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WAYNE STATE UNIVERSITY

Jets and heavy quarkonia production in small system collisions at RHIC

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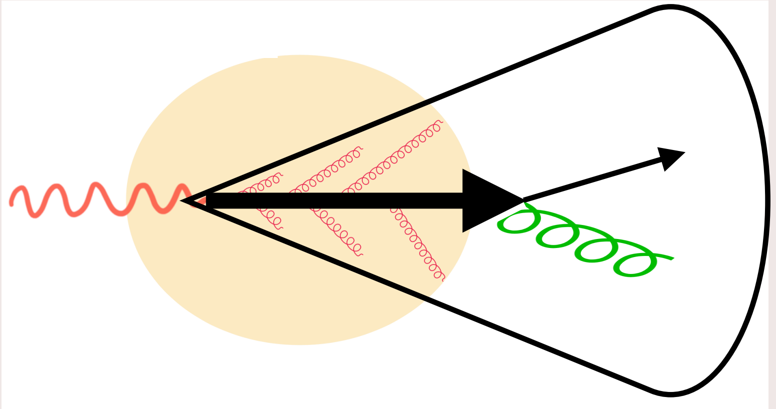
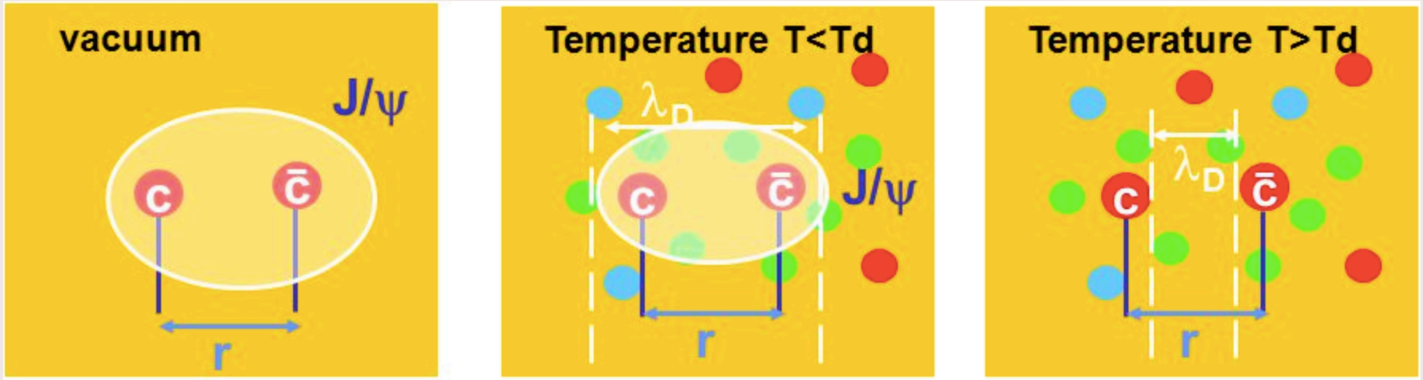
RHIC/AGS Annual Users' Meeting (online)
June 9, 2021

*Jets, quarkonia produced in hard process before QGP formation (< 1 fm)

Hard probes of the QGP





Colored partons of varying virtuality resolve structure of medium at different scales;
jets are broadened and softened

$Q\bar{Q}$ pairs are Debye screened by color charges in the medium;
excited states dissociate (➔ suppressed di-lepton yields) at different Ts

2015 NP LRP

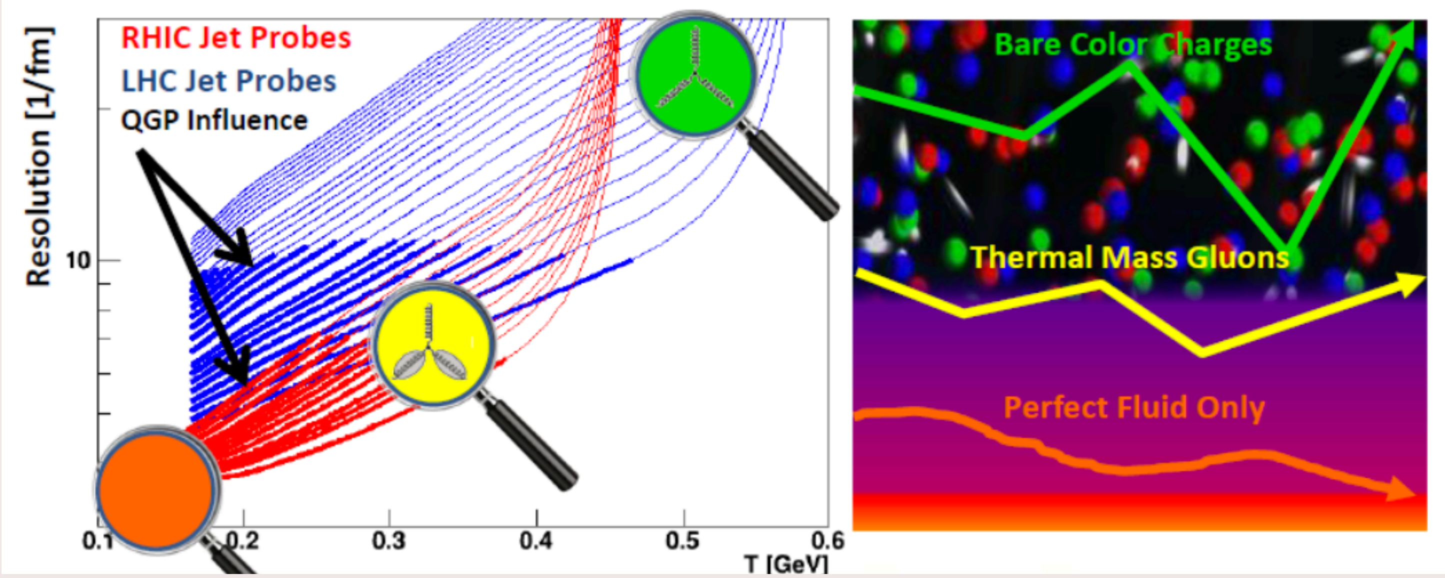
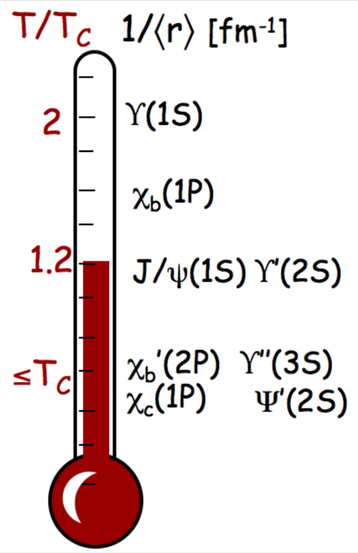
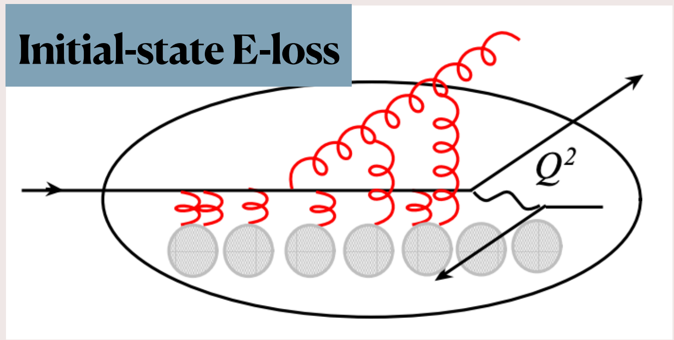


Image: Ágnes Mócsy

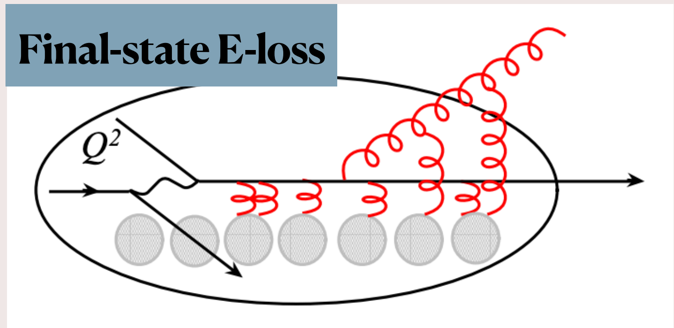


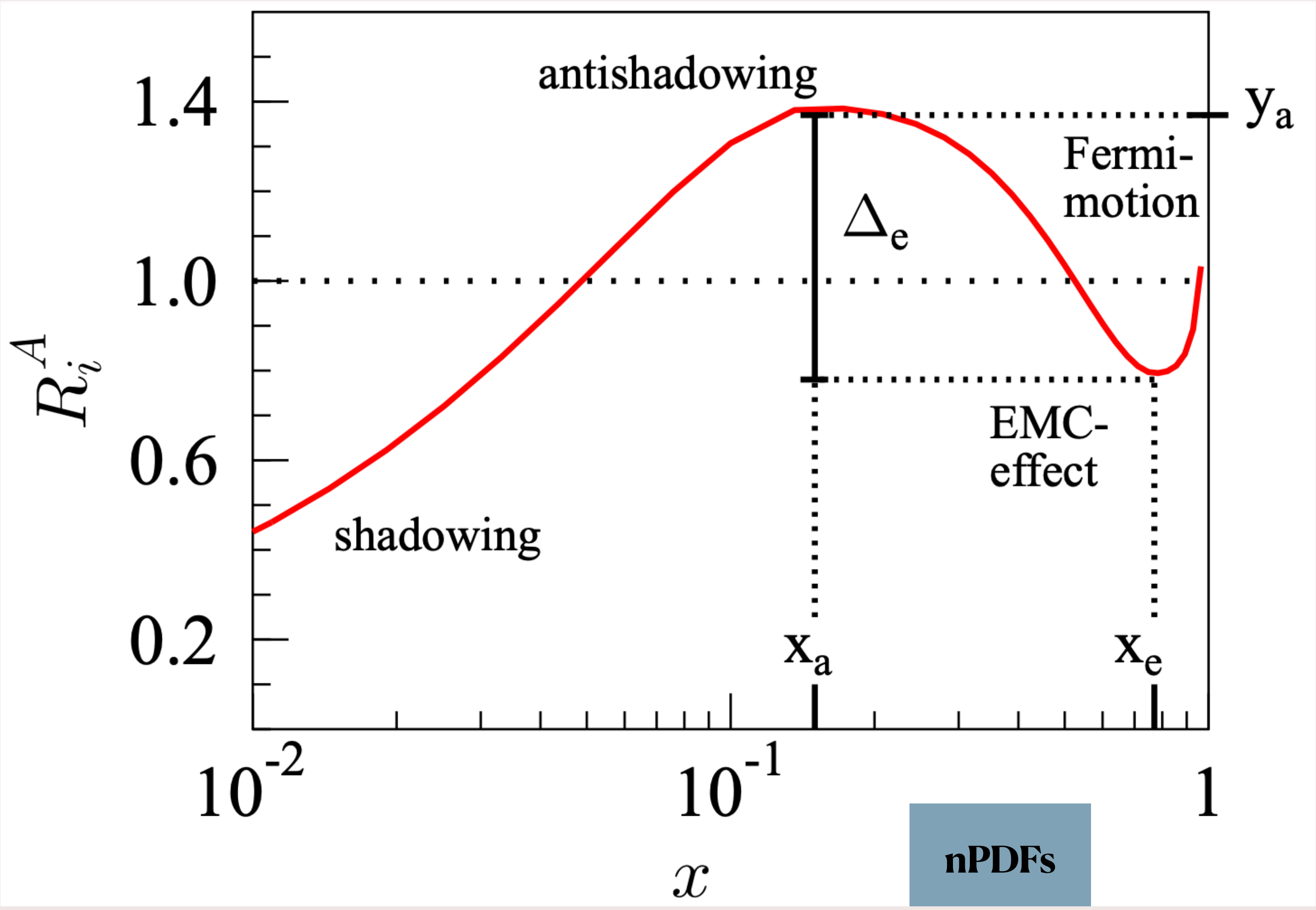


[Vitev, PRC 75, 064906 (2007)]

CNM effects

(on jets)



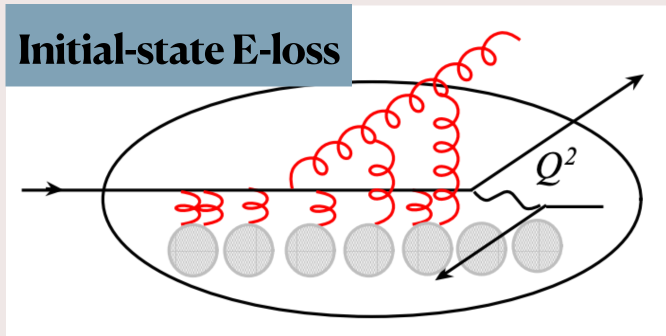


[Eskola, Paukkunen, Salgado, JHEP 07 102 (2008)]

$x \approx 2p_T e^{-y}/\sqrt{s_{NN}}$ [1]

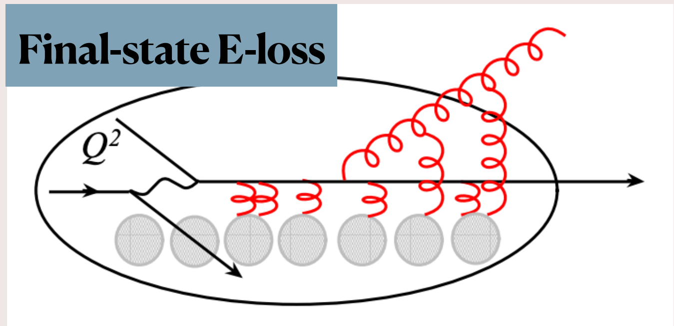
[1]Andronic *et al.*, Eur. Phys. J. C 76, 107 (2016)

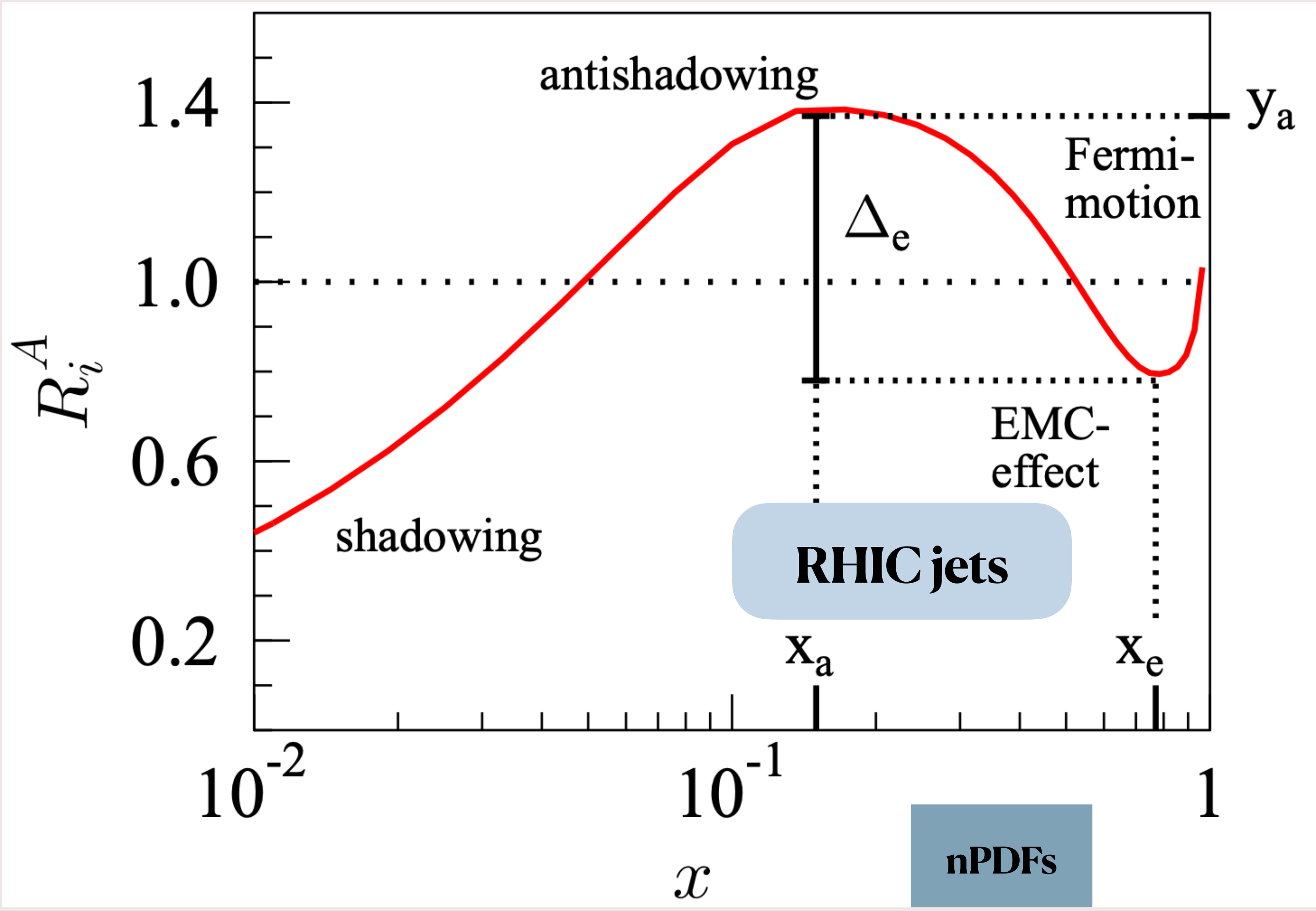
[Vitev, PRC 75, 064906 (2007)](#)



CNM effects

(on jets)





$x \approx 2p_T e^{-y} / \sqrt{s_{NN}}$ [1]

[Eskola, Paukkunen, Salgado, JHEP 07 102 (2008)](#)

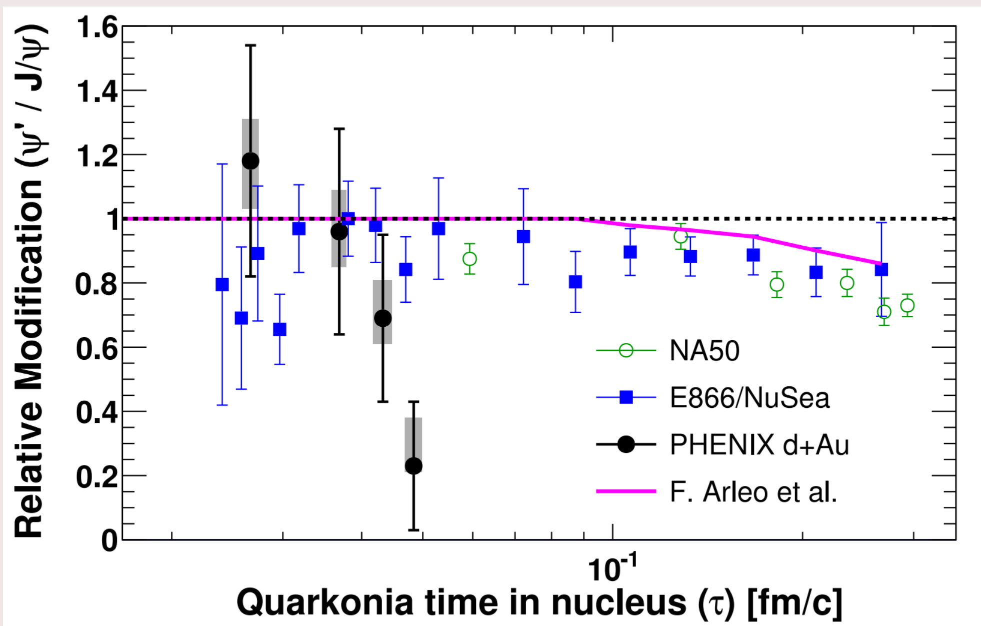
$y = 0,\ 5 < p_T < 30$ GeV/c: $0.1 \lesssim x \lesssim 0.5$ for *p*Au

[1]Andronic *et al.*, Eur. Phys. J. C 76, 107 (2016)

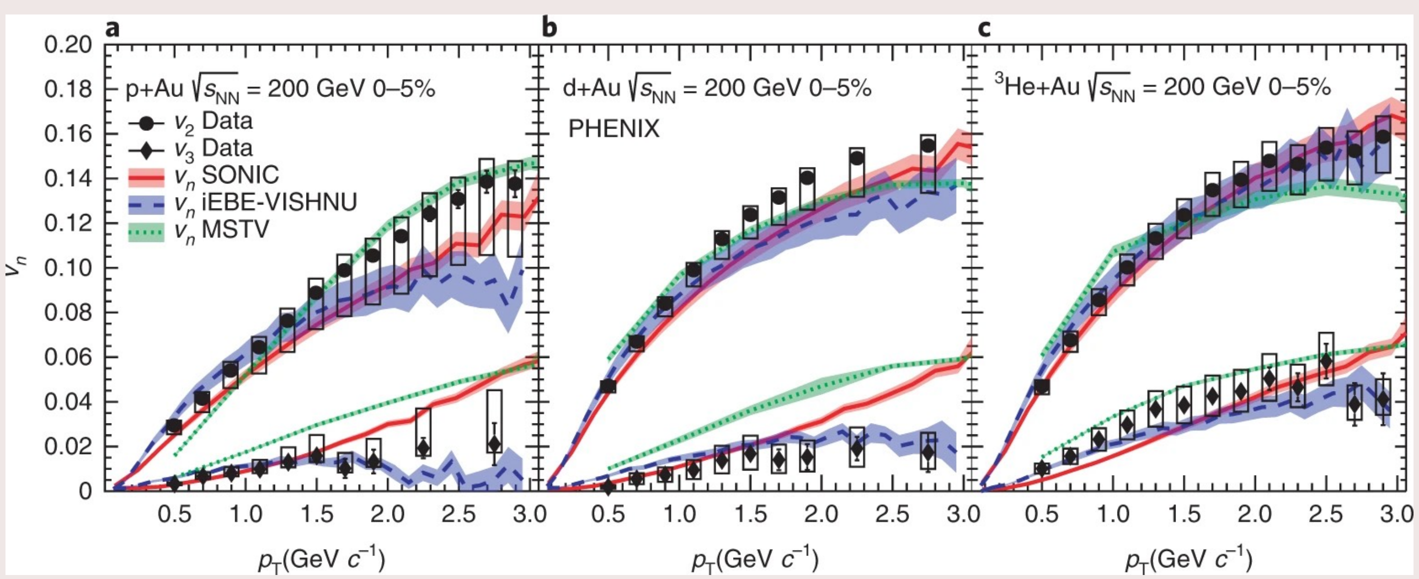
Introduction to small systems

(Potential) hot nuclear matter effects

PHENIX, PRL 111, 202301 (2013)



PHENIX measured different nuclear modification of $\psi(2S)$ and J/ψ
→ final state effect



PHENIX, Nat. Phys. 15, 214–220 (2019)

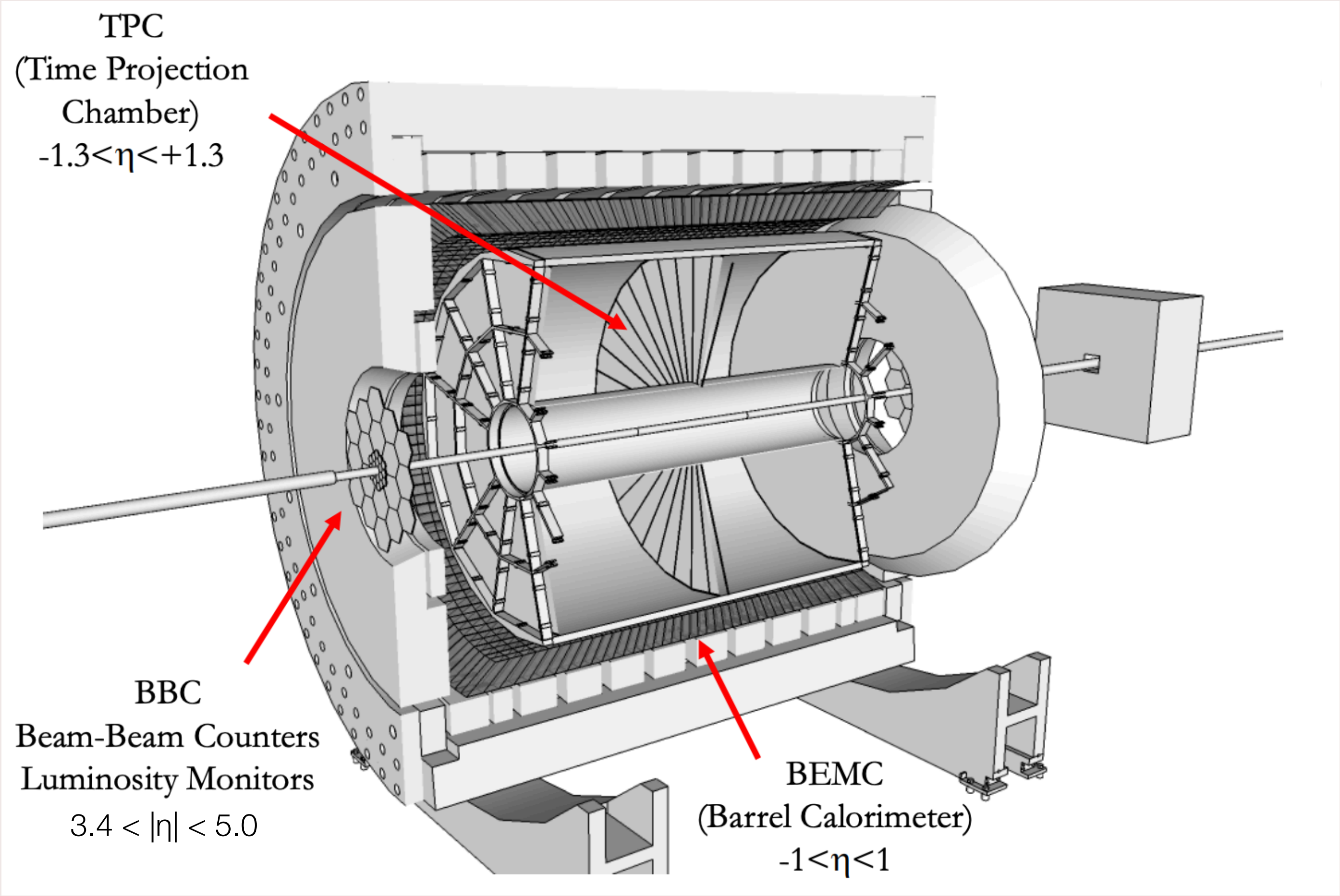
PHENIX observes flow in small systems (going back to 2013[1]) (although disagreement with STAR, see Belmont, RHIC/AGS AUM 2020)

Can we test for hot nuclear matter effects with hard probes?

[1] PHENIX, PRL 111, 212301 (2013)

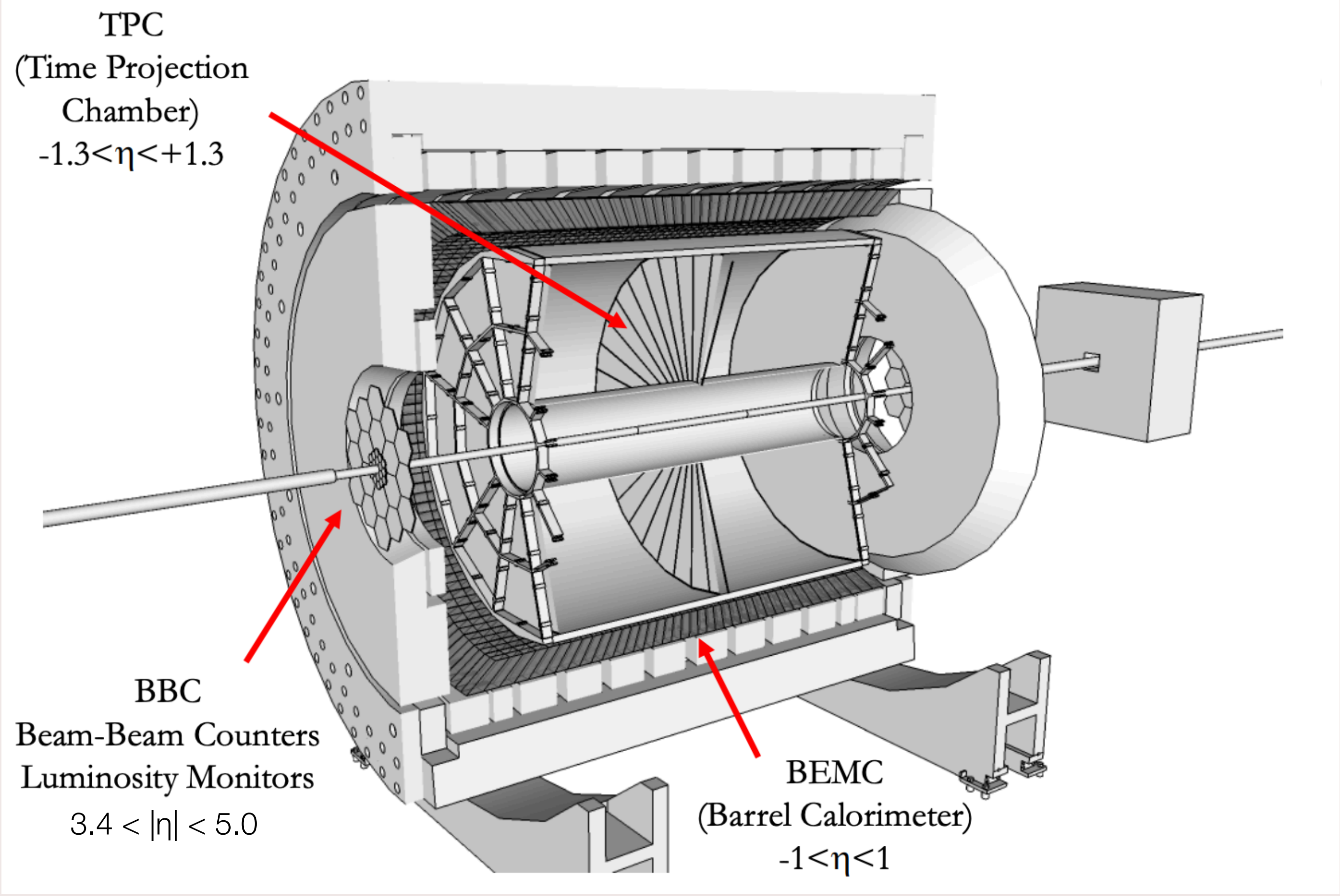
Detectors

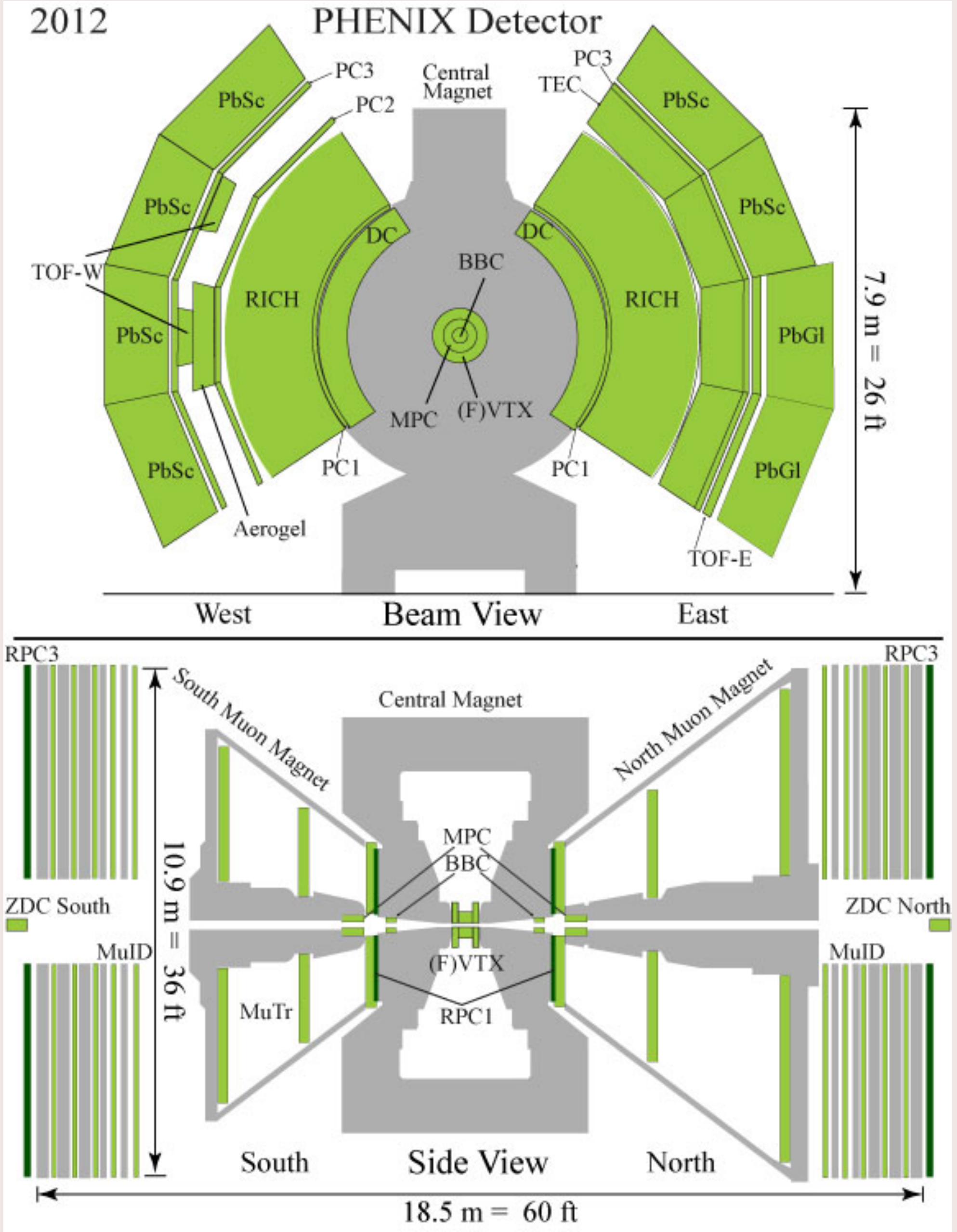
STAR: $h, e^{\pm}, \gamma$ in $|\eta| < 1, \phi \in 2\pi; 3.4 < |\eta| < 5.0$



Detectors

STAR: $h, e^{\pm}, \gamma$ in $|\eta| < 1, \phi \in 2\pi$; $3.4 < |\eta| < 5.0$

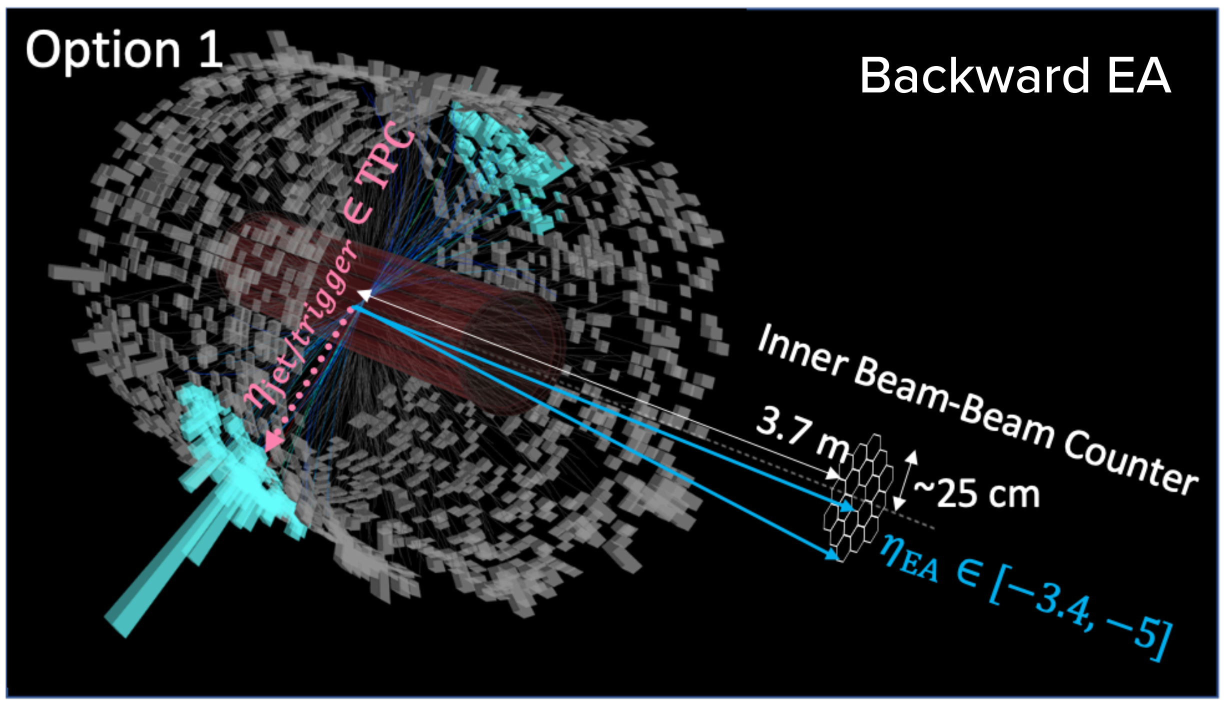


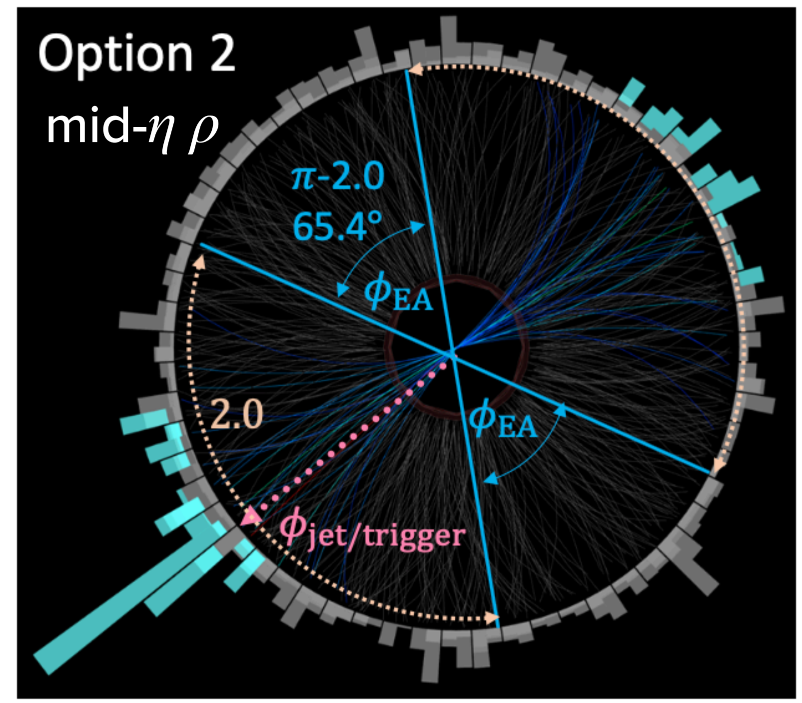


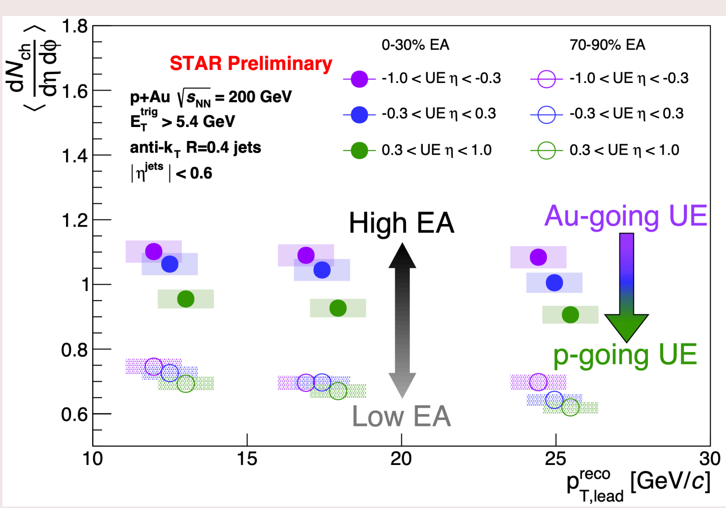
PHENIX: $h, e^{\pm}, \gamma$ in $|\eta| < 0.35, \phi \in 2 \times \pi/2$; μ in $1.2 < |\eta| < 2.2$

Event activity / centrality

In STAR, two options for definition of the activity of an event away from the jet in pA collisions



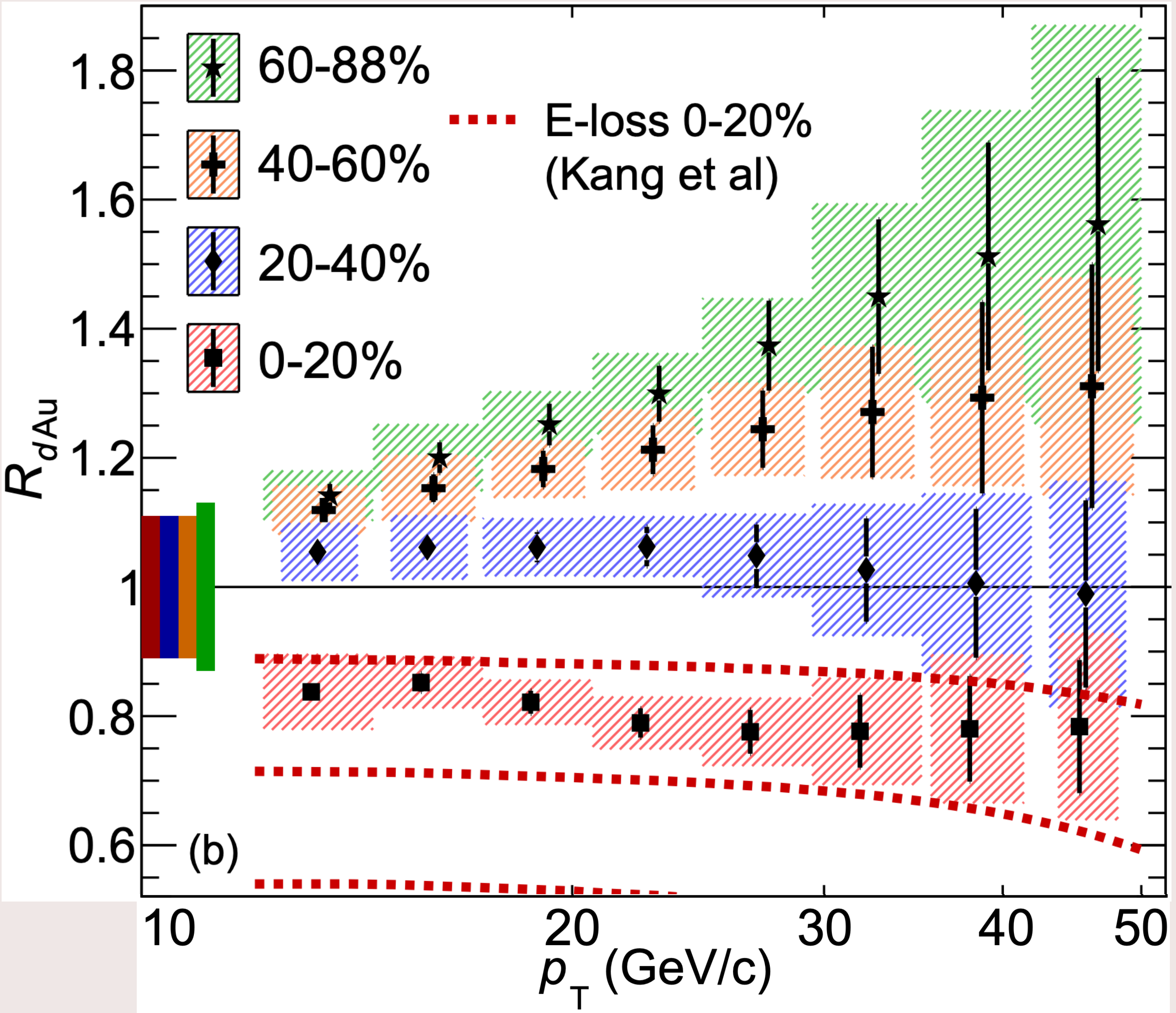




strongly correlated!

PHENIX uses a BBC (Čerenkov, $-3.9 < \eta < -3.1$) and reports centrality
(PHENIX, PRC 90, 034902 (2014))

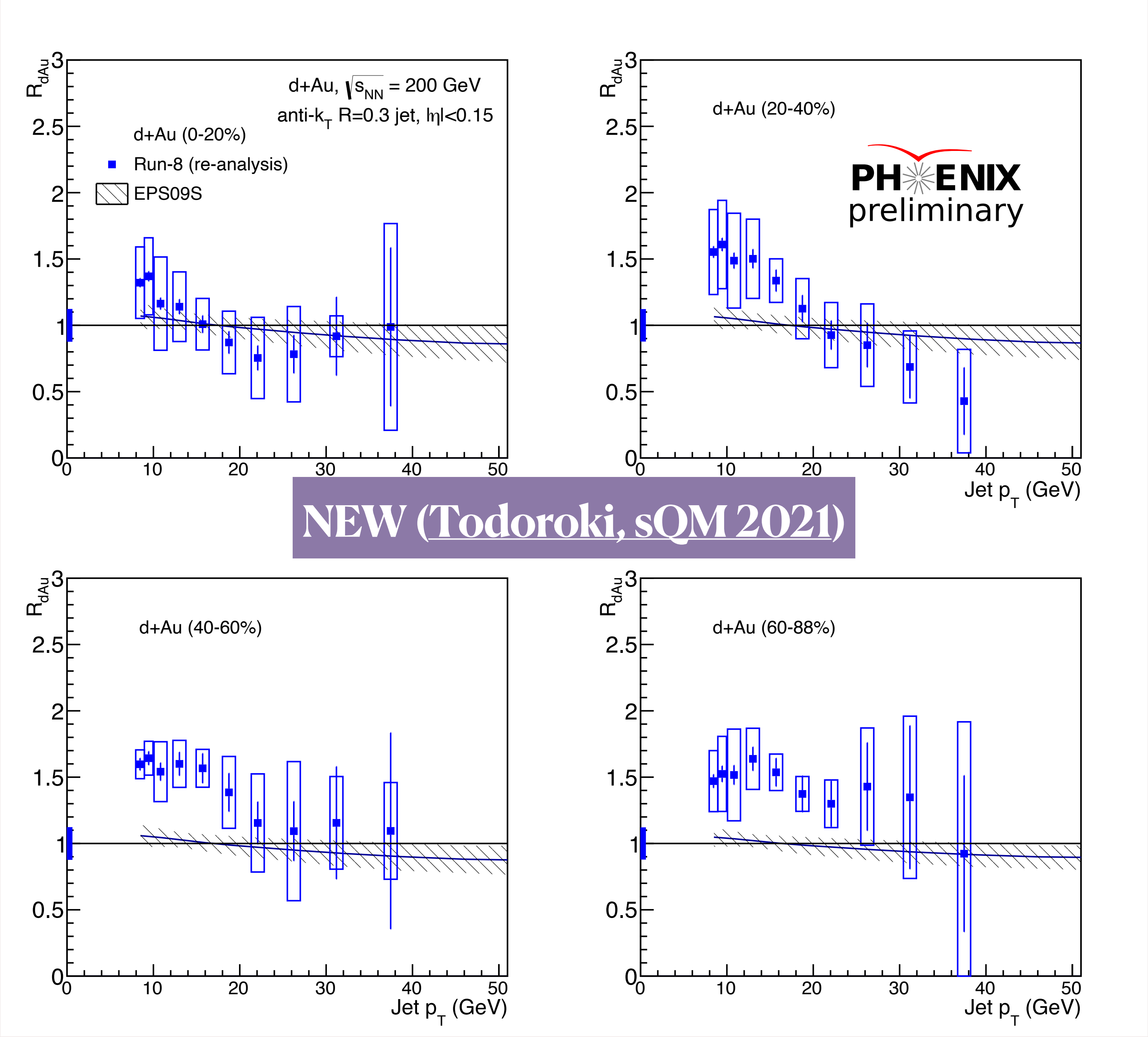
PHENIX jet R_{dAu}



PHENIX, PRL 116 (2016), 122301

"...an enhancement in 40%–88% events...is challenging to understand as a distinct physics effect."

PHENIX jet $R_{d\mathrm{Au}}$



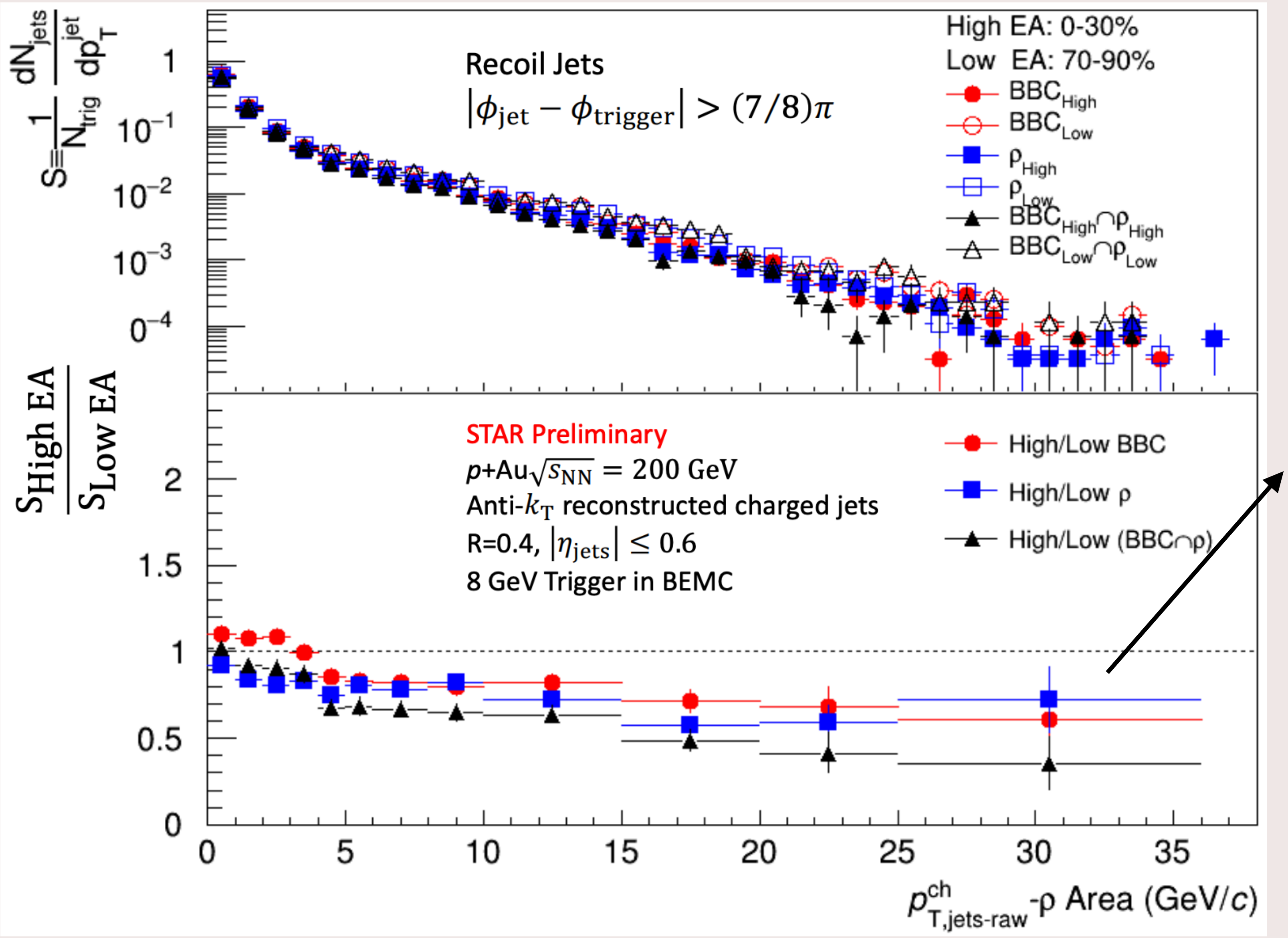
2016: centrality-dependent yield suppression in central collisions **2021**: similar relative centrality-dependence to 2016; different $p_{\mathrm{T,jet}}$ dependence; no suppression within systematics

Model including nPDF effects is centrality-independent

Model predicts $R_{d\mathrm{Au}} \sim 1$, low p_T enhancement is not captured

Could it be a correlation between the energy of the hard process and the centrality? (See next)

STAR semi-inclusive jet spectra

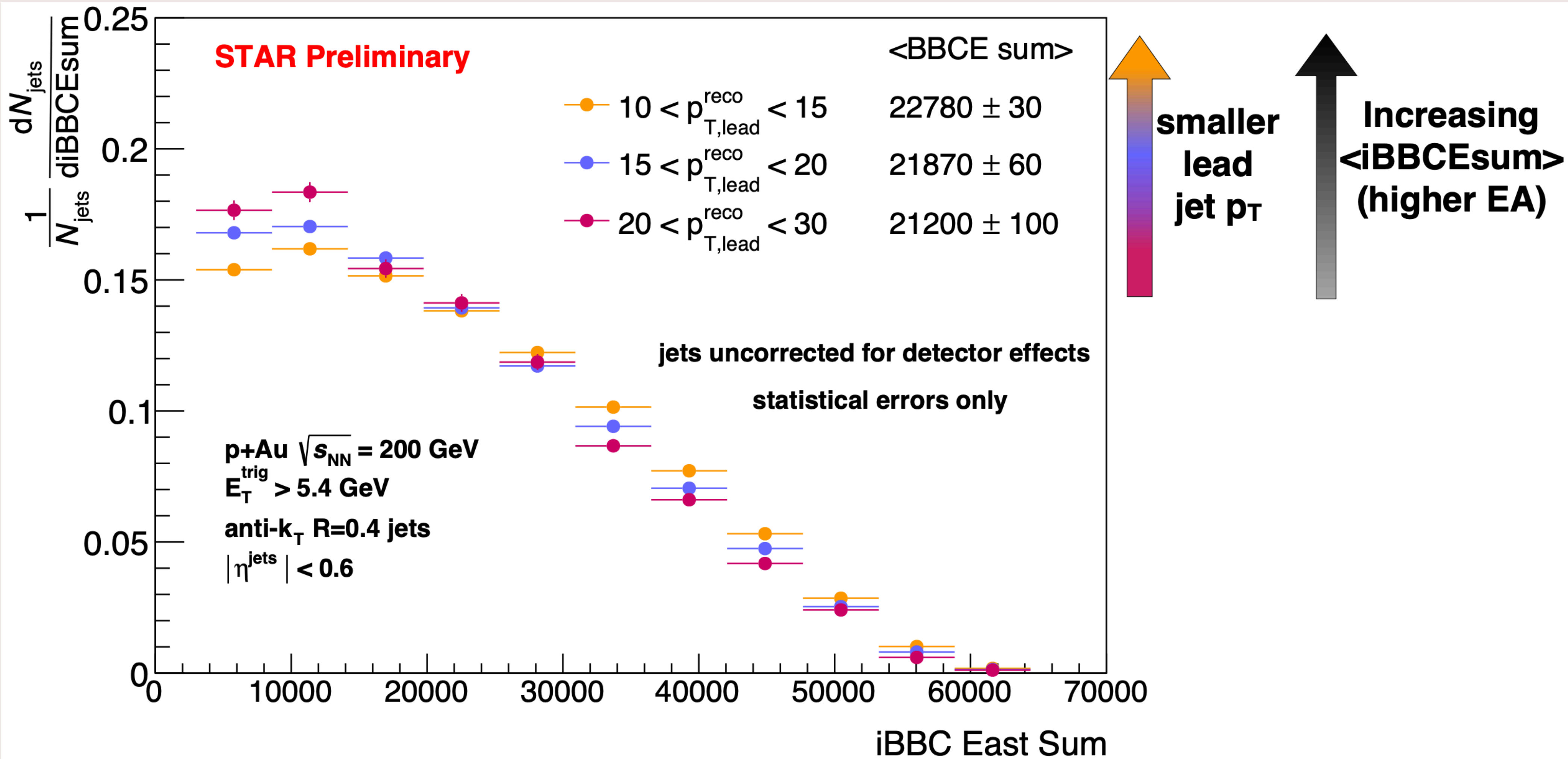


Recoil charged jet on away-side from high-E_T trigger suppressed in high-EA compared to low-EA

Path-length dependent energy loss in nuclear environment?

But no broadening of acoplanarity for high-EA recoil jets +
Trigger and recoil are modified similarly (backup)

STAR event activity at backward-η



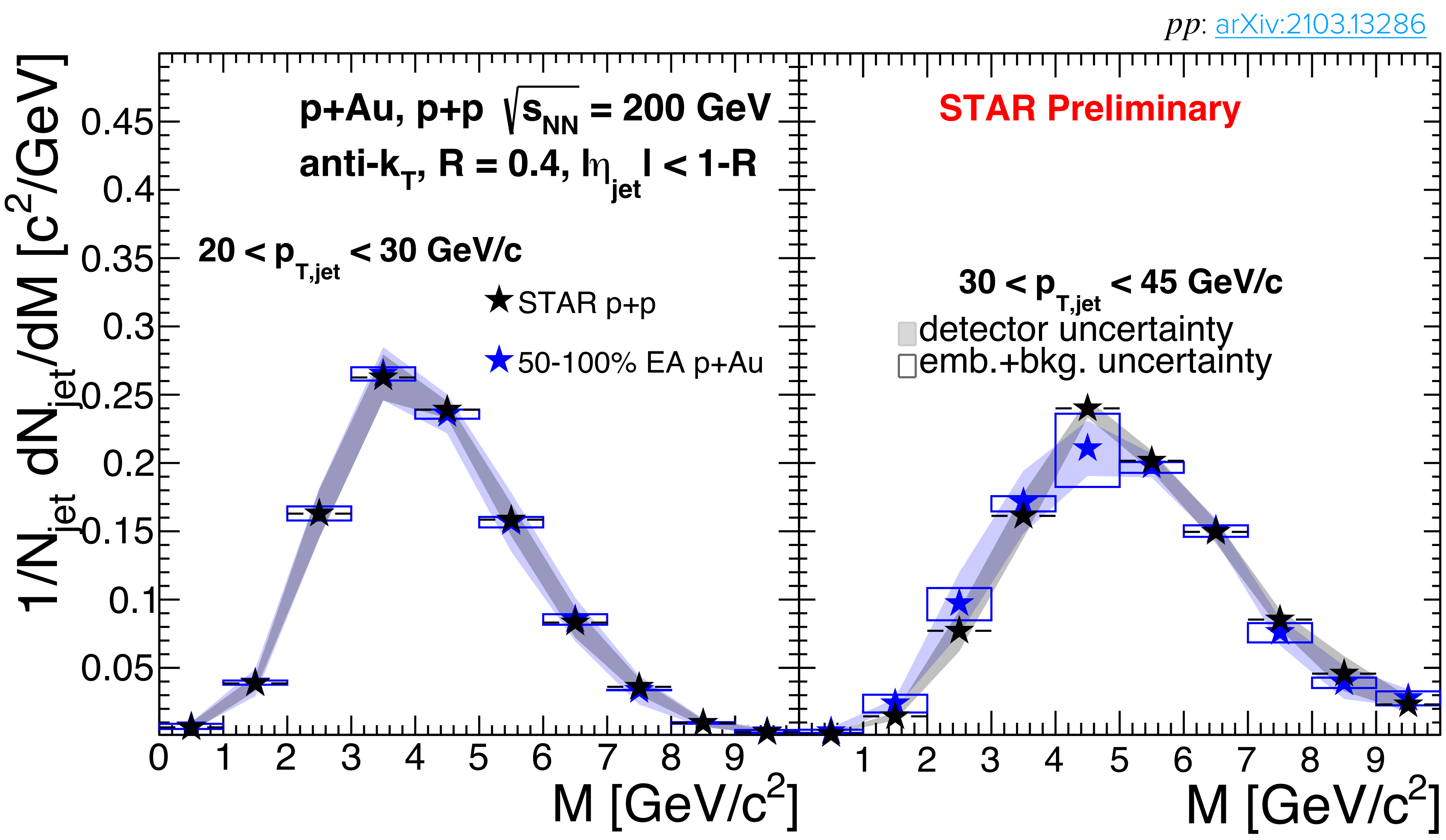
<u>BBC signal anti-correlated with jet p_T</u>

Similar effect observed in PYTHIA-8 Angantyr at generator-level (Stewart, DNP 2020)

Mid-rapidity jet + large-rapidity EA anticorrelation → early-time effect
E.g. initial proton configuration: higher-x → smaller cross section; simple E conservation; etc.

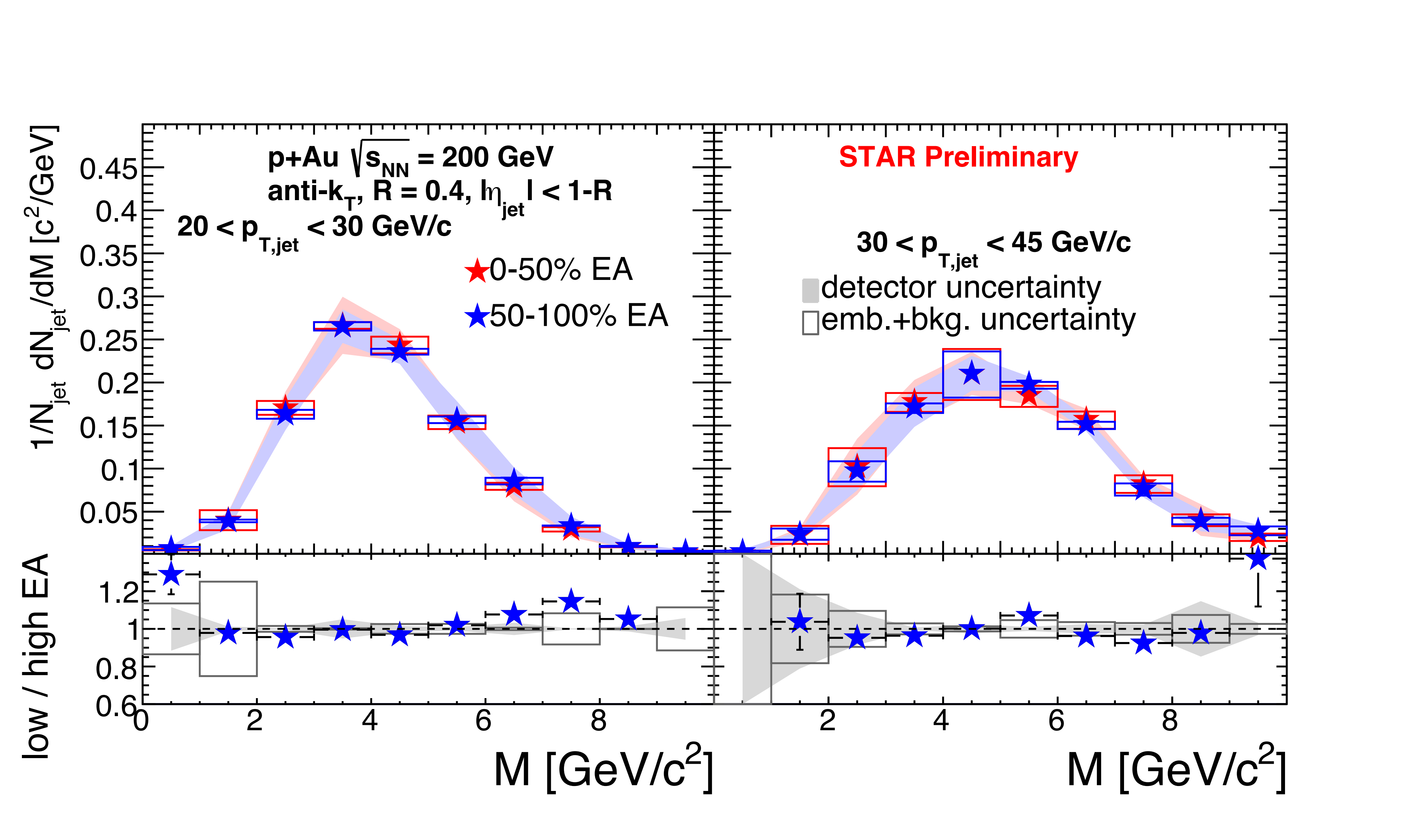
[Alvioli, Cole, Frankfurt, Perepelitsa, Strikman, PRC 93, 011902(R) (2016)]

*p*Au inclusive jet mass at STAR



Low-EA jet mass is comparable to *pp* in systematic and statistical uncertainties

*p*Au inclusive jet mass at STAR

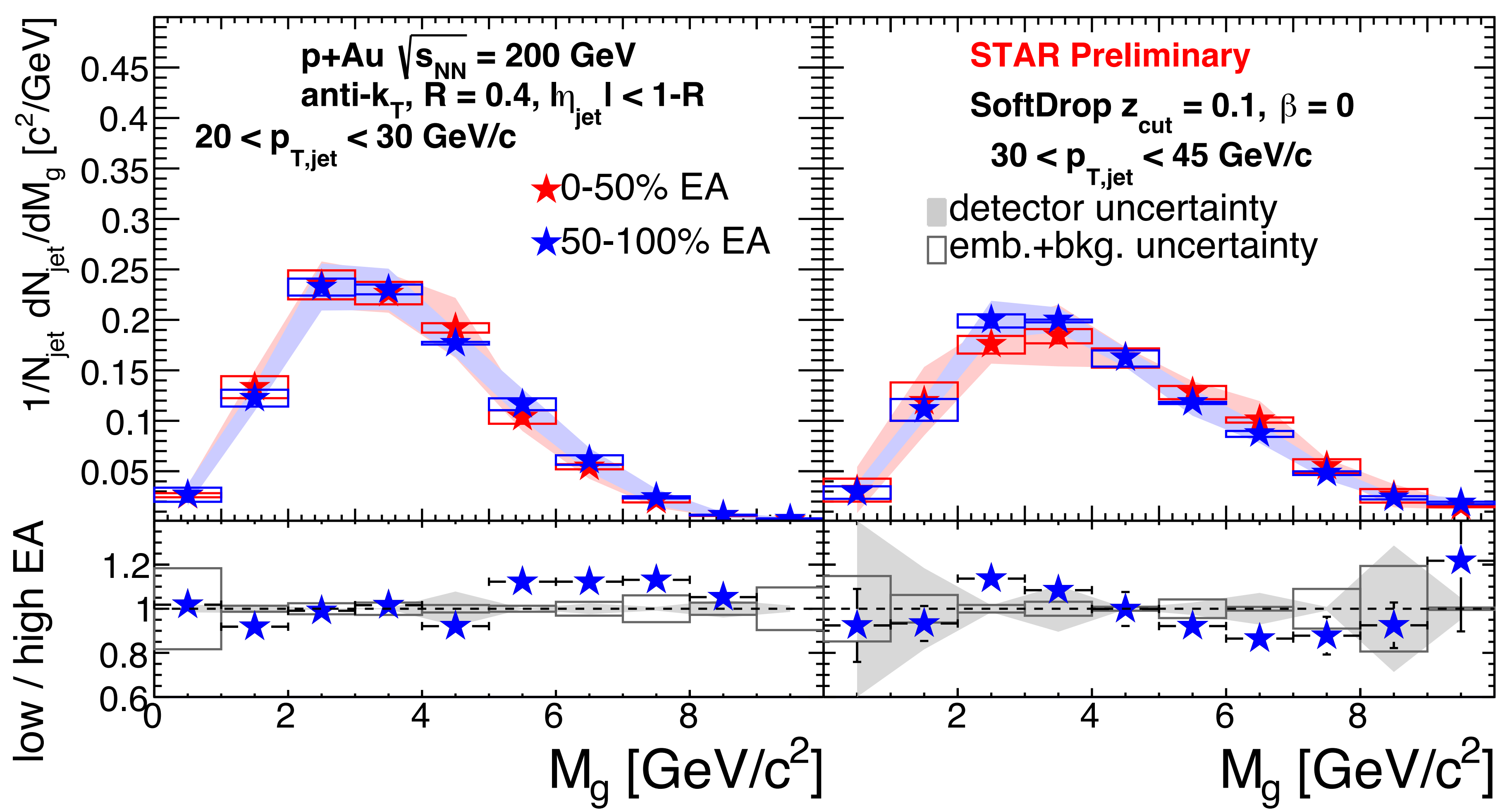


Low- and high-EA mass ratio is unity within systematic and statistical uncertainties

No significant modification to the jet mass

pAu inclusive jet mass at STAR

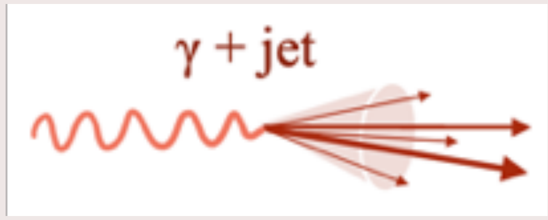
Note: p_T panels are *ungroomed* jet p_T

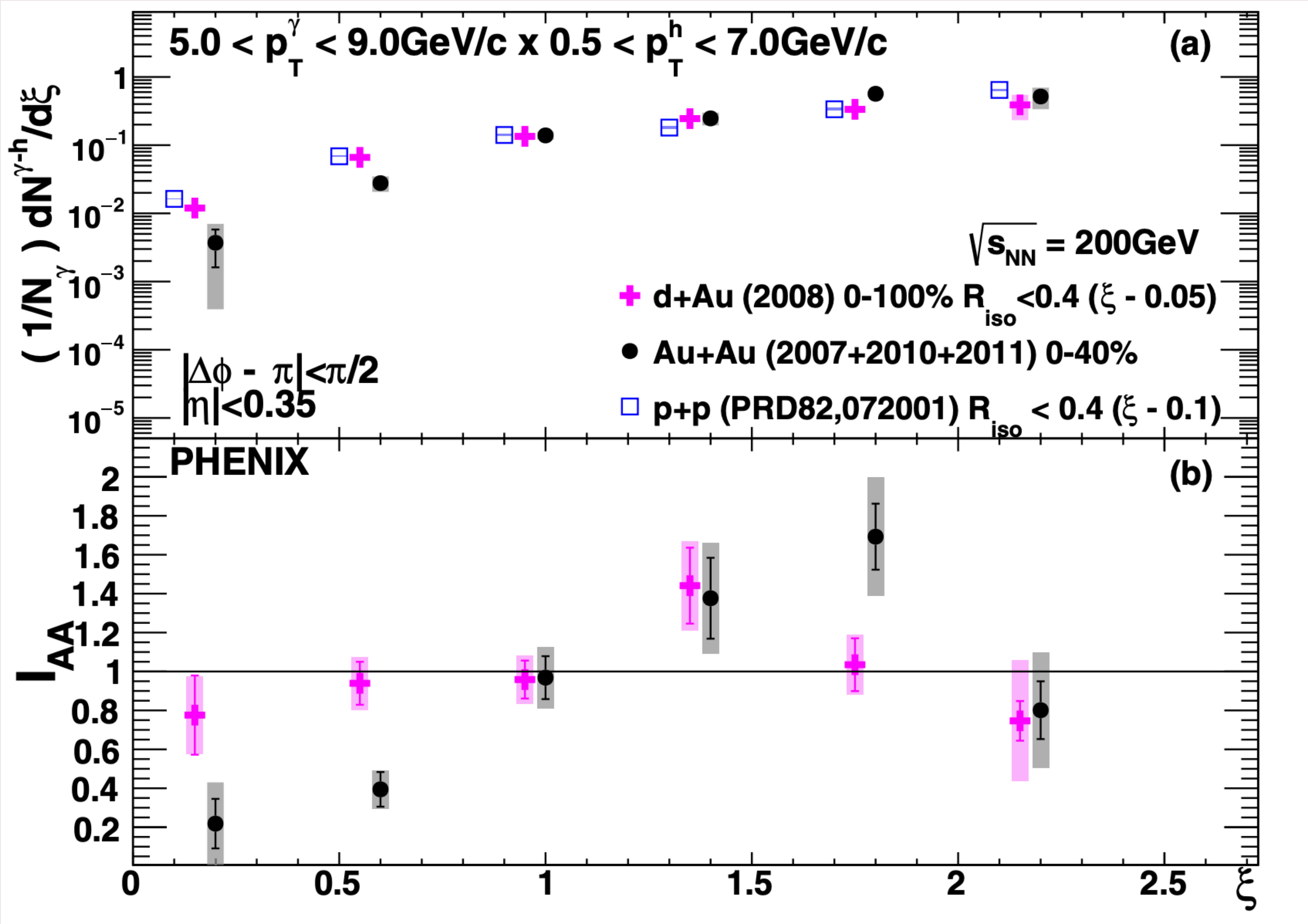


Low- and high-EA mass ratio is unity within systematic and statistical uncertainties

No significant modification to the jet mass, core of jets unmodified as well

PHENIX $\gamma_{\text{dir}} - h$ correlations





[PHENIX, PRC 102, 054910 (2020)](#)

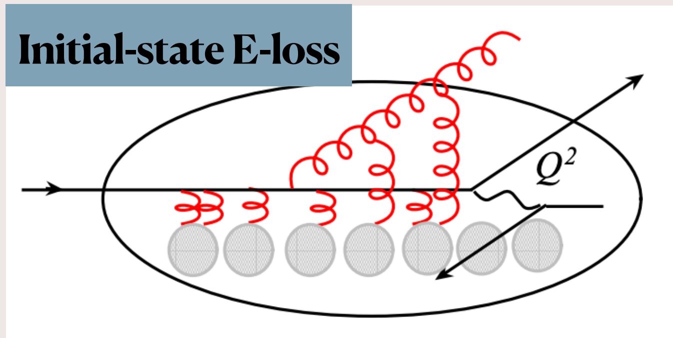
Hadrons recoiling from a hard direct photon experience CNM effects, fragmentation potentially modified

Hadron mom. frac.:
$\xi = \log(1/z_T)$

Fragmentation:
$I_{d\text{Au}} = Y_{d\text{Au}}/Y_{pp}$, Y = per-trigger yield

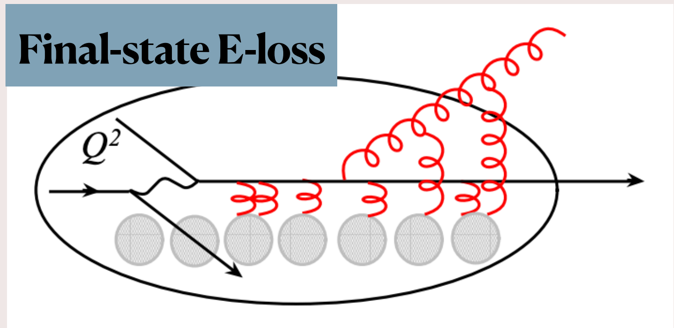
PHENIX observes *no significant modification* of jet fragmentation in dAu collisions for any z.

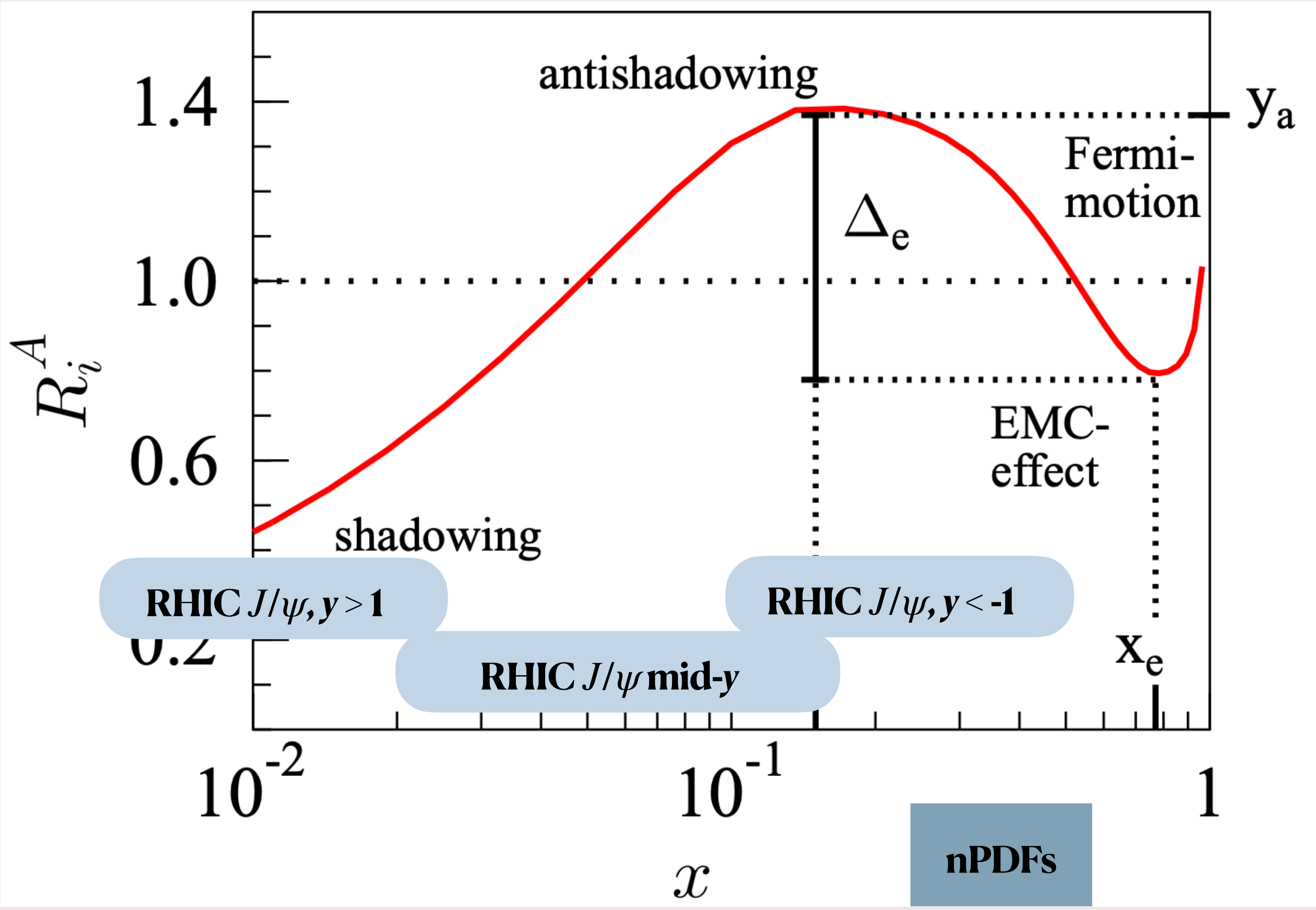
Vitev, PRC 75, 064906 (2007)



CNM effects

(on quarkonia)





Eskola, Paukkunen, Salgado, JHEP 07 102 (2008)

$x \approx (p_T + m_T)e^{-y}/\sqrt{s_{NN}}$ [1]

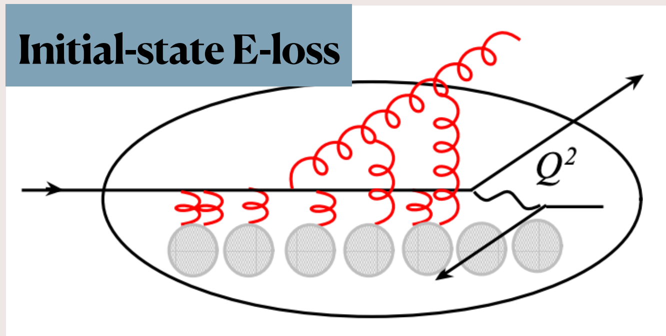
$y = 0,\ 1 < p_T < 10$ GeV/c: $0.03(2) \lesssim x \lesssim 0.16(1)$ for *p*(*d*)Au J/ψ

$y = -1.5,\ 1 < p_T < 10$ GeV/c: $0.1 \lesssim x \lesssim 0.5$ for *d*Au J/ψ

$y = 1.5,\ 1 < p_T < 10$ GeV/c: $0.005 \lesssim x \lesssim 0.025$ for *d*Au J/ψ

[1]Andronic *et al.*, Eur. Phys. J. C 76, 107 (2016)

Vitev, PRC 75, 064906 (2007)



CNM effects

(on quarkonia)

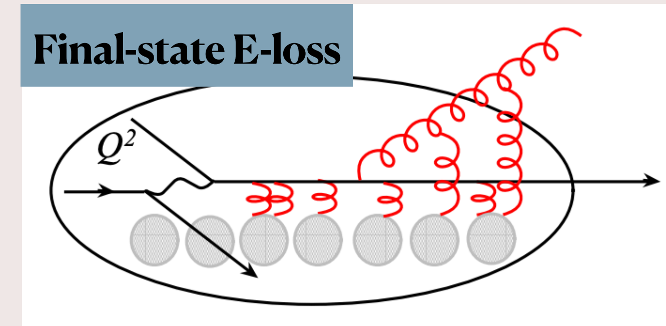
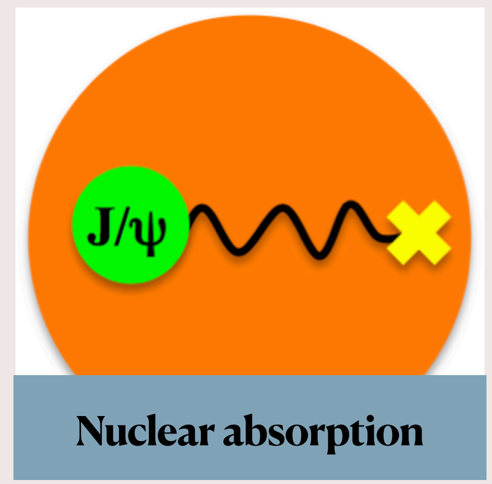
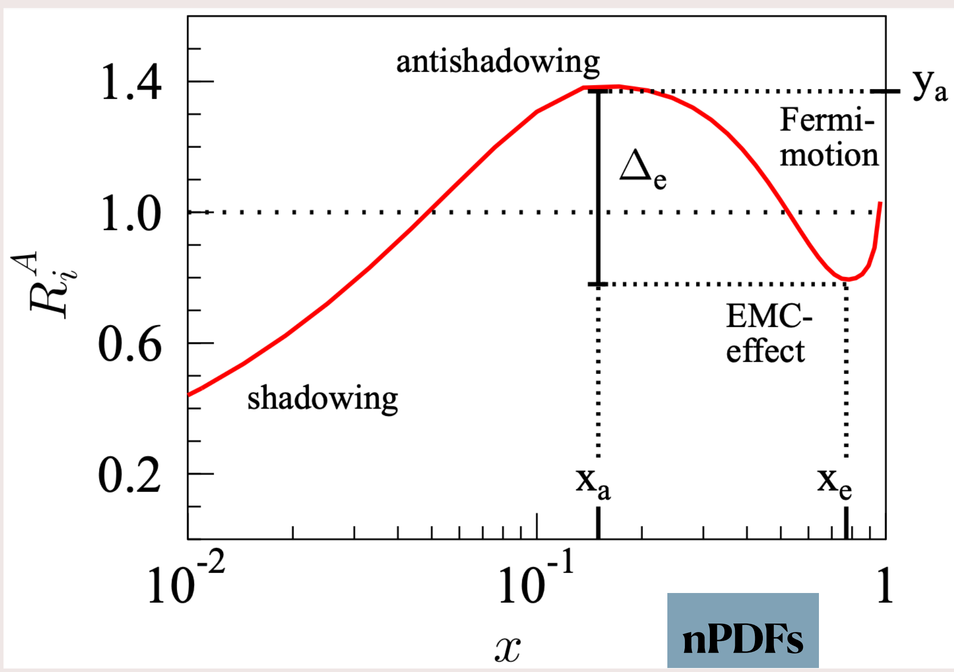


Image: Shuai Yang



$$S_A = \exp\{-\int_z^{\infty} dz \rho_A(b,z)\sigma_{\psi N}\}$$



Eskola, Paukkunen, Salgado, JHEP 07 102 (2008)

E.g. $J/\psi + \pi \rightarrow D + D + X$

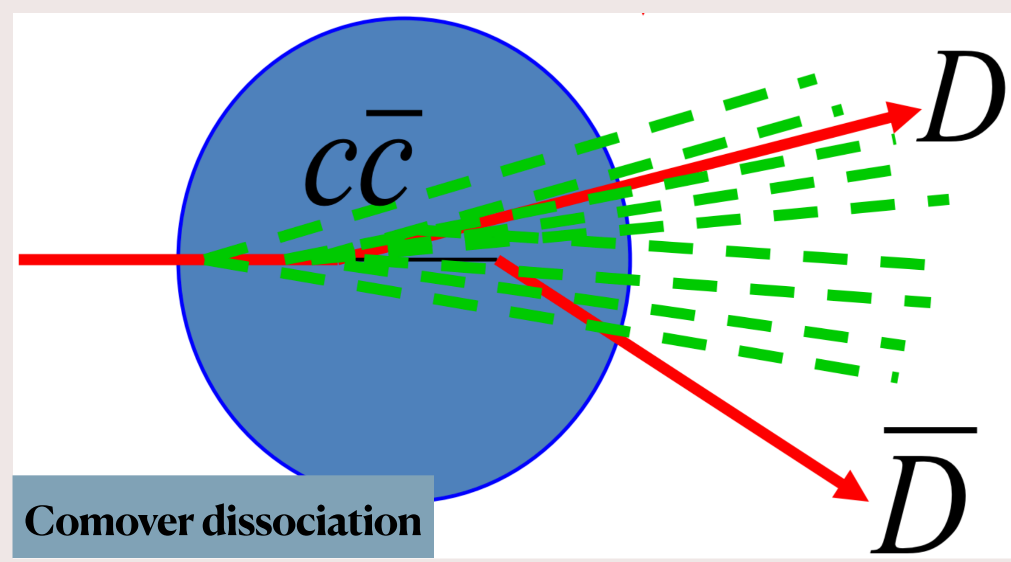
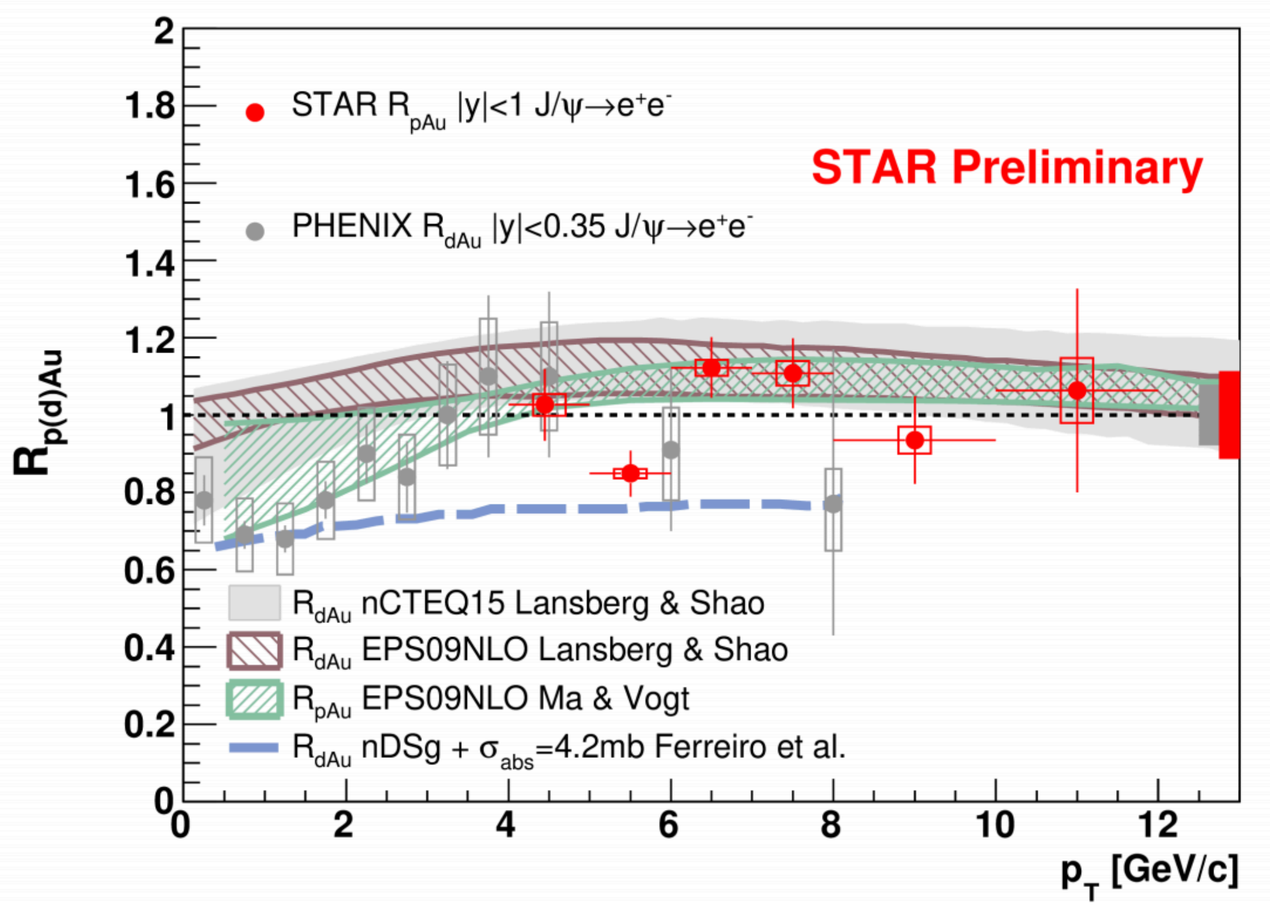


Image: Sanghoon Lim

$$S_{co} = \exp\{-\int d\tau n \sigma_{co} v_{rel}\}$$

[1]Andronic *et al.*, Eur. Phys. J. C 76, 107 (2016)

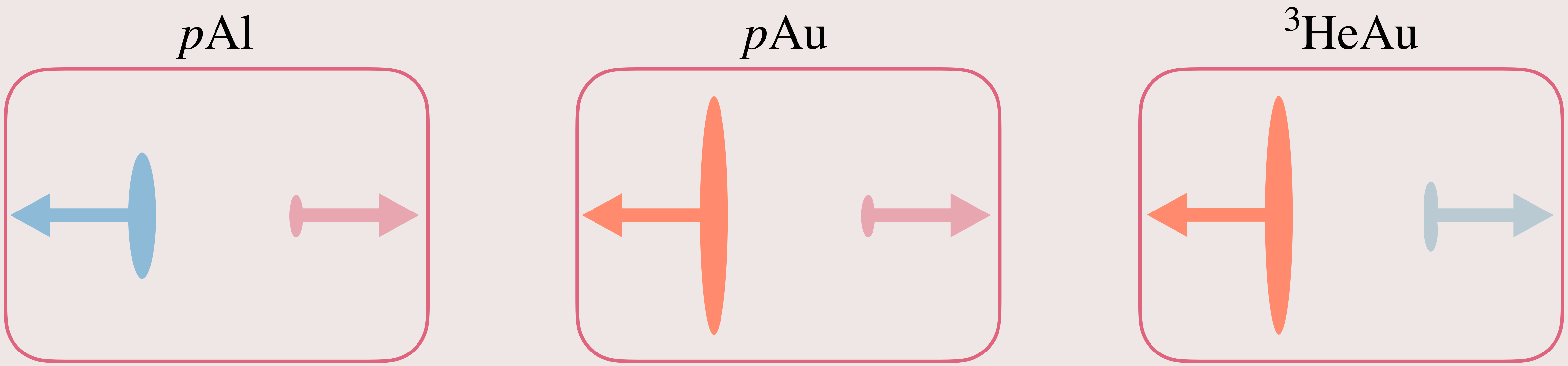
STAR mid-η J/ψ R_{pAu}



[PHENIX, PRC 87 (2013) 034904]
[EPS09+NLO, Ma & Vogt, Private Comm.]
[nCTEQ, EPS09+NLO, Lansberg & Shao:
Eur.Phys.J. C77 (2017) no.1, 1;
Comp. Phys. Comm. 198 (2016) 238-259;
Comp. Phys. Comm. 184 (2013) 2562-2570]
[Ferreiro et al., Few Body Syst. 53 (2012) 27]

$R_{pAu} \sim 1$, consistent with PHENIX at high-p_{T}, and with models including nPDFs

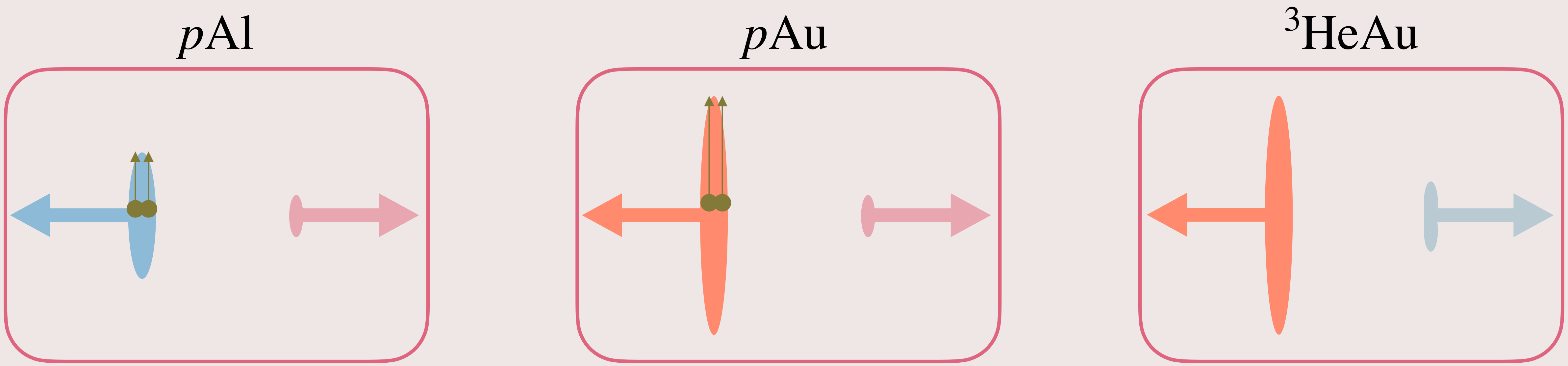
PHENIX forward/backward-η J/ψ R_{AB}



J/ψ nuclear modification measured in the di-muon channel at large rapidity in 3 systems, testing projectile and target sizes

PHENIX forward/backward-η J/ψ R_{AB}

Target-dependence

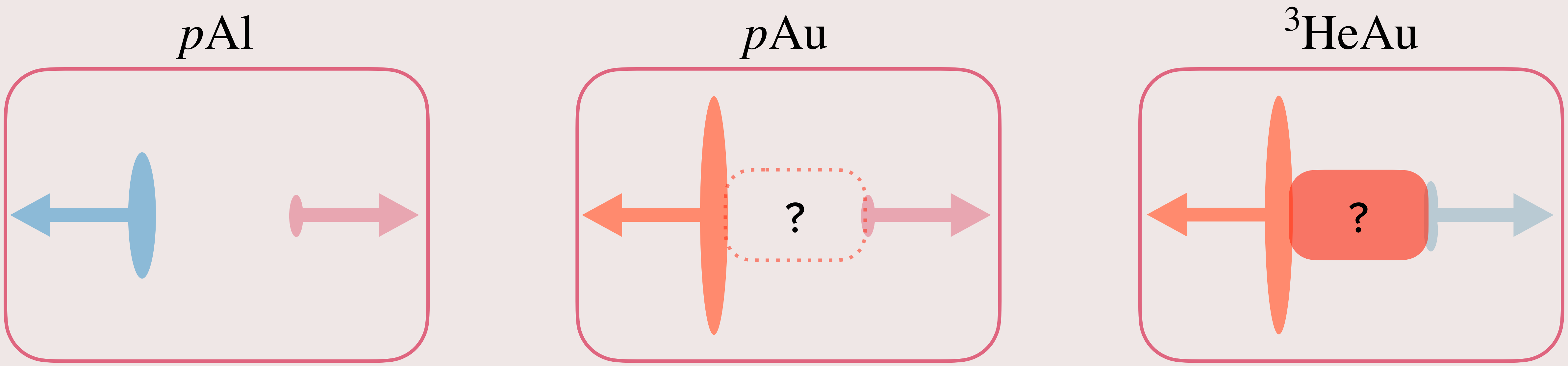


J/ψ nuclear modification measured in the di-muon channel at large rapidity in 3 systems, testing projectile and target sizes

Al → Au: longer path through cold nucleus

PHENIX forward/backward-η J/ψ R_{AB}

Projectile-dependence



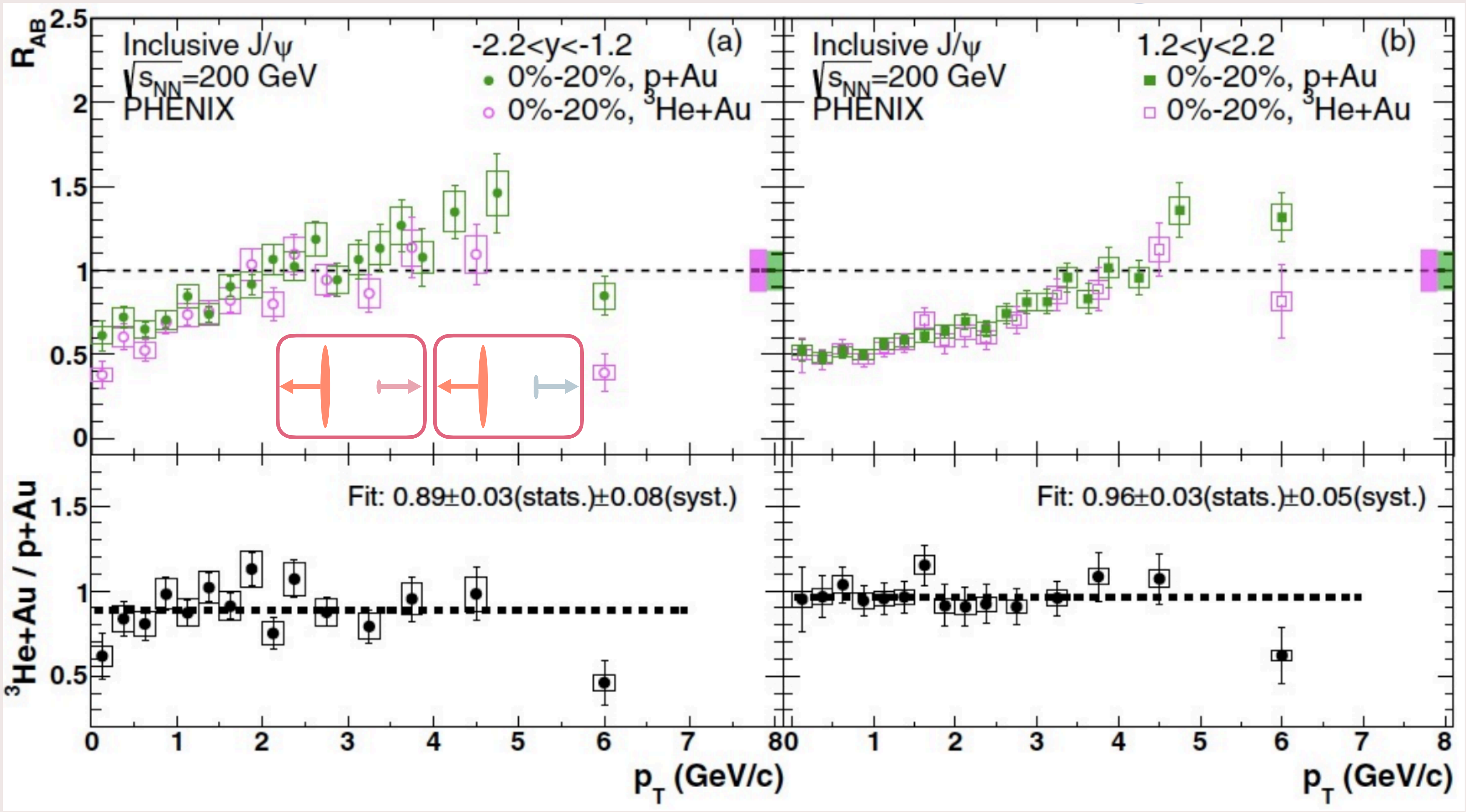
J/ψ nuclear modification measured in the di-muon channel at large rapidity in 3 systems, testing projectile and target sizes

$p \rightarrow {}^3$He: energy density dependence

PHENIX forward/backward-η J/ψ R_{AB}

Projectile-dependence

PHENIX, PRC 102, 014902 (2020)



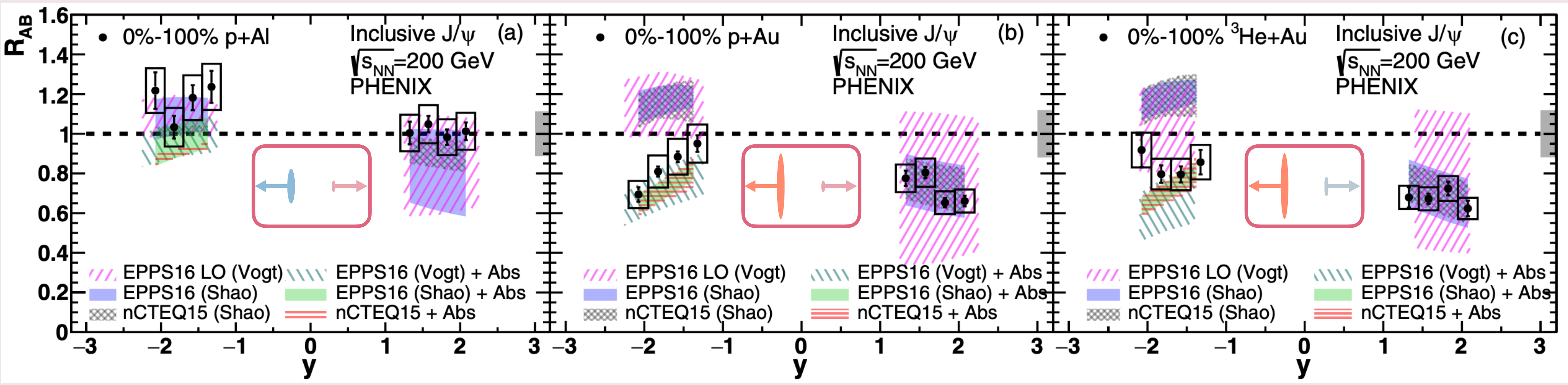
pAu ~ ^{3}HeAu (slight relative suppression at backward y)

➔ little energy density dependence

PHENIX forward/backward-η J/ψ R_{AB}

Rapidity-dependence

PHENIX, PRC 102, 014902 (2020)



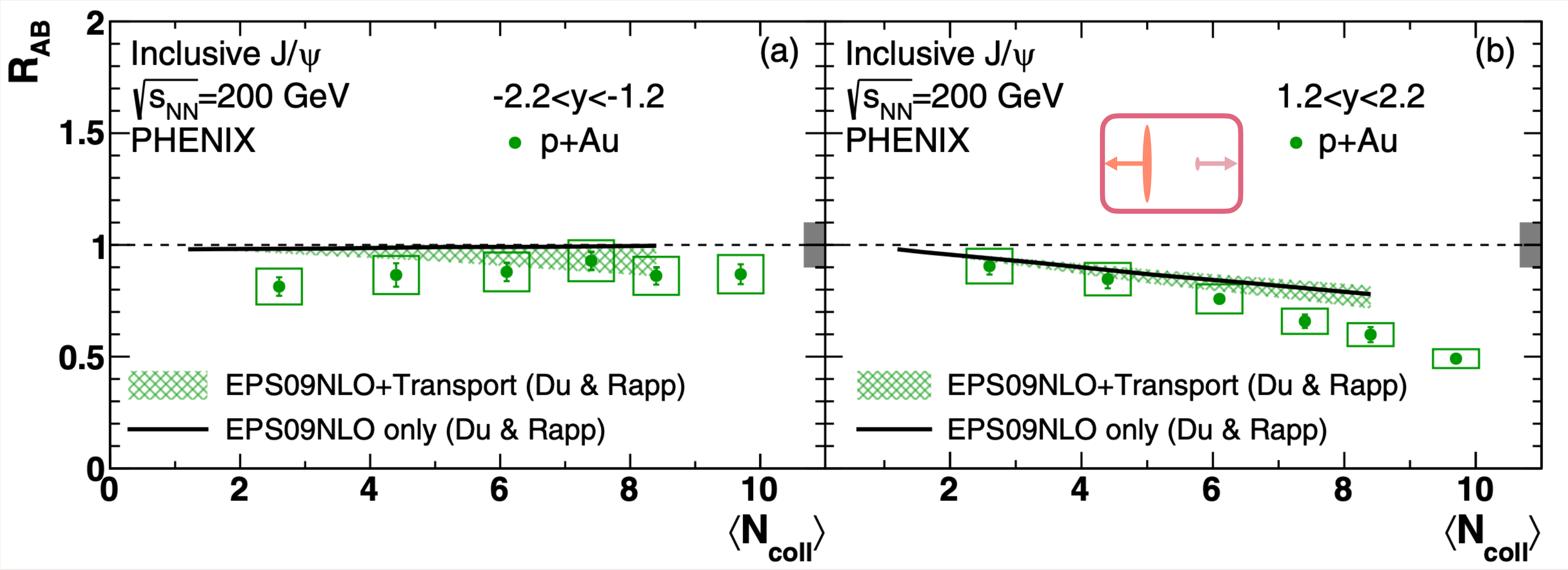
R_{pAl} (centrality-integrated) is described by models with nPDF effects, but this alone can't describe pAu or ^{3}HeAu

Forward (p-going): Shadowing dominant; models with only nPDFs describe data

Backward (Au-going): When nuclear absorption is included for large nuclei, rapidity-dependent data reasonably described

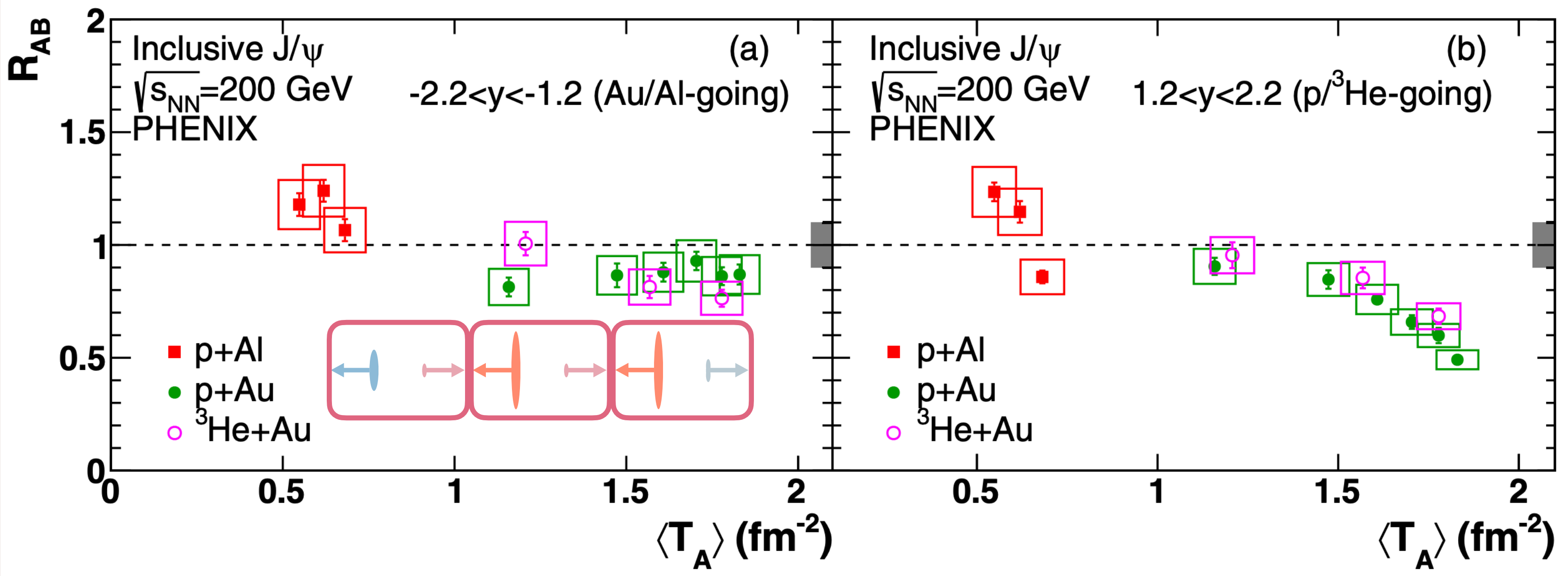
PHENIX forward/backward-η J/ψ R_{AB}

Beyond CNM effects?



Transport effect either negligible (*left*) or insufficient (*right*) ➜ is plasma phase necessary?

PHENIX, PRC 102, 014902 (2020)

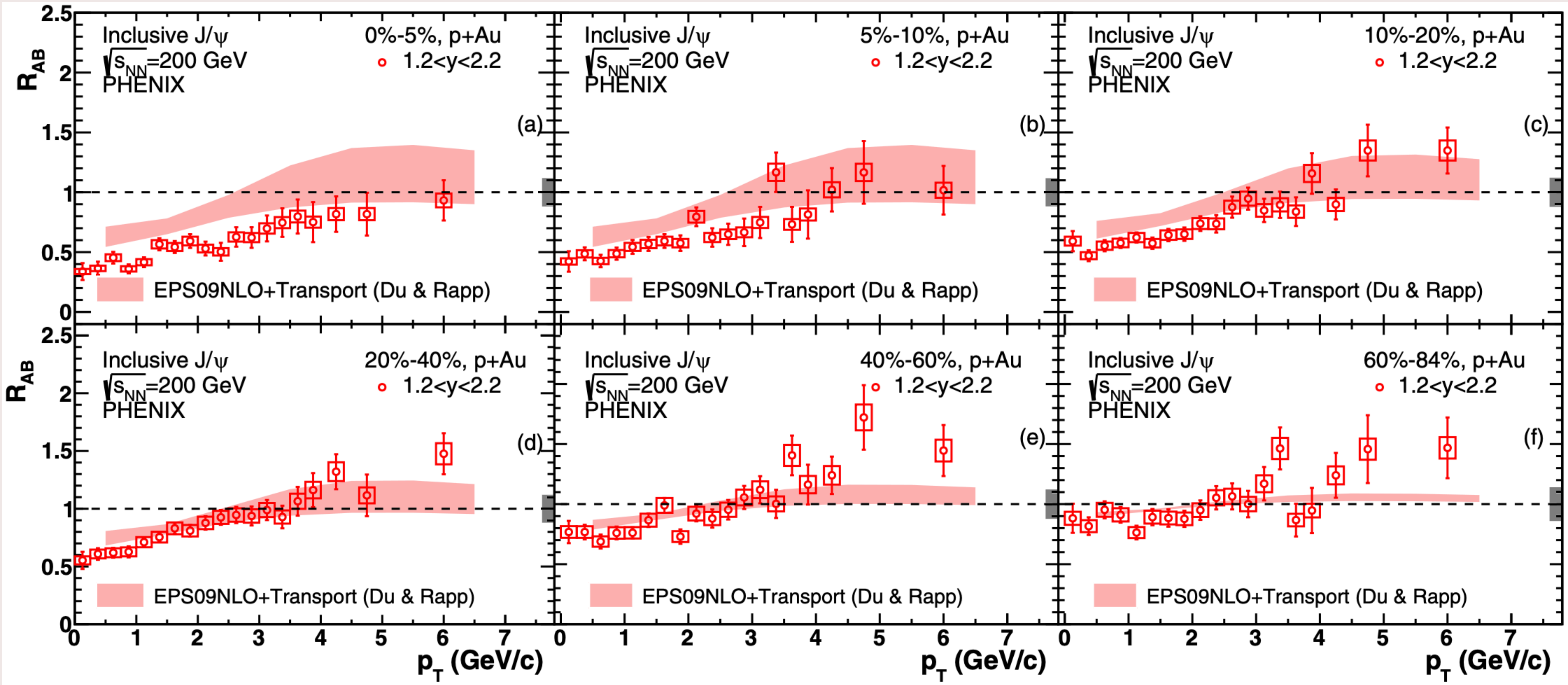


The three systems' p_T -integrated R_{AB} fall on a common curve as a function of target nucleus thickness ➜ dominated by CNM effects

PHENIX forward-η J/ψ R_{AB}

Centrality-dependence

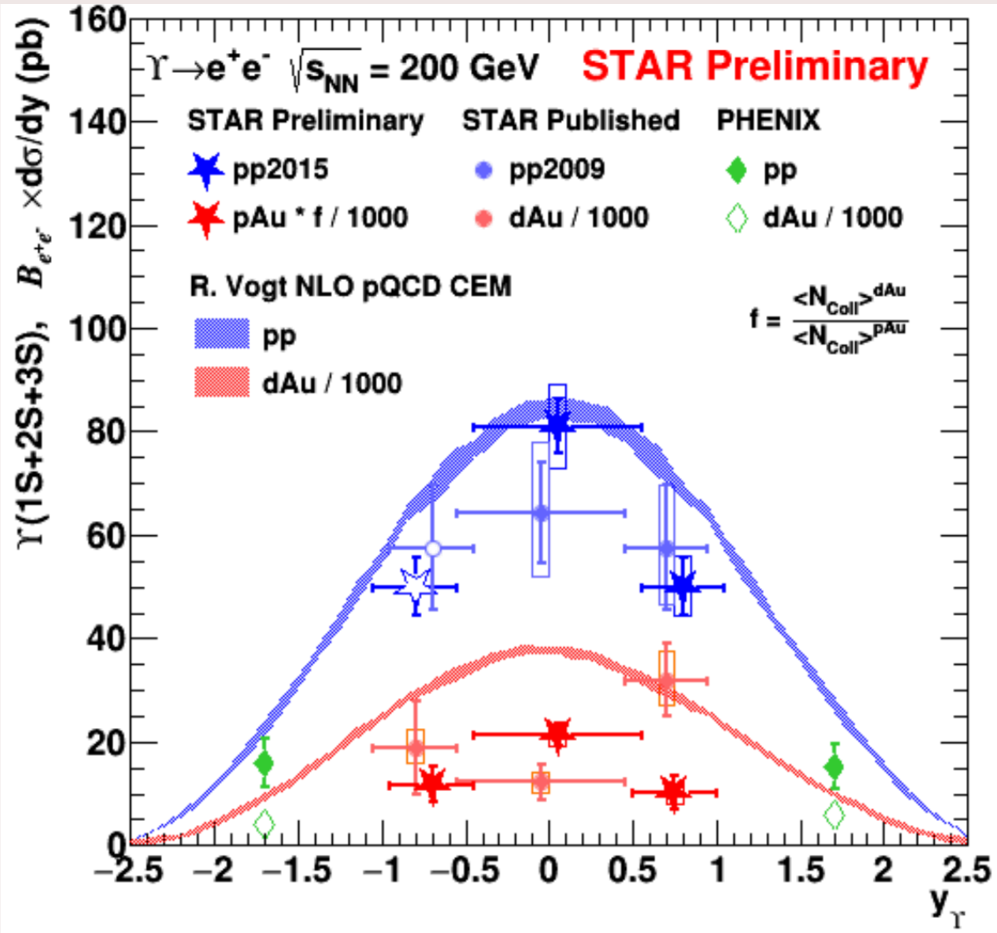
PHENIX, PRC 102, 014902 (2020)



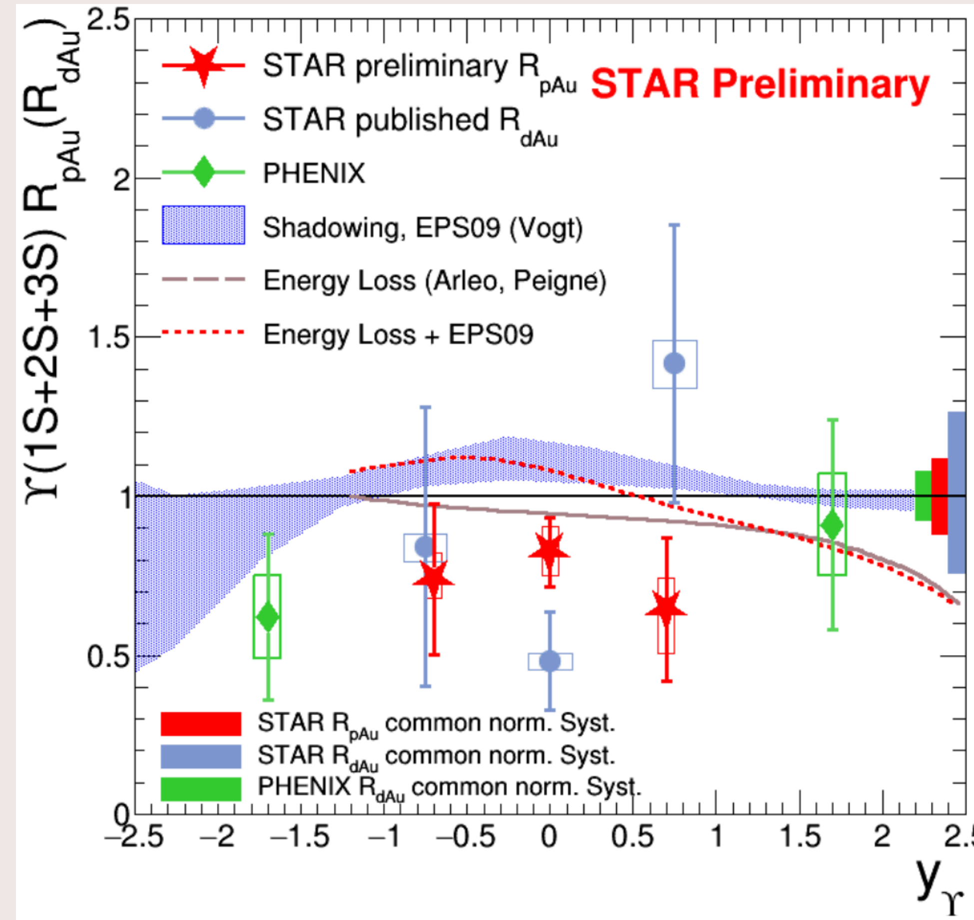
Forward: Highly centrality-dependent; consistent with unity for peripheral collisions, heavily suppressed for low p_T in central

Transport model (including plasma phase) at central (dominated by shadowing at low-p_T) shows further suppression in data than predicted

STAR Υ $R_{p\mathrm{Au}}$



[STAR: PLB 735 (2014) 127]
[PHENIX: PRC 87 (2013) 044909]
[R. Vogt NLO pQCD CEM: PoS ConfinementX 203 (2012)]



[STAR: PLB 735 (2014) 127]
[PHENIX: PRC 87 (2013) 044909]
[JHEP 1303, 122 (2013)]

$\Upsilon + \Upsilon' + \Upsilon''$ X-sec & $R_{p\mathrm{Au}}$ measured at mid-rapidity through di-electron channel with increased statistical precision (296 nb^{-1}) a few years ago

Indication that models with nPDFs / initial state E-loss not enough to describe Υ X-sec or suppression w/r/t pp

Conclusions

In **jets**, observed modification in yields with centrality seem to be due to **anti-correlation** of soft, **forward activity** with **high-Q^2** process at **mid-rapidity**.

More jet substructure observables to come, different cone sizes, …

Jet **substructure unmodified** in small systems;
Centrality/EA-dependence of jet **yields** possibly due to “**bias” in centrality measure**

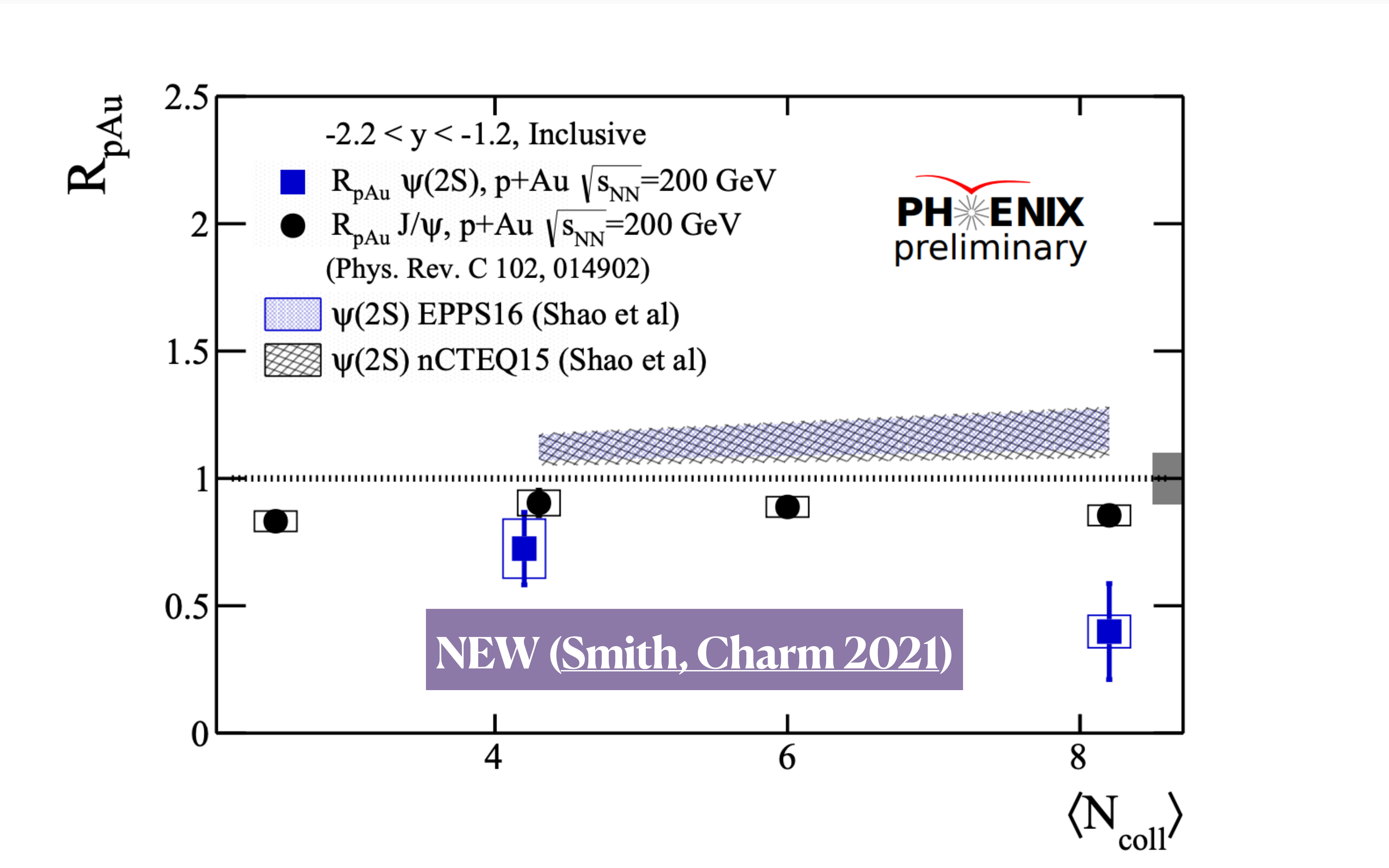
Heavy quarkonia measurements are more sensitive than jets to CNM effects, and are now able to **distinguish between models** with various CNM (and even HNM) effects due to increased precision and statistics.

nPDF effects are the **dominant** contribution at **forward** rapidity, but for **negative** rapidity **nuclear absorption** in large nucleus contributes as well

Quarkonia production qualitatively **described by CNM effects** in small systems;
Model refinement may be necessary for Υ

Bonus

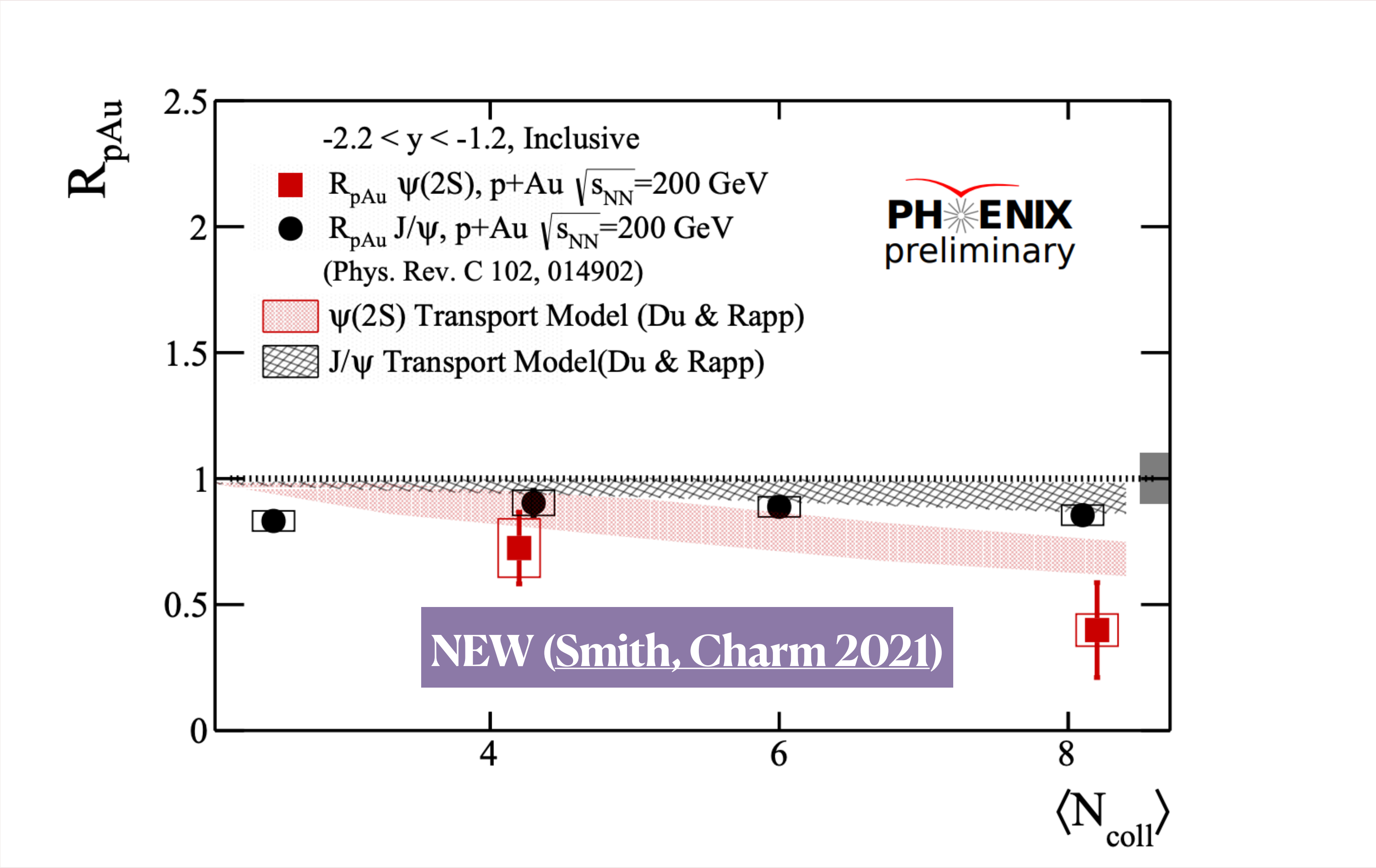
PHENIX $\psi(2S)$ nuclear modification



$\psi(2S)$ and J/ψ different centrality dependence
nPDF effects not enough to describe suppression on Au-going side
Must be final state effect: QGP or comovers!

Bonus

PHENIX $\psi(2S)$ nuclear modification

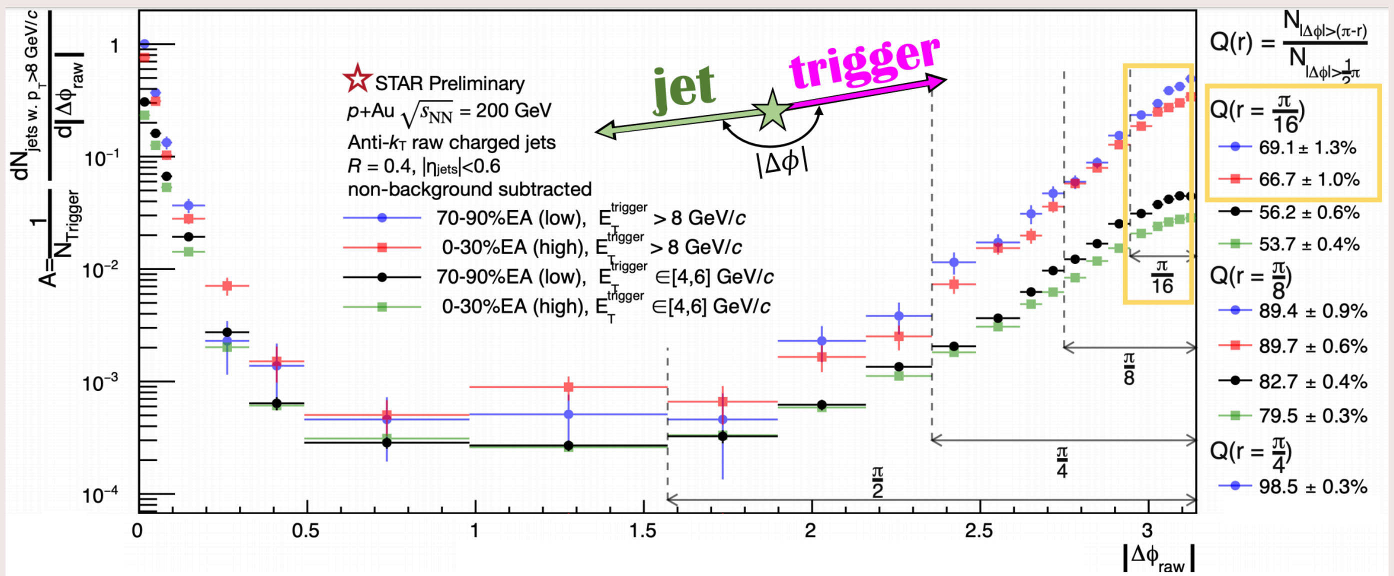


Transport (including plasma phase) is close

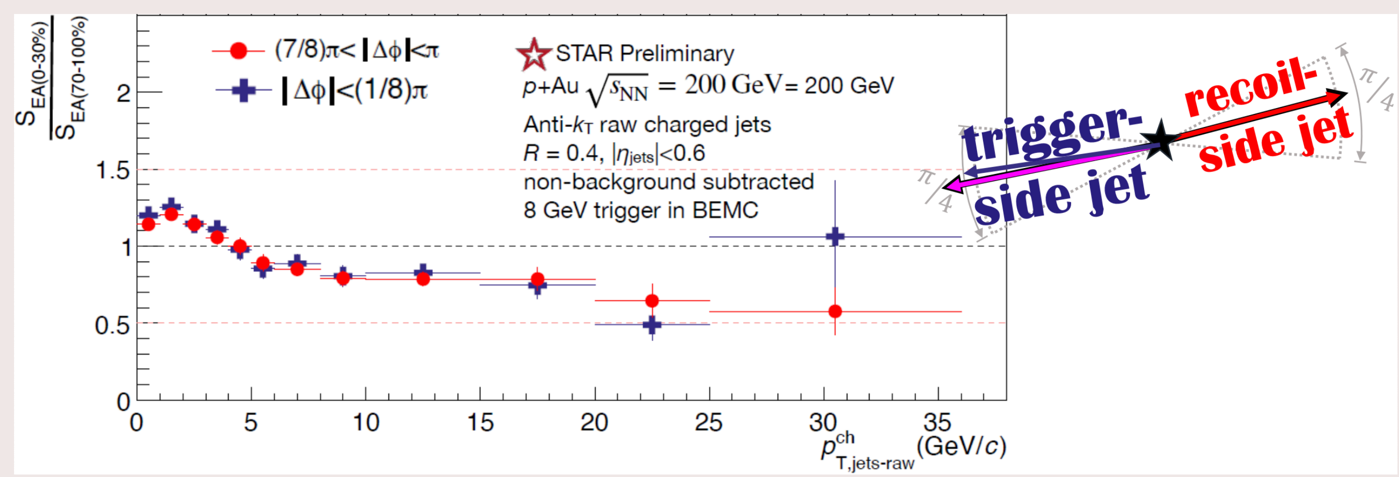
Backup

STAR semi-inclusive jets

Acoplanarity and trigger v. recoil



No broadening of acoplanarity for high-EA recoil jets



Trigger and recoil are modified similarly

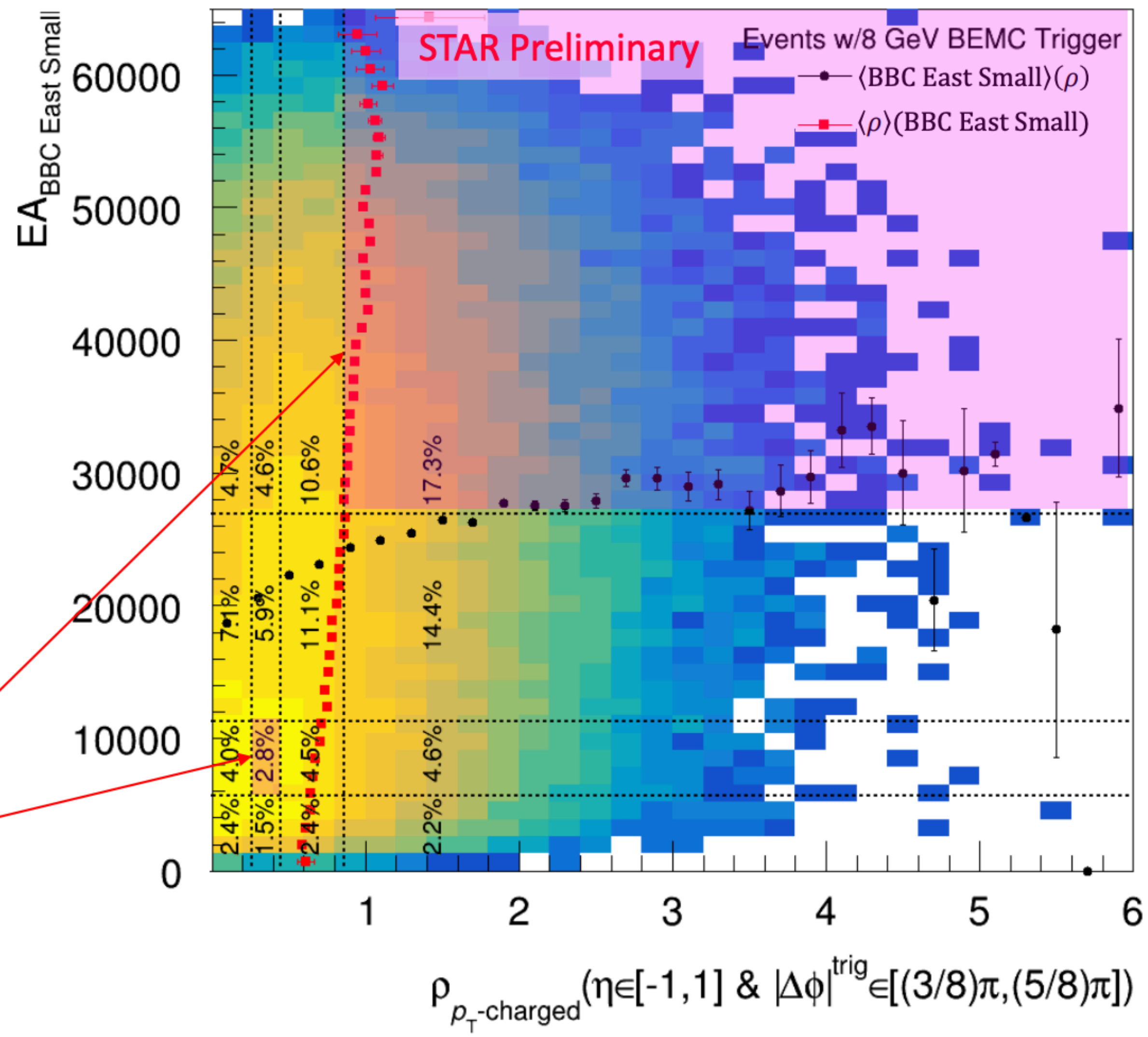
➡ No evidence for QGP-like path-length dependent energy loss

STAR semi-inclusive jets

EA-selection

STAR data: EA

- EA_{BBC} & EA_{TPC} positively correlated
- Can compare **high-EA** events to **low-EA** events using:
  - EA_{BBC}
  - EA_{TPC}
  - Both: $EA_{BBC} \cap EA_{TPC}$



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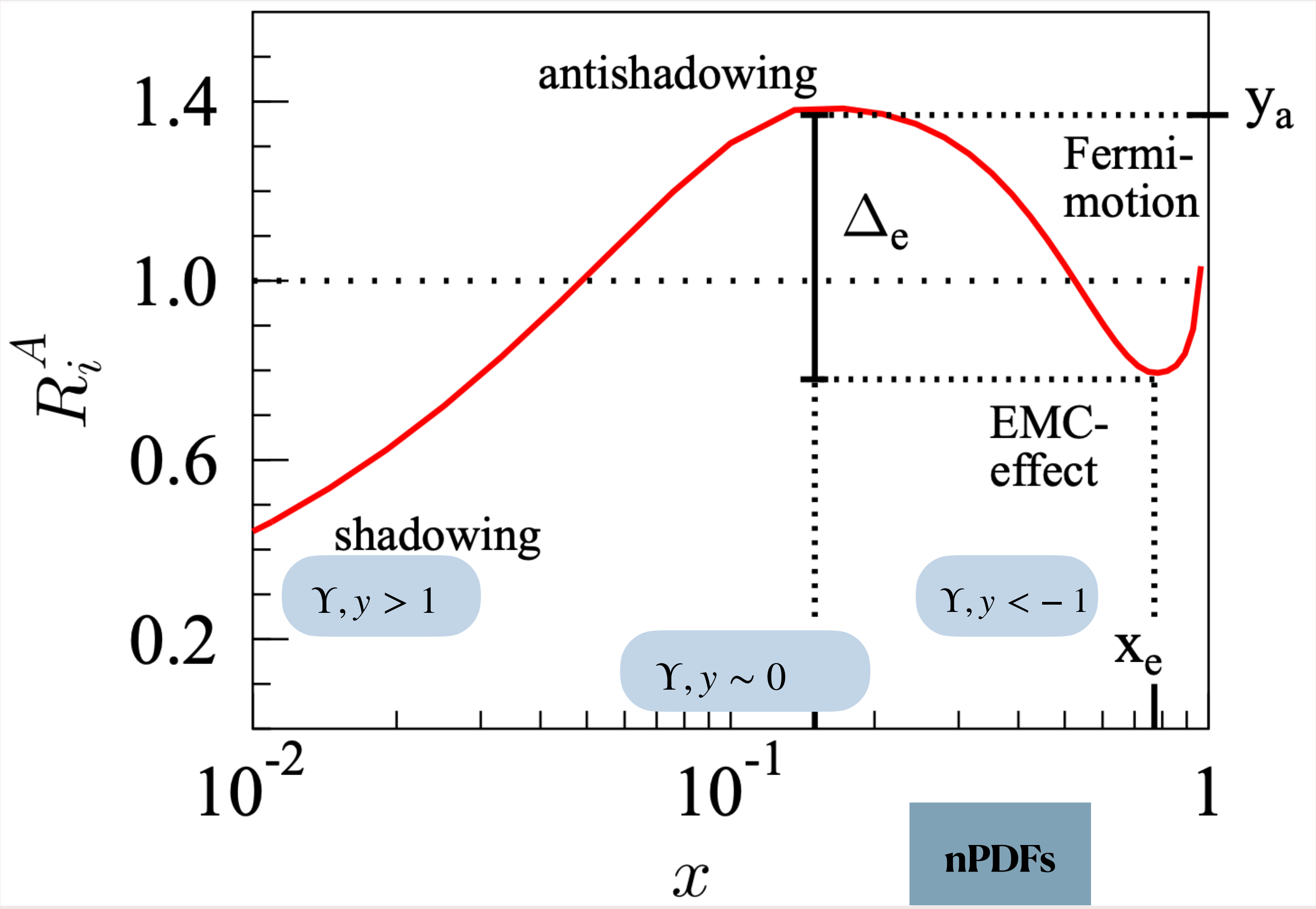
nPDF effects for bottomonia



Eskola, Paukkunen, Salgado, JHEP 07 102 (2008)

$x \approx (p_T + m_T)e^{-y}/\sqrt{s_{NN}}$ [1]

$y = 0,\ 1 < p_T < 10$ GeV/c: $0.08(6) \lesssim x \lesssim 0.19(3)$ for *p*(*d*)Au Υ

$y = -1.5,\ 1 < p_T < 10$ GeV/c: $0.26 \lesssim x \lesssim 0.59$ for *d*Au Υ

$y = 1.5,\ 1 < p_T < 10$ GeV/c: $0.013 \lesssim x \lesssim 0.030$ for *d*Au Υ

[1]Andronic *et al.*, Eur. Phys. J. C 76, 107 (2016)