



Quasi Free Scattering with S444 Data (2020)

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Analysis WG Meeting
22.07.2021

$^{12}\text{C}(p,2p)^{11}\text{B}$ reaction

$^{12}\text{C}(p,\text{ppn}/\text{pd})^{10}\text{B}$ reaction

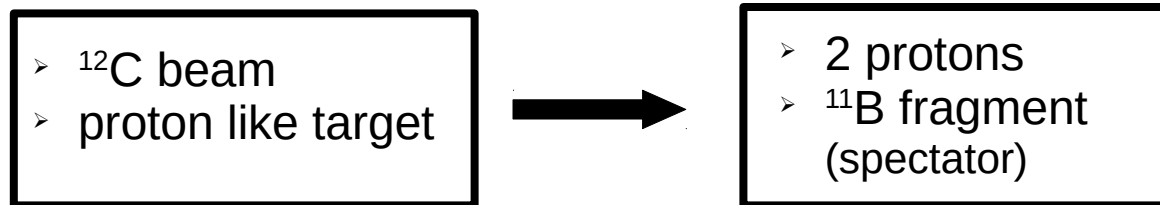
SRC Analysis



Supported by BMBF 05P15WOFNA and 05P19WOFN1.

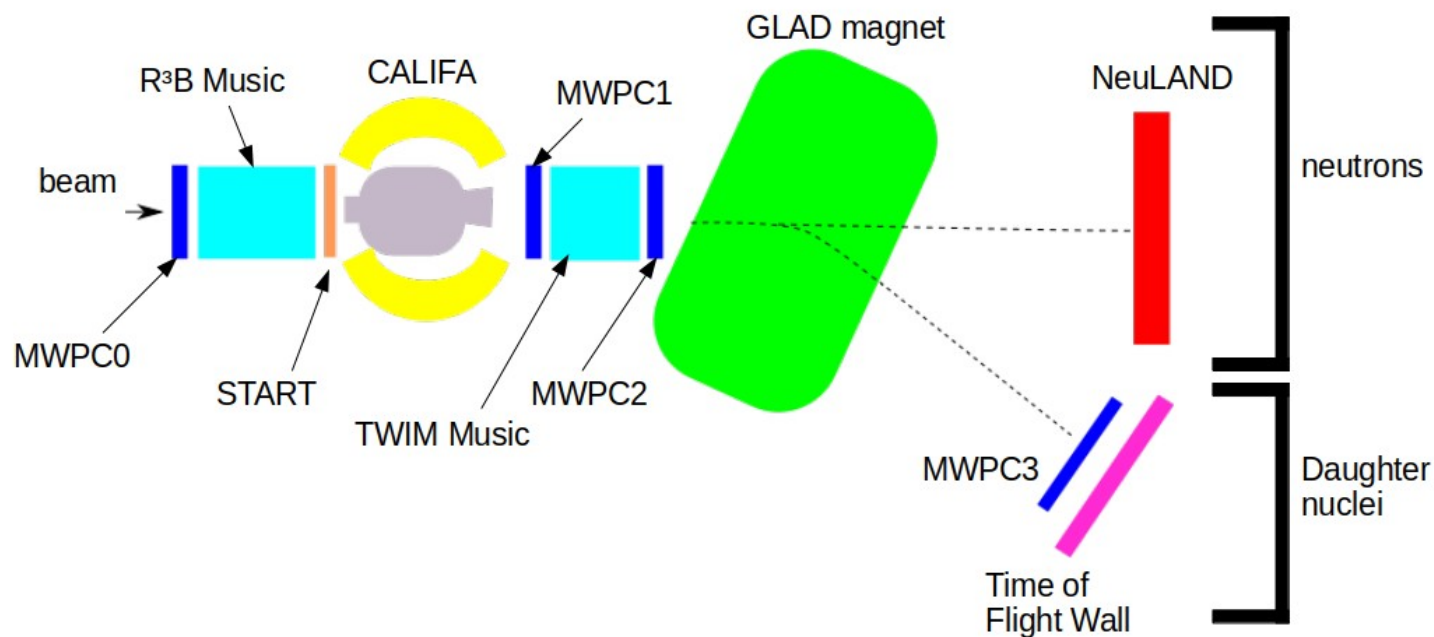
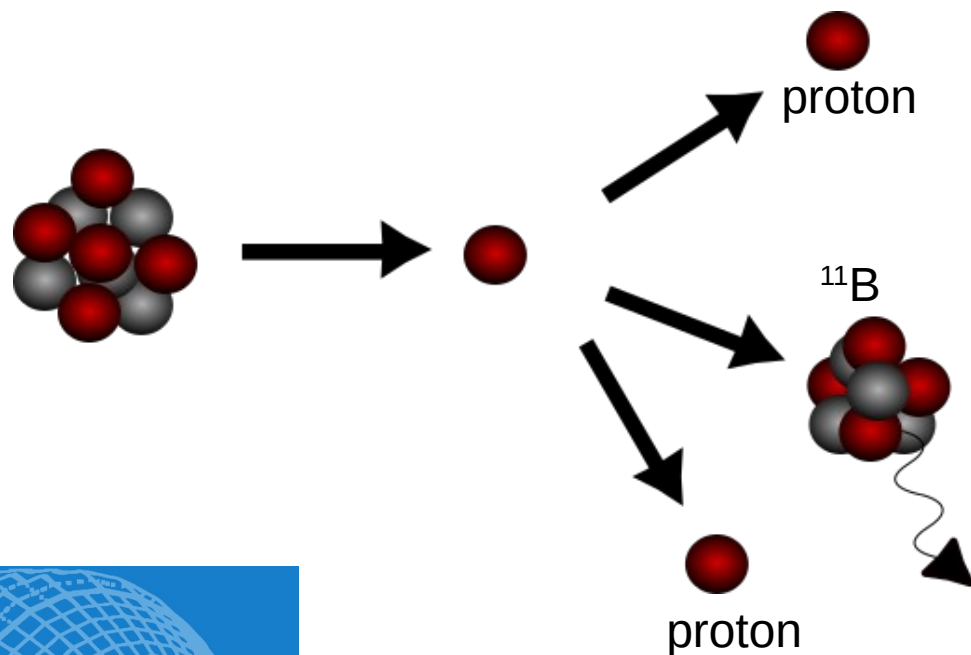
The results presented here are based on the experiment s444/s473, which was performed at the beam line/infrastructure Cave C at the GSI Helmholtzzentrum für Schwerionenforschung, Darmstadt (Germany) in the frame of FAIR Phase-0.

$^{12}\text{C}(p,2p)^{11}\text{B}$ reaction:



SETUP:

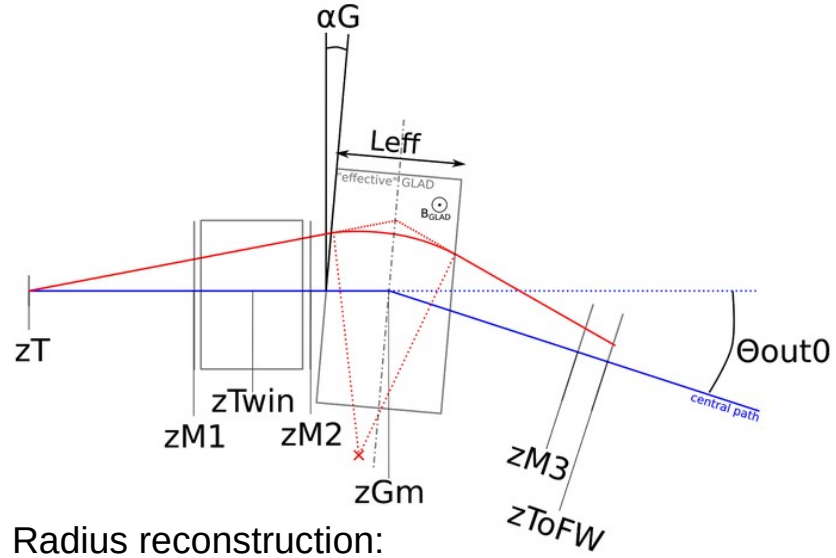
Beam energy: 400 AMeV
Beamtype: ^{12}C
Target: CH_2





Fragment Particle Identification

Flightpath reconstruction:

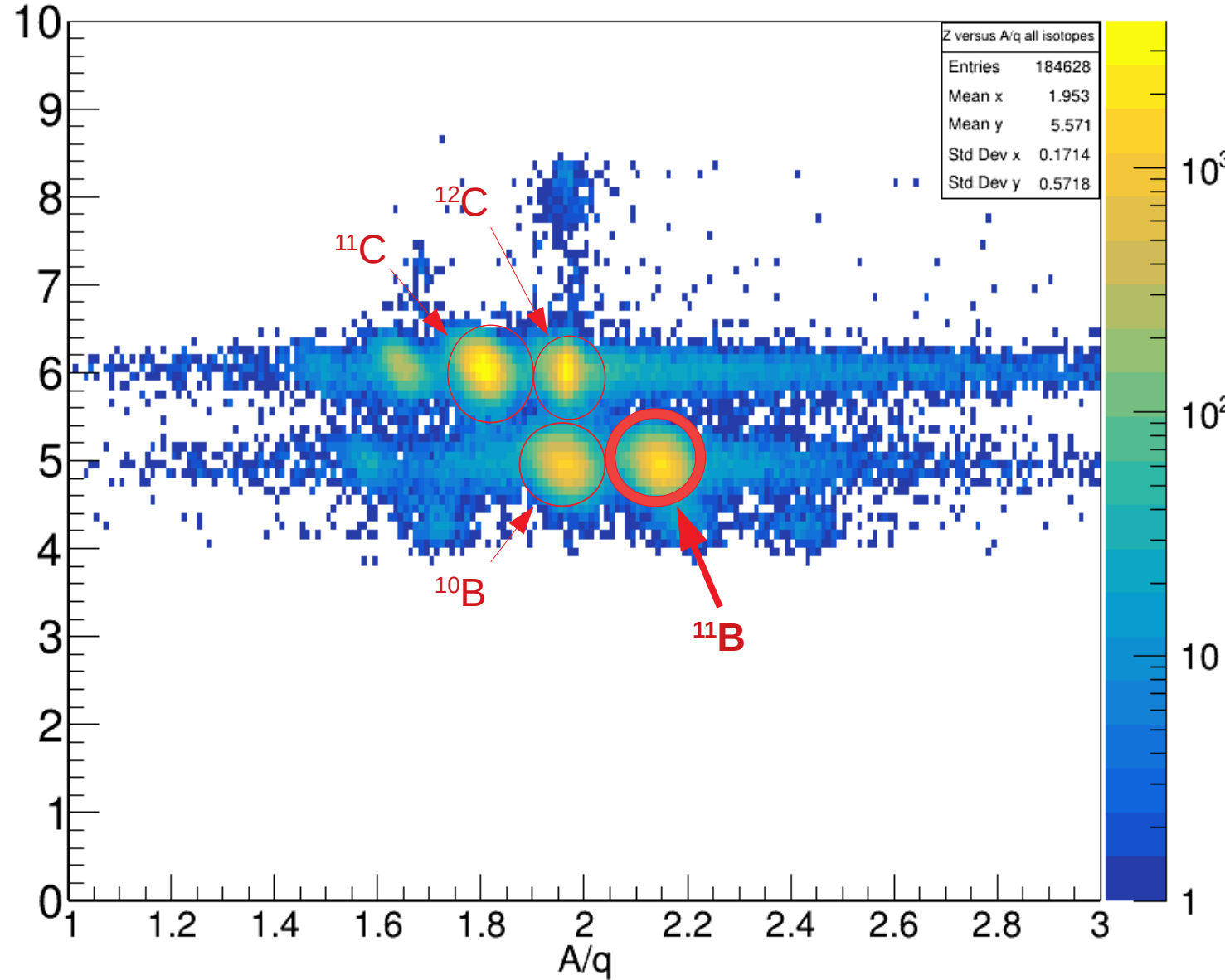


Radius reconstruction:

$$R = \frac{L_{eff}}{2 \sin\left(\frac{\theta_{in} + \theta_{out}}{2}\right)}$$

$$B * \rho = \frac{\beta * \gamma * M}{q}$$

Z (charge)

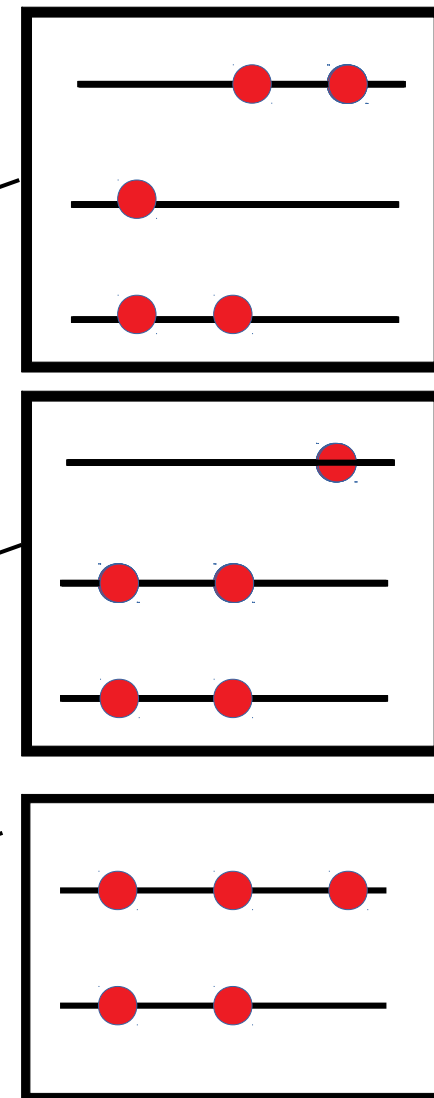
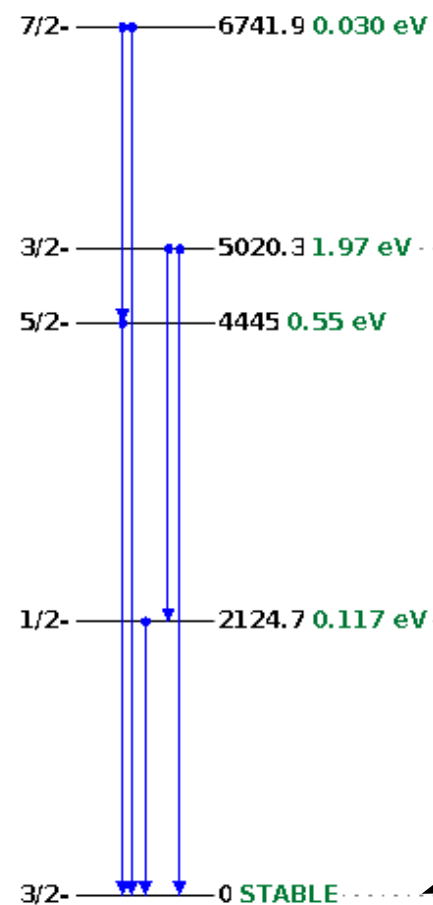
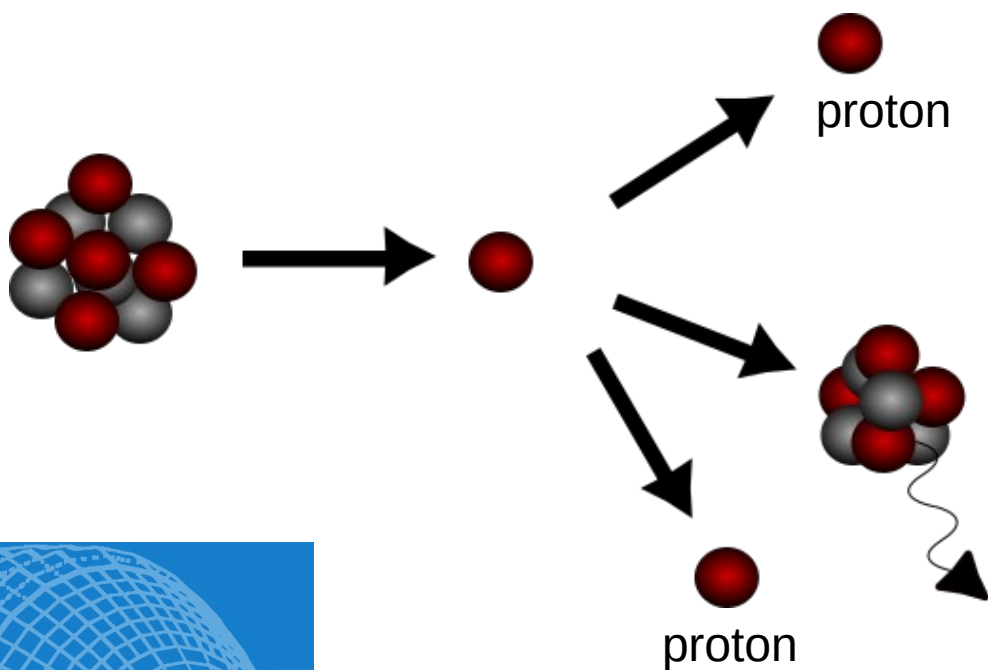




$^{12}\text{C}(p,2p)^{11}\text{B}$ reaction

Two Proton Identification:

→ two hits with $E_{\text{hit}} > 30 \text{ MeV}$

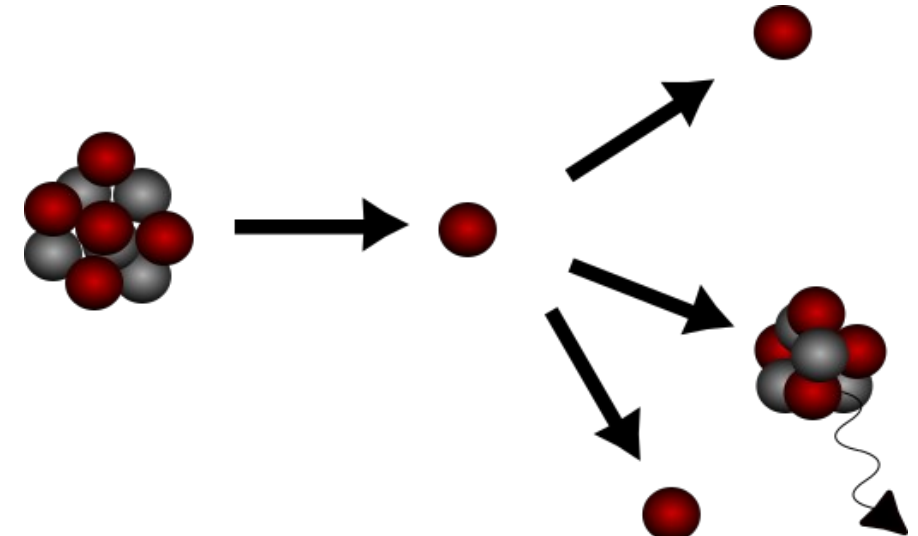
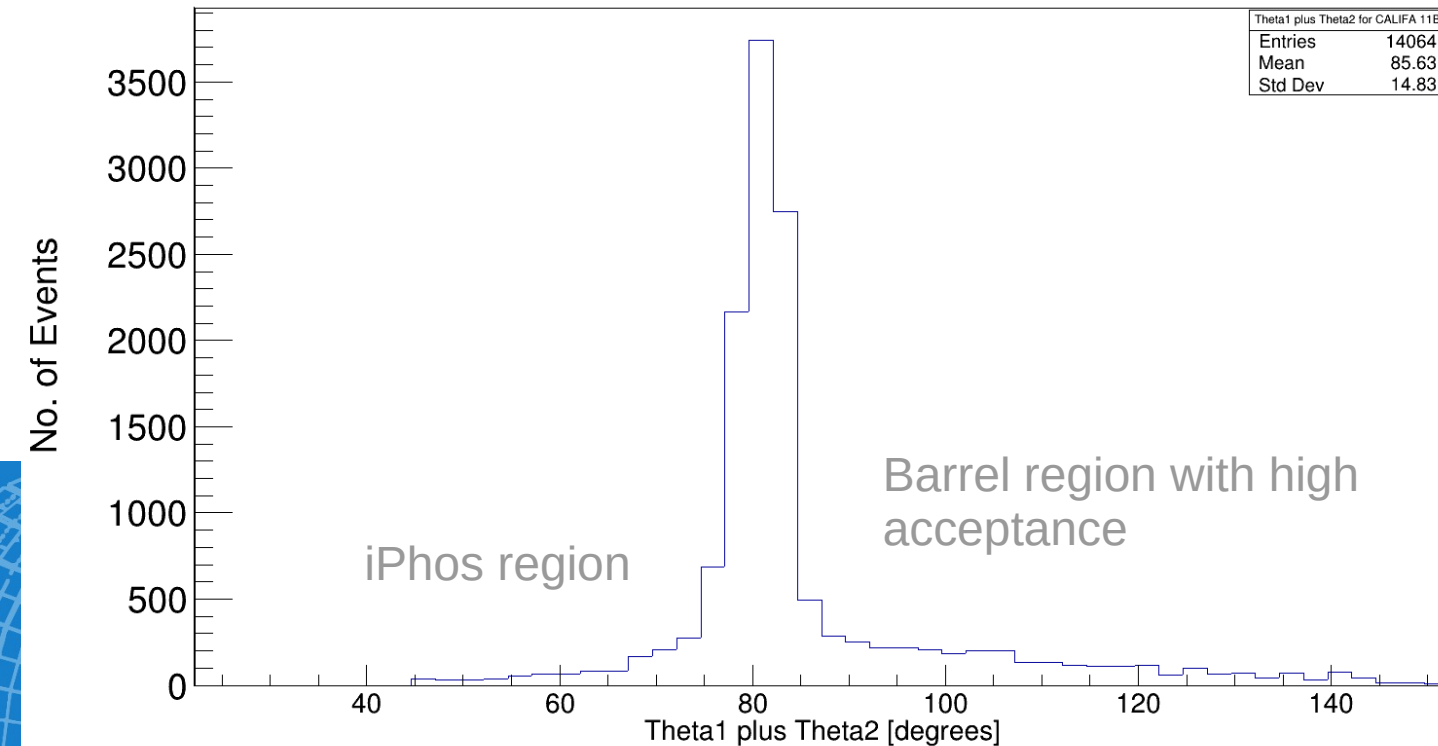
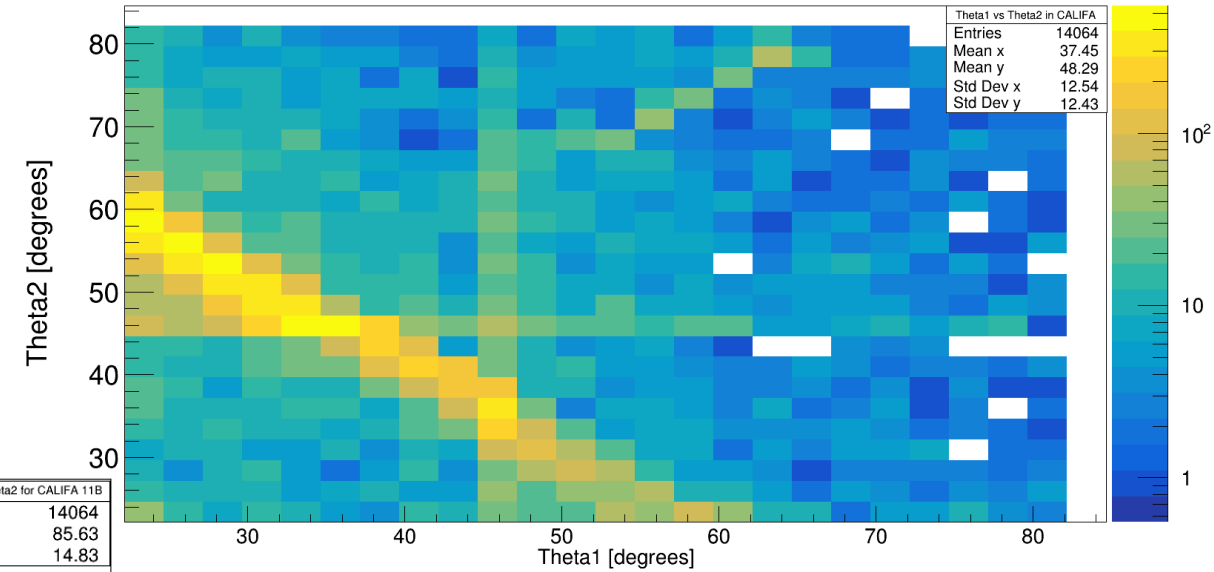
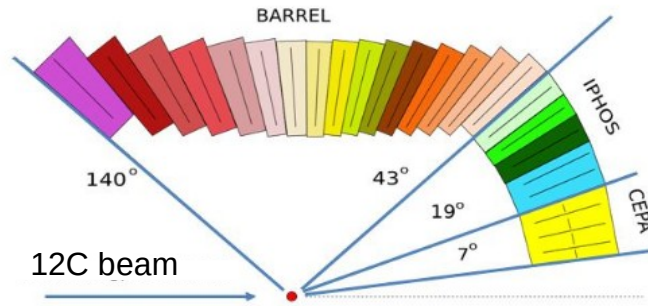




Polar Angular Distribution of protons for $^{12}\text{C}(p,2p)^{11}\text{B}$

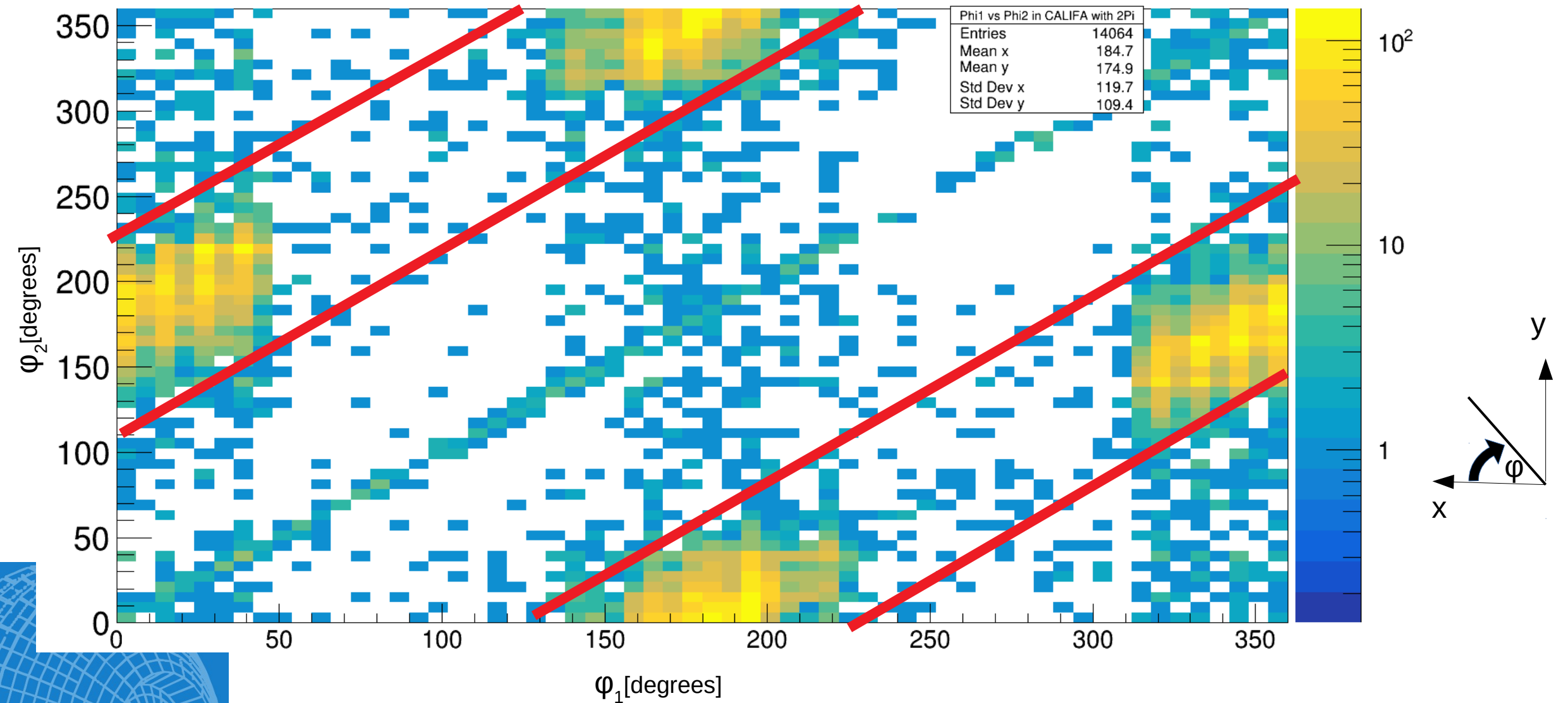


Theta1 vs Theta2 in CALIFA





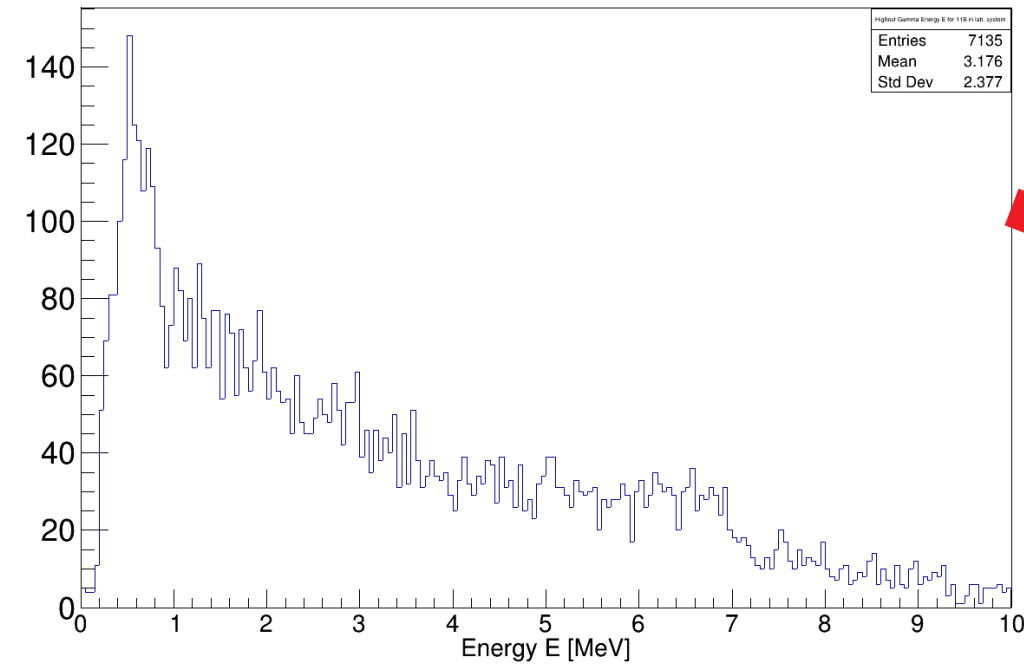
Arzimuthal Distribution of protons for $^{12}\text{C}(p,2p)^{11}\text{B}$





Gamma Spectrum of ^{11}B

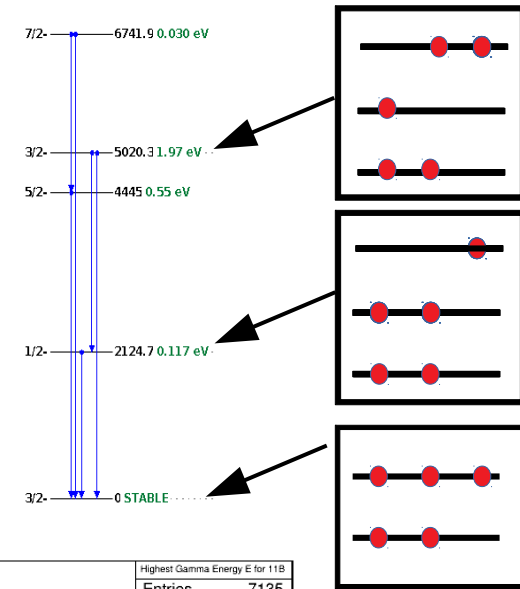
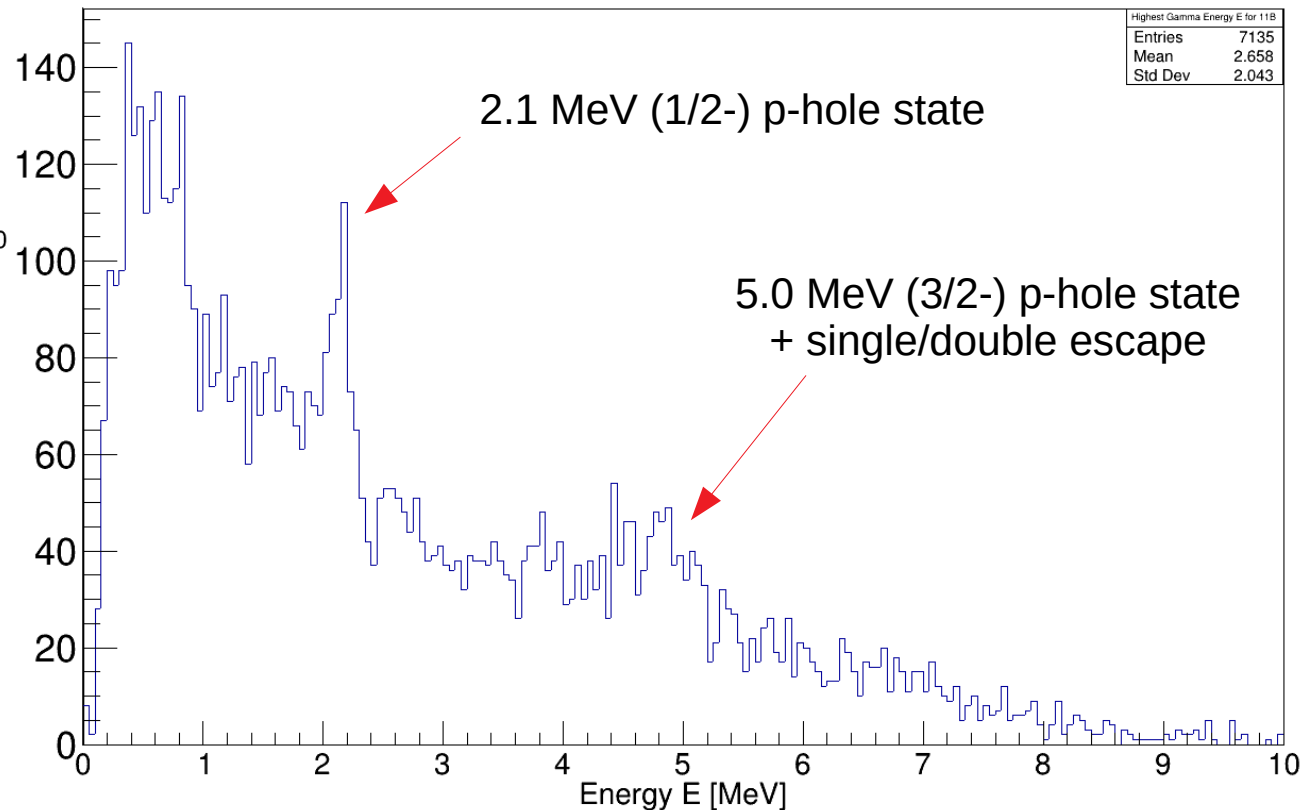
laboratory system



Doppler Correction:

$$E_{\gamma} = \gamma E_{lab} (1 - \beta \cos(\theta))$$

^{11}B rest frame



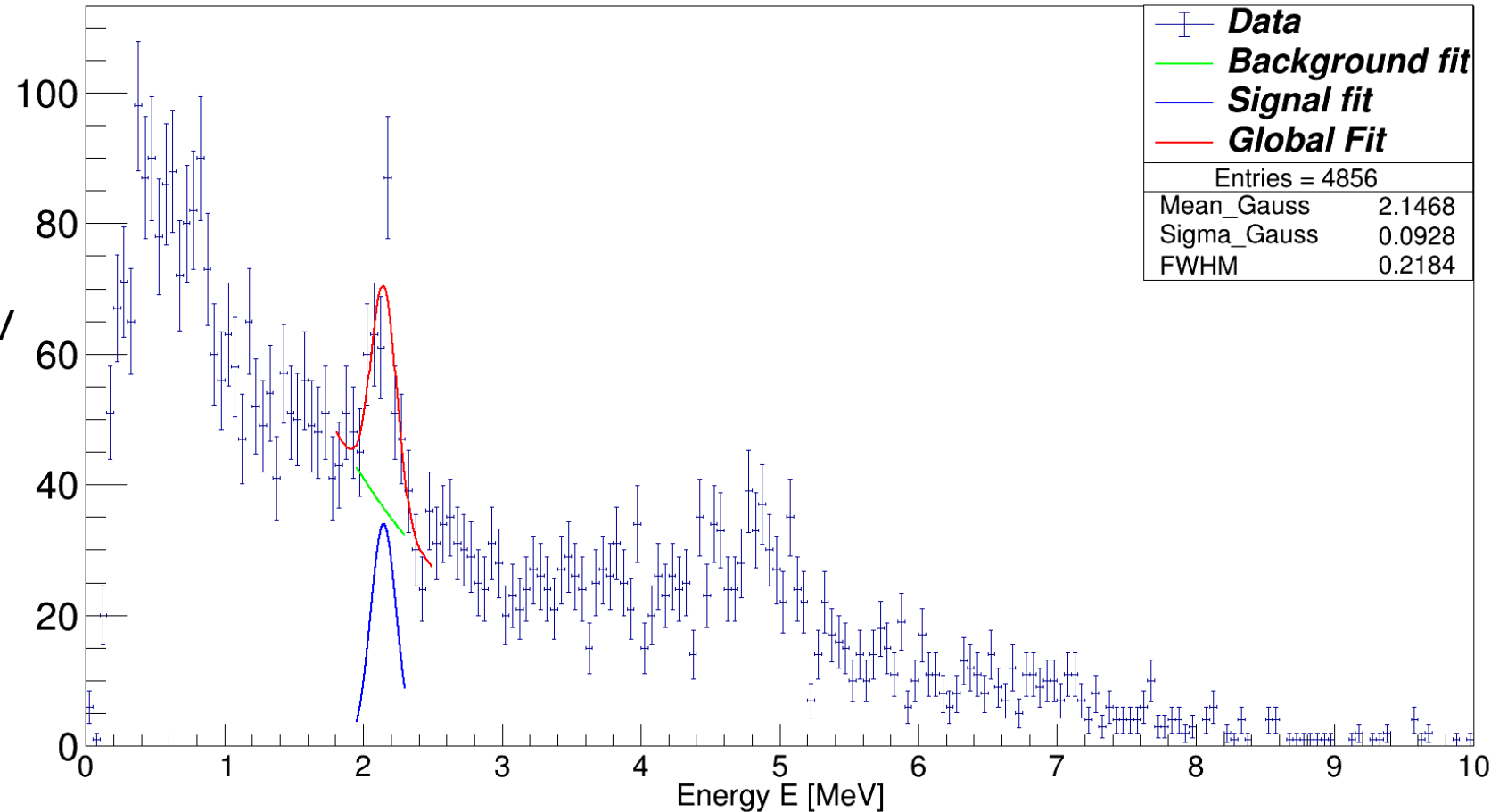


Gamma Spectrum with Angular Cuts

CALIFA Gamma Energy Spectrum

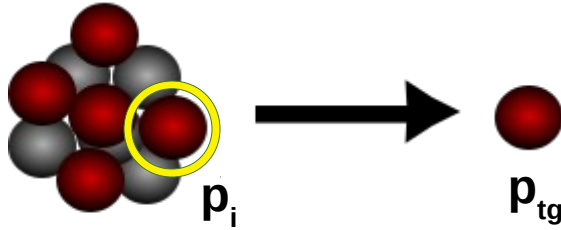
Event selection criteria for CALIFA:

- 11B fragment identification
- two hits (protons) with $E_{\text{hit}} > 30$ MeV
- $\theta_1 + \theta_2 < 90^\circ$
- $\Delta\phi = 180^\circ \pm 40^\circ$

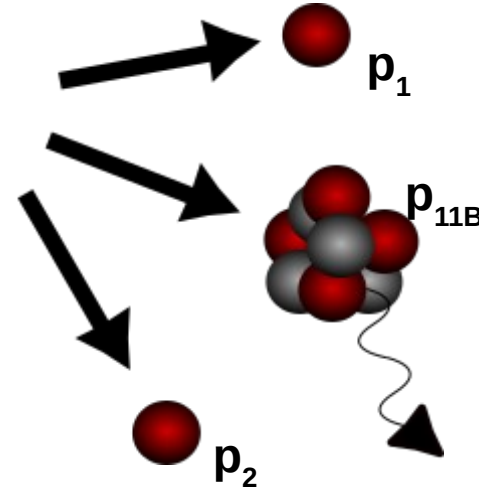


Reconstruction of Inner Momenta

Before Scattering:



After Scattering:



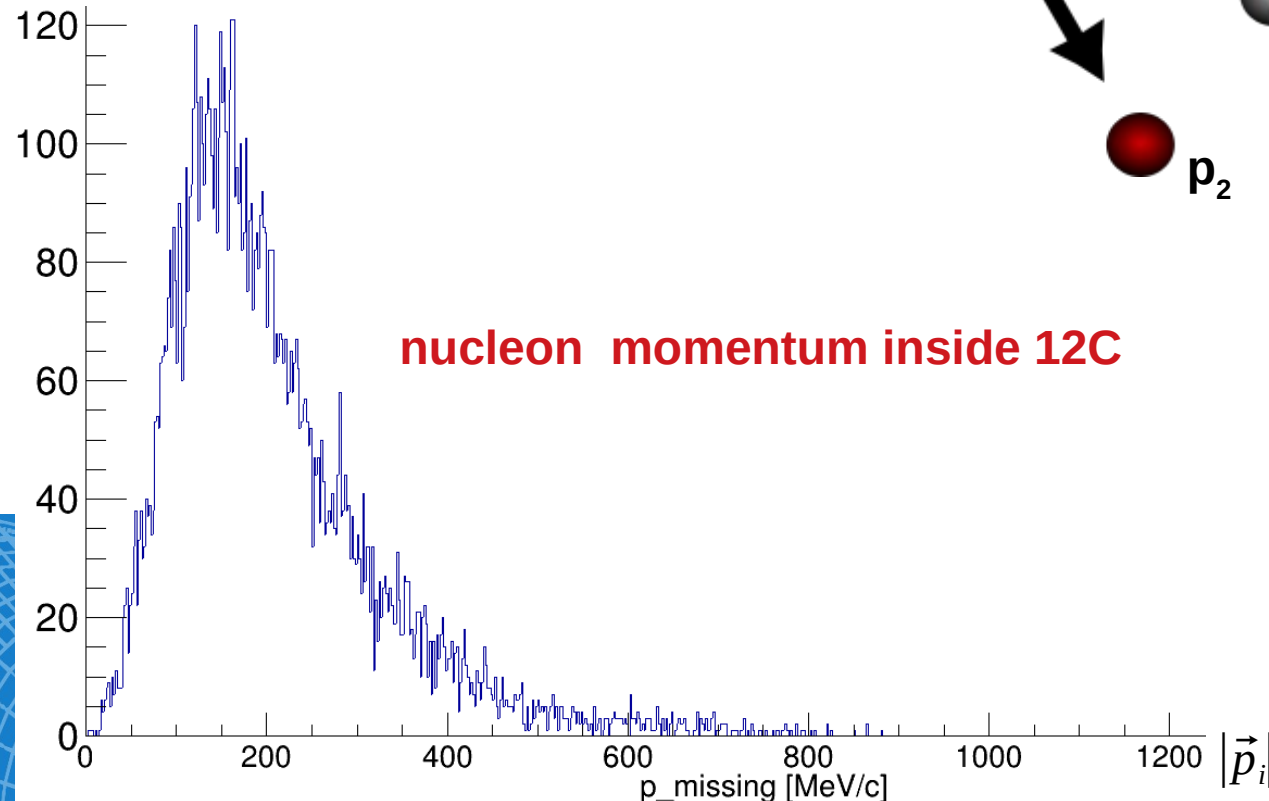
(Four-)Momentum conservation relation:

$$p_{12C} + p_{tg} = p_1 + p_2 + p_{11B}$$

assuming QE scattering in
mean field potential:

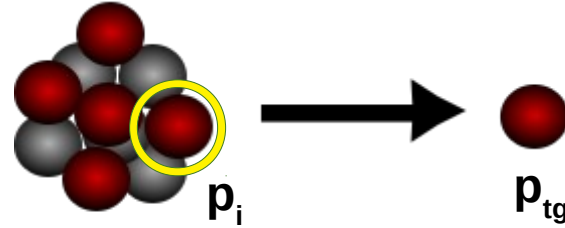
$$p_{12C} = p_i + p_{11B}$$

$$p_i \approx p_{missing} = p_1 + p_2 - p_{tg} \text{ (no ISI / FSI)}$$

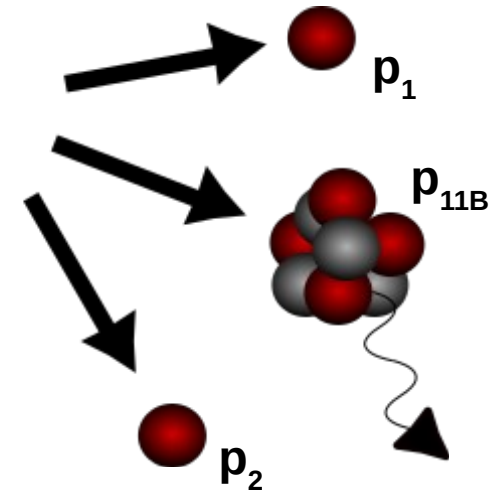


Momentum components of p_i

Before Scattering:

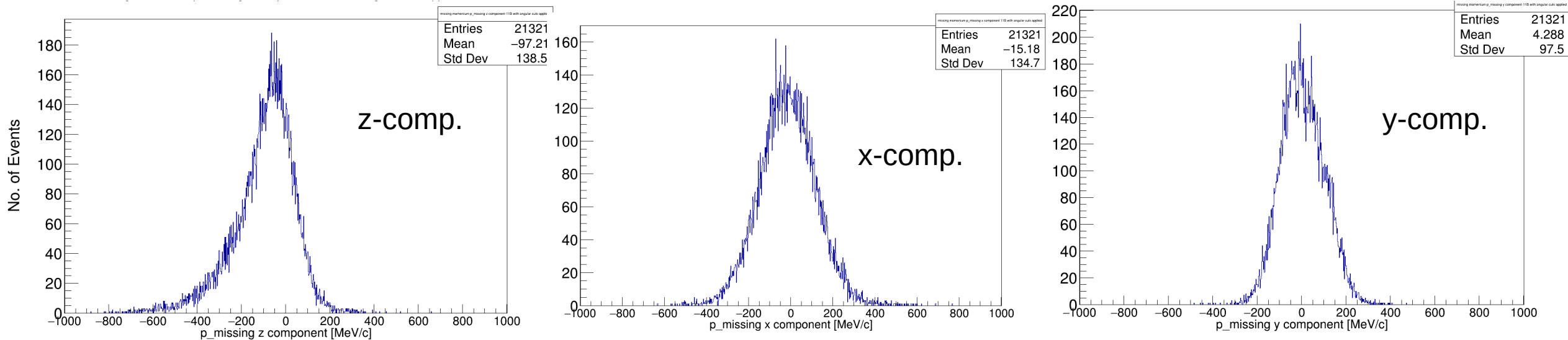


After Scattering:



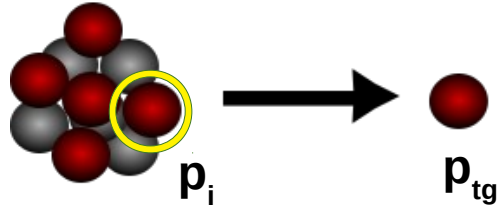
$$p_i \approx p_{missing} = p_1 + p_2 - p_{tg} \text{ (no ISI/FSI)}$$

p_i Momentum-Components (with angular cuts applied)

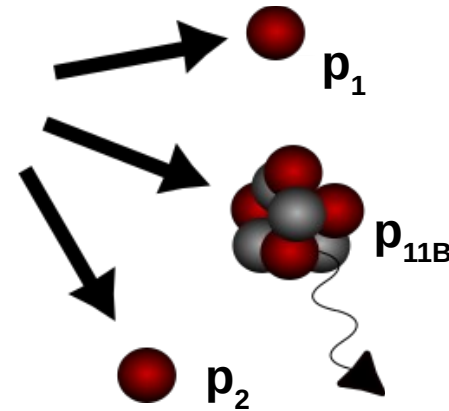


Mass reconstruction of p_i

Before Scattering:

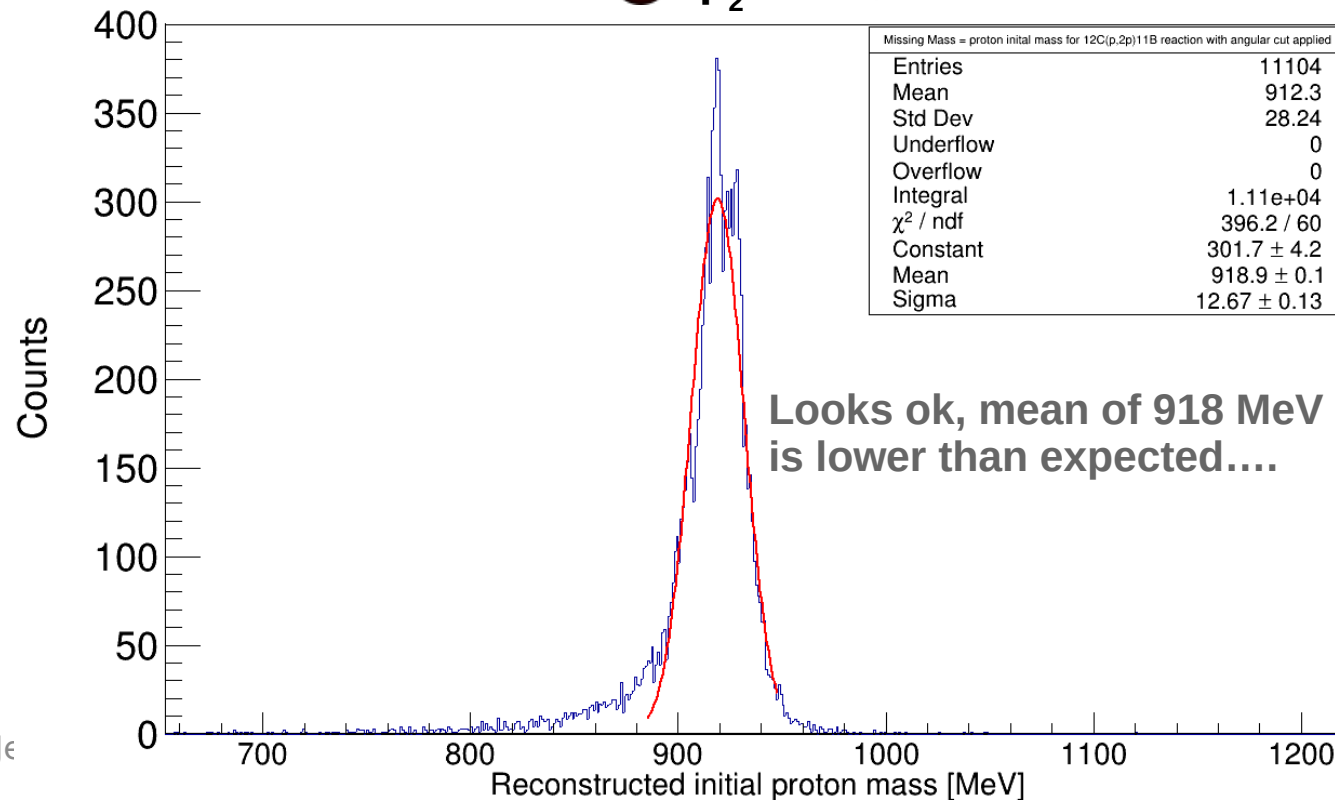


After Scattering:



$$p_i \approx p_{\text{missing}} = p_1 + p_2 - p_{\text{tg}} \text{ (no ISI/FSI)}$$

$$M_i = \sqrt{(p_1 + p_2 - p_{\text{tg}})^2}$$



Definition of Missing Energy *:

$$E_{\text{miss}} = m_p - e_{\text{miss}} = E_{\text{tgkin}} - E_{p1\text{kin}} - E_{p2\text{kin}} \quad (\text{in } 12\text{C cms})$$

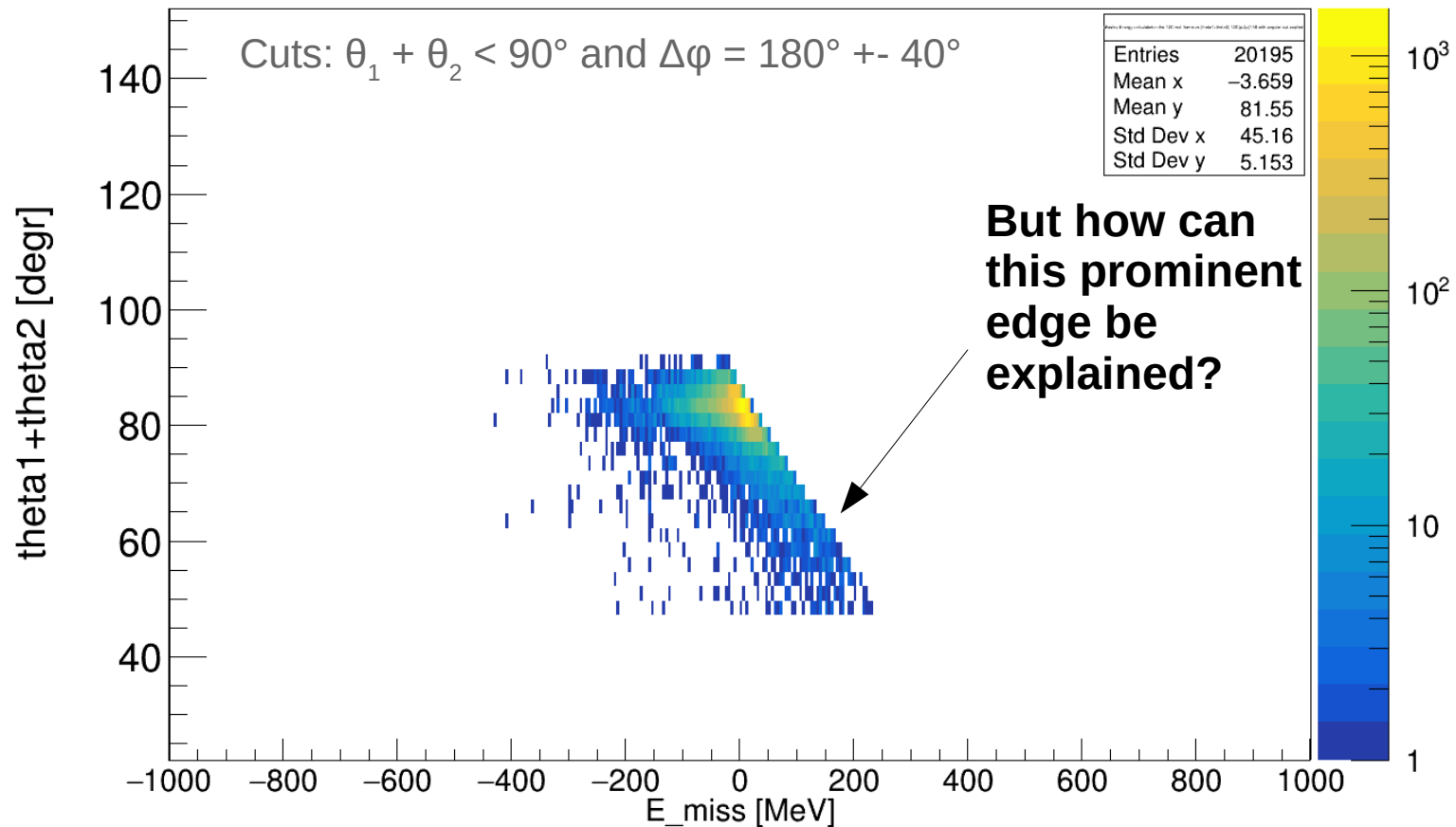
(where e_{miss} is the energy component of $\mathbf{p}_{\text{missing}}$)

$$\mathbf{p}_i \approx \mathbf{p}_{\text{missing}} = \mathbf{p}_1 + \mathbf{p}_2 - \mathbf{p}_{\text{tg}} \quad (\text{no ISI / FSI})$$

$$E_{\text{miss}} = - (E_{\text{final}} - E_{\text{initial}})$$



$$E_{\text{miss}} = E_{\text{Sep}} + \bar{E}_{\text{Exc}}$$





Analysis Missing Energy Distribution

Explicit calculation of the Missing Energy (in the ^{12}C frame):

$$E_{\text{miss}} = E_{\text{tgkin}} - E_{\text{p1kin}} - E_{\text{p2kin}}$$

$$E_{\text{miss}} = 400 - \underbrace{\left(\gamma * (E_{\text{kin1}} + 938) - \gamma * \beta * \sqrt{(E_{\text{kin1}} + 938)^2 - 938^2} * \cos(\theta_1) - 938 \right)}_{E'_{\text{p1}}} - \underbrace{\left(\gamma * (E_{\text{kin2}} + 938) - \gamma * \beta * \sqrt{(E_{\text{kin2}} + 938)^2 - 938^2} * \cos(\theta_2) - 938 \right)}_{E'_{\text{p2}}}$$

$E_{\text{tgkin}} \quad E_{\text{kin1}} \quad E_{\text{kin2}} \quad E_{\text{pot}_{\text{p1}}} \quad E_{\text{pot}_{\text{p2}}}$

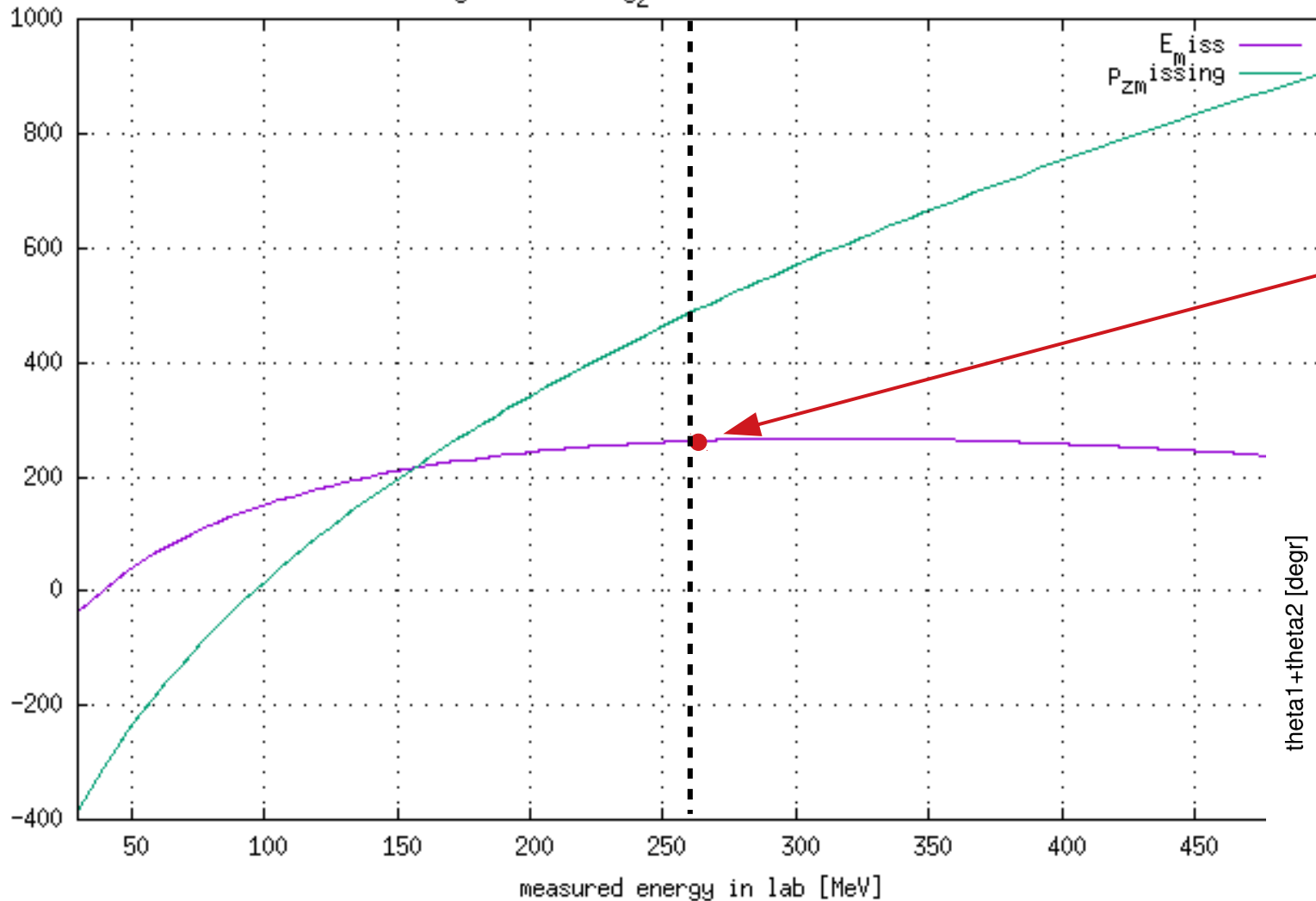




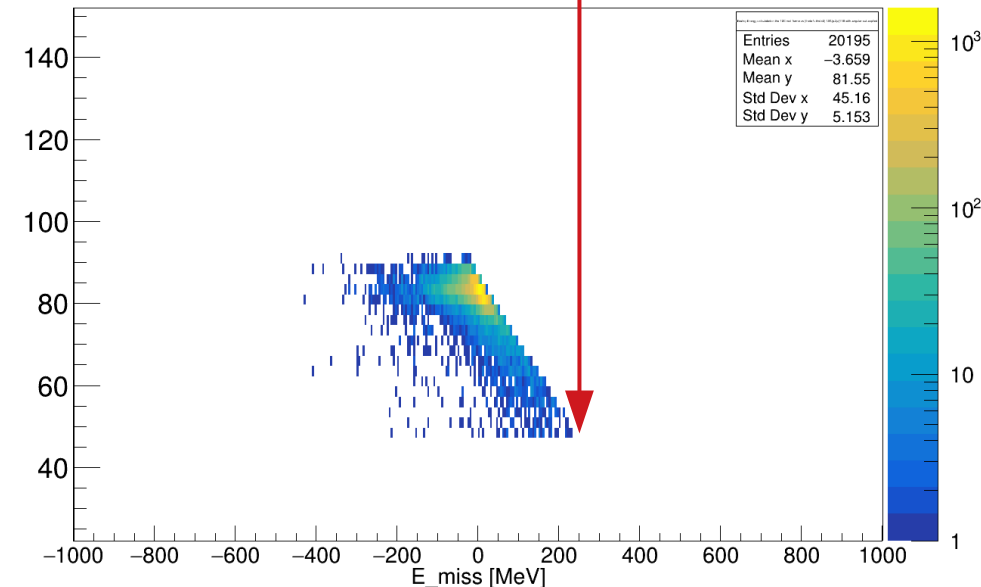
E_missing and p_z_missing for different opening angles

For simplicity let's say $\theta_1 = \theta_2$ and $E_{\text{kin1}} = E_{\text{kin2}}$. That means for $\theta_{\text{sum}} = 44^\circ \rightarrow \theta_1 = \theta_2 = 22^\circ$

E_{missing} and $p_{\text{missing}z}$ versus measured energy in lab

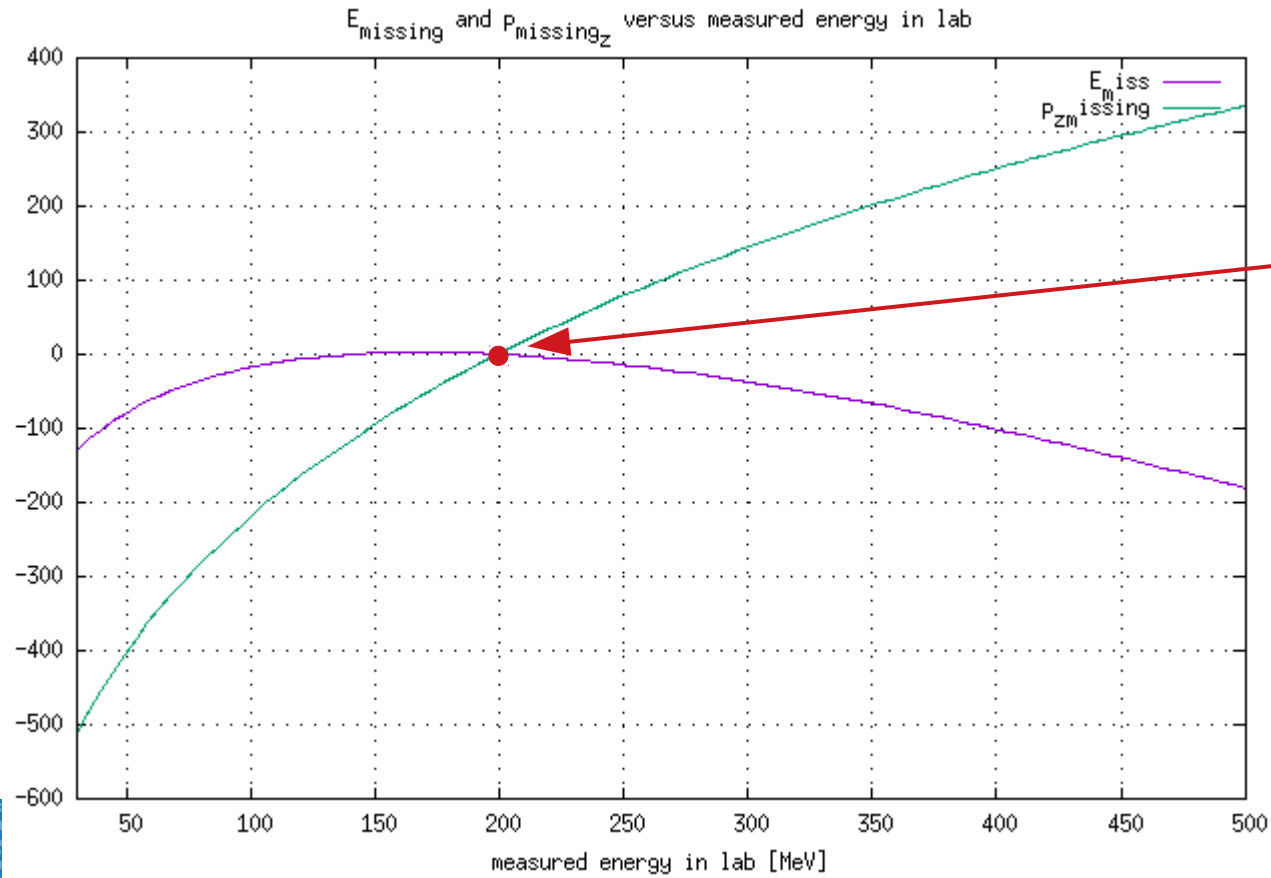


theta1+theta2 [degr]

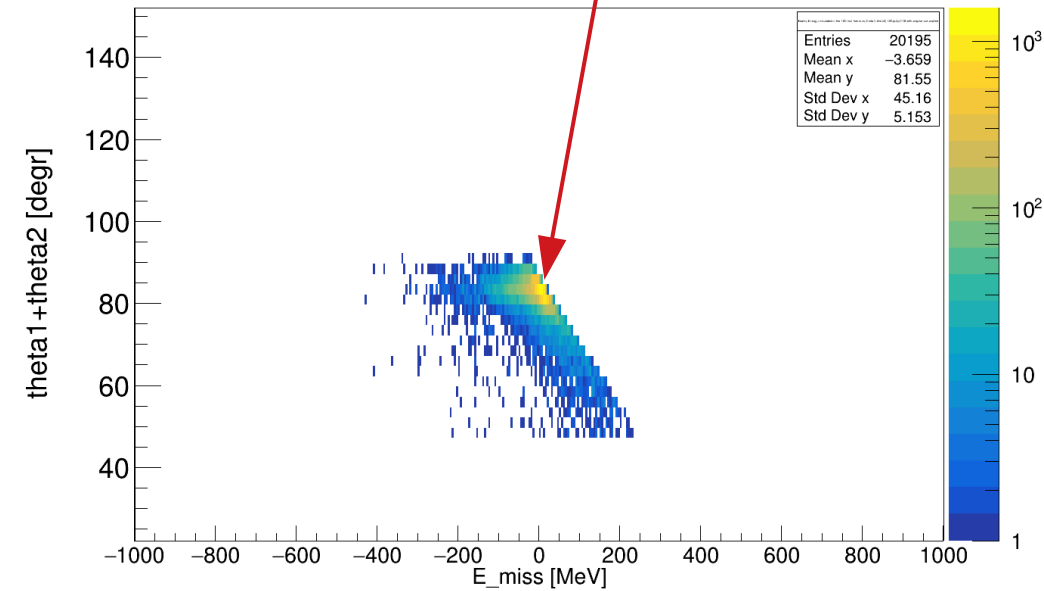




E_missing and p_z_missing for $\theta_1 = \theta_2 = 42^\circ$

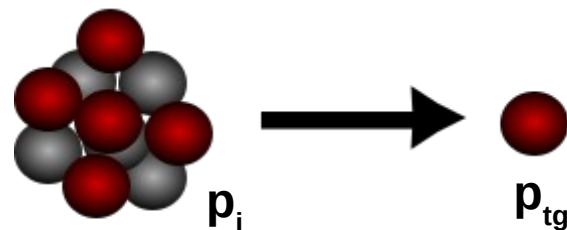


Quasi-Free Scattering reaction
 $\approx 84^\circ$

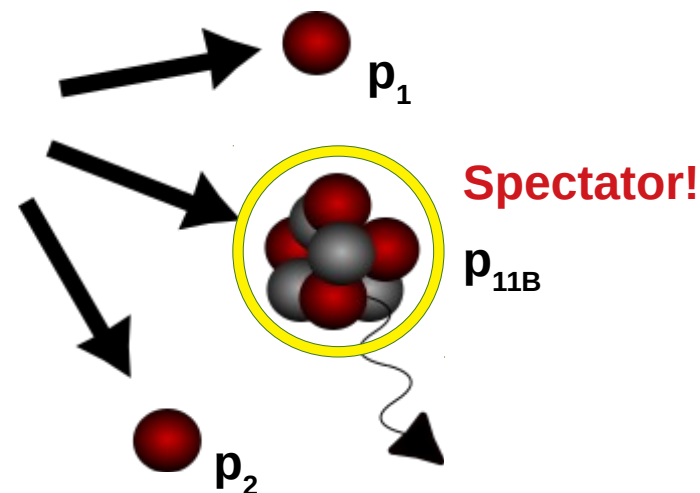


Momentum components of p_{11B}

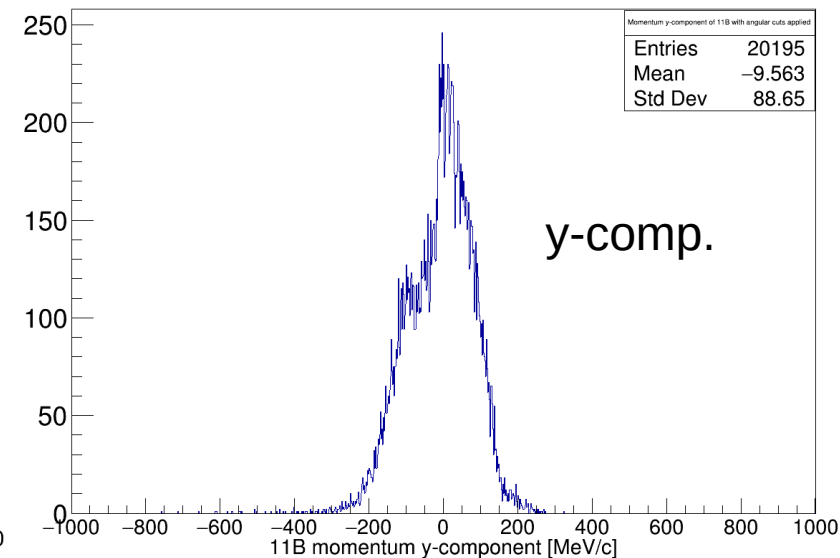
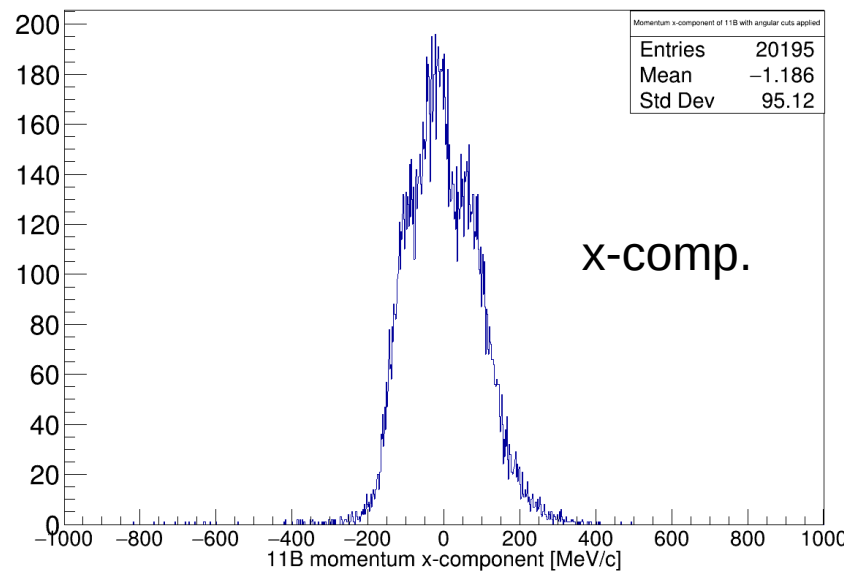
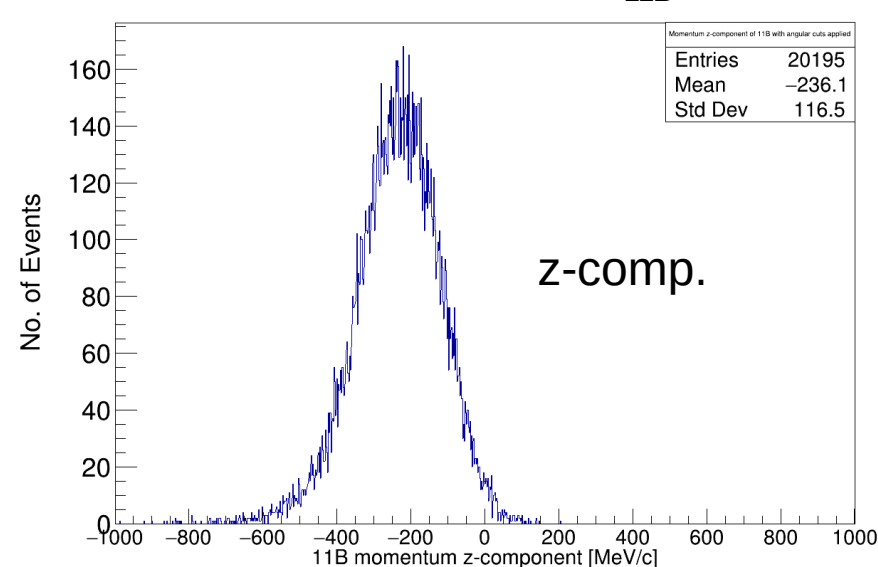
Before Scattering:



After Scattering:

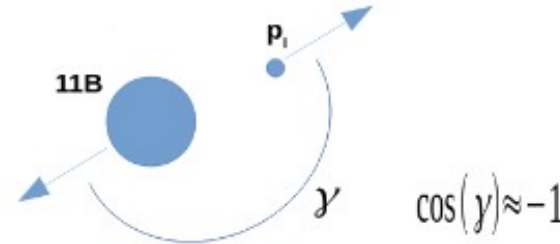


p_{11B} Momentum-Components (with angular cuts applied)

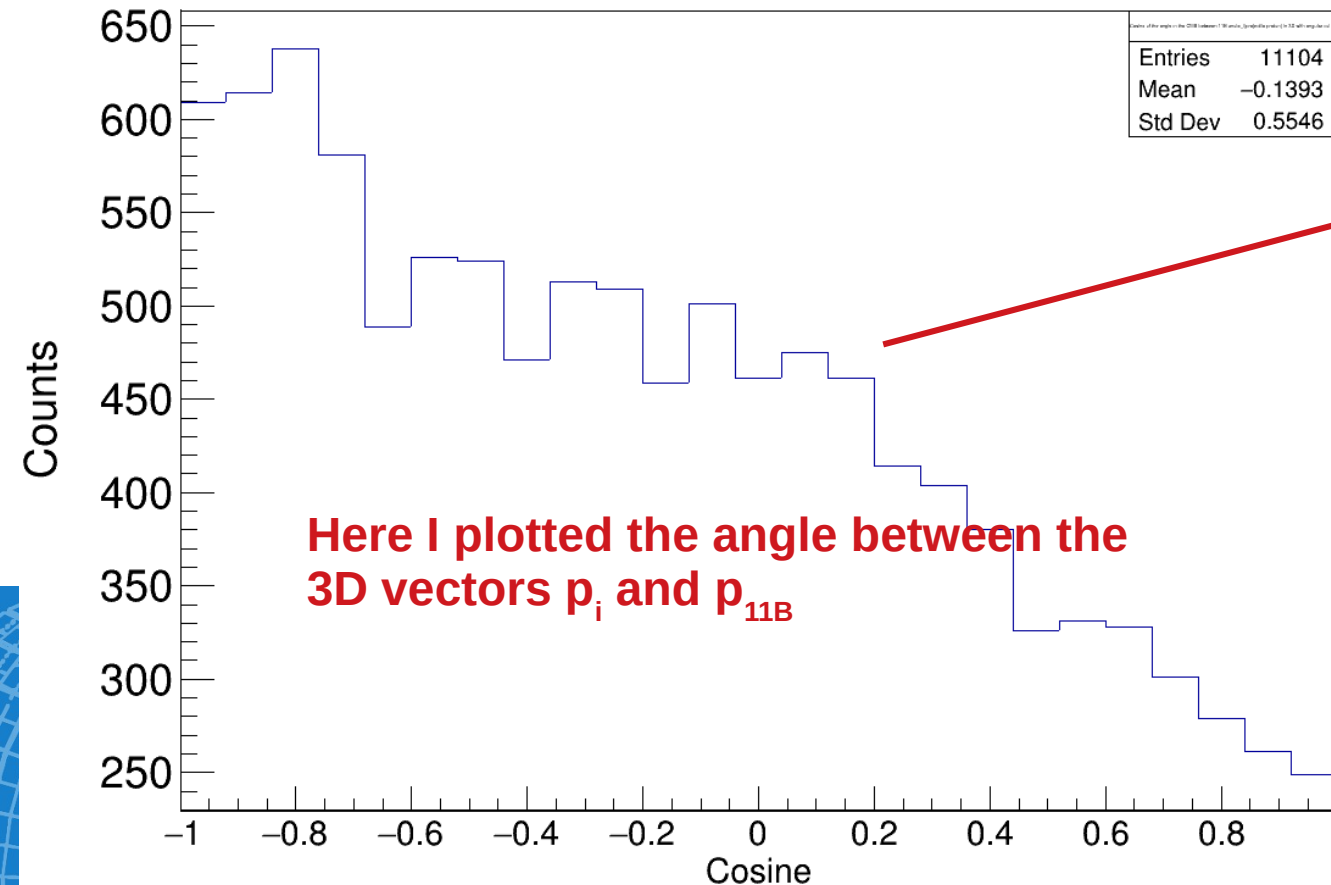


- \mathbf{p}_i determined by angle and energy deposition of p1 and p2
- \mathbf{p}_{11B} determined by ToF and tracking detectors (MWPCs)

(p11B_y was calculated by y-position in MW1 and MW2)



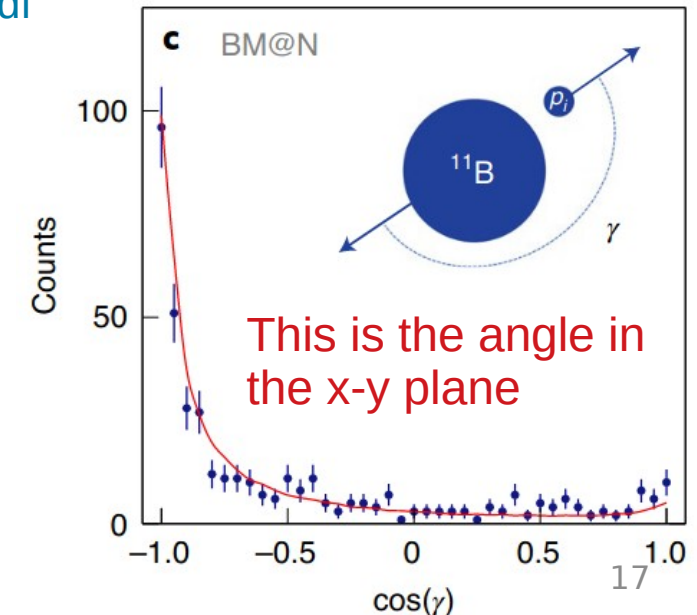
$$\mathbf{p}_{12C} = \mathbf{p}_i + \mathbf{p}_{11B}$$



Not satisfactory....

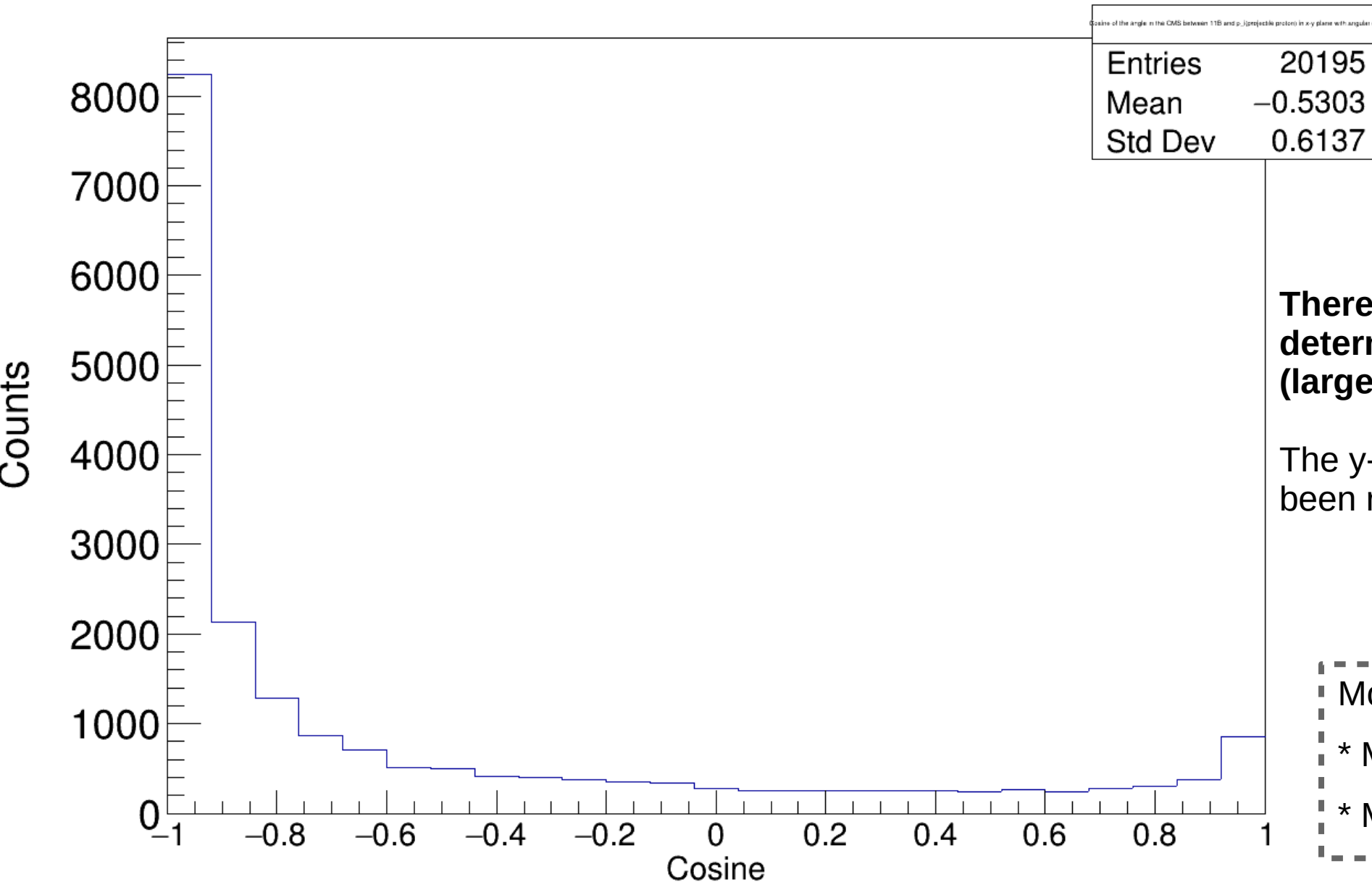
See:

<https://www.nature.com/articles/s41567-021-01193-4.pdf>





Angular Distribution in x-y plane



Therefore the y position was determined using MWPC3 (larger lever arm)

The y-position of MWPC3 has been reversed (+y → -y and -y → +y)

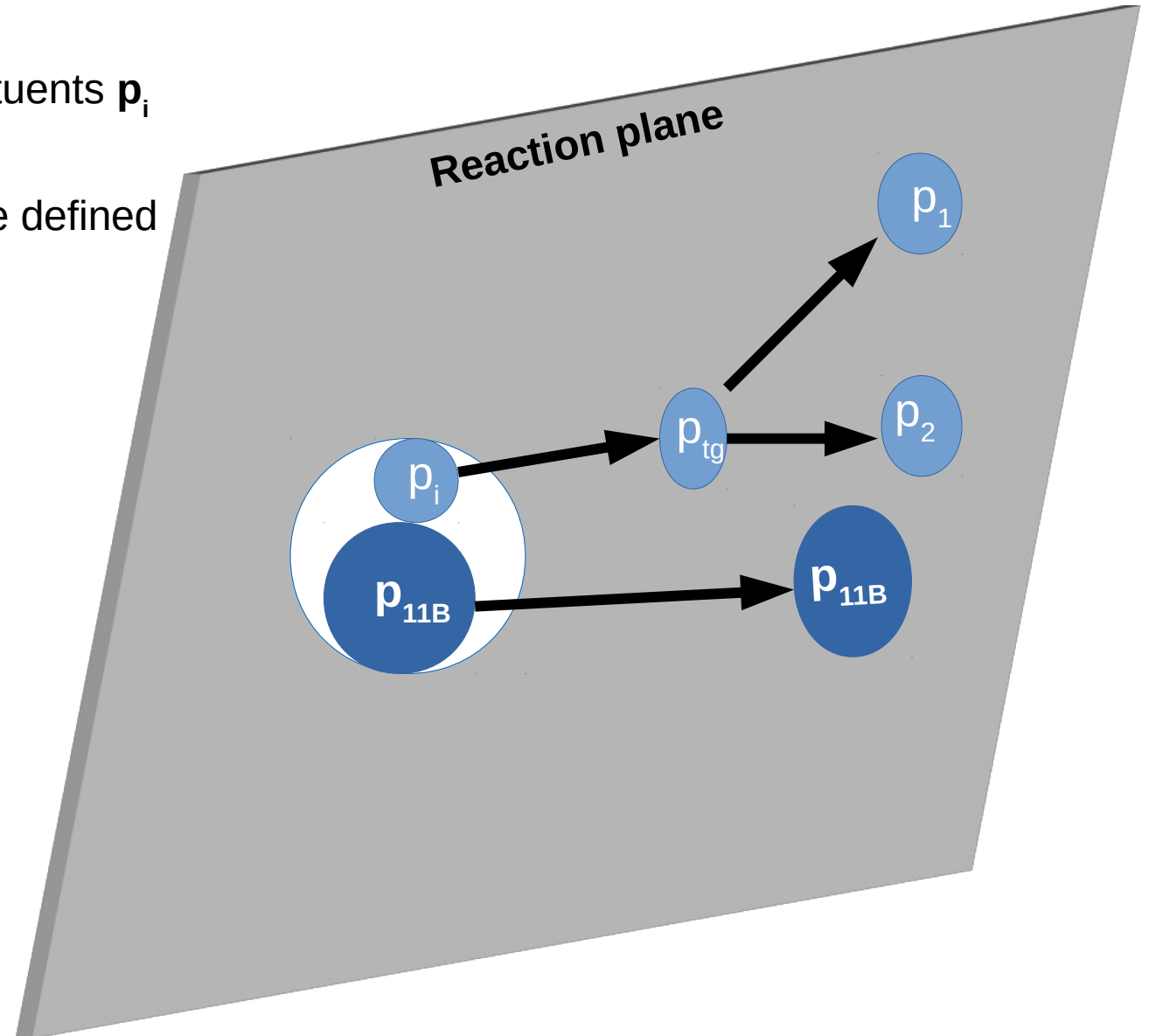
Moreover:

* MW0X inverted

* MW1Y and MW2Y swapped

Assuming no inner momenta of the ^{12}C constituents \mathbf{p}_i and $\mathbf{p}_{^{11}\text{B}}$:

→ scattering would take place in reaction plane defined by $\vec{\mathbf{p}}_{^{12}\text{C}}$ and $\vec{\mathbf{p}}'_{\text{tg}}$

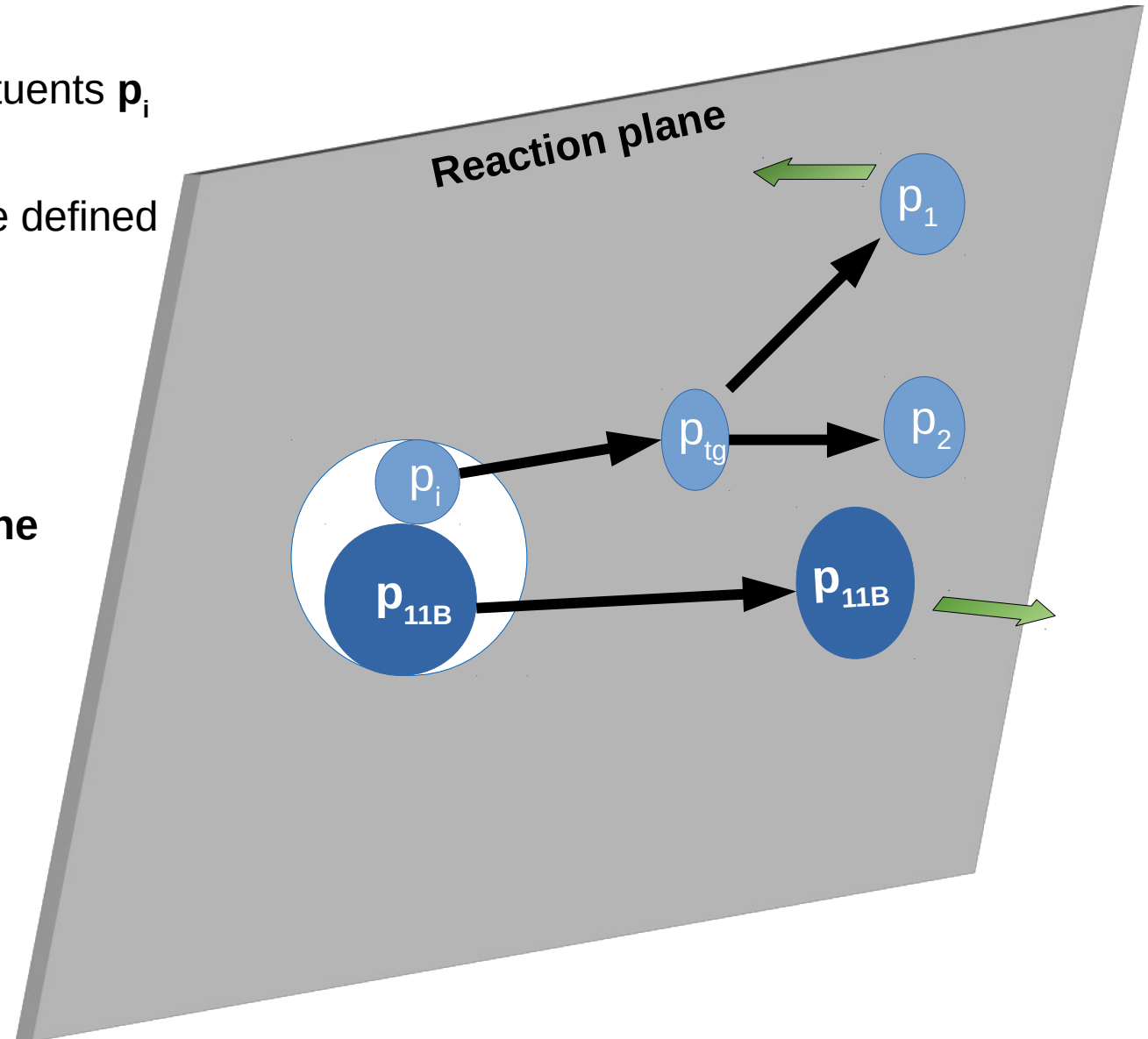


Assuming no inner momenta of the ^{12}C constituents \mathbf{p}_i and $\mathbf{p}_{11\text{B}}$:

→ scattering would take place in reaction plane defined by $\vec{\mathbf{p}}_{12\text{C}}$ and $\vec{\mathbf{p}}_{1/2}$

BUT: $|\vec{p}_i| \approx |p_{11\text{B}}| \neq 0$

→ there are components perpendicular to the reaction plane!

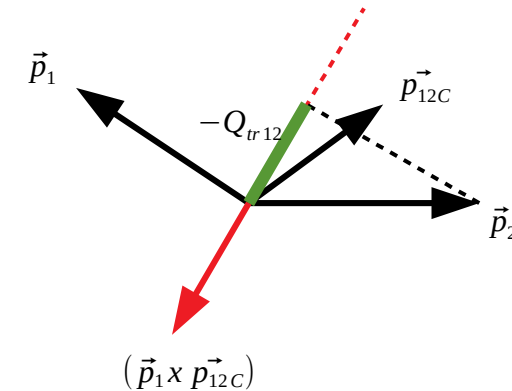
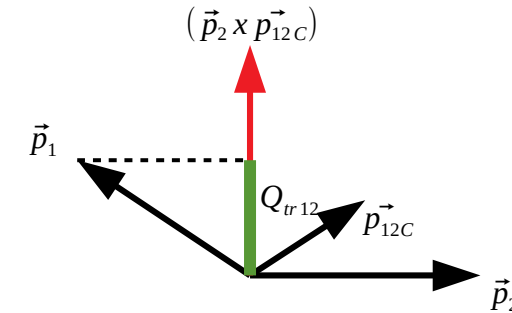


As measure of the overall perpendicular fraction to the reaction plane*:

$$Q_{tr12} = |\vec{p}_1| \frac{\vec{p}_1 * (\vec{p}_2 \times \vec{p}_{12C})}{|\vec{p}_1| |\vec{p}_2 \times \vec{p}_{12C}|}$$

or

$$Q_{tr21} = |\vec{p}_2| \frac{\vec{p}_2 * (\vec{p}_1 \times \vec{p}_{12C})}{|\vec{p}_2| |\vec{p}_1 \times \vec{p}_{12C}|} = -Q_{tr12}$$

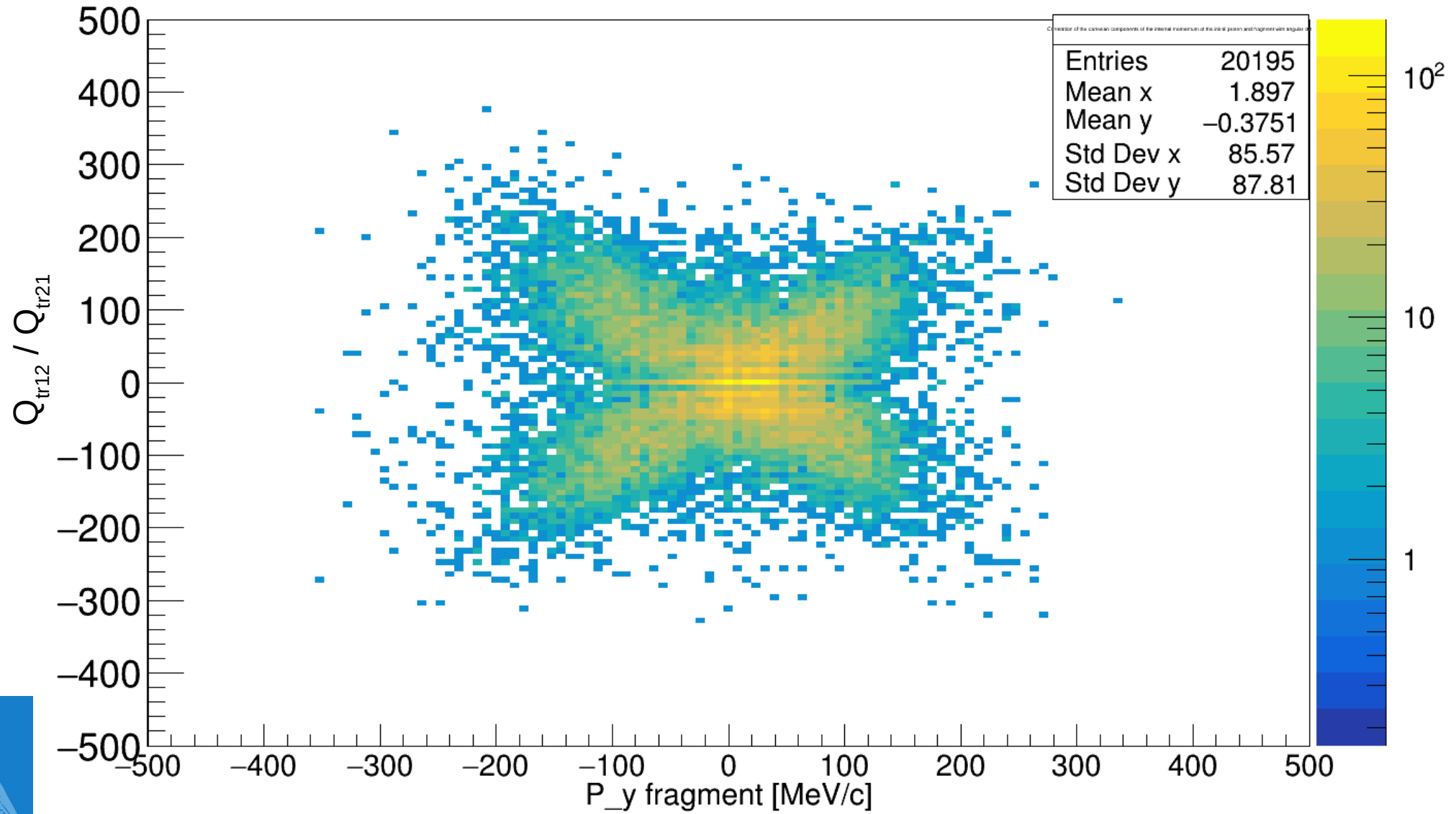


Due to momentum conservation:

$$Q_{tr12} = -Q_{trFragment}$$

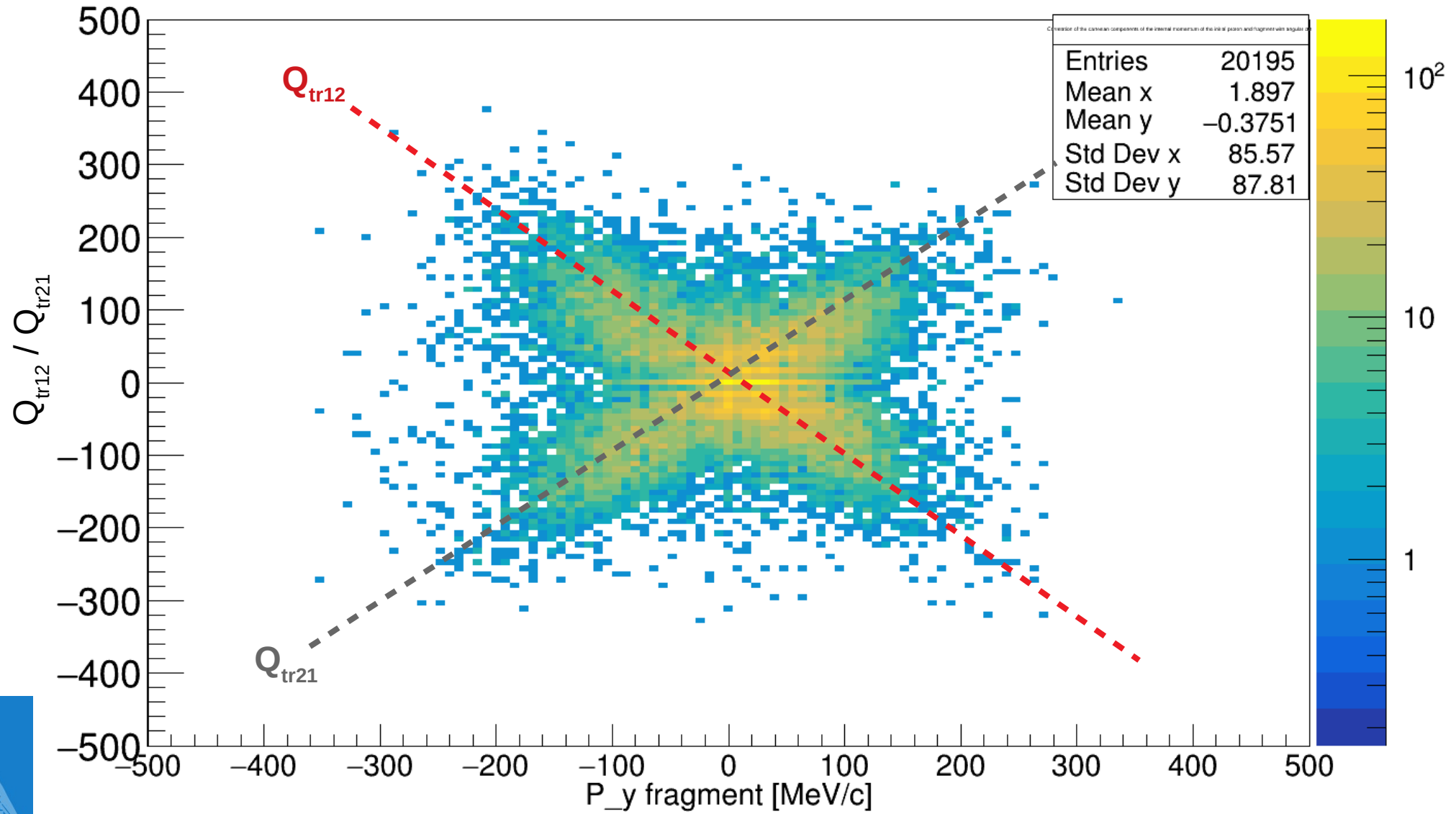


Q_{tr12} vs. $|\vec{p}_{y11B}|$



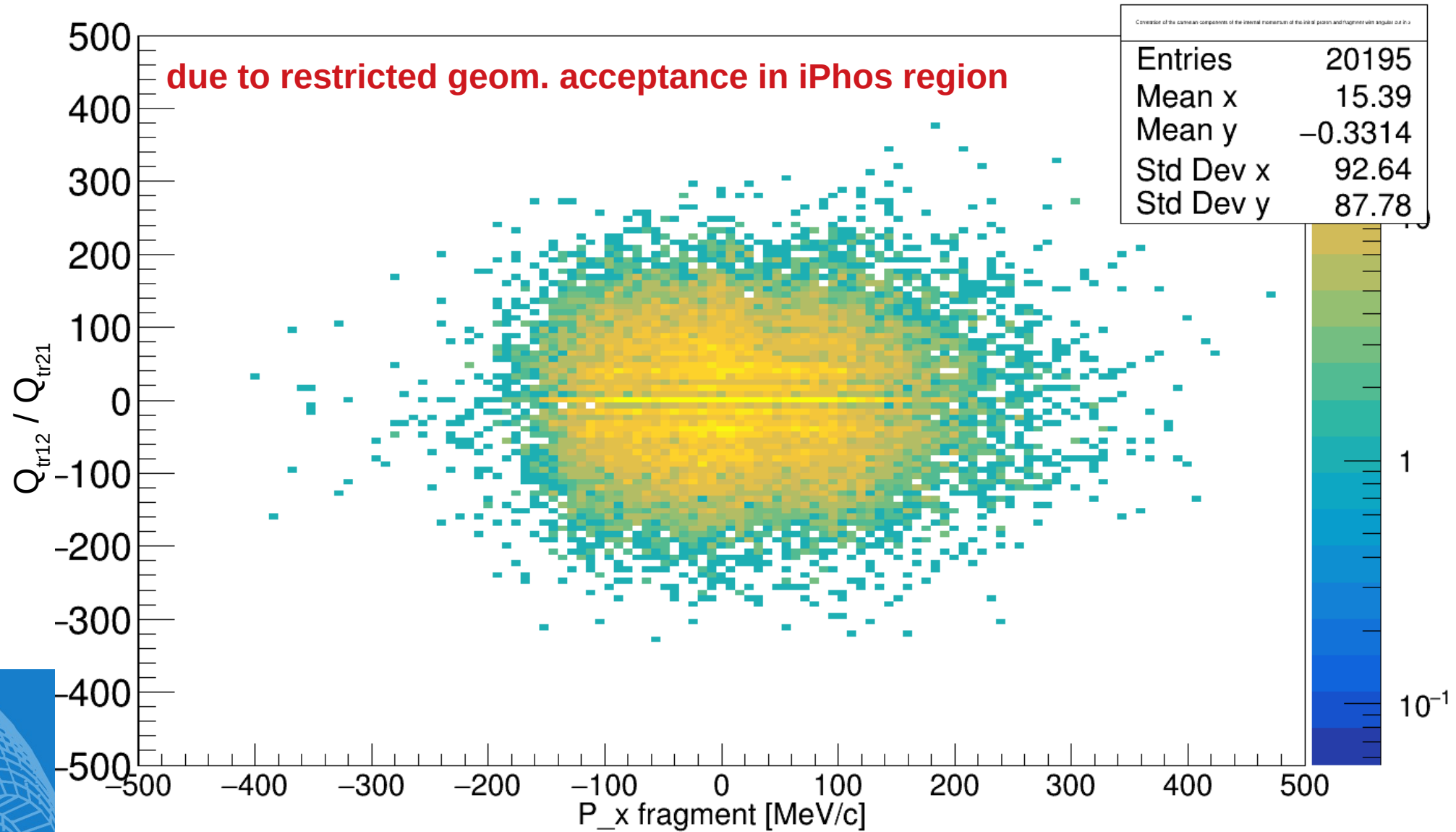


Q_{tr12} vs. $|\vec{p}_{\vec{y}}_{11B}|$



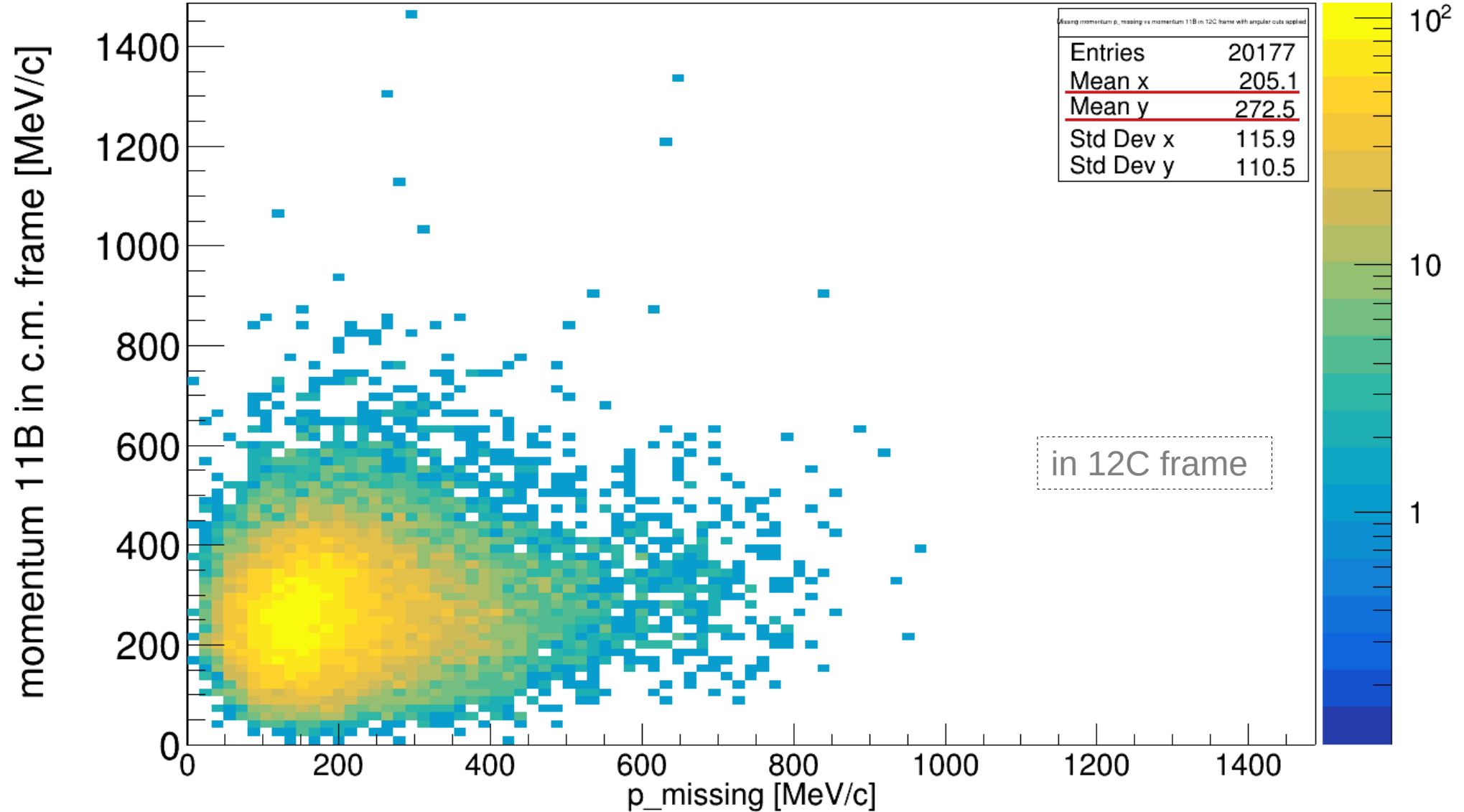


$Q_{\text{tr}12}$ vs. $|\vec{p}_{\text{x}11\text{B}}|$

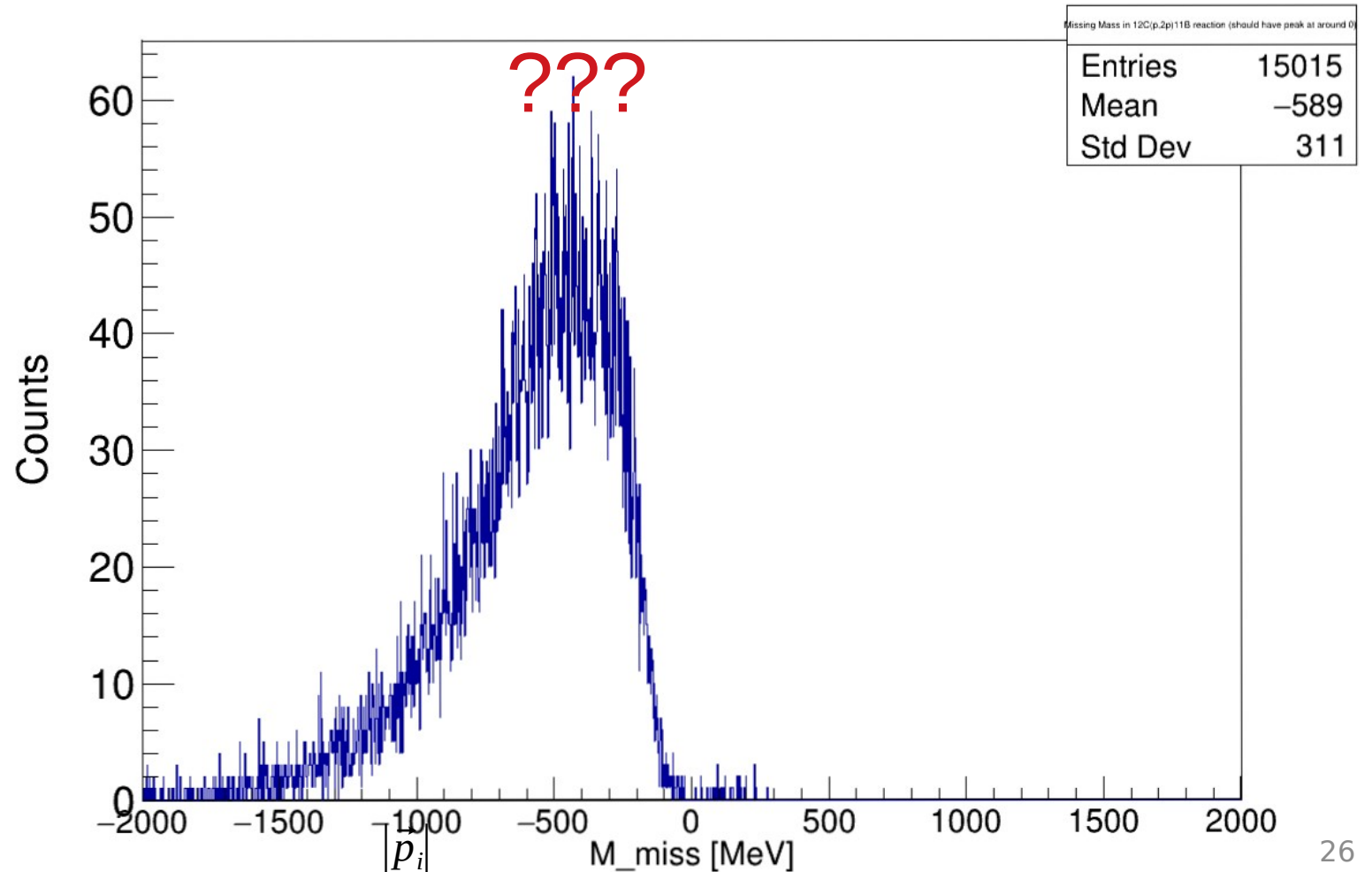
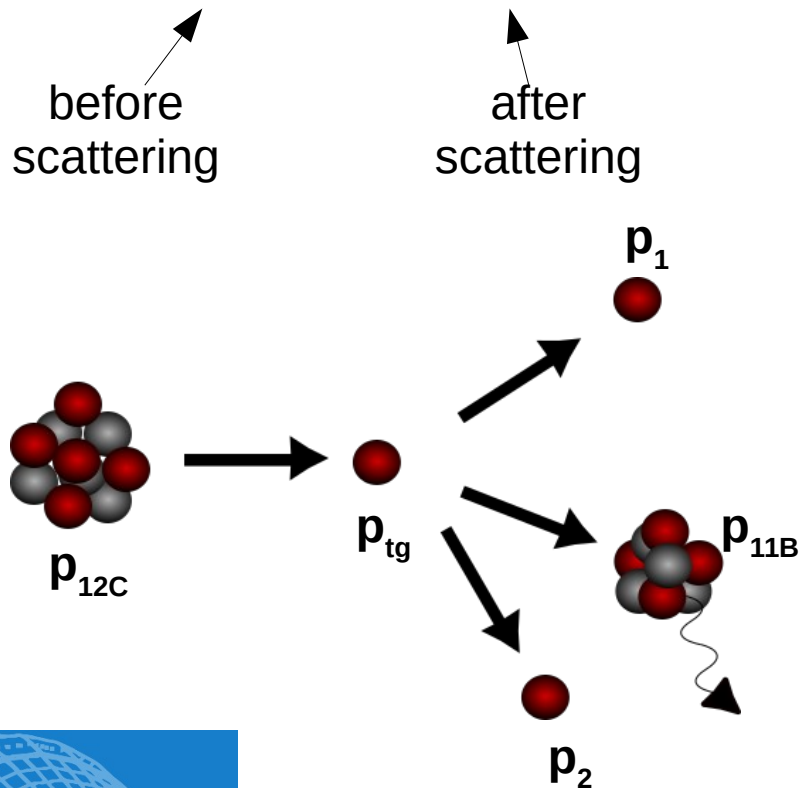




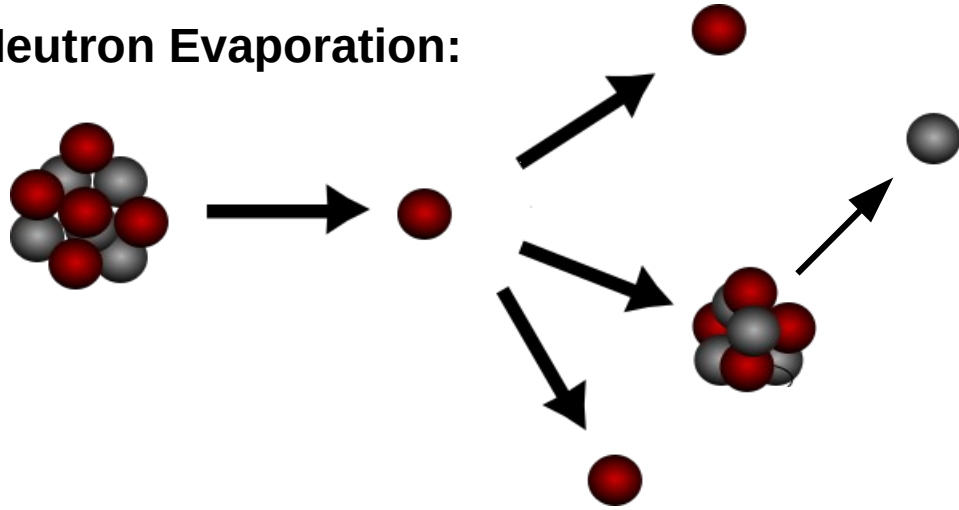
Momentum p_i vs p_{11B} in 12C



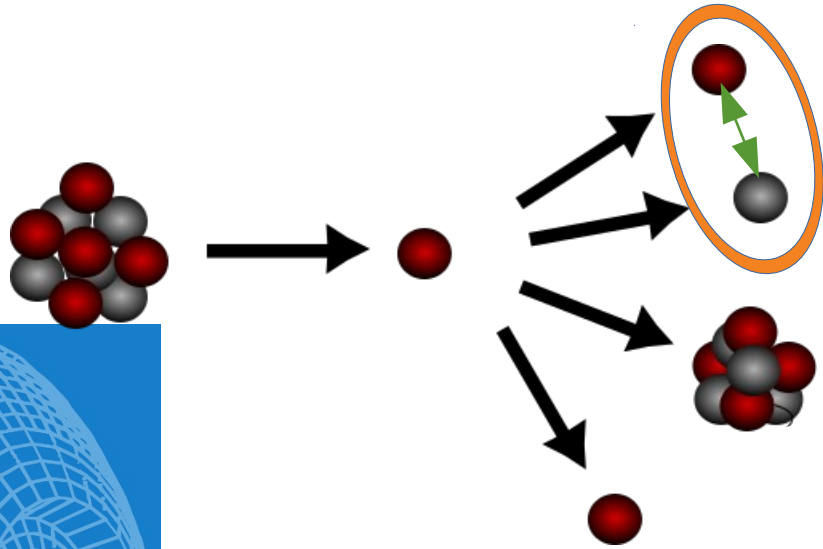
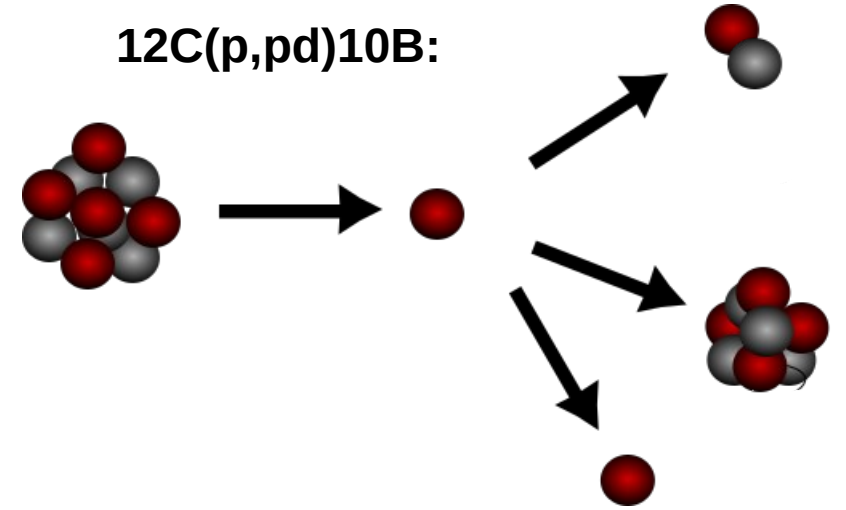
$$M_{\text{miss}} = \sqrt{(\underbrace{p_{12C} + p_{tg}}_{\text{before scattering}} - \underbrace{p_1 + p_2 + p_{11B}}_{\text{after scattering}})^2} \quad (\text{should be } \approx 0)$$



Neutron Evaporation:



12C(p,pd)10B:

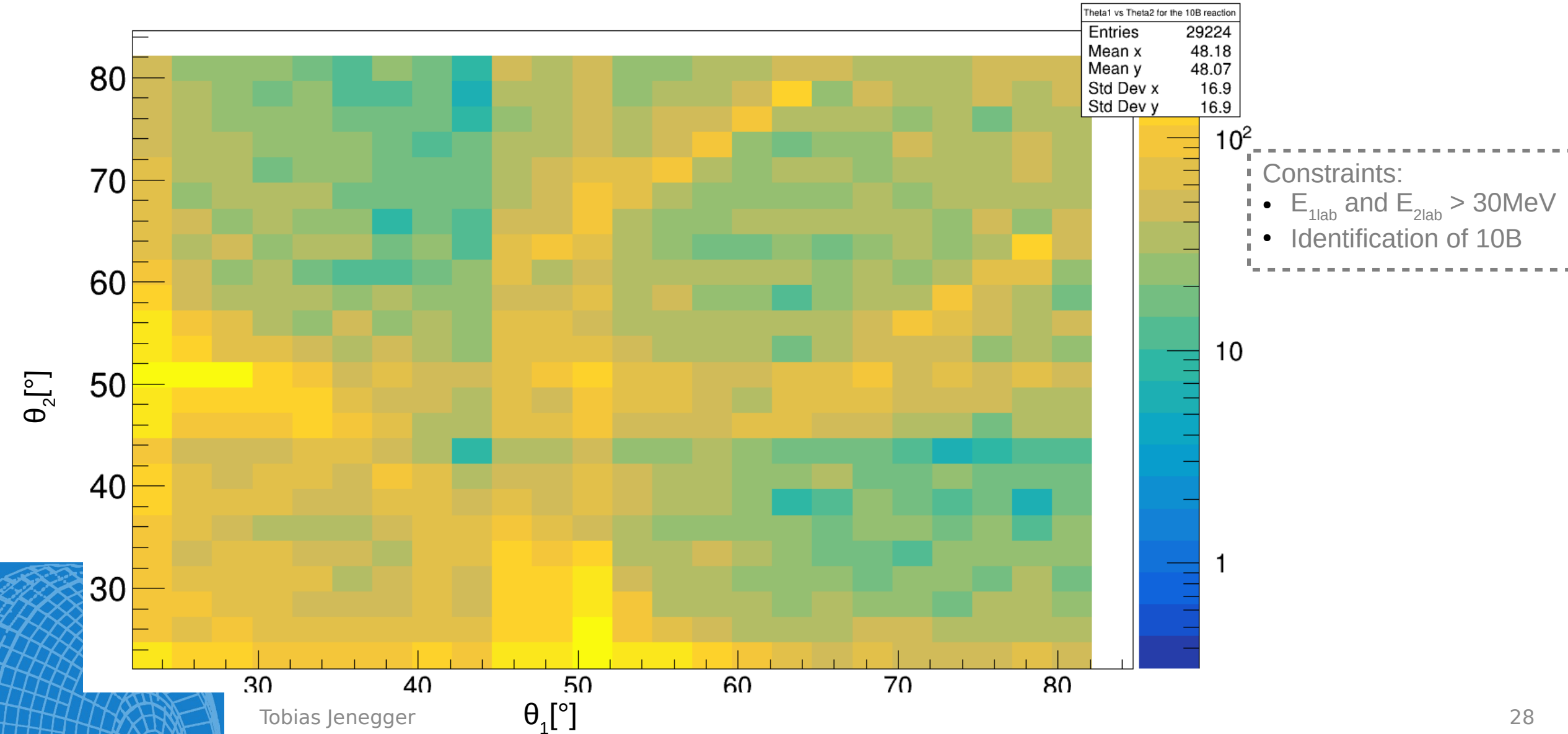


Short-Range-Correlated (SRC) Pair:

- possible explanation for the EMC – effect
- nucleon pairs with high relative and low c.m. momentum (compared to Fermi momentum k_F)

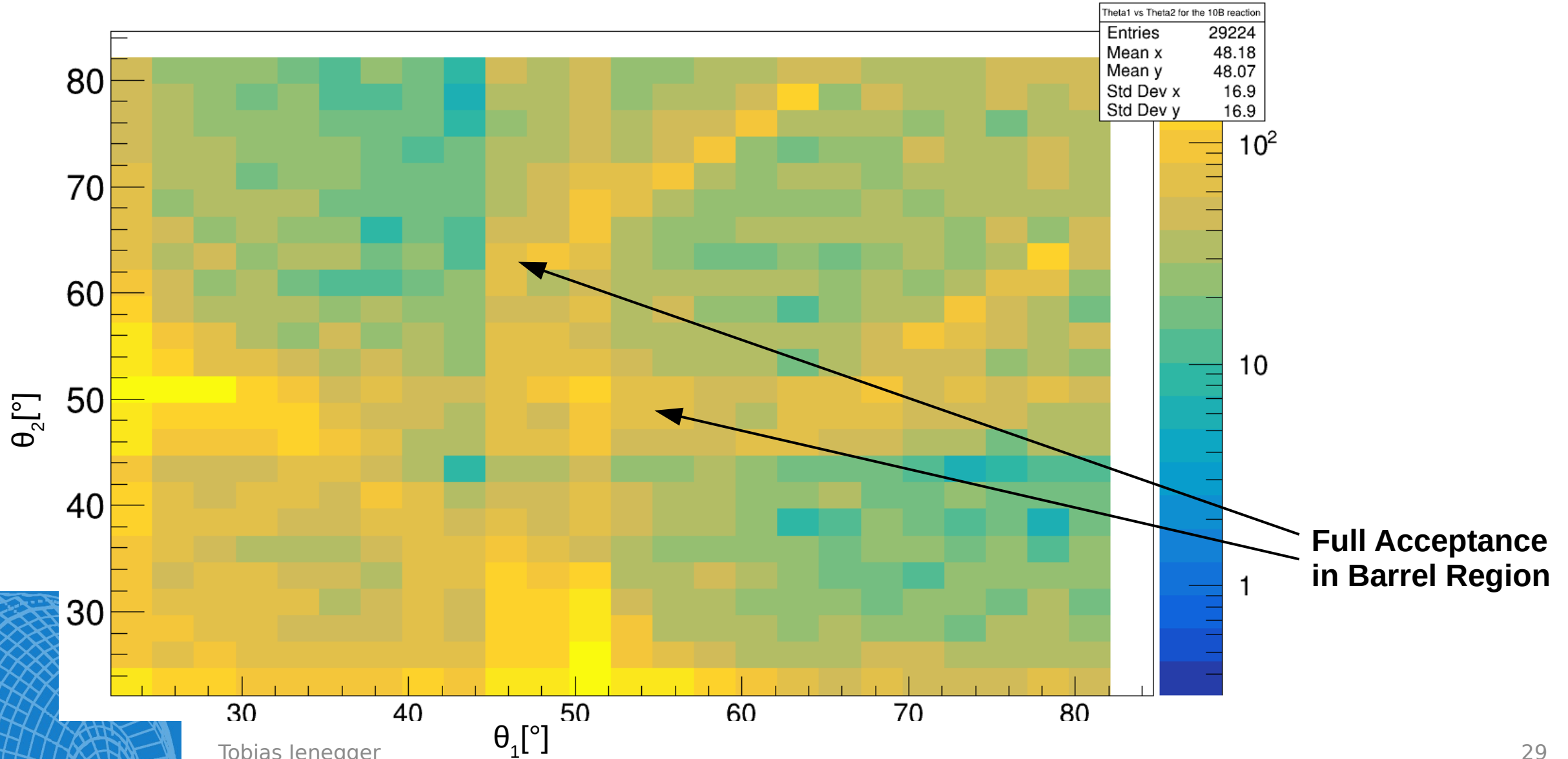
First (Polar) Angular Plots ...

θ_1 (proton 1) vs. θ_2 (proton2) without any angular restrictions:



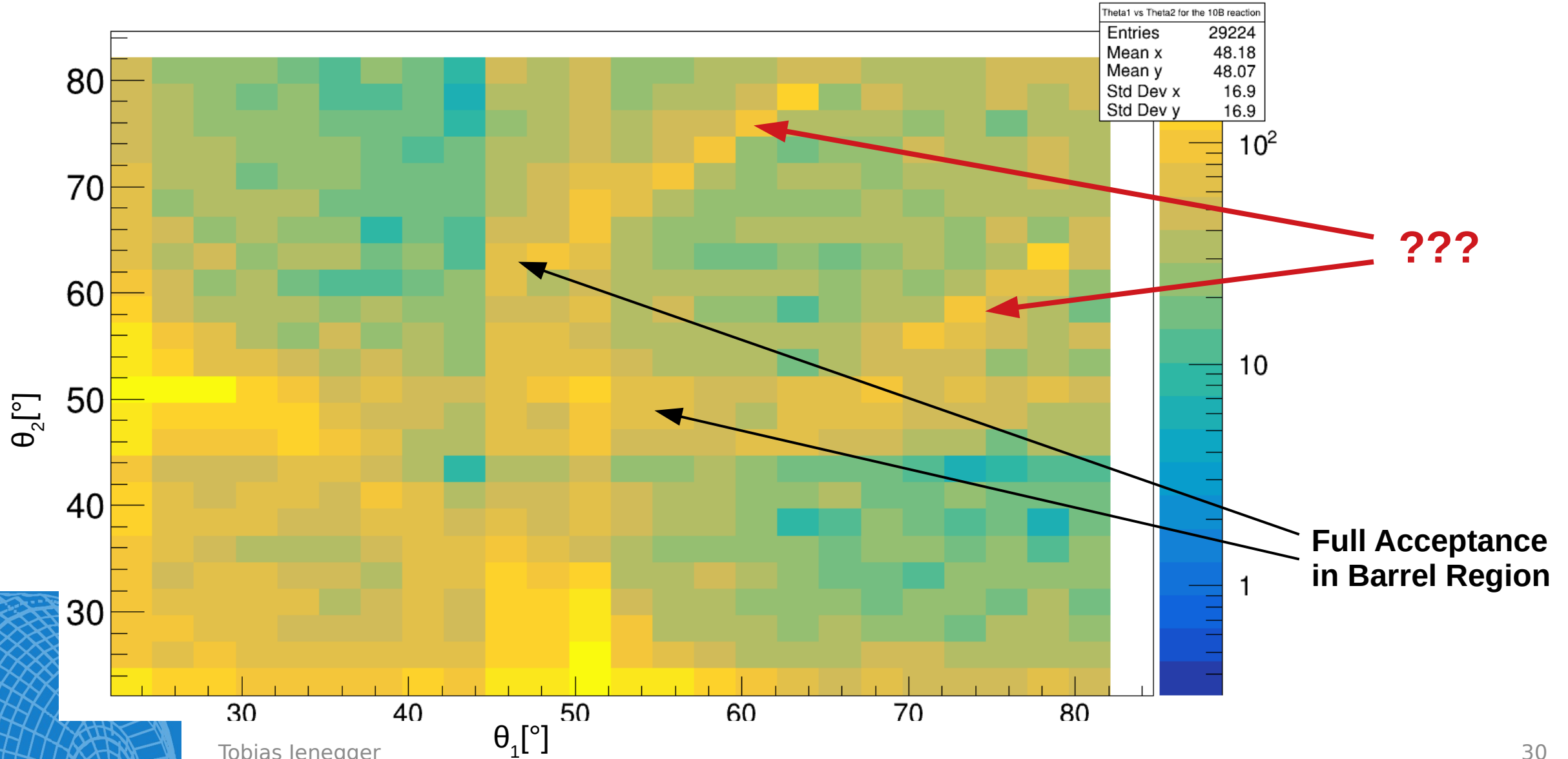
First (Polar) Angular Plots ...

θ_1 (proton 1) vs θ_2 (proton2) without any angular restrictions:



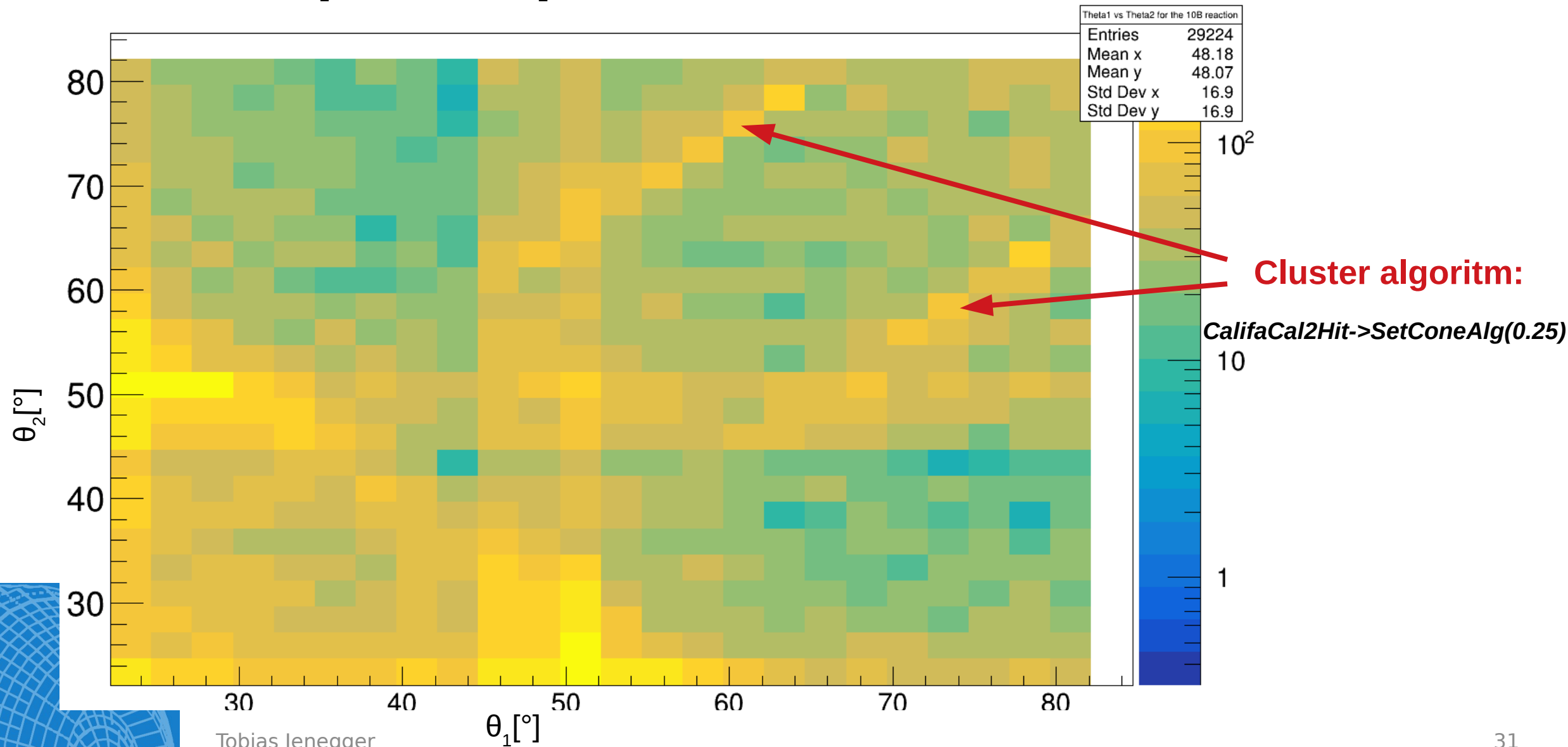
First (Polar) Angular Plots ...

θ_1 (proton 1) vs θ_2 (proton2) without any angular restrictions:



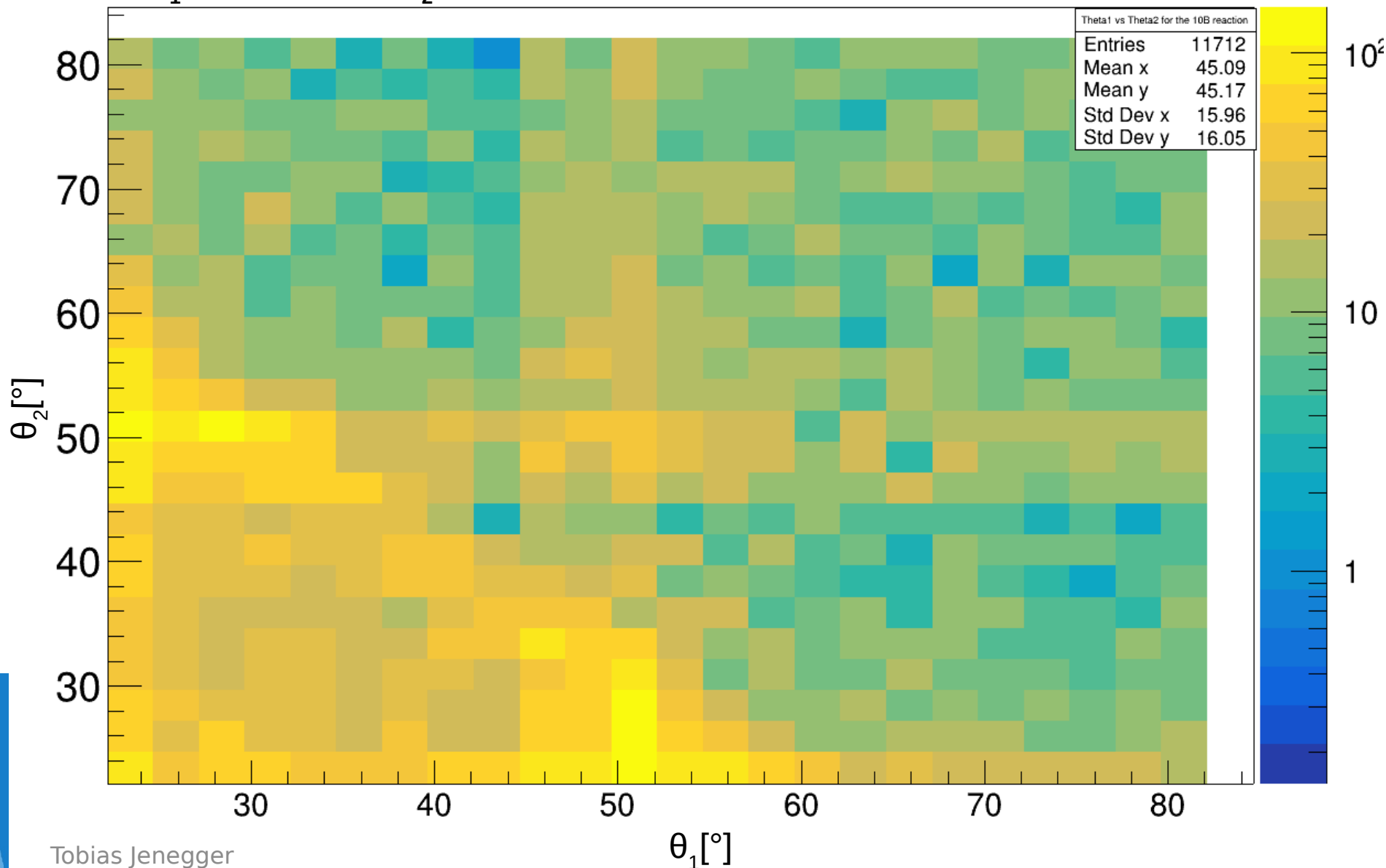
First (Polar) Angular Plots ...

θ_1 (proton 1) vs θ_2 (proton2) without any angular restrictions:



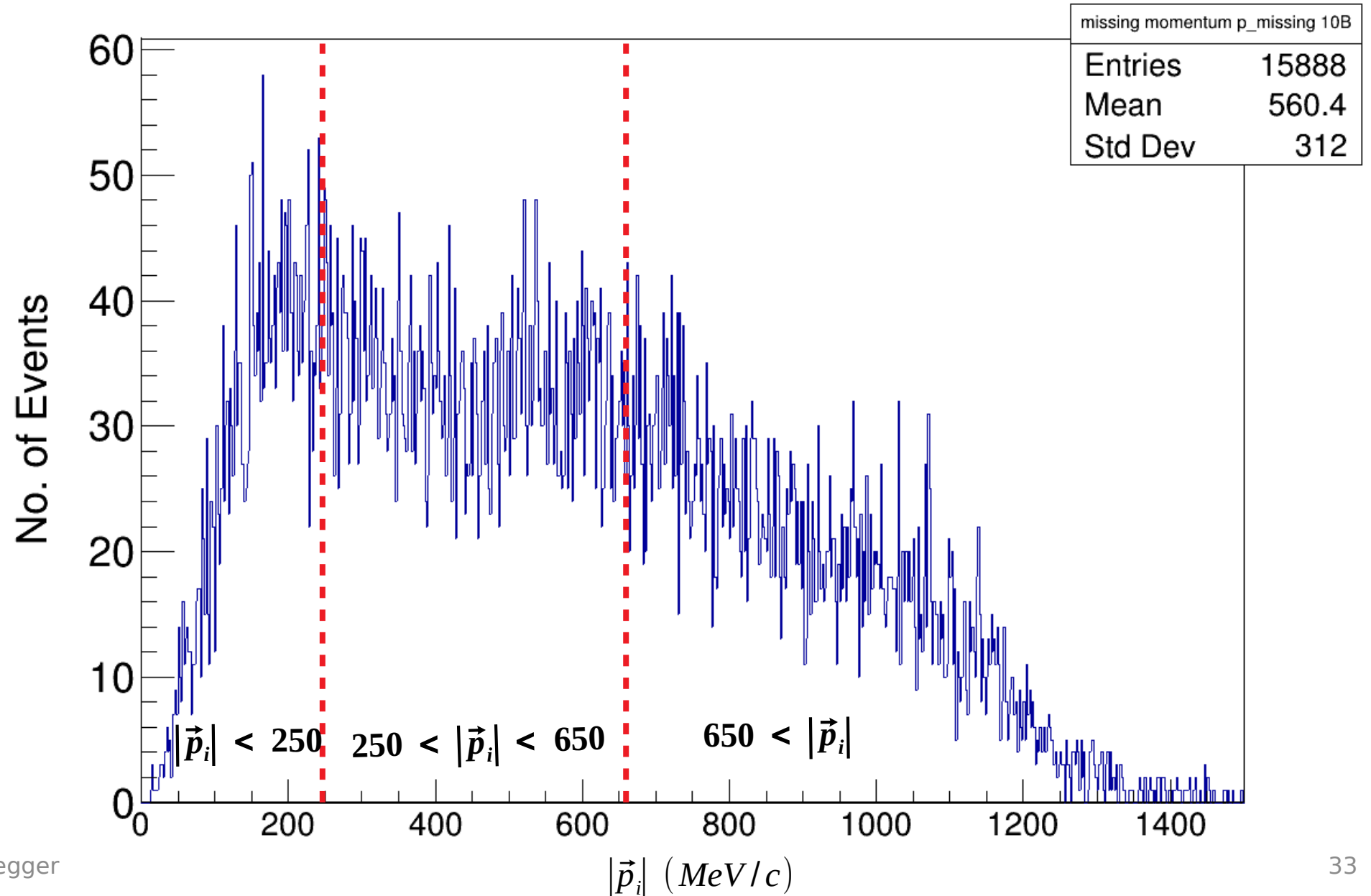
First (Polar) Angular Plots ...

θ_1 (proton 1) vs θ_2 (proton2) **with** angular cut: $\Delta\phi > 100^\circ$



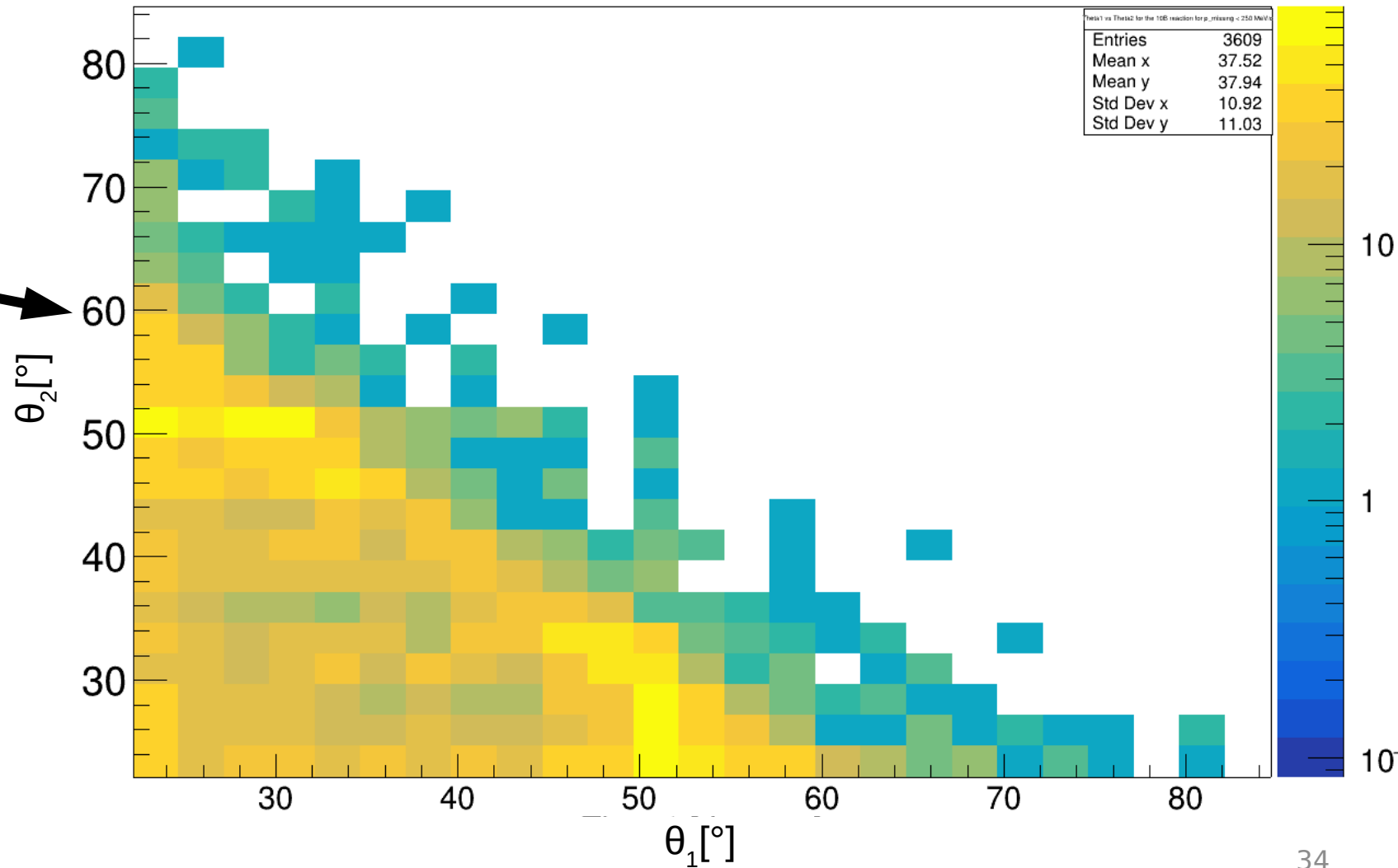
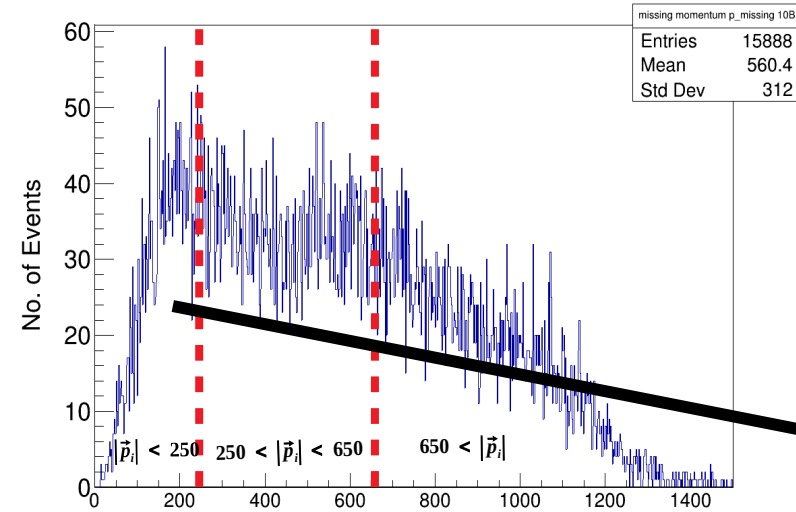
Reconstruction of inner momentum \vec{p}_i

$$\vec{p}_i = \vec{p}_1 + \vec{p}_2 - \vec{p}_{tg}$$



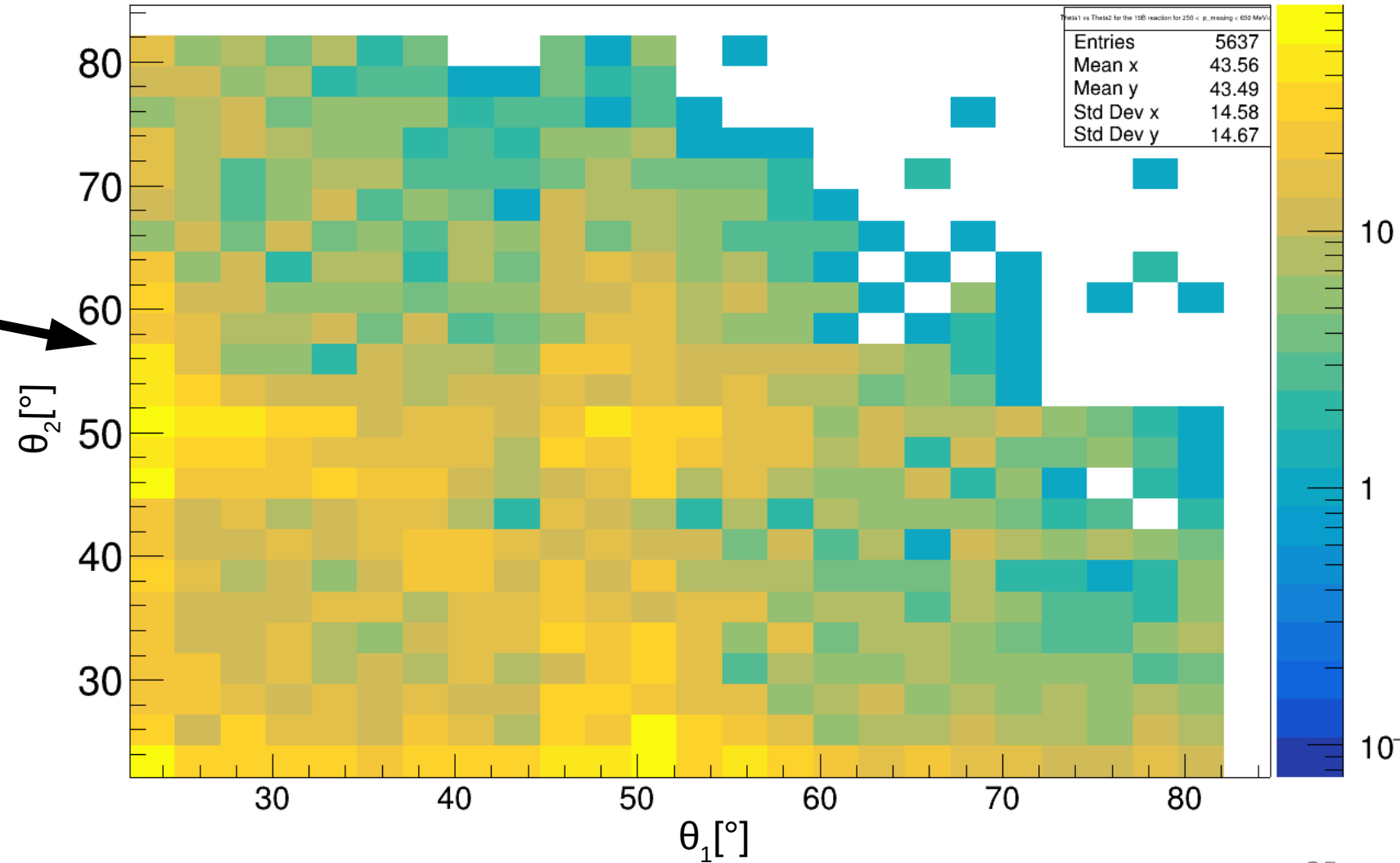
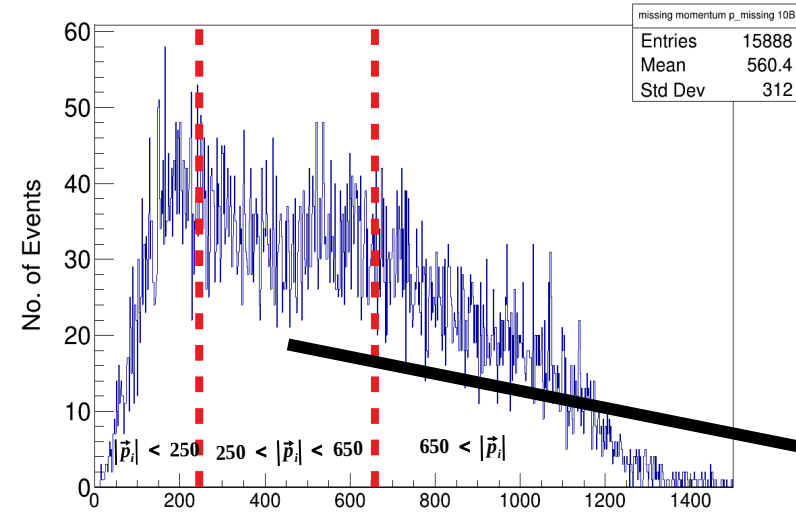


Angular Distribution for $|\vec{p}_i| < 250$



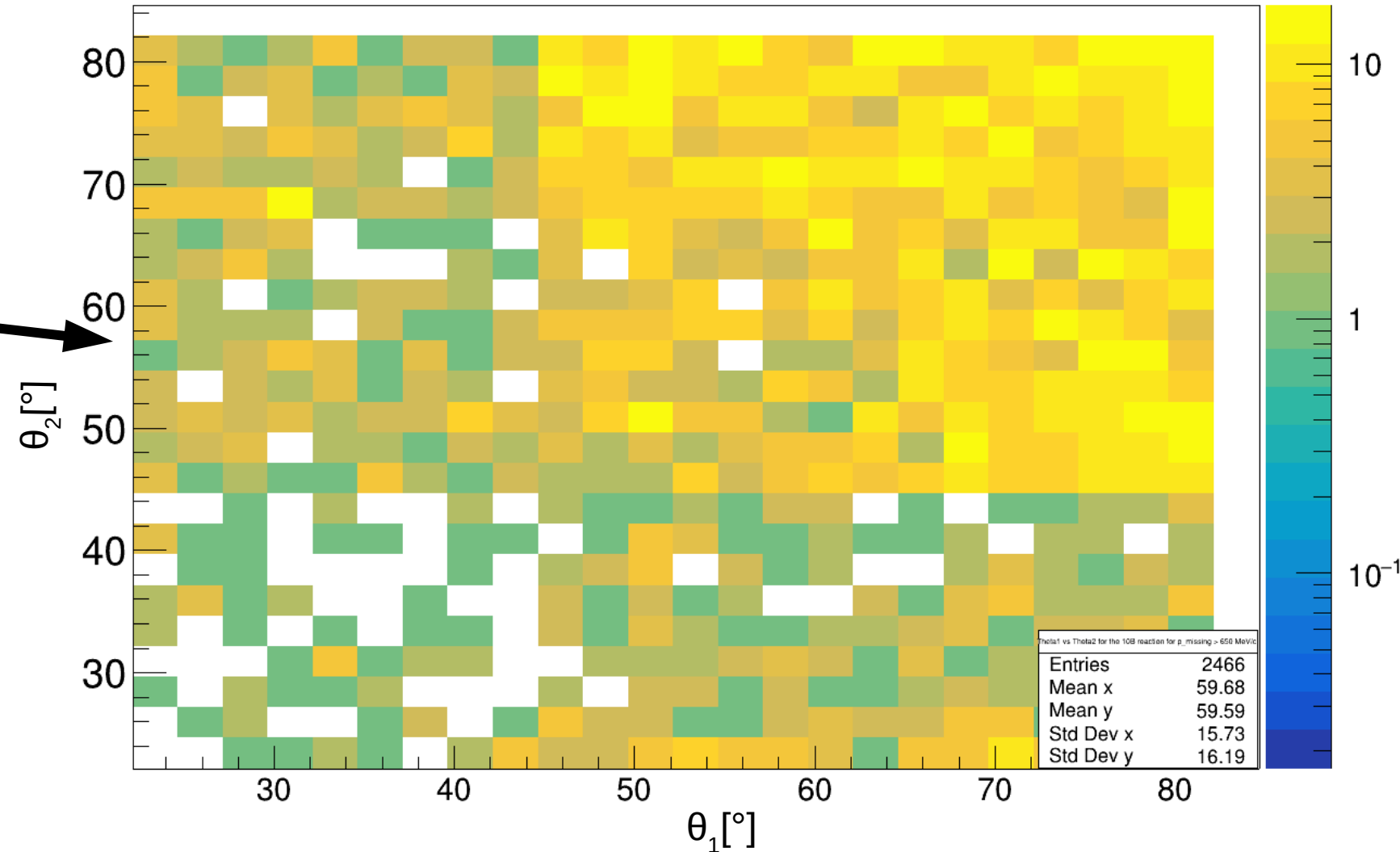
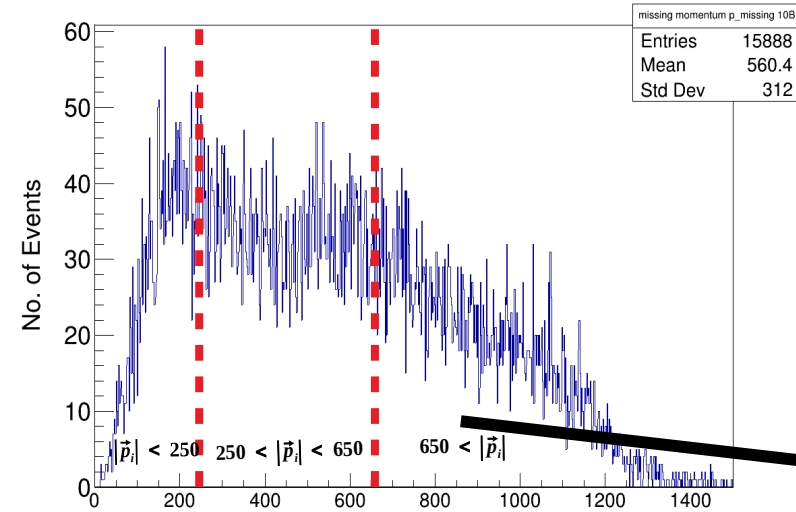


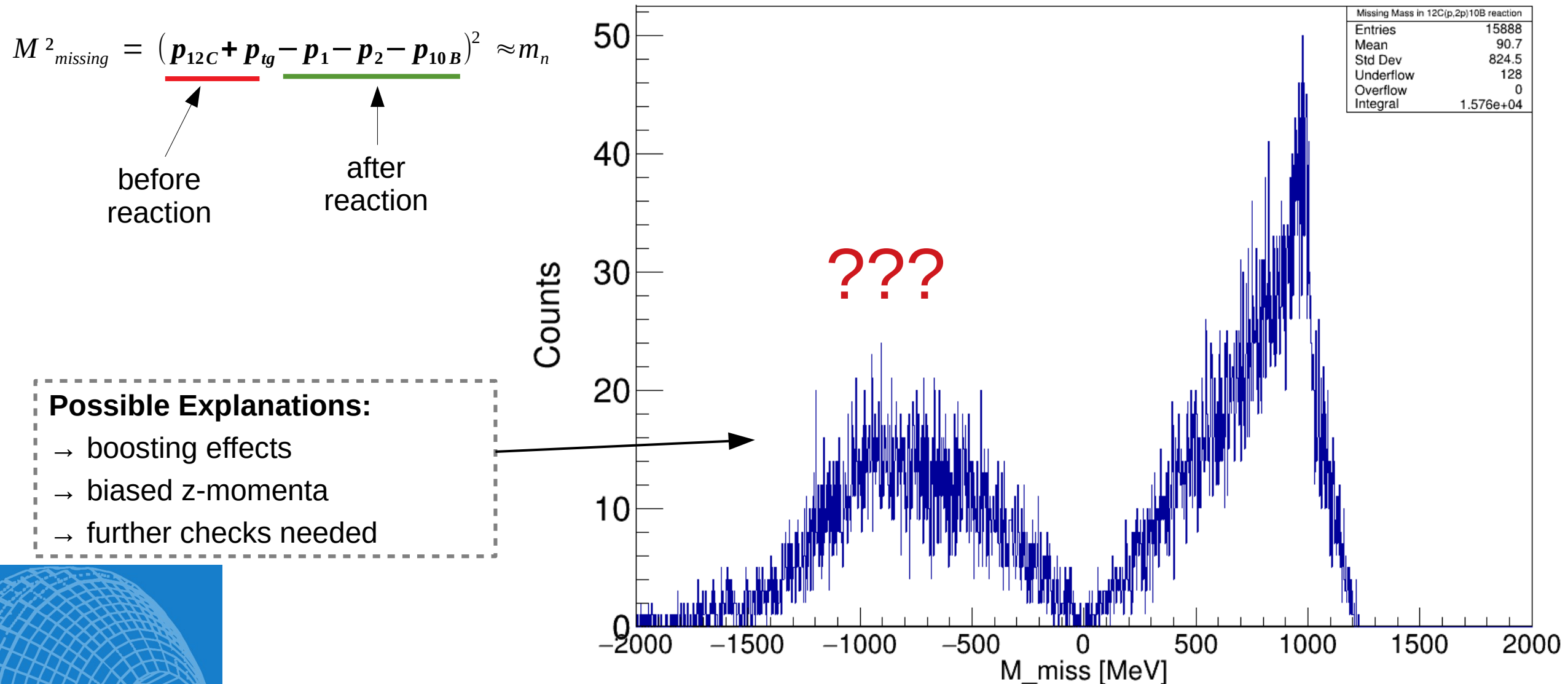
Angular Distribution for $250 \text{ MeV}/c < |\vec{p}_i| < 650 \text{ MeV}/c$





Angular Distribution for $|\vec{p}_i| > 650 \text{ MeV}/c$







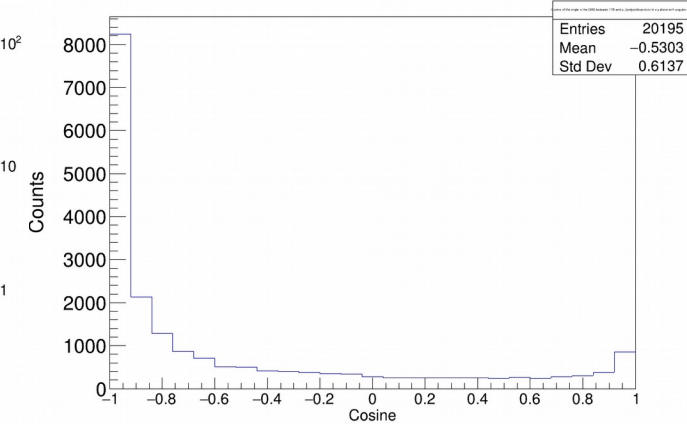
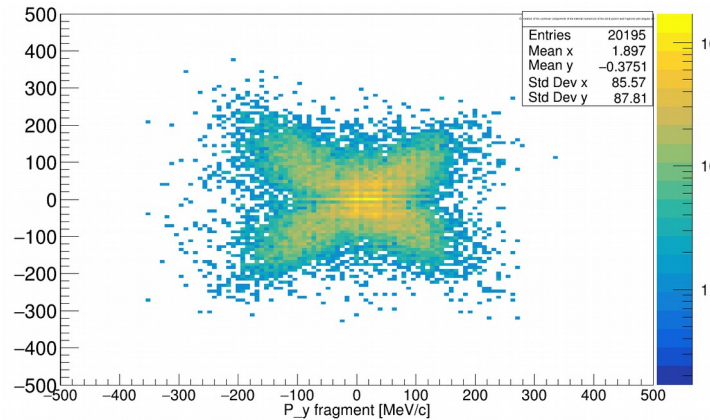
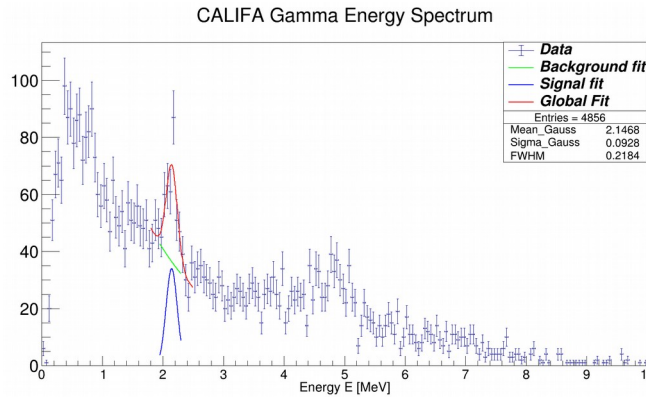
To do:

Angular correlations fo the proton and
reconstructed neutron

Angular correlation of src pair and 10B



➤ $^{12}\text{C}(p,2p)^{11}\text{B}$ Quasi Free Scattering looks promising

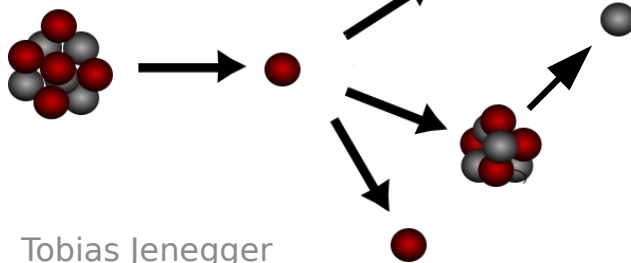


➤ But: Momentum shift in z-direction has to be further analyzed

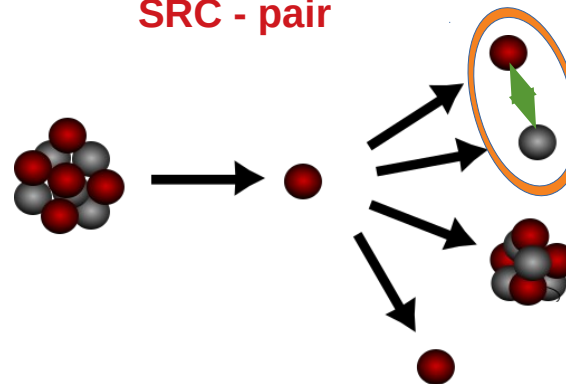
➤ For $^{12}\text{C}(p,ppn/pd)^{10}\text{B}$ already first results

➤ How to distinguish between the three reaction types? (Deuteron detection with N_f-N_s information from CALIFA? Reasonable cuts?)

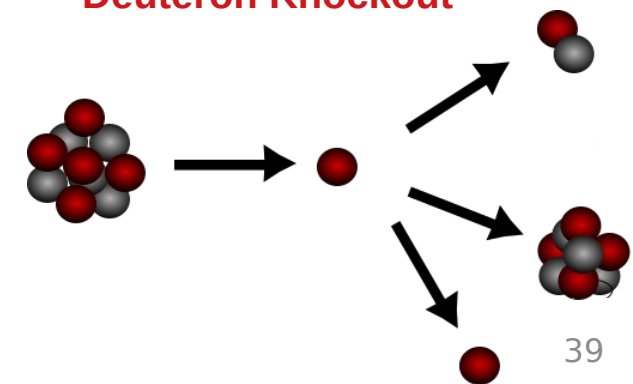
Neutron Evaporation



SRC - pair



Deuteron Knockout



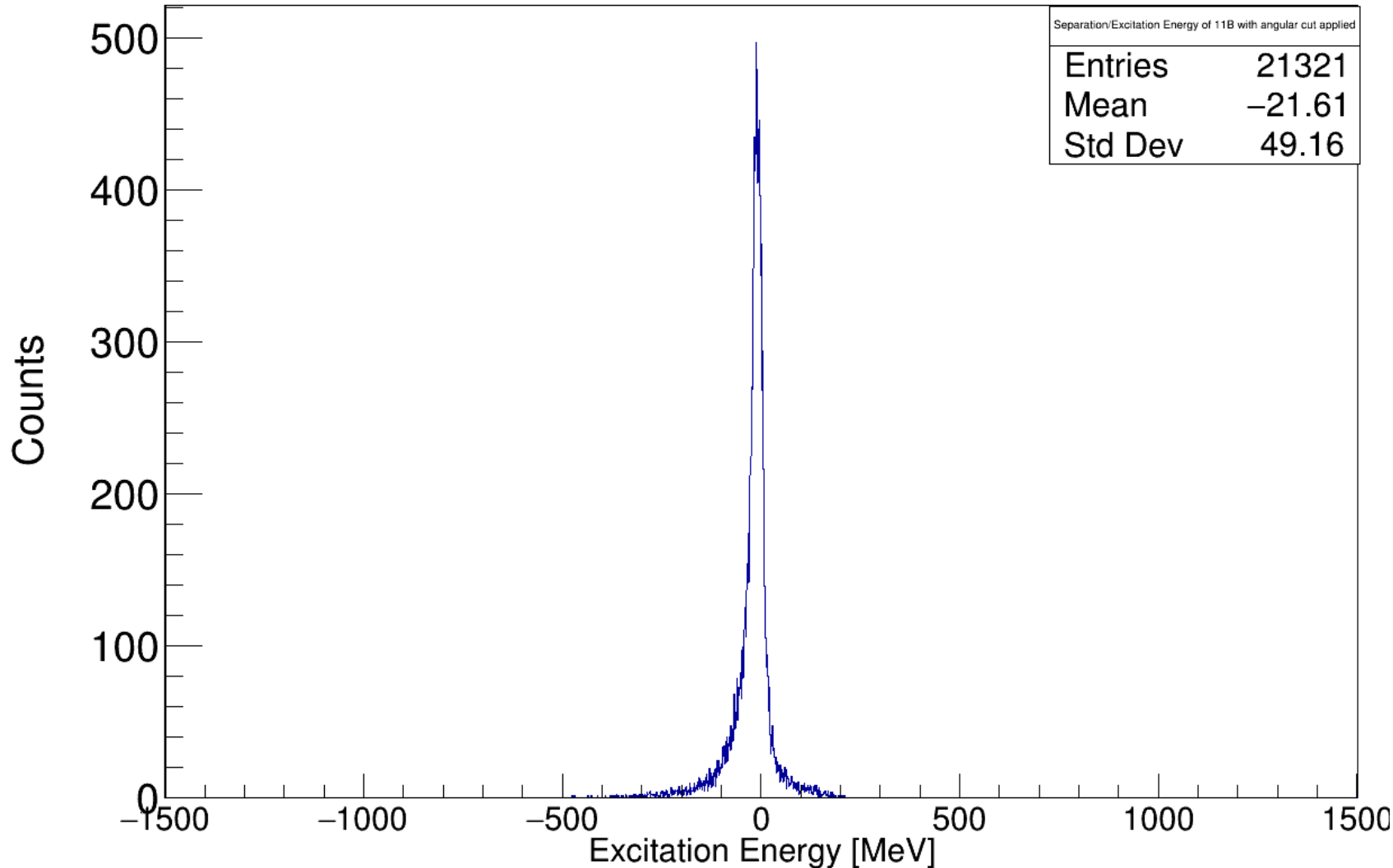


Backup



Excitation Energy of ^{11}B

$$E_{exc} = \left(\underbrace{P_{^{12}\text{C}} + p_{tg} - p_1 - p_2}_{-p_i} \right) \cdot M - M_{^{11}\text{B}}$$



Is this formula valid?



Excitation Energy vs. E_miss

