Recent hard and soft probe measurements with STAR at RHIC

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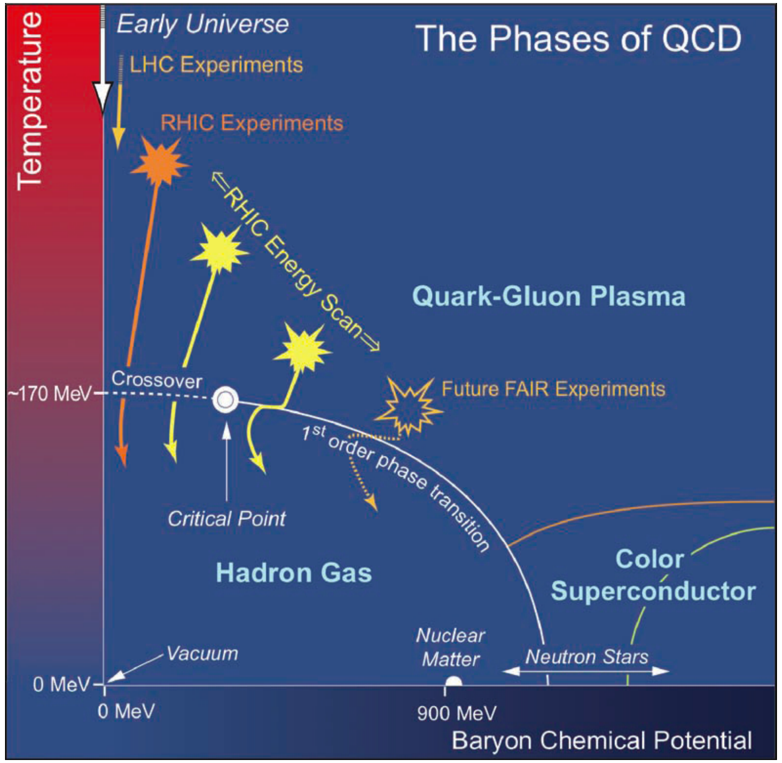
Exploration of the QCD phase diagram

- nature of the phase transition and search for the critical point
- properties of the quark-gluon plasma at high temperature (RHIC/LHC) and large density (GSI FAIR/NICA)

RHIC is a versatile collider (collision energy, collision species including asymmetric collision systems)

- top collision energy: $\sqrt{s_{NN}}$ = 200 GeV (p+p up to 510 GeV)
- dedicated Beam Energy Scan (BES) program at RHIC to search for onset of deconfinement, phase boundary and critical point in Au+Au collisions

BES-I completed: 7.7, 11.5, 14.5, 19.6, 27, 39, 54.4, 62.4
BES-II ongoing: 7.7 – 19.6 GeV collider mode
3.0 – 7.7 GeV fixed-target mode



Reach in μ_B at RHIC:
collider mode: 20-420 MeV
fixed target: up to 720 MeV

Note: lifetime of QGP is very short
→ we need in-situ probes

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.

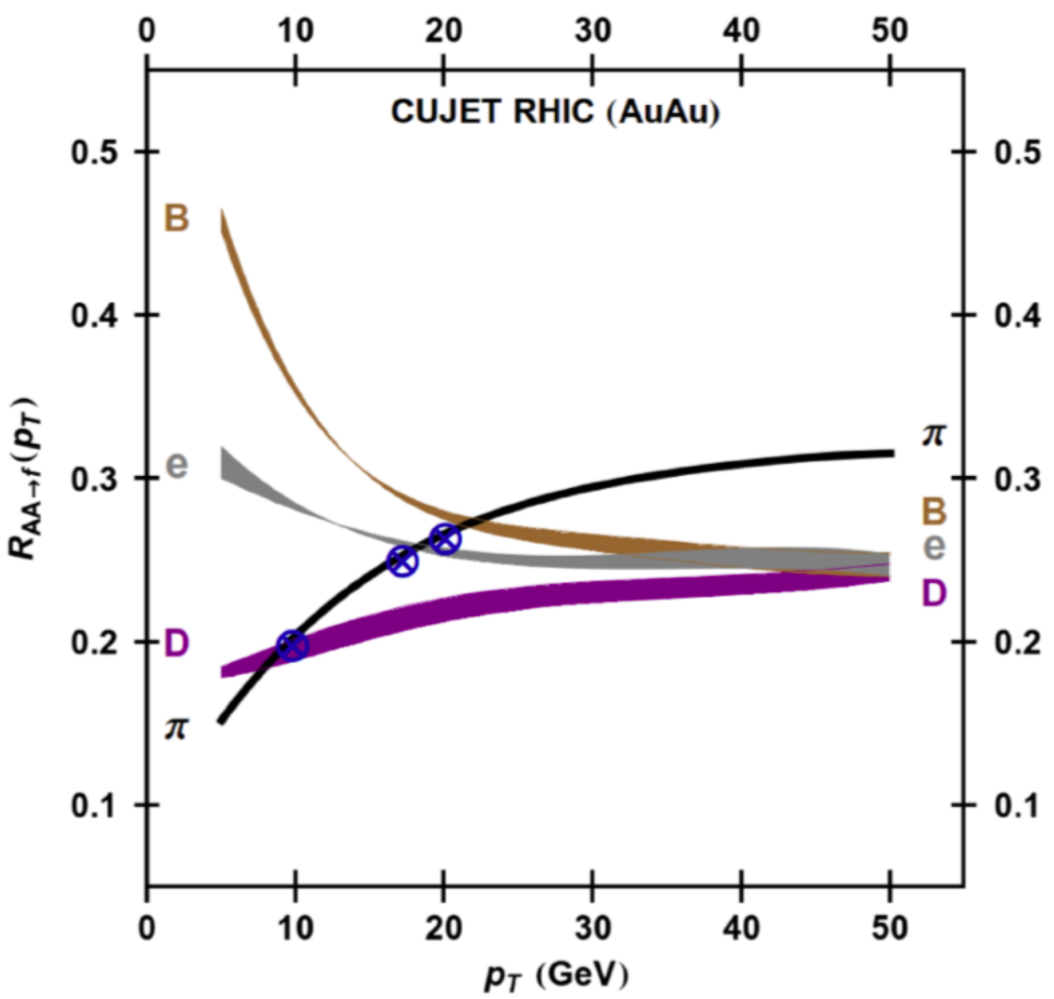
Photons, W and Z bosons:
do not carry a color charge,
provide information about initial state
nuclear parton distribution functions.

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

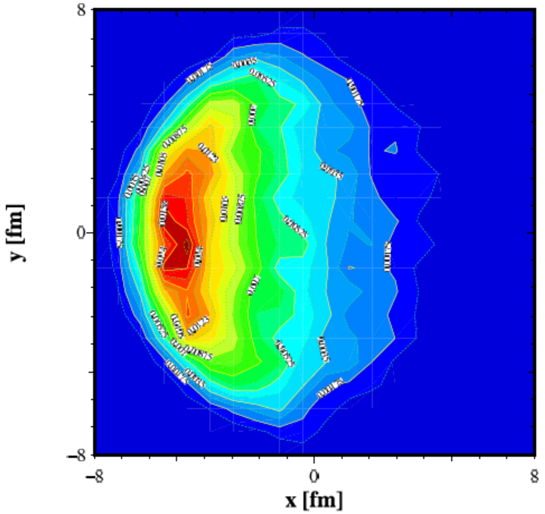


Quarkonia: see talk
by Leszek Kosarzewski (Thu, 16:45)

Sensitivity of different observables

Renk, Eskola, PRC 75, 054910 (2007)

single h



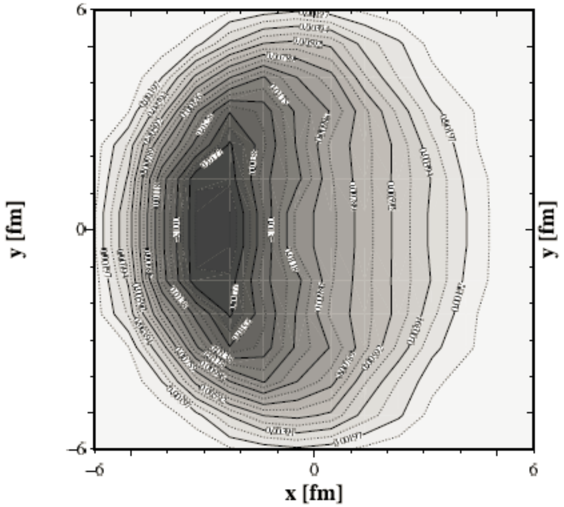
Surface bias dependence:

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

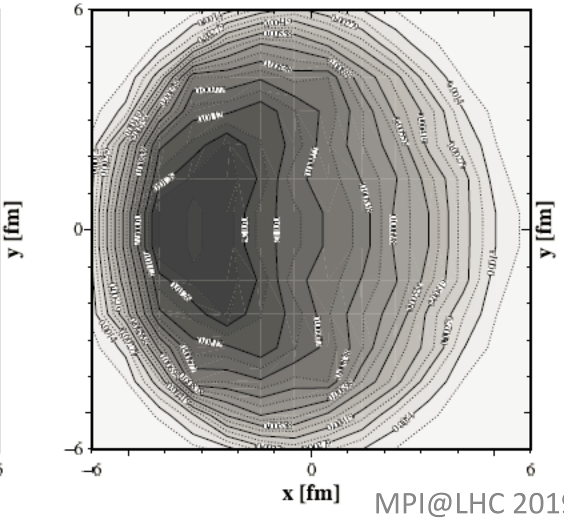
… challenge for experimentalists to measure them all

T. Renk, YaJEM

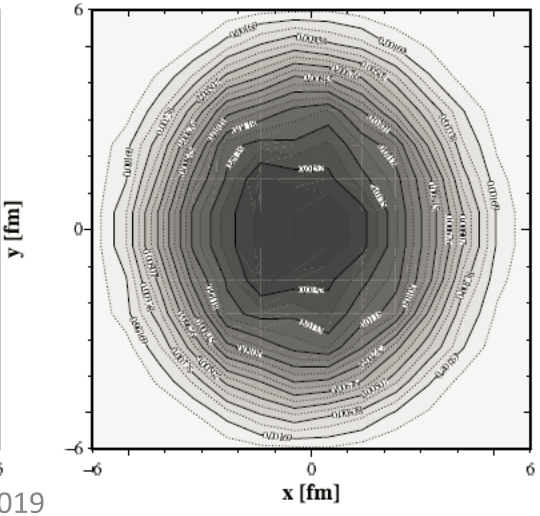
h - h



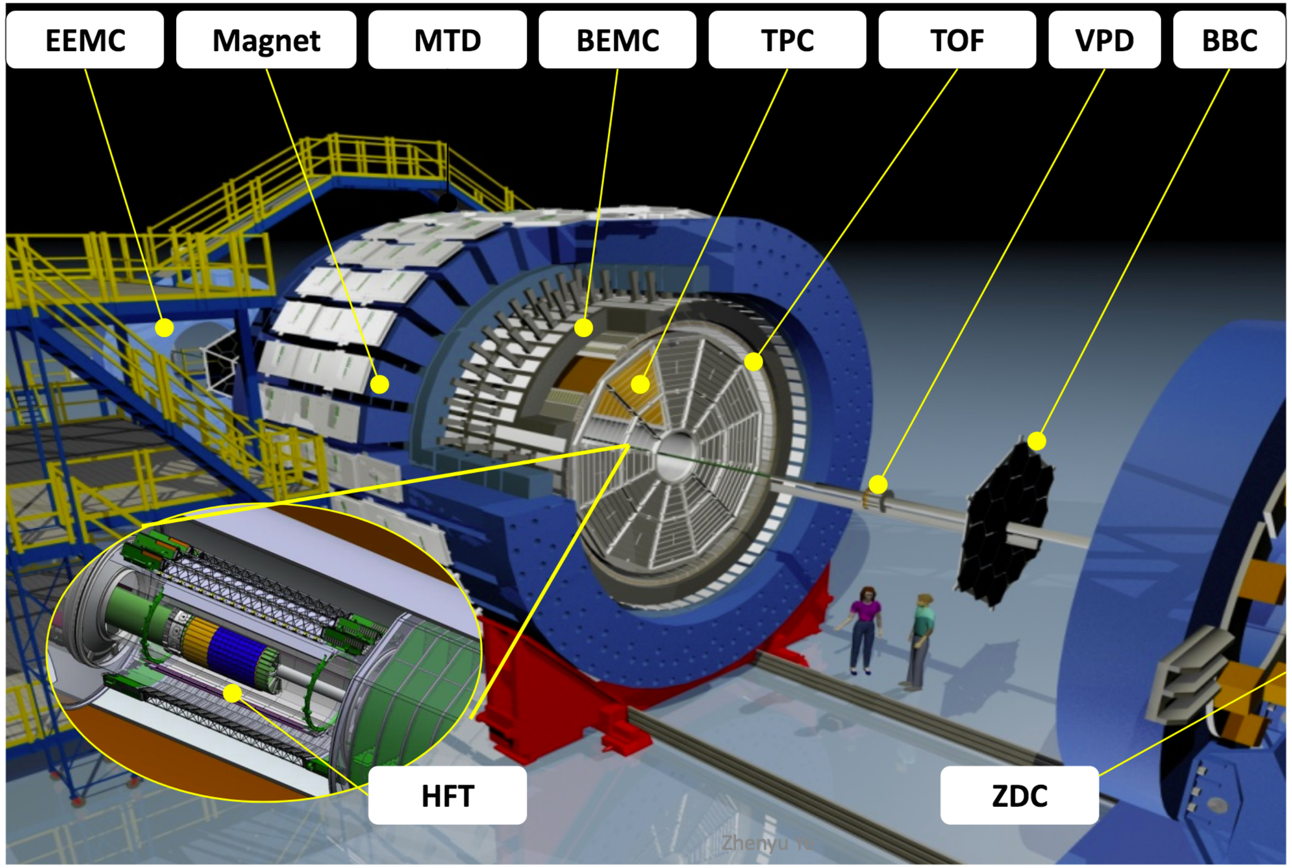
jet - h

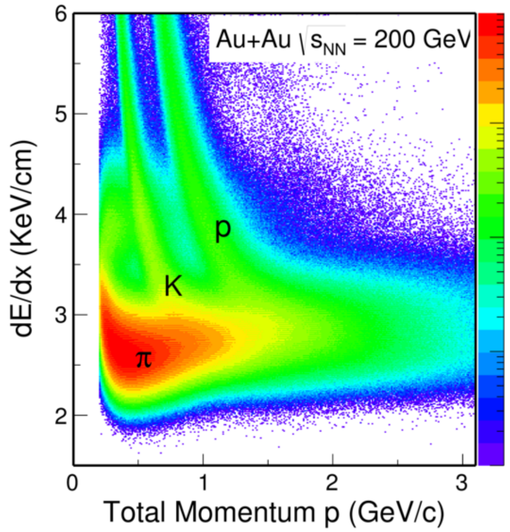


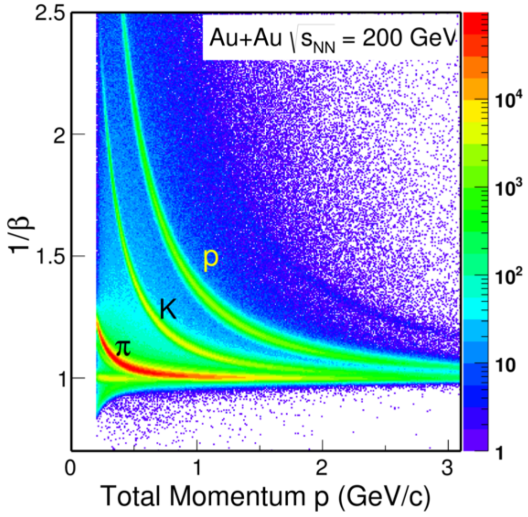
γ - h

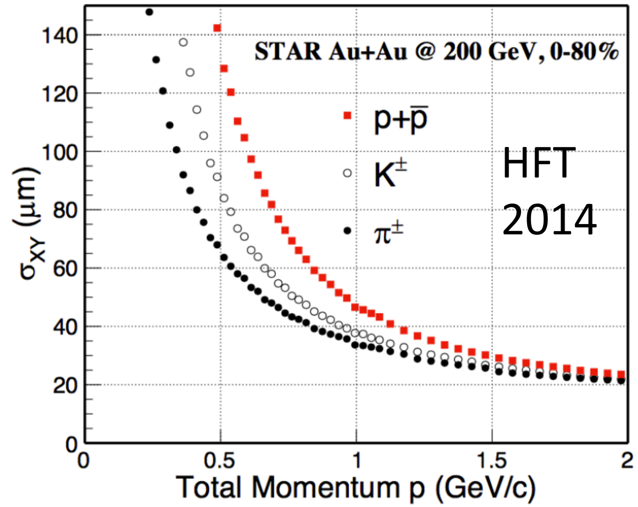


Solenoidal Tracker At RHIC









- 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)

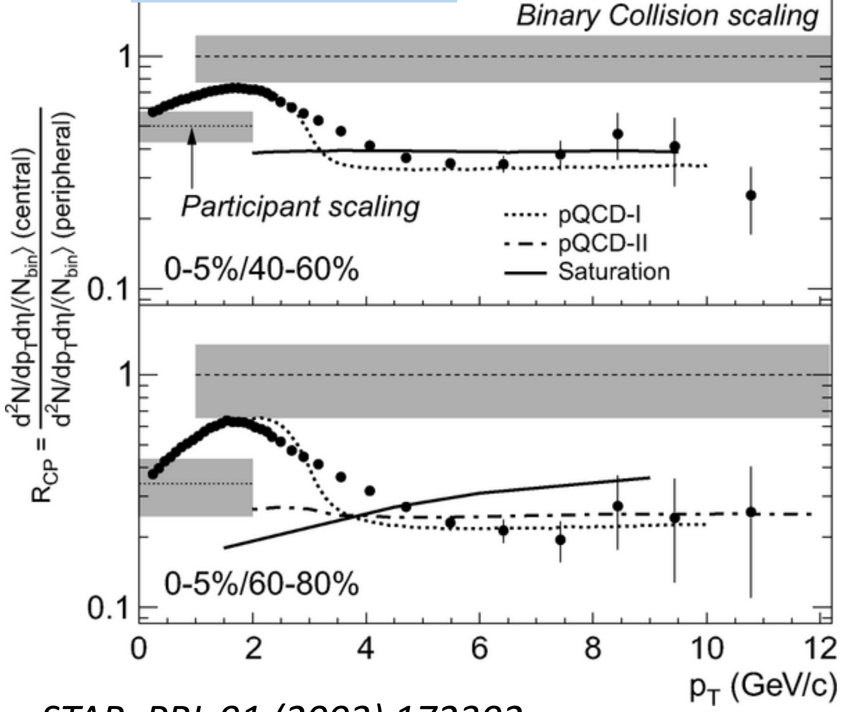
Energy dependence of nuclear modification factor

"Nuclear modification factor" R_{AA} or R_{CP} is the way to compare an observable in A+A collisions to the reference (p+p or peripheral A+A)

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

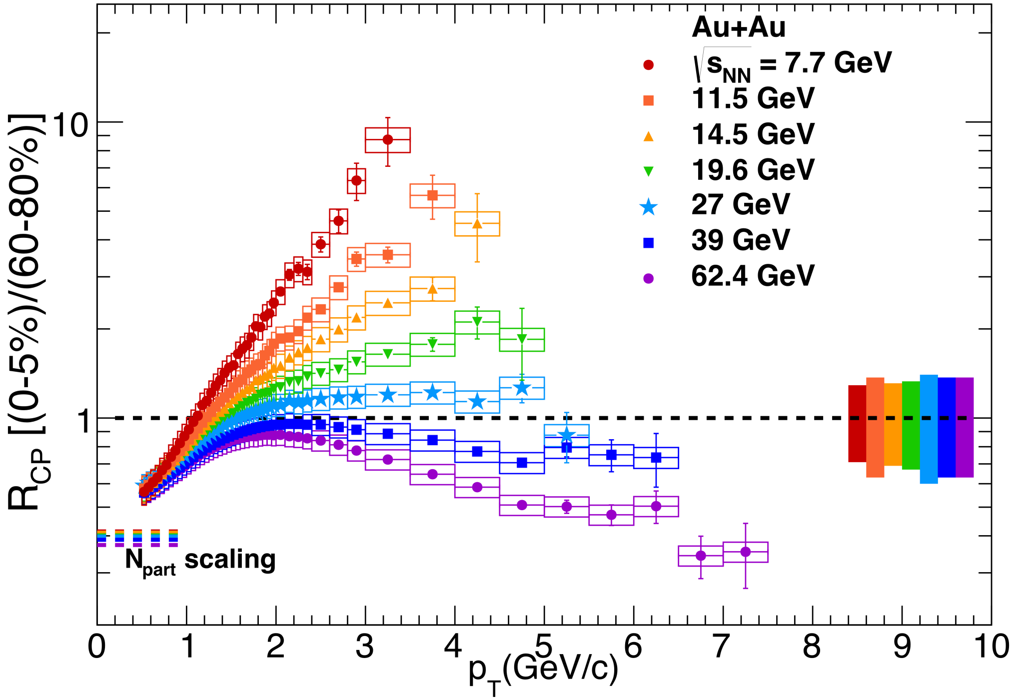
$N_{coll}/\sigma_{inel}^{NN}$

$\sqrt{s_{NN}}$= 200 GeV



STAR, PRL 91 (2003) 172302

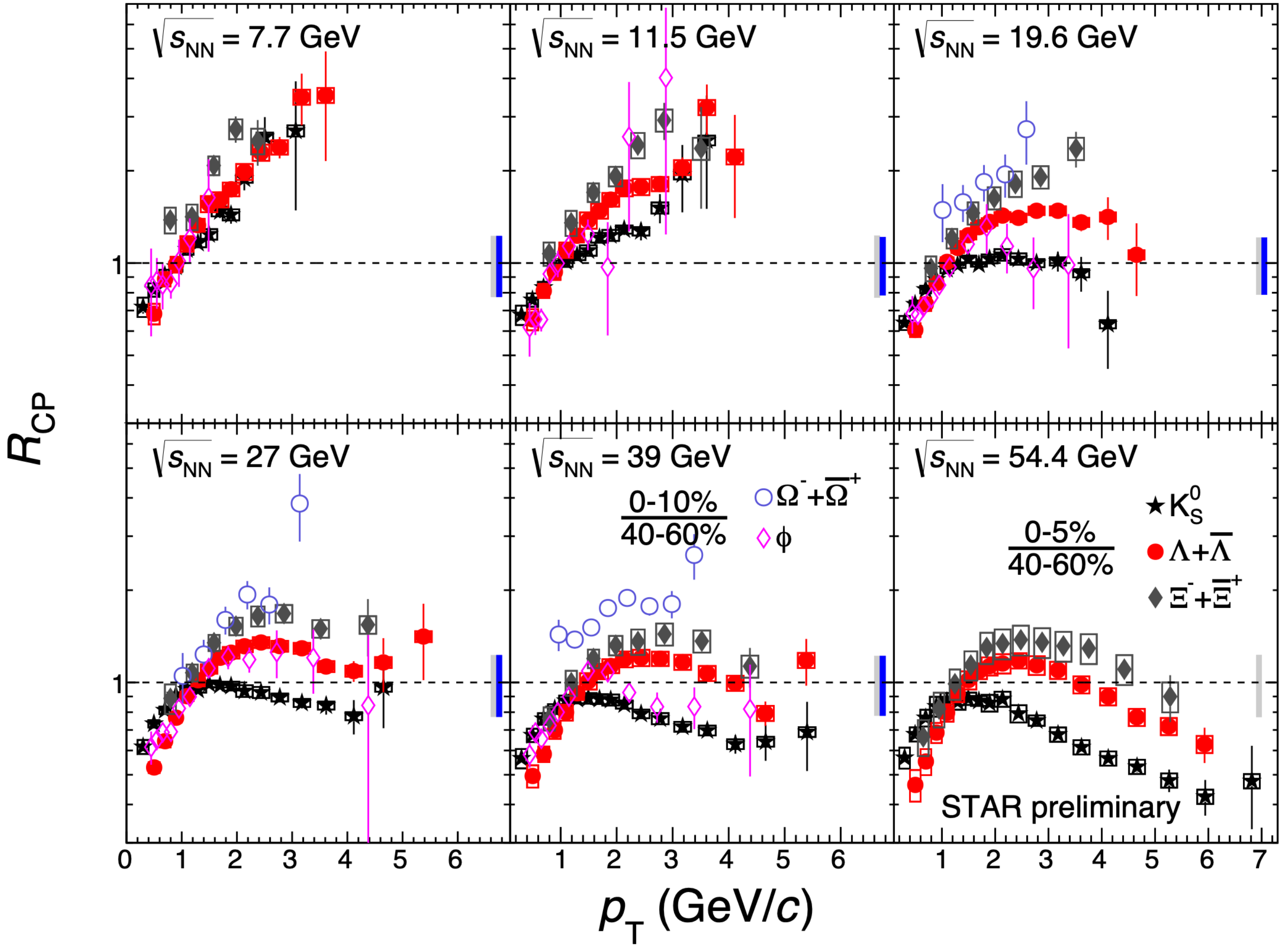
*STAR, PRL **121** (2018) 32301*



R_{CP} increases progressively from a suppression regime to a pronounced enhancement at lower beam energies ($\sqrt{s_{NN}}$ < 39 GeV)

Enhacement: Cronin effect, radial flow, and relative dominance of coalescence over fragmentation in hadronization

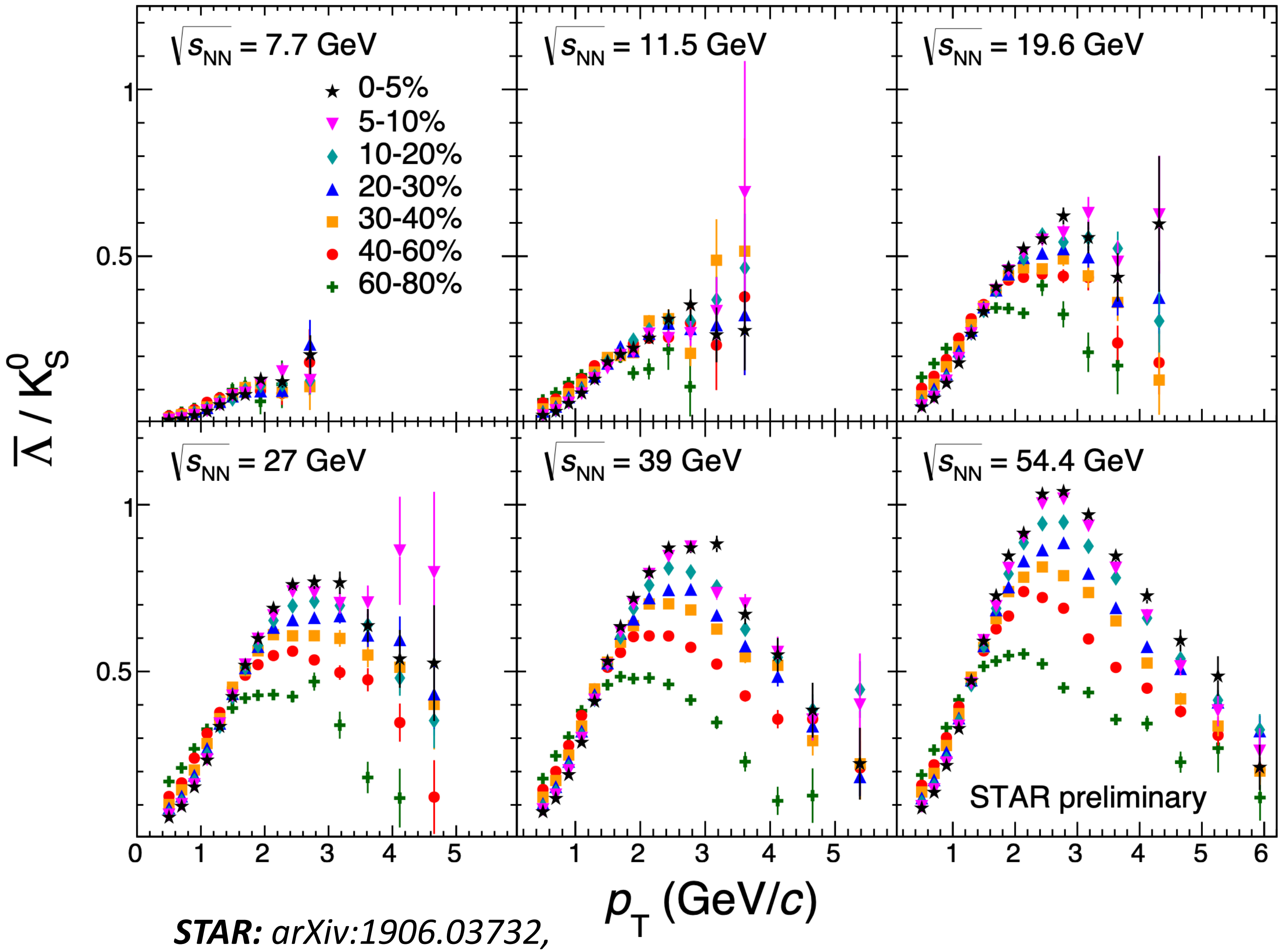
R_{CP} energy dependence for strange particles



STAR: BES-I (0-5%), arXiv:1906.03732
NEW 54.4 GeV: preliminary for QM2019

- energy evolution of strange hadron R_{CP} reflects decreasing partonic effects with decreasing $\sqrt{s_{NN}}$
- nuclear effects take over at $\sqrt{s_{NN}}$ < 11 GeV
- high-p_T:
  suppression of K^0_S at $\sqrt{s_{NN}}$ >39 GeV, similar to charged hadrons
- intermediate-p_T:
  baryon/meson separation:
  role of parton recombination
- particle difference apparent at $\sqrt{s_{NN}}$ > 19 GeV and become smaller/vanish at lower $\sqrt{s_{NN}}$

Baryon/meson enhancement at intermediate p_T



STAR: *arXiv:1906.03732,*
NEW: 54.4 GeV preliminary

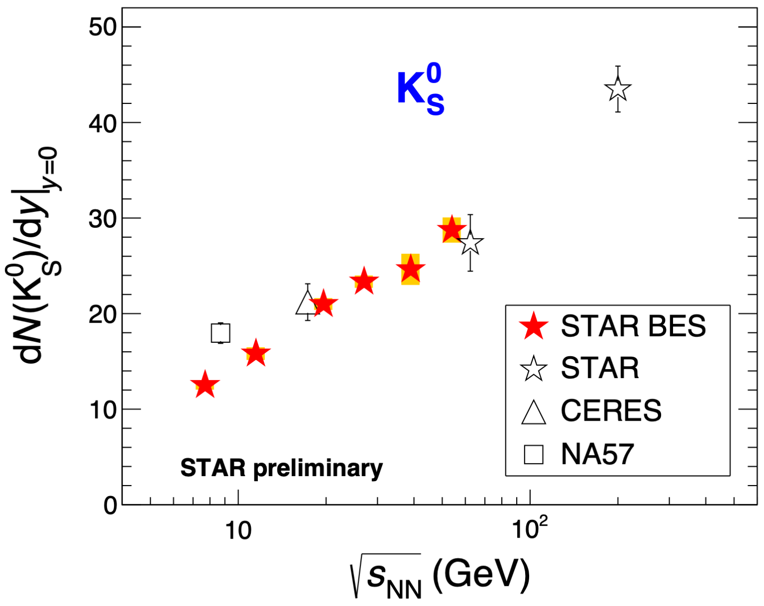
Baryon/meson enhancement at intermediate p_T = 2-5 GeV/c at BES energies $\sqrt{s_{NN}}$ > 19.6 present (more statistics needed at lower $\sqrt{s_{NN}}$)

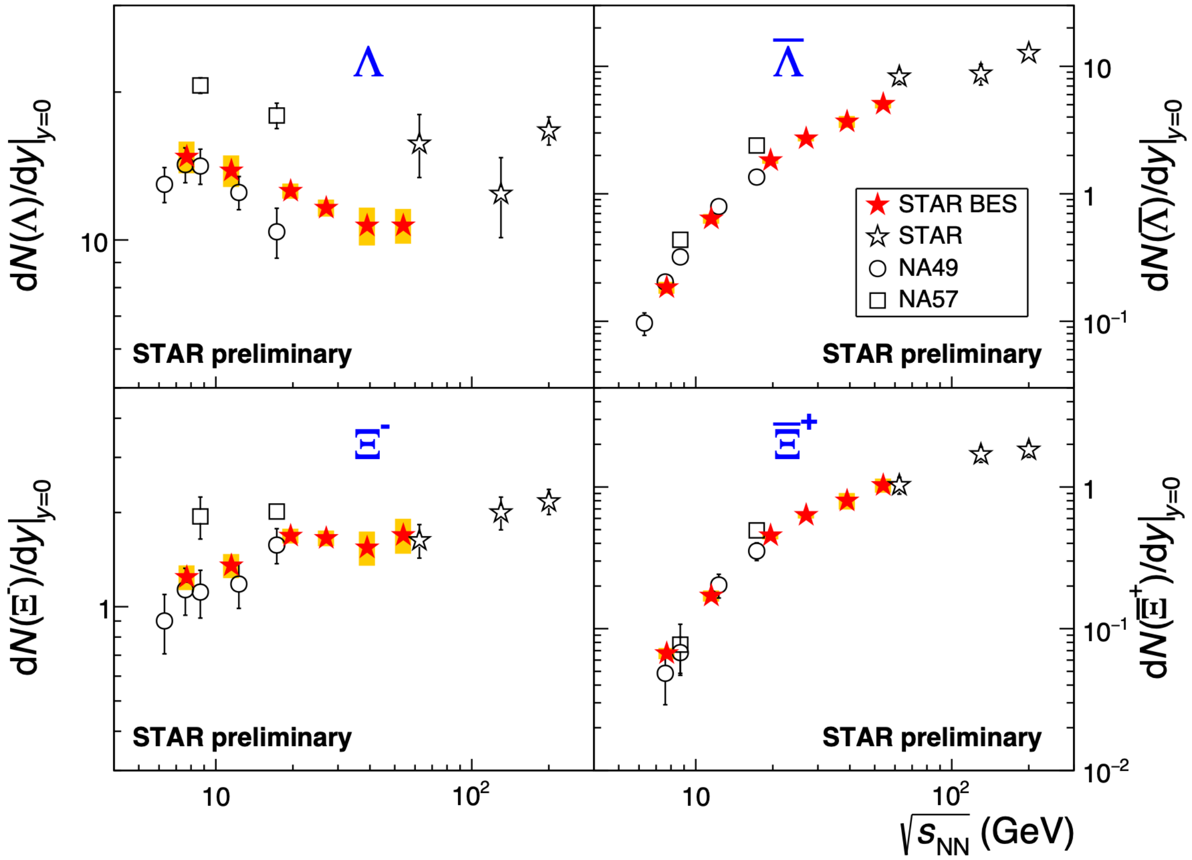
The measurement corroborates earlier findings at $\sqrt{s_{NN}}$ = 200 GeV and also LHC.

- Enhancement is strongly dependent on centrality and increases toward higher $\sqrt{s_{NN}}$

→ hadron formation through parton recombination and parton collectivity

Energy dependence of strange particle yields



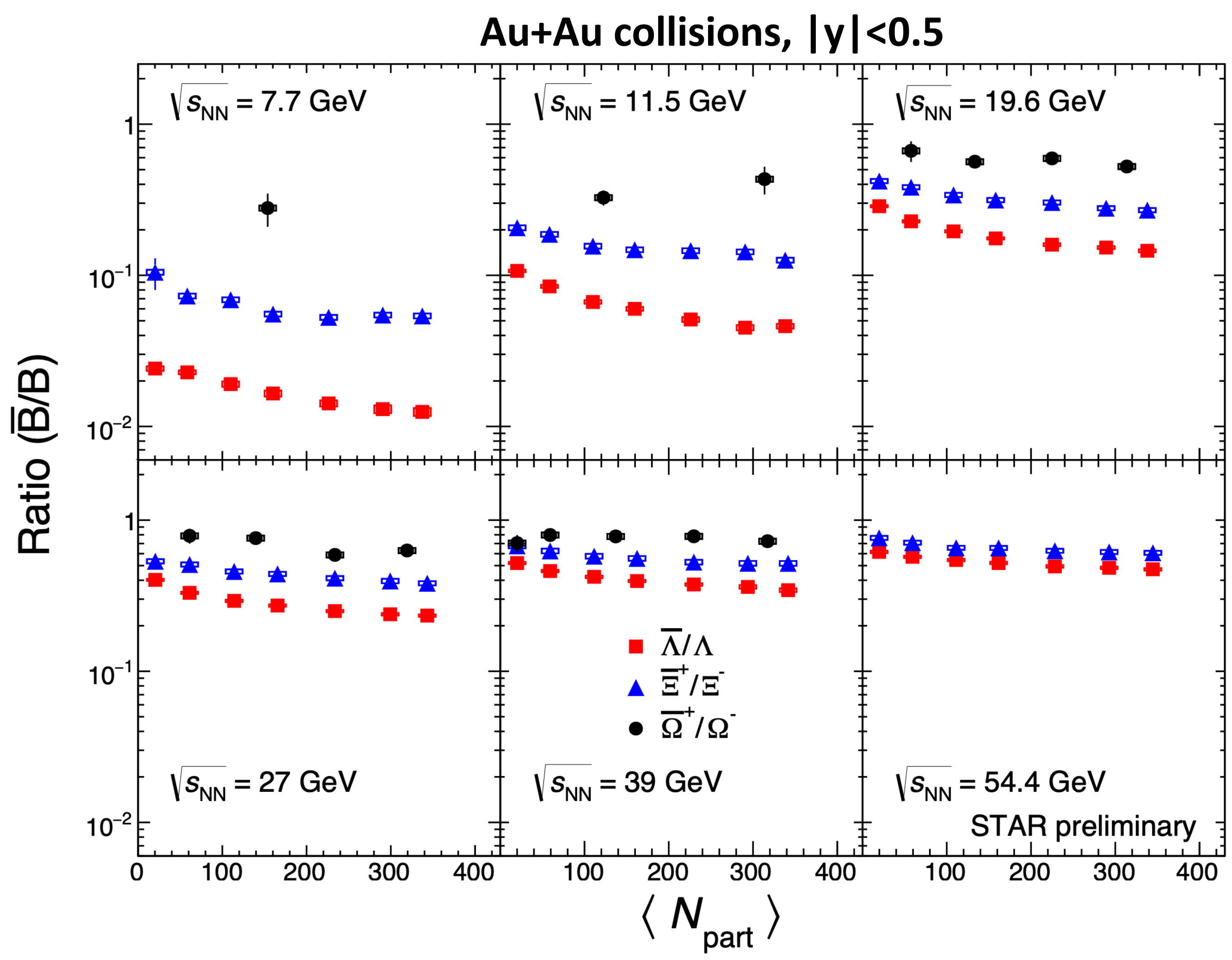


- dN/dy of strange baryons (Λ and Ξ^-): non-monotonic energy dependence
- dN/dy of the corresponding antibaryons, K^0_S and ϕ (not shown) mesons: monotonic increase with energy
- Λ more complicated: pair production at high energy vs associated production at low energy

Possible cross over between the two mechanisms around 50 GeV?

STAR: *BES-I (0-5%), arXiv:1906.03732;*
NEW: 54.4 GeV preliminary for QM2019
62.4 GeV (0-5%), PRC83, 024901 (2011)
130 GeV (0-10%), PRL92, 182301 (2004);
200 GeV (0-5%), PRL 108, 072301 (2012)
SPS, 158AGeV: NA49 *(0-10%), PRC78, 034918 (2008);*
NA57 *(0-4.5%), J. Phys. G32, 427 (2006),*
CERES *J. Phys. G32 (2006) S97.*

Strange antibaryon/baryon ratios



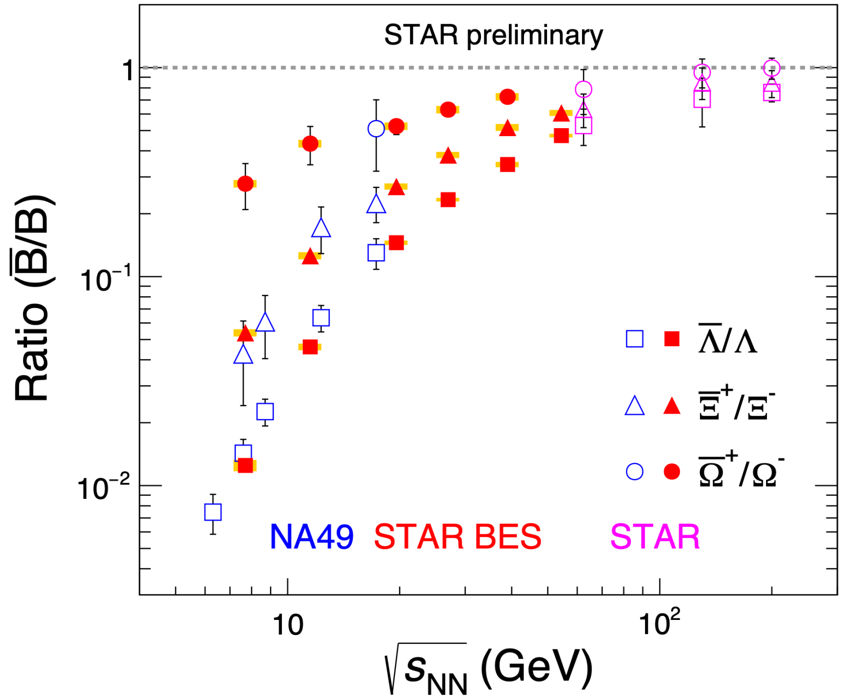
- decrease with increasing centrality at all BES energies measured
- increase with number of strange quarks at a given energy and centrality:

$$\Omega^+/\Omega^- > \Xi^+/\Xi^- > \Lambda/\overline{\Lambda}$$

consistent with thermal model predictions

- at lower BES energies:

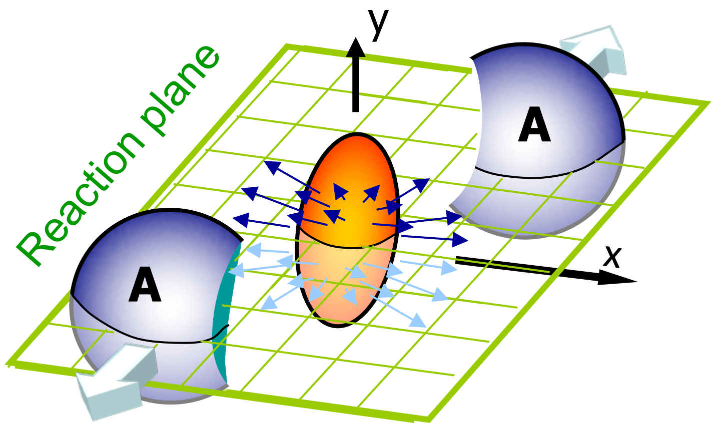
→ baryon stopping and/or antibaryon absorption

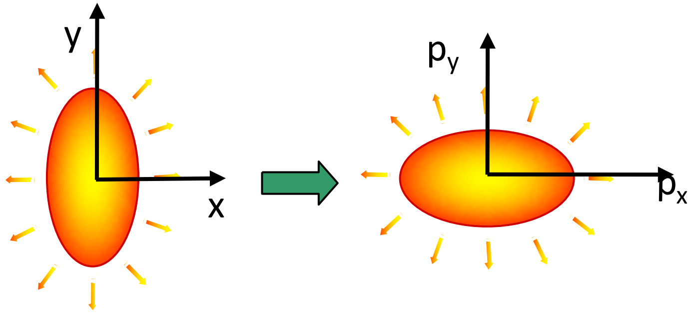


STAR: *arXiv:1906.03732, PRC96, 044904, 2017; PRC 83, 024901 (2011); PRL 108, 072301 (2012)*
NEW: 54.4 GeV preliminary

NA49: *PRC 78, 034918 (2008), PRC 66, 054902 (2002), PRC 77, 024903 (2008), PRC73, 044910 (2006)*

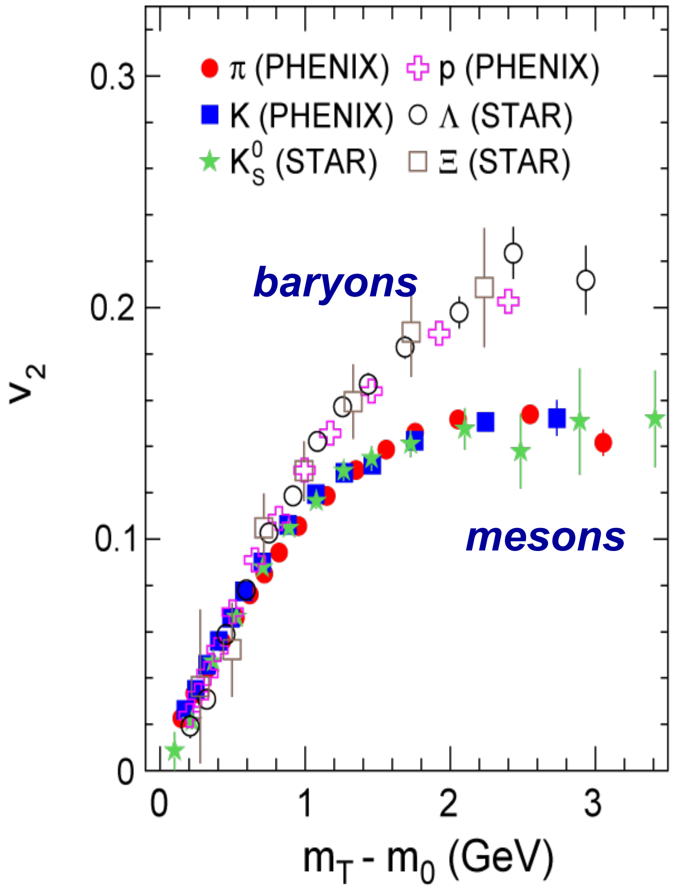
Anisotropic flow and NCQ scaling

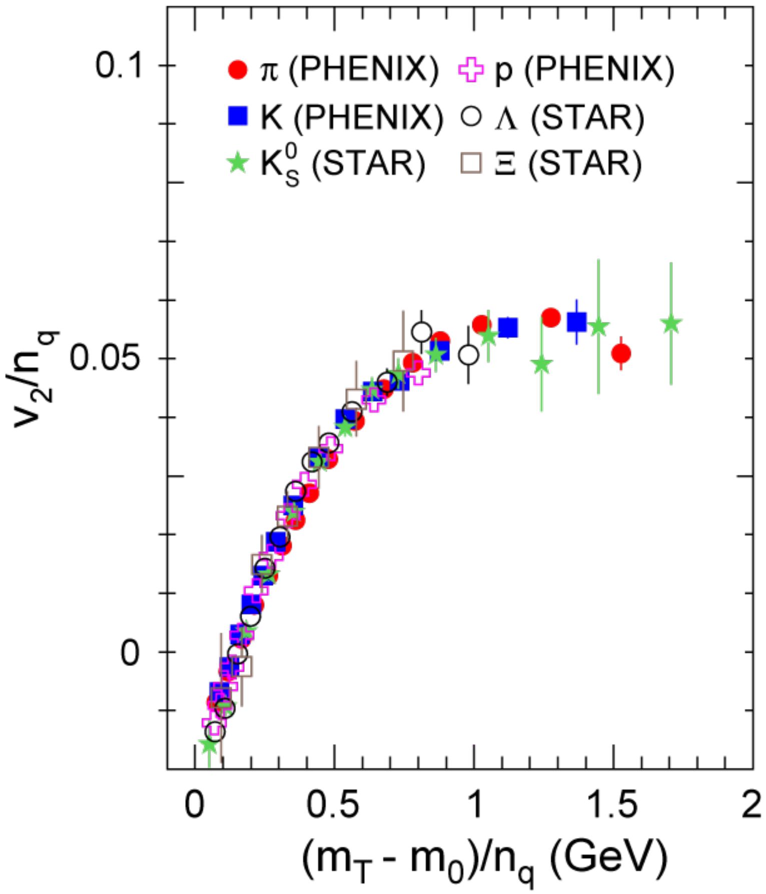




Initial spatial anisotropy → Strong pressure gradients → Anisotropy of produced particles

Sensitivity to early expansion





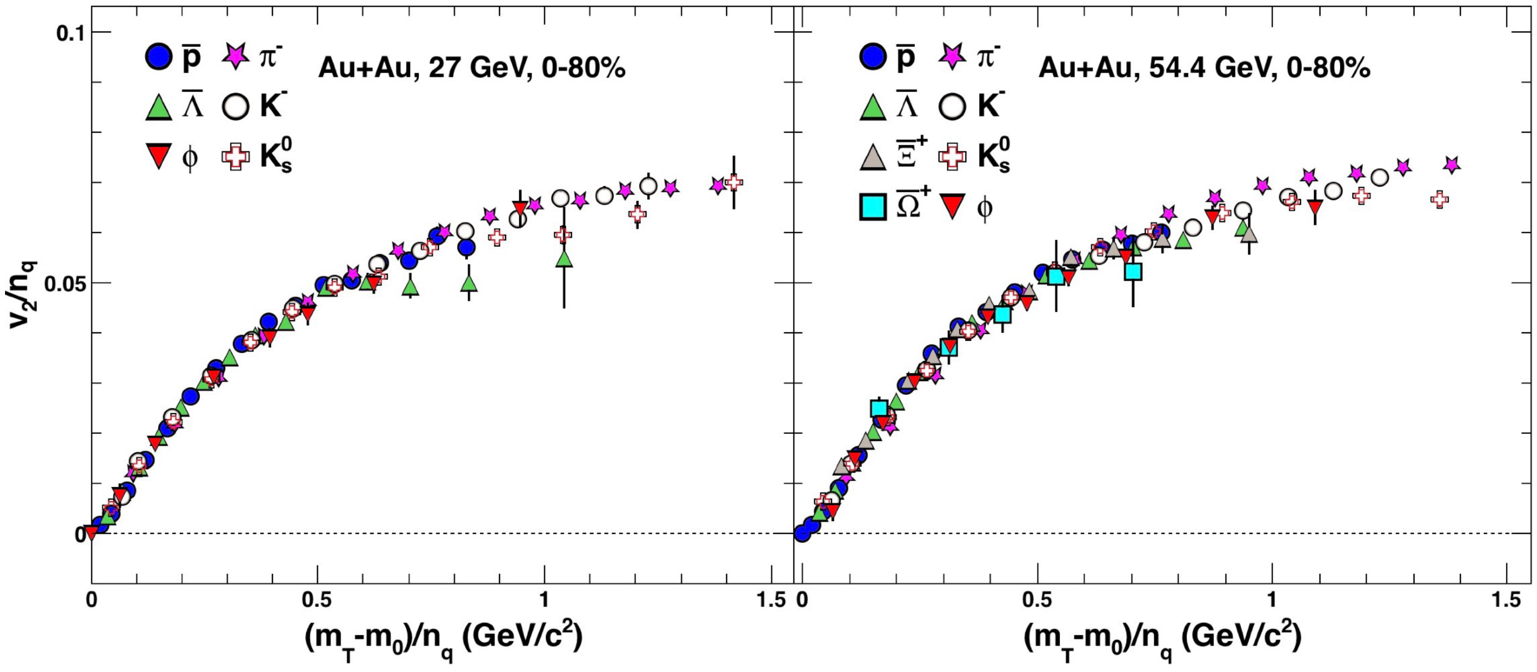
Fourier analysis of particle distribution relative to reaction plane:

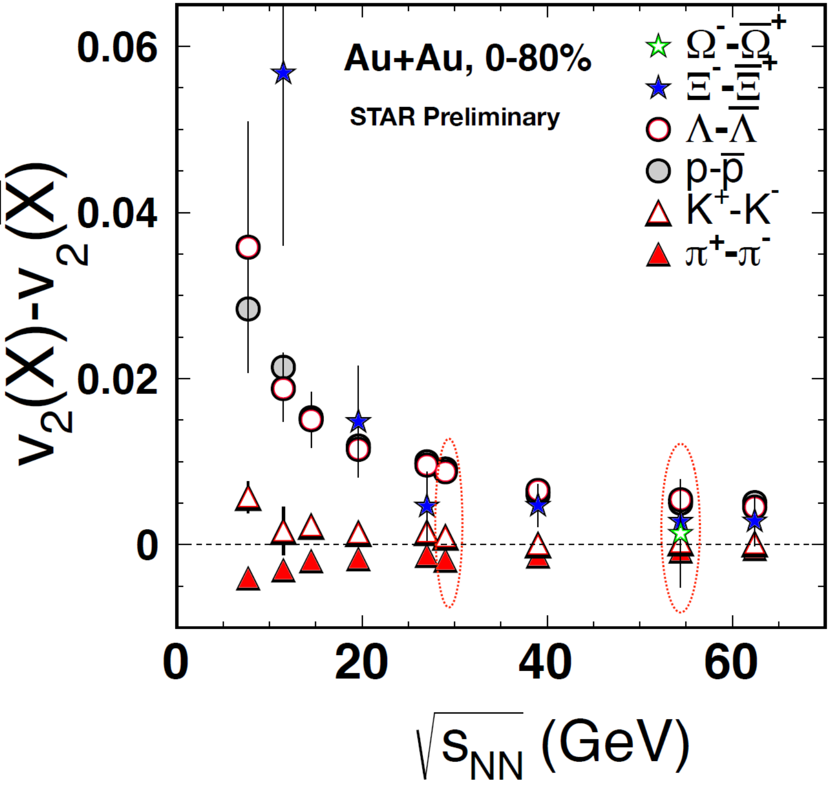
- v_1 … directed flow
- v_2 … elliptic flow

n_q : number of constituent quarks
baryon n_q = 3
meson n_q = 2
m_0: particle mass
m_T: transverse particle mass

How well does NCQ scaling work at lower energies?

STAR, PRL110 (2013) 142301





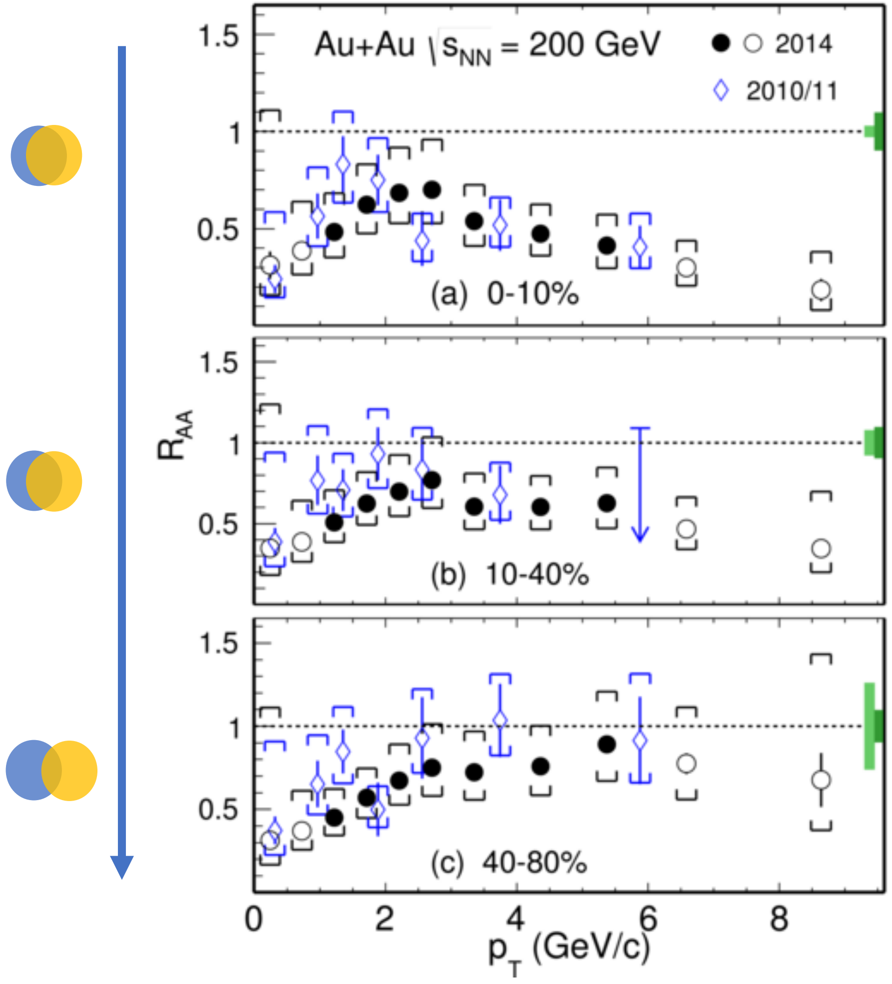
NCQ scaling for strange and multistrange hadrons tested down to $\sqrt{s_{NN}}$ = 27 GeV.

NCQ scaling is broken at lower energies, where larger v_2 for baryons than antibaryons is observed.

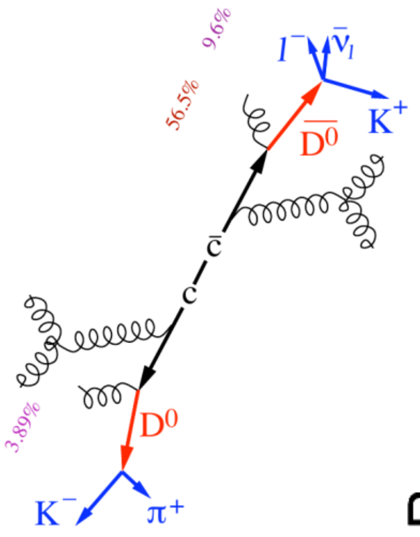
Moving toward heavier quarks …

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

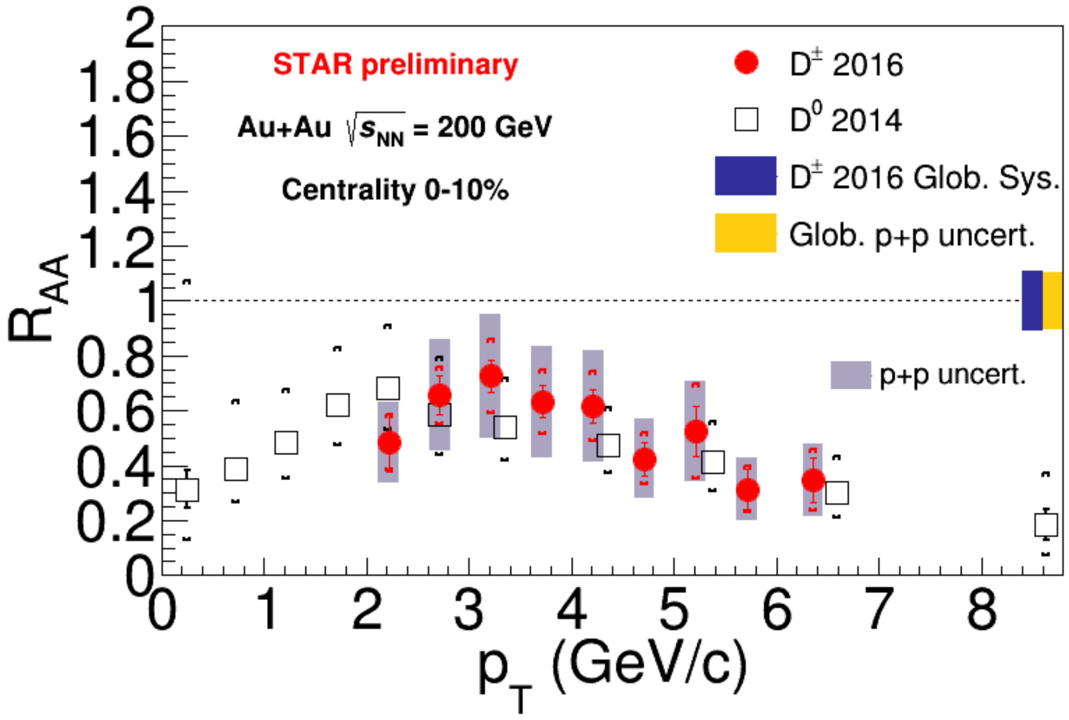
D⁰ meson



STAR, PRC99 (2019) 034908

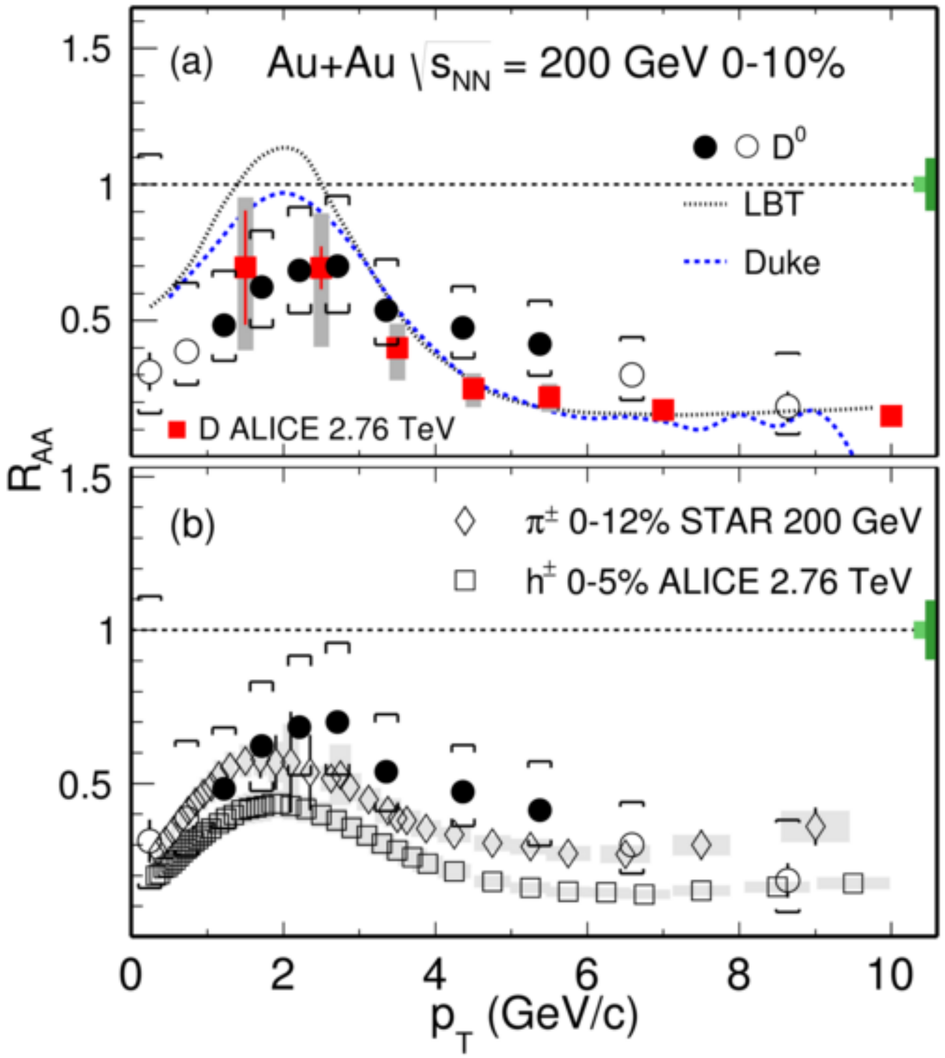


Decay channel	$c\tau$ [μm]	Branching ratio [%]
$D^0 \longrightarrow K^- + \pi^+$	122.9 ± 0.4	3.93 ± 0.04
$D^+ \longrightarrow K^- + \pi^+ + \pi^+$	311.8 ± 2.1	9.46 ± 0.24



- 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, PRC99 (2019) 034908

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.

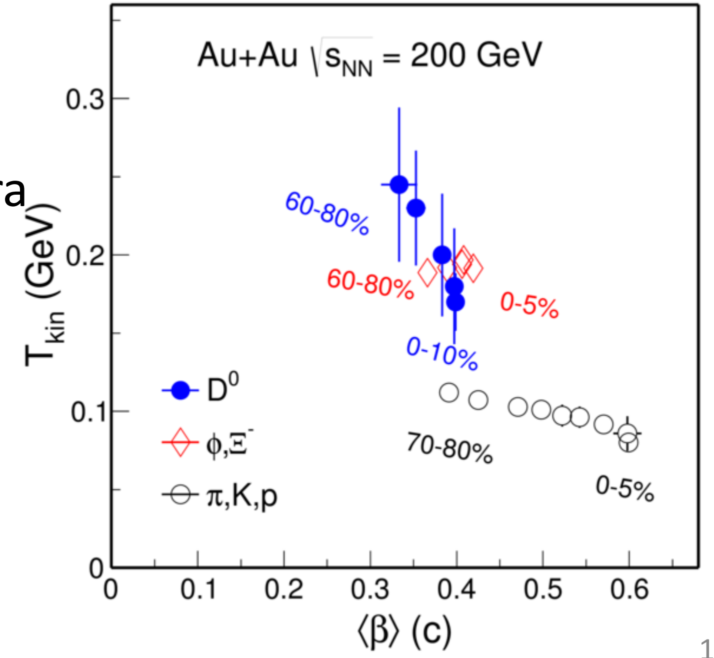
Model comparison:

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

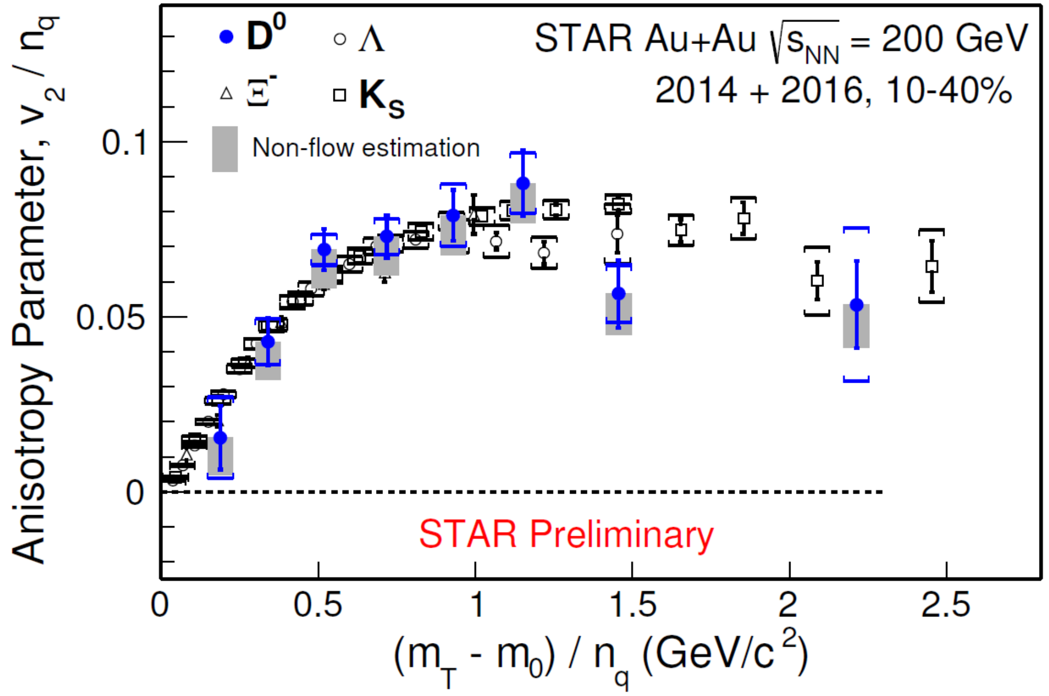
LBT: Cao, Luo, Qin, Wang, Phys. Rev. C 94 (2016) 014909
DUKE: Cao, Qin, Zhong, Bass, PRC 92 (2015) 024907

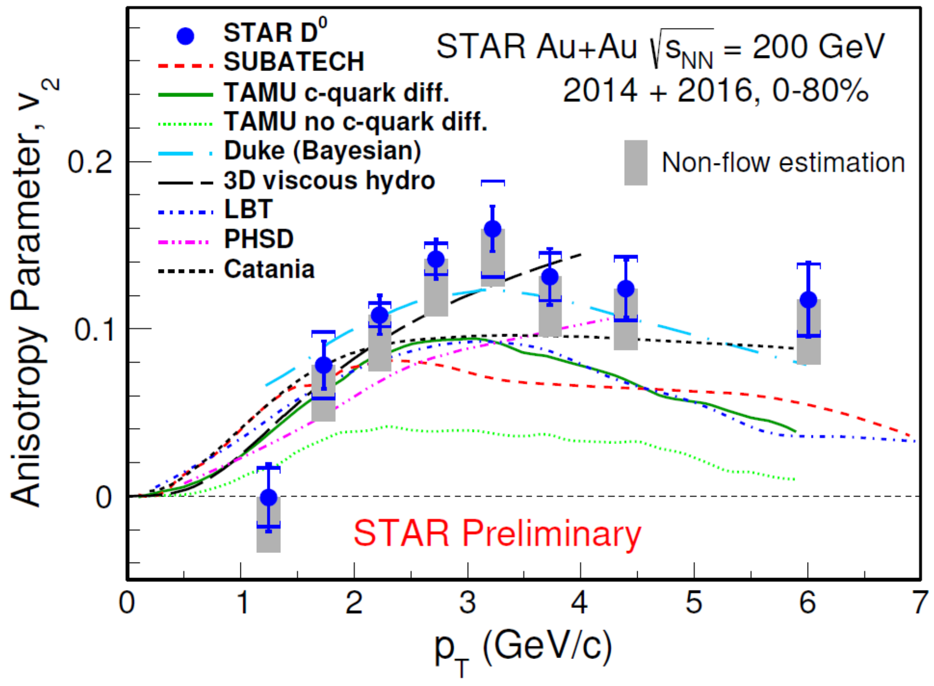
- Blast wave fits of D^0 p_T spectra (p_T < 5 GeV/c) :

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



Does charm quark flow?





2014: STAR, PRL 118 (2017) 212301

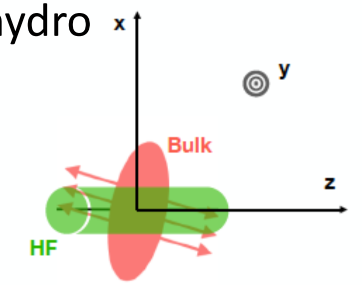
Charm quarks acquire similar elliptic flow as light flavor quarks
→ data suggest strong interaction of charm quarks with QGP.

n_q … number of constituent quarks
m_0/m_T … particle/transverse particle mass

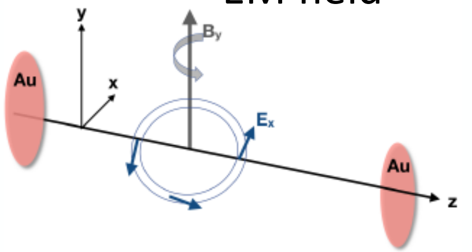
Data described by models with temperature dependent charm diffusion coefficient $2\pi TD_s \sim 2$–12 predicted by lattice QCD.

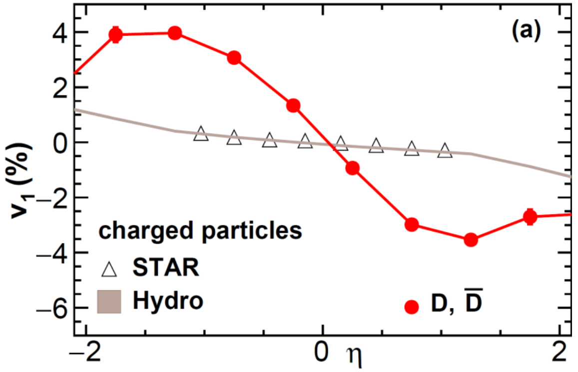
Directed flow of D^0 mesons

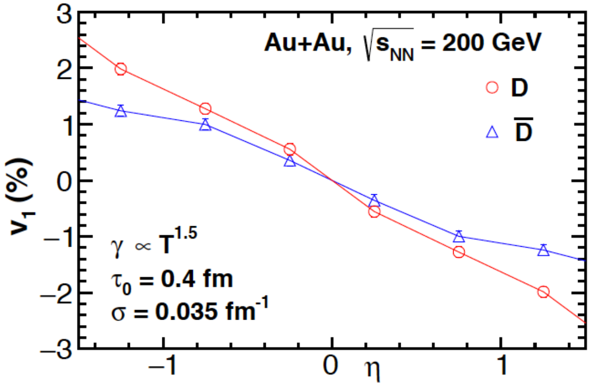
hydro



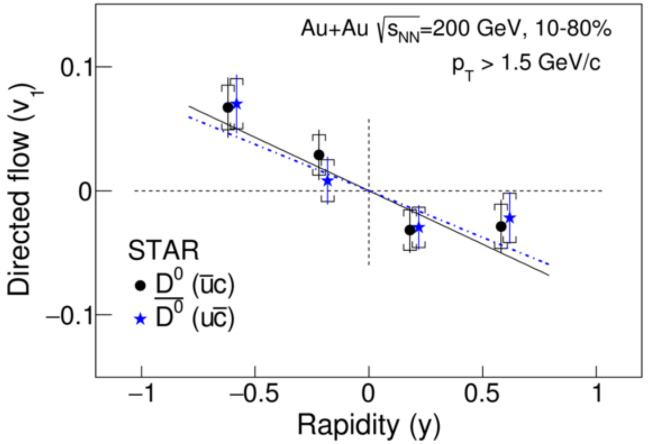
EM field

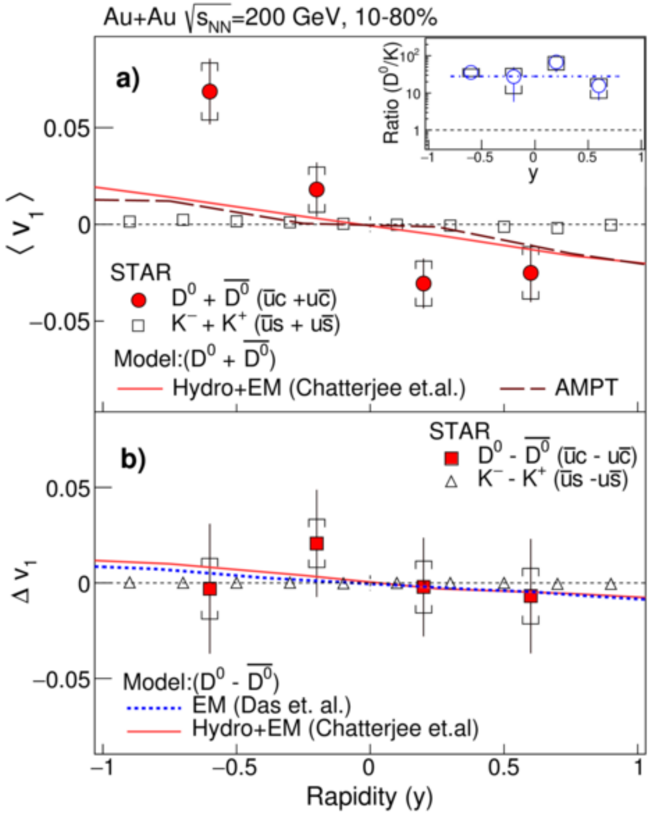






STAR, PRL 123 (2019) 162301





dv_1/dy

D^0: −0.086 ± 0.025 (stat) ± 0.018 (syst)

$\overline{D}^0$: −0.075 ± 0.024 (stat) ± 0.020 (syst)

- 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 anti-D^0 mesons and would not influence the average v_1 of D^0 mesons.

D^0 mesons exhibit much larger v_1 than light flavor hadrons → strong interaction of c-quarks with initially tilted source.

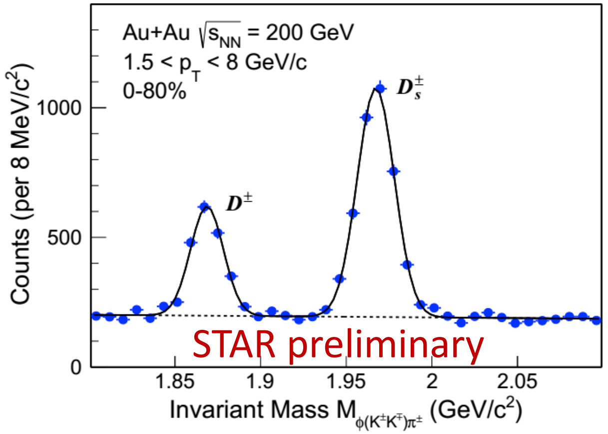
More data needed to draw conclusions on magnetic field induced v_1 splitting of c and anti-c quarks.

Chatterjee, Bozek: PRL 120, 192301 (2018)
PLB 798, 134955 (2019)

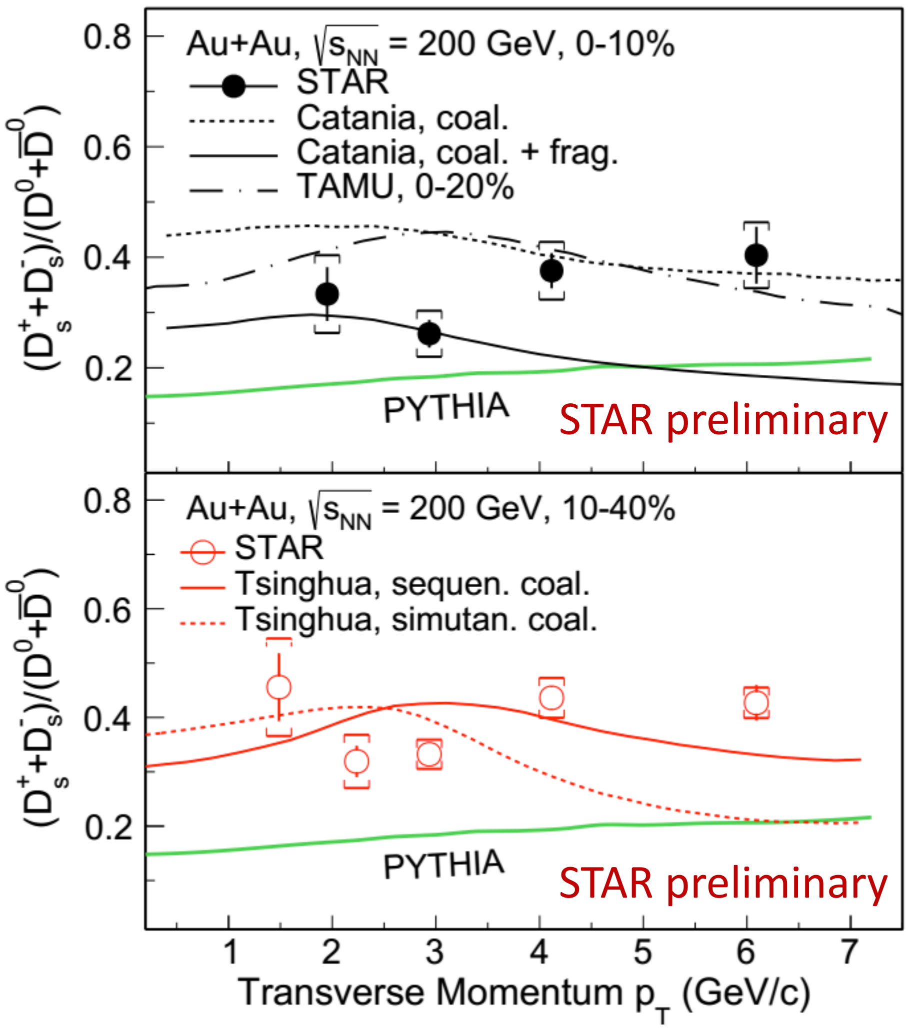
D_s/D^0 enhancement

- 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.

BDT method, data 2014+2016
Significance = 45



$D_S^\pm \longrightarrow \phi\ (\longrightarrow K^+ + K^-) + \pi^\pm$

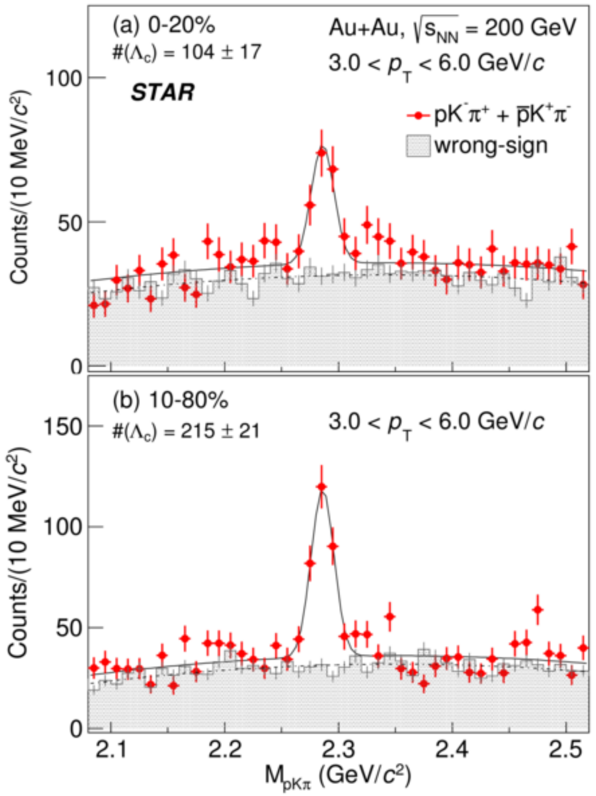


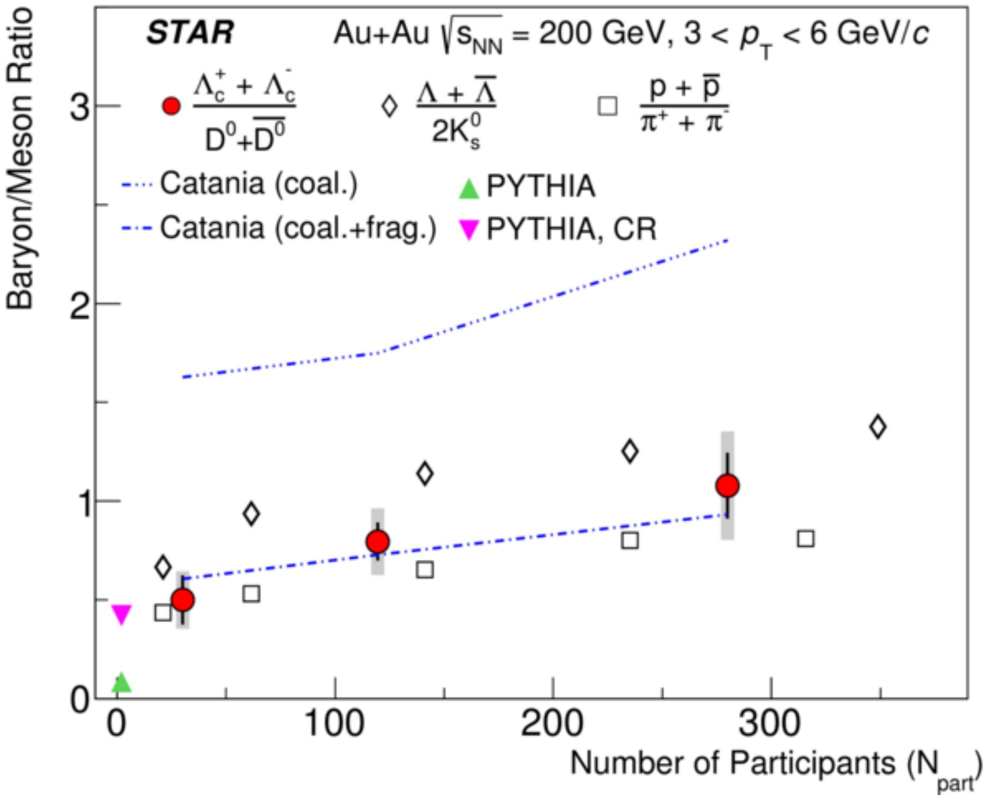
D_s/D^0 ratio:
- strong enhancement observed in central Au+Au collisions relative to PYTHIA
- qualitatively described by model calculations incorporating strangeness enhancement and (sequential) coalescence hadronization of charm quarks
- data suggest important role of coalescence in charm quark hadronization at RHIC energy.

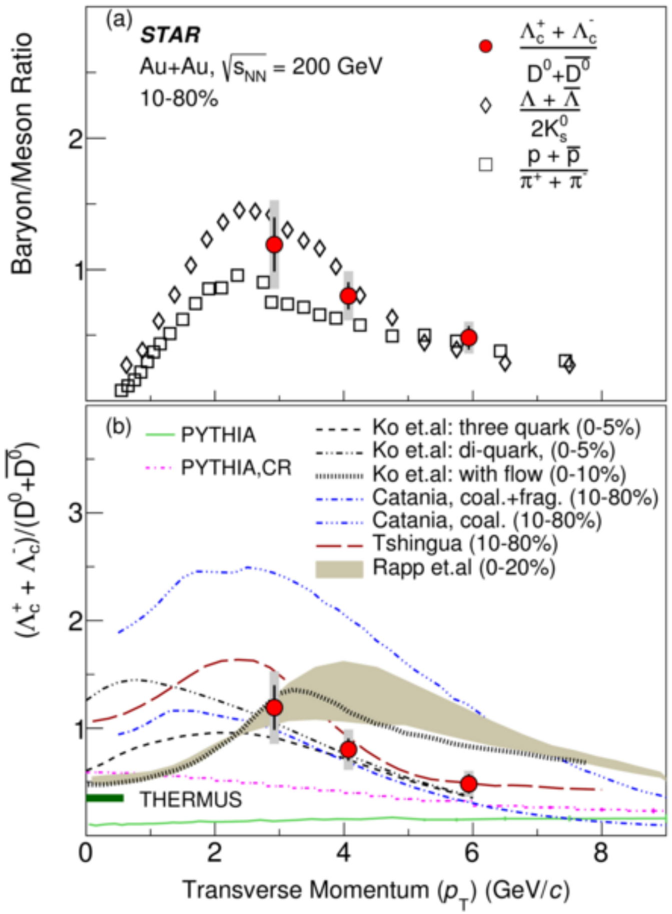
Model calculations:
Catania: *S. Plumari, V. Minissale V, S.K. Das et al., EPJ C78 (2018) 348*
TAMU: *M. He, R. Rapp, in preparation*
Tsinghua: *J. Zhao, S. Shi, N. Xu, P. Zhuang, arXiv:1805.10858.*

Λ_c and heavy quark hadronization

STAR, arXiv:1910.14628







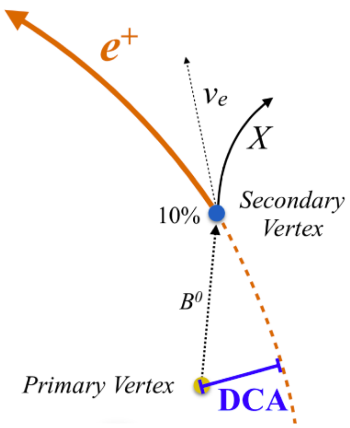
Supervised machine learning TMVA BDT analysis used to improve signal extraction.

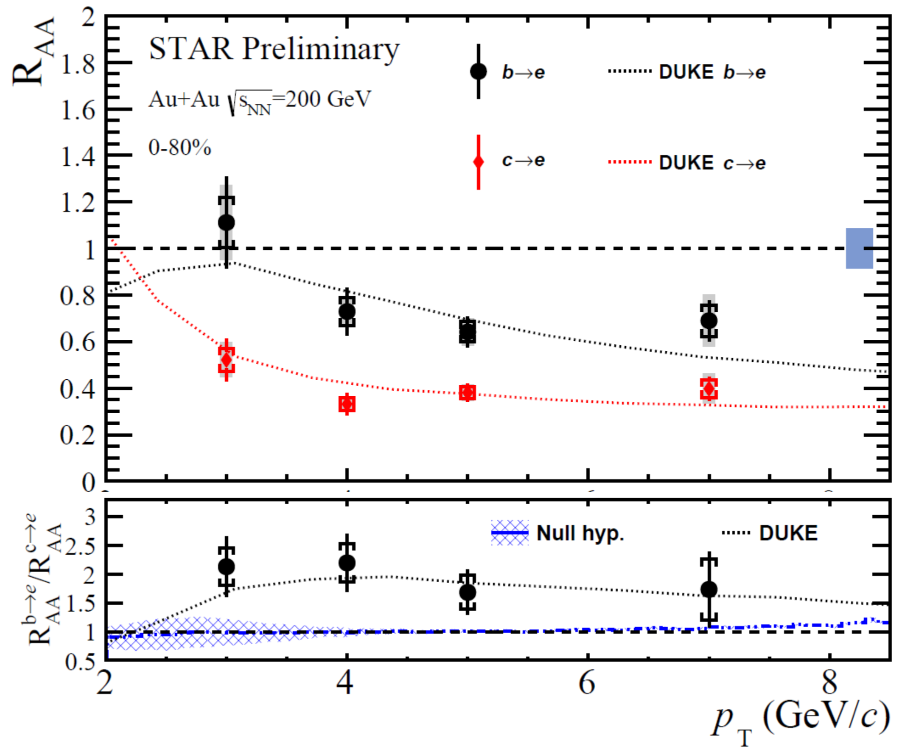
- Strong enhancement of Λ_c/D^0 production in Au+Au collisions compared to PYTHIA with/without color-reconnection (CR).
- Data suggest coalescence hadronization of charm quarks in QGP at intermediate p_T (2-6 GeV/c) similar to light-flavor quarks.

Model calculations:
Ko: *PRC 79, 044905 (2009), arXiv:1905.09774*
Catania: *EPJ C78 (2018) 348*
Tshingua: *arXiv:1805.10858*
Rapp: *arXiv:1910.14628*

How strongly does bottom interact with medium?

Open bottom hadron production can be e.g. measured via electron decay channels



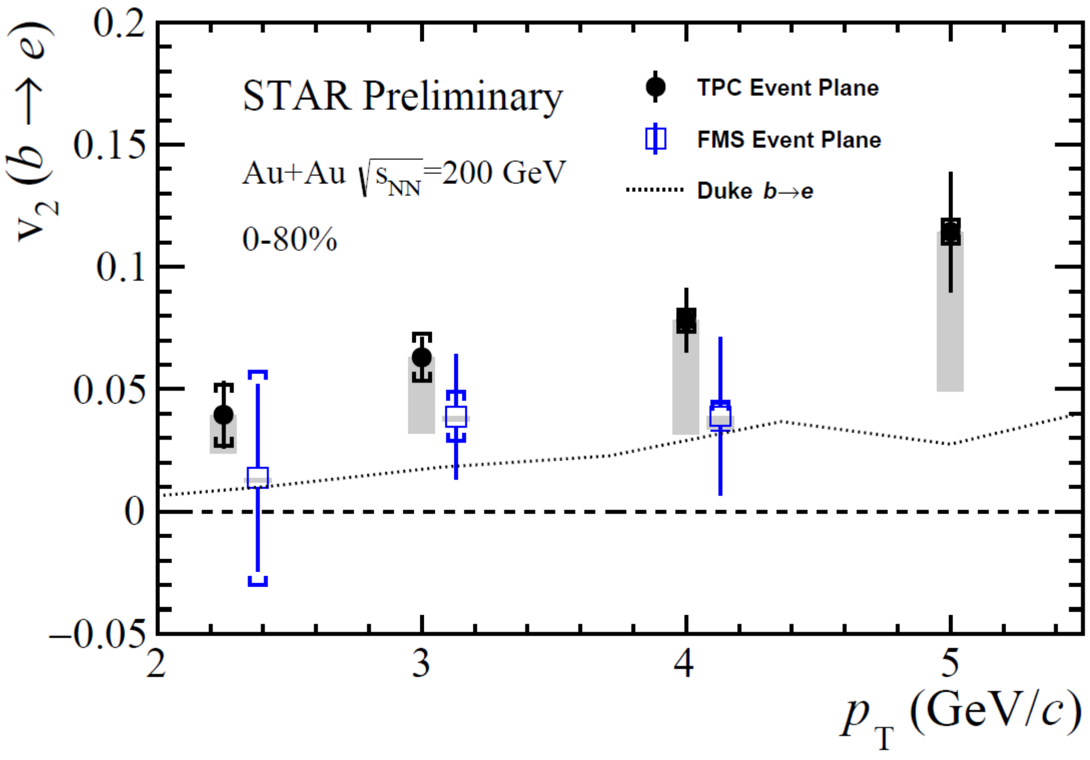


Duke model:
PRC 92, 024907

TPC event plane measurement null hypothesis with full non-flow subtraction:

χ^2/ndof = 17.1/3

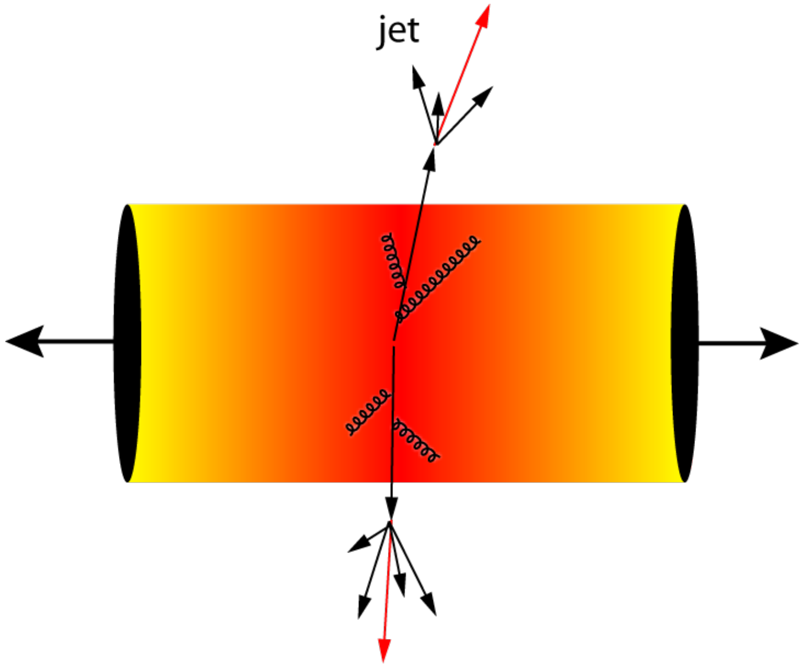
p-value = 0.00067 (3.4 σ)



$R_{AA}(B \longrightarrow e) < R_{AA}(D \longrightarrow e)$ > 3σ effect
Consistent with flavor ordering of parton energy loss: $\Delta E_c > \Delta E_b$.

First observation of significant non-zero bottom hadron flow (>3σ) at RHIC.

Tomography of QCD medium with jets



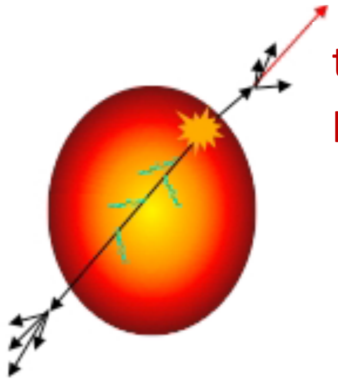
Focus on:

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

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

Semi-inclusive recoil jet studies

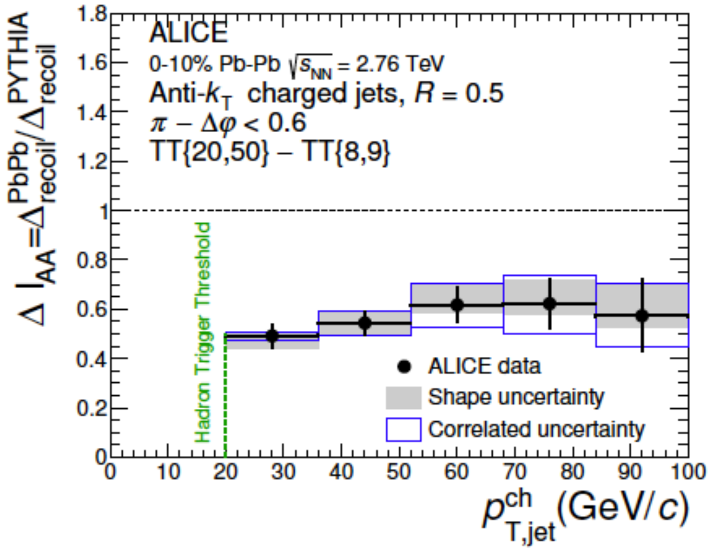
trigger particle



recoil jet

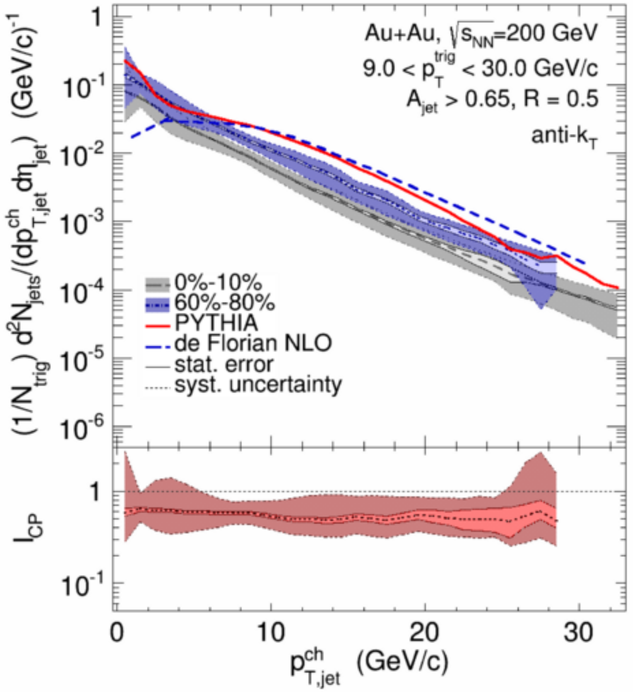
Trigger particle: charged hadron, π^0, direct photon (γ_{dir}) …

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

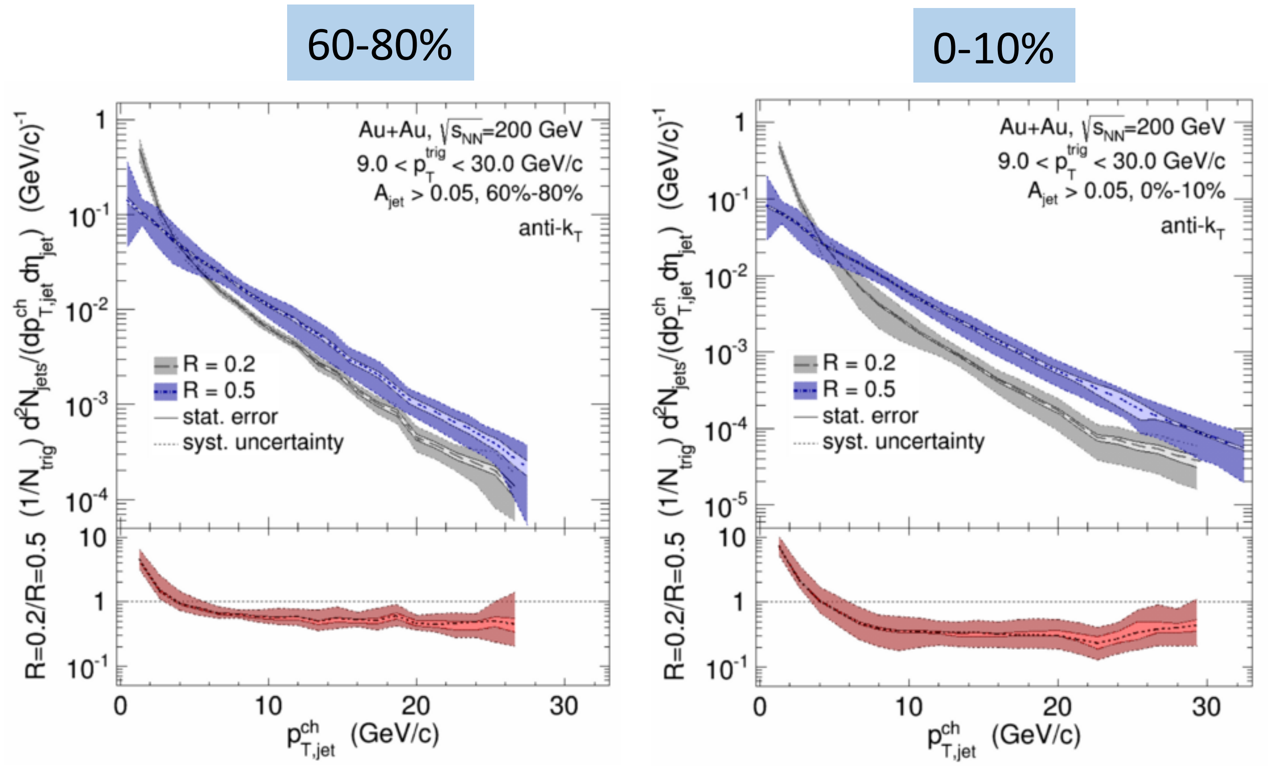
A unique observable:

- 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").

- 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:

→ 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.

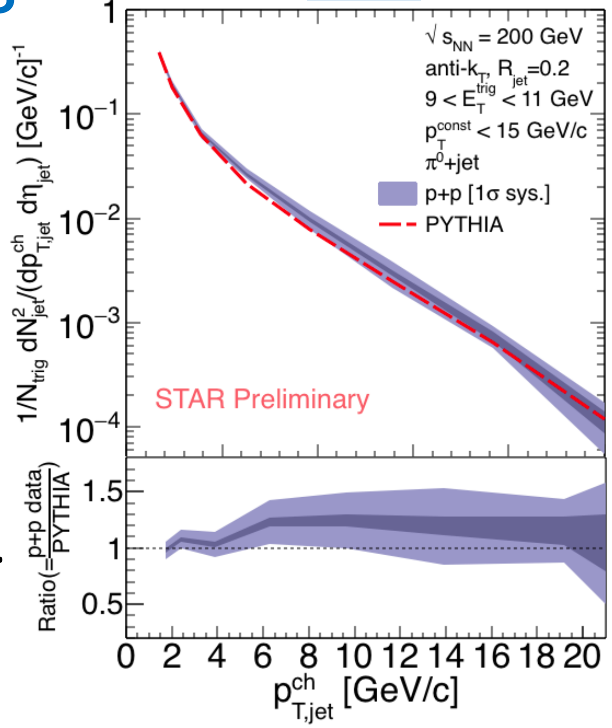
→ PYTHIA8 can be used as the p+p reference.

Au+Au collisions:

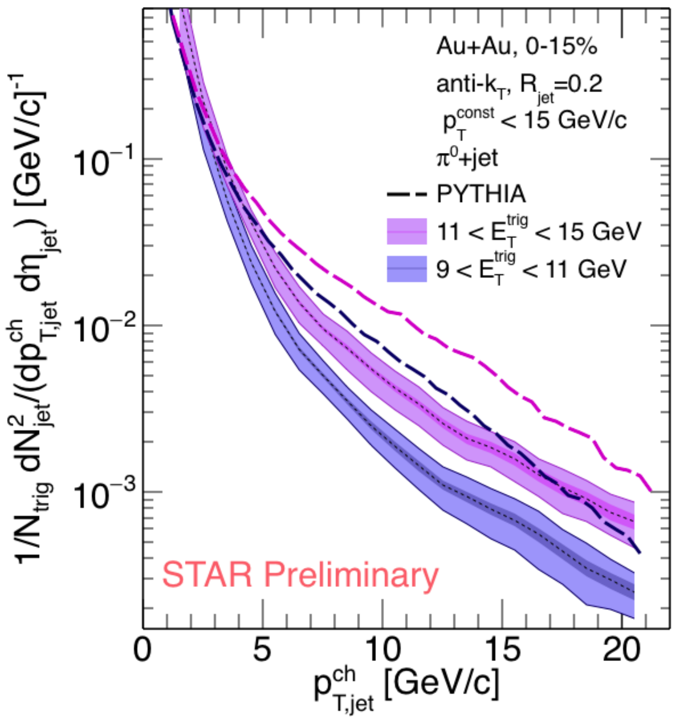
- Dominant systematic uncertainty is from unfolding.
- Clear difference between recoil charged jet spectra for different π^0 trigger E_T.
- Evaluate I_{AA} (ratio of per trigger recoil charged jet yield in Au+Au to pp collisions):

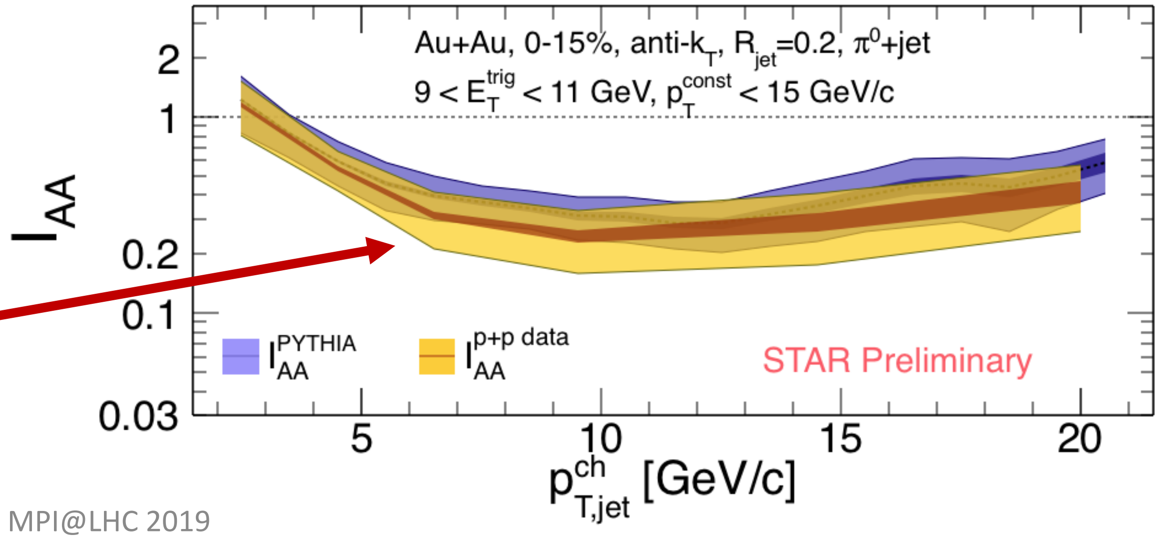
I_{AA} shows a clear suppression of recoil jets in central Au+Au collisions with respect to p+p reference, consistent with charged hadron+jet measurements.

p+p



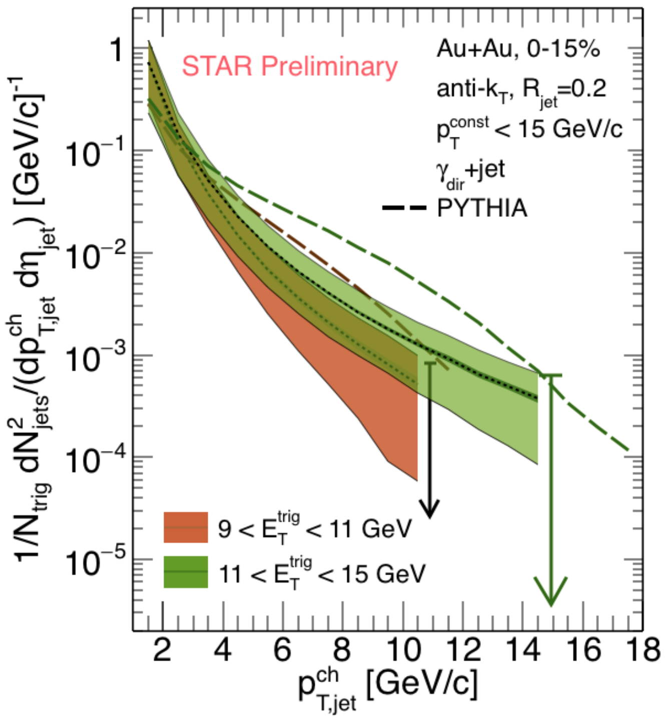
Au+Au



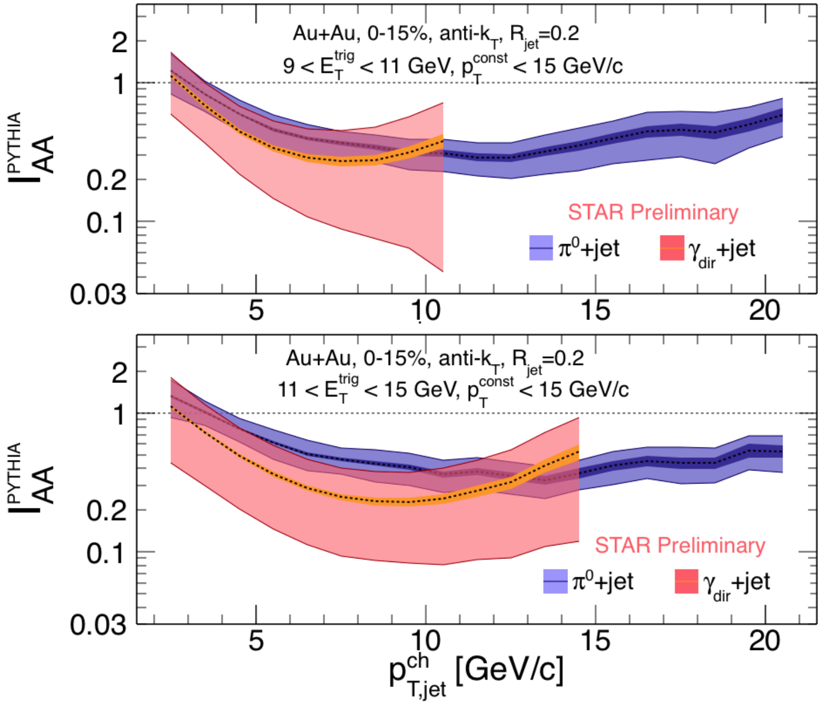


γ_{dir}-triggered recoil charged jets

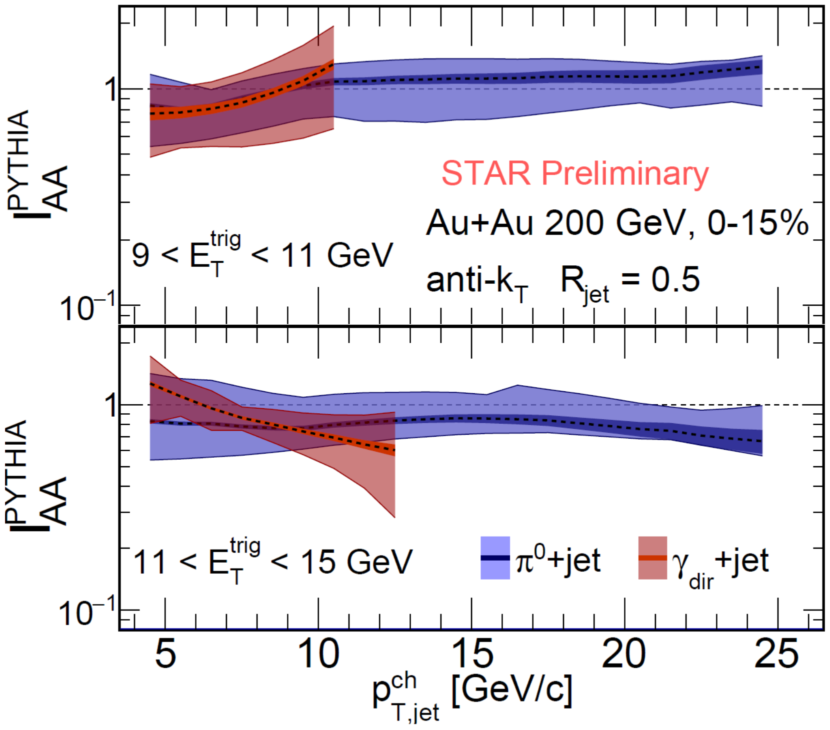
- Purity of direct photons varies between 65% and 89% for $9 < E_T^{trig} < 20$ GeV.
- Dominant systematic uncertainties are from unfolding and from γ_{dir} background subtraction.



R=0.2



R=0.5



Suppression of recoil jets with R = 0.2 in central Au+Au collisions with respect to PYTHIA observed. It is consistent with that for π^0+jet correlations.

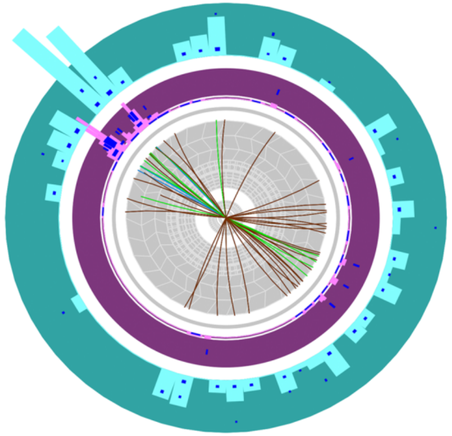
NEW: noticeable recovery of jet energy loss is observed at R = 0.5 for both the γ and π^0 trigger cases.

Dijet imbalance

Dijet asymmetry A_J quantifies momentum imbalance between dijets:

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

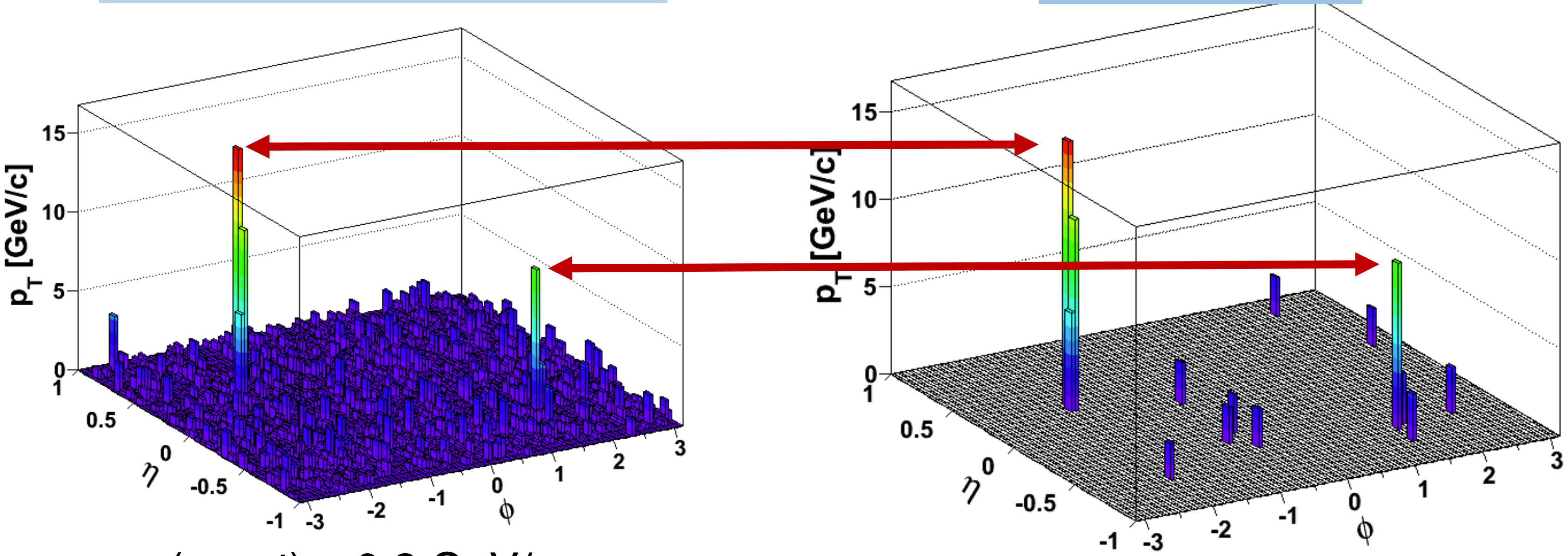
LHC: Strong dijet asymmetry without angular de-correlation observed



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:

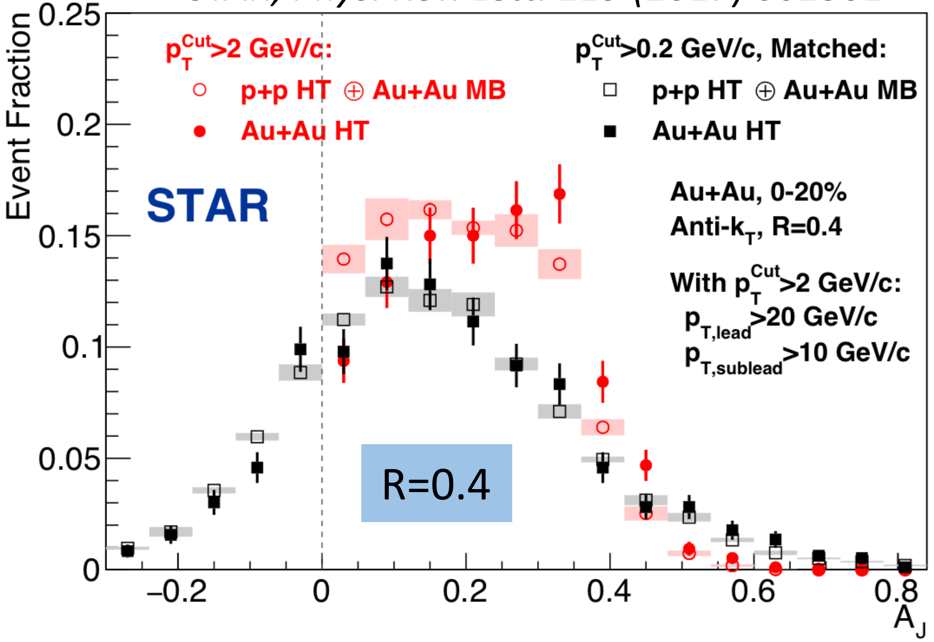
- Hard-core dijets more imbalanced with respect to p+p.

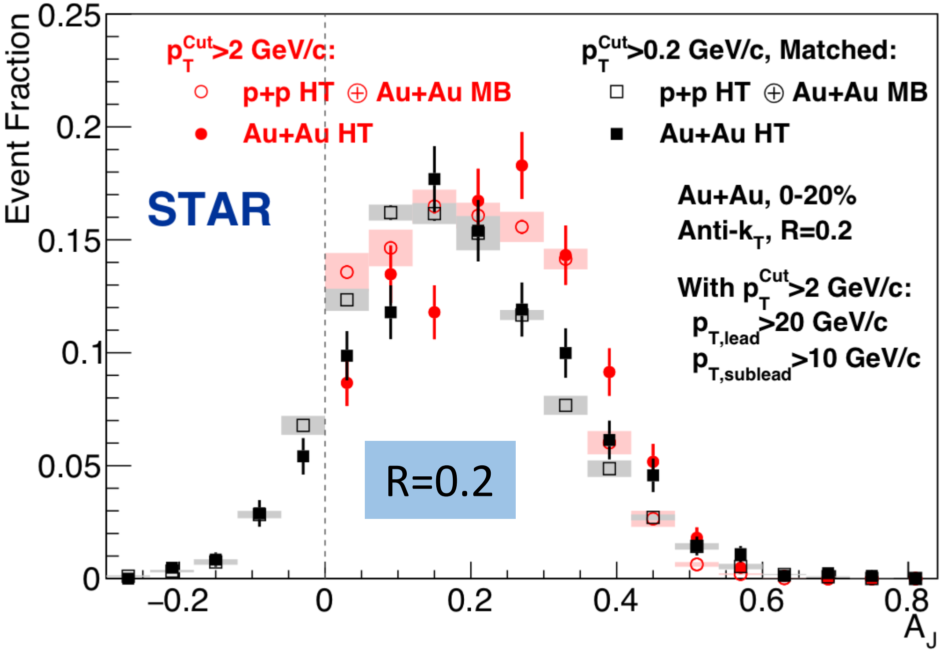
- R=0.4: inclusion of soft constituents restores the balance to the level of the p+p reference.

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

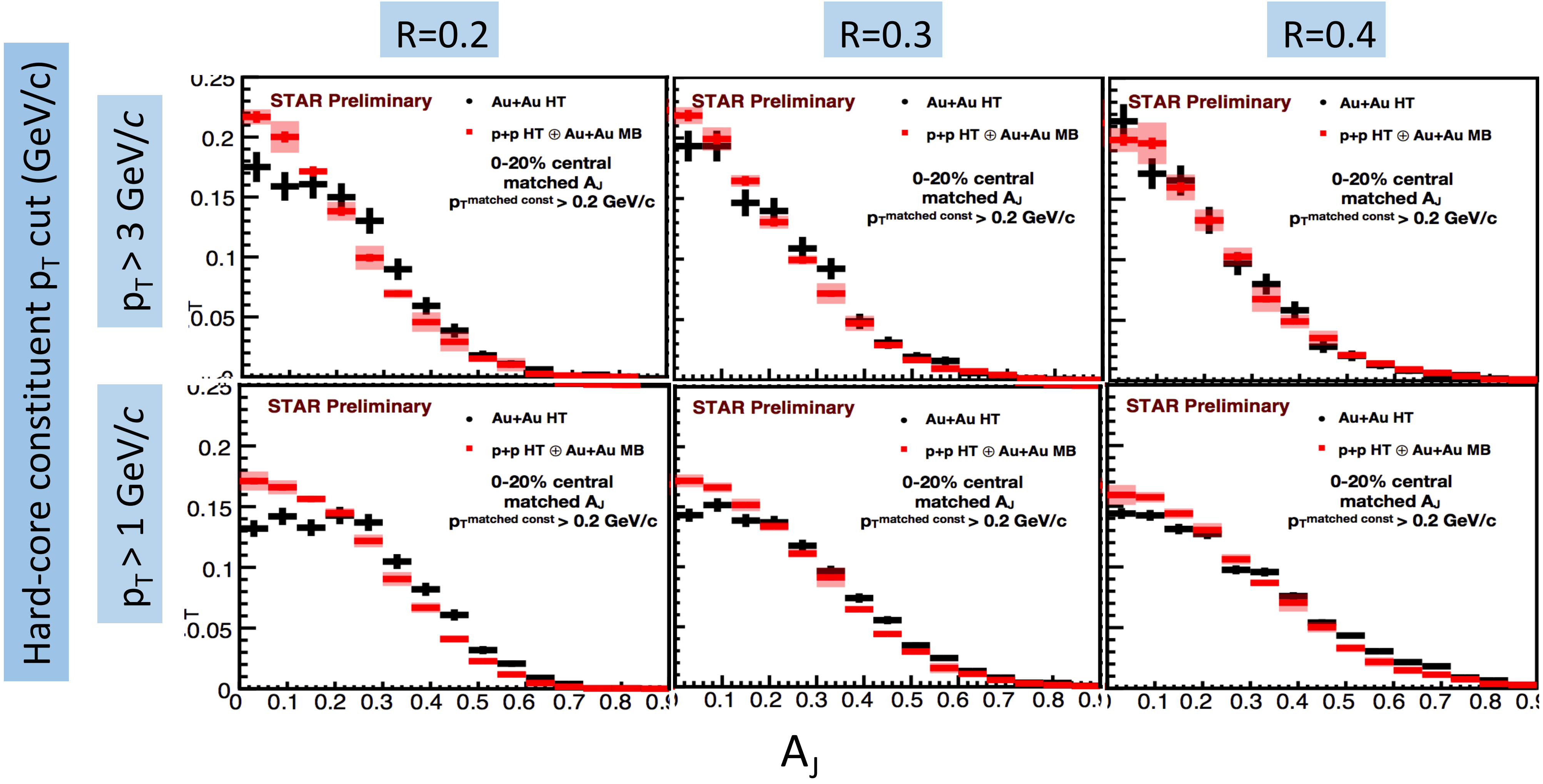
Softening of jet constituents and broadening of jets from R = 0.2 to R = 0.4 in central Au+Au collisions.

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





Jet geometry engineering



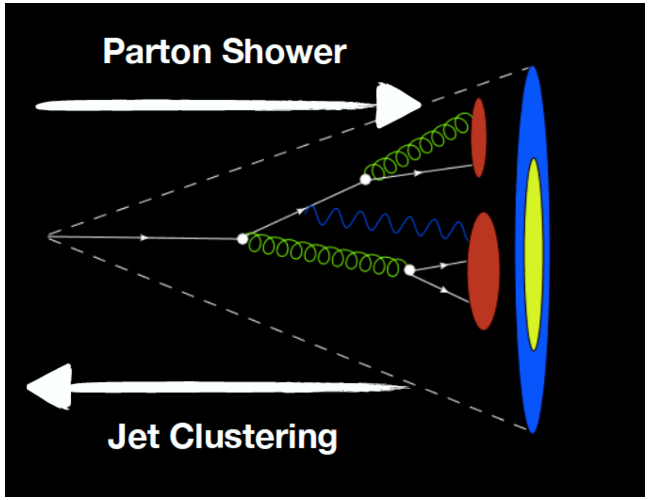
Dijet imbalance evolution with R and p_T constituent cut

- 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.



Medium:

Majumder, Putschke, PRC93 (2016) 054909
Mehtar-Tani, Tywoniuk, PRD98 (2018) 051501

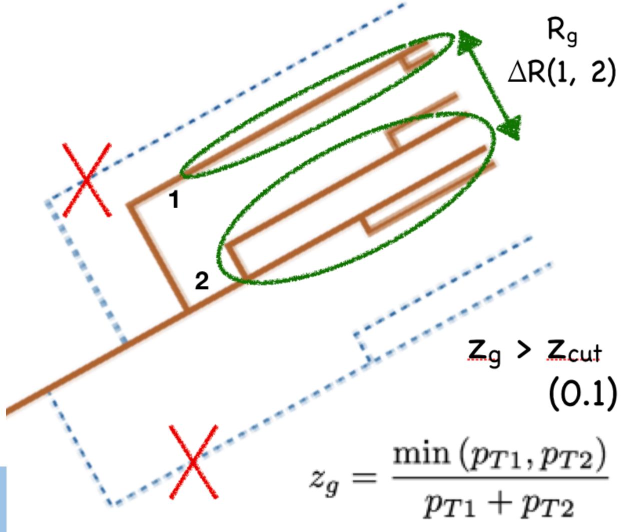
Angular/virtuality scale can be related to a "resolution scale" at which the jet probes the medium.

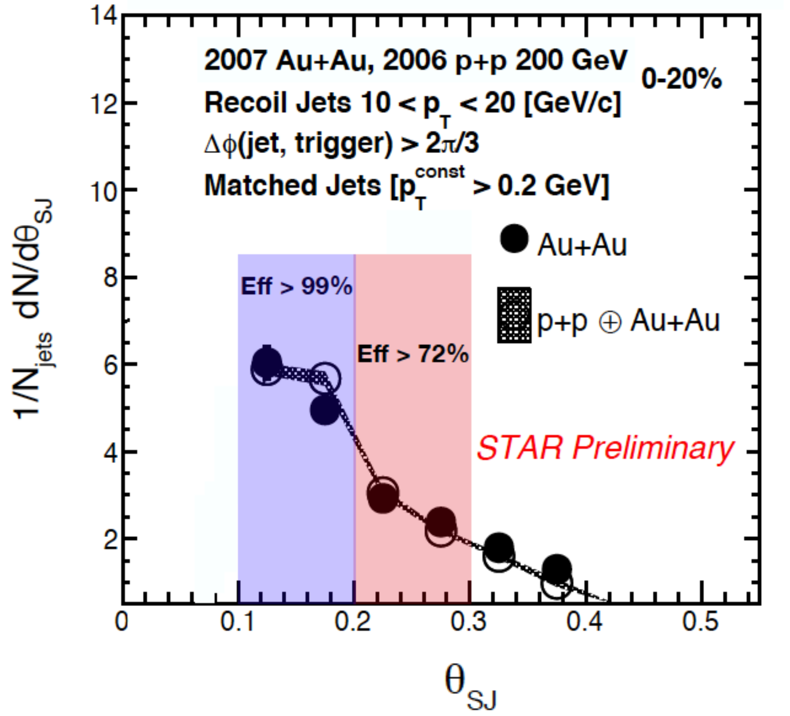
Utilize SoftDrop algorithm
- momentum scale – $z_{g,}$
- virtuality/angular scale – R_g.

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}

θ_{SJ} = ΔR(LeadingSJ axis, SubleadingSJ axis)





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

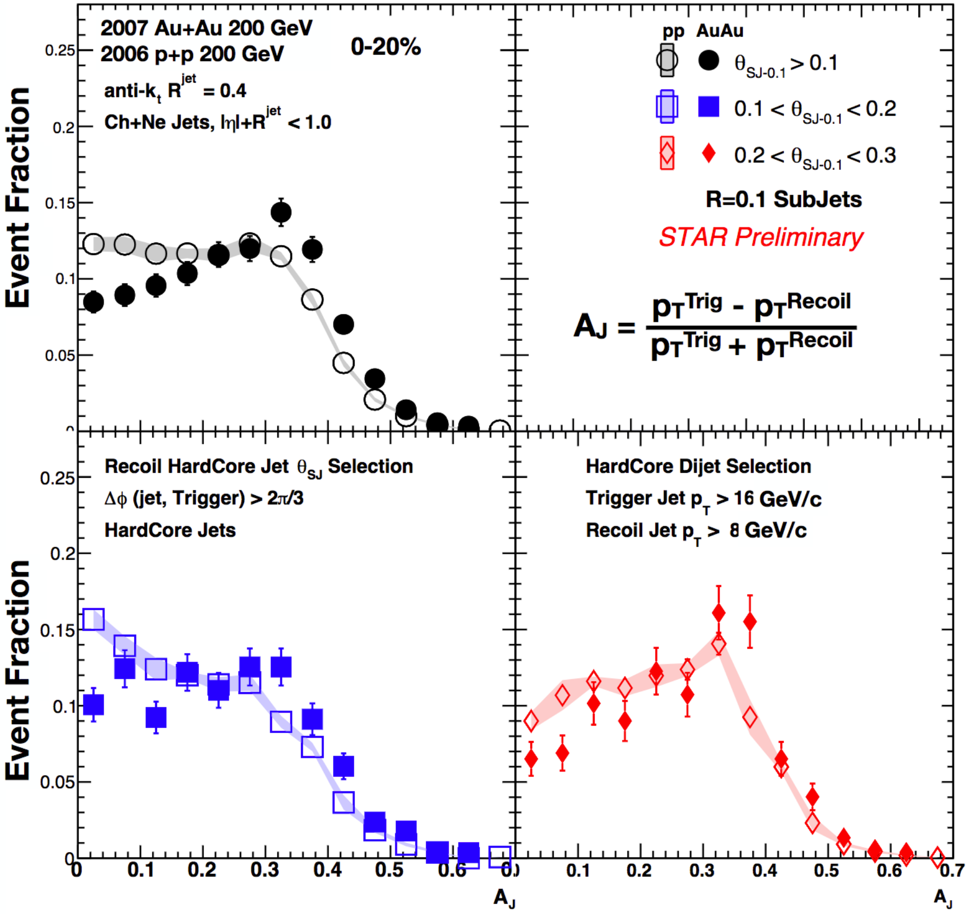
and study again "standard" observables e.g. A_J, recoil jet yield, …

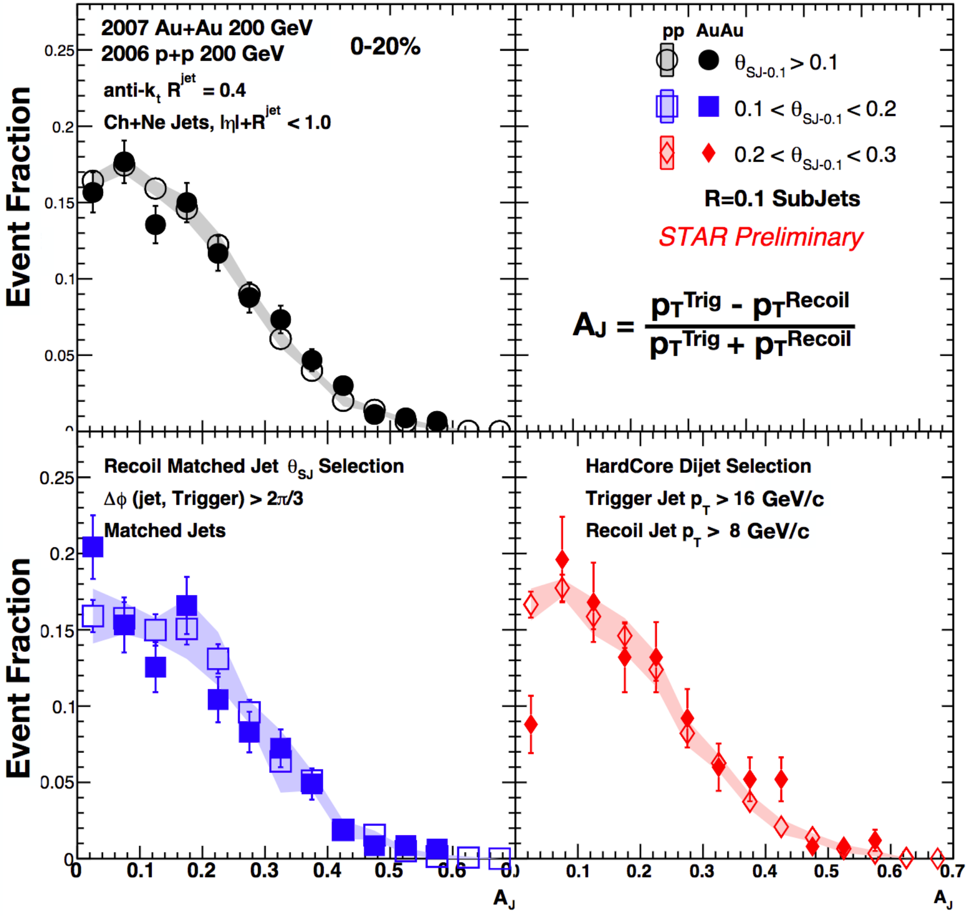
A_J for different jet angular scales

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 allow:
- detailed mapping of QCD phase diagram in BESI (completed) and BESII (ongoing) program + fixed target mode (ongoing, not shown)
- precision measurements of hard probes at top RHIC energy

Charm and bottom quarks:
- interact strongly with the QGP: modification of c-quark production is similar to that of light flavor hadrons, but b-quarks show less suppression:

→ hadrochemistry is significantly modified

→ evidence for charm hadronization via coalescence at intermediate p_T

Jets:
- h, γ, π^0 – jet correlations: lost energy is transferred to soft particles, recovery of energy loss is observed at R = 0.5
- 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.

Thank you for your attention!

In 2020 RHIC will celebrate 20 years!

Courtesy (photo and delicious RHIC cake) to Renata Kopecna, a former student at CTU Prague

Spares

Quarkonia as QGP thermometer

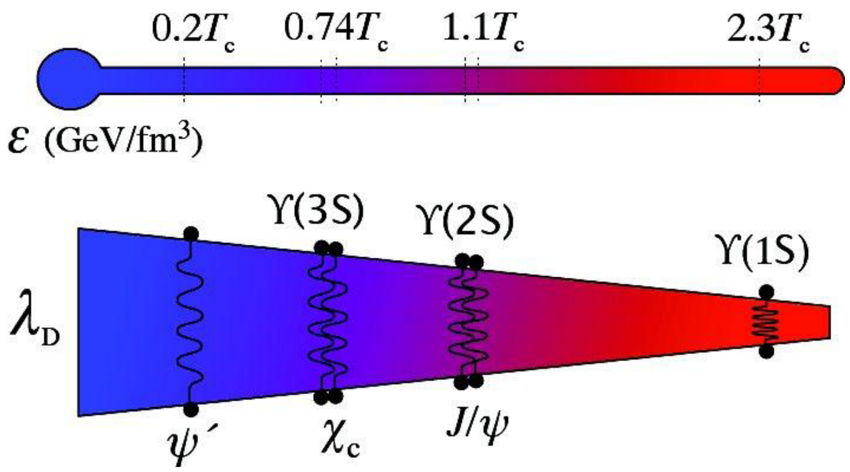
Quarkonia are bound states of a quark and an anti-quark of the same flavor:

c-quark:
charmonia: J/ψ, Ψ', χ_c

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

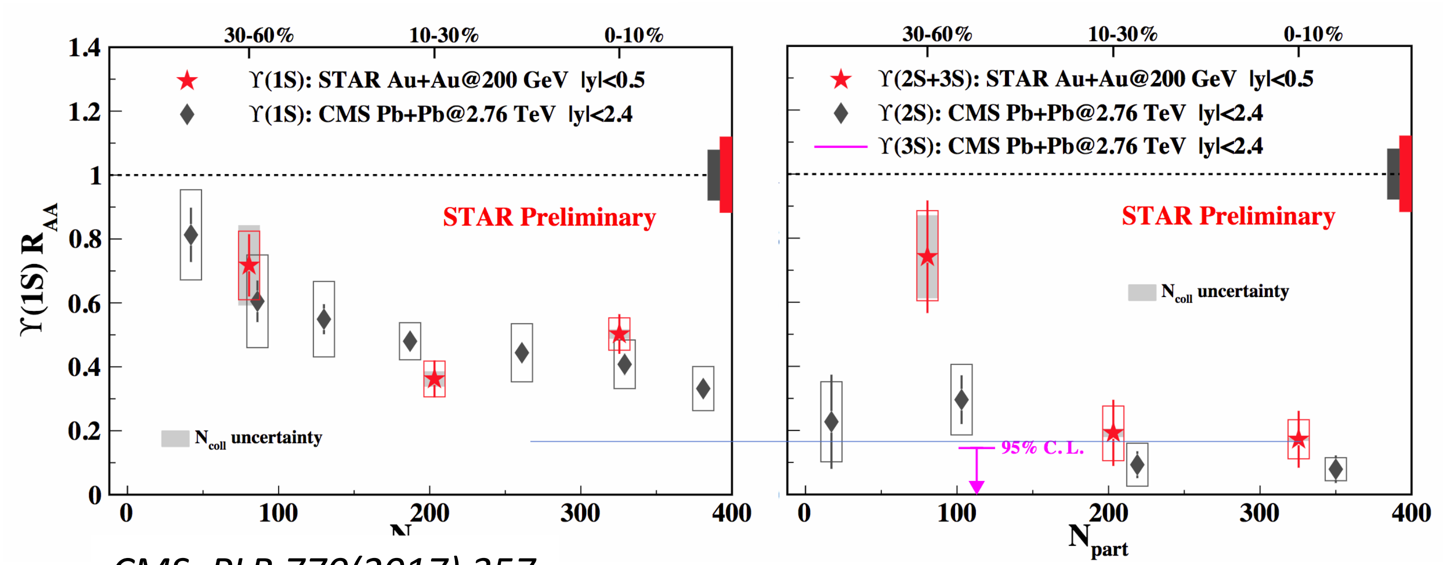
Quarkonia dissociate in QGP
due to color screening of potential between heavy-quarks.

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

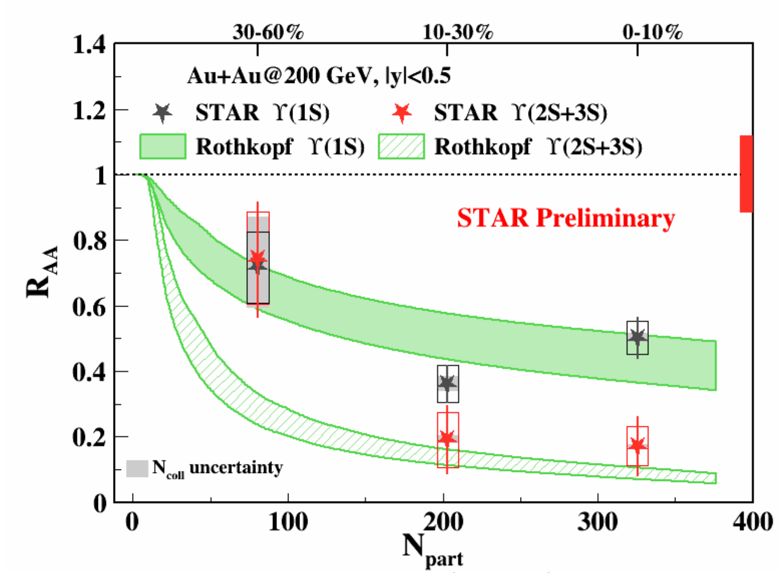


Temperature dependent sequential melting of quarkonium states predicted.

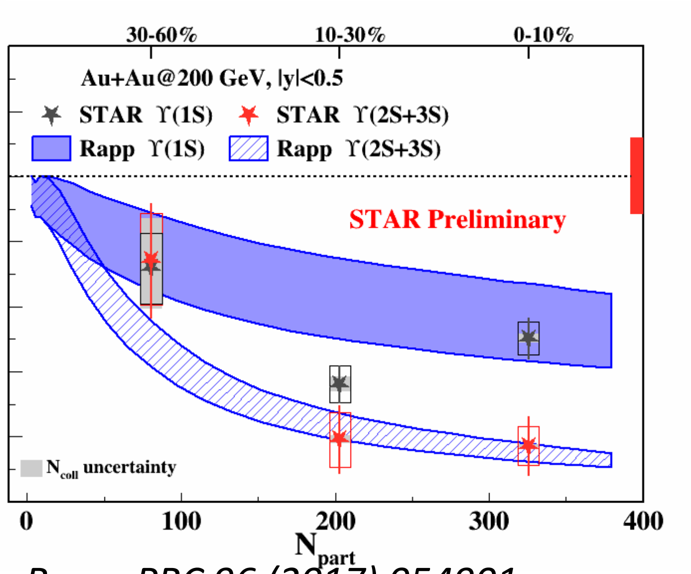
ϒ suppression in heavy-ion collisions



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)

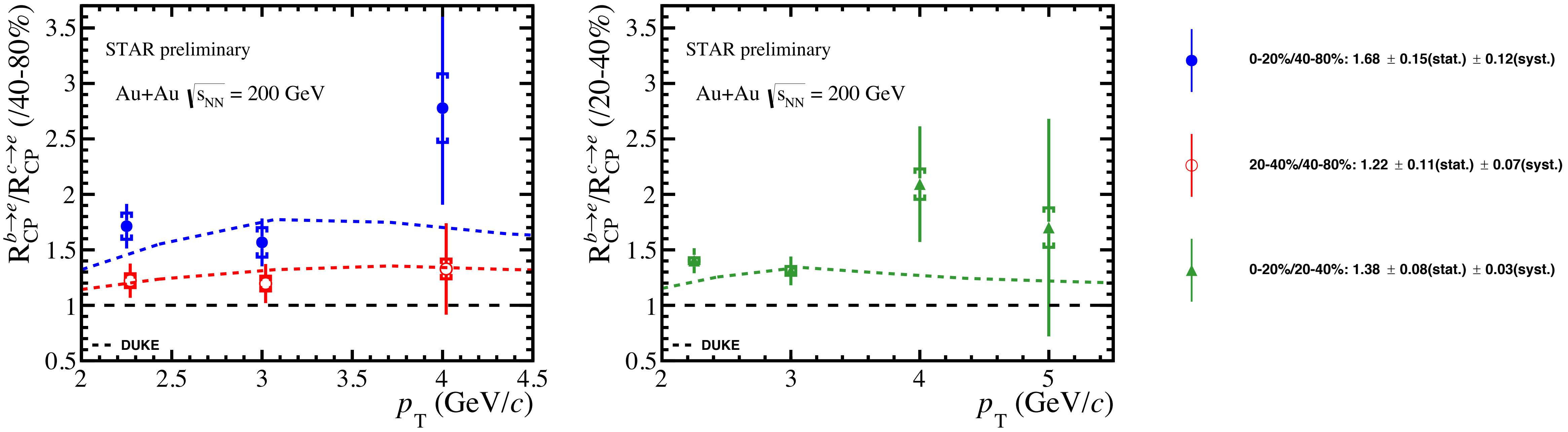
→ consistent with sequential melting.

Model comparison:

ϒ(1S): agreement with data,

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

R_{CP} double ratio (b →e/c→e)



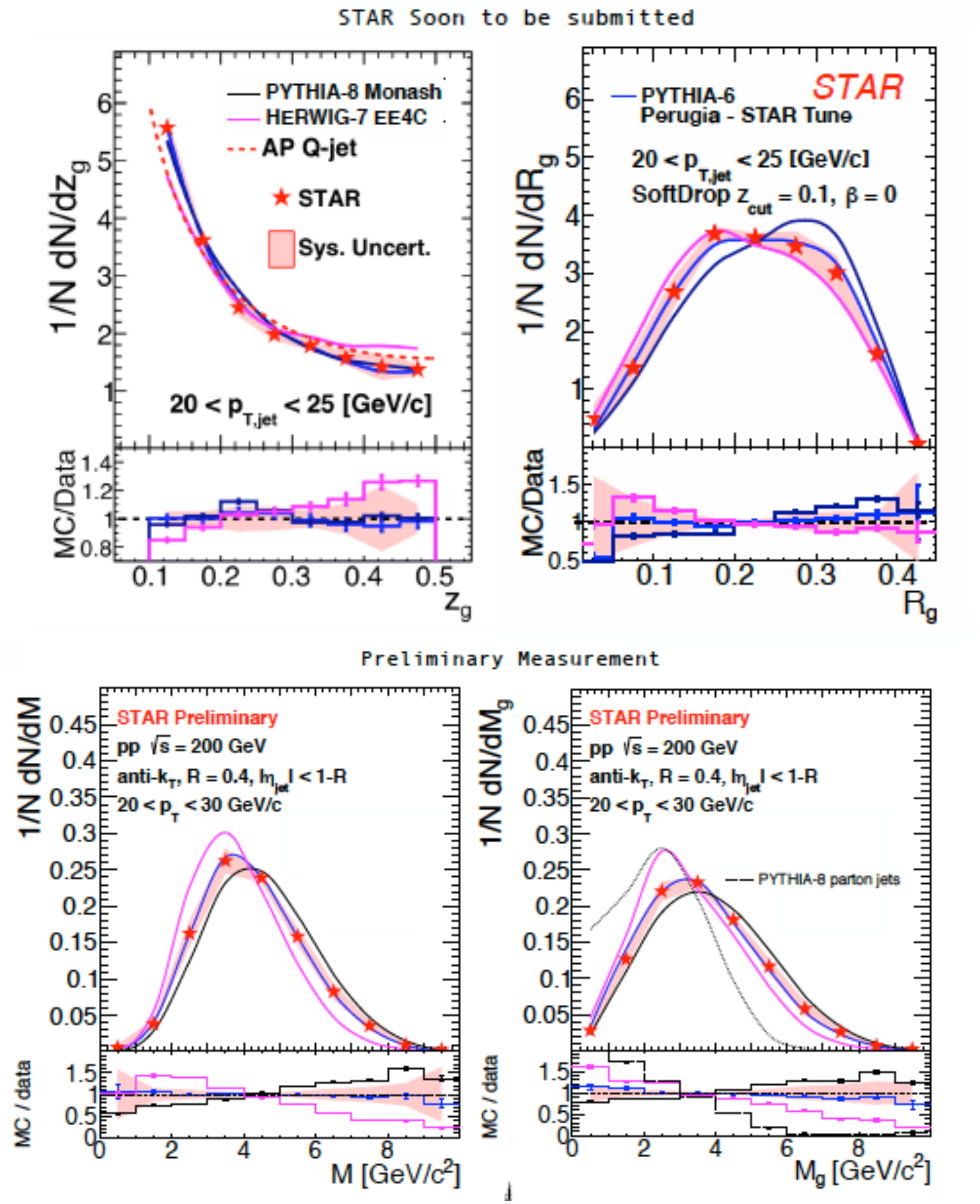
Constant fit to double R_{CP} ratio > 1

3.5σ for R_{CP}(0-20%/40-80%)

4.4σ for R_{CP}(0-20%/20-40%)

DUKE: Phys. Rev. C 92, 024907 Private Communication

Jet substructure observables in p+p collisions



STAR measured several jet substructure related observables in p+p collisions at 200 GeV (Run 12):

- Splitting functions: momentum scale z_g
  angular scale R_g
- Invariant and groomed jet mass: M, M_g

Jet substructure observables generally described by leading order tuned MC generators.

- PYTHIA 6 tuned for RHIC kinematics works best
- PYTHIA 8 and HERWIG 7 LHC tunes show deviations
  → need to be tuned to RHIC kinematics!

Let us come back to Au+Au collisions …