Highlights from the heavy-ion program in STAR

Petr Chaloupka

for the STAR collaboration

Czech Technical University
in Prague

STAR

Outline

sQGP at top RHIC energy

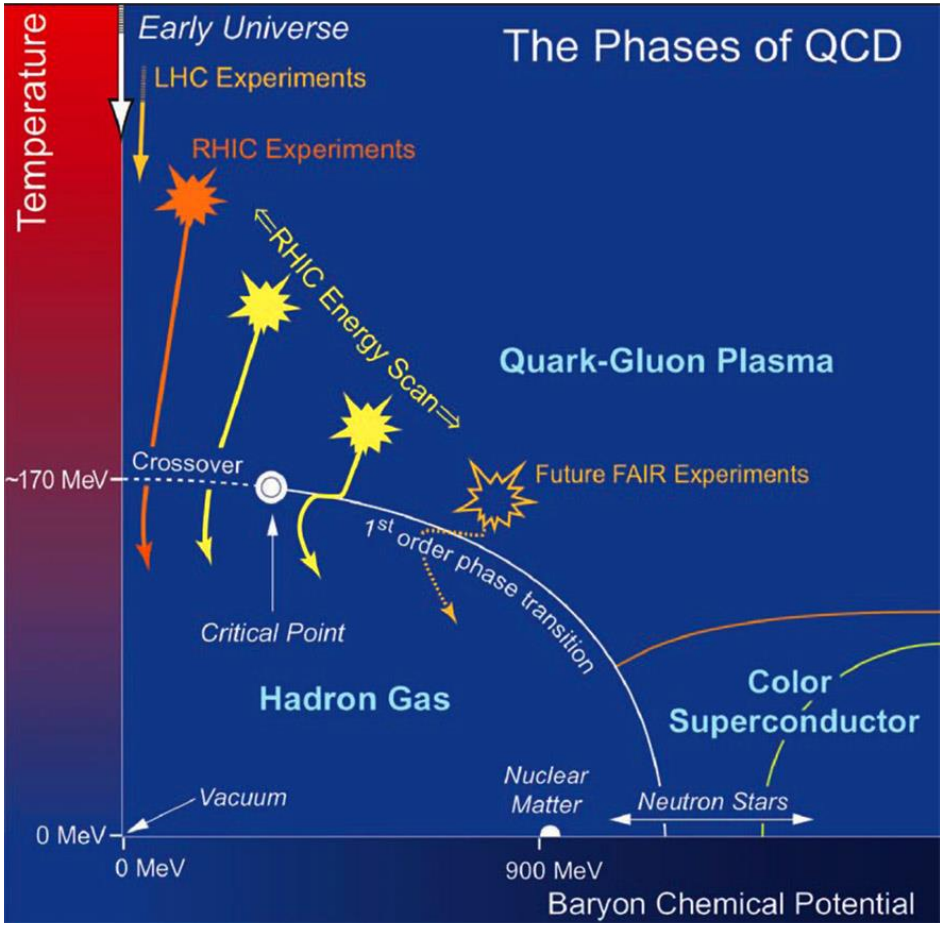
- Recent heavy flavor results with new detectors

(parallel talk by M. Lomnitz)

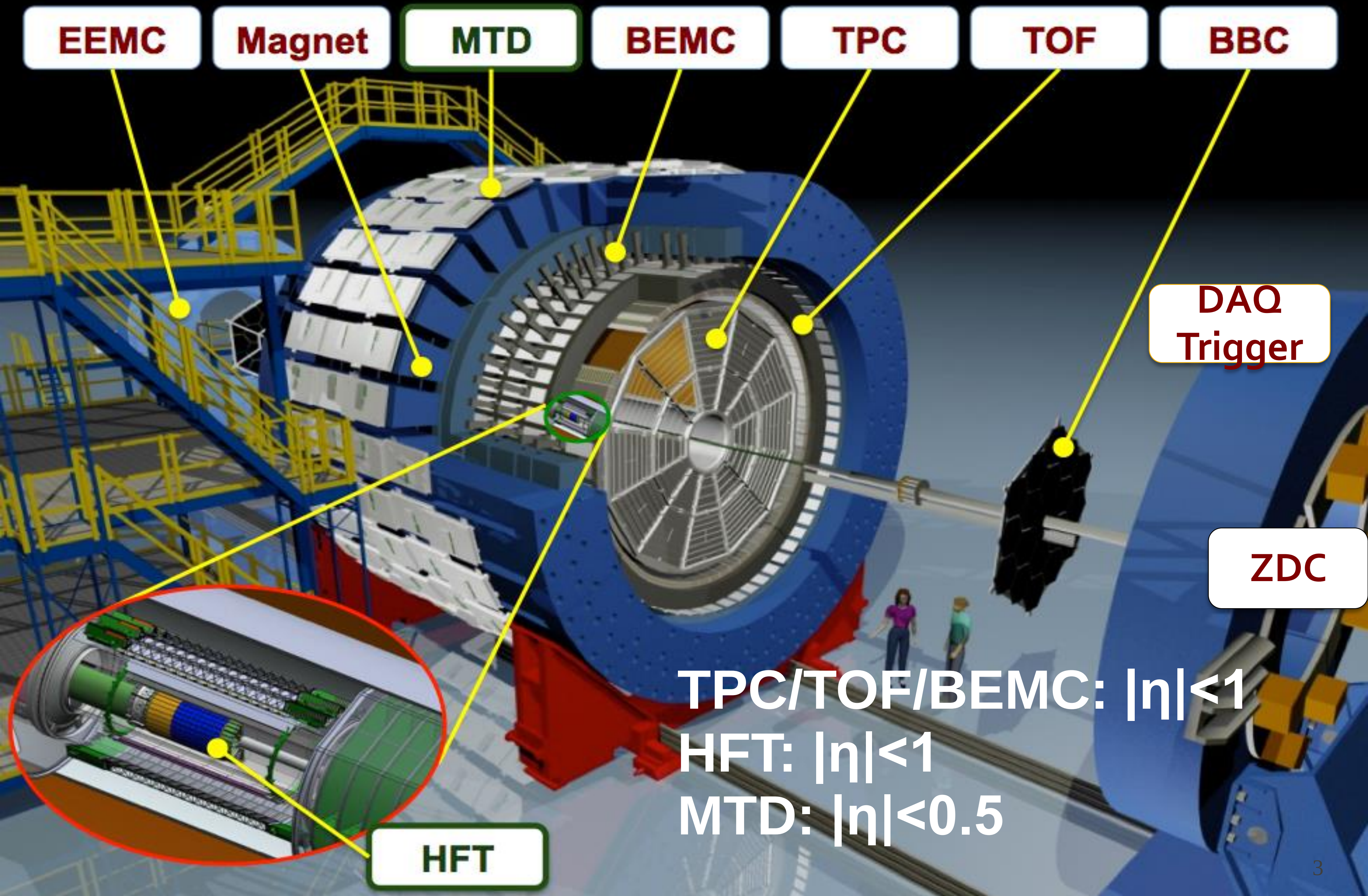
Beam Energy Scan (BES)

- Onset of sQGP
- Phase boundary and critical point
- Chiral effects and global polarization

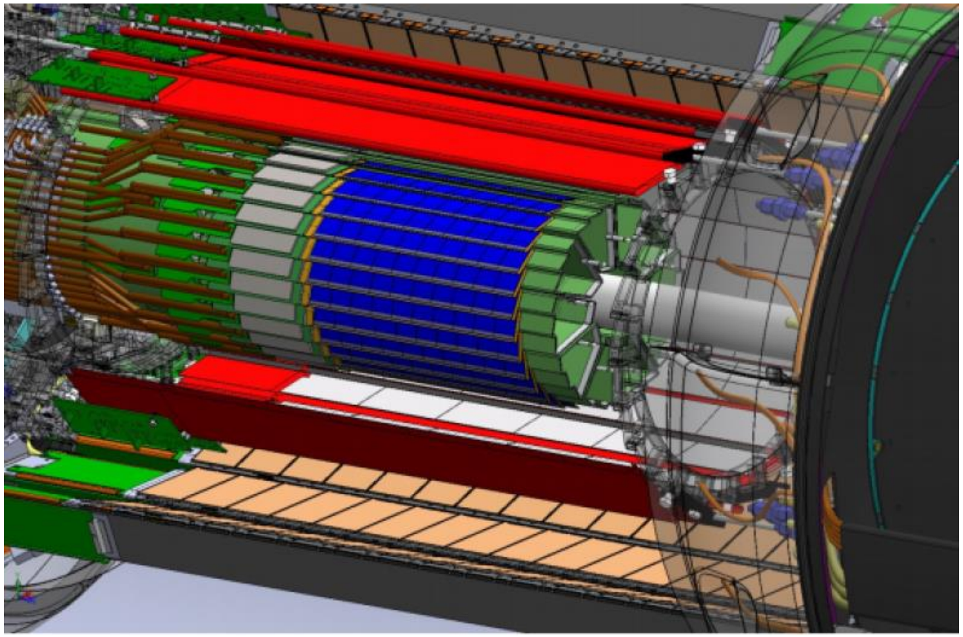
Beam Energy Scan - Phase II (BES)



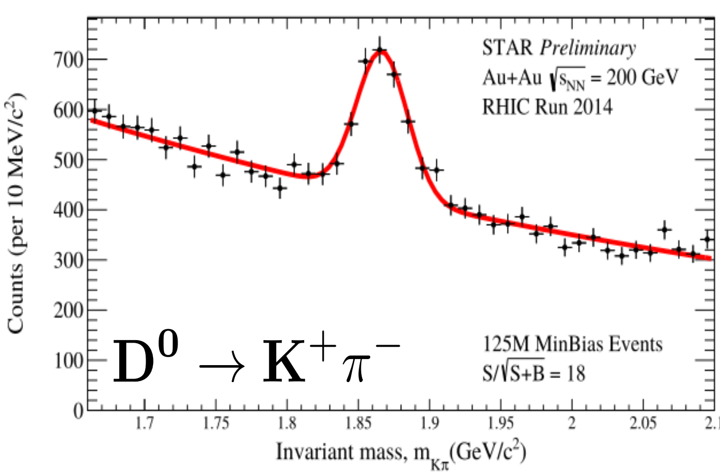
STAR experiment

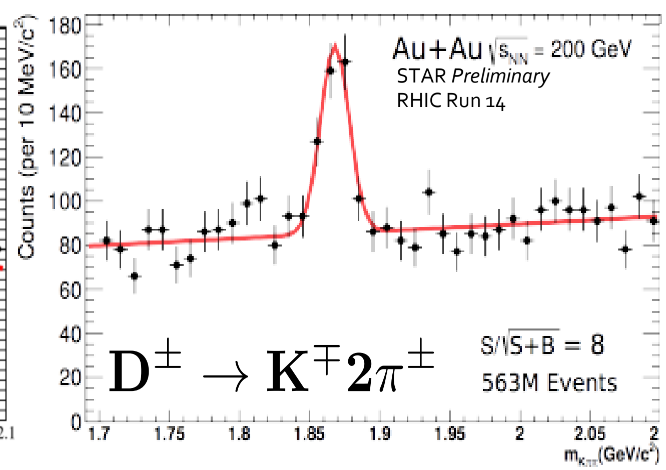


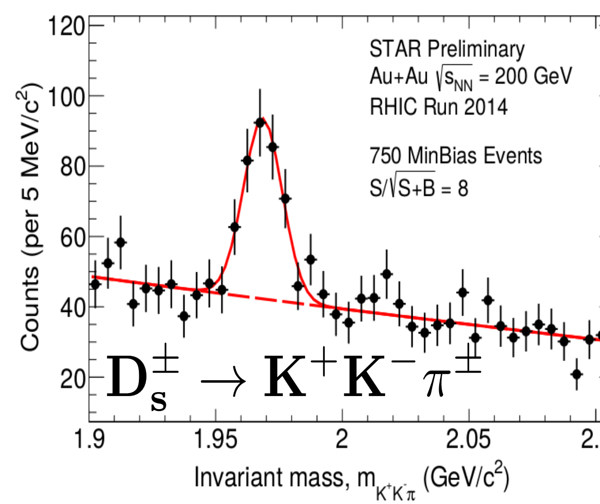
Heavy Flavor Tracker (HFT)



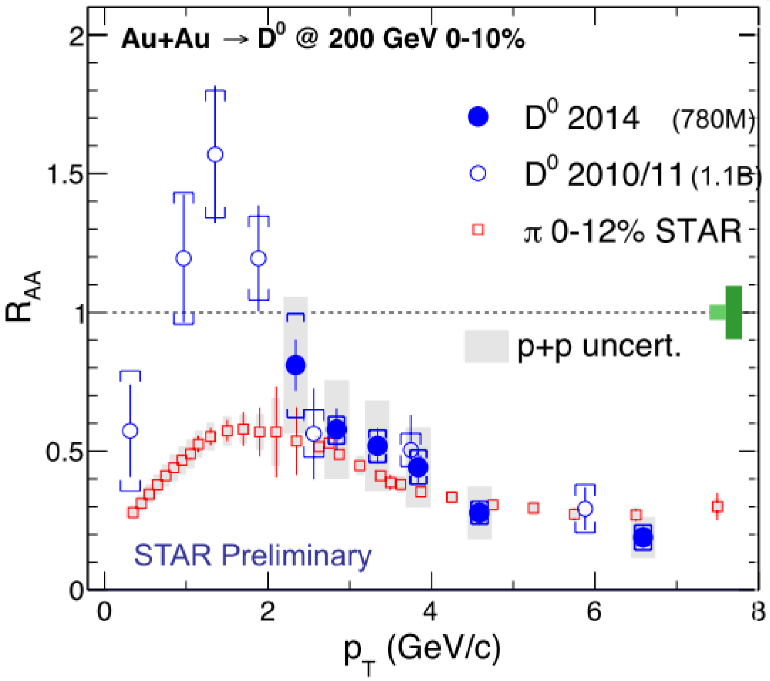
- Installed for year 2014
- First application of Monolithic Active Pixel Sensor technology in collider experiments.
- DCA resolution <50 μm for p_T =750 MeV/c Kaon







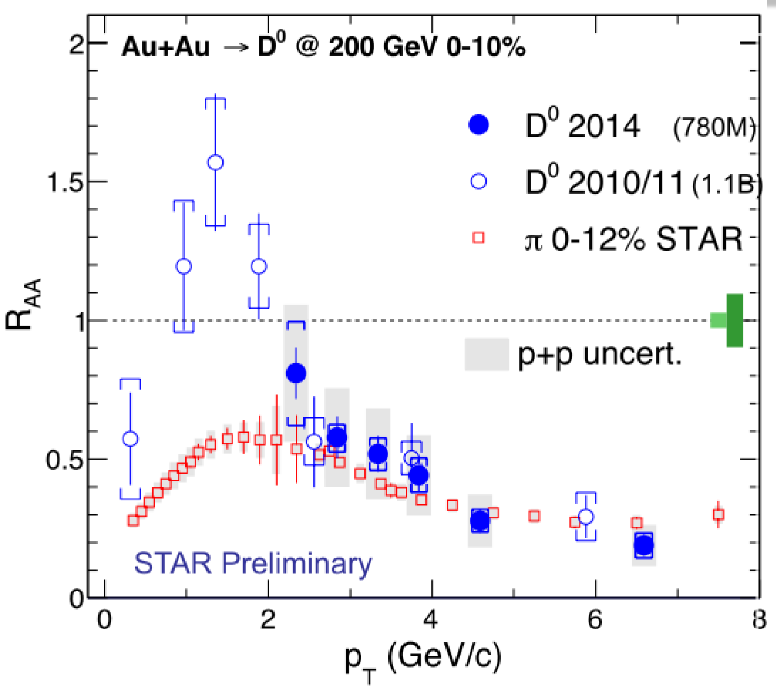
D_0 results from the HFT – R_{AA}, v_2

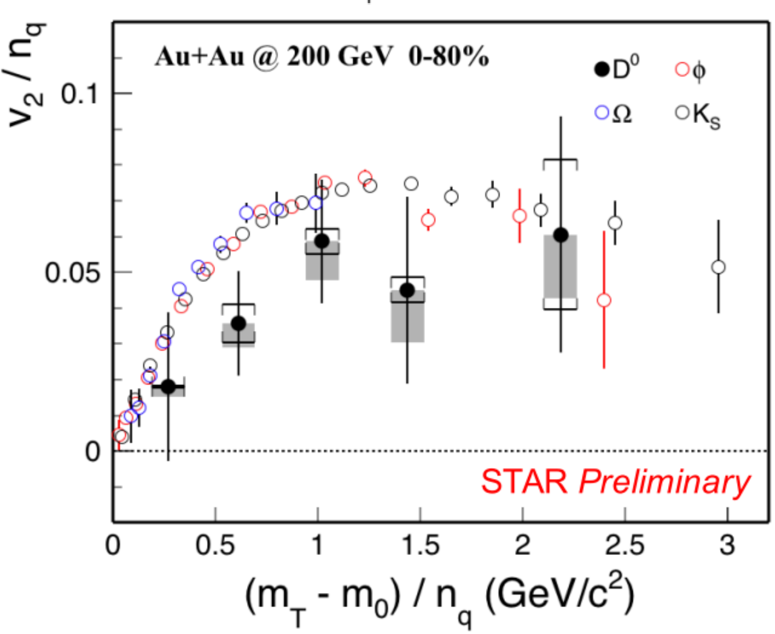


$$R_{AA} = \frac{1}{\langle N_{coll} \rangle} \frac{dN/dy^{AuAu}}{dN/dy^{pp}}$$

- Greatly enhanced D_0 significance w HFT
- Low p_T R_{AA}
  - for $p_T \sim 1.5$ GeV/c $R_{AA} > 1$
  - Charm coalescence with a radially flowing bulk medium
- High p_T R_{AA}
  - significant suppression in central Au+Au collisions.
  - Similar suppression as for light partons
  - Suggests charm-medium interaction

D_0 results from the HFT – R_{AA} , v_2



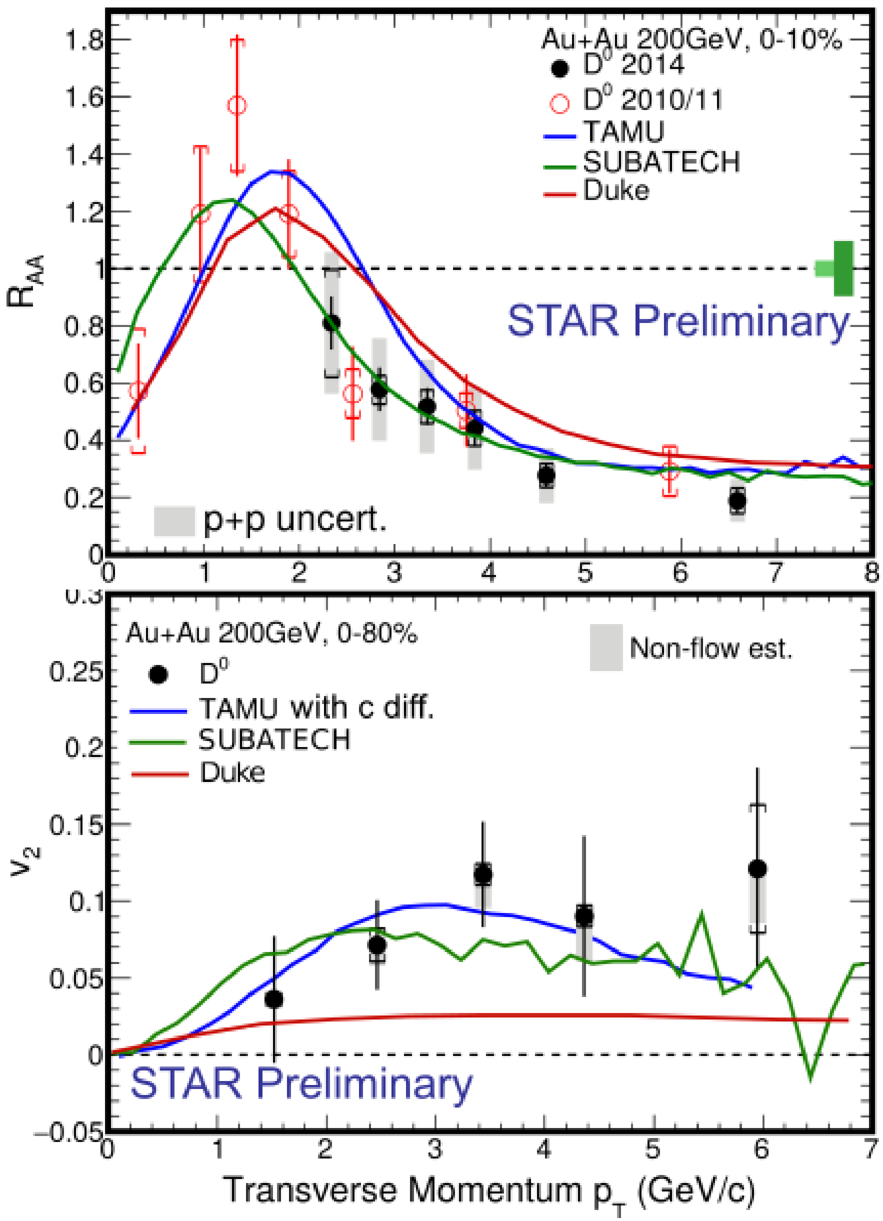


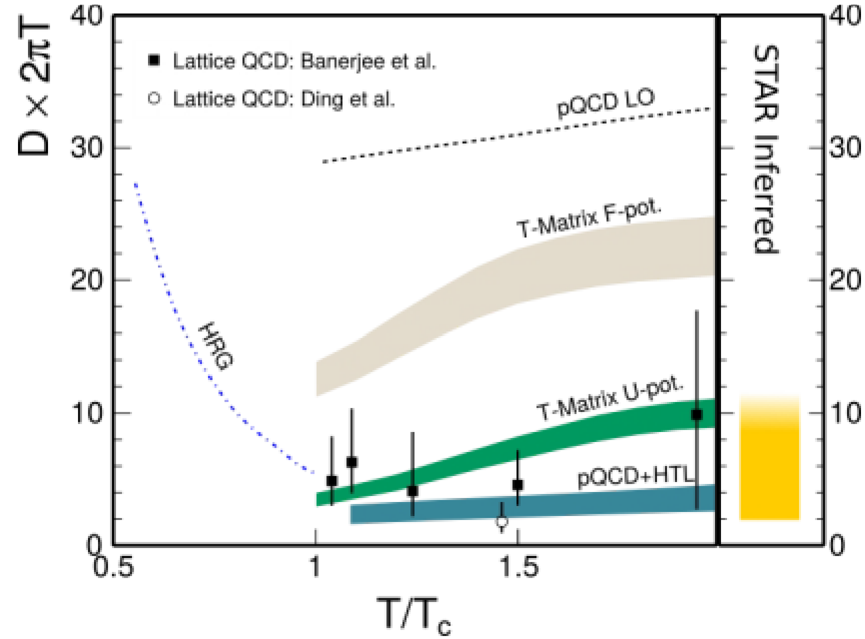
$$R_{AA} = \frac{1}{\langle N_{coll} \rangle} \frac{dN/dy^{AuAu}}{dN/dy^{pp}}$$

- Greatly enhanced D_0 significance w HFT
- Low p_T R_{AA}
  - for p_T ~1.5 GeV/c R_{AA} >1
  - Charm coalescence with a radially flowing bulk medium
- High p_T R_{AA}
  - significant suppression in central Au+Au collisions.
  - Similar suppression as for light partons
  - Suggests charm-medium interaction
- Non-zero v_2 for p_T>2 GeV/c
  - Favors charm quark diffusion
- Lower than light hadron v_2
  - charm quarks not fully thermalized?
- Better statistics and narrower centrality bins are needed

PRL 113 (2014) 142301
PRL 116(2016) 062301
PLB 655 (2007) 104

Comparison to models



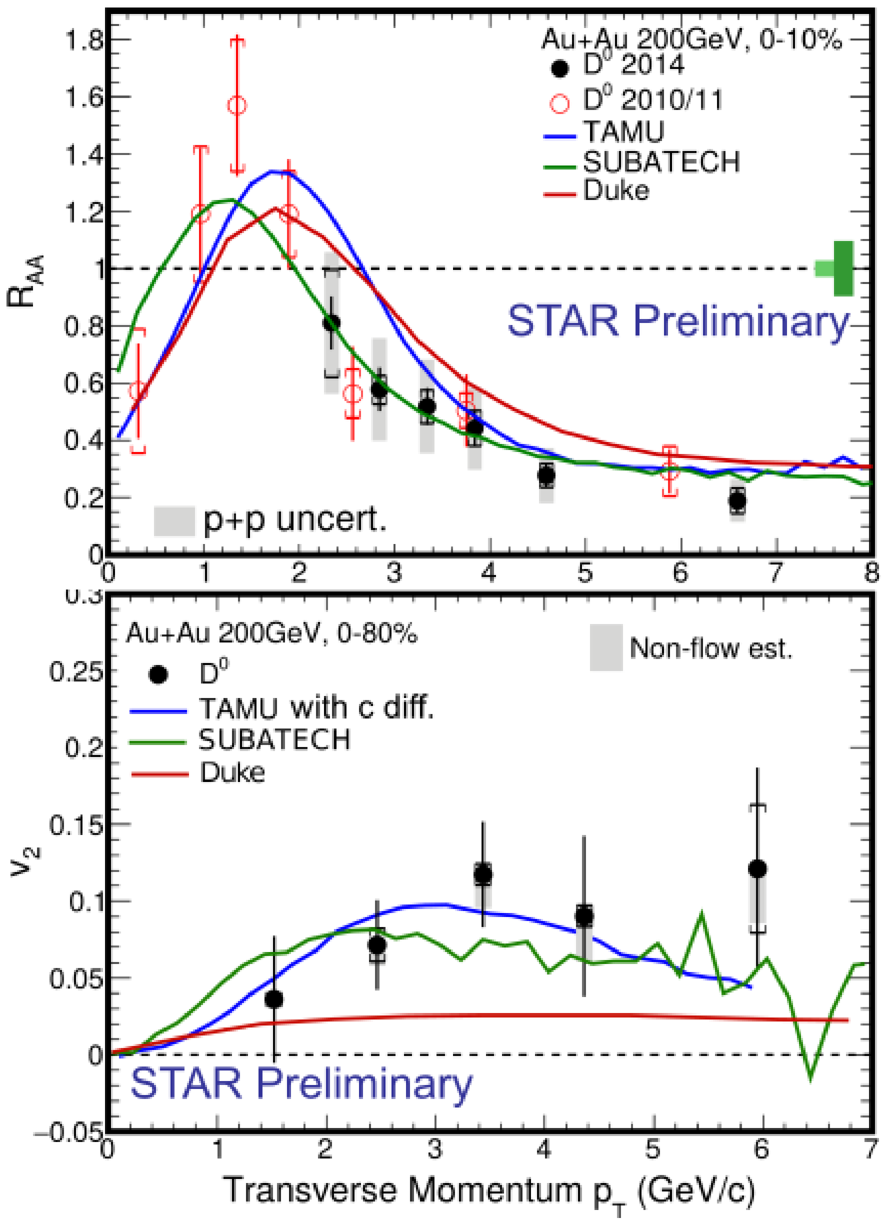


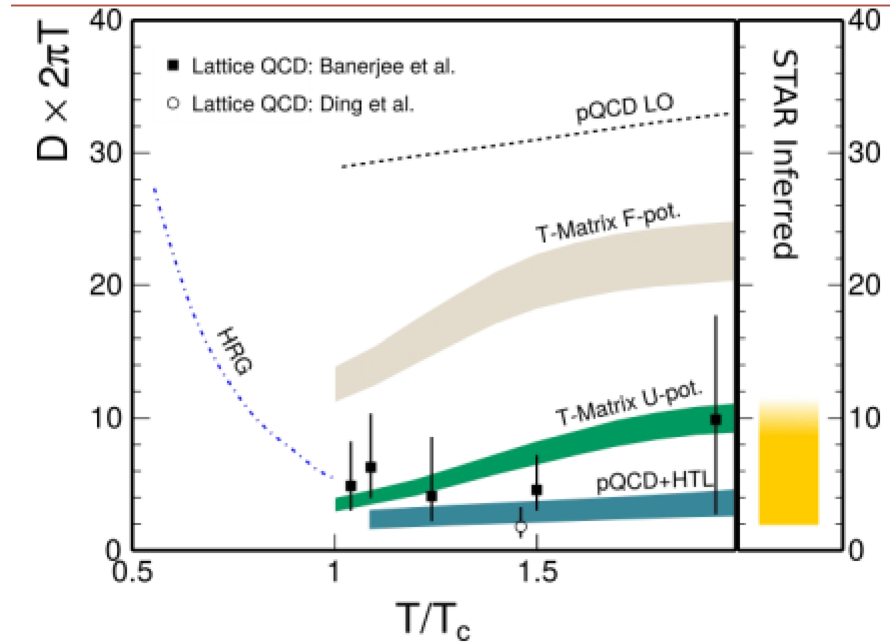
Values for the diffusion coeff. extracted from models and compared to STAR data

	D x 2πT	Diff. Calculation
TAMU	2-11	T-Matrix
SUBATECH	2-4	pQDC+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



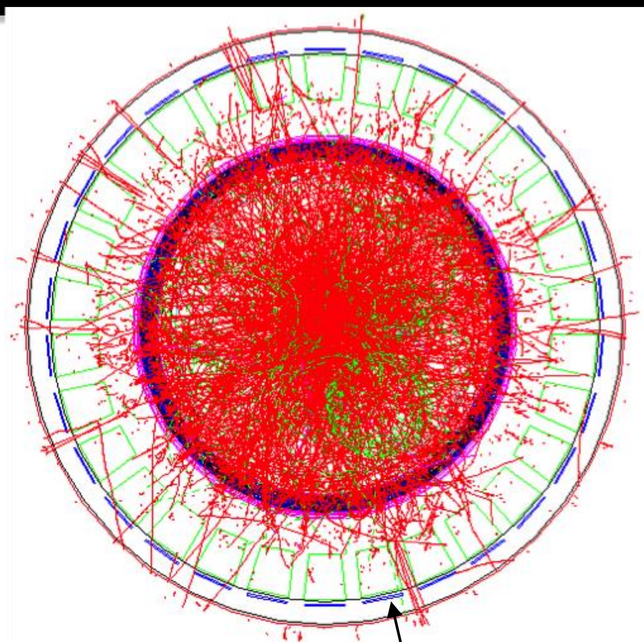


Values for the diffusion coeff. extracted from models and compared to STAR data

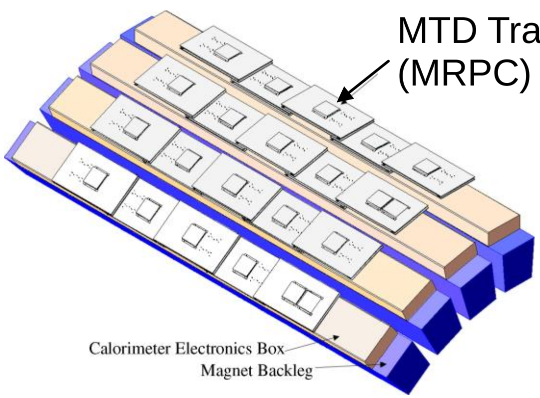
Models with charm diffusion coefficient of 2-11 describe STAR D_0 R_{AA} and v_2 results.

Lattice calculations are consistent with these values inferred from data.

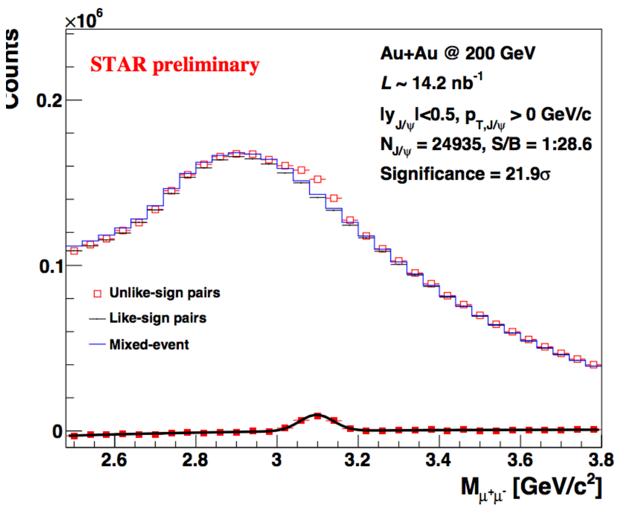
Quarkonia measurements with MTD

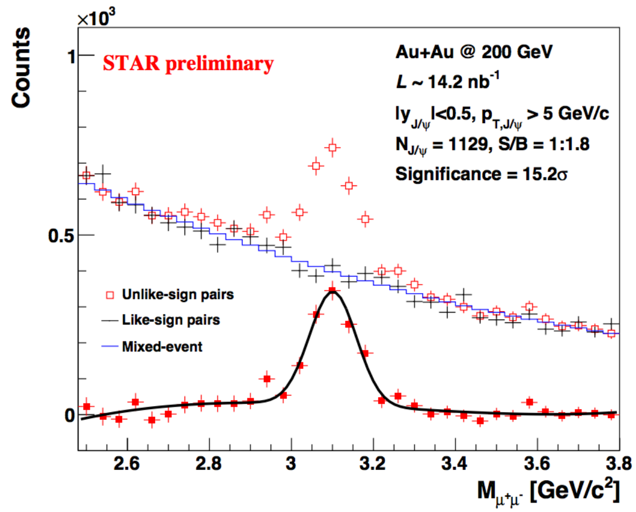


- Based on the same proven MRPC technology as TOF
- Precise timing info (~100ps) for p_T>1.2GeV/c
  - muon online triggering and offline identification
- Recorded 28 pb^{-1}, 120 pb^{-1}, 400 nb^{-1} and 22 nb^{-1} dimuon-triggered 500 GeV p+p, 200 GeV p+p, p+Au and Au+Au
- data for J/ψ and Y studies

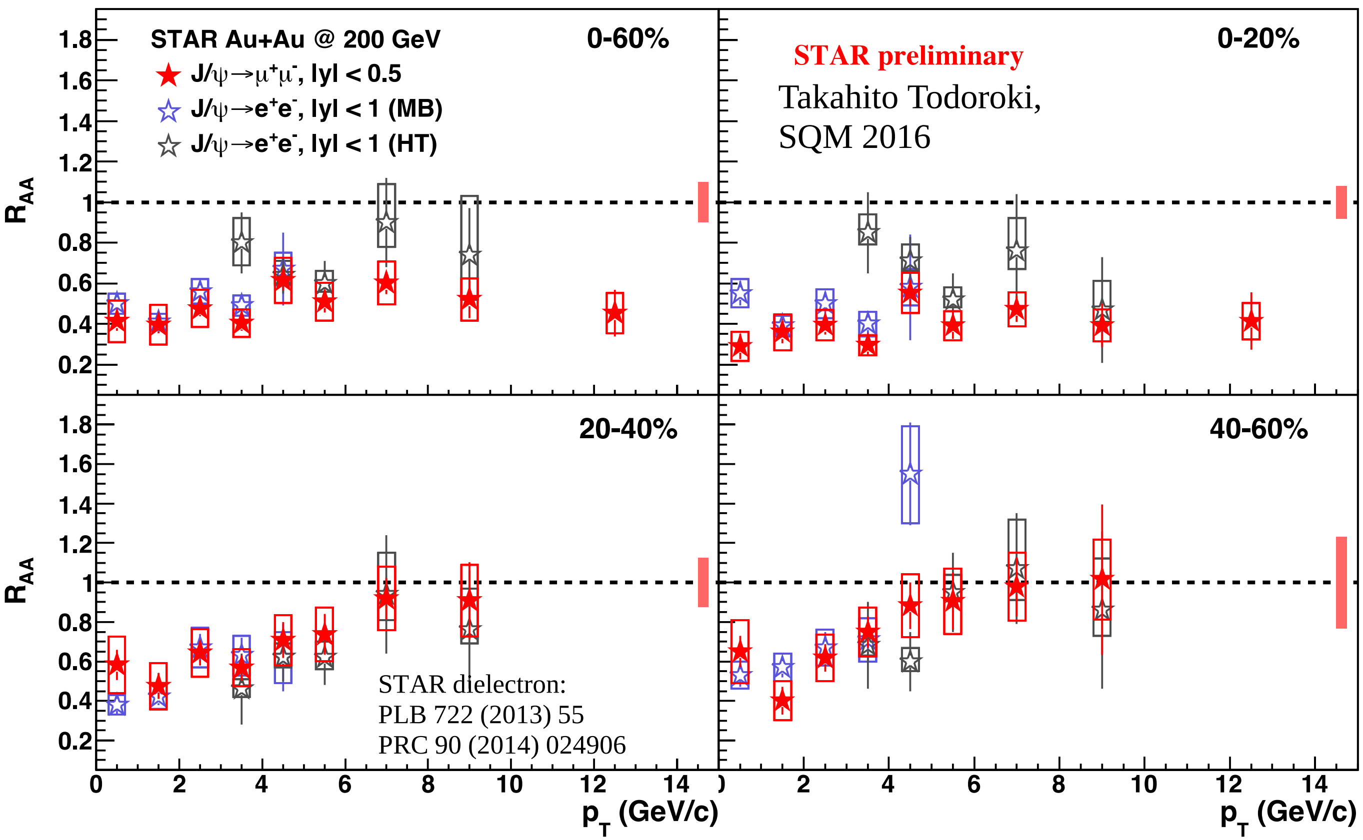


MTD Tray (MRPC)





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

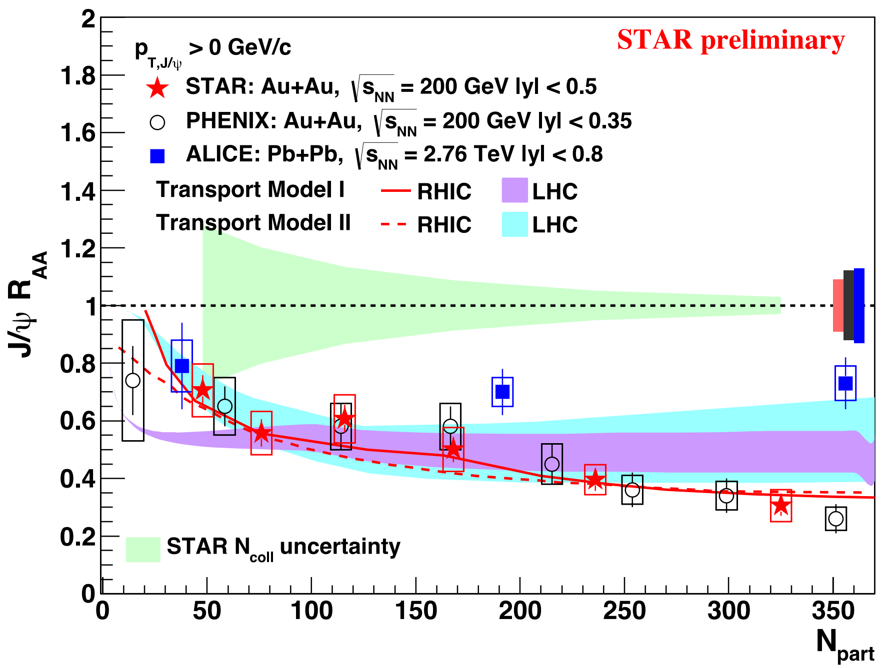
High-p_T
- Strong suppression in 0-20%
- Rising trend in 20-60%
  - Dissociation
  - Formation time effect; B feed down

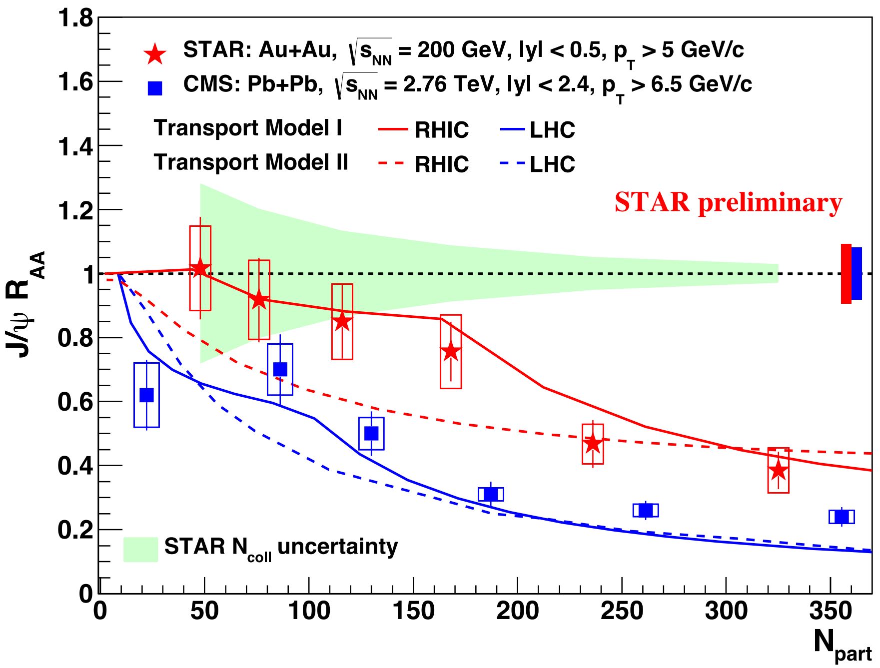
J/ψ R_{AA} – comparison to LHC and models

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

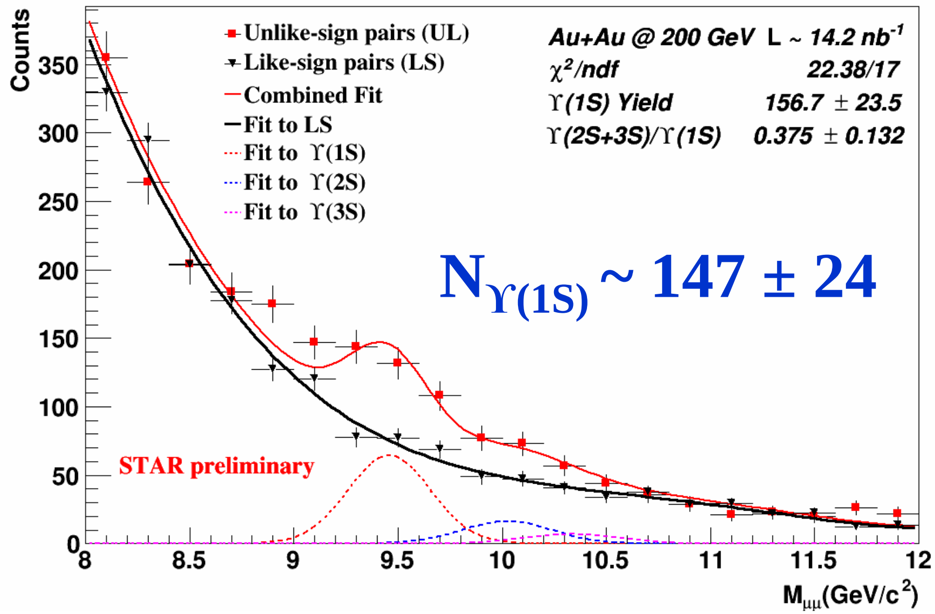
Model II at RHIC: PRC 82 (2010) 064905
Model II at LHC: NPA 859 (2011) 114

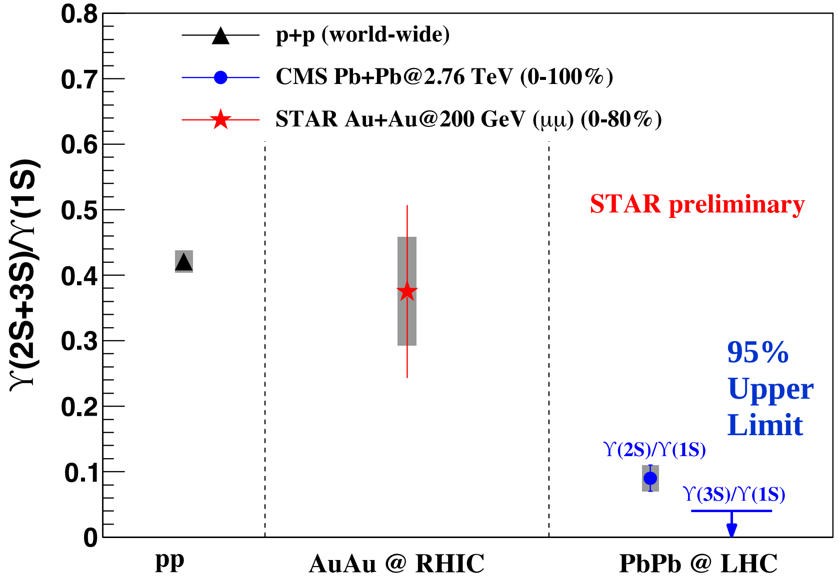




- J/ψ R_{AA} for p_T >0 GeV/c: RHIC is smaller than LHC -> more recombination at LHC
- J/ψ R_{AA} for p_T >5 GeV/c : LHC is smaller than RHIC -> stronger dissociation at LHC
- Transport models with dissociation and recombination qualitatively describe data

ϒ(2S+ 3S)/ ϒ(1S) ratio





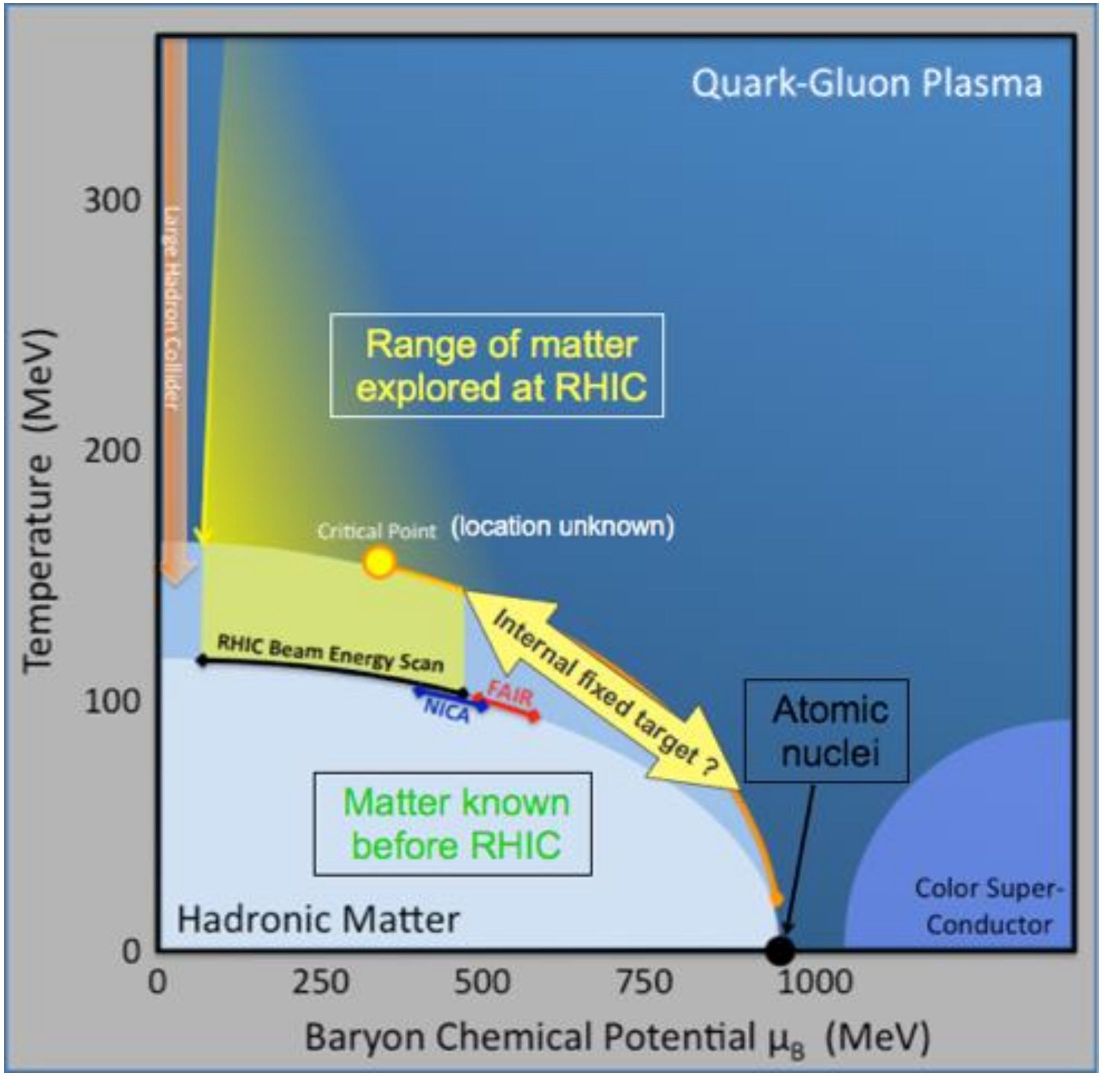
- Combined signal of Y(2S+3S) from the di-muon channel
  - Challenging for di-electron channel due to Bremsstrahlung
- Less melting of Y(2S+3S) at RHIC than at LHC ?

Beam Energy Scan

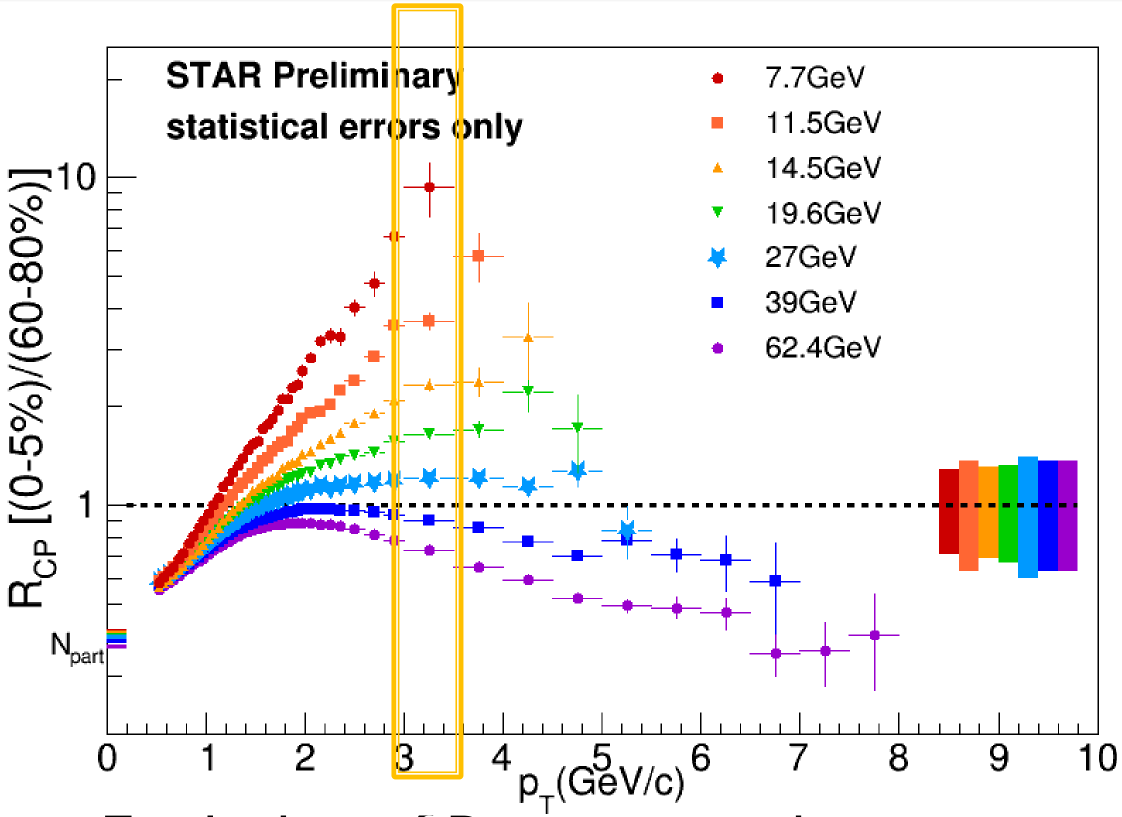
Key physics questions:

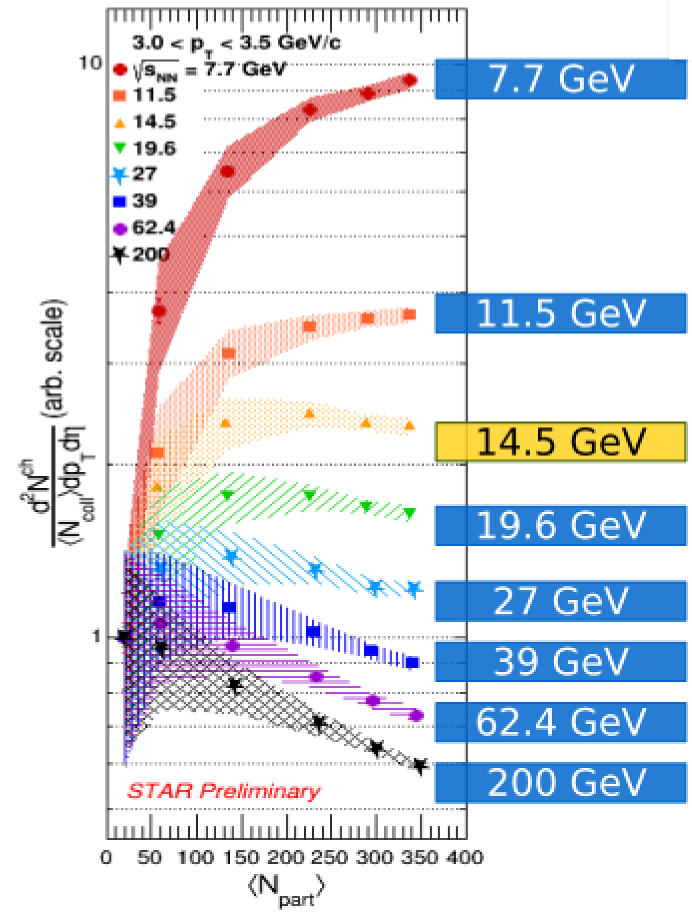
- Where is the onset of sQGP formation
  - Can we "turn it on/off"?
- Where starts the 1st order phase transition
  - Is there a critical point?
- What are the symmetries (degree of freedom) of the sQGP
  - Chiral symmetry restoration
  - Quark and gluon degree of freedom
  - Response to external field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

Mapping the QCD Phase Diagram



Search for onset of sQGP signatures





Evolution of R_{CP} suppression

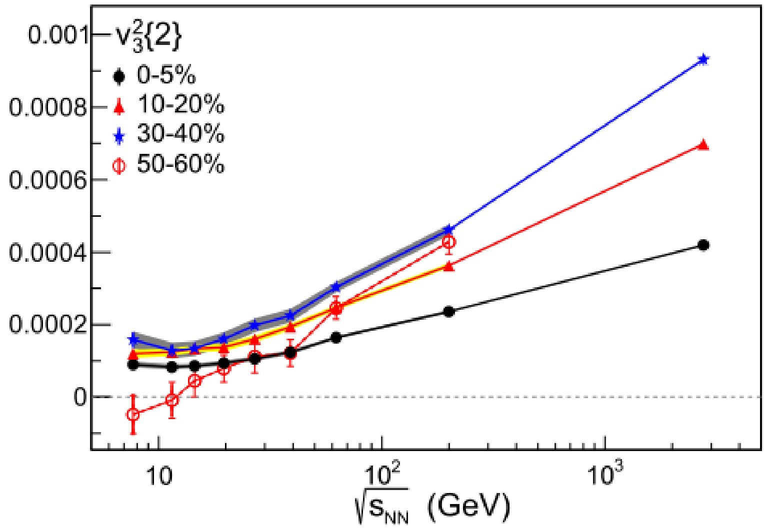
$$Y(\langle N_{\rm part}\rangle) = \frac{1}{\langle N_{\rm coll}\rangle}\frac{d^2N}{dp_{\rm T}d\eta}(\langle N_{\rm part}\rangle)$$

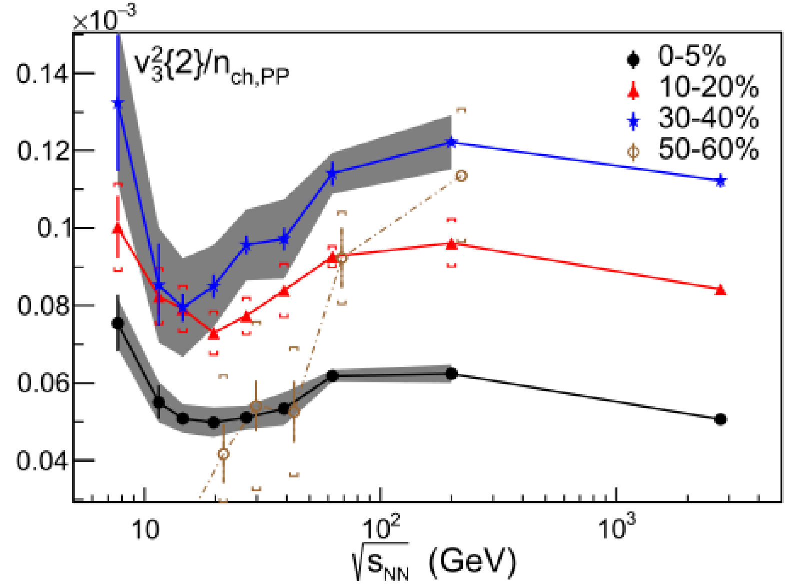
- R_{CP} exhibits suppression down to 39 GeV
- Cronin effects play a bigger role at lower energies.
- Yields per binary collision indicate a balance of enhancement and suppression effects at $\sqrt{s_{NN}}$ = 14.5 GeV.

Search for onset of QGP formation

Triangular flow v_3 –is a sensitive indicator for the presence of a low viscosity QGP phase

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



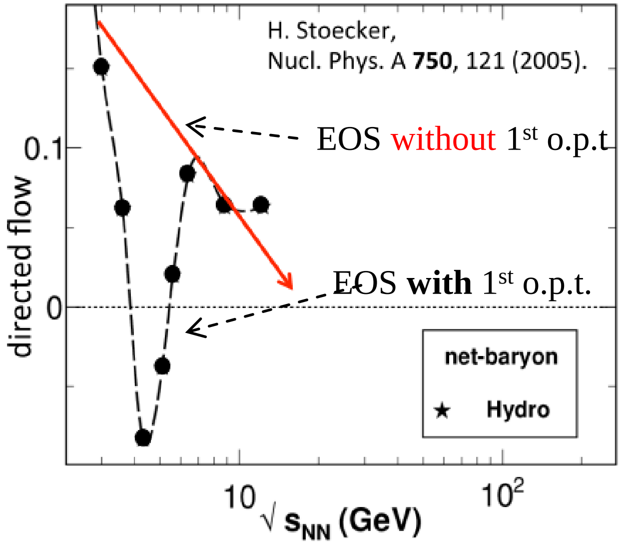


- Sizable v_3 at lower energies in central to mid-central centralities
- While the v_3 grows as ~log(√s) at higher energy, it is nearly independent of energy below 20 GeV.
- Peripheral collisions consistent with zero for $\sqrt{s_{NN}}$ less than 14.5 GeV

v_3 scaled by $n_{\mathrm{ch,PP}} = \frac{2}{N_{\mathrm{part}}} dN_{\mathrm{ch}}/d\eta$

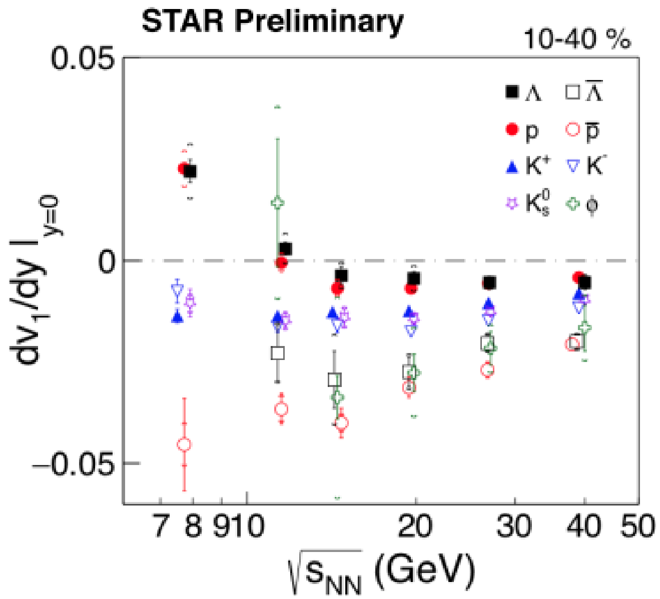
- Local minima $\sqrt{s_{NN}}$ = 7.7 – 20 GeV
- Softening of EoS?

Search for 1st order phase transition: dv_1/dy

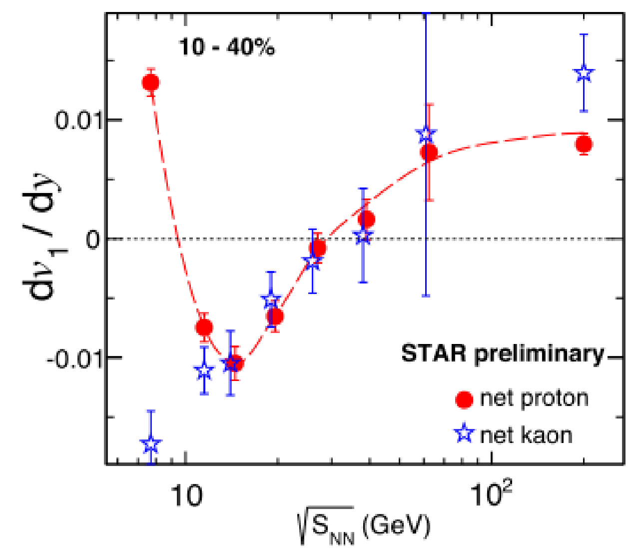


Directed flow v_1

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



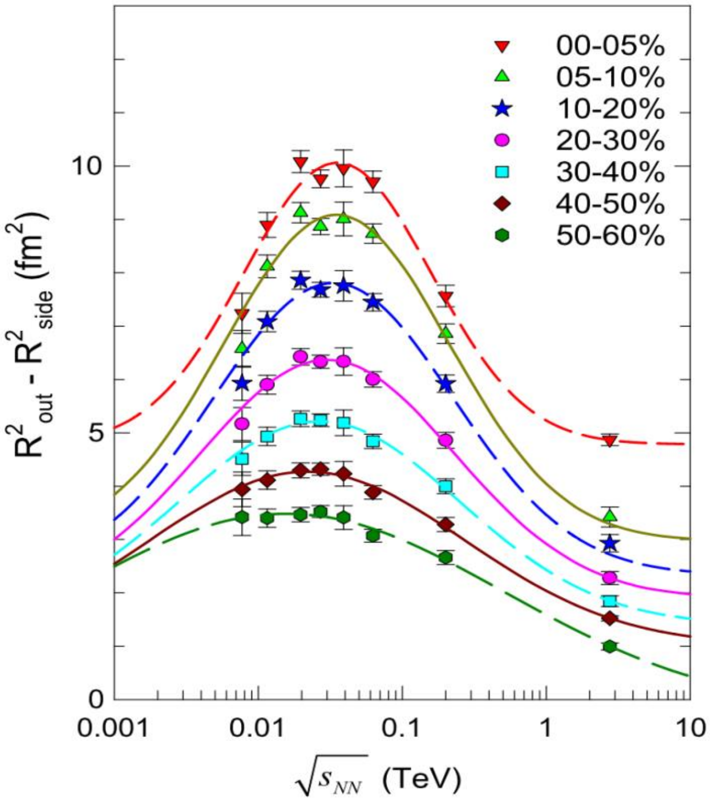
- Minimum in $dv_1/dy|_{y=0}$ –hydro and baryon transport interplay
- (Anti)-Lambdas follow those of (anti)-protons
- Net-K and net-p are consistent with each other down to ~14.5 GeV
  - net-K stays negative for $\sqrt{s_{NN}}$ < 14.5 GeV

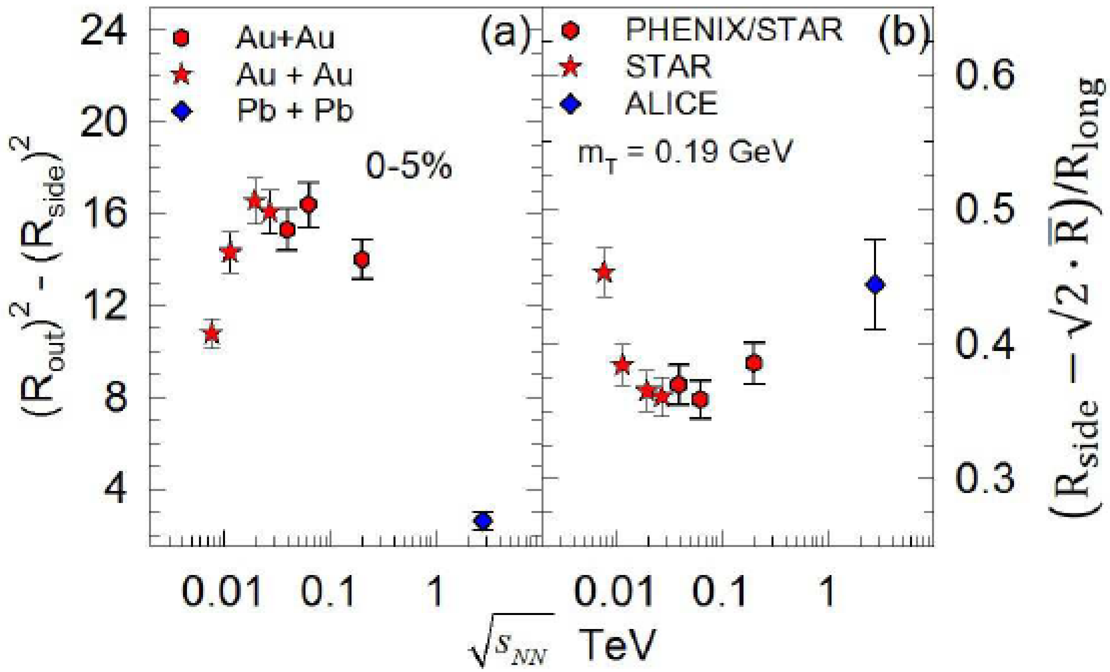


Subhash Singha SQM 2016

Search for 1st order phase transition: HBT

R. Lacey, PRL **114**, 142301 (April 2015)
STAR, PRC92(2015)





- High precision azimuthally sensitive HBT
- Significant non-monotonic behavior of (R^2_{out}-R^2_{side})
  - (R^2_{out}-R^2_{side}) ~ emission duration
  - Peaking around 20 GeV – increased emission duration, lower pressure?

Search for critical point

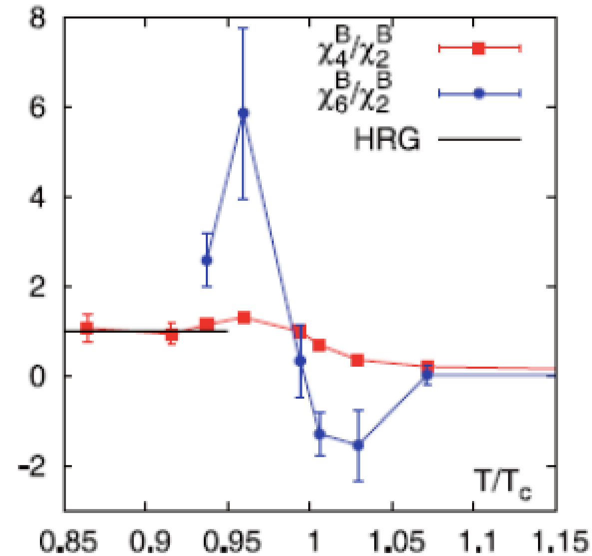
critical point

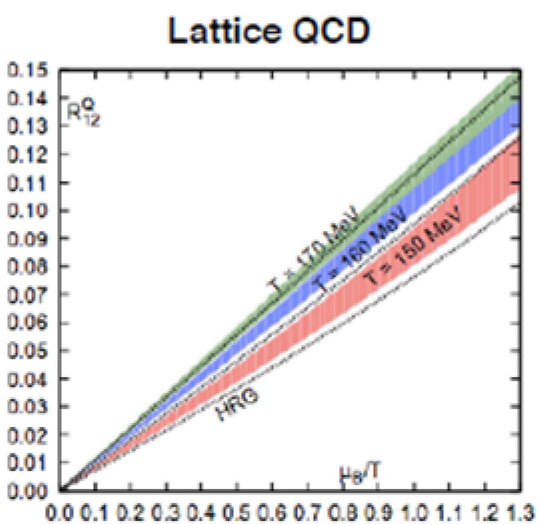
- susceptibilities and correlation length diverge
- large fluctuation

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

Observables

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





HotQCD, PRL109, 192302 (2012)
WB Group, PRL111, 062005 (2013)

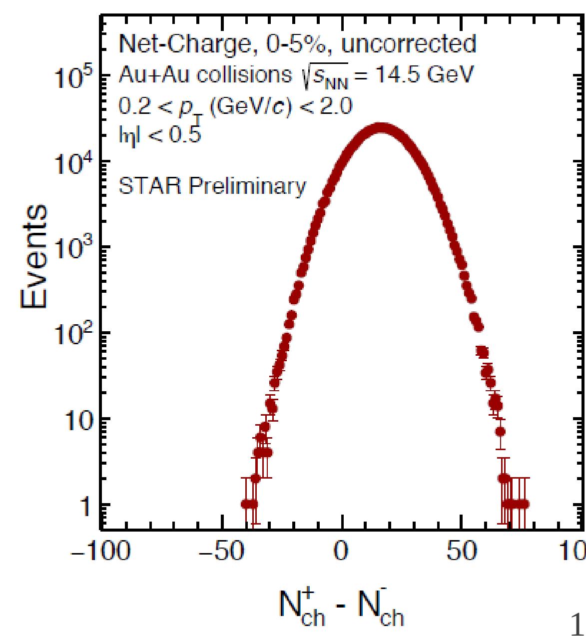
$$\frac{\chi_2^i}{\chi_1^i} = (\sigma^2/M)^i = \frac{c_2^i}{c_1^i}$$

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

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

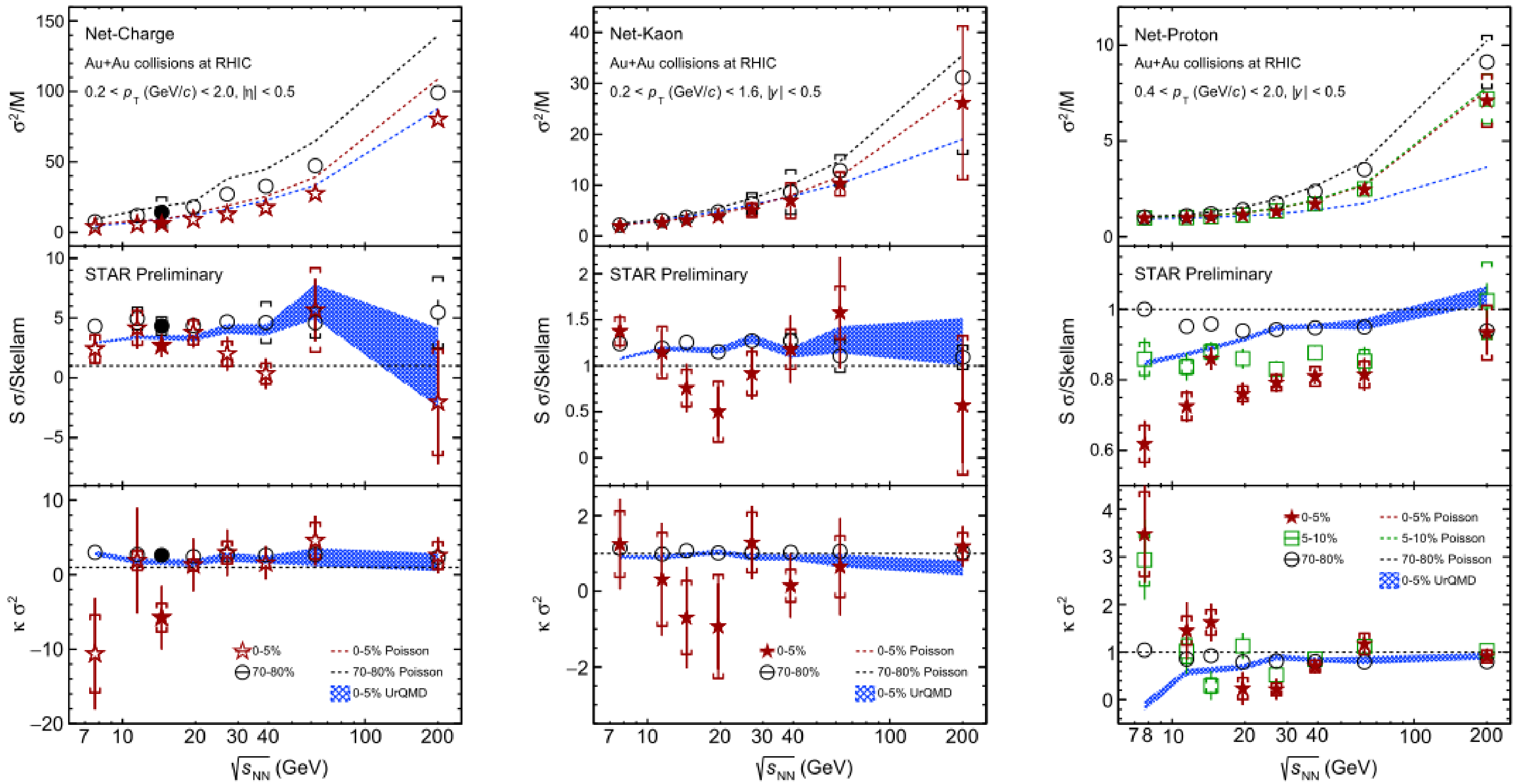
$$i = B, Q, S$$

Experiment

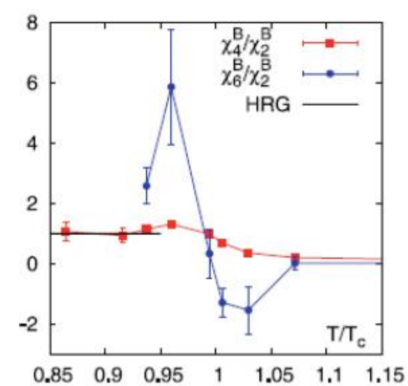


Net-charge, kaon, proton fluctuations

Jochen Thader QM2015



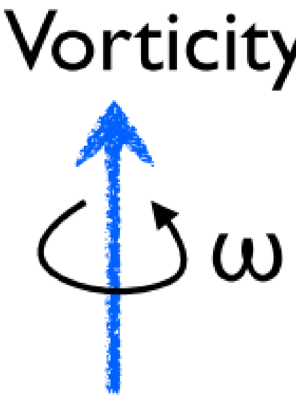
- **Non-monotonic** behavior of **net-proton** κσ² seen in top 5% central collisions
  - Largest deviation from Poisson and uRQMD around 19.6 GeV
- Need more precise measurements below 20 GeV
  - Finer steps in μ_B
  - Increase accepted rapidity window



Search for chiral effects

Chiral Magnetic Effect vs **Chiral Vortical Effect**

Chirality Imbalance (μ_A)	--	Chirality Imbalance (μ_A)
Magnetic Field ($\omega\mu_e$)	--	Fluid Vorticity ($\omega\mu_B$)
↓		↓
Electric Charge (j_e)	--	Baryon Number (j_B)



Peak magnetic field ~ **10^{15} Tesla !** (Kharzeev et al. NPA 803 (2008) 227)

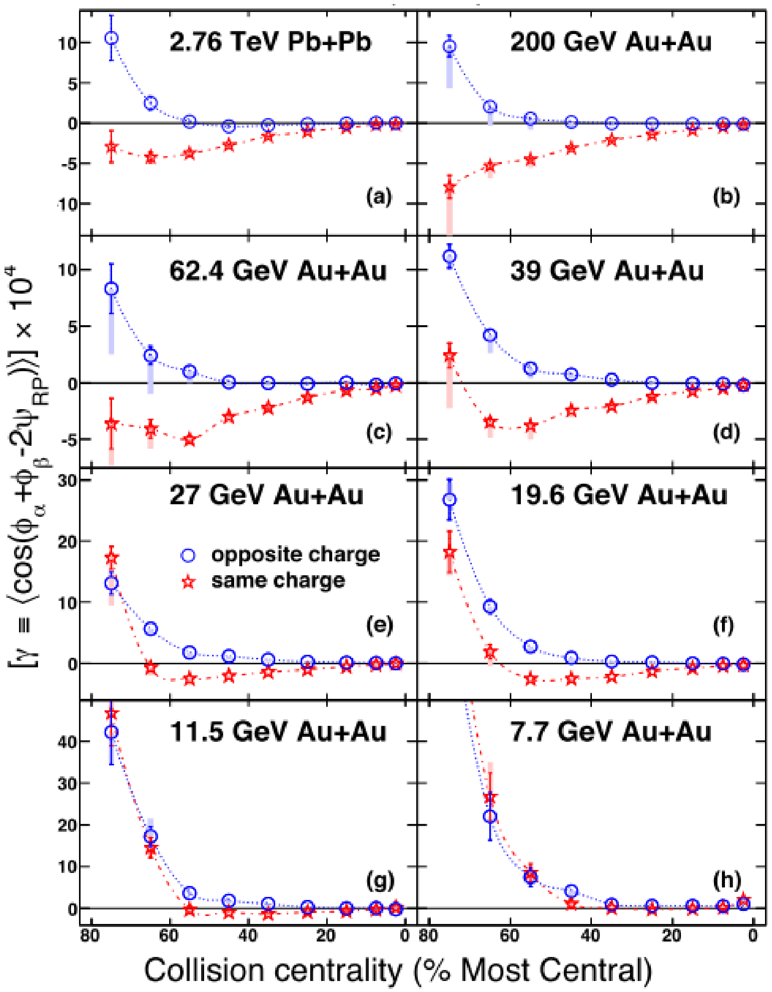
Electric charge separation

Baryonic charge separation

D. Kharzeev, A. Zhitnitsky, NPA797:67-79(2007)
D. Kharzeev, D. T. Son, PRL 106 (2011) 062301

Charge separation wrt. Event plane

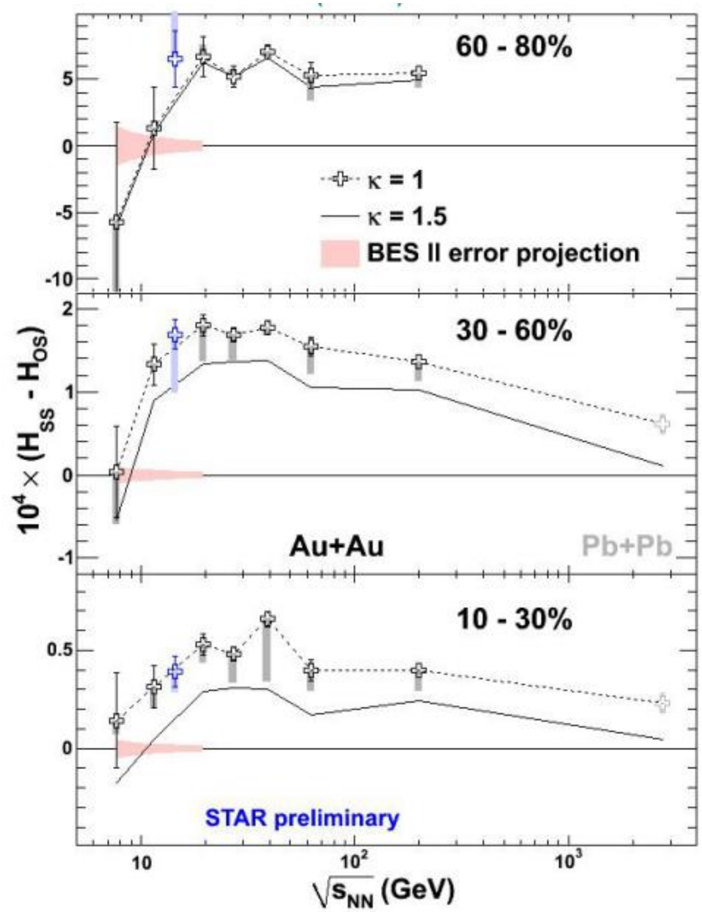
STAR: PRL103, 251601 (2009), PRL113, 052302 (2014),
ALICE: PRL110, 012301 (2013)



$$\gamma \equiv \langle \cos(\phi_1 + \phi_2 - 2\Psi_{RP}) \rangle = \kappa v_2 F - H$$
$$\delta \equiv \langle \cos(\phi_1 - \phi_2) \rangle = F + H,$$

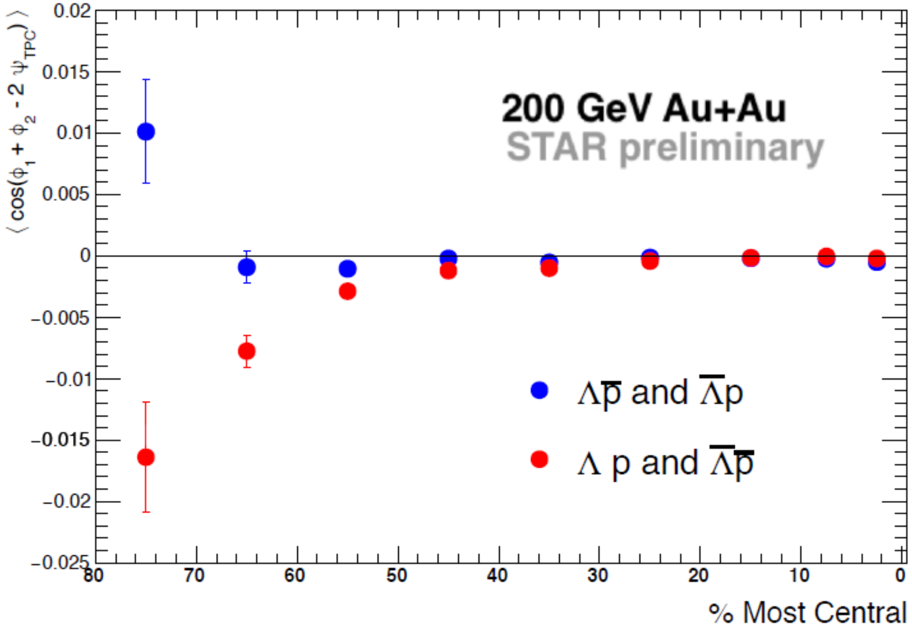
H and F are the CME and background

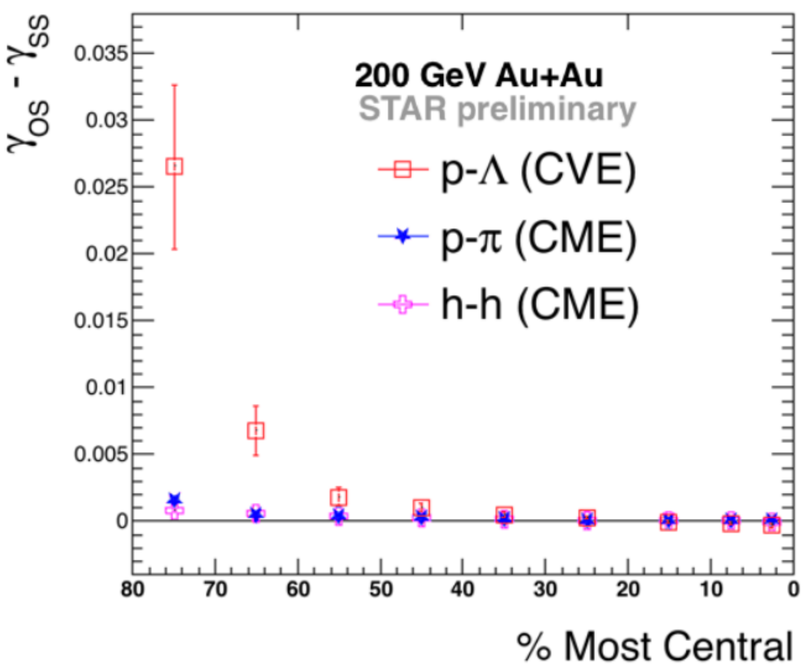
Extracted CME contribution:



- CME signal (ΔH) drops to 0 from 19.6 to 7.7 GeV
  - Probable domination of hadronic interactions over partonic ones

Baryonic charge separation



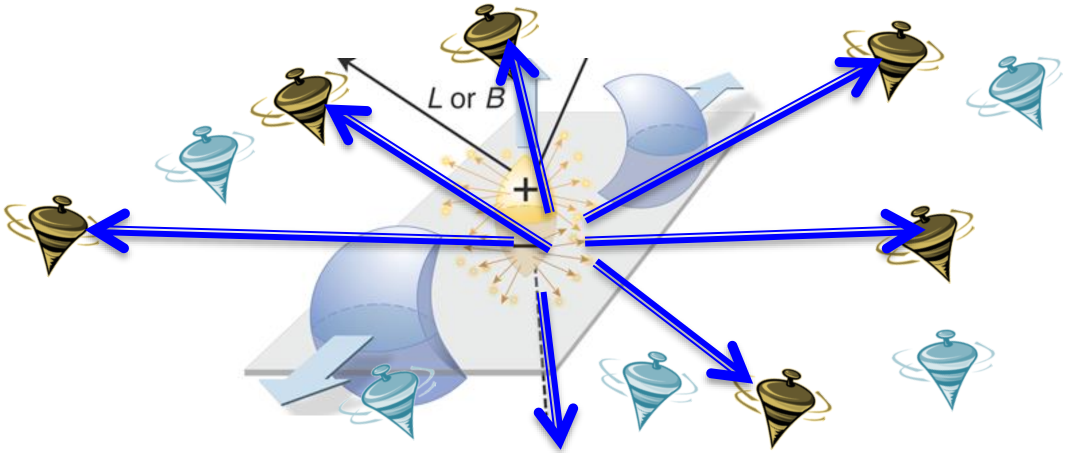


Liwen Wen
SQM 2016

- Significant baryonic charge separation signal is observed.
- The magnitude is larger than electric charge separation signal of h-h correlations. CVE predicts qualitatively the same order of hierarchy.
- Ongoing background studies to decouple B-field, v_2 and charge separation
  - Study impact of initial E-field independently (Cu+Au)
  - Collide nuclei with special configurations (238 U+ 238 U, 96 Ru+ 96 Ru, 96 Zr+ 96 Zr) Proposed isobar experimental program for 2018
  - Measuring the B-field and vorticity of the system

Global Λ polarization

- Large initial angular momentum
  $|L| \sim 10^5\ \hbar$ in non-central collisions
- Fluid vorticity may generate **global polarization**



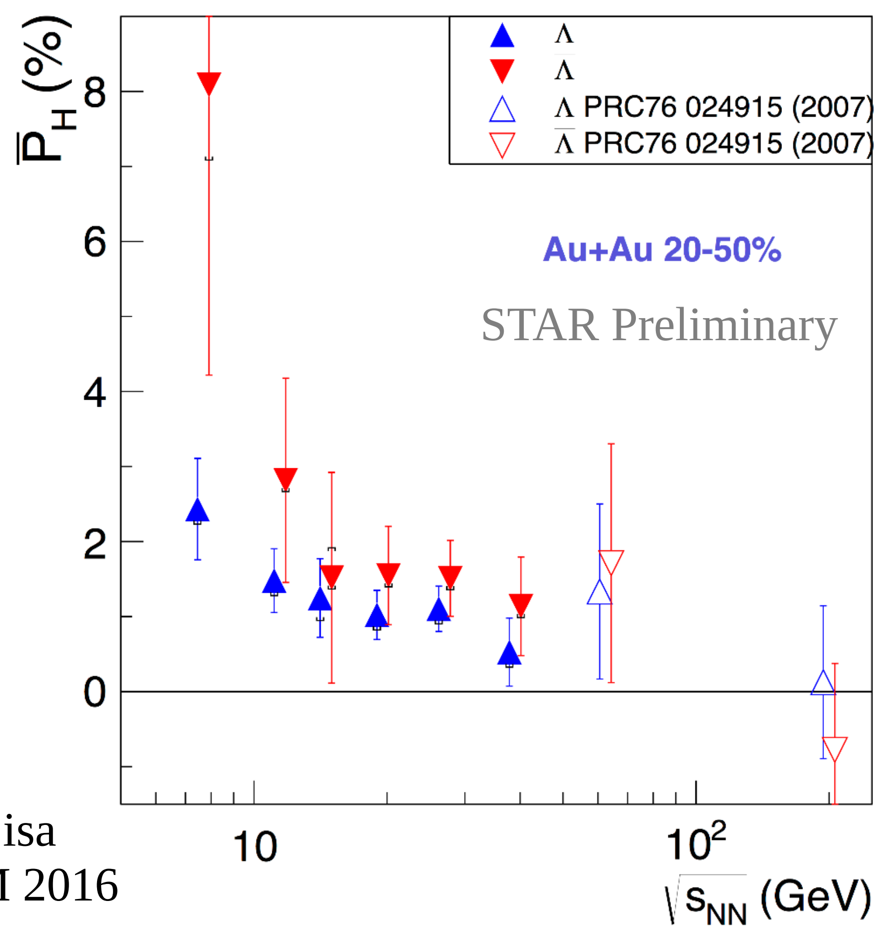
- Using Lambdas
  - "self-analyzing" decay - preferentially emitting daughter proton in spin direction
  - For AntiLambdas spin is opposite to anti-proton direction

Global Λ polarization

Acceptance integrated polarization:

$$\bar{P}_{H} = \frac{8}{\pi\alpha}\frac{\langle \sin(\phi_{p}^{*} - \Psi_{EP}^{(1)})\rangle}{R_{EP}^{(1)}}$$

- **First clear positive signal of global polarization in heavy ion collisions**
- Both Lambdas and AntiLambdas show positive polarization
- Splitting
  - suggests additional magnetic effect
- Allows Model-dependent estimate of B-field and plasma vorticity



M. Lisa
SQM 2016

Summary of results

First results from the HFT and MTD

- Successful data taking with MTD and HTT
- 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
- Υ in Au+Au collisions:
  - hint for less Υ(2S+2S) suppression at RHIC than LHC
- More results to come from run 2016

Summary of results

Beam Energy Scan

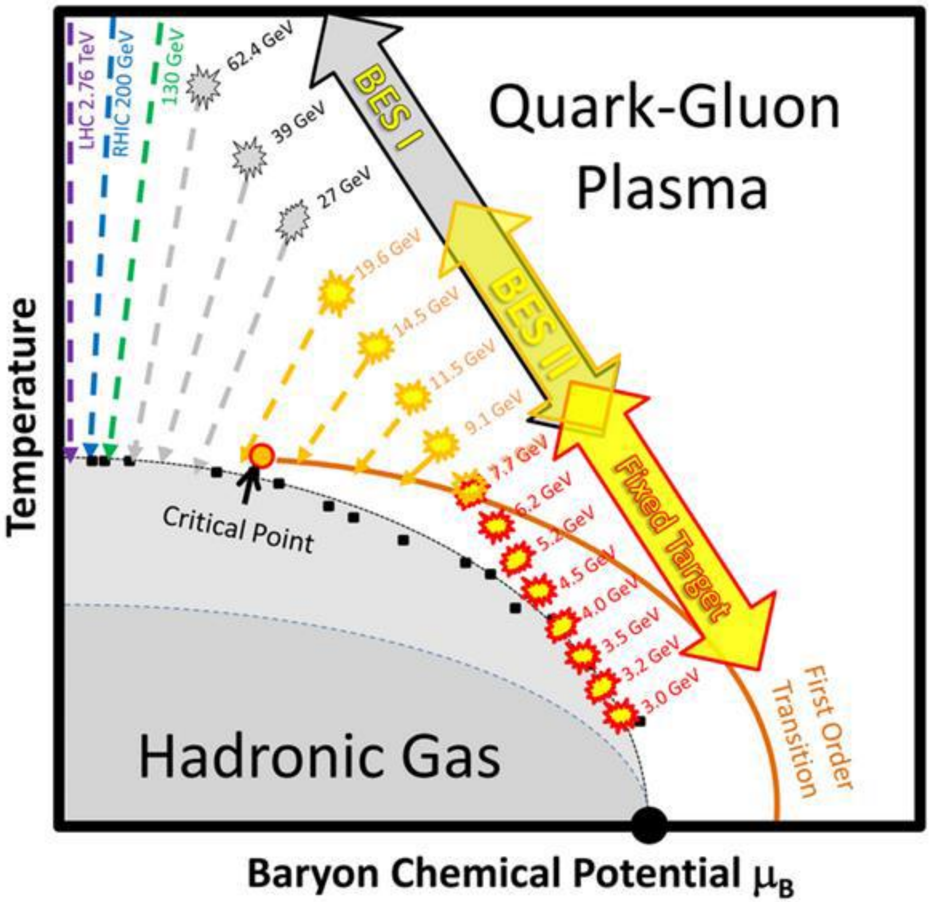
- Spaning a range of μB that could contain features of the QCD phase diagram.
- Observed signatures consistent with disappearance of parton dominated regime
- Indicators pointing towards a softening of the equation of state which
  - possible evidence for a first order phase transition.
- Critical phenomena – signal from higher moment fluctuations
  - Statistically demanding
- Observation of charge and baryon charge separation
  - Possible signal of chiral magnetic and vortical effects
- First results on global hyperon polarization

Near future

- Beam Energy Scan II with fixed target program

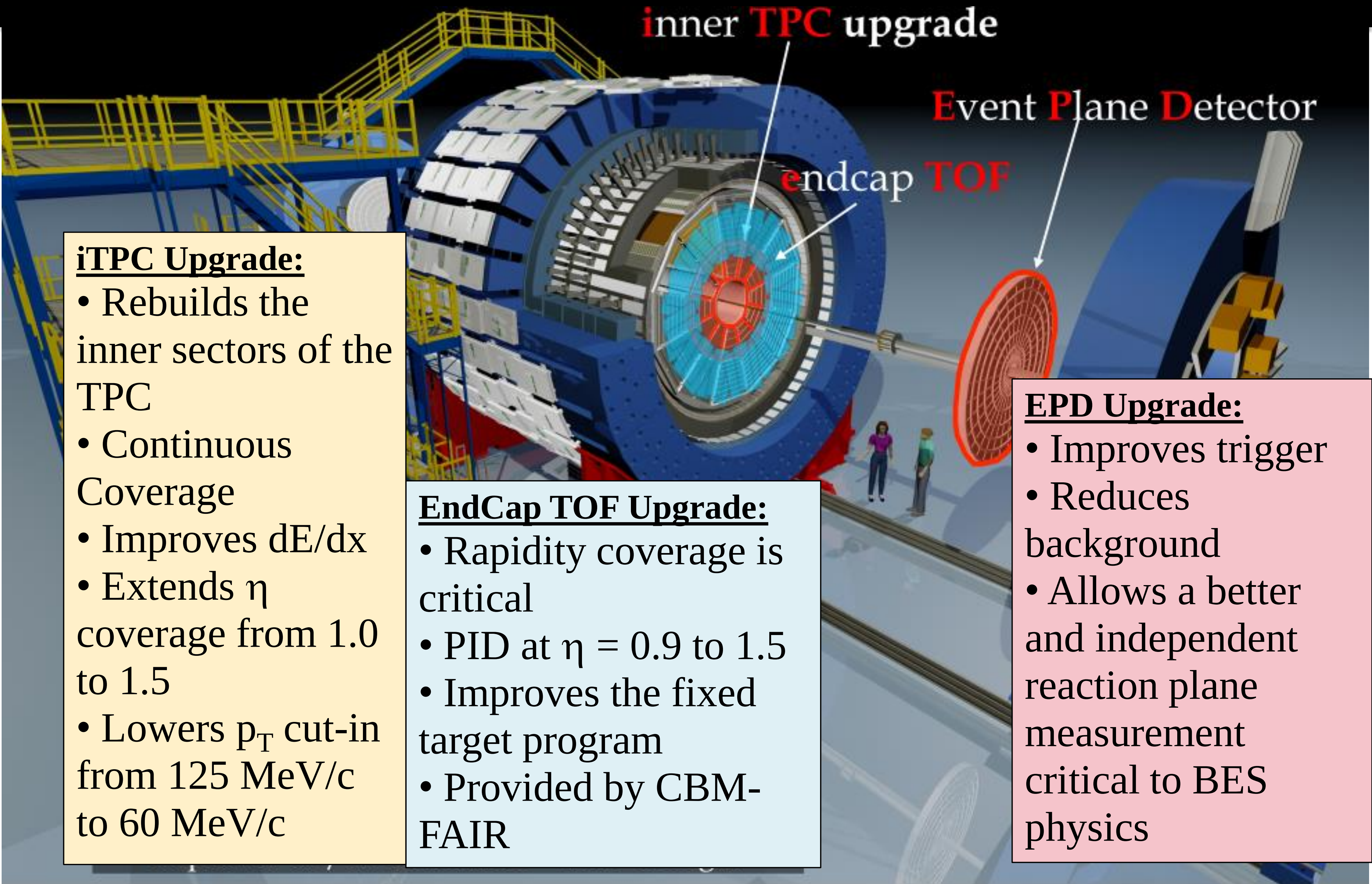
Beam Energy Scan – phase II

2019-2010



- Zoom to the energy range of interest 5 to 20 GeV
  - Finer steps in μ_B
- Improve significance
  - Long runs
  - Higher luminosity (eCooling)
- Detector upgrades
- Extend Range -Fixed Target Program

Upgrades for BES II

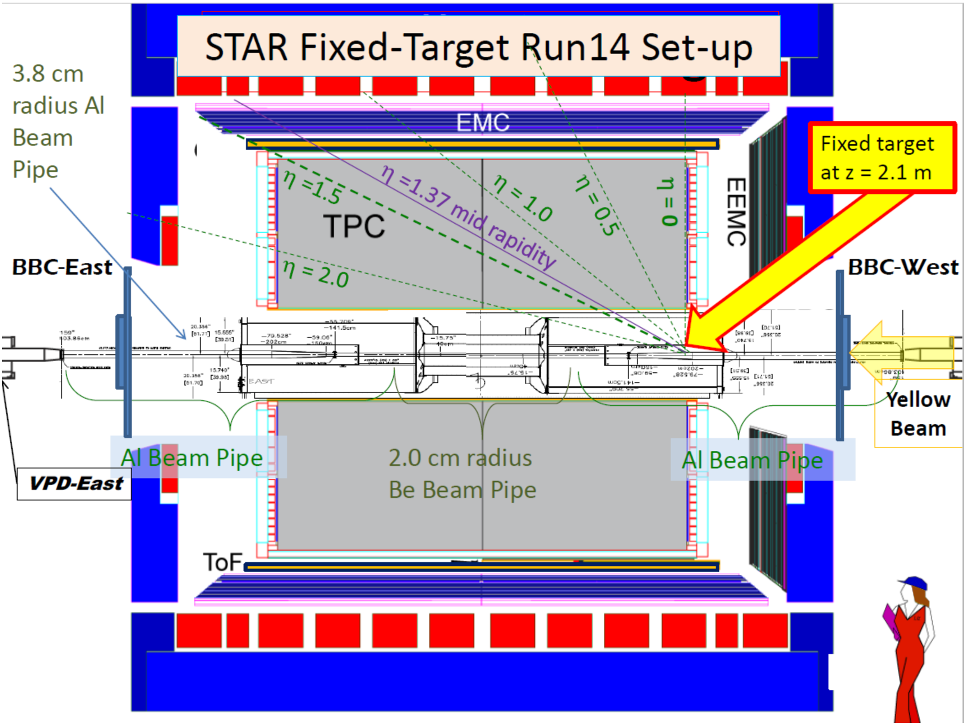


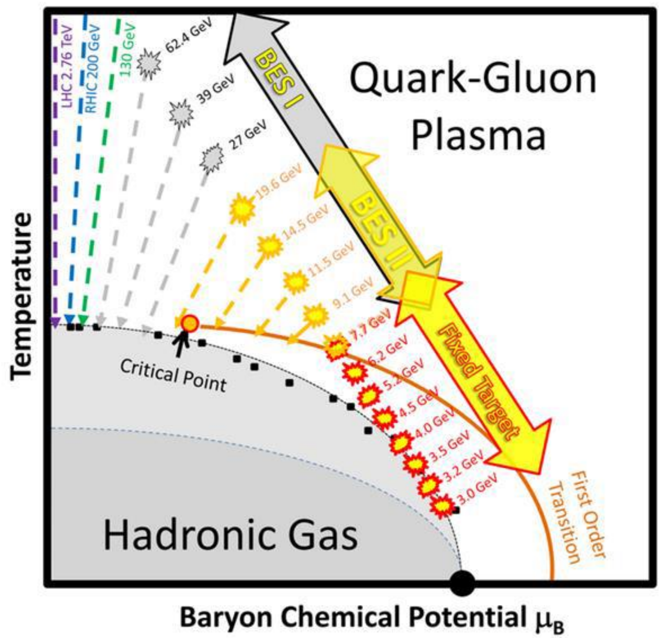
iTPC Upgrade:
- Rebuilds the inner sectors of the TPC
- Continuous Coverage
- Improves dE/dx
- Extends η coverage from 1.0 to 1.5
- Lowers p_T cut-in from 125 MeV/c to 60 MeV/c

EndCap TOF Upgrade:
- Rapidity coverage is critical
- PID at η = 0.9 to 1.5
- Improves the fixed target program
- Provided by CBM-FAIR

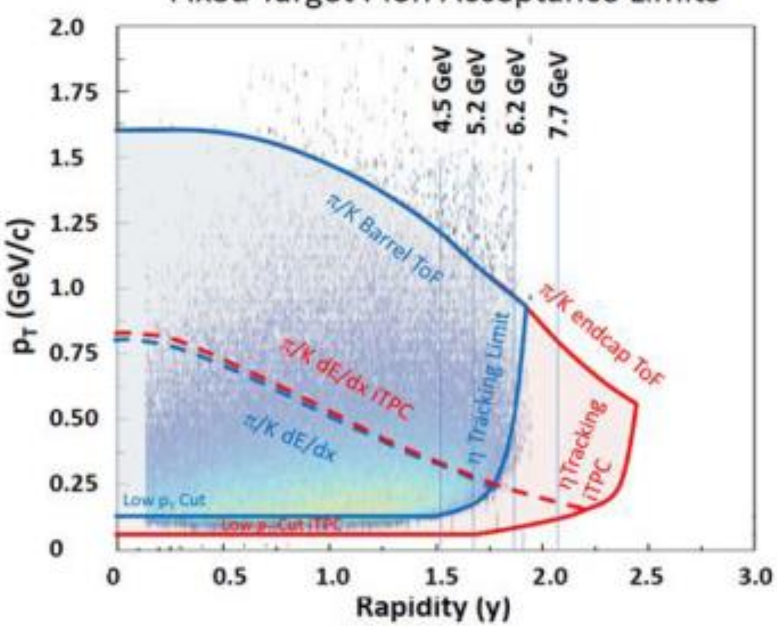
EPD Upgrade:
- Improves trigger
- Reduces background
- Allows a better and independent reaction plane measurement critical to BES physics

Fixed Target Program with STAR



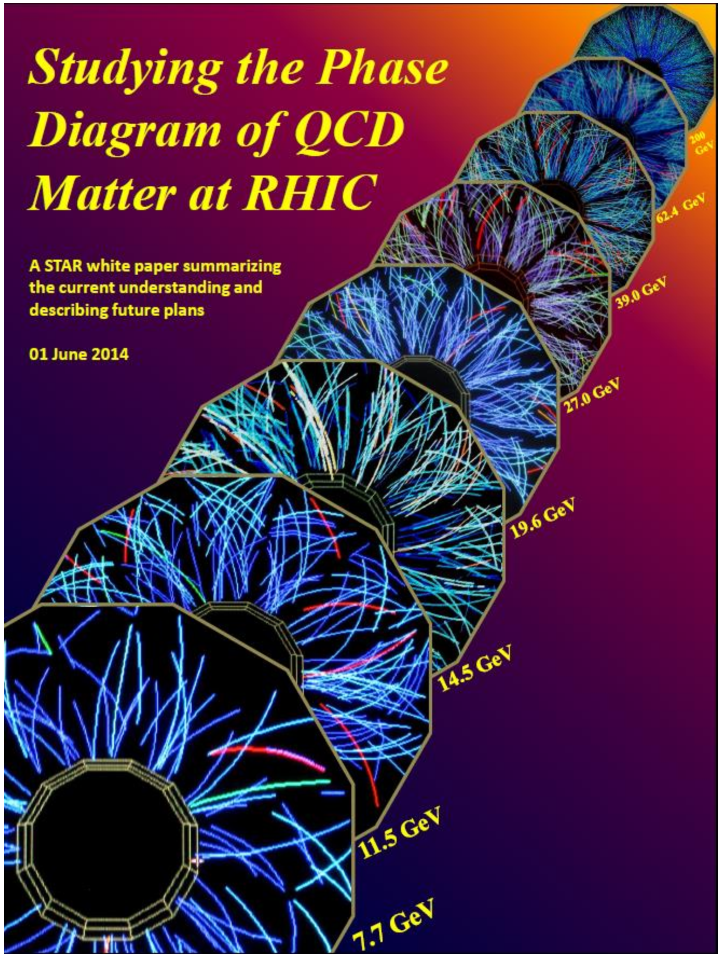


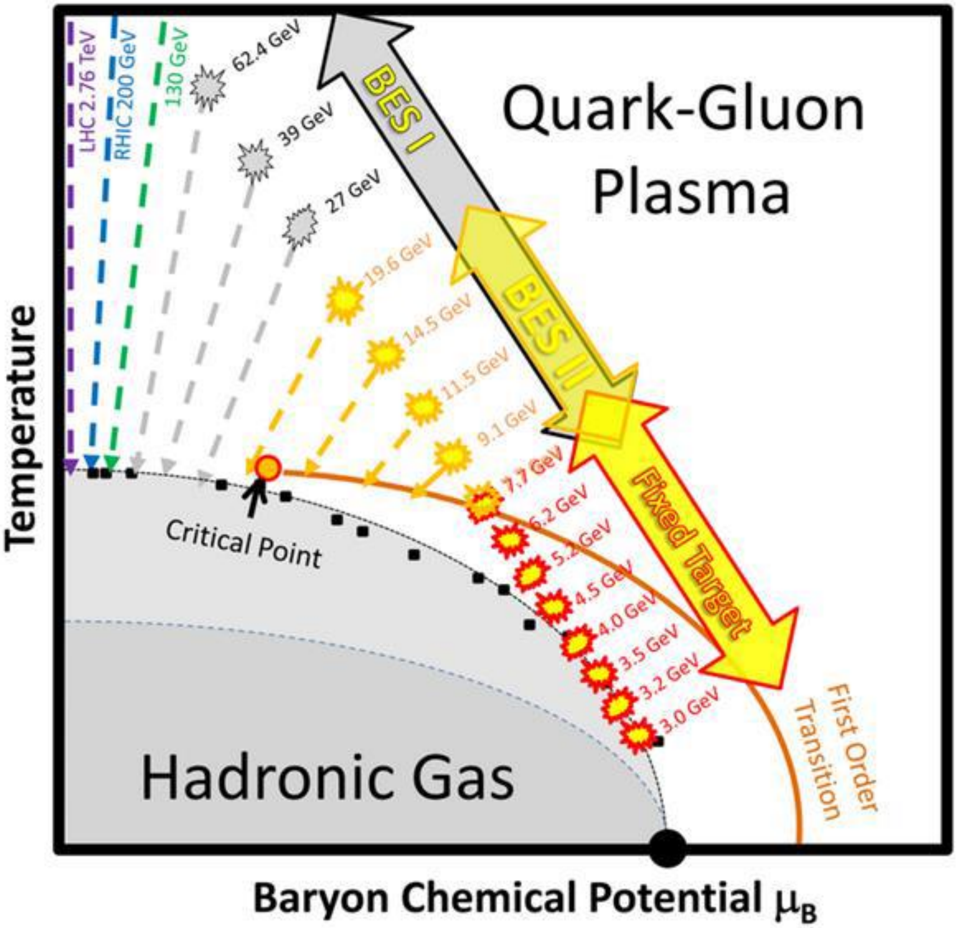
Fixed Target Pion Acceptance Limits



- Extend energy reach down to 3GeV
- overlap/complementary AGS/FAIR/JPARC
- Upgrades (iTPC+eTOF+EPD) crucial
- Unprecedented coverage and PID for Critical Point search in BES-II
- Real collisions taken in run 2014

Thank you for your attention





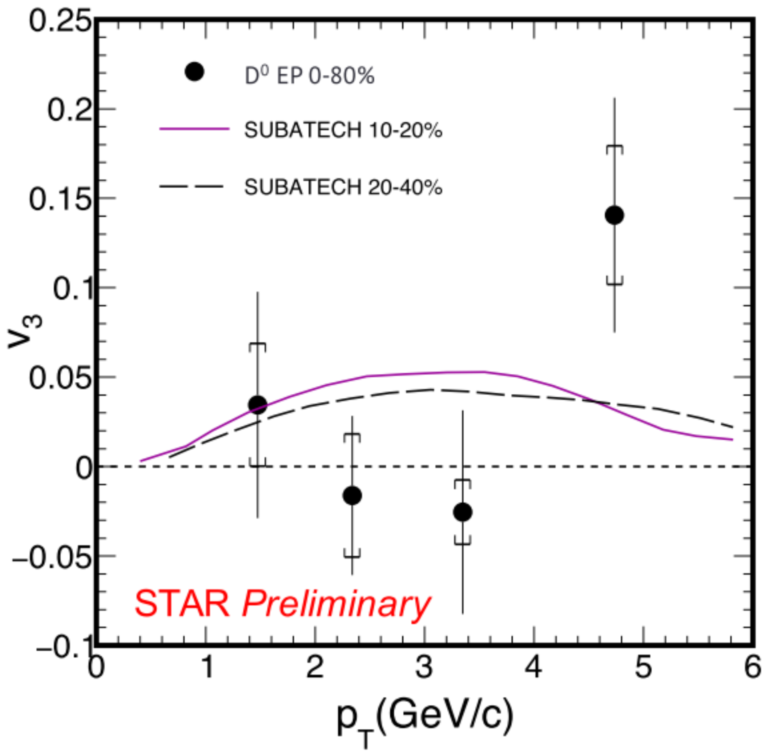
Backup slides

Planned data taking runs

Year	System and Energy	Physics/Observables	Upgrade
2017	• p+p @ 500 GeV • Au+Au @ 62.4 GeV	• Spin sign change diffractive • Jets	FMS post-shower, EPD (1/8th), eTOF prototype
2018	• Zr+Zr, Ru+Ru @ 200 GeV • Au+Au @ 27 GeV	• CME, di-leptons • Lambda polarization	Full EPD? eTOF prototype
2019	Au+Au @ 11-20 GeV + fixed target	• QCD critical point • Phase transition • CME,…	Full iTPC, eTOF, and EPD
2020	Au+Au @ 7-11 GeV + fixed target	• QCD critical point • Phase transition • CME,…	

D_0 triangular flow

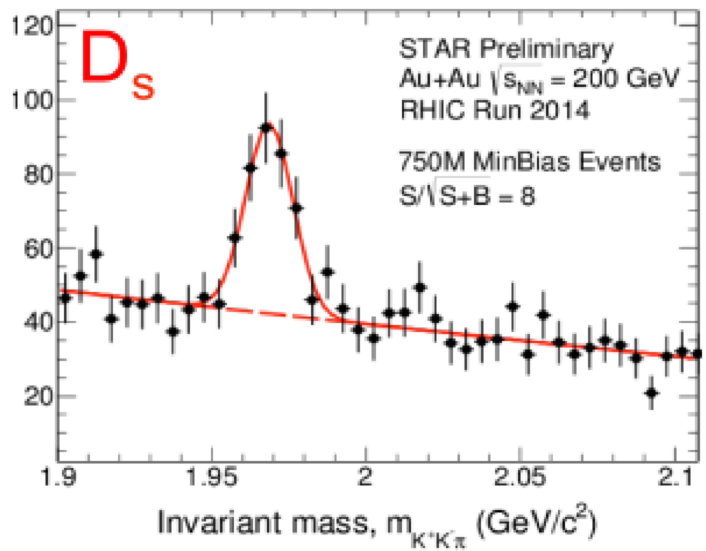
Fluctuations in initial conditions – expectations of a finite D_0 v_3

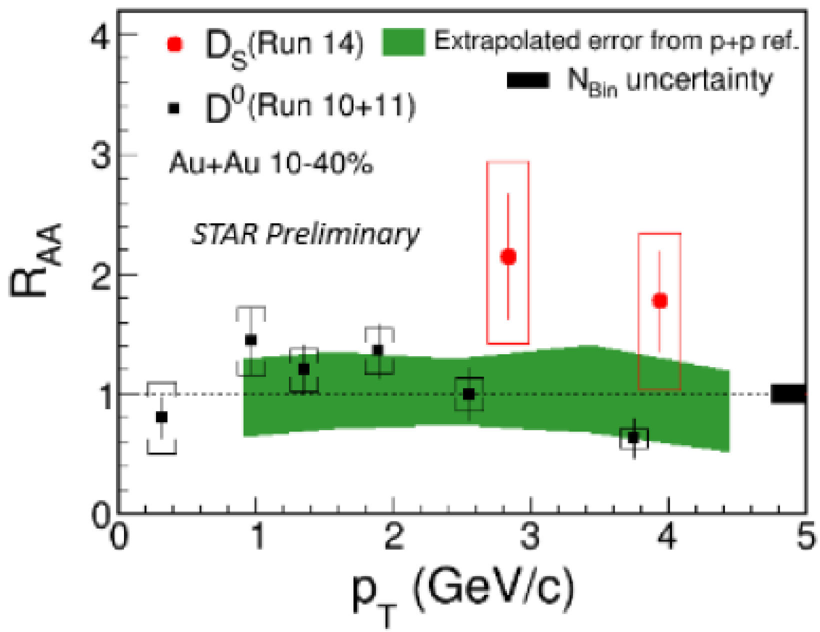


Theory: PRC 91(2015) 014904 & private comm.

- First measurement of D_0 v_3
- Large uncertainties
- Should improve.
  - Currently reprocessing year 2014 data - discovered decoder issue in PXL
  - Run 16:
    - Full aluminum cables for inner layer of PXL
    - Factor 2 -3 further improvement for D_0 significance @ 1 GeV -> centrality dependence for v_2

First D_S signal at RHIC





- D_S - study of the mechanism of charm hadronization and QGP properties
- The R_{AA} of D_S is higher than D_S, but statistically not significant
- Hint of finite D_S v_2 at RHIC.
- Run 14+16 - increased statistics