Hard Probes 2018: International Conference on Hard & Electromagnetic Probes of High-Energy Nuclear Collisions

Aix-Les-Bains

Highlights from STAR

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U.S. DEPARTMENT OF ENERGY | Office of Science

STAR

Hard and EM probes at STAR

➡ Open heavy flavor

- How do charm quarks interact with and lose energy in QGP? How about bottom?
- How do charm quarks in QGP hadronize?
- Does total charm cross-section in HI collisions scale with N_{binary}?

➡ Quarkonium production

- Are more weakly bound quarkonium states more suppressed in HI collisions? Cold nuclear matter effects? Uderstand better charmonium production in p+p collisions.

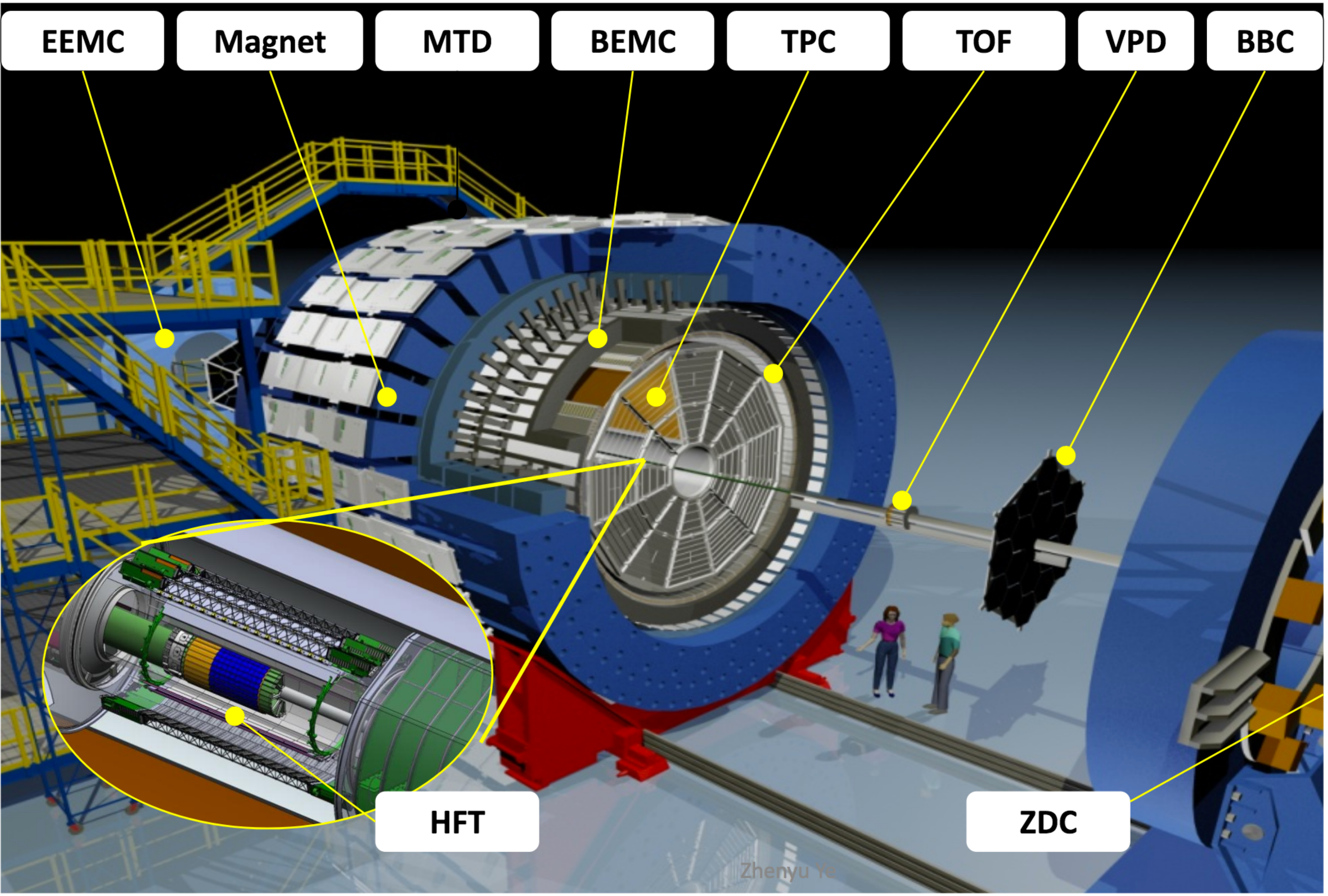
➡ Jet and di-hadron correlation measurements at RHIC energy

- Features of jet modification in QGP: dependences on jet angular scale, jet radius, constituent p_{T}, event geometry etc
- Suppression of γ_{dir} - triggered jet

➡ Di-lepton production

- Low p_T di-electron excess in peripheral collisions
- Di-muon spectra with improved muon identification

The STAR detector



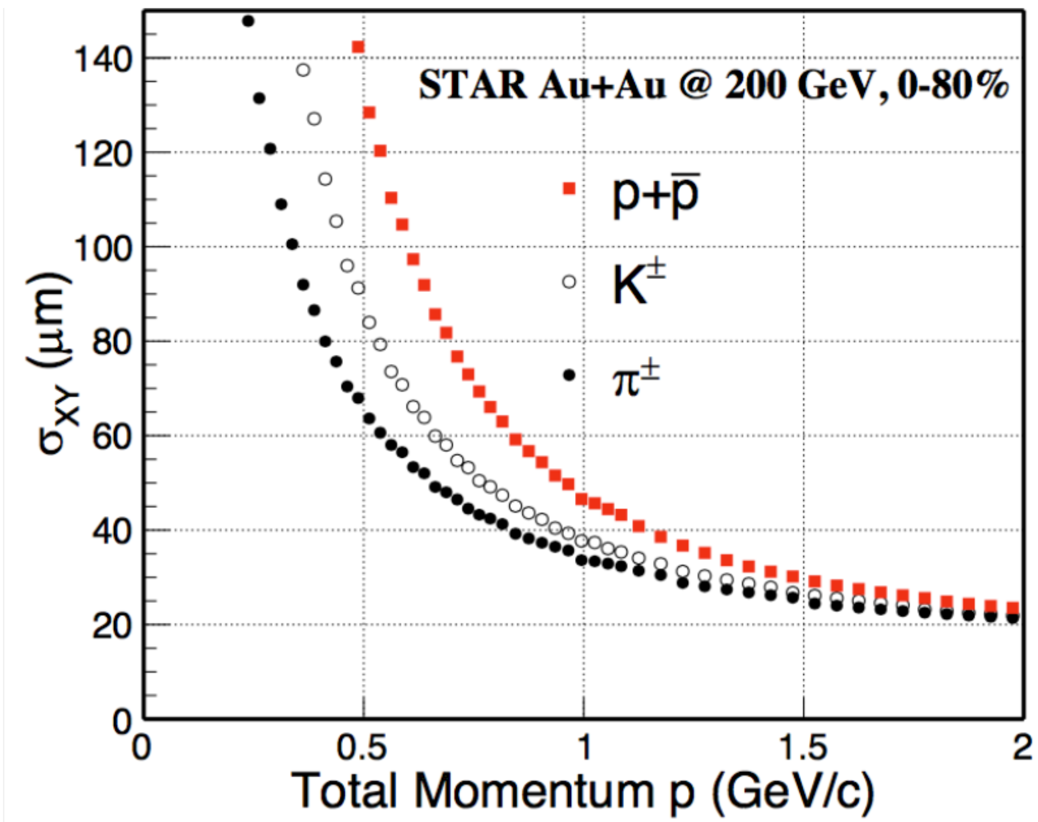
- **HFT: 2014 - 2016**
  $|\eta| < 1.0$
- **MTD: 2014 -**
  $|\eta| < 0.5$, 45% in ϕ
- **EMC:**
  Barrel, $|\eta| < 1.0$
  Endcap, $1 < \eta < 2$
- **Tracking and PID**
  TPC, $|\eta| < 1.0$
  TOF, $|\eta| < 1.0$
  Full azimuthal coverage

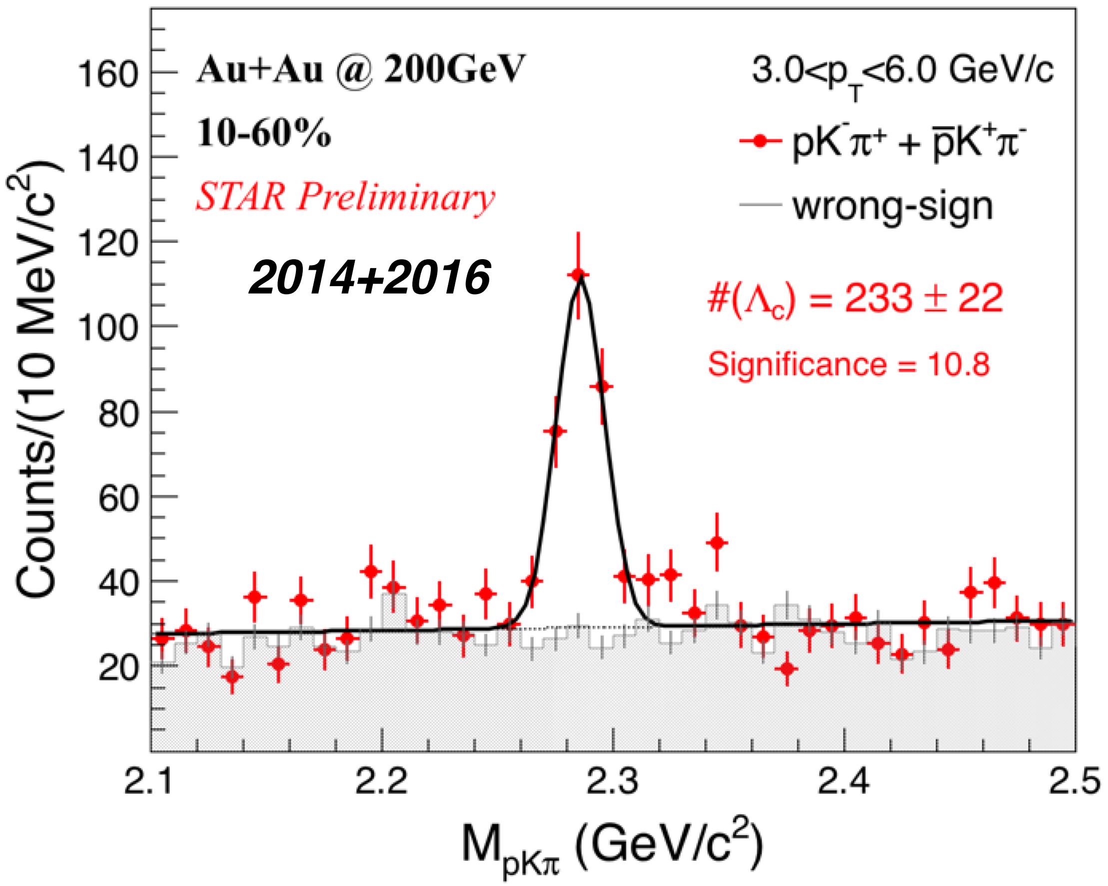
- HFT significantly improves charm and bottom hadron measurements
- MTD enables muon identification, improve quarkonium measurements

Λ_c production in heavy ion collisions

- Λ_c/D^0 yield ratio provide insight into charm hadronization mechanism in QGP

- HFT provides excellent vertex resolution, allows topological reconstruction of heavy flavor hadrons

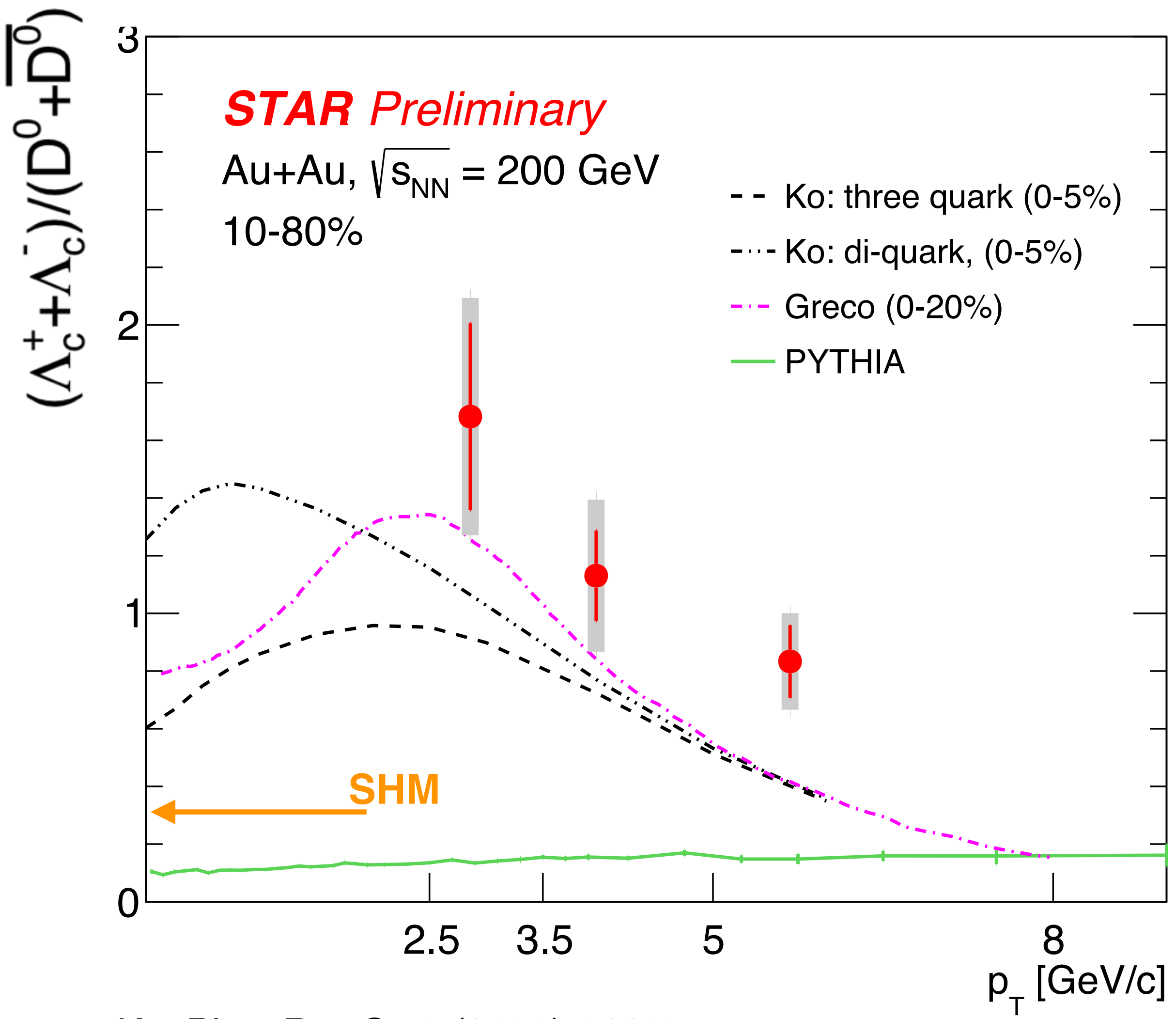




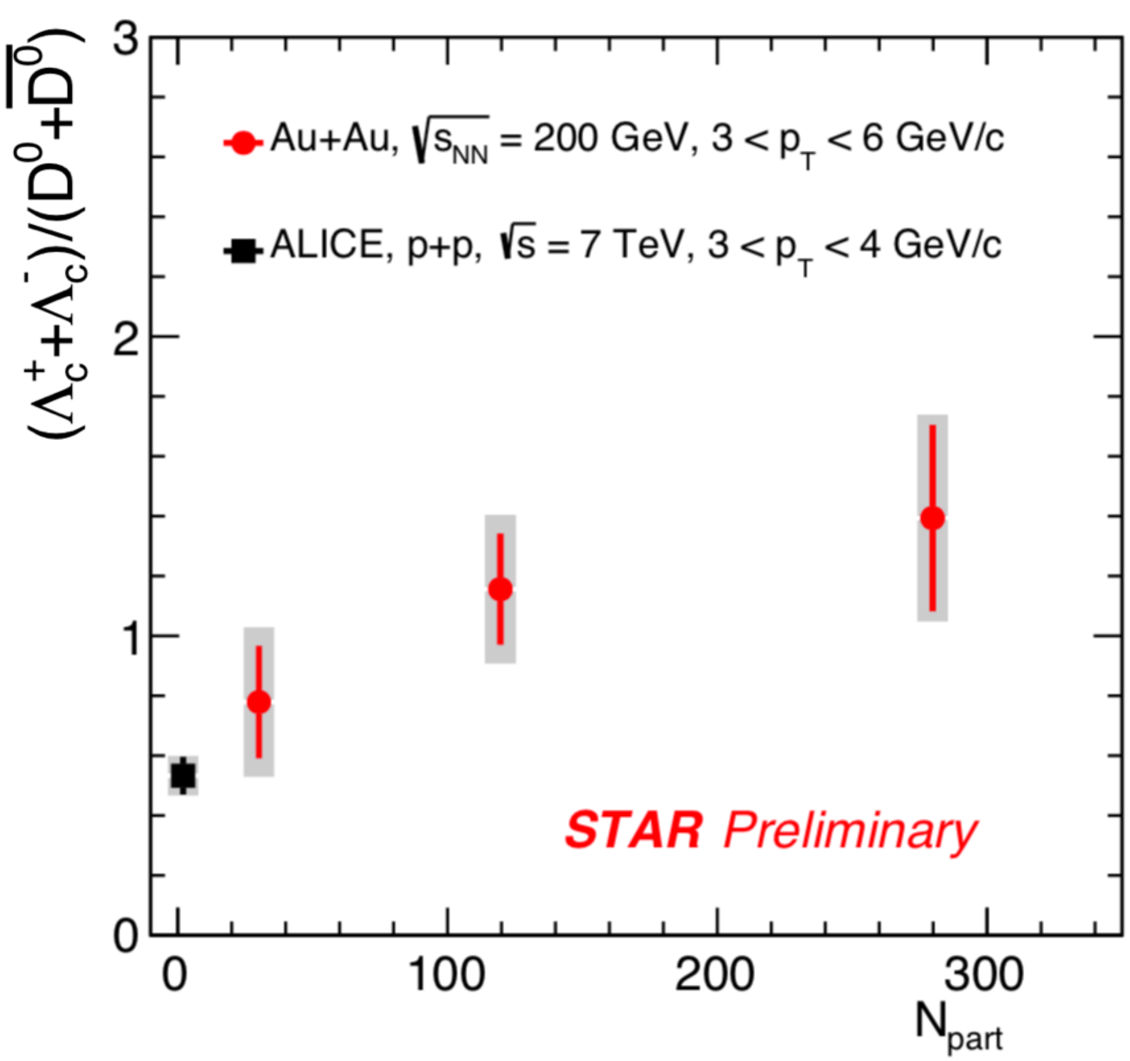
- $c\tau$ for Λ_c = 60 μm!
- Supervised Learning Methods (BDT) used to improve signal-background separation for Λ_c reconstruction

Talk by G. Xie: 04/10 Thu, 11.25 (P3)

Λ_c production in heavy ion collisions



Ko: Phys.Rev.C 79 (2009) 044905
Greco: Eur.Phys.J.C (2018) 78:348
SHM: Phys.Rev.C 79 (2009) 044905



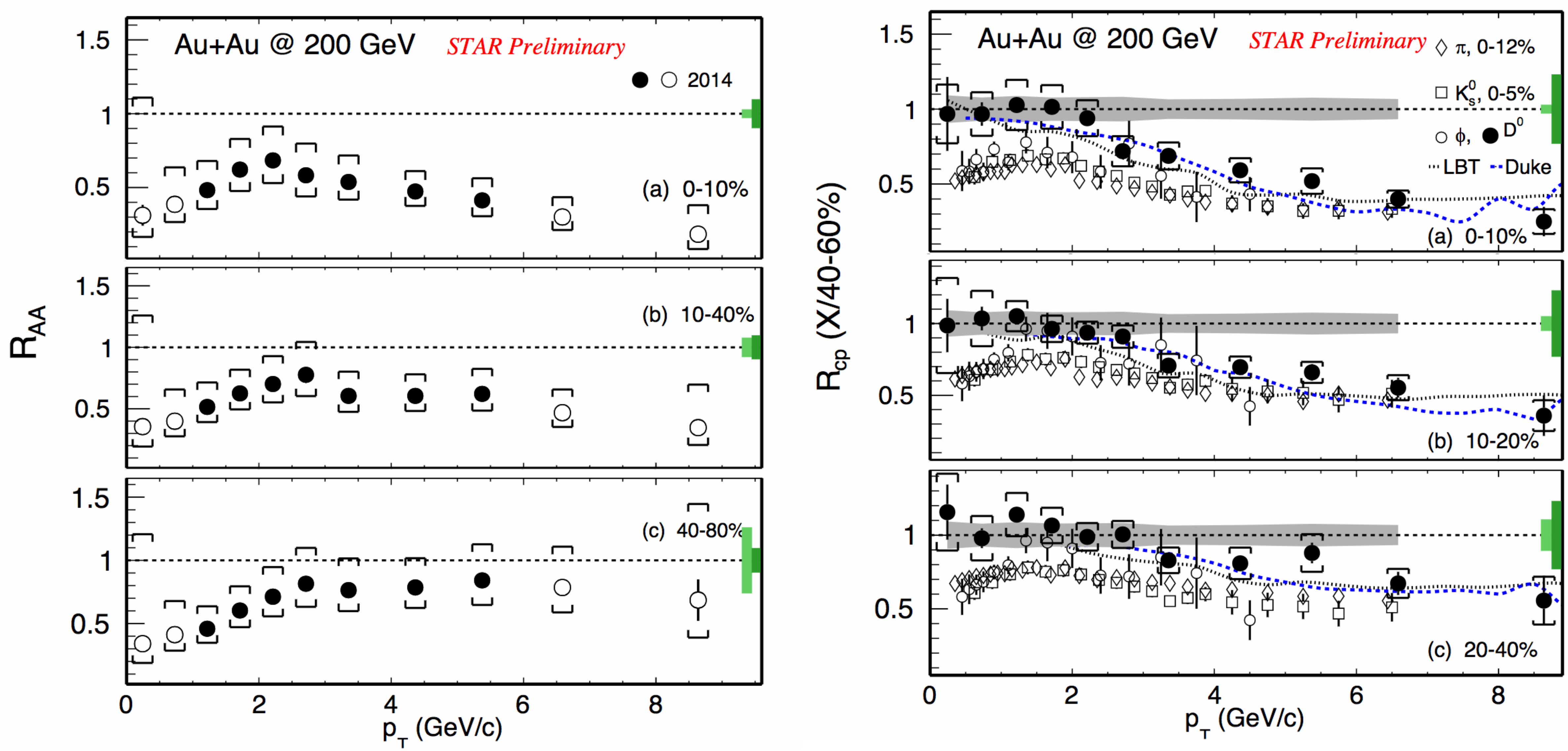
ALICE : JHEP 04 (2018) 108

- Strong enhancement of Λ_c production compared to PYTHIA calculations
- Suggest coalescence hadronization of charm quarks in QGP at intermediate p_T (2-6 GeV/c)

Talk by G. Xie: 04/10 Thu, 11.25 (P3)

Probing charm quark energy loss: D^0 R_{AA} and R_{cp}

- Measurement of D^0 spectra extending to zero p_T in HI collisions!

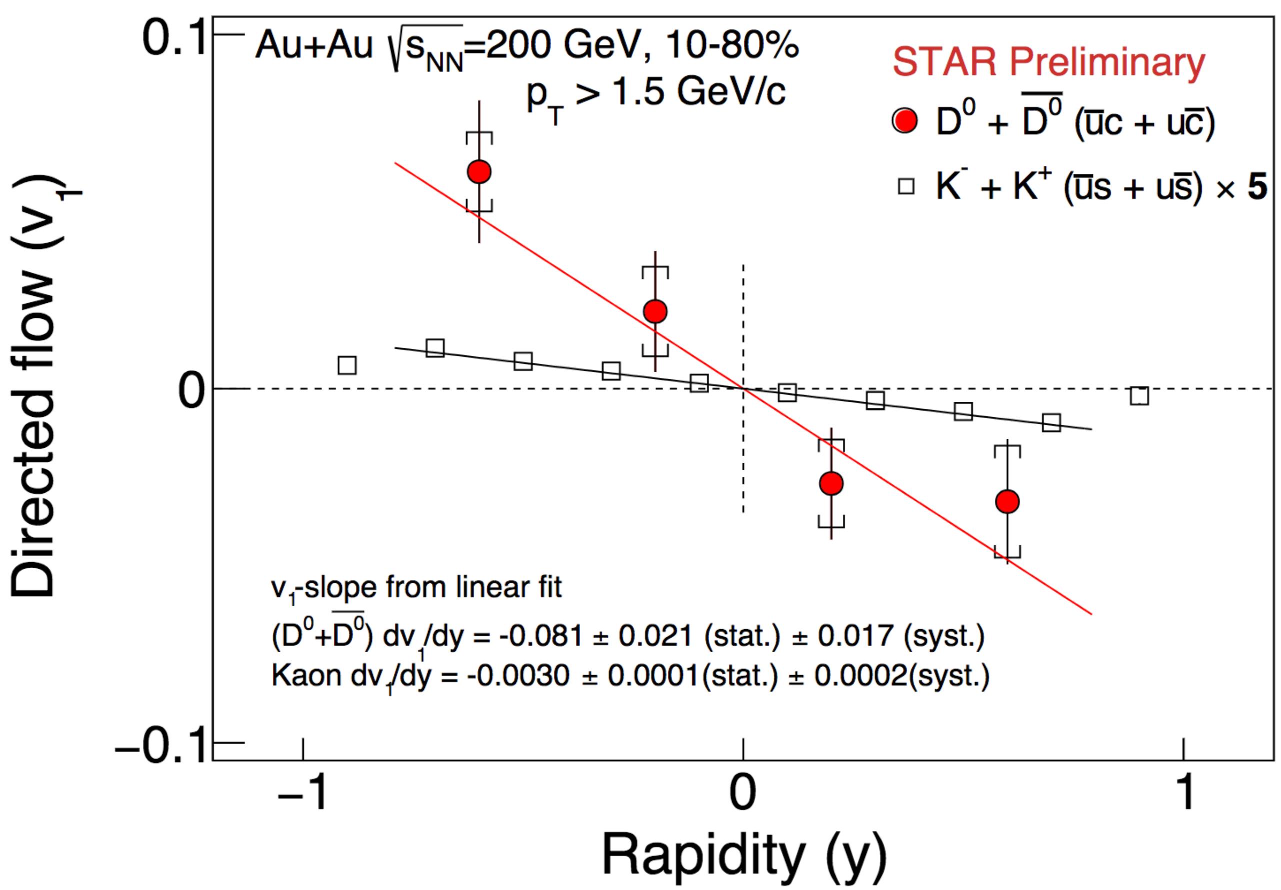


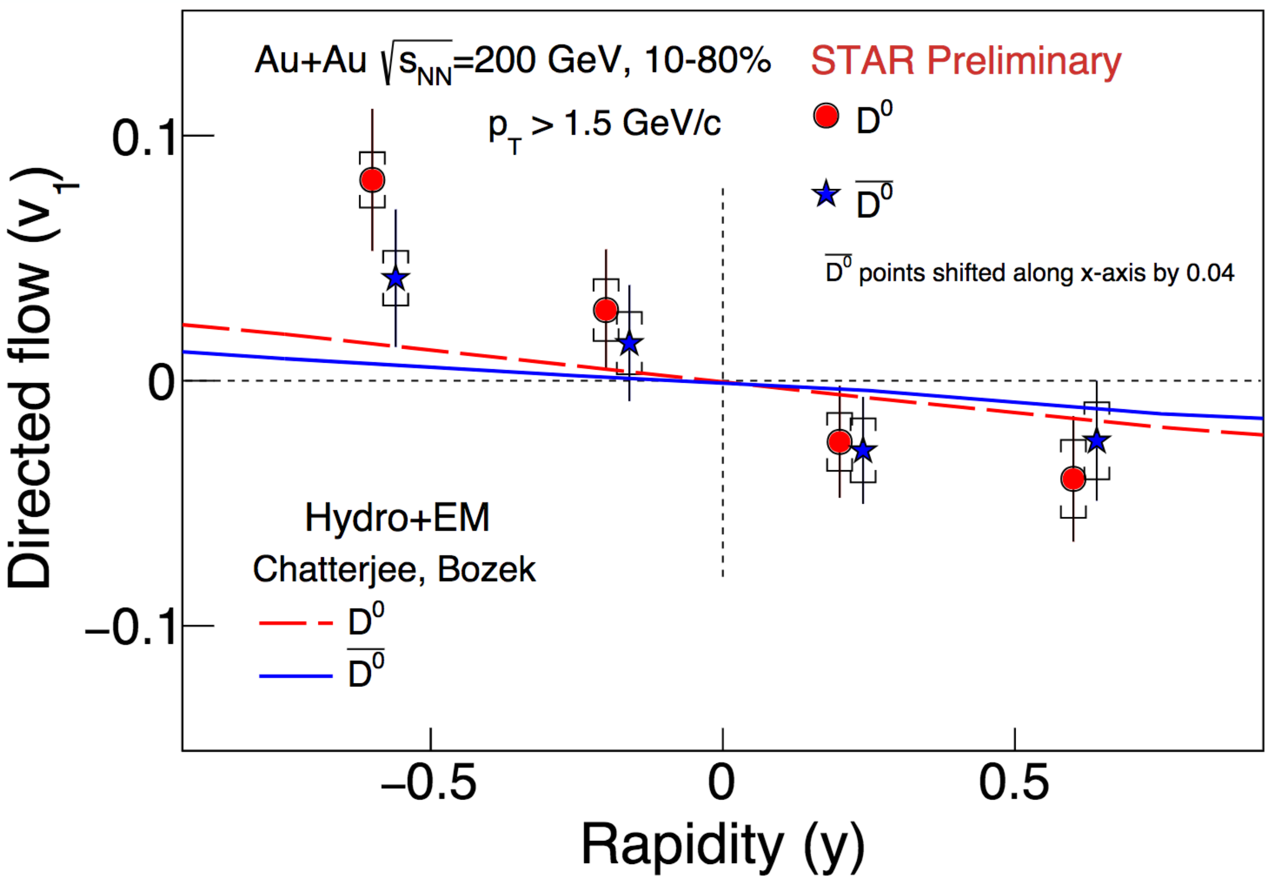
- D^0 shows similar suppression as light hadrons at high p_T in central collisions
- Transport models with charm quark energy loss can describe the data

Talk by G. Xie: 04/10 Thu, 11.25 (P3)

Directed flow (v_1) of D^0

- Sensitive to initial tilt of fireball and viscous drag on charm quarks from QGP [1].
- Also difference between D^0 and anti-D^0 v_1 predicted to be sensitive to initial EM field





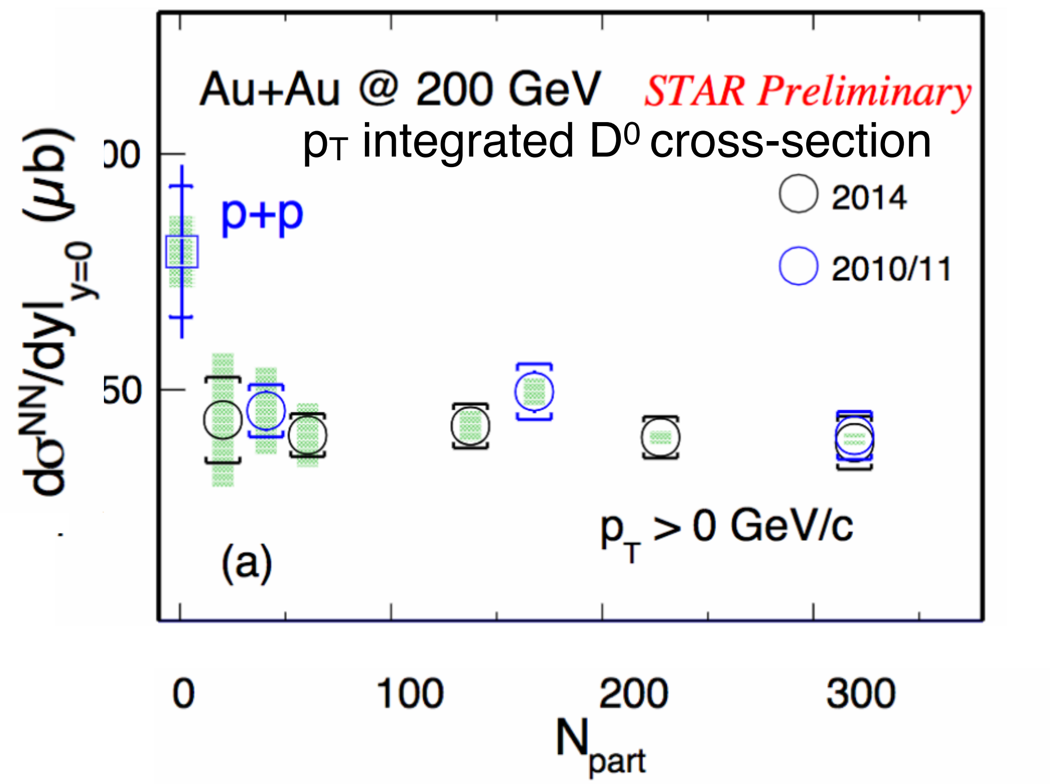
[1] Chatterjee, Bozek: Phys Rev Lett 120, 192301 (2018)

- Order of magnitude larger v_1 than for light flavor hadrons!
- In agreement with the prediction of large D^0 v_1 by hydro models

Talk by L. He: 02/10 Tue, 11.05 (P3)

Charm production in Au+Au collisions

- Cross-section for D^0 production lower than in p+p



- Also measurements on D_s and $D^{+/-}$ production

Charm Hadron		Cross-section (μb)
AuAu 200 GeV (10-40%)	D^0	41 ± 1 ± 5
	D^+	18 ± 1 ± 3
	D_s^+	15 ± 1 ± 5
	Λ_c^+	78 ± 13 ± 28*
	Total	**152 ± 13 ± 29**
pp 200 GeV	**Total**	**130 ± 30 ± 26**

*** derived using Λ_c^+ / D^0 ratio in 10-80%**

- Enhancement for Λ_c (and D_s) and suppression for D^0
- But total charm cross-section is found to be consistent with p+p

Talk by G. Xie: 04/10 Thu, 11.25 (P3)

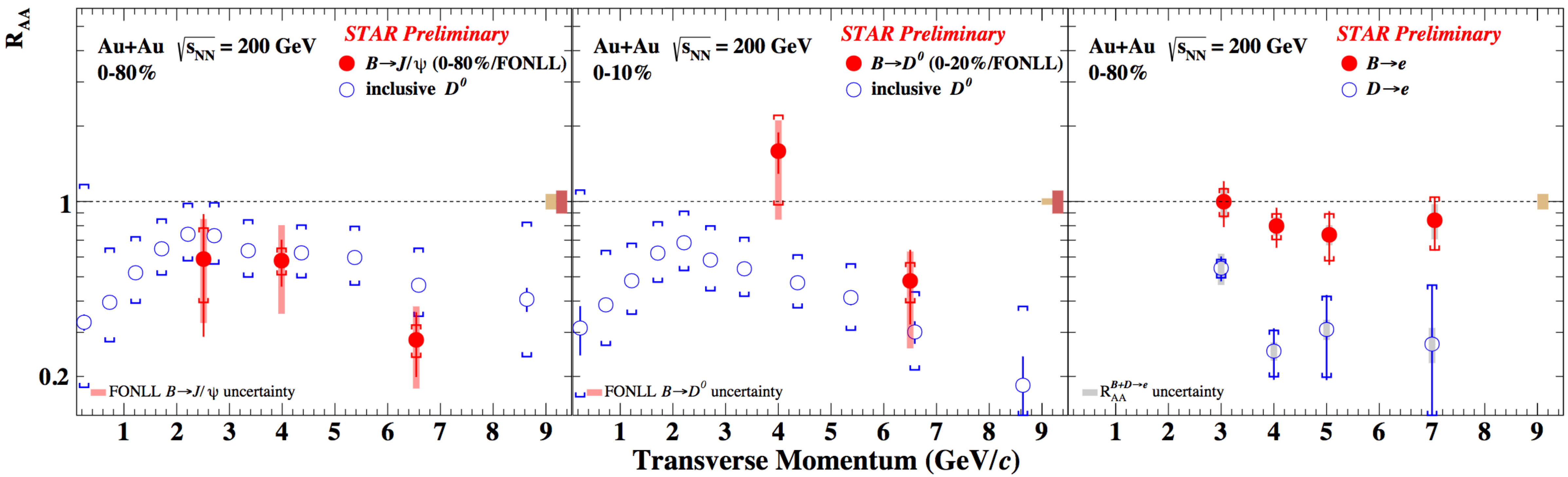
Bottom production and R_{AA}

- Charm quarks interact strongly with QGP, how about bottom?
- Is there a flavor (mass) dependent energy loss? Is $\Delta E_b < \Delta E_c$?

B —> J/ψ

B —> D^0

B —> e

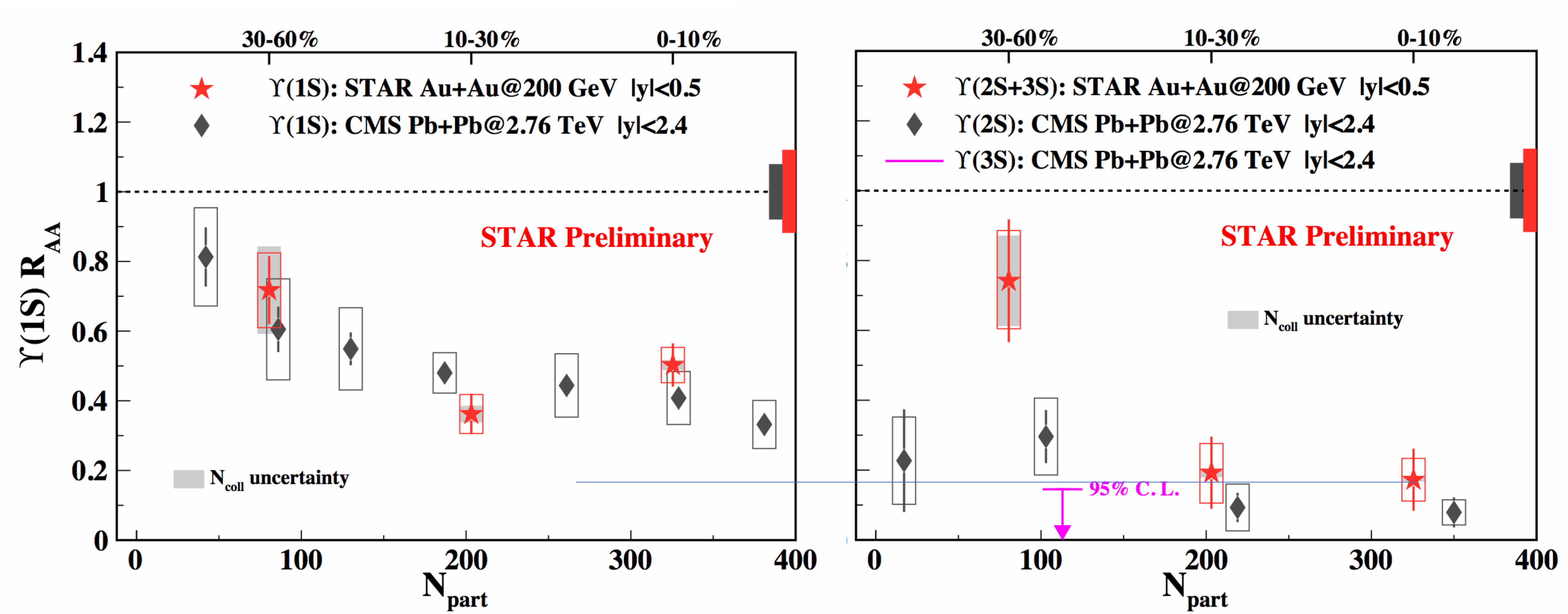


- Indication of less suppression for B—>e than D—>e (~ 2σ difference)
- Results from 2014 data (except B—> J/ψ), 2 - 5 times more data from 2016 being analyzed

Talk by X. Chen: 02/10 Tue, 09.20 (P3)

Upsilon suppression in 200 GeV Au+Au collisions

- Bottomonia a better probe for sequential melting?



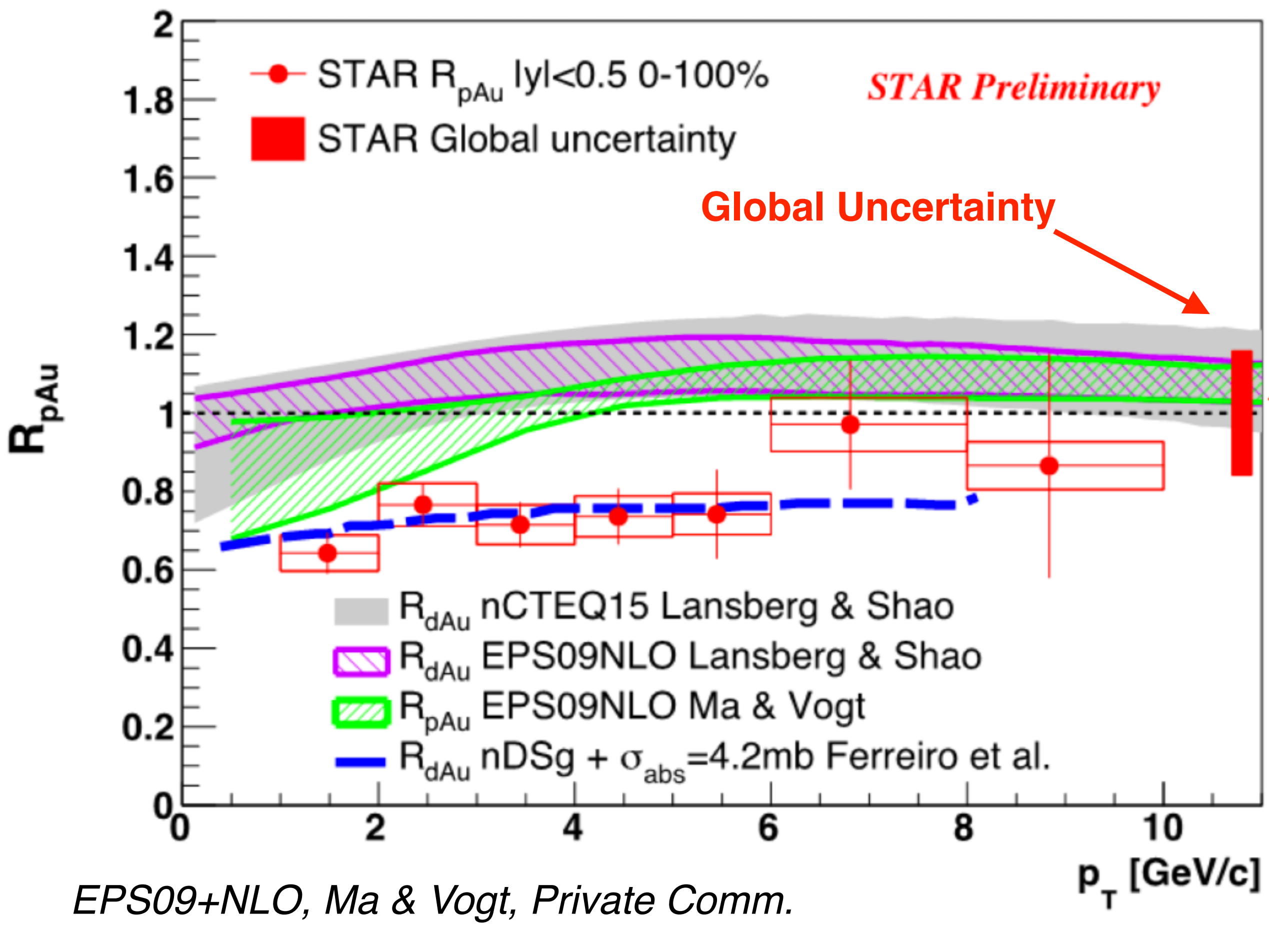
CMS PLB 04, 031 (2017)

- Improved precision by combining 2011 di-electron, 2014+2016 di-muon datasets
- Y(2S+3S) R_{AA} smaller than Y(1S) R_{AA} in central collisions

Talk by Z. Liu: 03/10 Wed, 09.00 (P3)

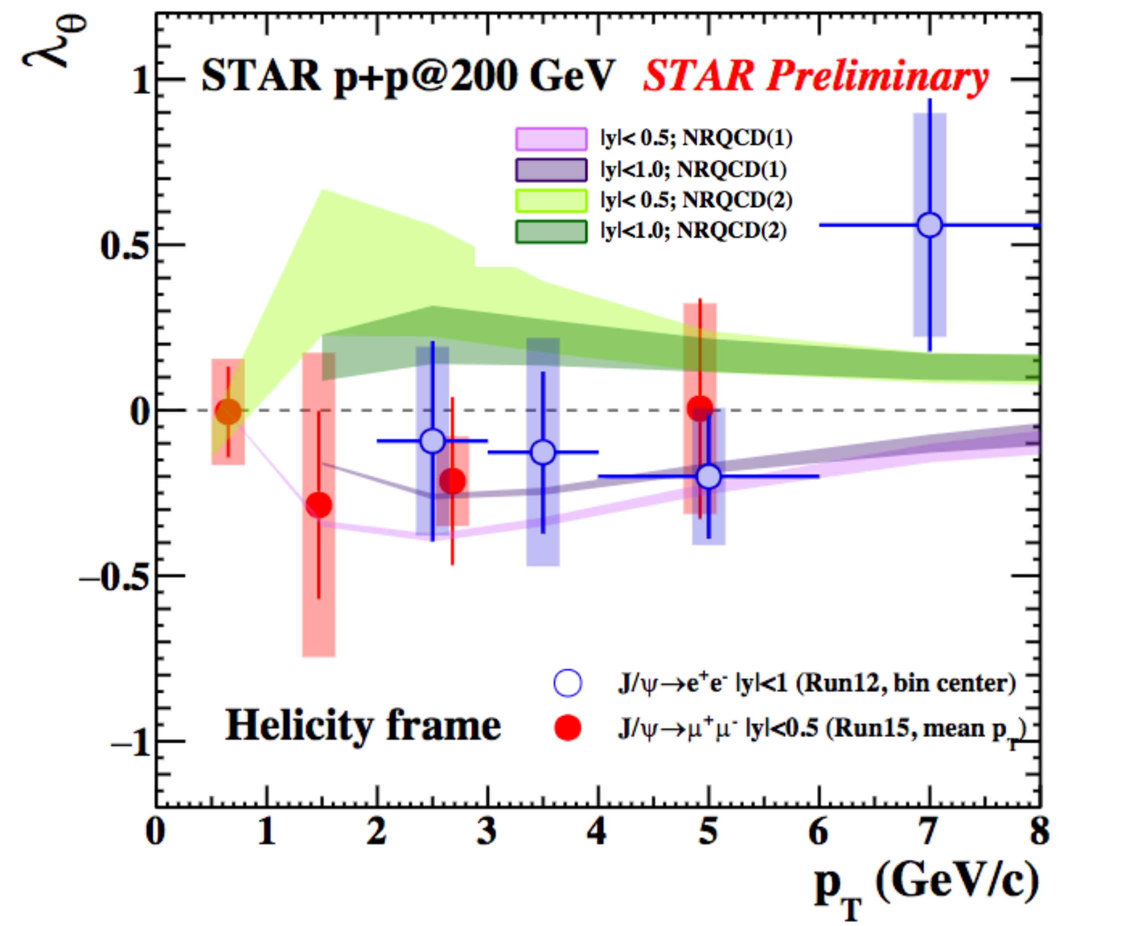
Quarkonia production in p+p and p+Au

J/ψ R_{pAu}



EPS09+NLO, Ma & Vogt, Private Comm.
nCTEQ, EPS09+NLO:
Lansberg Shao, Eur.Phys.J. C77 (2017) no.1, 1
Ferreriro et al., Few Body Syst. 53 (2012) 27

J/ψ polarization



NRQCD1: Hong-Fei Zhang et al. Phys. Rev. Lett 114 (2015) 092006
NRQCD2: Bin Gong et al. Phys. Rev. Lett 110 (2013) 042002

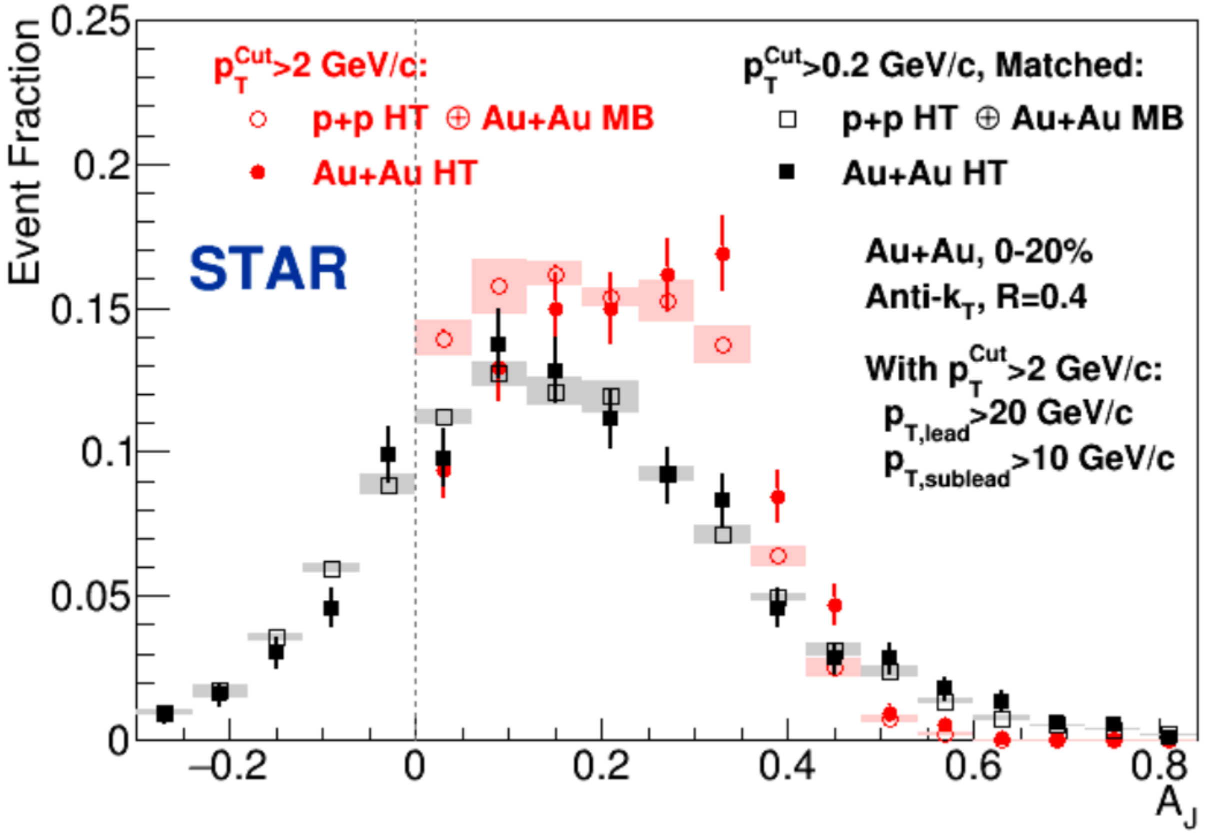
- J/ψ R_{pAu} lower than models with nPDF effects
- NRQCD: includes color octet contributions to J/ψ production, can describe the data

Talk by Z. Liu: 03/10 Wed, 09.00 (P3)

Features of jet modification: Di-jet imbalance

- How jets are modified in the presence of QGP?
- Dijet asymmetry quantifies momentum imbalance between dijets

STAR Collaboration. Phys. Rev. Lett 119, 062301 (2017)



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

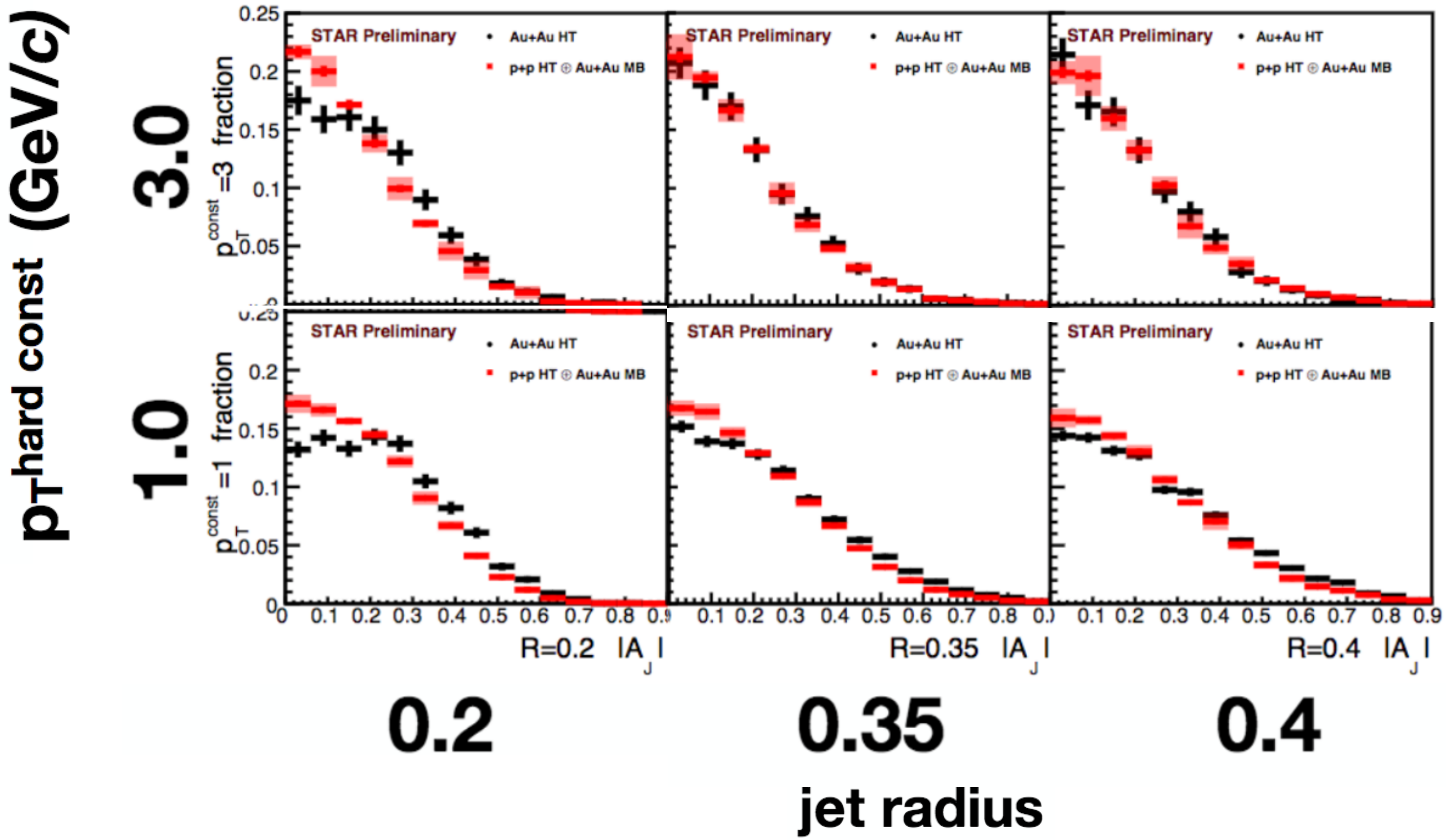
- **Hard-core jets**: Jets reconstructed with constituents above a high p_T cut
- **Matched jets**: Hard-core jets with soft particles above p_T = 0.2 GeV/c included

- p+p events embedded into Au+Au
- Hard-core dijets in Au+Au more imbalanced than in p+p
- A_J consistent with p+p for R=0.4 jets, with soft particles included

Talk by N. Elsey: 02/10 Tue 11:25 (P2)

Do all jets get balanced?

- How does the momentum imbalance evolve with hard constituent p_T cut and jet radius?
- Looking at matched jets with different hard constituent p_T cuts



- All jets unbalanced at small jet radius
- Jets with higher hard constituent p_T cuts get balanced as jet radius is increased and soft contribution is included

Talk by N. Elsey: 02/10 Tue 11:25 (P2)

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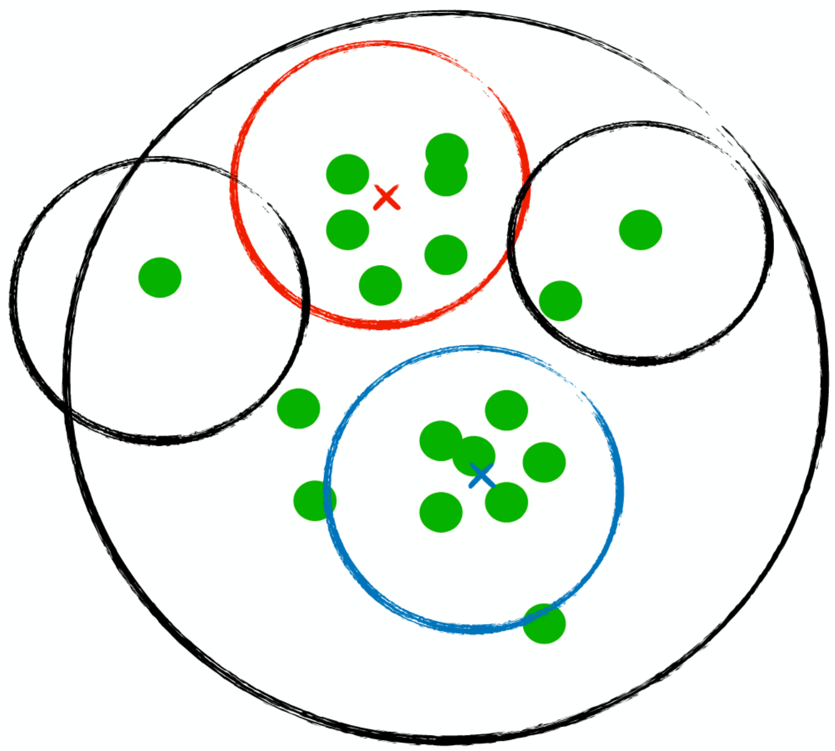
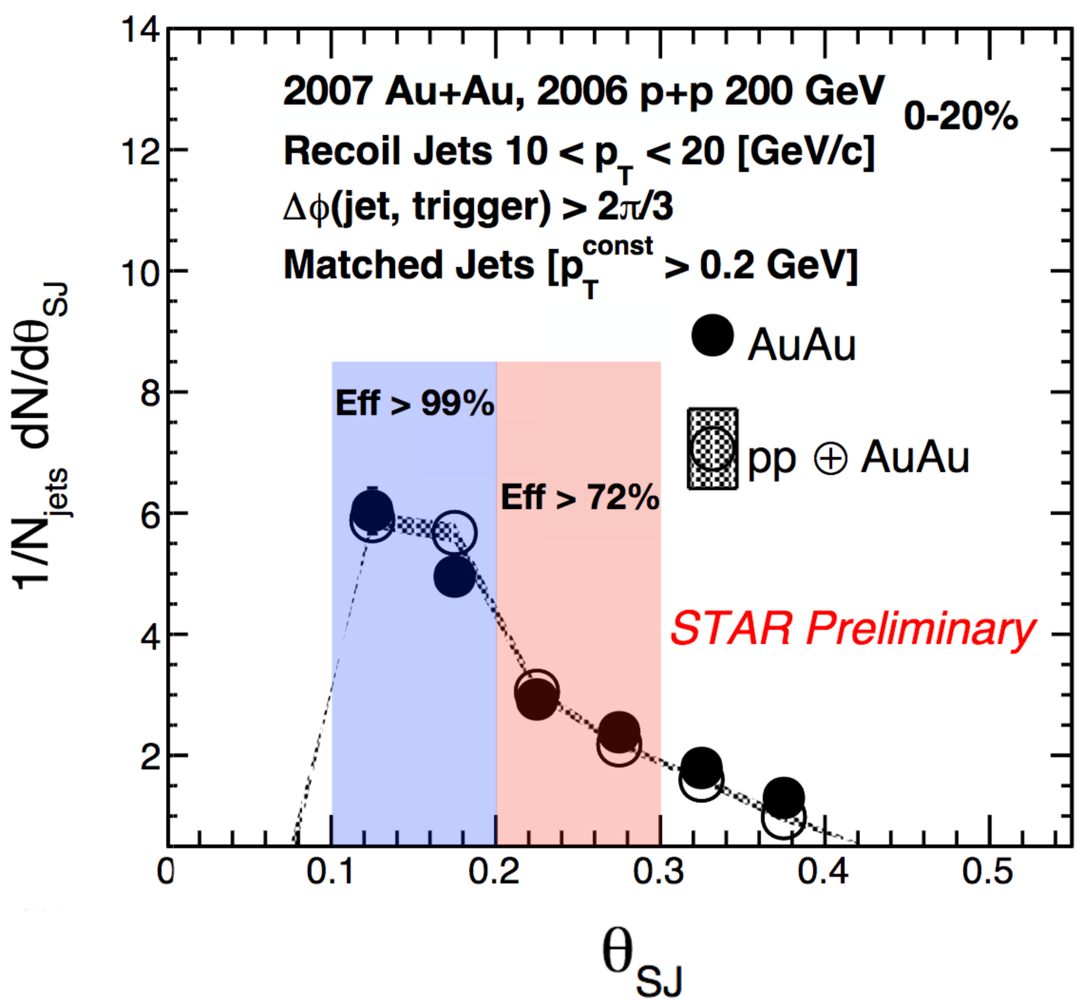
Jet angular scale dependence





- Cluster all constituents into anti-k_T jets of smaller radii (R = 0.1)
- Choose leading and subleading subjets
- $z_g = p_T^{SubleadingSJ}/(p_T^{LeadingSJ} + p_T^{SubleadingSJ})$
- $\theta_{SJ} = \Delta R$(LeadingSJ axis, SubLeading SJ axis)

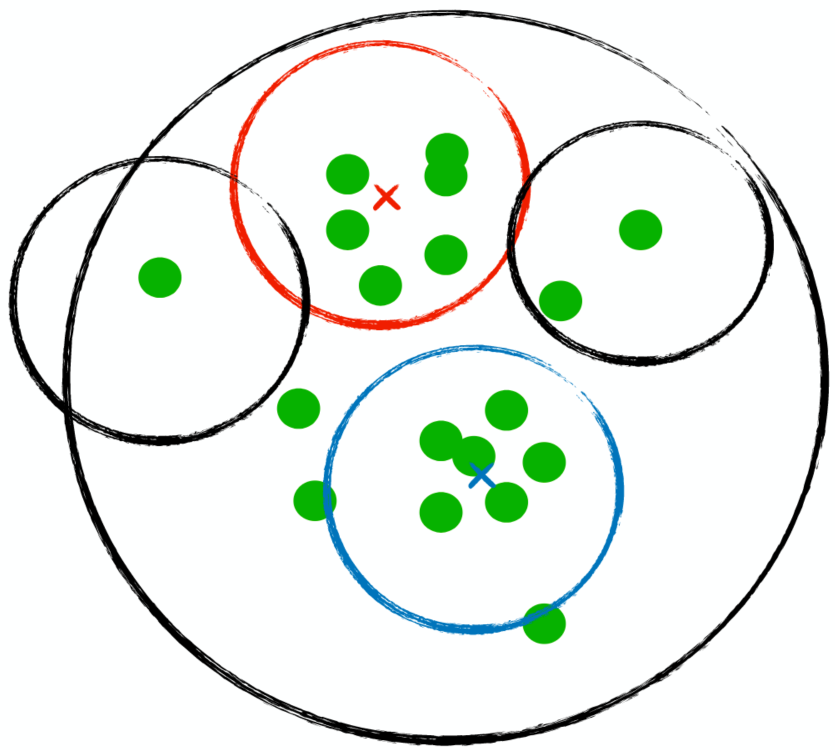
- Interaction of the jet with medium could depend on the jet's angular scale

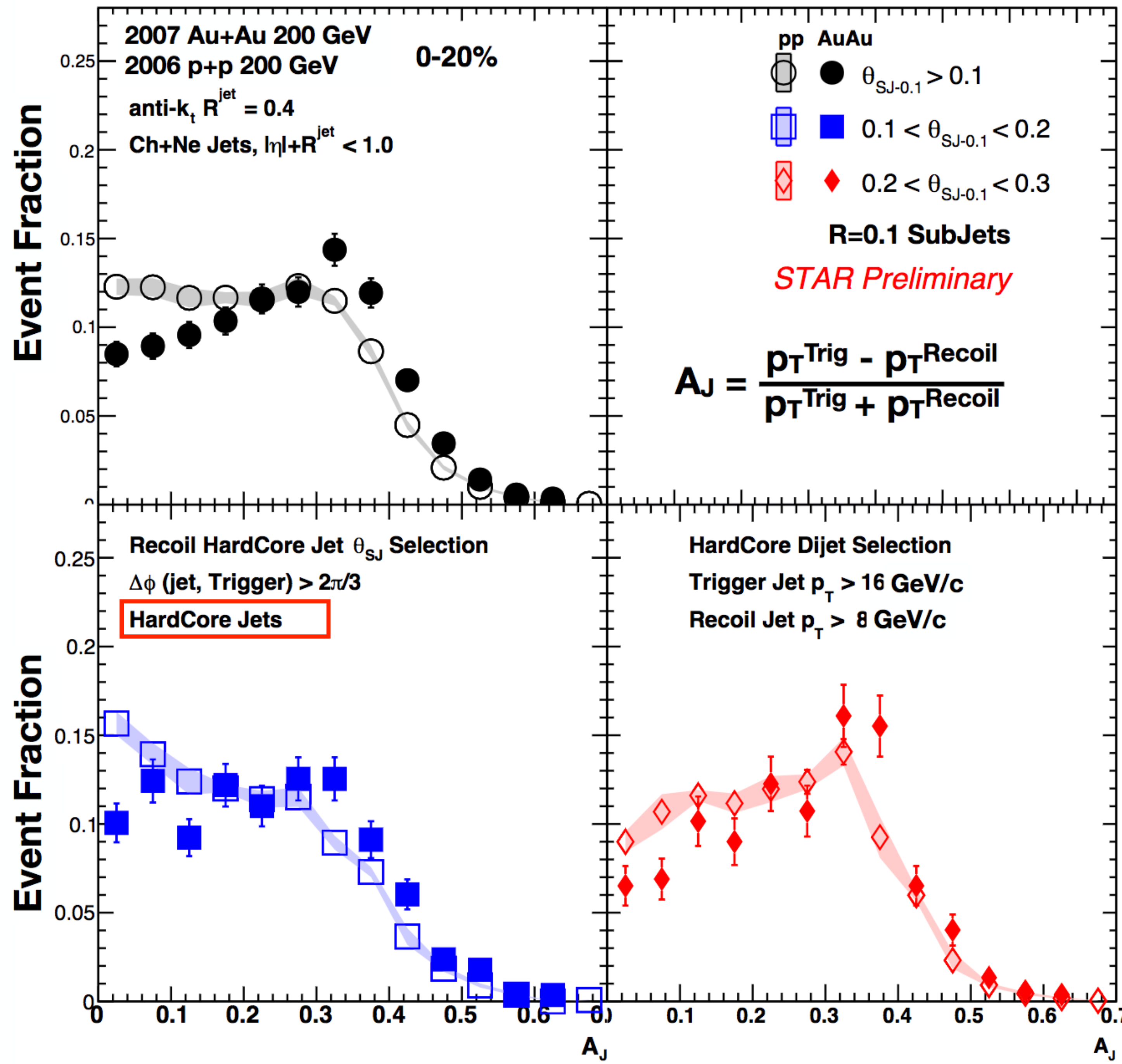
Majumder, A and Putschke, J Phys Rev C 93 054909
Mehtar Tani, Y and Tywoniuk, K arXiv:1707.07361

- Look separately at jets with different θ_{SJ}

Talk by R. Elayavalli: 04/10 Thu, 11.25 (P2)

Jet angular scale dependence



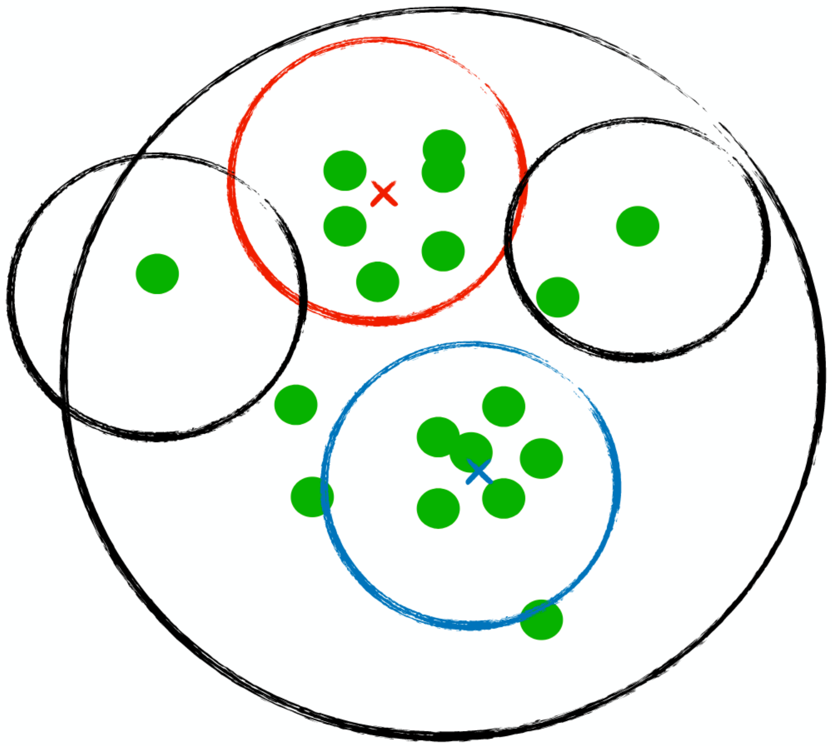


$\theta_{SJ} = \Delta R$(LeadingSJ axis, SubLeading SJ axis)

- ***Hard-core jets*** unbalanced for all θ_{SJ} selections
- No large difference among different θ_{SJ} selections

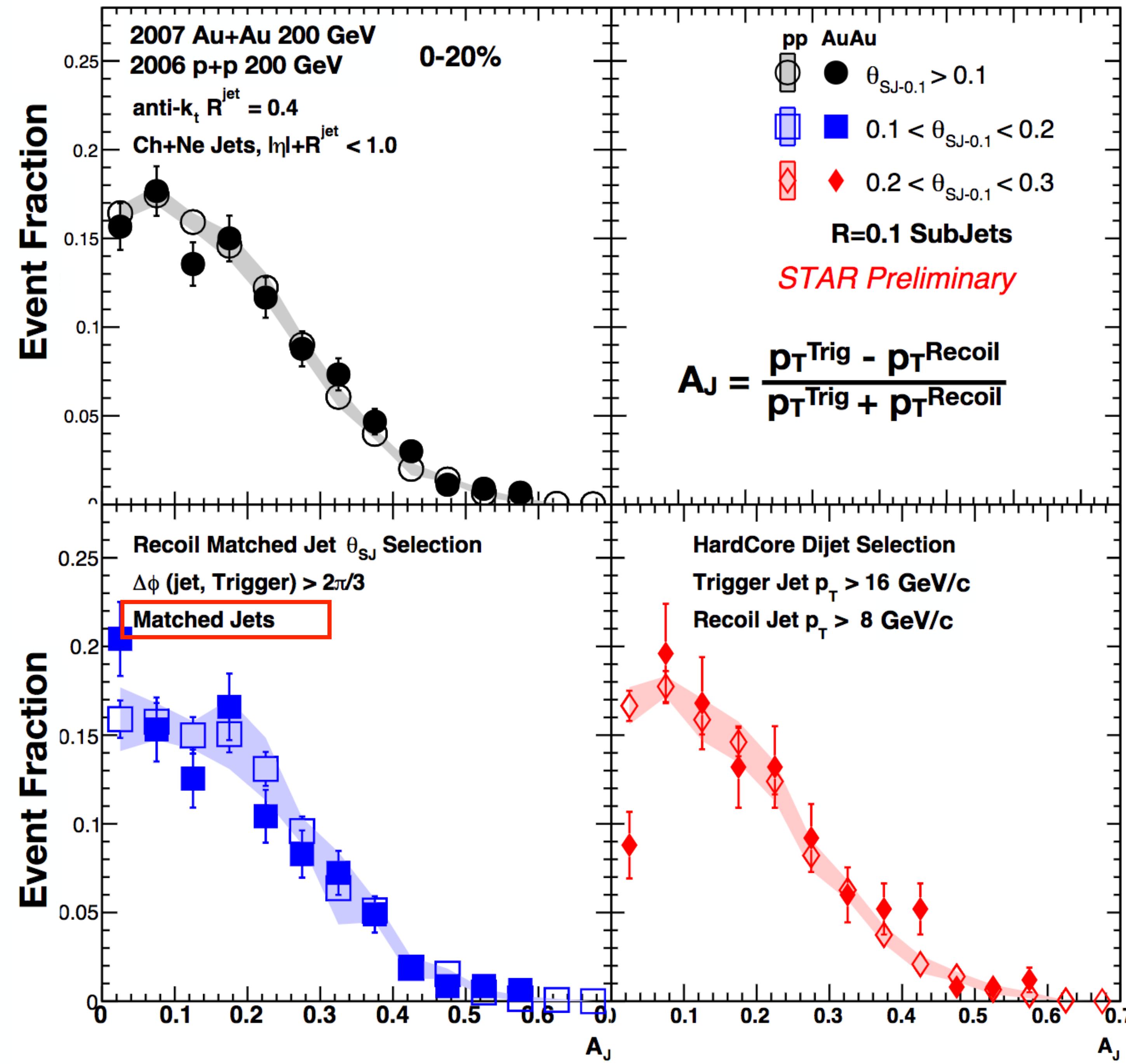
Talk by R. Elayavalli: 04/10 Thu, 11.25 (P2)

Jet angular scale dependence



$\theta_{SJ} = \Delta R($LeadingSJ axis, SubLeading SJ axis$)$

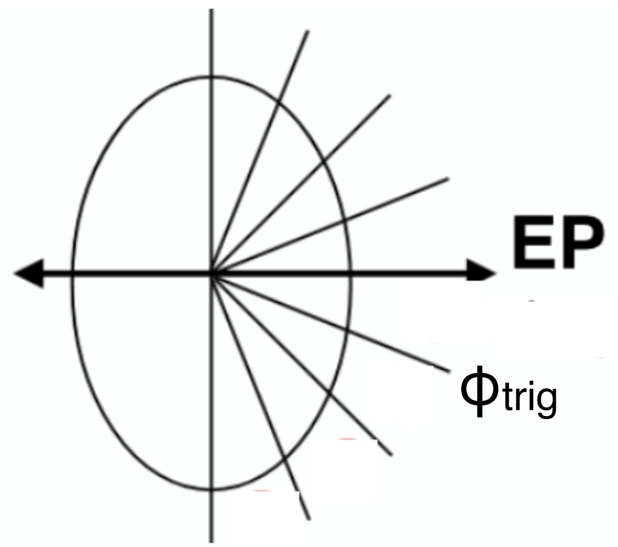
- ***Matched jets*** (R = 0.4) recover balance (w.r.t p+p) for all θ_{SJ} selections



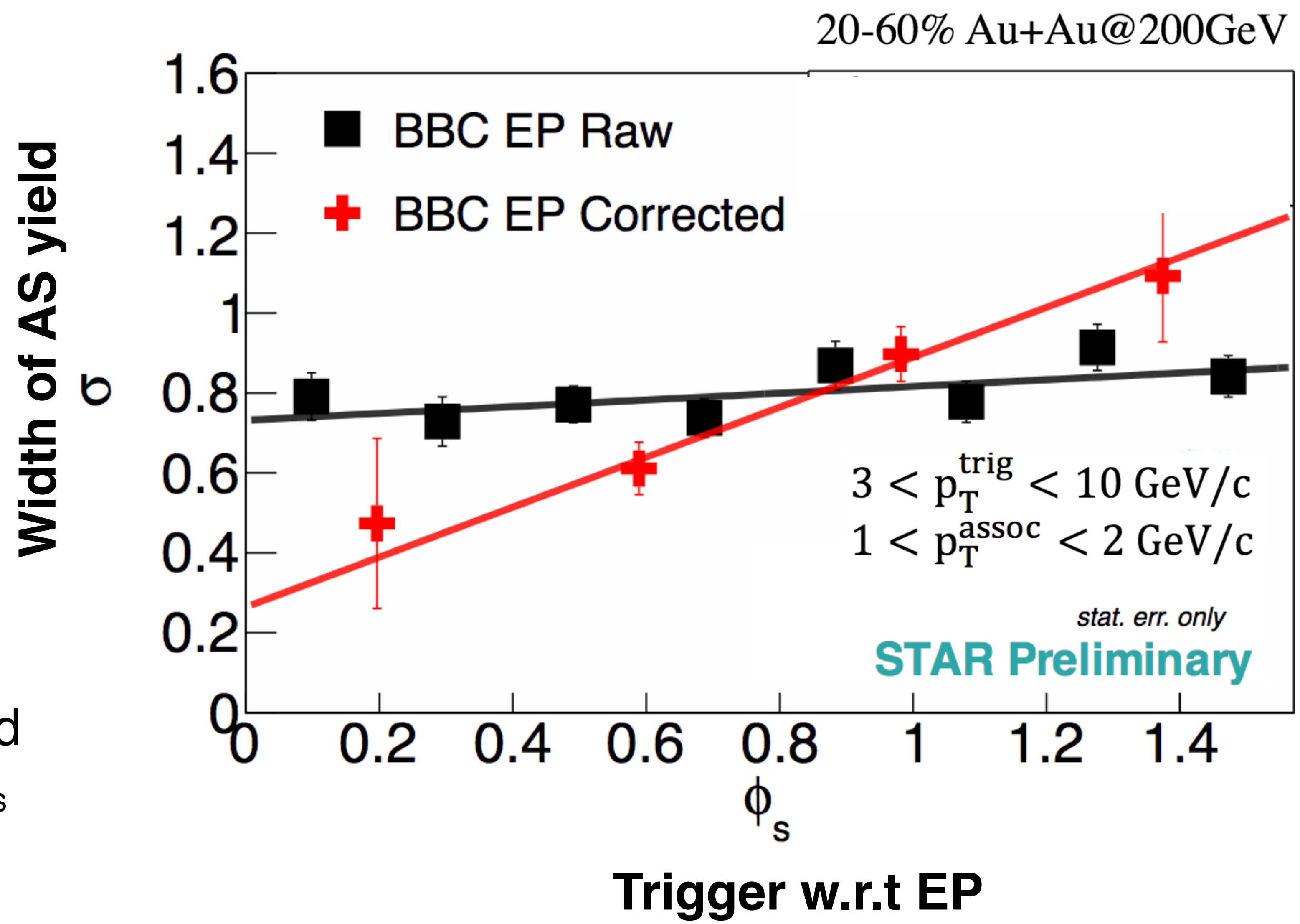
Talk by R. Elayavalli: 04/10 Thu, 11.25 (P2)

Away side broadening with path length

- Width of away-side jet-like peak for high p_T trigger particles



$$\phi_s = \phi^{trig} - \Psi_{2,\,EP}$$



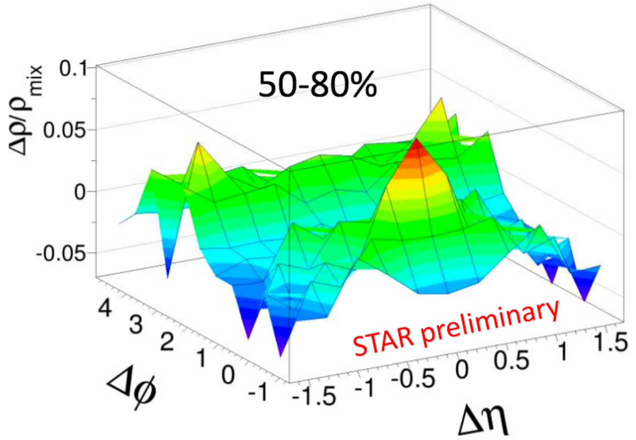
- Flow background subtracted
- Unfolded for smearing of ϕ_s from EP resolution

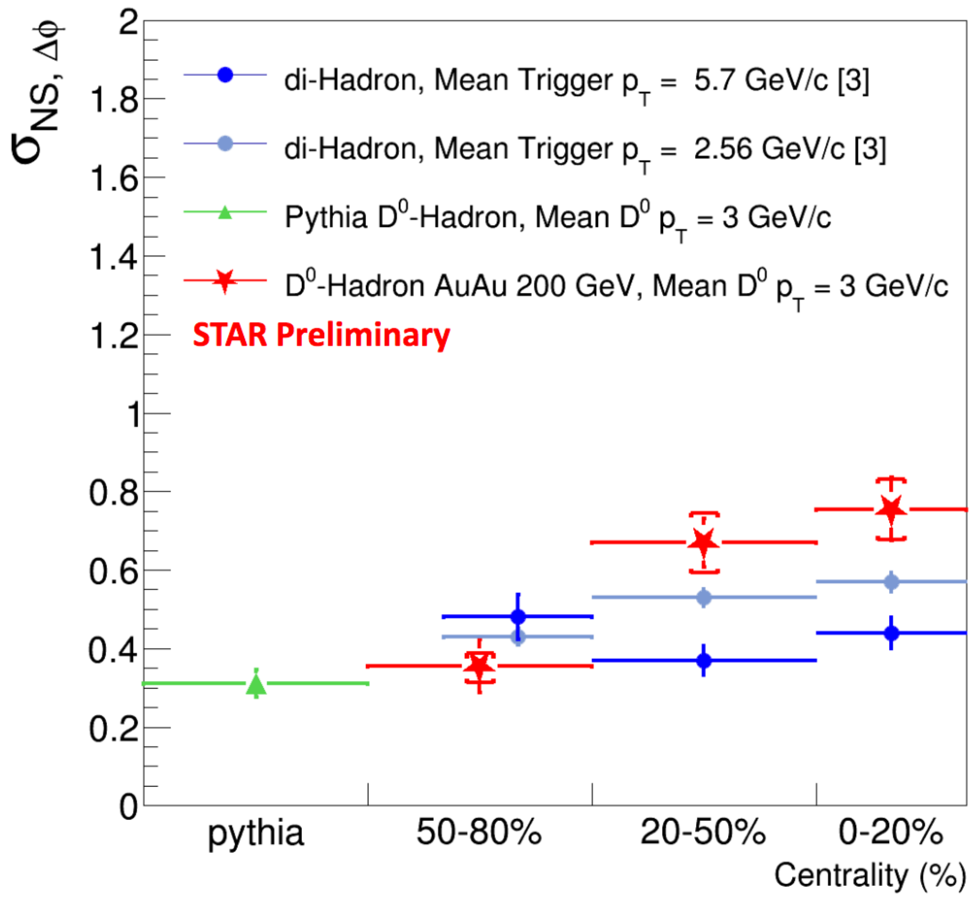
- Path length dependent increase of away-side peak width

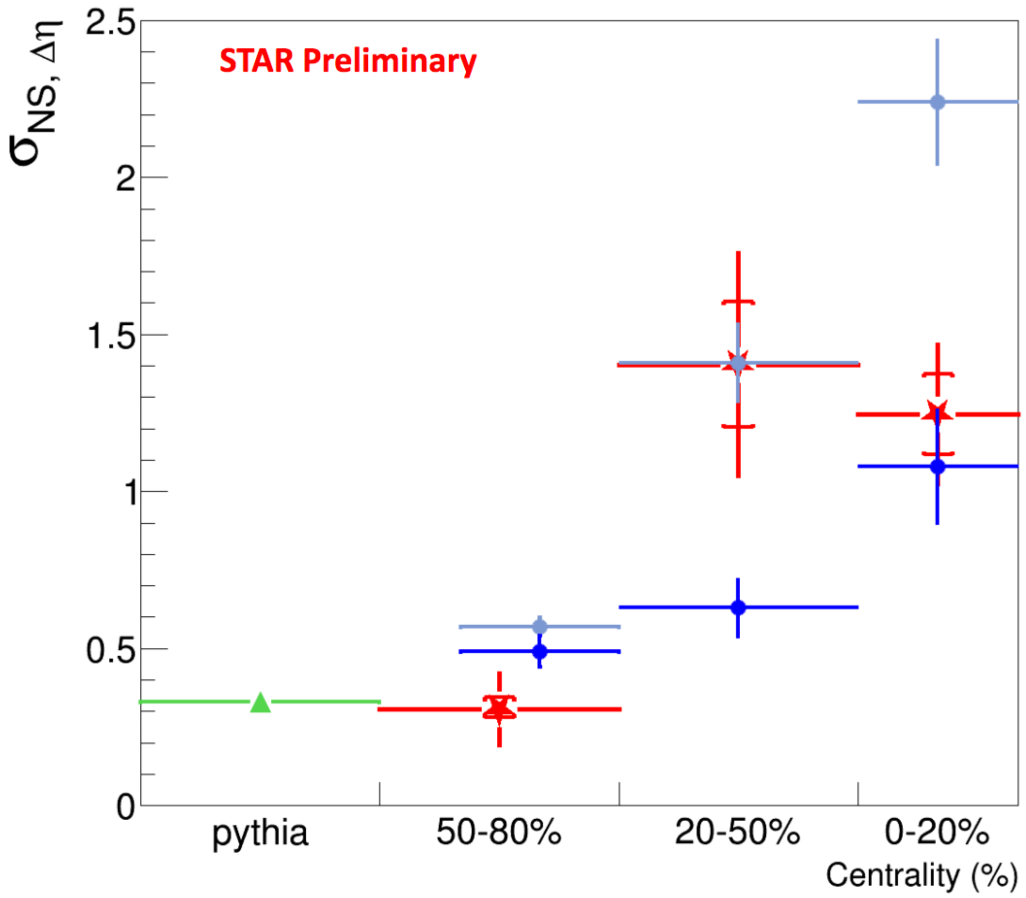
Talk by L. Zhang/Y.Li: 02/10 Tue, 16.45 (P2)

Modification of jet-like peak in D^0-hadron correlations

- Measurement of correlated production of hadrons with D^0, sensitive to charm energy loss mechanisms
- Widths of Near Side (NS) peak measured from fit to data





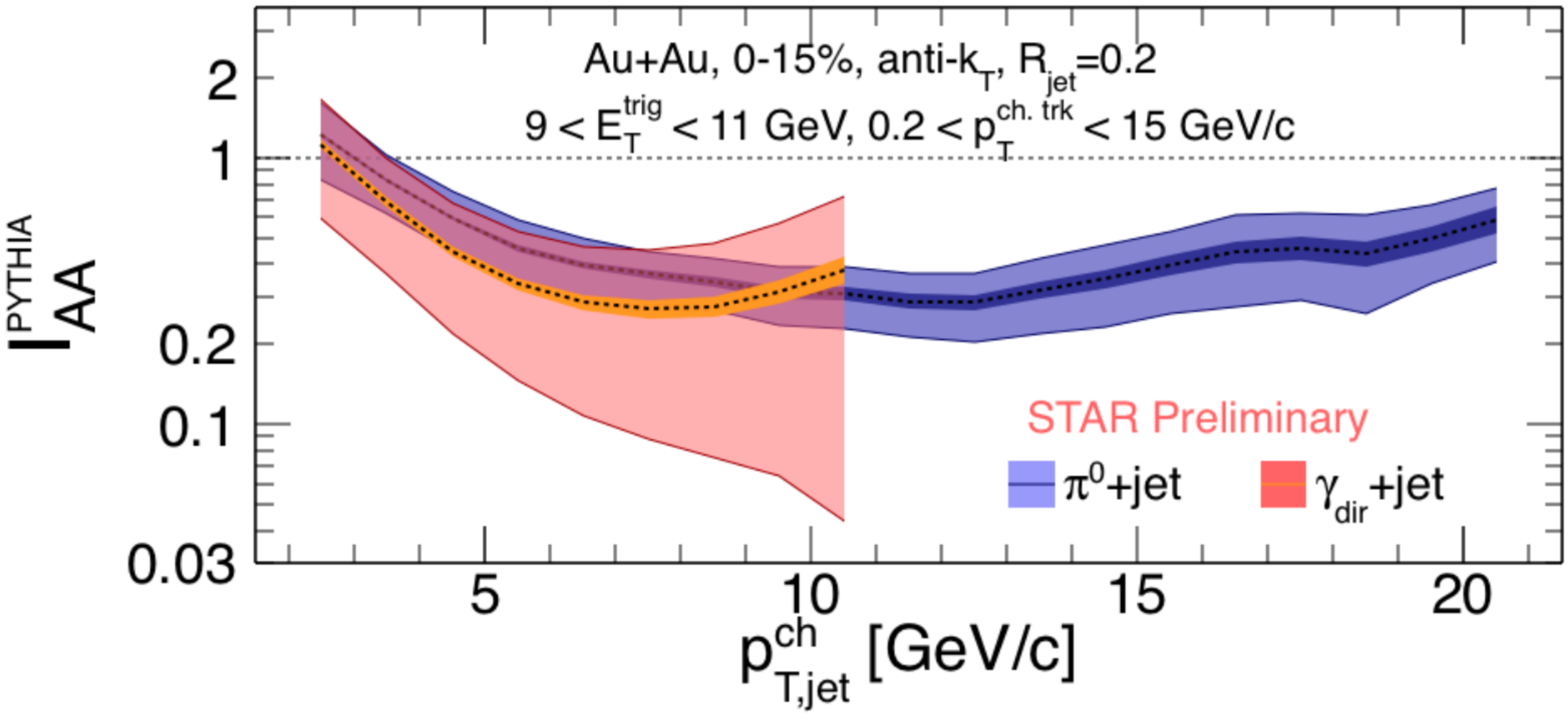


- Increase in widths of NS peak in $\Delta\eta$ and $\Delta\phi$ from peripheral to central collisions
- Broadening of jet-like peak, increase by medium interactions

Talk by A. Jentsch: Time

Direct photon + jet at RHIC

- Charged jets recoiling from γ_{dir} trigger are excellent probes to study energy loss

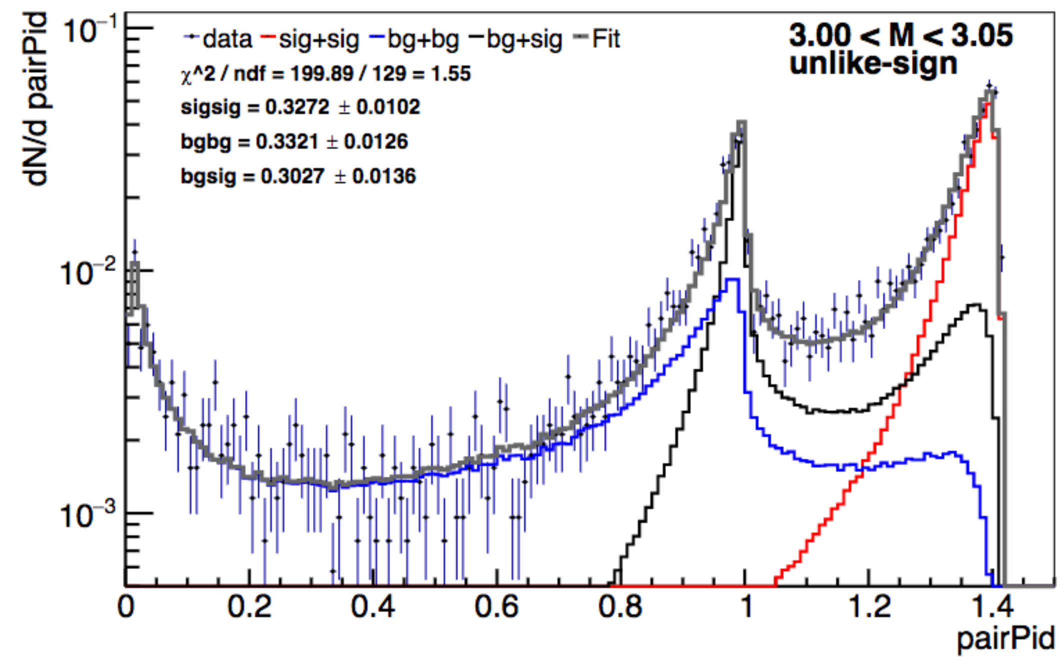


- First measurement of fully unfolded γ_{dir} + jet spectra at RHIC energy
- Similar suppression for away-side jets associated with γ_{dir} and with π^0 (p+p reference taken from PYTHIA)

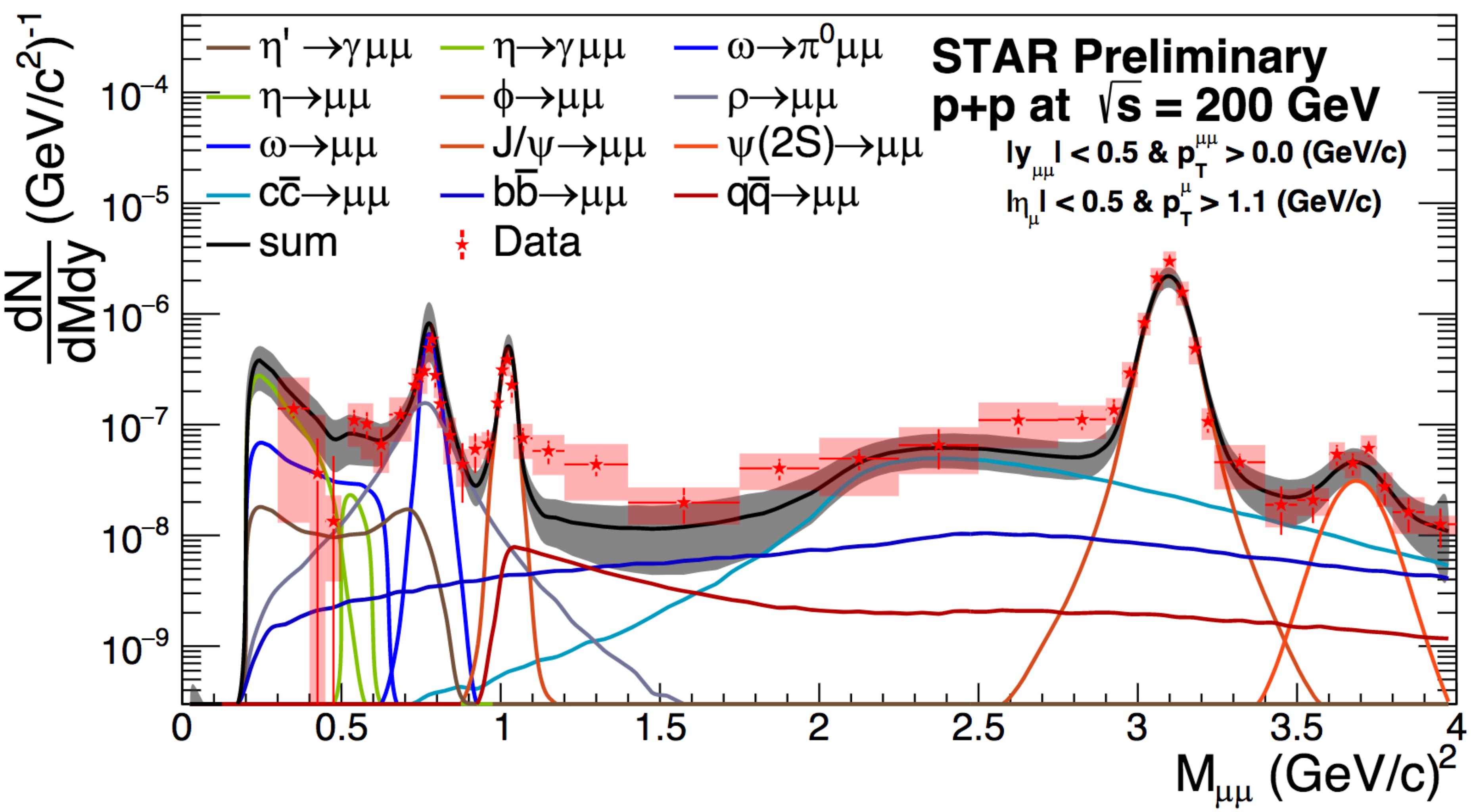
Talk by N. Sahoo: 02/10 Tue, 15.00 (P1)

Di-muon spectra in p+p with MTD

- MTD provides precise time resolution (~100 ps) and good spatial resolution for hits, allowing Muon identification
- Muon id. is improved with use of Deep Neural Networks
- Templates for DNN response generated from MC and then fit to data



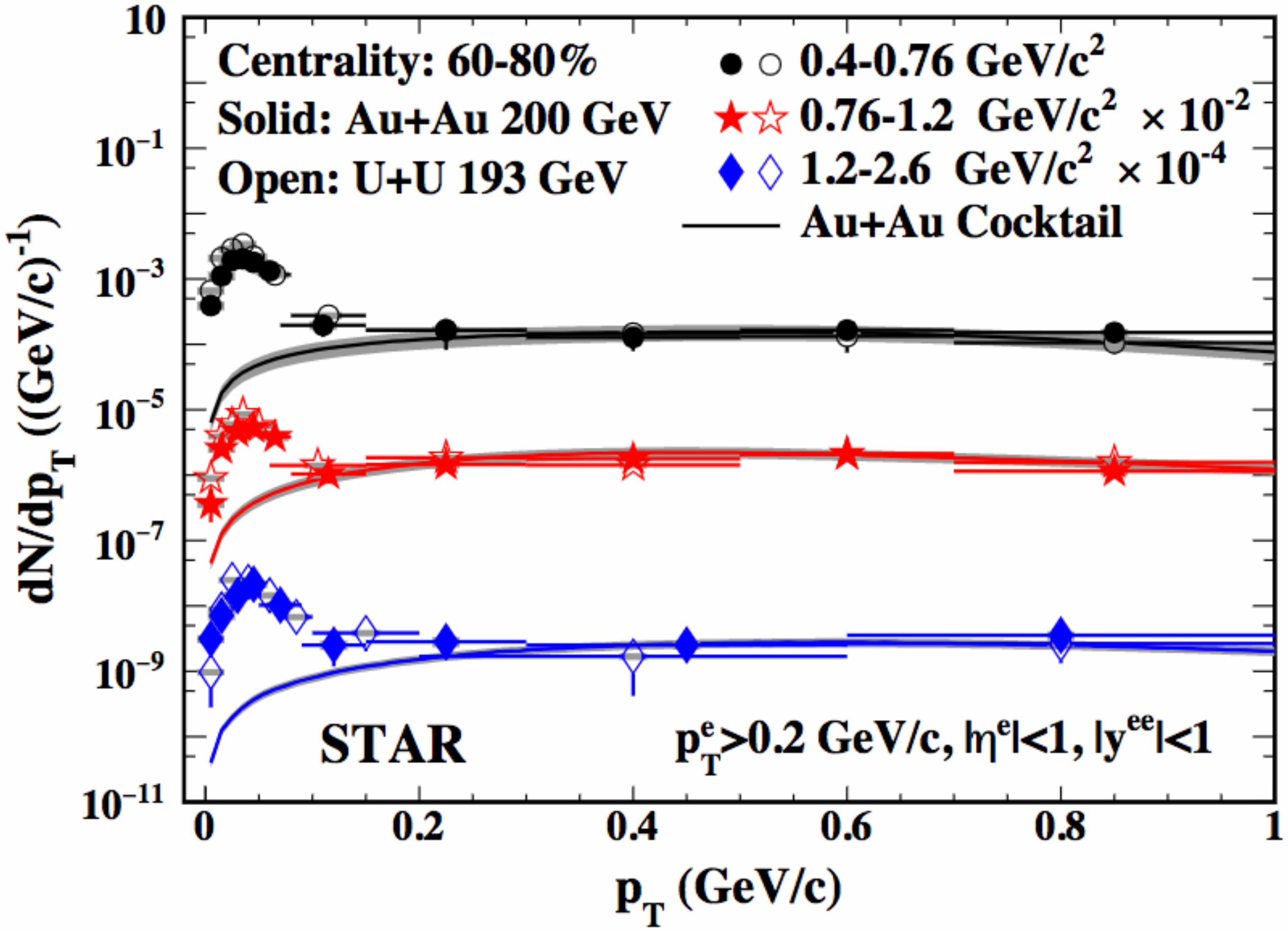
DNN response for pairs

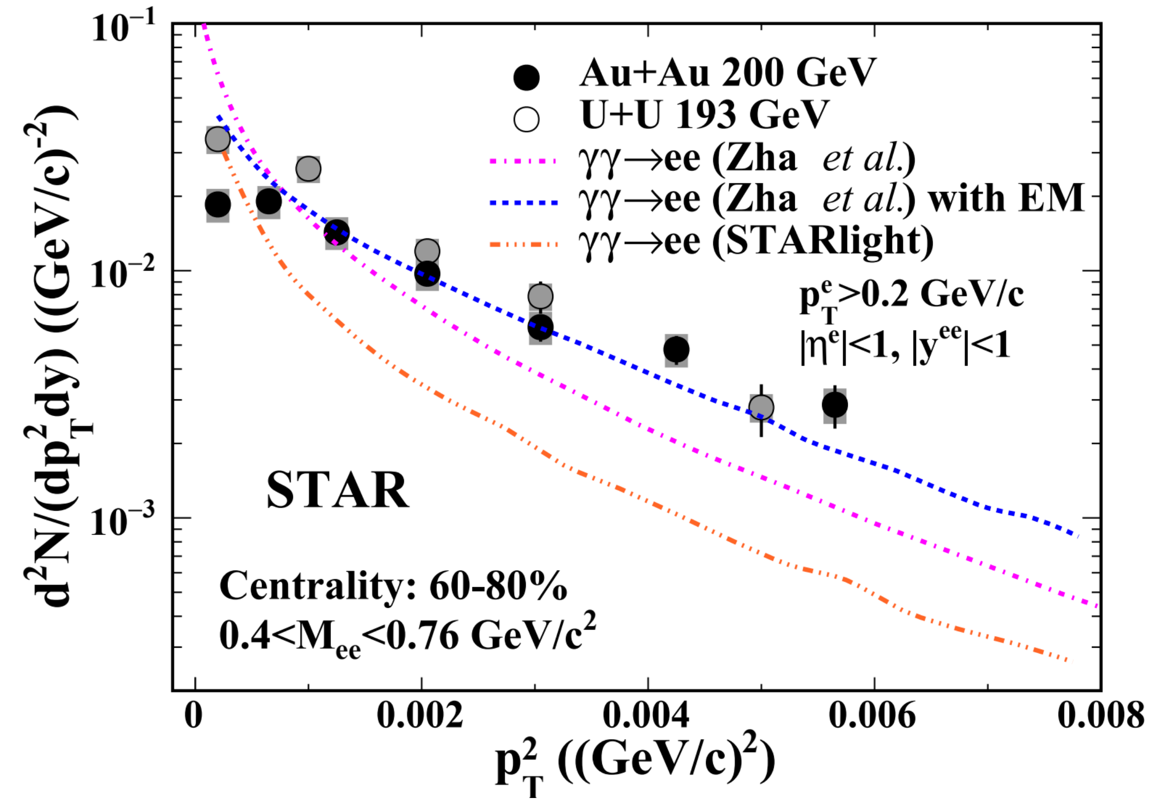


- First $\mu^+ \mu^-$ mass spectra from STAR

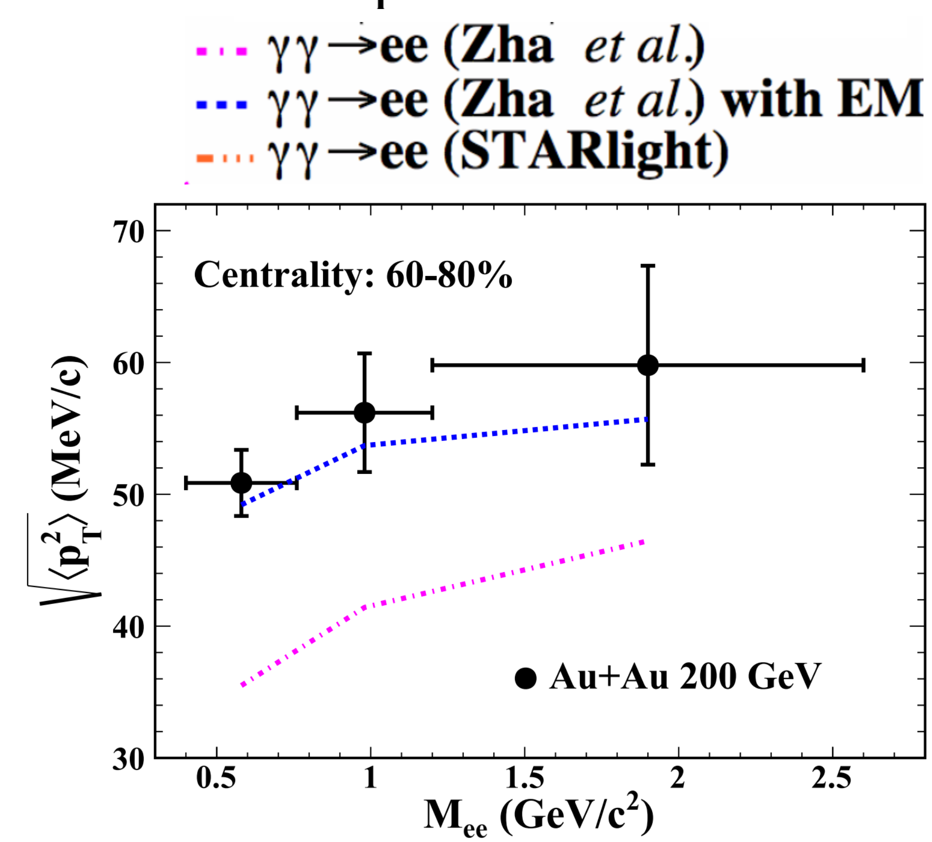
Talk by D. Brandenburg: 03/10 Wed, 11.05 (P4)

Low p_T di-electron excess





STAR Collaboration. Phys. Rev. Lett 121, 132301 (2018)
W. M. Zha et al., PLB 781 (2018) 18
STARlight: S. R. Klein, PRC 97 (2018) 054903



- Large excess of di-electron yields at very low p_T ($p_T < 0.15$ GeV/c) in peripheral collisions

- The average p_T^2 larger than from just photon-photon interactions.
- Could be a probe for the strong EM field trapped in the QGP!

Talk by S. Yang:02/10 Tue, 09.20 (P4)

Summary

✦ Strongly interacting charm quarks in QGP

- Similar high p_T R_{AA}, (and v_2) for D^0 as light flavor hadrons
- Much larger D^0 v_1, compared to light flavor hadrons. Predicted by hydro

✦ Evidence for coalescence hadronization of charm quarks

- Strong enhancement of Λ_c production
- Charm cross section consistent with p+p, but hadrochemistry significantly modified

✦ Stronger suppression of Υ(2S+3S) than Υ(1S) in central Au+Au

✦ Jets in QGP: Momentum transfer to soft particles. Broadening of angular distributions of associated particles with path length

- A_J for jets with higher hard const. p_T cut get balanced (w.r.t p+p) with increase in jet radius and inclusion of soft constituents
- No strong dependence on jet angular scale seen
- Broadening of away side when going from in-plane trigger to out-of-plane trigger
- Broadening of jet-like peak in D^0-hadron correlations from peripheral to central

✦ Low p_T di-electron excess - probe for initial photon flux and (potentially) EM field

List of talks from STAR

- **Xiaolong Chen, 02/10 Tue, 09.20 (P3):** *Measurements of open bottom hadron production via displaced J/Psi, D0 and electrons in Au+Au collisions at sqrt(s_NN) = 200 GeV at STAR*
- **Shuai Yang, 02/10 Tue, 09.20 (P4):** *Low-pT e+e- pair production in Au+Au collisions at sqrt(s_NN) = 200 GeV and U+U collisions at sqrt(s_NN) = 193 GeV at STAR*
- **Liang He, 02/10 Tue, 11.05 (P3):** *Measurement of directed flow of D0 and D0bar mesons in 200 GeV Au+Au collisions at RHIC using the STAR detector*
- **Nick Elsey, 02/10 Tue 11:25 (P2):** *Systematic studies of di-jet imbalance measurements at STAR*
- **Nihar Sahoo, 02/10 Tue, 15.00 (P1):** *Measurement of the semi-inclusive distribution of jets recoiling from direct photon and pi0 triggers in central Au+Au collisions at sqrt(s_NN) = 200 GeV with the STAR experiment*
- **Liang Zhang/Li Yi, 02/10 Tue, 16.45 (P2):** *Event-plane dependent away-side jet-like correlation shape in 200 GeV Au+Au collisions from STAR*
- **Zhen Liu, 03/10 Wed, 09.00 (P3):** *Quarkonium measurements in heavy-ion collisions at sqrt(s_NN) = 200 GeV with the STAR experiment*
- **Daniel Brandenburg, 03/10 Wed, 11.05 (P4):** *Measurement of the \mu+\mu Invariant Mass Spectra in p+p and p+Au Collisions at sqrt(s_NN) = 200 GeV with the Muon Telescope Detector at STAR*
- **Raghav Elayavalli, 04/10 Thu, 11.25 (P2):** *Measurements of the jet internal structure and its relevance to parton evolution in p+p and Au+Au collisions at STAR*
- **Guannan Xie, 04/10 Thu, 11.25 (P3):** *Measurements of Lambda_c^{\pm}, D_s^{\pm}, D*^{\pm} and $D^{0}(\overline{D^{0}})$ Production in Au+Au Collisions at sqrt(s_{NN) = 200 GeV at STAR*
- **Alex Jentsch, Time:** *Studies of Heavy-Flavor Jets Using D0-Hadron Correlations in Azimuth and Pseudorapidity in Au+Au Collisions at 200 GeV at the STAR Experiment*