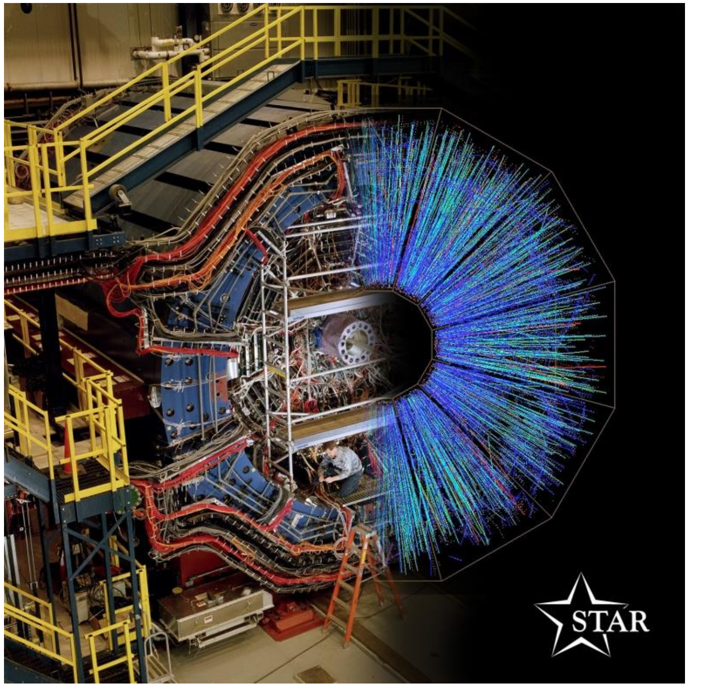
Highlights from the heavy-ion program in STAR

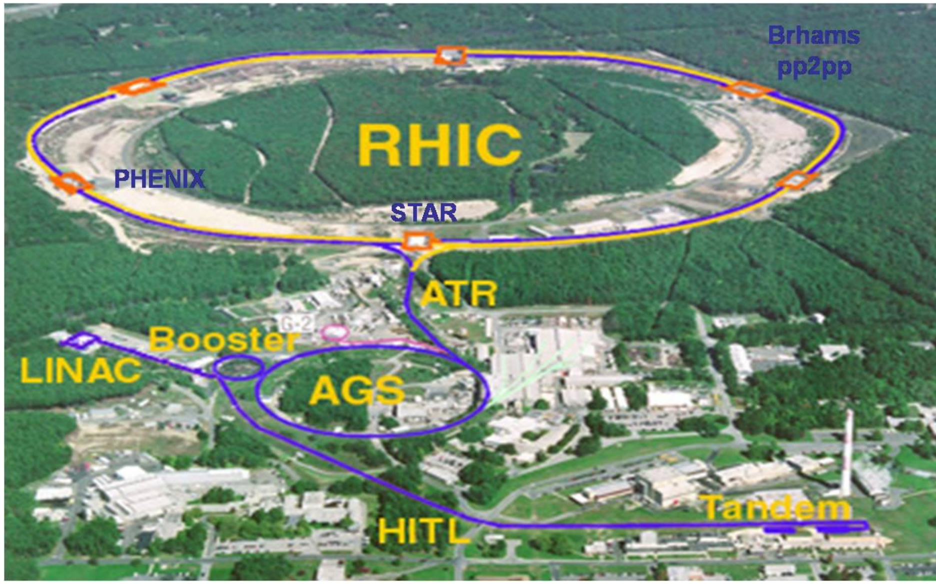


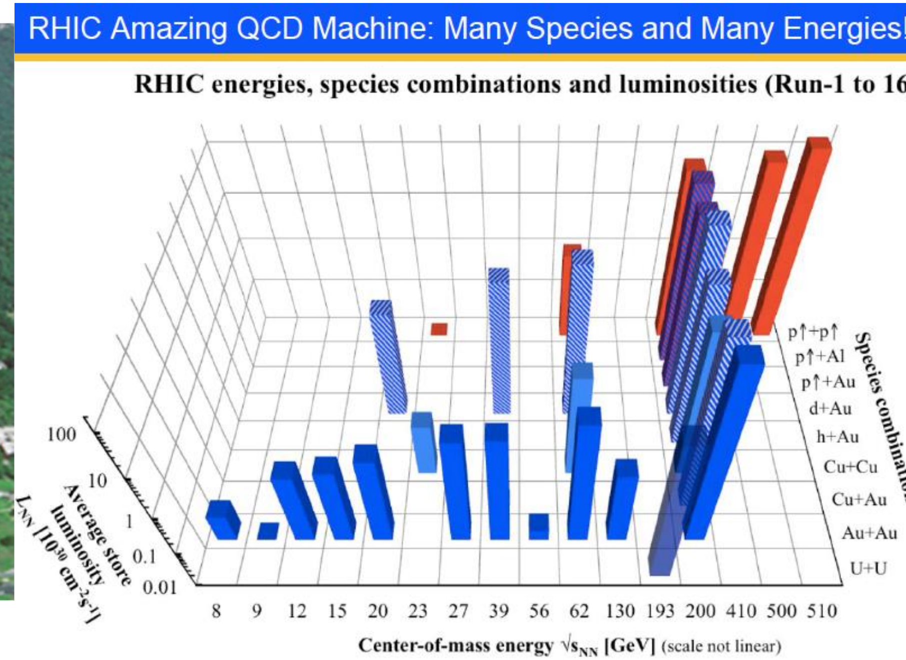
Jaroslav Bielcik
for the STAR collaboration

Czech technical university in Prague

2nd International Conference on Particle Physics and Astrophysics, Moscow, 10-14th October

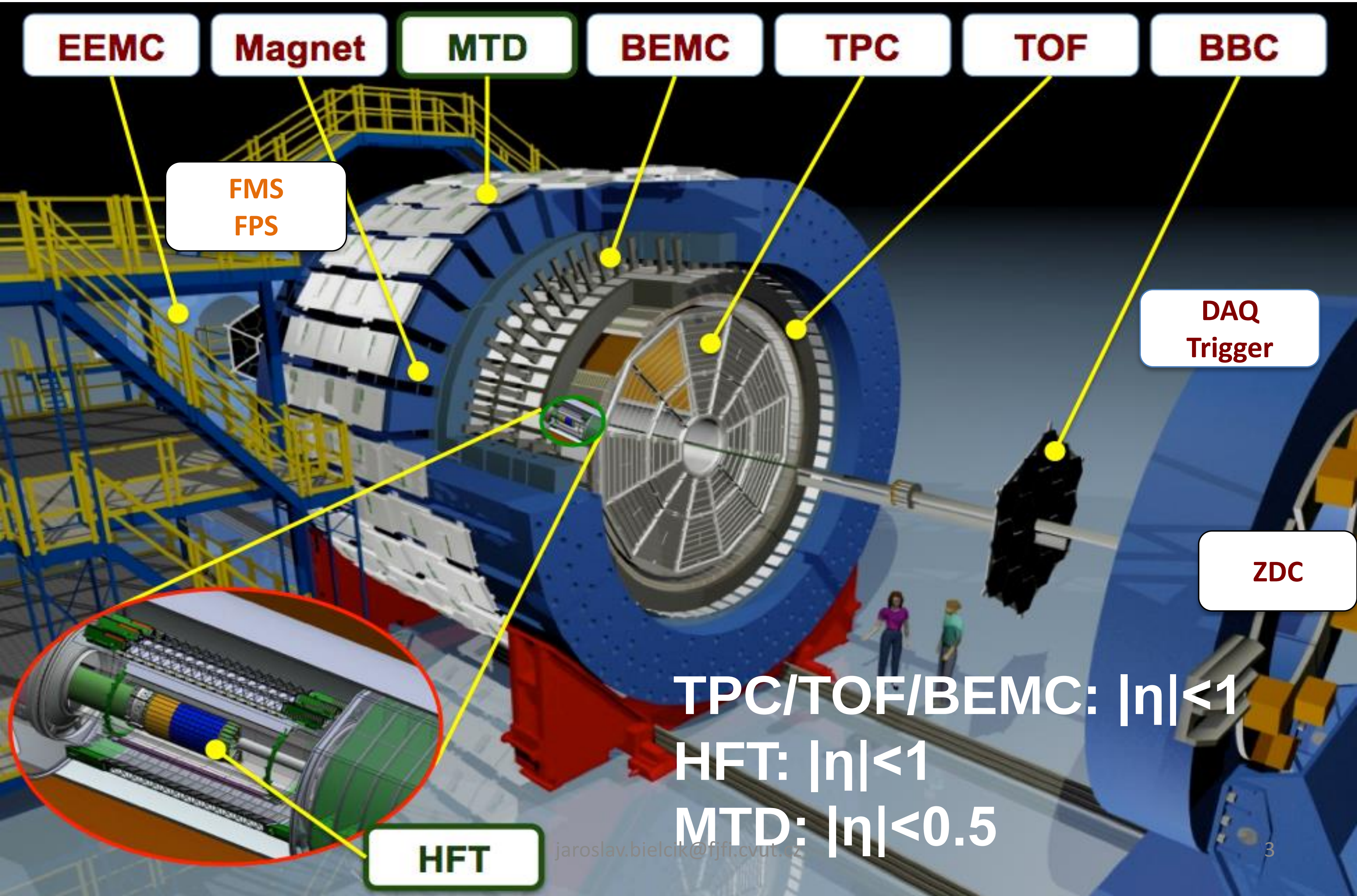
Relativistic Heavy-Ion Collider



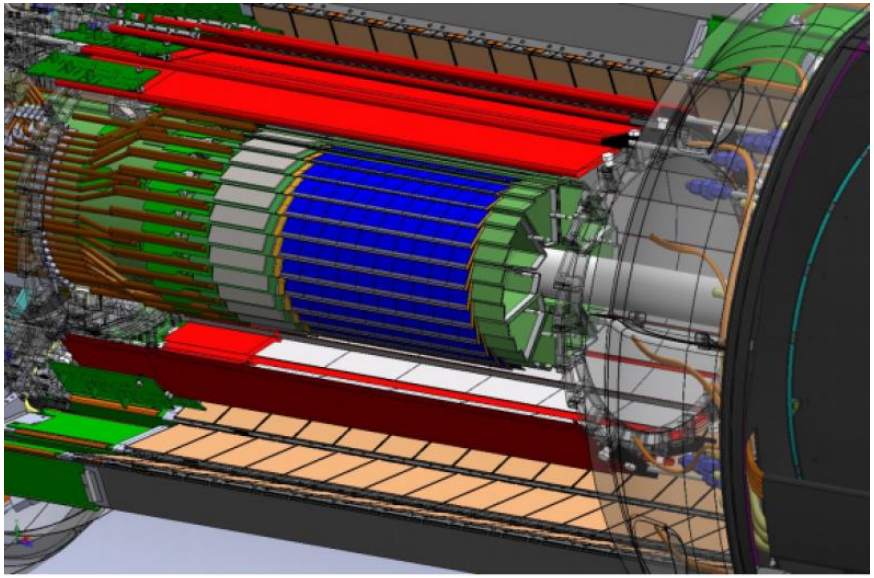


- Extremely versatile: has collected data colliding a large array of different heavy ions
  - Luminosity Au+Au: 2 x 10^{26} cm^{-2} s^{-1} ; p+p : 2 x 10^{32} cm^{-2} s^{-1}
- Only polarized proton collider in the world
  - Beam polarizations P=70%

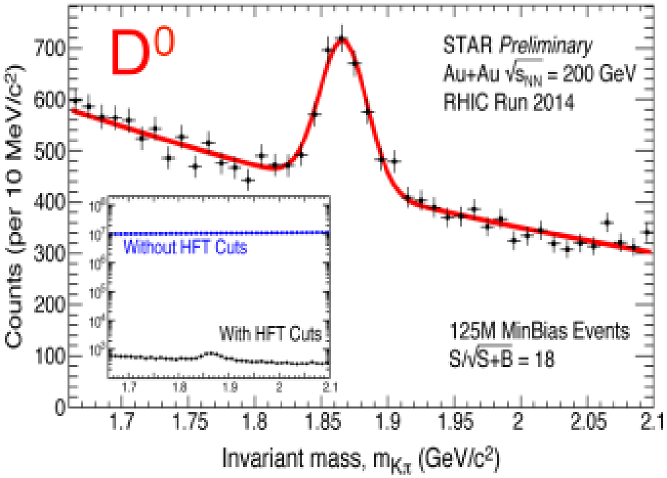
STAR experiment

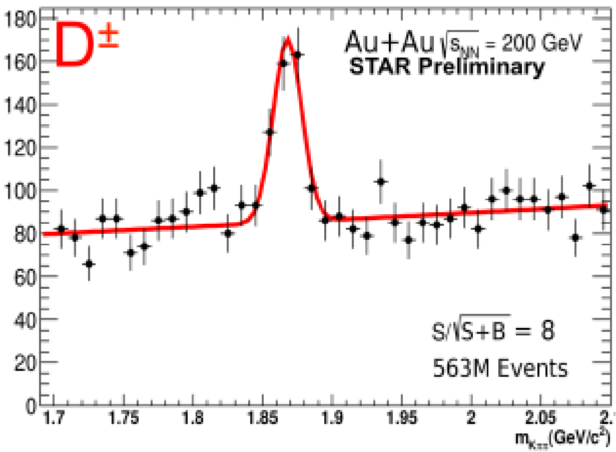


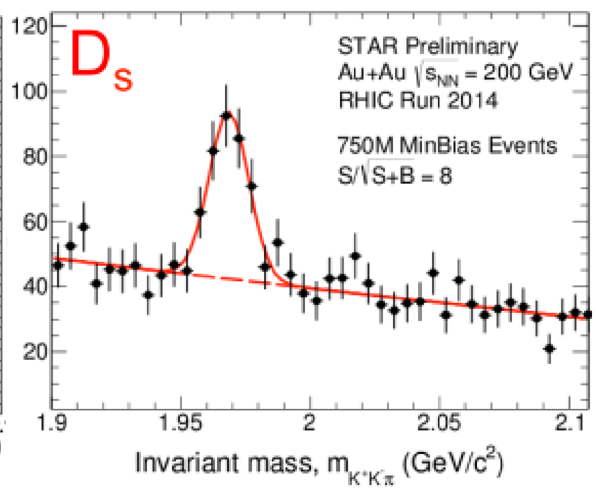
Heavy Flavor Tracker (HFT)



- Took data in 2014-2016
- First application of Monolithic Active Pixel Sensor technology in collider experiments.
- DCA resolution <50 μm for p_T =750 MeV/c Kaon





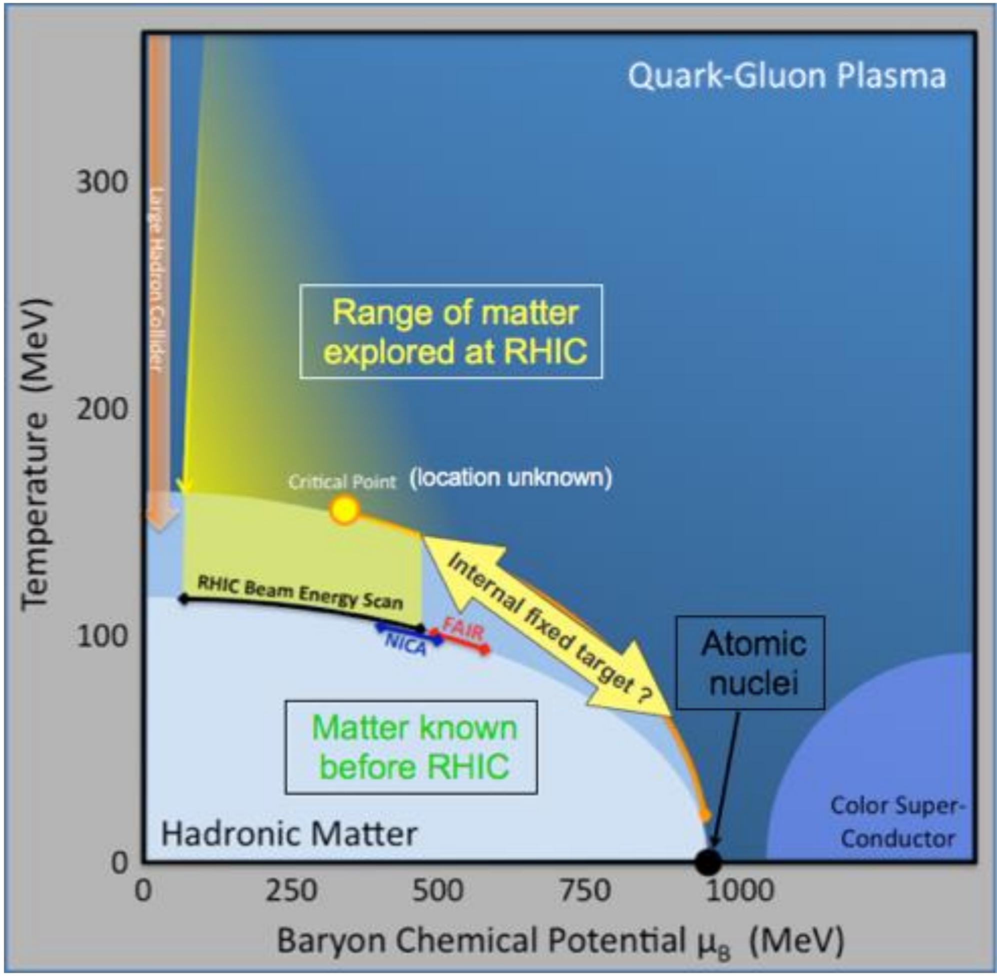


Beam Energy Scan

Key physics questions:

- Where is the onset of sQGP formation
  - Can we "turn it on/off"?
- Where starts the 1st order phase transition
  - Is there a critical point?
- What are the symmetries (degree of freedom) of the sQGP
  - Chiral symmetry restoration
  - Quark and gluon degree of freedom
  - Response to external field
- What is Equation of State (soft)

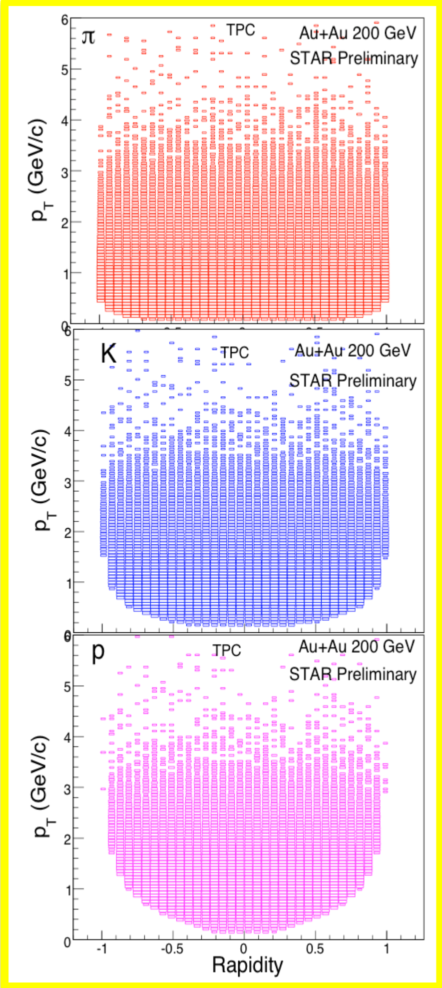
Mapping the QCD Phase Diagram



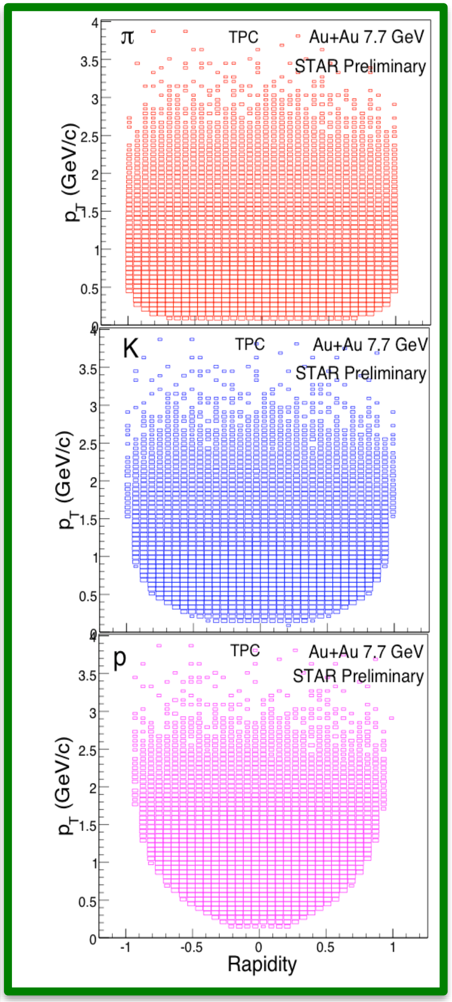
Beam Energy Scan I

$\sqrt{s_{NN}}$ (GeV)	μ_B (MeV)	#Events	#Weeks	Year
200	20	350 M	11	2010
62.4	70	67 M	1.5	2010
39.0	115	130 M	2	2010
27.0	155	70 M	1	2011
19.6	205	36 M	1.5	2011
14.5	260	20 M	3	2014
11.5	315	12 M	2	2010
7.7	420	4 M	4	2010

Au+Au 200 GeV

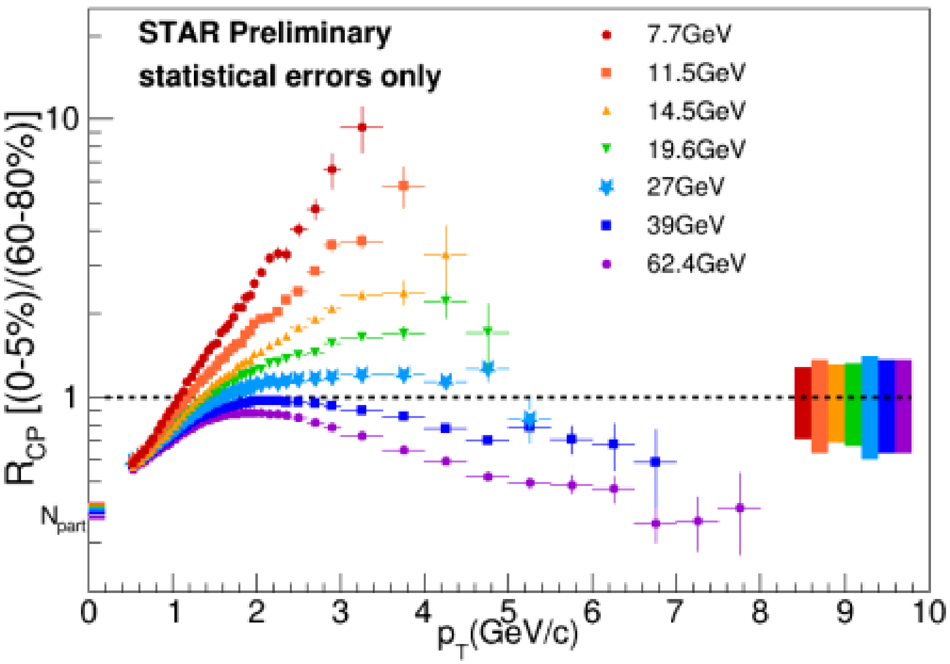


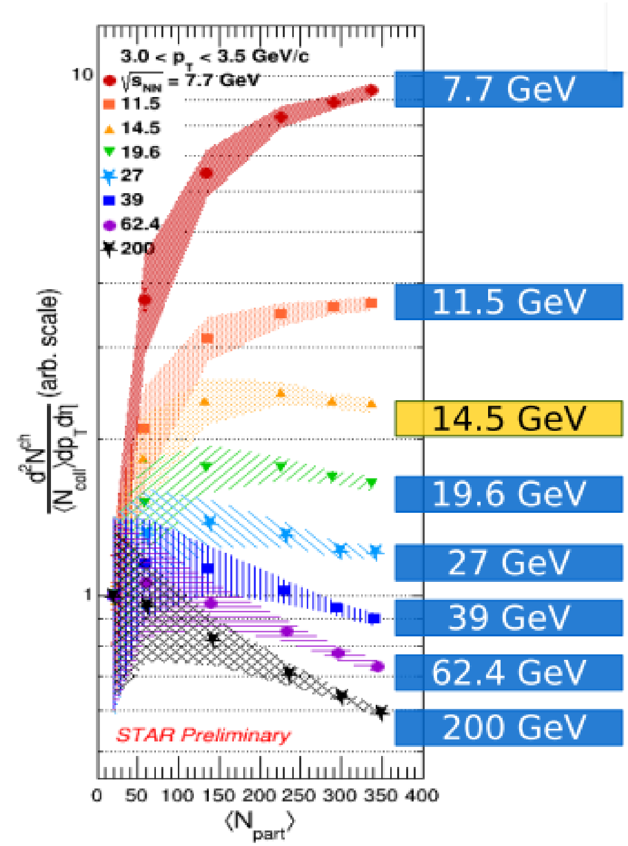
Au+Au 7.7 GeV



- Large, Uniform Acceptance at Mid-rapidity
- Ideal detector for BES
- Eight energies scanned

Search for onset of QGP signatures





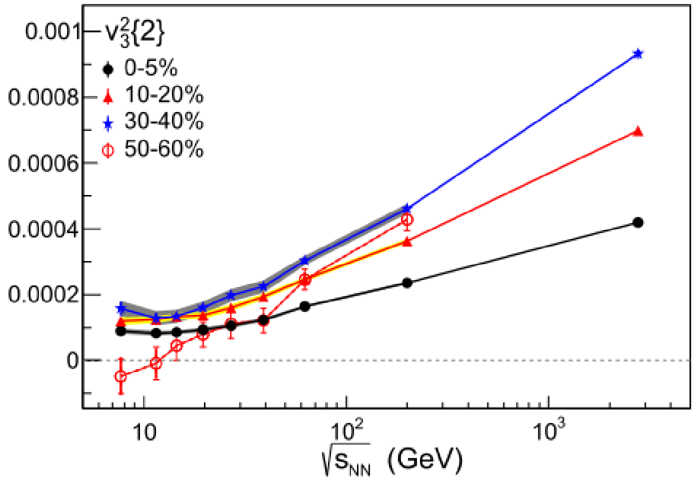
Evolution of R_{CP} suppression

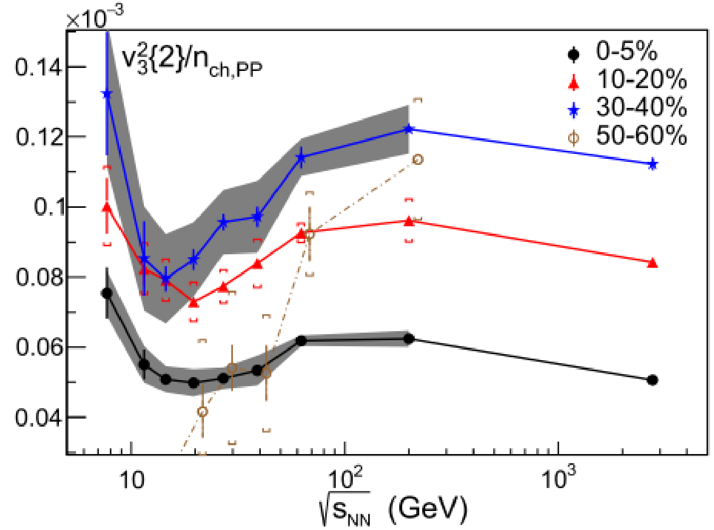
- R_{CP} Exhibits suppression down to 39 GeV
- Cronin effects play a bigger role at lower energies.
- Yields per binary collision show indicate a balance of enhancement and suppression effects at $\sqrt{s_{NN}}$ = 14.5 GeV.

Search for onset of QGP formation

Triangular flow v_3 – a third harmonics in the fourier decomposition of the two-particle azimuthal correlations
– is a sensitive indicator for the presence of a low viscosity QGP phase
– higher energy collisions produces more particles and higher pressure should be more effective to convert geometry fluctations to v_3

Phys. Rev. Lett. **116** (2016) 112302



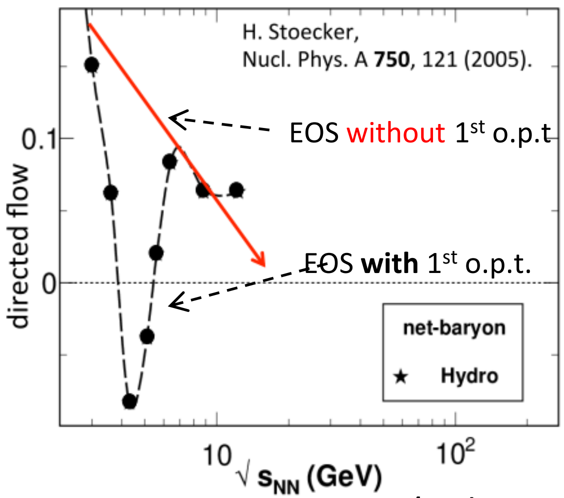


- Sizable v_3 at lower energies in central to mid-central centralities
- While the v_3 grows as ~log(√s) at higher energy, it is nearly independent of energy below 20 GeV.
- Peripheral collisions consistent with zero for $\sqrt{s_{NN}}$ less than 14.5 GeV (absence of low viscose QGP phase)

v_3 scaled by $n_{ch,PP} = dN_{ch}/d\eta/(N_{part}/2)$ ~ energy density

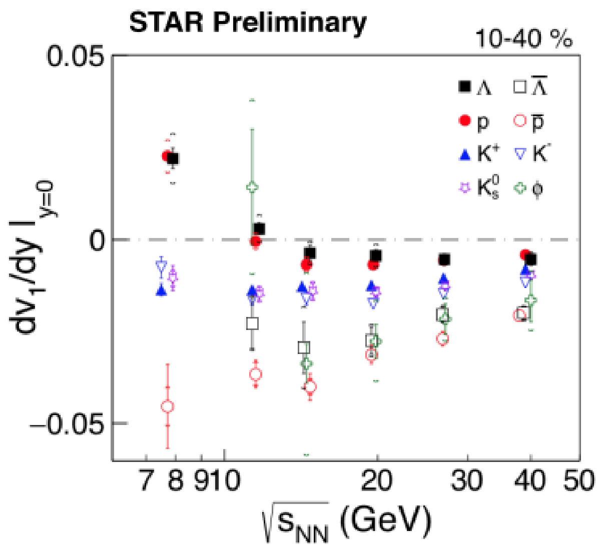
- Local minimum around 20 GeV
- Softening of EoS?

Search for 1st order phase transition: v_1

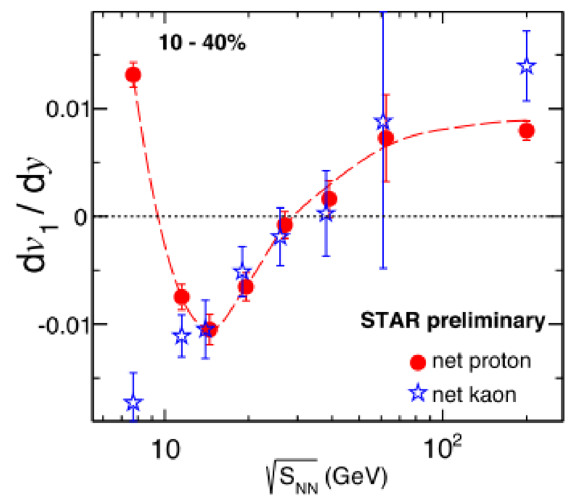


Directed flow v_1

- Sensitive to the pressure
- Sensitive to EoS
- Dip in dv_1/dy – softening of EOS



- Minimum in $dv1/dy|_{y=0}$ –hydro and baryon transport interplay
- (Anti)-Lambdas follow those of (anti)-protons
- Net-K and net-p are consistent with each other down to ~14.5 GeV
  - net-K stays negative for $\sqrt{s_{NN}}$ < 14.5 GeV
- The non-monotonic variation for slope of net-proton directed flow could be related to the softening of equation-of-state due to the first order phase transition



Search for critical point

Critical point

- susceptibilities and correlation length diverge
- large fluctuation

$$\frac{\chi_2^i}{\chi_1^i} = (\sigma^2/M)^i = \frac{c_2^i}{c_1^i}$$

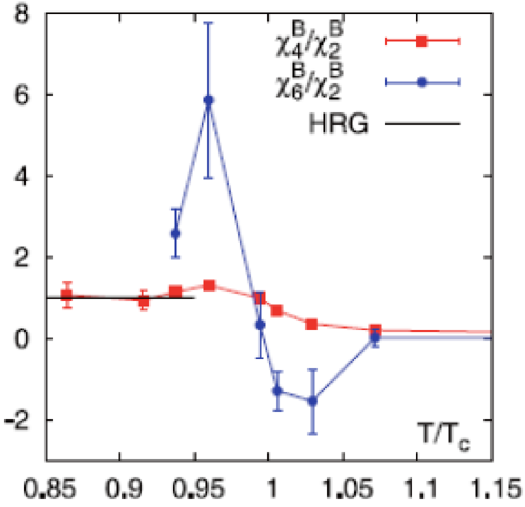
$$\frac{\chi_3^i}{\chi_2^i} = (S\sigma)^i = \frac{c_3^i}{c_2^i}$$

$$\frac{\chi_4^i}{\chi_2^i} = (\kappa\sigma^2)^i = \frac{c_4^i}{c_2^i}$$

$$i = B, Q, S$$

Observables

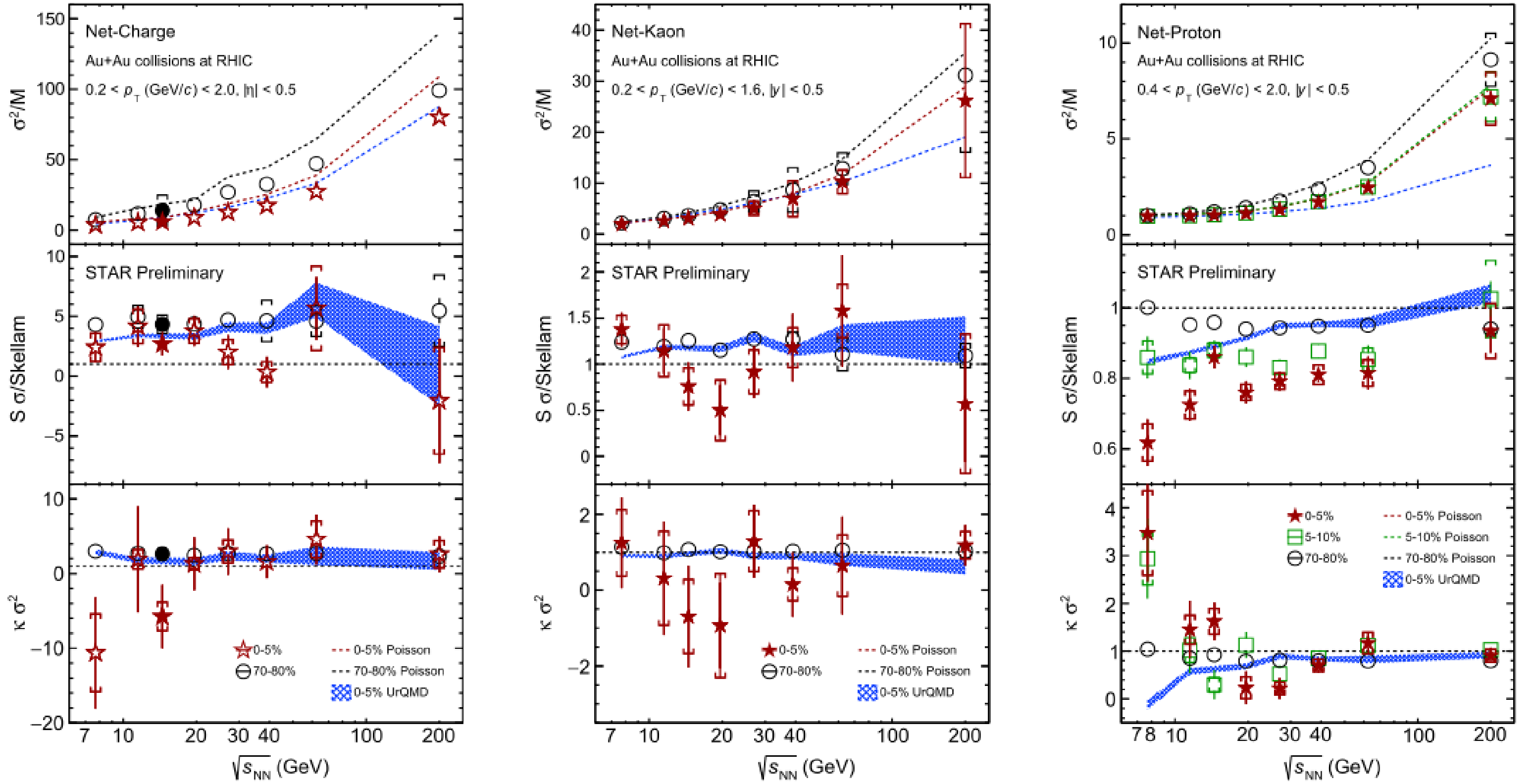
- Higher moments of conserved quantum numbers (Q, S, B)
  - Direct link between theory and moments of distributions (cumulant ratios)



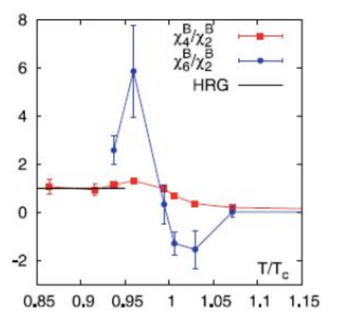
$$\chi_q^{(n)} = \frac{1}{VT^3} \times C_{n,q} = \frac{\partial^n (p/T^4)}{\partial(\mu_q)^n}, q = B,Q,S$$

S. Ejiri et al, Phys.Lett. B 633 (2006) 275.
Cheng et al, PRD (2009) 074505. B. Friman et al., EPJC 71 (2011) 1694.
F. Karsch and K. Redlich , PLB 695, 136 (2011).
S. Gupta, et al., Science, 332, 1525(2011).
A. Bazavov et al., PRL109, 192302(12) // S. Borsanyi et al., PRL111, 062005(13) // P. Alba et al., arXiv:1403.4903

Net-charge,kaon,proton fluctuations



- The values of net-Kaon's and net-Charge's κσ^2 and Sσ/Skellam are consistent with Poisson distributions within errors.
- **Non-monotonic** behavior of **net-proton** κσ^2 seen in top 0-5%, 5-10% central collisions
  - Largest deviation from Poisson and uRQMD around 19.6 GeV
- Need more precise measurements below 20 GeV
  - Finer steps in μ_B
  - Increase accepted rapidity window



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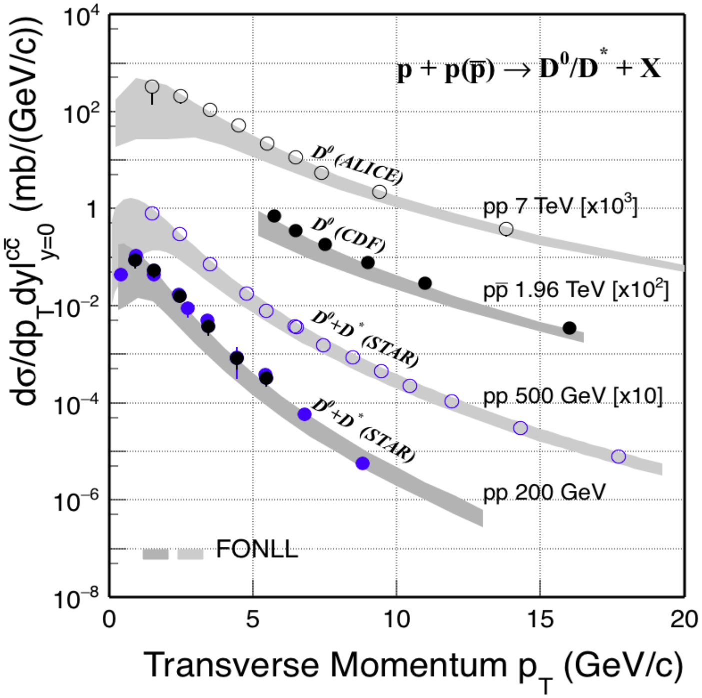
Probing Quark Gluon Plasma with charm quark

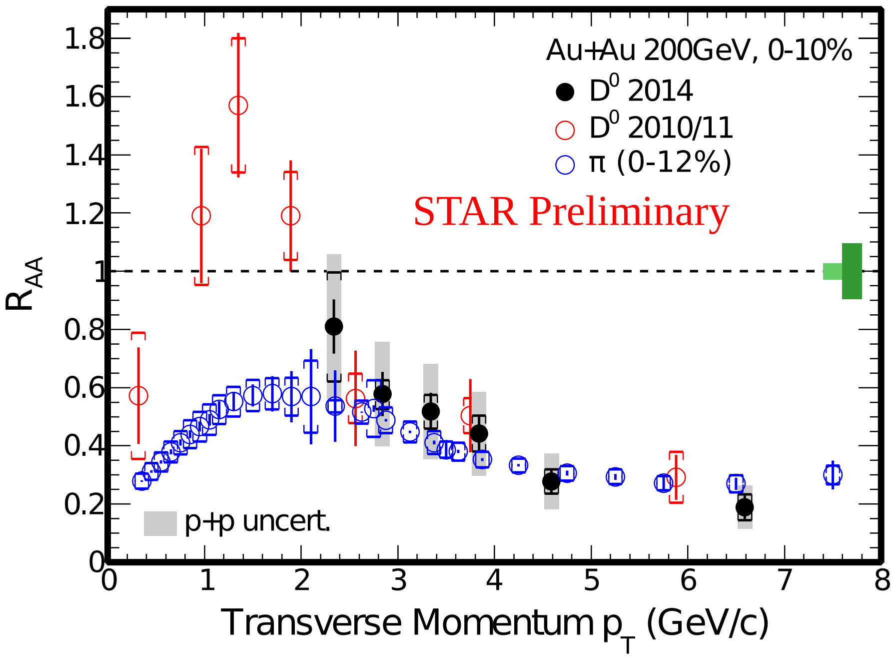
- **Charm quark: $m_c >> T_{QGP}, \Lambda_{QCD}$**
  - Produced in the hard scatterings at the early stage of nuclear collisions → experience the entire evolution of medium
  - Charm cross section scales with N_{coll} in Au+Au collisions → important input for models to calculate regeneration contribution to charmonium
    - Currently, 16% uncertainty in 0-10% Au+Au events*
  - Clean probe at RHIC as contributions from gluon splitting and bottom quark are small.
  - Its production rate is well described by pQCD in elementary collisions



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

**PRL 113 (2014) 142301*

D^0 R_{AA} in central Au+Au collisions



STAR: PRL 113 (2014) 142301

- $R_{AA} > 1$ for $p_T \sim 1.5$ GeV/c

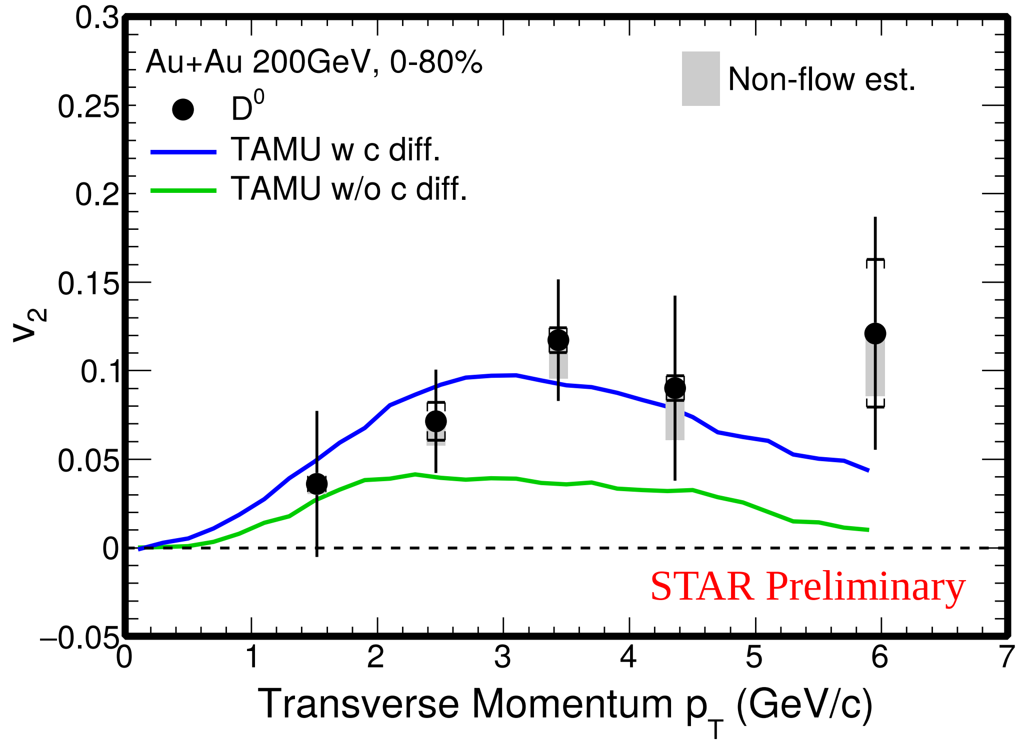
Charm coalescence with the flowing medium

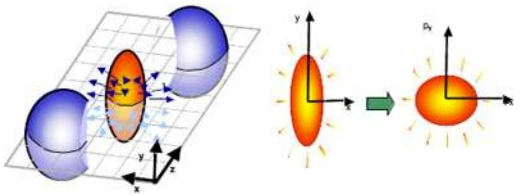
- $R_{AA} << 1$ for $p_T > 2.5$ GeV/c

Strong charm-medium interaction leading to sizable energy loss

- Similar suppression as pions at high p_T
  - Collisional energy loss is important
  - Shapes of parton spectrum & fragmentation function need to be taken into account.

First D^0 v_2 measurement at RHIC



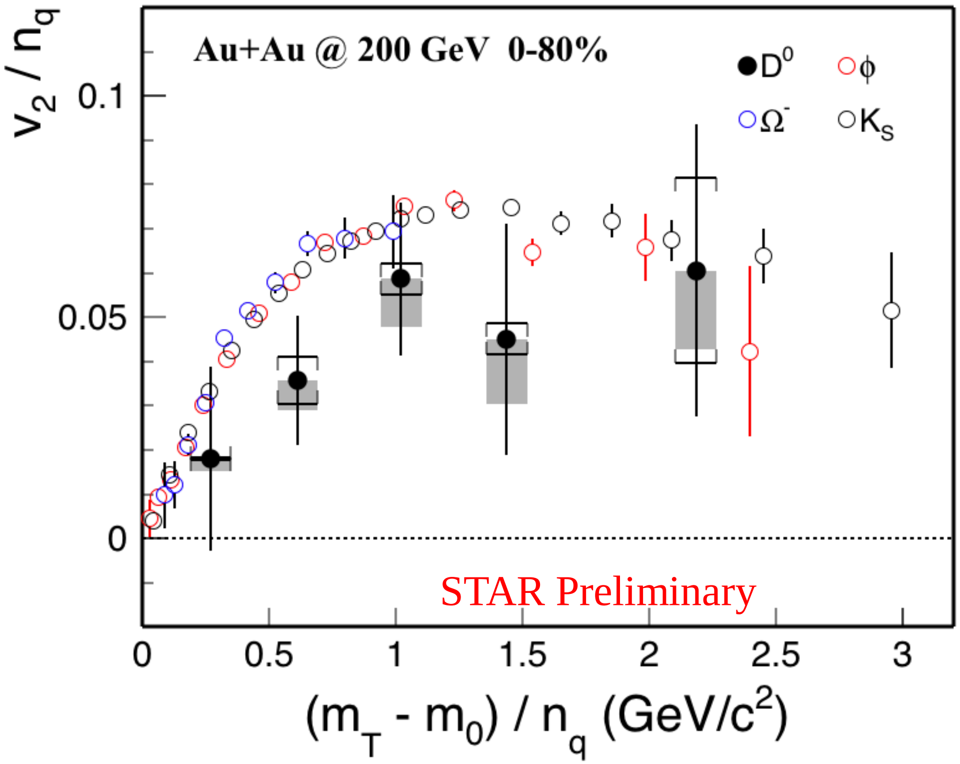


$$E\frac{d^3N}{d^3p} = \frac{1}{2\pi}\frac{d^2N}{p_t dp_t dy}\left(1 + \sum_{n=1}^{\infty} 2v_n \cos[n(\phi - \Psi_r)]\right)$$

- Finite D^0 v_2 observed above 2 GeV/c
- Data favor a model with charm diffusion

Charm quark flows in the medium

v_2: D^0 vs light hadrons

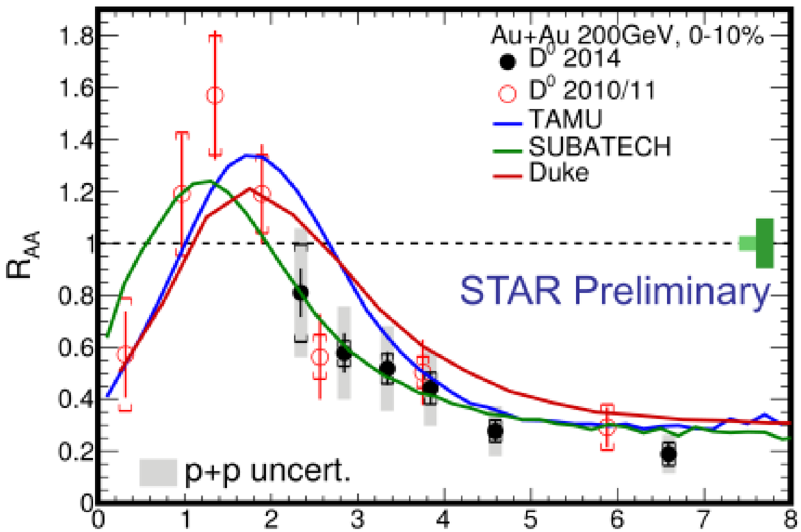


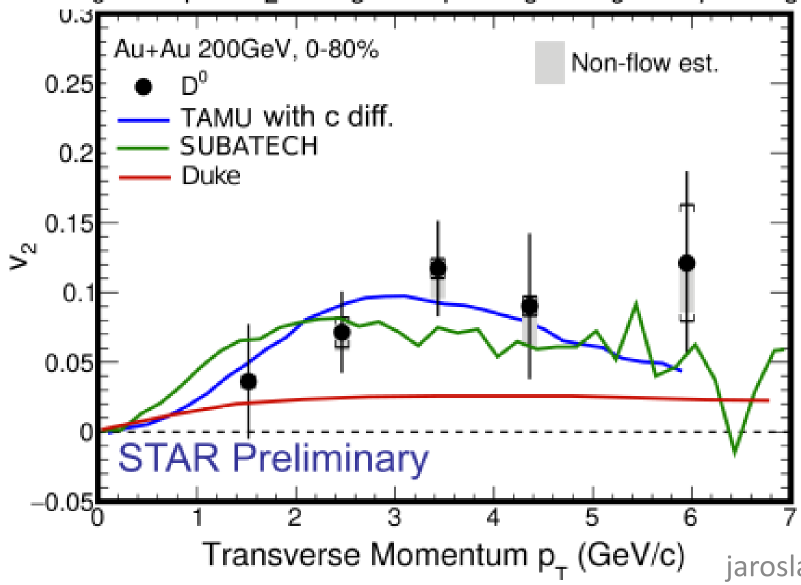
STAR: PRL 116 (2016) 062301

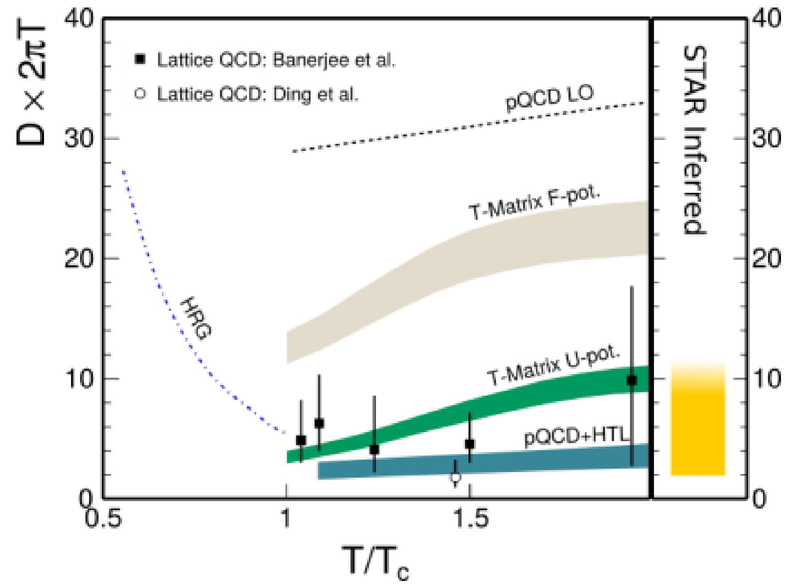
✓ v_2 for D^0 is systematically lower than those of light hadrons

→ Hints that charm quarks might not be fully thermalized with medium

Comparison to models





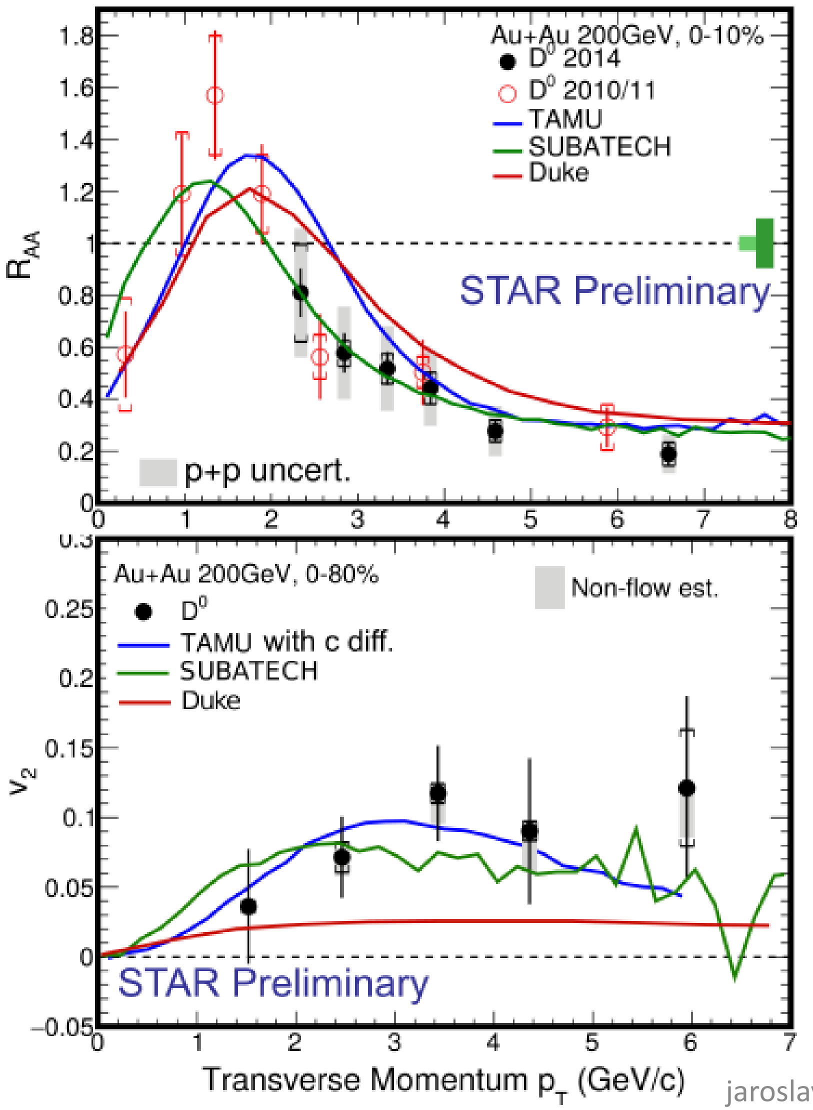


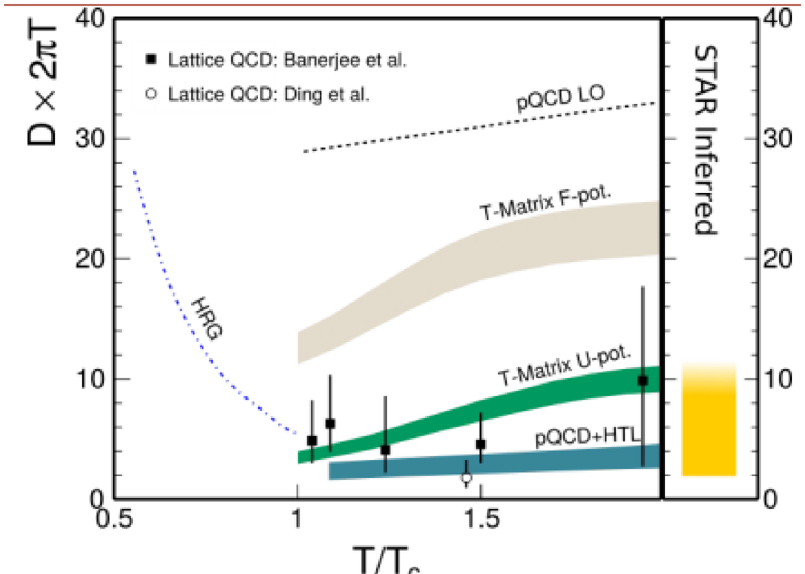
Values for the diffusion coeff. extracted from models and compared to STAR data

	D × 2πT	Diff. Calculation
TAMU	2-11	T-Matrix
SUBATECH	2-4	pQCD+HTL
Duke	7	Free parameter

STAR D_0 2010/11: PRL 113 (2014) 142301
Theory curves private communications
DUKE: PRC 92 (2015) 024907
A.Andronic arXiv:1506.03981(2015)

Comparison to models





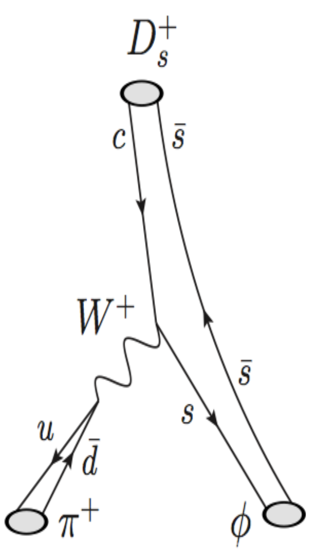
Values for the diffusion coeff. extracted from models and compared to STAR data

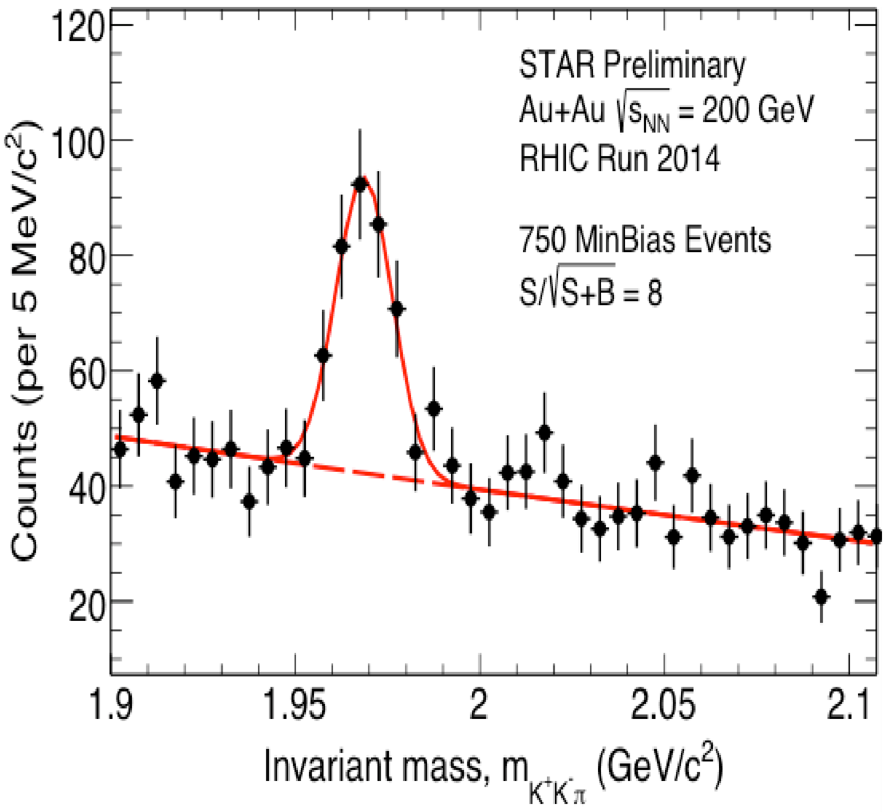
Models with charm diffusion coefficient of 2 - ~12 describe STAR D_0 R_{AA} and v_2 results.

Lattice calculations are consistent with these values inferred from data.

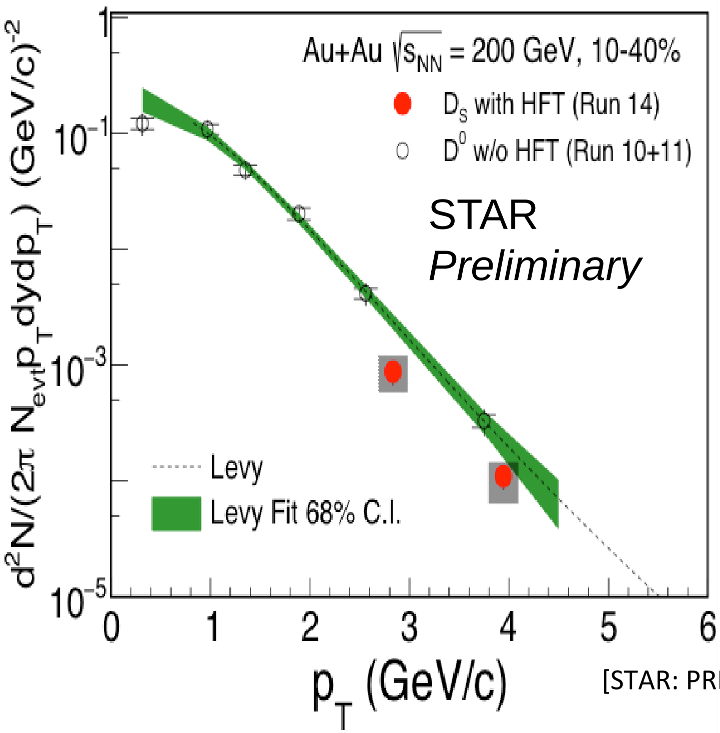
D_s reconstruction

- $D_s^{\pm} \rightarrow \pi^{\pm}\phi(1020) \rightarrow \pi^{\pm}K^{\pm}$
- $c\tau = 150\ \mu m$
- B.R. 2.32 %
- Mass 1968.47 MeV/c^2
- First measurement of D_s at RHIC

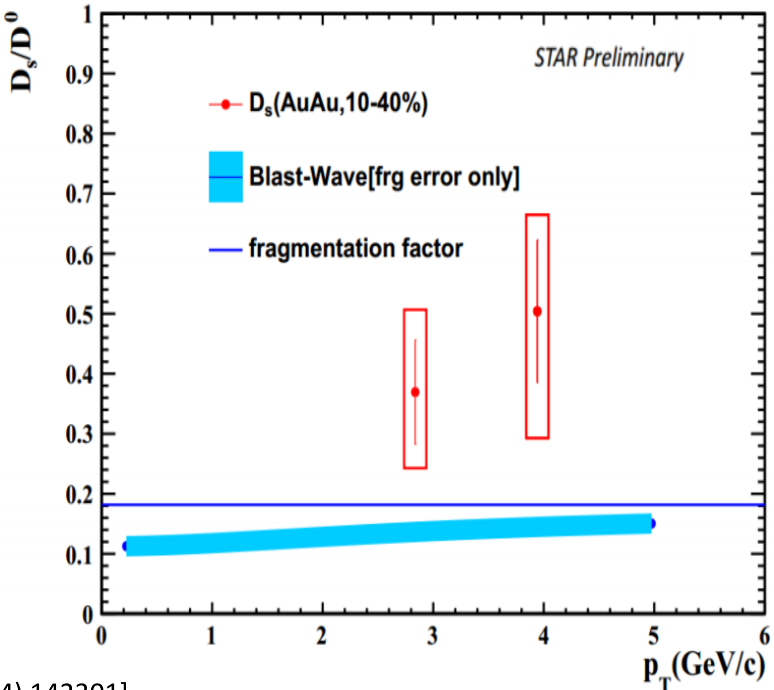




D_s yield and D_s/D_0 ratio



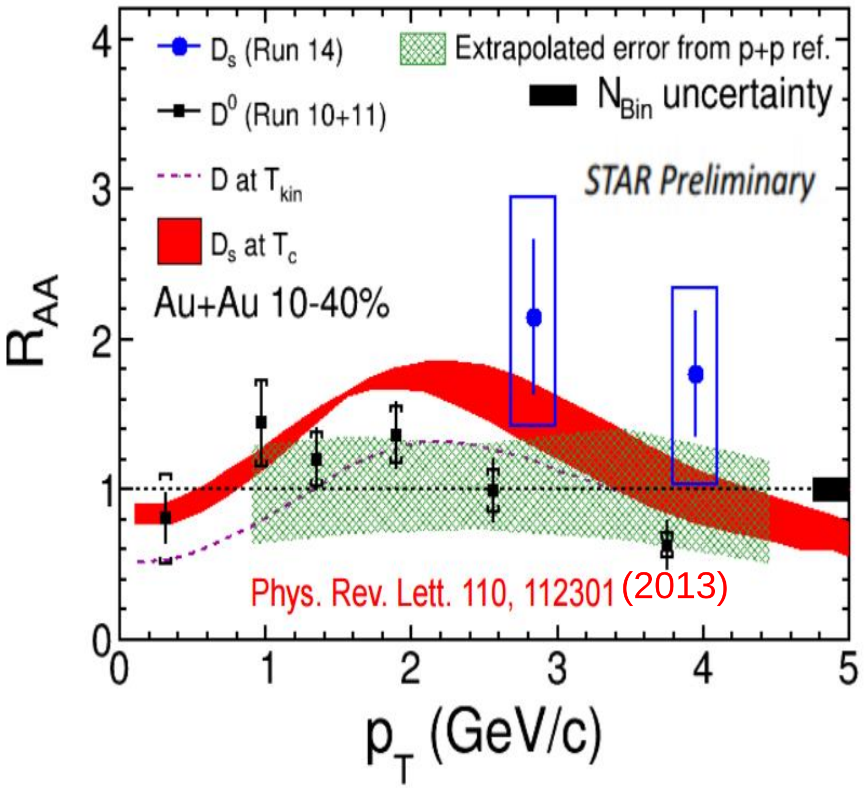
[STAR: PRL 113 (2014) 142301]



[H1 Collaboration, Eur.Phys.J.C38(2005)447] [ZEUS Collaboration, Eur.Phys.J.C44(2005)351]

- Hint of D_s enhancement compared to D^0

R_{AA} compared to a model calculation



- p+p reference obtained from the charm cross-section measured by STAR scaled by $c \rightarrow D_s$ fragmentation factor [H1 Collaboration, Eur.Phys.J.C38(2005)447] [ZEUS Collaboration, Eur.Phys.J.C44(2005)351]
- Consistent with the He-Rapp model calculations within uncertainties
- Hint of D_s enhancement

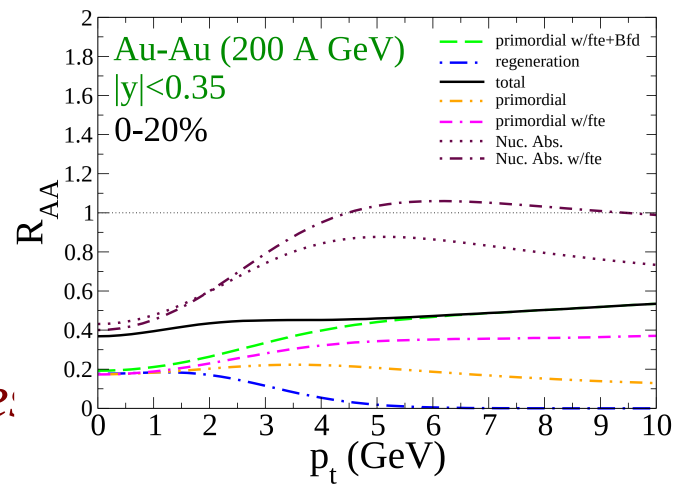
Probe QGP with quarkonium

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

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

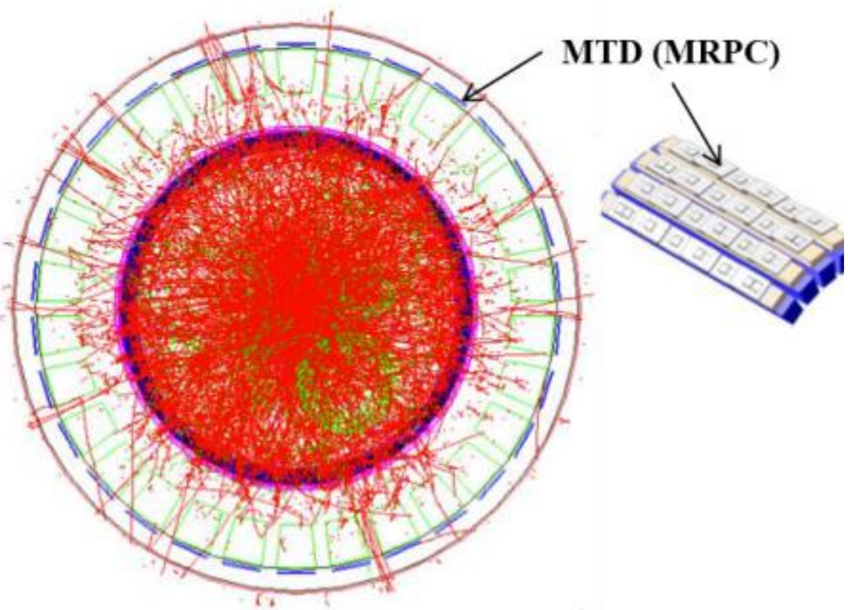
T. Matsui and H. Satz PLB 178 (1986) 416

- 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*

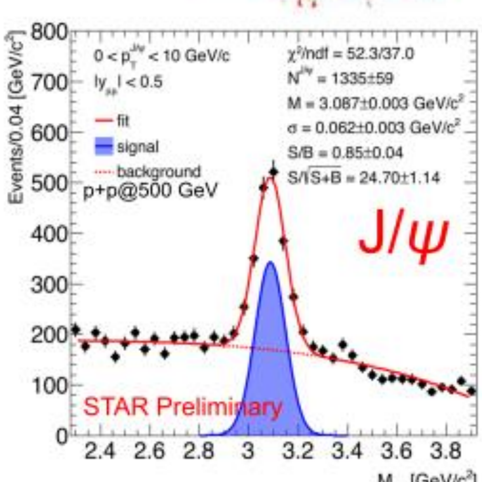


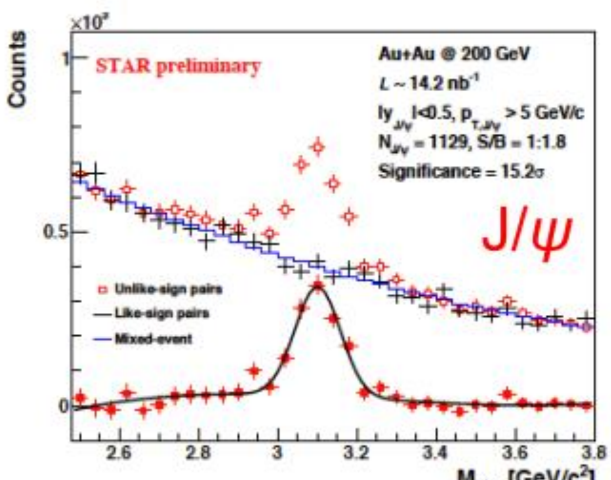
Phys. Rev. C 82, 064905 (Modified)

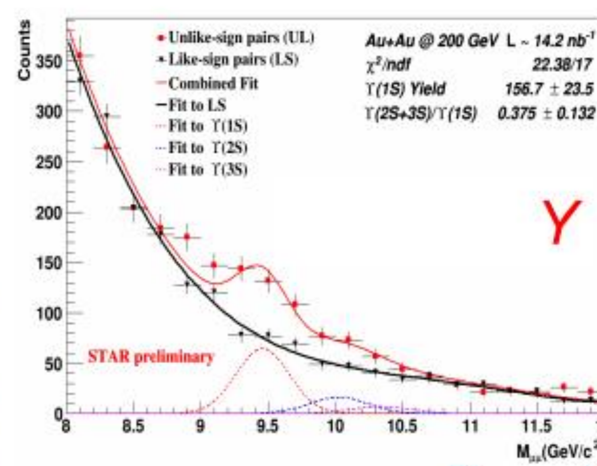
Quarkonia measurements with MTD



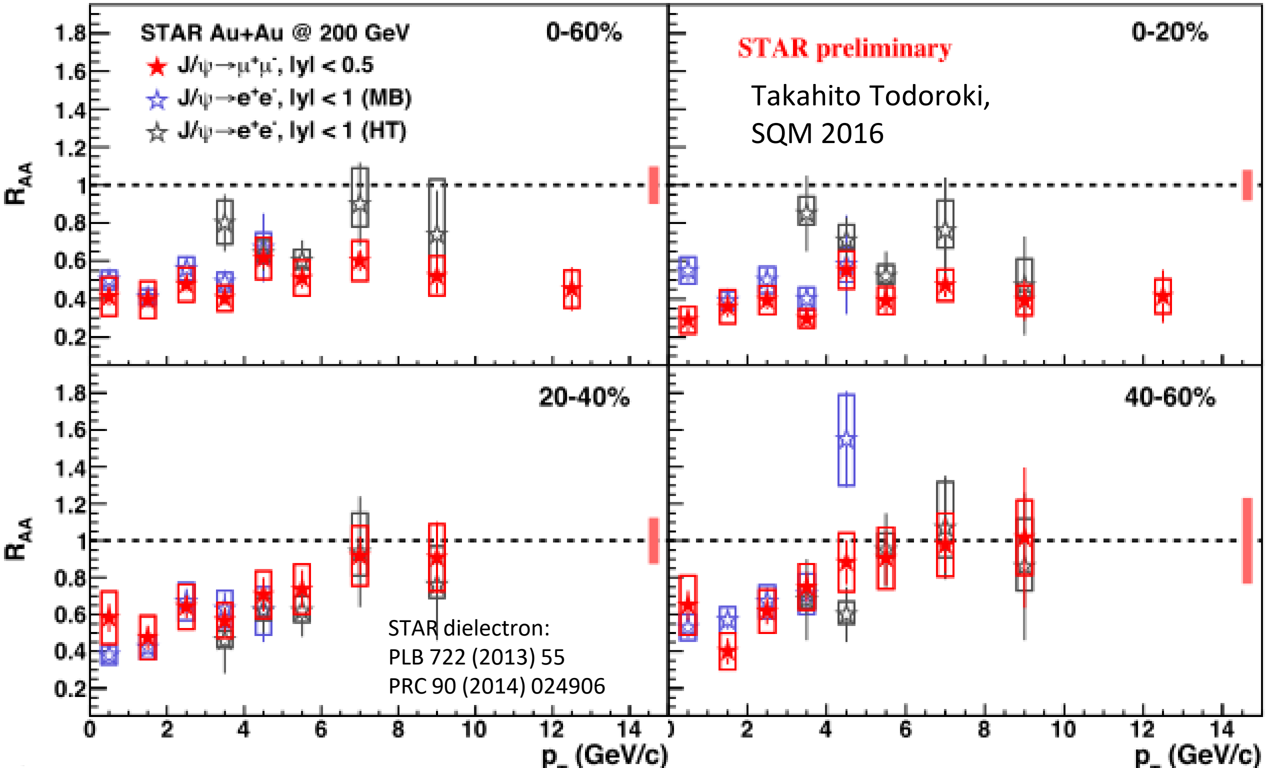
- Based on the same proven MRPC technology as TOF
- Precise timing info (~100ps) for p_T>1.2GeV/c
  - muon online triggering and offline identification
- Recorded 28 pb $^{-1}$, 120 pb $^{-1}$, 400 nb $^{-1}$ and 22 nb $^{-1}$ dimuon-triggered 500 GeV p+p, 200 GeV p+p, p+Au and Au+Au
- data for J/ψ and Y studies







J/ψ R_{AA} in Au+Au at 200 GeV



- First J/ψ results from the dimuon channel at mid-rapidity in Au+Au collisions at RHIC
- Full statistics from 2014 Au+Au 200 GeV run
- Consistent with di-electron channel

Suppression at low-p_T

- Dissociation
- Regeneration
- Cold nuclear matter effect

High-p_T

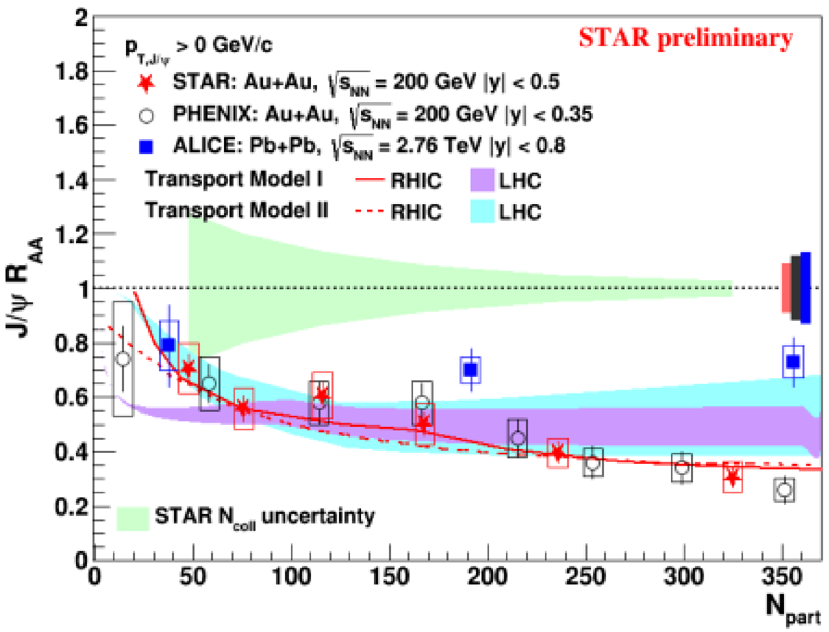
- Strong suppression in 0-20%
- Rising trend in 20-60%
  - Dissociation
  - Formation time effect; B feed down

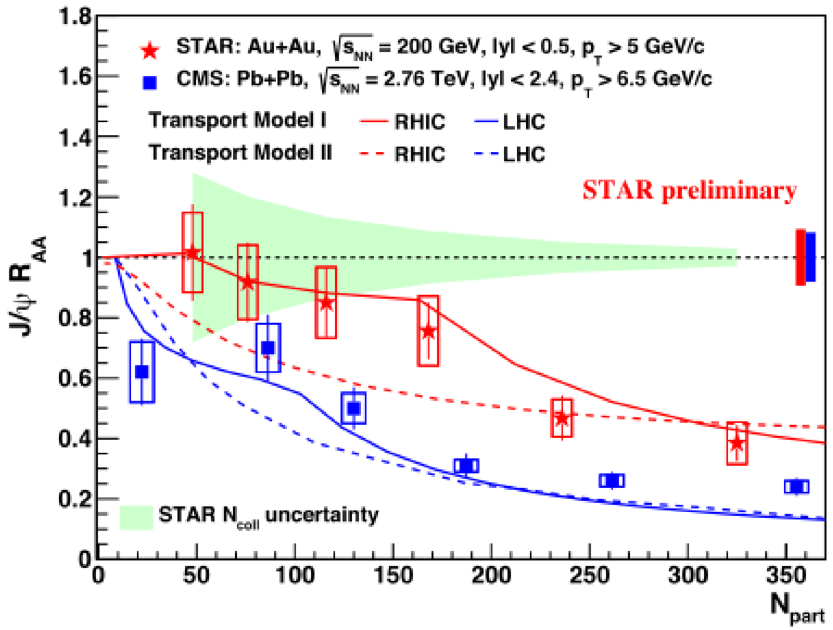
J/ψ R_{AA} – comparison to LHC and models

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

Transport models:
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

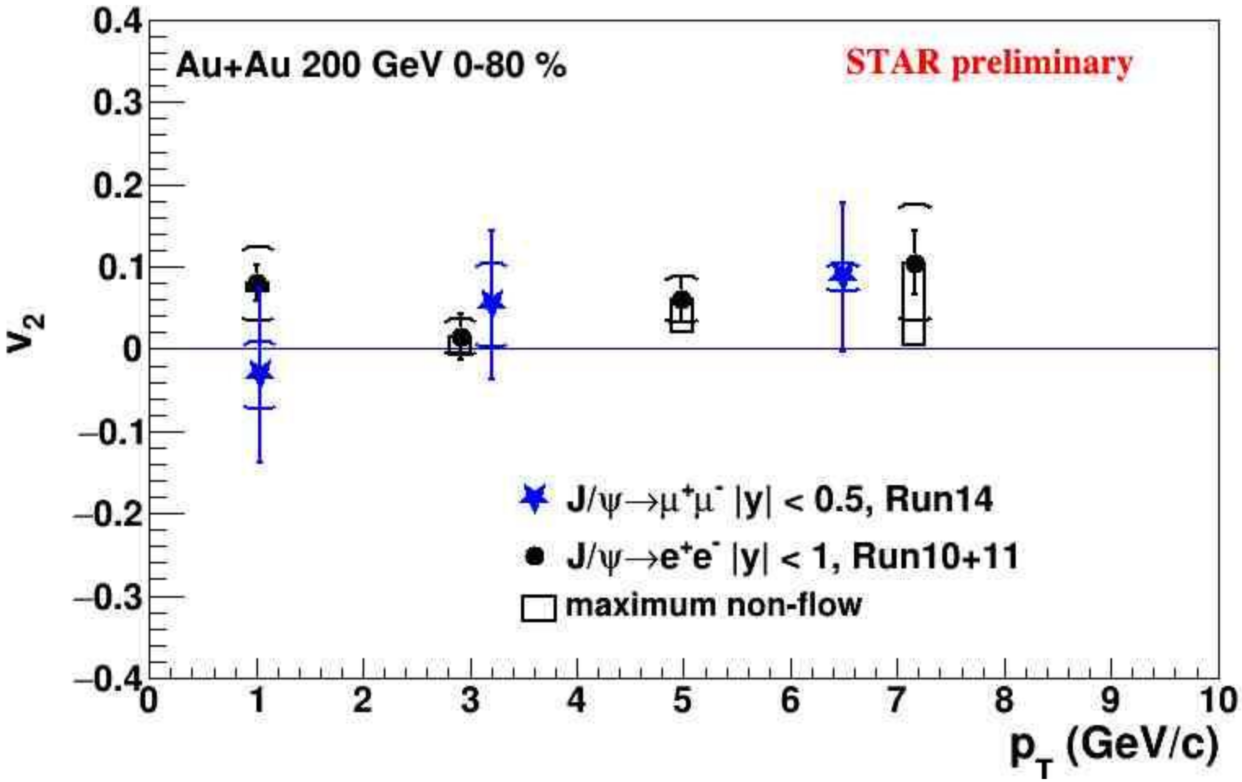




- J/ψ R_{AA} for p_T >0 GeV/c: RHIC is smaller than LHC -> more recombination at LHC
- J/ψ R_{AA} for p_T >5 GeV/c : LHC is smaller than RHIC -> stronger dissociation at LHC
- Transport models with dissociation and recombination qualitatively describe data

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



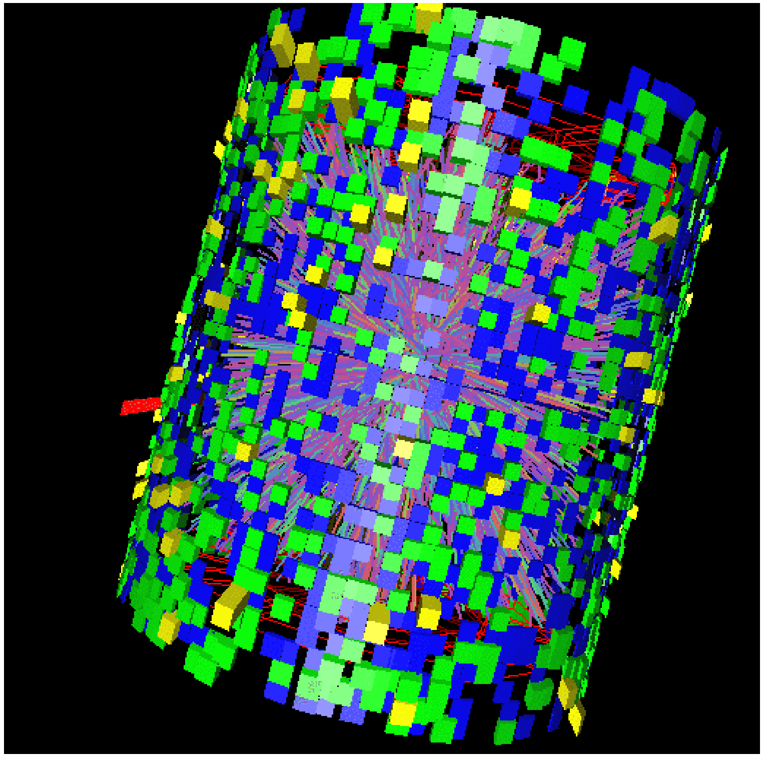
- Updated J/ψ v_2 in di-electron channel combining Run10 and Run11 data favors small contribution from regeneration above 2 GeV/c
- **Consistent results from di-muon channel**

Upsilon measurements

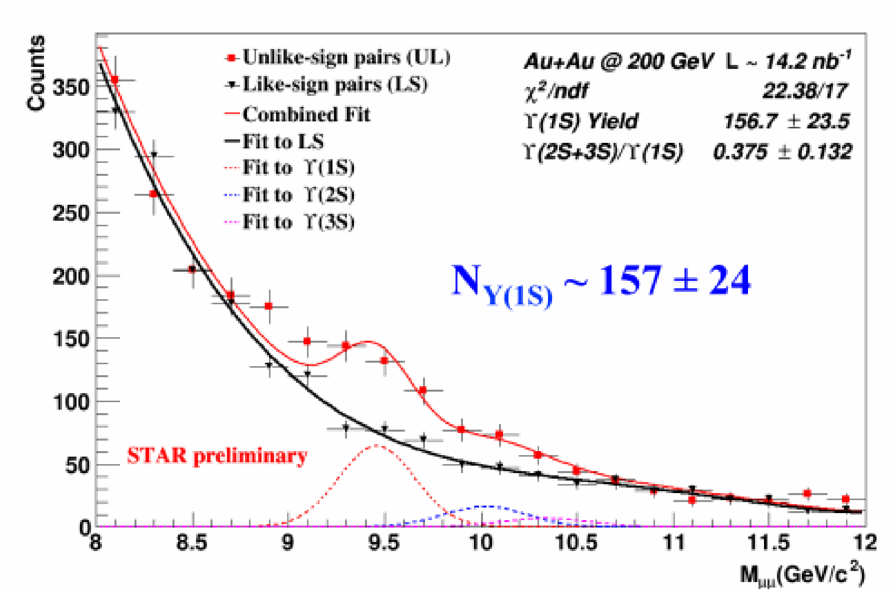
Υ -cleaner probe compared to J/ψ

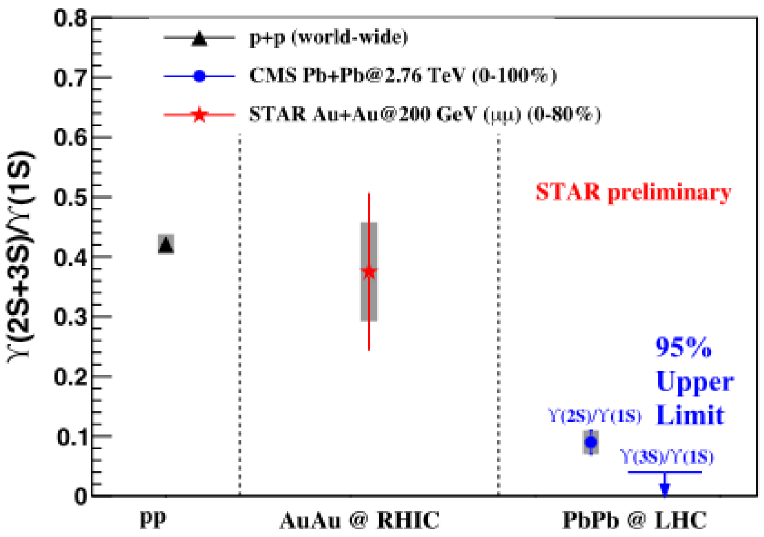
- co-mover absorption → negligible
  - Υ(1S): tightly bound, larger kinematic threshold.
    - Expect σ~ 0.2 mb, 5-10 times smaller than for J/ψ

      Lin & Ko, PLB 503 (2001) 104
- recombination → negligible
  - at RHIC: σ_{cc} ~800μb >> 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
  - STAR upgrades



ϒ(2S+ 3S)/ ϒ(1S) ratio

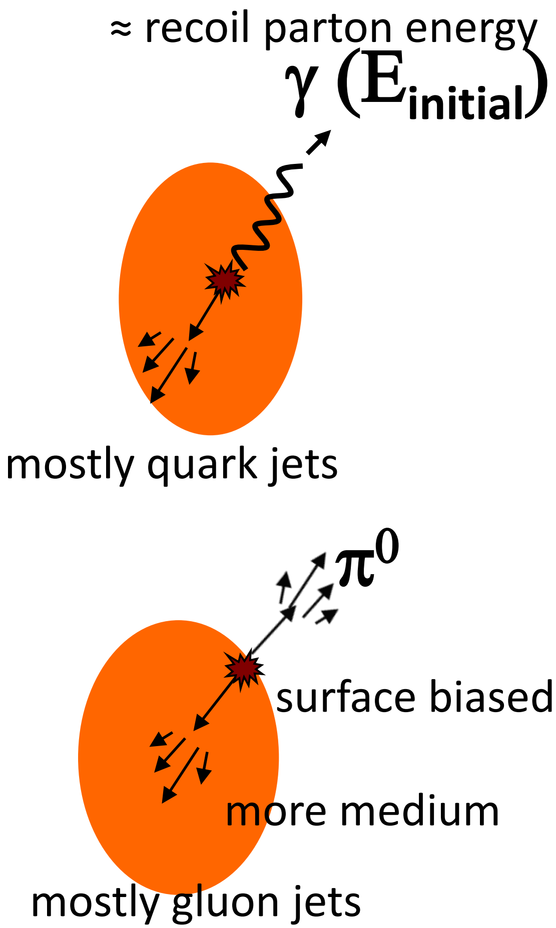




World-wide PRC 88(2013) 067901
CMS : PRL 109(2012) 222301
CMS : JHEP 04 (2014) 103

- Combined signal of Y(2S+3S) from the di-muon channel
  - Challenging for di-electron channel due to Bremsstrahlung
- Less melting of Y(2S+3S) at RHIC than at LHC ?

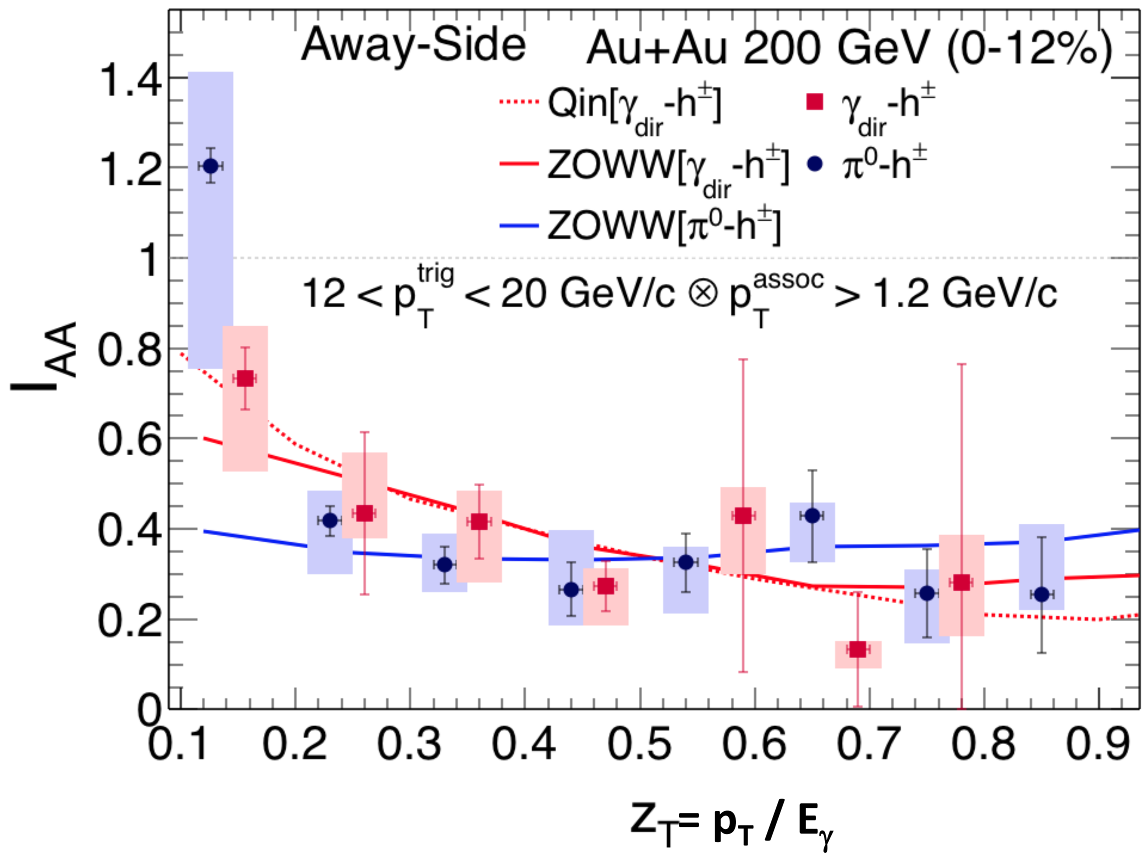
Direct photon-hadron/π^0 – hadron correlations



$$I_{AA}(x) = \frac{Y^{Au+Au}(x)}{Y^{p+p}(x)}$$

$$z_T = \frac{p_T^{assoc}}{p_T^{trig}}$$

STAR PLB 760 (2016) 689 arXiv:1604.01117



- Suppression: hadron triggers ≈ photon triggers
  No clear path length and color factor effect observed

Summary of results

Beam Energy Scan

- Spanning a range of μ_B that could contain features of the QCD phase diagram.
- Observed signatures consistent with disappearance of parton dominated regime
- Indicators pointing towards a softening of the equation of state which
  - possible evidence for a first order phase transition.
- Critical phenomena – signal from higher moment fluctuations
  - Statistically demanding

Heavy flavor

- Successful data taking with MTD and HFT
- D^0 R_{AA} and v_2 in Au+Au collisions:
  - favors models calculation with charm quark diffusion
  - Diffusion coefficient compatible with lattice calculations
- J/ψ R_{AA} in Au+Au collisions: larger (smaller) R_{AA} at low (high) p_T than LHC
  - Effect of recombination
- Upsilon in Au+Au collisions:
  - hint for less Upsilon(2S+2S) suppression at RHIC than LHC

Jets

- No clear path length and color factor effect observed in gama/π^0 hadron correlations

Thank you for your attention