STAR Open Heavy Flavor Measurements

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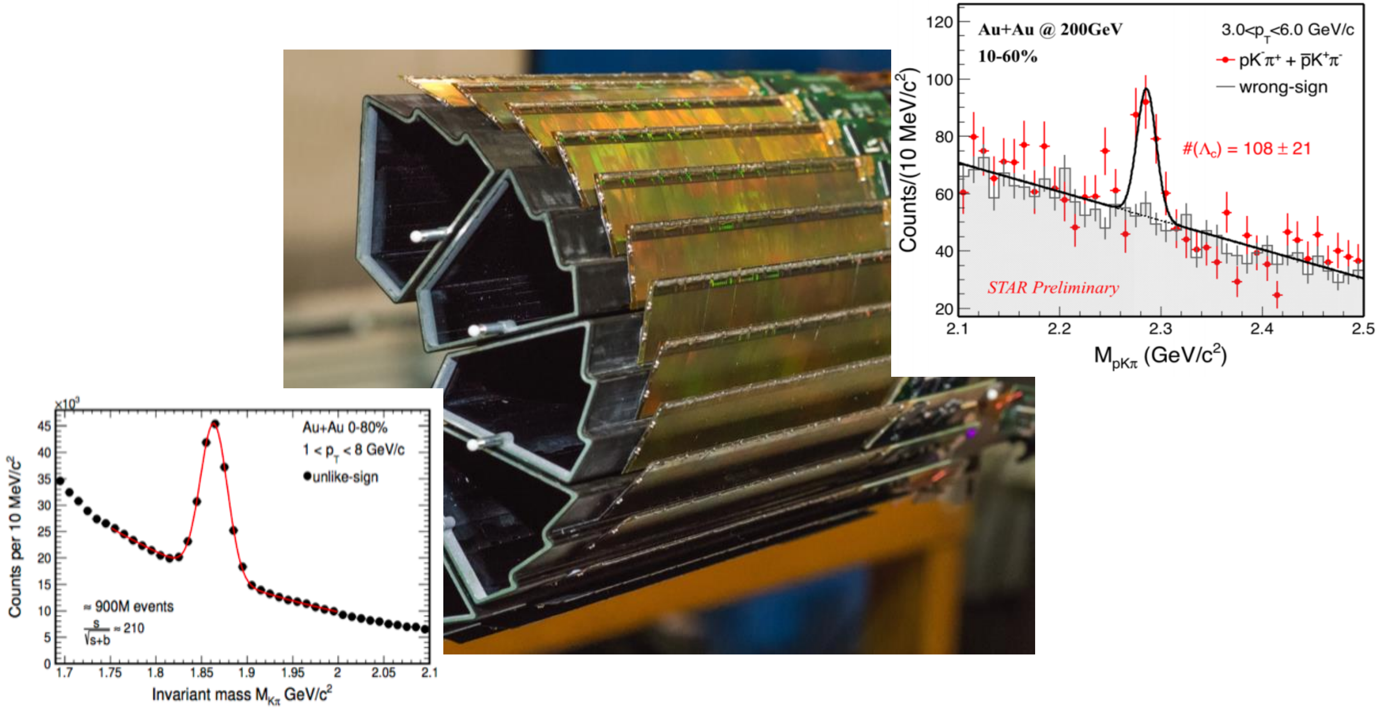
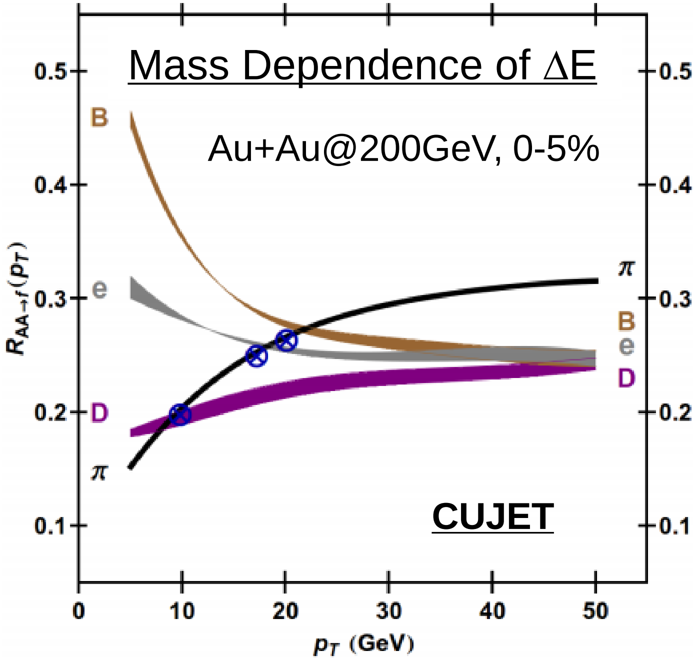
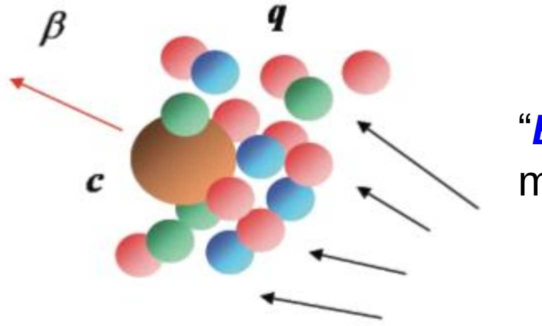


Physics Goals



PRL 108 (2012) 022301



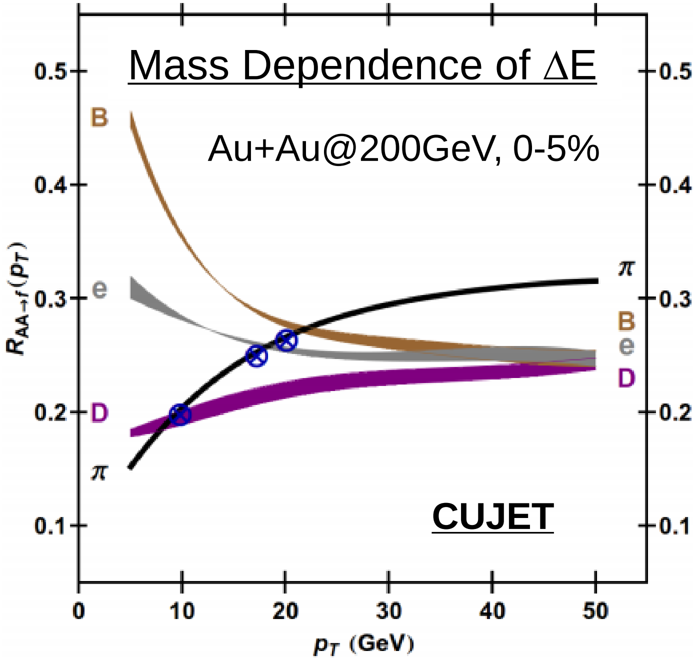
“***Brownian***” motion

$$\frac{dp^i}{dt} = \underset{\substack{\uparrow \\ \text{drag}}}{-\eta_D p^i} + \underset{\substack{\uparrow \\ \text{fluctuations}}}{\xi^i(t)},$$

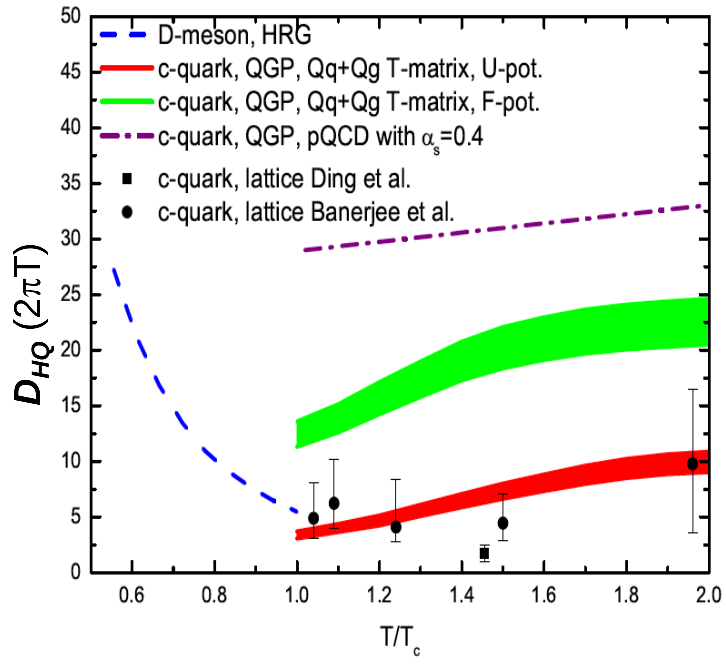
Diffusion coefficient ***D_{HQ}***

To understand the heavy quark energy loss in the QGP
To extract the emergent QGP transport parameters

Physics Goals



PRL 108 (2012) 022301



QCD white paper - arXiv: 1502.02730

Full momentum coverage, especially at low p_T
- better sensitivity to the collisional energy loss
- better constraint to the diffusion coefficient parameter
- better constraint to the total charm yield

Experimental Methods

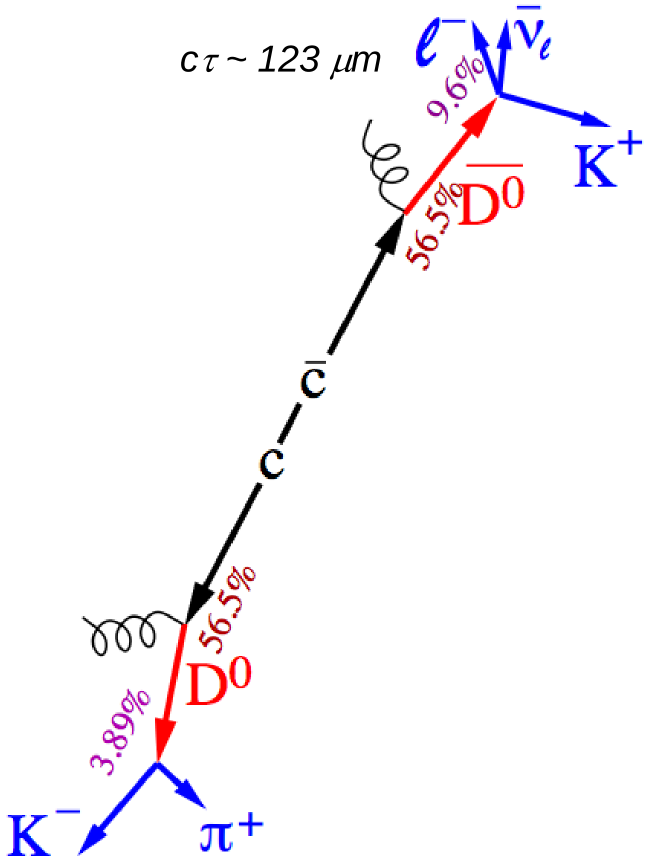
Indirect - through inclusive semi-leptonic/J/ψ channels

- easy to trigger
- high statistics
- background sources
- kinematic smearing due to decays

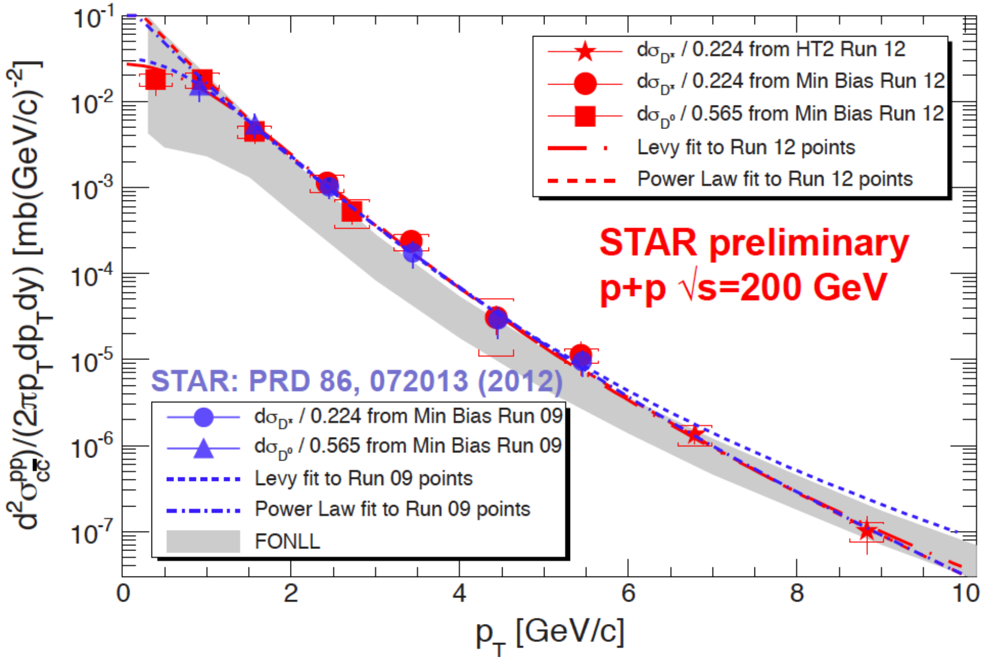
Direct - through exclusive hadronic channels

- full charmed hadron kinematics
- hard to trigger
- smaller branching ratios
- need precision vertex detector to reduce combinatorial background

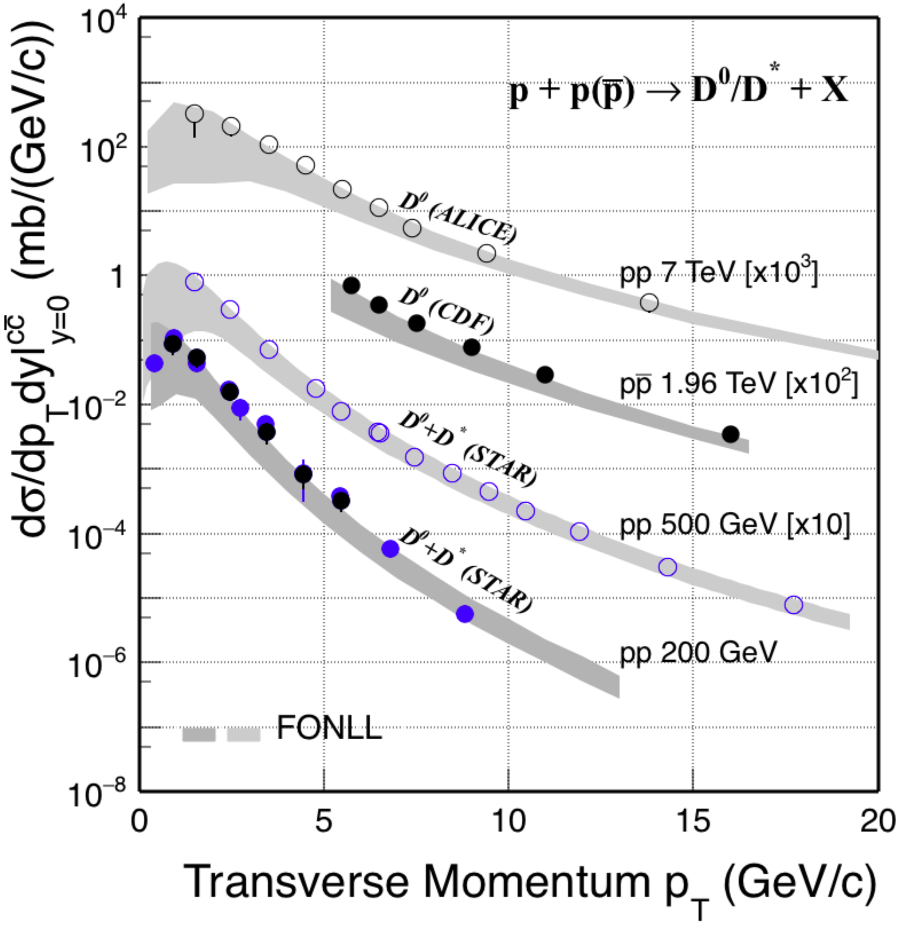
Hadron	Abundance	cτ (μm)
D^0	56%	123
D^+	24%	312
D_s	10%	150
Λ_c	10%	60
B^+	40%	491
B^0	40%	456



Creation of Heavy Quarks

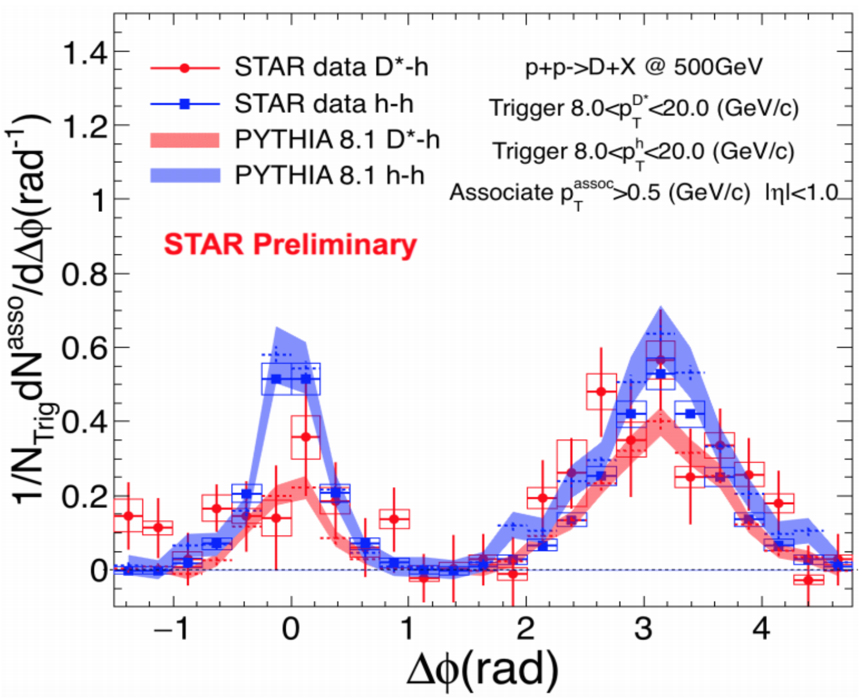


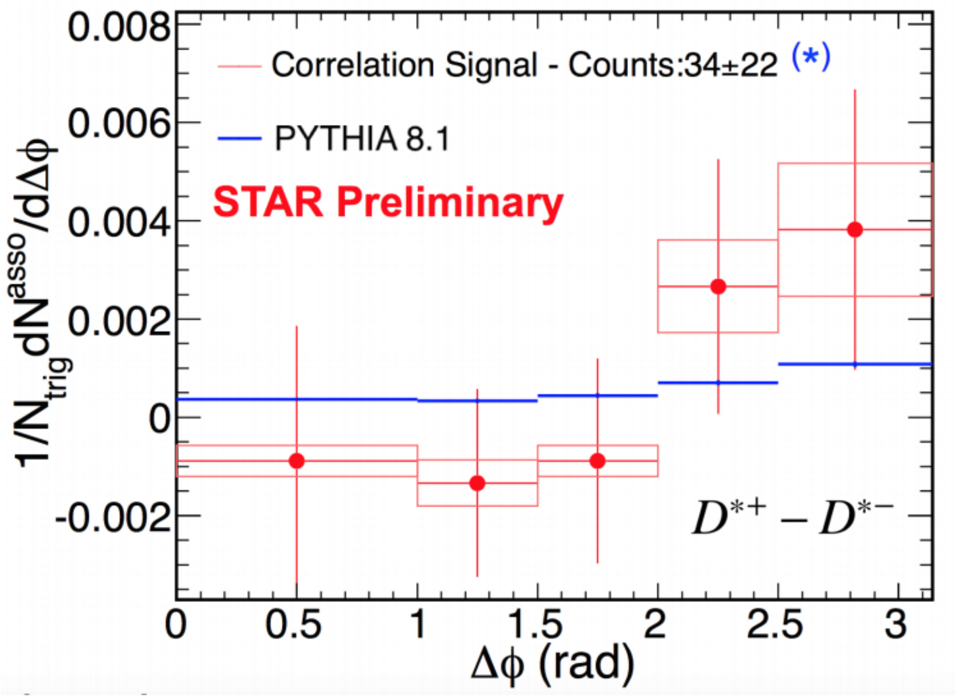
Measurements with prior-HFT data



- FONLL pQCD describes charm production in p+p from 200 GeV –13 TeV

Heavy Quark Correlations in p+p Collisions

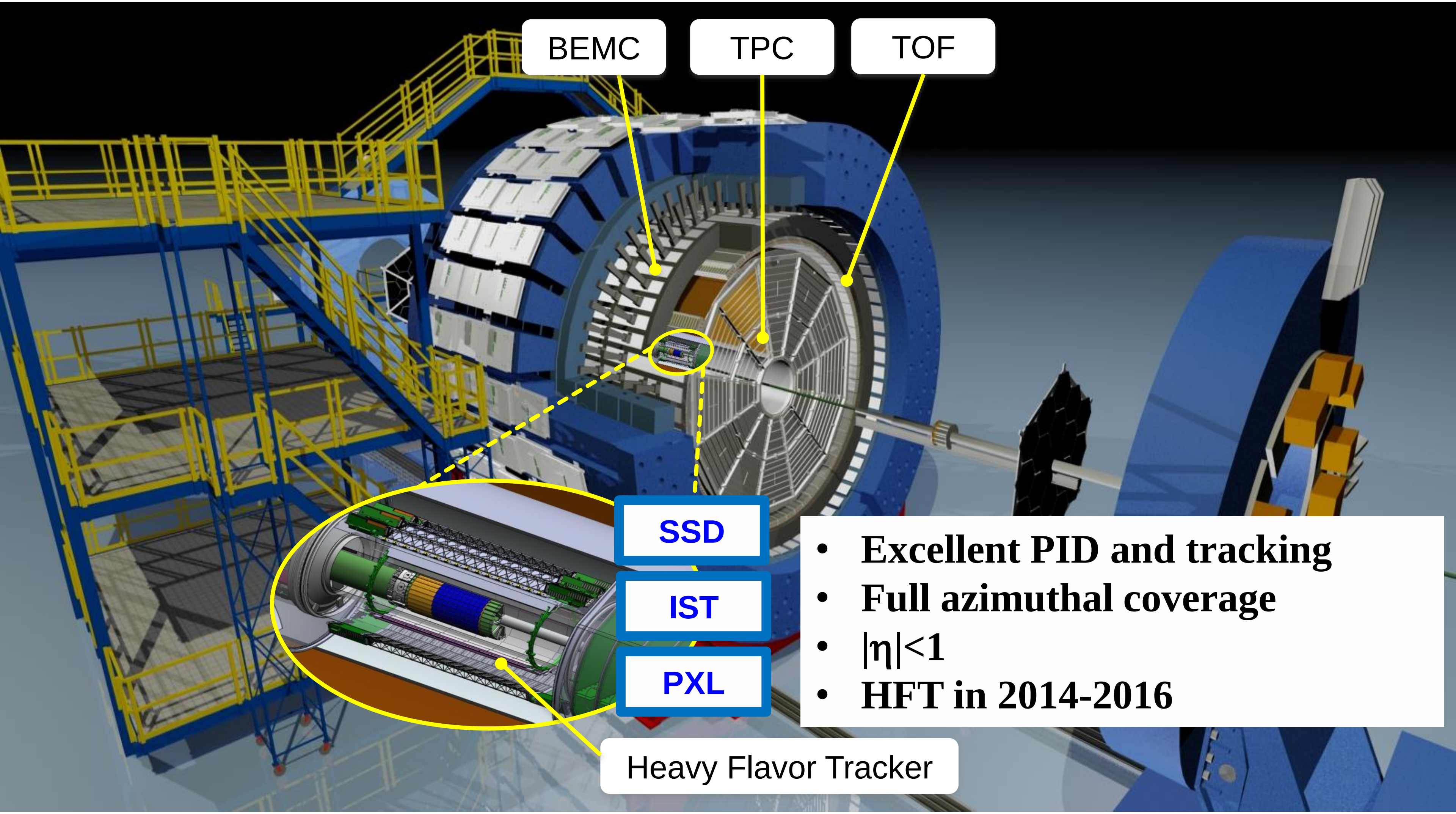




- D*-h azimuthal correlation
  - consistent with h-h correlation in the away side
  - lower correlation yield in the near side – harder fragmentation for charm
  - PYTHIA calculations describe the correlations well

- Proof-of-principle measurement of D-Dbar azimuthal correlations

Detector Setup



- **Excellent PID and tracking**
- **Full azimuthal coverage**
- **$|\eta|<1$**
- **HFT in 2014-2016**

Heavy Flavor Tracker

Precision measurements of heavy flavor hadrons need a detector with:

- Ultimate position resolution and solid mechanical support *
- Thin detector material to allow precision measurement over a broad p_T region *
- Full azimuthal angle coverage at mid-rapidity
- Fast DAQ readout to be able to handle RHIC-II luminosity
- Sufficient radiation tolerance to be operated in RHIC collider environment

** Uniqueness of the STAR HFT*

Detector	Radius (cm)	Hit Resolution R/φ - Z (μm - μm)	Thickness
Silicon **S**trip **D**etector	22	30 / 860	1% X_0
Intermediate **S**ilicon **T**racker	14	170 / 1800	1.3%X_0
Pi**X**e**L**	8	**12 / 12**	0.4%X_0
	2.9	**12 / 12**	**0.4%X_0** *

** 0.5%X_0 in Run14*

Key Instruments – Pixel Silicon Detector

	ALICE	ATLAS	CMS	LHCb	PHENIX	STAR
Sensor tech.	Hybrid	Hybrid	Hybrid	Hybrid	Hybrid	**MAPS**
Pitch size (μm^2)	50x425	50x400	100x150	200x200	50x425	**20x20**
Radius of first layer (cm)	3.9	5.1	4.4	N/A	2.5	2.8
Thickness of first layer	1%X_0	~1%X_0	~1%X_0	~1%X_0	1%X_0	**0.4%X_0**

STAR Pixel – first application of MAPS technology in collider experiments

(MAPS - Monolithic Active Pixel Sensor)

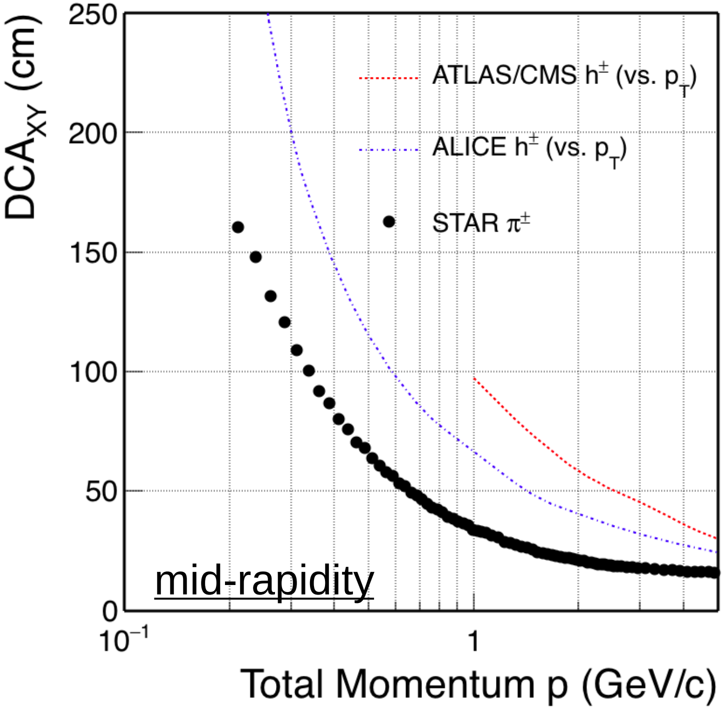
Next generation MAPS planed for future experiments:

ALICE ITS upgrade, sPHENIX MVTX

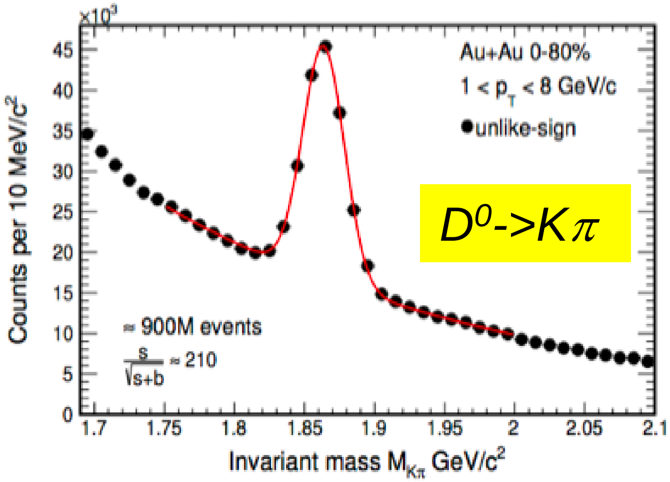
- to address the QGP medium properties

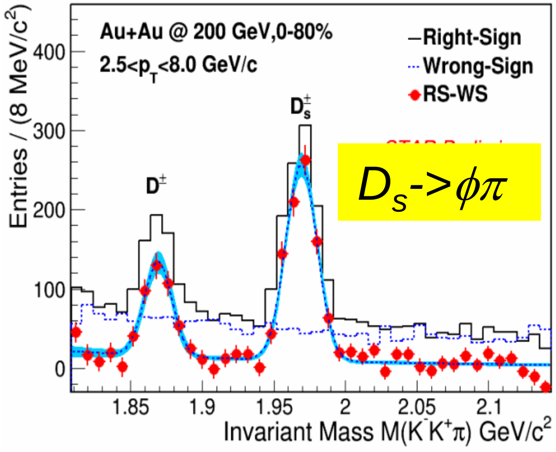
Also for CBM, EIC detector R&D

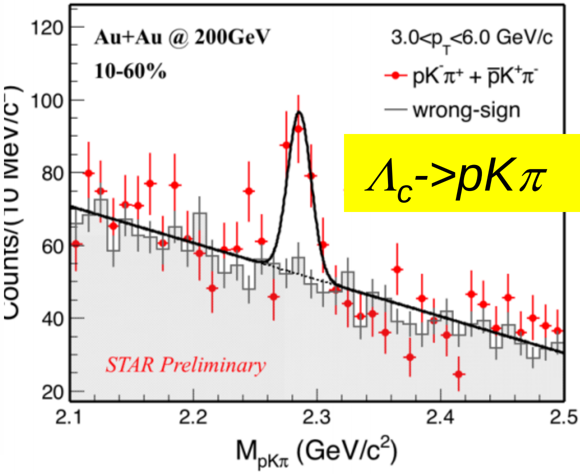
Pixel Detector Performance



Exclusive reconstruction of HF hadrons in heavy-ion collisions





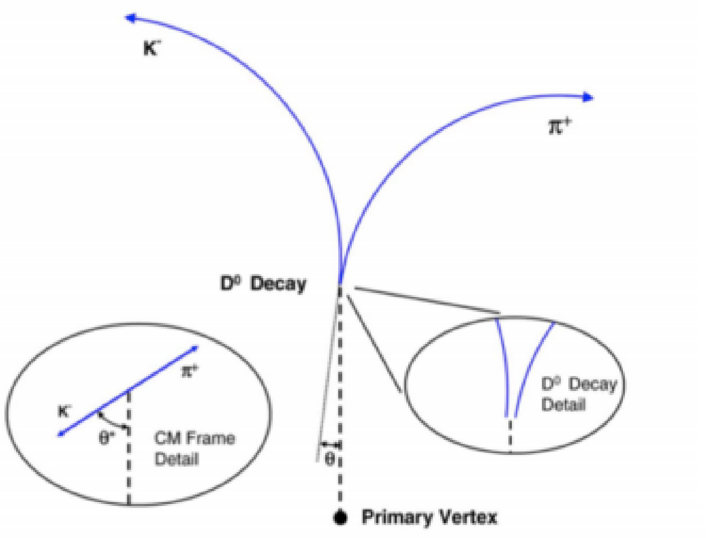


STAR	30 μm @ 1 GeV/c (p)
ALICE	70 μm @ 1 GeV/c (p_T)
ATLAS/CMS	100 μm @ 1 GeV/c (p_T)

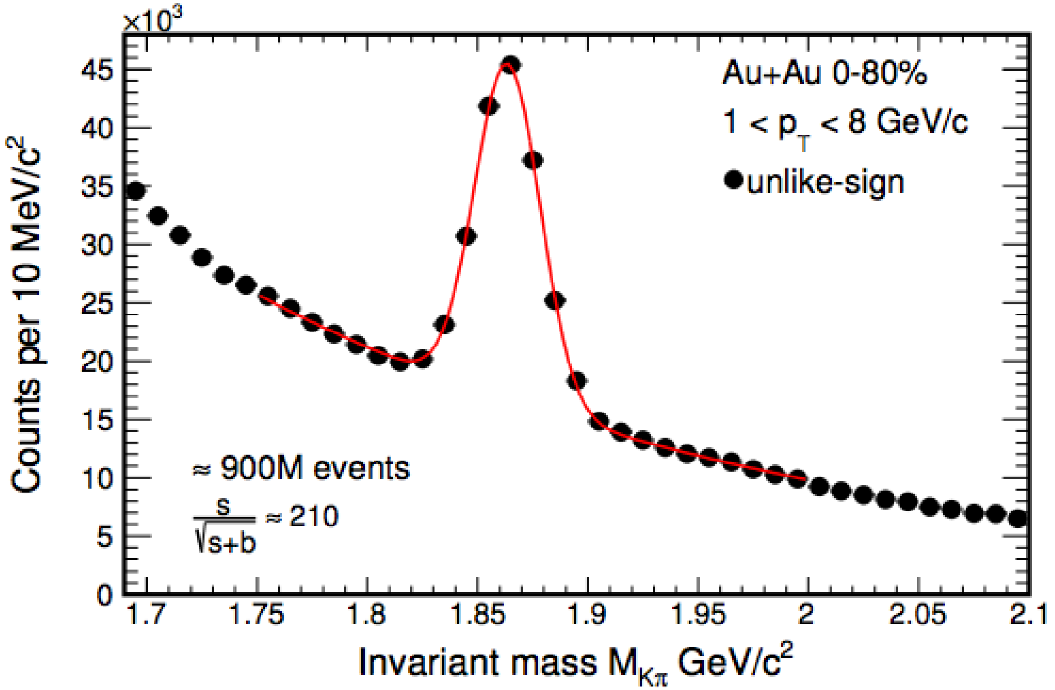
D^0 Reconstruction

$D^0(\overline{D^0}) \rightarrow K^{\mp}\pi^{\pm}$

B.R. 3.9% $c\tau \sim 120\ \mu m$



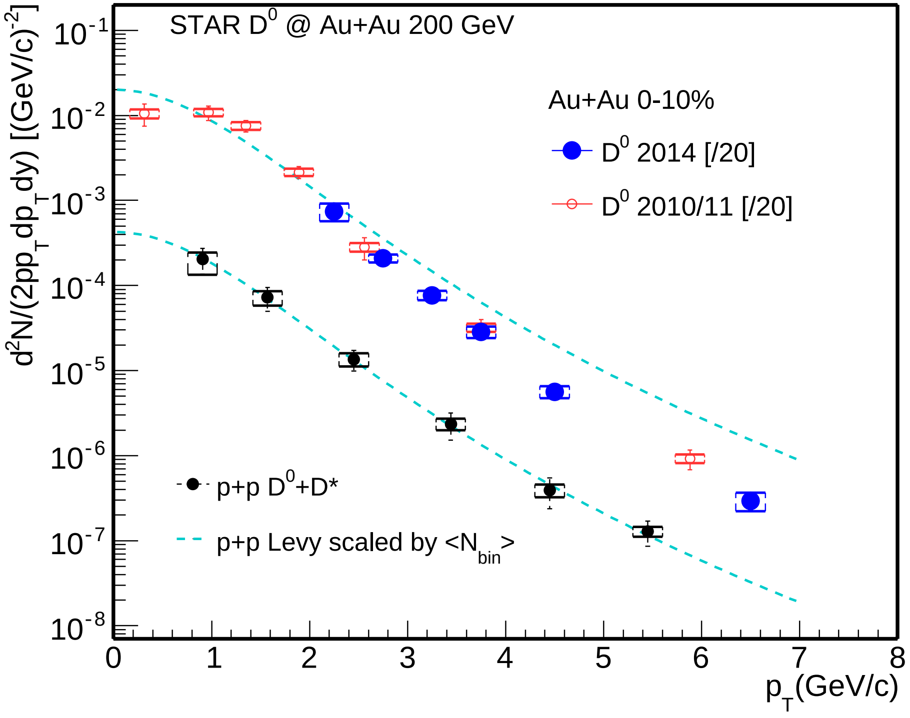
Topological cuts optimized using TMVA (Toolkit for Multivariate Analysis)

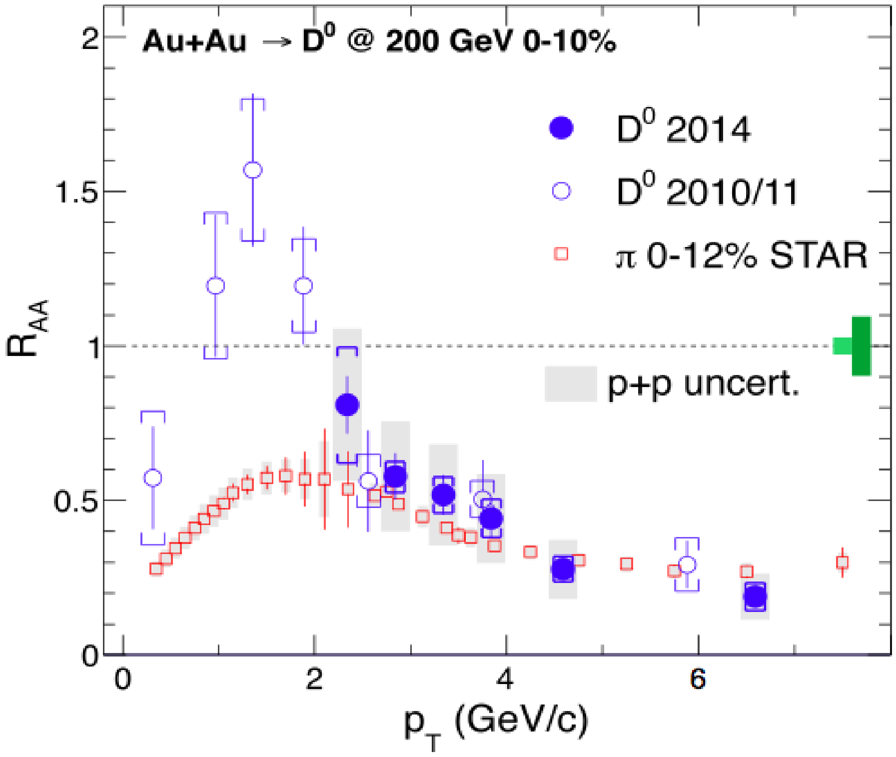


	w/o HFT	w/ HFT
	2010+2011	2014
#events(MB) analyzed	1.1 billion	~900 million
sig. per billion events	13*	220

*L. Adamczyk et al. (STAR), PRL113 142301

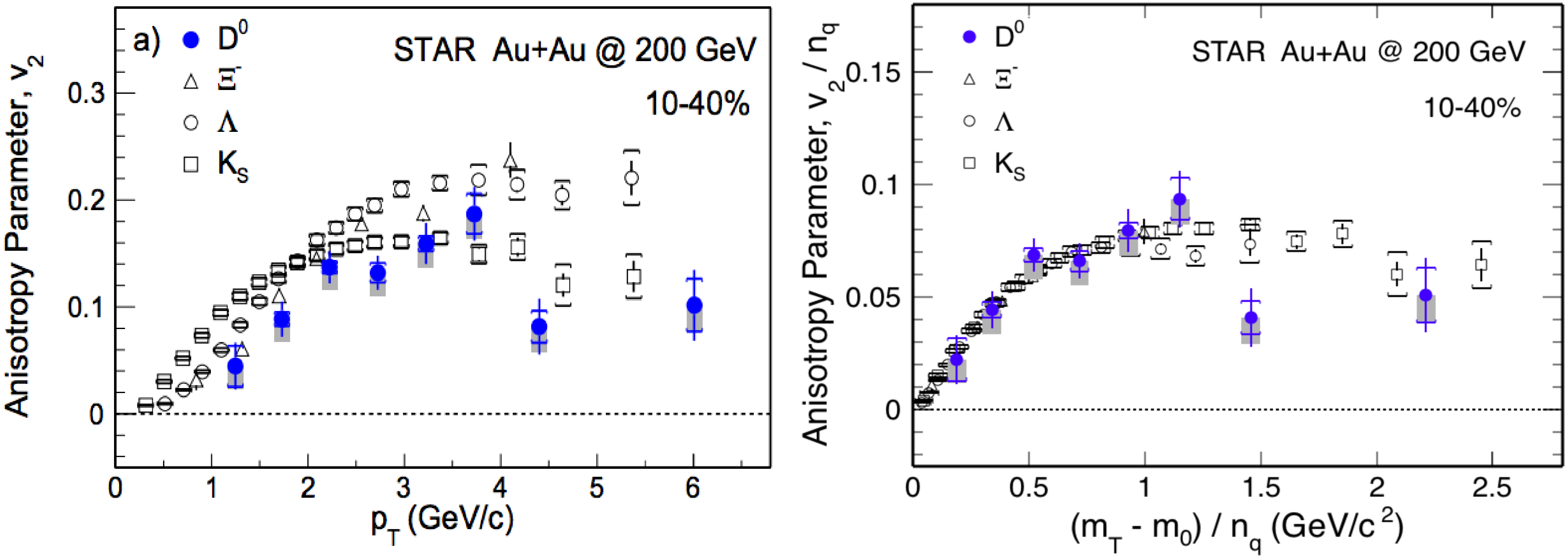
Charm Hadron R_{AA}





- Significant charm hadron suppression in central Au+Au collisions at p_T>3 GeV/c
- R_{AA}(D) ~ R_{AA}(h) at p_T > 3 GeV/c
  - suggesting significant charm quark energy loss

Charm Hadron v_2



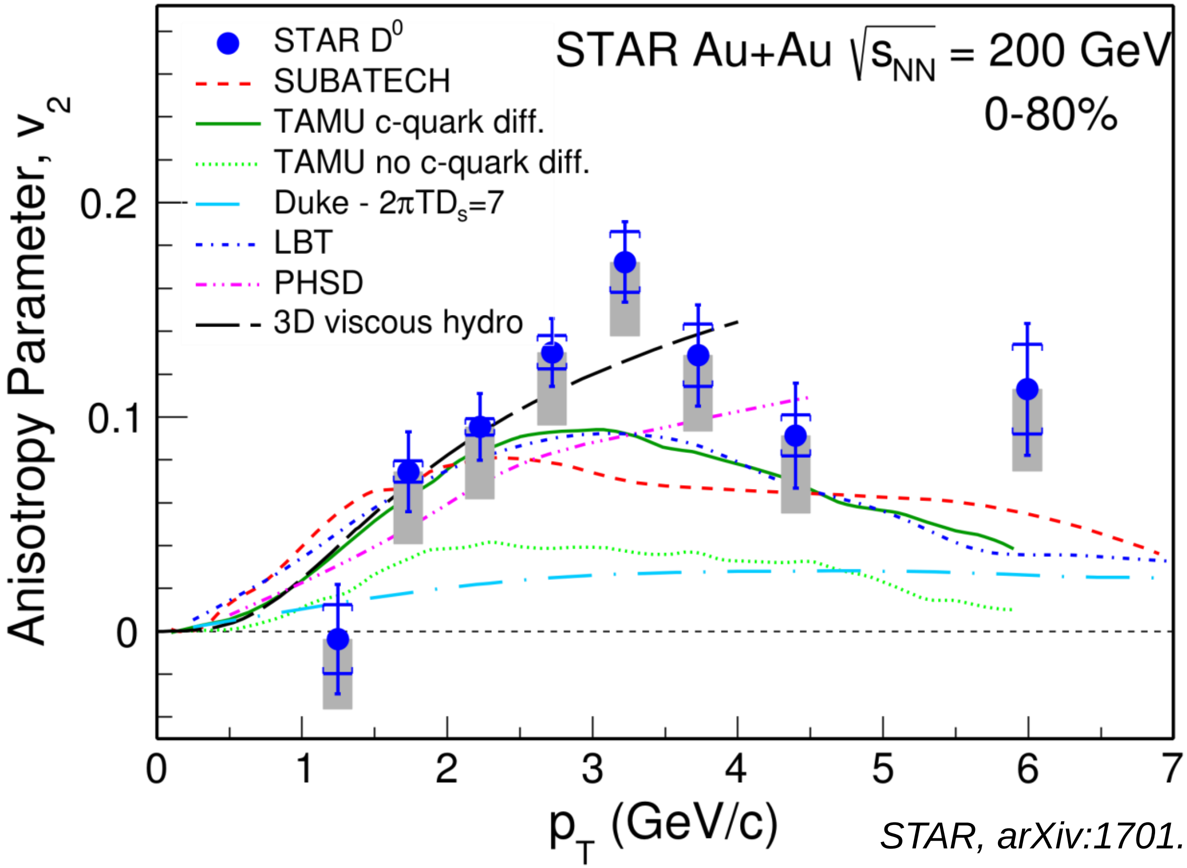
STAR, arXiv:1701.06060, PRL in press

- Mass ordering at $p_T < 2$ GeV/c (hydrodynamic behavior)
- v_2(D) follows the (m_T-m_0) NCQ scaling as light hadrons below 1 GeV/c^2

Evidence of charm quarks flowing the same with the medium

- suggest charm quarks may have achieved thermalization

Charm Hadron v_2 Compared to Models



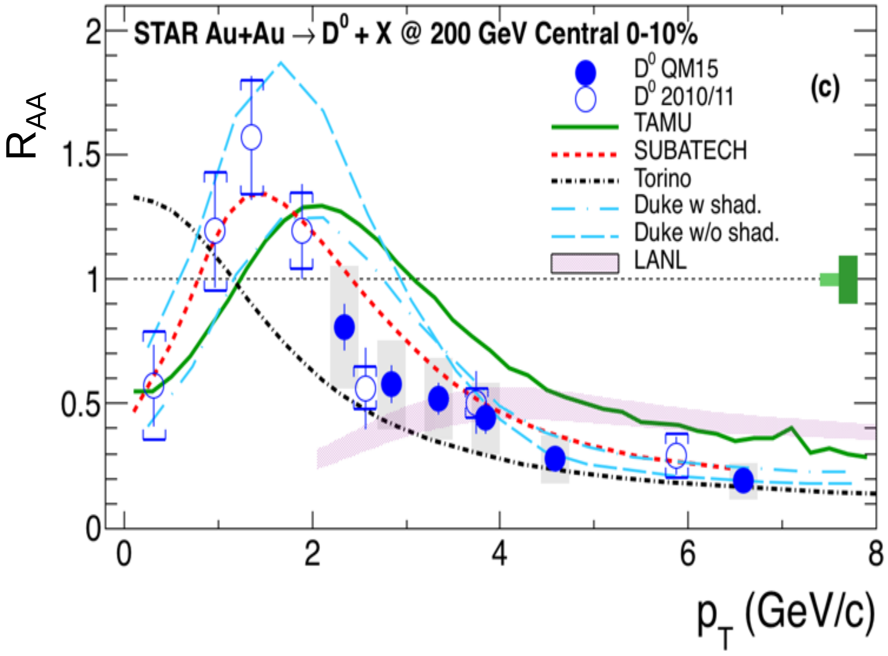
STAR, arXiv:1701.06060, PRL in press

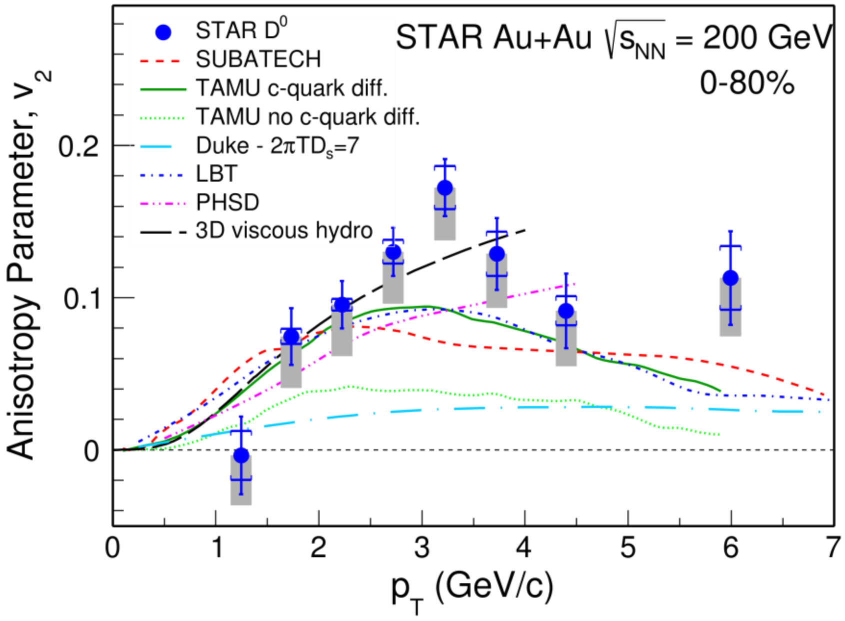
- 3D viscous hydro model calculations describe the D^0 v_2 at p_T< 3-4 GeV/c

  - Indication of charm quark thermalization in the QGP

- Data precision good enough to constrain model calculations

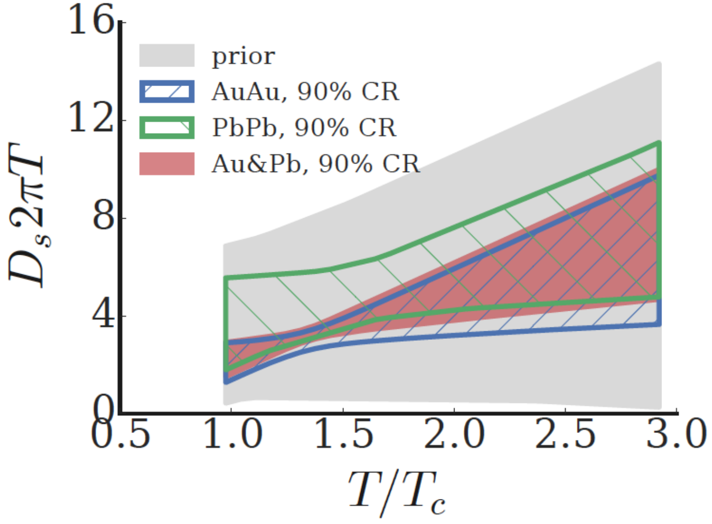
R_{AA} and v_2 Compared to Models



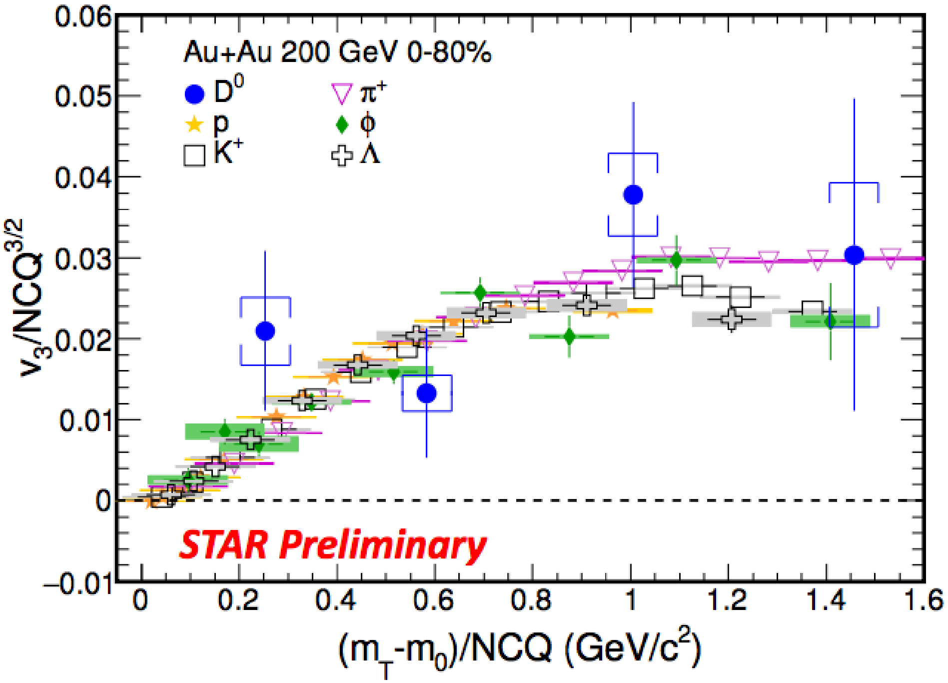


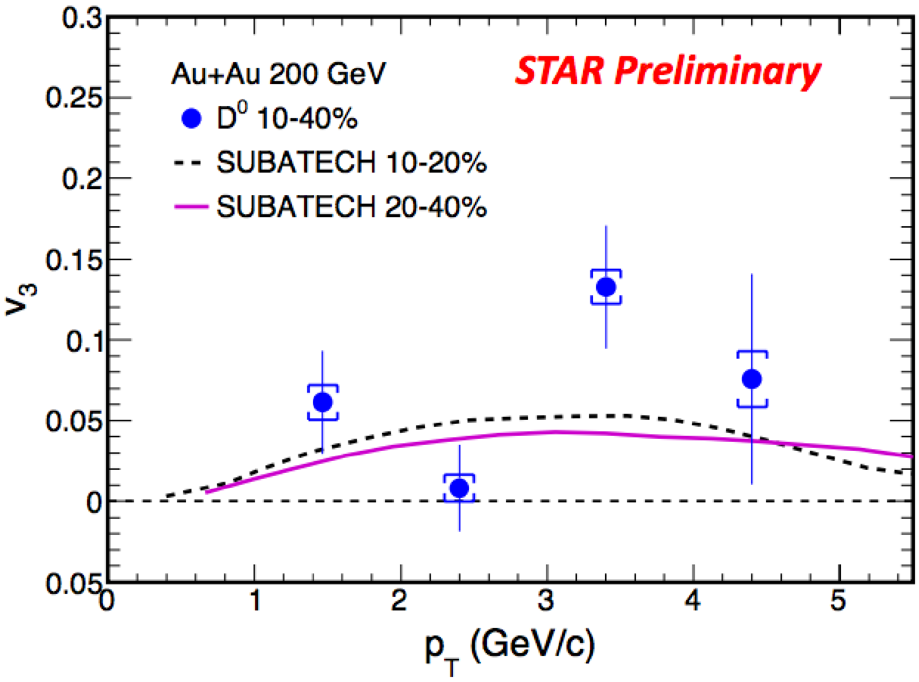
- Understand the trivial/non-trivial differences between models
- Precision data starts to provide constraints on medium transport parameter

  - e.g. Bayesian analysis - Yingru Xu QM17



D^0 Triangular Flow



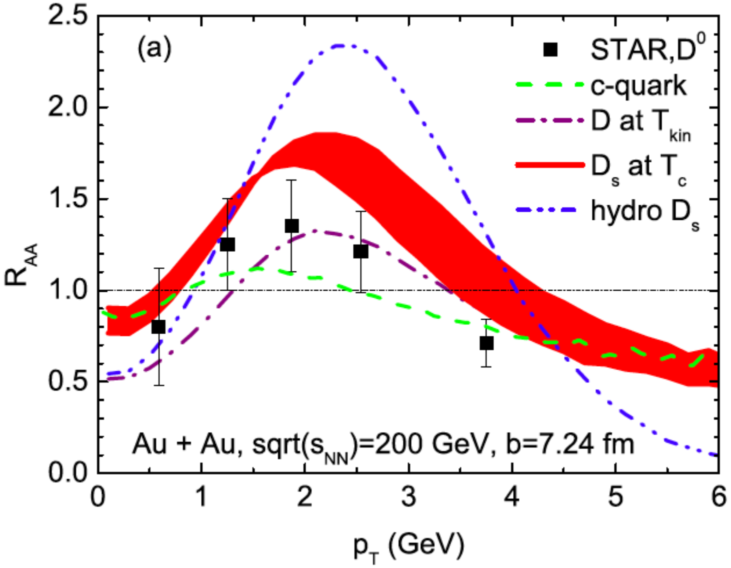


SUBATECH: M. Nahgrang et al, PRC 91, 014904 (2015)

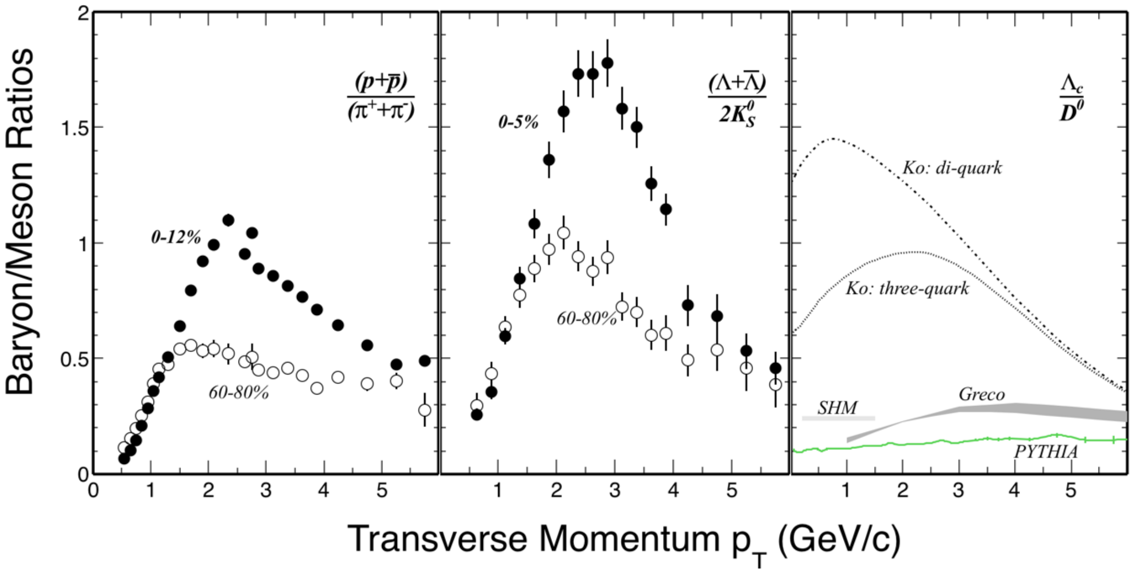
- Significant D^0 v_3 at RHIC
- D^0 v_3 follows the same scaling as light hadrons

-> consistent with significant charm flow, suggesting thermalization of charm quarks

Charm Hadronization



H. Min et al. PRL 110,112301 (2013)



Ko model : Y. Oh, et.al. PRC 79,044905 (2009)

Greco model : S.Ghosh, et. al. PRD 90,054018 (2014)

Coalescence hadronization

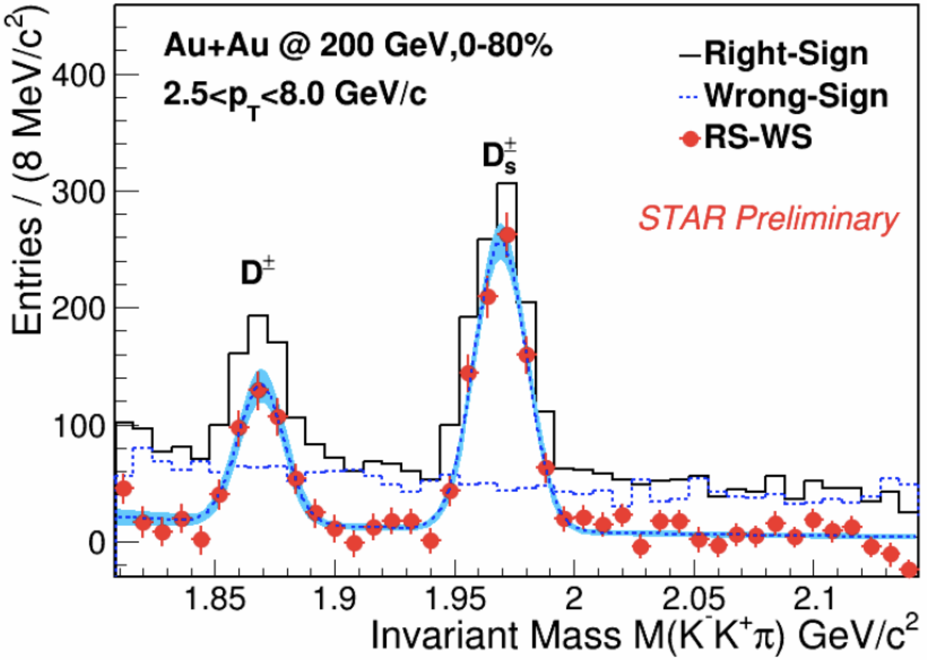
- Strangeness enhancement -> D_s enhancement
- Baryon enhancement -> Λ_c enhancement

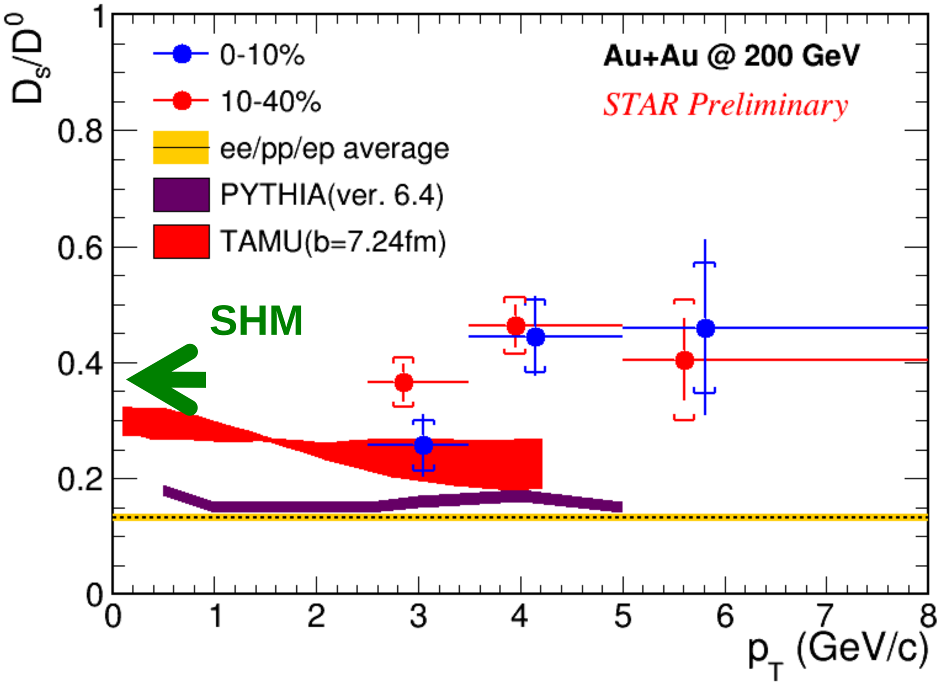
$$2\sigma_{c\bar{c}} = D^0 + D^+ + D_s^+ + \Lambda_c^+$$ + c.c.

60.8% 24.0% 8.0% 6.2%

M Lisovyi, et. al. EPJ C 76, 397 (2016)

D_s Enhancement

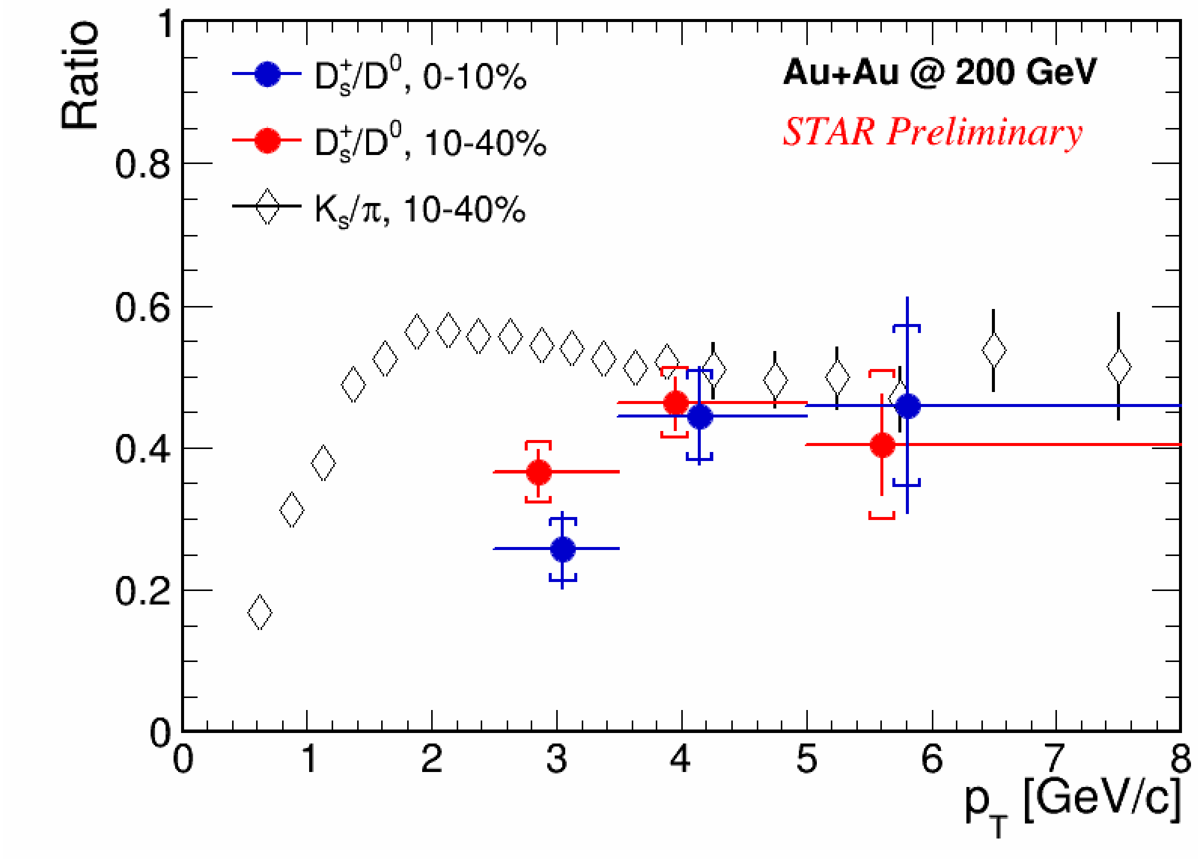




TAMU: H. Min et al. PRL 110,112301 (2013)

- A strong enhancement w.r.t PYTHIA and ee/pp/ep fragmentation ratio average
- D_s/D^0 ratio larger than the TAMU prediction
    - D_s/D^0 for TAMU: $R_{AA}(D_s)/R_{AA}(D)|_{TAMU}$ * 0.187
- SHM predicts D_s/D^0 ratio ~ 0.35-0.40 (central) *A. Andronic et al., PLB 571, 36 (2003)*

Strangeness-to-nonstrangness Meson Ratios



Similar amplitude as light hadrons at 3.5-8 GeV/c, smaller at lower p_T

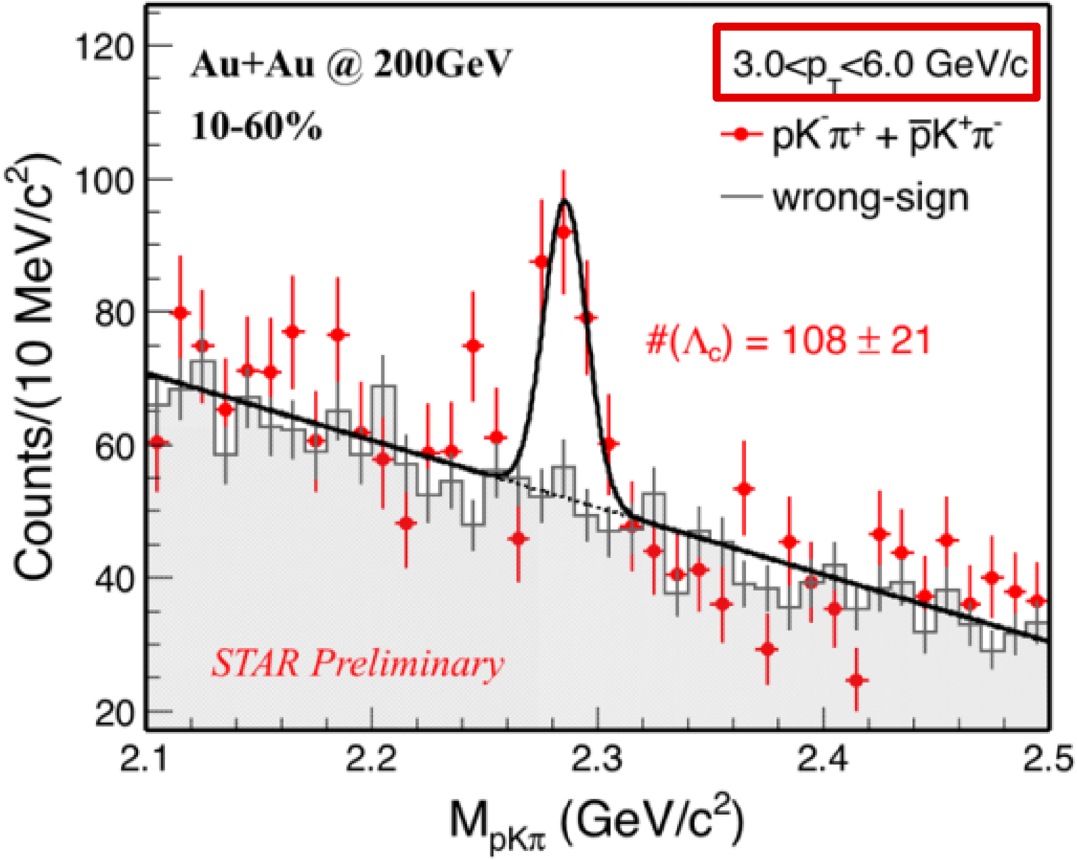
Λ_c Reconstruction in Heavy Ion Collisions

$\Lambda_c^+ \to pK^-\pi^+$

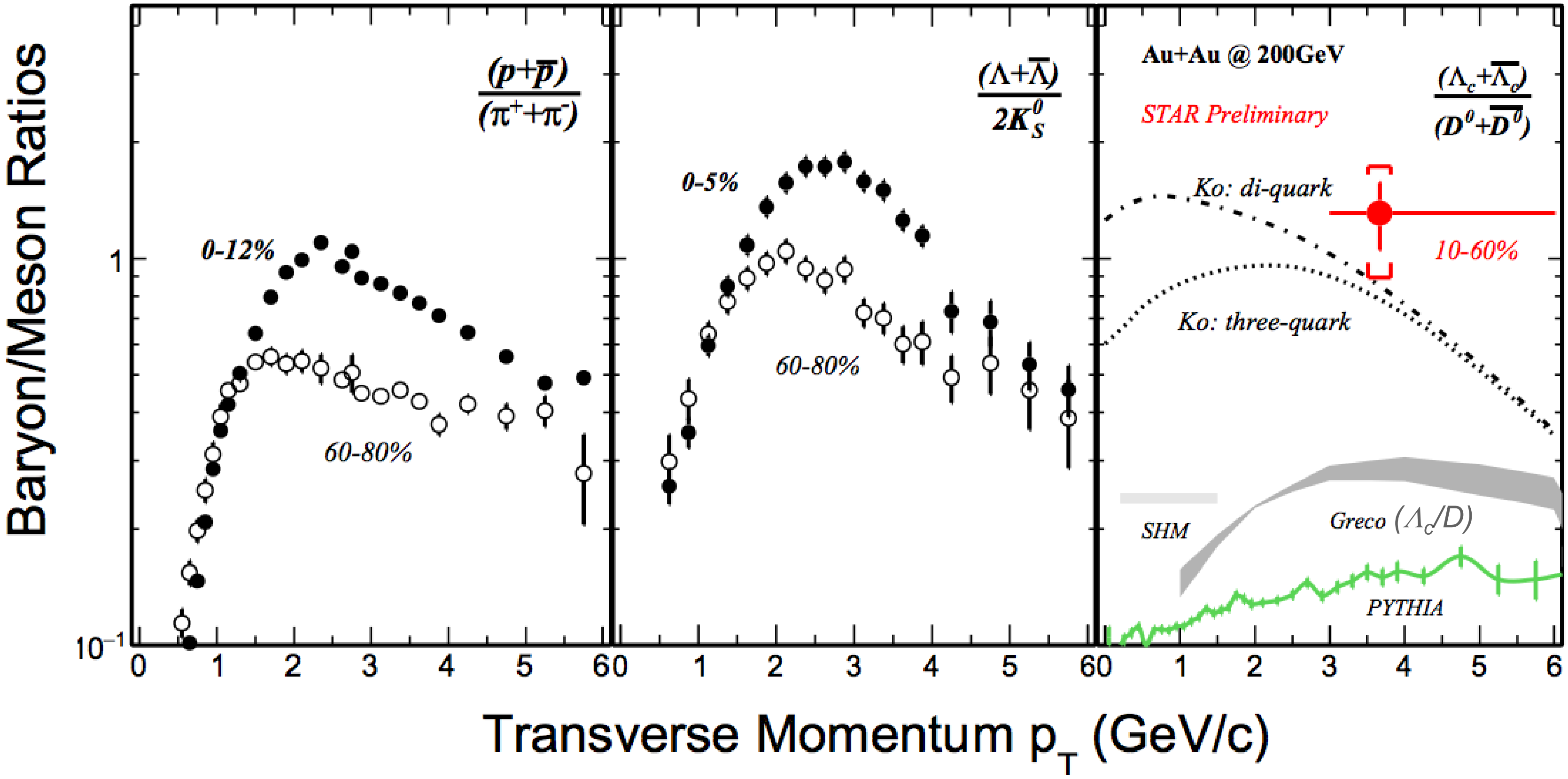
$c\tau = 60\,\mu m$

$B.R. = 6.35\%$

- pK* 1.98% ∗ 66.7% = 1.32%
- $\Delta^{++}K^-$ 1.09% ∗ 100% = 1.09%
- $\Lambda(1520)\,\pi^+$ 2.2% ∗ 22.5% = 0.495%
- Non-resonant 3.5%



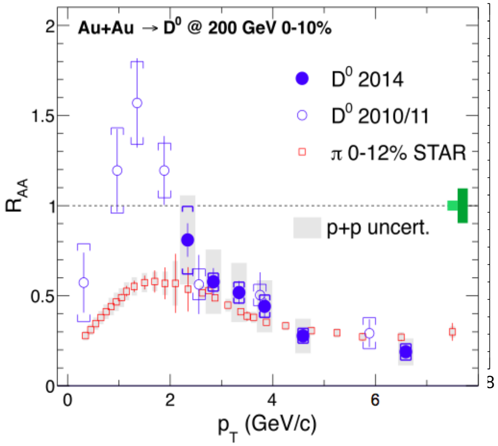
Λ_c Enhancement in Heavy Ion Collisions

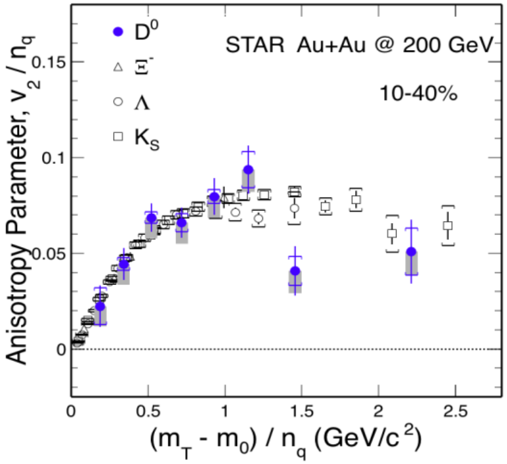


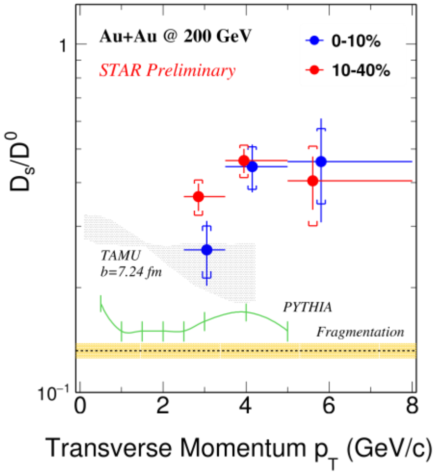
Ko model : Y. Oh, et.al. PRC 79 (2009) 044905; Greco model : S.Ghosh, et. al. PRD 90 (2014) 054018

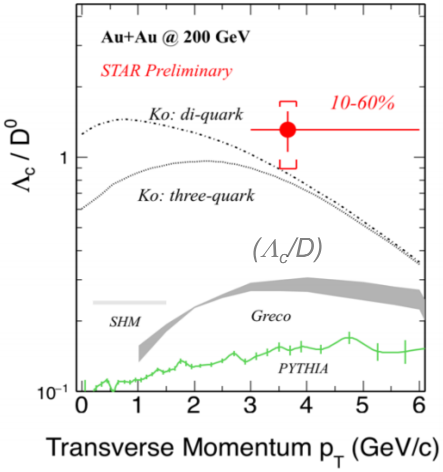
- Significant enhancement in Λ_c/D compared to PYTHIA/fragmentation baseline
- The Λ_c/D^0 ratio is compatible with light flavor baryon-to-meson ratios
- Consistent with coalescence + thermalized charm quarks

Summary - Charm









$R_{AA}(D) \sim R_{AA}(h)$ (p_T>3 GeV/c)	- charm quarks lose significant energy
$v_2(D) \sim v_2(h)$ vs. m_T	- charm quarks flow like light quarks
Λ_c/D^0 and D_s/D^0 enhancement	- coalescence hadronization

Charm quarks very strongly coupled with QGP

Evidence of charm quark flowing and possibly thermalized in the QGP

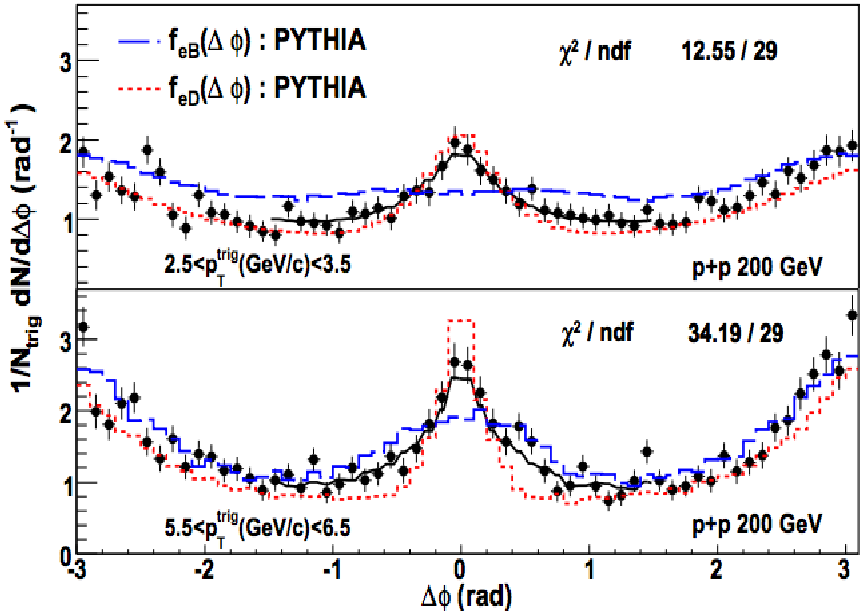
Near Term Plan: Charm

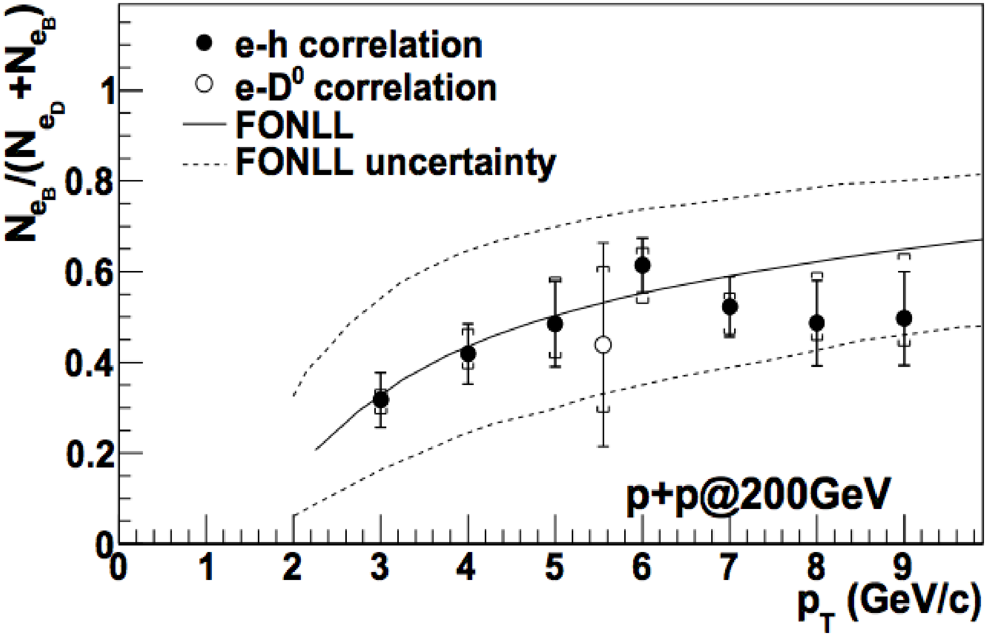
2016 datasets
Au+Au 200 GeV, 2x more minimum bias, x5 times sampled luminosity
d+Au 200 GeV, 300M minimum bias

- Centrality dependence of D^0 spectra and v_2
- D^0 v_1 – unique access to initial magnetic field
- D_s/Λ_c R_{cp}
- D^0 CNM measurement
- D^0 v_2 in d+Au collisions

- Di-electrons at IMR for correlated charm and QGP radiation

D/B->e in p+p Collisions





STAR, PRL 105, 202301 (2010)

Method: Template fit to e-h azimuthal correlation in p+p collisions

- Challenging to do this in Au+Au collisions due to various background

- $e_B/(e_D+e_B)$ fraction is consistent with the FONLL pQCD calculation

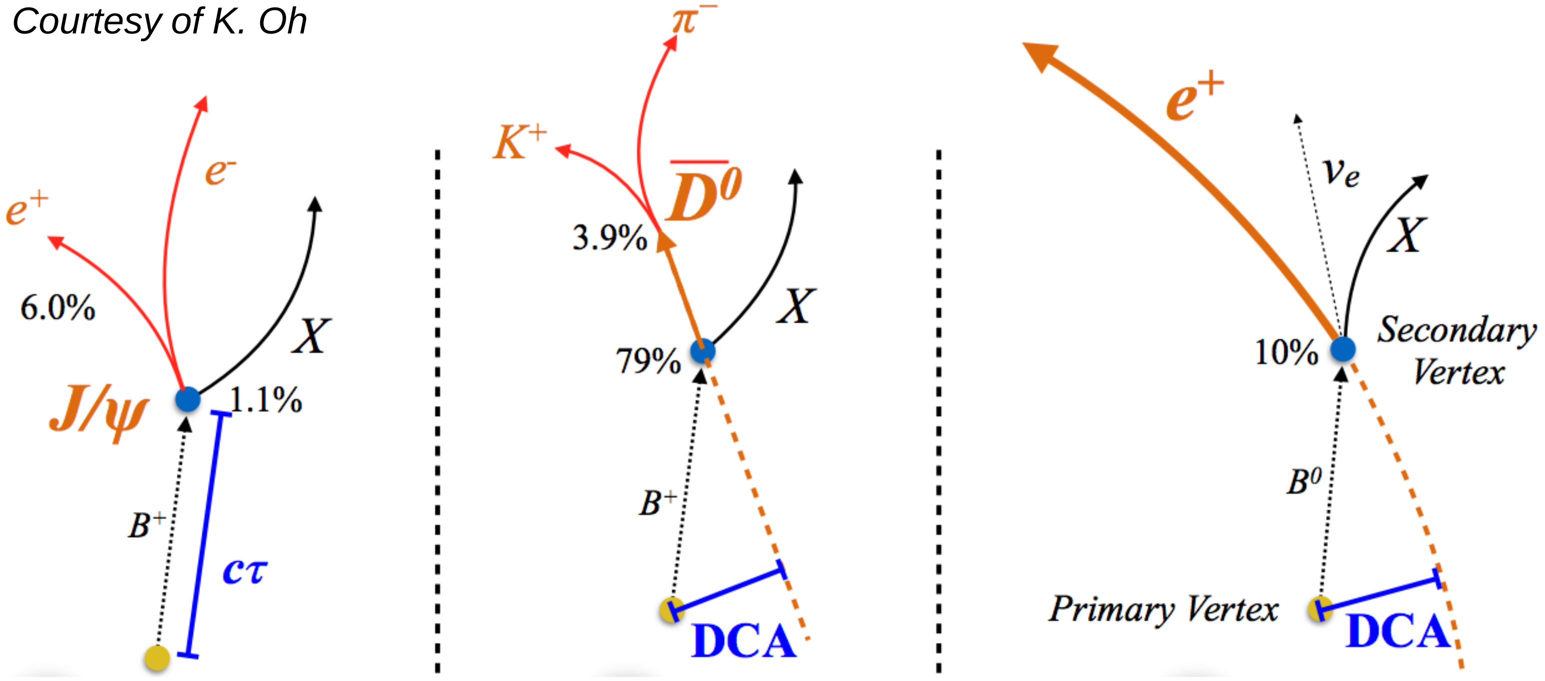
Topological Separation of Bottom Decays with HFT

Hadron	Abundance (fragmentation)	cτ (μm)
D^0	56%	123
D^+	24%	312
D_s	10%	150
Λ_c	10%	60
B^+	40%	491
B^0	40%	456

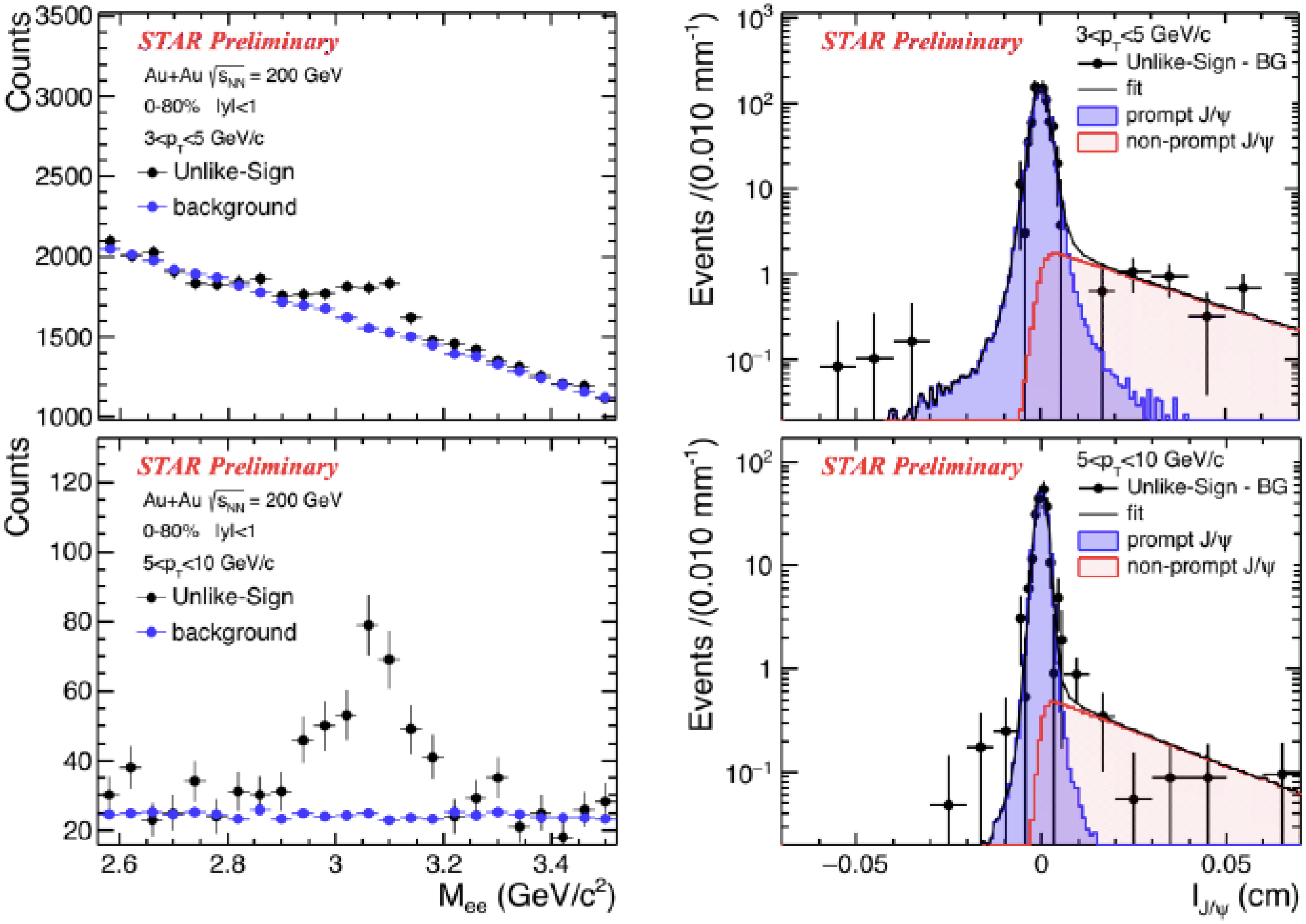
Inclusive impact parameter method
e.g. *D/B->e, B->D, B->J/ψ …*

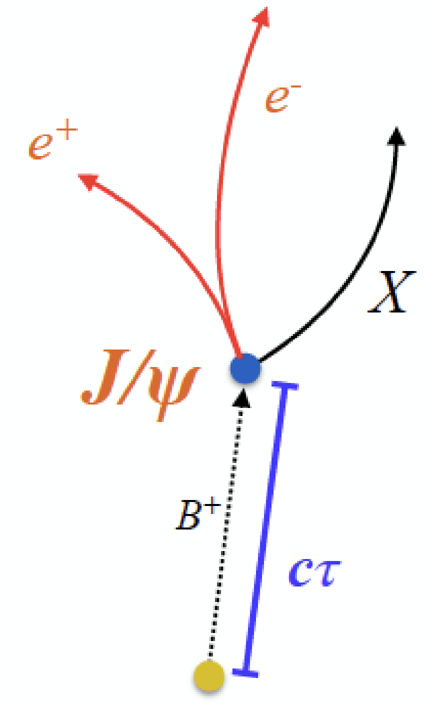
Precision silicon vertex tracker is crucial

Courtesy of K. Oh



Non-prompt J/ψ pseudo-cτ

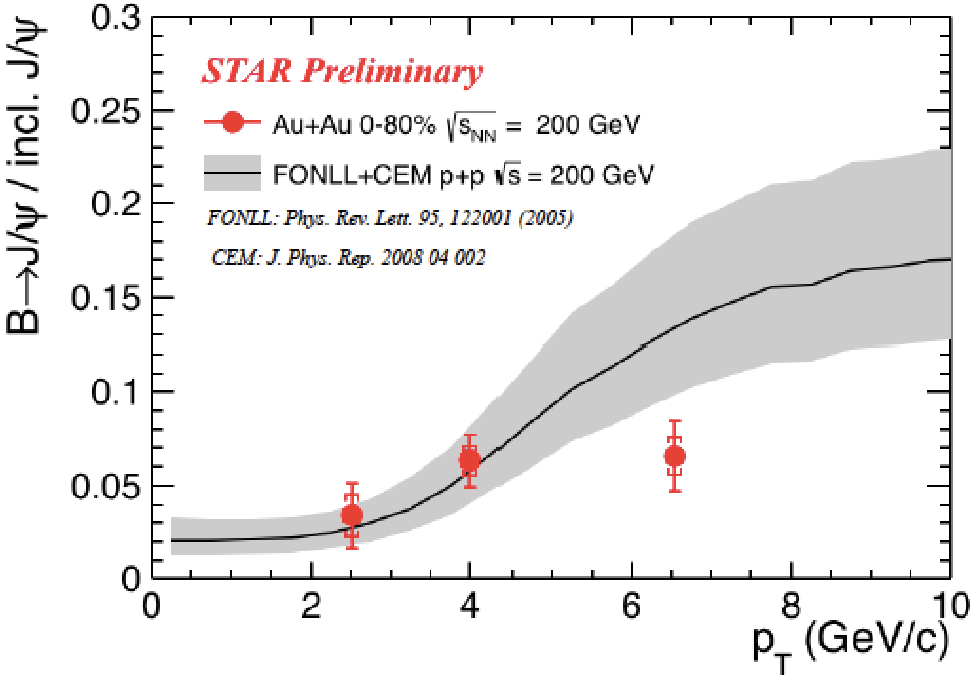


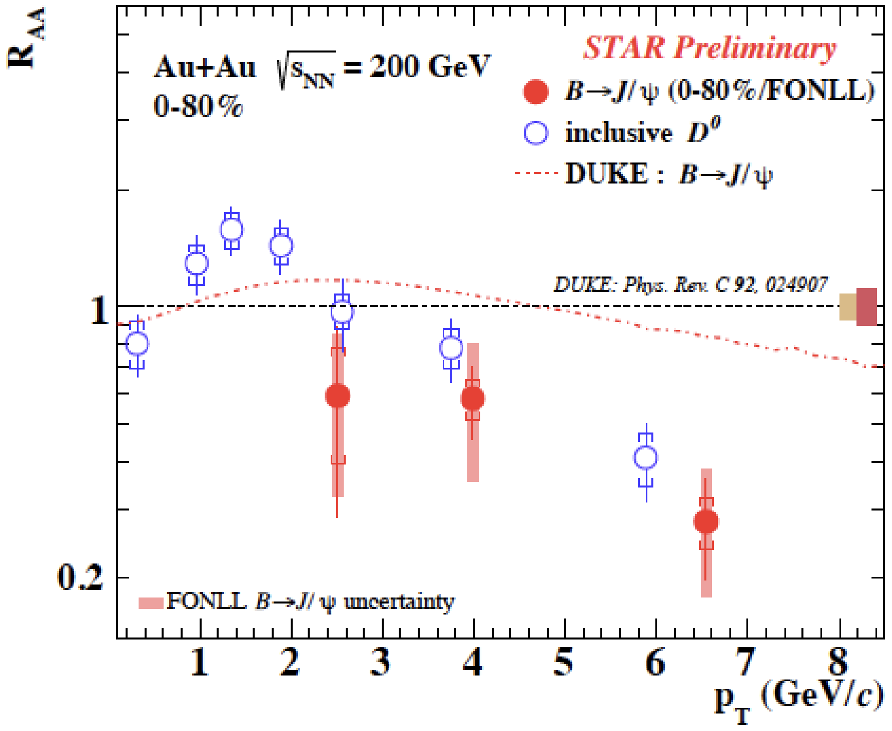


$$l_{J/\psi} = \frac{\vec{L}\cdot\hat{p}}{|p|/c} M_{J/\psi}$$

Non-prompt J/ψ R_{AA}

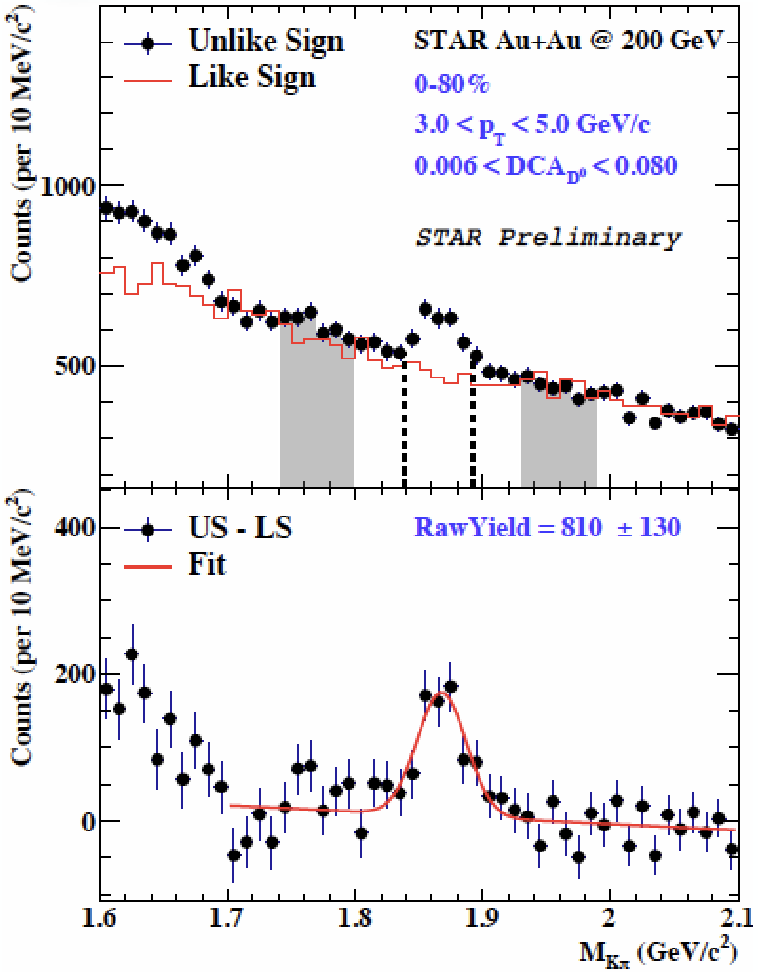
$$R_{AA}^{B\to J/\psi} = \frac{f_{Au+Au}^{B\to J/\psi}(data)}{f_{p+p}^{B\to J/\psi}(theory)} R_{AA}^{inc.\ J/\psi}(data)$$

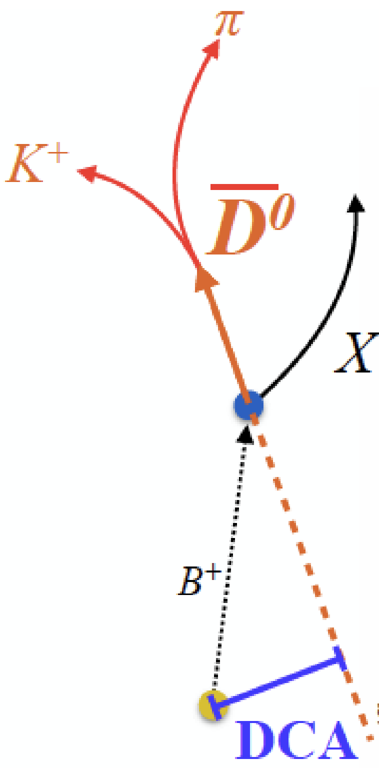


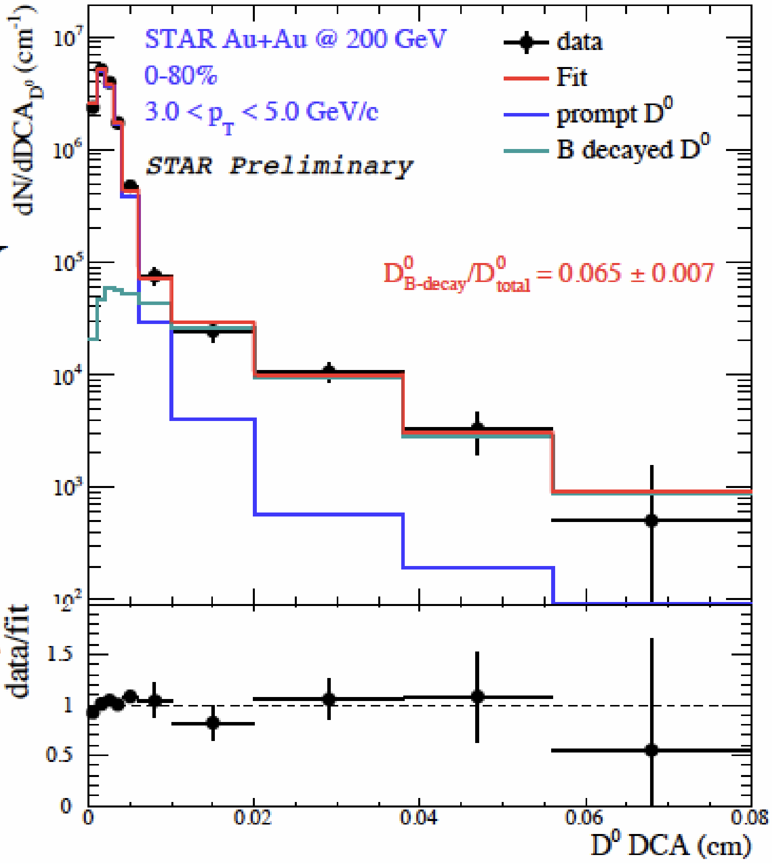


- Non-prompt J/ψ suppressed at p_T > 6 GeV/c (FONLL baseline)

Non-prompt D^0 DCA

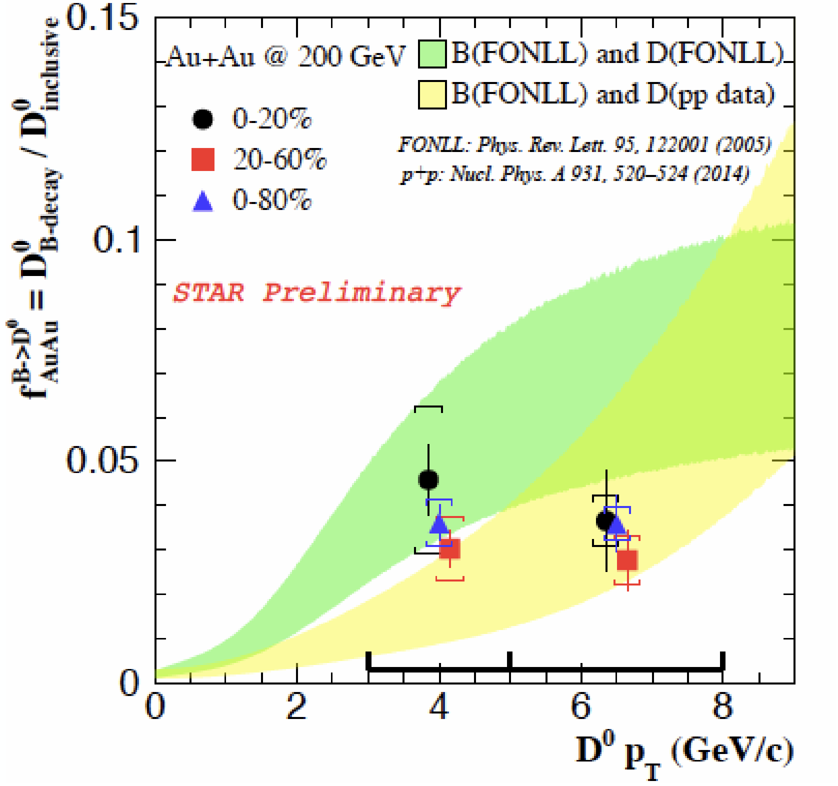


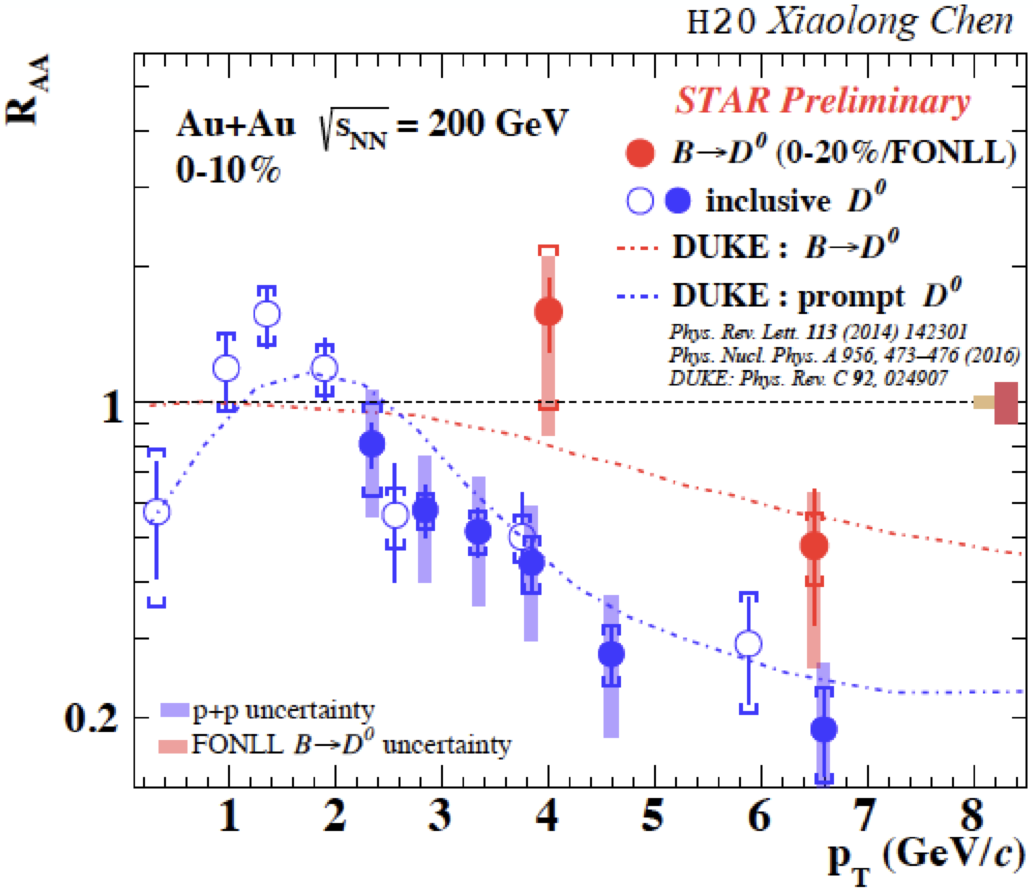




Non-prompt D^0 R_{AA}

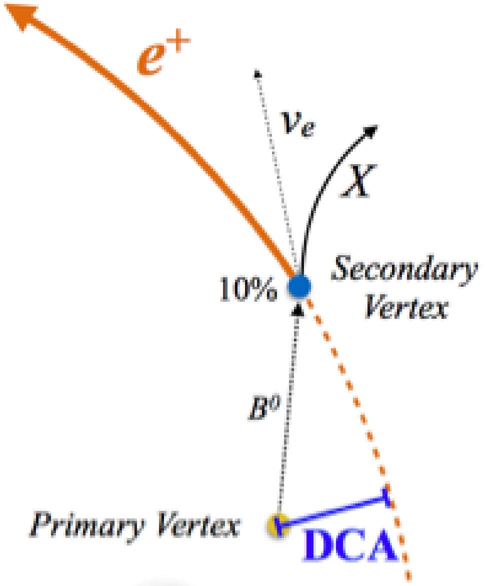
$$R_{AA}^{B\to D^0} = \frac{1}{\langle N_{coll}\rangle}\,\frac{f_{Au+Au}^{B\to D^0} \times dN_{Au+Au}^{incl.\ D^0}/dp_T}{dN_{FONLL}^{B\to D^0}/dp_T}$$

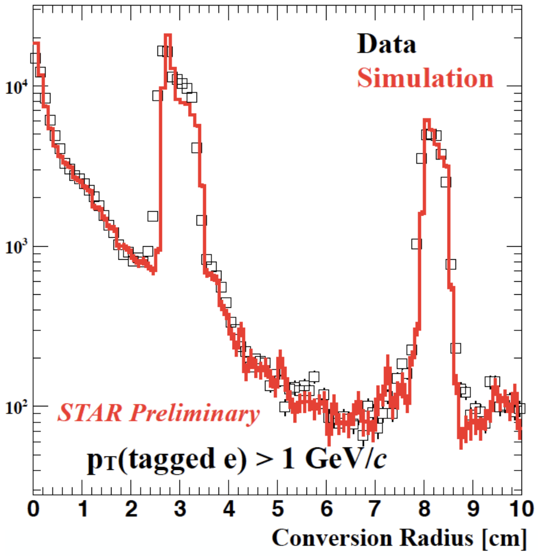


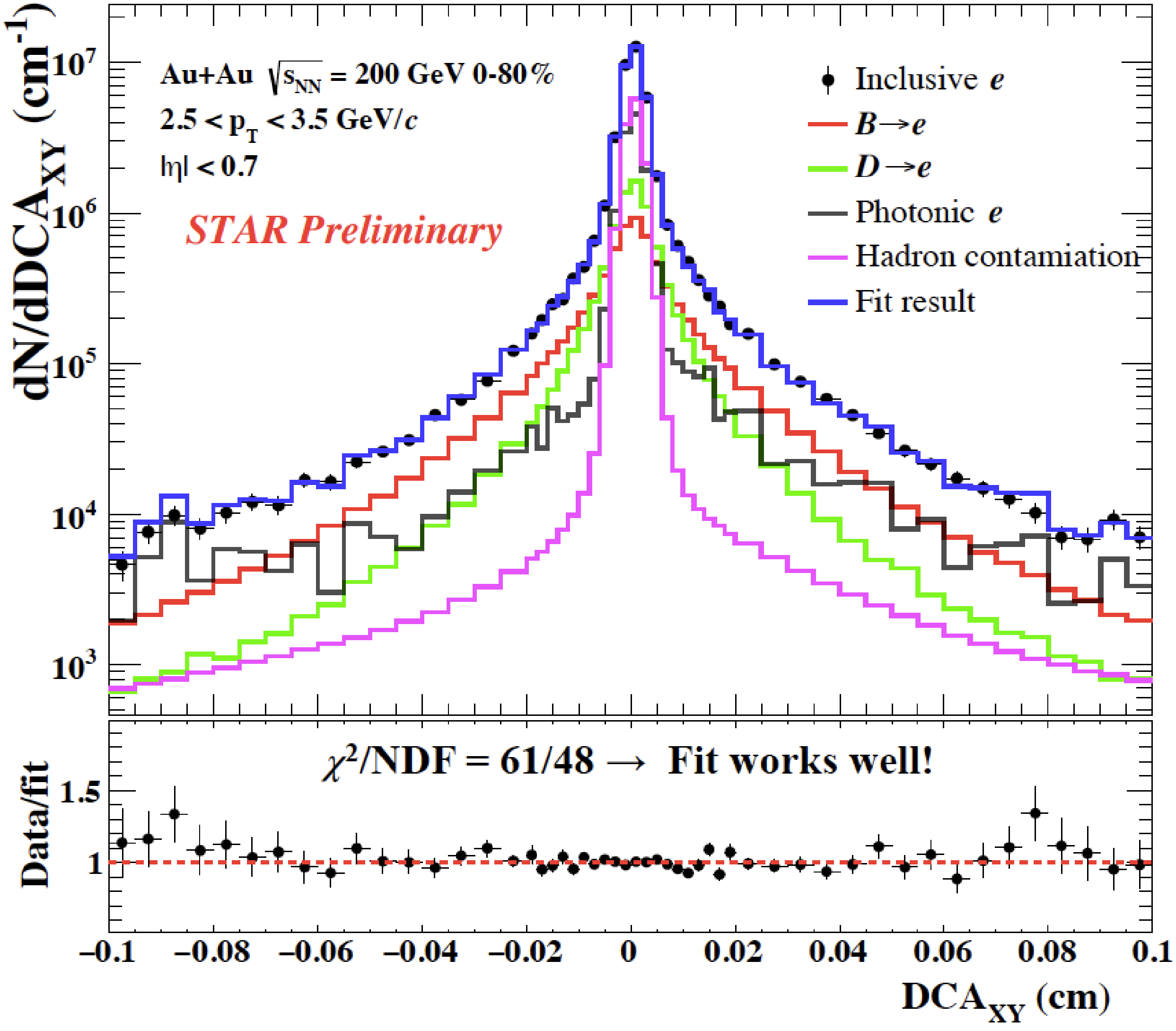


- Non-prompt D^0 suppressed at p_T > 6 GeV/c
- Indication of less suppression for non-prompt D^0 compared to inclusive D^0

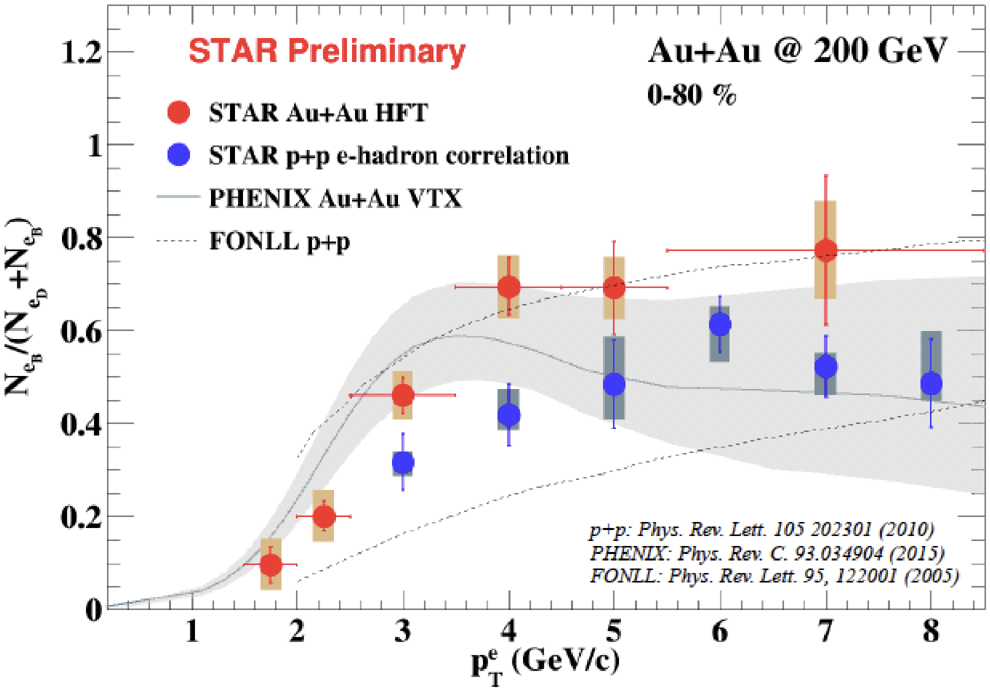
Template Fit to Electron DCA Distributions

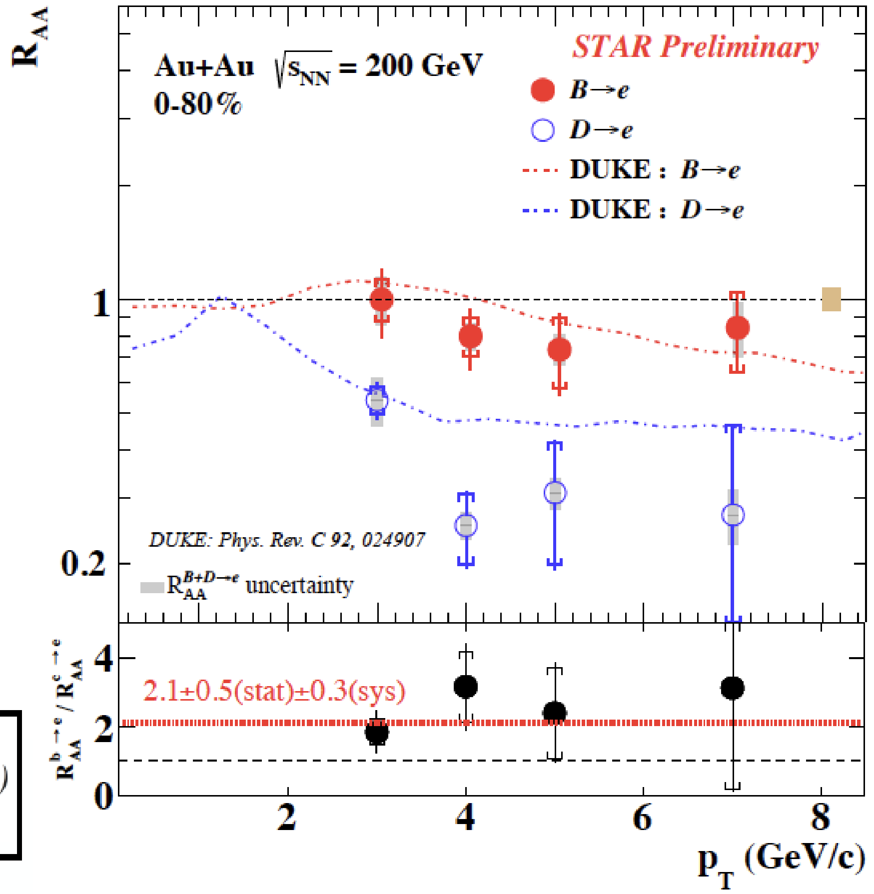






Charm/Bottom Separated Electron R_{AA}

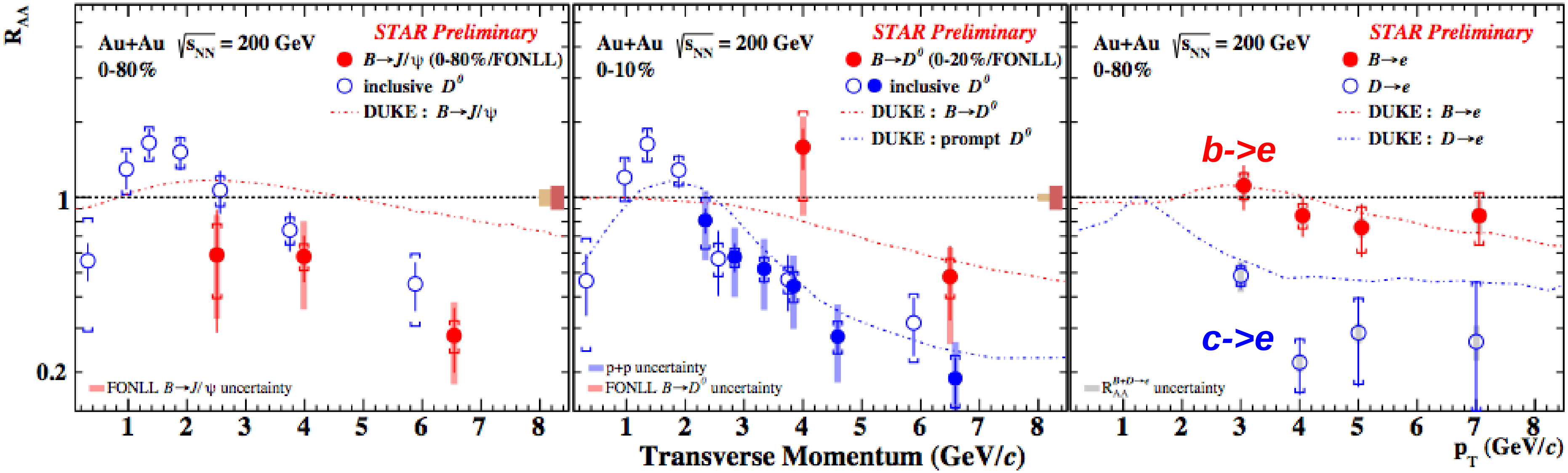




$$R_{AA}^{B\to e}=\frac{f_{Au+Au}^{B\to e}(data)}{f_{p+p}^{B\to e}(data)}R_{AA}^{inc.\ e}(data),\quad R_{AA}^{D\to e}=\frac{1-f_{Au+Au}^{B\to e}(data)}{1-f_{p+p}^{B\to e}(data)}R_{AA}^{inc.\ e}(data)$$

- $R_{AA}(e_D) < R_{AA}(e_B)$ (~2σ at 3-8 GeV/c)
  - Consistent with mass hierarchy for parton energy loss

Bottom Measurements at STAR



b->e

c->e

Impact parameter method to separate c/b electrons and non-prompt D^0, J/ψ

- $R_{AA}(e_B) < R_{AA}(e_D)$ at 3 – 8 GeV/c (2σ) ***mass hierarchy of parton energy loss***

Near term plan:
2016 datasets: x2 mb data, x5 more sample luminosity
- centrality dependence, bottom decay electron v_2

HF Program in 2020+ at RHIC

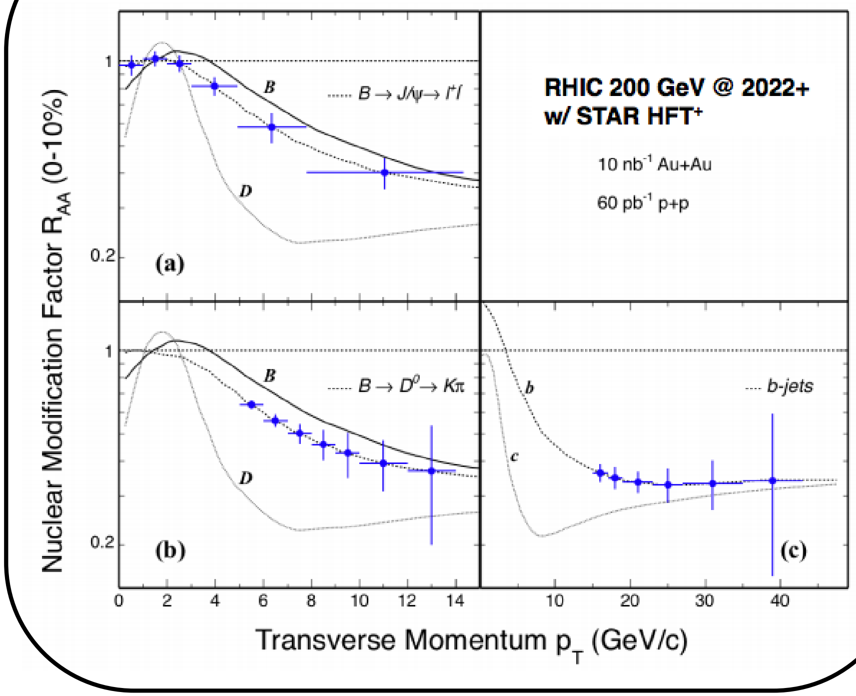
Precision bottom (B-meson and b-jet) measurements over a broad momentum region (especially at low p_T)

- systematic investigation of mass dependence of parton energy loss

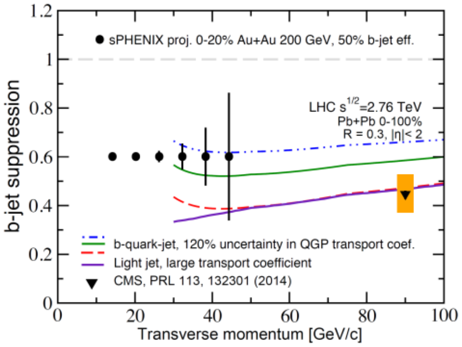
- precision determination of heavy quark diffusion coefficient $\boldsymbol{D_{HQ}}$

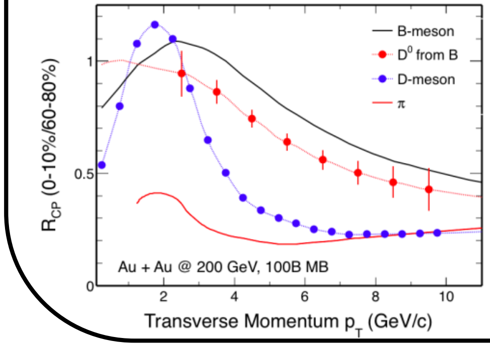
ITS upgrade at ALICE, MVTX@sPHENIX, HFT+@STAR

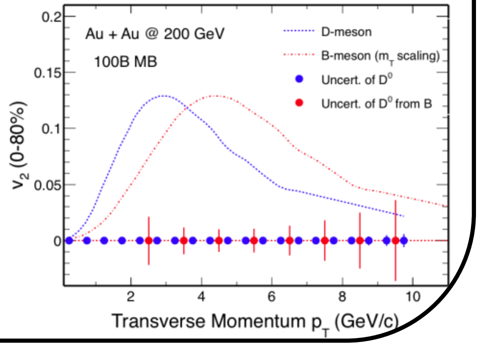
STAR HFT+



sPHENIX MVTX

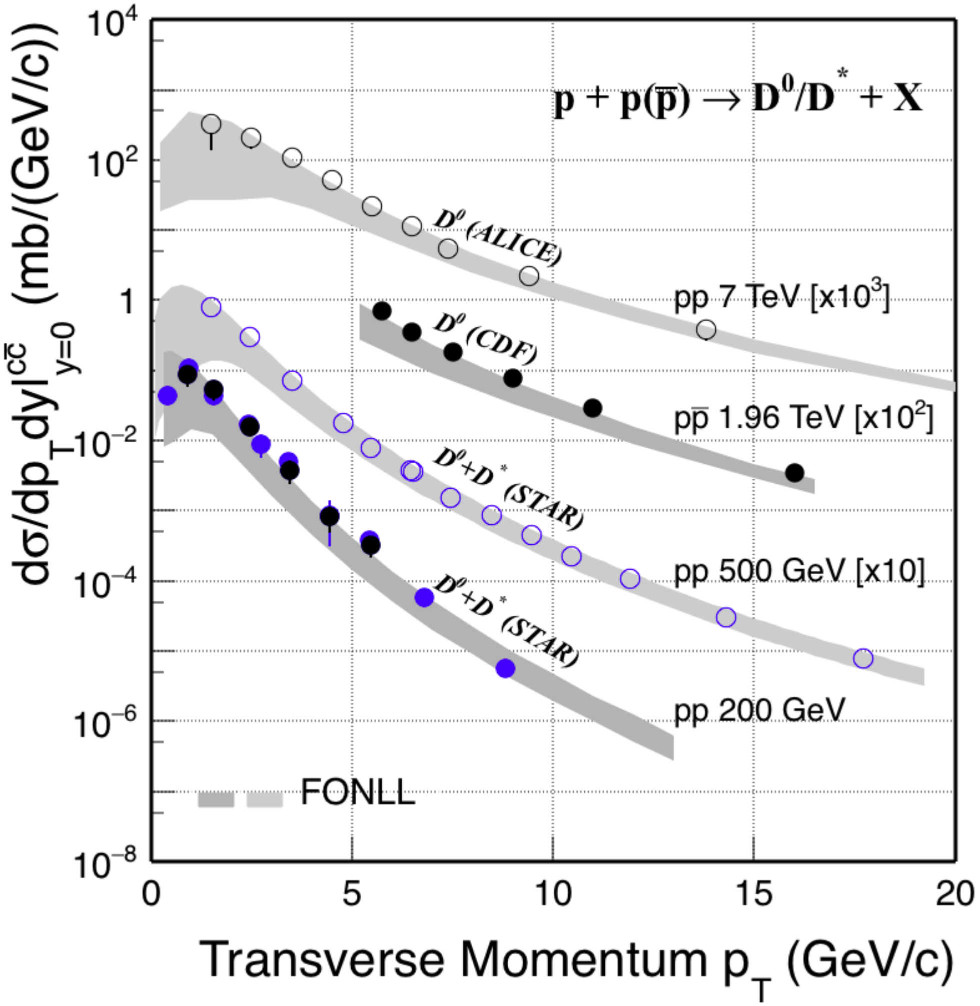






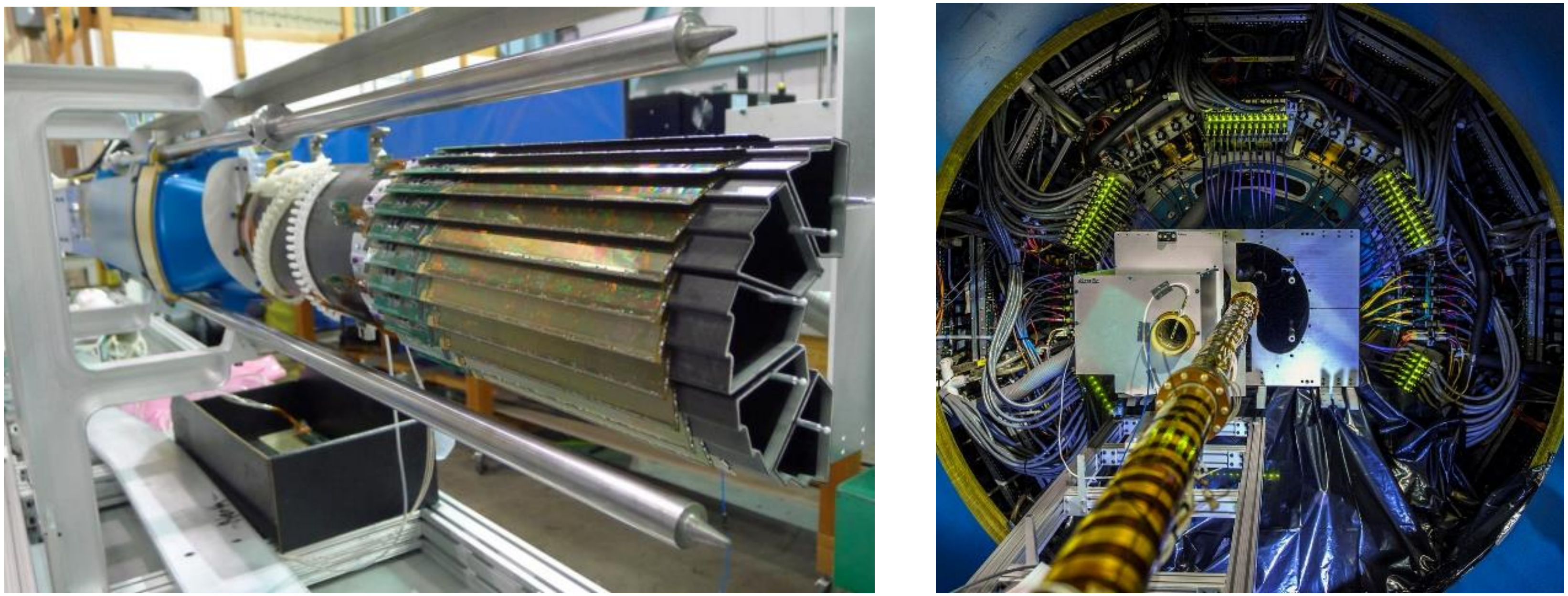
Backups

Charm Production in p+p Collisions



- Charm hadron spectra well described by pQCD FONLL
  - data prefer upper bounds of FONLL calculations

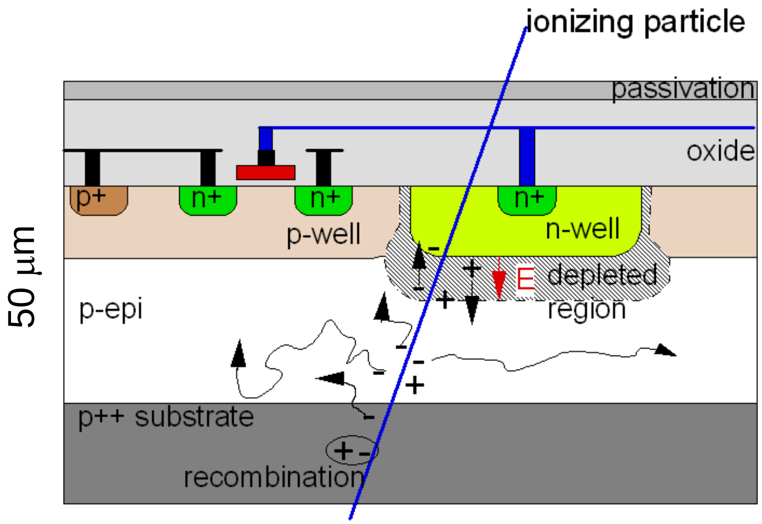
STAR Heavy Flavor Tracker



2013 May	– PXL prototype engineering run with 3 sectors (out of 10 in total)
2014 Spring	– Commissioning in Au+Au 200 GeV collisions. Physics mode since then
2014 Sept	– HFT project closeout. Project finished on time and under budget
2015 Spring	- p+p and p+Au 200 GeV runs with HFT
2016 Spring	- Au+Au and d+Au 200 GeV runs with HFT

Monolithic Active Pixel Sensors (MAPS)

MAPS pixel cross-section (not to scale)



Properties:

- Standard commercial CMOS technology
- Sensor and signal processing are integrated in the same silicon wafer
- Signal is created in the low-doped epitaxial layer (typically ~10-15 µm) → MIP signal is limited to <1000 electrons
- Charge collection is mainly through thermal diffusion (~100 ns), reflective boundaries at p-well and substrate

MAPS and competition	MAPS	Hybrid Pixel	CCD
Granularity	+	-	+
Small material budget	+	-	+
Readout speed	+	++	-
Radiation tolerance	+	++	-

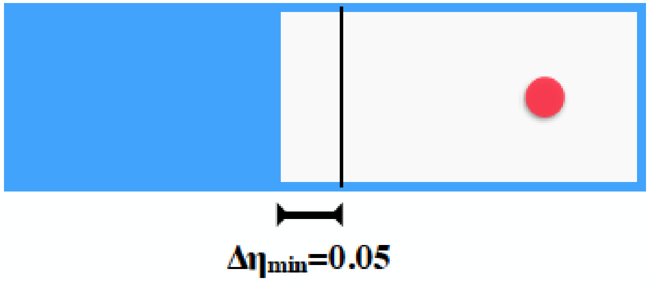
MAPS - particularly chosen for measuring HF hadron decays in heavy ion collisions

STAR HFT – first application of MAPS pixel detector at a collider

Event plane method

- Event plane (EP) reconstructed using TPC tracks with acceptance non-uniformity corrected

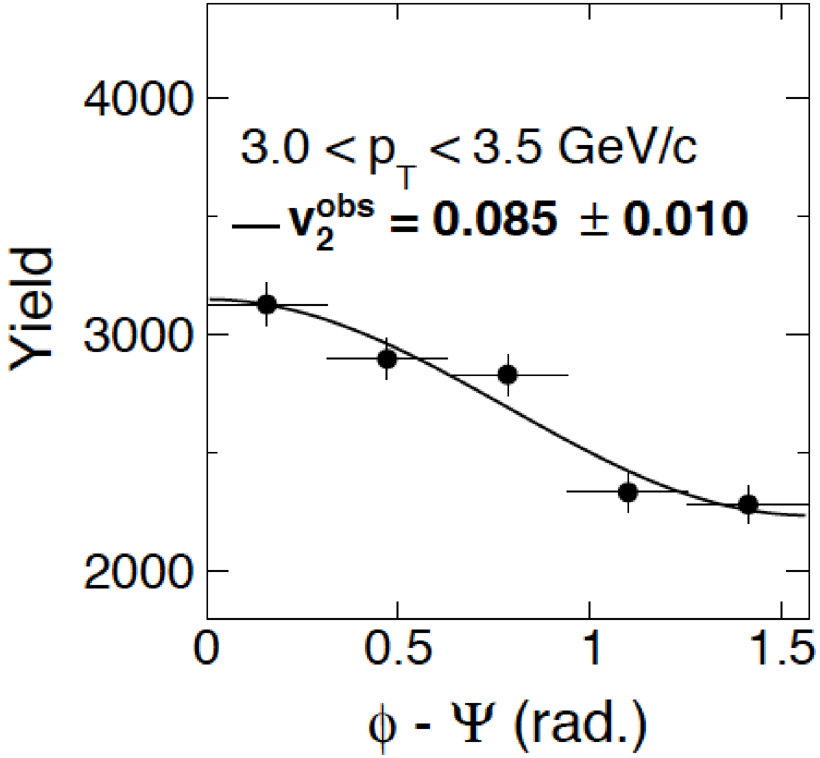
- Tracks in η-sub region are used to reconstruct EP to suppress non-flow effects



● D^0 candidate 🟦 η-sub region

$$v_n\{EP\} = v_n^{obs}\{EP\} \times \left\langle \frac{1}{\text{EP Resolution}} \right\rangle$$

A.M. Poskanzer and S.A. Voloshin. PRC 58 (1998) 1671



Two-particle correlation method

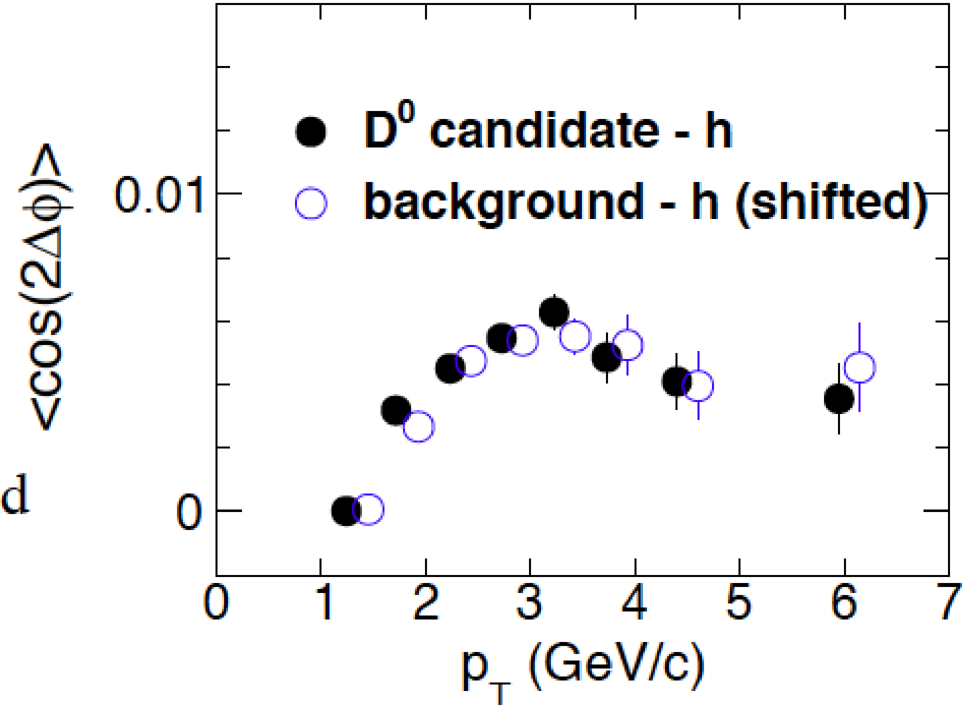
- $$V_2^{D\cdot h} = \langle \cos(2\varphi_D - 2\varphi_h) \rangle = v_2^D \bullet v_2^h$$

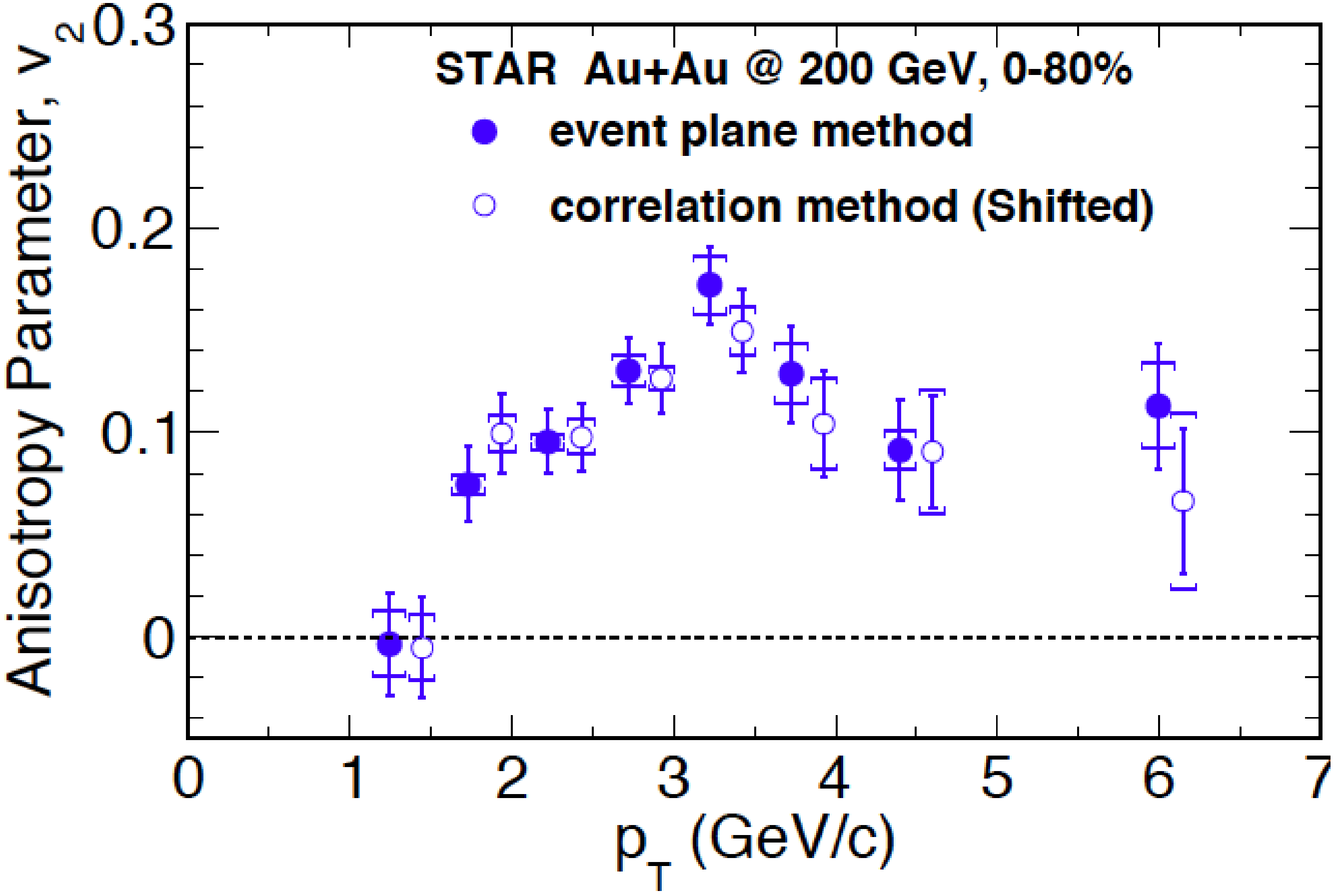
  $$V_2^{h\cdot h} = \langle \cos(2\varphi_{h1} - 2\varphi_{h2}) \rangle = (v_2^h)^2$$

- $$v_2^{signal} = \frac{N_{cand} \bullet v_2^{cand} - N_{bkg} \bullet v_2^{bkg}}{N_{signal}}$$

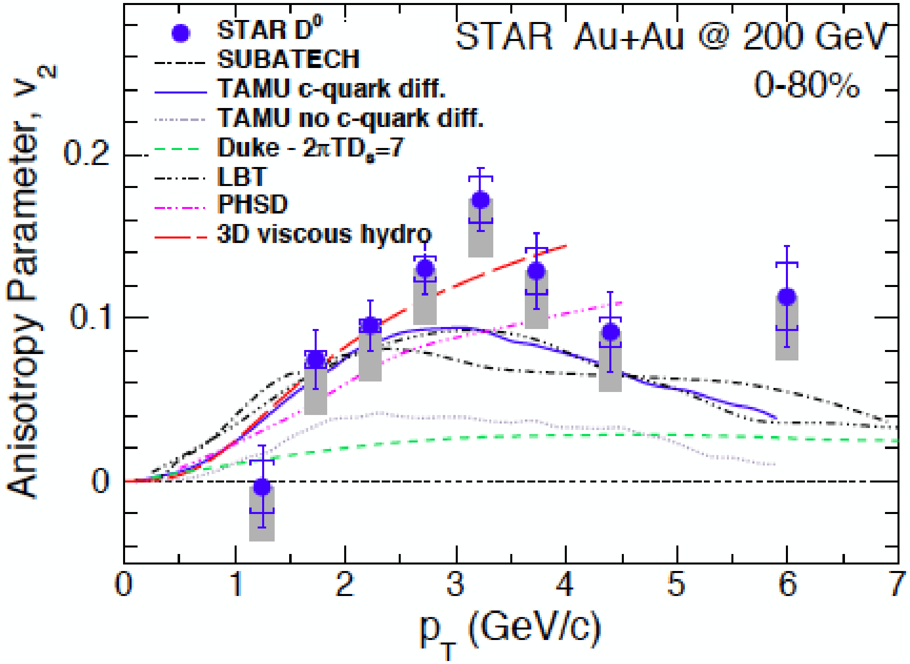
  Background estimated from side-band

- Same $\Delta\eta$ gap as used in EP method




STAR Au+Au @ 200 GeV, 0-80%
● event plane method
○ correlation method (Shifted)
Anisotropy Parameter, v_2
0.3
0.2
0.1
0
0
1
2
3
4
5
6
7
p_T (GeV/c)

D^0 v_2 Compared to Models

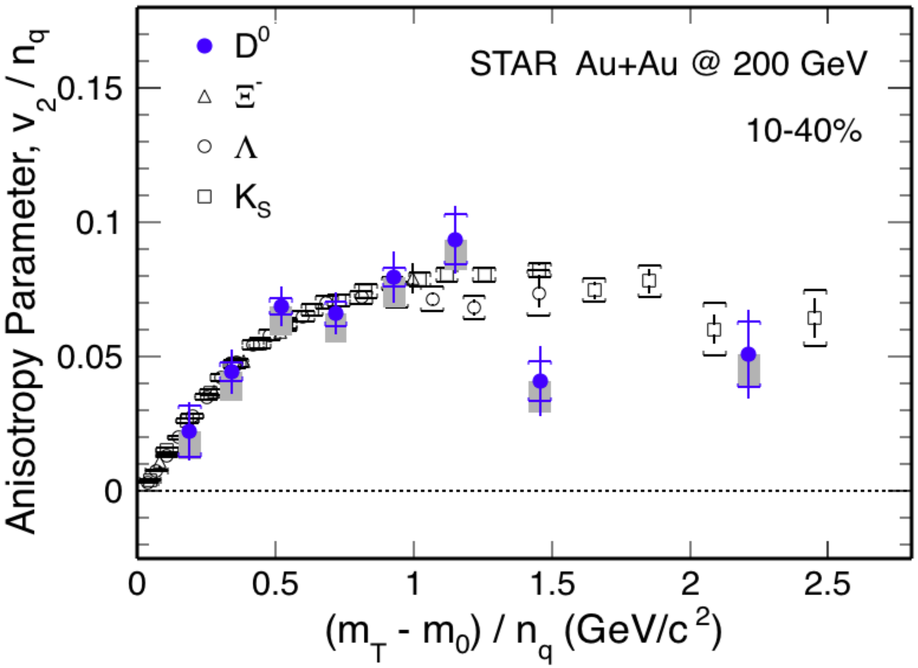


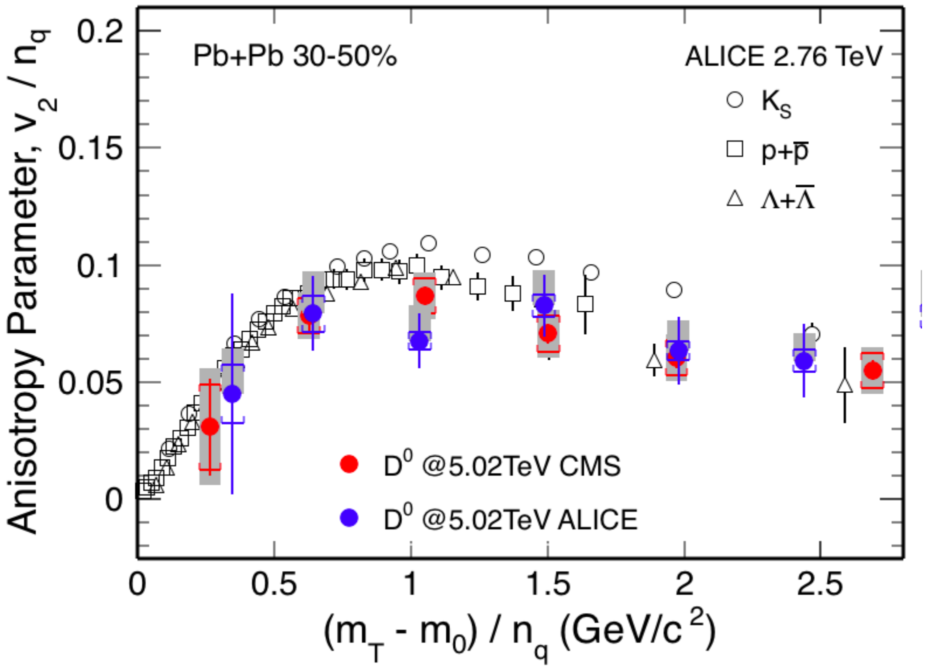
Different models:

- **SUBATECH: pQCD + hard thermal loop**
  - *P. B. Gossiaux, J. Aichelin, T. Gousset, and V. Guiho, Strangeness in quark matter*
- **TAMU: T-matrix, non-perturbative model with internal energy potential**
  - *M. He, R. J. Fries, and R. Rapp, PRC86, 014903 (2012)*
- **Duke: free constant D_s, fit to LHC high p_T R_{AA}**
  - *S. Cao, G.-Y. Qin, and S. A. Bass, PRC88, 044907 (2013)*
- **hydro: A 3D viscous hydrodynamic model**
  - *L.-G. Pang, Y. Hatta, X.-N. Wang, and B.-W. Xiao, PRD91, 074027 (2015)*
- **PHSD: Parton-Hadron-String Dynamics, a transport model**
  - *H. Berrehrah et al. PRC90 (2014) 051901*
- **LBT: A Linearized Boltzmann Transport model**
  - *S. Cao, T. Luo, G.-Y. Qin, and X.-N. Wang, PRC94, 014909 (2016)*

compare with	$2\pi TD_s$	χ2/n.d.f.	*p*-value
3D viscous hydro	-	3.6 / 6	0.73
LBT	3-6	11.1 / 8	0.19
PHSD	5-12	8.7 / 7	0.28
TAMU c quark diff.	2-12	10.0 / 8	0.26
SUBATECH	2-4	15.2 / 8	0.06
TAMU no c quark diff.	-	29.5 / 8	2 x 10-4
DUKE	7	37.5 / 8	2 x 10-5

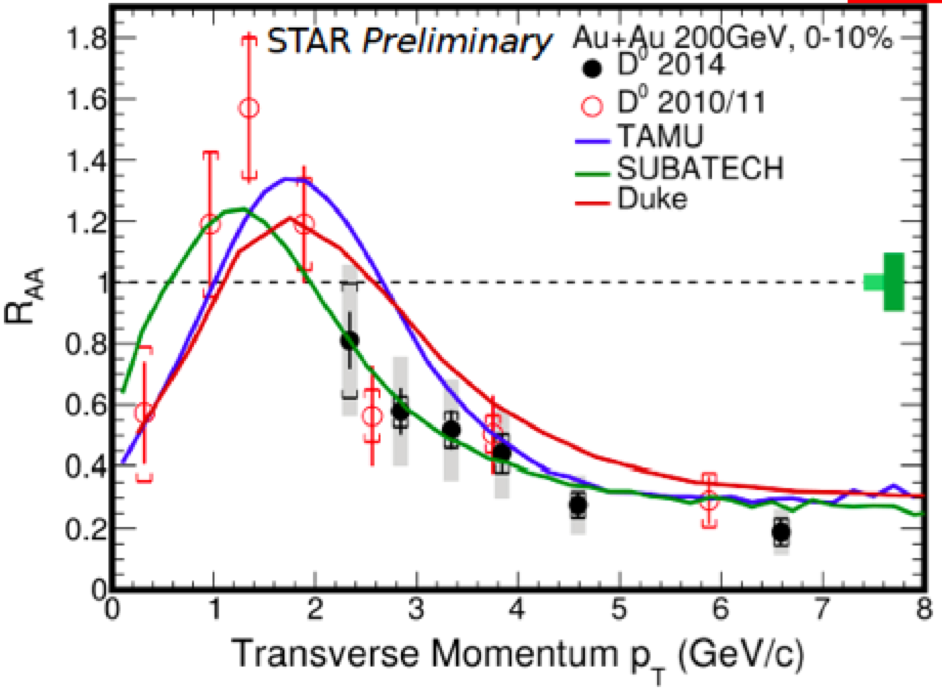
V2 Comparisons: RHIC vs. LHC

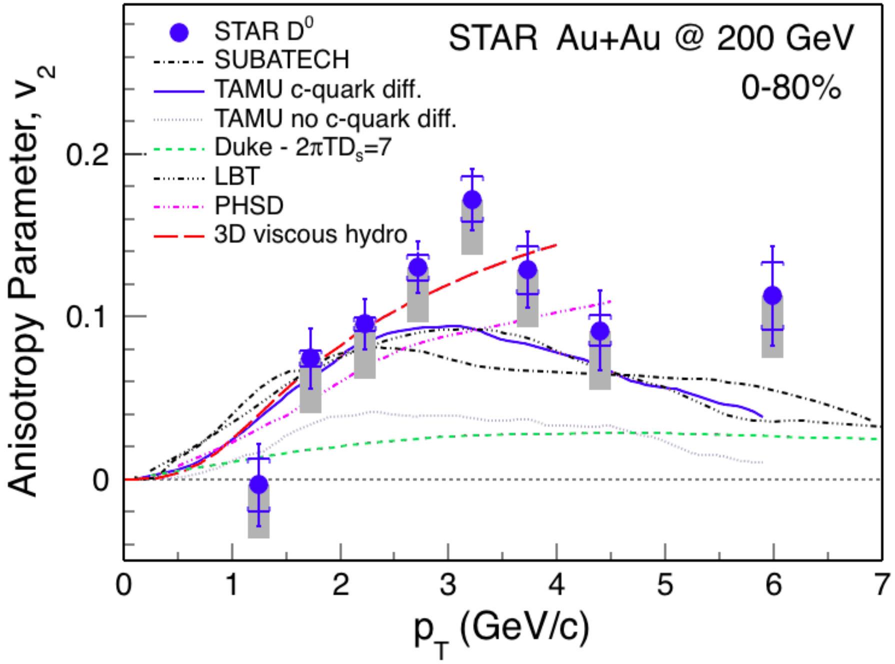




D^0 R_{AA} and v_2 Compared to Models at RHIC

STAR 200 GeV



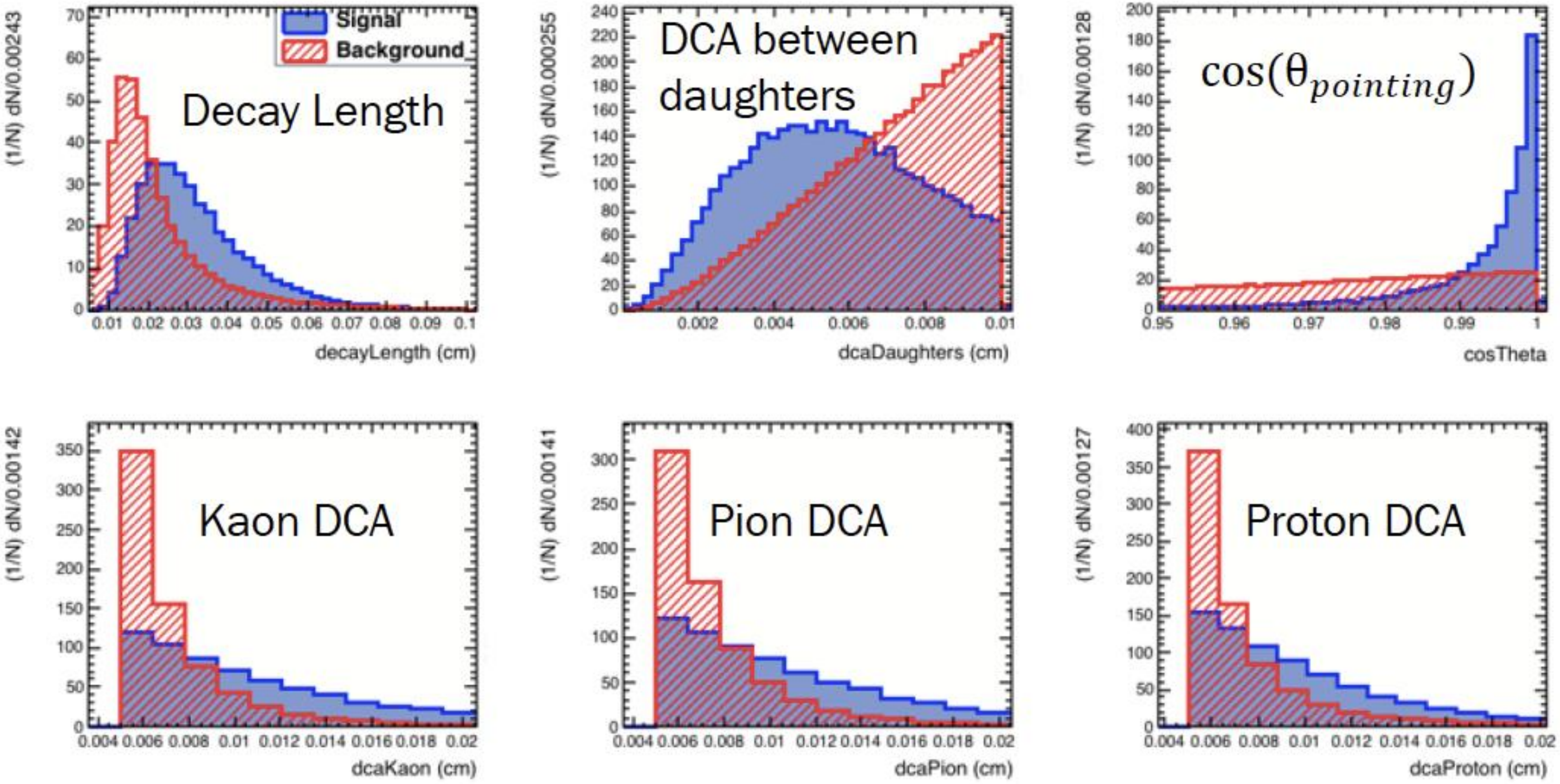


- Charm mesons at RHIC show

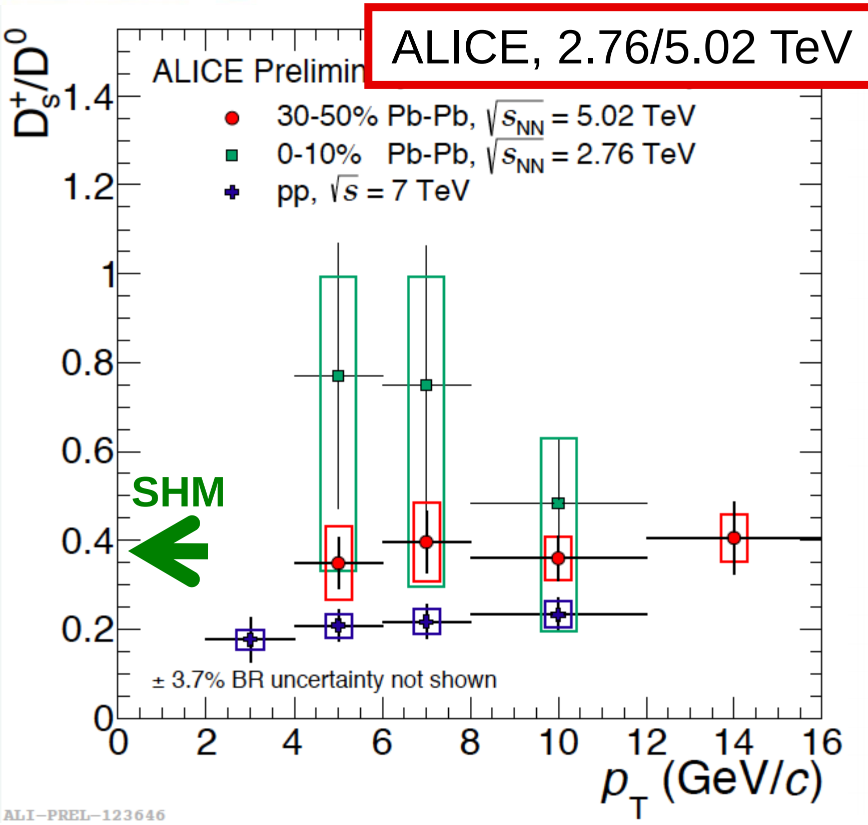
  significant suppression at high p_T, $R_{AA}(D) \sim R_{AA}(h)$

  significant flow at low-intermediate p_T, $v_2(D) \sim v_2(h)$ vs. m_T-m_0
- Models with a diffusion coefficient $2\pi T\boldsymbol{D_s} \sim 2$-$12$ describe both D^0 R_{AA} and v_2

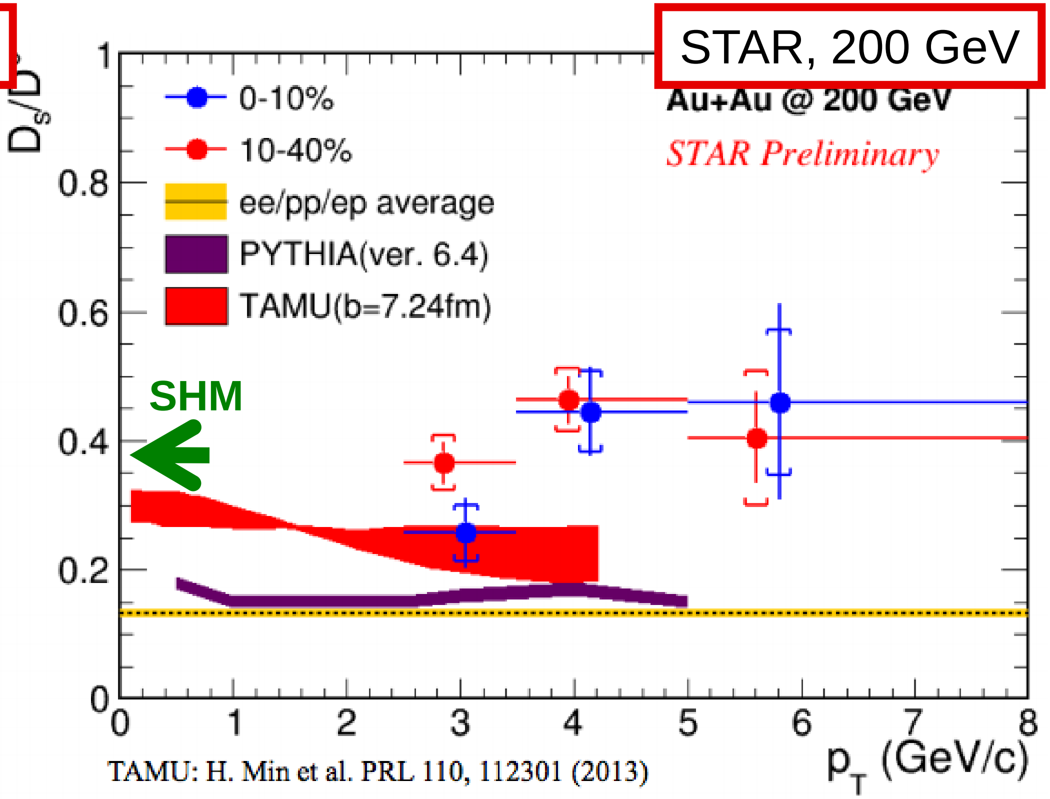
  differences between models to be settled


Signal
Background
Decay Length
(1/N) dN/0.00243
decayLength (cm)
DCA between daughters
(1/N) dN/0.000255
dcaDaughters (cm)
$\cos(\theta_{pointing})$
(1/N) dN/0.00128
cosTheta
Kaon DCA
(1/N) dN/0.00142
dcaKaon (cm)
Pion DCA
(1/N) dN/0.00141
dcaPion (cm)
Proton DCA
(1/N) dN/0.00127
dcaProton (cm)

D_s Enhancement in Heavy Ion Collisions



ALICE, 2.76/5.02 TeV



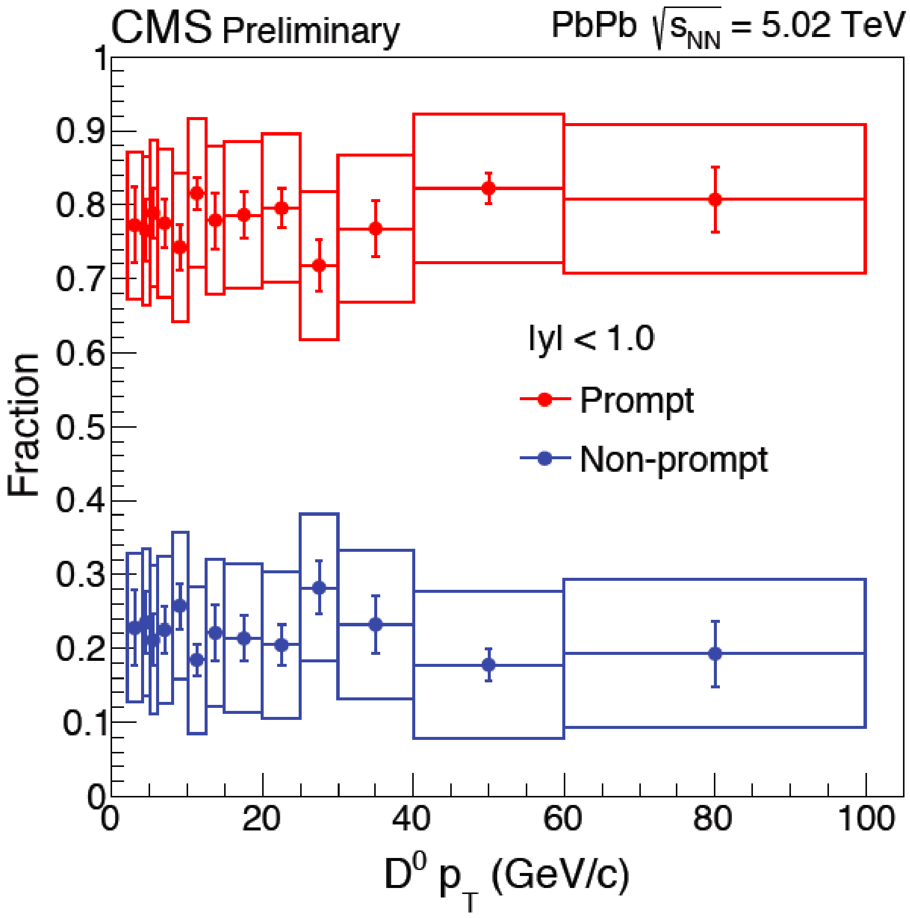
STAR, 200 GeV

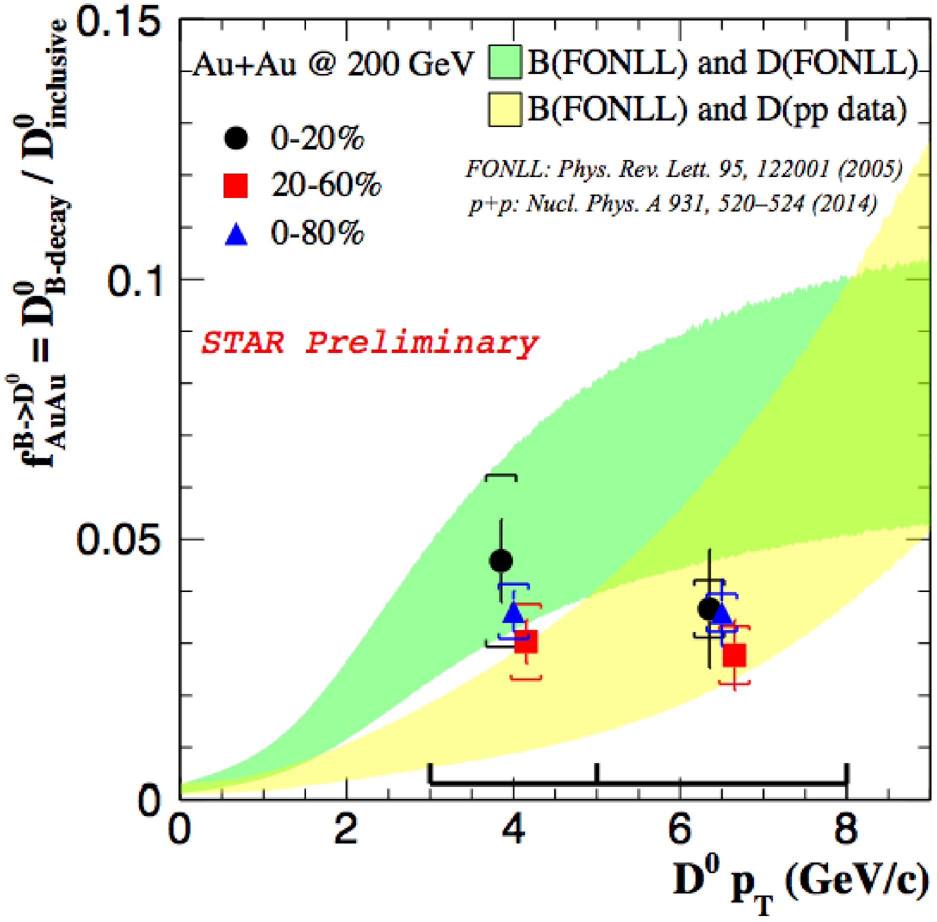
TAMU: H. Min et al. PRL 110, 112301 (2013)

•Significant D_s/D^0 enhancement in mid-central Au+Au and Pb+Pb collisions w.r.t fragmentation baseline or p+p measurement

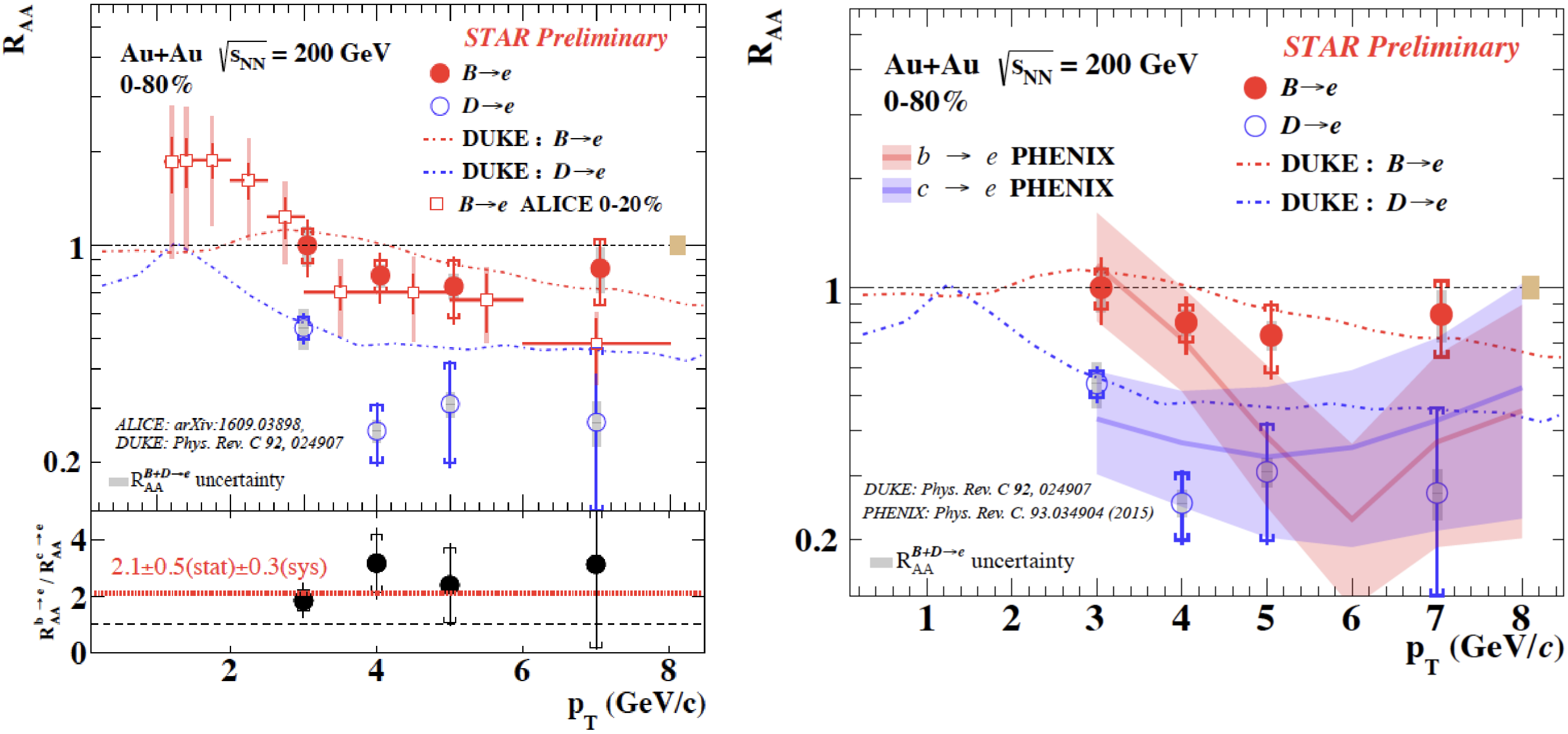
- Coalescence hadronization
- SHM predicts D_s/D^0 ratio ~ 0.35-0.40 (central) *A. Andronic et al., PLB 571 (2003) 36*
- relation to charm quark thermalization in QGP?

Non-prompt D^0 Fraction



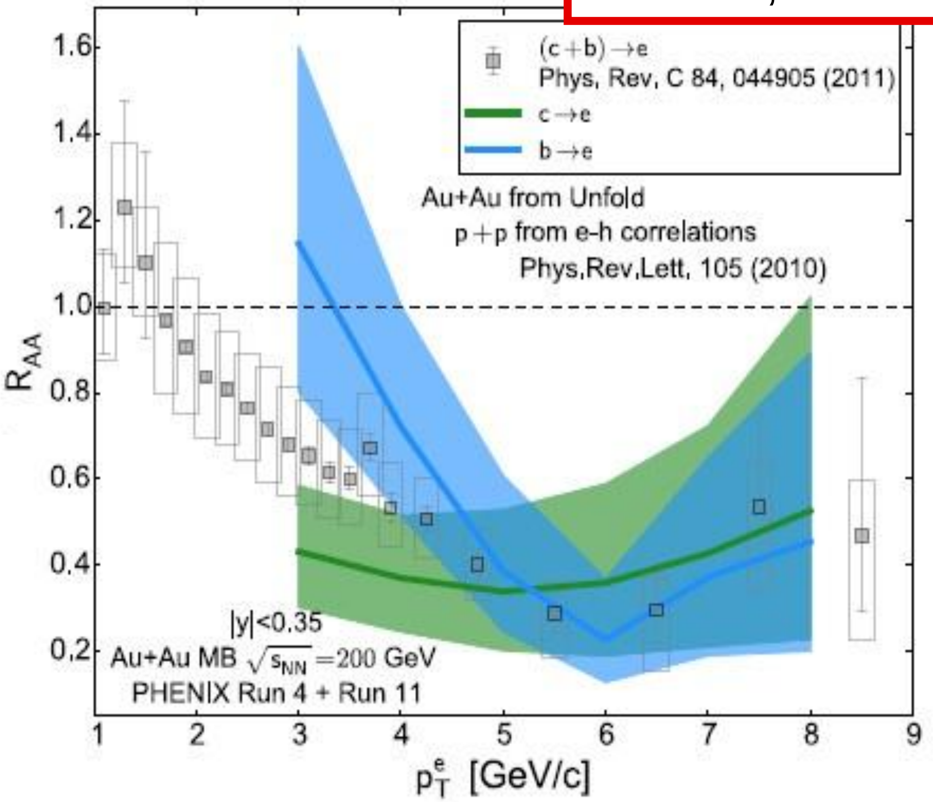


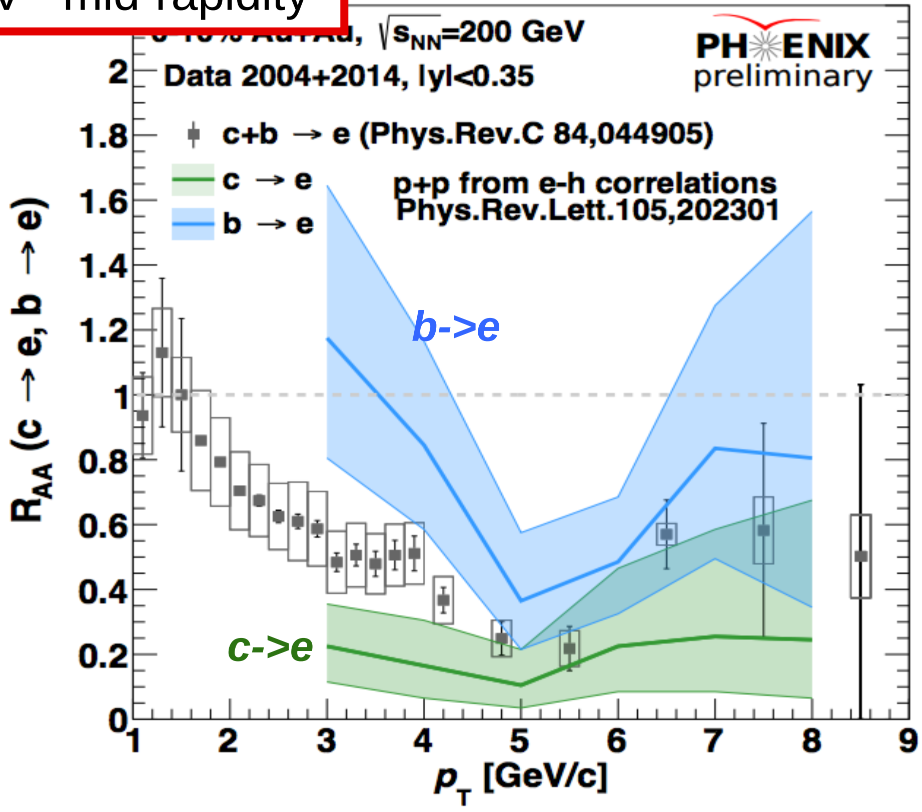
Comparison to PHENIX and ALICE



Bottom Electron R_{AA} at RHIC

PHENIX, 200 GeV mid-rapidity



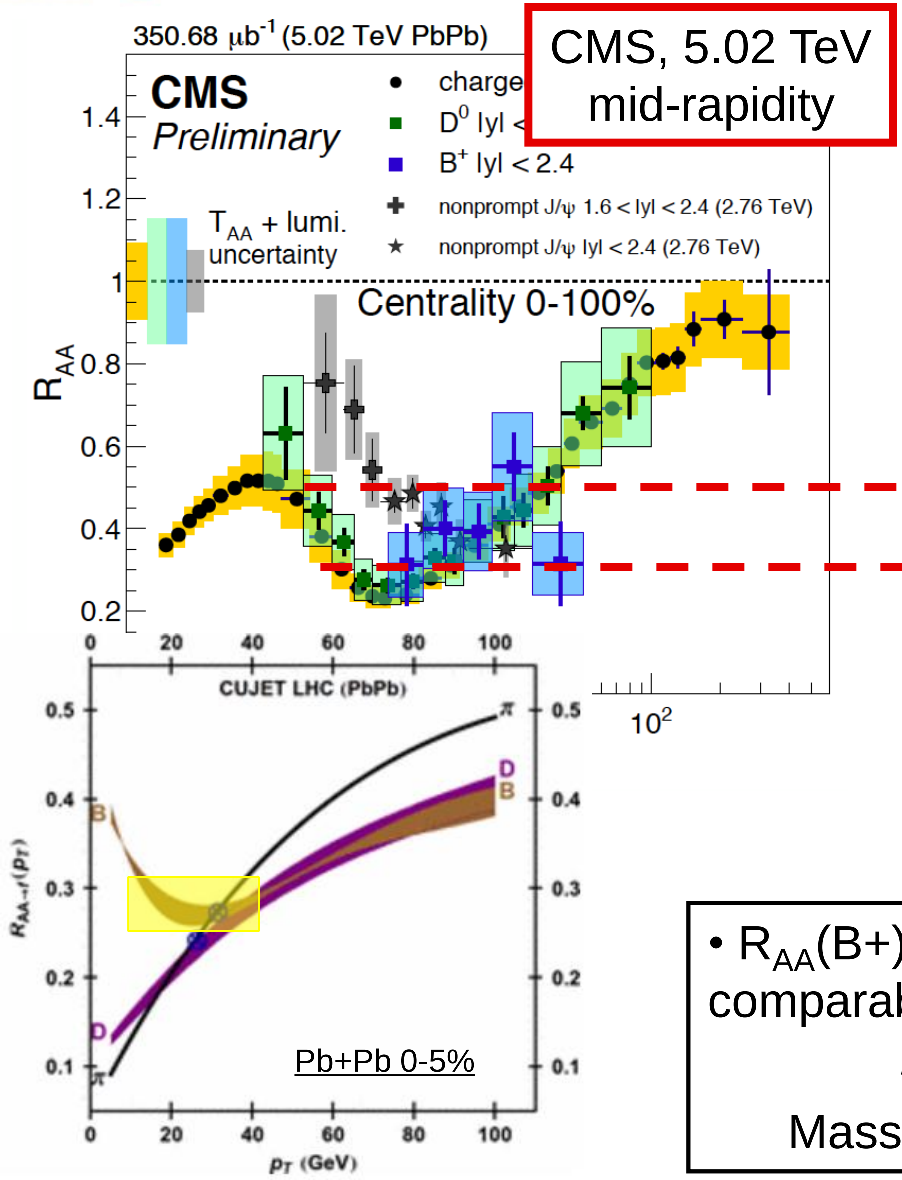


PHENIX, PRC 93 (2016) 034904

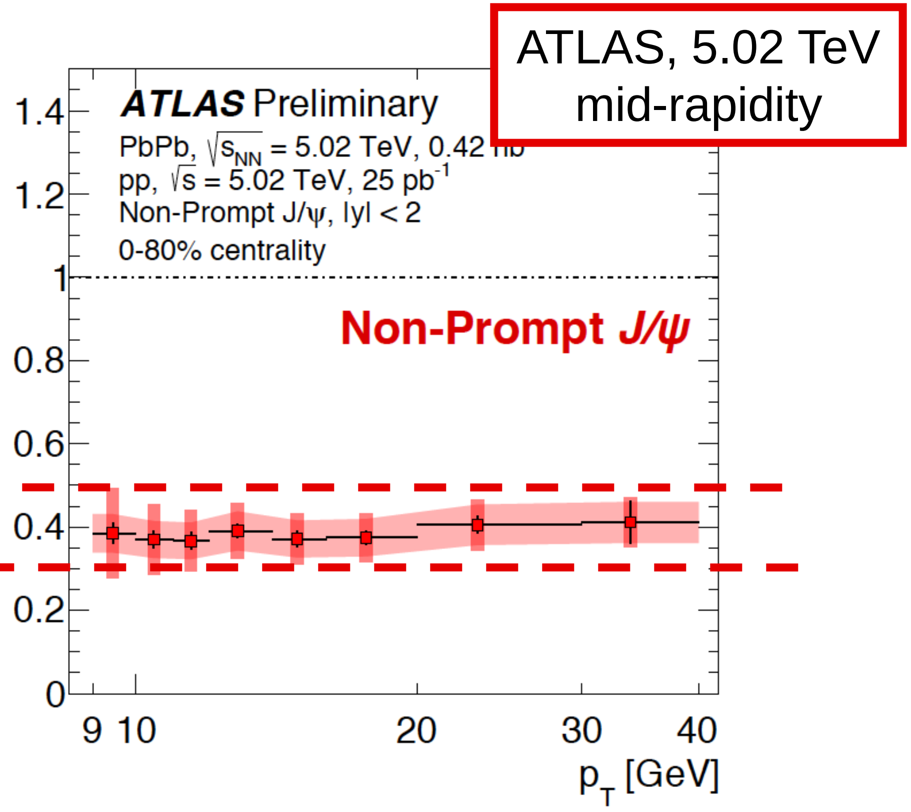
- $R_{AA}(e_B) < R_{AA}(e_D)$ at 3 – 5 GeV/c in central Au+Au 200 GeV collisions

  mass hierarchy of parton energy loss

B-meson and non-prompt J/ψ at high p_T



CMS, 5.02 TeV
mid-rapidity



ATLAS, 5.02 TeV
mid-rapidity

- $R_{AA}(B+) \sim R_{AA}(J/\psi_B)$ at $p_T > 10$ GeV, and comparable to R_{AA} (D) ~ R_{AA}(h) at $p_T > 10$ GeV

Note: rapidity window difference

Mass hierarchy? -> Going to lower p_T