Coulomb Dissociation Measurement in Isobar UPC at $\sqrt{s_{NN}} = 200$ GeV with The STAR Experiment

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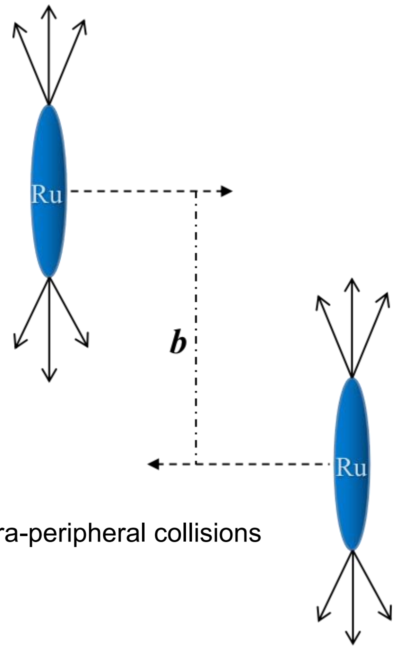
Hot Quarks 2025, Hefei, May 11-17 2025

Supported in part by the U.S. DEPARTMENT OF ENERGY Office of Science

Outline

- Introductions
- Detector and data processing
- Approaching method
- Trigger luminosity and cross-section
- Summary and outlook

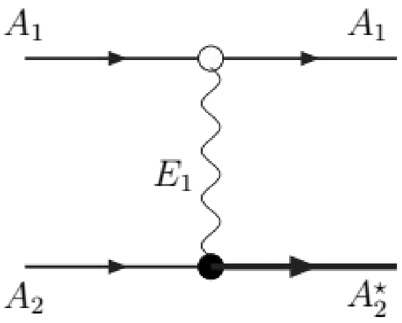
Electromagnetic Field in Heavy Ion Collisions



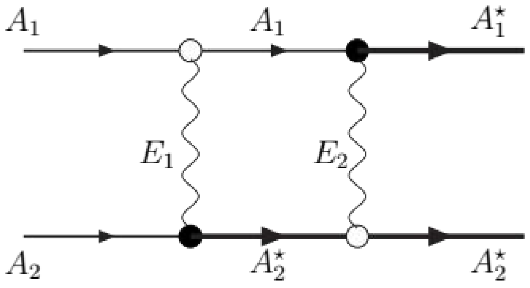
a). Ultra-peripheral collisions

- ☐ Ultra-Peripheral Collisions (UPC):
  - Two ions pass each other ($b > R_1 + R_2$)
  - Interaction dominated by relativistic electromagnetic field

- ☐ Photonuclear Interactions:
  - One or both ions emit virtual photons absorbed by the other, causing nuclear excitation and breakup
  - Neutron emission occurs through a process known as Coulomb Dissociation (CD)



b). Single Coulomb dissociation (**SCD**)



c). Mutual Coulomb dissociation (**MCD**)

Isobaric Nuclei (Ru+Ru & Zr+Zr) Collisions

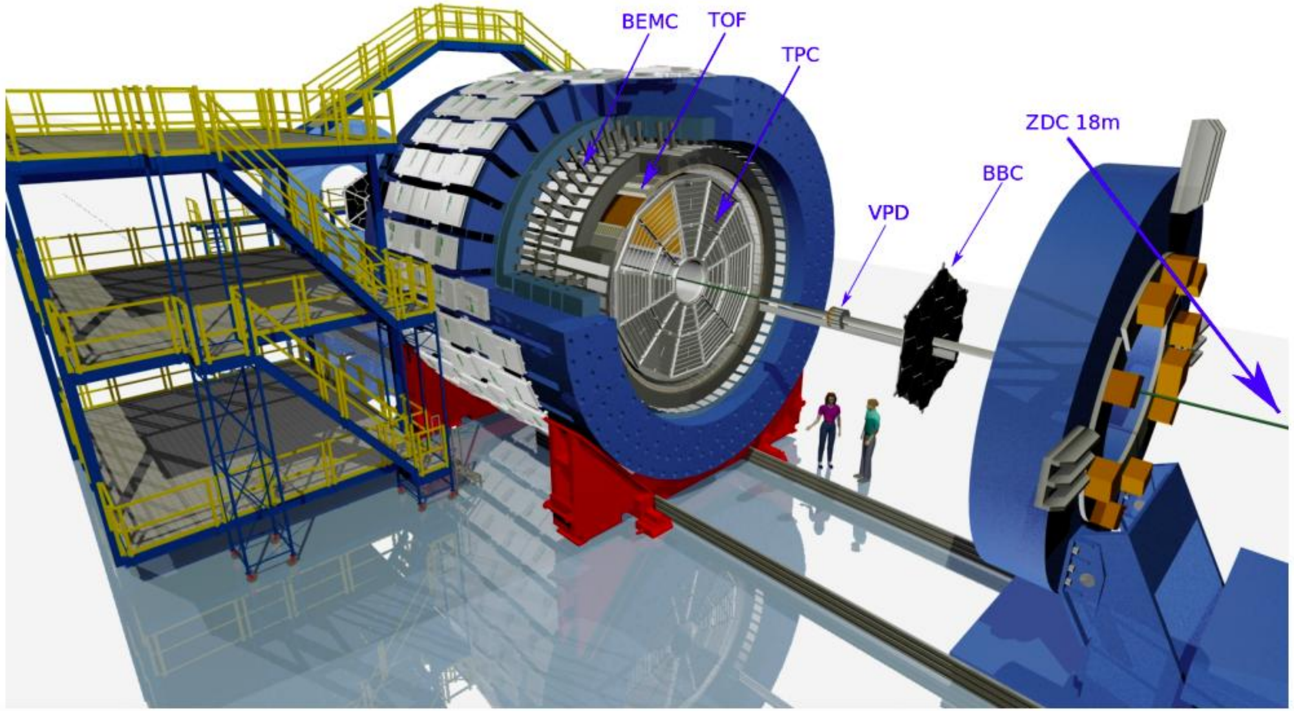
Ru	Zr	Ru/Zr
A = 96	A = 96	1.00
Z = 44	Z = 40	1.10
N / Z ≈ *1.18*	N / Z ≈ *1.40*	*0.84*

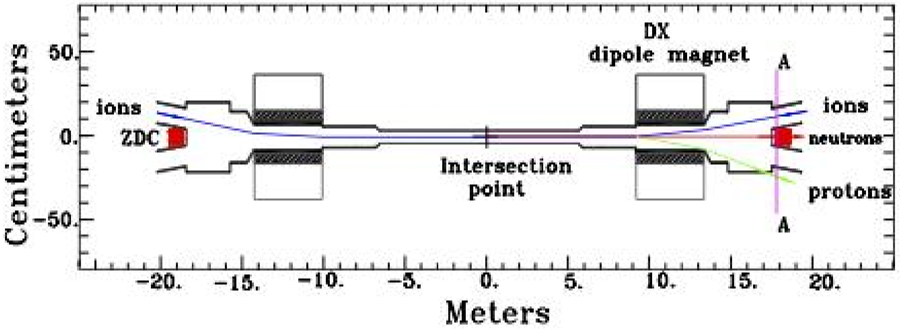
- Isobaric Nuclei: Ruthenium (A=96, Z=44) and Zirconium (A=96, Z=40)
  - Same mass number, different proton number
  - Direct comparison of nuclear structures
  - Probing the influence of proton number on nuclear properties ($\gamma \propto Z^2$)

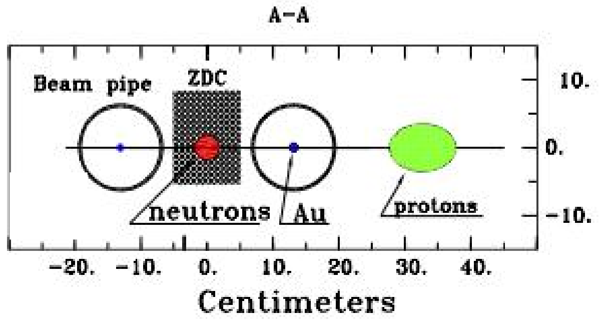
Key points:

- $\gamma \propto Z^2$
- (N/Z)
- $(Z^2_{Ru} / Z^2_{Zr}) \approx$ **1.21**
- $(N/Z)_{Ru} < (N/Z)_{Zr}$

STAR-ZDC Detector







- STAR Experiment and ZDC Detector:
  - The STAR experiment at RHIC is equipped with the ZDC detector
  - The ZDC detects neutrons emitted in CD events

Data Processing

Data set:

Run18 RuRu / ZrZr @200 GeV

Trigger :

ZDC-Mon

Zerobias

ZDC-Mon	
Collisions Species	**Number of Event**
Ru+Ru	5.113 M
Zr+Zr	4.988 M

Zerobias	
Collisions Species	Number of Event
Ru+Ru	4.935 M
Zr+Zr	4.843 M

Neutron channels:

ZDC-Mon -> MCD {1n1n, 1nXn, XnXn}

ZB -> SCD {1n, Xn}

MCD

zdc-mon (history)	37	600017	1.81K	8.81K
zdc-mon (history) --> Requirements:	+ZDC-TAC +ZDC-E +ZDC-W -Laser-protection			

SCD

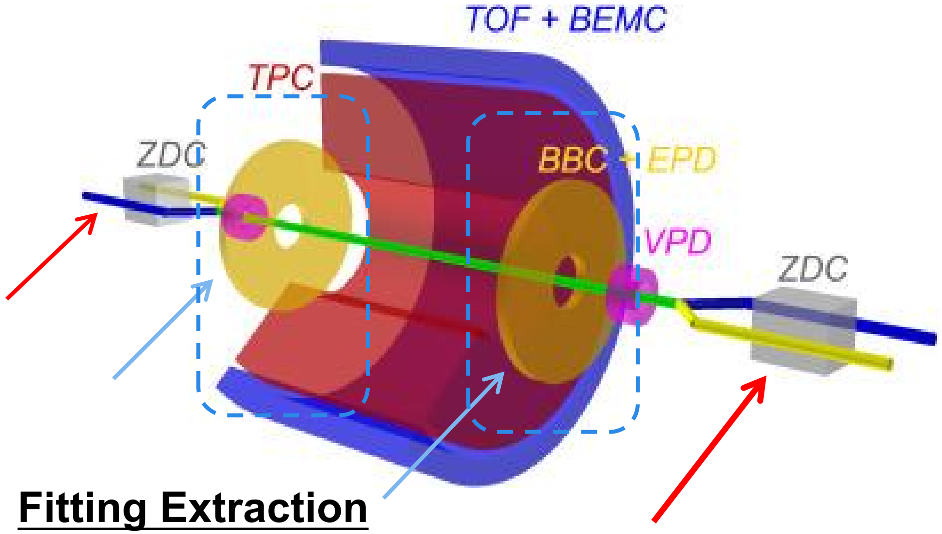
ZEROBIAS (history)	60	9300	844.48K	4.18M
ZEROBIAS (history) --> Requirements:	-Laser-protection			

Approaching method

1. **Event Filtering:**
   The BBC detector vetoing hadronic events:

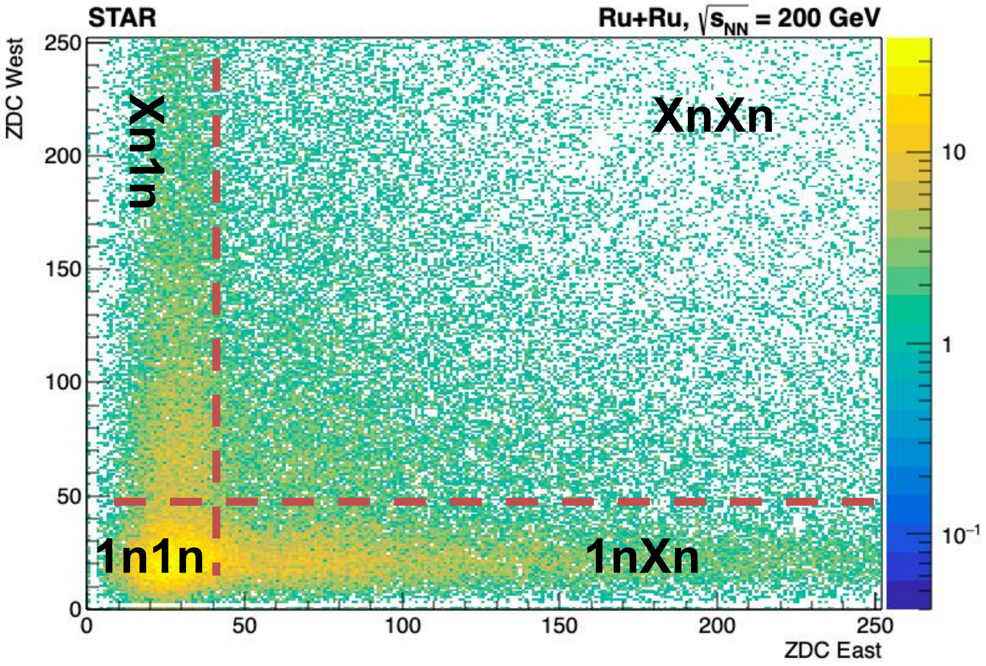
- at least one side $BBC_n \leq 20$ (ZDC-Mon)
- at least one side $BBC_n \leq 1$ (Zero-Bias)

BBCn = BBC coincidence tagging of hadrons, allowing neutron emissions to pass through and be detected by the ZDC.



3. **Fitting Extraction**
   Perform multi-gaussian fit to extract neutron emission distribution

2. **Neutron tagging of UPC**:
   Neutron-tagged events are selected using the ZDC

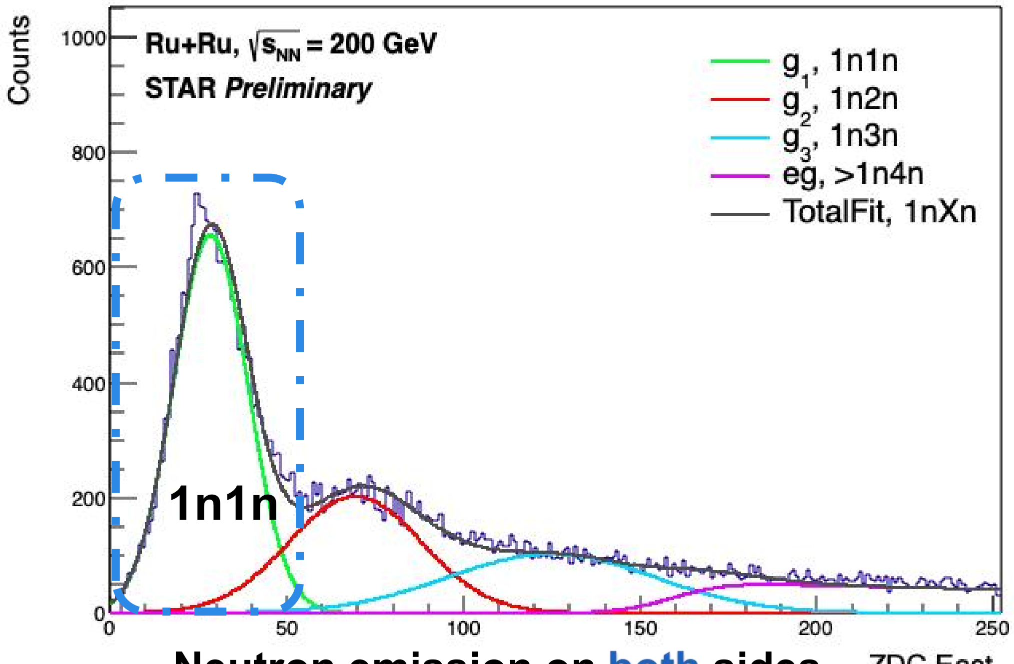


4. **Cross-Section Calculation:**
   Calculate σ_{cd} for each neutron emission channel

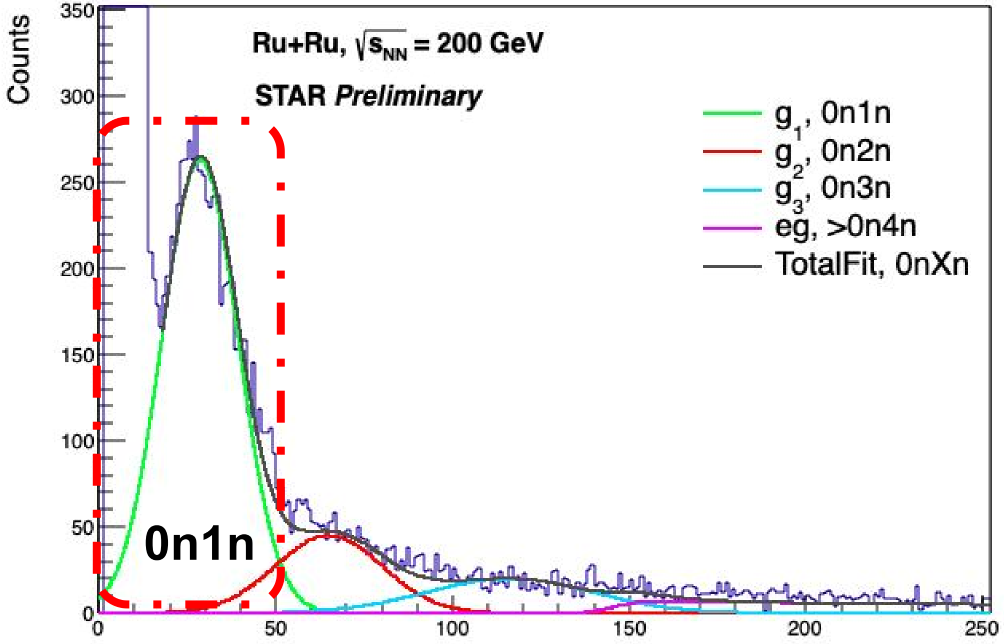
Neutron emission extraction

Ru (A=96, Z=44)

We extracted neutron emission by fiting function $\underbrace{\text{TotalFit}}_{\text{Xn}} = \underbrace{g_1(x)}_{\text{1n}} + \underbrace{g_2(x)}_{\text{2n}} + \underbrace{g_3(x)}_{\text{3n}} + \underbrace{eg(x)}_{>\text{4n}}$



Neutron emission on **both** sides



Neutron emission on **one** side

Multi-gaussian fit

$$\underbrace{\mathrm{TotalFit}}_{\mathrm{Xn}} = \underbrace{g_1(x)}_{\mathrm{1n}} + \underbrace{g_2(x)}_{\mathrm{2n}} + \underbrace{g_3(x)}_{\mathrm{3n}} + \underbrace{eg(x)}_{>\mathrm{4n}}$$

- **Gaussian Peaks (n-neutron events)**:

$$g_i(x, \mu_i, \sigma_i) = \frac{A_i}{\sigma_i\sqrt{2\pi}} \exp\left(-\frac{(x-\mu_i)^2}{2\sigma_i^2}\right) \quad \text{for } i = 1, 2, 3$$

$$\mu_2 = 2\mu_1, \quad \sigma_2 = \sqrt{2}\sigma_1 \quad \text{(2n peak)}$$

$$\mu_3 = 3\mu_1, \quad \sigma_3 = \sqrt{3}\sigma_1 \quad \text{(3n peak)}$$

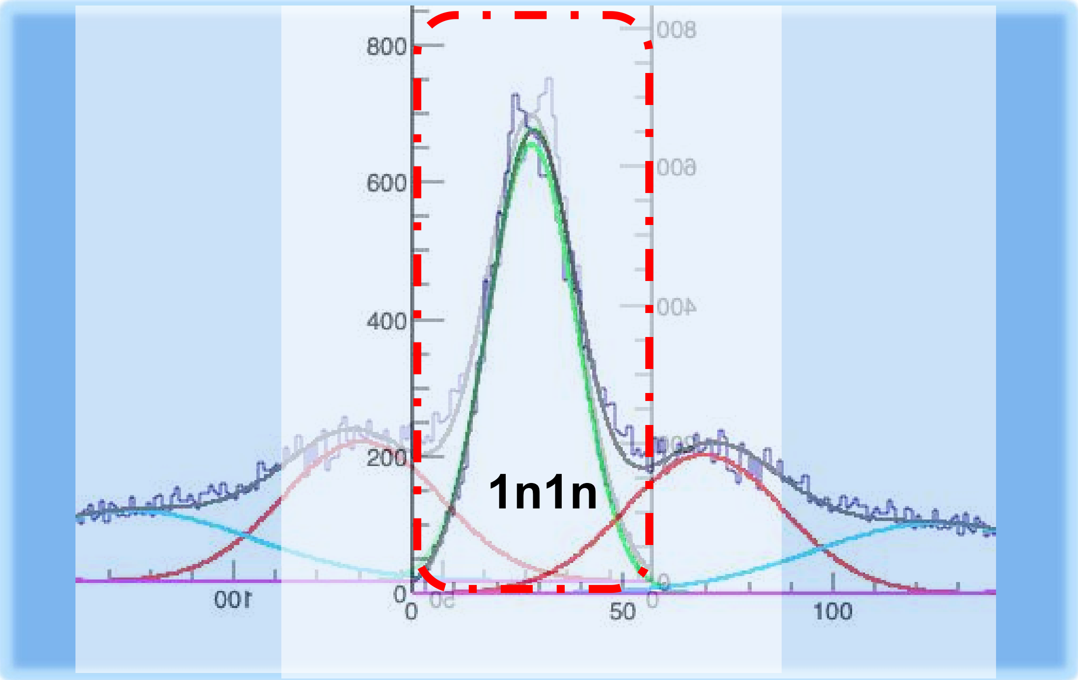
- **Exponential Modified Gaussian (>4n)**:

$$eg(x, \mu_4, \sigma_4) = A_4 \left(\frac{\lambda}{2}\right) \exp\left(\frac{\lambda}{2}(2\mu_4 + \lambda\sigma_4^2 - 2x)\right) \left[1 + \mathrm{erf}\left(\frac{x - \mu_4 - \lambda\sigma_4^2}{\sigma_4\sqrt{2}}\right)\right]$$

Efficiency and purity of 1n event

Ru (A=96, Z=44)

The 1n emission probably also contains 2n. Therefore, we calculate efficiency & purity



$$1\mathrm{n}_{(corrected)} = \underbrace{g_1(x)}_{1\mathrm{n}} \cdot \frac{\epsilon_{1n}}{p_{1n}}$$

with $\epsilon = \dfrac{N_{1\mathrm{n,selected}}}{N_{1\mathrm{n,total}}}$ (Efficiency) $p = \dfrac{N_{1\mathrm{n,selected}}}{N_{\mathrm{all,selected}}}$ (Purity)

ZDC-Mon Luminosity

The STAR recorded data was analyzed to obtain *luminosity of the ZDC-mon triggered events* (L_{zdcmon})

Name	Species	Tid	Lum [ub^-1]	Nev [M]
zdc-mon	RuRu		1.499	6.956
zdc-mon	RuRu	600007	0.019	0.086
zdc-mon	RuRu	600017	1.480	6.870
zdc-mon	ZrZr		1.530	7.098
zdc-mon	ZrZr	600007	0.001	0.004
zdc-mon	ZrZr	600017	1.529	7.094

ZDC_Mon	
Collision Species	**Number of Event**
Ru+Ru	5.113M
Zr+Zr	4.988M

- $L_{\mathrm{zdcmon[Ru]}}(\mathrm{Xn,Xn}) = \dfrac{\sum N(Xn,Xn)_{\mathrm{Ru}} \,.\, L_{\mathrm{zdc\_coinc(Ru)}}}{\sum N_{\mathrm{zdc\_coinc}}(Xn,Xn)_{\mathrm{Ru}}} = \dfrac{5.113\mathrm{M} \bullet 1.499}{6.956\mathrm{M}} \approx 1.101\ \mu b^{-1}$

- $L_{\mathrm{zdcmon[Zr]}}(\mathrm{Xn,Xn}) = \dfrac{\sum N(Xn,Xn)_{\mathrm{Zr}} \,.\, L_{\mathrm{zdc\_coinc(Zr)}}}{\sum N_{\mathrm{zdc\_coinc}}(Xn,Xn)_{\mathrm{Zr}}} = \dfrac{4.989\mathrm{M} \bullet 1.530}{7.096\mathrm{M}} \approx 1.076 \mu b^{-1}$

ZDC-Coincidence

Name	Species	Tid	Lum [ub^-1]	Nev [M]
zdc-mon	RuRu		1.499	6.956
zdc-mon	RuRu	600007	0.019	0.086
zdc-mon	RuRu	600017	1.480	6.870
zdc-mon	ZrZr		1.530	7.098
zdc-mon	ZrZr	600007	0.001	0.004
zdc-mon	ZrZr	600017	1.529	7.094

The STAR recorded data enables to calculate the *ZDC-coincidence* cross-section, $\boldsymbol{\sigma}_{\mathbf{coinc}}$, which follow this formula:

$$\sigma_{coinc} = \frac{\sum N_{coinc}}{L}$$

where $\sum N$ is number of event of coincidence, and L is integrated luminosity

$\boxed{\sigma_{\mathrm{Ru}} \approx 4.64 \text{ b}}$

$\boxed{\sigma_{\mathrm{Zr}} \approx 4.64 \text{ b}}$

ZB Trigger Luminosity Estimation

We estimate luminosity of Zerobias trigger (L_{zb}) with the (Xn,Xn) channel :

Zerobias	Ru	Zr
	$\sum N$	$\sum N$
(Xn,Xn)	13381	13304

followed by *ZDC coincidence* cross-section, $\boldsymbol{\sigma}_{\mathbf{coinc}}$, thus :

- $L_{zb[\mathrm{Ru}]}$(Xn,Xn) = $\frac{\sum N(Xn,Xn)}{\sigma_{\mathrm{coinc(Ru)}}} = \frac{13381}{\boxed{4.64}} = 2883.83\ b^{-1}$
- $L_{zb[\mathrm{Zr}]}$(Xn,Xn) = $\frac{\sum N(Xn,Xn)}{\sigma_{\mathrm{coinc(Zr)}}} = \frac{13304}{\boxed{4.64}} = 2867.85\ b^{-1}$

Coulomb dissociation cross-section

We compute Coulomb dissociation cross-section by formula :

$$\boldsymbol{\sigma_{cd}} = \frac{\sum N_{n-channel}}{L_{trigger}} ,$$

where $\sum N_{n-channel}$ associated with each neutron emission channels, for SCD ($\sum N_{[0n1n]}$, $\sum N_{[0nXn]}$) and MCD ($\sum N_{[1n1n]}$, $\sum N_{[1nXn]}$, & $\sum N_{[XnXn]}$) include luminosity-trigger as L_{zb} and $L_{zdc\text{-}mon}$, respectively.

Preliminary Result

Table 1: Mutual Coulomb dissociation (MCD) cross-section of Isobar data

Neutron	Ru (mb)			Zr (mb)			Ratio (Ru/Zr)		
1n1n	14.21	± 0.08	± 1.70	6.51	± 0.05	± 0.79	2.18	± 0.02	± 0.21
1nXn	47.61	± 0.14	± 5.53	33.23	± 0.11	± 3.80	1.43	± 0.05	± 0.12
XnXn	168.00	± 0.39	± 20.95	190.19	± 0.42	± 23.51	0.88	± 0.02	± 0.09

Table 2: Single Coulomb dissociation (SCD) cross-section of Isobar data

Neutron	Ru (b)			Zr (b)			Ratio (Ru/Zr)		
0n1n	2.05	± 0.02	± 0.20	1.25	± 0.01	± 0.13	1.60	± 0.02	± 0.04
0nXn	4.48	± 0.02	± 0.45	4.36	± 0.02	± 0.44	1.03	± 0.06	± 0.02
0nXn+Xn0n	8.96	± 0.04	± 0.90	8.72	± 0.04	± 0.89	1.03	± 0.06	± 0.02

Summary

- **Conclusion**

- The first measurement of Coulomb dissociation in STAR Isobar data include the cross-section calculation of both SCD and MCD events
- The ratios 1.60 ± 0.02 (1n SCD) & 2.18 ± 0.02 (1n1n MCD) of (Ru/Zr) demonstrate:
  - Clear Z-dependence, exceeding Z^2 scaling (Z^2_{Ru} / Z^2_{Zr} ≈ 1.21)
  - At Low-energies, 1n emission results may be explained by Giant Dipole Resonance (GDR) excitations, where cross-section is enhanced for higher proton of Ru-96.
  - Hints at nuclear structure effect of the Isobar
- The ratios 1.03 ± 0.06 (Xn SCD) and 0.88 ± 0.02 (XnXn MCD) of (Ru/Zr) are near unity. It indicates:
  - Both Isobars are geometrically identical (*A=96*)
  - No Z-dependence which may indicate no significant EM effects

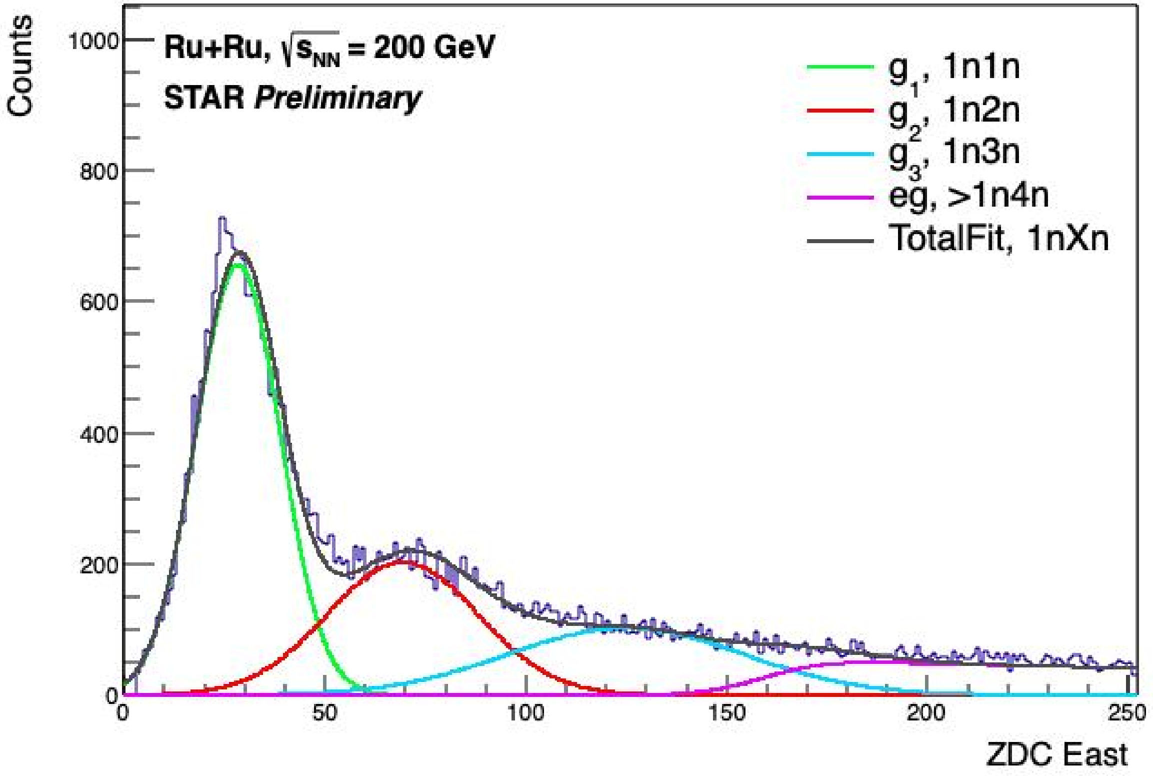
- **Outlook**

- We will perform model calculation for neutron emission with Giant resonance, Quasi-deuteron, and higher energy pomeron contribution to cover photon energy up to RHIC regime.

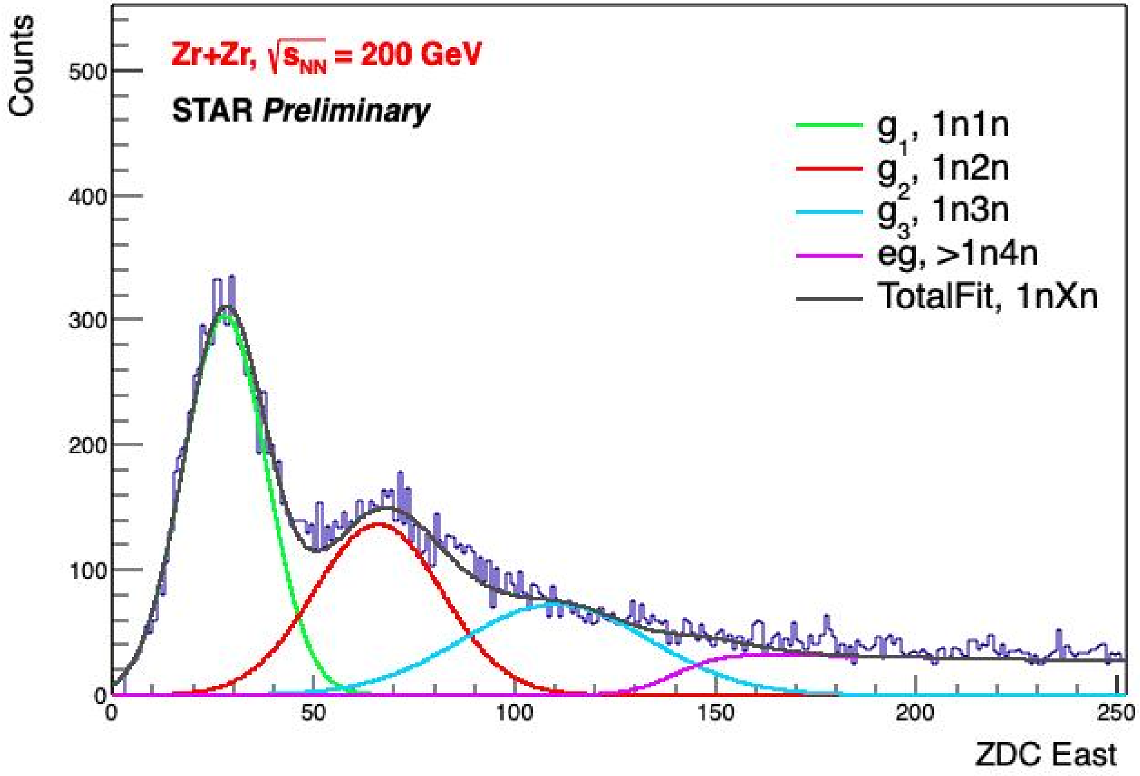
Thank You!

Backup

1nXn (Ru vs Zr)

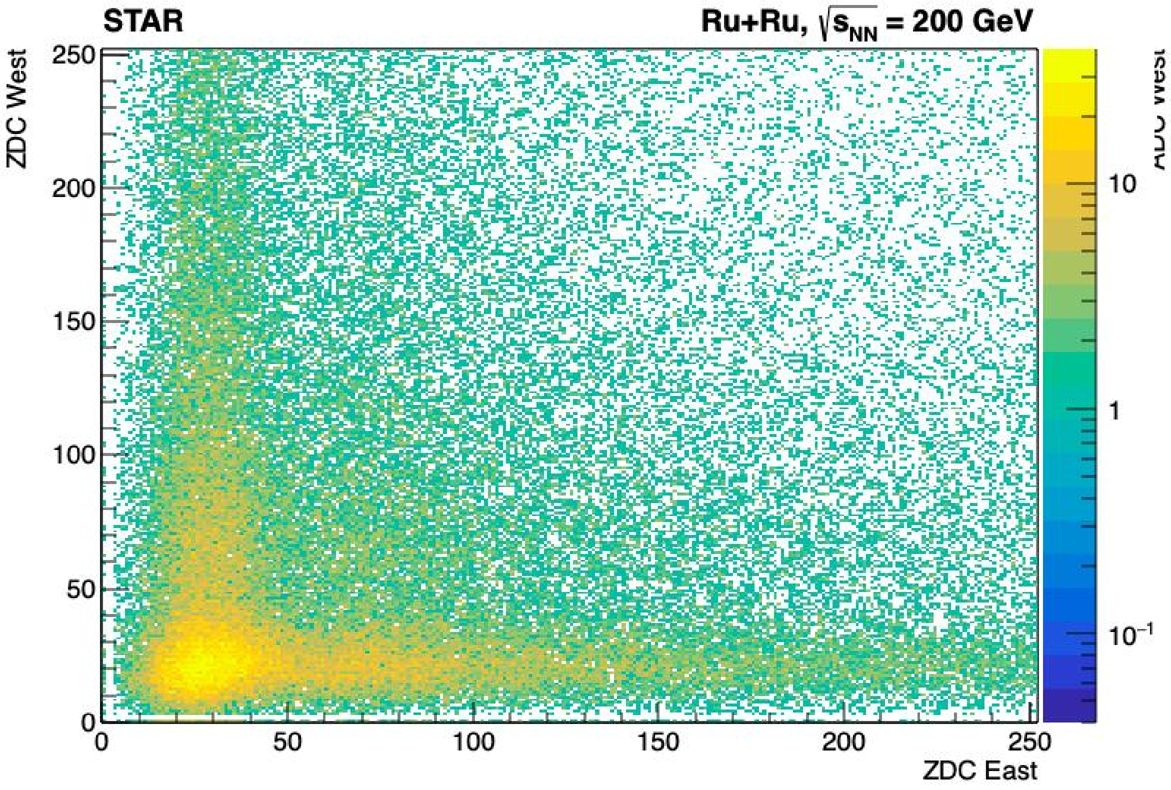


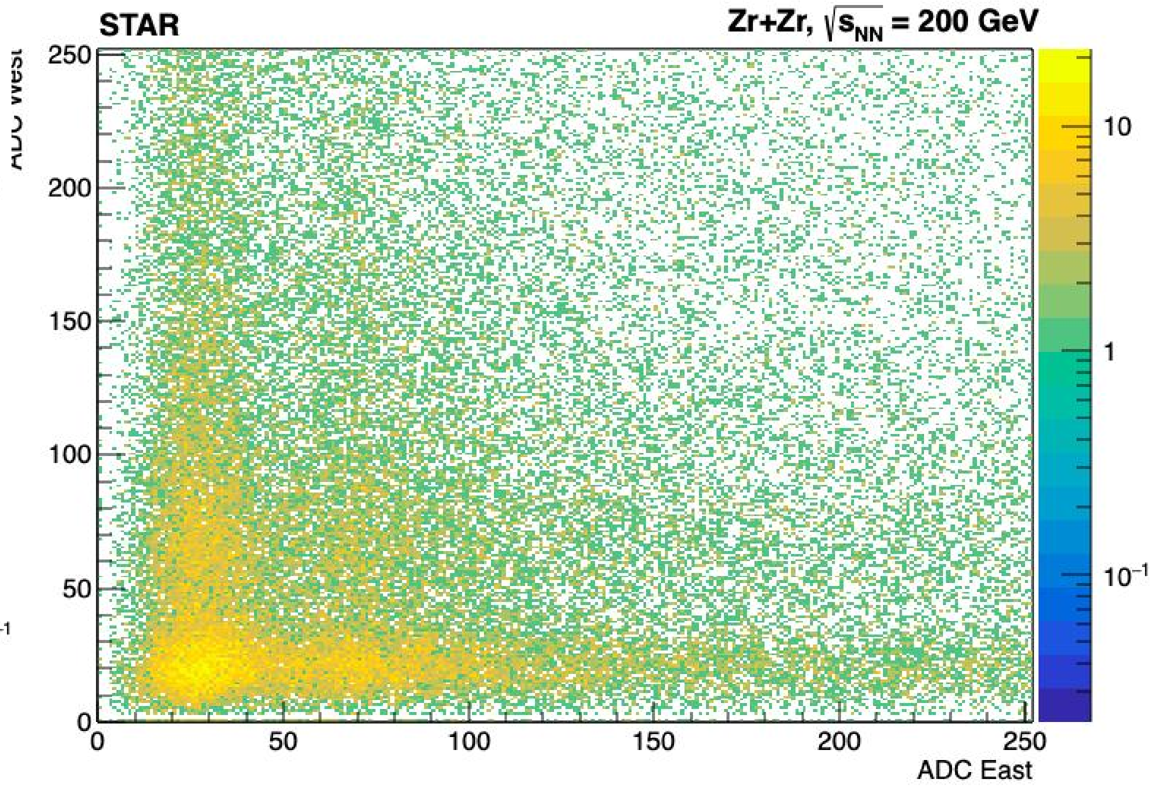
Ru+Ru, $\sqrt{s_{NN}}$ = 200 GeV
STAR *Preliminary*
g_1, 1n1n
g_2, 1n2n
g_3, 1n3n
eg, >1n4n
TotalFit, 1nXn
Counts
ZDC East



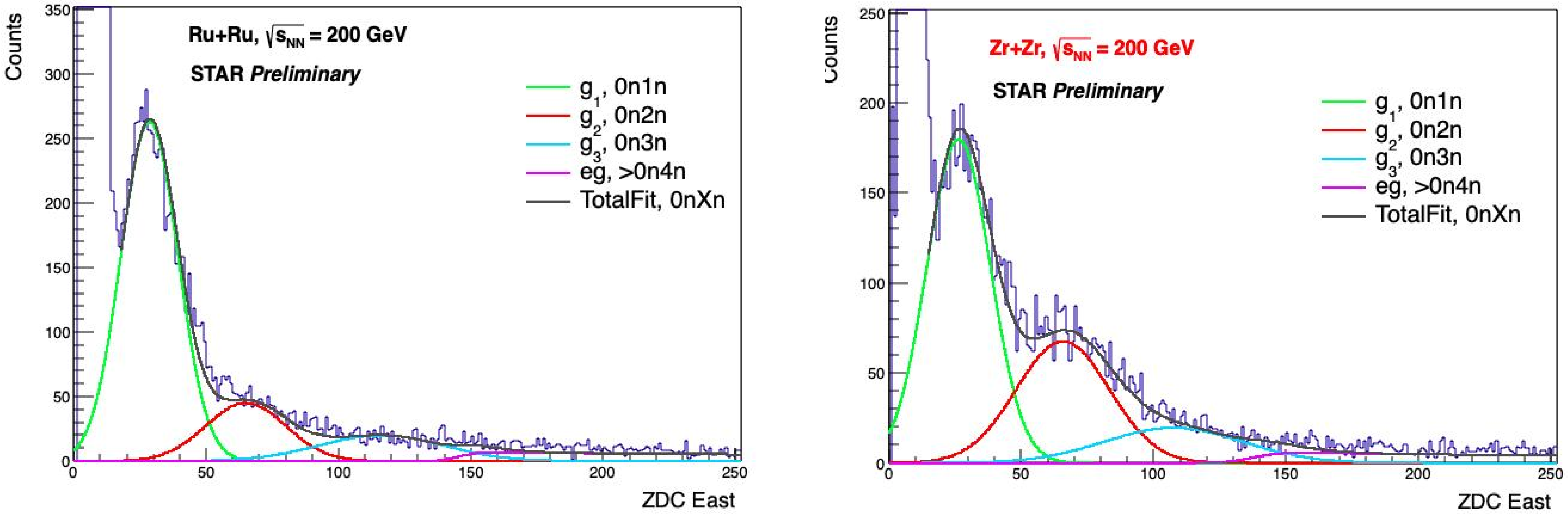
Zr+Zr, $\sqrt{s_{NN}}$ = 200 GeV
STAR *Preliminary*
g_1, 1n1n
g_2, 1n2n
g_3, 1n3n
eg, >1n4n
TotalFit, 1nXn
Counts
ZDC East

XnXn (Ru vs Zr)


STAR
Ru+Ru, $\sqrt{s_{NN}}$ = 200 GeV
ZDC West
ZDC East
10
1
10^{-1}
0
50
100
150
200
250


STAR
Zr+Zr, $\sqrt{s_{NN}}$ = 200 GeV
ADC East
10
1
10^{-1}
0
50
100
150
200
250

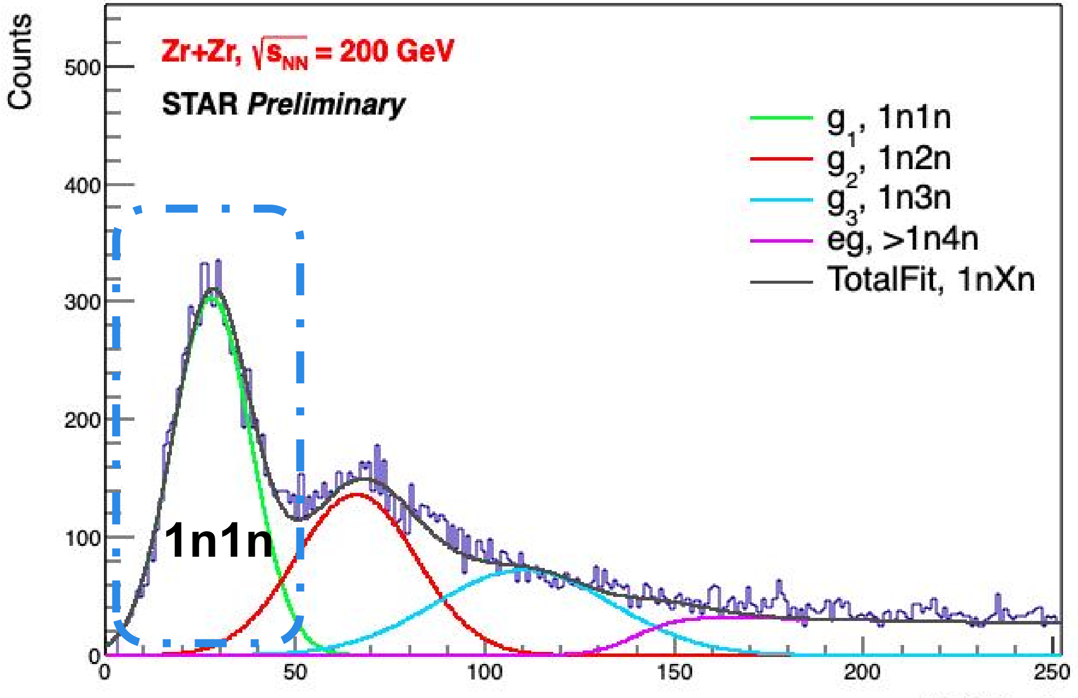
0nXn (Ru vs Zr)


Ru+Ru, $\sqrt{s_{NN}}$ = 200 GeV
STAR *Preliminary*
g_1, 0n1n
g_2, 0n2n
g_3, 0n3n
eg, >0n4n
TotalFit, 0nXn
Counts
ZDC East
Zr+Zr, $\sqrt{s_{NN}}$ = 200 GeV
STAR *Preliminary*
g_1, 0n1n
g_2, 0n2n
g_3, 0n3n
eg, >0n4n
TotalFit, 0nXn
Counts
ZDC East

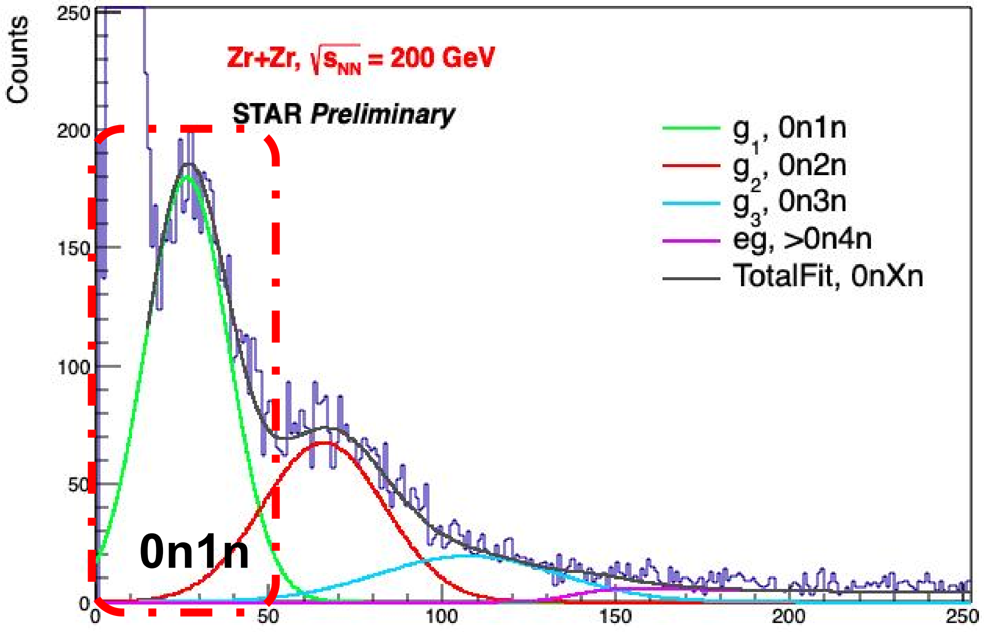
Neutron emission extraction

Zr (A=96, Z=40)

We extracted neutron emission by fiting function $\underbrace{\text{TotalFit}}_{\text{Xn}} = \underbrace{g_1(x)}_{\text{1n}} + \underbrace{g_2(x)}_{\text{2n}} + \underbrace{g_3(x)}_{\text{3n}} + \underbrace{eg(x)}_{>\text{4n}}$



Neutron emission on both sides



Neutron emission on one side