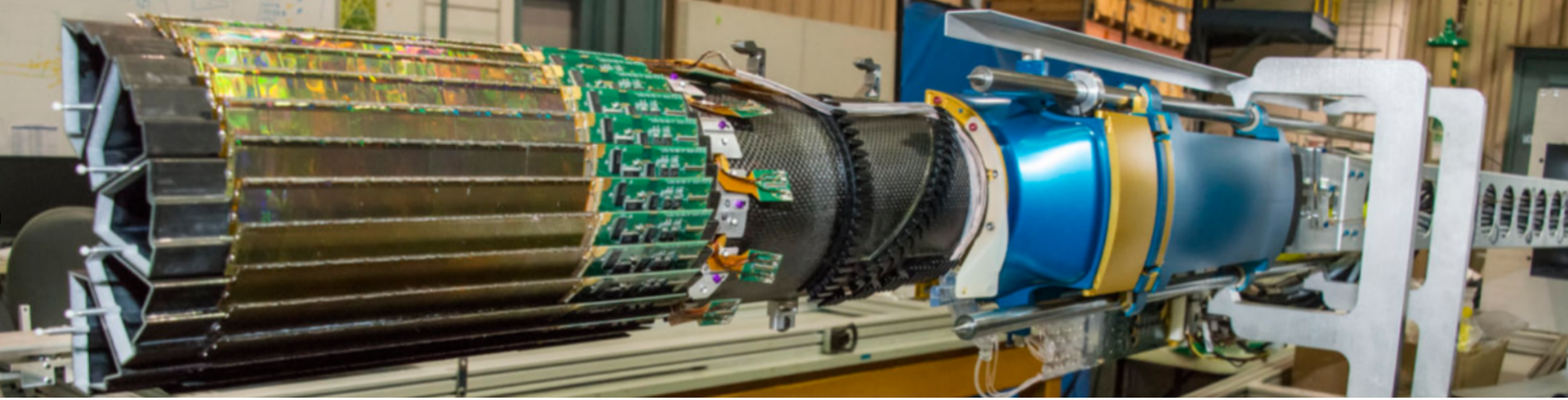


'Charm'ing new results from STAR!

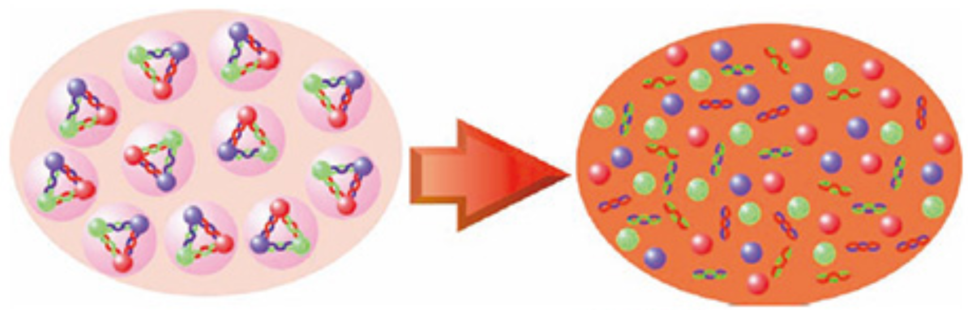
NSD Staff Meeting, January 22, 2019
Sooraj Radhakrishnan
Relativistic Nuclear Collisions, LBNL

BERKELEY LAB

U.S. DEPARTMENT OF ENERGY | Office of Science

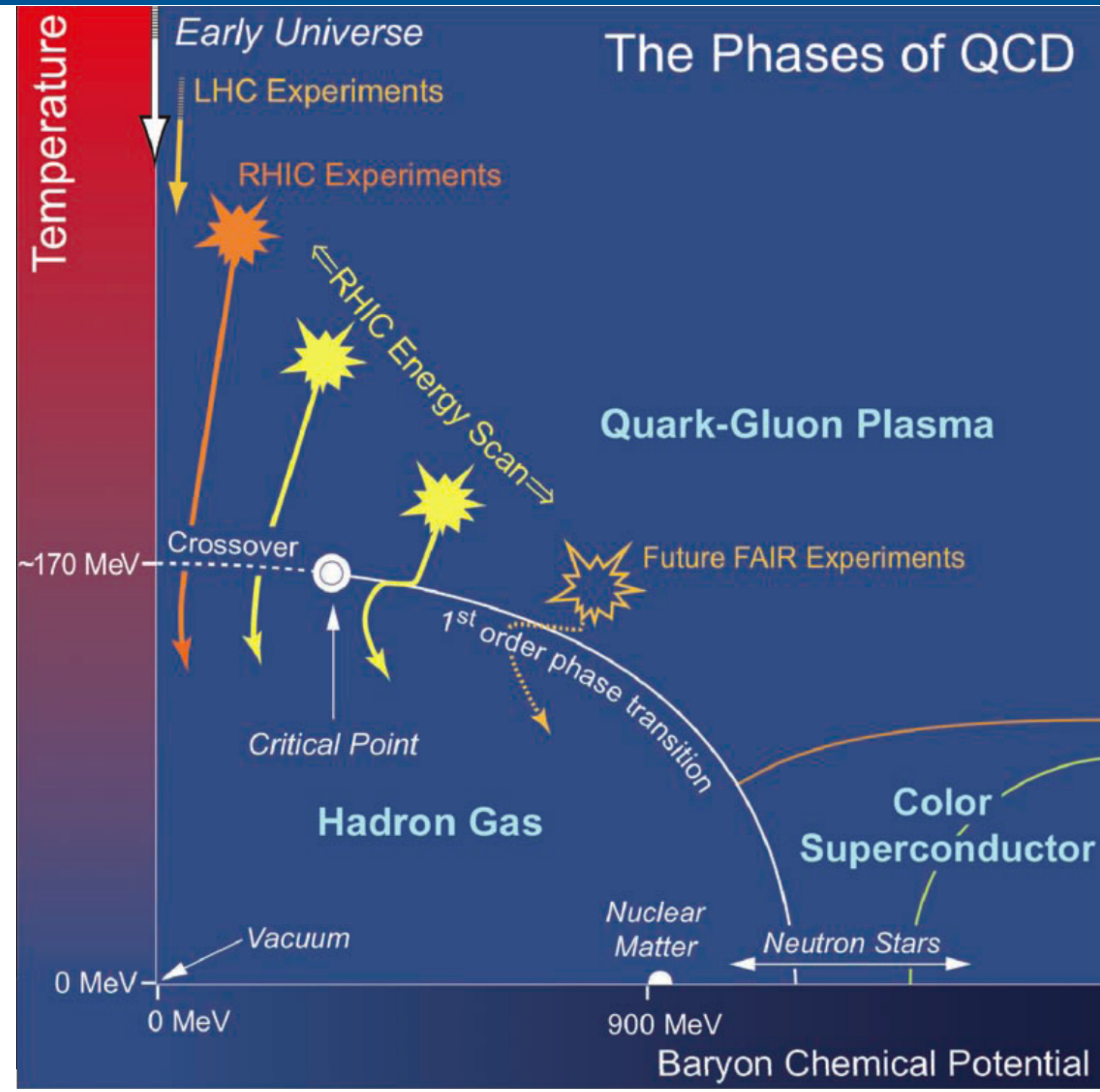
STAR

Relativistic Nuclear Collisions



Ordinary nuclear matter

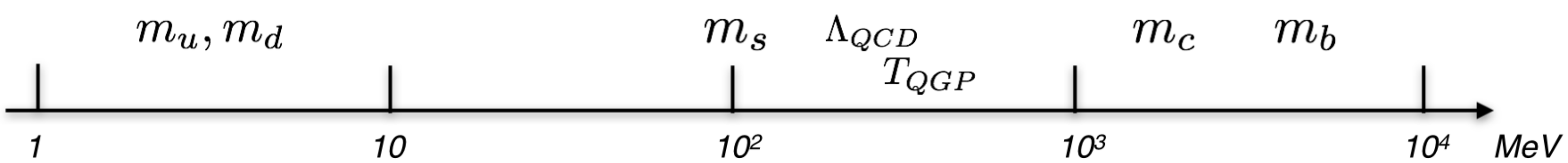
Quark-Gluon Plasma (QGP)



- Nuclear matter transitions to QGP phase at very high temperatures and densities
- Study properties of QGP, evolution, interactions with color charged probes, nature of phase transition, QCD phase diagram,..

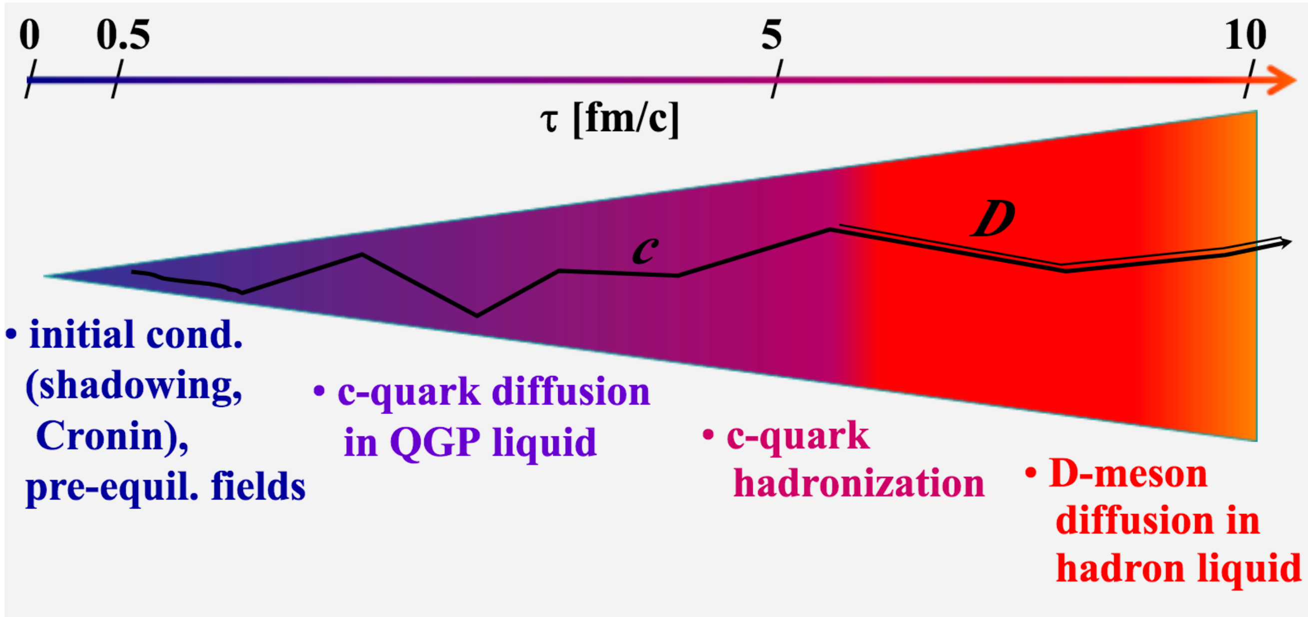
- Active experimental programs at Relativistic Heavy Ion Collider (RHIC) and Large Hadron Collider (LHC)

Heavy quarks in QGP



Charm (and bottom) quarks produced predominantly in initial hard scatterings:
Ideal probes to study medium interactions and QGP properties

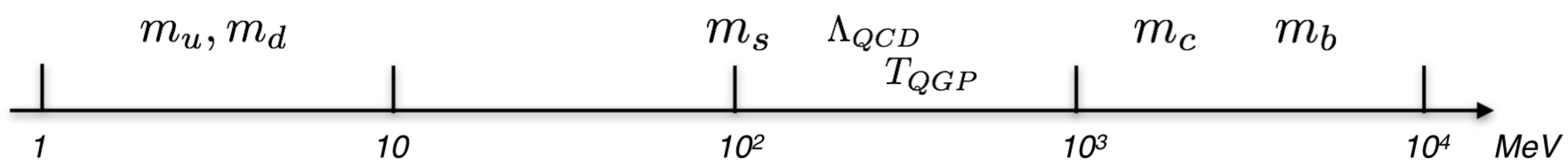
Can study various aspects of charm quark evolution in the QGP



- Charm quark energy loss:
  - D^0 R_{AA} and R_{CP} *[arXiv:1812.10224 (2018)]*
- Transport in QGP:
  - Elliptic (v_2) [*PRL.118.212301 (2017)*]
  - and directed (v_1) flow of D^0
- Hadronization:
  - Λ_c production, D_s production

New results from STAR!

Heavy quarks in QGP



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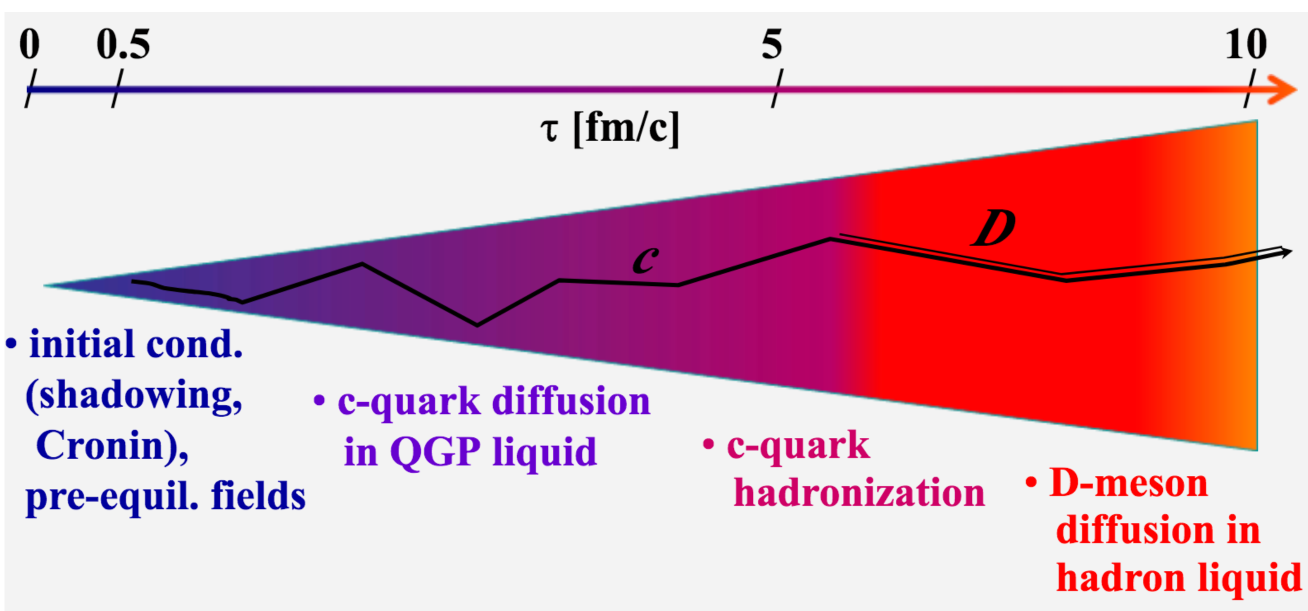

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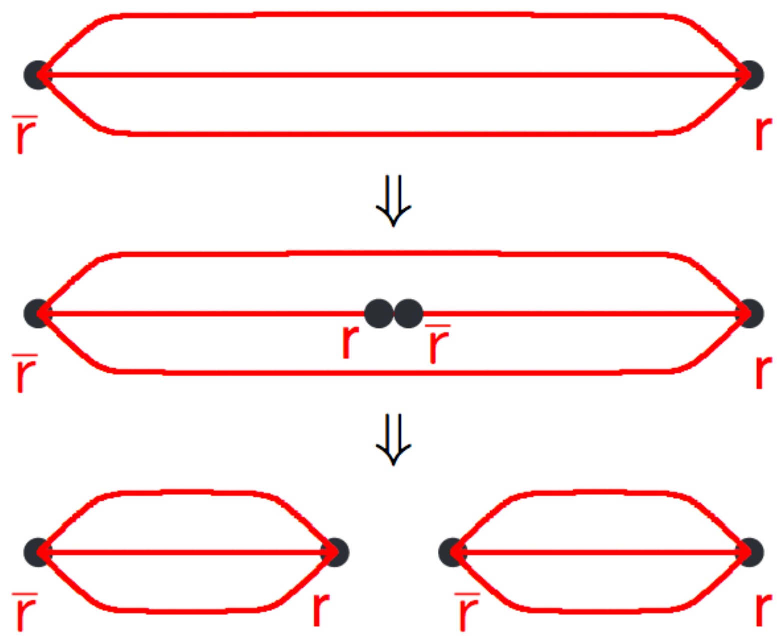
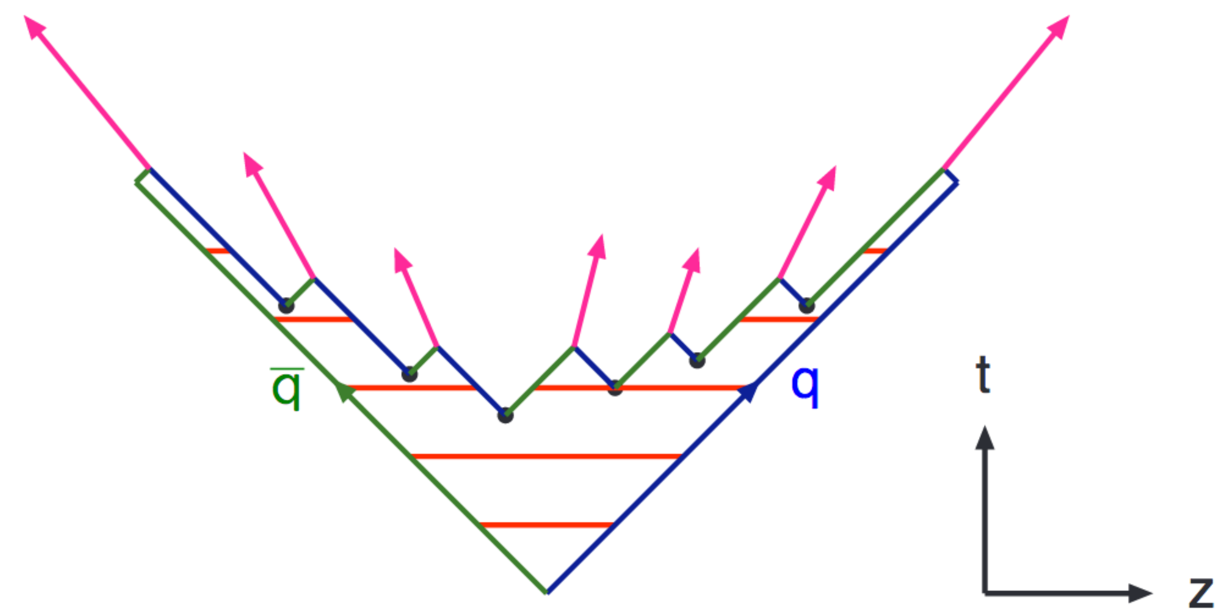
  and directed (v_1) flow of D^0
- **Hadronization:**
  Λ_c production, D_s production

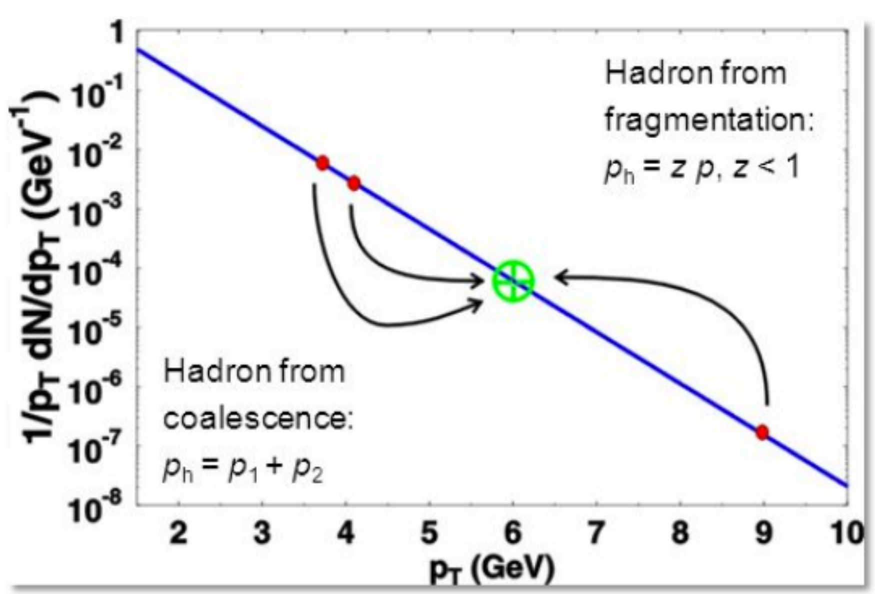
Hadronization: Λ_c production

- Hadronization implemented in PYTHIA via string fragmentation.





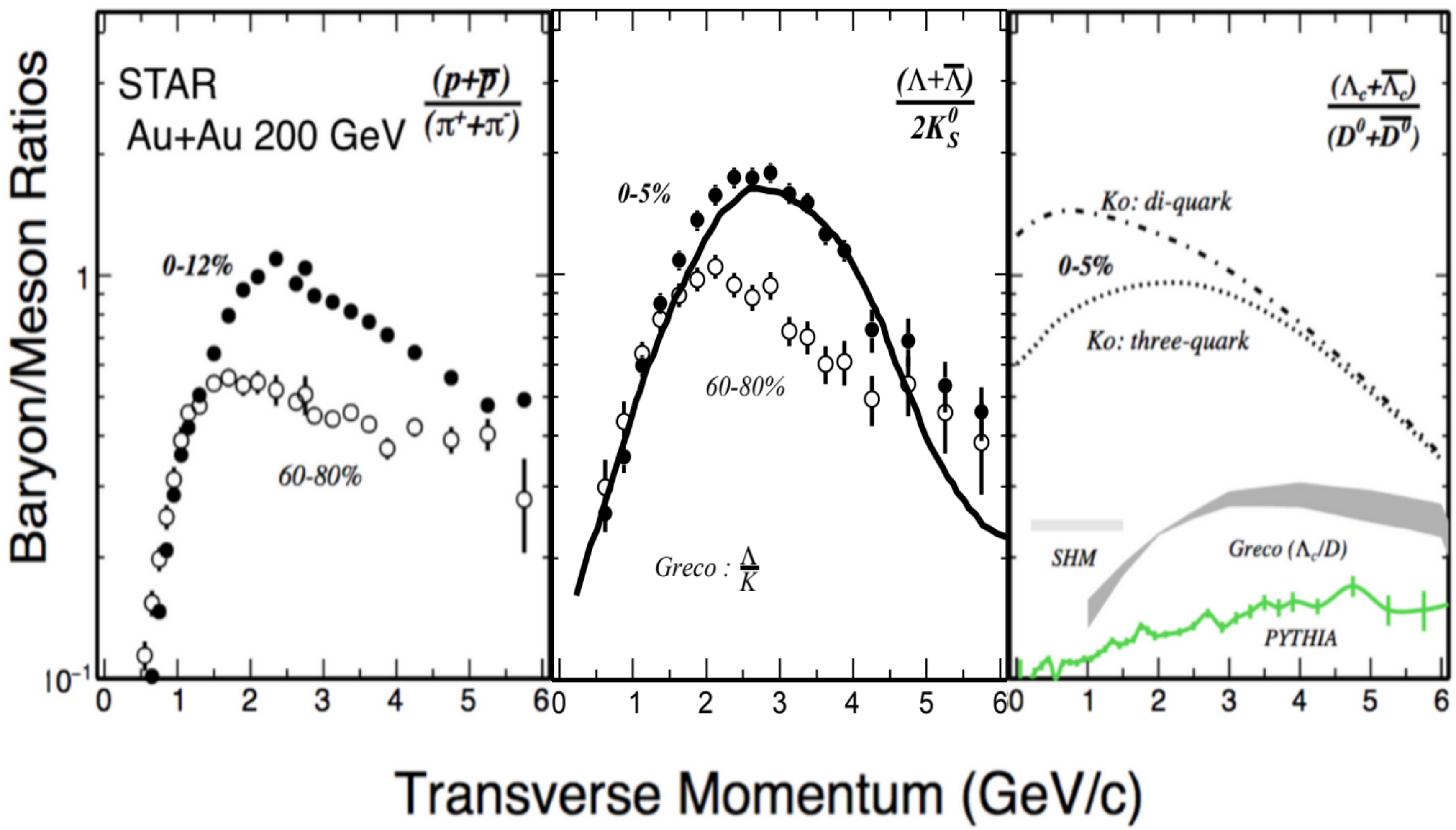
- In heavy-ion collisions the deconfined quarks can hadronize via coalesence
- Enhances baryon production compared to string fragmentation



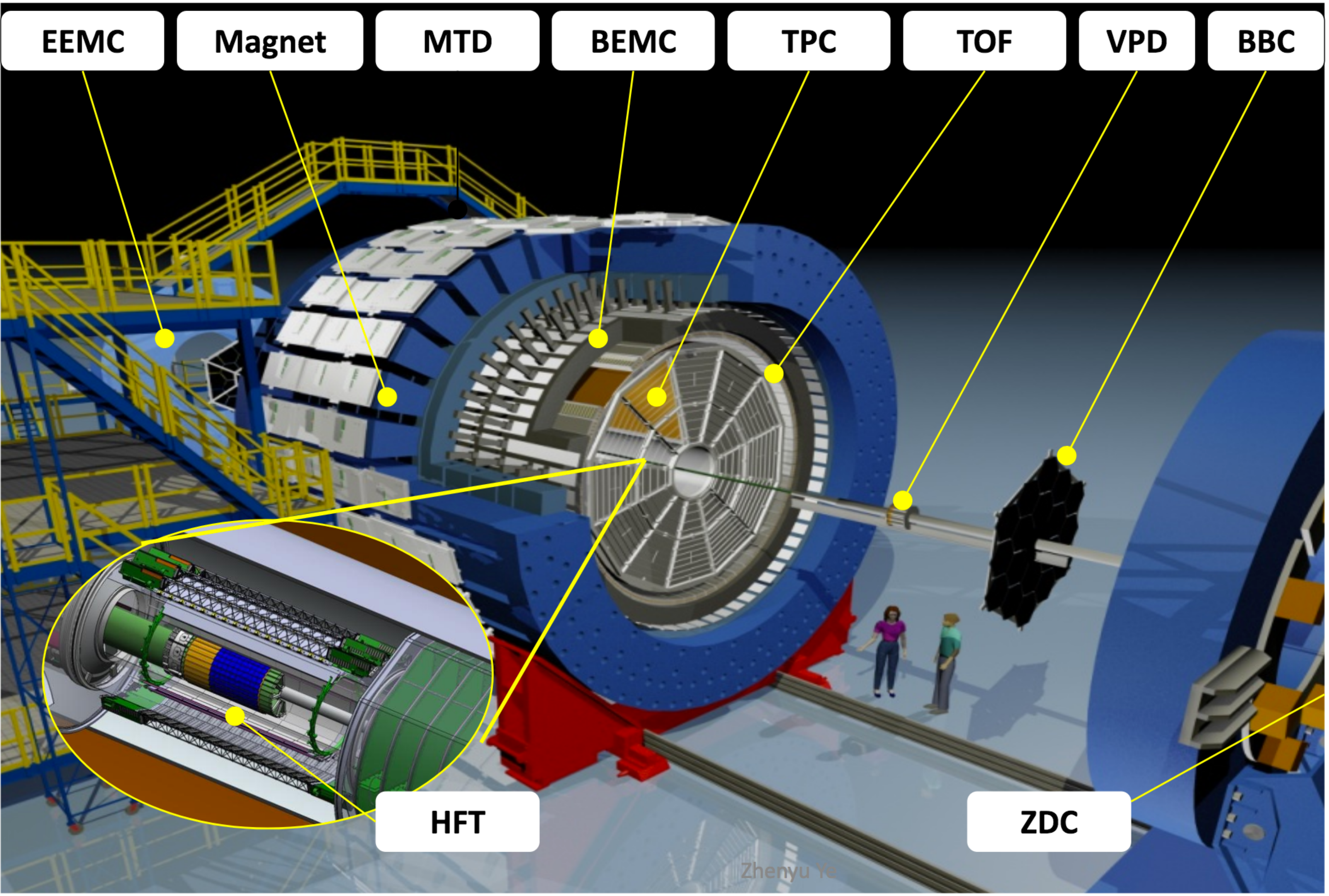
Hadronization: Λ_c production

- Enhancement in B/M ratio at intermediate p_T if hadronization by coalesence
- Observed for light and strange flavor hadrons

- Also important to understand charm hadron (eg: D^0) modification and energy loss in QGP and total charm cross-section



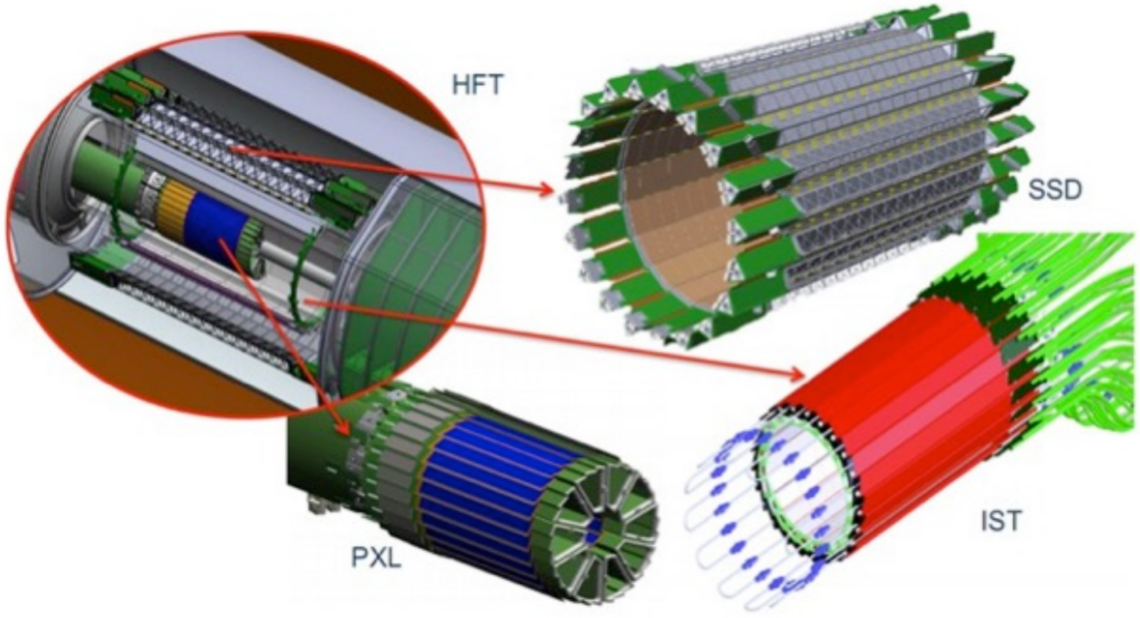
The STAR Detector

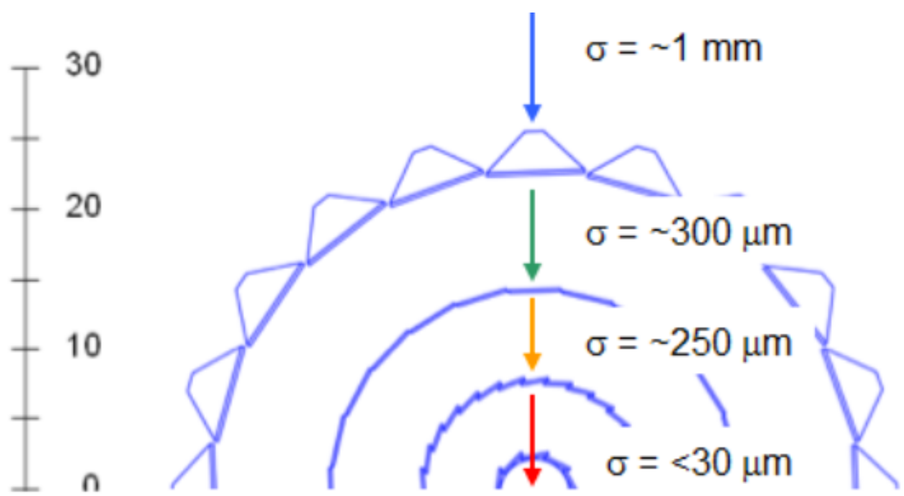


- Charged particle tracks reconstructed with TPC (and HFT)
- Particle identification from ionization energy loss in TPC and time of flight from TOF detector

- Heavy Flavor Tracker (HFT) installed for runs in 2014-2016

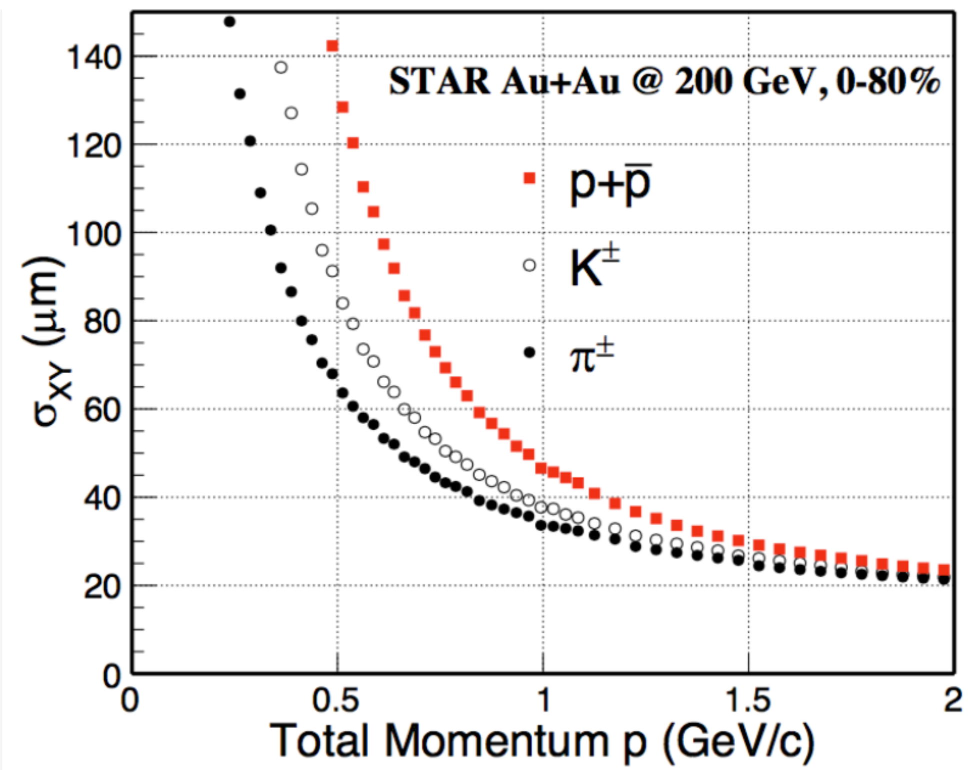
Heavy Flavor Tracker





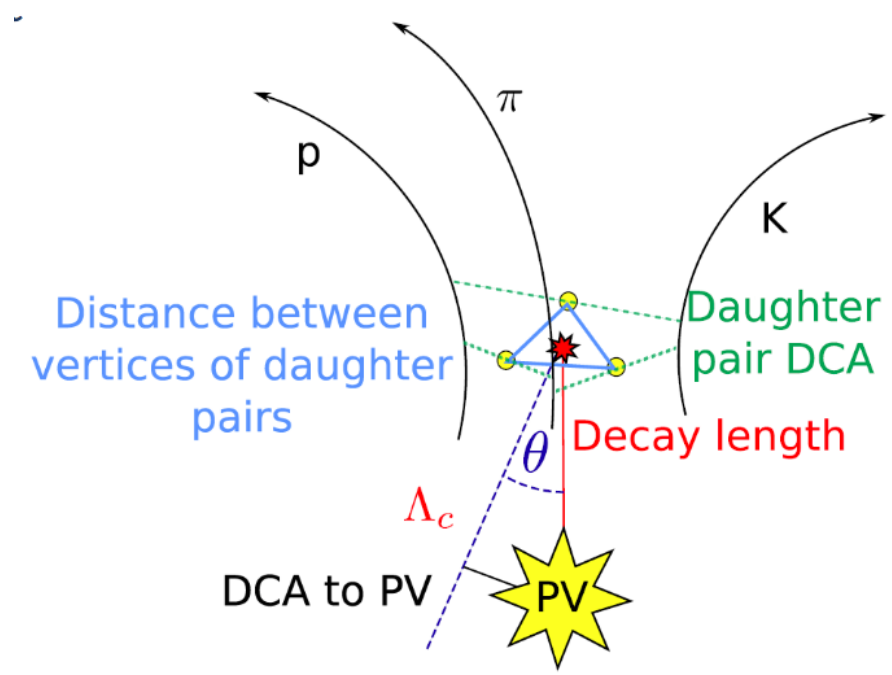
- HFT: 2 layers of Si pixels with MAPS and 2 layers of Si strips
- Full azimuthal coverage
- Provides excellent vertex position resolution and allows reconstruction of charm hadron decays

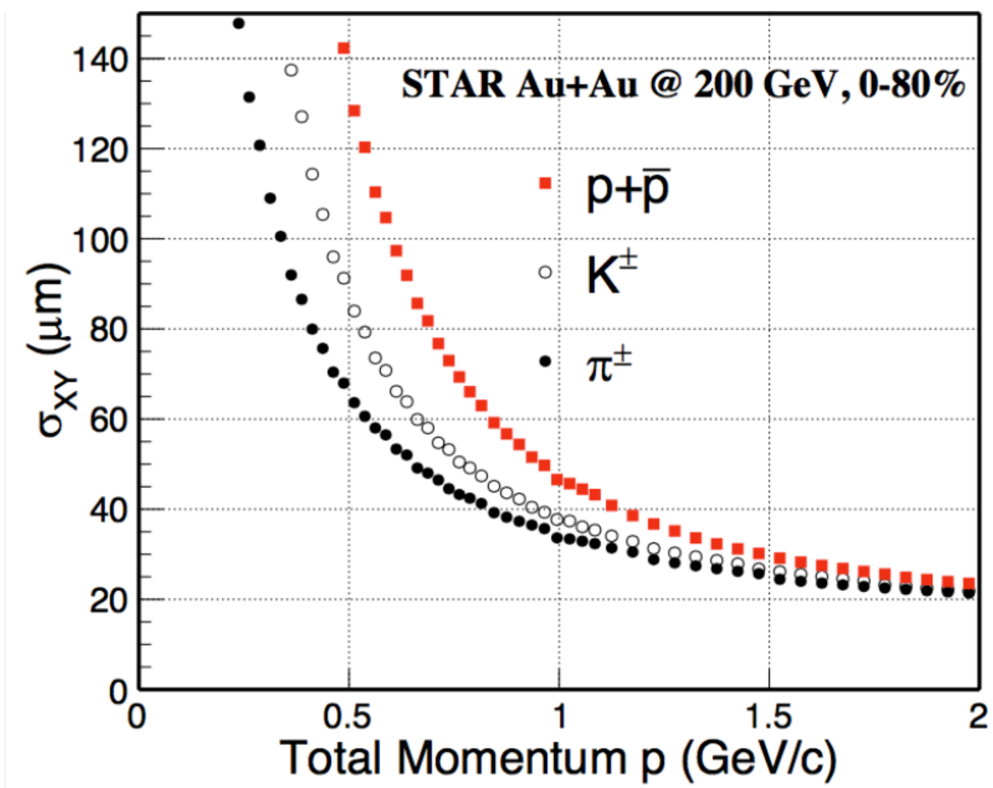
- Designed and constructed primarily at LBNL



Λ_c signal reconstruction

- Λ_c reconstructed with the pKπ channe, Life time about 60 μm!
- HFT improves S/B ratio for reconstructing Λ_c decay
- Three body decay, huge combinatorial background in HI collisions

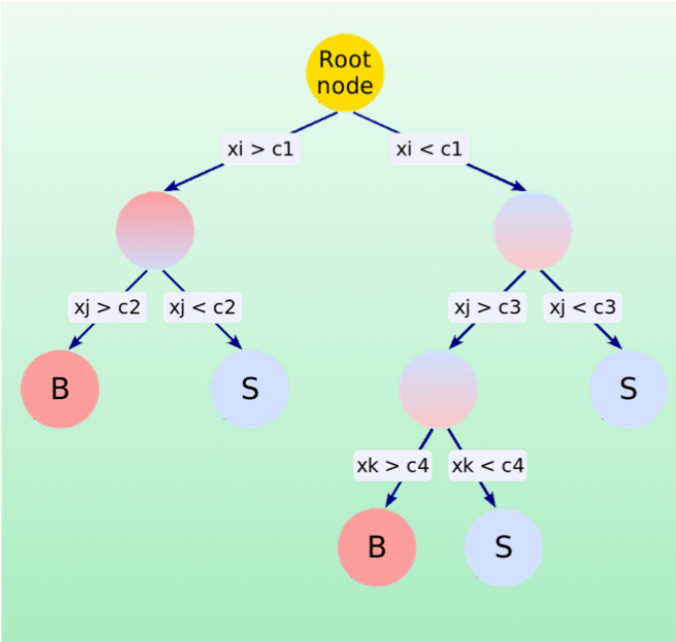




- Use Supervised Learning Methods to improve signal to background separation

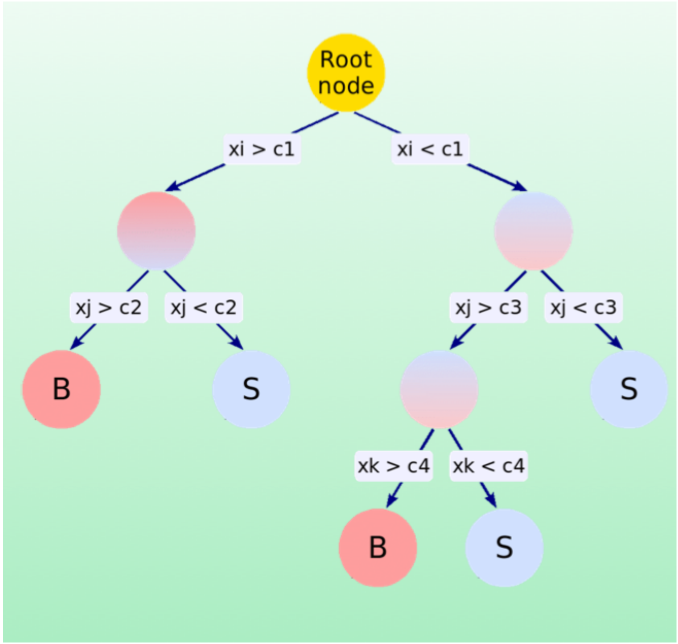
Λ_c signal reconstruction

- ***Boosted Decision Trees:*** Decision trees recursively split the data into subsets. At each decision node a binary classification is made untill a classification a reached
- 'Boosting' improves classification power and reduce overtraining

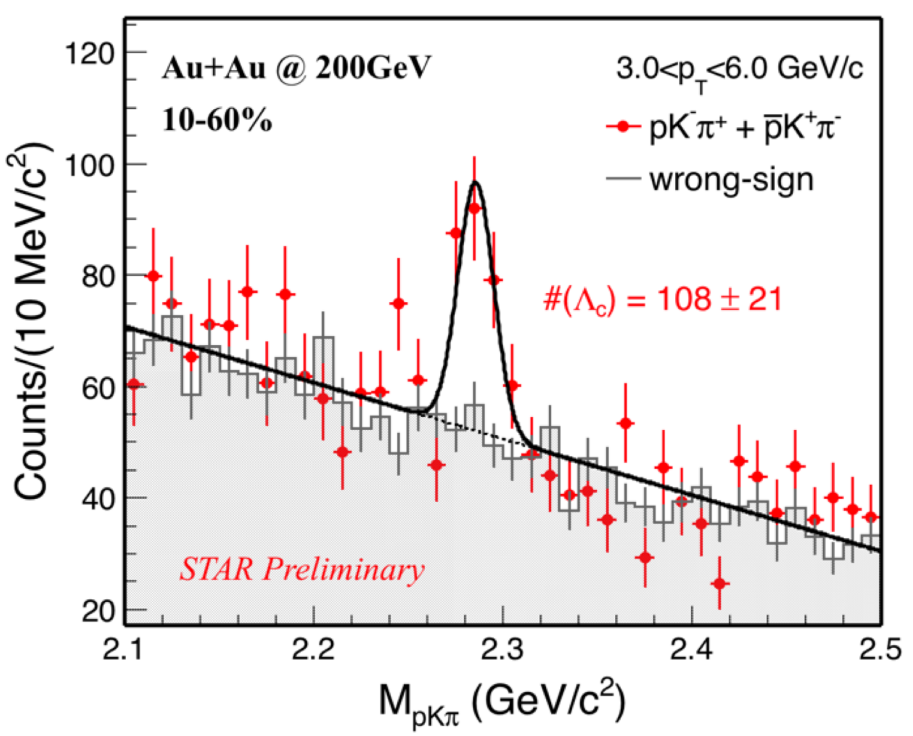


Λ_c signal reconstruction

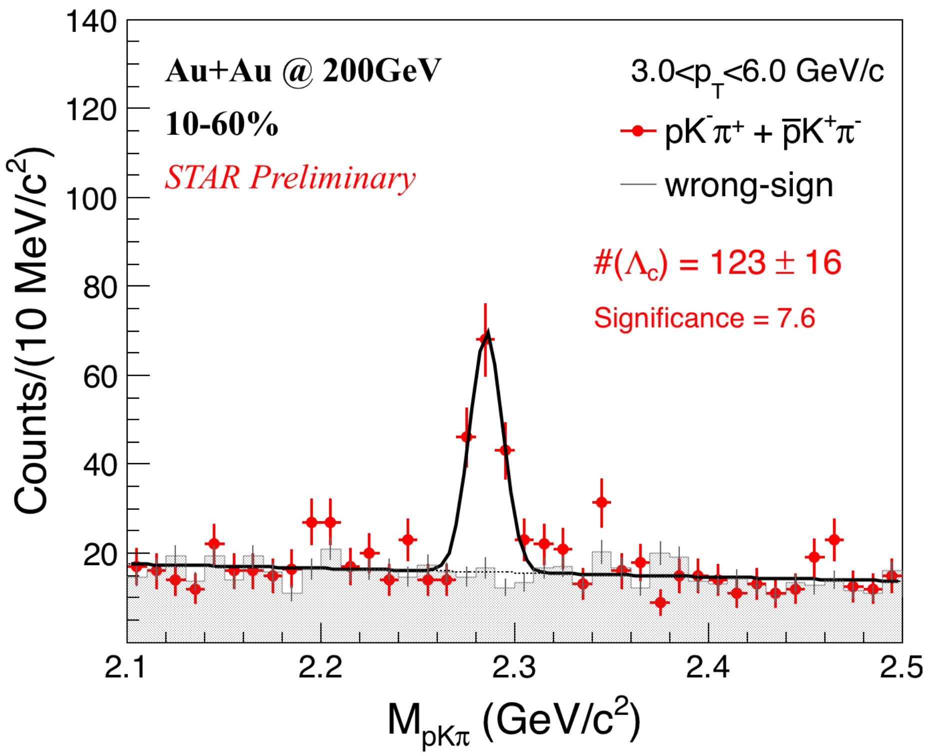
- ***Boosted Decision Trees:*** Decision trees recursively split the data into subsets. At each decision node a binary classification is made untill a classification a reached
- 'Boosting' improves classification power and reduce overtraining
- More than 50% signal significance improvement with BDT



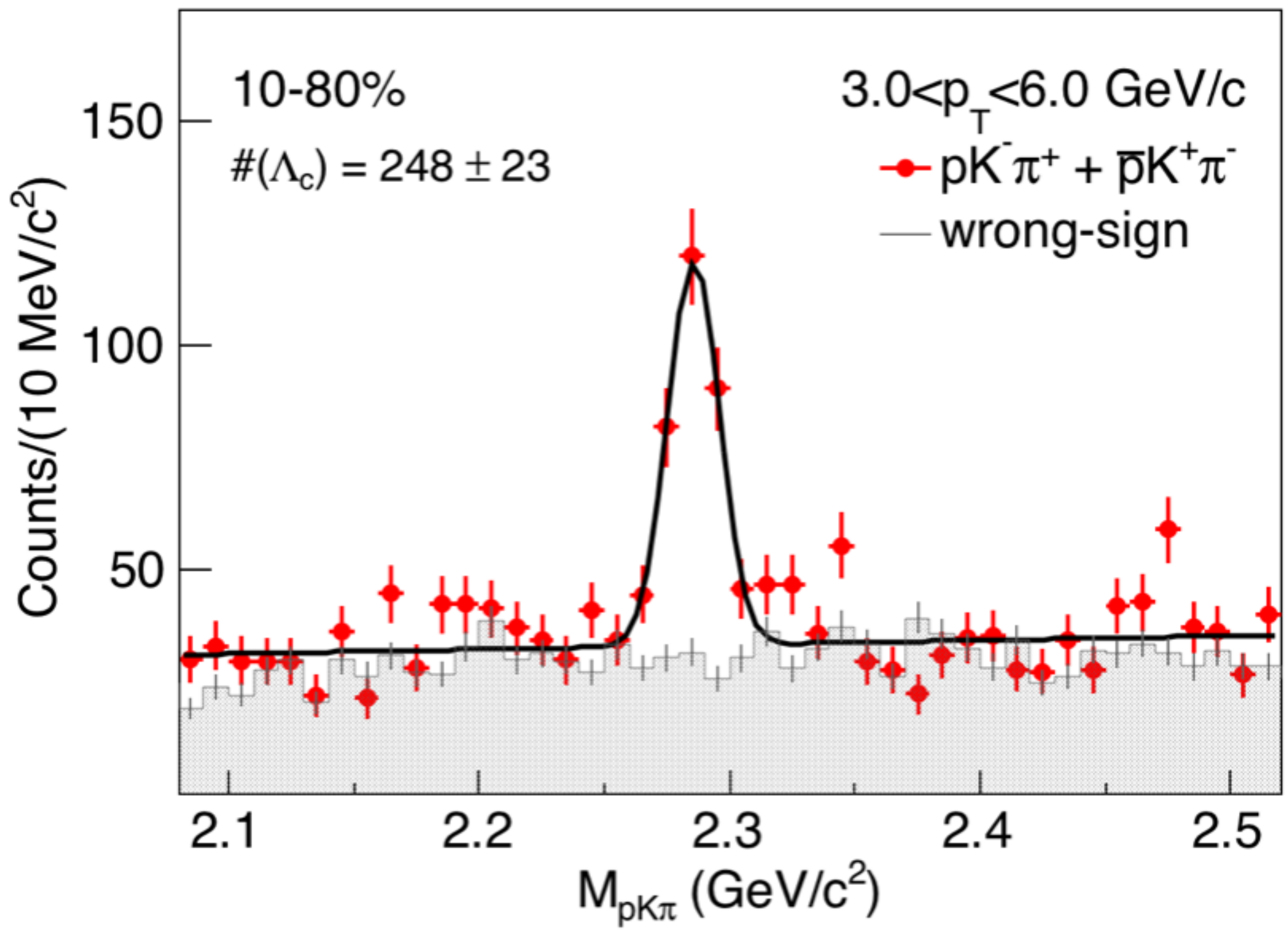
Rectangular Cuts (QM17)



BDT Cuts (QM18)



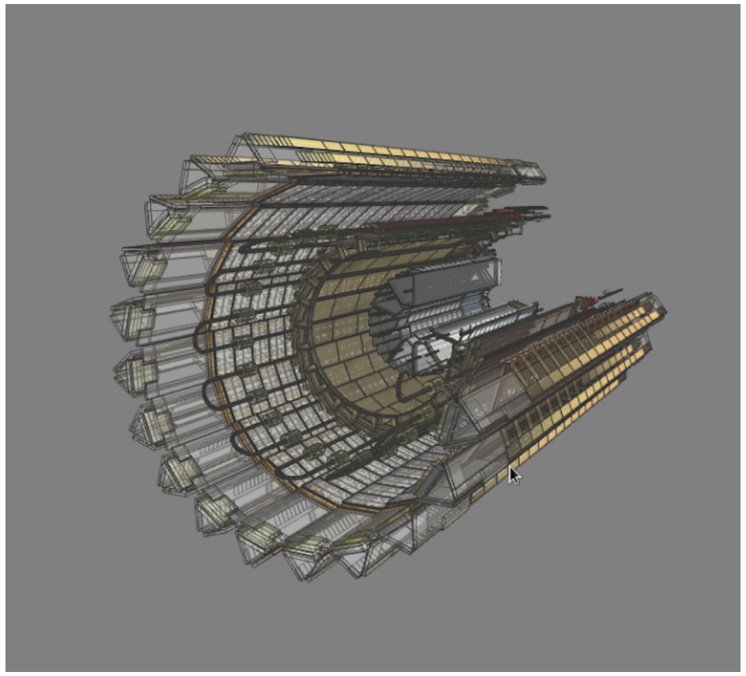
Λ_c signal reconstruction

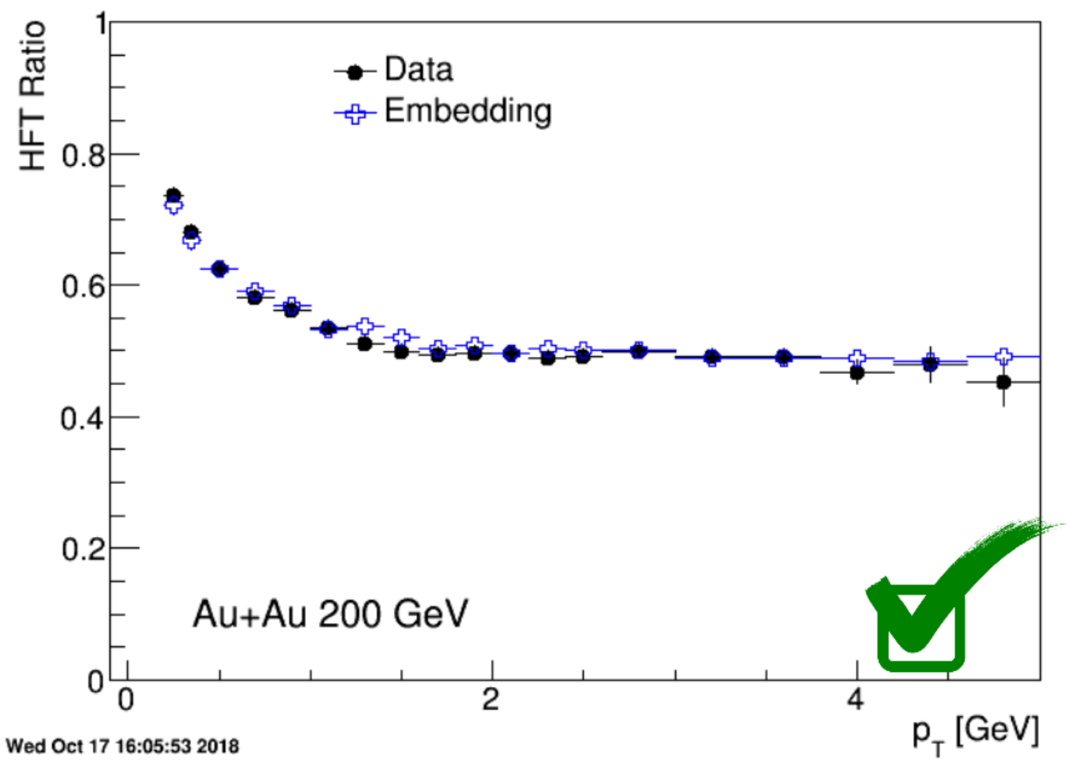


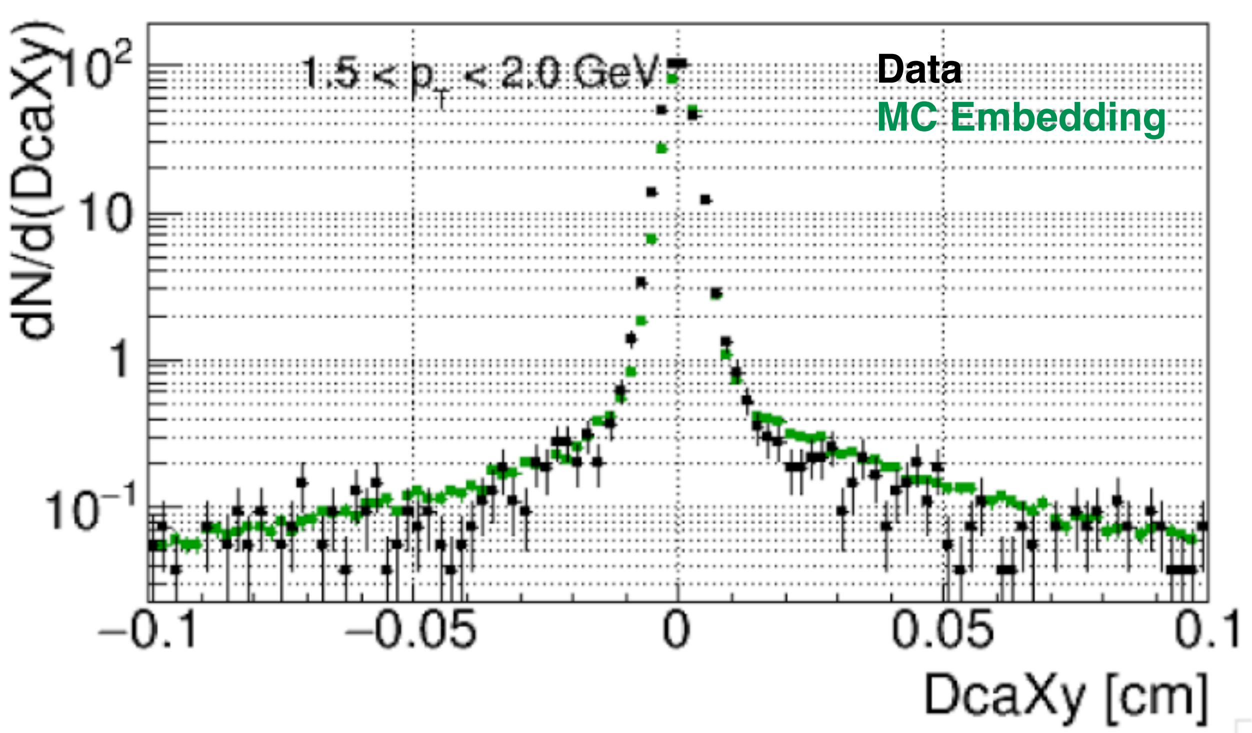
- With statistics from 2016, signal significance of about 11 sigma
- Allows measurement of p_T and centrality dependence of Λ_c production in HI collisions

Modelling detector response

- HFT detector description with fully misaligned geometry incorporated into STAR GEANT for full event reconstruction and corrections for detector effects.
- Tuning with data and cosmic data for hit efficiency, hit resolution.
- Also tune TPC performance also to reproduce the high precision tracking







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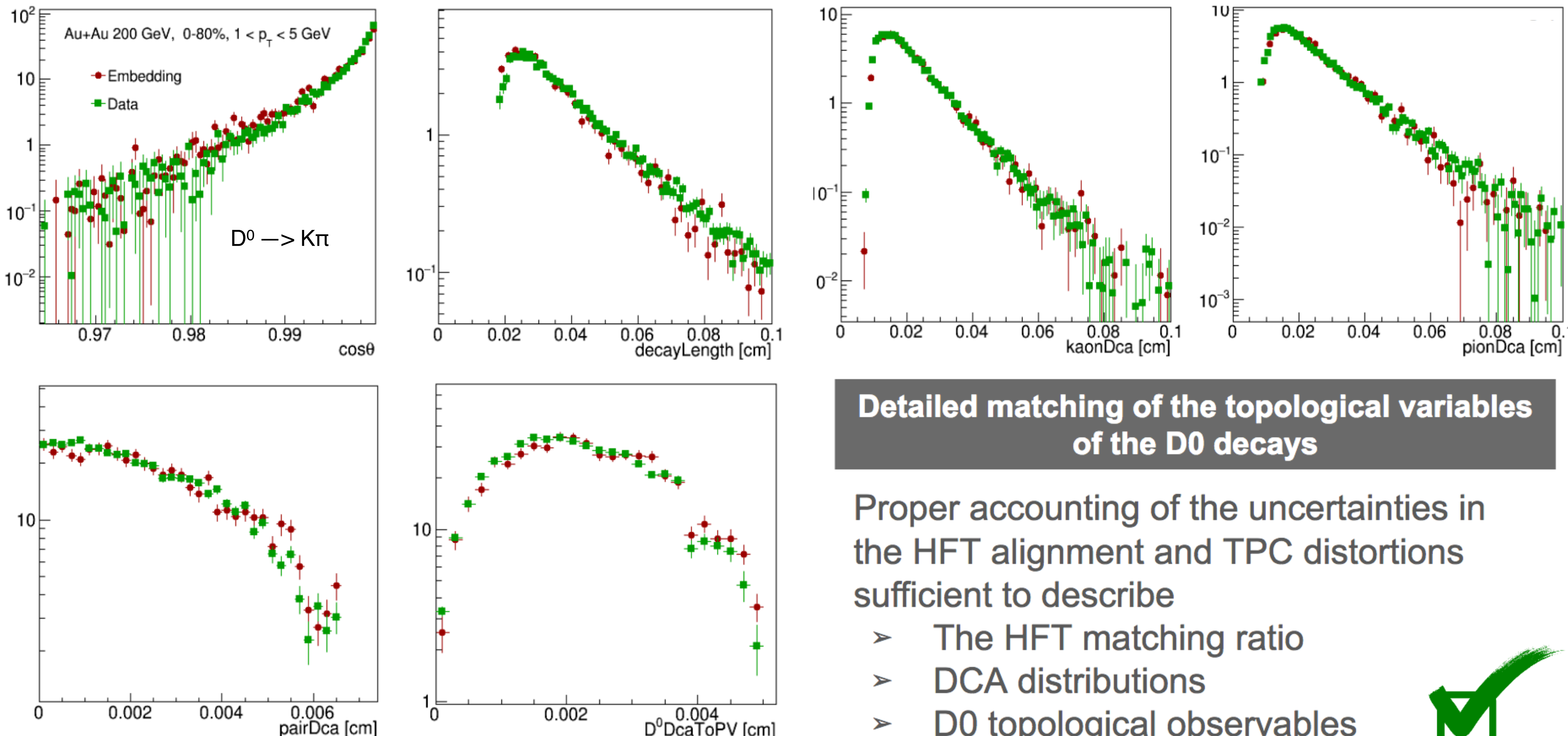


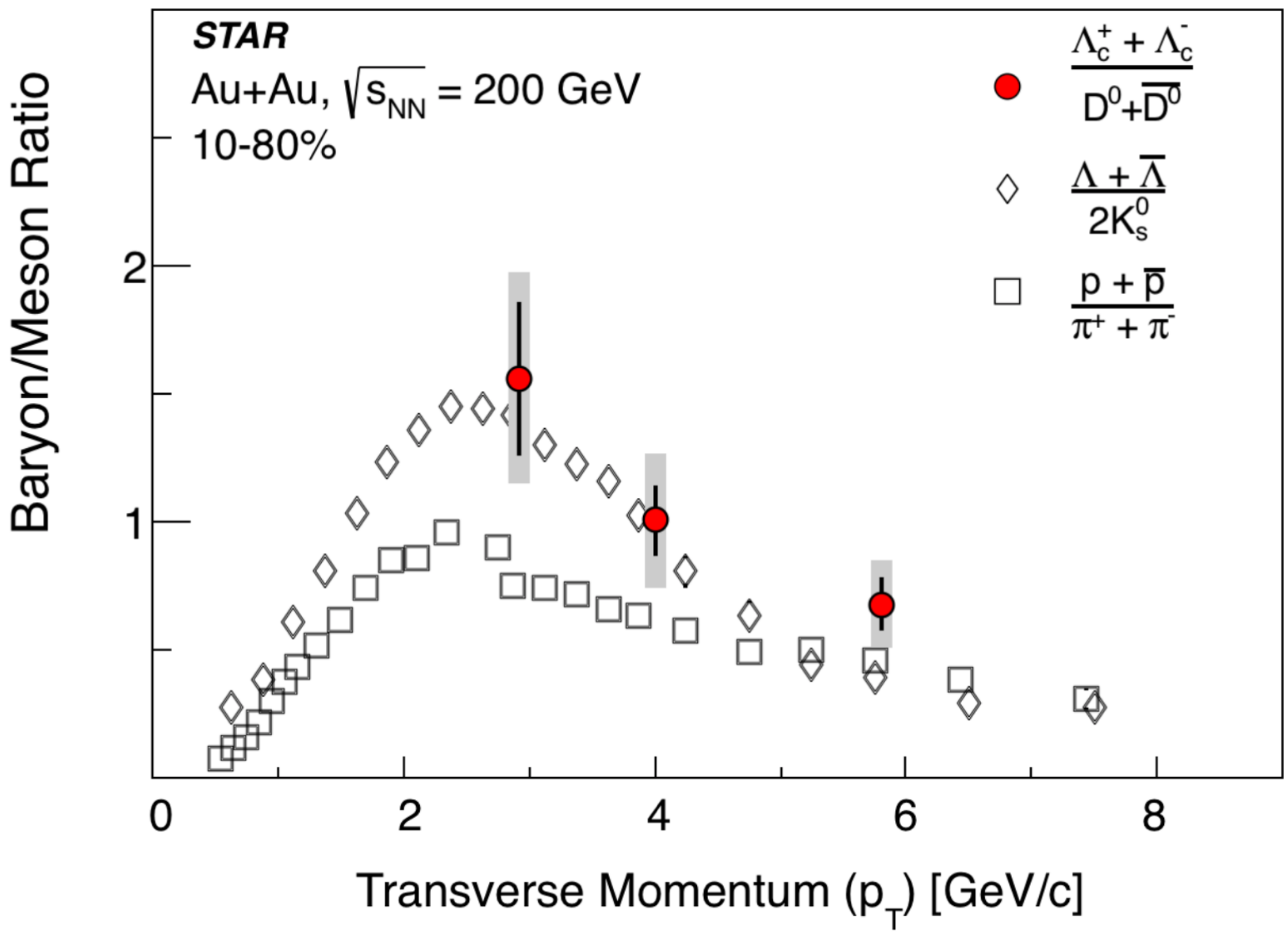
Detailed matching of the topological variables of the D0 decays

Proper accounting of the uncertainties in the HFT alignment and TPC distortions sufficient to describe

- The HFT matching ratio
- DCA distributions
- D0 topological observables

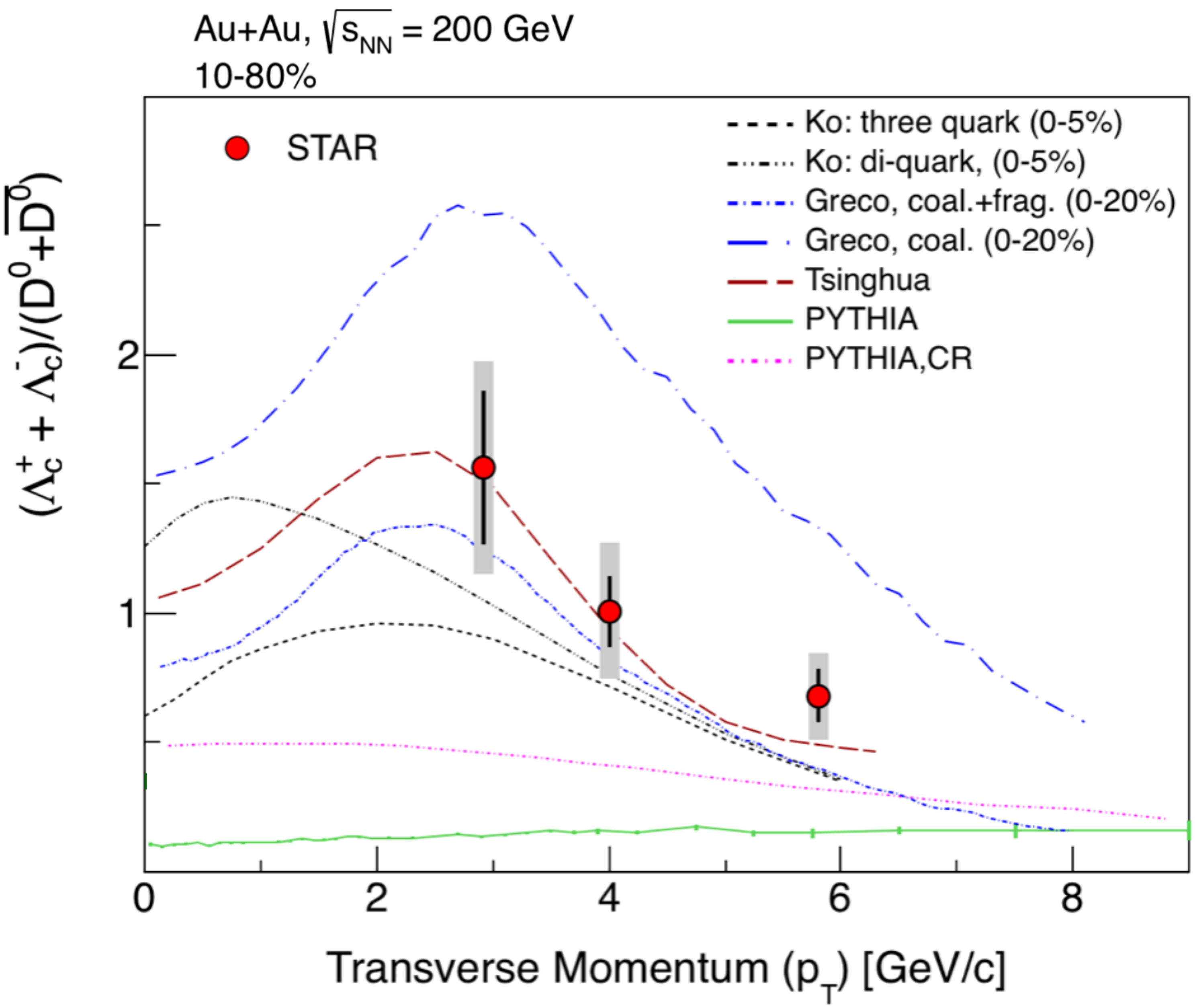
- Excellent description of detector response in simulations

Results: Comparison to light flavor



- Large values of B/M ratio for charm hadrons, comparable to those of light and strange flavor hadrons
- Similar p_T dependence as for light flavor hadrons

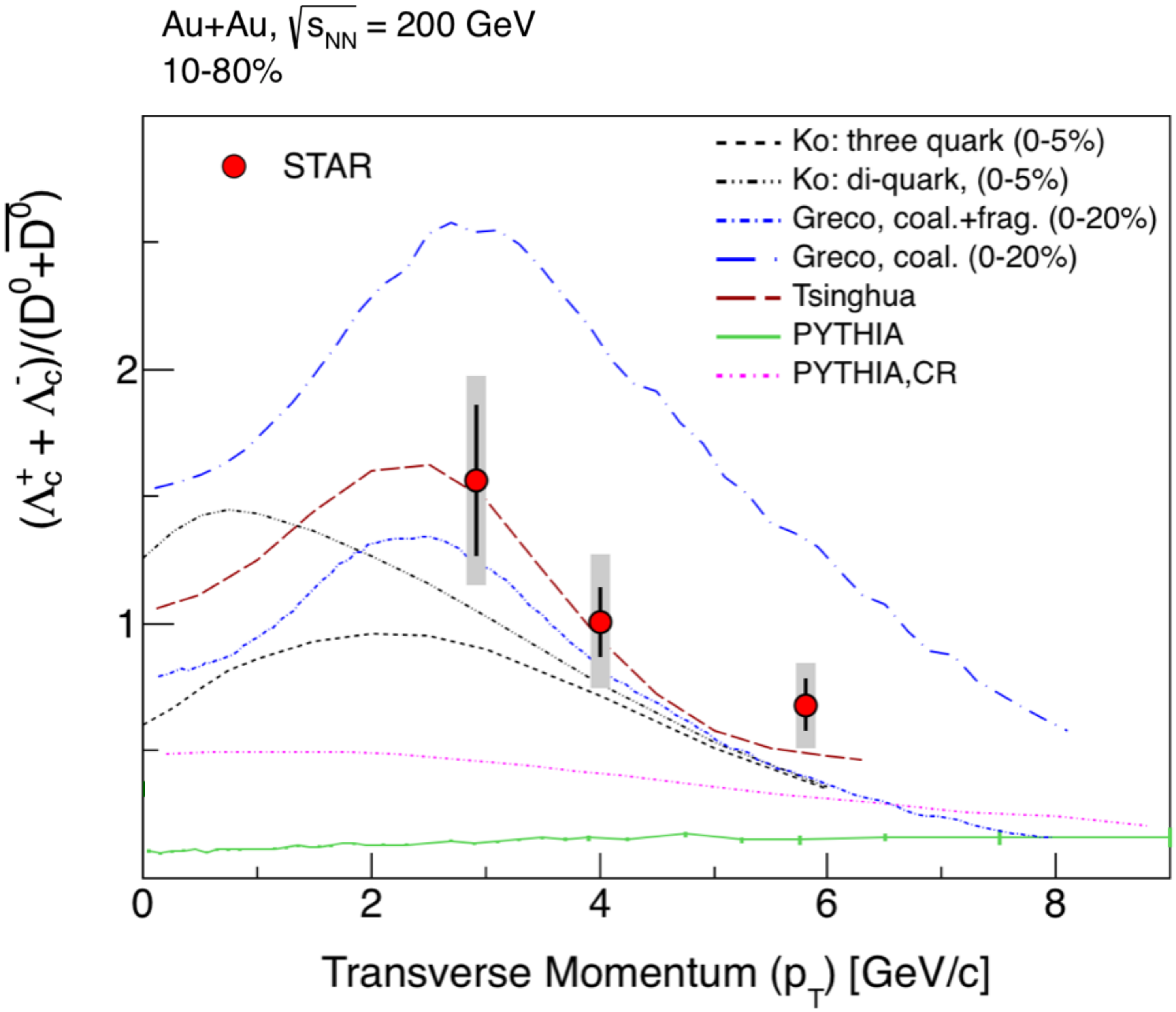
Results: Model comaprisons



- Significant enhacement of Λ_c/D^0 ratio compared to p+p values from PYTHIA
- PYTHIA with Color Reconnection enhances baryon production, but still underpredicts data

χ^2 to PYTHIA default = 23.86; $P(\chi^2_{\text{if true}} > \chi^2_{\text{measured}})$ = 2.7e-5
χ^2 to PYTHIA CR = 7.74 ; $P(\chi^2_{\text{if true}} > \chi^2_{\text{measured}})$ = 0.052

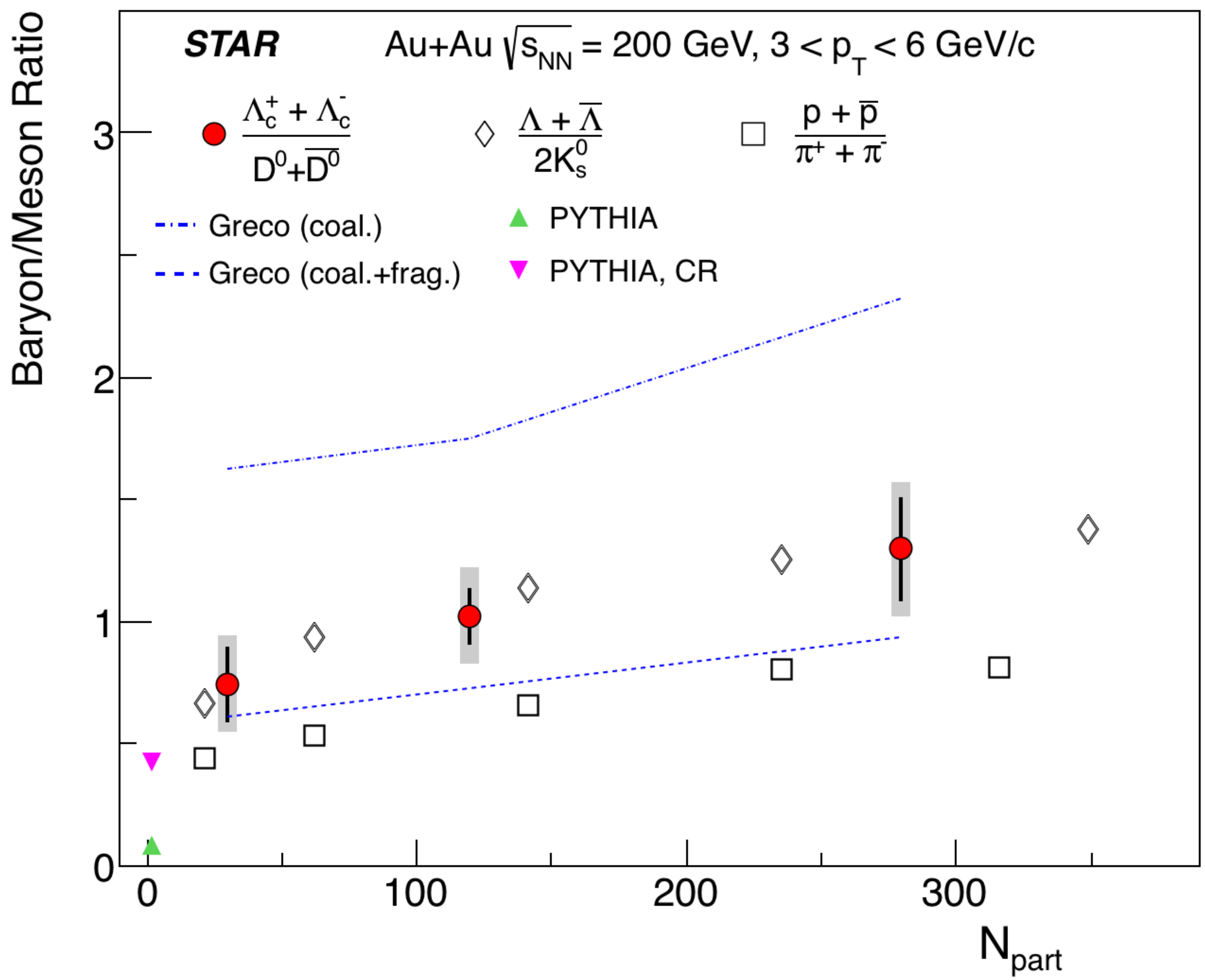
Results: Model comaprisons



- Coalesence models: phase-space recombination of partons to hadrons
- Quarks that dont hadronize by coalesence hadronized by fragmentation
- Models differ in choice of spectra for light and charm quarks, Wigner functions for hadrons

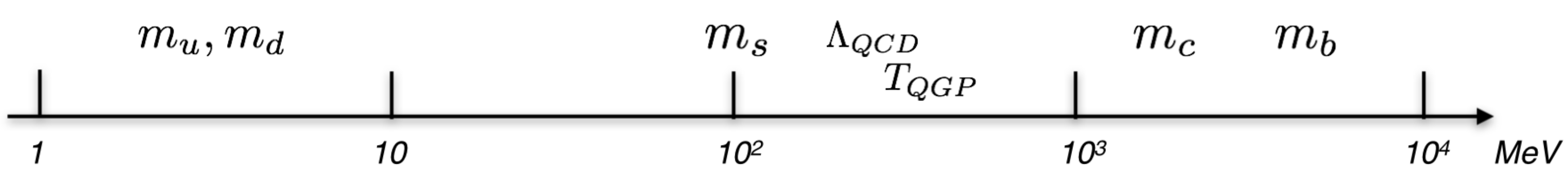
- Models with coalesence hadronization of charm quarks show similar enhancement as in data

Results: Centrality dependence



- Λ_c/D^0 ratio show increasing trend towards more central collisions, similar to that for light and strange flavor hadrons

Heavy quarks in QGP



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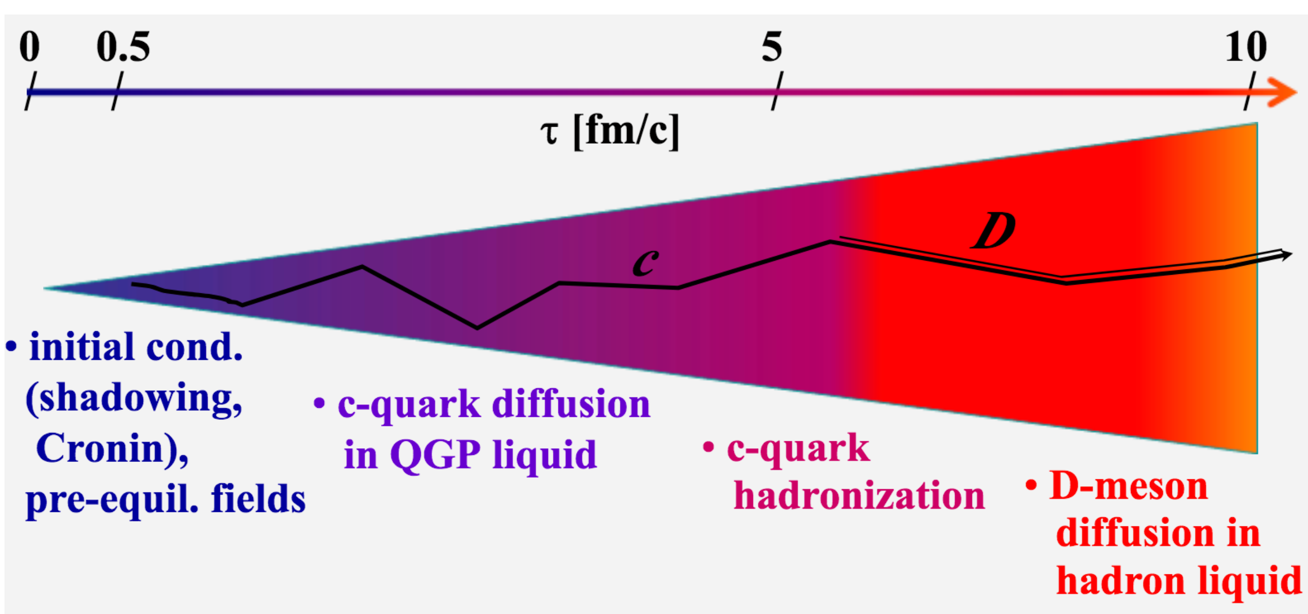

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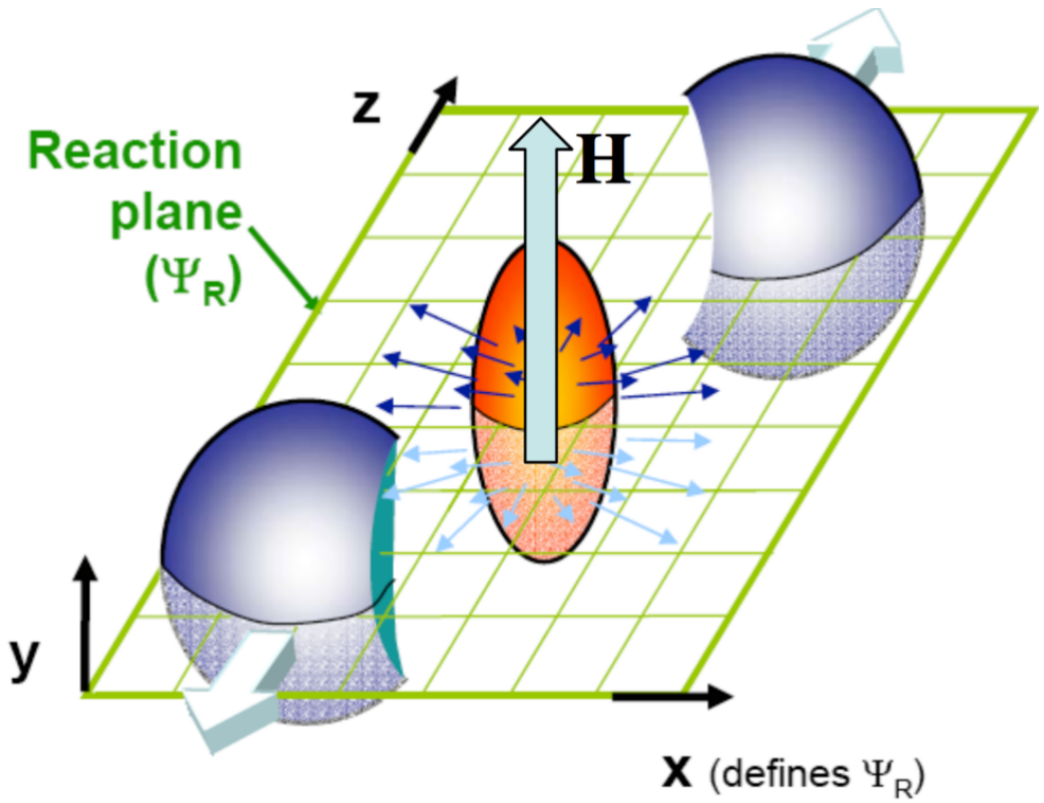
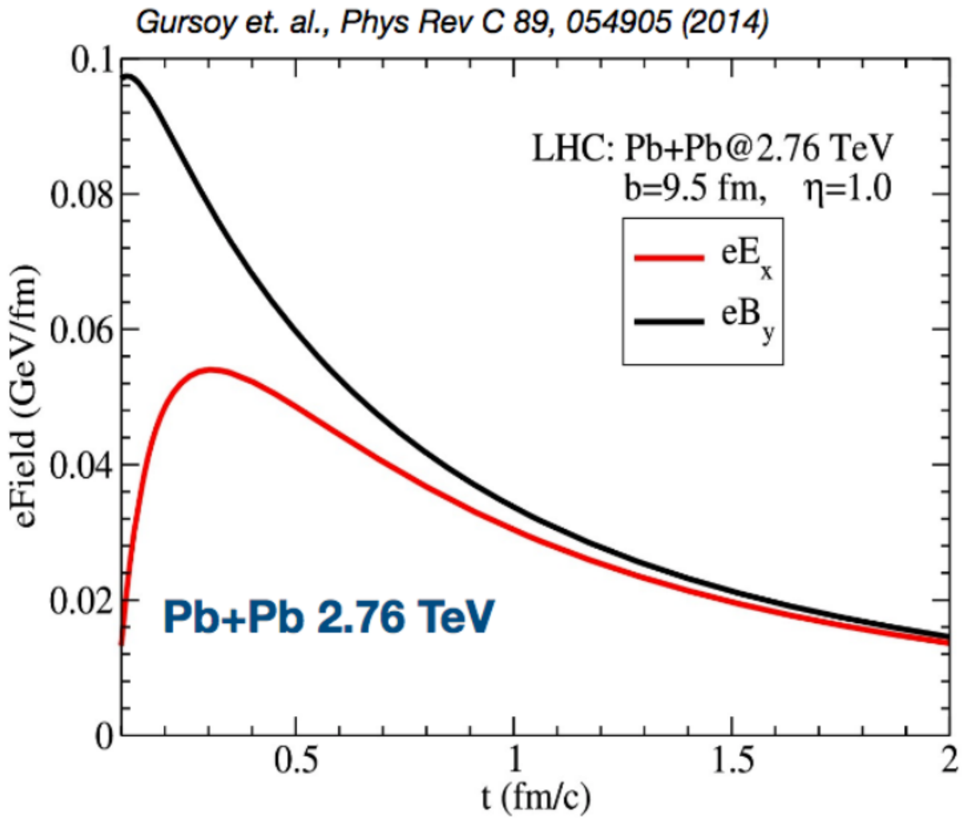
Charm quarks and intial magnetic fields in HI colliisions



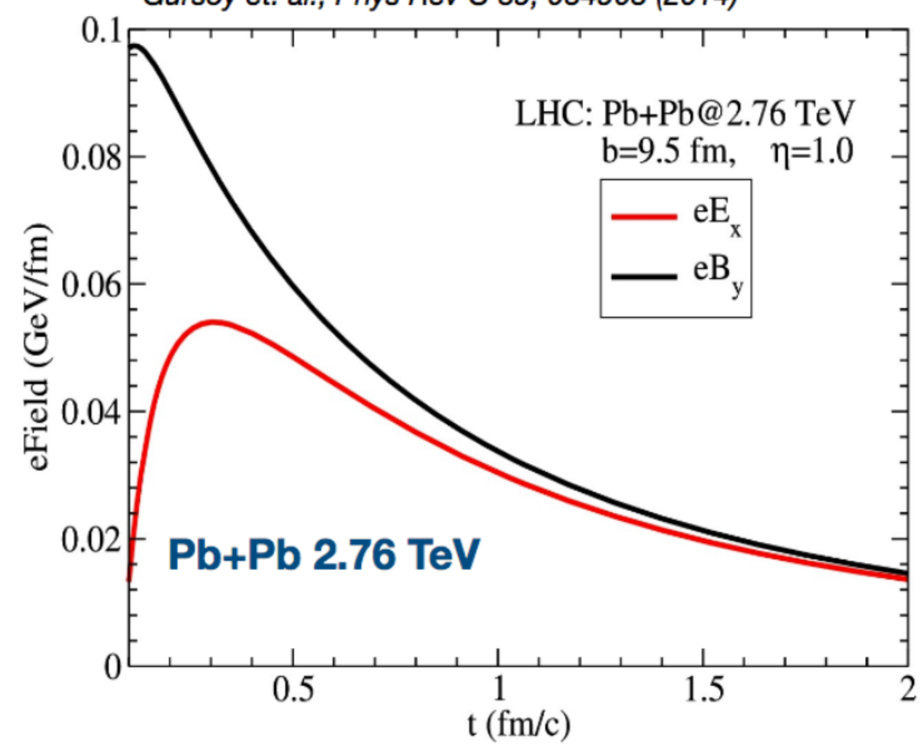


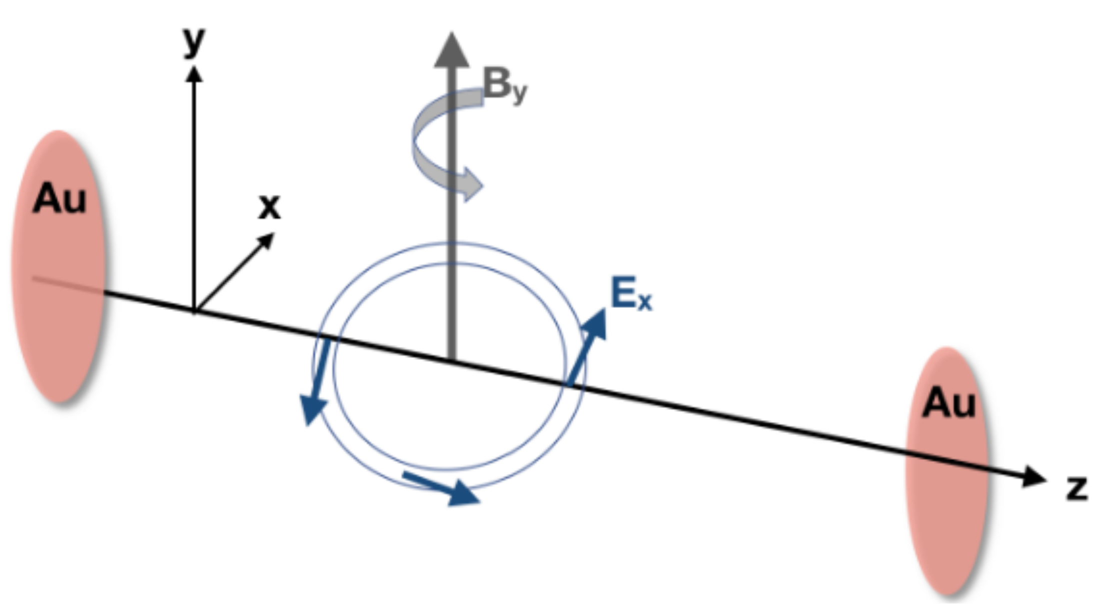
- Moving spectator protons induce extremely strong magnetic fields in initial stages of HI collisions
- Correlated in direction to the reaction plane

Charm quarks and intial magnetic fields in HI colliisions

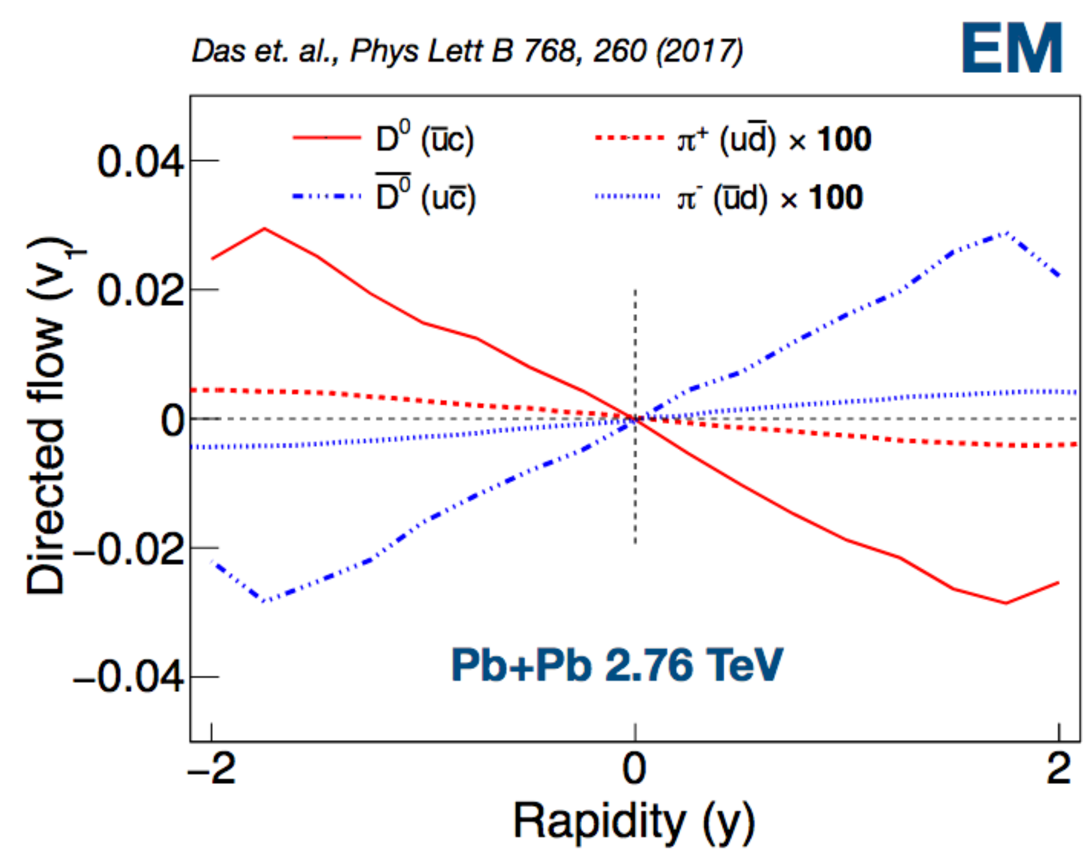
- Charm quarks produced very early in collisions when initial B field are significant
- Also relaxation time large for charm quarks
- Results in v_1 (directed flow) with opposite slopes w.r.t rapidity for D^0 and anti-D^0

Gursoy et. al., Phys Rev C 89, 054905 (2014)





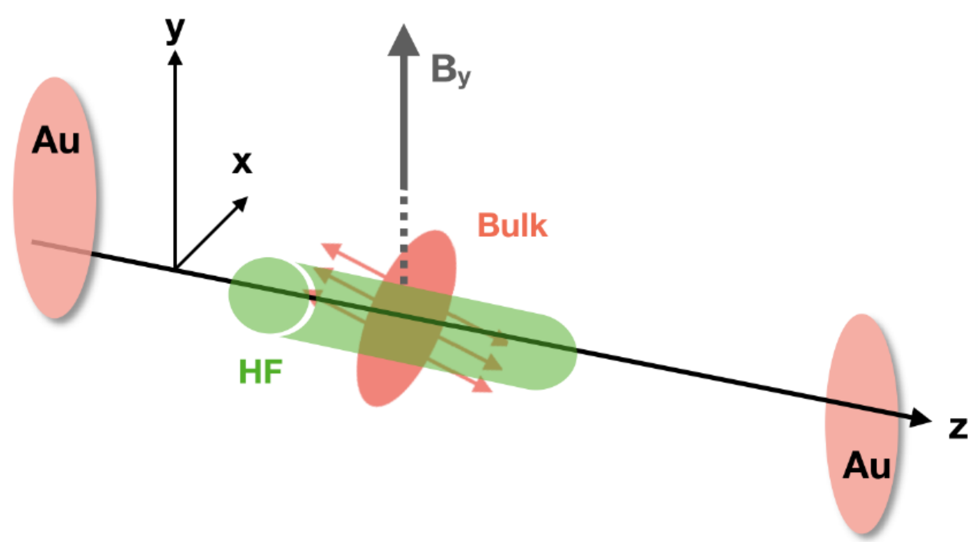
Das et. al., Phys Lett B 768, 260 (2017)



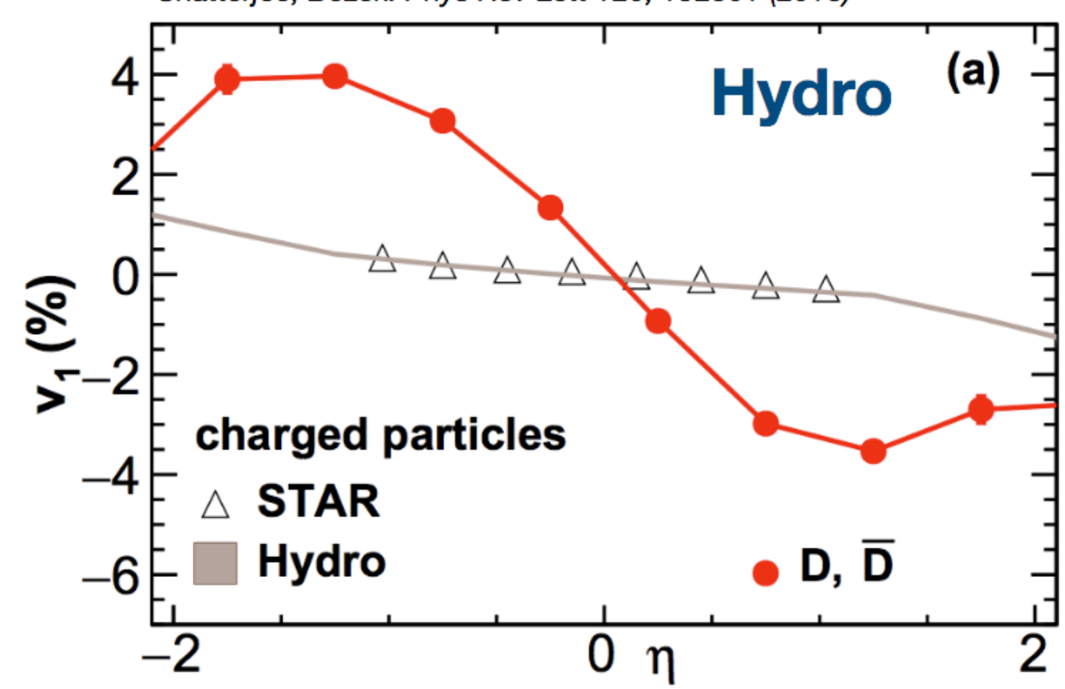
Directed flow from initial geometry

- Significant directed flow (v_1) predicted for charm quarks from flow!
- Charge independent

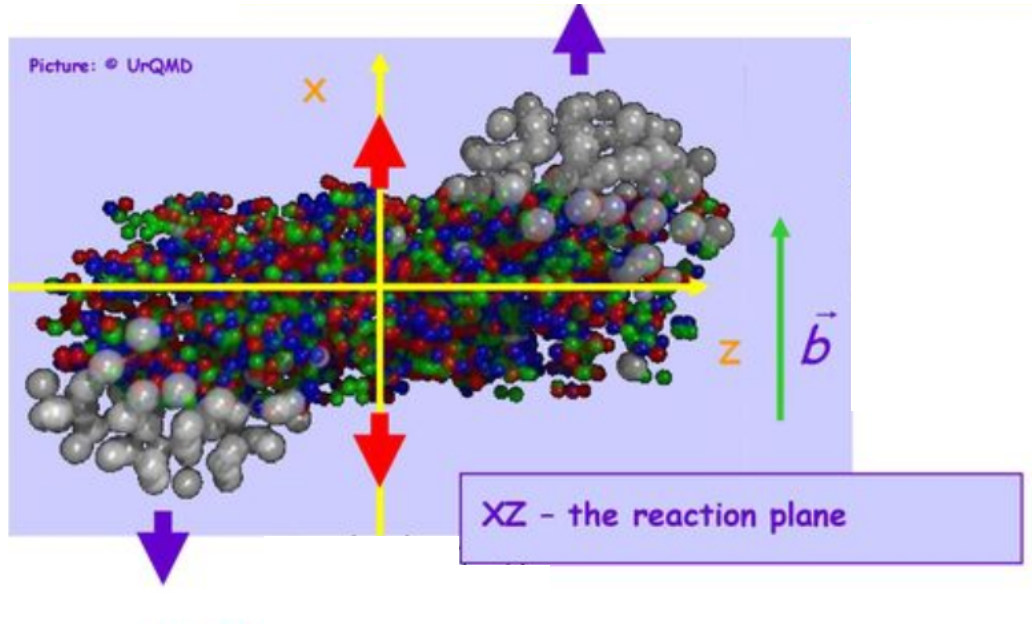
- 'Tilted bulk' in longitudinal direction, but HF quark production profile is symmetric — first order density anisotropy
- Viscous drag on c quarks by the expanding tilted bulk — generates D^0 v_1
- Sensititive to initial tilt and viscous drag experienced by *c* quarks in medium

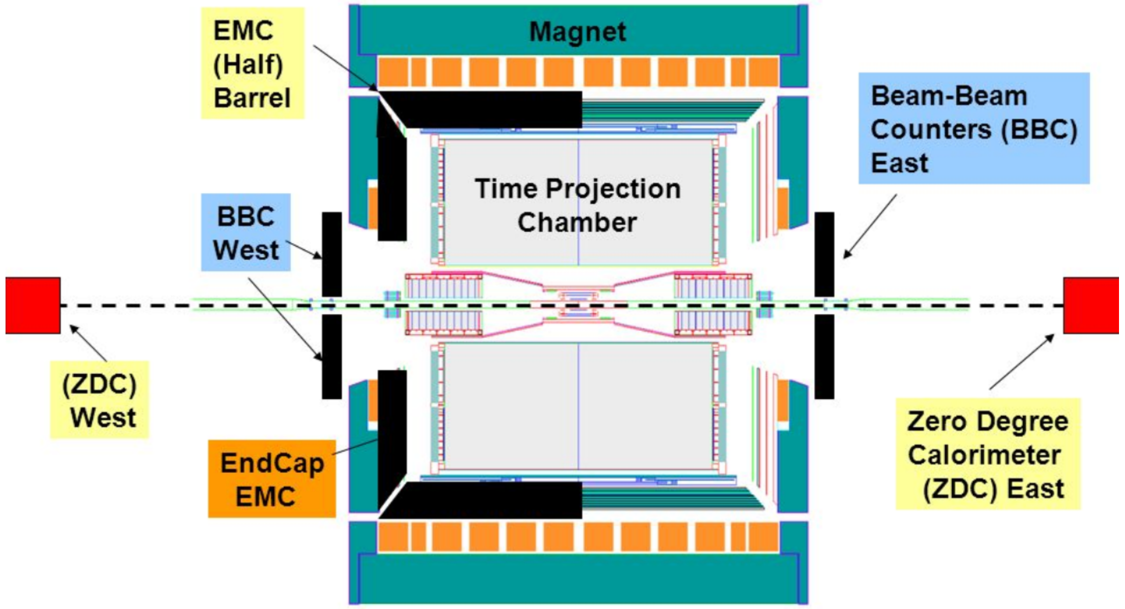


Chatterjee, Bozek: Phys Rev Lett 120, 192301 (2018)



Measurement of D^0 directed flow

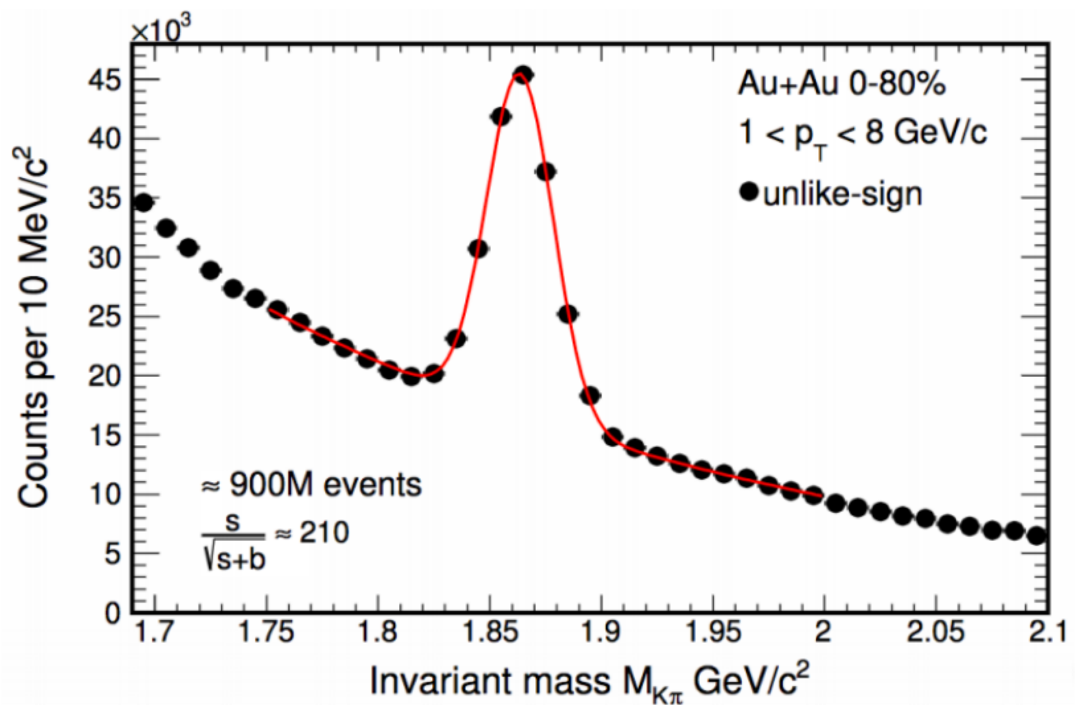




- Spectator neutrons pushed out along the impact parameter
- Used to determine RP direction with Zero Degree Calorimeters

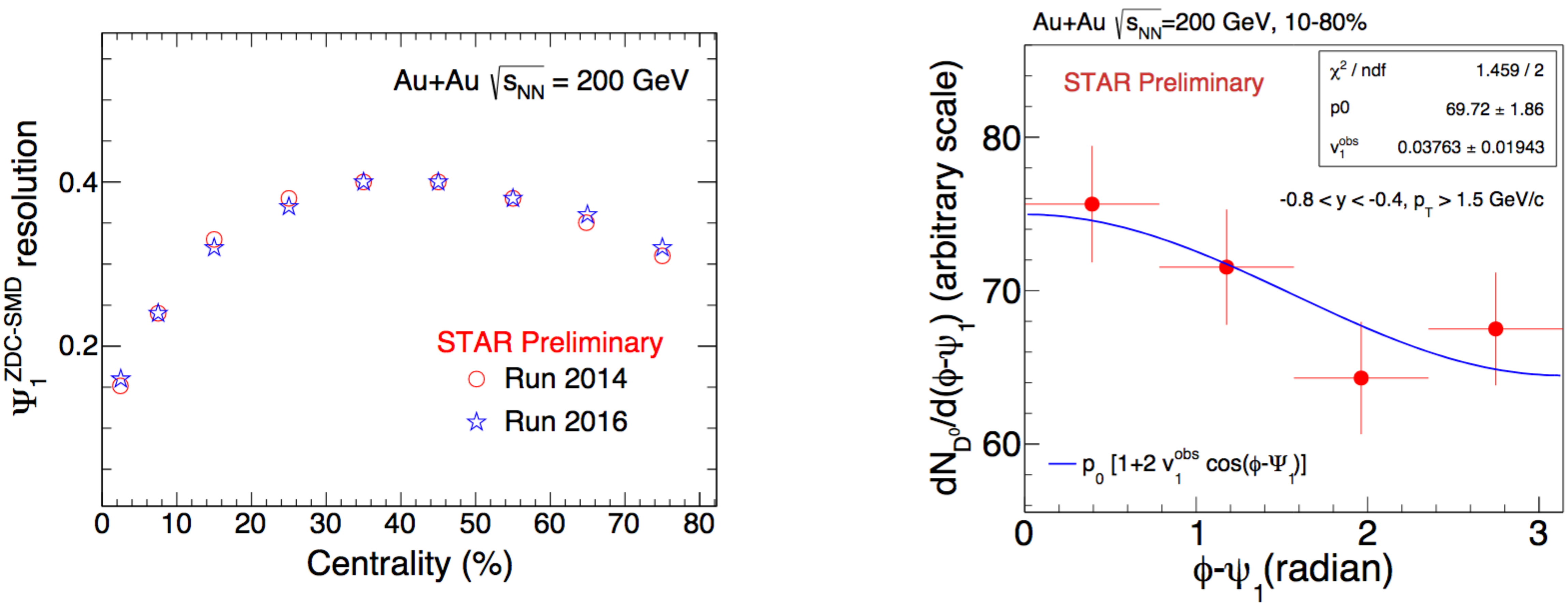
- D^0 reconstrcuted at midrapidity using HFT

Quark content: D^0 ($\bar{u}c$), $\overline{D^0}$ ($u\bar{c}$),
Decay channel: $D^0 \rightarrow K^-\pi^+$
$\overline{D^0} \rightarrow K^+\pi^-$
Decay length ($c\tau$): 120 μm
Mass: 1864.84 +/- 0.18 MeV/c^2
Branching ratio: 3.89%



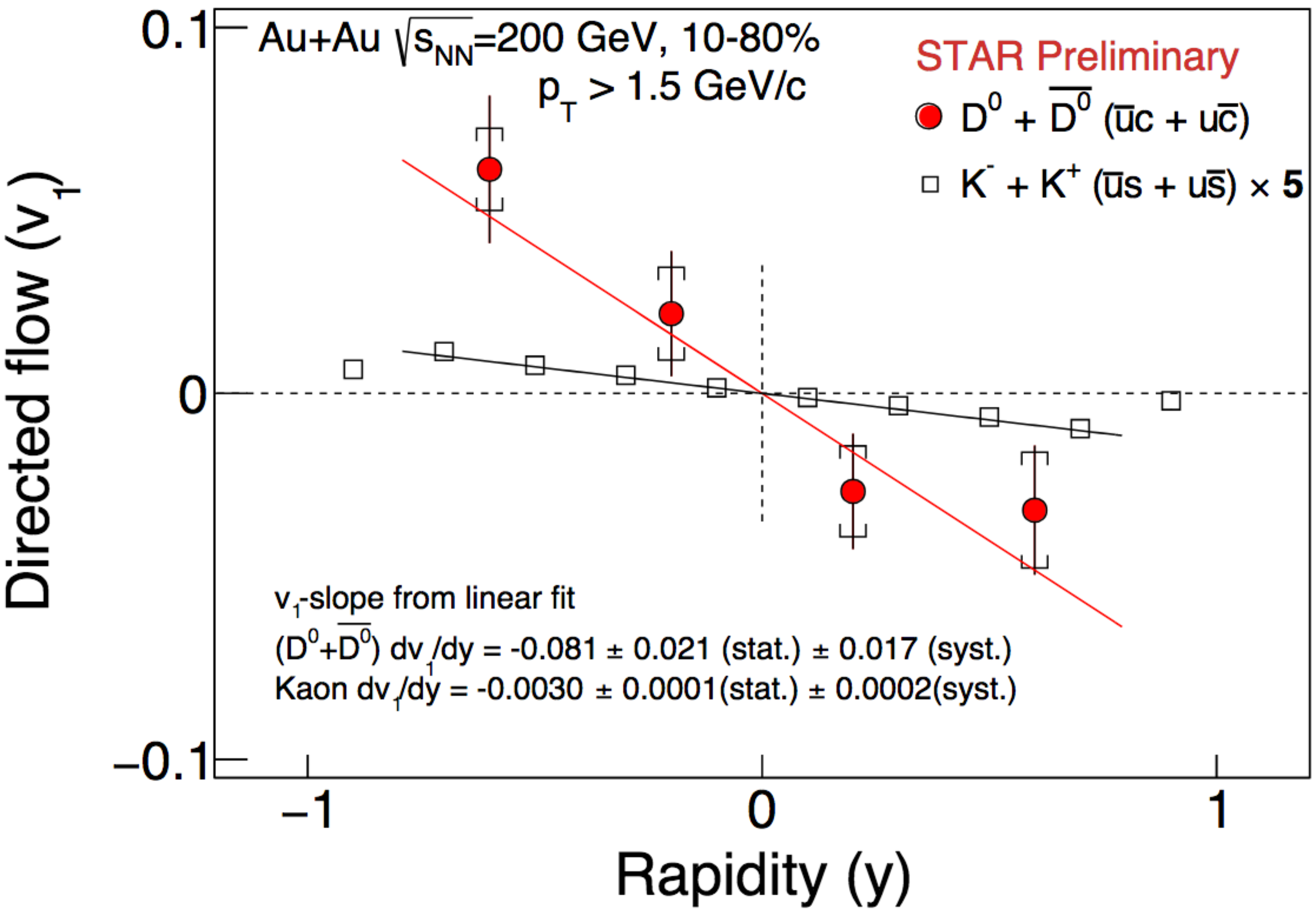
Measurement of D^0 directed flow

- v_1 measured by correlating D^0 with the spectator plane from ZDC
- Corrected for RP resolution



$$v_1 \sim \frac{\langle \cos(\phi - \psi_1) \rangle}{\psi_1 \text{ res.}} \sim \frac{v_1^{obs}}{\psi_1 \text{ res.}}$$

Results: D^0 directed flow at mid-rapidity

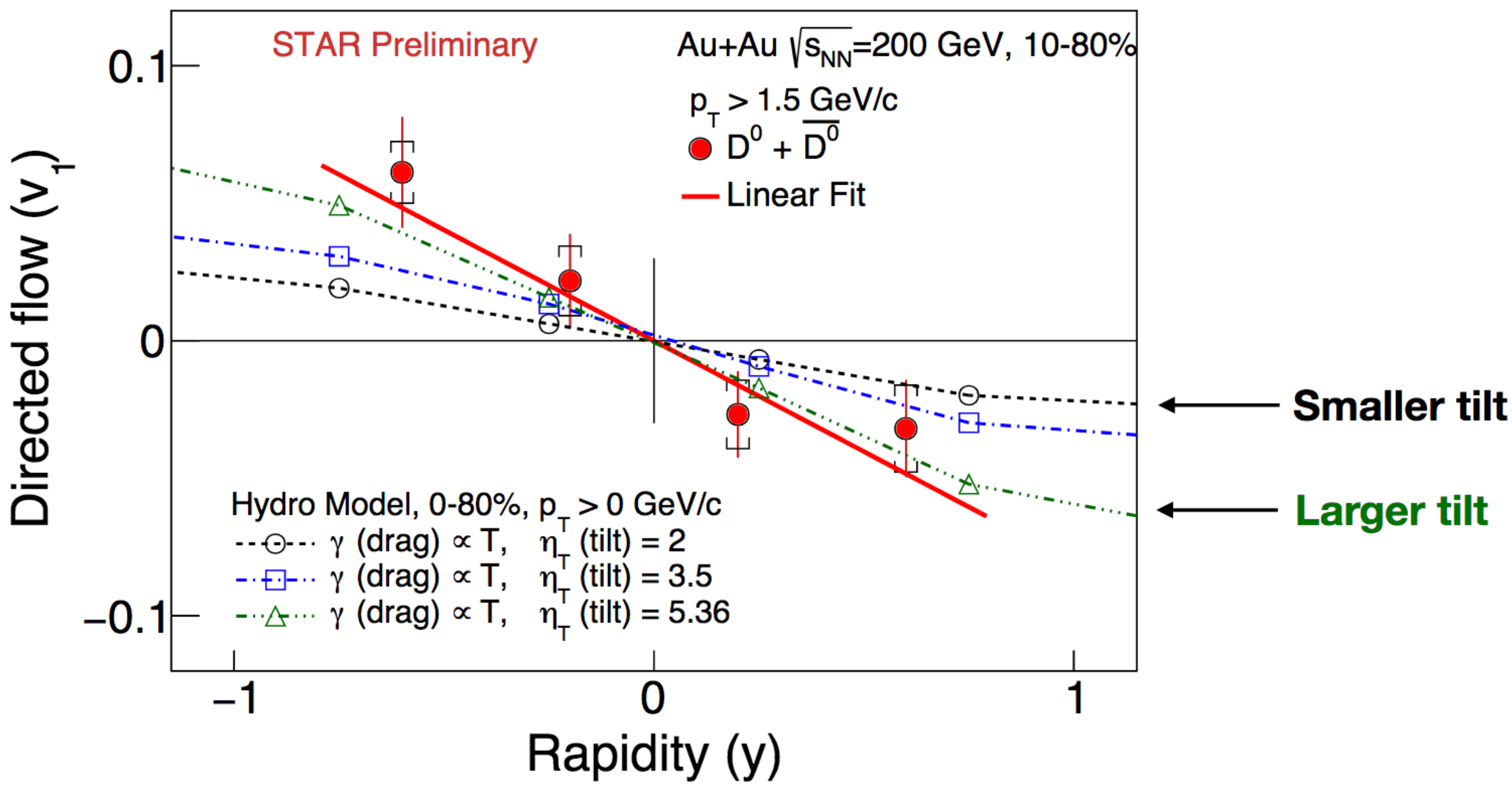


Charged Kaons:
L Adamczyk et. al. (STAR Collaboration),
Phys Rev. Lett. 120, 62301 (2018)

- Evidence of non-zero v_1 for D^0 at mid-rapidity
- Slope at mid-rapidity much larger than that for charged kaons

Results: Model comparisons

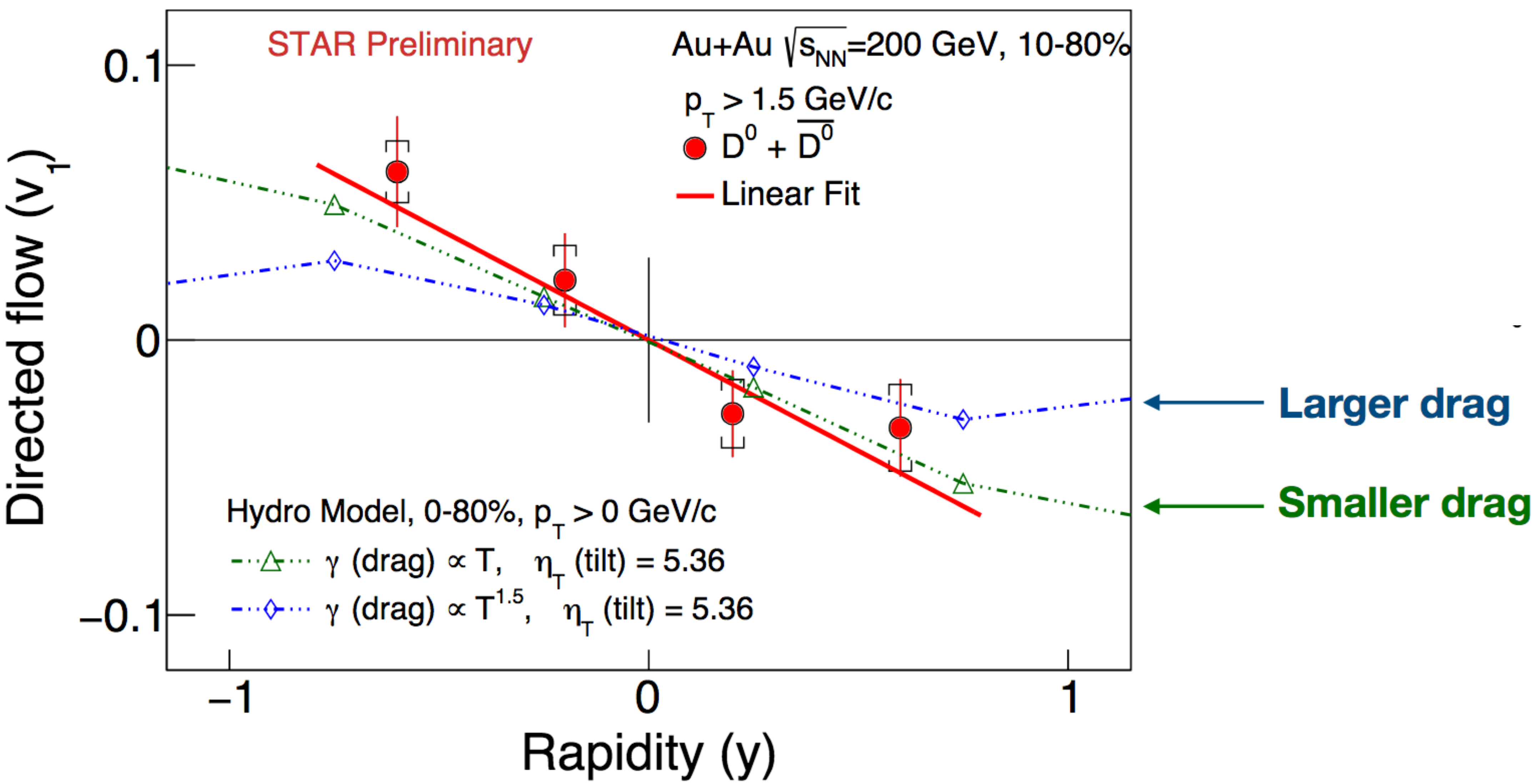
Chatterjee, Bozek: Phys Rev Lett 120, 192301 (2018)



- Magnitude of D^0 v_1 sensitive to initial tilt of the source
- Can help constrain the model parameter

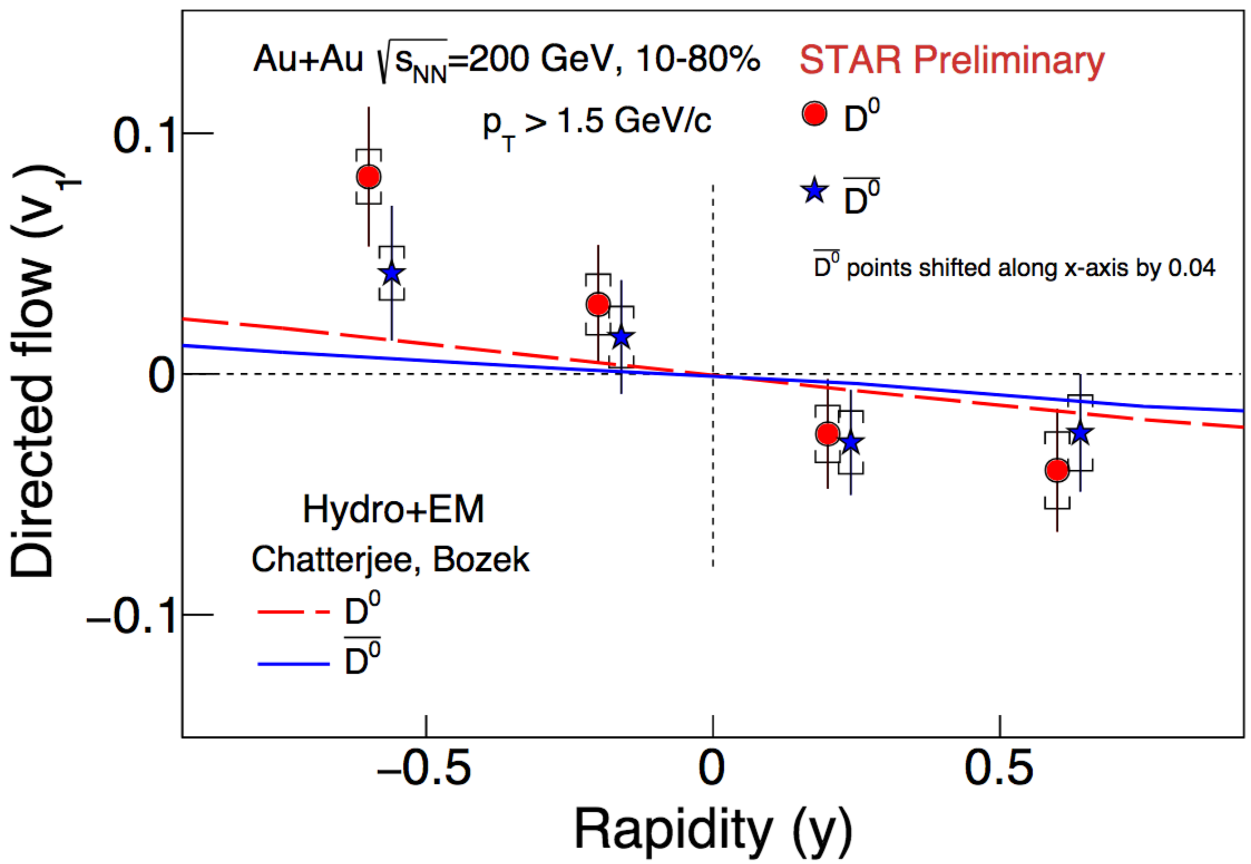
Results: Model comparisons

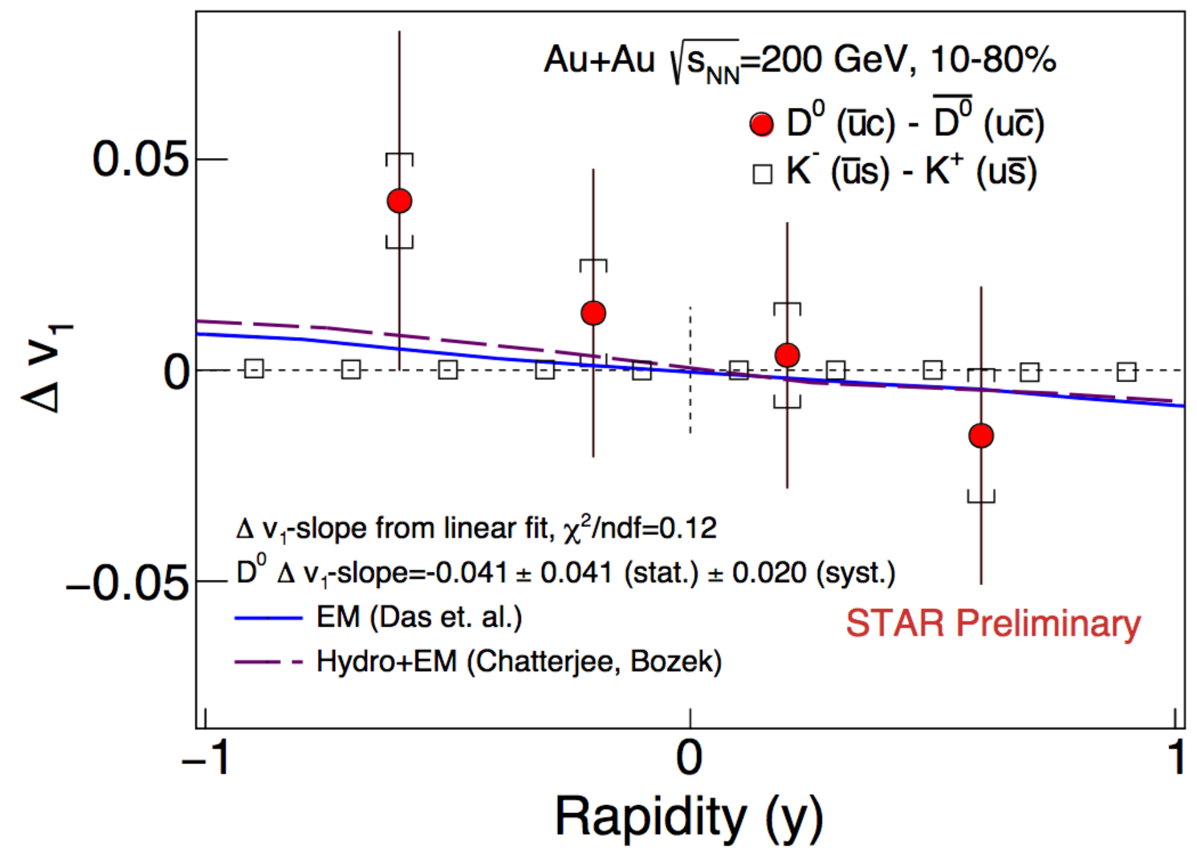
Chatterjee, Bozek: Phys Rev Lett 120, 192301 (2018)



- Sensitive to temperature dependence of the drag coefficient
- Together with D^0 R_{AA} and v_2 can better constrain the tranport parameters

Results: Charge dependence

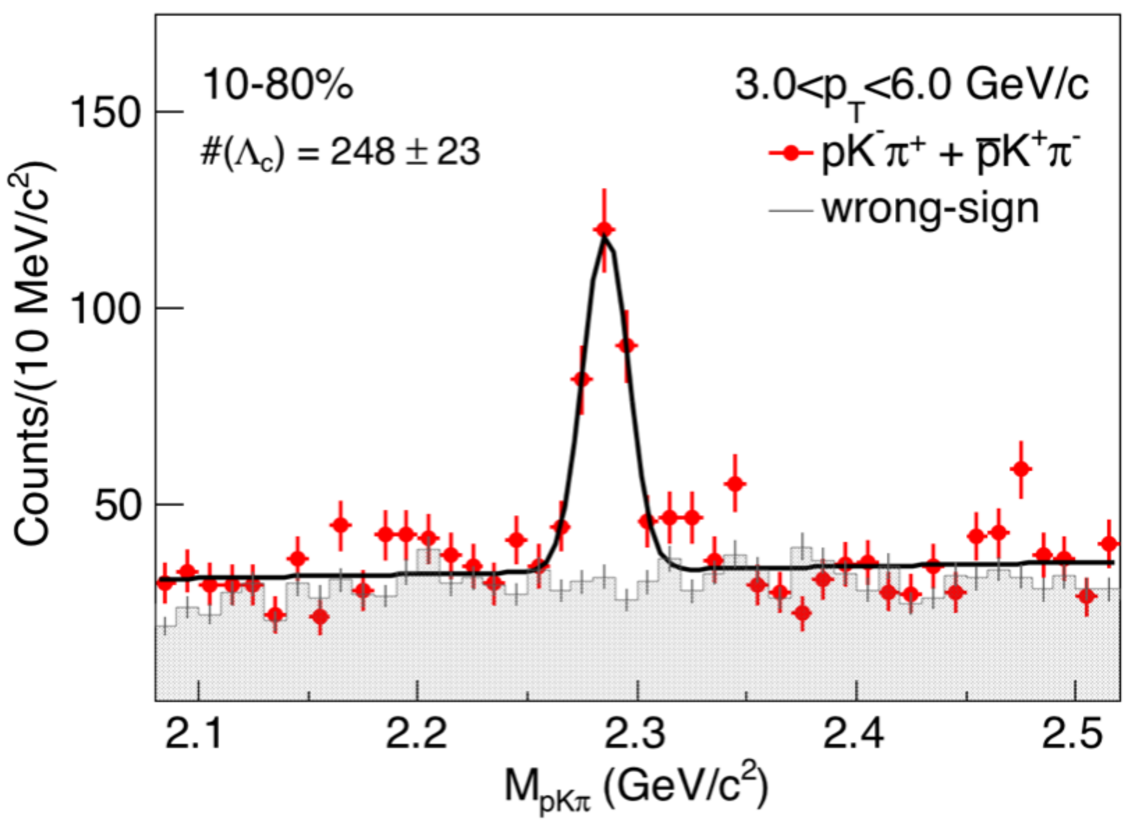


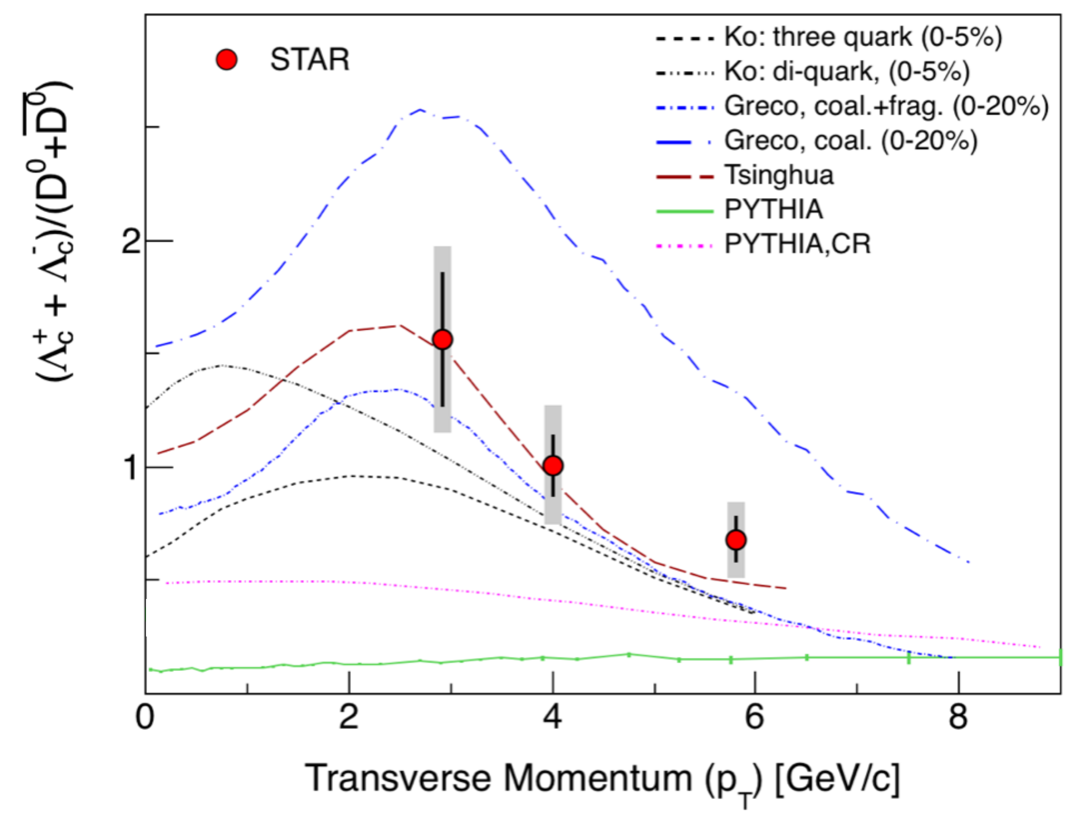


- Negative slope for both D^0 and anti-D^0 v_1
- No significant difference observed at current precision (within ~1σ)
- Magnitude of charge dependent signal predicted by Hydro+EM calculations are also small

Summary & Conclusions

- **Λ_c production in Au+Au collisions:**
  - Significant enhancement of Λ_c/D^0 ratio compared to p+p values from PYTHIA
    - Evidence for coalesence hadronization of charm quarks
    - Large Λ_c production cross-section in HI collisions

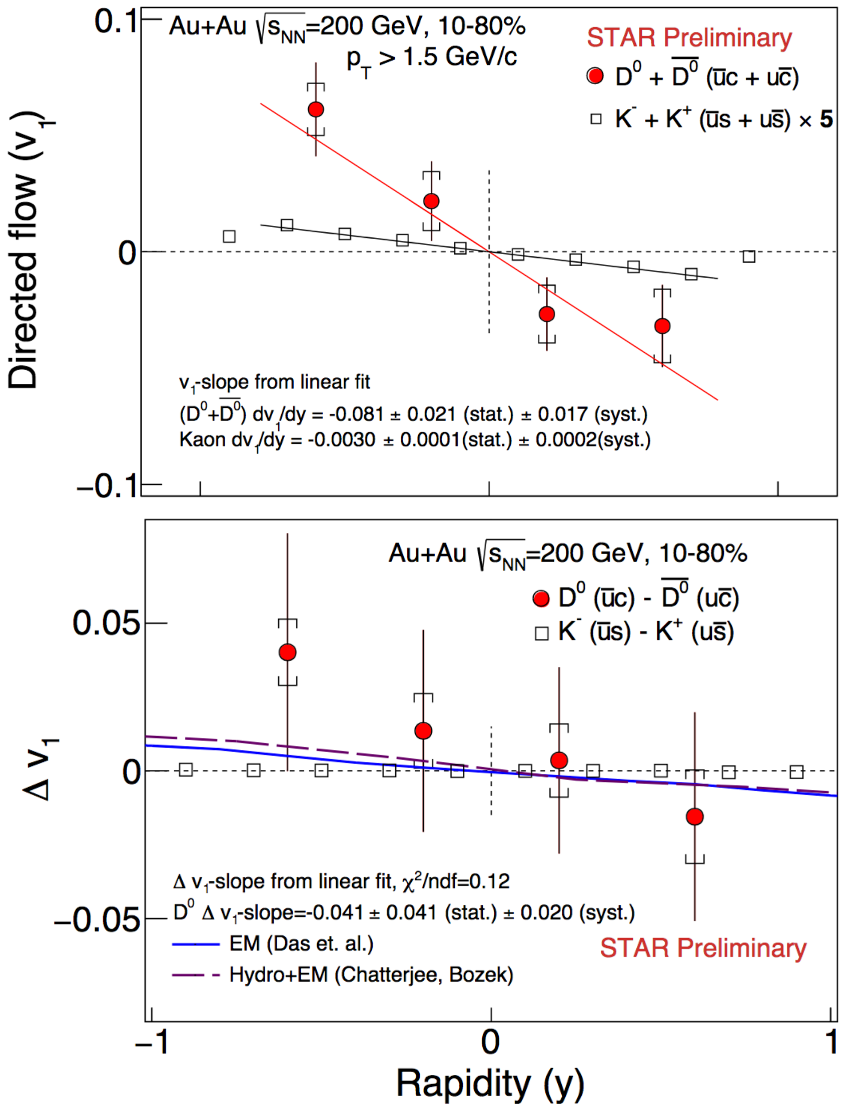




Summary & Conclusions

- **Directed flow of D^0**
  - Evidence of non-zero directed flow for D^0 mesons
    - Magnitude much larger than for light flavor hadrons
    - Can constrain c quark transport coefficients and initial conditions in the longitudinal direction

  - No significant charge dependence observed, within uncertainties

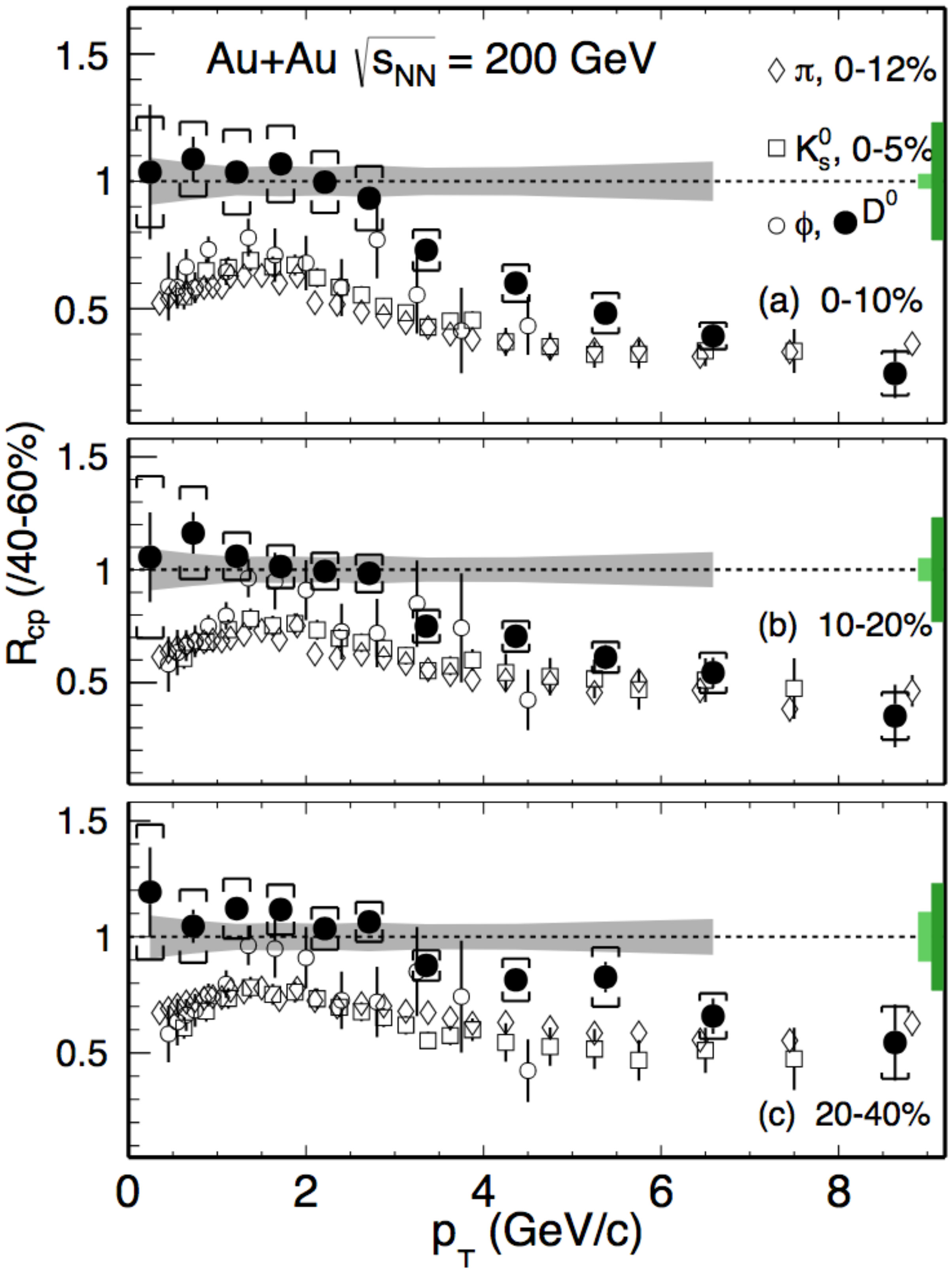


- **Future experiments (sPHENIX, ALICE ITS upgrade)**
  - Improve precision and push to lower p_T for Λ_c measurements
  - Differentiate between models

  - Predicted v_1 signal from B field measurable at statistics projected for sPHENIX

Back Up

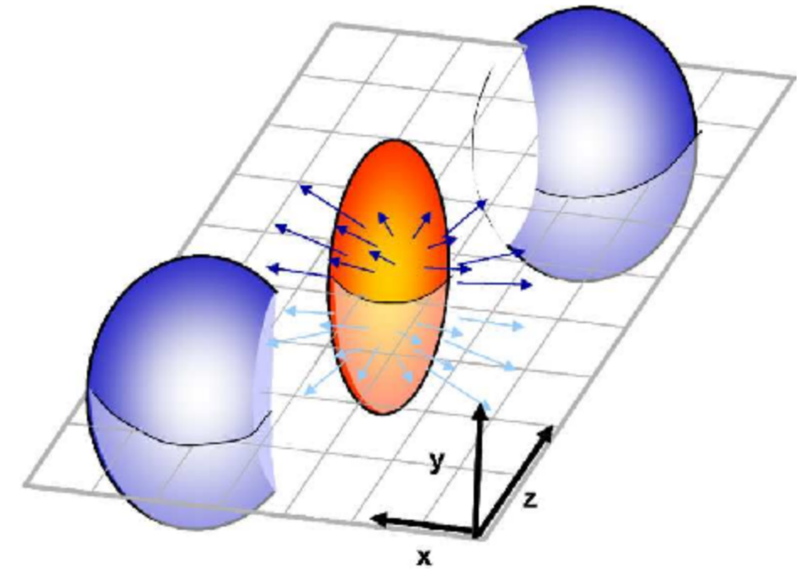
Energy Loss [*arXiv:1812.10224 (2018)*]



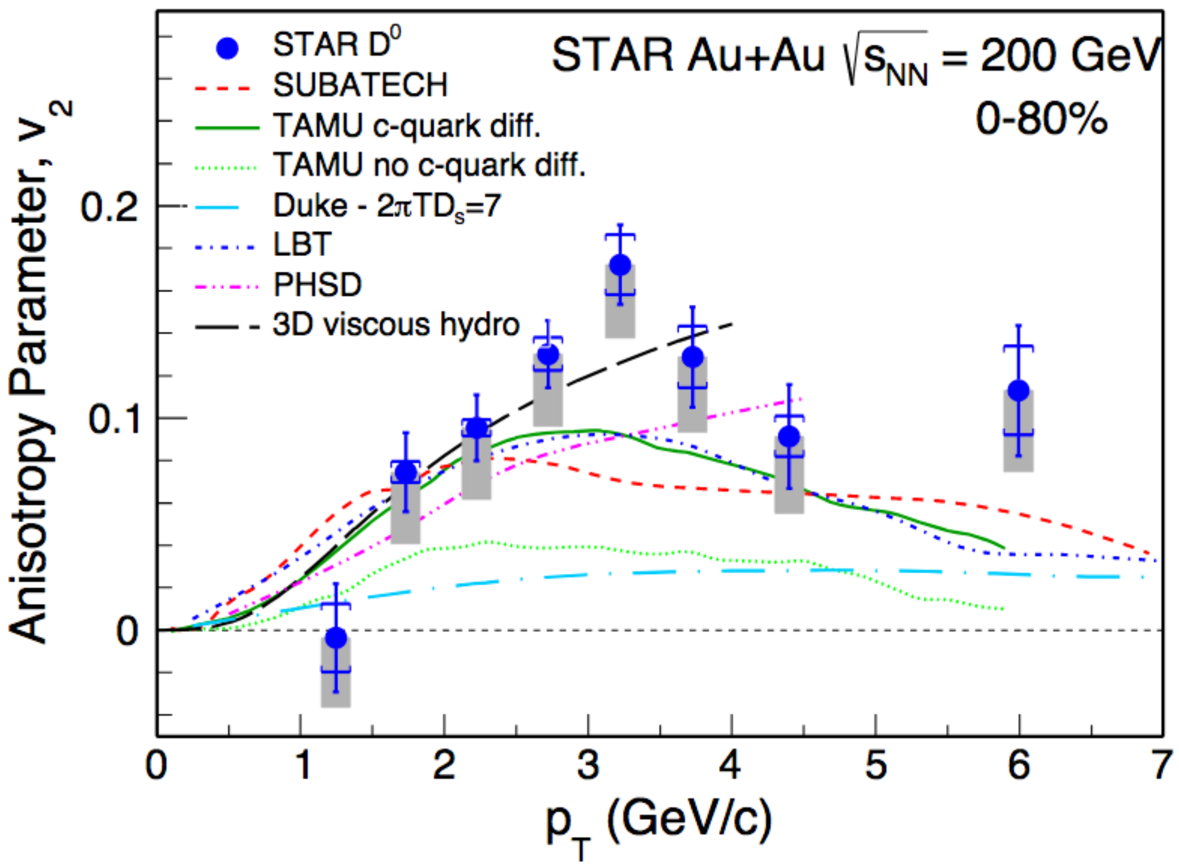
- Strong suppression of D^0 mesons, increasing towards central collisions
- Suppression smaller than light flavor hadrons at intermediate p_T
- Most precise D^0 measurements in heavy-ion collisions, constrain the charm quark energy loss in the QGP

Elliptic flow [*PhysRevLett.118.212301 (2017)*]

- Pressure driven expansion of the QGP medium
- Azimuthal anisotropies in the momentum distribution of produced particles
- Seeded by initial geometry of the fireball
- QGP viscosity, transport properties



$$\frac{dN}{d\phi} \propto 1 + 2\sum_{n=1}^{\infty} v_n \cos n(\phi - \Phi_n).$$

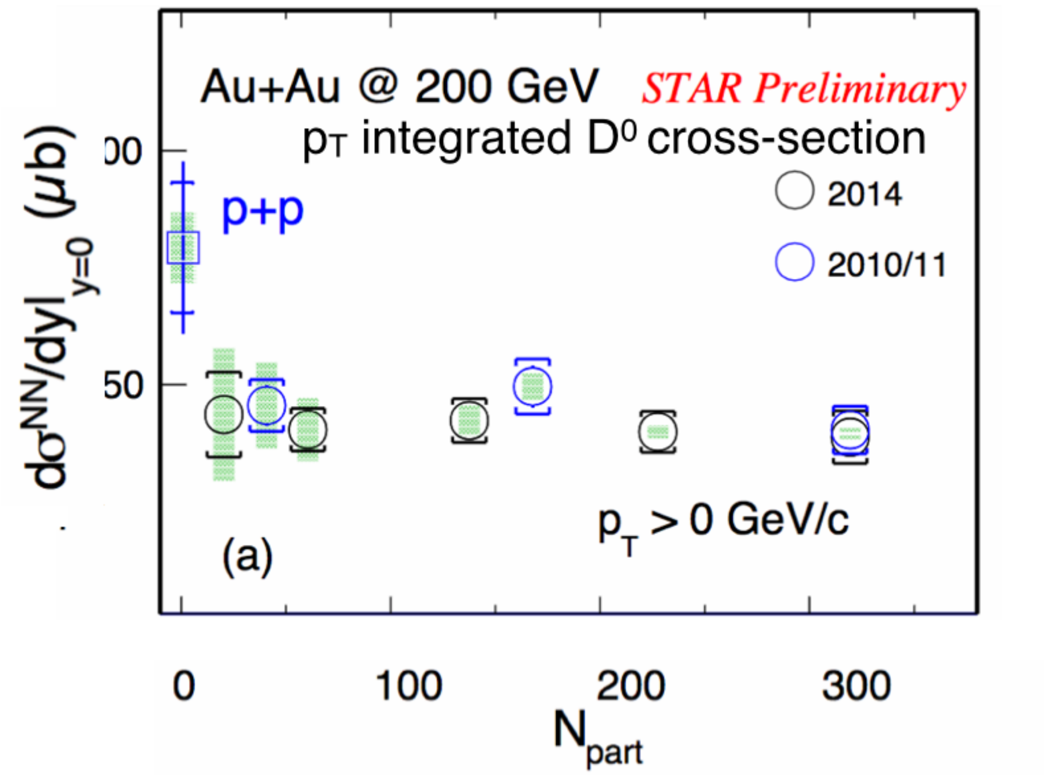


compare with	$2\pi T D_s$	χ^2/NDF	p-value
SUBATECH [17]	2–4	15.2 / 8	0.06
TAMU c quark diff. [20]	5–12	10.0 / 8	0.26
TAMU no c quark diff. [20]	-	29.5 / 8	2×10^{-4}
Duke [19]	7	35.7 / 8	2×10^{-5}
LBT [21]	3–6	11.1 / 8	0.19
PHSD [16]	5–12	8.7 / 7	0.28
3D viscous hydro [45]	-	3.6 / 6	0.73

- Charm quarks acquire flow from diffusion through QGP

Results: Charm cross section

- Cross-section for D^0 production lower than in p+p



- Also measurements on D_s and $D^{+/-}$ production

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^+	69 ± 11 ± 27*
	Total	**143 ± 11 ± 28**
pp 200 GeV	**Total**	**130 ± 30 ± 26**

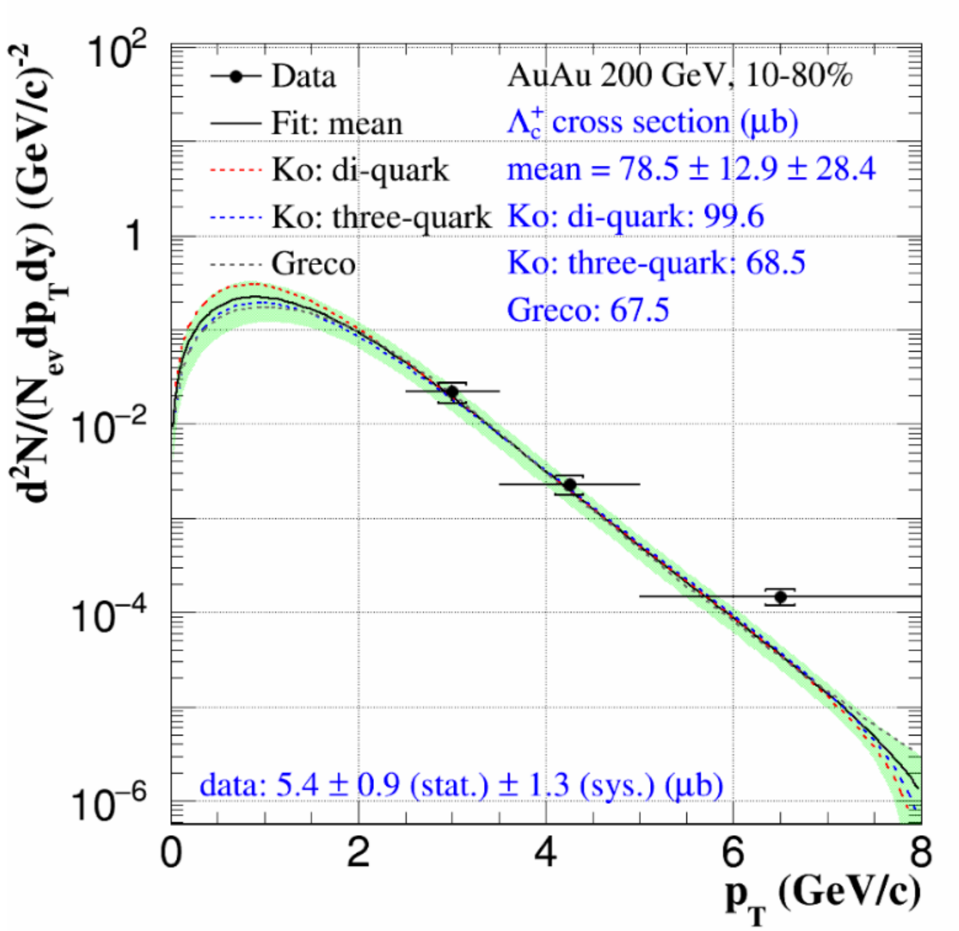
*** derived using Λ_c^+ / D^0 ratio in 10-80%**

- Enhancement for Λ_c and D_s and suppression for D^0
- But total charm cross-section is found to be consistent with p+p

Λ_c cross-section

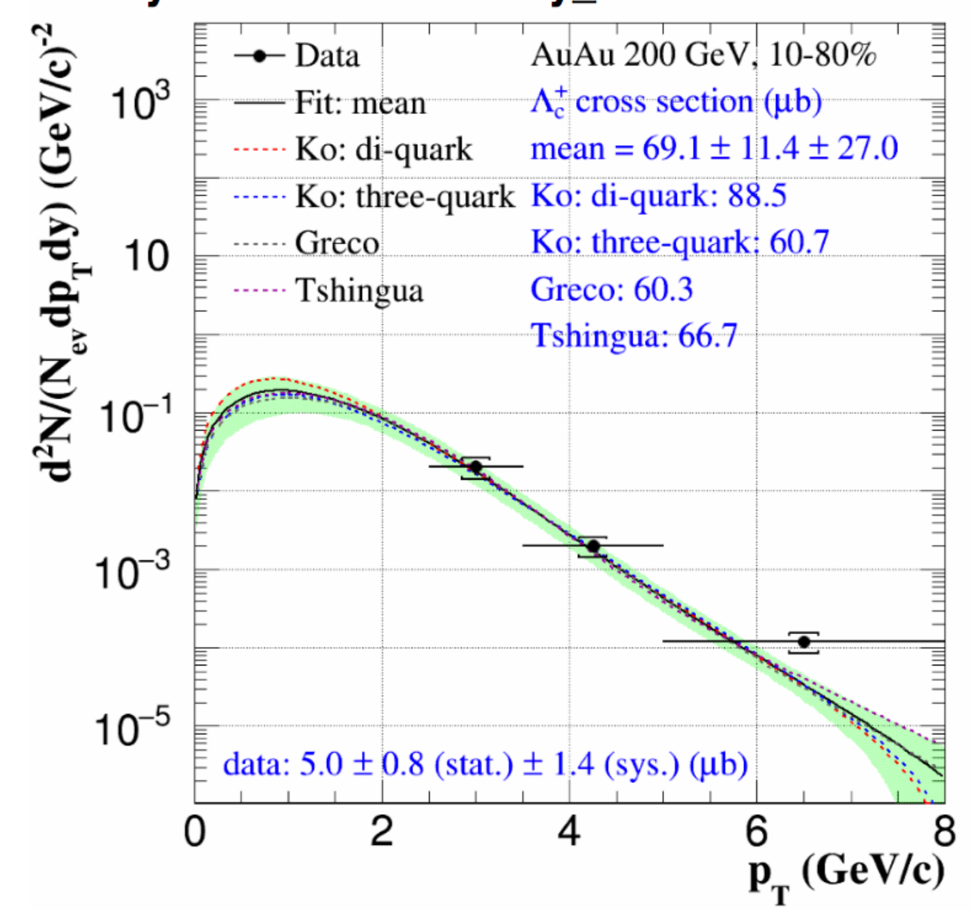
Lc cross section update

Old results



updated Lc spectra

sys from data: 0.18 * y_value is correlated part



Old results:

10-80%

pt	data	stat.	sys.	di-quark	three-quark	Greco	mean	diff(nSigma)
2.5-3.5	0.021807	0.00418592	0.00533427	0.0217311	0.0202819	0.0229574	0.0216568	0.0221546
3.5-5	0.00226732	0.000312316	0.000523047	0.00266194	0.00269616	0.00262791	0.002662	0.647882
5-8	0.000146672	2.18035e-05	2.84159e-05	9.46113e-05	0.000100248	8.75238e-05	9.41276e-05	1.46702

Updated:

pt	data	stat.	sys.	di-quark	three-quark	Greco	Tshingua	mean	diff(nSigma
2.5-3.5	0.0202388	0.00388898	0.00597229	0.019322	0.0179641	0.0204975	0.0212112	0.0197487	0.0687619
3.5-5	0.00201695	0.000279065	0.000592138	0.00236684	0.00238805	0.00234633	0.00230445	0.00235142	0.510944
5-8	0.000119426	1.8018e-05	3.34517e-05	8.41228e-05	8.87916e-05	7.81457e-05	8.14049e-05	8.31163e-05	0.955641

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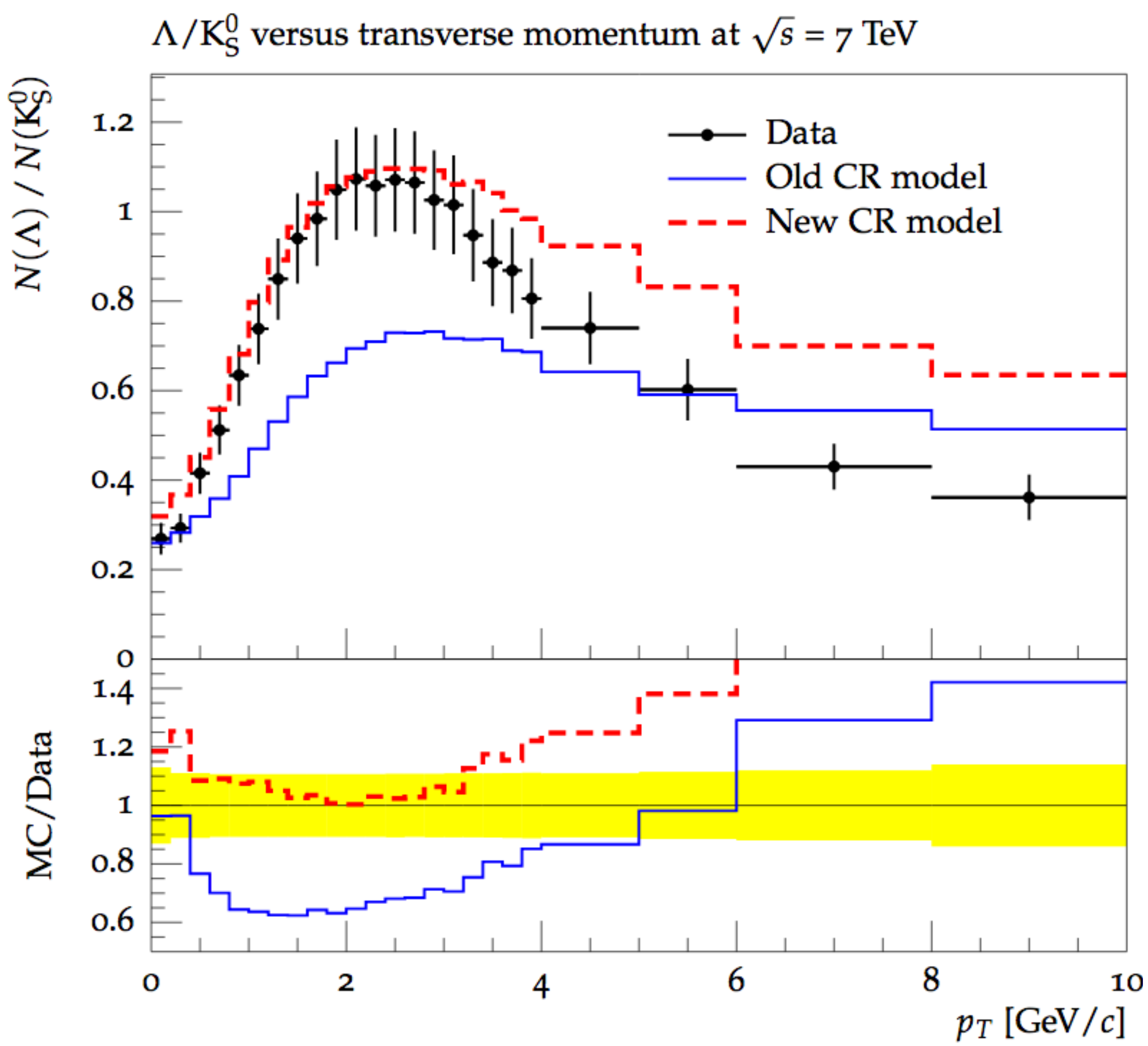
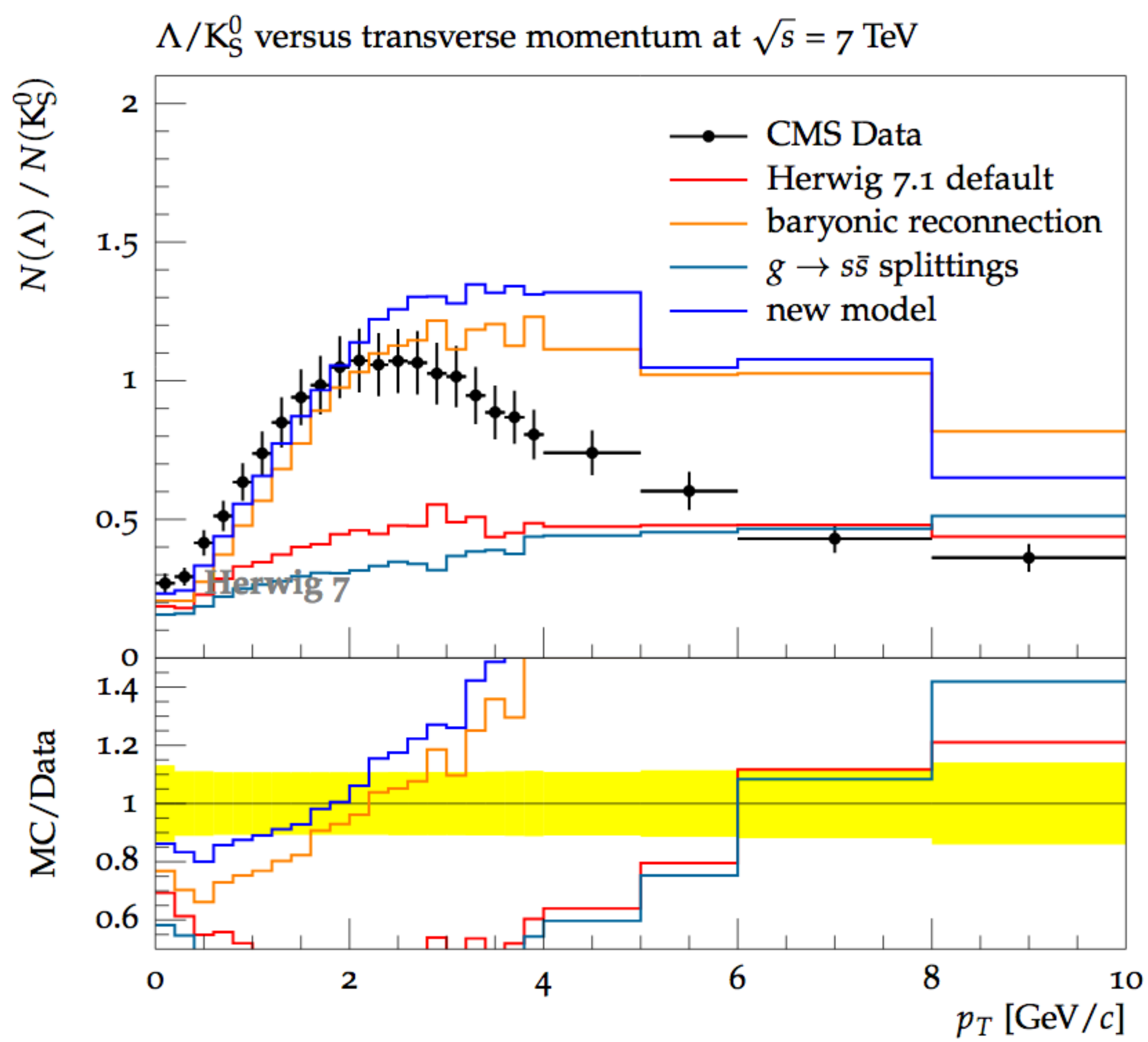
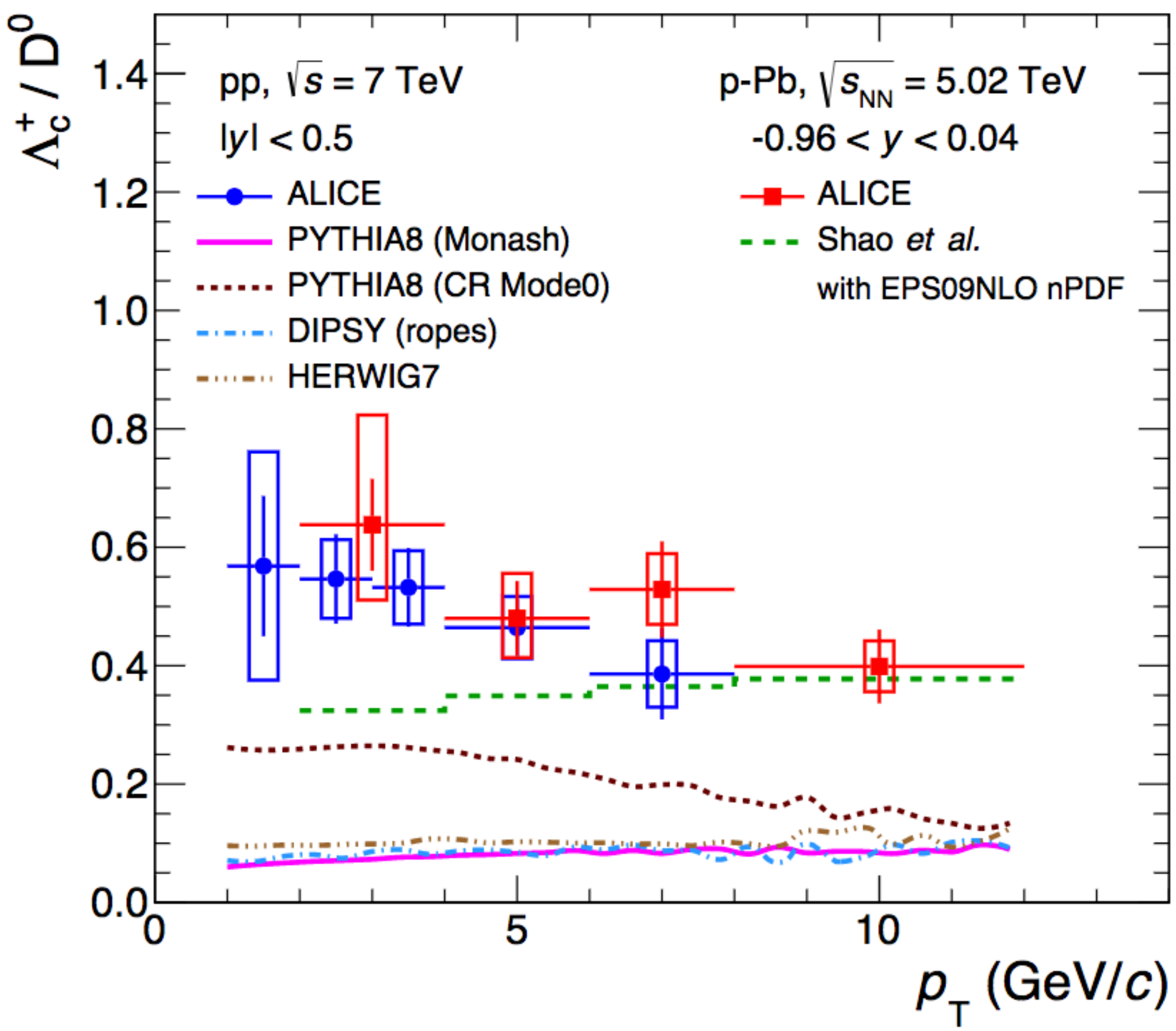
String fragmentation vs cluster hadronization





Λ_c production in p+p collisions

ALICE: arXiv:1712.09581



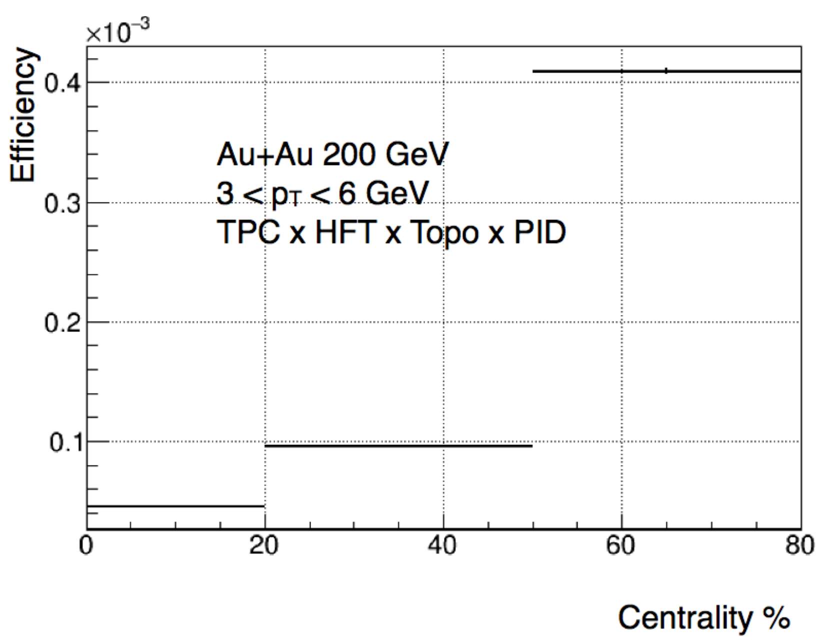
Efficiency corrections

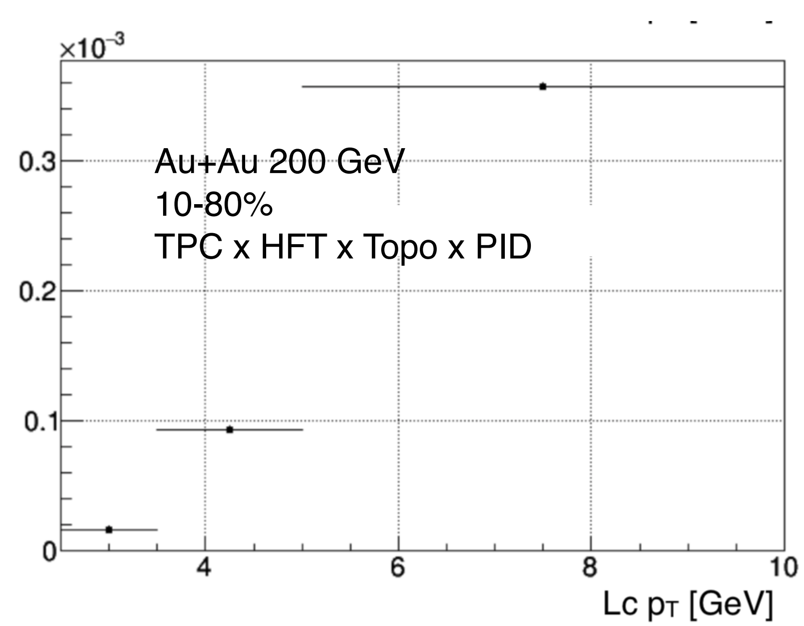
- Efficiency correction from data driven fast simulation (also used for D^0)
  - Extensively validated with HIJING+GEANT simulations
  - Uses as inputs HFT ratio and dca resolution from data, TPC efficiency and momentum resolution from Embedding

$$\varepsilon_{FS} = \varepsilon_{TPC} \times \varepsilon_{HFT} \times \varepsilon_{PID} \times \varepsilon_{BDT}$$

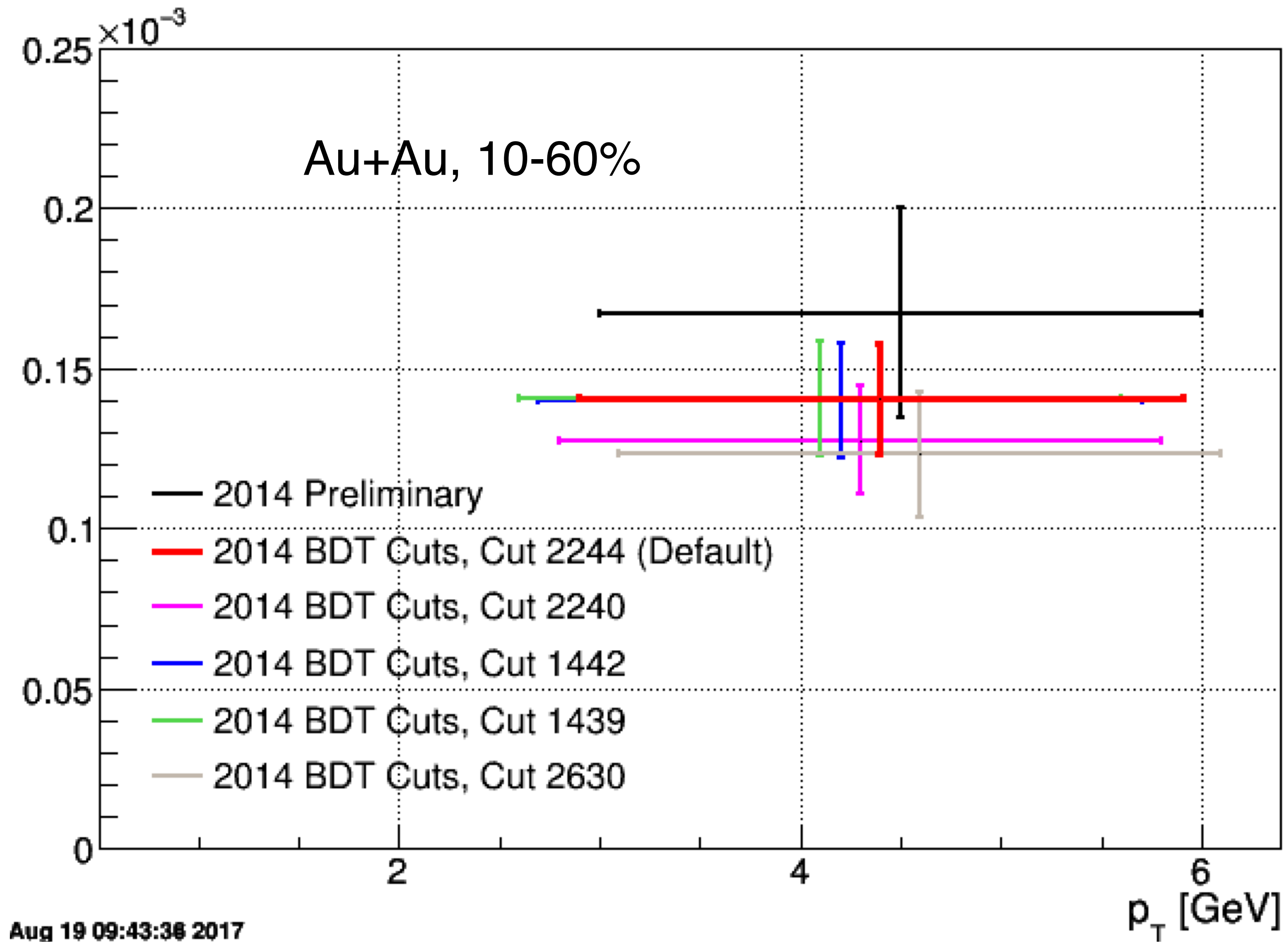
- Corrections from Embedding:
  - Secondary protons from Λ are not matched in HFT.
  - Secondary tracks cause a broadened Dca tail in data
  - Primary vertex resolution effects not accounted for in FastSim
  - Uses Λ_c embedded into HIJING+ZB events to evaluate these

$$\varepsilon_{\Lambda c} = \varepsilon_{FS} \times \varepsilon_{sec} \times \varepsilon_{vtx}$$





Comparison with rectangular cuts



- Error bars are much reduced.
- Cuts are from different tress with different efficiencies
- BDT values are lower than that from rectangular cuts
- BDT FastSim performance need to be validated with HIJING