# Measurements of Charm Quark Interaction with the QGP in Heavy-Ion collisions at STAR

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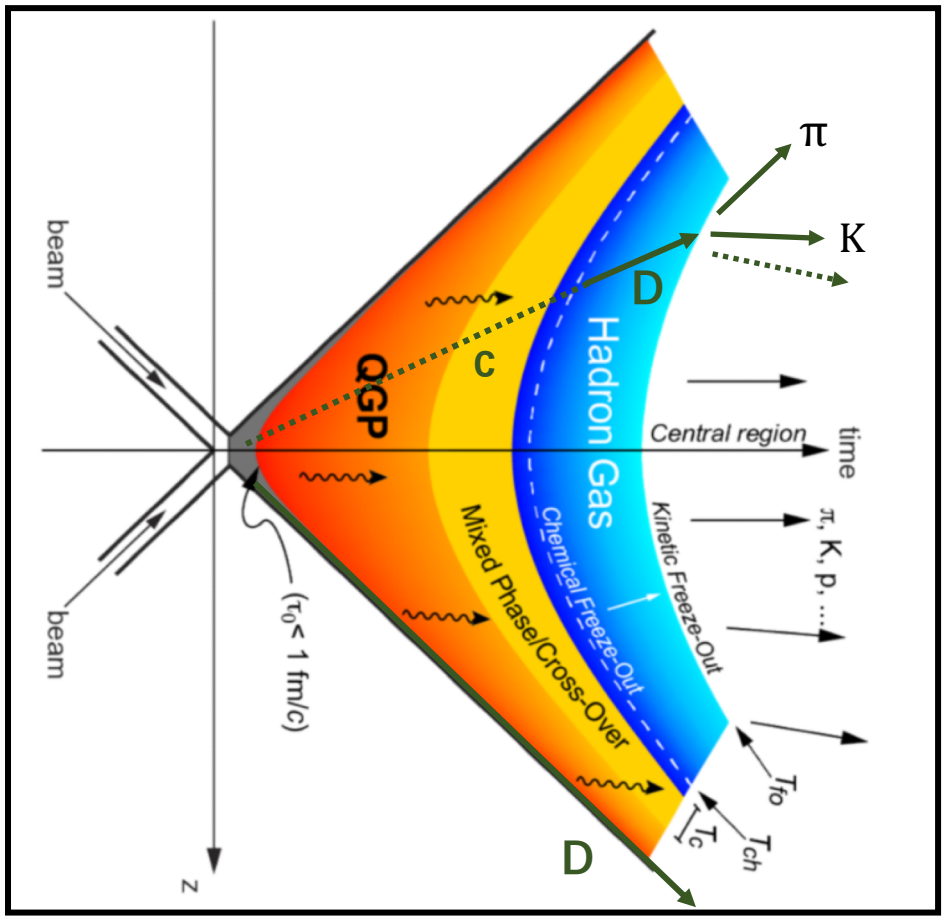
# Heavy-flavour as QGP probe



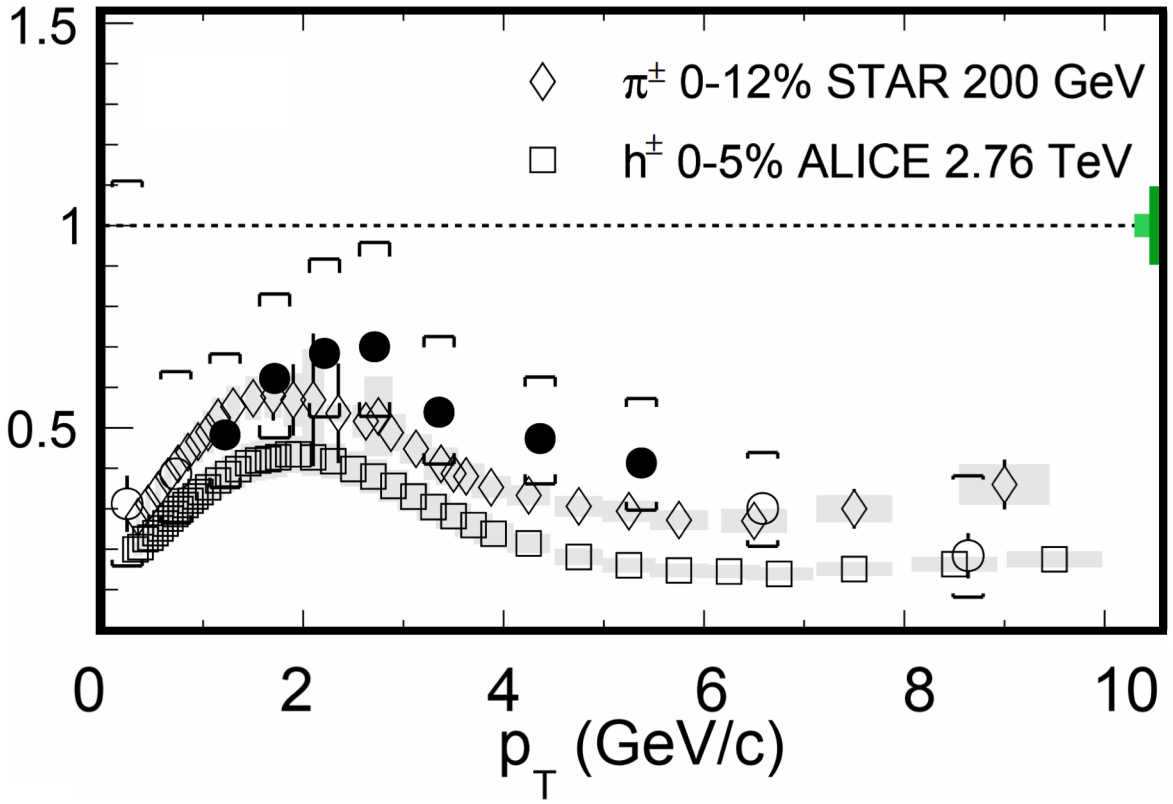

Open heavy-flavour offers **unique insight** into QGP properties:

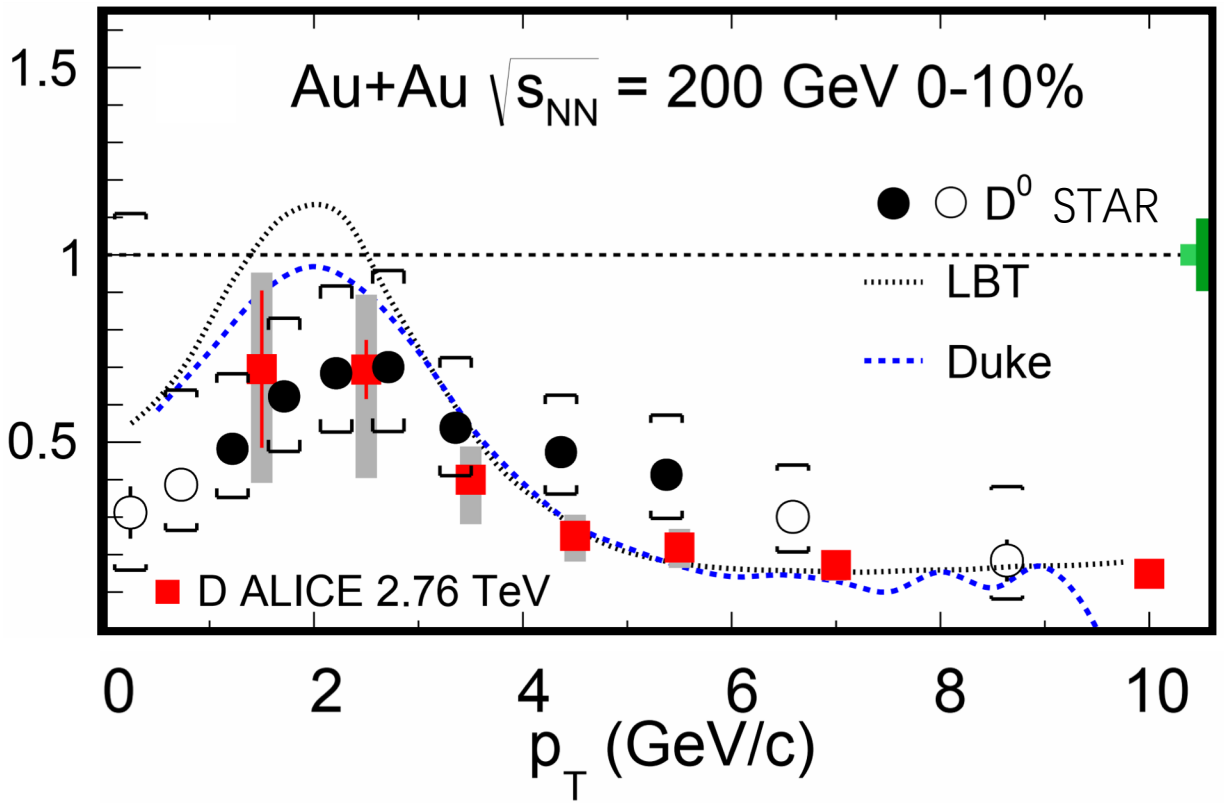
- $m_C > \Lambda_{QCD}$ → **initial hard scatterings** → calculable with pQCD (well-calibrated probe)
- Experience the entire evolution of the QGP; **energy loss in the medium**
  - Gluon radiation
  - Collisional energy loss
- **Nuclear modification factor $R_{AA}$** of heavy flavor hadrons can be used to measure energy loss

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

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

STAR, Phys. Rev. C 99, 034908

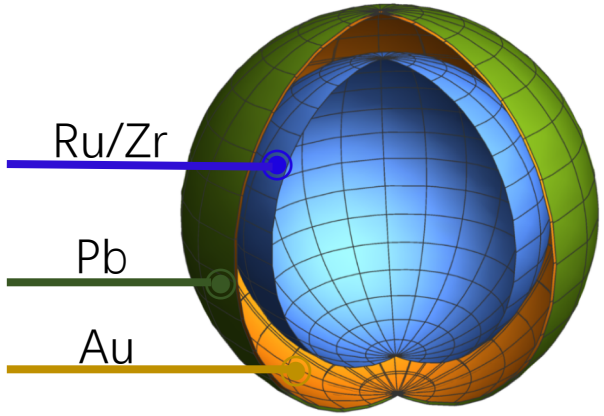


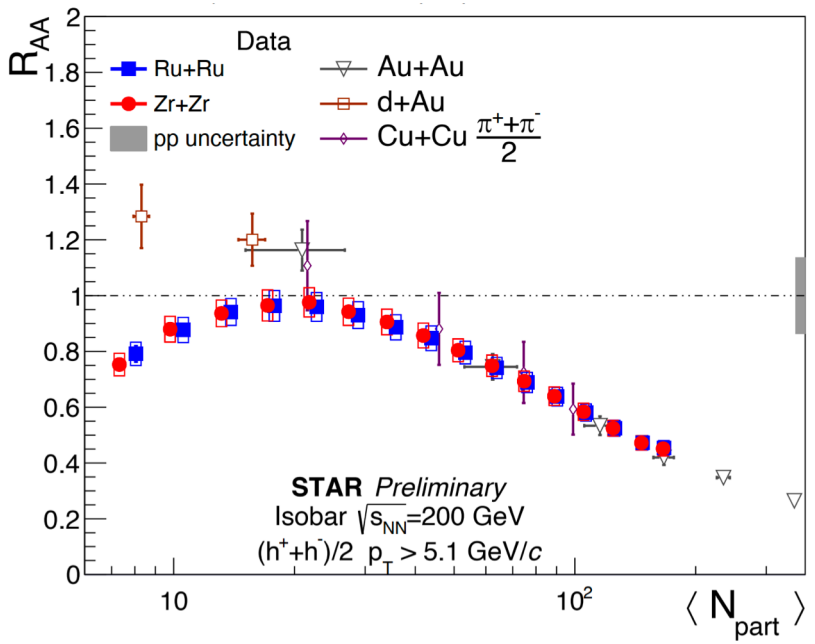




- Suppression level comparable to that of light hadrons in 0-10%
- Similar suppression in Au+Au and Pb+Pb
- What is the system size dependence of charm quark energy loss and hadronization?

# 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 $D^0$?

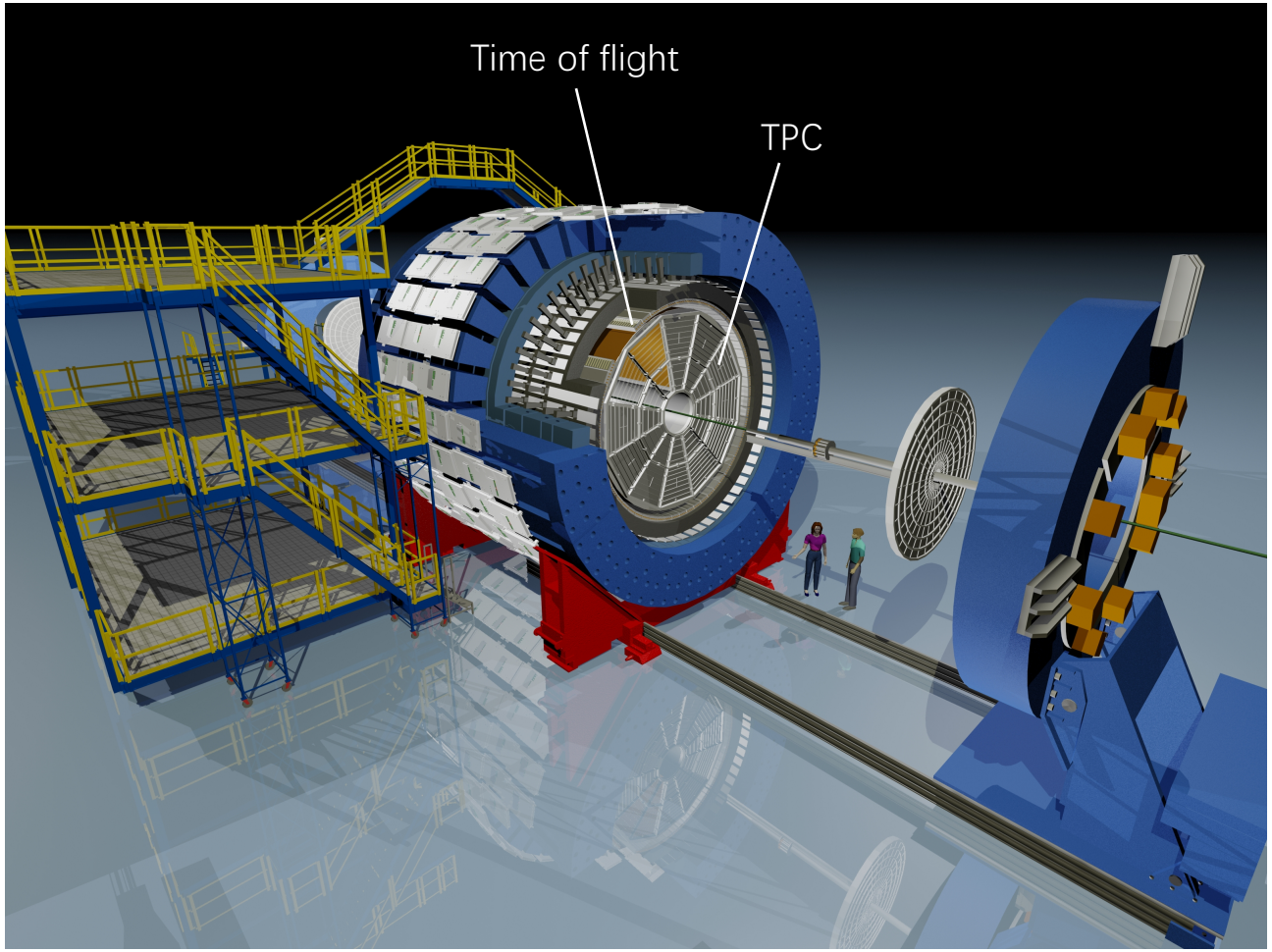


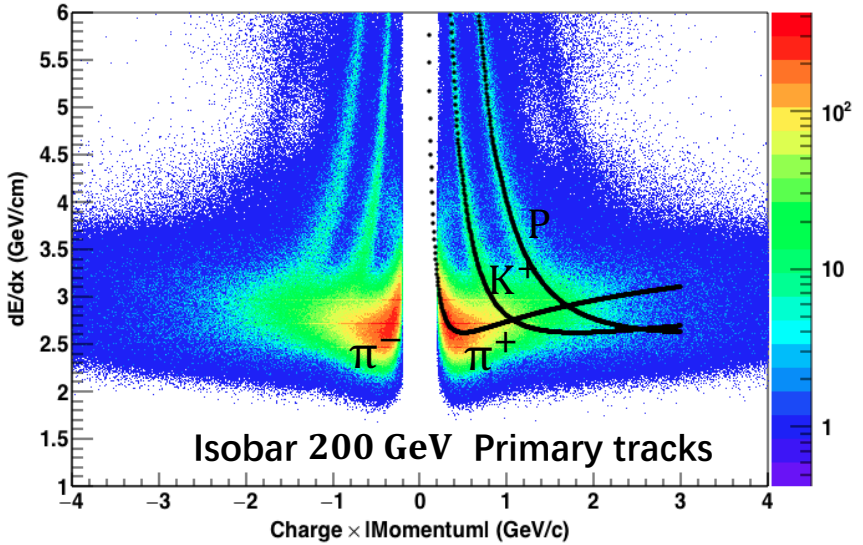



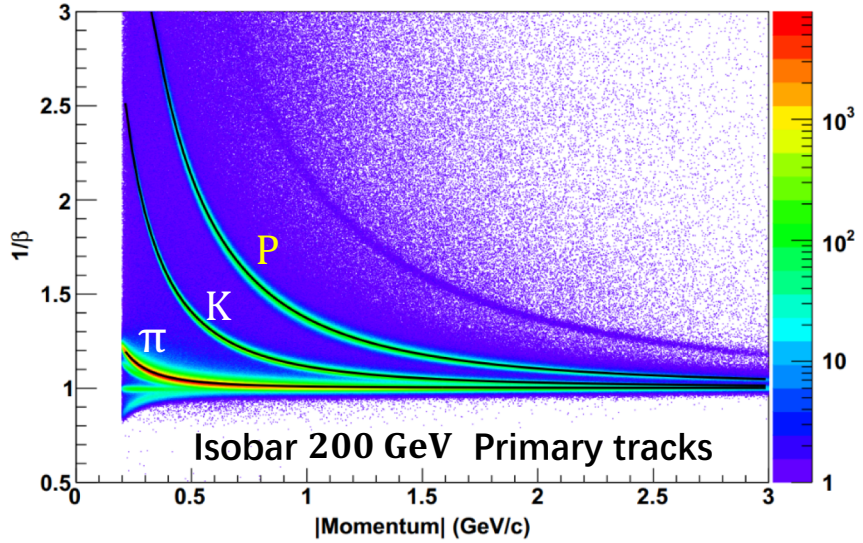

STAR Phys. Rev. Lett. 91, 172302 (2003) STAR Phys. Rev. C 81, 054907 (2010)

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

# STAR detector



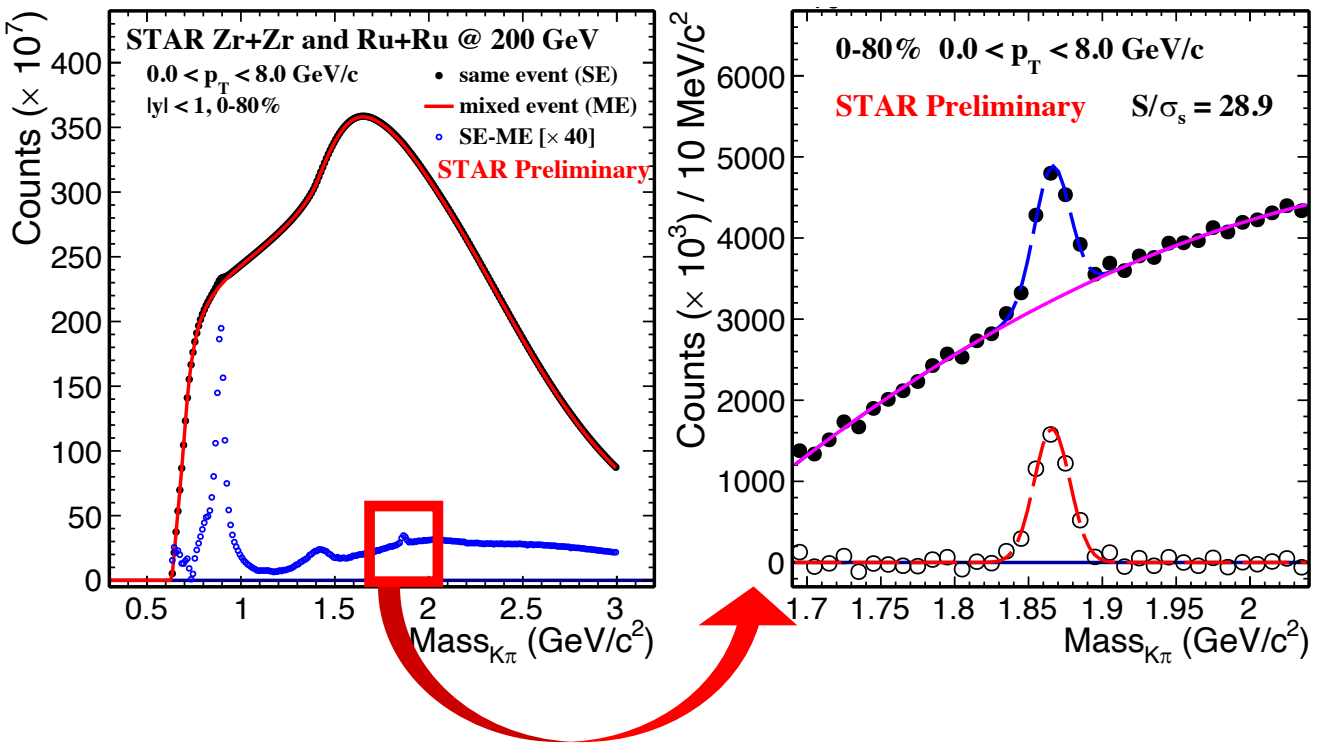



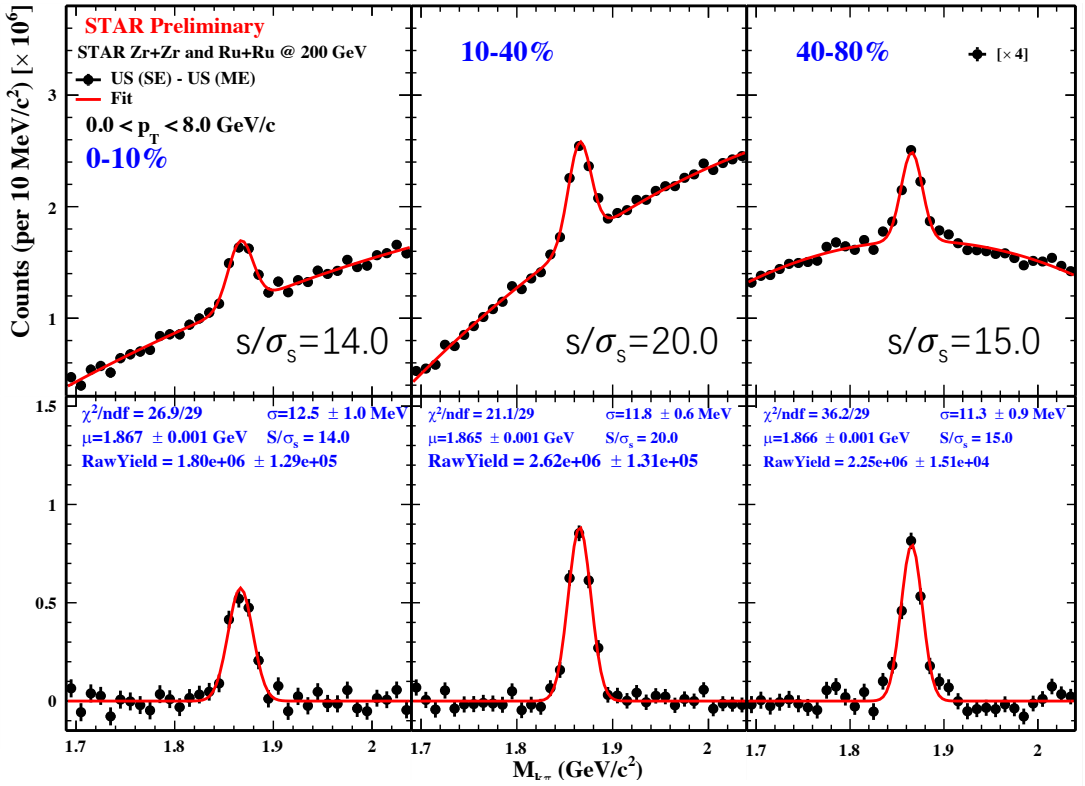




- Time Projection Chamber (TPC)
  - ~ 350 μm, vertex resolution with more than 1000 tracks
- Time Of Flight detector (TOF)
  - the precise 1/β extends PID reach

# $D^0$ signal reconstruction

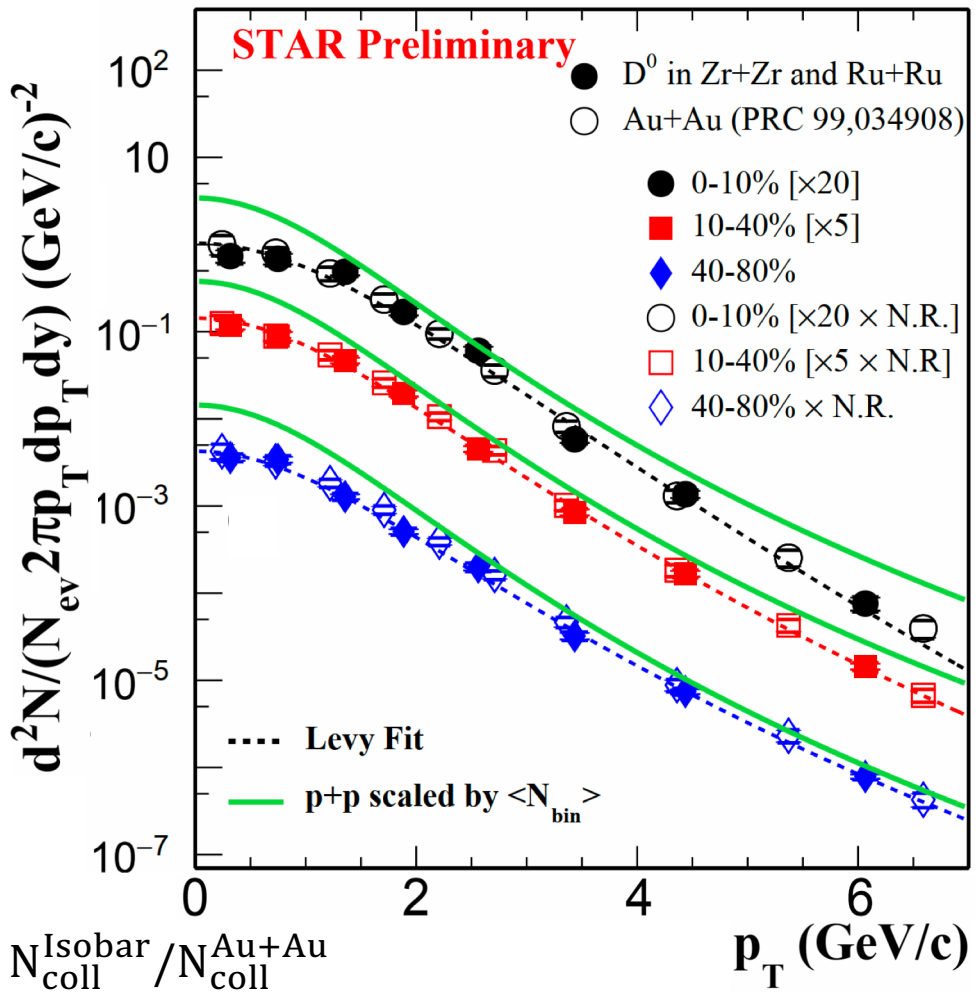
**Hadronic mode:** $D^0 \rightarrow K^- + \pi^+; \bar{D}^0 \rightarrow K^+ + \pi^- (\Gamma_i/\Gamma \sim 3.9\%)$



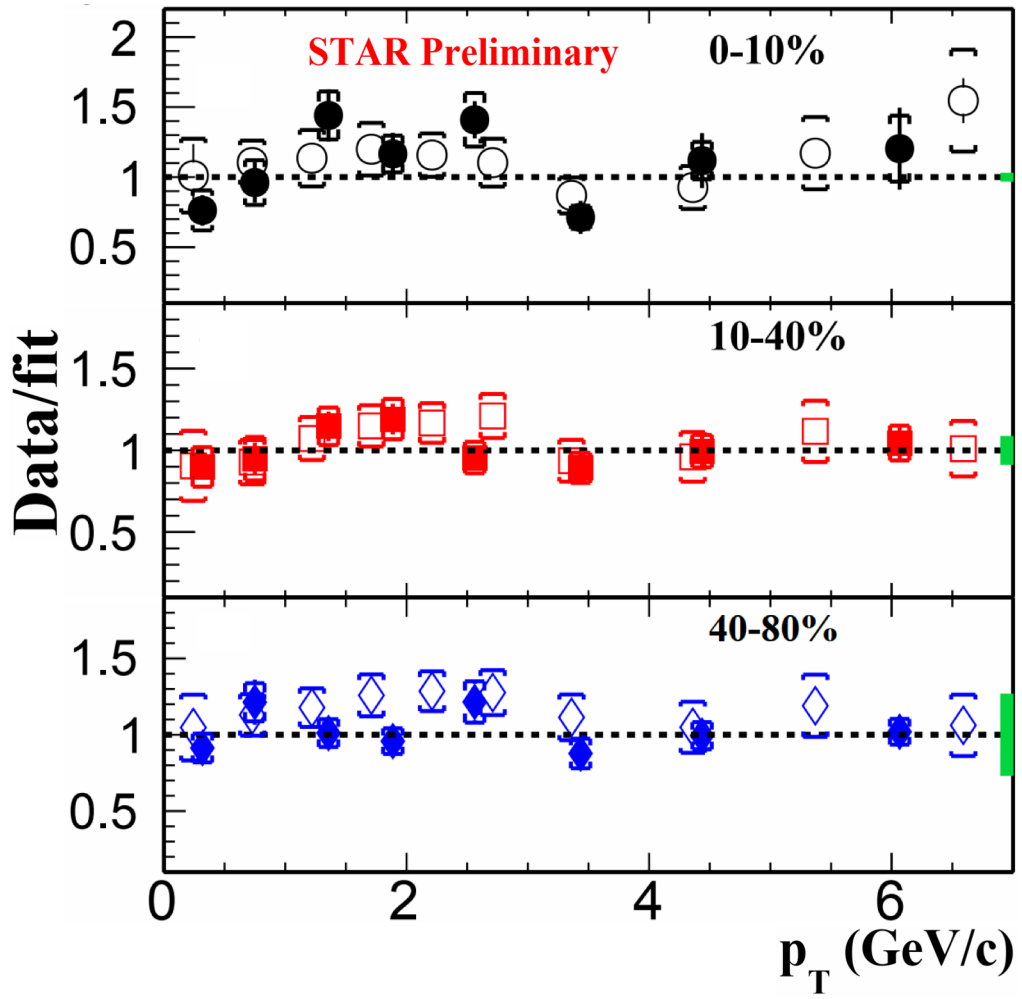




- Signal is extracted via an invariant-mass analysis
- The mixed event method can reproduce the combinatorial background well
- Good signal significance enables us to study the dependence of $D^0$ yields on centrality and transverse momentum

# $D^0$ production in Isobar collisions

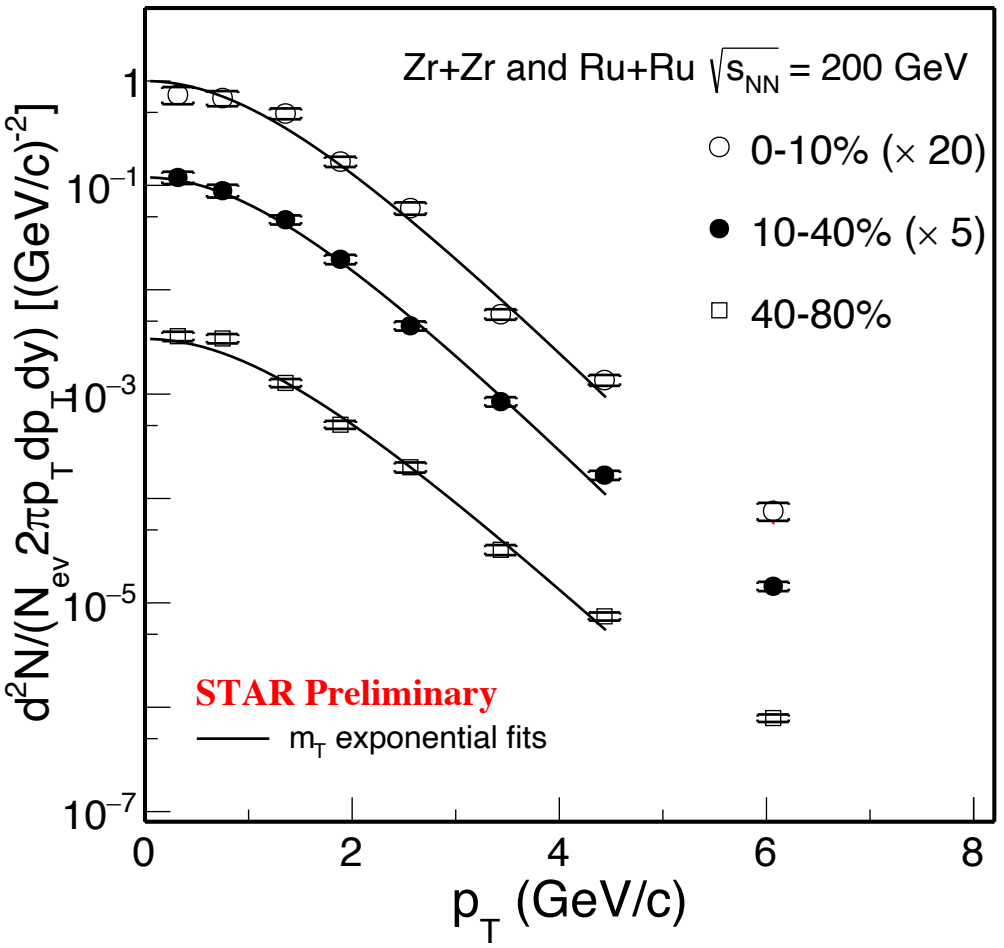


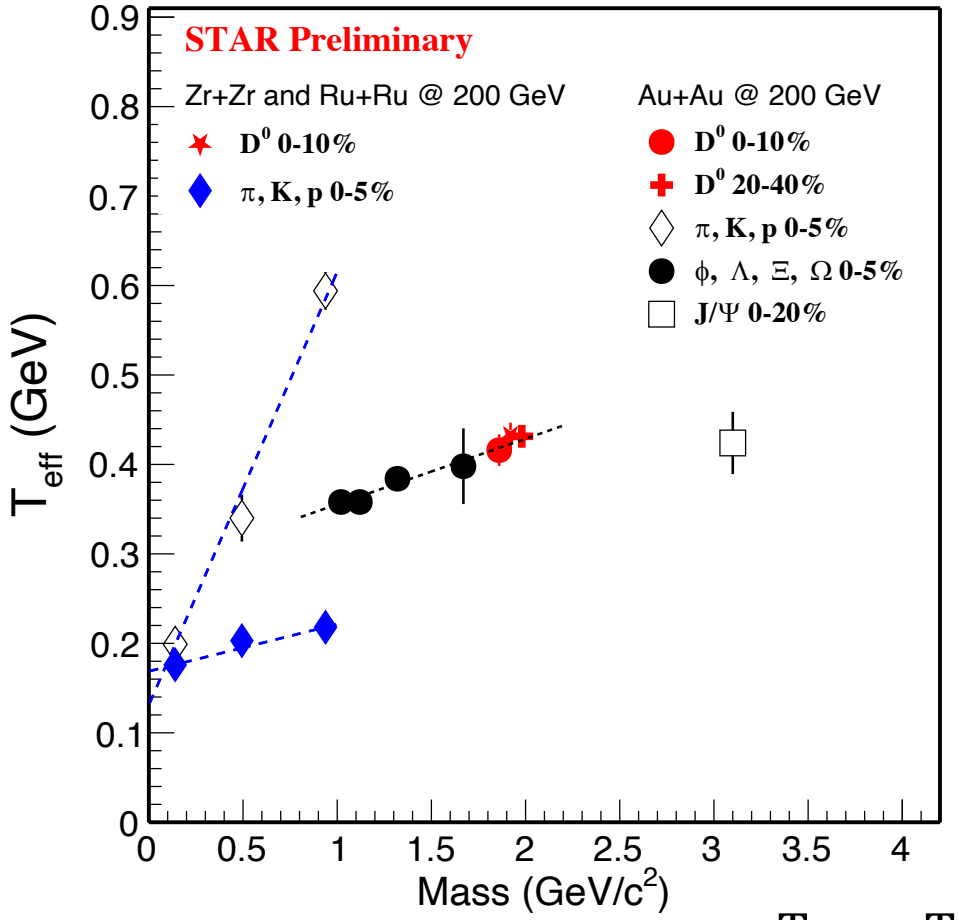

$$N.R. = N_{coll}^{Isobar} / N_{coll}^{Au+Au}$$




- $D^0$ production cross section **follows $N_{coll}$ scaling within uncertainties** between isobar and Au+Au collisions at the same collision energy

# $D^0$ spectra and collectivity

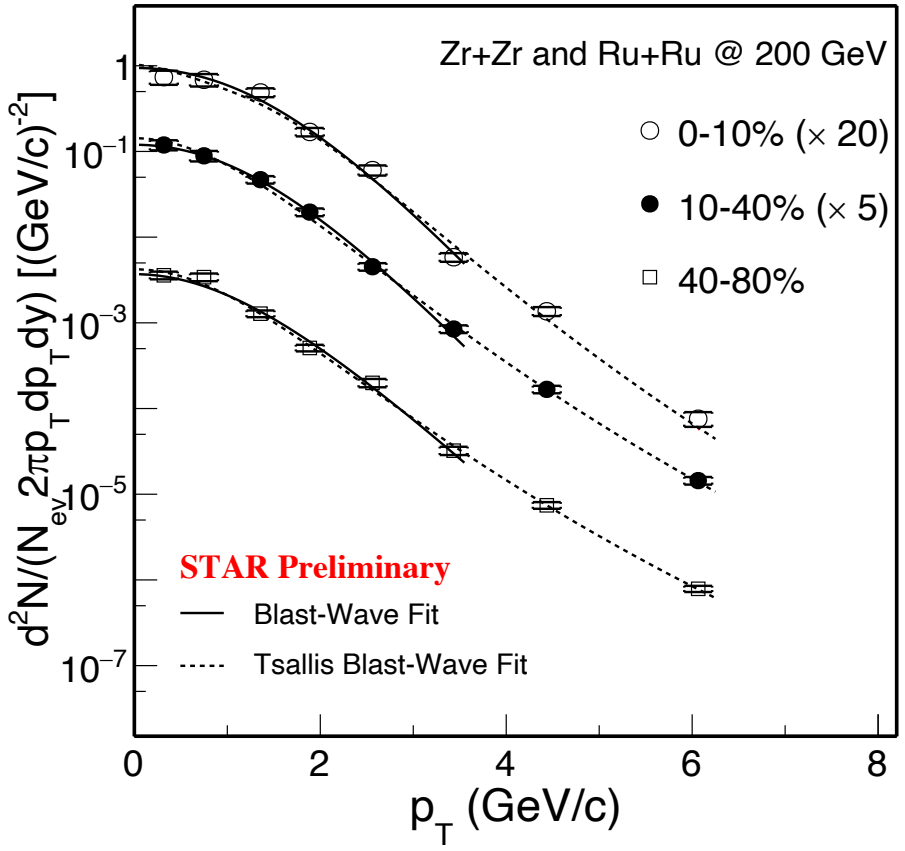


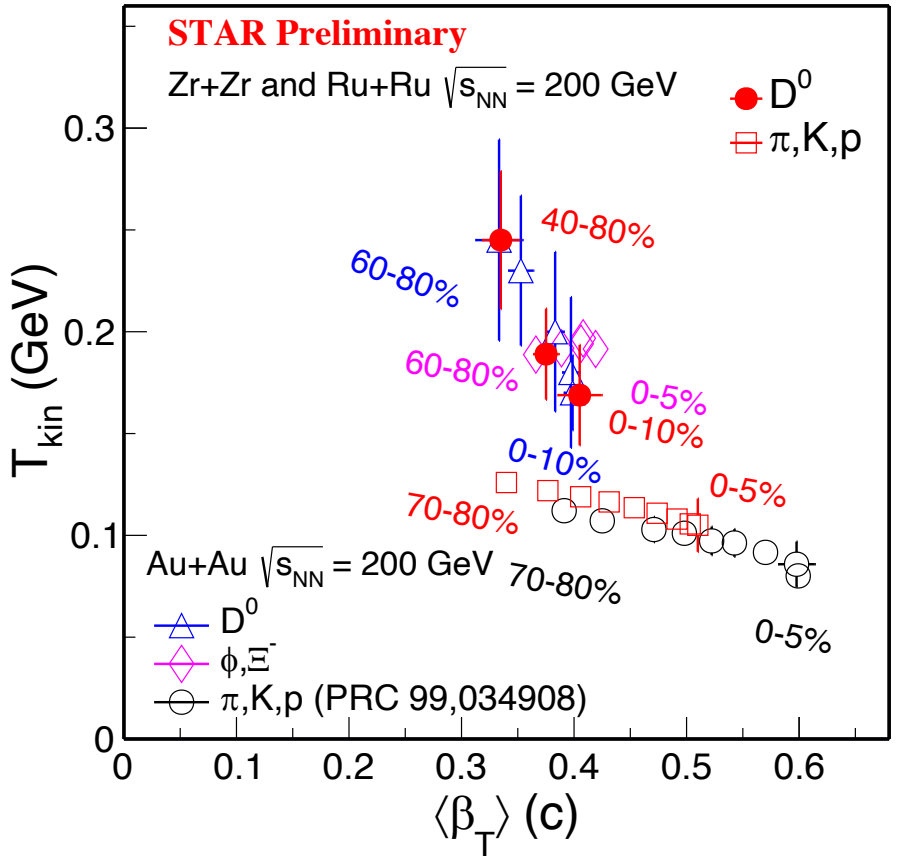




$$T_{eff} = T_{th} + m \langle \beta_T \rangle^2$$

- $D^0$ $T_{eff}$ is consistent with result in Au+Au collisions in same centrality within uncertainties
- Smaller radial flow (slope of $T_{eff}$) for light hadrons in isobar collisions than in Au+Au

# Blast-Wave fits



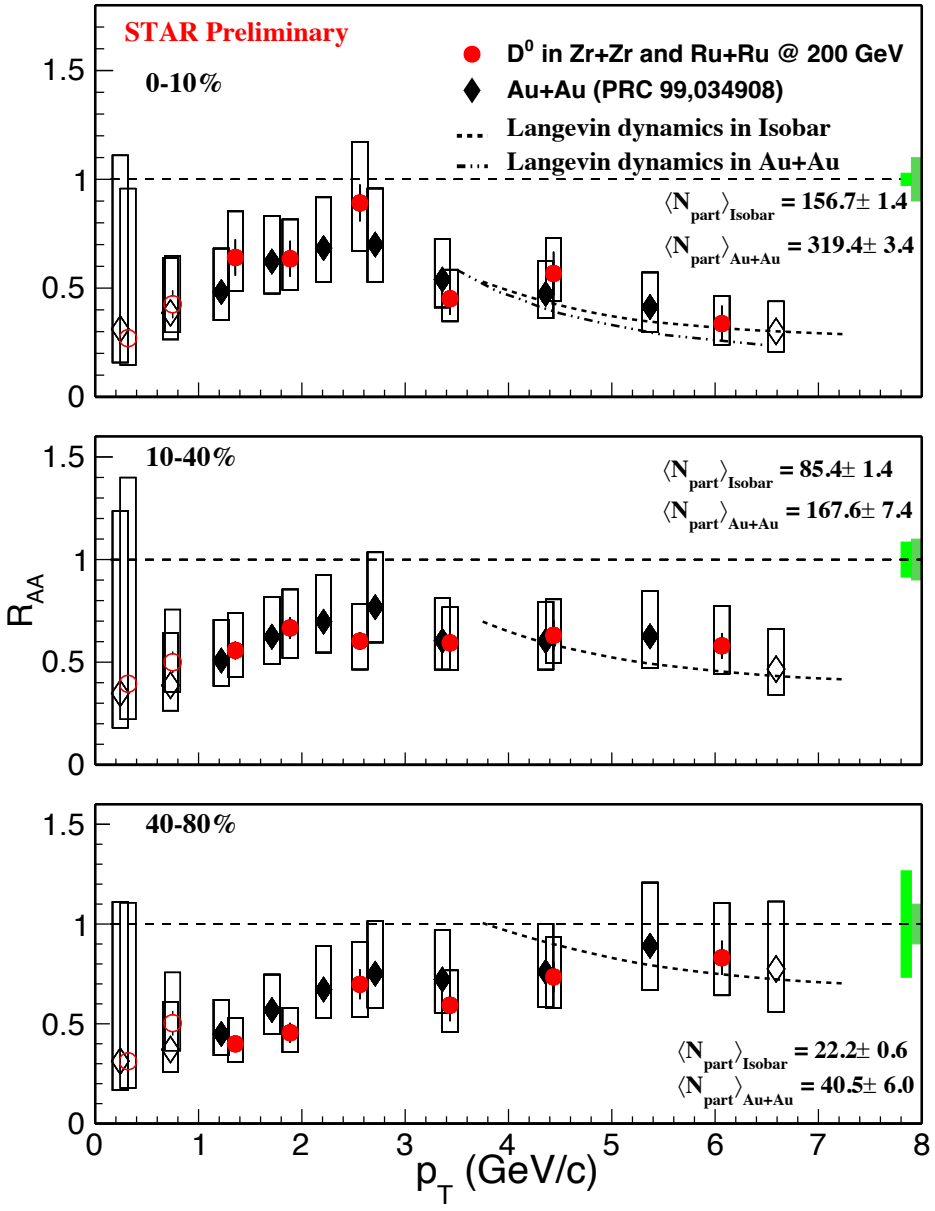




- $T_{kin}$ decreases with centrality while $\langle\beta_T\rangle$ has the opposite trend
- $D^0$ seems to freeze out earlier than light hadrons
- At same centrality, $D^0$ freeze-out parameters in isobar are consistent with those in Au+Au within uncertainties, while light hadrons behave differently

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

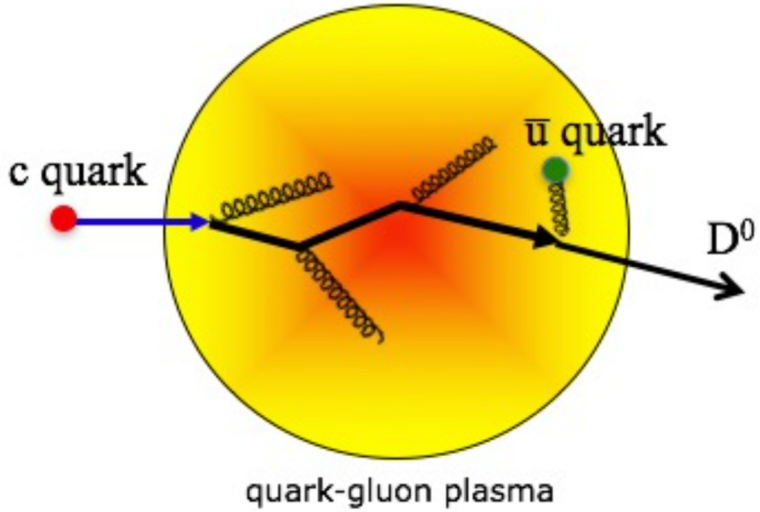
- Significant $D^0$ $R_{AA}$ suppression observed at high-$p_T$ in central collisions
- Suppression decreases from central to peripheral collisions → consistent with decreasing hot medium effects
- Similar suppression between isobar and Au+Au collisions in same centrality
- Theoretical model that includes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

Model calculation: G. Qin, private communication



# $D^0$ tagged jet in heavy-ion collisions

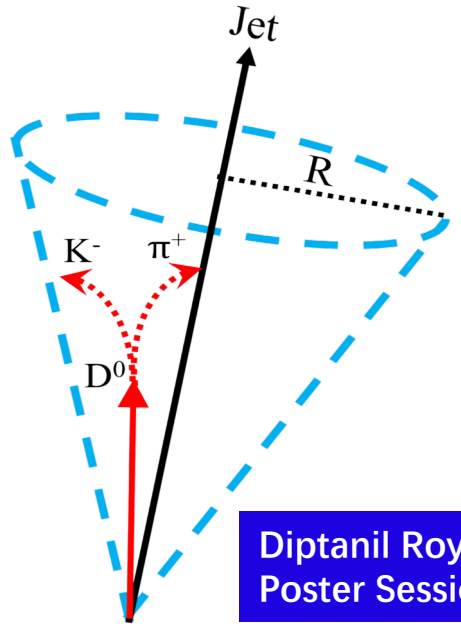
- $D^0$ tagged jets probe energy loss mechanism in more details
  - Redistribution of the lost energy
  - Modification to the shower pattern




- Observables
  - Inclusive $D^0$ jet yield: **$R_{CP}$ as a function of $p_{T,Jet}$**
  - Transverse and longitudinal structure

**Radial profile** $\frac{1}{N_{Jet}^{D^0}}\frac{dN_{Jet}^{D^0}}{d(\Delta r)}$ ; $\Delta r = \sqrt{(\eta_{Jet}^2 - \eta_{D^0}^2) + (\phi_{Jet}^2 - \phi_{D^0}^2)}$

**Fragmentation function** $z_{Jet} = \frac{\vec{p}_{T,Jet}\cdot\vec{p}_{T,D^0}}{p_{T,Jet}^2}$




- $D^0$ tagged jet at lower kinematics **$1 < D^0\ p_T < 10$ GeV/c**

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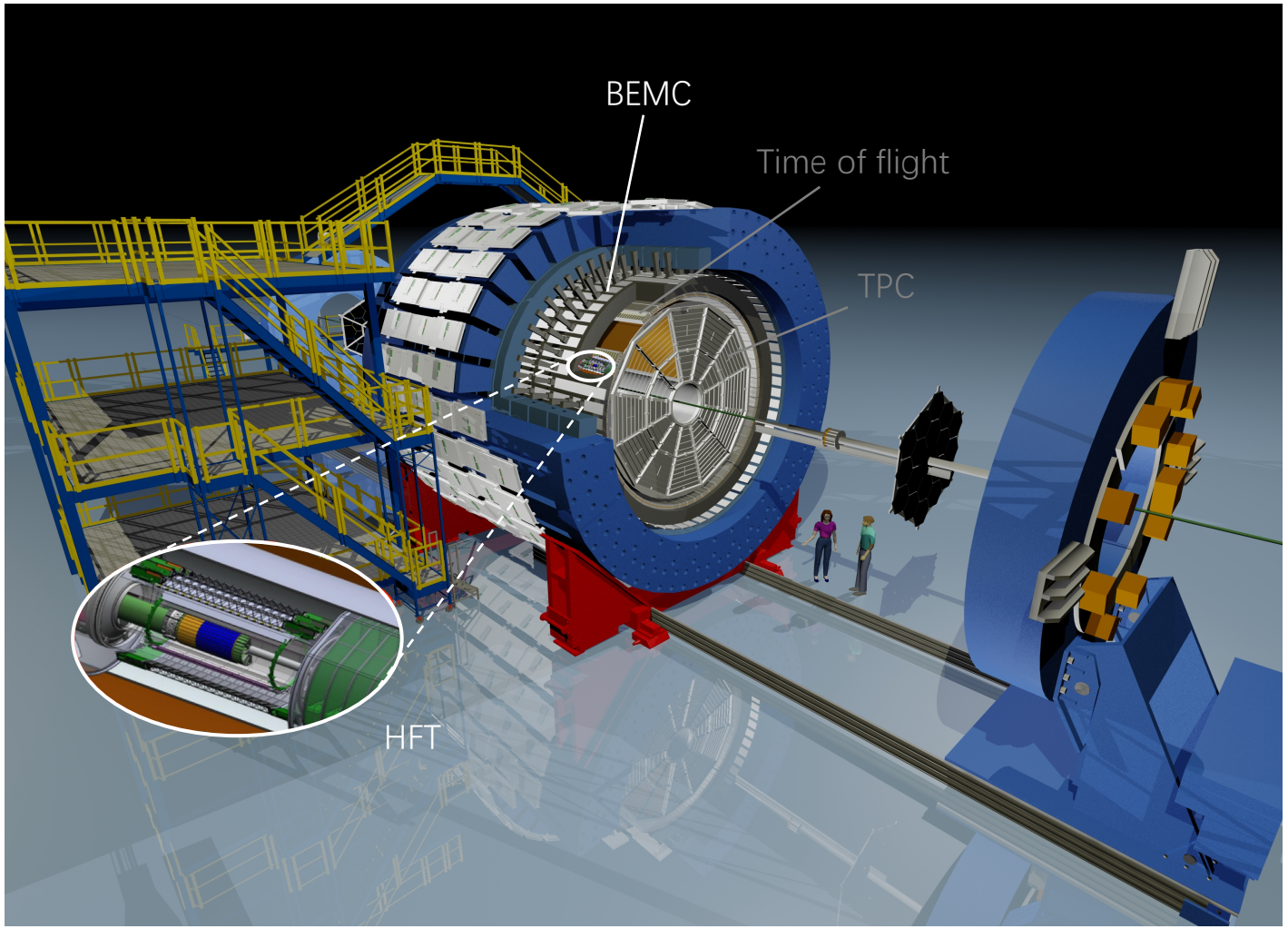
**Poster Session ID 124**

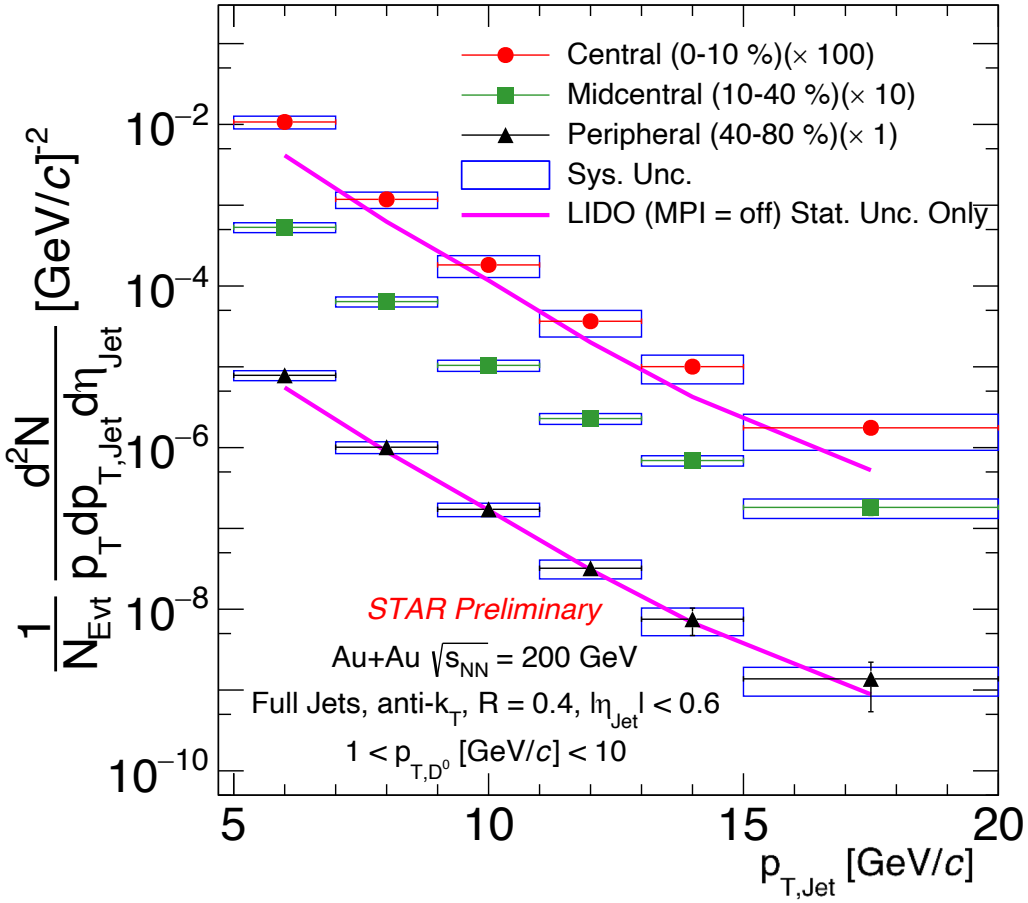
# STAR detector and dataset

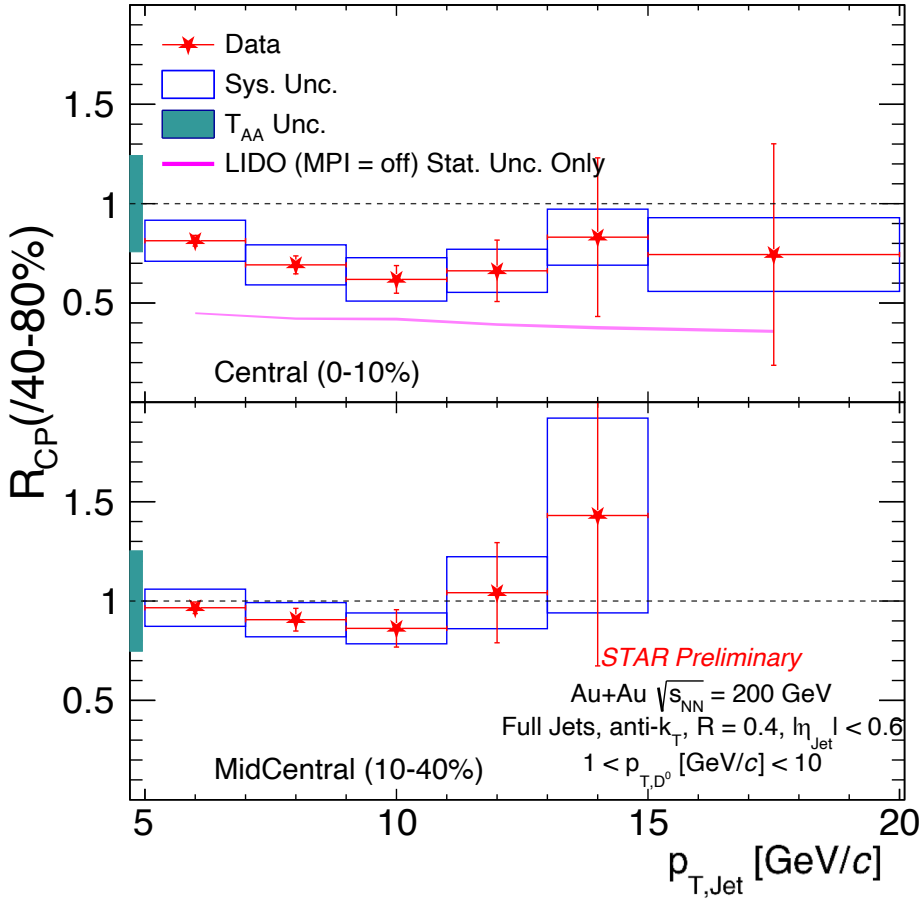



Au+Au @ 200 GeV, 2014

- Heavy Flavor Tracker (HFT)
  - ~ 30 μm, adding PXL hits into TPC track
- Barrel Electromagnetic Calorimeter (BEMC)
  - measures neutral component of energy in jets

# $D^0$-jet transverse momentum spectra




LIDO, Phys. Rev. C 98, 064901

- Hint of suppression of $D^0$ meson tagged jet yield in central collisions
- LIDO, which considers heavy quark evolution in medium with collisional and radiative energy losses, is consistent with the data in peripheral, but underestimates in central

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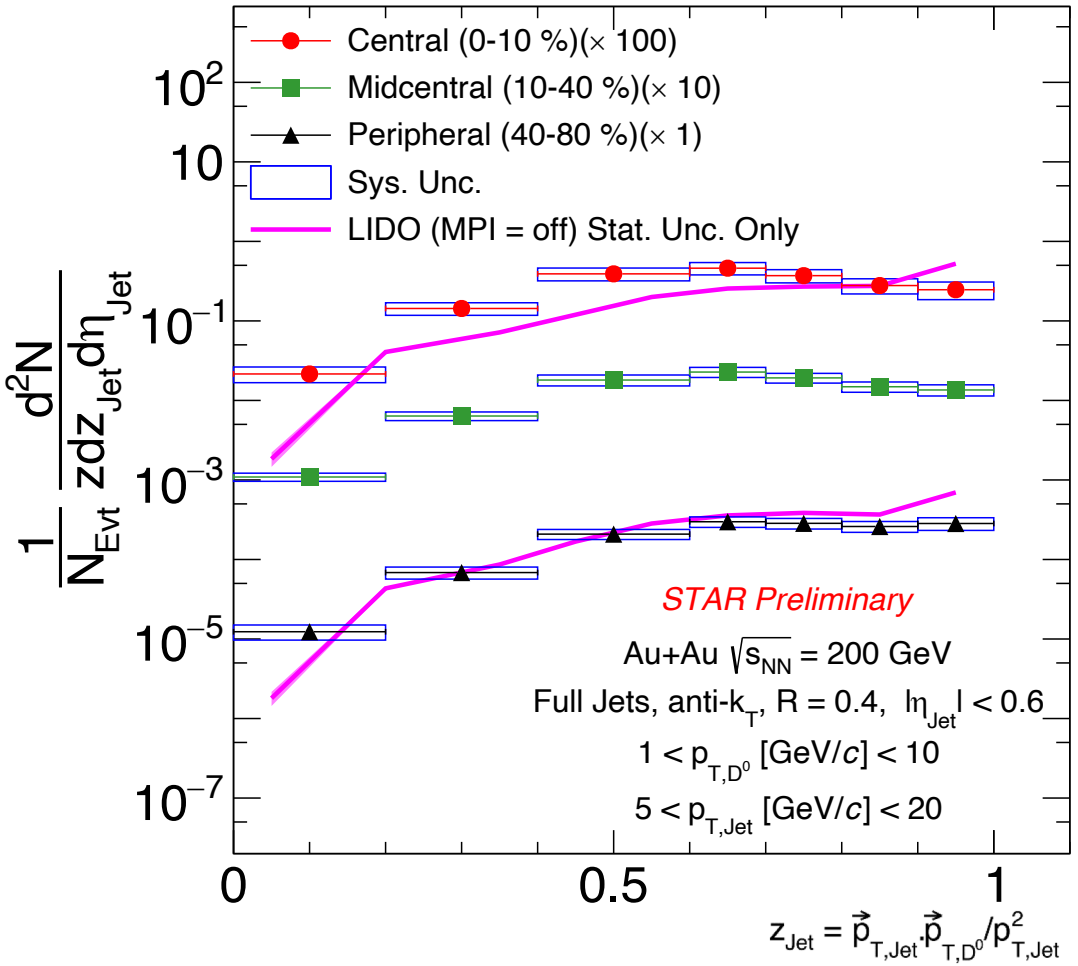
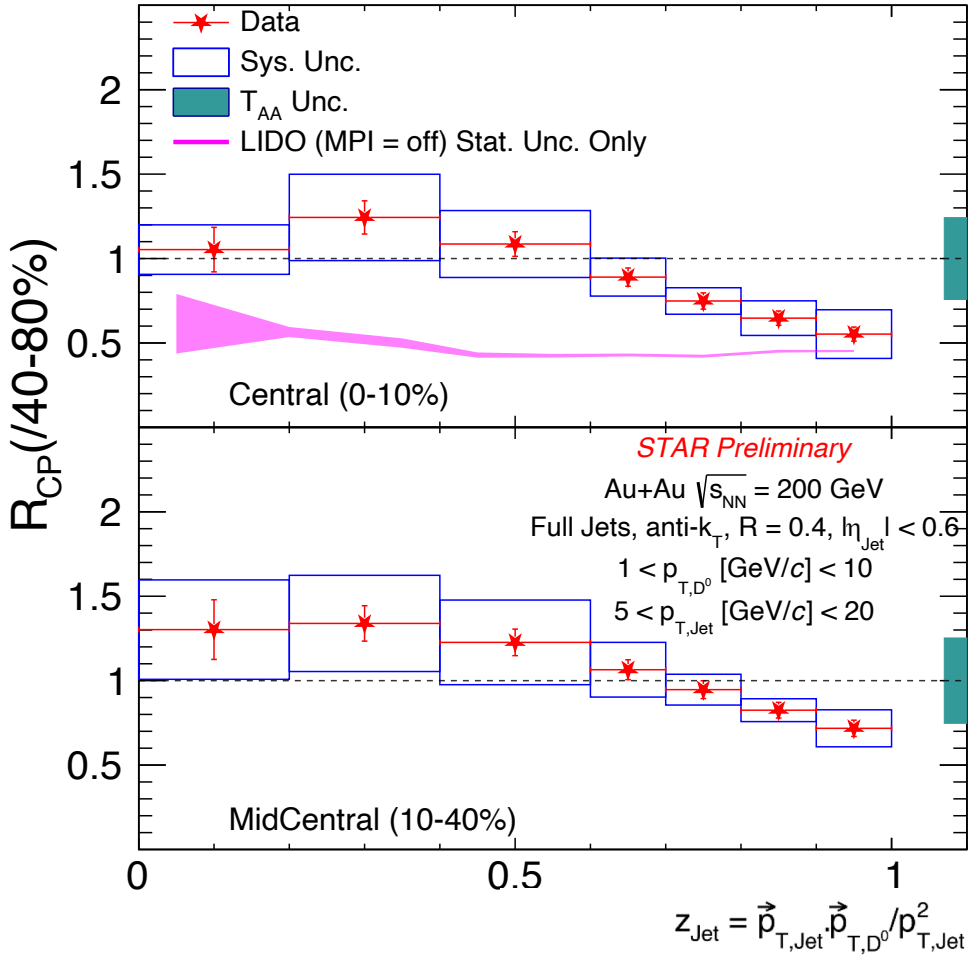
# $D^0$-jet fragmentation function




LIDO, Phys. Rev. C 98, 064901

- $D^0$ tagged jet differential yield as a function of momentum fraction $z_{Jet}$
- Hard fragmented charm jets show signs of suppression, while soft fragmented jets have $R_{CP}$ consistent with 1

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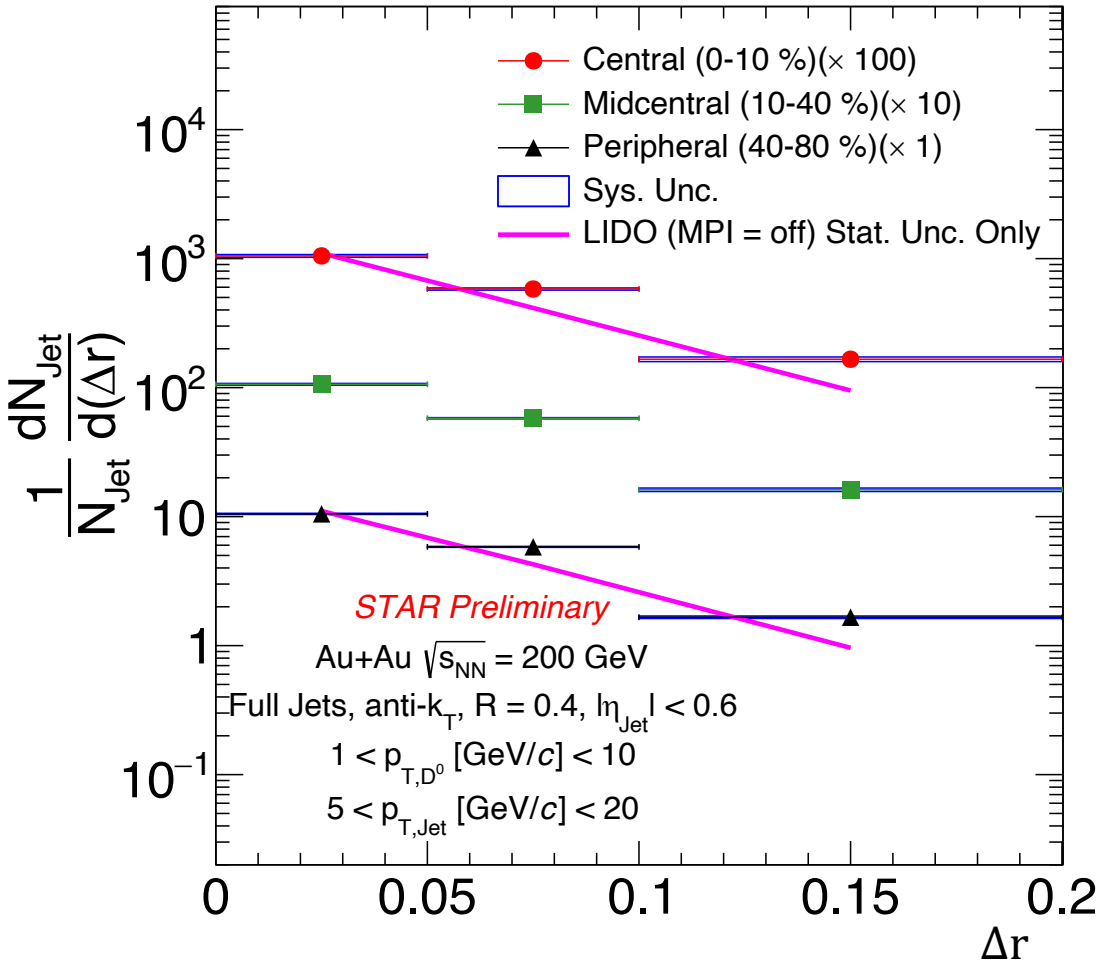
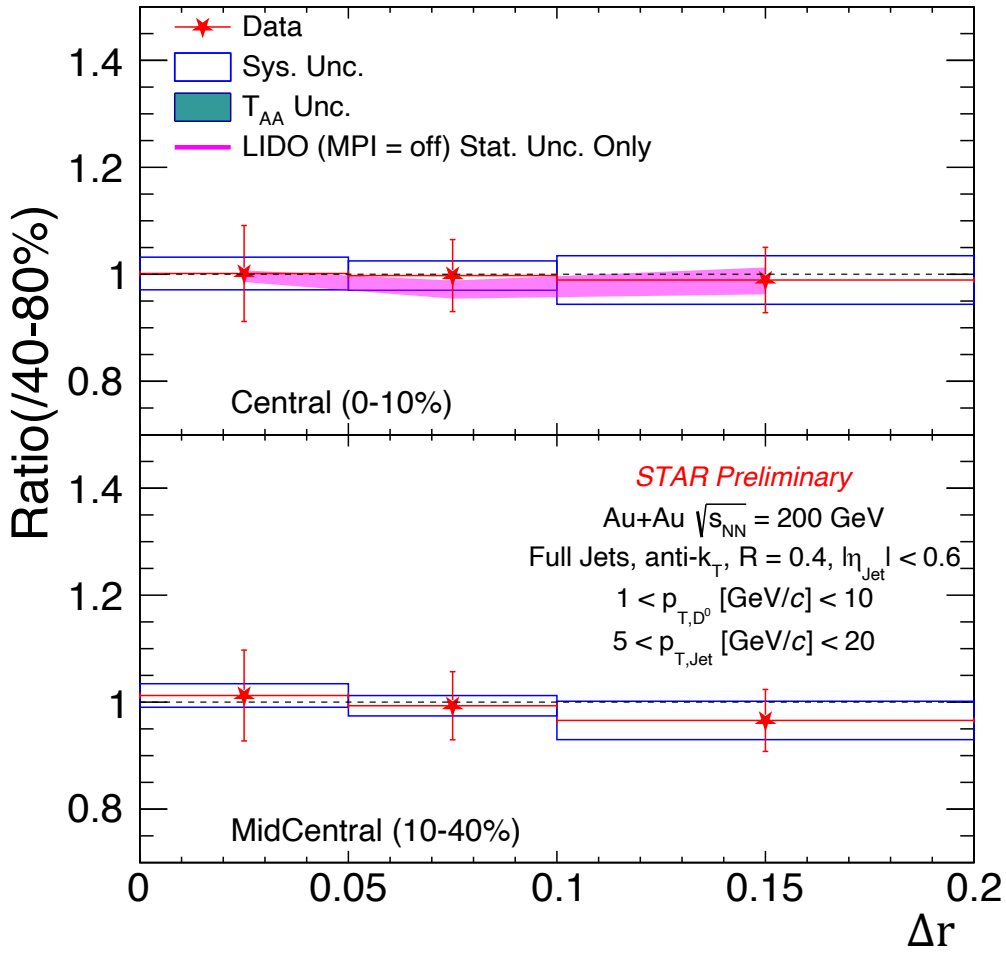
# Radial profile of $D^0$ jets




LIDO, Phys. Rev. C 98, 064901

- Ratio of radial profile in central and peripheral consistent with unity, within uncertainty
- LIDO model (MPI = off) describes ratio of radial profile in data

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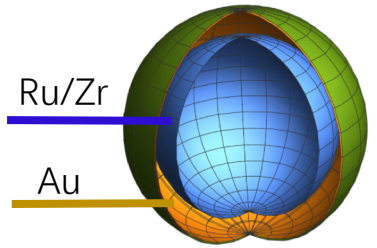
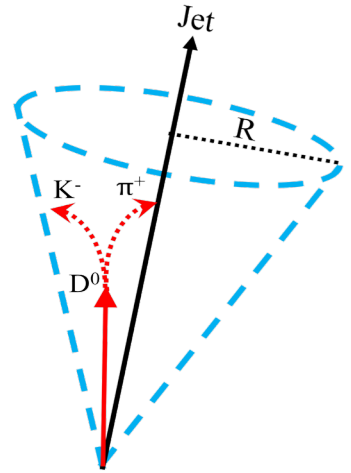
# Summary

- **$D^0$ $p_T$ 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

- **$D^0$ tagged jets in Au+Au collisons at STAR for 1 < $p_{T,D^0}$ < 10 GeV/c**




  - Hint of $D^0$ jet suppression in central collisions, mainly from hard fragmented jets
  - $D^0$ jet radial profile consistent in central and peripheral collisions
  - LIDO model underpredicts yield suppression in central collisions, but can describe radial profile ratio in central to peripheral collisions

# Backup

# Analysis details

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## Event Selection:

- Au+Au $\sqrt{s_{NN}}$ = 200 GeV, Year 2014
- Minimum bias (MB)
- Centrality ∈ [0, 80]% (3 bins: [0-10], [10-40], [40-80])

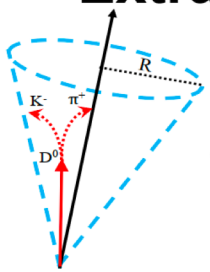
## Constituent Selection:

- $0.2 < p_{T,track}\ [GeV/c] < 30$ ; $0.2 < E_{T,tower}\ [GeV] < 30$
- $|\eta_{track}| < 1$ ; $|\eta_{tower}| < 1$
- $D^0 \rightarrow K^{\mp} + \pi^{\pm}$
- For $D^0$ reconstruction: Tracks contain at least three hits on HFT
- $1 < p_{T,D^0}\ [GeV/c] < 10$

## $D^0$ Jet Selection:

- Anti-$k_T$ full jets of radius $R = 0.4$, area-based background subtraction
- $|\eta_{Jet}| < 0.6$

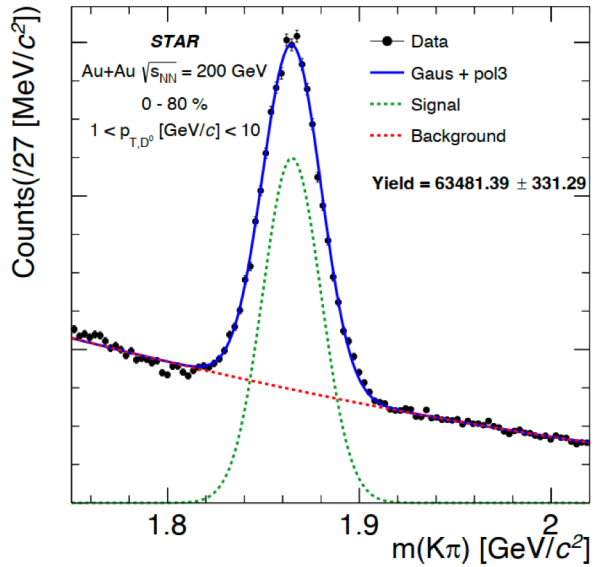
## Extracting $D^0$ Meson Tagged Jet Yield




*sPlot*

$$ {}_s\mathcal{P}_n(m_{K\pi,i}) = \frac{\sum_{j=1}^{N_T} V_{nj} f_j(m_{K\pi,i})}{\sum_{k=1}^{N_T} N_k f_k(m_{K\pi,i})} $$

Visit https://arxiv.org/abs/physics/0602023 for more details on *sPlot*




**Unbinned Maximum Likelihood Fit**

***n*** = $n^{th}$ fit component(sig/bkg)

$\boldsymbol{N_k}$ = $k^{th}$ yield (T=2)

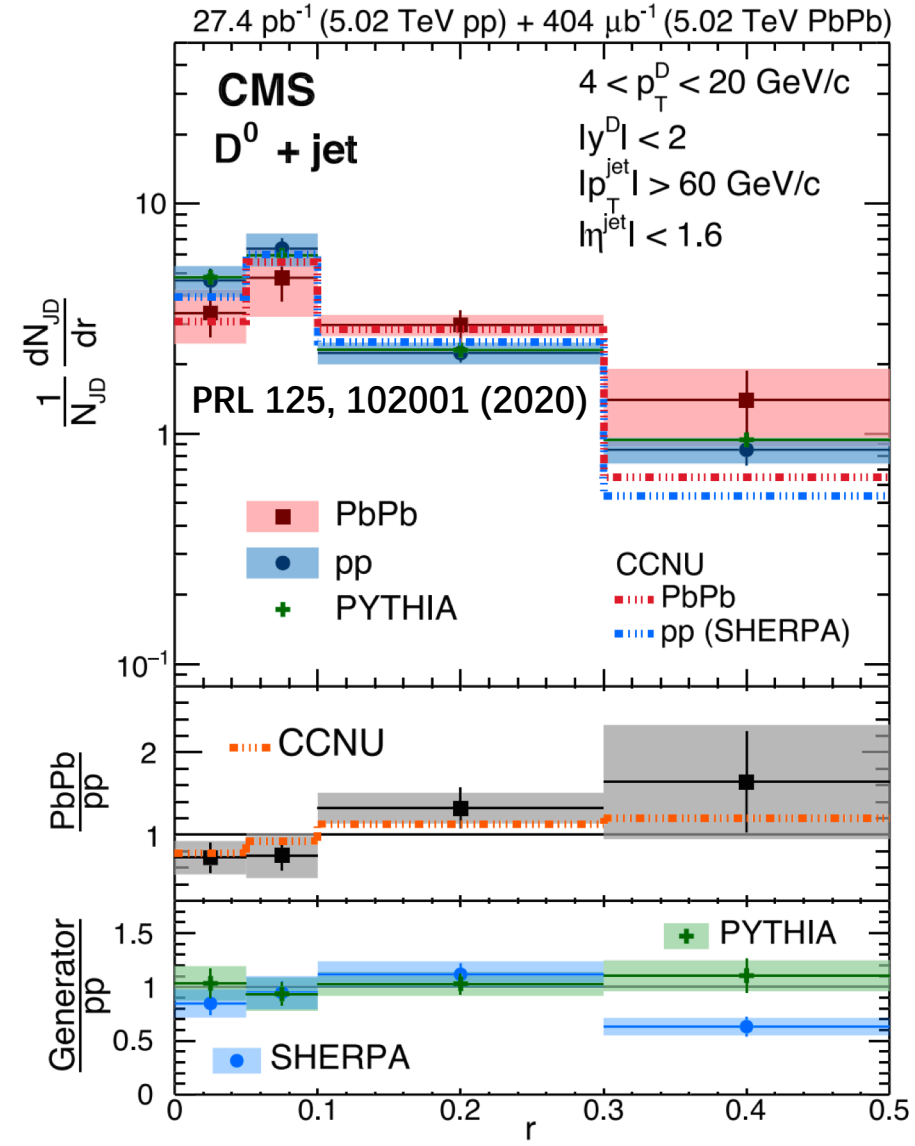
$\boldsymbol{f_k(m_{K\pi,i})}$ = per-event PDF value with $k^{th}$ hypothesis

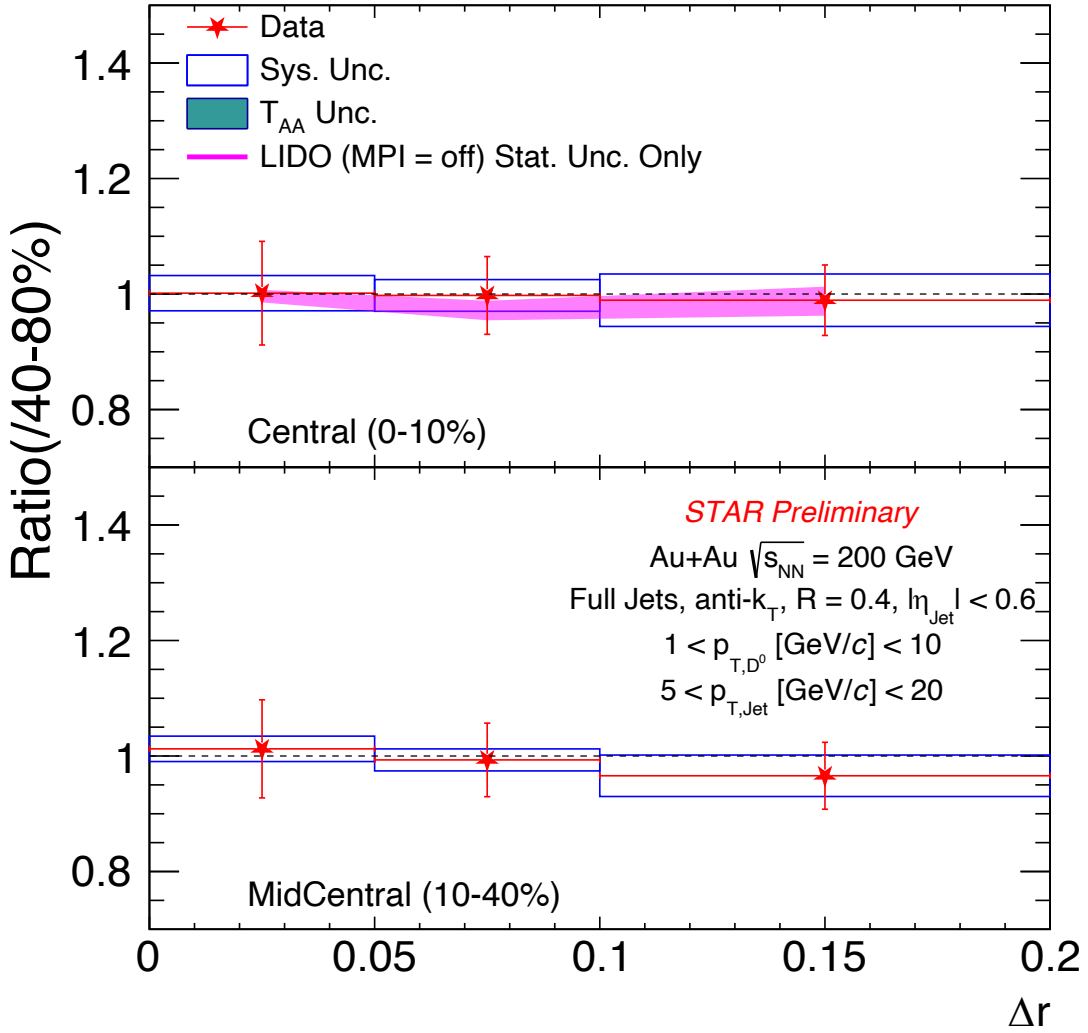
**V** = cov. matrix

**Efficiency Correction** → $ {}_s\mathcal{P}_n(m_{K\pi,i}) \rightarrow \frac{{}_s\mathcal{P}_n(m_{K\pi,i})}{\varepsilon(m_{K\pi,i})} $

**First application of *sPlot* to STAR data**

# Charm jet radial profile



# System size dependence of $R_{AA}$