Recent Heavy Ion Results from STAR

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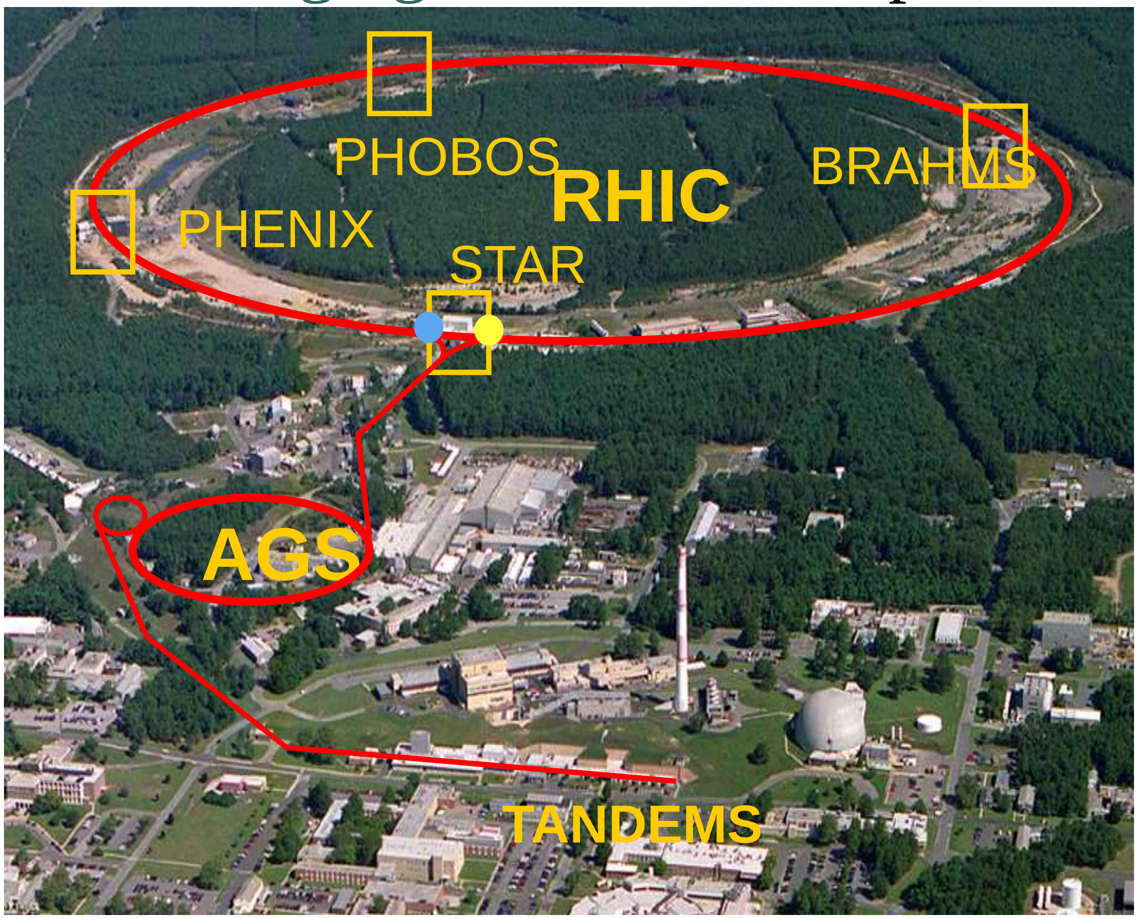
for the STAR collaboration

Outline

- STAR program at RHIC
- Data collection (e.g. collection of data-sets)
- Selected recent results
  - Beam energy scan
  - Jets, jet-like correlations and medium properties
  - STAR Heavy flavor program
- Summary and outlook

Relativistic Heavy Ion Collider

- Design goal - studies of phase structure of nuclear matter



- Counter-rotating ion beams

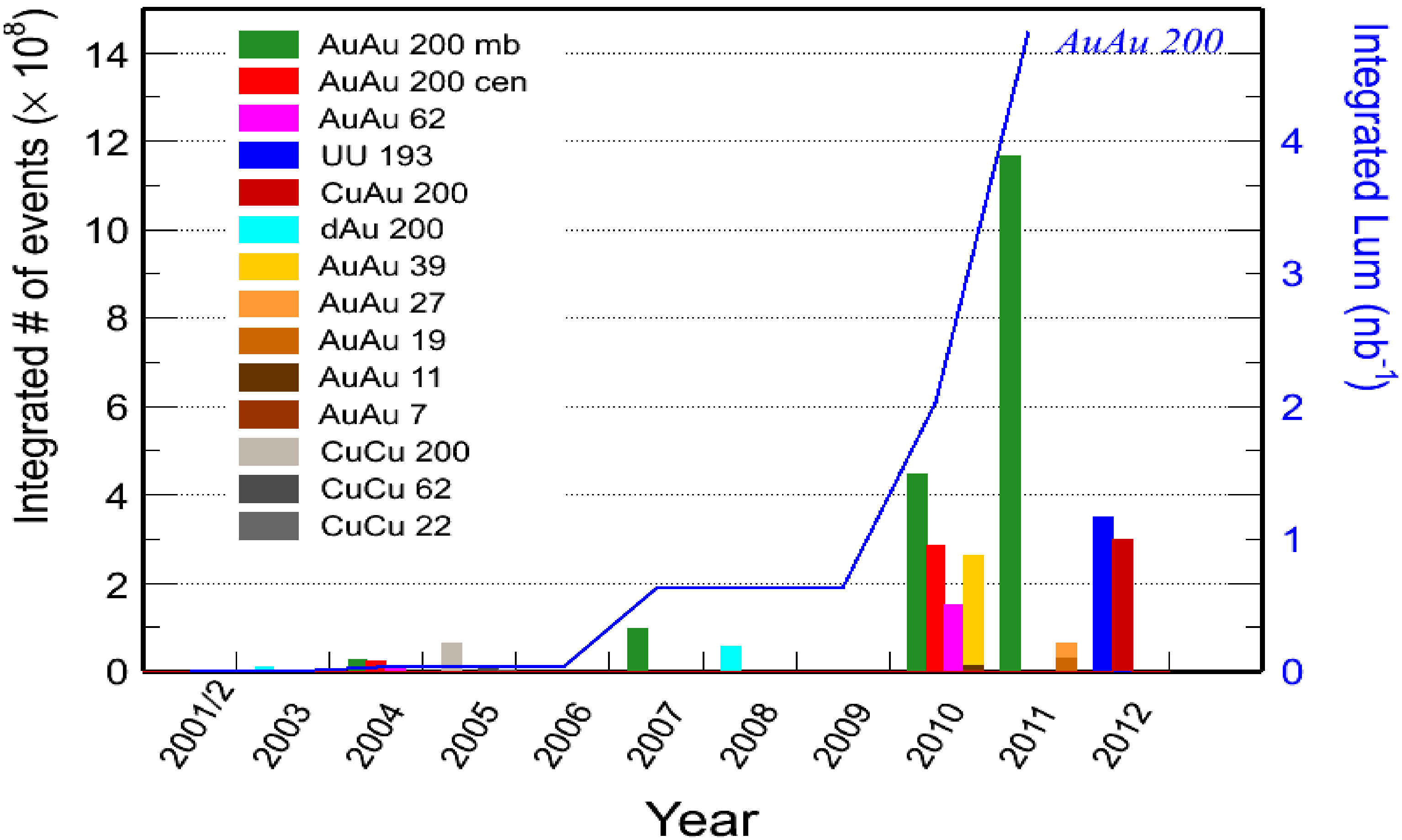
  $p \rightarrow U$

- Maximum center-of-mass energy:

  200 GeV for Au+Au

  500 GeV for *pp*

AA Data Collection



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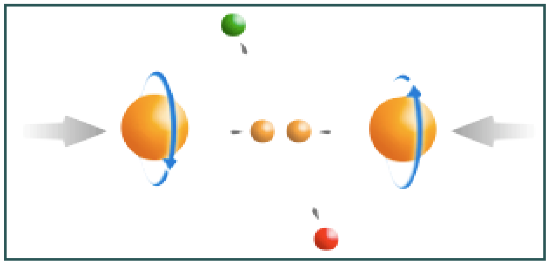
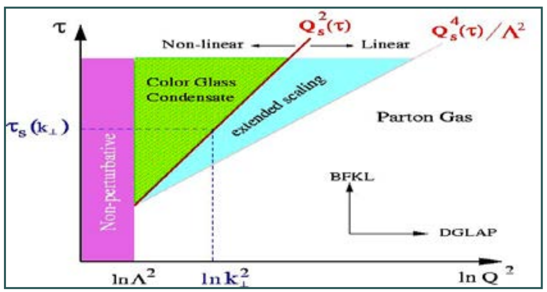
STAR Physics Program



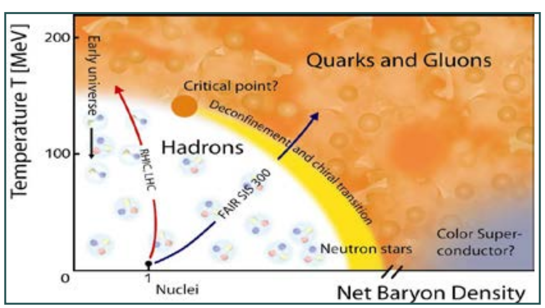
- Polarized pp program
  - Focus on proton's intrinsic properties

    (not a part of this talk)



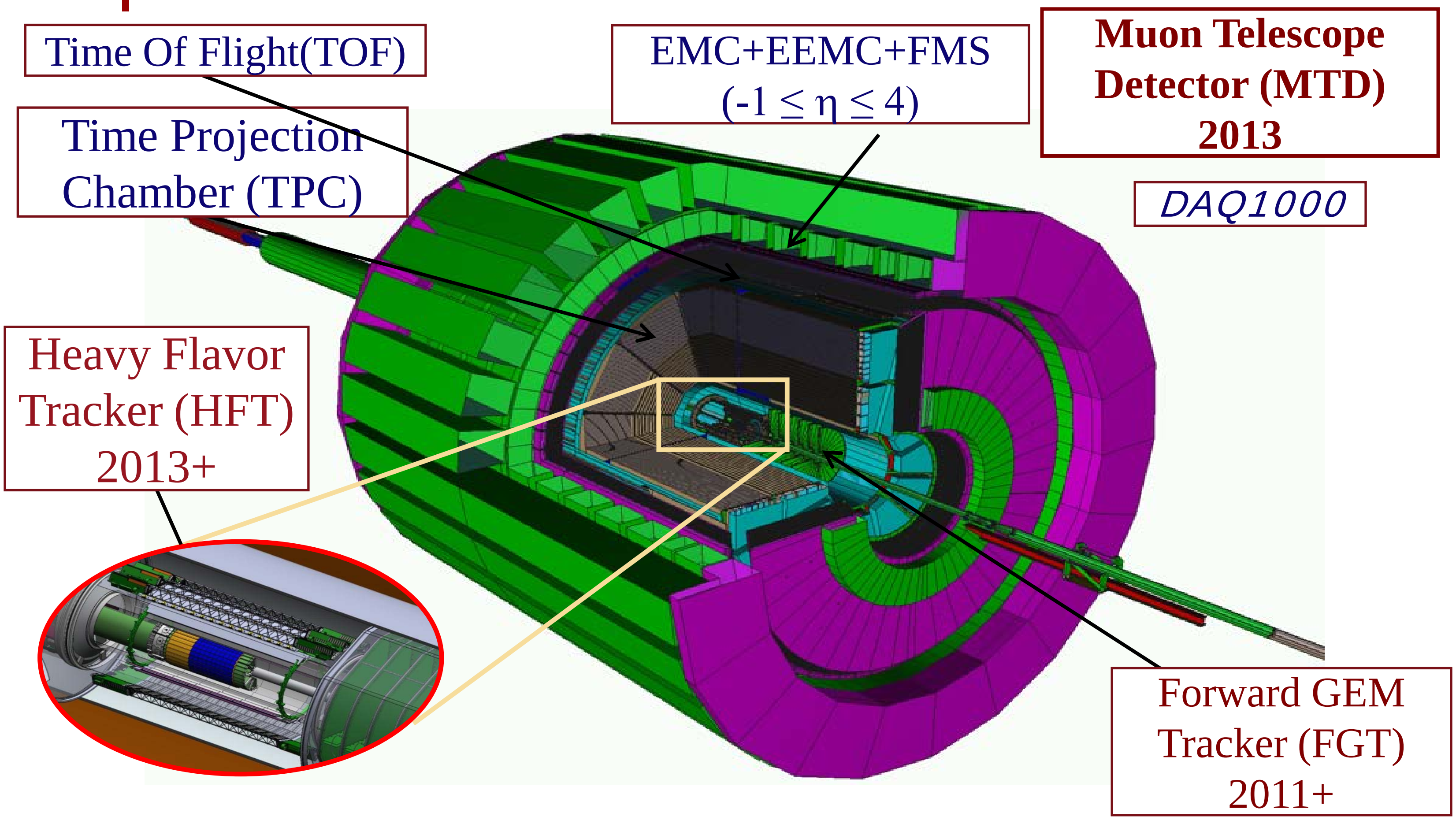
- Forward Physics program
  - Low-x physics, initial conditions, CGC
  - Elastic and inelastic processes in *pp2pp*

    (not a part of this talk)

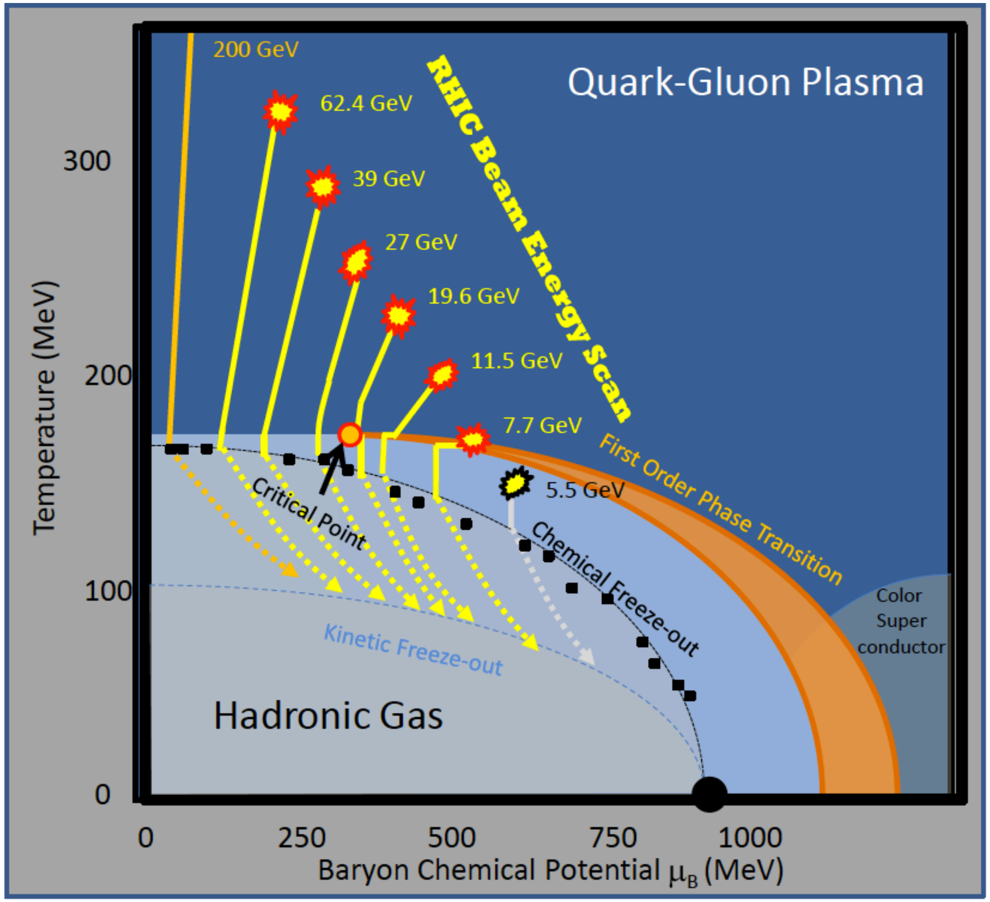


- QCD matter under Extreme Conditions
  - sQGP Studies (EoS, E_{loss} in QCD medium,…)
  - Beam energy scan (QCD critical point chiral symmetry restoration,…)

STAR Detector – the Evolution



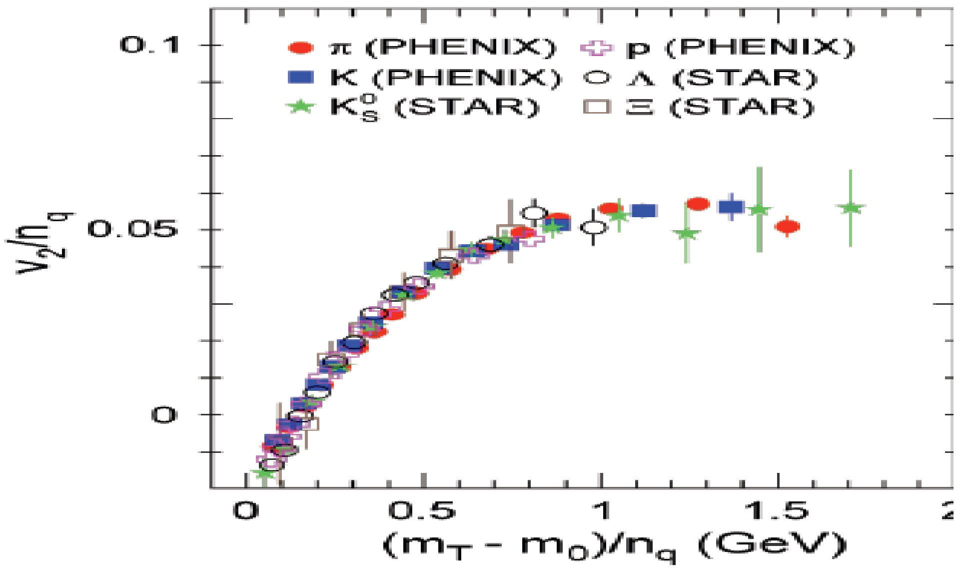
Part 1 – Beam Energy Scan



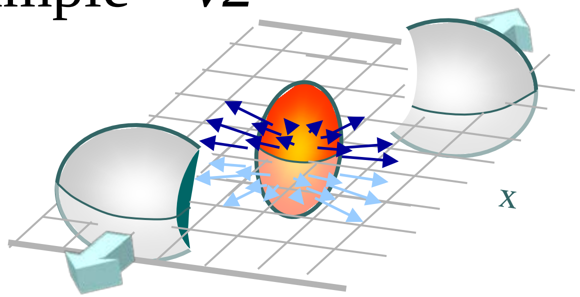
- Vary the beam energies to scan the (T,μ_B) space
- Look for turn-on/turn-off of sQGP signatures, onset of deconfinement
- Search for QCD critical point/first order phase transition

What are the sQGP signatures?

- From not-so-recent results:
  - High density opaque medium
  - Partonic collectivity
  - Deconfinement



In multiple measurements, example – *v2*

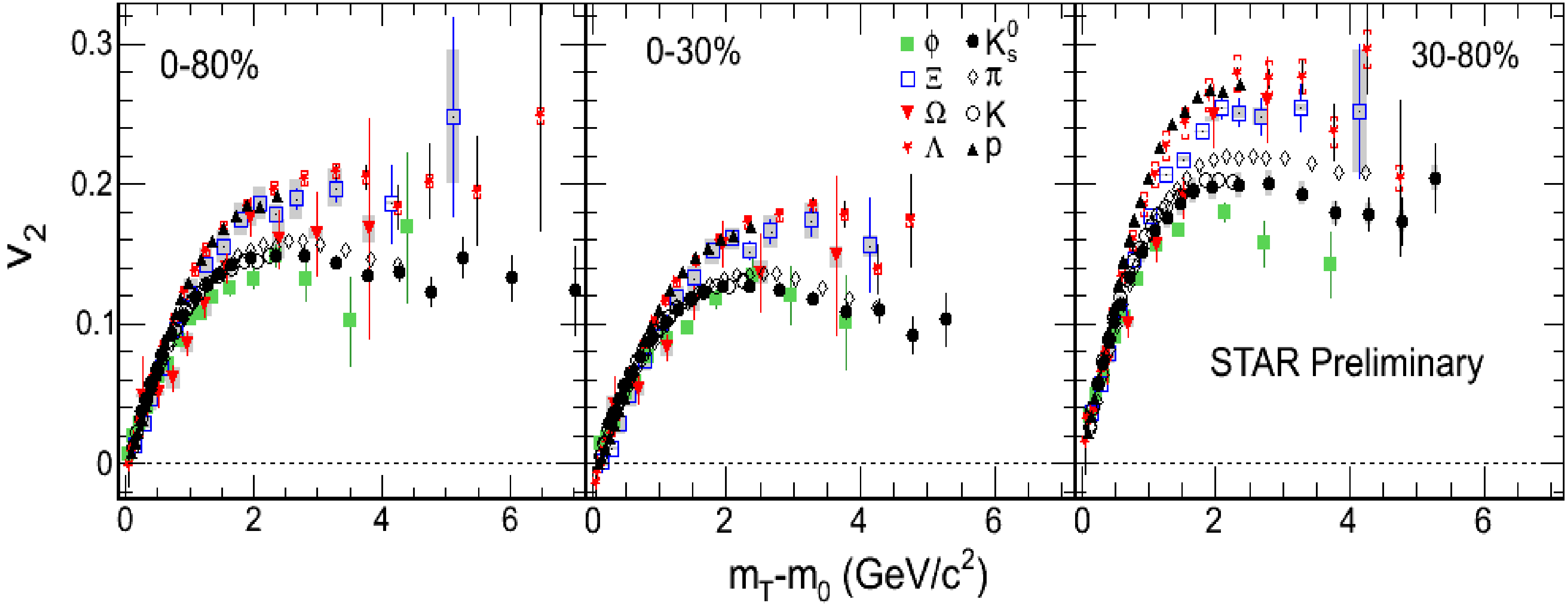


$$\frac{dN}{d\varphi} \propto 1 + 2v_2\cos[2(\varphi - \psi_R)] + \ldots$$

- Strong anisotropy in the final state, including Ω and ϕ!
- Low p_T - mass ordering, consistency with hydrodynamic calculations
- Higher p_T – NCQ scaling

Elliptic Flow - Update

High precision identified hadron *v2* results from high statistics 200 GeV Au+Au



- Central data: baryon-meson splitting, NCQ scaling (to ~10% level)
- Peripheral data: break-down of scaling features for multi-strange hadrons
- Even high p_T – anisotropy related to jet attenuation (also – in R_{AA})

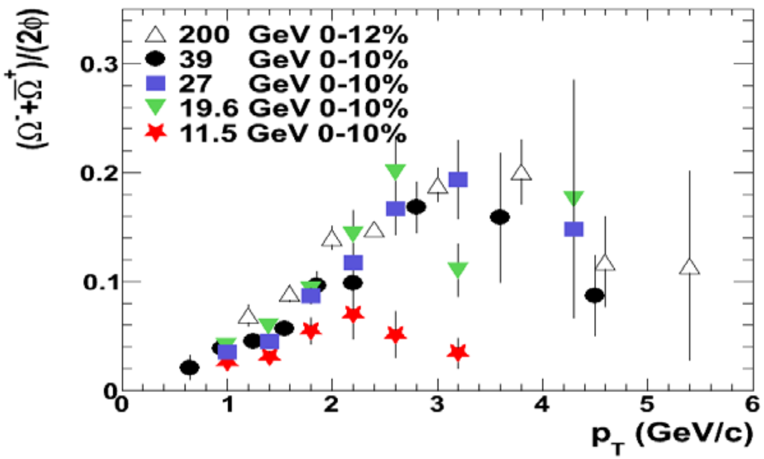
Back to BES program

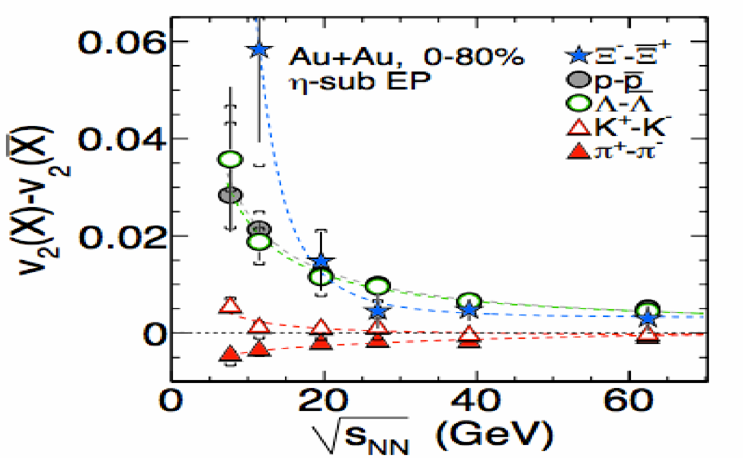
- Disappearance of partonic DOF signals
  - disappearance of NCQ scaling
  - disappearance of hadron suppression
  - disappearance of ridge
  - …
- Signals of Critical Point & 1st order phase transition
  - non-monotonic variations in fluctuation observables
  - divergence of correlation length (higher moments of net-proton distribution)

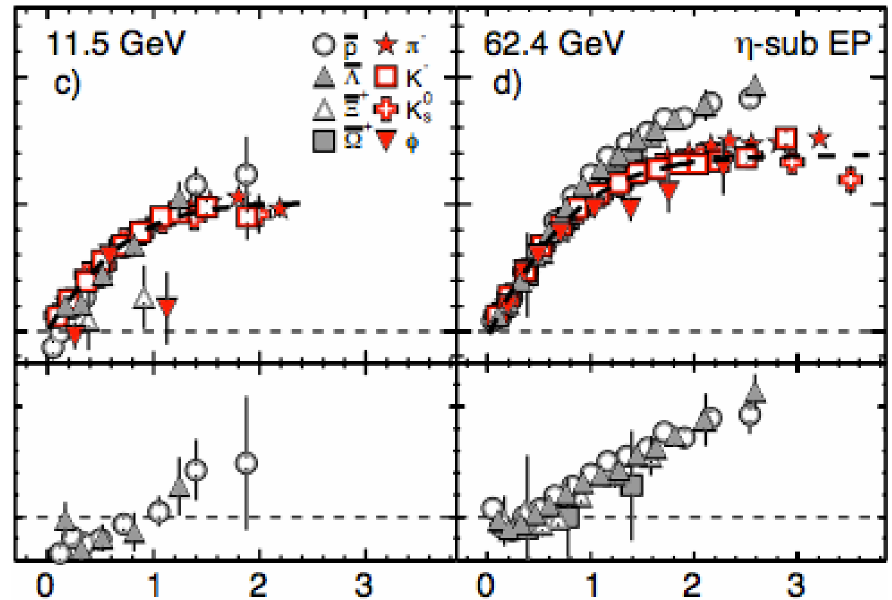
$$<(\delta N)^2> \approx \xi^2, <(\delta N)^3> \approx \xi^{4.5}, <(\delta N)^4> - 3<(\delta N)^2>^2 \approx \xi^7$$

  - elliptic & directed flow
  - ….

The Dawn of NCQ Scaling?

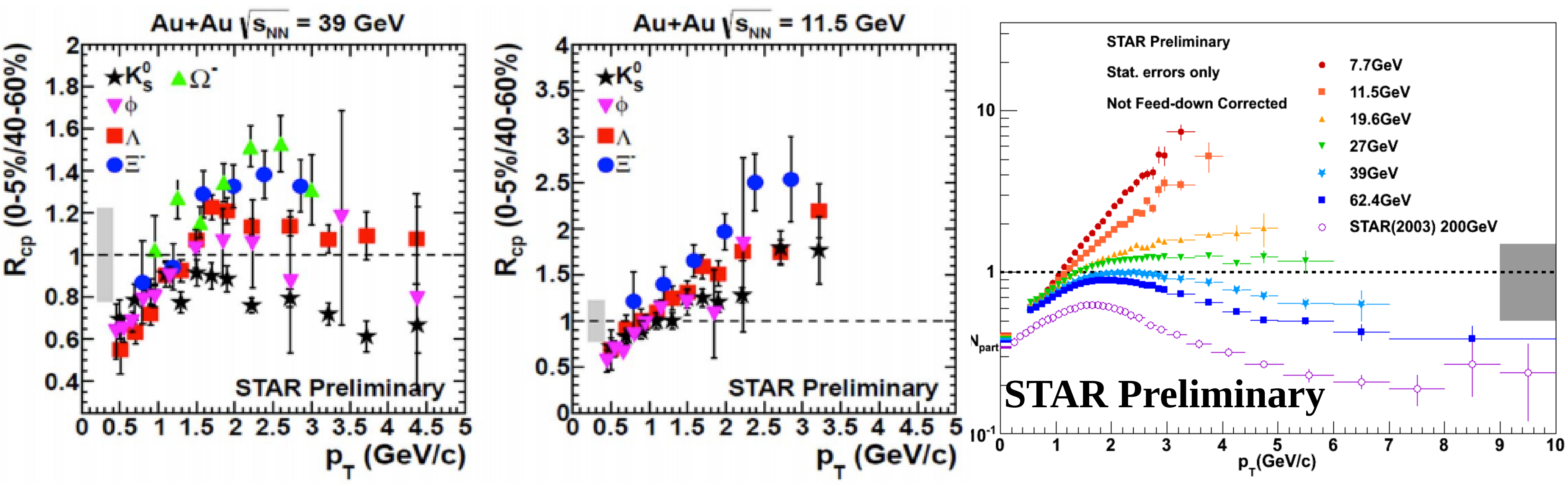






- Broken trend in Ω/ϕ ratio at 11.5 GeV
- No clear baryon/meson grouping for anti-particles at 11.5 GeV &below
- New feature: Differences between baryon & anti-baryon *v2* at lower energies

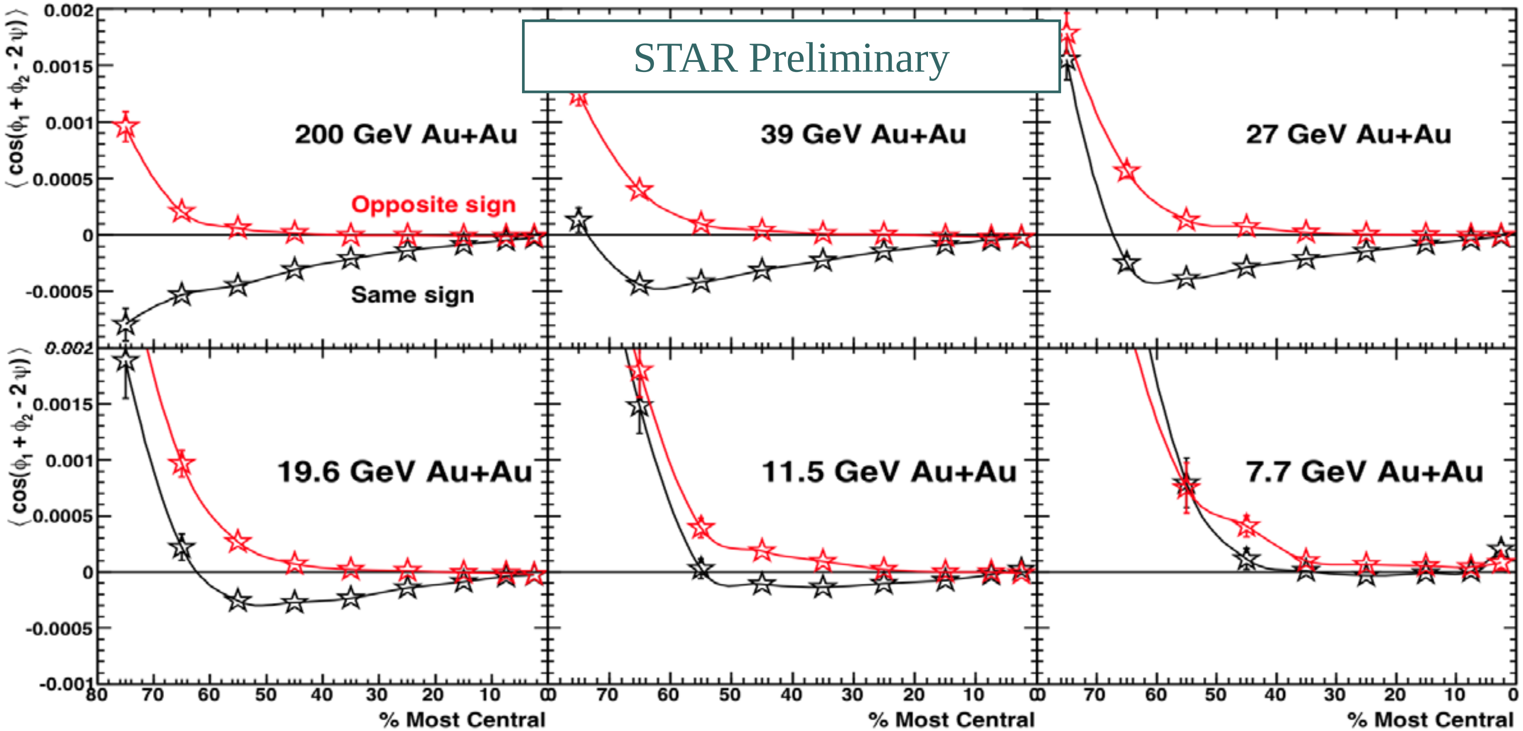
Higher Momenta:



Nuclear modification factor R_{CP}

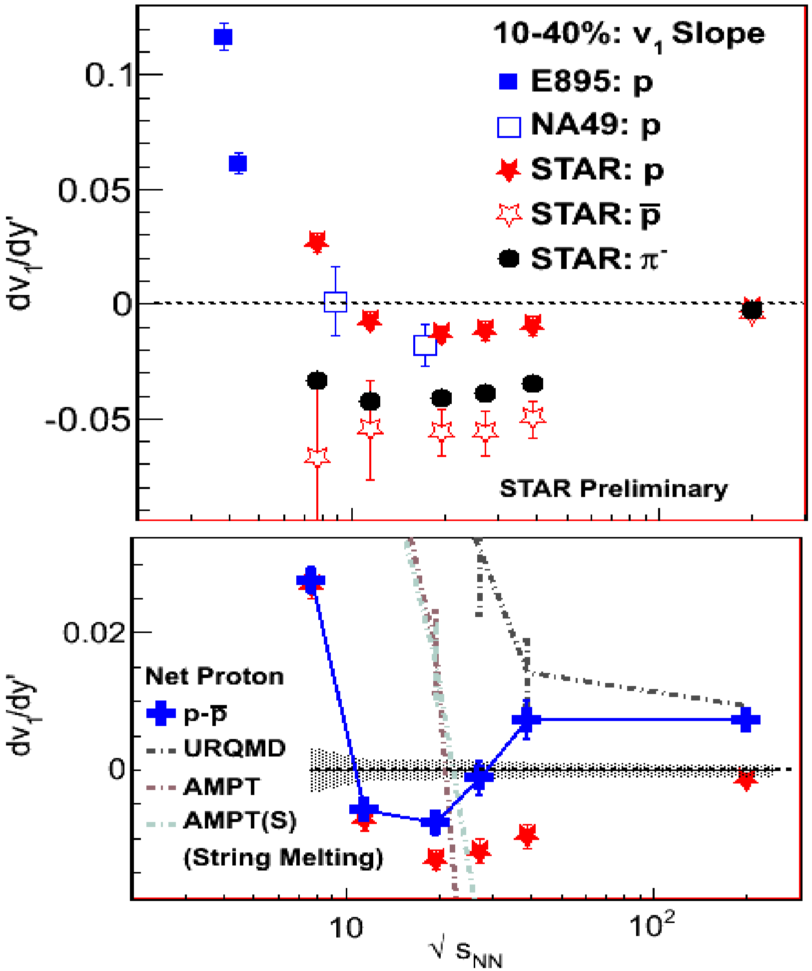
- Disappearance of baryon-meson splitting at intermediate p_T
- Suppression → (Cronin) enhancement

Charge Separation Observable



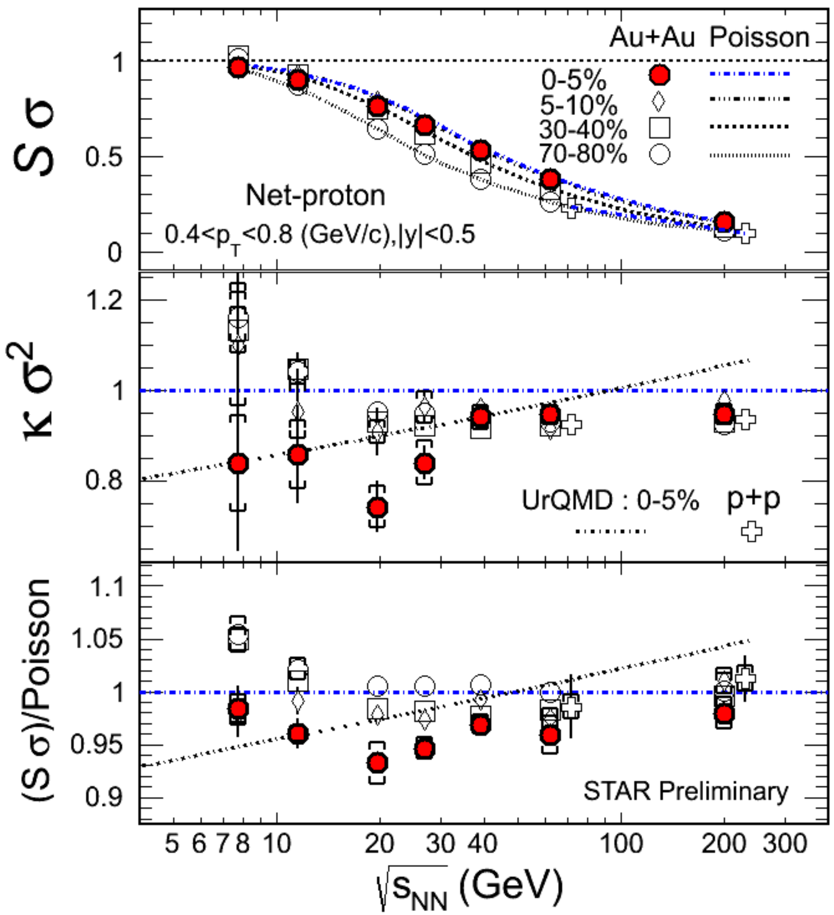
- Motivated by search for local parity violation. Require sQGP formation.
- The splitting between correlations for like-sign and opposite sign pairs disappears at/below 11.5 GeV

Proton Directed Flow



- The slope of proton $v_1(y)$ distribution is expected to be sensitive to 1st order phase transition
- Proton v_1 changes slope between 7.7 and 11.5 GeV
- Net-proton v_1 slope becomes negative between 7.7 and 11.5 GeV

Higher Moments of Net-proton Distribution



$$\sigma^2 = \langle (N - \langle N \rangle)^2 \rangle$$
$$S = \langle (N - \langle N \rangle)^3 \rangle / \sigma^3$$
$$\kappa = \langle (N - \langle N \rangle)^4 \rangle / \sigma^4 - 3$$

Possible deviations from Poisson baseline in most central collisions at low energies

Need higher precision measurements for conclusive statement

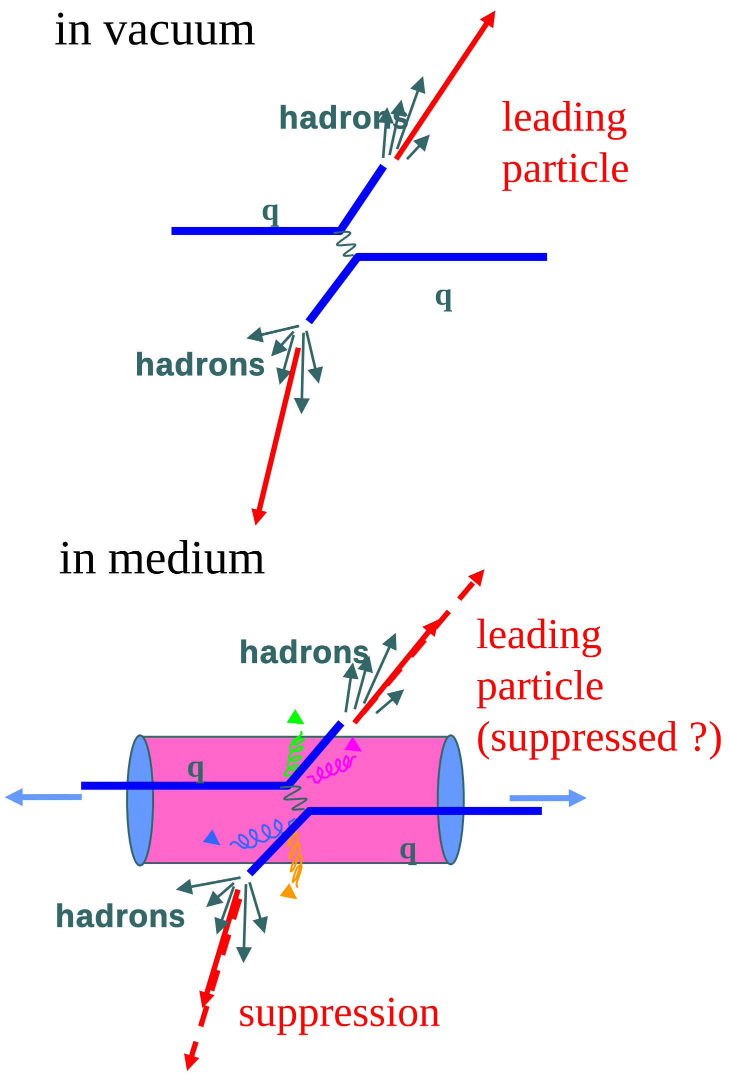
Part 1 - Summary

STAR BES program

- Very successful start of the program Phase-I
- Several “QGP-signatures” are not seen at low energies
  - NCQ scaling breaks down for multistrange particles <=11.5
  - Charge separation signal vanishes
  - Change in v2 systematic between particles and antiparticles
- Critical point / 1st order phase transition
  - Proton v1 slope changes sign between 7.7 and 11.5 GeV
  - Inconclusive signs from higher moments (and monotonic behavior in second moments, e.g. ratio fluctuations)
- Stay tuned for Phase-II

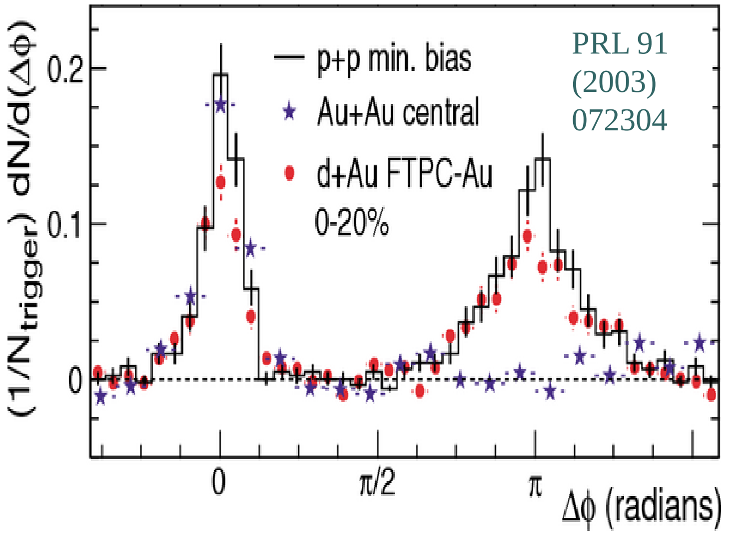
Part 2: Jets

- From not-so-recent results:
  - High-pT hadron suppression (factor of 5 in central events)
  - Suppression/modifications of away-side azimuthal correlations
  - Both due to final state effects: jet-quenching

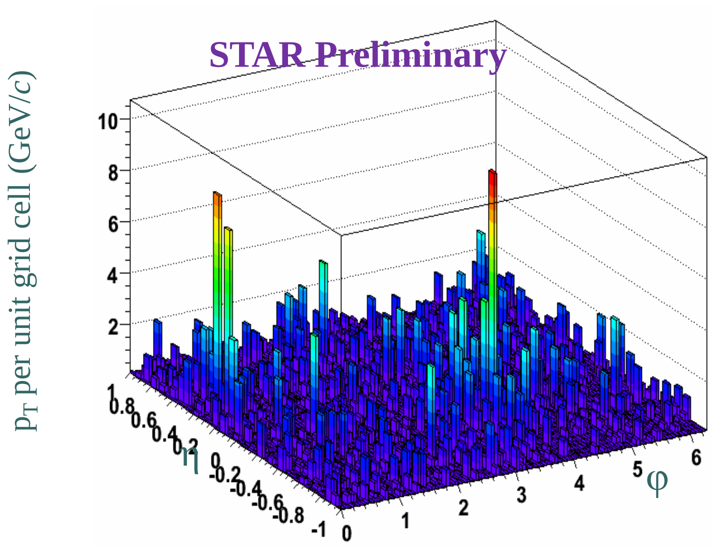


Tools for Jet Quenching Studies

Di(multi)-hadron correlations



Full jet reconstruction



…and their combinations

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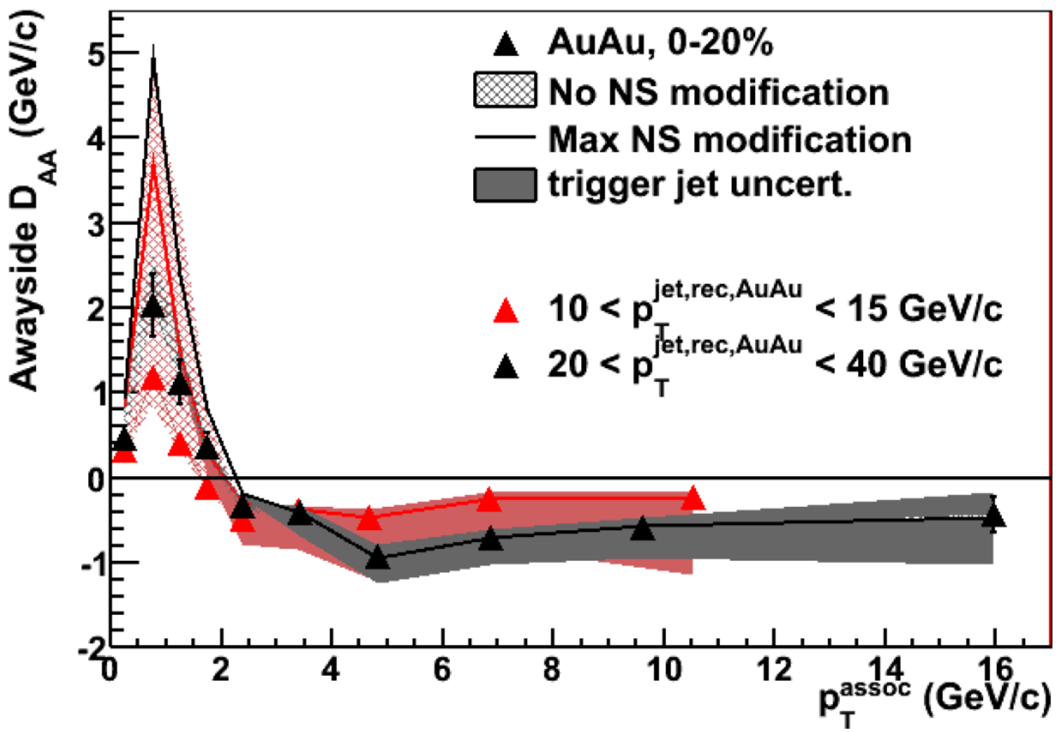
Jet-hadron Correlations

$$D_{AA}(p_T^{assoc}) = Y_{AuAu}(p_T^{assoc}) \cdot \langle p_T^{assoc} \rangle_{AuAu} - Y_{pp}(p_T^{assoc}) \cdot \langle p_T^{assoc} \rangle_{pp}$$

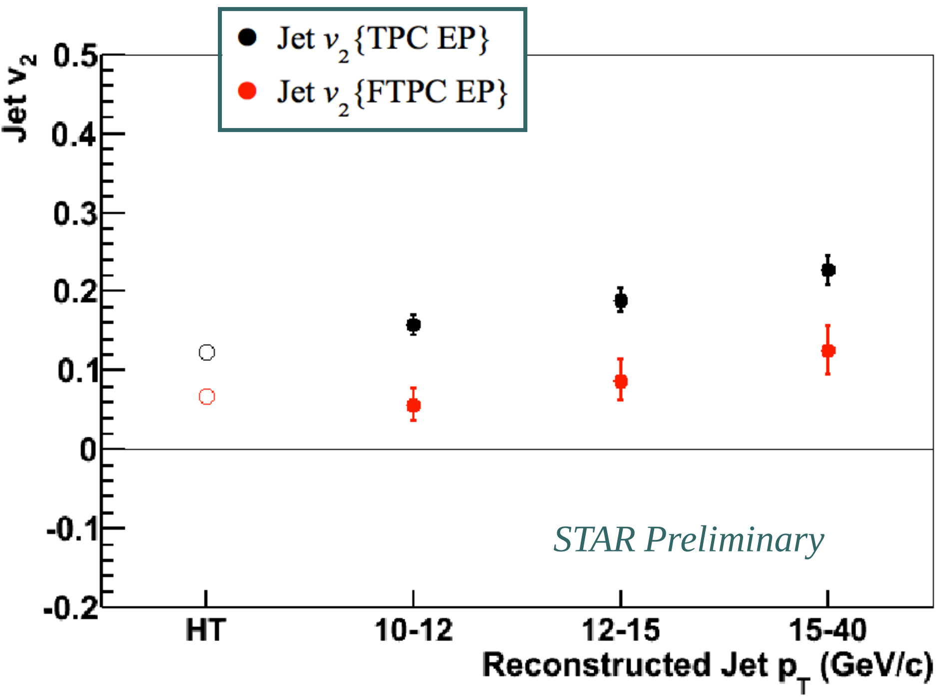


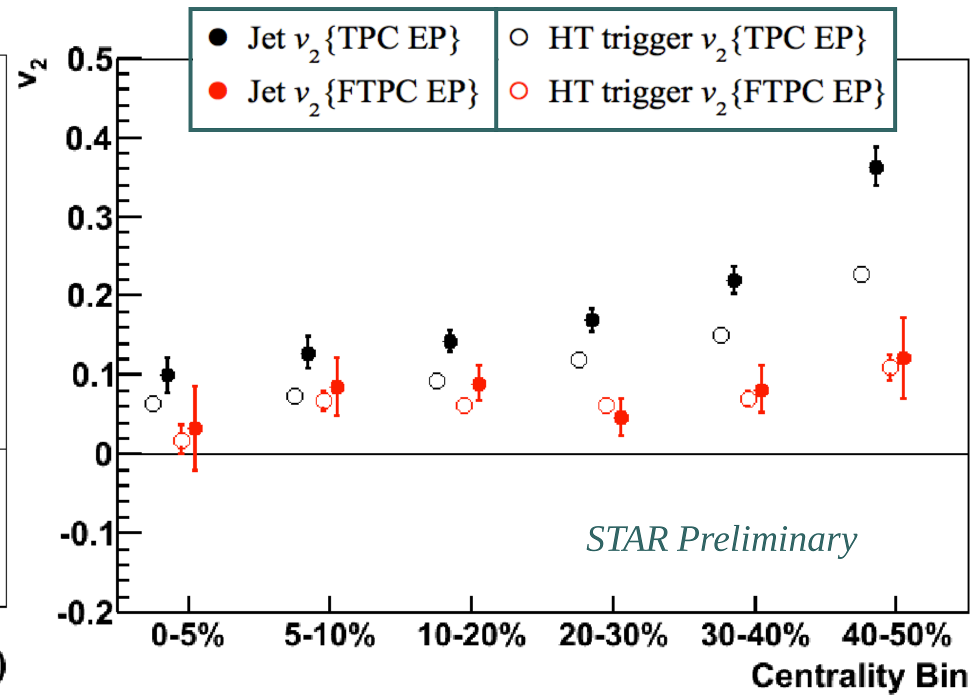
- Trigger jet (near-side) population is highly (surface) biased
- Recoil (away-side) jet fragmentation should be unbiased
- Away-side Energy Balance:

  Suppression of high-p_T associated hadron yields is (mostly) balanced by low-p_T enhancement

Jet v_2 Measurements

Jet v_2: correlation between jets and the event plane, probes path-length dependence of the jet quenching.

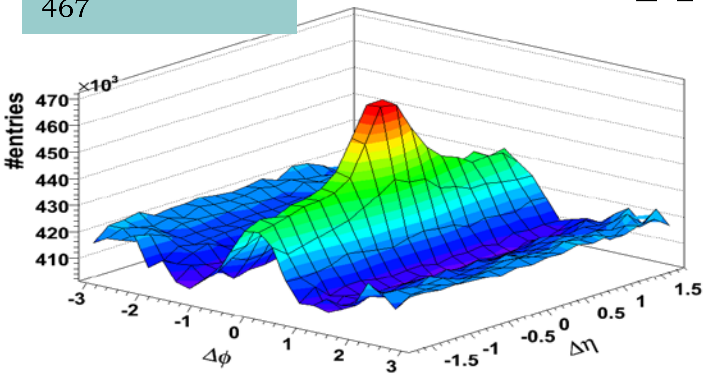




Non-zero jet v_2\{FTPC EP\}: path-length dependence of energy loss

Jet-like Correlations: Ridge

PLB 704 (2011) 467



From not-so-recent results:

- Discovered first in Au+Au collisions at RHIC
- Extends to acceptance boundary and to the highest trigger p_T measured
- Production mechanisms for jet and ridge differ

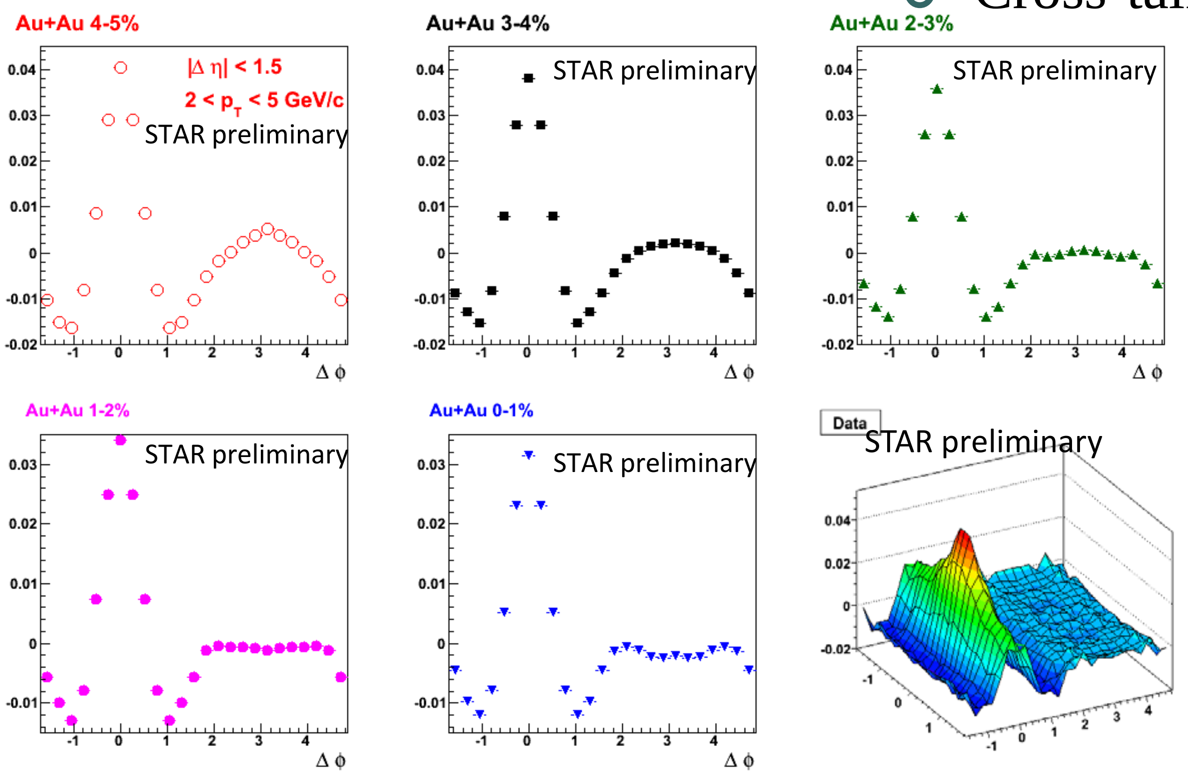
The ridge open question:

manifestation of the jet quenching or coincidental nuisance?

Ultra-central Events

Motivation for "v_n fit"

- Cross-talk between data and theory:
  - Extra-central collisions
  - Transport model predictions



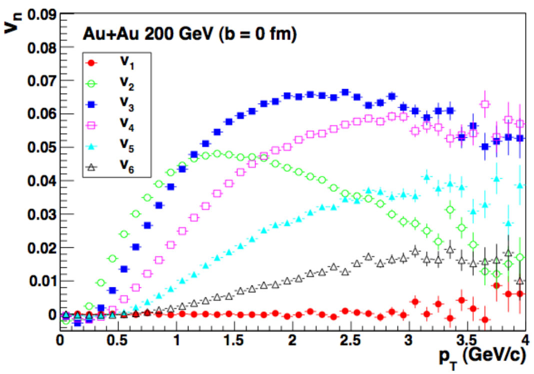
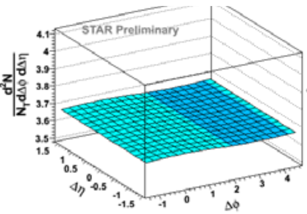


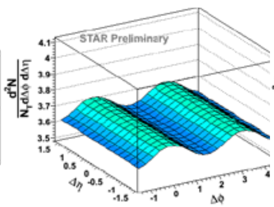
FIG. 2: (Color online) Azimuthal anisotropies of hadron spectra $v_n(p_T)$ $(n = 1-6)$ in central $(b = 0)$ $Au + Au$ collisions at $\sqrt{s} = 200$ GeV from AMPT model calculation.

Long Range Correlation – Fourier fits

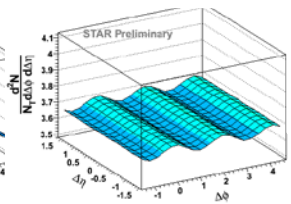
cos(Δϕ)



cos(2Δϕ)

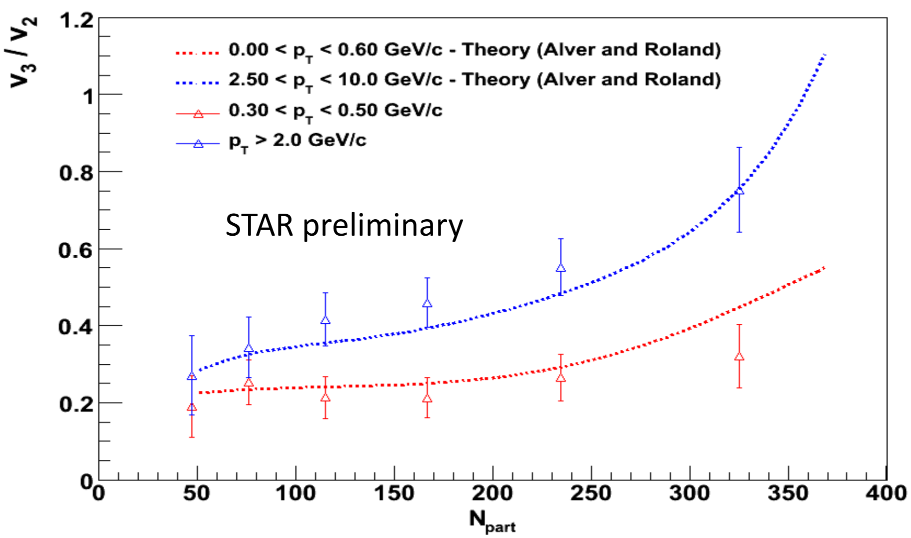


cos(3Δϕ)



+…

- Comparison with flow:



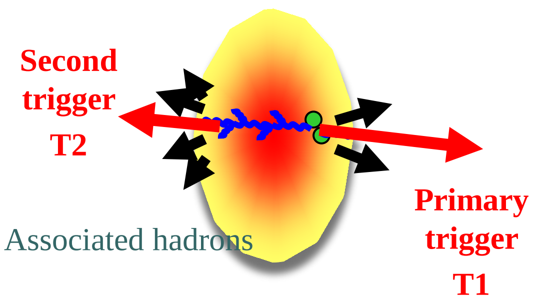
Alver and Roland, *PRC 81, 054905 (2010)*

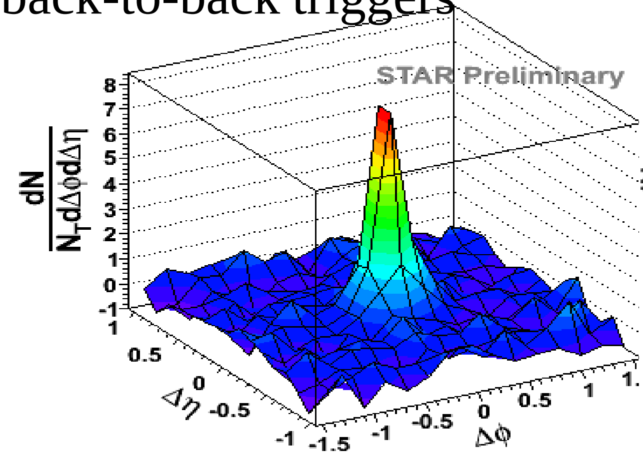
- Long range correlations near- and away from the trigger are tested via Fourier decomposition
- Could be simultaneously described via higher order v_n terms
- v_n fit results are consistent with flow expectations

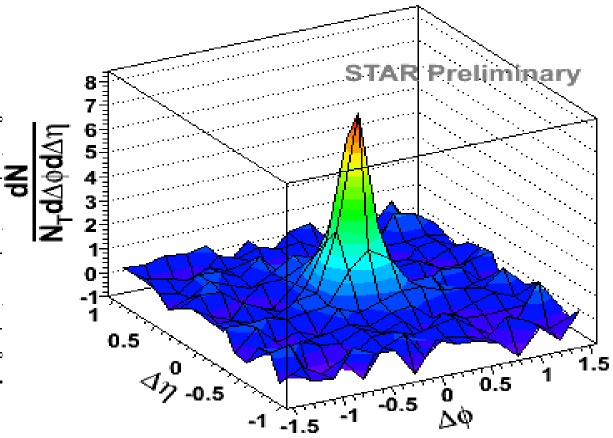
Multihadron Correlations: Di-jets

- 2+1 to study di-jets

"pin" the jet axis selecting back-to-back triggers

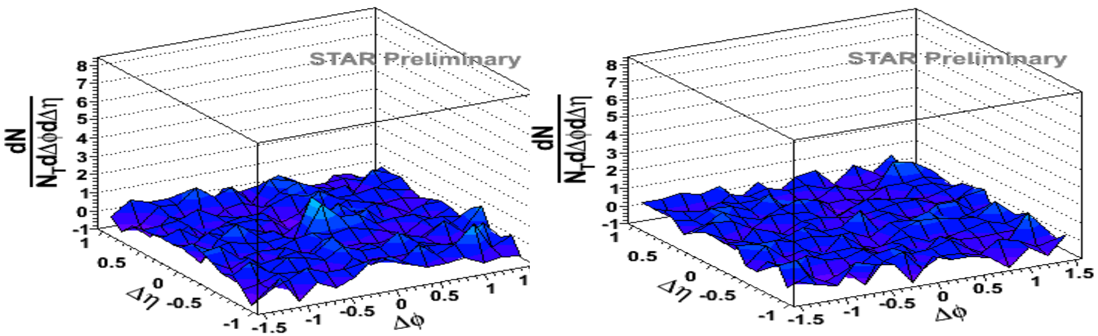




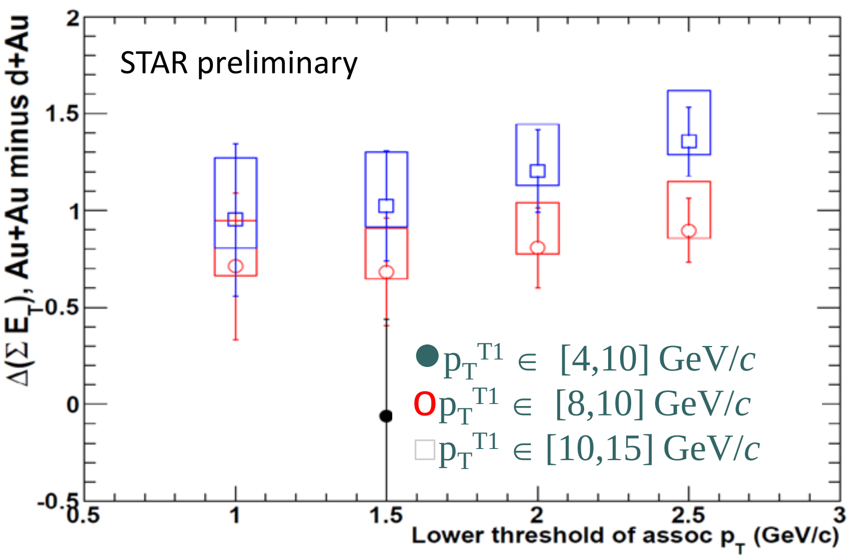


- Central Au+Au ~ d+Au. No away-side suppression
- Shapes of near- and away-sides are similar
  - no significant shape/yield modifications
  - no apparent ridge

Di-jet Energy Imbalance



2+1 Residuals:
Au+Au – d+Au



Jet energy ~ Σp_T within the 0.5x0.5 ($\Delta\eta$ x $\Delta\phi$)

Relative energy imbalance
$\Delta\Sigma E_T$= (near- away)|Au+Au-d+Au

Observed trends indicates softening of fragmentation function for di-jets selected

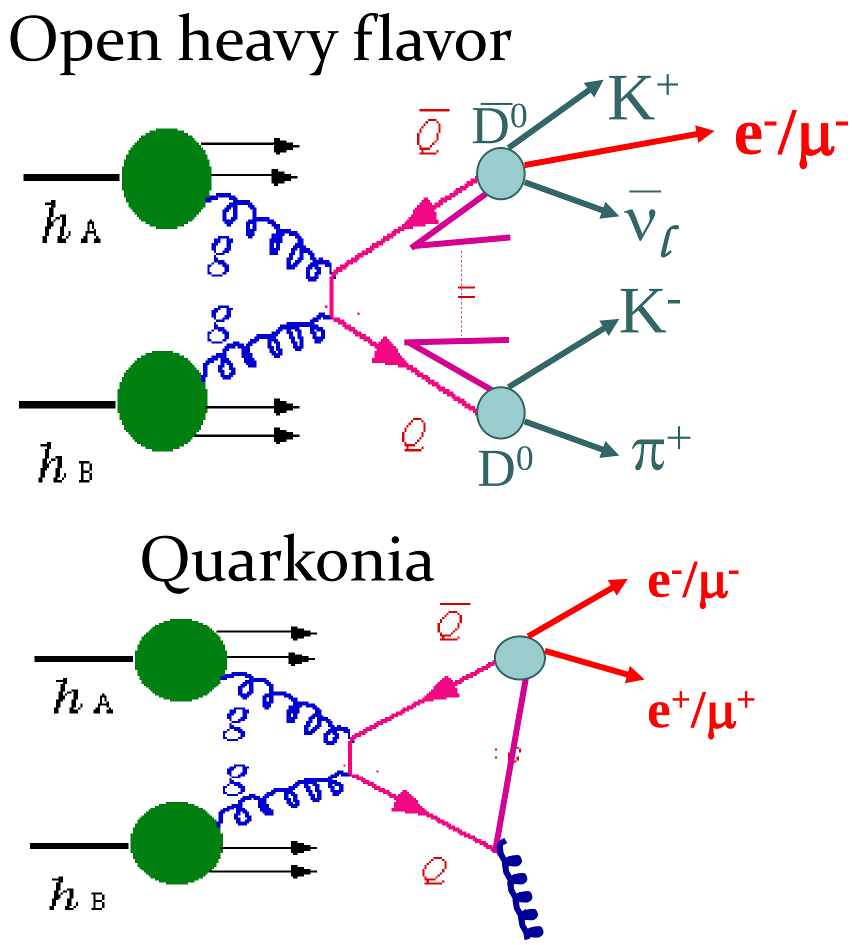
Part 2: Summary

STAR jet-medium interaction studies

- Consistent picture from jet-h and h-h correlation
  - Triggered jets and leading hadrons>4GeV/*c* select unmodified jet sample ("surface bias")
  - Jet-h and 2+1 correlation results suggest softening of fragmentation for selected di-jets
- Jet v_2
  - Azimuthal anisotropy of jets is indicative of path-length dependence of energy loss
- The origins of "ridge"
  - Could be flow…

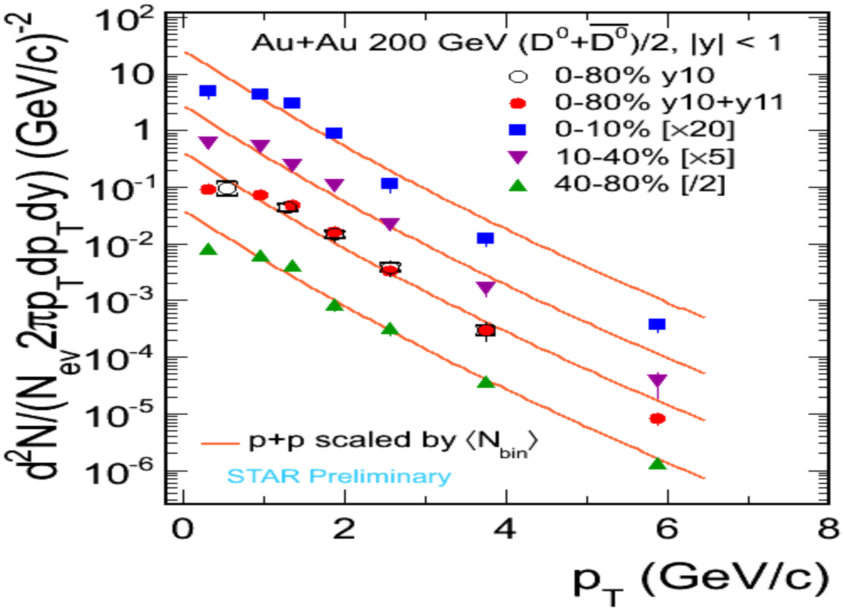
Part 3: Heavy Flavor

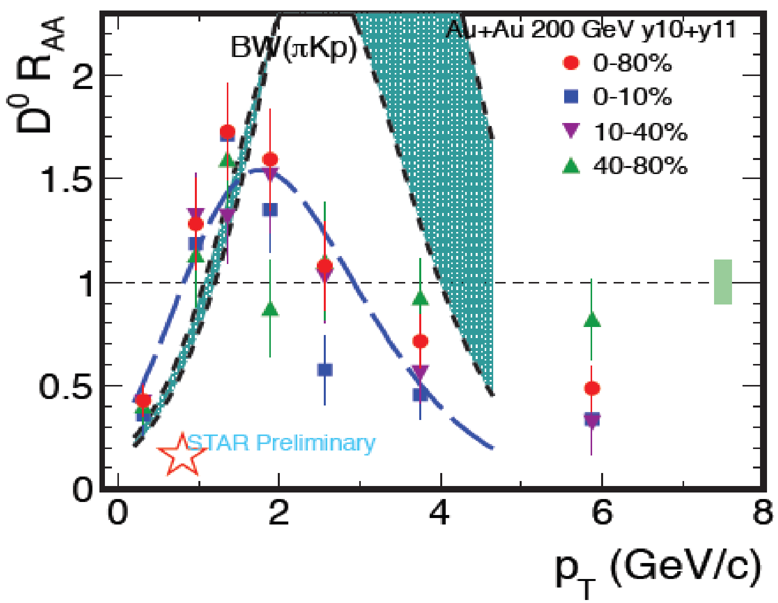
- Expected to be less affected by strong interactions in the medium →early-time probes
- Sensitive tool to access gluon distribution
- Test medium properties on different levels (color screening effects, coalescence contributions)



Open Heavy Flavor

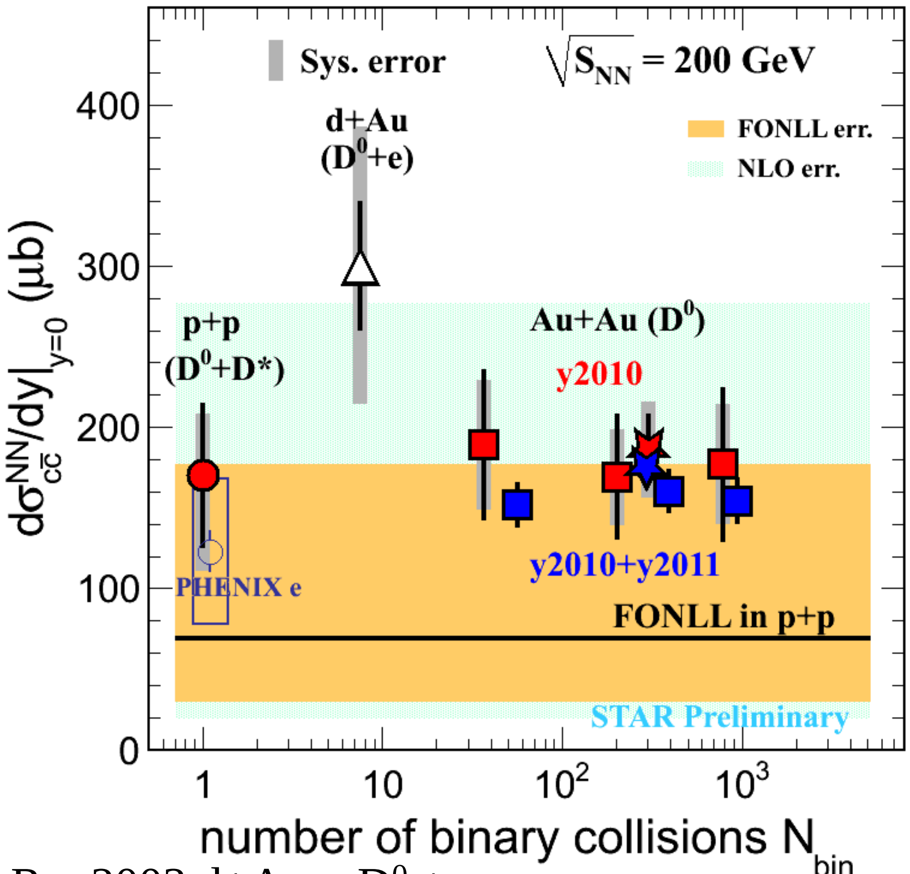
D^0 Spectra and R_{AA} in 200 GeV Au+Au collisions





- Suppression at high p_T in central and mid-central collisions
- Enhancement at intermediate p_T
- Early freeze-out/smaller radial flow compared to light-quark hadrons

Charm Cross-section



The charm total cross-section at mid-rapidity*:

$$\left.\frac{d\sigma_{c\bar{c}}}{dy}\right|_{y=0}^{pp} = 170 \pm 45(\text{stat.})^{+38}_{-59}(\text{sys.})\ \mu b$$

$$\left.\frac{d\sigma_{c\bar{c}}}{dy}\right|_{y=0}^{AuAu} = 175 \pm 13(\text{stat.}) \pm 23(\text{sys.})\ \mu b$$

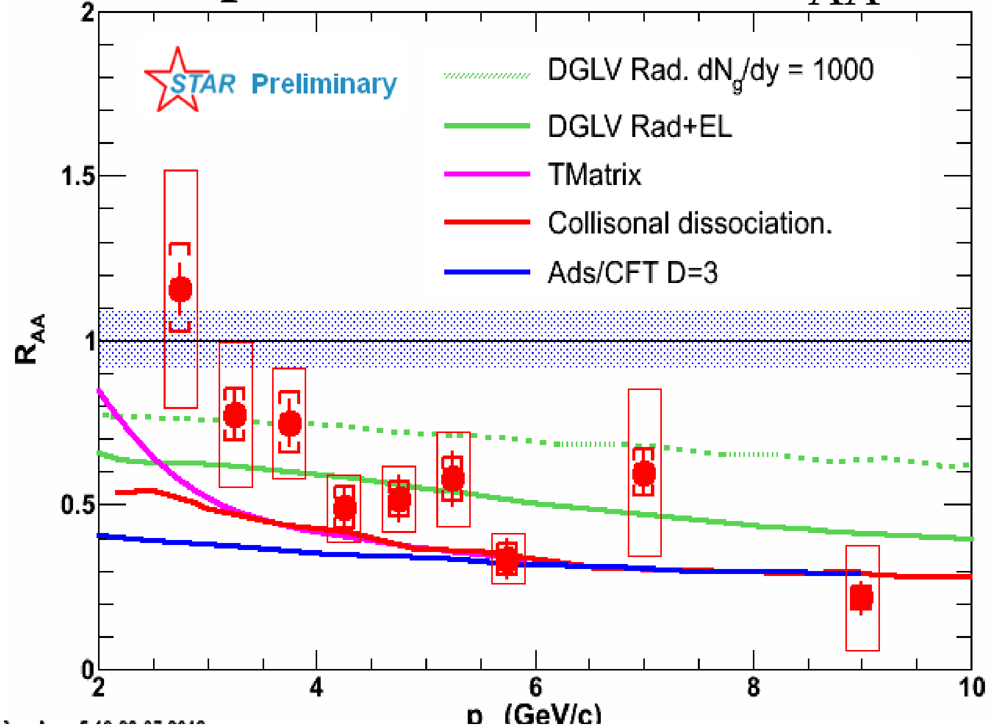
Charm cross-section follows N_{bin} – scaling → production dominated by initial (gluon) hard scatterings

Run2003 d+Au : D^0 + e

Run2009 p+p: $D^0 + D^*$, Runs 2010, 2011 Au+Au: D^0

Heavy Flavor Energy Loss

Non-photonic electron R_{AA} in 200 GeV Au+Au collisions

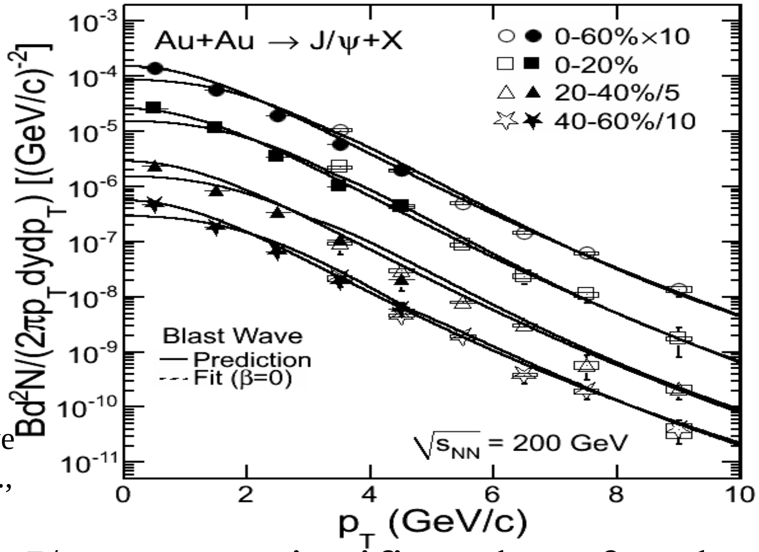


DGLV: Djordjevic, PLB632, 81 (2006)
T-Matrix: Van Hees et al., PRL100,192301(2008).
Coll. Dissoc. R. Sharma et al., PRC 80, 054902(2009).
Ads/CFT: W. Horowitz Ph.D thesis.

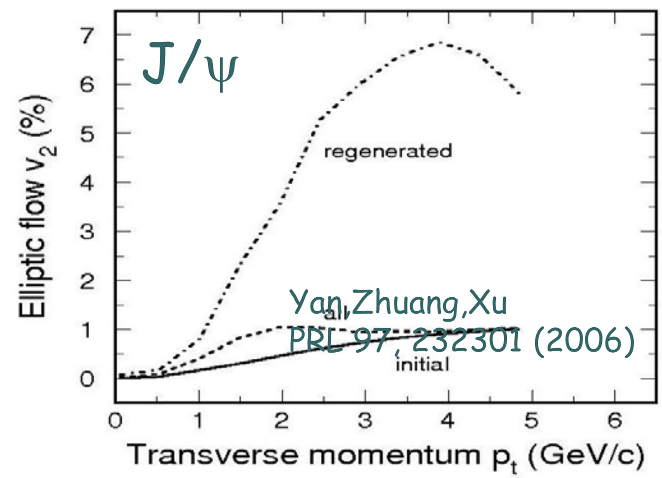
- Strong suppression of heavy flavor at high p_T
- Expect significant improvement of uncertainties with analysis on the new *pp* data
- Begin to provide quantitative constraints on models: models with radiative energy loss seem to underpredicts the suppression

Quarkonia Measurements

J/ψ Spectra in 200 GeV Au+Au collisions

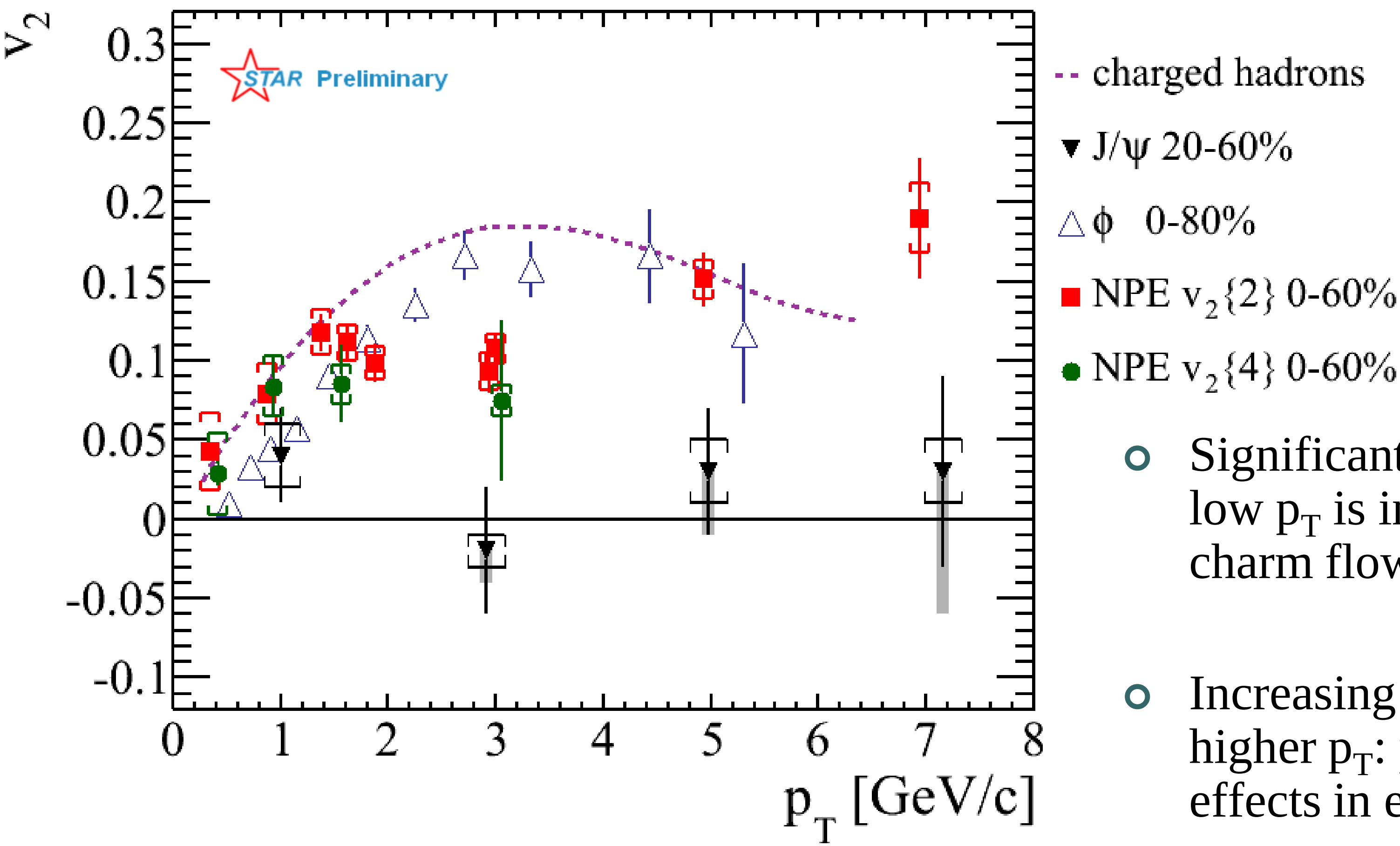


Tsallis Blast-Wave model: ZBT *et al.*, arXiv:1101.1912



- J/ψ spectra significantly softer than light hadrons:
  - smaller radial flow?
  - Significant regeneration contributions?
- Let's look at J/ψ v_2: if charm quark flows, so will J/ψ from recombination! But will need a combination of open/closed HF measurement to disentangle different scenarios

Heavy Flavor v_2



- Significant NPE v_2 at low p_T is indicative of charm flow
- Increasing v_2 trend at higher p_T: path-length effects in energy loss?
- Finite J/ψ v2 at low p_T : charm coalescence?

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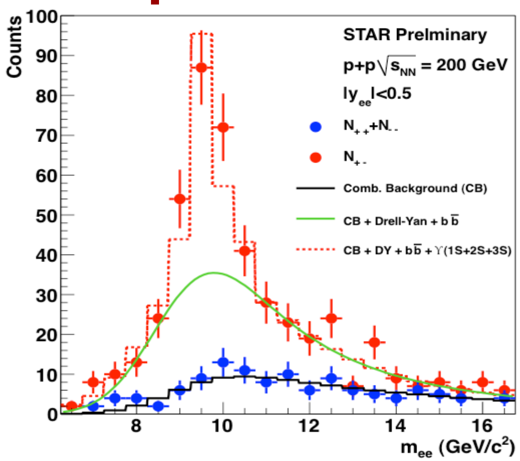
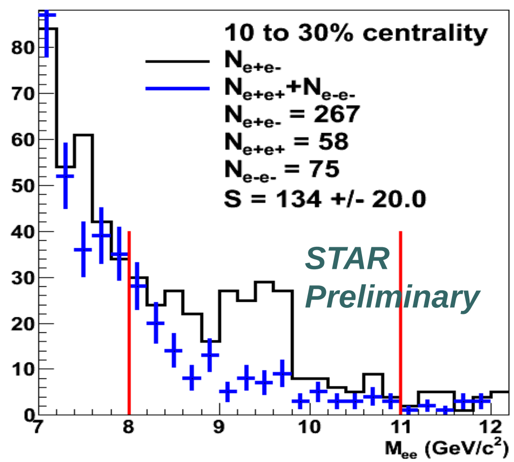
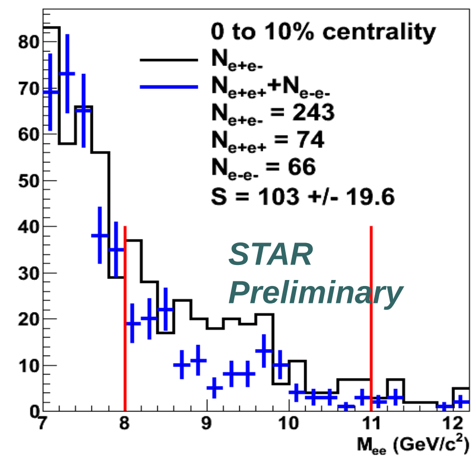
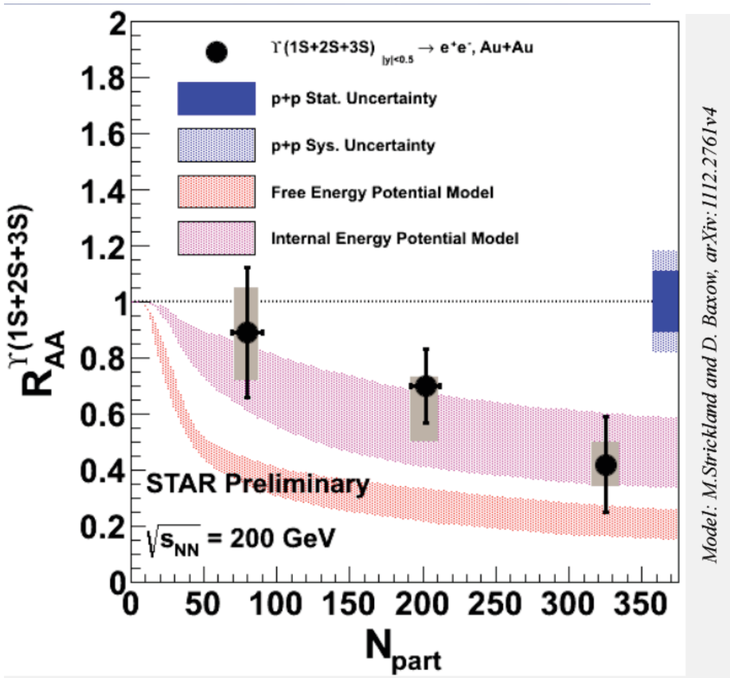
Upsilon Measurements









- A cleaner probe than J/ψ:
  - Negligible recombination contributions
  - Low co-mover absorption
- Quarkonia melting is sensitive to the medium temperature

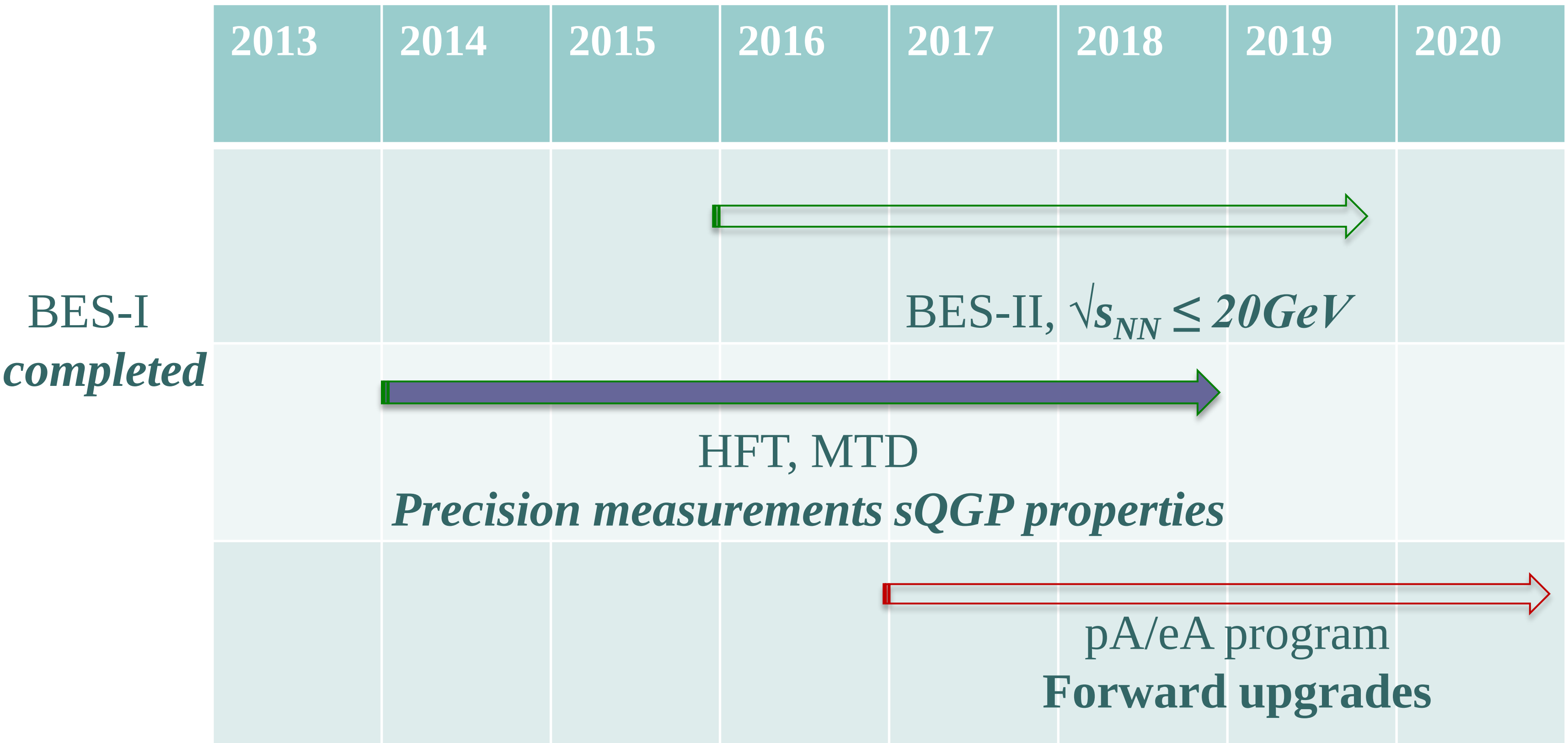
- Significant Υsuppression in central collisions
- Consistent with melting of 2S and 3S states

Part 3: Summary

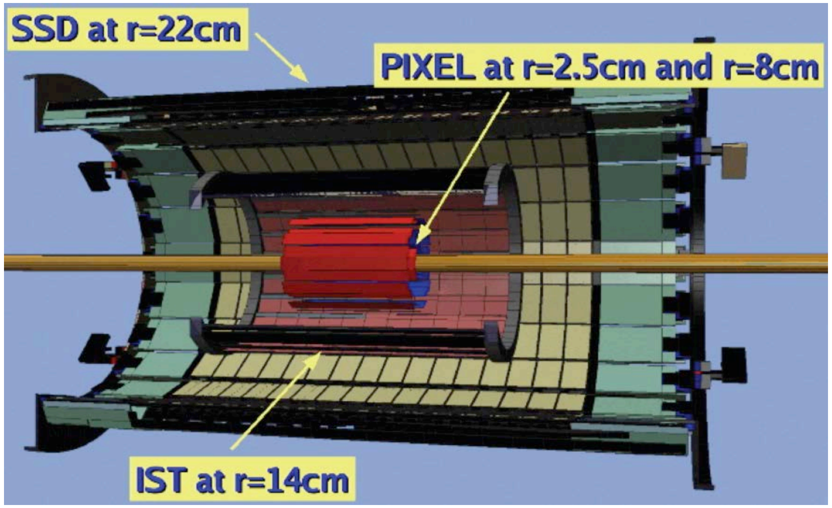
STAR Heavy Flavor program:

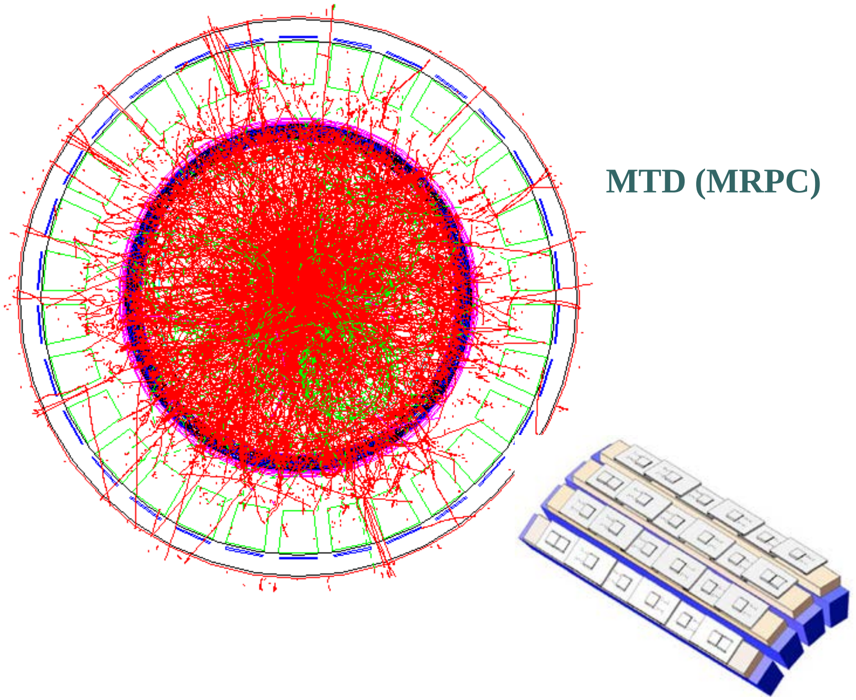
- Charm flows
  - Significant v_2 for NPE, D^0 flow
  - Early freeze-out/smaller radial flow than light hadrons
  - From J/ψ studies – coalescence dominance is disfavored at high p_T
- Charm energy loss
  - Significant suppression of NPE and D^0 at high p_T
- Upsilon suppression
  - Consistent with full S3 and strong S2 melting

STAR Program Outlook



Upcoming Upgrades





Advancement of STAR HF capabilities:

- Direct reconstruction of heavy flavor decays
- B-tagging via J/ψ displaced vertex
- Muon identification and trigger (B→J/ψ→μμ +X, B-jet tagging)
- Measurement of Upsilon states
- QGP thermal radiation (background constraints through e-μ correlations)