Quasi Free Scattering with S444 Data (2020)

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Analysis WG Meeting
22.07.2021

12C(p,2p)11B reaction

12C(p,ppn/pd)10B 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.

GEFÖRDERT VOM
Bundesministerium für Bildung und Forschung

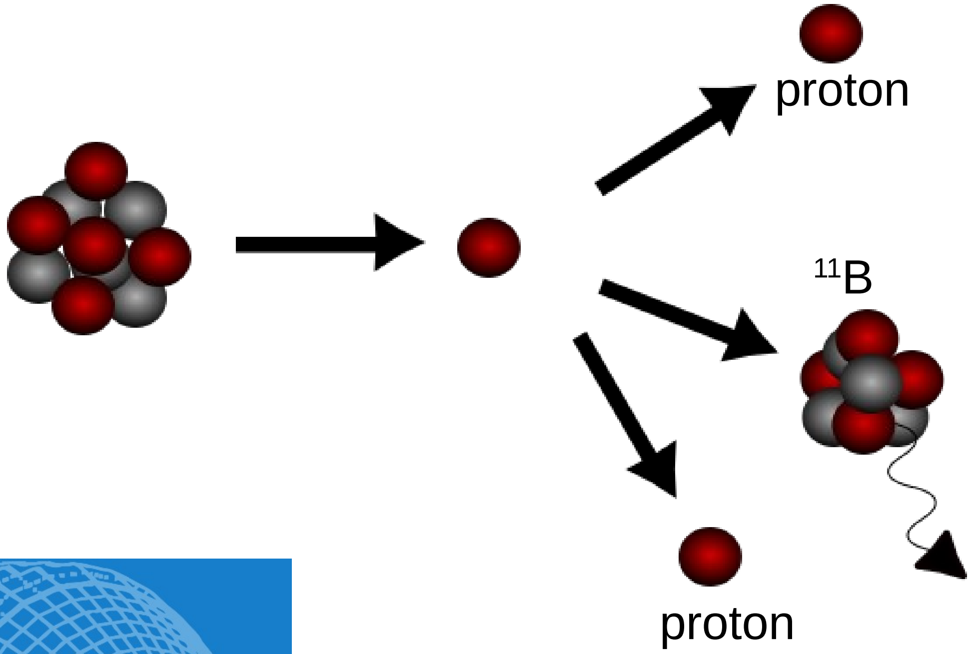
FAIR Phase 0 Research Program

Quasi Free Scattering Analysis with Experiment S444/467 (2020)

12C(p,2p)11B reaction:

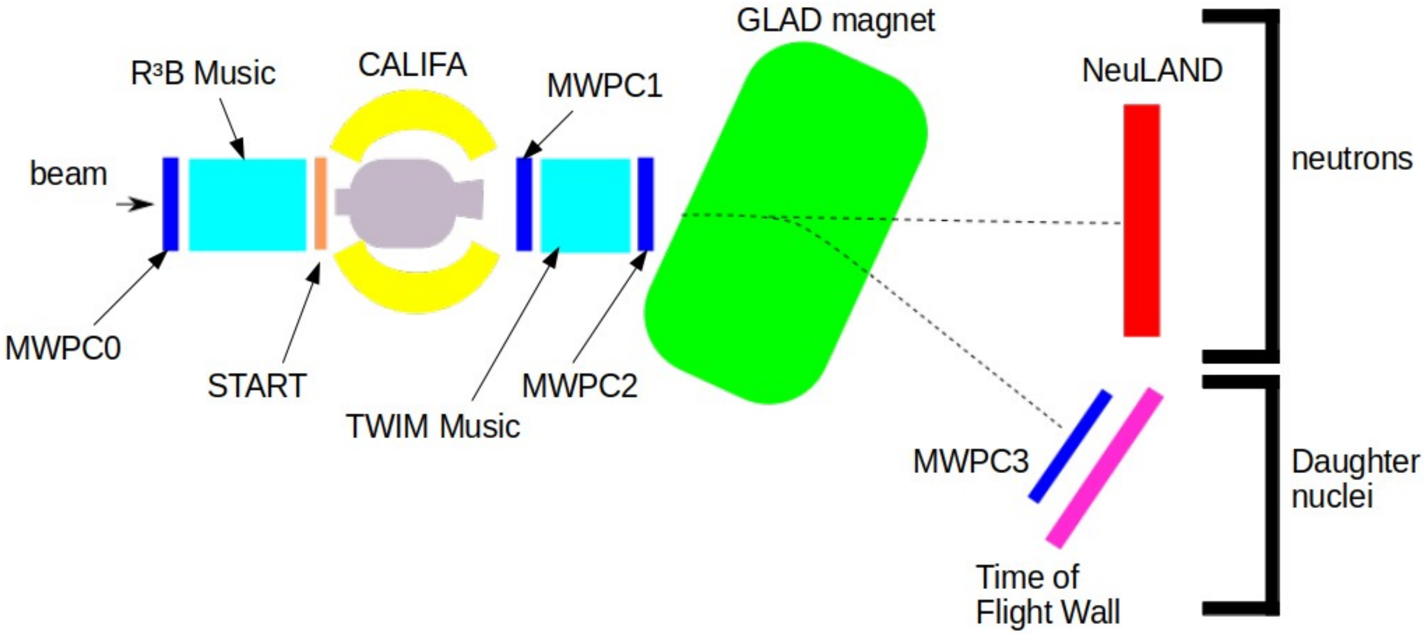
- ^{12}C beam
- proton like target

- 2 protons
- ^{11}B fragment (spectator)



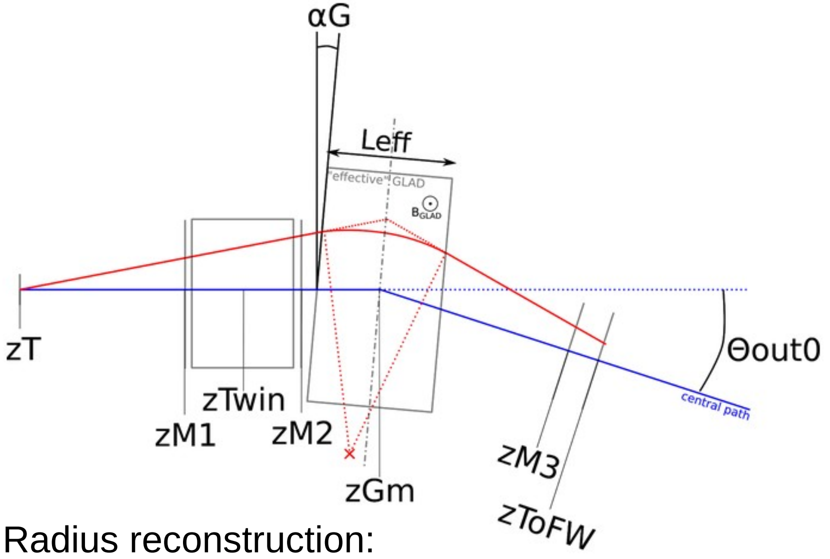
SETUP:

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



Fragment Particle Identification

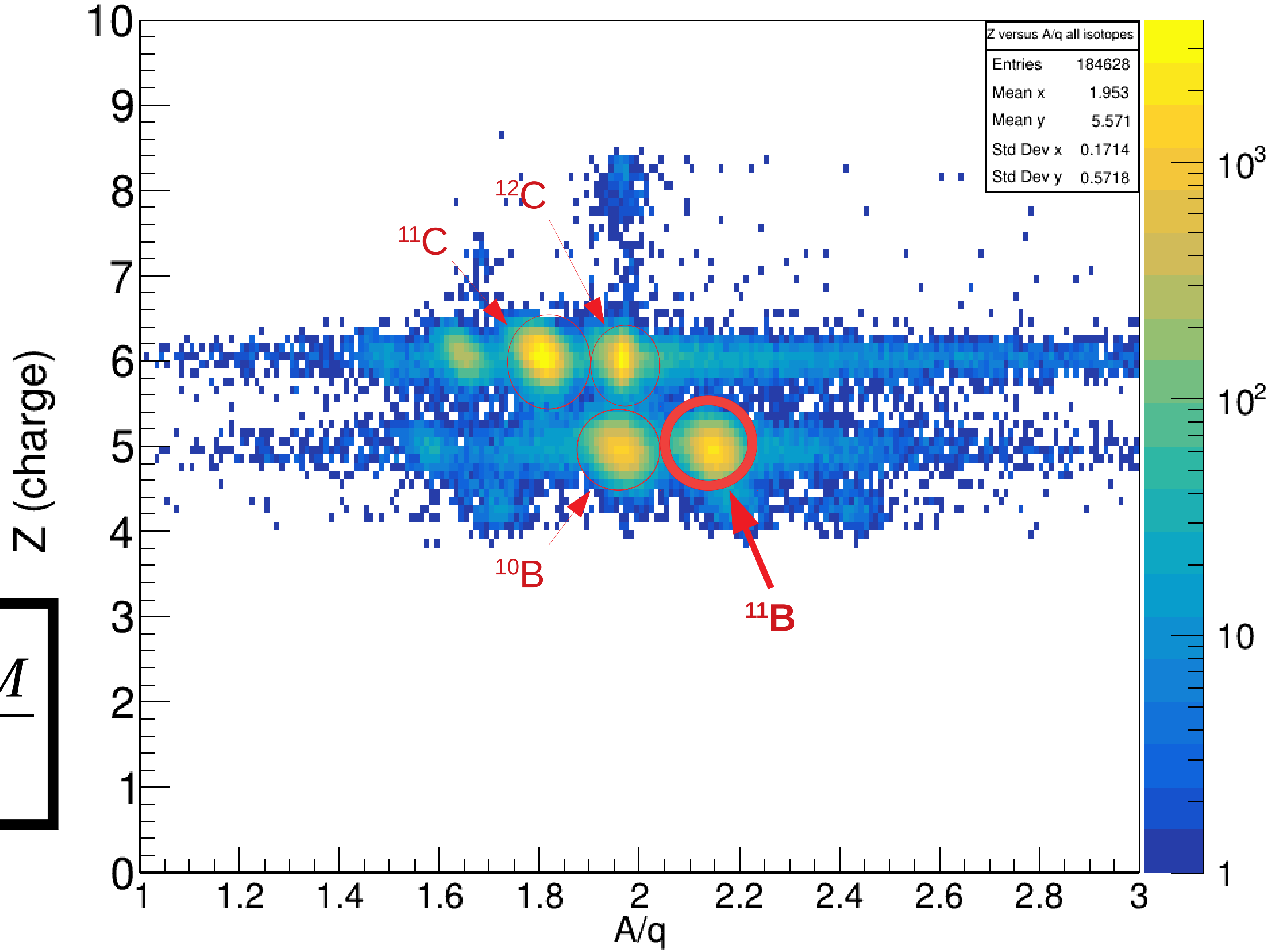
Flightpath reconstruction:



Radius reconstruction:

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

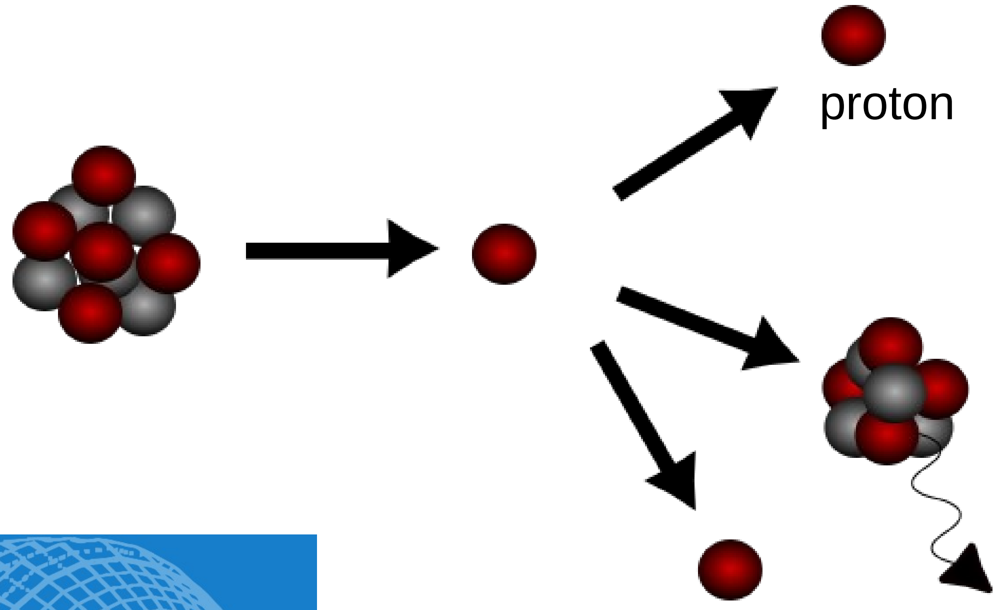
$$\boxed{B*\rho = \frac{\beta*\gamma*M}{q}}$$

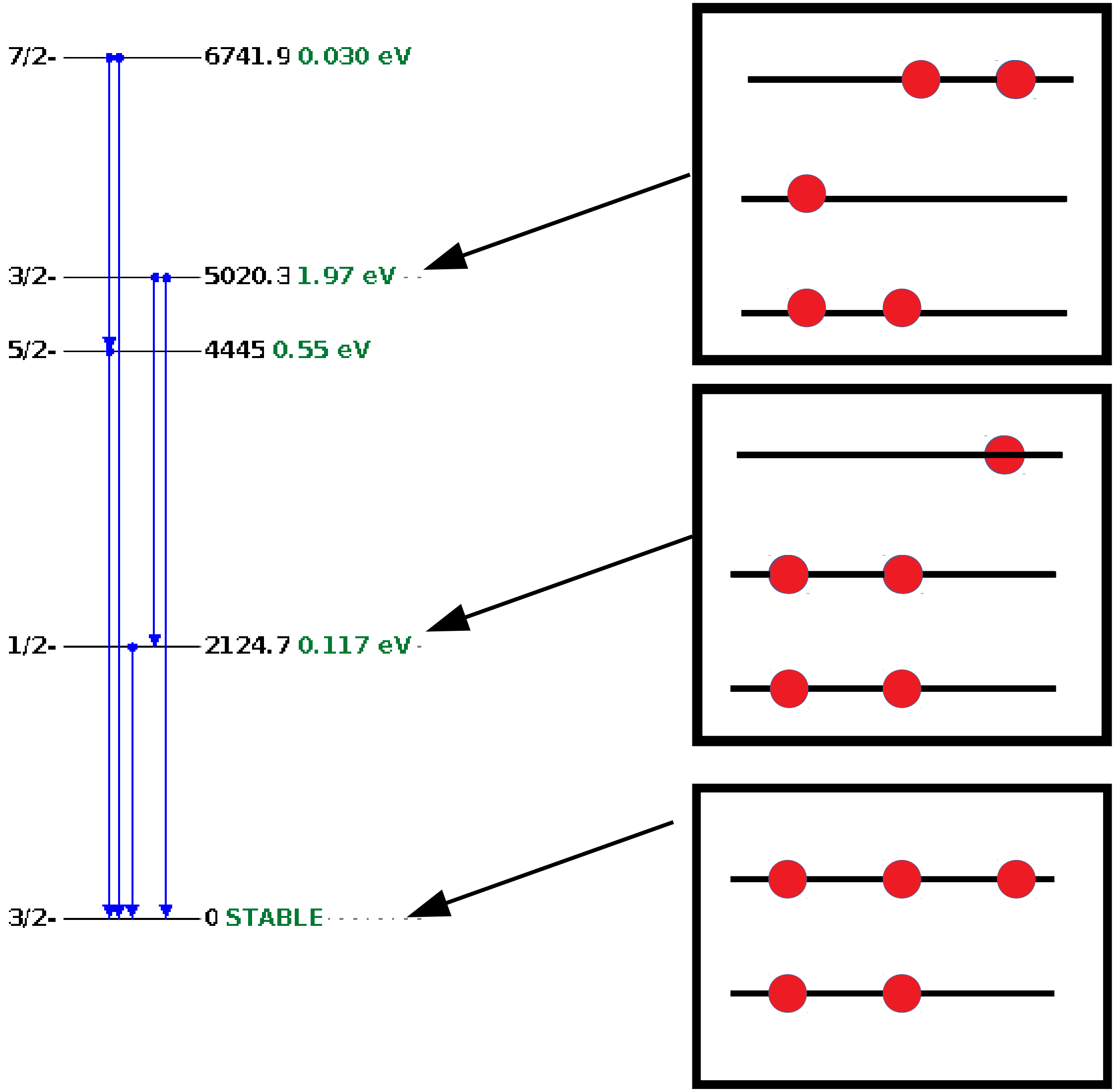


12C(p,2p)11B reaction

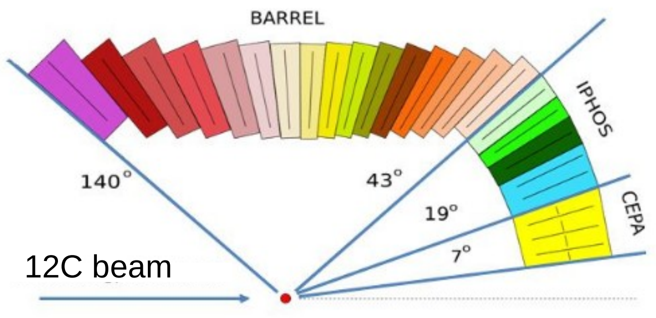
Two Proton Identification:

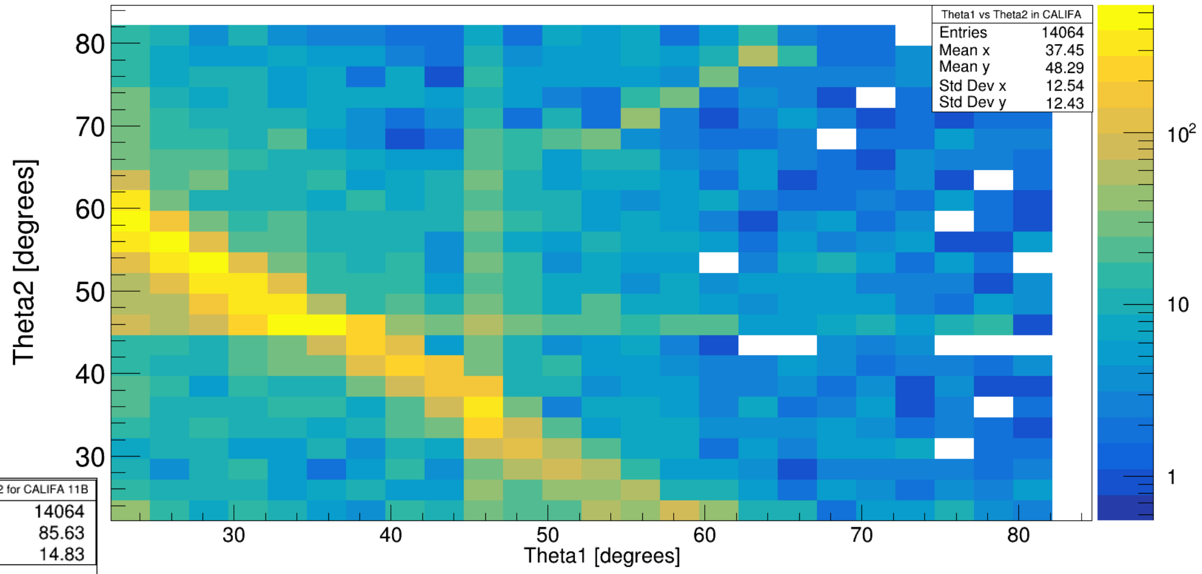
→ two hits with $E_{hit} > 30$ MeV

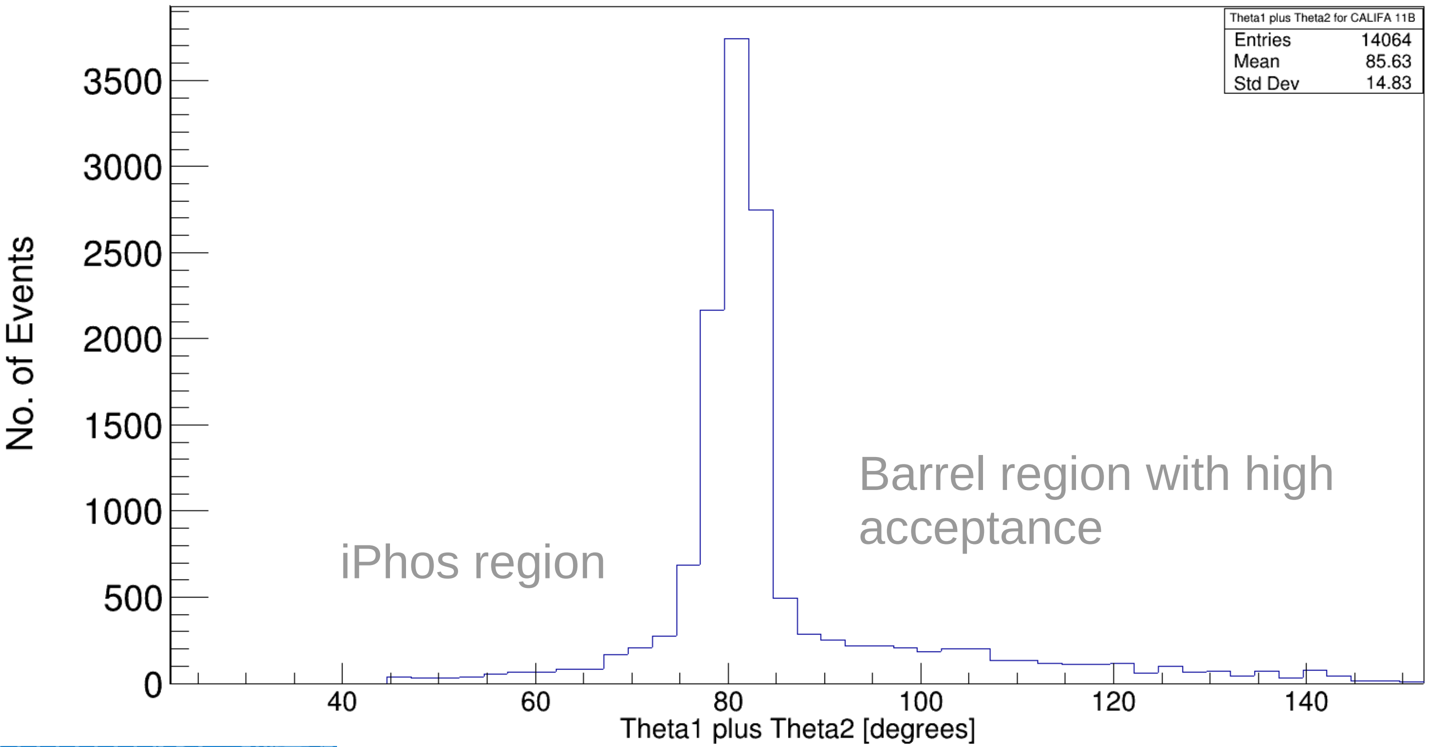


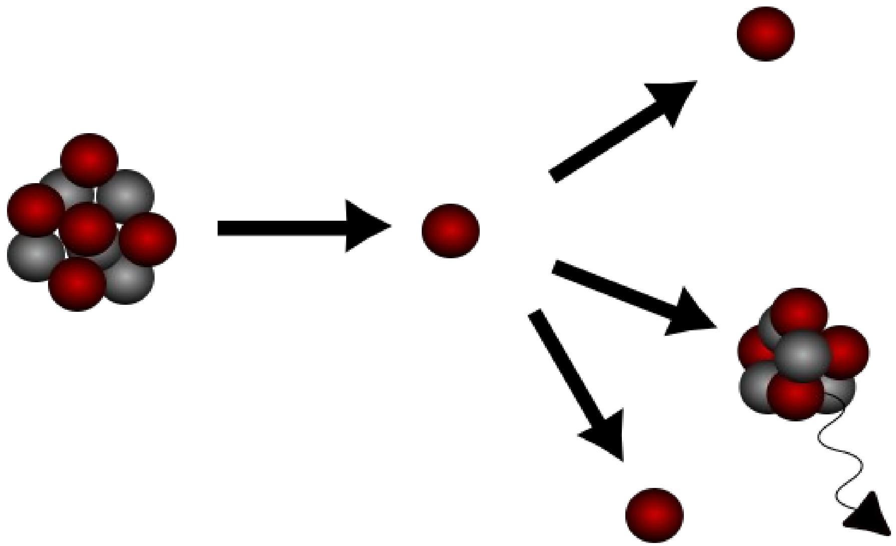


Polar Angular Distribution of protons for 12C(p,2p)11B

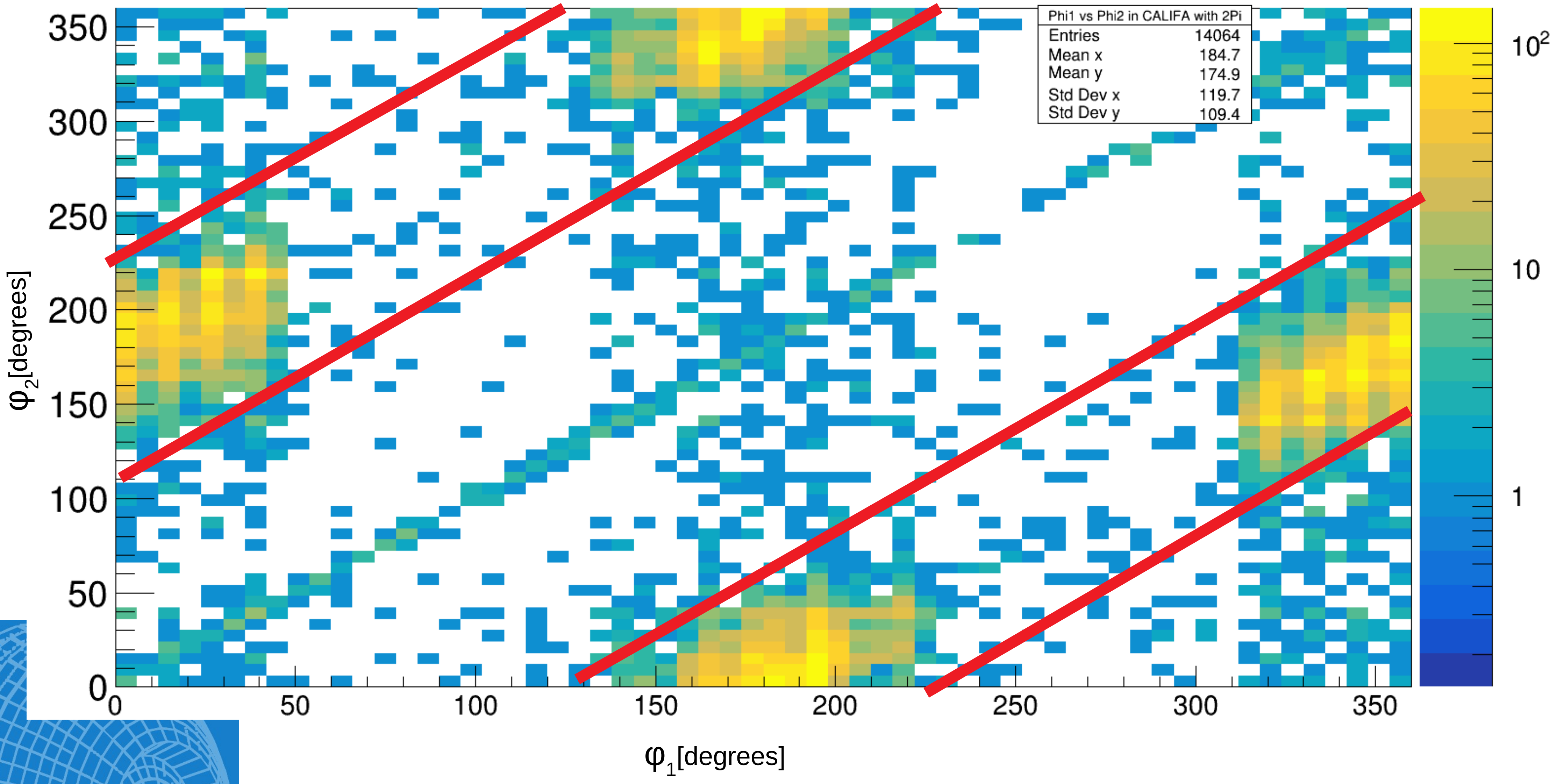


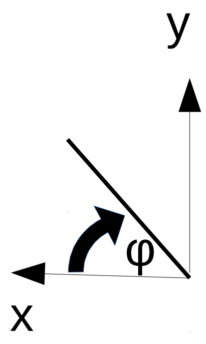






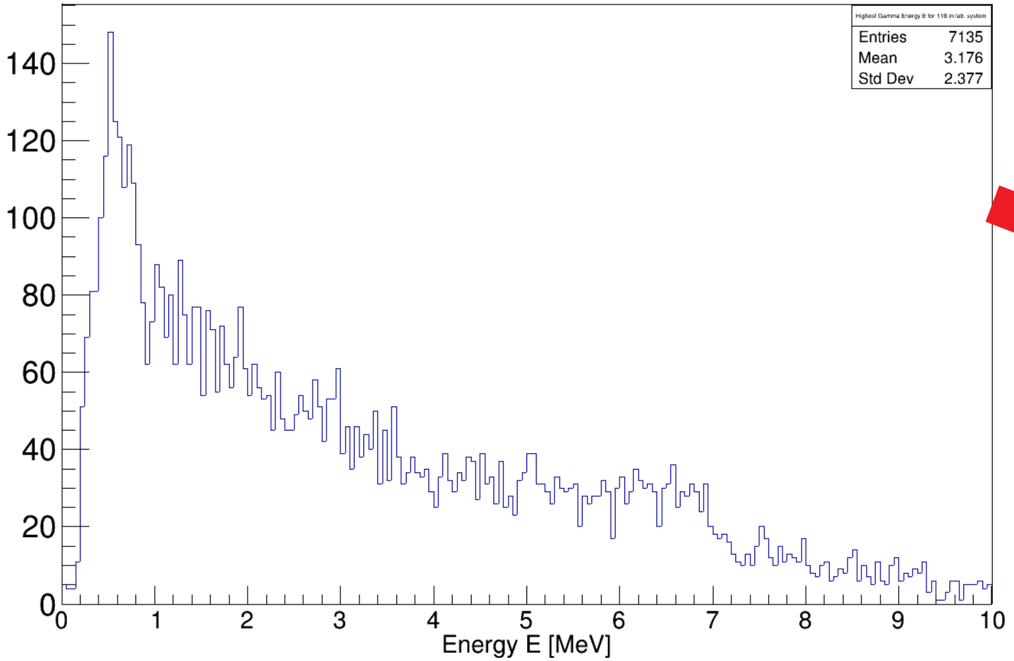
Arzimuthal Distribution of protons for 12C(p,2p)11B





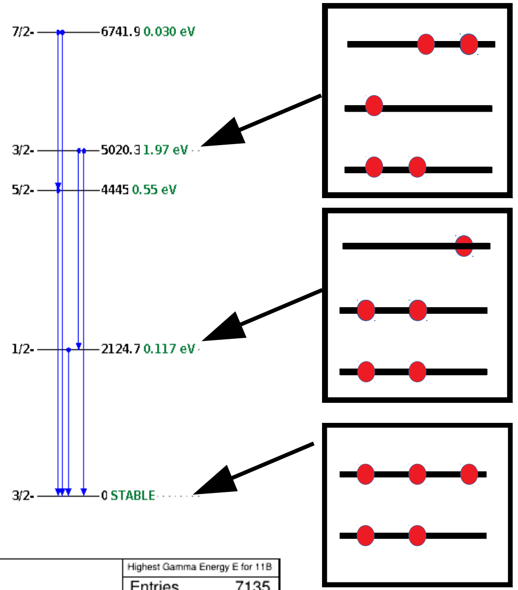
Gamma Spectrum of 11B

laboratory system

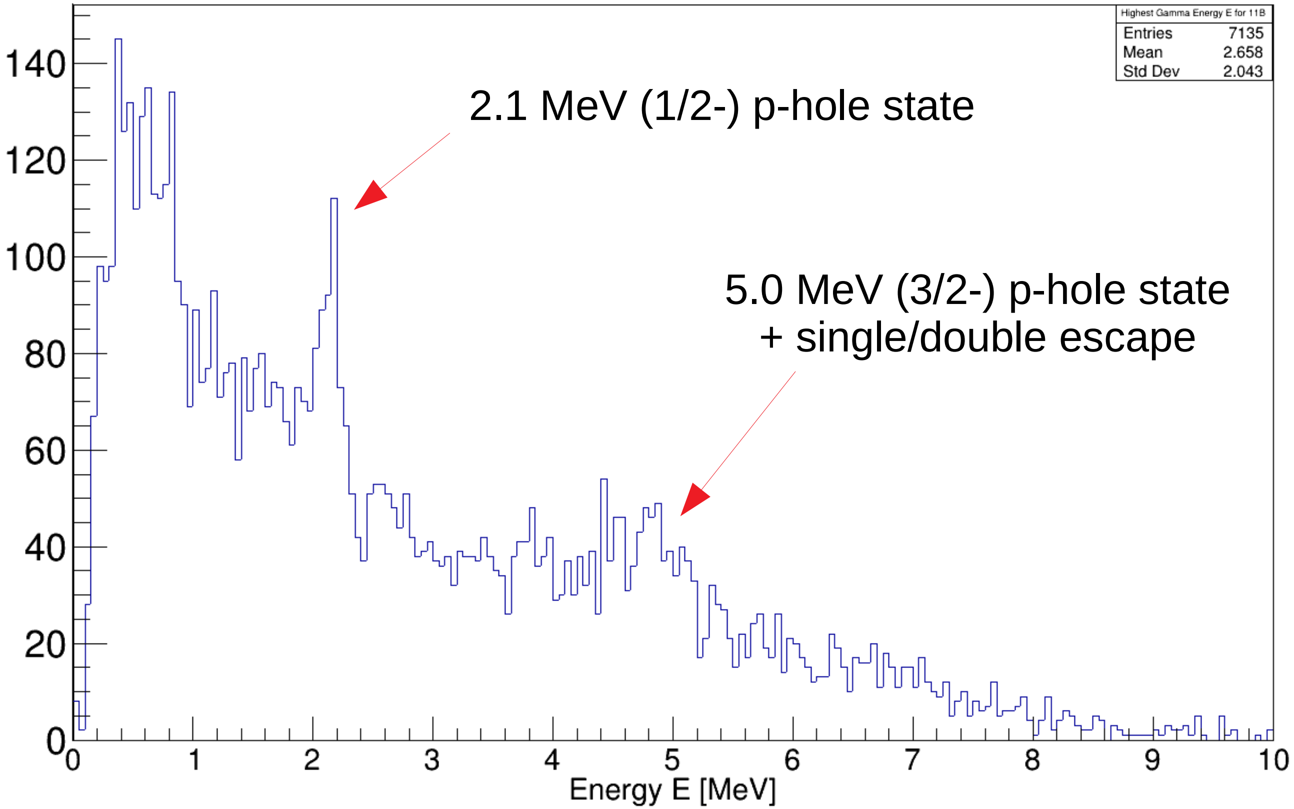


Doppler Correction:

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



^{11}B rest frame



Gamma Spectrum with Angular Cuts

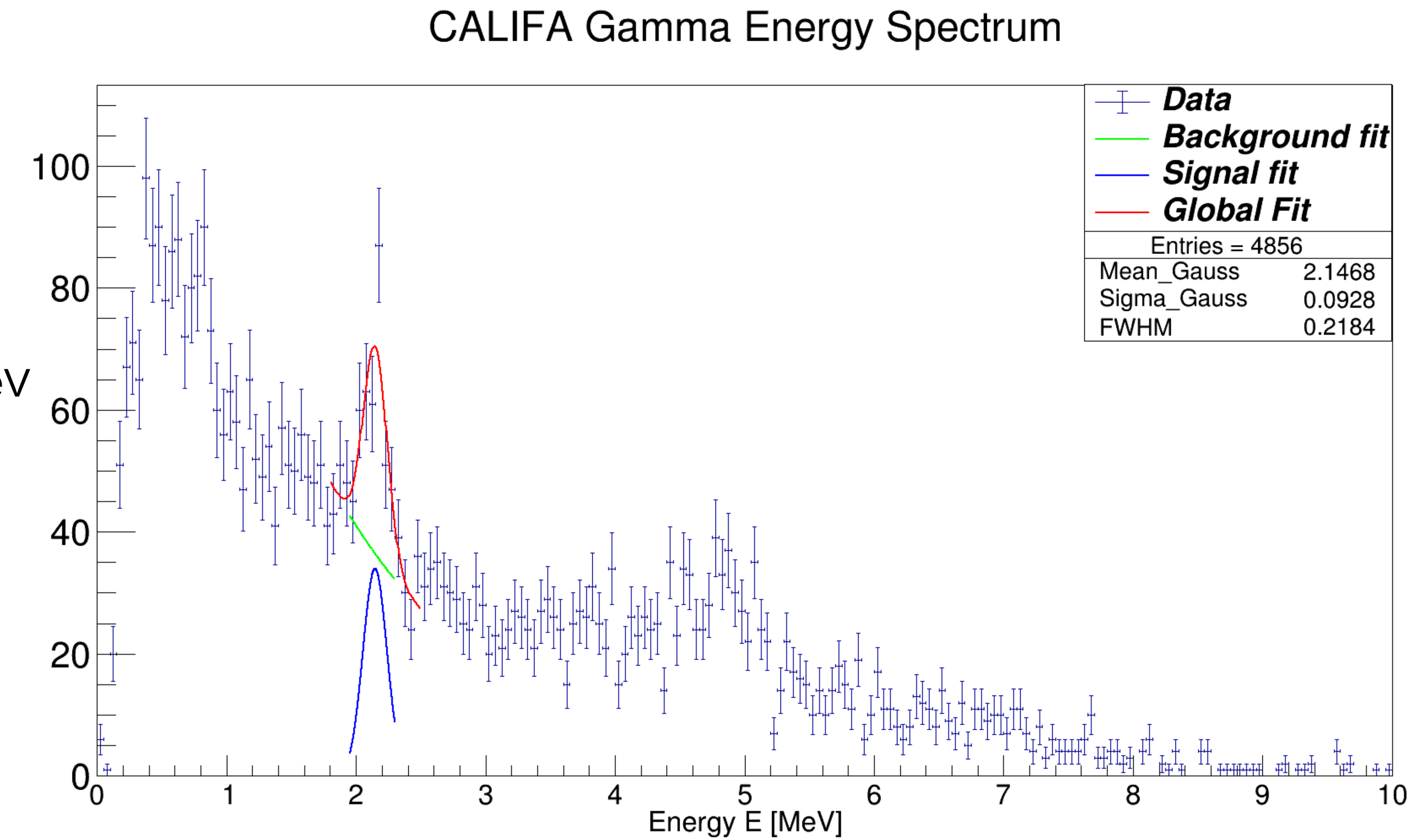
Event selection criteria for CALIFA:

→ 11B fragment identification

→ two hits (protons) with $E_{hit} > 30$ MeV

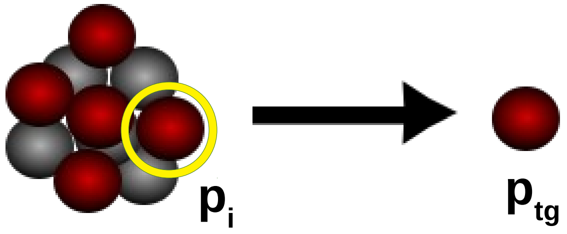
→ θ1 + θ2 < 90°

→ Δφ = 180° +- 40°

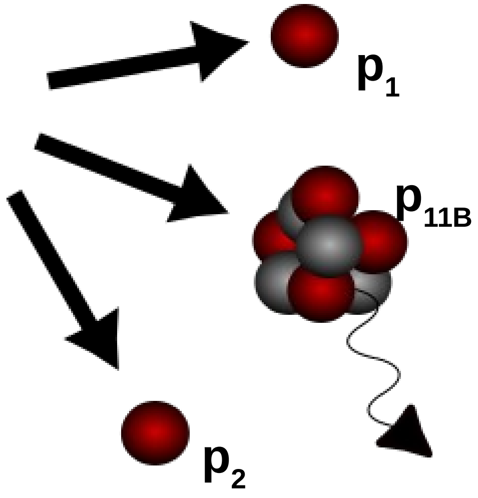


Reconstruction of Inner Momenta

Before Scattering:



After Scattering:



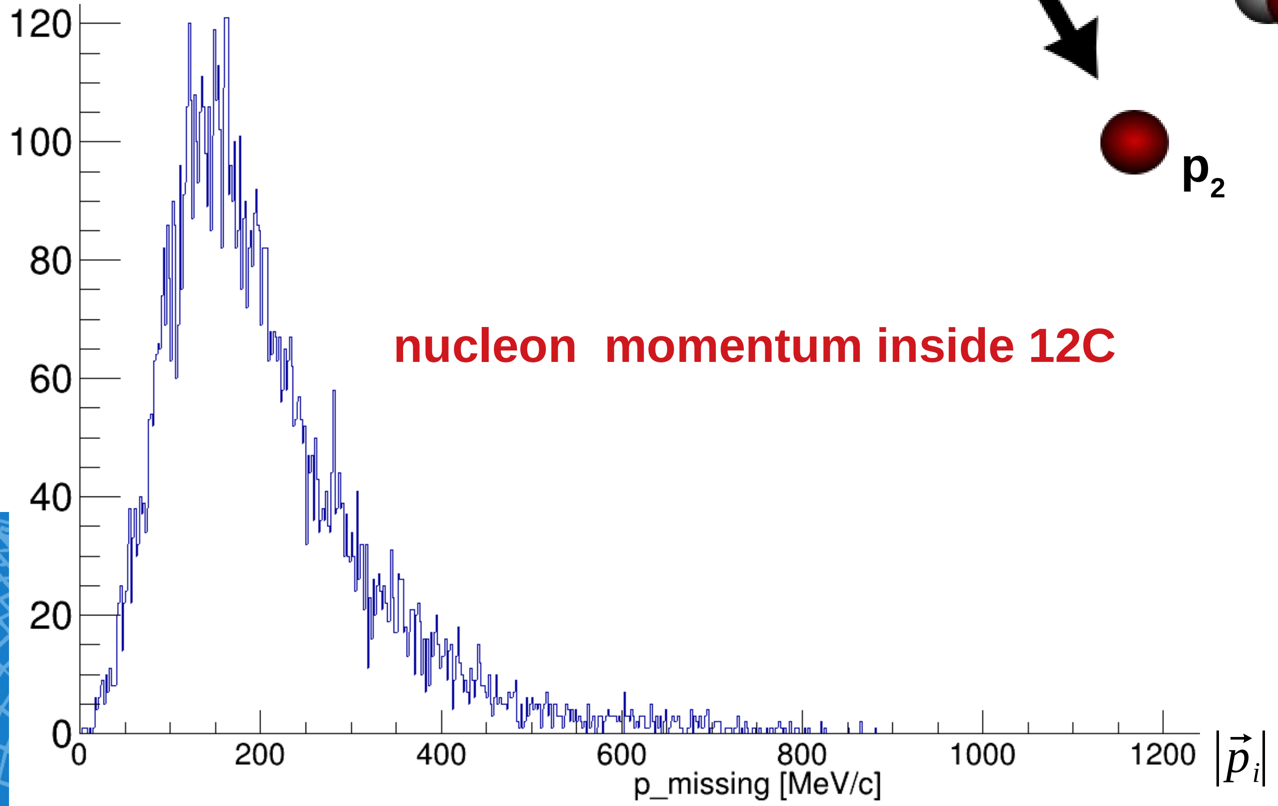
(Four-)Momentum conservation relation:

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

assuming QE scattering in mean field potential:

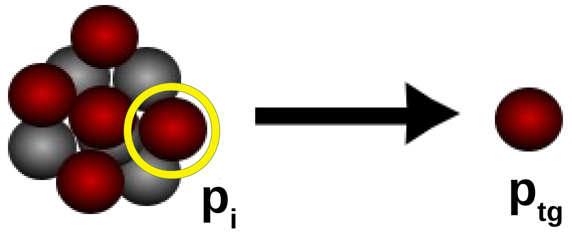
$$p_{12C} = p_i + p_{11B}$$

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

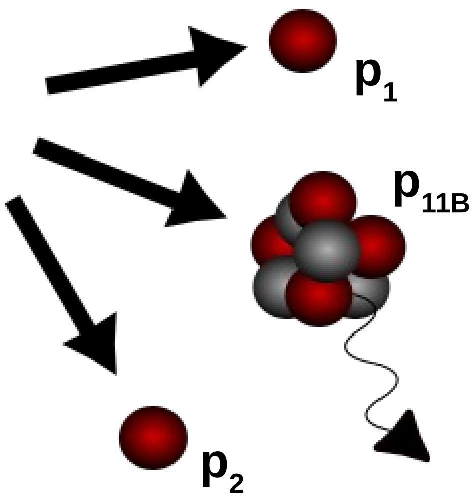


Momentum components of p_i

Before Scattering:

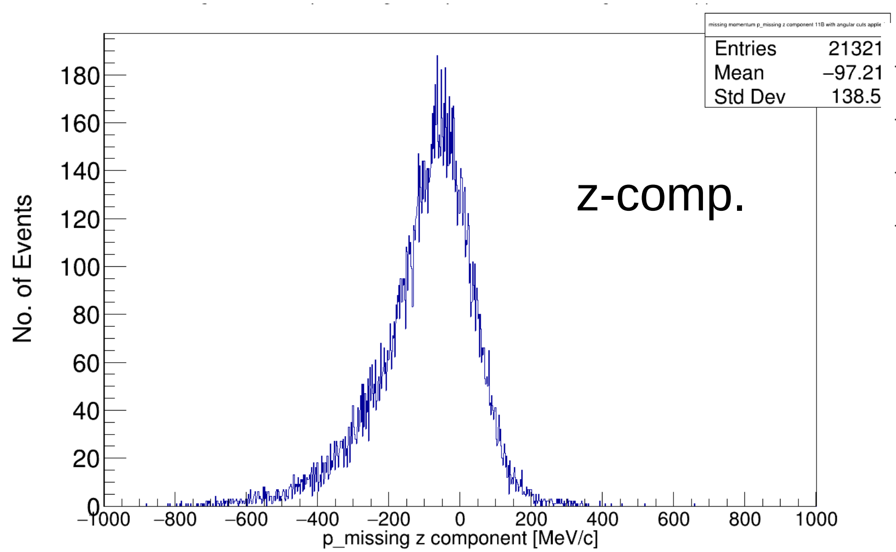


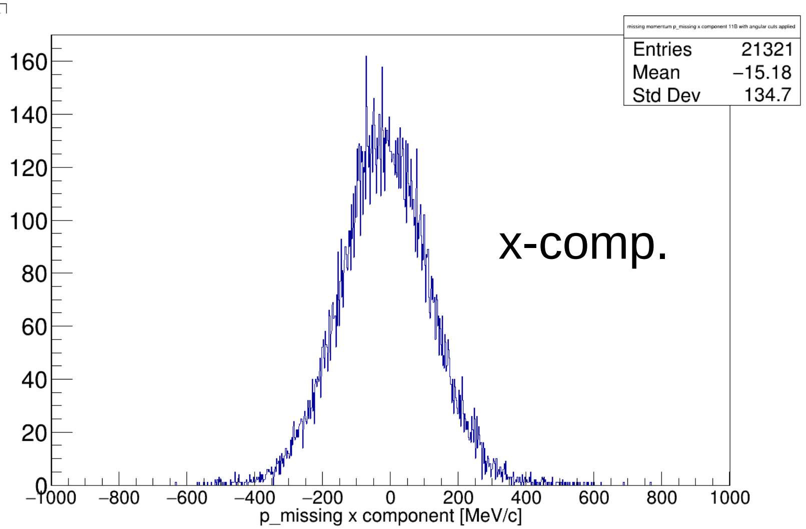
After Scattering:

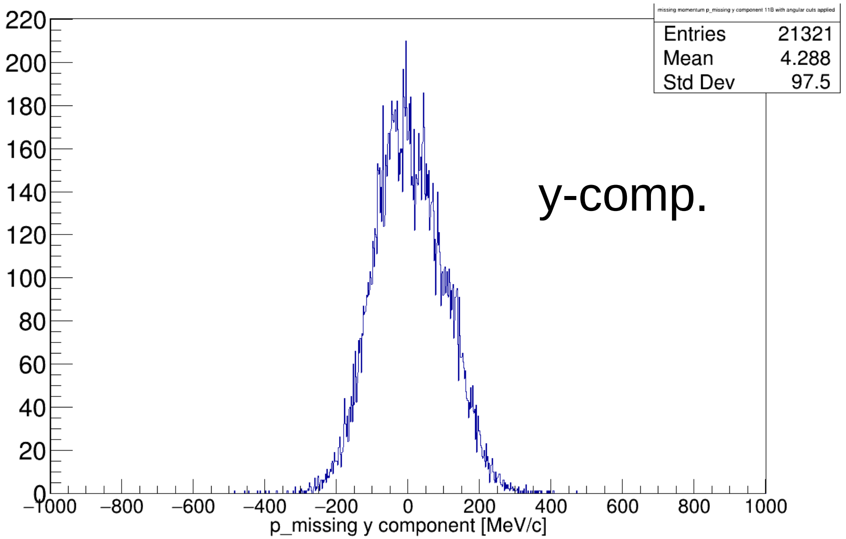


$$p_i \approx p_{missing} = p_1 + p_2 - p_{tg} \, (no\ ISI / FSI)$$

p_i Momentum-Components (with angular cuts applied)



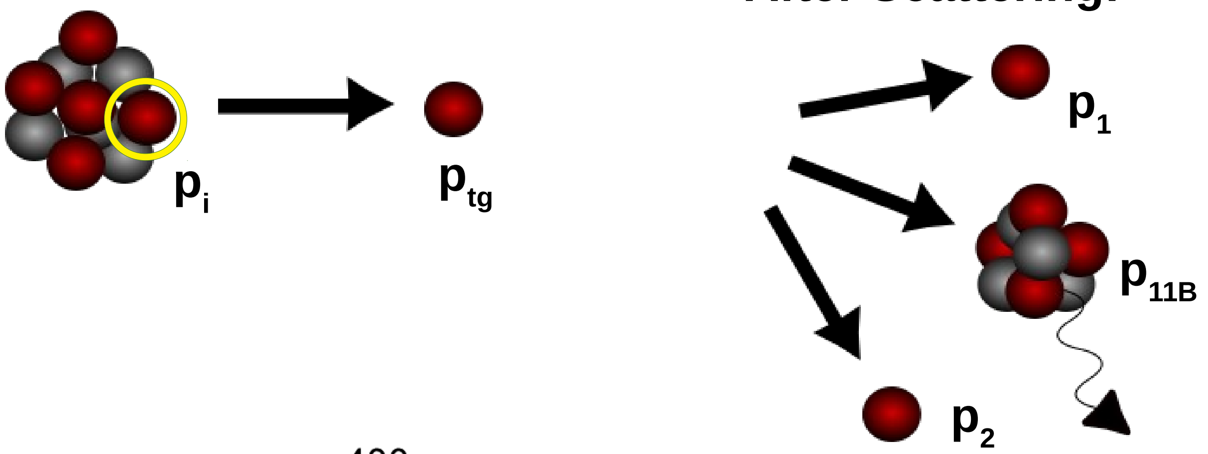




Mass reconstuction of p_i

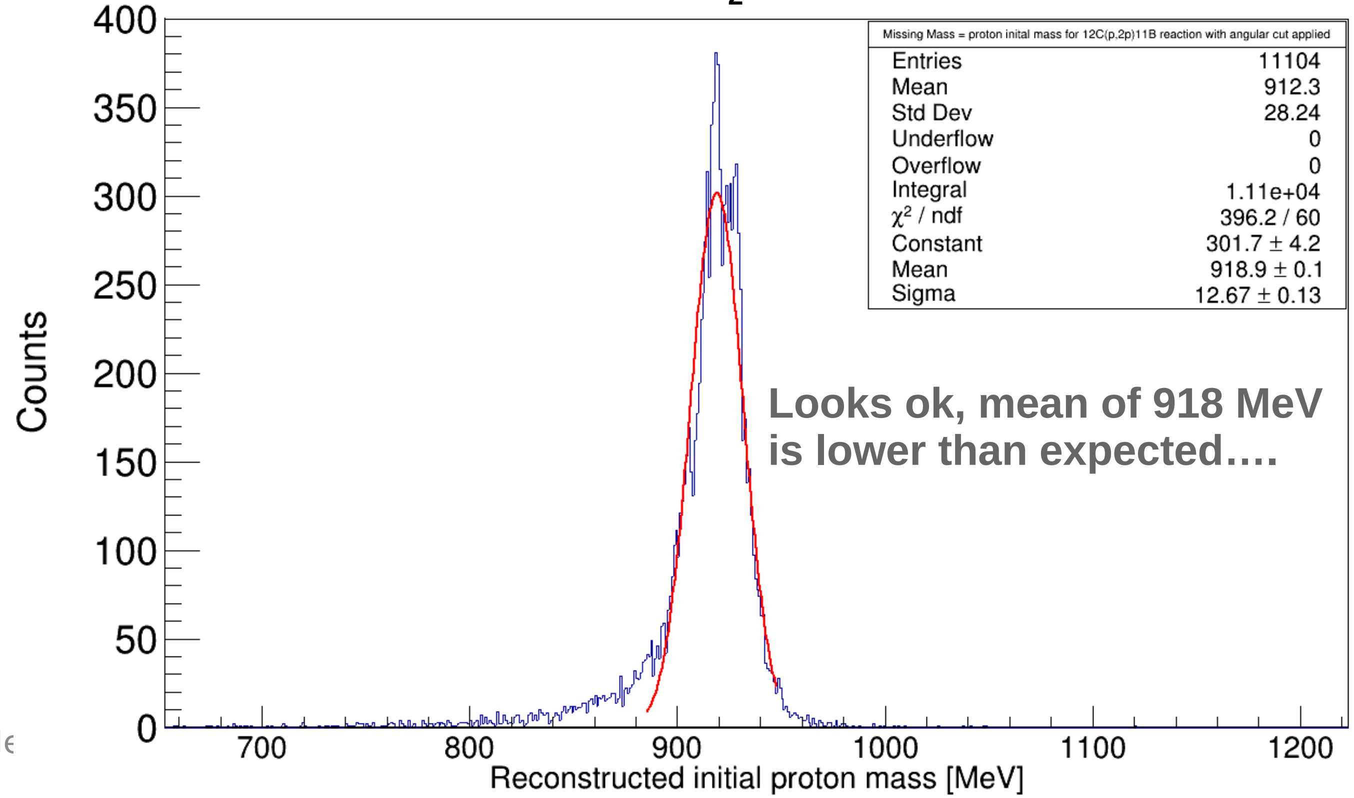
Before Scattering:

After Scattering:



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

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



Looks ok, mean of 918 MeV is lower than expected….

Missing Energy Distribution

Definition of Missing Energy *:

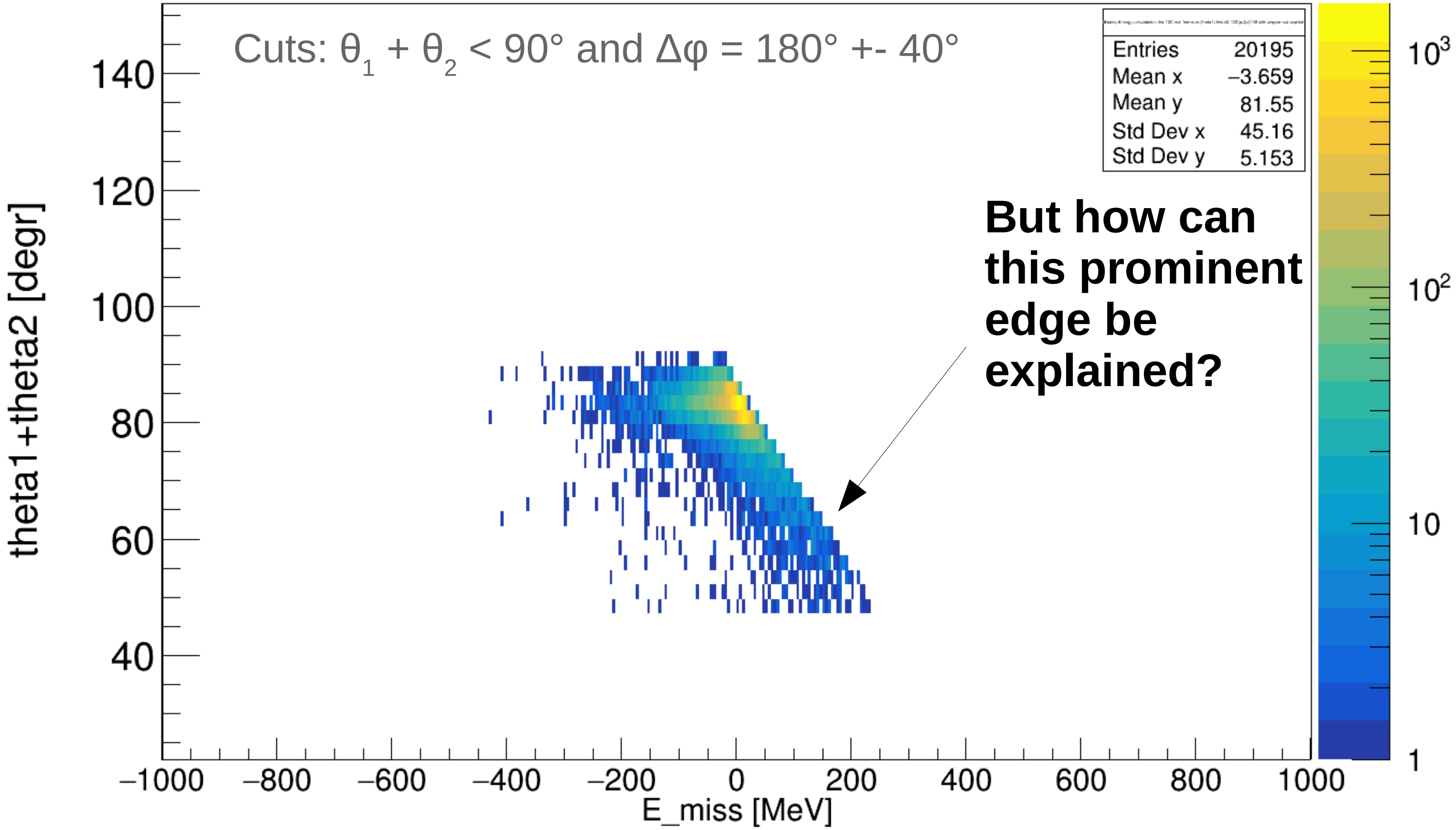
$$E_{miss} = m_p - e_{miss} = E_{tgkin} - E_{p1kin} - E_{p2kin}$$ (in 12C cms)

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

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

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

$$\boxed{\mathbf{E_{miss} = E_{Sep} + \overline{E}_{Exc}}}$$



But how can this prominent edge be explained?

*From: https://www.nature.com/articles/s41567-021-01193-4.pdf

Analysis Missing Energy Distribution

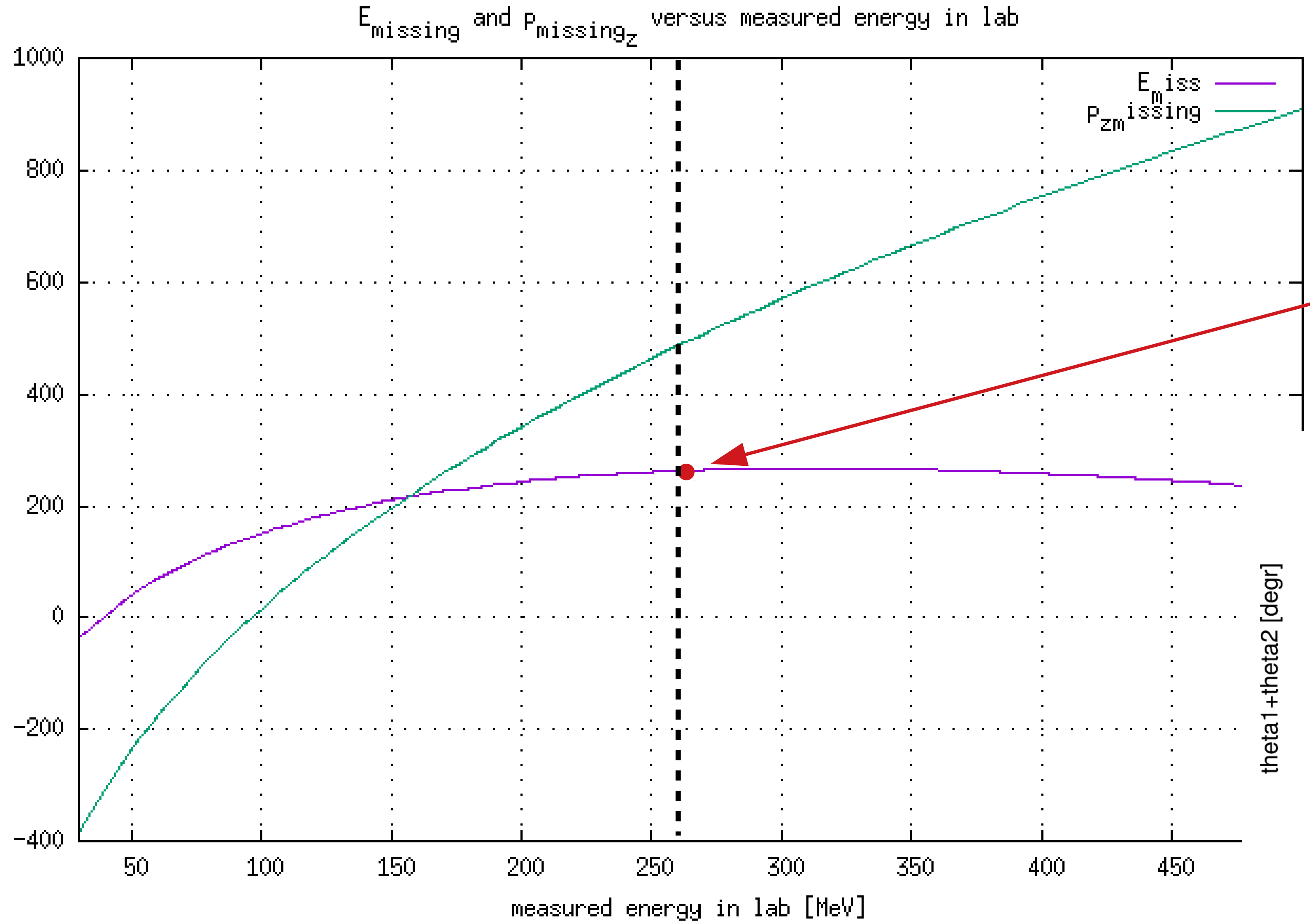
Explicit calculation of the Missing Energy (in the 12C frame):

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

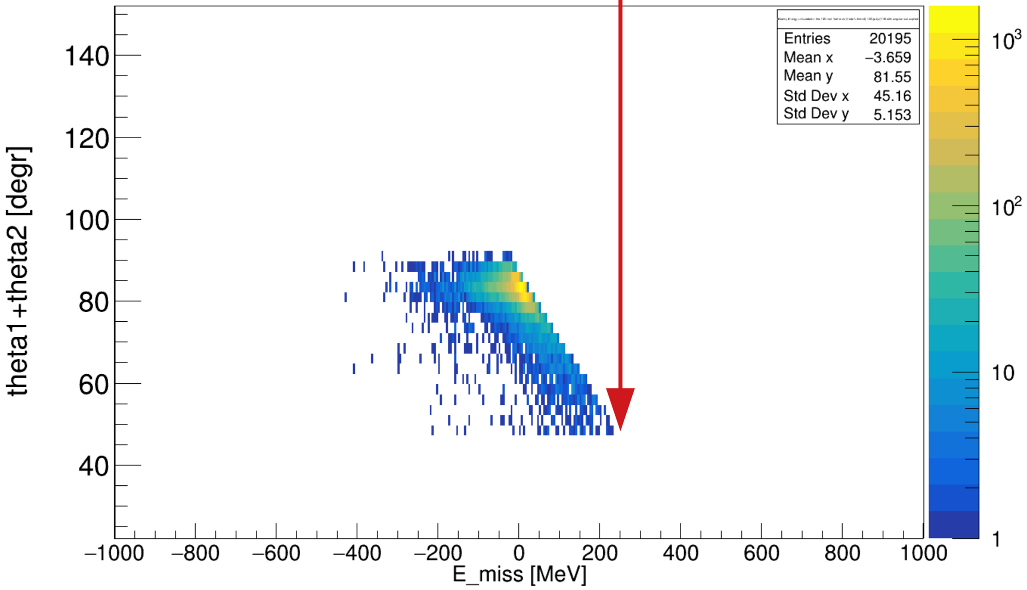
$$E_{miss} = \underbrace{400}_{E_{tgkin}} \underbrace{-\left(\underbrace{\gamma*(E_{kin1}+938) - \gamma*\beta*\sqrt{(E_{kin1}+938)^2-938^2}*\cos(\theta_1)}_{E'_{p1}} \underbrace{-938}_{E\_pot_{p1}}\right)}_{E_{kin1}} \underbrace{-\left(\underbrace{\gamma*(E_{kin2}+938) - \gamma*\beta*\sqrt{(E_{kin2}+938)^2-938^2}*\cos(\theta_2)}_{E'_{p2}}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

E_missing and p_z_missing for different opening angles

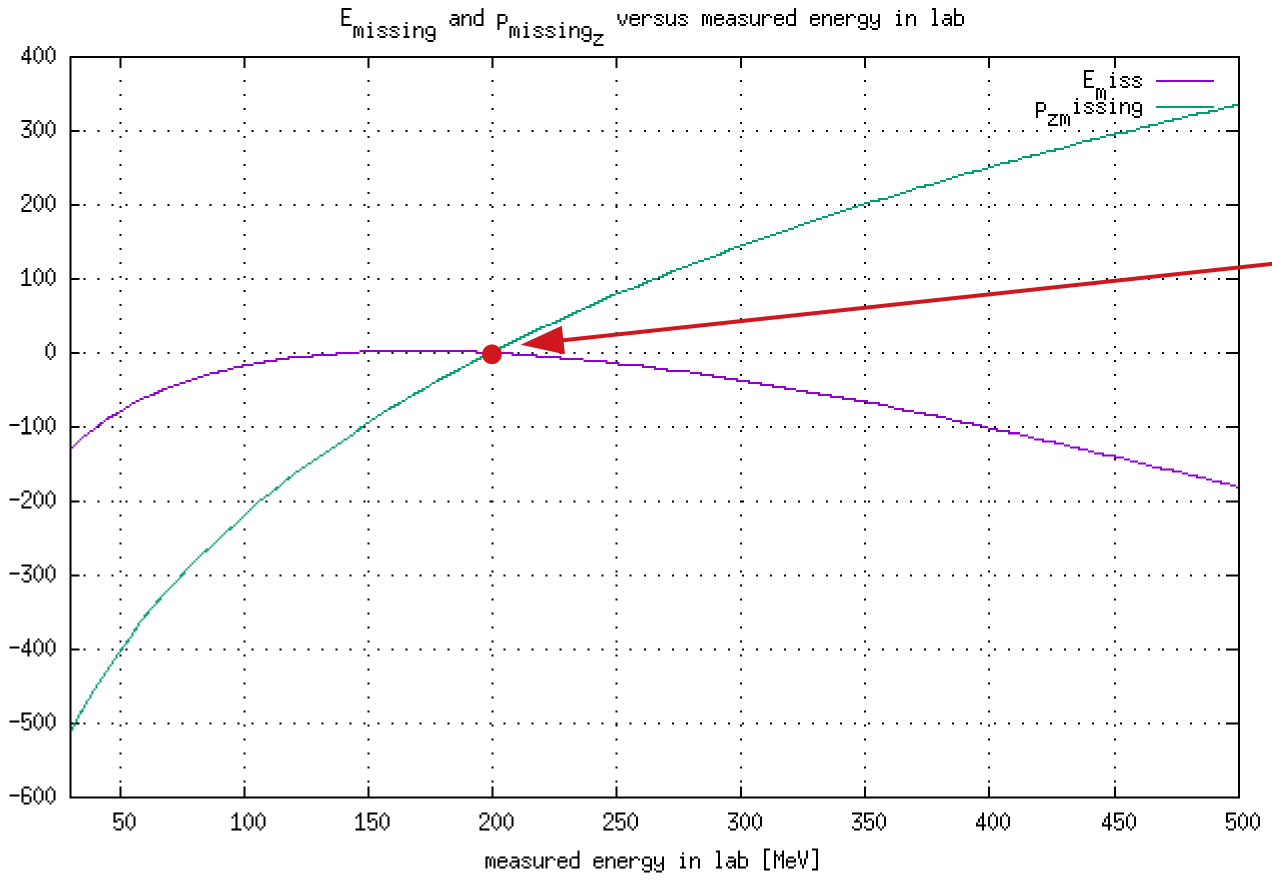
For simplicity let's say $\theta_1 = \theta_2$ and $E_{kin1} = E_{kin2}$. That means for theta_sum = 44 ° → $\theta_1 = \theta_2 = 22°$



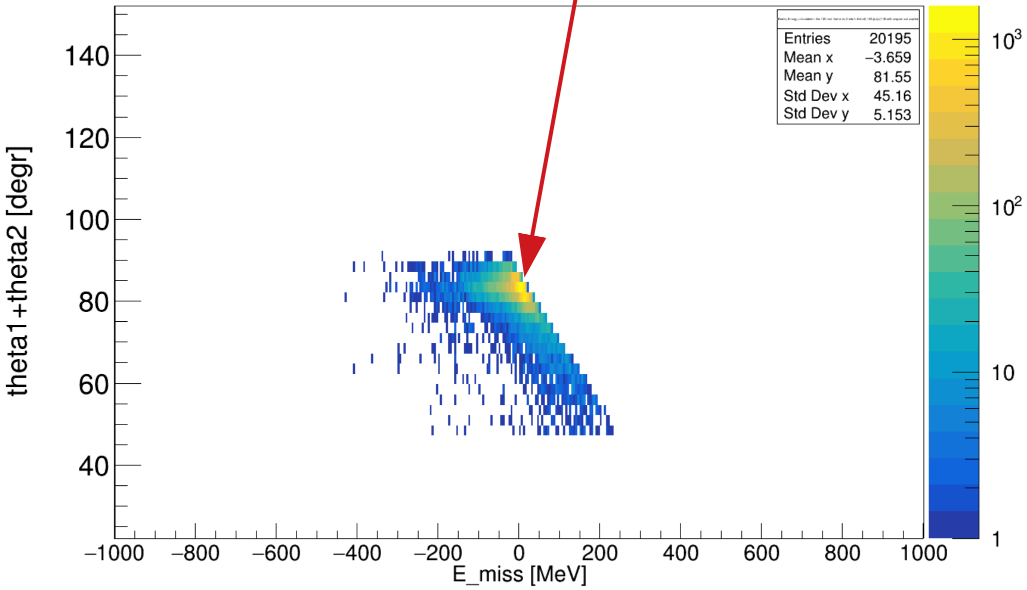
Maximum ≈ 270 MeV



E_missing and p_z_missing for $\theta_1 = \theta_2 = 42°$

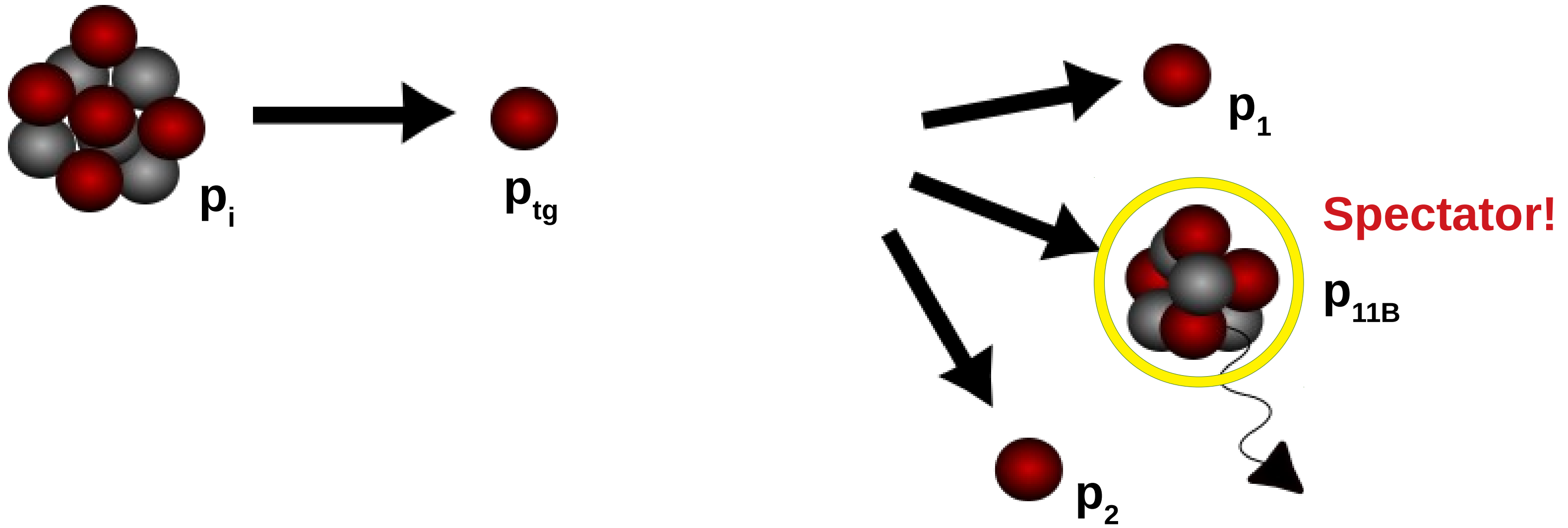


Quasi-Free Scattering reaction ≈ 84°

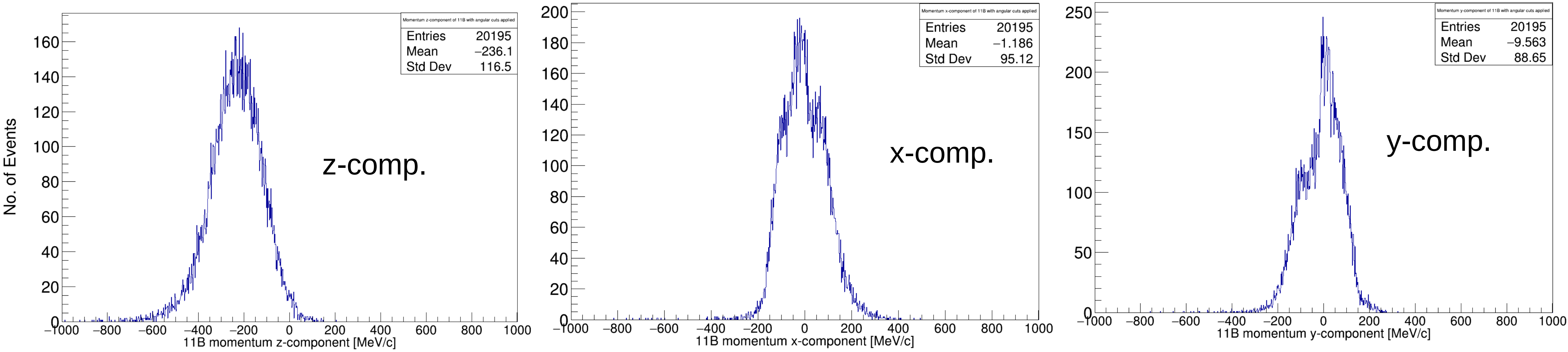


Momentum components of p_{11B}

Before Scattering: **After Scattering:**



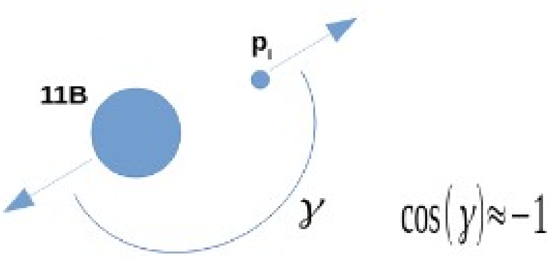
p_{11B} Momentum-Components (with angular cuts applied)



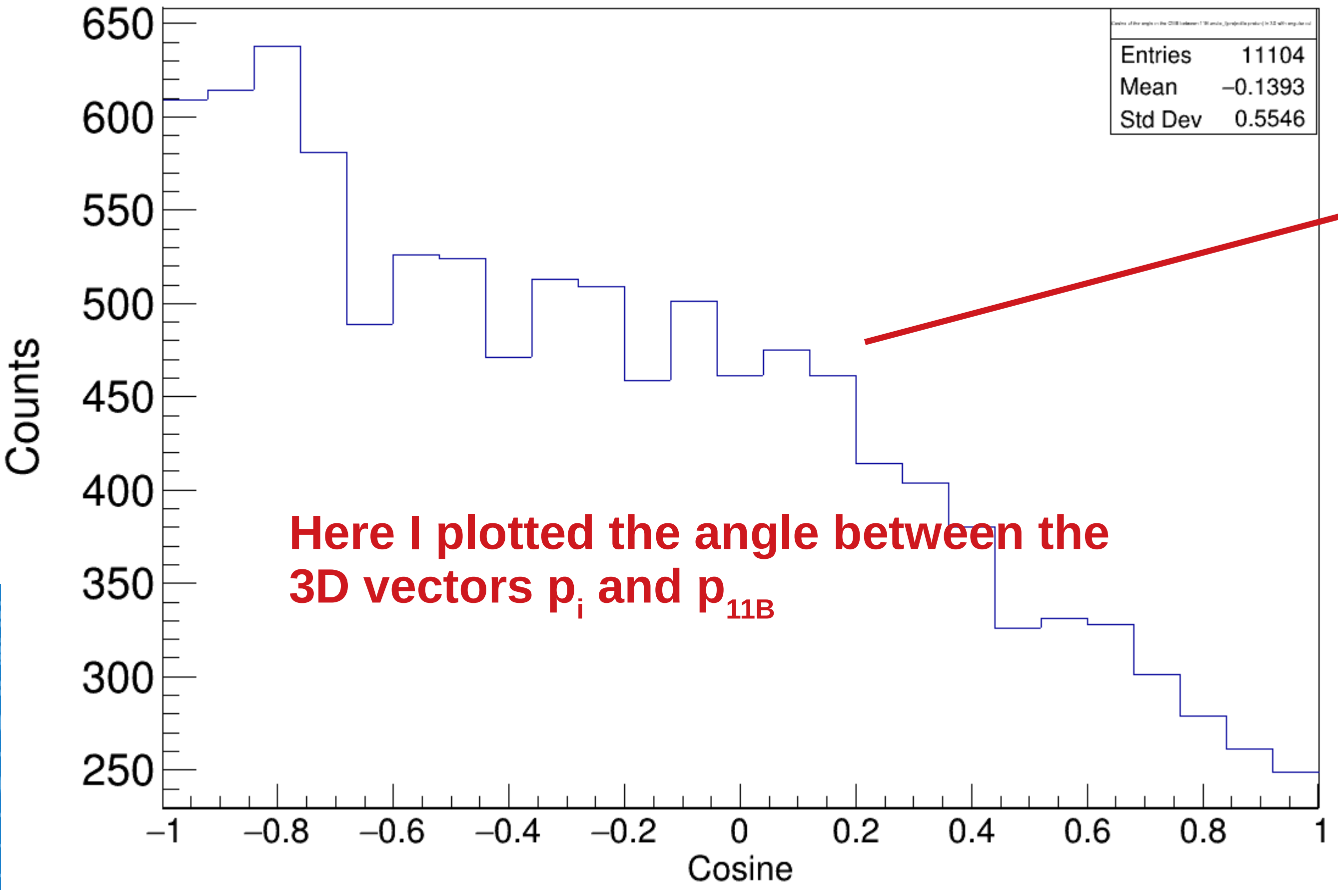
Inner angular distributions

- $\mathbf{p_i}$ determined by angle and energy deposition of p1 and p2
- $\mathbf{p_{11B}}$ determined by ToF and tracking detectors (MWPCs)

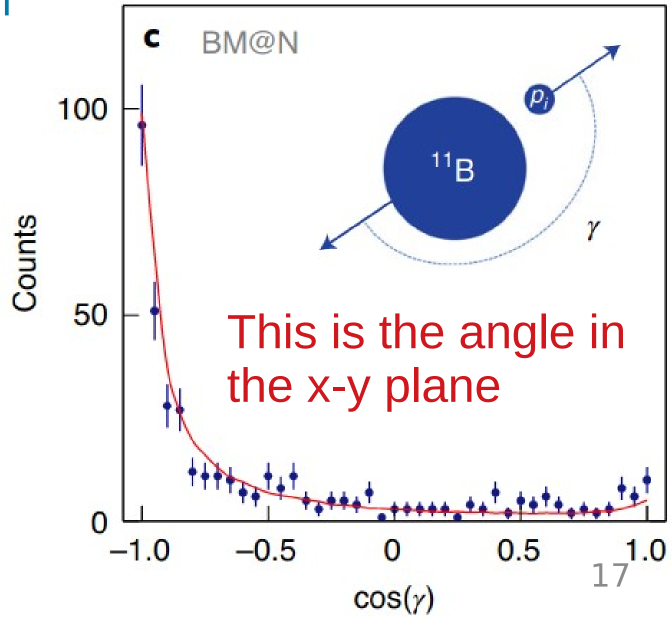
  (p11B_y was calculated by y-position in MW1 and MW2)



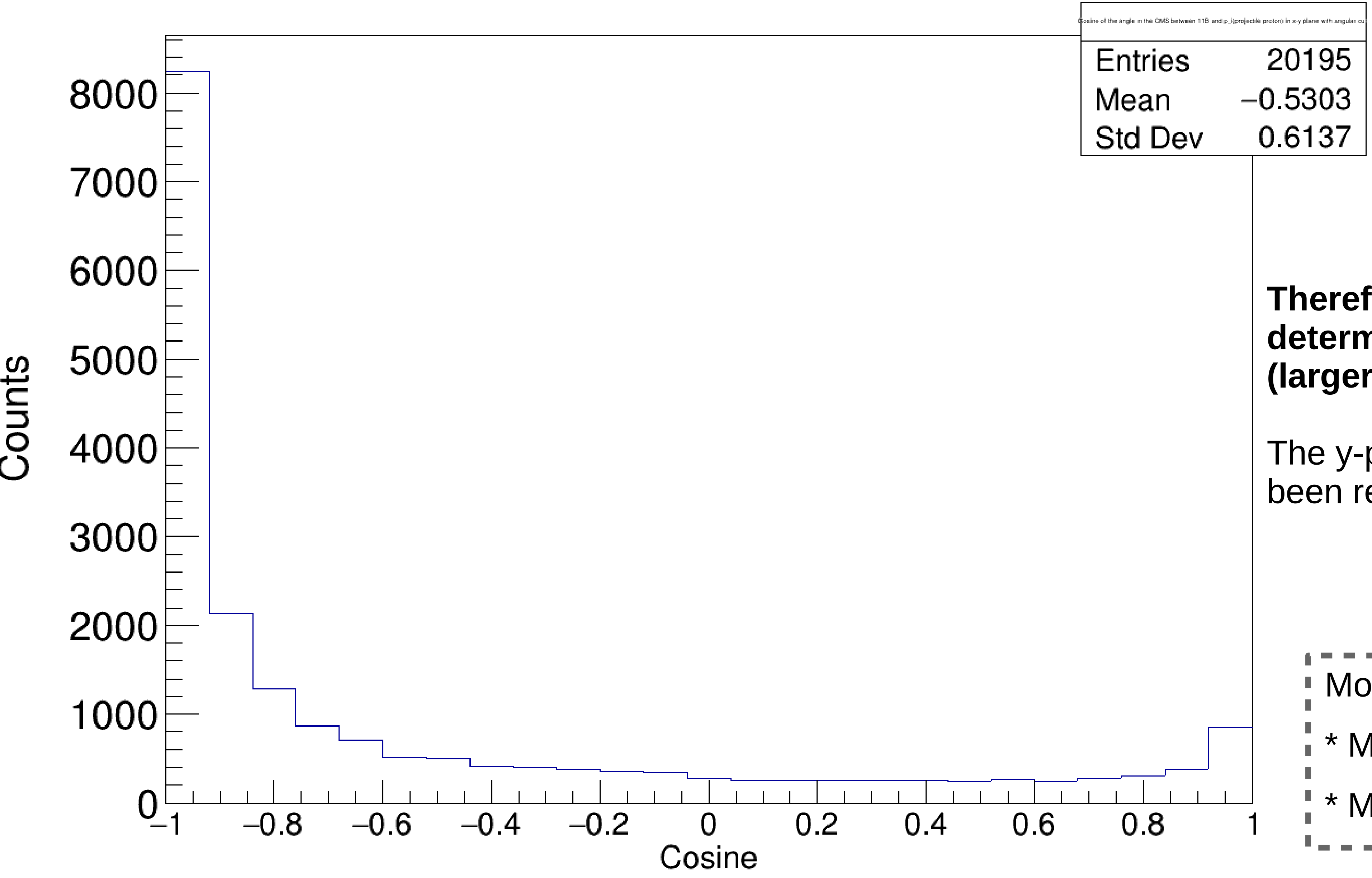
$$p_{12C} = p_i + p_{11B}$$



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:

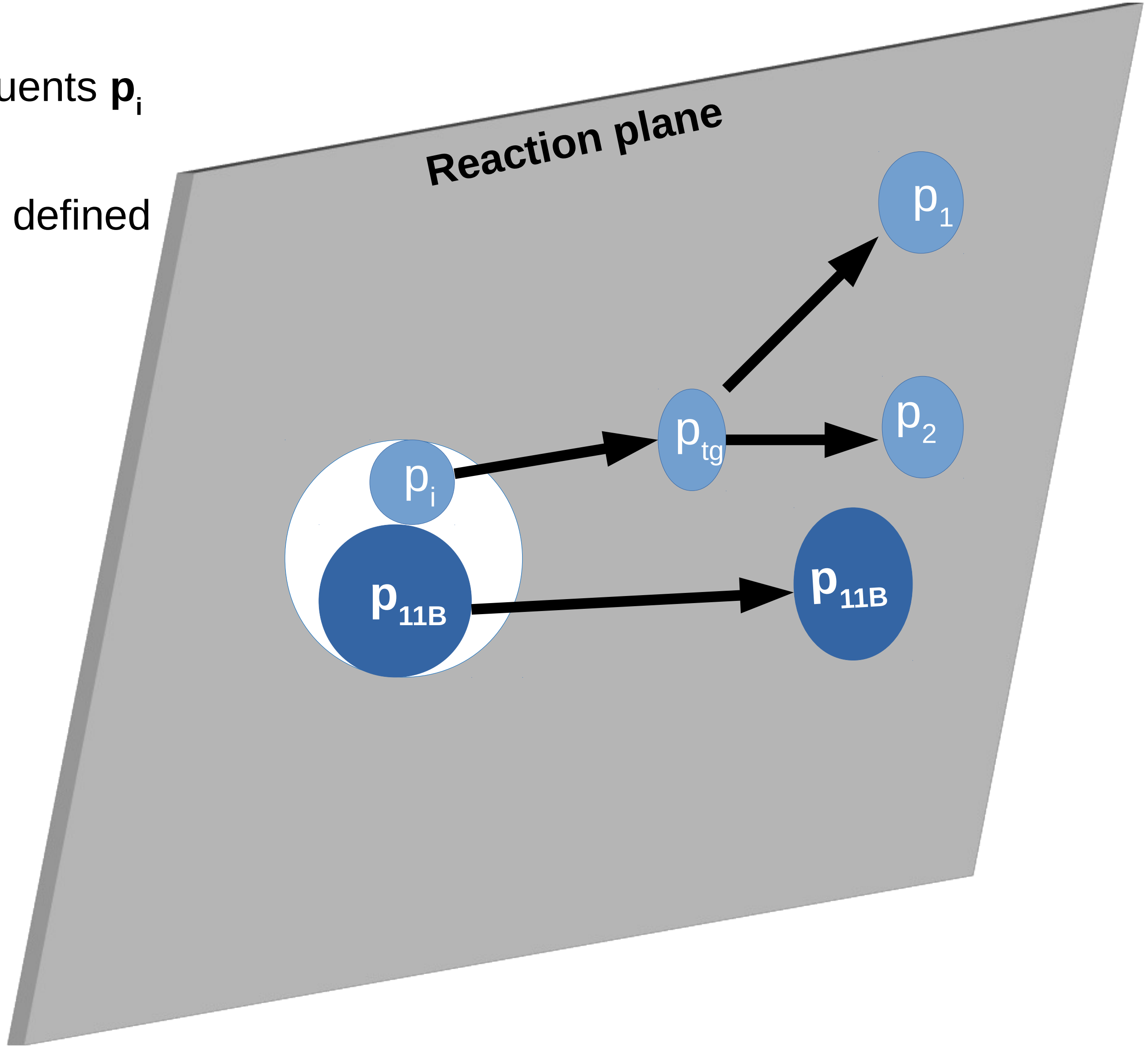
* MW0X inverted

* MW1Y and MW2Y swapped

Spatial Correlation of the Reaction Products

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

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



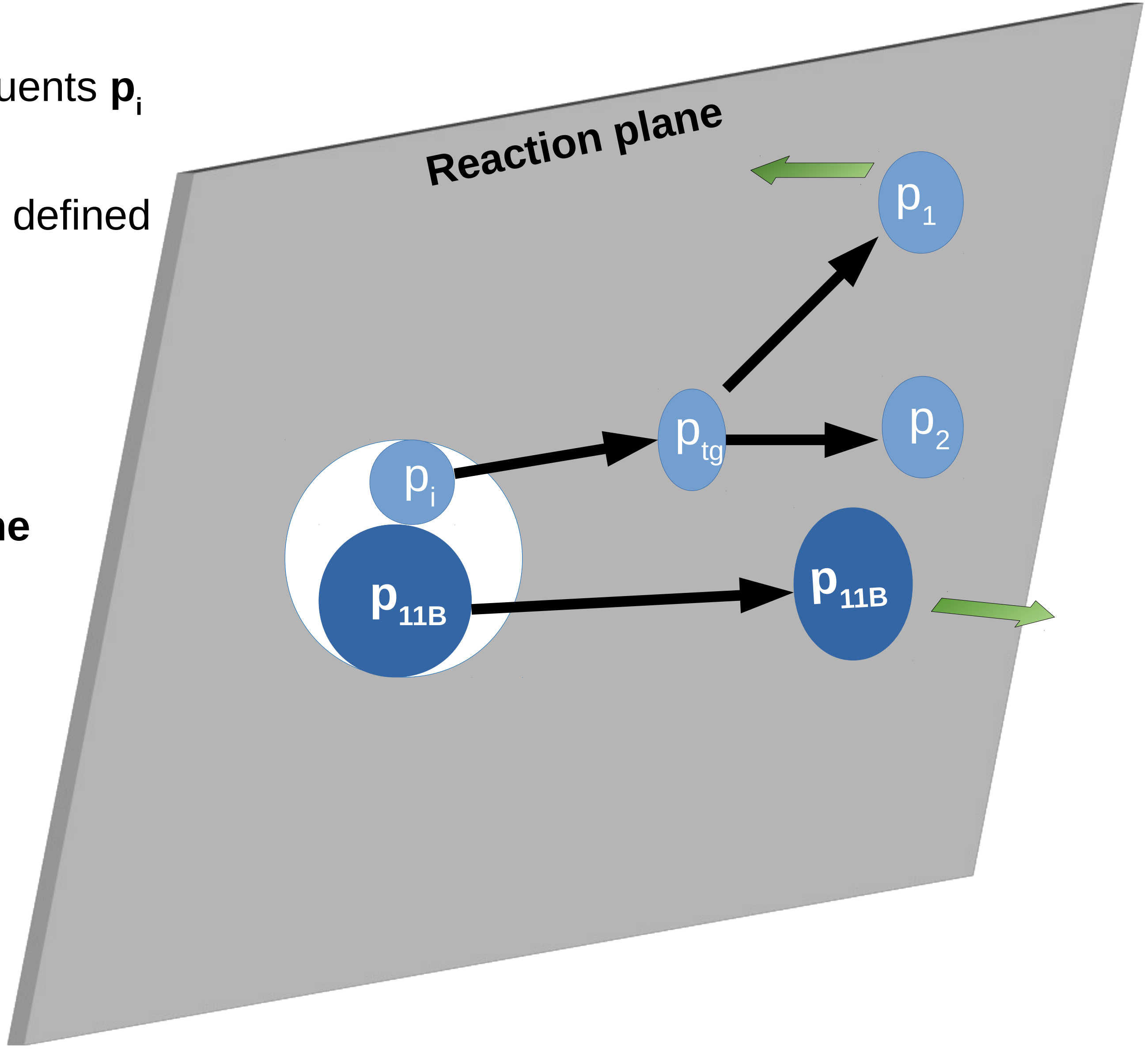
Spatial Correlation of the Reaction Products

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

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

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

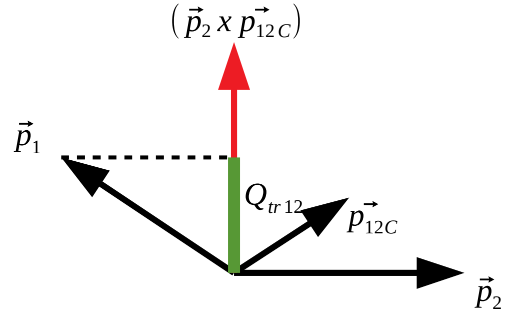
→ there are components perpendicular to the reaction plane!



Spatial Correlation of the Reaction Products

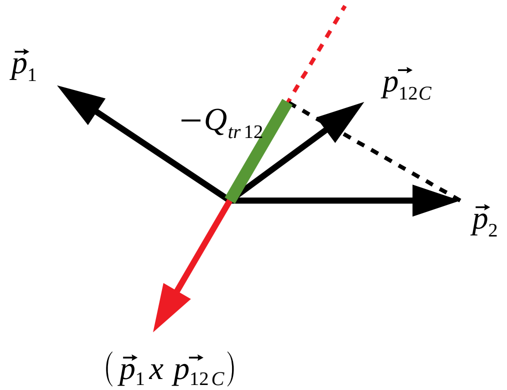
As measure of the overall perpendicular fraction to the reaction plane*:

$$Q_{tr\,12} = |\vec{p}_1| \frac{\vec{p}_1 * (\vec{p}_2 \, x \, \vec{p}_{12C})}{|\vec{p}_1| |\vec{p}_2 \, x \, \vec{p}_{12C}|}$$



or

$$Q_{tr\,21} = |\vec{p}_2| \frac{\vec{p}_2 * (\vec{p}_1 \, x \, \vec{p}_{12C})}{|\vec{p}_2| |\vec{p}_1 \, x \, \vec{p}_{12C}|} = -Q_{tr\,12}$$

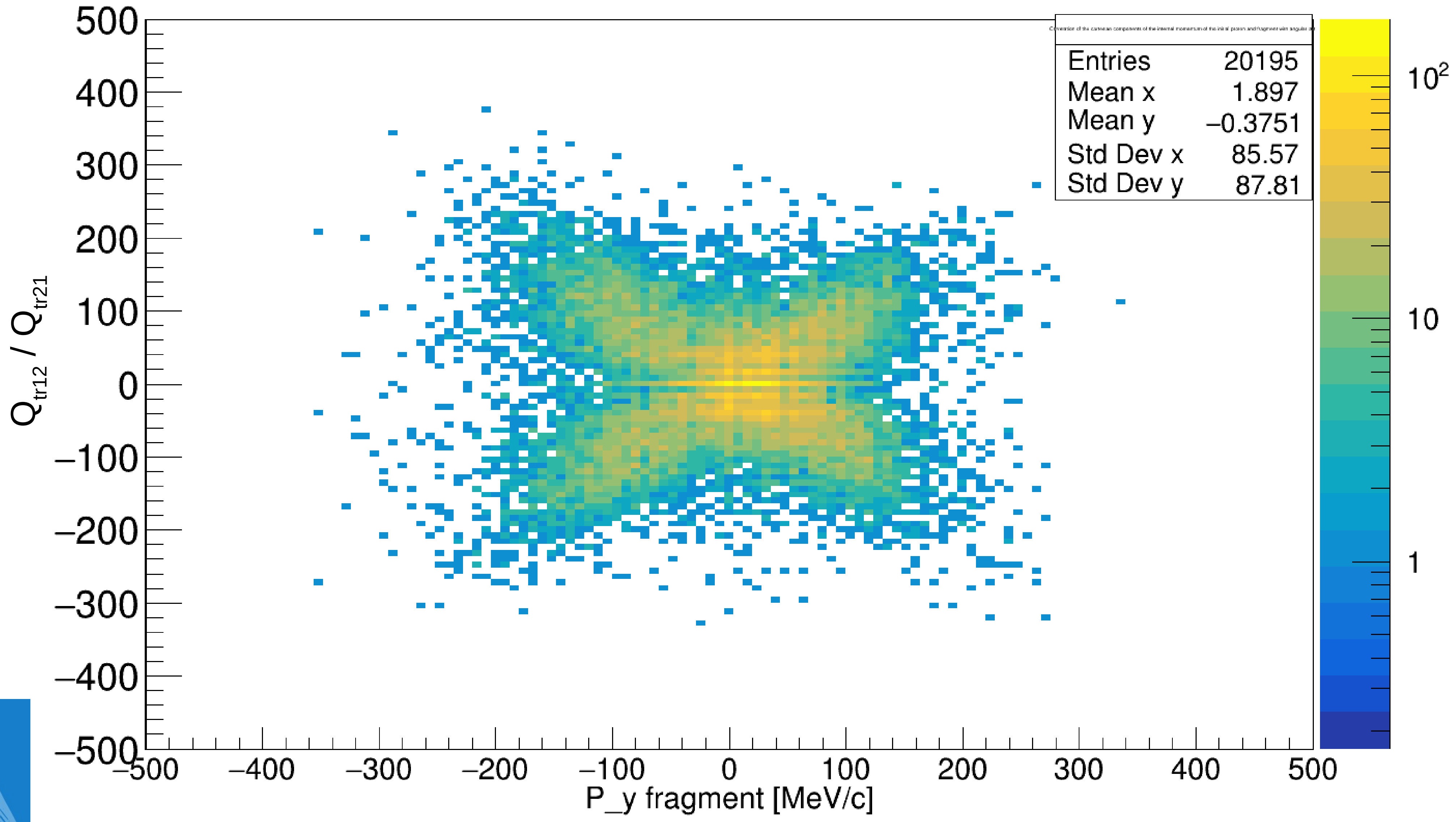


Due to momentum conservation:

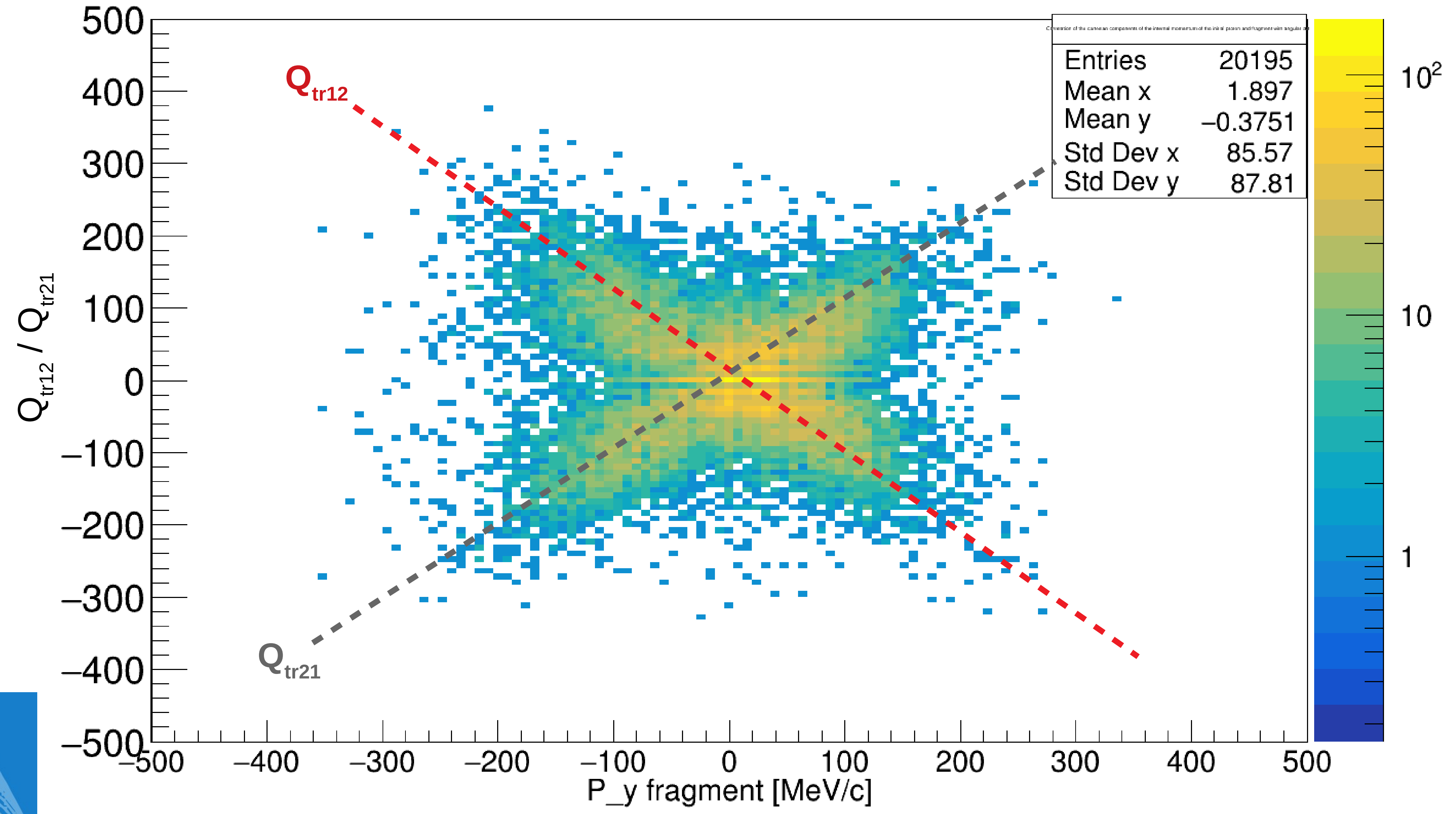
$$Q_{tr\,12} = -Q_{trFragment}$$

*Further details: https://www.sciencedirect.com/science/article/abs/pii/S0375947405008523

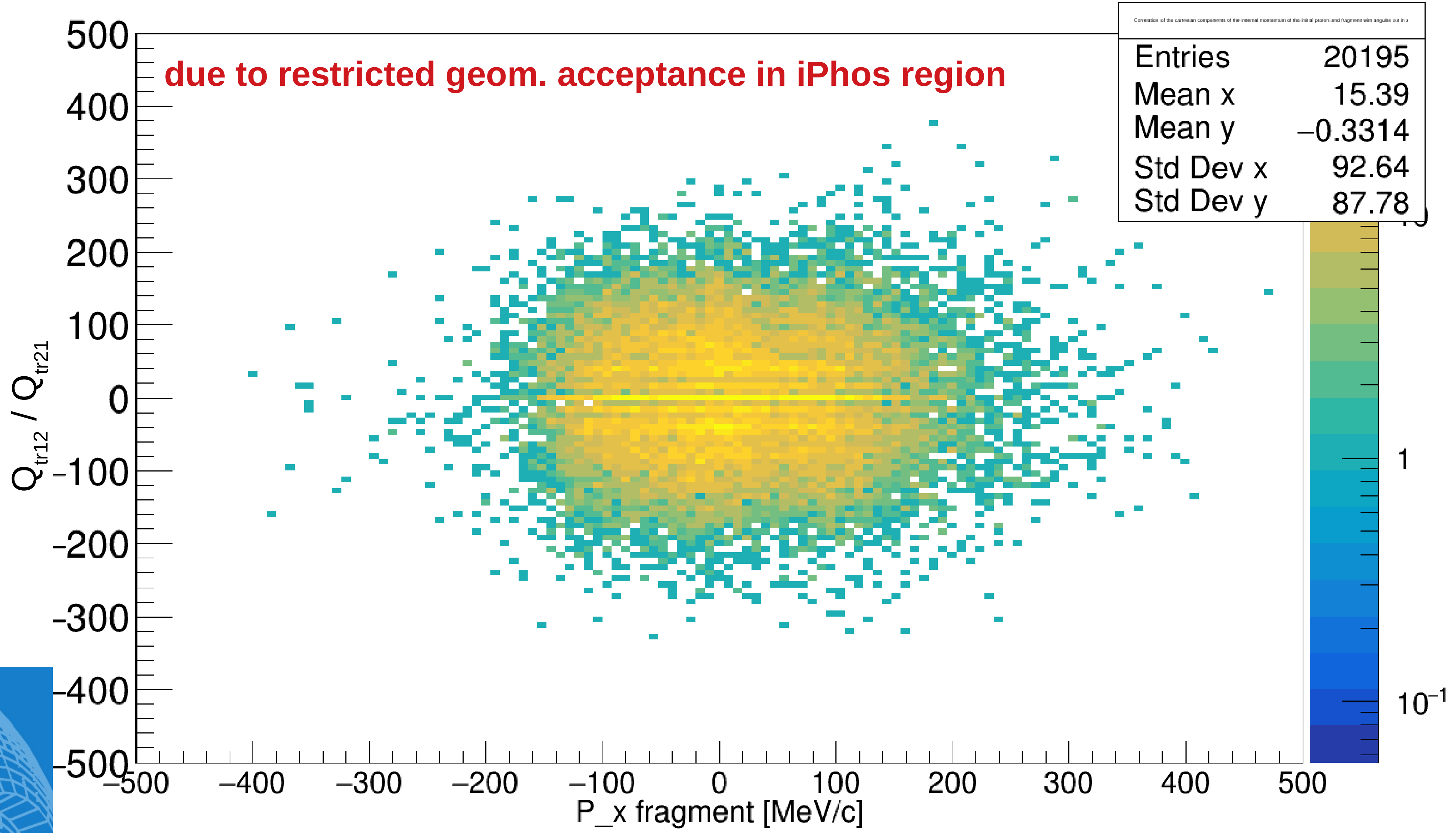
Q_{tr12} vs. $|\overrightarrow{p\_y}_{11B}|$



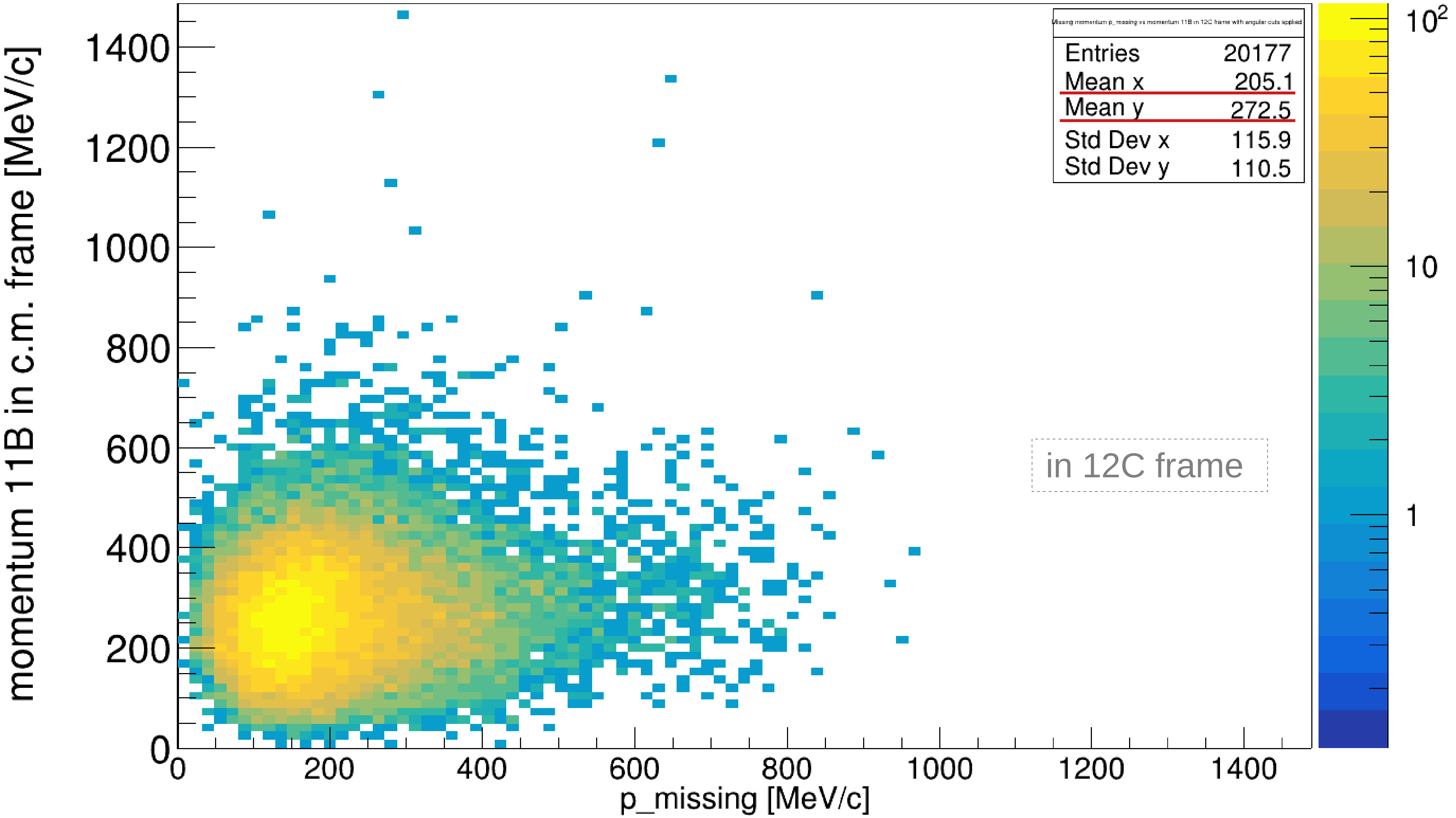
Q_{tr12} vs. $|\overrightarrow{p\_y}_{11B}|$



Q_{tr12} vs. $|\overrightarrow{p\_x_{11B}}|$



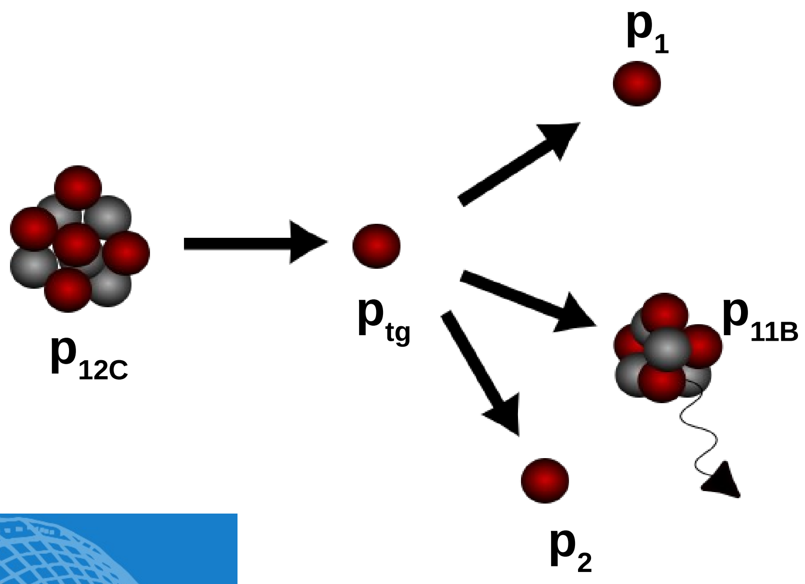
Momentum p_i vs p_11B in 12C

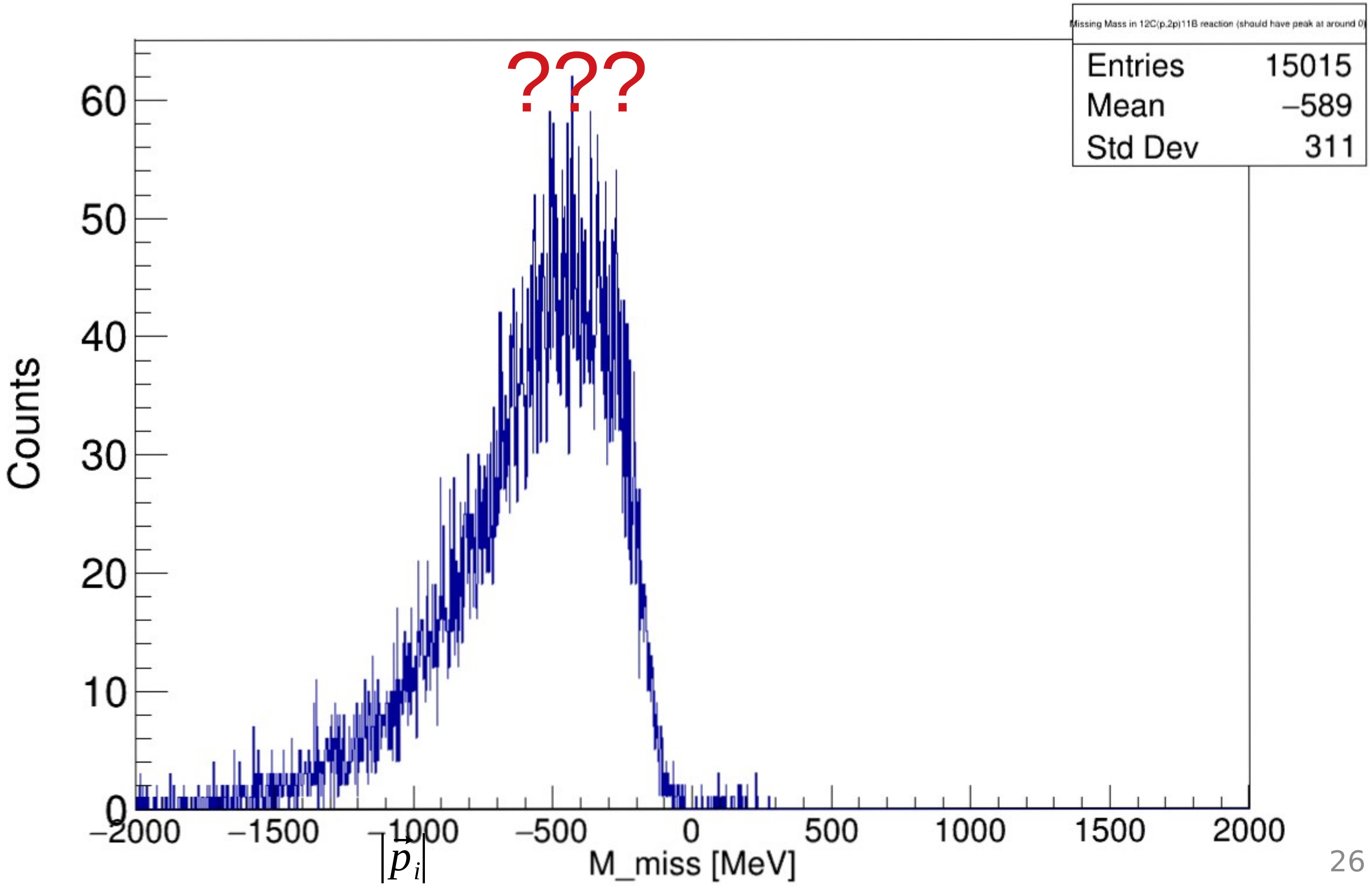


Missing Mass Reconstruction

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

(should be ≈ 0)

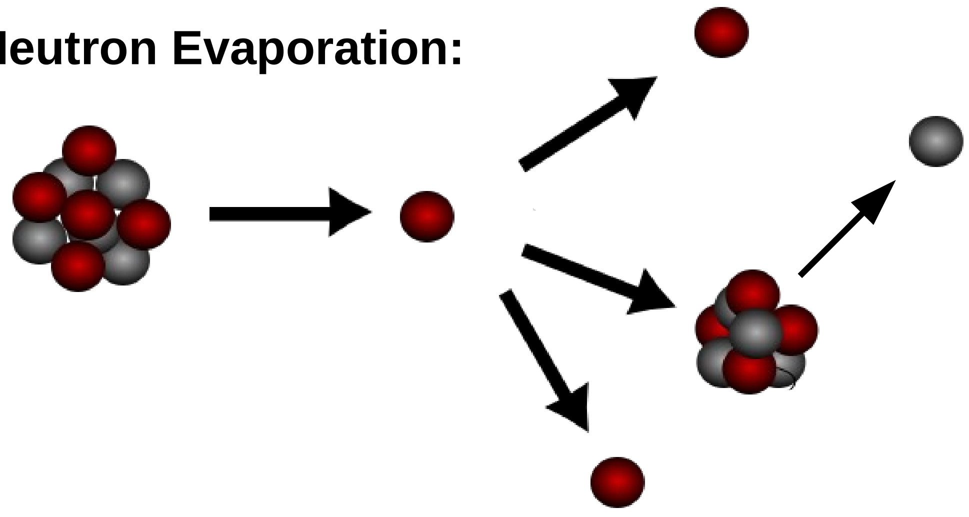




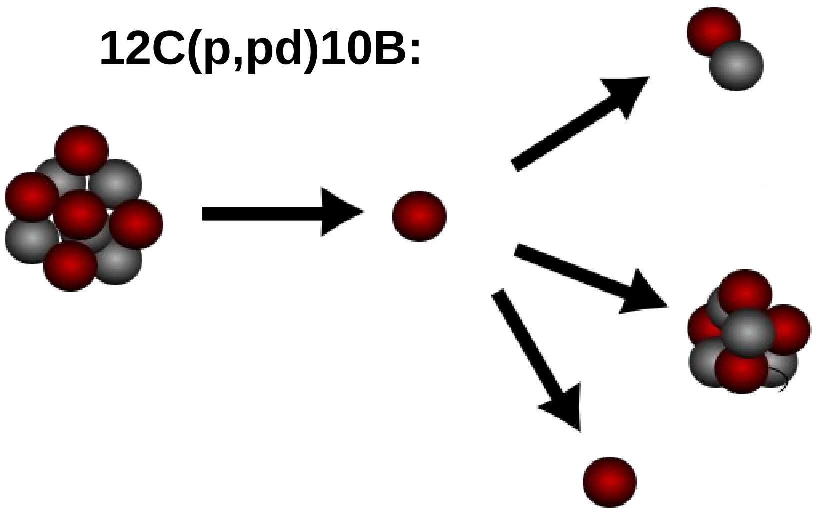
$|\vec{p}_i|$

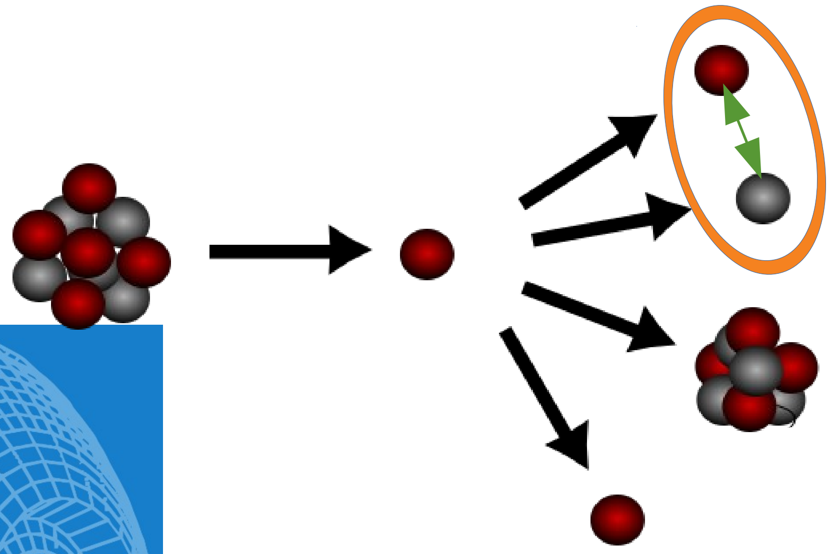
12C(p,ppn/pd)10B Reaction

Neutron Evaporation:



12C(p,pd)10B:



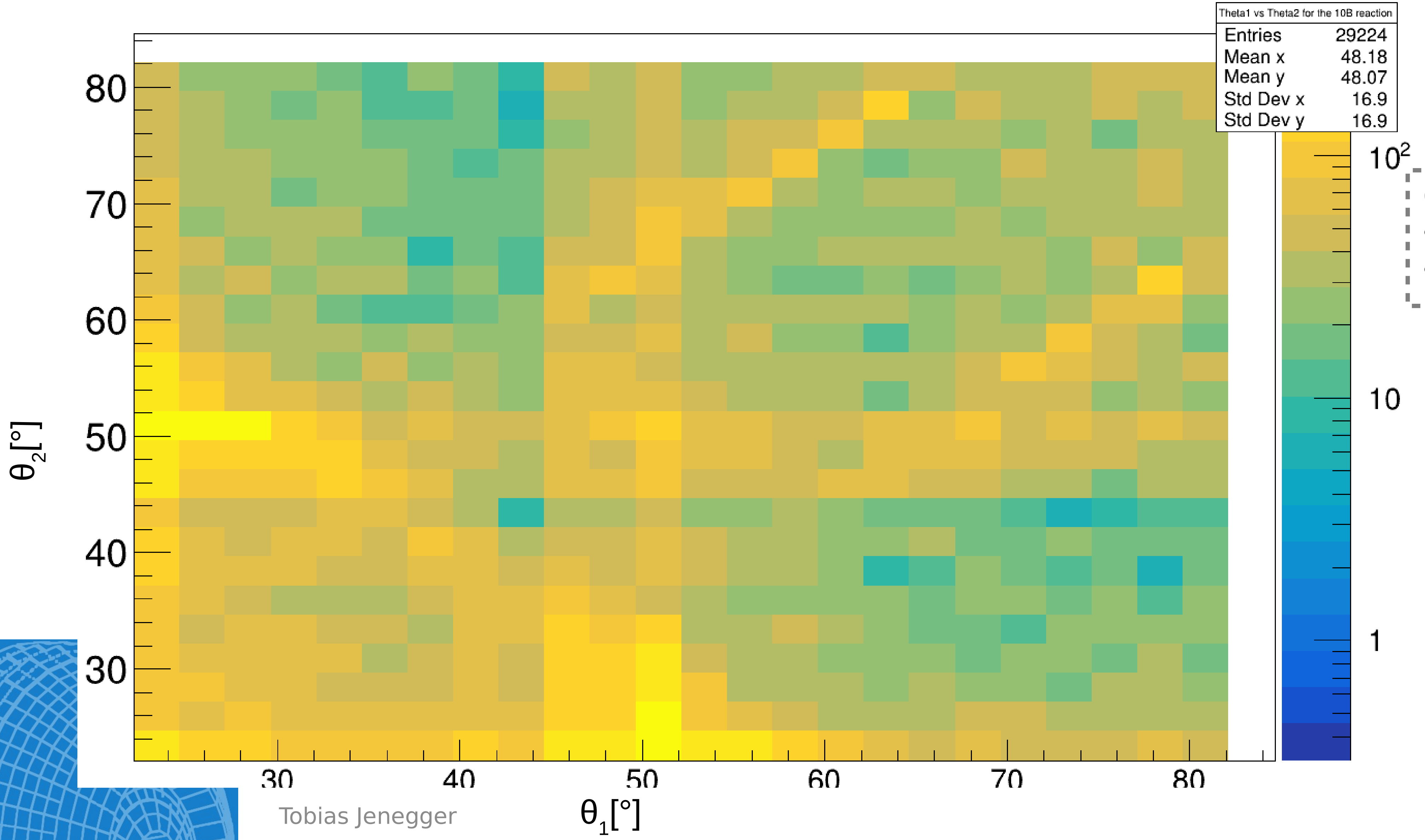


Short-Range-Correlated (SRC) Pair:

- 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 ...

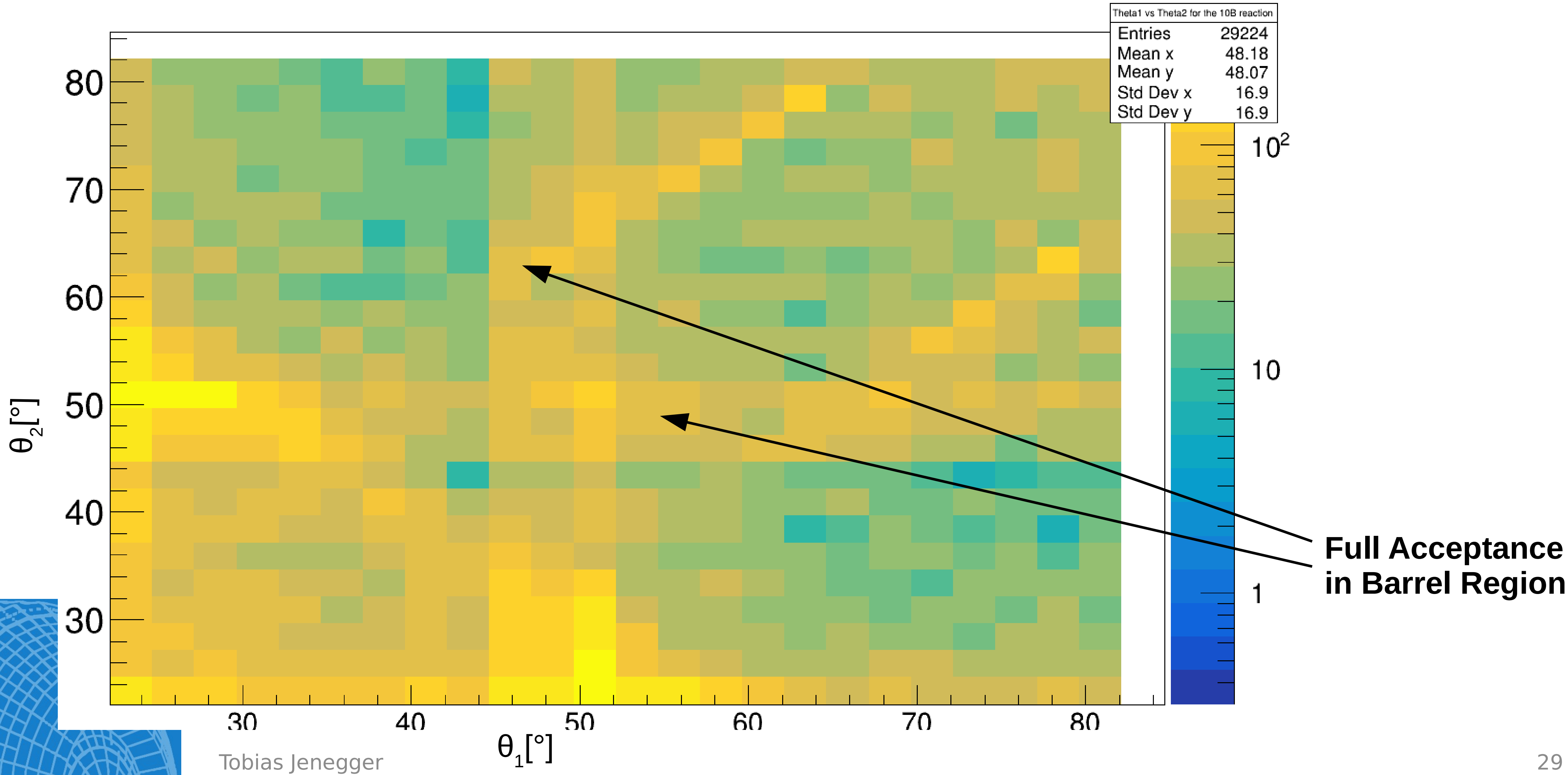
θ_1(proton 1) vs. θ_2 (proton2) without any angular restrictions:



Constraints:
- E_{1lab} and E_{2lab} > 30MeV
- Identification of 10B

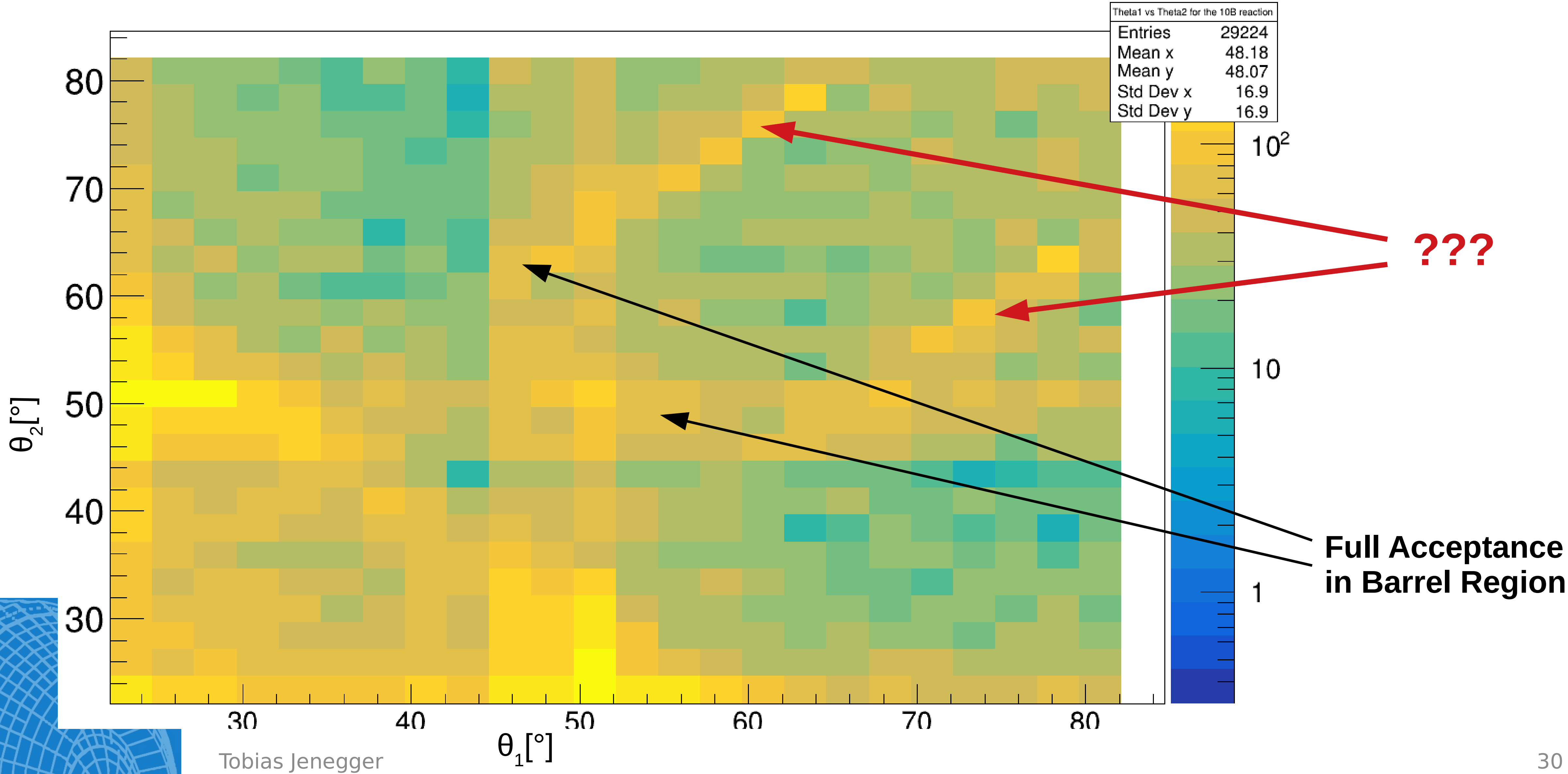
First (Polar) Angular Plots ...

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



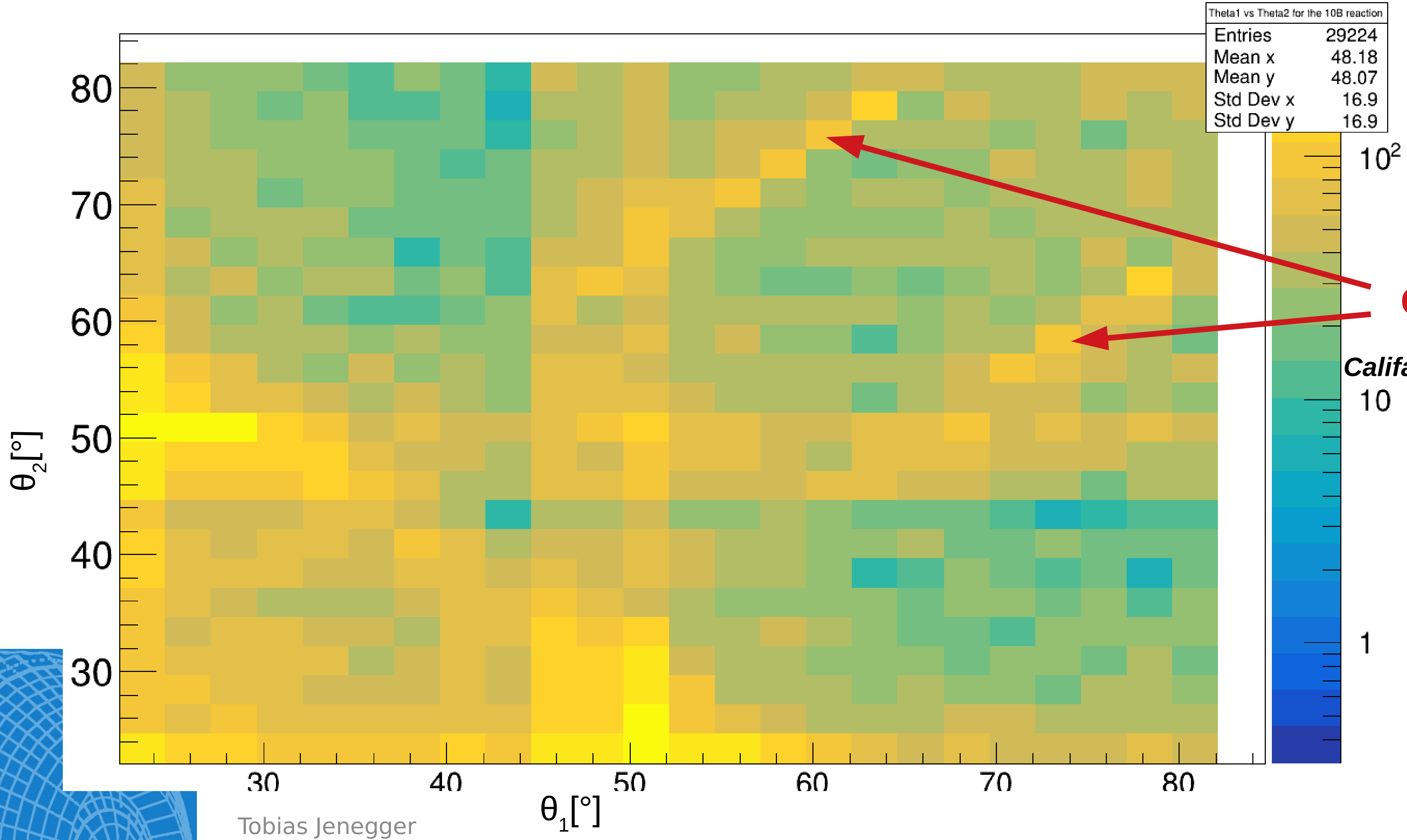
First (Polar) Angular Plots ...

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:

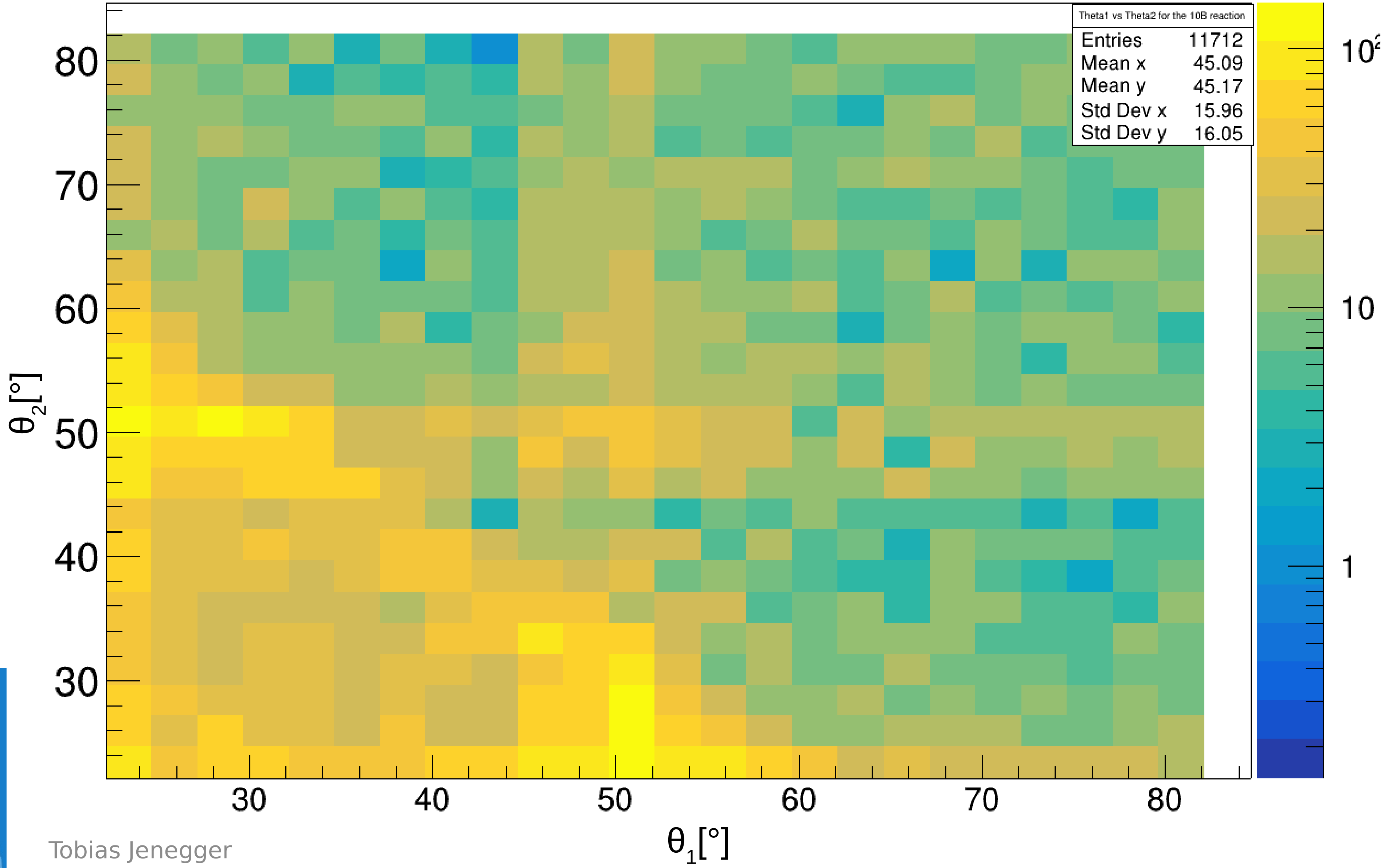


Cluster algoritm:

CalifaCal2Hit->SetConeAlg(0.25)

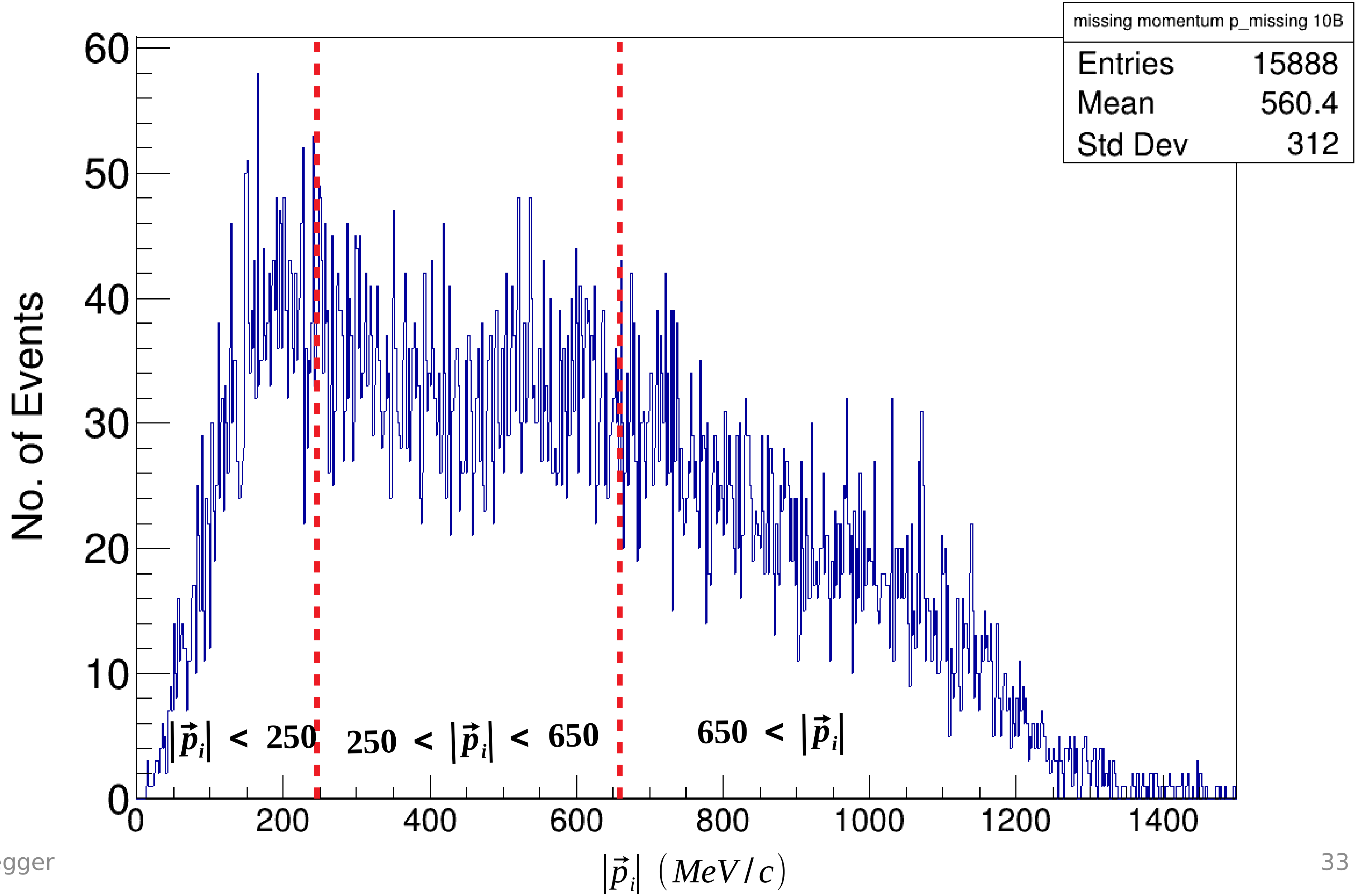
First (Polar) Angular Plots ...

θ_1(proton 1) vs θ_2 (proton2) with angular cut: $\Delta\varphi > 100°$

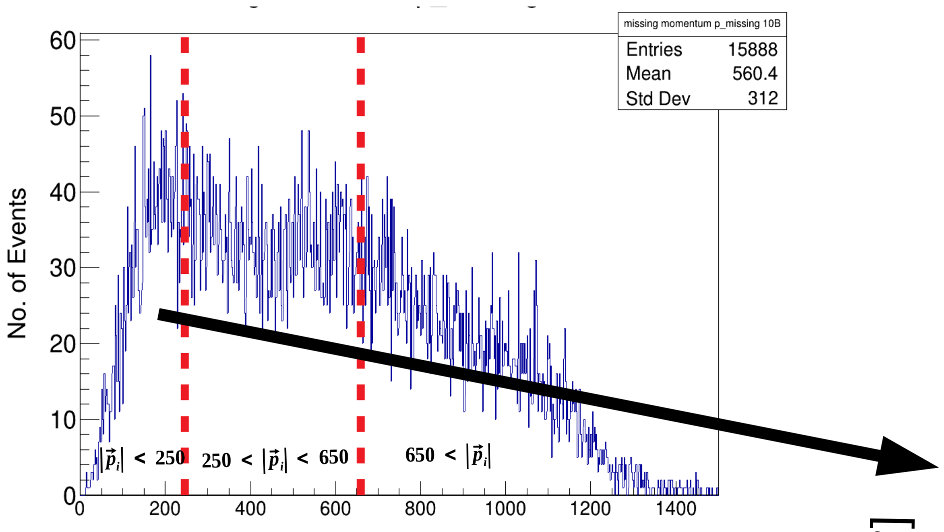


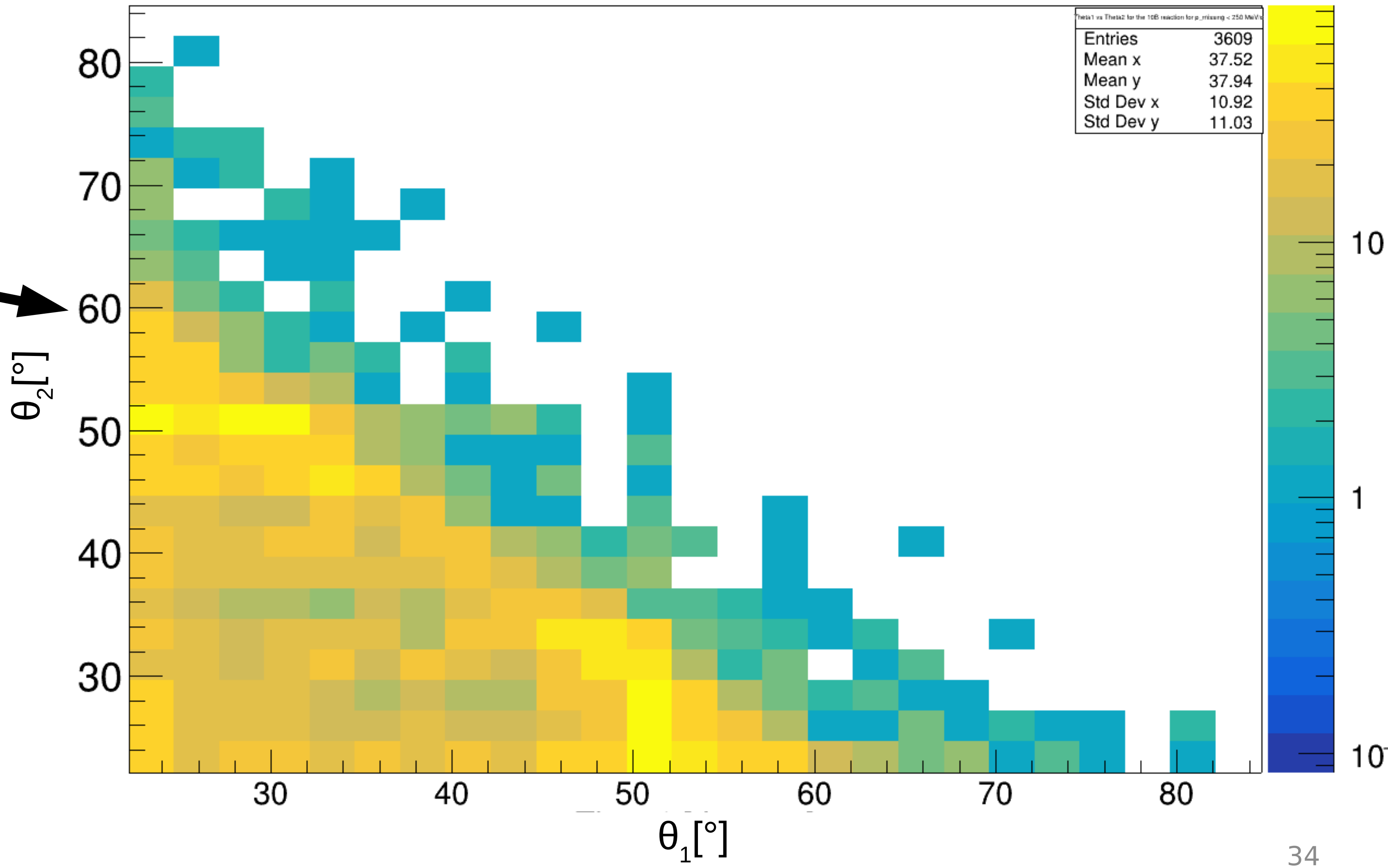
Reconstruction of inner momentum p_i

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

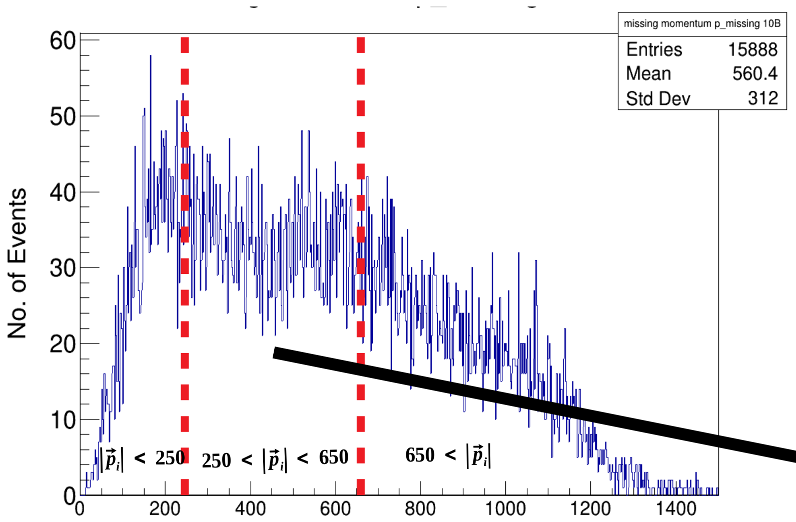


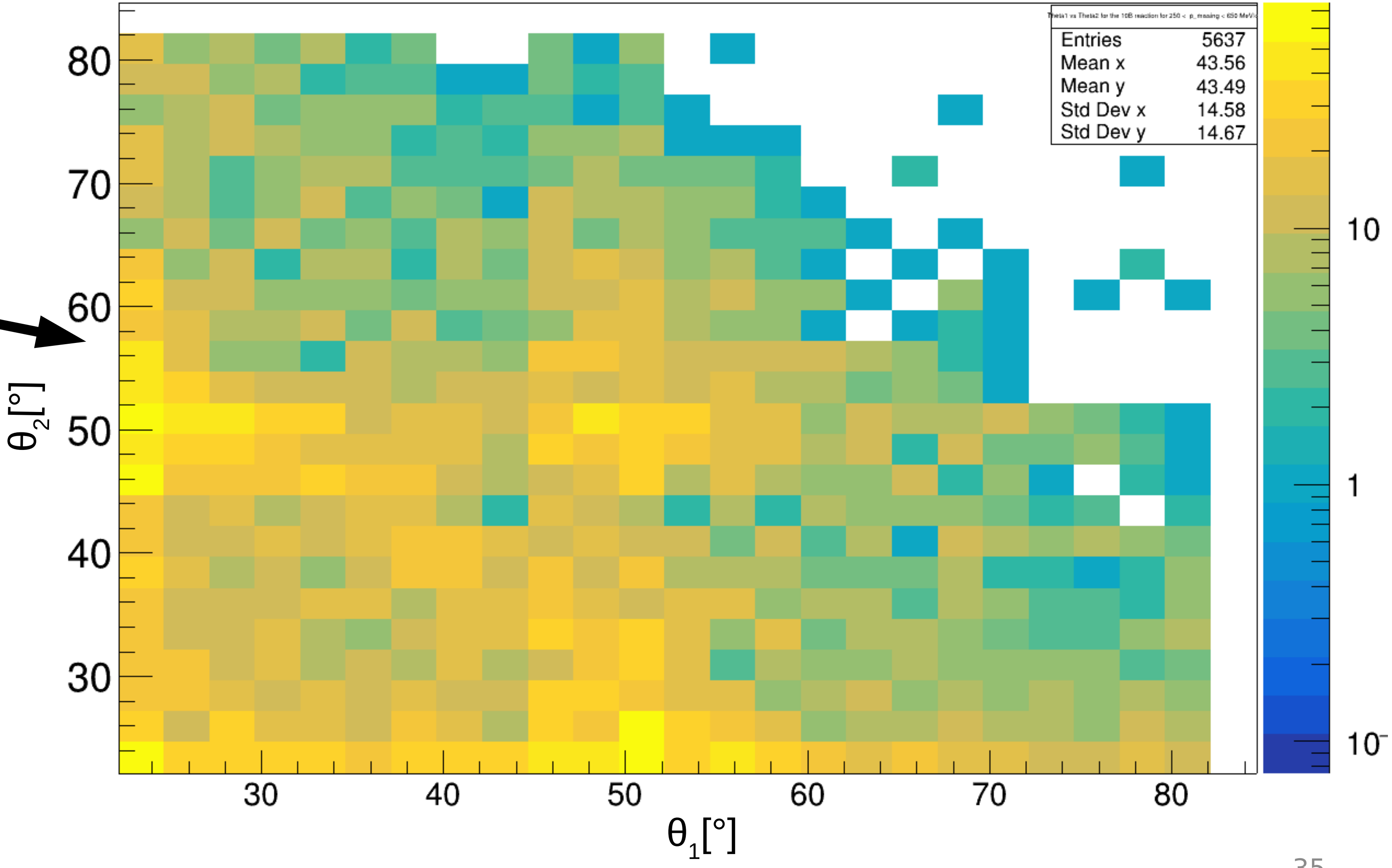
Angular Distribution for $|\vec{p\_i}| < 250$



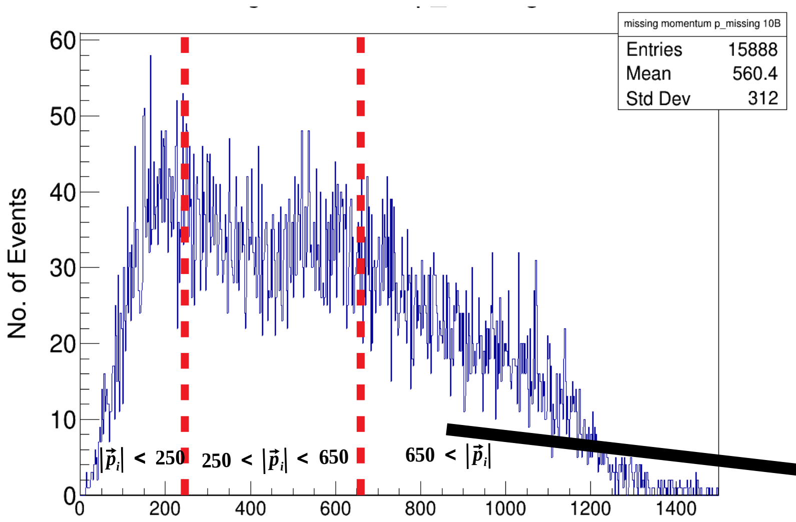


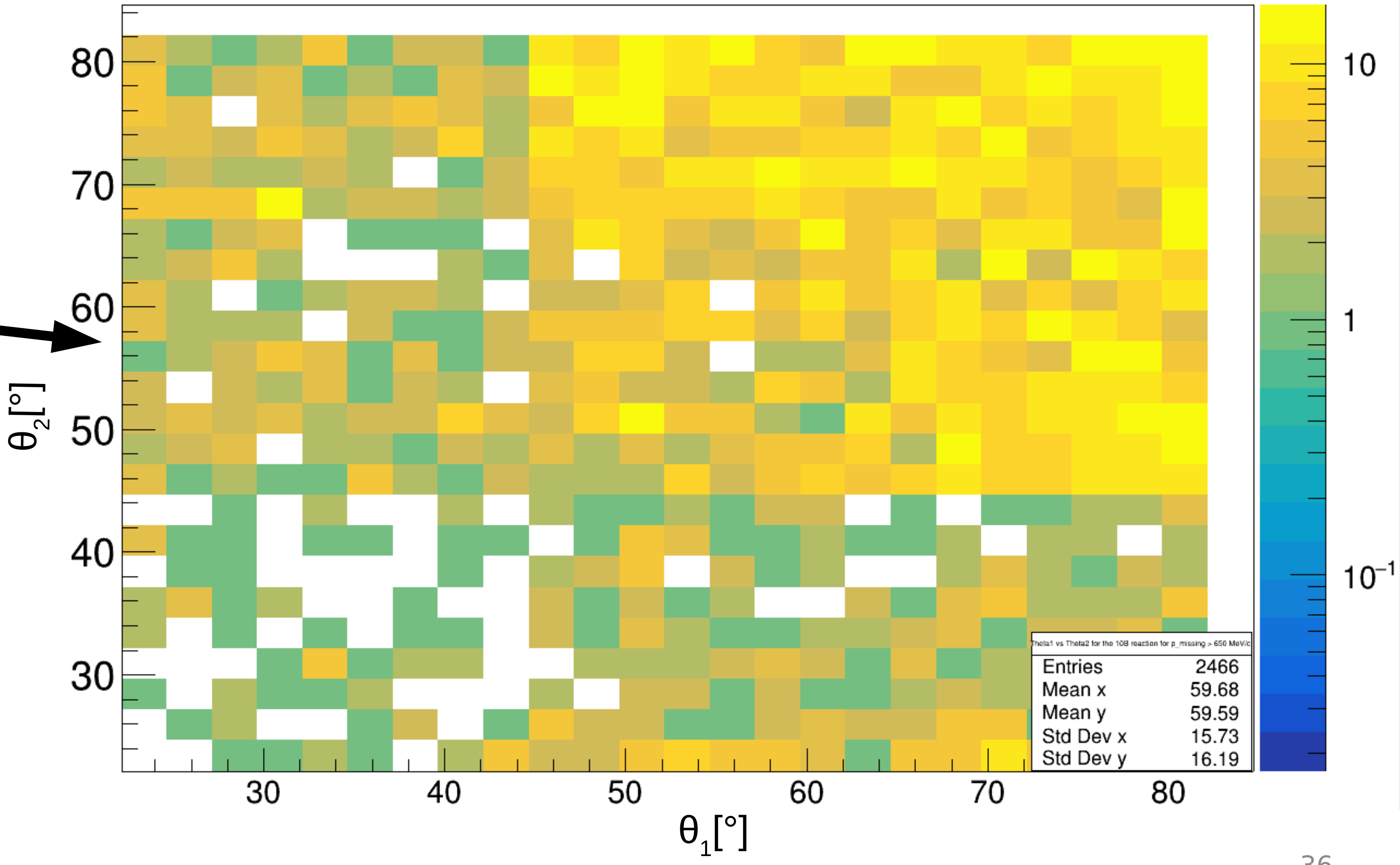
Angular Distribution for 250 MeV/c < $|\vec{p\_i}|$ < 650 MeV/c





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

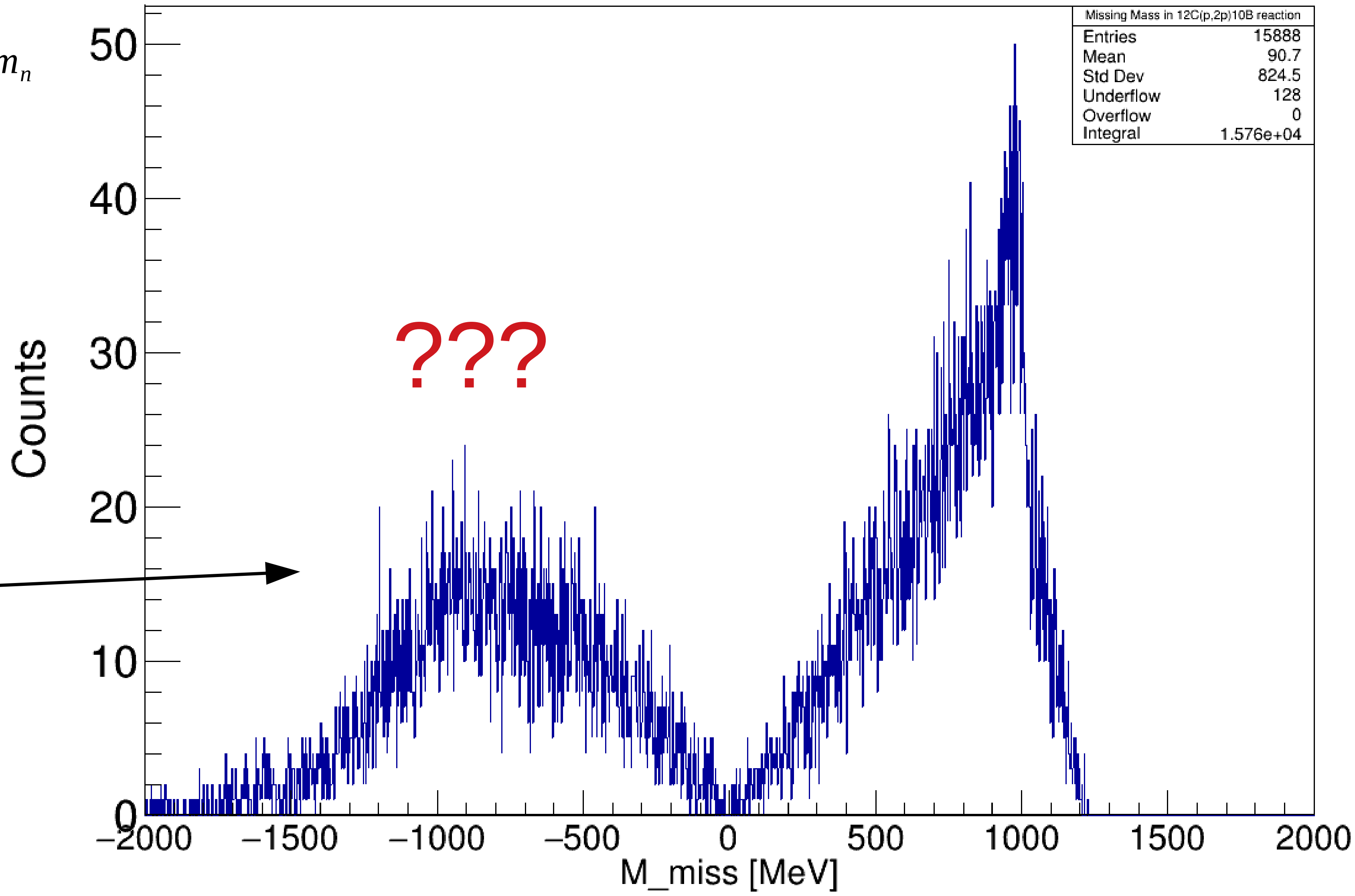




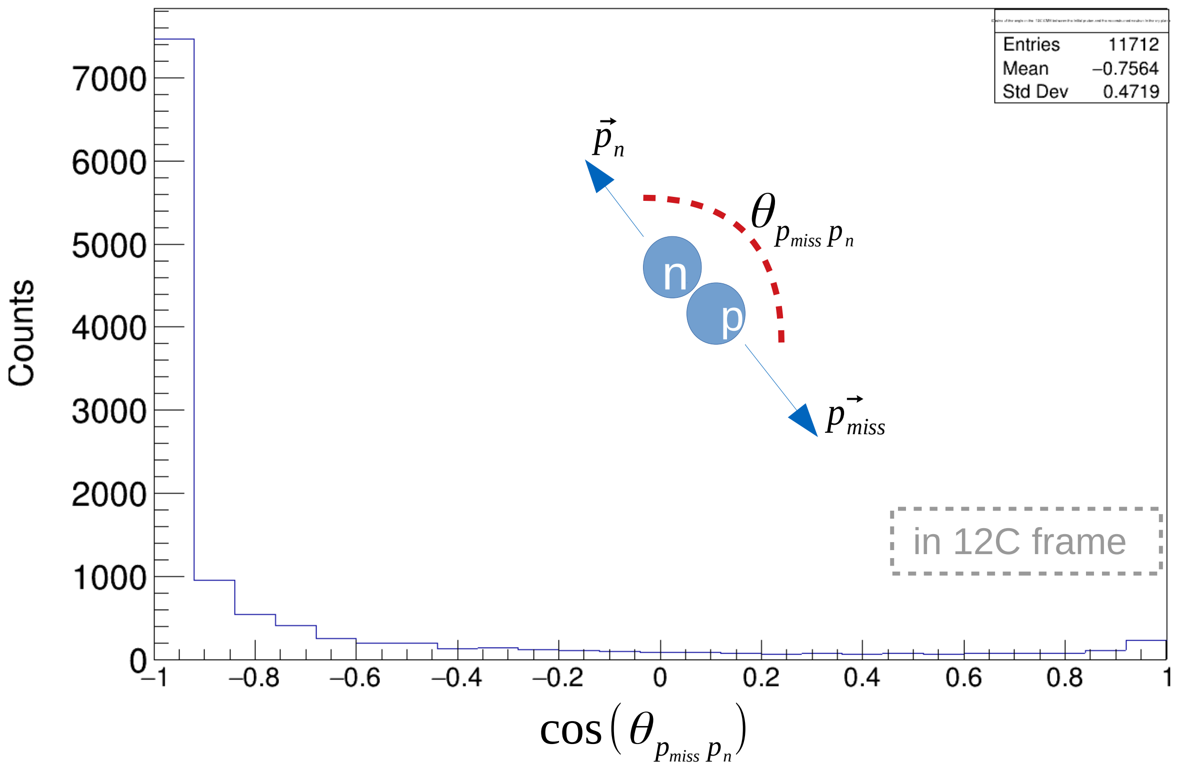
Neutron Mass Reconstruction

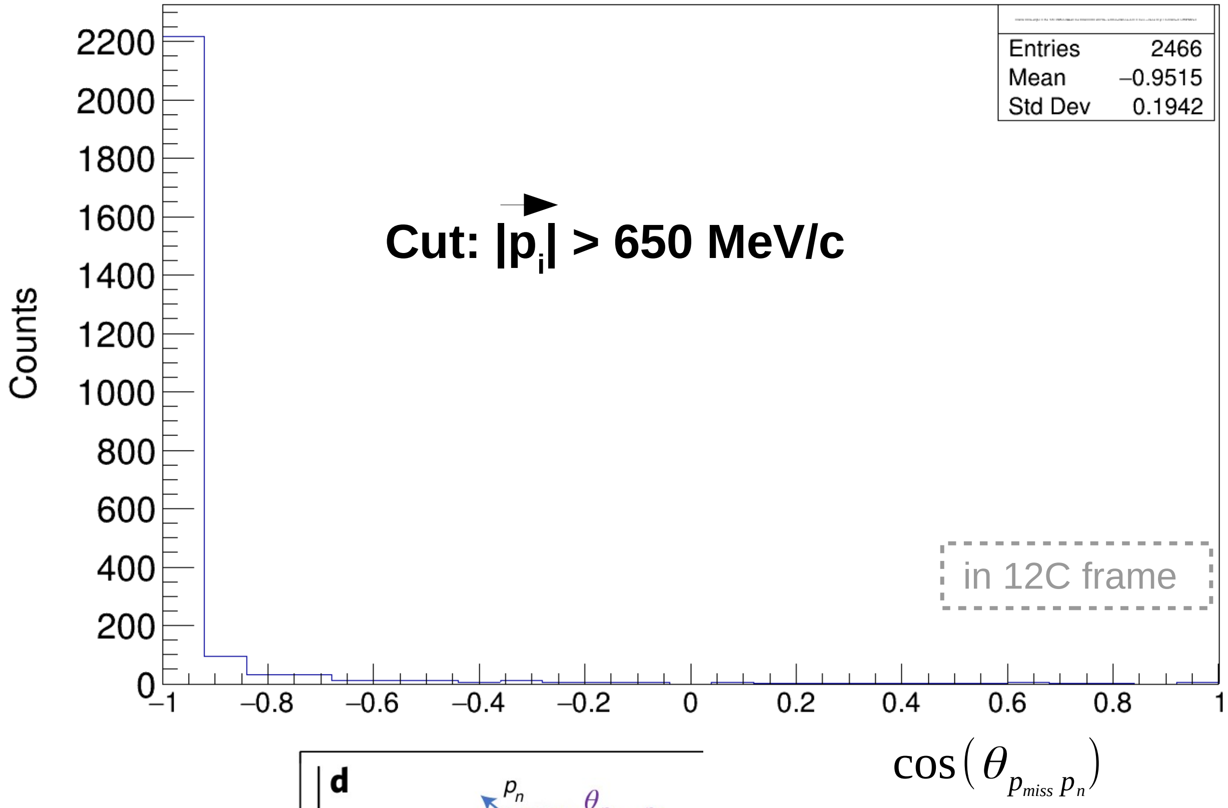
$$M^2_{missing} = \left(\underbrace{p_{12C} + p_{tg}}_{\text{before reaction}} \underbrace{- p_1 - p_2 - p_{10B}}_{\text{after reaction}}\right)^2 \approx m_n$$

Possible Explanations:
→ boosting effects
→ biased z-momenta
→ further checks needed

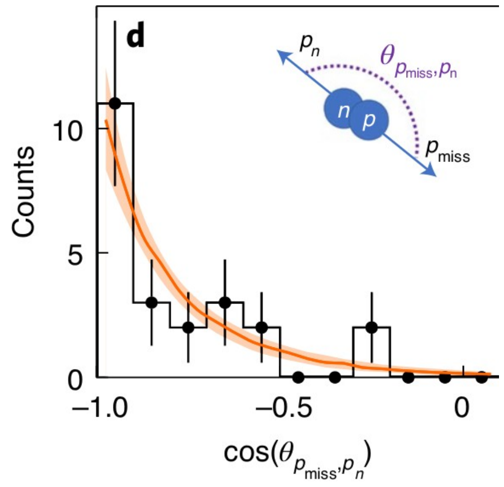


Angular Correlations for 12C(p,ppn/pd)10B in the x-y plane

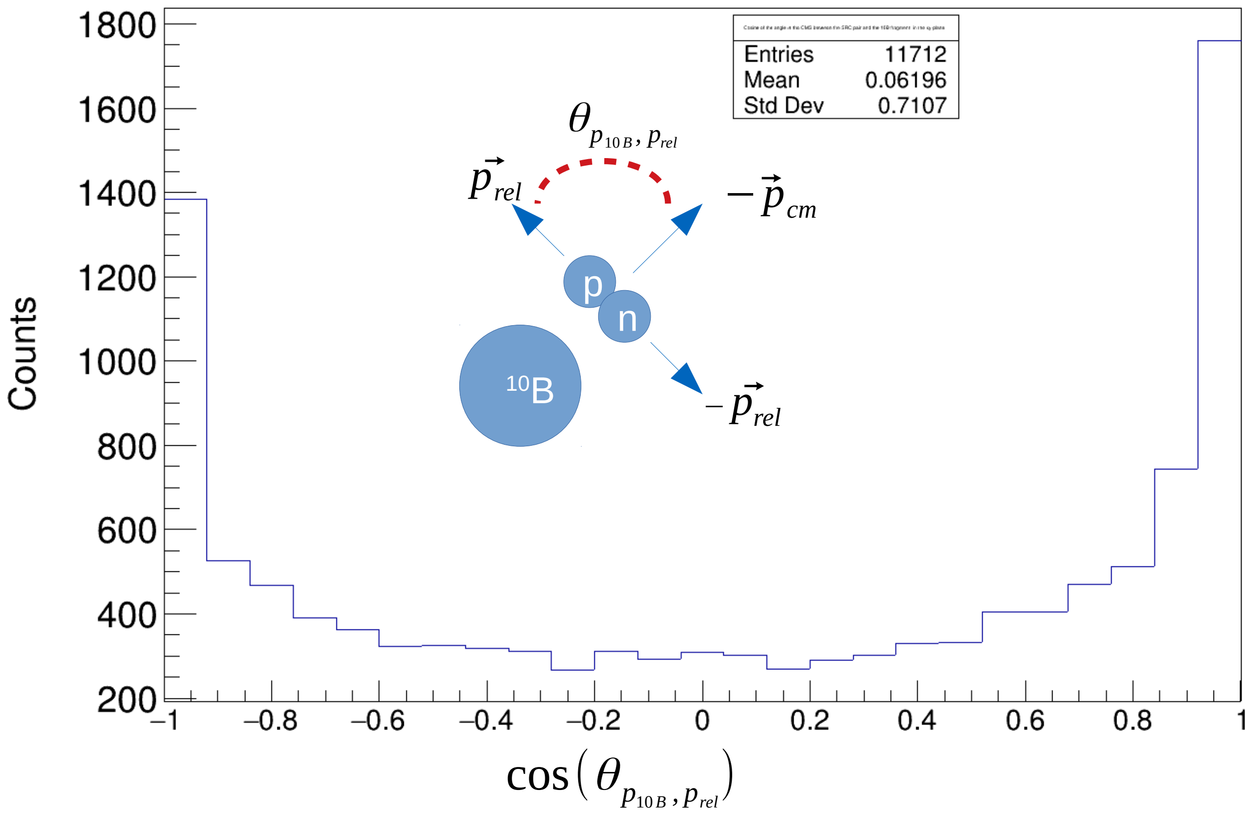


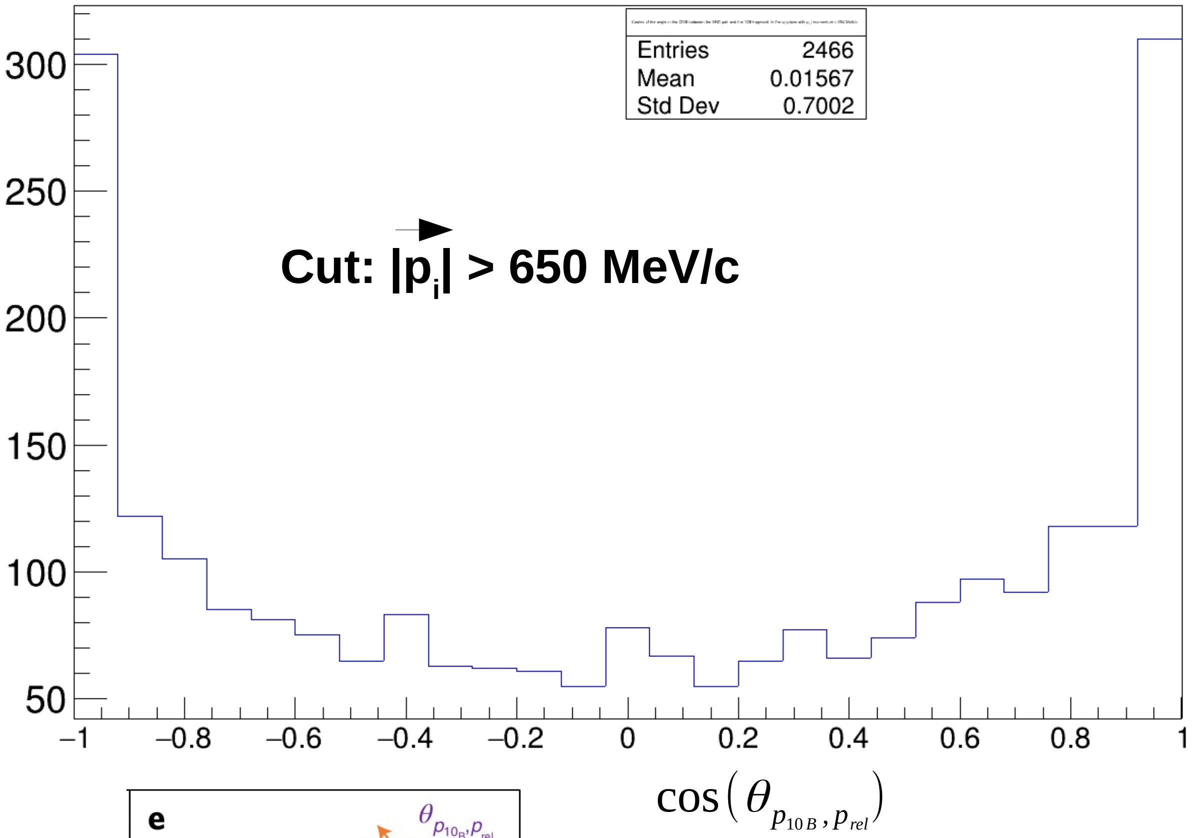


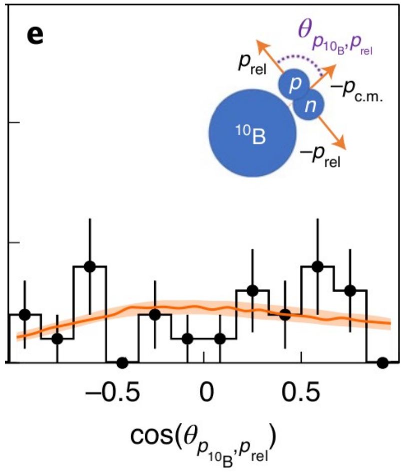
Compare to:
https://www.nature.com/articles/s41567-021-01193-4.pdf



Angular Correlations for 12C(p,ppn/pd)10B in the x-y plane



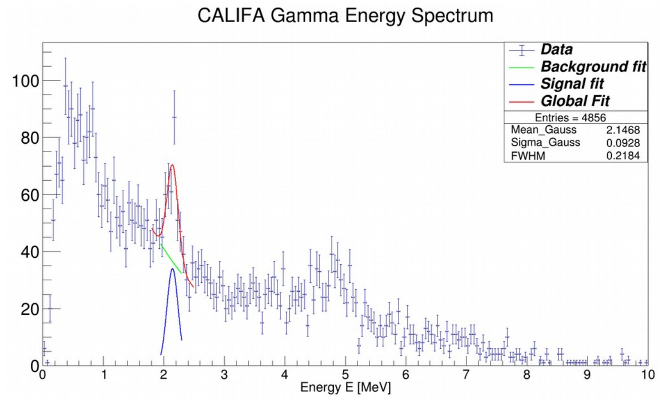


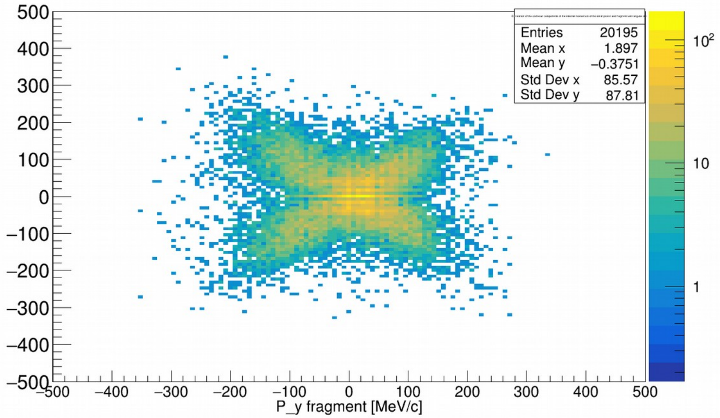


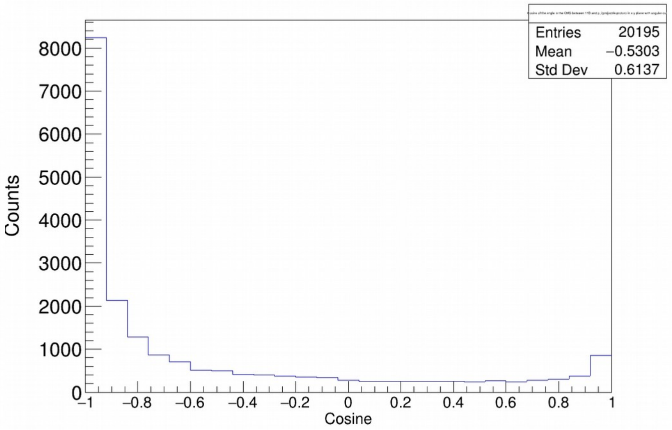
Compare to:
https://www.nature.com/articles/s41567-021-01193-4.pdf

Summary & Outlook

- **12C(p,2p)11B Quasi Free Scattering looks promising**





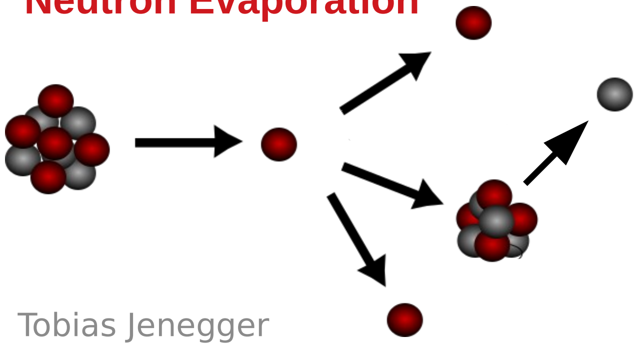


- But: Momentum shift in z-direction has to be further analyzed

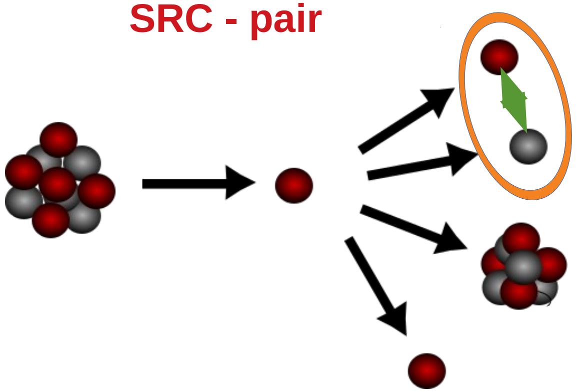
- **For 12C(p,ppn/pd)10B already first results**

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

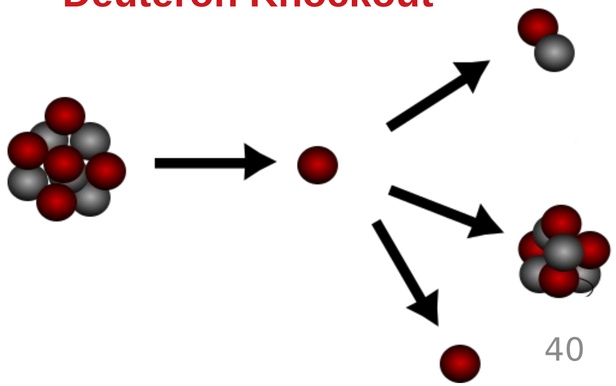
Neutron Evaporation



SRC - pair



Deuteron Knockout



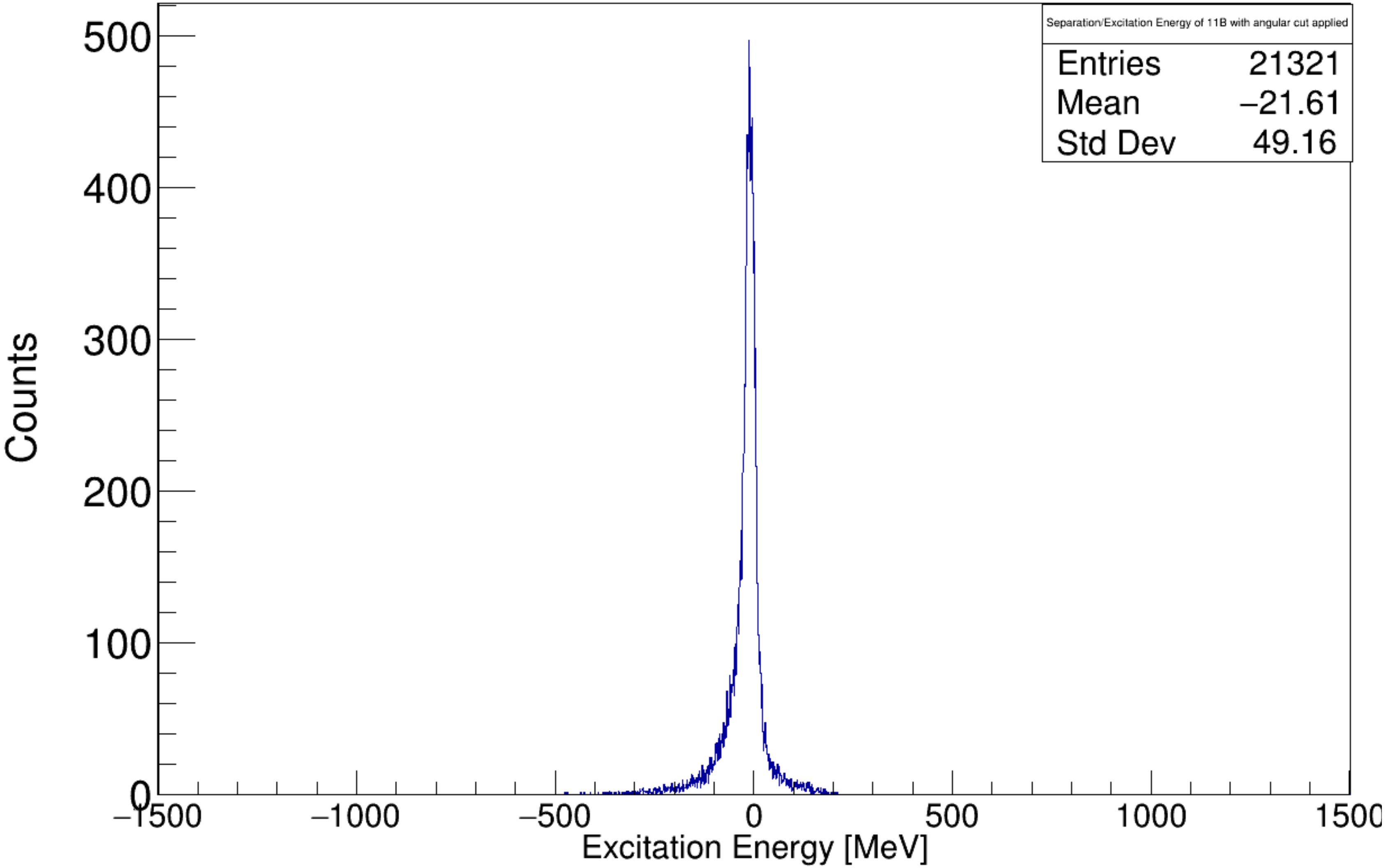
Thank you!

GEFÖRDERT VOM
Bundesministerium
für Bildung
und Forschung

Backup

Excitation Energy of 11B

$$E_{exc} = \left(\boldsymbol{P}_{12C} + \underbrace{\boldsymbol{p}_{tg} - \boldsymbol{p}_1 - \boldsymbol{p}_2}_{-\boldsymbol{p}_i}\right).M - M_{11B}$$



Is this formula valid?

Excitation Energy vs. E_miss