Search for Collectivity in Photonuclear Processes at RHIC using the STAR detector

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*for the **STAR Collaboration***

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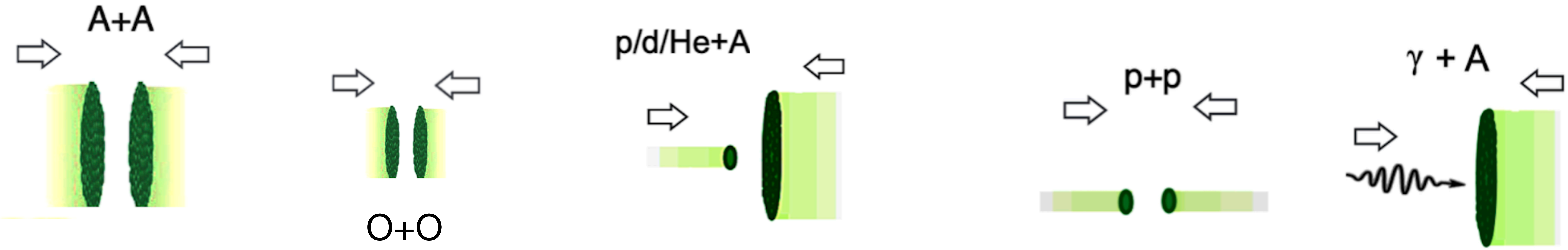
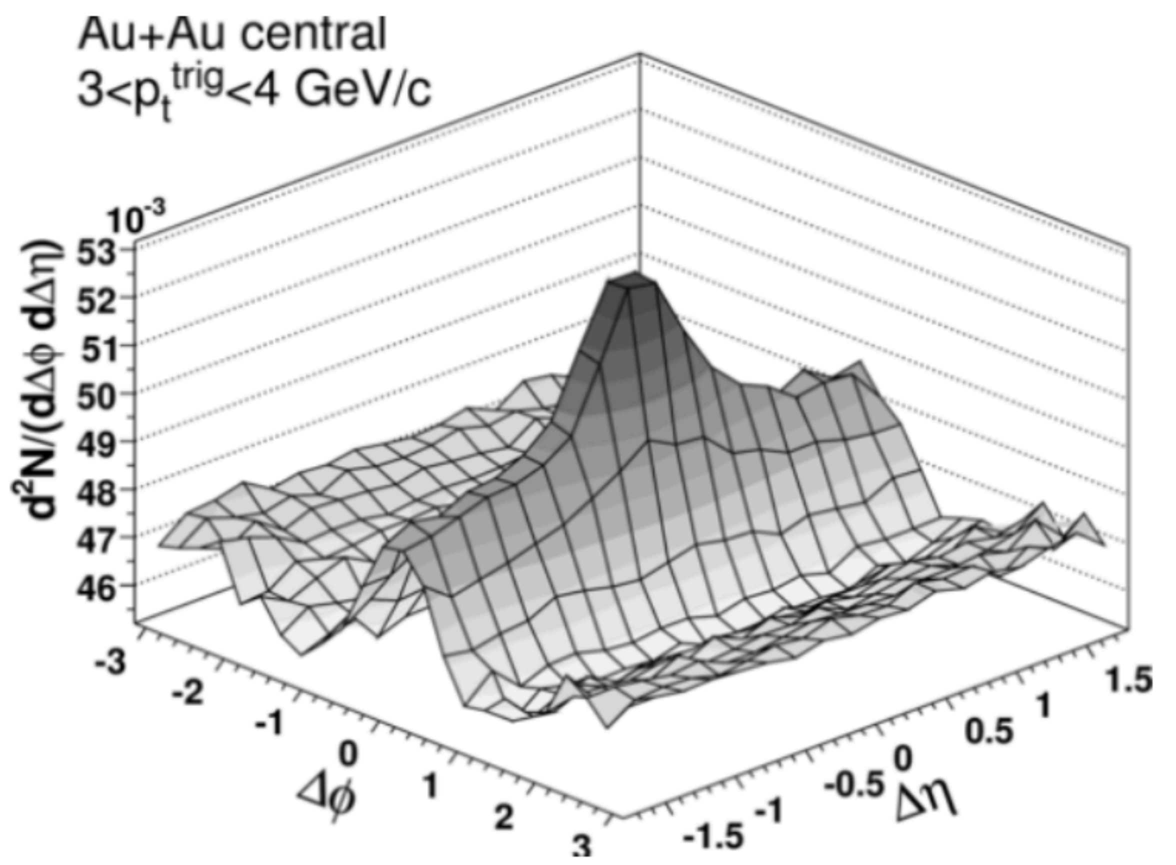
STAR

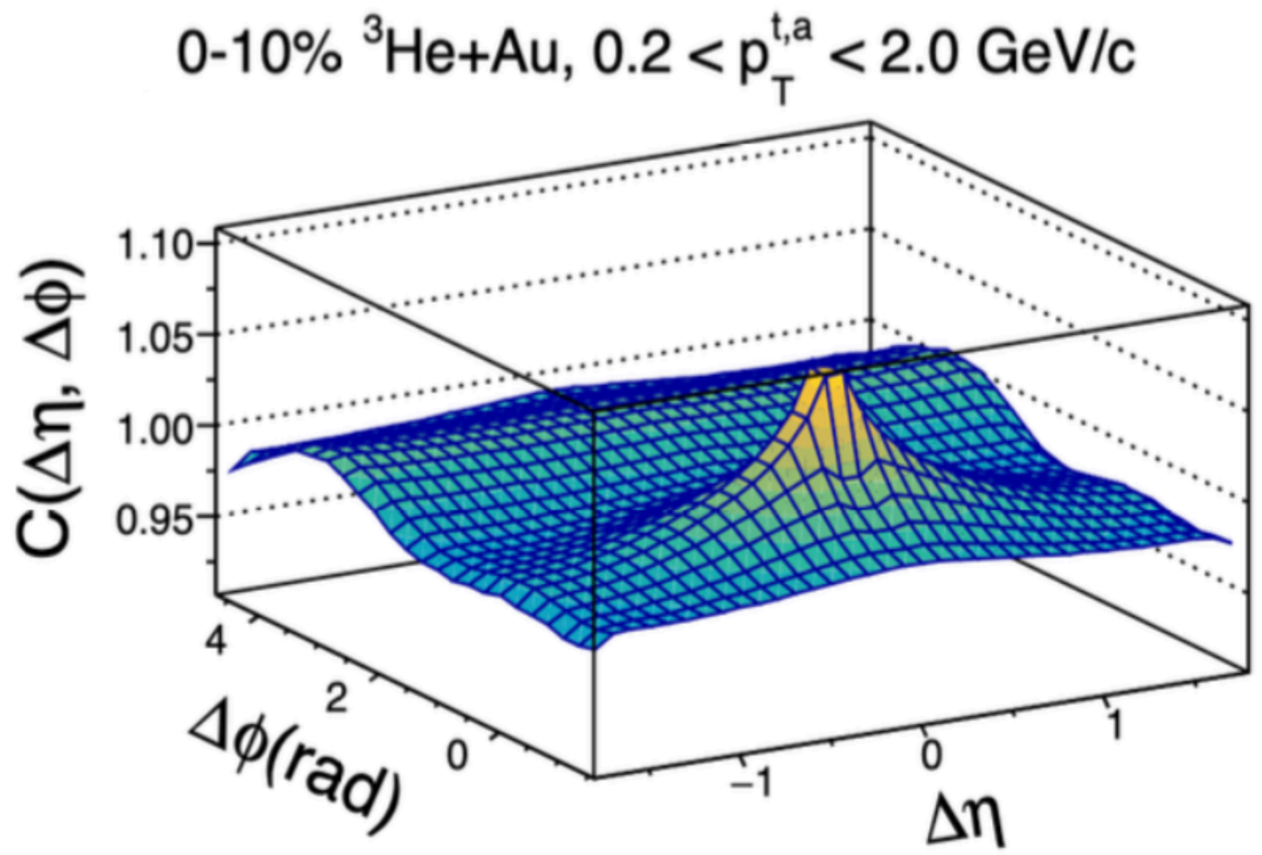
Stony Brook University

How small can a Hydrodynamic droplet be?

Final state anisotropic flow dominated by hydrodynamics in hadronic collisions - AA, ^{3}HeA, dA, pA





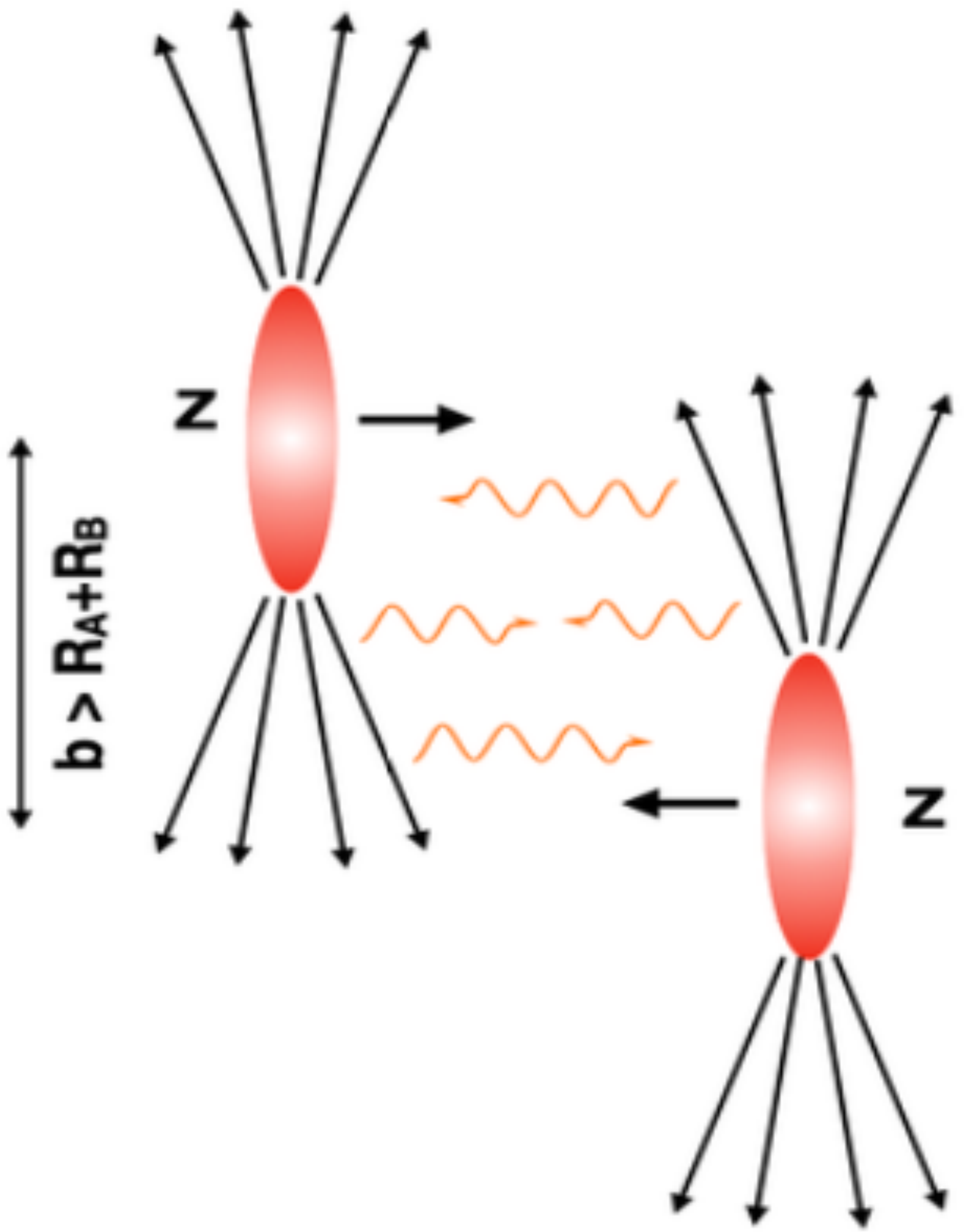


Collective behaviour in even smaller systems? e^-+p/A, γ+p/A, e^+e^-, q/g

Origin of collectivity in systems without QCD objects in colliding beams

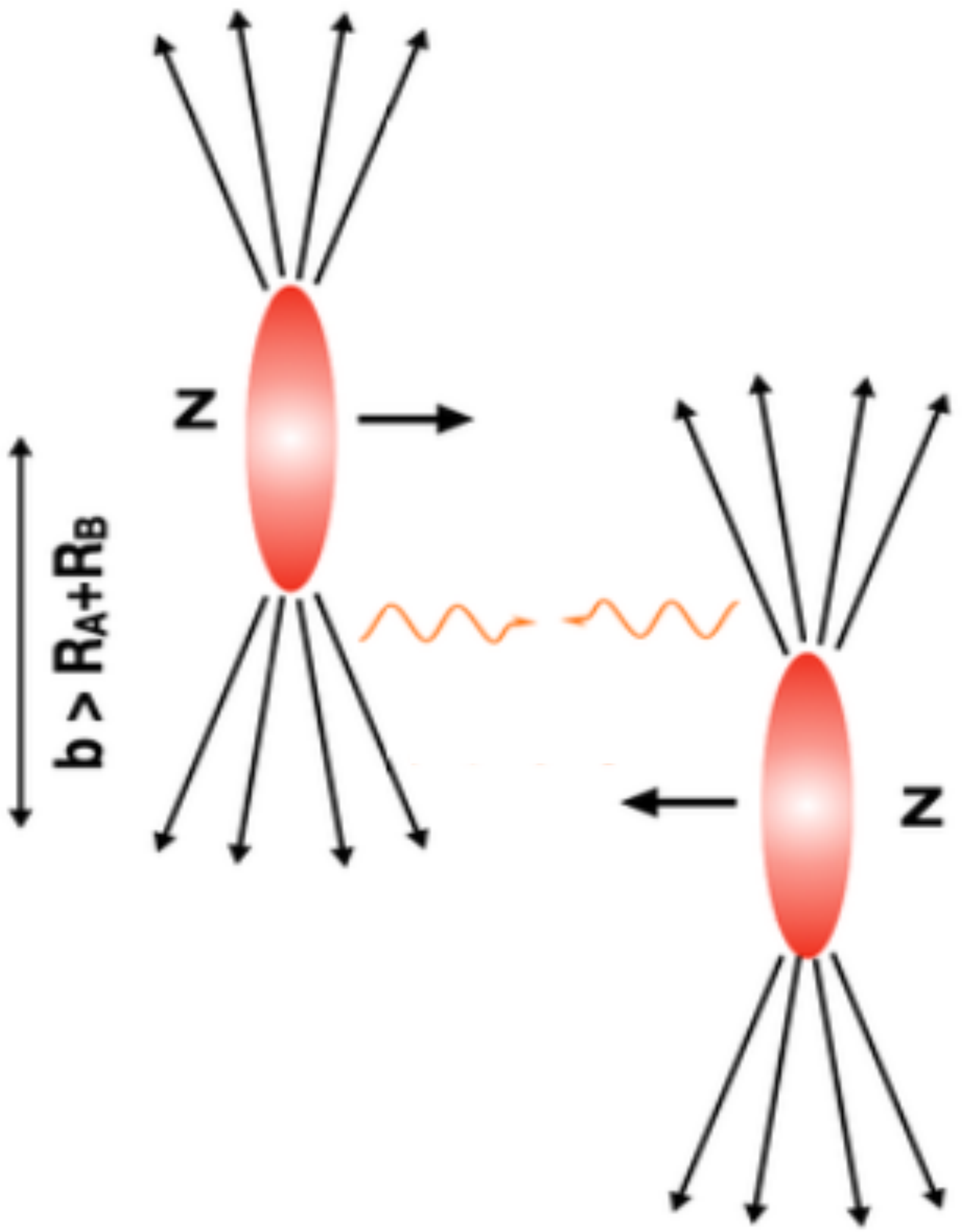
- Introduction to photonuclear processes
- Triggering photonuclear processes
- Purity of γ+Au collisions
- Choice of d+Au as a reference for γ+Au collisions
- Analysis Details
- Results: Correlation functions and flow coefficients: γAu vs dAu39 (reference)

γA processes in Ultra-Peripheral AuAu Collisions



- In heavy-ion collisions, moving charged nuclei produce highly Lorentz contracted electromagnetic (EM) field
- EM field corresponds to large flux of virtual photons in ultra-peripheral collisions (b > 2R)
- Ultra-peripheral collisions minimize hadron-hadron interactions

γA processes in Ultra-Peripheral AuAu Collisions



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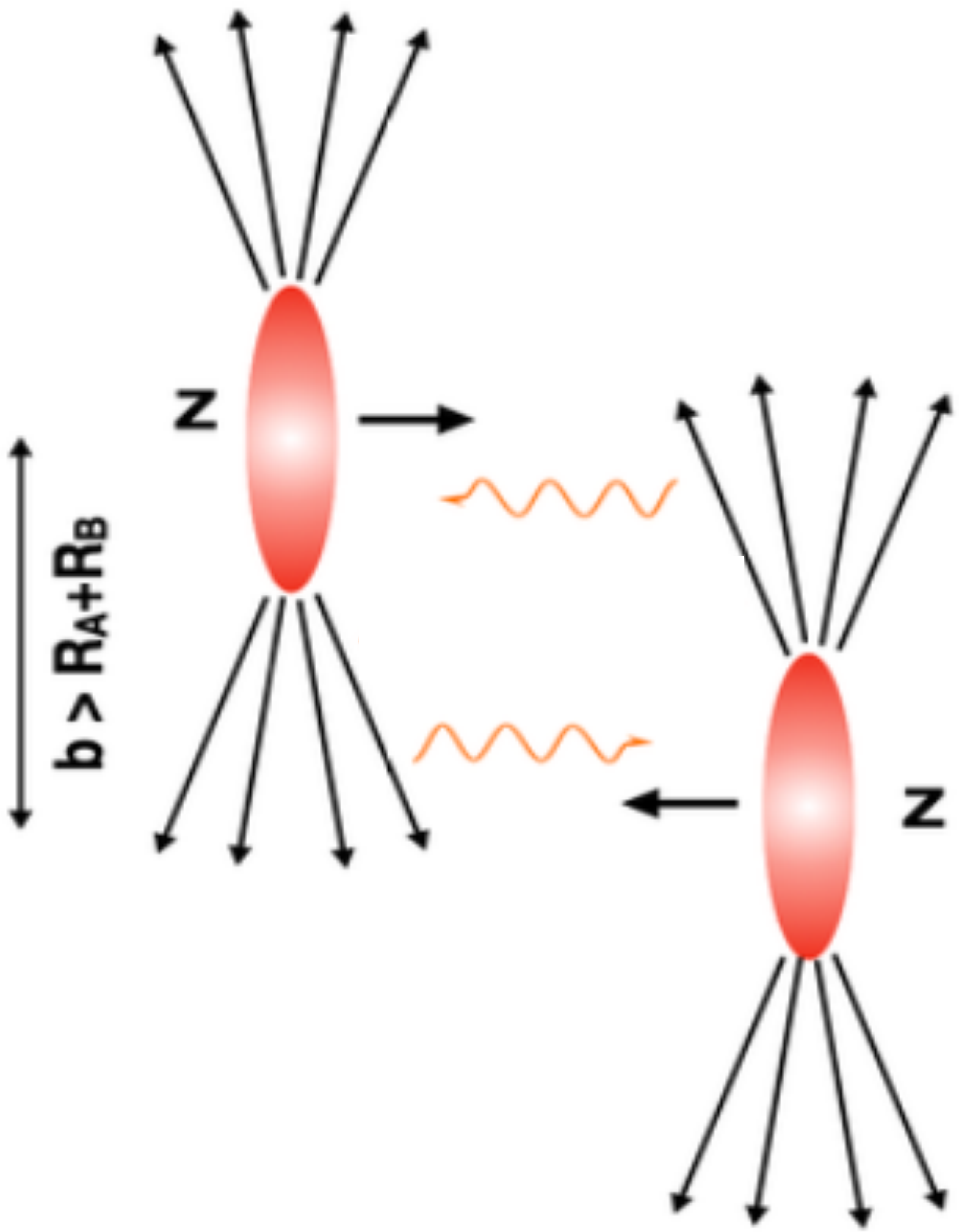
1. **Photon-photon interactions (Breit-Wheeler Process)**

γA processes in Ultra-Peripheral AuAu Collisions



- In heavy-ion collisions, moving charged nuclei produce highly Lorentz contracted electromagnetic (EM) field
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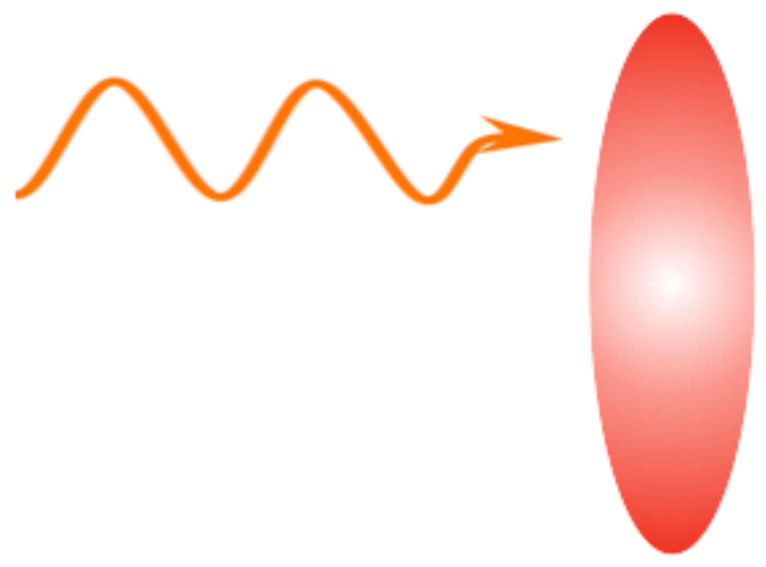
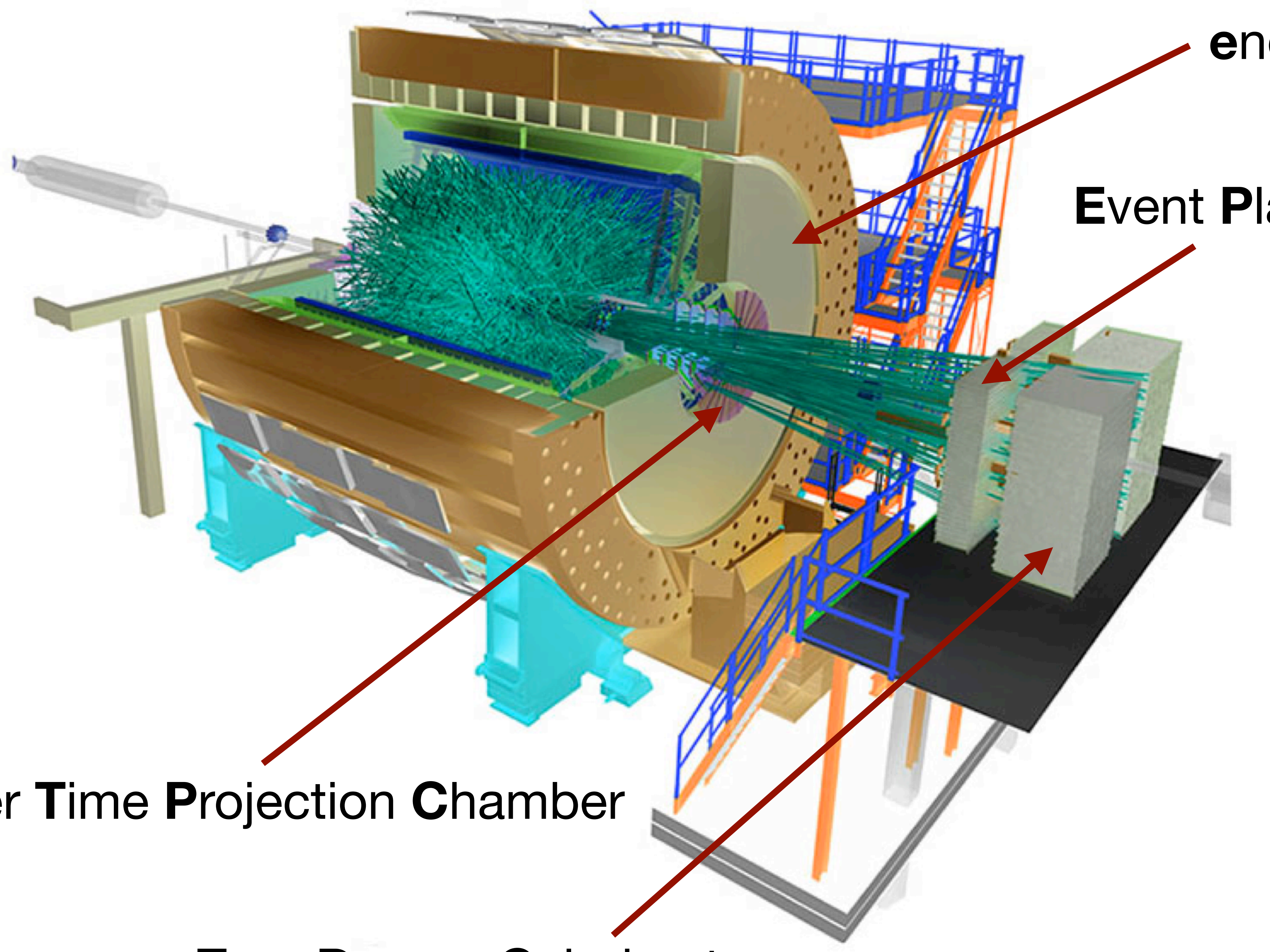
2. **Photo-nuclear interactions**



- Introduction to photonuclear processes
- **Triggering photonuclear processes**
- Purity of γ+Au collisions
- Choice of d+Au as a reference for γ+Au collisions
- Analysis Details
- Results: Correlation functions and flow coefficients: γAu vs dAu39 (reference)

STAR Detector Upgrades & Dataset



Wider η coverage:

< 2019		2019+
$\lvert\eta\rvert < 1.0$	----▶	$\lvert\eta\rvert < 1.5$ (iTPC)
		$2.13 < \lvert\eta\rvert < 5.1$ (EPD)

γ+Au

- Year 2019 AuAu
- $\sqrt{s_{NN}}$ = 200GeV
- Events: ~100M

d+Au: Reference

- Year 2016 dAu
- $\sqrt{s_{NN}}$ = 39GeV
- Events: ~235M

Vertex Selection

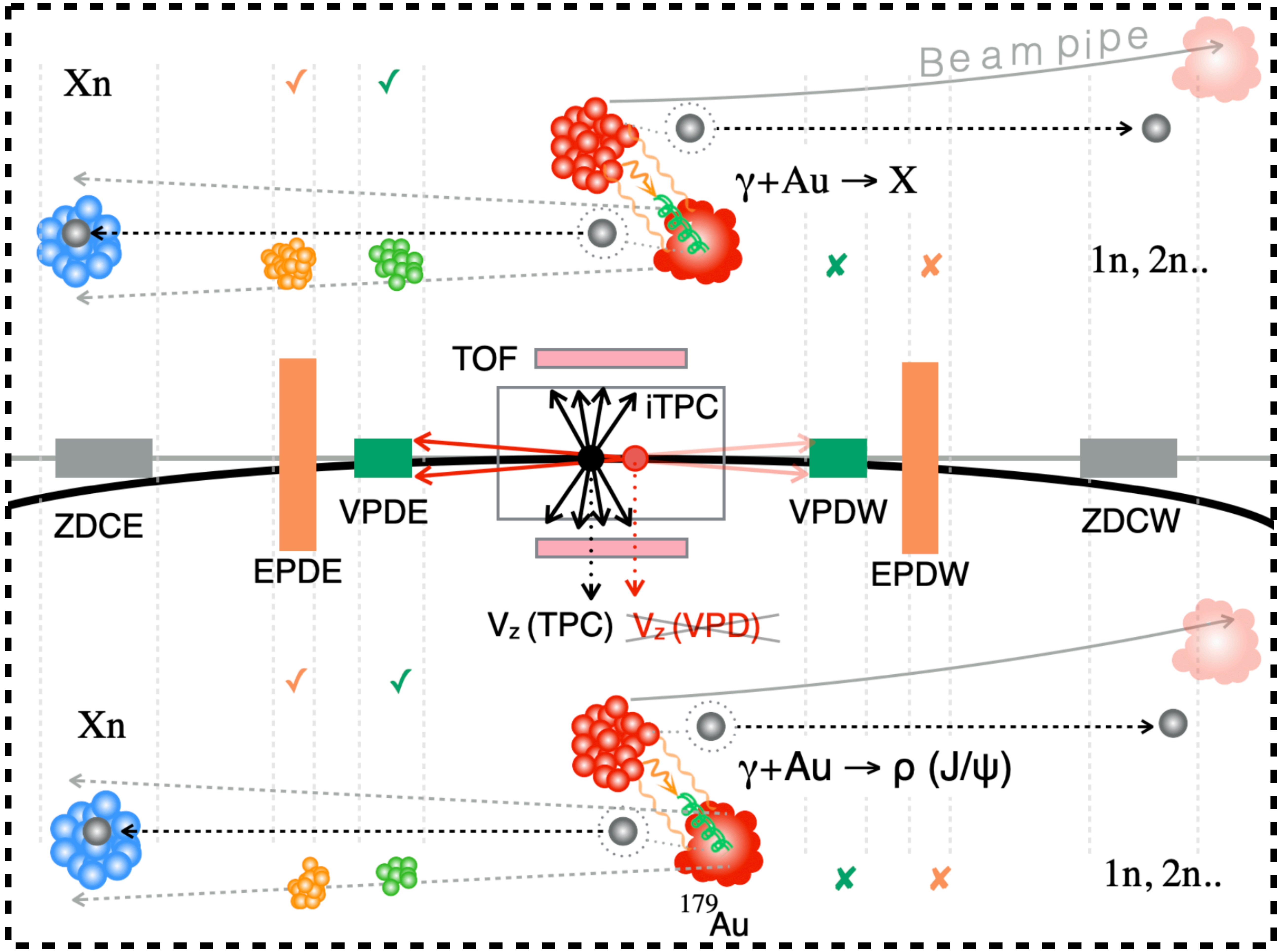
- $\sqrt{V_x^2 + V_y^2} < 2.0$ cm
- $|V_z| < 100$ cm
- |TPC Vz - VPD Vz| (Vz_diff)
  - Vz_diff < 5 cm (dAu39)
  - Vz_diff > 10 cm (γAu)

Track Selection

- DCA < 3.0 cm (dAu39), DCA < 3.5 cm (γAu)
- pT > 0.1 GeV/c
- $|\eta| < 1.5$
- nHitsFit > 10, nHitsFitRatio > 0.52

Triggering Photonuclear Processes in AuAu UPC

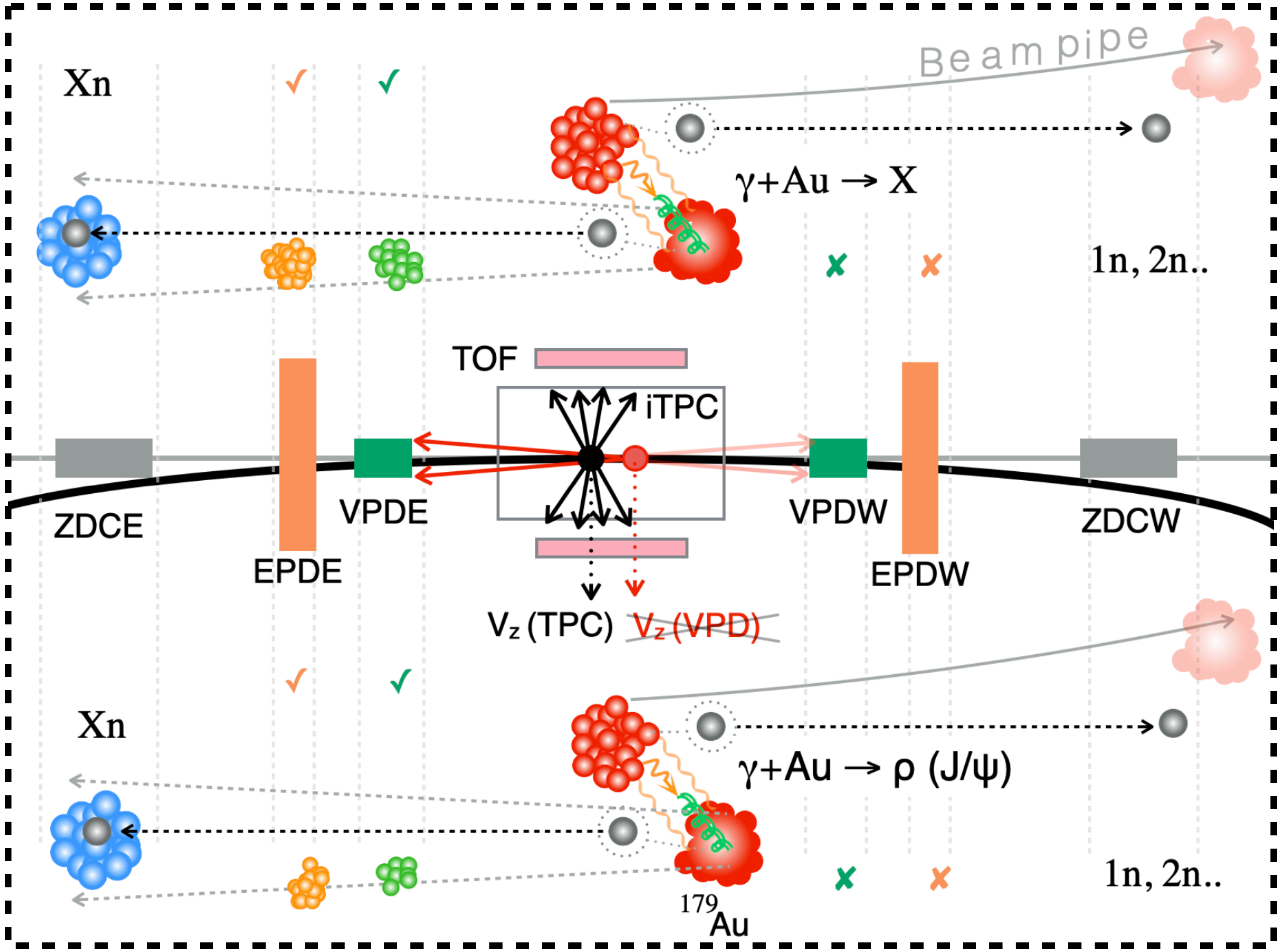
Kinematic similarities between inclusive γ+Au and exclusive ρ-production



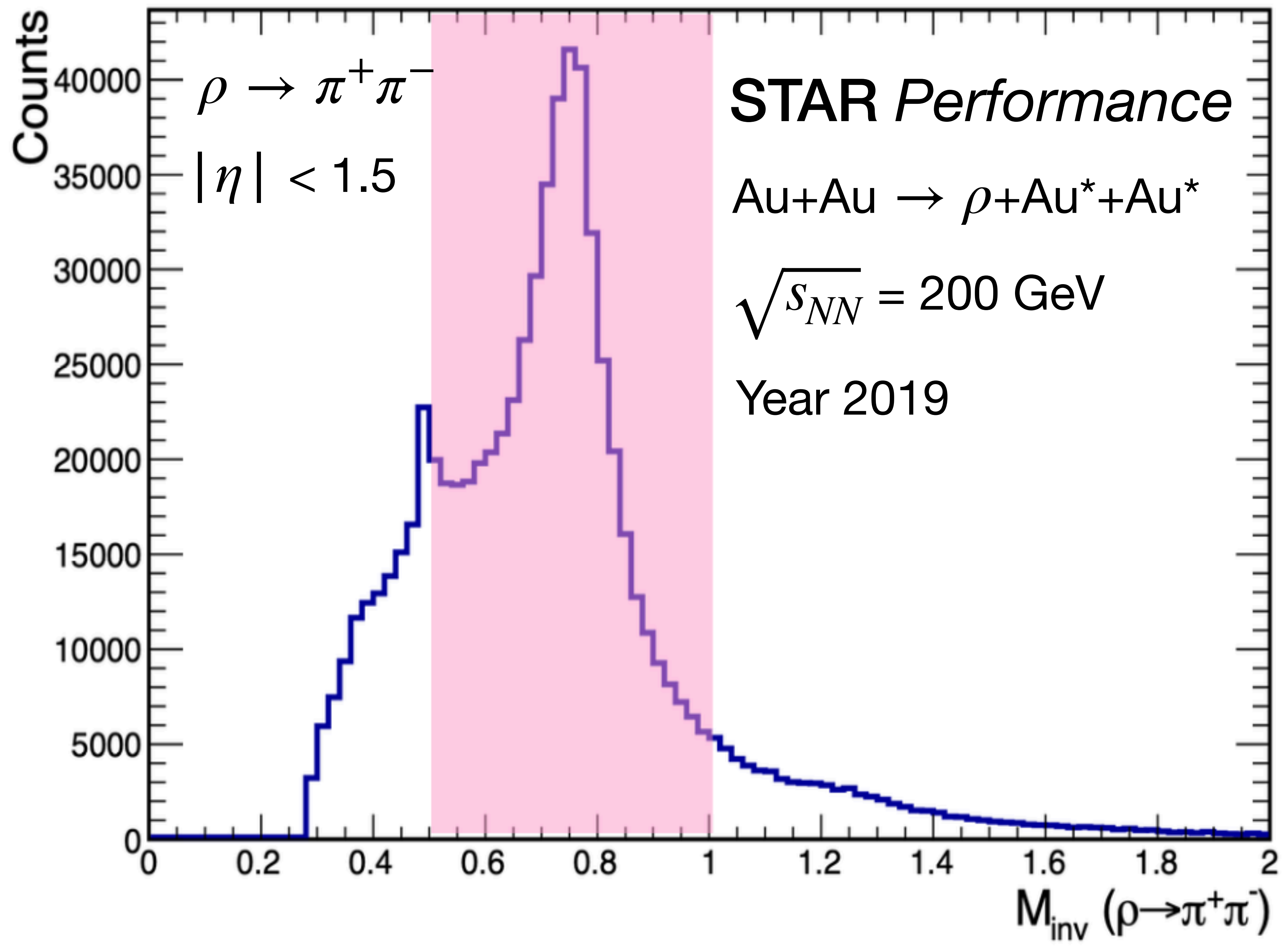
S. Paul, QM2025, https://indi.to/v3rmx

Triggering Photonuclear Processes in AuAu UPC

Photo-nuclear cuts decided based on "standard candle":
Exclusive ρ-production as a trigger for inclusive $\gamma + A$ process



Events with only 2 iTPC tracks from $\rho \to \pi^+\pi^-$



Triggering Photonuclear Processes in AuAu UPC

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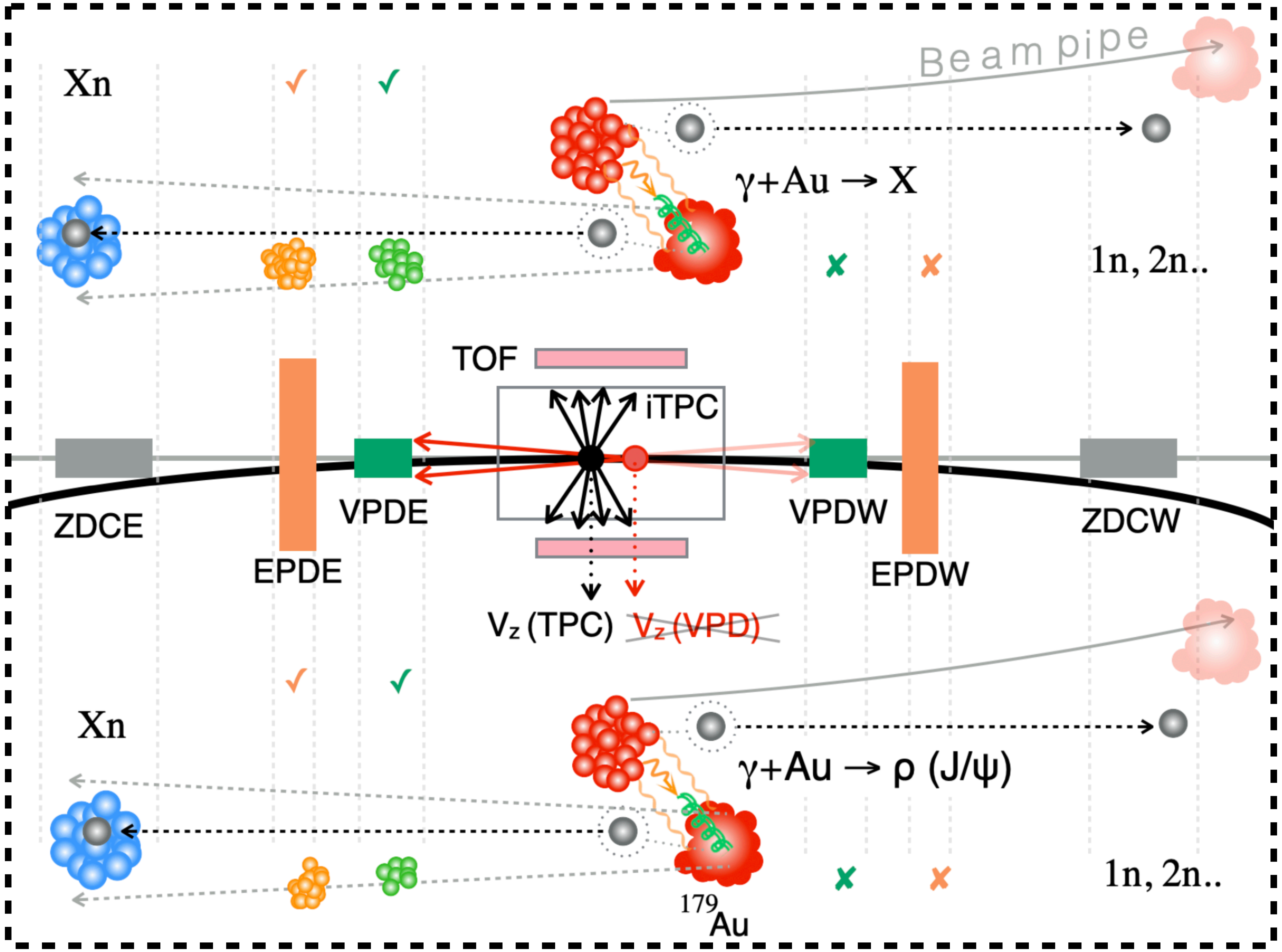
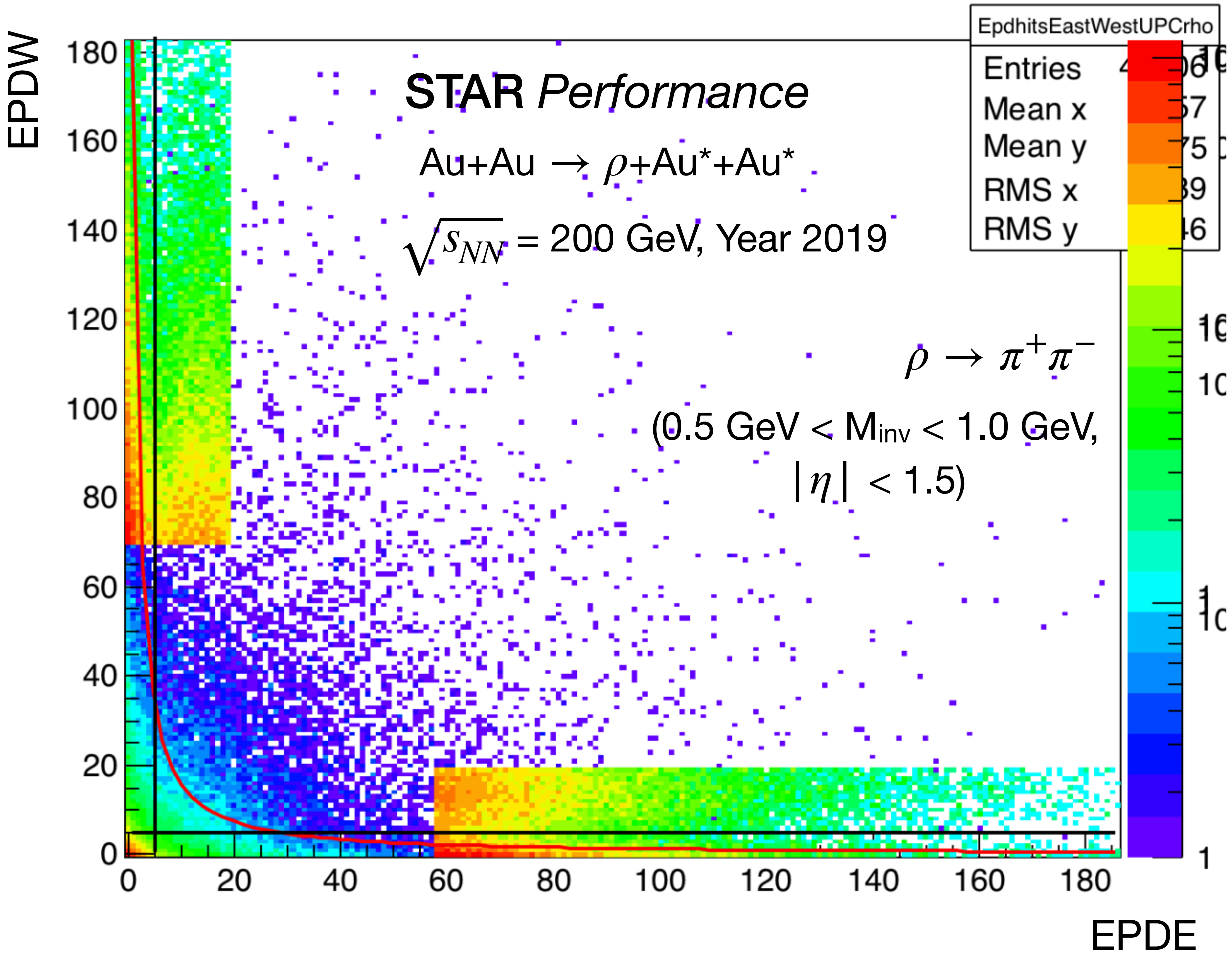


Asymmetric multiplicity and spectator distributions in γ+Au collisions



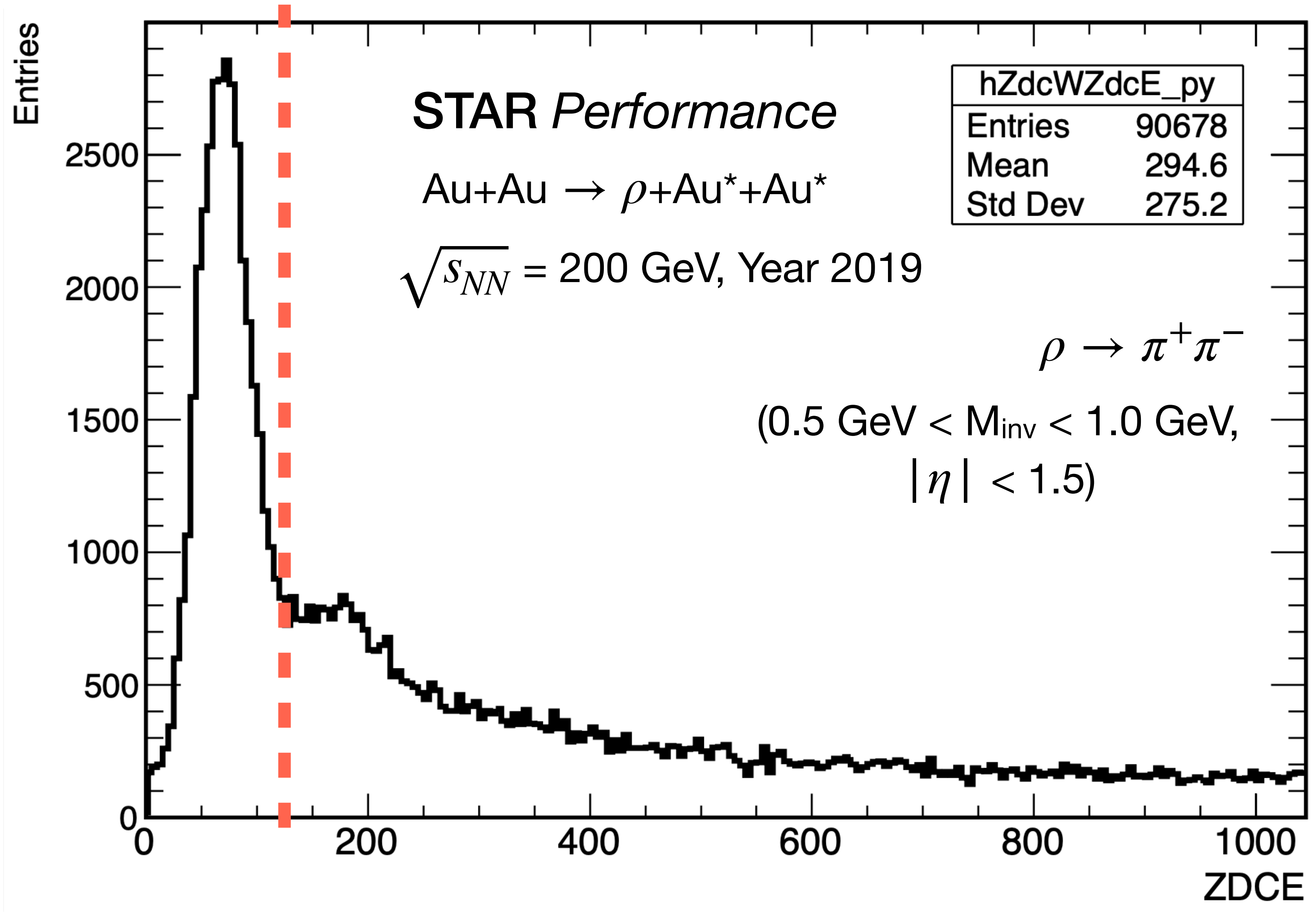
Two iTPC tracks with reconstructed ρ select

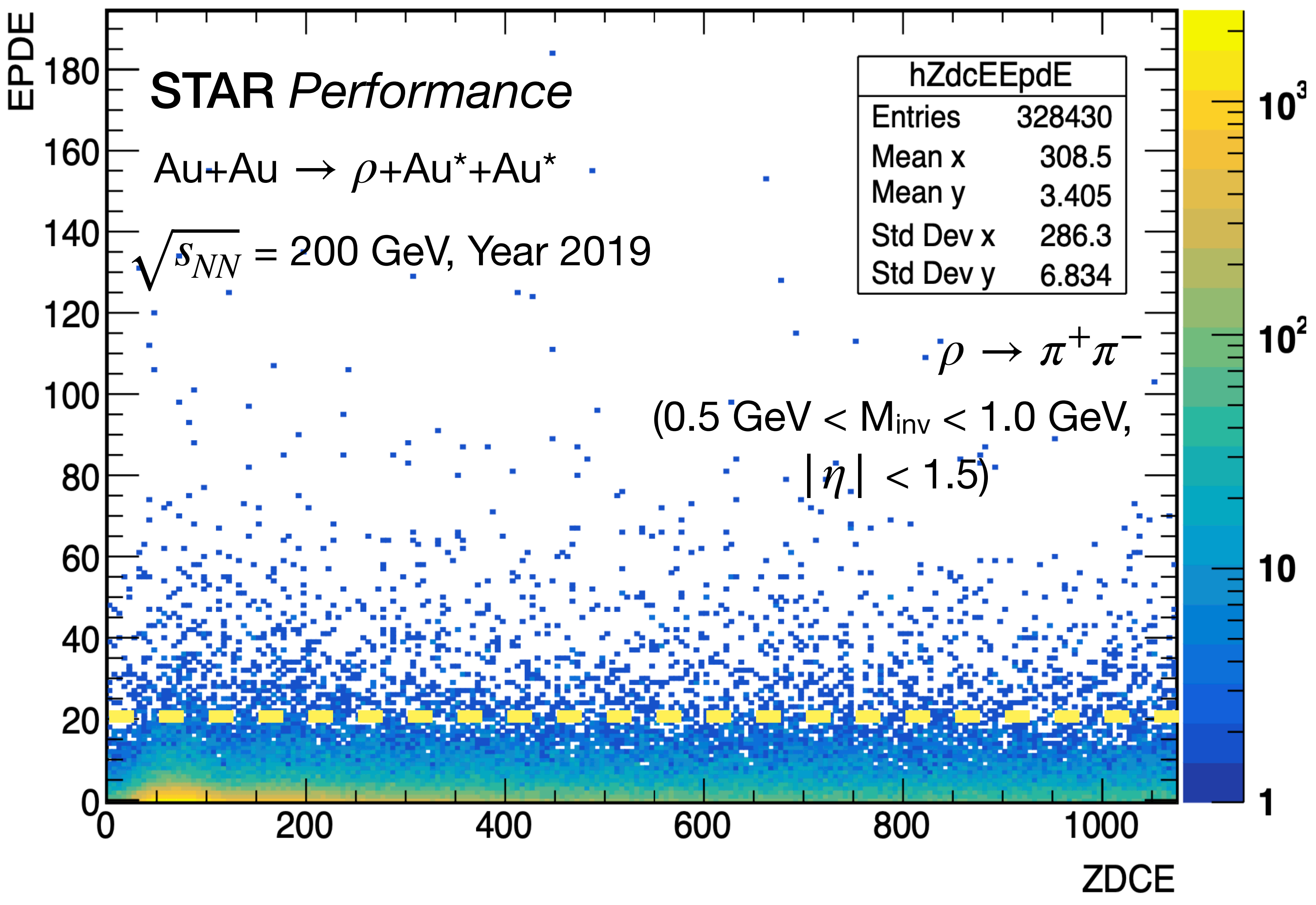
$\gamma + Au \to \rho$ processes:

Small hits & east-west anti-correlation

Photonuclear Cuts

Exclusive ρ-production as a "standard candle" to define ZDC and EPD cuts for γAu event selection



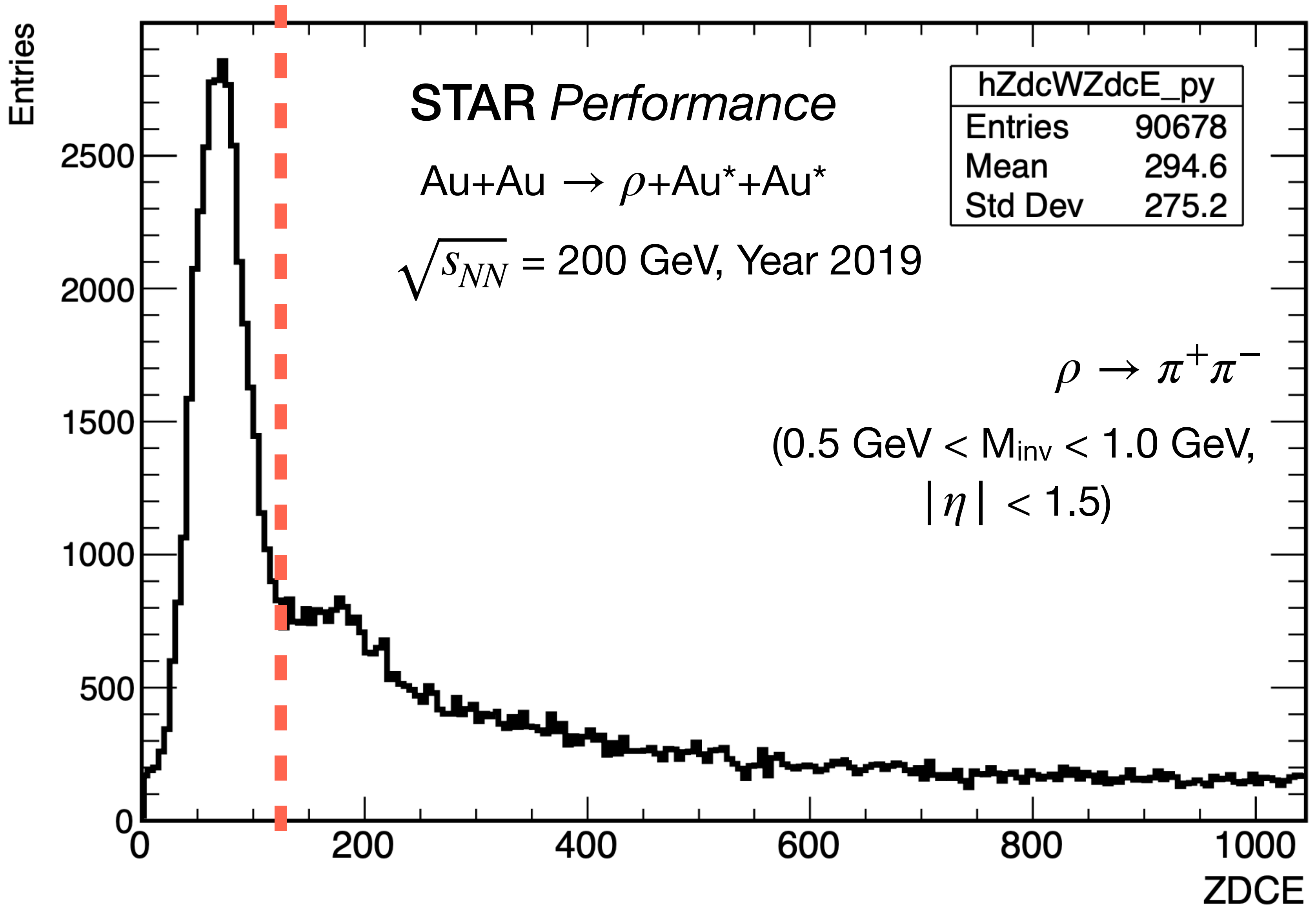


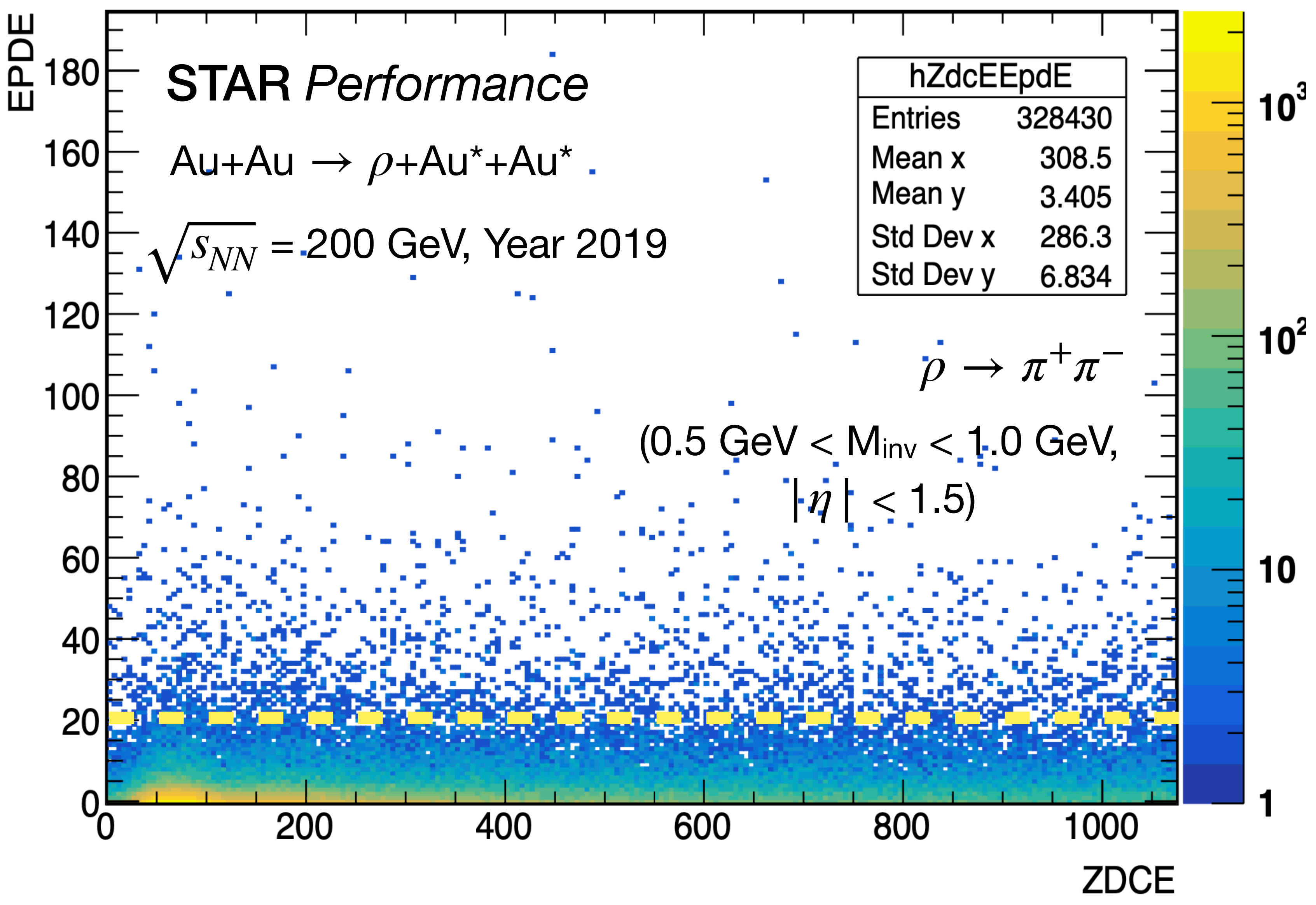
East γ-going side:

- ZdcAdcE < 120
- EpdMipE < 20
- ZdcAdcW > 100
- EpdMipW > 20

Photonuclear Cuts

Exclusive ρ-production as a "standard candle" to define ZDC and EPD cuts for γAu event selection





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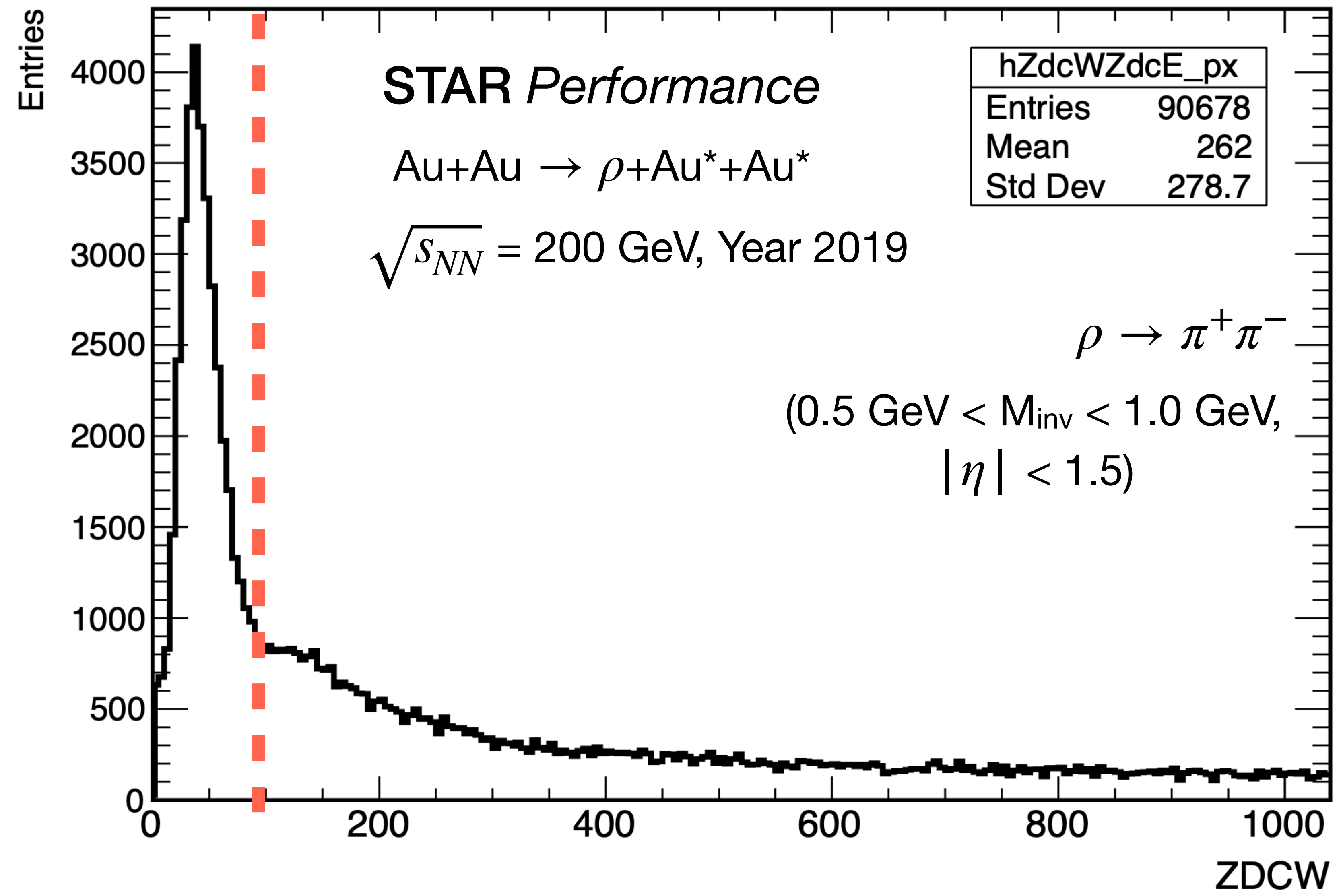
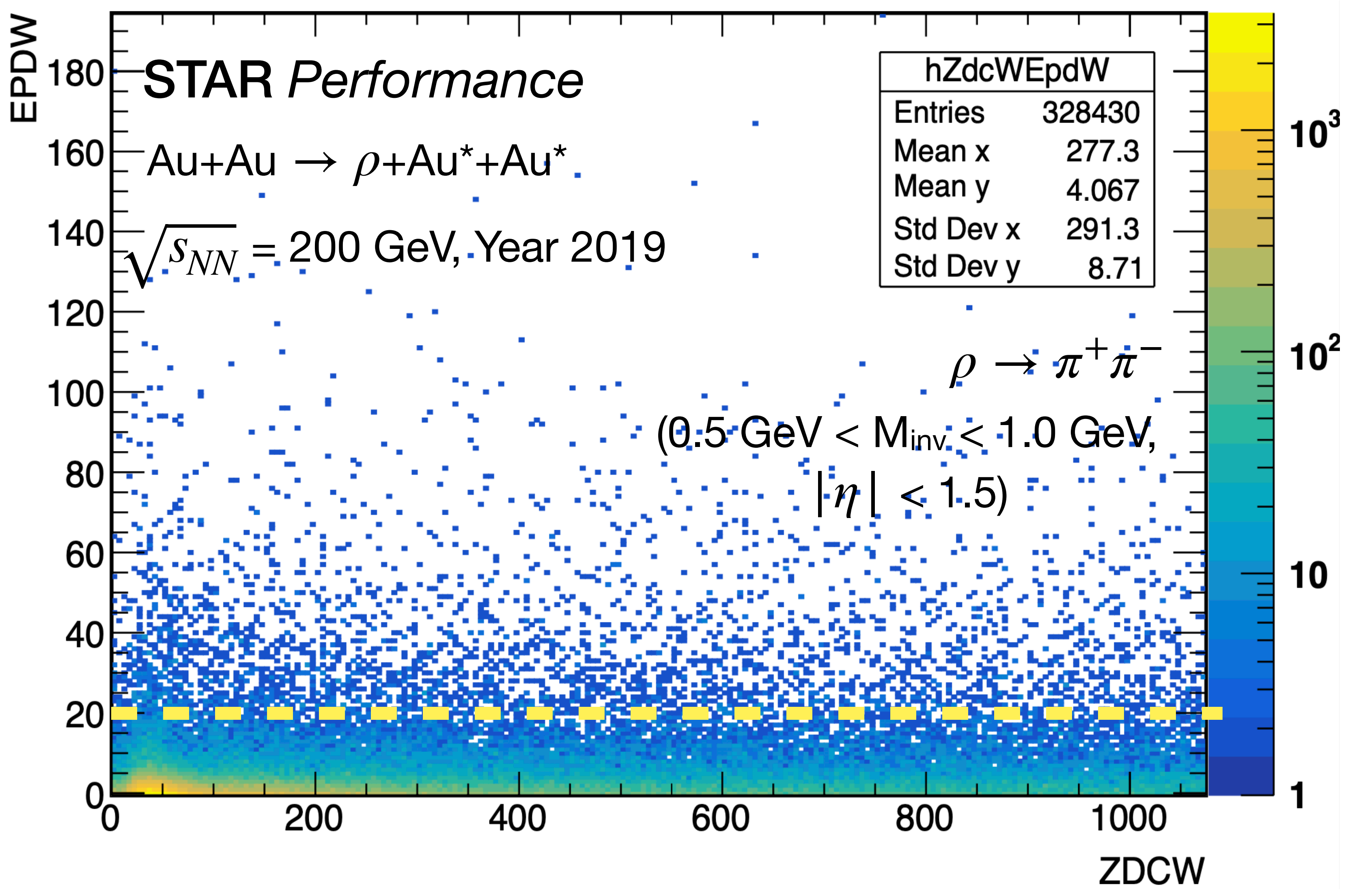




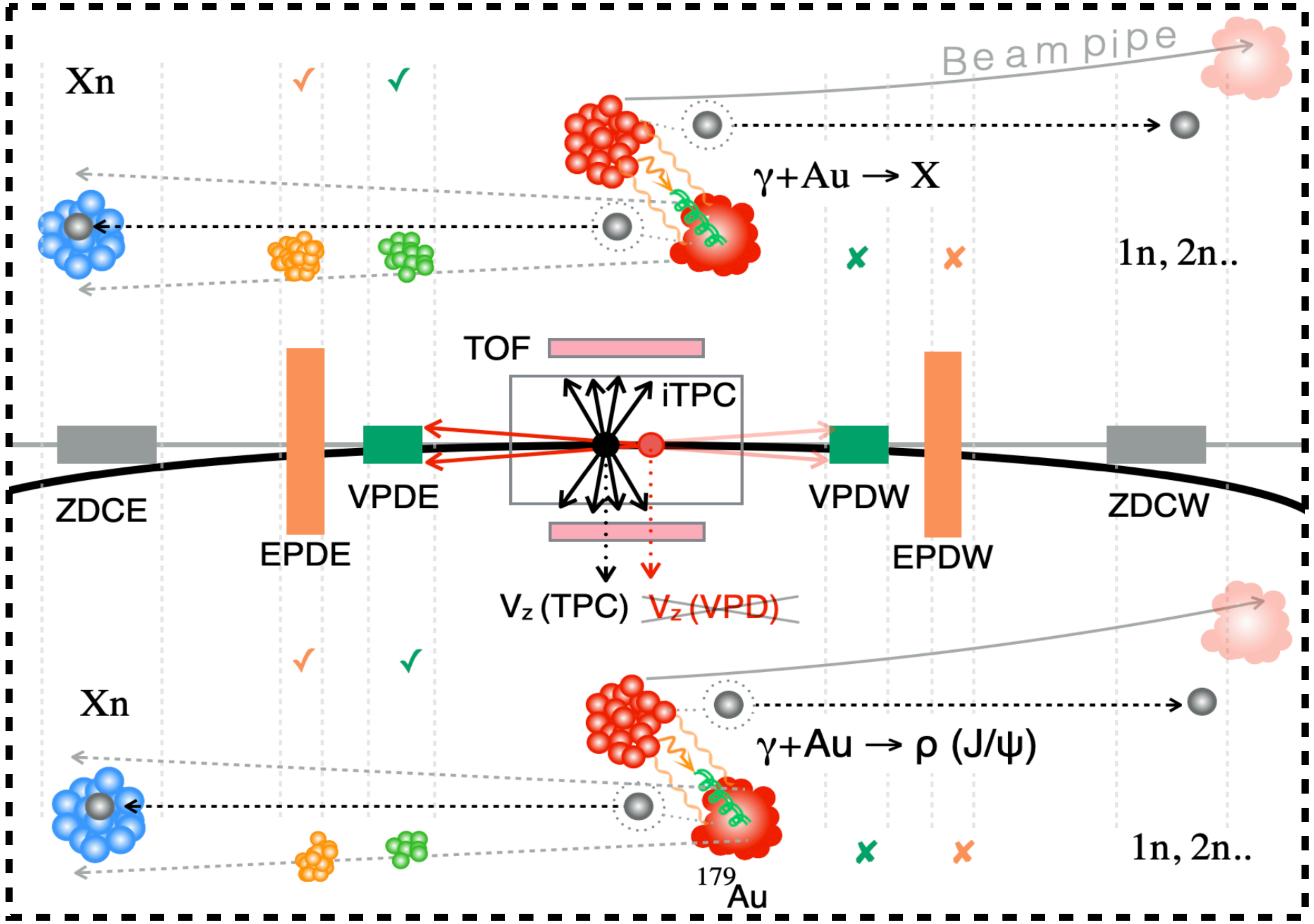
West γ-going side:

- ZdcAdcE > 120
- EpdMipE > 20
- ZdcAdcW < 100
- EpdMipW < 20

Additionally, Vz_diff > 10 cm helps select asymmetric γAu event

Triggering Photonuclear Processes in AuAu UPC

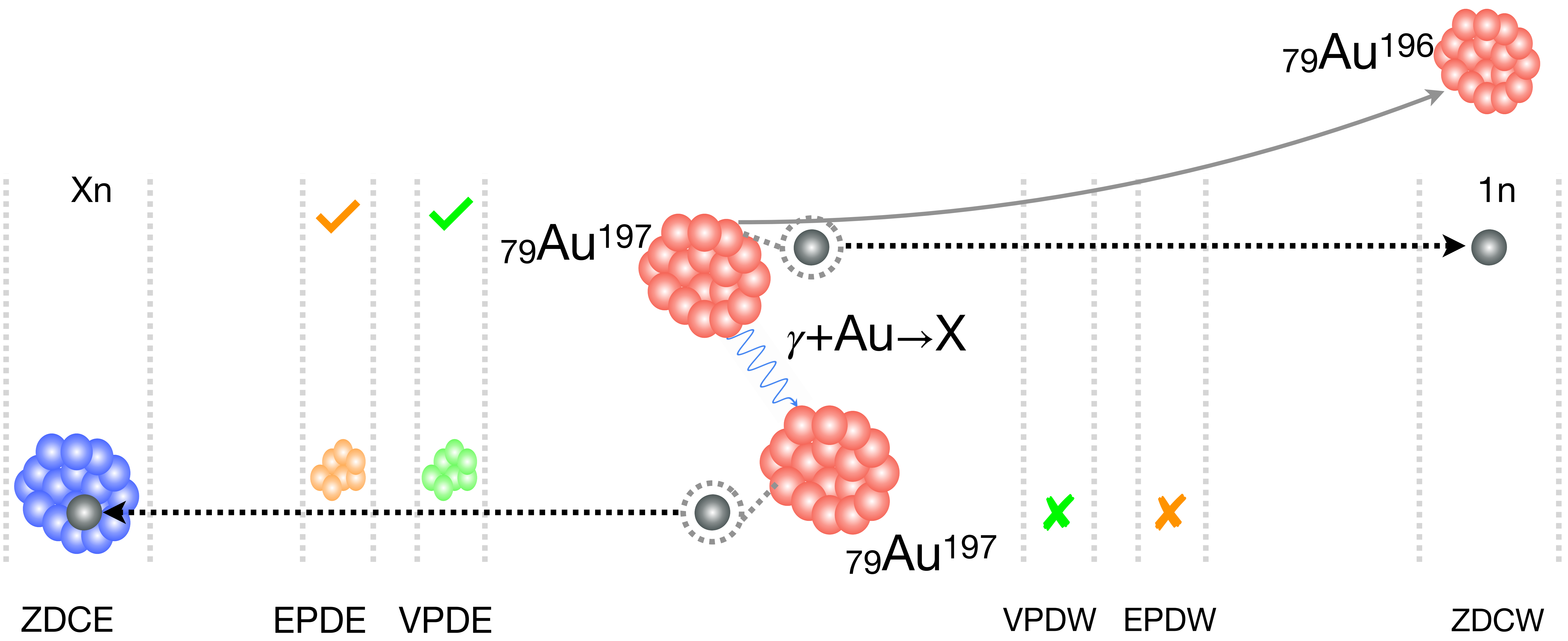
Photo-nuclear cuts decided based on “standard candle”:
Exclusive ρ-production as a trigger for inclusive $\gamma + A$ process



1. Start with ZDC triggered Au+Au min-bias data
2. Select γ+Au $\rightarrow$ ρ events. Take events with only 2 iTPC tracks from $\rho \rightarrow \pi^+\pi^-$ to identify cuts on EPD and ZDC
3. Relax 2 iTPC track requirement and put detector cuts (EPD, ZDC) to trigger on γ+Au $\rightarrow X$
4. Put Vz difference cut for asymmetric event

- Introduction to photonuclear processes
- Triggering photonuclear processes
- **Purity of γ+Au collisions**
- Choice of d+Au as a reference for γ+Au collisions
- Analysis Details
- Results: Correlation functions and flow coefficients: γAu vs dAu39 (reference)

Purity of γAu collisions: Source of Hadronic Contamination

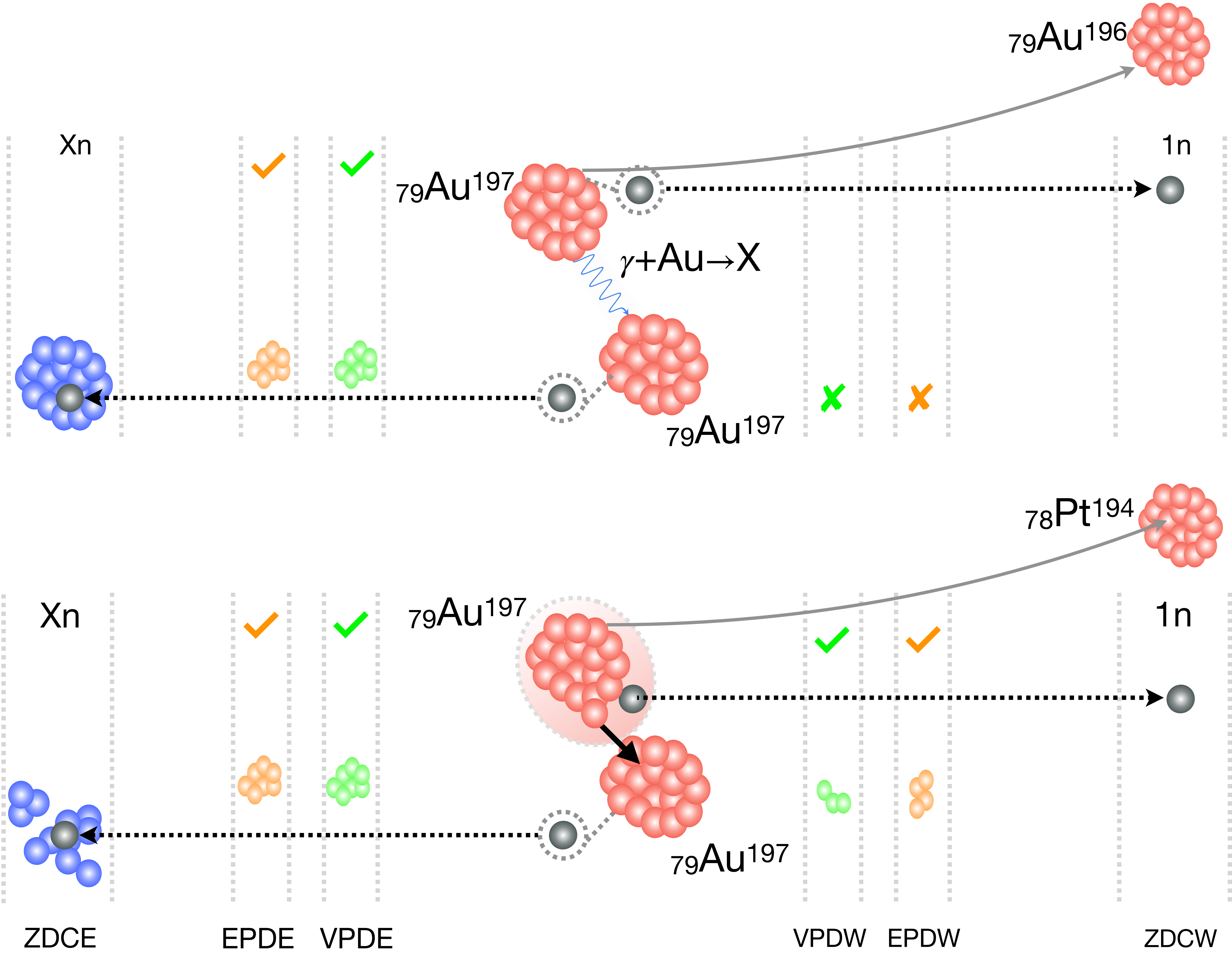


Process interested in:

→ UPC Photonuclear Collision

- ZDC (Au-going side) > 100
- Vz_diff > 10 cm

Purity of γAu collisions: Source of Hadronic Contamination



Process interested in:

→ UPC Photonuclear Collision

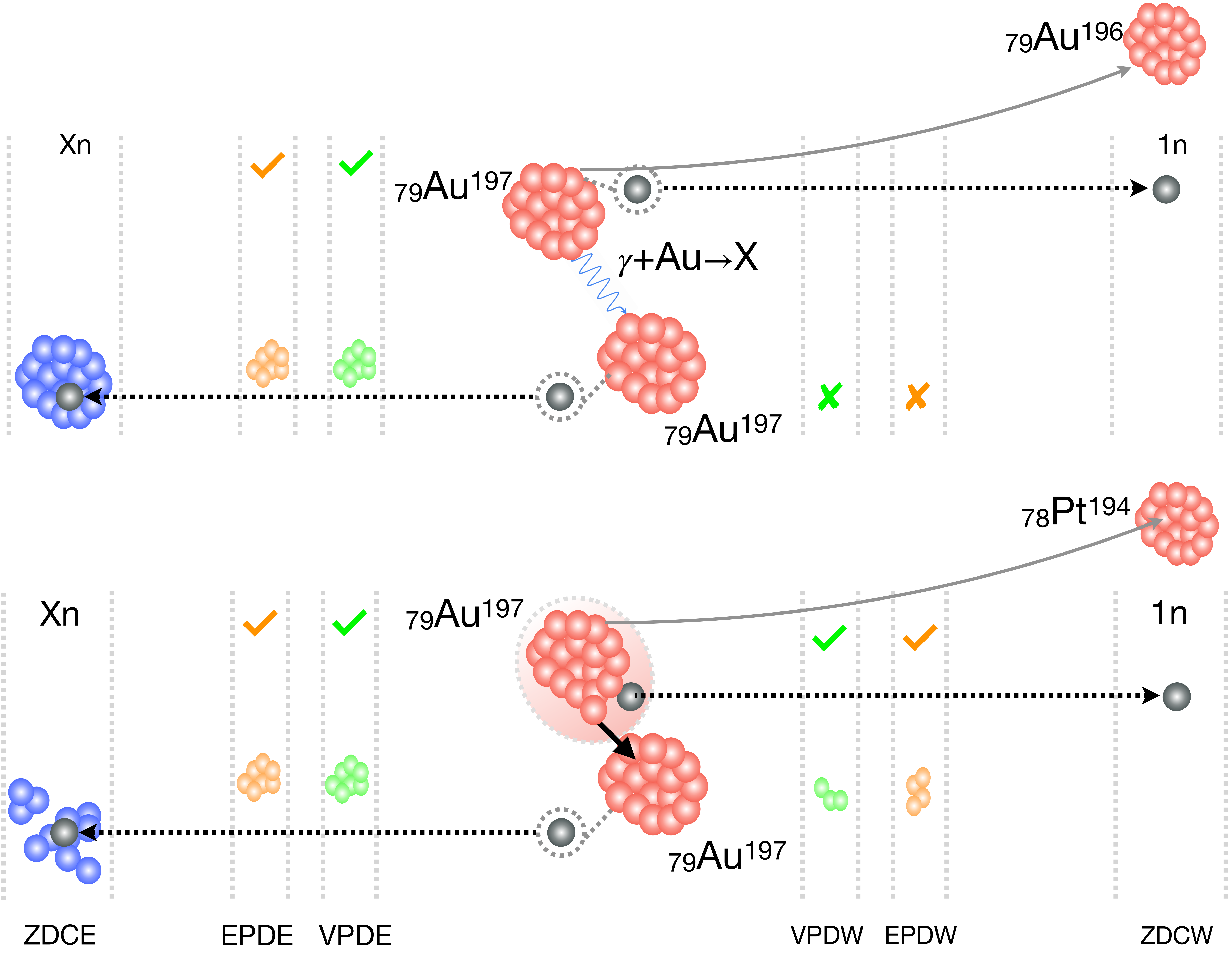
- ZDC (Au-going side) > 100
- Vz_diff > 10 cm

Processes that contaminate:

→ Peripheral Hadronic Collision

- ZDC (Au-going side) > 100
- Vz_diff < 5 cm

Purity of γAu collisions: Source of Hadronic Contamination



Process interested in:

→ UPC Photonuclear Collision

- ZDC (Au-going side) > 100
- Vz_diff > 10 cm

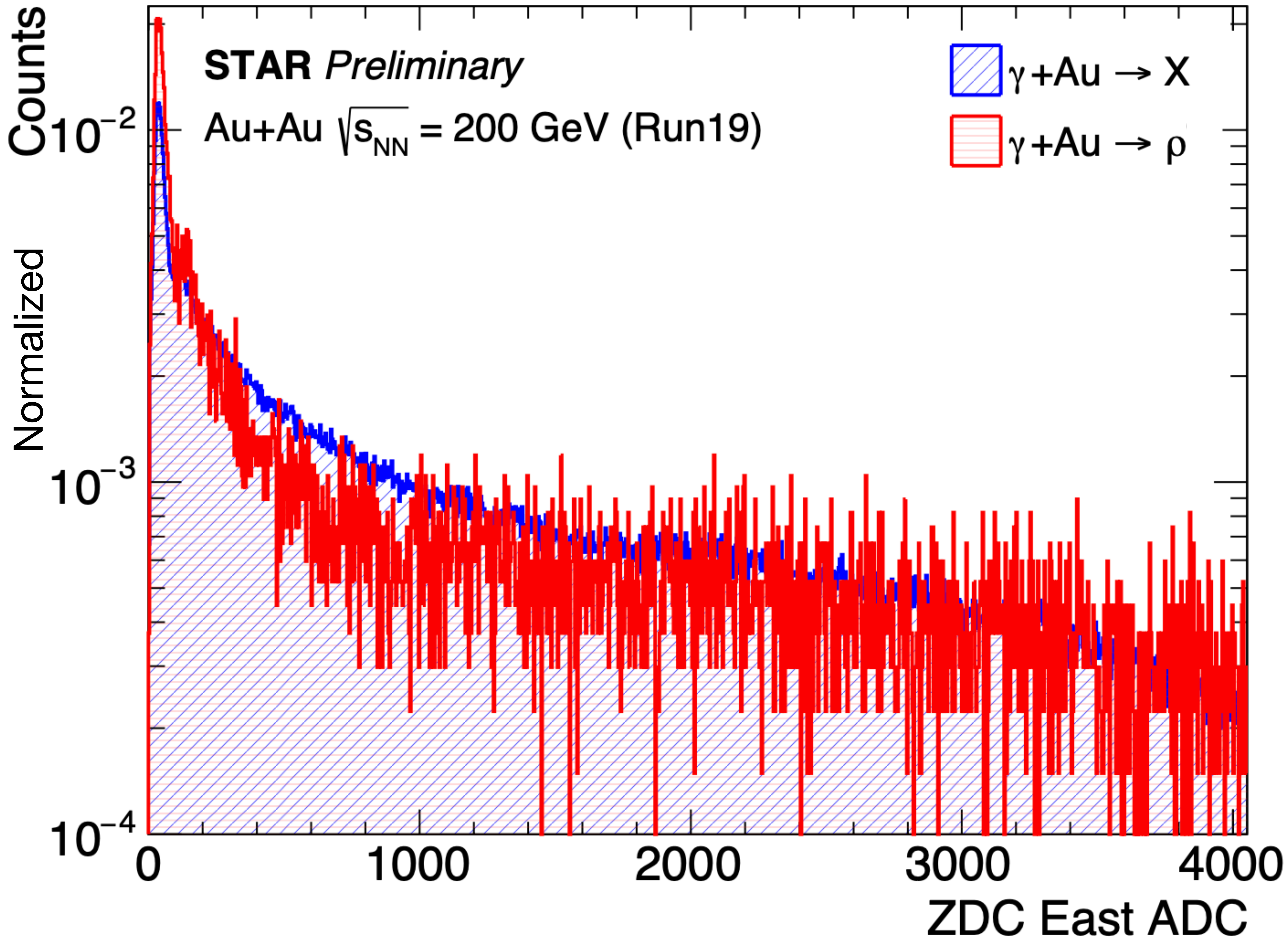
ZDC (γ-going side)

Processes that contaminate:

→ Peripheral Hadronic Collision

- ZDC (Au-going side) > 100
- Vz_diff < 5 cm

Purity of γAu collisions: Estimate of Hadronic Contamination



ZDC neutron distribution of γ+Au → X closely resembles that of γ+Au → ρ

↓

Small hadronic contamination

- Introduction to photonuclear processes
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- Purity of γ+Au collisions
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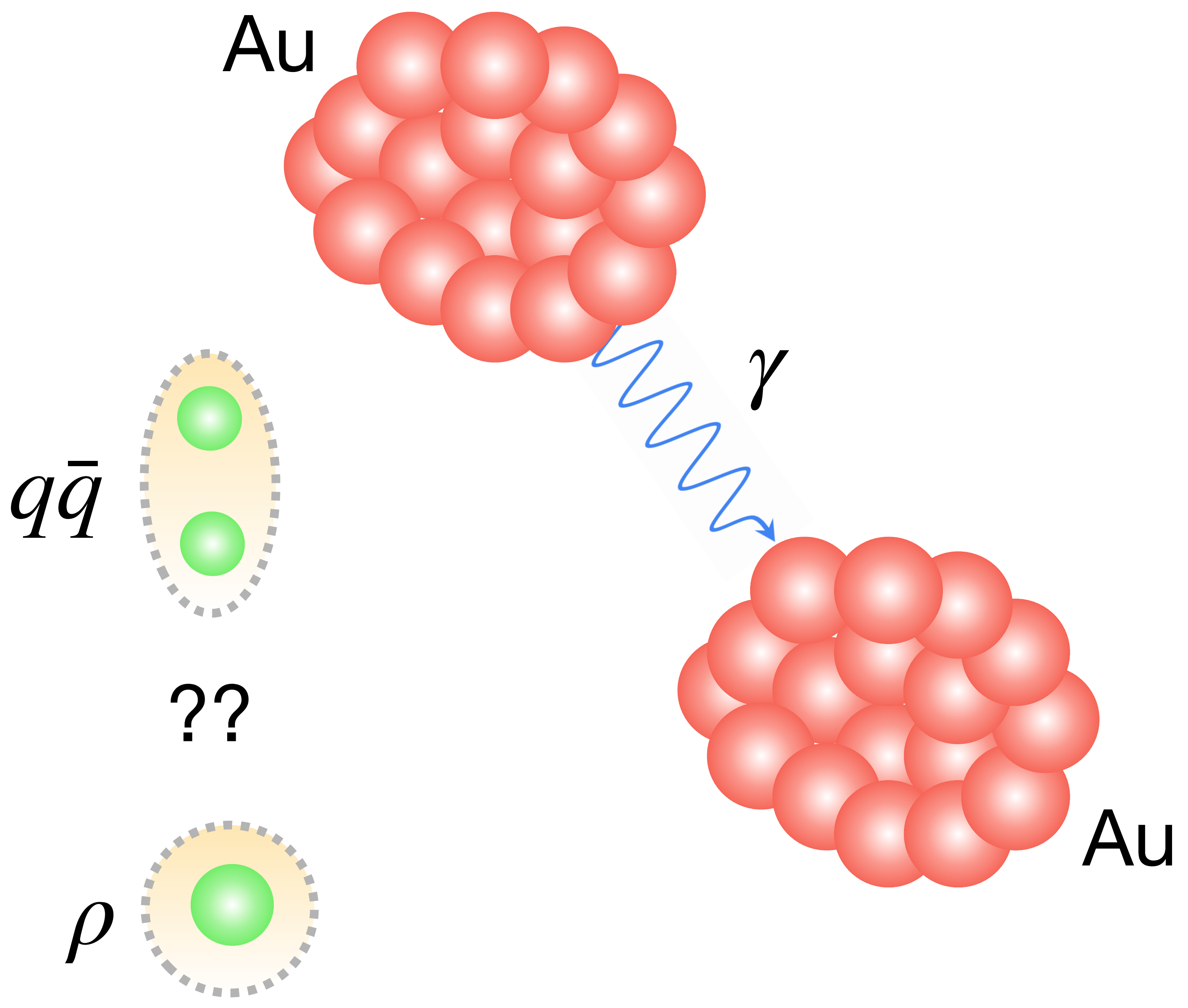
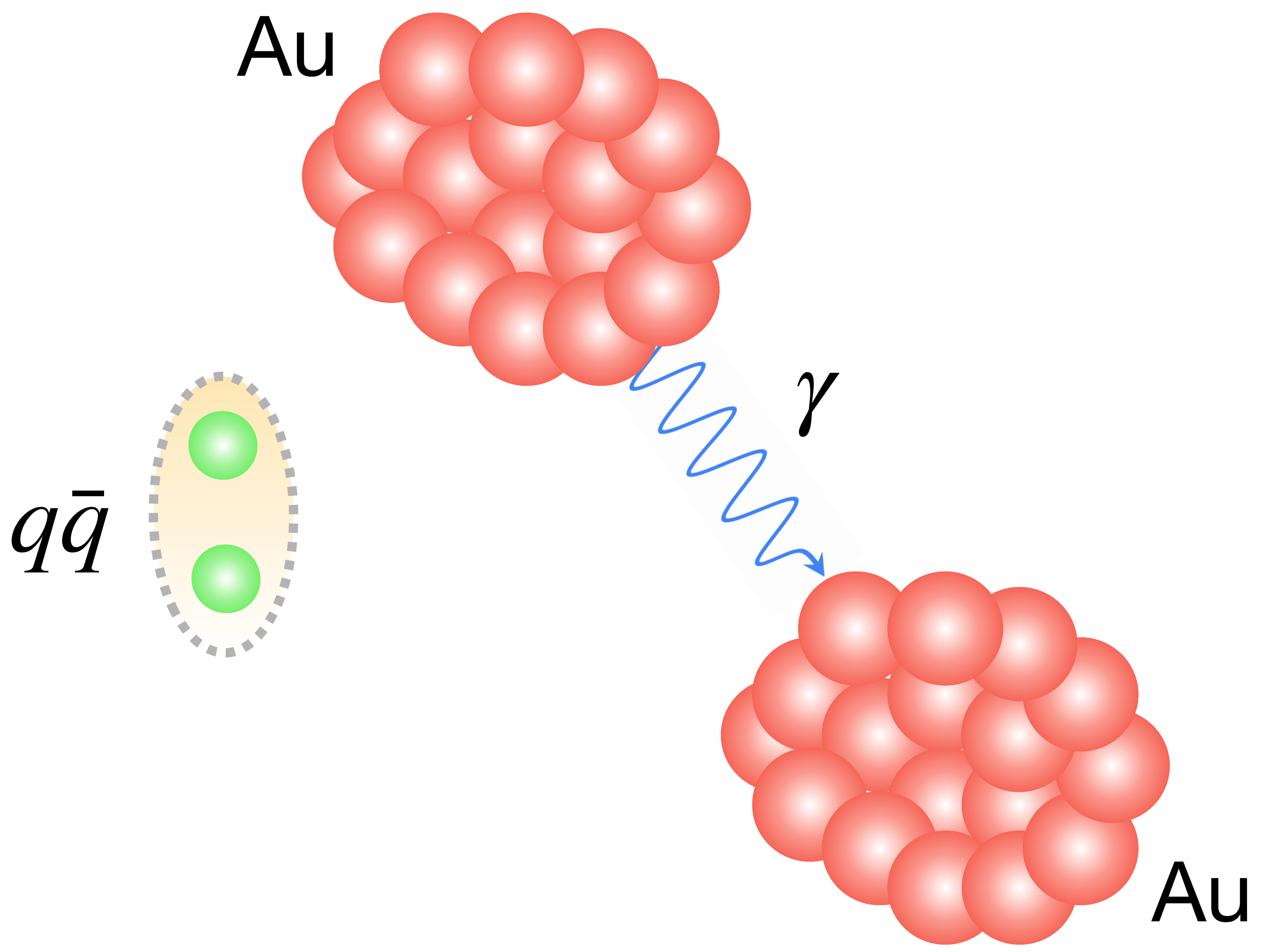
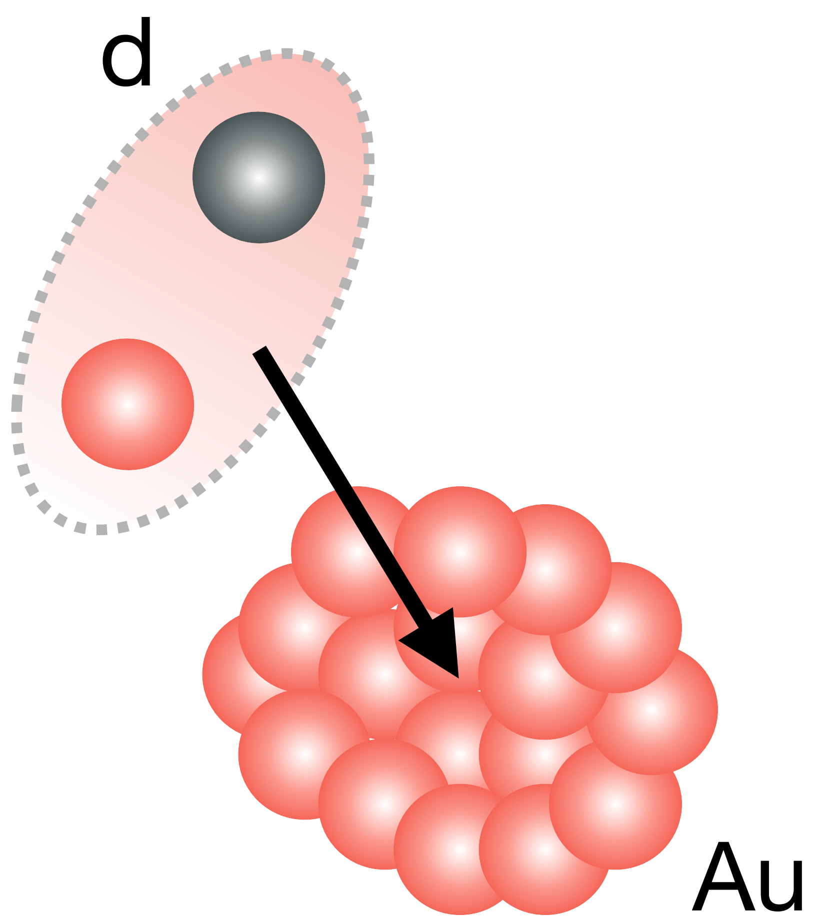
- Analysis Details
- Results: Correlation functions and flow coefficients: γAu vs dAu39 (reference)

Choice of dAu: Reference for γAu collisions



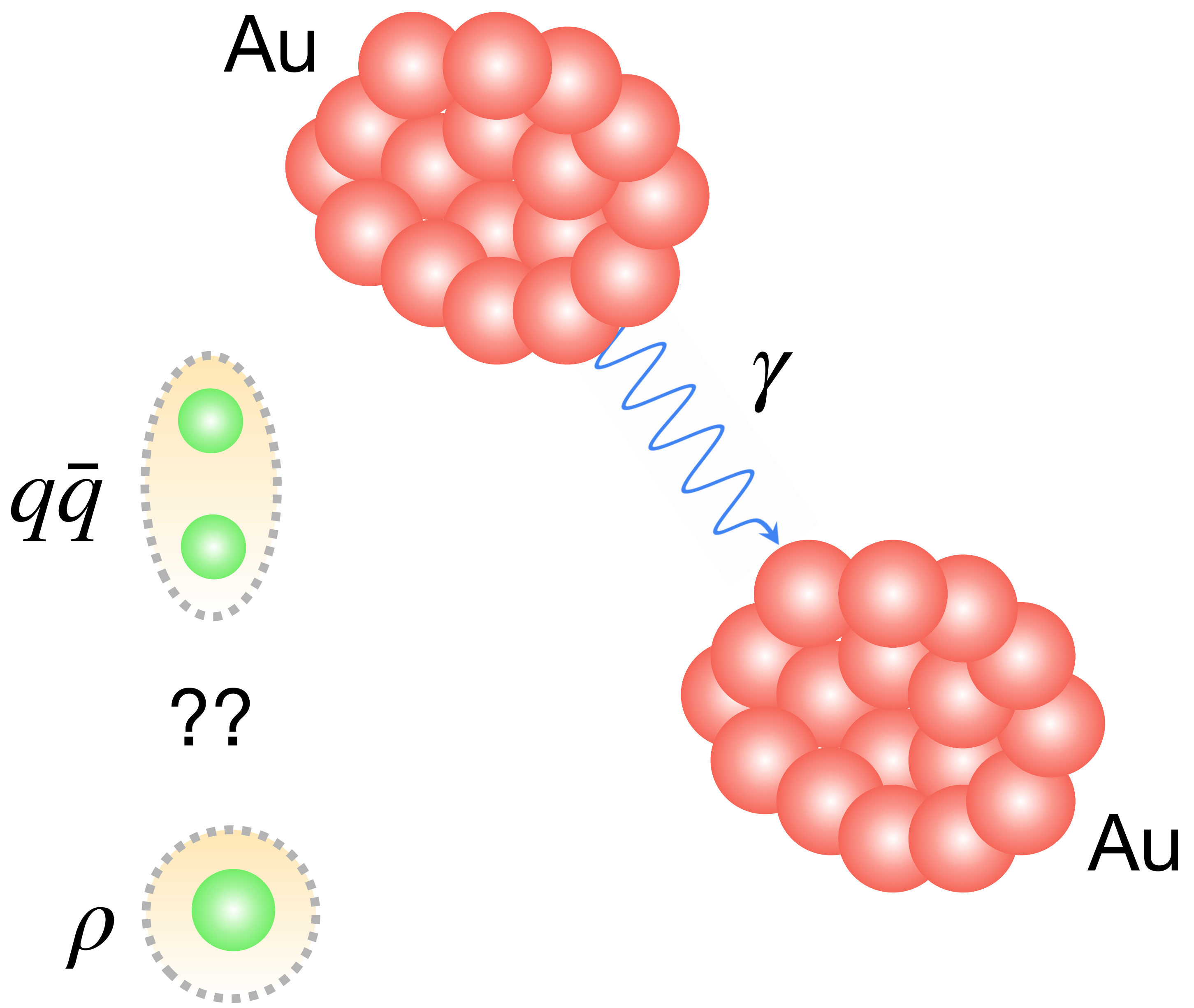
Choice of dAu: Reference for γAu collisions

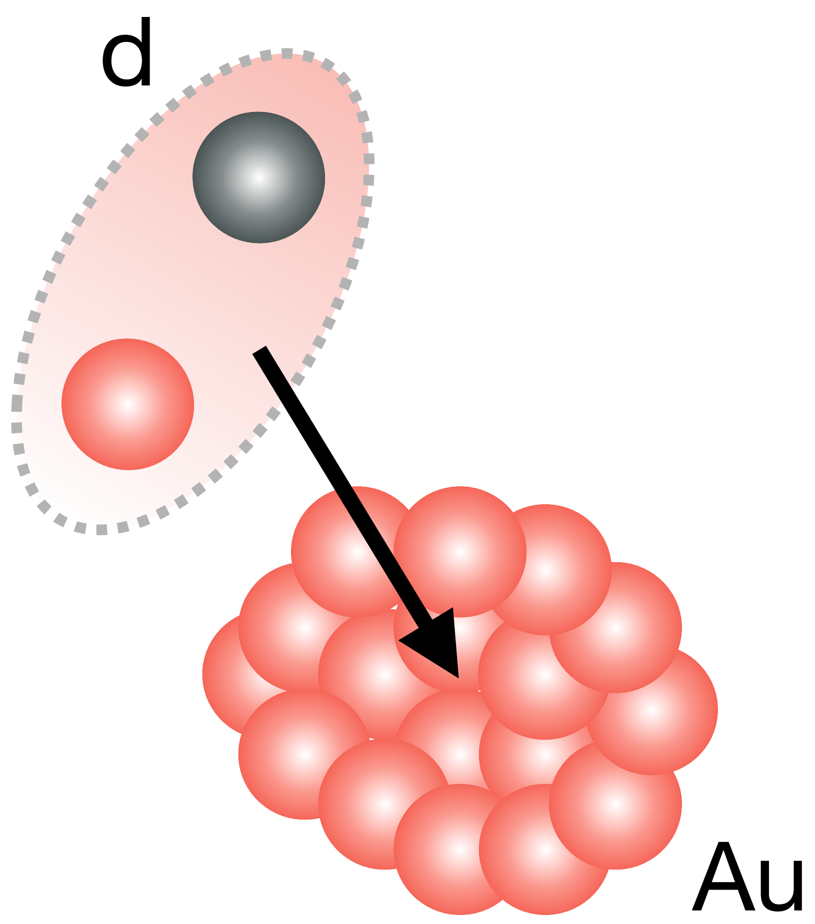




Expectation: v_2(d+Au) ~ $v_2(\gamma \to q\bar{q}$+Au)

Choice of dAu: Reference for γAu collisions



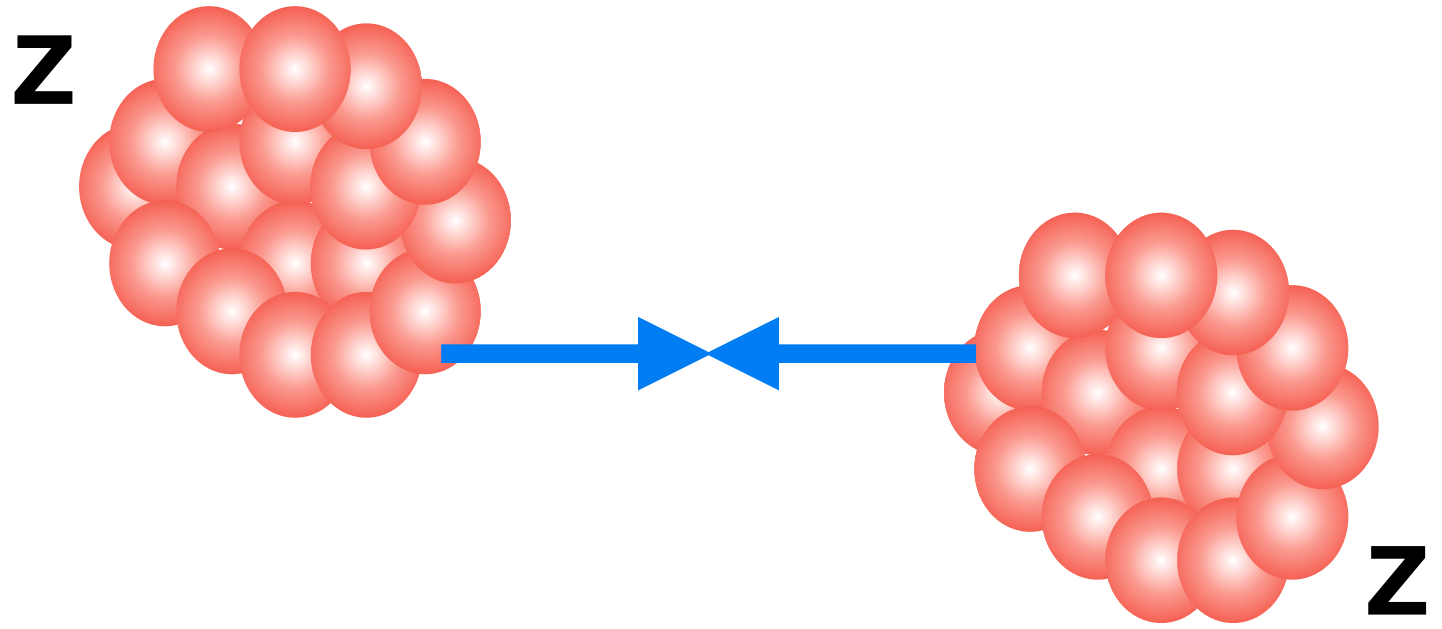


Expectation: v_2(d+Au) ~ $v_2(\gamma \to q\bar{q}$+Au) OR v_2(d+Au) > $v_2(\gamma \to \rho$+Au)

- Measurements in γAu processes at $W_{\gamma N} \approx 34$ GeV, comparable to dAu collisions at $\sqrt{s_{NN}} = 39$ GeV
- Similar multiplicity range for dAu and γAu accessible at STAR

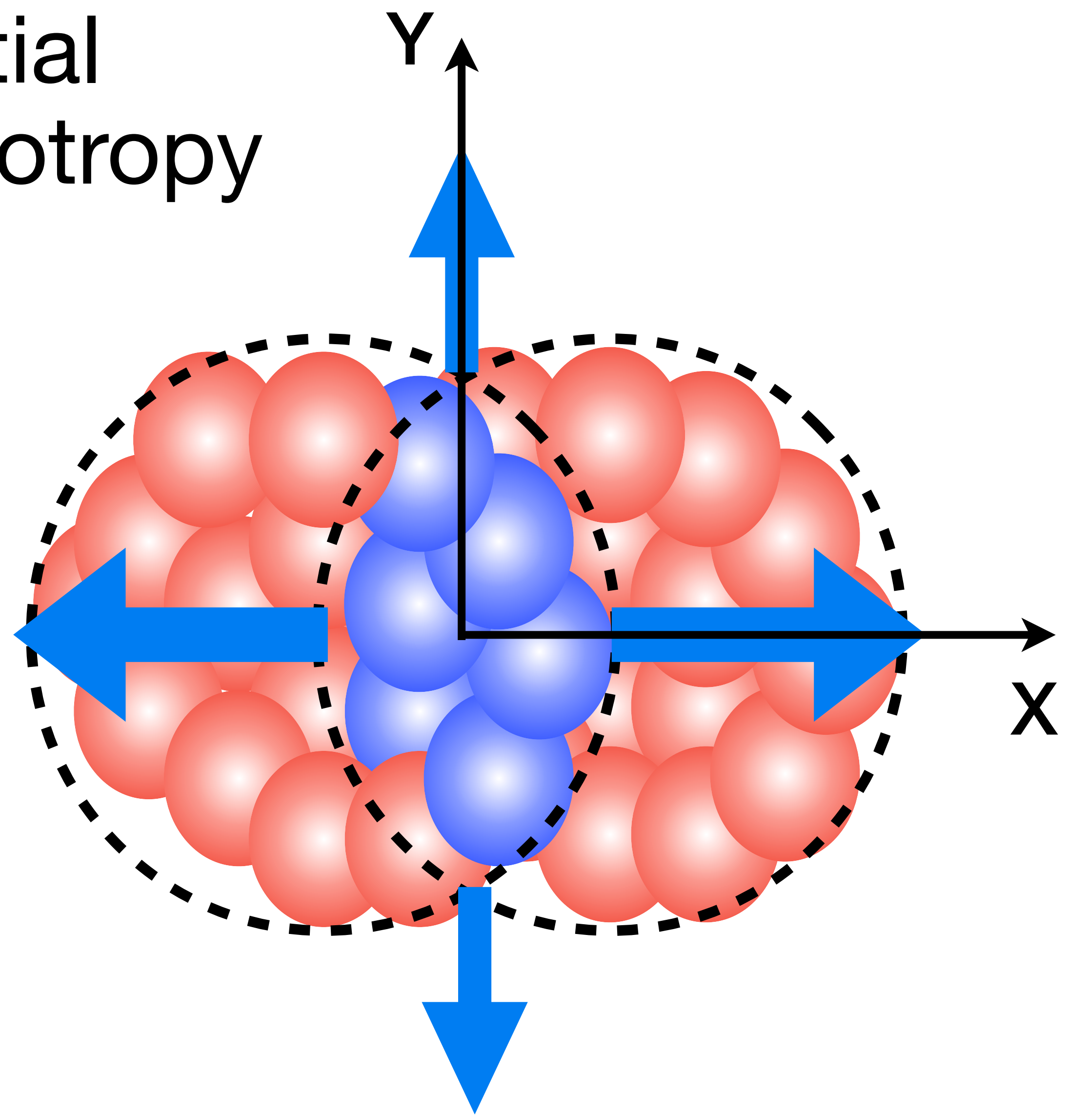
- Introduction to photonuclear processes
- Triggering photonuclear processes
- Purity of γ+Au collisions
- Choice of d+Au as a reference for γ+Au collisions
- **Analysis Details**
- Results: Correlation functions and flow coefficients: γAu vs dAu39 (reference)

Initial State & Two-Particle Correlations



- Collective medium created (Quark-Gluon Plasma)
- Dominated by hydrodynamics

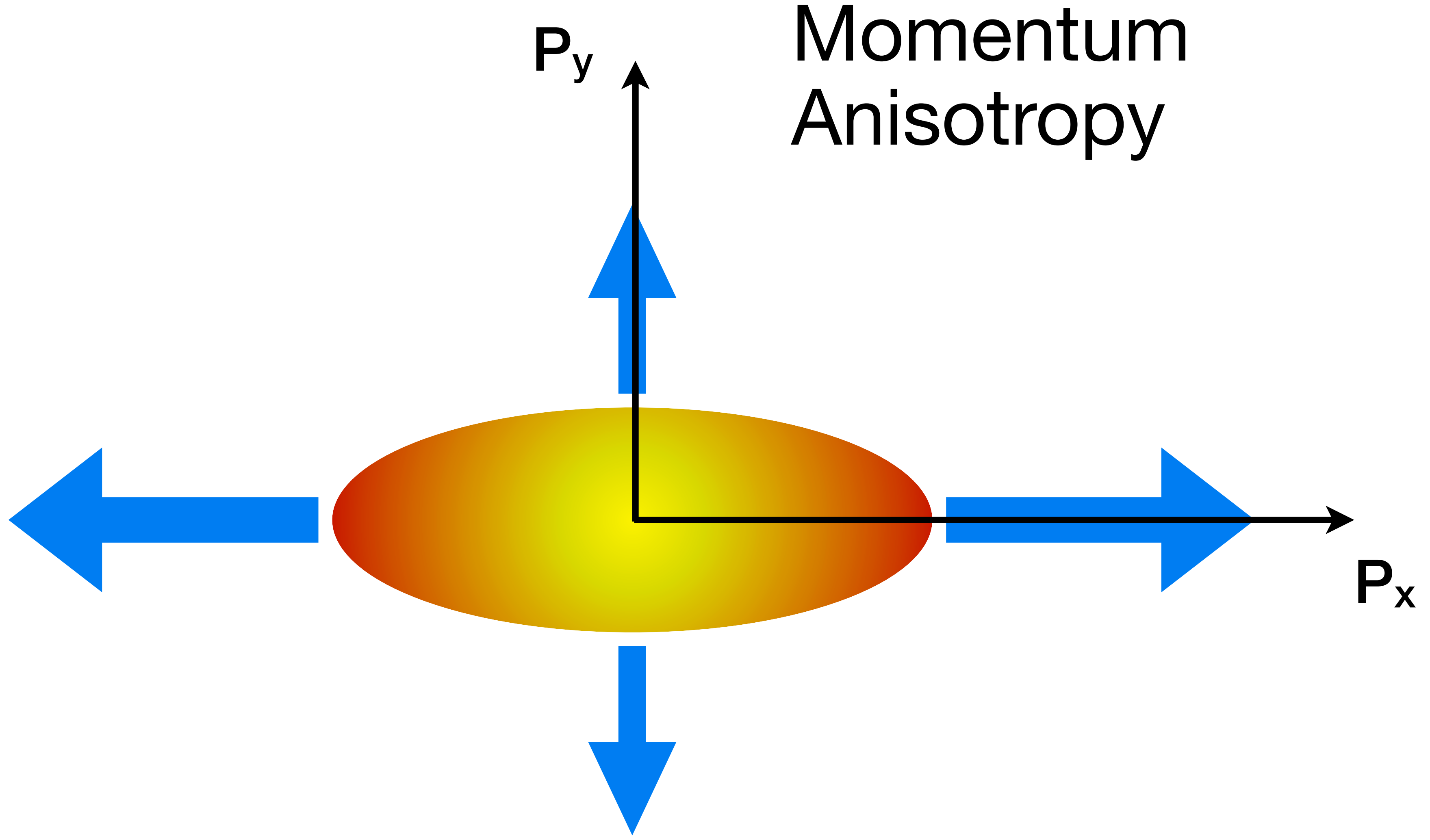
Spatial Anisotropy



Collective Interaction Pressure

$$v_n = \kappa_n \epsilon_n$$

Momentum Anisotropy



$$\epsilon_n = \frac{\sqrt{\langle r_i^n \cos(n\varphi_i)\rangle^2 + \langle r_i^n \sin(n\varphi_i)\rangle^2}}{\langle r_i^n \rangle}$$

$$\frac{dN}{d\Delta\phi} \propto 1 + 2\sum_{n=1}^{\infty} c_n(p_T^t, p_T^a)\cos(n\Delta\phi)$$

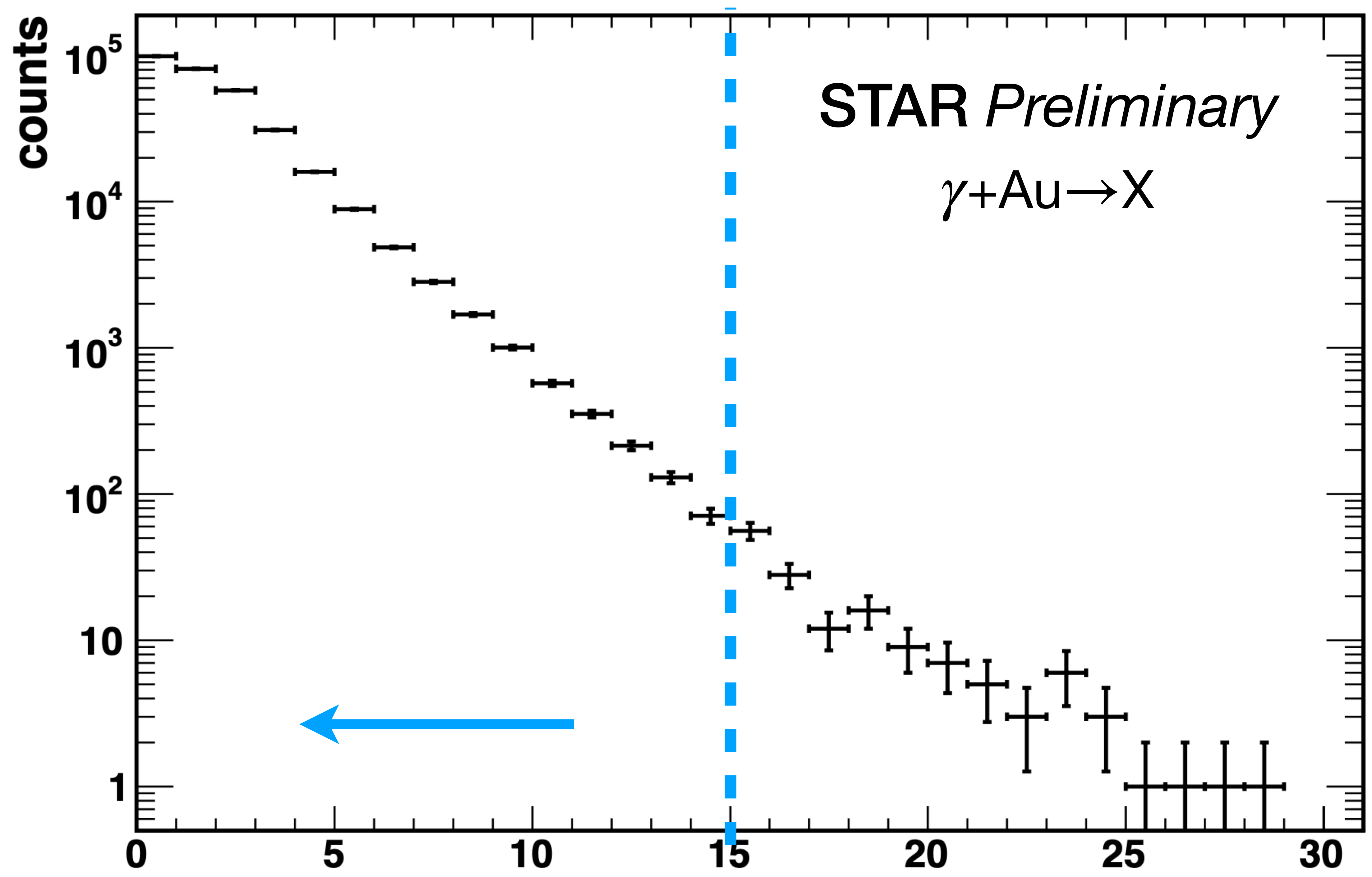
$$v_n\left(p_{\mathrm{T}}^{\mathrm{t}}\right) = \frac{c_n\left(p_{\mathrm{T}}^{\mathrm{t}}, p_{\mathrm{T}}^{\mathrm{a}}\right)}{\sqrt{c_n\left(p_{\mathrm{T}}^{\mathrm{a}}, p_{\mathrm{T}}^{\mathrm{a}}\right)}}$$

C_n : Two-particle flow coefficients

Event Categorization: N_{trk}^{TOF} distribution

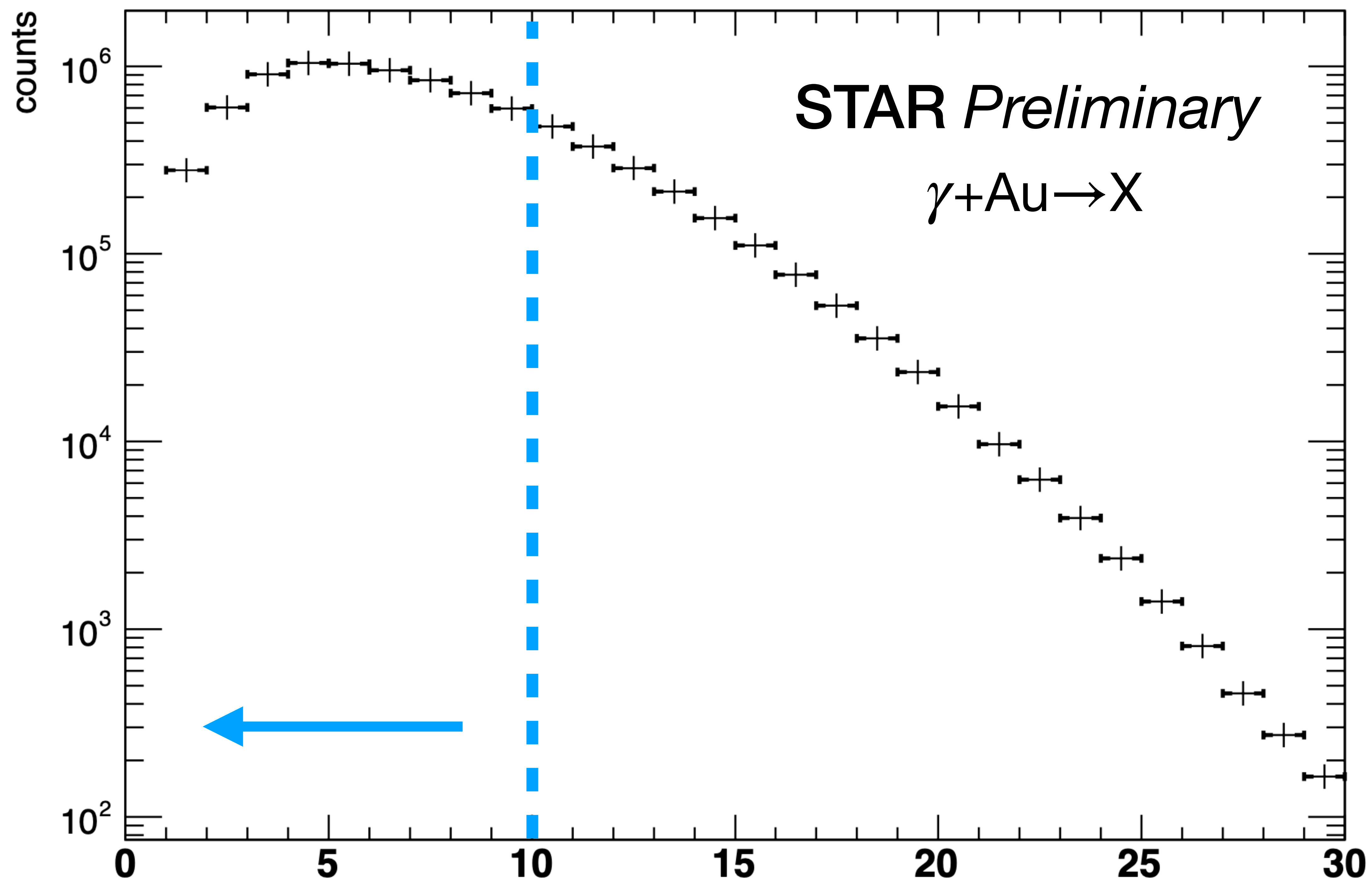
N_{trk}^{TOF} (Uncorrected TPC tracks matched with ToF detector) used for defining event class and for 2-particle correlations

Year 2019, Au+Au, $\sqrt{s_{NN}}$ = 200 GeV: UPC 1nXn



1. $0 < N_{trk}^{TOF} \leq 5$ (Low multiplicity)
2. $5 < N_{trk}^{TOF} \leq 15$ (High multiplicity)

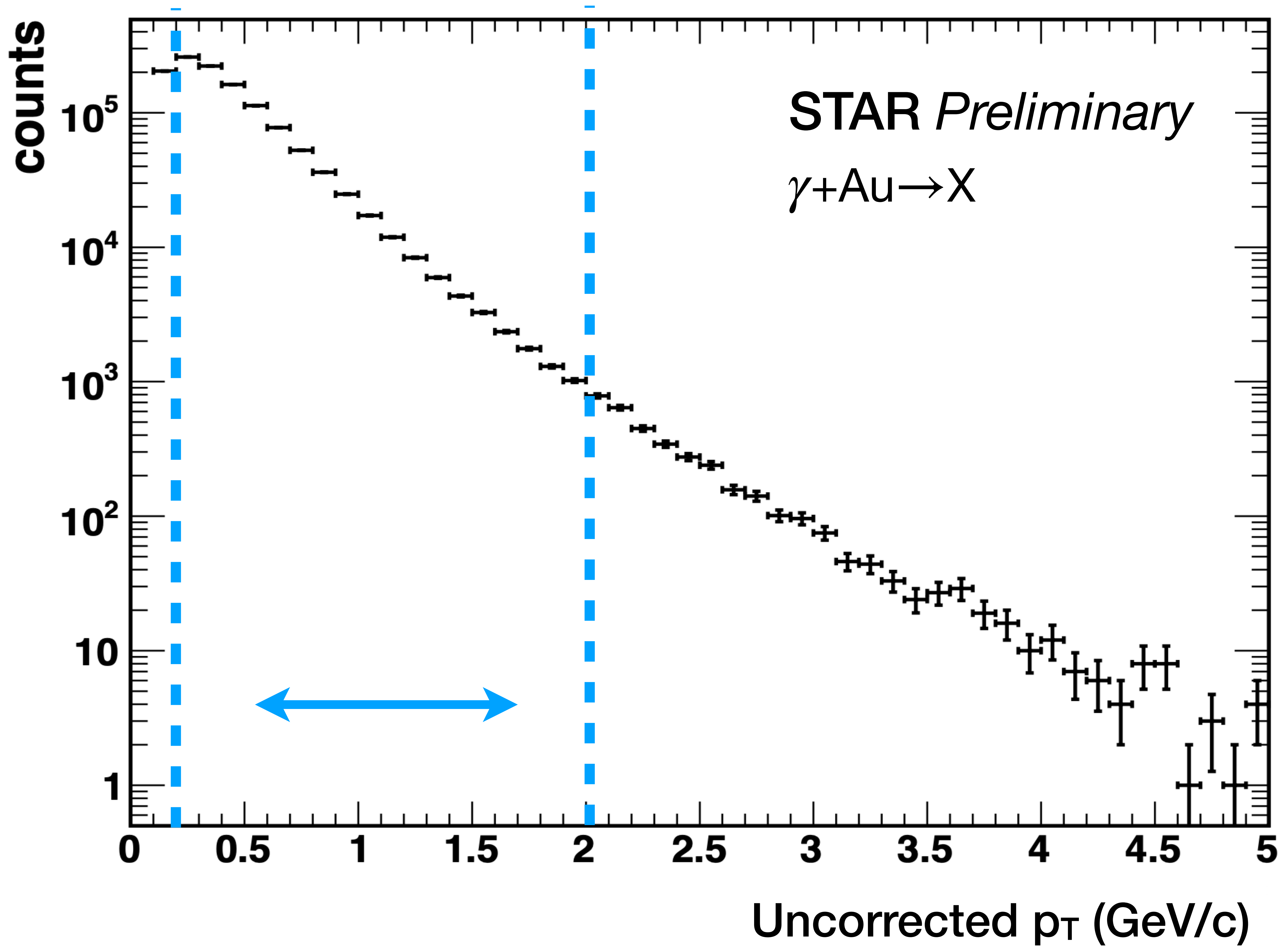
Year 2016, d+Au, $\sqrt{s_{NN}}$ = 39 GeV



1. $0 < N_{trk}^{TOF} \leq 5$
2. $N_{trk}^{TOF} = 6$
3. $N_{trk}^{TOF} = 7$
4. $N_{trk}^{TOF} = 8$
5. $9 \leq N_{trk}^{TOF} \leq 10$

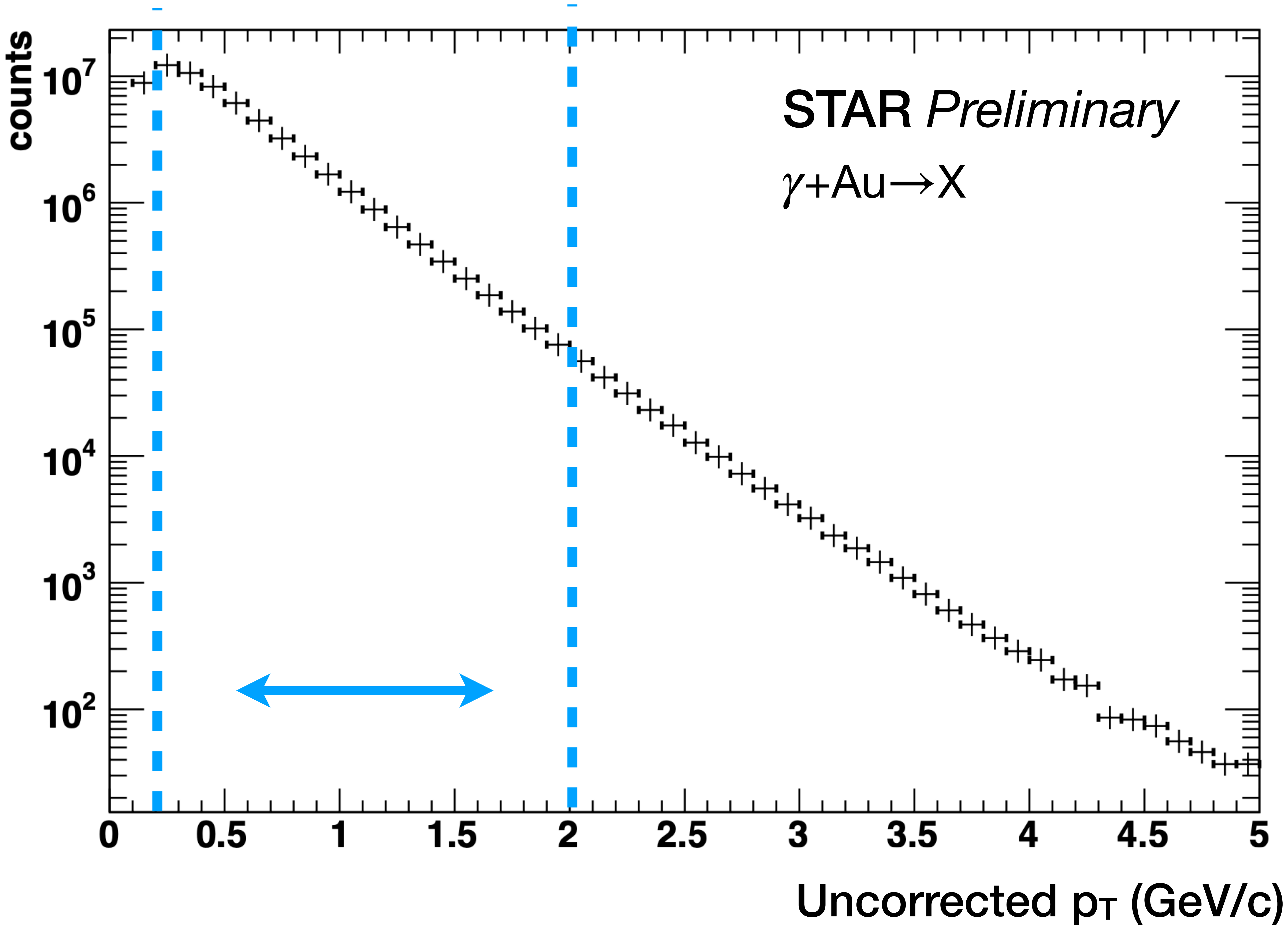
Event Categorization: p_T distribution

Year 2019, Au+Au, $\sqrt{s_{NN}}$ = 200 GeV: UPC 1nXn



1. $0.2 \leq p_T < 0.5$
2. $0.5 \leq p_T < 1.0$
3. $1.0 \leq p_T < 2.0$

Year 2016, d+Au, $\sqrt{s_{NN}}$ = 39 GeV



1. $0.2 \leq p_T < 0.5$
2. $0.5 \leq p_T < 1.0$
3. $1.0 \leq p_T < 2.0$

Systematic Uncertainties

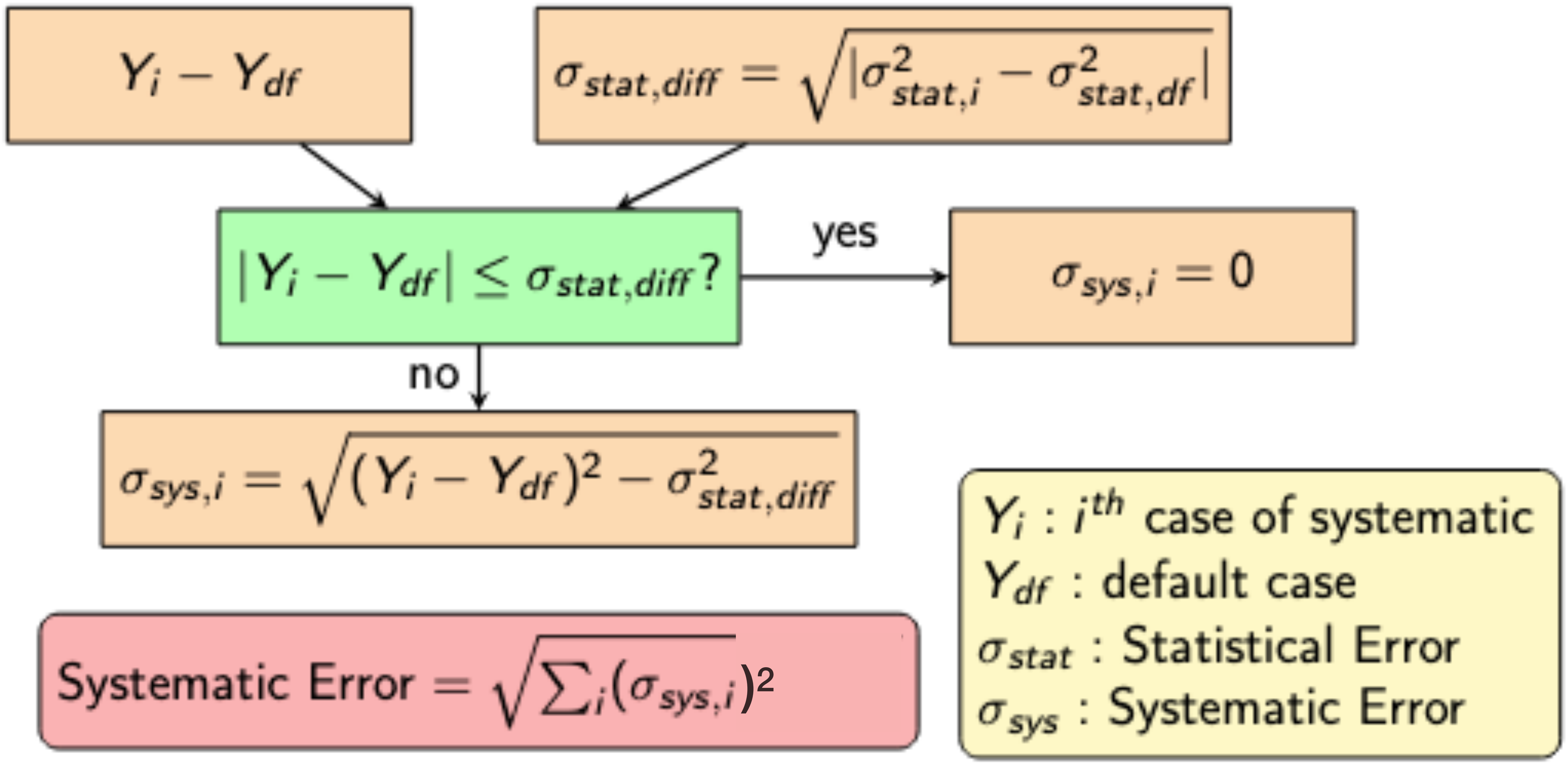
Cuts parameters:

γ+Au

1. Vary γ+Au→X Selection cut:
   ZDC Neutron cut on γ-going side
2. DCA
3. |TPC Vz - VPD Vz|
4. TPC Vz
5. $\Delta\eta$

d+Au

1. DCA
2. TPC Vz
3. $\Delta\eta$



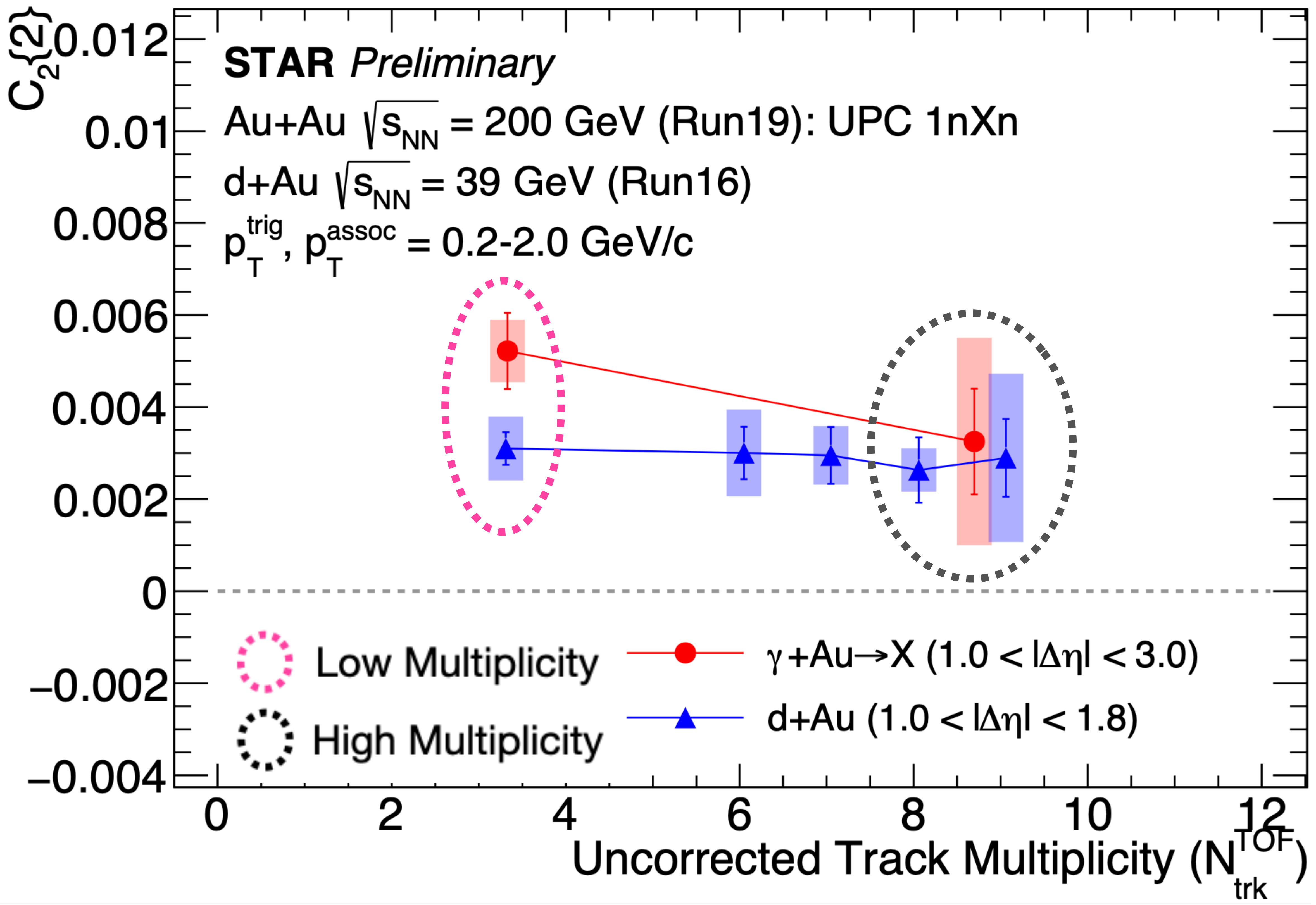
Barlow Test

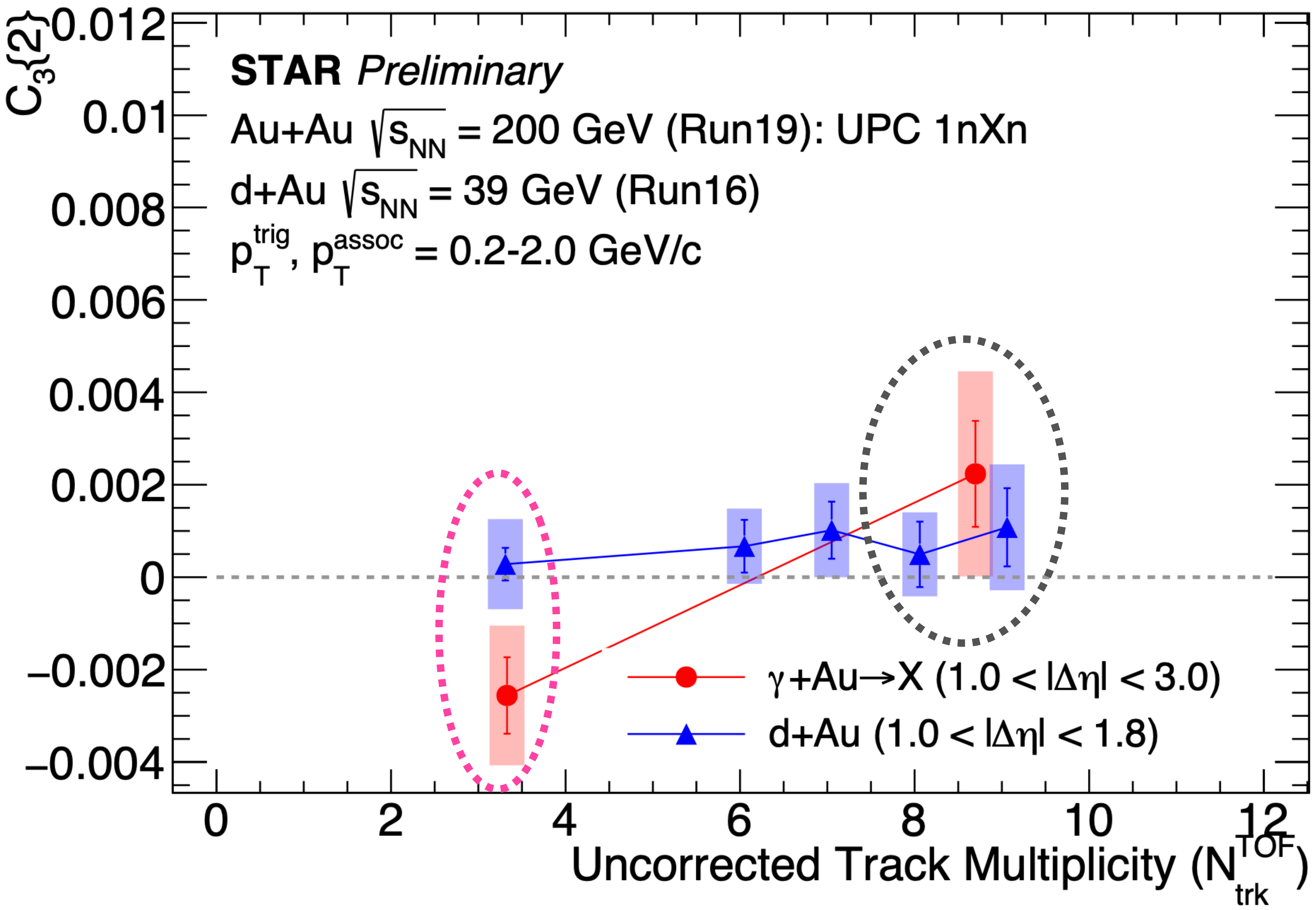
- Systematic Uncertainties from p_T-integrated C_n vs multiplicity
- Cuts parameters are varied one-by-one, Barlow test is performed for each cut, and the quadrature sum of each systematic run gives the total systematic uncertainty

- Introduction to photonuclear processes
- Triggering photonuclear processes
- Purity of γ+Au collisions
- Choice of d+Au as a reference for γ+Au collisions
- Flow in Heavy-Ion collisions
- Results: Correlation functions and flow coefficients: γAu vs dAu39 (reference)

C_n as a function of multiplicity

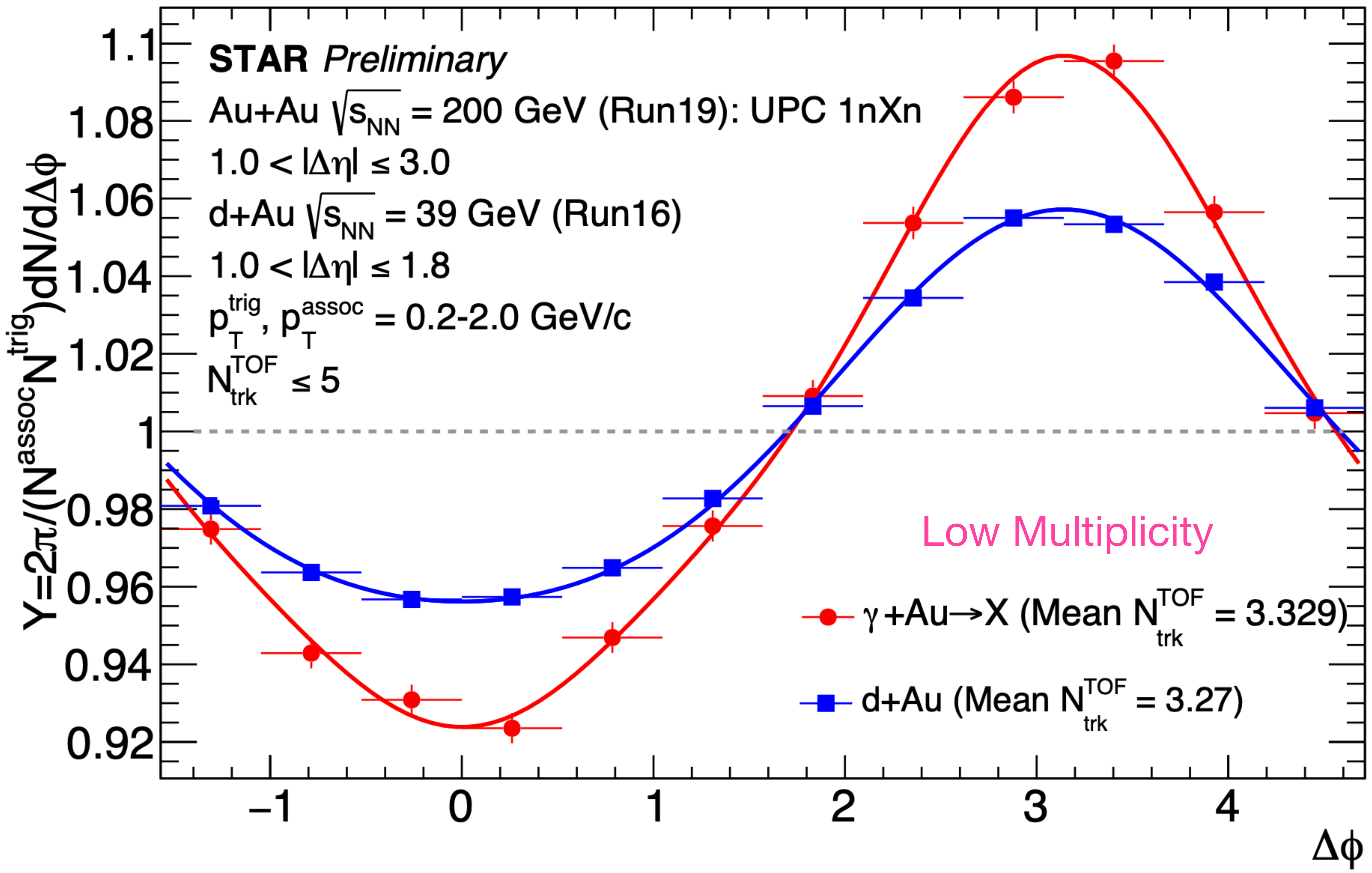
First-ever results of photonuclear collectivity search at RHIC

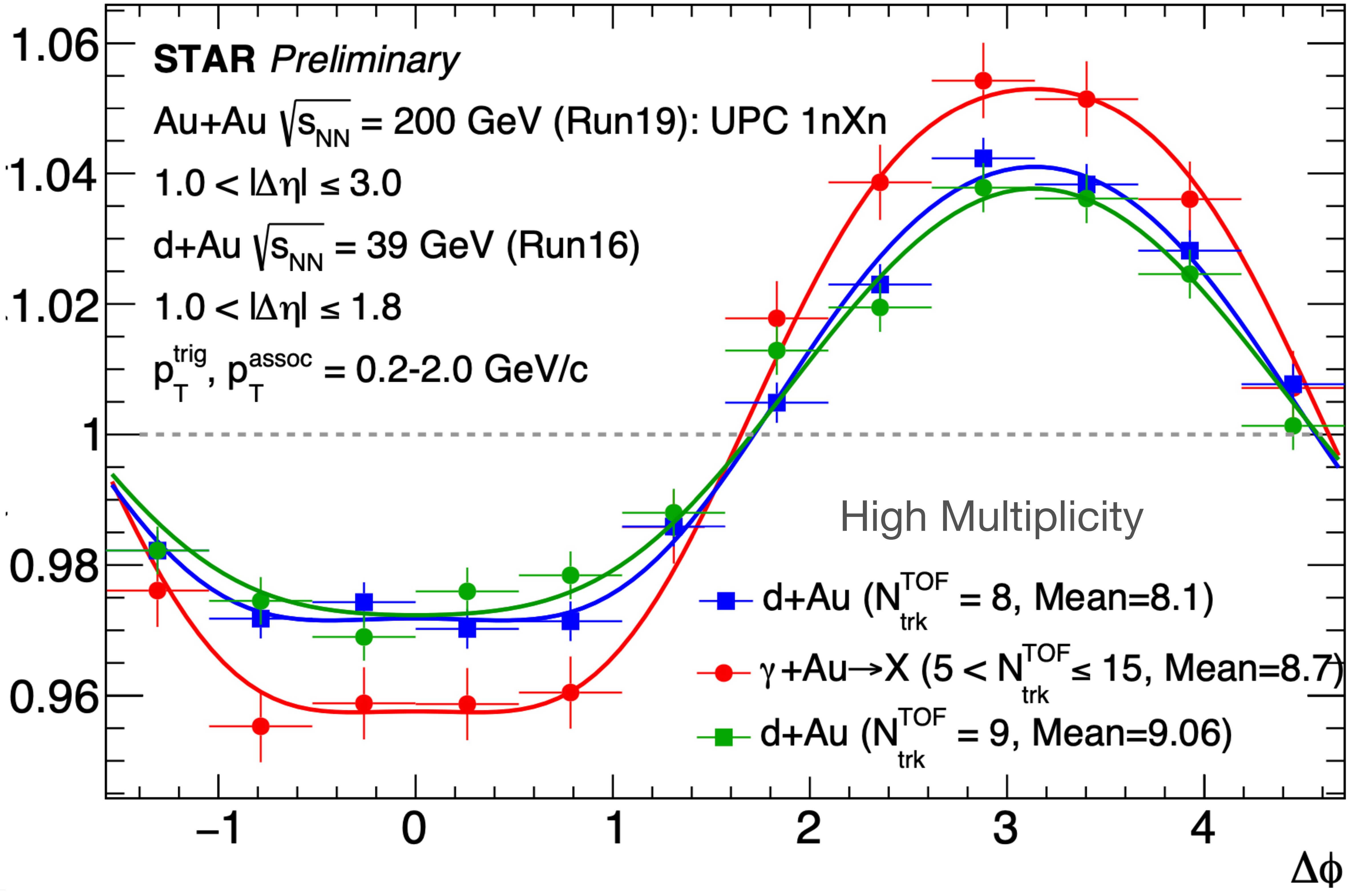




- C_n results comparable for γ+Au and d+Au: Weak multiplicity dependence within uncertainties
- Low $N_{trk}^{TOF} \Longrightarrow$ Small number of tracks $\Longrightarrow$ Dominance of non-flow processes

Comparing CF at similar multiplicity: γAu vs dAu39 (reference)

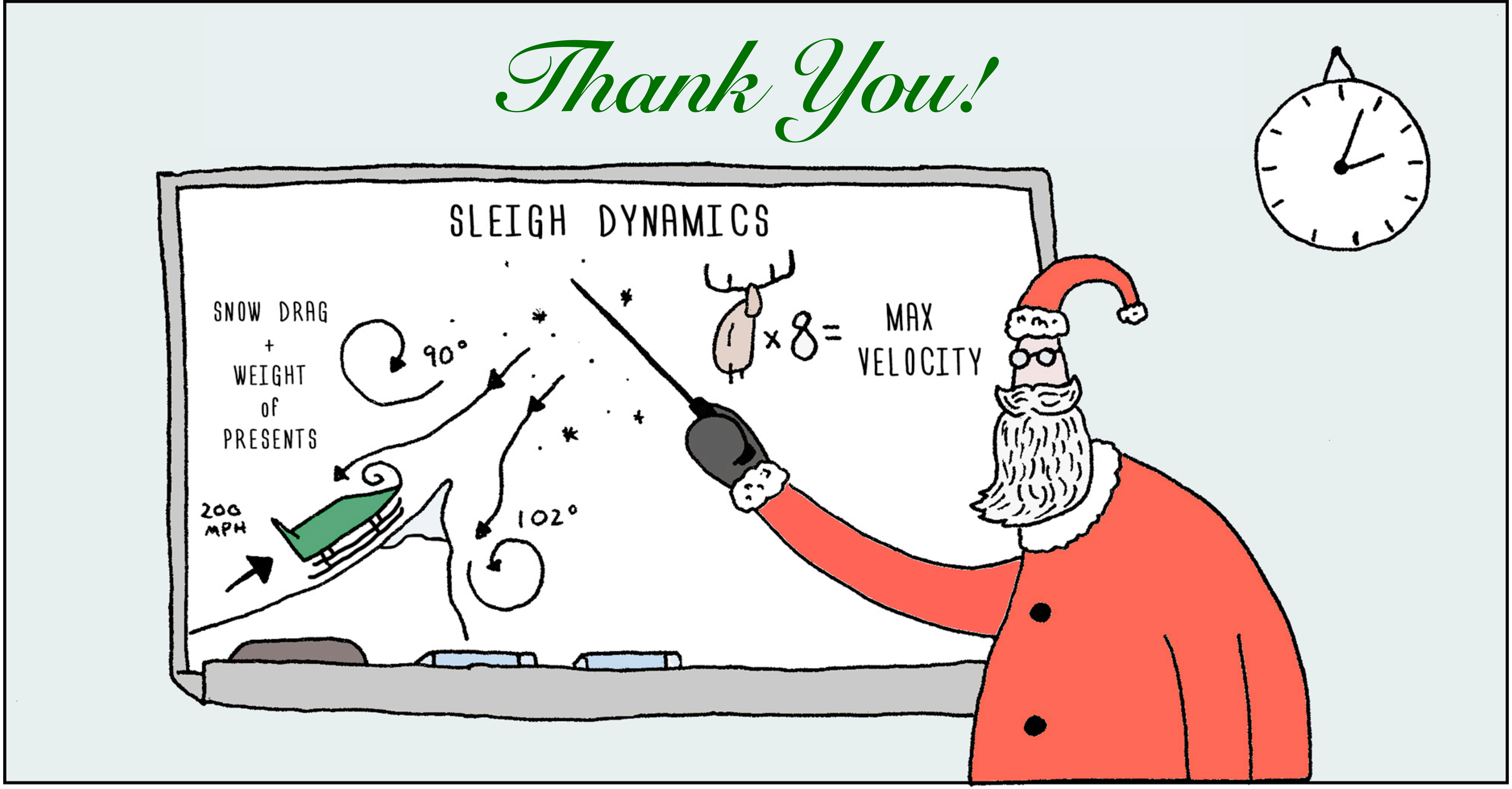




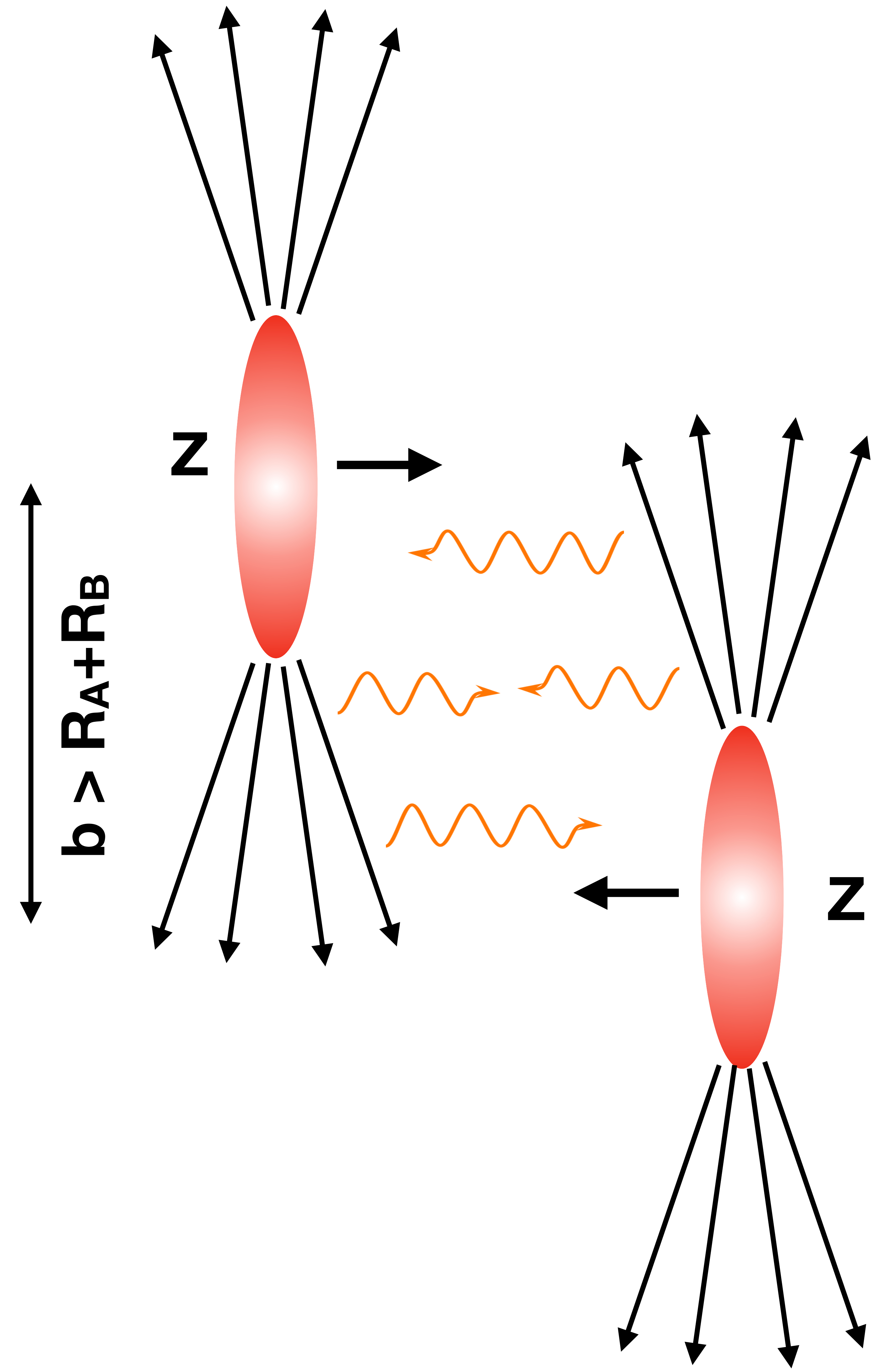
- Large non-flow observed. Non-flow subtraction will be explored
- New Run 23 high-multiplicity Au+Au @ 200 GeV for better precision and improved control over non-flow subtraction

Summary

- Photo-nuclear cuts decided based on “standard candle”: Trigger inclusive γ+A process using exclusive ρ-production
- Kinematic similarities between d+Au and γ+Au collisions: d+Au as reference
- ZDC neutron distribution of inclusive photo-nuclear process closely resembles that of pure photo-nuclear process → Small hadronic contamination
- First-ever results of photonuclear collectivity search at RHIC:
  - C_n results comparable for γ+Au and d+Au at similar multiplicity
  - Large effect of non-flow. Non-flow subtraction will be explored

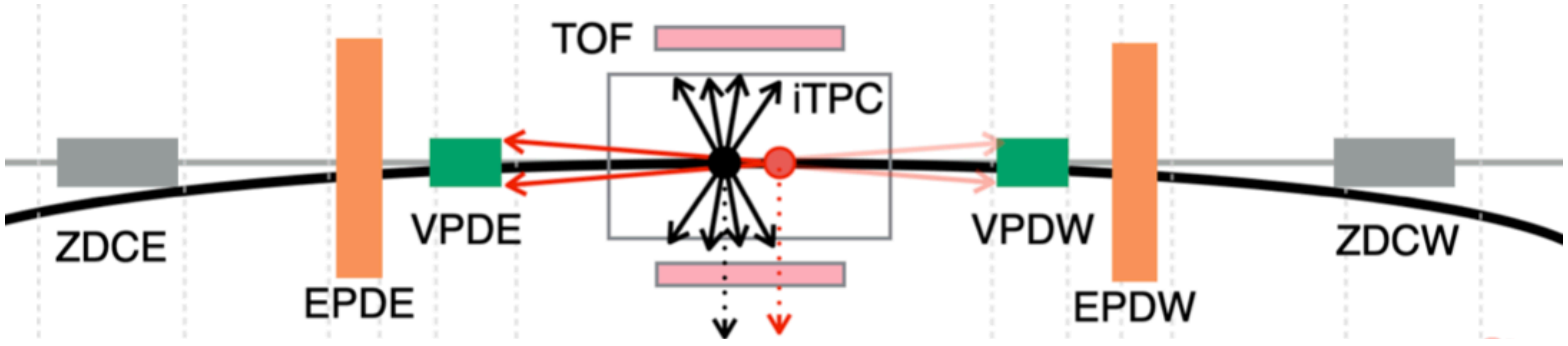


We can't identify a university in the Santa Claus Village, as their research is top secret, but we do have a GRID record for the University of Lapland!



Z
Z
b > RA+RB

STAR Detector Upgrades & Dataset



Wider η coverage:

$|\eta| < 1.0$ → $|\eta| < 1.5$ (iTPC), $2.13 < |\eta| < 5.1$ (EPD)

γ+Au

- Run-19 Au-Au, $\sqrt{s_{NN}}$ = 200GeV
- Events: ~100M

d+Au: Baseline

- Run-16 dAu, $\sqrt{s_{NN}}$ = 39GeV
- Events: ~235M

Vertex Selection

- $\sqrt{V_x^2 + V_y^2} < 2.0$ cm
- $|V_z| < 100$ cm
- |TPCVz - VPDVz| < 5 cm (dAu39)
- 10 cm < |TPCVz - VPDVz| < 10^4 cm (γAu)

Track Selection

- DCA < 3.0 cm (dAu39), DCA < 3.5 cm (γAu)
- pT > 0.1 GeV/c
- $|\eta| < 1.5$
- nHitsFit > 10, nHitsFitRatio > 0.52

Systematic Uncertainties

Point index = 1	ZDCSum	DCA (cm)	Vzdiff (cm)	TPCVz(cm)	Deta	Sys C2 (%)	Sys C3 (%)
default	120 (East), 100 (West)	3.0	10	100	1.0		
ZDC3n_gamma	600 (East), 550 (West)					10.96	57.59
low_dca		1.0				0	0
high_vzdiff			15			0	0
low_vzdiff			5			0	2.8
low_tpcvz				50		0	0
deta_1_1					1.1	6.92	8.01
deta_1_2					1.2	0	9.72

Point index = 2	ZDCSum	DCA (cm)	Vzdiff (cm)	TPCVz(cm)	Deta	Sys C2 (%)	Sys C3 (%)
default	120 (East), 100 (West)	3.0	10	100	1.0		
ZDC3n_gamma	600 (East), 550 (West)					46.99	95.26
low_dca		1.0				0	0
high_vzdiff			15			1.71	0
low_vzdiff			5			0	3.37
low_tpcvz				50		0	0
deta_1_1					1.1	7.47	0
deta_1_2					1.2	5.31	27.62

- Systematic Uncertainties from p_T-integrated C_n vs multiplicity (γAu)
- Cut parameters are varied one-by-one, Barlow test is performed for each cut, and the quadrature sum of each systematic run gives the total systematic uncertainty
- Expected uncertainties not evaluated yet: nHitsFit

Systematic Uncertainties

Point index = 1	DCA (cm)	TPCVz(cm)	Deta	Sys C2 (%)	Sys C3 (%)
default	3.0	100	1.0		
low_dca	1.0			0	0
low_tpcvz		50		0	0
deta_1_1			1.1	0	96.89
deta_1_2			1.2	22.36	332.39

Point index = 2	DCA (cm)	TPCVz(cm)	Deta	Sys C2 (%)	Sys C3 (%)
default	3.0	100	1.0		
low_dca	1.0			0	0
low_tpcvz		50		0	0
deta_1_1			1.1	31.31	0
deta_1_2			1.2	0	121.57

Point index = 3	DCA (cm)	TPCVz(cm)	Deta	Sys C2 (%)	Sys C3 (%)
default	3.0	100	1.0		
low_dca	1.0			21.55	35.02
low_tpcvz		50		0	0
deta_1_1			1.1	0	52.65
deta_1_2			1.2	0	77.66

Point index = 4	DCA (cm)	TPCVz(cm)	Deta	Sys C2 (%)	Sys C3 (%)
default	3.0	100	1.0		
low_dca	1.0			17.9	0
low_tpcvz		50		0	0
deta_1_1			1.1	0	101.2
deta_1_2			1.2	0	153.62

Point index = 5	DCA (cm)	TPCVz(cm)	Deta	Sys C2 (%)	Sys C3 (%)
default	3.0	100	1.0		
low_dca	1.0			43.66	111.45
low_tpcvz		50		0	0
deta_1_1			1.1	42.38	0
deta_1_2			1.2	16.74	59.09

- Systematic Uncertainties from p_T-integrated C_n vs multiplicity (dAu39)
- Cut parameters are varied one-by-one, Barlow test is performed for each cut, and the quadrature sum of each systematic run gives the total systematic uncertainty
- Expected uncertainties not evaluated yet: nHitsFit

Pseudorapidity distributions

After Vertex & Track selection