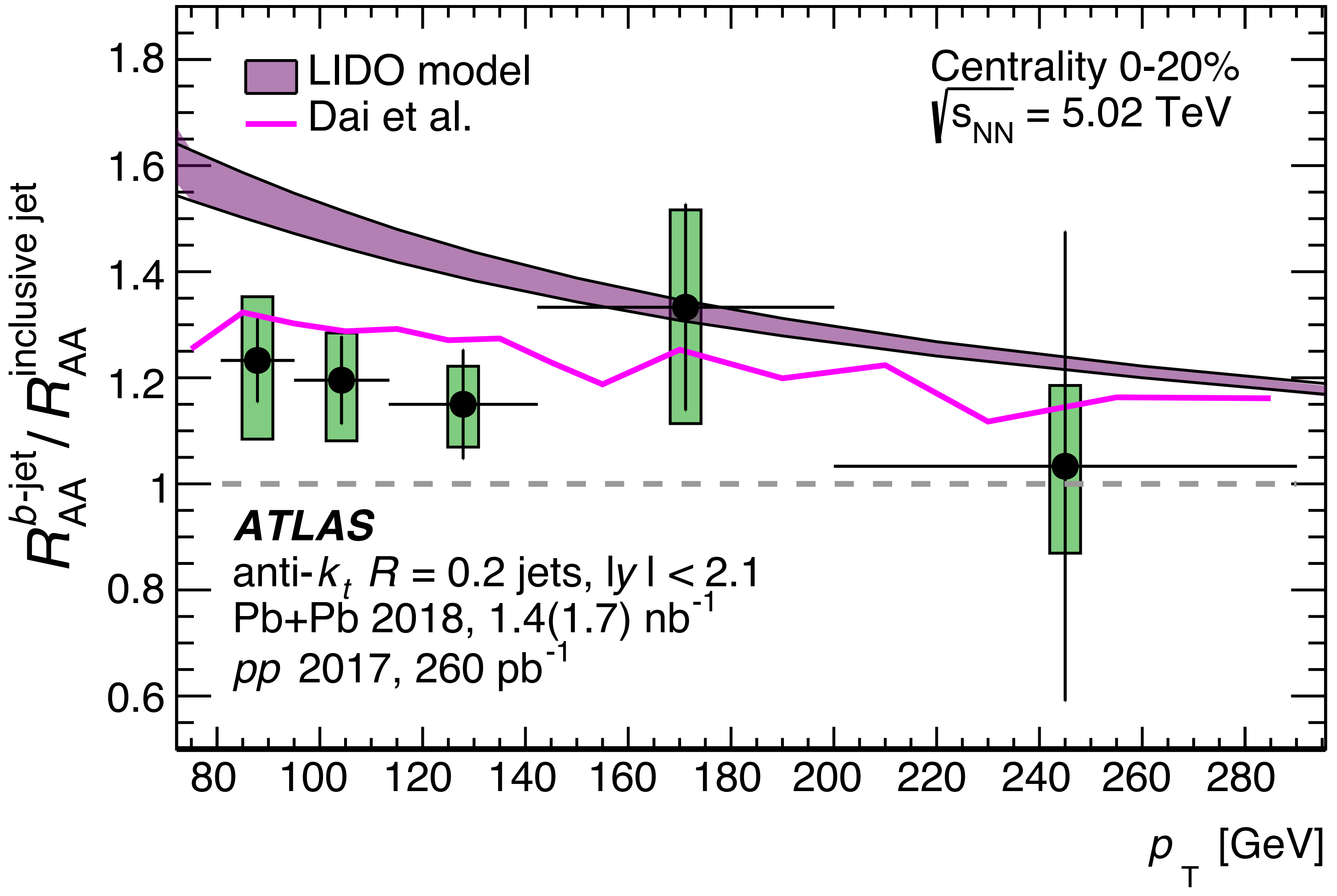
arXiv:2204.13530



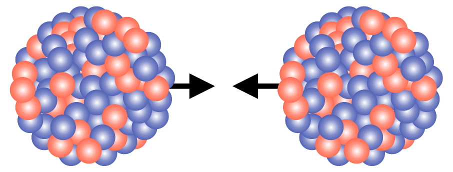
$R_{AA}^{b-\text{jet}} \sim R_{AA}^{\text{inclusive jet}}$



50-80%



$R_{AA}^{b-\text{jet}} > R_{AA}^{\text{inclusive jet}}$



0-20%

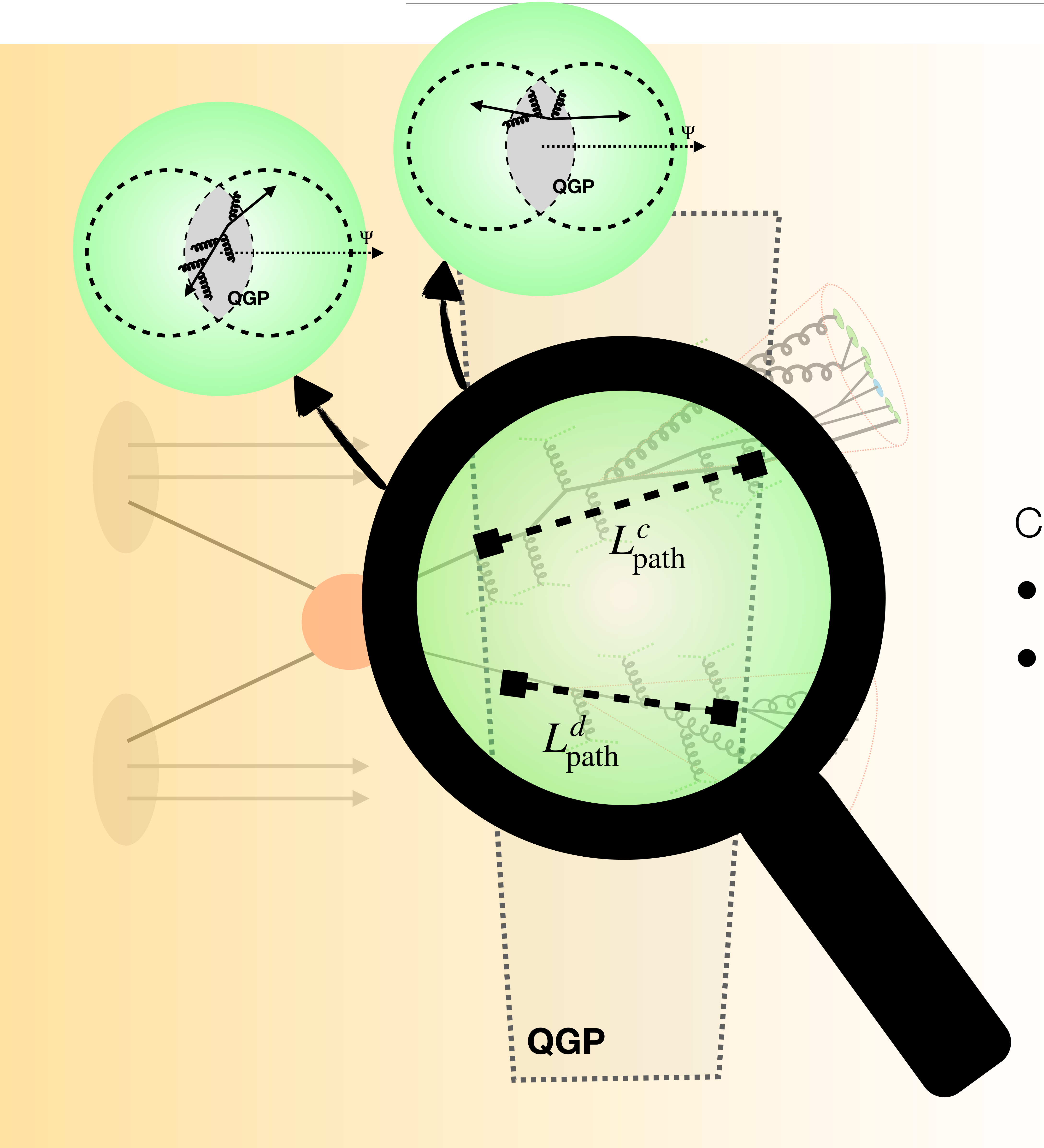
Models	Details	Uncetaitnty
LIDO*	FONLL + Boltzmann-Langevin transport	Medium-jet coupling
Dai et al.*	Sherpa + Langevin transport w/ radiation	N/A

- LIDO (Boltzmann + Langevin) overpredicts relative difference
- Dai (modified Langevin) describes the relative difference better

Selected models cannot describe b-jet vs. inclusive jet simultaneously

Difference at different centralities: more likely a mass dependence driven effect

Jet quenching — path-length dependence

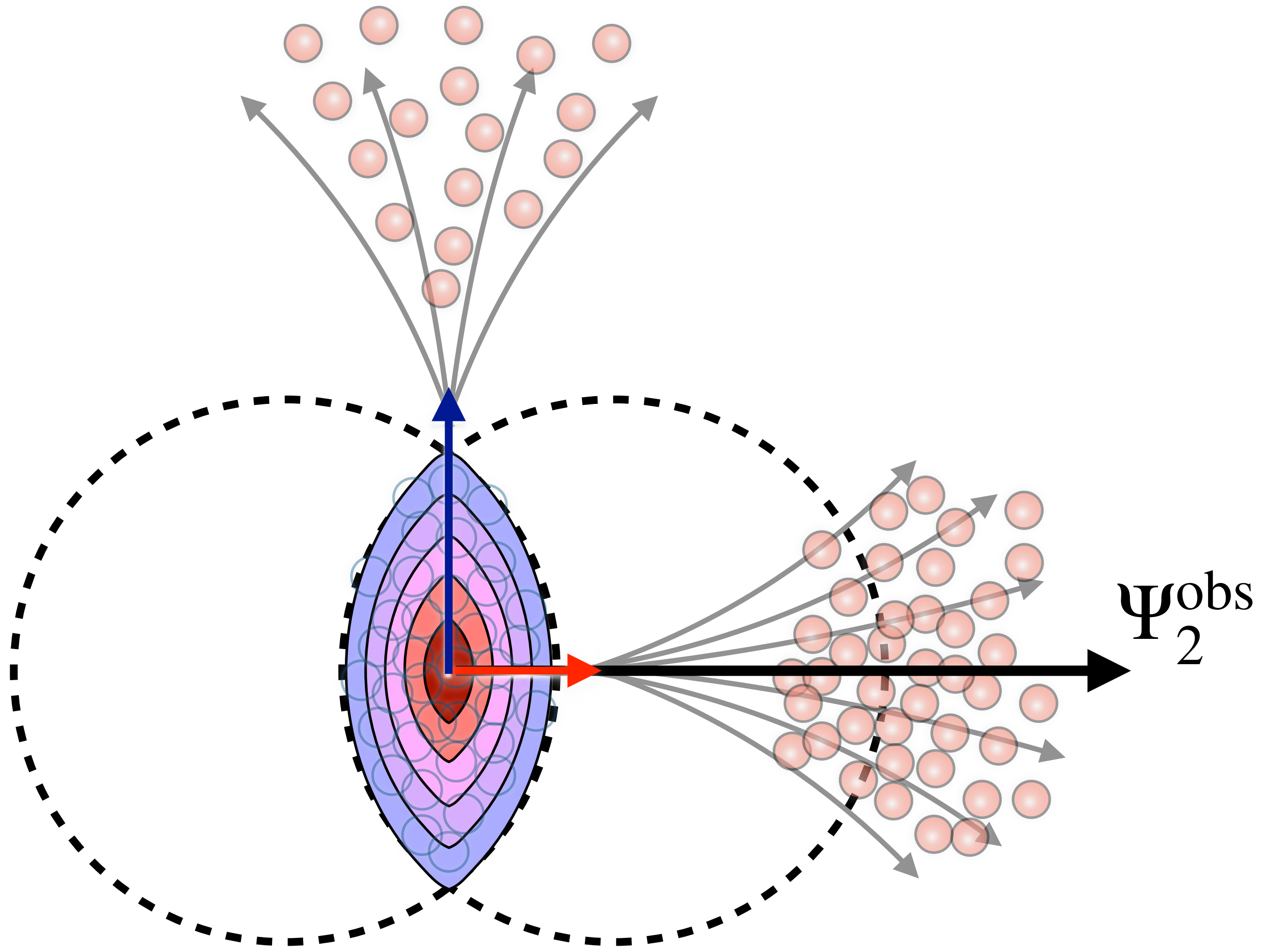


Control jet path-length through the QGP medium

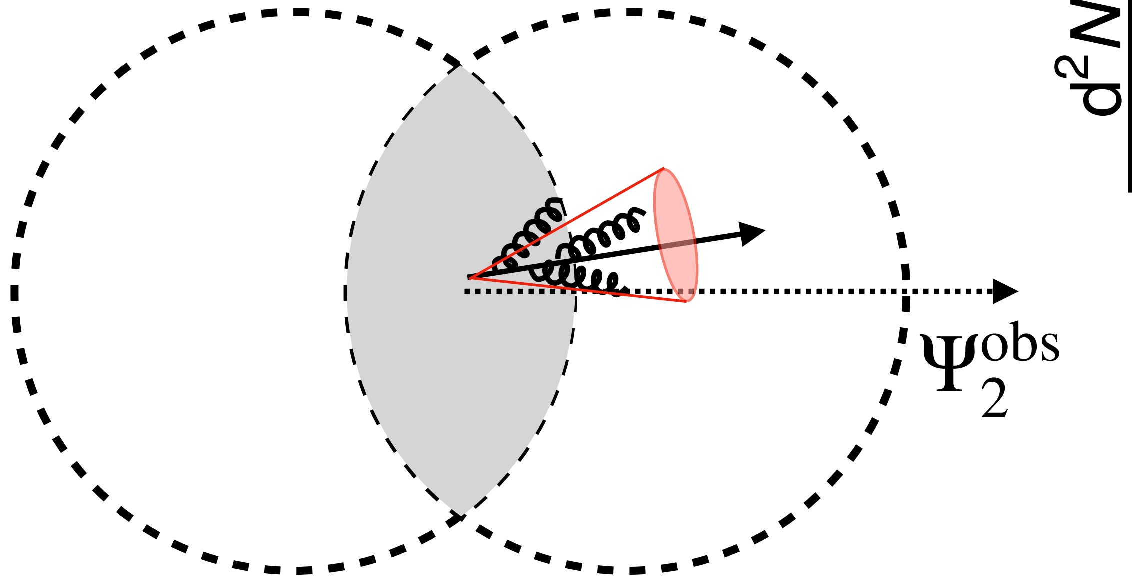
- Correlate jet with event plane angle →
- Correlate back-to-back dijet events →

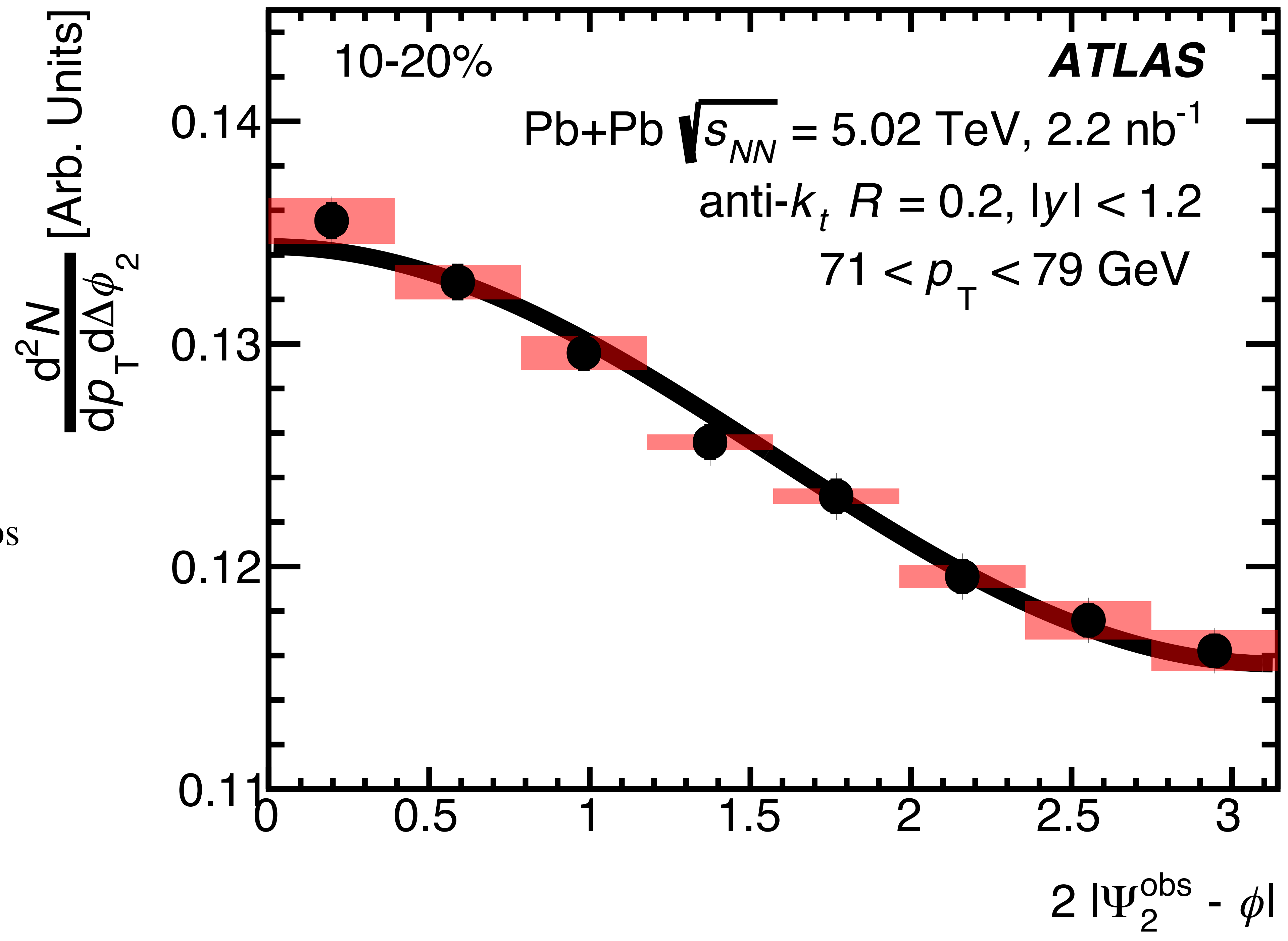
- Jet azimuthal anisotropy
- Dijet asymmetry

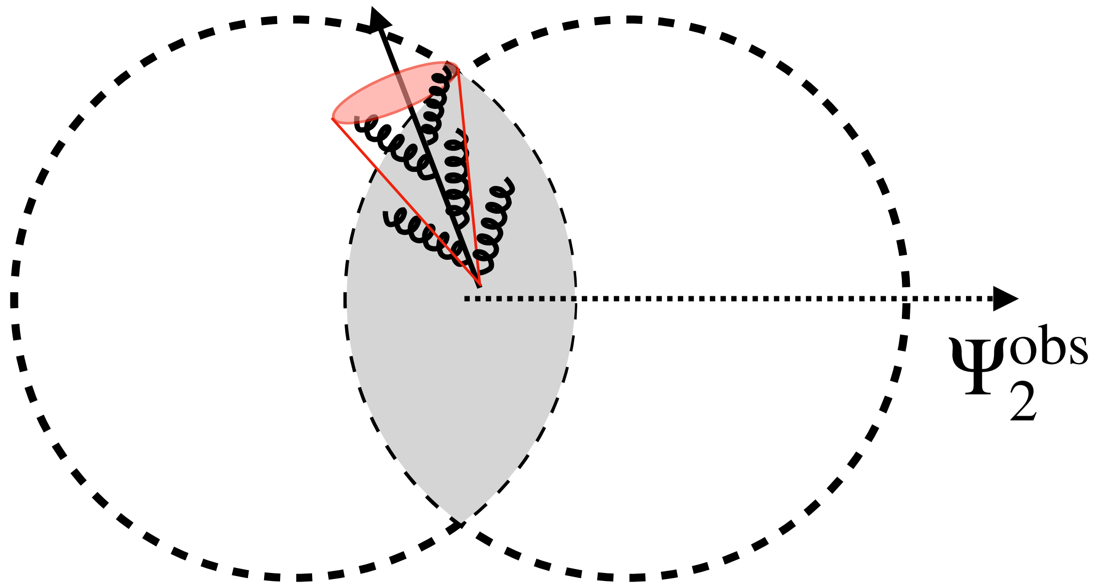
Jet production wrt. event plane angle



$$\frac{dN_{jet}}{d\phi} \propto 1 + 2v_n \cos\left(n(\phi_{jet} - \Psi_2^{obs})\right)$$

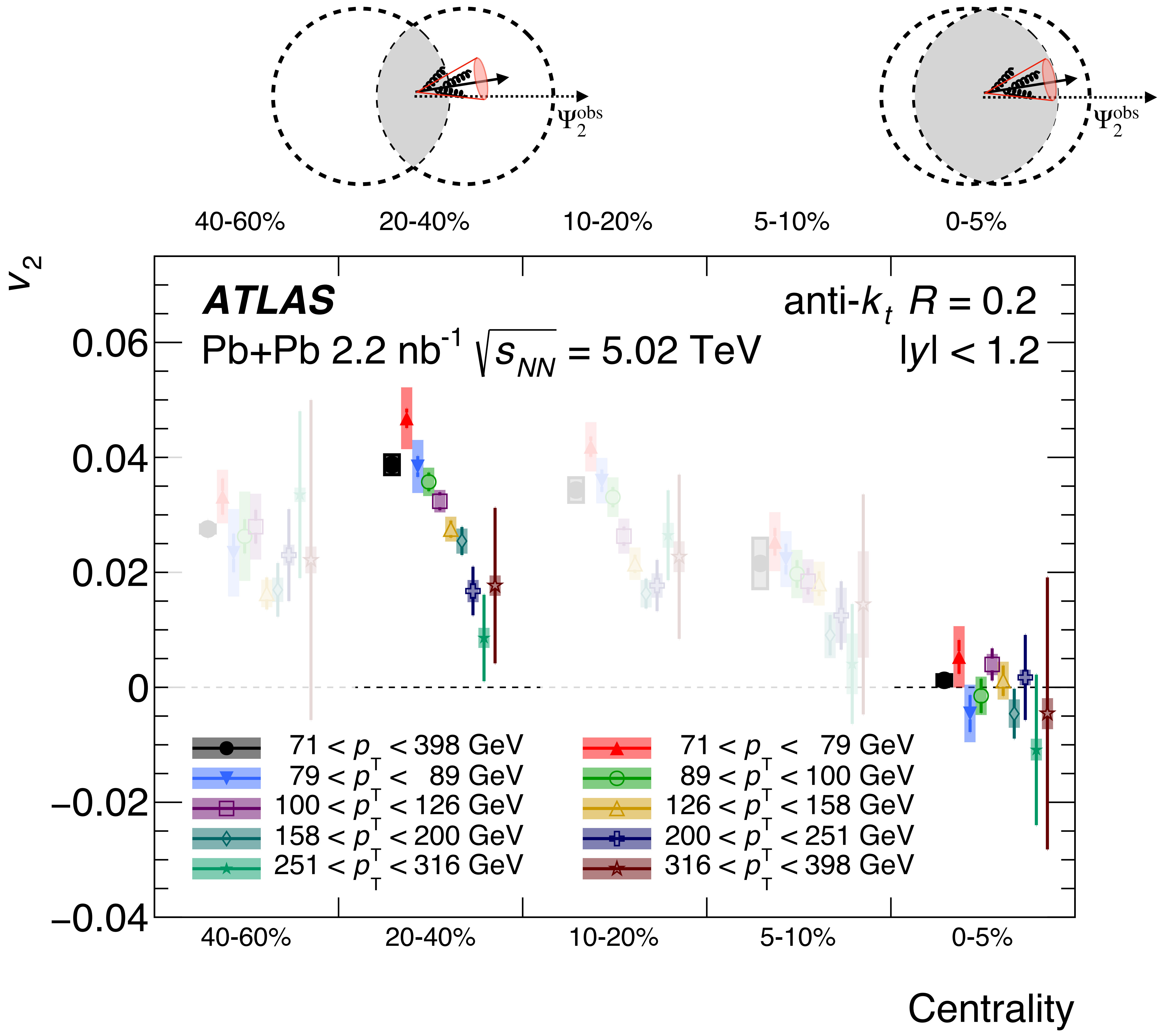






Jet v_2 results

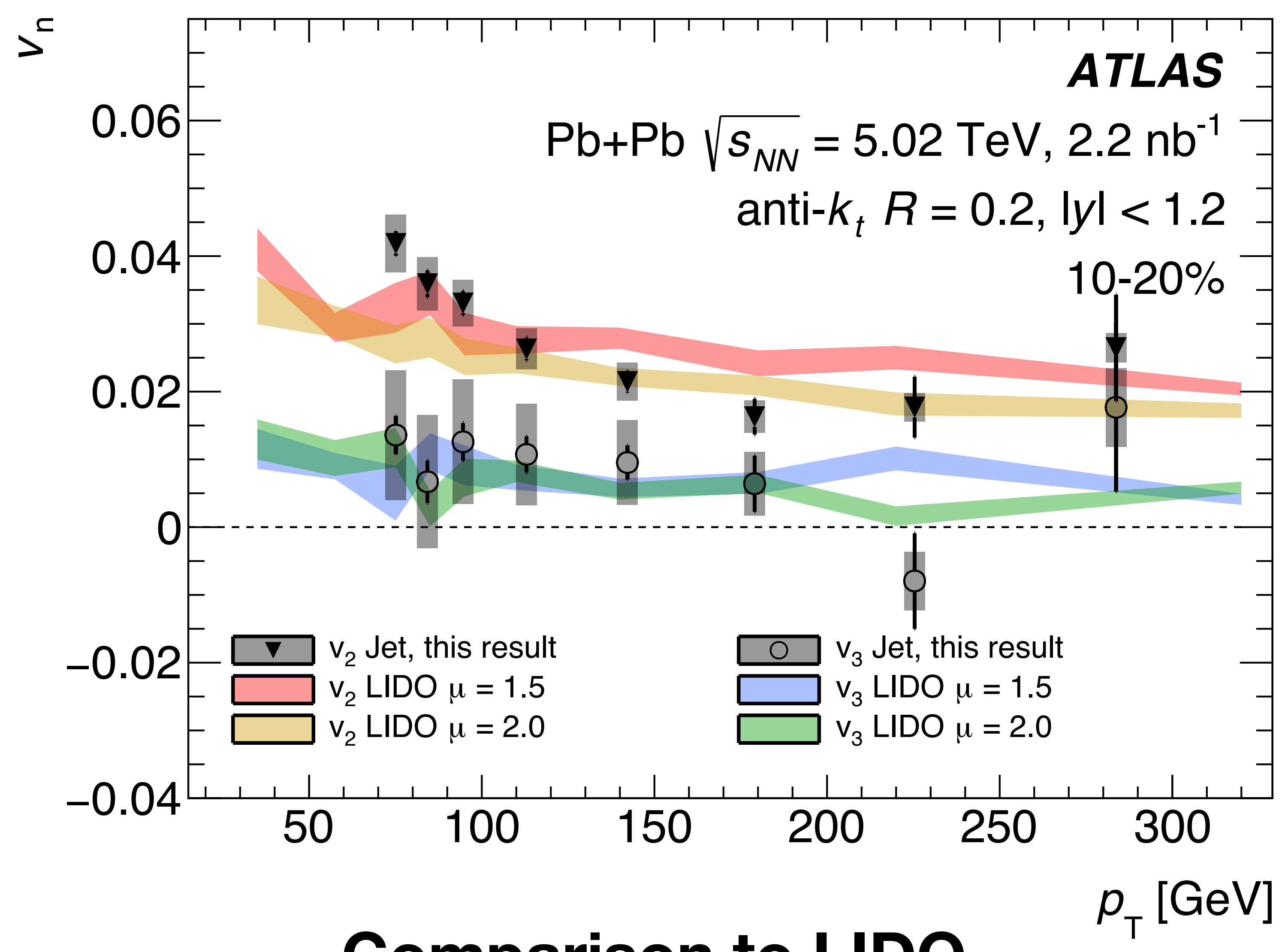
arXiv:2111.06606



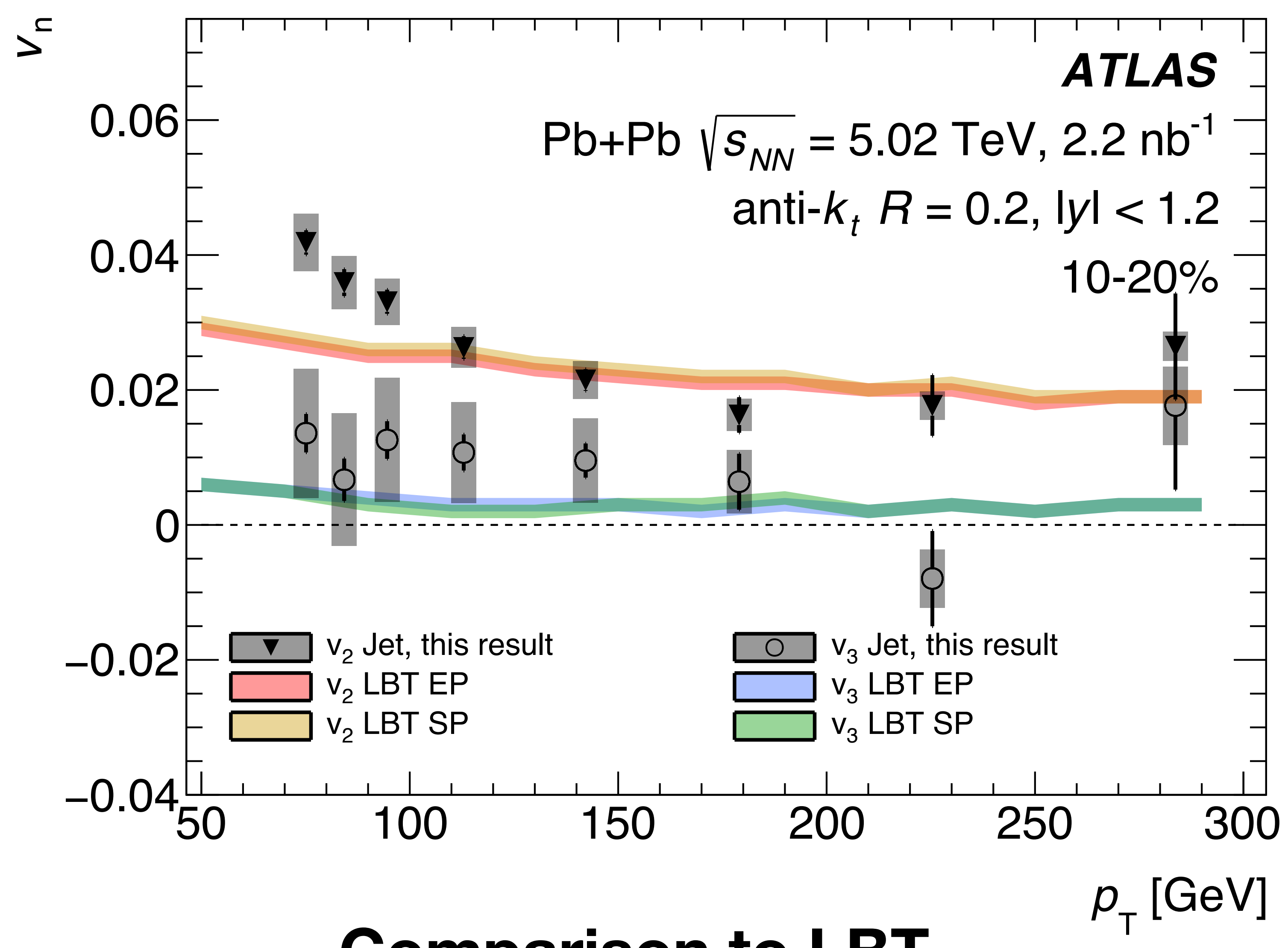
- Centrality dependence → Initial geometric anisotropy
- p_T dependence → less suppression at higher p_T, surface bias

Jet v_n results — model comparisons

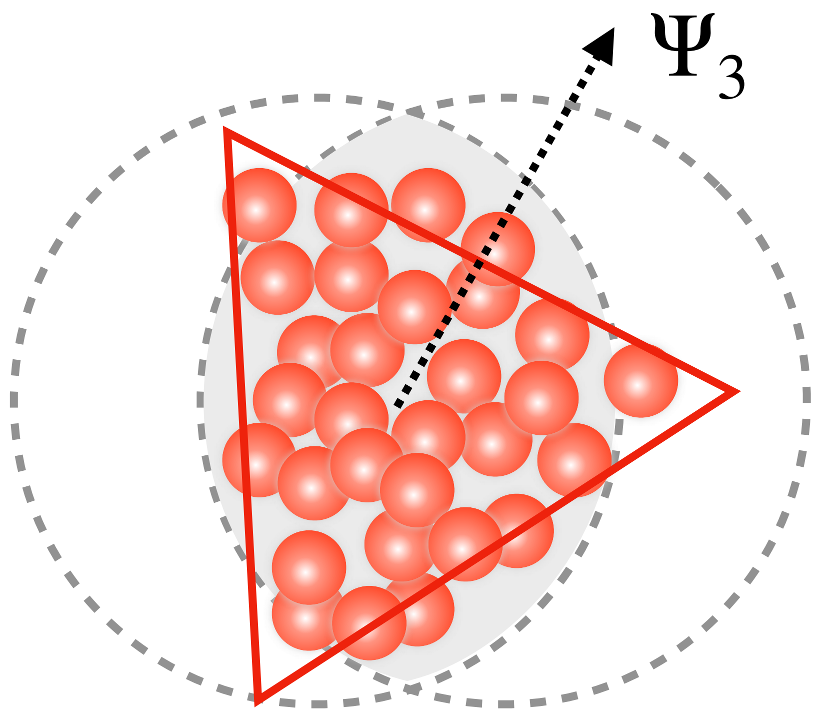
arXiv:2111.06606



Comparison to LIDO



Comparison to LBT

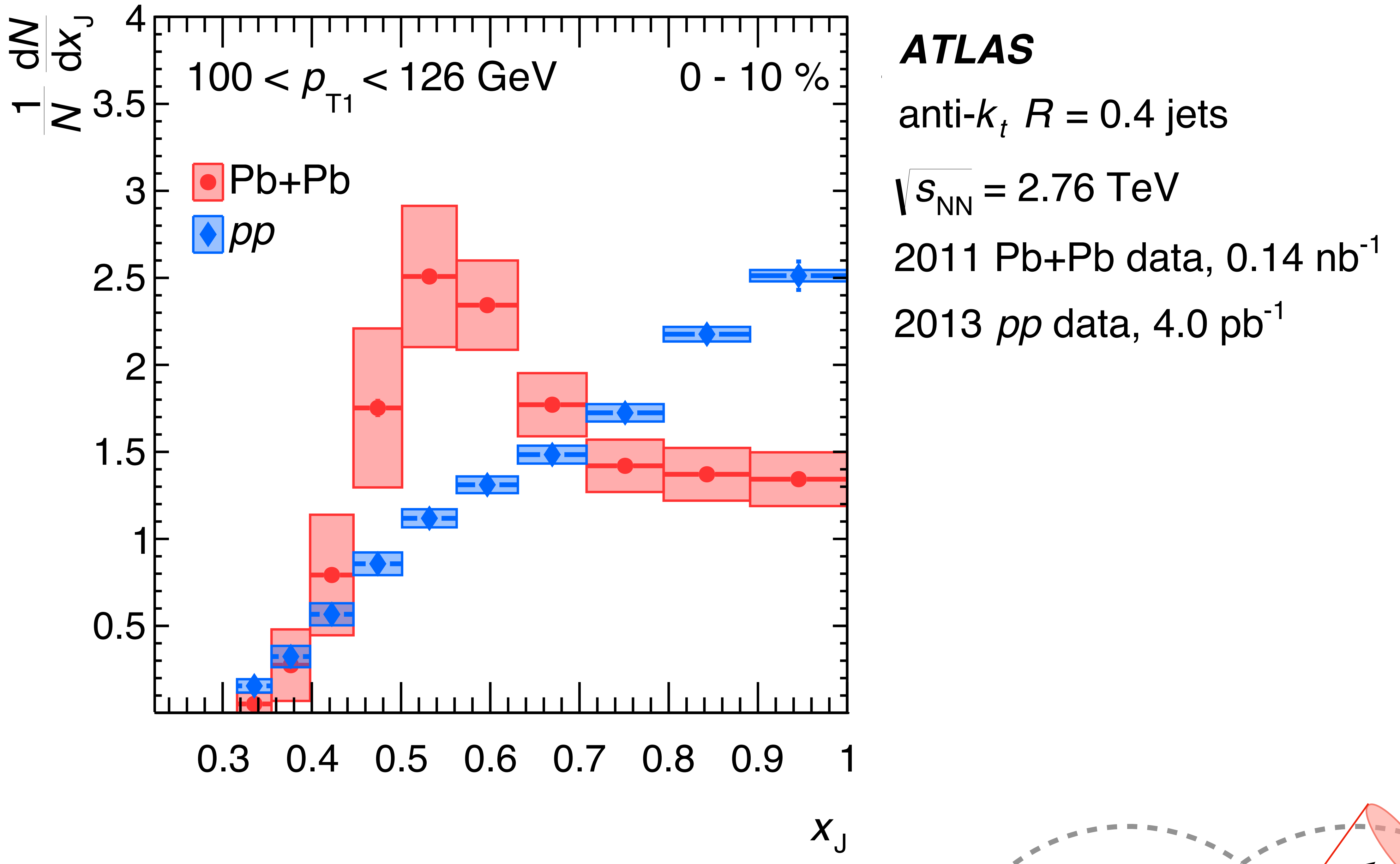


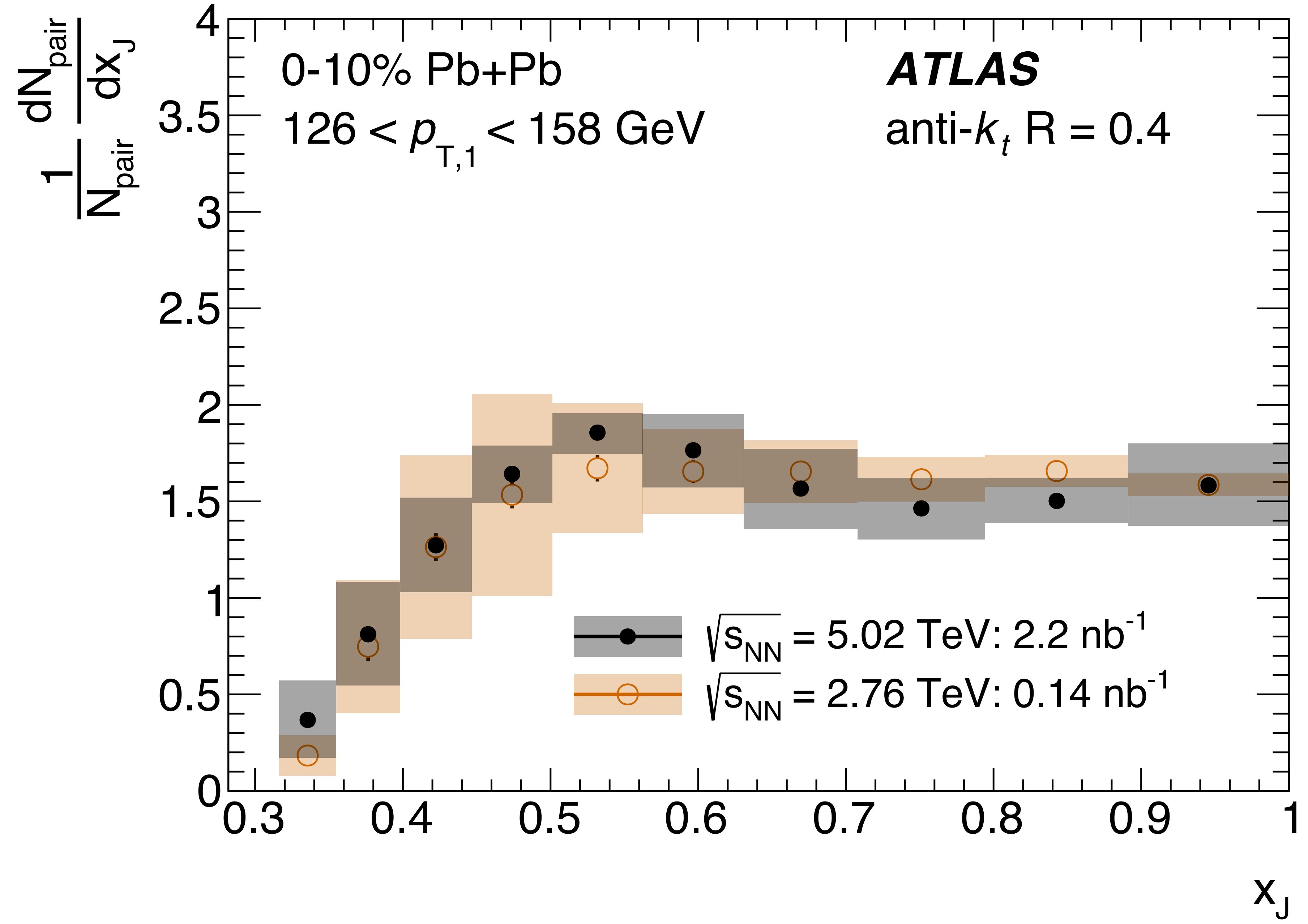
- LIDO※: Pythia8 + Boltzmann + Langevin transport
- LBT※: Pythia8 + Boltzmann transport

- Both transport models get the size of the v_2 & v_3 well, except for v_2 below ~100 GeV

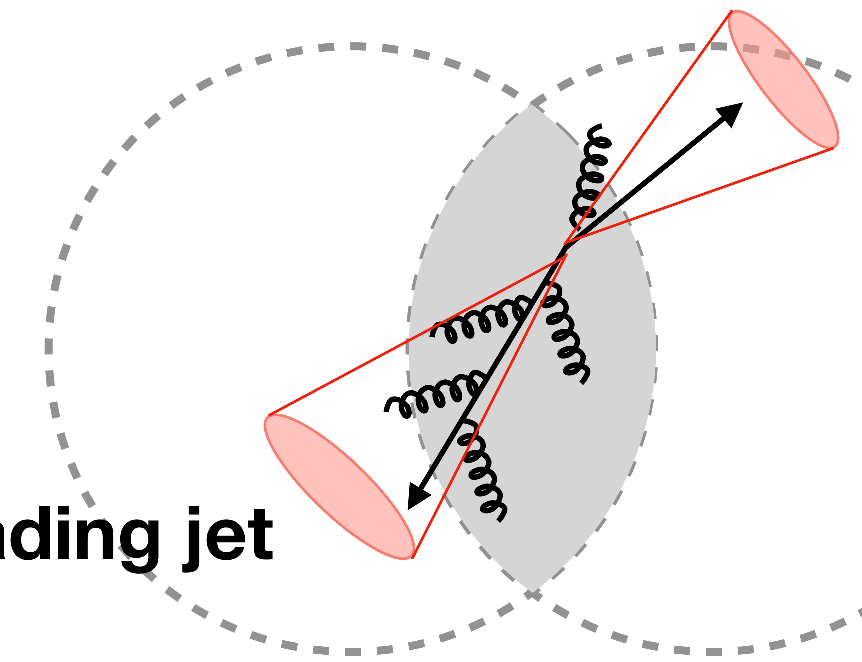
Normalized dijet x_J distribution

Physics Letters B 774 (2017) 379
arXiv:2205.00682



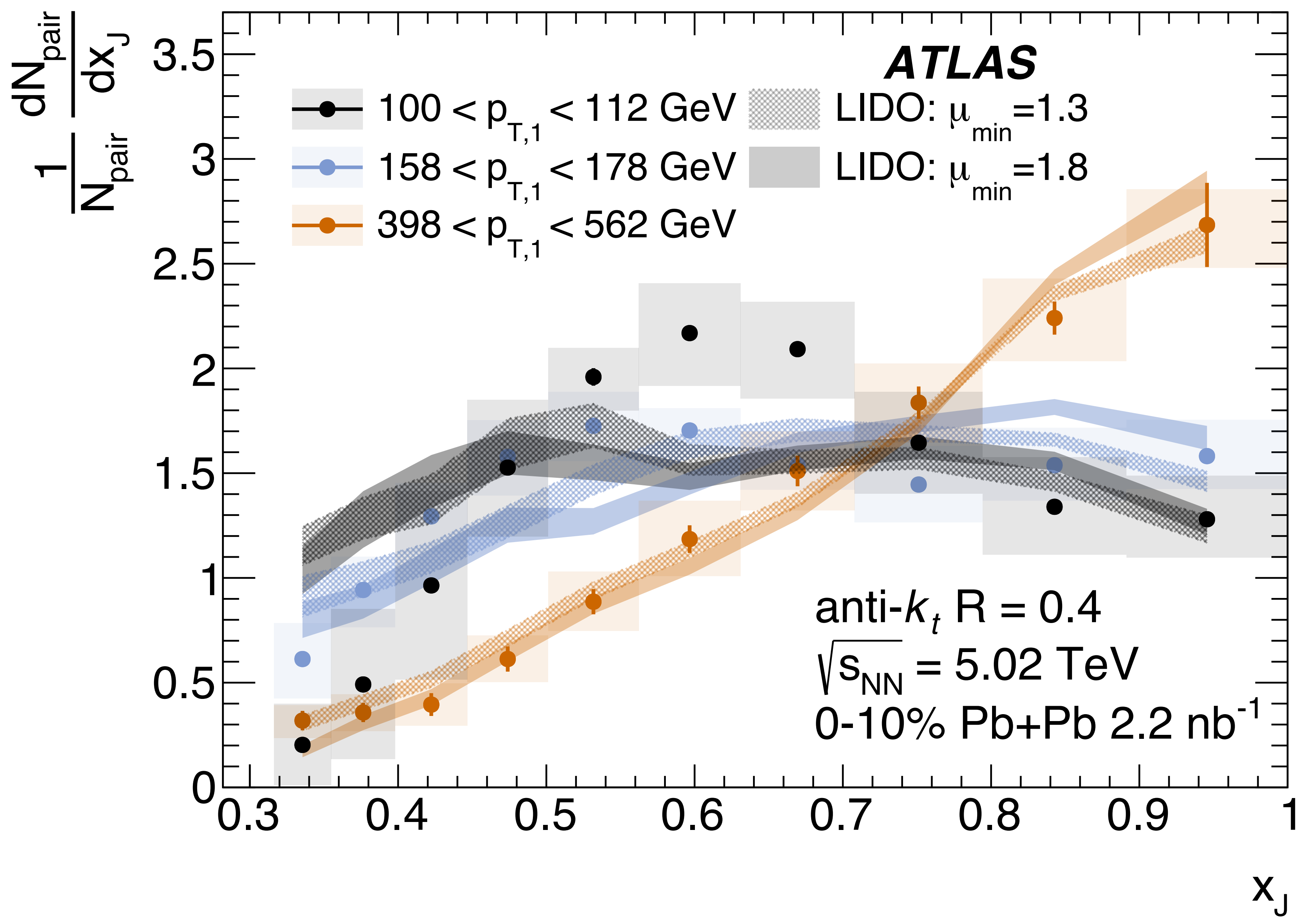


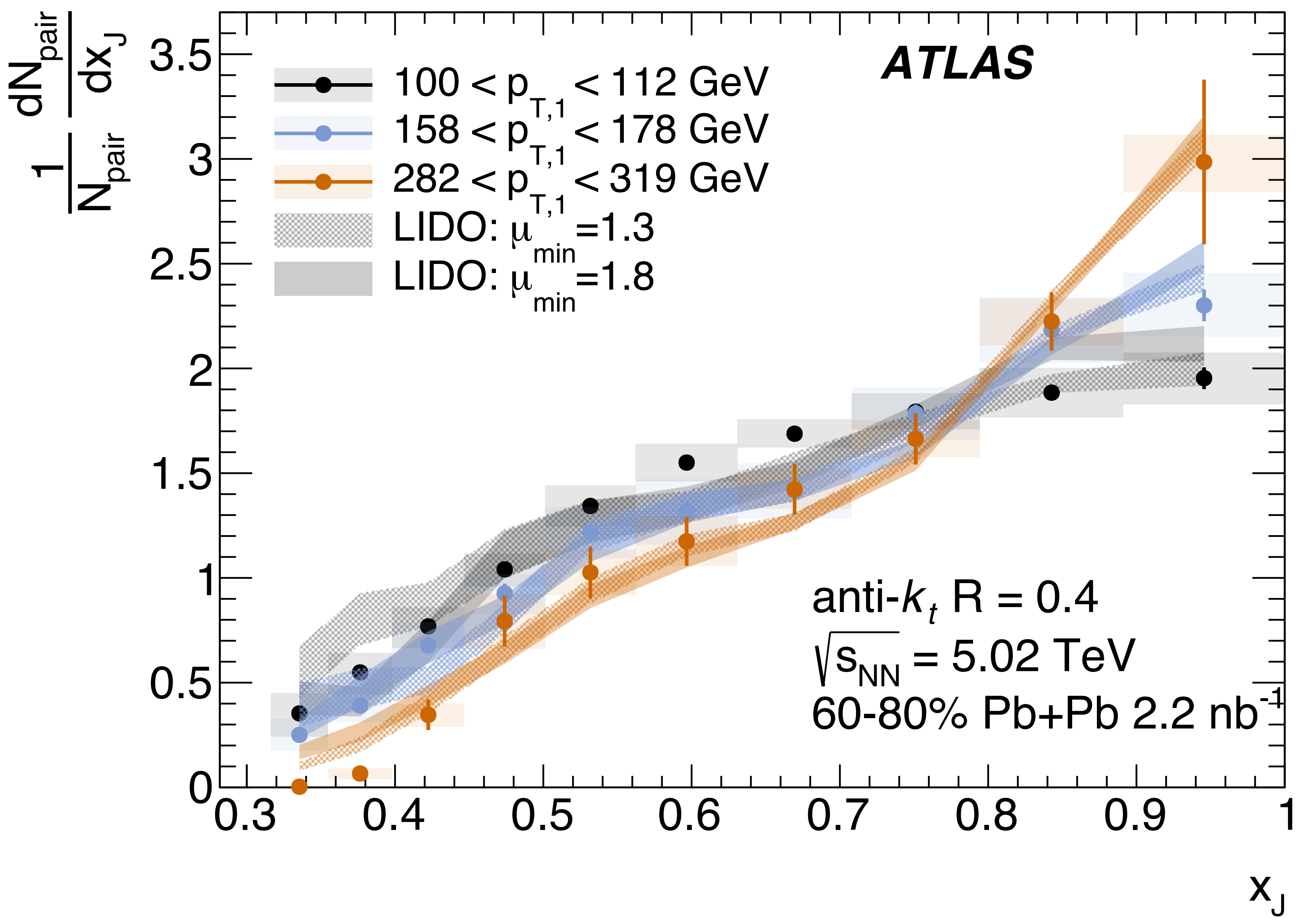
$$x_J = \frac{p_T^{\text{sub-leading}}}{p_T^{\text{leading}}}$$

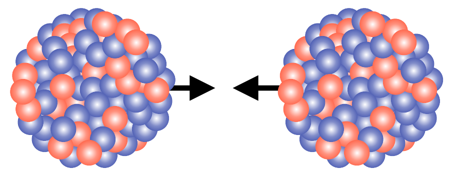


Normalized dijet x_J model comparison

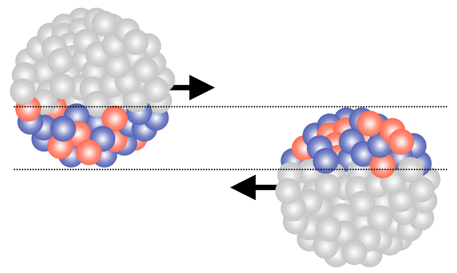
arXiv:2205.00682







0-10%

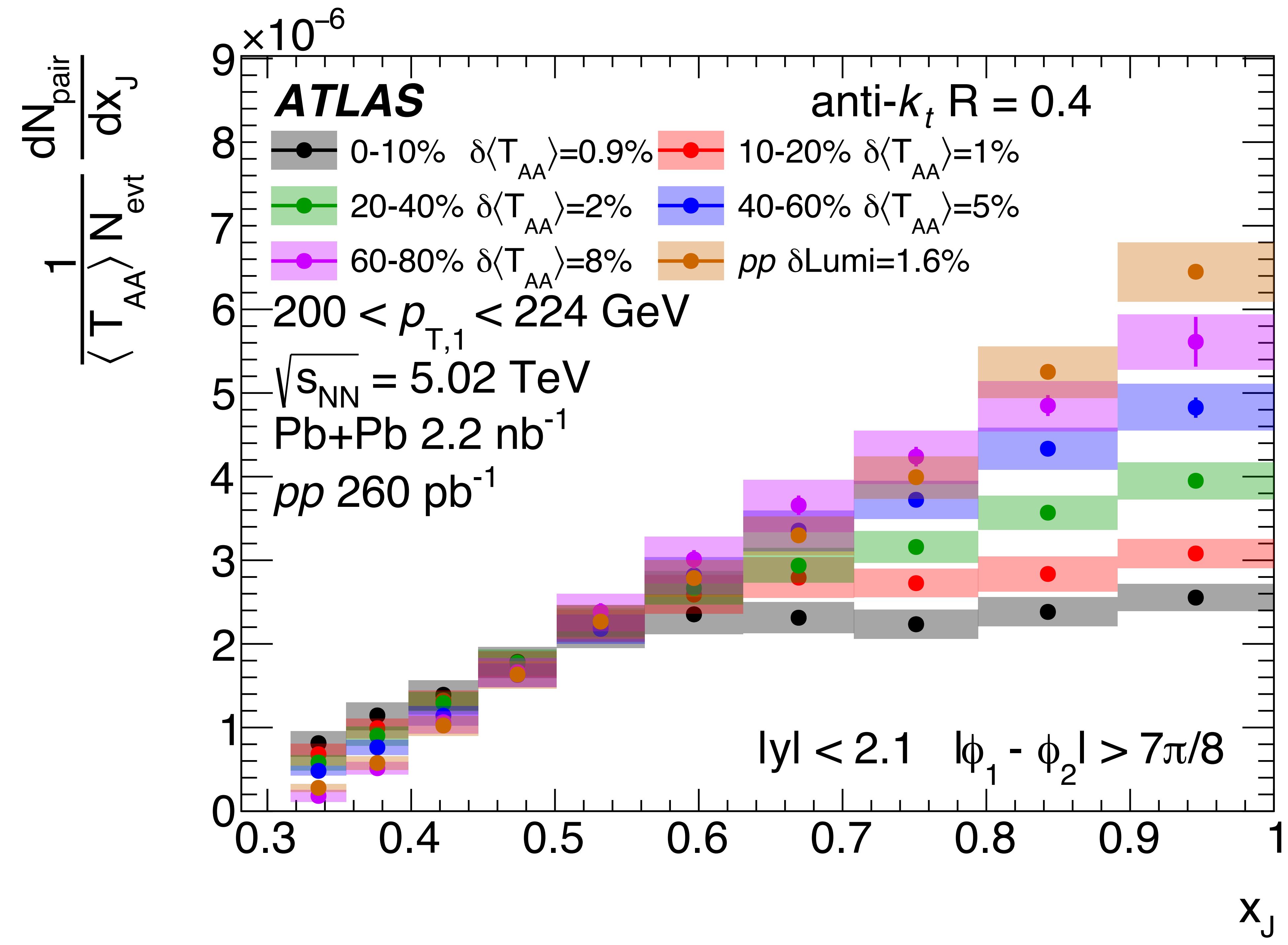


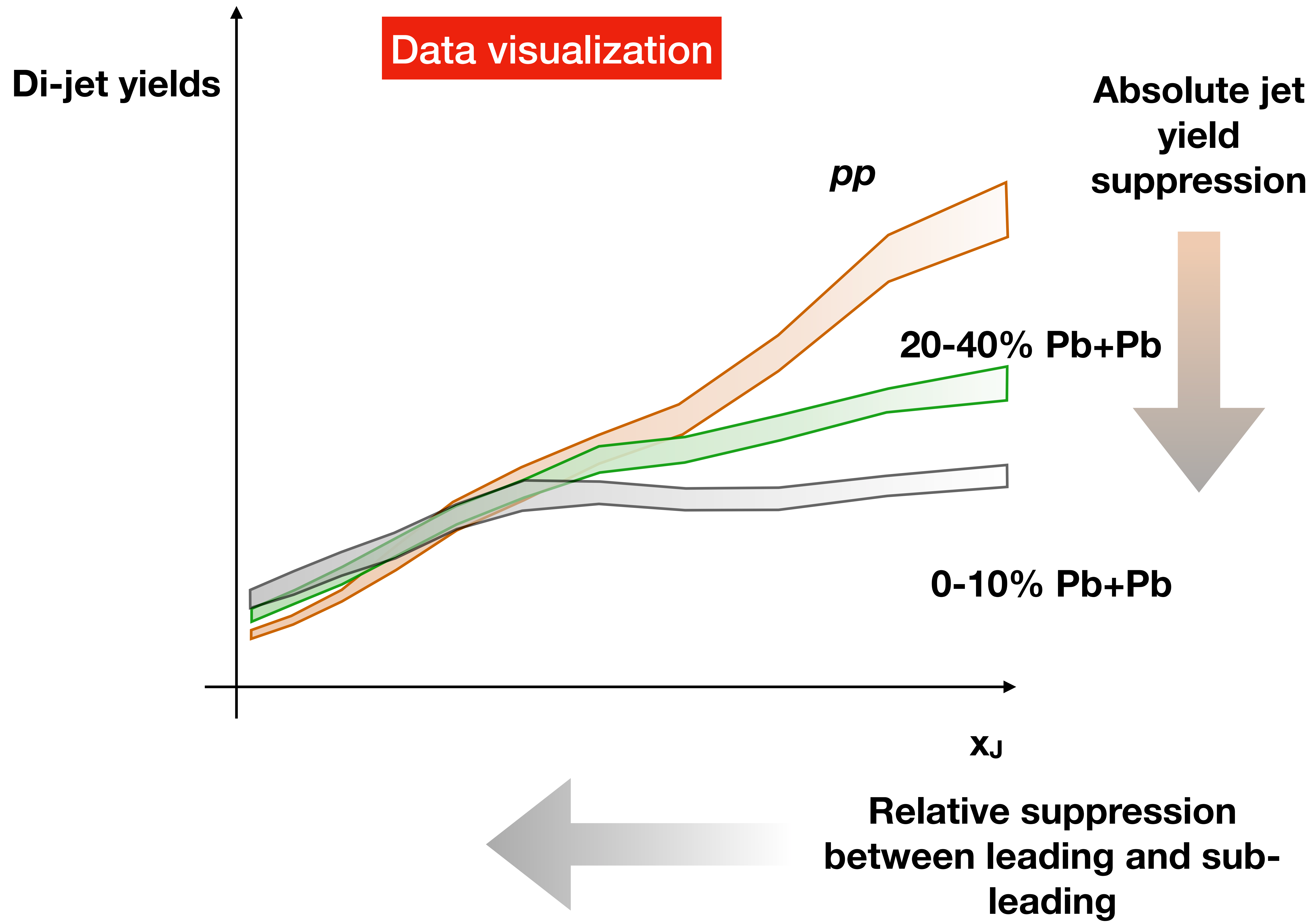
60–80%

LIDO transport model reproduces high p_T and peripheral results, not low p_T and in central collision

Absolutely normalized dijet x_J distribution

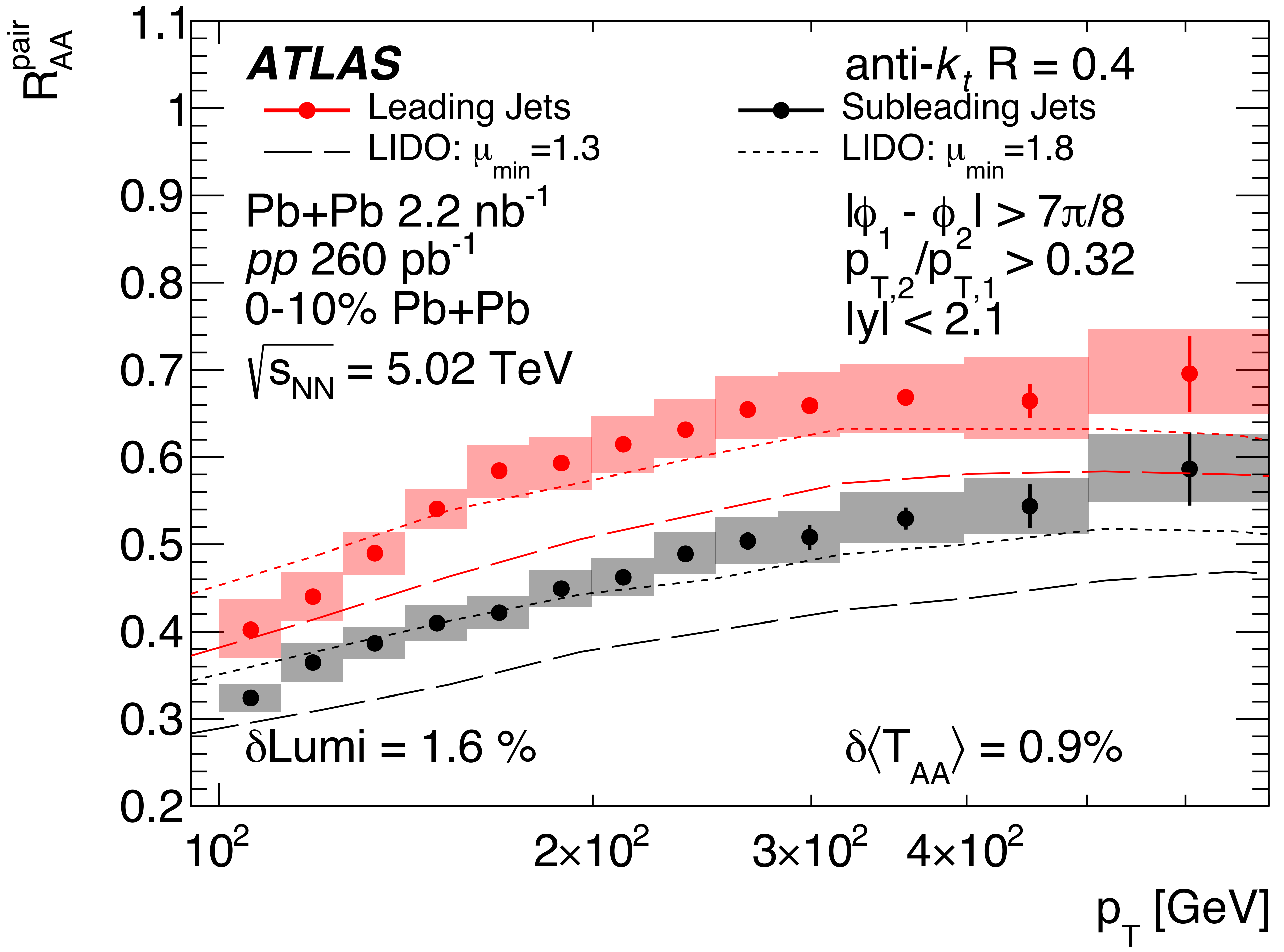
arXiv:2205.00682

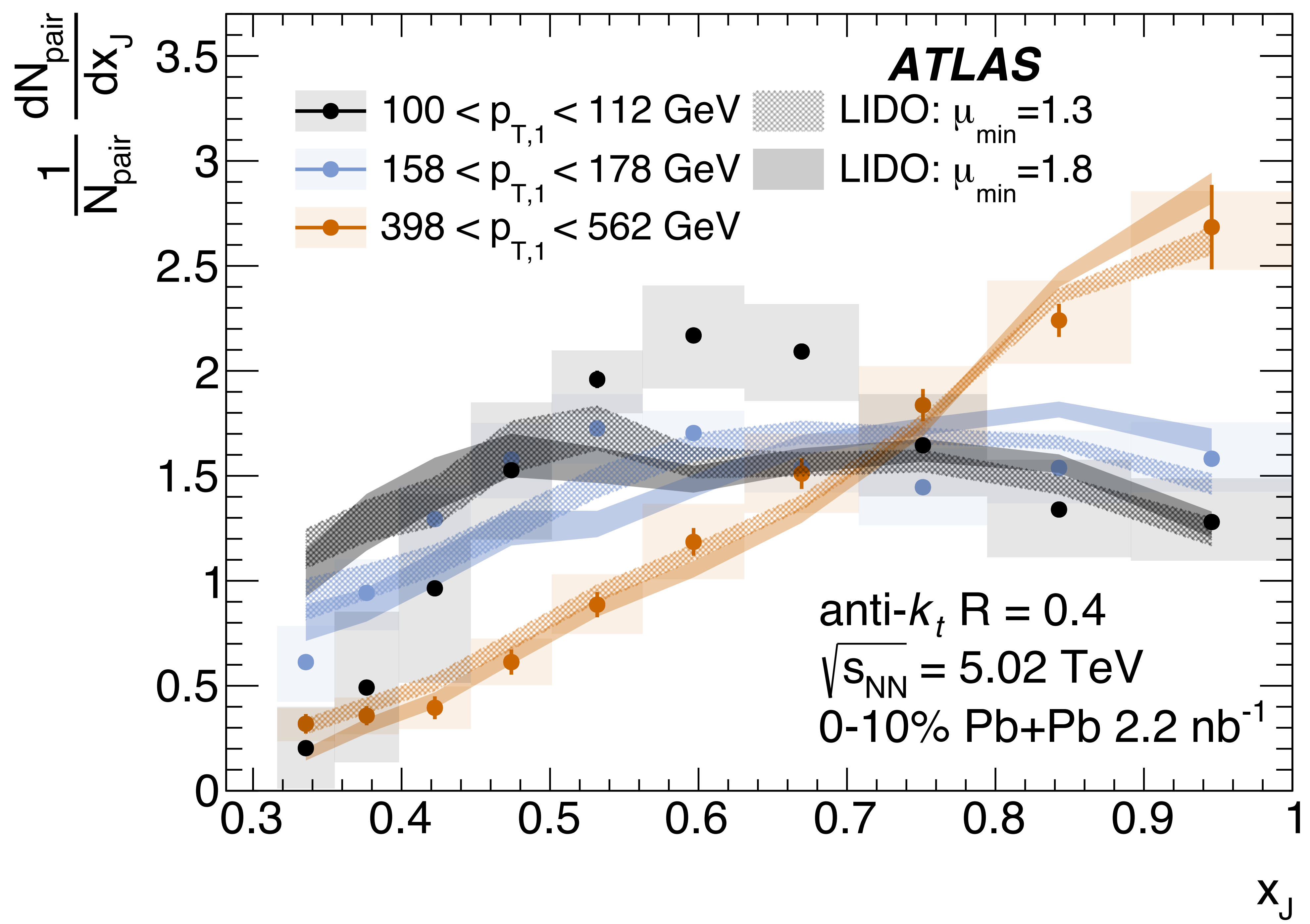




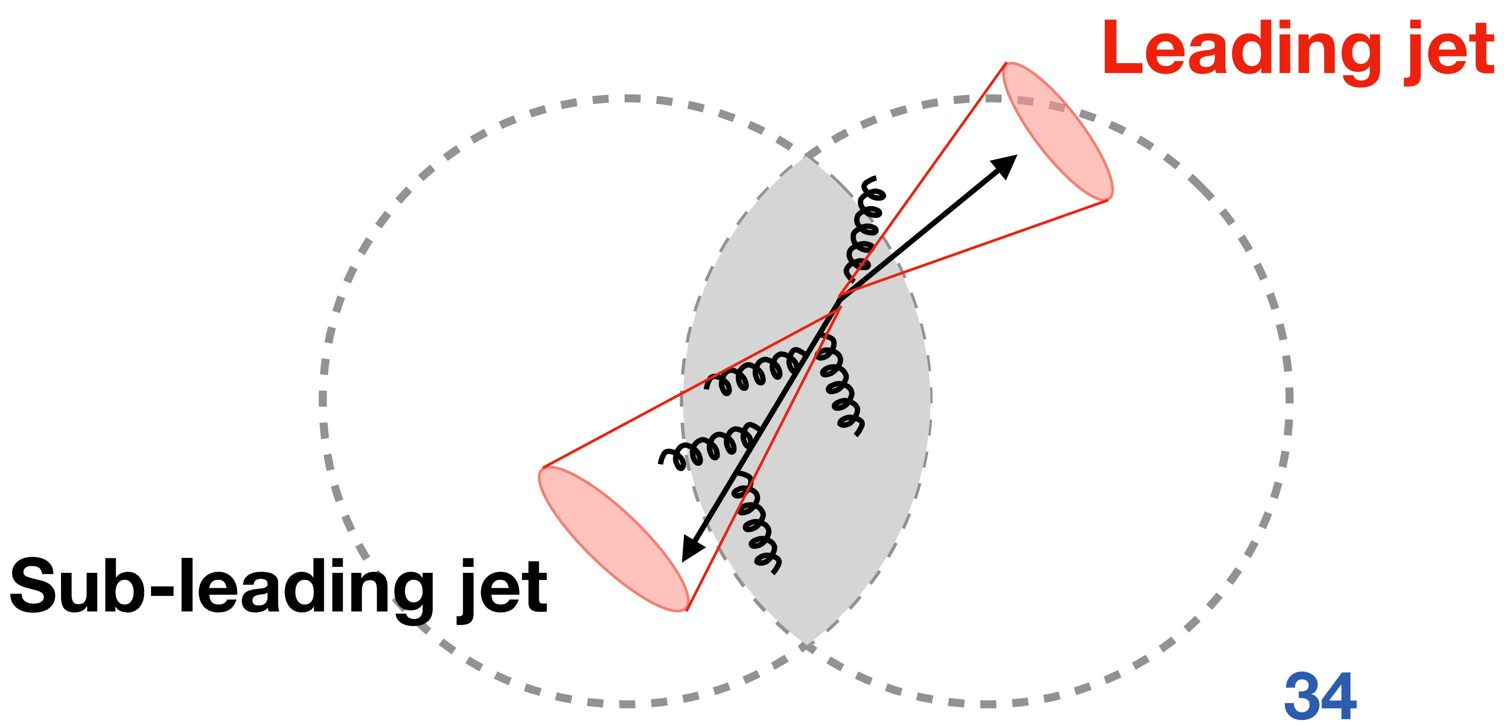
Dijet R_{AA}

arXiv:2205.00682





$$R_{AA}^{\rm pair}(p_{\rm T}^{\rm leading}) \propto \frac{\int_{\rm Pb+Pb} N(p_{\rm T}^{\rm leading}, p_{\rm T}^{\rm sub})\, {\rm d}p_{\rm T}^{\rm sub}}{\int_{pp} N(p_{\rm T}^{\rm leading}, p_{\rm T}^{\rm sub})\, {\rm d}p_{\rm T}^{\rm sub}}$$



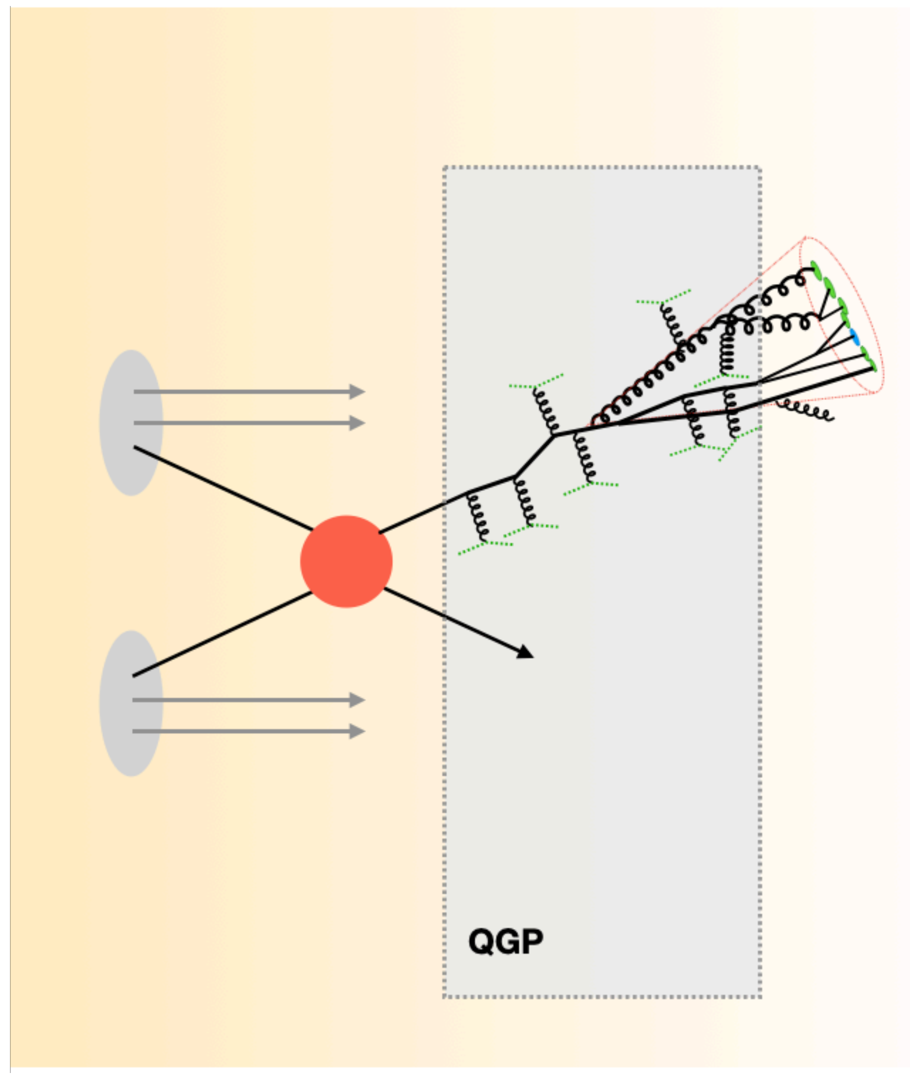
Summary

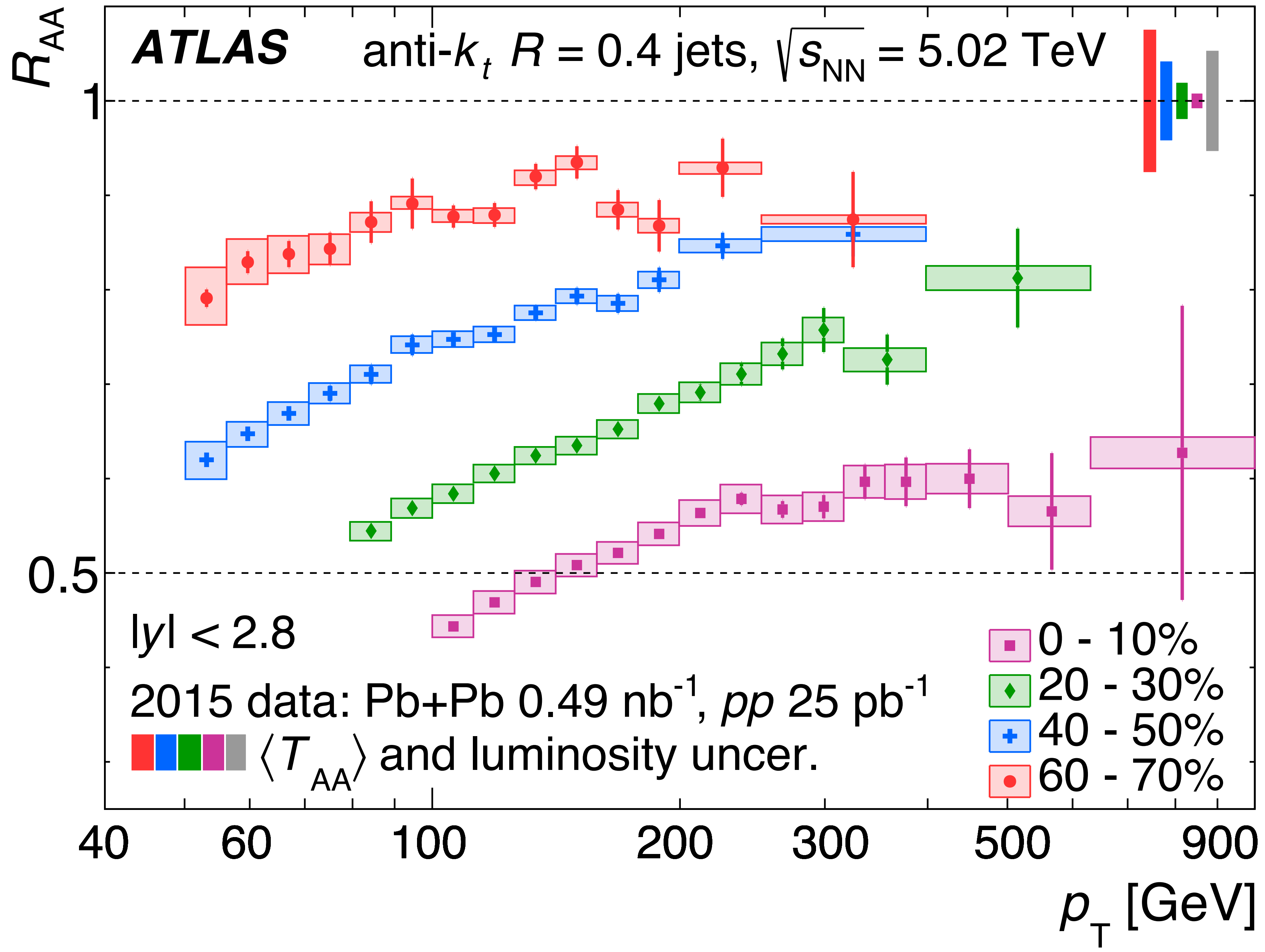
PLB 790 (2019) 108

Parton-QGP interaction —observation→ **Jet quenching**

QGP size/temperature

Centrality dependence



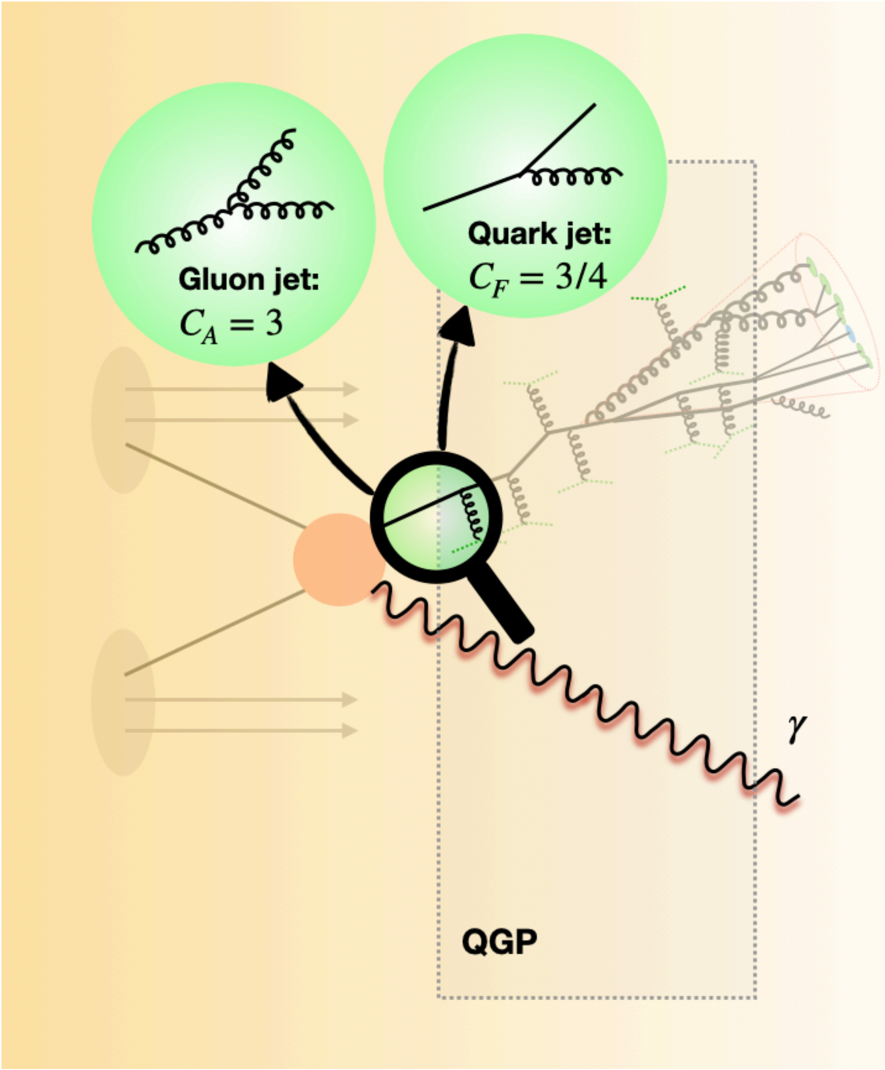


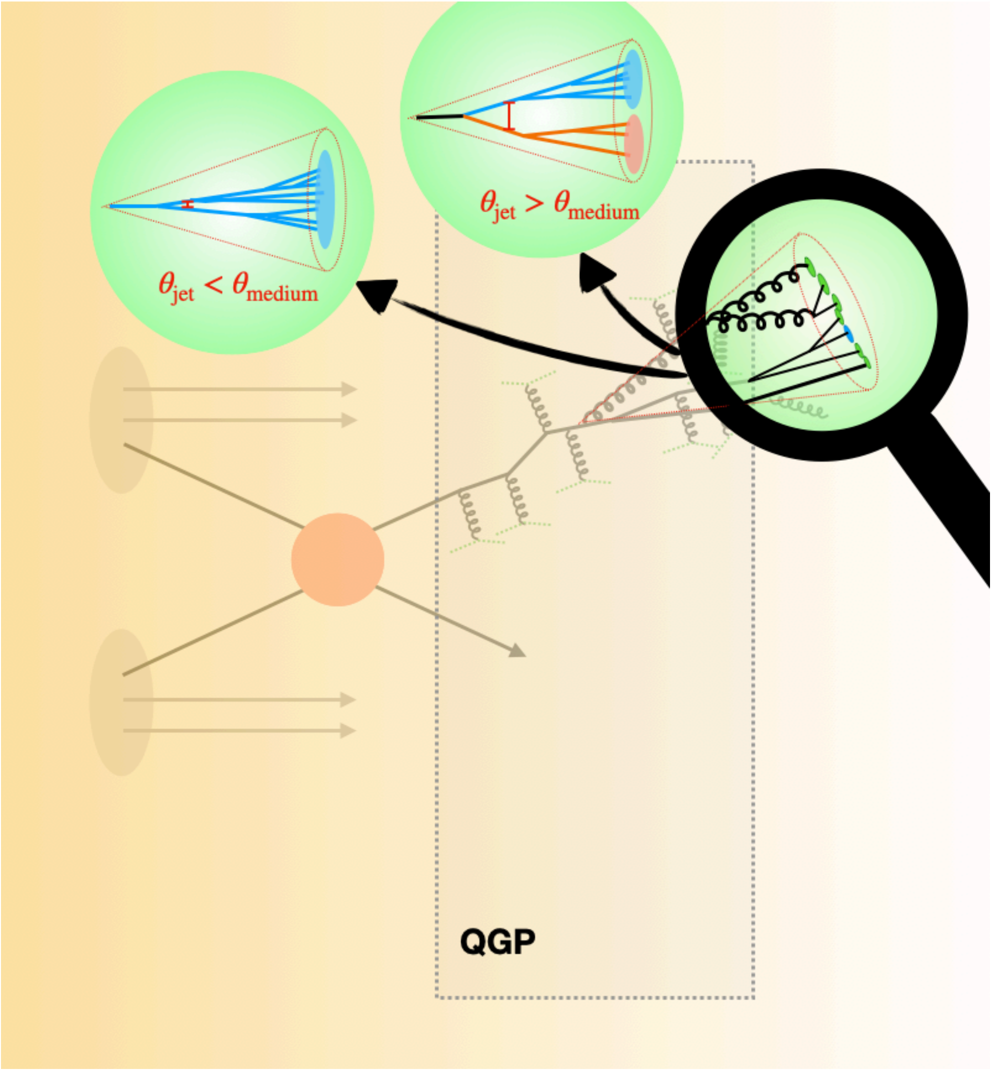
Summary

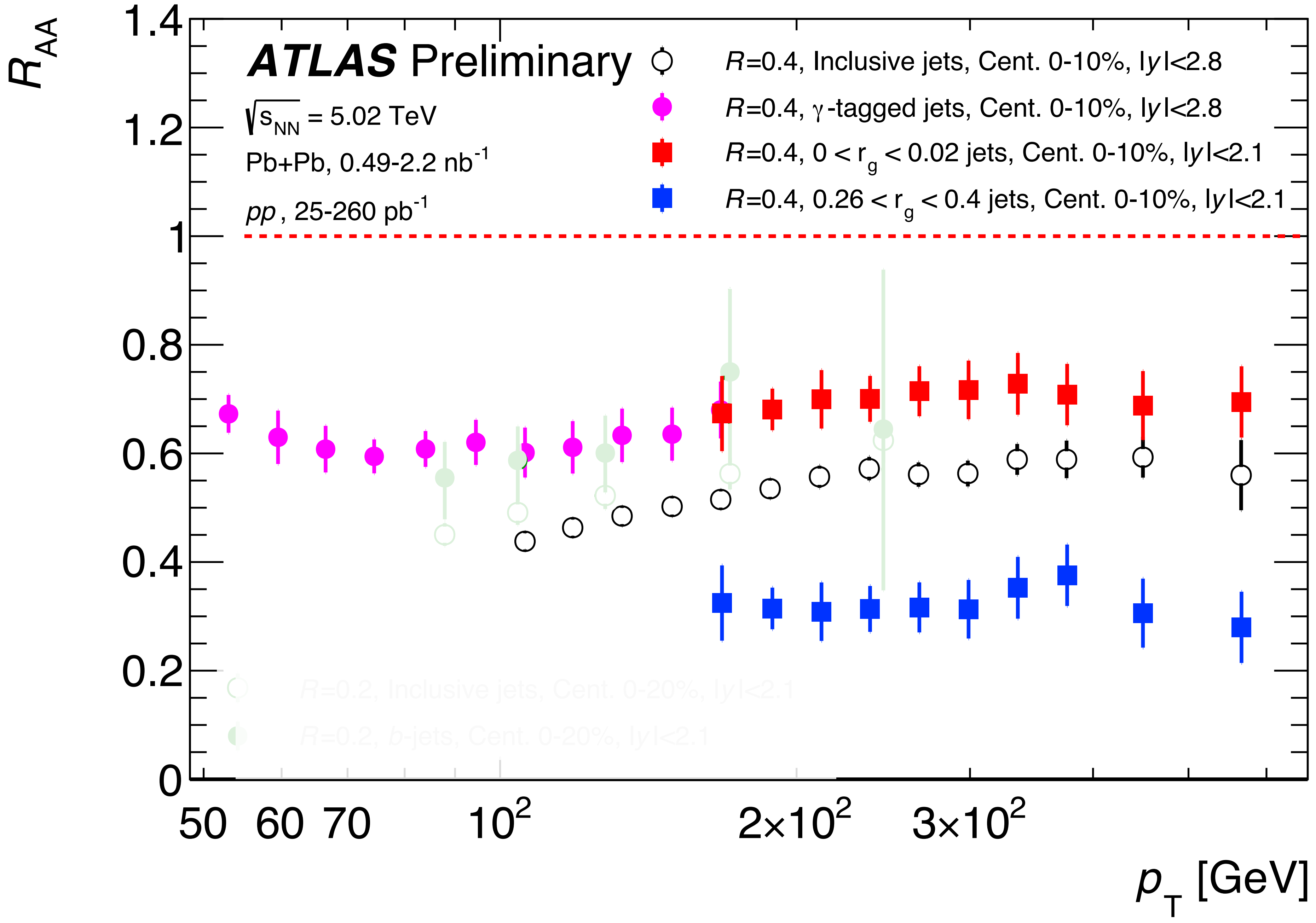
[ATL-PHYS-PUB-2022-020]

Parton-QGP interaction —observation→ **Jet quenching**

Parton-QGP interaction	Jet quenching
QGP size/temperature	Centrality dependence
QGP color coherence	Color charge / substructure dependence





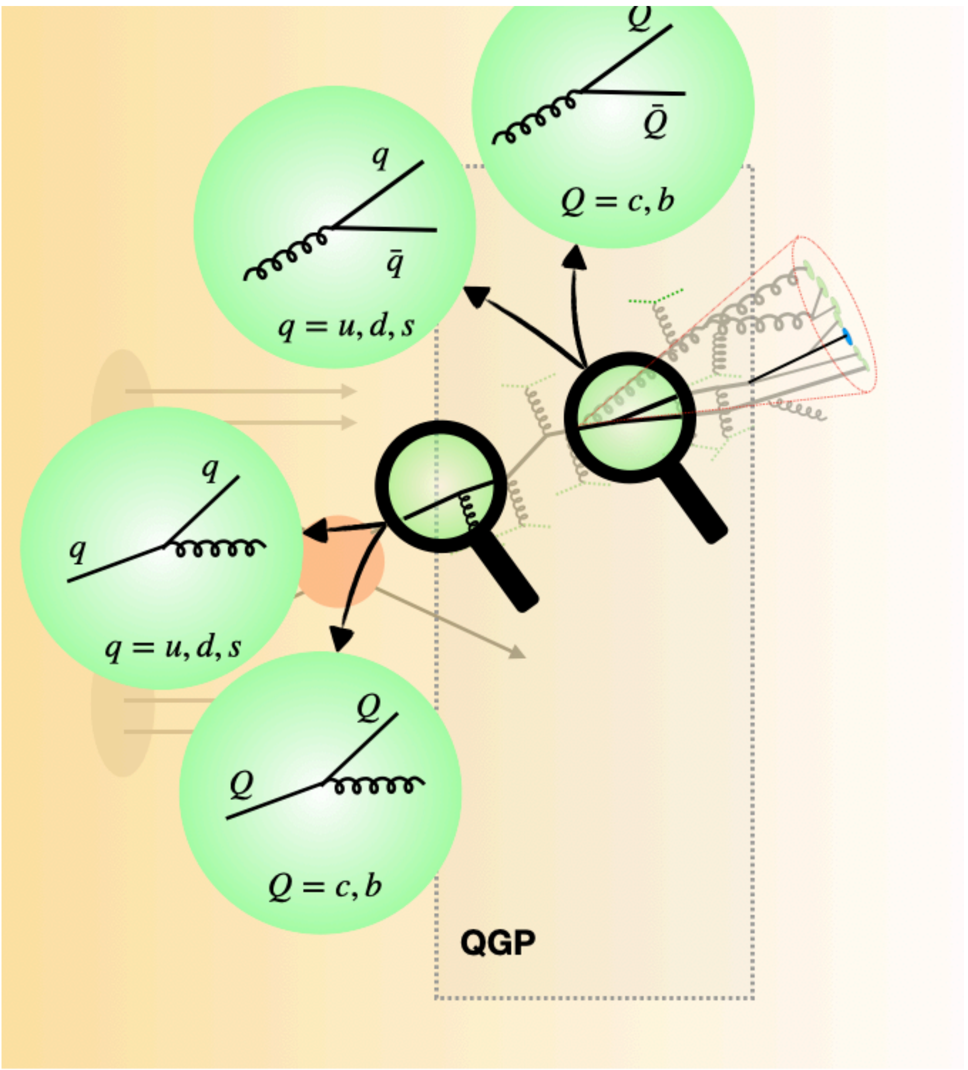


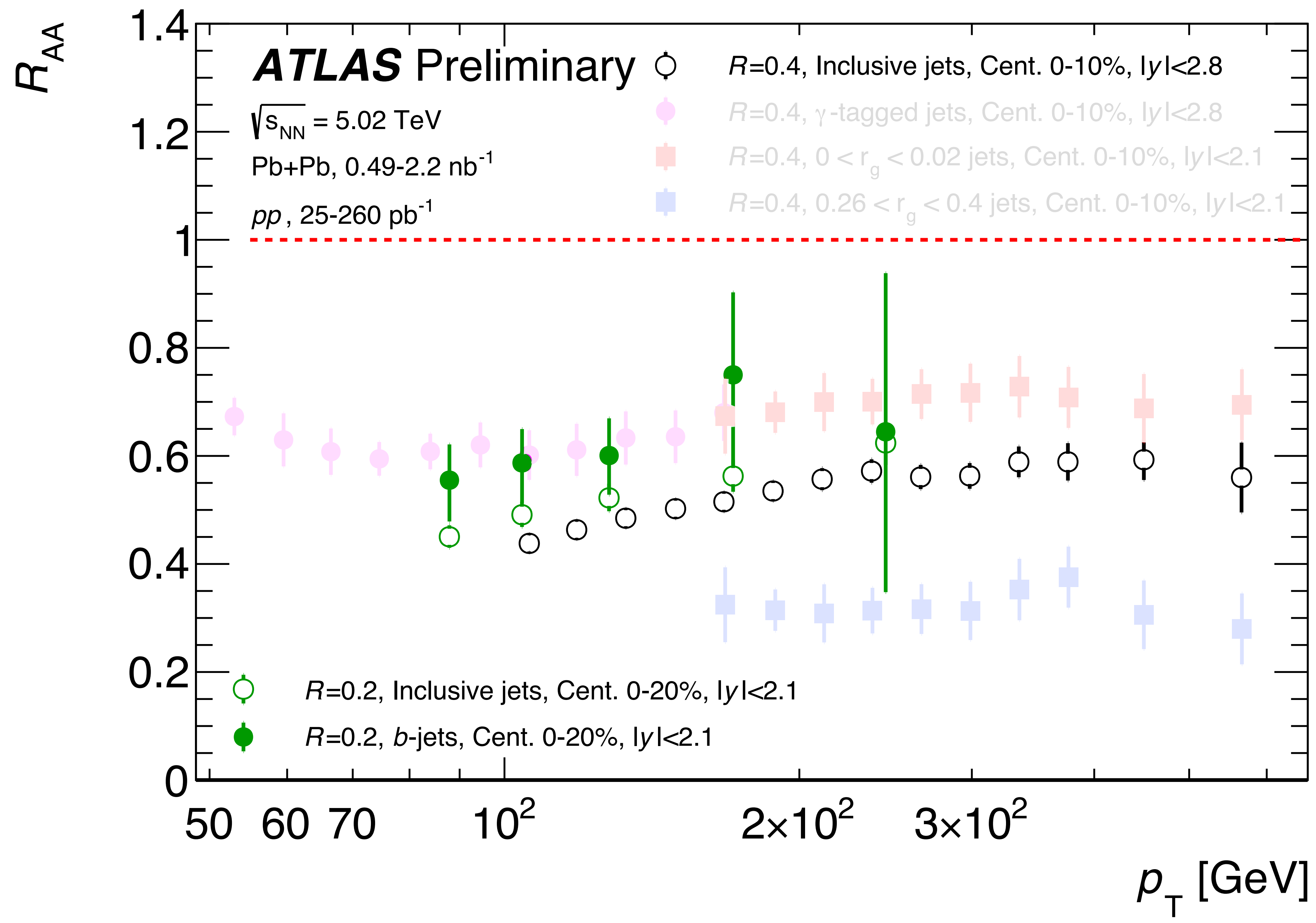
Summary

ATL-PHYS-PUB-2022-020

Parton-QGP interaction —observation→ **Jet quenching**

QGP size/temperature	Centrality dependence
QGP color coherence	Color charge / substructure dependence
Parton mass	Flavor dependence



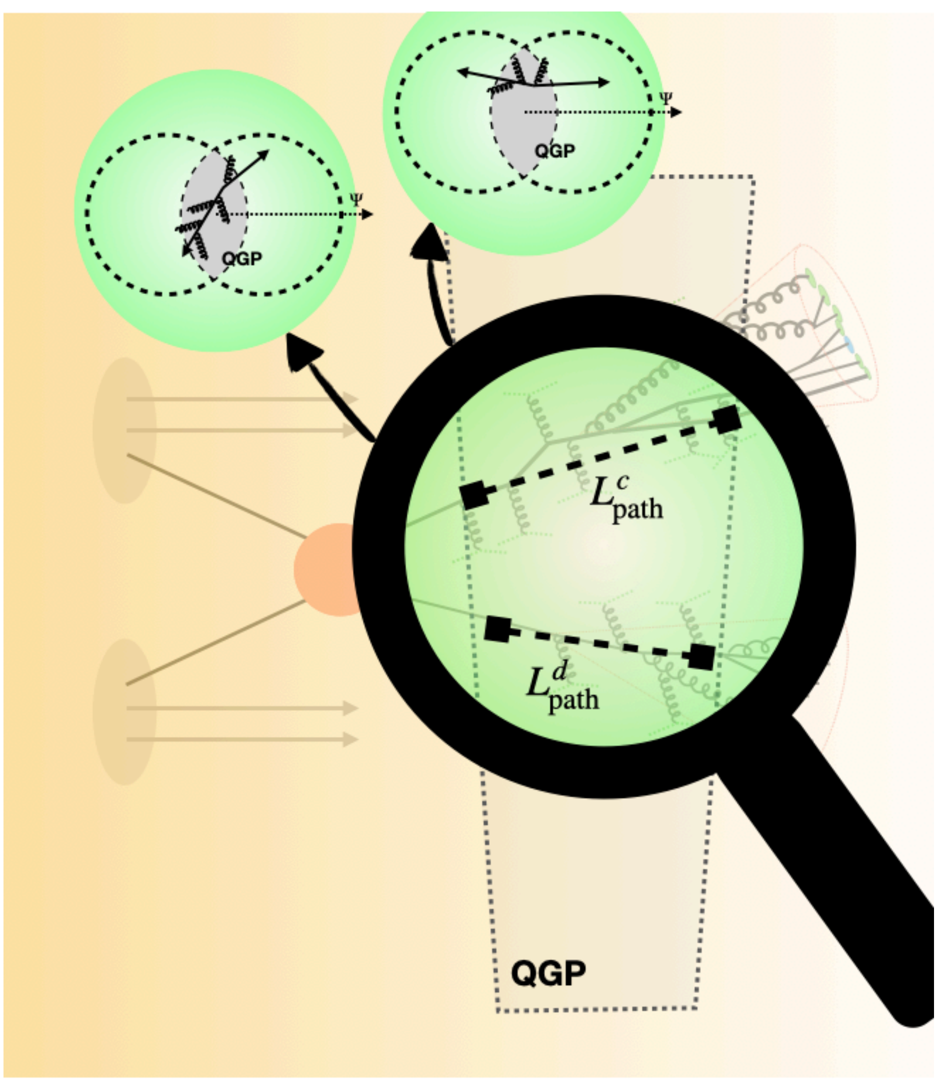


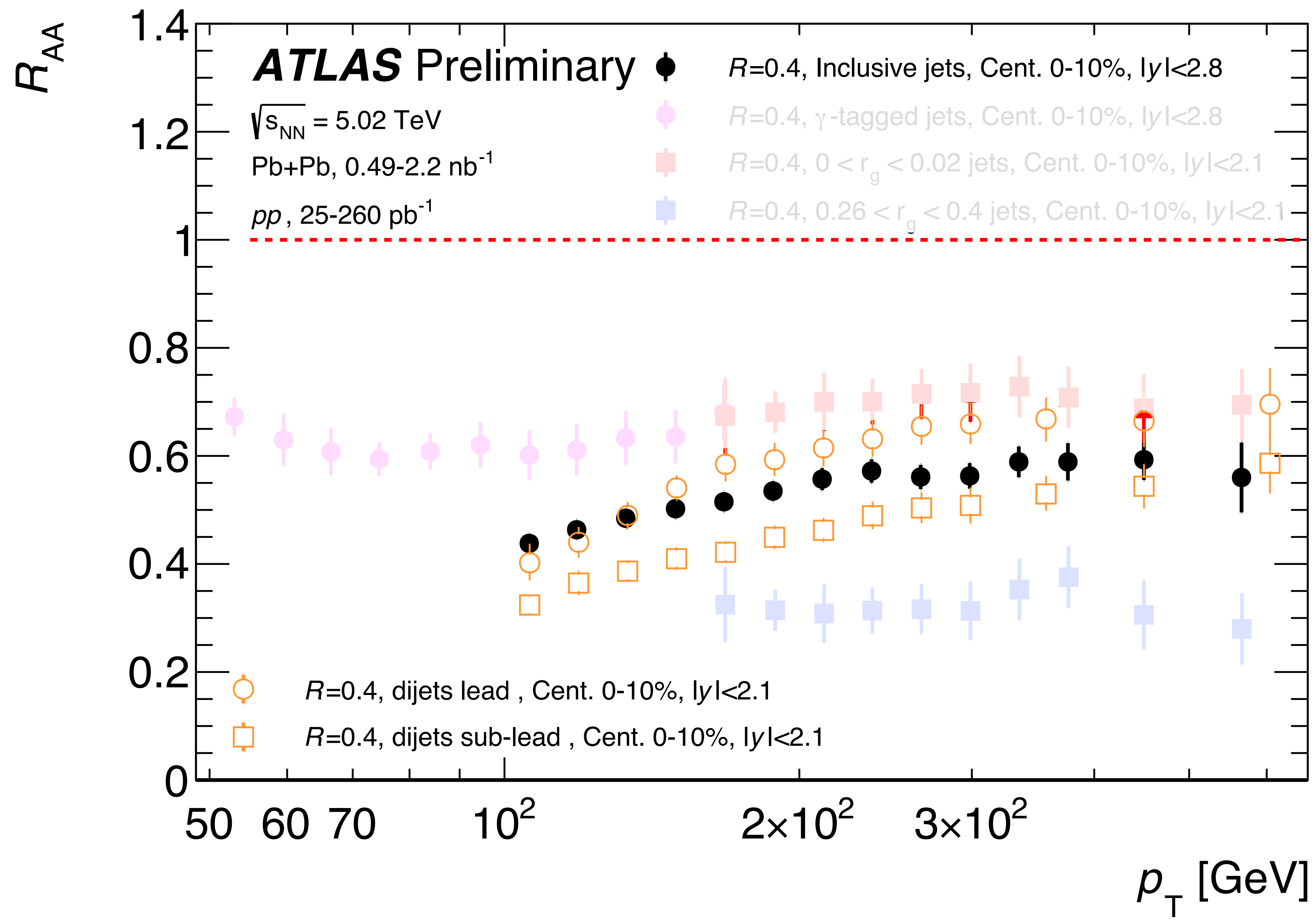
Summary

ATL-PHYS-PUB-2022-020

Parton-QGP interaction —observation→ **Jet quenching**

Parton-QGP interaction	Jet quenching
QGP size/temperature	Centrality dependence
QGP color coherence	Color charge / substructure dependence
Parton mass	Flavor dependence
Parton path-length in QGP	Inclusive jet v_n / dijet asymmetry





Recent ATLAS HI jet measurements and beyond

- Jet v_n, arXiv:2111.06606
- Di-jet asymmetry, arXiv:2205.00682
- *b*-jet suppression, arXiv:2204.13530

Final

- γ-tagged jet suppression, ATLAS-CONF-2022-019
- Substructure dependence of jet suppression, ATLAS-CONF-2022-026

Preliminary

Run3 outlook:

- More data → better statistical precision
- Improved jet reconstruction and calibration → better systematic precision
- New collision system (O-O) → explore jet quenching in smaller systems

see all ATLAS Heavy Ion results here: https://twiki.cern.ch/twiki/bin/view/AtlasPublic/HeavyIonsPublicResults

Backup Slides