STAR

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Wright Laboratory

Yale

Jets at STAR

39th Winter Workshop on Nuclear Dynamics

Jackson, Wyoming
February 12, 2024

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

How to understand jet evolution in vacuum

Two ways: the How and the What

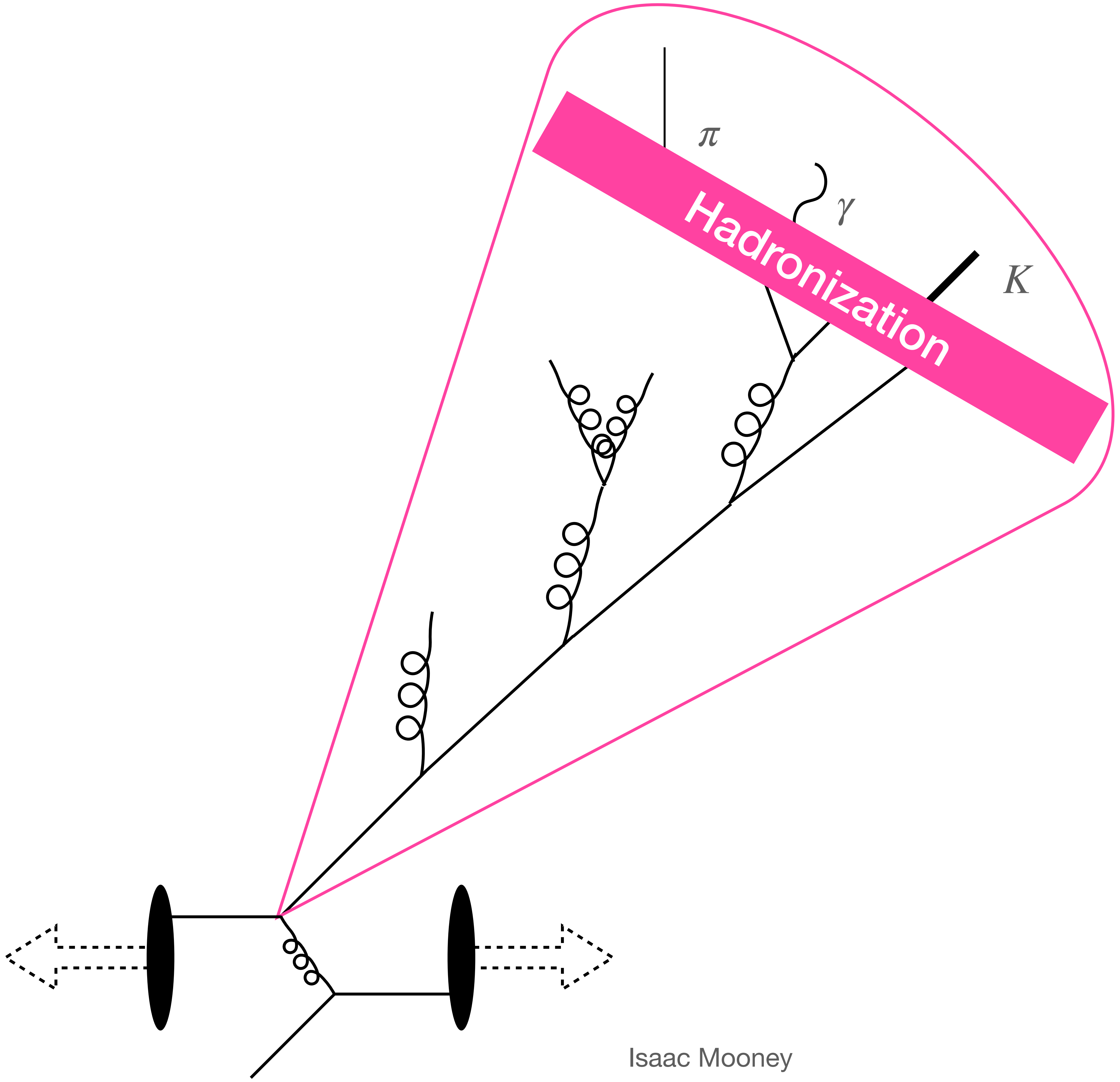

Image inspired by Kamel Khelifa Kerfa

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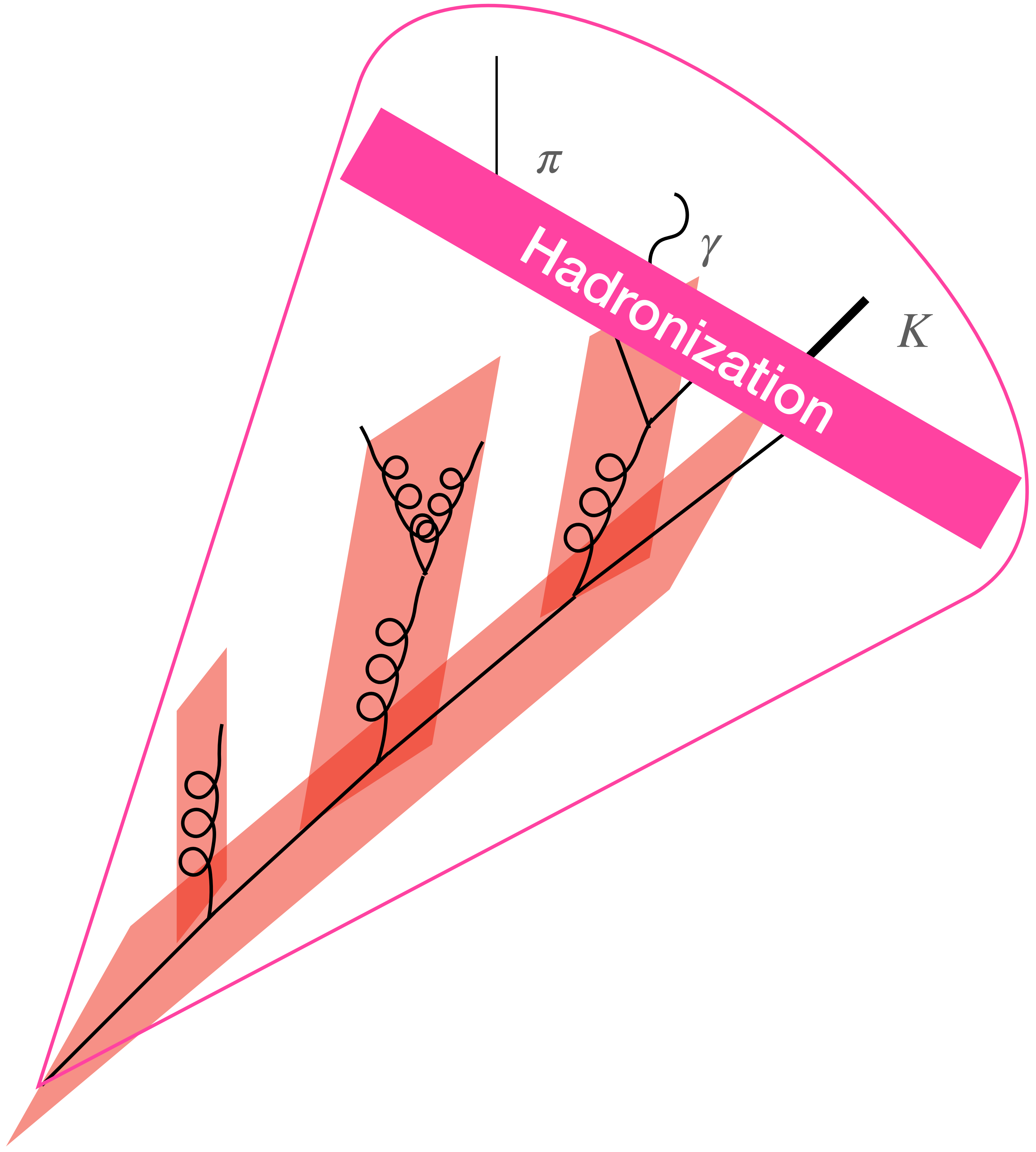
Energy flows



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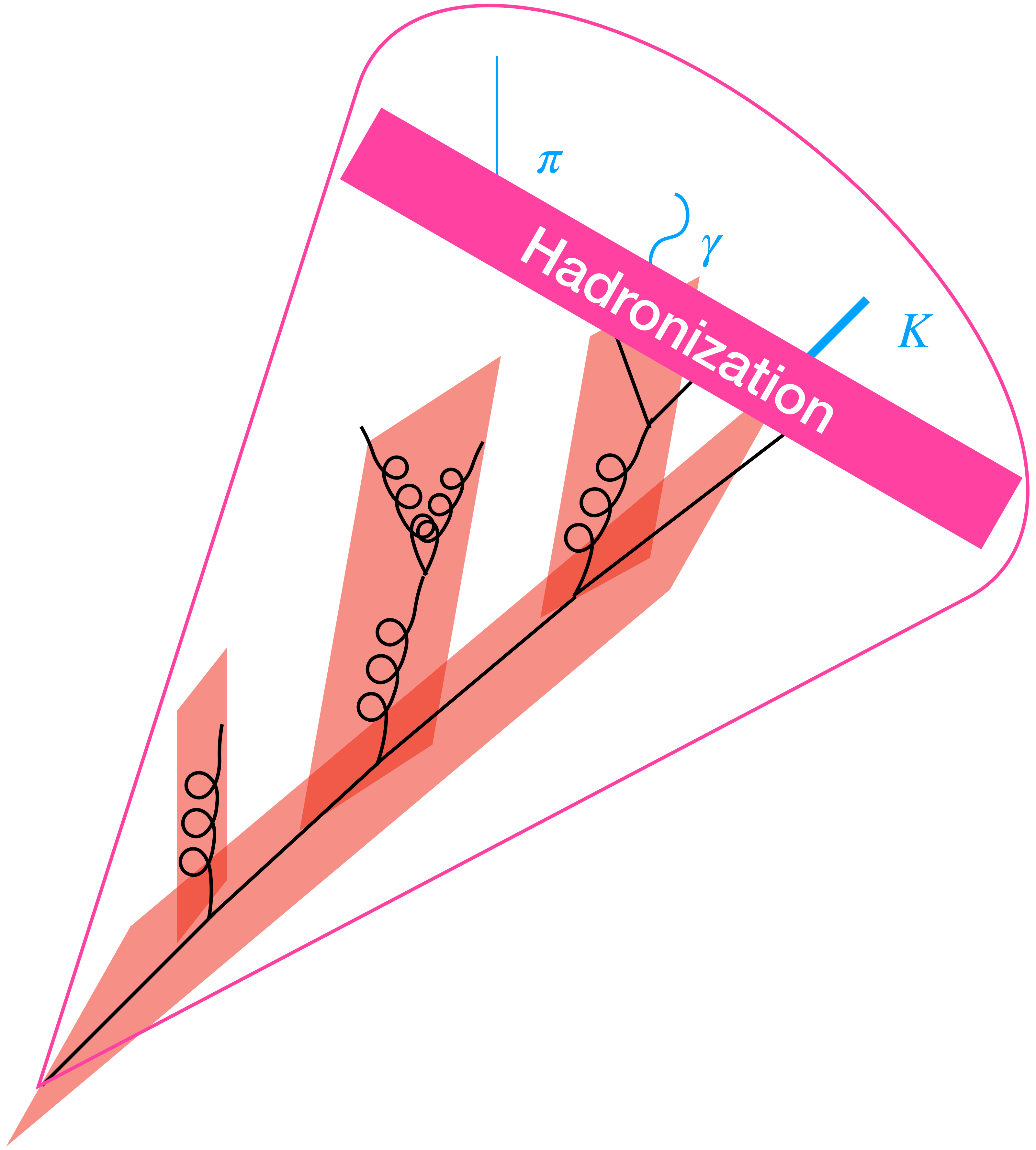
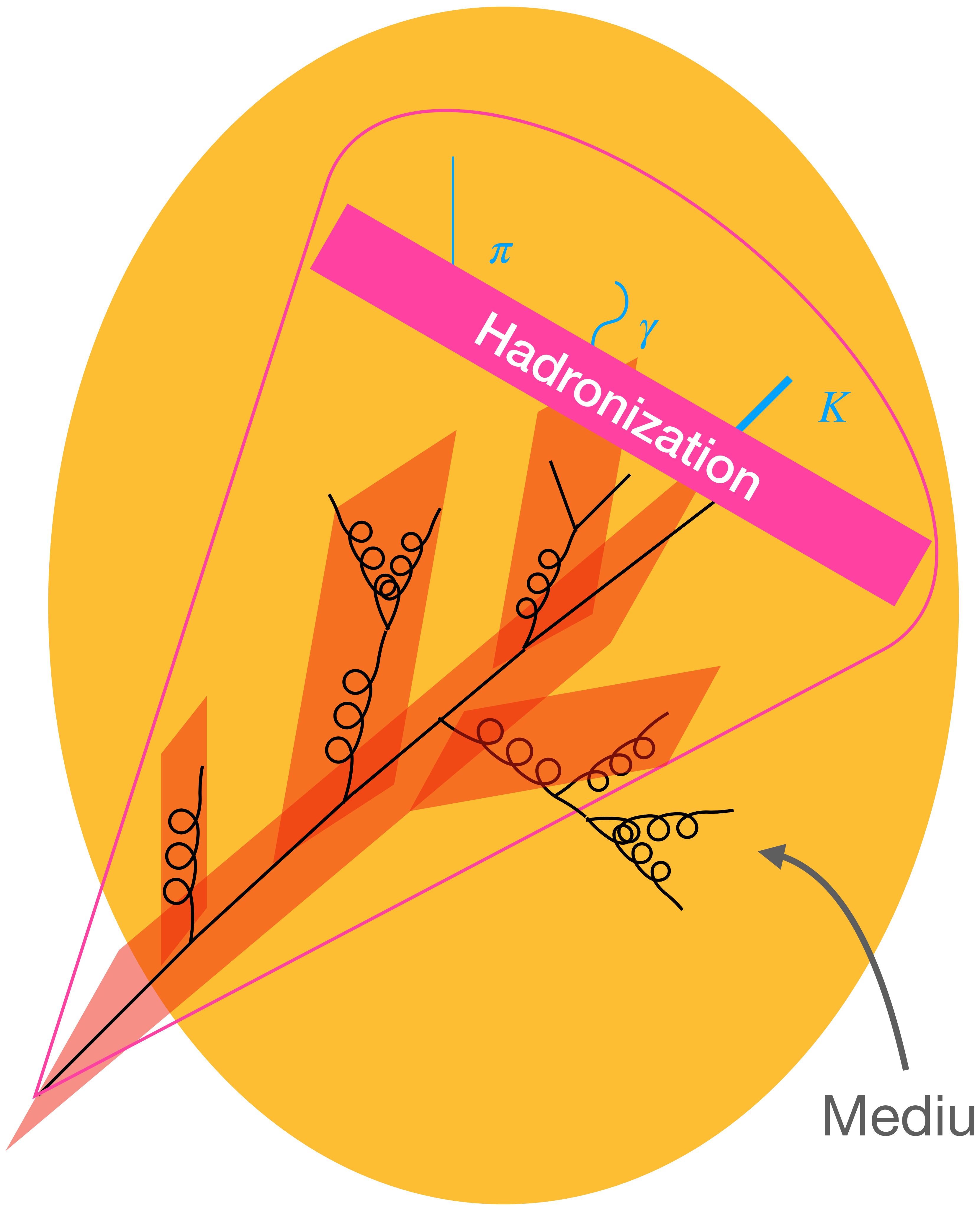


Constituent identity

How to understand jet evolution in media

Two ways: the How and the What

Energy flows



Constituent identity

Medium-induced gluon bremsstrahlung

How to understand jet evolution in media

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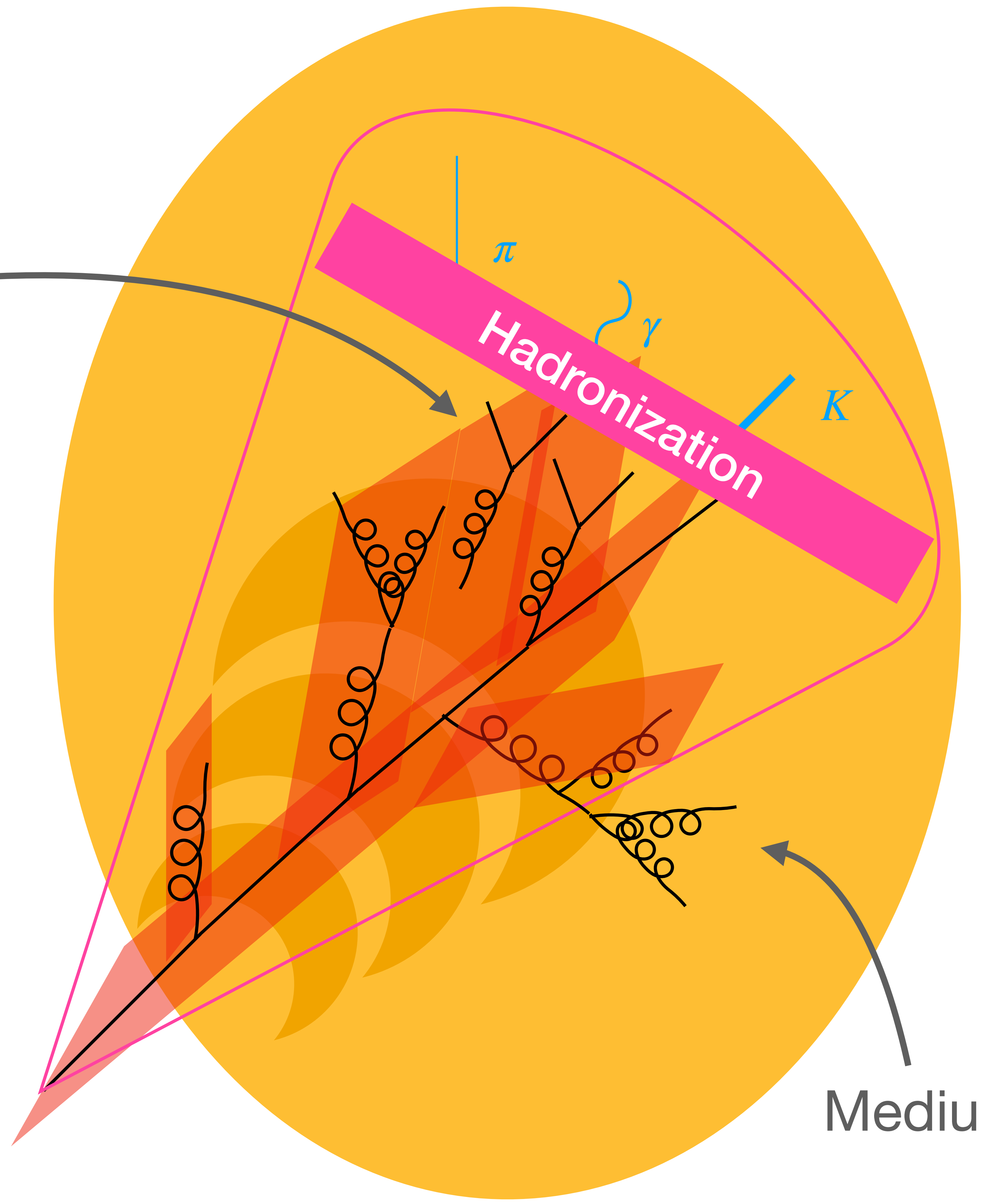
Jet-induced medium response

Energy flows



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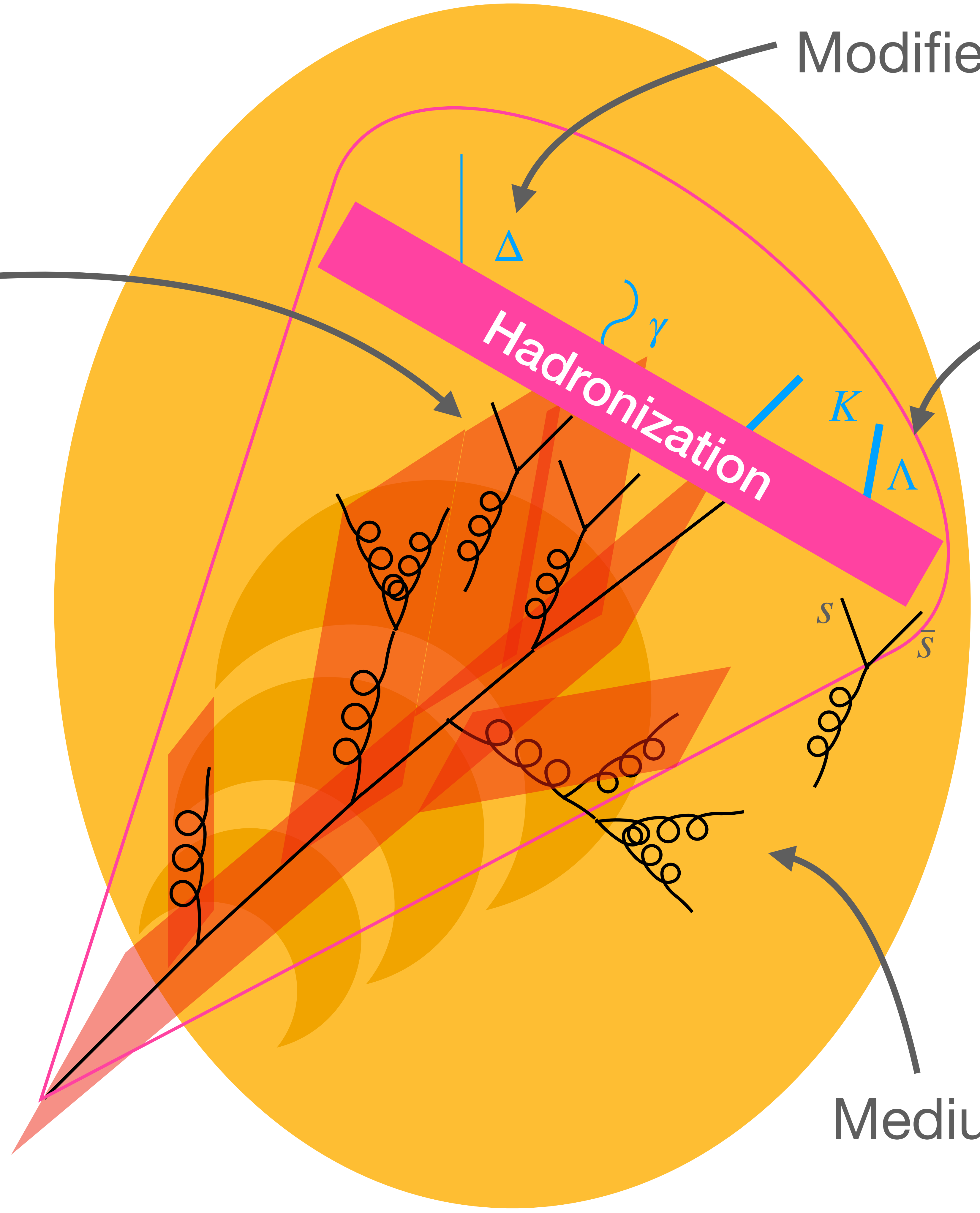

Constituent identity

Solenoidal Tracker at RHIC (STAR)

Main subdetectors

Relativistic Heavy Ion Collider (RHIC)
collides *p*+*p*, *p*+Au, O+O, Zr+Zr, Ru+Ru, Au+Au, etc.
beams at $\sqrt{s_{NN}}$ = 200 GeV, etc.

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

Barrel Electromagnetic Calorimeter (BEMC) [$|\eta| < 1$]:
neutral energy deposits + provides online trigger
(Jet Patch: $E_T^{patch} > 7.4$ GeV, High Tower: $E_T > 4.2$ GeV)

Inner Beam-Beam Counter (iBBC) [$3.4 < |\eta| < 5.0$]:
forward detector,
east/Au-going side activity used as centrality proxy in *p*+Au

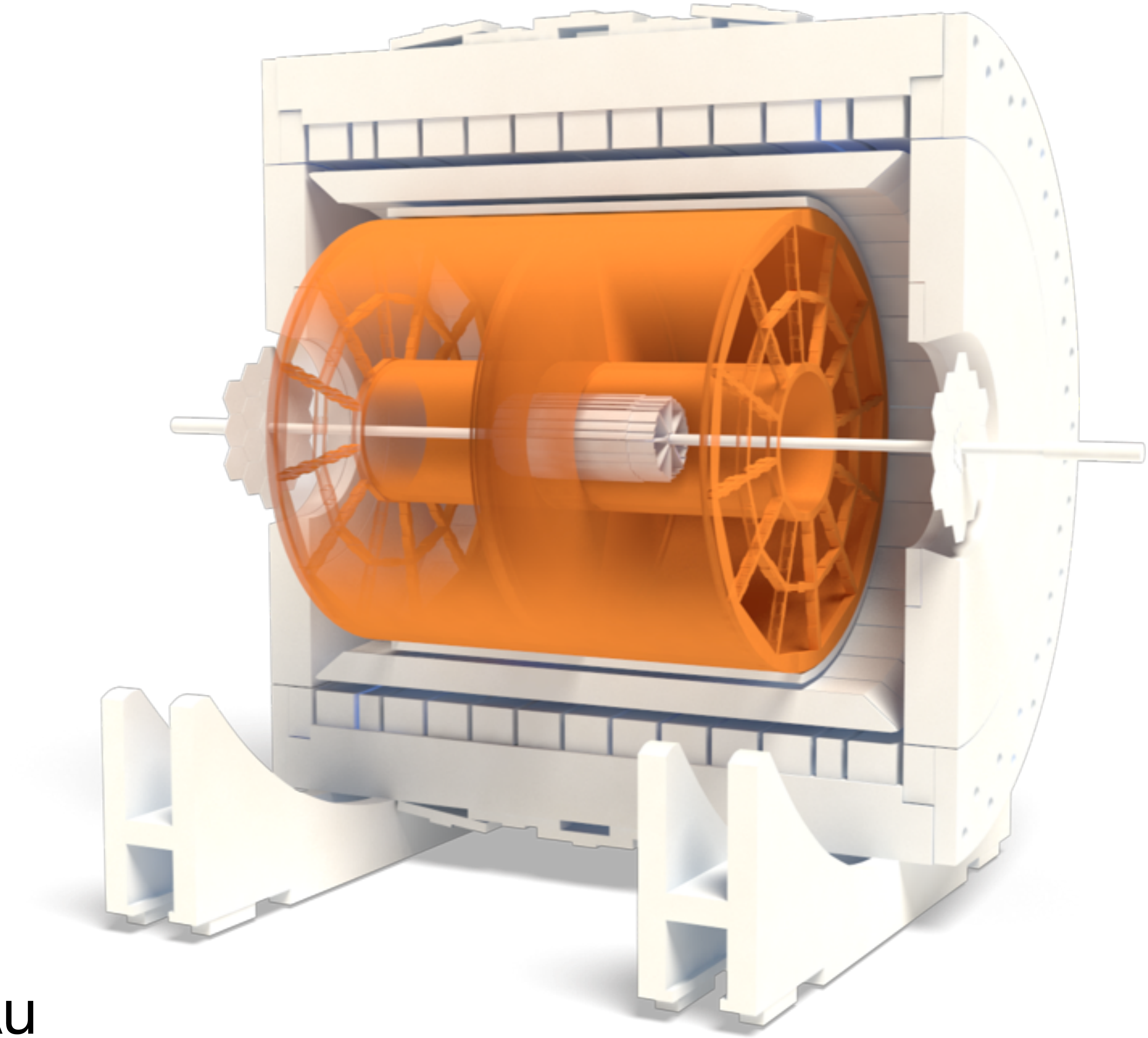

Image: NSWW

Solenoidal Tracker at RHIC (STAR)

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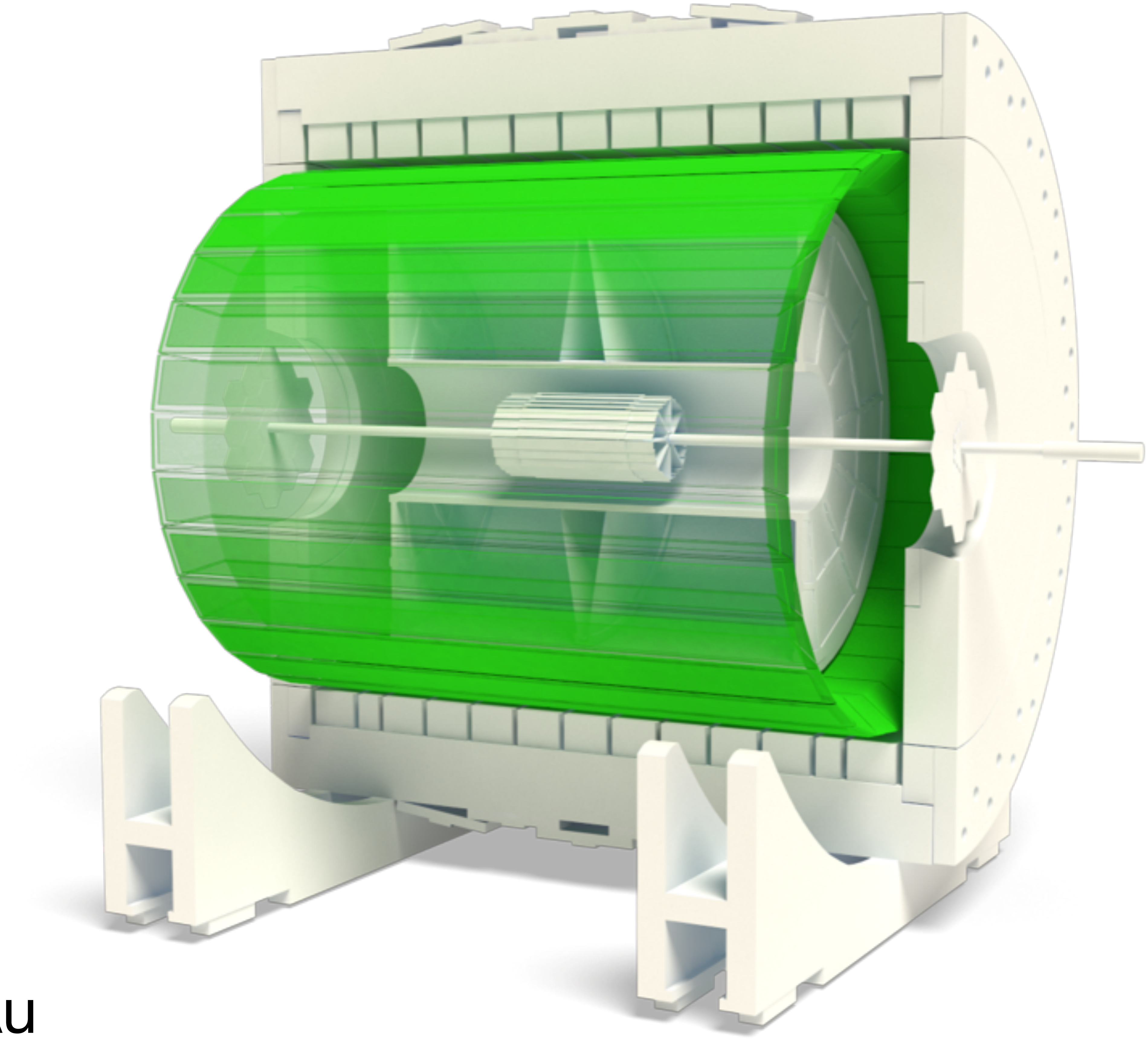

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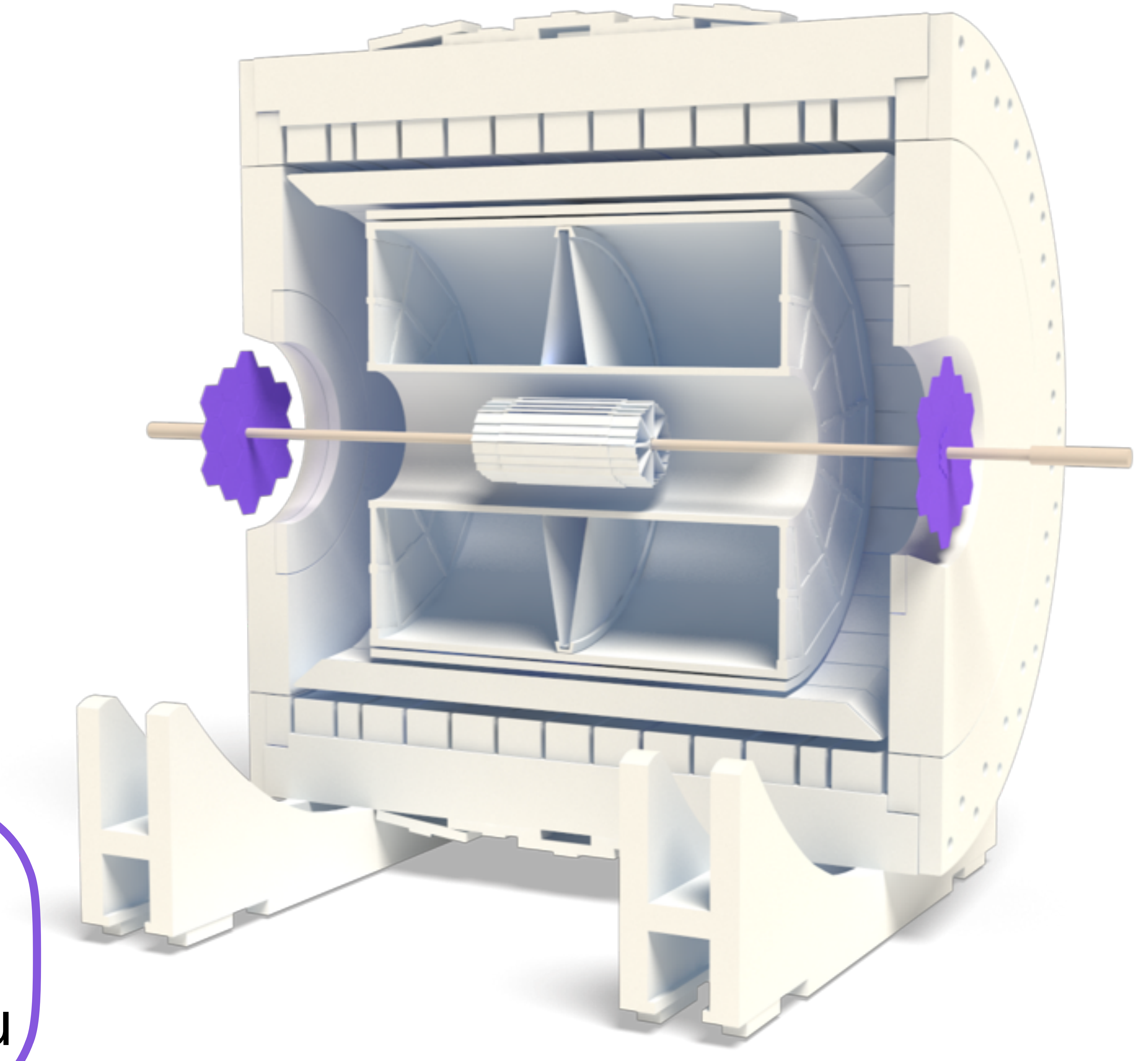

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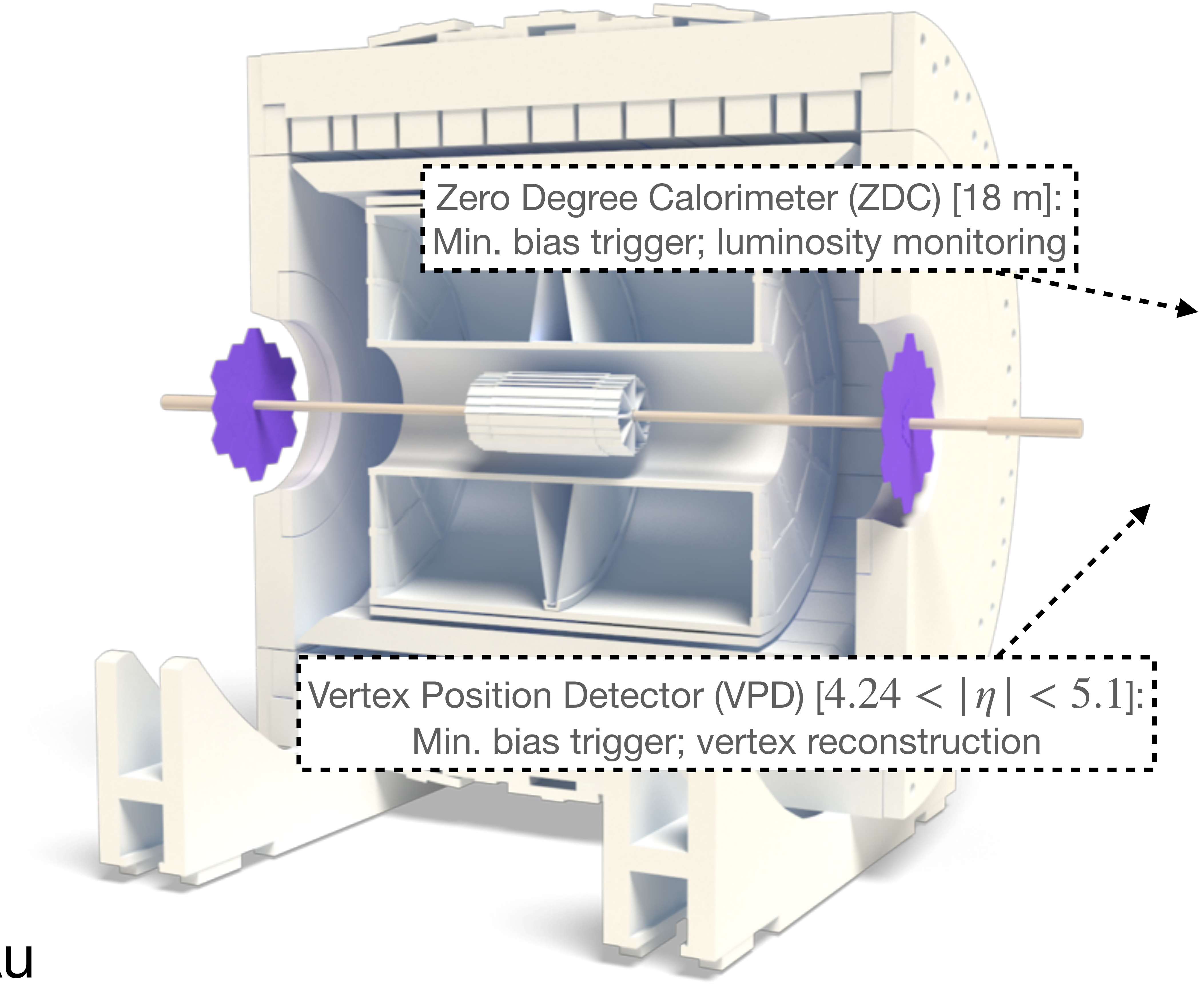

Precision QCD; exploring the Lund plane with *multi-dimensional jet substructure*

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

Energy flows

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

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*

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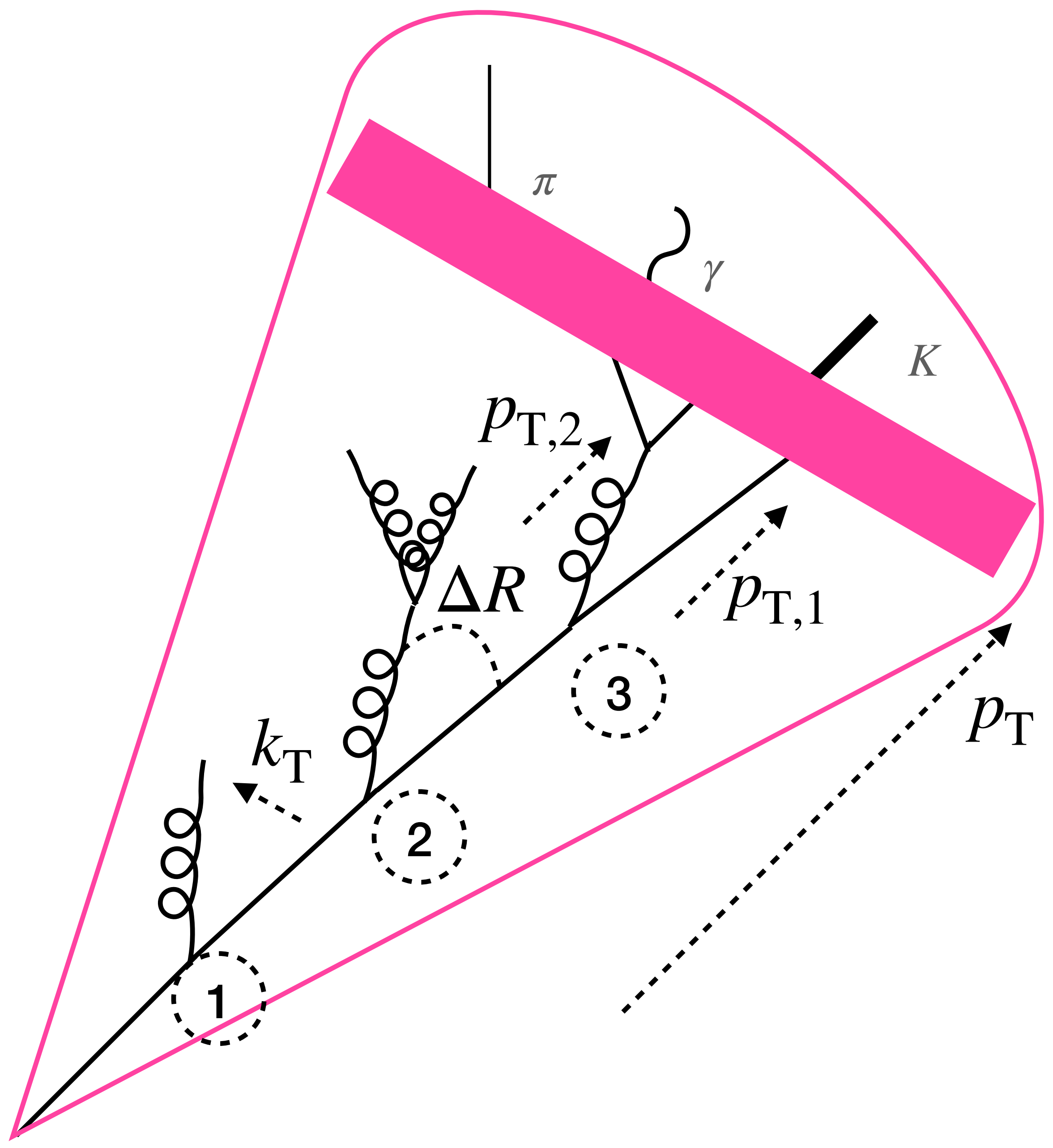
Jet substructure



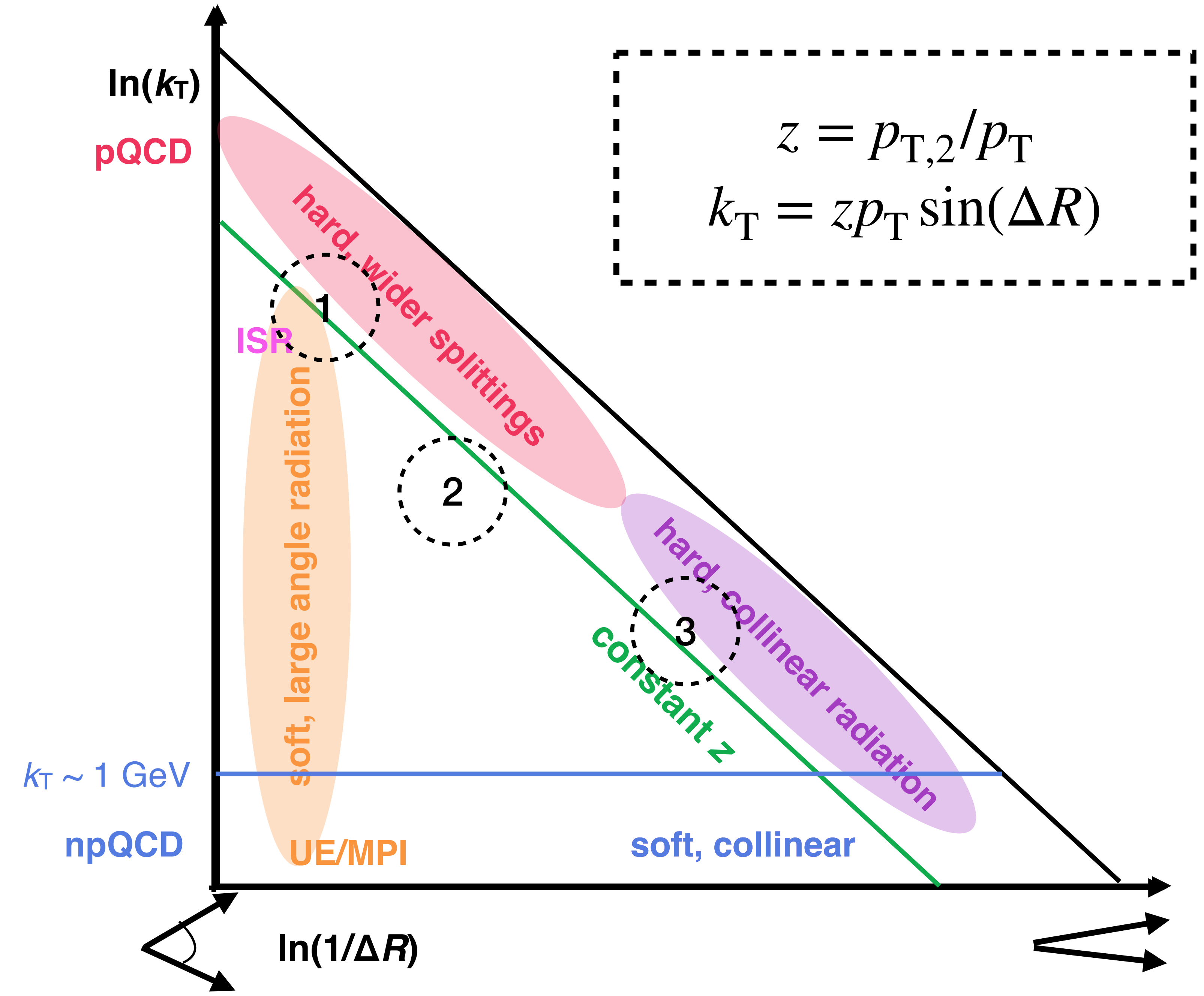
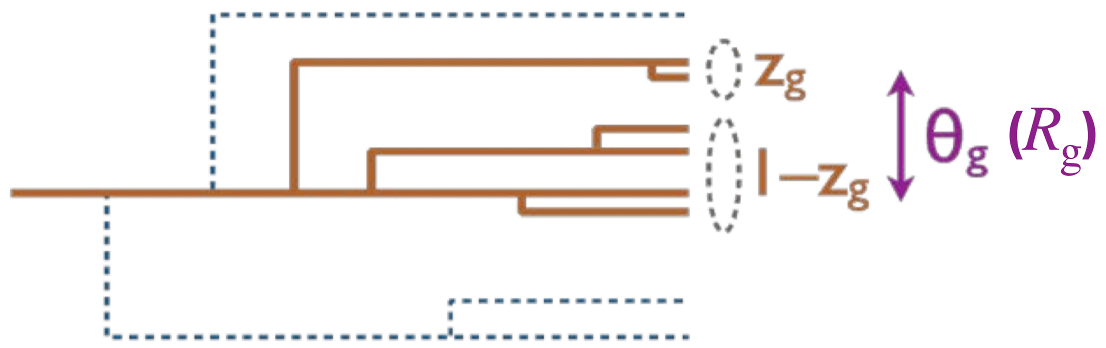


Image: Laura Havener, modified from Andrews et al., J.Phys.G 47 (2020) 6, 065102

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

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



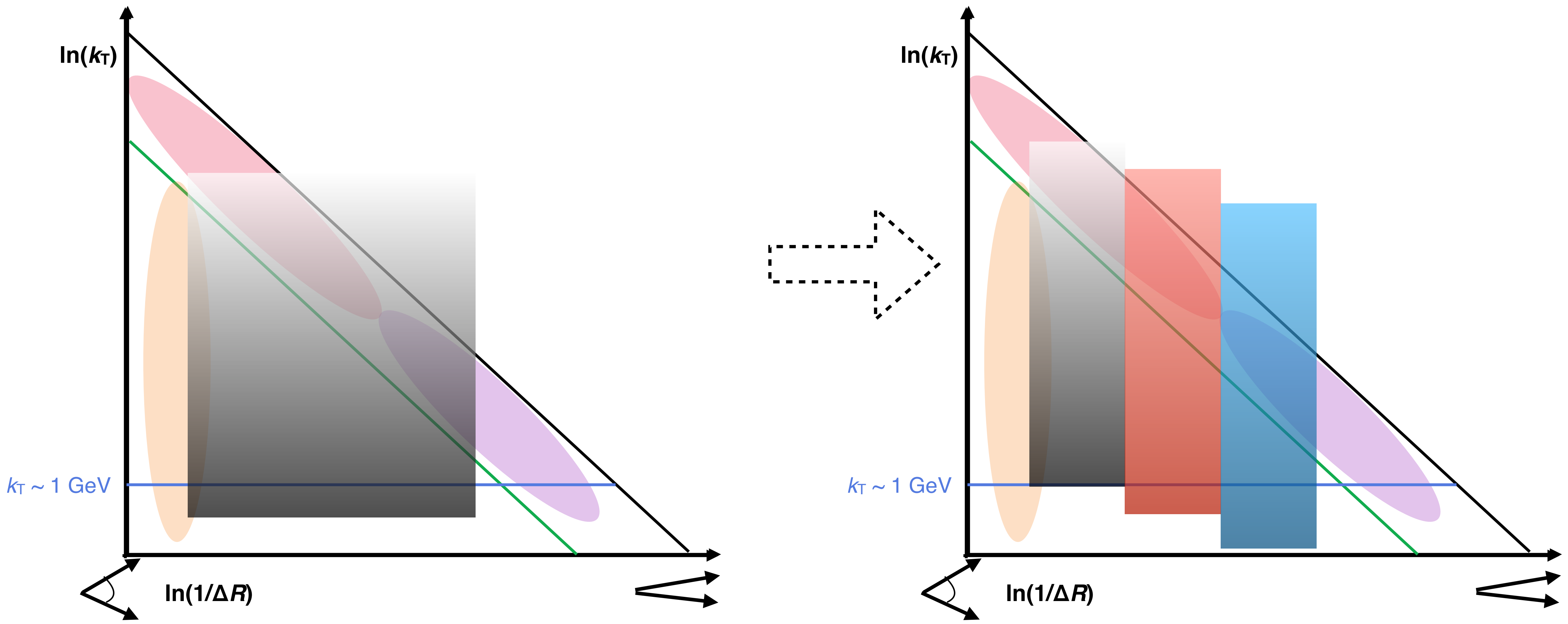
$$M_g = \left|\sum_{i \in J_g} p_i\right|$$

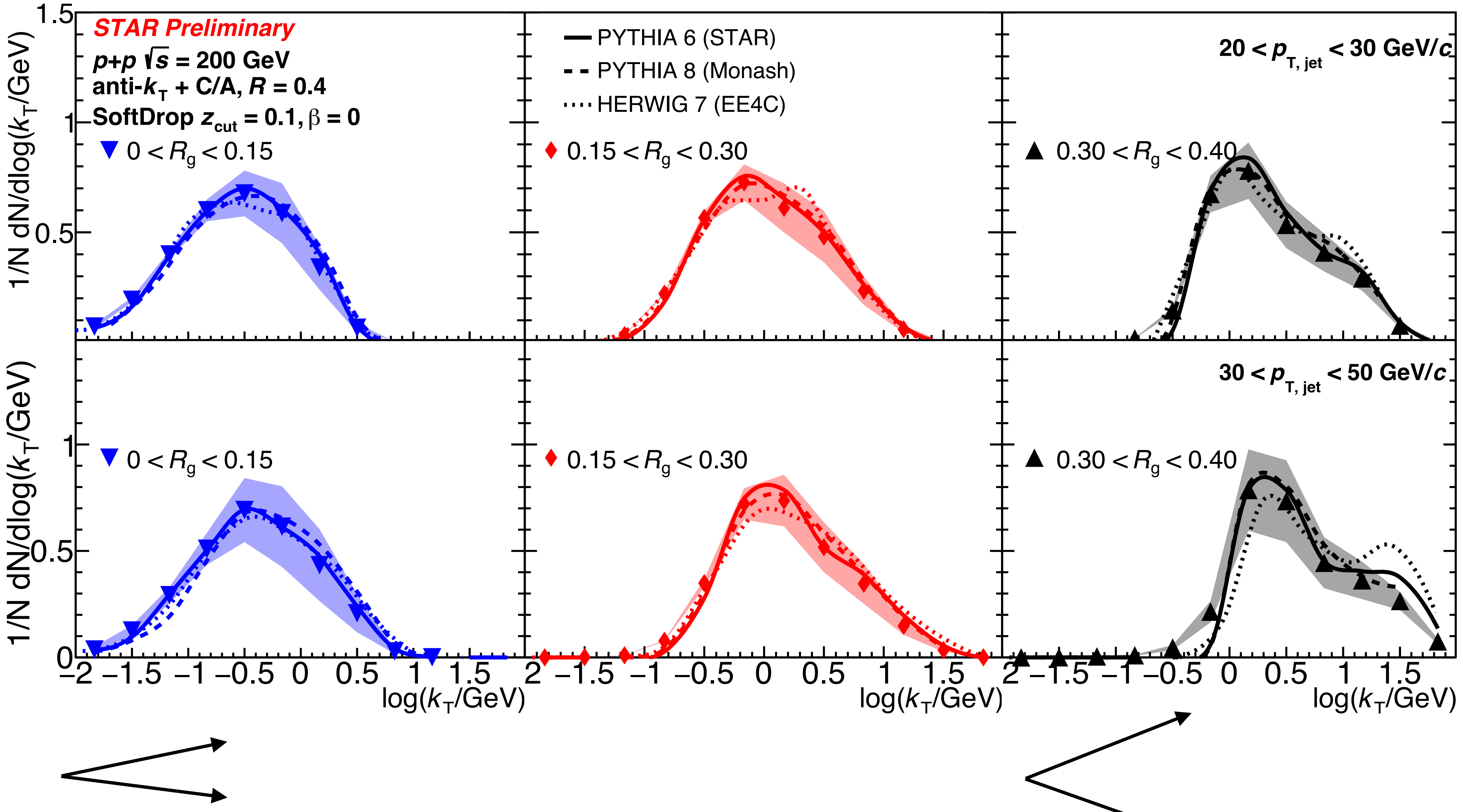
Image: Larkoski, Marzani, Thaler, Xue, PRL 119 (2017) 13, 132003

SoftDrop[1] grooming: reduce soft non-perturbative contribution
→ better theoretical control

[1]Larkoski, Marzani, Soyez, Thaler, JHEP 05 (2014), 146

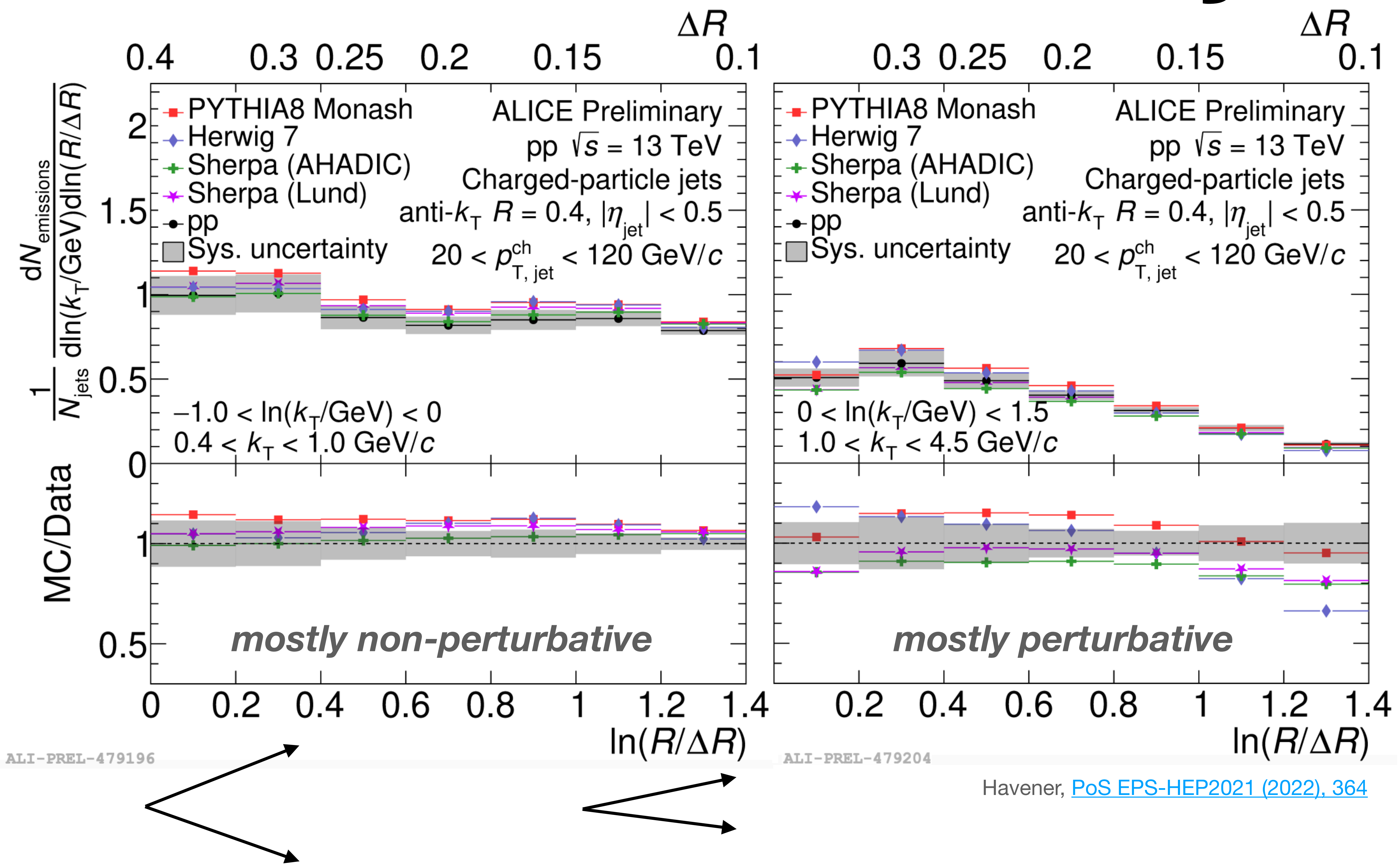
Multi-dimensional jet substructure



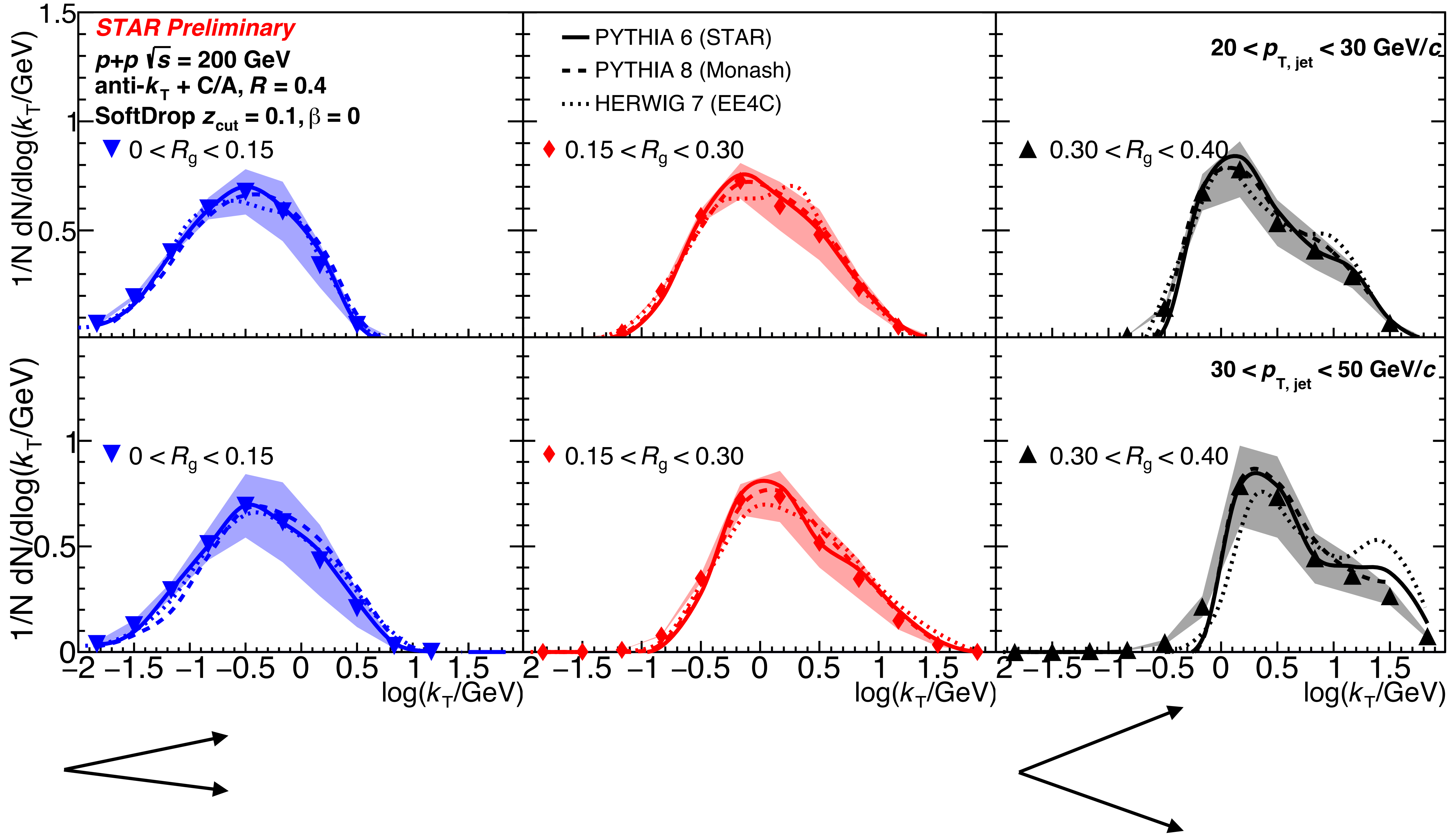


- Now able to make slices in the Lund Plane → more stringent tests of Monte Carlo (MC) models
- Observe: wider splits are harder. MCs in good agreement.

Multi-dimensional jet substructure



Havener, PoS EPS-HEP2021 (2022), 364



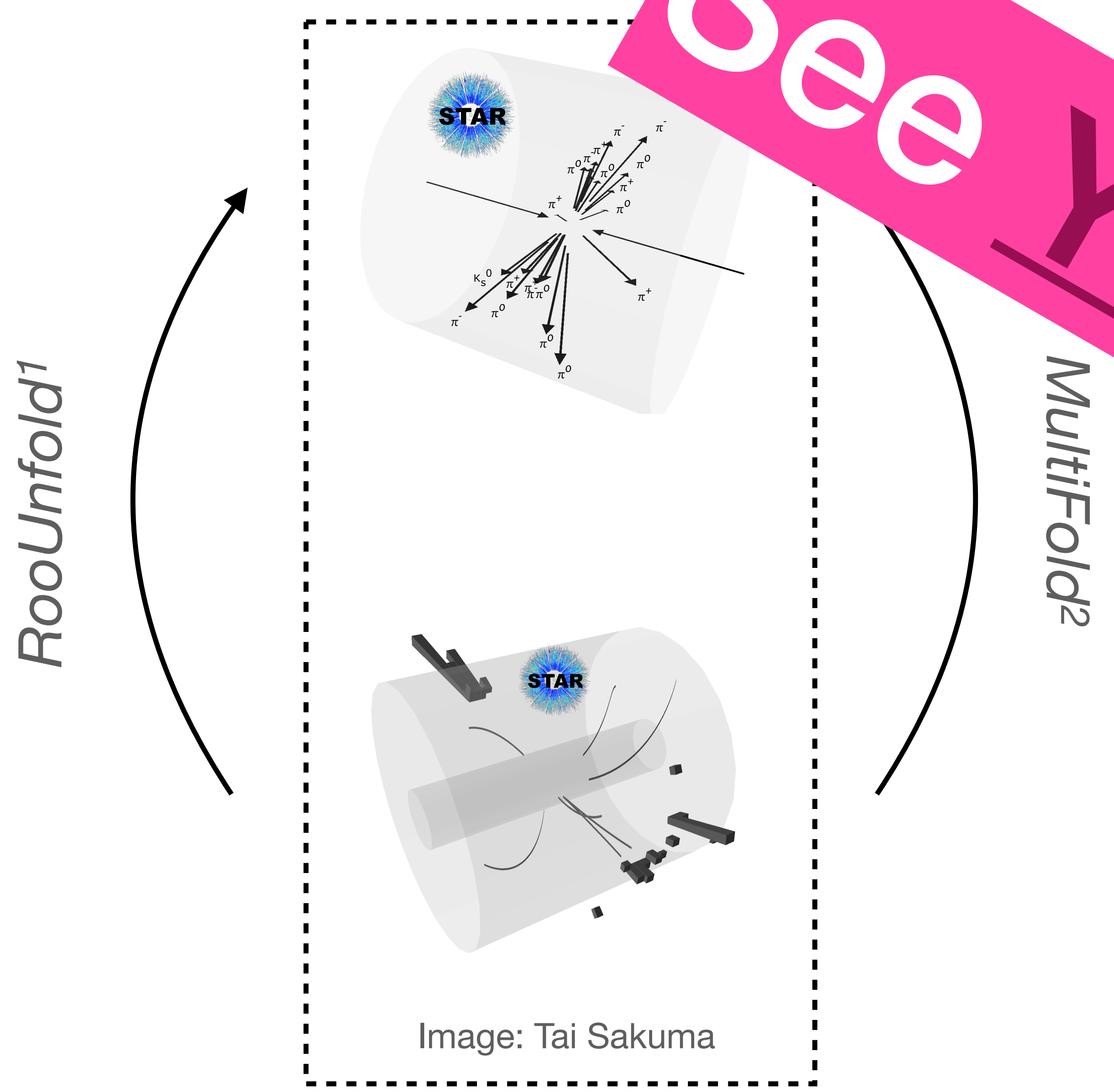
- Now able to make slices in the Lund Plane → more stringent tests of Monte Carlo (MC) models

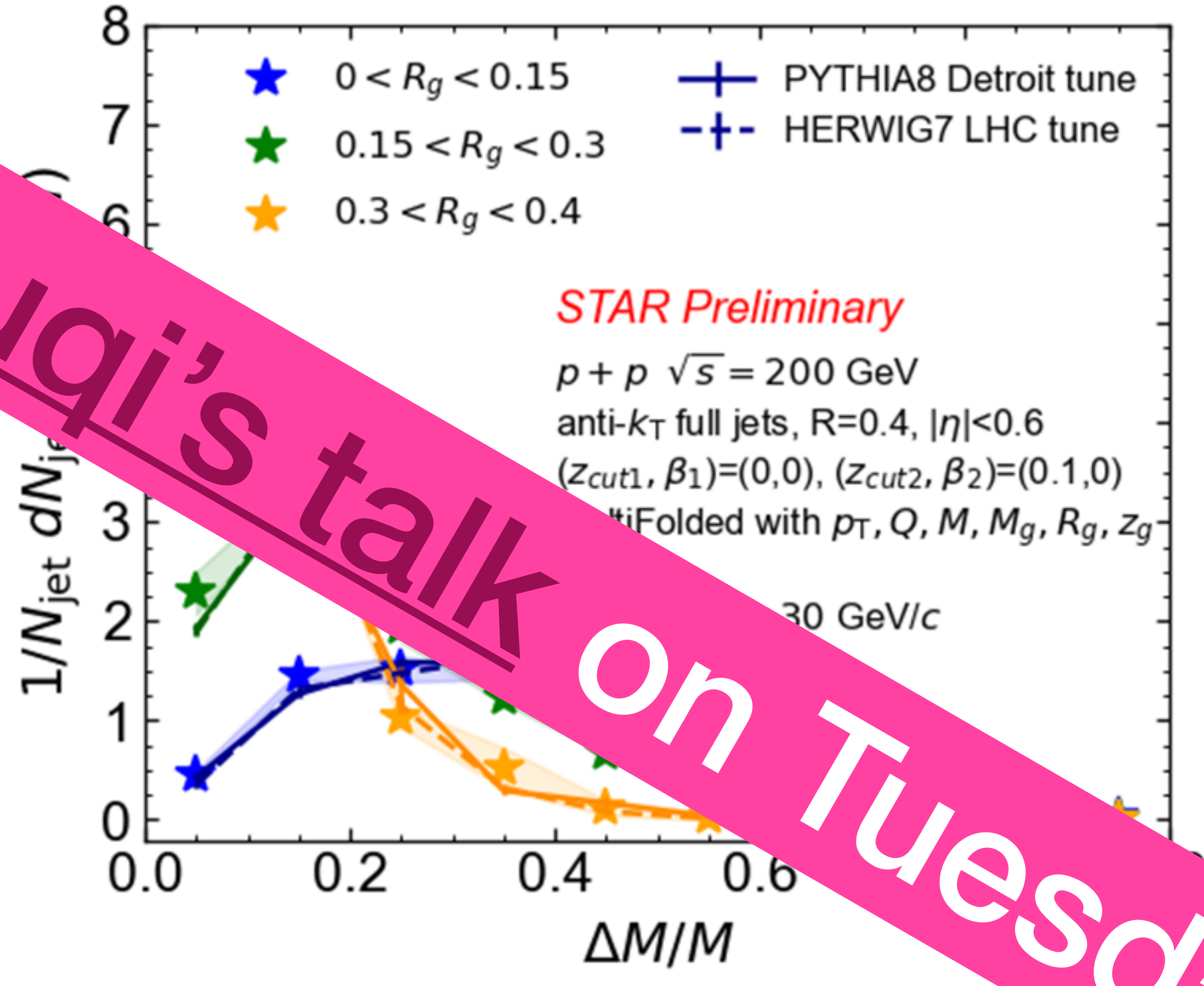
- Observe similarly in ALICE: high-k_T splits are wider. But tension with models for narrow splits with high k_T

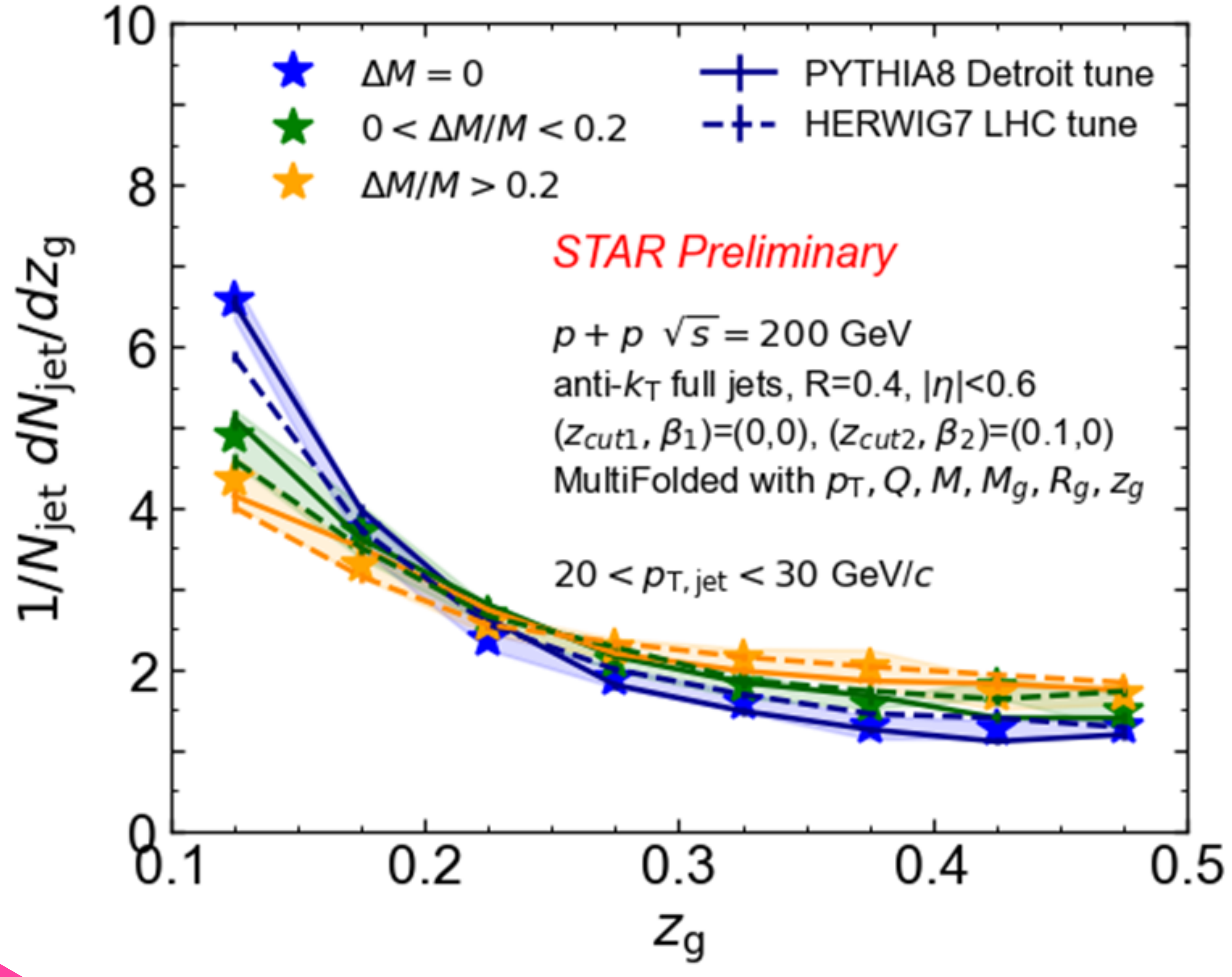
N-dimensional observables

With MultiFold

$\Delta M = M - M_g$







See Youqi's talk on Tuesday at 11 AM!

- First application of MultiFold at RHIC
- Consistent with angular ordering + kinematic constraint b… early and late time splittings

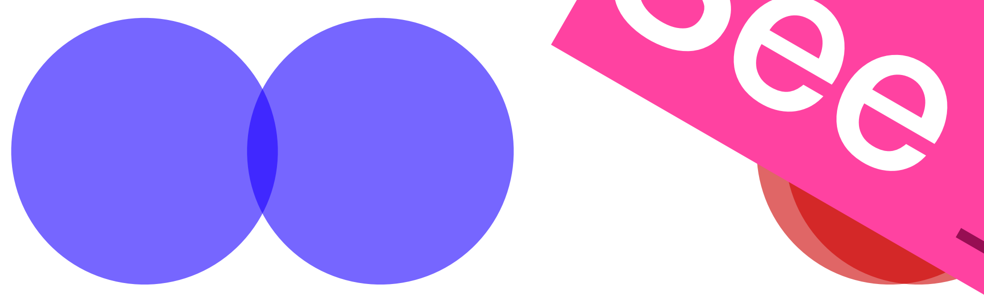
[1]D'Agostini, arXiv:1010.0…
[2]Andreassen, Komiske, Metodiev, Nachman, Thaler, PR… 124 (2020) 18, 182001

Generalized angularities in AA

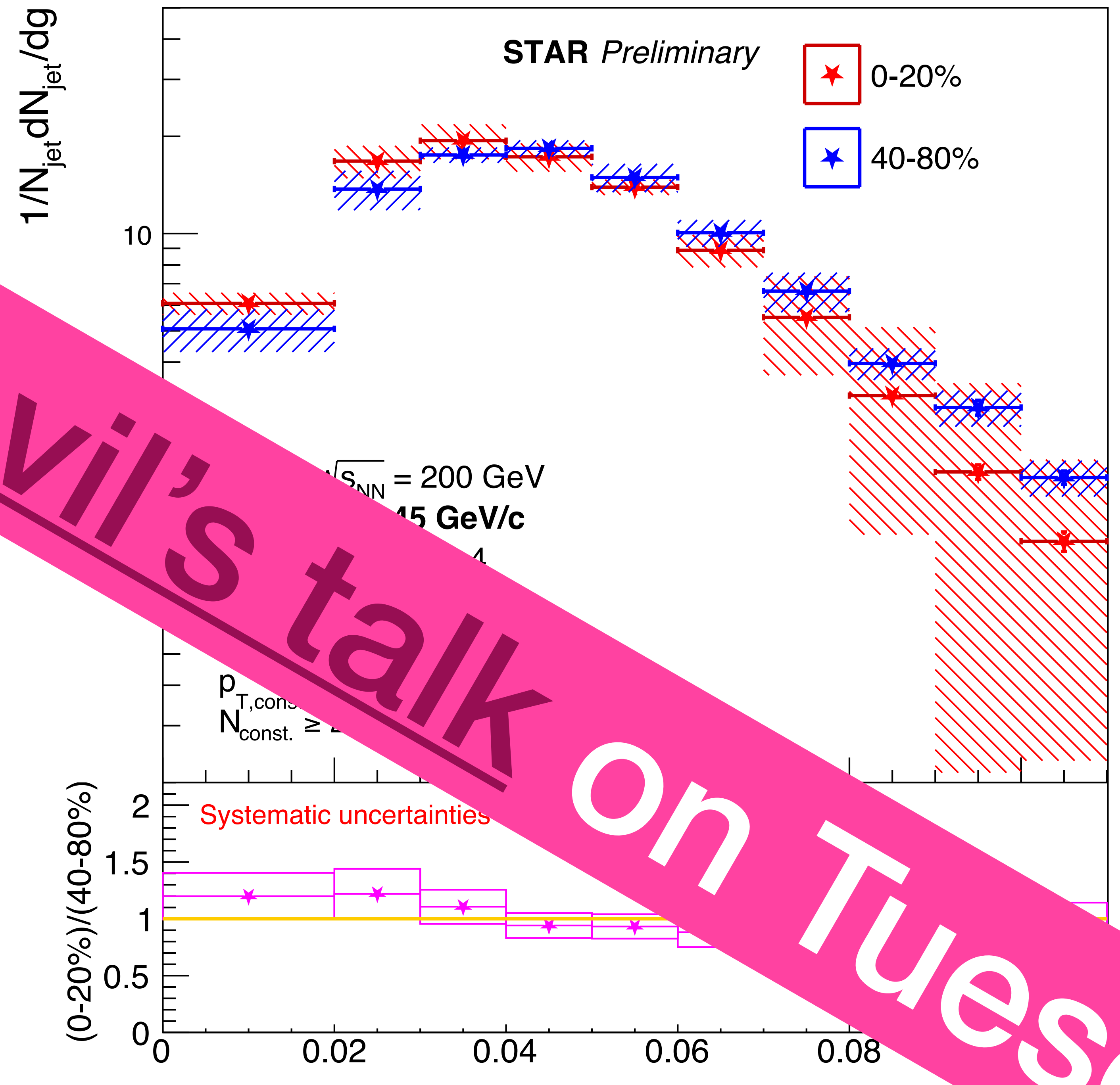
With MultiFold

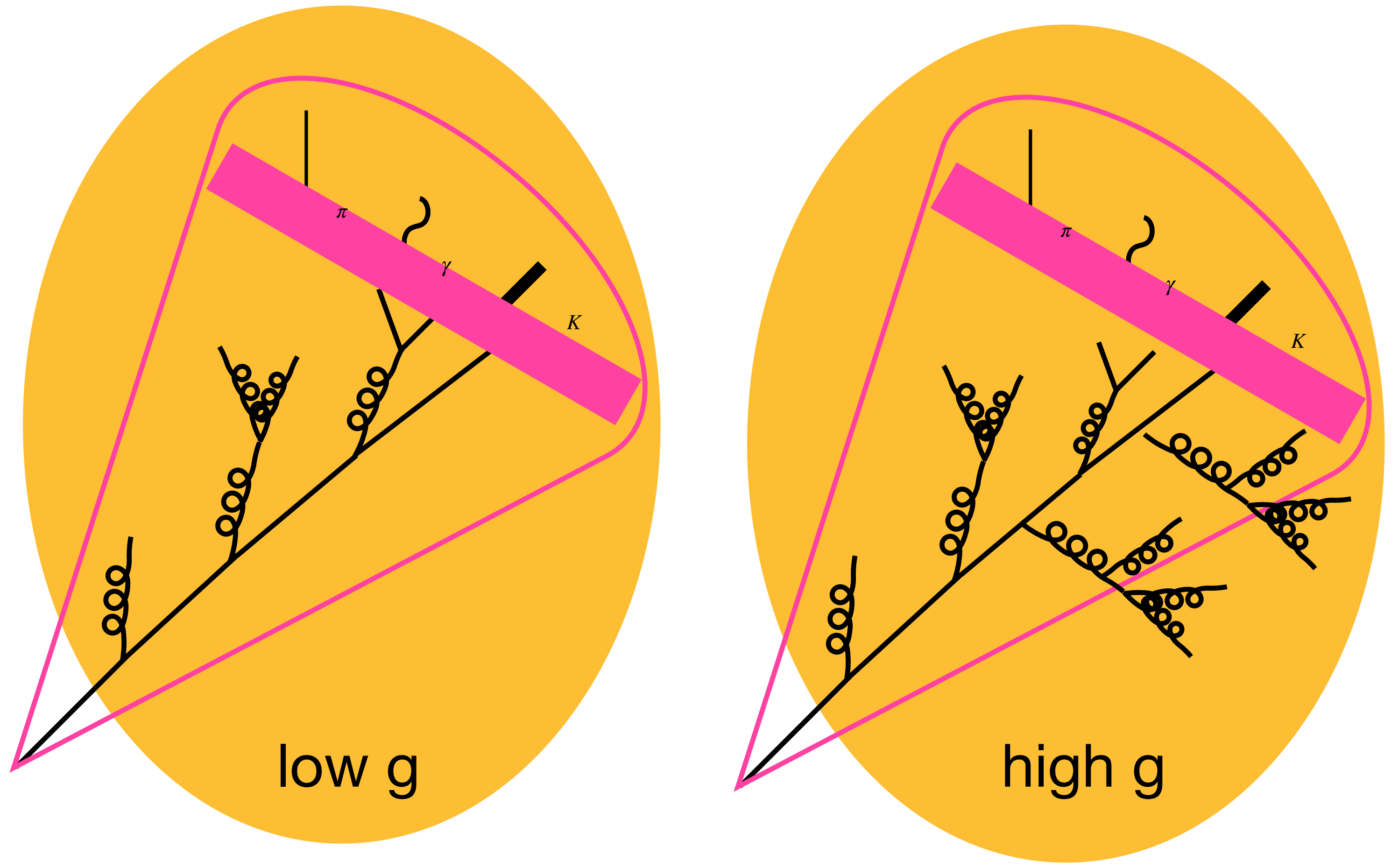
$$\lambda_\beta^\kappa = \sum_{\text{cons}\in\text{jet}} \left(\frac{p_{T,\text{cons}}}{p_{T,\text{jet}}}\right)^\kappa \Delta R\,(\text{cons},\text{jet})^\beta$$

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



Data corrected using MultiFold in 7D





See Sevil's talk on Tuesday at 11:30 AM!

- Generalized angularities allow tunable contributi... mentum, angular scales in IRC safe way
- With conservative systematic uncertainties *in biased pop.*, g... ipheral and central collisions are consistent

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

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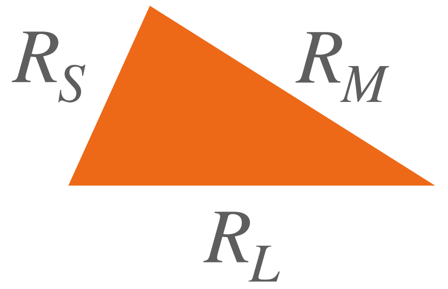
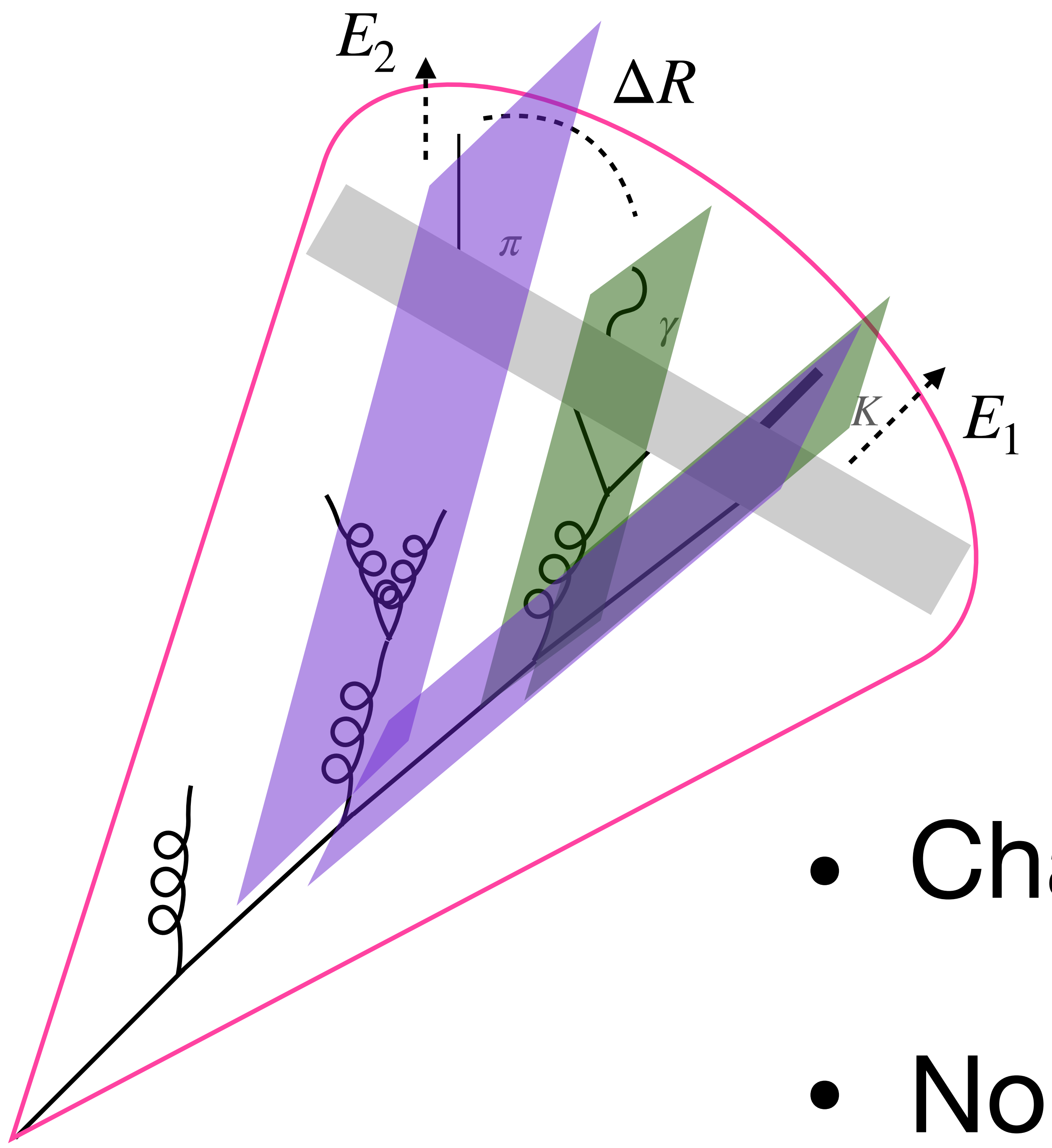
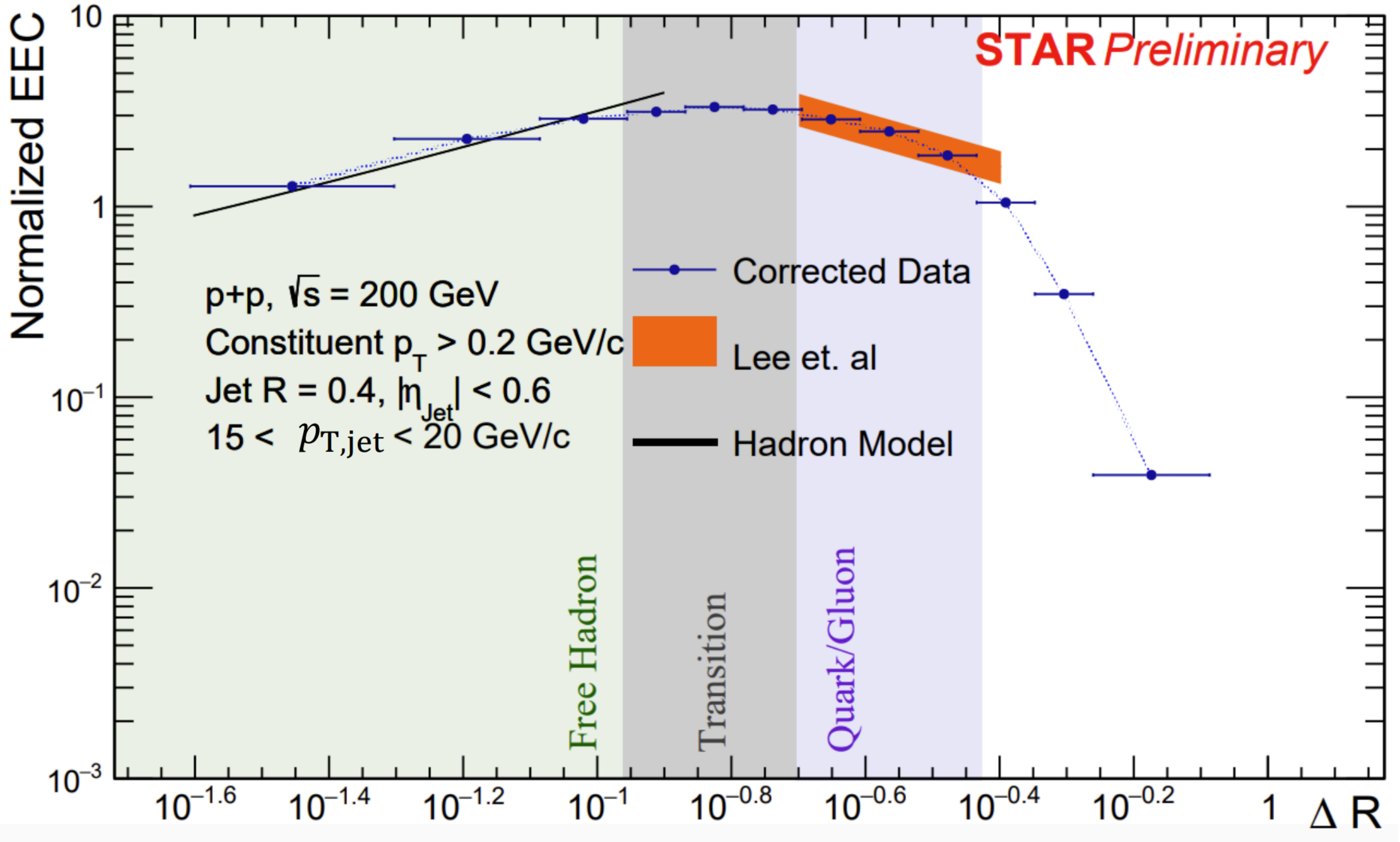
Energy correlators



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



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



- Change in scaling when virtuality $\sim p_T R_L \sim \Lambda_{QCD}$ so $R_L^{\mathrm{transition}} \propto 1/p_T$
- No need to recluster or remove npQCD contributions
- Simple scaling in the hadronic and partonic regimes

[1]Basham, Brown, Ellis, Love, PRL 41 (1978), 1585
[2]Chen, Moult, Zhang, Zhu, PRD 102 (2020) 5, 054012
[3]Komiske, Moult, Thaler, Zhu, PRL 130 (2023) 5, 051901

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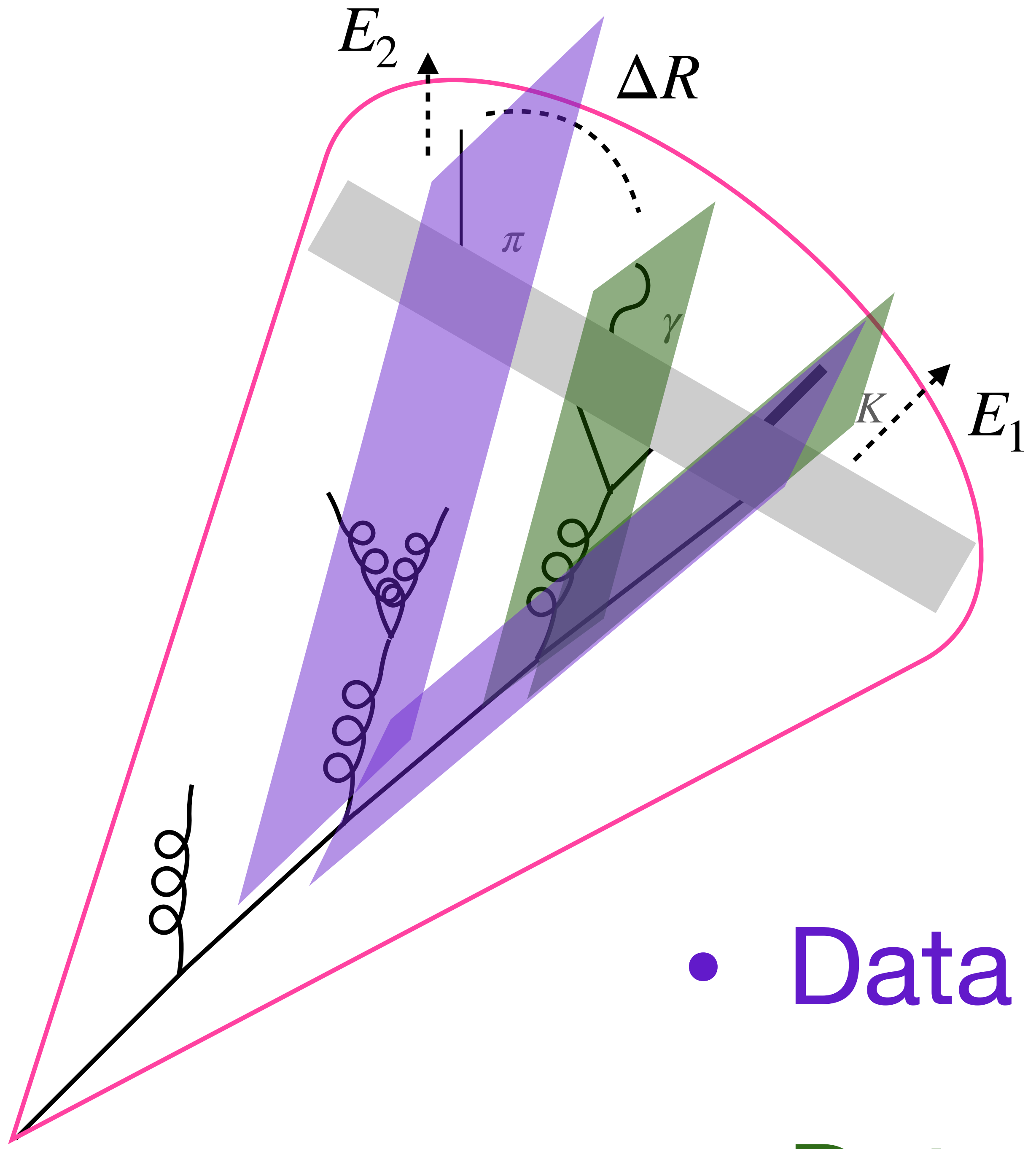

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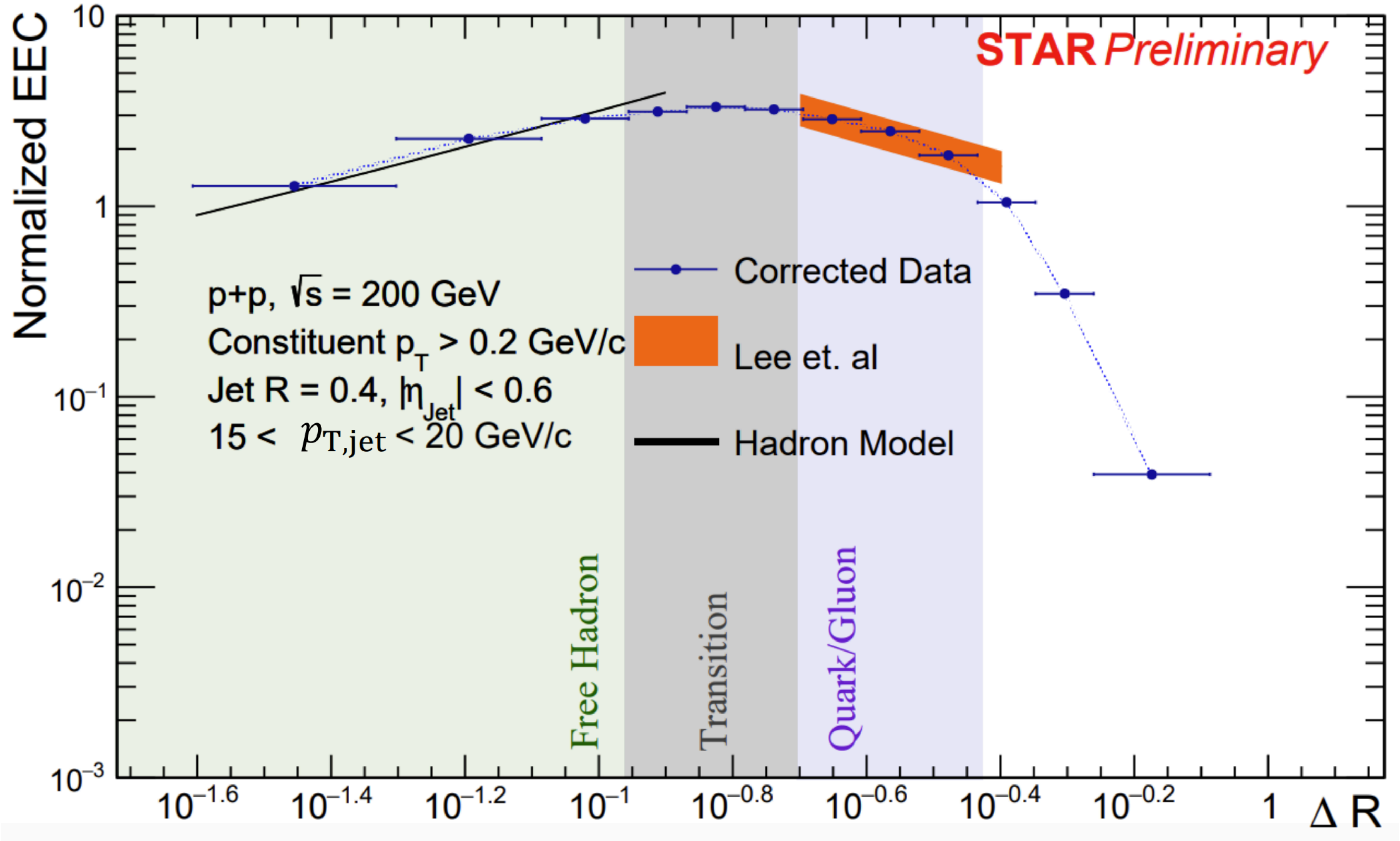

- Data agree well with NLL pQCD calculation (& MC model, not shown)
- Data agree well with model assuming non-interacting hadrons

[1] Basham, Brown, Ellis, Love, PRL 41 (1978), 1585
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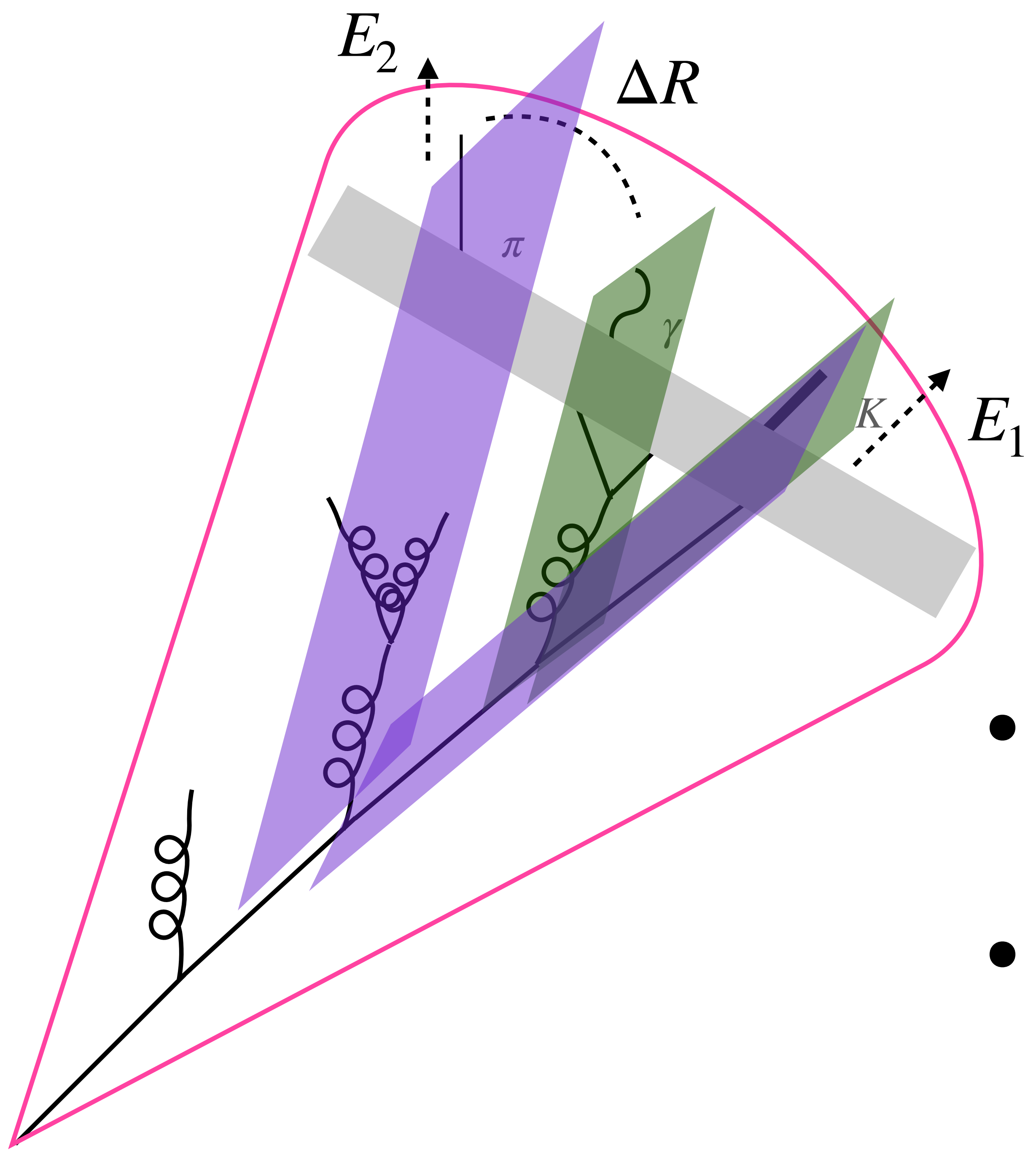

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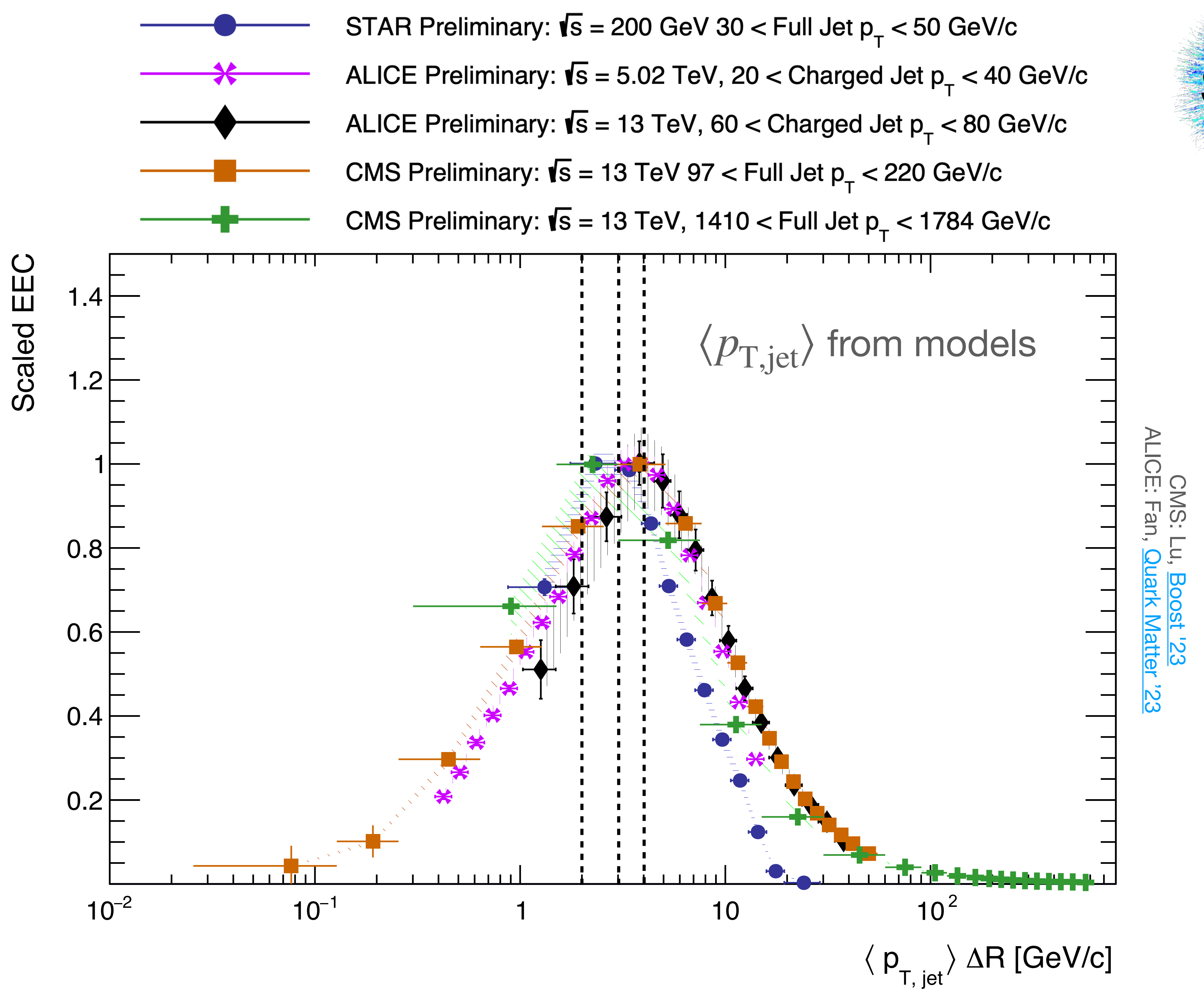

- Testing universality of transition region by comparing to LHC data:
- ~ 2 orders of magnitude in $\sqrt{s}$ and $p_{\mathrm{T,jet}}$ from STAR → ALICE → CMS, transition ~ 2 – 4 GeV/c
- STAR more similar to CMS high-p_T (high-x) jets than ALICE or CMS low-p_T jets — **q vs. g** differences

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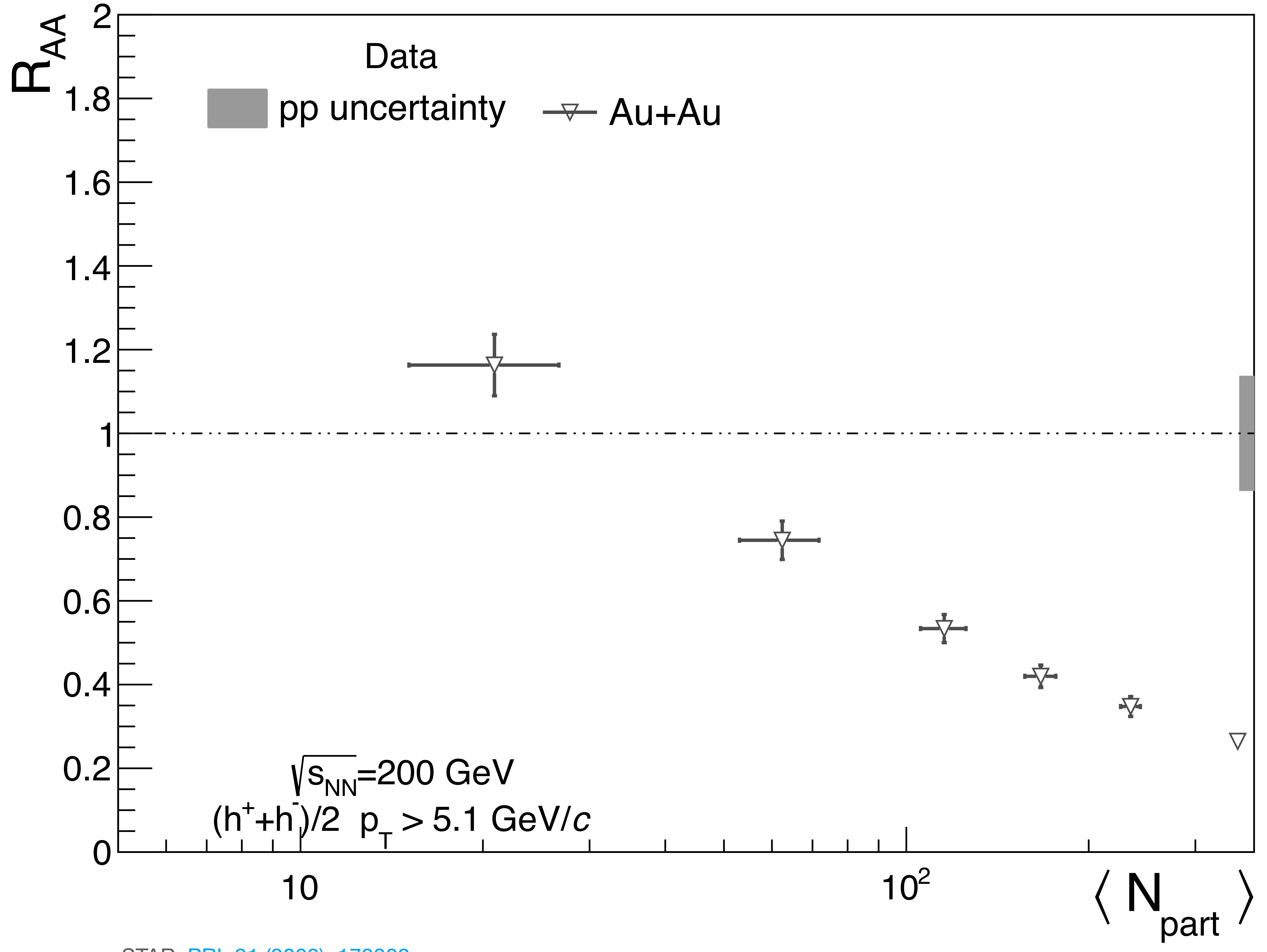
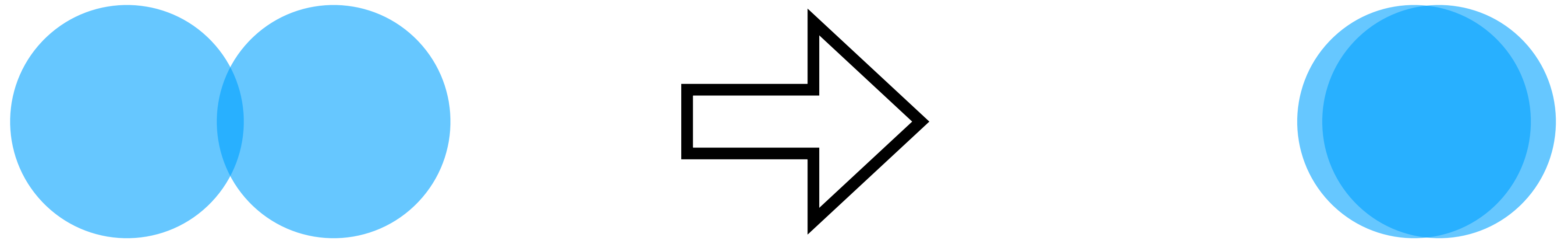
Inclusive yield modification

$$R_{AA} = \frac{1}{N_{ev}^{AA}} \frac{d^2N^{AA}/d\eta dp_T}{\langle T_{AA}\rangle\, d^2\sigma^{NN}/d\eta dp_T},\ \langle T_{AA}\rangle = \langle N_{coll}\rangle / \sigma_{inel}^{NN}$$



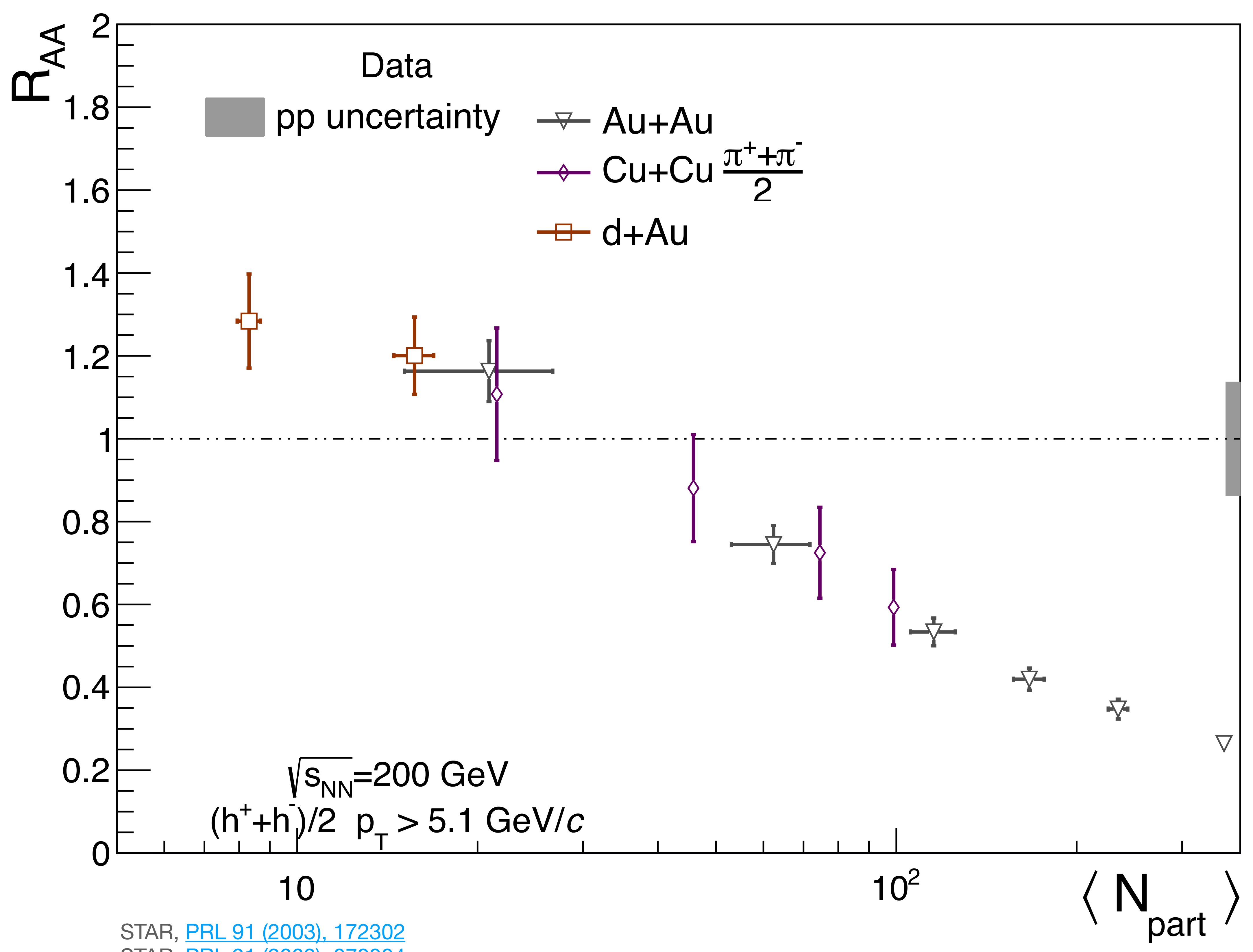
STAR, PRL 91 (2003), 172302



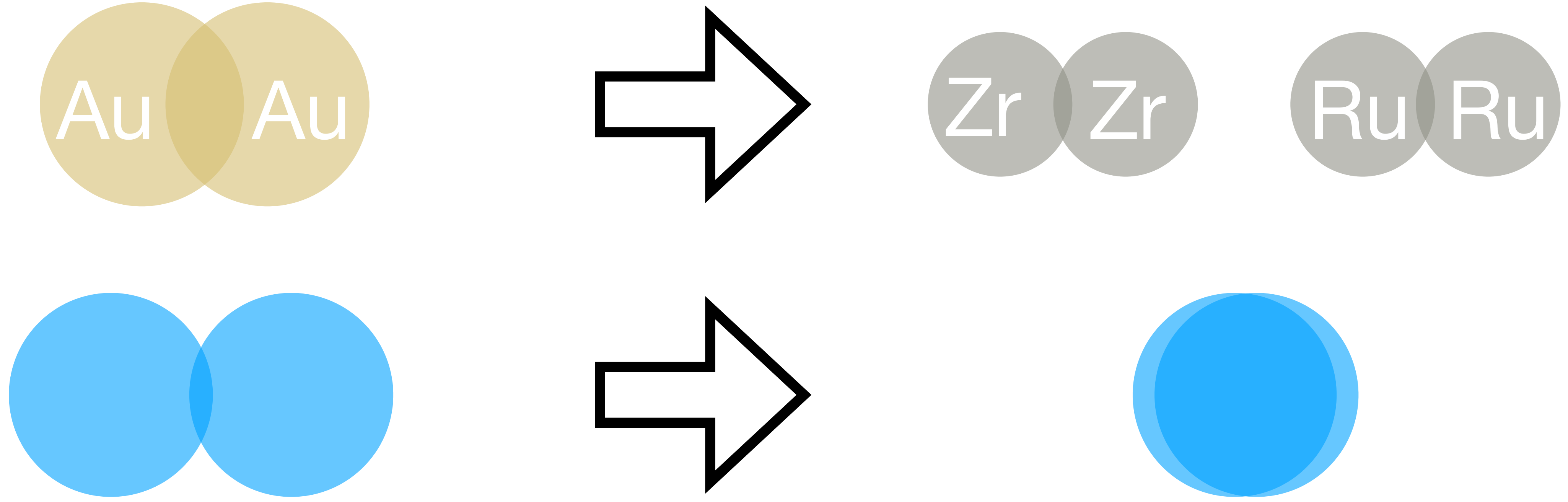
- Suppression strongly increases with $\langle N_{part}\rangle$

Inclusive yield modification

$$R_{\rm AA} = \frac{1}{N_{\rm ev}^{\rm AA}} \frac{d^2N^{\rm AA}/d\eta dp_{\rm T}}{\langle T_{\rm AA}\rangle\, d^2\sigma^{\rm NN}/d\eta dp_{\rm T}},\ \langle T_{\rm AA}\rangle = \langle N_{\rm coll}\rangle / \sigma_{\rm inel}^{\rm NN}$$



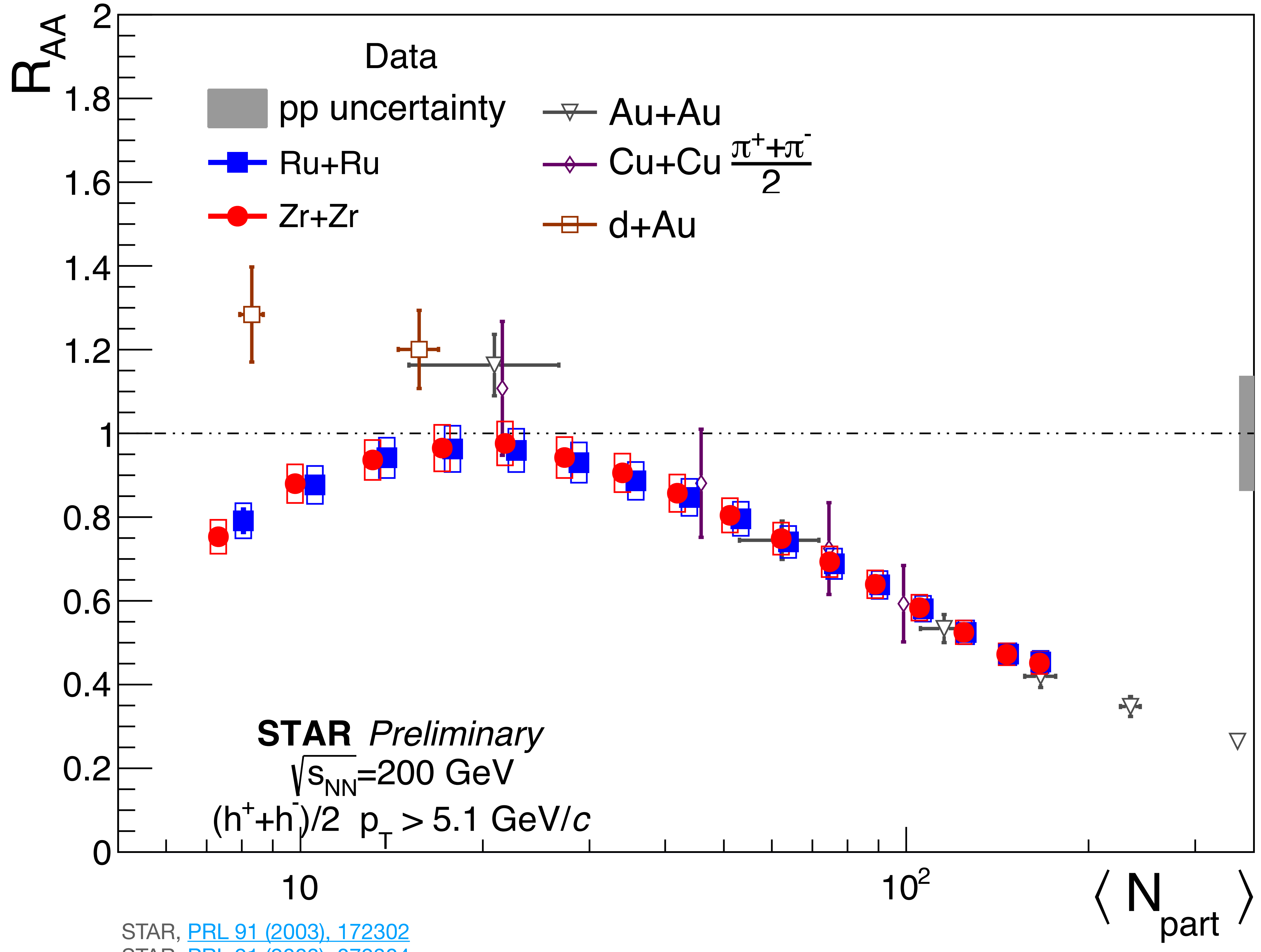
STAR, PRL 91 (2003), 172302
STAR, PRL 91 (2003), 072304
STAR, PRC 81 (2010), 054907



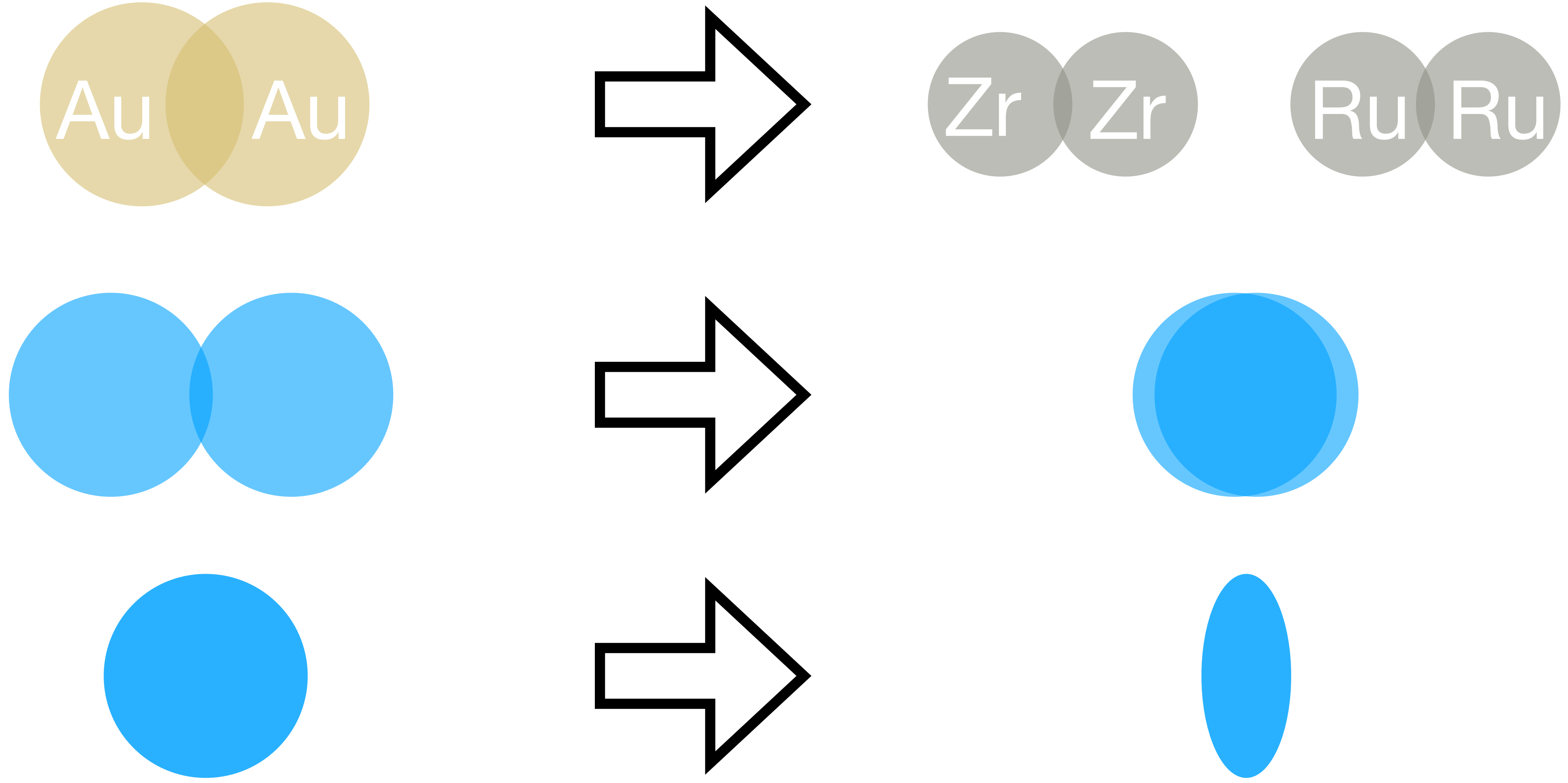
- R_{AA} falls with $\langle N_{\rm part}\rangle$ independent of collision species (system size)

Inclusive yield modification

$$R_{AA} = \frac{1}{N_{ev}^{AA}} \frac{d^2N^{AA}/d\eta dp_T}{\langle T_{AA} \rangle\, d^2\sigma^{NN}/d\eta dp_T},\ \langle T_{AA} \rangle = \langle N_{coll} \rangle / \sigma_{inel}^{NN}$$



STAR, PRL 91 (2003), 172302
STAR, PRL 91 (2003), 072304
STAR, PRC 81 (2010), 054907

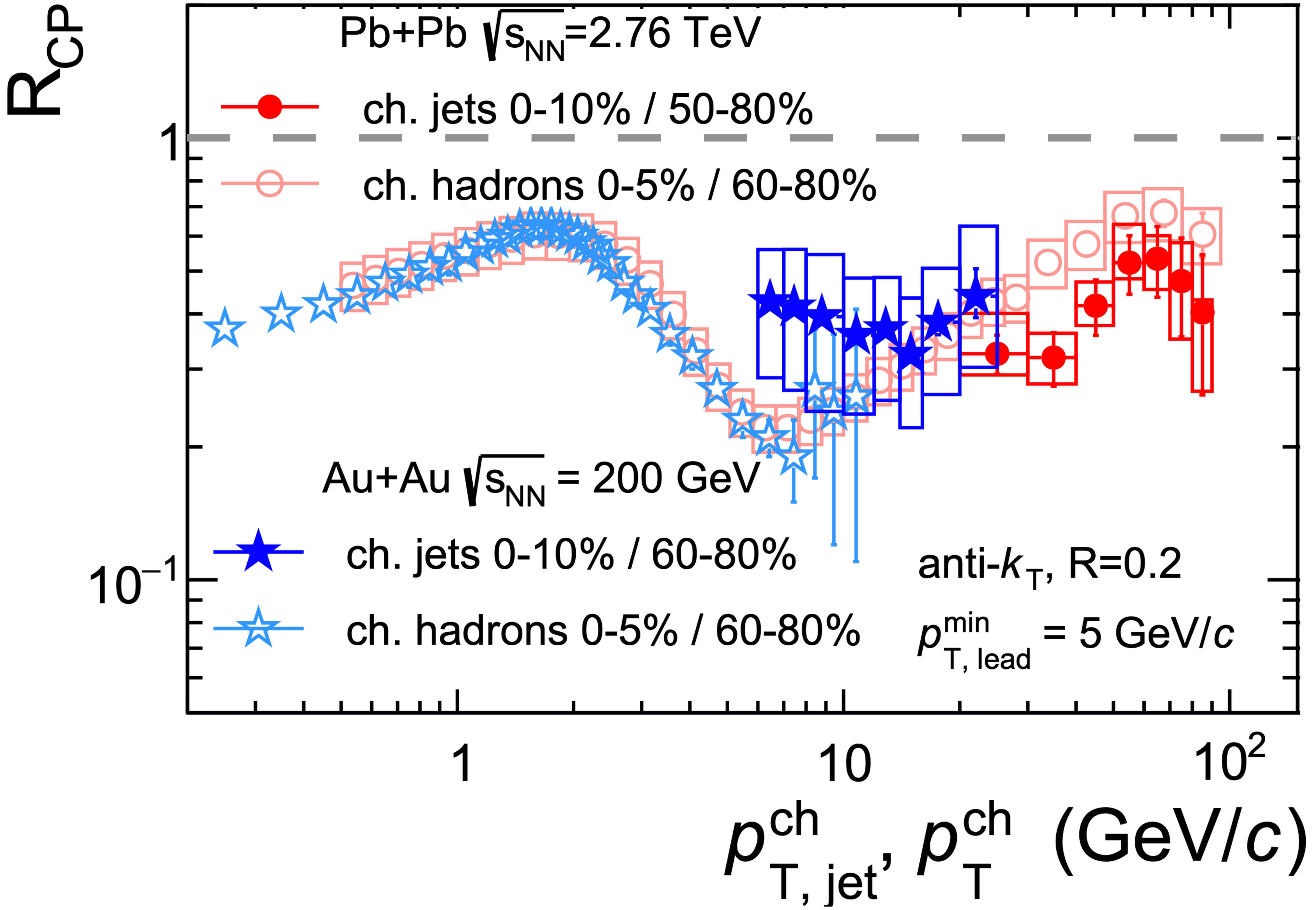


- R_{AA} falls with $\langle N_{part} \rangle$ independent of collision species (system size), above ~ 20
- Later: for given $\langle N_{part} \rangle$, how does geometry influence E-loss?

Inclusive yield modification

$$R_{CP} = \frac{N_{ev}^{P}}{N_{ev}^{C}} \frac{\langle T_{AA,P} \rangle}{\langle T_{AA,C} \rangle} \frac{d^2N^{C}/d\eta dp_T}{d^2N^{P}/d\eta dp_T}, \langle T_{AA} \rangle = \langle N_{coll} \rangle / \sigma_{inel}^{NN}$$

STAR, PRC 102 (2020) 5, 054913, STAR, PRL 91 (2003) 172302, ALICE, JHEP 03 (2014) 013, ALICE, JHEP 09 (2015) 050

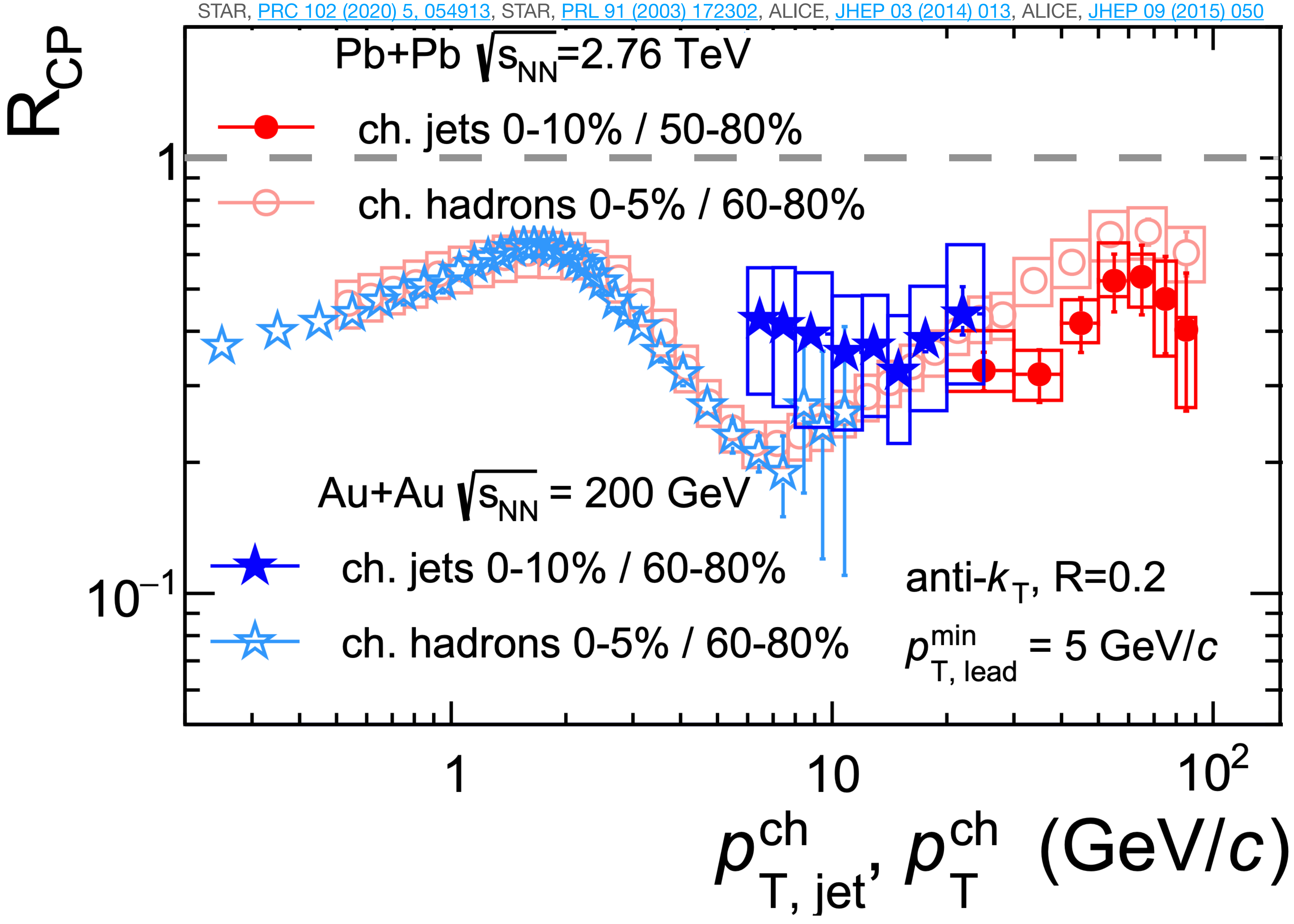


- Jet R_{AA} consistent with hadron R_{AA}
- Strong suppression across p_T
- RHIC and LHC jets already have kinematic overlap
  - Similar quenching?

Inclusive yield modification

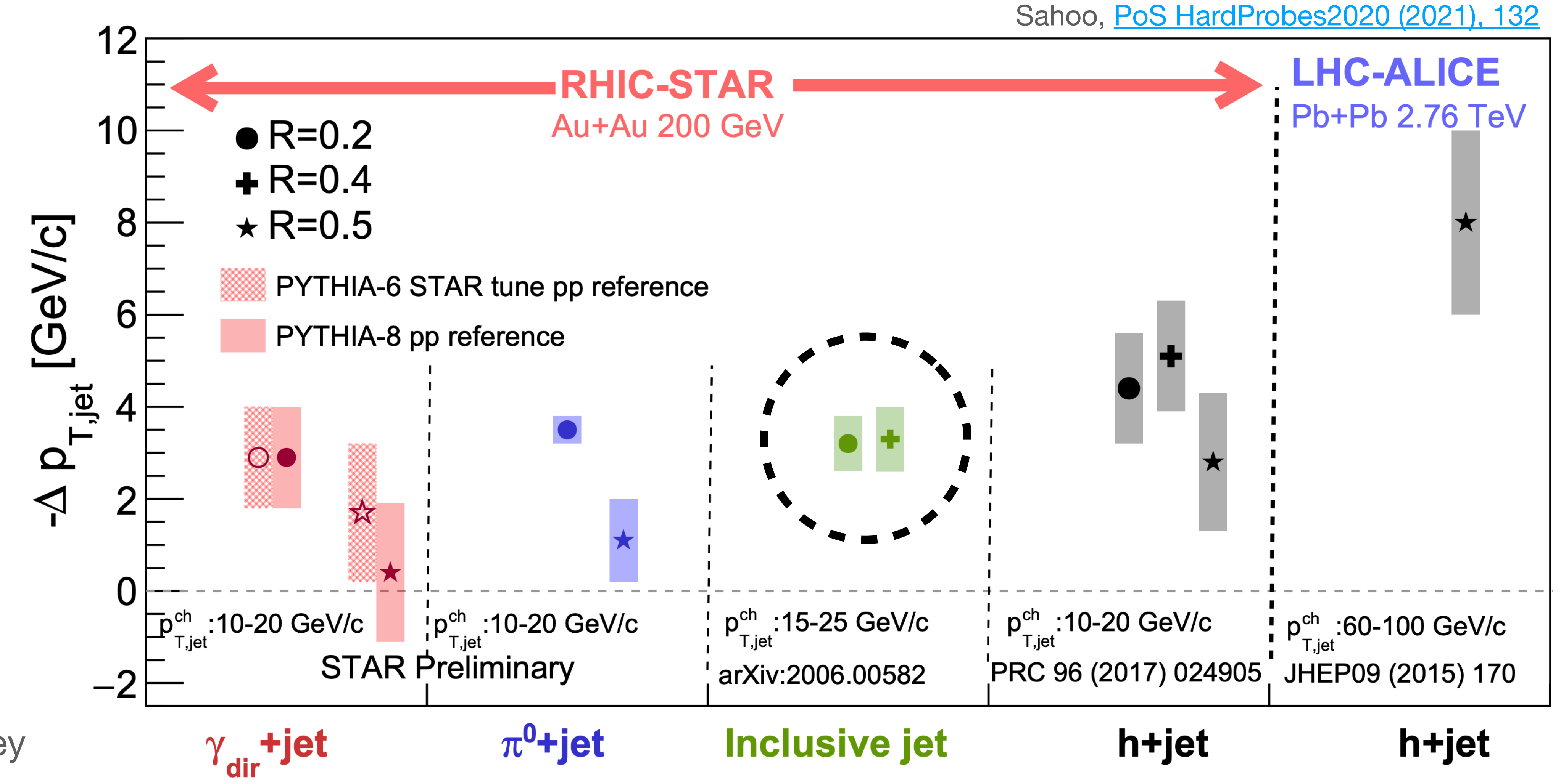
$$R_{CP} = \frac{N_{ev}^{P}}{N_{ev}^{C}} \frac{\langle T_{AA,P} \rangle}{\langle T_{AA,C} \rangle} \frac{d^2N^C/d\eta dp_T}{d^2N^P/d\eta dp_T}, \langle T_{AA} \rangle = \langle N_{coll} \rangle / \sigma_{inel}^{NN}$$

STAR, PRC 102 (2020) 5, 054913, STAR, PRL 91 (2003) 172302, ALICE, JHEP 03 (2014) 013, ALICE, JHEP 09 (2015) 050



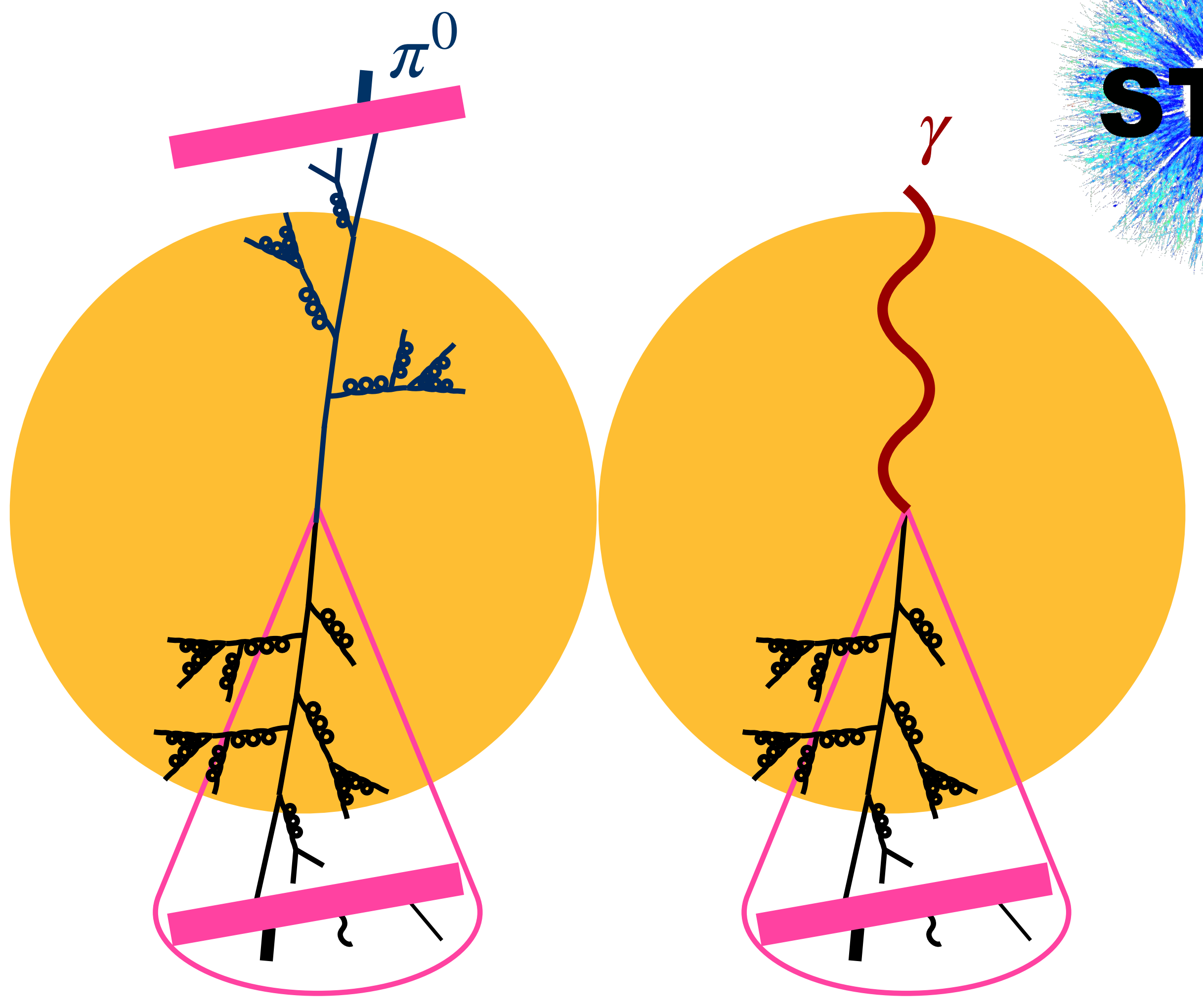
- Jet R_{AA} consistent with hadron R_{AA}
- Strong suppression across p_T
- RHIC and LHC jets already have kinematic overlap
  - Similar quenching?
    Absolute, smaller. Relative, *larger!*

Sahoo, PoS HardProbes2020 (2021), 132

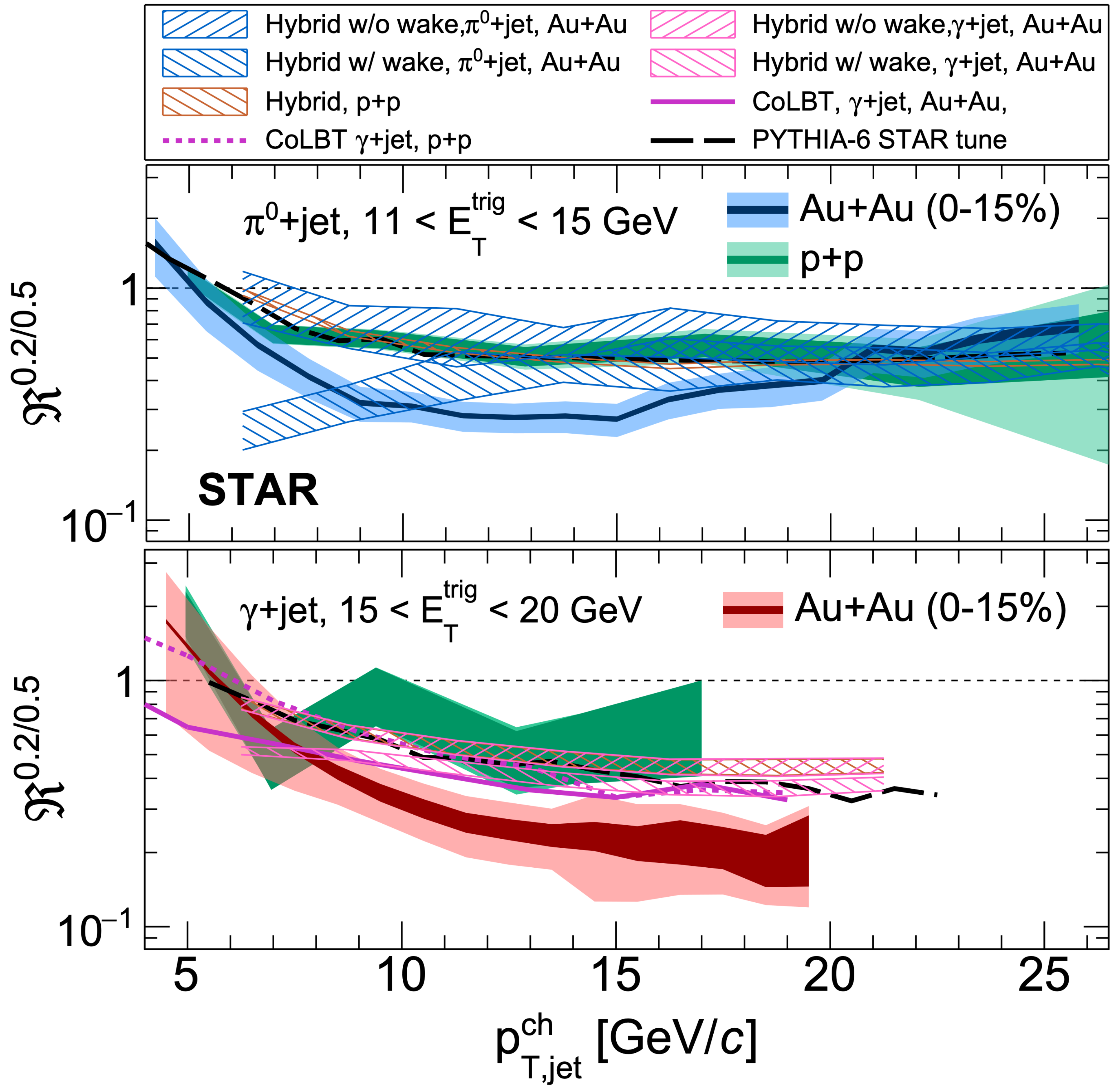


Semi-inclusive yield modification

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

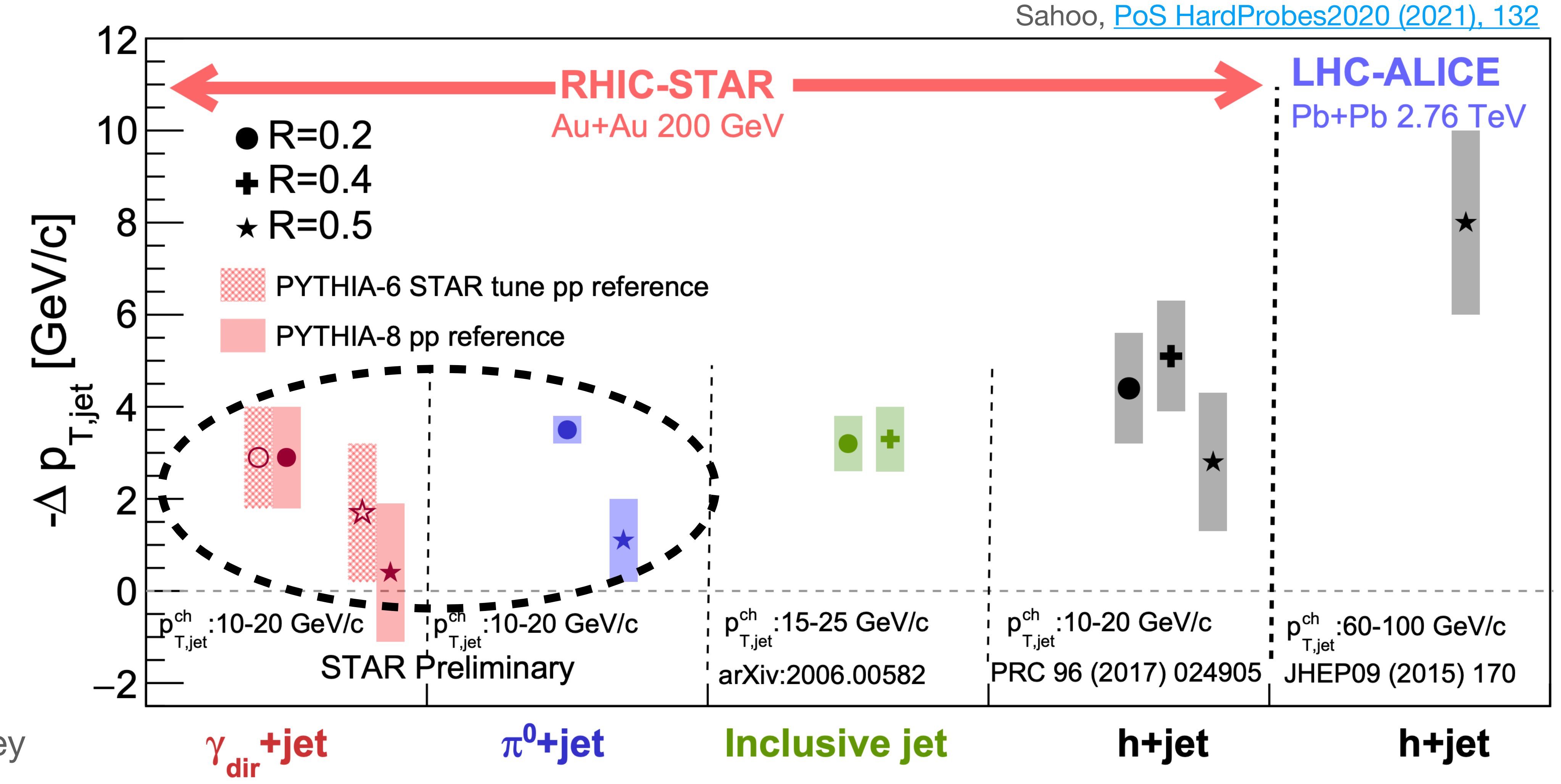


STAR, arXiv:2309.00145, STAR, arXiv:2309.00156



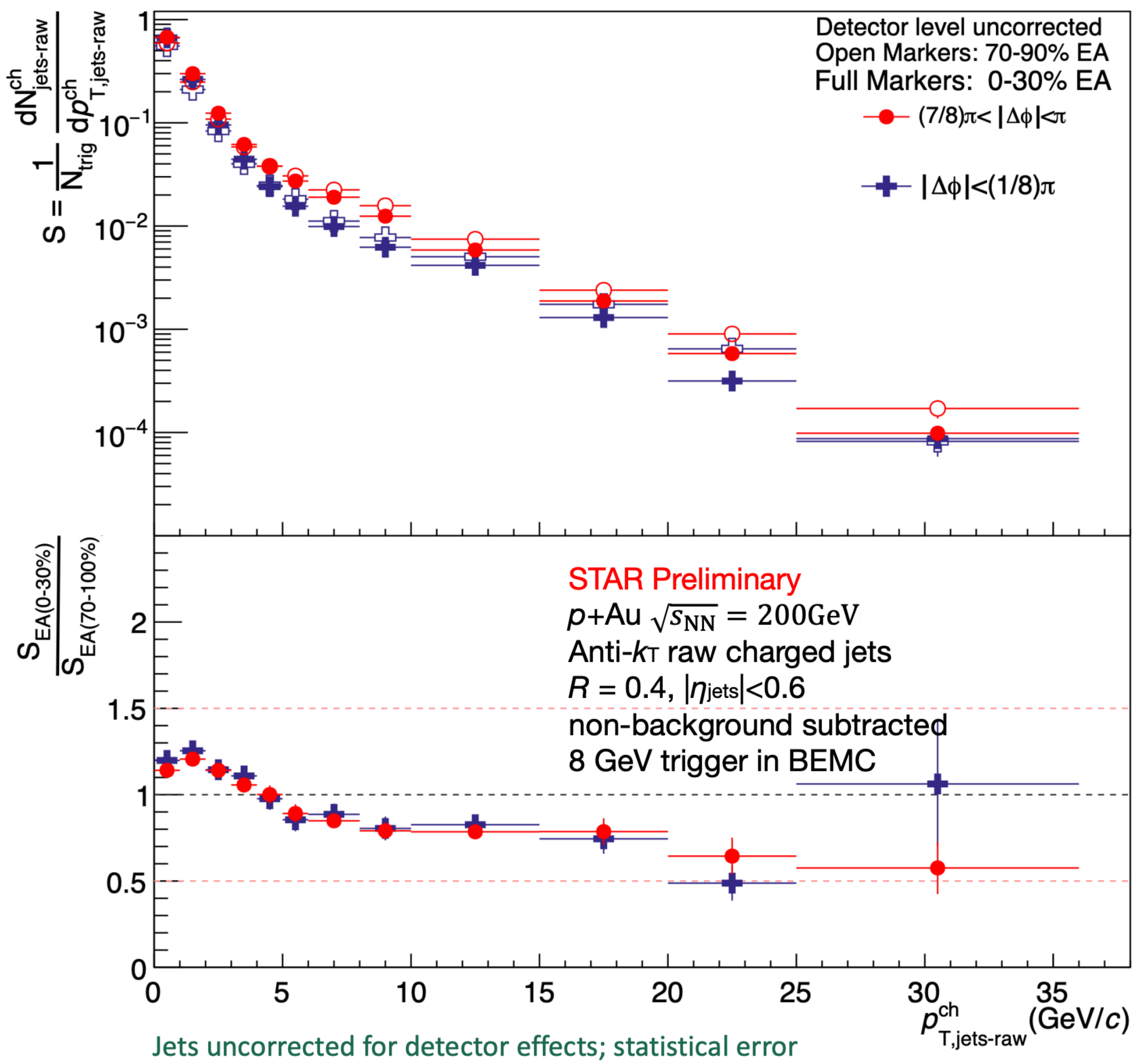
- Recoil jet yield suppression in AuAu, stronger in small R jets
- Clear observation of *intra-jet broadening*
- Models unable to quantitatively describe the effect

Sahoo, PoS HardProbes2020 (2021), 132

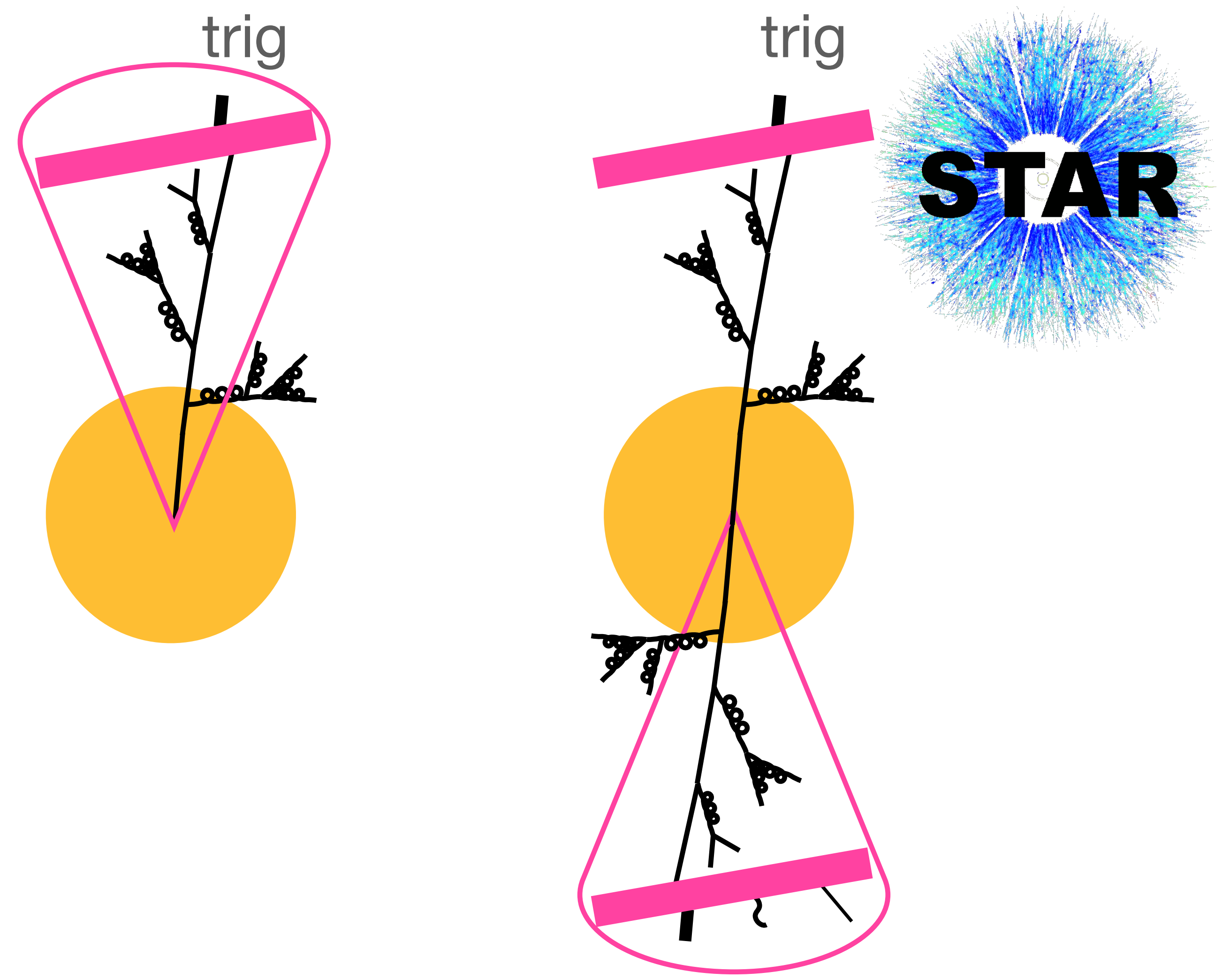


Semi-inclusive yield modification

in pAu collisions



Jets uncorrected for detector effects; statistical error bars only; however, detector effects cancel in the ratio



[1]CMS, JHEP 09 (2010), 091
[2]CMS, PLB 718 (2013), 795
[3]ALICE, PLB 719 (2013), 29
[4]ATLAS, PLB 748 (2015), 392
[5]PHENIX, PRL 116 (2016), 122301
[6]ALICE, Nat. Phys. 13 (2017), 535

- Hot nuclear matter effects in pAu collisions?[1,2,3,4,5,6,...]
- Jet yield suppression, but on both *near* and *away* side → not surface bias as typical in AA with high p_T trigger…
- Jet substructure*, dijet p_T balance A_J* also unmodified
- Anti-correlation of event activity at large rapidity with jet p_T at mid-rapidity* suggests $t \sim 0$ kinematics[7,8]

*not shown

[7]Alvioli, Cole, Frankfurt, Perepelitsa, Strikman, PRC 93 (2016), 011902(R)
[8]Armesto, Gülhan, Milhano, PLB 747 (2015), 441

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

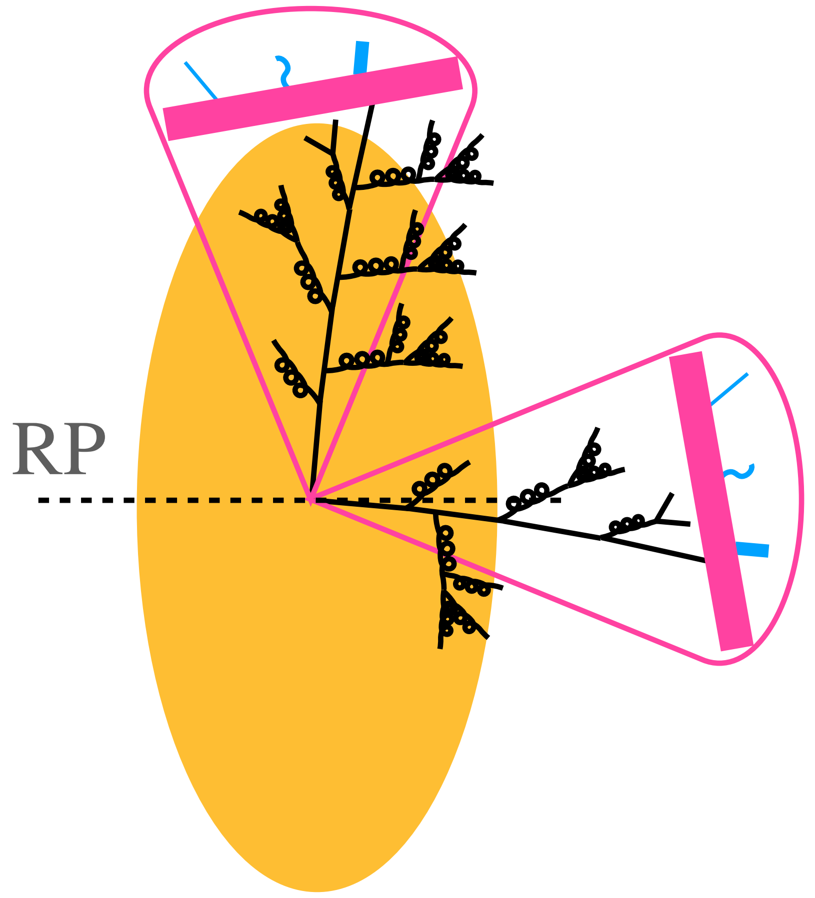
Separating p-QCD and np-QCD with *energy correlators*

Energy flows

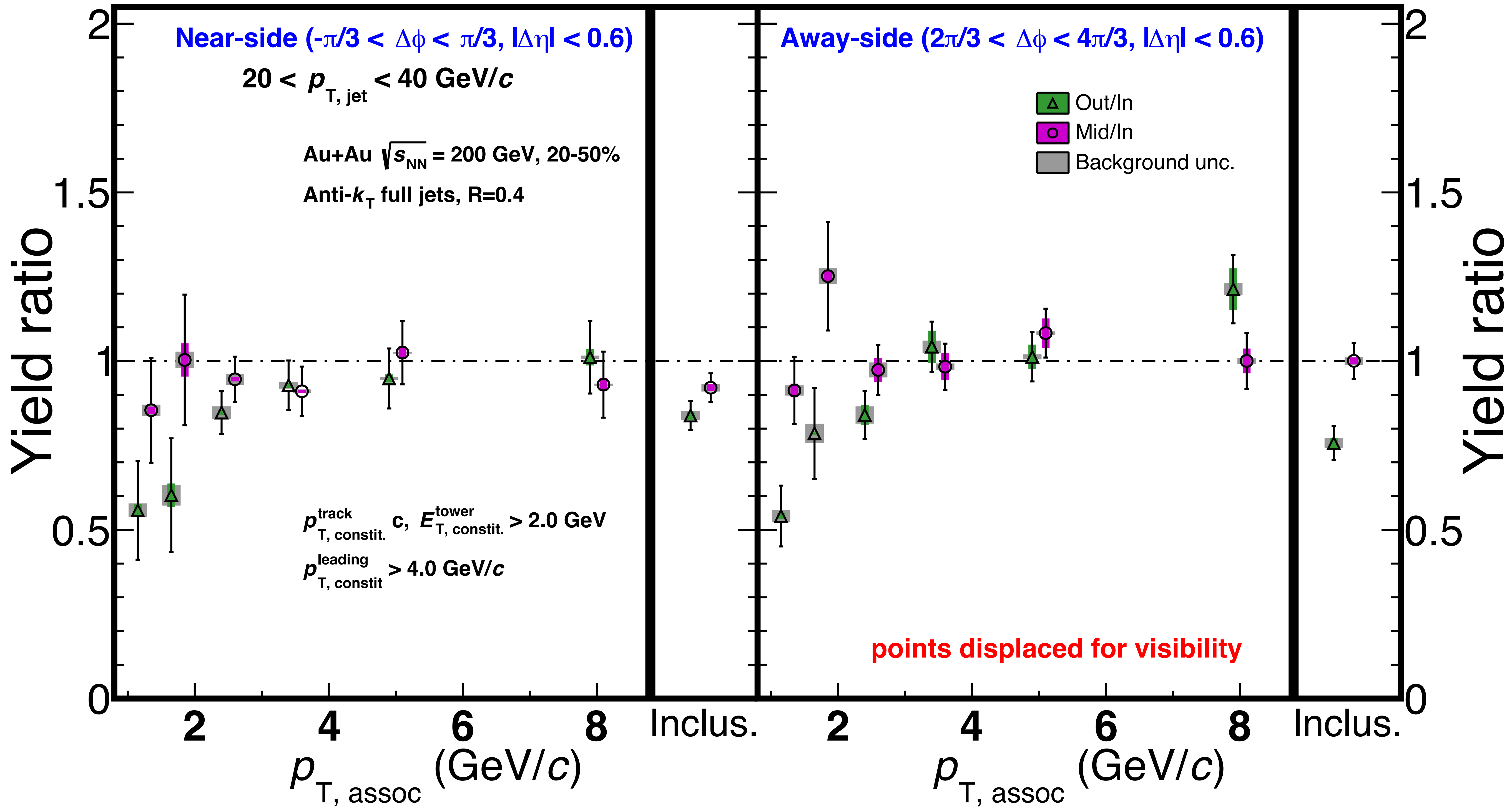
Path-length dependence of jet energy loss in medium with *jet anisotropies (with respect to event plane)*

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*

Event plane (EP) dep. of associated hadron yields



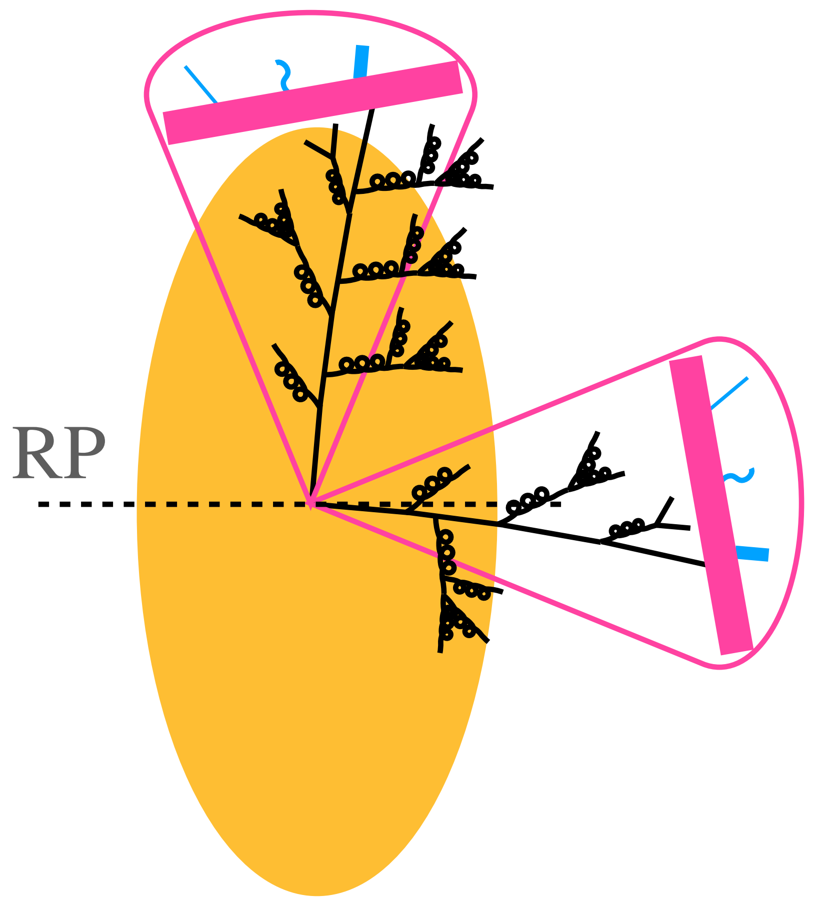
STAR, arXiv:2307.13891



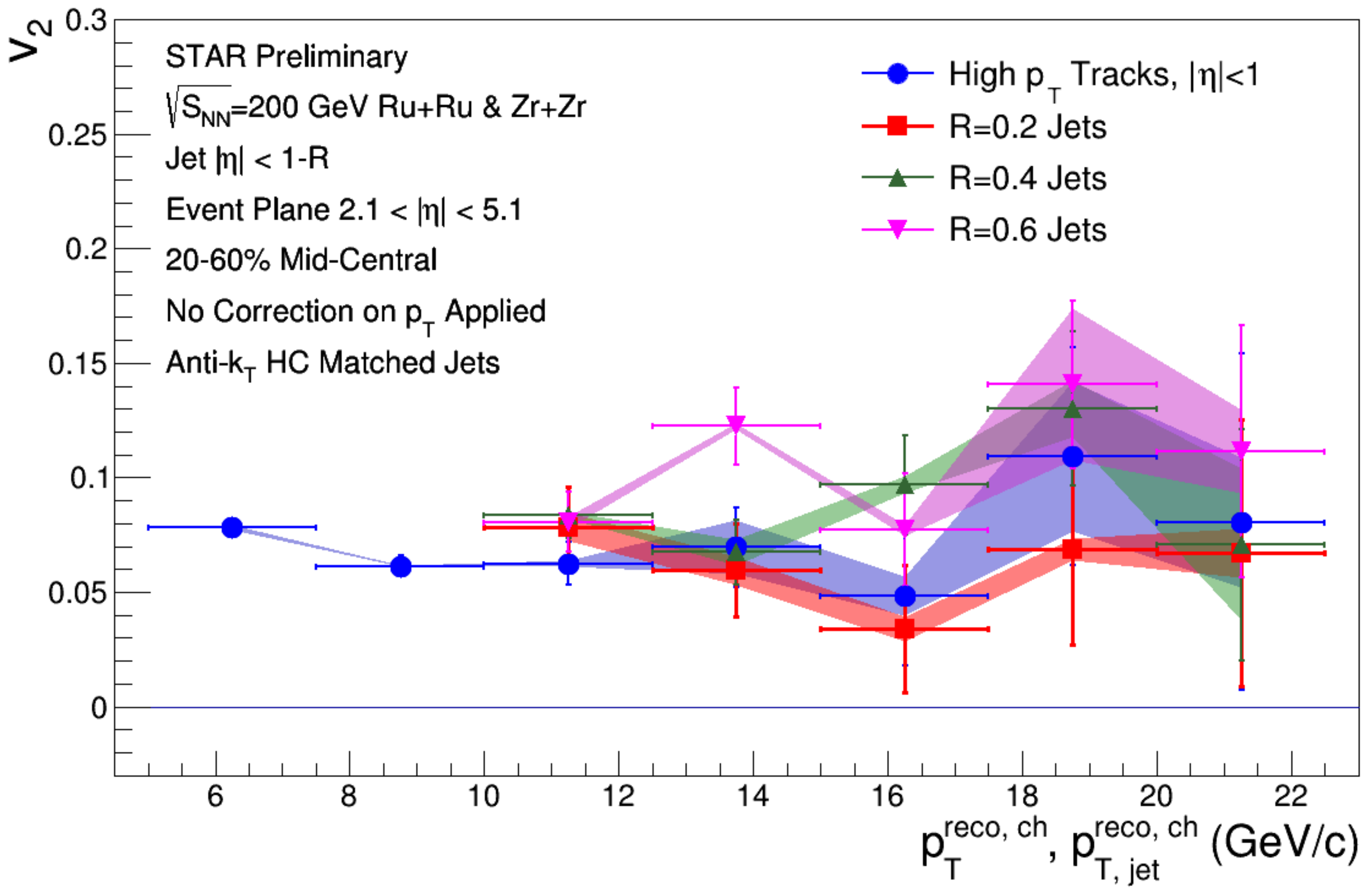
- *Expectation*: high (low)-p_T suppression (enhancement) for out-of-plane (OOP) vs. in-plane (IP) jets: path-length dependent quenching
- No significant deviation from unity within uncertainties
- Jet energy loss / medium density fluctuations spoiling effect?

Jet v_2

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



- New forward detector at STAR, *EPD*, gives improved reaction plane (RP) resolution, no autocorrelation with mid-rapidity measurement
- v_2 in this context linked to **path-length dependent quenching**, not flow
- Clear v_2 signal, independent of jet R, p_T, in high-statistics isobar data

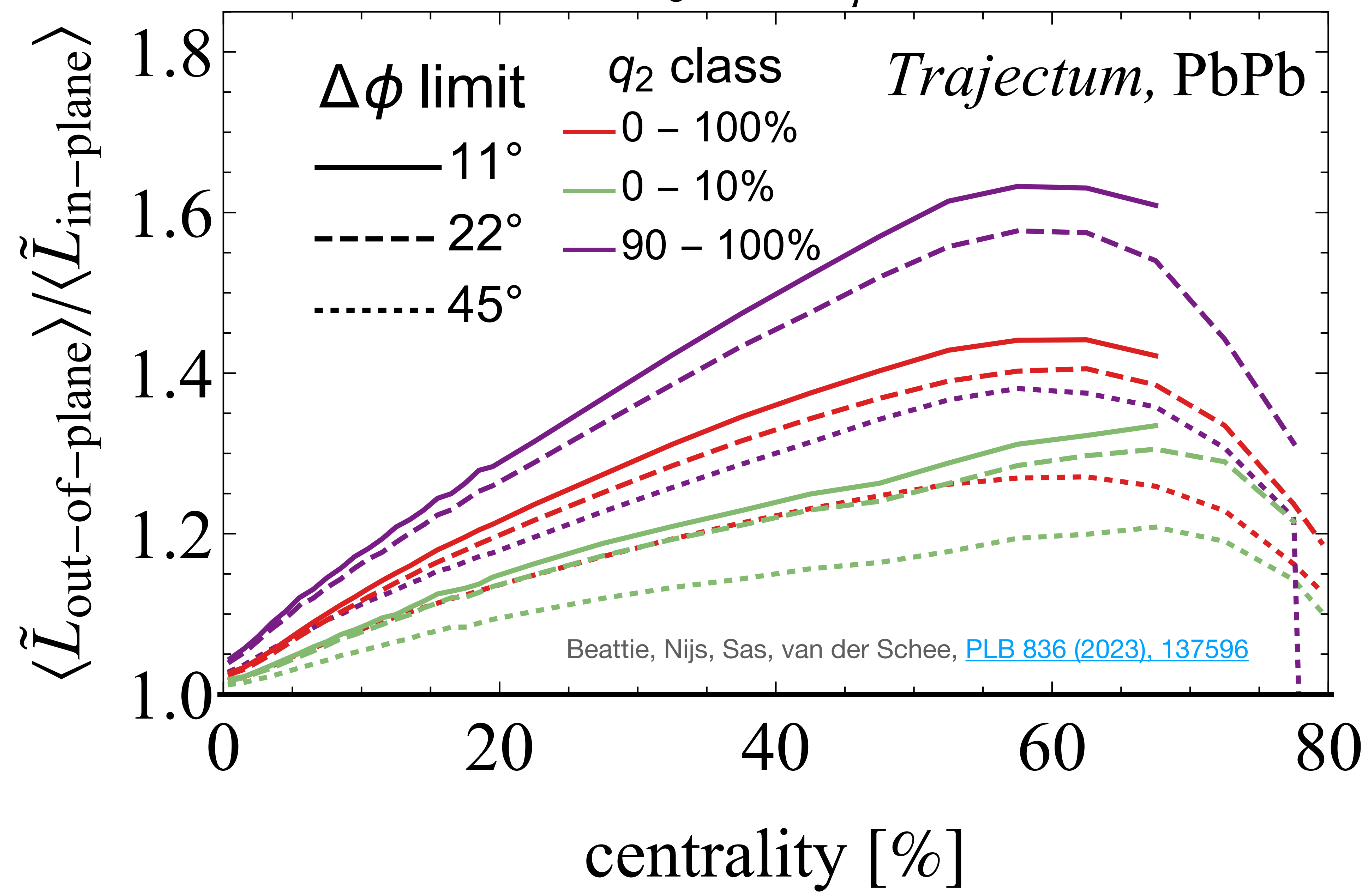


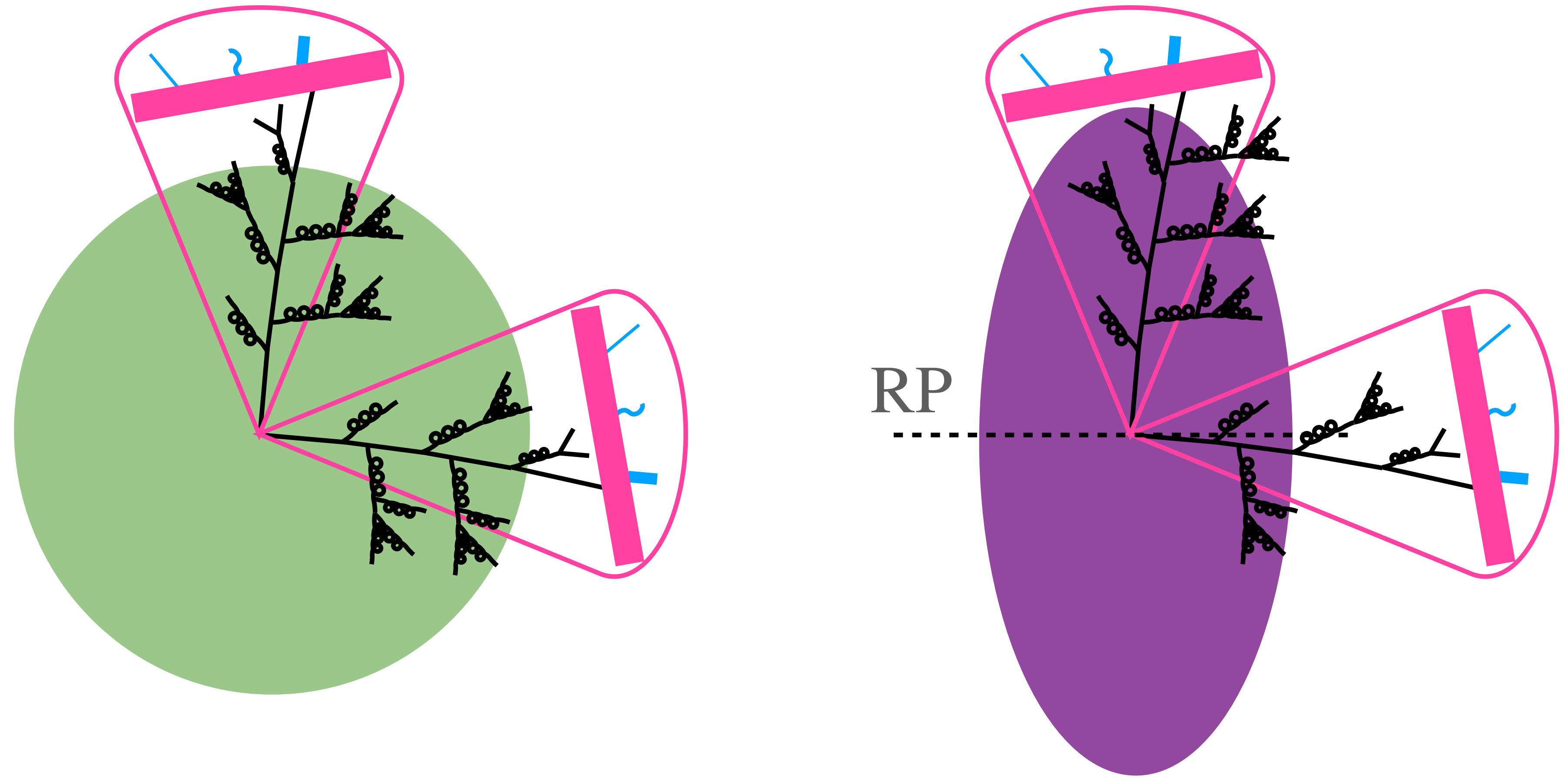
Event-shape engineering[1]

$$Q_2 = \left(\sum_{i=1}^{M} w_i \cos(2\phi_i), \sum_{i=1}^{M} w_i \sin(2\phi_i)\right),\ q_2 = |Q_2|/\sqrt{M},$$
w_i: nMIP weight, M: multiplicity

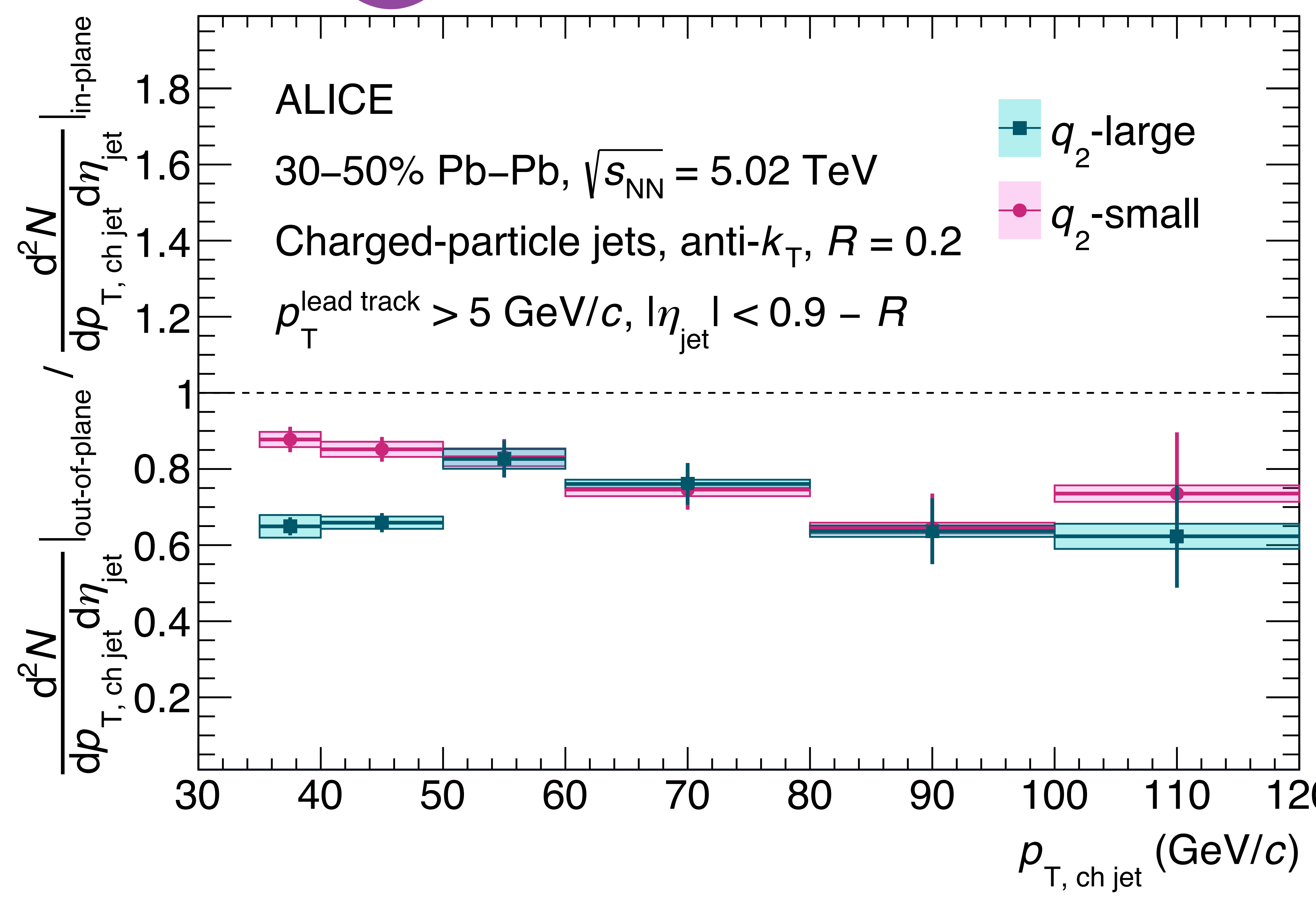
$$v_2 = \langle \cos(2(\phi - \Psi_2)) \rangle$$

$\tilde{L} = \int 1/\gamma\, u_\mu\, \mathrm{d}L^\mu$





ALICE, 2307.14097



- Select on the shape using reduced flow vector q_2
  → average path length difference in Trajectum model
- ALICE: low-p_T difference in IP, OOP yields for highly elliptical events

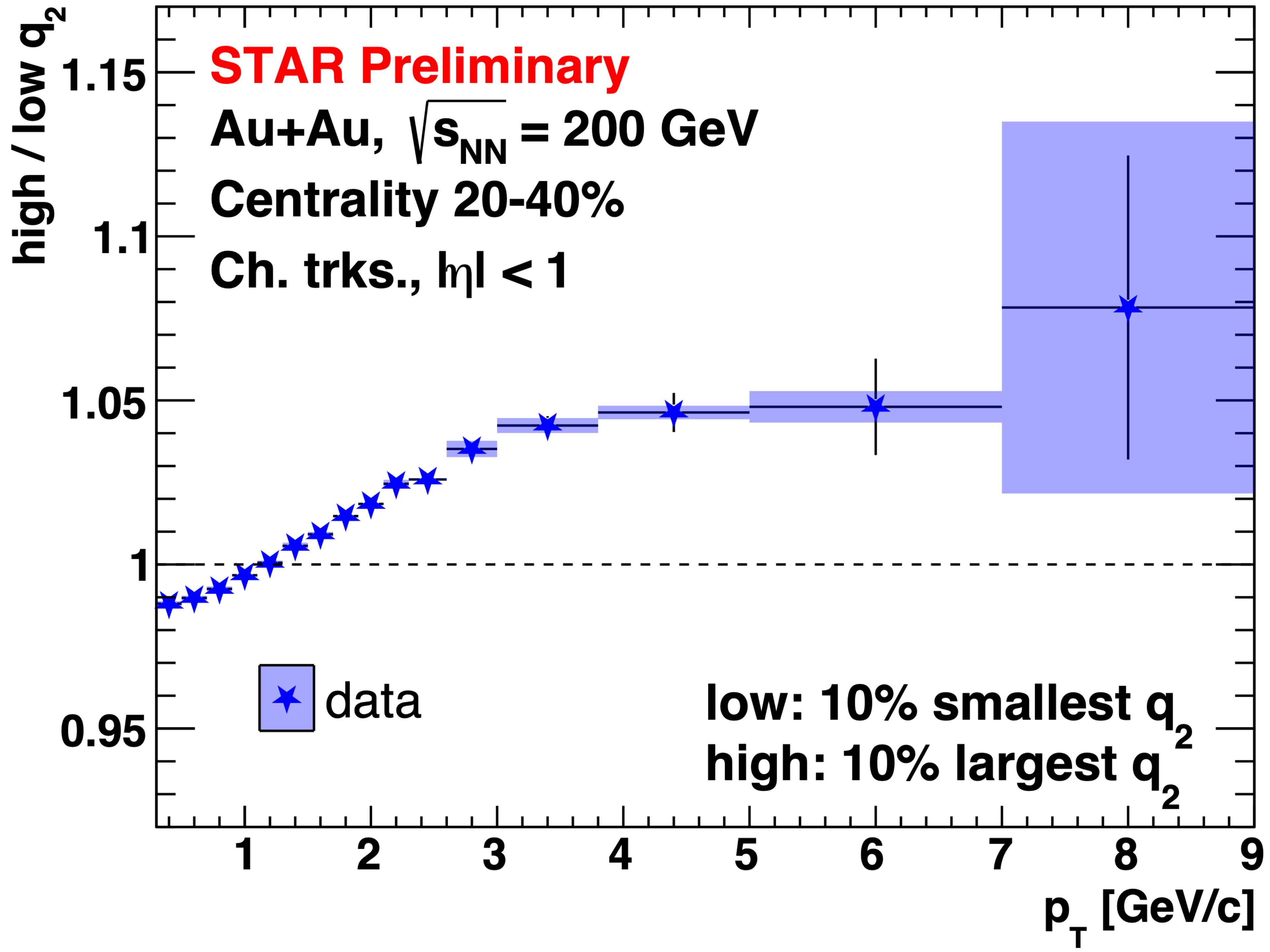
[1] Schukraft, Timmins, Voloshin, PLB 719 (2013), 394-398

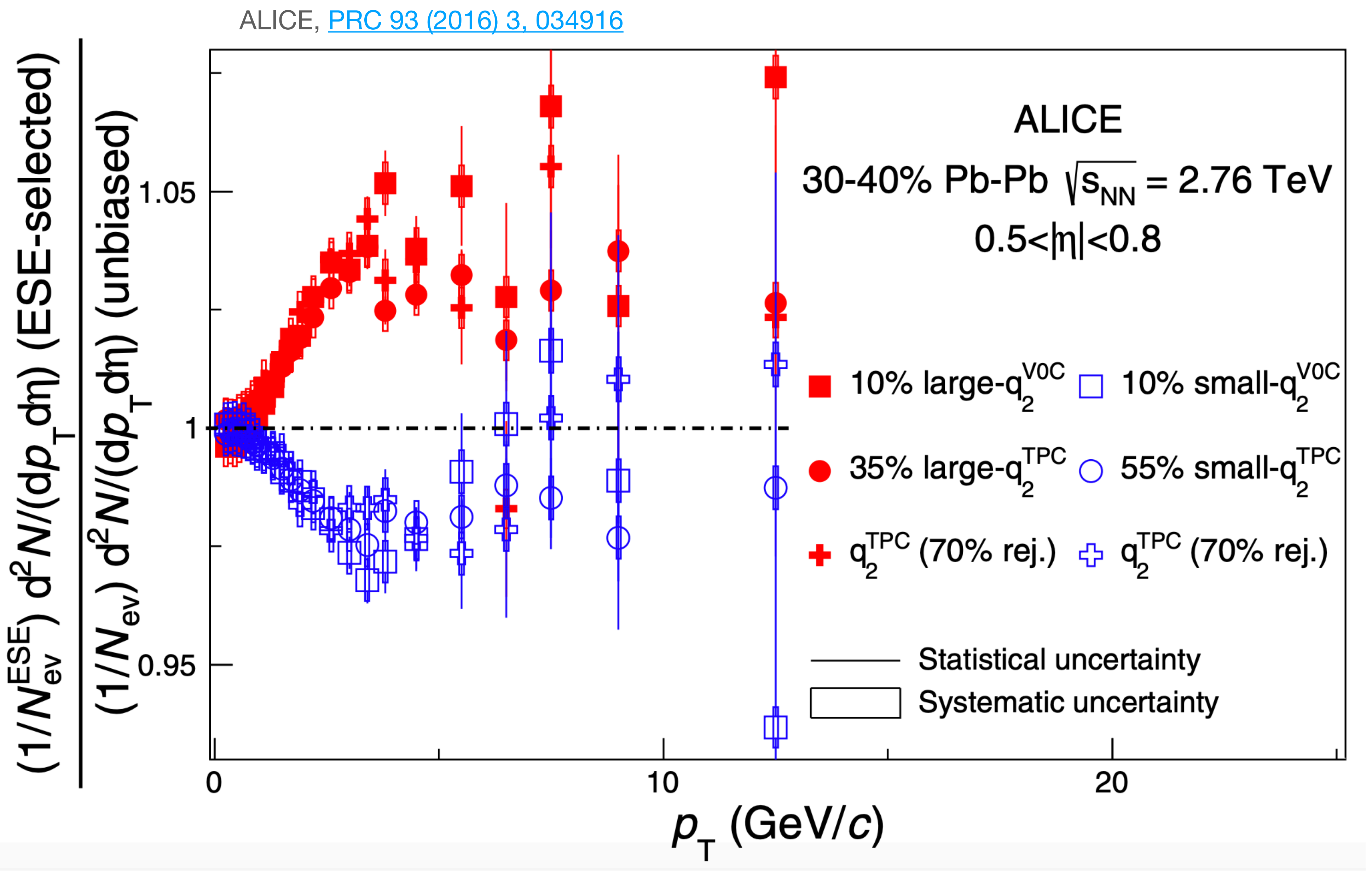
Event-shape engineering

$$Q_2 = \left(\sum_{i=1}^{M} w_i \cos(2\phi_i), \sum_{i=1}^{M} w_i \sin(2\phi_i)\right),\ q_2 = |Q_2|/\sqrt{M},$$

w_i: nMIP weight, M: multiplicity

$$v_2 = \langle \cos(2(\phi - \Psi_2)) \rangle$$





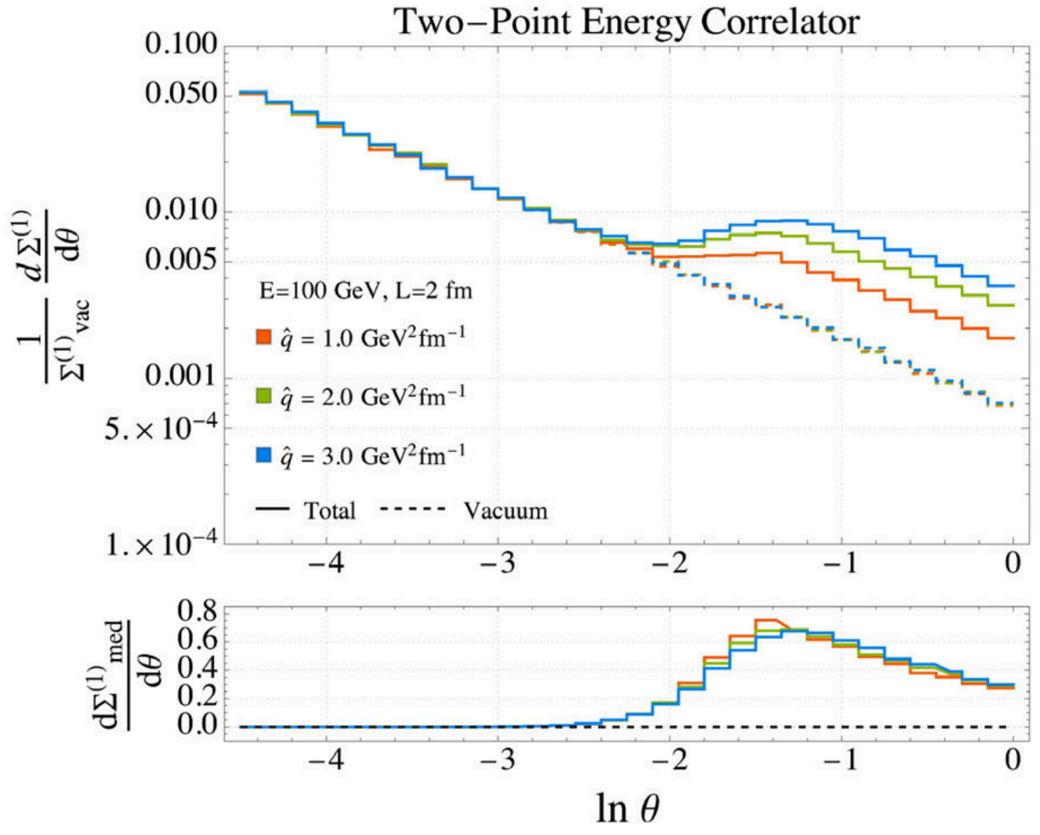
- STAR analysis ongoing — without selecting on EP angle, see enhancement at mid-p_T of charged track yields, for high vs. low q_2 events
- Interplay between eccentricity/density, elliptic/radial flow. Also observed by ALICE

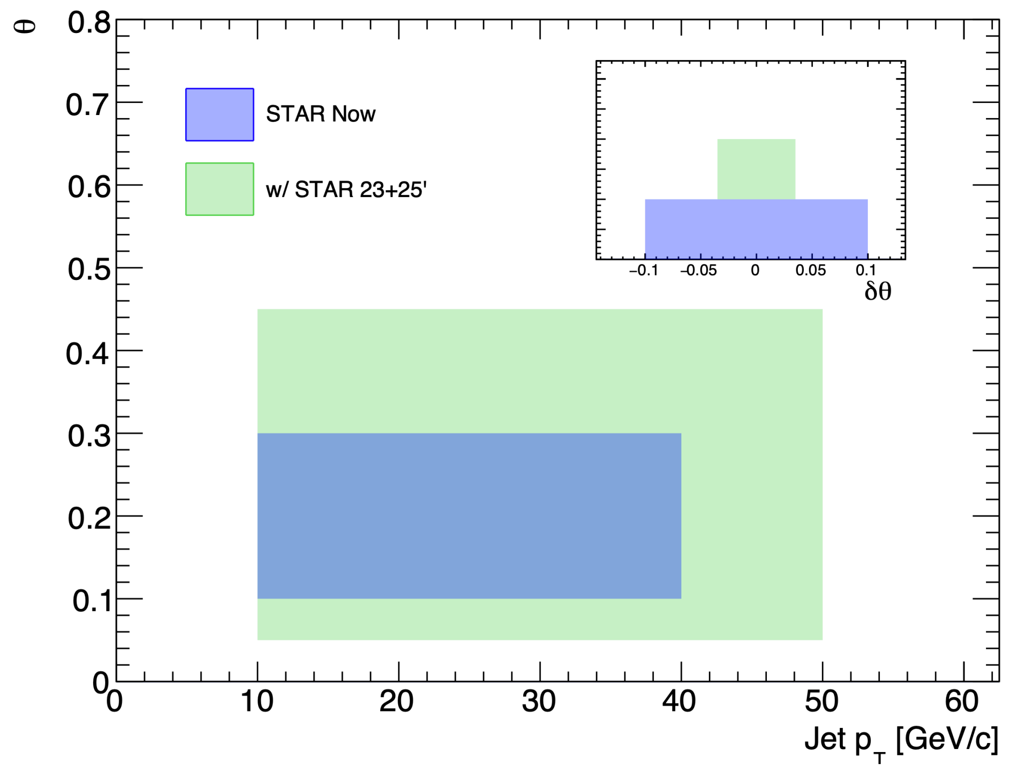
Future prospects

Energy flows

Andres, Dominguez, Kunnawalkam Elayavalli, Holguin, Marquet, Moult, PRL 130 (2023) 26, 262301

- *Generalized angularities*: less conservative systematic uncertainties, extension to jet momentum profile $\rho(r)$
- *EECs*: higher orders; charge-dependent; in heavy-ion collisions
- *R_{AA}*: analyzing R_{pAu}
- *Jet v_2*: extended to OO collisions, studying non-flow contribution
- *Event shape engineering*: event-plane angle dependence study in progress
- *Runs 23+25*[1,2]: expected ~3x increase in statistics relative to current AA analyses w/ Run 14 → improved uncertainties e.g. for γ_{dir}+jet I_{AA}, and **kinematic reach / overlap with LHC**





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

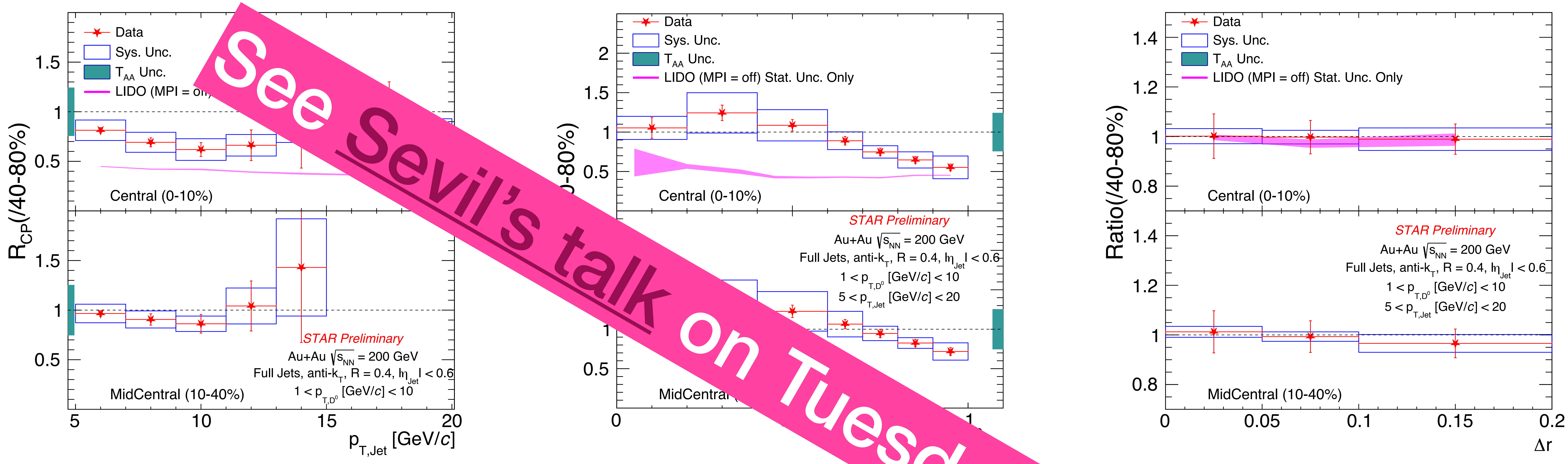
Hadronization mechanism with *flavor correlators*

Constituent identity

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

D⁰-jet spectra, profile, fragmentation

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



See Sevil's talk on Tuesday at 11:30 AM!

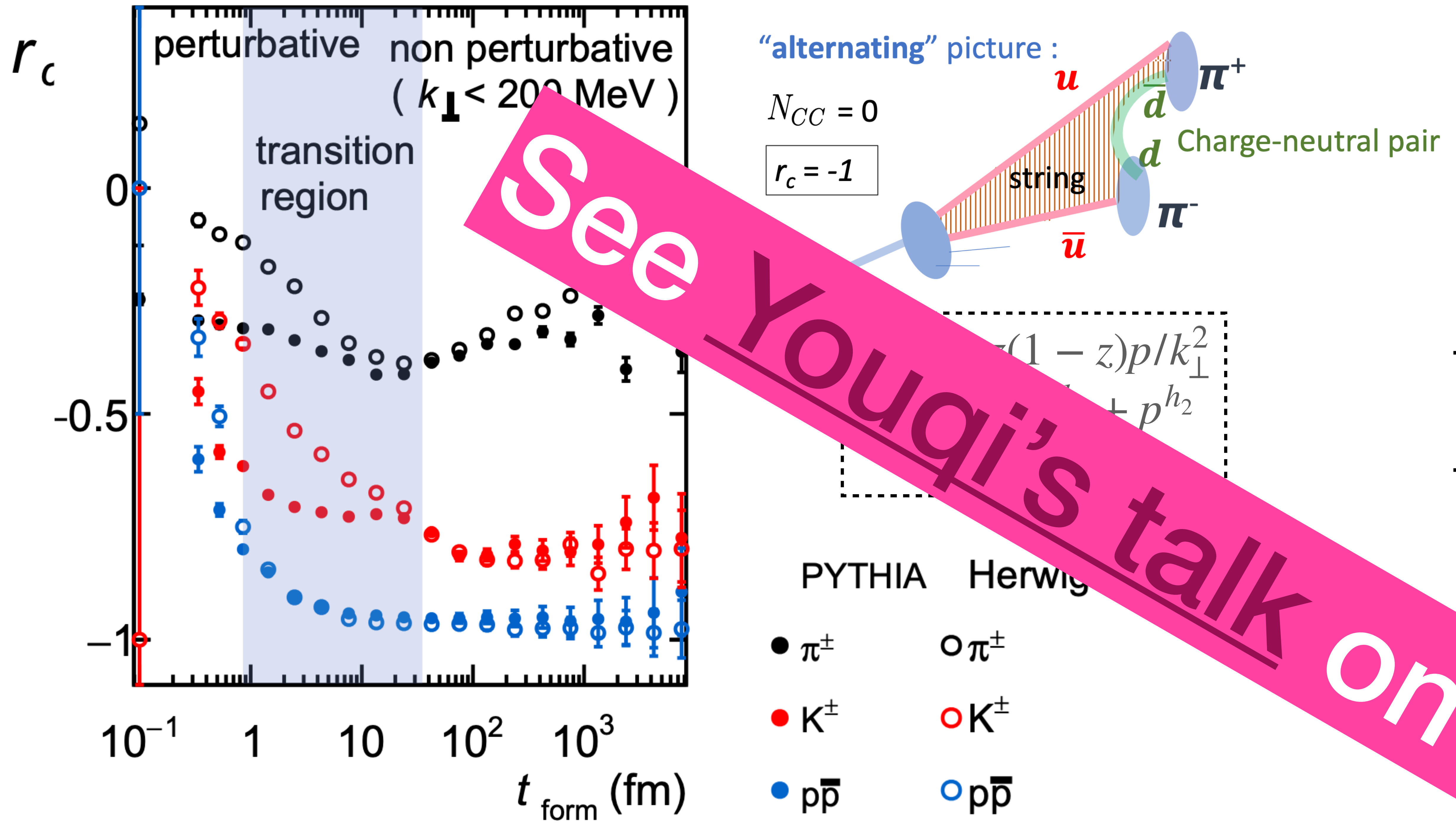
- Testing charm quark energy loss, diffusion, and fragm[illegible]dification
- *Hint of suppression of yield at low-p_T. Hard-fragmenting charm* [illegible] *ppressed*. *No diffusion*.
- Model including radiative and collisional energy loss during heavy qua[illegible]n underpredicts central yields — MPI might be important for D⁰ p_T this low

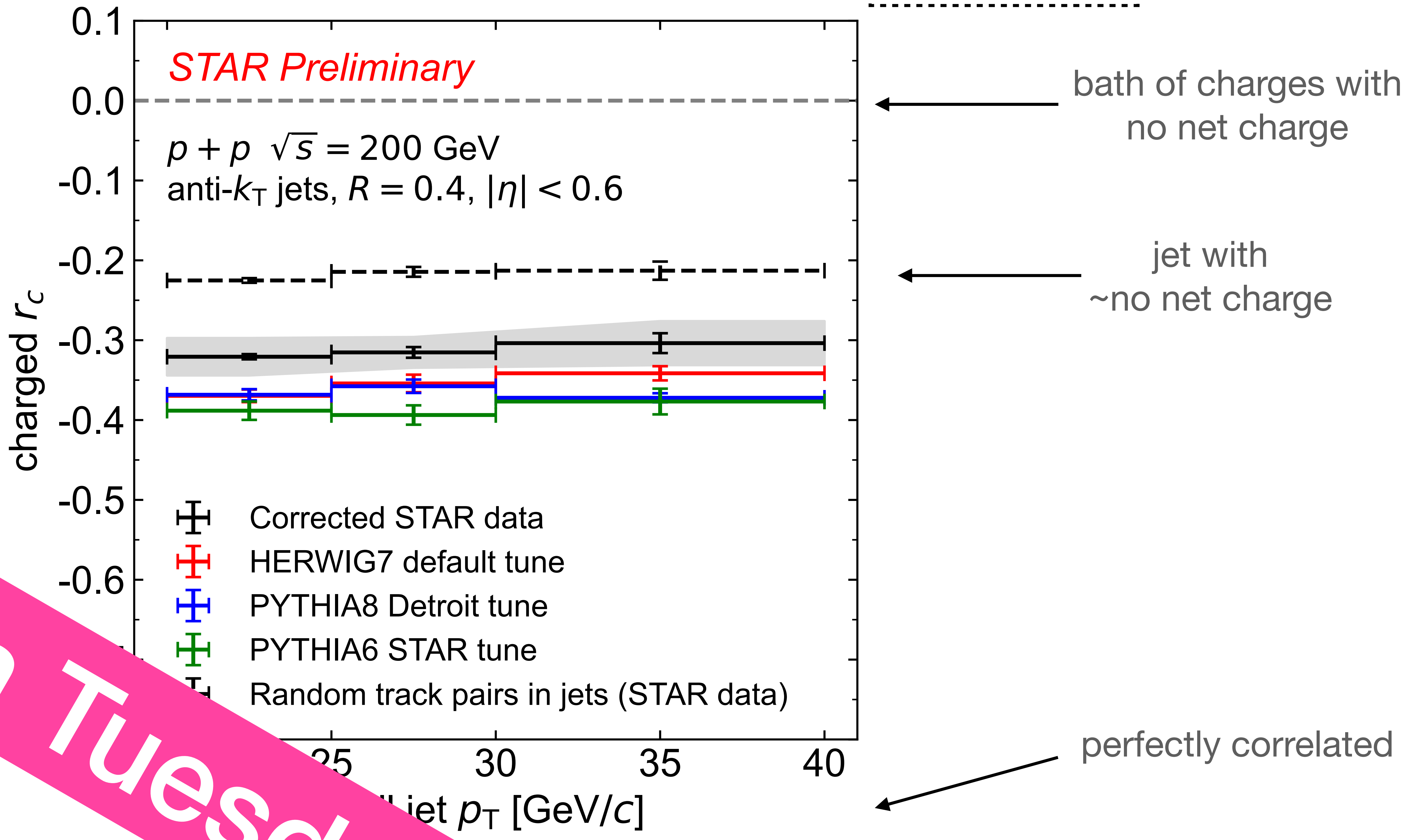
Flavor correlators in jets

$$r_c(X) = \frac{d\sigma_{h_1h_2}/dX - d\sigma_{h_1\bar{h}_2}/dX}{d\sigma_{h_1h_2}/dX + d\sigma_{h_1\bar{h}_2}/dX}$$

$$r_c = \frac{N_{ss} - N_{os}}{N_{ss} + N_{os}}$$

Chien, Deshpande, Mondal, Sterman, PRD 105 (2022) 5, L051502





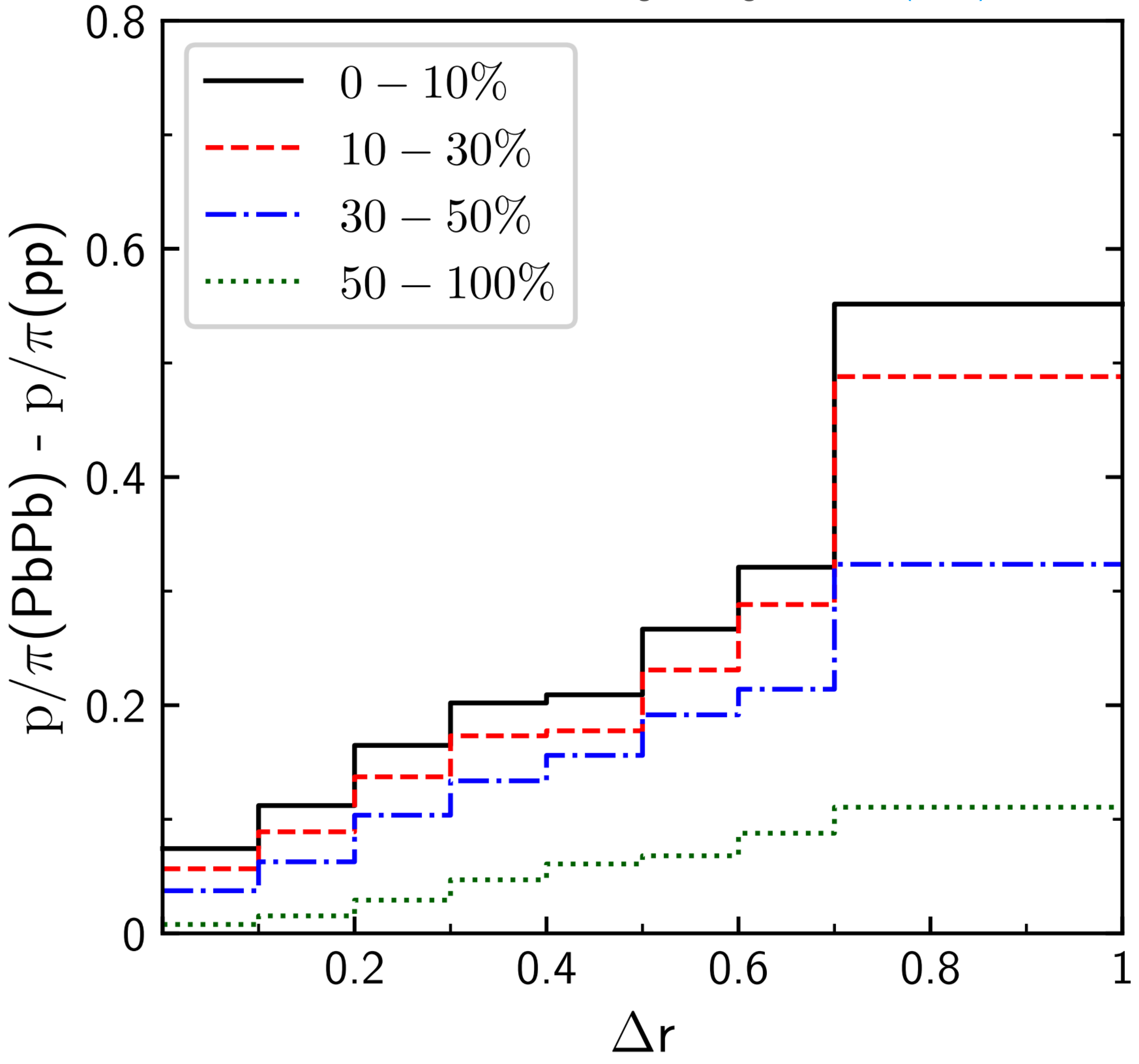
See Youqi's talk on Tuesday at 11 AM!

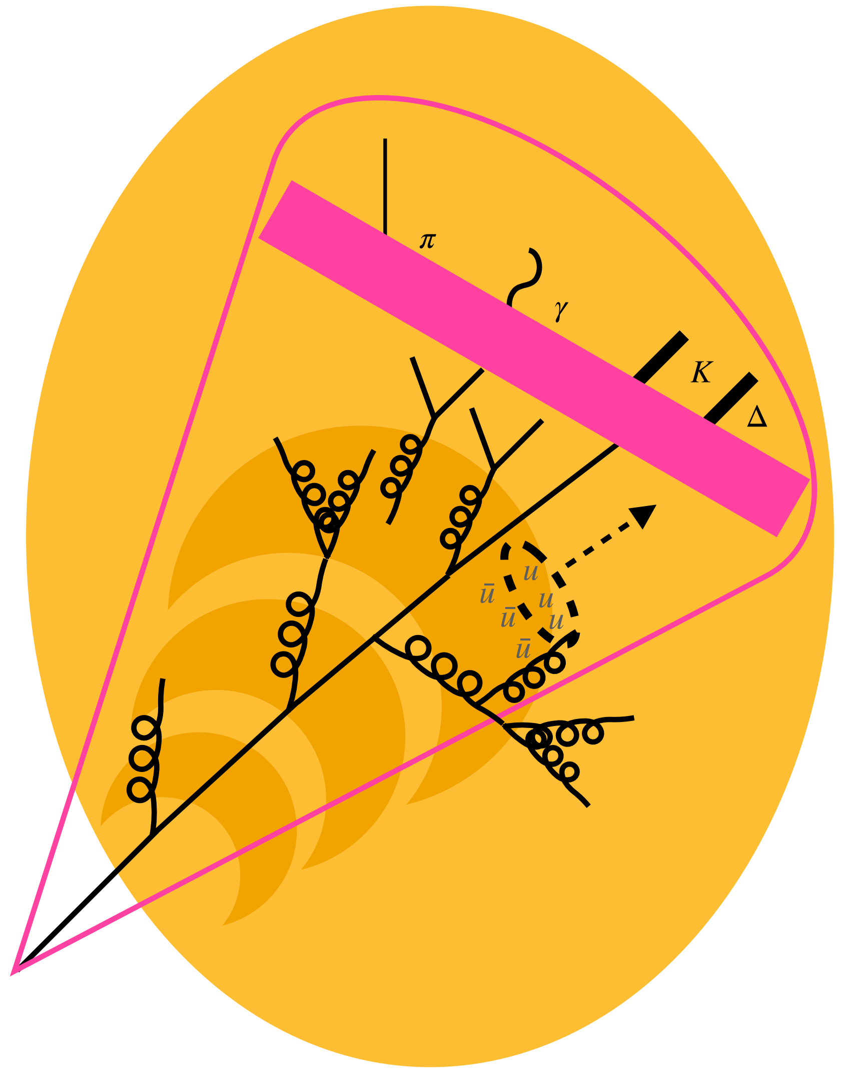
- r_c can probe contribution of string-like fragme[ntation]
- First measurement in pp: Pythia predicts more string [fragmen]tation than supported by data, but difficult to conclude with default [...]ne

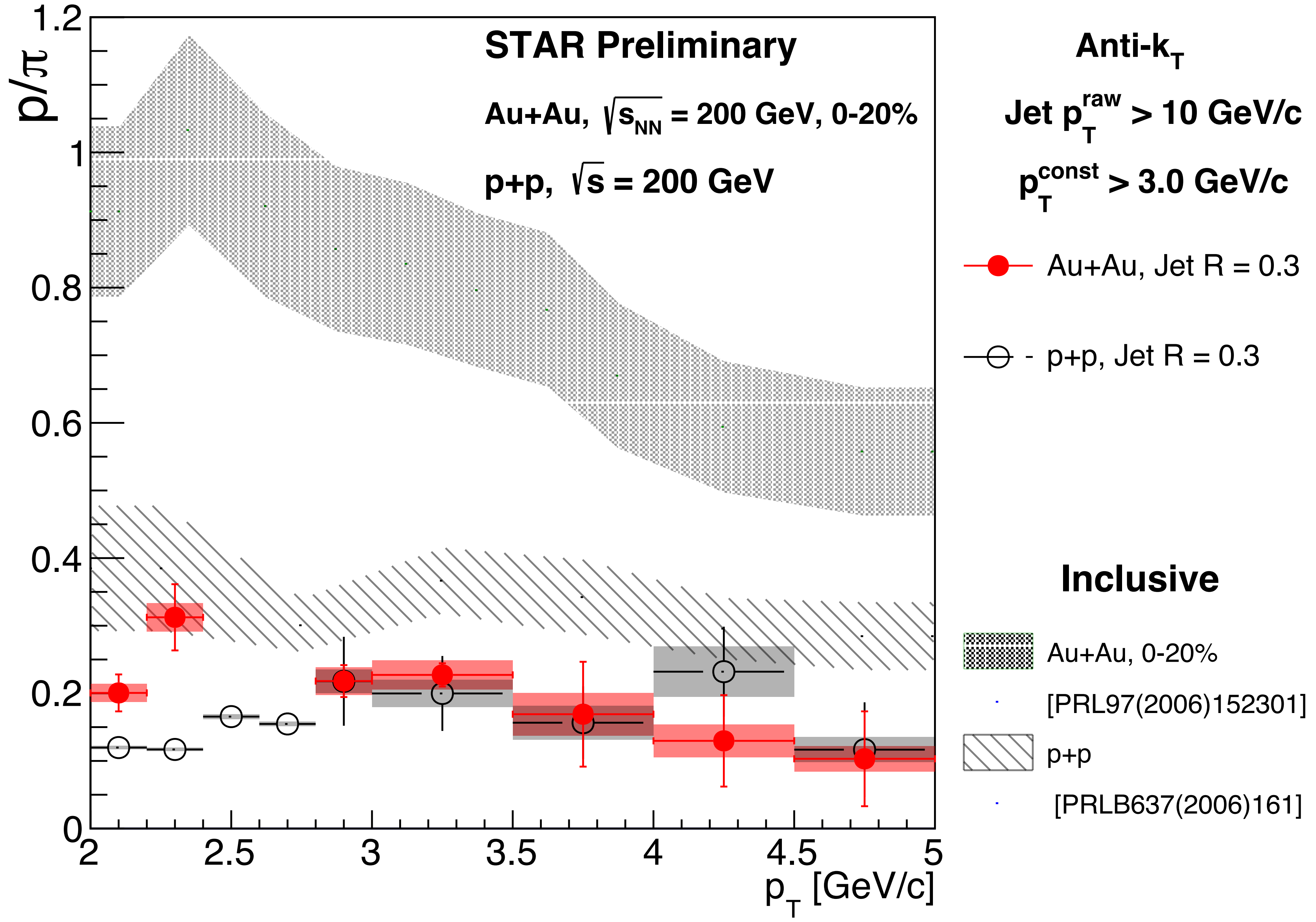
Baryon-to-meson ratios

Signature of medium response?

Luo, Mao, Qin, Wang, Zhang, PLB 837 (2023) 137638







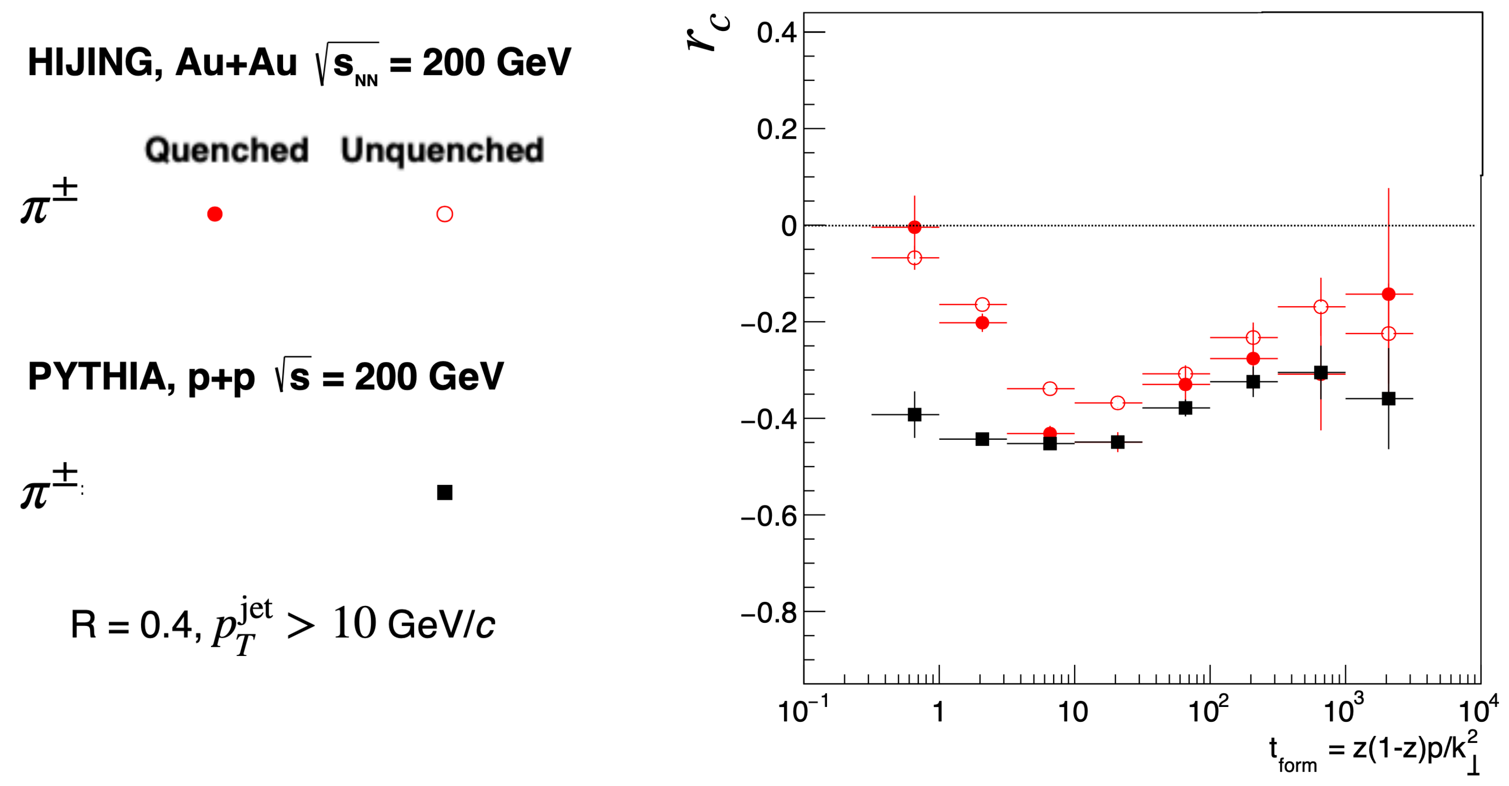
- Possible sign of parton coalescence in jet: enhanced baryon-to-meson ratio in AA
- No observed modification of *in-jet* p/π ratio for R = 0.3 jets

Future prospects

Constituent identity

- *D^0-jet*: adding another dataset to increase statistics; adding generalized angularities; tightening D^0 p_T threshold

Esha, Hard Probes 2023



- r_c: extension to heavy-ion collisions underway

- Herwig tune to RHIC kinematics ongoing

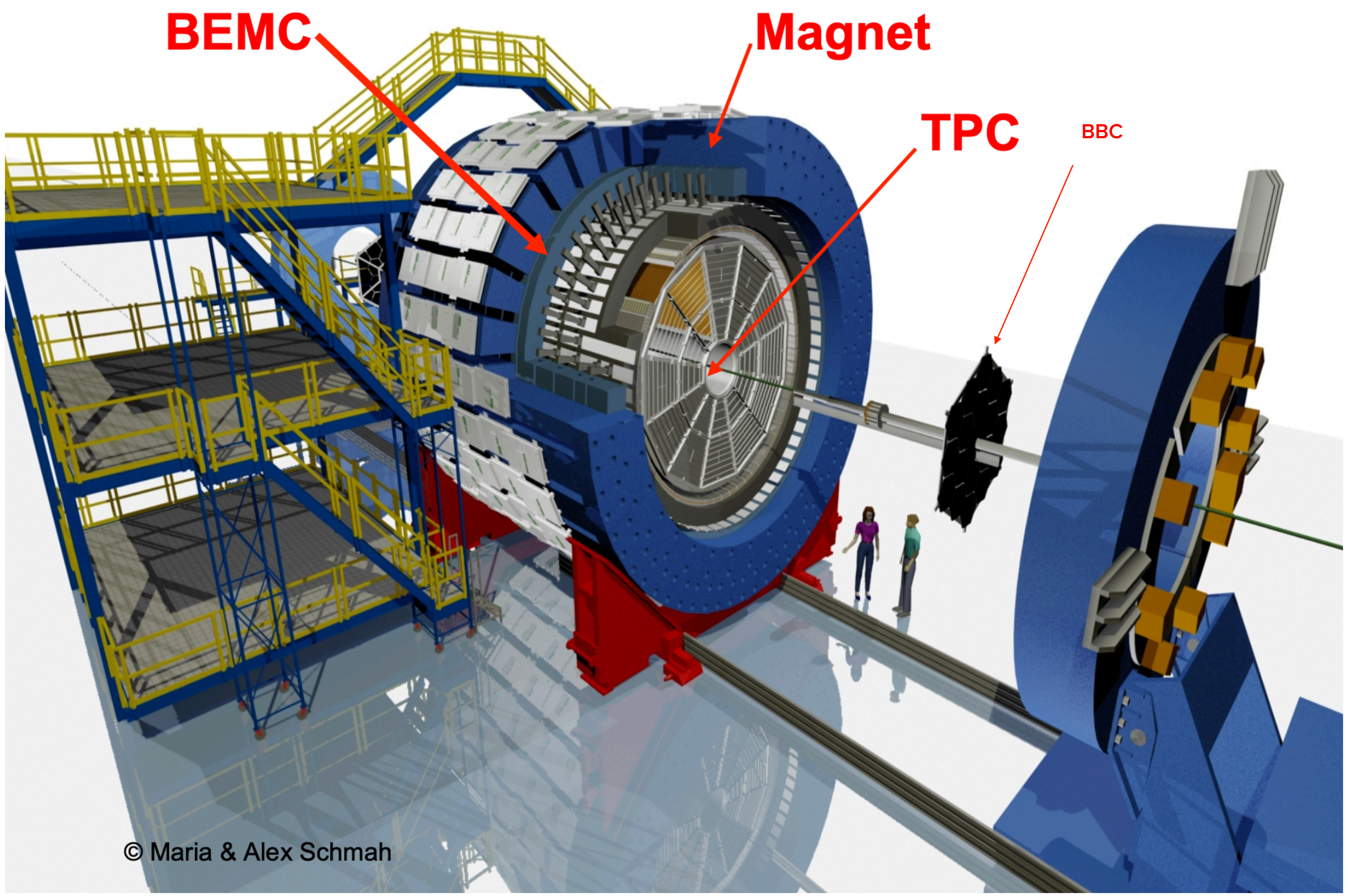
- *Baryon-to-meson ratios*: studying dependence on constituent p_T threshold

What we've learned

- **Precision era of jet substructure**: many-dimensional corrections and correlations, systematically mapping the phase space for QCD radiation in vacuum at lower $\sqrt{s}$
- **First measurements** of new observables **EECs and** r_c separate perturbative and non-perturbative physics cleanly for **improved theoretical control**
- Demonstrated **strong dependence of quenching** on N_{part} (**~similar energy density**) across collision species; **more energy lost at RHIC** than LHC, relative to jet p_T; **jet profile broadening**, with radiation roughly recovered by ~0.5 radians; and **finite jet v_2. No quenching** observed in **pAu** collisions.
- **No medium-induced hadrochemistry** effect observed. **Suppression of jets with hard-fragmenting charm hadrons** but as yet no observed corresponding enhancement of soft-fragmented charm jets or diffusion to broader angles

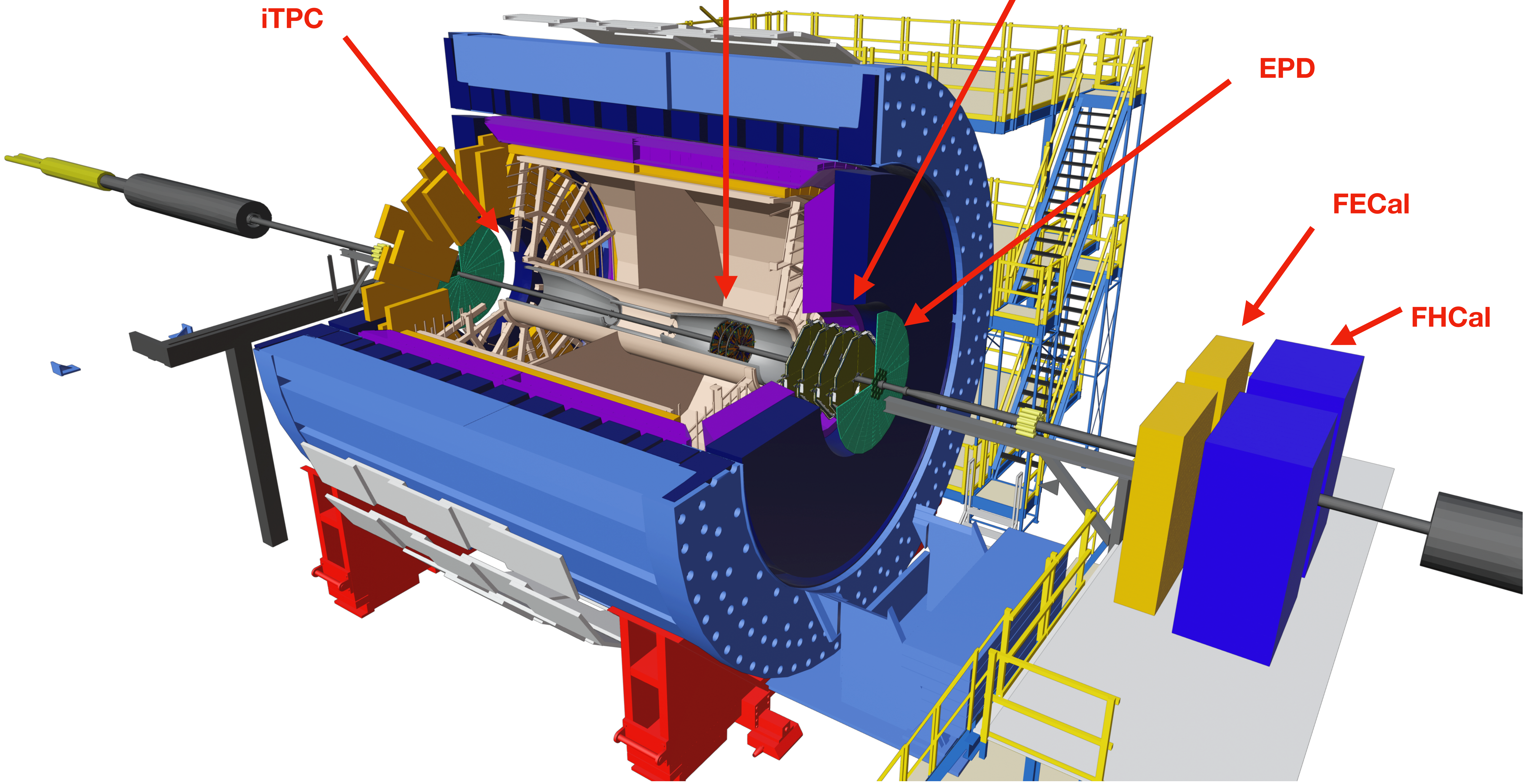
Jets at STAR

In the 2010s



Jets at STAR

In the 2020s!



Precision tracking

Forward jets → different x; q v. g

Unbiased centrality/ EP determination

Etc!

Backup

STAR Zero Degree Calorimeters