Open heavy-flavor and quarkonia production in STAR

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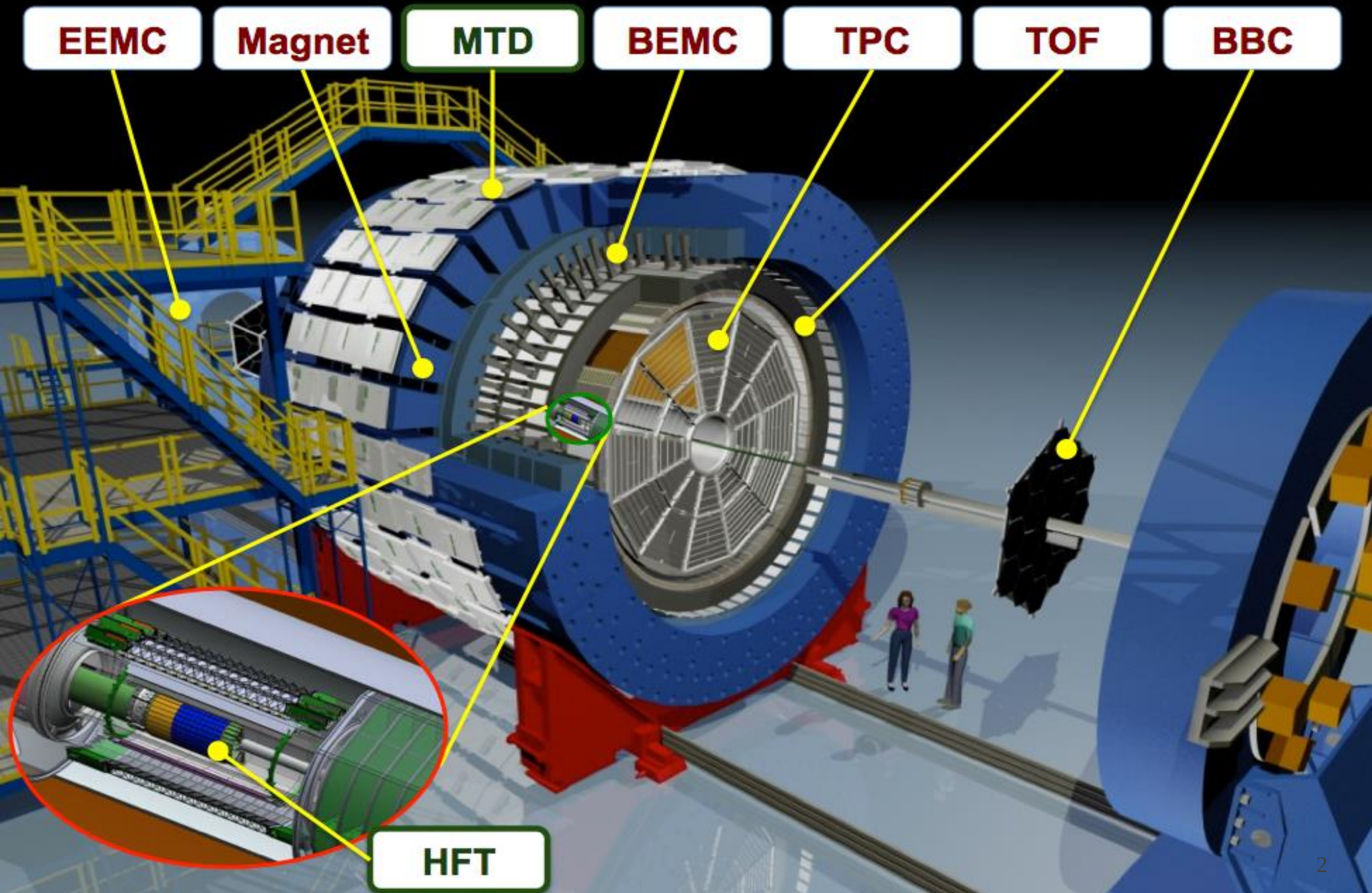
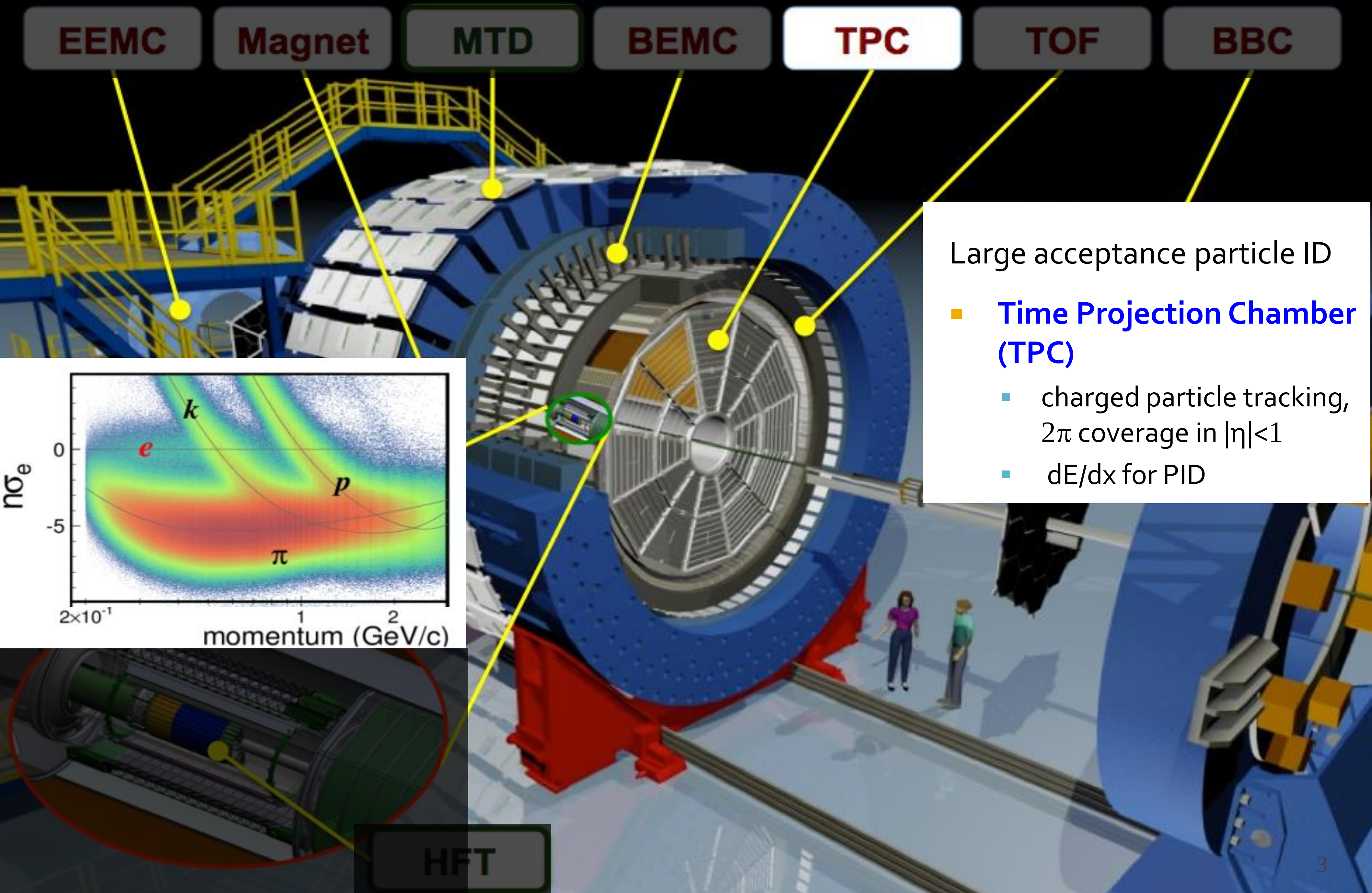
for the STAR collaboration

Czech Technical University
in Prague

STAR experiment



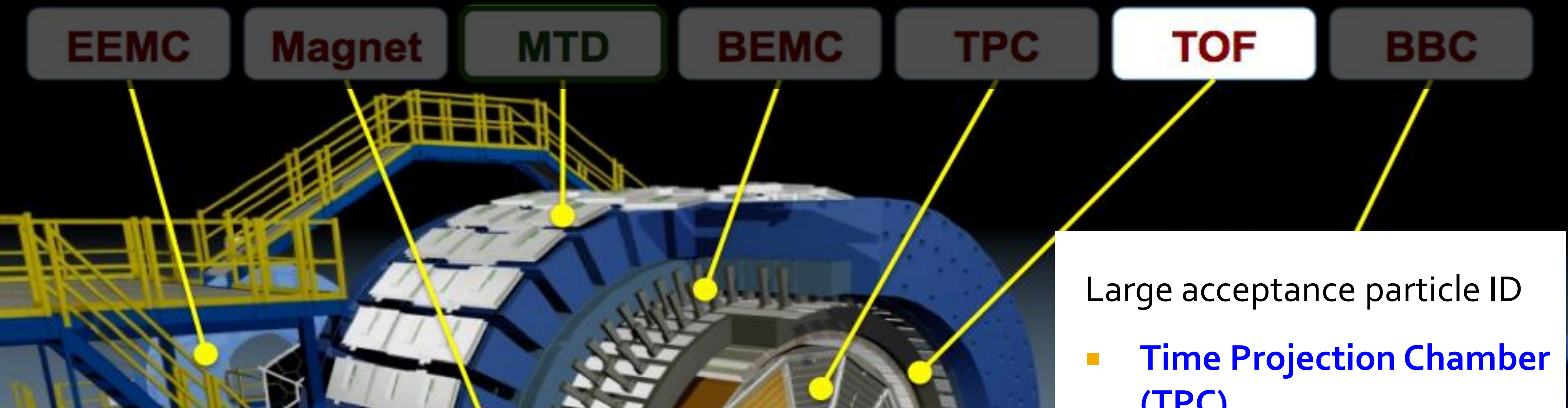
Particle identification at STAR

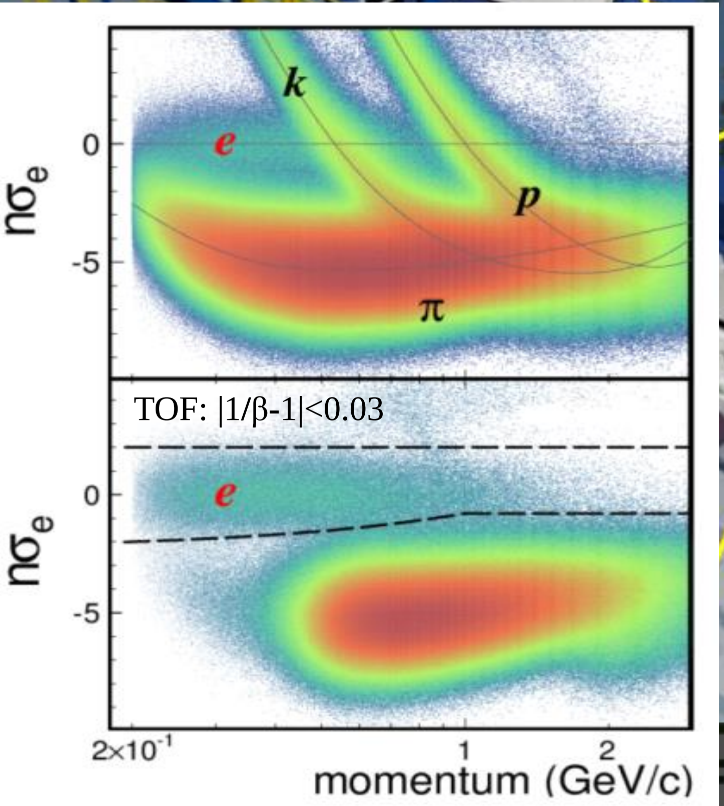


Large acceptance particle ID

- **Time Projection Chamber (TPC)**
  - charged particle tracking, 2π coverage in $|\eta|<1$
  - dE/dx for PID

Particle identification at STAR

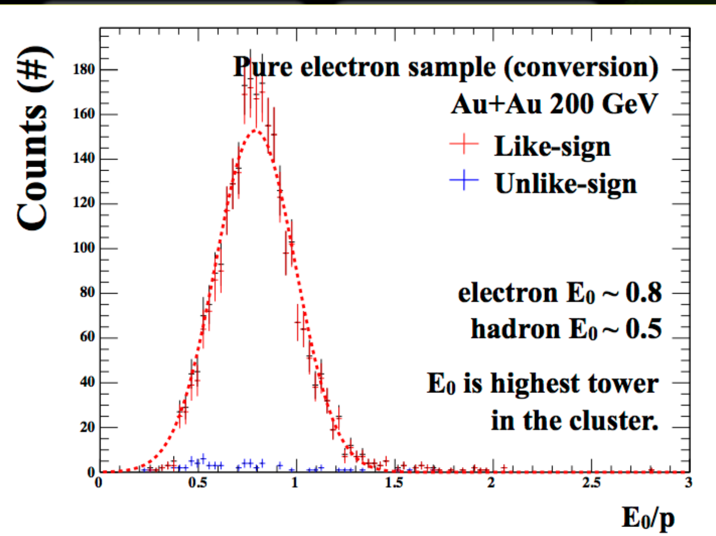


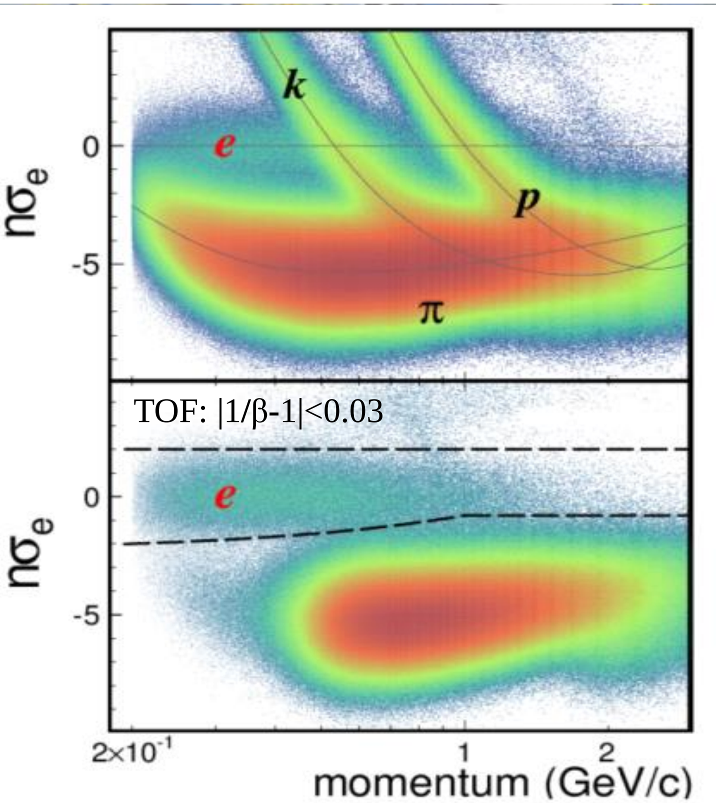


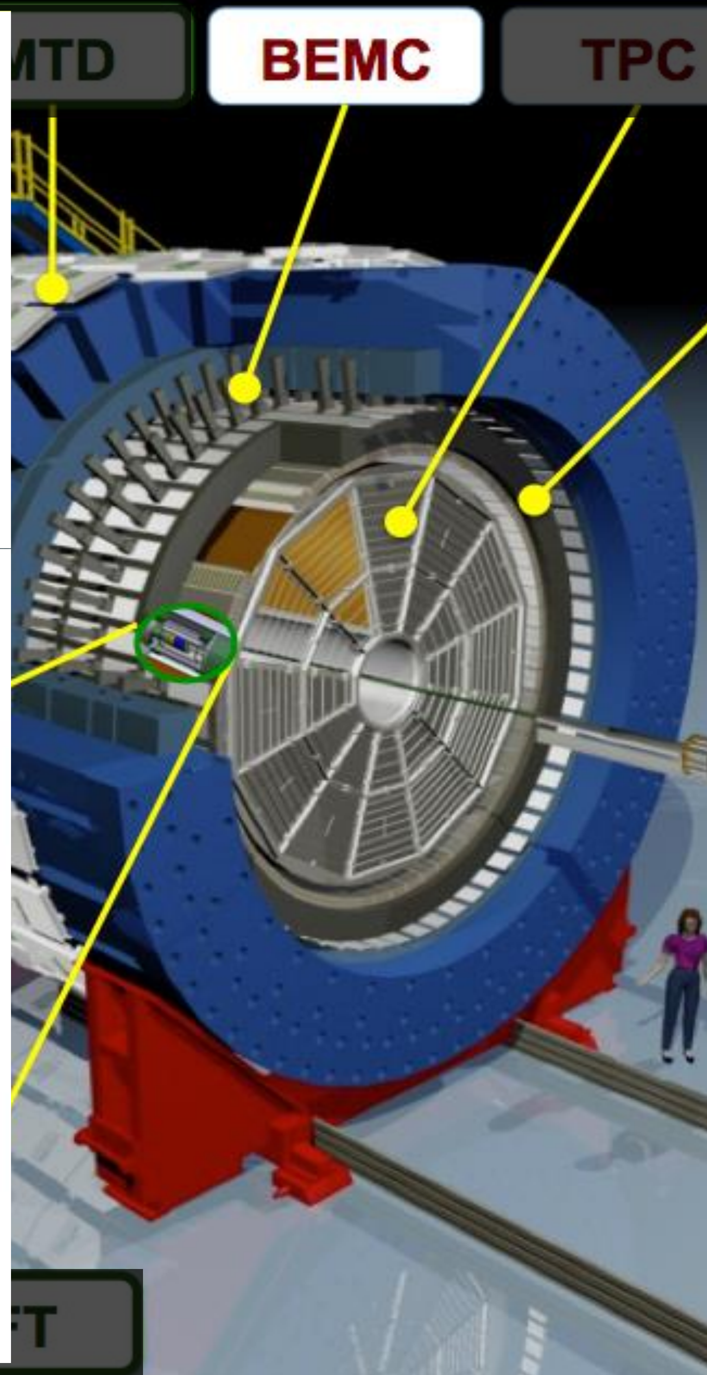
Large acceptance particle ID

- **Time Projection Chamber (TPC)**
  - charged particle tracking, 2π coverage in $|\eta|<1$
  - dE/dx for PID
- **Time Of Flight (TOF)**
  - Timing resolution <100 ps
  - $1/\beta$ for PID

Particle identification at STAR



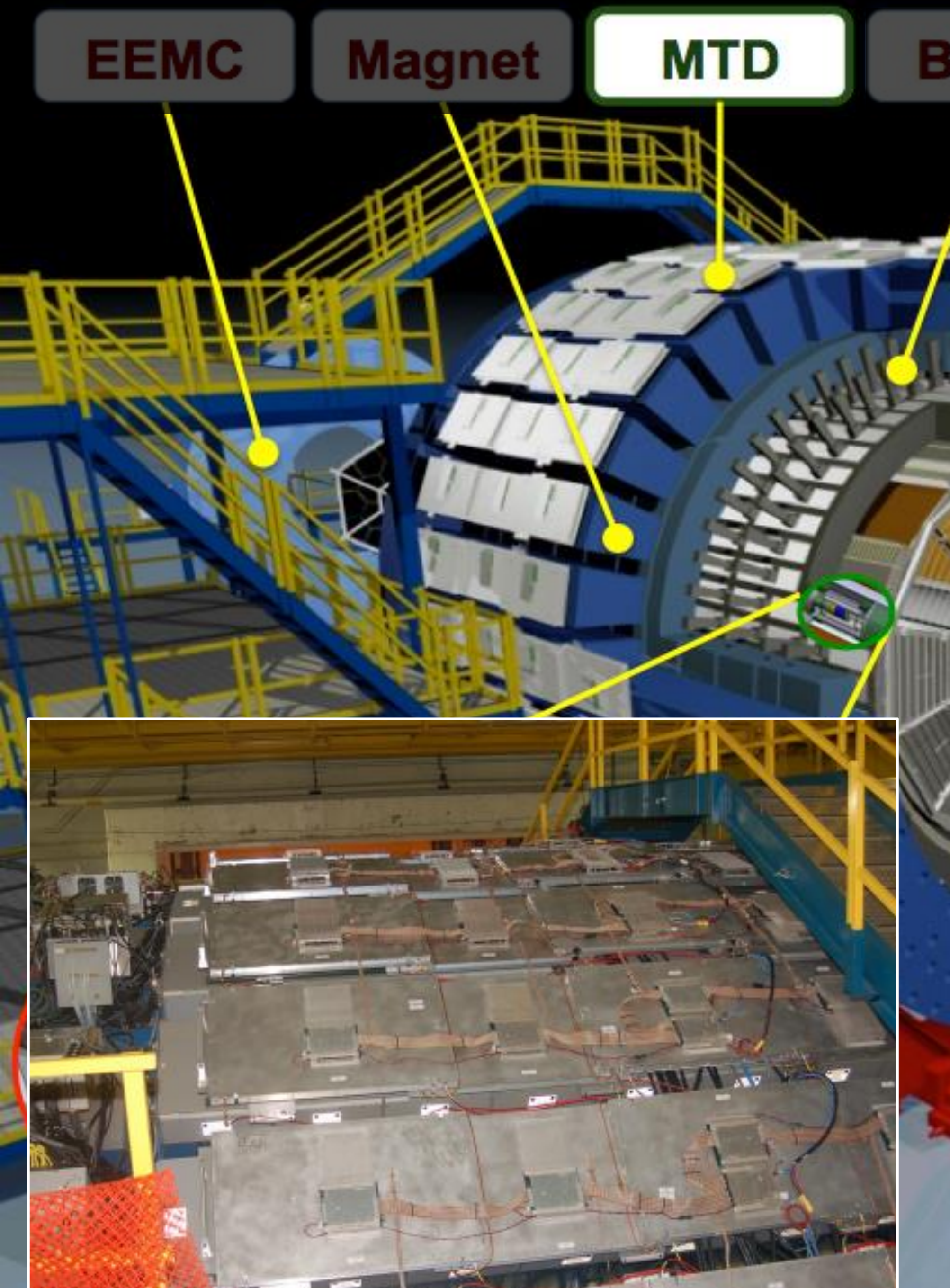




Large acceptance particle ID

- **Time Projection Chamber (TPC)**
  - charged particle tracking, 2π coverage in $|\eta|<1$
  - dE/dx for PID
- **Time Of Flight (TOF)**
  - Timing resolution <100 ps
  - $1/\beta$ for PID
- **EM Calorimeter**
  - 2π coverage in $|\eta|<1$
  - Electron ID via E/p ~ 1
  - Triggering capability

Muon telescope detector (MTD)



$J/\psi \rightarrow \mu^+\mu^-$ (B.R. 5.9%)

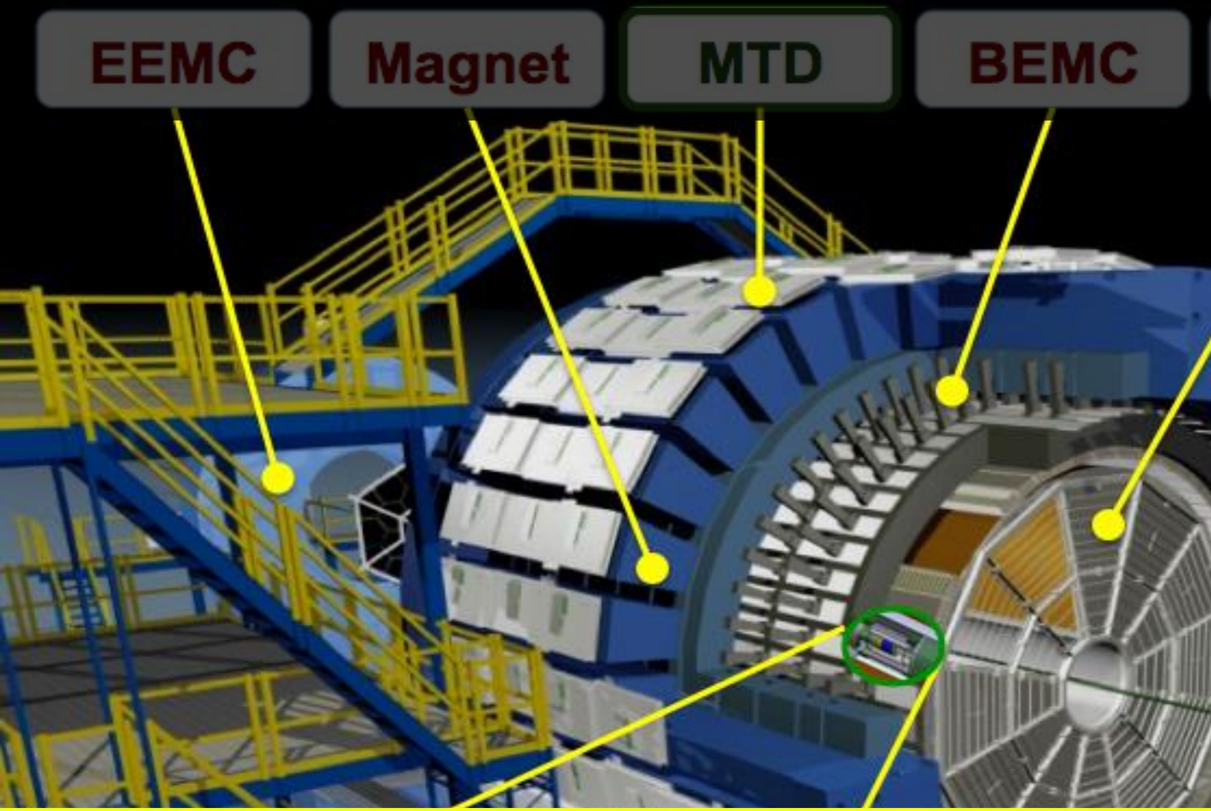
$\Upsilon \rightarrow \mu^+\mu^-$ (B.R. 2.5%)

- Multi-gap Resistive Plate Chamber (MRPC) technology
  - Precise timing < 100 ps
  - Accurate hit position ~ 1 cm (intrinsic)
- **Dimuon trigger** improves low p_T J/ψ measurement precision

Luminosity sampled by the dimuon trigger:

2013 p+p 500 GeV	**~ 28.3 pb^{-1}**
2014 Au+Au 200 GeV	**~ 14.2 nb^{-1}**
2015 p+p 200 GeV	**~ 122 pb^{-1}**
2015 p+Au 200 GeV	**~ 409 nb^{-1}**
2016 d+Au 200 GeV	**~ 94 nb^{-1}**
2016 Au+Au 200 GeV	**~12.8 nb^{-1}**

Heavy Flavor Tracker (HFT)

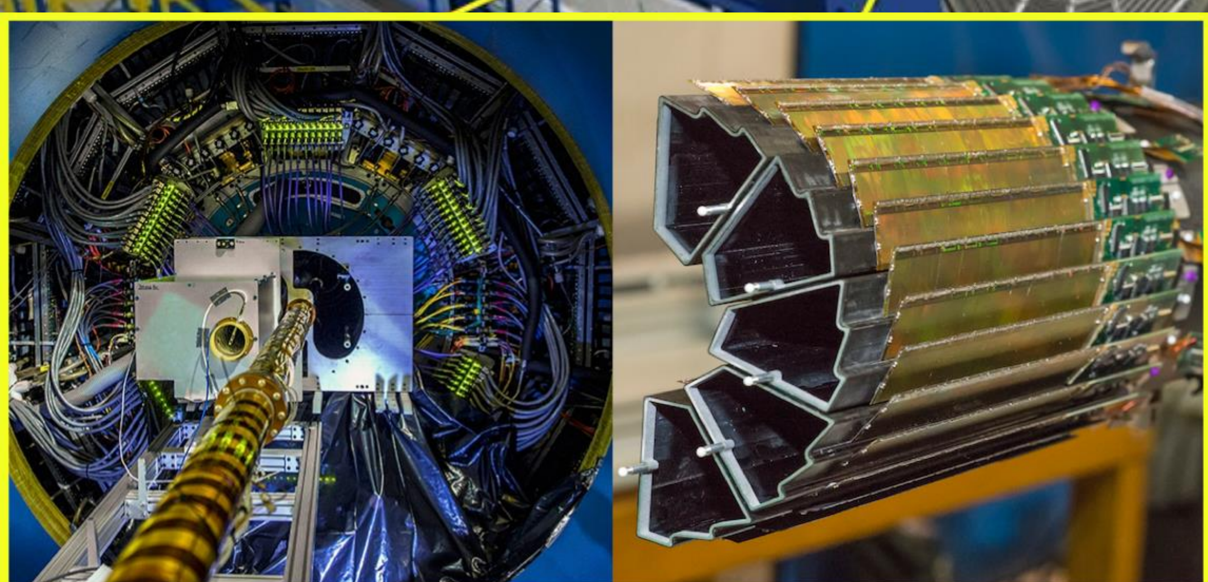


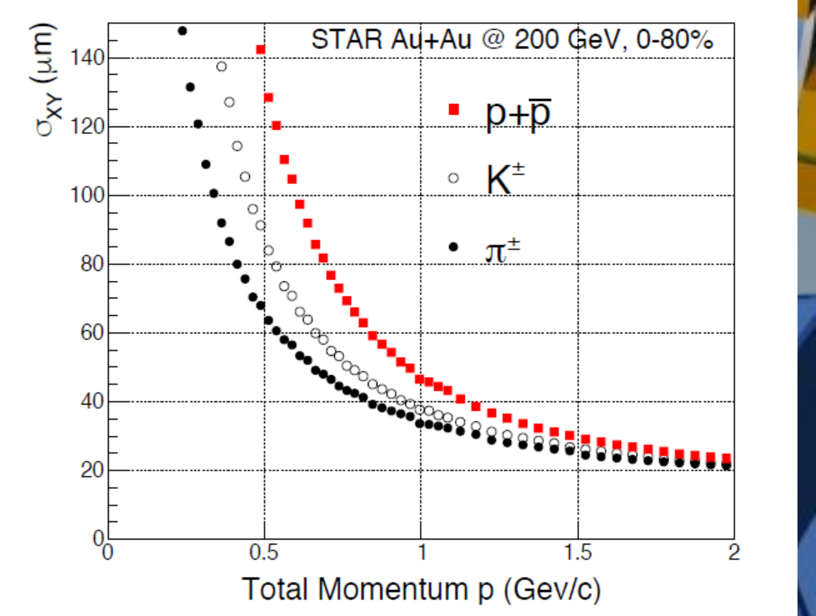
IST & SSD: Silicon pad/strip detectors

- Fast signals to remove pileup
- 14 cm and 22 cm from beam

PXL: 2 layers of silicon pixel (MAPS)

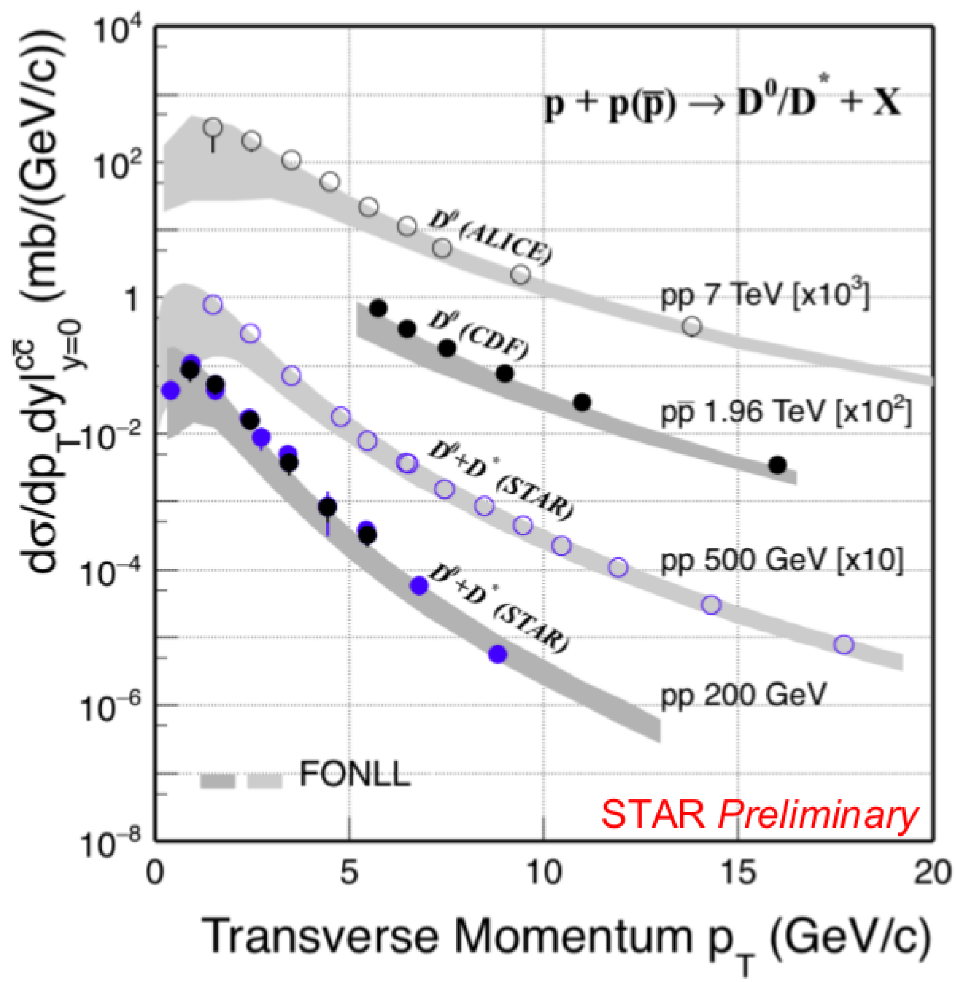
- Low material budget, 0.5% * X_0 (2014)
- Excellent resolution
- Pitch 20.7 µm x 20.7 µm
- 2.8 cm and 8 cm from beam





Open heavy flavor

- Produced early -> experience the entire evolution of the system
- Mass hierarchy:
  - Energy loss mechanisms: radiative vs. collisional
  - Thermalization in medium is mass dependent: Are charm and bottom quarks thermalized?
- Compare different charm hadron yields to study hadronization process



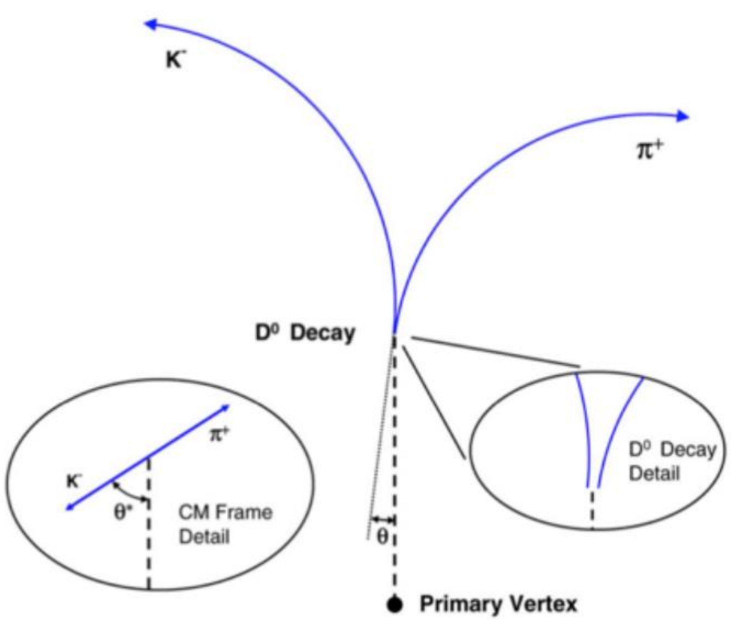
STAR: PRD 86 (2012) 072013, NPA 931 (2014) 520
CDF: PRL 91 (2003) 241804; ALICE: JHEP01 (2012) 128
FONLL: PRL 95 (2005) 122001

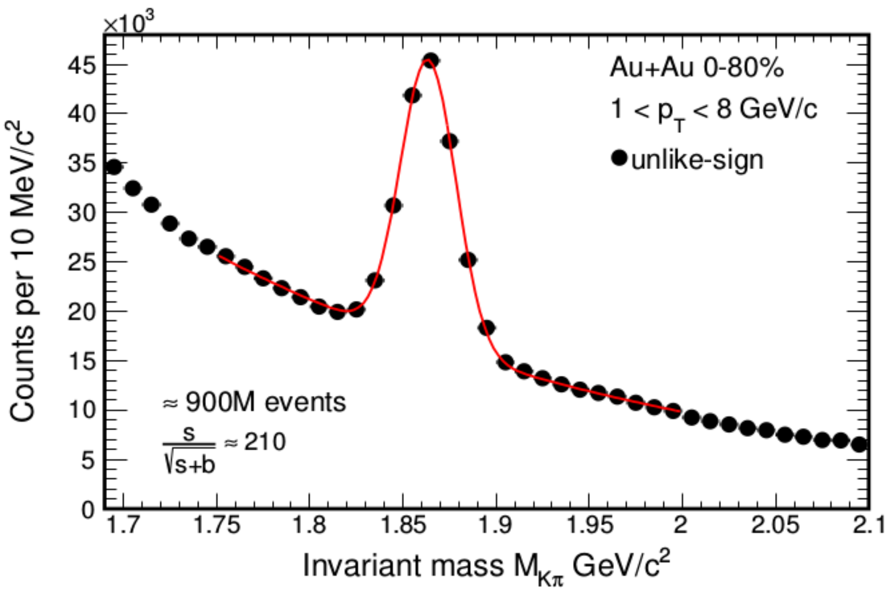
D^0 reconstruction with HFT

- Topological reconstruction with HFT

  $$D^0(\overline{D^0}) \rightarrow K^{\mp}\pi^{\pm}(BR\ 3.89\%)$$
  $$c\tau \approx 120\,\mu m$$

  - ~ 4 orders reduction of combinatorial background
  - cuts optimized using TMVA

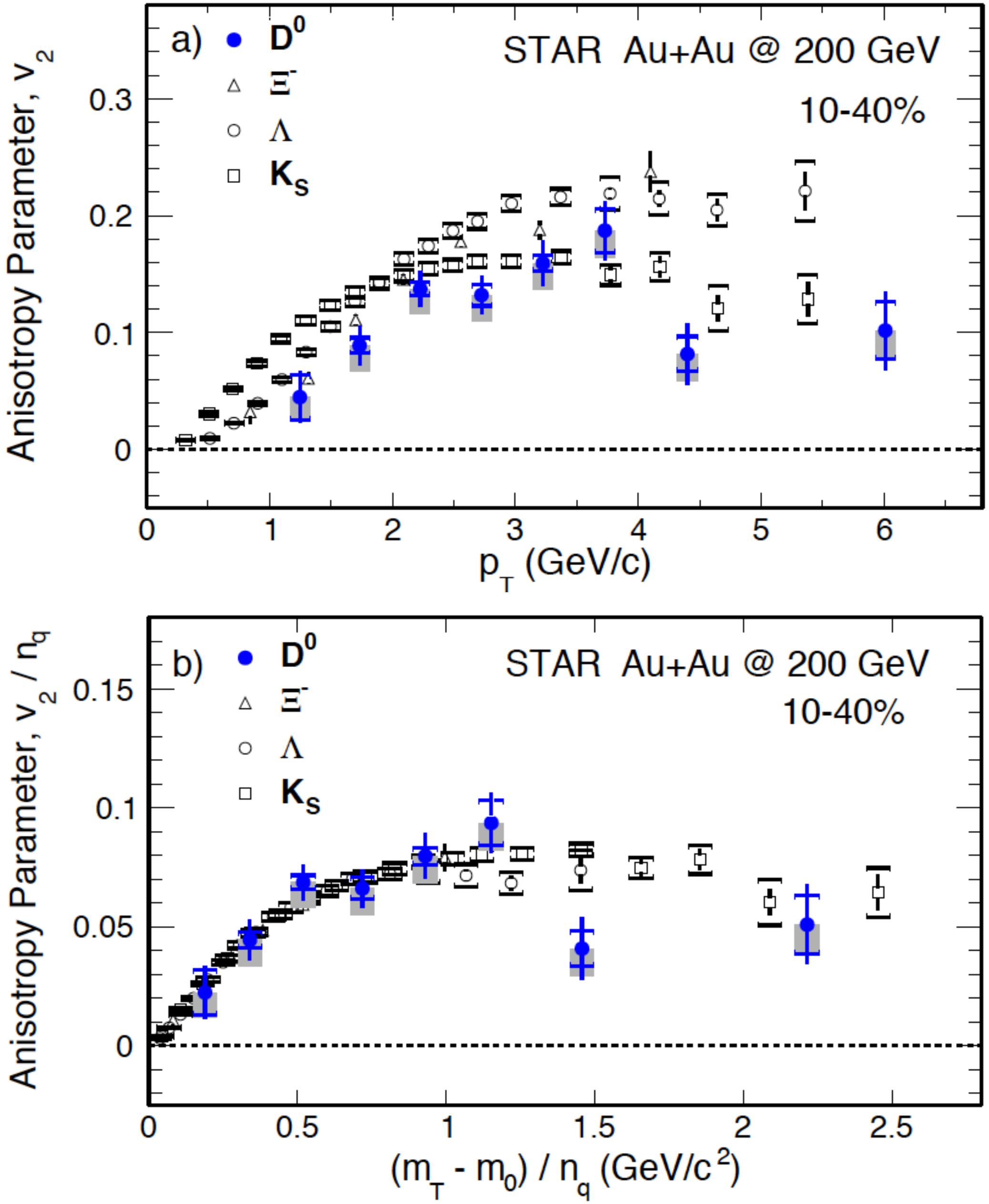




	w/o HFT	w HFT
	2010+2011	2014
# events (MB)	1.1 billion	~900 million
Sig./ bill. evts.	13*	220

*L. Adamczyk et al. (STAR), PRL113 142301
arXiv:1701.06060

Elliptic Flow of D^0

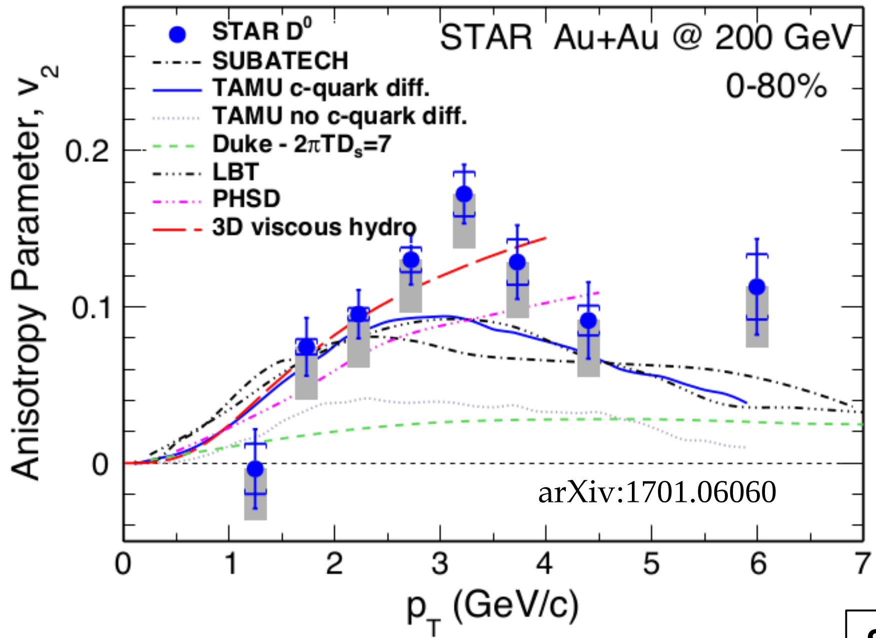


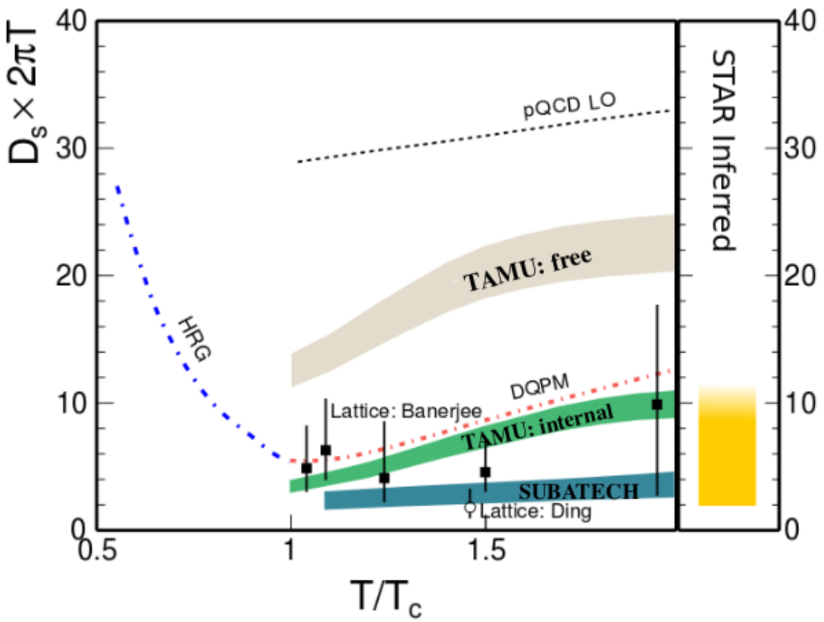
Submitted:
arXiv:1701.06060

- Mass ordering for $p_T < 2$ GeV/c
- Similar to other light mesons for $p_T > 2$ GeV/c
- D^0 v_2 follows NCQ scaling

Suggest that charm quarks flow with the medium.

Comparison to models





- Values for the diffusion coeff. extracted from models and compared to STAR data
  - Agree with models with charm diffusion coefficient of 2-5 at T_C and temperature dependent range of ~2-12 at T_C to $2T_C$
  - Consistent with Lattice calculations

SUBATECH: pQCD + hard thermal loop

P. B. Gossiaux, J. Aichelin, T. Gousset, and V. Guiho, SQM

TAMU: T-matrix, non-perturbative model w. internal energy potential

M. He, R. J. Fries, and R. Rapp, PRC86, 014903 (2012)

Duke: free constant Ds, fit to LHC high-p_T R_{AA}

S. Cao, G.-Y. Qin, and S. A. Bass, PRC88, 044907 (2013)

hydro: 3D viscous hydrodynamic model

L.-G. Pang, Y. Hatta, X.-N. Wang, B.-W. Xiao,PRD91, 074027 (2015)

PHSD: Parton-Hadron-String Dynamics, a transport model

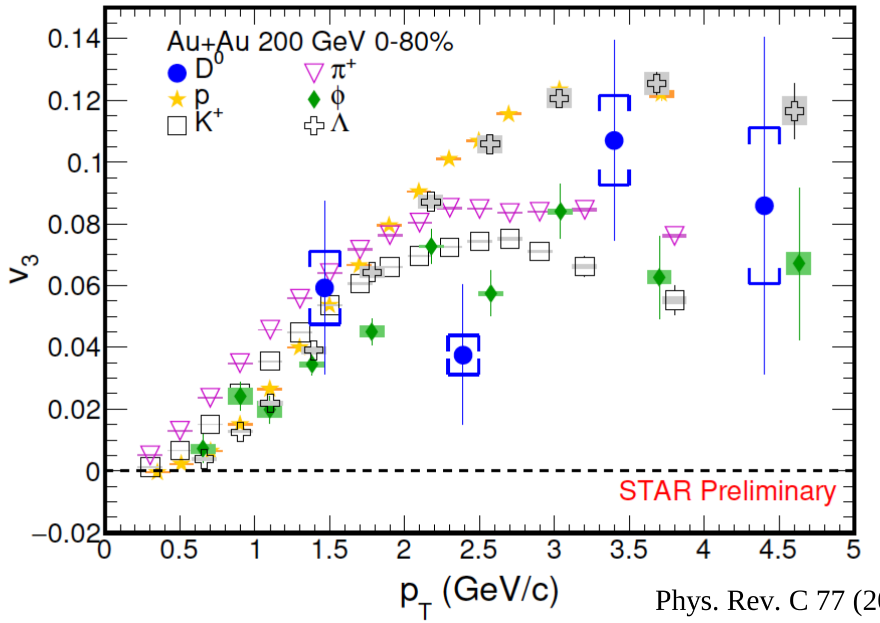
H. Berrehrah et al. PRC90 (2014) 051901

LBT: A Linearized Boltzmann Transport model

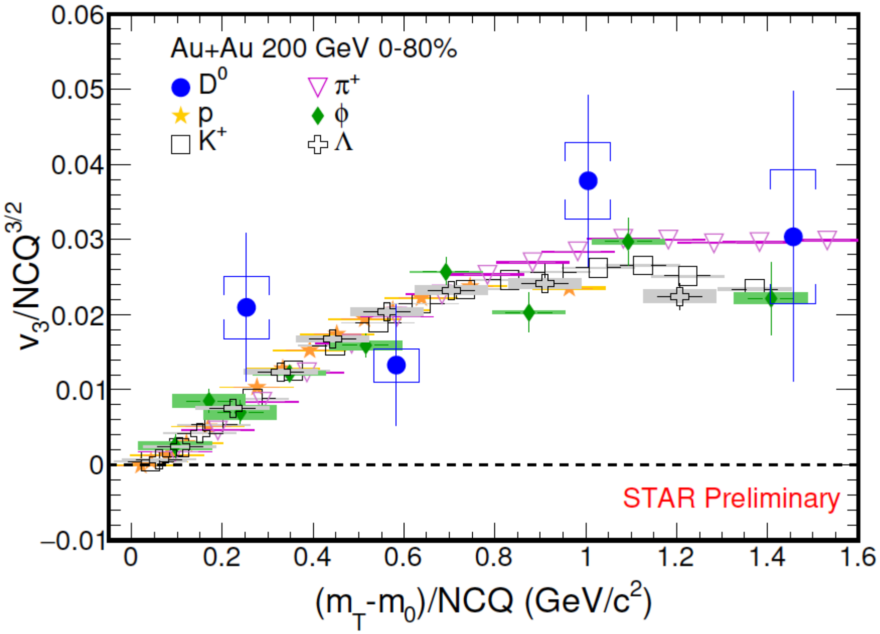
S. Cao, T. Luo, G.-Y. Qin, and X.-N. Wang, PRC94, 014909 (2016)

Lattice: *H.T.Ding et al., Int. J. Mod. Phys., E24, 1530007 (2015)*
D. Banerjee et al., Phys. Rev. D85, 014510 (2012).

Triangular Flow of D^0



Phys. Rev. C 77 (2008) 54901



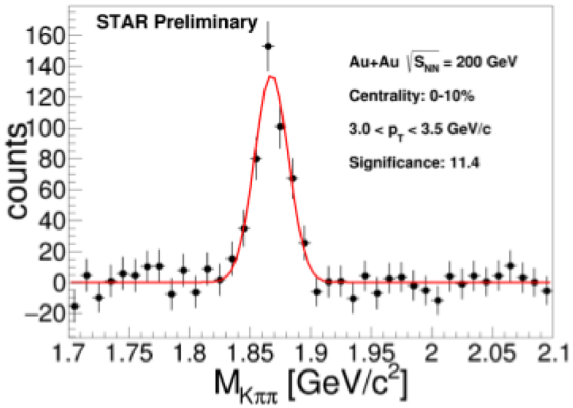
First D^0 v_3 measurement at RHIC

- D^0 v_3 is non-zero
  - importance of initial fluctuations.
  - consistent with NCQ scaling within large error bars.
- D^0 v_2 and v_3 -> strong collective behavior
- Further improvement - 2B events from 2016

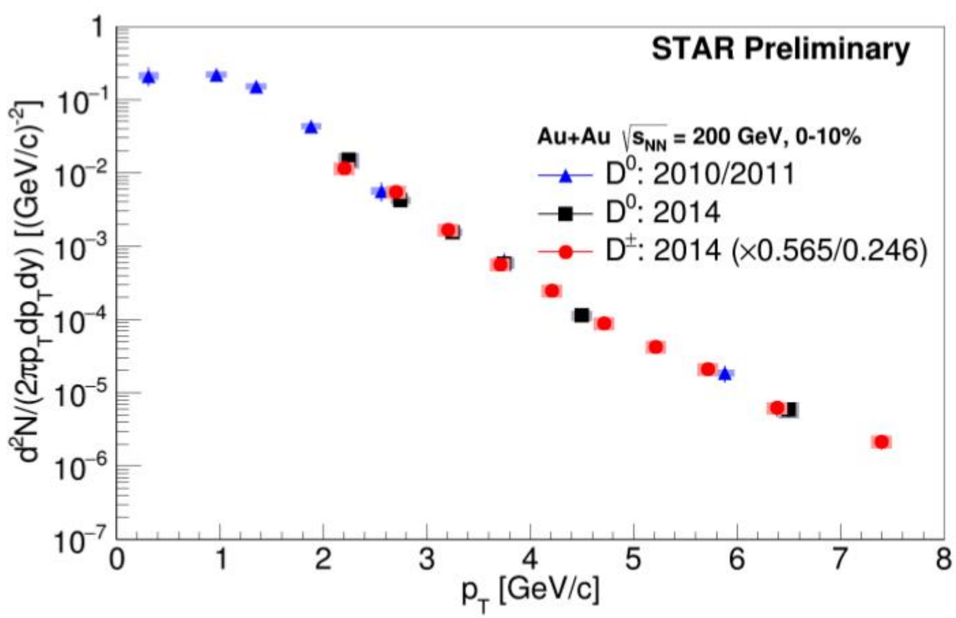
$D^{\pm}$ production

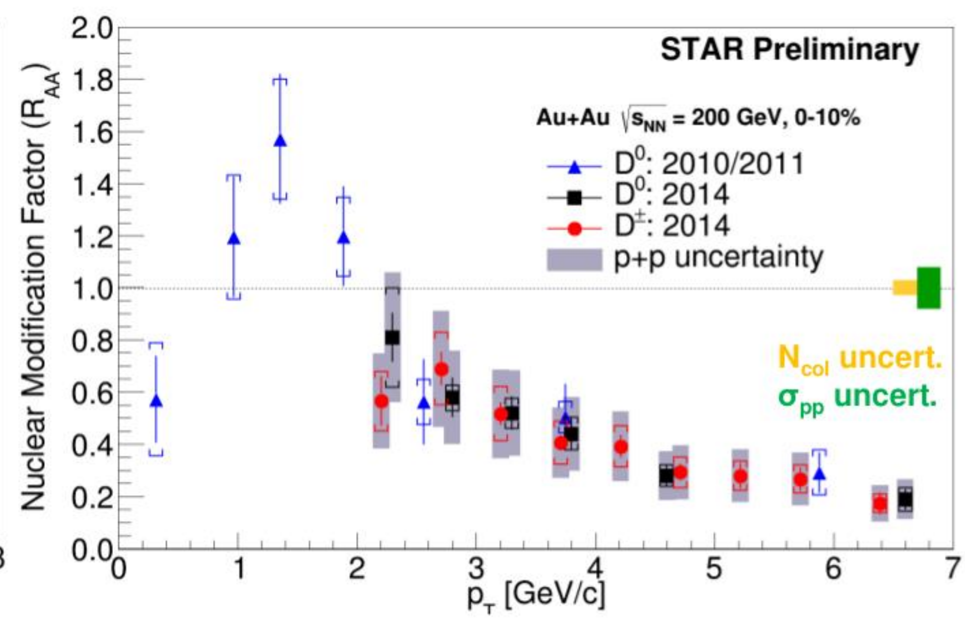
$D^{\pm} \rightarrow K^{\mp} \pi^{\pm} \pi^{\pm}$

$c\tau = 311.8\ \mu m$



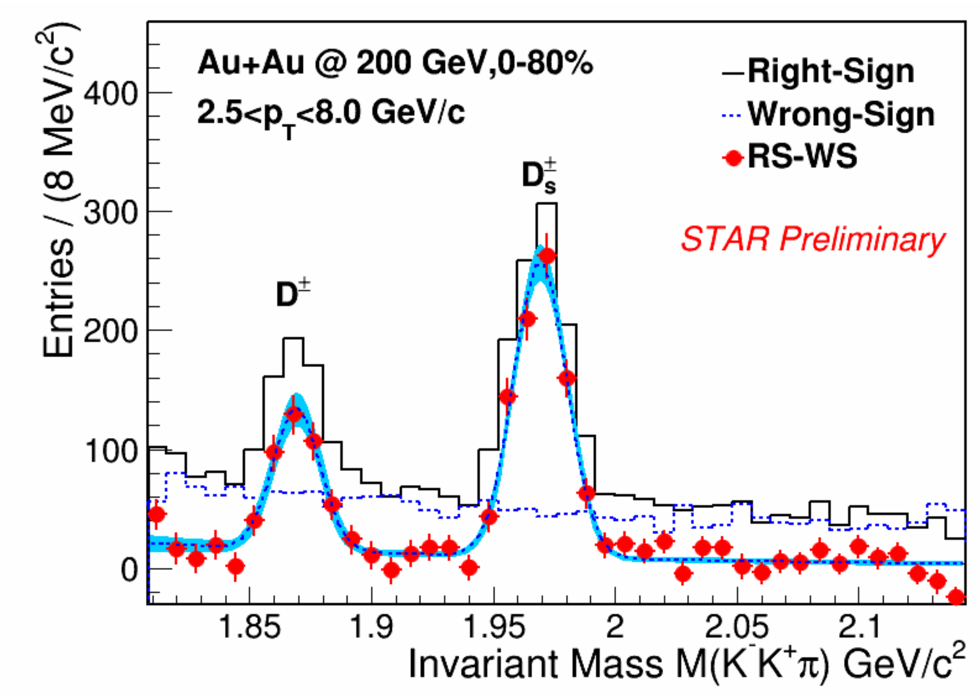
- Topological reconstruction in 0-10% central Au+Au collisions using 2014 data
- Extracted yield for 2< p_T <8 GeV/c
  - Consistent with D^0
- Strong suppression at high p_T
  - Indication of substantial energy loss

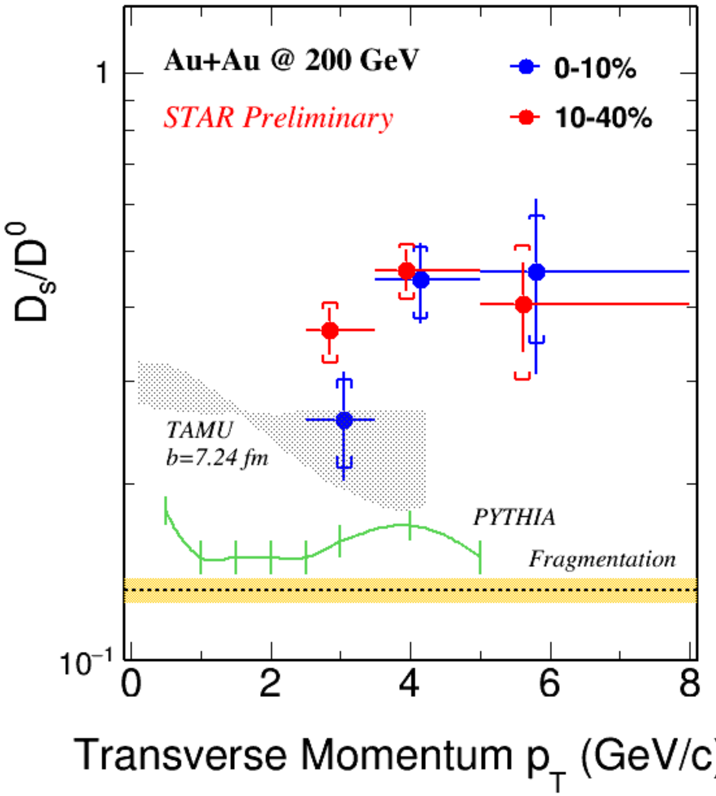




[D^0:2010/2011]Phys. Rev. Lett. 113 (2014) 142301

D_s production





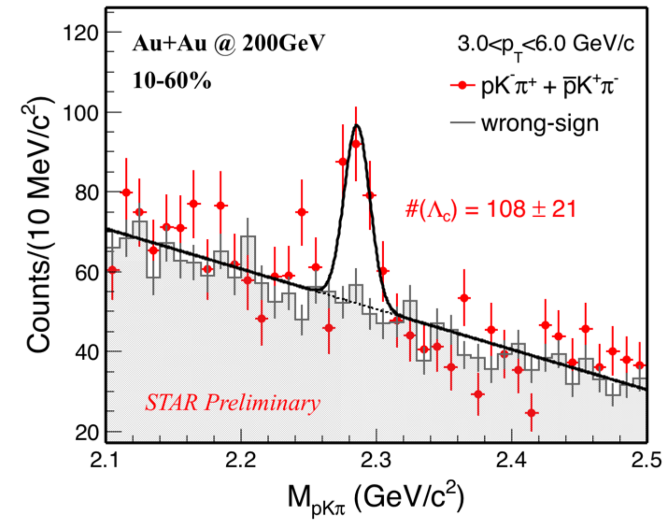
TAMU: H. Min et al. PRL 110, 112301 (2013)
M Lisovyi, et. al. EPJ C 76, 397 (2016)

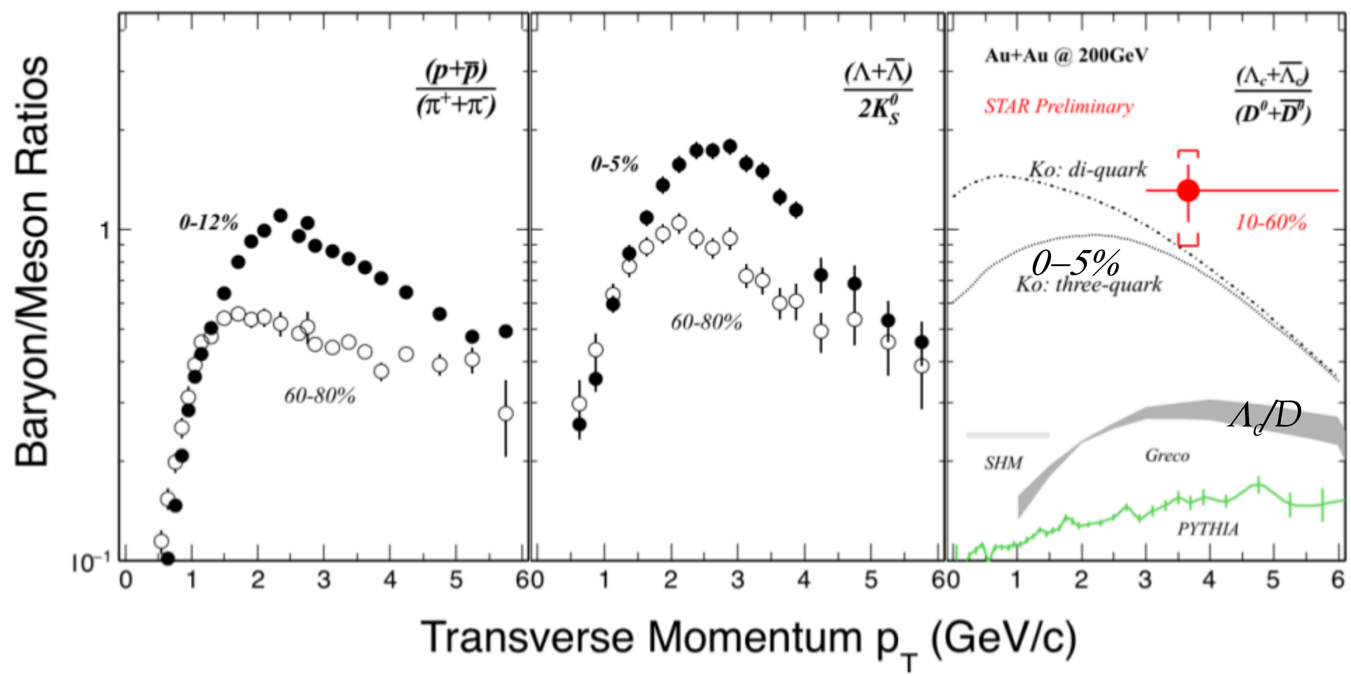
- Study of hadronization mechanism
- Strong enhancement of D_s/D^0 ratio over PYTHIA
  - TAMU model underestimates data in 2.5-3.5 GeV/c
- No strong centrality dependence observed

Λ_c production

First Λ_c reconstruction in A+A collisions

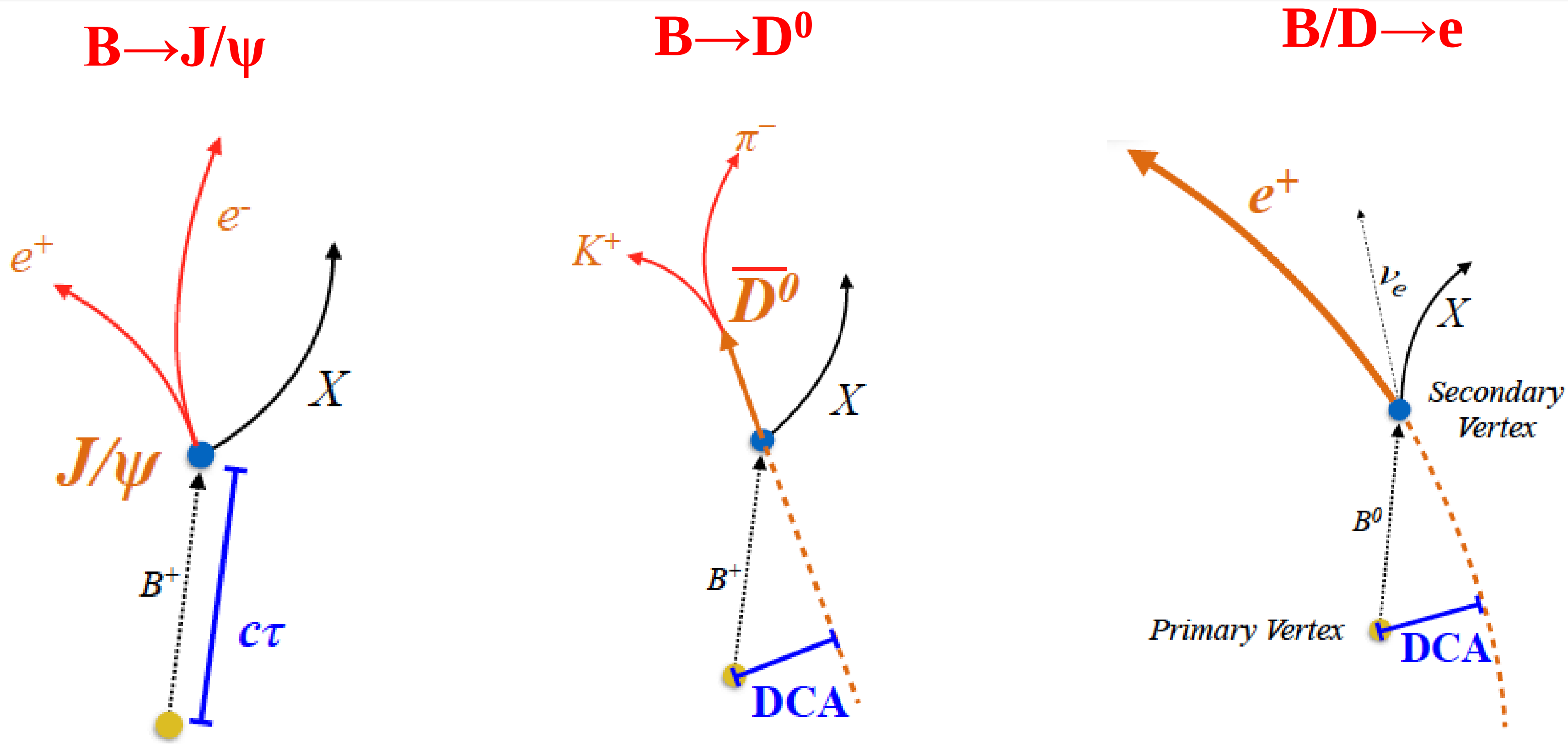
- Study of baryon-to-meson ratio
  - Coalescence
- Observed an enhancement of Λ_c /D^0 ratio over PYTHIA
  - similar amplitude to light flavor hadrons
  - STAR: 1.3 ± 0.3(stat) ± 0.4(sys), PYTHIA: 0.1 - 0.15
  - Ko model (0-5%) with coalescence and thermalized charm quarks is consistent with data





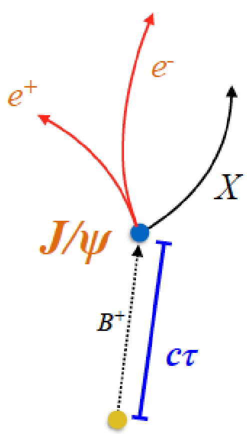
STAR arXiv:nucl-ex/0601042
Ko model : Y. Oh, et.al. PRC 79,044905 (2009)
Greco model : S.Ghosh, et. al. PRD 90,054018 (2014)

B - production

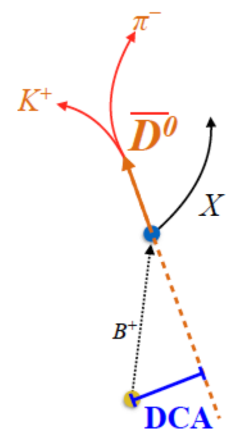


- Separate measurements of c and b energy losses in the medium.
- Three ways of measuring B production at STAR

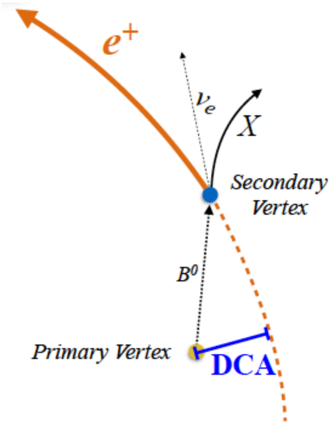
B - production



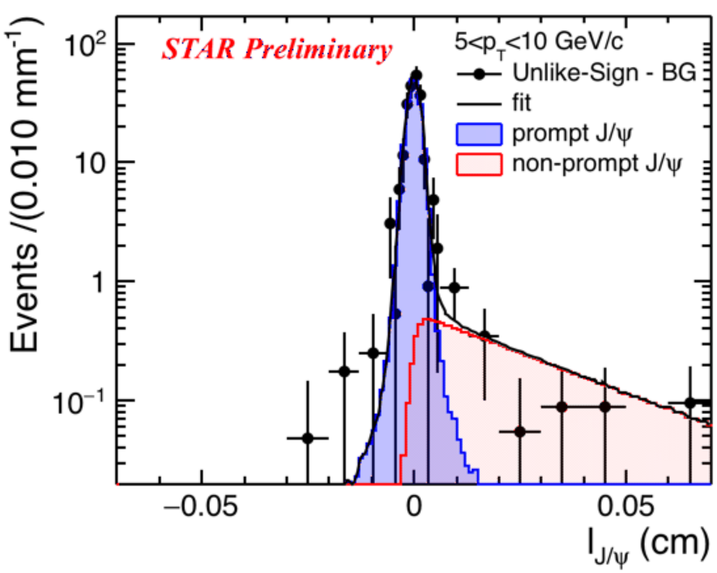
B→J/ψ

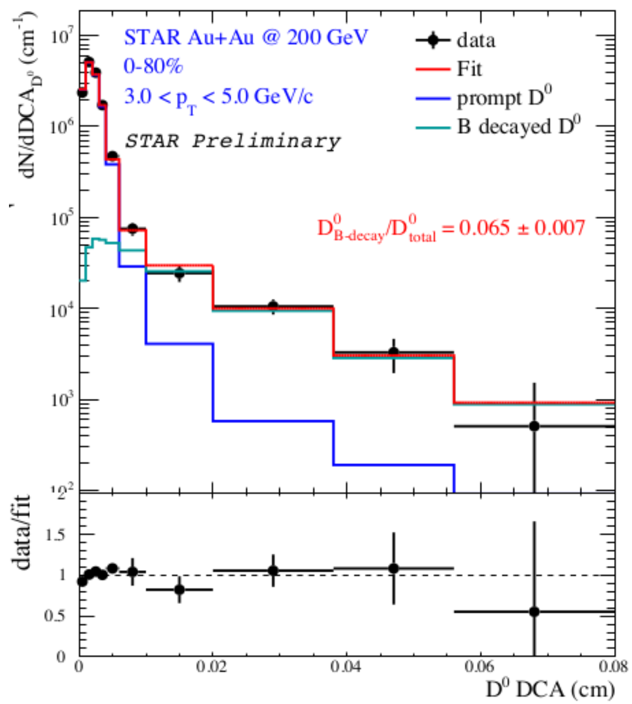


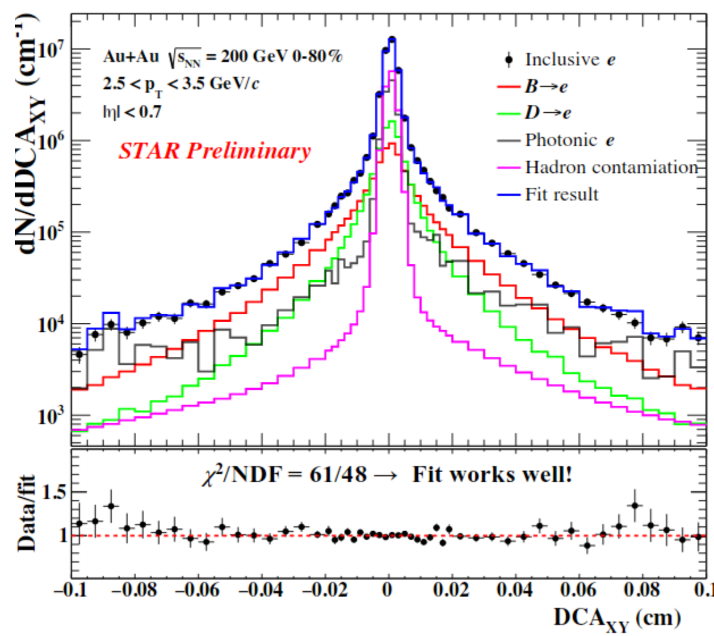
B→D⁰



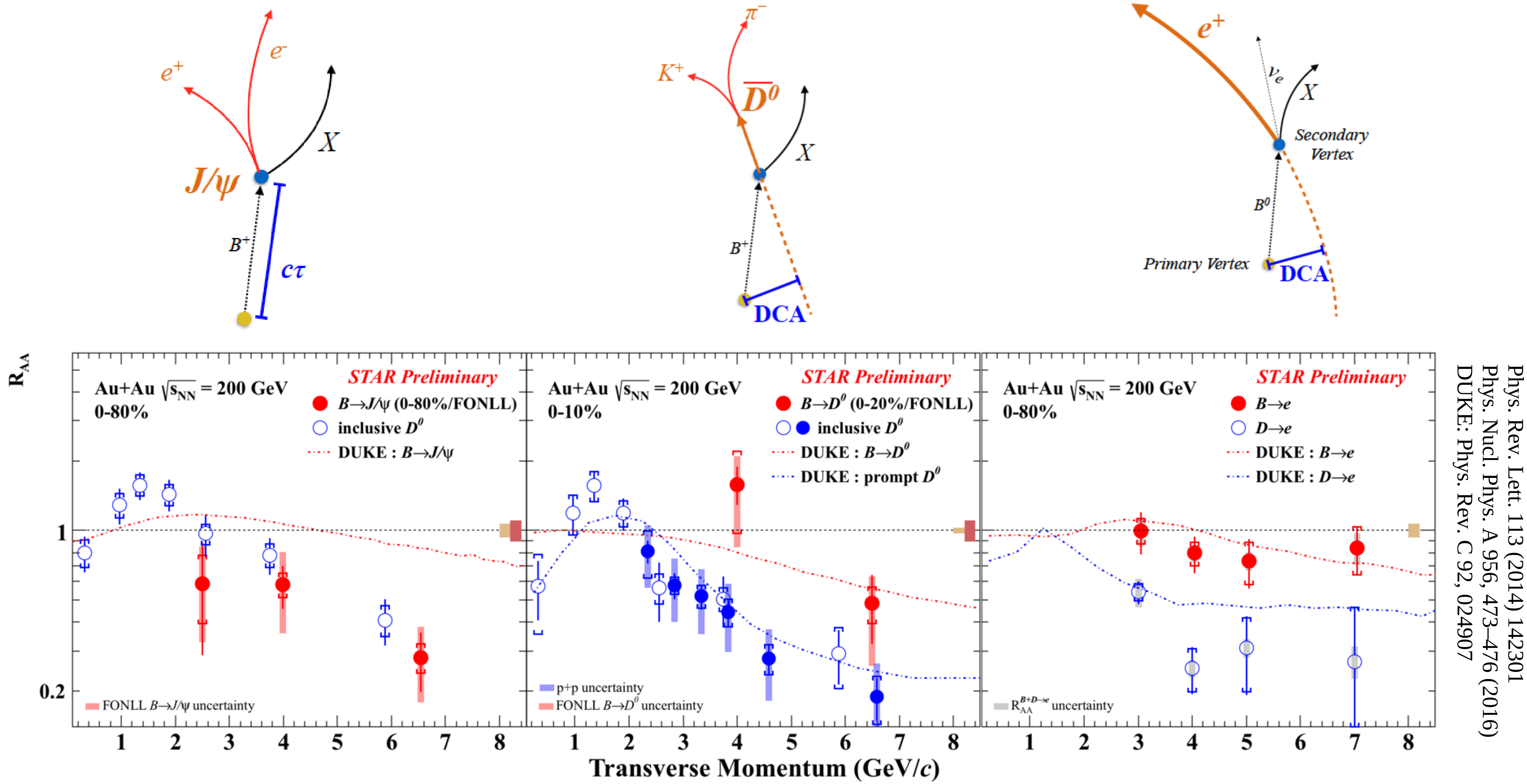
B/D→e







B - production



- Suppression observed in B->J/ψ and D^0
- B->e is less suppressed than D->e (2σ effect)

Open heavy-flavor summary

- Large non-zero D^0 v_2 and v_3 exhibiting strong collective behavior
  - suggesting charm quark thermalization with the medium
- Large suppression of D^0 and $D^{\pm}$ at high p_T
  - strong interactions between charm quarks and the medium
- First measuremnt of Λ^+_c production in heavy-collisions
- Enhancement of Λ^+_c / D^0 and D^+_s / D^0 ratios with respect to PYTHIA
  - Ratios comparable with light hadrons
  - Hadronization of charm quarks via coalescence
- B production measured via J/ψ, D^0 and electron decay channels in 200 GeV Au+Au collisions
  - Consistent with mass hierarchy in energy loss ($\Delta E_c > \Delta E_b$)
  - Suppression of $B \rightarrow J/\Psi$ and $B \rightarrow D^0$ in high p_T region
  - More high statistic data need for Bottom measurements.
- Outlook: 2016 Au+Au data (2B MB events and 1 nb^{-1} (5 times 2014 data) high-p_T electron sample on disk

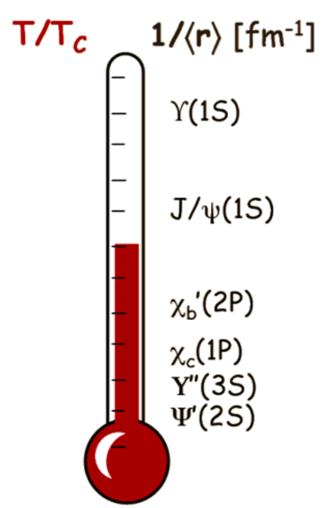
Quarkonia as a probe of QGP

- Large masses of c, b quarks
  - created during initial stages of collision
- Due to color screening of quark-antiquark potential in QGP, **quarkonium dissociation is expected**

Quarkonia family:
$\bar{c}$-c: J/ψ, ψ′, χ_c …
$\bar{b}$-b: Υ(1S), Υ(2S), Υ(3S) …

H. Satz, Nucl. Phys. A (783):249-260(2007)

Illustration: A.Rothkopf



- Suppression determined by medium temperature and binding energy.

Sequential suppression of different quarkonium states is expected.

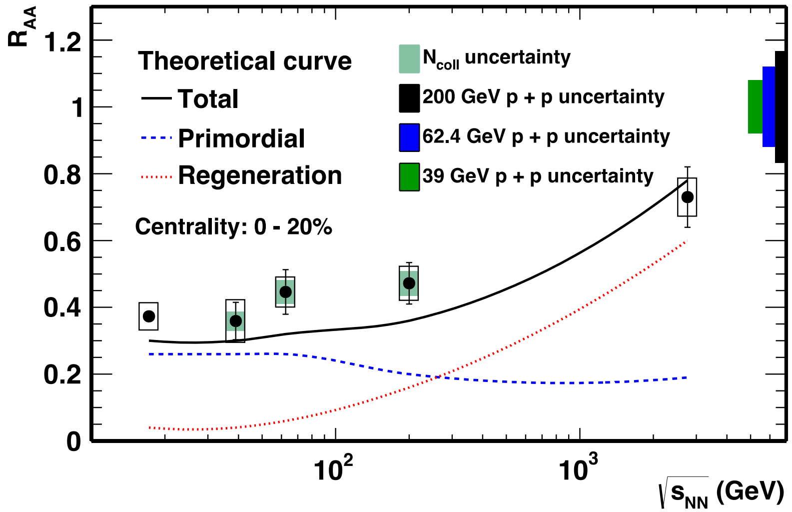
A. Mocsy, EPJ C61 (2009) 705

Other effects

- Quarkonium production mechanism is not well understood.
- Observed yields are a mixture of direct production + feed-down
  - Direct J/ψ (~60%) +feed-down ~30% χ_c & ~10% ψ ′
  - B-hadron decay
- Hot/dense medium effects
  - Coalescence from uncorrelated charm pairs.
- Suppression and enhancement in the "cold" nuclear medium
  - PDF modification in nucleus - shadowing/anti-shadowing , color glass condensate
  - Initial state energy loss
  - Nuclear absorption – break up of bound state precursor by collisions with passing nucleons
  - Dissociation by interaction with co-movers in final state

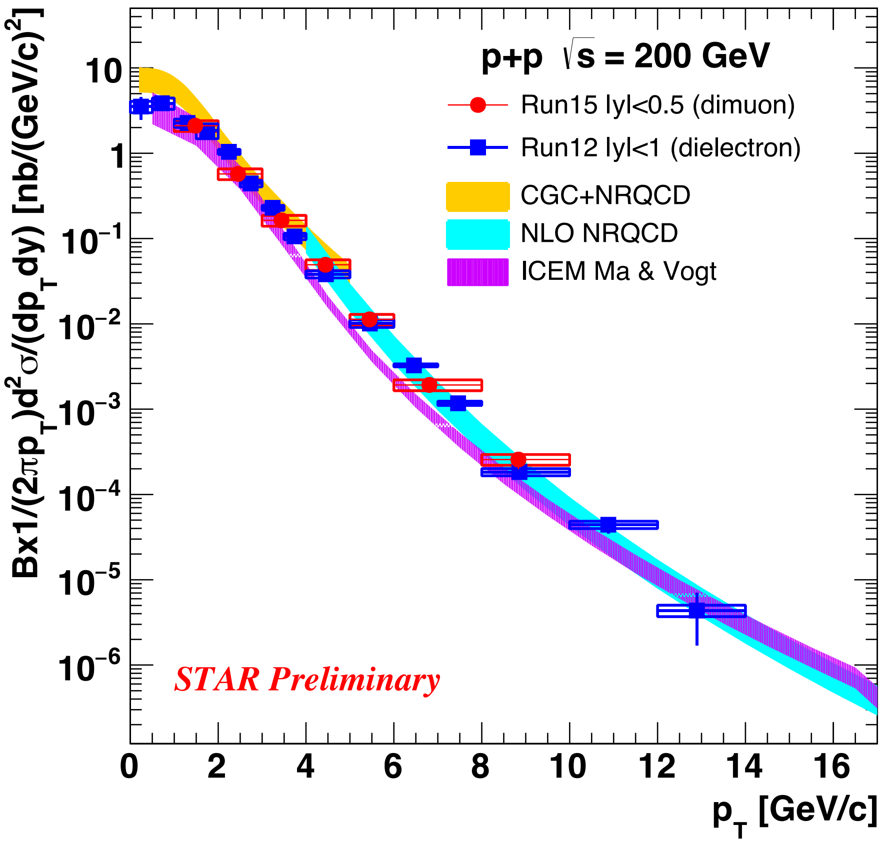
X. Zhao, R.Rapp, PRC82, 064905 (2010)

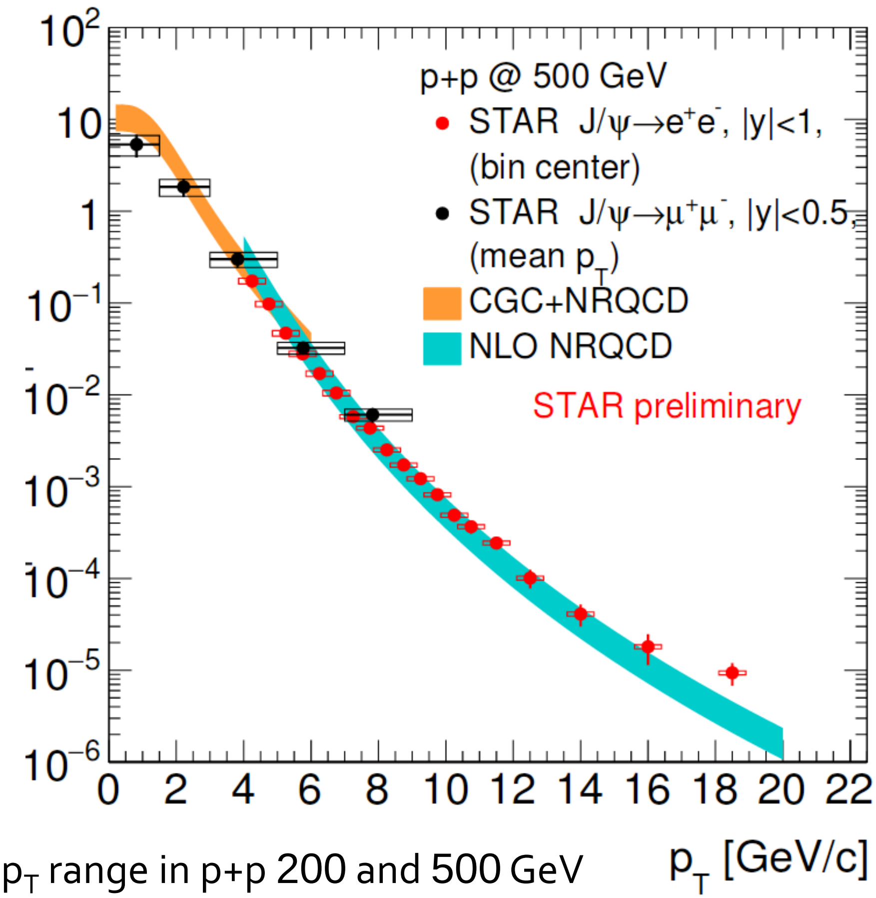
STAR arXiv:1607.07517



Measure J/ψ at different p_T, in different colliding systems, and collision energies.

J/ψ in p+p at 200 and 500 GeV

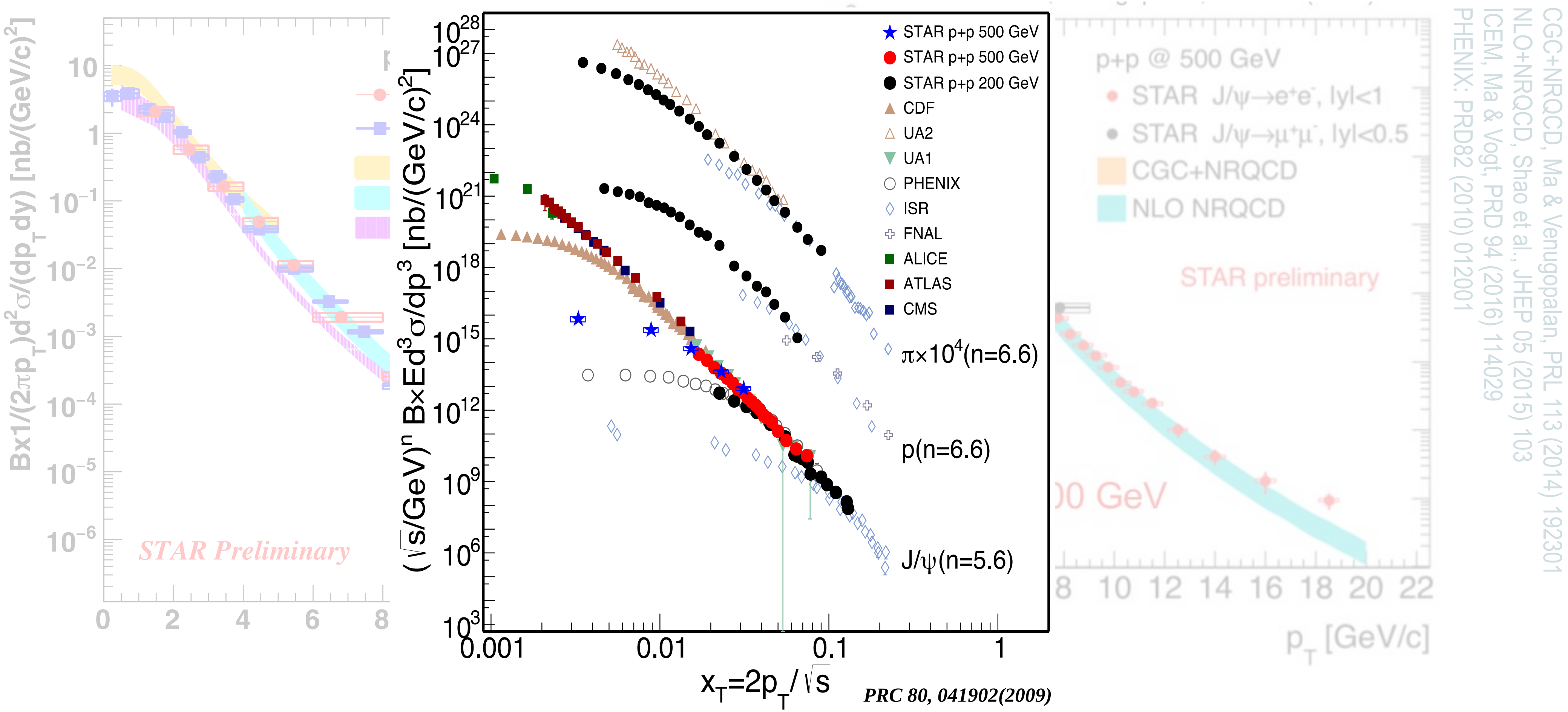




CGC+NRQCD, Ma & Venugopalan, PRL 113 (2014) 192301
NLO+NRQCD, Shao et al., JHEP 05 (2015) 103
ICEM, Ma & Vogt, PRD 94 (2016) 114029

- J/ψ production cross-section measured over wide p_T range in p+p 200 and 500 GeV
- Dimuon channel – extending kinematic reach to low p_T at 500 GeV
  - Agreement with dielectron channel
- CGC+NRQCD & NLO NRQCD describe data above 1 GeV/c
  - NRQCD includes direct and feed-down from excited states
- Improved CEM model describes 200 GeV data well at low p_T
  - Includes direct production only
  - Data are above ICEM calculation at $3.5 < p_T < 12$ GeV/c

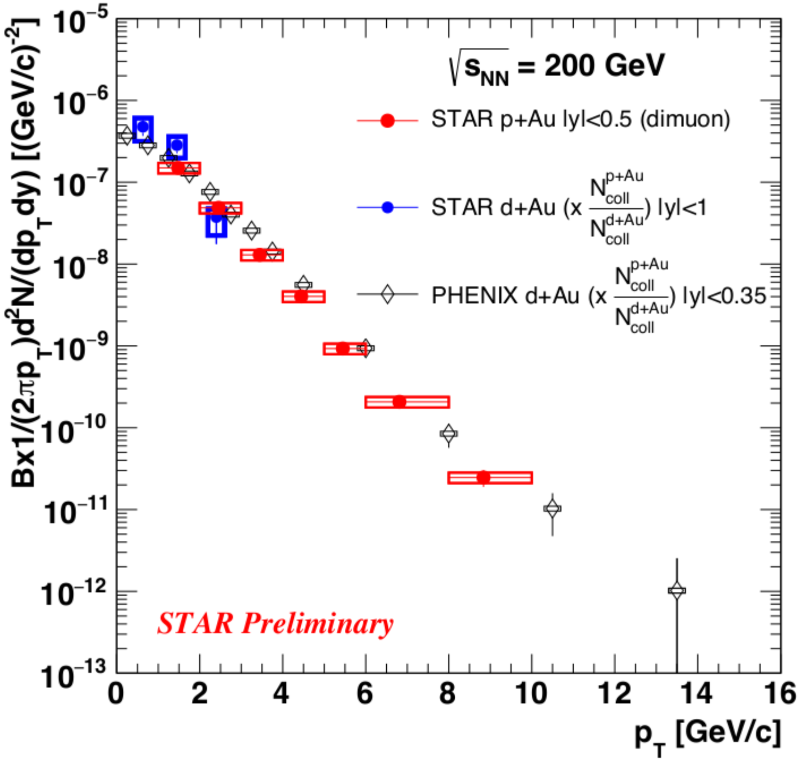
J/ψ in p+p at 200 and 500 GeV

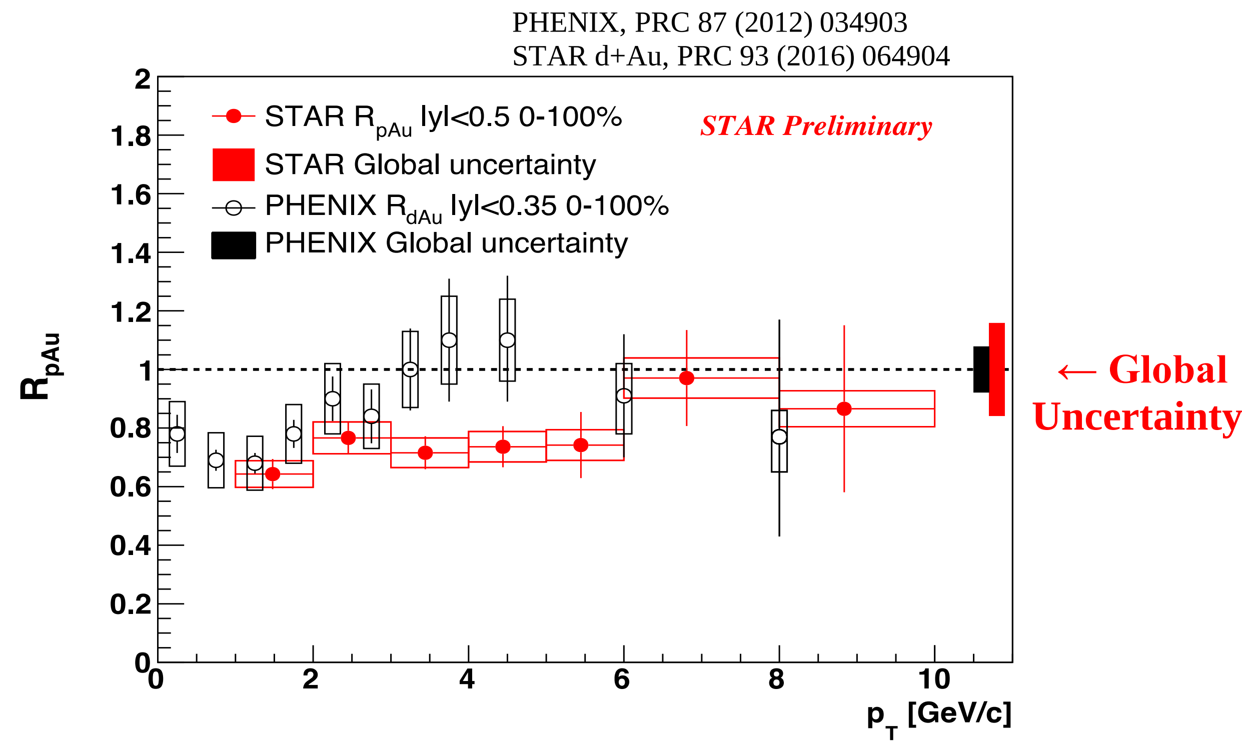


- p_T > 5 GeV/c – J/ψ production follows the x_T scaling of cross-section at mid-rapidity, with n ~ 5.6.
  - x_T scaling breaking - transition from hard to soft processes

J/ψ R_{pAu} at 200 GeV

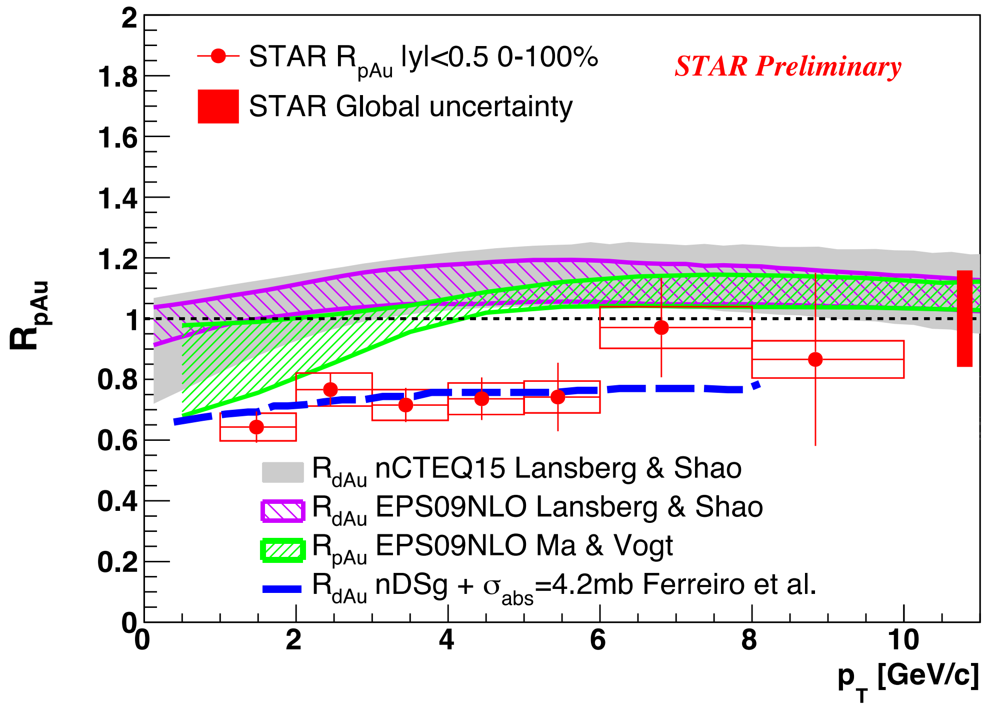
First J/ψ R_{pAu} measurement at RHIC





- R_{pAu} is consistent with unity at high p_T and is less than unity at low p_T
- R_{pAu} is consistent with R_{dAu} within uncertainties
  - Bit of tension at p_T 3.5 – 5 GeV/c with a significance of 1.4σ
- Suggest similar CNM effects in these collision systems

J/ψ R_{pAu} at 200 GeV



EPS09+NLO, Ma & Vogt, Private Comm.

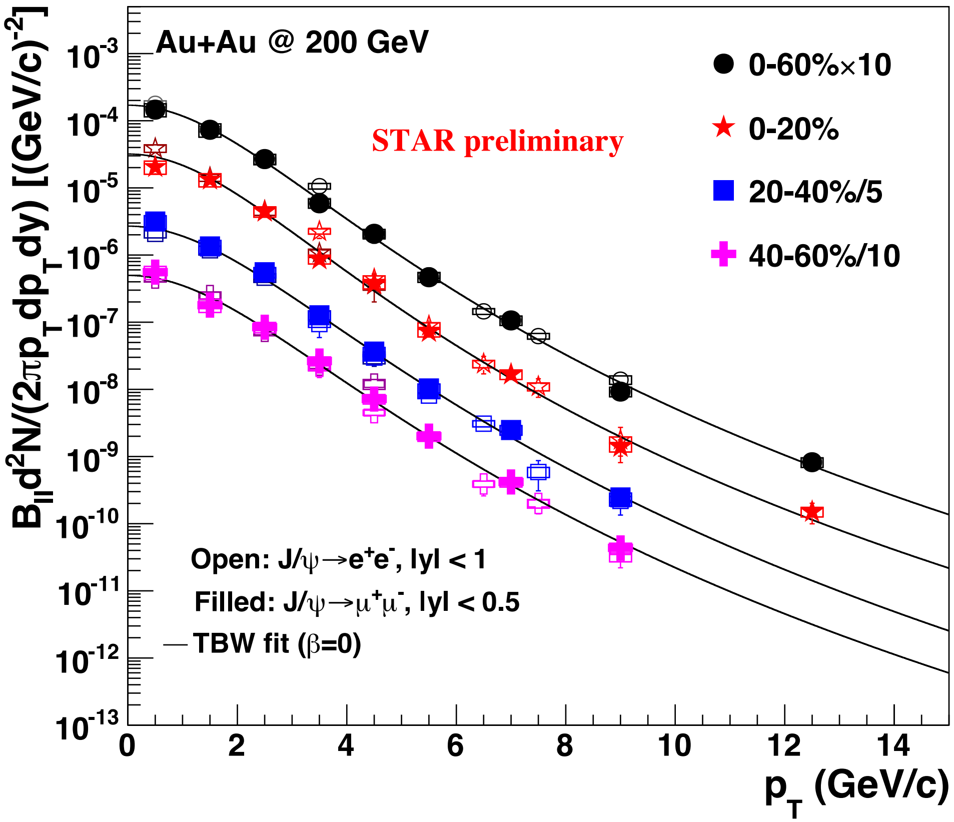
nCTEQ, EPS09+NLO, Lansberg Shao, Eur.Phys.J. C77 (2017) no.1, 1
Comp. Phys. Comm. 198 (2016) 238-259
Comp. Phys. Comm. 184 (2013) 2562-2570

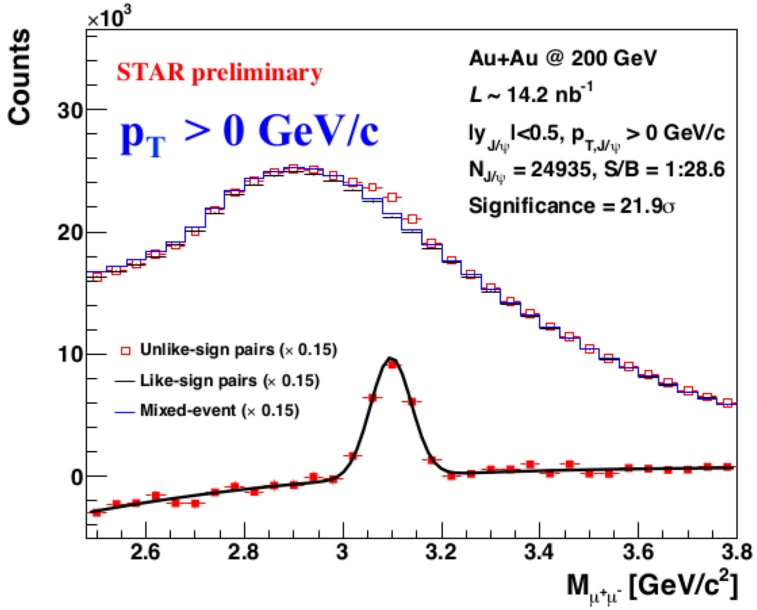
Ferreriro et al., Few Body Syst. 53 (2012) 27

← **Global Uncertainty**

- Models with only nPDF effects are on the upper limit of the data
  - Large global uncertainty
- Data suggest additional nuclear absorption on top of nPDF effects

J/ψ in Au+Au at 200 GeV





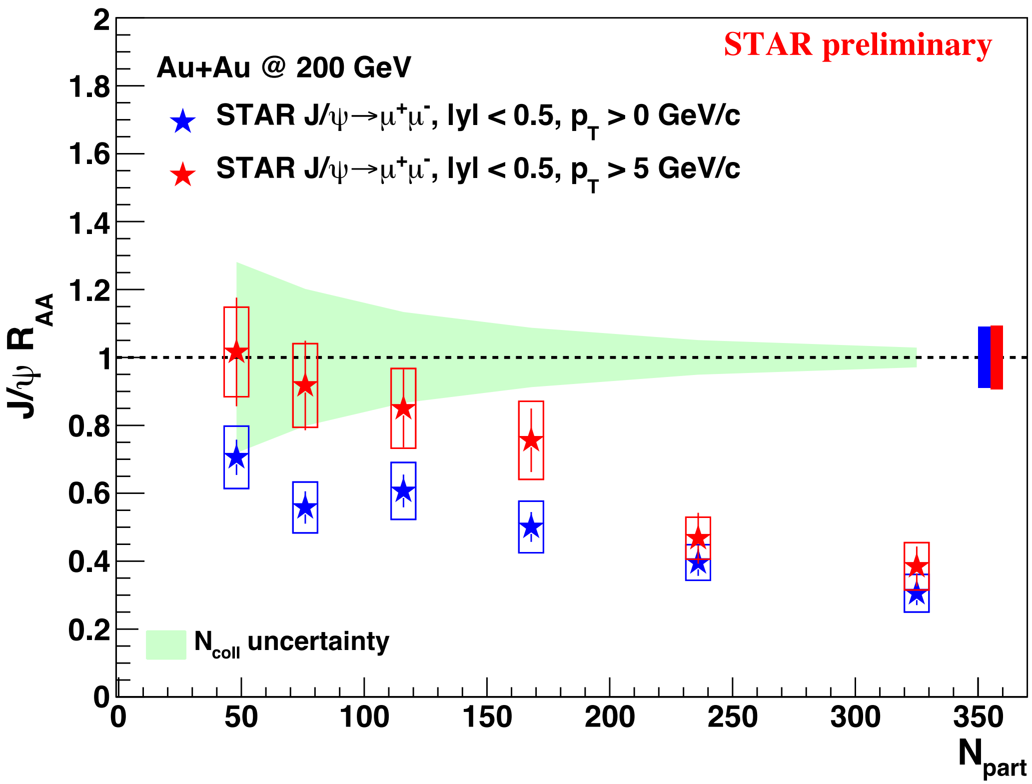
Di-electron:
STAR PLB 722 (2013) 55
STAR PRC 90, 024906 (2014)

Tsallis Blast-Wave
Tang et al., PRC 79, (2009) 051901(R)

First mid-rapidity measurement of J/ψ yield in Au+Au collisions via the di-muon channel for $0 < p_T < 15$ GeV/c at RHIC

- Consistent with the published di-electron results using 2010 data over the entire kinematic range.

J/ψ R_{AA} – centrality dependence



Central collisions

- suppression for both $p_T > 0$ GeV/c and $p_T > 5$ GeV/c

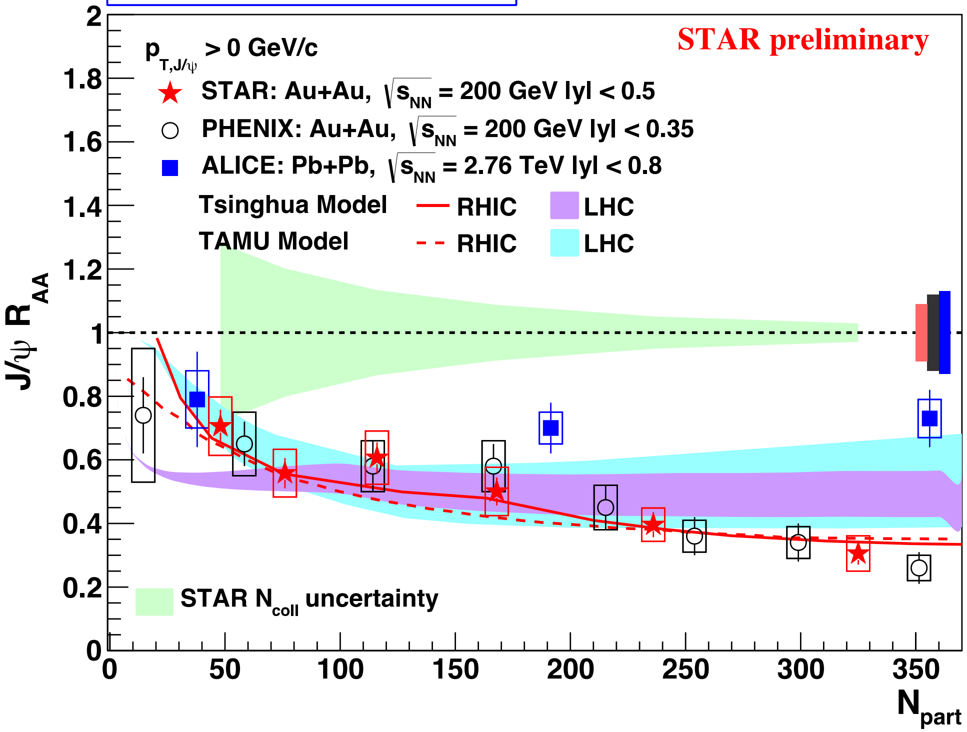
Peripheral collisions:

- larger suppression for $p_T > 0$ GeV/c than for $p_T > 5$ GeV/c
  - likely cold nuclear matter effects

J/ψ R_{AA} comparison to LHC

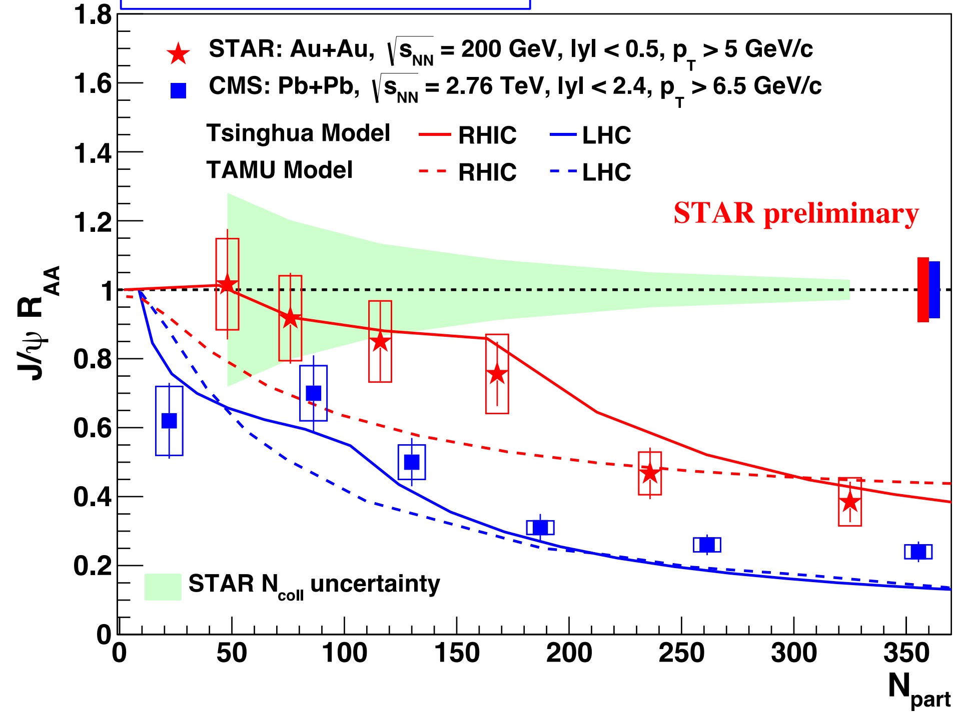
p_T > 0 GeV/c

ALICE : PLB 734 (2014) 314
PHENIX : PRL 98 (2007) 232301



p_T > 5 GeV/c

CMS: JHEP 05 (2012) 063



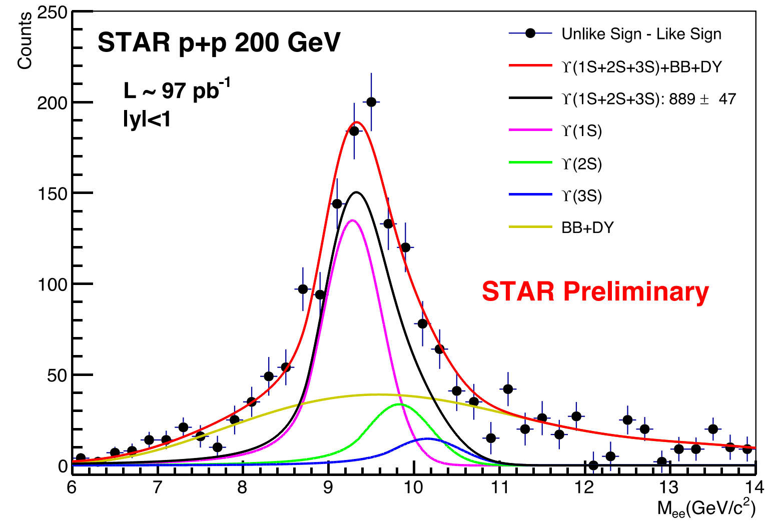
Transport model:
Tsinghua at RHIC: PLB 678 (2009) 72, Tsinghua at LHC: PRC 89 (2014) 054911
TAMU at RHIC: PRC 82 (2010) 064905, TAMU at LHC: NPA 859 (2011) 114

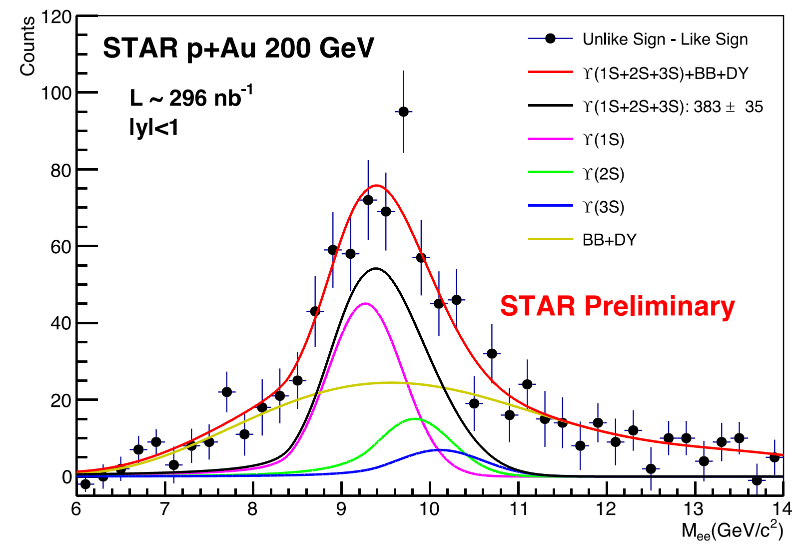
- p_T > 0 GeV/c: more suppressed than LHC in central events – regeneration
- p_T > 5 GeV/c: less suppressed than LHC in all centralities - temperature effect
- **Transport models** - dissociation and regeneration effects
  - p_T > 0 GeV/c: both models can describe centrality dependence at RHIC, but tend to overestimate suppression at LHC
  - p_T > 5 GeV/c: both models can qualitatively describe data

Upsilon measurements

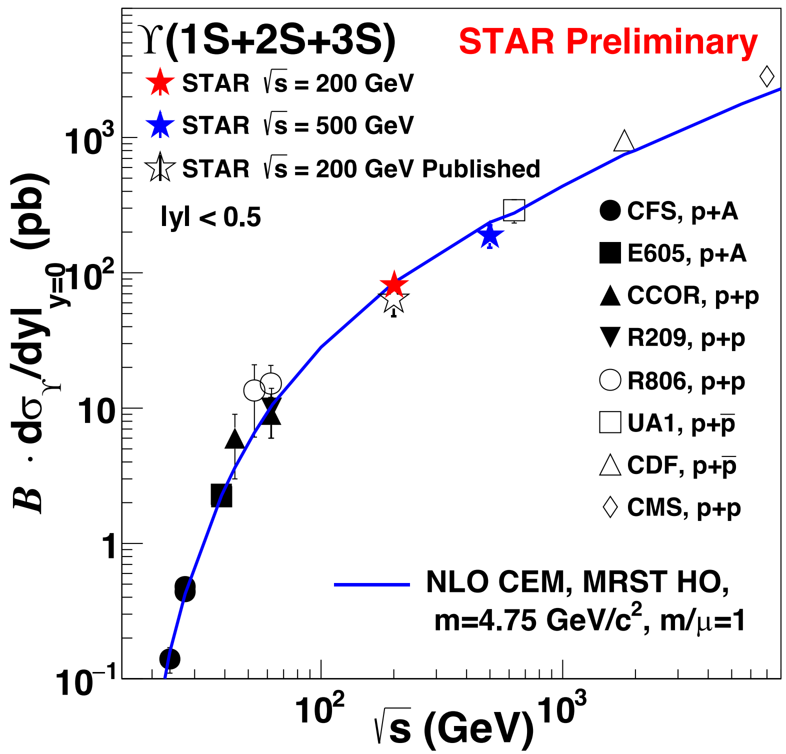
Υ -cleaner probe compared to J/ψ

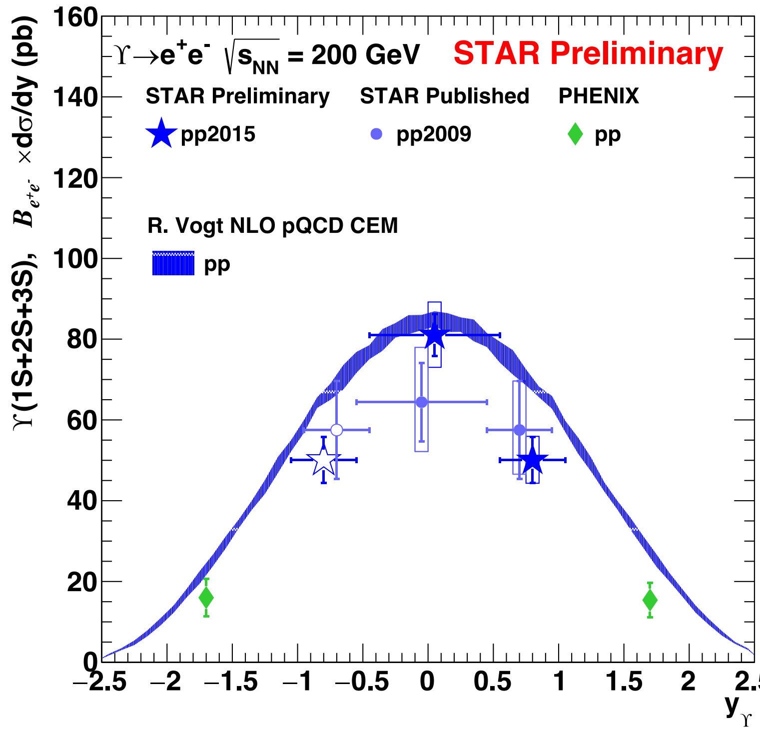
- Co-mover absorption ⟶ negligible
  - Υ(1S): tightly bound, larger kinematic threshold.
    - Expect σ~ 0.2 mb, 5-10 times smaller than for J/ψ
      Lin & Ko, PLB 503 (2001) 104
- Recombination ⟶ negligible
  - at RHIC: σ_{cc} ~800 μb >> σ_{bb} ~(1-2) μb
- Excited states: expect sequential suppression of Υ(1S), Υ(2S), Υ (3S) states
- Challenge: low rate, rare probe
  - Need large acceptance, efficient trigger





Υ cross-section in p+p collisions

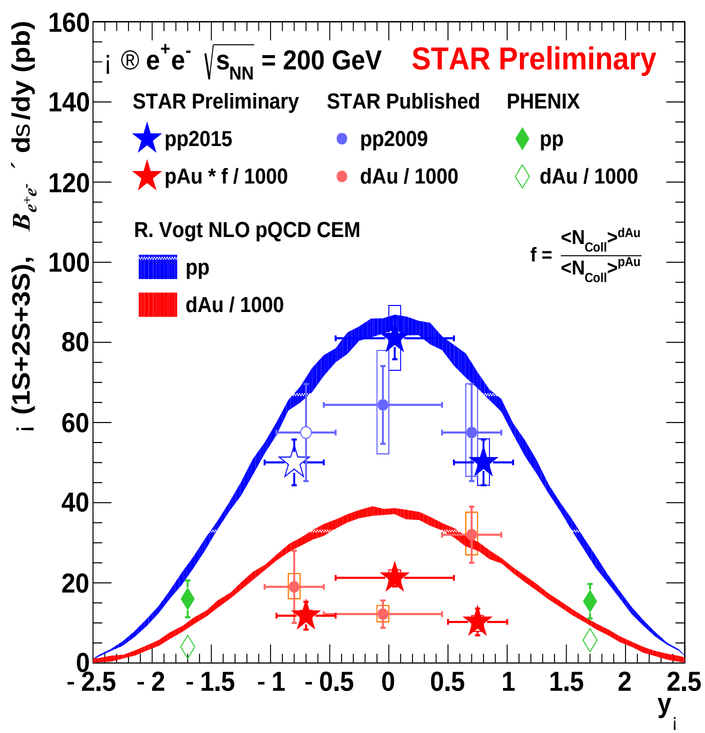




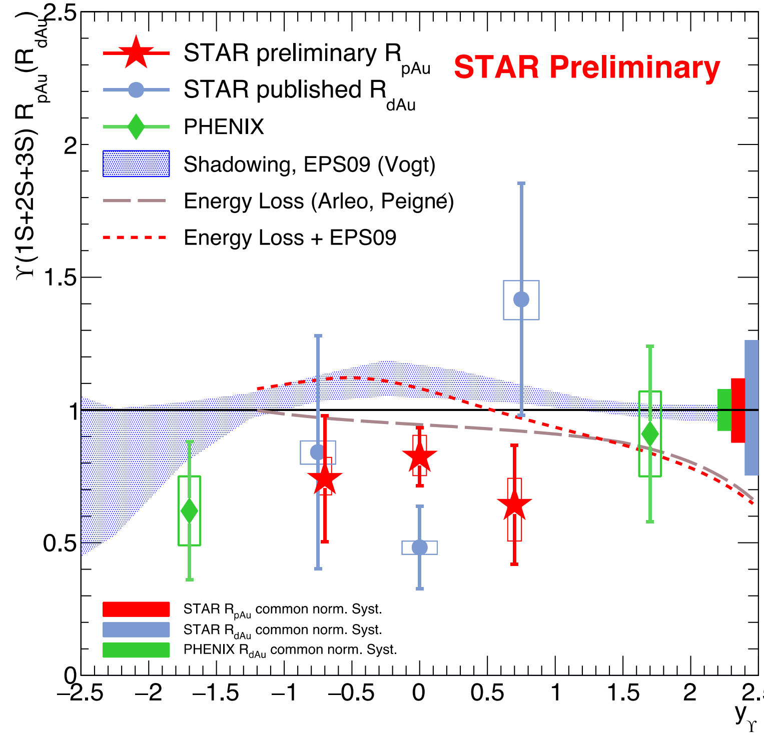
New measurements in p+p collisions at 200 and 500 GeV

- Follow world-wide data trend predicted by CEM
- Improved p+p reference for p+Au and Au+Au studies

ϒ in p+Au collisions at 200 GeV



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



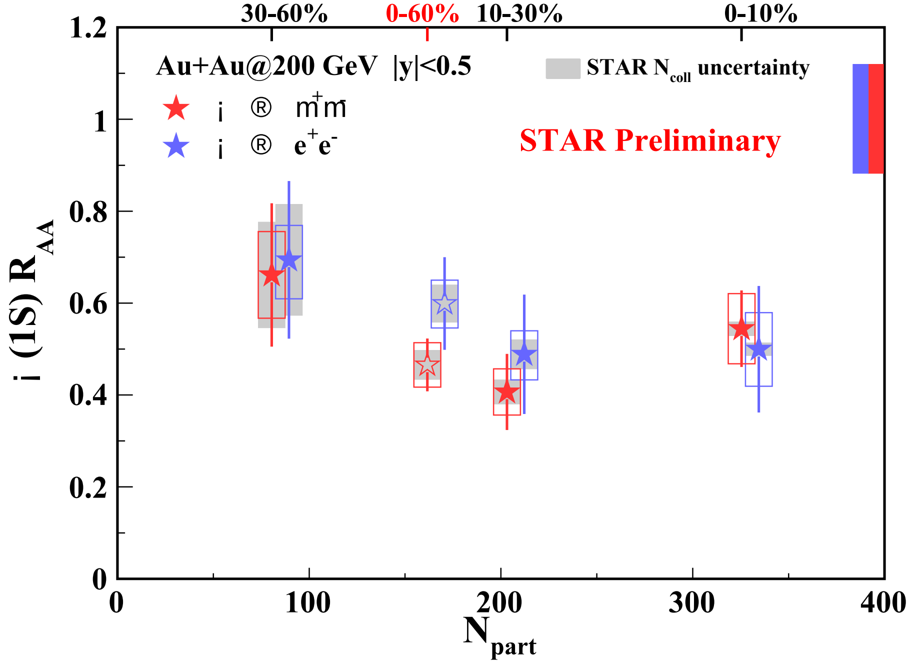
[STAR: PLB 735 (2014) 127]
[PHENIX: PRC 87 (2013) 044909]

K. J. Eskola, et. al, JHEP 0904 (2009) 065
F. Arleo, S. Peigne, JHEP 1303 (2013) 122
R. Vogt, et. al, PoS ConfinementX 203 (2012)

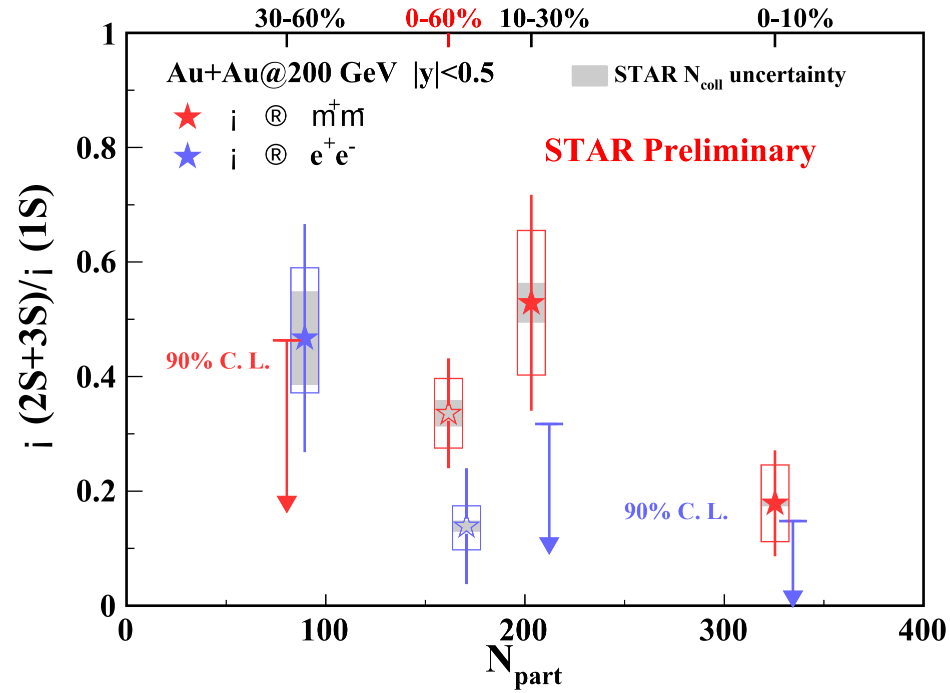
- Indication of Υ(1S+2S+3S) suppression in p+Au collisions – CNM
  - much better precision than the published R_{dAu}
- Suggesting an additional suppression mechanism is needed beyond nPDF effects

Υ in Au+Au collisions at 200 GeV

Υ(1S) R_{AA}



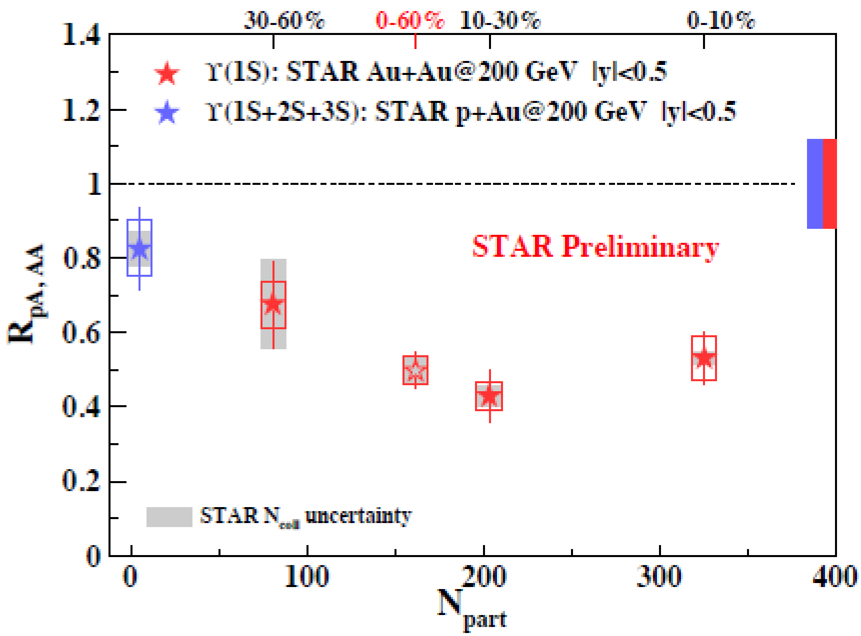
Υ(2S+3S)/Υ (1S)



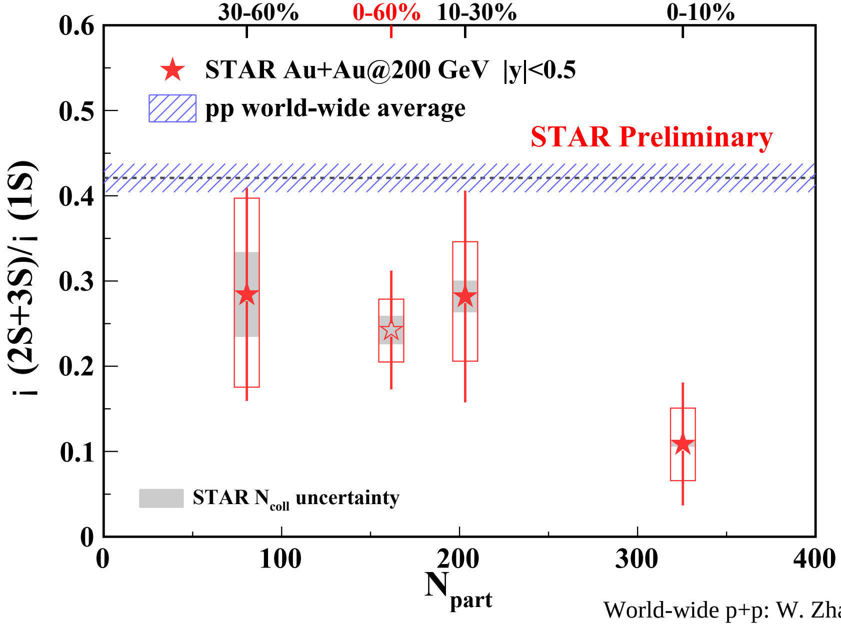
- Di-muon: 2014 data; di-electron: 2011 data
- Consistency between dielectron and dimuon channels
  - Combined for final results

Υ suppression

Υ(1S) R_{AA}



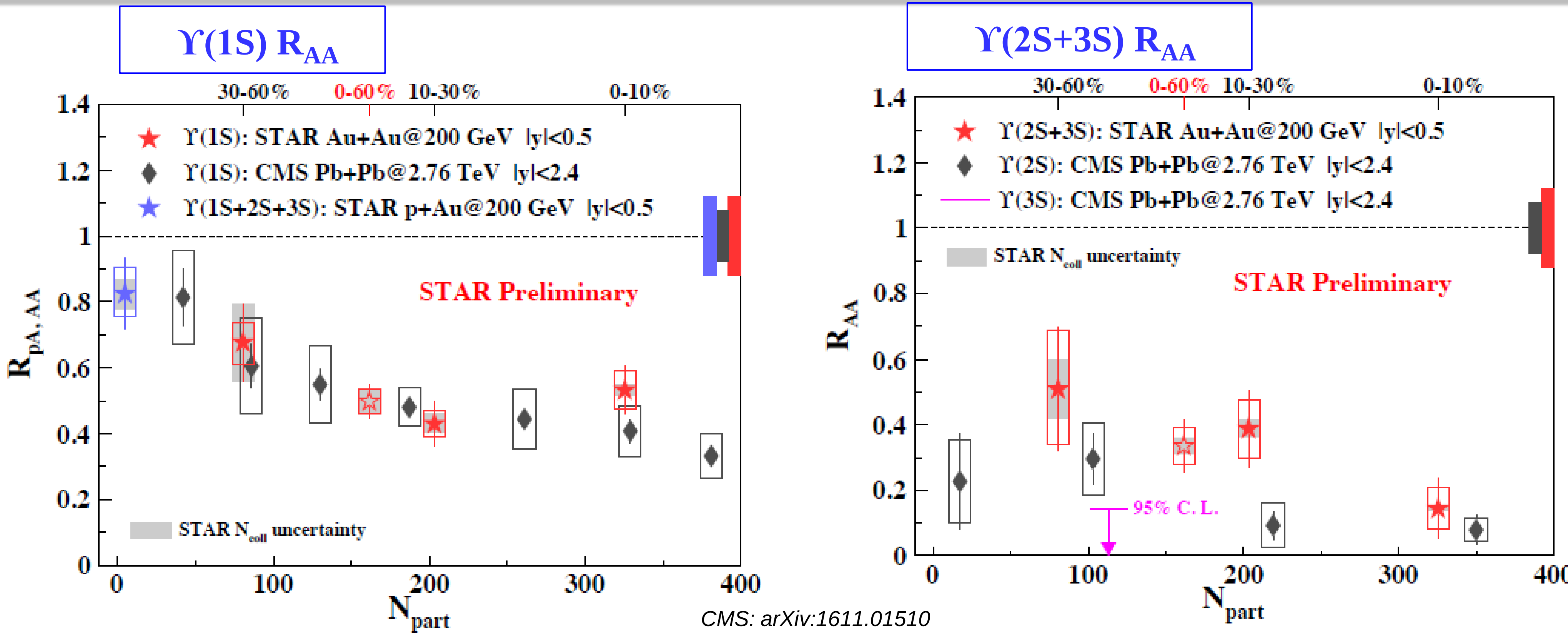
Υ(2S+3S)/Υ (1S)



World-wide p+p: W. Zha, et. al, PRC 88 (2013) 067901

- Υ(1S): more suppression towards more central collisions
- Υ(2S+3S)/ Υ(1S): Υ(2S+3S) more suppressed than Υ(1S) in the 0-10% central collisions - **sequential melting**

Comparison to LHC



CMS: arXiv:1611.01510

- ϒ(1S) : similar suppression at the RHIC and at the LHC
- ϒ(2S+3S): hint of less suppression at RHIC
- For both, more suppression towards central collisions

Quarkonia summary

p+Au collisions

- J/ψ R_{pAu} ~ R_{dAu}: suggests similar CNM effects between p+Au and d+Au collisions
- J/ψ R_{pAu} favors additional nuclear absorption effect on top of nPDF effect
- ϒ R_{pAu} : indication of suppression → CNM effects

Au+Au collisions

- J/ψ R_{AA} < 1 with p_T > 5 GeV/c -> dissociation in effect
- Smaller J/ψ R_{AA} at RHIC in low-p_T → smaller regeneration contribution due to lower charm cross-section
- Larger J/ψ R_{AA} at RHIC in high-p_T → smaller dissociation rate due to lower temperature
- Direct ϒ(1S) may be suppressed at RHIC → constrain medium T
- 0-10%: ϒ(2S+3S) R_{AA} < ϒ(1S) R_{AA} → sequential melting

Outlook

- Two times Au+Au data on disk for both dielectron and dimuon channels