Heavy Flavour measurements

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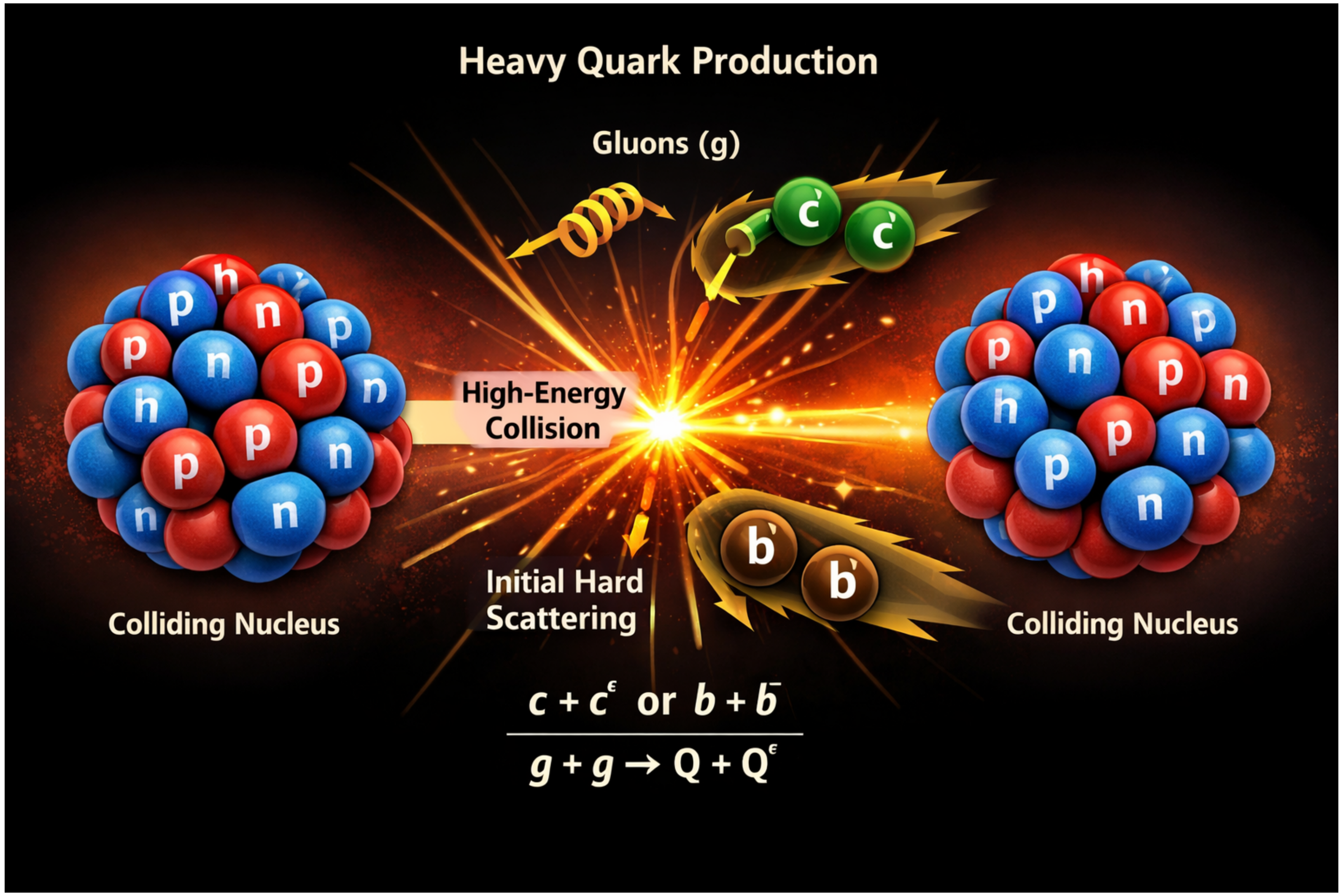
Why Heavy Flavour?

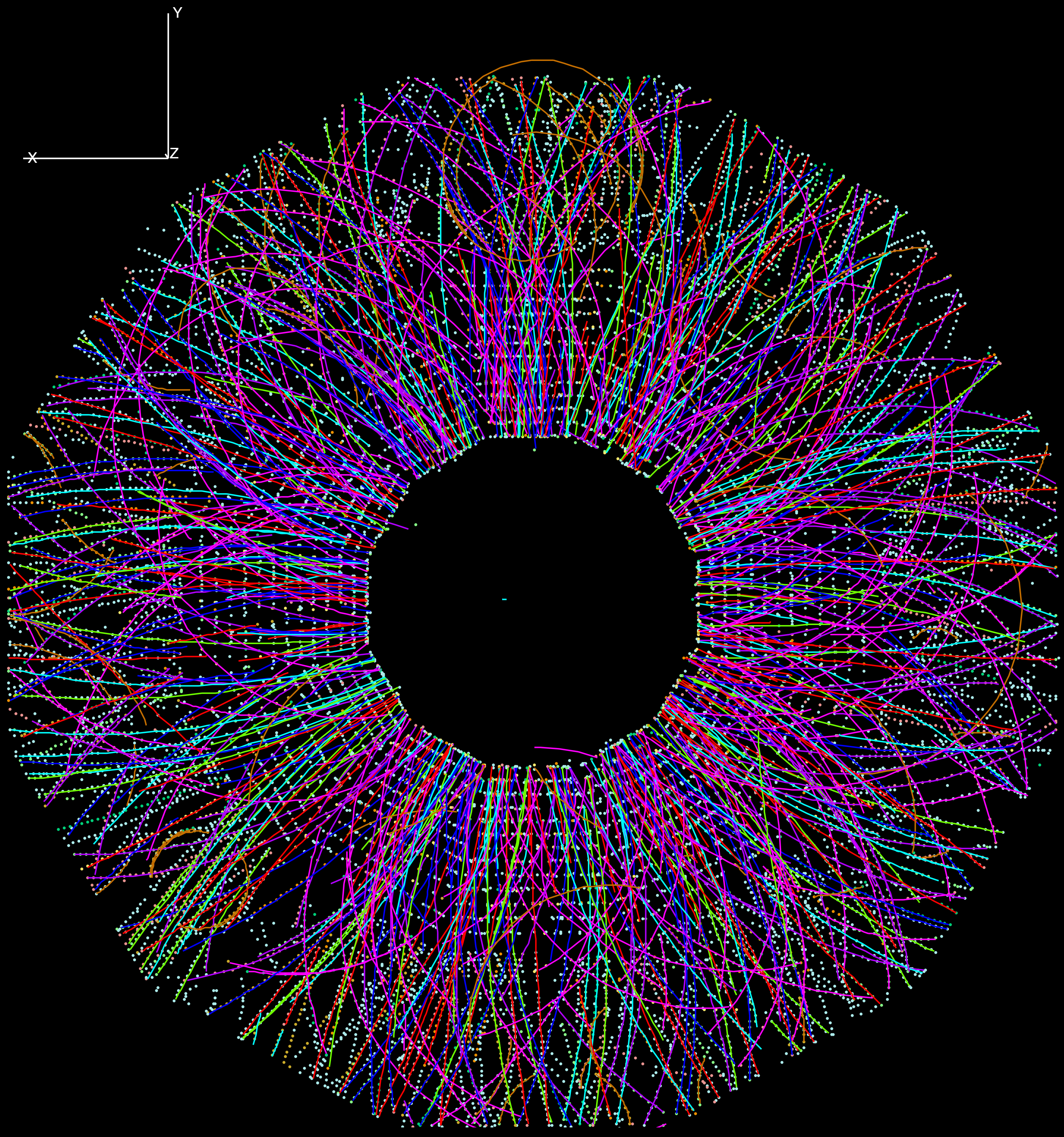
- Heavy quarks (c, b) produced in initial hard scattering
- Formation time ~ $1/(2m_Q)$ → earlier than QGP formation
- They propagate through the entire medium
- dead cone effect, mass hierarchy of energy loss, thermalization



Credit: ChatGPT

Let's discuss in collider experiments (like p+p and A+A collisions),

how do we measure them?



Au+Au collision event display at STAR

Heavy flavour probes typically classified into:

- Open heavy flavour: $D^0, D^{\pm}, D_s, \Lambda_c, B$

- Quarkonia: $[J/\psi, \psi(2S)], [\Upsilon(1S, 2S, 3S)]$

	Particle	Quark Content	Mass (GeV/c^2)	Typical Decay Channel
Open heavy flavour	D^0	$c\bar{u}$	1.865	$D^0 \to K^- \pi^+$
	$D^\pm$	$c\bar{d}$	1.869	$D^+ \to K^- \pi^+ \pi^+$
	$D_s^\pm$	$c\bar{s}$	1.968	$D_s^+ \to \phi \pi^+$
	Λ_c^+	cud	2.286	$\Lambda_c^+ \to p K^- \pi^+$
	B^0	$b\bar{d}$	5.279	$B^0 \to J/\psi K^0$
	$B^\pm$	$b\bar{u}$	5.279	$B^+ \to J/\psi K^+$
Quarkonium	J/ψ	$c\bar{c}$	3.097	$J/\psi \to e^+ e^-, \mu^+ \mu^-$
	$\psi(2S)$	$c\bar{c}$	3.686	$\psi(2S) \to e^+ e^-, \mu^+ \mu^-$
	$\Upsilon(1S)$	$b\bar{b}$	9.460	$\Upsilon \to \mu^+ \mu^-$
	$\Upsilon(2S)$	$b\bar{b}$	10.023	$\Upsilon \to \mu^+ \mu^-$
	$\Upsilon(3S)$	$b\bar{b}$	10.355	$\Upsilon \to \mu^+ \mu^-$

Open heavy flavour

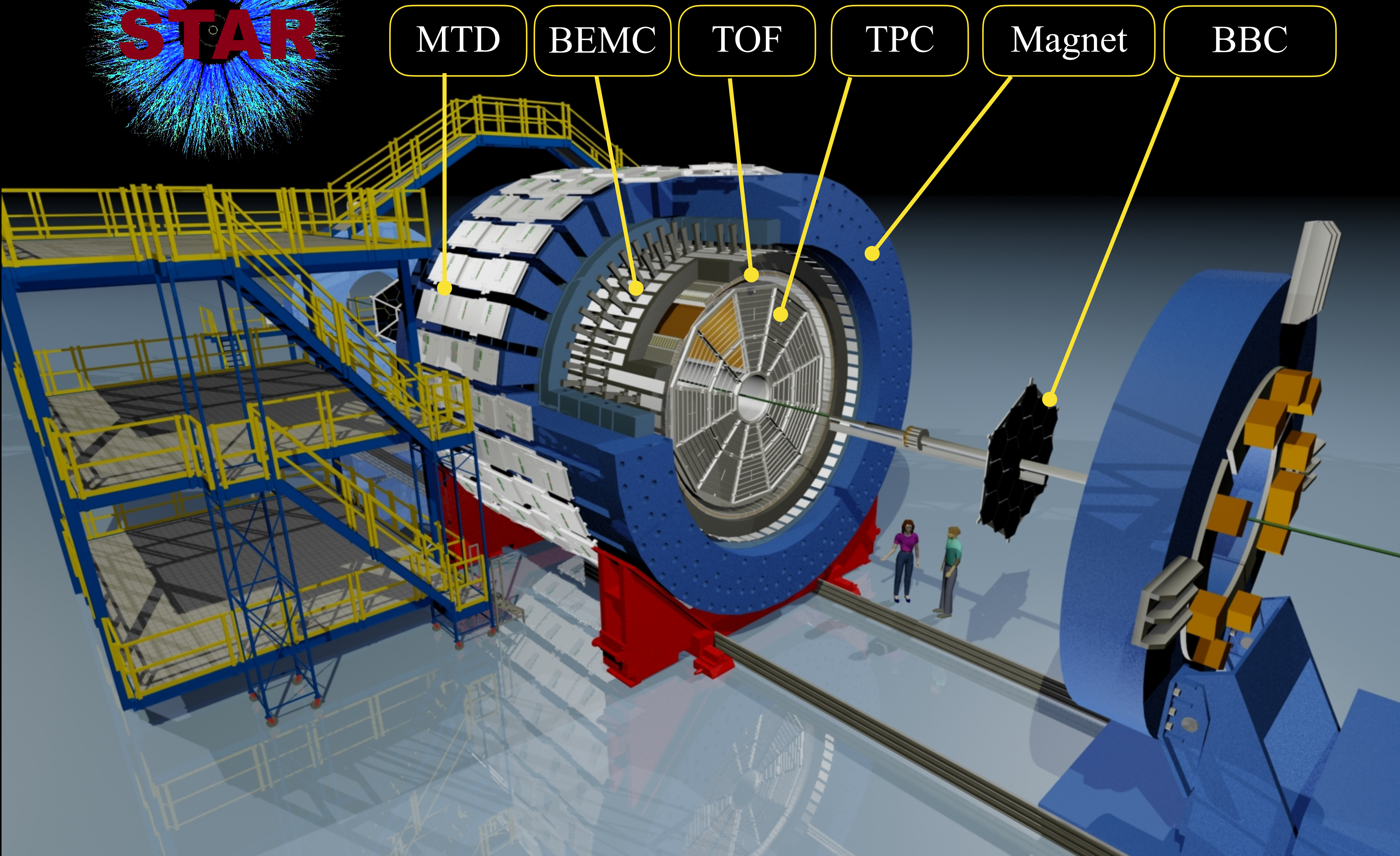
- Weak decays and long lifetime
- Decay length cτ~100–500 μm:
  (requires secondary vertex reconstruction)

Quarkonium

Very short lifetime

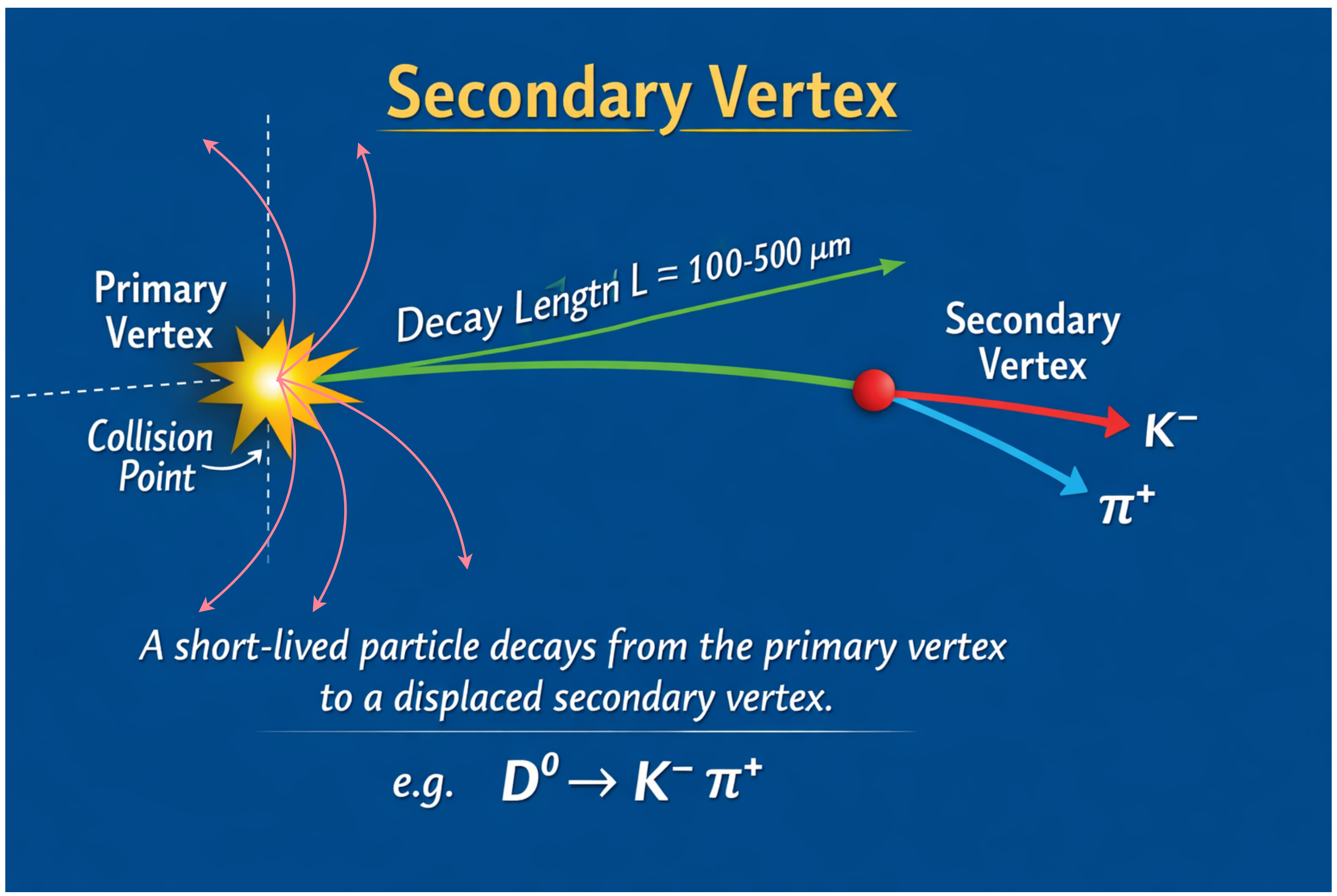
Measurements of open heavy-flavour in experiment

Solenoidal Tracker At RHIC (STAR) Experiment

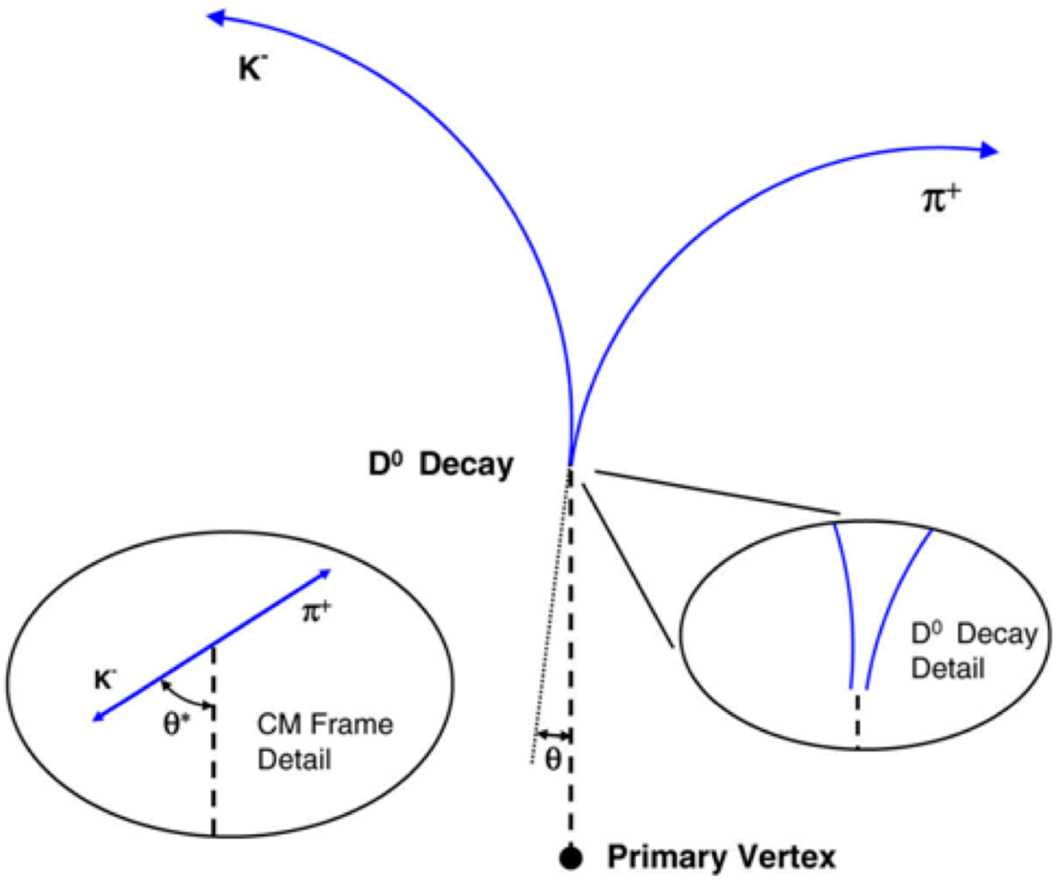


Open heavy flavour

Requires secondary vertex reconstruction: $c\tau \sim 100-500$ μm



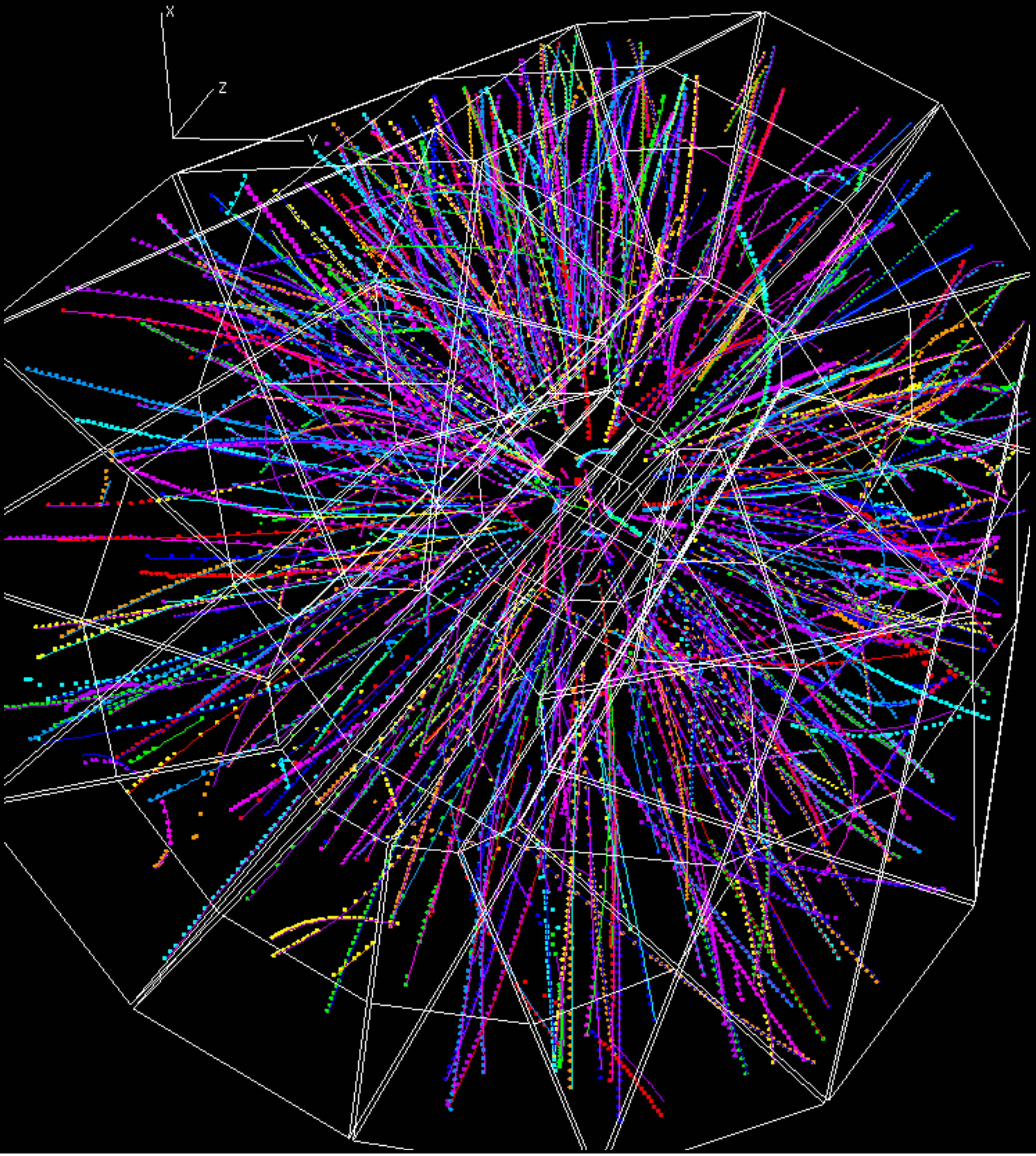
Credit: ChatGPT



STAR HFT Margeti's talk

STAR TPC hits and reconstructed tracks

(Longitudinal view)



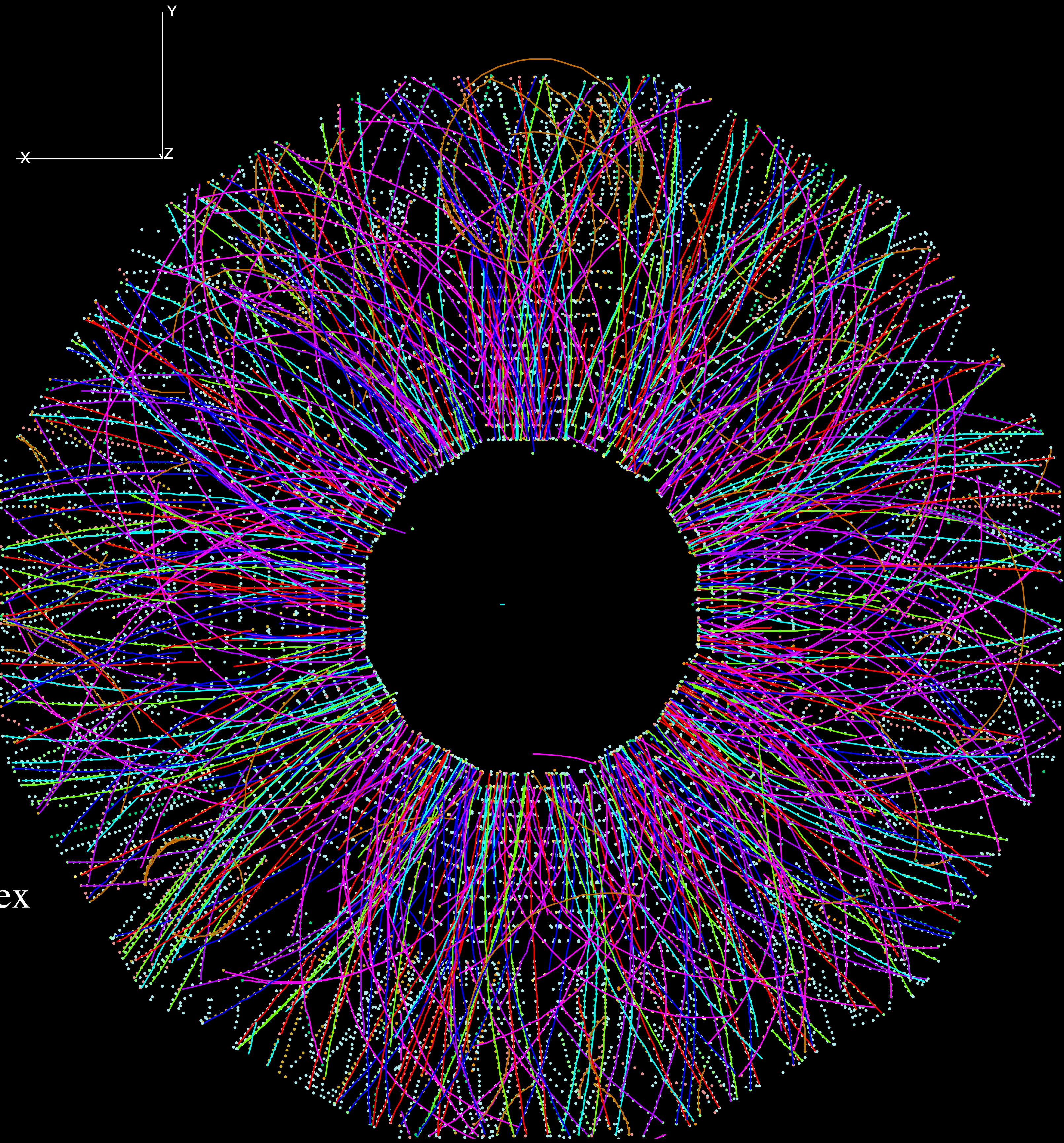
STAR TPC hits and reconstructed tracks

(Transverse view)

TPC inner field cage radius: ~ **50 cm**

Weak decay:
L ~ γcτ ~ O(100 μm−few mm)

Decay happens very close to the primary vertex, typically **sub-mm to mm scale**.



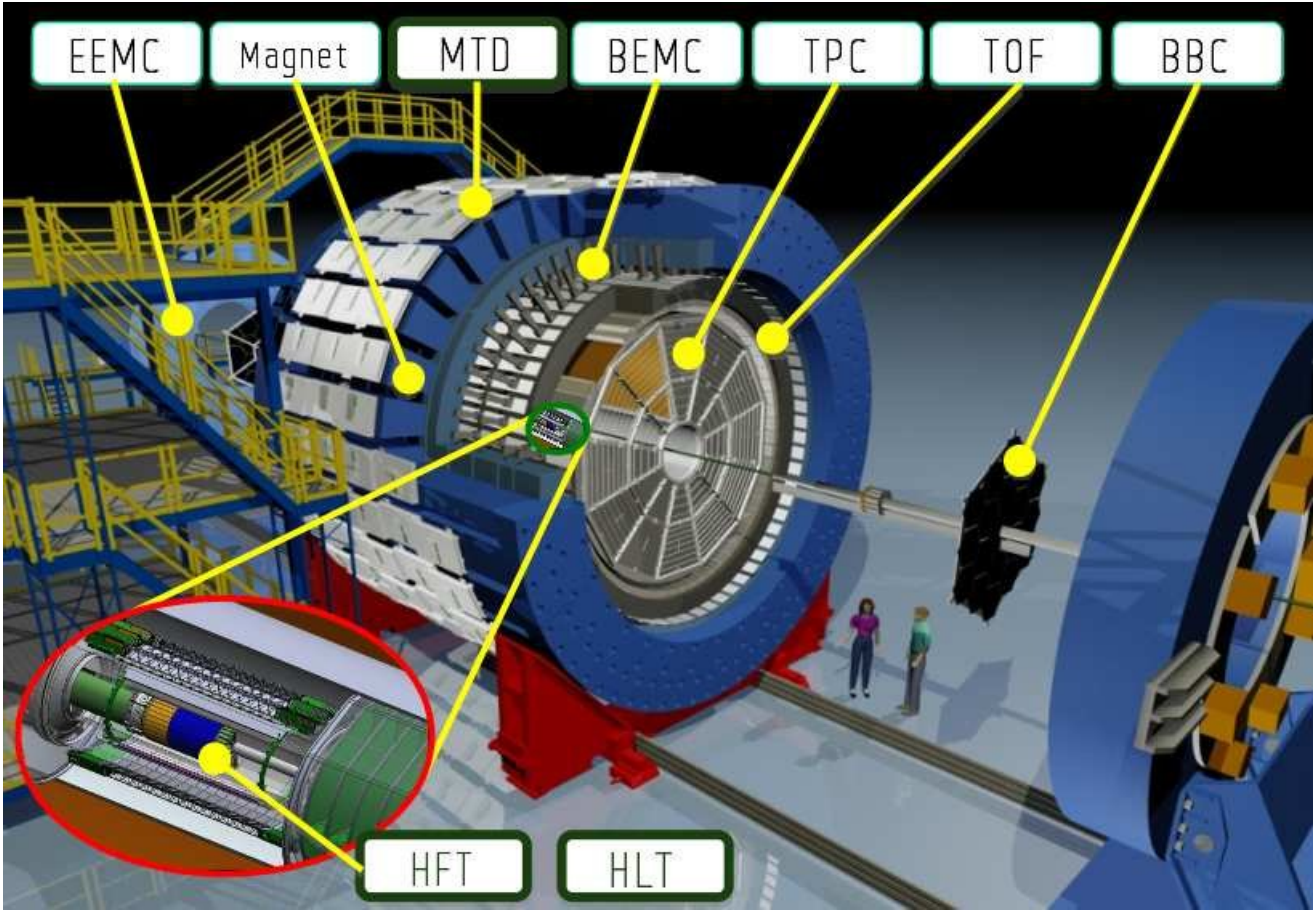
TPC-only limitation:

- Difficult to resolve secondary vertex
- Small displacement from primary vertex

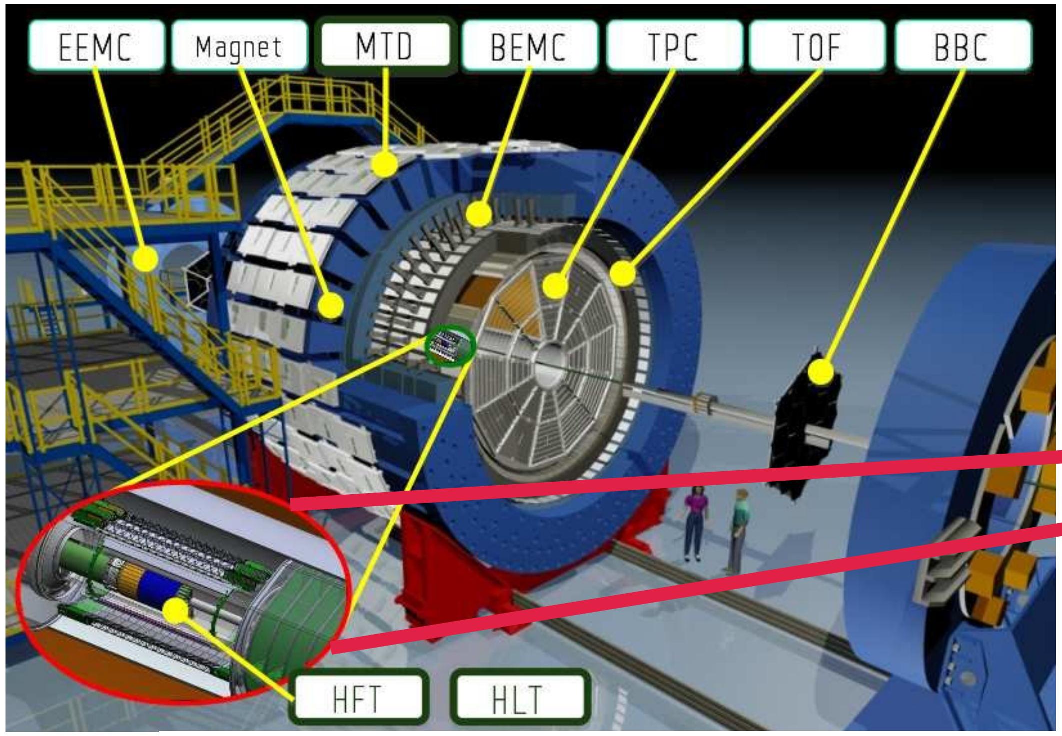
Otherwise,

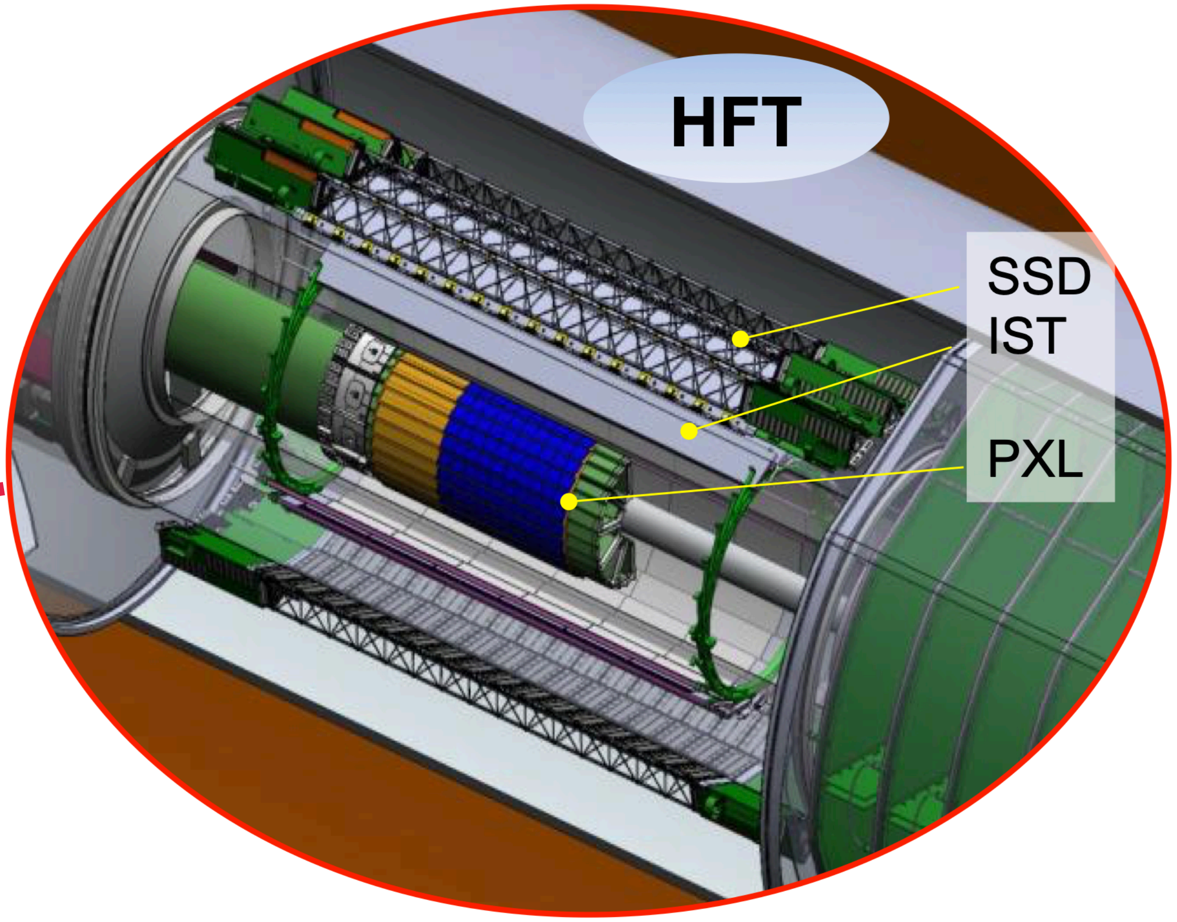
- Huge **combinatorial background**
- No clean D-meson reconstruction

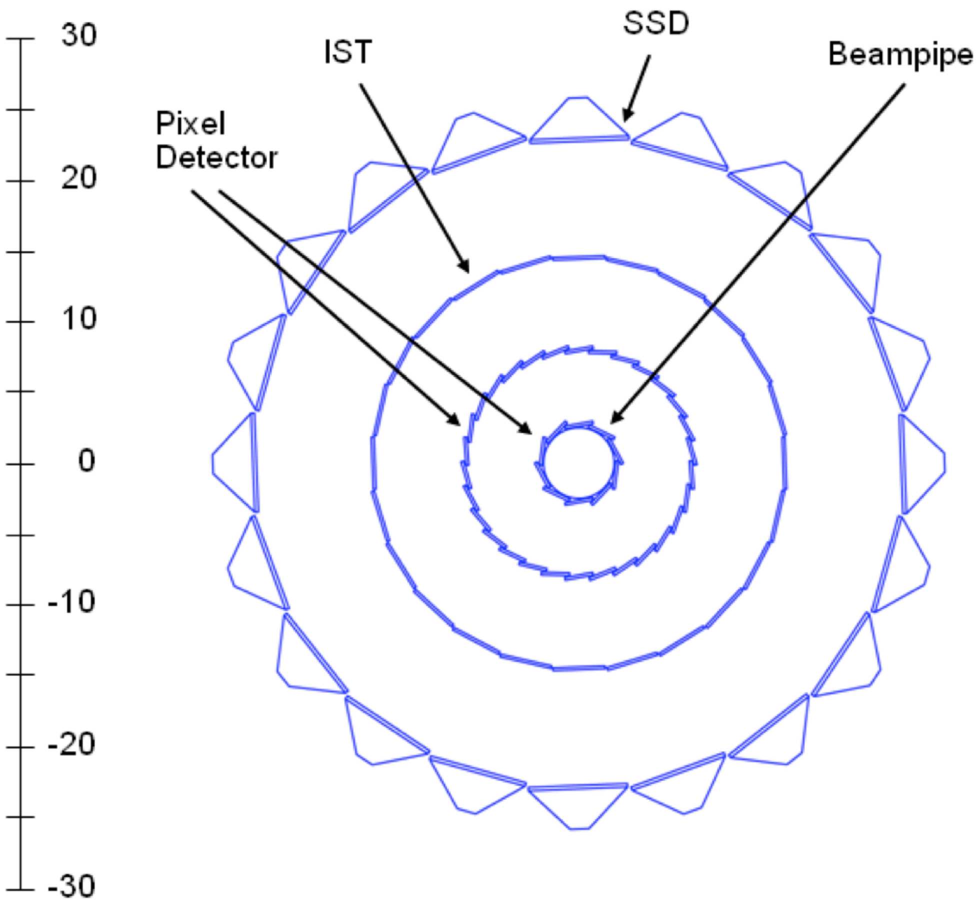
STAR detector



Heavy-Flavour Tracker (HFT) at STAR







SSD: Silicon Strip Detector

IST: Intermediate Silicon Tracker

PXL: Pixel detector

To get good resolution of Distance of Closest Approach (DCA) of a track to the primary vertex

Reconstruction of Open Heavy Flavour (D mesons)

Let's take an example to measure: $D^0 \rightarrow K^- + \pi^+$

1. Track reconstruction

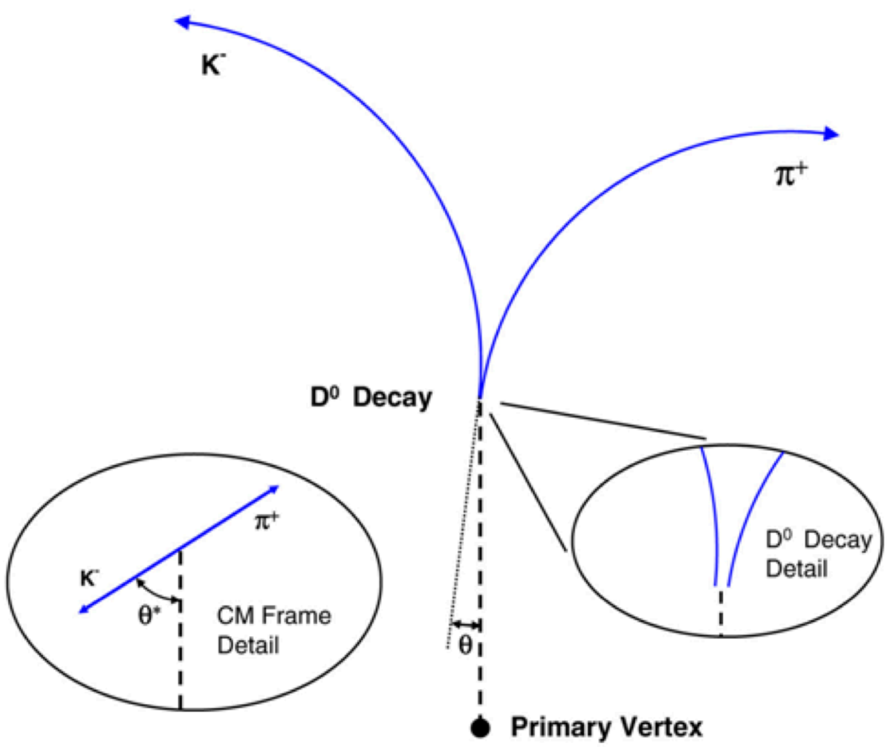
TPC + silicon detectors (Matching)

2. Particle ID

Identify K and π using: dE/dx and TOF

3. Secondary vertex reconstruction

Key variables:
1) decay length,
2) DCA between daughters,
3) pointing angle



For better signal to background ratio:

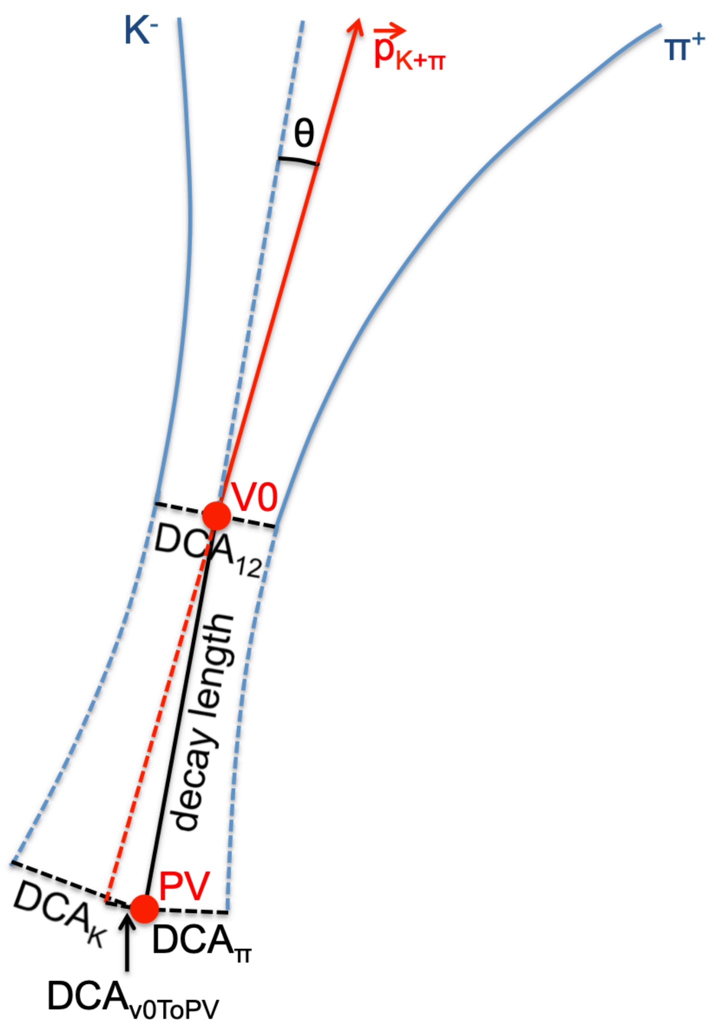
- Topological cuts
- Additional BDT/ML methods

$$M_{K\pi} = \sqrt{(E_K + E_\pi)^2 - (\overrightarrow{p_K} + \overrightarrow{p_\pi})^2}$$

Reconstruction of Open Heavy Flavour (D mesons)

Signal vs. Background

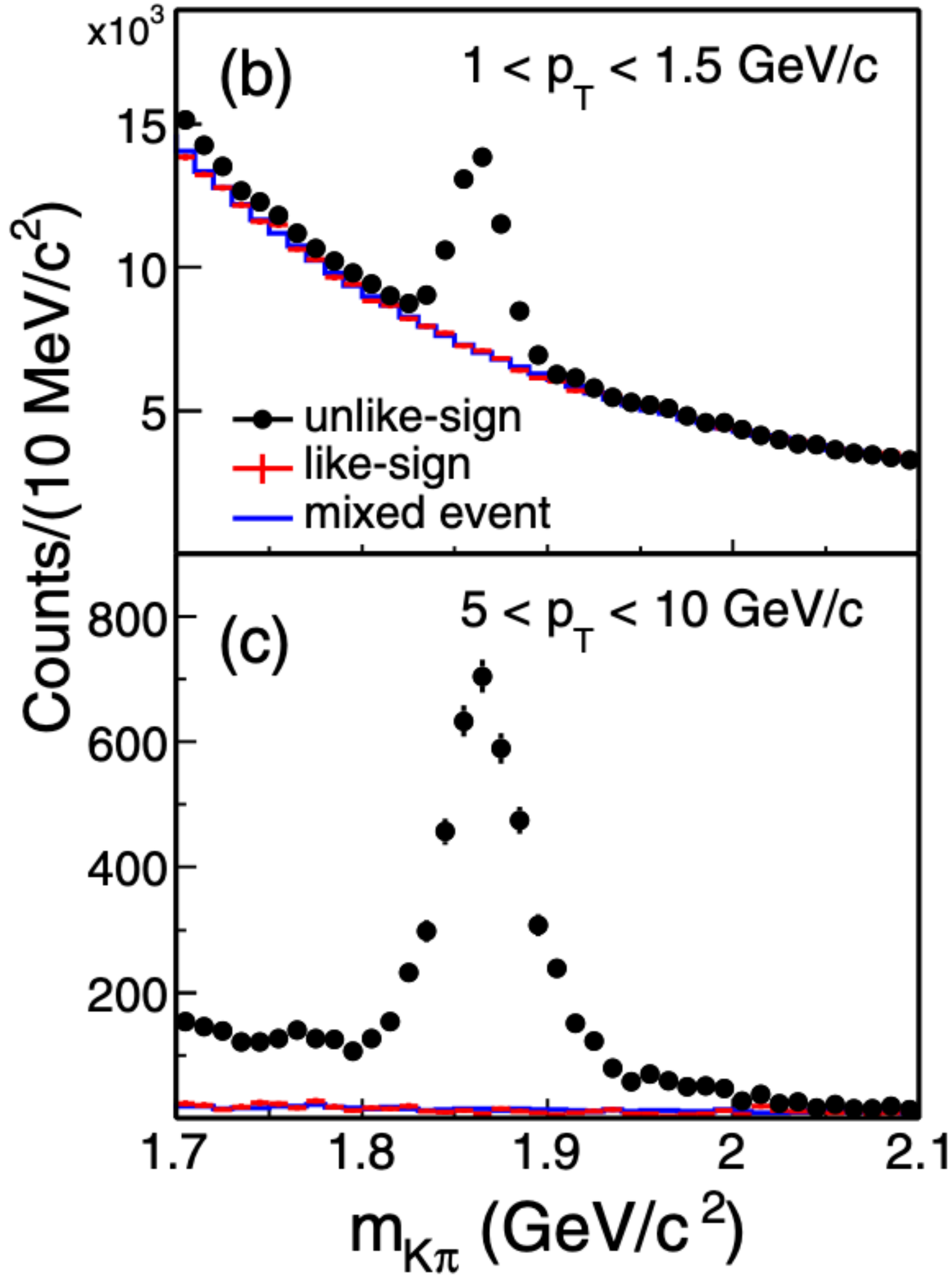
- Signal to background ratio can be significantly reduced by constraining measurement parameters (cuts)
  For example: DCA of tracks, distance between primary to secondary vertex, etc.
- These cuts are optimised by Toolkit for Multivariate Data Analysis (TMVA) package (or using advanced ML techniques)



Detector correction

- Detection efficiency of hadrons and purity
- Misidentification and double counting
- Momentum resolution correction
- Different correction depending upon observables

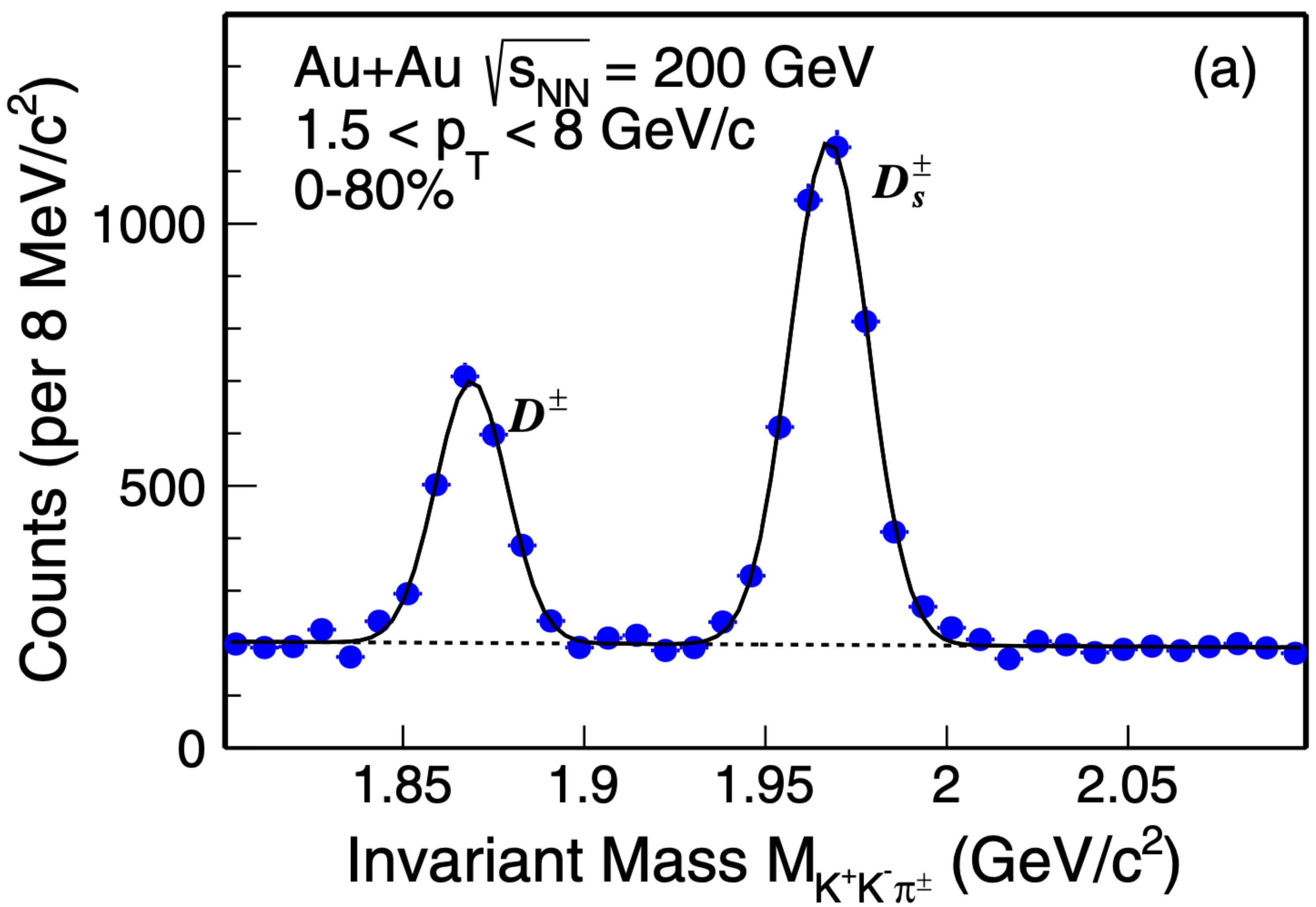
D^0 invariant mass using STAR HFT detector



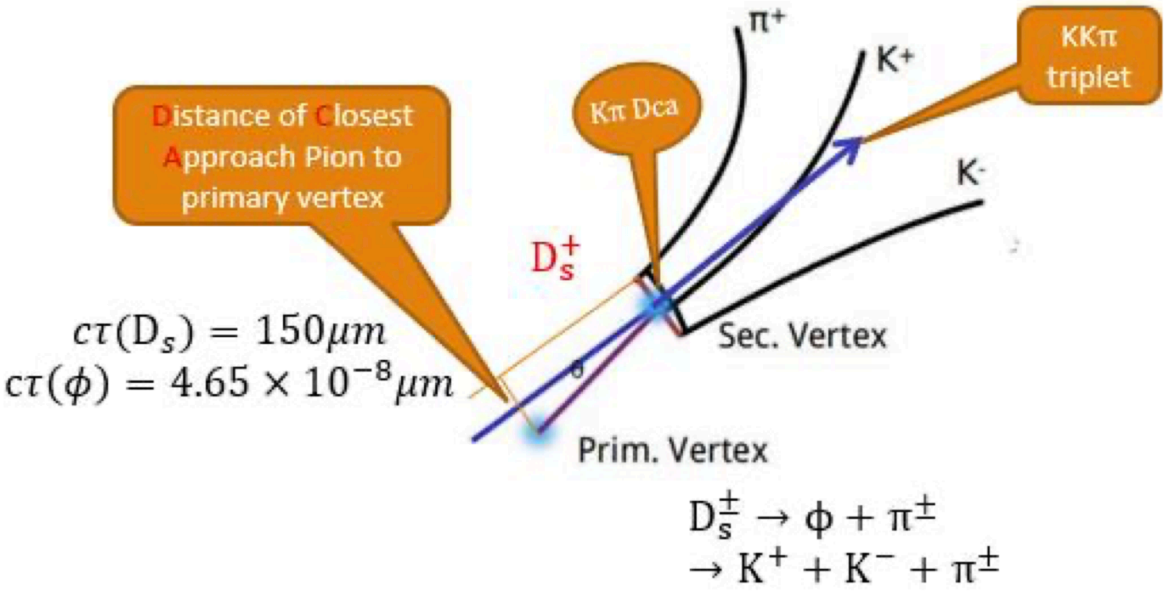
STAR: PRL 118, 212301 (2017)

$$M_{K\pi} = \sqrt{(E_K + E_\pi)^2 - (\overrightarrow{p_K} + \overrightarrow{p_\pi})^2}$$

$D^{\pm}$ and $D_s^{\pm}$ invariant mass using STAR HFT detector



STAR: PRL 127, 092301 (2021)



Measurements of Quarkonia in experiment

Reconstruction of Quarkonia

Quarkonia Example:

- J/ψ, $\psi(2S)$
- $\Upsilon(1S)$
- $\Upsilon(2S)$

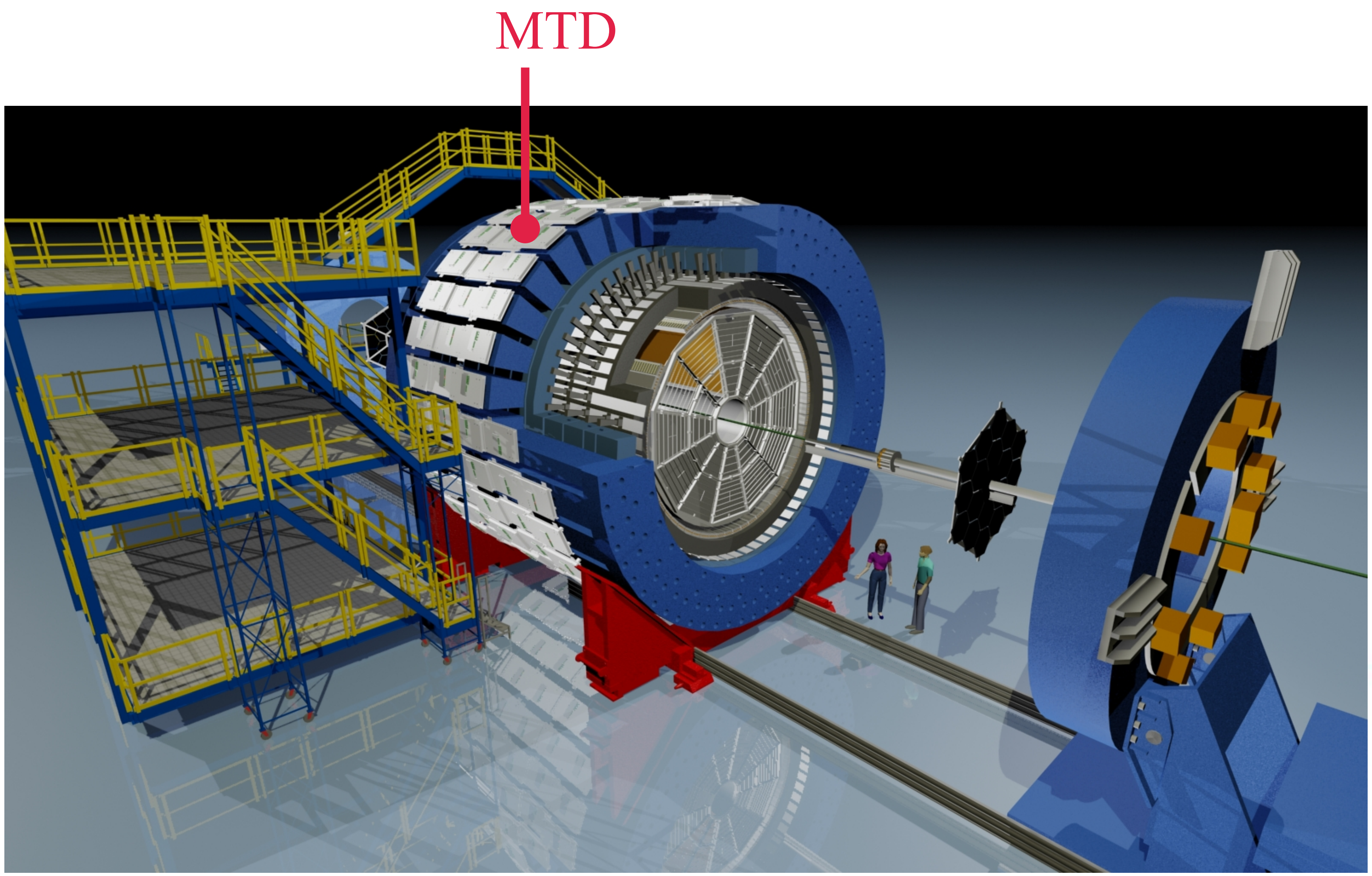
$J/\psi \rightarrow e^+e^-$

$J/\psi \rightarrow \mu^+\mu^-$

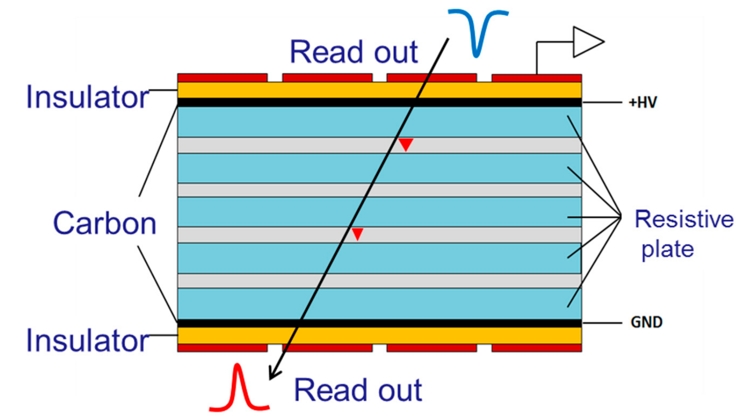
Technique:

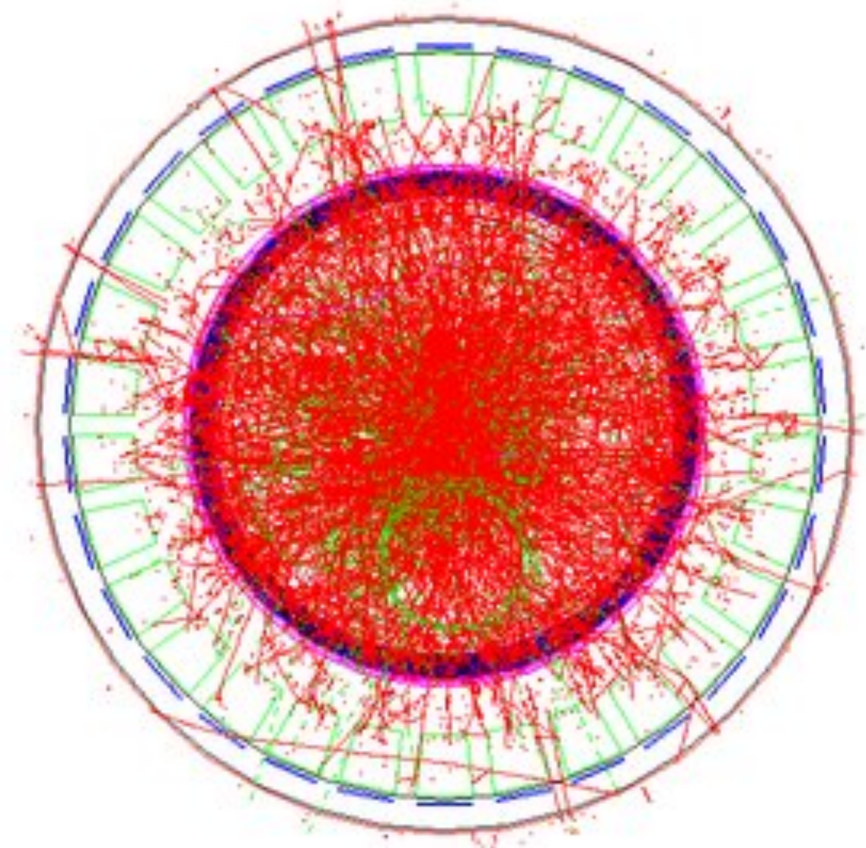
1. Identify leptons (μ, e)
2. Opposite-sign pair and Invariant mass peak

Detection on dilepton ($\mu^+\mu^-$) at STAR



MTD is Multi-gap Resistive Plate Chambers





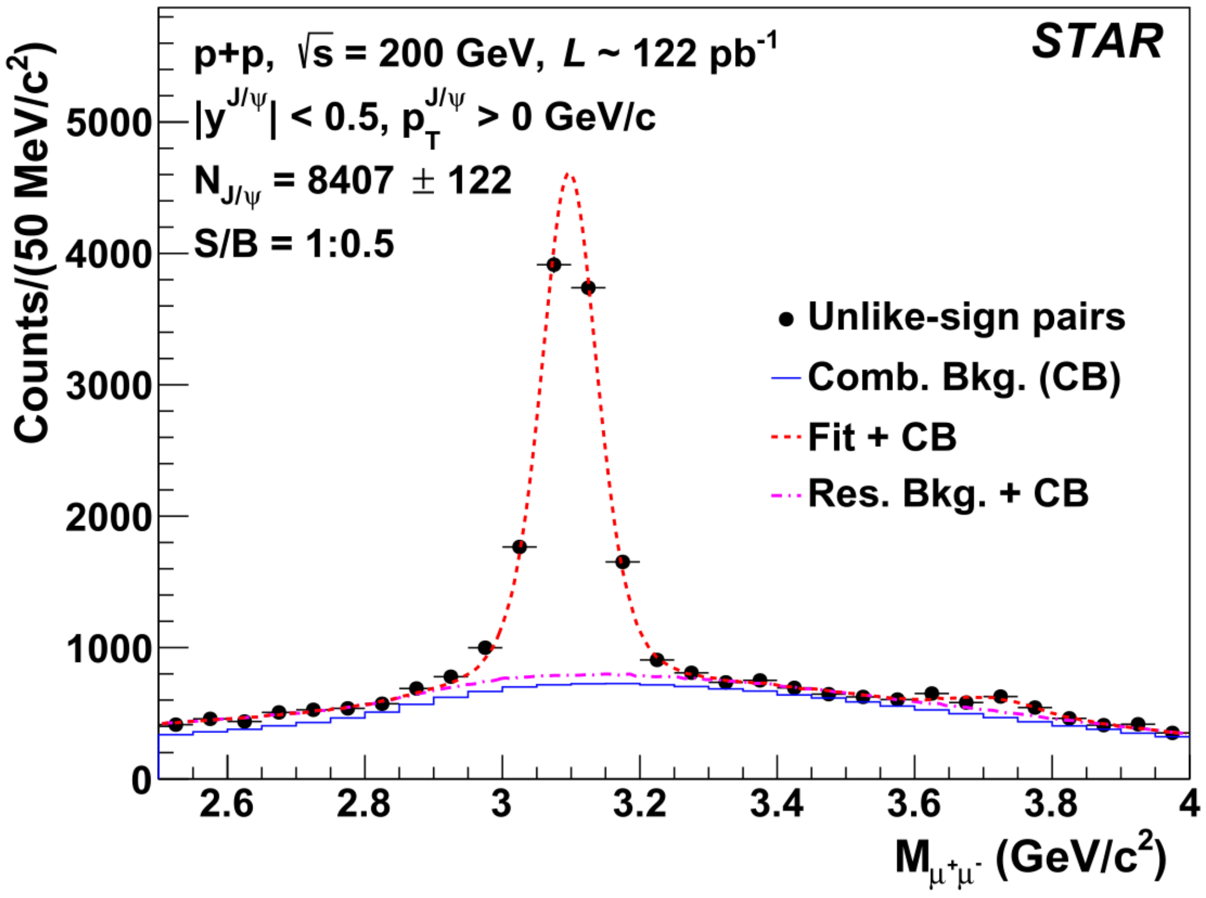
$J/\psi \to \mu^+\mu^-$ measurements at STAR

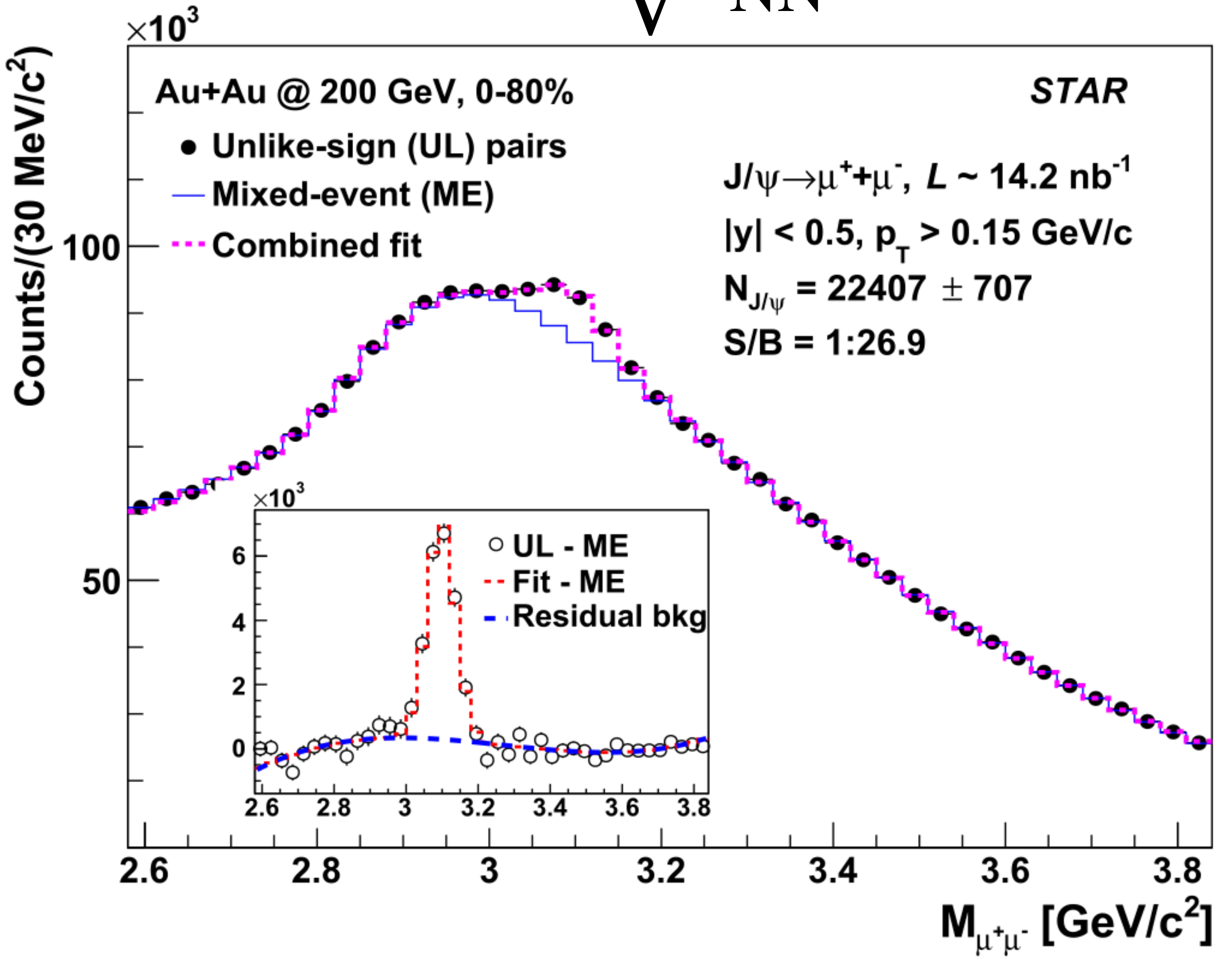
STAR: PLB 825 (2022) 136865

PLB 797 (2019) 134917

pp $\sqrt{s} = 200$ GeV

Au+Au $\sqrt{s_{NN}} = 200$ GeV

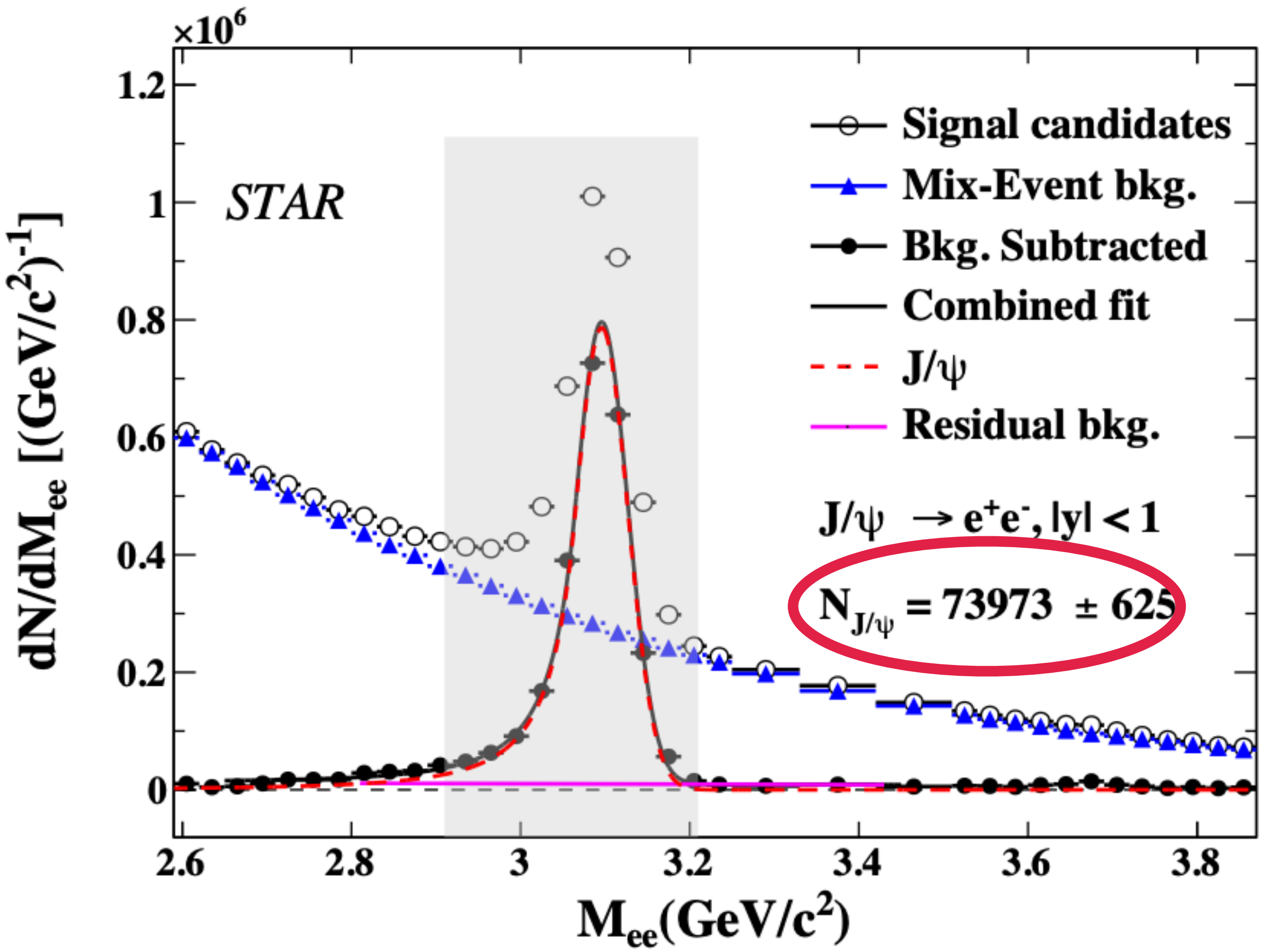


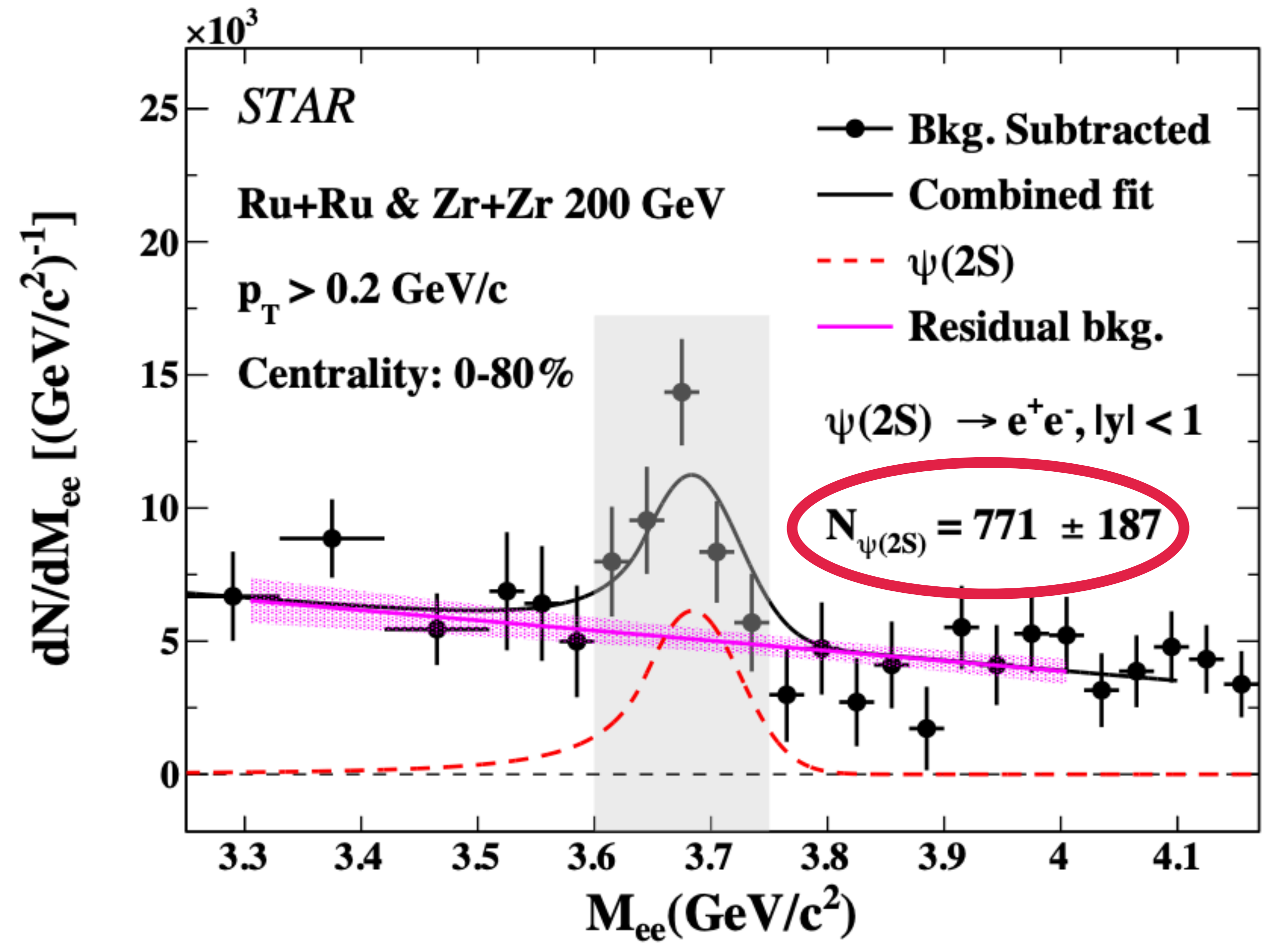


Compare the background contributions between pp and Au+Au

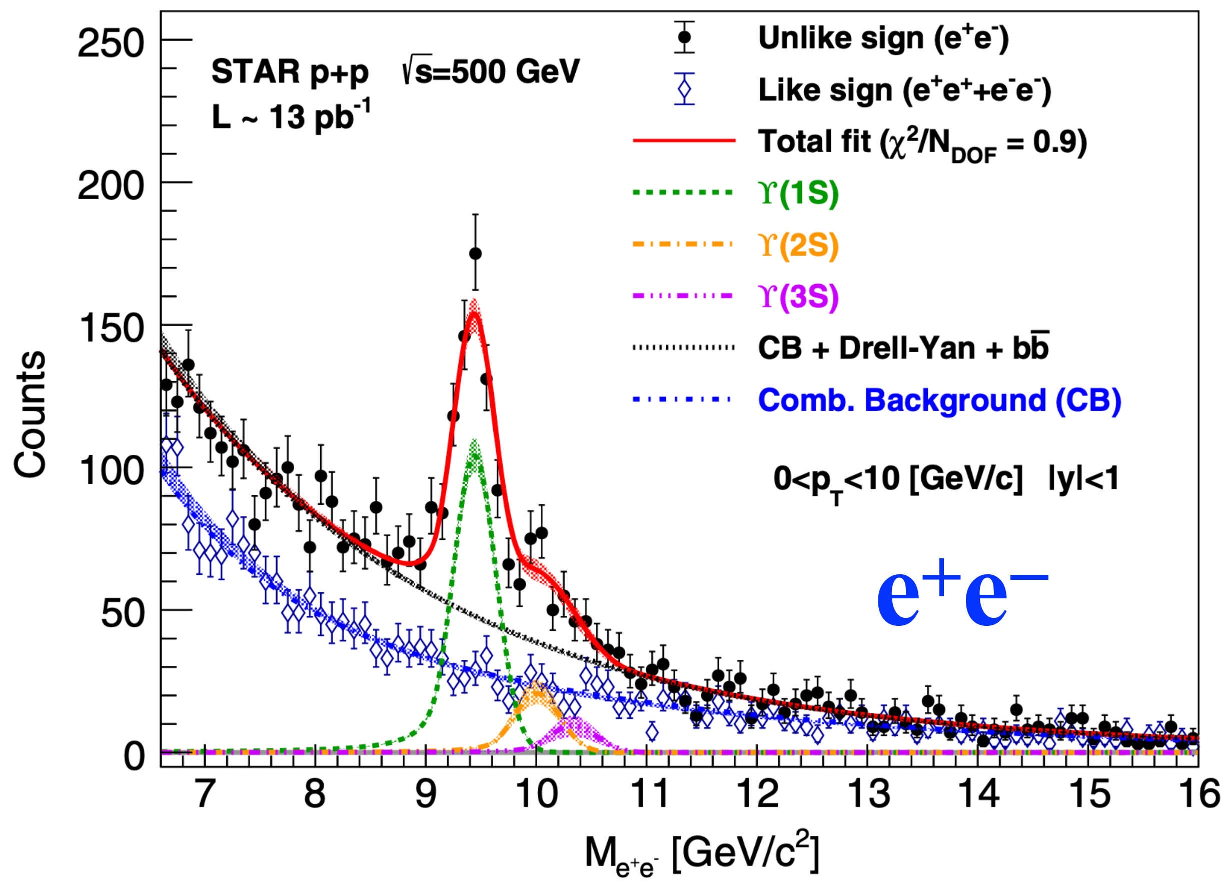
J/ψ, ψ (2S)→e⁺e⁻ measurements at STAR

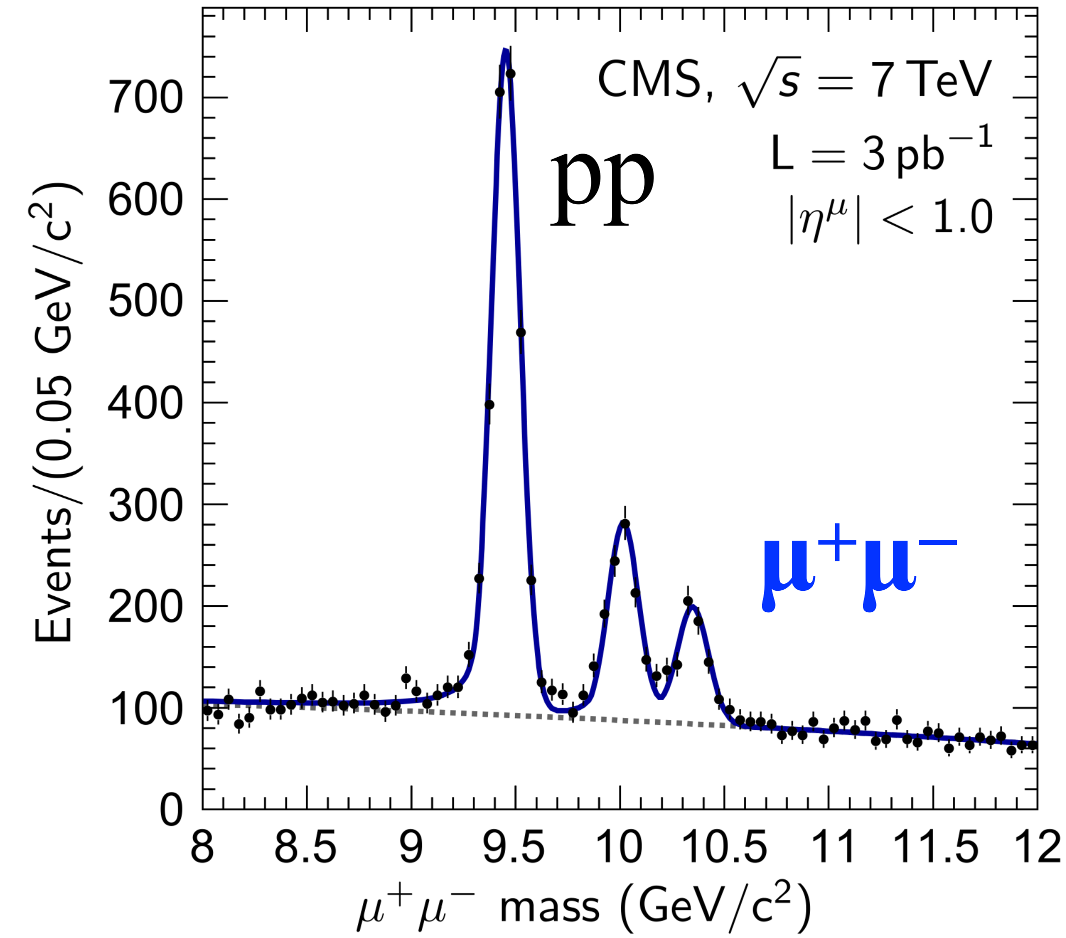
STAR: arXiv: 2509.12842 [Accepted by PRL]

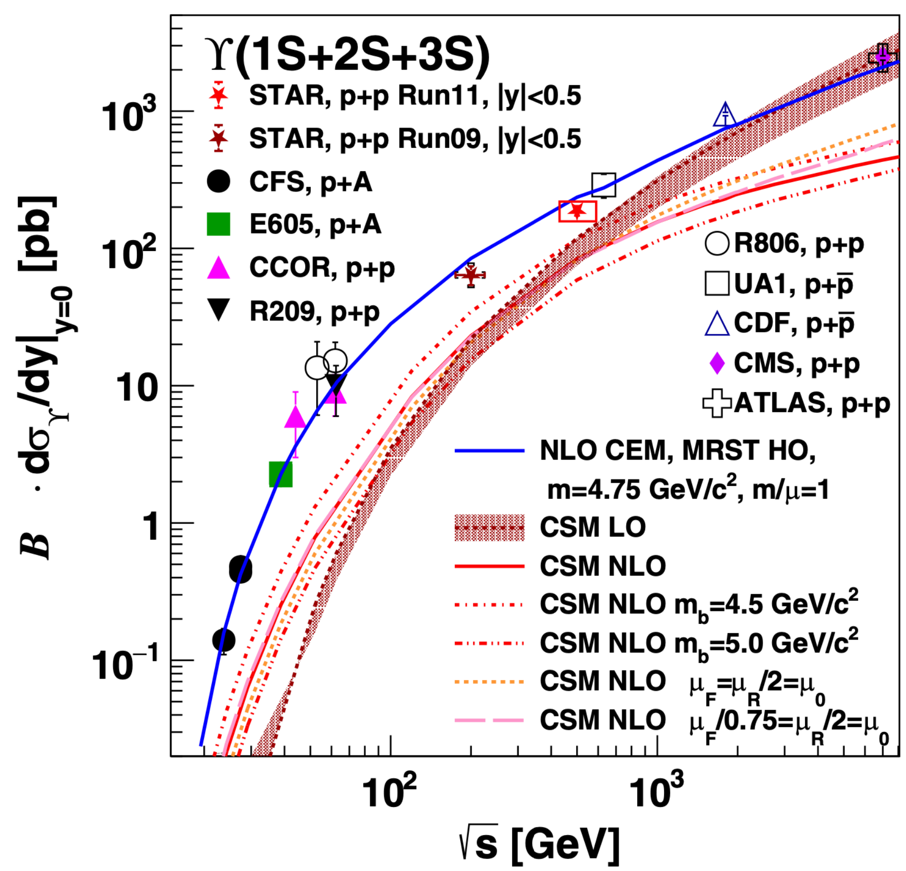




$\Upsilon(1S,2S,3S)$ measurements







Integrated cross-section of $\Upsilon(1S + 2S + 3S)$

Observables related to HF measurements

Relation Between Cross Section and Number of Events

Number of interactions, $N \propto \sigma$

$$N = L\,\sigma$$

L = Luminosity
(how many particles pass per area per time)

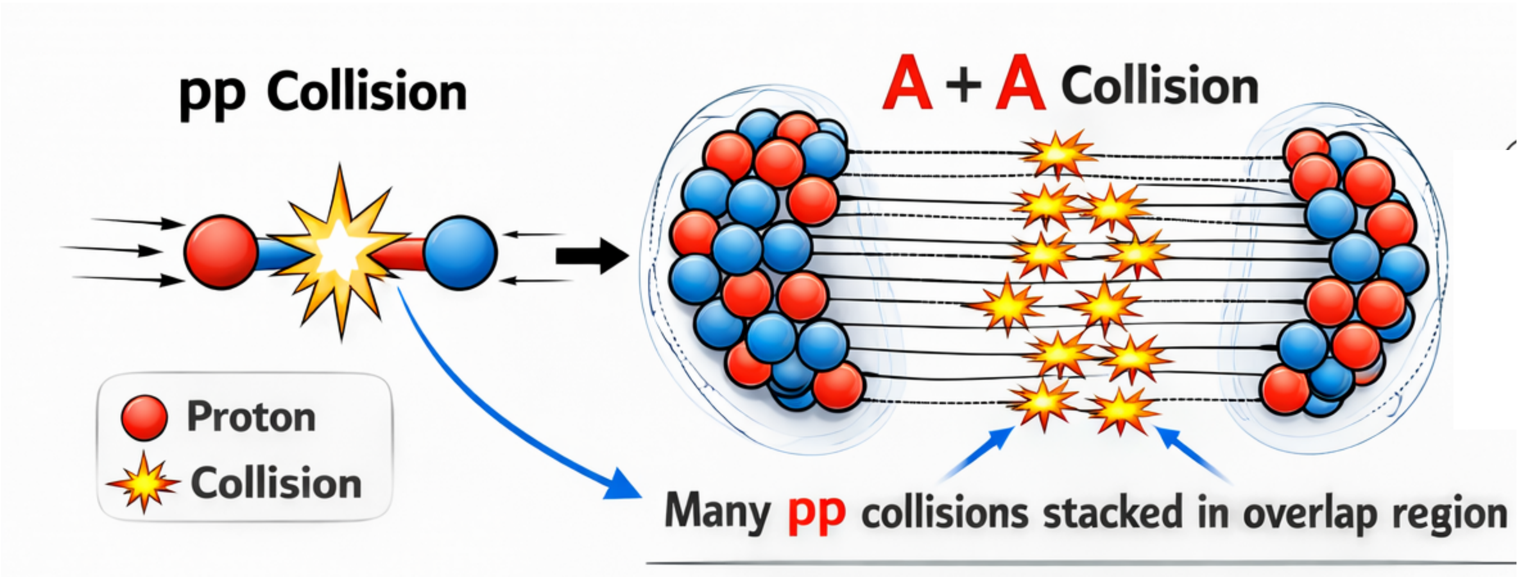
σ = Cross section

Applying this in heavy-ion collisions:

$$N_{\text{coll}} = T_{\text{AA}} \times \sigma_{pp}^{\text{inel}}$$

N_{coll} = number of binary p+p collisions

T_{AA} = nuclear overlap function



$L \rightarrow$ machine luminosity

$T_{\text{AA}} \rightarrow$ event-wise effective luminosity (encodes pure geometry, overlap of nuclei)

Nuclear modification factor (R_{AA})

Ansatz:

Hard processes in A+A collisions are expected to scale with N_{coll}, assuming independent p+p collisions—*binary collision scaling*

(Validated in $R_{AA}^{\gamma,Z,W^{\pm}} \approx 1$ measurements)

$$(dN_{AA}/dp_T) = N_{coll}\ (dN_{pp}/dp_T)$$

$$(dN_{AA}/dp_T) = T_{AA}\ (d\sigma_{pp}/dp_T)$$

p+p gives us the vacuum reference

$$R_{AA}(p_T) = \frac{1}{N_{coll}} \frac{dN_{AA}/dp_T}{dN_{pp}/dp_T}$$

$$R_{AA}(p_T) = \frac{1}{T_{AA}} \frac{dN_{AA}/dp_T}{d\sigma_{pp}/dp_T}$$

dN_{AA}/dp_T = particle yield in A+A collisions

dN_{pp}/dp_T = particle yield in p+p collisions

$d\sigma_{pp}/dp_T$ = cross-section in p+p collisions

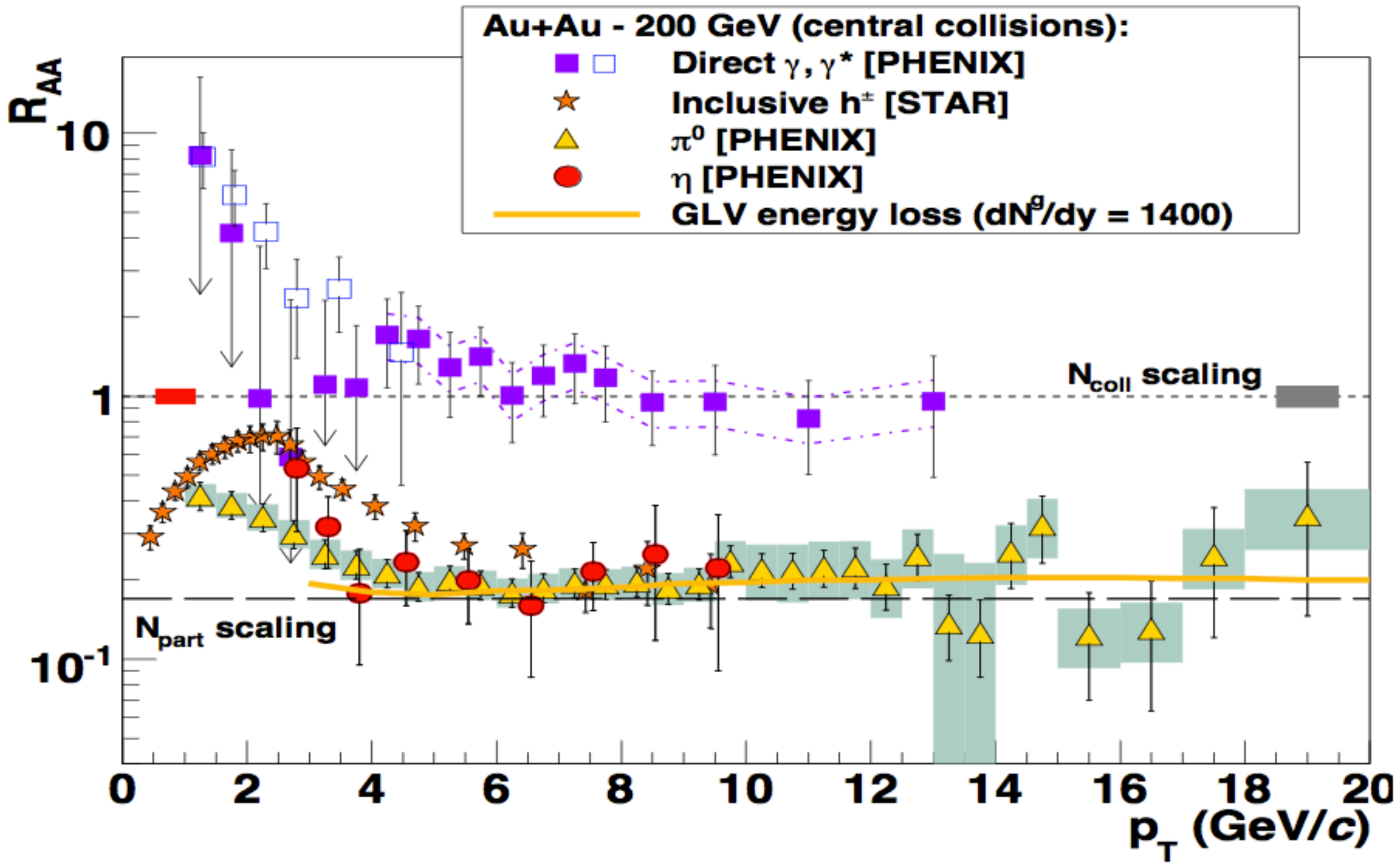
$R_{AA}(p_T) = 1$ No medium effect

< 1 Energy loss in medium (QGP)

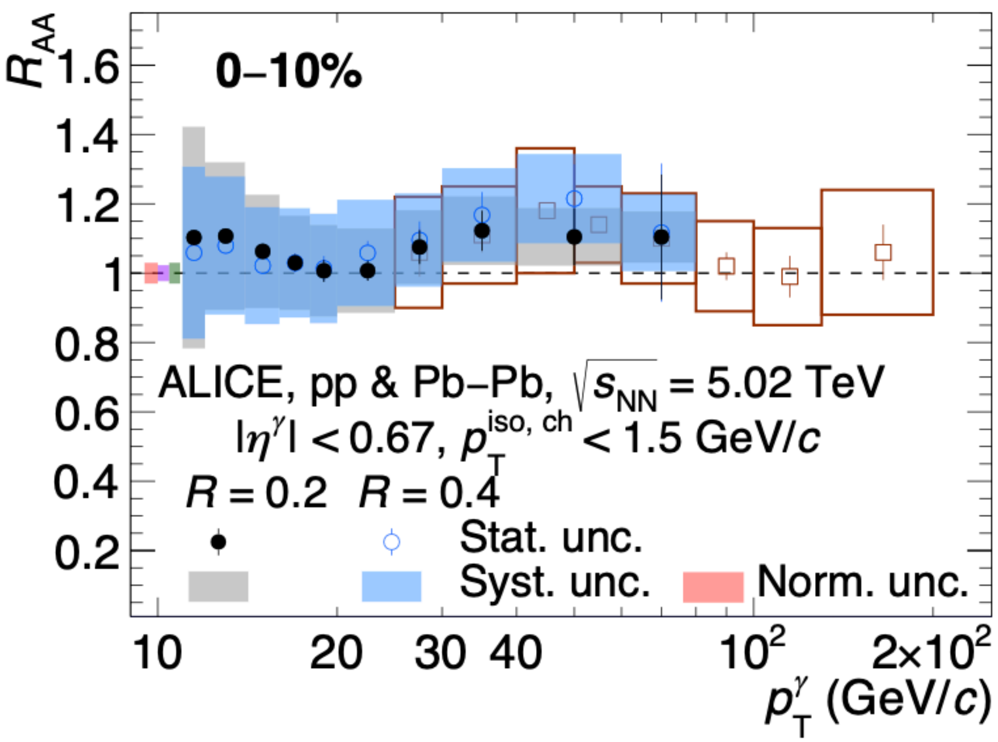
> 1 Cold Nuclear Matter (CNM)effect

Nuclear modification factor (R_{AA})

PHENIX: PRC 75 (2007) 024909

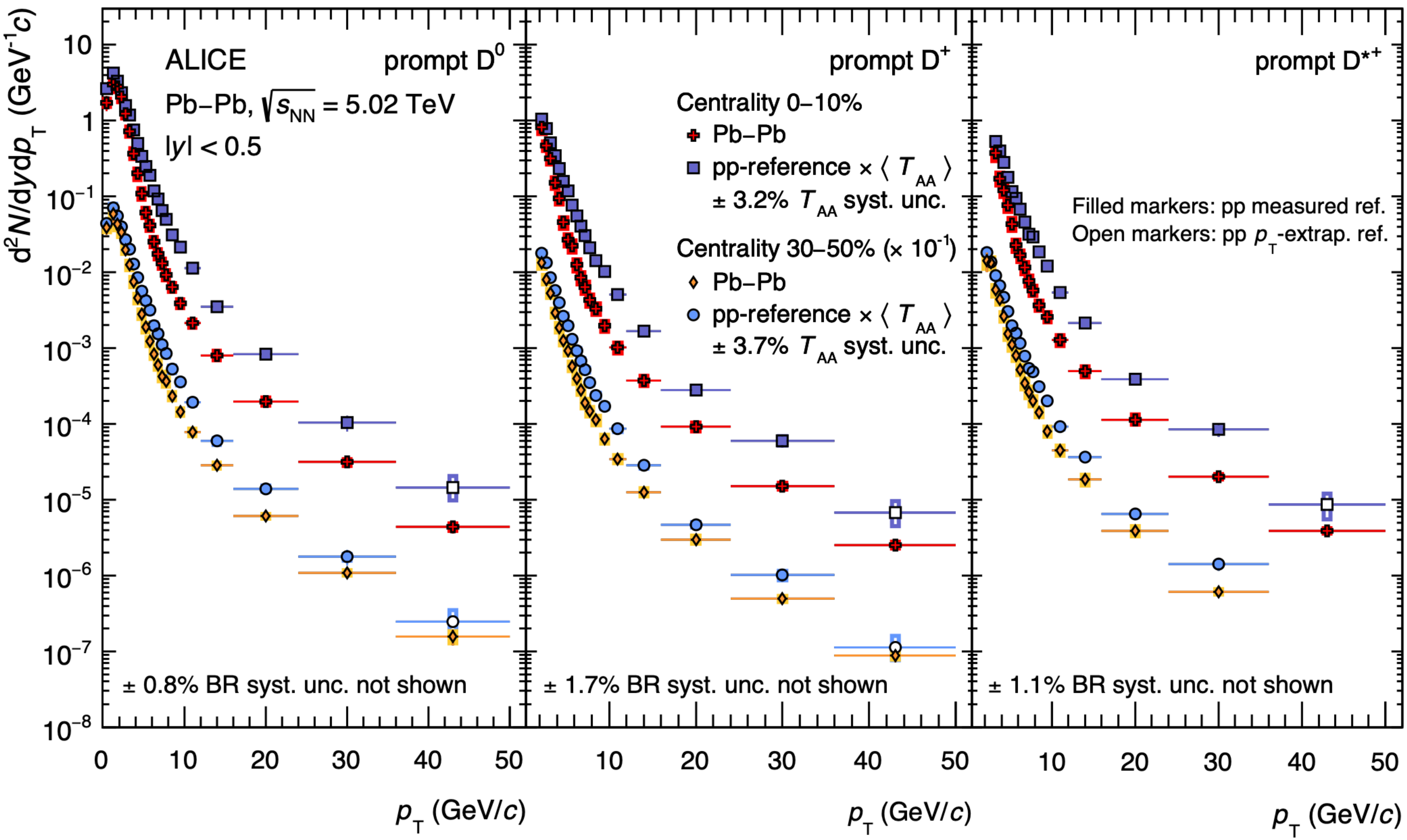


ALICE: EPJC (2025) 85

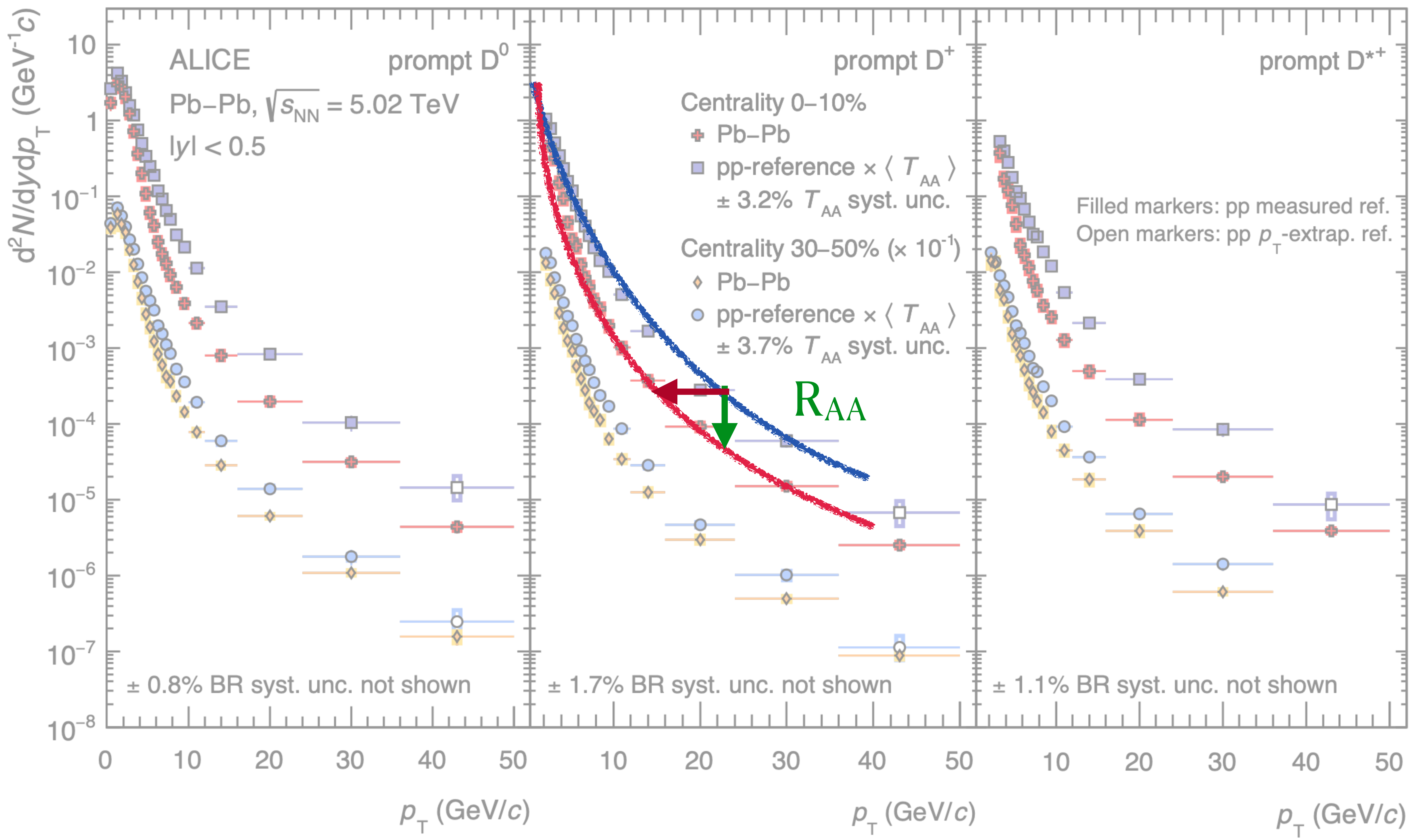


Direct photons $R_{AA} = 1$ validate binary collision scaling for hard processes

ALICE: JHEP 174 (2022)



ALICE: JHEP 174 (2022)

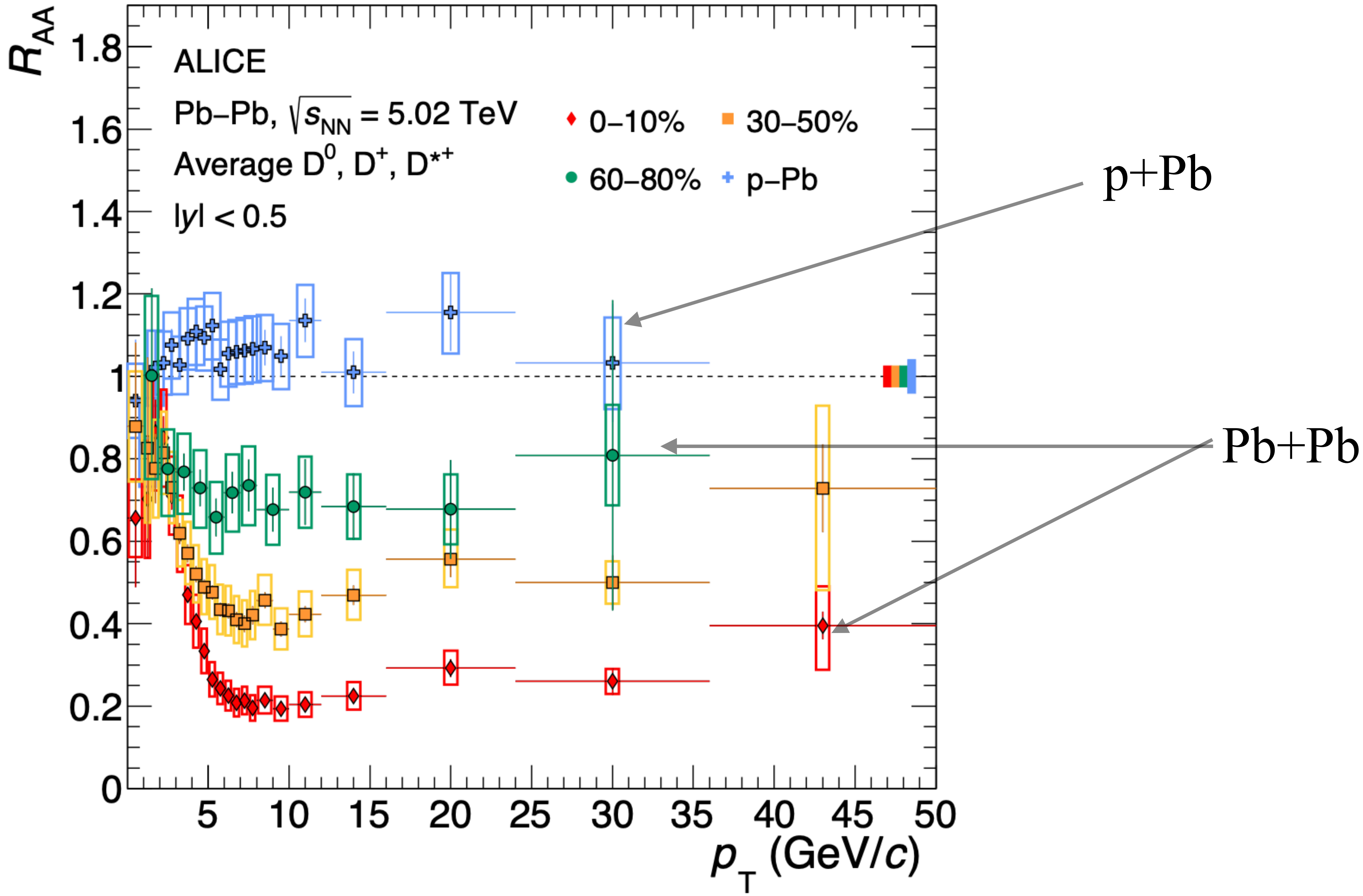


$-\Delta p_T$: the measure of Horizontal (pT) shift

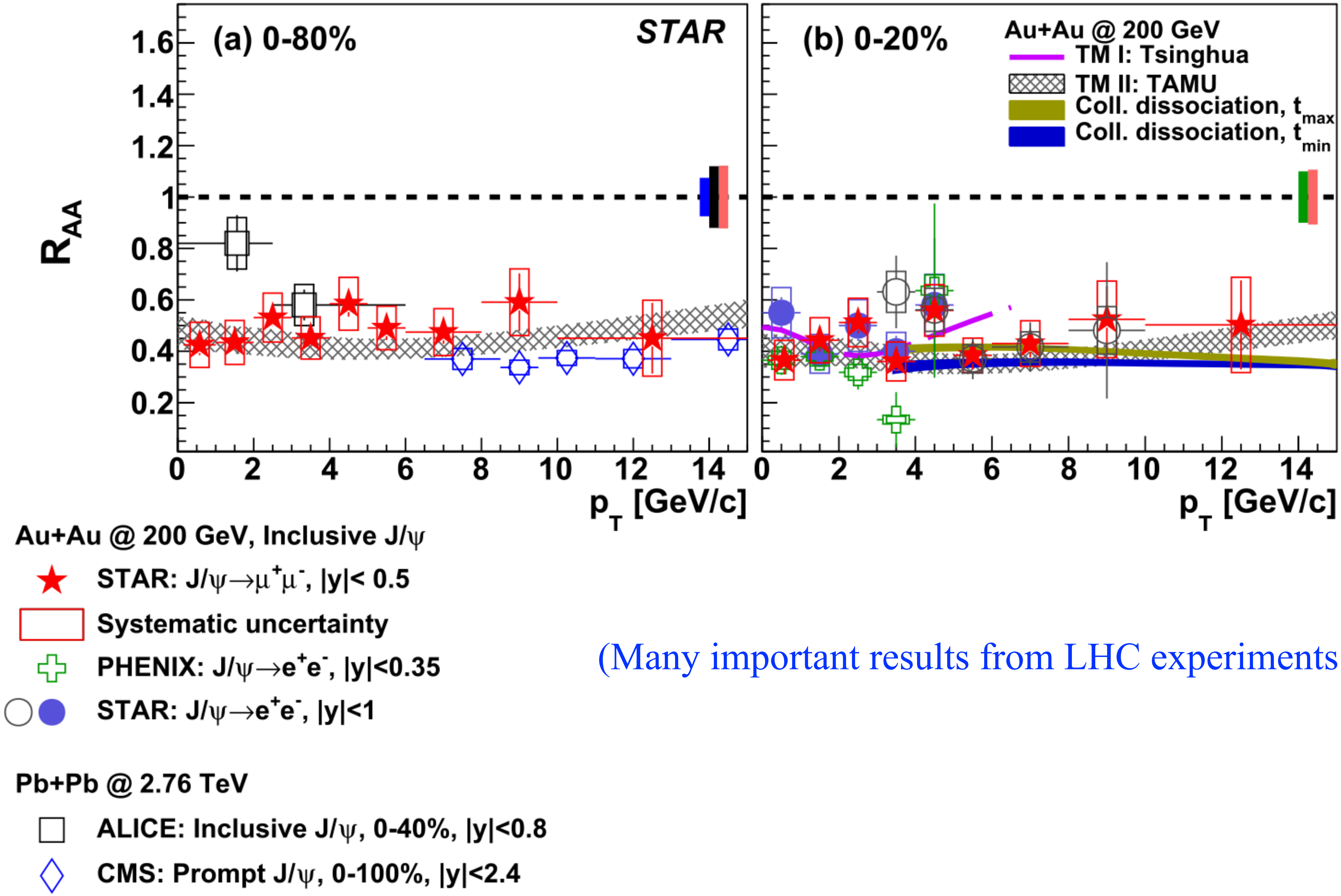
R_{AA} is the measure of vertical shift

Nuclear modification factor (R_{AA}) of D-mesons

ALICE: JHEP 174 (2022)

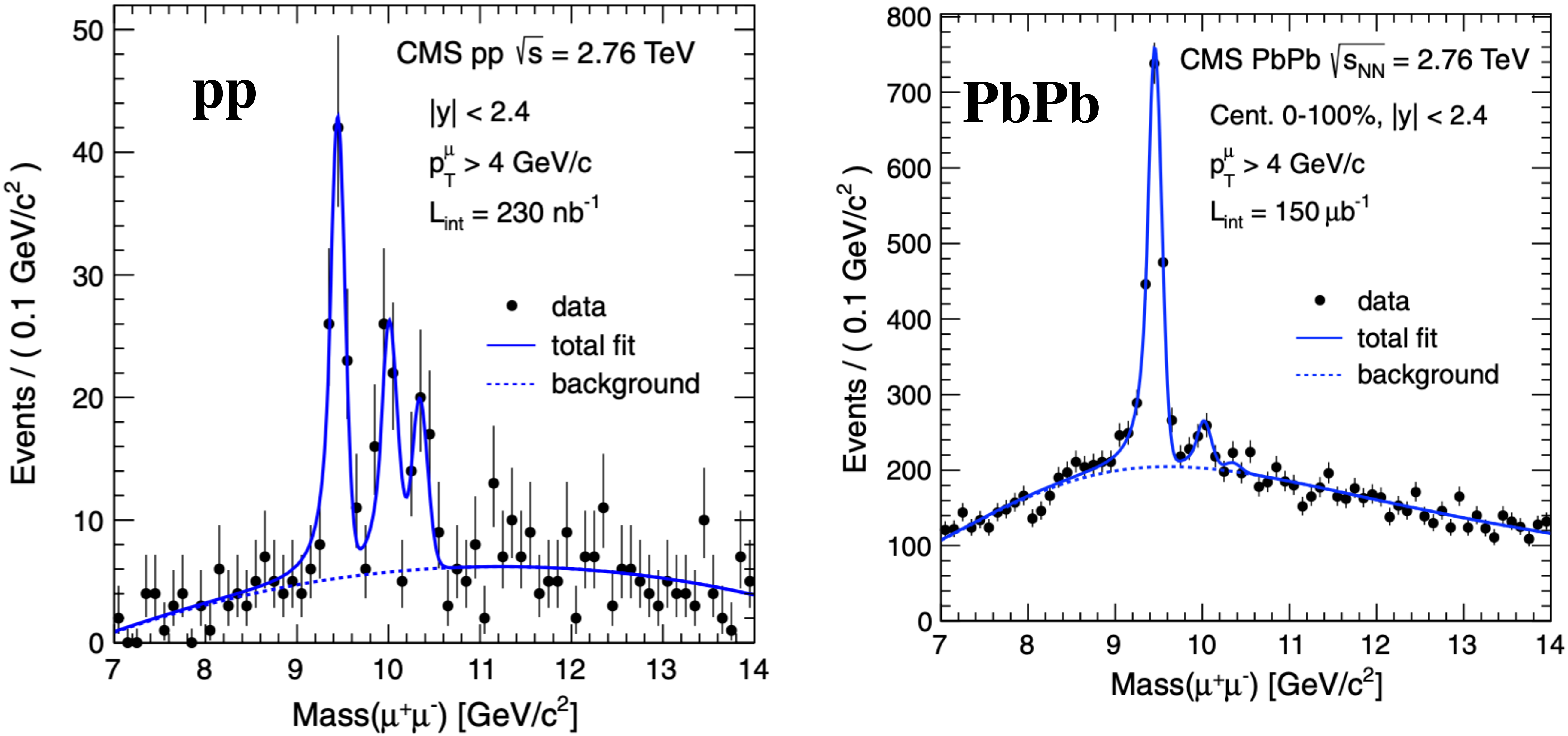


Nuclear modification factor (R_{AA}) of J/ψ in Au+Au



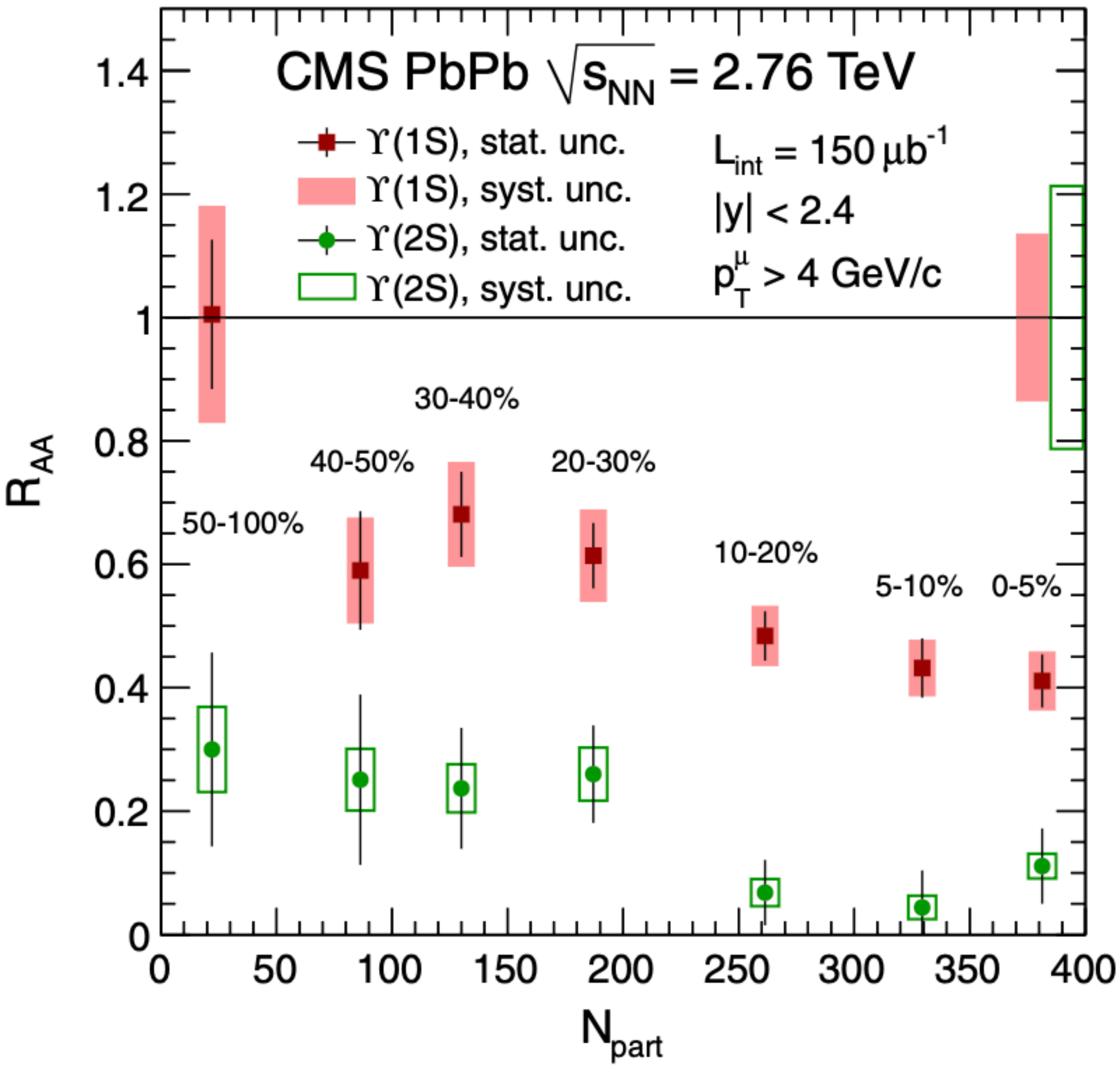
(Many important results from LHC experiments also)

Dimuon invariant mass distribution in pp and PbPb



$\Upsilon(1S,2S,3S)$ Suppression

Nuclear modification factor (R_{AA}) of $\Upsilon(1S,2S)$ in Pb+Pb



Double ratios

Sequential suppression in QGP

Double ratio:

$$\frac{(N_{\psi(2S)}/N_{J/\psi})_{AA}}{(N_{\psi(2S)}/N_{J/\psi})_{pp}} = 1$$ no medium effect

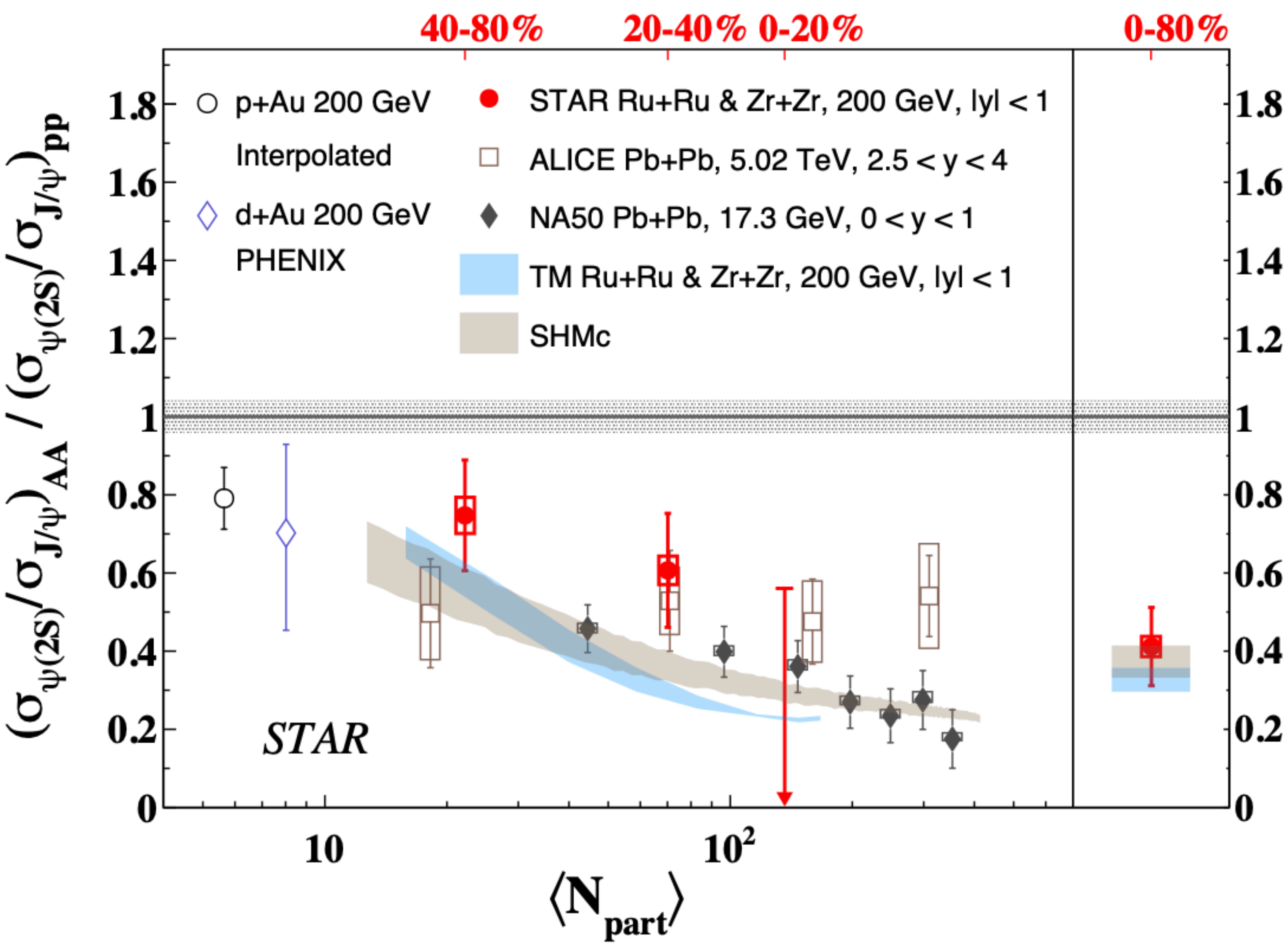
$$\frac{(N_{\psi(2S)}/N_{J/\psi})_{AA}}{(N_{\psi(2S)}/N_{J/\psi})_{pp}} < 1$$ medium effect

- Relative yield of excited to ground state in A+A collisions and p+p collisions
- $\psi(2S)$ large radius and weakly bound → melts easily than J/ψ
- additional suppression of ψ(2S) relative to J/ψ in the QGP beyond the CNM effects

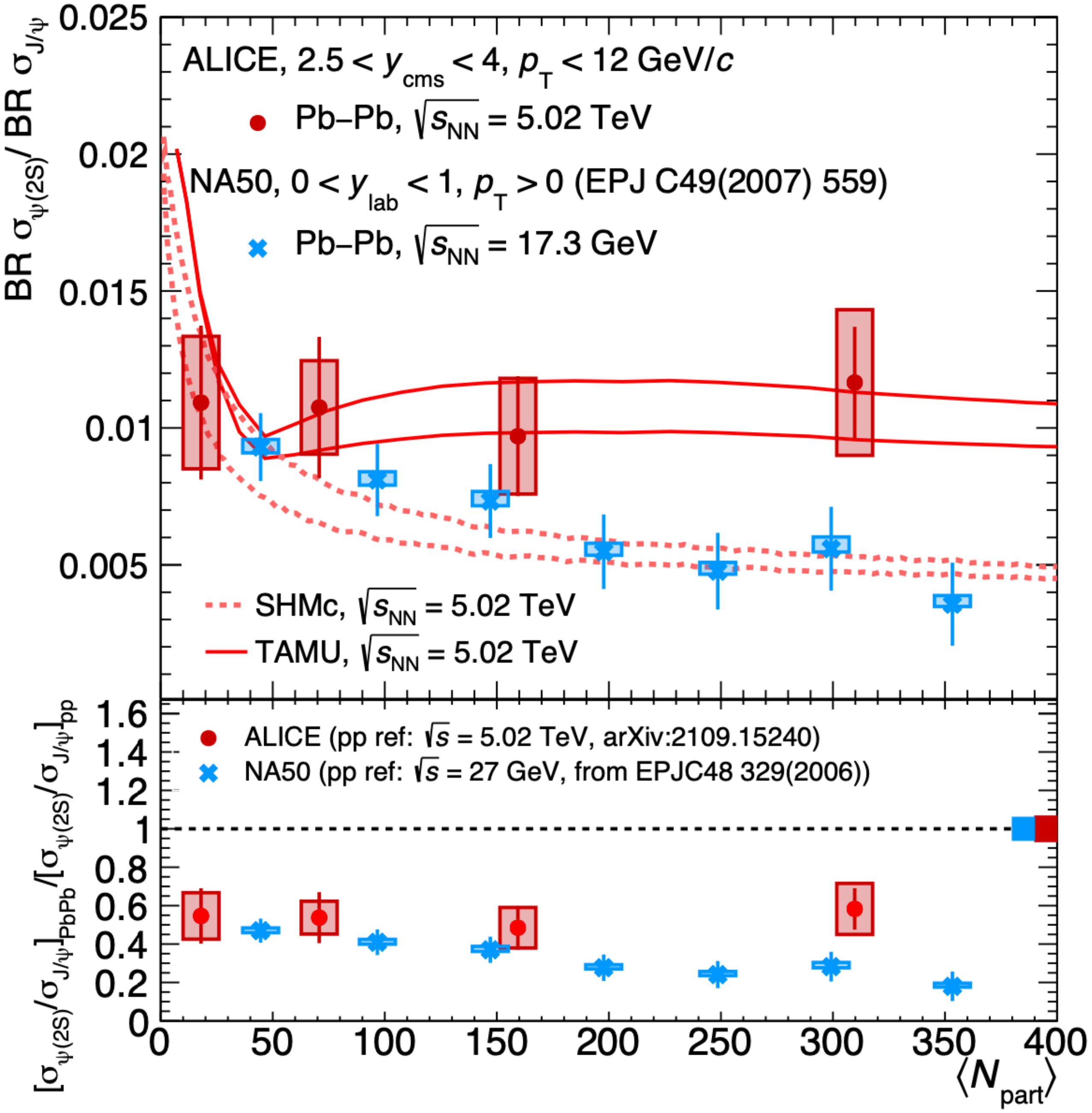
Sequential suppression in QGP

Double ratio: $\dfrac{(N_{\psi(2S)}/N_{J/\psi})_{AA}}{(N_{\psi(2S)}/N_{J/\psi})_{pp}} < 1$

STAR: arXiv: 2509.12842 [Accepted by PRL]



ALICE: *PRL* 132 (2024) 4, 042301



Different experiments

For secondary vertex reconstruction

Examples:

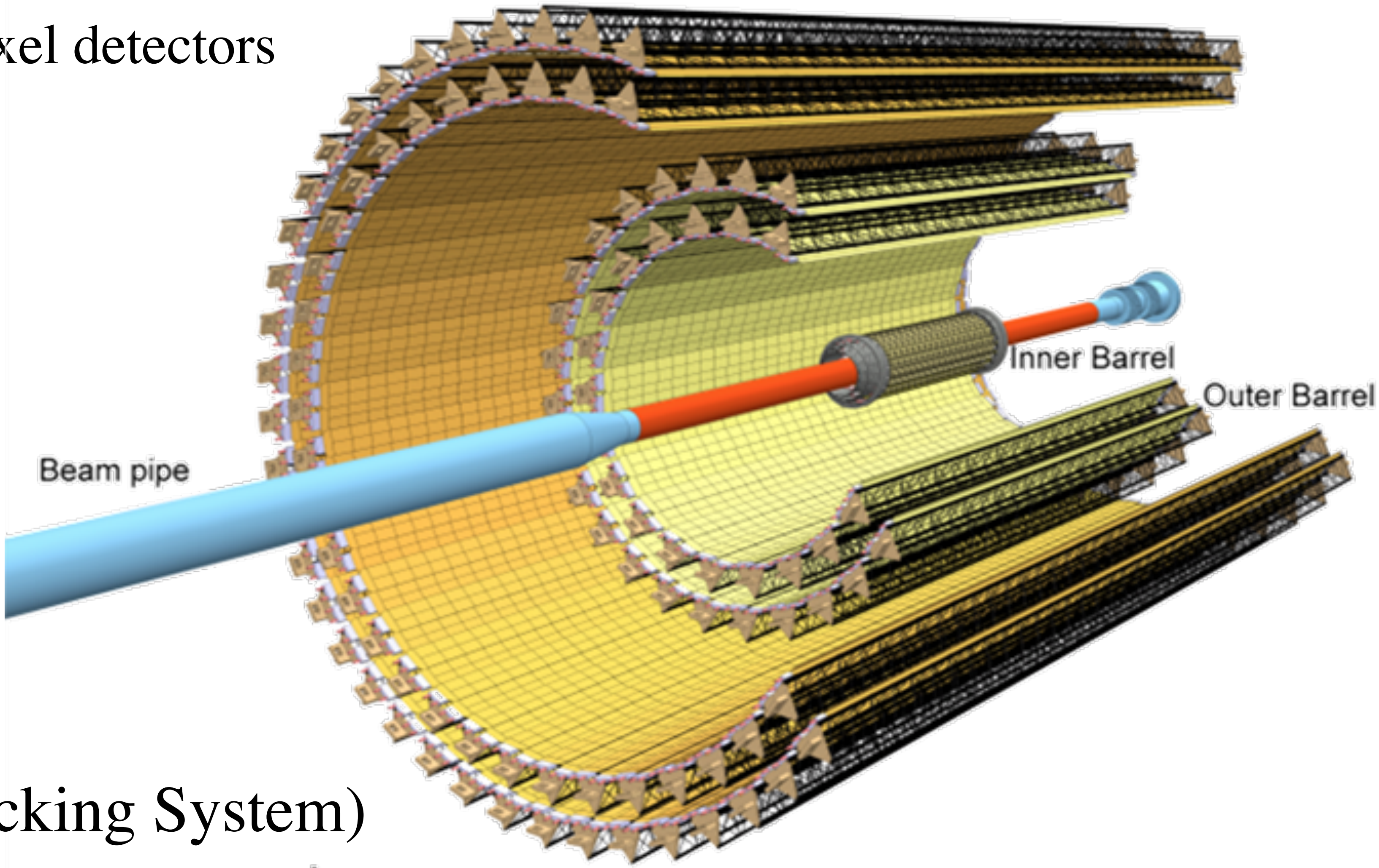
ALICE: ITS (Inner Tracking System)

STAR: HFT (Heavy Flavor Tracker)

CMS / ATLAS: Silicon pixel detectors

Particle Identification (PID)

Used to identify daughter particles.



ALICE: ITS (Inner Tracking System)

7 layers of silicon pixel detectors

Prof. B. Mohanty's talk will highlight recent measurements and physics …

Thank you

Backup