Group Meeting Presentations

Measurements of inclusive D^0-meson production in isobar collisions at $\sqrt{s_{NN}} = 200$ GeV

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Sep. 12th, 2025

Outline

- Motivation and STAR Experiment
- Energy loss
  - Measurements of D^0 p_T spectra and R_{AA} in isobar collisions at $\sqrt{s_{NN}} = 200$ at RHIC
- Collectivity
  - Measurement of D^0 elliptic flow v_2 at mid-rapidity in isobar collisions
- Summary

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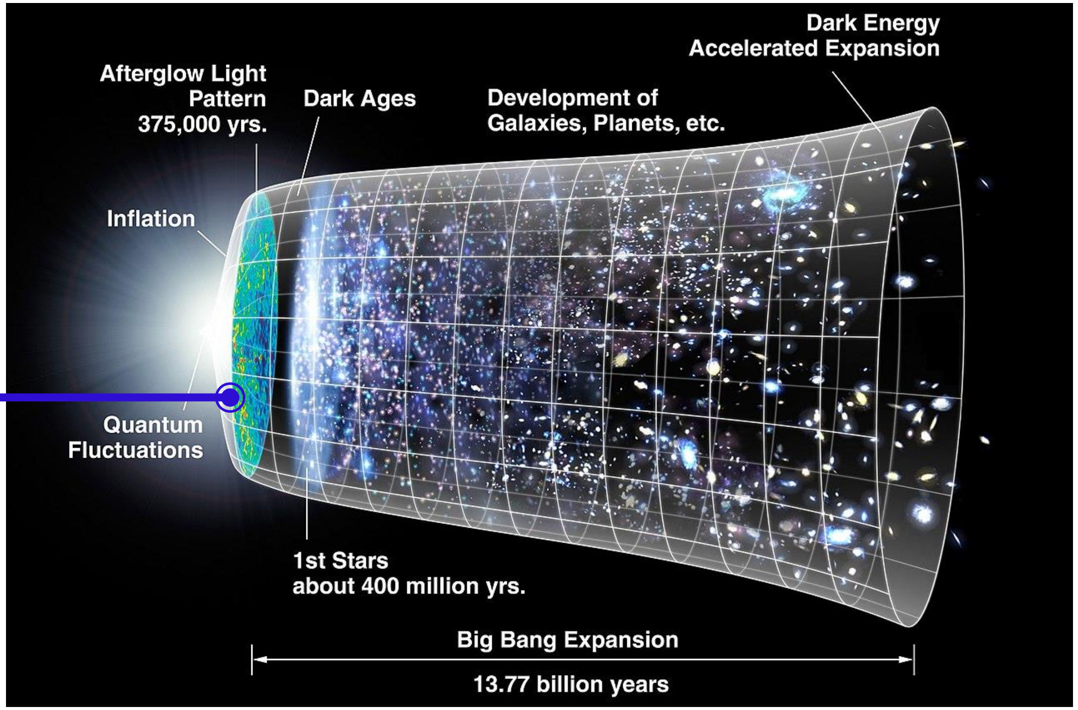
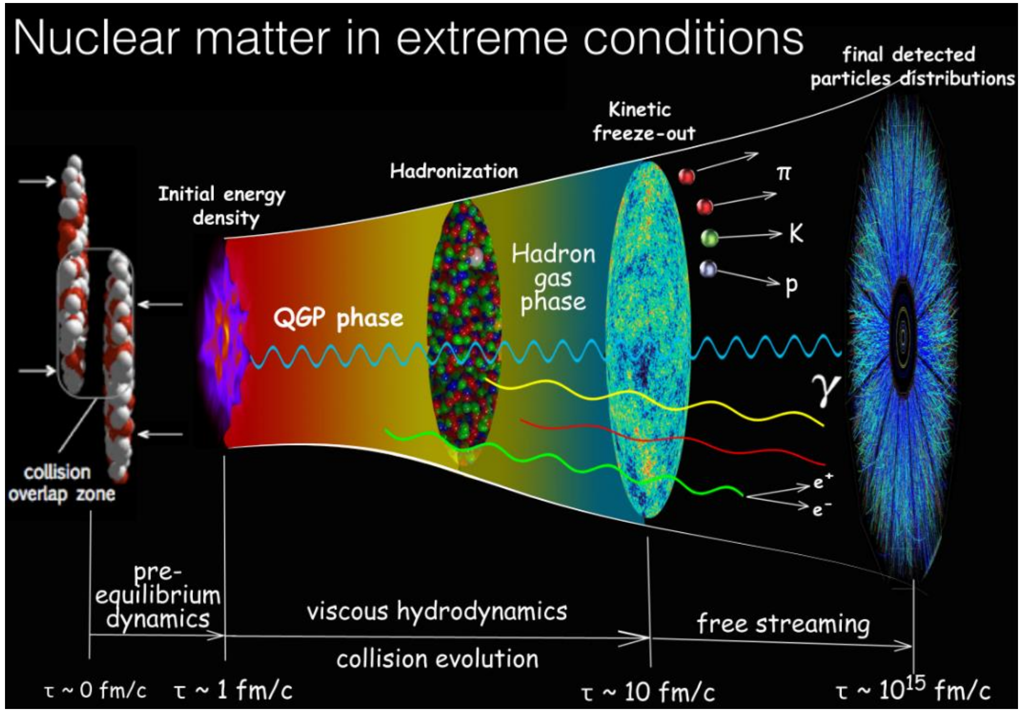
Relativistic Heavy Ion Collision

Energies involved in the Quark epoch are **directly accessible** in RHIC (“Little” Big Bang)

The early universe

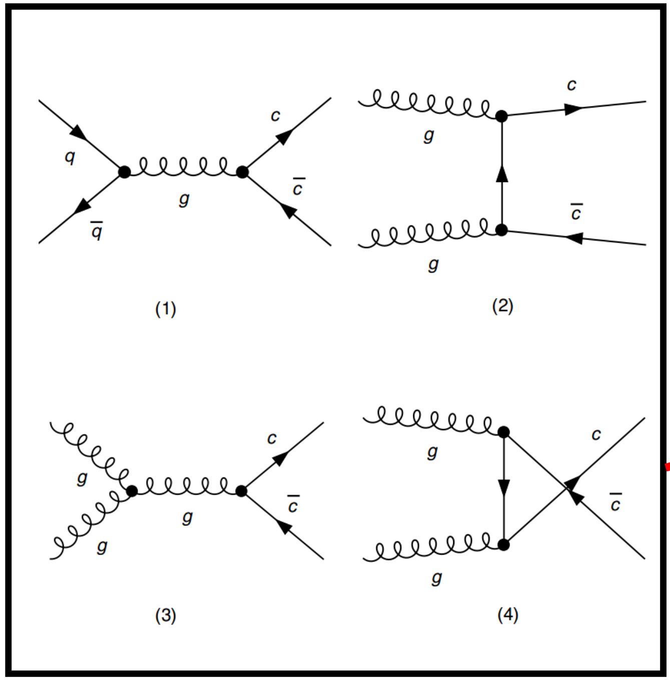
T_c~150-180 MeV



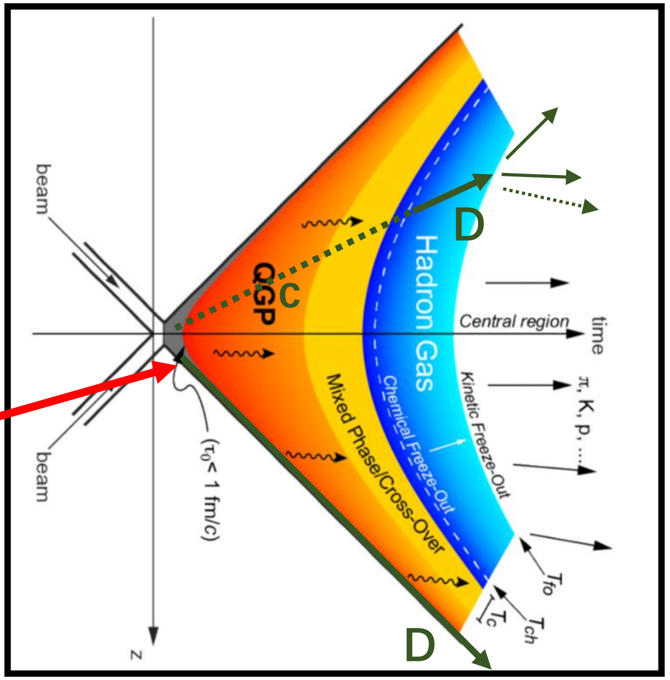


- **QGP is the hottest ($\sim 10^{12}$ K), smallest, and the most perfect fluid (0.08~0.2 $\hbar/k_B$) in nature!**
- Hadronization and chemical freeze-out stages
  - Confined again & inelastic interactions & The relative yields of different hadron species are fixed.
- Kinetic freeze-out stages
  - elastic interactions & The momenta of particles get fixed.

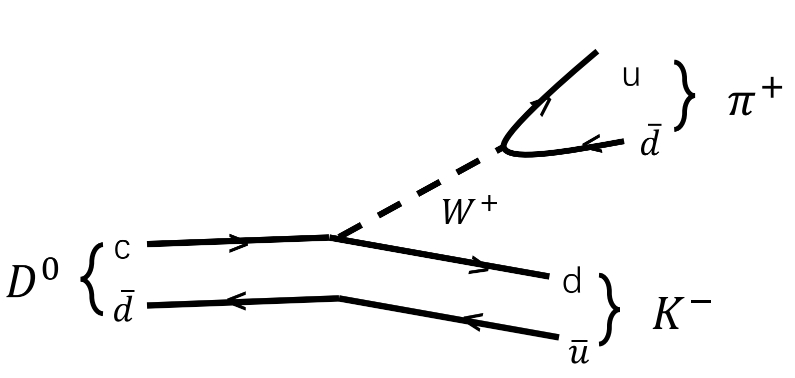
Open heavy-flavour produciton



< 1 fm/c, initial partonic hard scattering



$m_c > \Lambda_{QCD}$, an ideal probe with a high probability of penetrating QGP



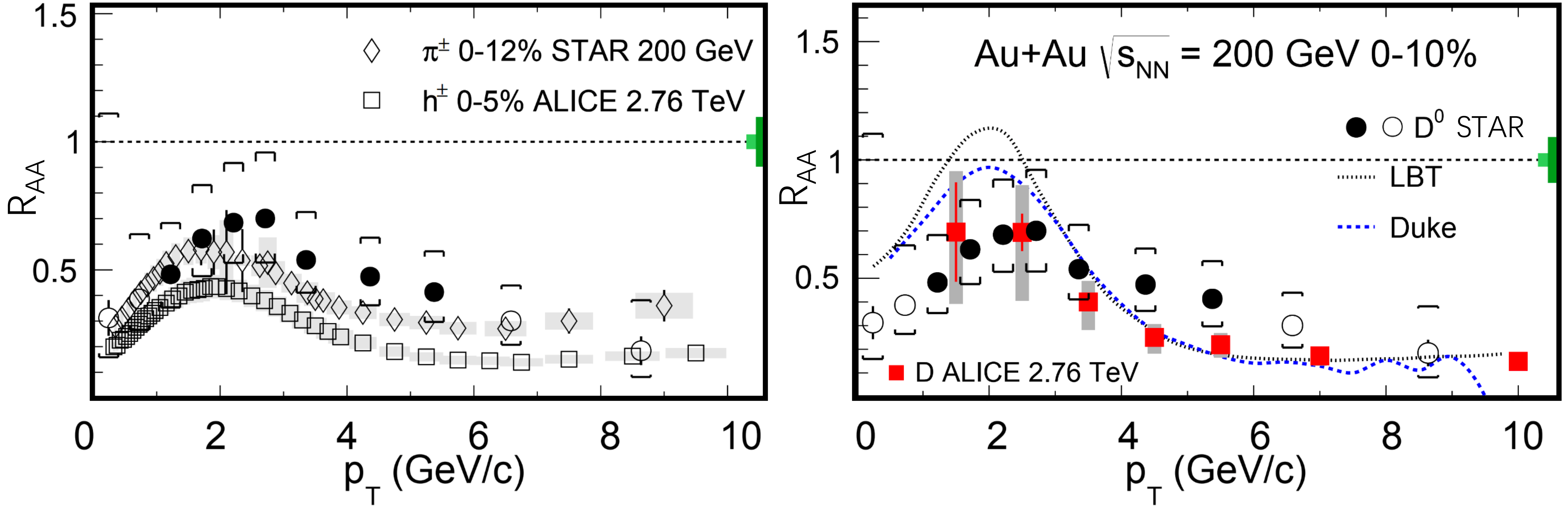
Γ_i/Γ ~ 3.95%

Open heavy-flavour production plays **a unique role** in heavy-ion physics:

- Production restricted to **early collision stages (mainly gluon fusion)** and **retain a "memory"** of their evolution through the QGP
- Consistent with the theoretical calculation (**pQCD in p+p collisions**) and partons have energy loss in the medium
  - Gluon radiation (dead cone effect; suppressed at θ < m_Q/E_Q)
  - Collisional energy loss (**Brownian motion**)
- Heavy quarks **retain their flavour and mass identity**; can be "tagged" by the measurement of heavy-flavour hadrons

D^0 R_{AA} in Au+Au collisions

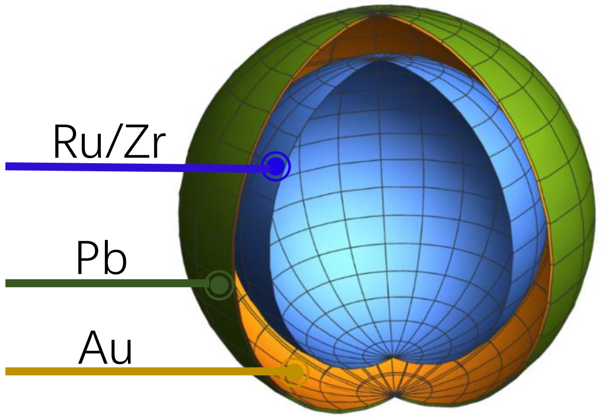
STAR, Phys. Rev. C 99, 034908

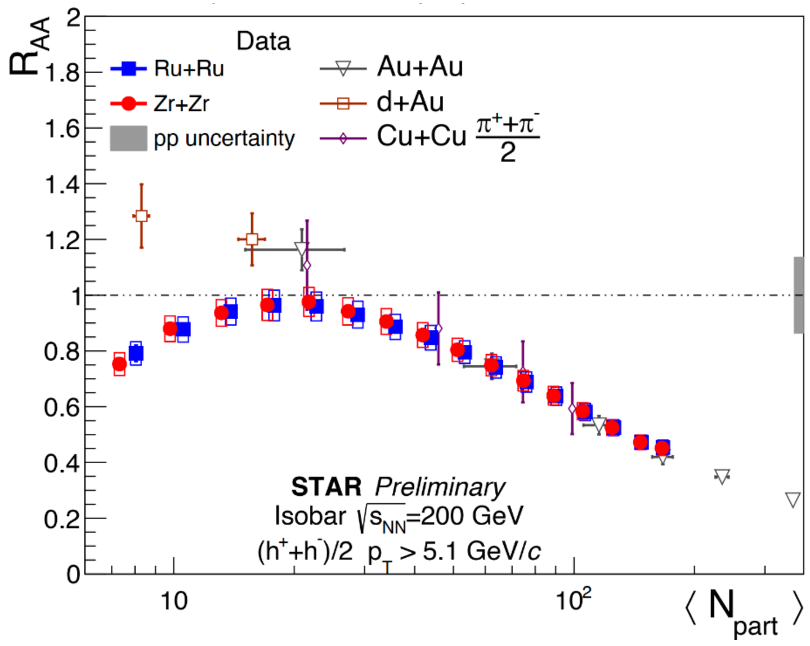


- Suppression level comparable to that of light hadrons in 0-10%
- Similar suppression in Au+Au and Pb+Pb
- What is the system size dependence of charm quark energy loss and hadronization?

How about system size dependence?

- STAR recorded large sample of **isobar collisions (Ru+Ru & Zr+Zr) at $\sqrt{s_{NN}}$ = 200 GeV** in 2018
- Provide a great opportunity to study the system size dependence
- High-p_T charged hadrons: R_{AA} scales with $\langle N_{part} \rangle$ in different systems → driven by average energy density and volume
- How about D^0?

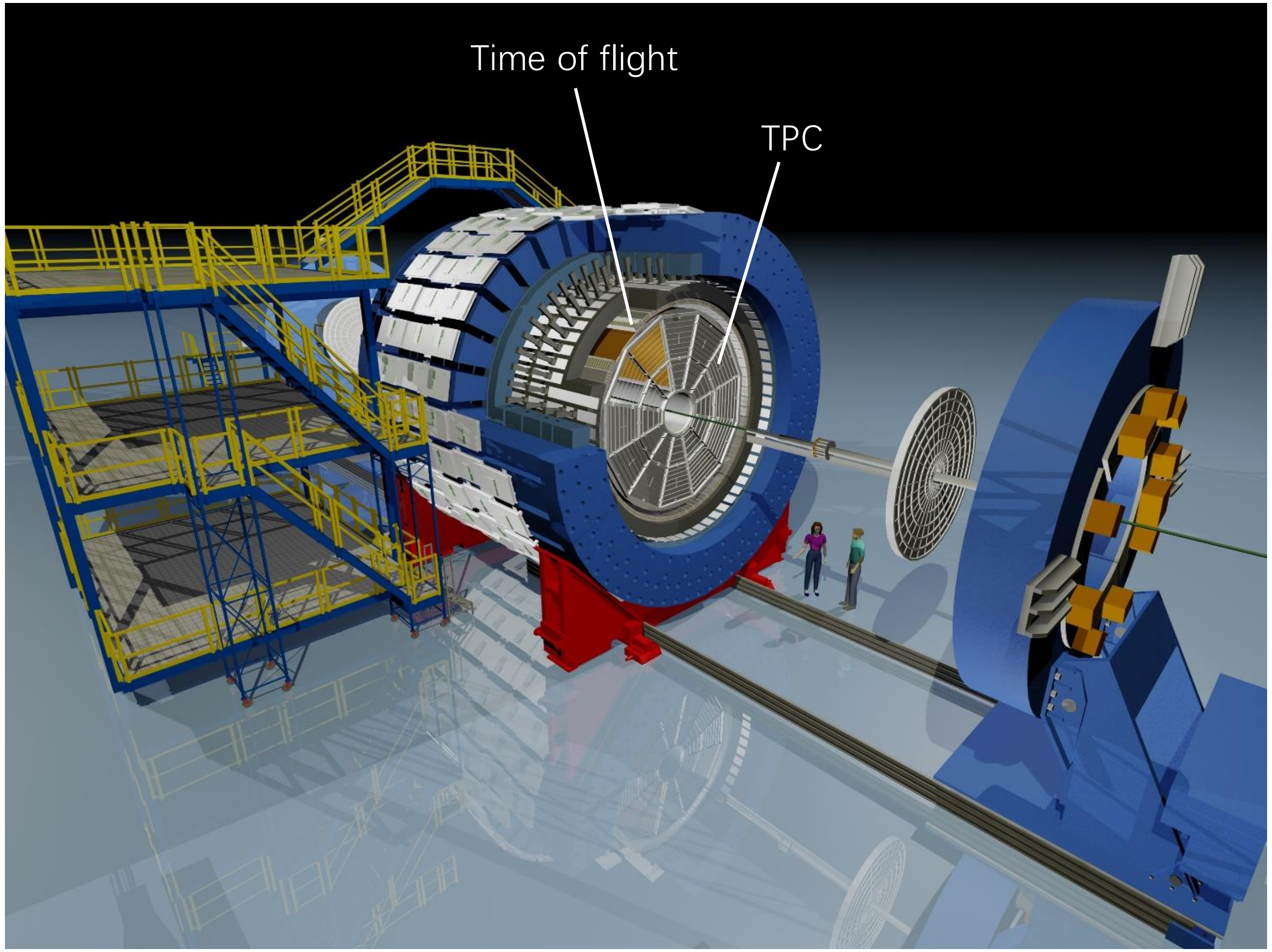


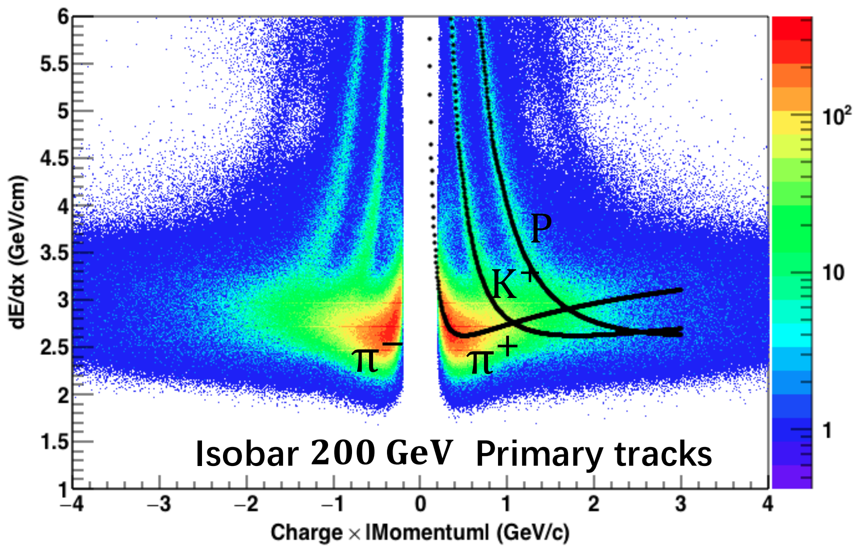


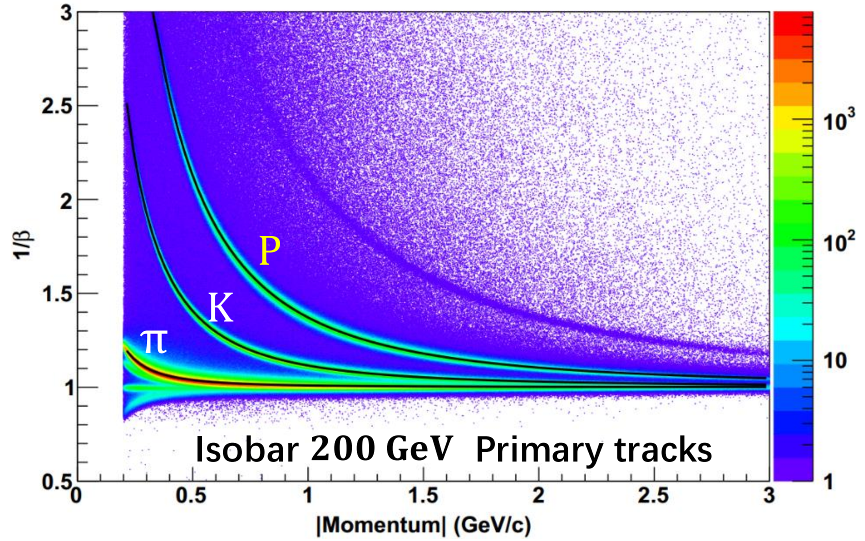
STAR Phys. Rev. Lett. 91, 172302 (2003) STAR Phys. Rev. C 81, 054907 (2010)

STAR Phys. Rev. Lett. 91, 072304 (2003)

STAR Detectors







- Time Projection Chamber (TPC)
  ~ 350 μm, vertex resolution with more than 1000 tracks
- Time Of Flight detector (TOF)
  the precise 1/β extends PID reach

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Data set and Analysis cuts

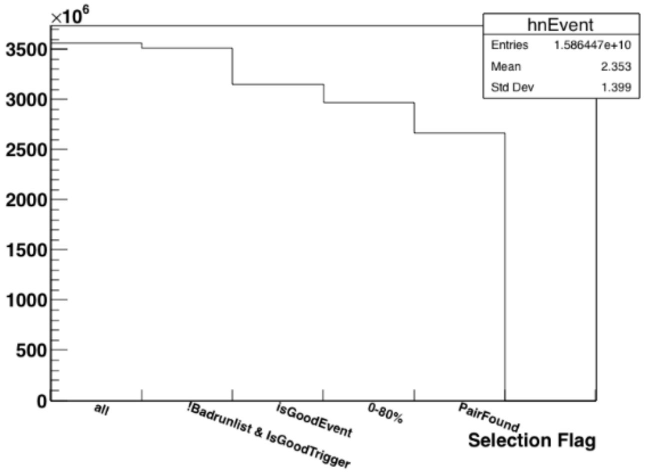
- **Dataset:** production_isobar_2018
- **Year:** 2018
- **Production tag:** P20ic
- **Triggers used:** 600001, 600011, 600021, 600031 (MB)
- **Embedding request id:** 20201503

hybrid PID functions

$$f_{\pi}^{max}(p) = \begin{cases} 5.1-2.25p, & p\le1.6 \\ 1.5, & p>1.6 \end{cases}$$

$$f_{K}^{max}(p) = \begin{cases} 6.129-1.9316p, & p\le2.5 \\ 1.3, & p>2.5 \end{cases}$$

$$f_{K}^{min}(p) = \begin{cases} -7.54+5.83p-1.31p^2, & p\le1.7 \\ -1.4149, & p>1.7 \end{cases}$$

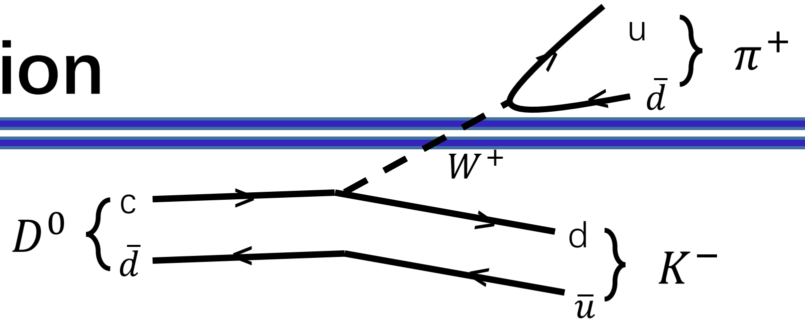


Event Level cuts	
Cuts	Value
$\lvert V_z \rvert$	(-35,25) cm
V_r	< 2. cm
VzDiff	< 3. cm
!Badrun_list	
GoodTrigger	
!isBadRun()	
passnTofMatchRefmultCut()	
0-80%	
# Events	2.7B

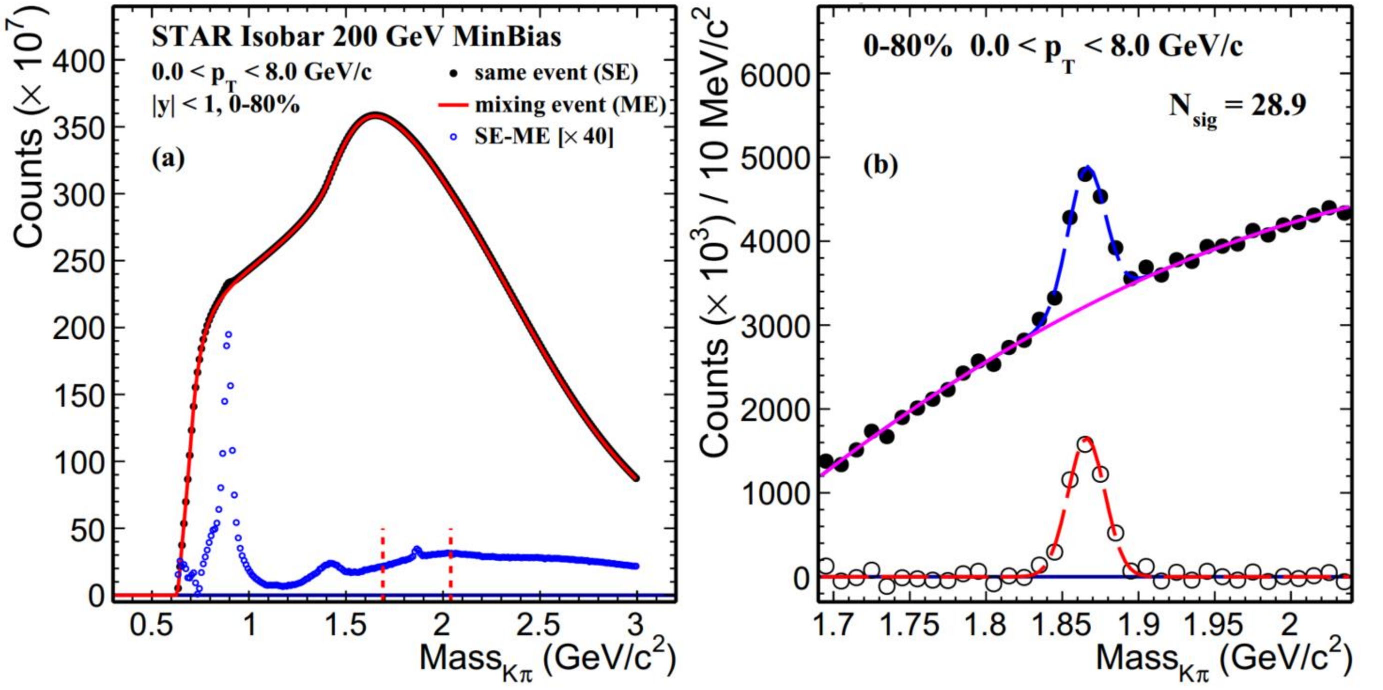
Track quality cuts	
Cuts	Value
p_T (GeV/c)	> 0.6
TPC Nhits	⩾20
nHits/HitsMax	[0.52, 1.2]
gDCA	⩽ 2.0 cm
$\lvert\eta\rvert$	< 1.
nHitsDedx	> 10.
charge	±1
Primary tracks	

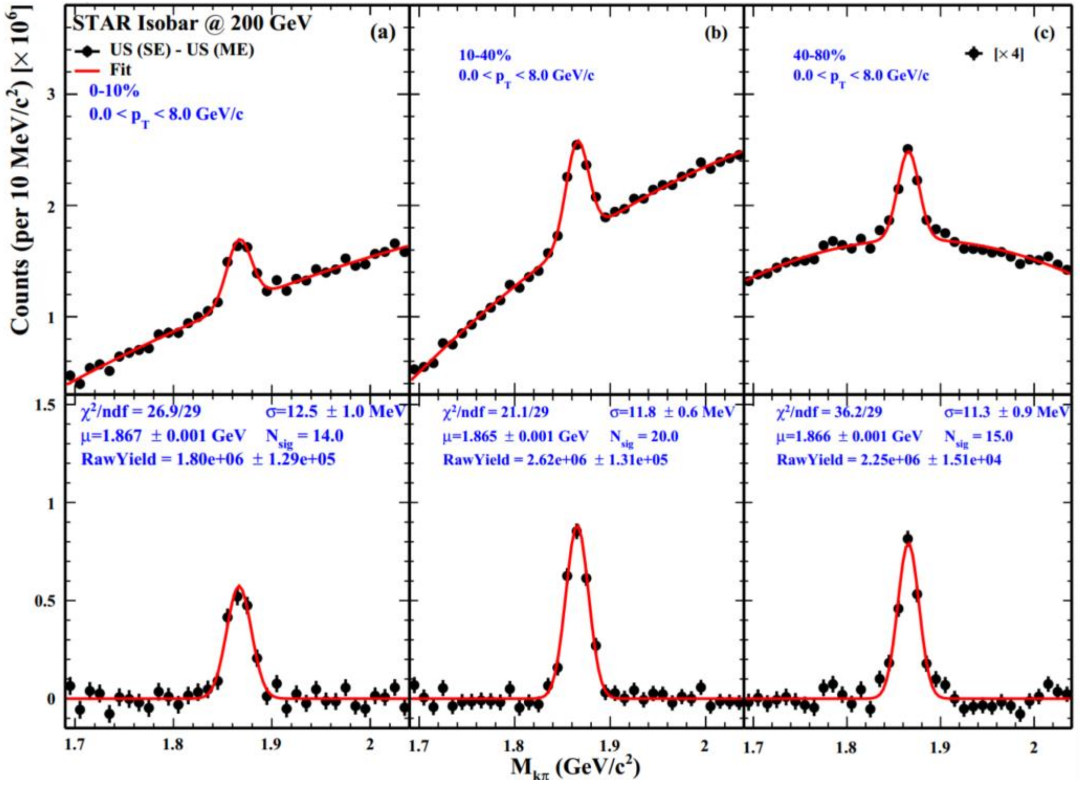
PID cuts	
Cuts	Value
btofYLocal (TOF matched)	[-1.8, 1.8]
p < 1.6 && β > 0	hybrid PID functions
p ≥ 1.6 && β > 0 (Pion)	hybrid PID functions
p ≥ 1.6 && !TofisAvailble	$\lvert n\sigma_K\rvert$< 2. && $\lvert n\sigma_\pi\rvert$< 2.
$\lvert y\rvert_{D^0}$	< 1.0

D^0 signal reconstruction



hadronic modes: $D^0 \rightarrow K^- + \pi^+$; $\bar{D}^0 \rightarrow K^+ + \pi^-$ (Γ_i/Γ ~ 3.95%)





- The K, π invariant mass distribution with centrality 0-80% and p_T range 0-8 GeV/c at midrapidity.
- The mix-event method can well reproduce the combination background (solid red line).

- D^0 signal at 0-10% (a), 10-40% (b), 40-80% (c) centrality bins with transverse momentum range 0-8 GeV/c at midrapidity.

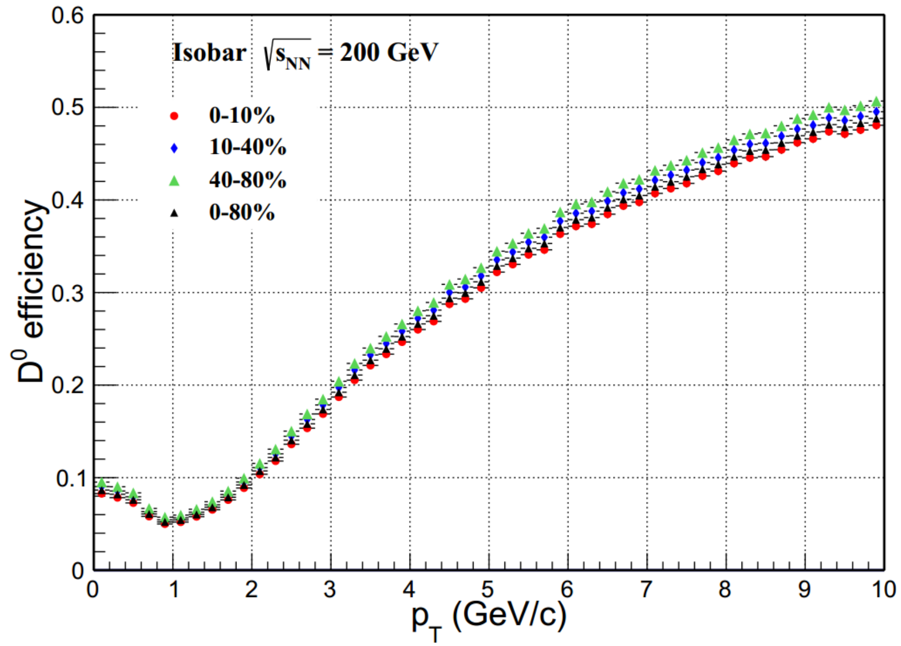
Efficiency correction procedures

$$\frac{d^2N}{2\pi p_T dp_T dy} = \frac{\Delta N^{raw}/\epsilon_{D^0}^{reco}/2}{2\pi p_T \Delta p_T \Delta y \times N_{events} \times B.R.}$$

$$\epsilon_{D^0}^{reco} = \epsilon_{Accept} \times \epsilon_{TPC} \times \epsilon_{PID}$$

$$\epsilon_{PID} = \epsilon_{n\sigma_X} \cdot \epsilon_{TOF} \cdot \epsilon_{n\sigma_X^{TOF}} + \epsilon_{n\sigma_X} \cdot (1 - \epsilon_{TOF})$$

- ΔN^{raw} : the raw yield measured in the bin $\Delta p_T \Delta y$;
- $\epsilon_{Accept} \times \epsilon_{TPC}$: TPC acceptance and tracking efficiency (embedding);
- ϵ_{PID} : particle identification efficiency (data, K_s^0, ϕ, Λ^0).



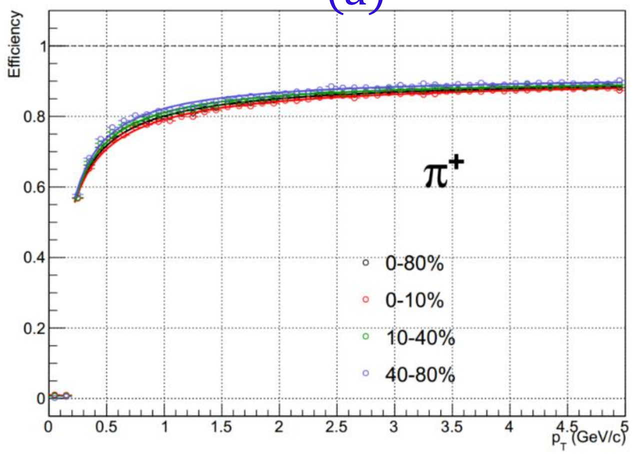
◉ D^0efficiency as a function of D^0 transverse momentum at different centrality bins.

◉ (a) TPC tracking efficiency for Pion

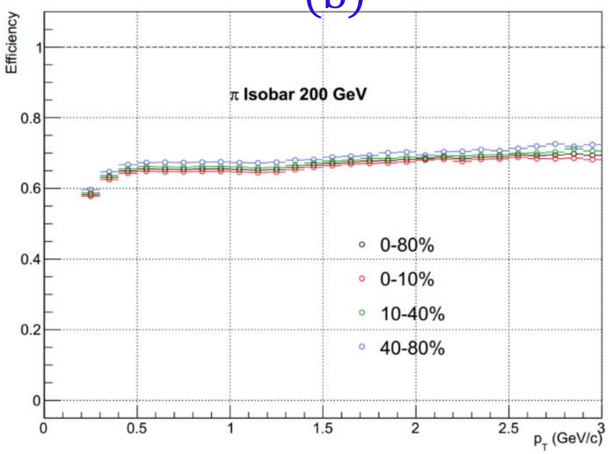
◉ (b) TOF matching efficiency for Pion

◉ (c) Pion TPC PID efficiency (black circles) and TOF PID efficiency (red circles)

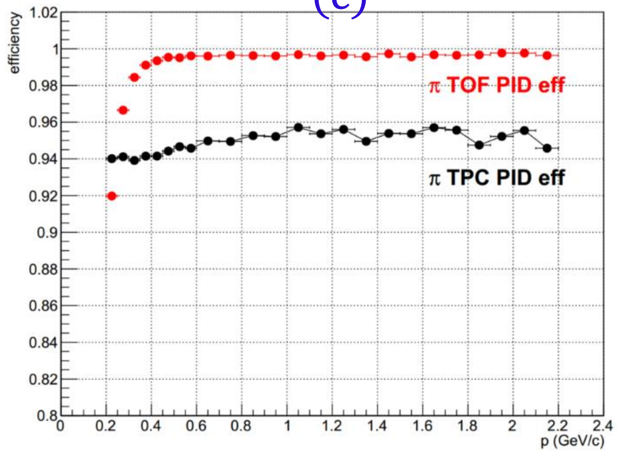
(a)



(b)



(c)



Systematic uncertainties

- Signal extraction
  - The difference between the fitting and counting methods (1.69, 2.04) GeV/c^2;
  - The order of polynomial function to depict the residual background (Pol3);
  - Signal fit range (1.73, 2.00) GeV/c^2;
  - p_T cut variation for daughter particles;
  - Mix-event like-sign normalization factor
- TPC tracking
  - DCA: 2cm (default);
  - nHitsFit: 20 (default)
- PID cuts 3%
- B.R. 0.5%
- p + p inelastic scattering cross section 8%

		0–10%	10–40%	40–80%
spectra	Raw yield	3.9-16.5%	3.7-10.5%	4.0-8.5 %
	Track p_T variation	10.6%	9.3%	7.3%
	ϵ_{PID}	3%	3%	3%
	TRE	2-6%	2-6%	2-6%
	BR	0.5%	0.5%	0.5%
R_{AA}	$\langle N_{bin} \rangle$	1.6%	0.6%	0.4%
	pp base	20.6-71.8%	20.6-71.8%	20.6-71.8%
Rcp (/40–80%)		0–10%		10–40%
	Raw yield	13.6-20.7%		12.4-16.5 %
Integrated cross section		$p_T > 0$		$p_T > 4$ GeV/c
	Total	12.7-15.8%		12.0-15.2 %

p_T Spectra and Integrated yields

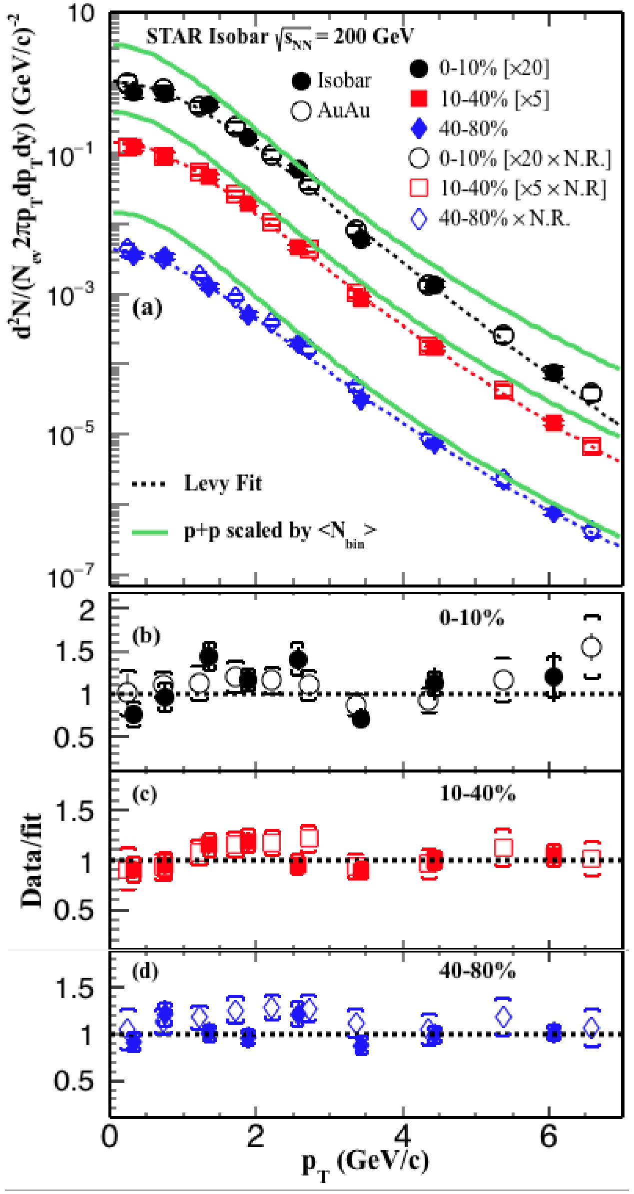
$$E\frac{d^3N}{d\boldsymbol{p}^3} = \frac{d^3N}{p_T dp_T dy d\phi} = \frac{d^2N}{2\pi p_T dp_T dy}$$

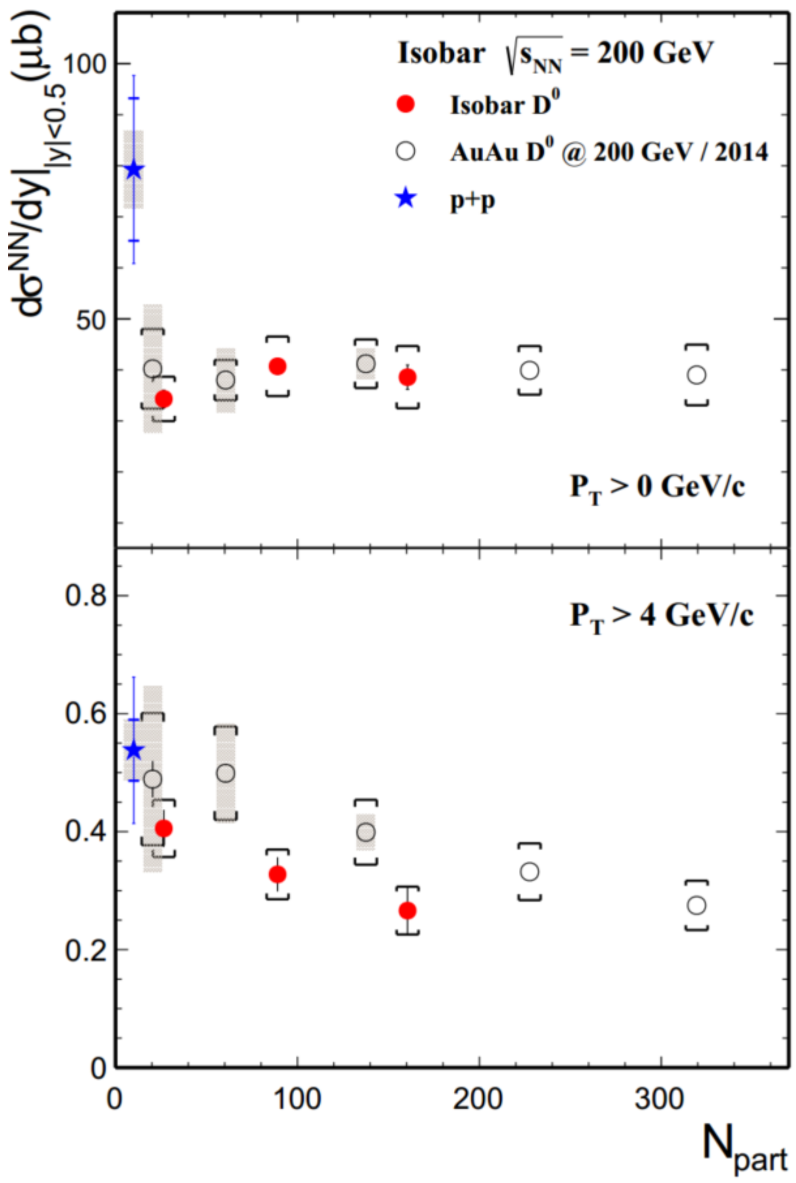
$$\frac{d^2N}{2\pi p_T dp_T dy} = \frac{\Delta N^{raw}/\epsilon_{D^0}^{tot}/2}{2\pi p_T \Delta p_T \Delta y \times N_{events} \times B.R.} = \frac{\Delta N_{D^0}^{AA}}{2\pi p_T \Delta p_T \Delta y} = E\frac{d^3\sigma_{D^0}^{AA}}{d\boldsymbol{p}^3}$$

- D^0 invariant yields at mid-rapidity (|y|<1) vs. transverse momentum for different centrality classes in isobar (solid) and Au + Au (open) collisions at $\sqrt{s_{NN}}$ = 200 GeV.

$$\frac{d\sigma_{D^0}^{NN}}{dy}|_{y=0} = \frac{dN_{D^0}^{AA}}{dy}|_{y=0} \times \frac{\sigma_{inel}^{pp}}{< N_{bin} >}$$

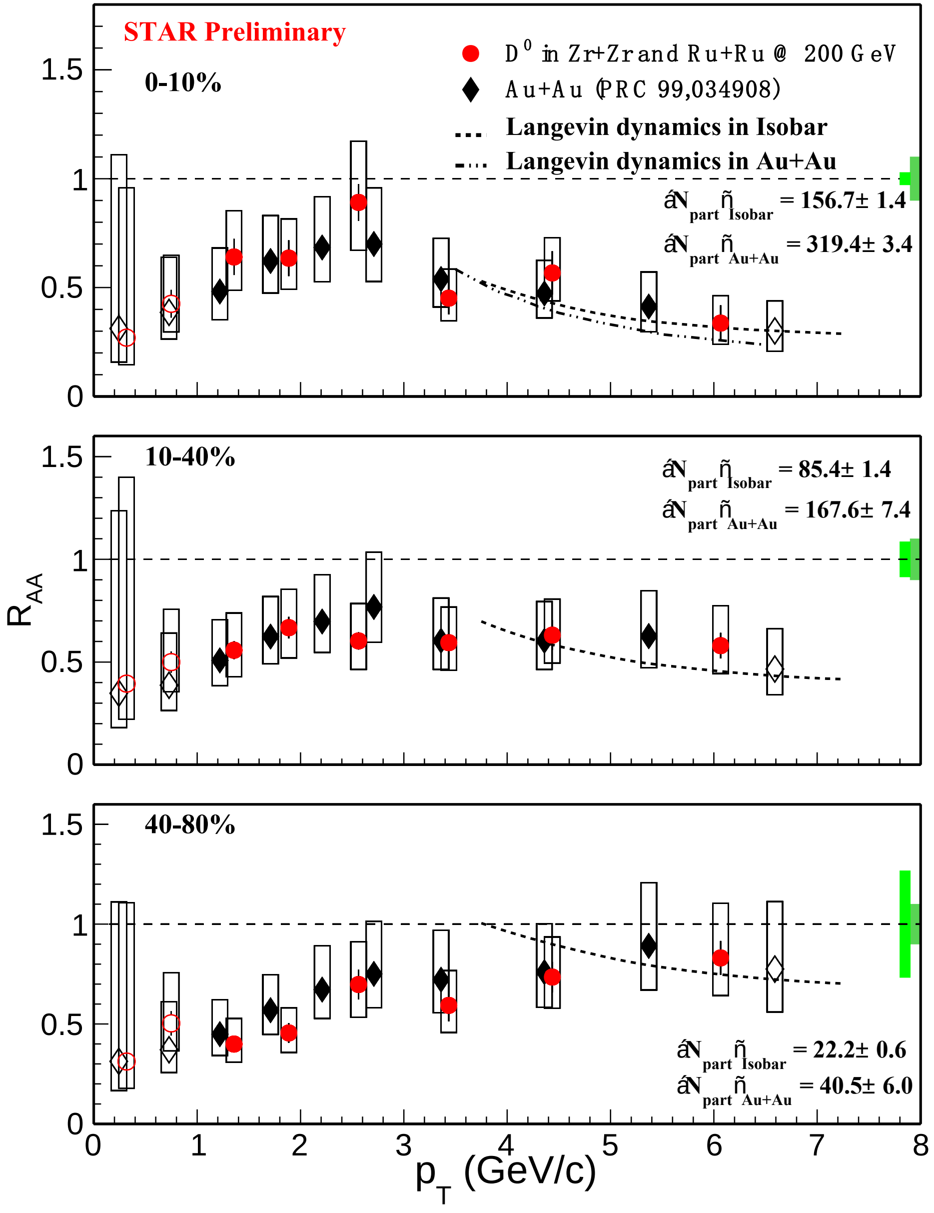
- D^0 integrated corss sections per nucleon-nucleon collision in isobar.





D^0 R_{AA}: Isobar vs. Au+Au

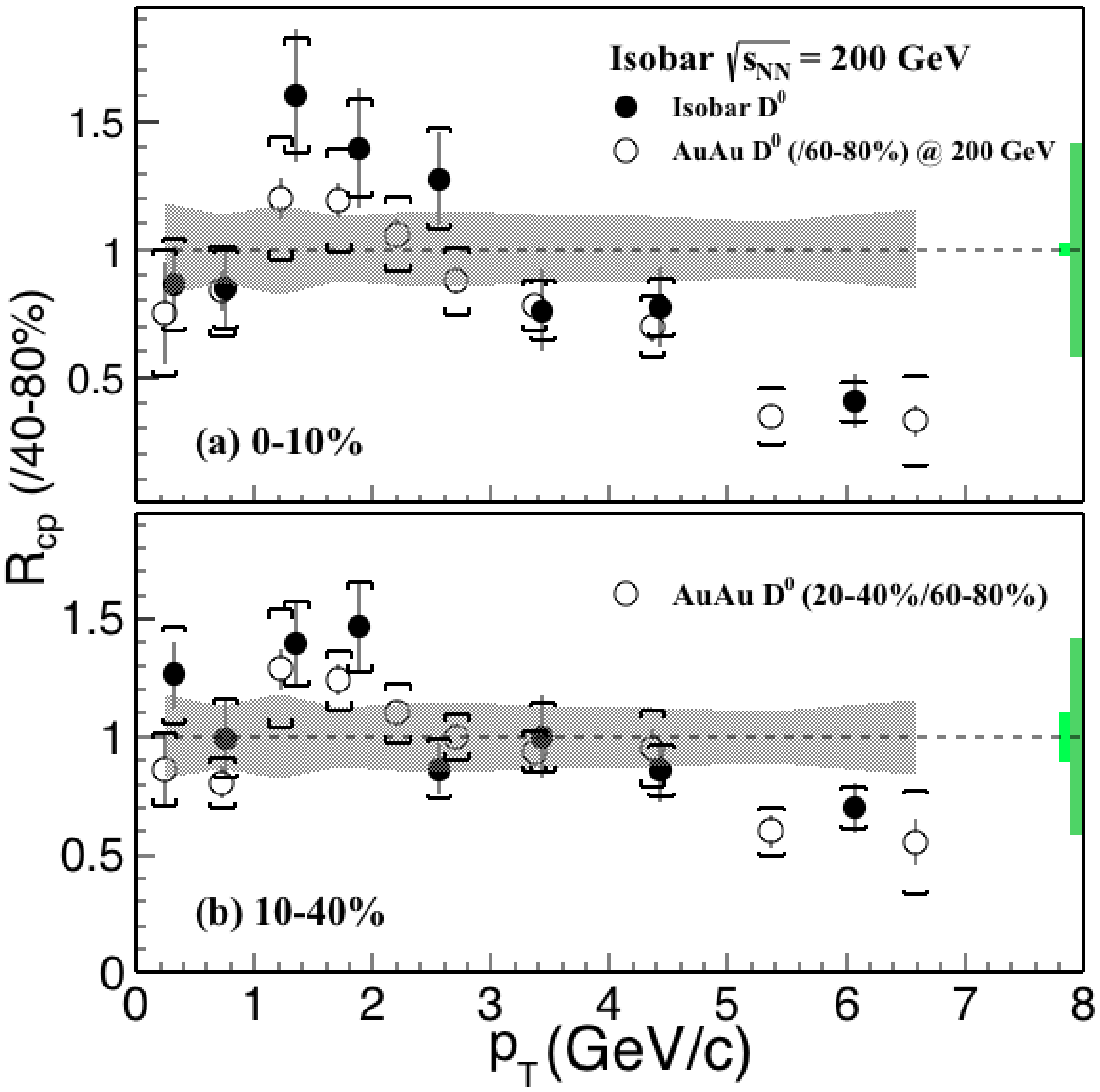
- Significant D^0 R_{AA} suppression observed at high-p_T in central collisions
- Suppression decreases from central to peripheral collisions → consistent with decreasing hot medium effects
- Similar suppression between isobar and Au+Au collisions in same centrality
- Theoretical model that includes collisional and radiative energy losses is consistent with observed suppression



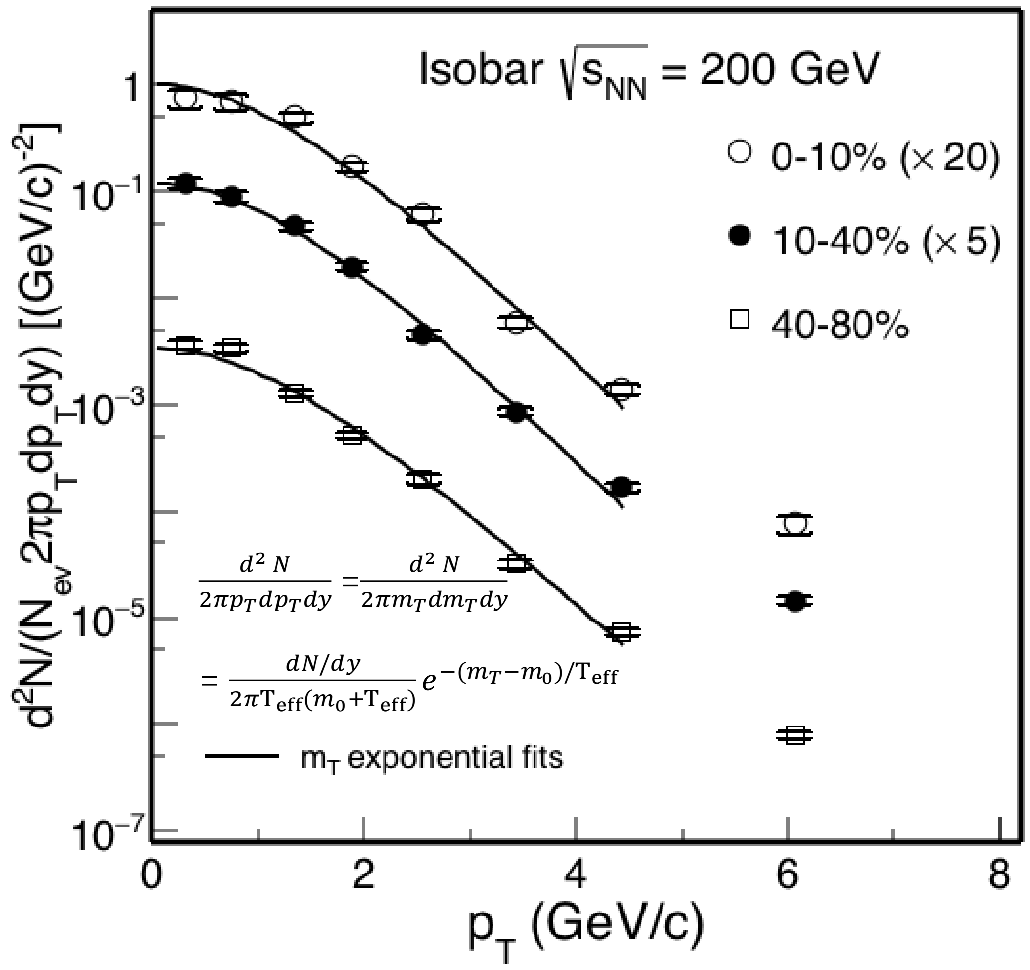
R_{cp} vs. p_T

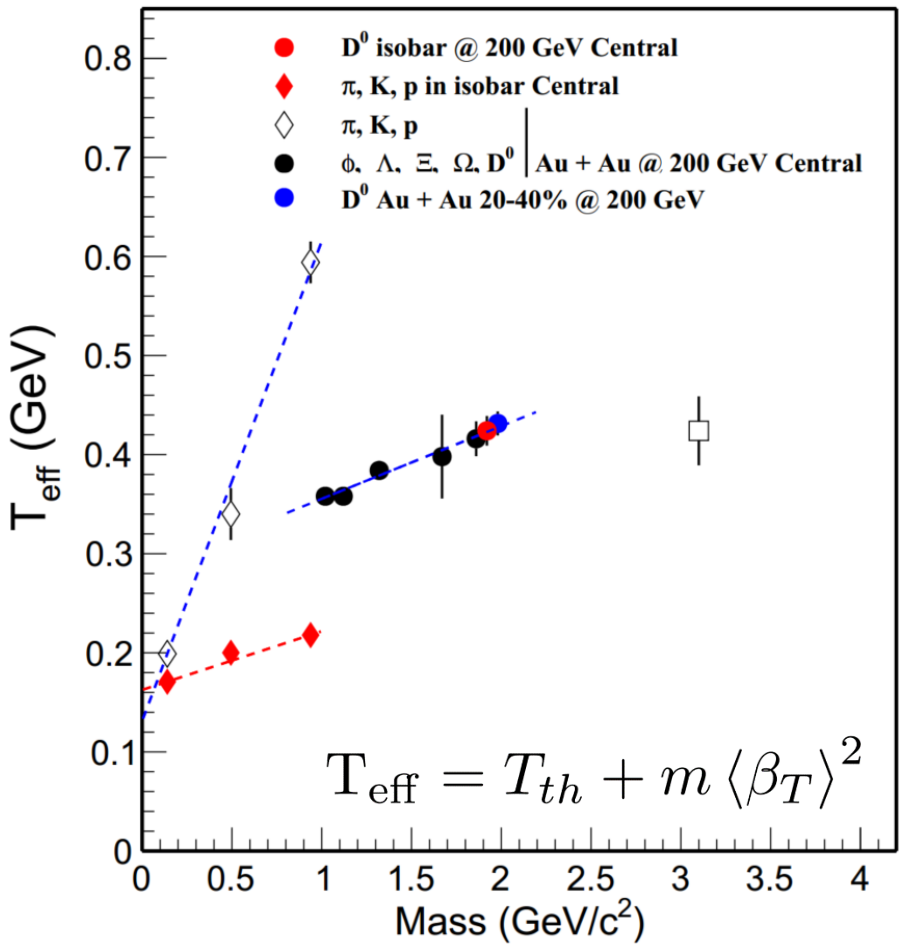
- R_{cp} with the 40-80% spectrum as the reference for 0-10% and 10-40% centrality in isobar collisions compared to that of Au + Au results.

- Charm quarks suffer signifcant energy loss in both system evolution



m_T Spectra and Collectivity

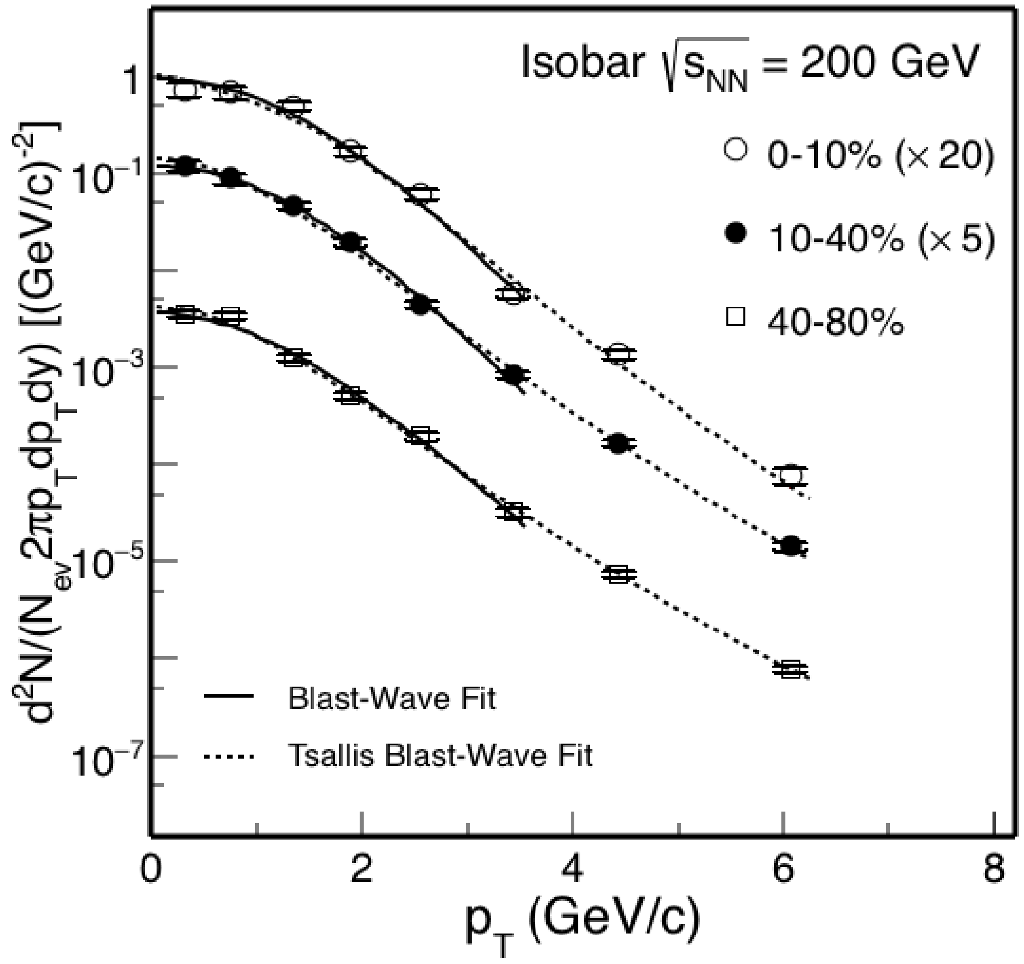


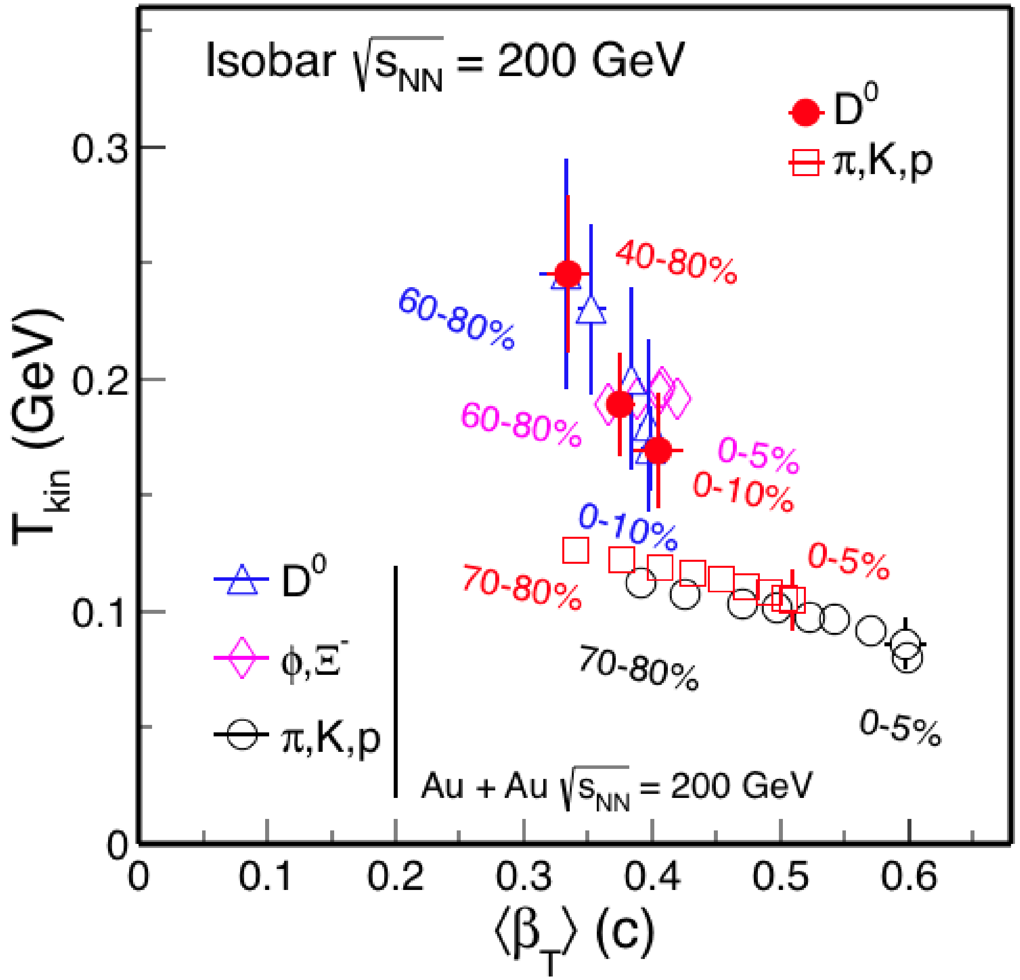


system	hadron	T_{eff}
isobar	π	0.176±0.001
	K	0.203±0.005
	p	0.218±0.001
	D^0	0.424±0.015
AuAu	π	0.199±0.002
	K	0.340±0.026
	p	0.594±0.020
	D^0	0.416±0.018
	D^0(20-40%)	0.431±0.012

- D^0 invariant yield at mid−rapidity (|y|<1) vs. p_T for different centrality bins fitted with m_T distribution.
- T_{eff} for D^0 in central isobar collisions is consistent with that of Au + Au results. The red rhombus from left to right show the fit results of π, K, and proton in isobar collisions respectively.

Blast – Wave Fits





- D^0 invariant yield at mid−rapidity(|y|<1) vs. p_T for different centrality bins fitted with blast-wave function.
- D^0 freeze out temperature in isobar collisions are consistent with that of in Au + Au collisions for the same centrality. The open red rectangles from left to right shows the result of fitting π, K, and proton simultaneously from peripheral to central collisons.
- The average flow velocity increases with central collision, and (q −1) is also found to be close to zero.

Tsallis blast-wave model fits parameters to D^0 p_T-differential spectra in isobar collisions.

Centrality	$\langle\beta_T\rangle$(c)	$q-1$
0-10%	0.282±0.018	0.070±0.007
10-40%	0.207±0.030	0.080±0.007
40-80%	0.189±0.031	0.089±0.005

Summary — D^0 p_T spectra and R_{AA}

- D^0-meson productions are measured at mid-rapidity (|y| < 1) in 200 GeV isobar collisions
- The number of binary collisions scale effect of D^0 production cross section between isobar and Au + Au collisions is observed
- The strong suppression of D^0 nuclear modification factor R_{AA} is observed for p_T > 3 GeV/c in central isobar collisions, demonstrating that charm quarks suffer significant energy loss in the QGP.
- No significant systematic dependence of D^0 kinetic freeze-out properties in central collisions between isobar and Au + Au collisions within uncertainties is observed.

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Collective flow in heavy-ion collisions

- Acceleration of collective flow

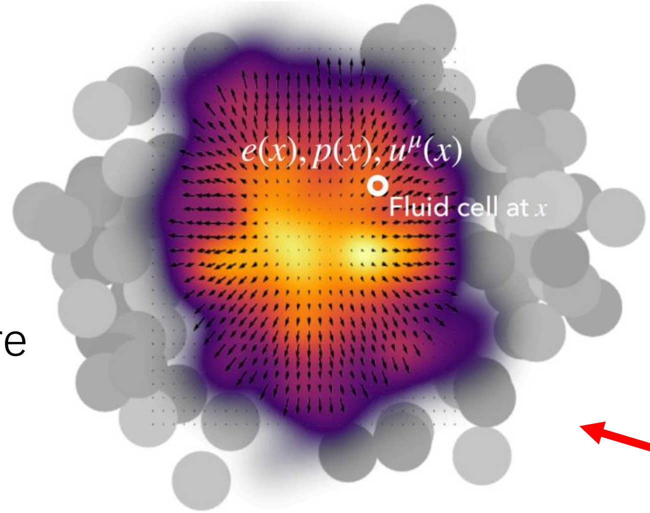
$$u^{\nu}\partial_{\nu}u^{\rho} = \frac{\Delta^{\rho\nu}\partial_{\nu}P}{e+P}$$ Euler equation

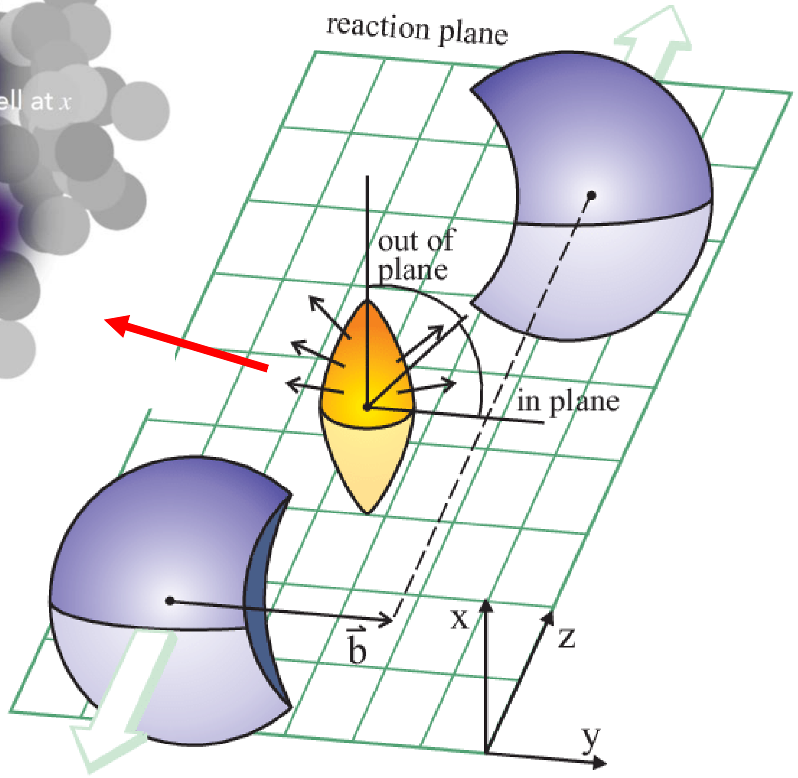
$$\partial_t u^i = \frac{\partial^i P}{e+P}$$

Spatial gradient of pressure

inertia of fluid

flow acceleration





Pressure gradients drive the hydrodynamic expansion
Anisotropic flow

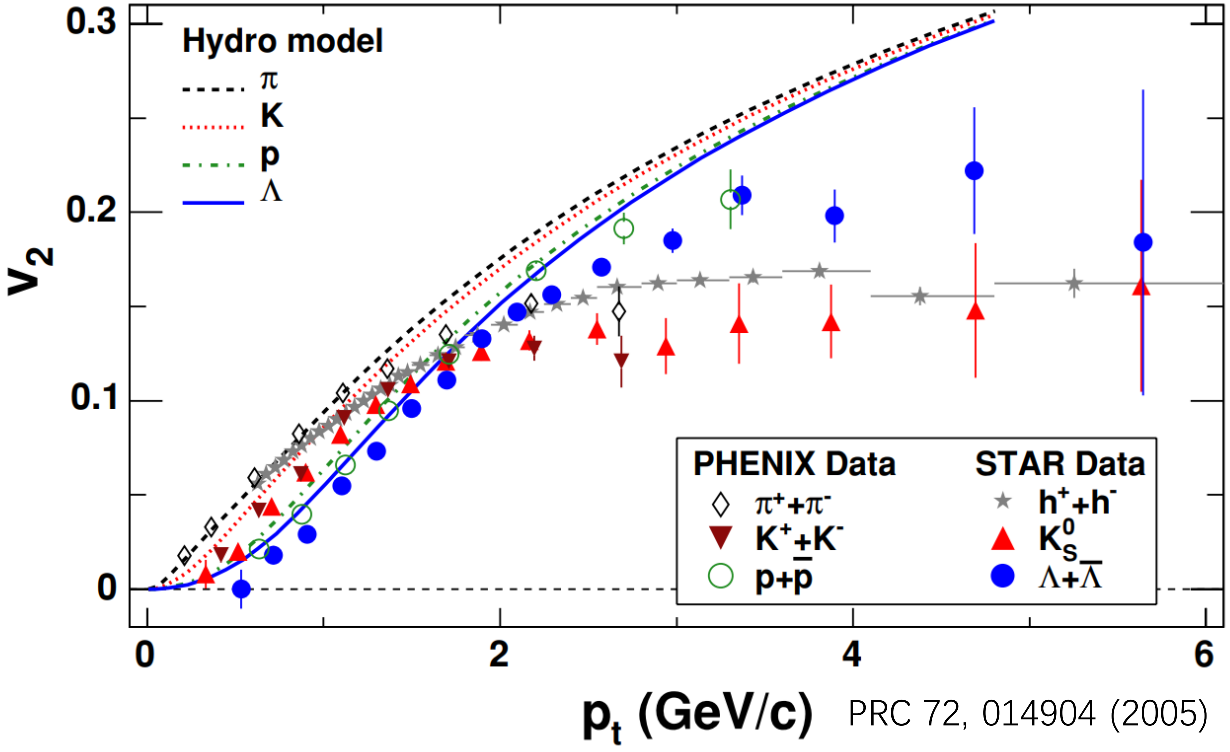
$$\frac{dN}{d\phi} = \frac{N}{2\pi}\left(1 + 2\sum_{n=1}^{\infty} v_n \cos[n(\phi - \Psi_n)]\right)$$

$$v_2 = \langle \cos[2(\phi - \Psi_2)] \rangle$$

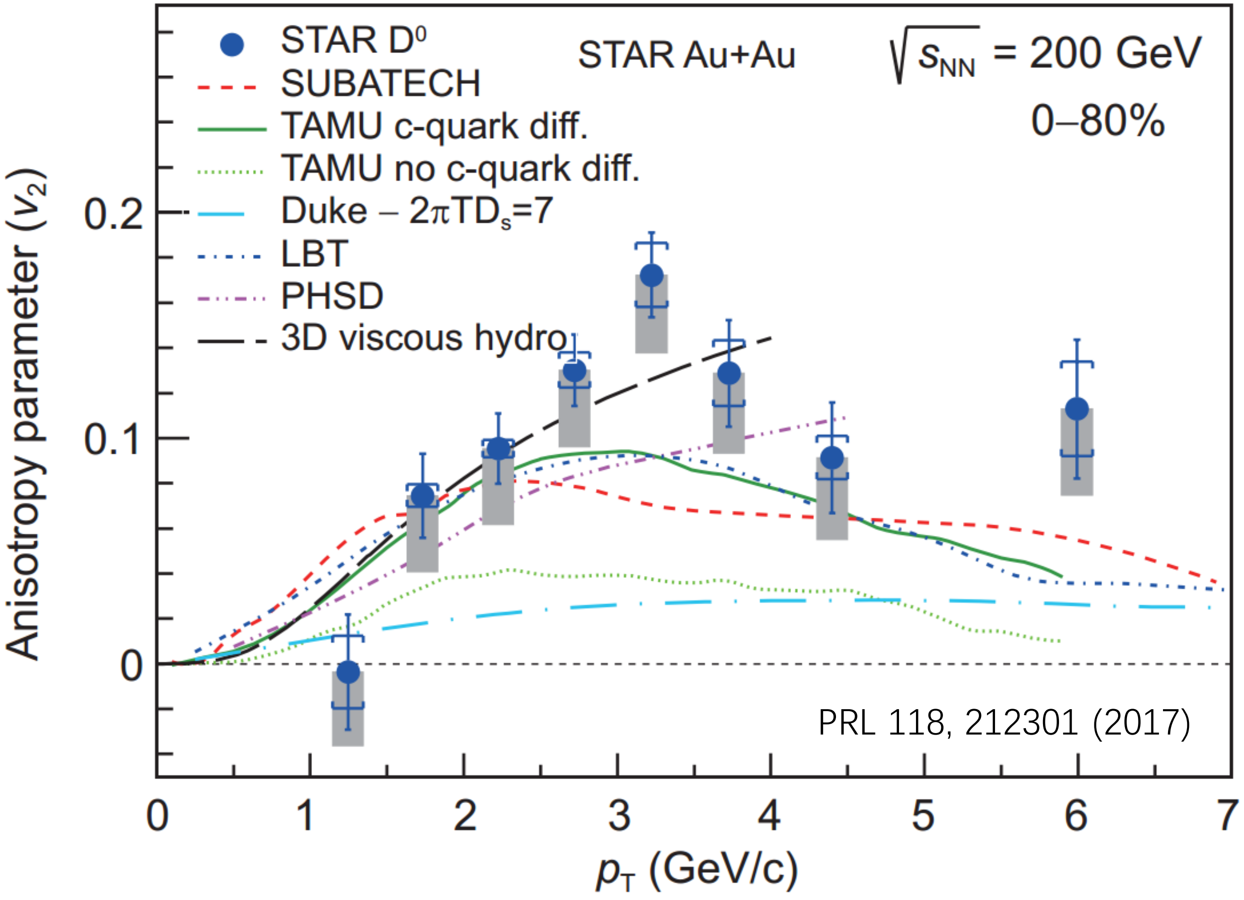
average over azimuthal distribution

v_2 elliptic flow, v_3 triangular flow, …

Elliptic flow at 200 GeV Au+Au collisons



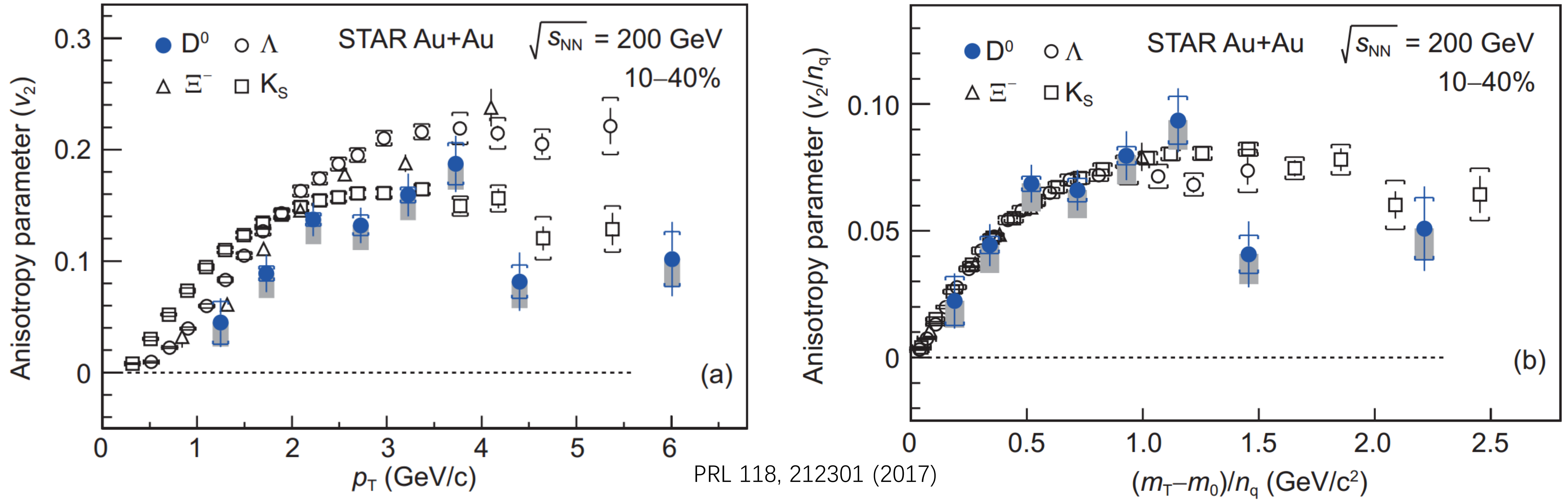
PRC 72, 014904 (2005)



- A significant elliptic flow indicate existence of light flavor-medium interactions

- TAMU model with charm quark diffusion can describe data, not vice versa;
- A 3D viscous hydro suggests that charm quarks have achieved thermal equilibrium.

D^0 v_2 at 200 GeV Au+Au collisons



PRL 118, 212301 (2017)

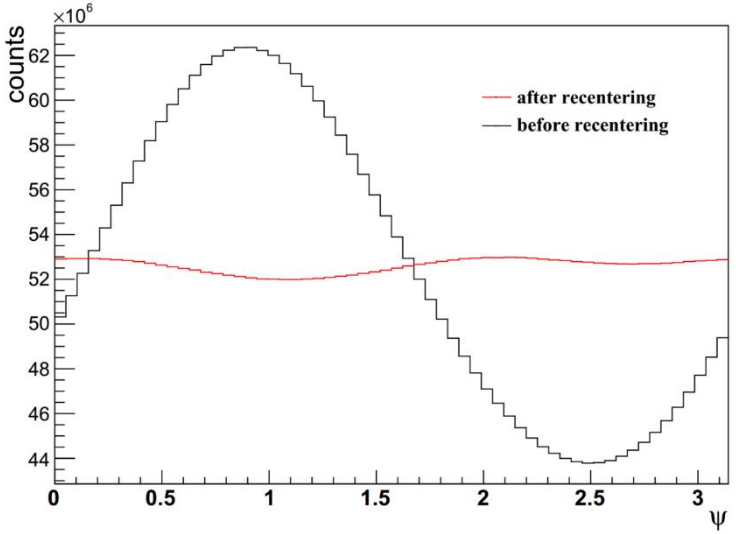
- A clear mass ordering for p_T < 2 GeV/c;
- Gained significant flow through interactions with the sQGP medium, and may thermalization;
- An experimental evidence for quark deconfinement.

A expected smaller hot nuclei systems in Isobar, so v_2 depends on the system?
Charm quark gets thermalized in Isobar like in Au-Au at 200 GeV?

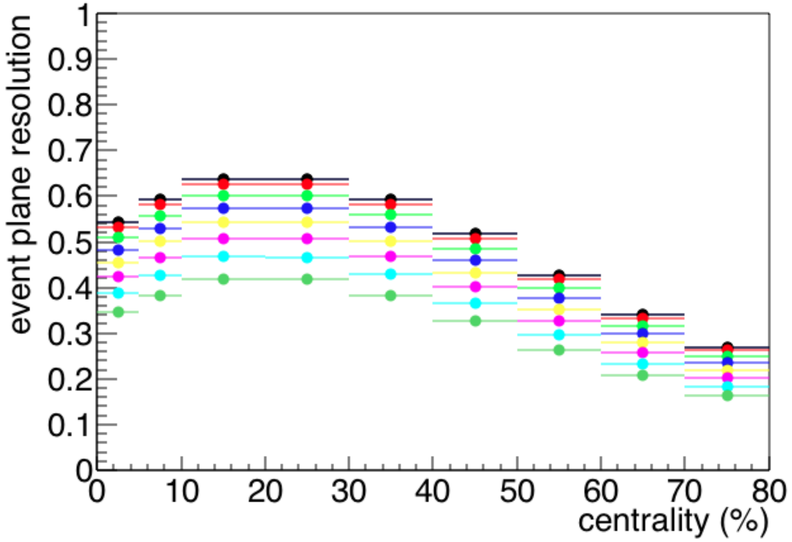
Event plane method to measure D^0 v_2

Event Level cuts	
Cuts	Value
$\|V_z\|$	(-35, 25) cm
V_r	< 2. cm
VzDiff	< 3. cm
Badrun_list	
!GoodTrigger	
isBadRun()	
!passnTofMatchRefmultCut()	
0-80%	

Track cuts for EP	
Cuts	Value
p_T (GeV/c)	(0.2, 2.)
|η|	< 1.
TPC Nhits	>= 15
nHits/HitsMax	[0.52, 1.2]
gDCA	<= 2. cm
charge	±1
Primary tracks	

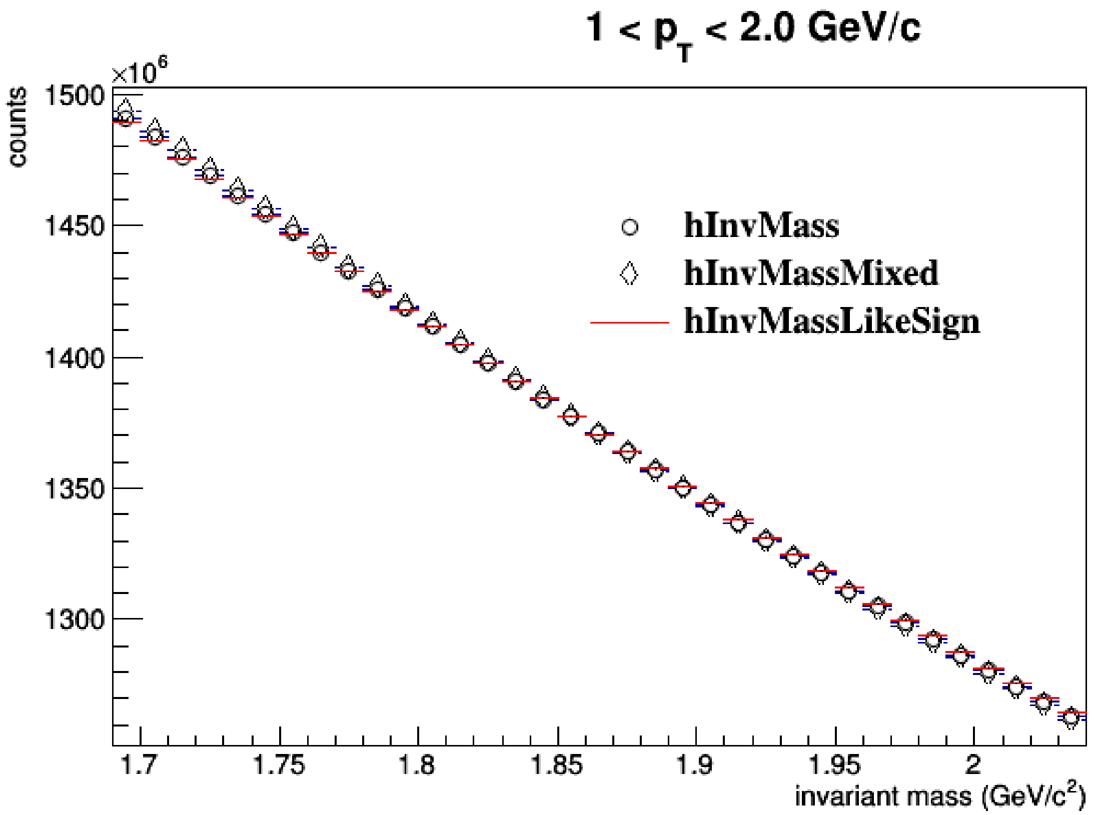


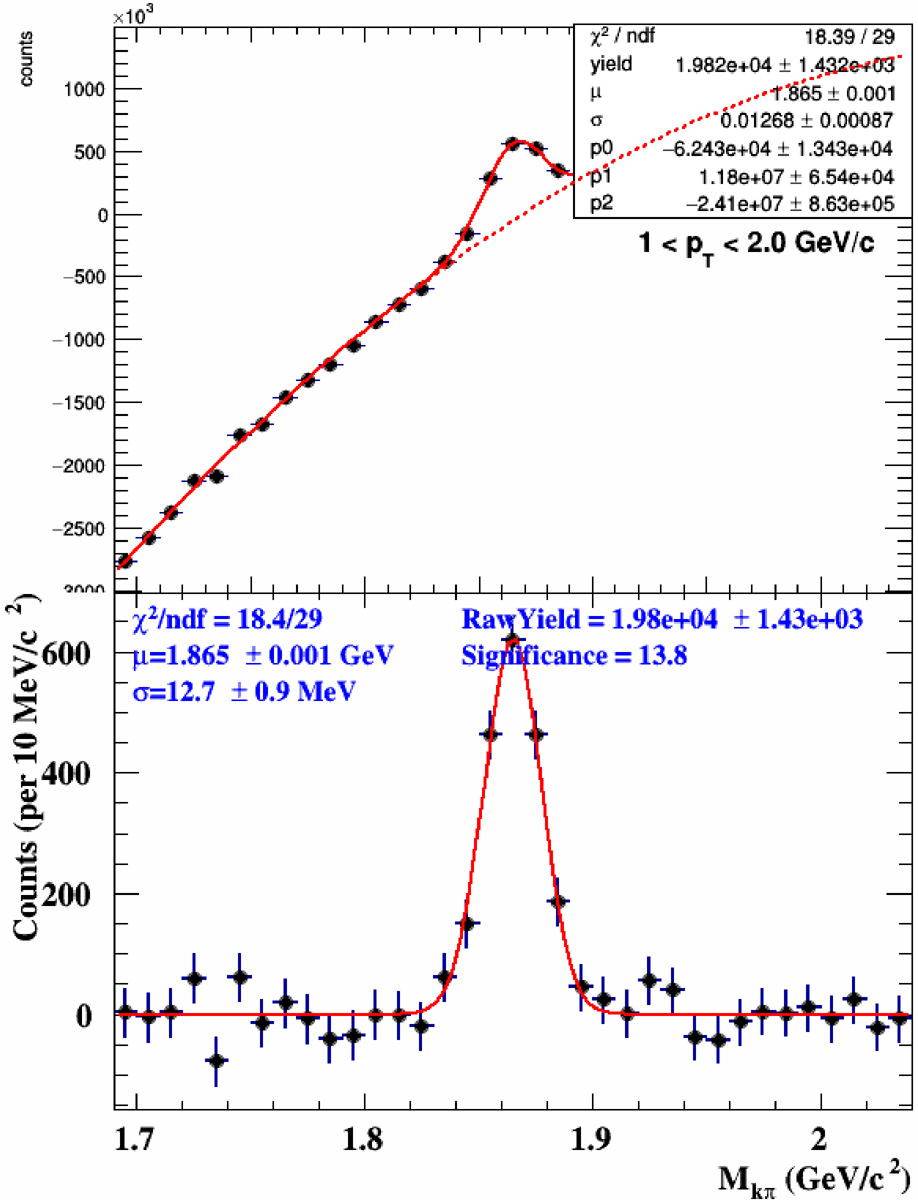
- Event plane reconstruction and recentering



- Event plane resolution vs. Centrality

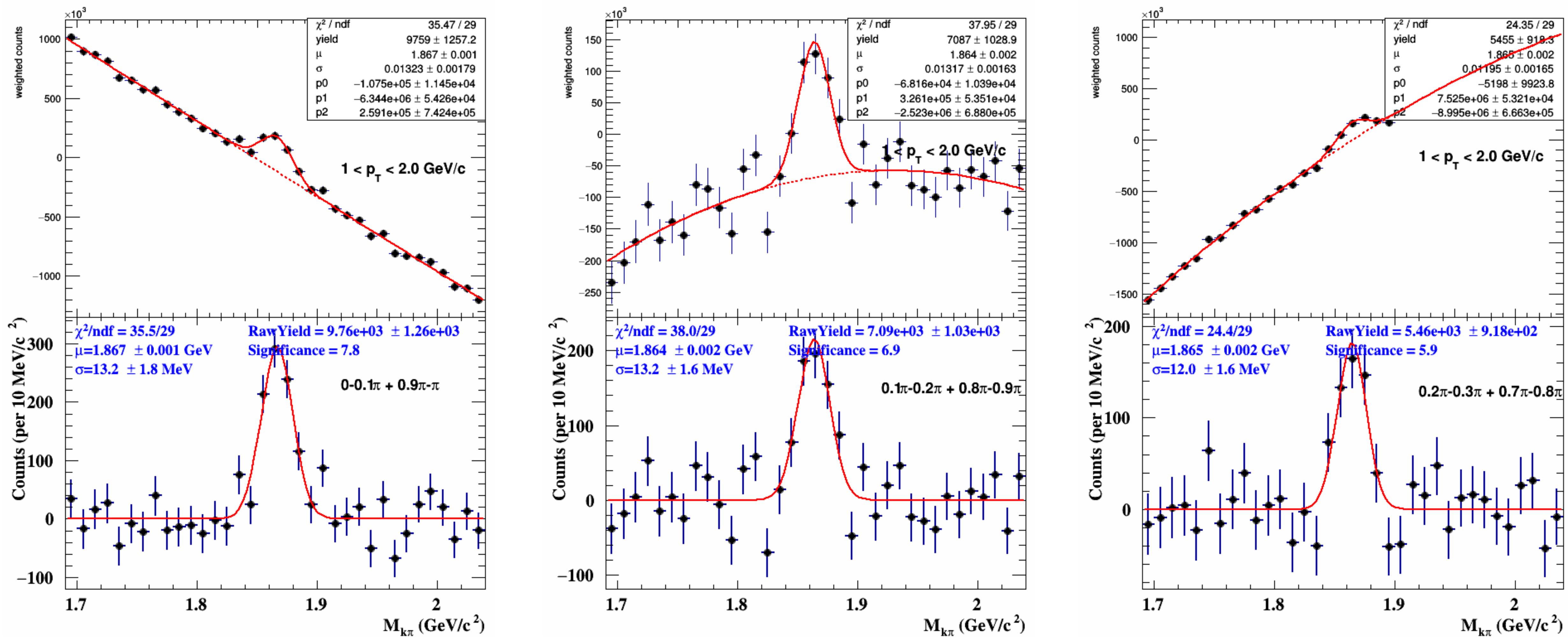
D^0 signal reconstruction



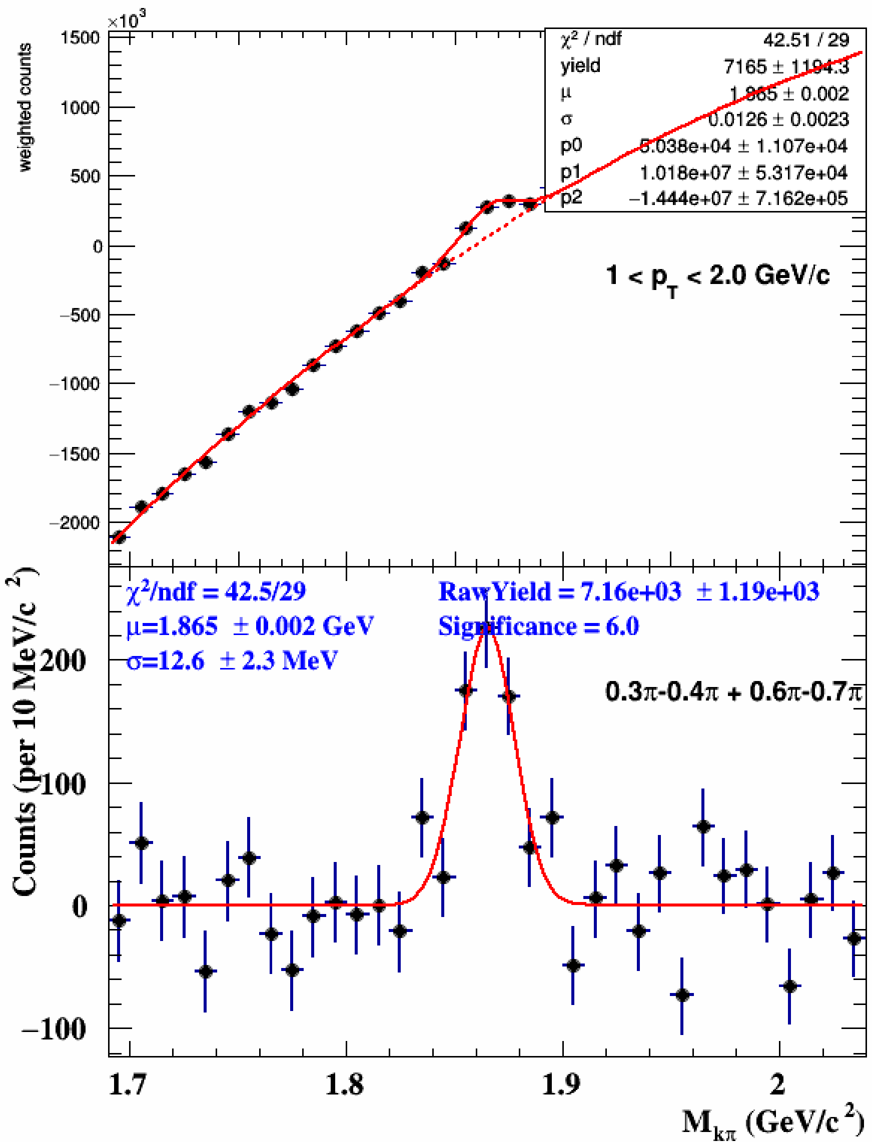


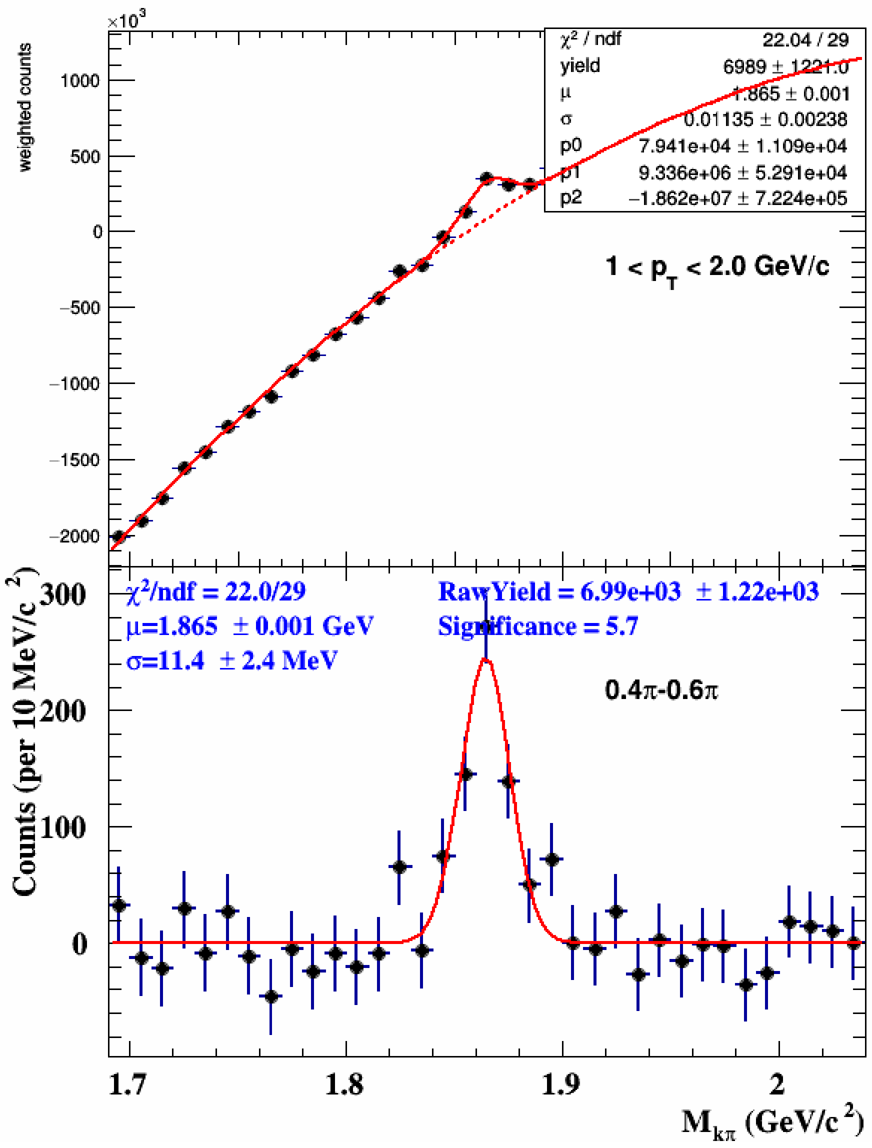
- Total D^0 signal at $1.0 < p_T < 2.0$ GeV/c

D^0 signal reconstruction

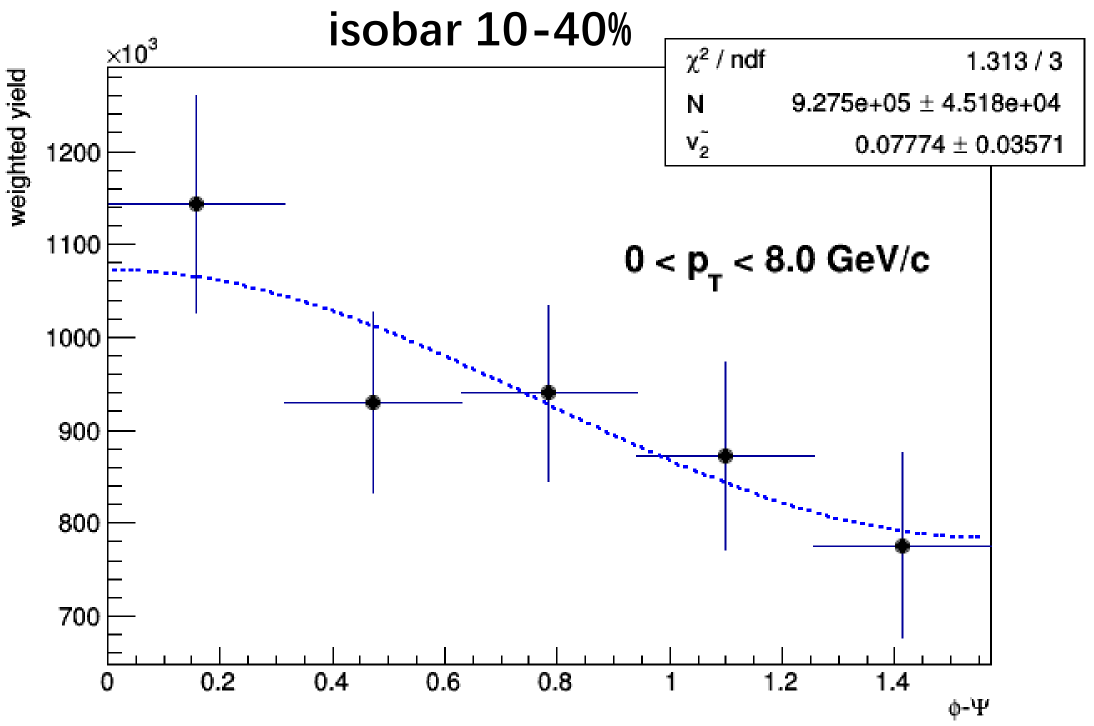


D^0 signal reconstruction

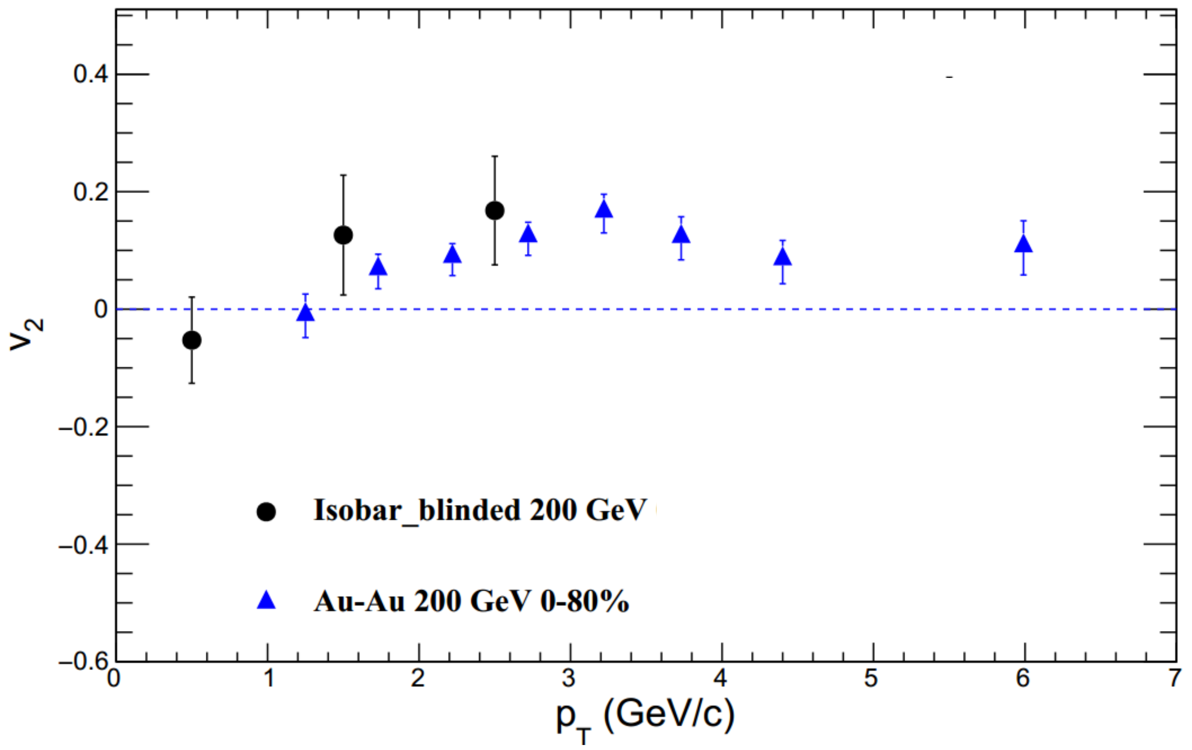




v_2 correction



$$N(1 + 2\tilde{v_2} cos(2(\phi - \Psi)))$$



- A scale of Δ/sinΔ = 1.01664 is done to correct for finite bin width Δ = 0.1π;
- The $\widetilde{v_2}$ is divided by <1/R>, weighted by the D^0 yield, to get physics v_2.
- Non-zero D^0 v_2 is observed.

Outline

- Motivation and STAR Experiment
- Energy loss
  - Measurements of D^0 p_T spectra and R_{AA} in isobar collisions at $\sqrt{s_{NN}} = 200$ at RHIC
- Collectivity
  - Measurement of D^0 elliptic flow v_2 at mid-rapidity in isobar collisions
- Summary

Summary

D^0 p_T spectra and R_{AA} in Zr+Zr & Ru+Ru collisions at STAR

- Significant suppression observed at $p_T > 3$ GeV/c in central collisions, indicating charm quarks strongly interact with medium and lose energy
- At the same centrality, D^0 seems to behave similarly in isobar and Au+Au collisions, while light hadrons do not

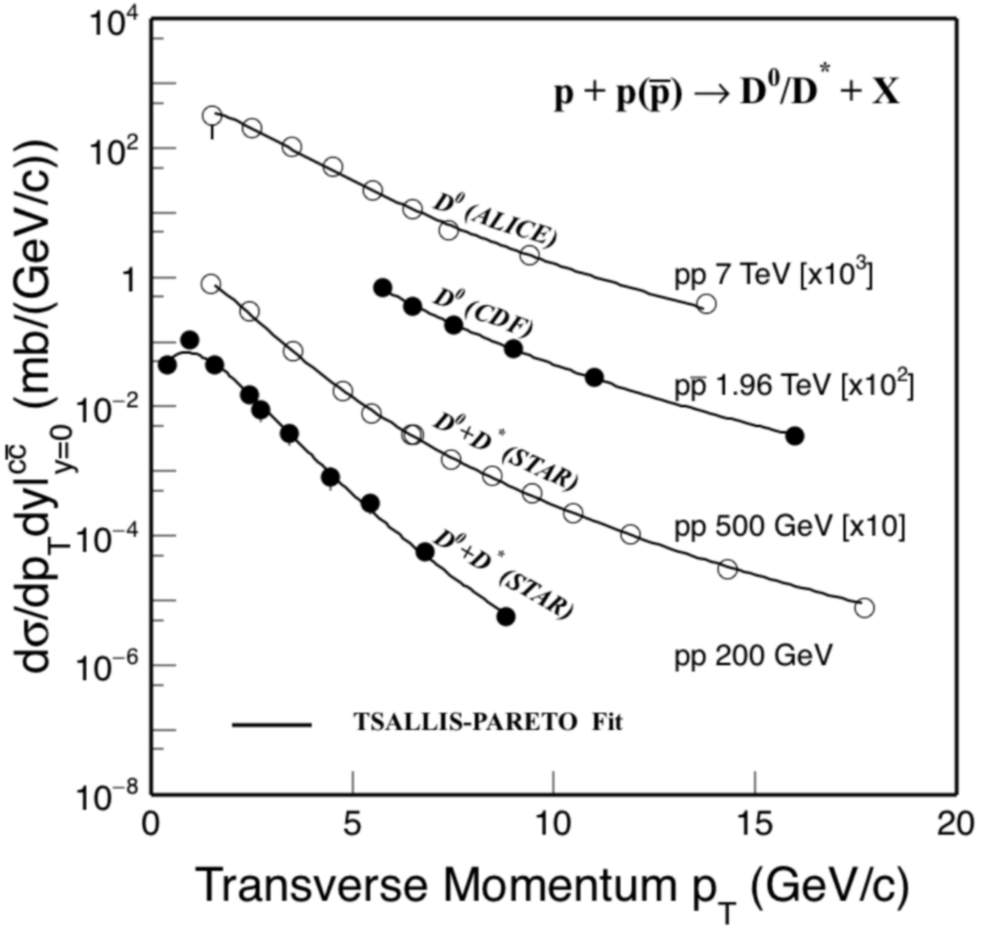
D^0 elliptic flow v_2 at mid-rapidity in Zr+Zr & Ru+Ru collisions at STAR

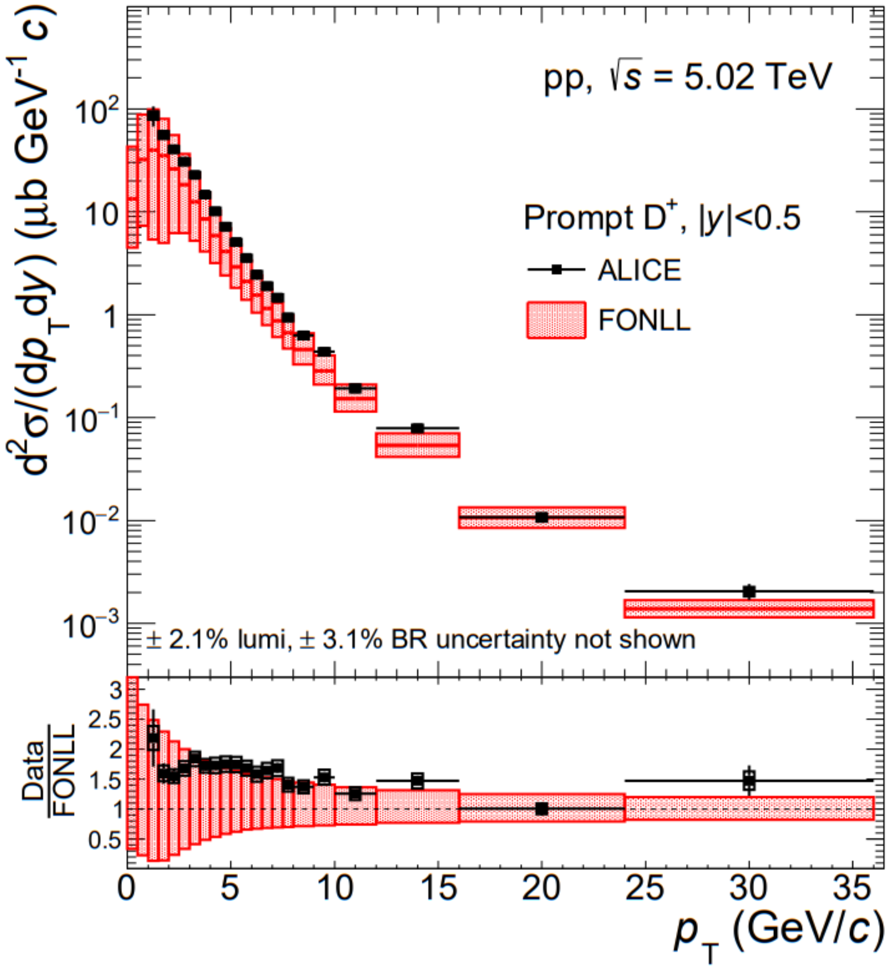
- A non-zero v_2 is measured and consistent with Au+Au collisions within the uncertainty.

Thank you!

Backup

D^0 production cross section in p+p collisions





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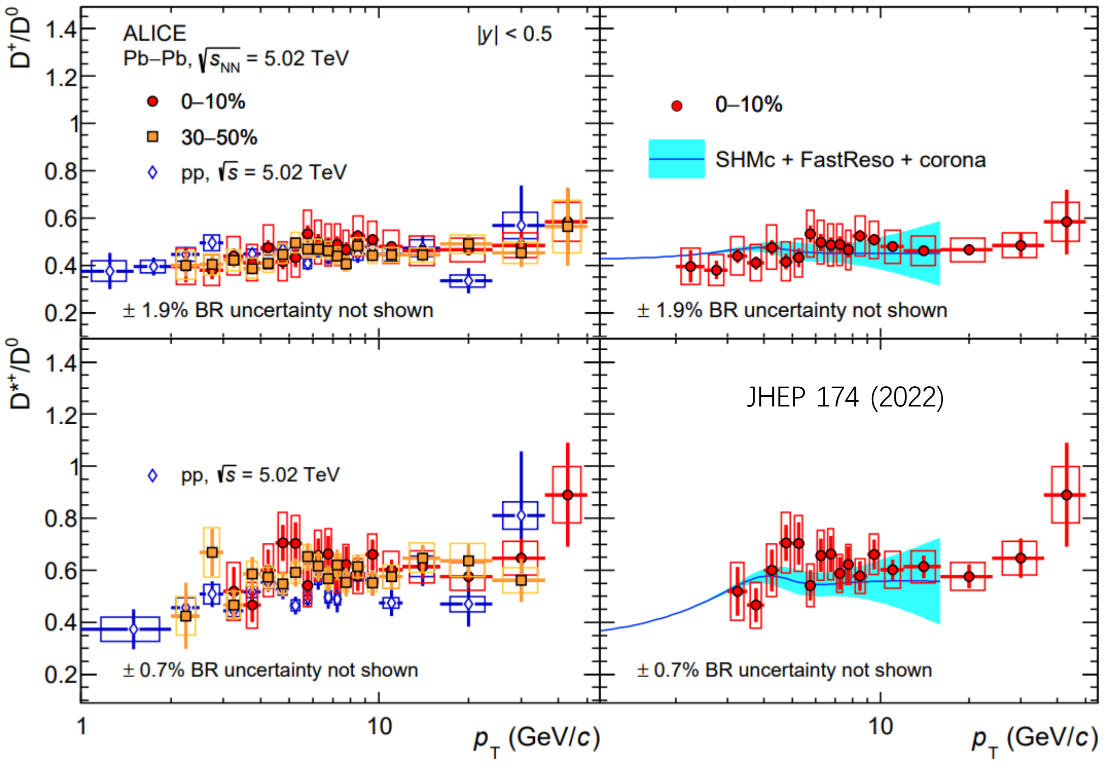
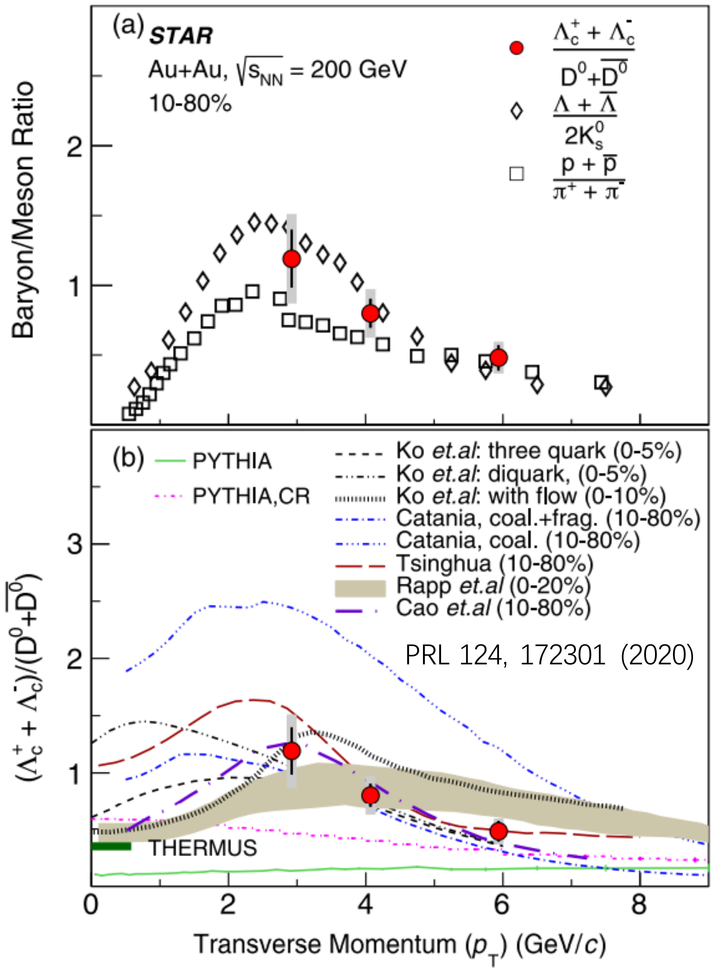
- pQCD calculations in p+p collisions, convolution
  - the parton distribution functions (PDFs) of the incoming protons
  - the partonic scattering cross section
  - the fragmentation function

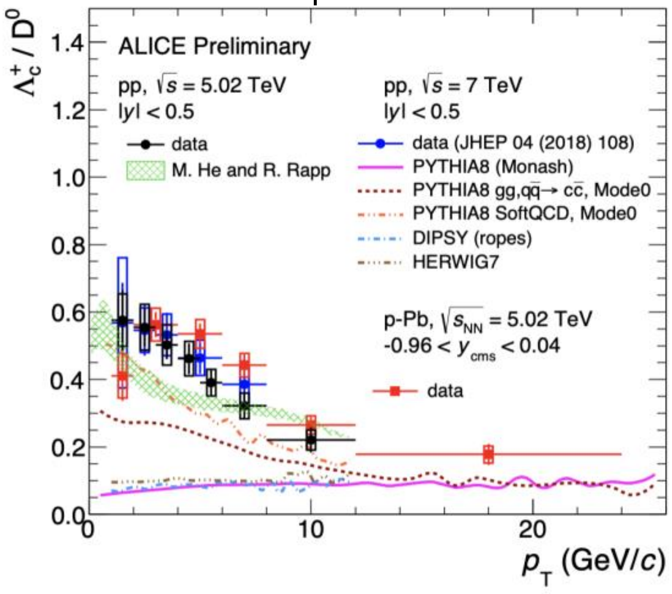
- Measured down to $p_T = 0$ in central collisions
- provide important constraints to pQCD calculations and to low-x gluon PDFs
- Represent an essential reference for the study of effects induced by cold and hot strongly-interacting matter

Particle specie ratios in pp, p-Pb, Au-Au and Pb-Pb





Pp?



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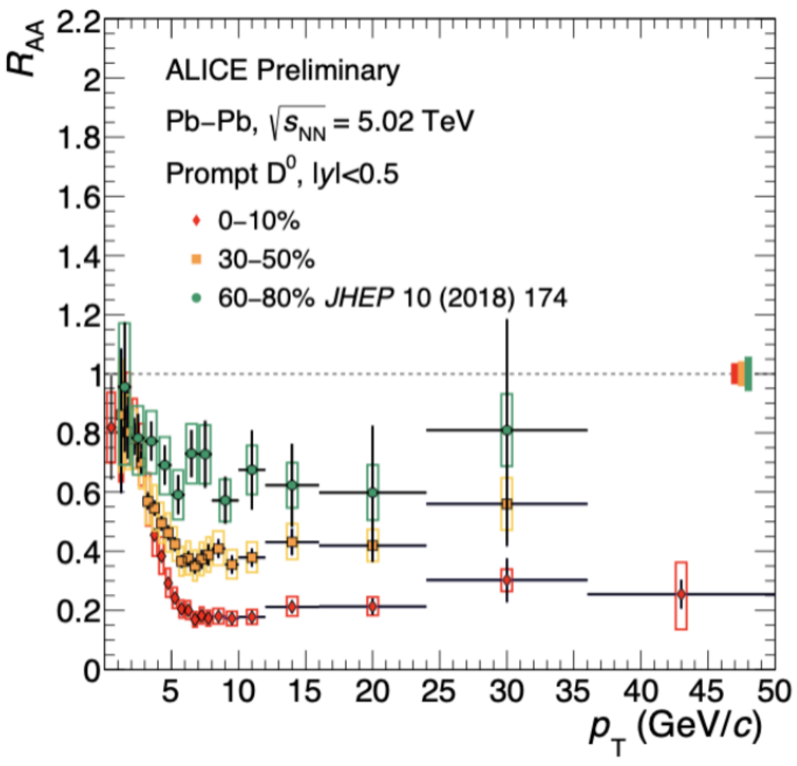
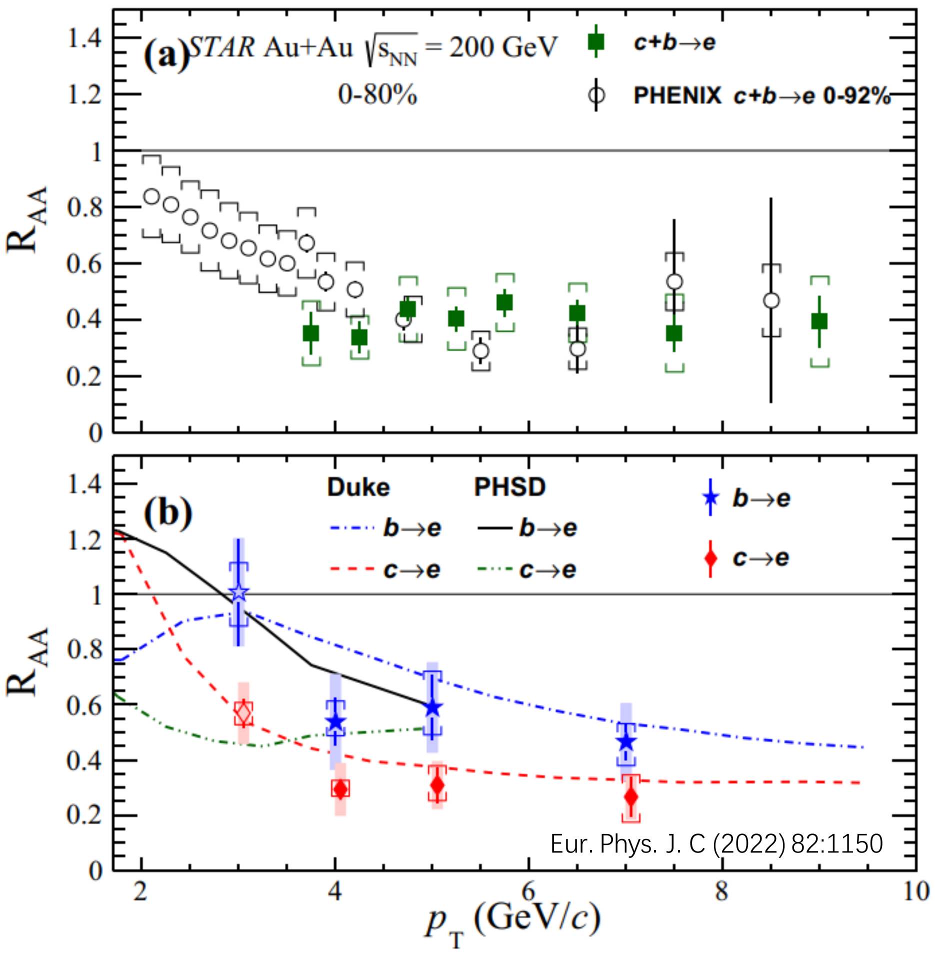
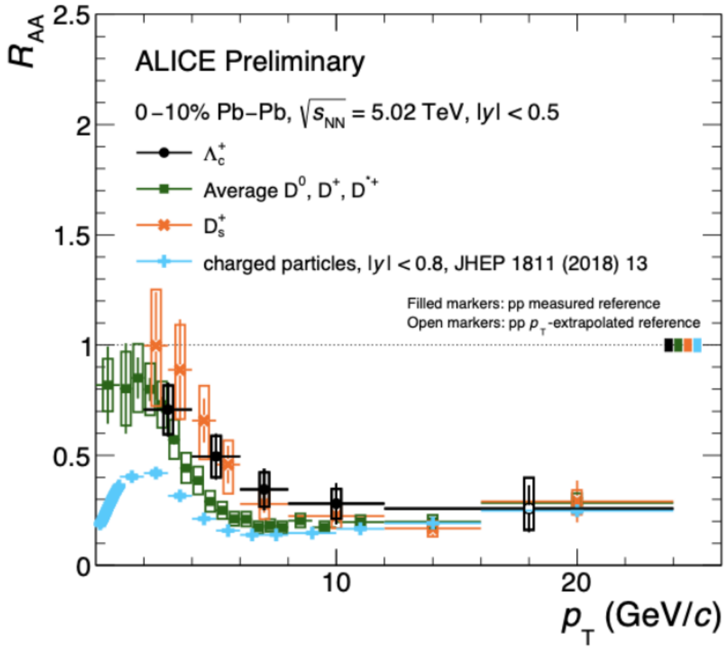
- Relative abundances
  - fragmentation fractions
  - hadronisation scenario (independent on system and energy)
- Universality of the fragmentation fractions for charm can not be ruled out in the meson sector.

- Λ_c/D^0 yield ratio is comparable to the baryon-to-meson ratios for light and strange-flavor hadrons
- Baryons contribute significantly to the total charm cross section
- Fragmentation fractions of charm quarks are non-universal

Energy loss mechanisms and Mass ordering







- Measured down to $p_T = 0$ in central collisions
- A large suppression is observed at low-intermediate p_T, and it is larger for the most central class

- Bottom decay electron R_{AA} to be significantly higher than those of charm-decay electrons
- $R_{AA}(\mathrm{gluons, u, d}) < R_{AA}(\mathrm{c}) < R_{AA}(\mathrm{b})$

Technical details: Formulas

Spectra

$$E\frac{d^3N}{d\boldsymbol{p}^3} = \frac{d^3N}{p_T dp_T dy d\phi} = \frac{d^2N}{2\pi p_T dp_T dy}$$

$$\frac{d^2N}{2\pi p_T dp_T dy} = \frac{\Delta N^{raw}/\epsilon_{D^0}^{tot}/2}{2\pi p_T \Delta p_T \Delta y \times N_{events} \times B.R.} = \frac{\Delta N_{D^0}^{AA}}{2\pi p_T \Delta p_T \Delta y} = E\frac{d^3\sigma_{D^0}^{AA}}{d\boldsymbol{p}^3}$$

Nuclear modification factor

$$R_{AA} = \frac{d^2N_{AA}^{D^0}/dp_T dy}{< T_{AA} > d^2\sigma^{PP}/dp_T dy} = \frac{\sigma_{inel}^{NN} d^2N_{AA}^{D^0}/dp_T dy}{< N_{coll} > d^2\sigma^{PP}/dp_T dy}$$

$$R_{cp} = \frac{Y(0-10\%)/< N_{coll\_0-10} >}{Y(40-80\%)/< N_{coll\_40-80} >}$$

$$< T_{AA} > \times \sigma_{inel}^{NN} = < N_{coll} >$$ 42 mb

Systematic uncertainties for integrated D^0 cross section

$$\frac{d\sigma_{D^0}^{NN}}{dy}|_{y=0} = \frac{dN_{D^0}^{AA}}{dy}|_{y=0} \times \frac{\sigma_{inel}^{pp}}{< N_{bin} >}$$ 3

1

$$\frac{dN_{D^0}^{AA}}{dy}|_{y=0} = \frac{(\Delta N^{raw} - D.C)/\epsilon_{D^0}^{tot}/2}{\Delta y \times N_{events} \times B.R.}$$ 2

Open Charm Hadron	Constitution
D^0	$c\bar{u}$
D^+	$c\bar{d}$
D_s^+	$c\bar{s}$
Λ_c^+	udc

Levy func

$$\frac{A(n-1)(n-2)}{nT(nT+m_0(n-2))} \times (1 + \frac{m_T - m_0}{nT})^{-n}$$

m_T Spectra

$$\frac{d^2N}{2\pi p_T dp_T dy} = \frac{d^2N}{2\pi m_T dm_T dy} = \frac{dN/dy}{2\pi T_{\text{eff}}(m_0 + T_{\text{eff}})} e^{-(m_T - m_0)/T_{\text{eff}}}$$

Blast-Wave func

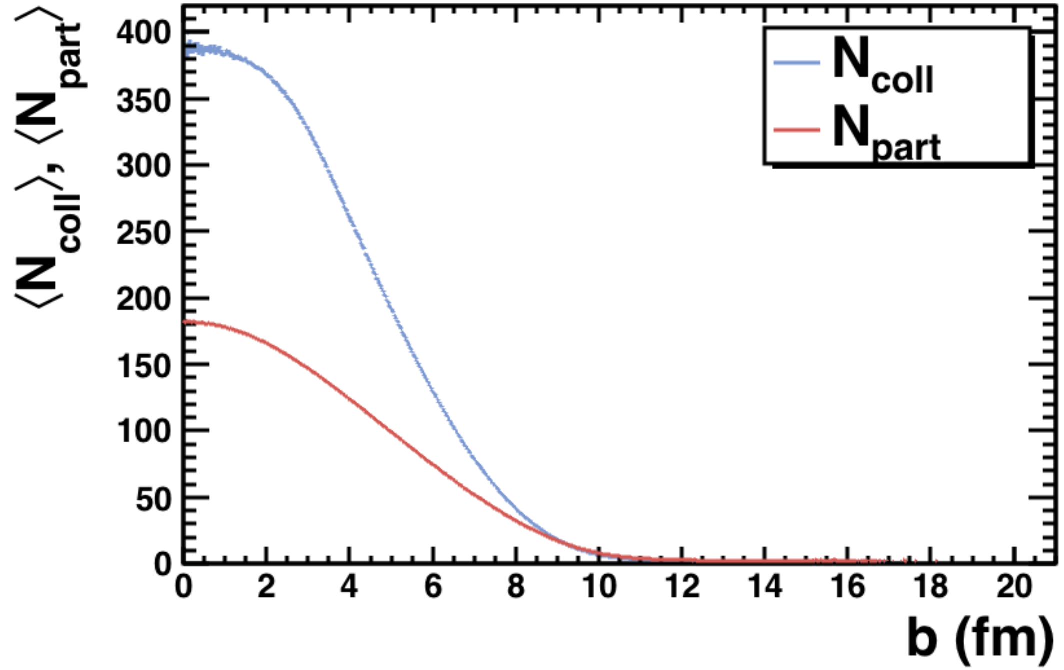
$$E\frac{d^3N}{dp^3} \propto \int_0^R r dr m_T I_0\left(\frac{p_T \sinh(\rho)}{T_{\text{kin}}}\right) K_1\left(\frac{m_T \cosh(\rho)}{T_{\text{kin}}}\right)$$

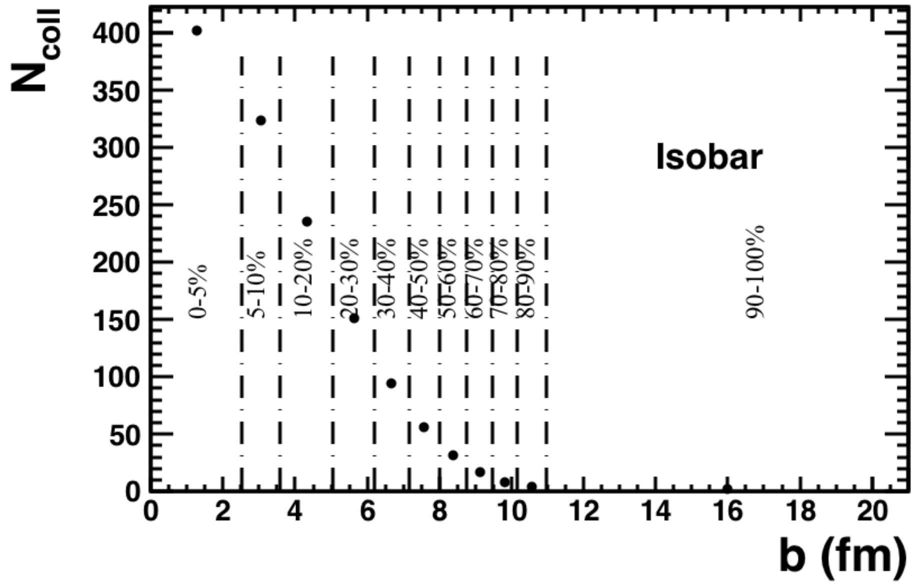
$$E\frac{d^3N}{dp^3} \propto m_T \int_{-Y}^{+Y} \cosh(y) dy \int_{-\pi}^{+\pi} d\phi \int_0^R r dr \left(1 + \frac{q-1}{T_{\text{kin}}}(m_T \cosh(y)\cosh(\rho) - p_T \sinh(\rho)\cos(\phi))\right)^{-\frac{1}{q-1}}$$

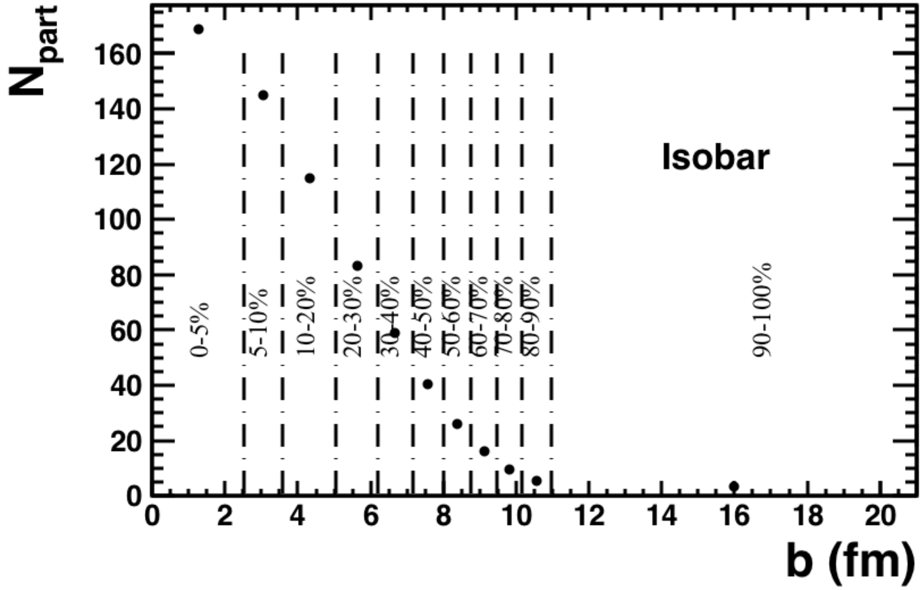
Glauber model simulation

R=5.02 fm   a=0.46 fm

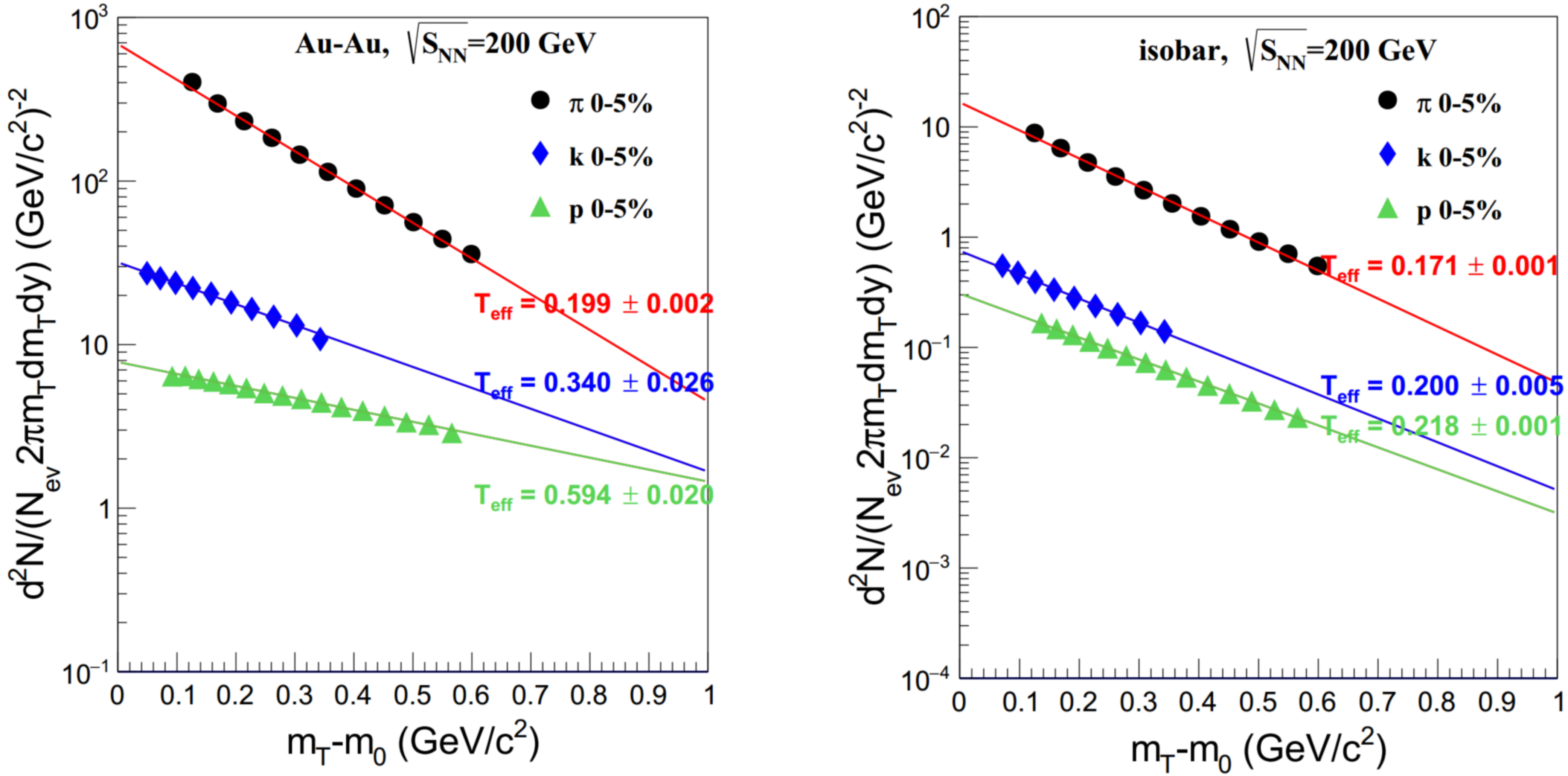
$\sigma_{inel}^{NN} = 42\,mb$





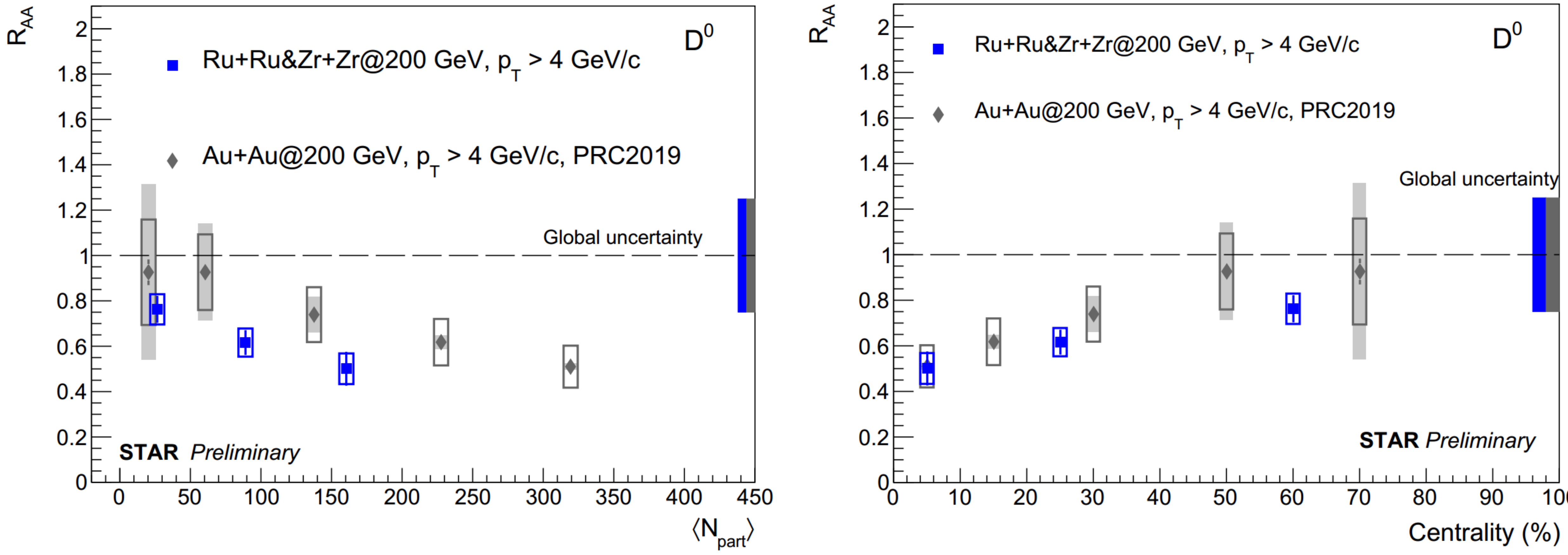


m_T-spectra fit details



- m_T-spectra fit details for Au + Au (left) and isobar (right).

System size dependence of R_{AA}



v_2 measurement

- Event plane construction

$$\Psi_2 = \frac{1}{2}\tan^{-1}\left(\frac{Q_y}{Q_x}\right)$$

$$Q_x = \Sigma\left(q_x - < q_x >\right)$$

$$Q_y = \Sigma\left(q_y - < q_y >\right)$$

$$q_x = p_T \cos(2\phi)$$

$$q_y = p_T \sin(2\phi)$$

- v_2 calculation

$$v_2 = \frac{\bar{v}_2}{R}$$

$$R =< \cos\left(2\left(\Psi_2 - \Psi_{rp}\right)\right) >$$

$$\bar{v}_2 =< \cos[2(\phi - \Psi_2)] >$$