



Jets and Heavy Flavor from STAR

Li Yi

Yale University

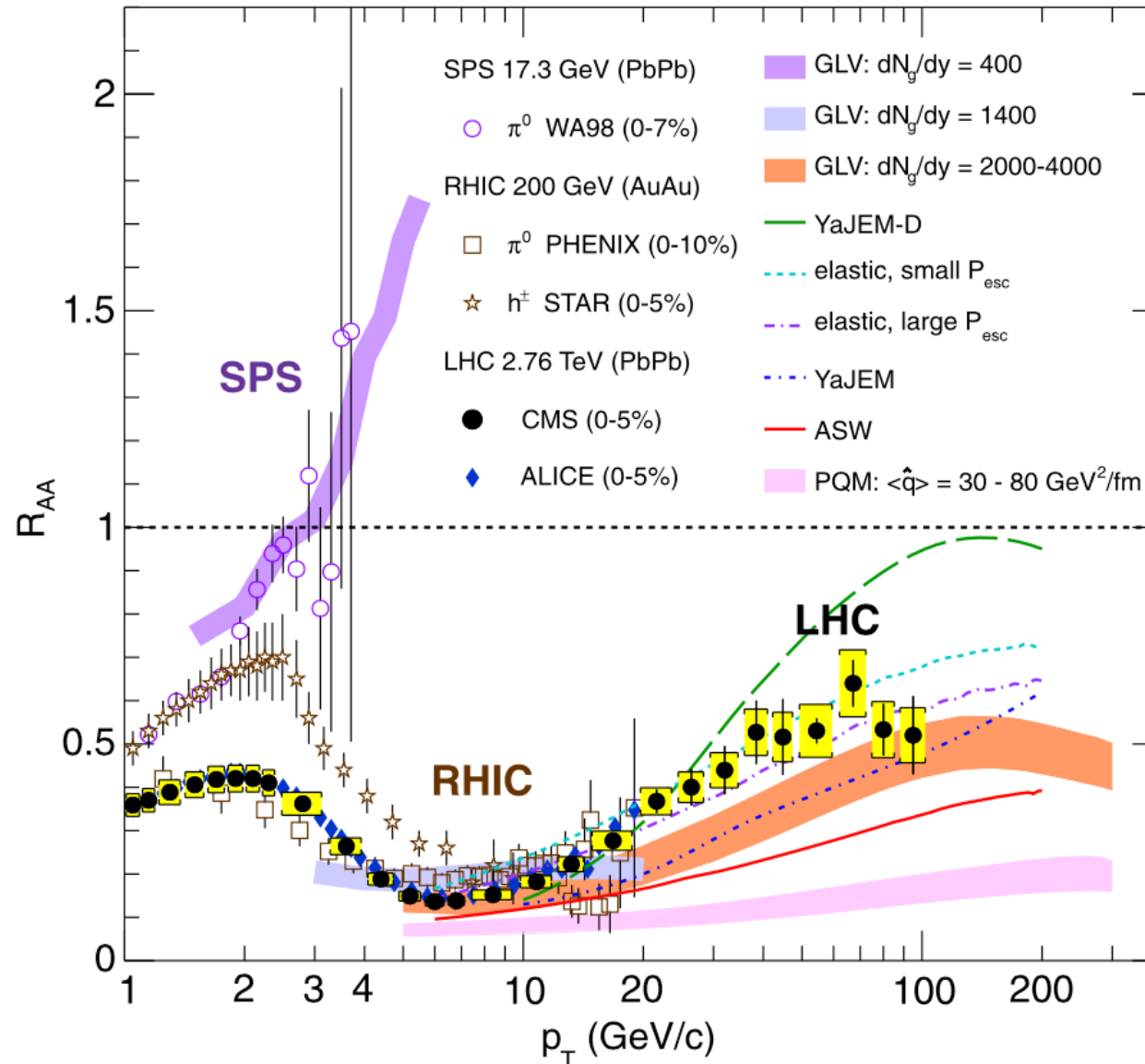
Santa Fe Workshop 2018

- **High p_T hadron and Jets**
- Quarkonium
- Open Heavy Flavor

Single Hadron High p_T Suppression

CMS, EPJC (2012) 72:1945

Connors, Nattrass, Reed, Salur, arXiv 1705.01974

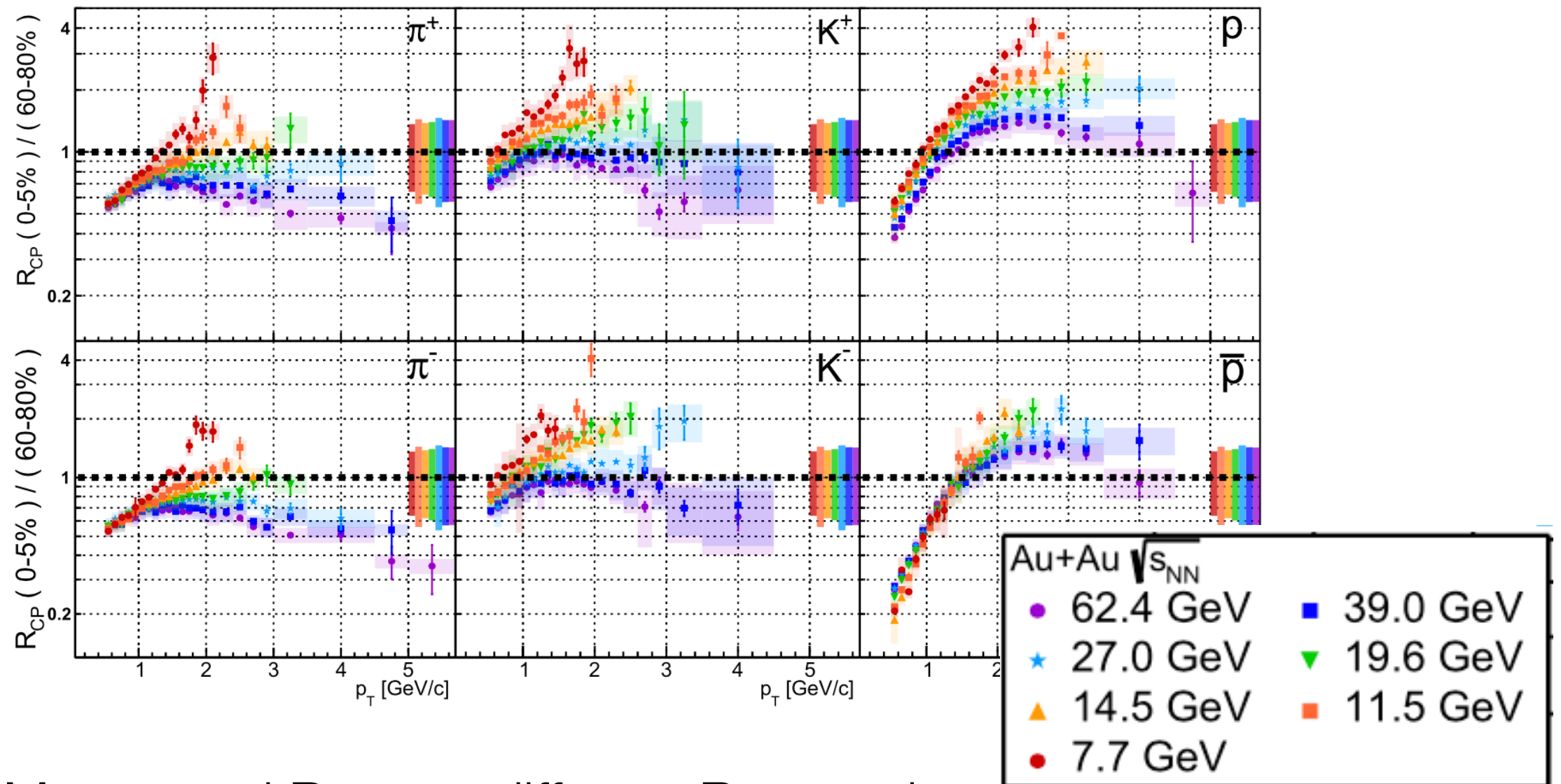


High p_T hadron suppression at RHIC and LHC energies

Single Hadron High p_T Suppression @ BES

feed-down subtracted

STAR, arXiv:1707.01988



Meson and Baryon: different R_{CP} trends

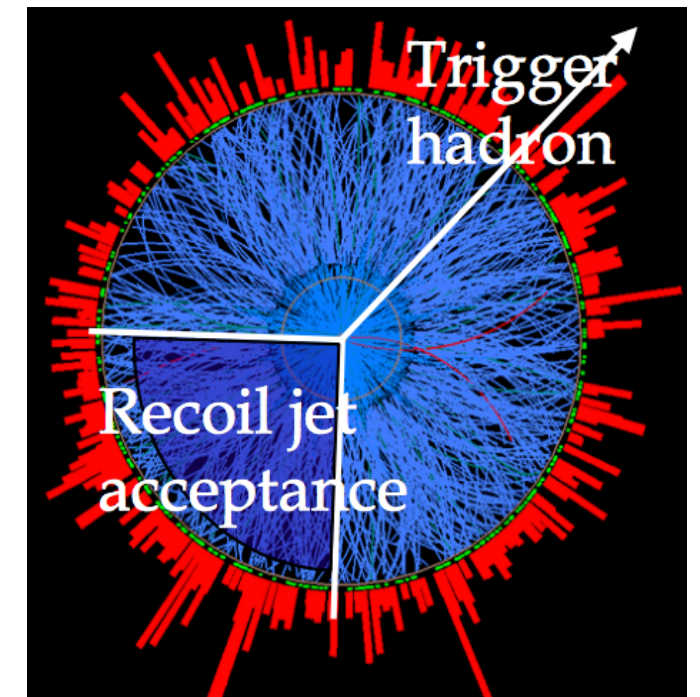
At high p_T , pion suppressed for $\sqrt{s_{NN}} > 27$ GeV
 proton enhanced at all BES energies

Semi-inclusive Jet Measurements

Spectrum shift $\rightarrow$ Energy transport out-of-cone

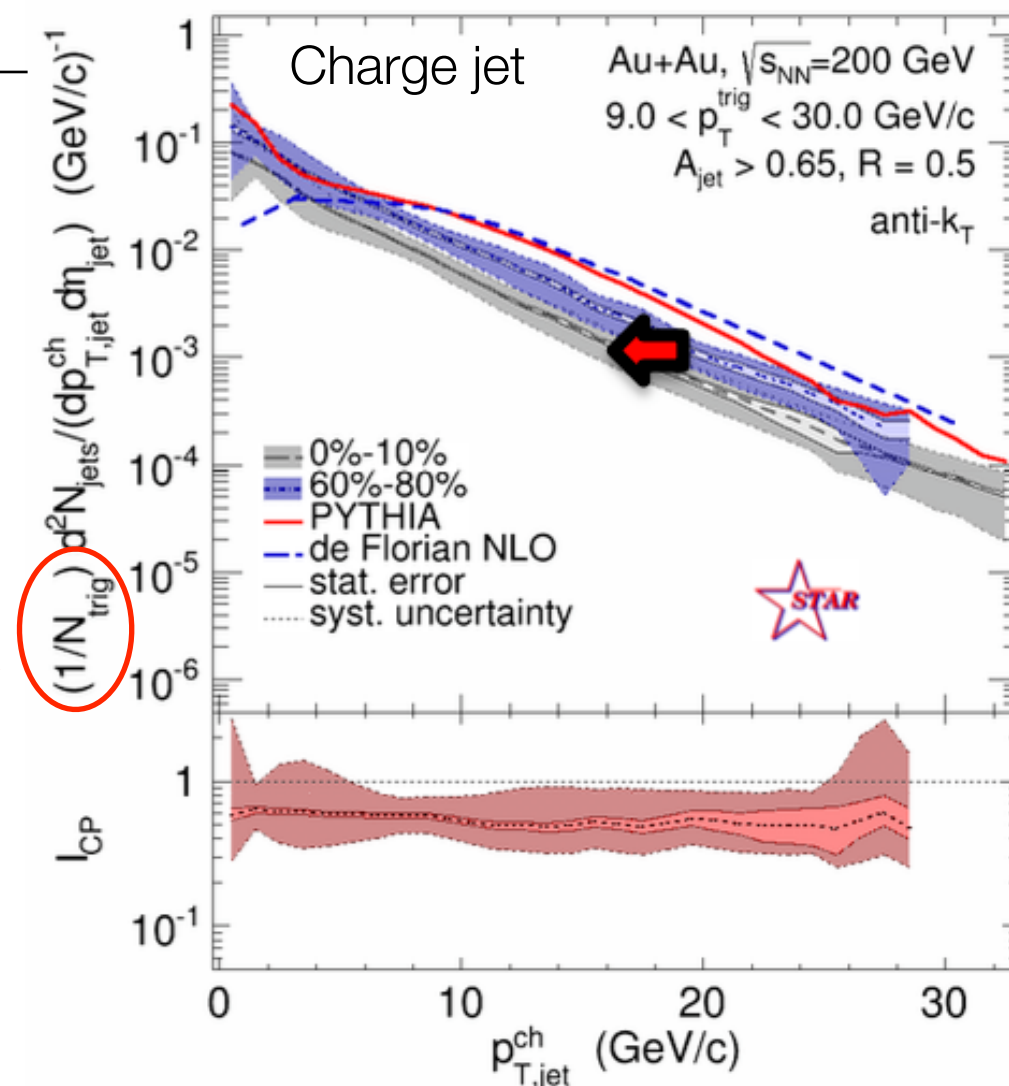
STAR, PRC **96**, 024905 (2017)
ALICE, arXiv: 1712.05603

System	R	Jet p_T (GeV/c)	Spectrum p_T shift (GeV/c)
Au+Au @ 200 GeV	0.5	10-20	$-2.8 \pm 0.2 \pm 1.5$
Pb+Pb @ 2.76 TeV	0.5	60-100	-8 ± 2
p+Pb @ 5.02 TeV	0.4	15-50	abs shift < -0.4



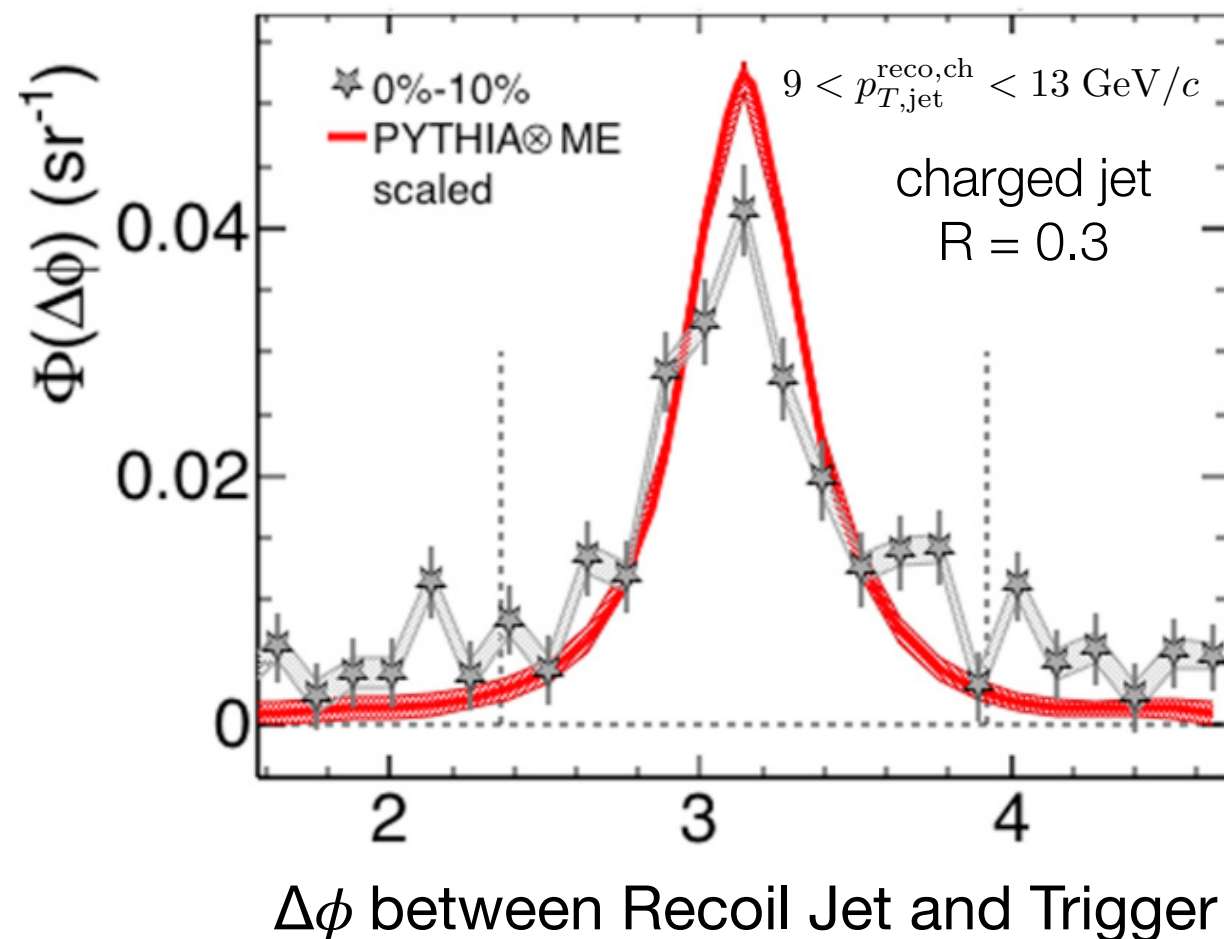
Smaller shift at RHIC than LHC
 $\rightarrow$ lower energy loss at RHIC
 but larger $\Delta p_T / p_T^{jet}$ at RHIC

★ No Glauber/ N_{coll} needed
 p+Au h-jet coming
 Au+Au γ -jet coming



Inter-jet Broadening: Scattering off the QGP

Conjecture for weak coupling:
dominated by single hard Molière scattering at “sufficiently large” $\Delta\phi$

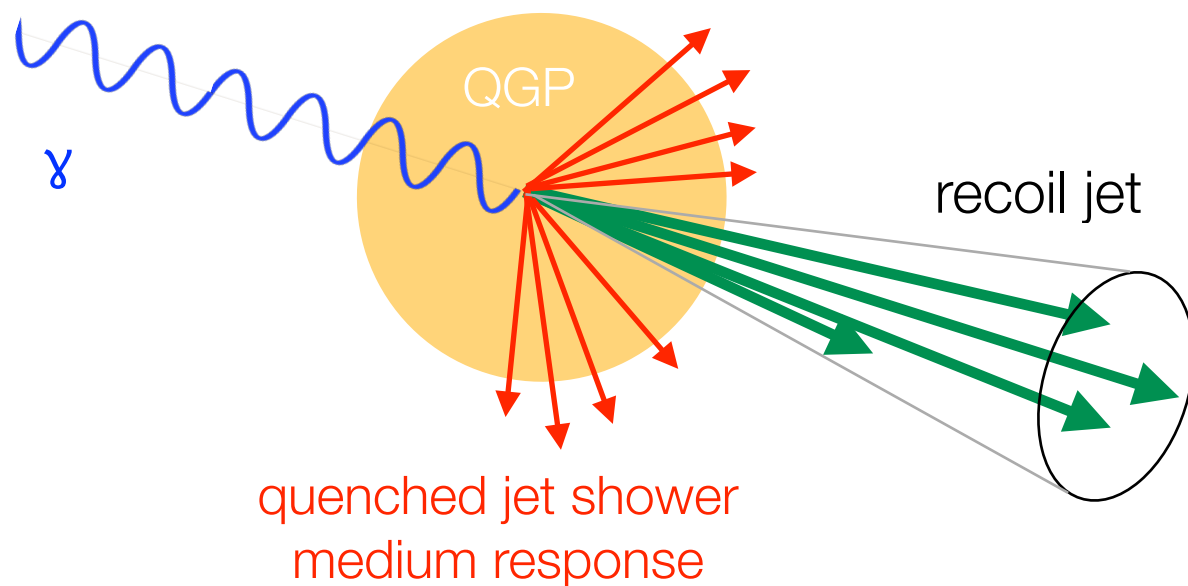


d'Eramo et al., JHEP 1305 (2013) 031
STAR, PRC **96**, 024905 (2017)

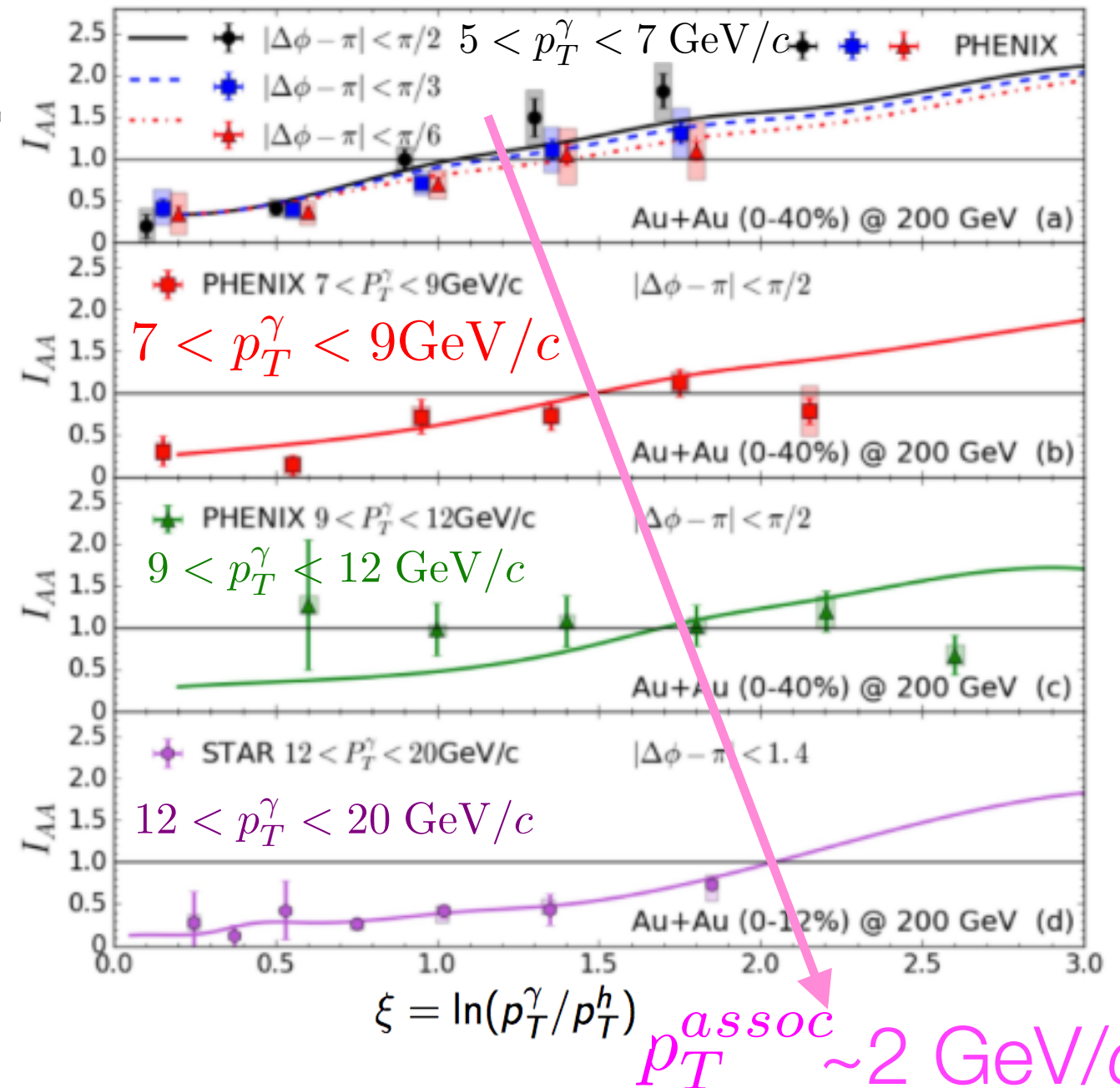
No significant evidence for large-angle scattering in central Au+Au

Photon-hadron Correlations

Calibrate initial parton energy
Avoid surface bias
Select more quark recoil jets



$$I_{AA} = \frac{Y^{Au+Au}}{Y^{p+p}}$$

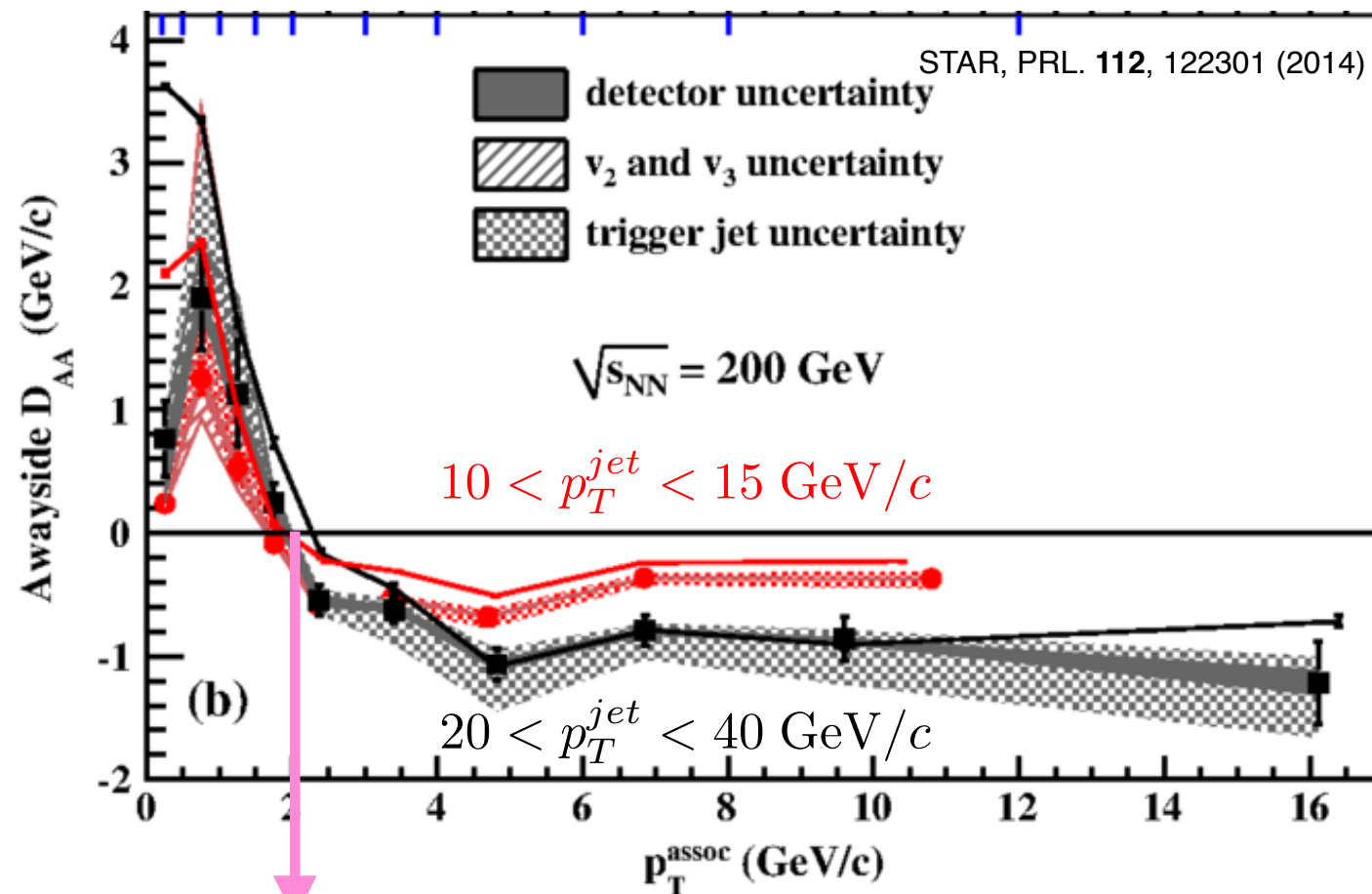


STAR, PLB **760** (2016) 689
PHENIX, NPA 967 (2017) 476 ; PRL. **111**, 032301
Chen, et al, 1704.03648

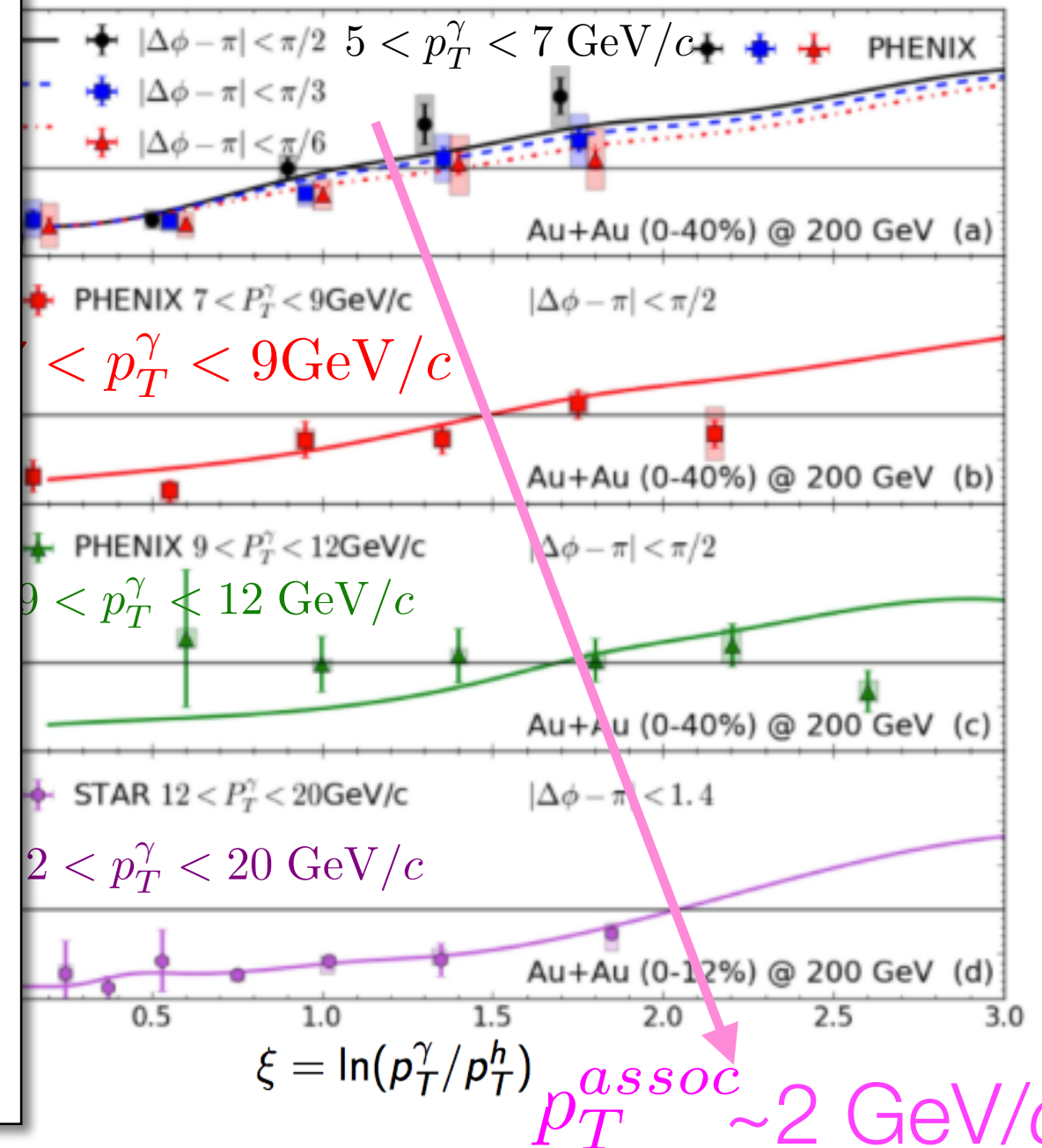
Absolute p_T rather than particle p_T fraction more relevant

Photon Triggered Recoil Jet

Jet-Hadron



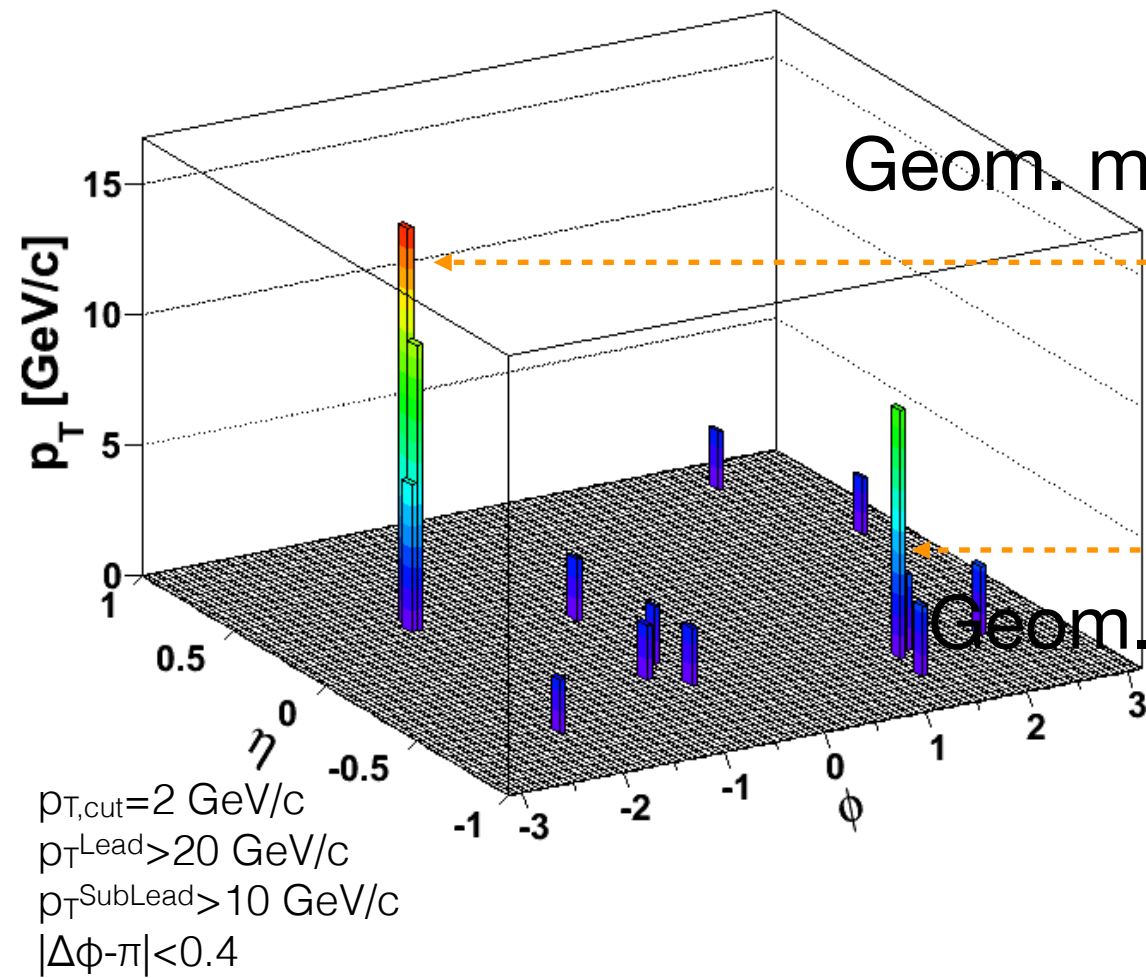
$p_T^{assoc} \sim 2 \text{ GeV}/c$



Absolute p_T rather than particle p_T fraction more relevant

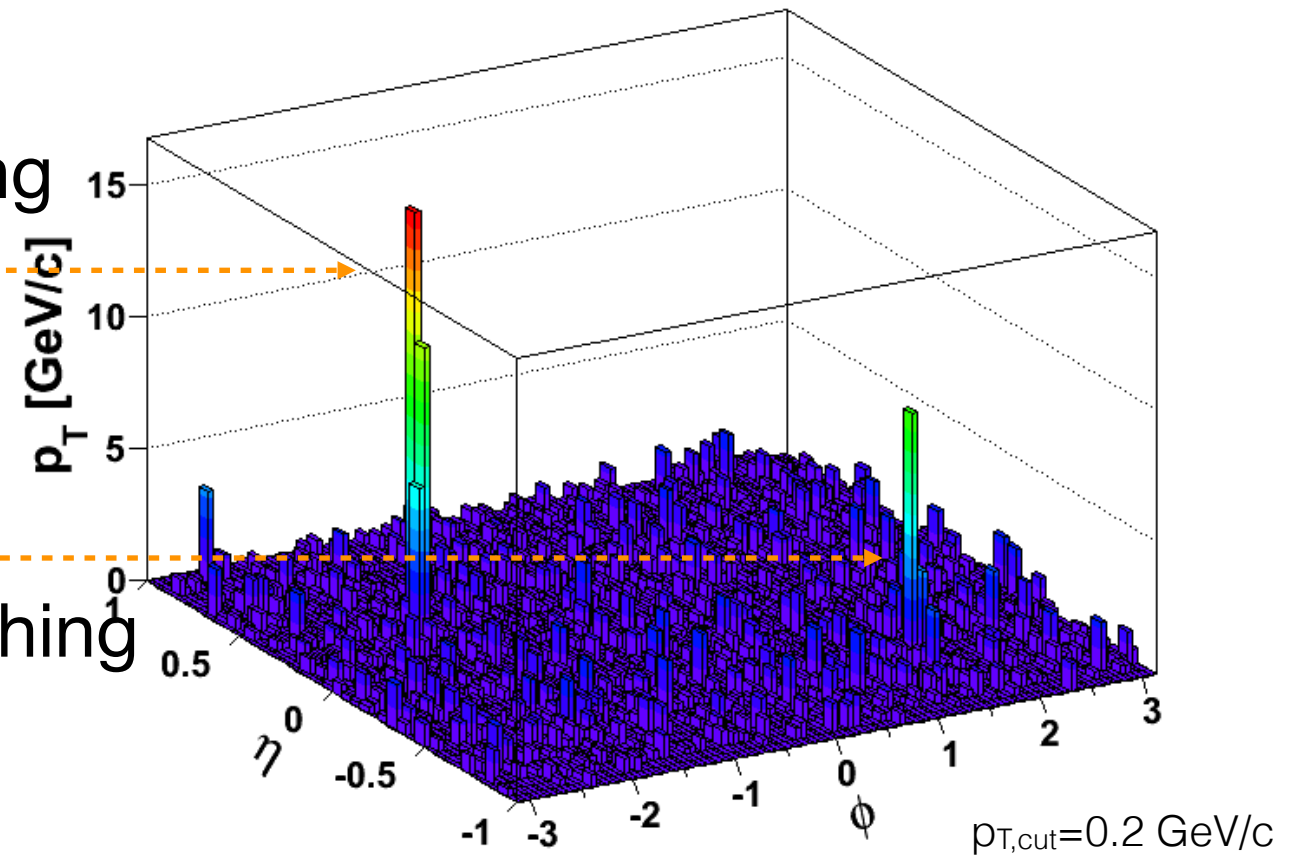
'Hard Core' Dijets

Au+Au w/o soft particles



locate hard core dijets

Au+Au w/soft particles



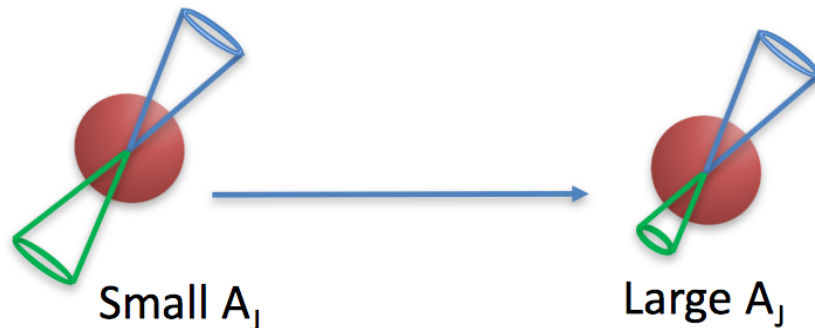
reconstruct matched dijets

Dijets Restore Balance with Low p_T

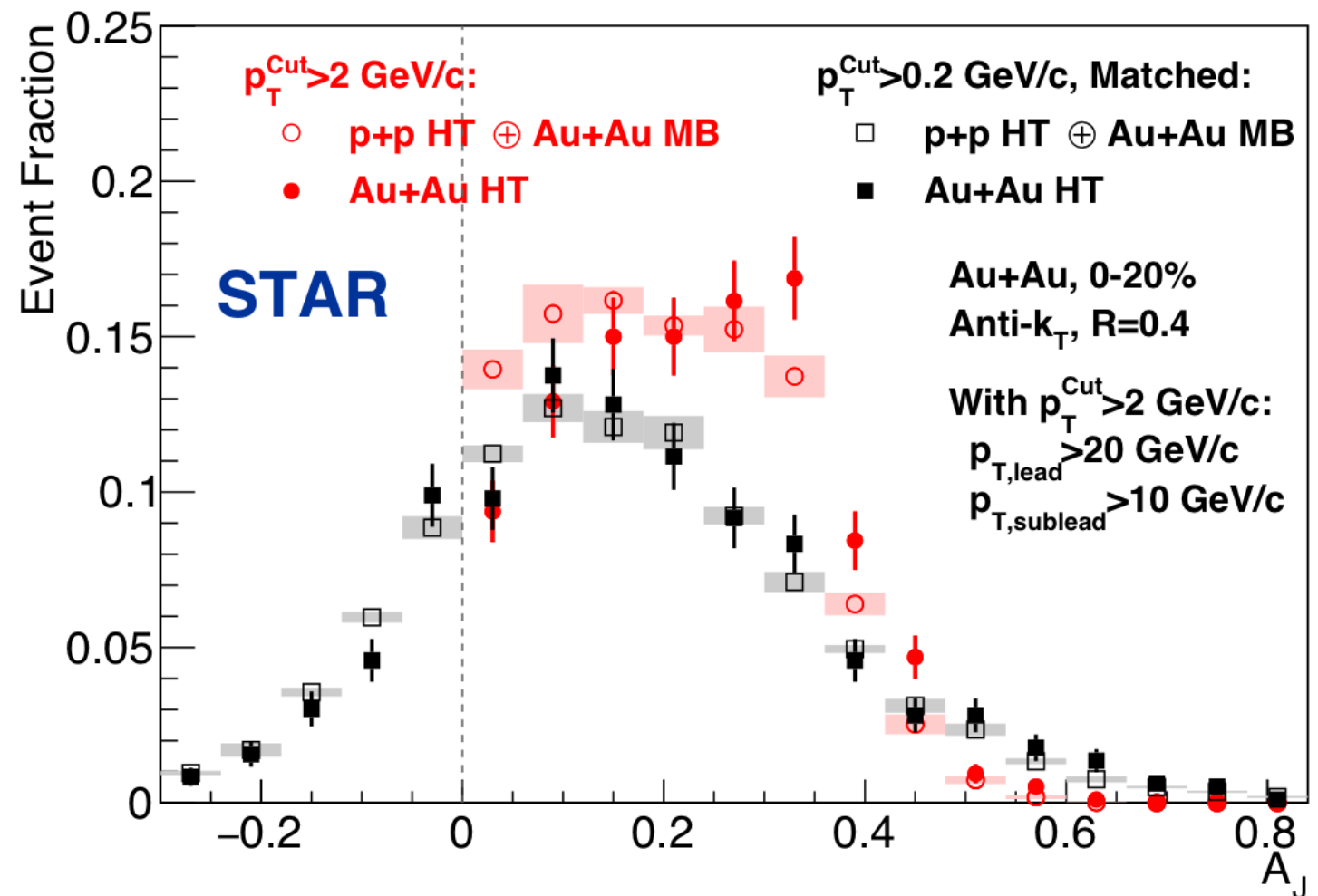
STAR, PRL **119**, 062301 (2017)

for **hard core** matched dijets

$$A_J = \frac{p_T^{\text{Lead}} - p_T^{\text{SubLead}}}{p_T^{\text{Lead}} + p_T^{\text{SubLead}}}$$



credit: K. Jung

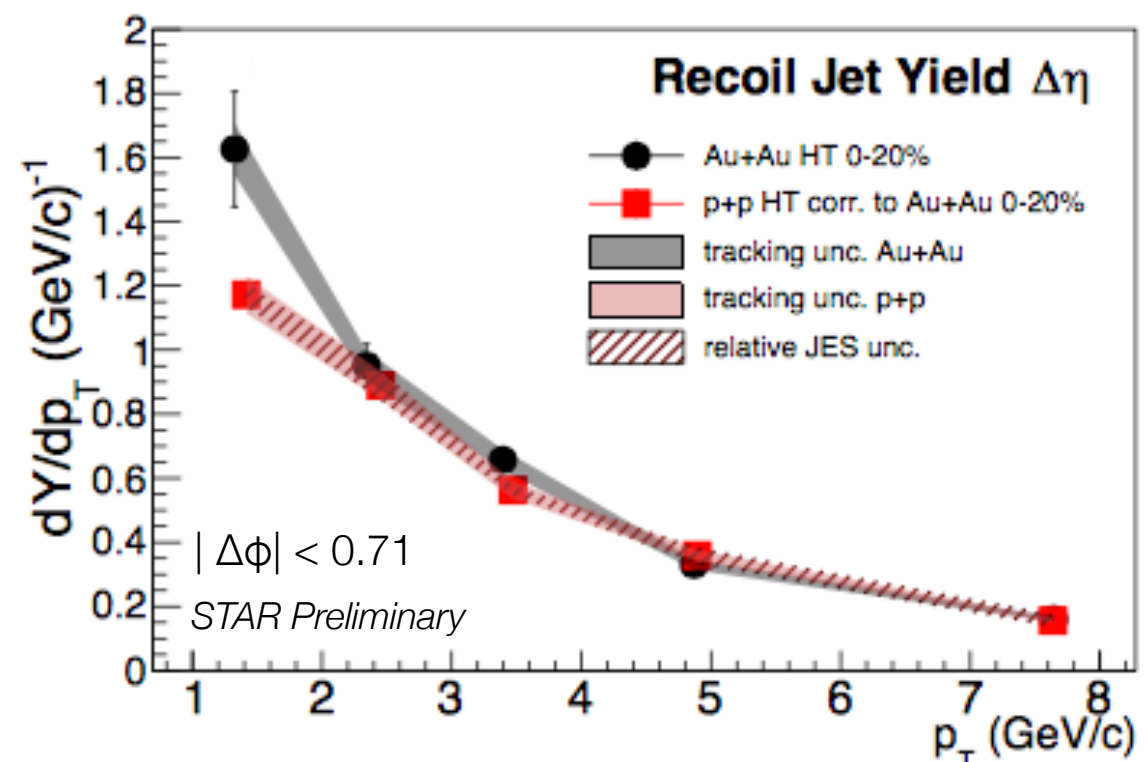
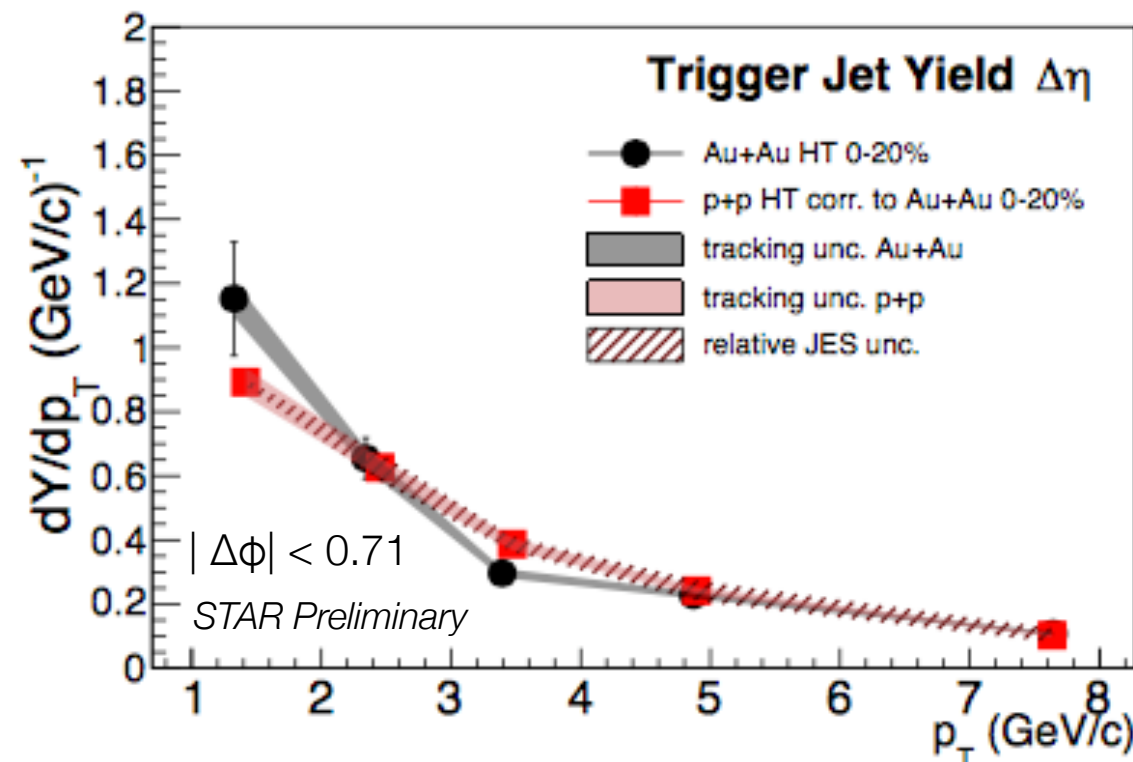


Momentum balance restored to pp baseline for $R = 0.4$,
after adding **particle $< 2\text{GeV/c}$**

Dijet-Hadron Correlations

for **hard core** matched dijets

Background subtracted with Gaussian+constant fit



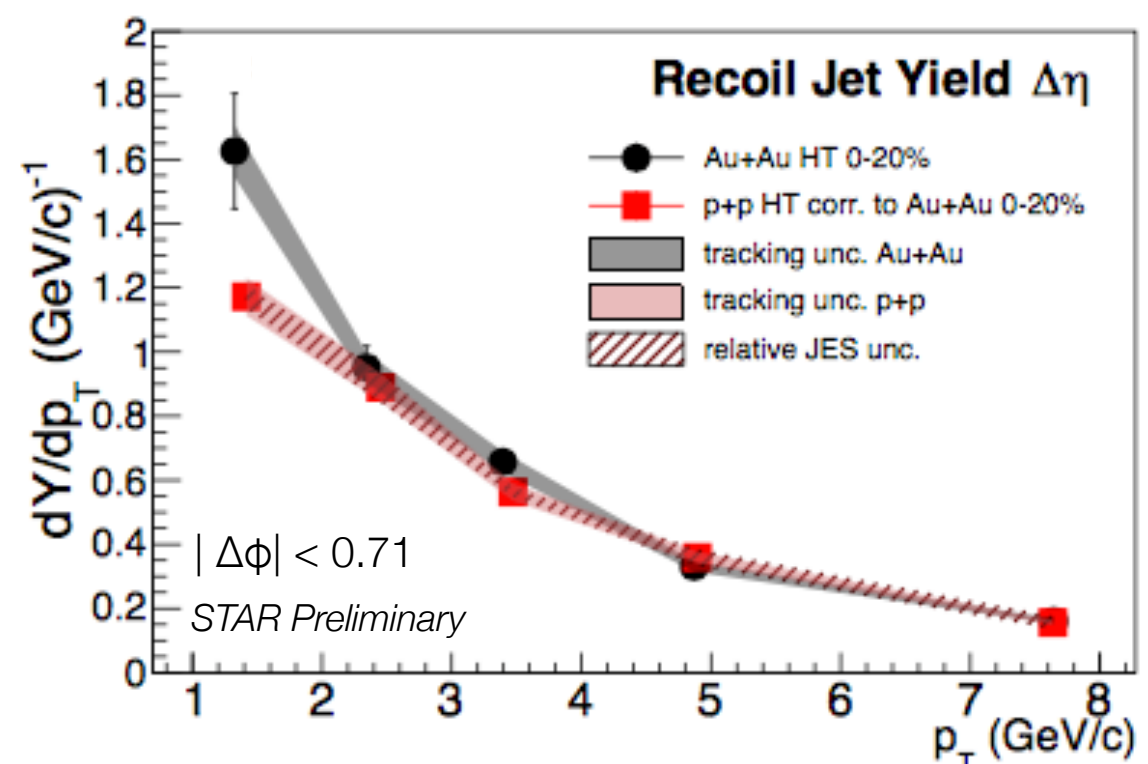
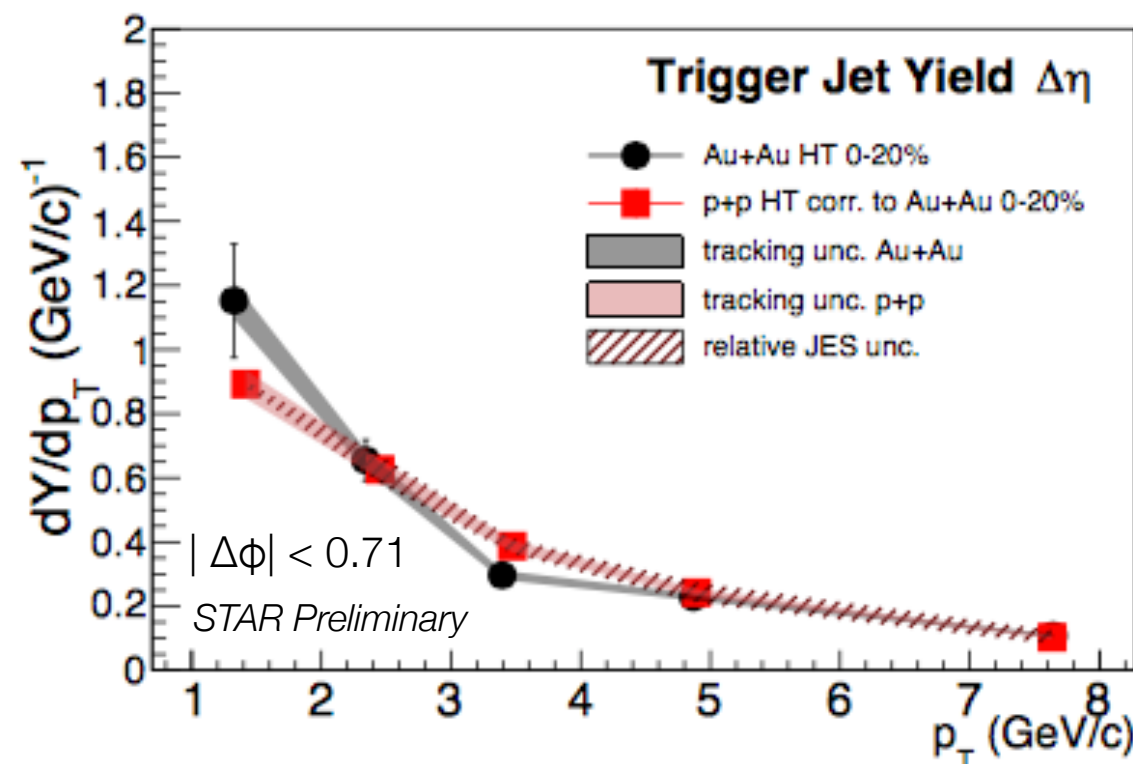
HT: $E_T > 4.5$ GeV

$p_{T}^{\text{assoc}} > 2$ GeV/c: No significant difference for jet constituent multiplicity
But jet energy changed — A_J different

Dijet-Hadron Correlations

for **hard core** matched dijets

Background subtracted with Gaussian+constant fit



HT: $E_T > 4.5$ GeV

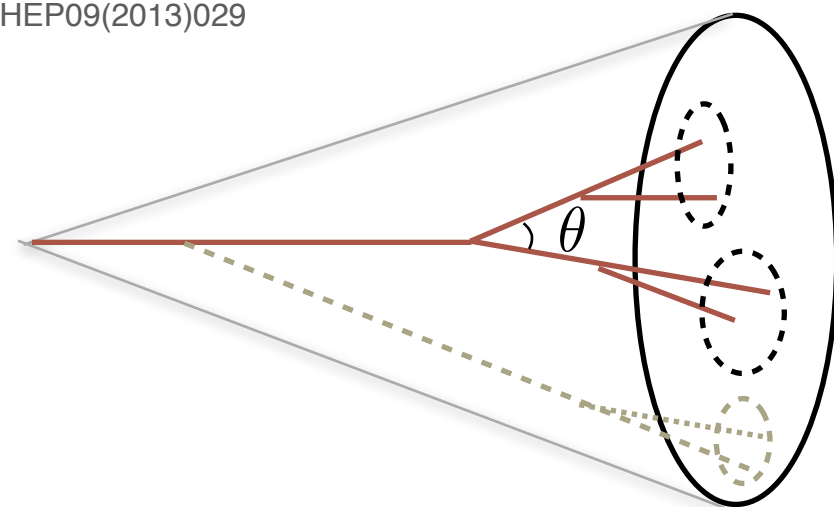
A_J sensitive to modification in few events
Effect diluted in ensemble measurements (dijet-hadron)
→ Dijet-Hadron A_J dependence

Jet Substructure: Soft Drop z_g

Goal: to search for modification of hardest jet splitting

Larkoski, *et al*, JHEP05(2014)146

Dasgupta, *et al*, JHEP09(2013)029

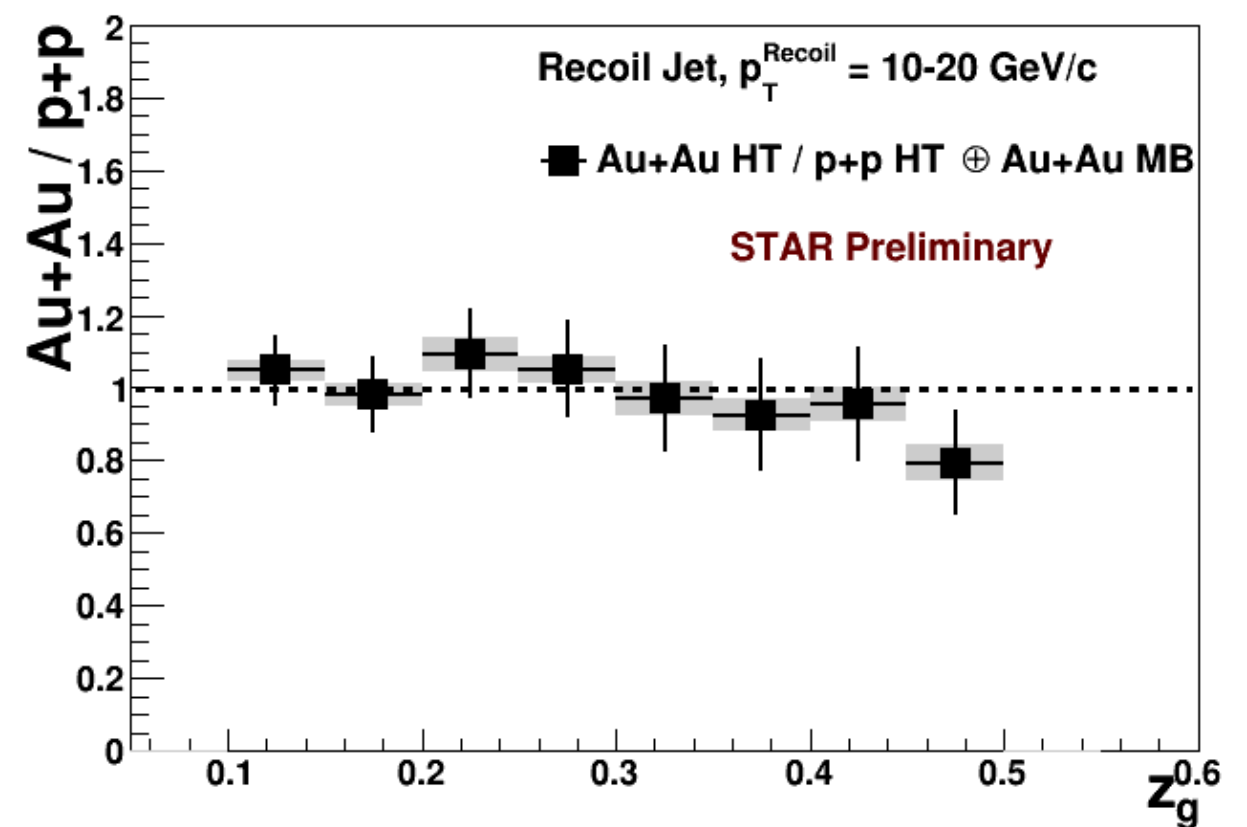


$$z_g = \frac{\min(p_{T1}, p_{T2})}{p_{T1} + p_{T2}} > z_{\text{cut}} \theta^\beta$$

↑ energy threshold ↑ angular exponent

Credit: Marta Verweij

z_g in **hard core** matched dijets with $p_{T,\text{cut}} > 0.2$ GeV/c

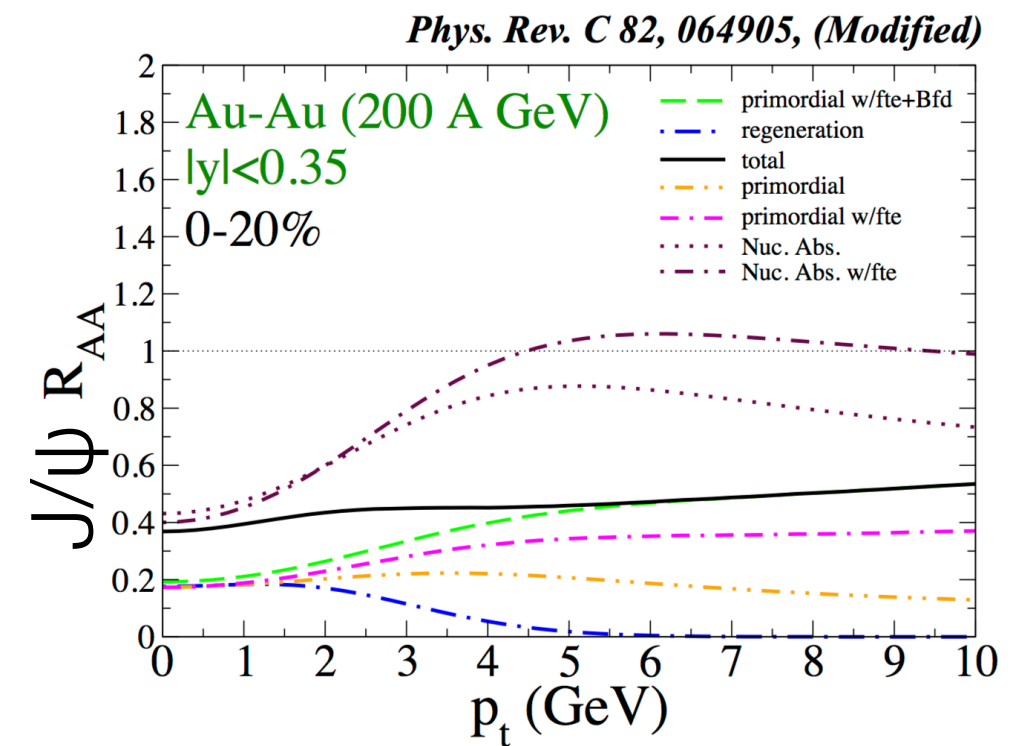


No significant splitting modification

- High p_T hadron and Jets
- **Quarkonium**
- Open Heavy Flavor

Quarkonium Productions

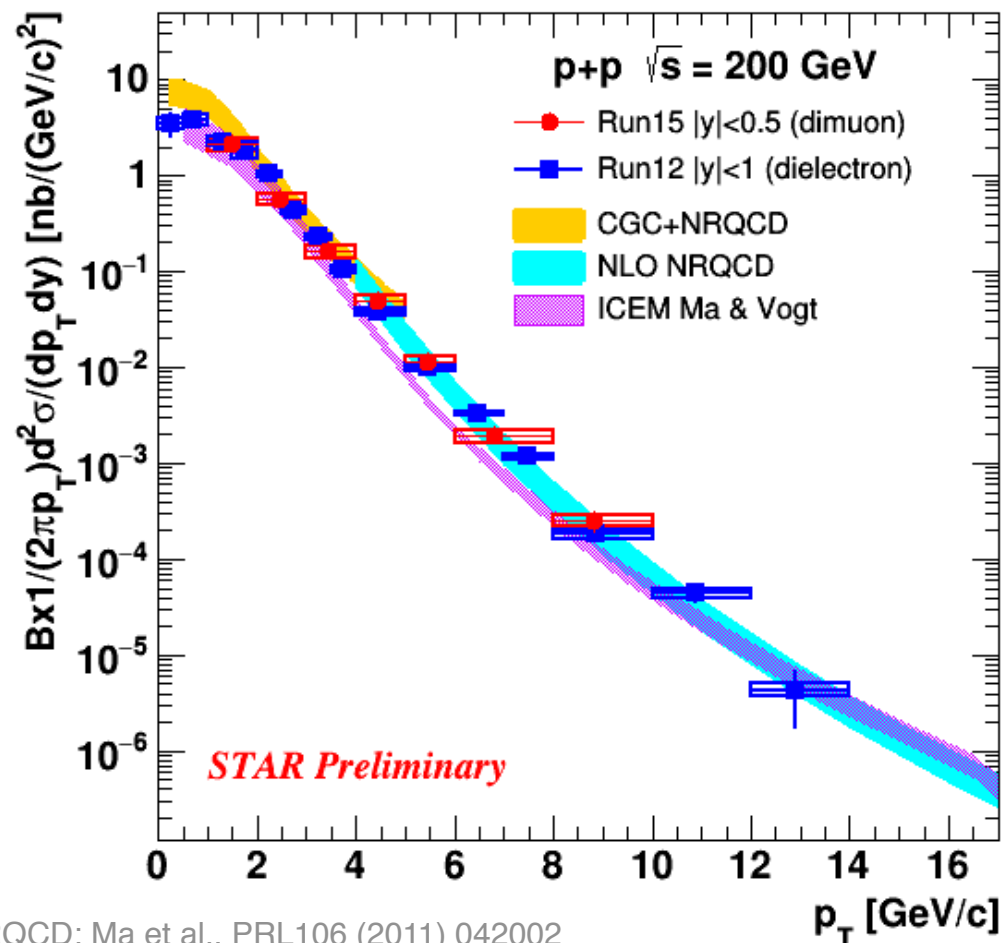
- The goal: Evidence for deconfinement; Thermometer
- Formation:
 - Mechanisms not fully understood even in p+p
 - Feed down contribution
- Modification:
 - Cold nuclear effects
 - Hot medium effects
- J/ψ photoproduction



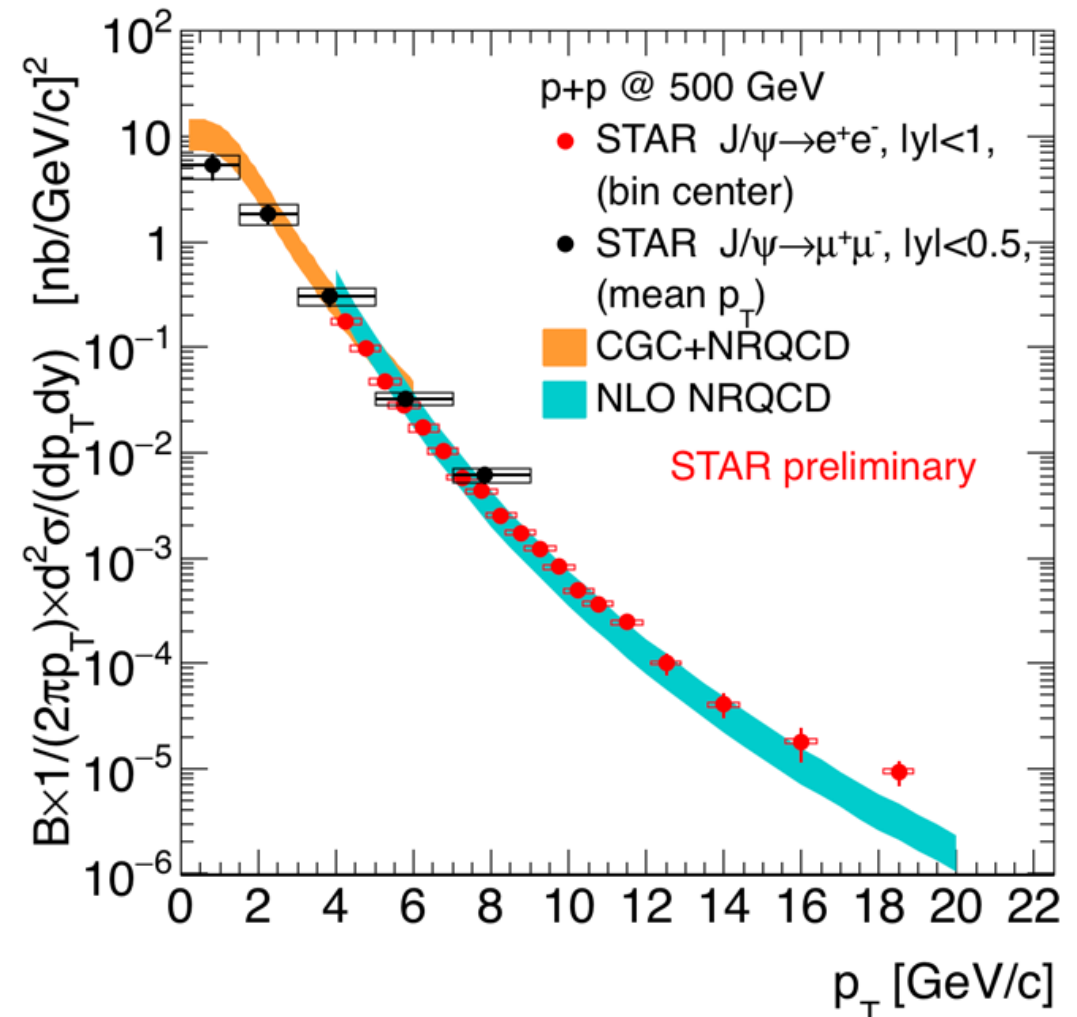
J/ψ Spectra in p+p Collisions

- CGC+NRQCD and NLO NRQCD (prompt) consistent with data (inclusive) at p+p @ 200 and 500 GeV

p+p@ 200 GeV



p+p@ 500 GeV



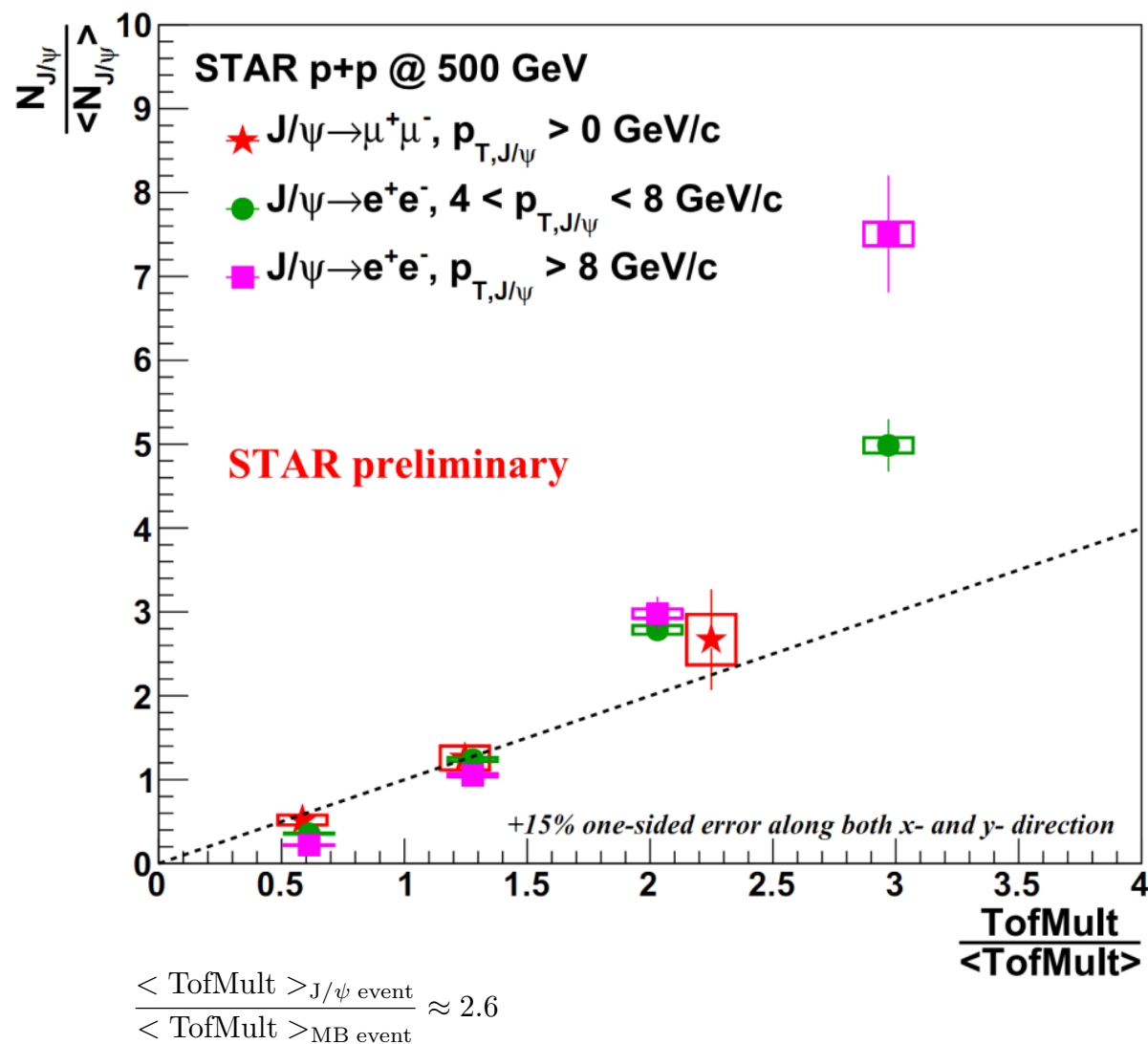
NLO NRQCD: Ma et al., PRL106 (2011) 042002

CGC+NRQCD: Ma, Venugopalan, PRL113 (2014) 192301

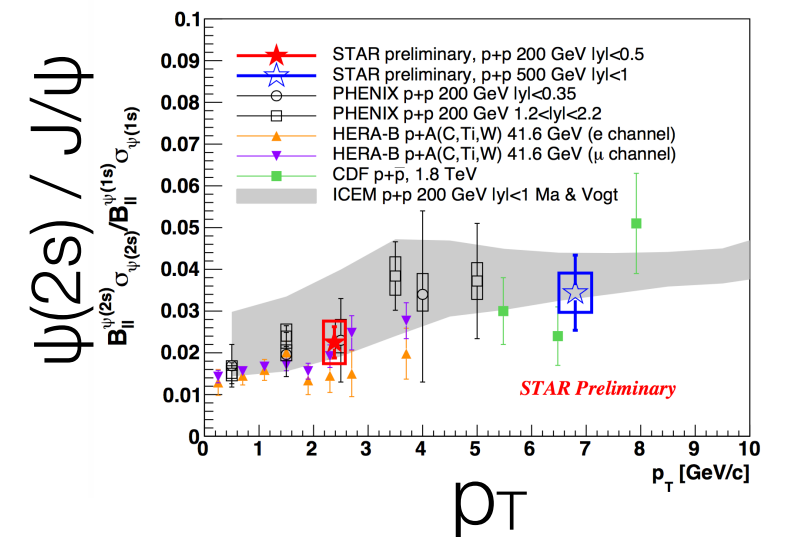


J/ψ vs. Event Activity in p+p

Stronger-than-linear growth for high p_T J/ψ



- Feed-down fraction depends on p_T
 χ_c , $\psi(2s)$, B-hadrons



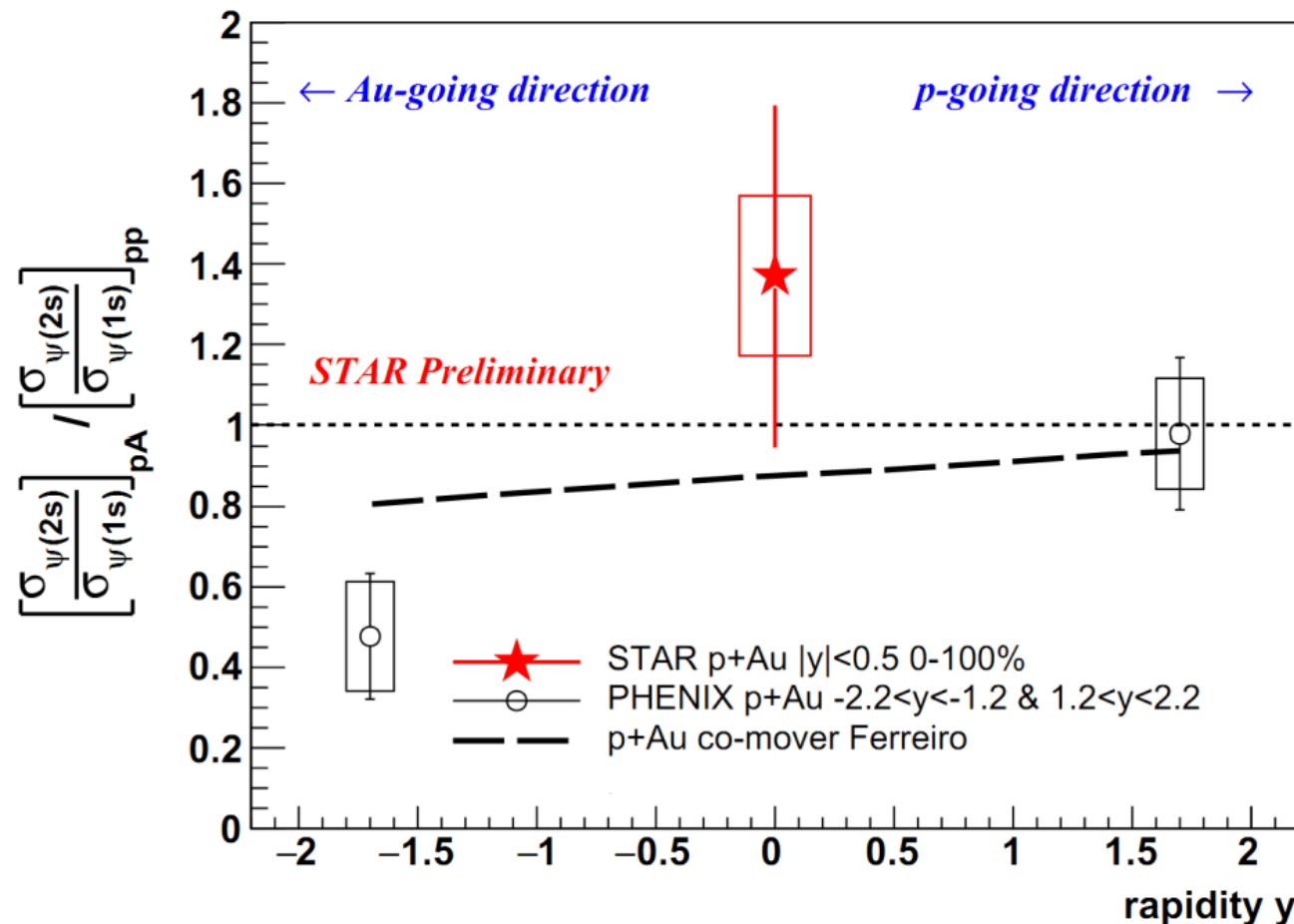
- Prompt J/ψ in jet populated at low z
 Less isolated than expected at LHC

LHCb, PRL 118, 192001 (2017)

Discussions on MPI effect: ALICE, arXiv 1202.2816, 1505.00664



$\psi(2S)$ to J/ψ Double Ratio in p+Au Collisions



Muon Telescope Detector (MTD) enables STAR's first $\psi(2S)$ to J/ψ double ratio measurement in p+p and p+Au

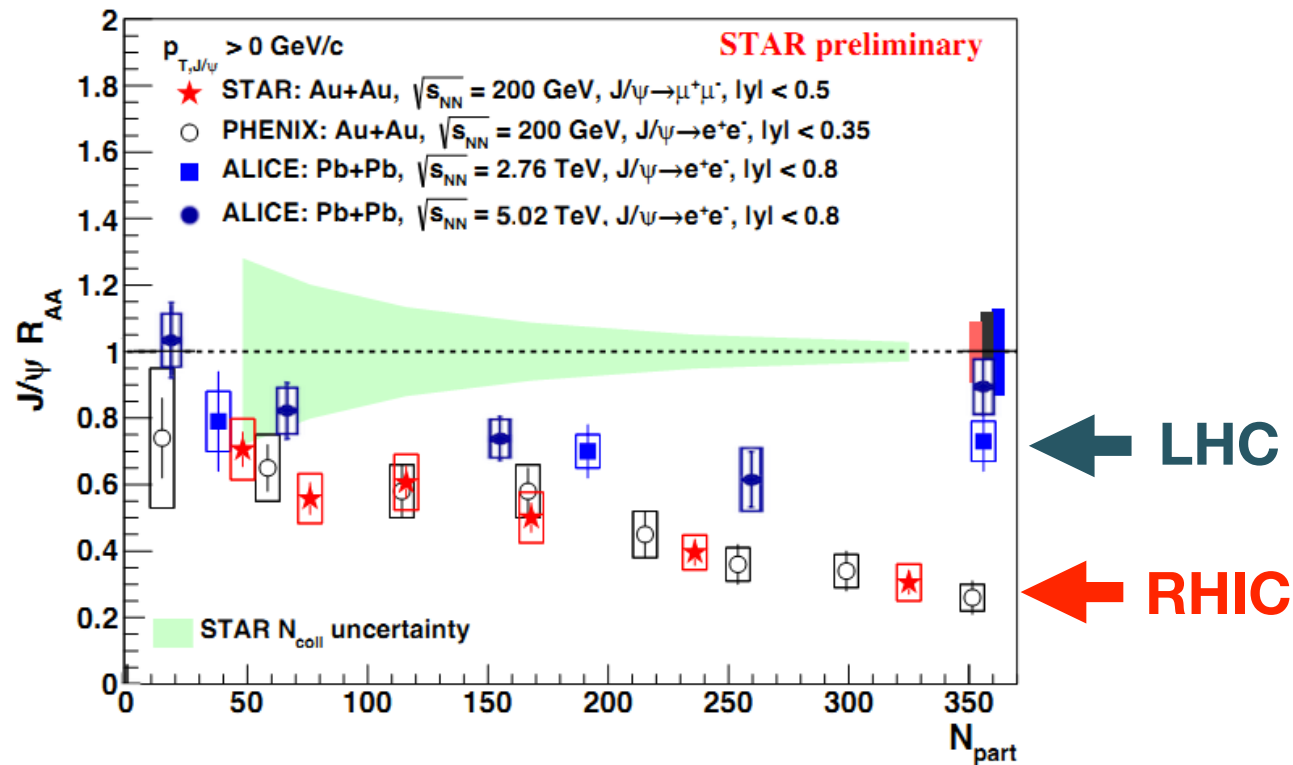
$$1.37 \pm 0.42(\text{stat.}) \pm 0.19(\text{syst.}).$$

J/ψ Suppression in Au+Au Collisions

PHENIX: PRL **98** (2007) 232301
ALICE: PLB **734** (2014) 314
ALI-PREL-121481

CMS: EPJC77(2017) 252
Tsinghua at RHIC: PLB **678** (2009) 72
Tsinghua at LHC: PRC **89** (2014) 054911
TAMU at RHIC: PRC **82** (2010) 064905
TAMU at LHC: NPA **859** (2011) 114

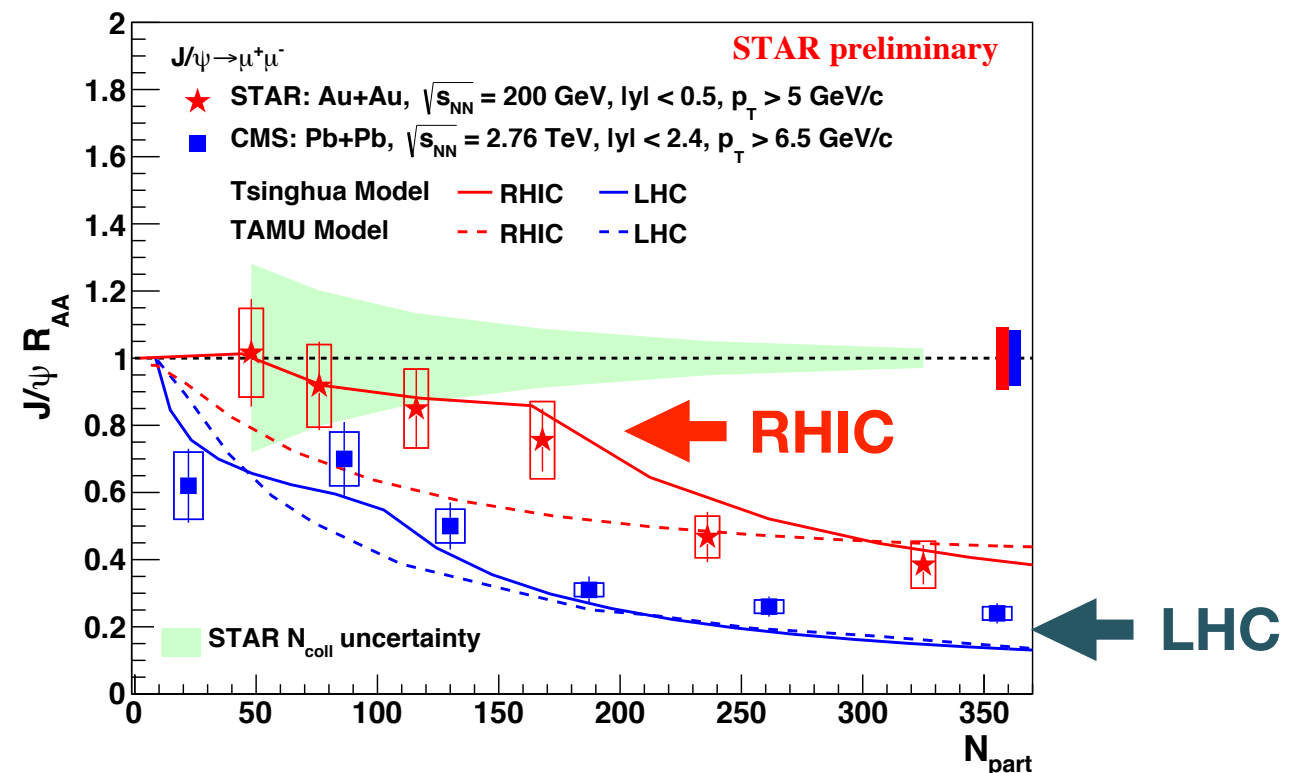
Low p_T J/ψ in central collisions:



$R_{AA}(200 \text{ GeV}) < R_{AA}(2.76 \text{ TeV}) \sim R_{AA}(5.02 \text{ TeV})$

Less regeneration at RHIC

High p_T J/ψ in all centralities:



$R_{AA}(200 \text{ GeV}) > R_{AA}(2.76 \text{ TeV}) \sim R_{AA}(5.02 \text{ TeV})$

Less color screening at RHIC

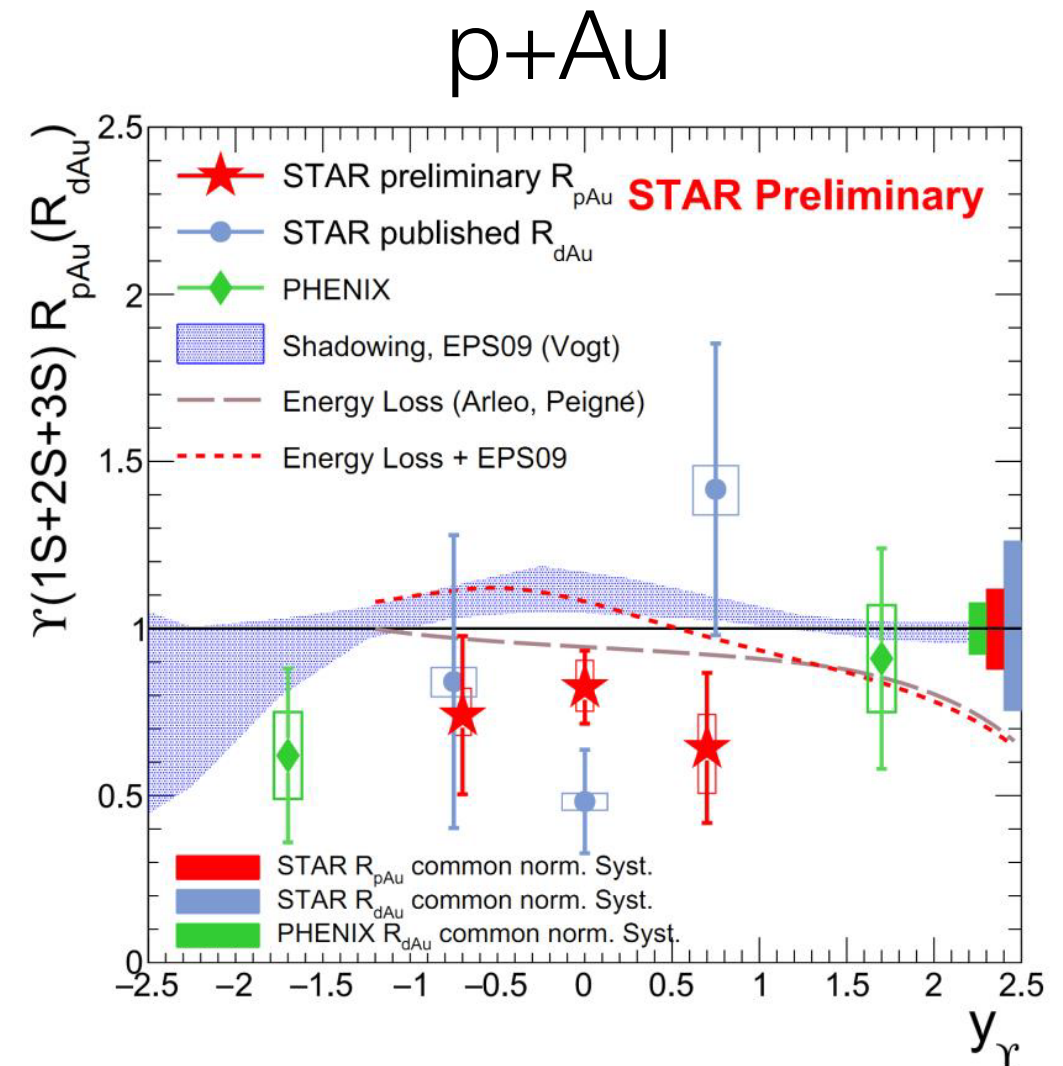
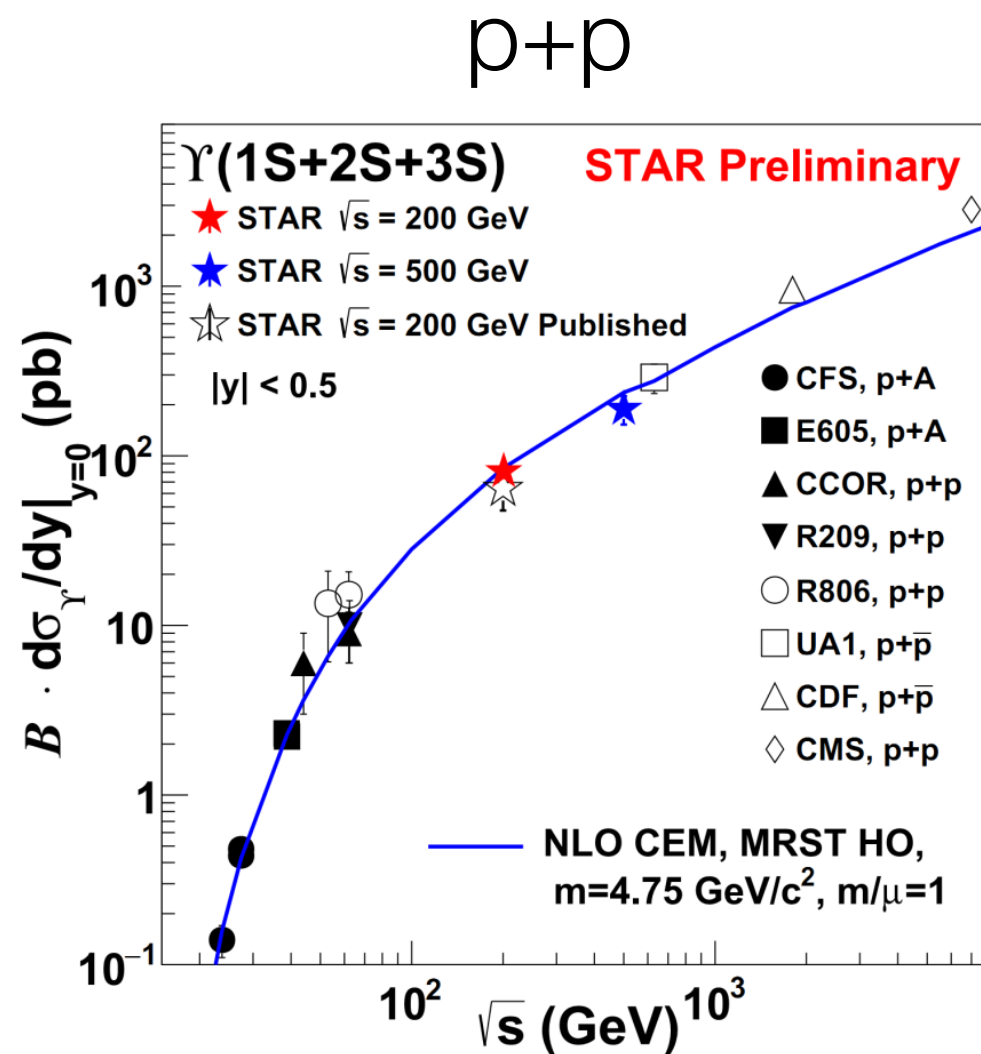
Υ Production in p+p and p+Au Collisions

R. Vogt, Phys. Rept. **462**(2008) 125

R. Vogt, et. al, PoS ConfinementX **203**(2012)

F. Arleo, S. Peigne, JHEP **1303**(2013) 122

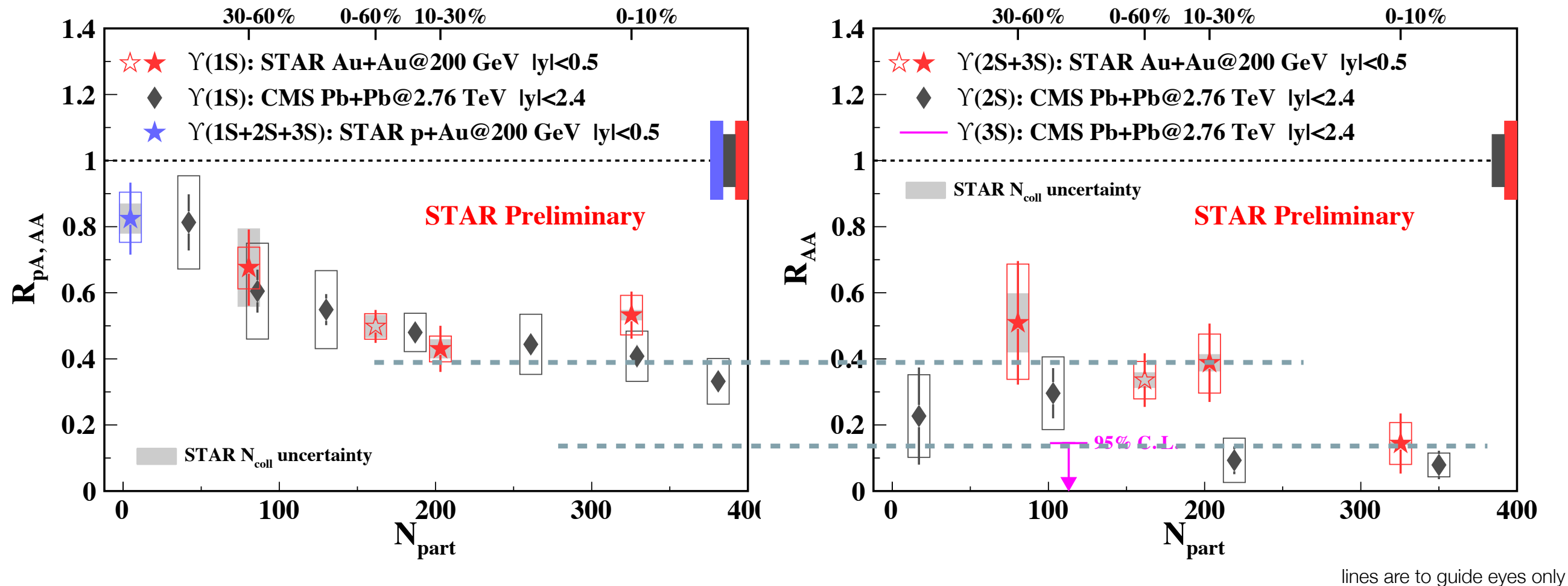
K. J. Eskola, et. al, JHEP **0904**(2009) 065



- Yields consistent with NLO model

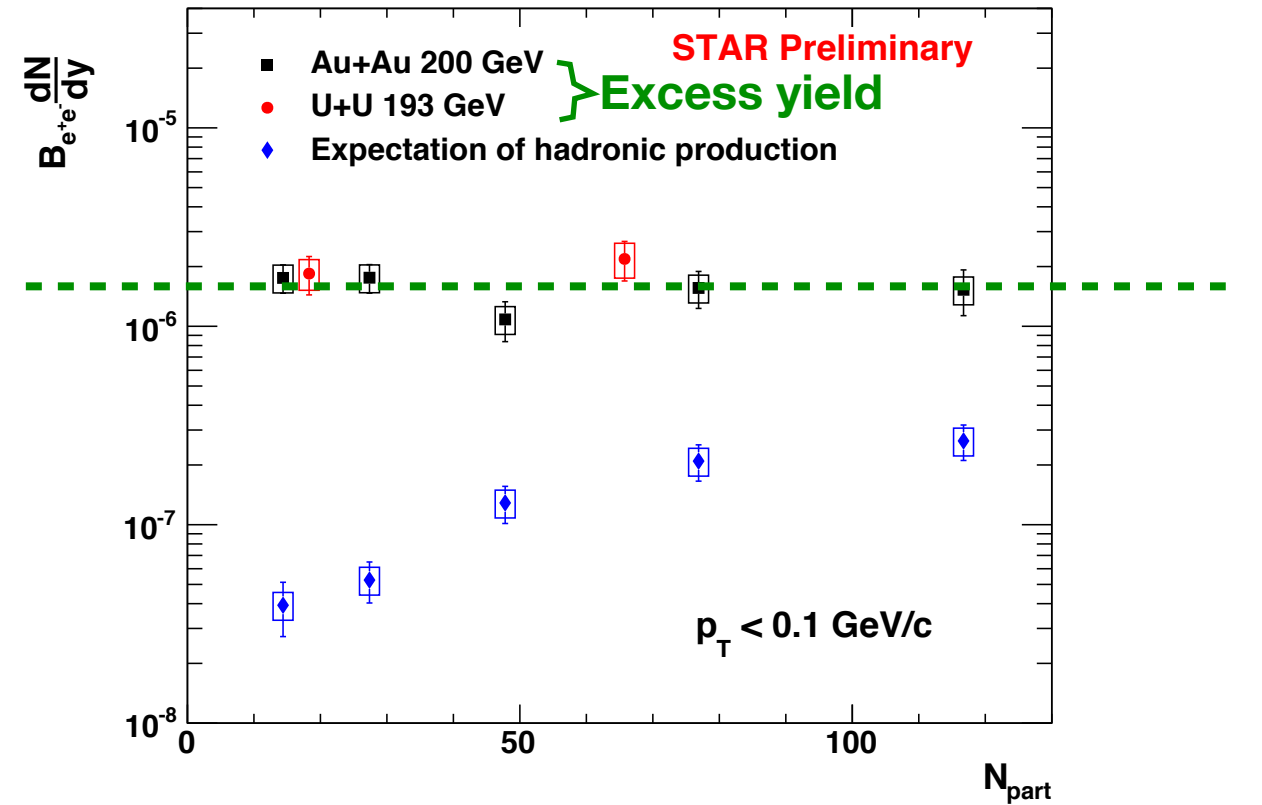
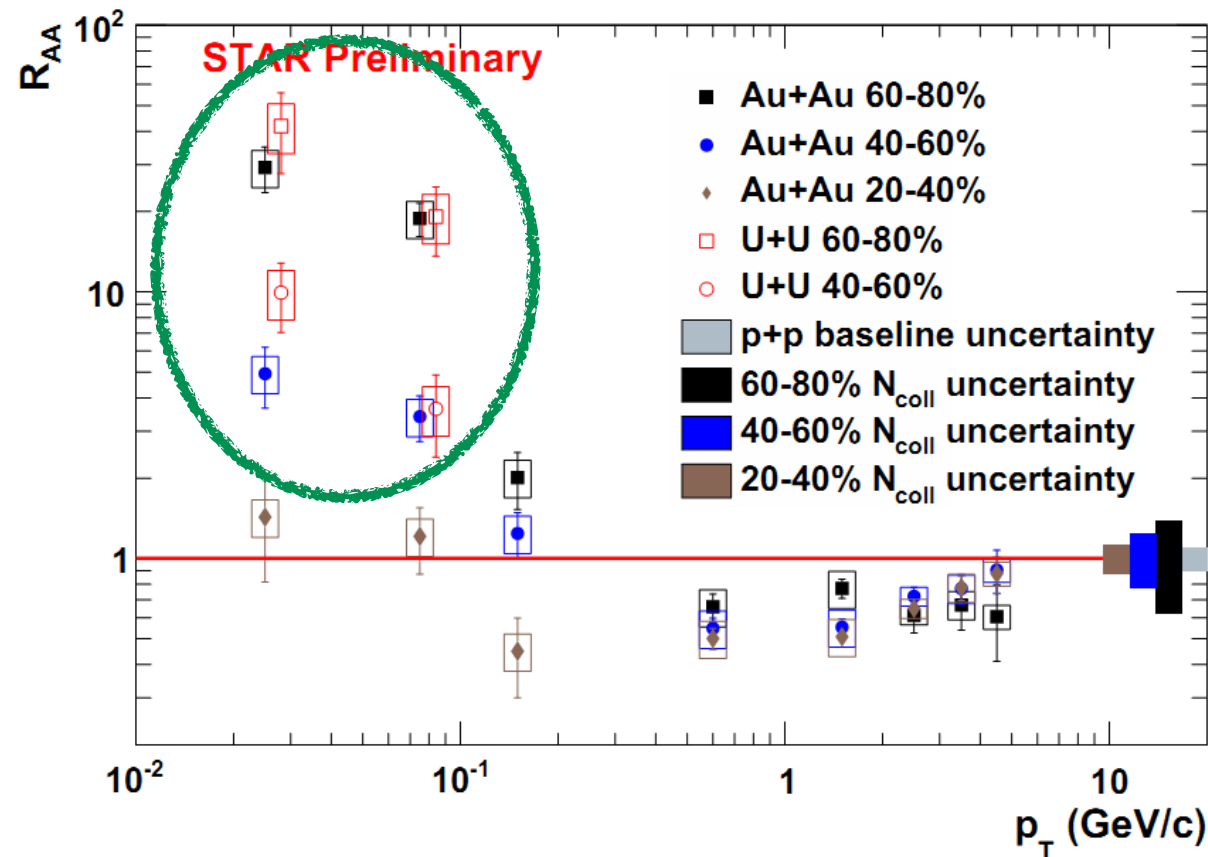
- R_{pA} quantifies CNM effects

Υ Suppression in Au+Au Collisions



Sequential melting observed at both RHIC and LHC energies

Excess of J/ψ at Very Low p_T

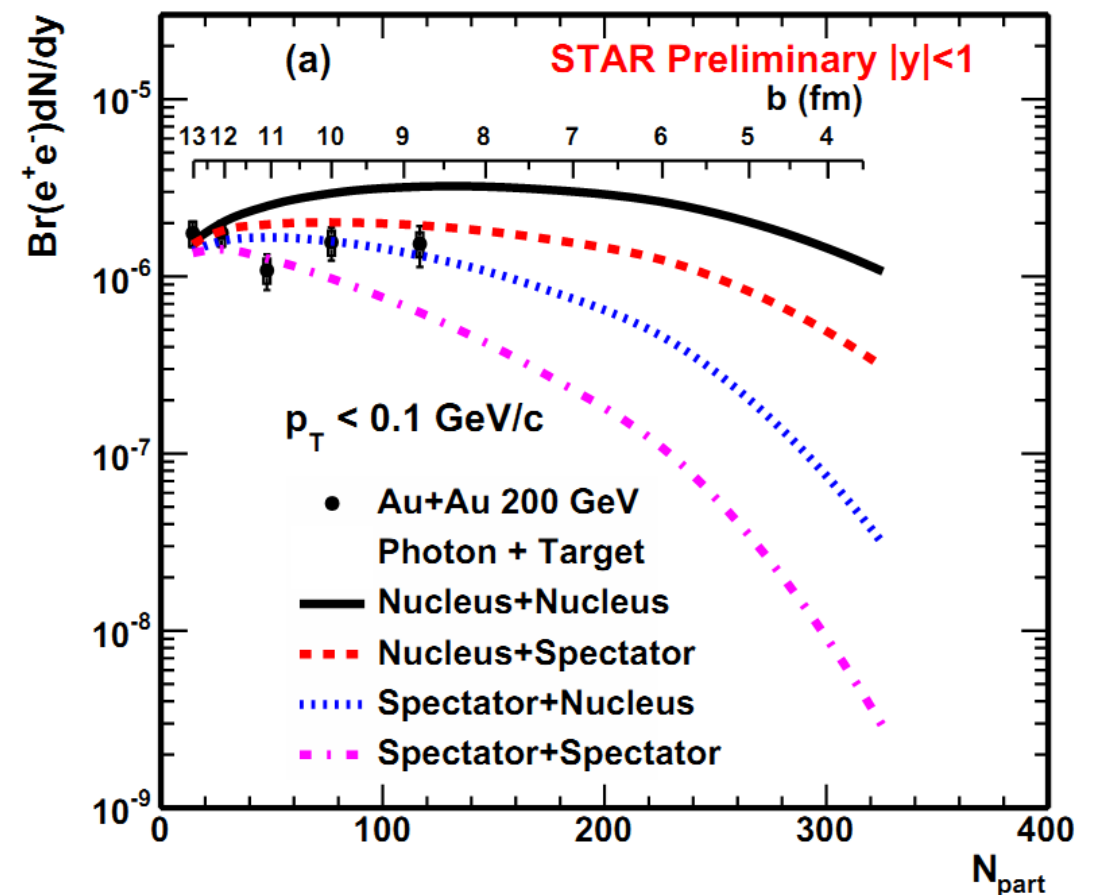
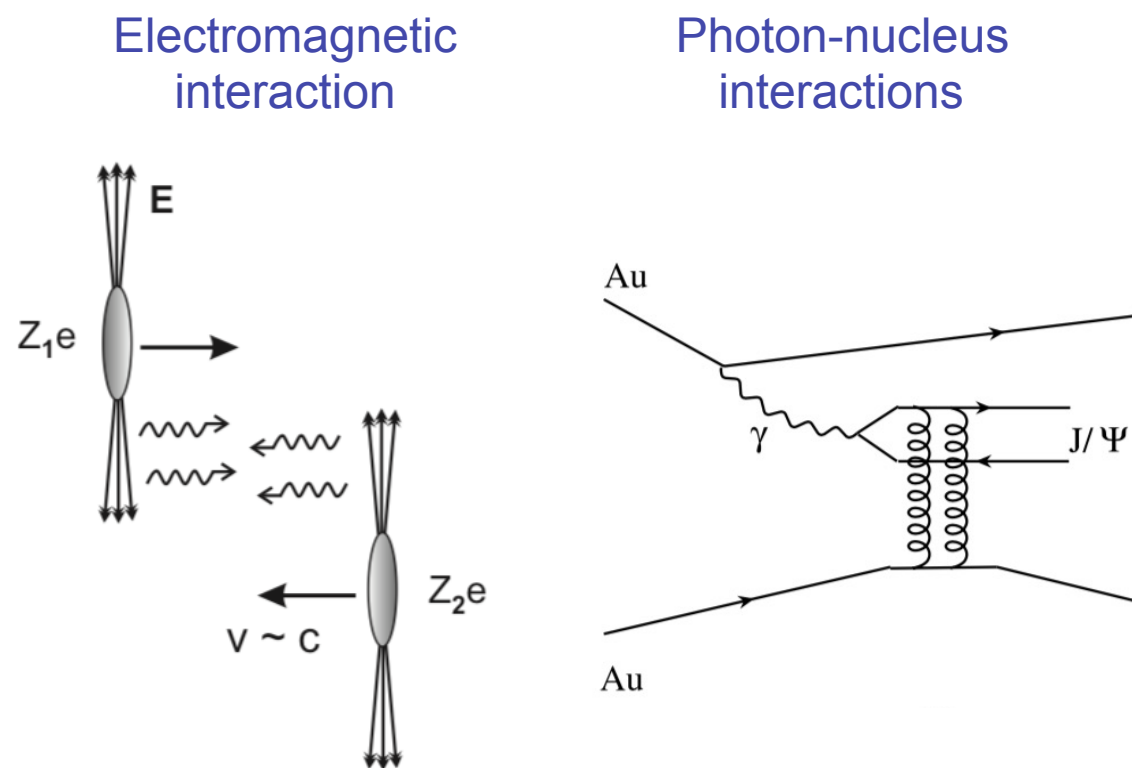


lines are to guide eyes only

- J/ψ $R_{AA} \sim 30$ at $p_T < 0.05 \text{ GeV/c}$ in 60-80% collisions
- No significant centrality dependence of the excess yield in 30-80% collisions, while hadronic production is small and expected to strongly depend on N_{part}

Photoproduction Model Comparison

Large flux of quasi-real photons makes a hadron collider also a photon collider



- Consistent with coherent photoproduction
- Central collisions have a larger discriminating power
- A novel probe to study the medium?
 - potential to discriminate dissociation and regeneration

Zha, et al., arXiv: 1705.01460
 Chen, et al, arXiv: 1801.01677
 PHENIX, PLB 679 (2009) 321
 Klein and Nystrand, PRL **84**2330 (2000)
 Bertulani, Klein, and Nystrand, Ann. Rev. Nucl. Part. Sci.55:271 (2005)

- High p_T hadron and Jets
- Quarkonium
- **Open Heavy Flavor**

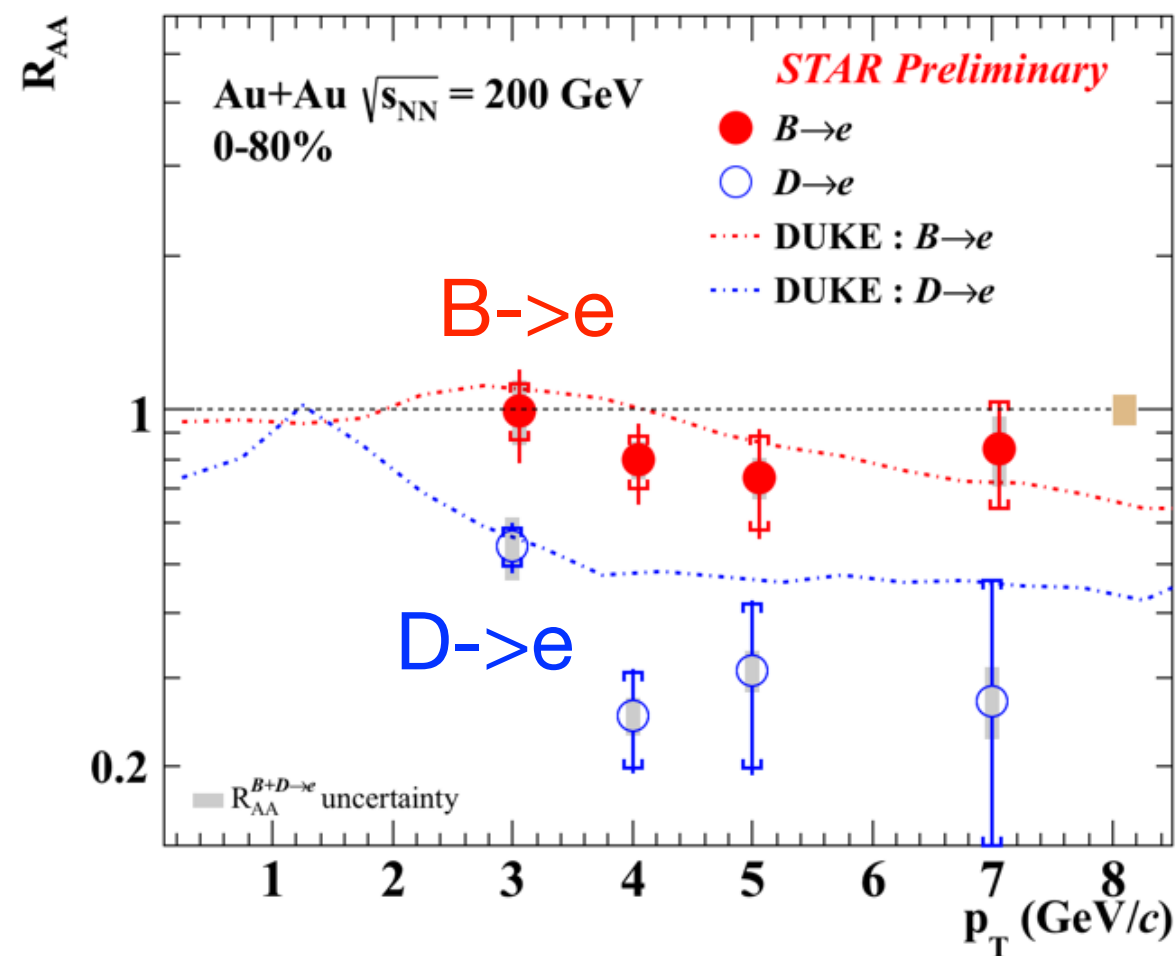
Open Heavy Flavor Probes

Produced early and probe the full QGP history:

- Flavor-dependence of in-medium energy loss
Nature of heavy quark-medium interaction
- Heavy quark collective behavior
Degree of thermalization, spatial diffusion coefficient
- Heavy quark hadronization
QGP dynamics

B vs D Mass Hierarchy of Energy Loss

Made possible by excellent Heavy Flavor Tracker (HFT) tracking resolution

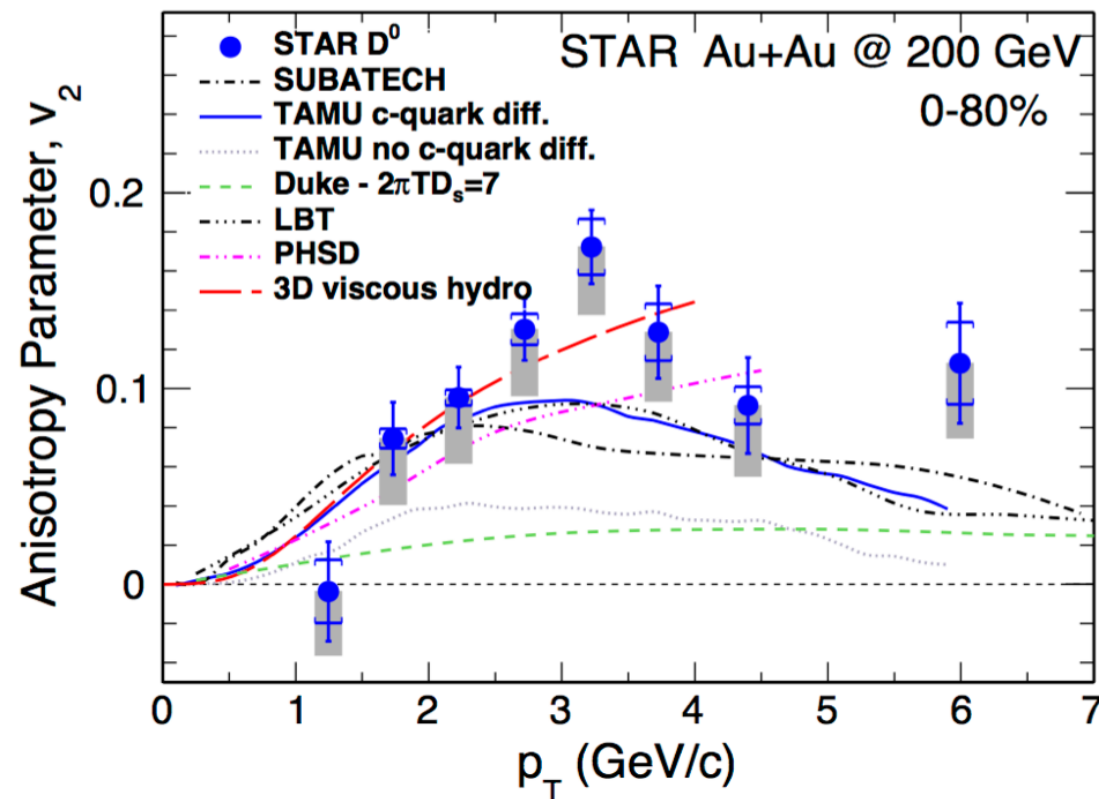


Smaller suppression for electrons from B than D

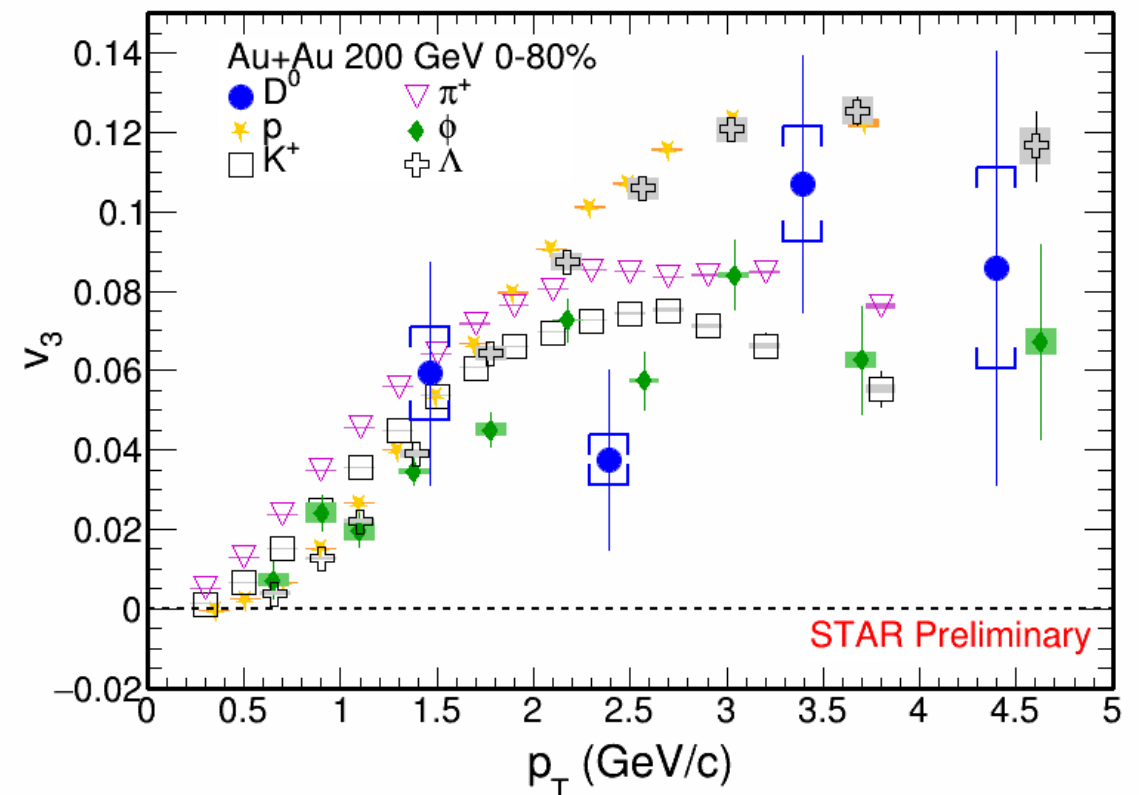
★ High precision measurements coming

D⁰ Anisotropic Flow

V₂



V₃



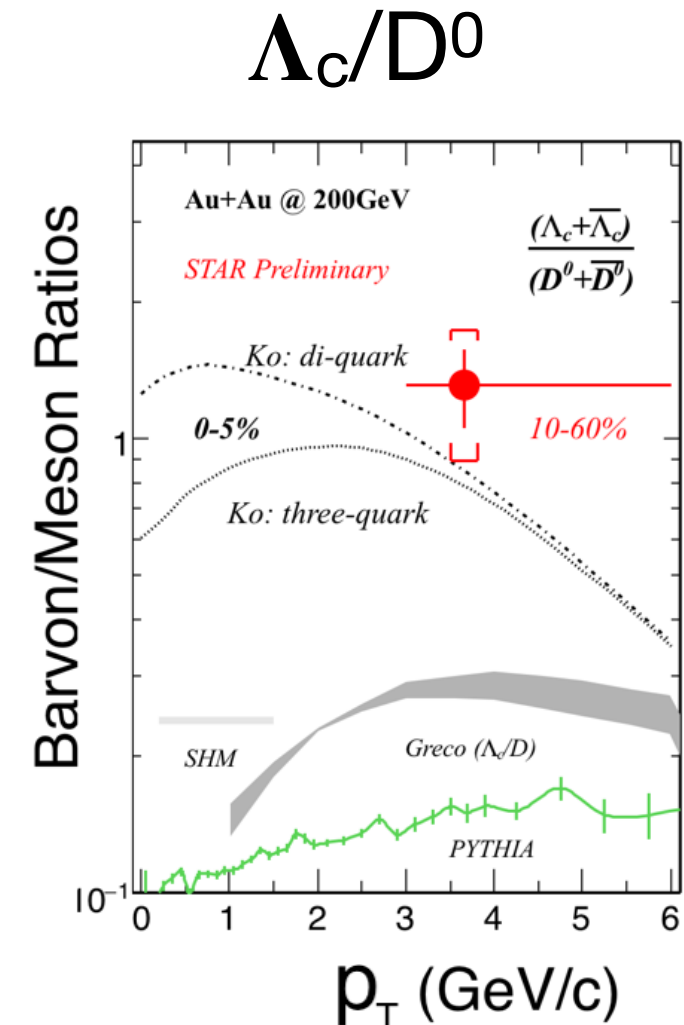
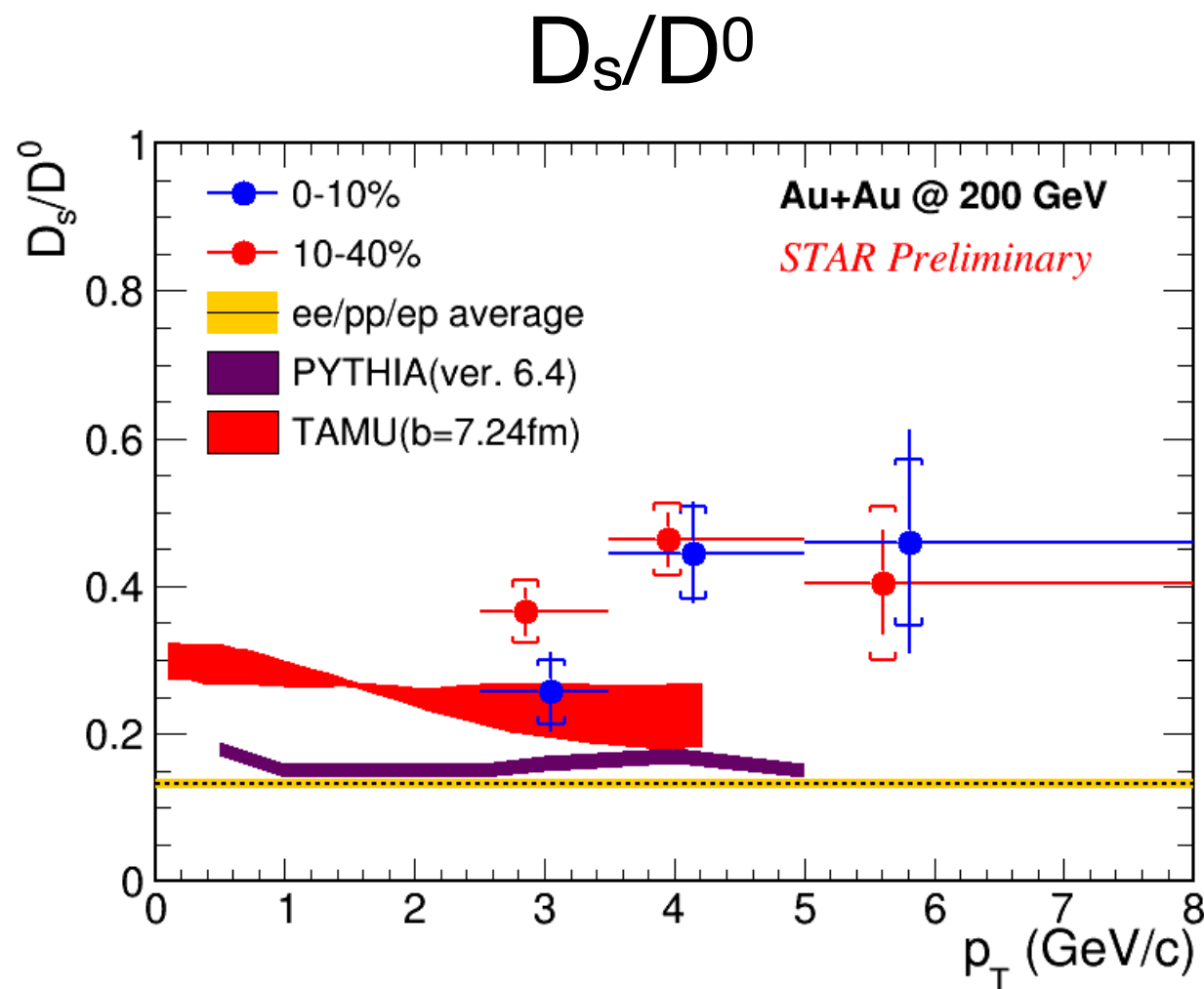
STAR, PRL 118 (2017) 212301
Theory refs cited in paper

Strong collectivity of D⁰ mesons

Consistent with charm quark achieving local equilibrium with the medium

★ D⁰ direct flow coming

Heavy Quark Hadronization



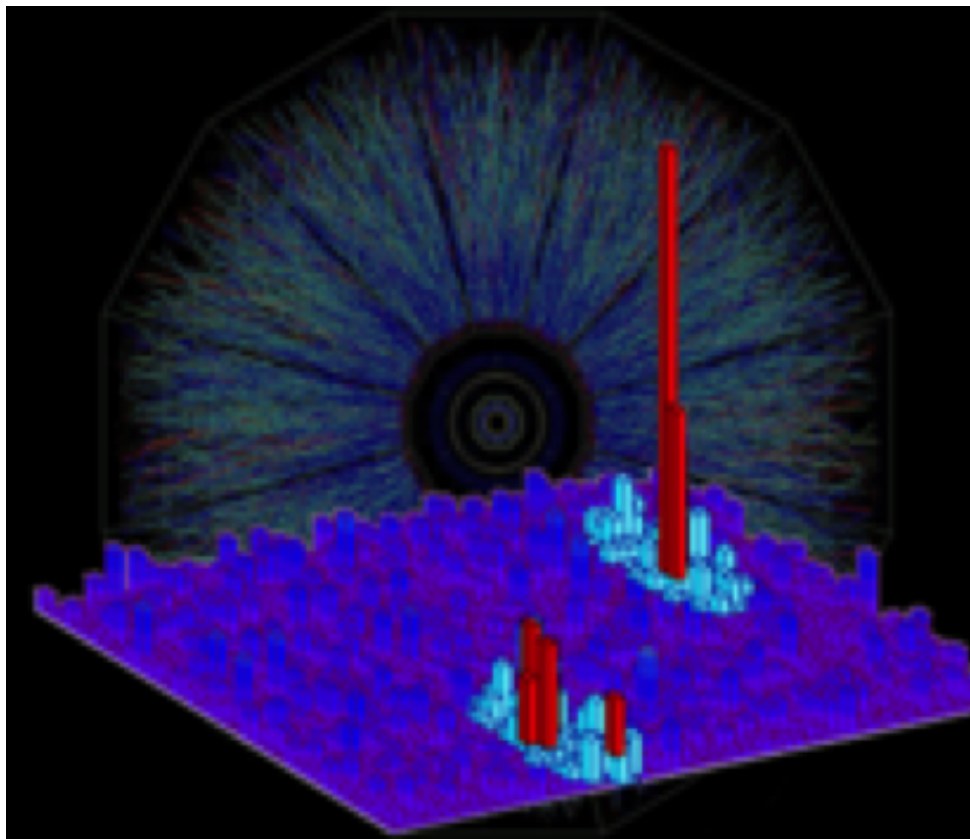
Enhanced D_s/D^0 and Λ_c/D^0 ratios compared to Pythia
Charm quarks may participate in coalescence hadronization

★ Detailed measurements coming

Summary

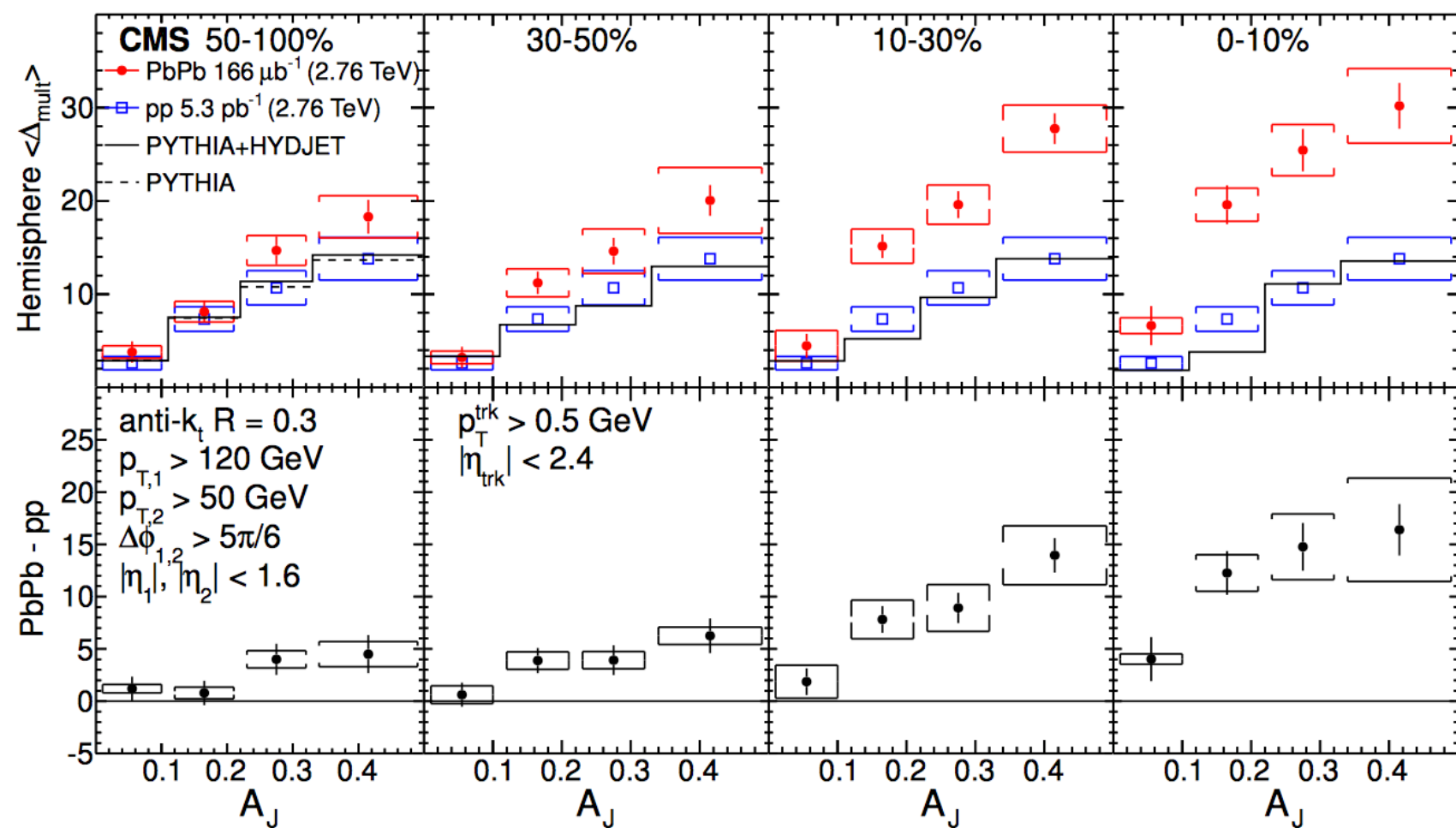
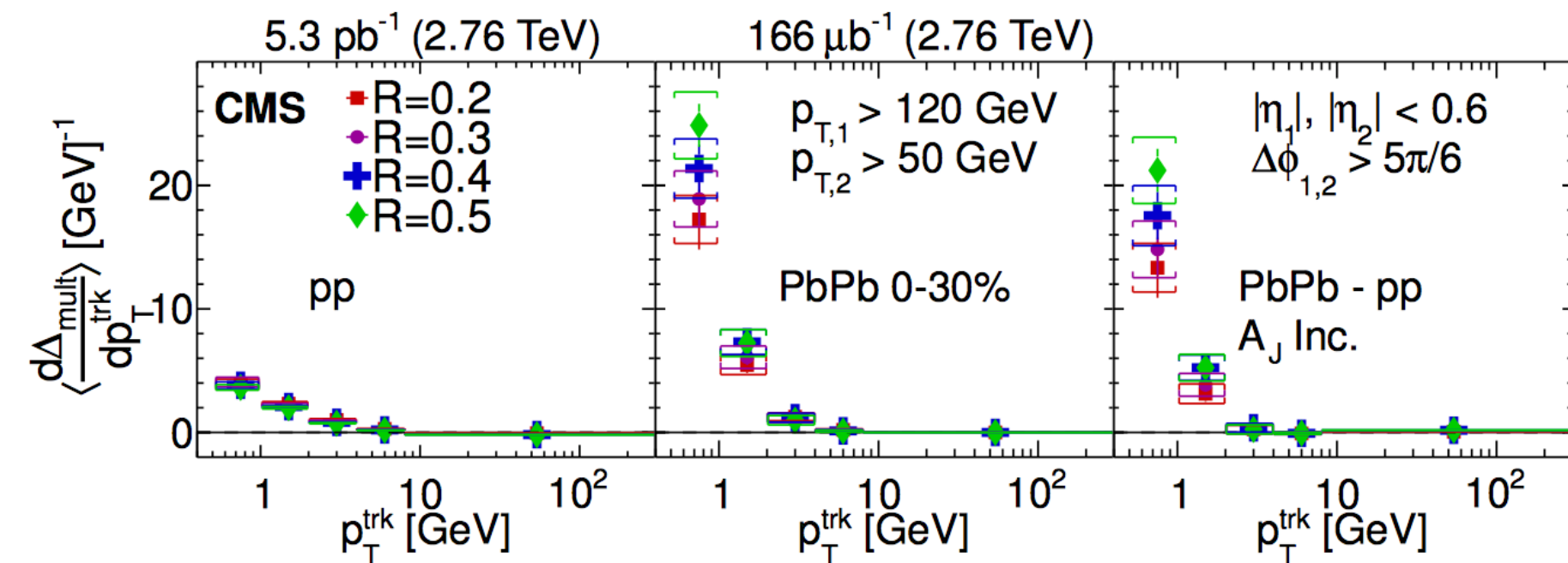
- Significantly enhanced understanding of jet modifications at RHIC
 - total jet energy loss less than at LHC
 - lost energy re-emerges at low p_T
 - z_g unmodified for hard core jets
- Explore heavy-flavor interaction with medium
 - mass hierarchy of c/b-quark energy loss observed
 - c-quark 'thermalized'
 - Quarkonium sequential melting, smaller regeneration than LHC
- Quarkonium formation and cold nuclear effect investigated
- Excess of J/ψ at very low p_T consistent with coherent photoproduction

Probing the jet modification at RHIC



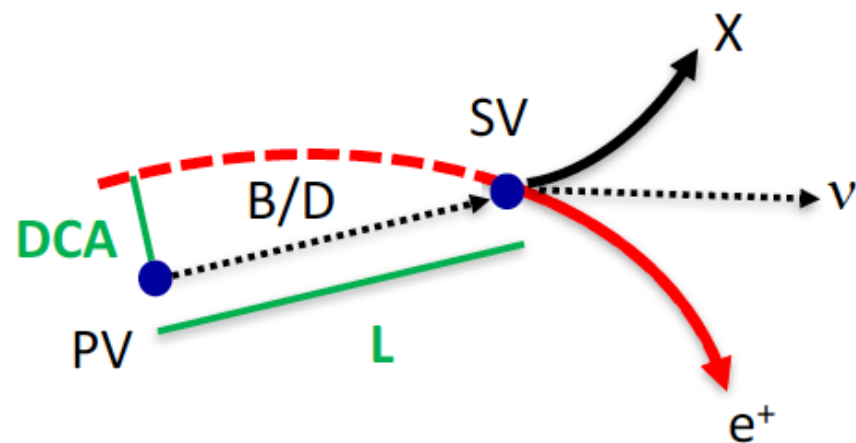
Significantly enhanced
understanding of jet
modifications at RHIC

- High p_T hadron suppression at BES
([arXiv:1707.01988](#))
- pp in very good agreement with theory
(Di-jets, *PRD* 95 (2017) 71103 (R))
- Unbiased recoil jets highly suppressed due to medium induced broadening
- Total E_{loss} less than at LHC
(Hadron-jet correlations, *PRC* 96 (2017) 24905)
- Lost energy re-emerges at low p_T **not** z_T
(γ -hadron correlations, *PLB* 760 (2016) 689)
- Di-jet energy imbalance largely recovered within $R=0.4$ when low p_T hadrons included
(Di-jet A_J , *PRL* 119 (2017) 062301 - Editor's suggestion)
- z_g unmodified for hard core jets
(preliminary release)
- γ -jet, jet in small systems, flavor jet ...
(stay tuned)

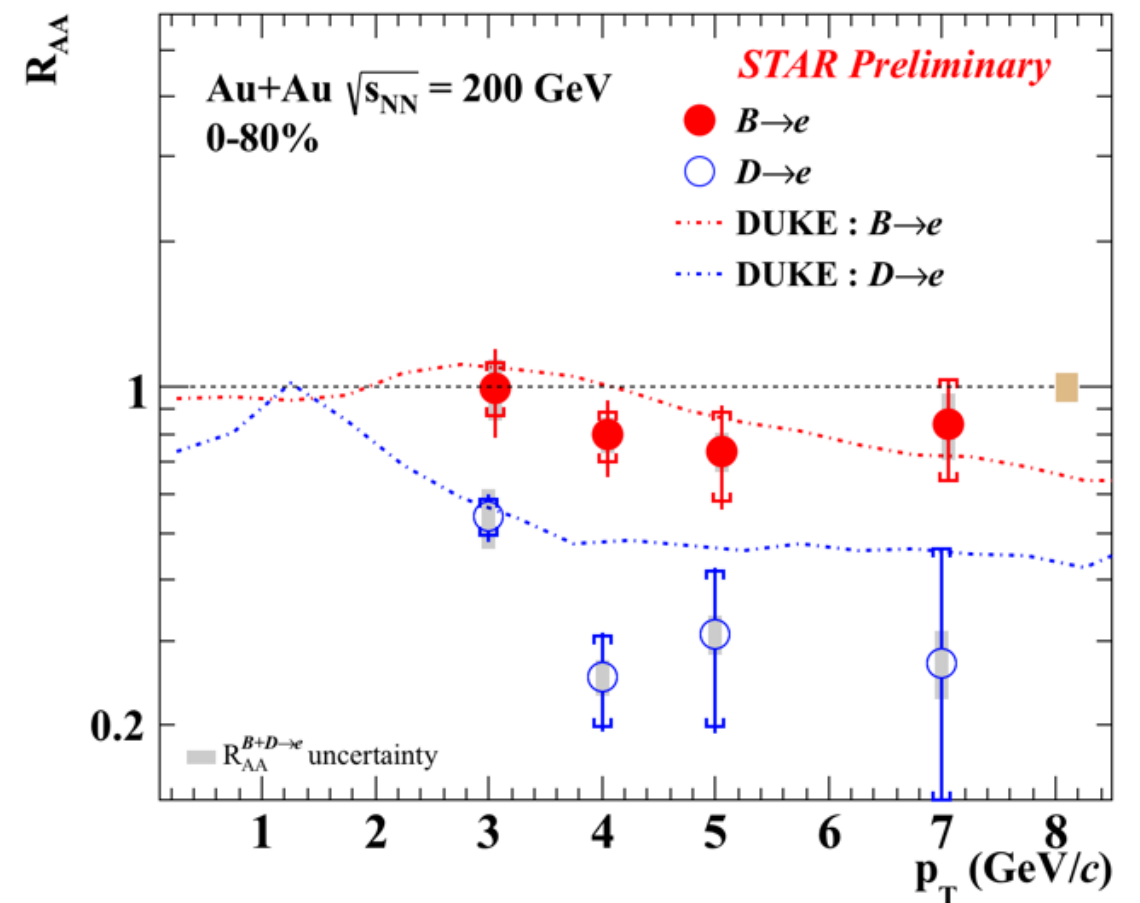


B/D → e Mass Hierarchy of Energy Loss

Excellent Heavy Flavor Tracker (HFT) resolution
Distinguish different electron sources by DCA



$$R_{AA}^{B/D \rightarrow e} = \frac{1 - f_{AA}^{B/D \rightarrow e}(\text{Data})}{1 - f_{pp}^{B/D \rightarrow e}(\text{Data})} R_{AA}^{HF_e}(\text{Data})$$



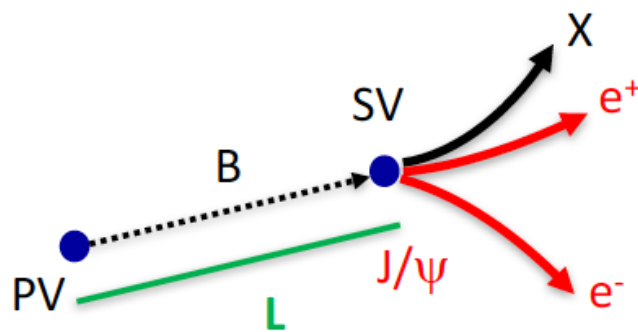
$$R_{AA}^{B \rightarrow e} > R_{AA}^{D \rightarrow e}$$

Consistent with mass hierarchy of energy loss

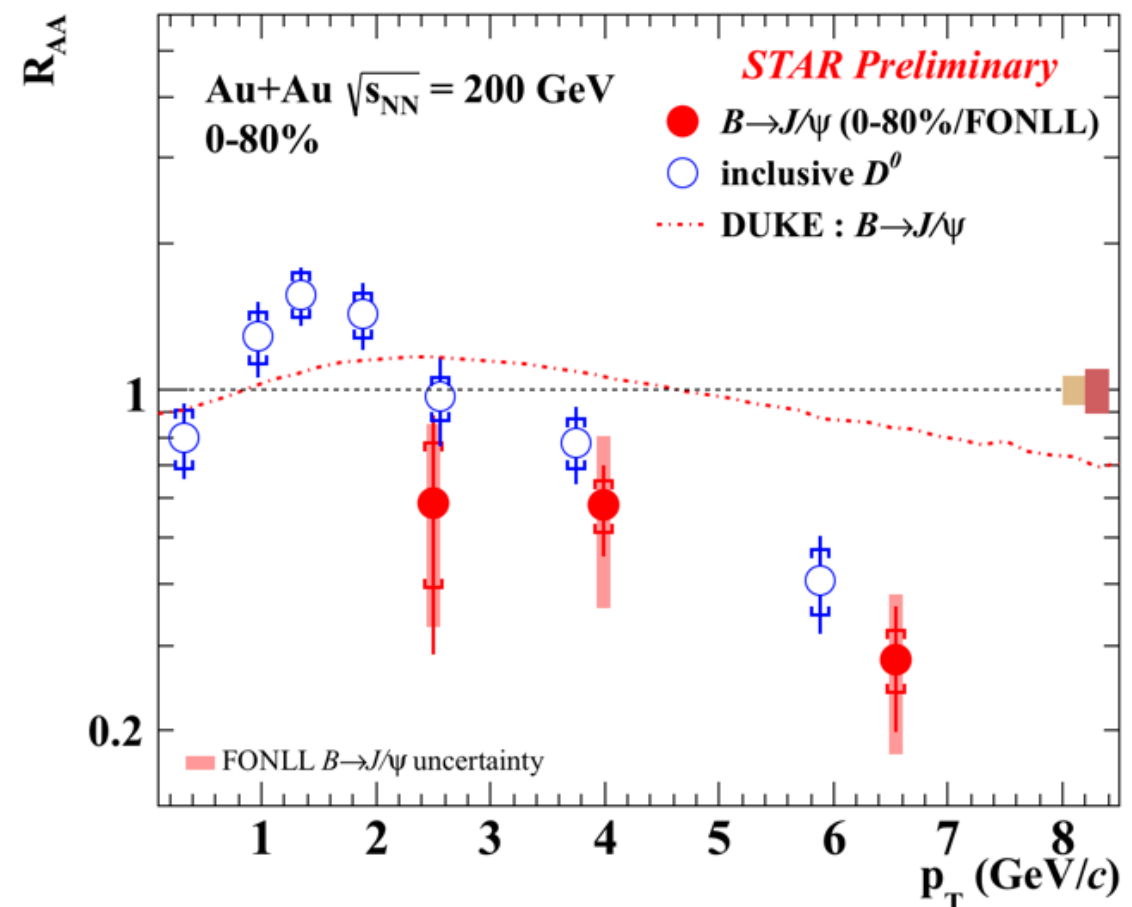
Non-prompt J/ψ R_{AA} in Au+Au Collisions

Fit pseudo proper decay length
Extract non-prompt J/ψ fraction

$$l_{J/\psi} = \frac{\vec{L} \cdot \hat{p}}{|\vec{p}|/c} \cdot M_{J/\psi}$$



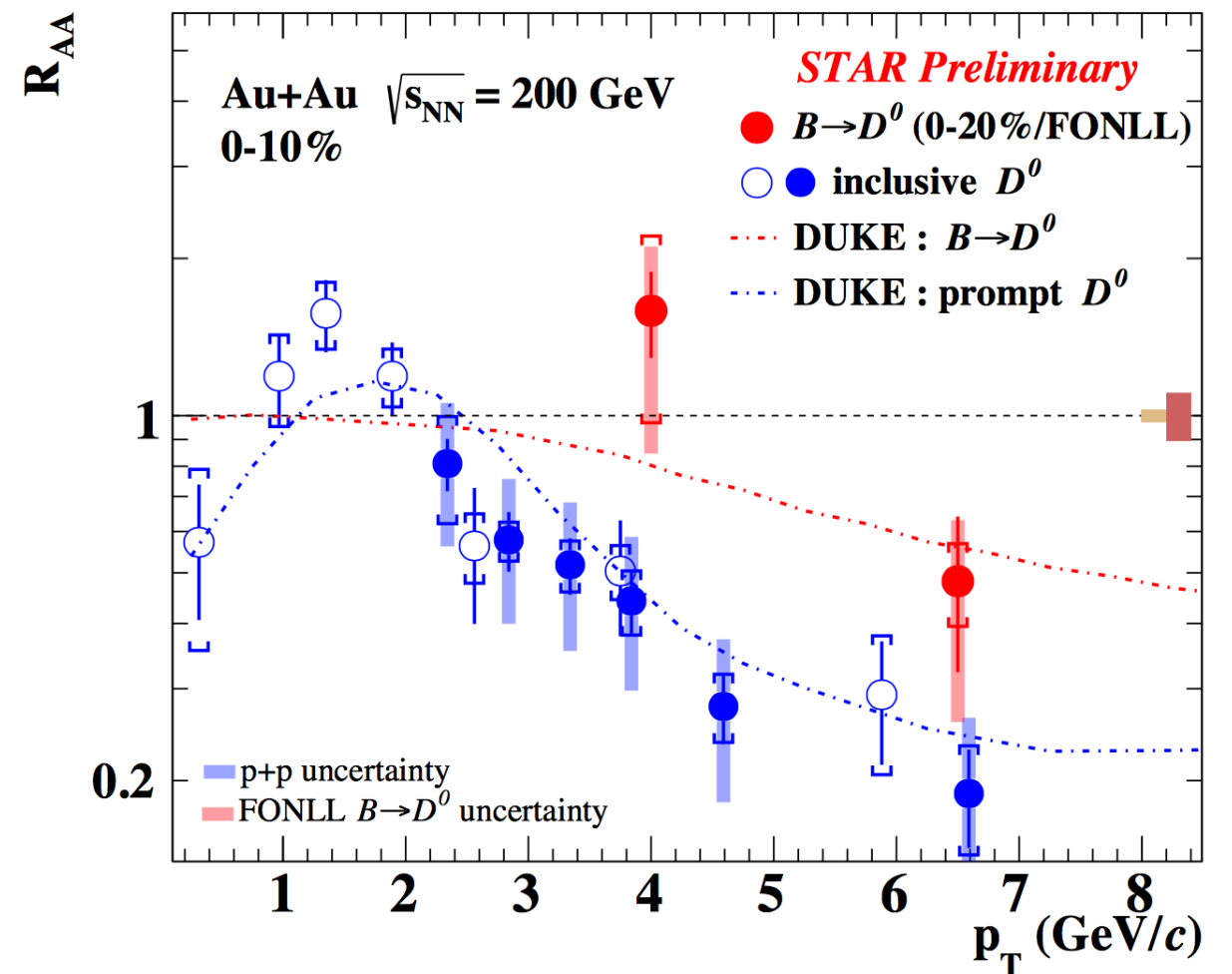
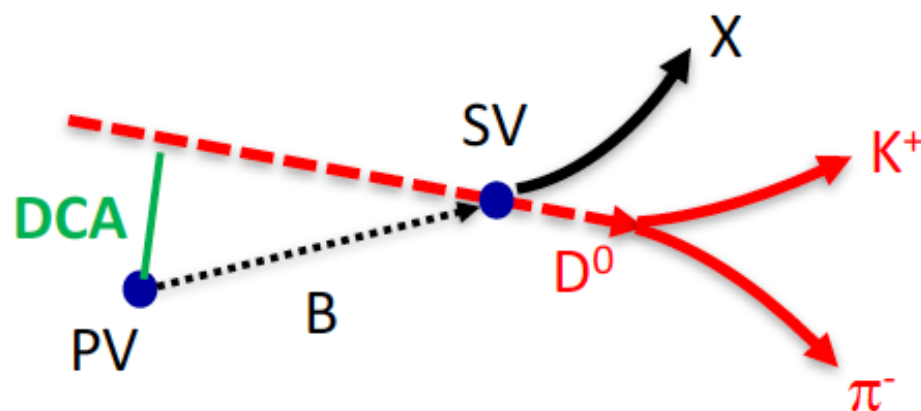
$$R_{AA}^{B \rightarrow J/\psi} = \frac{f_{Au+Au}^{B \rightarrow J/\psi}(Data)}{f_{p+p}^{B \rightarrow J/\psi}(Theory)} R_{AA}^{inc. J/\psi}(Data)$$



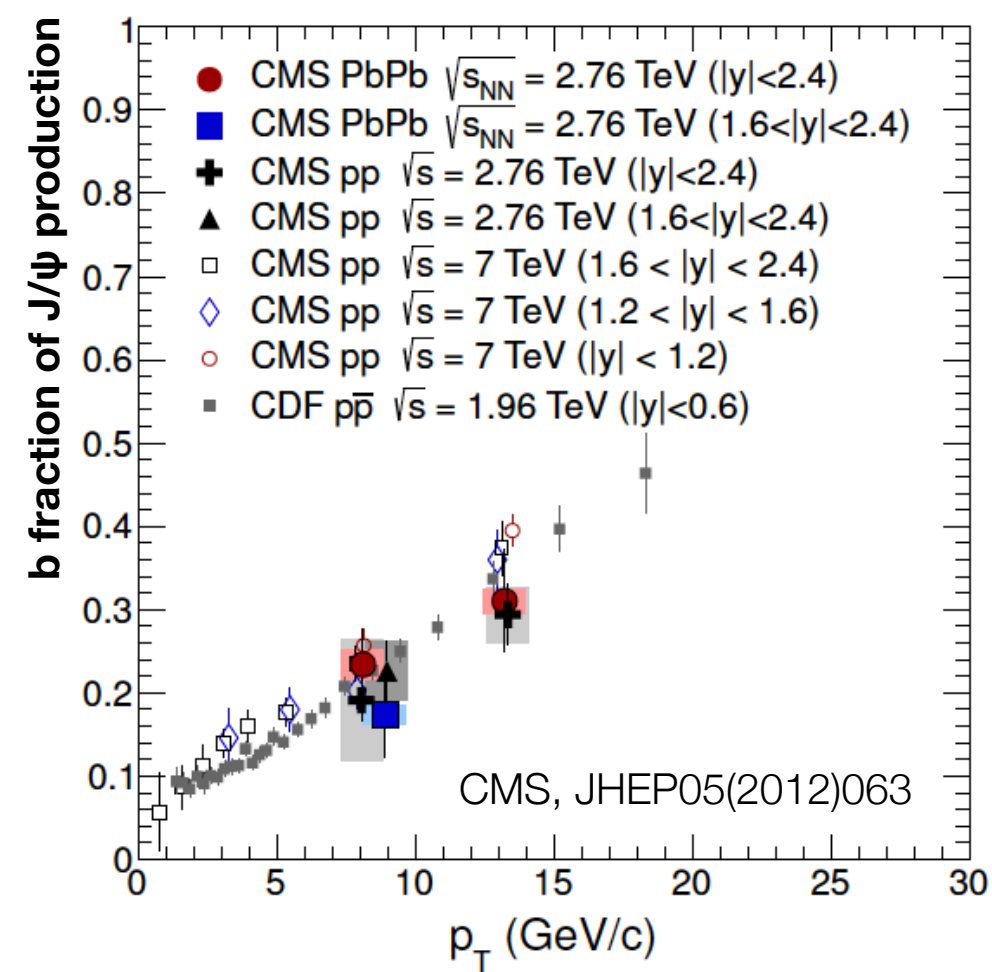
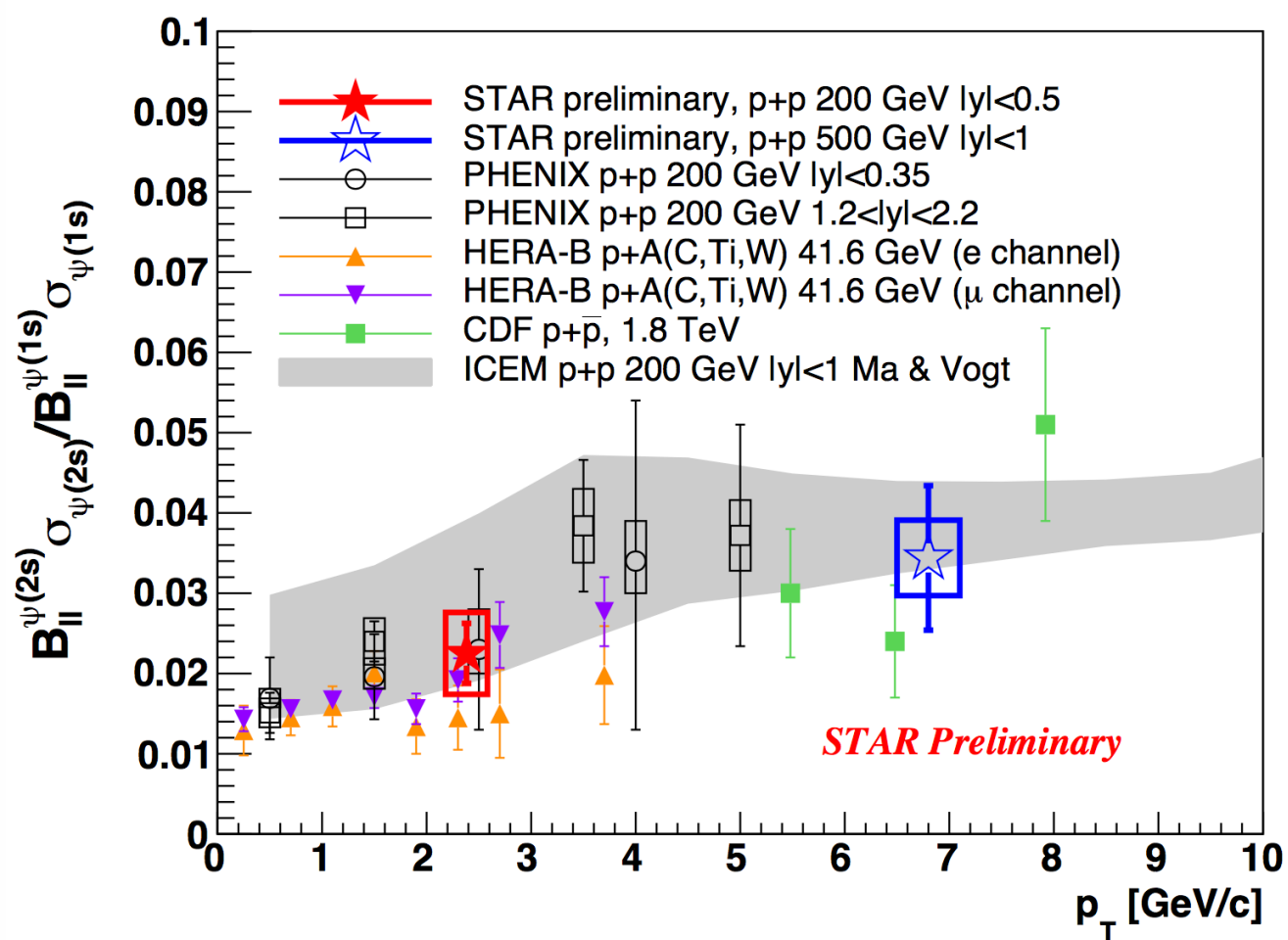
Strong suppression of $B \rightarrow J/\psi$ at high p_T (> 5 GeV/c)
Comparable with D^0

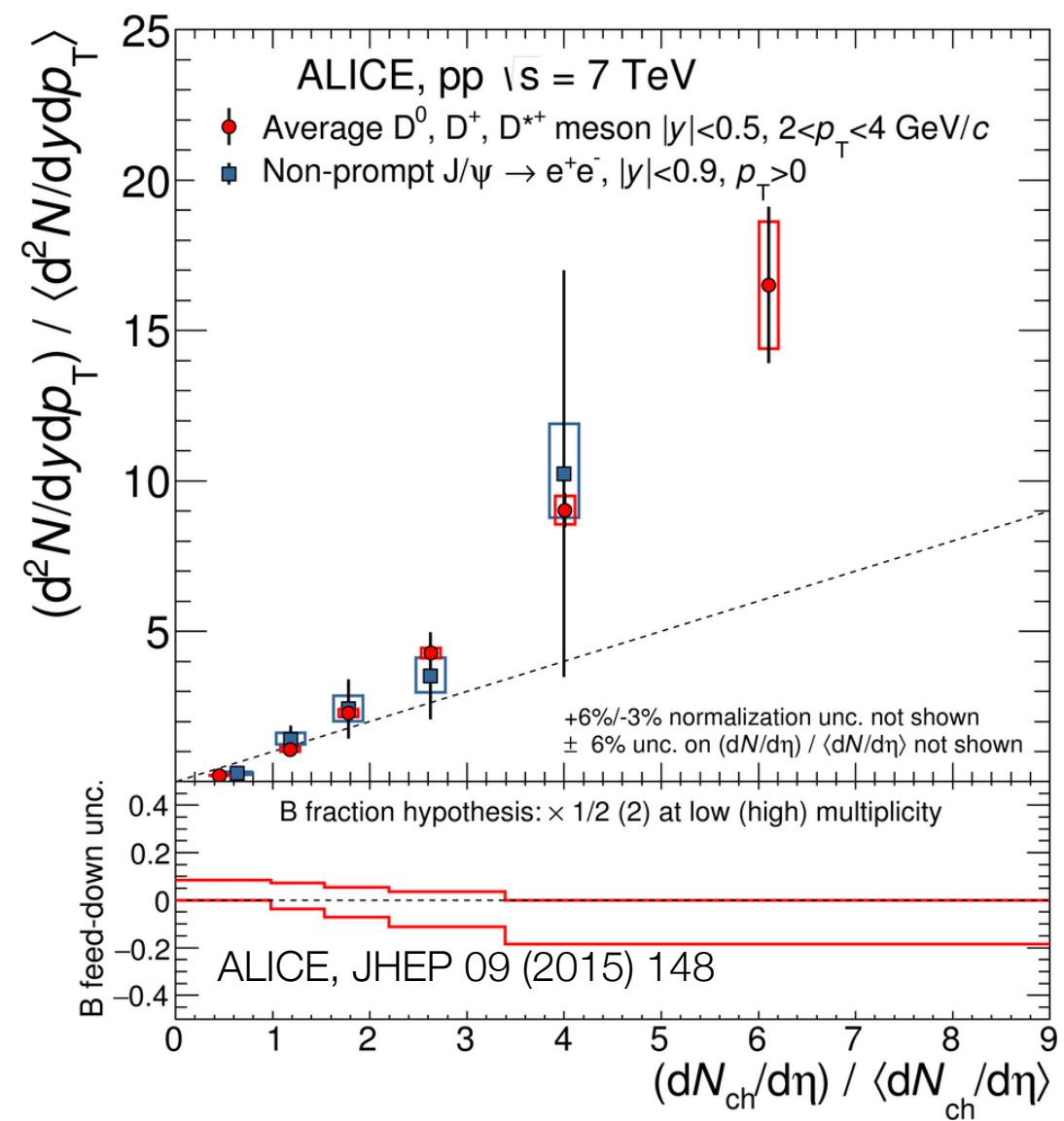
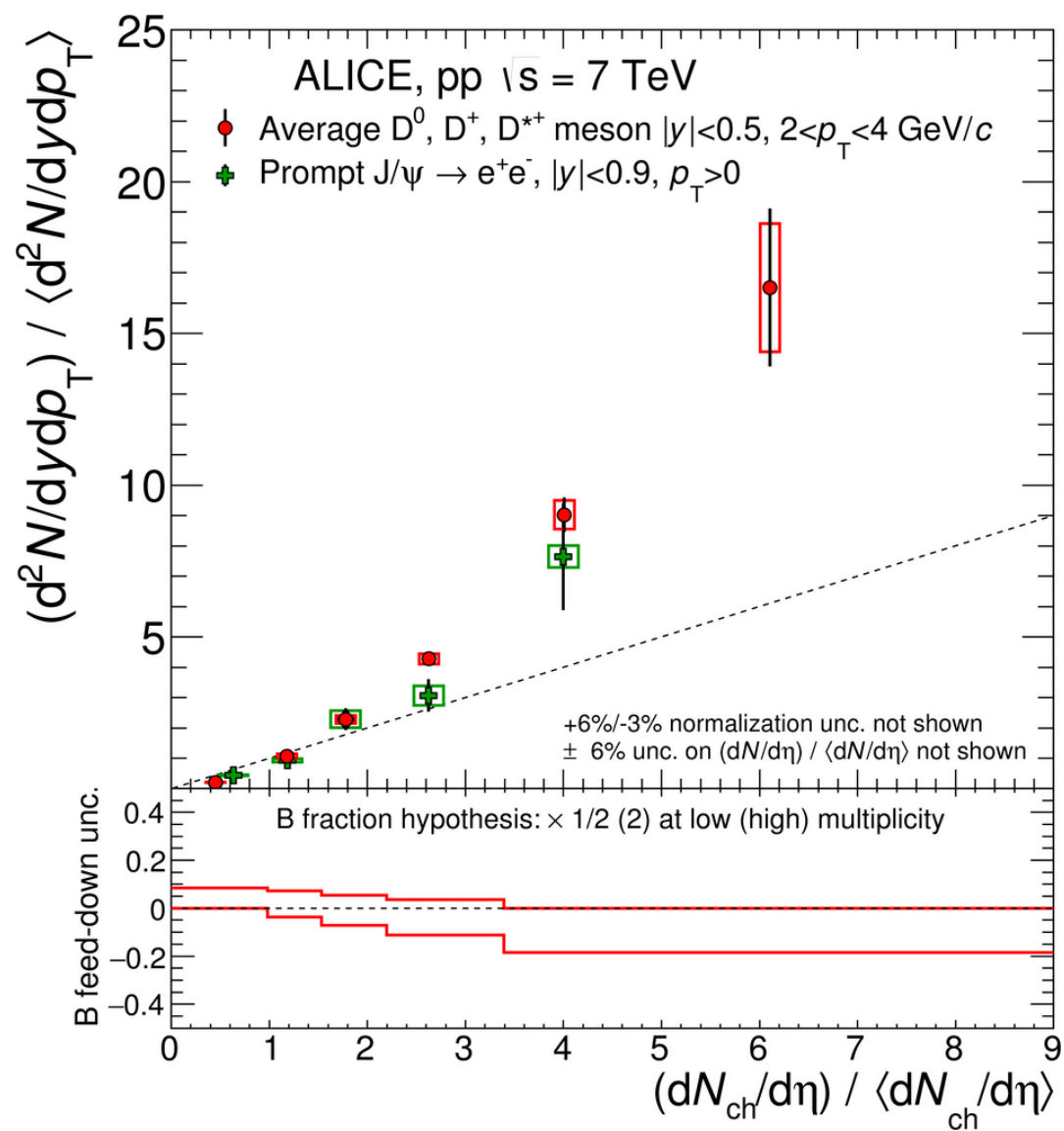
Non-prompt D^0 Suppression

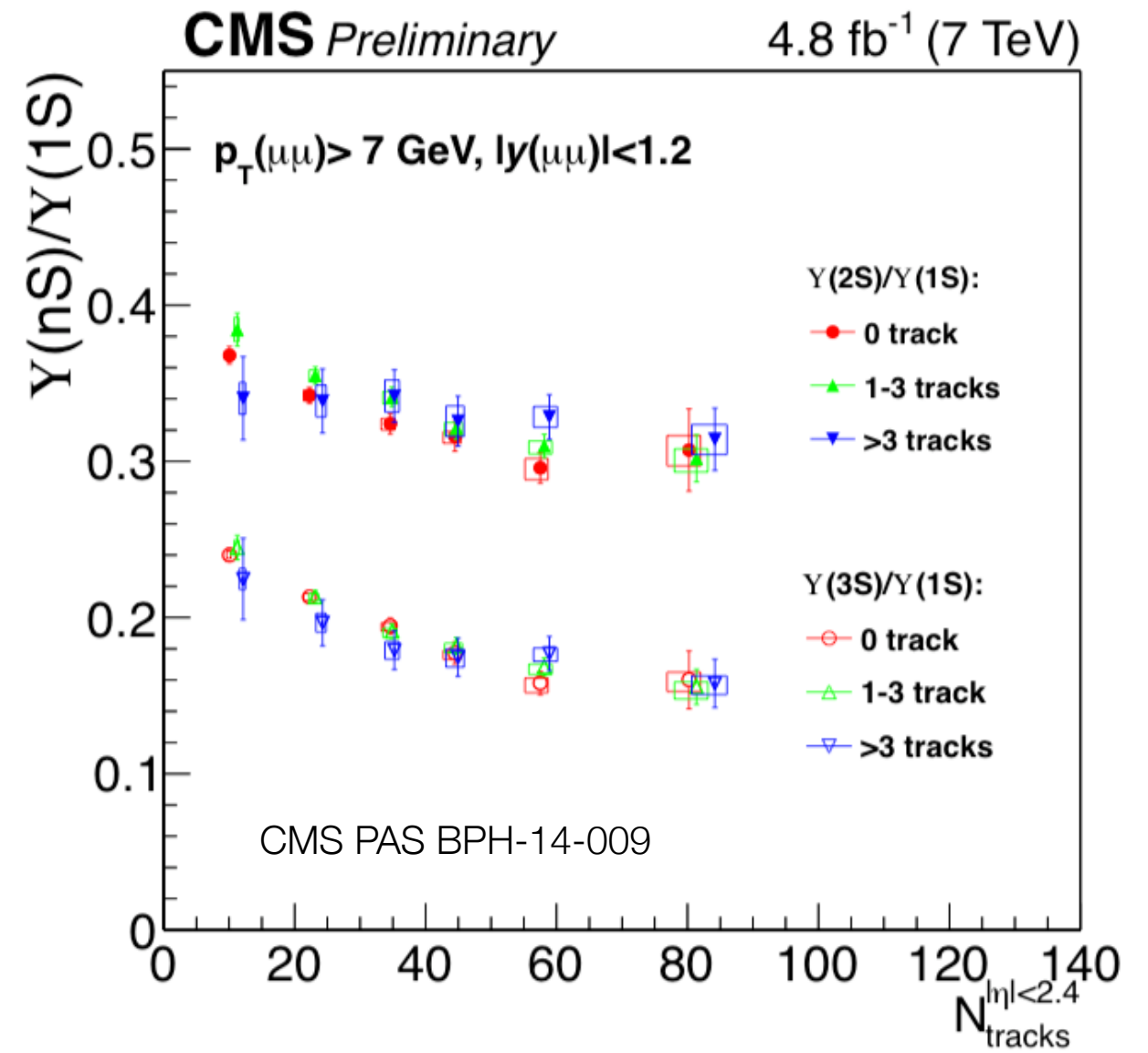
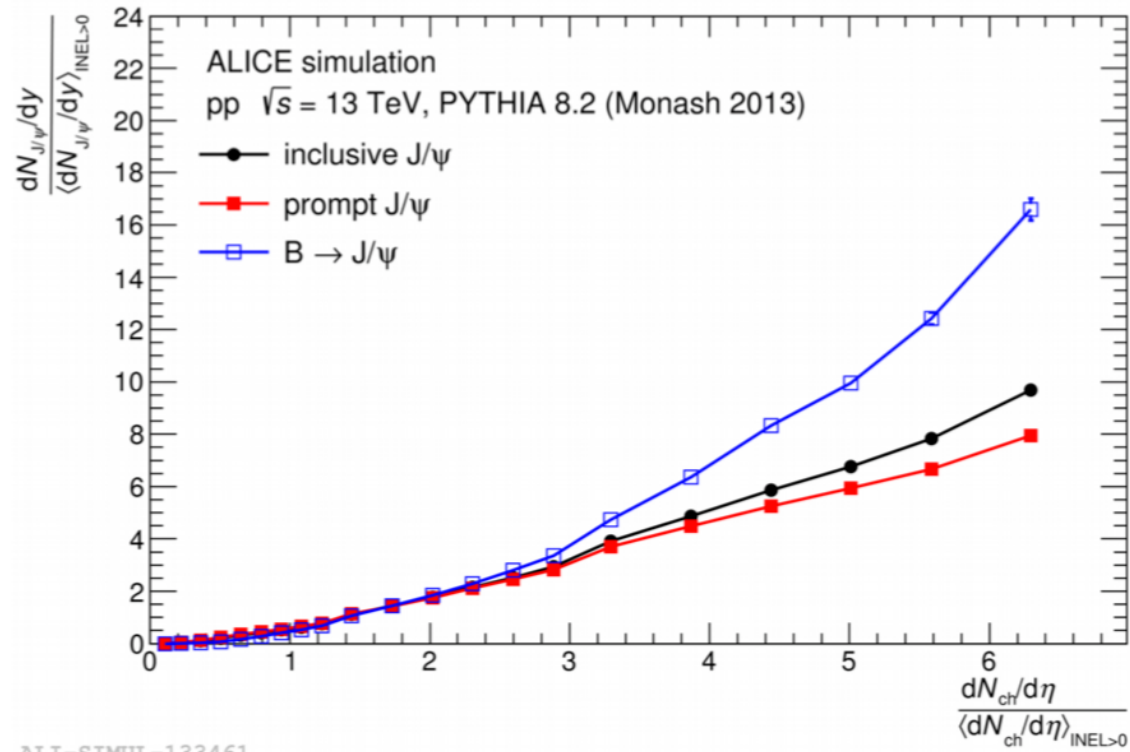
Template fit on DCA distribution to extract $B \rightarrow D^0$ contribution



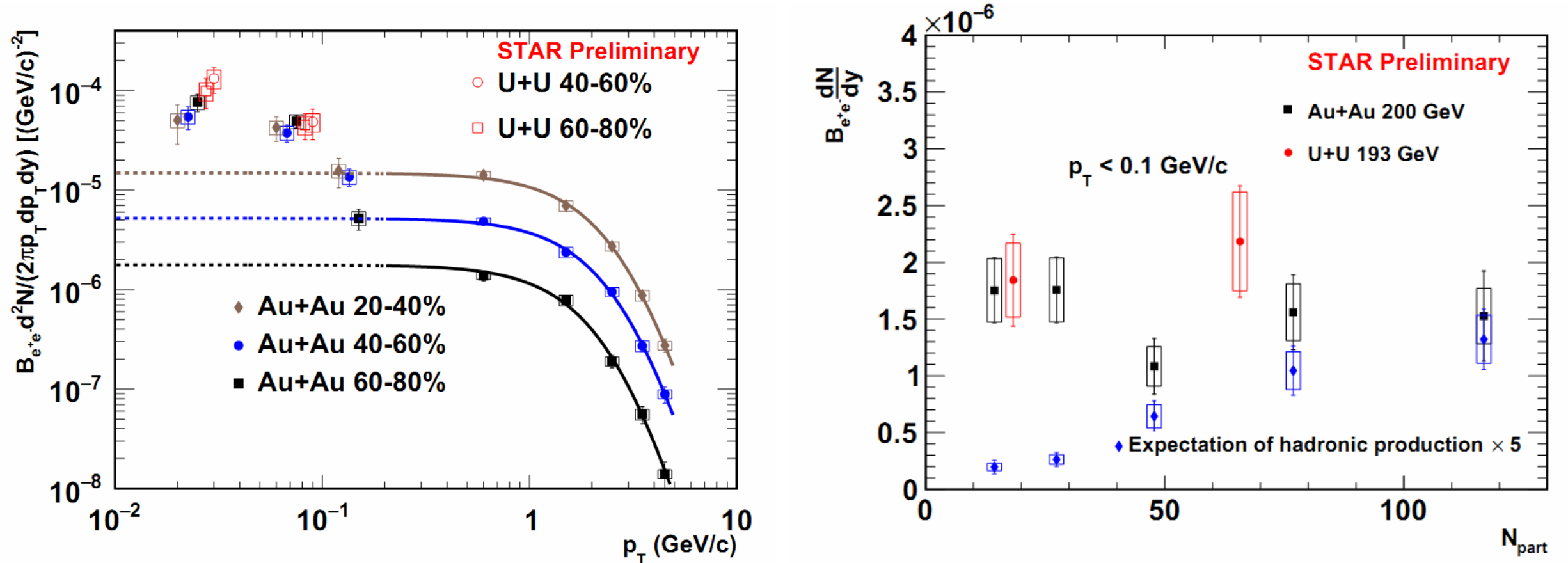
Less suppression for non-prompt D^0 than for inclusive D^0





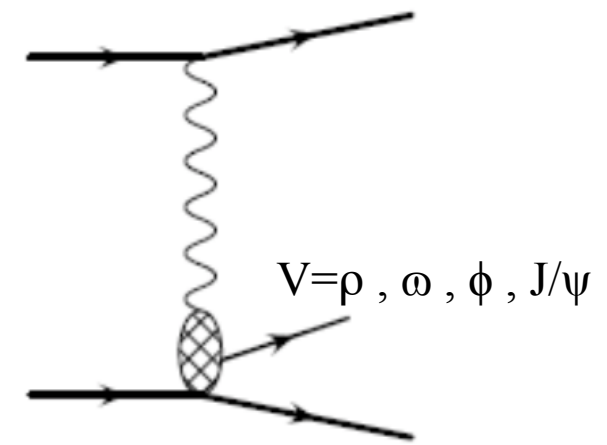


Excess of J/ψ at Very Low p_T

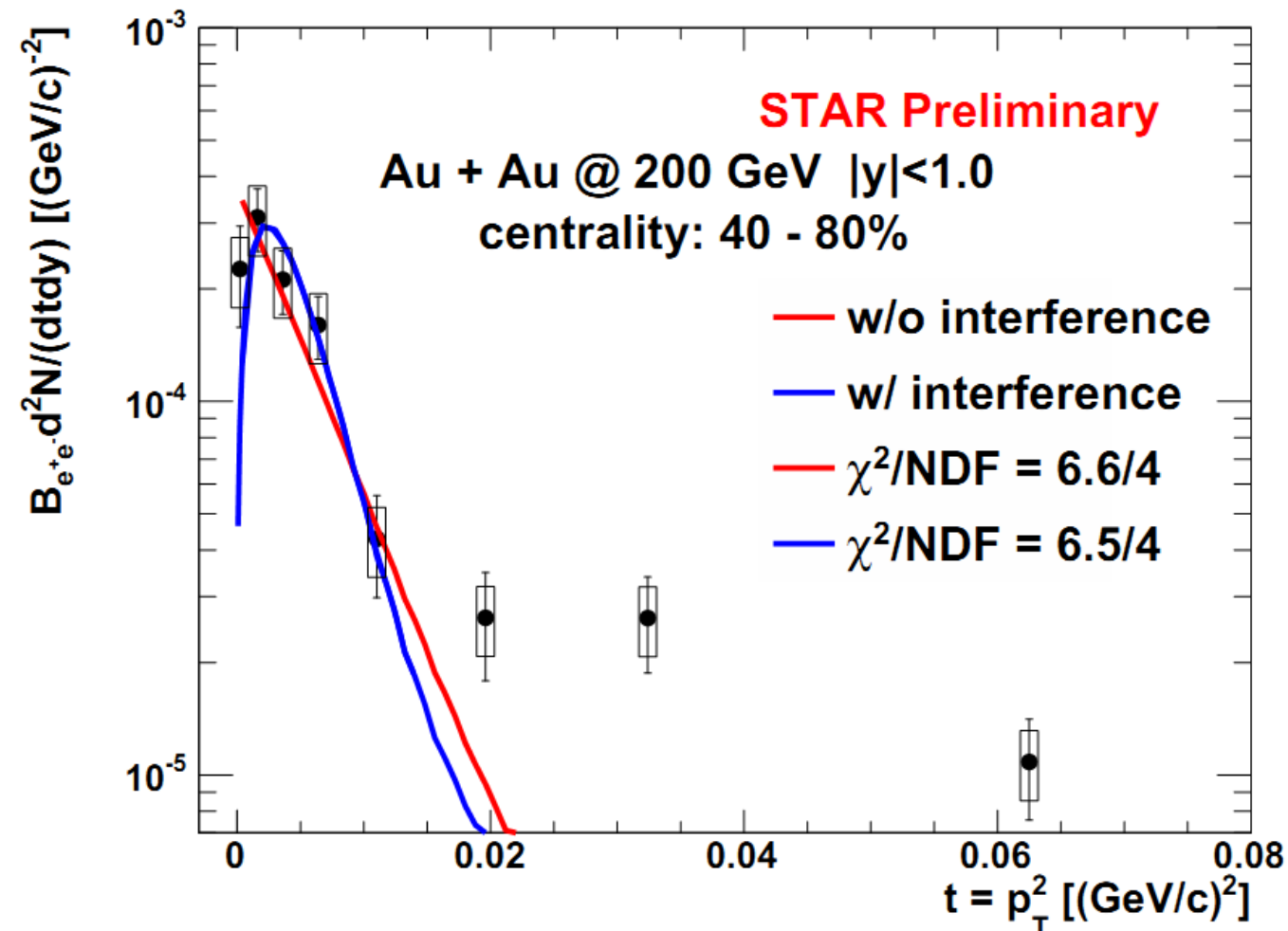


- Significant J/ψ enhancement at $p_T < 0.2$ GeV/c in peripheral collisions
- No significant centrality dependence of the excess yield, while hadronic production is expected to strongly depends on N_{part}

Low pT J/ψ excess from coherence photoproduction



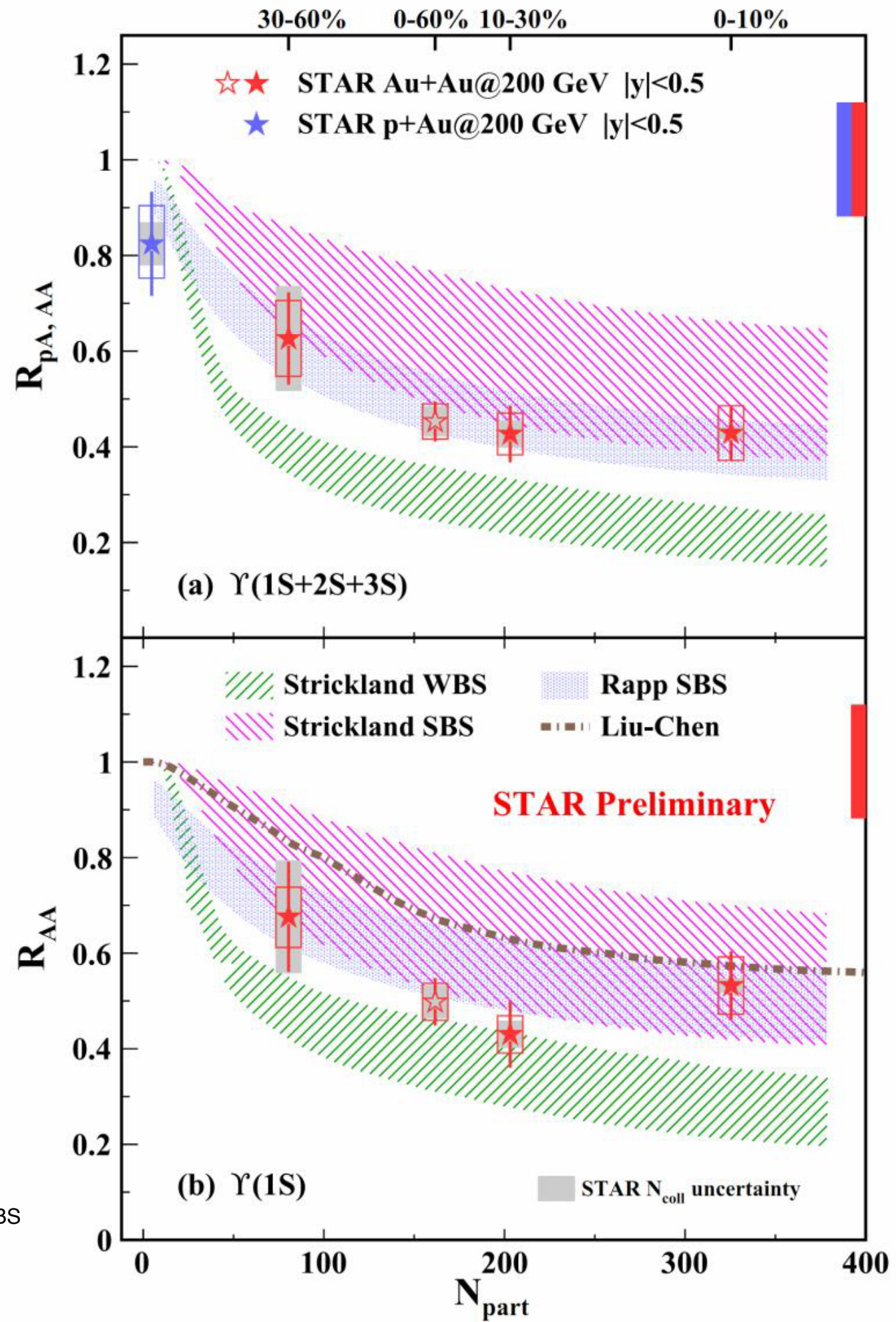
W. Zha, et al., arXiv: 1705.01460



Calculations from coherence photoproduction describe data

Υ Suppression in Au+Au Collisions

- SBS (Strongly Binding Scenario): fast dissociation—potential based on internal energy.
- WBS (Weakly Binding Scenario): slow dissociation—potential based on free energy.
- Data seem to favor the SBS model



Strickland, Bazov, NPA 879 (2012) 25
No CNM, no regeneration

Emerick, Zhao, Rapp, EPJ A48 (2012) 72,
Includes CNM, SBS case

Liu, Chen, Xu, Zhuang, PLB 697 (2011) 32
Dissociation only for excited states, suppression of ground state due to feed-down, SBS

