Heavy flavor measurements at the STAR experiment

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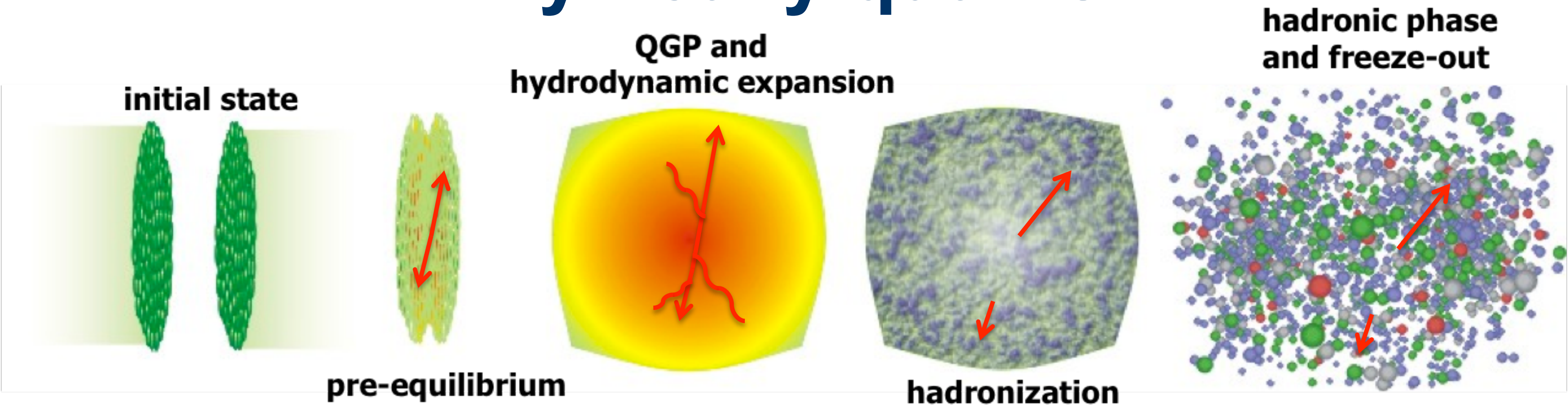
for the STAR Collaboration

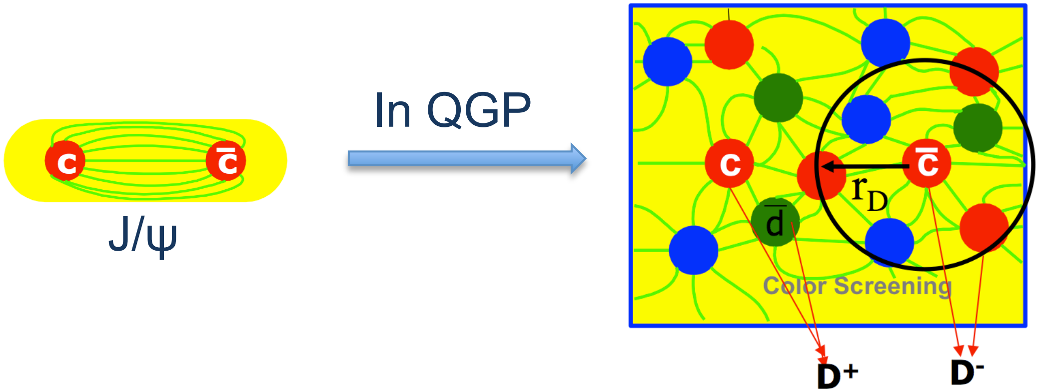
Outline

- Introduction – why heavy quarks?
- STAR detectors
    - Heavy Flavor Tracker
    - Muon Telescope Detector
- Open charm hadron measurements
    - D^0 R_{AA}
    - D^0 v_2
    - D_s yield
- Quarkonia measurements
    - J/ψ p_T spectrum
    - J/ψ production vs. event multiplicity
    - J/ψ R_{AA}
    - J/ψ v_2
    - Υ production
- Summary

Why heavy quarks?



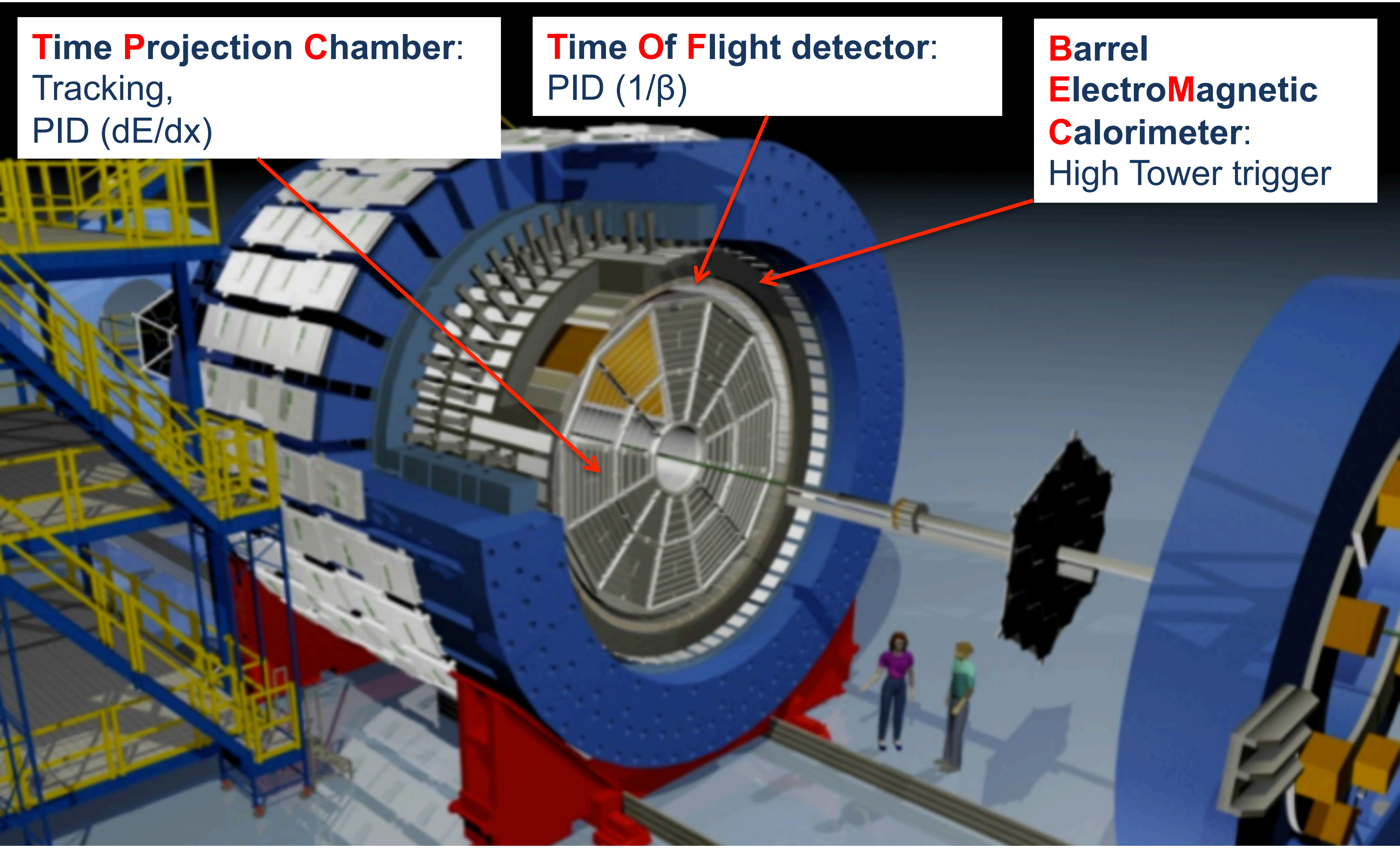
- $m_{b,c} >> T_C, \Lambda_{QCD}, m_{u,d,s}$
- Produced early in initial hard scatterings at RHIC
- Experience the whole evolution of the medium
- Good probe to the properties of the medium



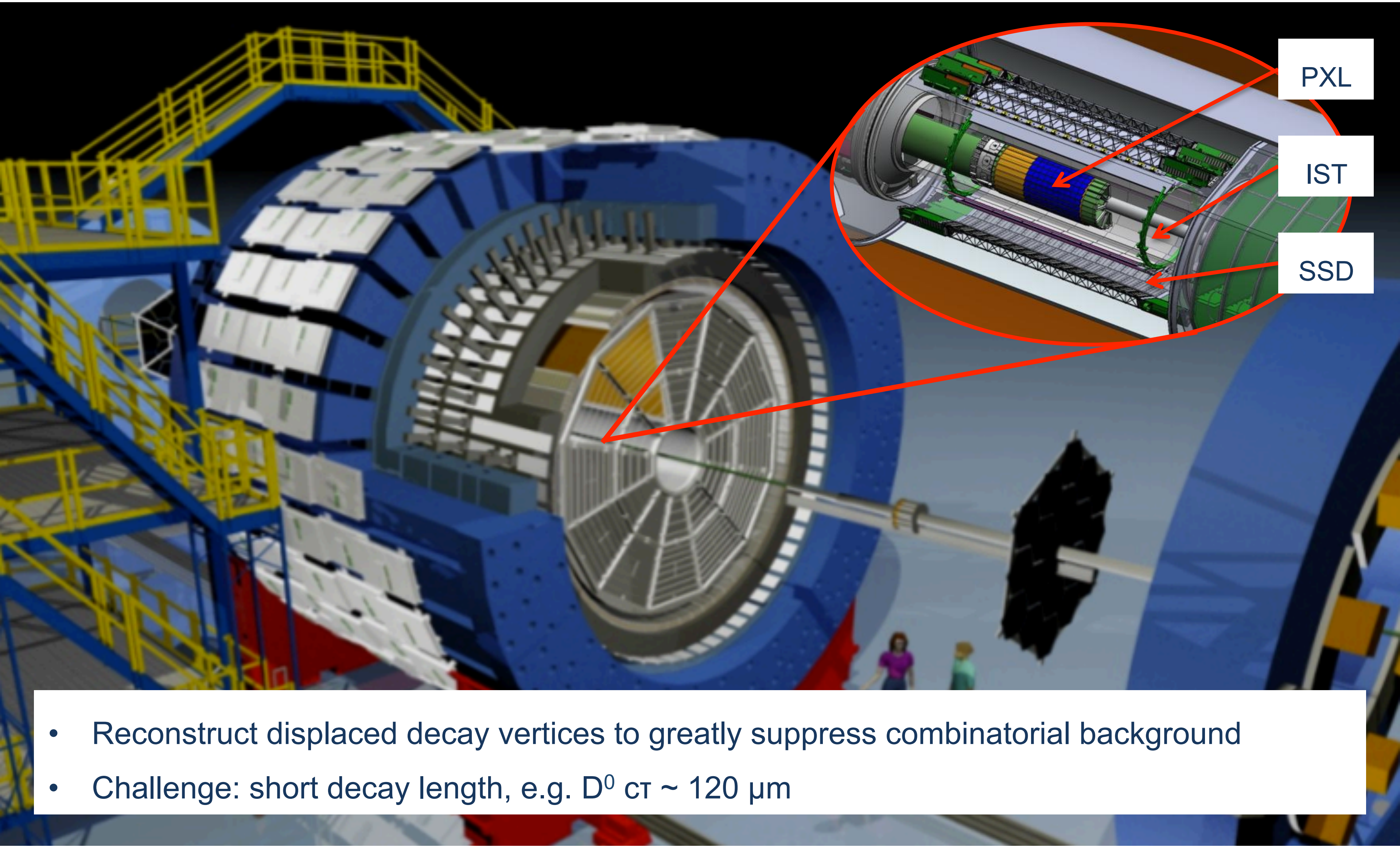
Quarkonium dissociation due to color screening

QGP signature

STAR experiment

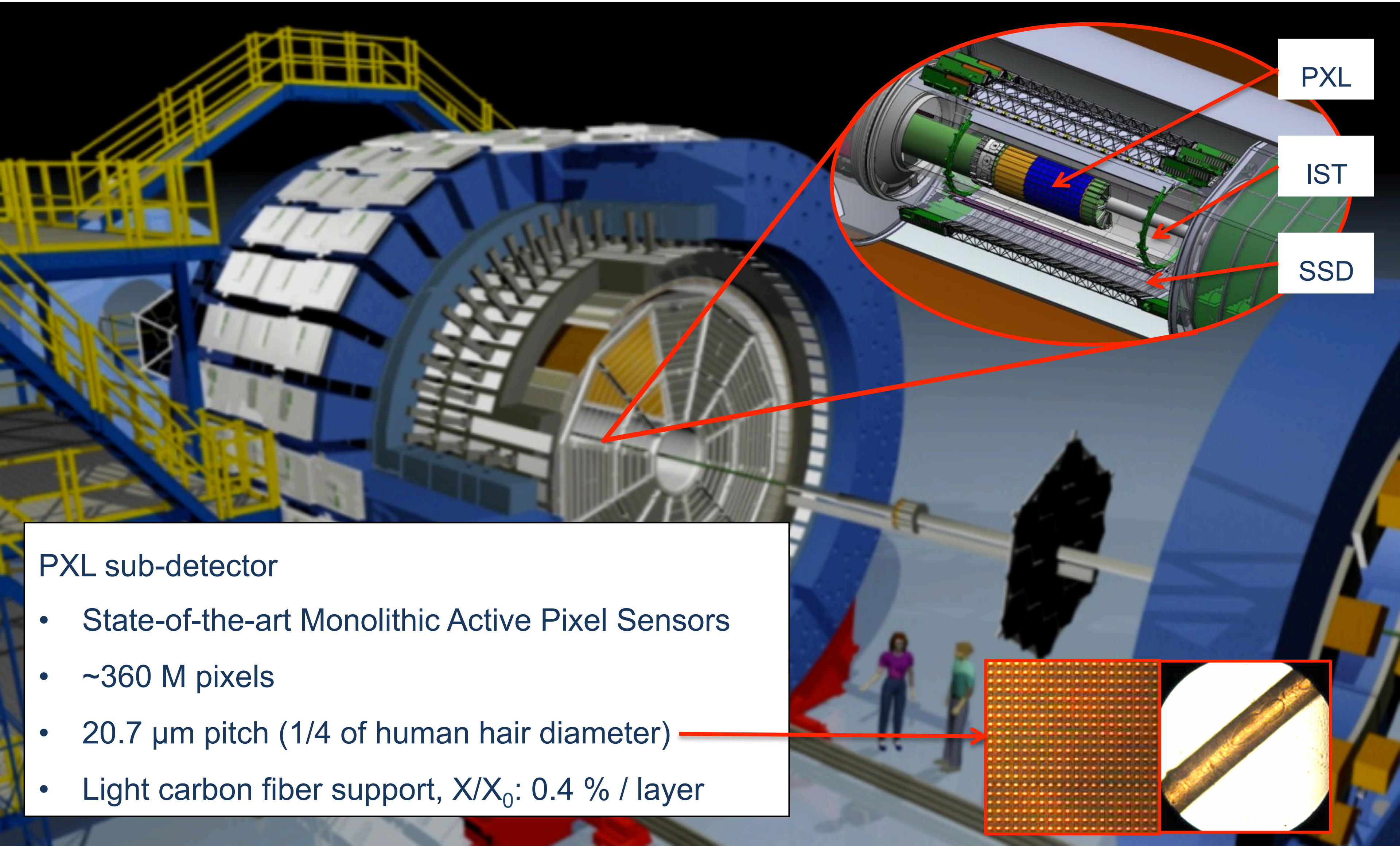


Heavy Flavor Tracker



- Reconstruct displaced decay vertices to greatly suppress combinatorial background
- Challenge: short decay length, e.g. D^0 cτ ~ 120 μm

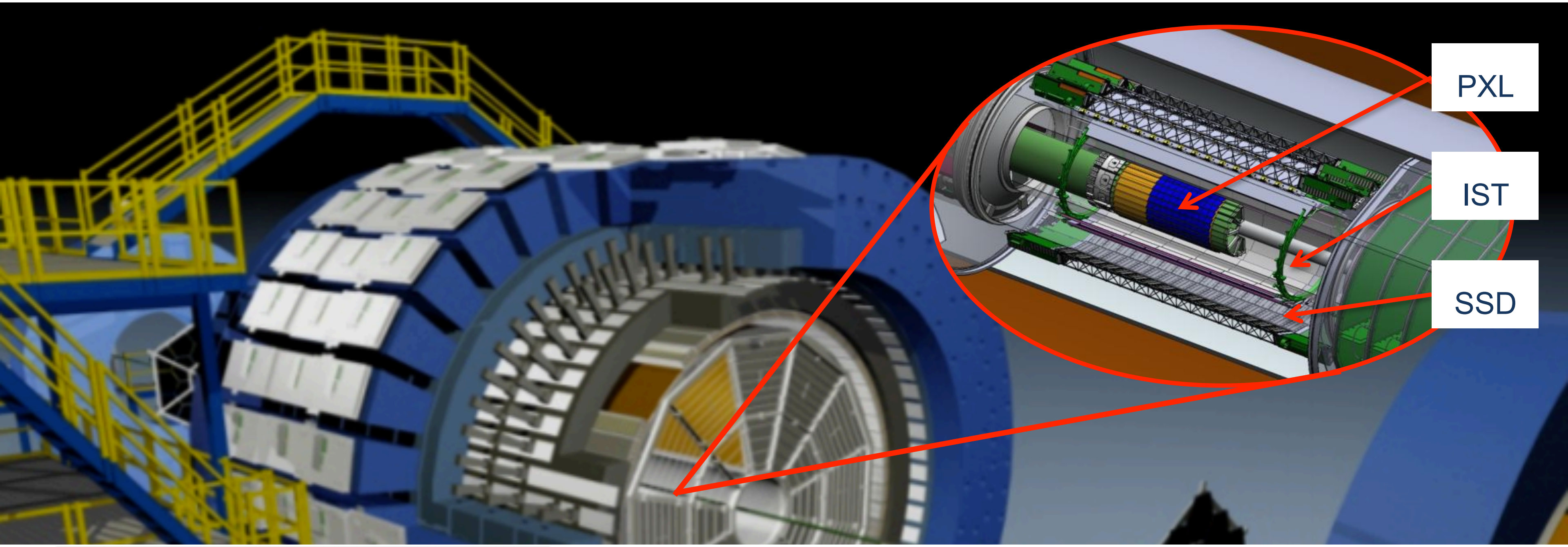
Heavy Flavor Tracker

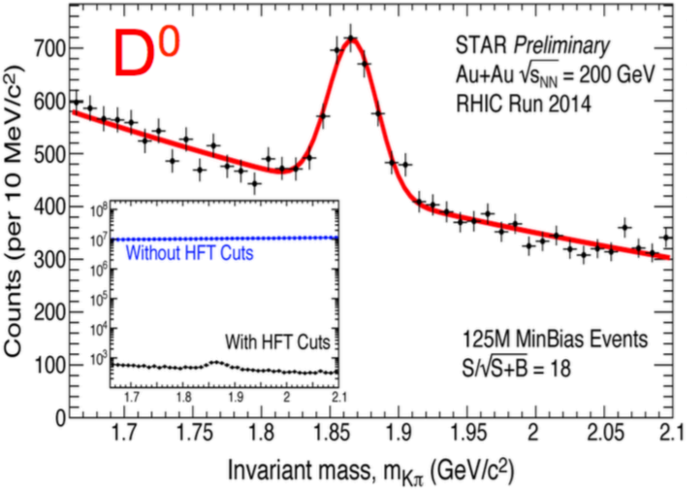


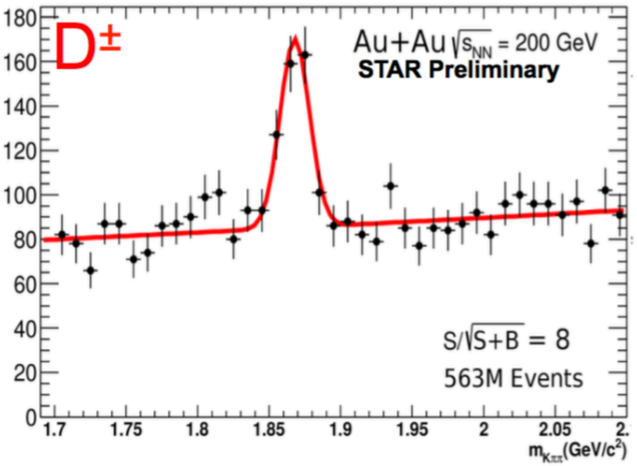
PXL sub-detector

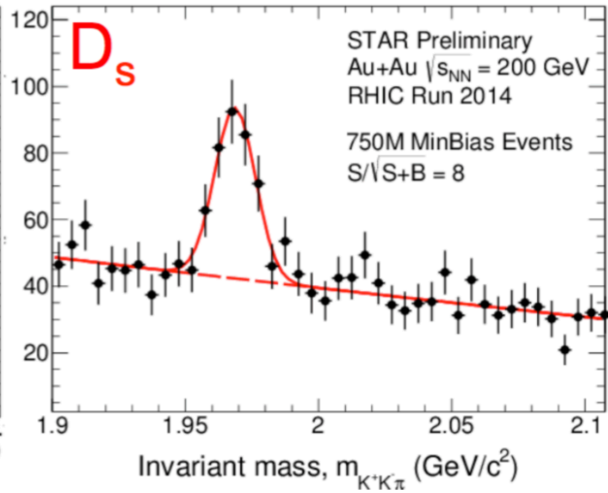
- State-of-the-art Monolithic Active Pixel Sensors
- ~360 M pixels
- 20.7 μm pitch (1/4 of human hair diameter)
- Light carbon fiber support, X/X_0: 0.4 % / layer

Heavy Flavor Tracker

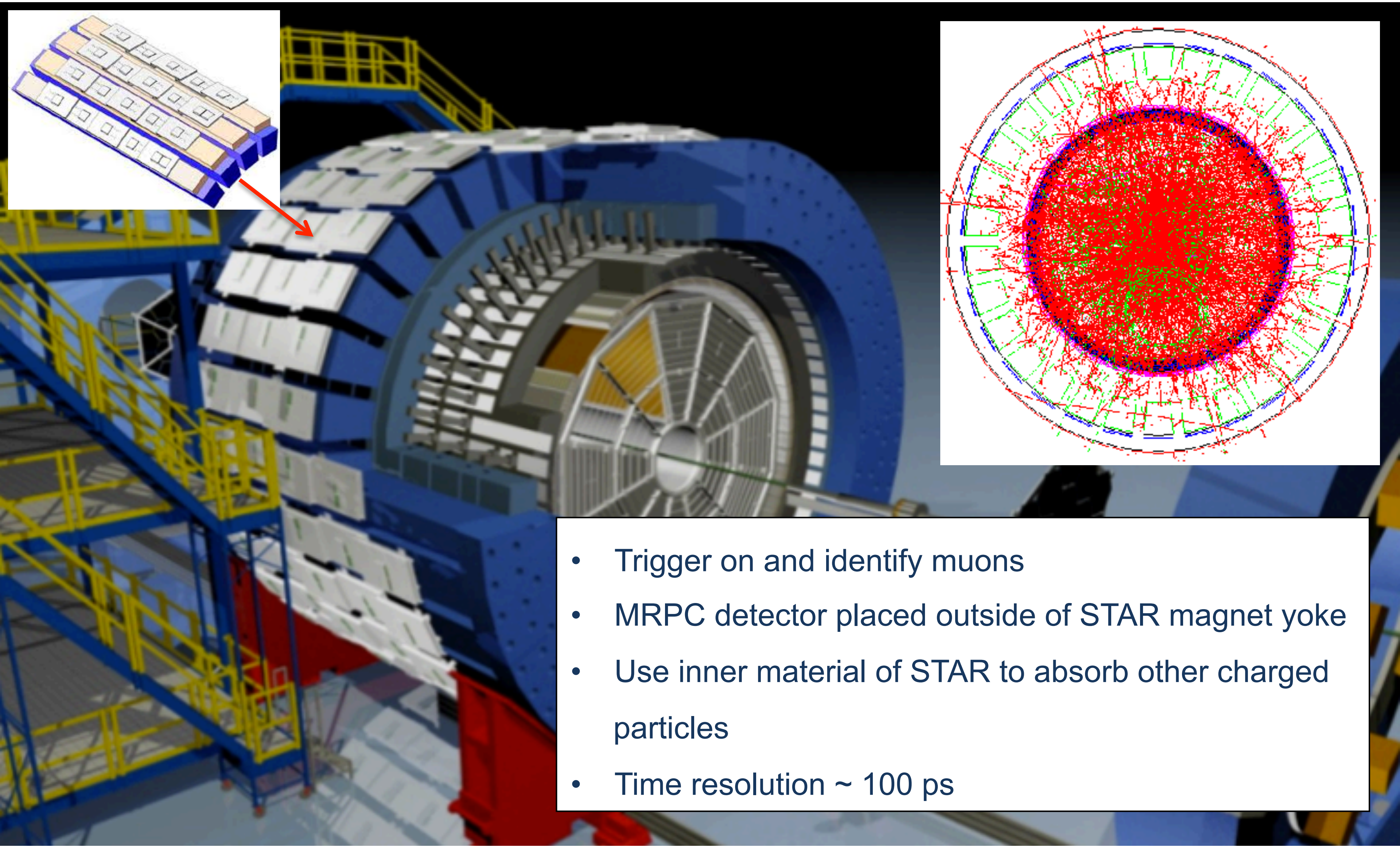






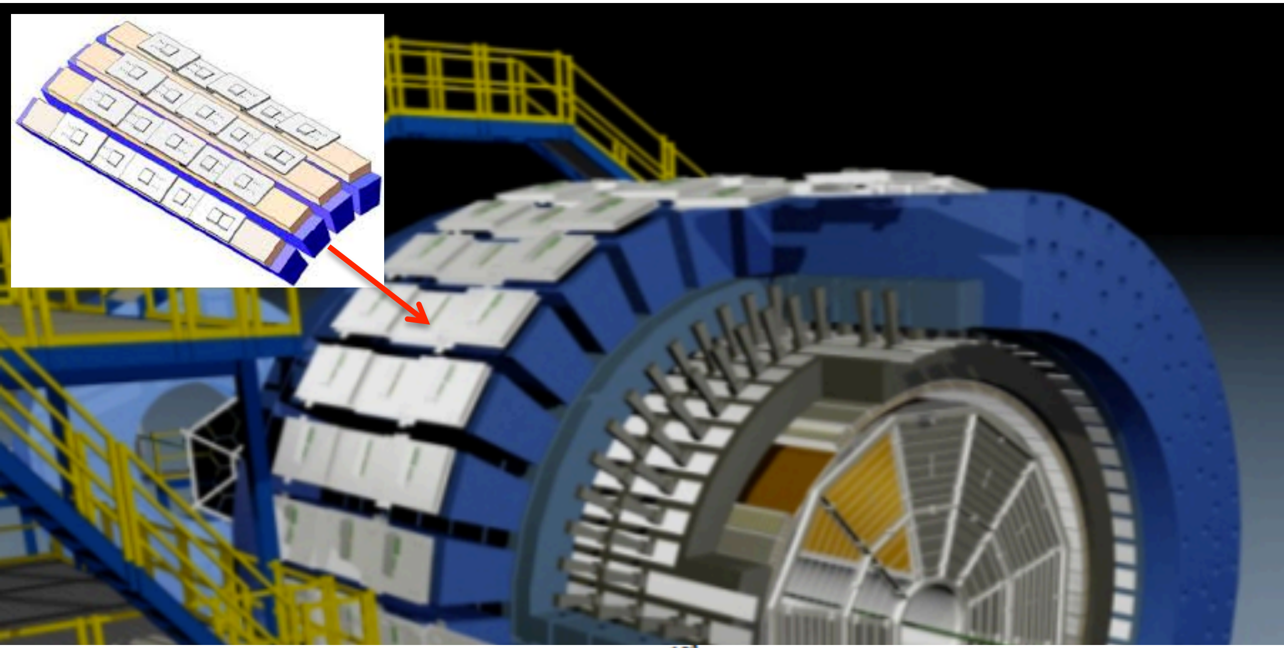


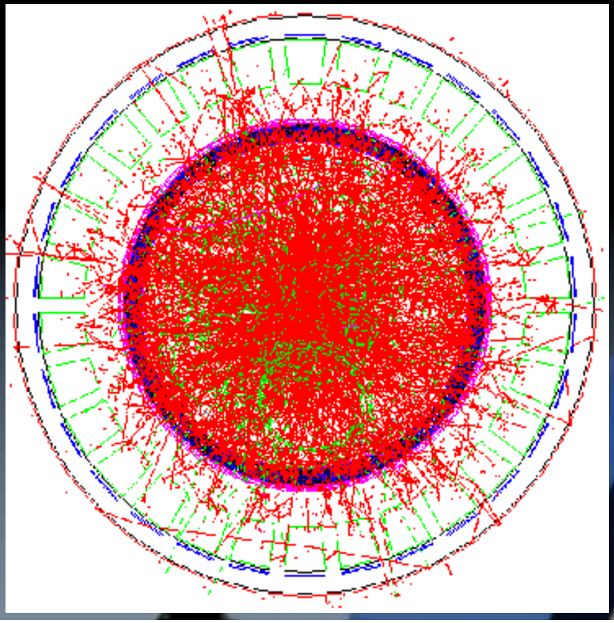
Muon Telescope Detector

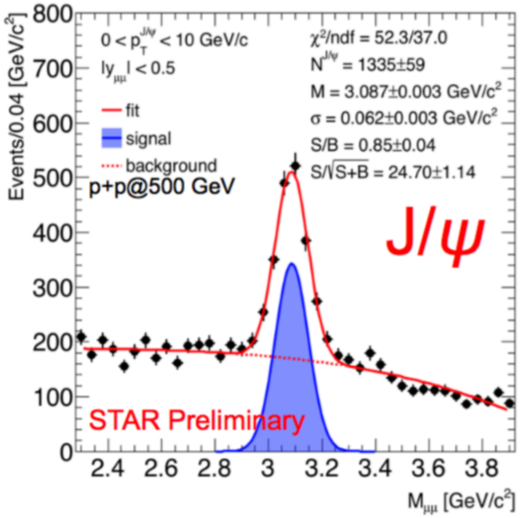


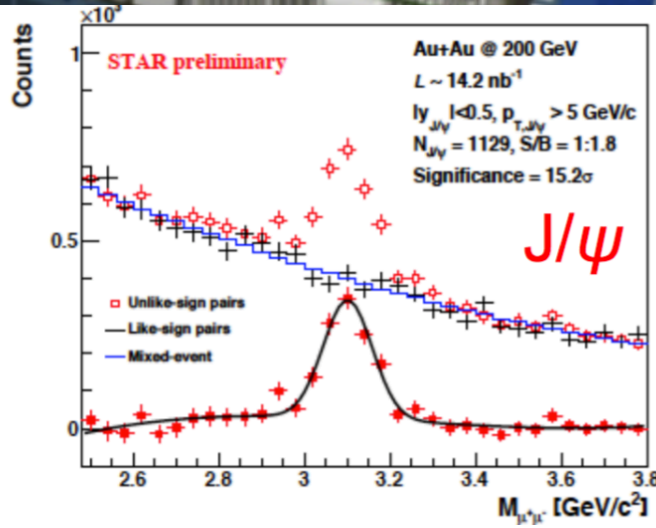
- Trigger on and identify muons
- MRPC detector placed outside of STAR magnet yoke
- Use inner material of STAR to absorb other charged particles
- Time resolution ~ 100 ps

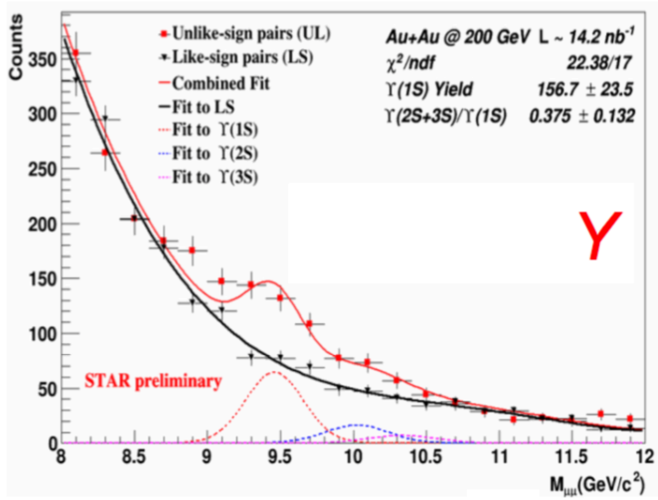
Muon Telescope Detector





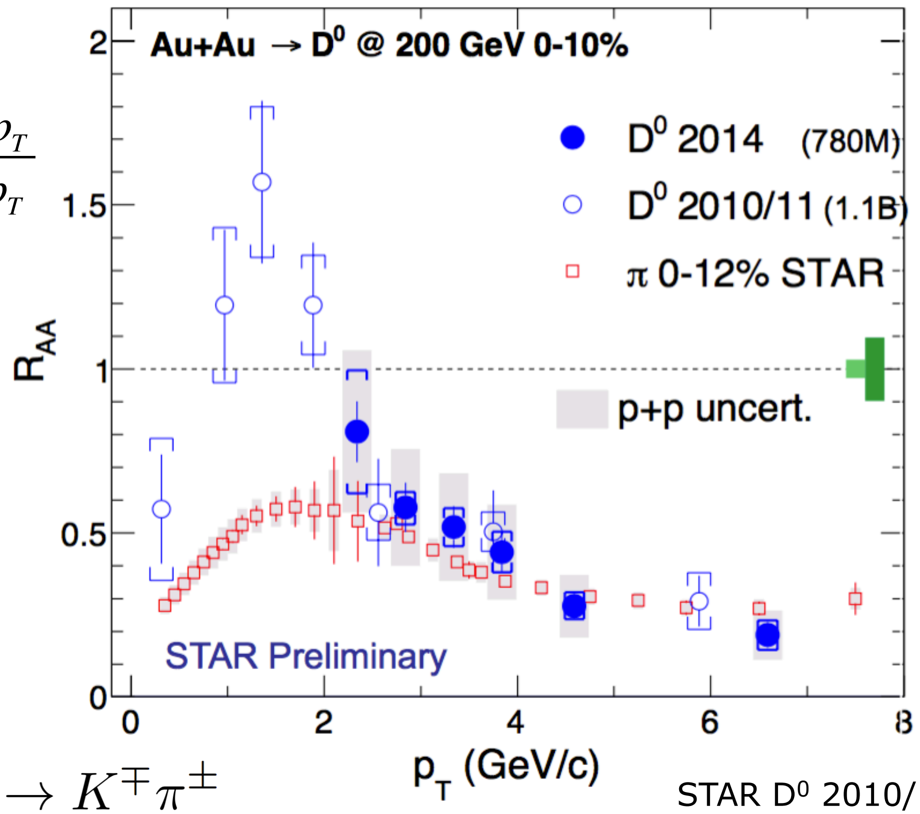






D^0 R_{AA}

$$R_{AA} = \frac{\sigma_{inel}}{\langle N_{coll} \rangle} \frac{d^2 N_{AA} / dydp_T}{d^2 \sigma_{pp} / dydp_T}$$



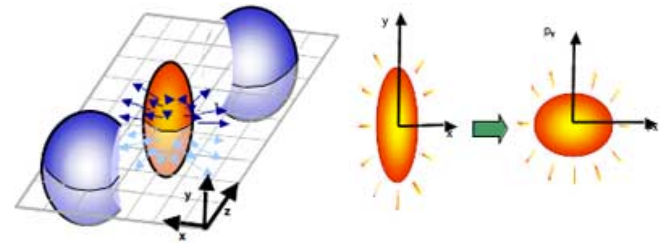
$$D^0(\overline{D^0}) \rightarrow K^{\mp}\pi^{\pm}$$

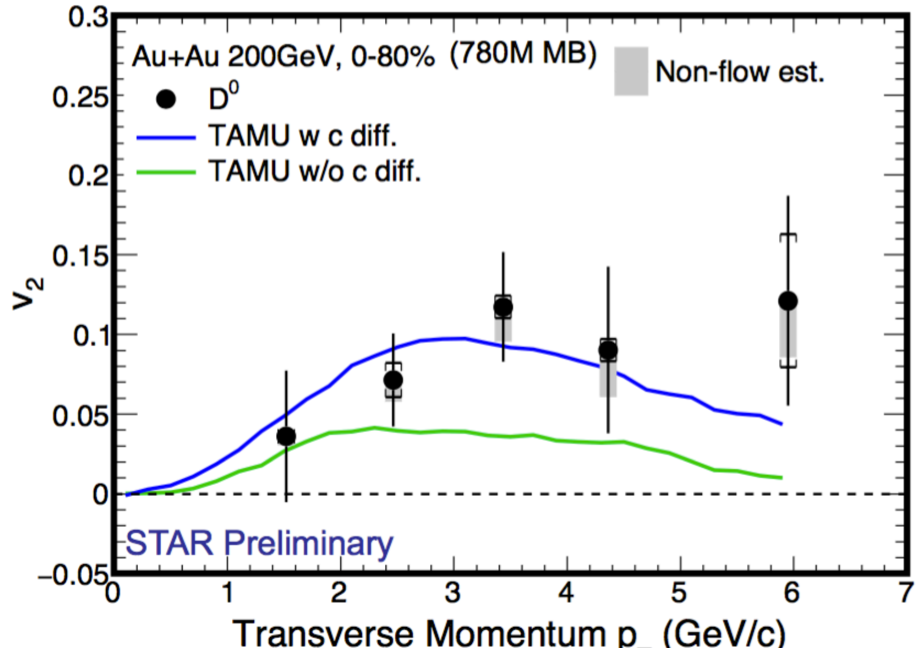
STAR D^0 2010/11: PRL 113 (2014) 142301
STAR π 0-12%: PLB 655 (2007) 104

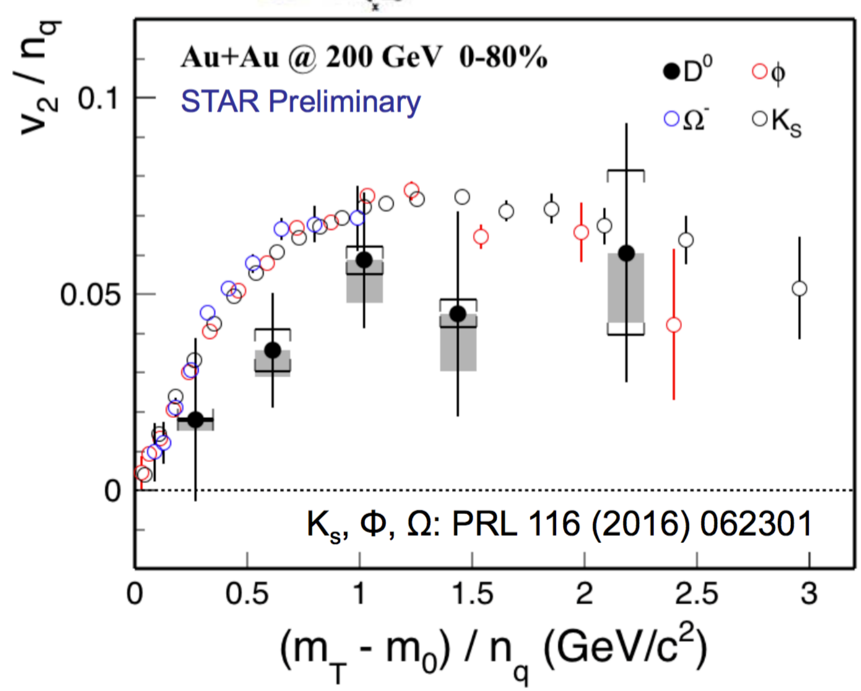
- R_{AA}>1 for p_T~1.5 GeV/c ➡ Charm coalescence with a radially flowing bulk medium
- Significant suppression at high p_T in central Au+Au collisions, R_{AA}(D) ~ R_{AA}(π) for p_T > 4 GeV/c ➡ Strong charm-medium interaction

D^0 v_2

$$E\frac{d^3N}{d^3p}=\frac{1}{2\pi}\frac{d^2N}{p_t dp_t dy}\left(1+\sum_{n=1}^{\infty}2v_n\cos[n(\phi-\Psi_r)]\right)$$





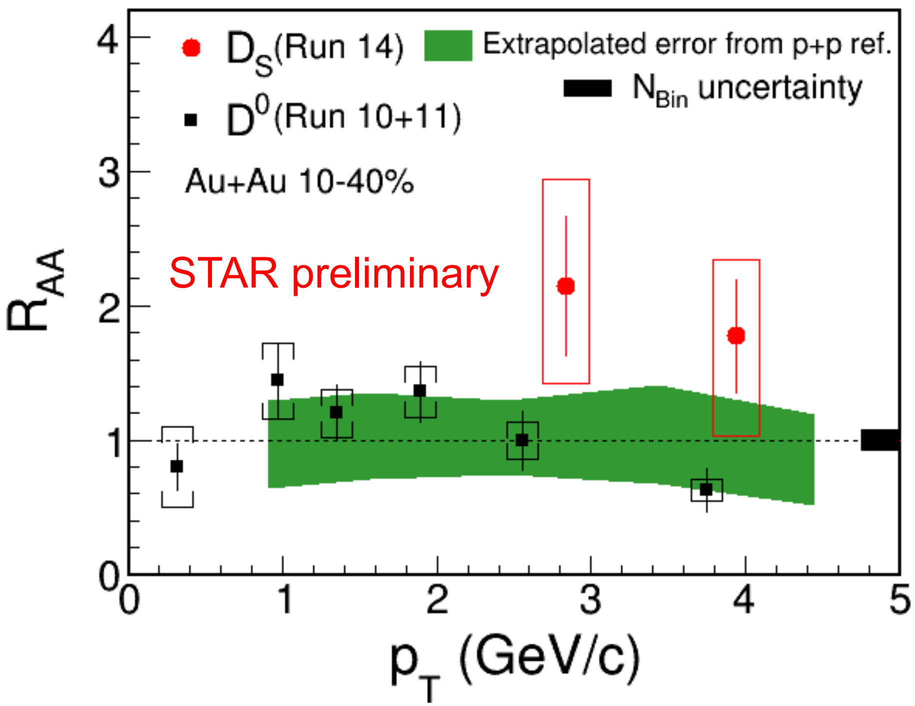


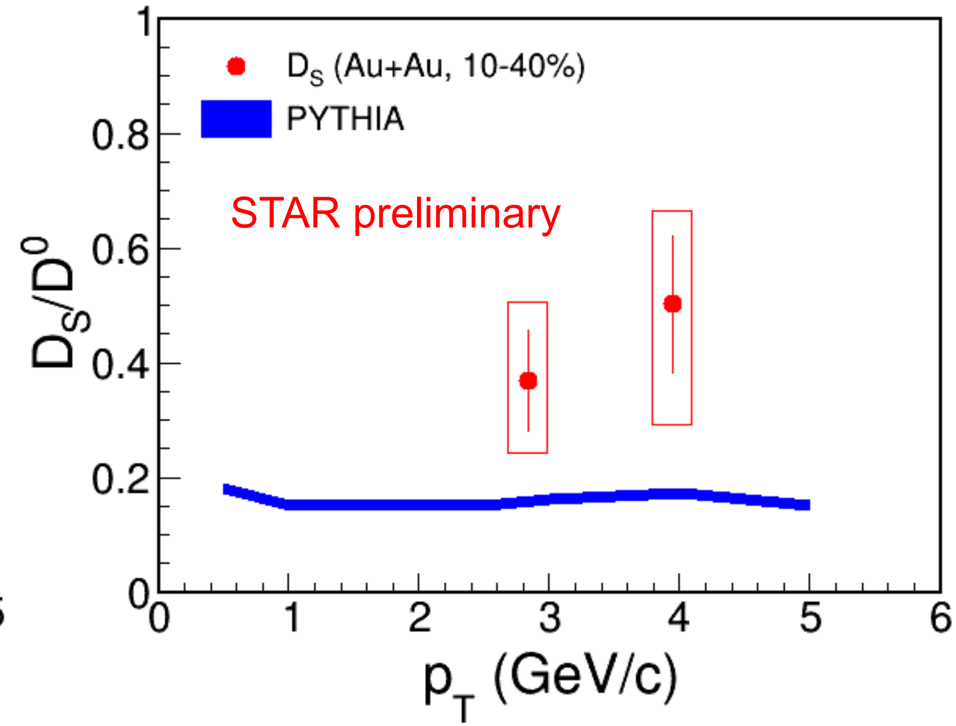
TAMU theory curves: private communications
PRC 86 (2012) 014903, PRL 110 (2013) 112301

$$m_T=\sqrt{p_T^2+m_0^2}$$

- Non-zero v_2 for p_T>2 GeV/c
- Favors charm quark diffusion, when comparing with model calculations
- Lower than light hadron v_2 ➡ Indication that charm quarks are not fully thermalized with the medium?

D_s production



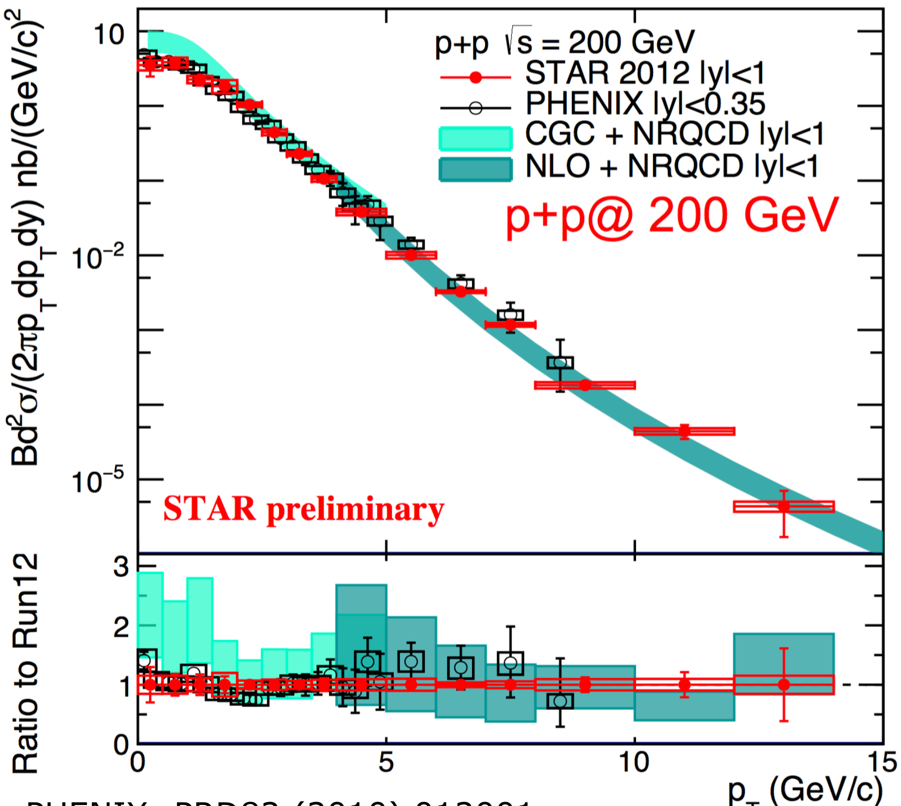


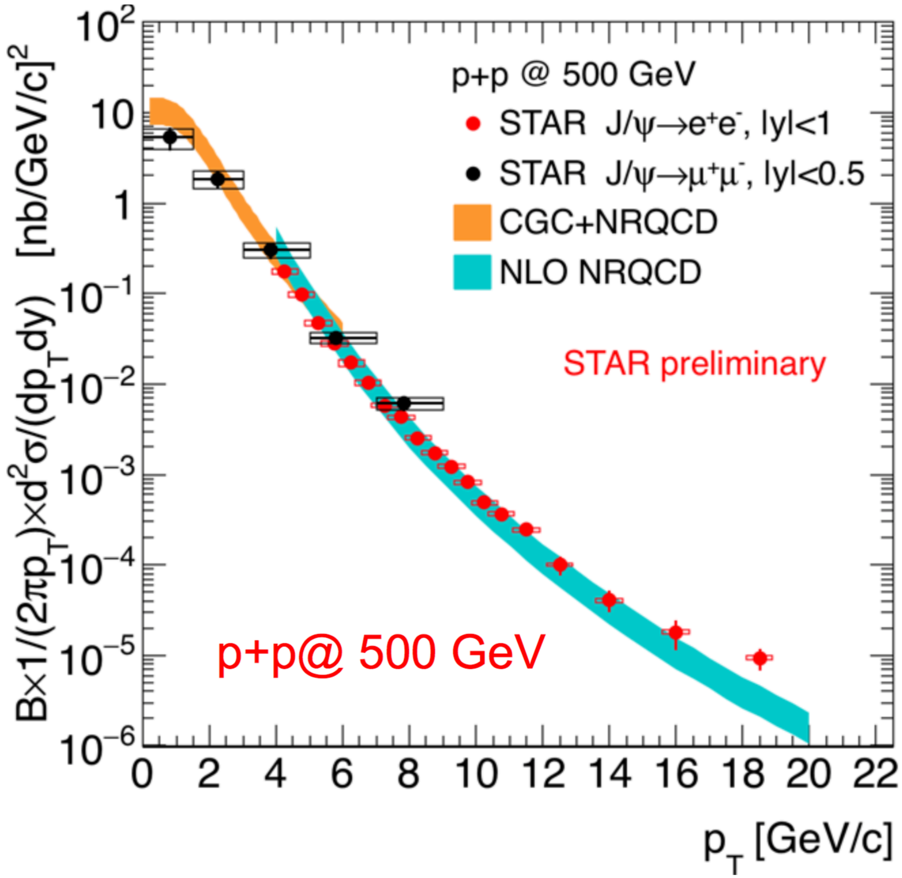
$$D_S^{\pm} \longrightarrow \phi\,(\longrightarrow K^{+}+K^{-}) + \pi^{\pm}$$

D^0 R_{AA}: Phys. Rev. Lett. 113 (2014) 142301
D_s in p+p deduced from STAR charm crosssection: Phys. Rev. D 86 (2012) 72013

- Strangeness enhancement in the QGP is expected to affect the yield of D_S.
- The R_{AA} of D_S is higher than unity and R_{AA} of D^0, but statistically not significant.
- The ratio D_S/D^0 seems to be higher than prediction for p+p collision from PYTHIA.

J/ψ p_T spectra in p+p collisions

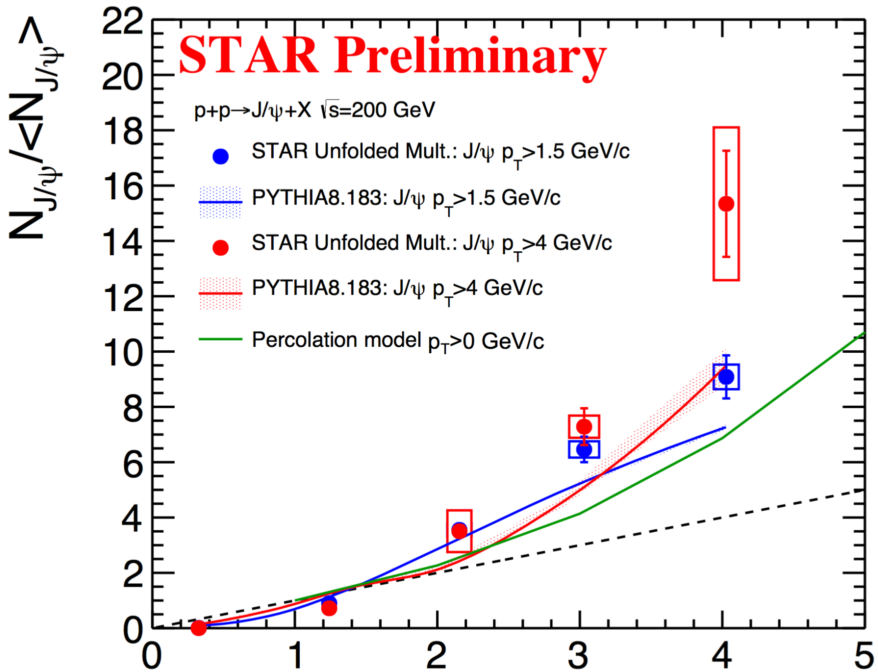




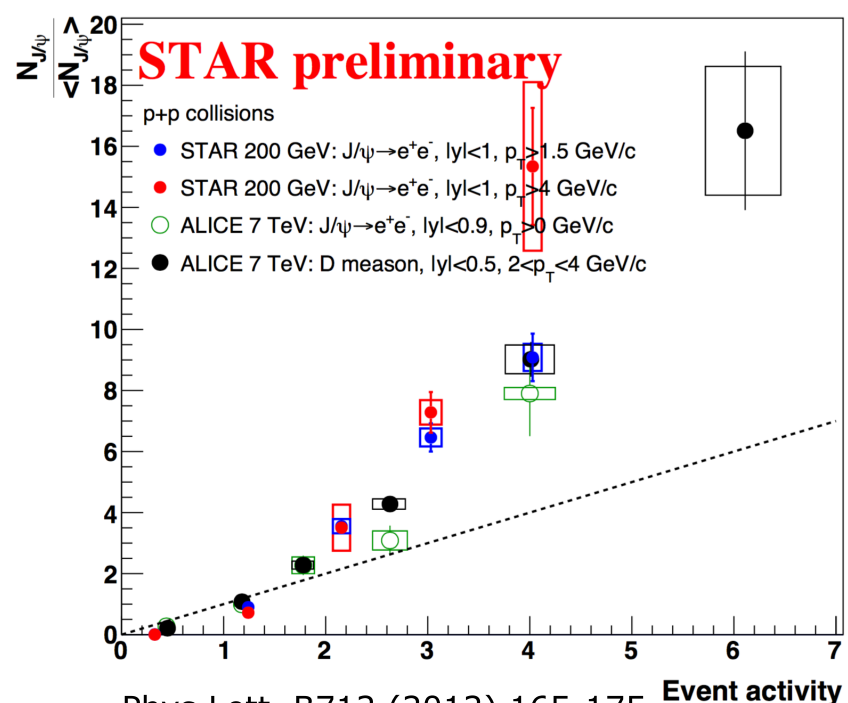
PHENIX: PRD82 (2010) 012001
NLO NRQCD: Ma et al., PRL106 (2011) 042002 CGC +NRQCD: Ma, Venugopalan, PRL113 (2014) 192301

- NRQCD describes data fairly well at both 200 and 500 GeV
- Small tension at p_T<1 GeV/c with CGC+NRQCD

J/ψ production vs. event multiplicity



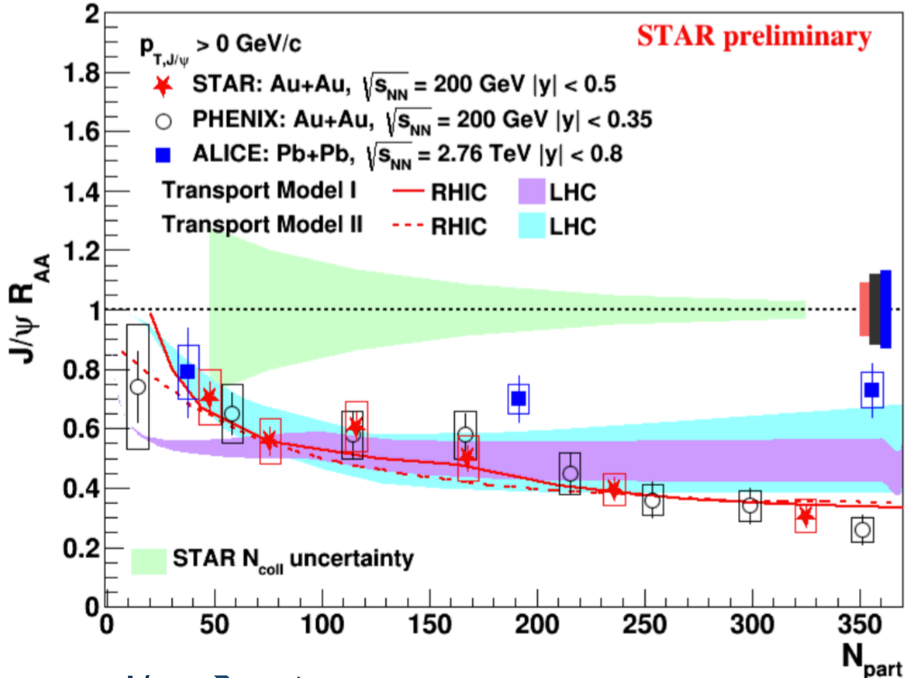
PRC 86 (2012) 034903, and private communication

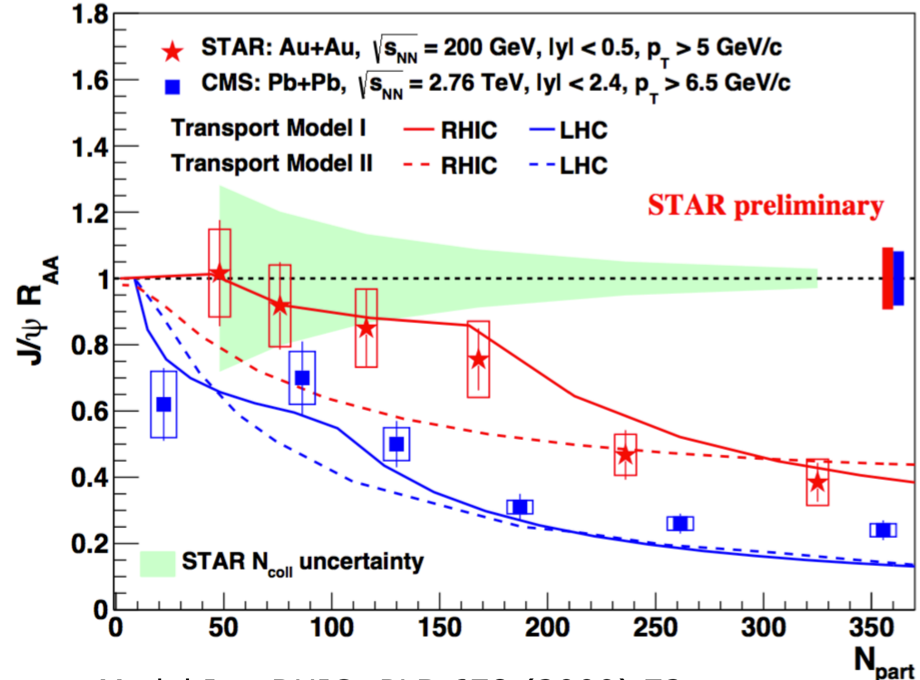


Phys.Lett. B712 (2012) 165-175
Nucl.Phys. A931 (2014) 552-557

- Stronger-than-linear growth for relative J/ψ yield ⇨ Soft and hard processes are correlated
- PYTHIA8 and Percolation model reproduce trends in data qualitatively
- Hint of different trends for low and high p_T J/ψ
- Similar trend as LHC results ⇨ new challenge for models (like EPOS3+Hydro) to explain

J/ψ R_{AA}





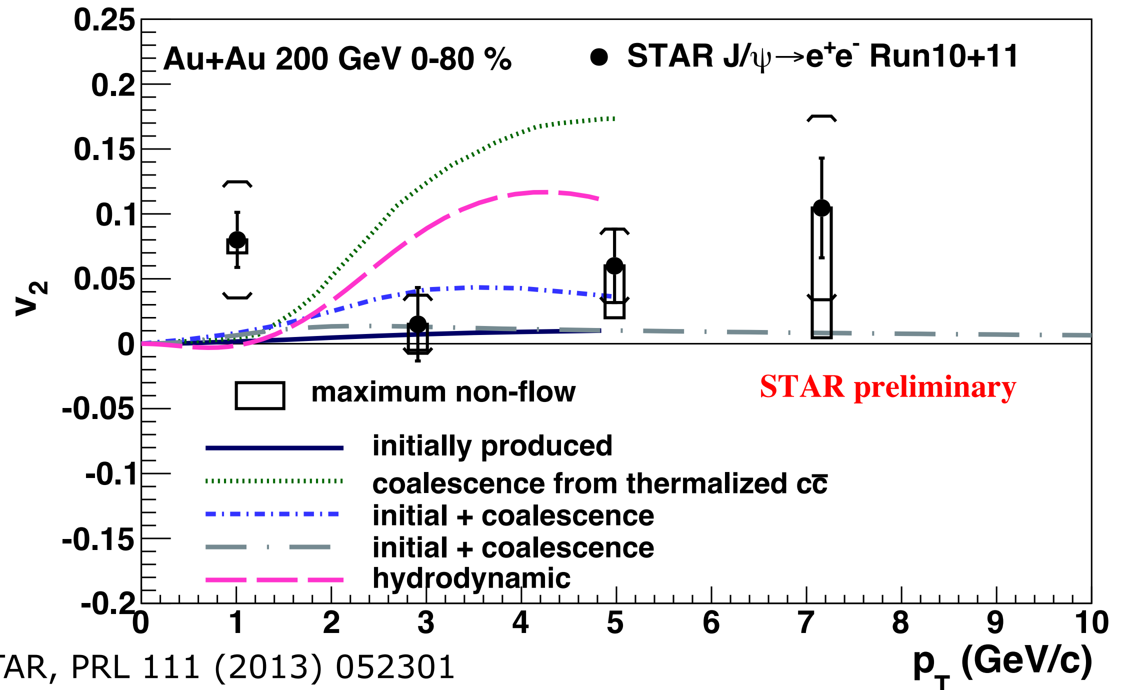
J/ψ ➔ $\mu^+\mu^-$

ALICE : PLB 734 (2014) 314
CMS: JHEP 05 (2012) 063
PHENIX: PRL 98 (2007) 232301

Model I at RHIC: PLB 678 (2009) 72
Model I at LHC: PRC 89 (2014) 054911
Model II at RHIC: PRC 82 (2010) 064905
Model II at LHC: NPA 859 (2011) 114

- J/ψ R_{AA} for p_T>0 GeV/c: RHIC is smaller than LHC ➔ more recombination at LHC
- J/ψ R_{AA} for p_T>5 GeV/c: LHC is smaller than RHIC ➔ stronger dissociation at LHC
- Transport models with dissociation and recombination qualitatively describe data

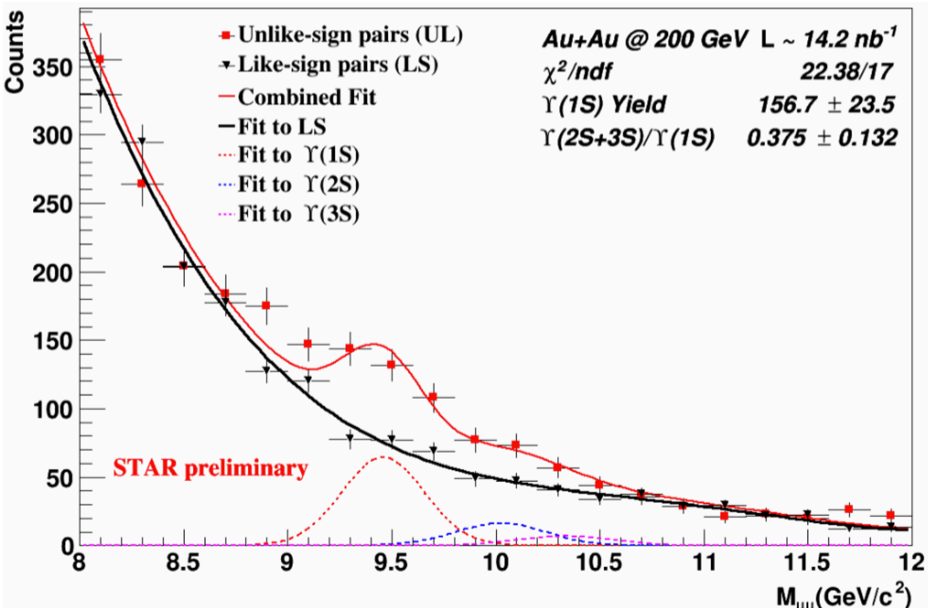
J/ψ v_2



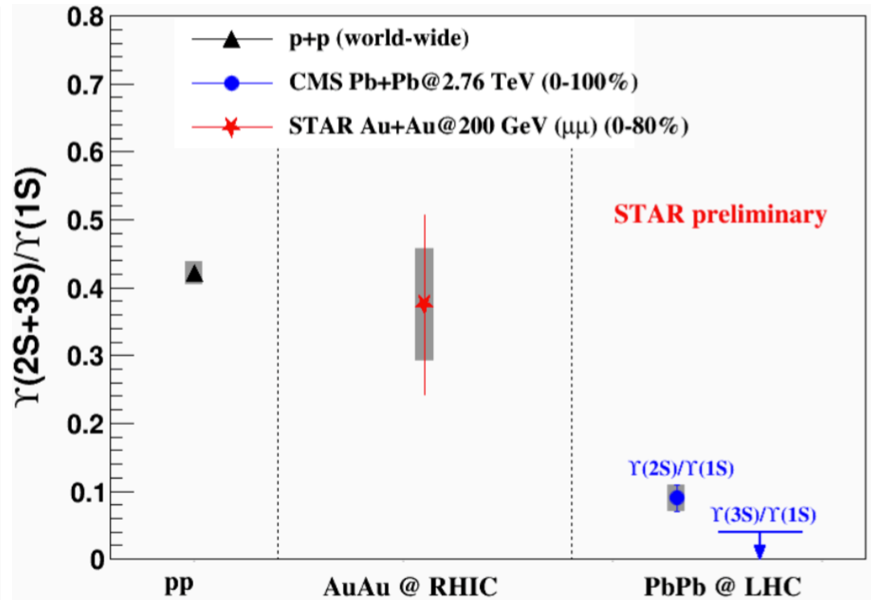
STAR, PRL 111 (2013) 052301
L. Yan, P. Zhuang, and N. Xu, PRL 97 (2006) 232301
V. Greco, C.M. Ko, and R. Rapp, PLB 595 (2004) 202
X. Zhao and R. Rapp, arXiv: 0806.1239
Y. Liu, N. Xu and P. Zhuang, NPA 834 (2010) 317
U.W. Heinz and C. Shen, (private communication)

- Initially produced J/ψ: little or zero v_2
- Recombined J/ψ: inherit v_2 of charm quarks
- For p_T above 2 GeV/c, measured v_2 is consistent with zero ⇨ contribution of recombined J/ψ is small

Υ production



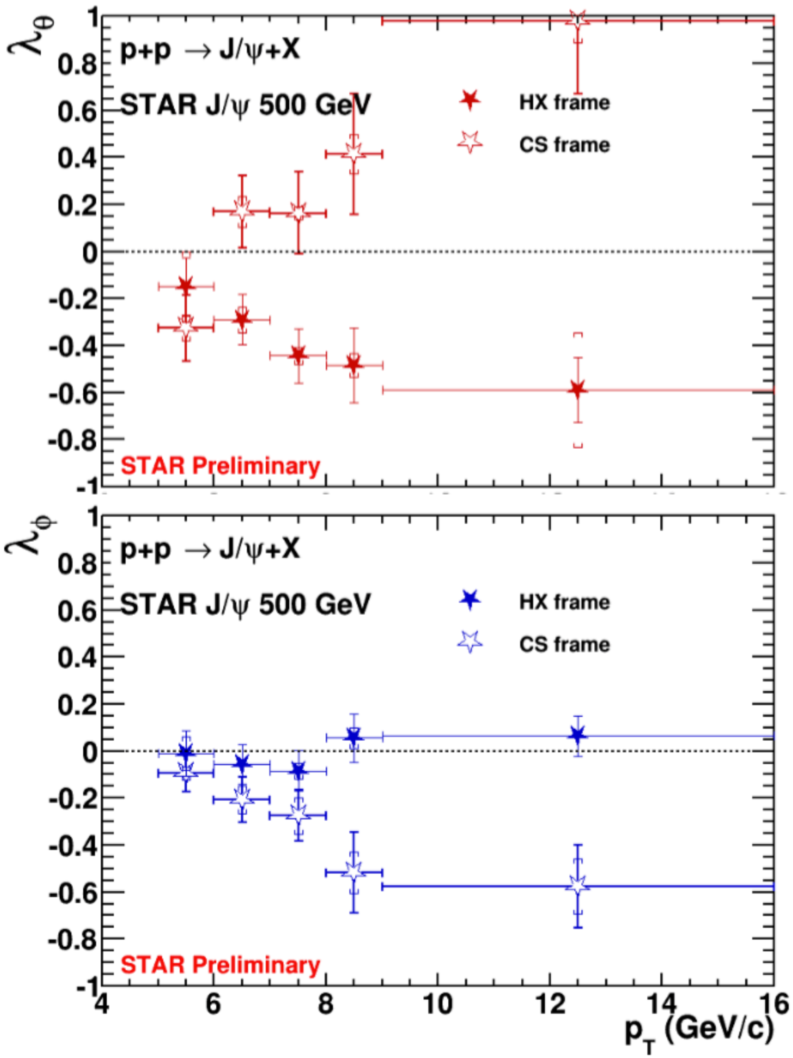
Υ ➔ $\mu^+\mu^-$



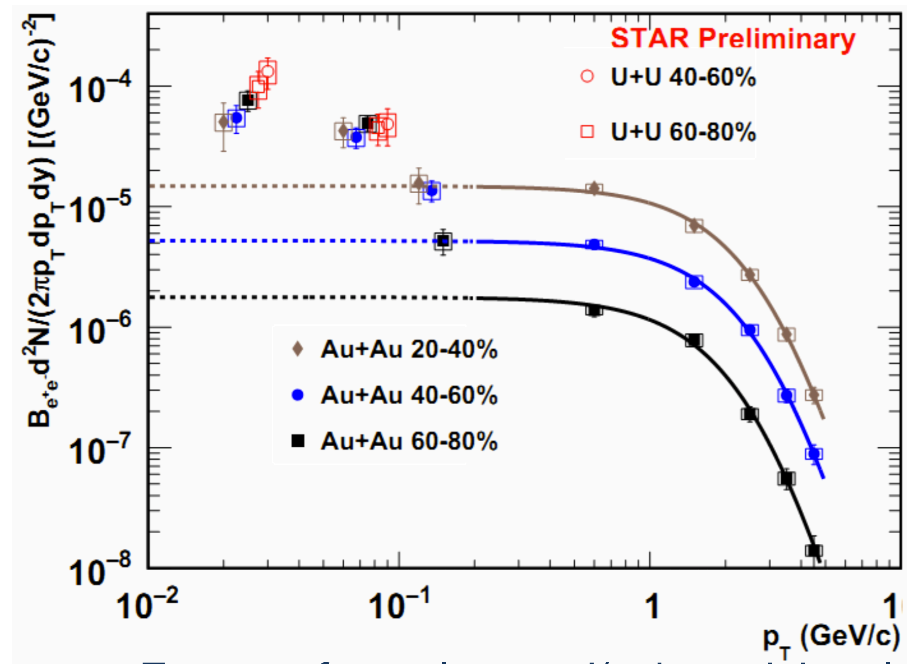
CMS : PRL 109 (2012) 222301 JHEP 04 (2014) 103

- Signs of Υ(2S+3S) from the di-muon channel
  - Challenging for di-electron channel due to Bremsstrahlung
- Hint of less melting of Υ(2S+3S) at RHIC than at LHC

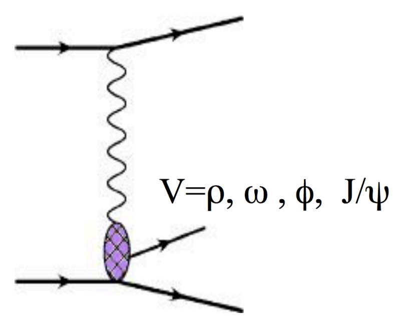
Other interesting results



- Longitudinal J/ψ polarization at high p_T in p+p 500 GeV collisions



- Excess of very low p_T J/ψ in peripheral A+A collisions
- Consistent with photoproduction



More details in back-up

Summary

- HFT and MTD greatly improve open heavy flavor and quarkonia studies at STAR.

- D^0 R_{AA} and v_2 show strong charm-medium interaction, but there is also an indication that charm is not fully thermalized.
- D_s yield is in accordance with predicted strangeness enhancement in the QGP.

- J/ψ p_T spectrum in p+p collisions can be described well by (CGC+)NRQCD.
- J/ψ production vs. event multiplicity shows correlation between soft and hard processes.
- J/ψ R_{AA}, v_2 and Υ production indicate that quarkonium dissociation is weaker at RHIC energy than LHC, and the recombination production is also much less.

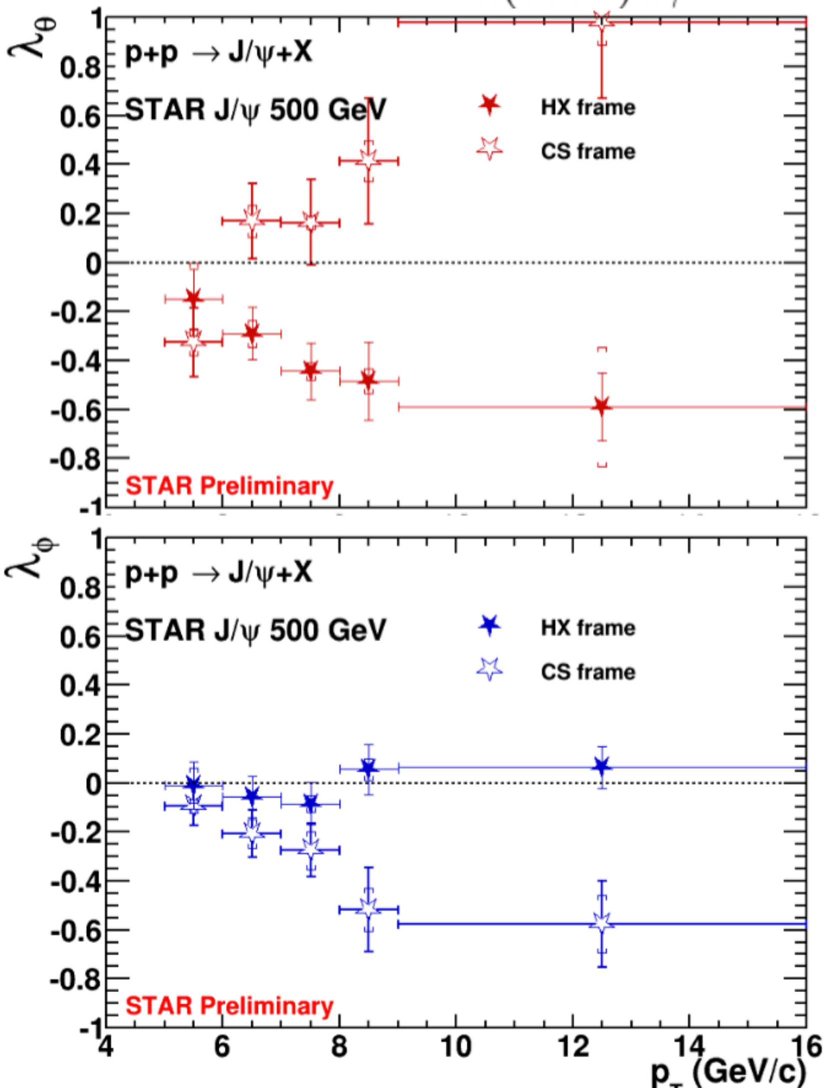
- More exciting results are expected:
  - Factor of 2-4 improvement in D^0 significance with new PXL offline reconstruction software
  - Factor of 2 (4) Au+Au data recorded on tape for the MTD (HFT)

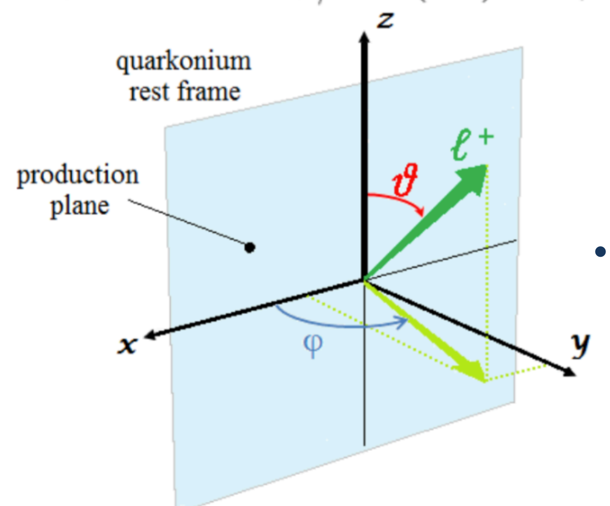
Thank you
☺

J/ψ polarization

$J/\psi \rightarrow e^+e^-$

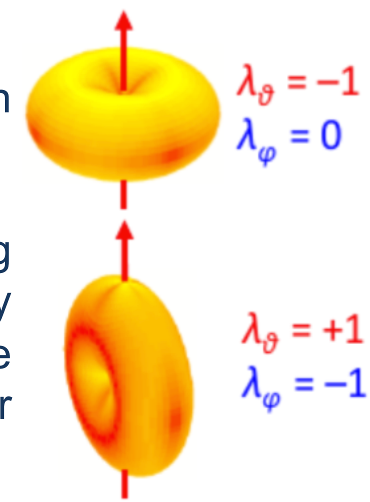
$$\frac{d\sigma}{d(\cos\theta)d\phi} \propto 1 + \lambda_\theta \cos^2\theta + \lambda_{\theta\phi}\sin(2\theta)\cos\phi + \lambda_\phi \sin^2\theta\cos(2\phi)$$





- Longitudinal polarization observed at high p_T

Helicity (HX) frame: z along $p_{J/\psi}$ in collision center of mass



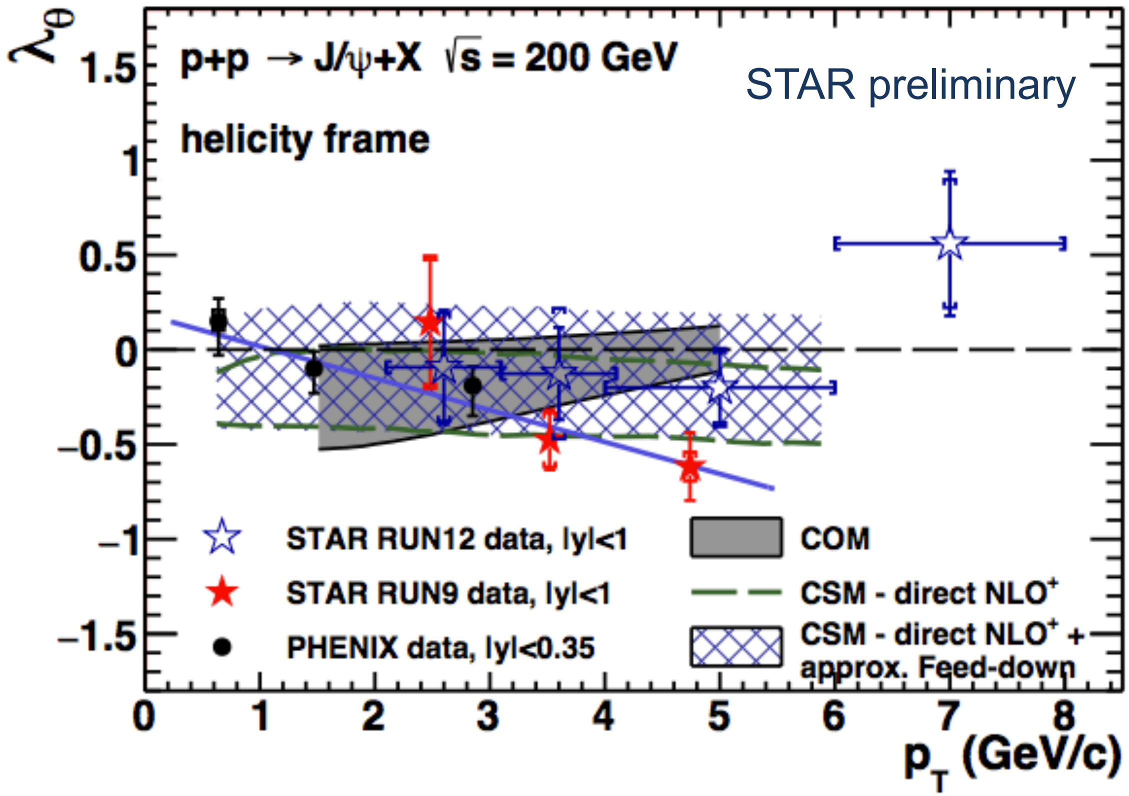
Collins-Soper (CS) frame: z along bisector of the angle formed by one beam direction and the opposite direction of the other beam in the J/ψ rest frame

- New constraint on models for J/ψ production in p+p collisions

J/ψ polarization

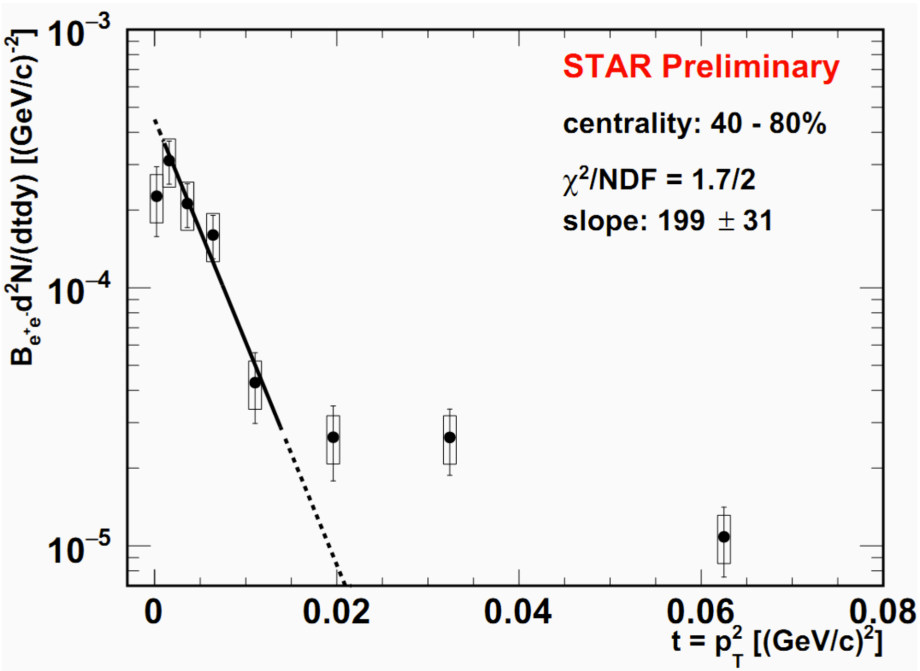
$J/\psi \rightarrow e^+e^-$

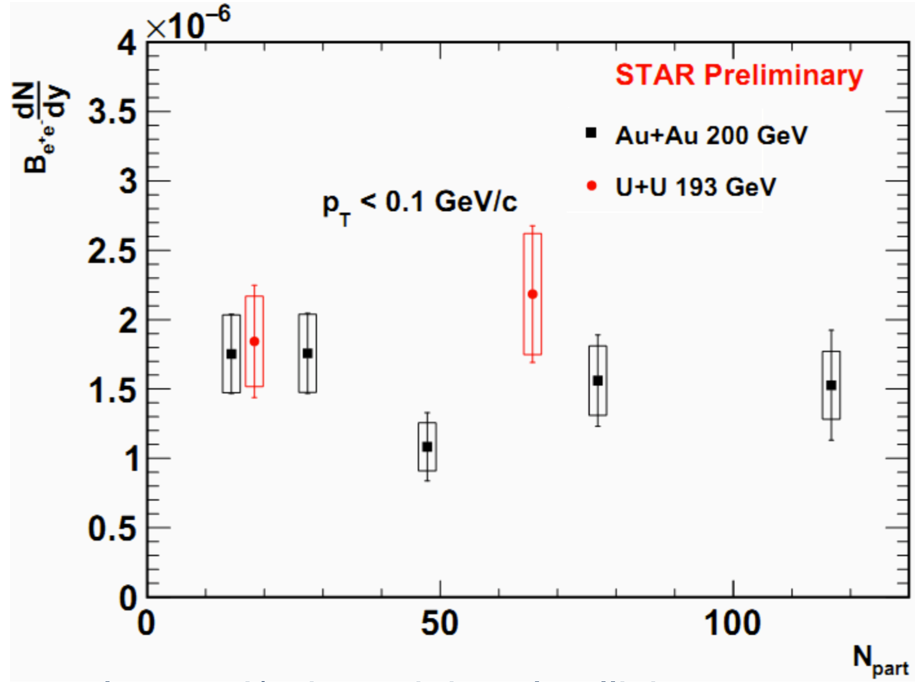
$$\frac{d\sigma}{d(cos\theta)d\phi} \propto 1 + \lambda_\theta cos^2\theta + \lambda_{\theta\phi} sin(2\theta)cos\phi + \lambda_\phi sin^2\theta cos(2\phi)$$

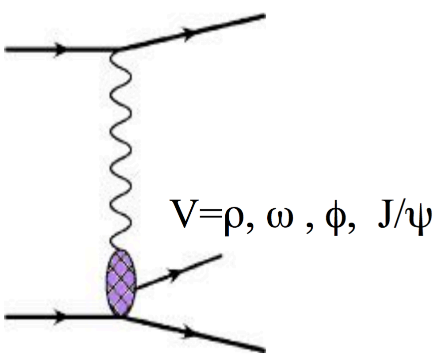


- The previous measurements indicate a declining trend of λ_θ to high p_T, but the result using Run12 data does not seem to follow this trend.

Very low p_T J/ψ excess







- Observe excess of very low p_T J/ψ in peripheral collisions
- Features consistent with coherent photoproduction
  - Slope: 199 ± 31 (GeV/c)$^{-2}$, similar as STARLIGHT prediction for Ultra-Peripheral Collisions: 196 (GeV/c)$^{-2}$
  - Interference at 0 < t < 0.001 (GeV/c)^2
- Production cross-section independent of centrality within uncertainties