Recent highlights from STAR

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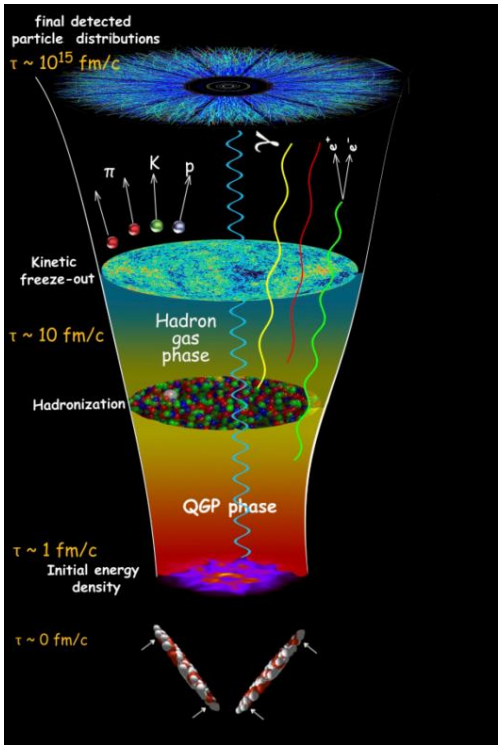
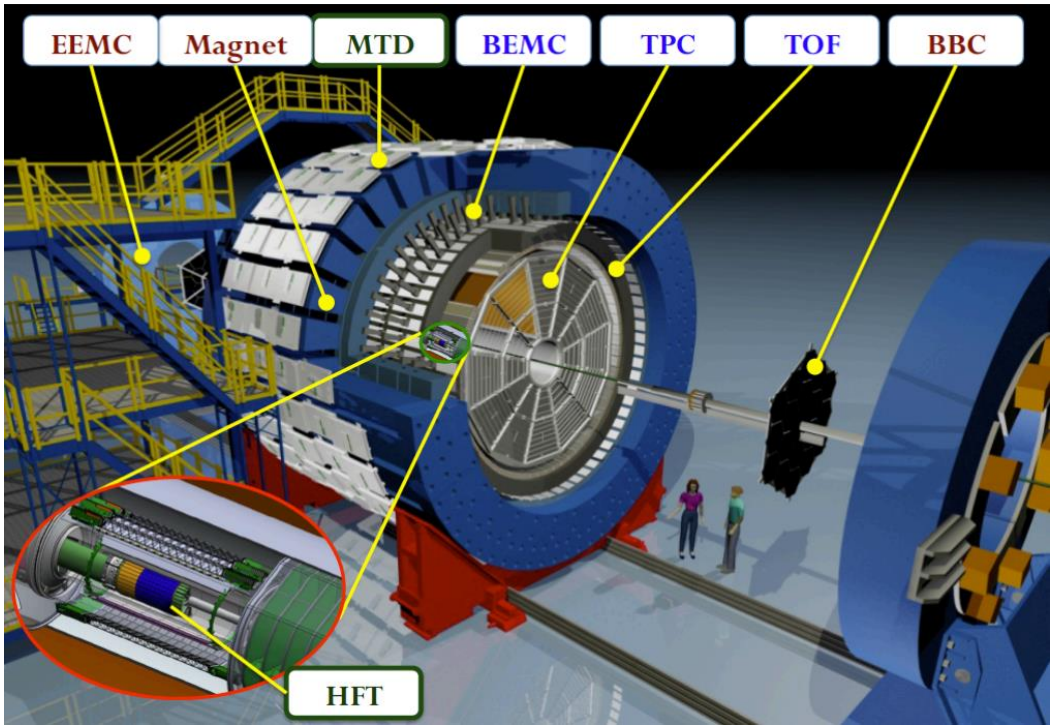
Outline

- STAR detectors
- Probes for QGP in Heavy-Ion Collisions
  - ✓Heavy flavor measurements
  - ✓Bulk observables
  - ✓Electro-magnetic probes
- Summary



STAR detectors



- Large acceptance:
  $|\eta| < 1, 0 < \phi < 2\pi$
- Time Projection Chamber (TPC)
  – tracking, particle identification, momentum
- Time of Flight detector (TOF)
  – particle identification
- Barrel ElectroMagnetic Calorimeter (BEMC)
  – electron identification, triggering
- Muon Telescope detector (MTD)
  – muon identification, triggering
- Heavy Flavor Tracker (HFT)
  – track pointing resolution ~50 μm at p_T ~0.8 GeV/c

STAR detector upgrades : **By Flemming Videbaek on Fri. 11:55**

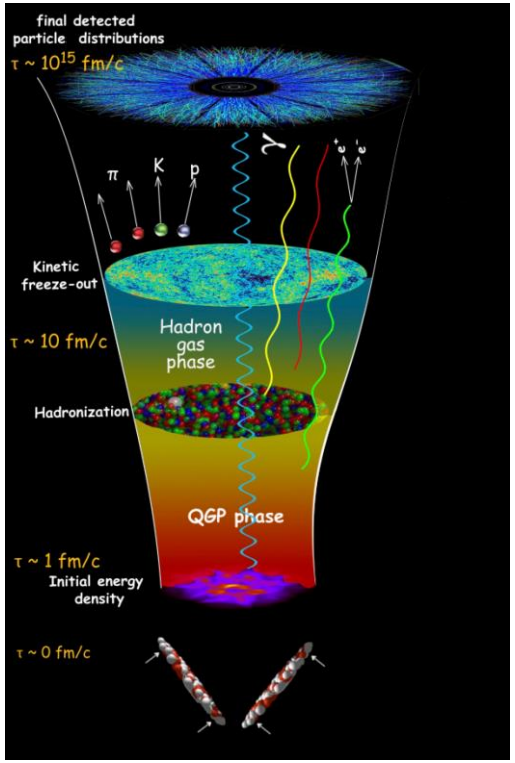
Part I

Heavy flavor measurements

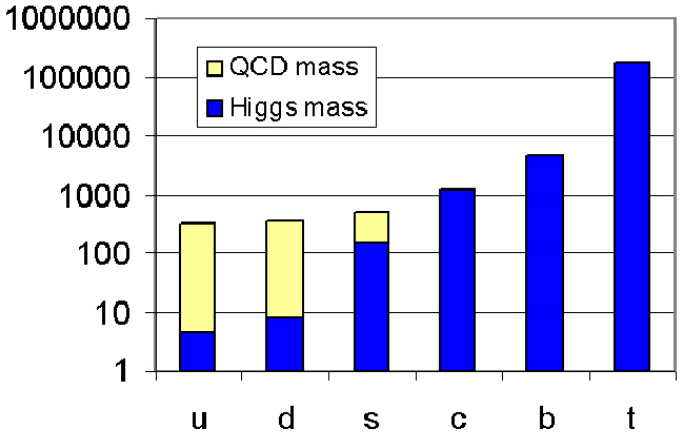
- Suppression pattern of J/ψ and Υ
- Anisotropic flow of D^0 mesons
- D_s and Λ_c production

Bulk observables

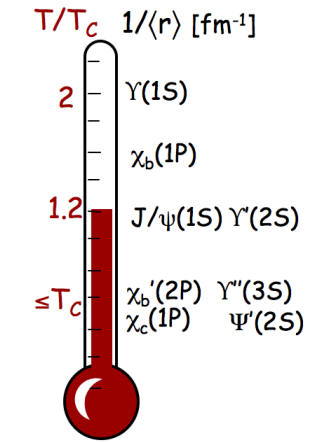
Electro-magnetic probes



Why heavy flavor?



- Symmetry breaking
  - **Higgs mass:** electroweak symmetry breaking
    → **current quark mass**
  - **QCD mass:** chiral symmetry breaking
    → **constituent quark mass**
- Ideal probe to study QGP
  - Masses are not affected by QCD medium
  - Experiences the whole evolution of QGP

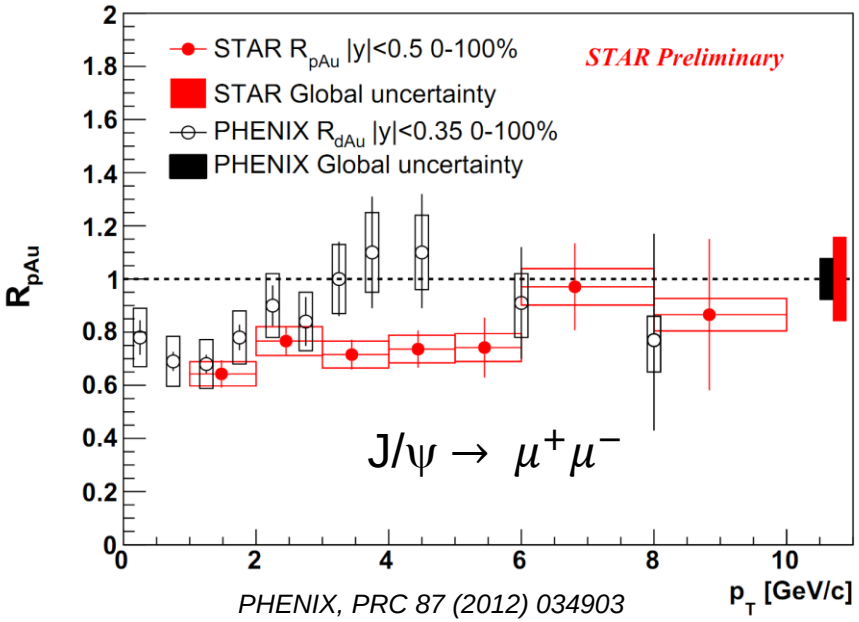


A. Mocsy, EPJC 61 (2009) 705

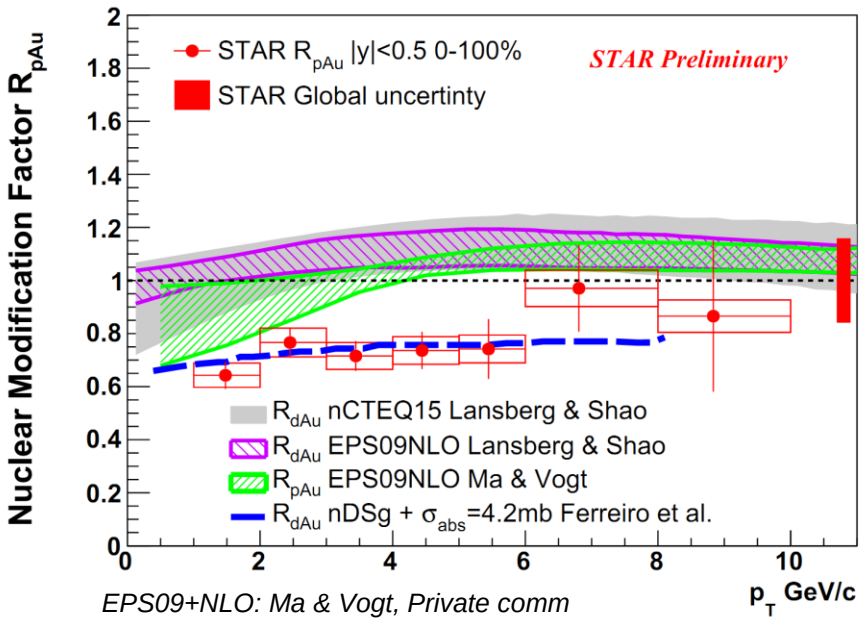
- Quarkonia:
  - Dissociation vs regeneration
  - Sequential melting
  - Cold Nuclear Matter (CNM) effects
- Open charm hadrons:
  - Harder to thermalize: probe the dynamics of the QGP
  - Brownian motion approach: heavy quark spatial diffusion coefficient in the QGP, e.g. $2\pi TD_s$

Inclusive J/ψ modification in p+Au

By Xinjie Huang on Fri. 16:25



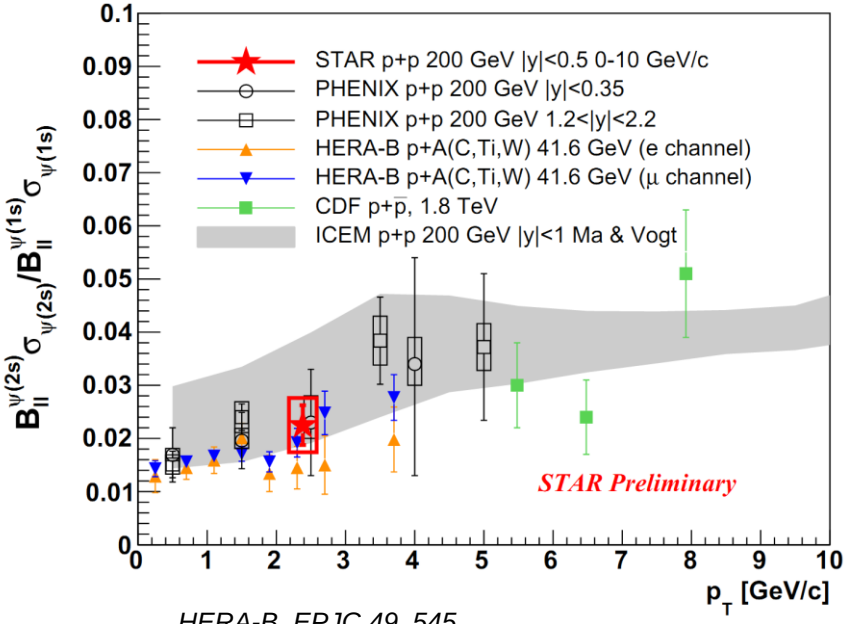
PHENIX, PRC 87 (2012) 034903



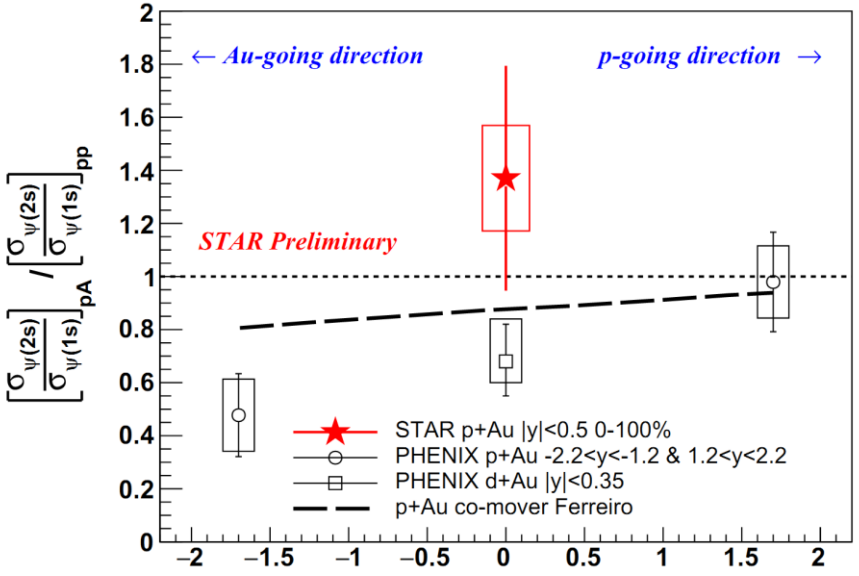
EPS09+NLO: Ma & Vogt, Private comm
nCTEQ, EPS09+NLO: Lansberg Shao, Eur. Phy. J. C77 (2017) no.1, 1
Comp. Phys. Comm. 198(2016) 238-259
Comp. Phys. Comm. 184(2013) 2562-2570
Ferreriro et al., Few Body Syst. 53(2012) 27

- ✓ **R_{pAu} vs. R_{dAu}:** Consistent within uncertainties, but there seems to be a tension at $3.5 < p_T < 5$ GeV/c (~ 1.4σ).
- ✓ **Data vs. model:** Data favor the model with additional nuclear absorption effect on top of the nuclear PDF effects!

ψ(2S)/ J/ψ ratio and double ratio



HERA-B, EPJC 49, 545
PHENIX mid y, PRD 85 (2012) 092004
PHENIX forward y, PRC (2017) 034904
CDF, 1.8 TeV, PRL79 (1997) 572
ICEM, Ma & Vogt, PRD 94 (2016) 114029

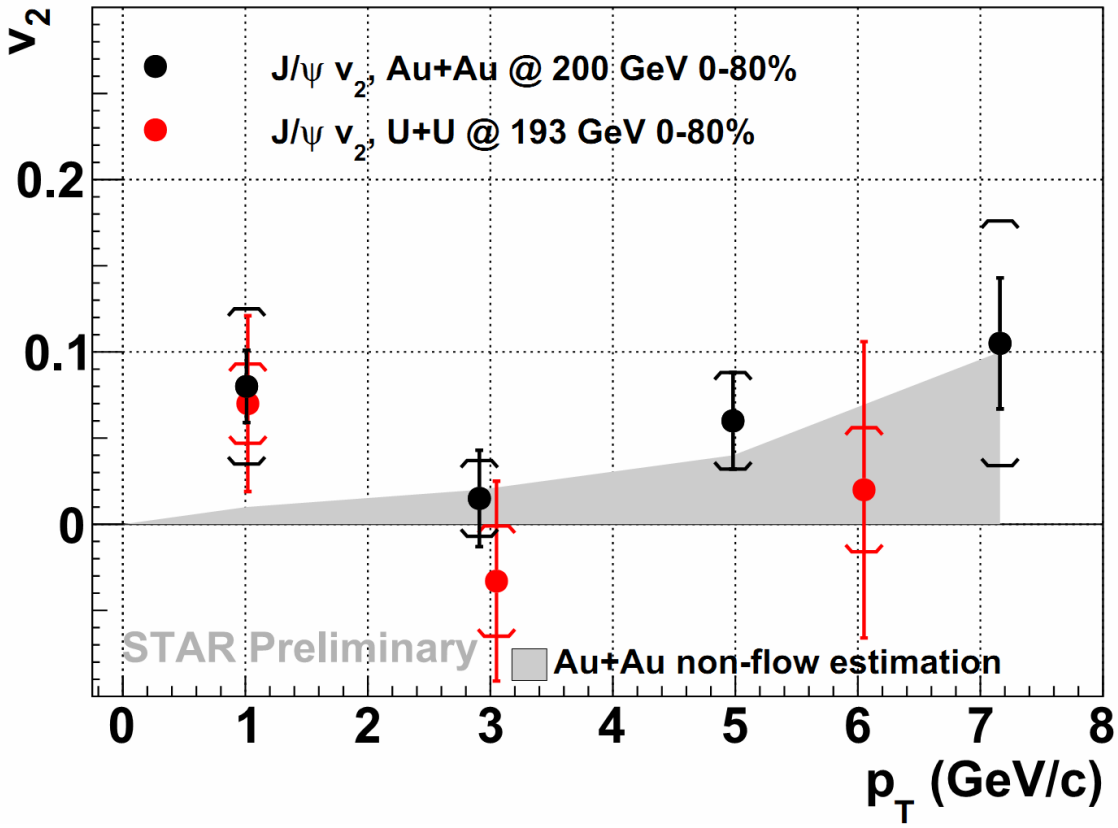


PHENIX p+Au, PRC (2017) 034904
PHENIX d+Au, PRL111 (2013) 202301
Co-mover calculation, Ferreiro, private comm.

- ✓ Measured ψ(2S)/J/ψ ratio in p+p 200 GeV is consistent with world-wide data.
- ✓ First ψ(2S) to J/ψ double ratio measurement between p+p and p+Au at mid-rapdity at RHIC:

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

J/ψ v_2 in U+U collisions

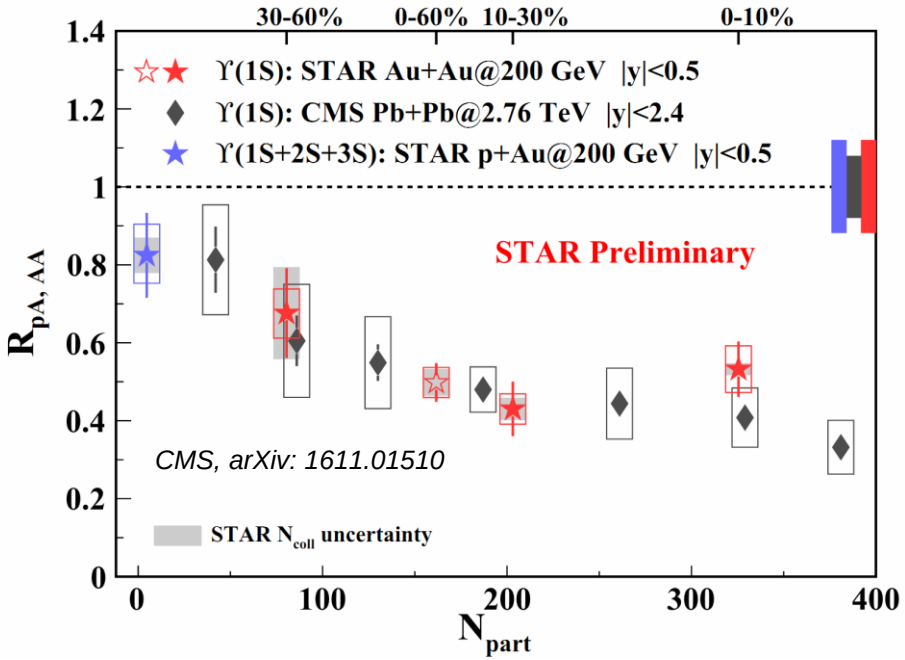


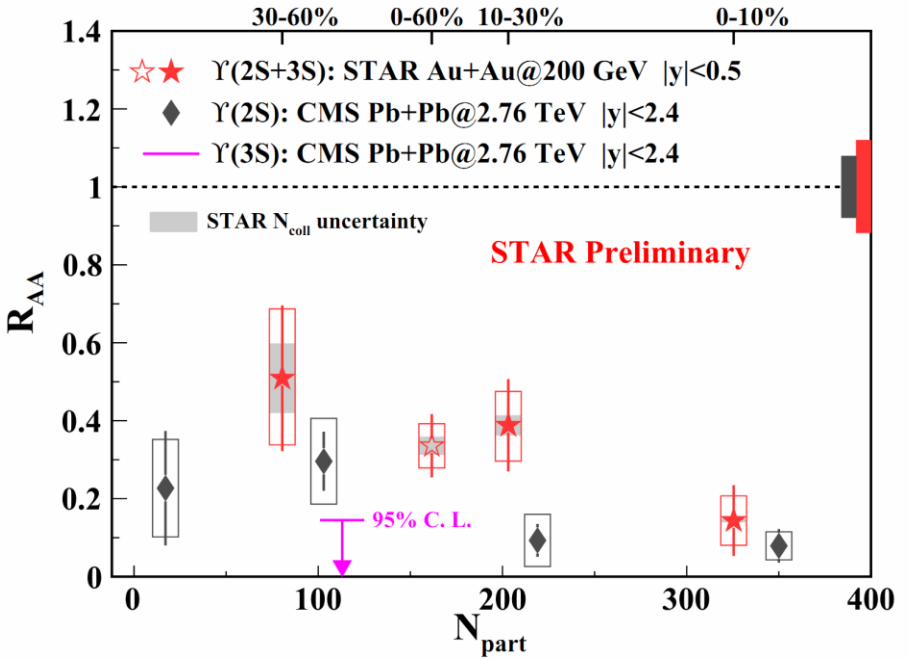
Au+Au results: Run 2010 and 2011 combined

Run 2010:
Phys. Rev. Lett. ***111*** *(2013) 52301*

- ✓ The first measurement of J/ψ v_2 in U+U collisions.
- ✓ Similar to 200 GeV Au+Au results, the value of J/ψ v_2, from minimum biased 193 GeV U+U collisions, are consistent to zero within uncertainties.

ϒ measurements



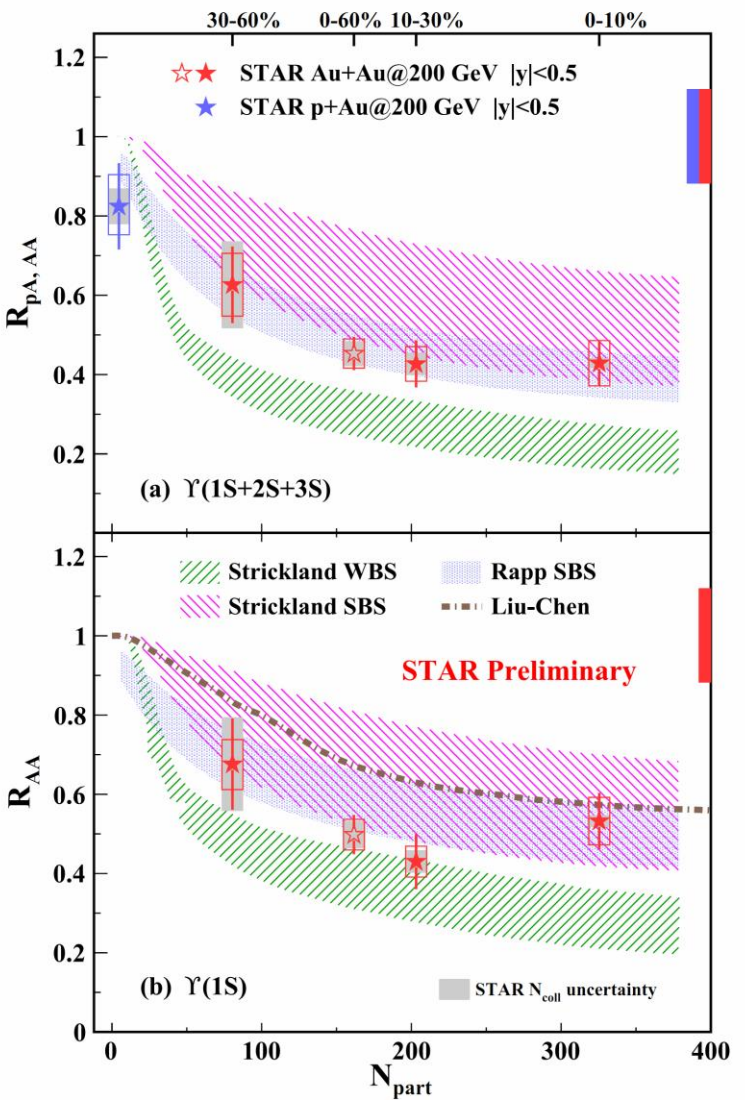


- ✓ Indication of more suppression with increasing centrality.
- ✓ ϒ(2S+3S) is more suppressed than ϒ(1S) in central collisions!
- ✓ Comparison with LHC results:
  - ϒ(1S) : Consistent with the CMS measurement!
  - ϒ(2S+3S) : Hint for less suppression at RHIC than at the LHC.

Comparison with models

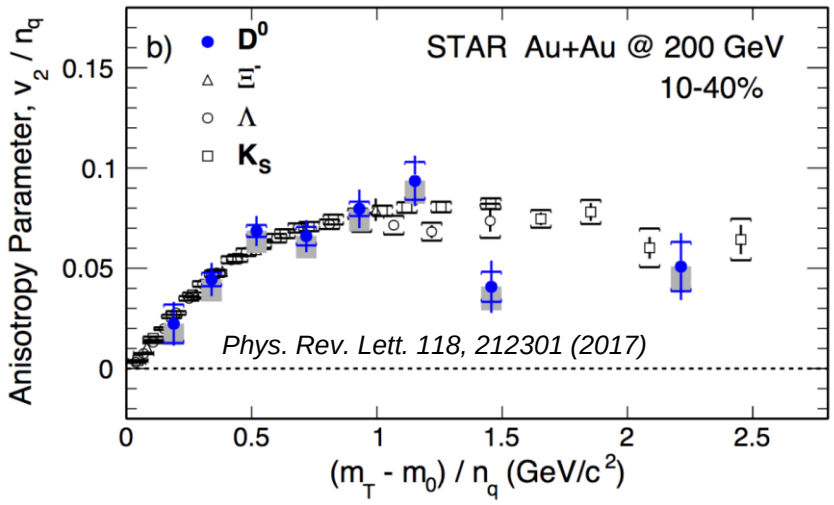
- ✓ SBS (Strongly Binding Scenario):
  fast dissociation—potential based on internal energy.
- ✓ WBS (Weakly Binding Scenario):
  slow dissociation—potential based on free energy.
- ☐ Strickland, Bazov:
  No CNM, no regeneration. *NPA 879 (2012) 25*
- ☐ Liu, Chen, Xu, Zhuang:
  Dissociation only for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

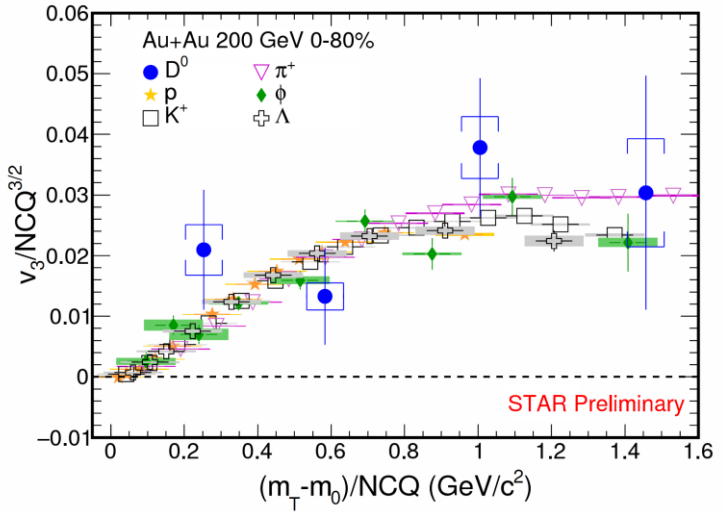
- ✓ Data seem to favor the SBS models!

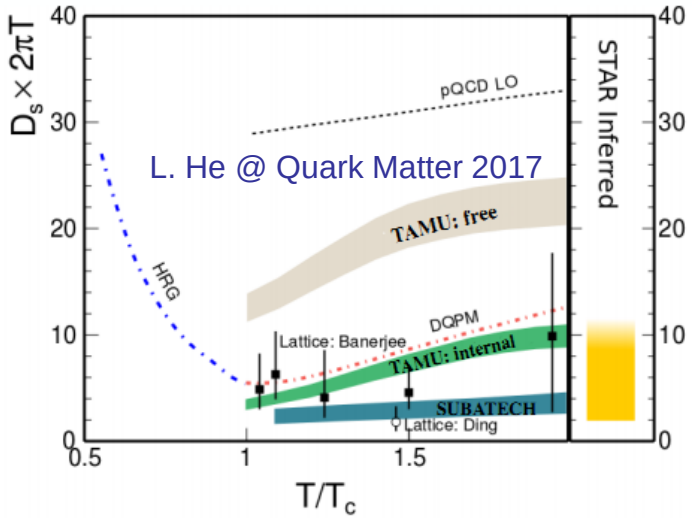


Elliptic and triangular flow of D^0

By Sooraj Radhakrishnan on Thu. 11:40

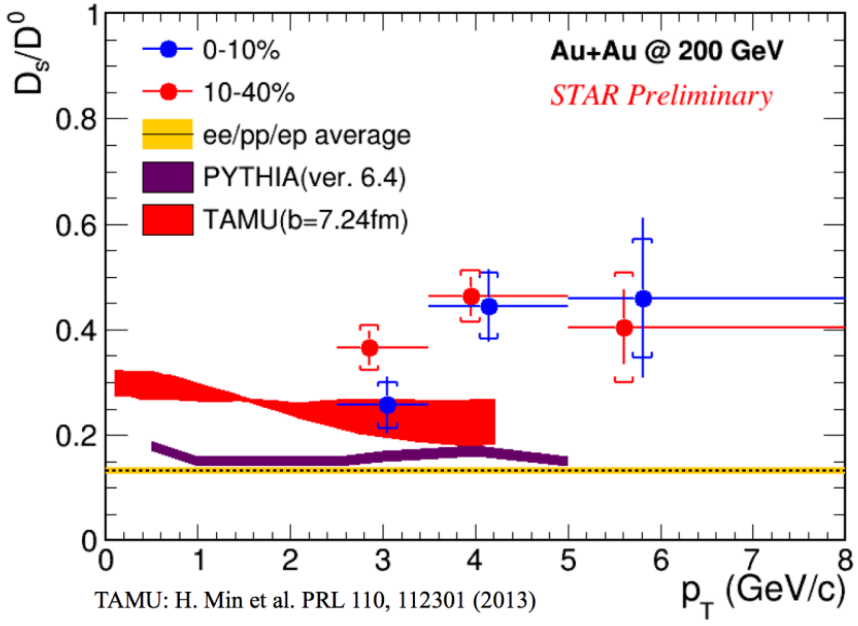


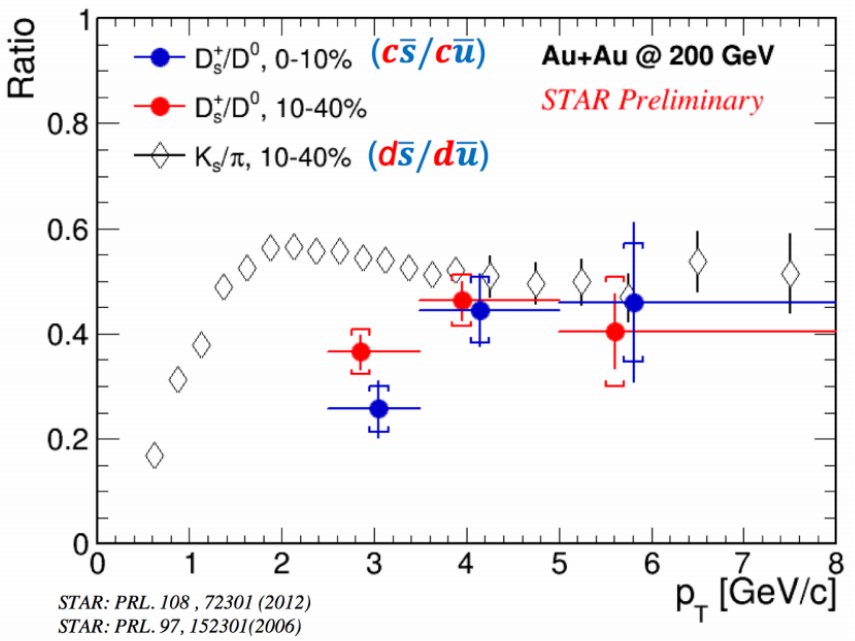




- ✓ Large v_2 and v_3 values, comparable to those of light hadrons!
- ✓ Consistent with the NCQ scaling!
- ✓ Charm quarks flow with the QGP!
- ✓ With $2\pi TD_s$ ~ 2-12 (in the range T_c – $2T_c$) models results are consistent with data!

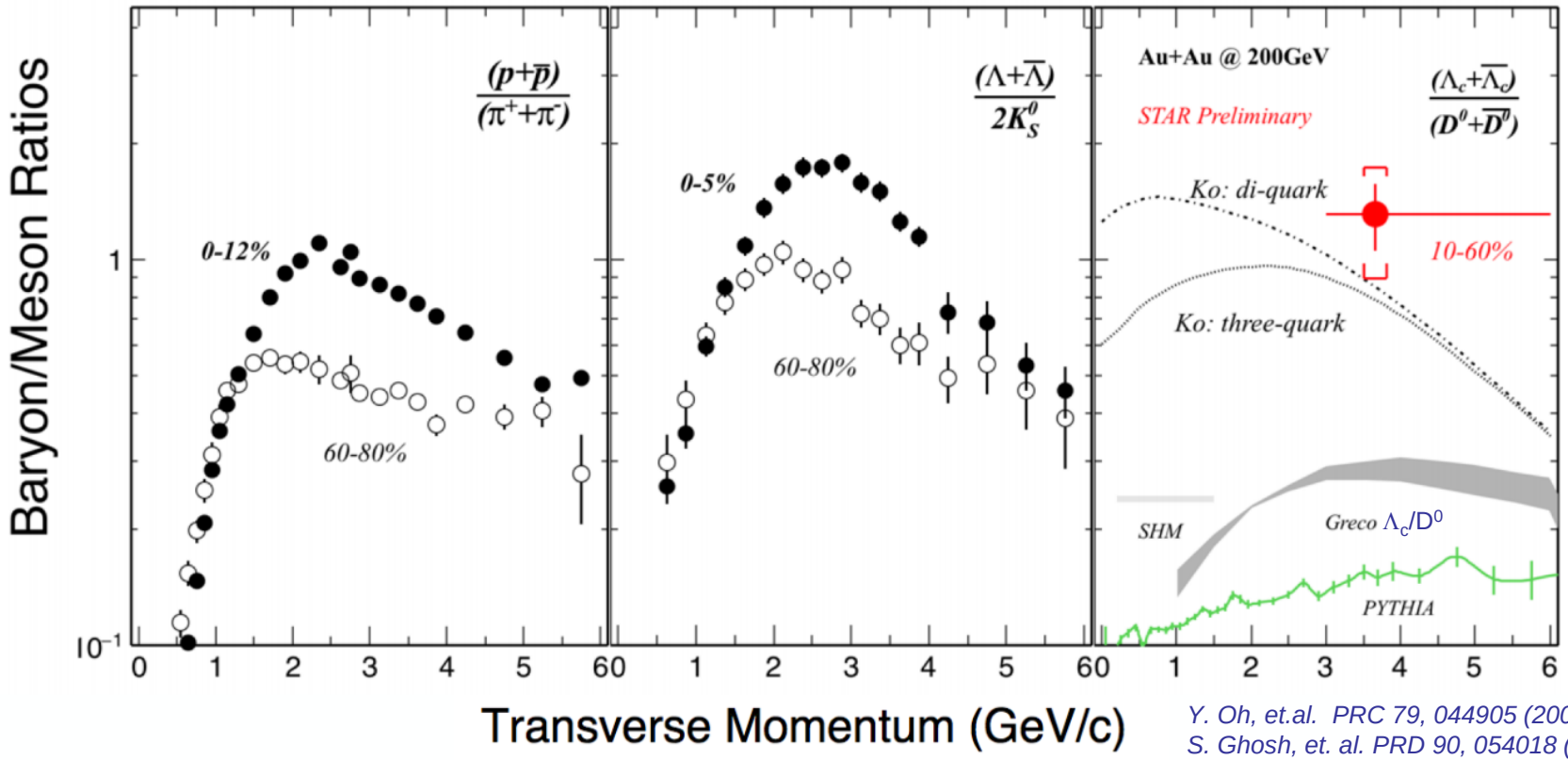
D_s enhancement at RHIC





- ✓ Strong enhancement seen for D_s production relative to PYTHIA !
  → Charm in QGP hadronizes very differently than in vacuum!
- ✓ Enhancement larger than TAMU model with coalescence.
- ✓ Similar enhancement as light flavor for p_T > 3.5 GeV/c, smaller values in 2.5 - 3.5 GeV/c.

Λ_c production in heavy-ion collisions



Y. Oh, et.al. PRC 79, 044905 (2009)
S. Ghosh, et. al. PRD 90, 054018 (2014)

- ✓ Significant baryon/meson enhancement in the charm sector!
- ✓ Magnitude consistent with that of light hadrons!
- ✓ Coalescence models with thermalized charm quarks in medium agree with measurement.

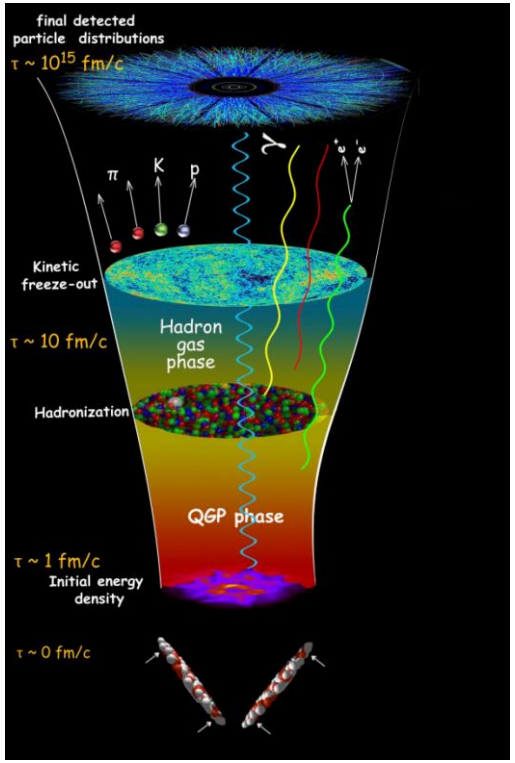
Part II

Heavy flavor measurements

Bulk observables

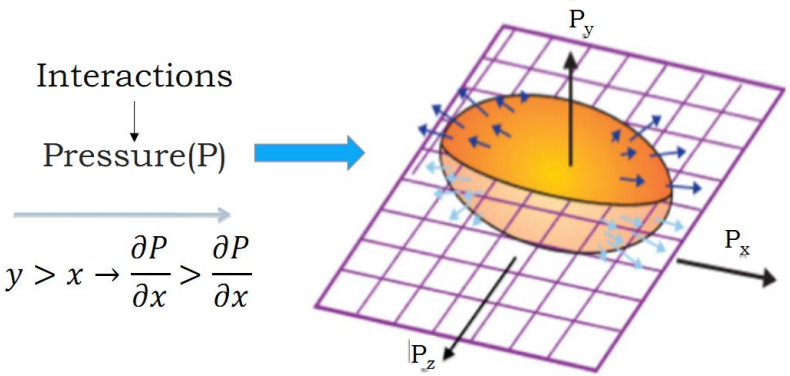
- Anisotropy flow of strange hadrons
- Dipolar flow
- Global polarization --- Λ and ϕ
- Kaon femtoscopy

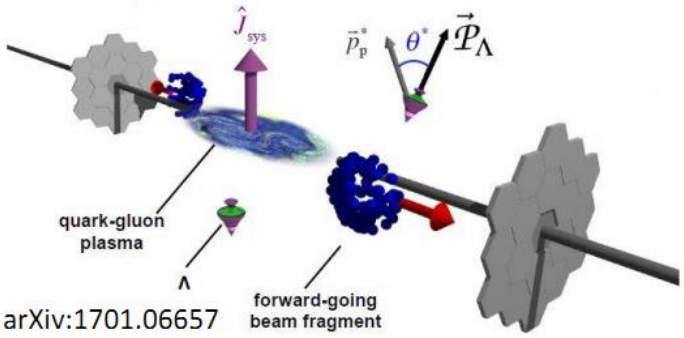
Electro-magnetic probes

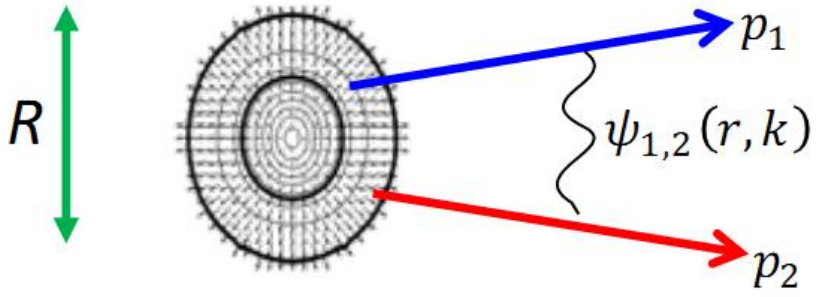


What do bulk observables tell?

- Anisotropic flow:
  - Initial-state eccentricity and its fluctuations
  - Sensitive to the evolution of the system at early times
  - Sensitive to the equation of state
  - Extract the transport coefficients of medium
- Global polarization:
  - Study the vorticity of the medium and the initial magnetic field
- Femtoscropy:
  - Measure the volume of the medium at thermal freeze-out

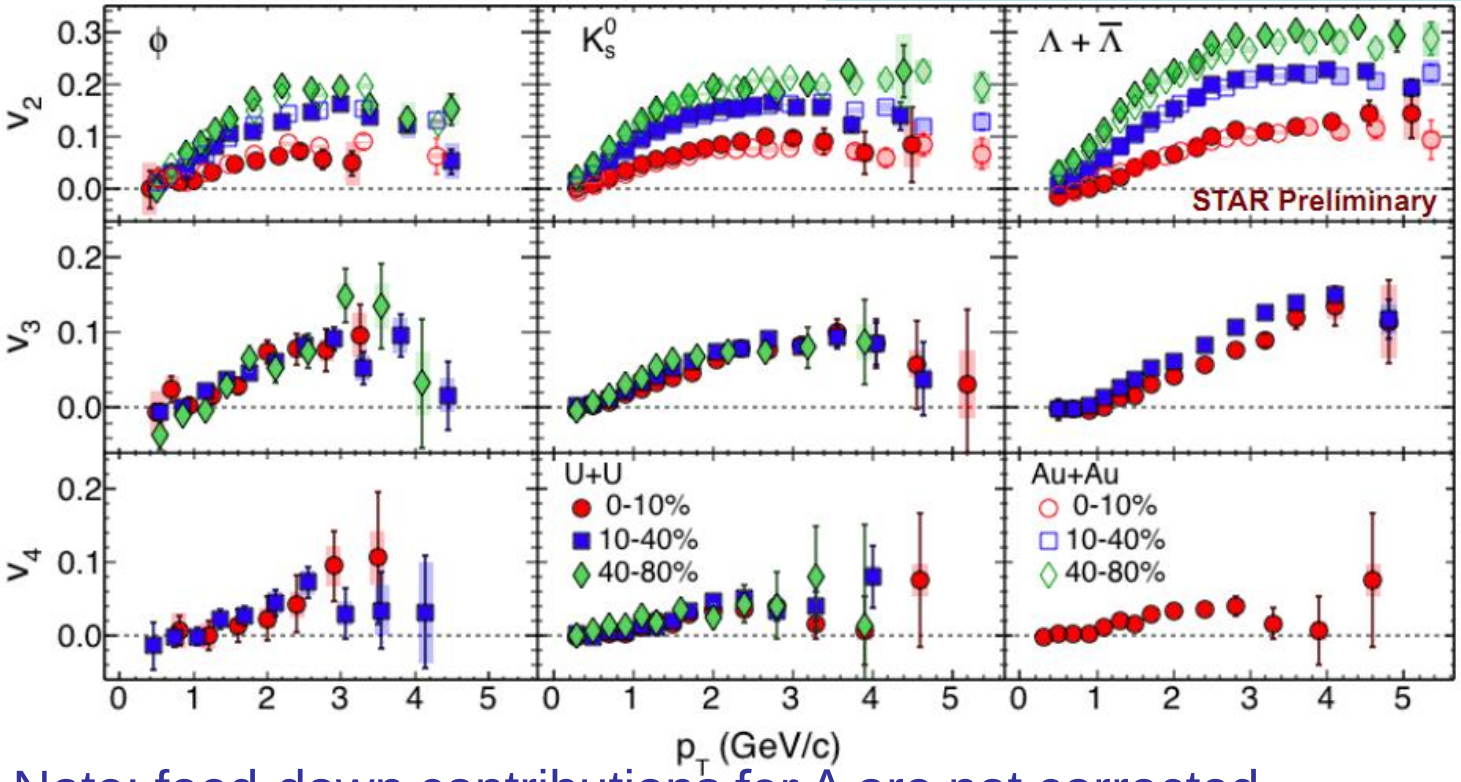






Flow harmonics of v_n strange hadrons

By Vipul Bairathi on Thu. 09:40

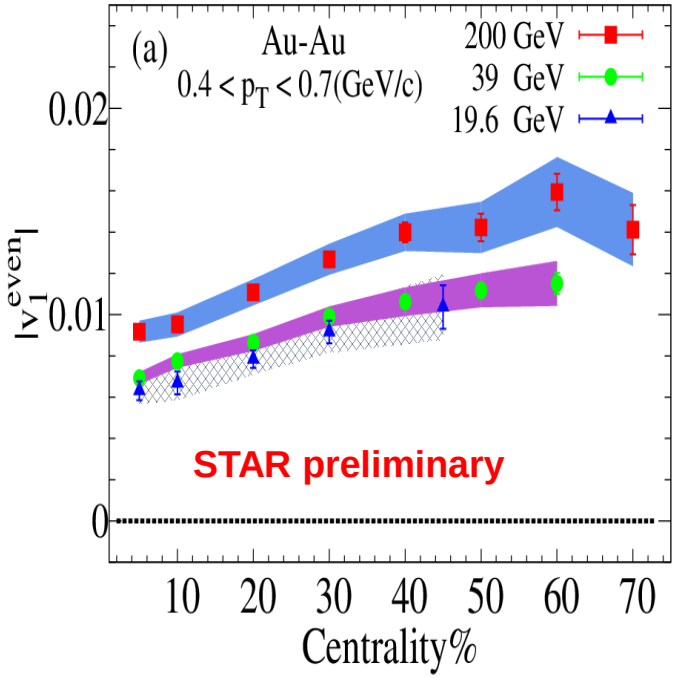


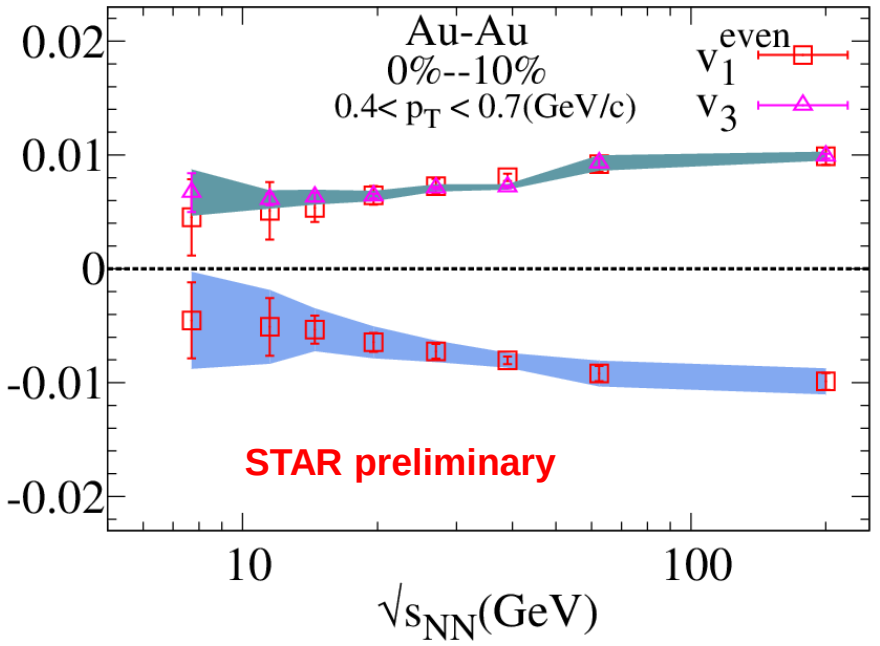
Au+Au:
Phys. Rev. C 77, 054901 (2008)

- ✓ Note: feed-down contributions for Λ are not corrected.
- ✓ Strong centrality dependence observed for v_2 of ϕ, K^0_s and Λ in both U+U and Au+Au collisions.
- ✓ Both v_3 and v_4 show a weak centrality dependence in U+U collisions.

Energy and centrality dependence of v_1^{even}

By Niseem Magdy on Thu. 11:10

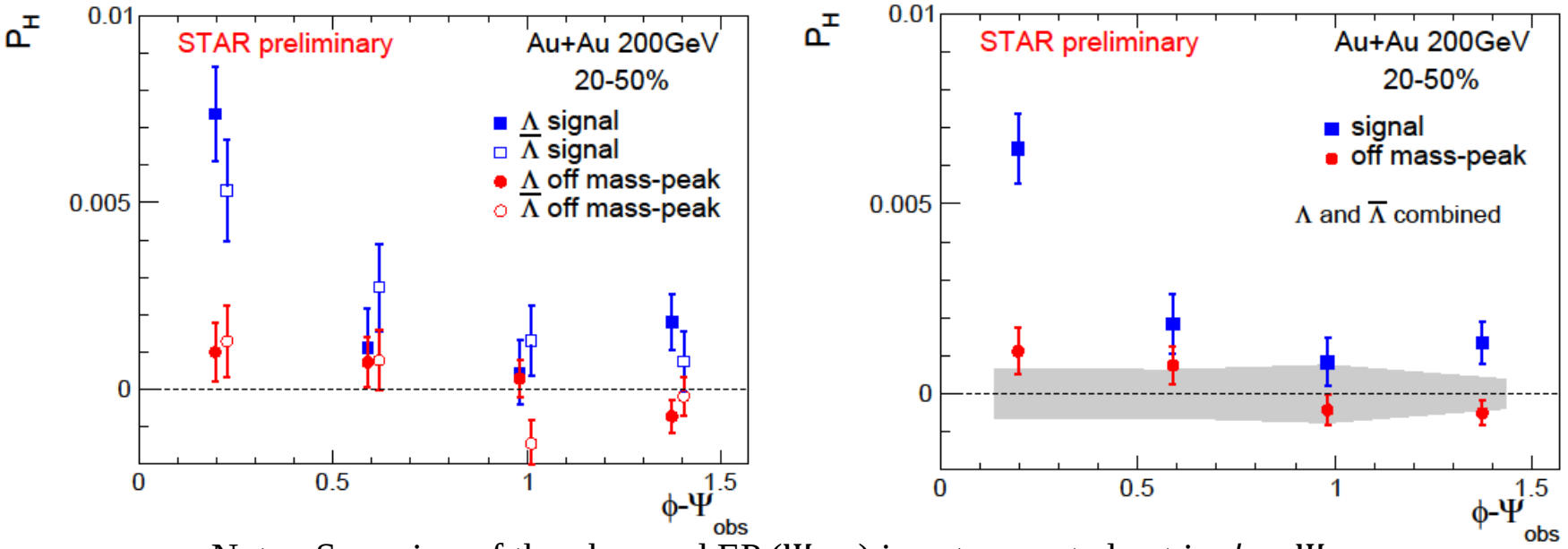




- ✓ v_1^{even} increases with centrality.
- ✓ v_1^{even} shows weak sensitivity to beam energy change.
- ✓ v_1^{even} shows similar values to v_3 at $0.4 < p_T < 0.7$ GeV/c.

Azimuthal angle dependence of P_H

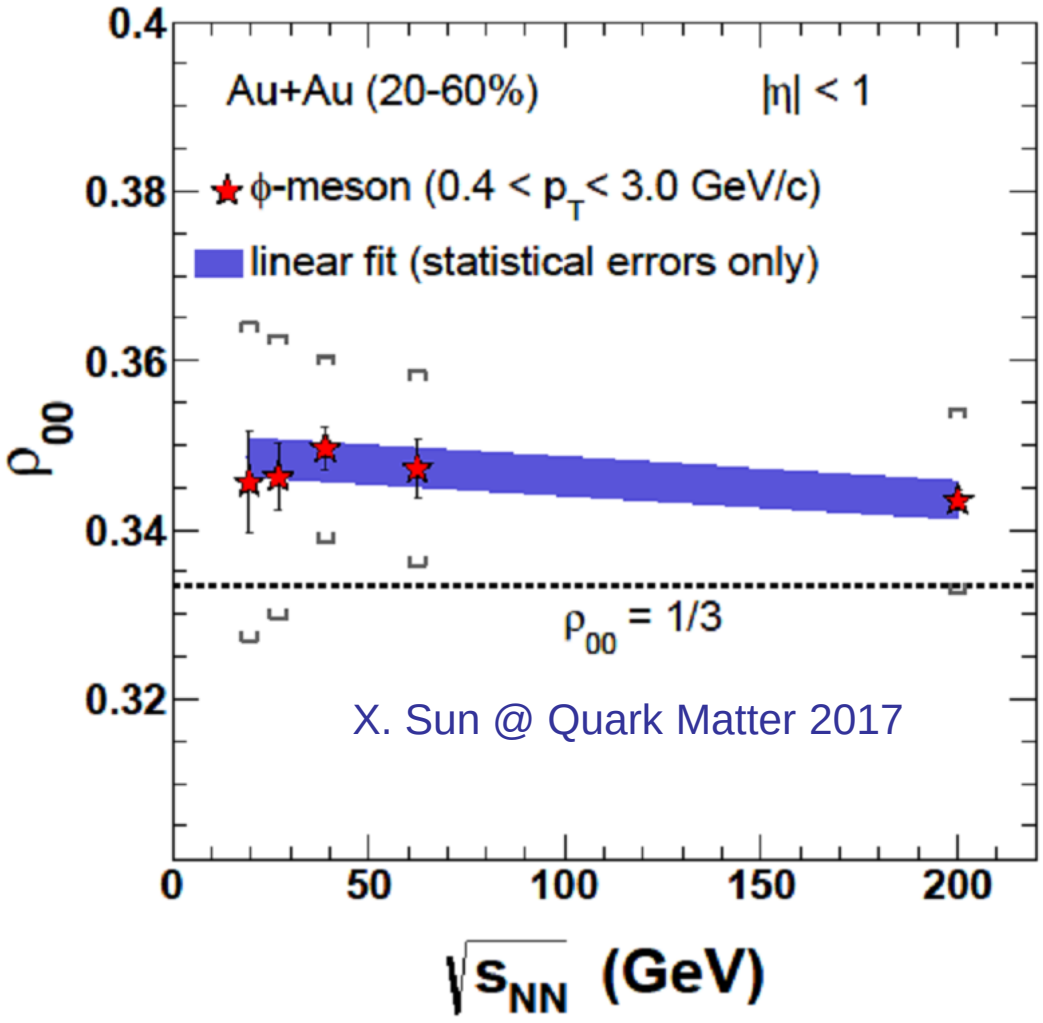
By Biao Tu on Fri. 14.35



Note : Smearing of the observed EP (Ψ_{obs}) is not corrected yet in $\phi - \Psi_{obs}$

- ✓ No significant P_H for off-peak lambda candidates (red points).
- ✓ P_H shows a similar azimuthal dependence for Λ and $\overline{\Lambda}$.
- ✓ The significance of ΔP_H, for Λ and $\overline{\Lambda}$ conbined, between $[0,\frac{\pi}{8}]$ and $[\frac{3\pi}{8},\frac{\pi}{2}]$ is 4.7σ.
- ✓ Consistent with the picture of maximum vorticity in the equator.

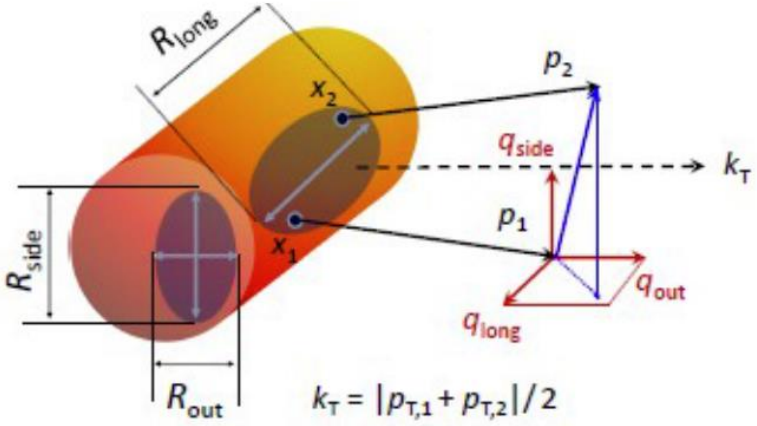
Energy dependence of ϕ ρ_{00}



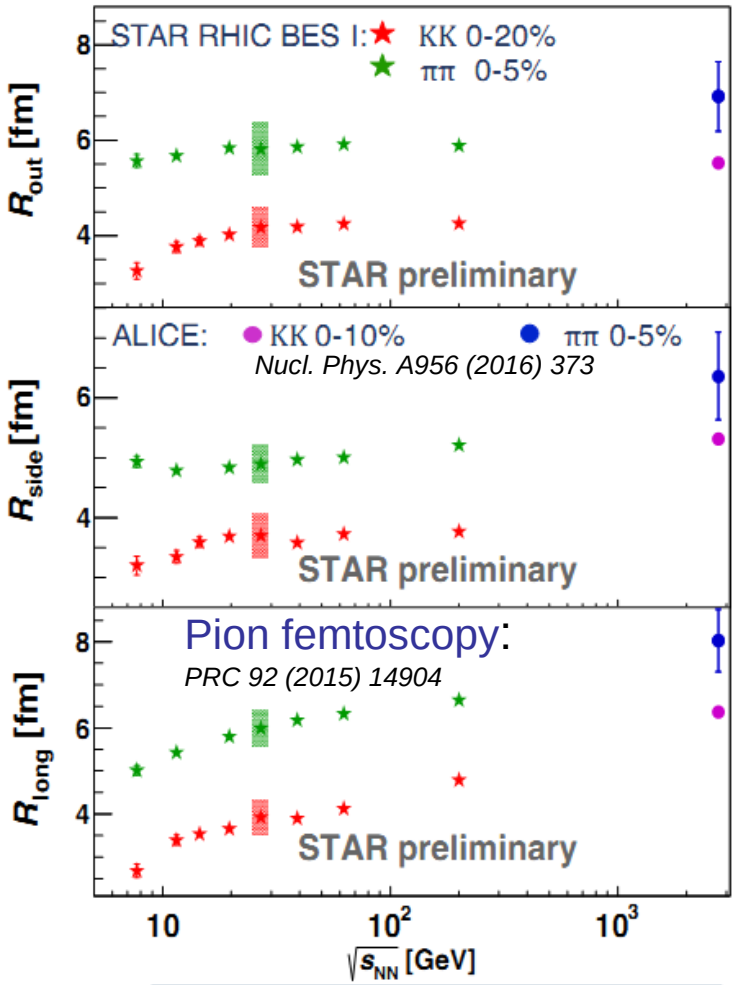
- ✓ ρ_{00} is expected to be sensitive to production mechanisms (ρ_{00} < 1/3 for recombination, ρ_{00} > 1/3 for fragmentation).
  J.Phys.G34, S323-330 (2007)
- ✓ Measurement of ϕ-meson spin alignment at 19 – 62 GeV.
- ✓ ρ_{00} shows weak beam-energy dependence.

Energy dependence of kaon source radii

By Jindřich Lidrych on Thu. 10:50



- ✓ Kaon source radii increase with increasing collision energy.
  - ✓ R_{long} increases - longer emission duration.
  - ✓ R_{side} and R_{out} increases - larger system at the moment of the particles emission.
- ✓ Similar trends as results from pion femtoscopy.



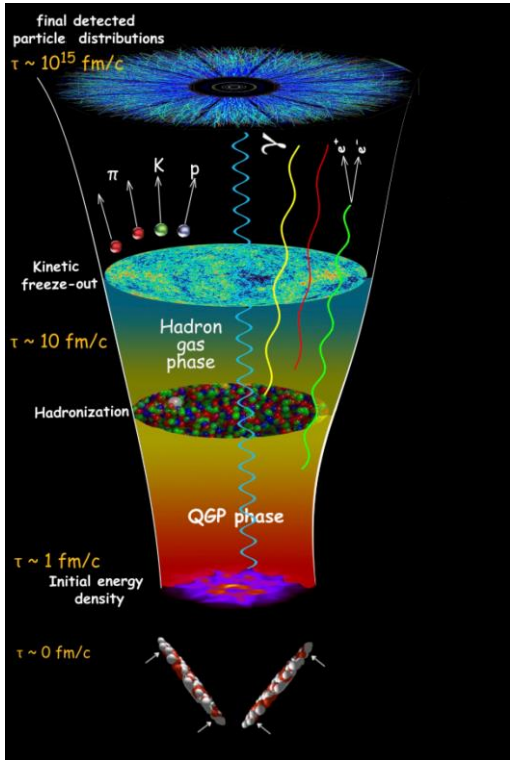
Part Ⅲ

Heavy flavor measurements

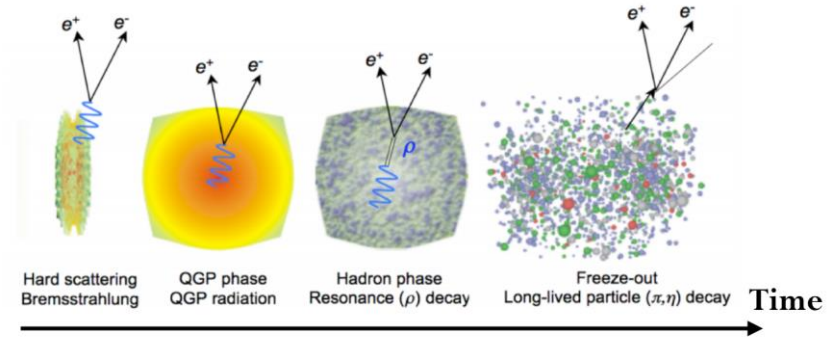
Bulk observables

Electro-magnetic probes

- e^+e^- production at very low p_T



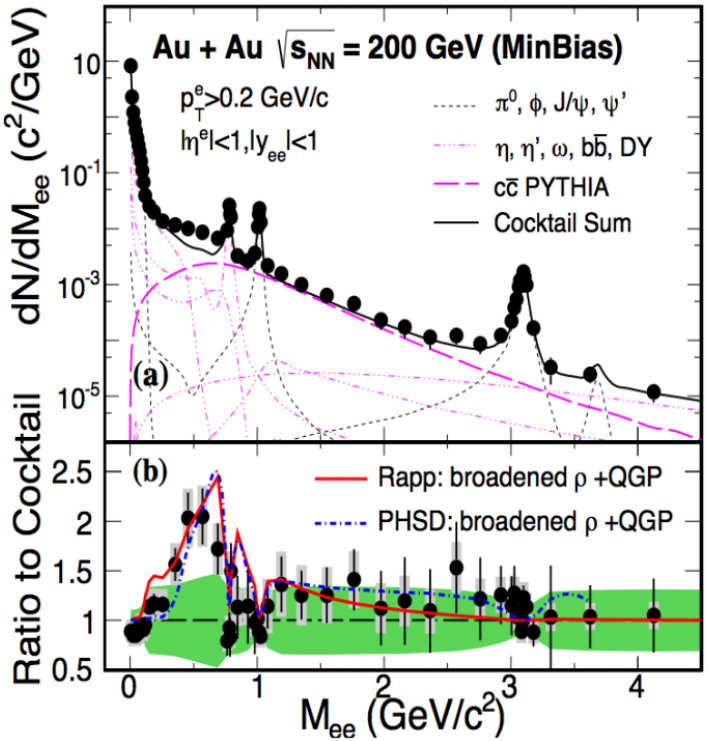
Electromagnetic probes



Dielectron – ideal electromagnetic probes

- Suffer no strong interaction, traverse the medium with minimum interaction.
- Produced throughout all stages of the evolution of the system.

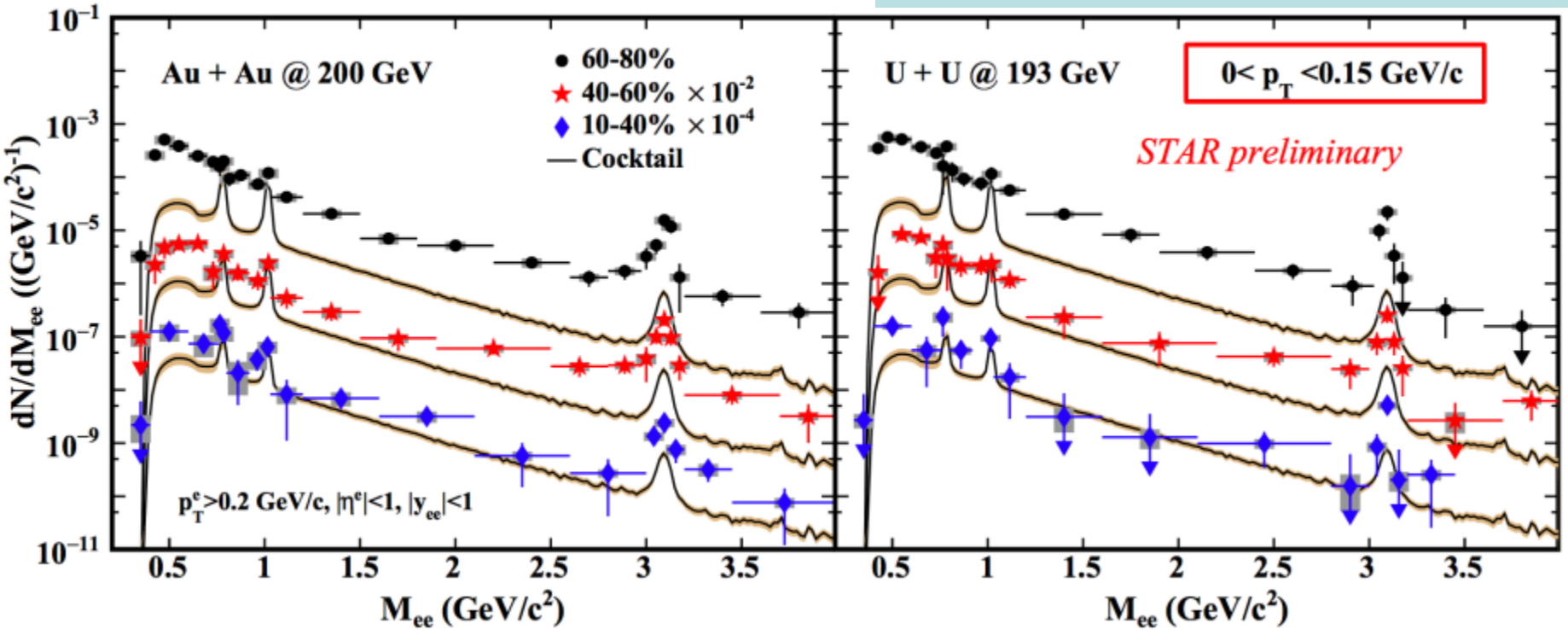
- ✓ Observed significant excess w.r.t hadronic sources at ρ-like mass region (0.3-0.76 GeV/c^2).
- ✓ Enhancement is consistent with a broadened ρ spectral function of theory expectation. [***R.Rapp, Adv. High Energy phy. 2013 (2013) 148253***]



Phys. Rev. Lett. 113 (2014) 22301

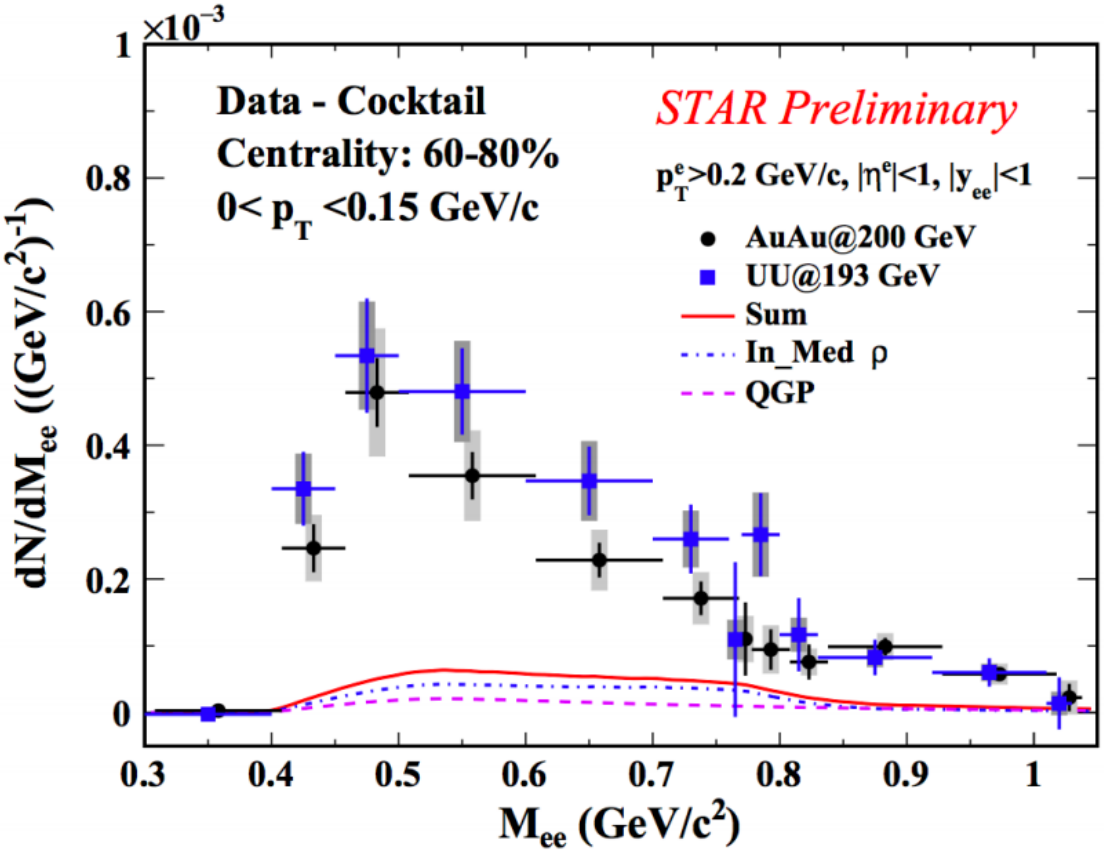
Low p_T e^+e^- in Au+Au and U+U

By Chi Yang on Fri. 16:45



- ✓ Clear excesses in peripheral collisions both in Au+Au and U+U.
- ✓ Excess observed over the whole mass range (< 4 GeV/c^2).

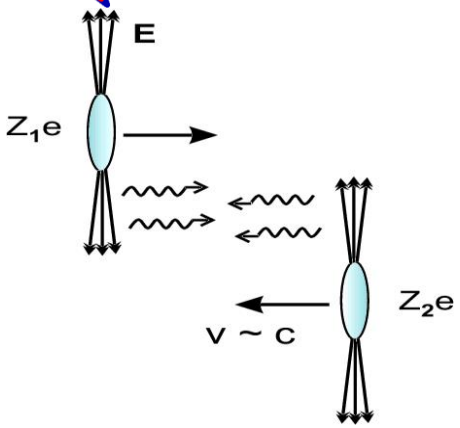
Excess versus model calculation



- Tend to be larger in U+U collisions, but still consistent with each other under the current precision.
- Can not be described by the model based on ρ broadening and QGP thermal radiation!
- Additional source for production!

✓ Does the e^+e^- excess originate from coherent photoproduction?

Coherent photon interactions in A+A



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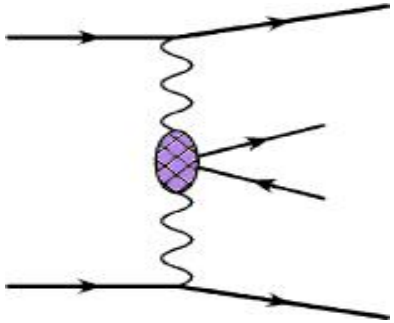

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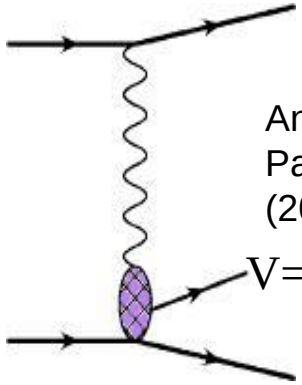


Ann. Rev. Nucl. Part. Sci.**55**:271 (2005)

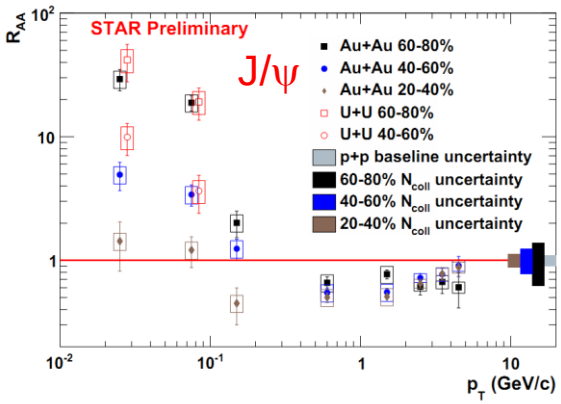
$V=\rho\ ,\ \omega\ ,\ \phi\ ,\ J/\psi$

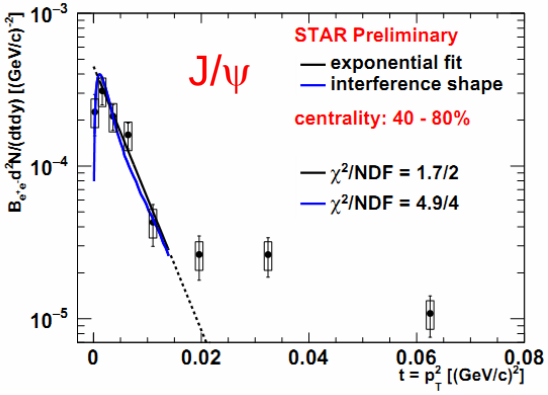
Electromagnetic interaction

Photon-photon interactions

Photon-nucleus interactions

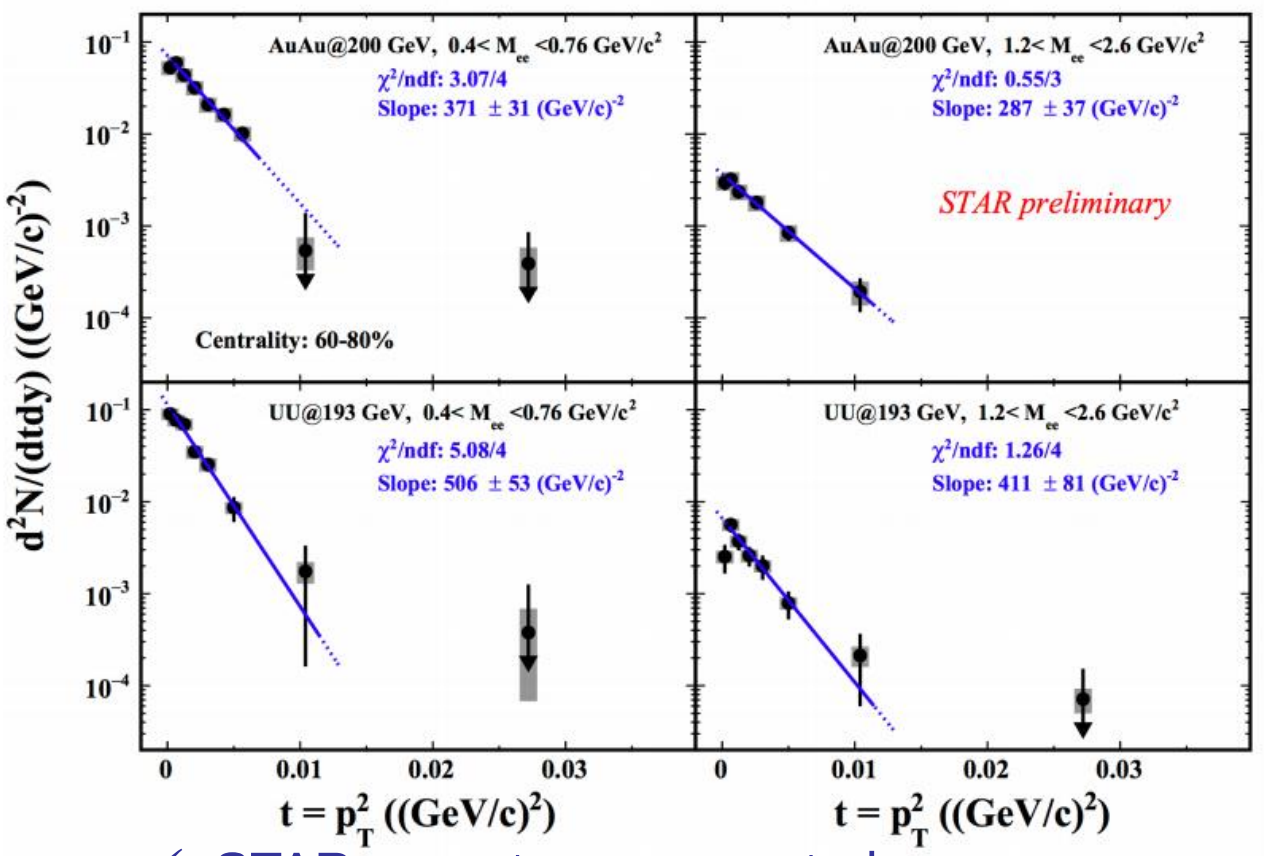
Conventionally, only exist in UPC!





Photon-nucleus Interactions in hadronic A+A collisions confirmed!

t distribution



- ✓ STAR acceptance corrected.
- ✓ Consistent with coherent production:
  - Large slope parameter => Large interaction size
  - Slope in U+U is sharper than that in Au +Au.

Summary

- ✓Heavy flavor measurements:
  - ◆New results of J/ψ R_{pAu} in p+Au collisions and v_2 in U+U collisions at RHIC.
  - ◆Υ(2S+3S) is more suppressed than Υ(1S) → Sequential melting.
  - ◆New results of D^0 triangular flow in heavy-ion collisions.
  - ◆Significant enhancement of D_s/D^0 and Λ_c/D^0 rations at RHIC.
- ✓Bulk observables:
  - ◆The anisotropic flow of strange hadrons has been studied and compared between U+U and Au+Au collisions, respectively.
  - ◆Charged $|v_1^{even}|$ shows weak dependence on the collision centrality and beam energy.
  - ◆The Λ and $\overline{\Lambda}$ global polarization shows azimuthal dependence.
  - ◆ Kaon femtoscopic radii (R_{out}, R_{side} and R_{long}) increases with collision energy .
- ✓Electro-magnetic probes:
  - ◆Clear excesses at very low p_T in peripheral collisions both in Au+Au and U+U → Consistent with the coherent production picture.

STAR presentations in SQM2017

- ✓ Quarkonium measurements in heavy-ion collisions with the STAR experiment — **Xinjie Huang on Fri. 16:25**
- ✓ Measurements of charm hadron production and anisotropic flow in Au+Au collisions at 200 GeV with the STAR experiment at RHIC — **Sooraj Radhakrishnan on Thu. 11:40**
- ✓ Anisotropic flow of strange hadrons in U+U collisions at $\sqrt{s_{NN}}$ = 193 GeV — **Vipul Bairathi on Thu. 09:40**
- ✓ Kaon femtoscopy in Au+Au collisions from the Beam Energy Scan at the STAR experiment — **Jindřich Lidrych on Thu. 10:50**
- ✓ Beam energy and system dependence of rapidity-even dipolar flow — **Niseem Magdy on Thu. 11:10**
- ✓ ϕ-Meson Spin Alignment and the Azimuthal Angle Dependence of $\Lambda(\overline{\Lambda})$ Polarization in Au+Au collisions at RHIC — **Biao Tu on Fri. 14:35**
- ✓ Coherent e^+e^- production at very low transverse momentum at STAR — **Chi Yang on Fri. 16:45**
- ✓ STAR detector upgrades — **Flemming Videbaek on Fri. 11:55**