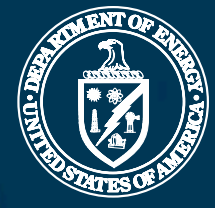




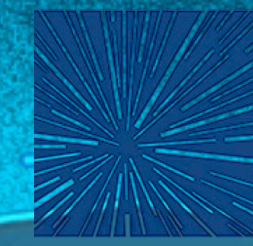
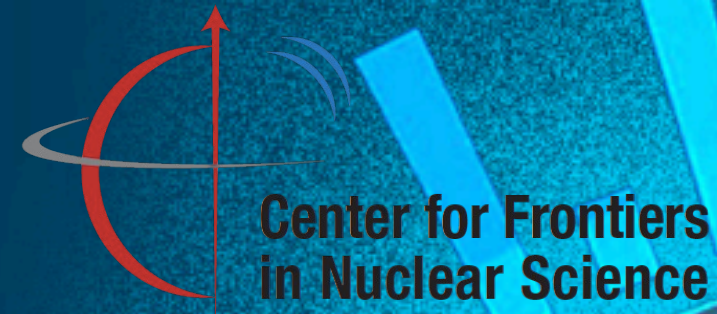
STAR

Supported in part by:



U.S. DEPARTMENT OF
ENERGY

Office of
Science



Wright
Laboratory

Yale

Jets at STAR

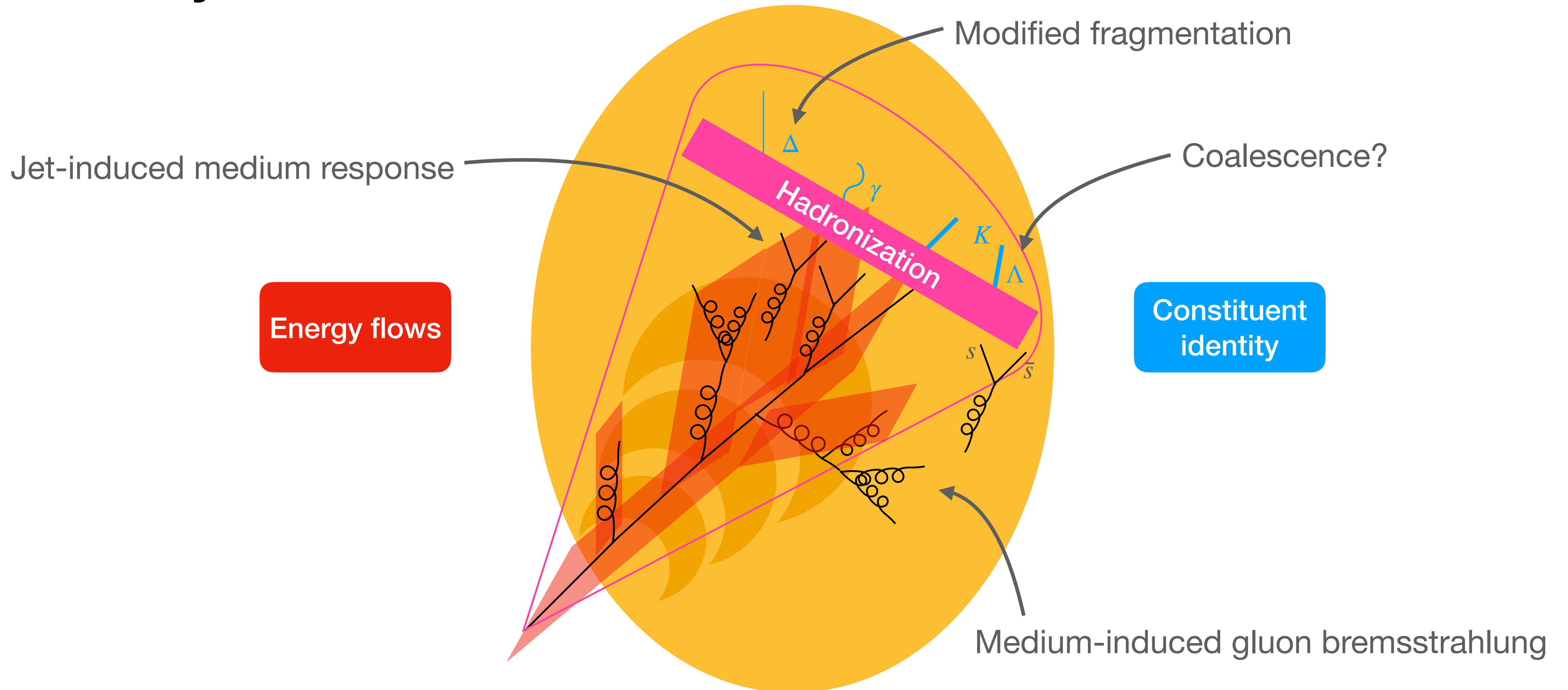
**RHIC & AGS Annual Users' Meeting:
Jets & Hard Probes workshop**

Brookhaven National Laboratory, NY
Monday, May 11, 2026

Isaac Mooney (Yale University, CFNS) for the STAR Collaboration, isaac.mooney@yale.edu

How to understand jet evolution in media

Two ways: the How and the What



Solenoidal Tracker at RHIC (STAR)

Main subdetectors, as of mid-2010s

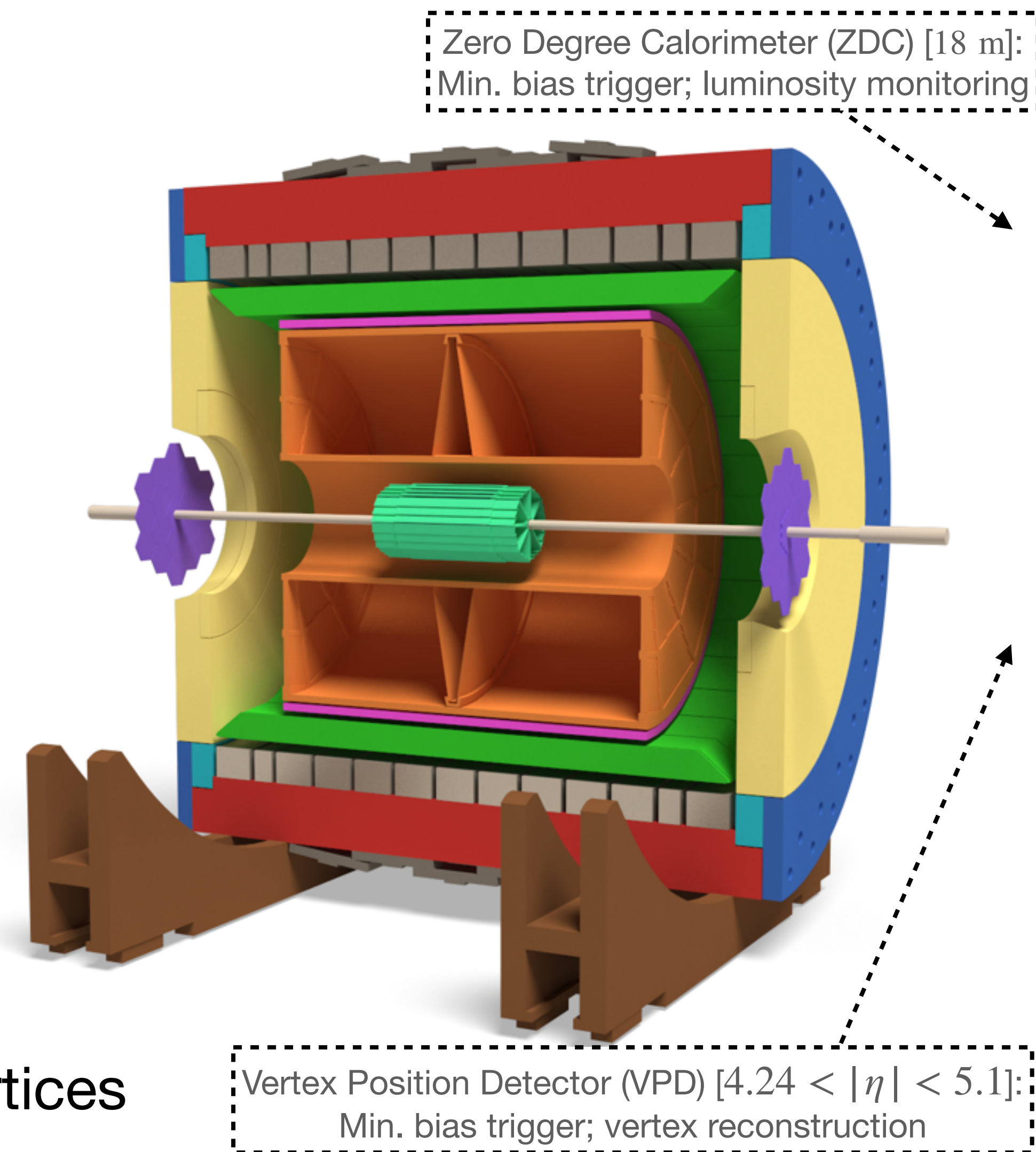
Relativistic Heavy Ion Collider (RHIC)
 collides $p+p$, $O+O$, $p/d/h/Cu+Au/Al$, $Cu+Cu$,
 isobars ($Zr+Zr$, $Ru+Ru$), $Au+Au$, $U+U$
 from $\sqrt{s_{NN}} = 3$ to 510 GeV

Time Projection Chamber (**TPC**) [$|\eta| < 1$]:
 momenta of charged tracks + centrality + PID

Barrel Electromagnetic Calorimeter (**BEMC**) [$|\eta| < 1$]:
 neutral energy deposits + online trigger

Time of Flight (**TOF**) [$|\eta| < 0.9$]: PID + pileup mitigation

Heavy flavor tracker (**HFT**) [$|\eta| < 1$]: displaced decay vertices



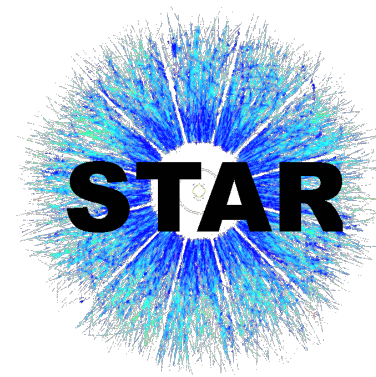
Precision QCD; exploring the Lund plane
with *multi-dimensional jet substructure*

Path-length dependence of jet energy
loss in medium with *jet anisotropies*
(with respect to event plane)

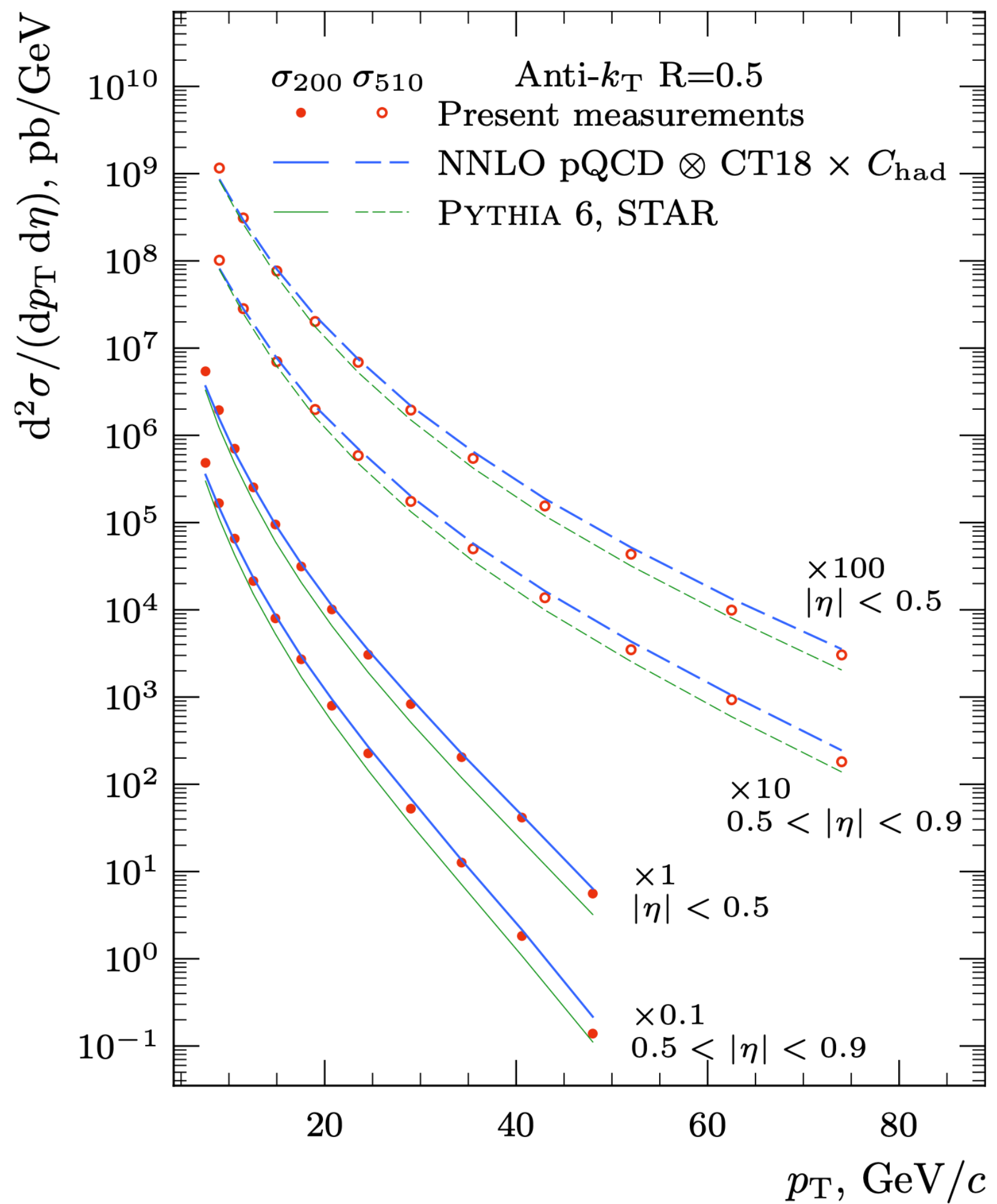
Separating p-QCD and np-
QCD with *energy correlators*

Energy flows

Energy-density dependence of jet energy loss in medium;
angular distribution of radiation in quenched jets
with *inclusive/semi-inclusive jet & high- p_T hadron yields*

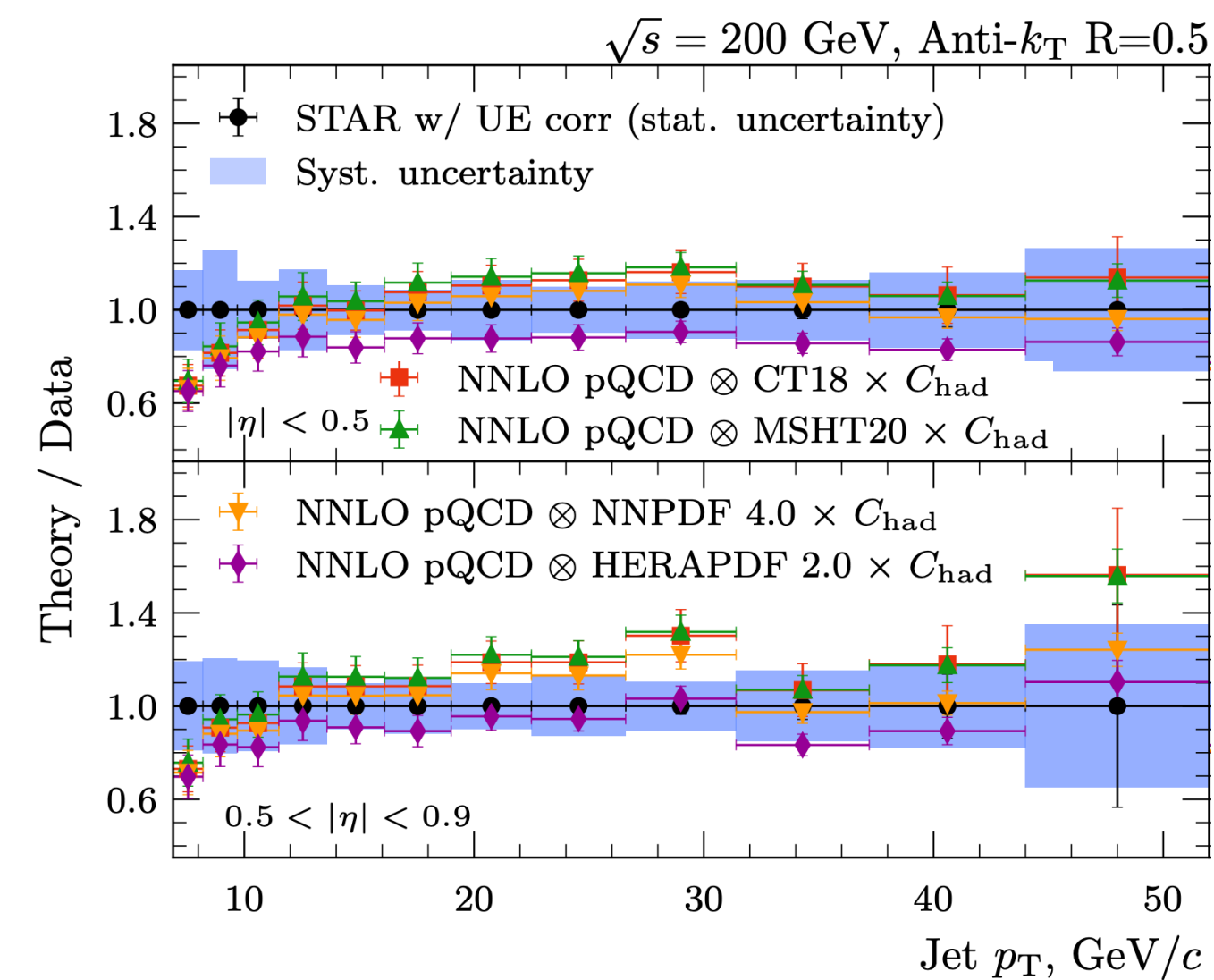


Inclusive jet cross sections



STAR, arXiv:[2603.28695](https://arxiv.org/abs/2603.28695) (Recently submitted to PRD!)

- Stringent test of vacuum pQCD
- Constrain PDFs, with x_T coverage 0.07 - 0.5 and 0.03 - 0.31 at 200 and 510 GeV



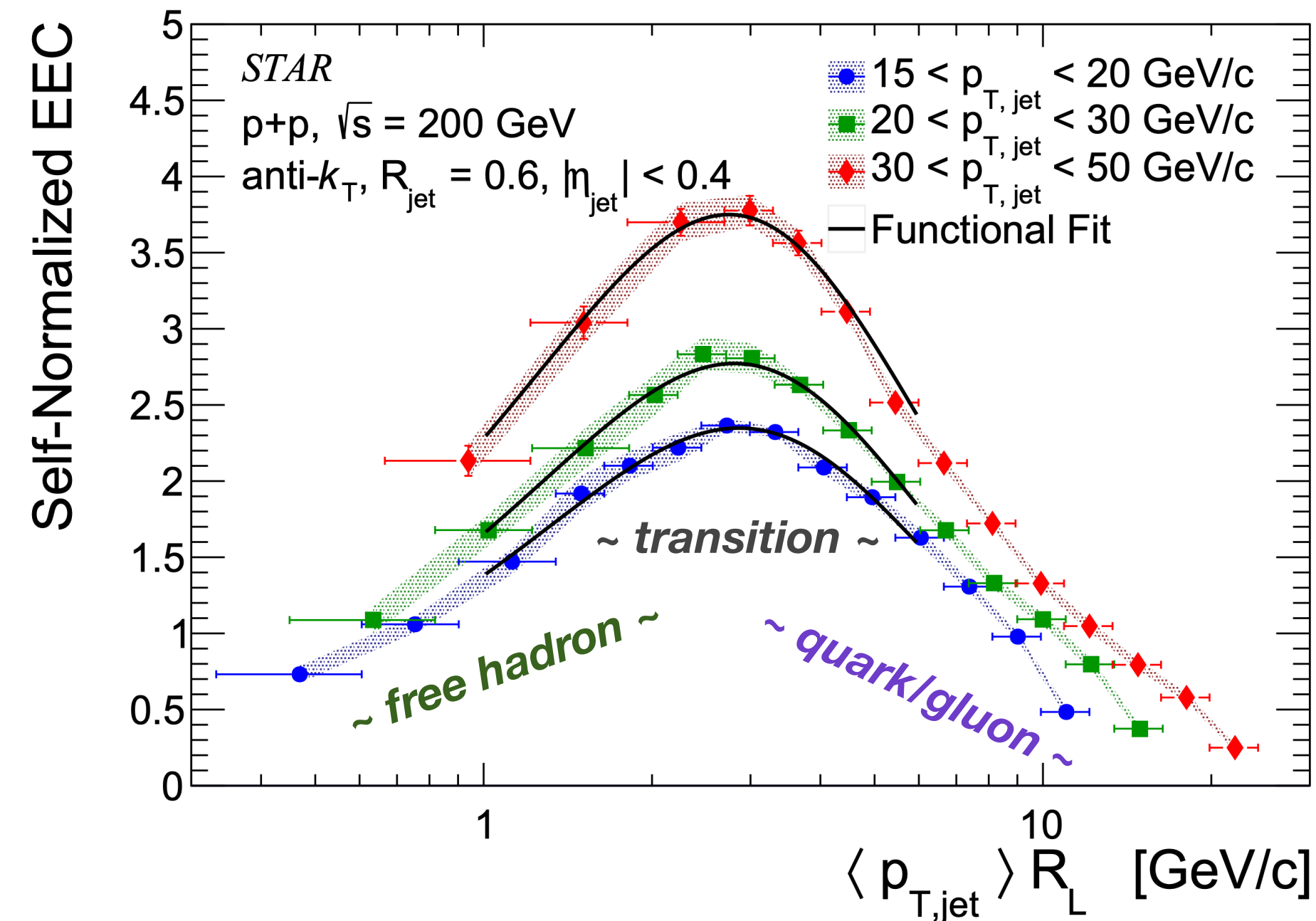
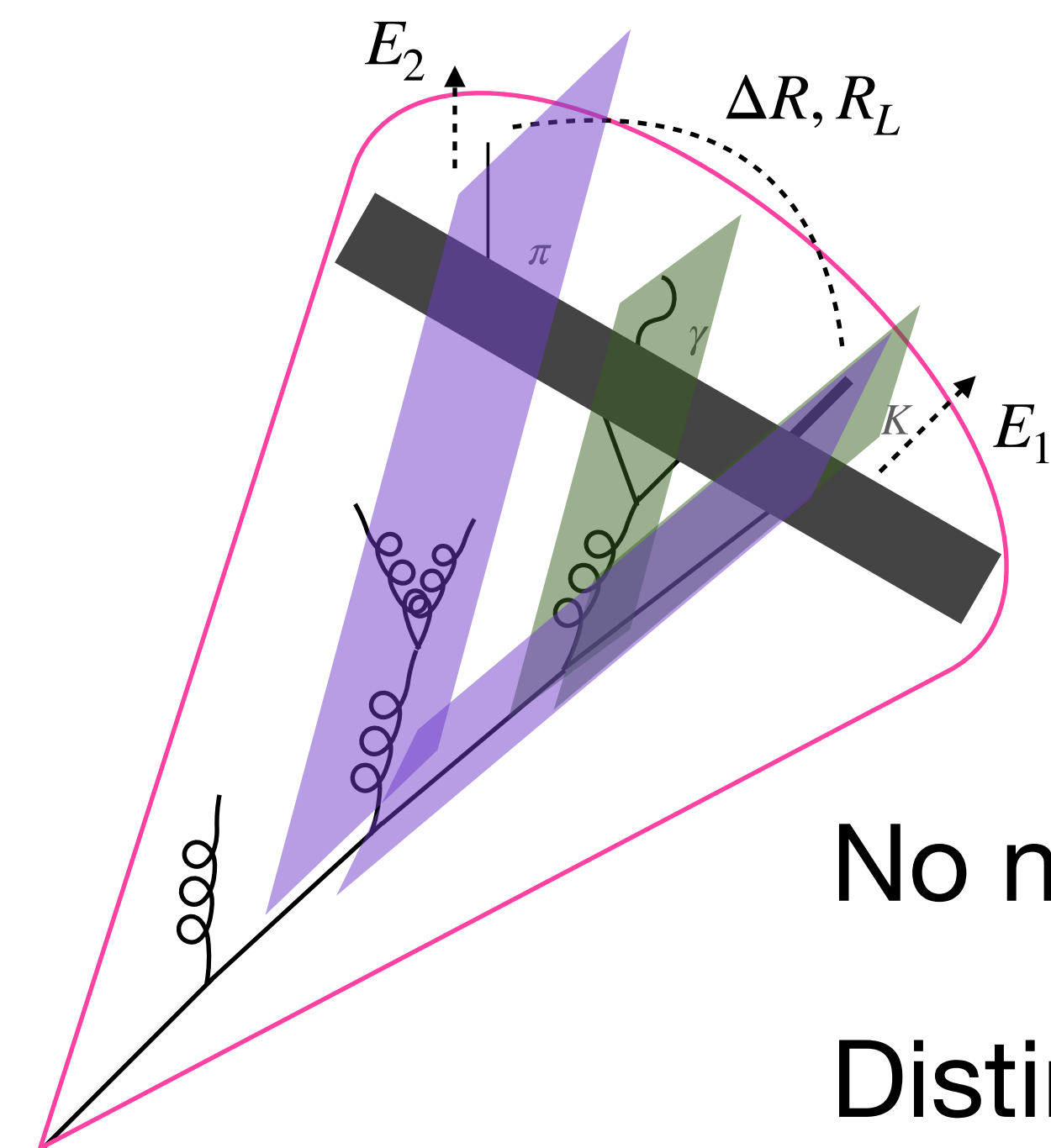
- Baseline for future studies with forward jets (varying x)

Energy correlators

Recently published! STAR, [PRL 135 \(2025\) 11, 111901](https://doi.org/10.1103/PhysRevLett.135.111901)

$$\text{ENC}(R_L) = \left(\prod_{k=1}^N \int d\Omega_{\vec{n}_k} \right) \delta(R_L - \Delta\hat{R}_L) \frac{1}{(E_{\text{jet}})^N} \langle \mathcal{E}(\vec{n}_1) \mathcal{E}(\vec{n}_2) \dots \mathcal{E}(\vec{n}_N) \rangle^{1,2,3}$$

$$\text{EEC}(\Delta R) = \frac{1}{\mathcal{O}} \frac{d\mathcal{O}}{d(\Delta R)}, \quad \mathcal{O} = \sum_{\text{jets}} \sum_{i \neq j} \frac{E_i E_j}{p_{T,\text{jet}}^2}$$



No need to recluster or remove npQCD contributions

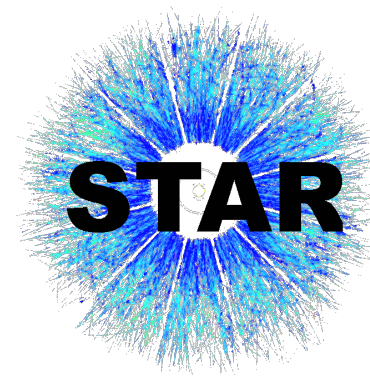
Distinct scaling behaviors in the **hadronic** and **partonic** regimes

Change in scaling when virtuality $\sim p_T R_L \sim \Lambda_{\text{QCD}}$ so $R_L^{\text{transition}} \propto 1/p_T$

¹Basham, Brown, Ellis, Love, [PRL 41 \(1978\), 1585](https://doi.org/10.1103/PhysRevLett.41.1585)

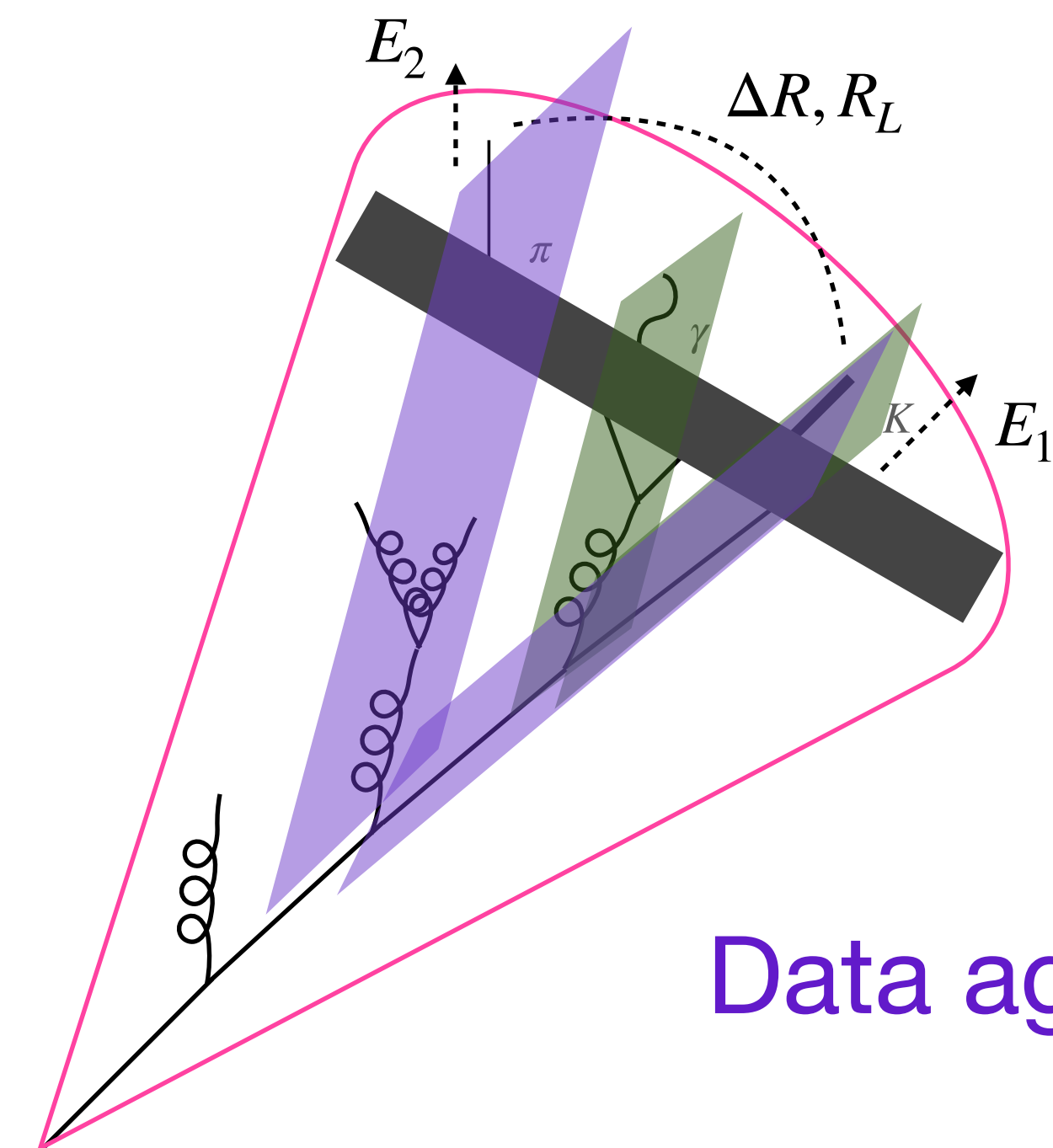
²Chen, Moul, Zhang, Zhu, [PRD 102 \(2020\) 5, 054012](https://doi.org/10.1103/PhysRevD.102.054012)

³Komiske, Moul, Thaler, Zhu, [PRL 130 \(2023\) 5, 051901](https://doi.org/10.1103/PhysRevLett.130.051901)

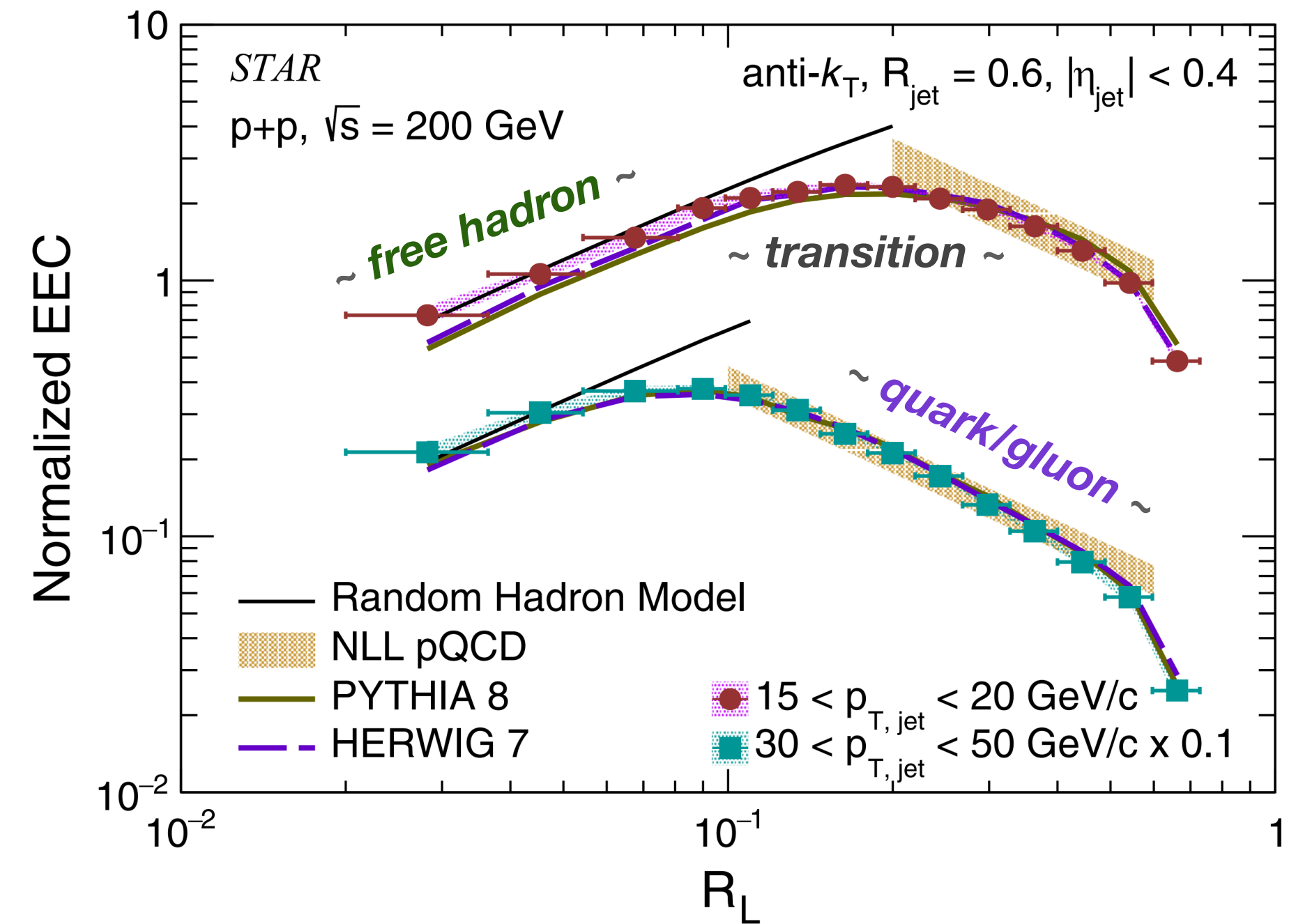


Energy correlators

Recently published! STAR, [PRL 135 \(2025\) 11, 111901](#)

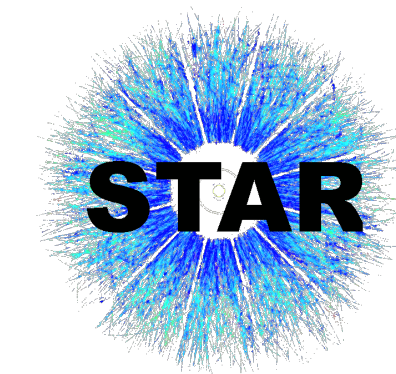


$$EEC(\Delta R) = \frac{1}{\mathcal{O}} \frac{d\mathcal{O}}{d(\Delta R)}, \quad \mathcal{O} = \sum_{\text{jets}} \sum_{i \neq j} \frac{E_i E_j}{p_{T,\text{jet}}^2}$$



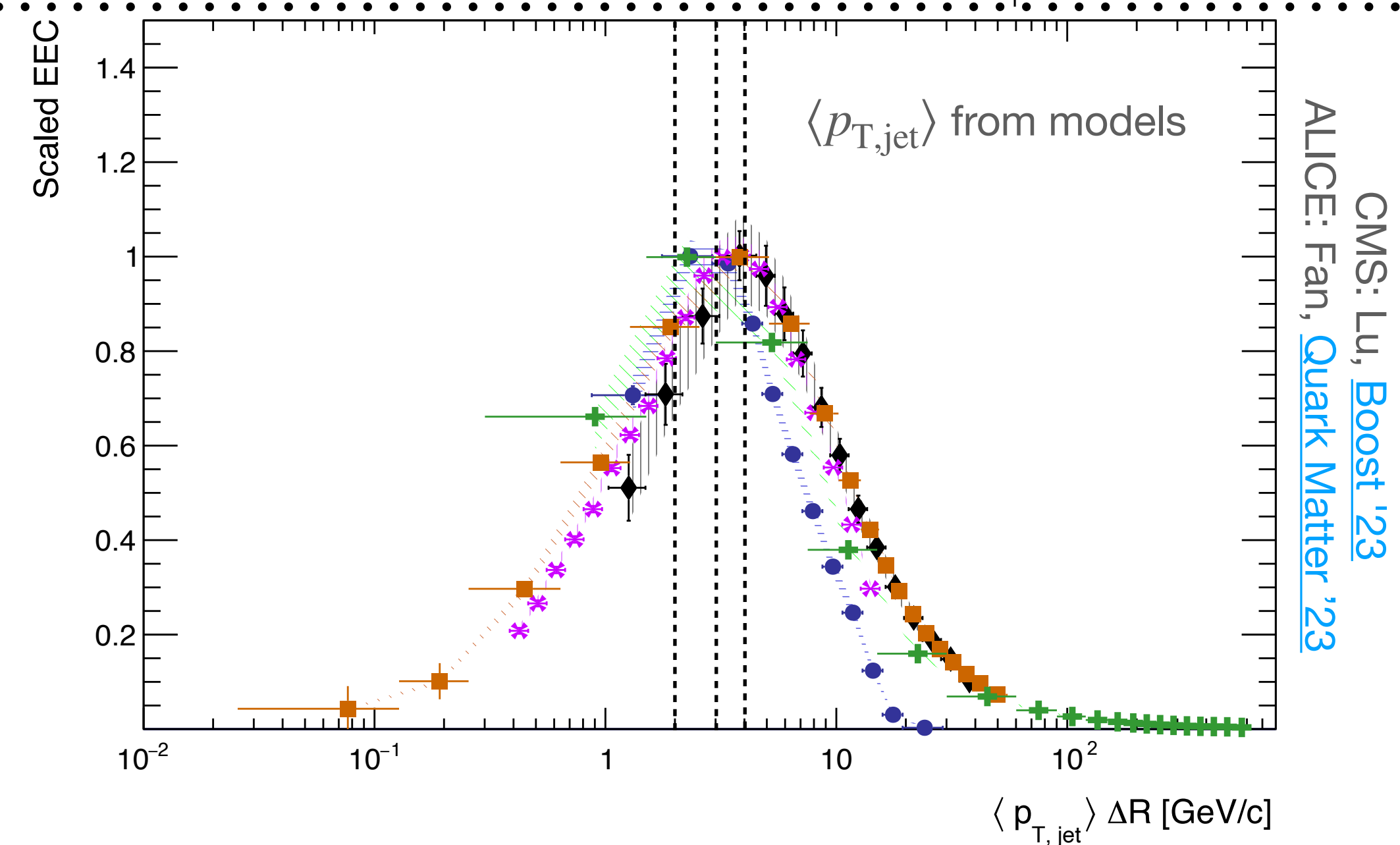
Data agree well with NLL pQCD calculation* (& MC models)

Data agree well with model assuming non-interacting hadrons

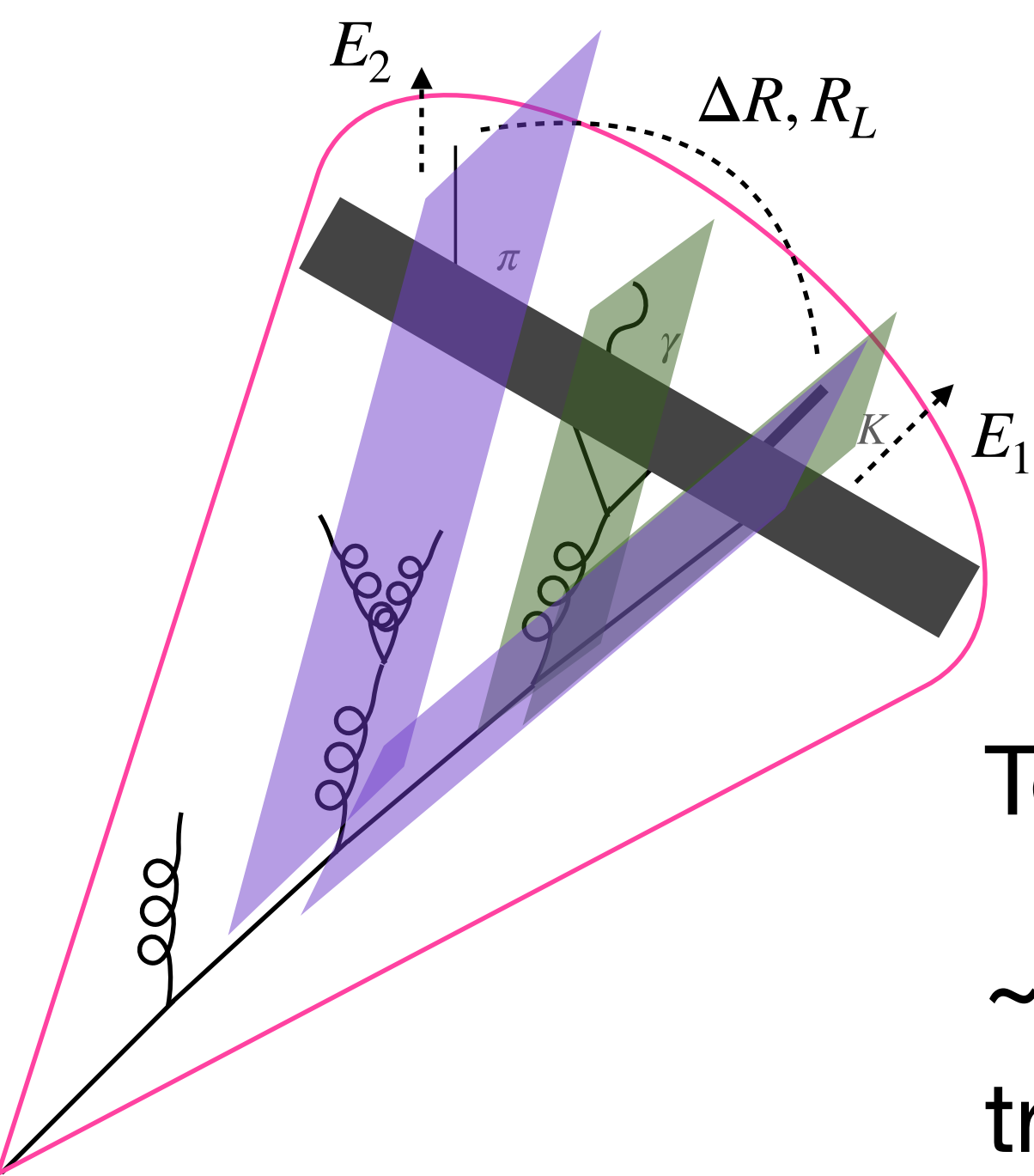


Energy correlators

- STAR Preliminary: $\sqrt{s} = 200$ GeV $30 < \text{Full Jet } p_T < 50$ GeV/c
- *— ALICE Preliminary: $\sqrt{s} = 5.02$ TeV, $20 < \text{Charged Jet } p_T < 40$ GeV/c
- ◆— ALICE Preliminary: $\sqrt{s} = 13$ TeV, $60 < \text{Charged Jet } p_T < 80$ GeV/c
- CMS Preliminary: $\sqrt{s} = 13$ TeV $97 < \text{Full Jet } p_T < 220$ GeV/c
- +— CMS Preliminary: $\sqrt{s} = 13$ TeV, $1410 < \text{Full Jet } p_T < 1784$ GeV/c



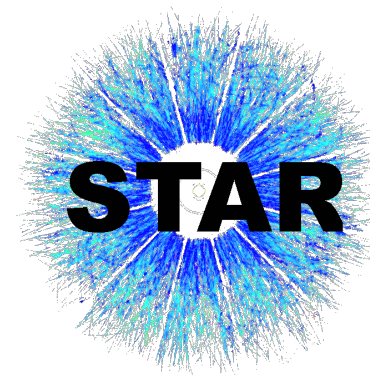
$$EEC(\Delta R) = \frac{1}{\mathcal{O}} \frac{d\mathcal{O}}{d(\Delta R)}, \quad \mathcal{O} = \sum_{\text{jets}} \sum_{i \neq j} \frac{E_i E_j}{p_{T,jet}^2}$$



Testing approx. universality of transition region by comparing to LHC data:

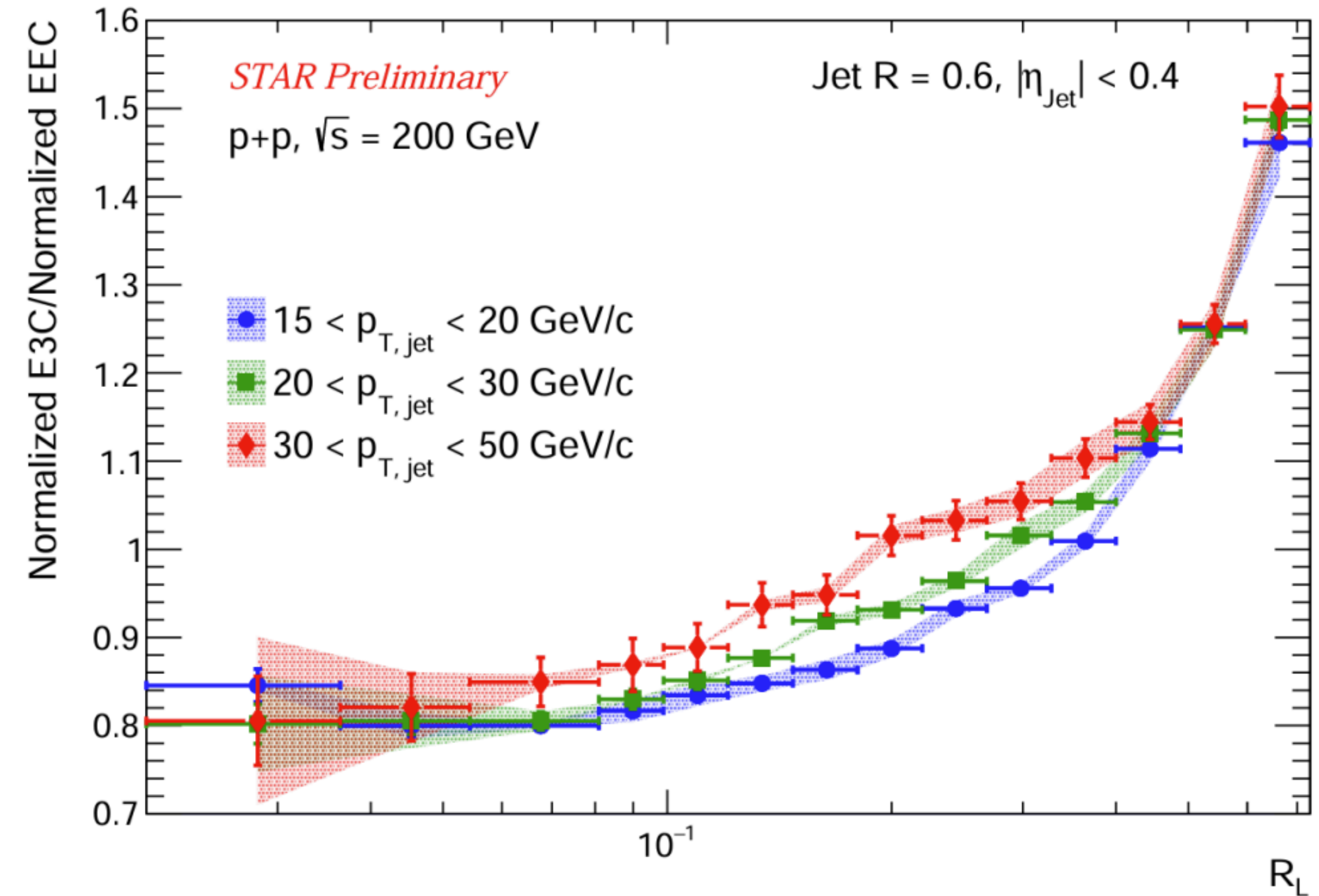
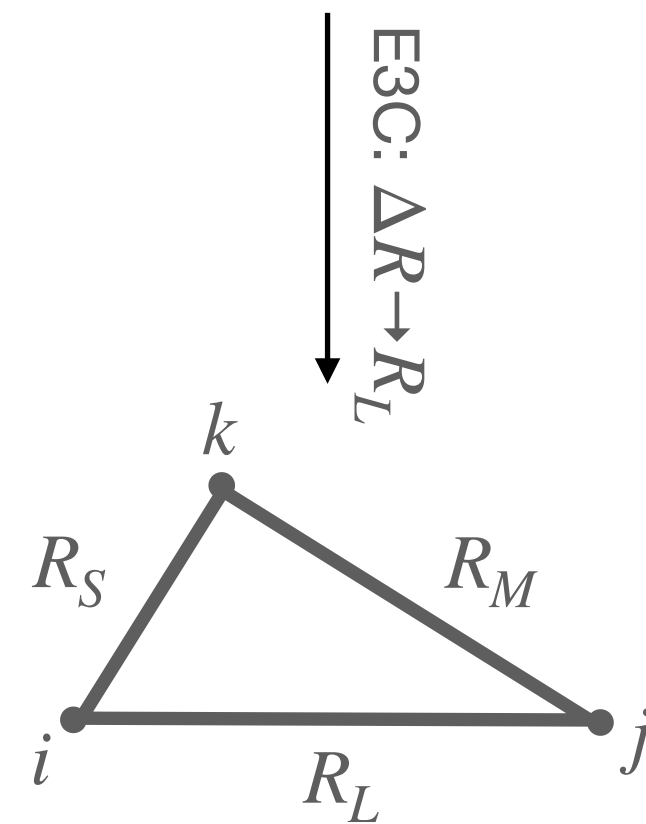
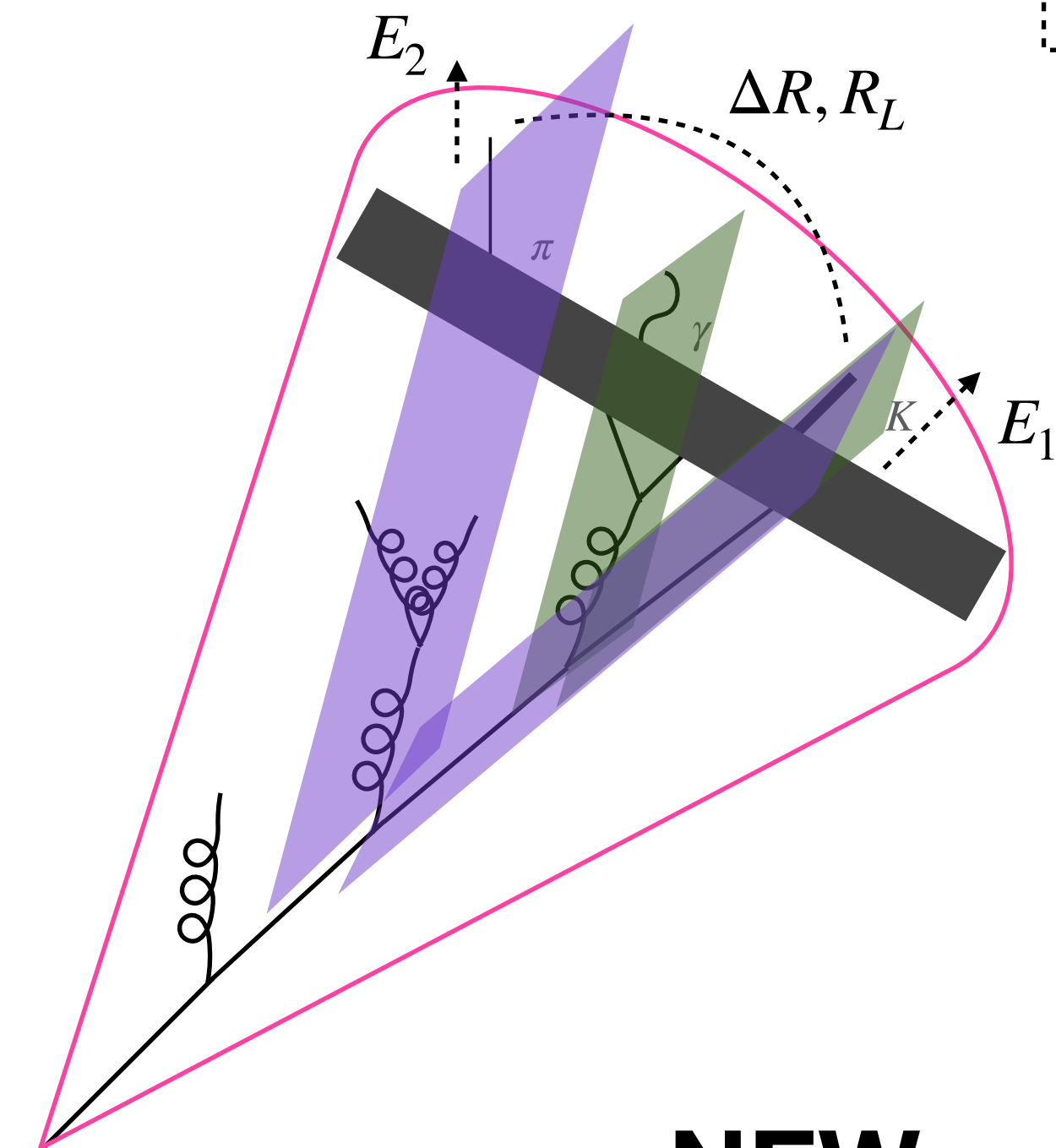
~ 2 orders of magnitude in \sqrt{s} and $p_{T,jet}$ from STAR \rightarrow ALICE \rightarrow CMS,
 transition region ~ 2 – 4 GeV/c

STAR x range more similar to CMS high- p_T (high- x) jets than ALICE or CMS low- p_T jets — **q vs. g** differences



Energy correlators

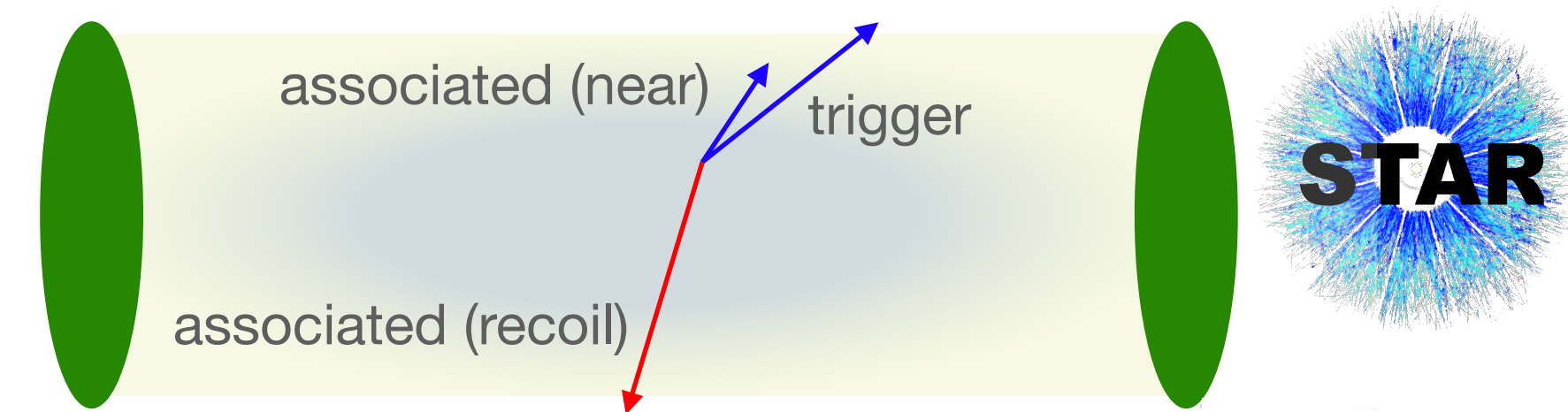
$$E3C(R_L) = \frac{1}{\mathcal{O}} \frac{d\mathcal{O}}{d(R_L)}, \quad \mathcal{O} = \sum_{\text{jets}} \sum_{i \neq j \neq k} \frac{E_i E_j E_k}{p_{T,\text{jet}}^3}$$



NEW: extended to E3C — running of α_s causes change in slope with p_T^*

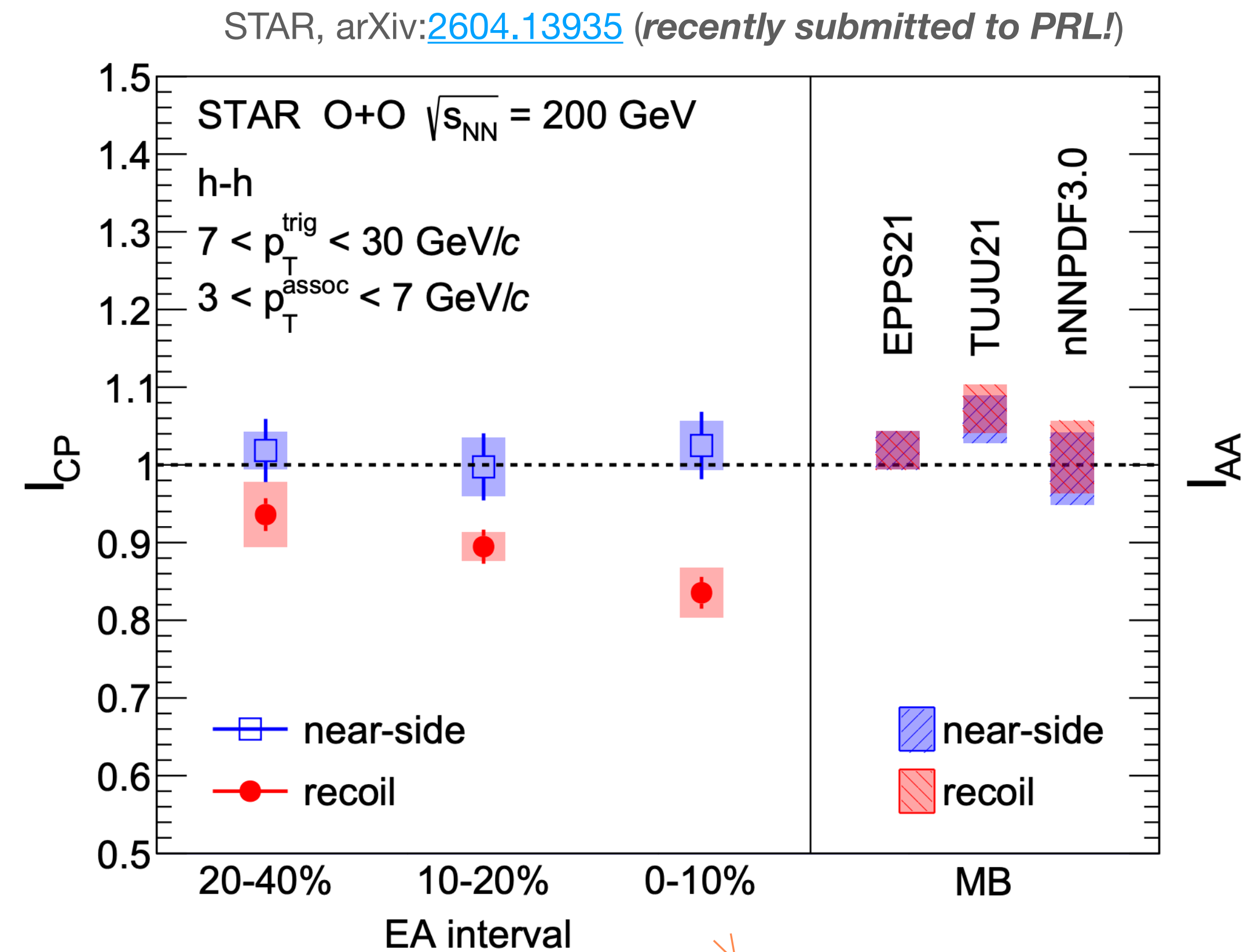


Quenching in small systems?



With hadron-hadron correlations in oxygen+oxygen collisions

- Indications from other sectors of QGP formation in small systems at RHIC; no previous indications of jet quenching
- Per-trigger normalization of coincidence measurements removes dependence on N_{coll} present for inclusive measurements, significantly reducing uncertainty
- Suppression from baseline w/ $2.7\sigma - 5.2\sigma$ significance in 0-10% EA*. **Suggests jet quenching** in central O+O



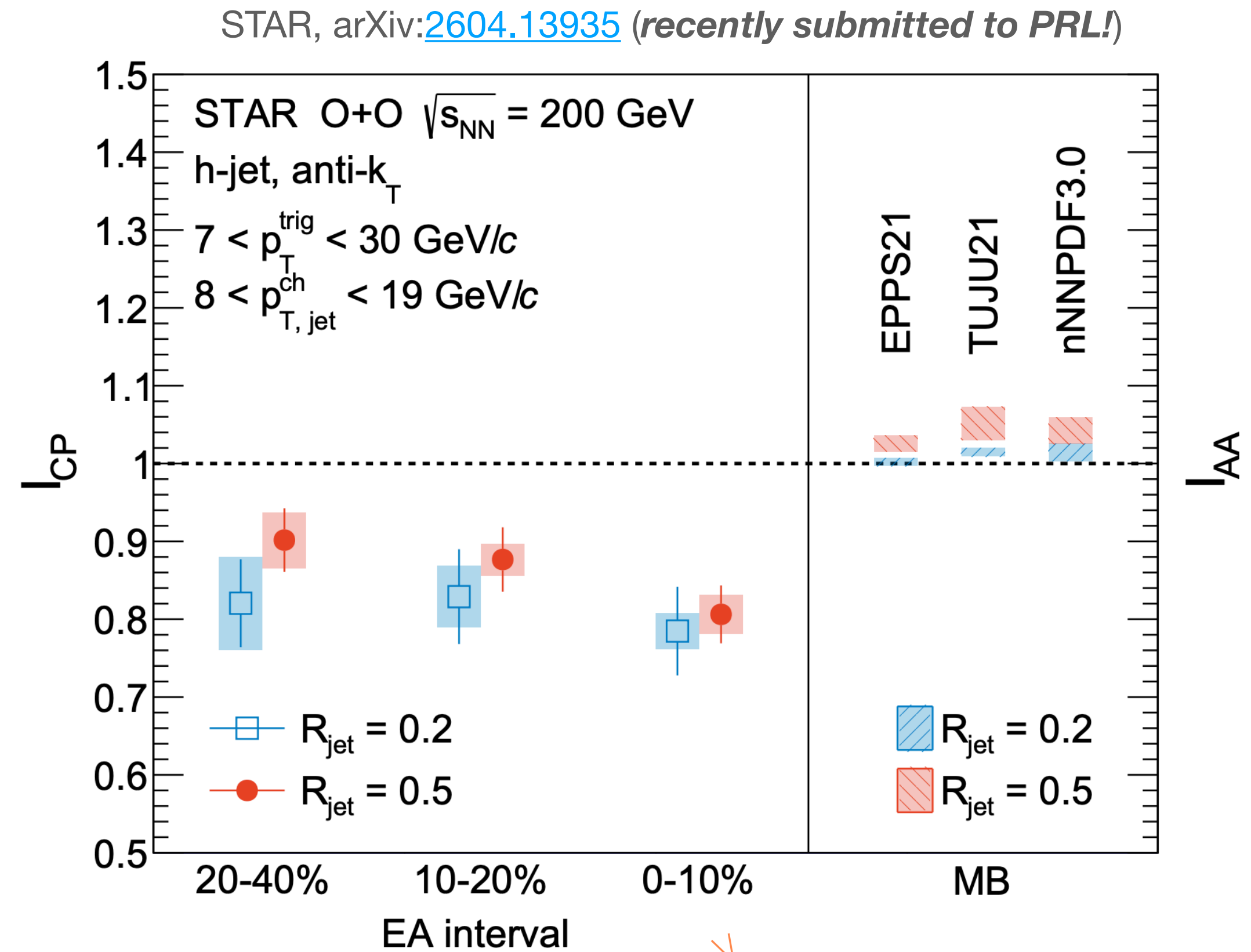


Quenching in small systems?



With hadron-jet correlations in oxygen+oxygen collisions

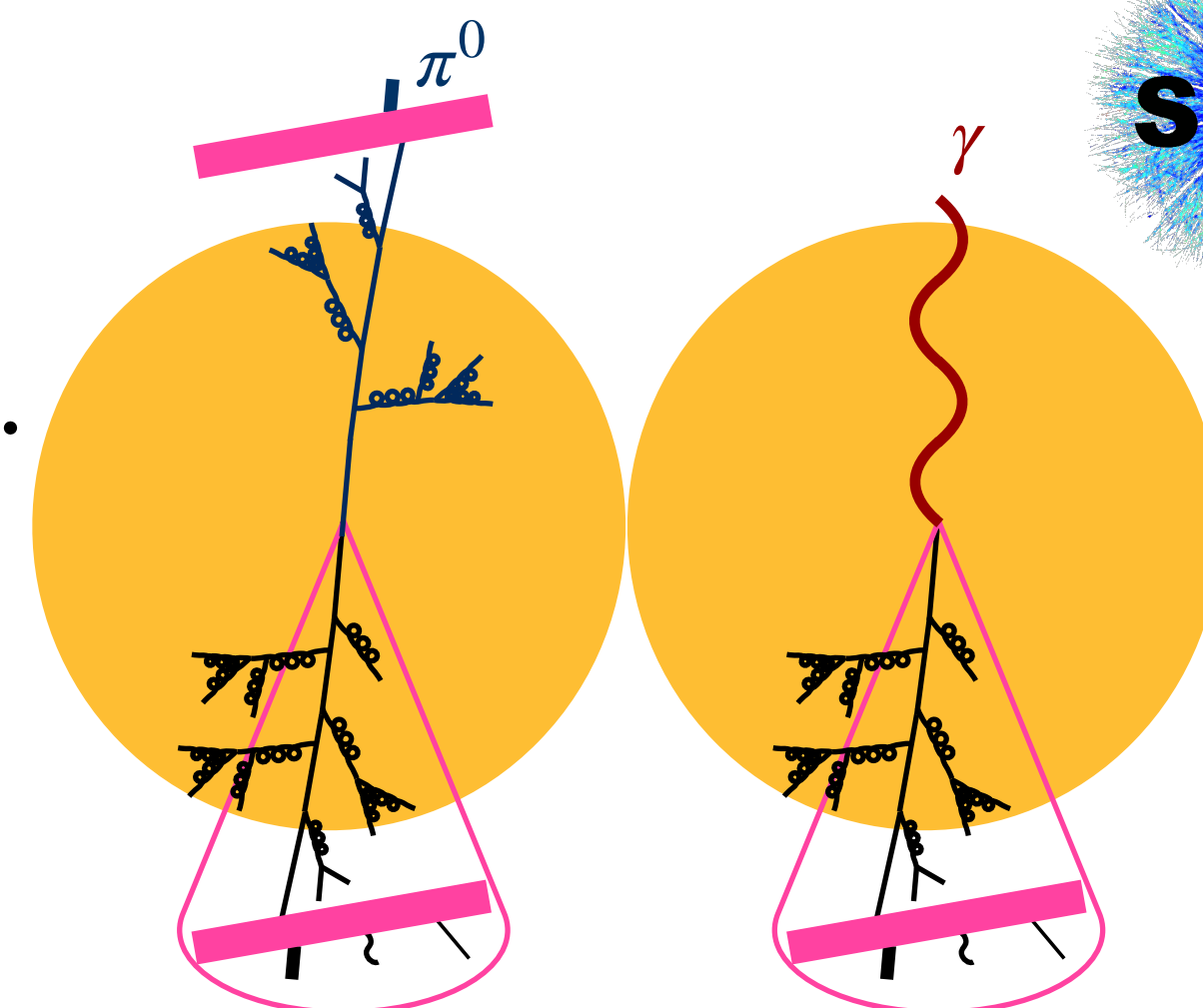
- Semi-inclusive hadron-jet measurement reduces bias; capture soft fragments from quenching; study R dependence from energy redistribution.
- Models based on nPDFs with no quenching predict O+O/p+p ~ 1 .
- Suppression from baseline w/ $3.5\sigma - 5.0\sigma$ significance in 0-10% EA*. **Suggests jet quenching in central O+O**



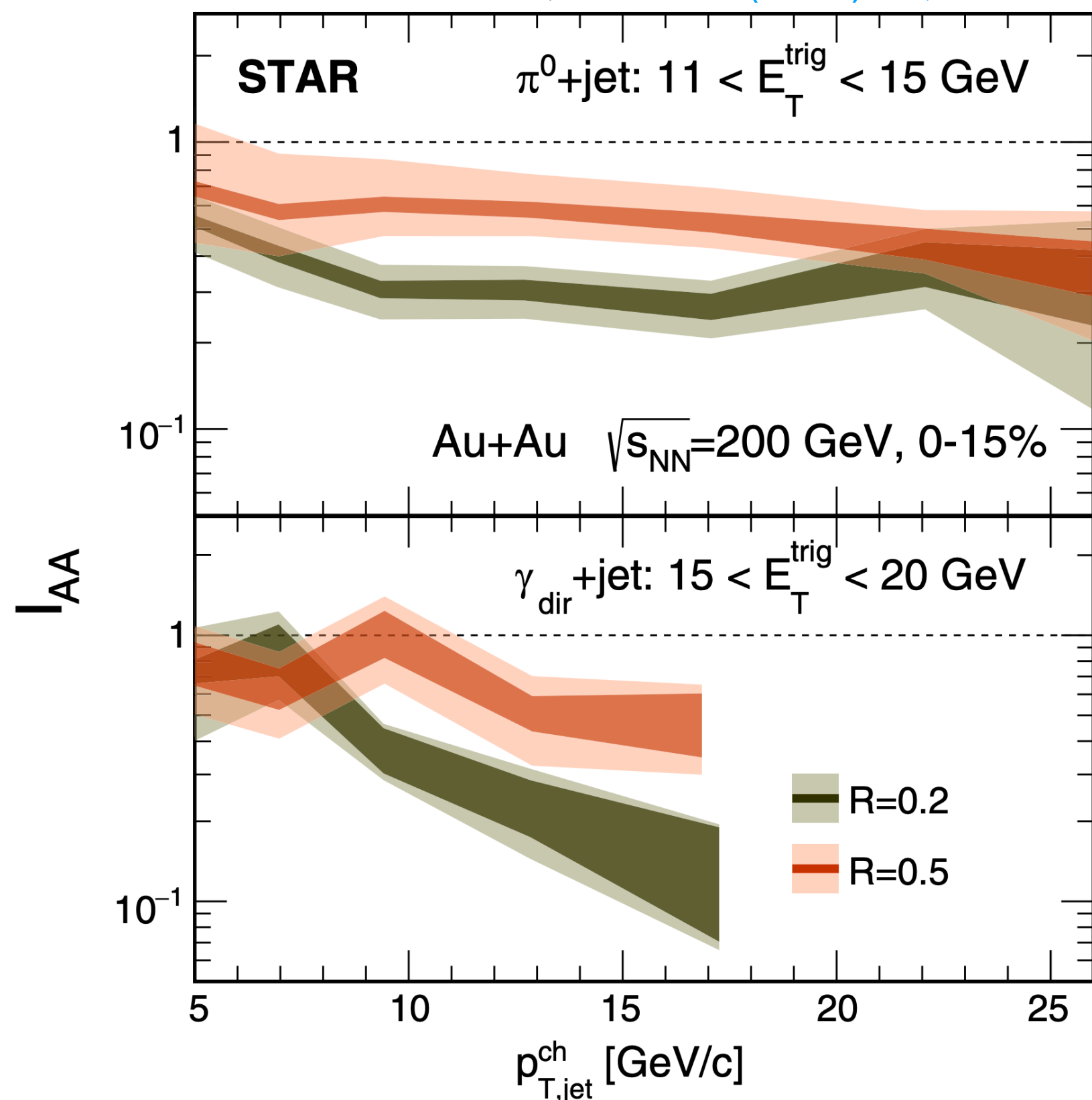


Semi-inclusive yield modification

$$I_{AA} = \frac{Y^{AA}(p_{T,jet}^{ch}, R)}{Y^{pp}(p_{T,jet}^{ch}, R)}, Y(p_{T,jet}^{ch}, R) = \frac{1}{N_{trig}} \int_{3\pi/4}^{5\pi/4} d\Delta\phi \left[\frac{d^2 N_{jet}(R)}{dp_{T,jet}^{ch} d\Delta\phi} \right]_{E_T^{trig} \in [E_T^{min}, E_T^{max}]}$$

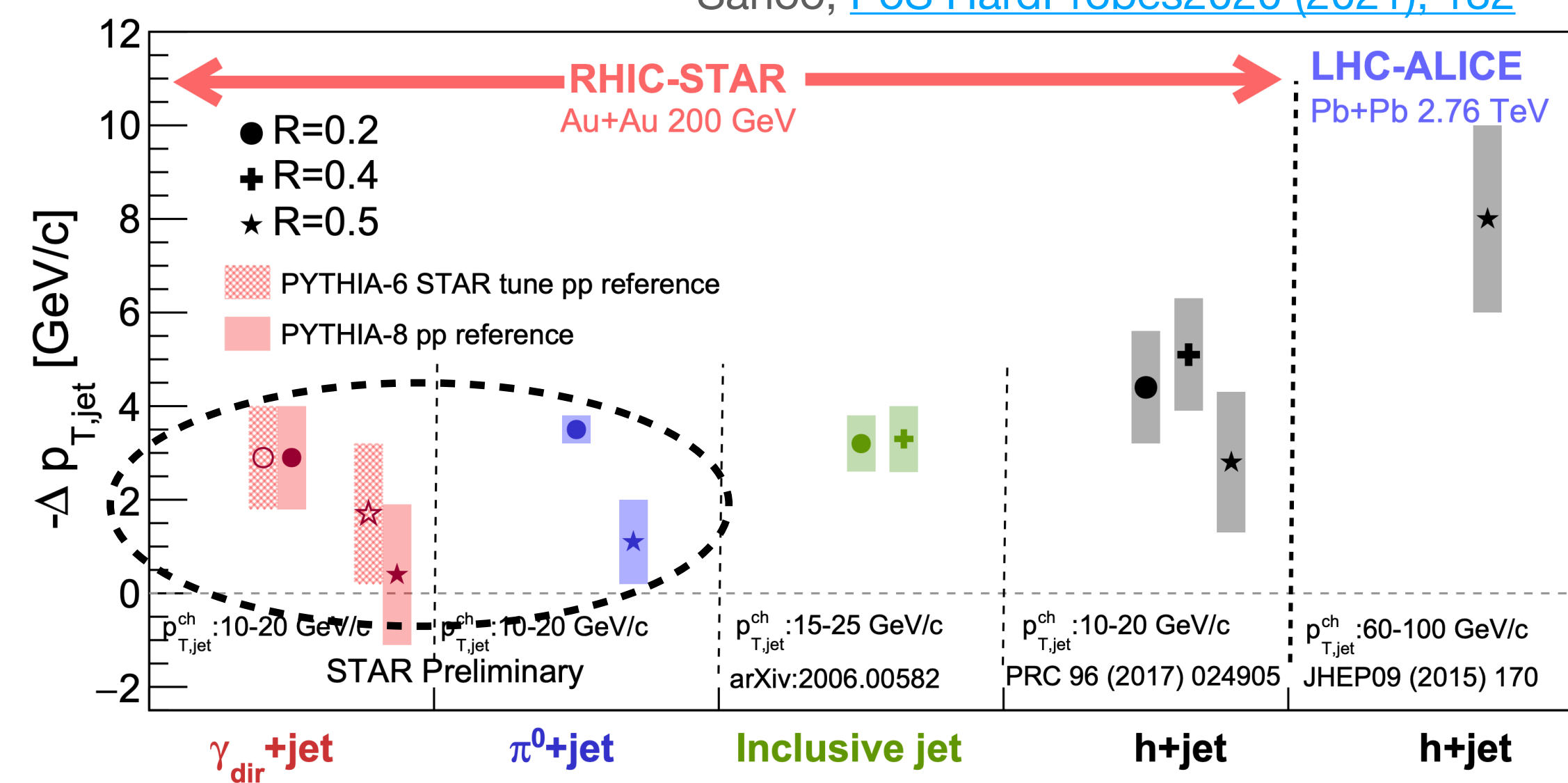


Recently published! STAR, [PRC 111 \(2025\) 6, 064907](#),
STAR, [PRL 134 \(2025\) 23, 232301](#)



Recoil jet yield suppression in Au+Au, reduced for larger-R jets

Sahoo, [PoS HardProbes2020 \(2021\), 132](#)

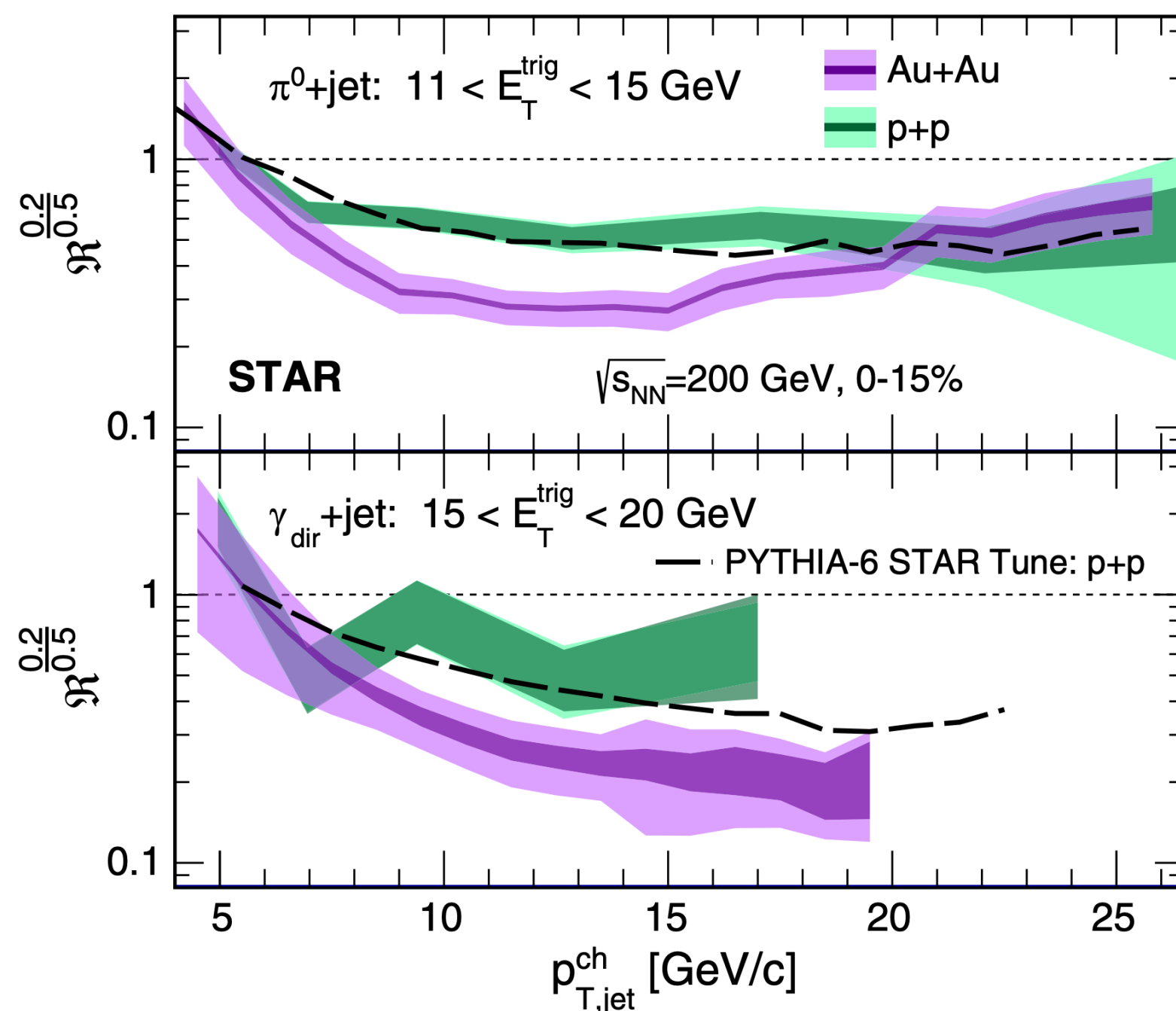
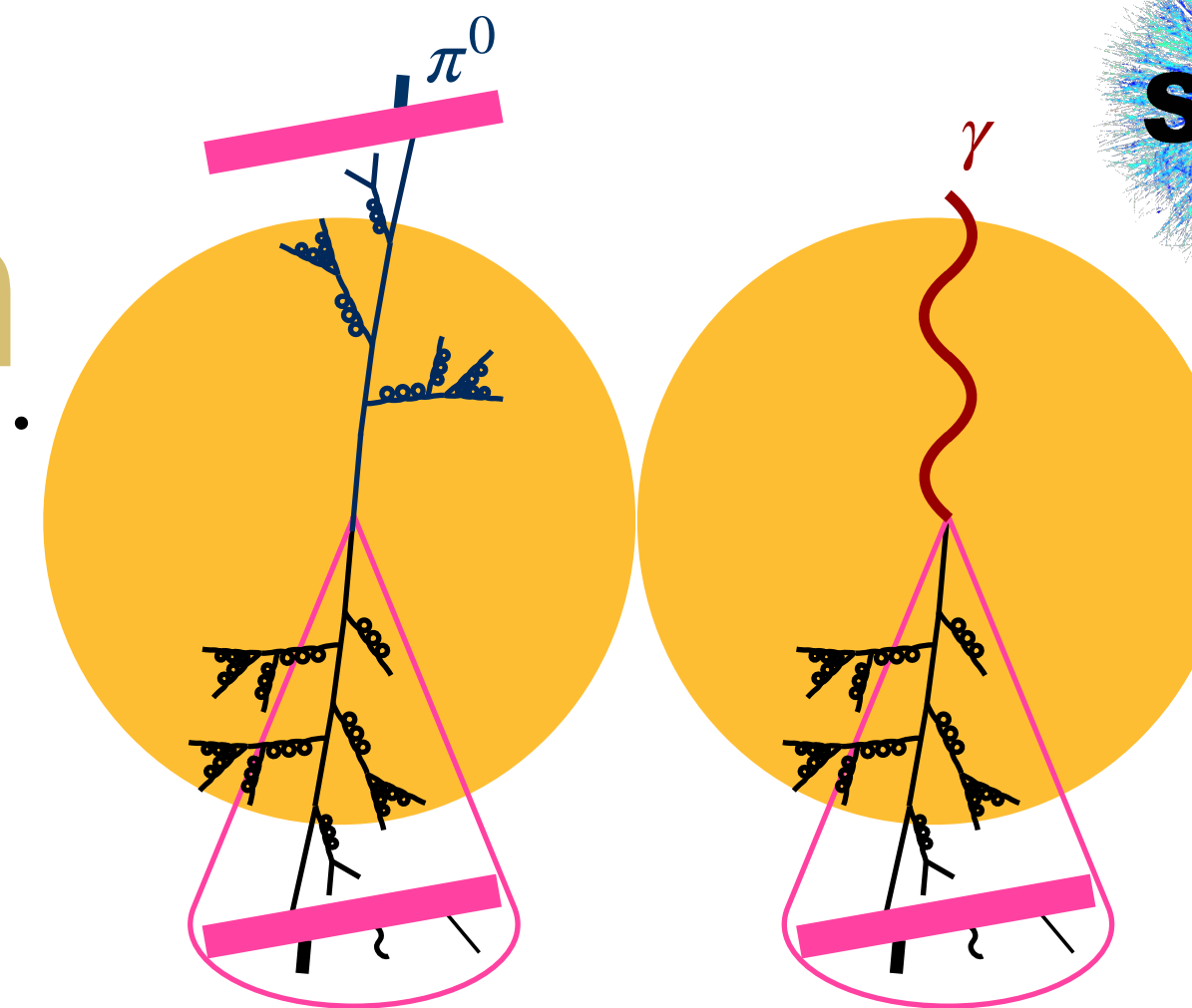




Semi-inclusive yield modification

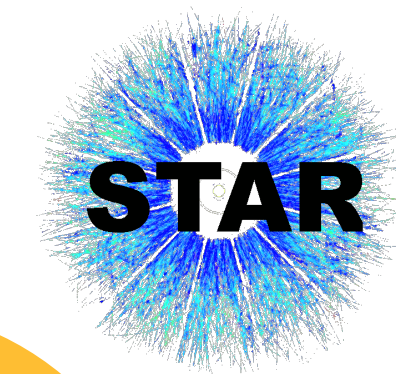
$$I_{AA} = \frac{Y^{AA}(p_{T,jet}^{ch}, R)}{Y^{pp}(p_{T,jet}^{ch}, R)}, Y(p_{T,jet}^{ch}, R) = \frac{1}{N_{trig}} \int_{3\pi/4}^{5\pi/4} d\Delta\phi \left[\frac{d^2 N_{jet}(R)}{dp_{T,jet}^{ch} d\Delta\phi} \right]_{E_T^{trig} \in [E_T^{min}, E_T^{max}]}$$

Recently published! STAR, [PRC 111 \(2025\) 6, 064907](#),
 STAR, [PRL 134 \(2025\) 23, 232301](#)



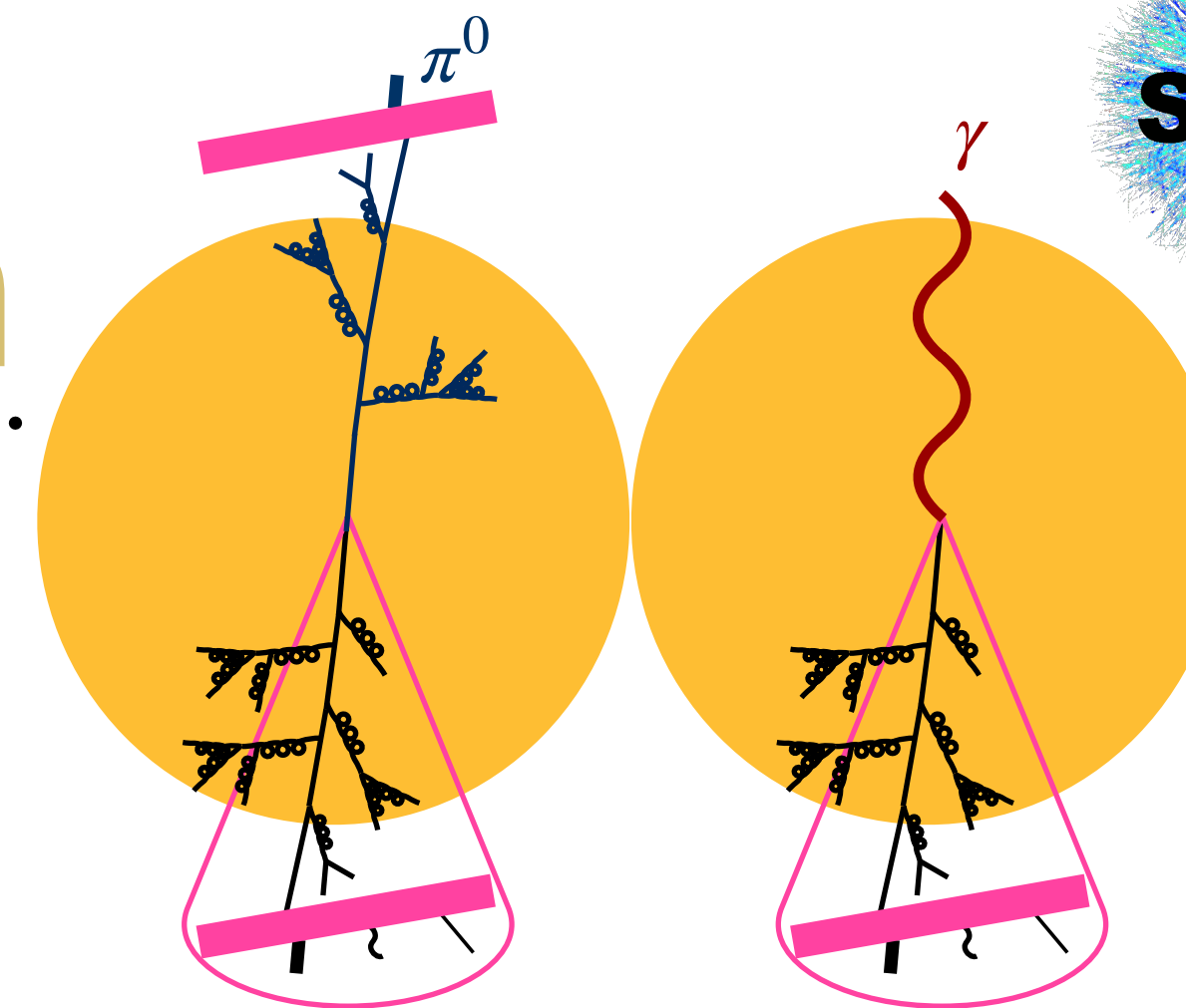
Recoil jet yield suppression in Au+Au, reduced for larger-R jets

Clear observation of **intra-jet broadening**

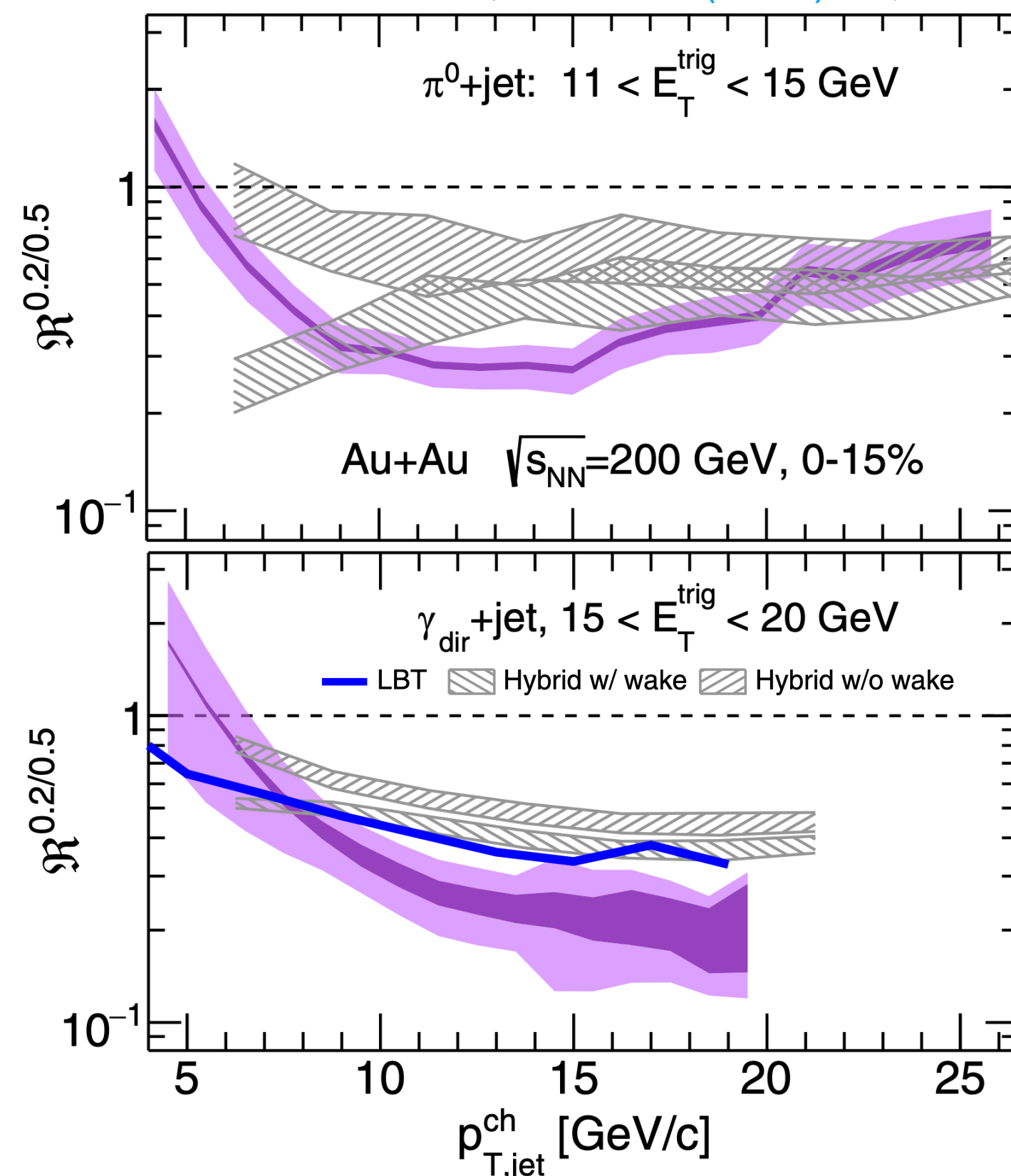


Semi-inclusive yield modification

$$I_{AA} = \frac{Y^{AA}(p_{T,jet}^{ch}, R)}{Y^{PP}(p_{T,jet}^{ch}, R)}, Y(p_{T,jet}^{ch}, R) = \frac{1}{N_{trig}} \int_{3\pi/4}^{5\pi/4} d\Delta\phi \left[\frac{d^2 N_{jet}(R)}{dp_{T,jet}^{ch} d\Delta\phi} \right]_{E_T^{trig} \in [E_T^{min}, E_T^{max}]}$$



Recently published! STAR, [PRC 111 \(2025\) 6, 064907](#),
STAR, [PRL 134 \(2025\) 23, 232301](#)



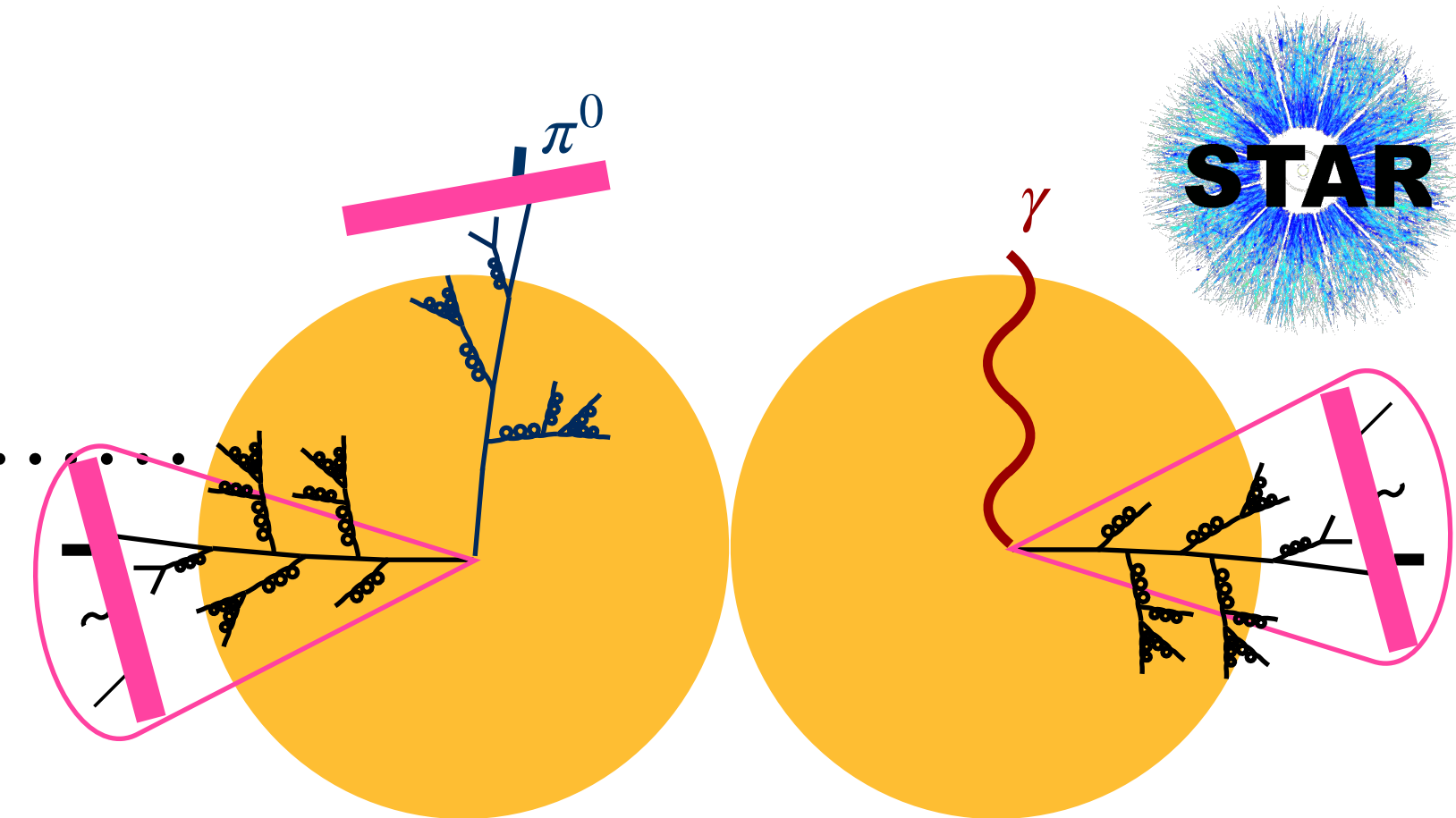
Recoil jet yield suppression in Au+Au, reduced for larger-R jets

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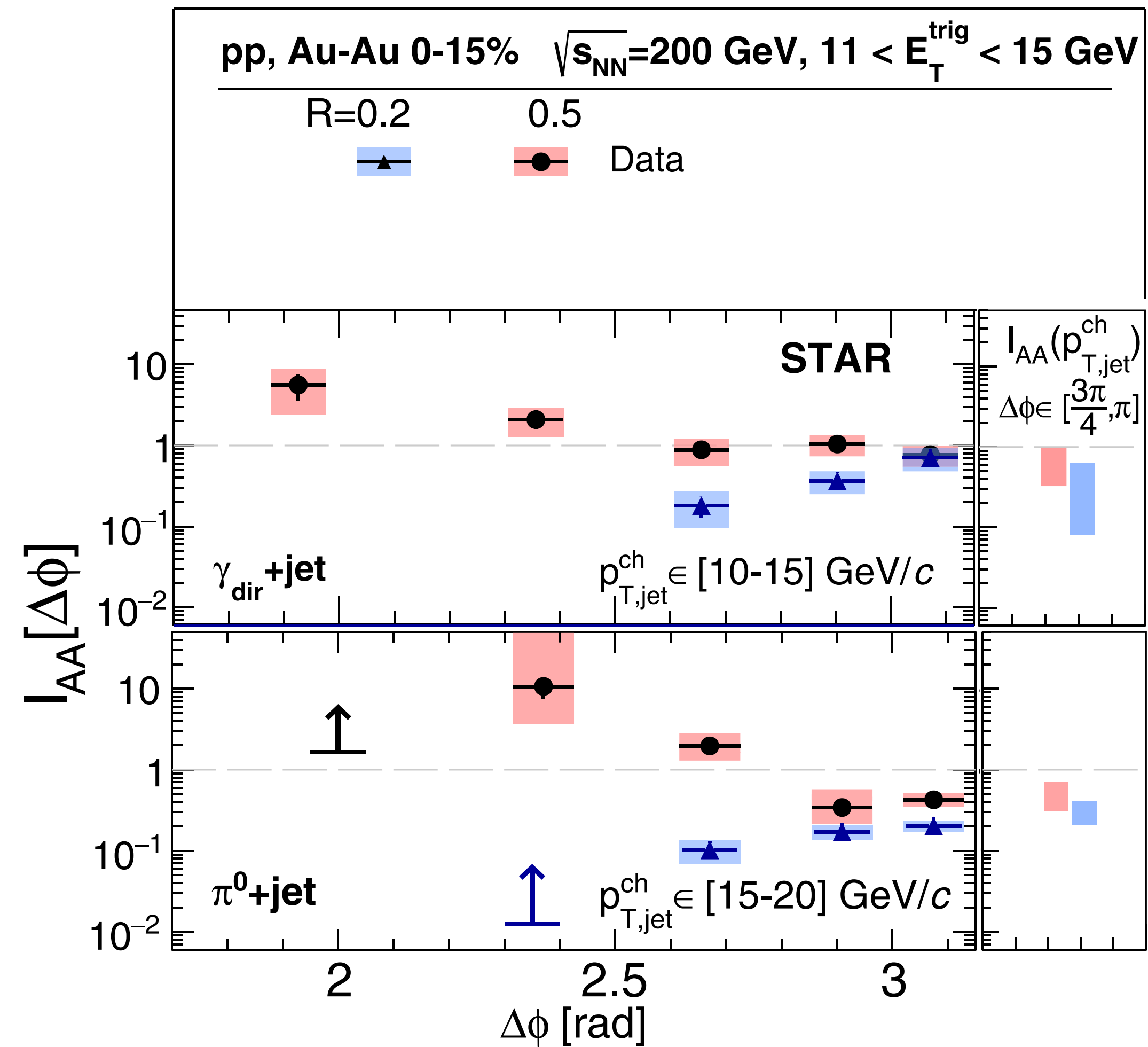
Models unable to quantitatively describe the effect



Medium-induced acoplanarity



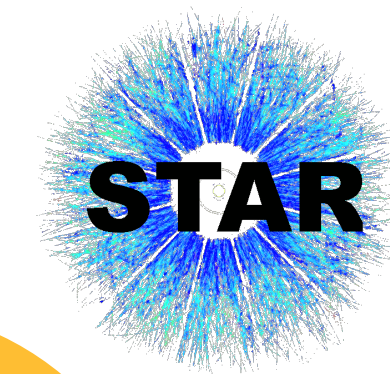
Recently published! STAR, [PRC 113 \(2026\) 1, 014902](https://arxiv.org/abs/2508.10001)



Substantial R -dependence of acoplanar yield:
small- R suppression, large- R enhancement

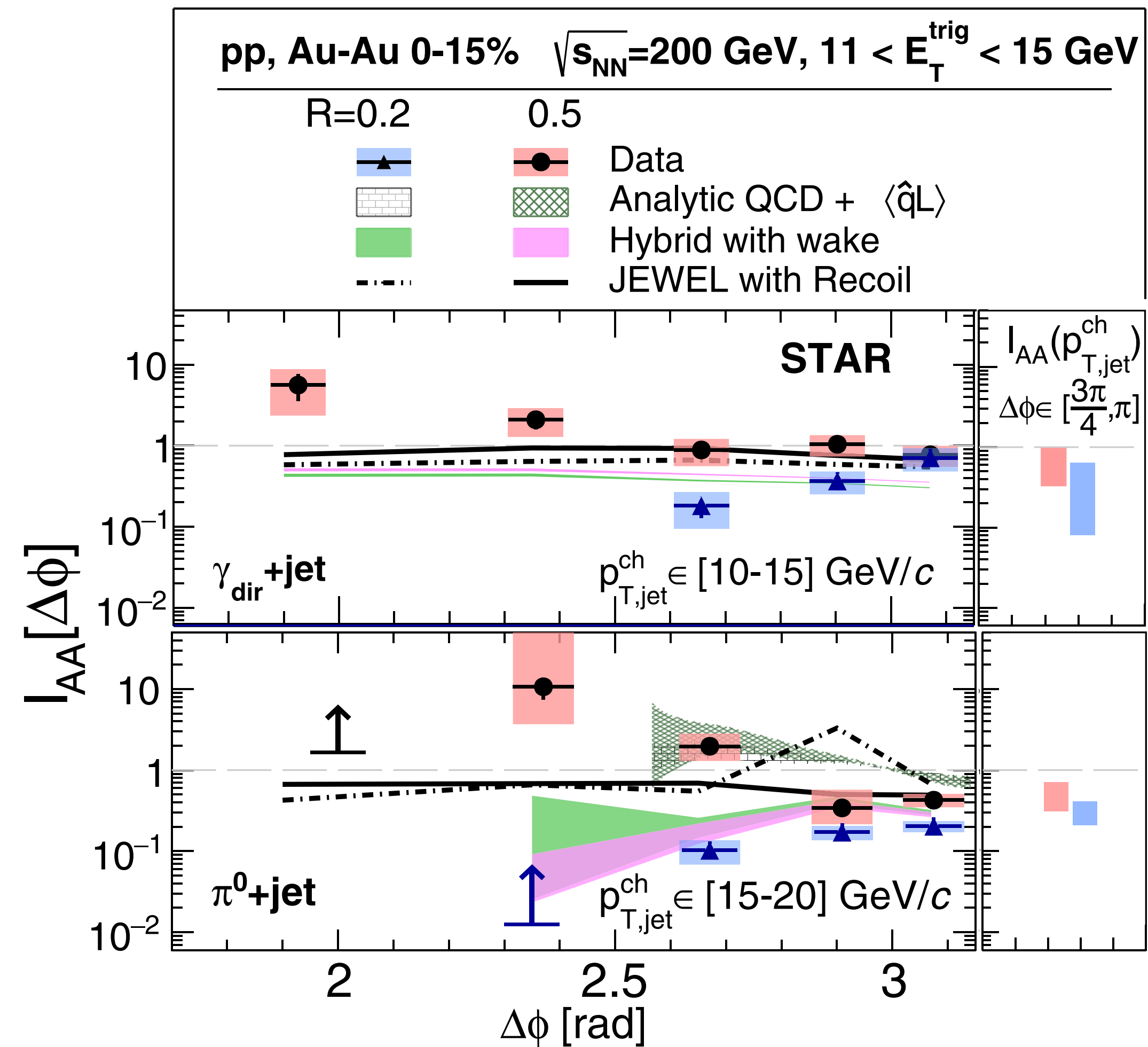
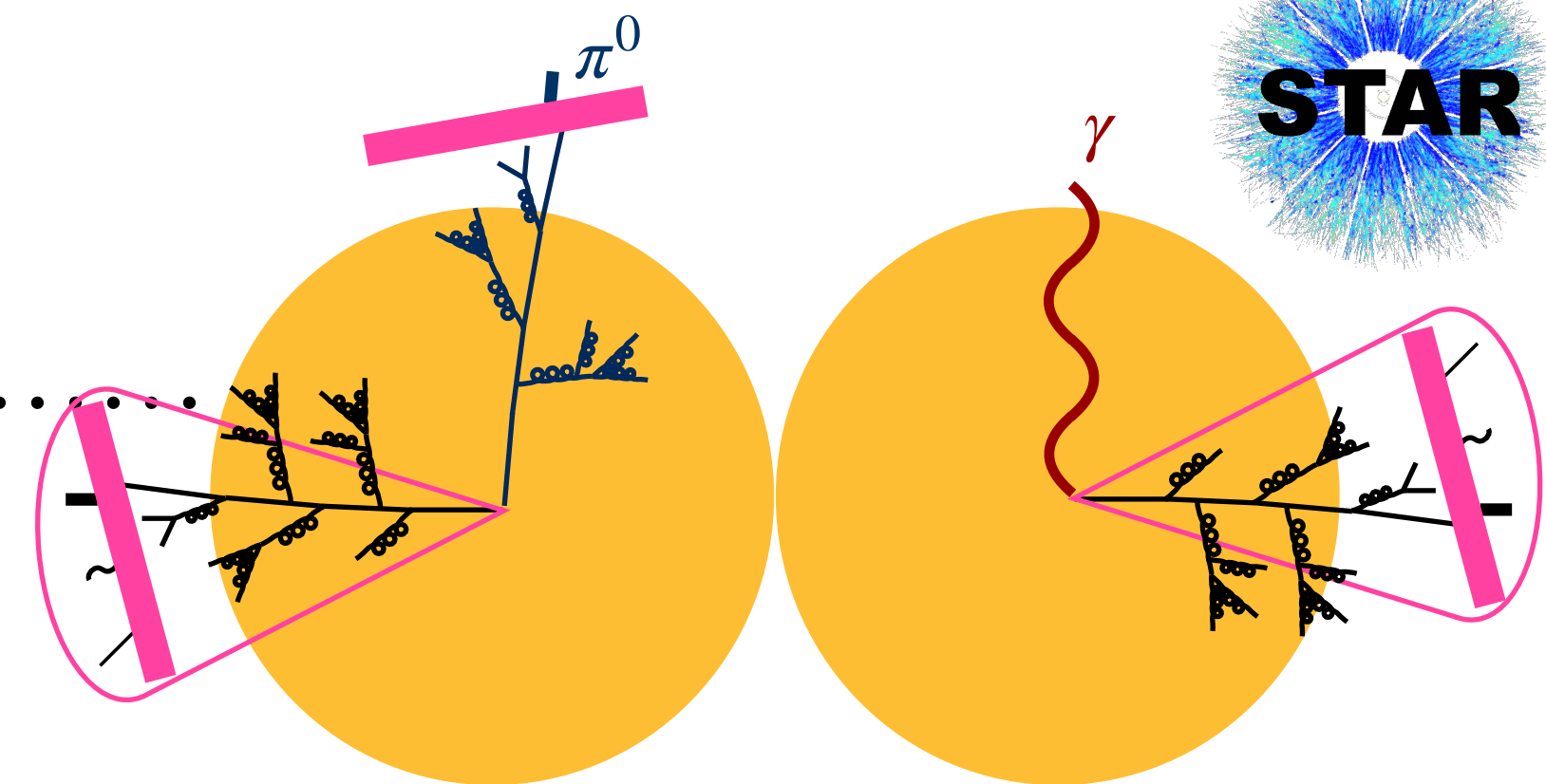
Disfavors Molière scattering picture (naïvely
radius-independent)

Potential medium response effect?



Medium-induced acoplanarity

Recently published! STAR, [PRC 113 \(2026\) 1, 014902](https://arxiv.org/abs/2508.14902)



Substantial R -dependence of acoplanar yield:
small- R suppression, large- R enhancement

Disfavors Molière scattering picture (naïvely
radius-independent)

Potential medium response effect?

Models unable to consistently capture trends



Charm quark energy loss,
diffusion, fragmentation
modification in medium
with *charmed-jet yields*

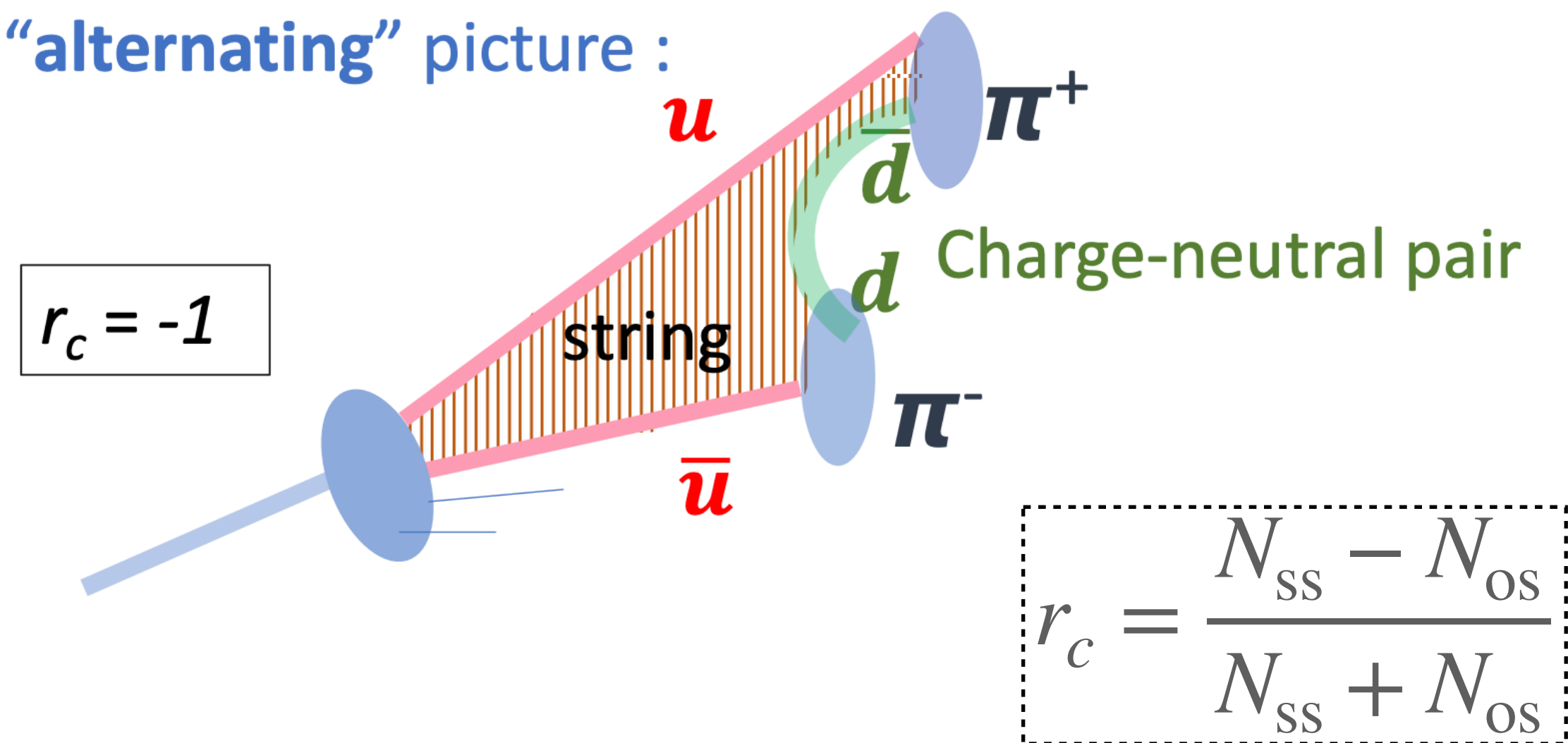
Hadronization
mechanism
with *flavor correlators*

Constituent identity

Hadrochemistry modification
via medium response
with *baryon-to-meson ratios*

Assessing fragmentation mechanism in jets

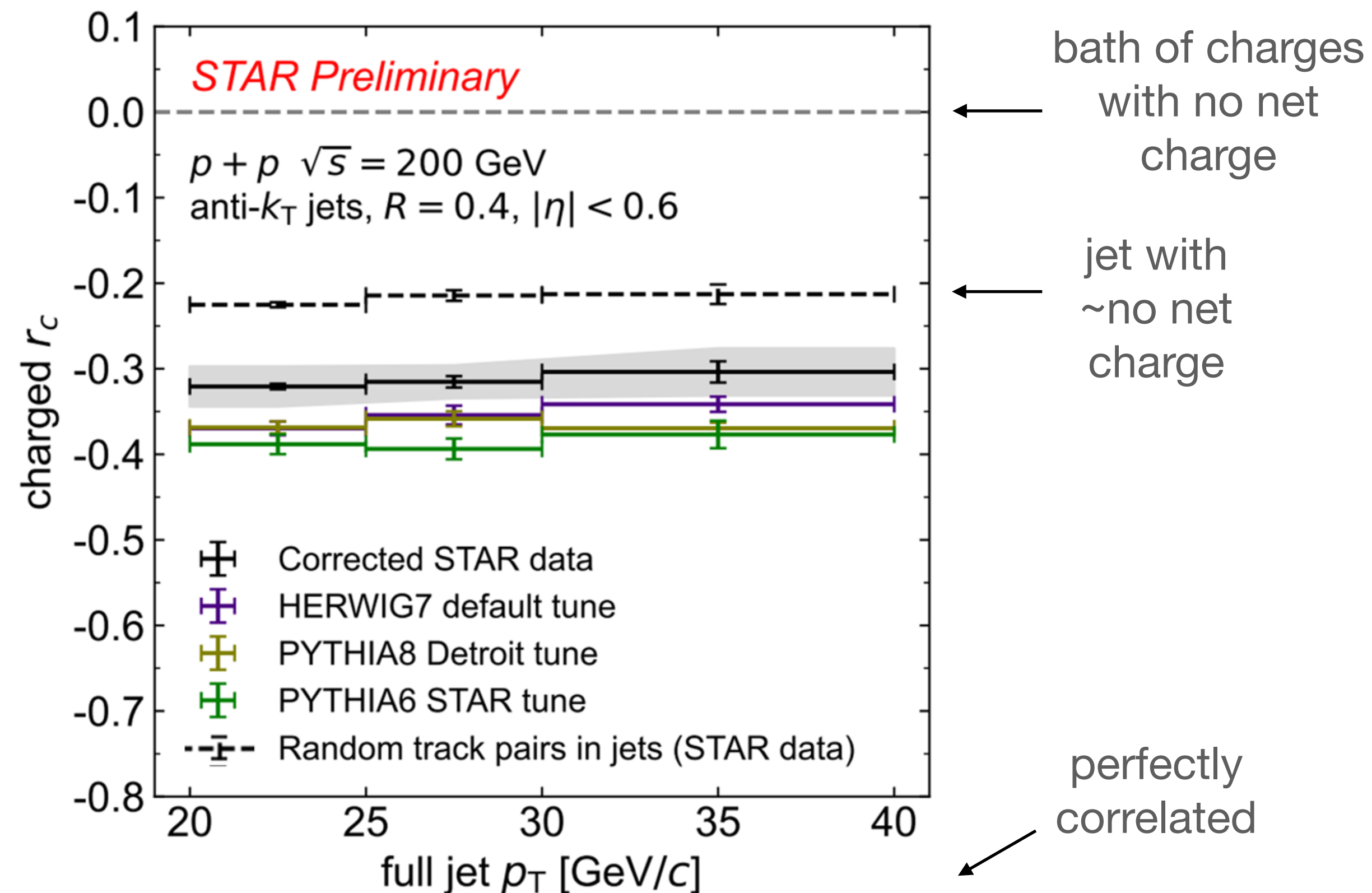
“alternating” picture :



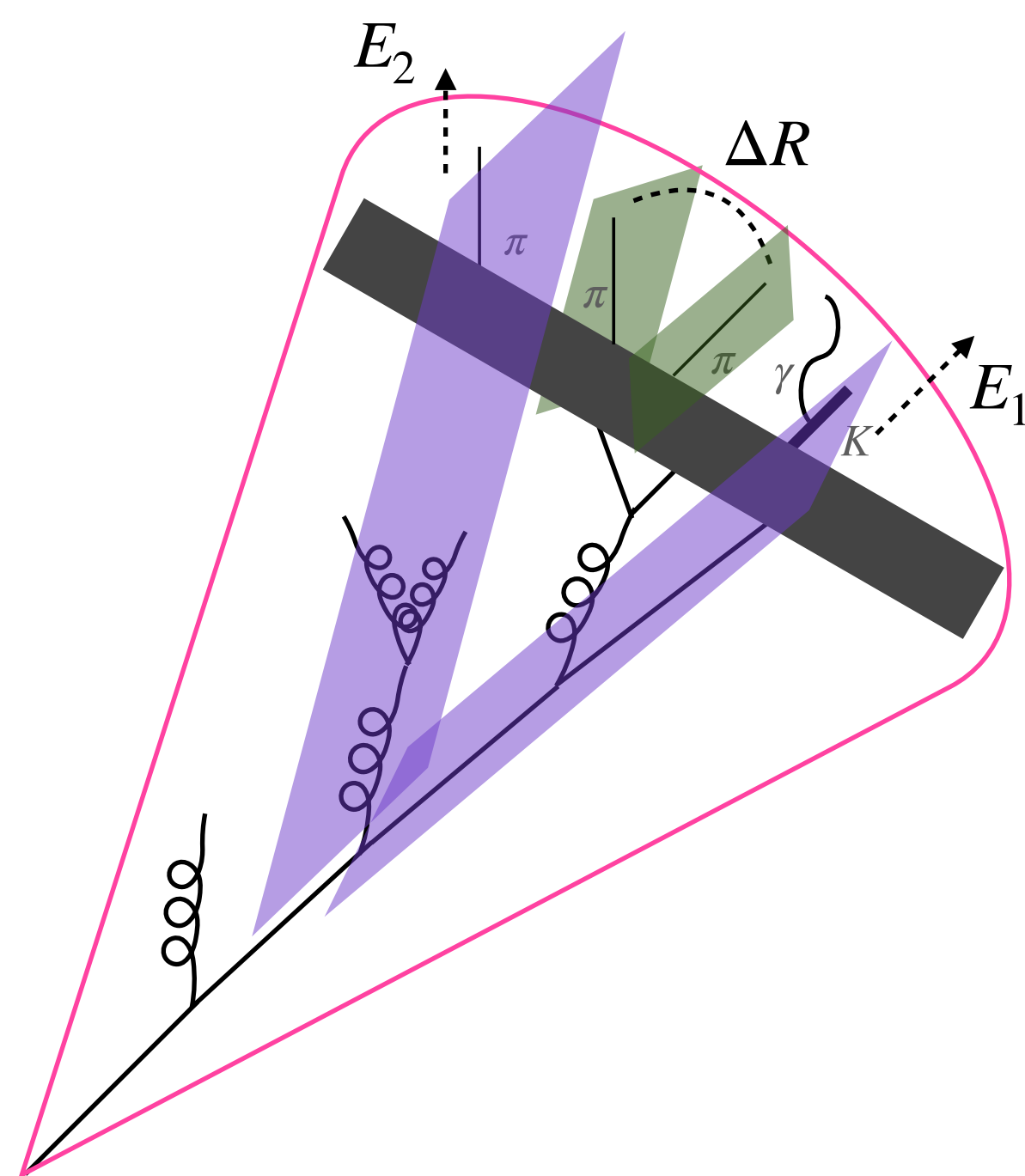
Leading charge correlator, r_c , can probe contribution of string-like fragmentation

First pp measurement: MCs predict more charge correlation than supported by data

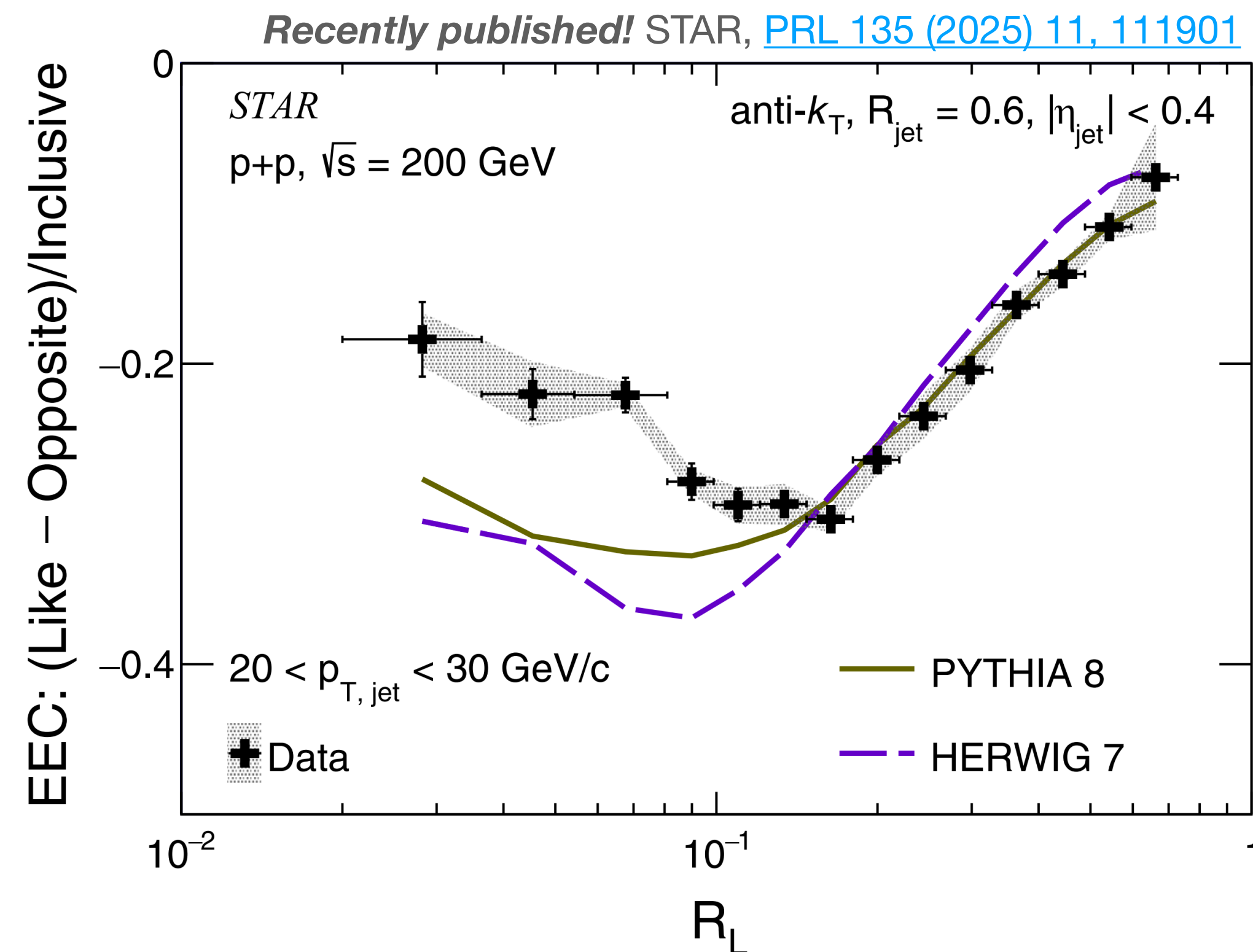
Outlook: extension to heavy-ion collisions ongoing



Assessing fragmentation mechanism in jets



$$EEC(\Delta R) = \frac{1}{\mathcal{O}} \frac{d\mathcal{O}}{d(\Delta R)}, \quad \mathcal{O} = \sum_{\text{jets}} \sum_{i \neq j} \frac{E_i E_j}{p_{T,\text{jet}}^2}$$

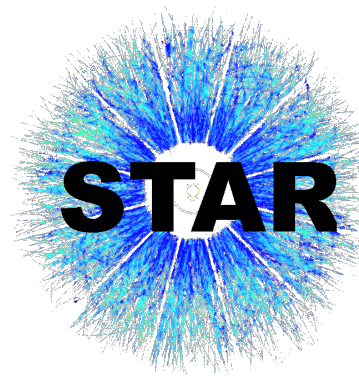


New charge-dependent EEC & E3C — in **hadronic regime**, both **MCs fail to capture data**; qualitatively consistent with behavior seen in r_c

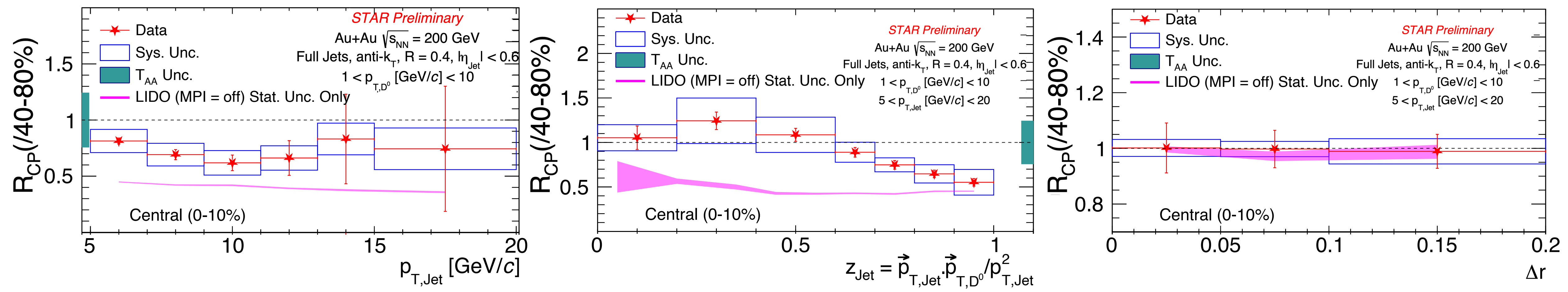
Outlook: Extension to heavy-ion collisions ongoing



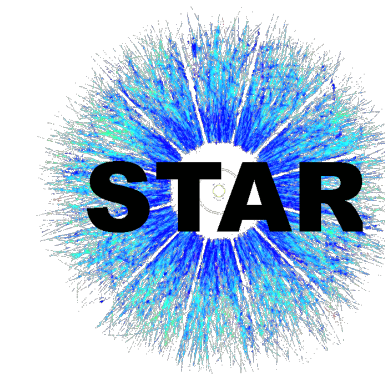
$$D^0 = c\bar{u}$$



D⁰-jet spectra, profile, fragmentation

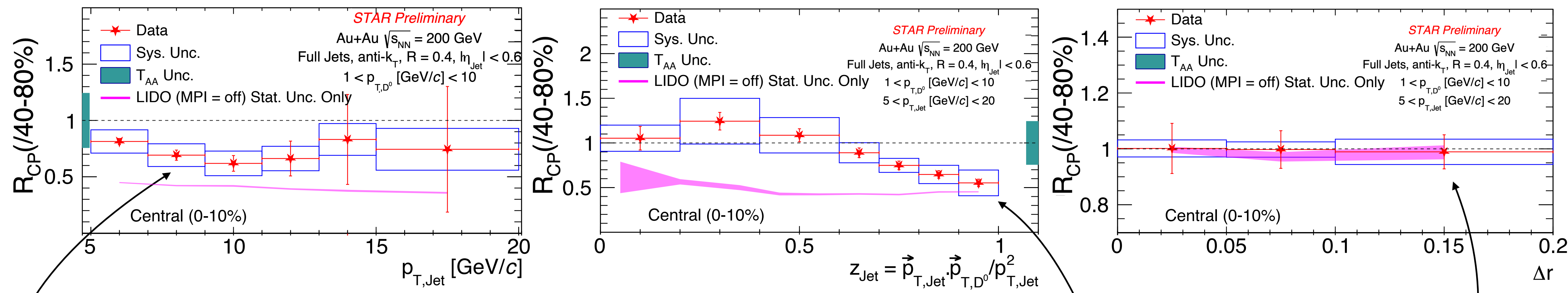


Testing charm quark energy loss, fragmentation modification, and diffusion



$$D^0 = c\bar{u}$$

D⁰-jet spectra, profile, fragmentation

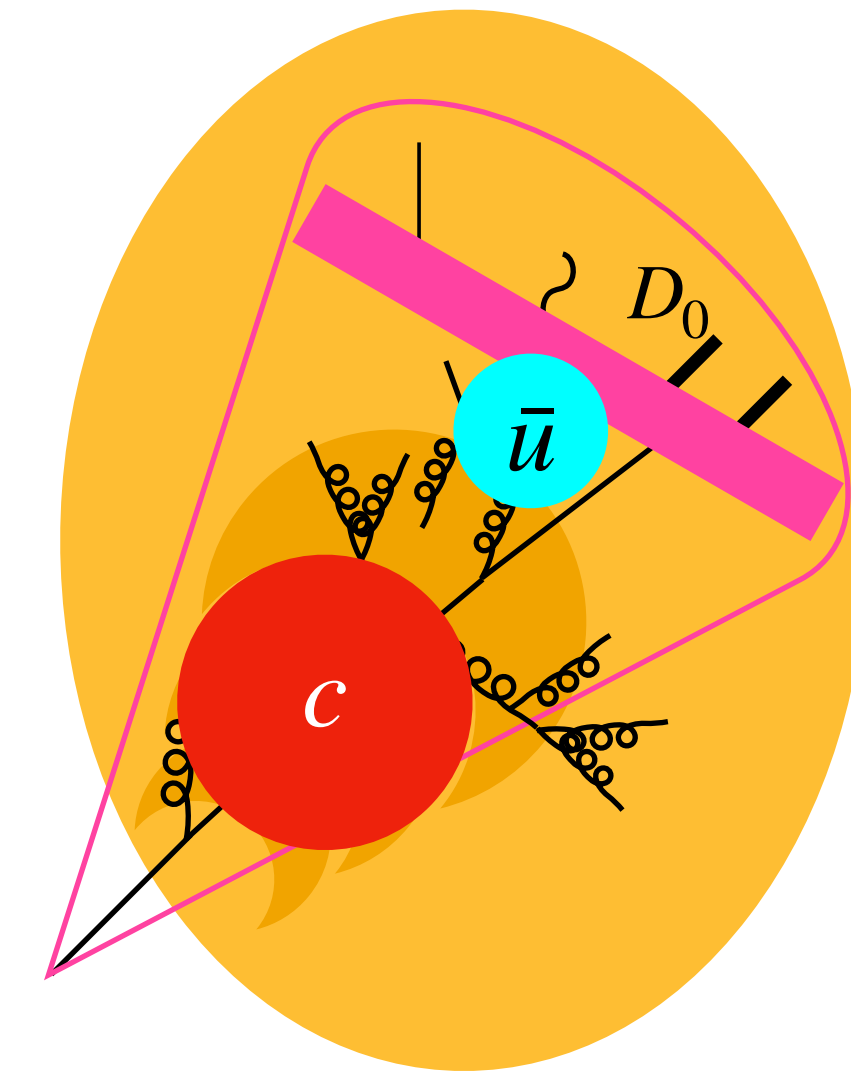
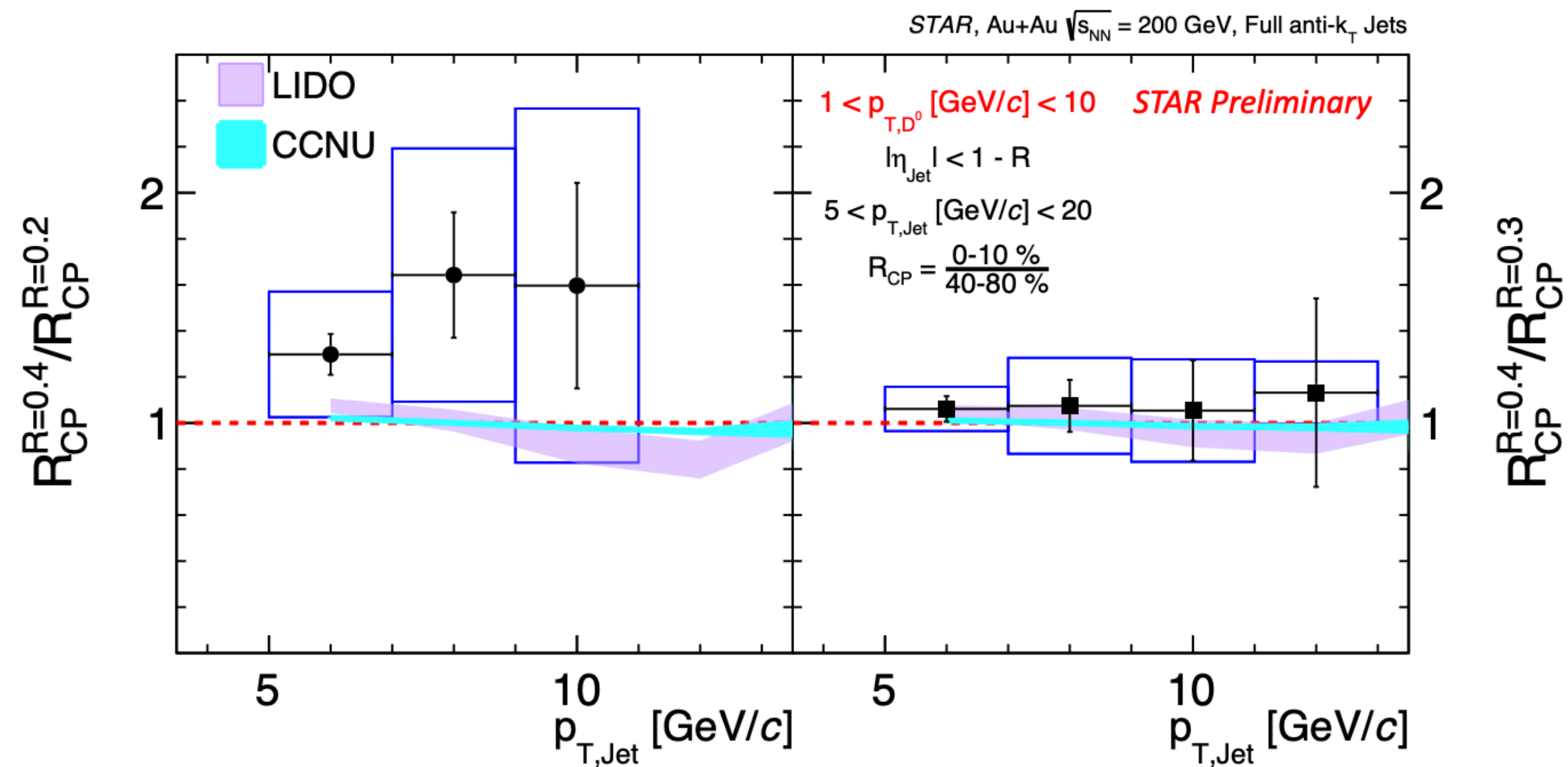


Testing charm quark energy loss, fragmentation modification, and diffusion

Hint of yield suppression. Hard-fragmented charm jets suppressed. No diffusion.

Model including radiative and collisional energy loss during heavy quark evolution underpredicts central yields — MPI might be important for D⁰ $p_T \sim 1$ GeV/c

Recovering charm-associated radiation

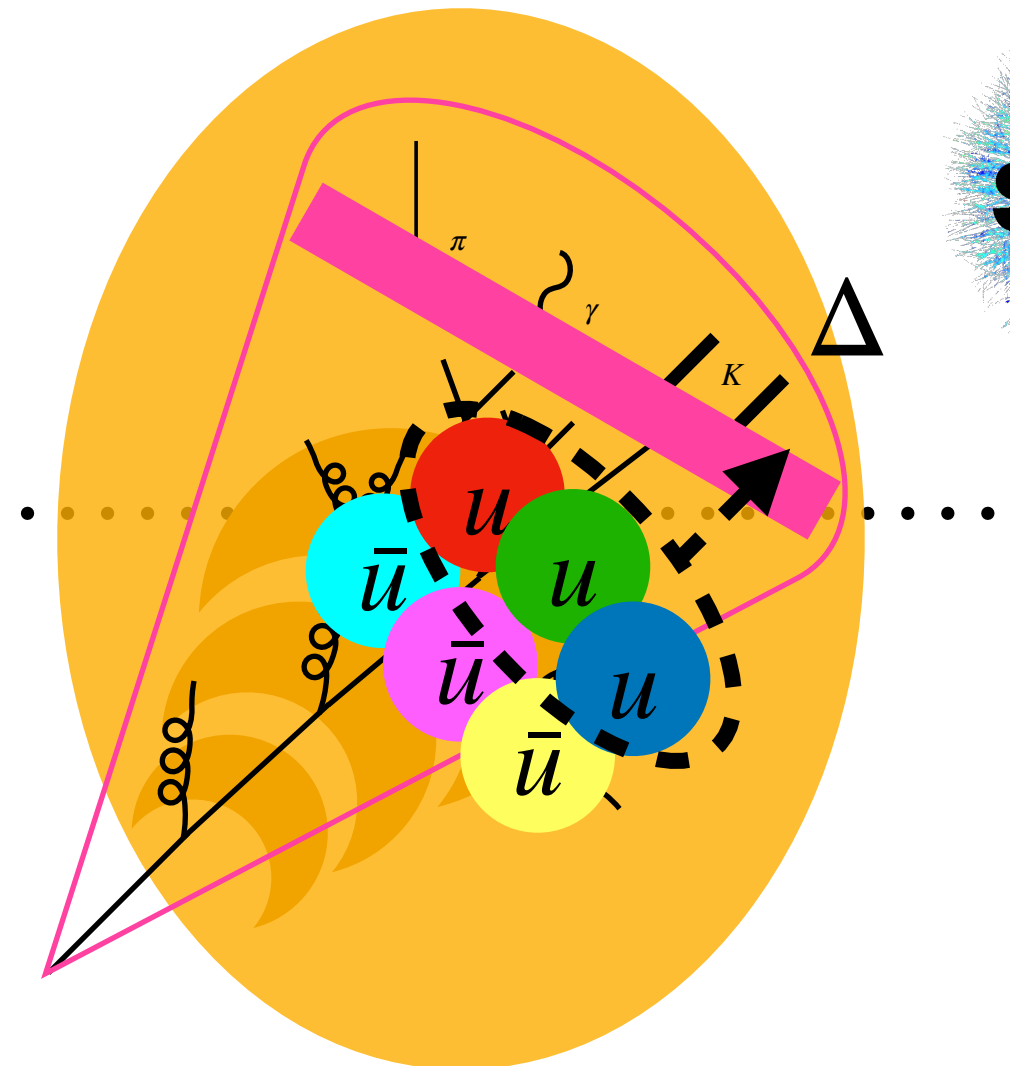


Wider jets \rightarrow more medium interaction/ E -loss \implies *ratio* < 1 ,
 but recover more energy + more potential for medium response \implies *ratio* > 1
 Observe: **No radius dependence of R_{CP}** within uncertainties.
 Agrees with models predicting minimal R -dependence of suppression.

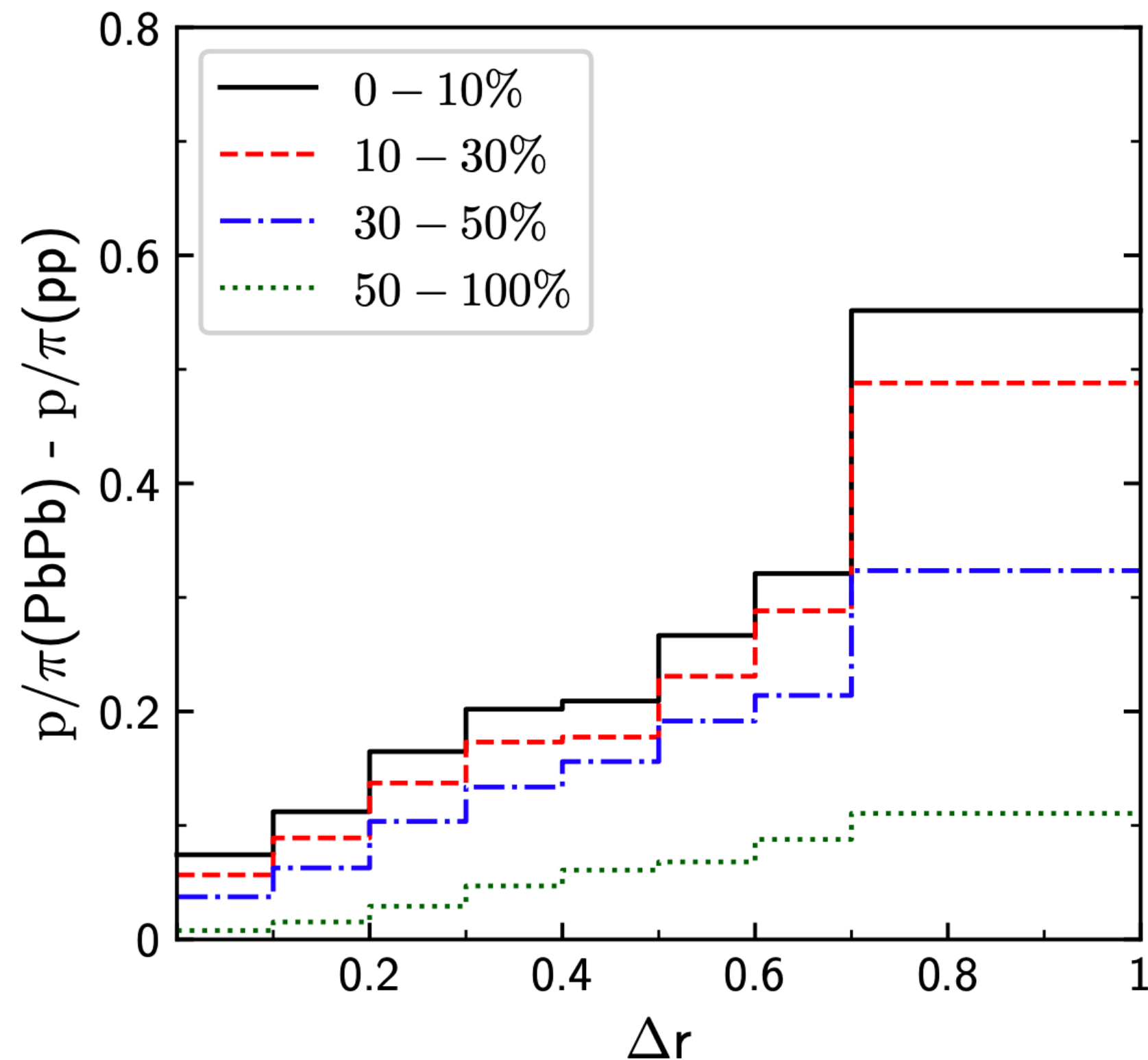
Outlook: measuring generalized angularities

Probing medium response

Using baryon-to-meson ratios in jets



¹Luo, Mao, Qin, Wang, Zhang, [PLB 837 \(2023\) 137638](#)



Medium affects the jet. The jet *also affects* the medium: “*medium response*”

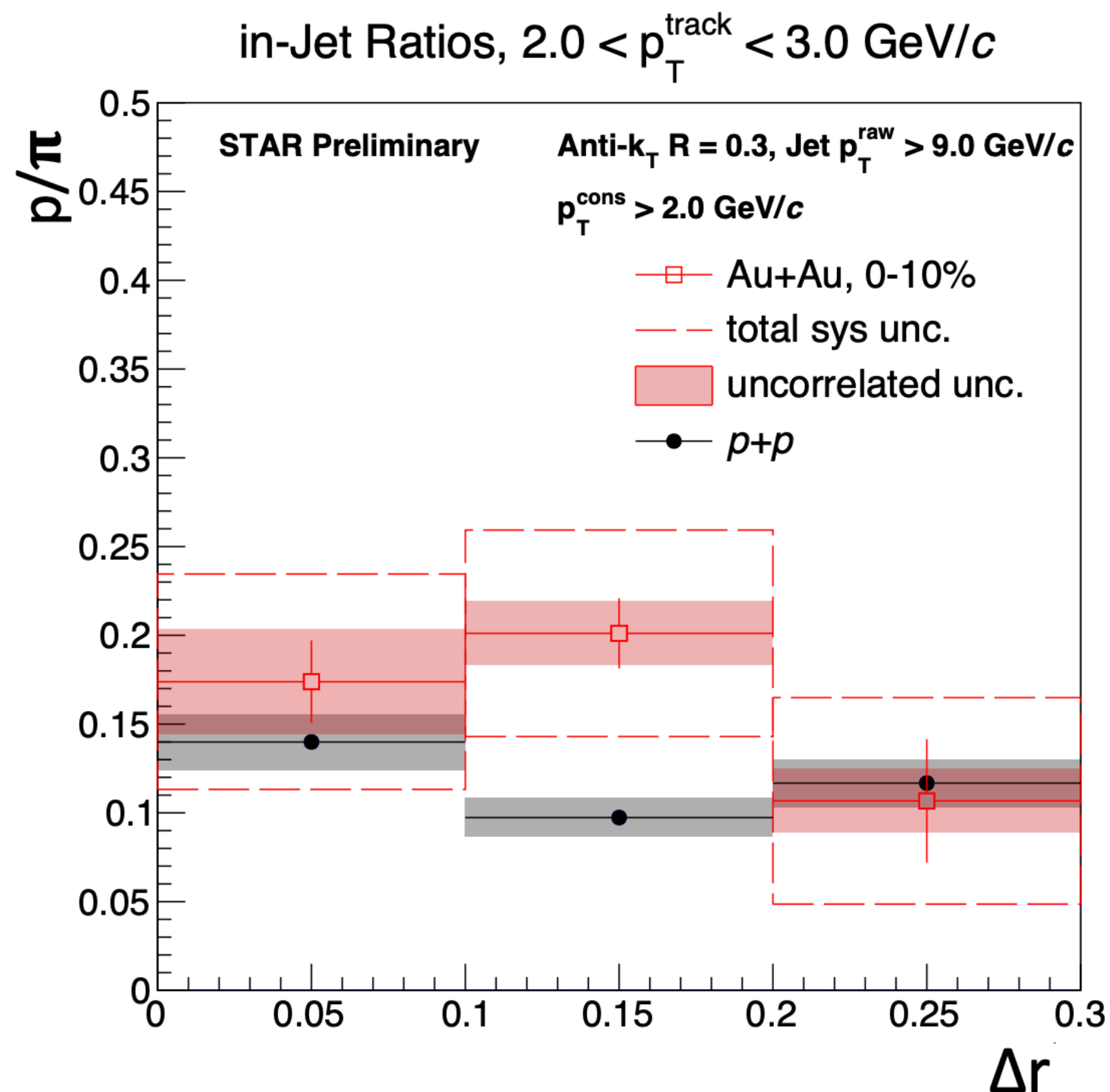
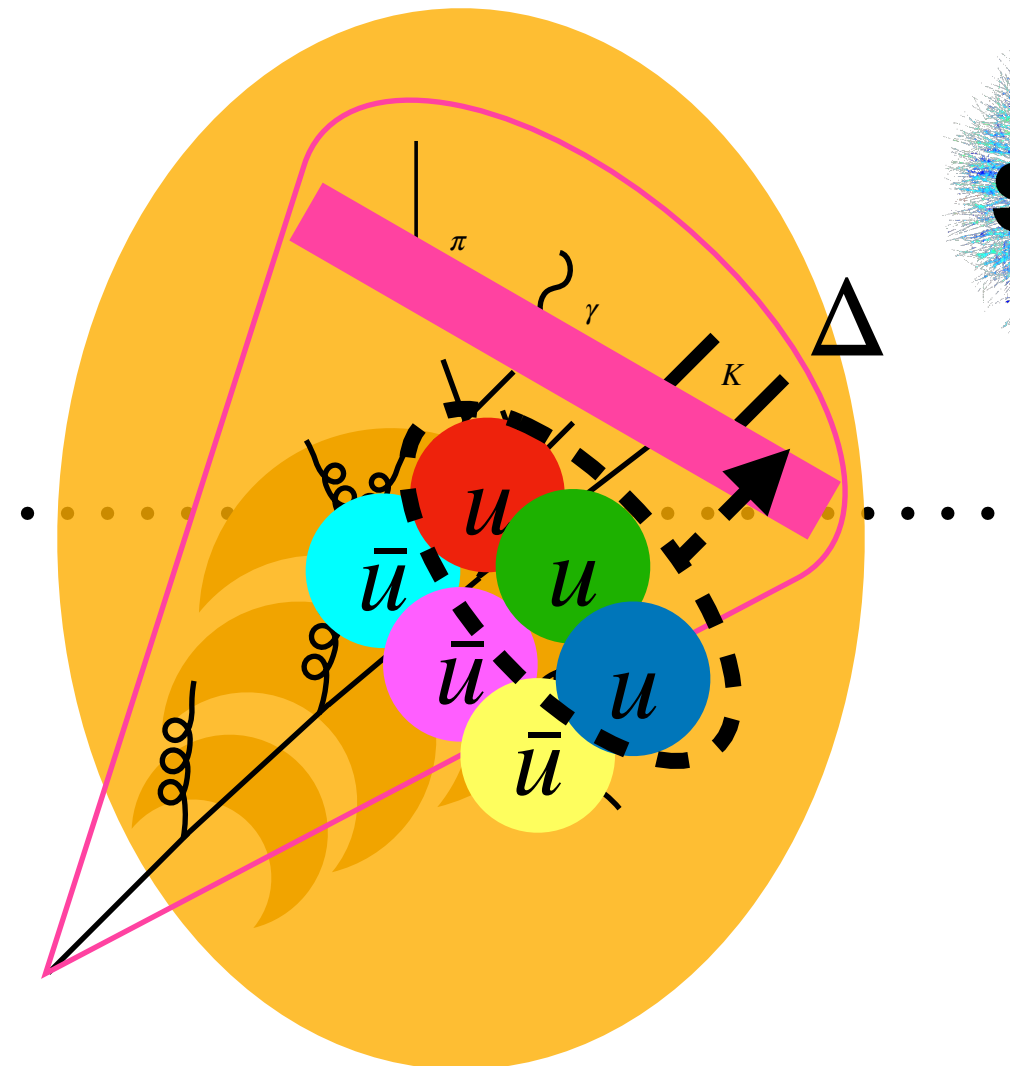
Wake pushing medium particles into jet¹

Thermal-shower recombination²

→ possible enhancement of in-jet baryon-to-meson ratio in A+A

Probing medium response

Using baryon-to-meson ratios in jets



Medium affects the jet. The jet *also affects* the medium: “*medium response*”

Wake pushing medium particles into jet
Thermal-shower recombination

→ possible enhancement of in-jet baryon-to-meson ratio in A+A

Do not observe linear modification of *in-jet* p/π ratio in the kinematic range studied, within uncertainties

Physics from the STAR jet program

Evidence for jet quenching in O+O collisions

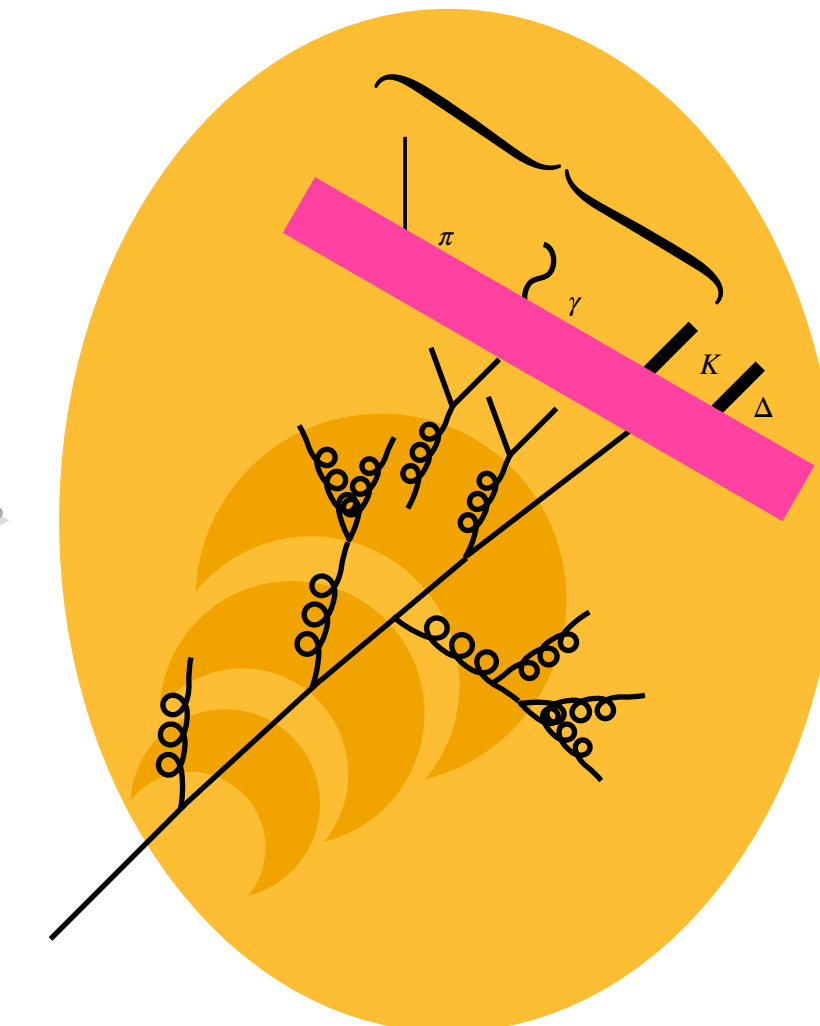
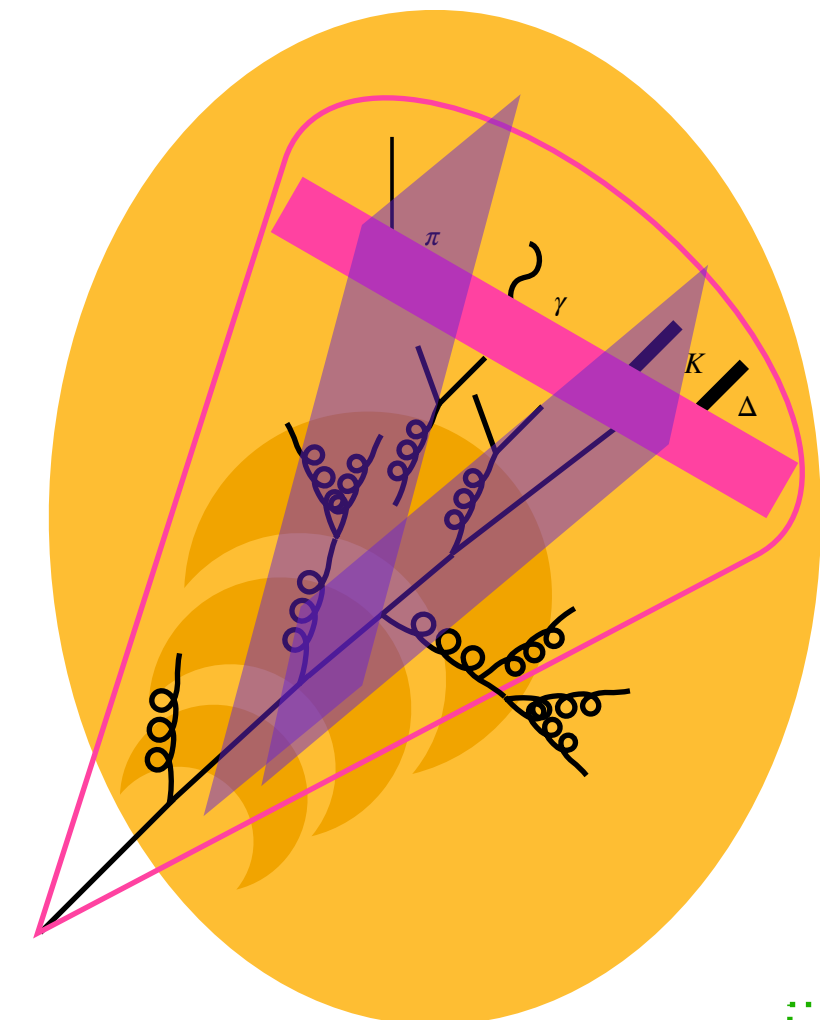
Testing limits of models' description of charge flow of hadronization

Stringent tests of pQCD and PDFs

Suppression of jets with hard-fragmenting charm hadrons

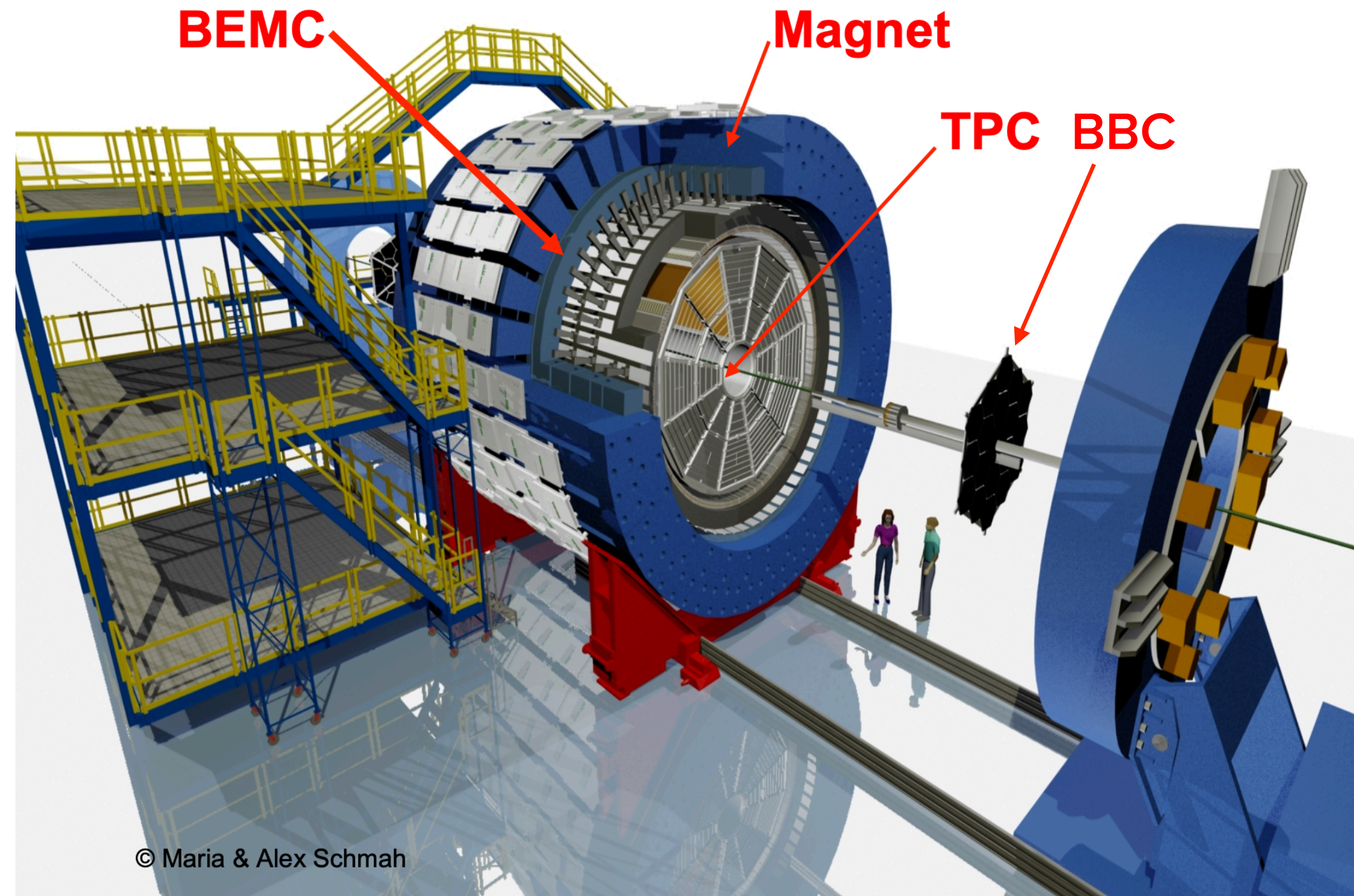
Evidence for medium response effect on recoil jet acoplanarity

Medium-induced hadrochemistry effect not observed in jets



Hard probes at STAR

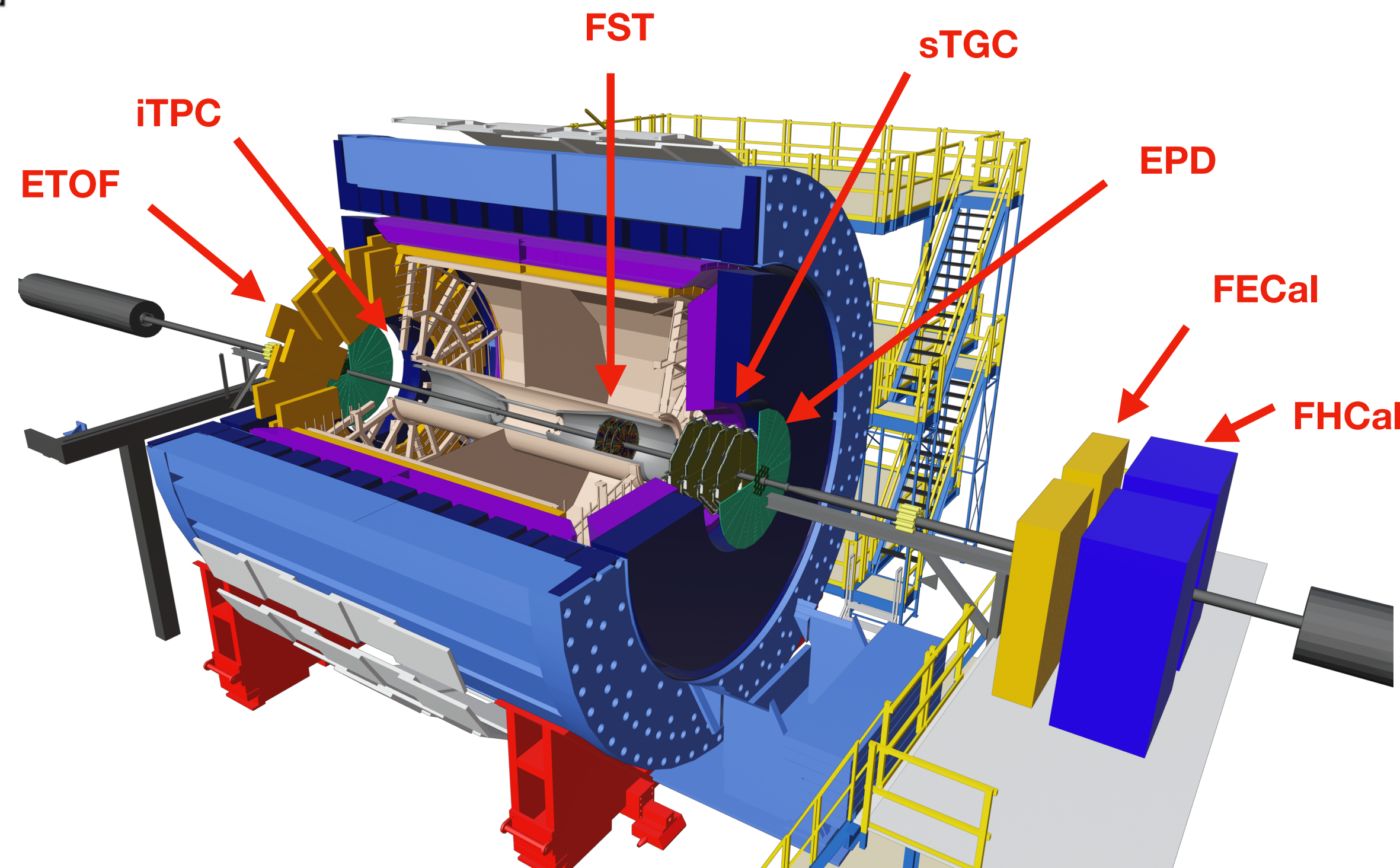
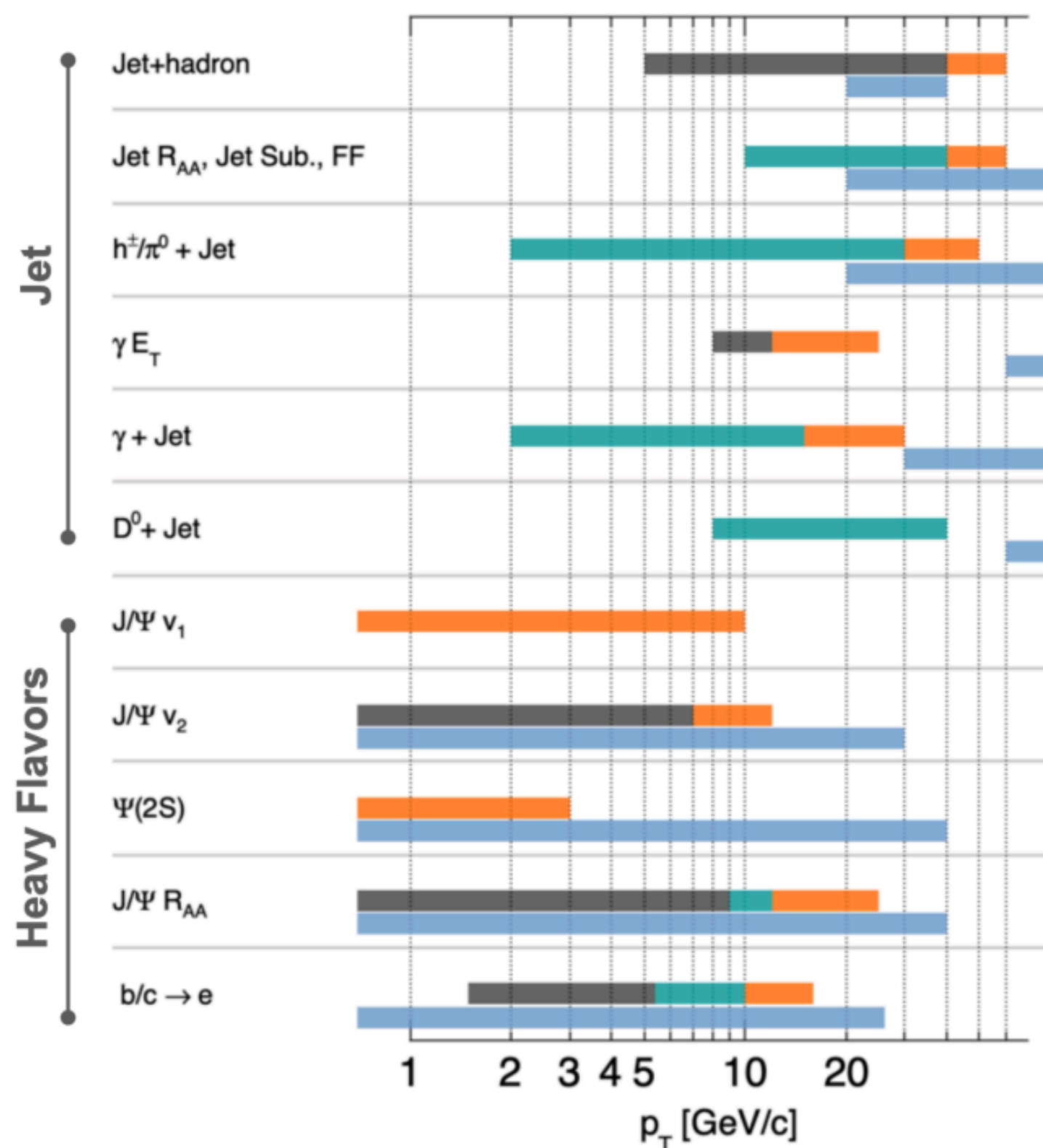
In the 2010s



© Maria & Alex Schmah

STARing into the future

● STAR Until 2015 ● STAR Today ● STAR 2023+2025 ● LHC Published



Precision tracking

Forward jets → different x; q v. g

Unbiased centrality/EP determination

DAQ rate: 5 kHz

Etc!

Runs 23+25^{1,2} 200-GeV Au+Au: 4.3B high-lumi/high-p_T triggered events + 35 nb⁻¹ additional high-p_T O+O: → improved acceptance, uncertainties, kinematic reach / overlap w/ LHC, etc. At least a decade of data analysis left!

Thank you!

SoftDrop and the Lund Plane

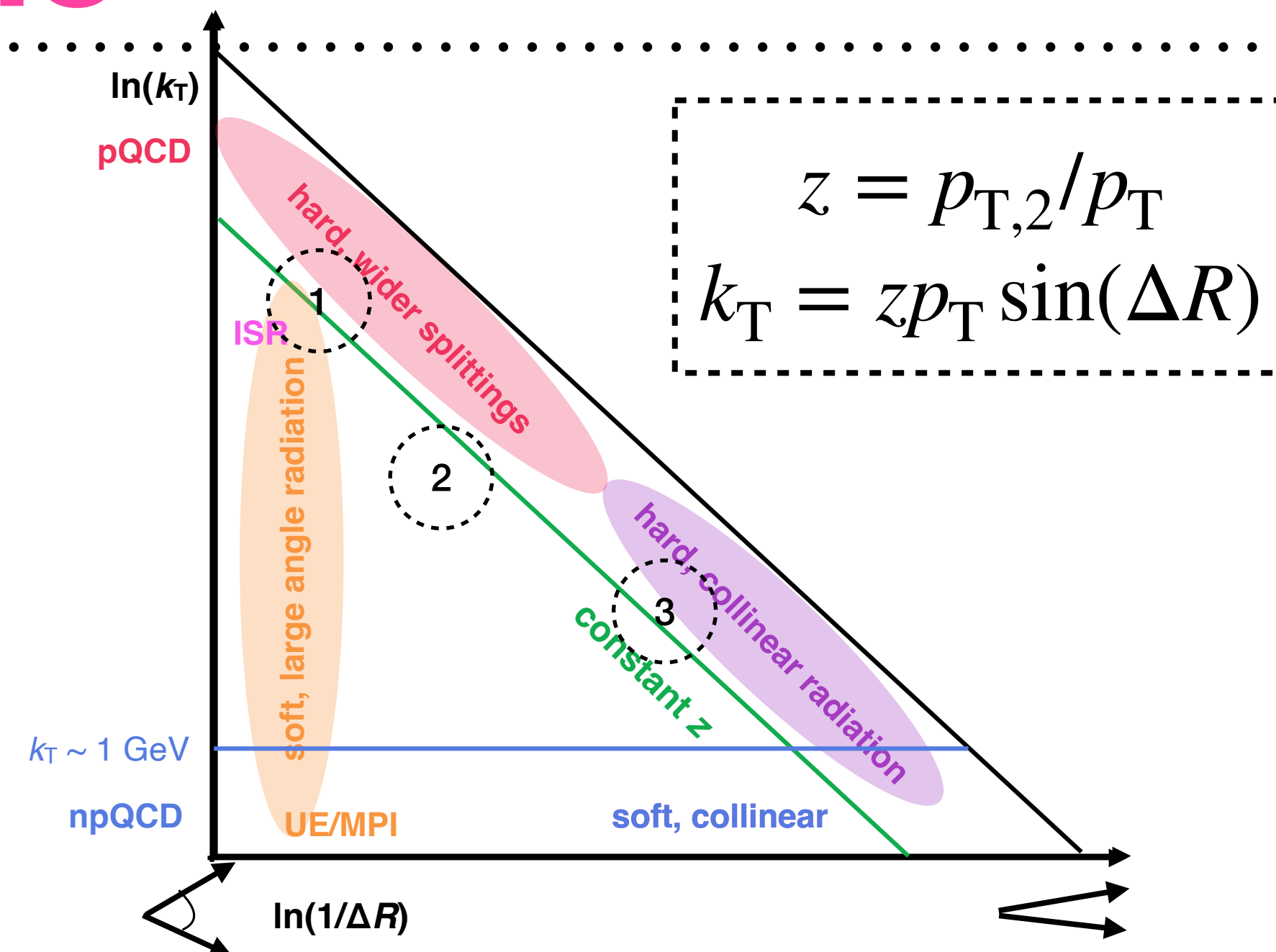
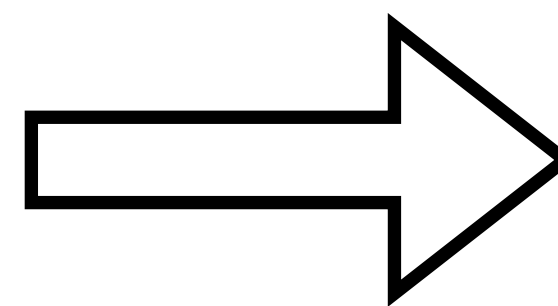
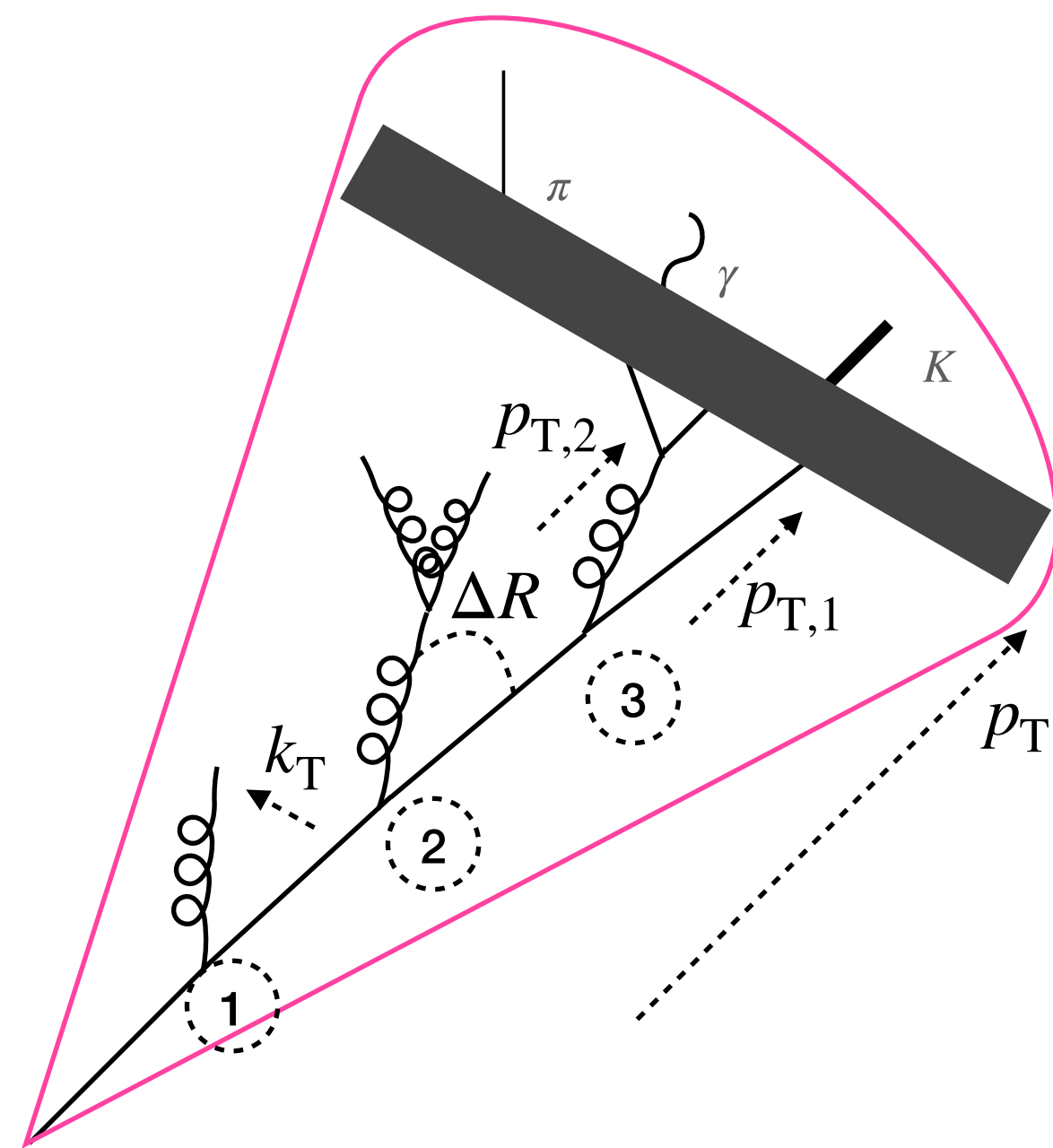
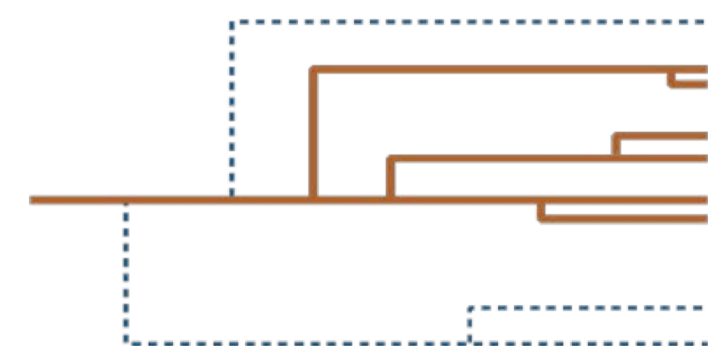


Image: Laura Havener, modified from Andrews et al., [J.Phys.G 47 \(2020\) 6, 065102](#)

$$\frac{\min(p_{T,i}, p_{T,j})}{p_{T,i} + p_{T,j}} > z_{\text{cut}} \left(\frac{\Delta R_{ij}}{R} \right)^\beta$$

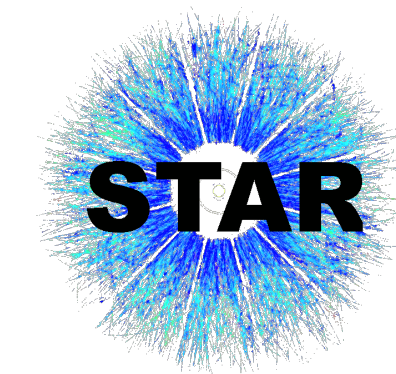
$$z_g = \frac{\min(p_{T,1}, p_{T,2})}{p_{T,1} + p_{T,2}}$$



$$M_g = \left| \sum_{i \in J_g} p_i \right|$$

Image: Larkoski, Marzani, Thaler, Xue, [PRL 119 \(2017\) 13, 132003](#)

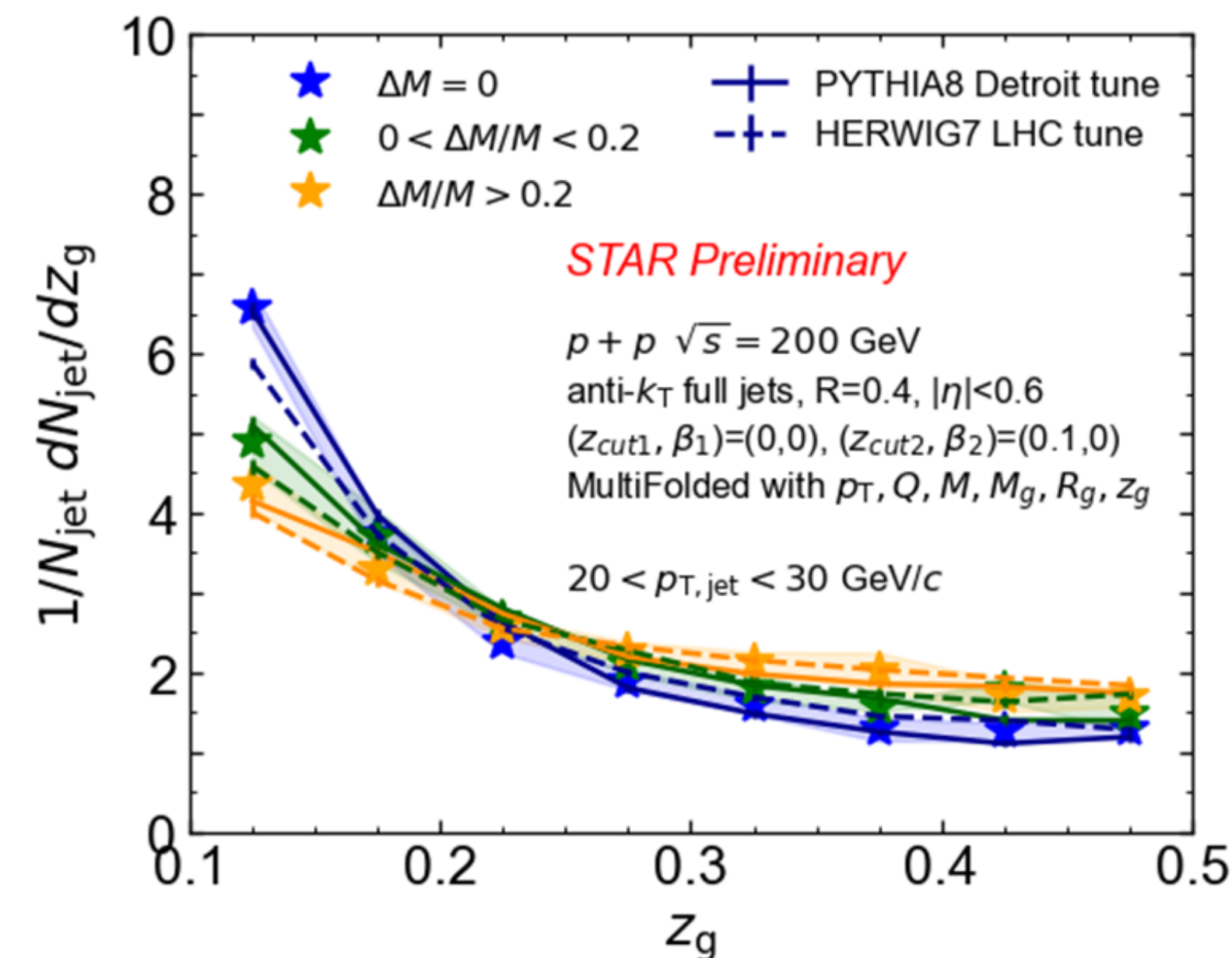
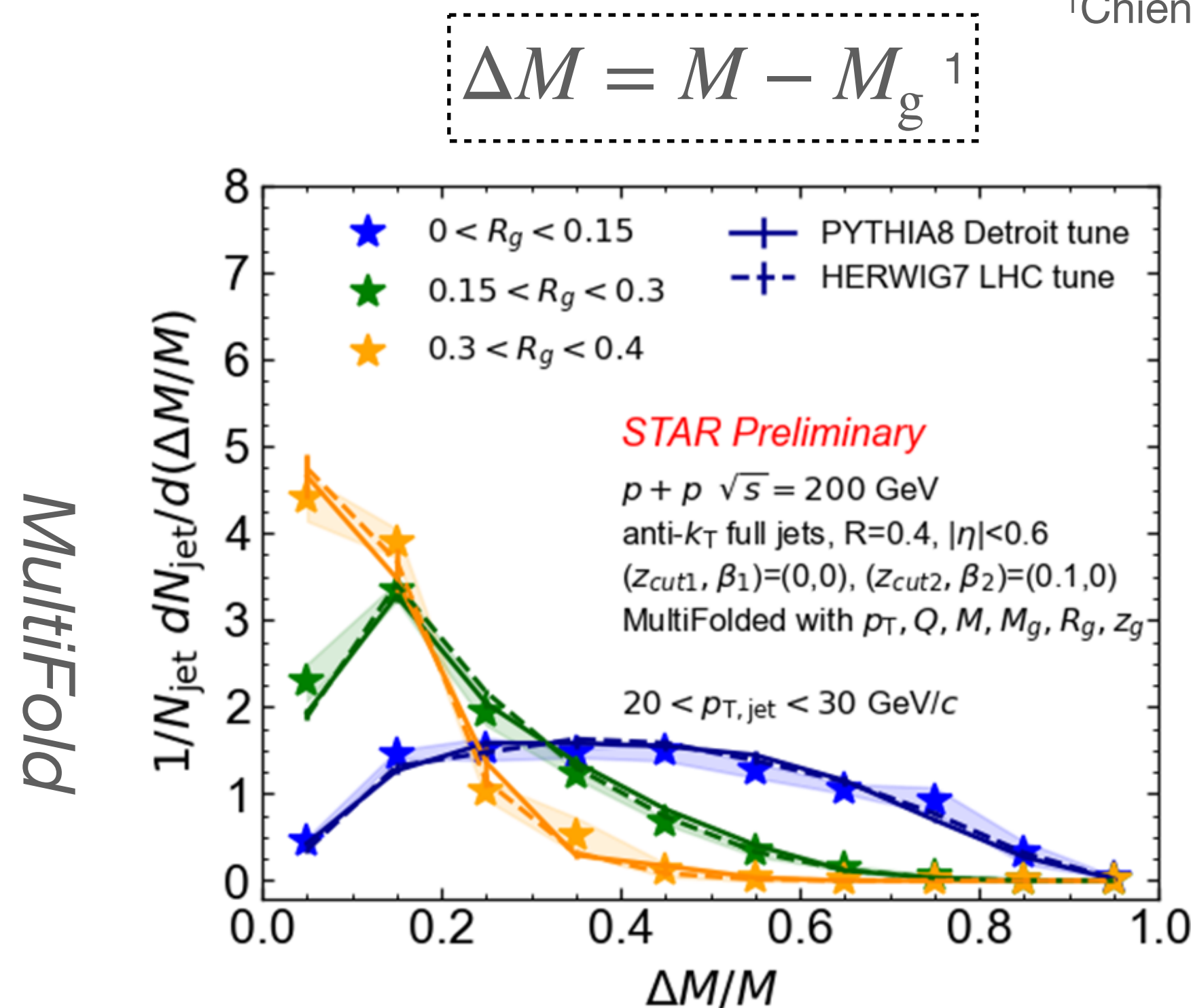
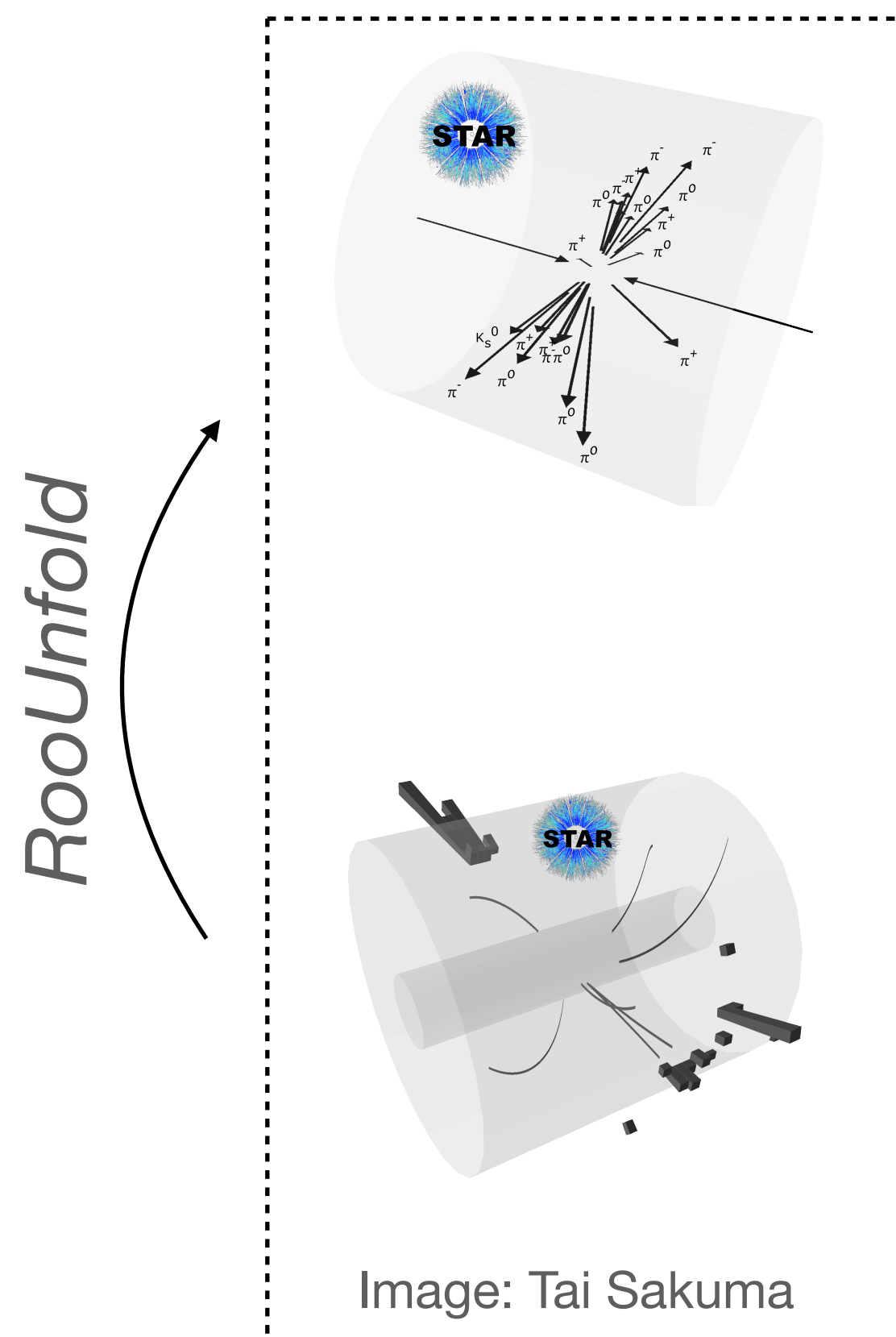
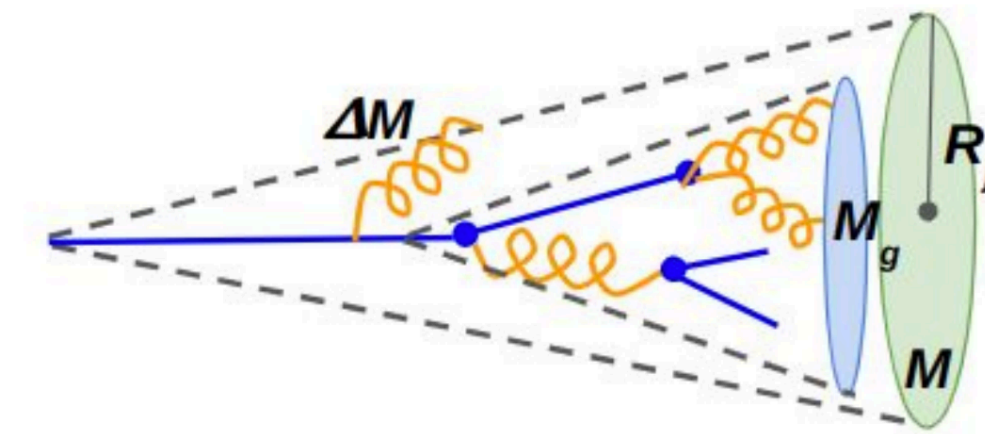
SoftDrop¹ grooming: reduce soft non-perturbative contribution
 → better theoretical control



N-dimensional substructure

With MultiFold

¹Chien, Stewart, [JHEP 06 \(2020\) 064](#)



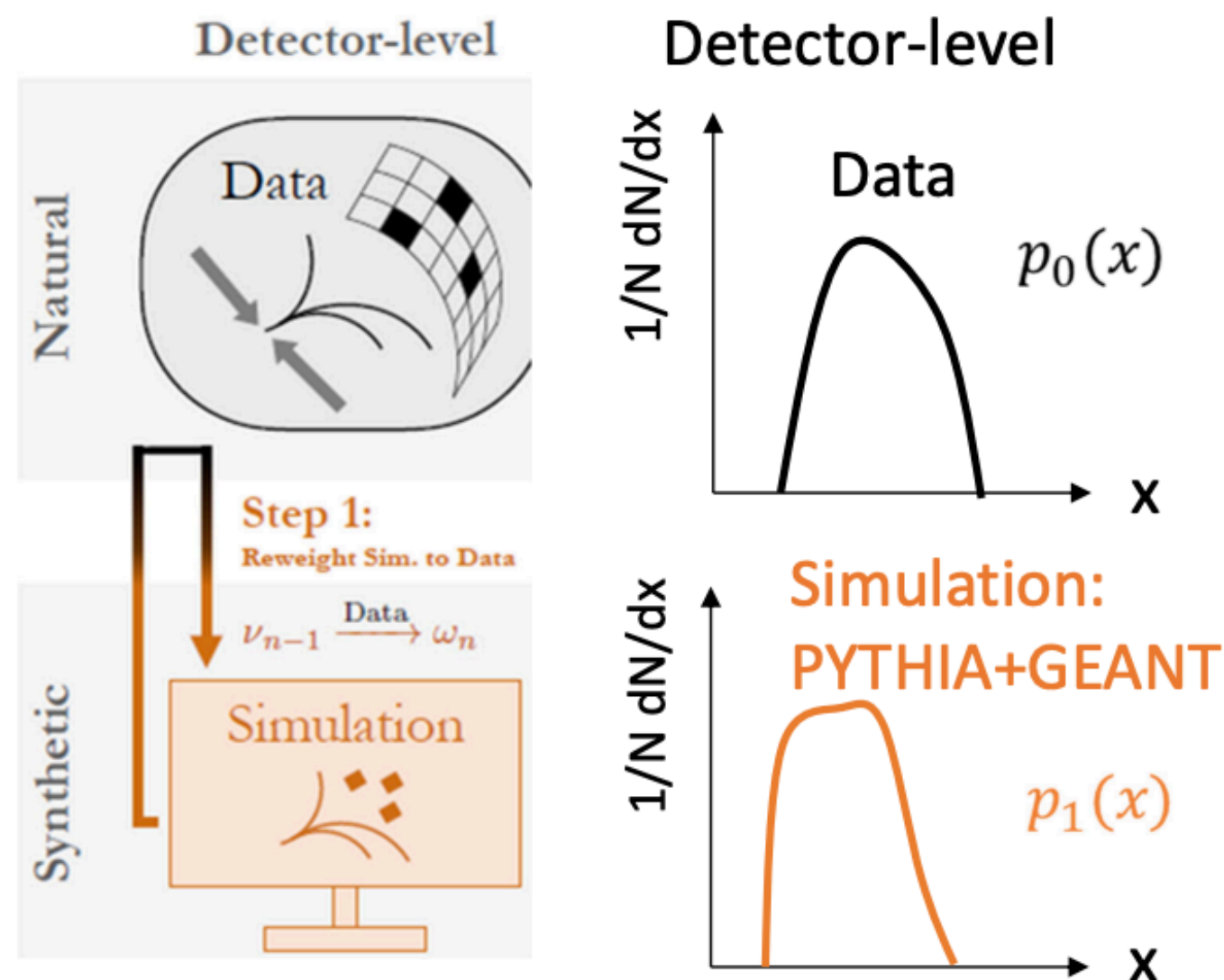
First application of MultiFold at RHIC

Correlation between R_g , z_g and ΔM consistent with angular ordering + kinematic constraint between early and late time splittings

MultiFold



Method: machine learning



E.g., Iteration 1, step 1:

Weights: $w(x) = p_0(x)/p_1(x)$ Ok for 1D
 $\approx f(x)/(1 - f(x))$ [\(Andreassen and Nachman PRD 101, 091901 \(2020\)\)](#)

where $f(x)$ is a neural network and trained with the binary cross-entropy loss function

to distinguish jets coming from data vs from simulation

Unfolding \rightarrow Reweighting histograms
 \rightarrow Classification \rightarrow Neural network

Where does the machine learning part come in?

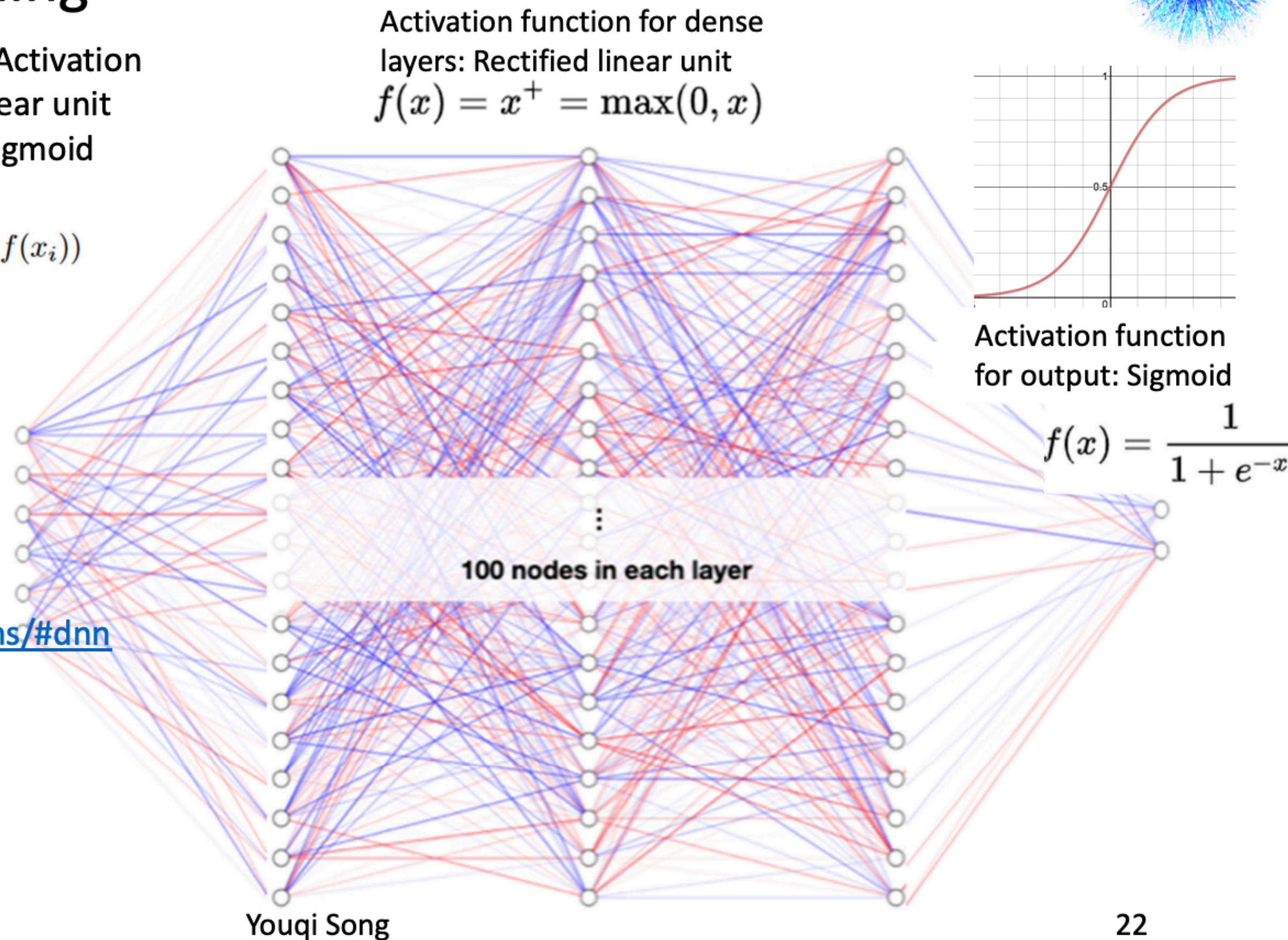
MultiFold

Method: machine learning

- Architecture: Dense neural network
- Activation function for dense layers: Rectified linear unit
- Activation function for output layer: Sigmoid
- Loss function: Binary cross entropy

$$\text{loss}(f(x)) = - \sum_{i \in 0} \log f(x_i) - \sum_{i \in 1} \log(1 - f(x_i))$$

- Optimization algorithm: Adam
<https://arxiv.org/pdf/1412.6980.pdf>
- Nodes per dense layer: [100,100,100]
- Output dimension: 2
- Input dimension: 6
- All hyperparameters are default:
<https://energyflow.network/docs/archs/#dnn>



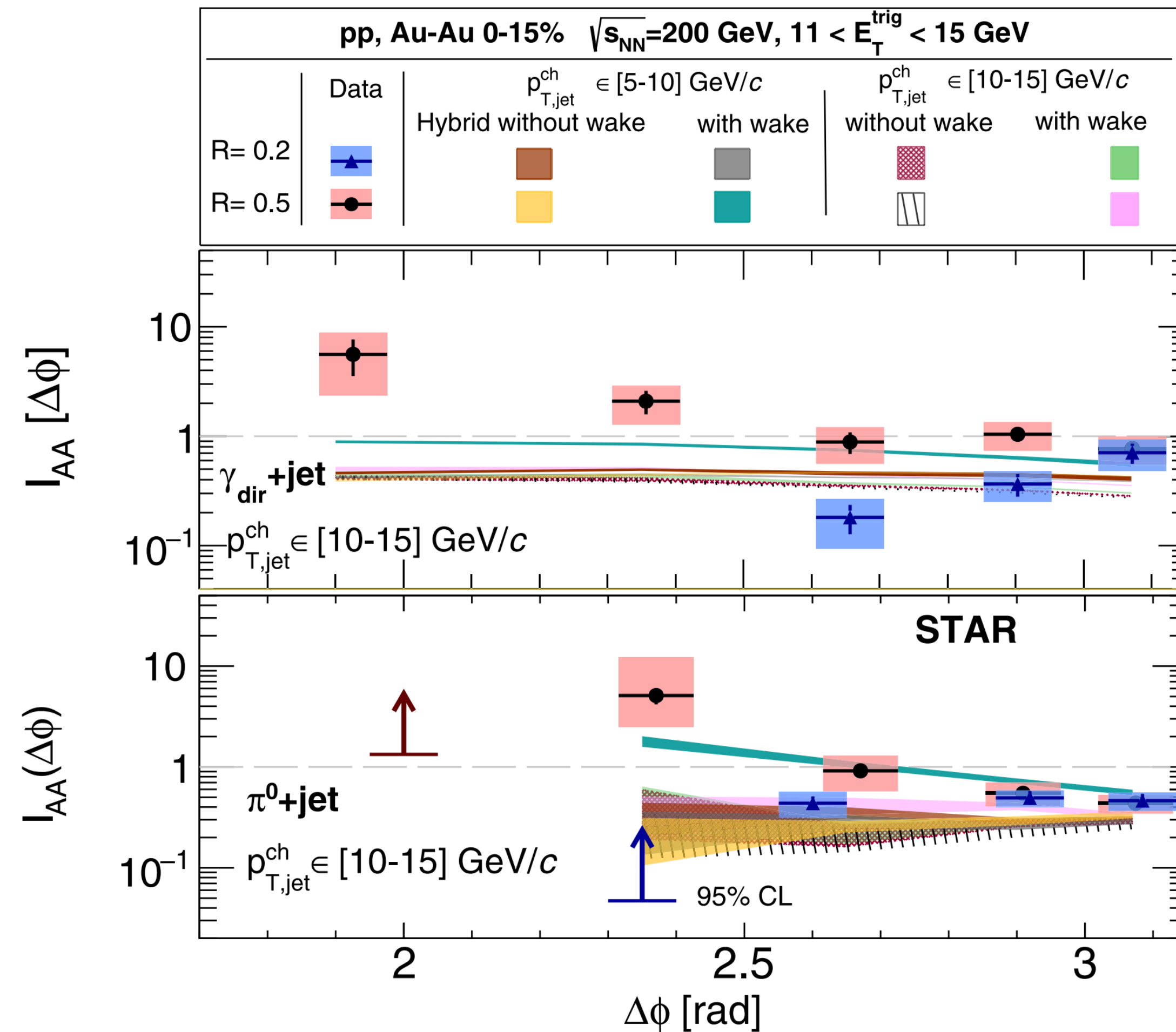
DIS, 3/28/23

Youqi Song

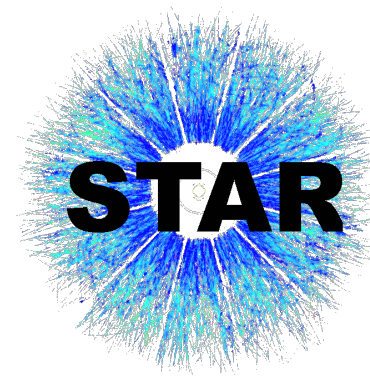
22

Acoplanarity hybrid model comparison

In more detail



The radius-dependence of the acoplanarity is qualitatively described by hybrid with wake, for a lower p_T range than the data



Path-length-dependent quenching

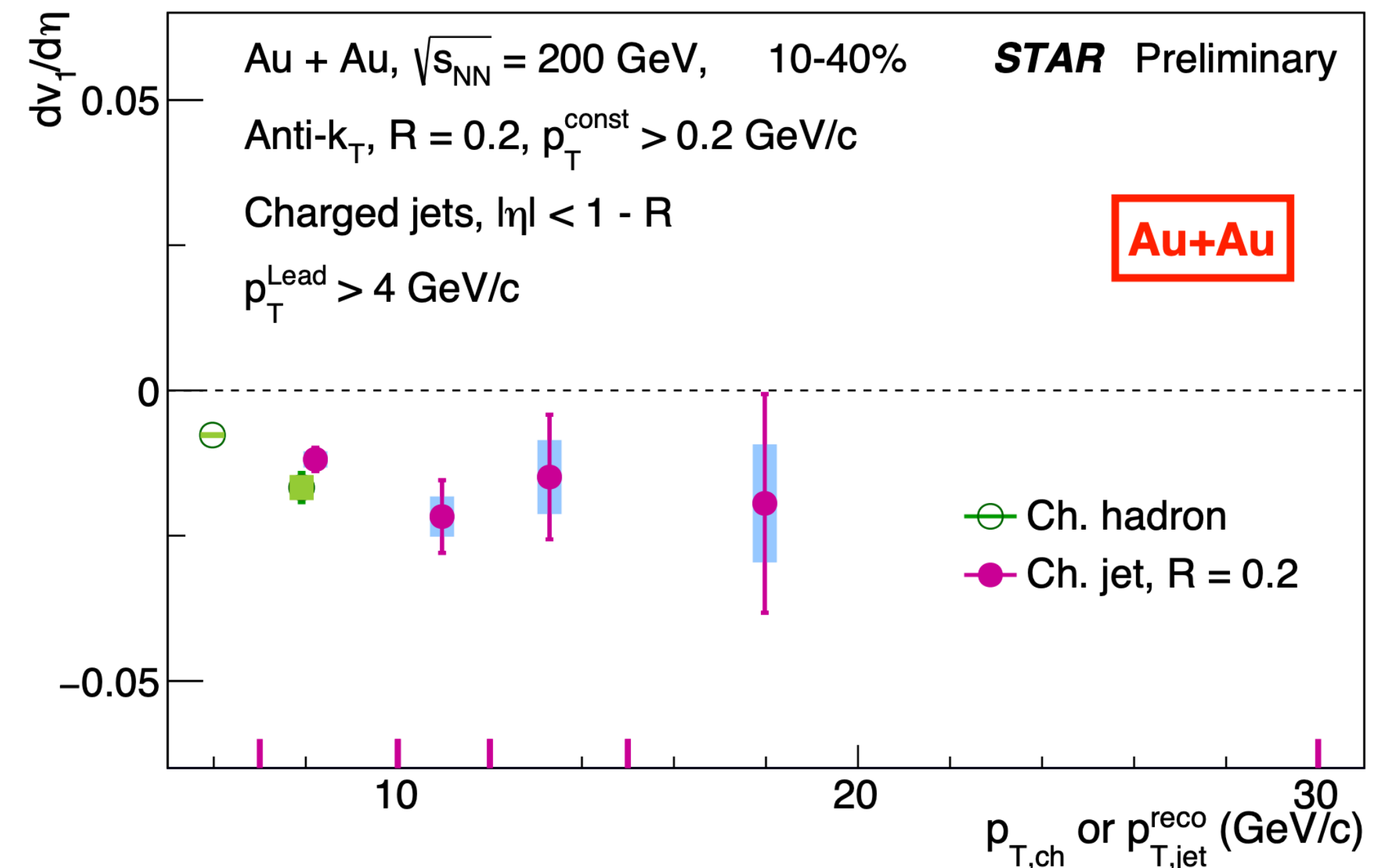
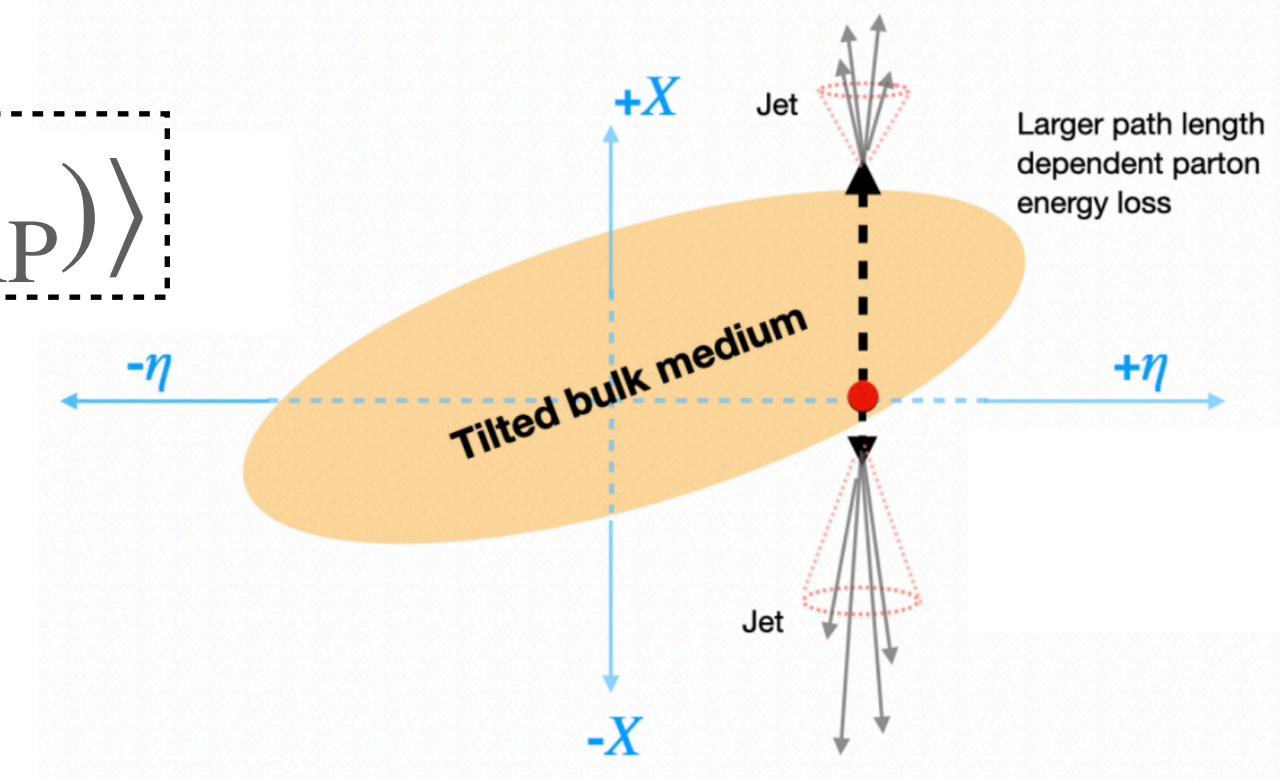
Bulk is tilted in heavy-ion collisions^{1,2} causing asymmetric paths for isotropically produced hard probes

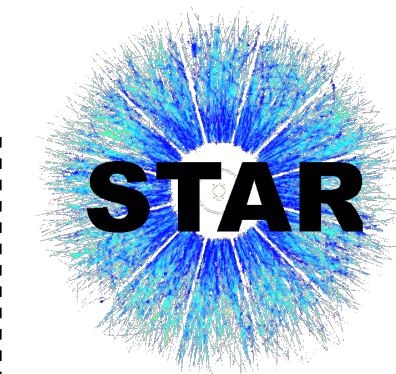
Jet v_1 : a new observable to probe *pathlength-dependent energy loss* in QGP

Clear v_1 signal for studied jet R , $p_T : 7 - 20 \text{ GeV}/c$, in **Au+Au** data, similar for **isobar** systems as well

Outlook: event-shape engineering with multiplicity fluctuations

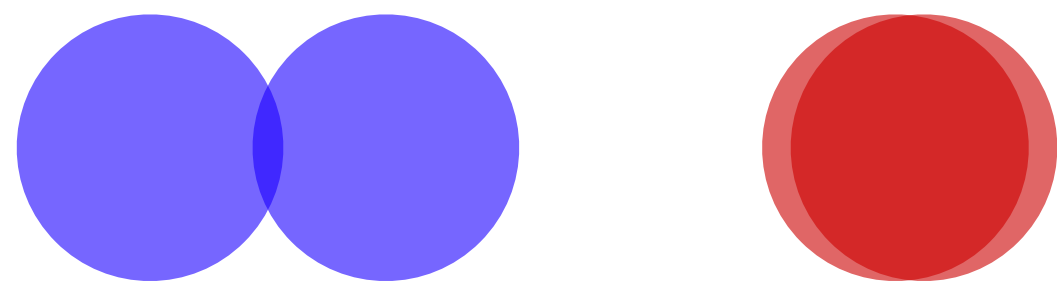
$$v_1(p_T, y) = \langle \cos(\phi - \Psi_{RP}) \rangle$$



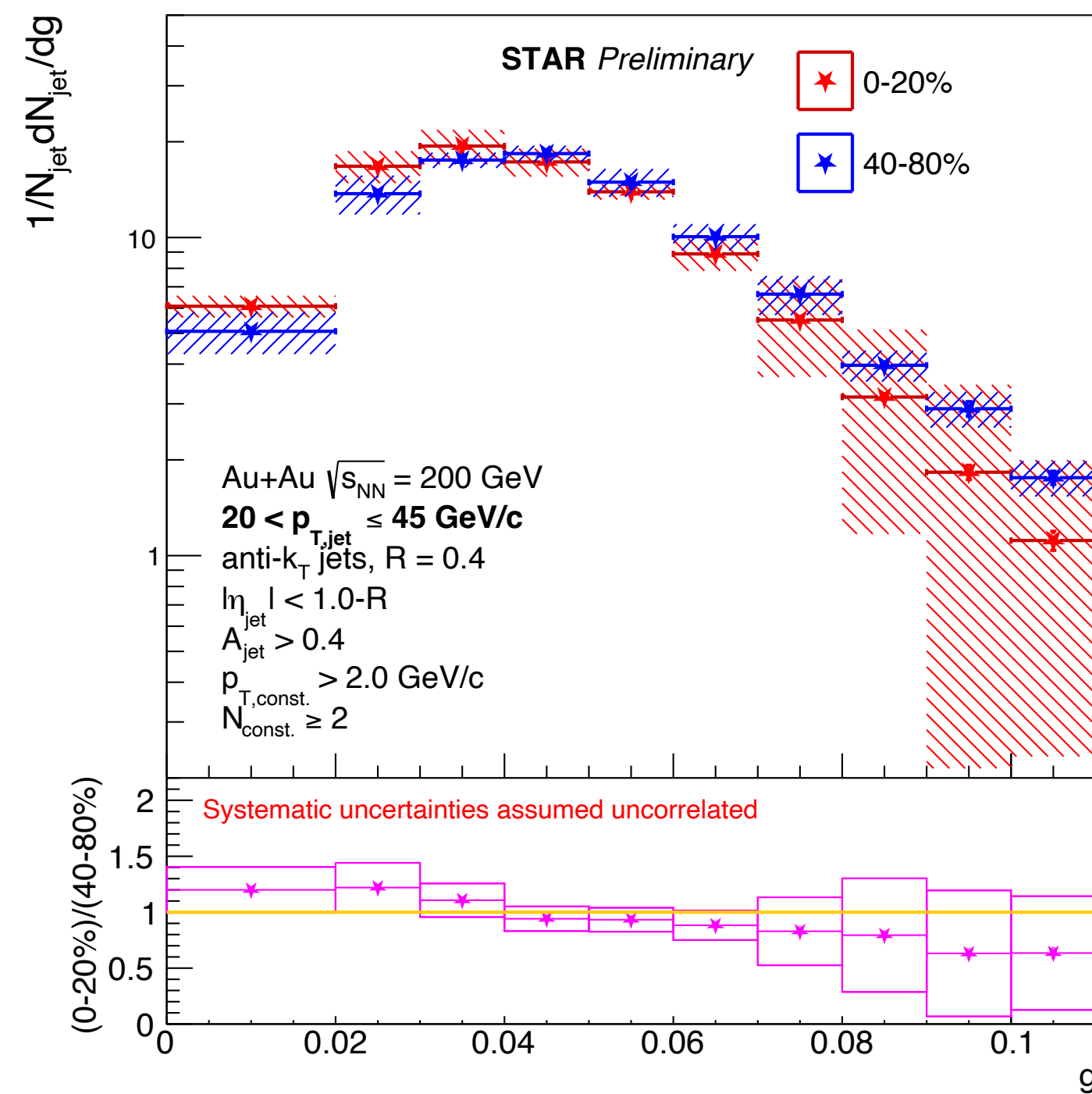


Generalized angularities

With MultiFold

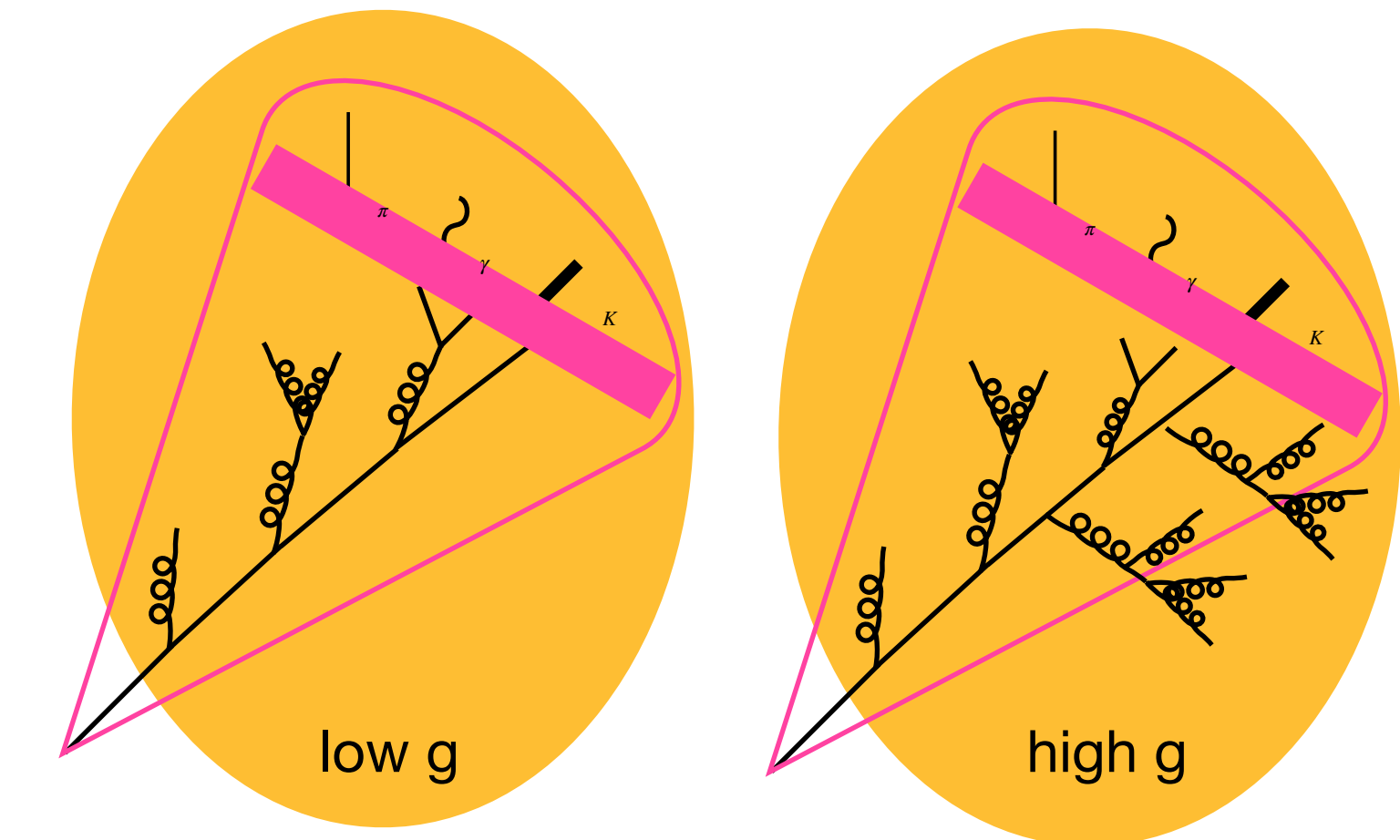


Data corrected using MultiFold in 7D



$$\lambda_{\beta}^{\kappa} = \sum_{\text{cons} \in \text{jet}} \left(\frac{p_{\text{T,cons}}}{p_{\text{T,jet}}} \right)^{\kappa} \Delta R (\text{cons, jet})^{\beta}$$

$$g = \lambda_1^1 = \frac{\sum_{\text{trk} \in \text{jet}} p_{\text{T,trk}} \Delta R}{p_{\text{T,jet}}}$$



Generalized angularities allow tunable contribution of momentum, angular scales in IRC safe way

With conservative systematic uncertainties *in biased population*, girth in peripheral and central collisions are consistent