Recent hard probe measurements with STAR at RHIC

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MINISTRY OF EDUCATION,
YOUTH AND SPORTS

Hard probes: tomography of nuclear matter

Jets, heavy quarks, quarkonia :
originate from initial hard scattering of partons which carry a color charge, interact with nuclear matter.

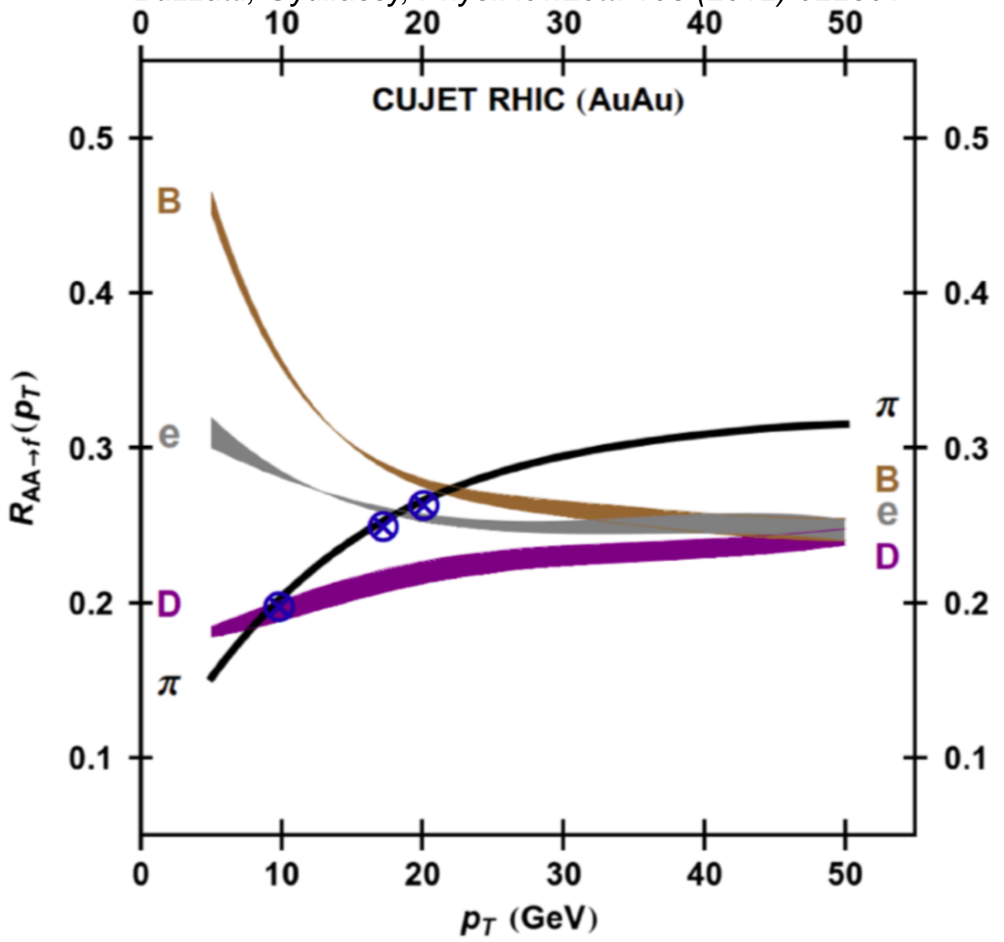
Photons, W and Z bosons:
do not carry a color charge,
provide information about initial state nuclear parton distribution functions.

Energy loss is different for gluons and light/heavy quarks
(color factor, dead cone effect).

Goal:
Use in-medium parton energy loss to quantify medium properties.

Parton interaction with medium not trivial,
depends on strength of coupling, dynamics of fireball.
… challenge for theorists

Buzzatti, Gyullassy, Phys.Rev.Lett. 108 (2012) 022301



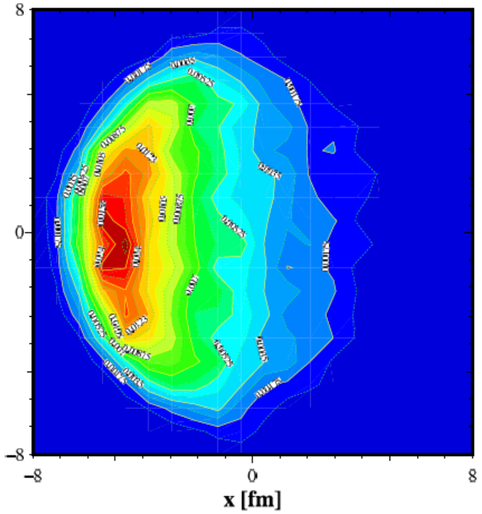
$$R_{AA}(p_T) = \frac{d^2N^{AA}/dp_T d\eta}{T_{AA} d^2\sigma^{NN}/dp_T d\eta}$$

$N_{coll}/\sigma_{inel}^{NN}$

Sensitivity of different observables

Renk, Eskola, PRC 75, 054910 (2007)

single h



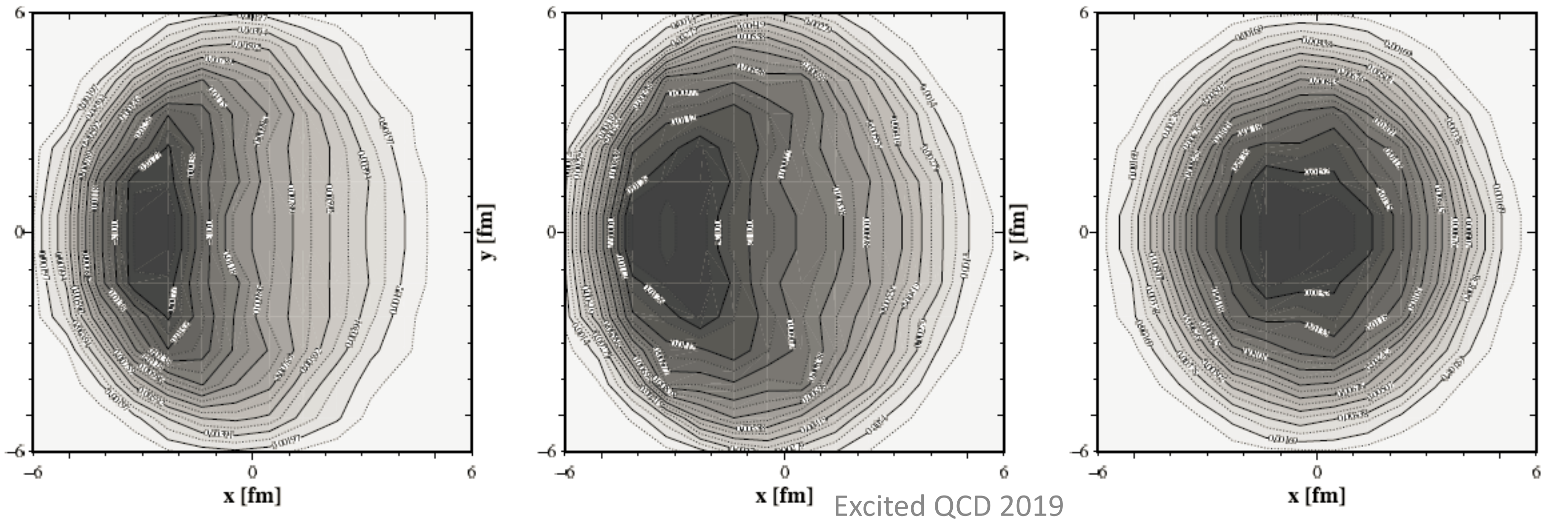
Surface bias dependence:

- single hadron and jet-hadron observables: strong surface bias,
- di-hadron correlations: show less bias,
- γ- triggered: offer unbiased measurement.

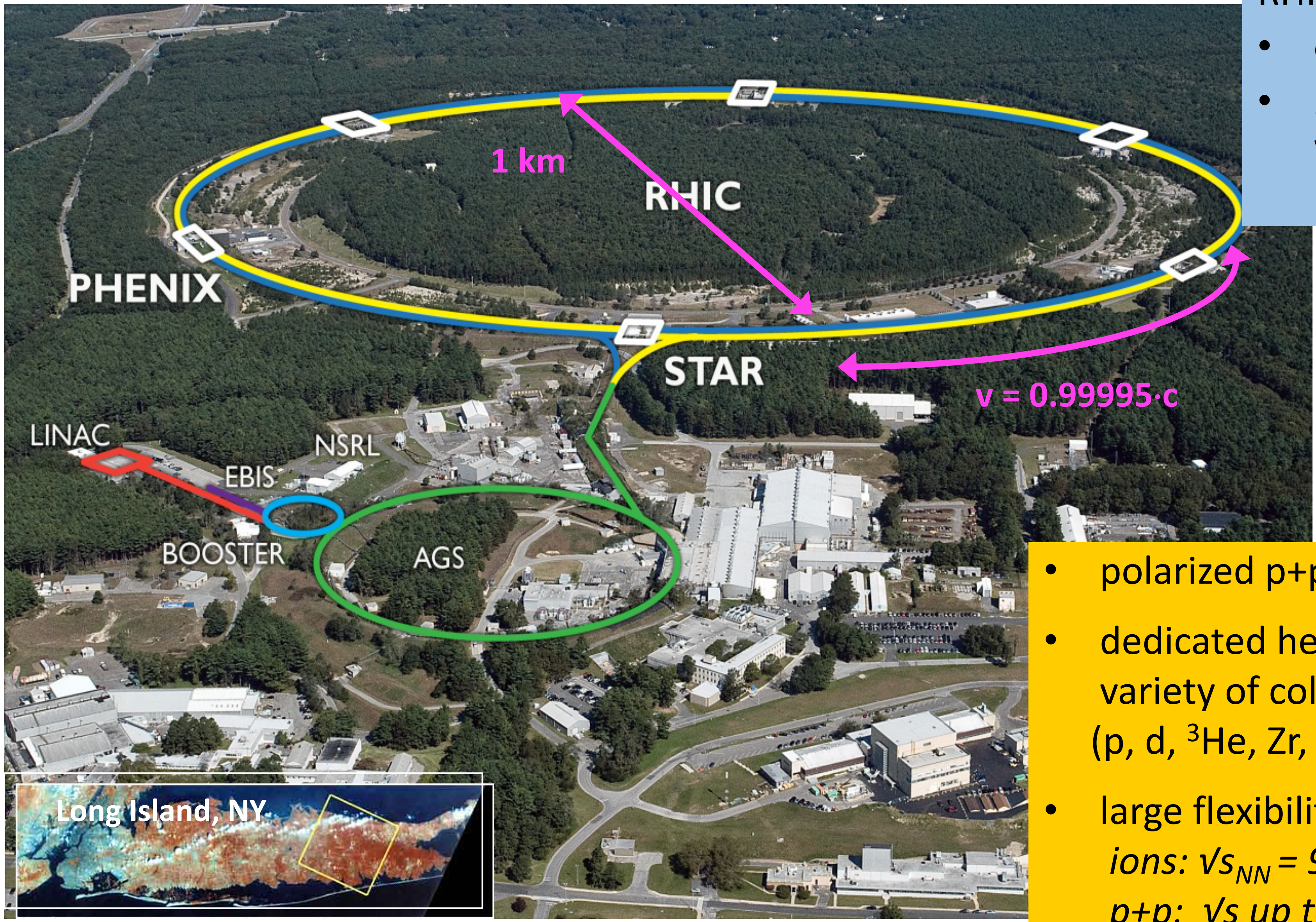
… challenge for experimentalists to measure them all

T. Renk, YaJEM

h - h | jet - h | γ - h



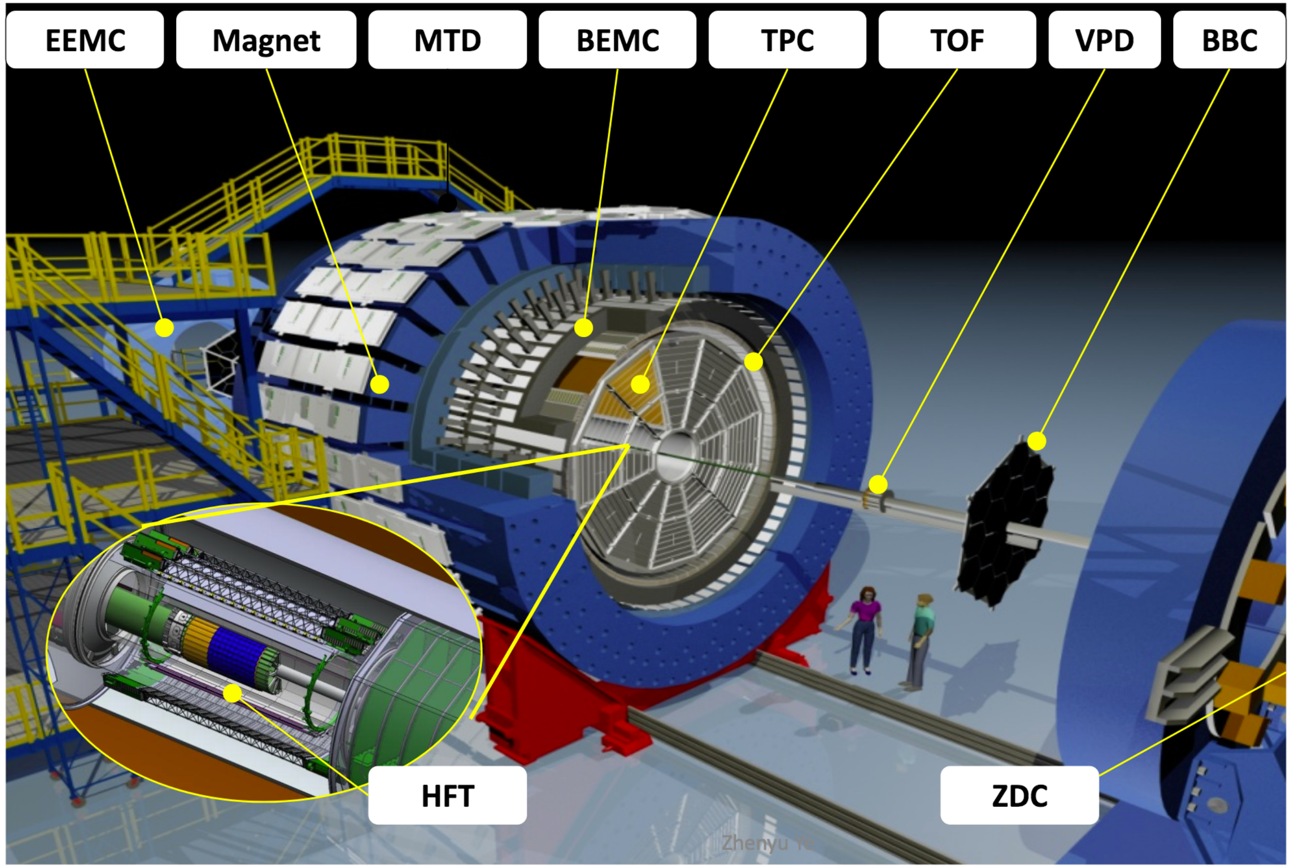
Relativistic Heavy Ion Collider

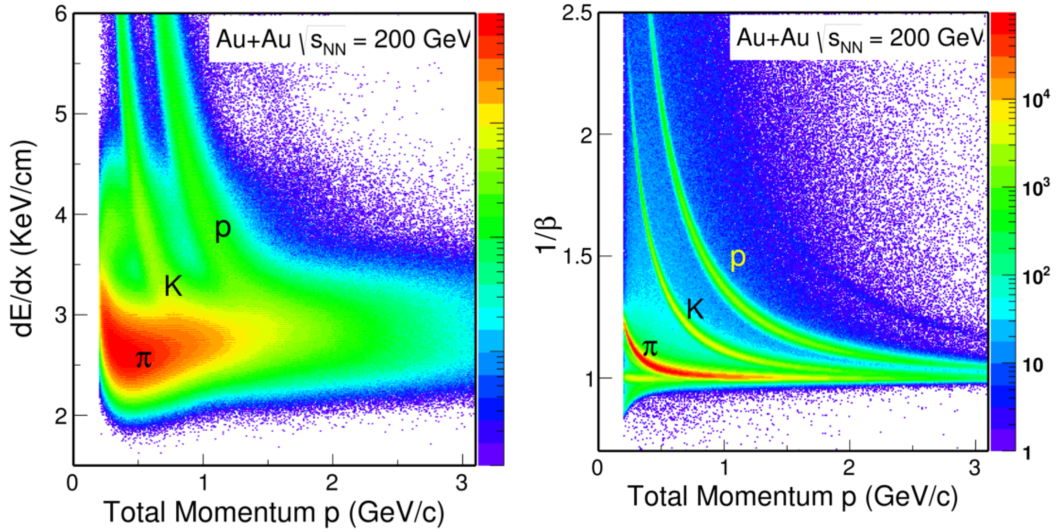


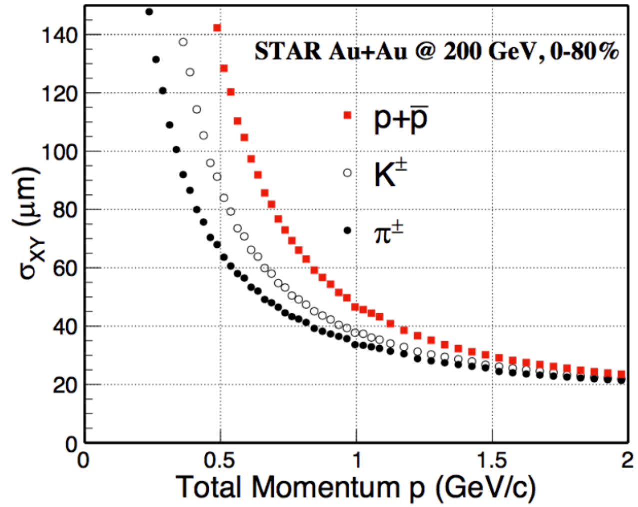
RHIC parameters:
- circumference 3.8 km
- 2 concentric rings with 1740 supraconducting magnets

- polarized p+p collisions
- dedicated heavy-ion collider with large variety of collision species (p, d, ^{3}He, Zr, Ru, Cu, Au, U)
- large flexibility in collision energy
  ions: $\sqrt{s_{NN}}$ = 9-200 GeV (+fixed target mode)
  p+p: $\sqrt{s}$ up to 510 GeV

Solenoidal Tracker At RHIC





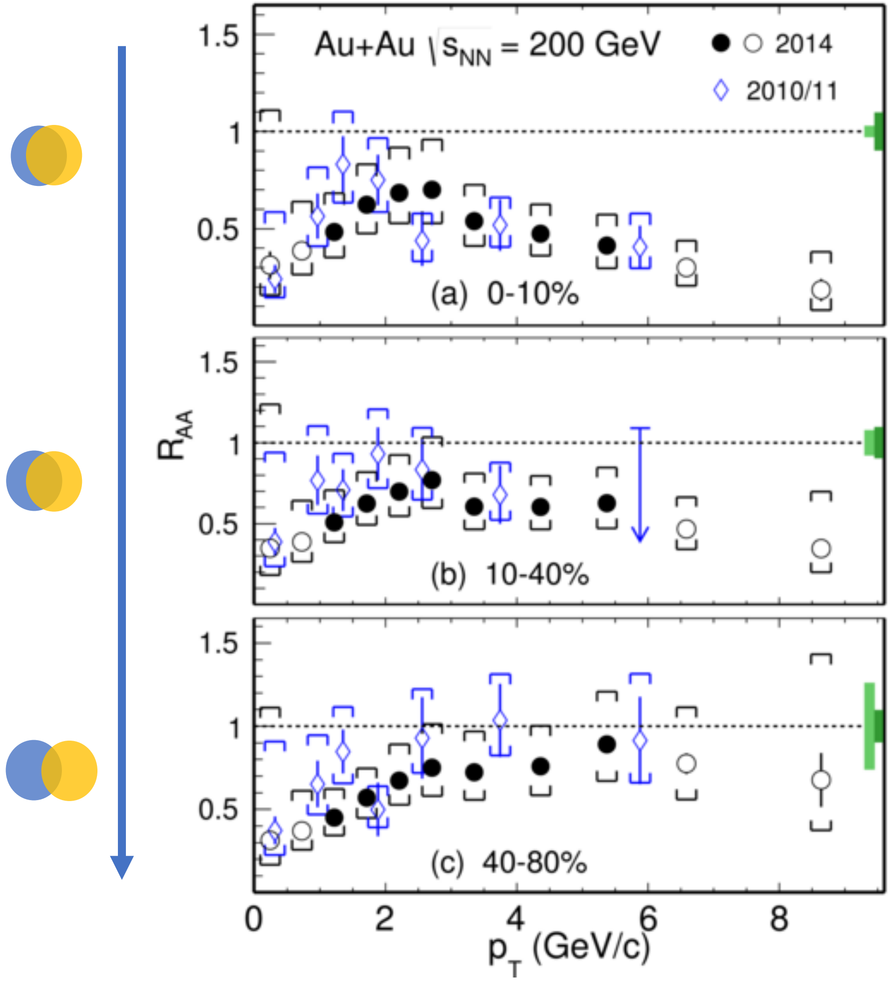


- Full azimuthal coverage, mid-rapidity experiment
- Magnetic field B = 0.5 T
- Precise charged particle tracking: Time Projection Chamber (TPC) + Heavy Flavor Tracker (HFT, 2014-16)
- Excellent particle identification: TPC, Time Of Flight detector (TOF), Muon Telescope Detector (MTD)
- Electromagnetic calorimeters (BEMC, EEMC)

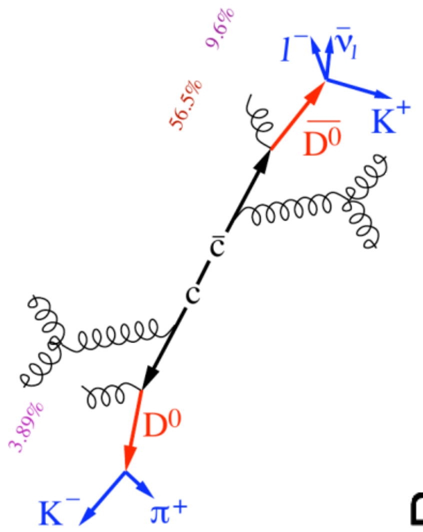
D^0 and $D^\pm$ meson production

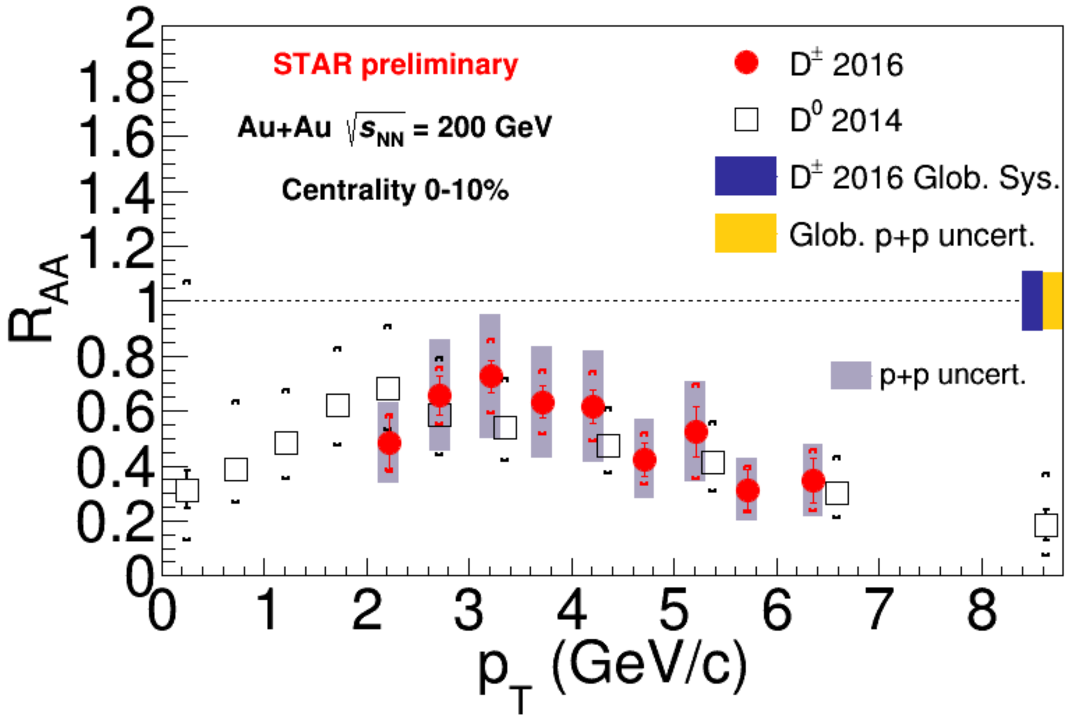
Decay channel	$c\tau$ [μm]	Branching ratio [%]
$D^0 \longrightarrow K^- + \pi^+$	122.9 ± 0.4	3.93 ± 0.04
$D^+ \longrightarrow K^- + \pi^+ + \pi^+$	311.8 ± 2.1	9.46 ± 0.24

D^0 meson



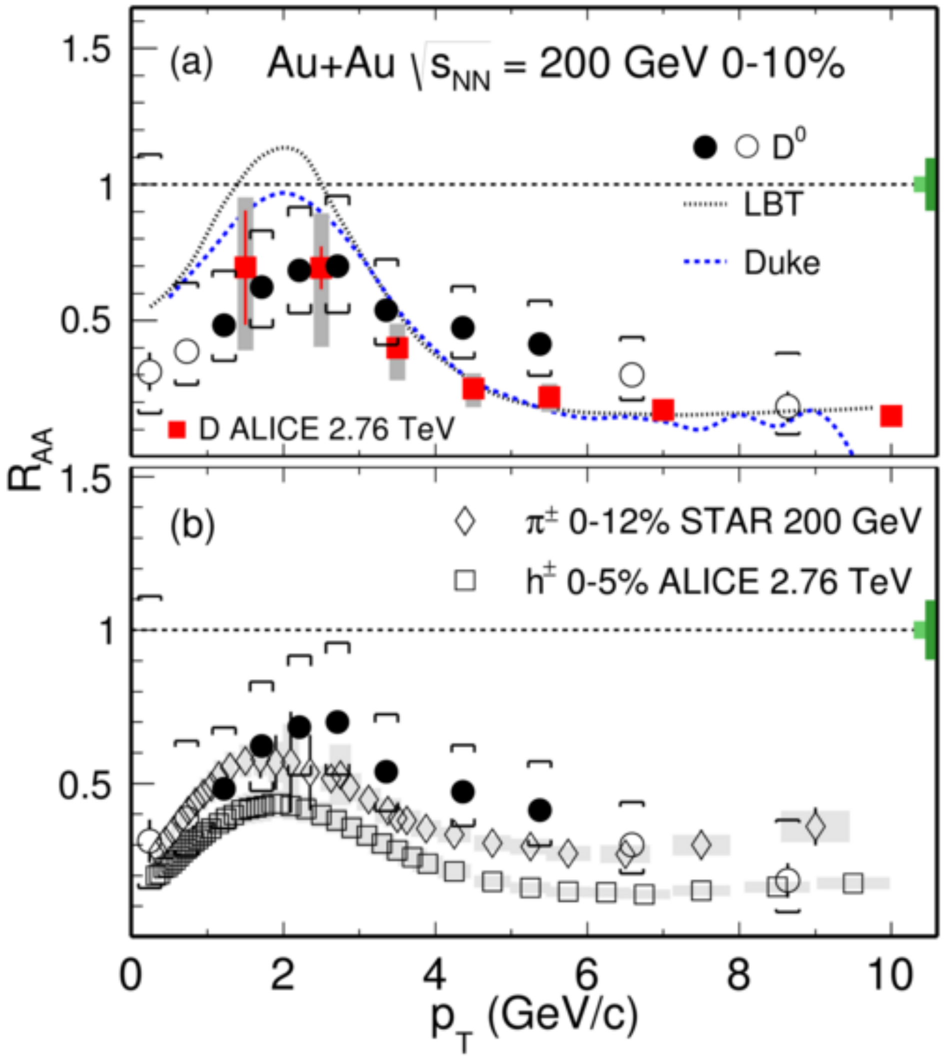
STAR, arXiv: 1812.10224





- Suppression at high p_T increases towards more central collisions.
- $R_{AA} < 1$ in the 0-10% Au+Au centrality interval for all p_T.
- D^0 and $D^\pm$ mesons show same level of suppression.

D^0 meson production



STAR, arXiv: 1812.10224

ALICE: JHEP 03 (2016) 081

- D mesons show similar suppression as light flavor hadrons at high p_T in central Au+Au collisions.
- Suppression is similar to that at LHC energy.

Model comparison:

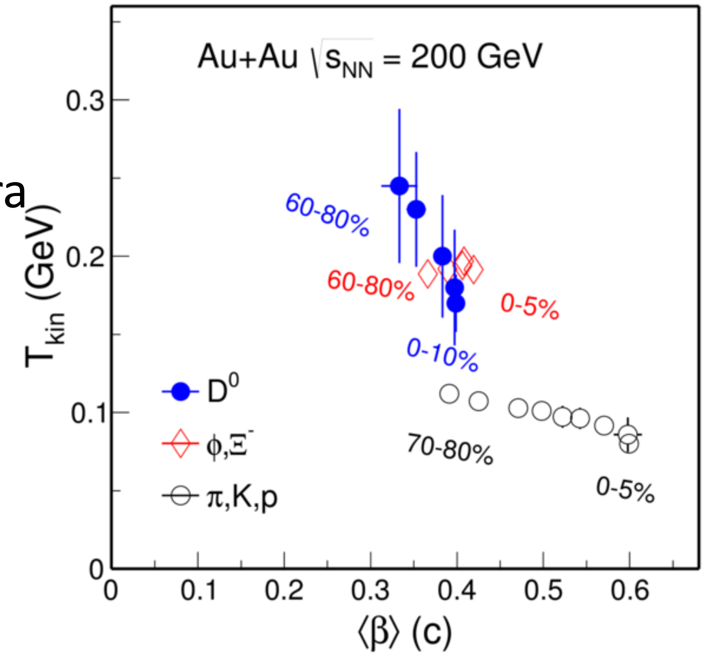
- Transport models with charm quark energy loss can describe the data.

LBT: Cao, Luo, Qin, Wang, Phys. Rev. C 94 (2016) 014909

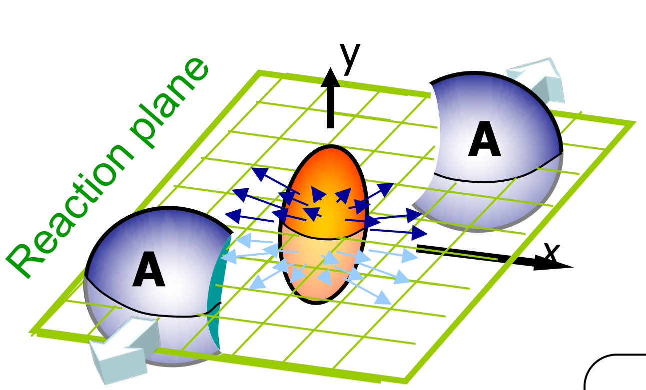
DUKE: Cao, Qin, Zhong, Bass, PRC 92 (2015) 024907

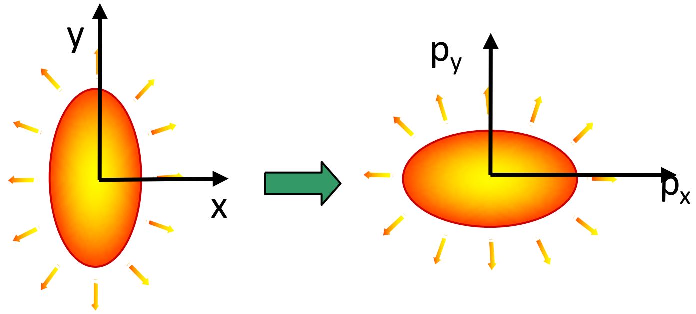
- Blast wave fits of D^0 p_T spectra ($p_T < 5$ GeV/c) :

suggest earlier freeze-out of D^0 mesons compared to light flavor hadrons.



Does charm flow?





Fourier analysis of particle distribution relative to reaction plane:

v_1 … directed flow

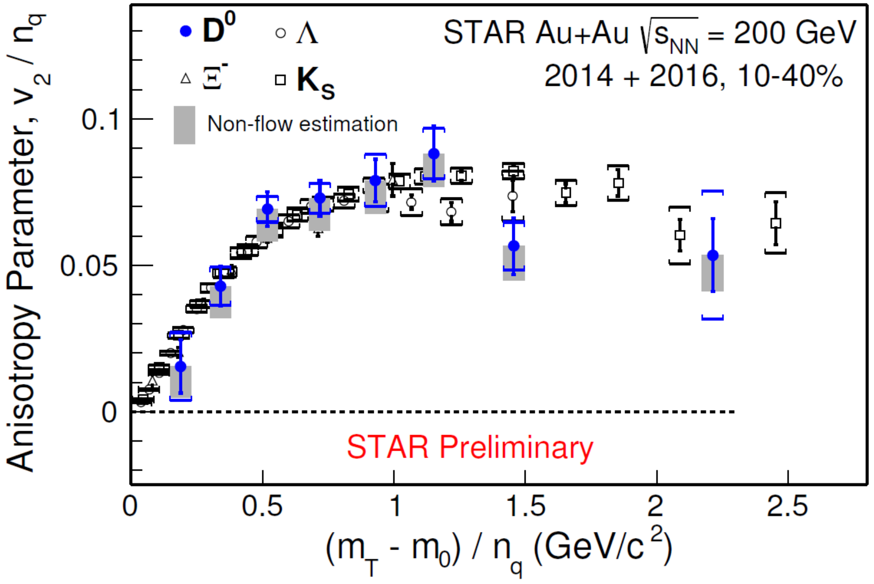
v_2 … elliptic flow

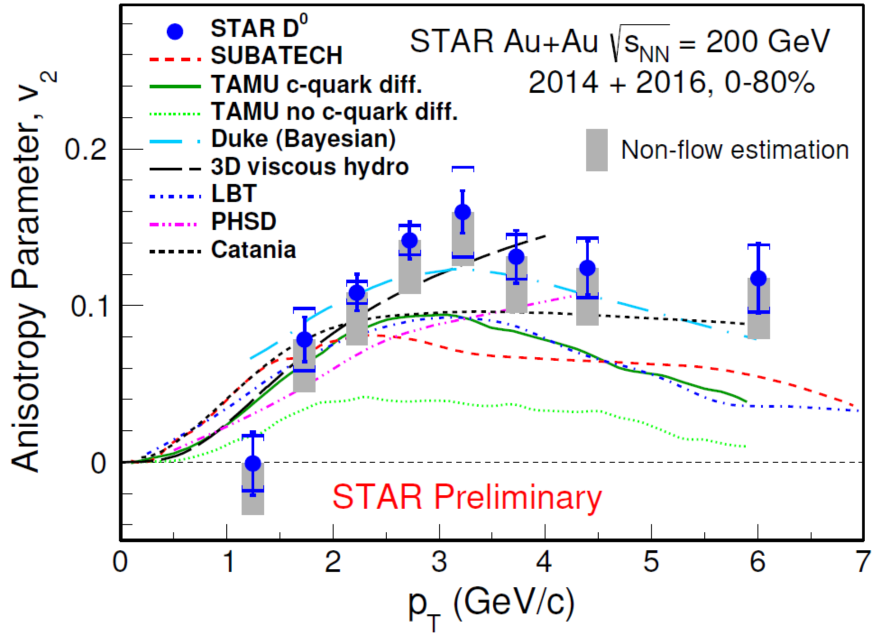
Initial spatial anisotropy → Strong pressure gradients → Anisotropy of produced particles

Sensitivity to early expansion

n_q … number of constituent quarks

m_0/m_T … particle/transverse particle mass





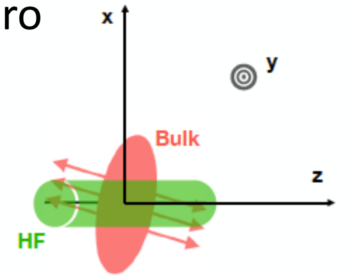
2014: STAR, Phys. Rev. Lett. 118 (2017) 212301

Charm quarks acquire similar elliptic flow as light flavor quarks
→ data suggest strong interaction of charm quarks with QGP.

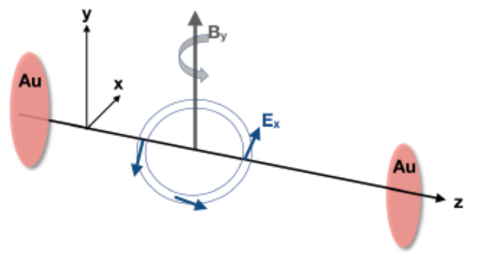
Data described by models with temperature dependent charm diffusion coefficient $2\pi TD_s \sim 2–12$ predicted by lattice QCD.

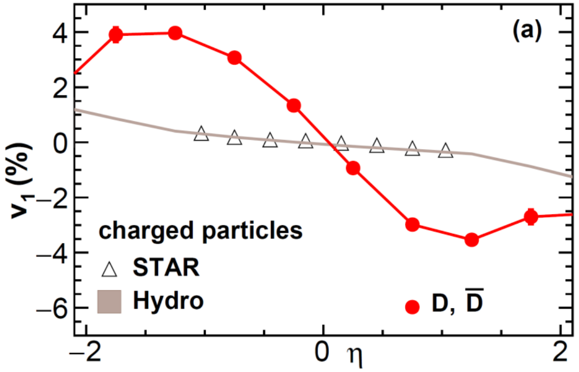
Directed flow of D^0 mesons

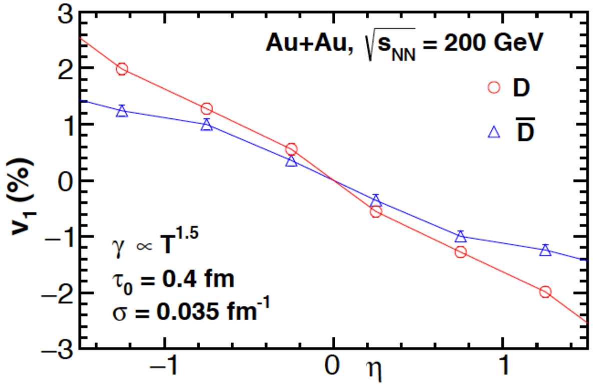
hydro

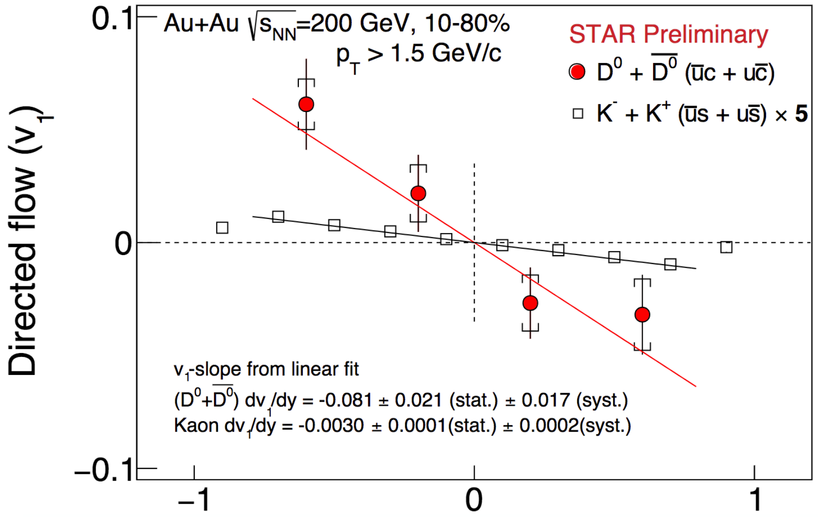


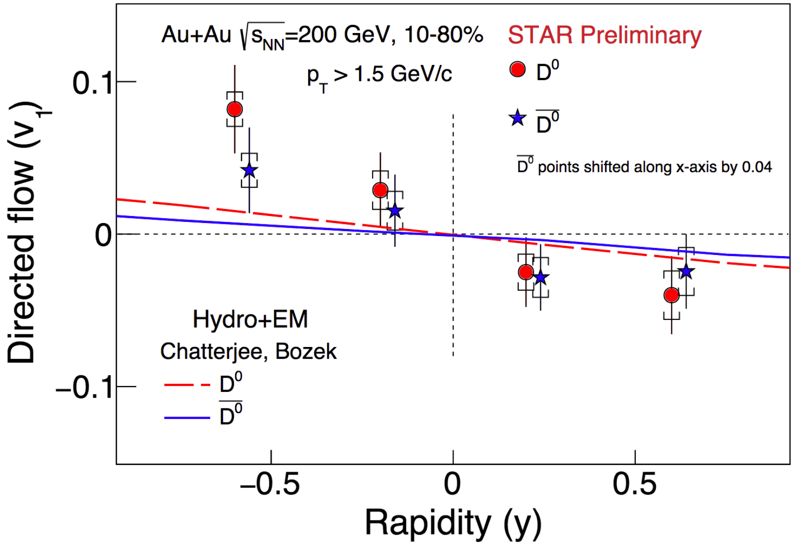
EM field











- Sensitive to initial tilt of fireball and viscous drag on charm quarks in QGP.
- Effect of EM fields is of opposite sign on D^0 and $\overline{D^0}$ mesons and would not influence the average v_1 of D^0 mesons.

Chatterjee, Bozek: Phys Rev Lett 120, 192301 (2018)
arXiv: 1804.04893

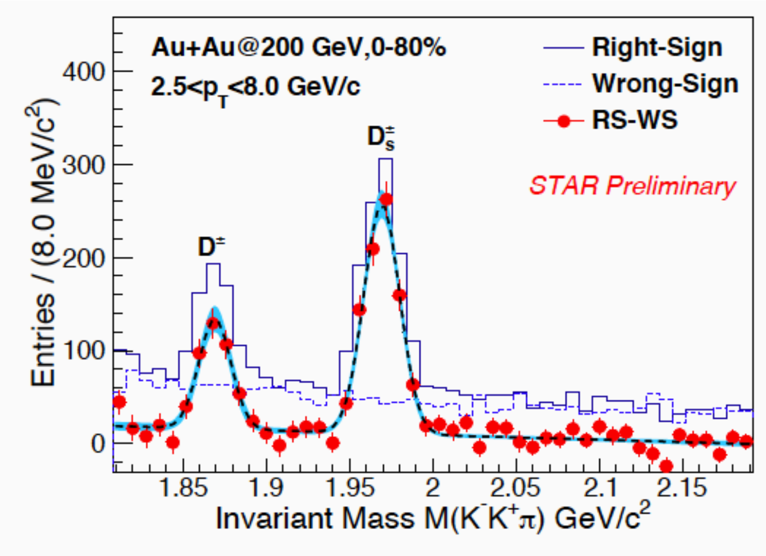
D^0 mesons exhibit much larger v_1 than light flavor hadrons
→ strong interaction of c-quarks with initially tilted source.
More data needed to draw conclusions on magnetic field induced v_1 splitting of c and $\bar{c}$ quarks.

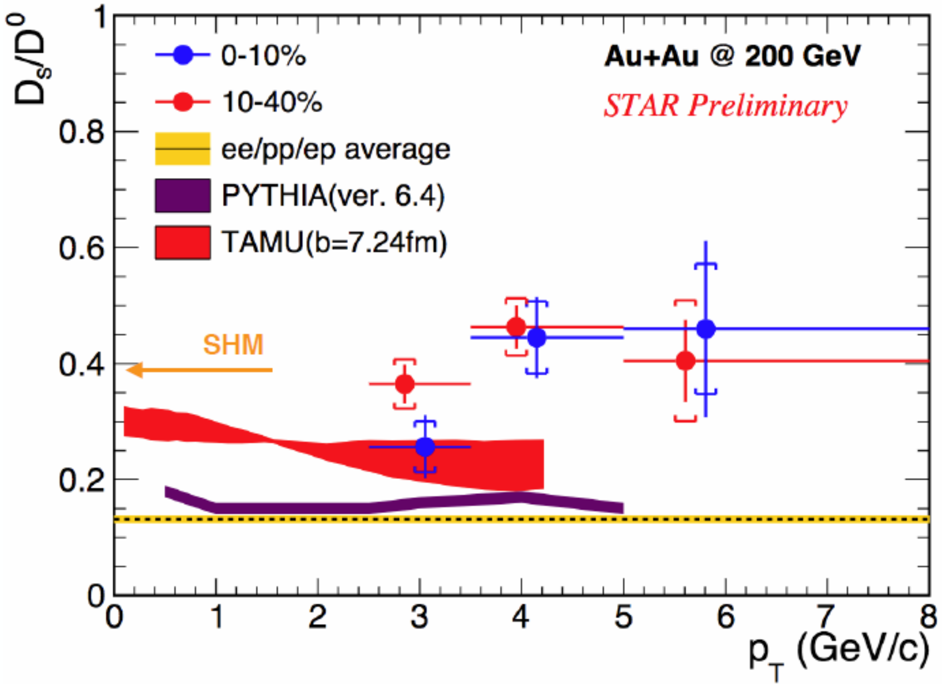
D_s/D^0 enhancement

- Strangeness enhancement in QGP is expected to affect the yield of D_S (if c quarks participate in coalescence).
- D_S freezes out early and has smaller hadronic interaction cross-section compared to D^0.

→ better sensitivity to partonic contribution to the charm hadron v_2

Decay channel	$c\tau$ [μm]	Branching ratio [%]
$D_S^{\pm} \longrightarrow \phi\ (\longrightarrow K^{+}+K^{-}) + \pi^{\pm}$	150.0 ± 2.0	2.32 ± 0.14

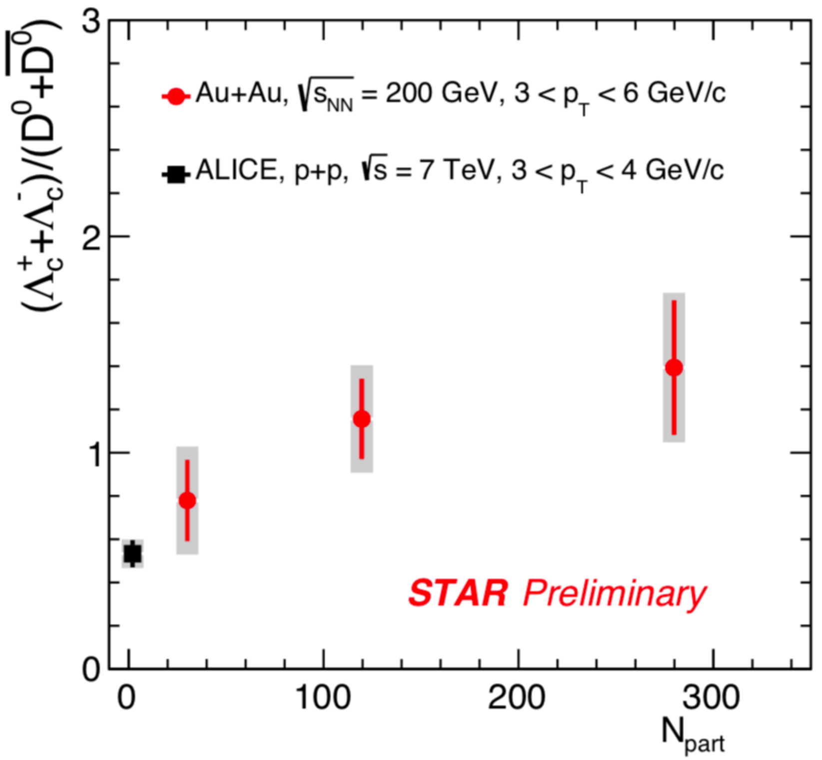


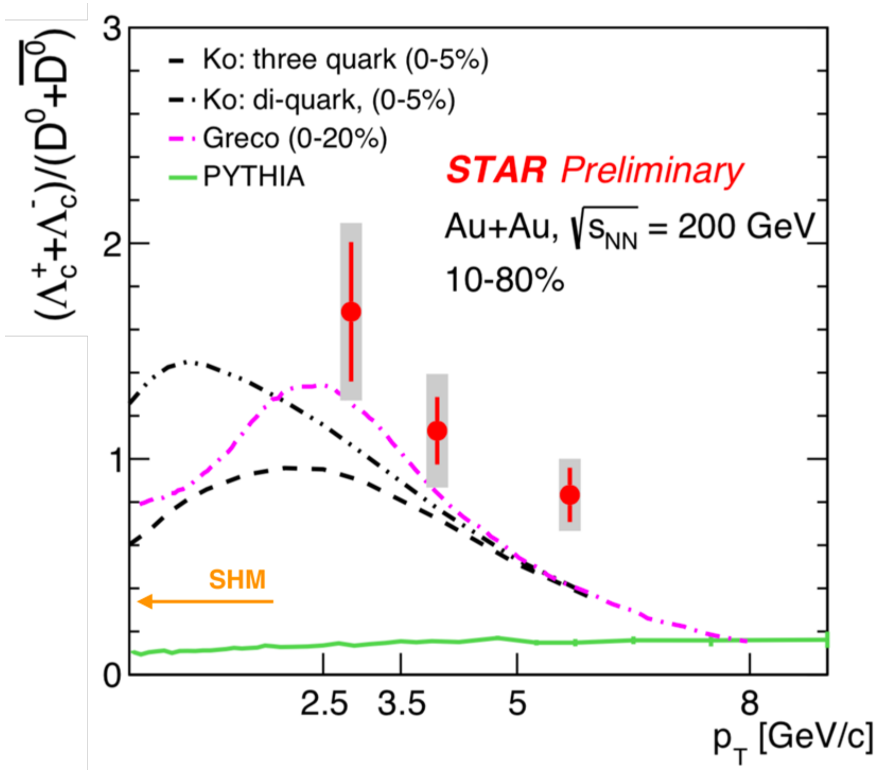


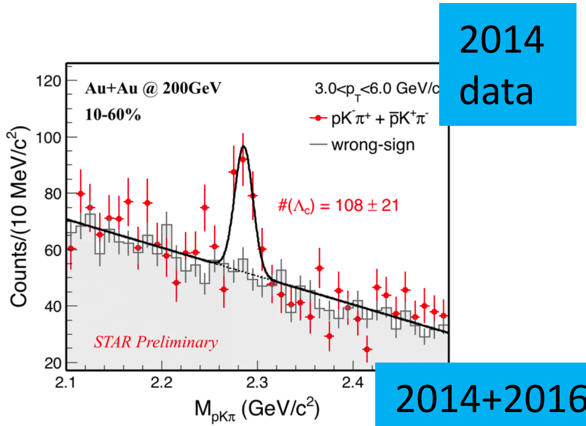
ep/pp/ep avg: M Lisovyi, et. al. EPJ C 76, 397 (2016)
TAMU: H. Min et al. PRL 110, 112301 (2013)
SHM: A. Andronic et al., PLB 571 (2003) 36

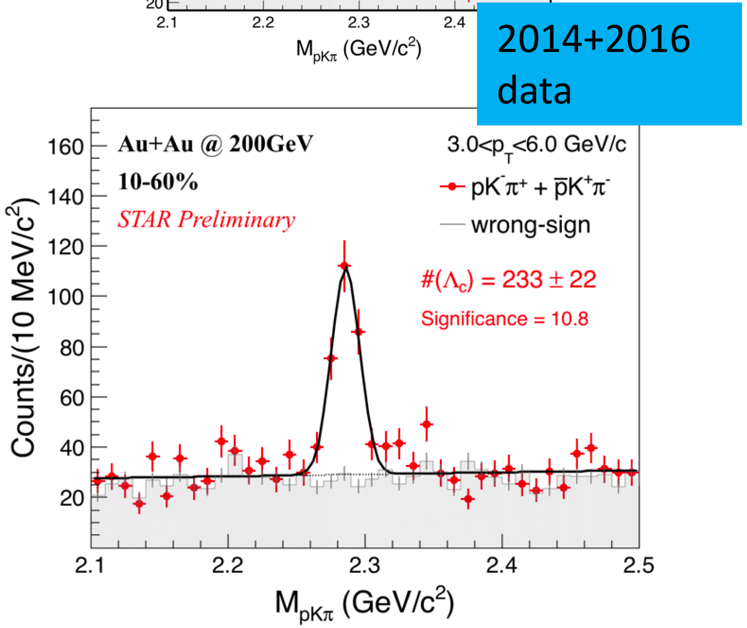
- Strong D_s/D^0 enhancement observed in central Au+Au collisions relative to fragmentation baseline.
- Enhancement is larger than model predictions, particularly at higher p_T.
- $v_2(D_S)$ comparable to $v_2(D^0)$, but statistics is limited (not shown).

Λ_c and heavy quark hadronization









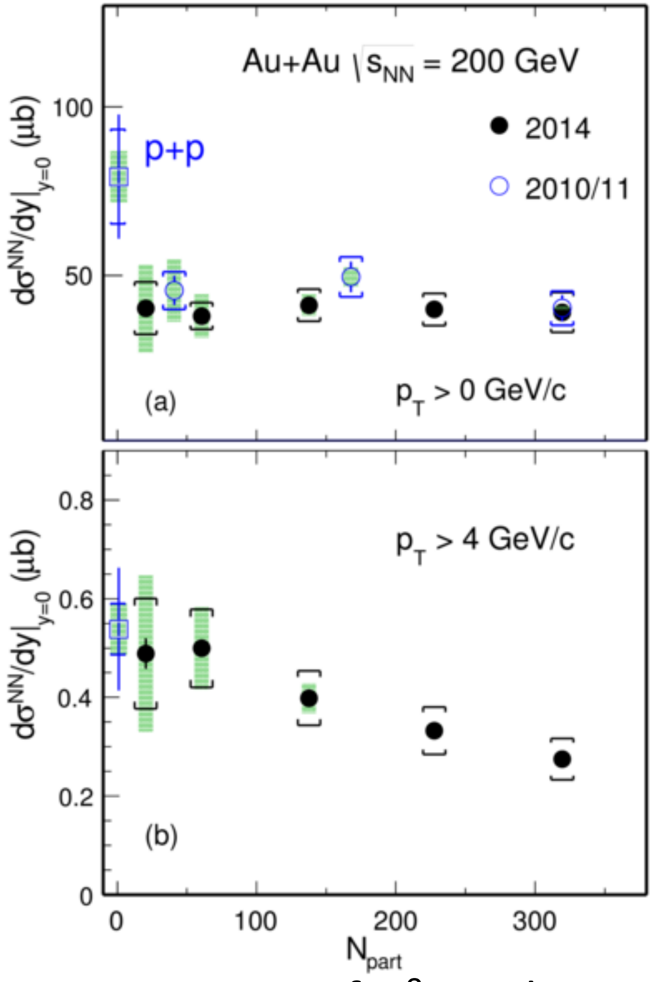
- Strong enhancement of Λ_c production in Au+Au collisions compared to PYTHIA (p+p) calculations.
- Data suggest coalescence hadronization of charm quarks in QGP at intermediate p_T (2-6 GeV/c).

Improvements:
- 50% with TMVA BDT analysis,
- higher statistics of 2016 data,

→ effectively 4x more data than earlier analysis of 2014 data.

Model calculations: Ko: Phys. Rev. C79 (2009) 044905 Greco: Eur. Phys. J.C78 (2018) 348
SHM: A. Andronic et al., PLB 571 (2003) 36

Charm cross section at RHIC



STAR, arXiv: 1812.10224

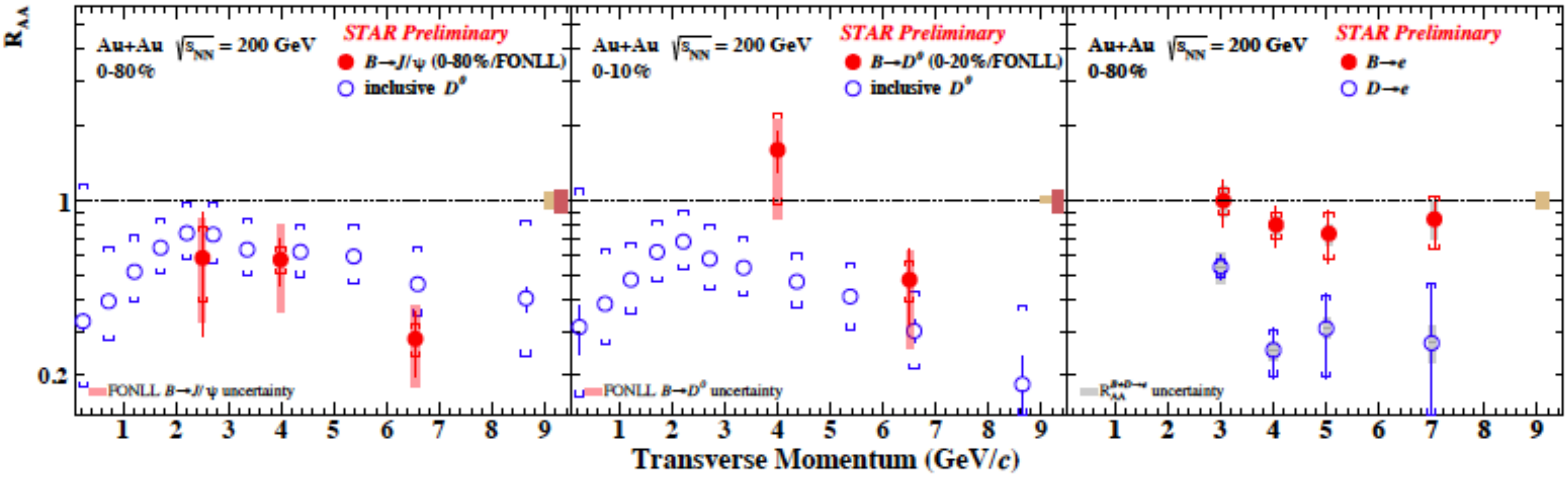
Cross section σ_{NN} of D^0 production in Au+Au collisions at 200 GeV at midrapidity is lower than in pp collisions.

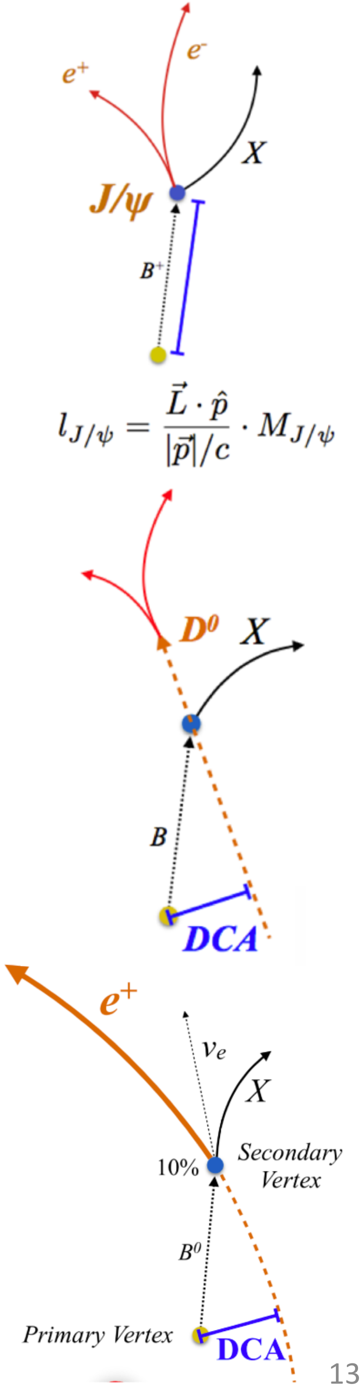
Charm Hadron		Cross Section dσ/dy (μb)
AuAu 200 GeV (10-40%)	D^0	41 ± 1 ± 5
	D^+	18 ± 1 ± 3
	D_s^+	15 ± 1 ± 5
	Λ_c^+	78 ± 13 ± 28 *
	Total	**152 ± 13 ± 29**
pp 200 GeV	**Total**	**130 ± 30 ± 26**

*** derived using Λ_c^+ / D^0 ratio in 10-80%**

Enhancement of Λ_c and D_s production compensates the suppression of D^0 cross section → total charm cross-section per binary collision is consistent with pp.

How strongly does bottom interact with medium?





Open bottom hadron production measured via displaced J/ψ, D^0 and electron decay channels.

- Strong suppression of B ⟶ J/ψ and B ⟶ D^0 at high p_T observed.
- Less suppression (2σ effect) for B ⟶ e than for D ⟶ e
  → consistent with flavor ordering of parton energy loss: $\Delta E_c > \Delta E_b$.

Quarkonia as QGP thermometer

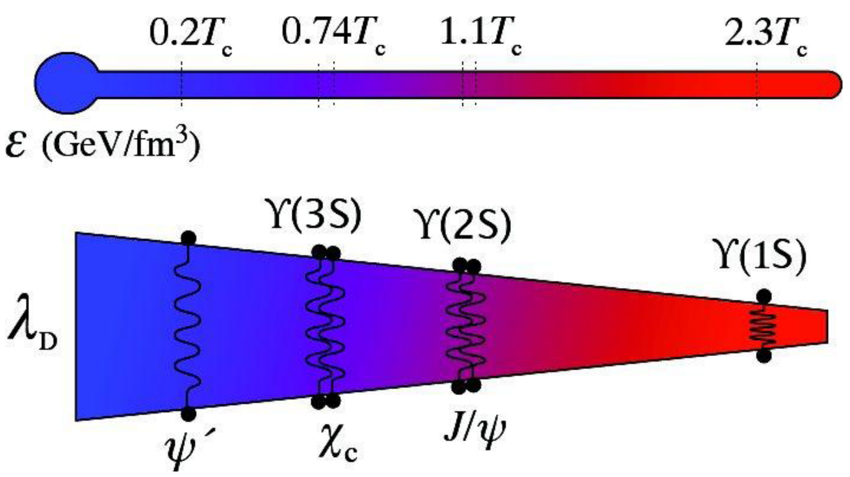
Quarkonia are bound states of a quark and an anti-quark
of the same flavor:

c-quark:
charmonia: J/ψ, Ψ', χ_c

b-quark:
bottomonia: $\Upsilon(1S)$, $\Upsilon(2S)$, $\Upsilon(3S)$

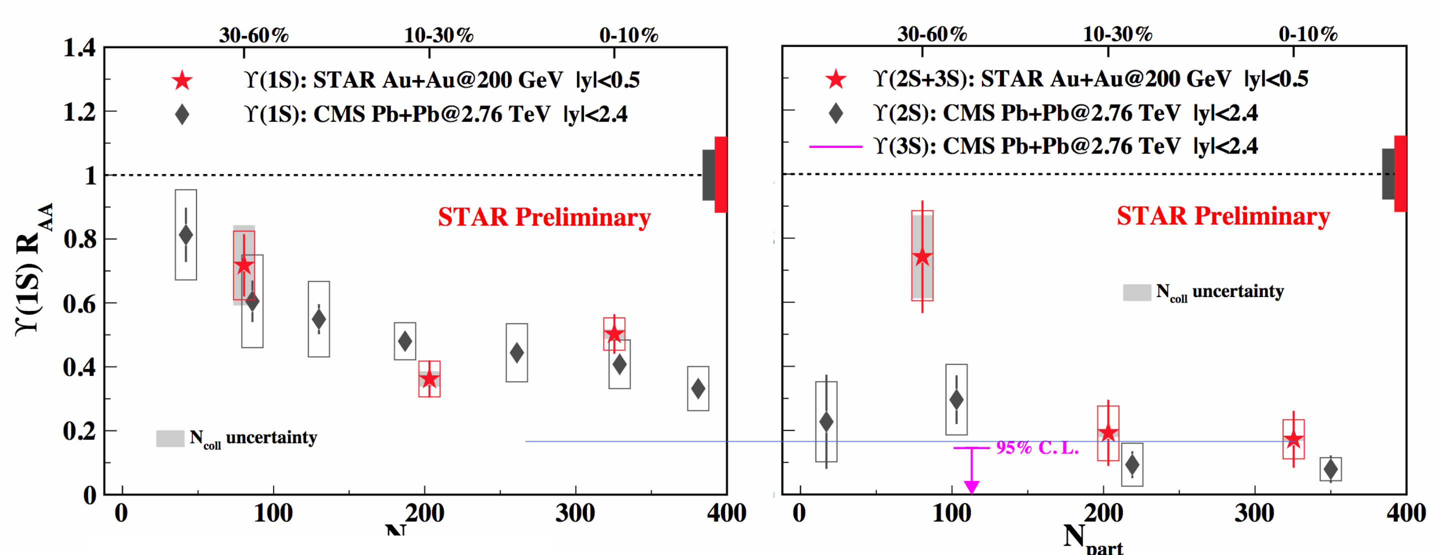
Quarkonia dissociate in QGP
due to color screening of potential between heavy-quarks.

Lattice QCD calculations
of spectral functions $\Rightarrow T_{diss}$

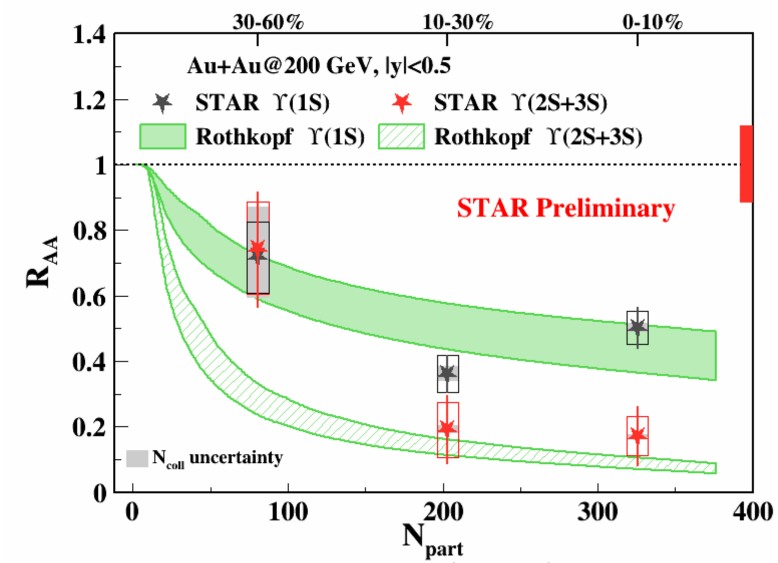


Temperature dependent sequential melting of quarkonium states predicted.

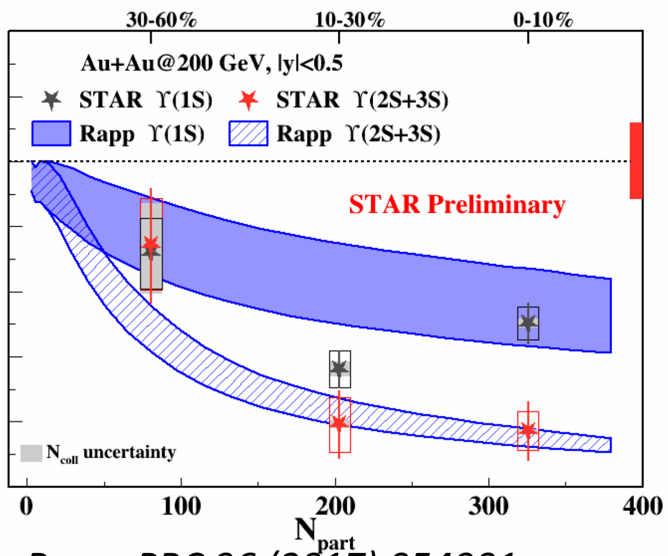
ϒ suppression in heavy-ion collisions



CMS: PLB 770(2017) 357



Rothkopf: PRD 97(2018) 016017



Rapp: PRC 96 (2017) 054901

Improved precision by combining 2011 di-electron and 2014+2016 di-muon datasets

- ϒ suppression increases from peripheral to central Au+Au collisions.
- ϒ(1S): suppression consistent with that measured by CMS at 2.76 TeV.
- ϒ(2S+3S): indication of less suppression at RHIC than LHC in peripheral collisions.

Central Au+Au collisions:

R_{AA} of ϒ(2S+3S) < R_{AA} of ϒ(1S)

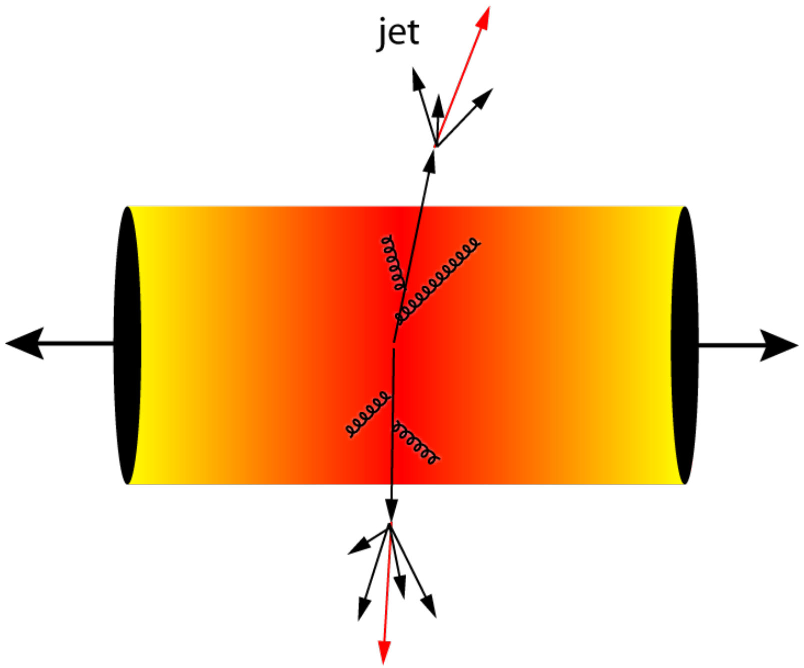
→ consistent with sequential melting.

Model comparison:

ϒ(1S): agreement with data,

ϒ(2S+3S): model of Rothkopf underestimates data in 30-60% centrality bin.

Tomography of QCD medium with jets

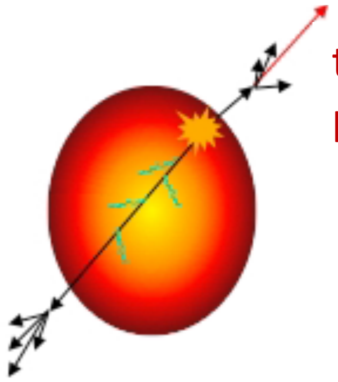


Focus on:

- Hadron/direct photon – jet correlations
- Dijet imbalance
- Jet internal structure

... but many more aspects of jet properties are being explored

Semi-inclusive recoil jet studies

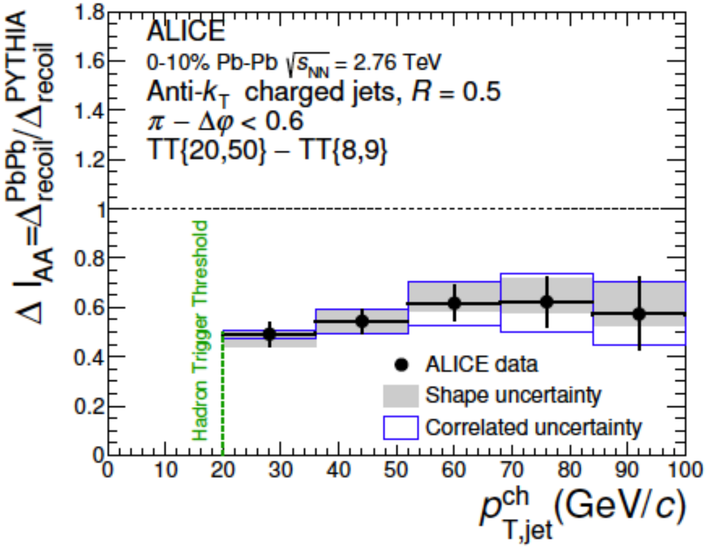


Trigger particle: charged hadron,
π^0 , direct photon (γ_{dir}) …

A unique observable:

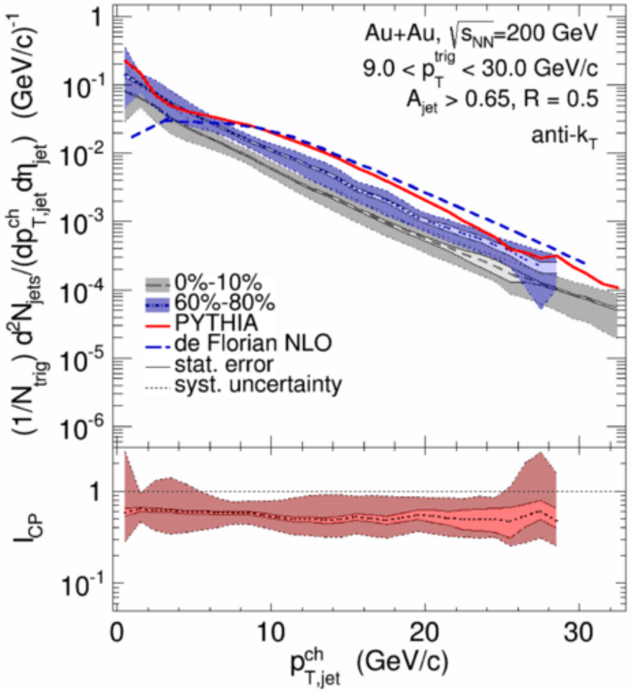
- enables study of intra and inter-jet angular broadening,
- directly comparable to analytic pQCD calculation,
- large-angle jet deflection studies can probe the nature of the quasi-particles in hot QCD matter (”QCD Molière scattering”).

ALICE@ LHC 2.76 TeV



Δp_T = -8±2 GeV/c

STAR @ RHIC 200 GeV



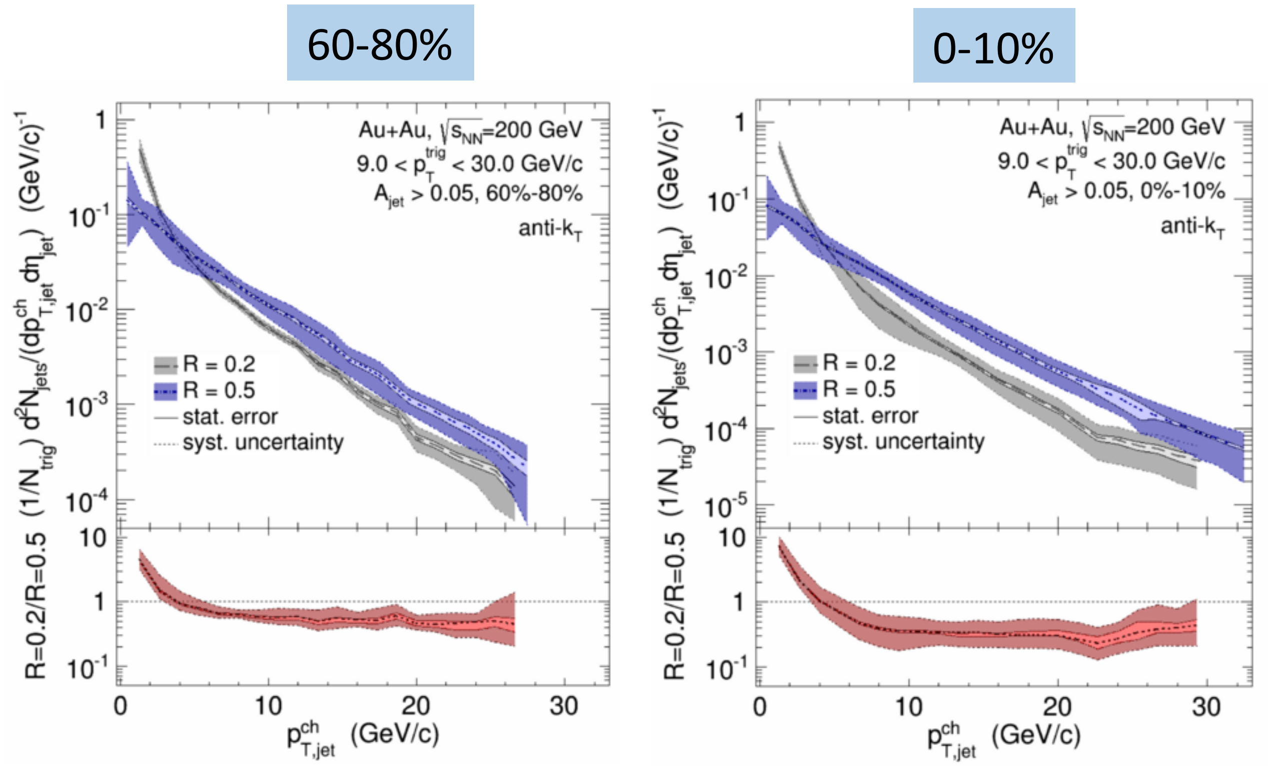
STAR: PRC 96, 024905 (2017)
ALICE: JHEP 1509 (2015) 170

Δp_T = -2.8±1.7 GeV/c

- Recoil per trigger jet yields in A+A collisions are suppressed relative to p+p reference (observable ΔI_{AA}, resp. I_{CP}).

Charged-particle energy transported to angles larger than R by interaction of jet with medium is systematically smaller at RHIC that at LHC energy for all studied jet radii.

Intra-jet distribution of energy transverse to jet axis



STAR: PRC 96, 024905 (2017)

Within uncertainties there is no evidence of broadening of jet shower due to jet quenching at RHIC energy. This is consistent with observations at the LHC.

- Study ratio of recoil jet yields at different jet radii:

→ the ratio for R=0.2/R=0.5 is less than 1 and reflects the intra-jet distribution of the energy relative to the jet axis.

- Quantify medium-induced broadening of the jet shower via horizontal shift of the p_T spectra:

Au+Au centrality	Δp_T shift (GeV/c)
60-80%	2.9 ± 0.4 (stat.) ± 1.9 (syst.)
0-10%	5.0 ± 0.5 (stat.) ± 2.3 (syst.)

π^0-triggered recoil charged jets

p+p collisions:

- π^0-triggered recoil charged jet spectrum is consistent with PYTHIA8.

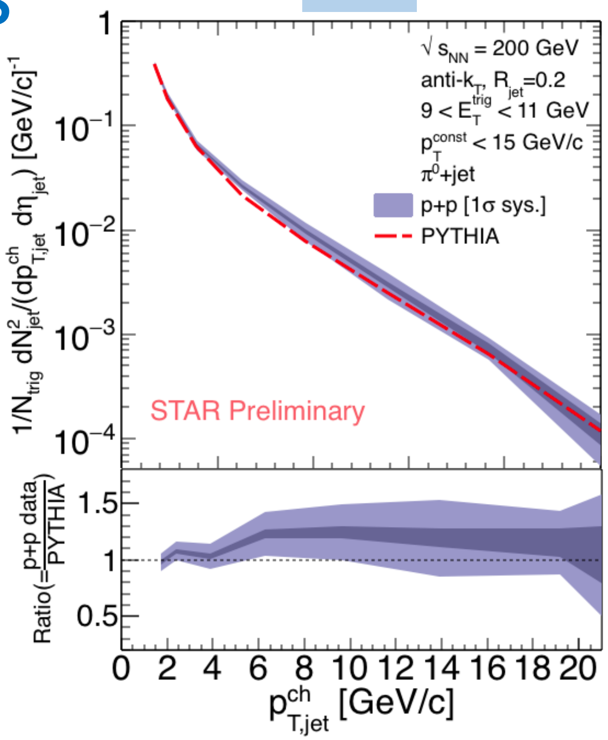
→ PYTHIA8 can be used as the p+p reference.

Au+Au collisions:

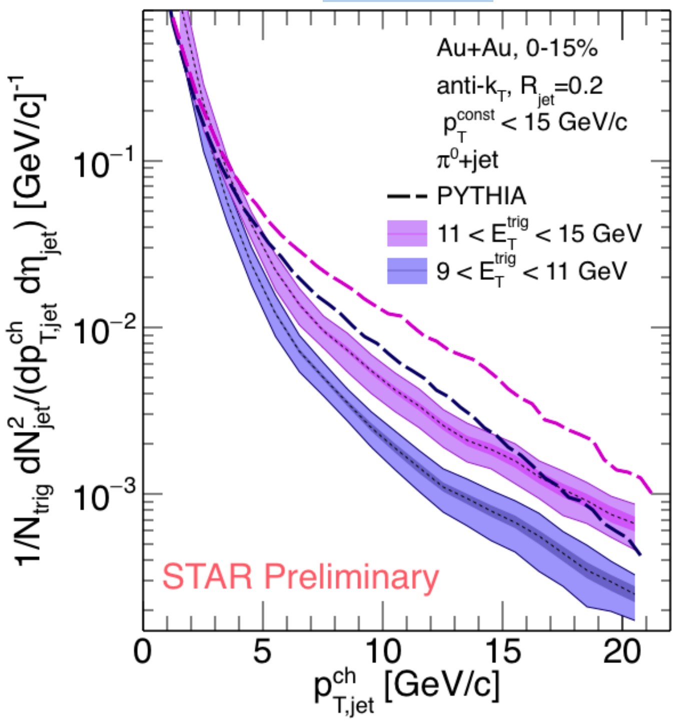
- Dominant systematic uncertainty is from unfolding.
- Clear difference between recoil charged jet spectra for different π^0 trigger E_T.
- Evaluate I_{AA} (ratio of per trigger recoil charged jet yield in Au+Au to pp collisions):

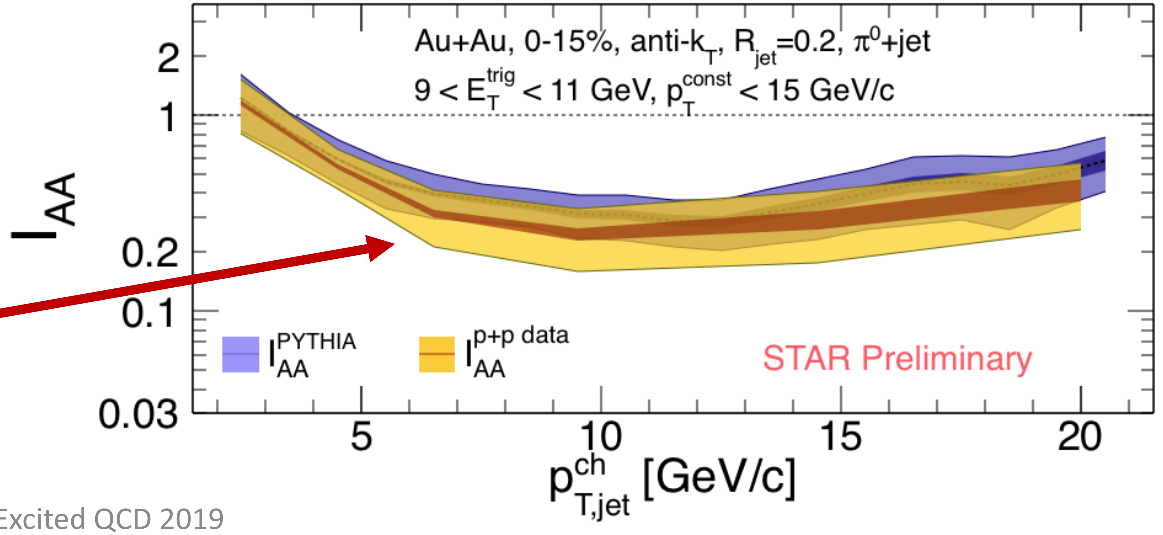
I_{AA} shows a clear suppression of recoil jets in central Au+Au collisions with respect to p+p reference, consistent with charged hadron+jet measurements.

p+p

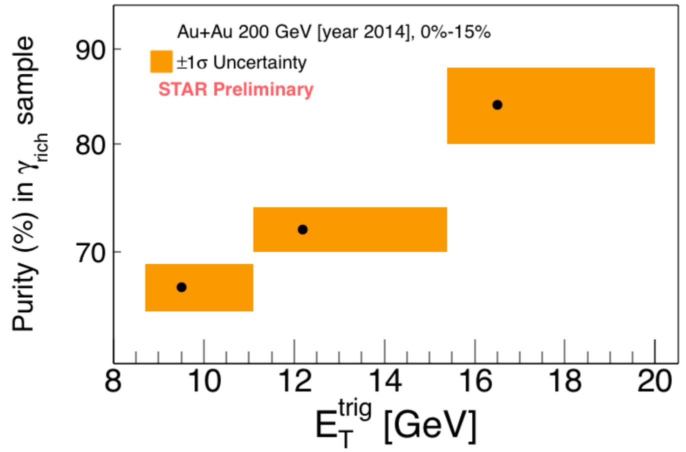


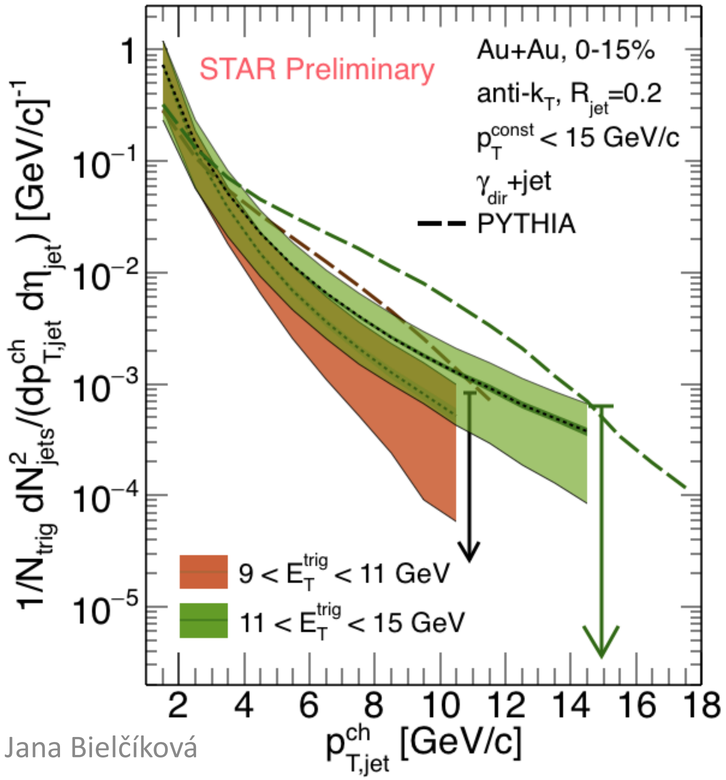
Au+Au



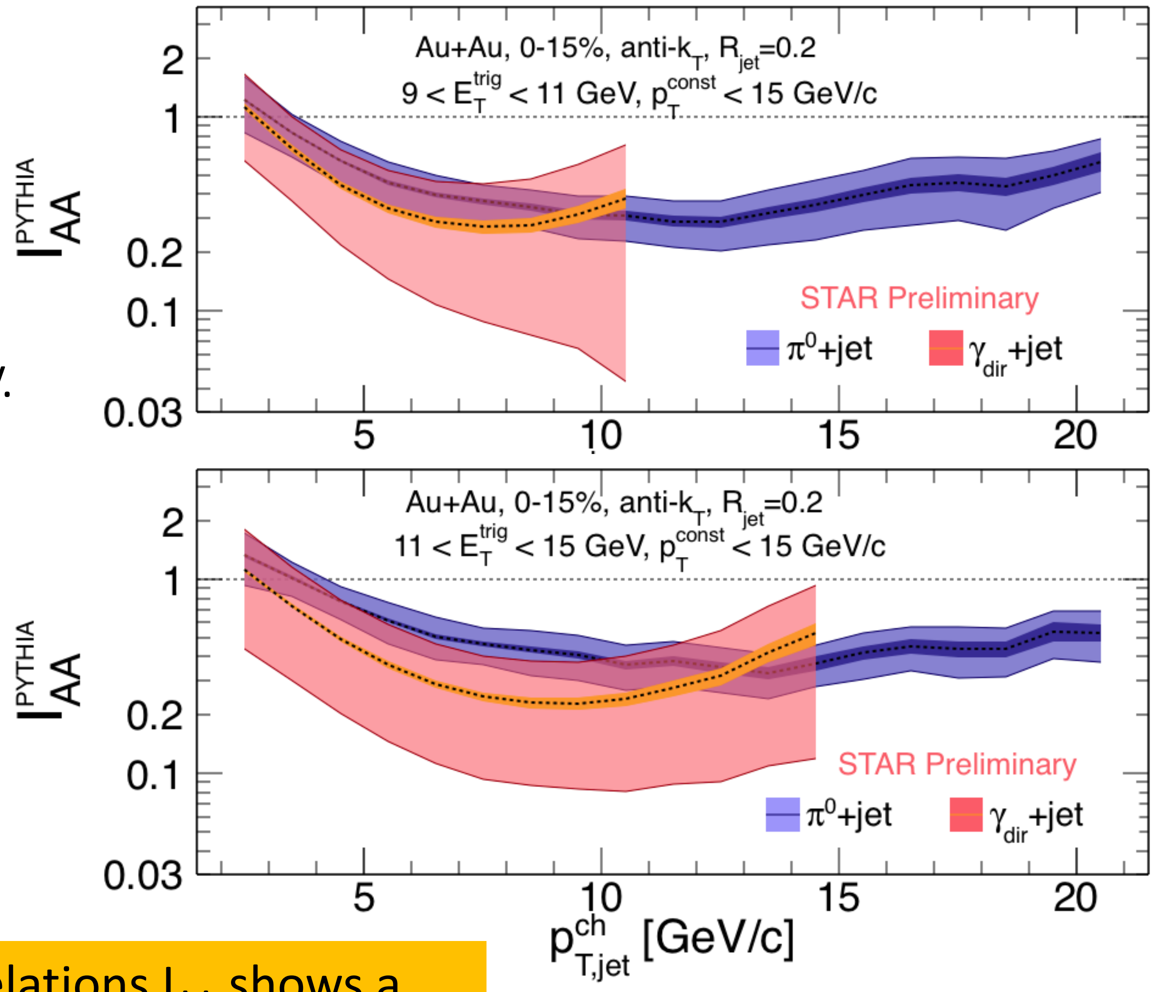


γ_{dir}-triggered recoil charged jets





- Purity of direct photons varies between 65% and 89% for $9 < E_T^{trig} < 20$ GeV.
- Dominant systematic uncertainties are from unfolding and from γ_{dir} background subtraction.



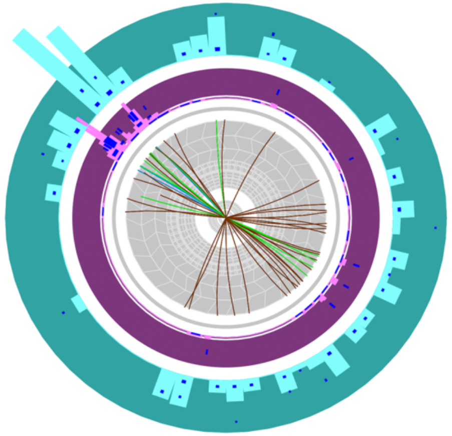
For γ_{dir} triggered correlations I_{AA} shows a suppression of recoil jets in central Au+Au collisions with respect to PYTHIA reference. Within uncertainties, the suppression is consistent with that for π^0+jet correlations.

Dijet imbalance

Dijet asymmetry A_J quantifies momentum imbalance between dijets:

$$A_J = \frac{p_T^{\rm Lead} - p_T^{\rm SubLead}}{p_T^{\rm Lead} + p_T^{\rm SubLead}}$$

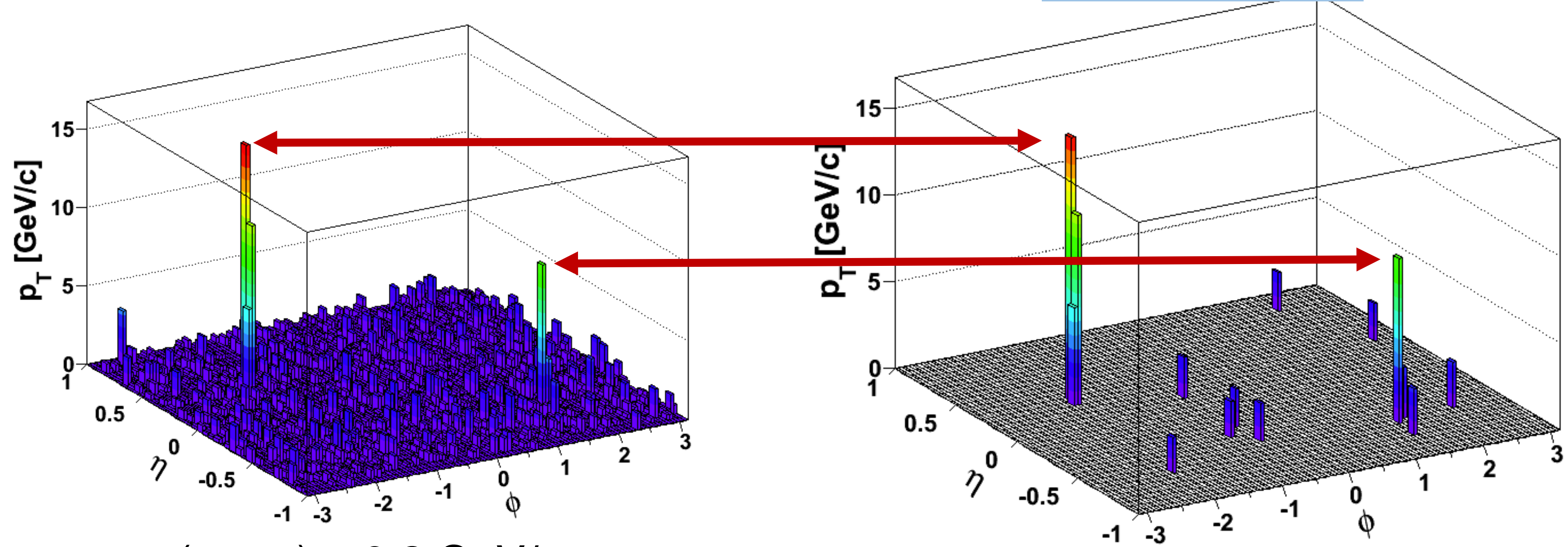
LHC: Strong dijet asymmetry without angular de-correlation observed



STAR approach to study A_J

Jets with soft constituents

Hard-core jets



p_T (const) > 0.2 GeV/c ⟷ p_T (const) > 2 GeV/c removes almost all background

Geometric matching of both type of jets ⟷ No combinatoric jets, recover soft constituents

ATLAS: PRL 105 (2010) 252303; CMS: PRC 84 (2011) 024906

Dijet imbalance

p+p reference:

- p+p data embedded to minbias Au+Au data

A_J distribution in central Au+Au collisions:

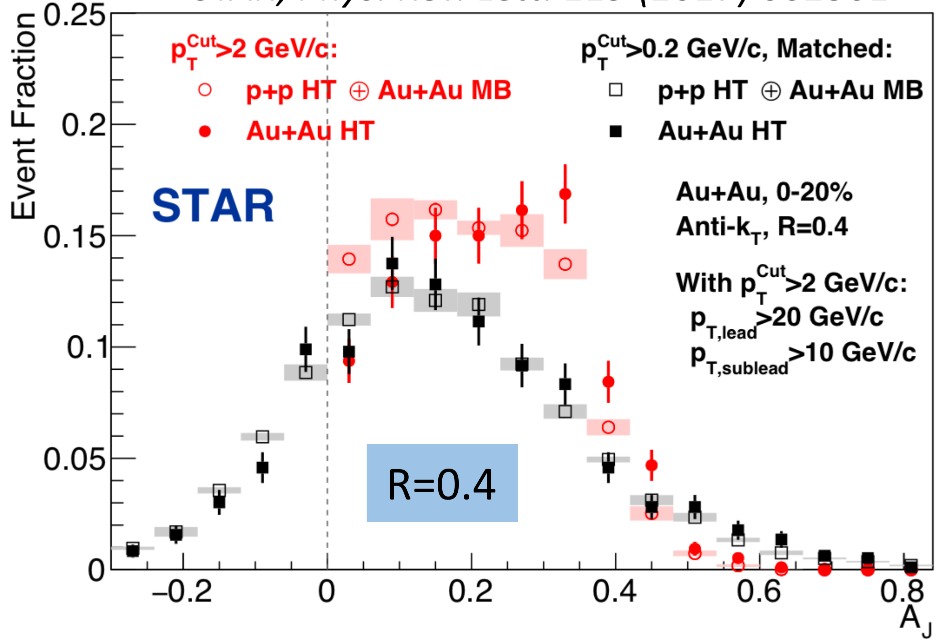
- Hard-core dijets more imbalanced with respect to p+p.

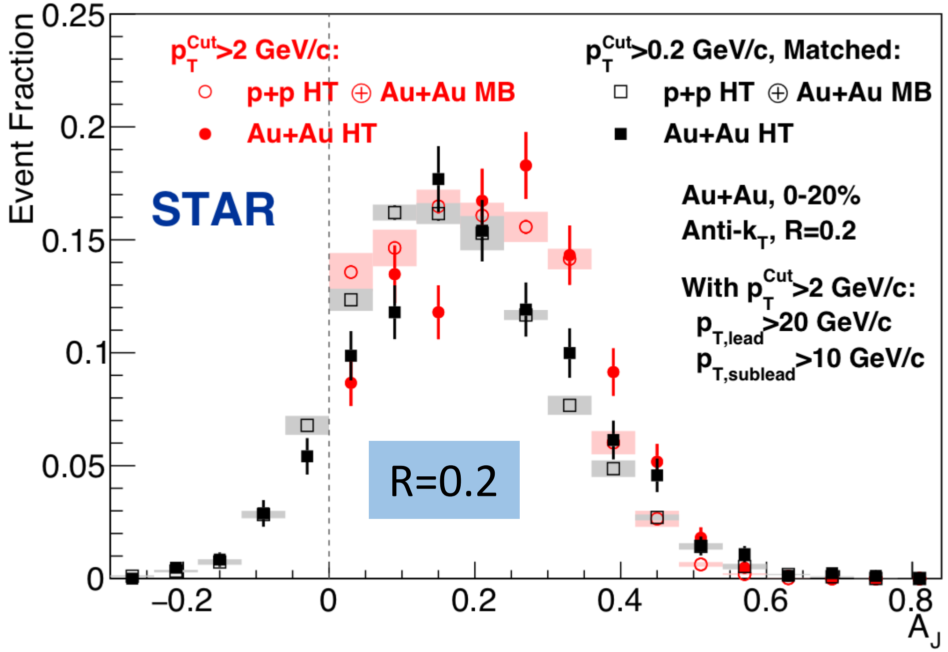
- R=0.4: inclusion of soft constituents restores the balance to the level of the p+p reference.

- R=0.2: balance no longer restored to the level of p+p even if soft constituents are included.

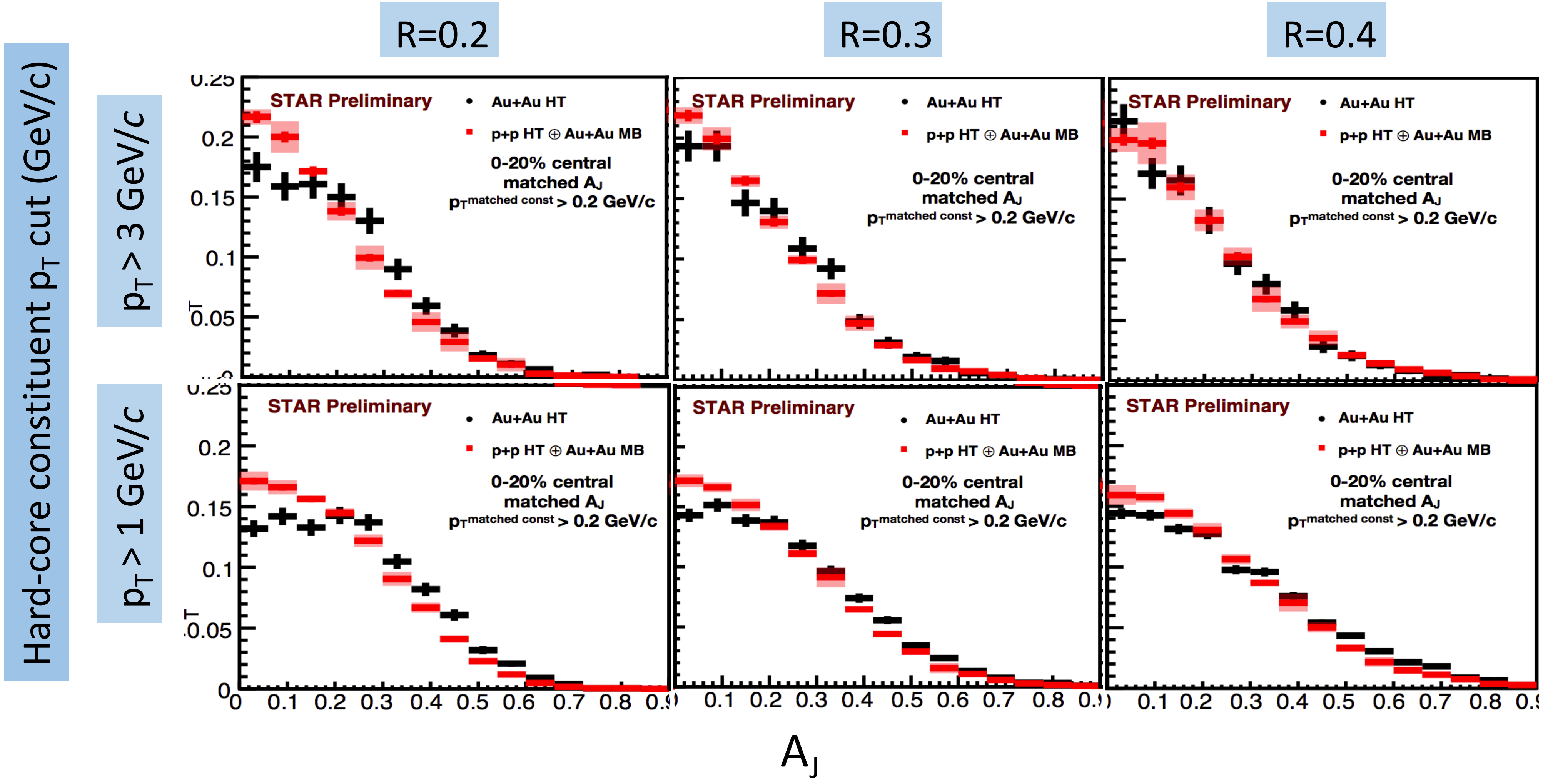
Softening of jet constituents and broadening of jets from R = 0.2 to R = 0.4 in central Au+Au collisions.

STAR, Phys. Rev. Lett. 119 (2017) 062301





Dijet imbalance evolution with R and p_T constituent cut



- Imbalance at small resolution parameters persists.
- Balance restored with increased R (≈0.35) when soft particles are included.

Jet angular scale

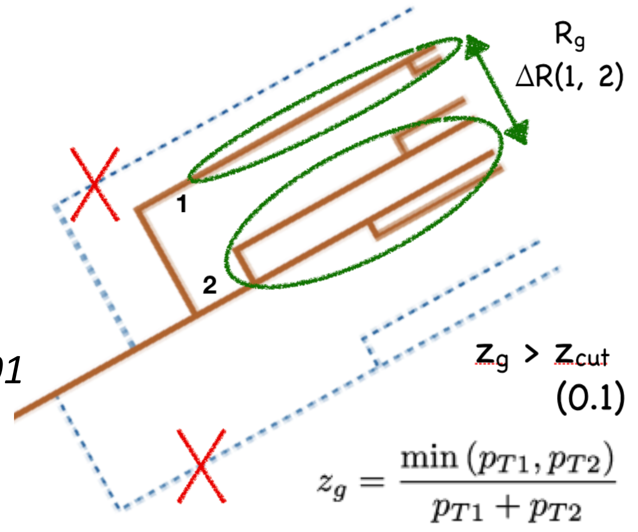
Vacuum:

Parton shower is a multi-scale process with a given momentum and angular/virtuality scale.

A. Majumder, J. Putschke, PRC93 (2016) 054909
Y. Mehtar-Tani, K. Tywoniuk, PRD98 (2018) 051501

Medium:

Angular/virtuality scale can be related to a "resolution scale" at which the jet probes the medium.



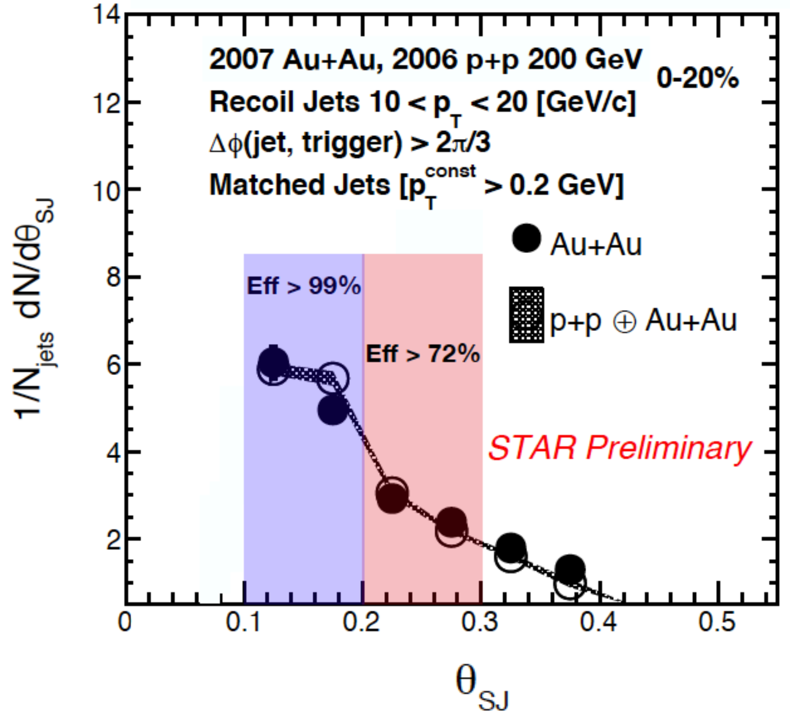
Utilize SoftDrop algorithm
- momentum scale – z_g,
- virtuality/angular scale – R_g.

SoftDrop:
Larkoski et al. JHEP 05 (2014) 146
Recursive SoftDrop:
Dreyer et al. JHEP 06 (2018) 093

- Cluster all constituents into smaller radius jets (R = 0.1)
  → leading and subleading subjets (SJ)
- Look separately at jets with different θ_{SJ}

$\theta_{SJ} = \Delta R$(LeadingSJ axis, SubleadingSJ axis)

and study again "standard" observables e.g. A_J, recoil jet yield, …



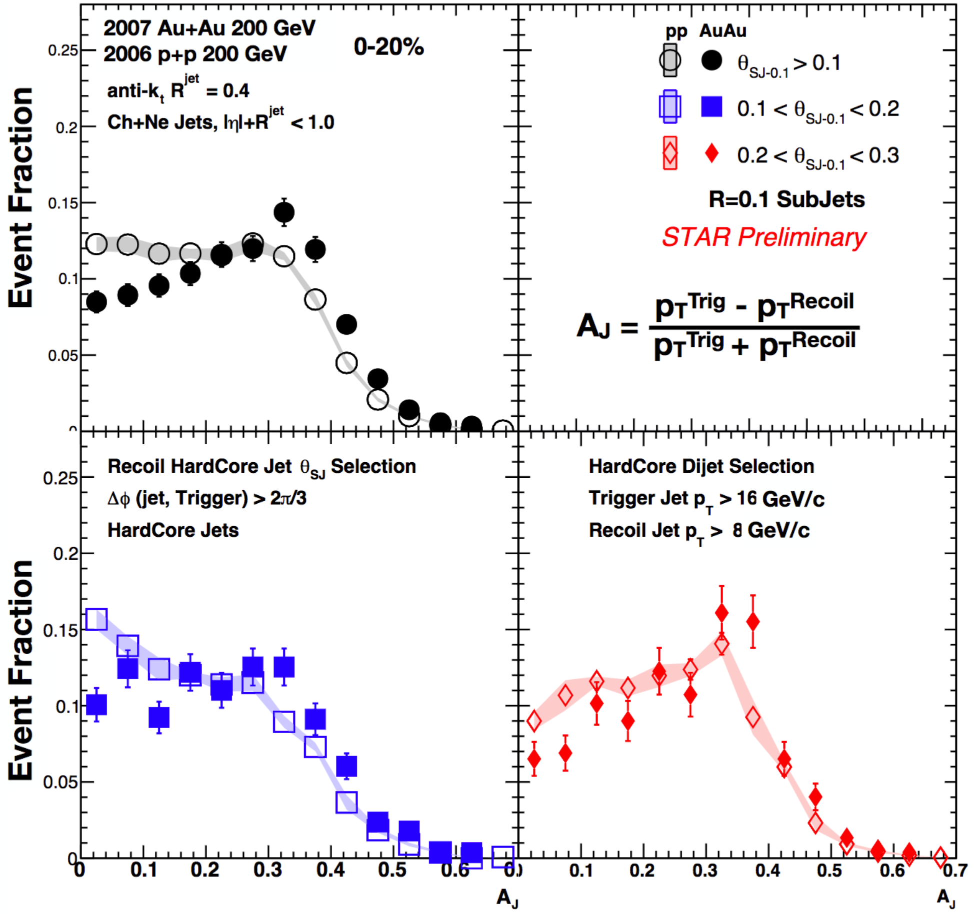
Efficiency: probability that p+p and p+p embedded in Au+Au have a resolved θ_{SJ} in the same range.

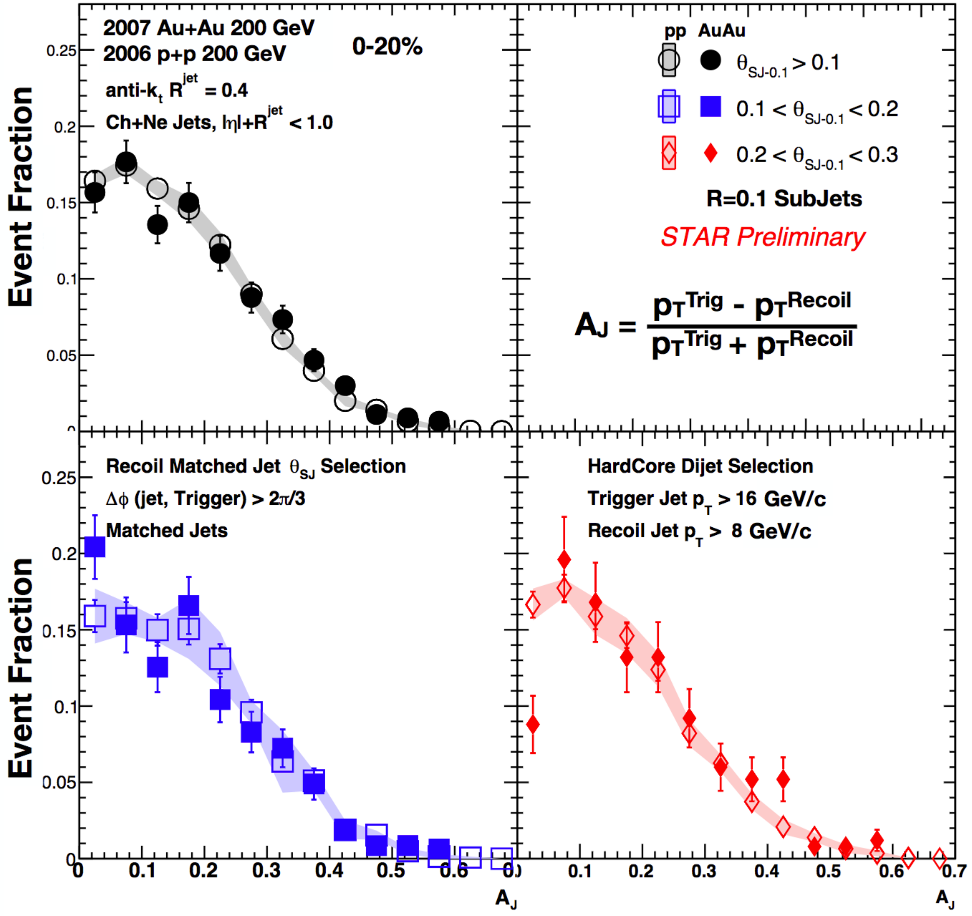
A_J for different jet angular scales

Hard-core jets

R = 0.4

Matched jets





Hard-core jets are unbalanced w.r.t. p+p for all θ_{SJ} selections.

- no large difference among different θ_{SJ} selections

Matched jets recover balance w.r.t. p+p for all θ_{SJ} selections.

Summary and outlook

New high statistics data and upgraded detectors of STAR enable precision measurements of hard probes in hot and dense QCD matter at top RHIC energy.

Charm quarks:

- Interact strongly with the QGP: modification of their production is similar to that of light flavor hadrons.
- Charm cross section is consistent with p+p, but hadrochemistry is significantly modified.

→ There is an evidence for charm hadronization via coalescence at intermediate p_T.

Bottom quarks:

- Also interact strongly with the QGP.

→ To confirm the hint of flavor dependent energy loss ordering for b-quarks more statistics is needed.

Quarkonia:

- Stronger suppression of Υ(2S+3S) than Υ(1S) in central Au+Au collisions observed.

→ Consistent with sequential melting scenario.

Jets:

- Lost energy is transferred to soft particles.
- Dijet asymmetry for hard-core jets gets balanced with increasing jet radius and inclusion of soft constituents.
- No strong dependence on jet angular scale observed.

Stay tuned: there are new analyses with improved methods and statistics underway.