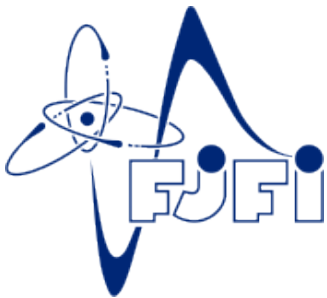
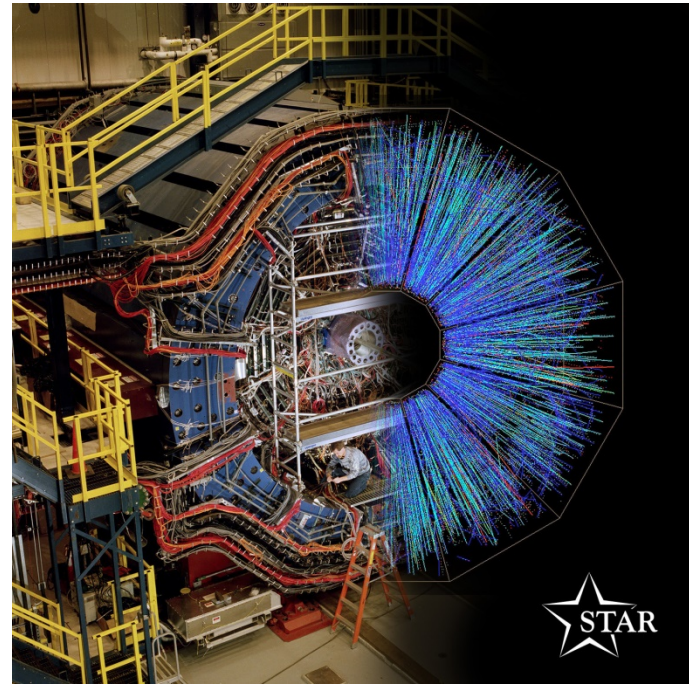


Overview of recent heavy-flavor and jet results from STAR

Jaroslav Bielicik
for the STAR collaboration

Czech technical university in Prague

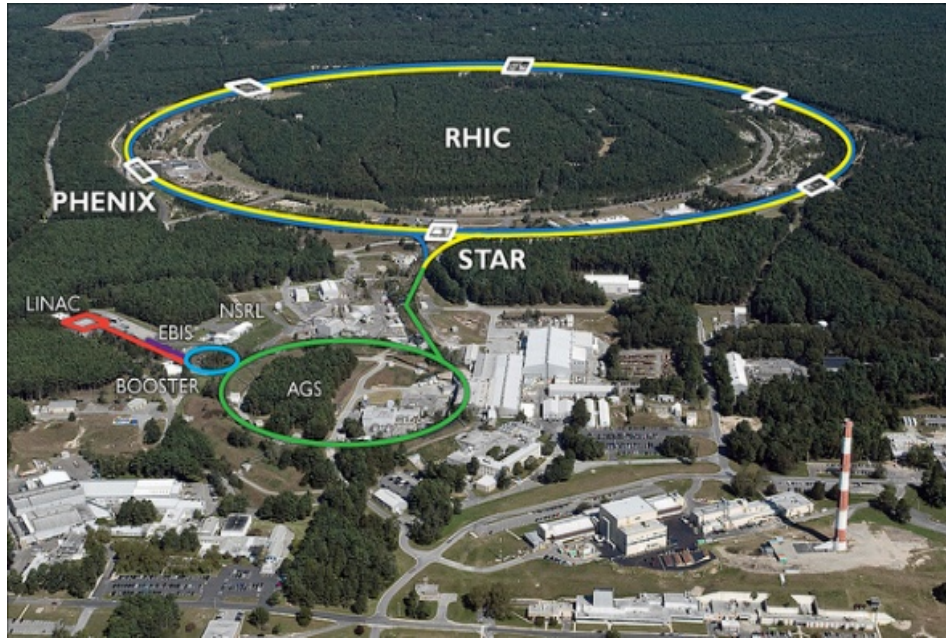


EUROPEAN UNION
European Structural and Investment Funds
Operational Programme Research,
Development and Education



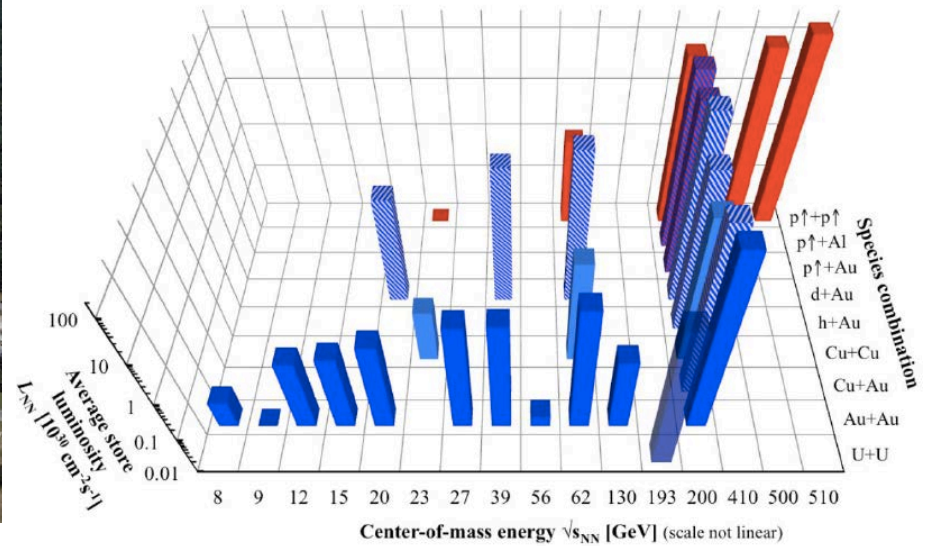
6th International Conference on New Frontiers in Physics, 17.-29. August 2017, Crete, Greece

Relativistic Heavy Ion Collider



RHIC Amazing QCD Machine: Many Species and Many Energies!

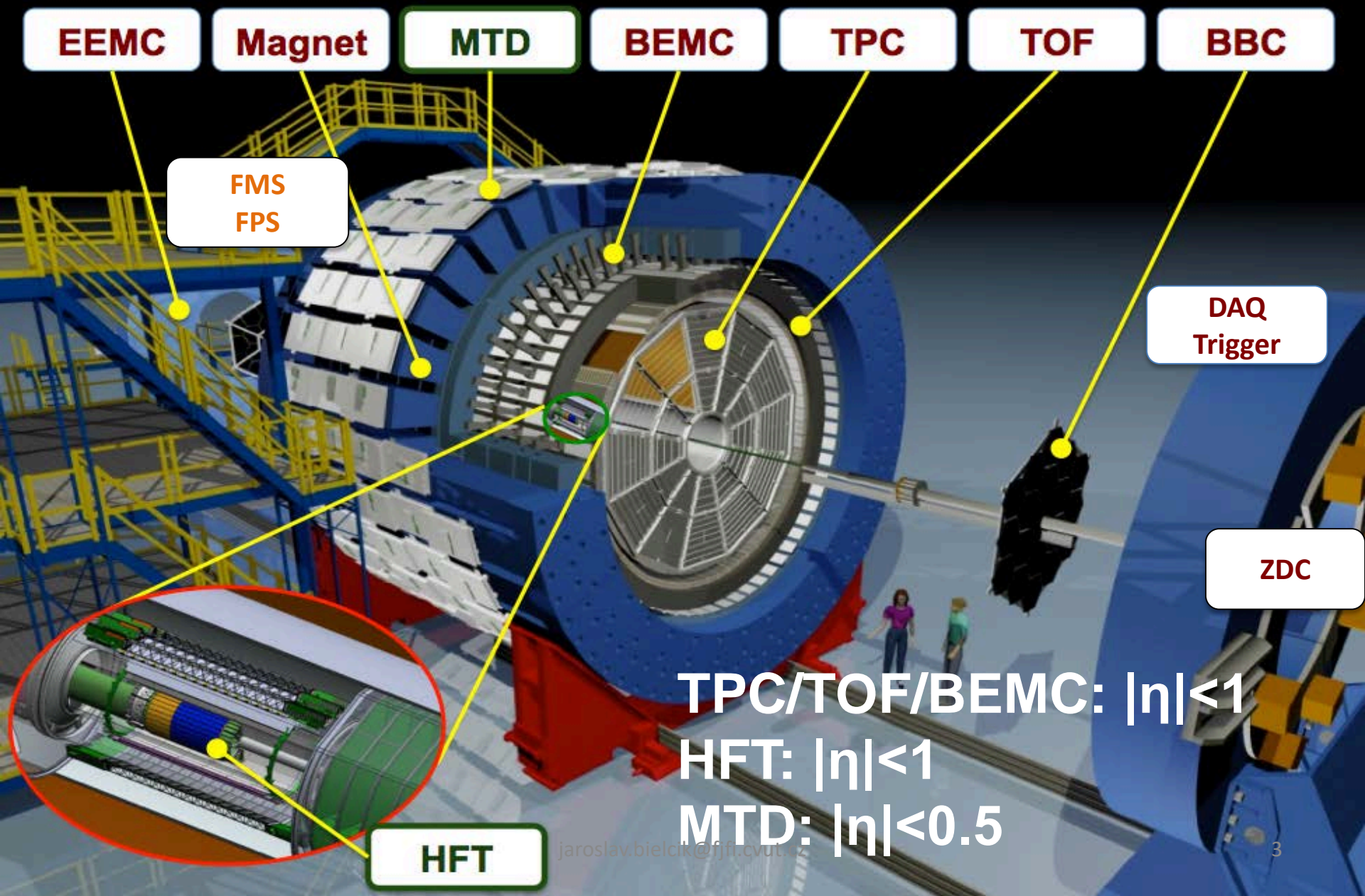
RHIC energies, species combinations and luminosities (Run-1 to 16)



- **Extremely versatile:** has collected data colliding a large array of different heavy ions
 - Peak luminosity Au+Au 200 GeV : $155 \times 10^{26} \text{ cm}^{-2} \text{ s}^{-1}$; p+p 200 GeV : $115 \times 10^{30} \text{ cm}^{-2} \text{ s}^{-1}$
- Only polarized proton collider in the world
 - Beam polarizations P=55%

<http://www.agsrhichome.bnl.gov/RHIC/Runs/>

STAR experiment

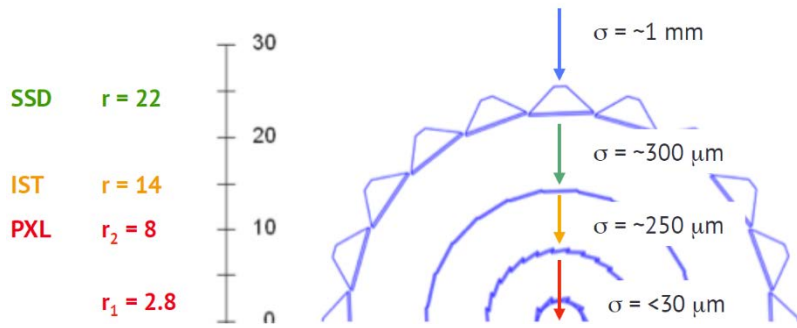


TPC/TOF/BEMC: $|\eta| < 1$

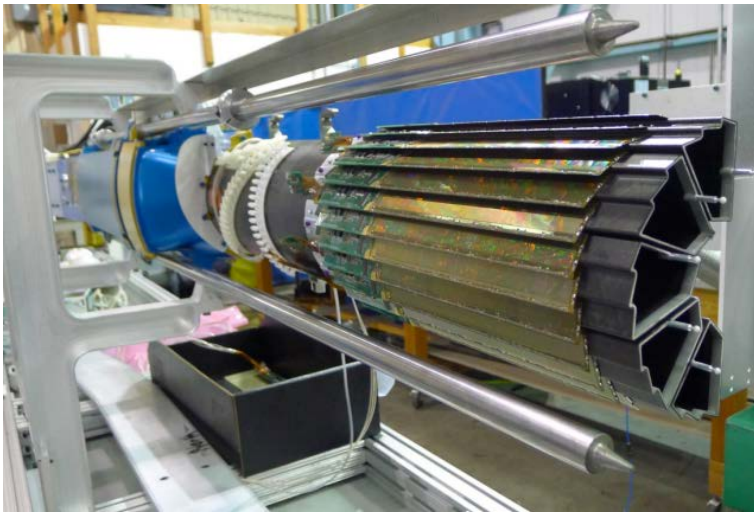
HFT: $|\eta| < 1$

MTD: $|\eta| < 0.5$

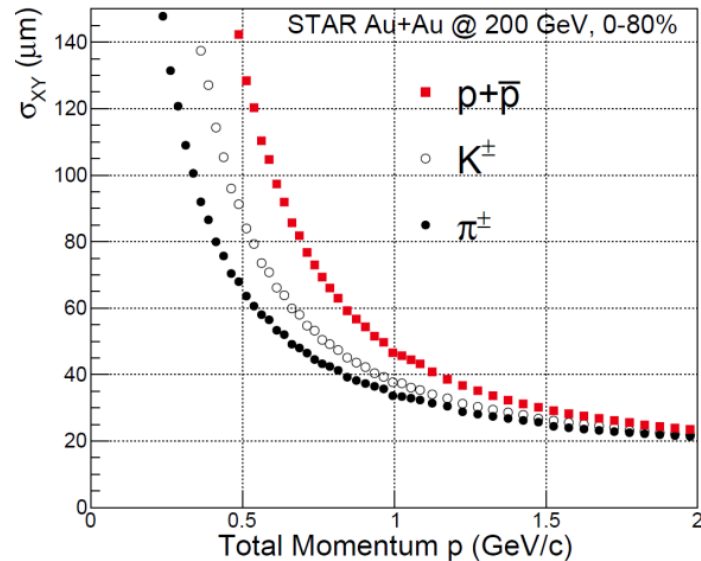
Heavy Flavor Tracker (HFT)



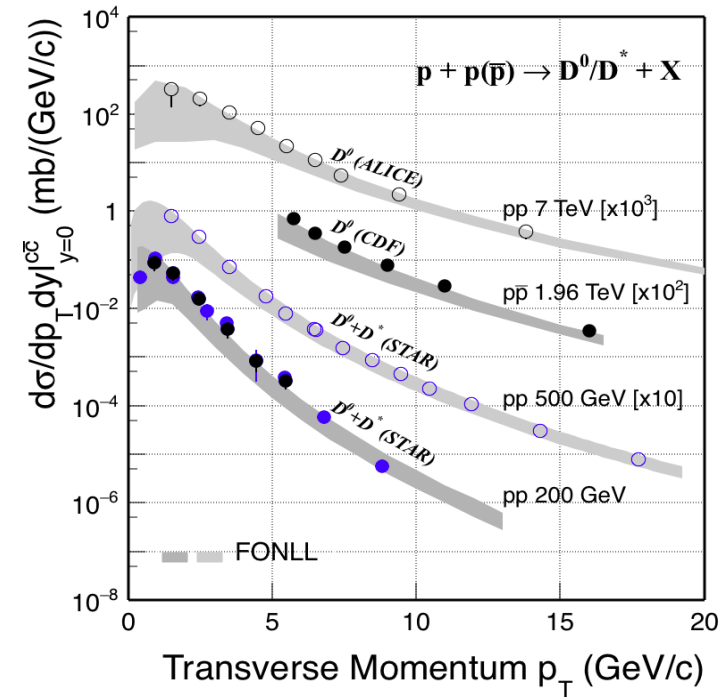
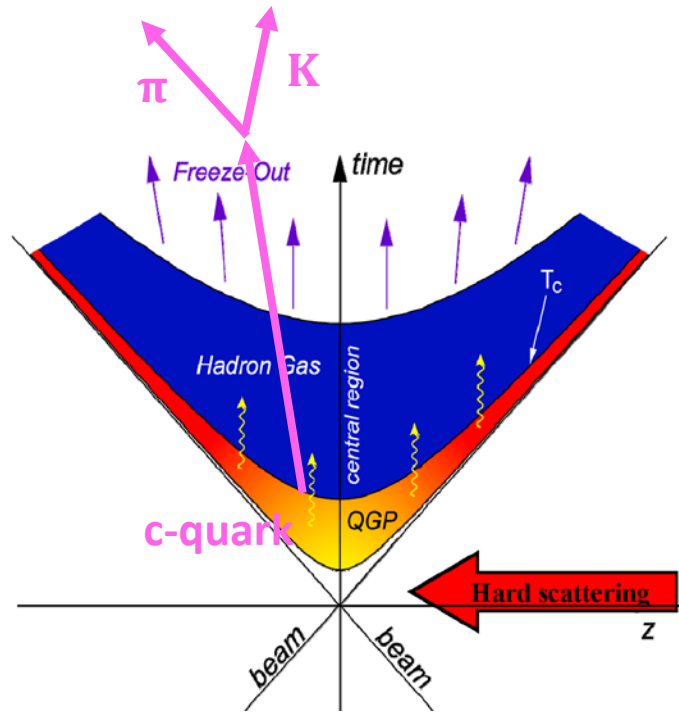
- Took data in 2014-2016.
- First application of Monolithic Active Pixel Sensors technology in collider experiments.
- Radiation length: 0.4 % X_0 for the 1st layer of pixel.
- Pointing resolution ~ 50 μm for $p_T = 750$ MeV/c Kaon.



STAR: PRL 118 (2017) 212301



Probing Quark Gluon Plasma with charm quark



STAR: PRD 86 (2012) 072013, NPA 931 (2014) 520
 CDF: PRL 91 (2003) 241804; ALICE: JHEP01 (2012) 128
 FONLL: PRL 95 (2005) 122001

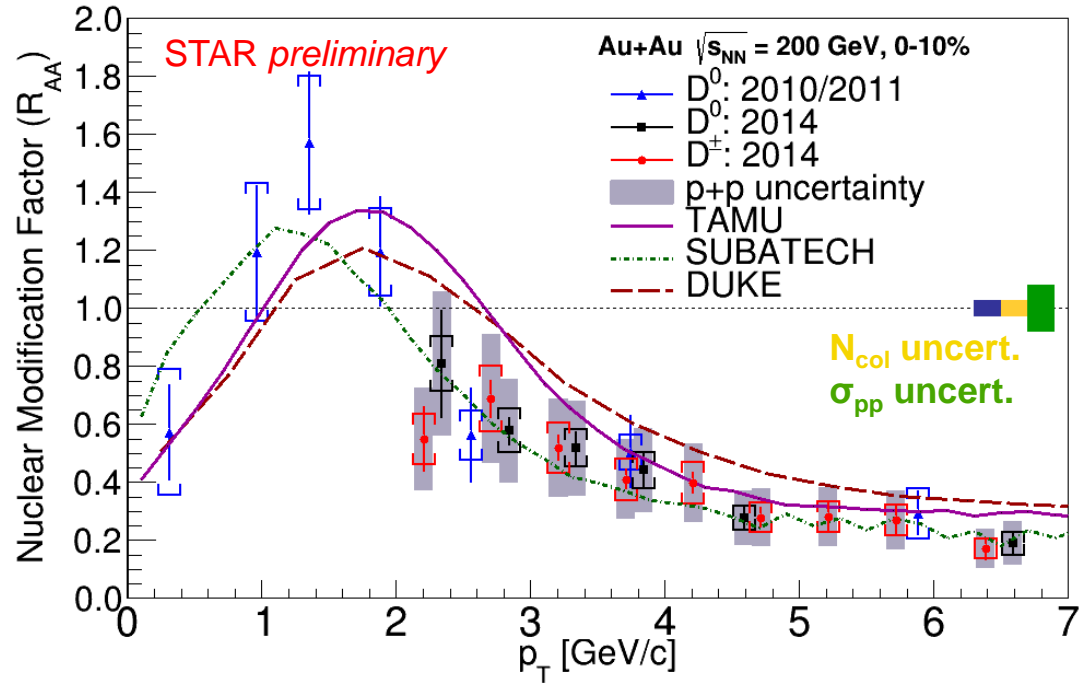
- **Charm quark: $m_c \gg T_{QGP}, \Lambda_{QCD}$**
- Produced in hard scatterings at the early stage of nuclear collisions \rightarrow experience the entire evolution of medium
- Charm cross section scales with N_{coll} in Au+Au collisions \rightarrow important input for models to calculate regeneration contribution to charmonium

- Its production rates are well described by pQCD in elementary collisions

Nuclear modification factor R_{AA} of D^0 and D^\pm

$$R_{AA} = \frac{dN_{AA}/dp_T}{\langle N_{coll} \rangle \times dN_{pp}/dp_T}$$

- Yield at $p_T > 2.5$ GeV/c greatly suppressed
 - Improved precision with the HFT
 - Results from D^0 and D^\pm are consistent
- Models with strong charm-medium interactions describe qualitatively the data



[STAR:2010/2011 PRL 113 (2014) 142301]

[Theory: TAMU: Eur. Phys. J. C (2016) 76: 107 & private comm.; SUBATECH: PRC 91(2015) 054902 & private comm.; Duke: PRC 92(2015) 024907 & private comm]

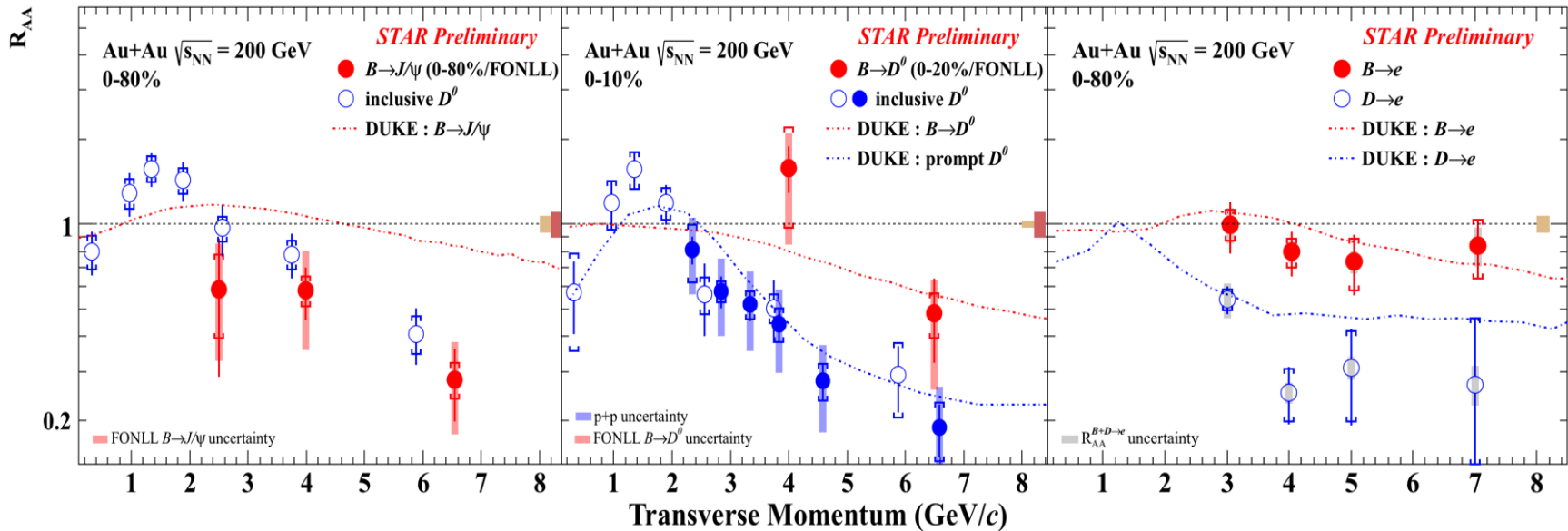
Nuclear modification factor of bottom quarks

$B \rightarrow J/\psi$

$B \rightarrow D^0$

$B/D \rightarrow e$

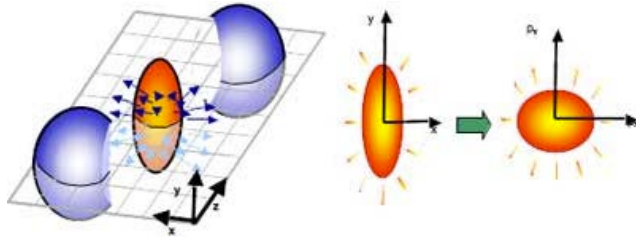
DUKE: PRC 92 (2015) 024907



STAR measured **B production** via non-prompt J/ψ , D^0 and electron decay channels in 200 GeV Au+Au collisions

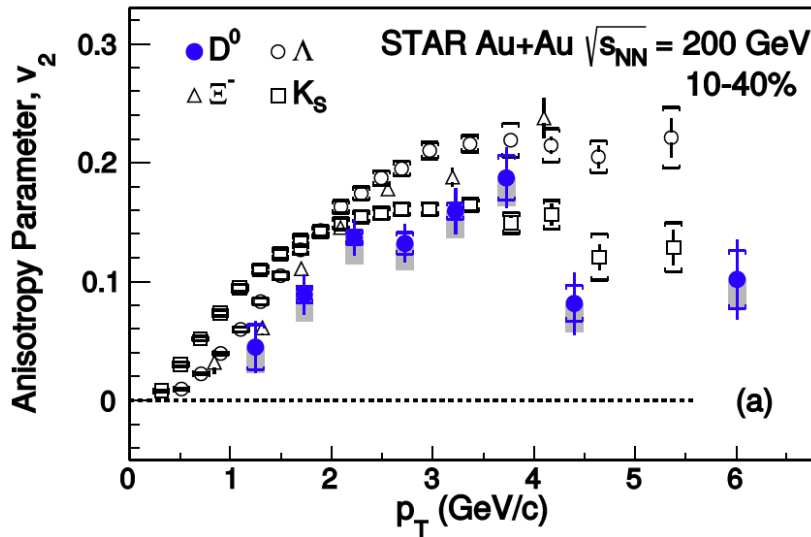
- Strong suppression for $B \rightarrow J/\psi$ and $B \rightarrow D^0$ at high p_T .
- Indication of less suppression for $B \rightarrow e$ than $D \rightarrow e$ ($\sim 2 \sigma$): consistent with expected mass hierarchy for parton energy loss $\Delta E_c > \Delta E_b$

D⁰ azimuthal anisotropy v_2

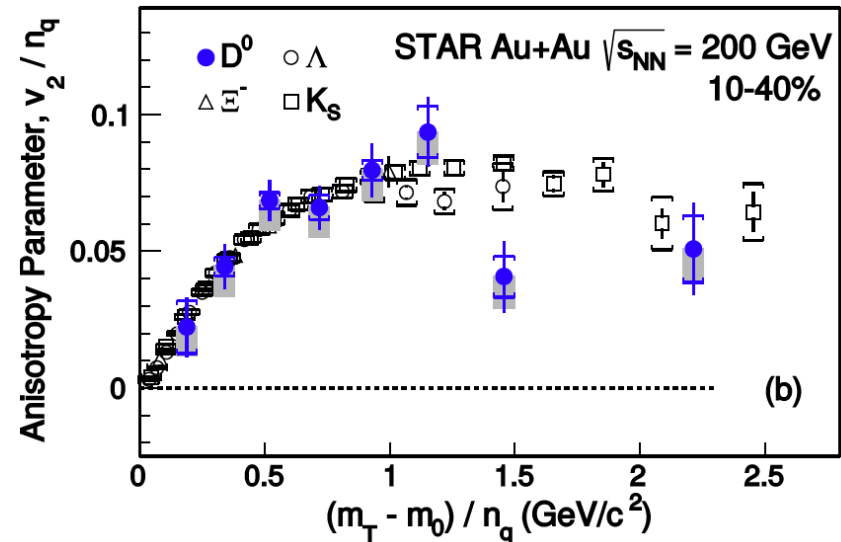


$$\frac{dN}{d\phi} = N_0 \left(1 + \sum_n 2v_n \cos[n(\phi - \psi_n)] \right)$$

- Significantly above zero for $p_T > 1.5$ GeV/c



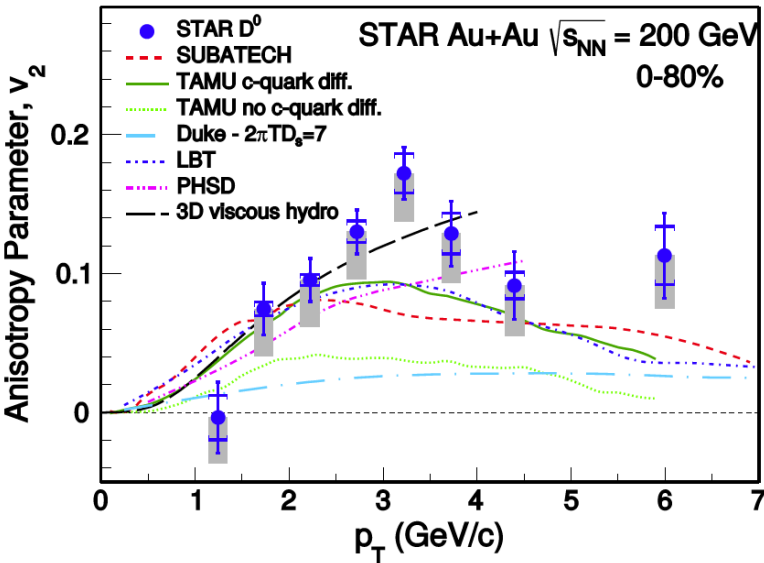
- D⁰ v_2 exhibits same NCQ scaling as light hadrons



[STAR: PRC 77 (2008) 54901, PRL 116 (2016) 62301, PRL 118 (2017) 212301]

- Charm quarks flow with the medium
- Follow NCQ scaling of other hadrons
→ Evidence for thermalization of charm quarks

Comparison of v_2 to theoretical predictions

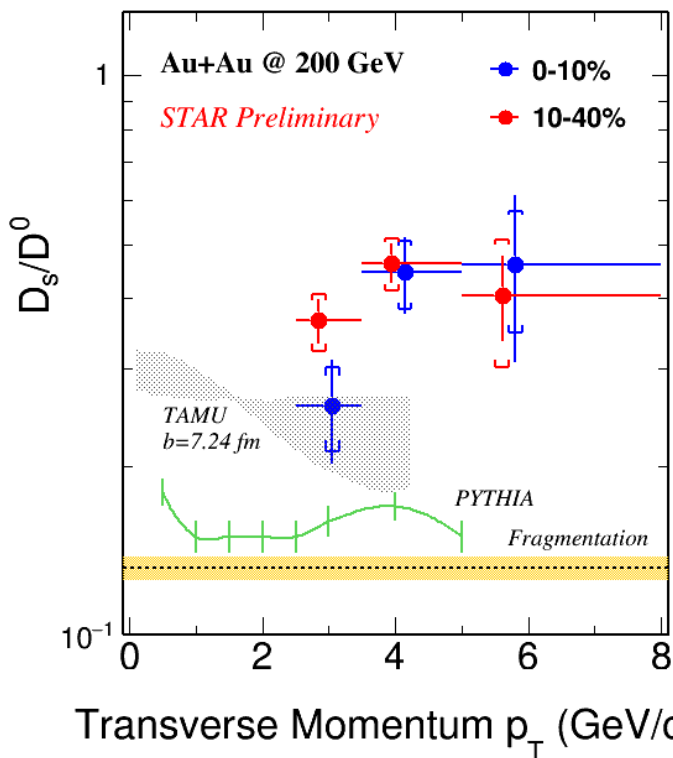


[Theory:
 TAMU: Eur. Phys. J. C (2016) 76: 107 & private comm.;
 SUBATECH: PRC 91(2015) 054902 & private comm.;
 Duke: PRC 92(2015) 024907 & private comm.;
 PHSD: PRC 90, 051901 (2014), PRC 92, 014910 (2015);
 LBT: Phys. Rev. C 94, 014909 (2016);
 3D viscous hydro: PRC 86, 024911 (2012), PRD 91, 074027 (2015)
 & private comm.]
 [STAR: PRL 118, 212301 (2017)]

TAMU model with no charm quark diffusion and Duke model and are inconsistent with data

- 3D viscous hydro, tuned to light hadrons
 - Charm quarks have achieved thermal equilibrium
- D_s spatial diffusion coefficient from models
- Linearized Boltzmann Transport
 - Jet transport model extended to heavy quarks
 - $(2\pi T)D_s = 3 - 6$
- Duke: Langevin simulation with transport properties tuned to LHC data
 - $(2\pi T)D_s = 7$
- Parton-Hadron-String Dynamics : effective potential of c-quarks:
 - $(2\pi T)D_s = 5 - 12$
- TAMU: non-perturbative T-matrix approach:
 - $(2\pi T)D_s = 5 - 12$
- SUBATECH: pQCD + hard thermal loops for resummation:
 - $(2\pi T)D_s = 2 - 4$
- **Together: $(2\pi T)D_s = \sim 2 - 12$**

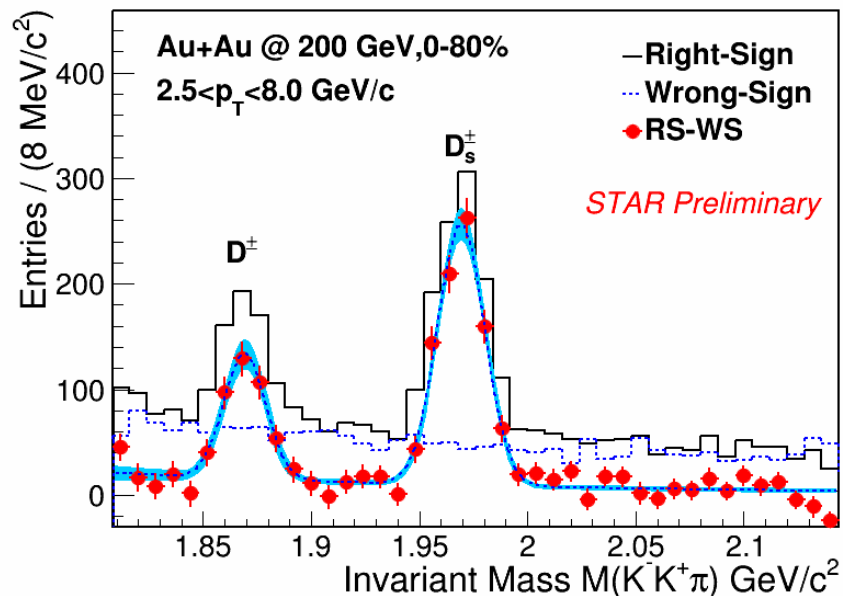
D_s/D^0 yield ratio



[TAMU: PRL 110 (2013) 112301]

[H1 Collaboration, Eur.Phys.J.C38(2005)447]

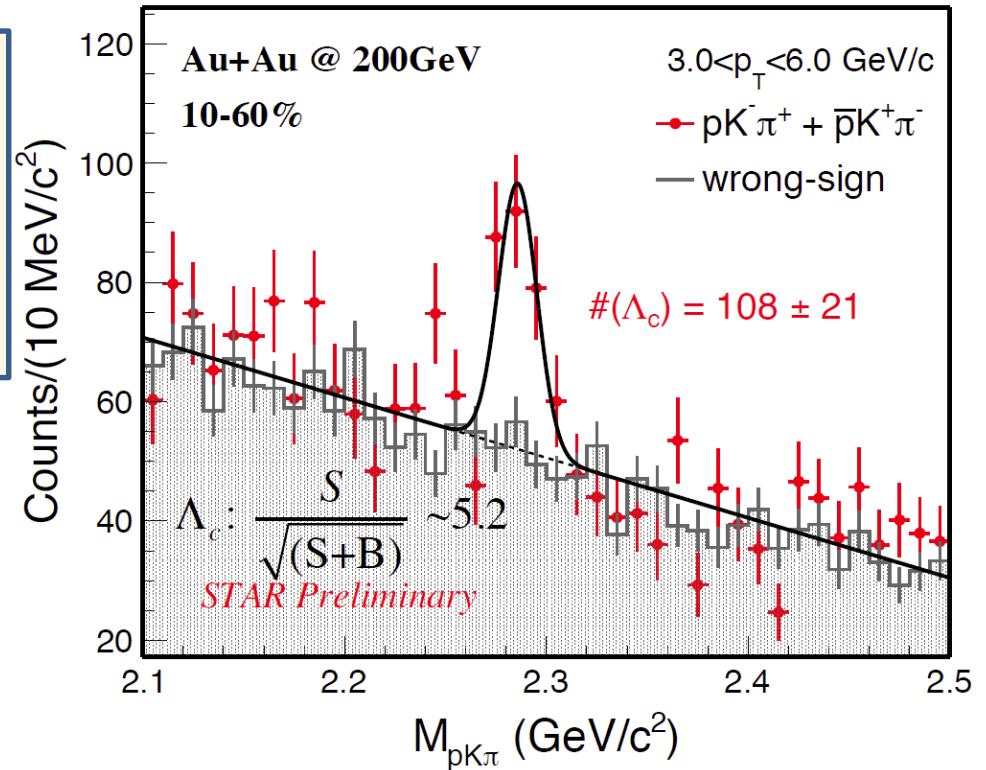
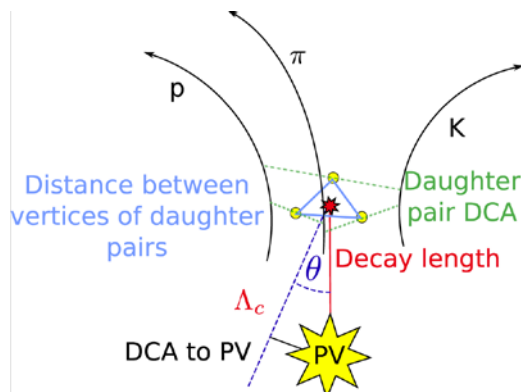
[ZEUS Collaboration, Eur.Phys.J.C44(2005)351]



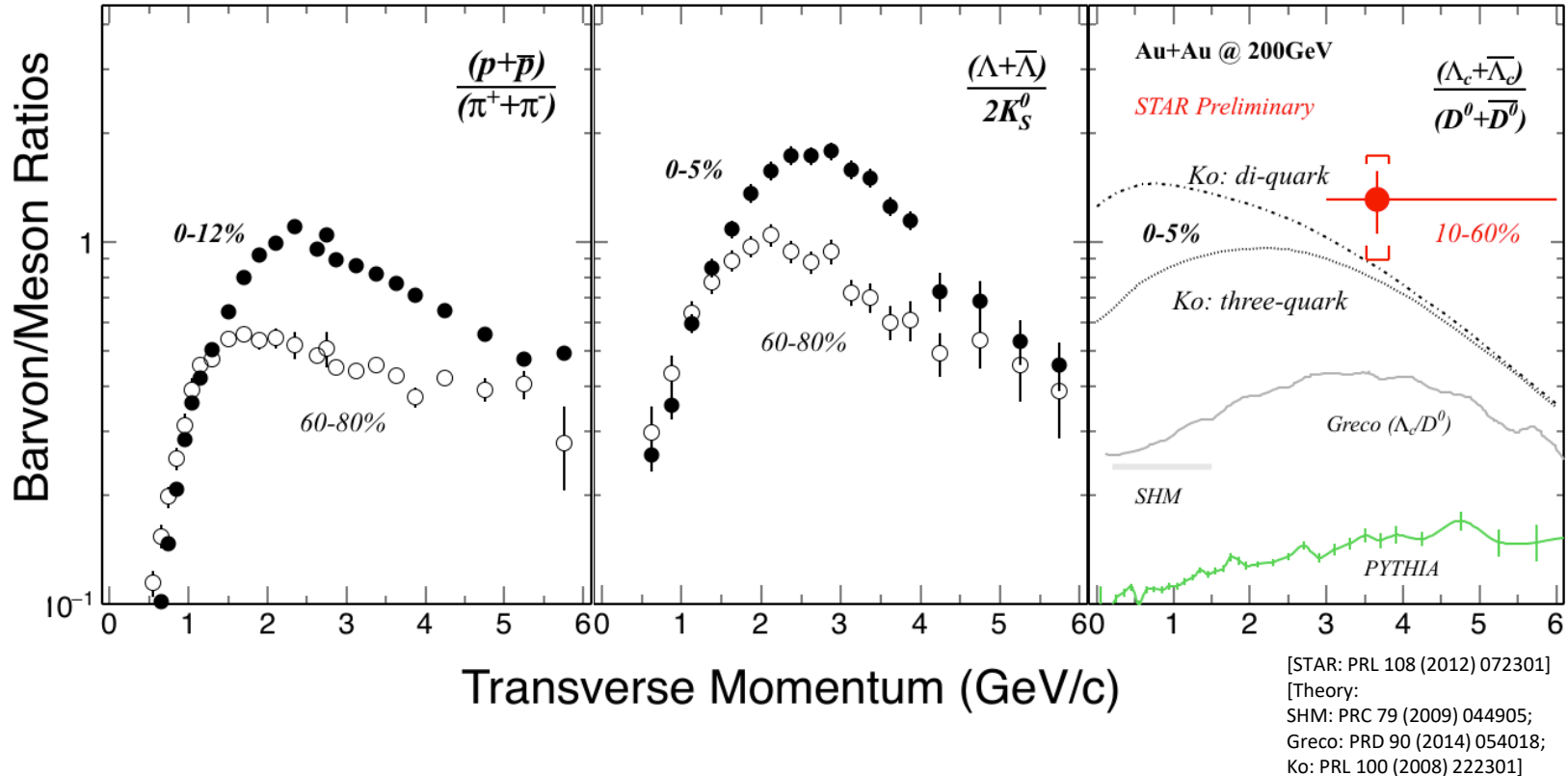
- **Observed strong enhancement of the D_s/D^0 ratio**, compared to:
 - Fragmentation ratio measured at HERA
 - PYTHIA version 6.4
- Enhancement in 10–40 % centrality is stronger than the TAMU model calculation with charm quark coalescence

Λ_c baryon

- $\Lambda_c^\pm \rightarrow p^\pm K^\mp \pi^\pm$ BR = 5 %
- $c\tau \sim 60 \mu\text{m}$
- First measurement of charmed baryons in high-energy heavy-ion collisions



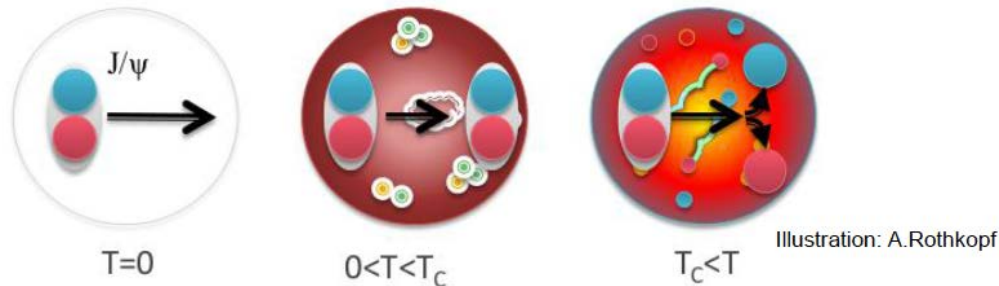
Λ_c/D^0 yield ratio



- Clear enhancement observed compared to PYTHIA
- Compatible with baryon-to-meson ratios of light hadrons
- Ko model describes the data for both di-quark + 1 quark, and three-quark coalescence scenarios
- The Greco model underpredicts the data; recent calculation shows better agreement
- SHM prediction is lower than the data

Probe QGP with quarkonium

- **Color-screening**: quarkonium dissociates in the medium



J/ψ suppression was proposed as a direct proof of QGP formation

T. Matsui and H. Satz PLB 178 (1986) 416

- However, interpreting J/ψ suppression is no easy job!

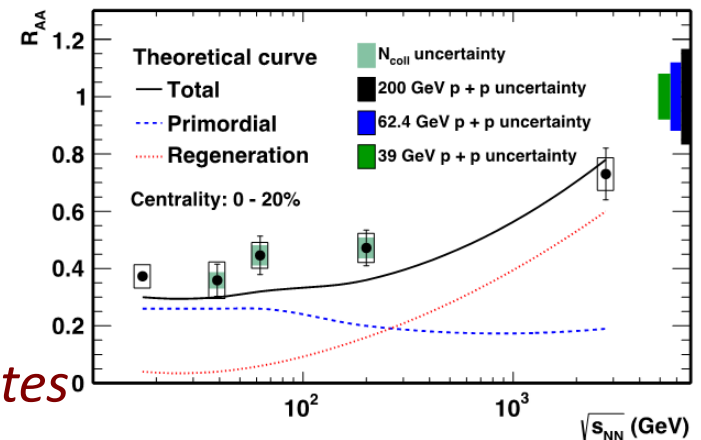
- *Hot nuclear matter effects*

- Dissociation
- Regeneration from uncorrelated quarks
- Medium-induced energy loss
- Formation time effects

- *Cold nuclear matter effects*

- *Feed-down of excited charmonium states and B-hadrons*

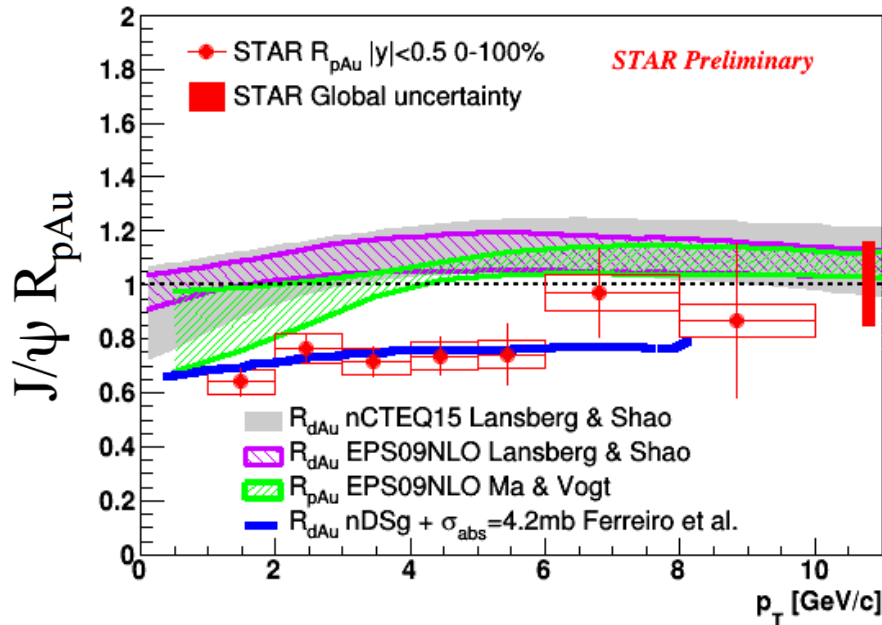
STAR Phys.Lett. B771 (2017) 13-20



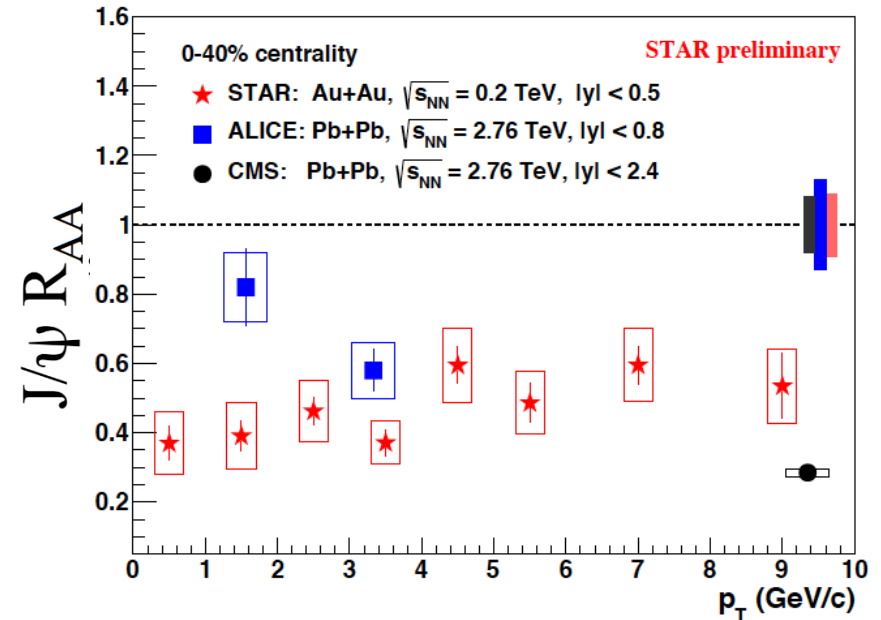
Charmonium production at RHIC

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
 Ferreriro et al., Few Body Syst. 53 (2012) 27

p+Au



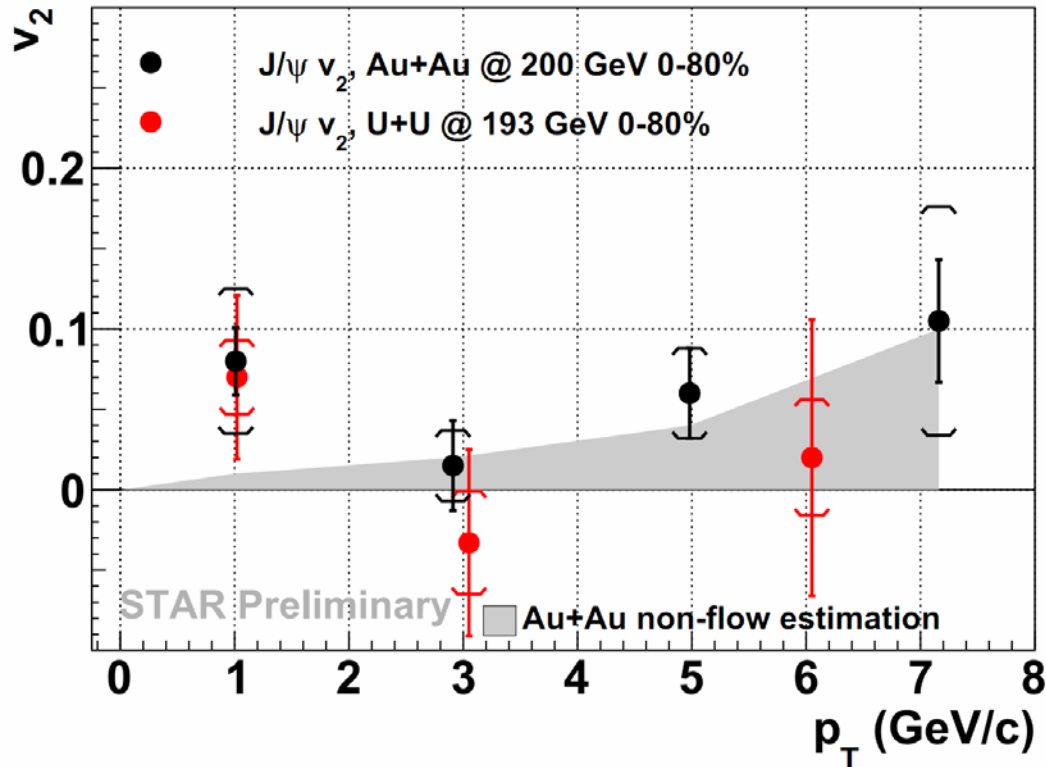
Au+Au



- R_{pAu} favors additional nuclear absorption effect on top of nPDF effects
- R_{AuAu} low p_T : more J/ ψ suppression than at the LHC
 → smaller regeneration due to lower charm cross section
- R_{AuAu} high p_T : less suppression than at the LHC
 → less dissociation due to lower medium temperature

Does J/ψ flow?

- Measure elliptic flow v_2
 - **Primordial** J/ψ : little or zero v_2
 - **Regenerated** J/ψ : inherit v_2 from the constituent charm quarks

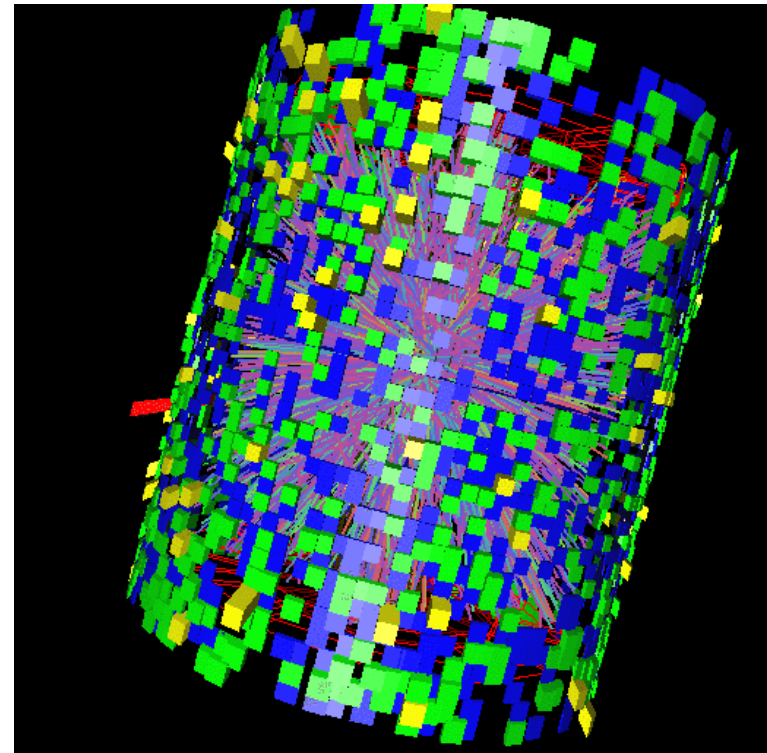


- The value of v_2 from 200 GeV Au+Au and from 193 GeV U+U collisions are consistent with zero within uncertainties for p_T above 2 GeV/c.
 - Disfavor the scenario that the regeneration is the dominant contribution in this kinematic range

Upsilon measurements

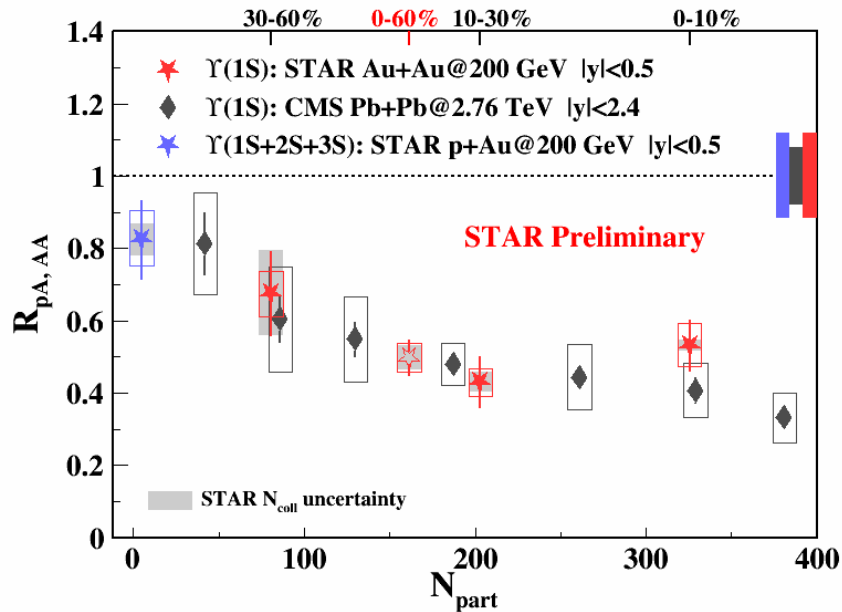
Υ -cleaner probe compared to J/ψ

- Co-mover absorption \rightarrow negligible
 - $\Upsilon(1S)$: tightly bound, larger kinematic threshold.
 - Expect $\sigma \sim 0.2$ mb, 5-10 times smaller than for J/ψ
Lin & Ko, PLB 503 (2001) 104
- Recombination \rightarrow negligible
 - at RHIC: $\sigma_{cc} \sim 800 \mu\text{b} \gg \sigma_{bb} \sim (1-2) \mu\text{b}$
- Excited states: expect sequential suppression of $\Upsilon(1S)$, $\Upsilon(2S)$, $\Upsilon(3S)$ states
- Challenge: low rate, rare probe
 - Need large acceptance; efficient trigger
 - MTD adds dimuon channel

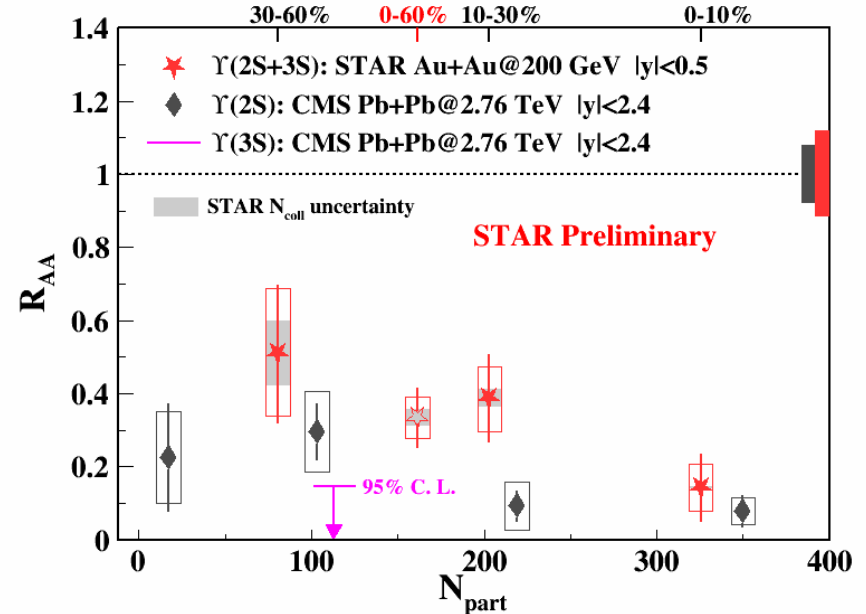


Upsilon nuclear modification factor

$\Upsilon(1S), \Upsilon(1S+2S+3S)$



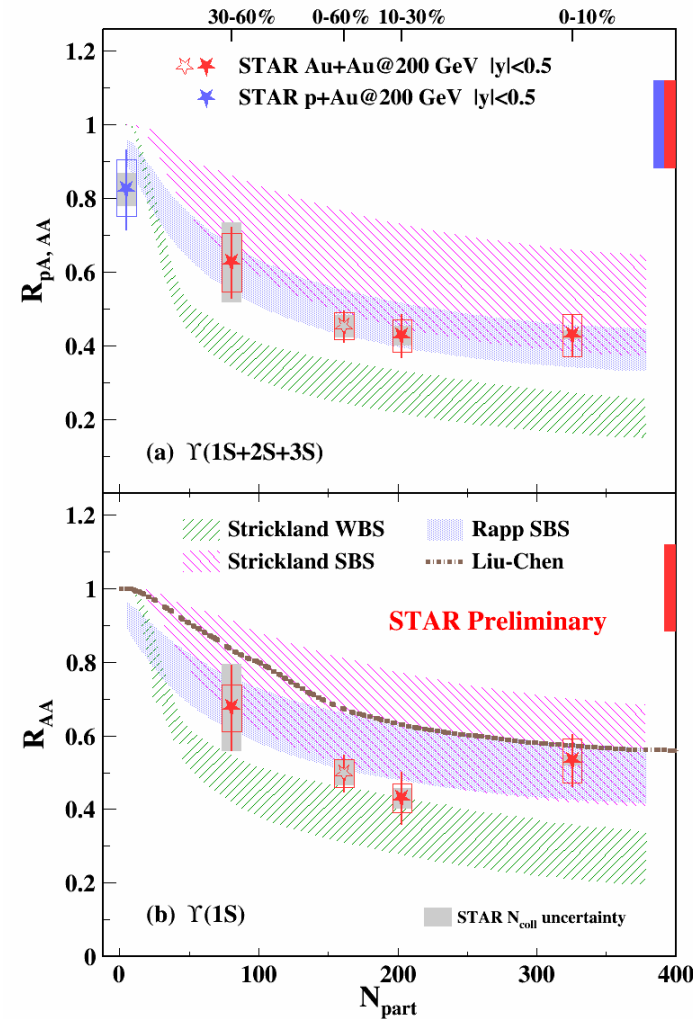
$\Upsilon(2S+3S)$



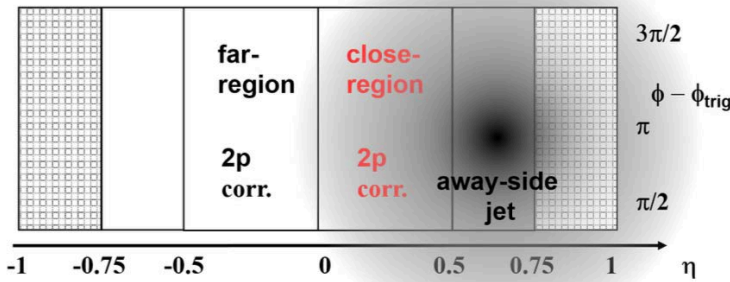
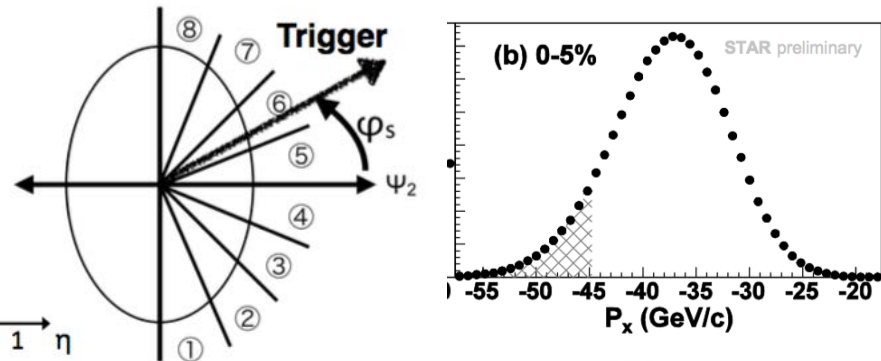
- $\Upsilon(1S+2S+3S) R_{pA}$: indication of sizable CNM effects
- $\Upsilon(1S) R_{AuAu}$: indication for more suppression towards central collisions
 - Compatible with LHC
- $\Upsilon(2S+3S) R_{AuAu}$:
 - More suppression in central collisions than $\Upsilon(1S)$
 - **sequential melting**
 - Indication for less suppression than at the LHC

Models vs. data

- Strickland, Bazov : *NPA 879 (2012) 25*
 - No CNM, no regeneration
 - SBS (Strongly Binding Scenario): fast dissociation—potential based on internal energy
 - WBS (Weakly Binding Scenario): slow dissociation—potential based on free energy
 - Liu, Chen, Xu, Zhang : *PLB 697 (2011) 32*
 - No CNM
 - Dissociation only for excited states, suppression of ground state due to feed-down
 - Emerick, Zhao, Rapp : *EPJ A48 (2012) 72*
 - Includes CNM, SBS case
- SBS models favoured by the data

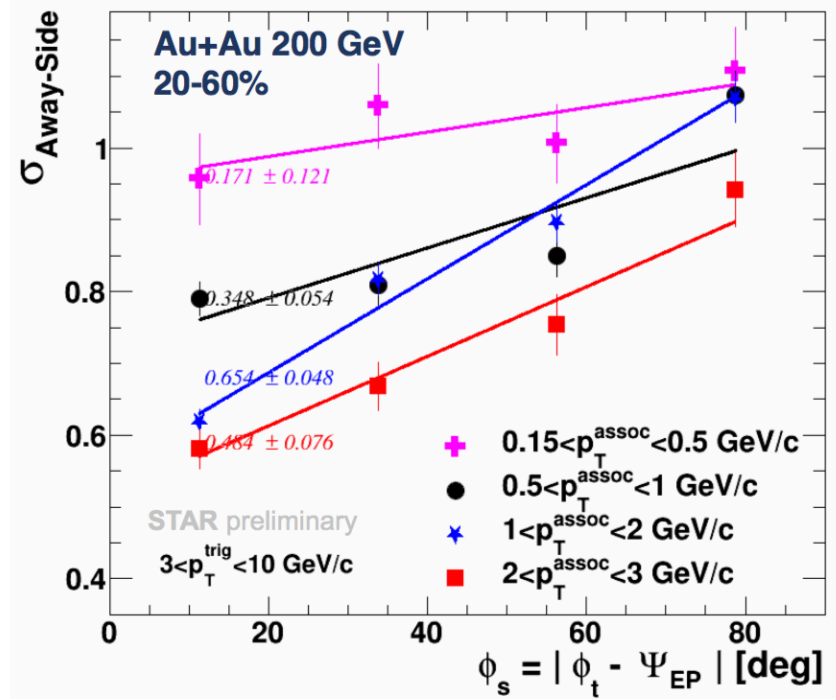


Event Plane Dependent Recoil Width



Cartoon: methodology for EP-dependent two-particle correlations.

away-side peak of two particle correlations

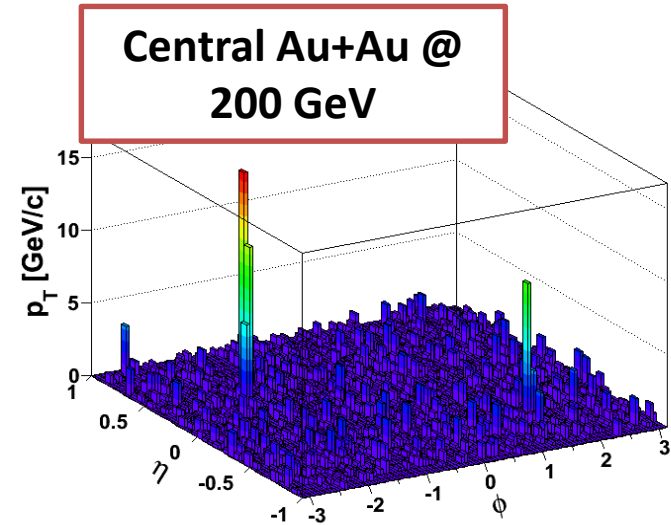
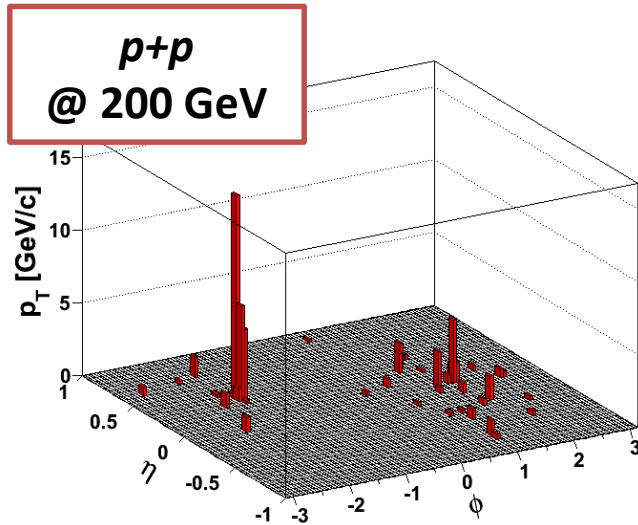


in-plane \rightarrow out-of-plane

- Robust flow subtraction on away-side
- Broadening for particles emitted from in-plane \rightarrow out-of-plane
- Consistent with in-medium path-length dependence

Further studies needed to rule out possible auto-correlation between jet and EP

Jets in Heavy Ions



$p+p$

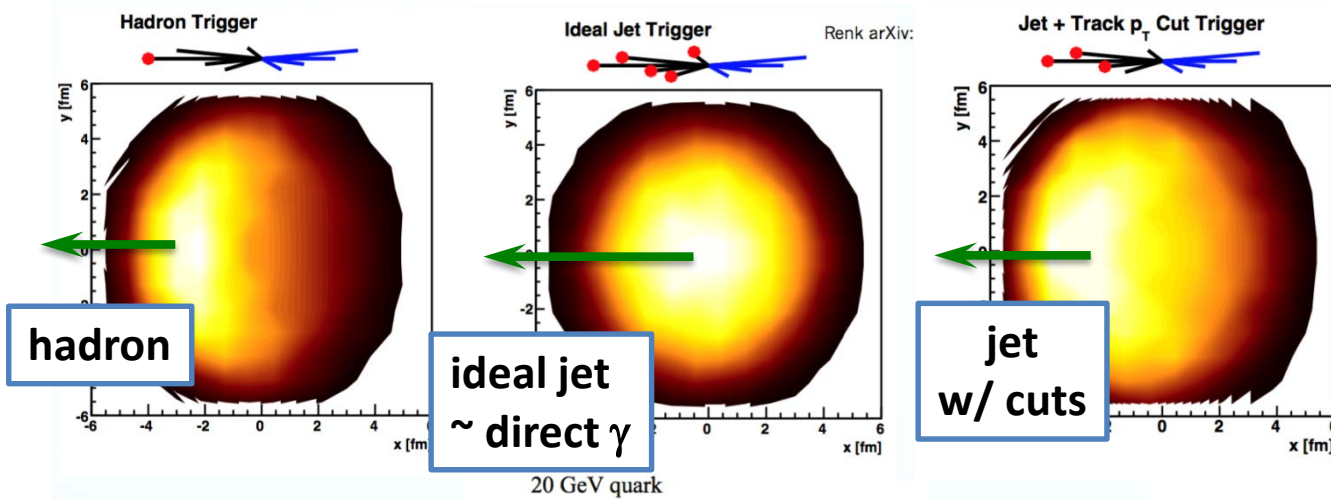
- Anti- k_T
- Resolution parameter R up to 0.6
- No background subtraction
- Many STAR results using inclusive and di-jets: gluon polarization, fragmentation, TMDs ...

Au+Au

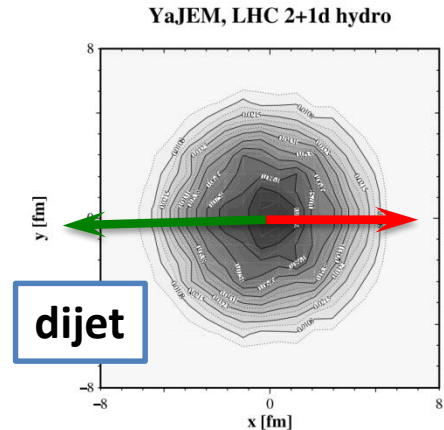
- Anti- k_T
- $R = 0.2, 0.3, 0.4, 0.5$
- Pedestal subtracted with area method (ρ from k_T)
- Additional cuts and techniques used to handle background

Au+Au: Geometries and Strategies

STAR



LHC Dijets



Selecting a hard scatter:

- High- p_T hadron
- High- p_T direct photon
- Jet, with cuts
- LHC: Geometry \sim unaffected

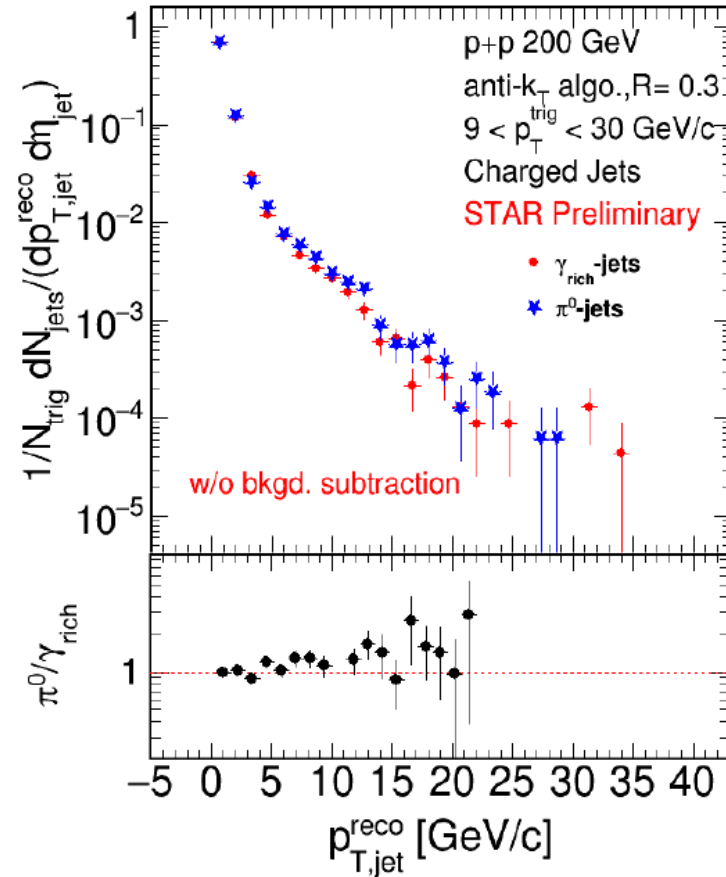
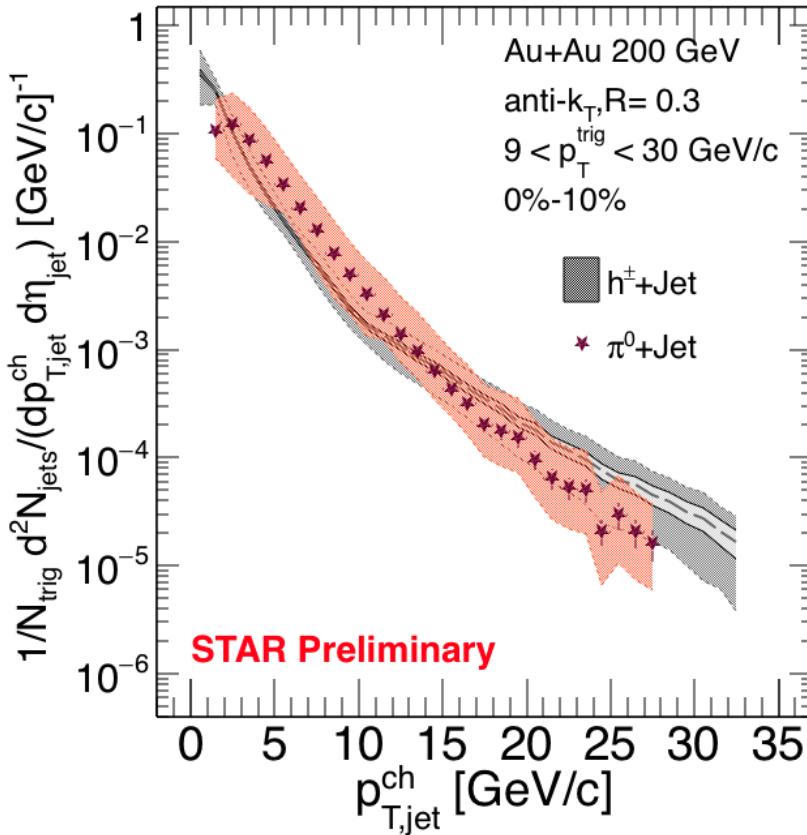
Analyze the recoil

- Correlation
- Semi-inclusive jets
→ maximum path length
- Jet, with cuts
→ shorter path length?

YaJEM: *T. Renk arXiv:1212.0646*,
PRC 85, 064908 (2012), *PRC 87, 024905 (2013)*

h/ γ -Triggered Recoil Jets

h-jet: Phys. Rev. C 96, 024905



- π^0 and $h^{+/-}$ triggered recoil jets are in agreement in central Au+Au
- Modest difference observed between π^0 and γ triggers for p+p
→ A+A measurement on the way

Di-Jet Imbalance

A_J : Phys. Rev. Lett. 119, 062301

Charged + neutral constituents

“Hard Core:”

High Tower (HT) trigger $E_T > 5.4$ GeV

$p_T^{\text{Cut}} = 2$ GeV/c

→ Reduce BG

→ Reduce combinatorial jets

Di-jet Selection:

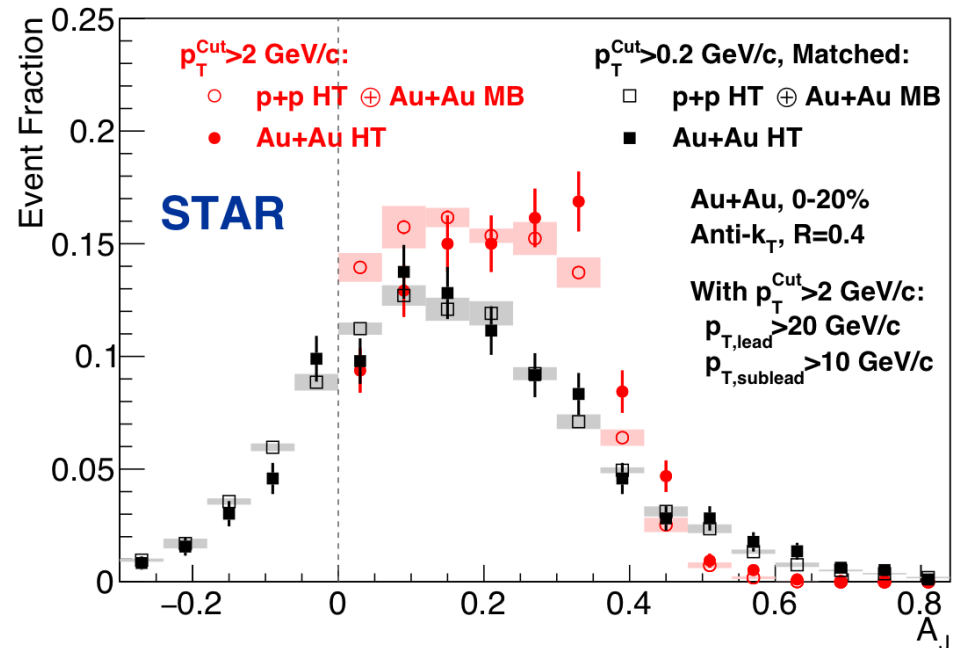
Jet $p_T^{\text{Lead}} > 20$ GeV/c

Jet $p_T^{\text{SubLead}} > 10$ GeV/c

$|\Delta\phi - \pi| < 0.4$

Recover soft component:

match to $p_T^{\text{Cut}} = 0.2$ GeV/c



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

- Au+Au di-jets more imbalanced than p+p for “hard core” selection
- p+p balance recovered for matched di-jets (for $R=0.4$, not $R=0.2$!)
→ Investigate redistribution on individual jets

Dijet-Hadron Correlations

Updated Hard Core selection:

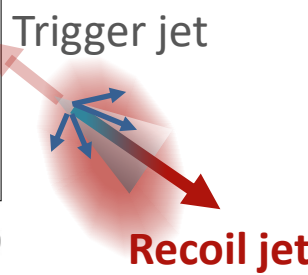
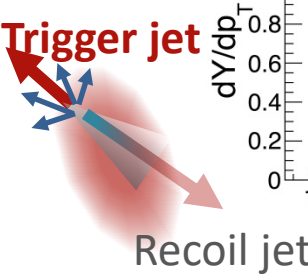
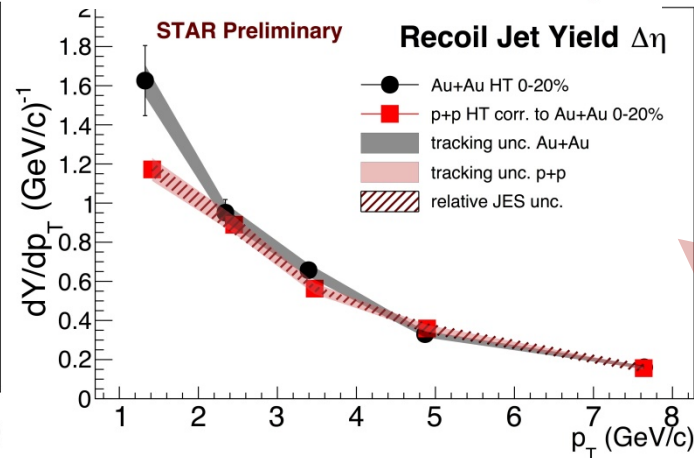
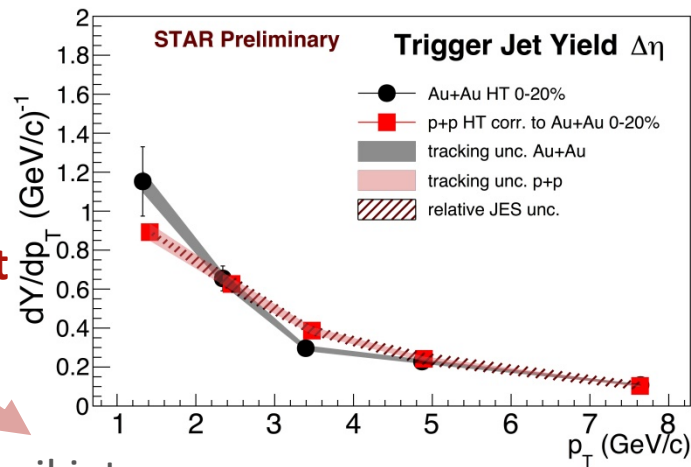
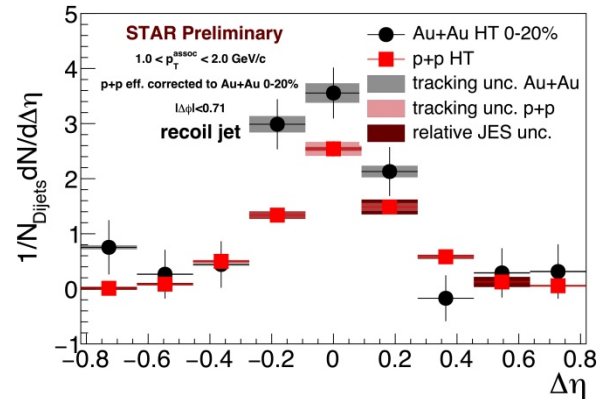
$$p_{T}^{\text{Cut}} = 2 \text{ GeV}/c$$

$$\text{Jet } p_{T}^{\text{Lead}} > 20 \text{ GeV}/c$$

$$\text{Jet } p_{T}^{\text{SubLead}} > 10 \text{ GeV}/c$$

$$|\Delta\phi - \pi| < 0.4$$

Trigger Jet contains HT with $E_T > 6 \text{ GeV}$



- No modification relative to p+p on the trigger side → Surface Bias
- Hints of excess soft yield on the recoil side
- Expect presence of balanced jets (no A_j cut) diluting measurement

Shared momentum fraction

$$z_g = \frac{\min(p_{T1}, p_{T2})}{p_{T1} + p_{T2}}$$

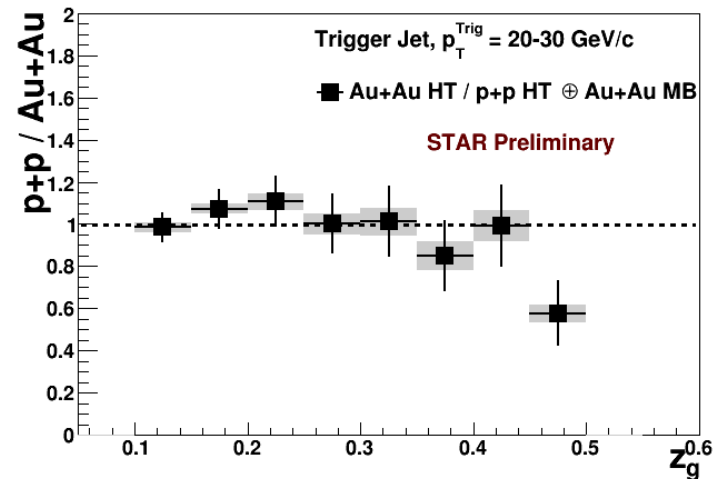
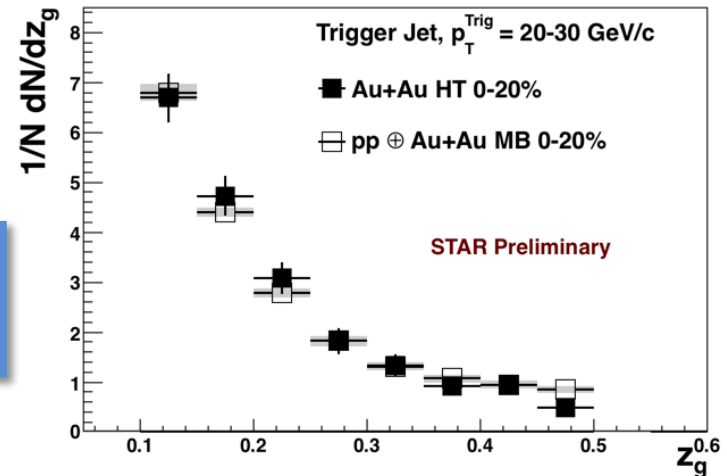
Di-jet Selection:

- Jet $p_T^{\text{Trig}} > 20$ GeV/c
- Jet $p_T^{\text{Recoil}} > 10$ GeV/c
- $|\Delta\phi - \pi| < 0.4$

$p_T^{\text{Trig,Recoil}}$: Calculated with $p_{T,\text{cut}} > 2$ GeV/c
 z_g : on matched jets with $p_{T,\text{cut}} > 0.2$ GeV/c

Hard core di-jets:

- As measured with z_g :
 No significant splitting modification on near- or away-side
- Discussion with theory ongoing!



Summary

Heavy flavor

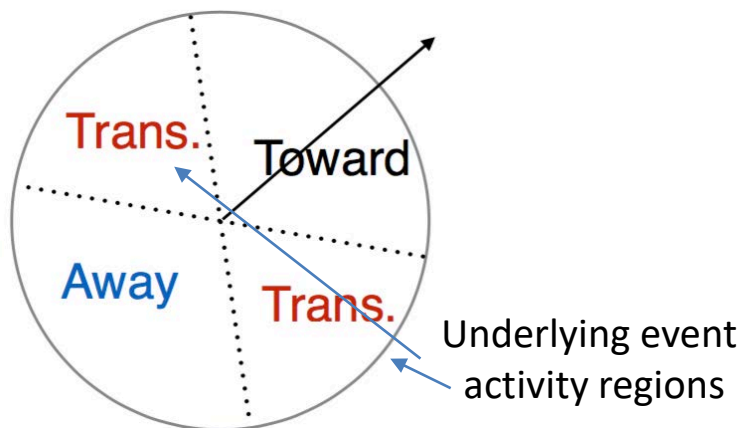
- Successful data taking with MTD and HFT
- D^0 R_{AA} and v_2 in Au+Au collisions:
 - Indicate strong charm-medium interactions
 - Favors model calculations with charm quark diffusion
- B measurements consistent with mass hierarchy of the parton energy loss
- Λ_c/D^0 ratio is compatible with baryon-to-meson ratios of light hadrons
 - Coalescence plays an important role in charm quark hadronization
- J/ψ R_{AA} in Au+Au collisions: high p_T J/ψ is strongly suppressed at RHIC
 - Strong evidence for QGP formation
- Upsilon in Au+Au collisions: stronger suppression of $\Upsilon(2S+3S)$ than $\Upsilon(1S)$
 - Signature of sequential melting

Jets

- Event plane and shape dependence of energy loss under investigation
- Full jet/hadron – jet/dijet measurements become quantitative
 - “Lost” energy contained within $R=0.4$
 - No modification of jet splitting (z_g) observed

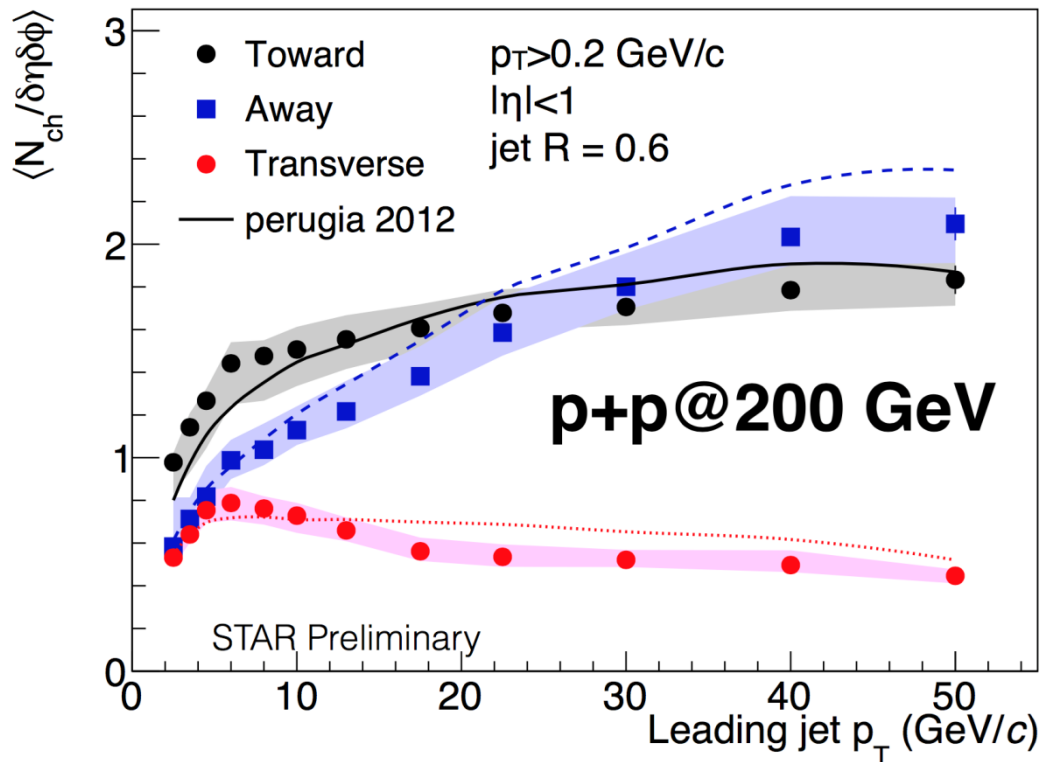
Underlying Event Activity in p+p

Leading jet ϕ angle



Jet reconstruction:

- Resolution Parameter $R=0.6$
- Found with anti- k_T
- No background subtraction
- charged+neutral constituents with $p_T > 0.2 \text{ GeV}/c$



- Particle production not directly from the final fragmentation of hard-scattered partons : ISR/FSR, Multi-Parton interaction, Color reconnection with beam remnants...
- Transverse charged particle multiplicity slightly decreases for higher leading jet p_T
- PYTHIA Perugia 2012 over-predicts transverse charged multiplicity by 25% +/- 15%