Measurements of Heavy Flavor Production and Properties of sQGP at RHIC

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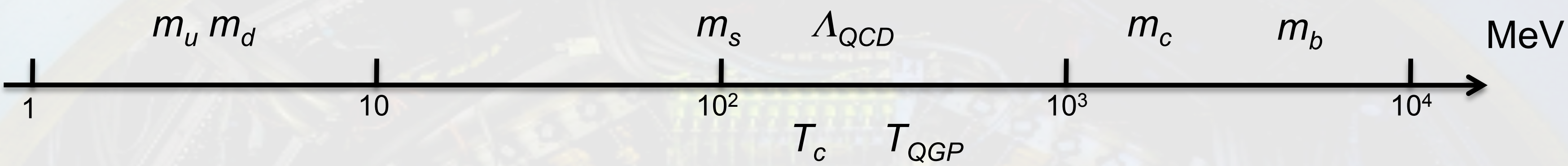
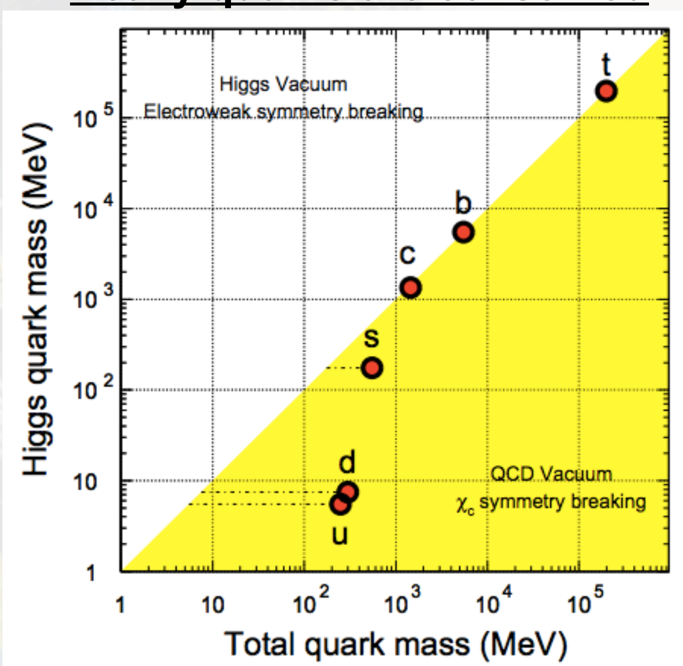
Uniqueness of Heavy Quarks in QCD



$m_{c,b} >> \Lambda_{QCD}$ *amenable to perturbative QCD*

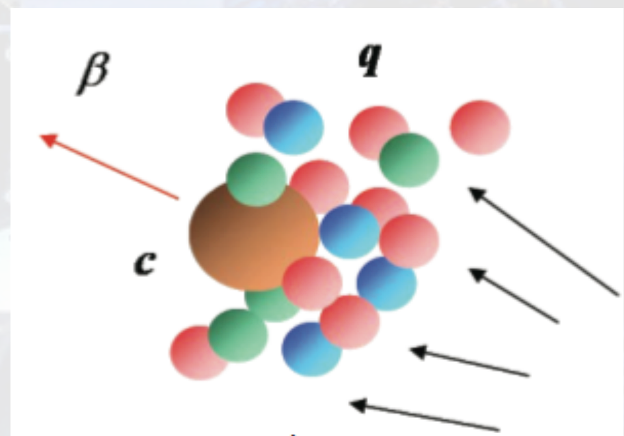
$m_{c,b} >> T_{QGP}$ *predominately created from initial hard scatterings*

Heavy quarks are conserved



Zhu et al., PLB 647(2007)366

Heavy quarks are tractable



$$\frac{dp^i}{dt} = -\eta_D p^i + \xi^i(t),$$

"Brownian" motion

→ Langevin simu.

drag → Diffusion coefficient D_{HQ} ← fluctuations

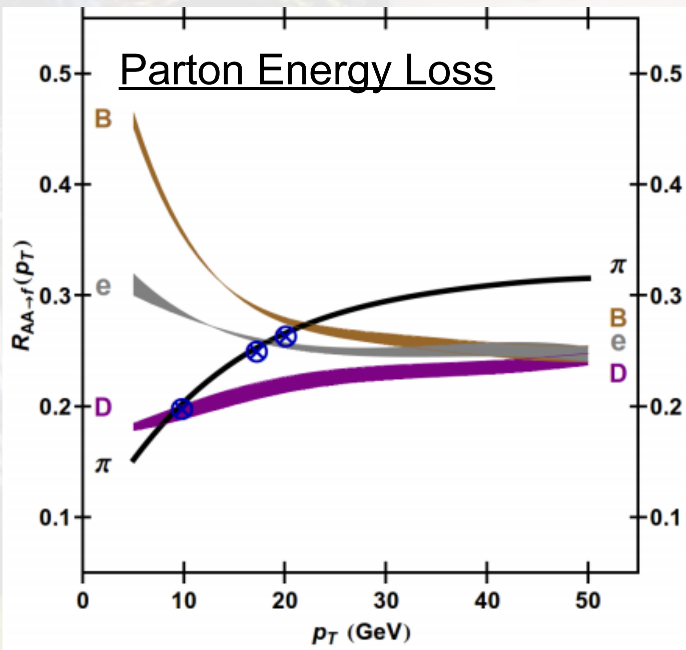
Heavy Quarks for Measuring sQGP Properties

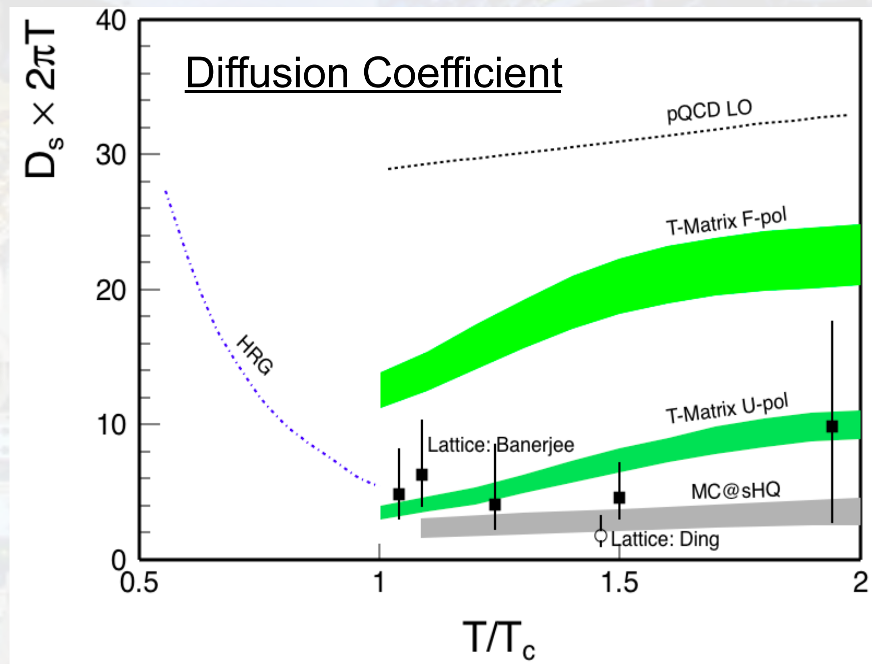
A) To establish a consistent framework

- to describe the strongly coupled medium and interactions

B) To measure intrinsic transport properties of sQGP medium: ***D_{HQ}, η/s*** *etc.*

Other Ingredients: p+p reference - pQCD, Cold Nuclear Matter (CNM) effects …





Buzzatti et al., PRL 108 (2012) 022301

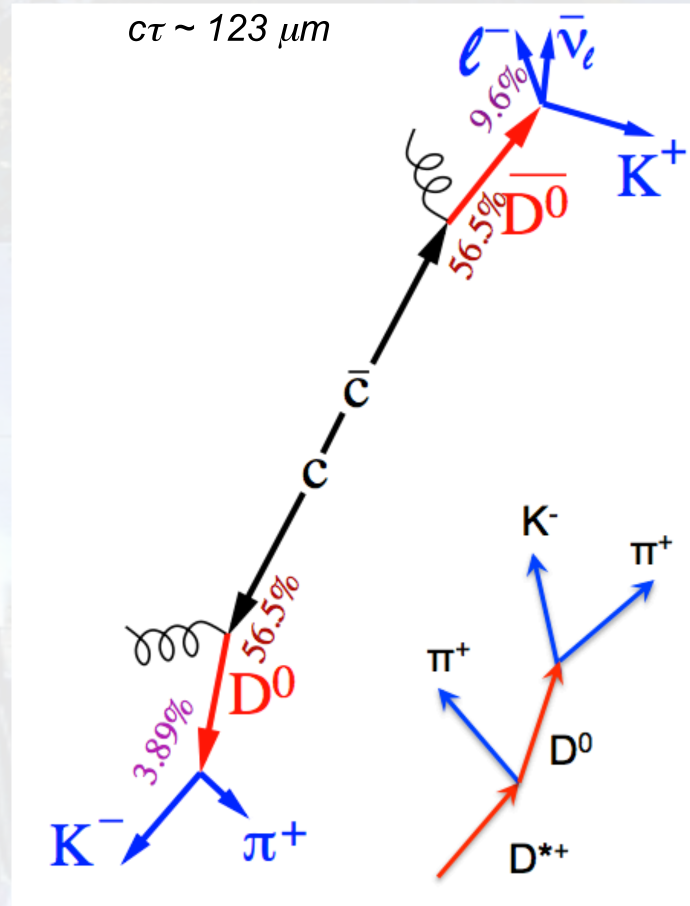
arXiv: 1502.02730, 1506.03981

Experimental Methods

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

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

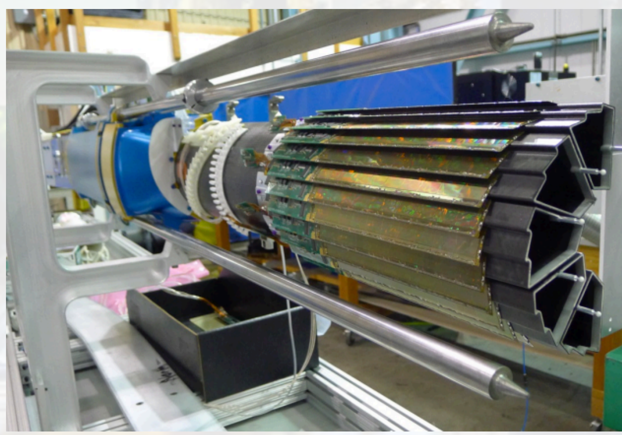


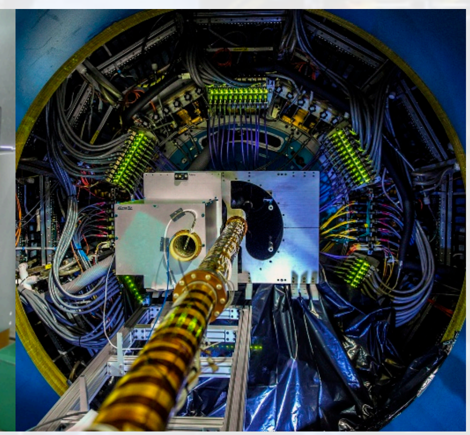
Courtesy: D. Tlusty

Key Instruments – Pixel Silicon Detector

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

STAR pixel detector

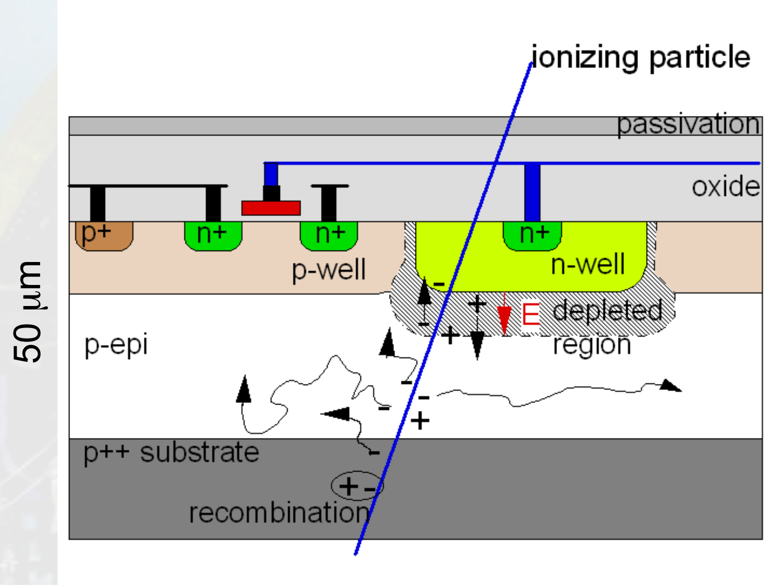




Next generation MAPS detector planned for ALICE/STAR/sPHENIX upgrades

Monolithic Active Pixel Sensors (MAPS)

MAPS pixel cross-section (not to scale)



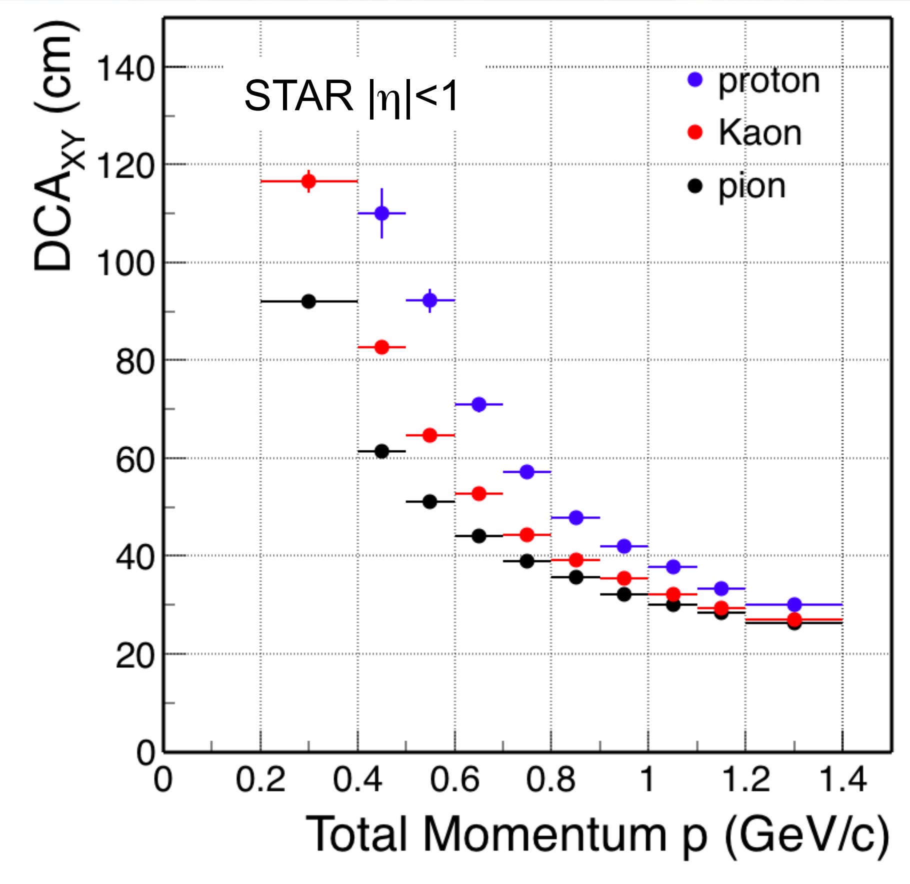
Properties:

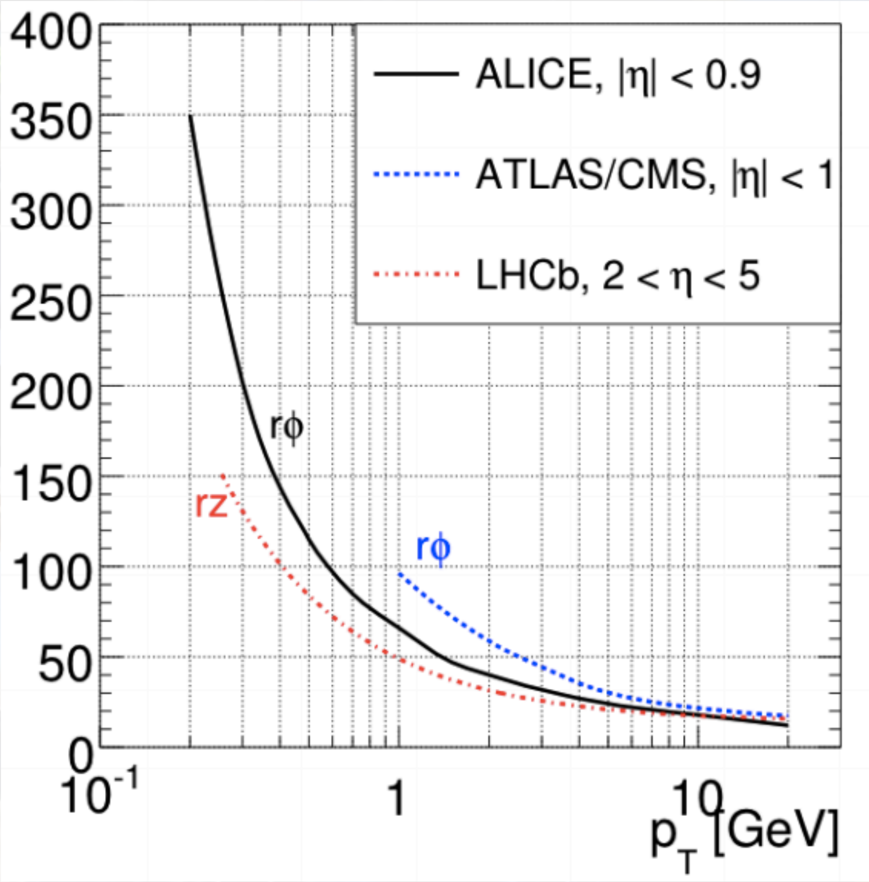
- Standard commercial CMOS technology
- Sensor and signal processing are integrated in the same silicon wafer
- Signal is created in the low-doped epitaxial layer (typically ~10-15 µm) → MIP signal is limited to <1000 electrons
- Charge collection is mainly through thermal diffusion (~100 ns), reflective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

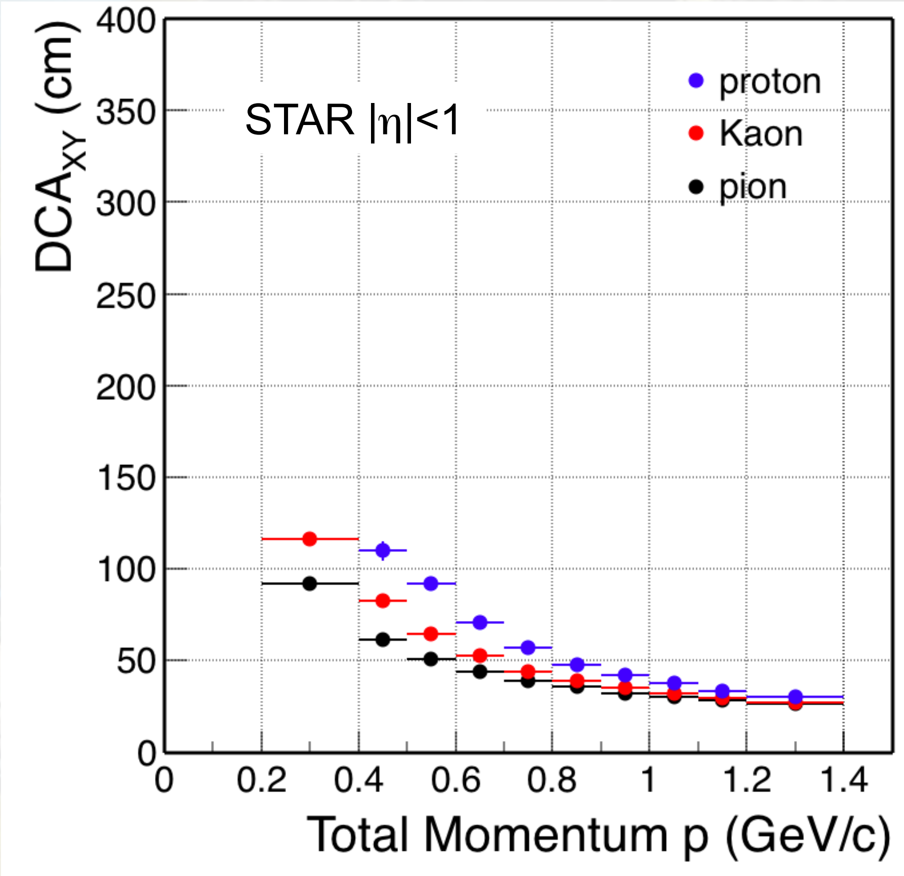
Pixel Detector Performance

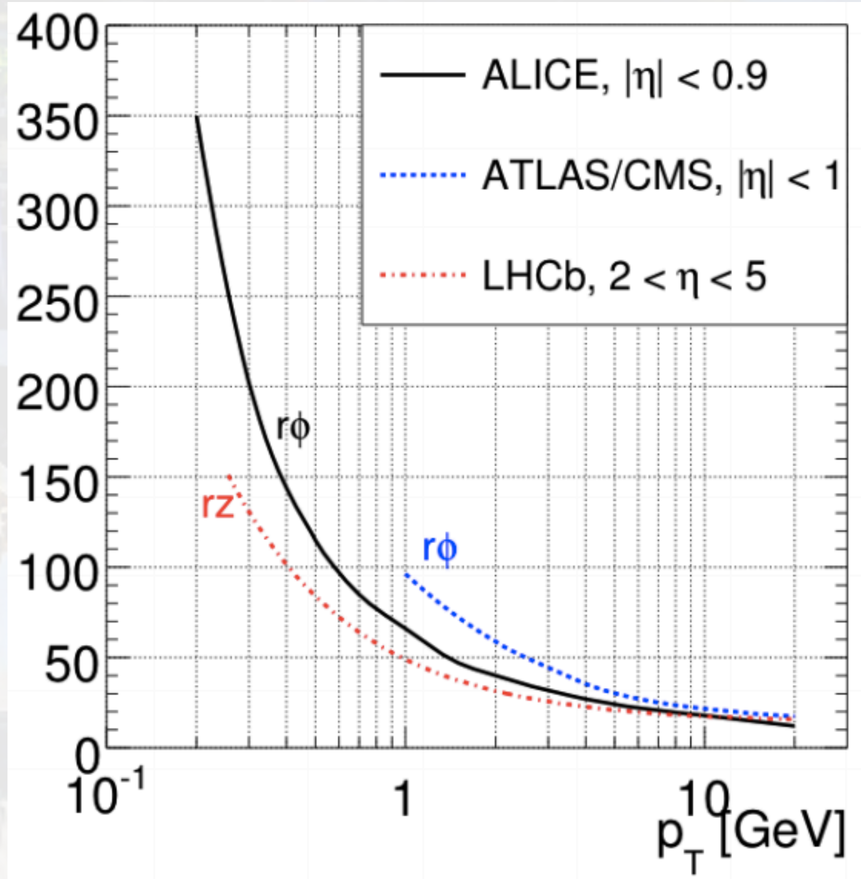




Excellent track pointing resolution for open heavy flavor physics

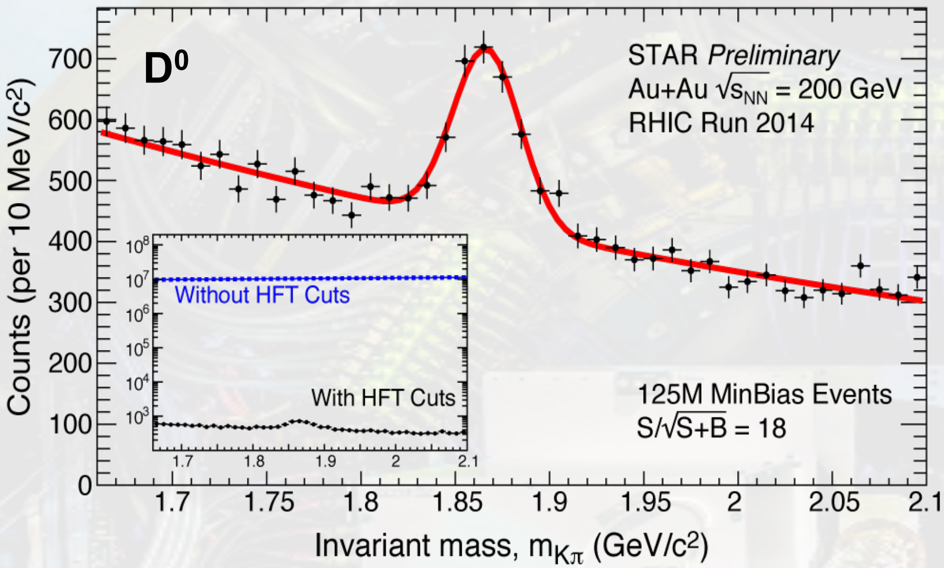
Pixel Detector Performance

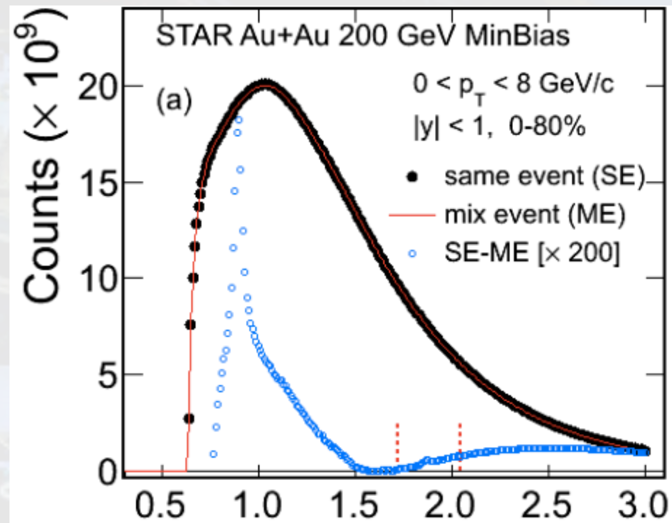




STAR	30 μm @ 1 GeV/c (p)
ALICE	70 μm @ 1 GeV/c (p_T)
ATLAS/CMS	100 μm @ 1 GeV/c (p_T)

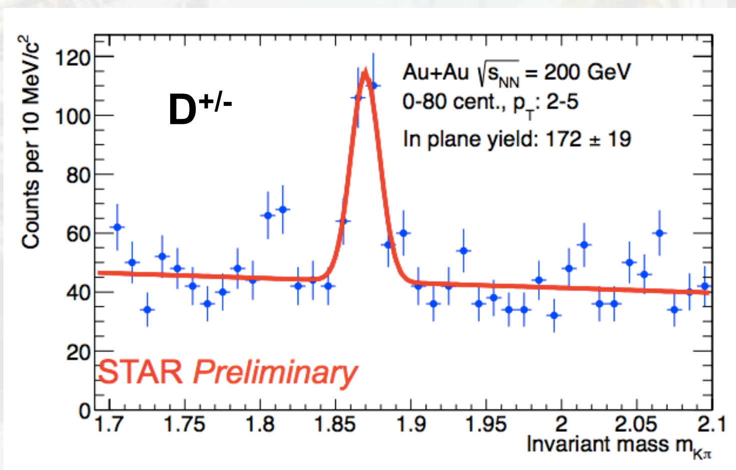
Pixel Detector Performance

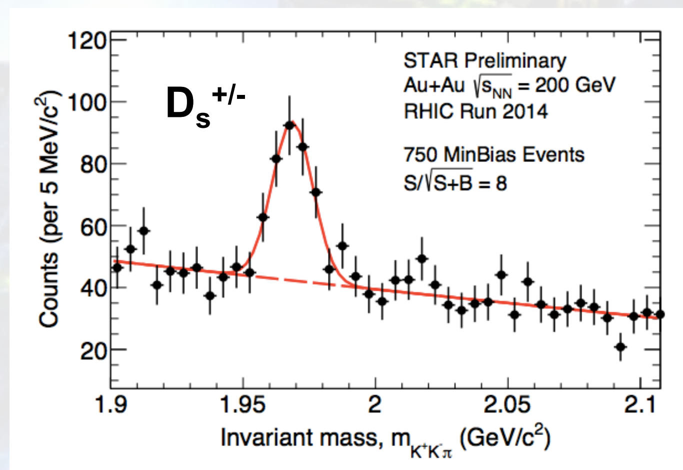




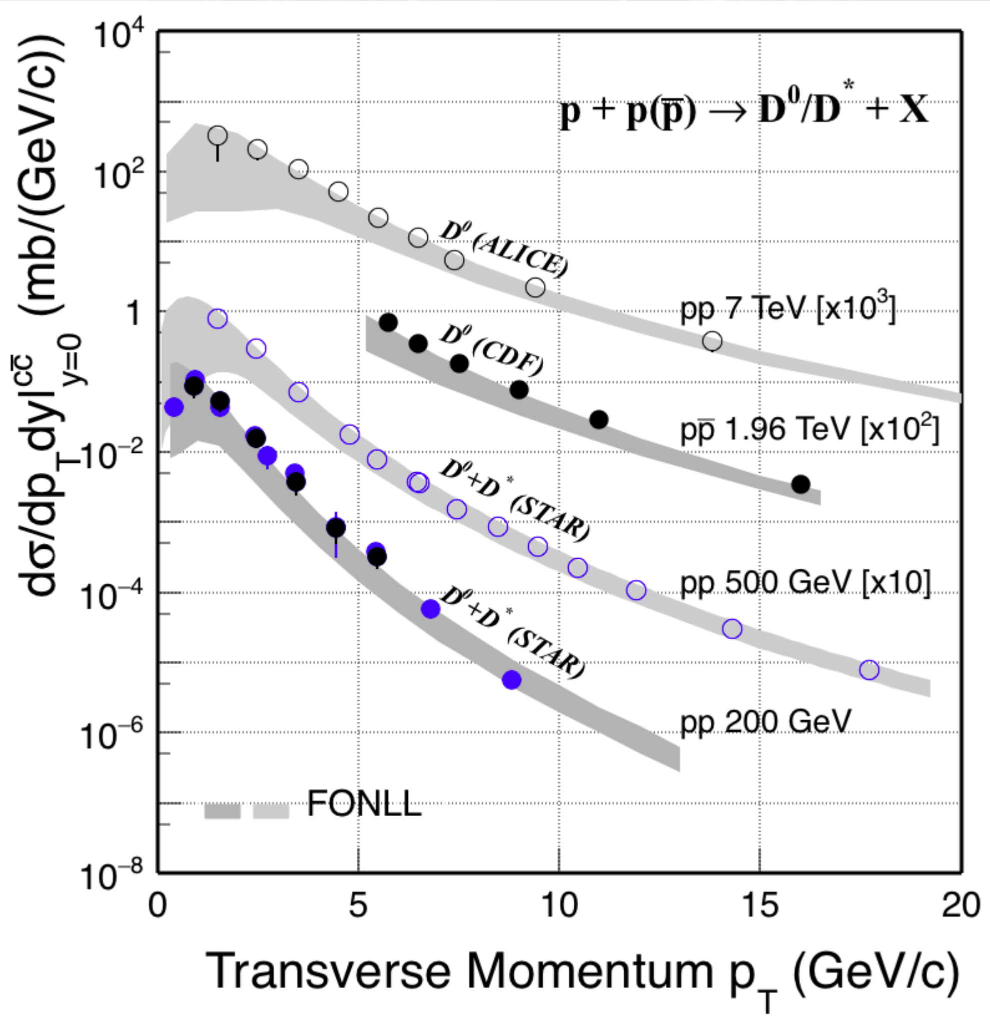
STAR, PRL 113 (2014) 142301

Significant improvement in S/B in D-meson reconstruction





Creation of Heavy Quarks in p+p Collisions



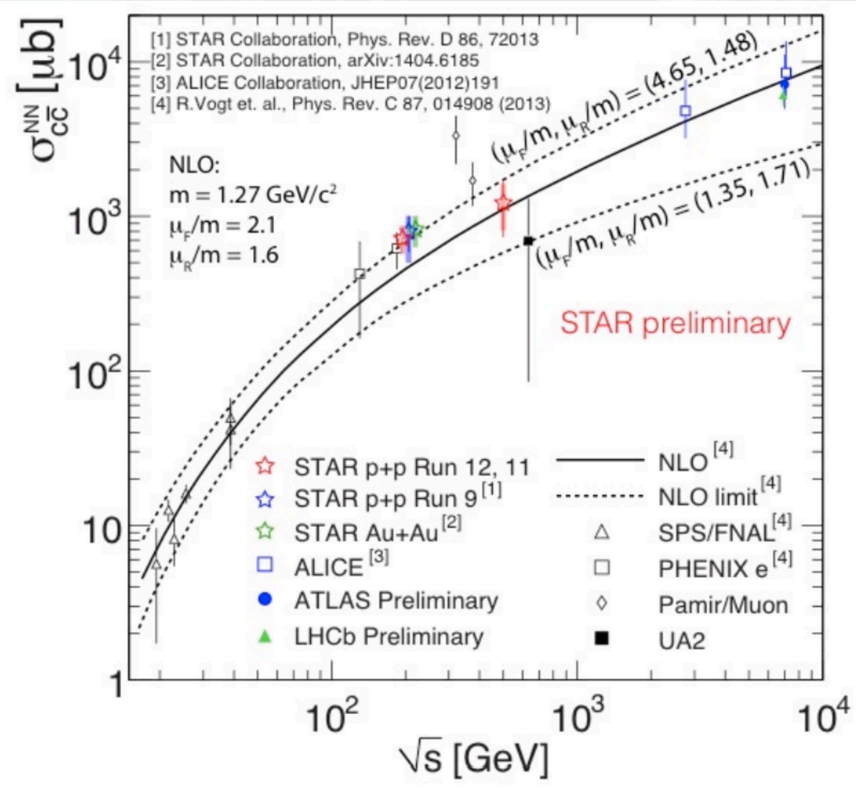
Charm/bottom hadron spectra well described by pQCD calculations (FONLL, MC@NLO etc.)

- Similar for data at Tevetron, HERA etc.

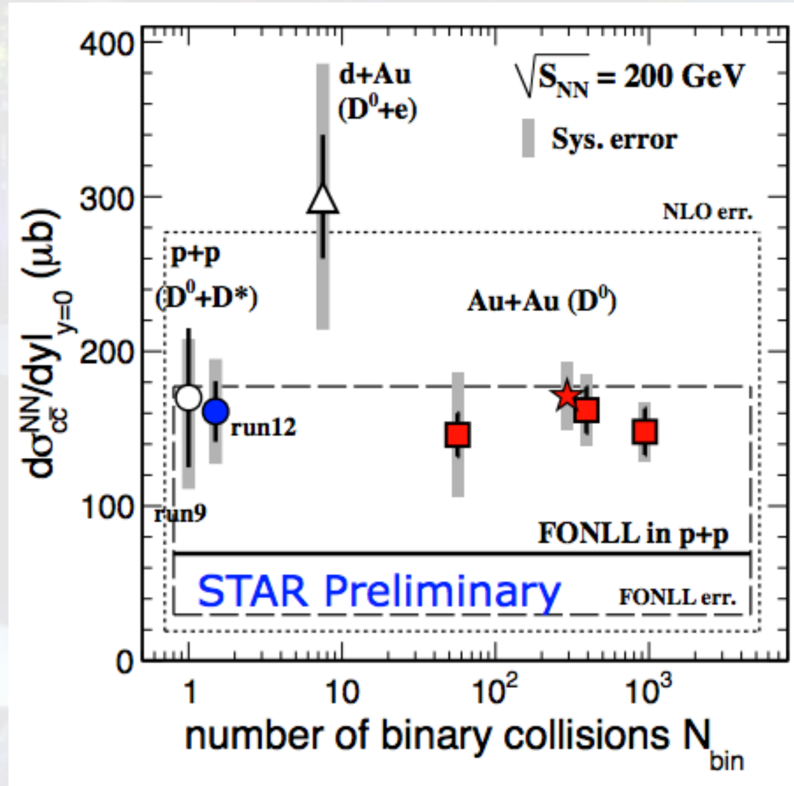
Data precision provides inputs to constrain pQCD calculations

- *Nelson et al, PRC 87(2013) 014908*

Heavy Quark Total Cross Section



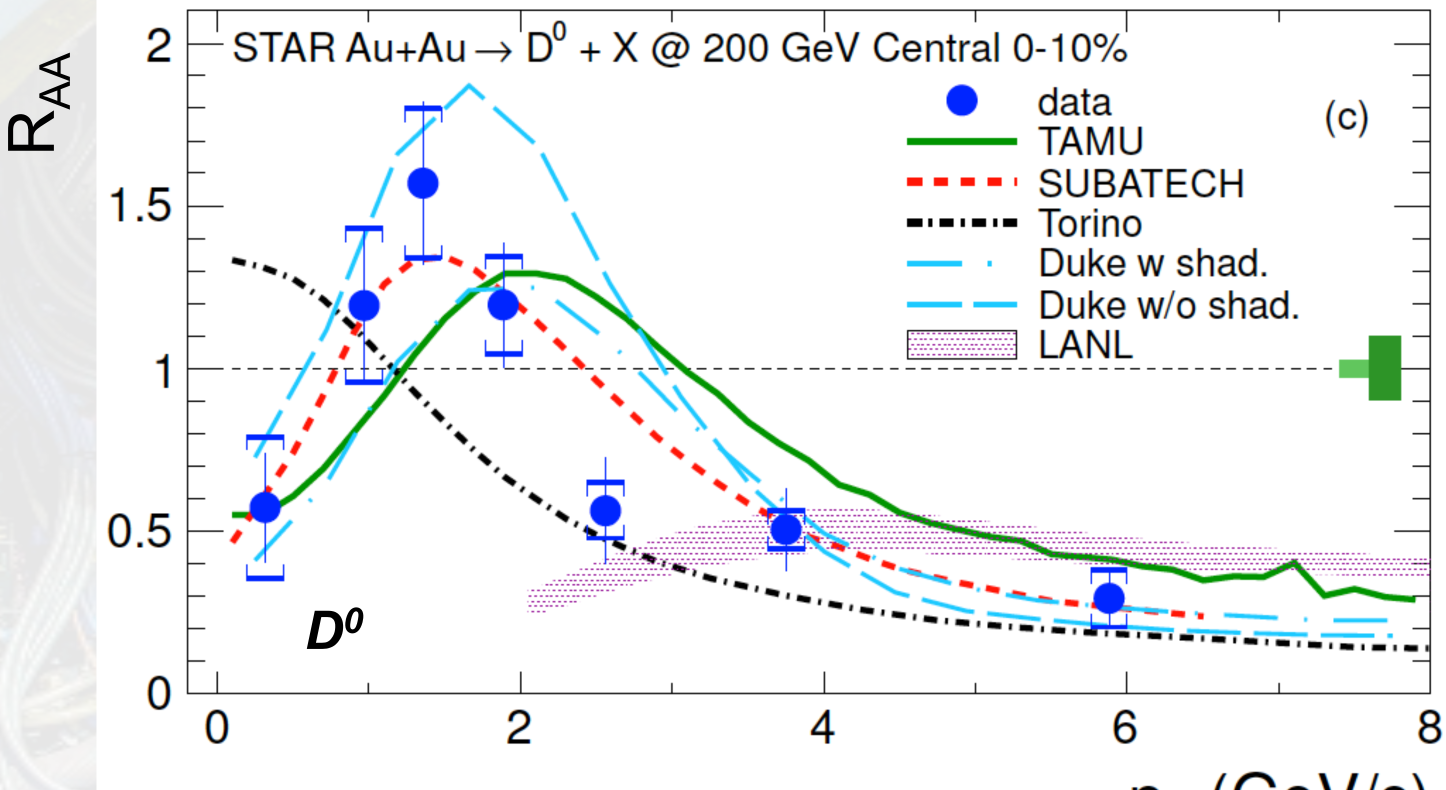
RHIC



Critical calibration for both open heavy flavor and heavy quarkonia in A+A collisions
- need to be vetted in heavy ion collisions

RHIC: Charm total cross section at mid-rapidity follows N_{bin} scaling
- pending checks on various charm hadrons (D_s, Λ_c etc)

Charm Modification in A+A Collisions at RHIC



STAR, PRL 113(2014)142301

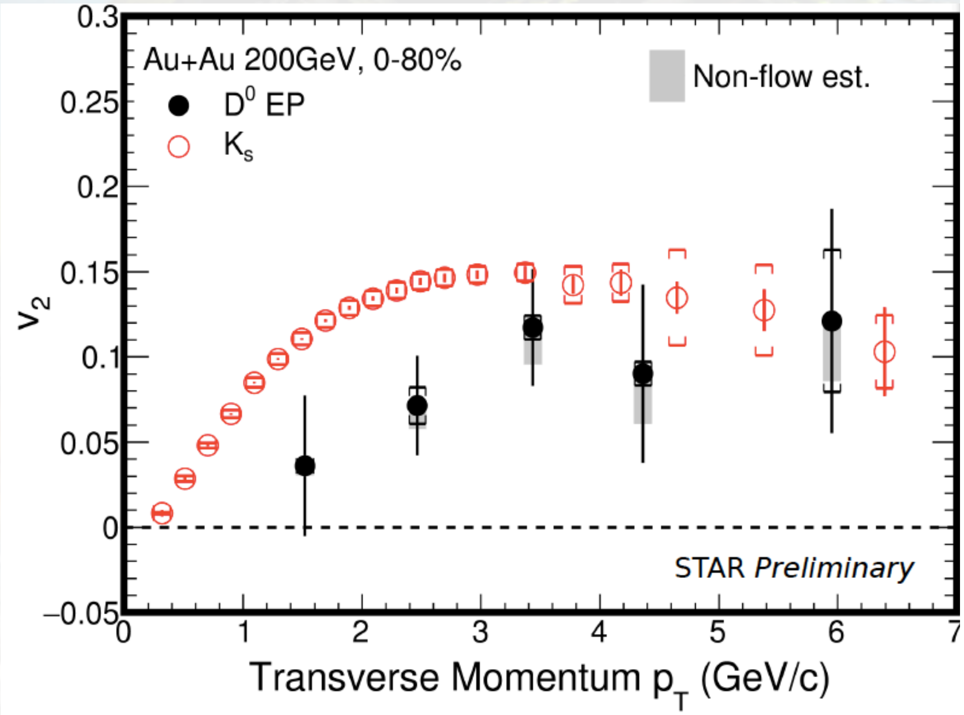
Significant charm energy loss in medium - $R_{AA}(D^0) \sim R_{AA}(e) \sim R_{AA}(h)$

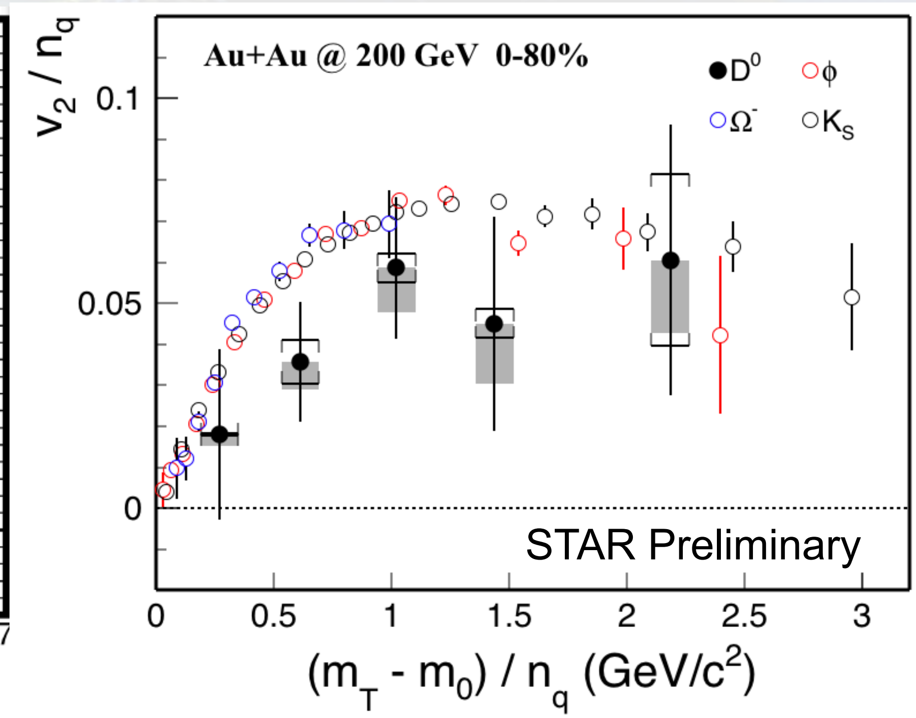
Modification of charm hadrons with bulk medium - coalescence important at low p_T

Charm quark flows? - complicated by interplays between cold/hot nuclear effects

D-meson v_2 at RHIC

70% of 2014 Au+Au 200 GeV Data



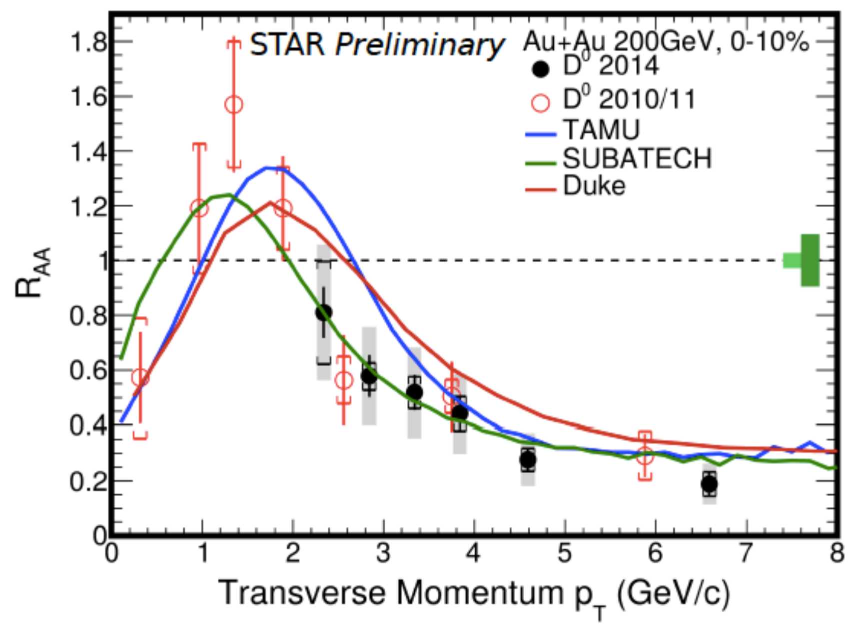


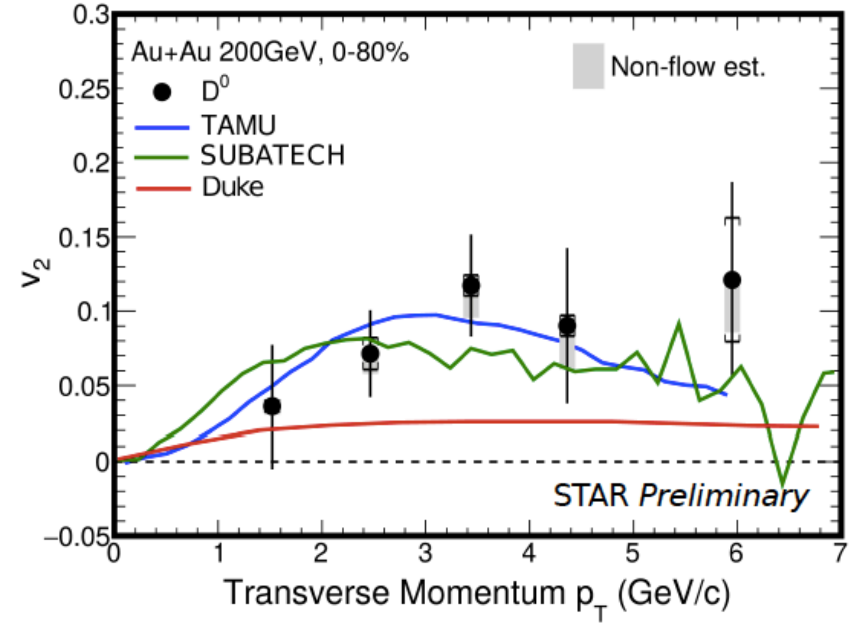
Significant charm hadron v_2 at p_T>2 GeV/c

v_2/n_q vs. $(m_T-m_0)/n_q$: indication of D-meson lower than Ks, ϕ, Ω

- centrality bias (D ~ N_{bin} scaling, light hadrons ~ N_{part} scaling)
- looking forward to comparisons in narrow centrality bins.

RHIC R_{AA} and v_2 Compared to Models

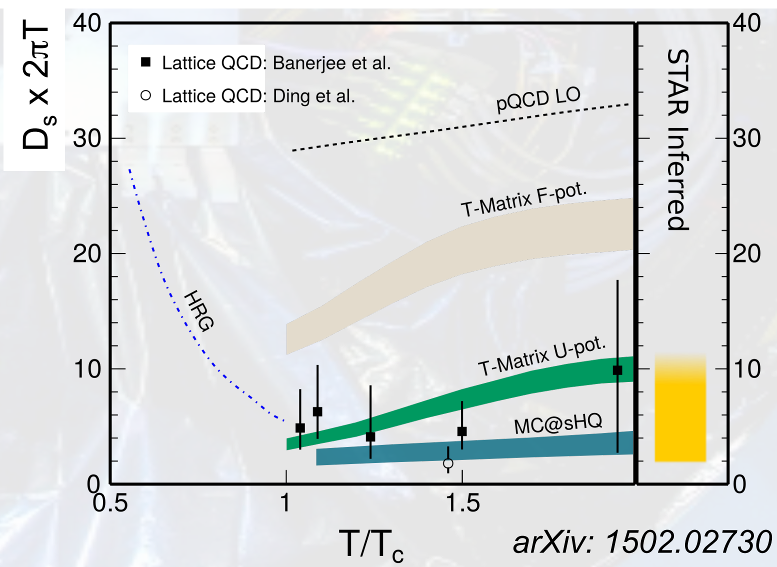




Models with charm diffusion + coalescence describe both R_{AA} and v_2 data of D-mesons

Data favors $2\pi T \boldsymbol{D_s}$ ~ 2-12

- Consistent with lattice QCD calculations



D-meson R_{AA} and v_2: RHIC vs. LHC

Comparable suppression at high p_T

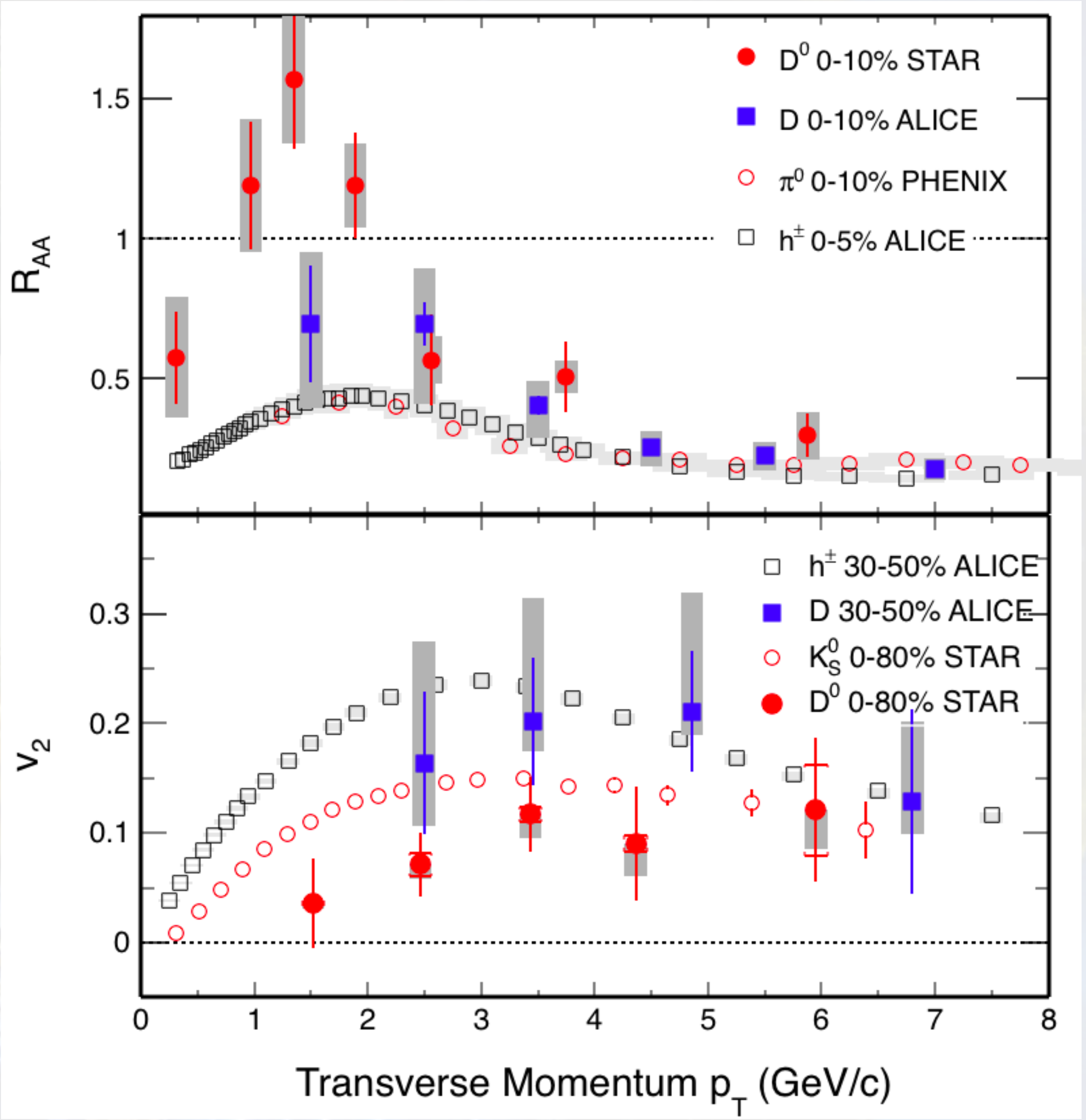
- collisional and radiative ΔE

Possibly different physics at low p_T

- Initial parton distributions
  x_T at 2 GeV/c ~ 10^{-2} (RHIC)
  ~ 10^{-3} (LHC)
- "Cronin" effect
- Charm quark flow

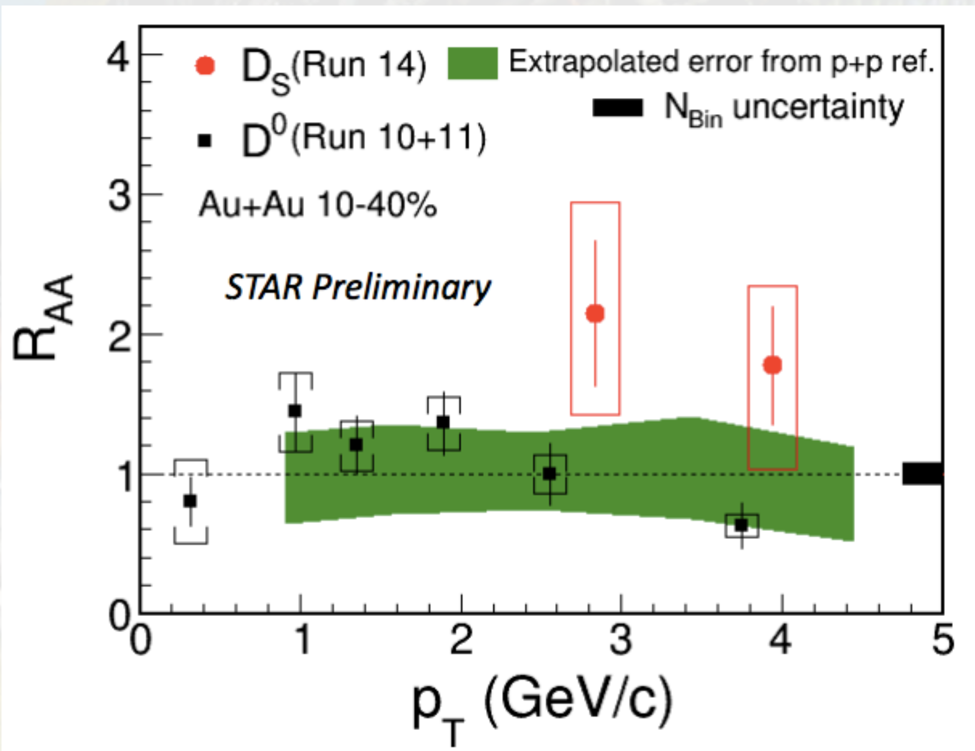
Precision charm v_2 data, particularly to low-intermediate p_T are critical for the extraction of sQGP D_{HQ}.

Upcoming:
- Precision HFT data from STAR
- High statistics Run-II data from ALICE/ ATLAS/CMS

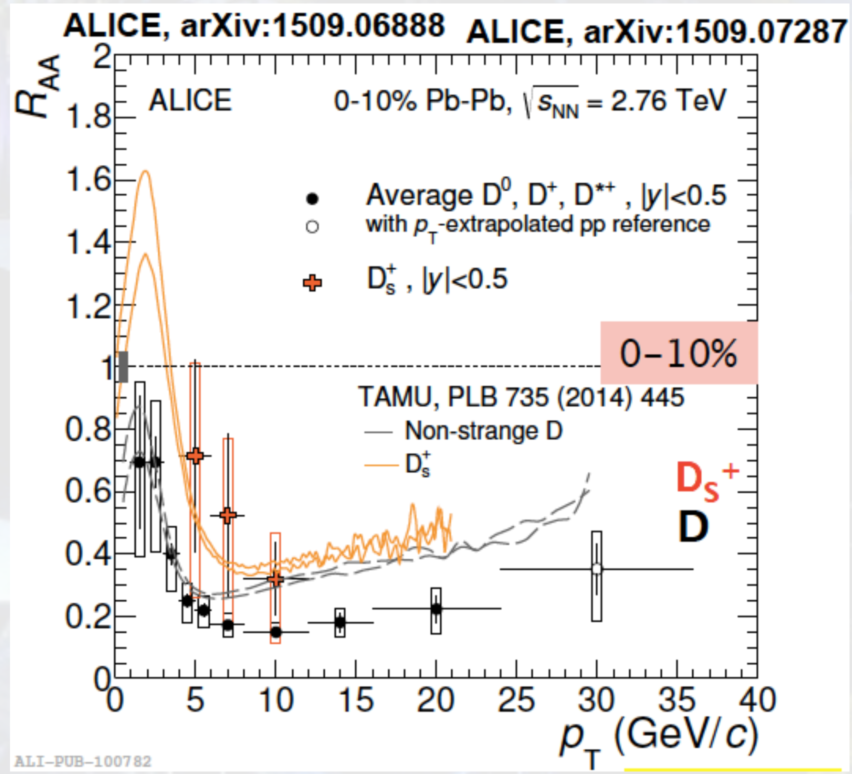


D_s – Hadronization and Strangeness Enhancement

RHIC



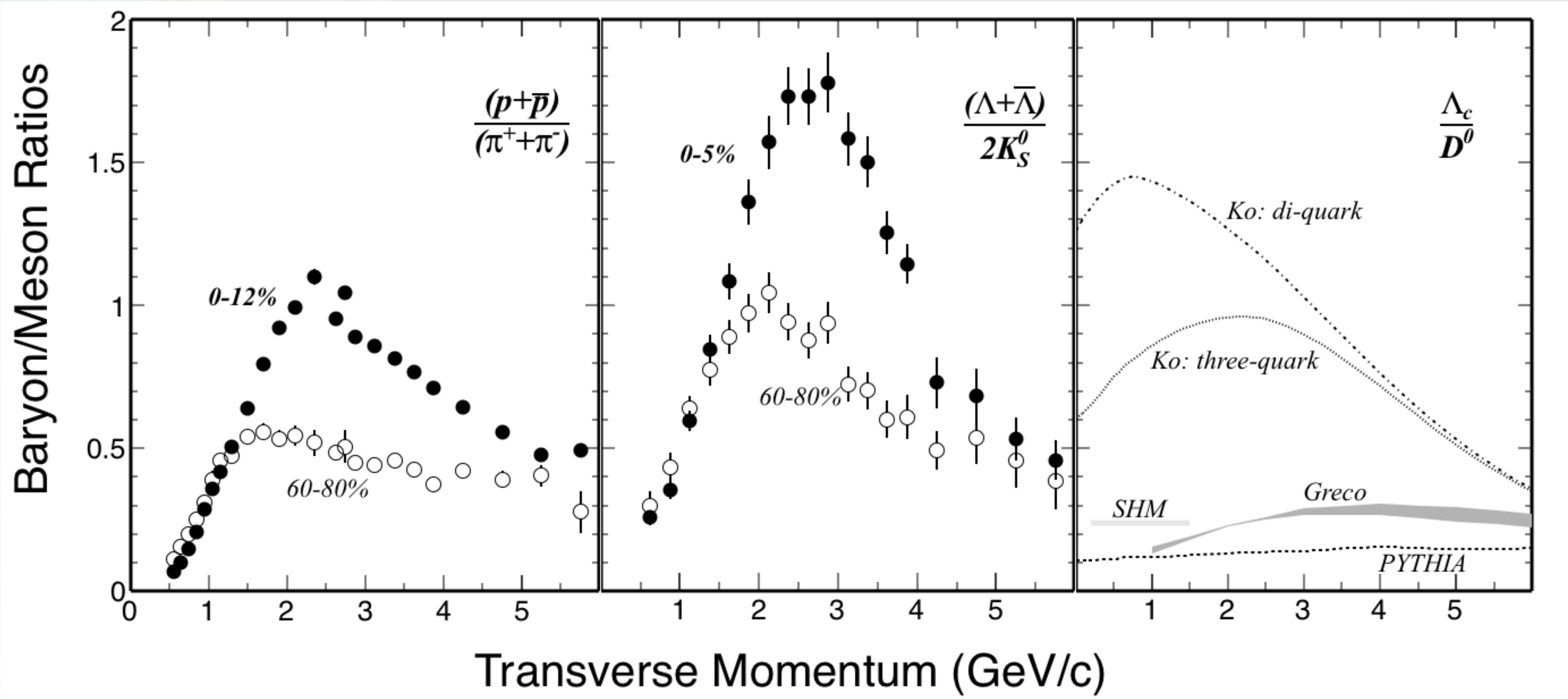
LHC



Strangeness enhancement in QGP + coalescence -> D_s/D^0 enhancement in HI collisions

Hint of D_s/D^0 enhancement in data from RHIC and LHC -> need more precise measurements

Λ_c - Charm Baryon Enhancement?



Various models predict different levels of enhancement for Λ_c/D^0 depending on
- hadronization, thermalization, domains in sQGP

No measurement of Λ_c in A+A collisions ($c\tau$ ~ 60 μm, $\Lambda_c^+ \rightarrow pK^-\pi^+$, B.R. 5%)

Prospective with the STAR HFT data at RHIC

Λ_c/D^0: Lee et al., PRL100 (2008) 222301; Ghosh et al., arXiv:1407.5069

Open Bottom Production

Open bottom production over a wide range of momentum

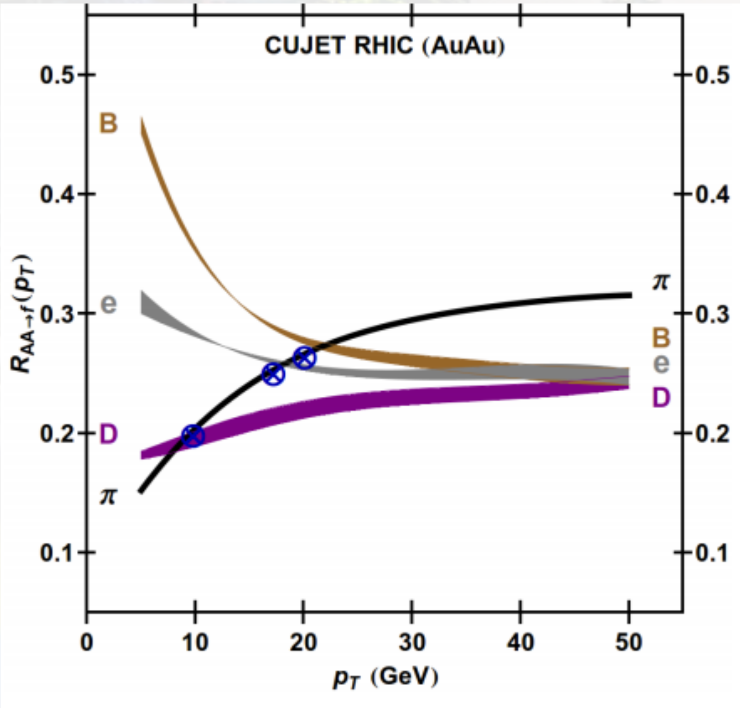
Flavor dependence of parton energy loss – medium properties at small scale

Cleanest probe to quantify medium transport properties – e.g. D_{HQ}

- medium properties at large scale

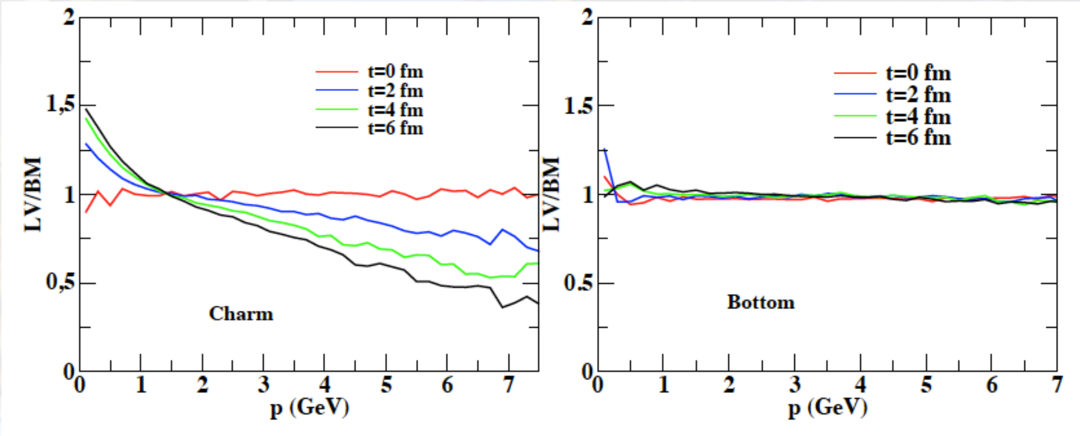
Total bottom yield

- verify CNM for precision interpretation of Upsilon suppression



Buzzatti et al., PRL 108 (2012) 022301

Das et al., PRC 90 (2014) 044901



Is charm heavy enough?

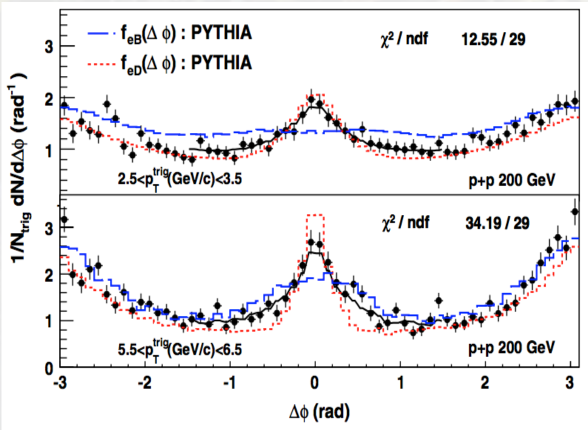
Sizable correction to the Langevin approach for charm

- may limit the precision in determining D_{HQ}

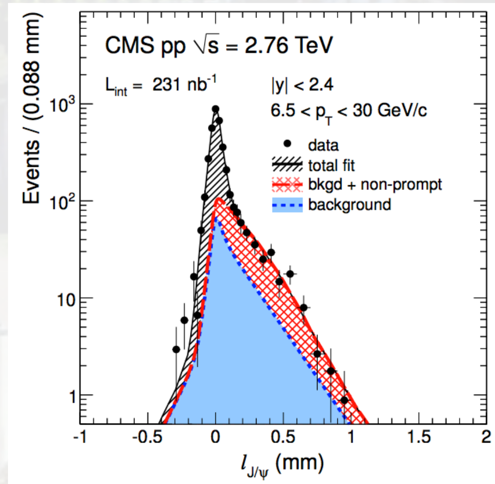
Measuring Bottom

Lower production rate! Lower branching ratios for exclusive reconstruction!

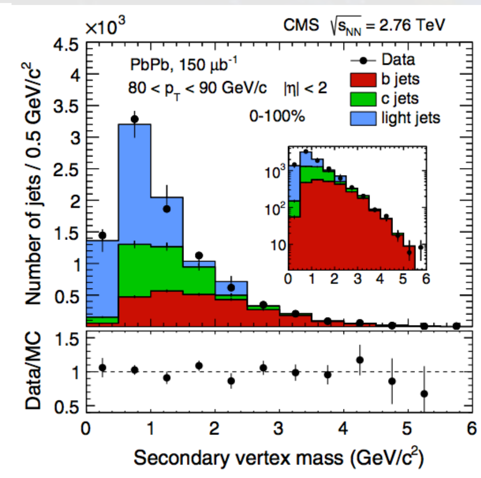
STAR e-h in p+p



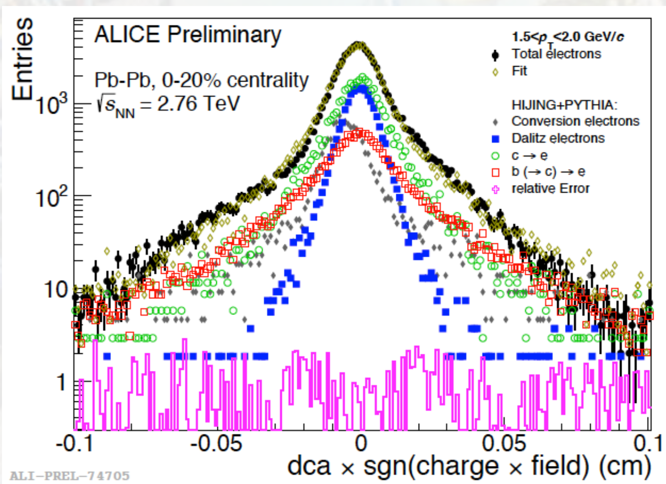
CMS displaced J/ψ



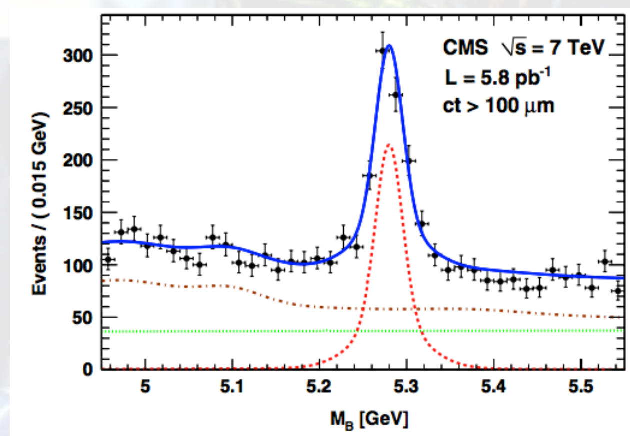
CMS b-jet



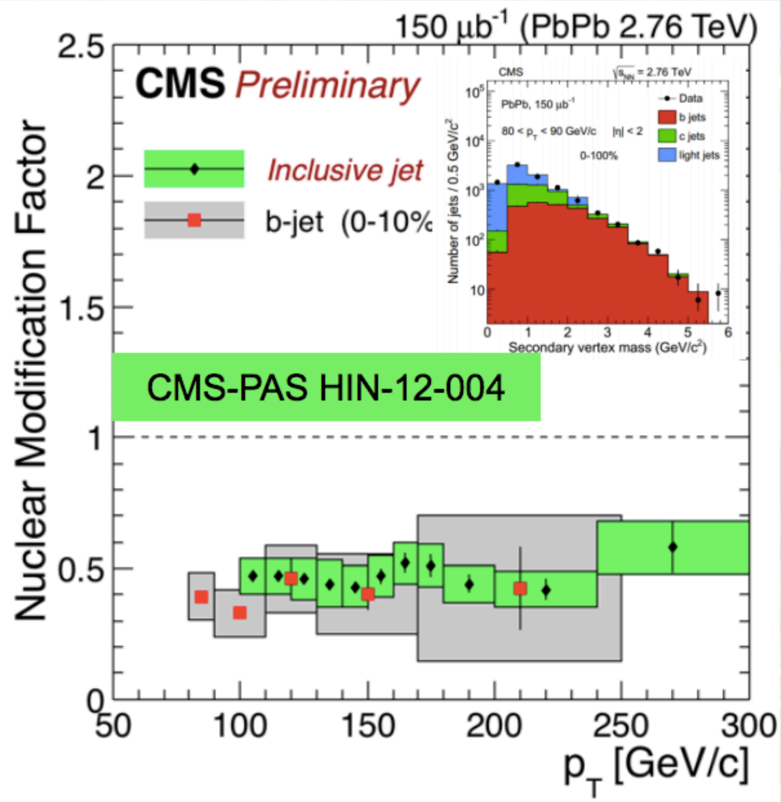
ALICE impact par. of e in Pb+Pb

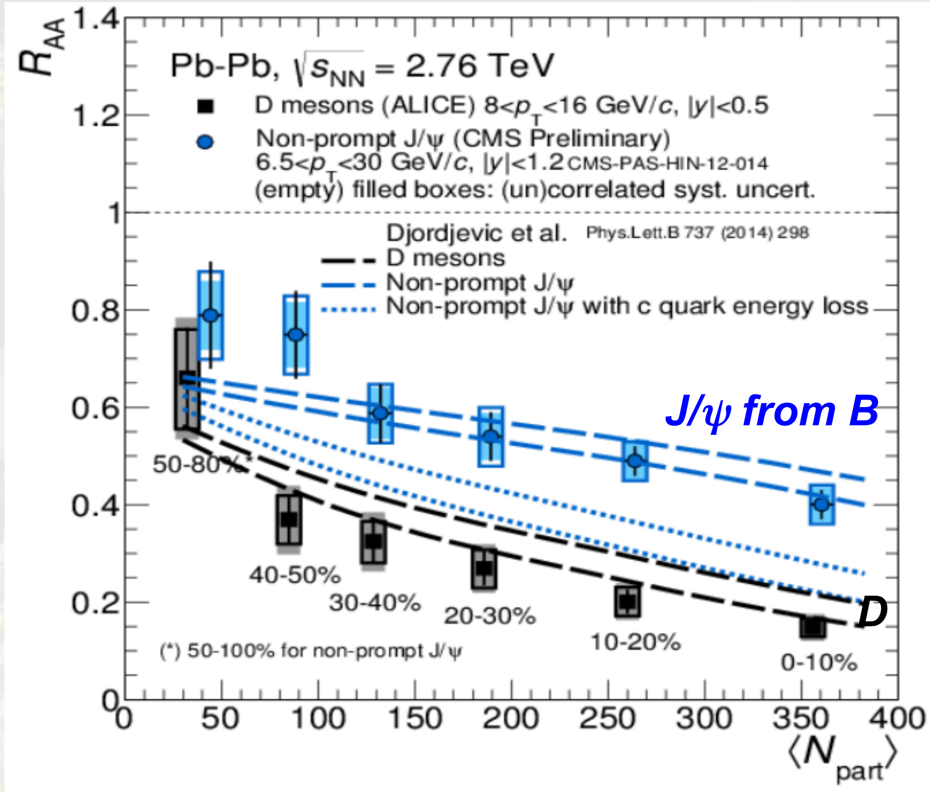


CMS B-meson in p+Pb



Bottom Suppression in Heavy Ion Collisions





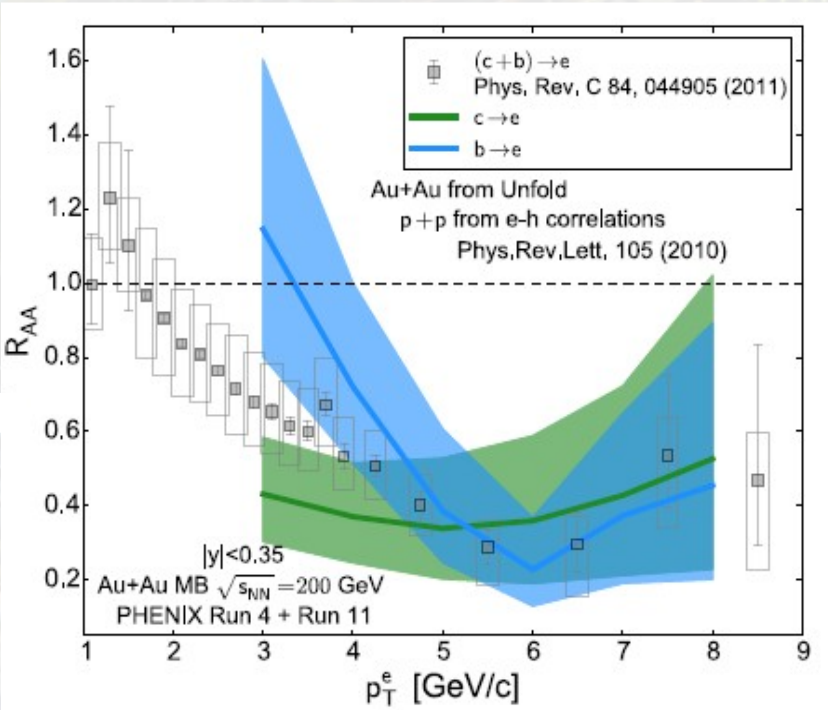
ALICE JHEP 09 (2012) 112, CMS-PAS-HIN-12-014, ALICE arXiv: 1506.06604

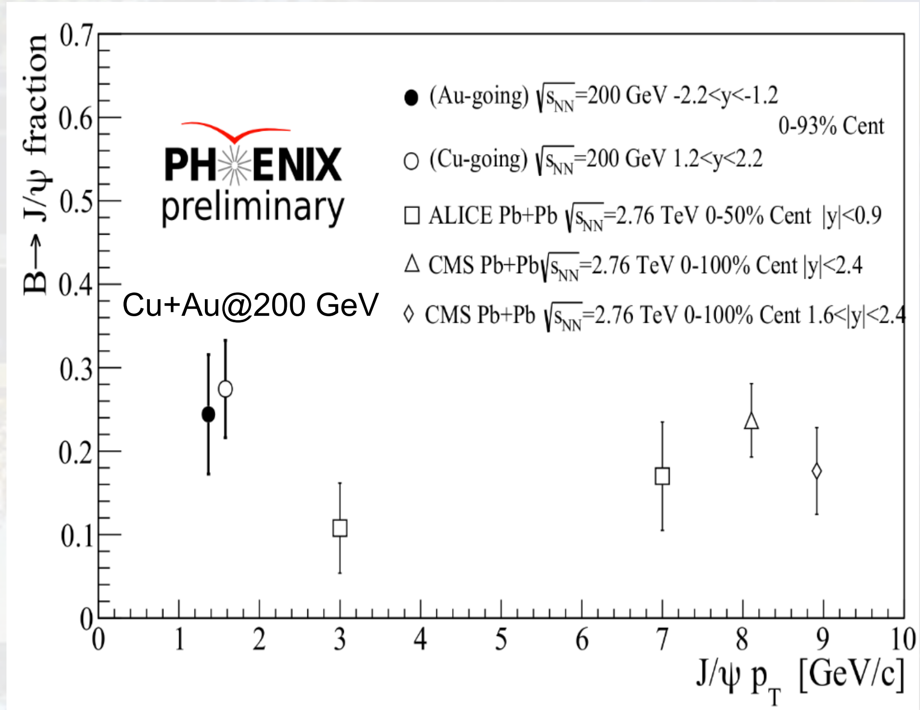
R_{AA} of b-jets at p_T>80 GeV/c comparable to that of light jets
caveat: sizable gluon splitting contribution

Suppression hierarchy between $R_{AA}(J/\psi^B)$ and $R_{AA}(D)$
– consistent with pQCD calculations

Measuring Bottom at RHIC

Separation of c and b contribution to electrons / non-prompt J/ψ using impact parameter method with VTX and FVTX at PHENIX





PHENIX, PRC 93 (2006) 034904

Statistics are challenging, hint of less suppression for bottom quark

→ High statistics measurement in future heavy flavor program at RHIC

What we have learned?

A) How do energetic heavy quarks lose energy in sQGP medium?

$R_{AA}(h) \sim R_{AA}(e) \sim R_{AA}(D) < R_{AA}(J/\psi^B)$ at high p_T at LHC and RHIC(?)

- described by pQCD calculations including collisional and radiative energy loss

- only revealed with heavy quark measurements

B) How do charm quark flow?

low-intermediate p_T:

R_{AA} and $v_2(D)$ at RHIC – hint of charm flow + coalescence

$v_2(D) \sim v_2(\pi)$ at LHC – indication of large charm flow?

C) Can we extract the medium transport properties (e.g. D_{HQ})?

Theory: Need to figure out other differences in different models

– Very actively on-going with task-forces/topical collaborations

Experiments: Precision data

Future Measurements:

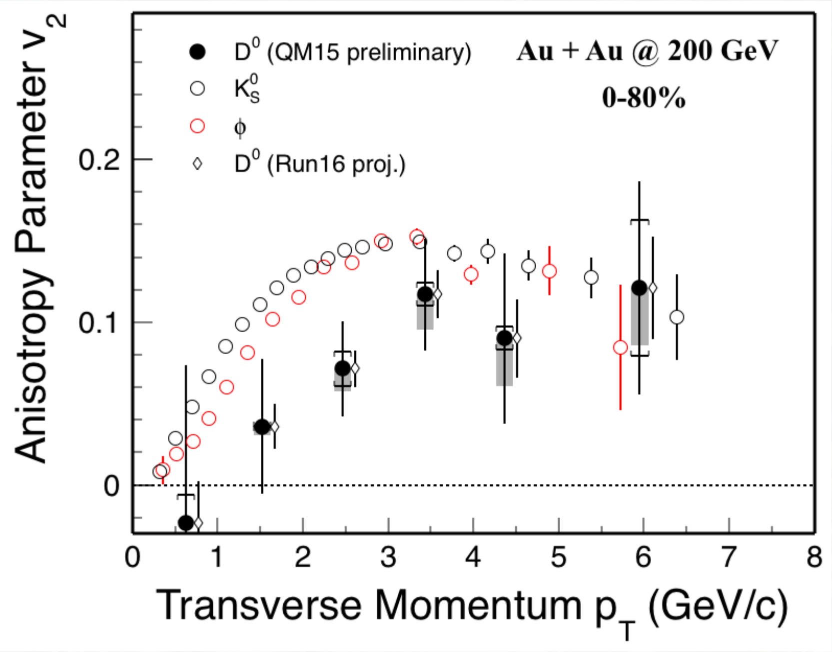
- Very near future - Precision charmed hadron data (STAR HFT and LHC Run2)
- Open bottom production over a broad momentum range
- Heavy quark correlations

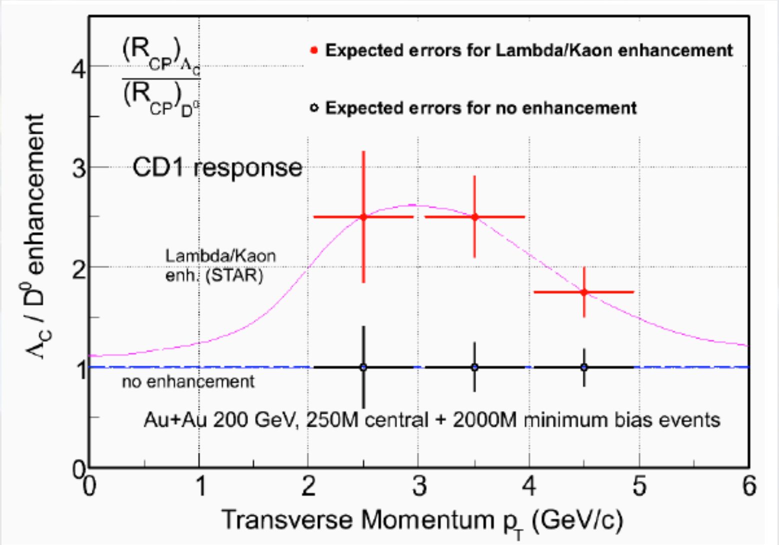
Calibration of charm/bottom total cross section

Cold nuclear matter effects

Near-Term: STAR HFT Physics Goals

STAR HFT: Precision measurement of charmed hadron production in heavy ion collisions

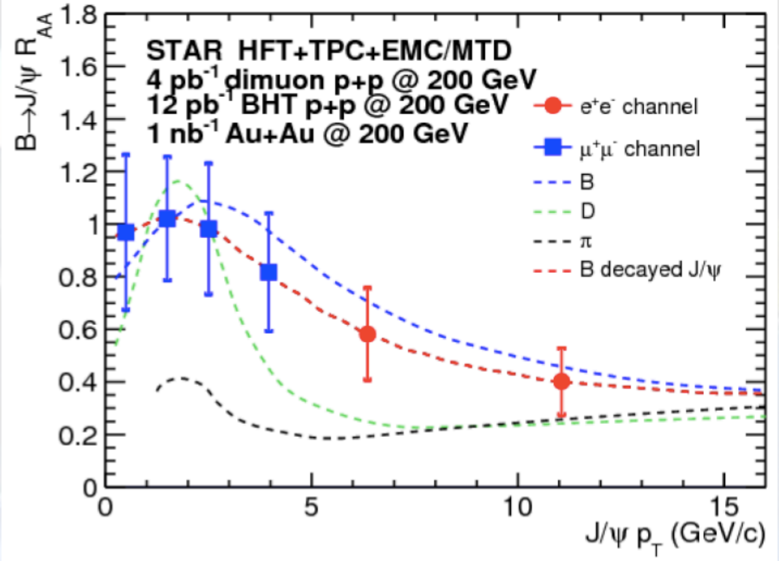




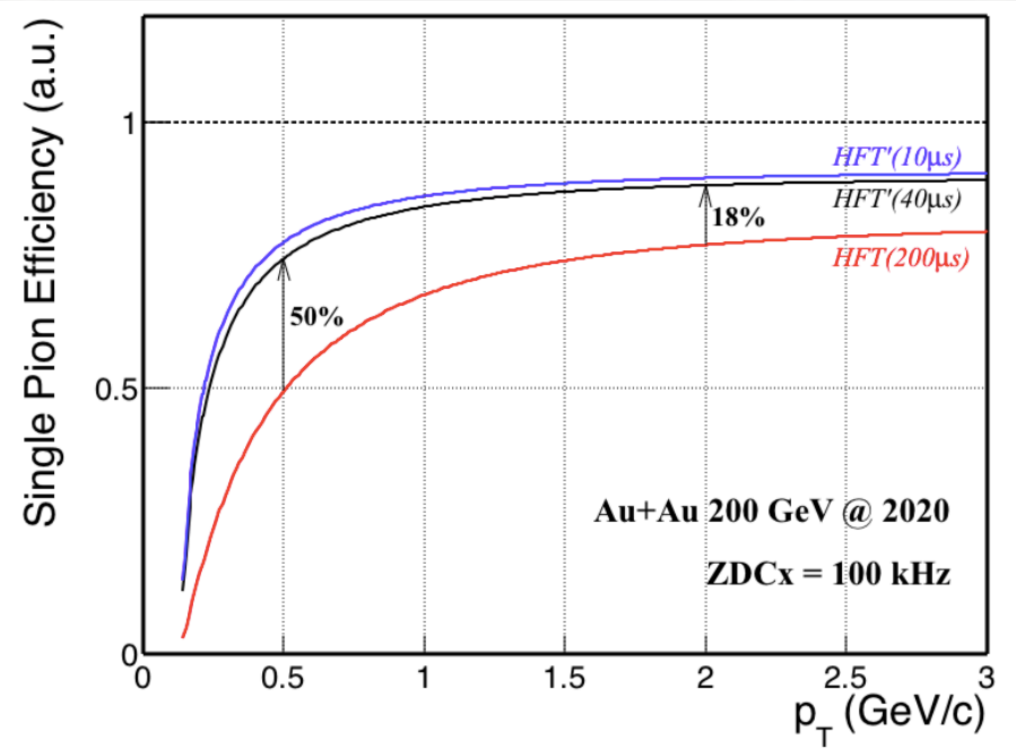
Centrality dependence of charm hadron v_2

First Λ_c measurement in HI collisions
- coalescence hadronization

B->J/ψ with displaced vertex at RHIC
- bottom quark energy loss



Fast MAPS Detector Upgrades at RHIC and LHC

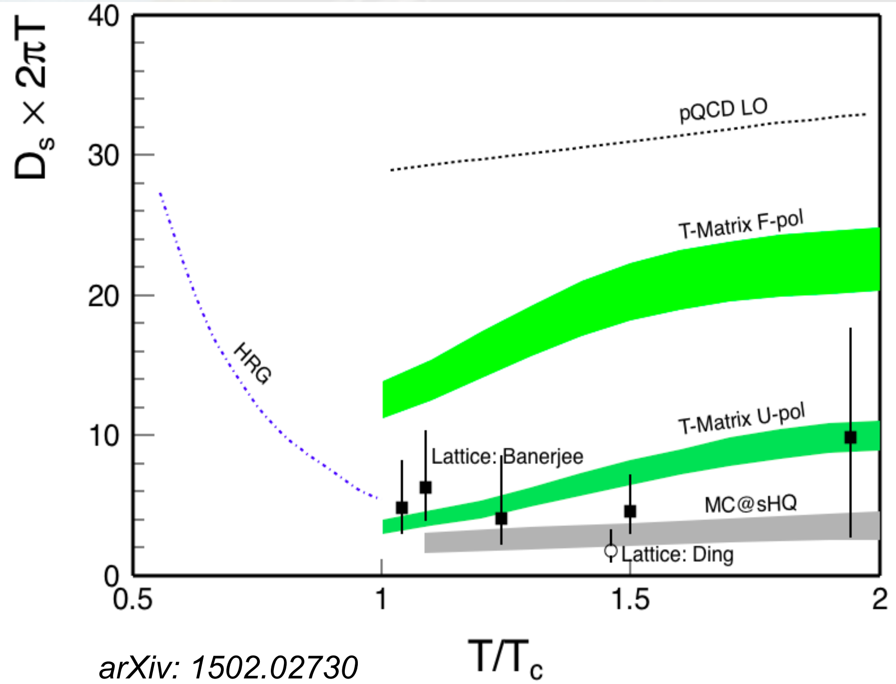


ALICE ITS upgrade / STAR HFT+ / sPHENIX MAPS pixel – 2021+

Next generation MAPS sensors with much shorter integration time < 20 μs (vs. 186 μs)

Goals:
- open bottom measurements over a broad range of momentum range
- heavy quark correlations
- precision charmed hadron (D^0, Λ_c) measurements down to low p_T (ALICE)

Summary



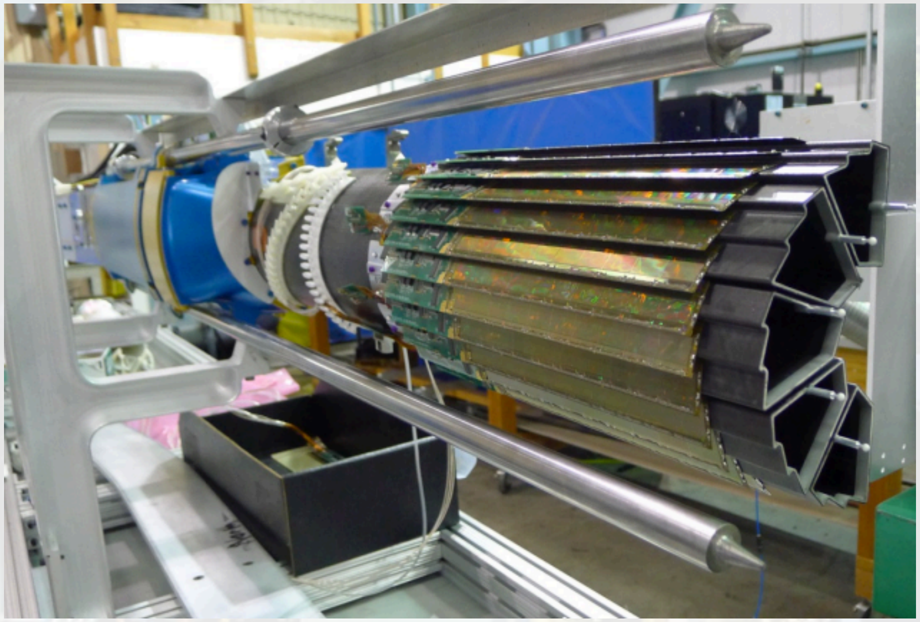
arXiv: 1502.02730

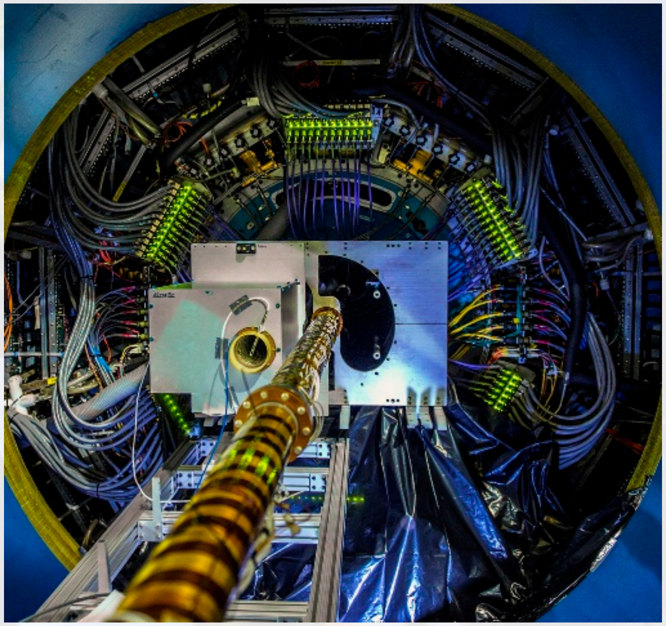
- **Precision data points in coming years**
- **Joint efforts between theorists**
  - task forces / topical collaborations
- **LHC vs RHIC**
  - **Complementarity**

	2014	2015	2016	2017	2018	2019	2020	2021	2022+
RHIC	STAR HFT PHENIX (F)VTX Precision charm			Spin		BES-II		STAR HFT+ sPHENIX Open bottom	
LHC		Run 2 (x10 statistics)					ALICE ITS upgrade CMS/ATLAS upgrades Run 3 (x100 statistics)		

Backups

STAR Heavy Flavor Tracker

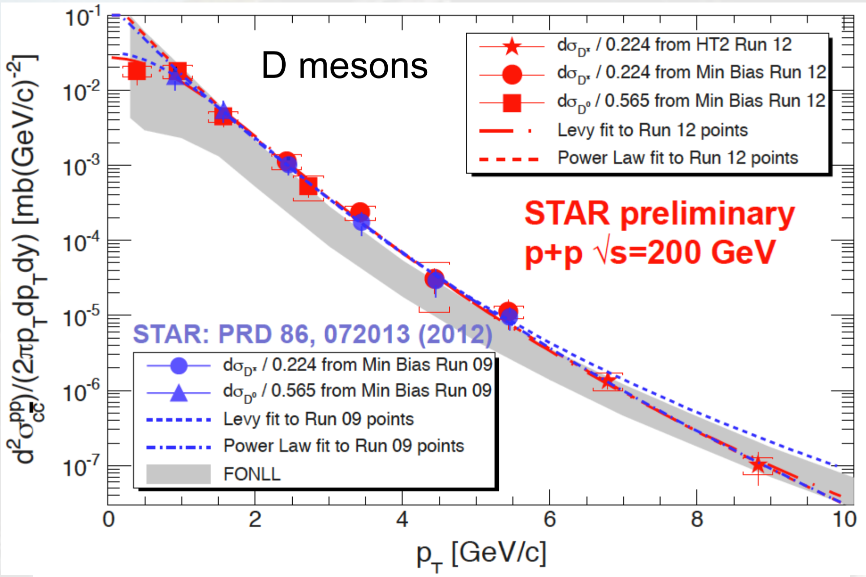


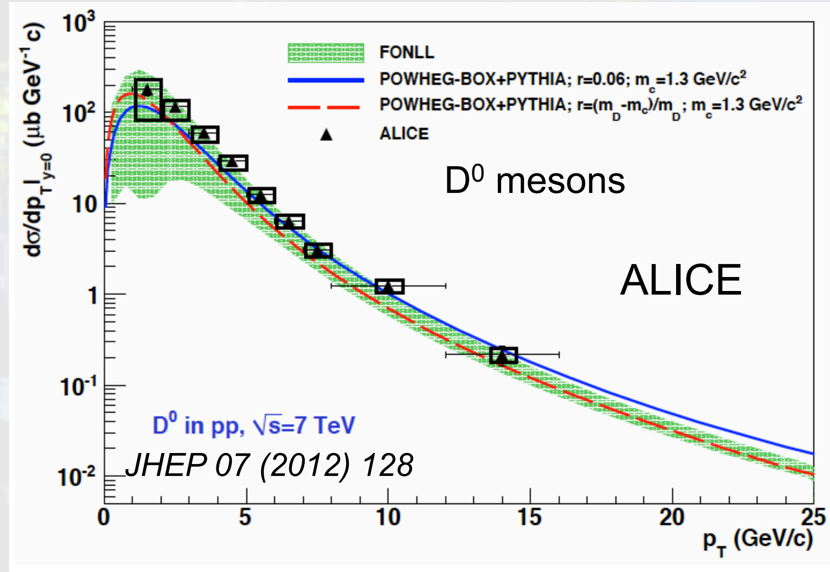


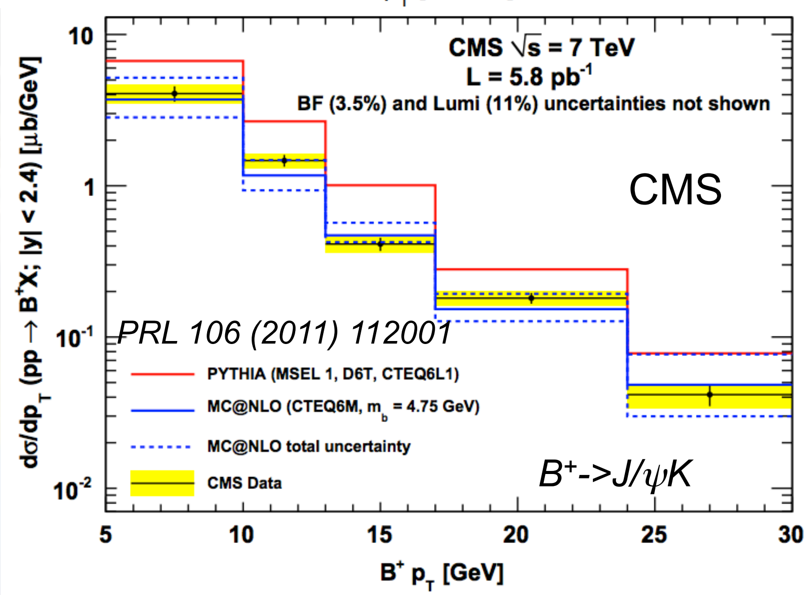
2013 May	– PXL prototype engineering run with 3 sectors (out of 10 in total)
2014 Spring	– Commissioning in Au+Au 200 GeV collisions. Physics mode since then
2014 Sept	– HFT project closeout. Project finished on time and under budget
2015 Spring	- p+p and p+Au 200 GeV run with HFT
2016 Spring	- Au+Au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

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

Heavy Quark Production in p+p Collisions







Charm/bottom hadron spectra well described by pQCD calculations (FONLL, MC@NLO etc.)

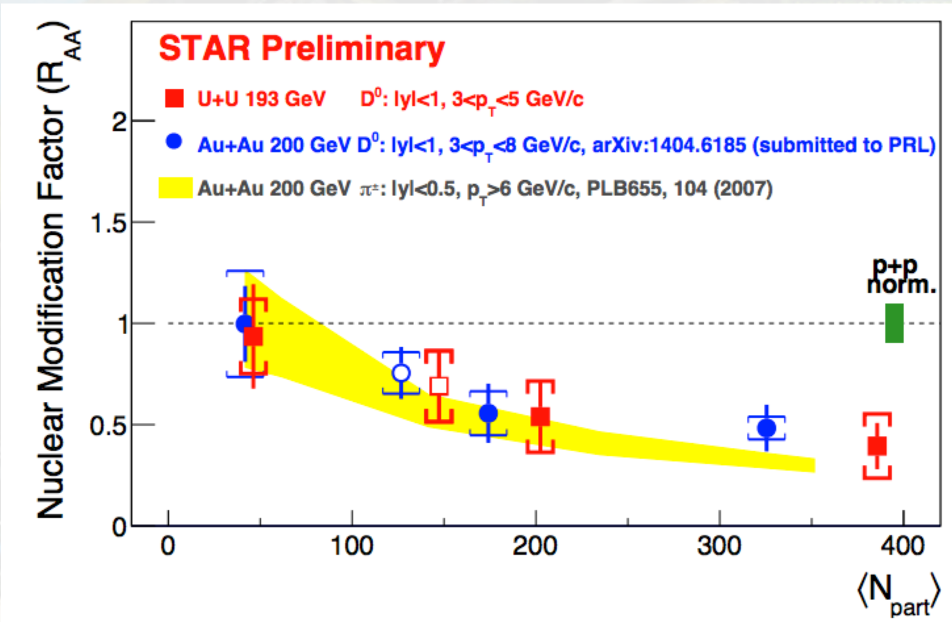
- Similar for data at Tevetron, HERA etc.

Data precision provides inputs to constrain pQCD calculations

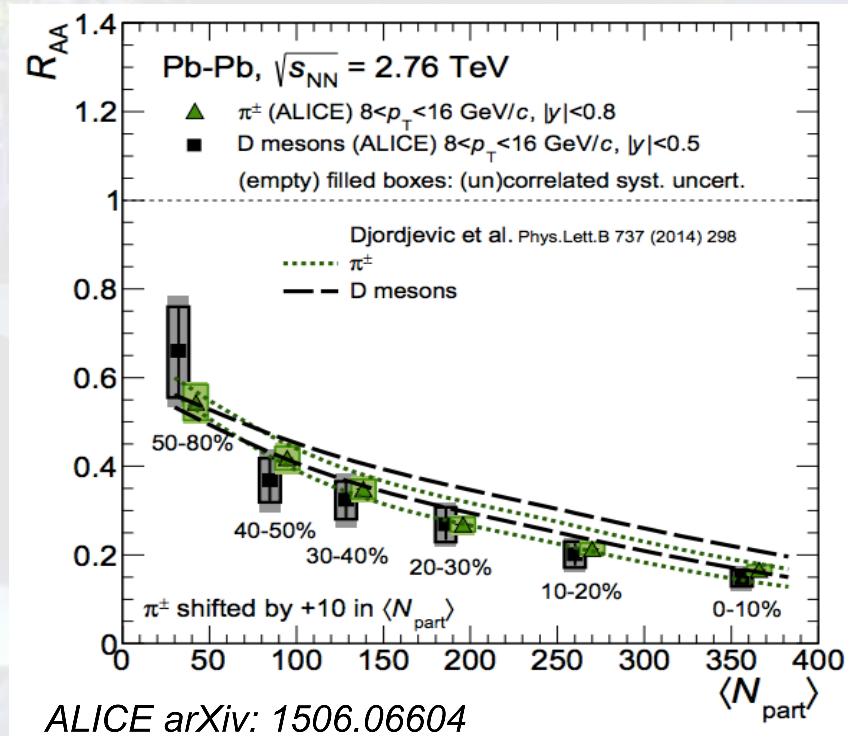
- R.E. Nelson et al, PRC 87(2013)014908

System Size Dependence of High p_T Suppression

RHIC



LHC

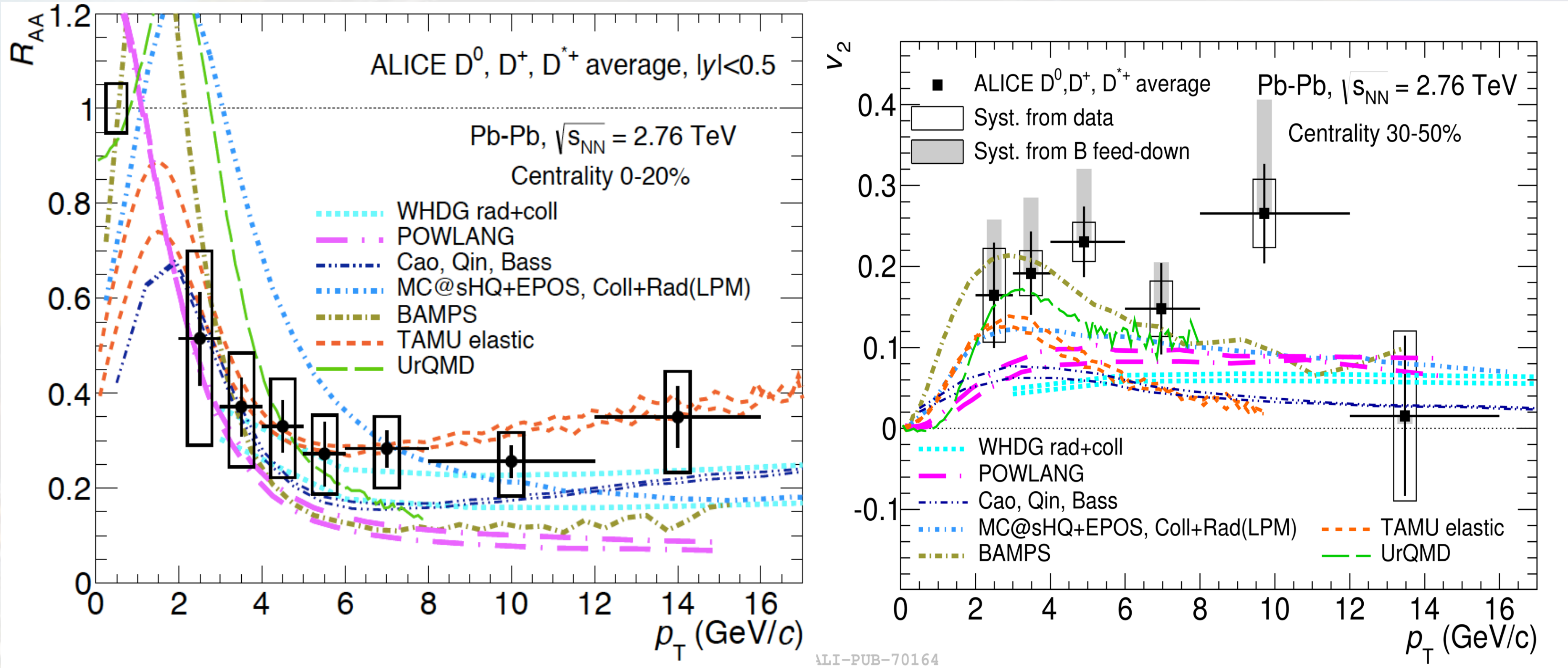


R_{AA}(D) has similar suppression level as $R_{AA}(\pi)$

Several pQCD calculations consistent with inclusive R_{AA}(D) data

- More differential measurements: v_2 at high p_T / correlations

Charm Modification in A+A Collisions at LHC



ALICE, JHEP 09 (2012) 112, PRL111 (2013) 102301, PRC 90 (2014) 034904

Significant charm hadron energy loss and flow in medium

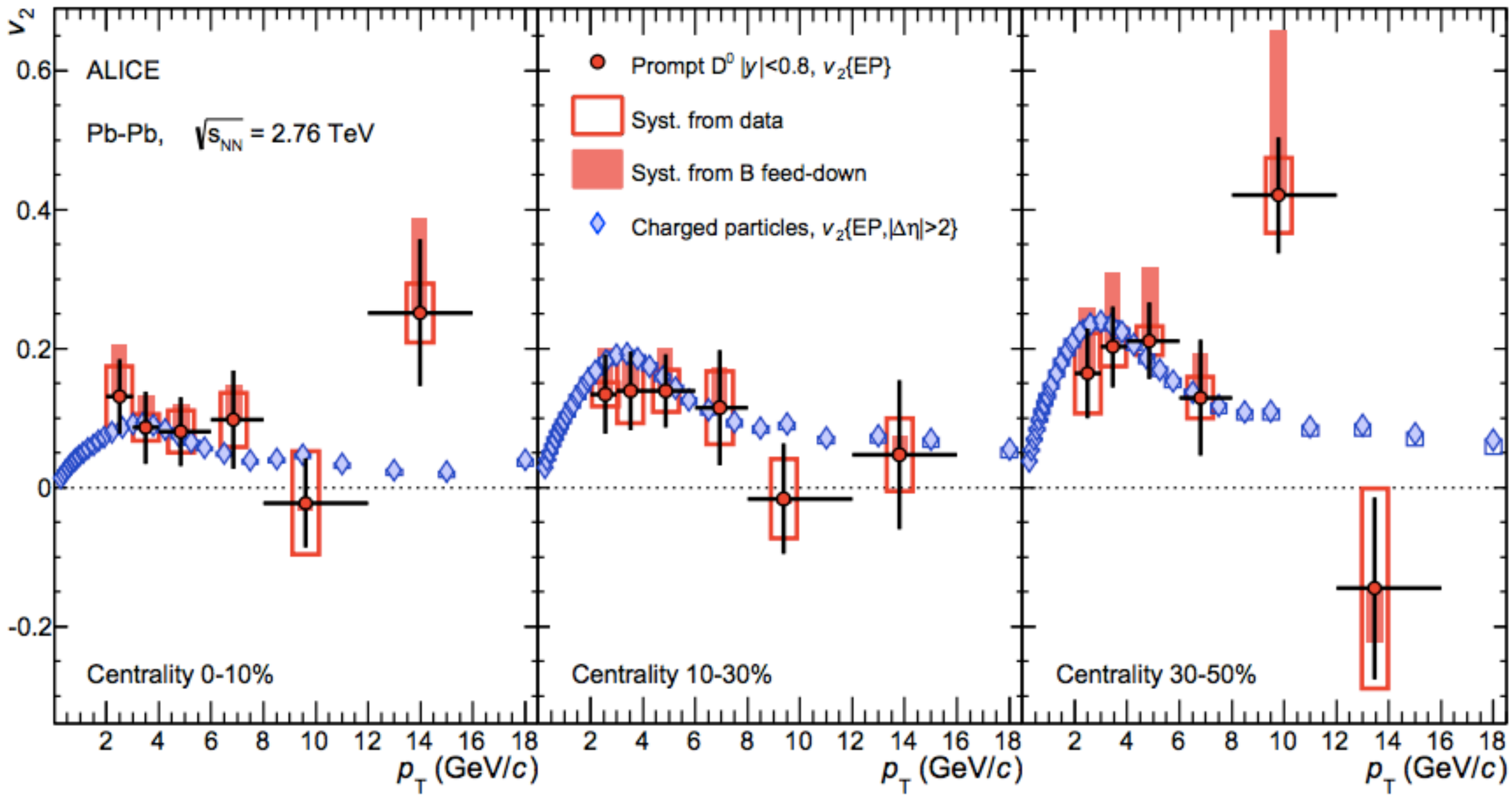
- $R_{AA}(D) \sim R_{AA}(e) \sim R_{AA}(h)$, $v_2(D) \sim v_2(\pi)$

Charm quark flows? - likely with the medium. Need precision for decisive answer

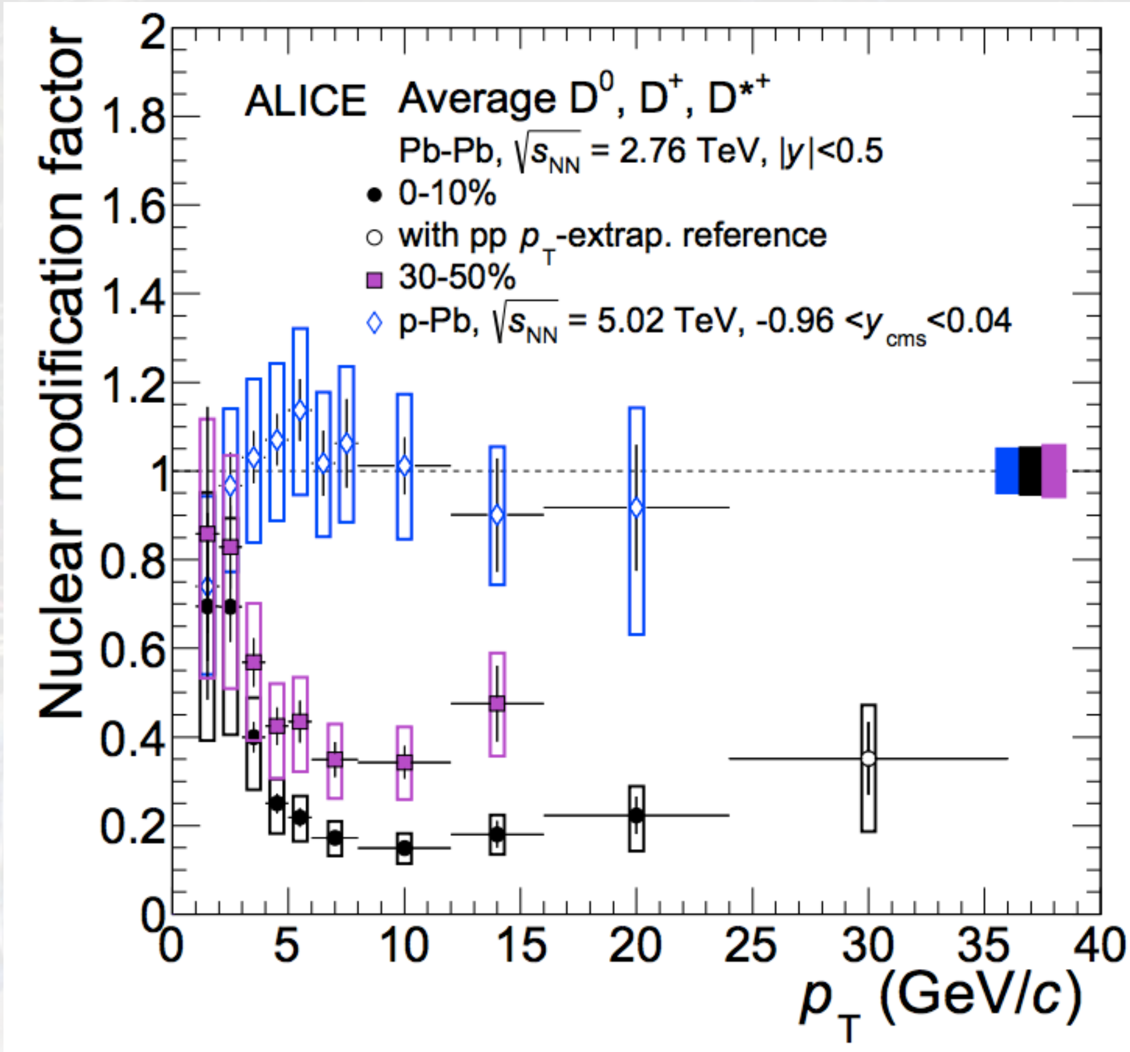
Challenge to models to consistently describe both R_{AA} and v_2

- positive progresses in some models recently

Centrality Dependence of v2



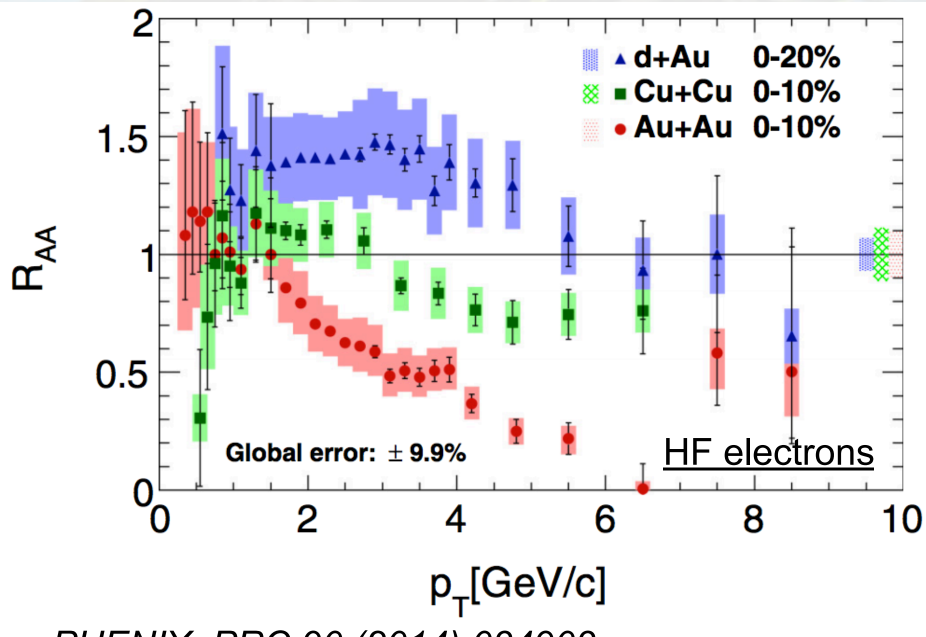
R_{AA} vs. R_{pA}



$R_{pPb}(D) \sim 1$, $R_{PbPb}(D) \sim 0.2$, suggest significant charm energy loss due to hot sQGP

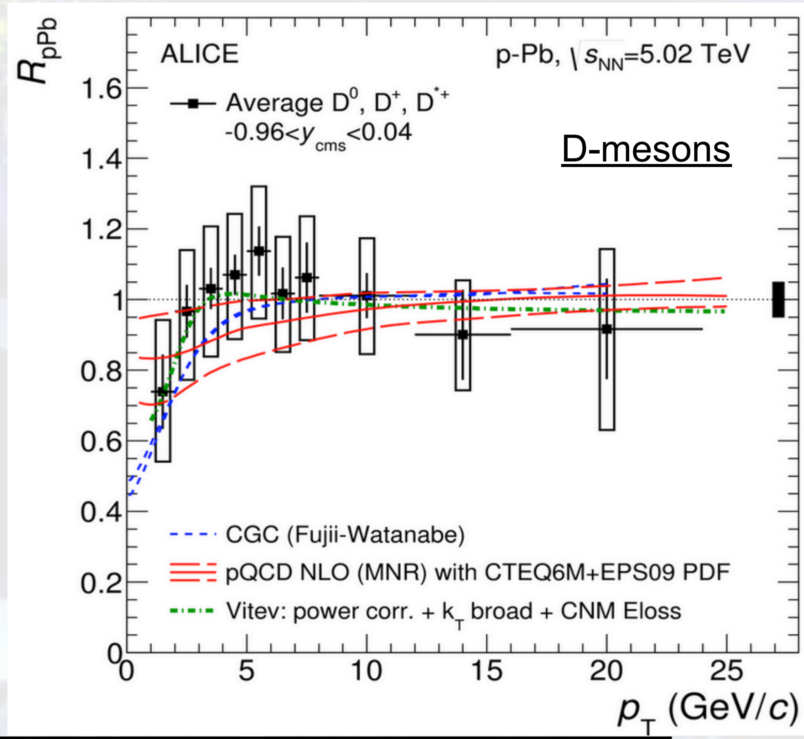
Cold Nuclear Matter Effect

RHIC



PHENIX, PRC 90 (2014) 034903
ALICE, PRL 113 (2014) 232301

LHC

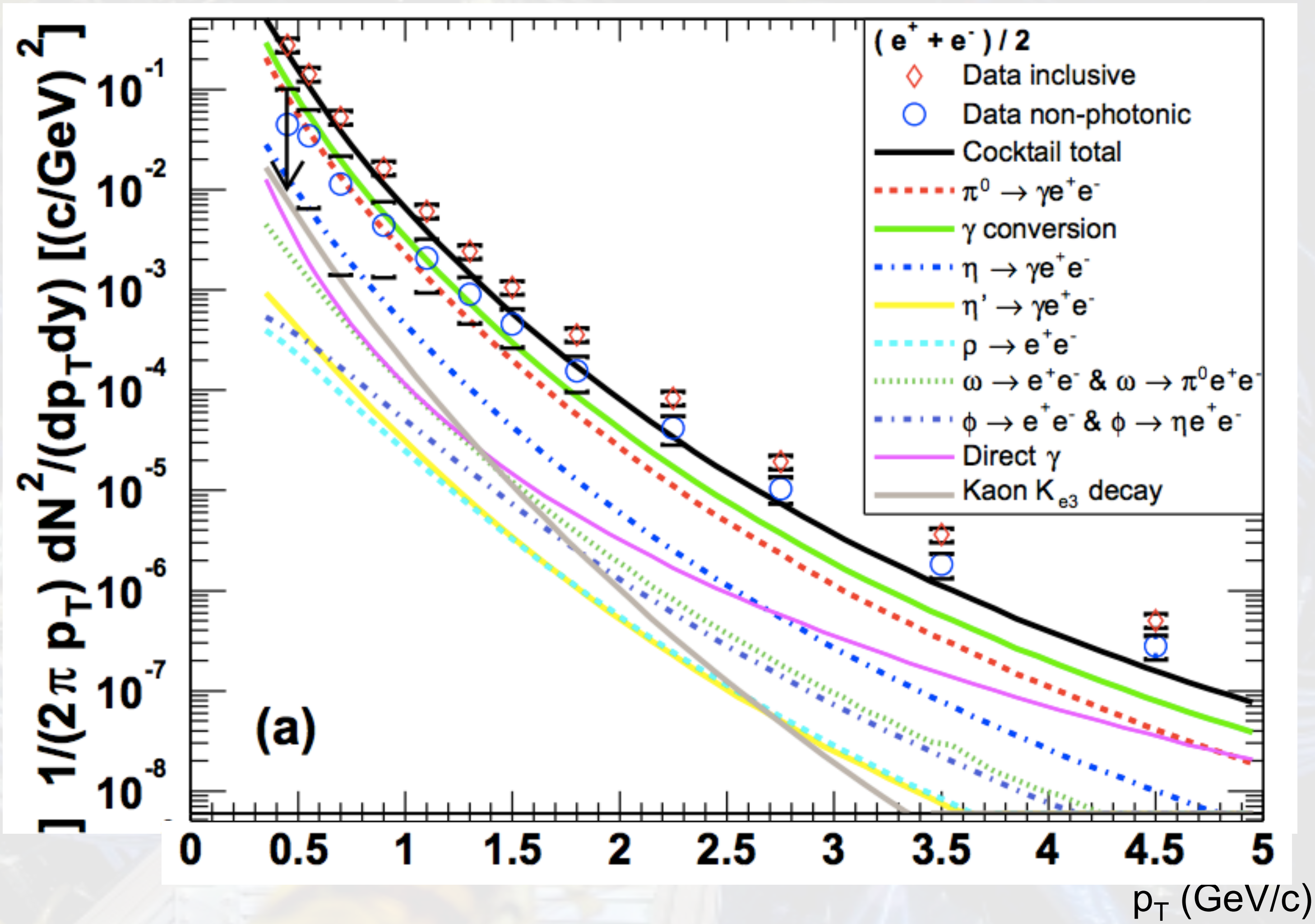


$R_{dAu}(e) > R_{pPb}(D) \sim 1$ at $2 < p_T < 5$ GeV/c
- interplay between initial nPDFs and possible final state effects

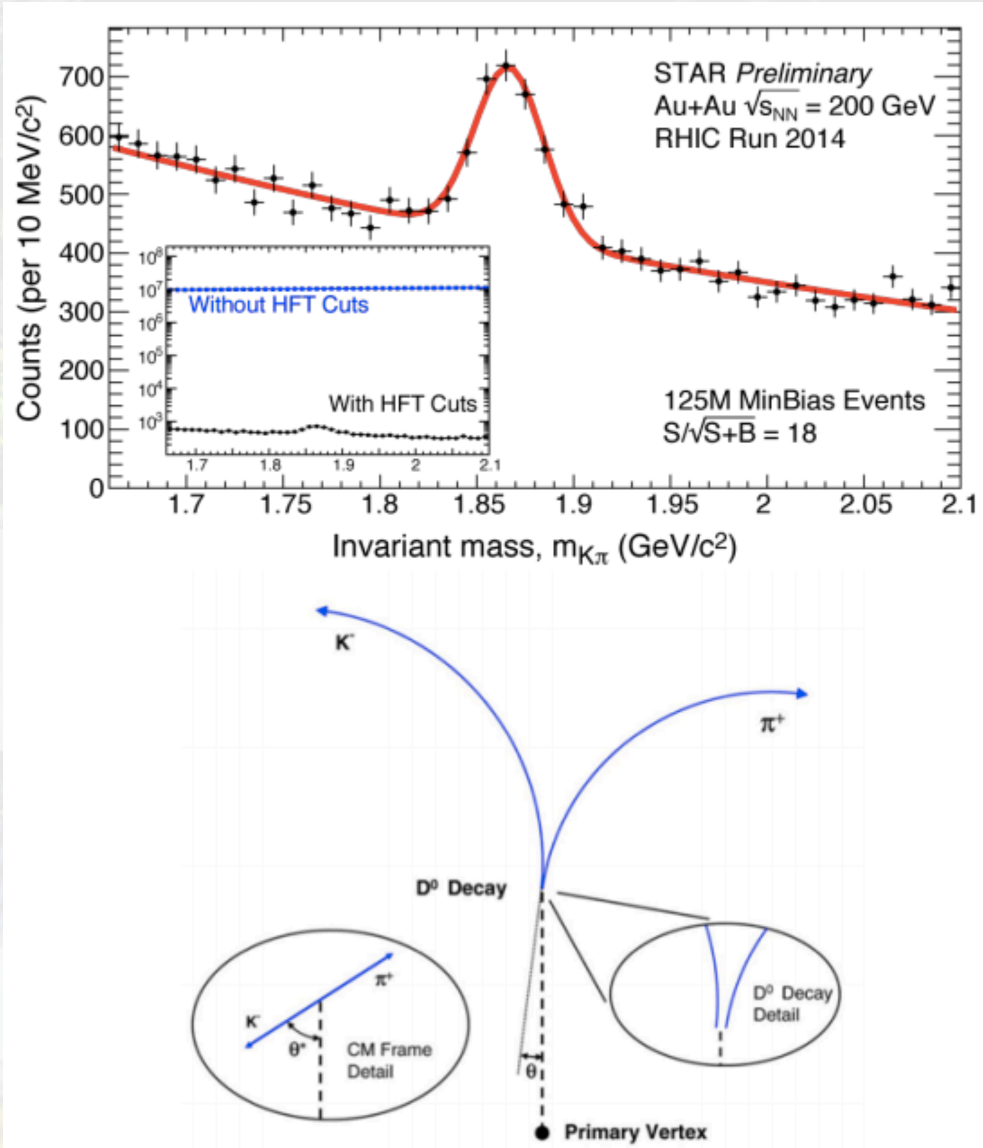
$R_{dAu}(e) \sim R_{pPb}(D) \sim 1$ at $p_T > 5$ GeV/c
- $R_{AA}(D) \sim R_{AA}(e) \sim R_{AA}(h)$ due to hot medium effect

p+Au/Al runs with HFT/VTX and p+Pb runs in LHC Run-II

Background Composition in Electron Measurement



Background in Direct Reconstruction



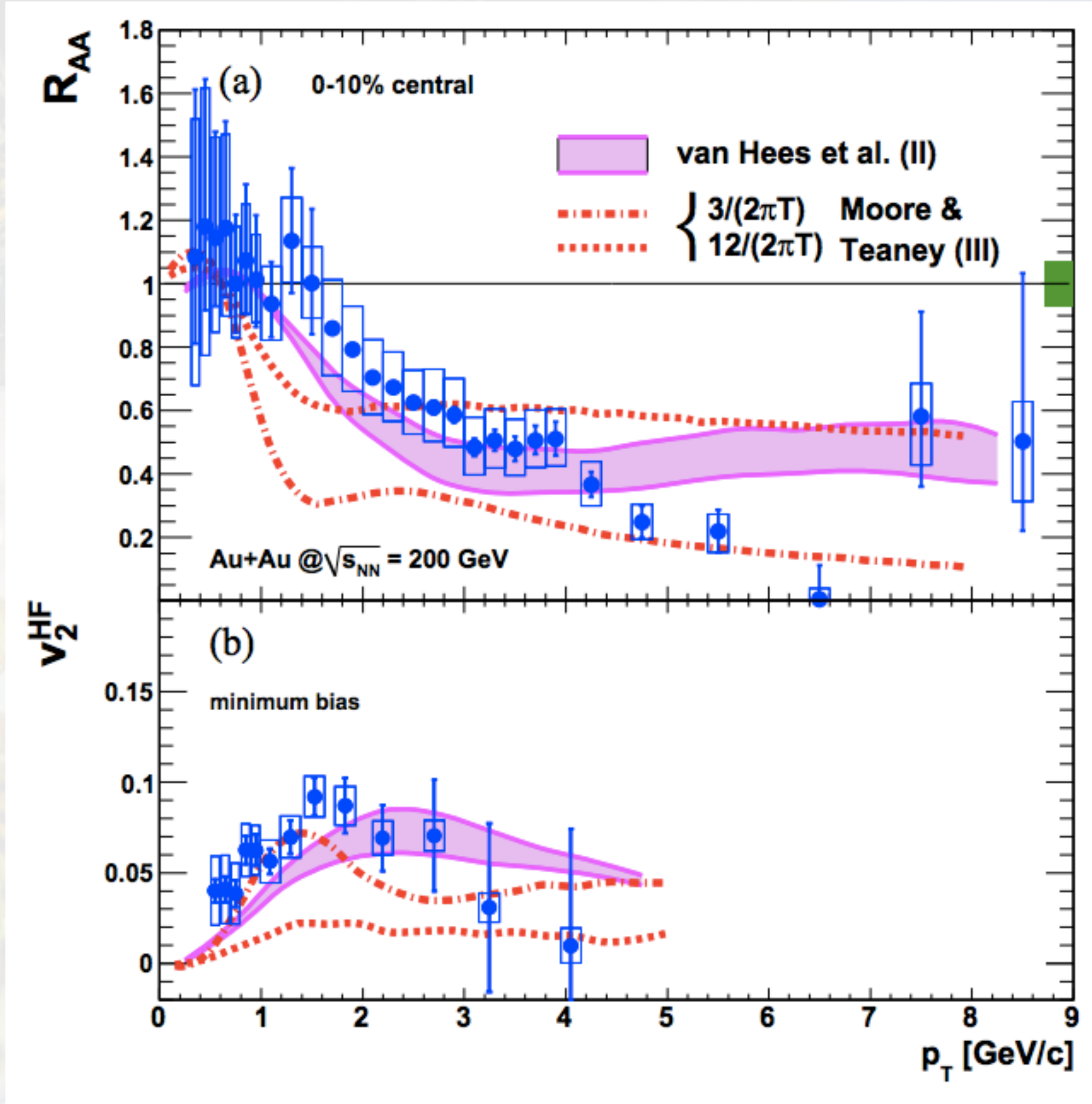
Single Electron R_{AA} and v_2 @ RHIC

Pioneering measurements!

$R_{AA}(e) \sim R_{AA}(h)$!!!

- *Collisional energy loss important*

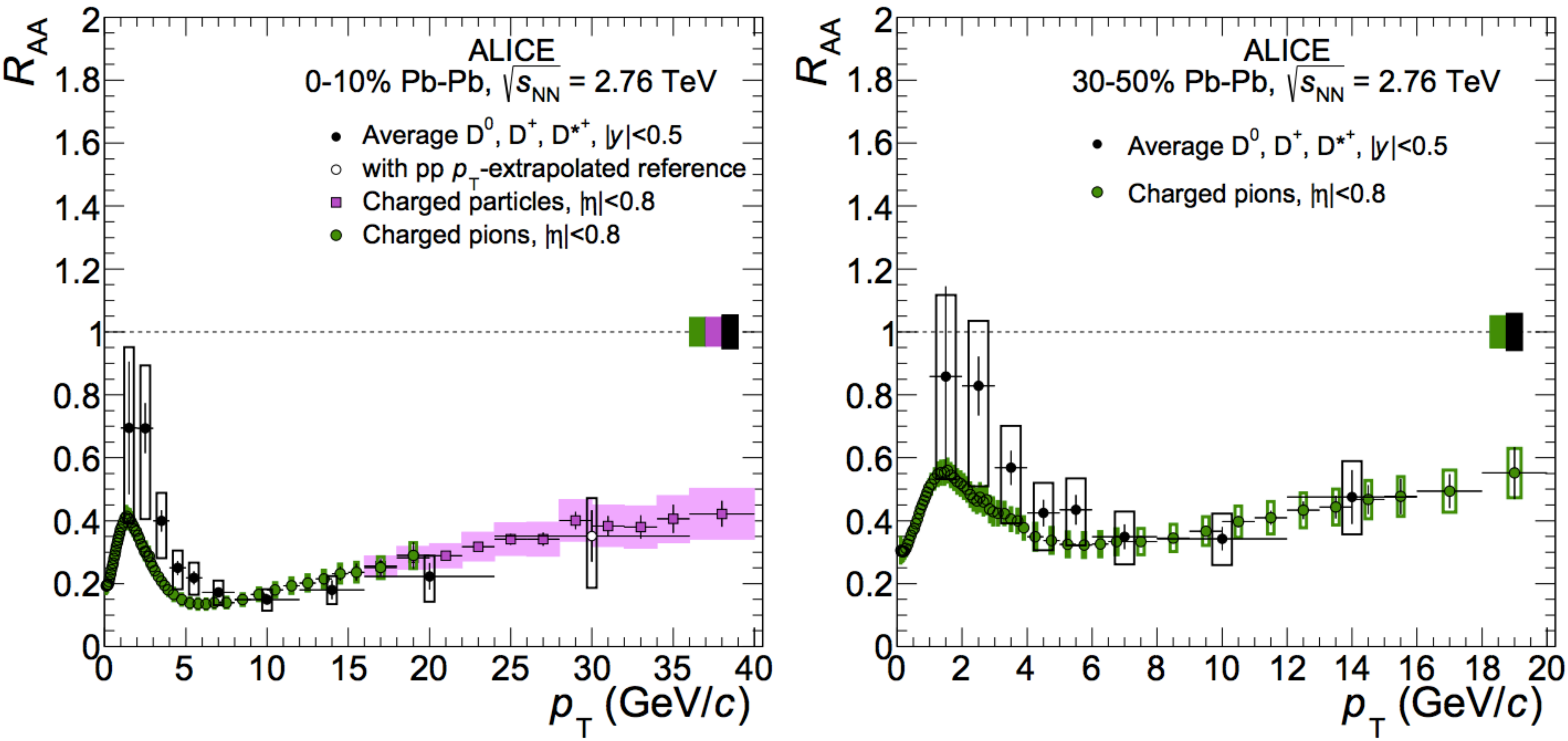
v_2 indication of charm flow



PHENIX PRL 96 (2006) 032301, PRC 84 (2010) 044905

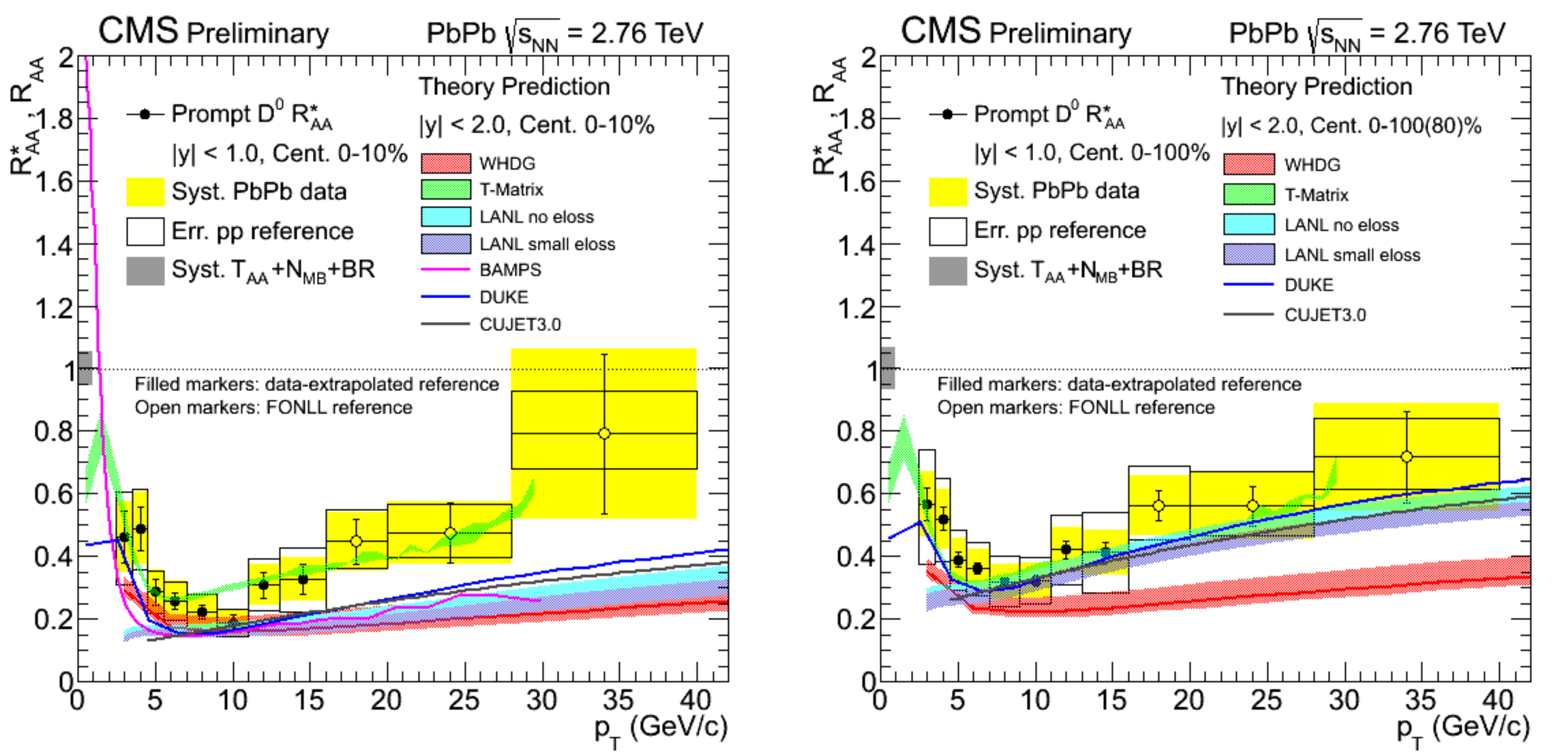
However, challenges:

- Experimental / physics background
- mixture of charm/bottom
- kinematic smearing due to decays



ALICE
0-10% Pb-Pb, $\sqrt{s_{NN}}$ = 2.76 TeV
Average D^0, D^+, D^{*+}, $|y|<0.5$
with pp p_T-extrapolated reference
Charged particles, $|\eta|<0.8$
Charged pions, $|\eta|<0.8$
R_{AA}
p_T (GeV/c)
ALICE
30-50% Pb-Pb, $\sqrt{s_{NN}}$ = 2.76 TeV
Average D^0, D^+, D^{*+}, $|y|<0.5$
Charged pions, $|\eta|<0.8$
R_{AA}
p_T (GeV/c)

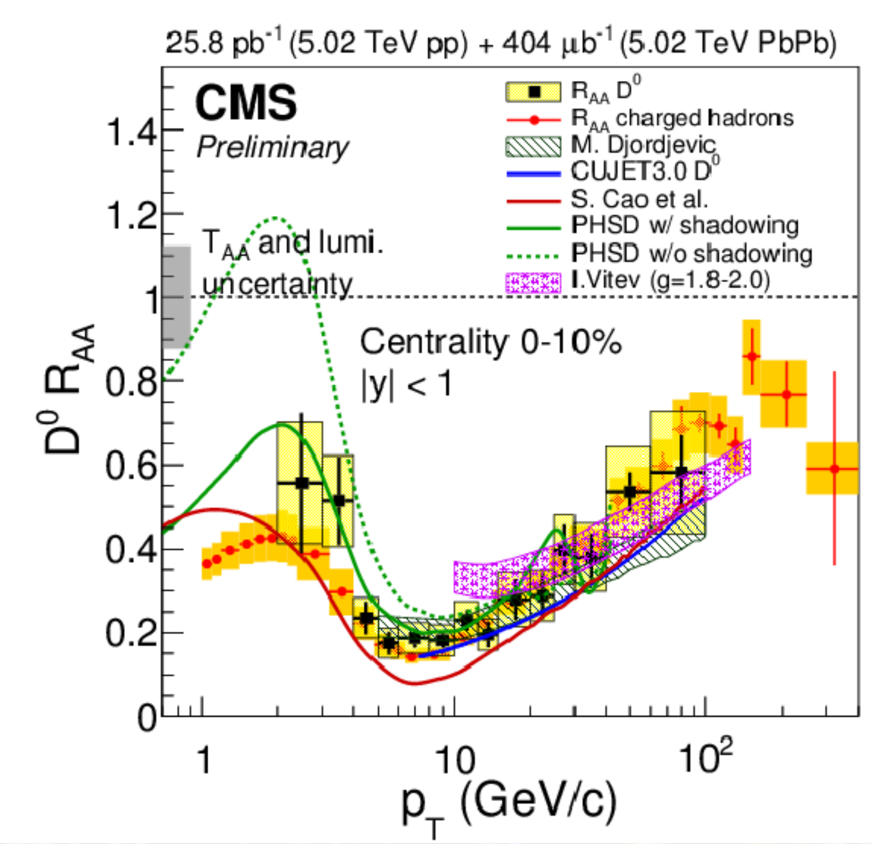
D meson production is suppressed in 2.76 TeV PbPb collisions

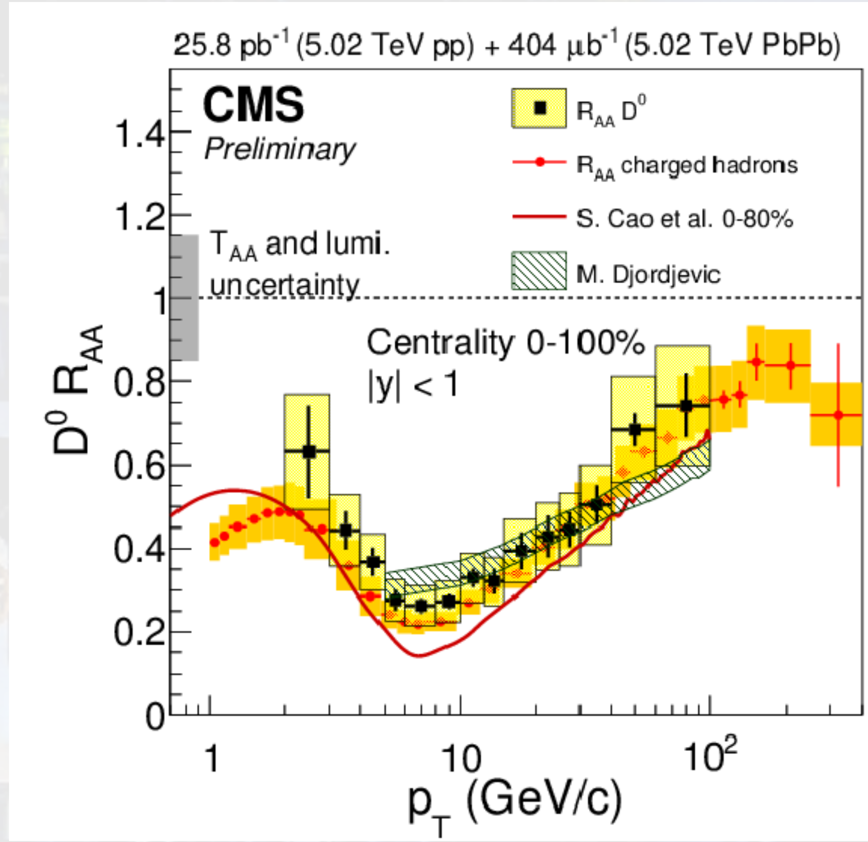


- **pp reference @ 2.76 TeV ➔ ALICE 7 TeV pp measurement + FONLL**
- R_{AA} going down for p_T < 10 GeV/c and going up at higher p_T
- No large dependence on centrality within uncertainties
  - different from some model predictions

CMS PAS HIN-15-005

D meson production is suppressed in 5.02 TeV PbPb collisions

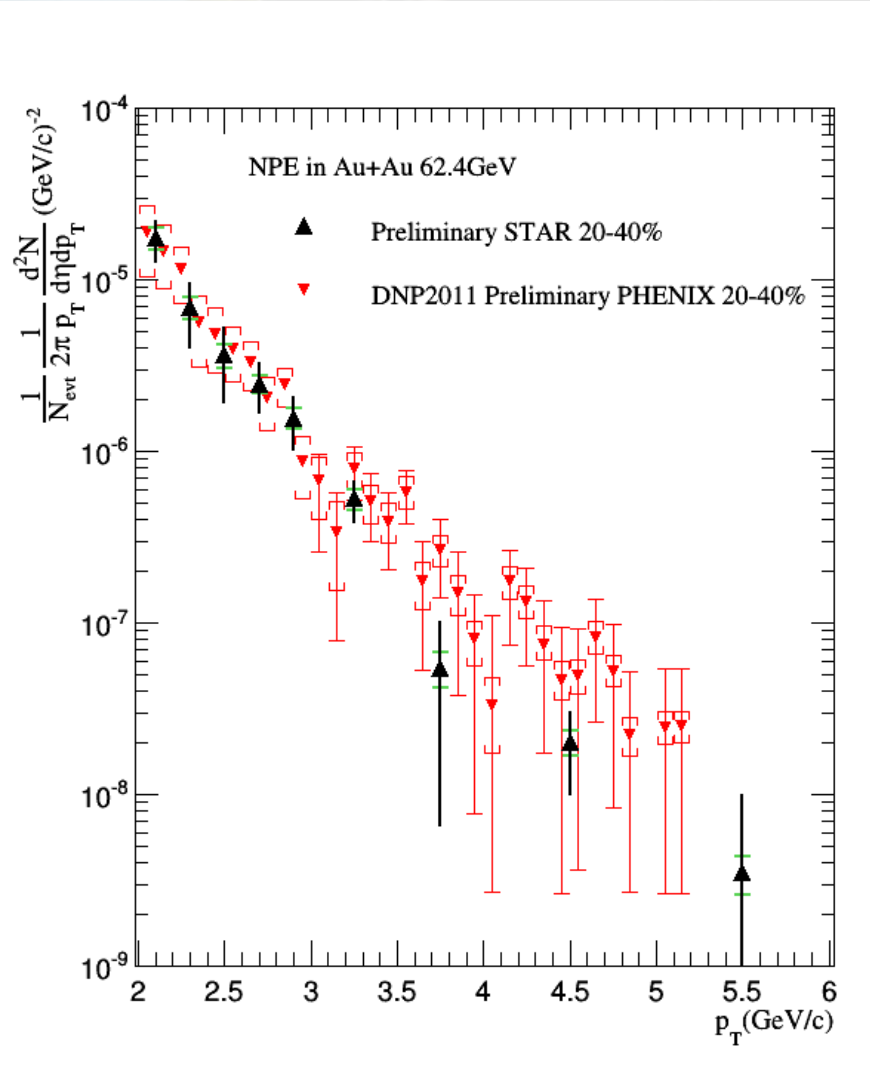


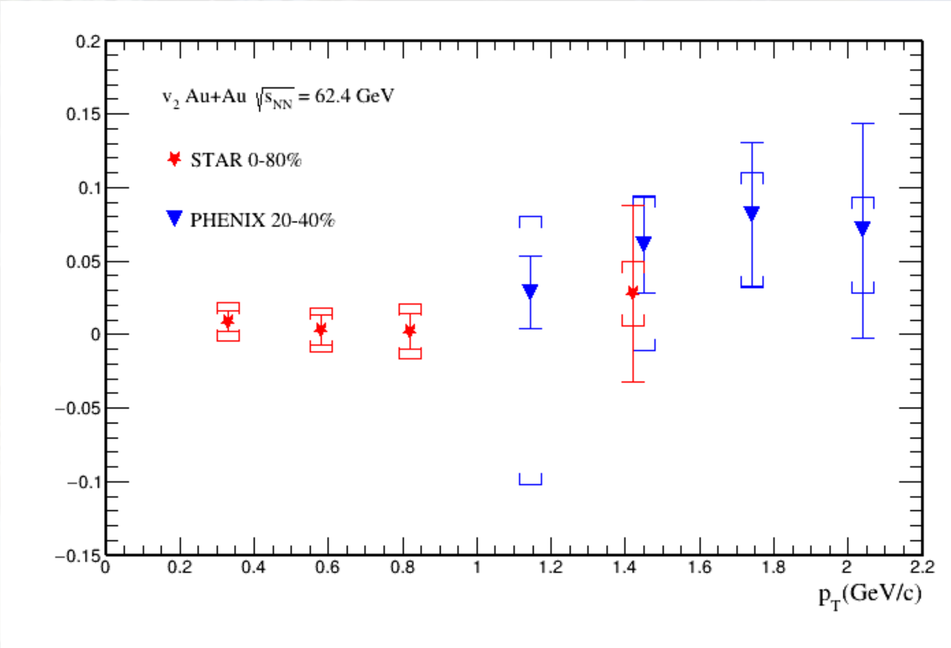


- **New measurements for D^0 and charged hadron from 5.02 TeV PbPb and pp**
  - D^0 up to 100 GeV/c, charged hadron up to 400 GeV/c
- R_{AA} dependence on p_T similar as at 2.76 TeV
  - Measured pp reference @ 5.02 TeV
- No significant dependence on centrality within uncertainties
  - well described by some model calculations
- Consistent with charged particle R_{AA}

CMS PAS HIN-16-001
CMS PAS HIN-15-015

NPE Results at 62.4GeV between PHENIX/STAR

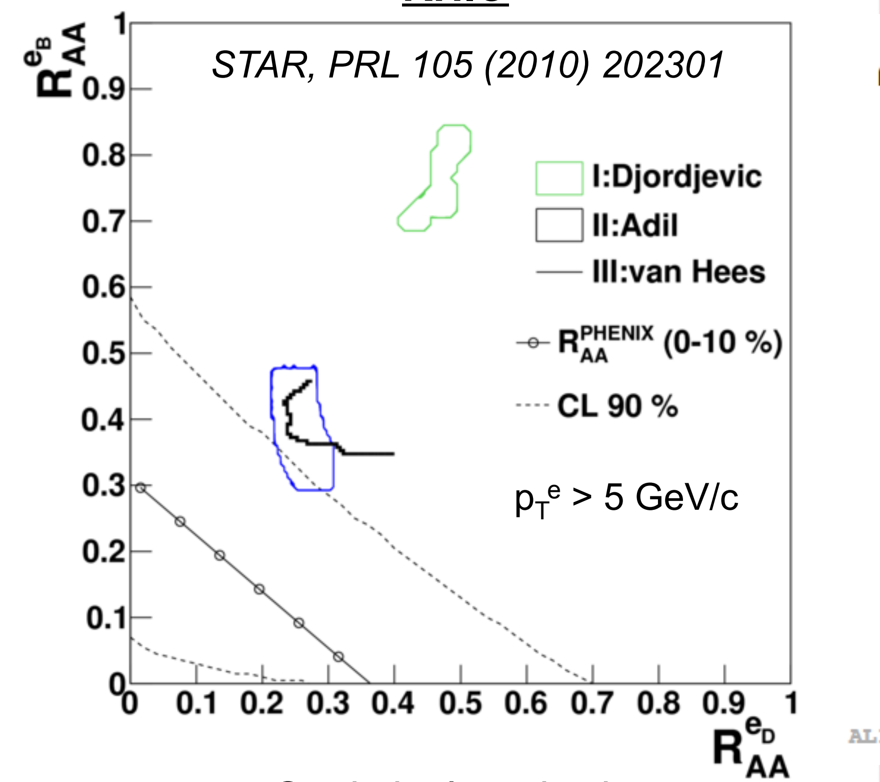




PHENIX/STAR measurements (spectra/v_2) are consistent in overlapping p_T regions

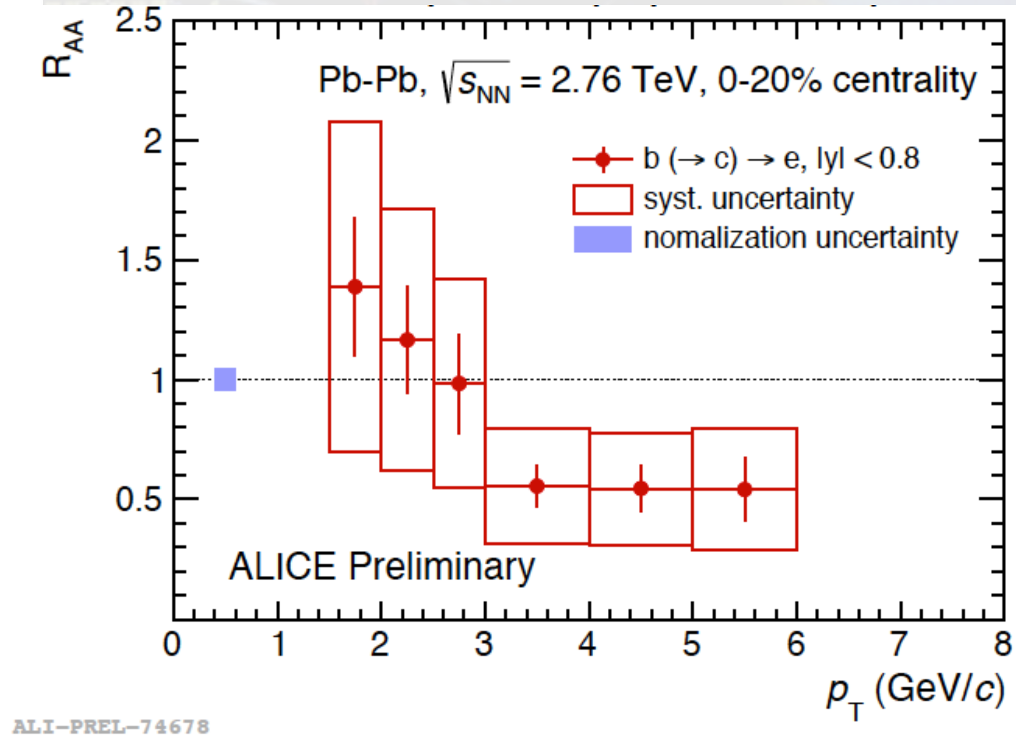
Bottom Suppression in Heavy Ion Collisions

RHIC



Statistical method

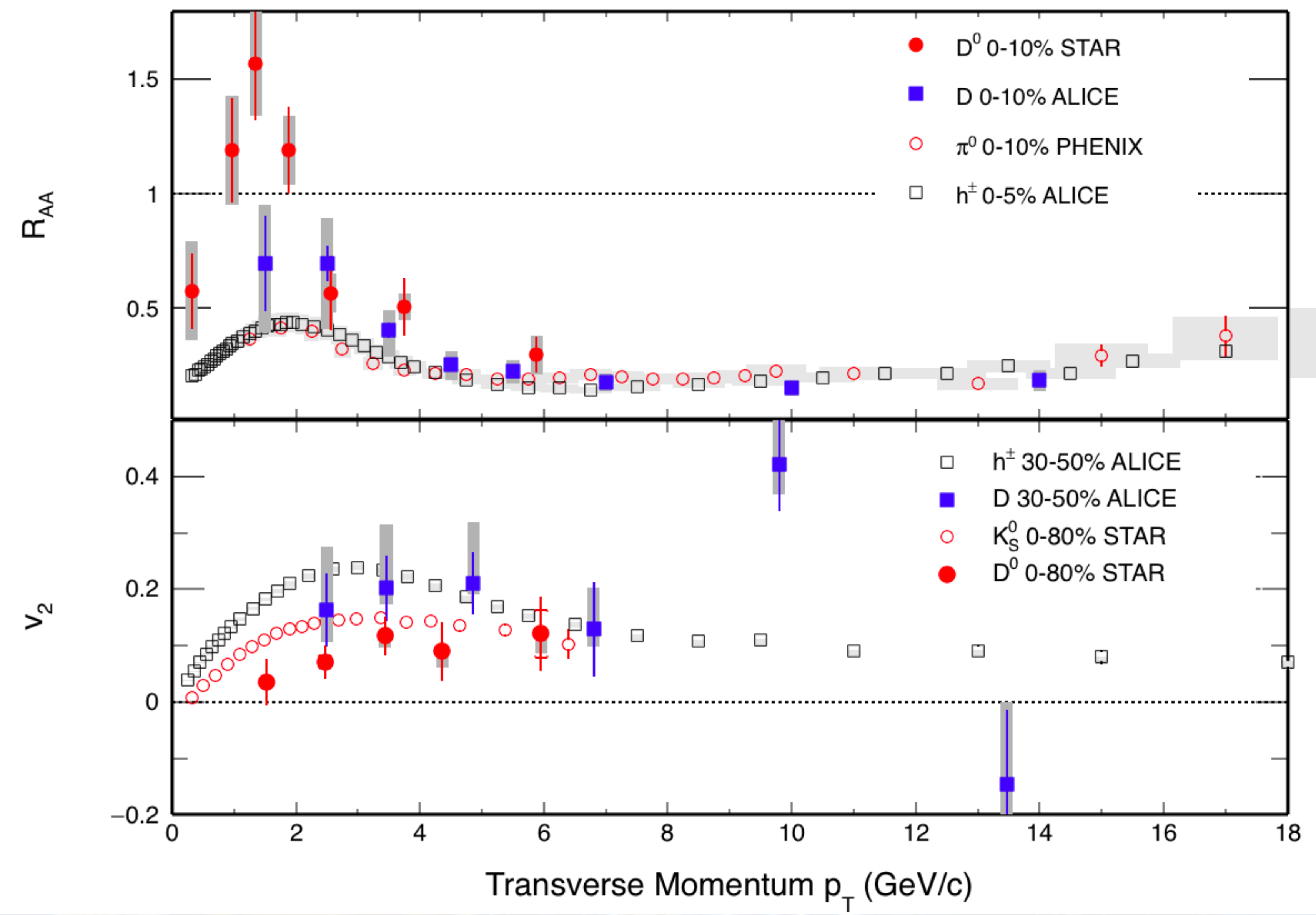
LHC



Impact parameter method

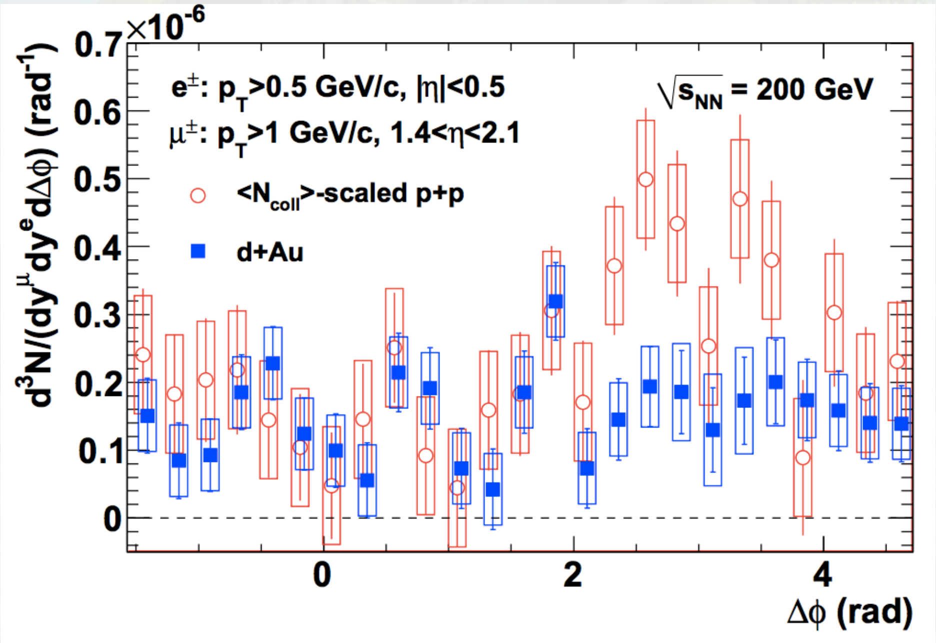
High p_T -> Flavor dependence of R_{AA} – "dead-cone" in pQCD
- $R_{AA}(e_D)$ vs. $R_{AA}(e_B)$ indicates bottom suppression in central A+A at RHIC/LHC
- Need precision measurement on both R_{AA}(D) and R_{AA}(B)

D-meson R_{AA} and v_2 at RHIC and LHC



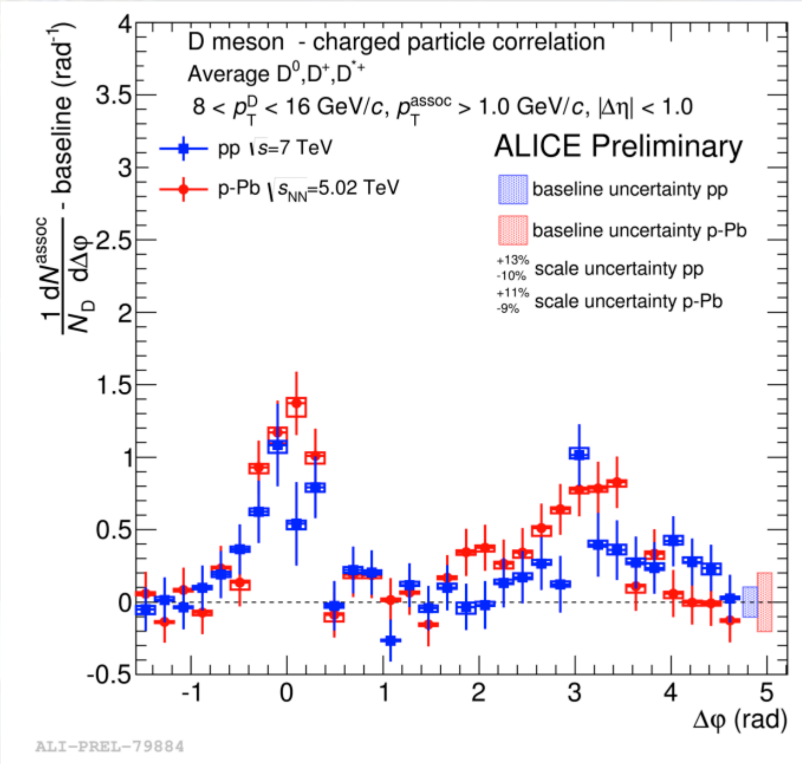
Heavy Quark Correlations

RHIC



PHENIX, PRC 89 (2014) 034915

LHC



Between p+p and p(d)+A:

- e–μ (mid-forward) correlations show difference in away side
  - initial nPDFs/saturation, final state effect
- D-h (mid-mid) correlations no significant difference beyond current uncertainties

Heavy quark correlations in A+A: to be explored

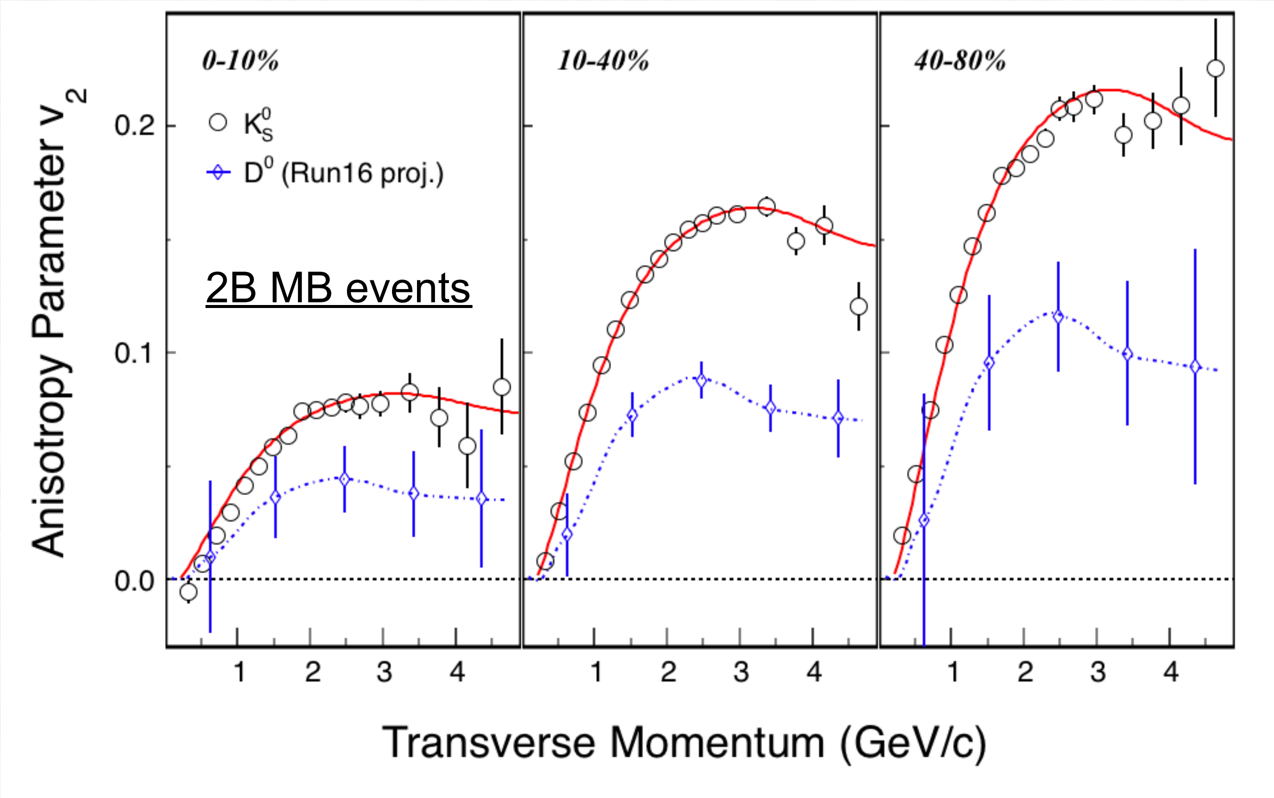
Centrality Dependence of D^0 v_2 – Run16 Projection from STAR

Estimation based on Run14 measurement

Run16 TPC efficiency/ HFT acceptance factors included (same as slide 2)

A factor of 2 improvement included due to the PXL decode bug fix

$v_2(D^0)/v_2(Ks)$ assumed to be the same for different centrality bins

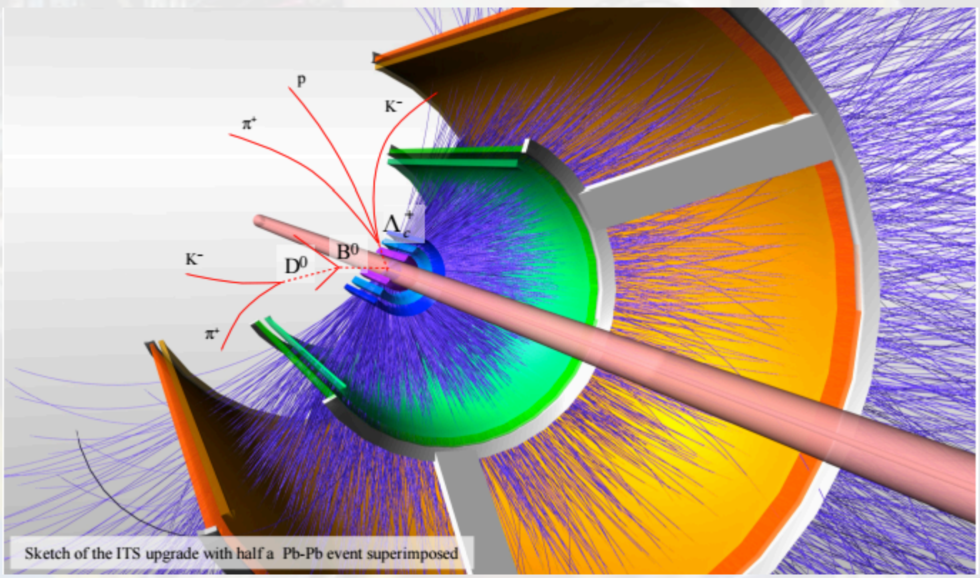


ALICE ITS-upgrade

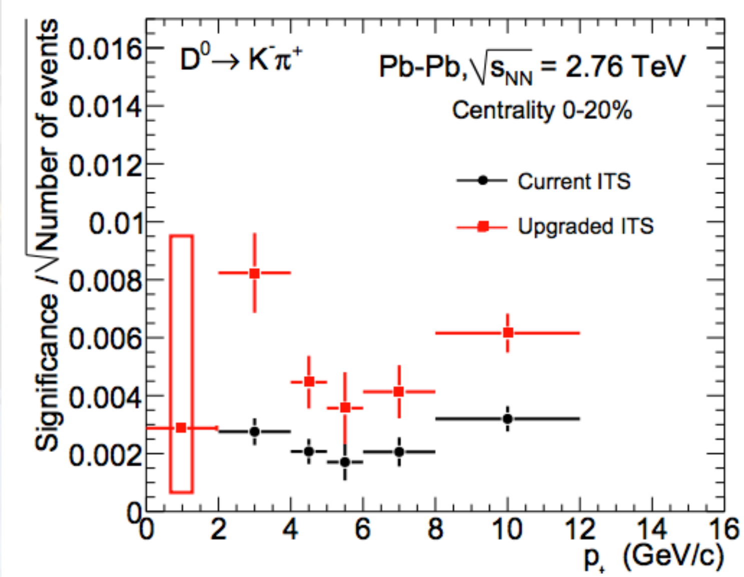
Next generation MAPS sensors with much shorter integration time (< 20 μs)

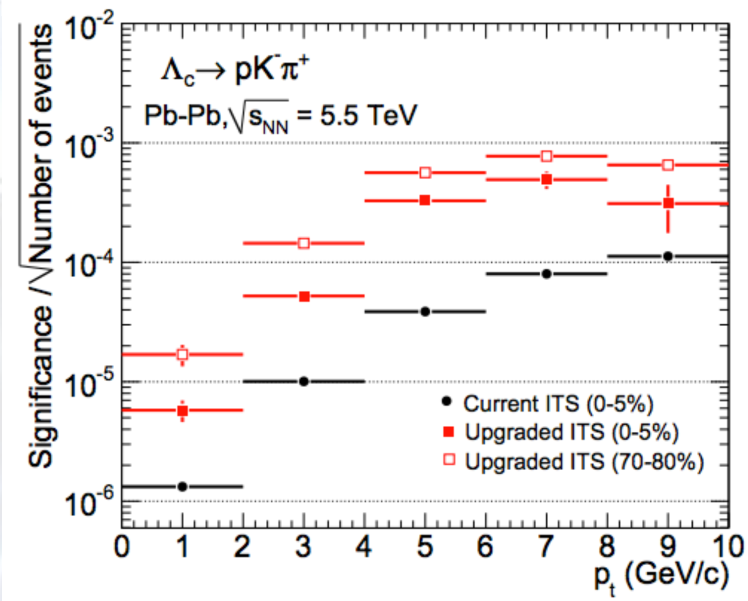
Goals:

- precision charmed hadron (D^0, Λ_c) measurements down to low p_T
- open bottom measurements

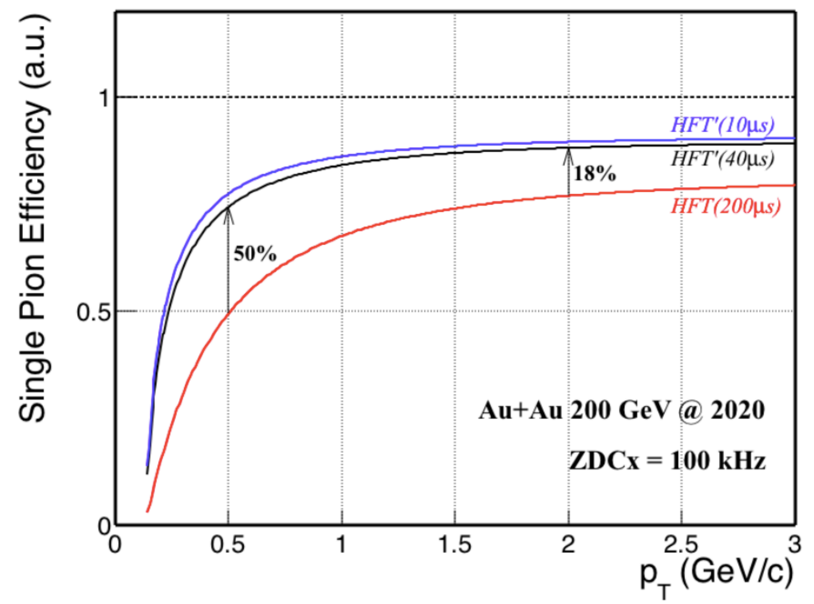


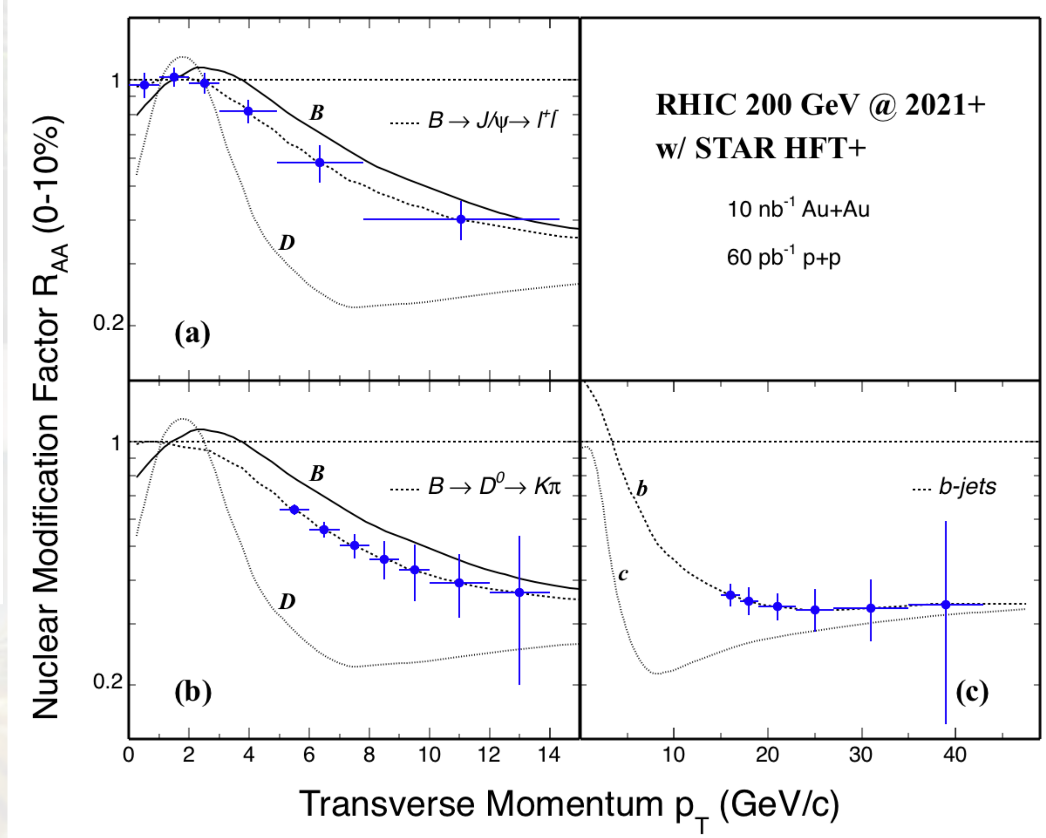
Sketch of the ITS upgrade with half a Pb-Pb event superimposed





Fast MAPS Detectors at RHIC





STAR HFT+ upgrade / sPHENIX pixel detector:
- Faster (<20μs) MAPS sensors – benefiting from ALICE ITS upgrade
- Aim for precision bottom measurements in 2021+ at RHIC

Complementary to LHC heavy flavor program