Neutron Detection Efficiency in the Forward Calorimeter

$$e\,p \longrightarrow e'\pi^{+}(n)$$

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Overview

Method to extract neutron detection efficiency (NDE).

Background Subtraction.

Calculate neutron efficiency for PCAL/ECAL.

NDE Results.

NDE Parameterization.

Data Set used:

Run Group A, inbending and outbending with beam energies 10.6 GeV and 10.2 GeV

Neutron Detection Efficiency (NDE)

Determine the neutron detection efficiency (NDE) by using:

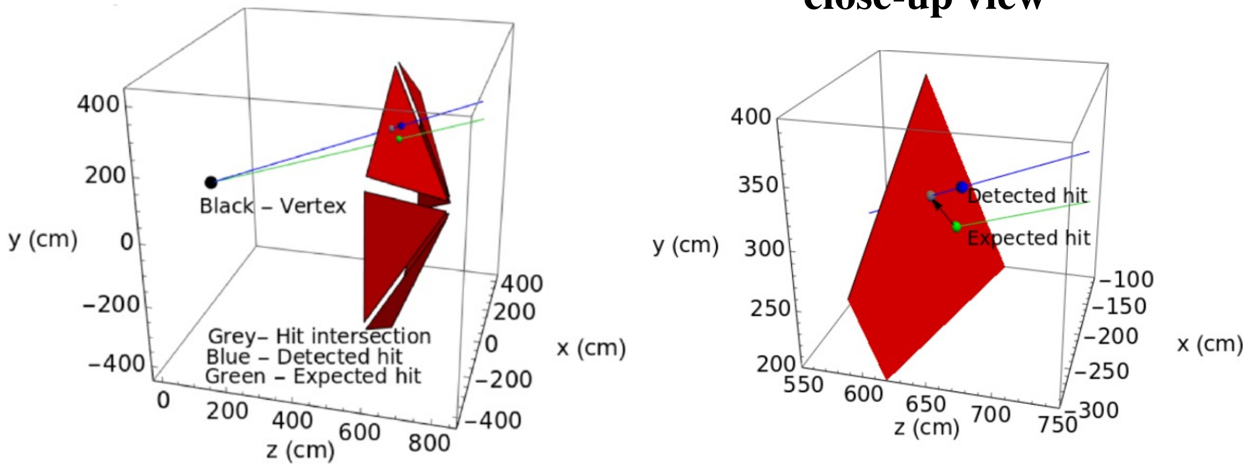
$$e\,p \rightarrow e'\,\pi^{+}(n)$$

- Select $e'\,\pi^{+}$ final state with no other charged particles in CLAS12.
- Assume the missing particle is a single neutron and calculate the missing momentum of the neutron P_{mm} and it's trajectory through CLAS12 from the e' vertex.
- Check if the neutron's path intersects the front face of ECAL and is at least 10 cm away from the edge.

Yes → define it as an expected neutron

NO → skip the event

close-up view



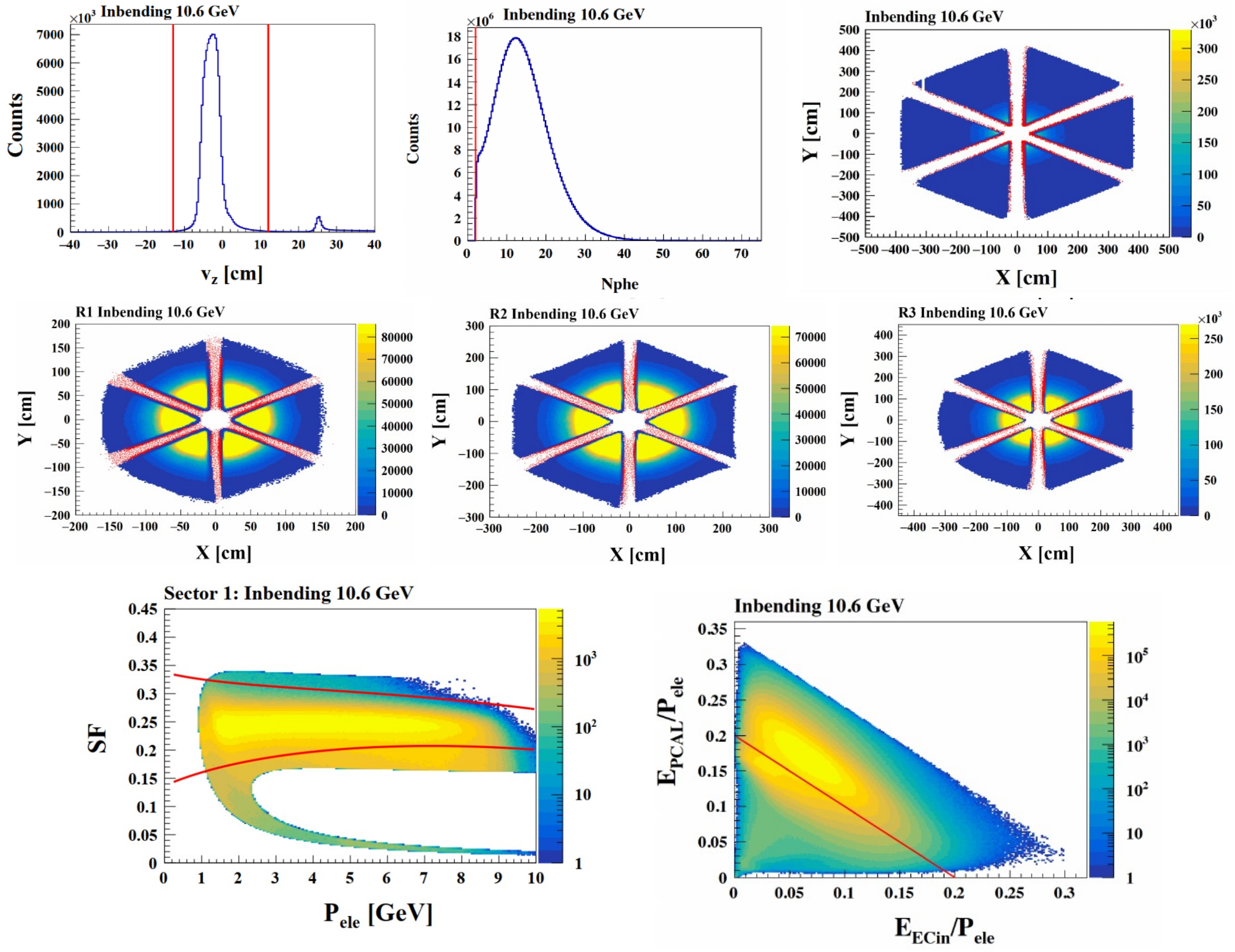
Red panels: ECAL front face

- Loop over neutral ECAL hits (neutron candidates):
  - ✓ Get intersection of ray with the ECAL face by drawing a line from the e′ vertex to the actual neutral ECAL hit.
  - ✓ To identify neutrons :
    - ✓ Calculate the direction cosine from the electron vertex to the ECAL face for the expected neutron and the neutron candidates.
    - ✓ Cut on the difference between the expected neutron direction cosine and the neutron candidate (ΔCx ΔCy)
    - ✓ Select the smallest ΔCx ΔCy neutron candidate for multiple hits.

$$NDE = \frac{H(e,e'\pi^{+}n)}{H(e,e'\pi^{+})n}$$

Electron ID Cut

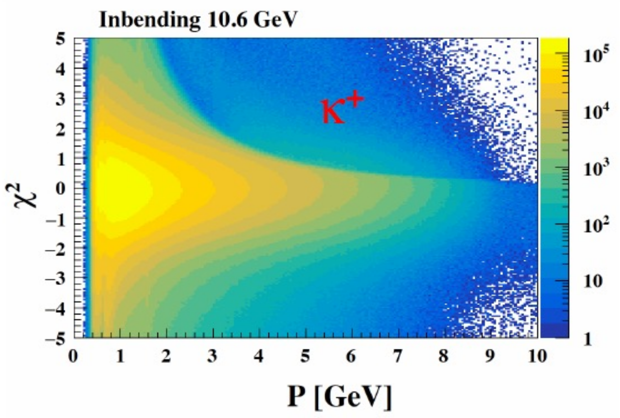
The cut used is based on the RGA analysis note

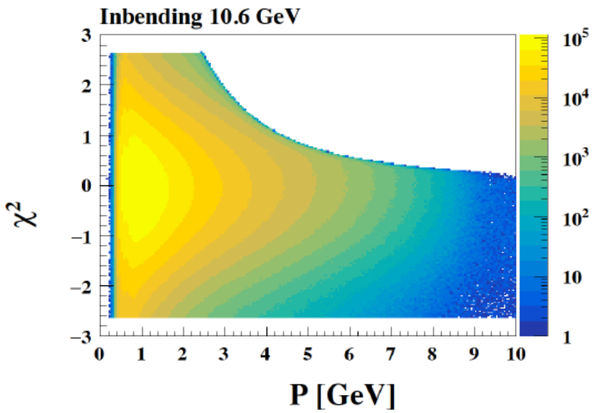


Cut	Limits
PID	11
vertex cut	v_z vertex position
Number of Photoelectrons	$N_{ph} > 2$
PCAL Fiducial Cut	V, W > 14 cm
DC Fiducial Cut for 3 DC regions	$x - y$ plane cuts
SF vs. P_{ele}	$\pm 3.5\sigma$
Diagonal cut	
chi2pid cut	$\lvert\chi^2\rvert < 3$ cut
Minimum PCAL Energy Deposited	$E_{dep} > 60$ MeV

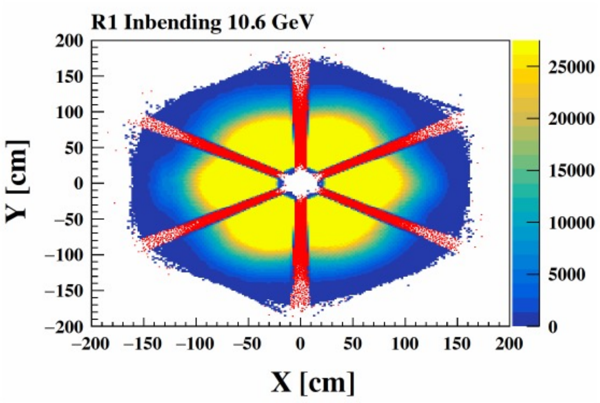
π^+ ID Cut

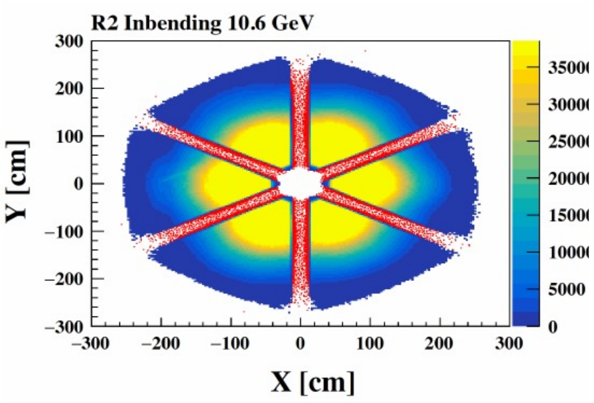
The cut used is based on the RGA analysis note

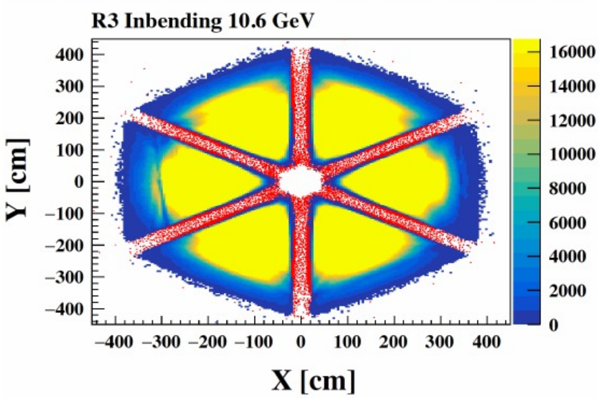


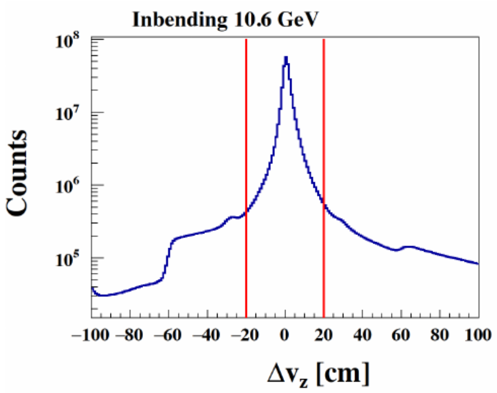


Cut	Limits
PID	211
vertex cut	$\lvert v_z(ele) - v_z(\pi^+)\rvert < 20$ cm
DC Fiducial Cut for 3 DC regions	$x - y$ plane cuts
chi2pid cut	$\lvert\chi^2\rvert < 3$ cut



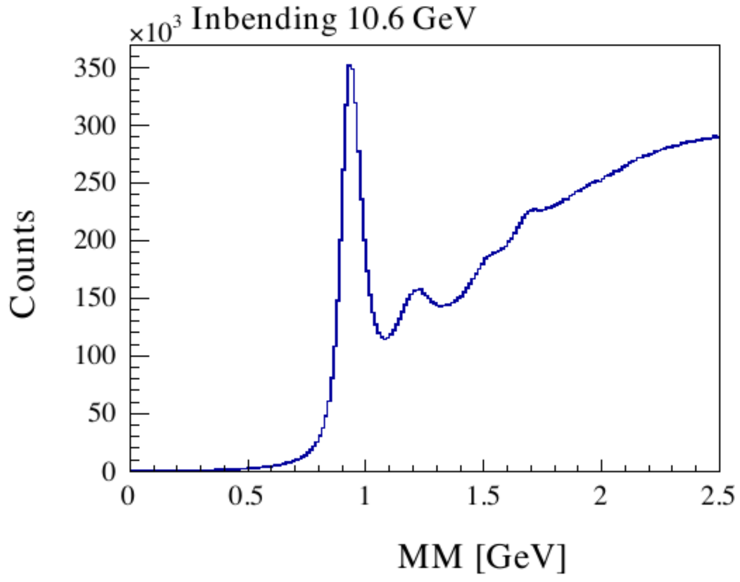






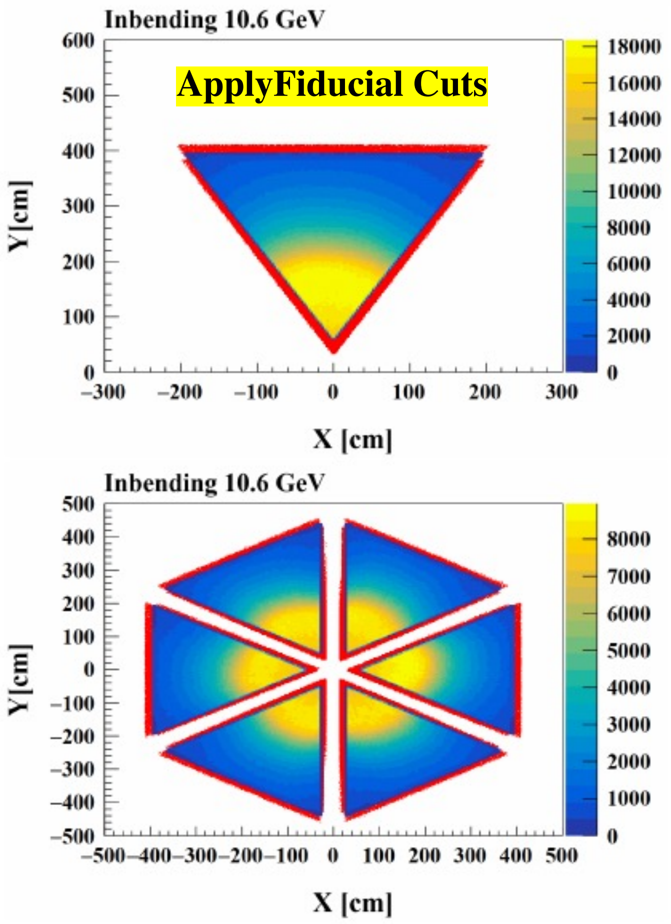
Missing Mass Distribution of $p(e,e'\pi^+)n$

Missing Mass of neutron



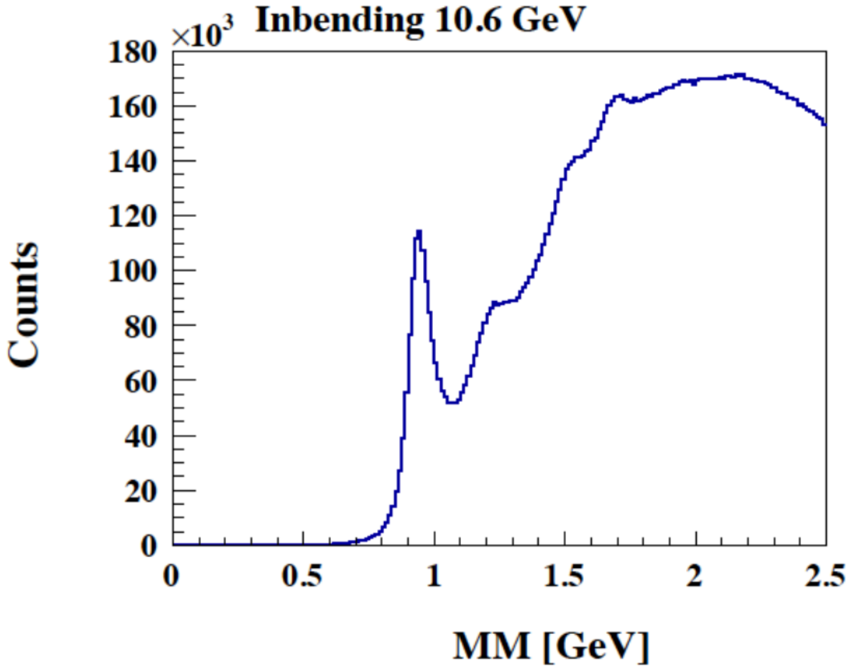
Neutron can be in CD or FD

Swimming neutron to the PCAL/ECAL



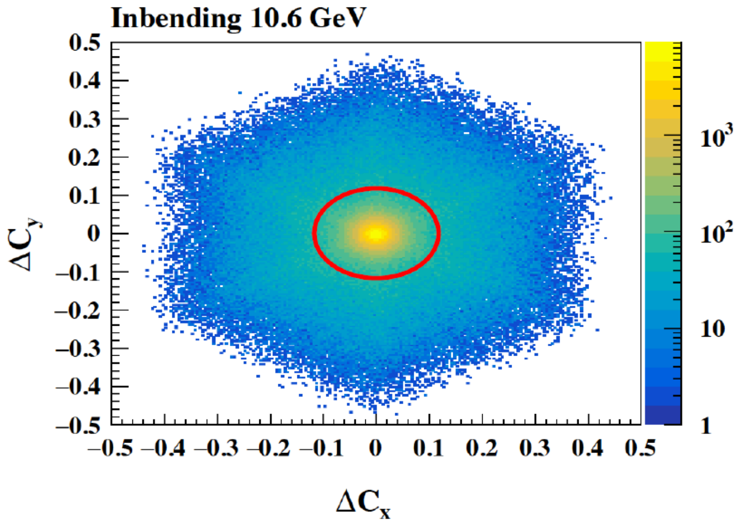
Missing Mass of neutron after swimming and applying fiducial Cuts

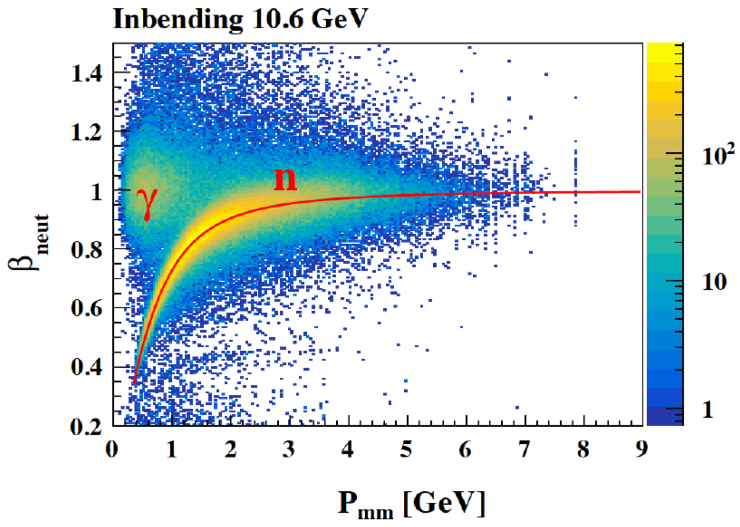
Missing Mass of Expected Neutron



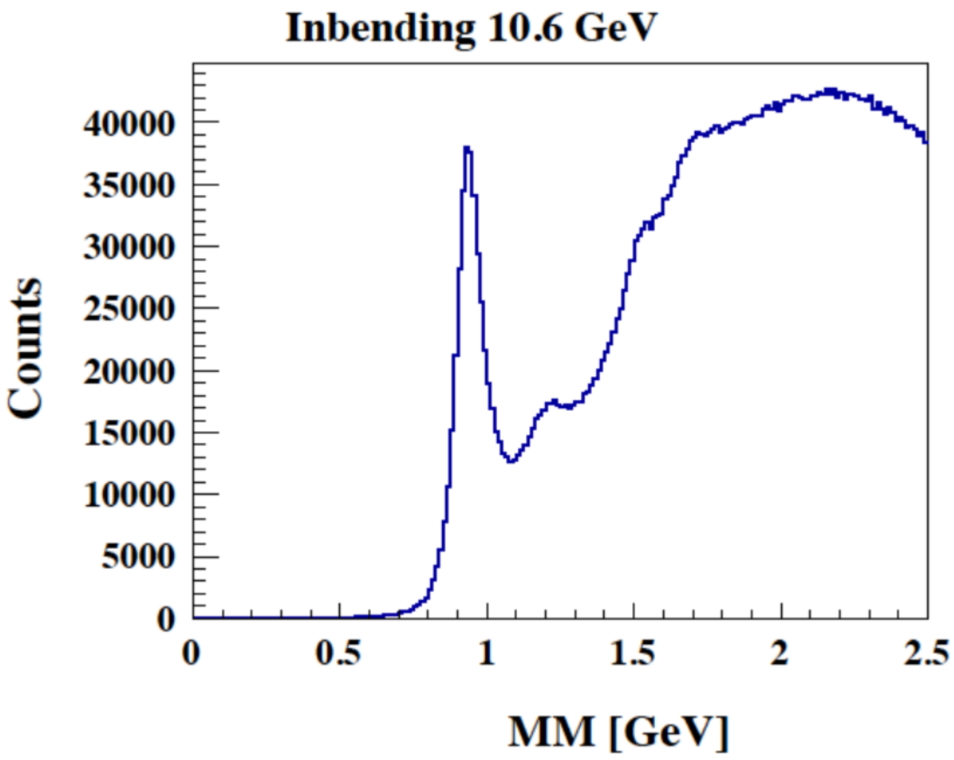
Neutron can be in FD only

Neutral Particles Measured in PCAL/ECAL



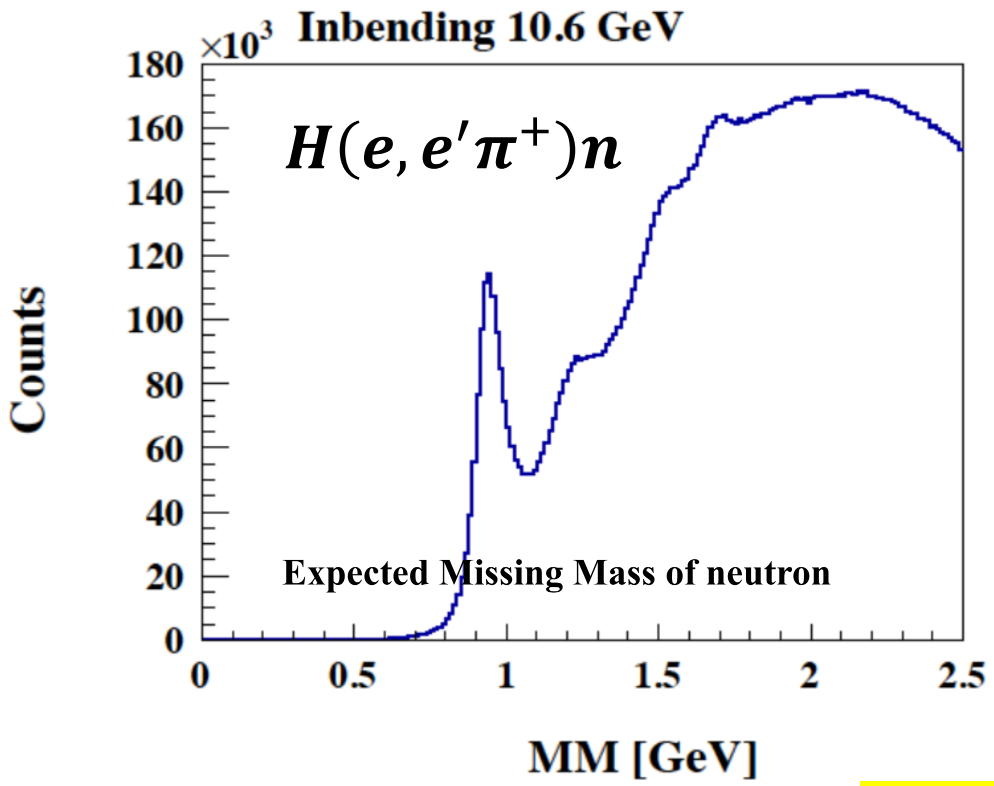


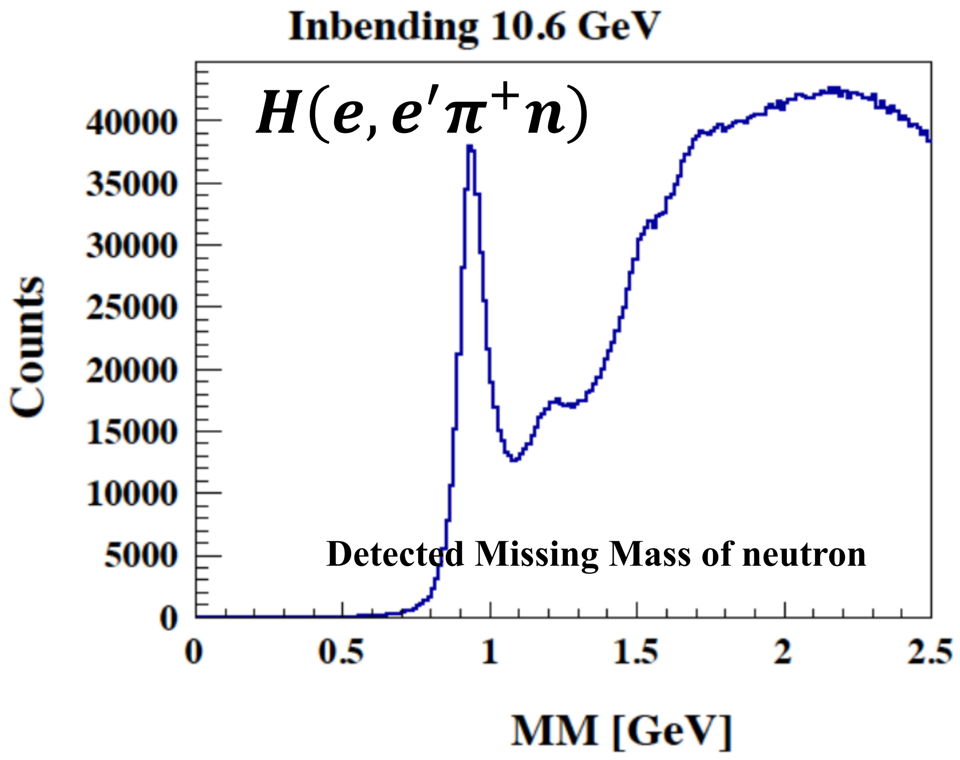
Missing Mass of detected neutrons that pass ΔCx ΔCy cut



Most of the background under the missing mass of detected neutron due to photons contribution..

Missing Mass Distribution





Missing mass of expected and detected neutron have background events that must be subtracted.

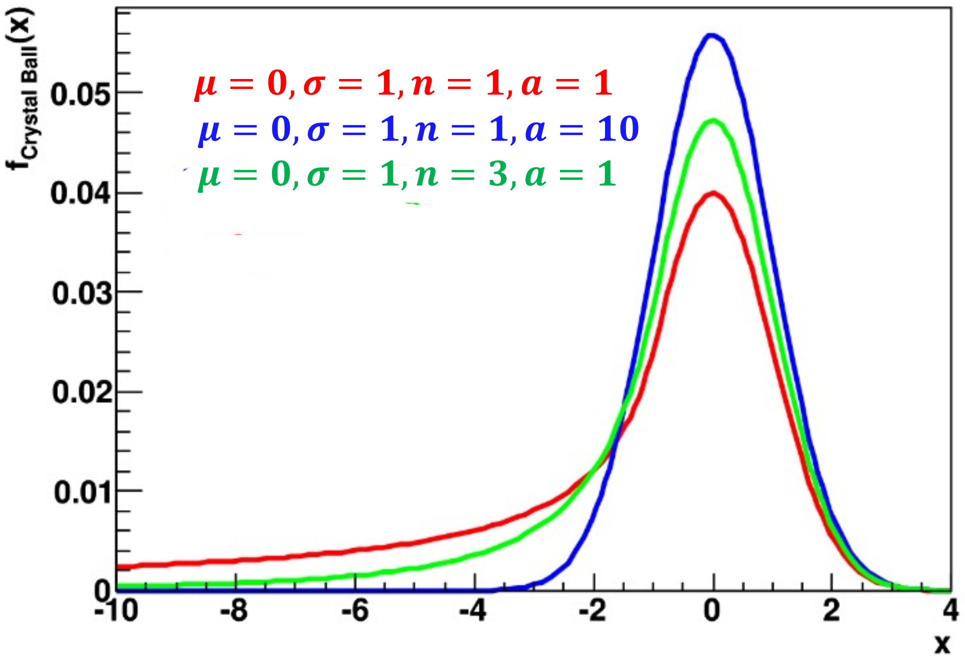
Background Subtraction

✓Fit both expected and detected neutrons at different P_{mm} Using two functions:

1- Gaussian Function

2- Crystal Ball Function

with Polynomial background



✓Crystal Ball Function defined as:

$$f_{CB}(x;\mu,\sigma,a,n) = e^{-\frac{1}{2}\left(\frac{x-\mu}{\sigma}\right)^2} \quad \text{for} \quad \frac{x-\mu}{\sigma} > -a$$

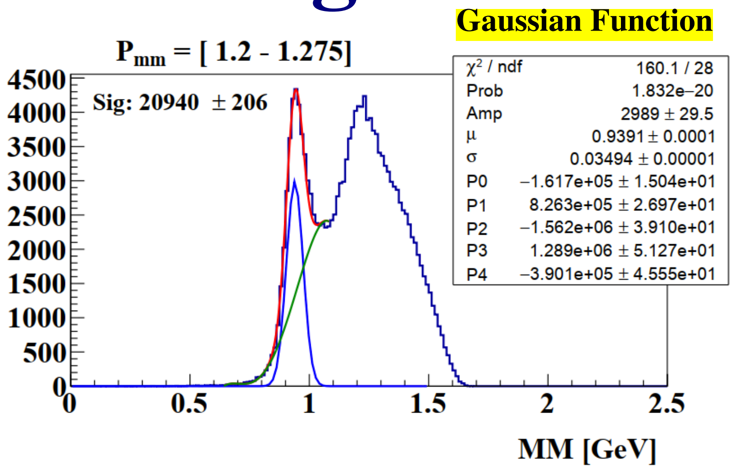
$$= \left(\frac{n}{|a|}\right)^n e^{-\frac{|a|^2}{2}} \left(\frac{n}{|a|} - |a| - \frac{x-\mu}{\sigma}\right)^{-n} \quad \text{for} \quad \frac{x-\mu}{\sigma} \leq -a.$$

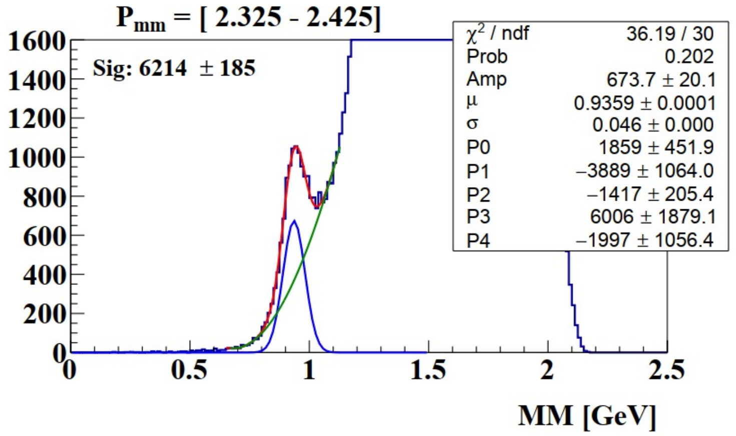
Where:

a: controls the location of the transition between the Gaussian and power-law parts of the function.

n: the steepness of the power-law tail.

Background Subtraction



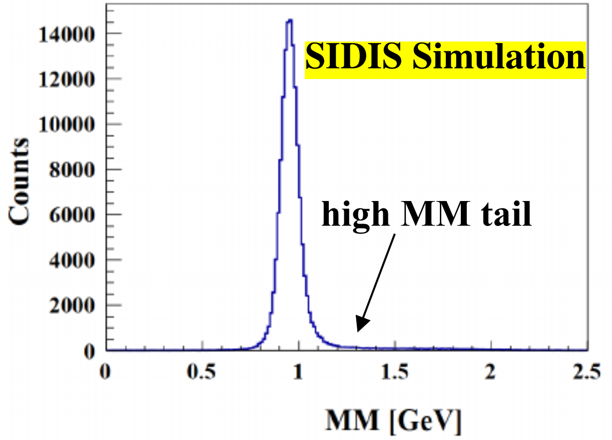


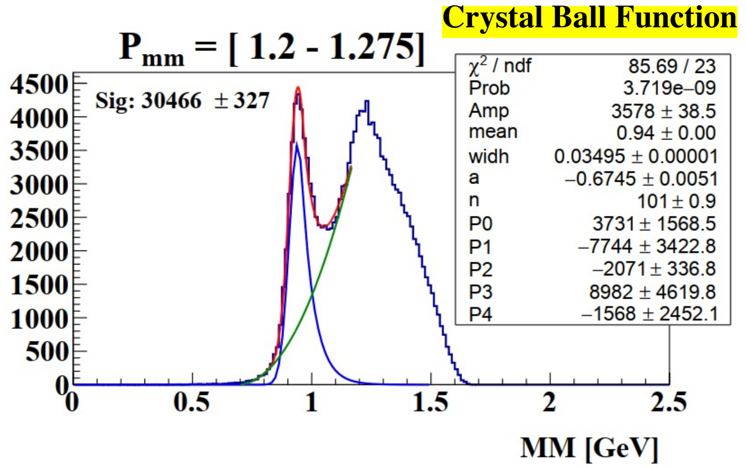
Gaussian+Poly:

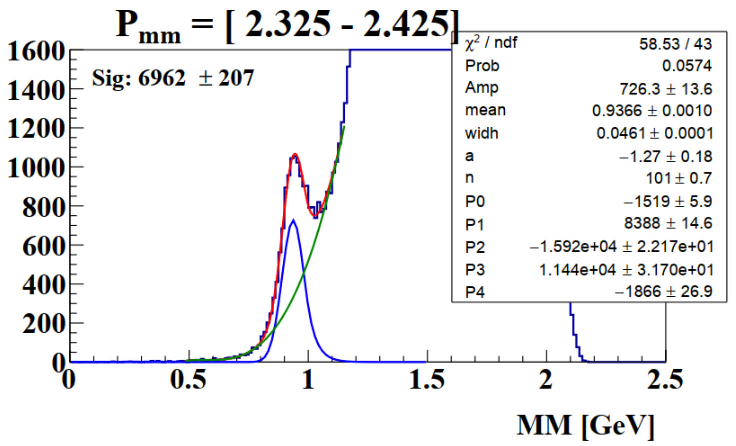
- ✓ Range of the fit is limited to MM < 1.1 GeV For P_{mm} < 2 GeV.
- ✓ For P_{mm} > 2 GeV and then extend this range to MM < 1.2 GeV.
- ✓ Couldn't fit the dip region.

CB+Poly:

- ✓ CB has high-MM tail to fit the dip region.
- ✓ Range of the fit is extended to MM < 1.2 GeV for all P_{mm} bins.
- ✓ MC shows high-MM tail.



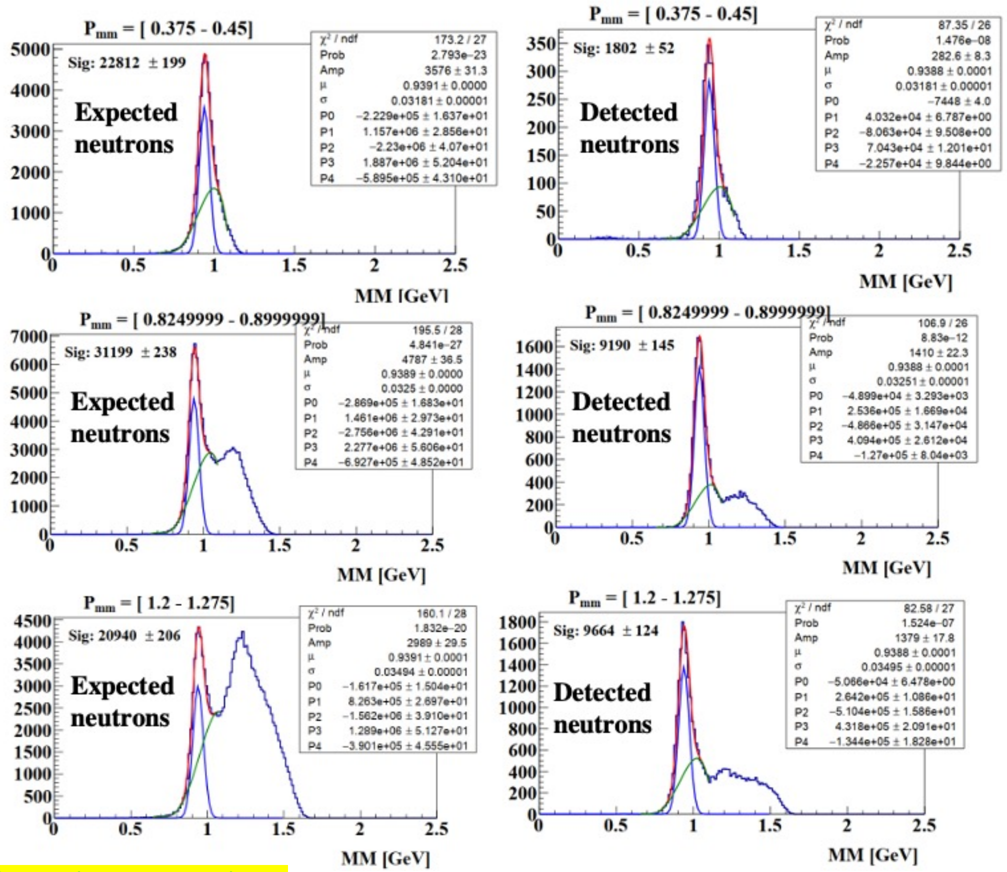




The high MM tail due to:

- ✓ The radiative effects.

1- Fit Neutrons peaks using Gaussian Function



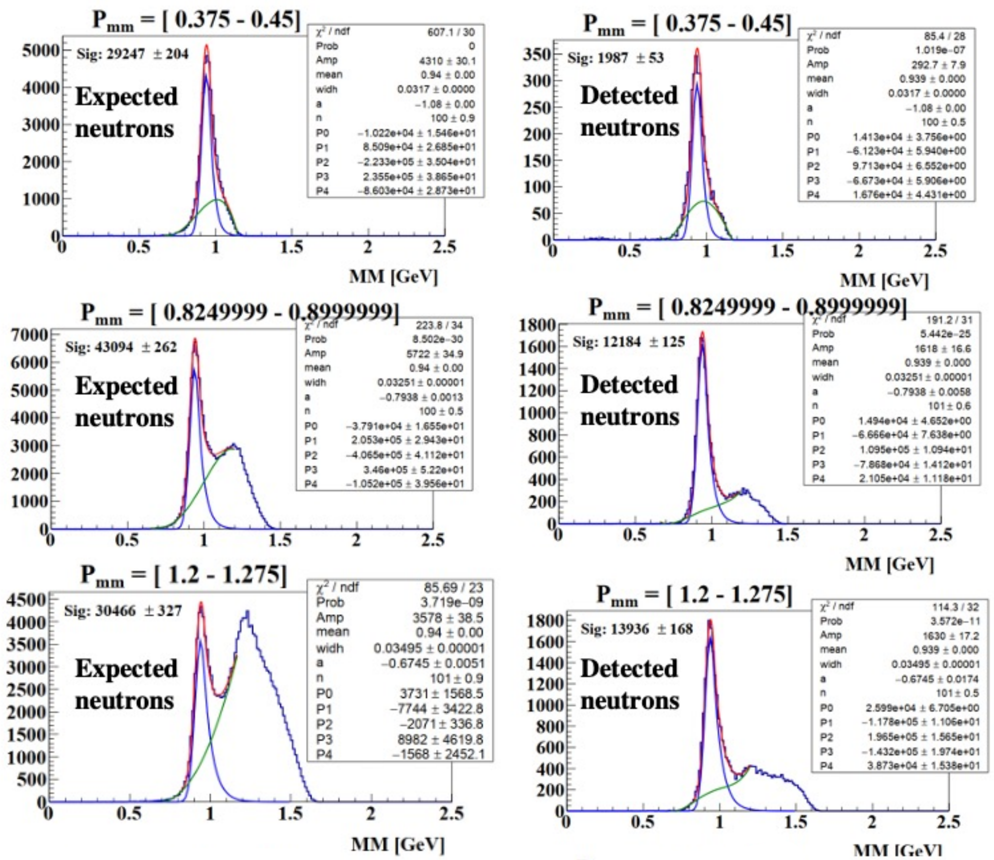
Gaussian Function:

1- First fit each detected neutron MM distribution using Gauss+Poly, allowing all parameters to vary. Range of the fit is limited to MM < 1.1 GeV For P_{mm} < 2 GeV where the neutron contribution is significant. For P_{mm} > 2 GeV and then extend this range to MM < 1.2 GeV.

2- Use the same mean and width for each MM bin from step 1 and fit the expected neutron MM distribution with the Gaus+Poly function over the same range as step 1.

3- The Gaussian amplitude and the polynomial coefficients are allowed to vary for the expected neutron. The mean and width are fixed.

2- Fit Neutrons peaks using Crystal Ball Function



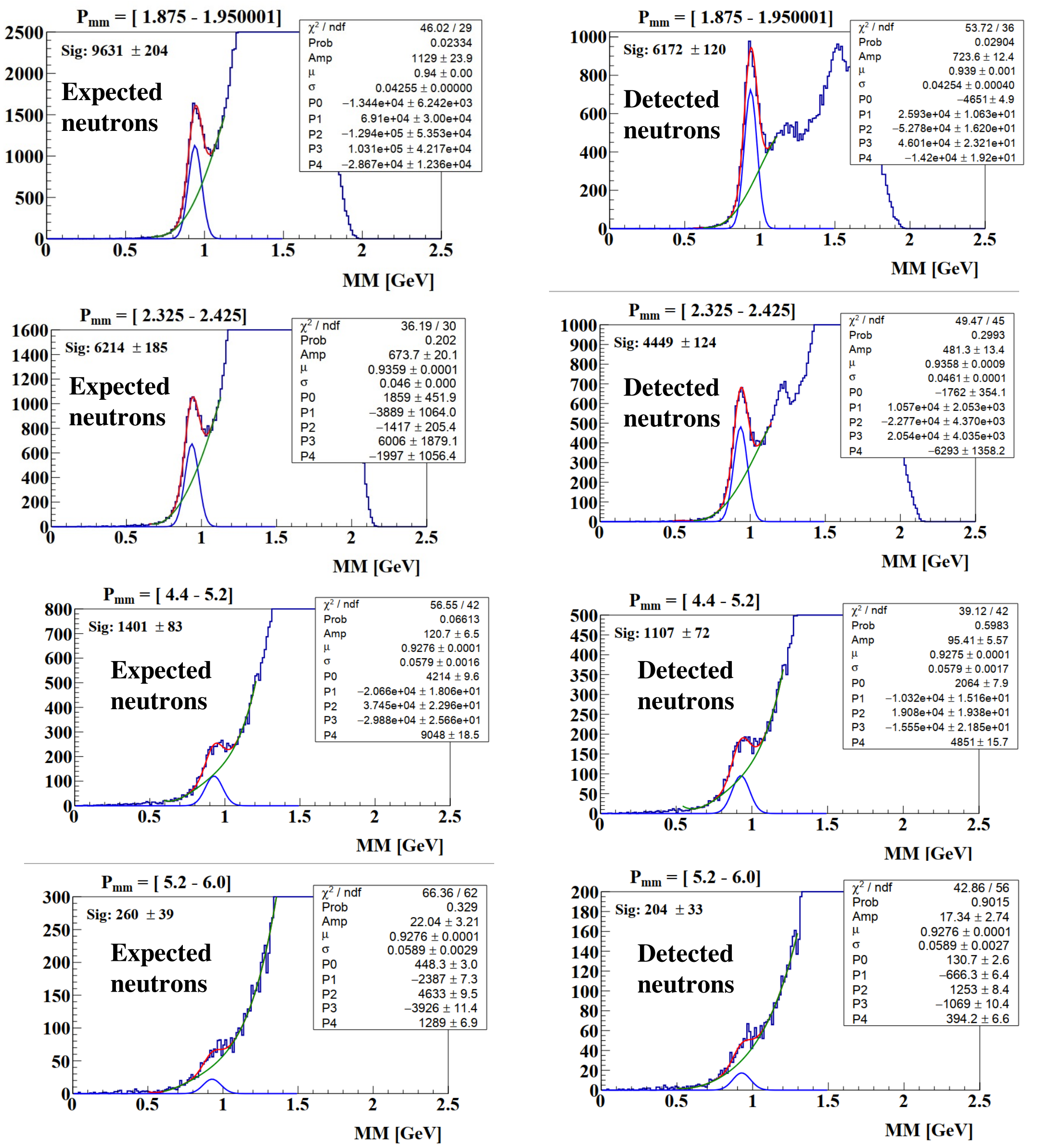
Crystal Ball Function (CB):

1- For each P_{mm} bin, use the same mean and width that were extracted from the detected neutron Gaussian fitting described in the left hand side.

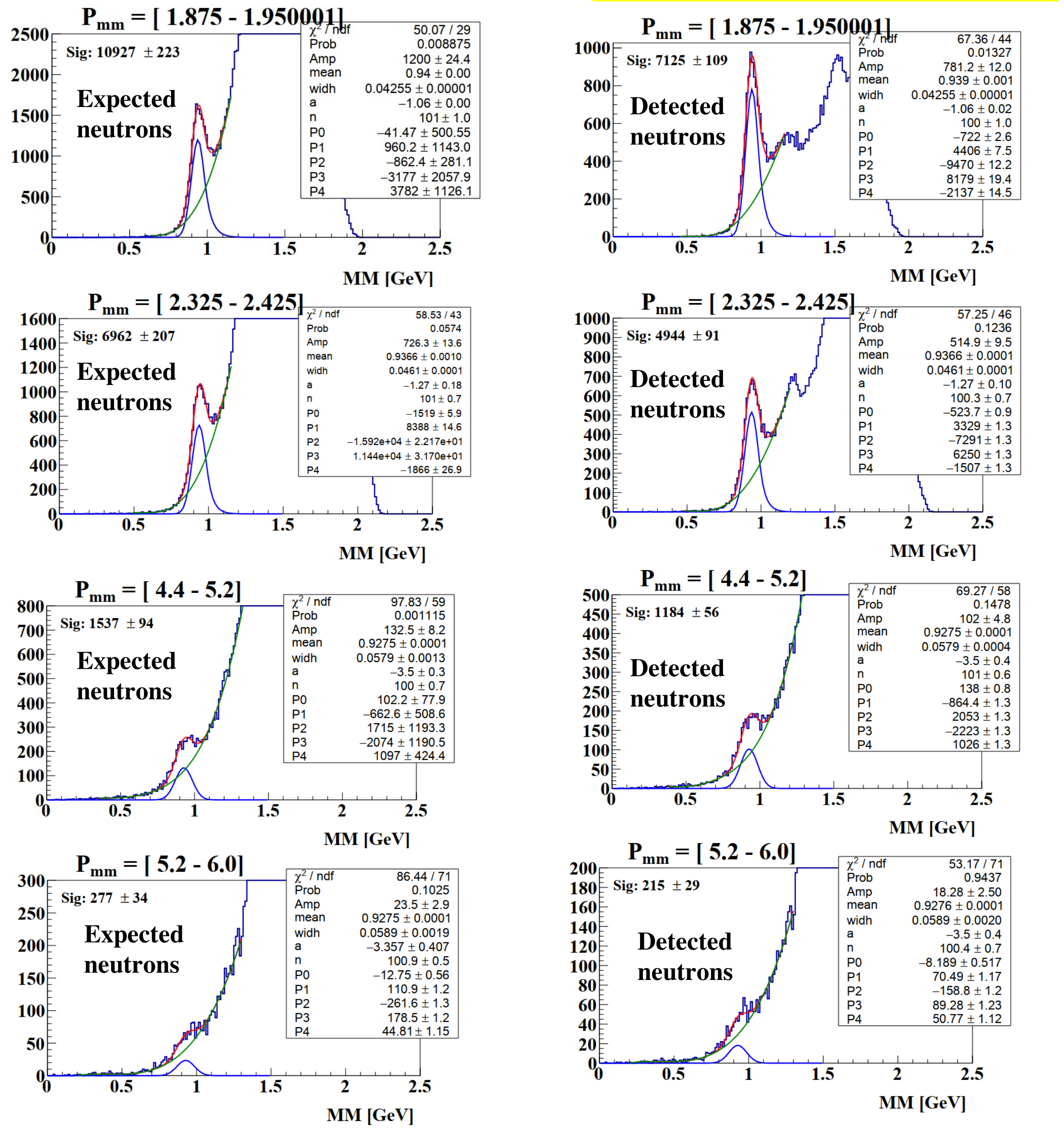
2- The parameters of the CB, high-MM tail for both expected and detected neutrons are fixed at the same values that give the lowest chi2. Range of the fit is extended to MM < 1.2 GeV for all P_{mm} bins.

3- CB amplitude and the polynomial coefficients are allowed to vary for the expected neutron. The CB mean, width, and tail parameters are fixed.

1- Fit Neutrons peaks using Gaussian Function



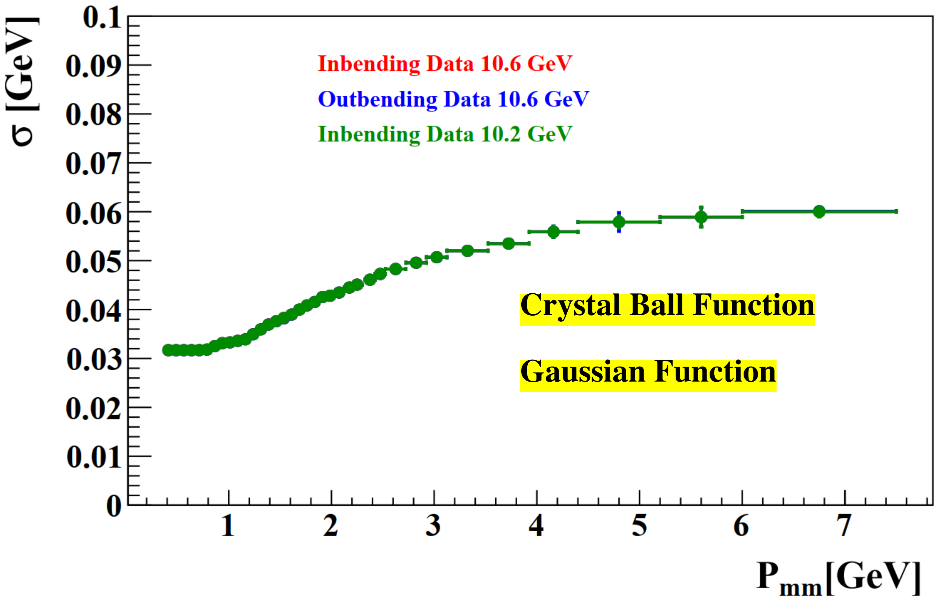
2- Fit Neutrons peaks using Crystal Ball Function

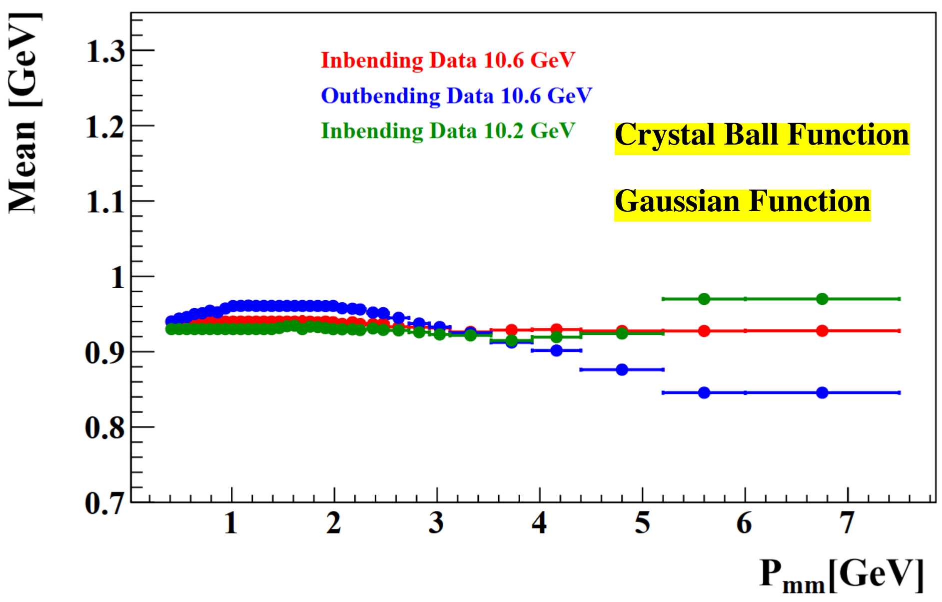


Parameters Fit Results

- Use the same width for both expected and detected neutron for each P_{mm} bin.
- Use the same width for all 3 data sets.
- σ vary smoothly with P_{mm} .

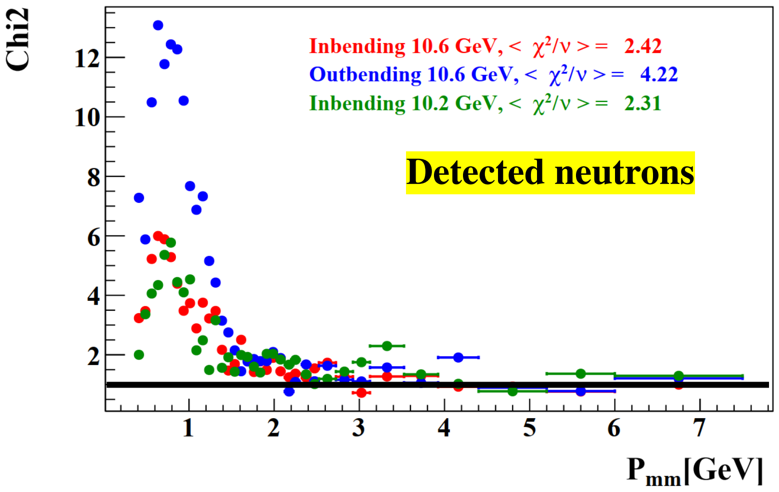
- Use the same mean for both expected and detected neutron for each P_{mm} bin.
- Neutron peak looks ok for inbending 10.6 GeV and 10.2 GeV but is shifted for outbending 10.6 GeV.

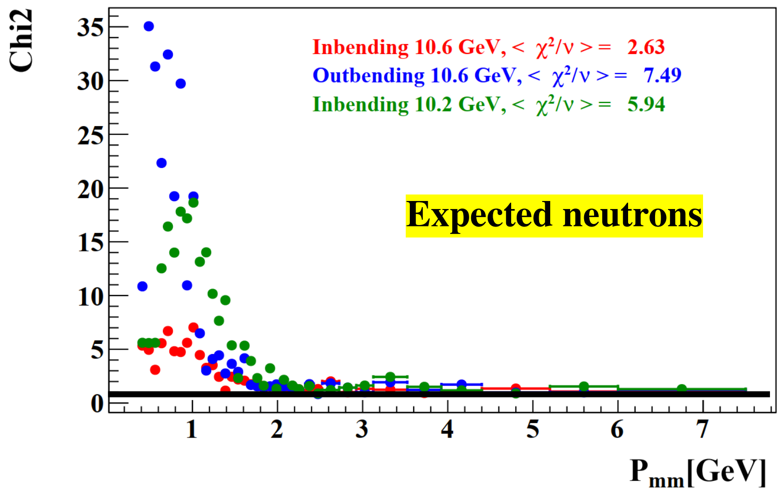




Parameters Fit Results

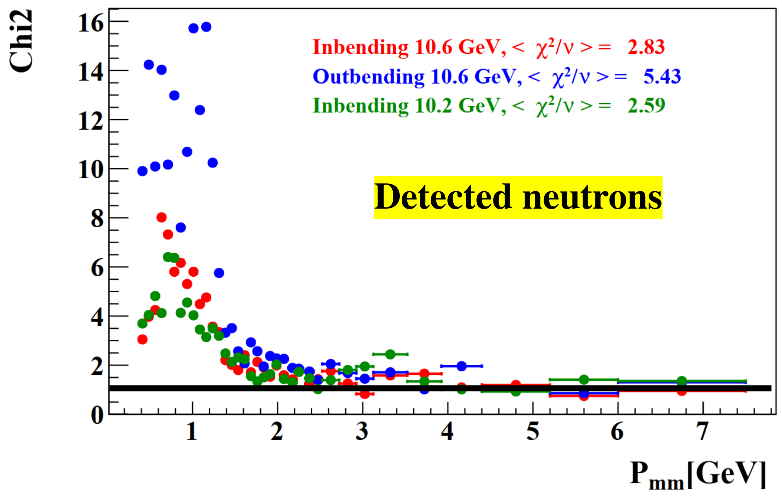
Gaussian Function

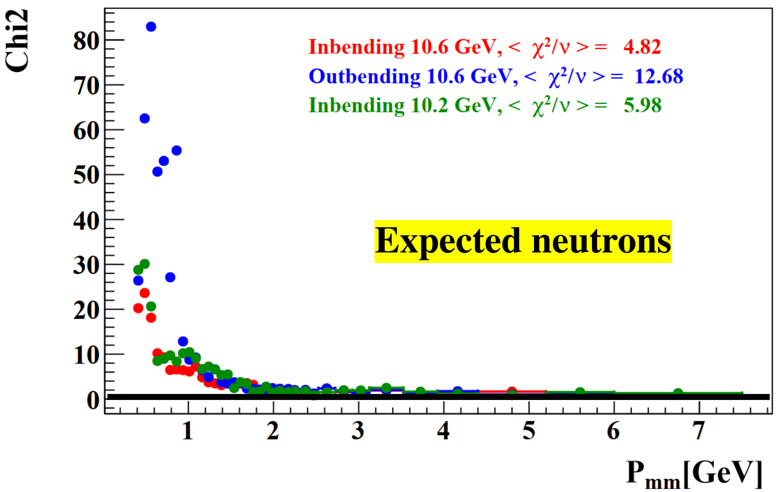




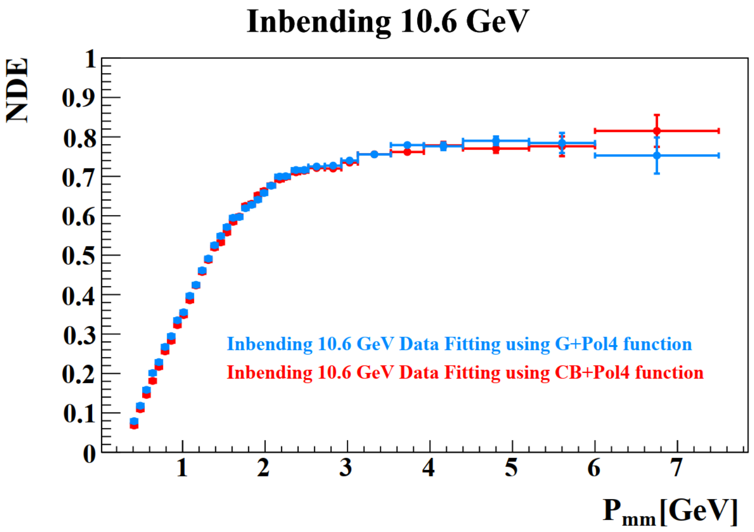
- **The fit quality is similar for Gauss and CB for detected neutrons.**
- **For expected neutron, the Gaussian function shows a better fit quality with a lower average χ^2 value.**

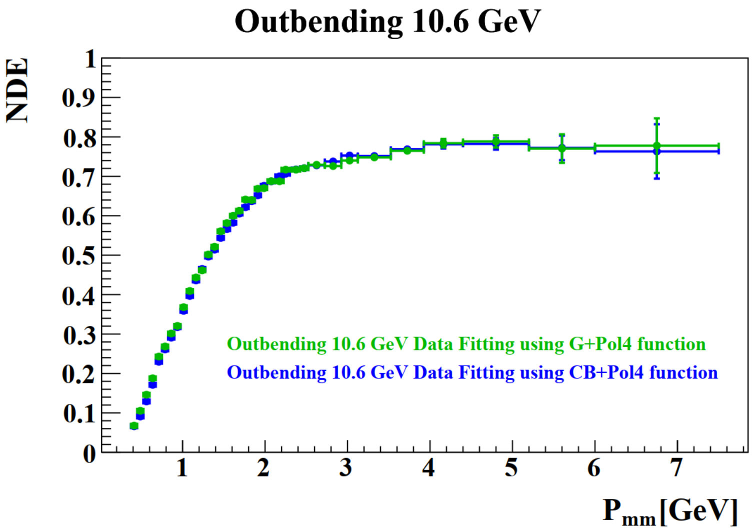
Crystal Ball Function

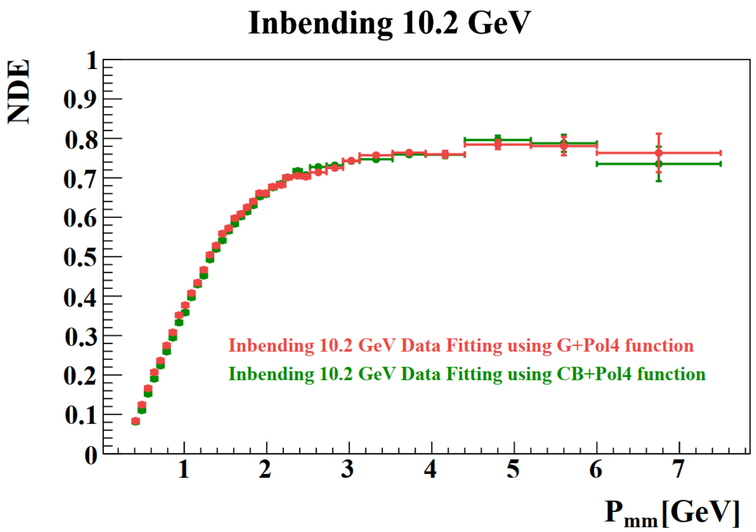


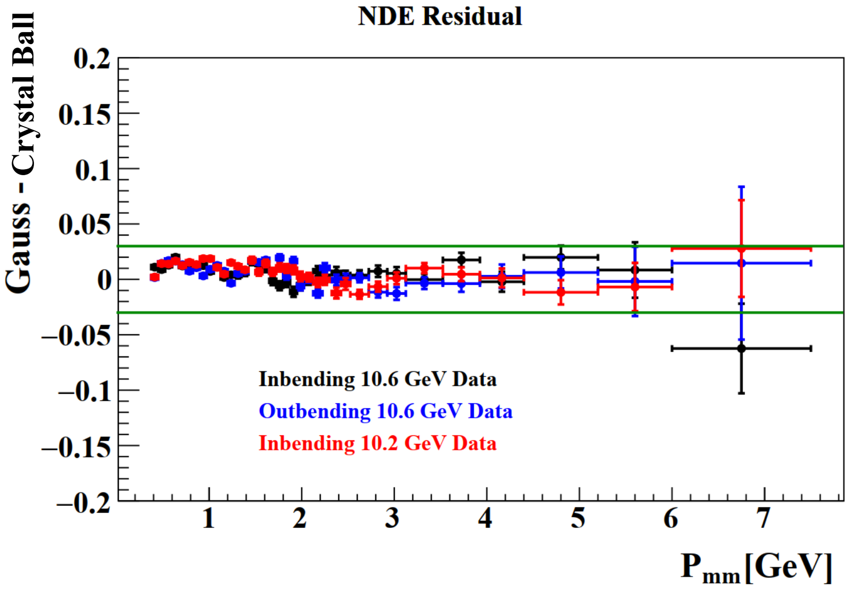


NDE Results



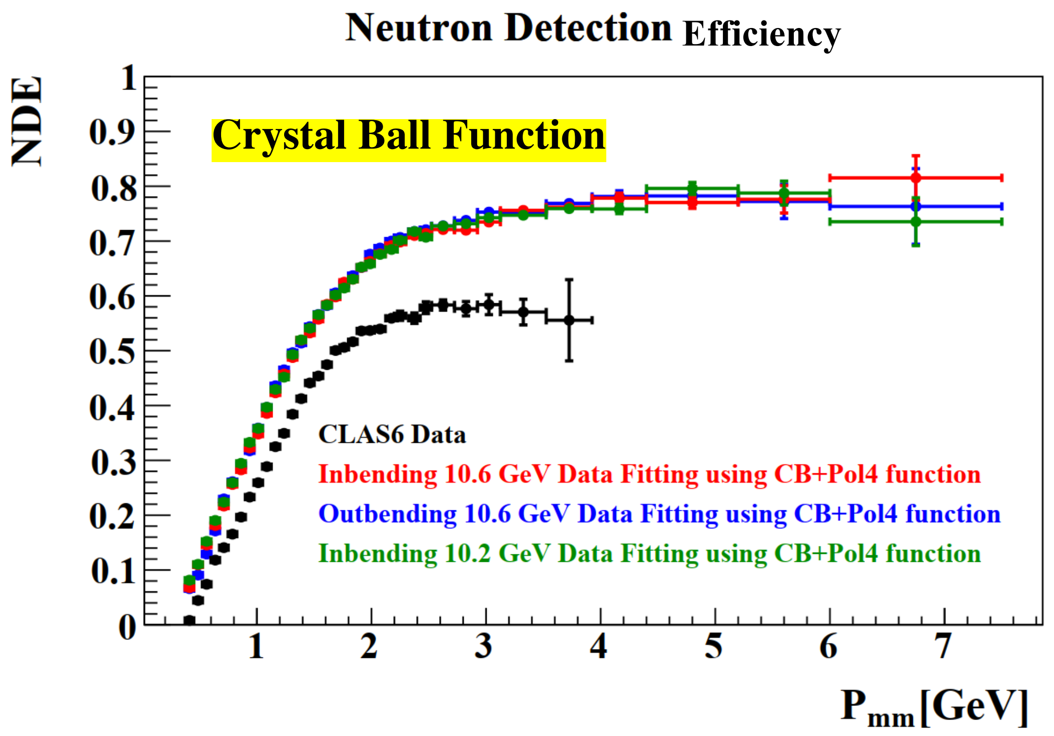


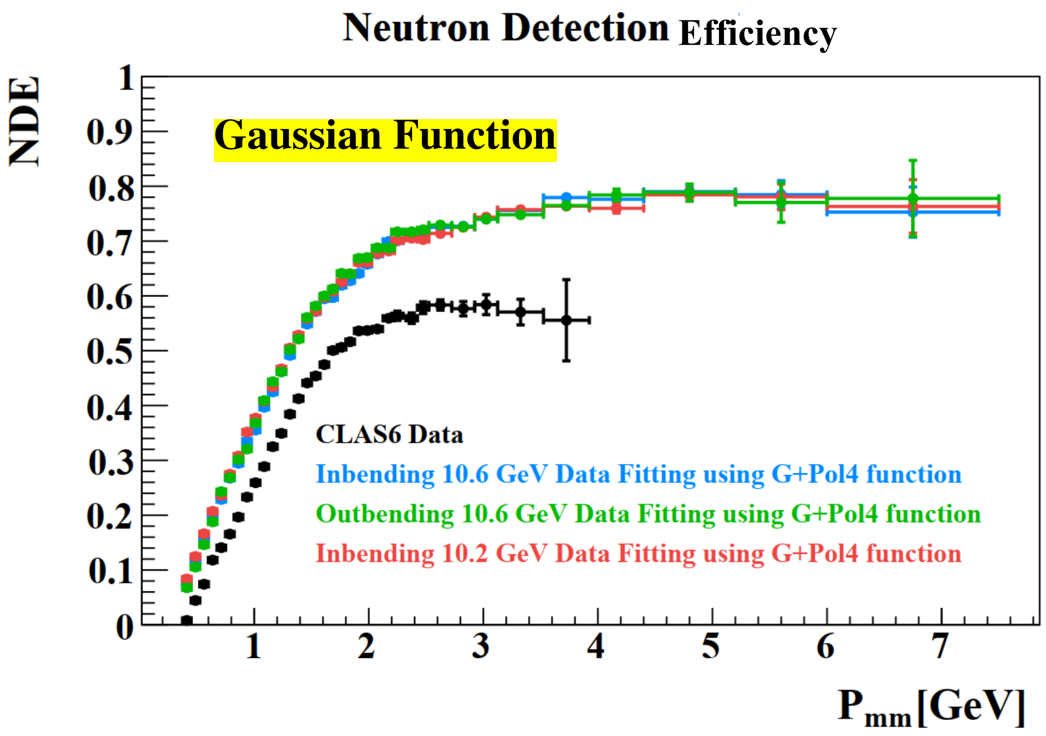




- ✓ NDE results show that below 2 GeV, the Gauss function is slightly higher compared to the CB function. However, above 2 GeV, the two functions provide consistent results within the uncertainty.
- ✓ Residual plot show the difference between Gauss and CB $< 3\%$

NDE Results





CLAS12 results show all three data sets consistent to each other.
NDE ~ 0.79 at the plateau ($P_{mm} > 3.5$ GeV) for outbending and inbending electrons.

Parameterized NDE

To use NDE results in the G_M^n analysis, we need a function that can describe it.

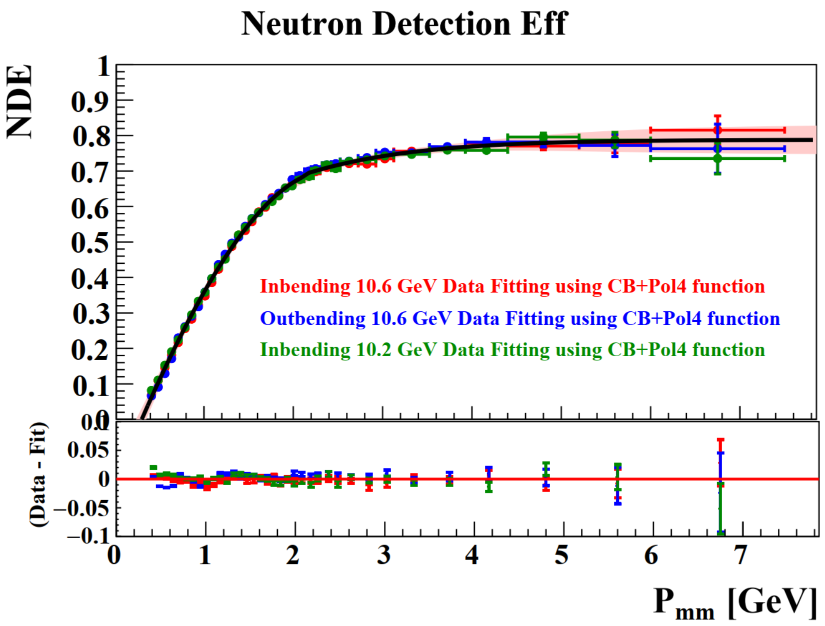
Fit the neutron detection efficiency (NDE) with:

$$\eta(P_{mm}) = a_0 + a_1 P_{mm} + a_2 P_{mm}^2 + a_3 P_{mm}^3 \qquad \text{for} \qquad P_{mm} < p_t$$

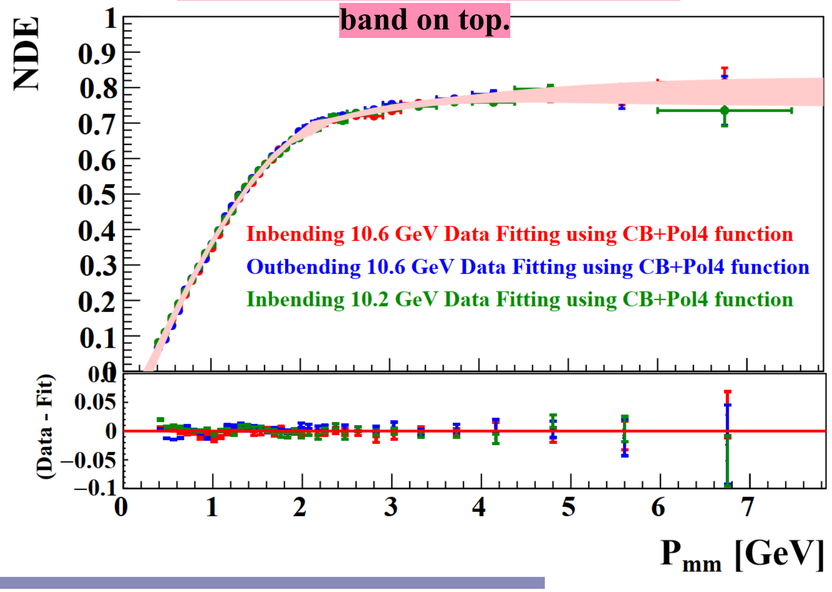
$$= a_4\left(1 - \frac{1}{1 + e^{\frac{P_{mm}-a_5}{a_6}}}\right) \qquad \text{for} \qquad P_{mm} > p_t$$

The uncertainty on the fit can be calculate from the error matrix:

$$\sigma_\eta{}^2 = \sum_{i,j} \epsilon_{ij} \frac{\partial \eta}{\partial a_i} \frac{\partial \eta}{\partial a_j},$$



Same as plot above with uncertainty band on top.



Summary

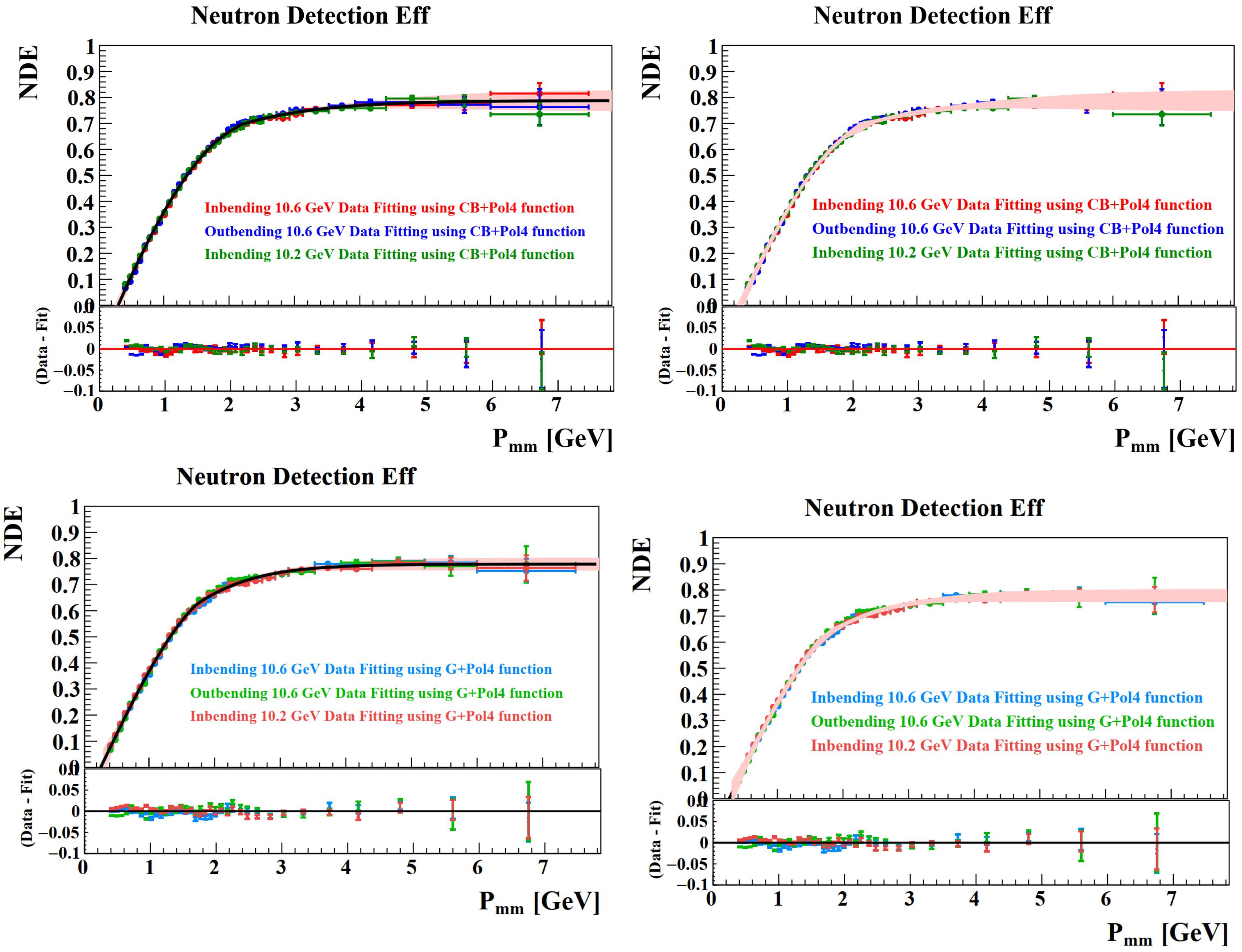
- NDE is necessary for G_M^n measurements in Run Group B and to other analyses/run groups.
- CLAS12 results show all three data sets are consistent to each other.
- NDE ~ 0.79 at the plateau (P_{mm} > 3.5 GeV) for outbending and inbending electrons.
- NDE results using Gauss function are slightly higher than Crystal Ball function below 2 GeV while above this value they are in agreement within the uncertainty.

Thank you !!

Parametrized NDE

Fit Parameters	Gaussian Function	Crystal Ball Function
χ^2	0.7976	0.4813
a_0	-0.1404 $\pm$ 0.0172	-0.1817 $\pm$0.0136
a_1	0.5282 $\pm$ 0.0035	0.6187 $\pm$ 0.0375
a_2	0.01837 $\pm$ 0.0179	-0.0605 $\pm$ 0.0332
a_3	-0.0392 $\pm$ 0.0015	-0.0179 $\pm$0.0090
a_4	0.7784 $\pm$ 0.0044	0.7884 $\pm$ 0.0087
a_5	0.7057 $\pm$ 0.0698	0.0086 $\pm$0.0.3067
a_6	0.7278 $\pm$ 0.0507	1.0796 $\pm$0.1876
p_t	1.7628 $\pm$ $5.9e^{-0.8}$	2.146 $\pm$0.0001

Table 3.7: The fit parameters of the neutron detection efficiency.



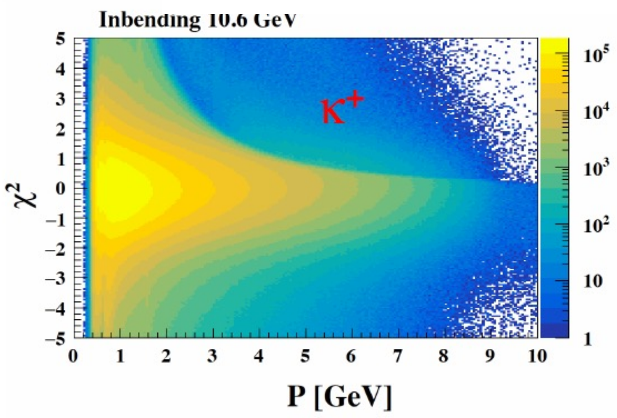
π^+ ID Cut

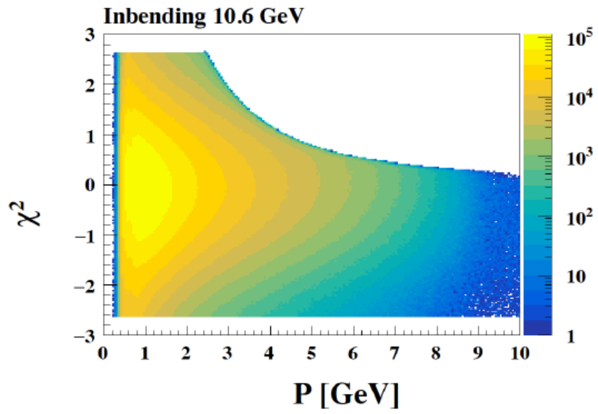
The cut used is based on the RGA analysis note

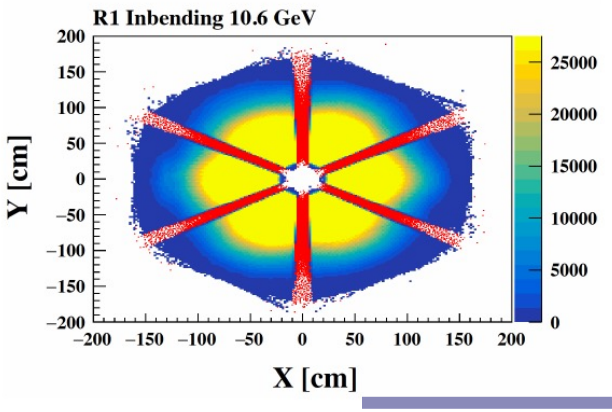
$$chi2pid < 3 \cdot 0.88 \quad \text{for} \quad p_{\pi^+} < 2.44 \text{ GeV}$$

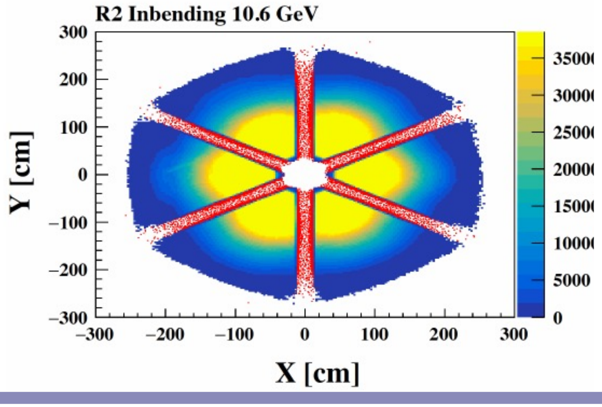
$$chi2pid < 0.88 \cdot (0.00869 + 14.98587 \cdot \exp(-p/1.18236) + 1.81751 \cdot \exp(-p/4.86394)) \quad \text{for} \quad p_{\pi^+} > 2.44 \text{ GeV}.$$

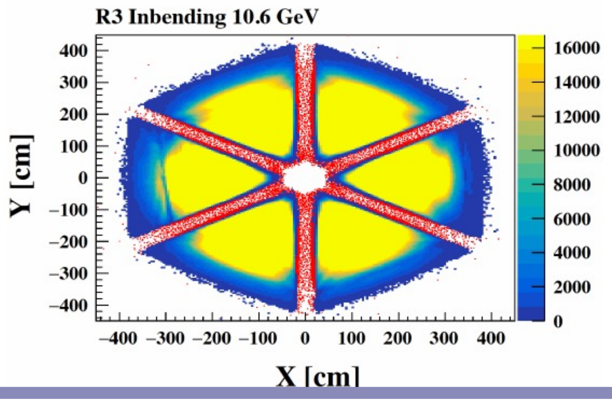
Cut	Limits
PID	211
vertex cut	$\lvert v_z(ele) - v_z(\pi^+)\rvert < 20$ cm
DC Fiducial Cut for 3 DC regions	$x - y$ plane cuts
chi2pid cut	$\lvert\chi^2\rvert < 3$ cut

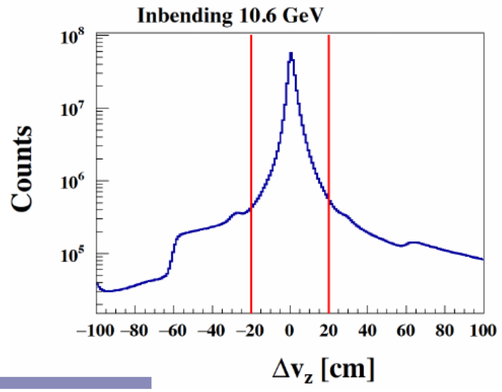












Data Set	Function	Gauss	CB
Inb. 10.6 GeV	expected neutron	2.63	4.82
	Detected neutrons	2.42	2.83
Outb. 10.6 GeV	expected neutron	7.49	12.68
	Detected neutrons	4.22	5.43
Inb. 10.2 GeV	expected neutron	5.94	5.98
	Detected neutrons	2.31	2.59

https://clasweb.jlab.org/wiki/index.php/CLAS12_Momentum_corrections:via_exclusive_channels:corrections_study#tab=ep_Channel

Code: $e\pi^+X$ (linear)

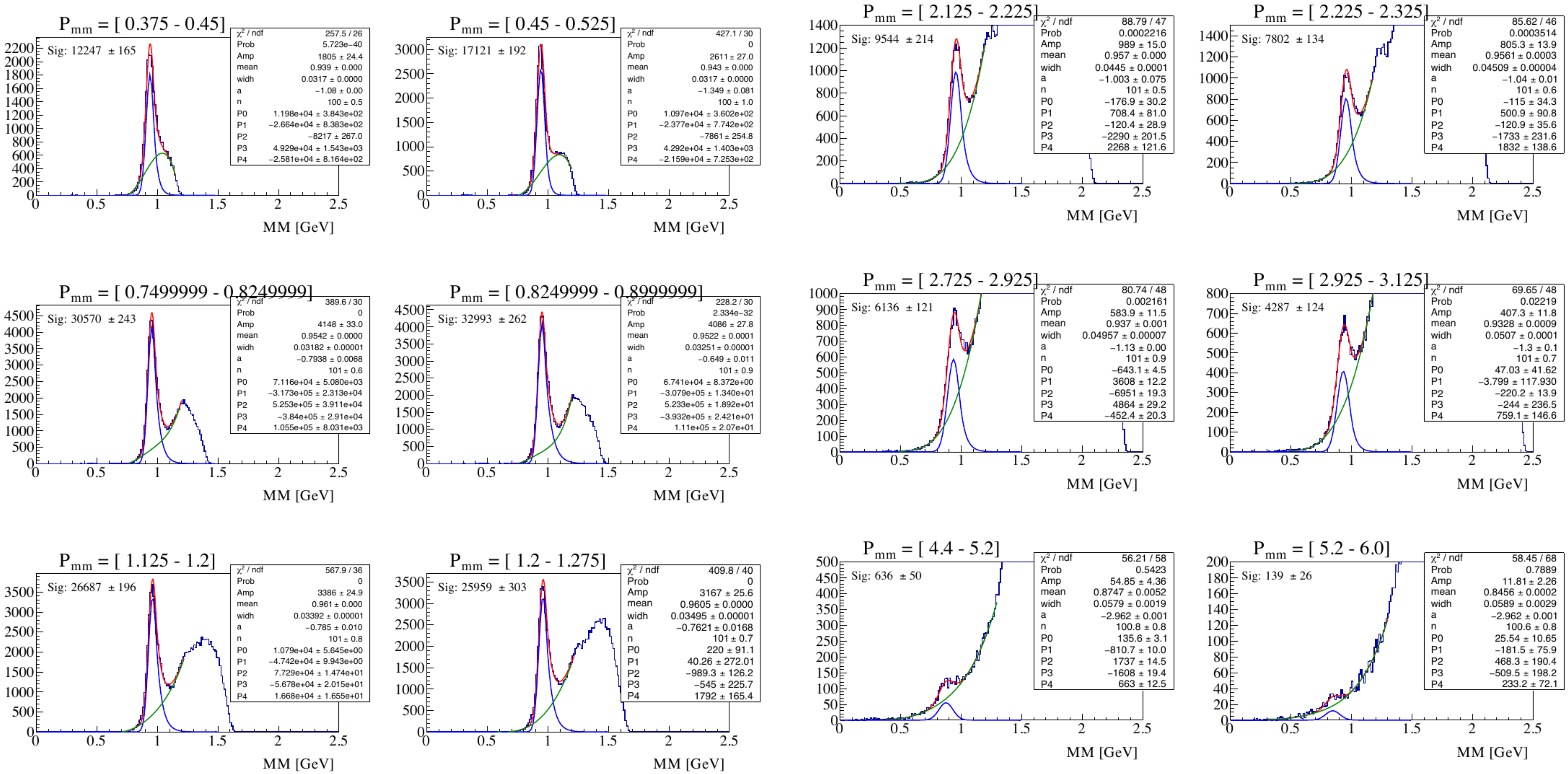
$\Delta p = b\ p + c$

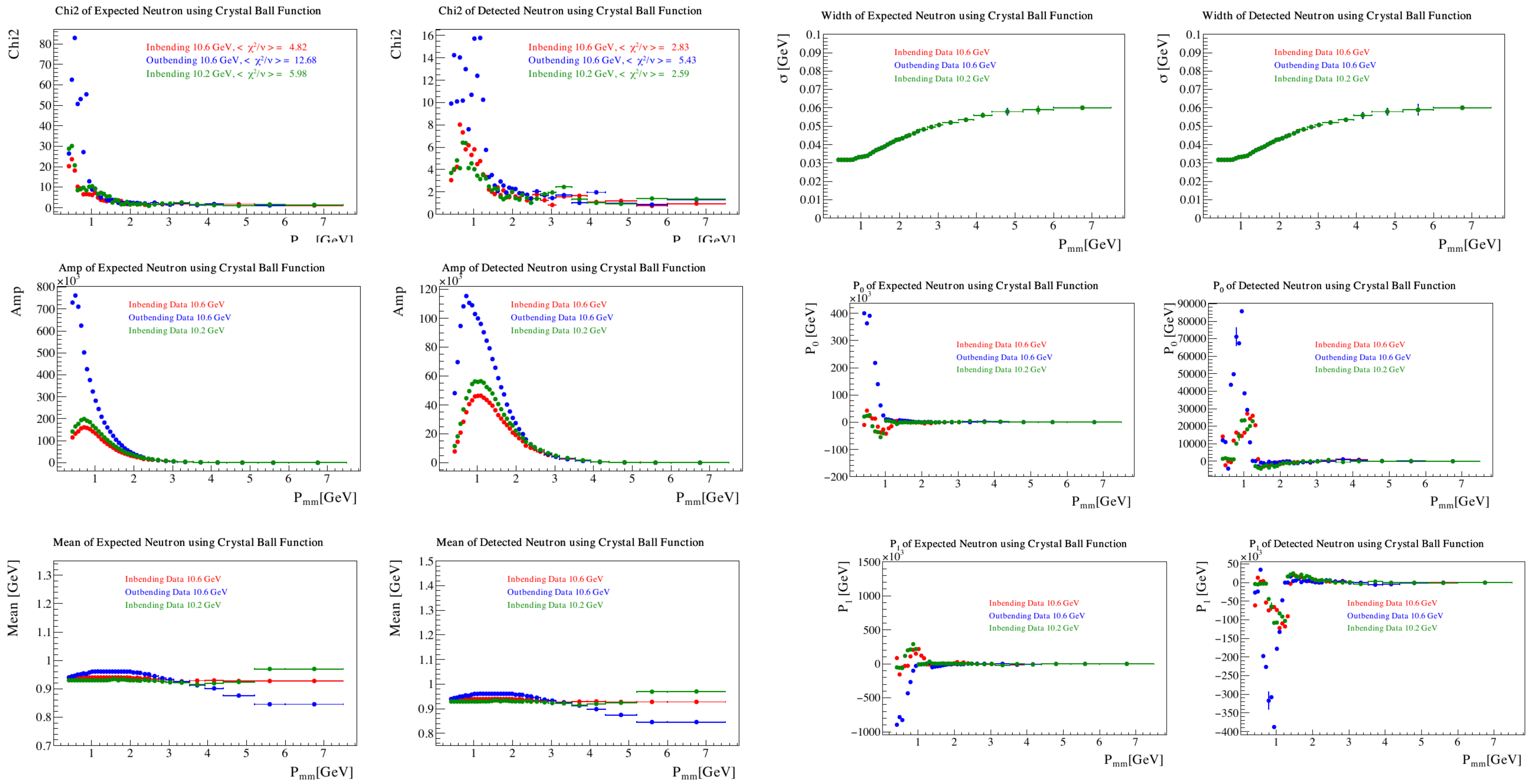
C++ version of the code

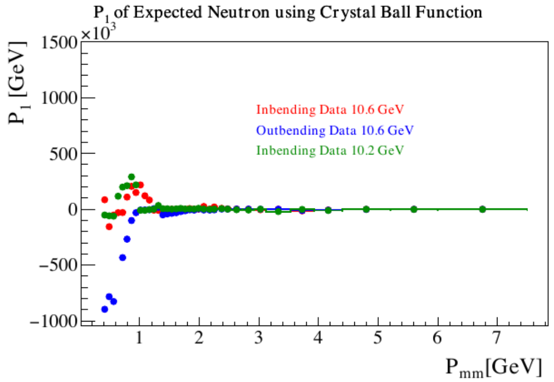
the only variables needed for code below are: **ex,ey,ez,esec, pipx,pipy,pipz,pipsec, pimx,pimy,pimz,pimsec**

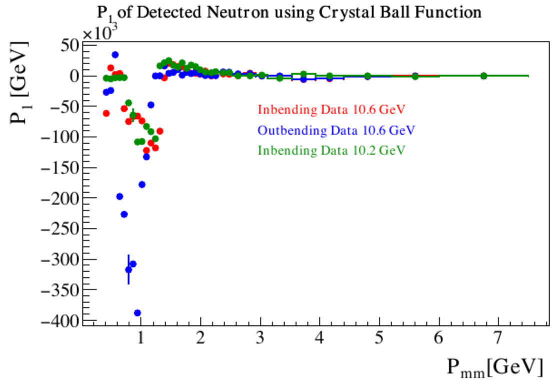
```
double xx[] =
{
    0.0263375, 0.0158871, 0.0130852, -0.00366006, 0.00694866, 0.0197195,
    0.00767067, 0.00480921, -0.0175756, 0.0252757, 0.0156601, 0.00984872,
    0.00244435, 0.00681414, 0.0294068, 0.0059881, 0.00286992, 0.0179319,
    0.0171495, 0.00359637, -0.0046115, 0.00314739, 0.0136338, 0.0768753,
    0.00675454, -0.0118234, -0.0288654, 0.0189465, 0.0131816, 0.0262004,
    0.00375165, 0.00907457, 0.0486894, 0.00806305, 0.0006999, 0.00527513,
    0.0116485, 0.0105681, 0.0149848, 0.000318094, -0.00480124, 0.0395545,
    0.00824216, -0.00070659, -0.0057075, 0.0213057, 0.0112999, 0.0100216,
    0.000653685, 0.0093174, 0.0822385, 0.00808384, 0.000898799, -0.0172692,
};

double pars[6][3][3];
int ipar=0;

for(int isec=0;isec<6;isec++)
for(int ivec=0;ivec<3;ivec++)
{
    double dp1=xx[ipar++], dp5=xx[ipar++], dp9=xx[ipar++];

    pars[isec][ivec][0] = (dp1 - 2*dp5 + dp9)/32.;
    pars[isec][ivec][1] = (-7*dp1)/16. + (5*dp5)/8. - (3*dp9)/16.;
    pars[isec][ivec][2] = (45*dp1)/32. - (9*dp5)/16. + (5*dp9)/32.;
}

auto dpp = [&](float px, float py, float pz, int sec, int ivec)
{
    double pp = sqrt(px*px + py*py + pz*pz);

    double a=pars[sec-1][ivec][0],
           b=pars[sec-1][ivec][1],
           c=pars[sec-1][ivec][2];

    double dp = a*pp*pp + b*pp + c; //pol2 corr func

    //electron pol1 corr func for each sec and each phi bins
    if(ivec == 0)
    {
        if(sec == 1)
        {
```

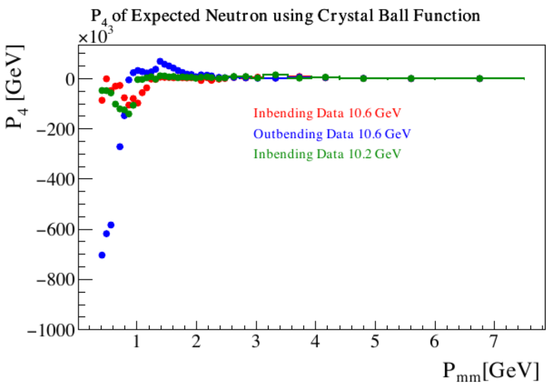
Outbending 10.6 GeV

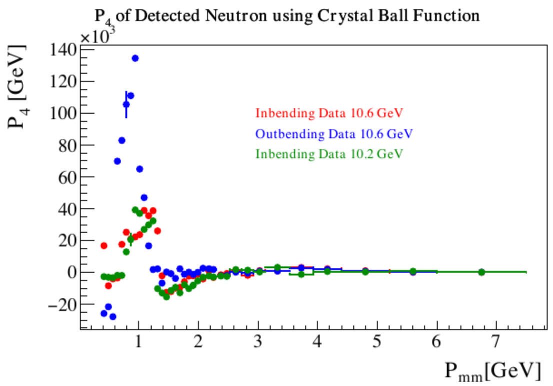


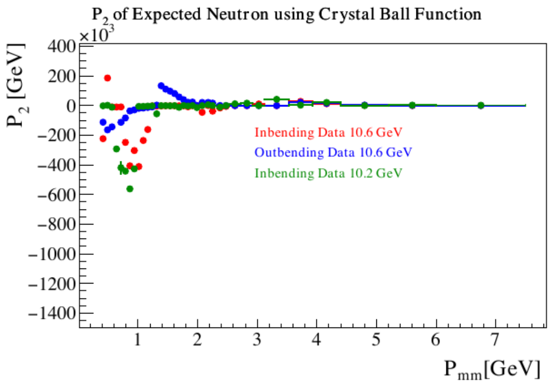

Chi2 of Expected Neutron using Crystal Ball Function
Chi2
Inbending 10.6 GeV, < χ²/ν > = 4.82
Outbending 10.6 GeV, < χ²/ν > = 12.68
Inbending 10.2 GeV, < χ²/ν > = 5.98
Chi2 of Detected Neutron using Crystal Ball Function
Inbending 10.6 GeV, < χ²/ν > = 2.83
Outbending 10.6 GeV, < χ²/ν > = 5.43
Inbending 10.2 GeV, < χ²/ν > = 2.59
Width of Expected Neutron using Crystal Ball Function
σ [GeV]
Inbending Data 10.6 GeV
Outbending Data 10.6 GeV
Inbending Data 10.2 GeV
Width of Detected Neutron using Crystal Ball Function
Amp of Expected Neutron using Crystal Ball Function
Amp
Amp of Detected Neutron using Crystal Ball Function
P0 of Expected Neutron using Crystal Ball Function
P0 [GeV]
P0 of Detected Neutron using Crystal Ball Function
Mean of Expected Neutron using Crystal Ball Function
Mean [GeV]
Mean of Detected Neutron using Crystal Ball Function
P1 of Expected Neutron using Crystal Ball Function
P1 [GeV]
P1 of Detected Neutron using Crystal Ball Function
Pmm[GeV]

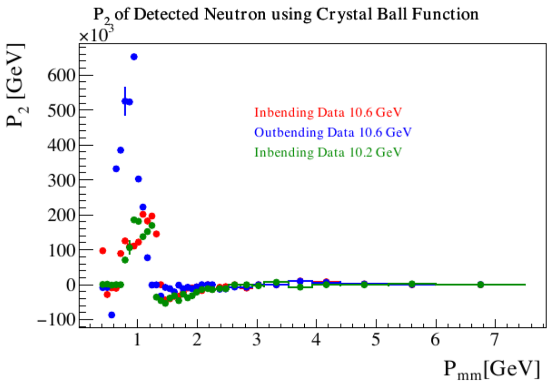

P_1 of Expected Neutron using Crystal Ball Function
Inbending Data 10.6 GeV
Outbending Data 10.6 GeV
Inbending Data 10.2 GeV
P_1 [GeV]
P_{mm}[GeV]

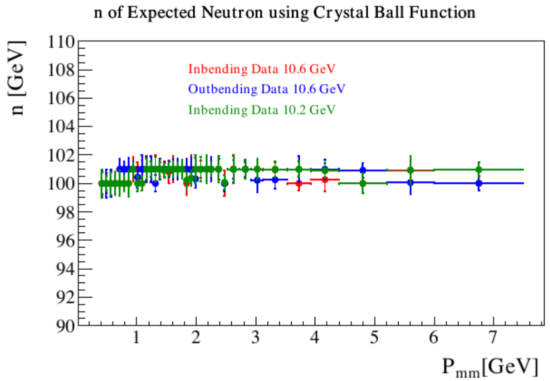

P_1 of Detected Neutron using Crystal Ball Function
Inbending Data 10.6 GeV
Outbending Data 10.6 GeV
Inbending Data 10.2 GeV
P_1 [GeV]
P_{mm}[GeV]

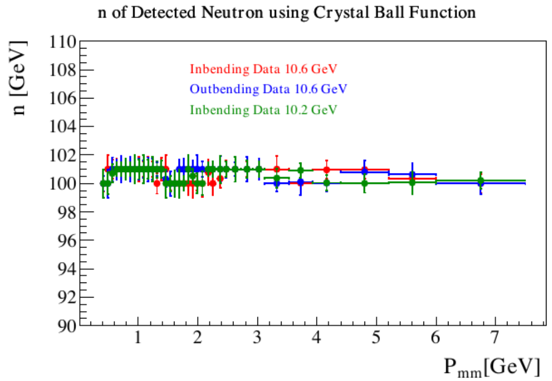

P_4 of Expected Neutron using Crystal Ball Function
Inbending Data 10.6 GeV
Outbending Data 10.6 GeV
Inbending Data 10.2 GeV
P_4 [GeV]
P_{mm}[GeV]

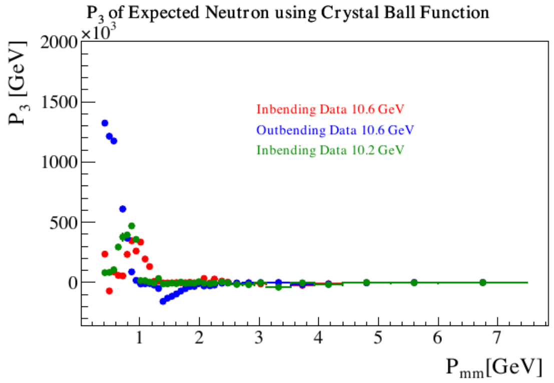

P_4 of Detected Neutron using Crystal Ball Function
Inbending Data 10.6 GeV
Outbending Data 10.6 GeV
Inbending Data 10.2 GeV
P_4 [GeV]
P_{mm}[GeV]

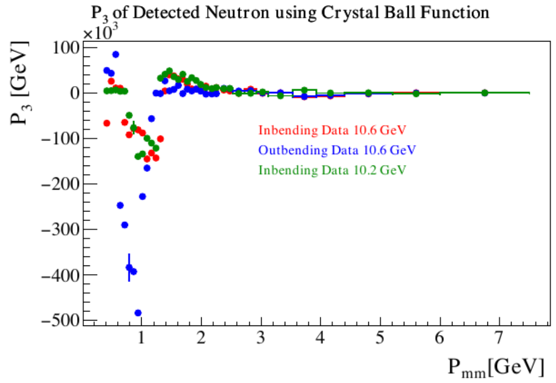

P_2 of Expected Neutron using Crystal Ball Function
Inbending Data 10.6 GeV
Outbending Data 10.6 GeV
Inbending Data 10.2 GeV
P_2 [GeV]
P_{mm}[GeV]

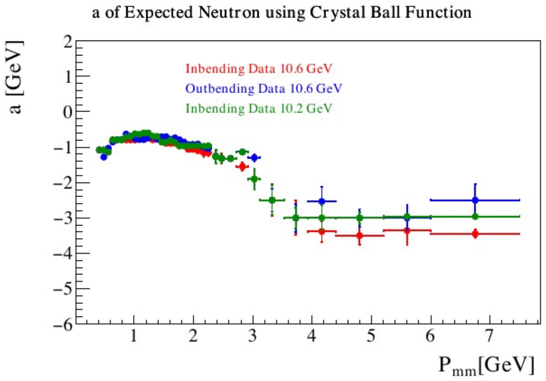

P_2 of Detected Neutron using Crystal Ball Function
Inbending Data 10.6 GeV
Outbending Data 10.6 GeV
Inbending Data 10.2 GeV
P_2 [GeV]
P_{mm}[GeV]

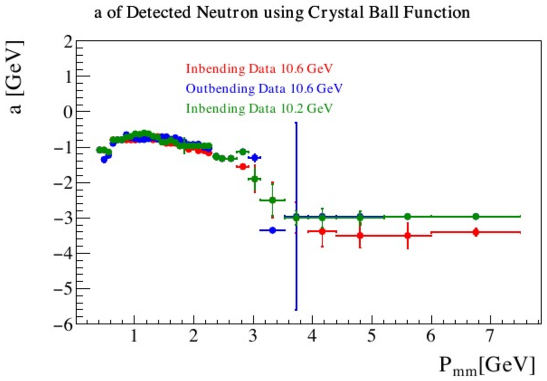

n of Expected Neutron using Crystal Ball Function
Inbending Data 10.6 GeV
Outbending Data 10.6 GeV
Inbending Data 10.2 GeV
n [GeV]
P_{mm}[GeV]

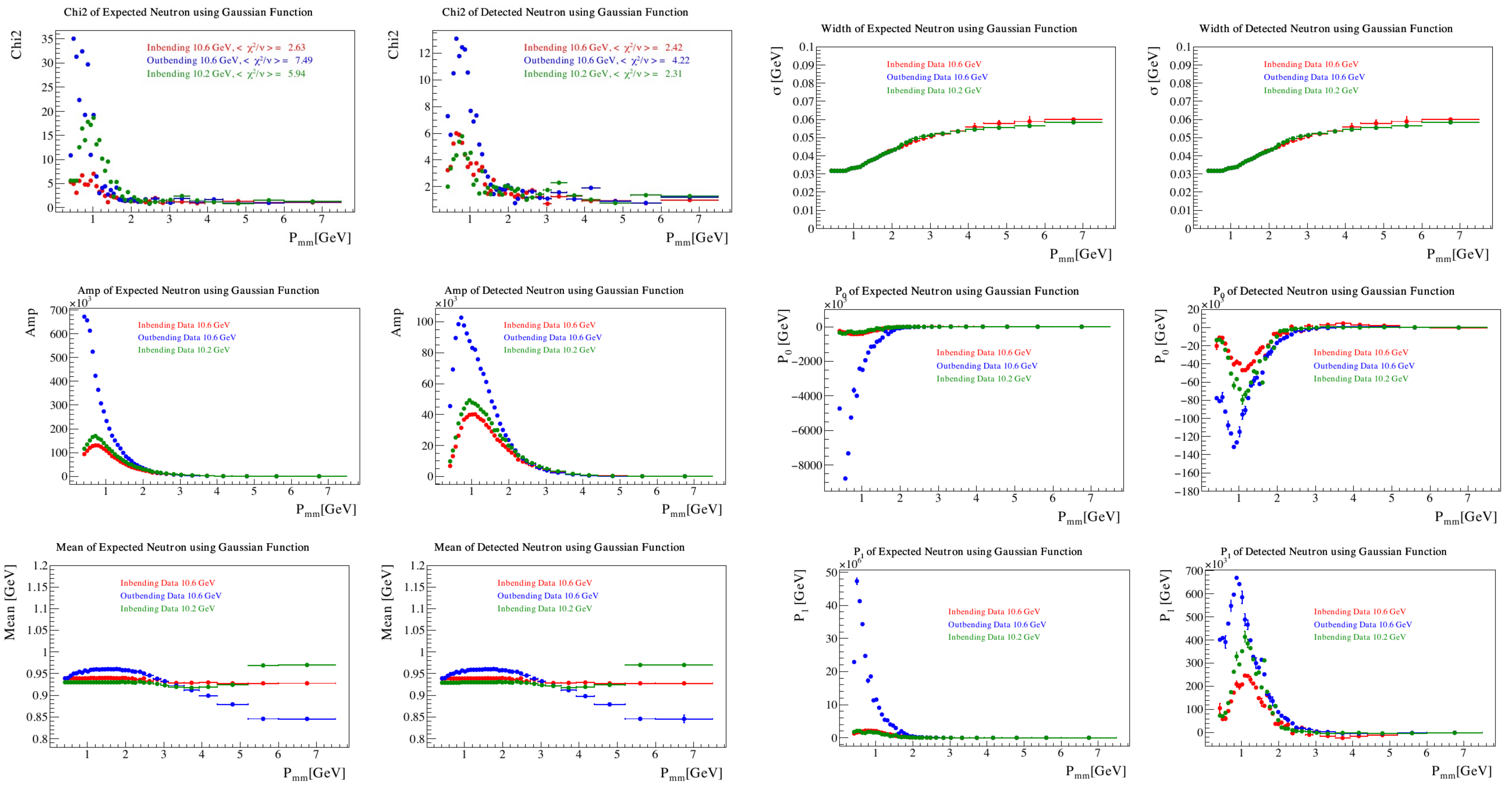

n of Detected Neutron using Crystal Ball Function
Inbending Data 10.6 GeV
Outbending Data 10.6 GeV
Inbending Data 10.2 GeV
n [GeV]
P_{mm}[GeV]

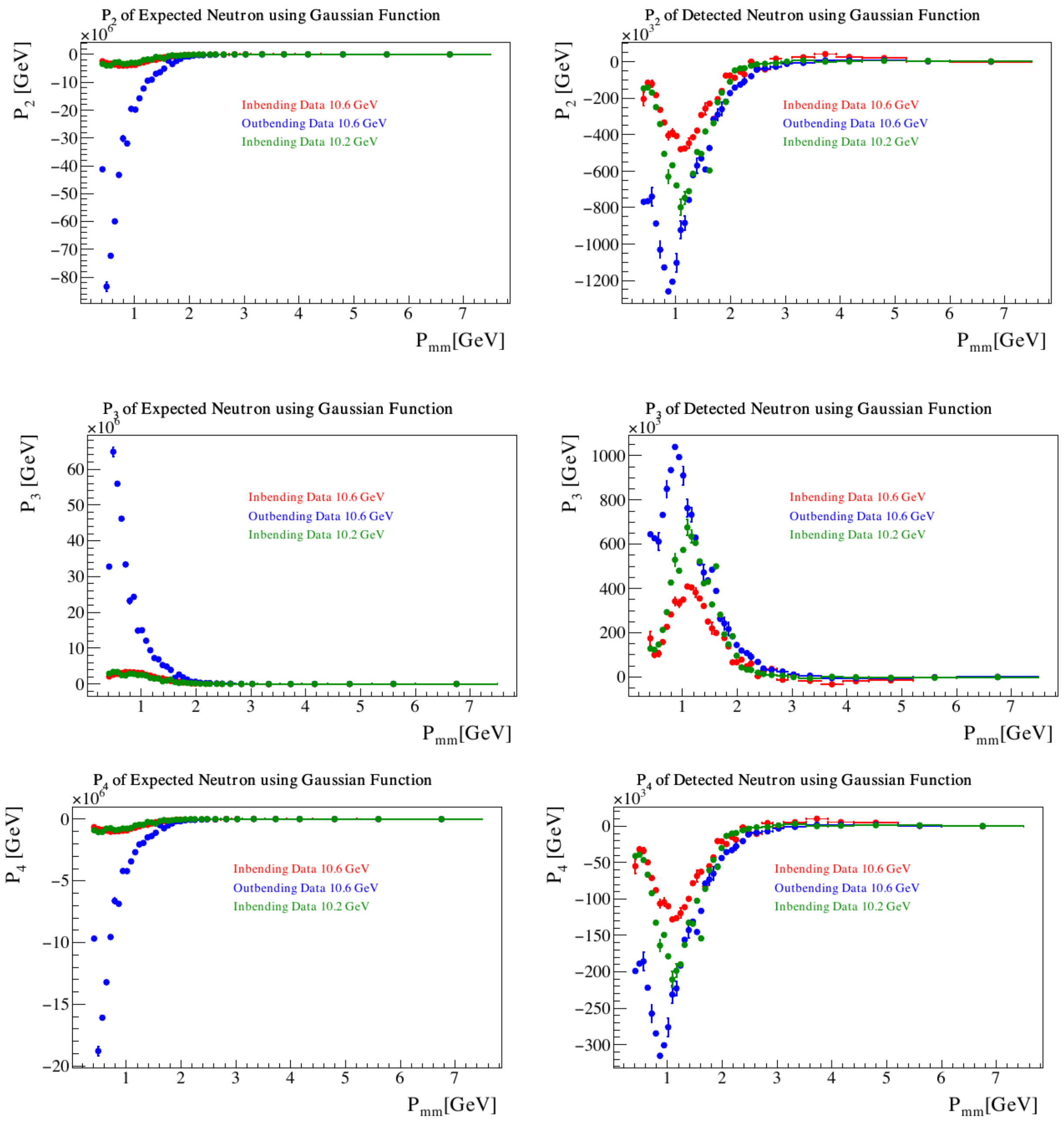

P_3 of Expected Neutron using Crystal Ball Function
Inbending Data 10.6 GeV
Outbending Data 10.6 GeV
Inbending Data 10.2 GeV
P_3 [GeV]
P_{mm}[GeV]


P_3 of Detected Neutron using Crystal Ball Function
Inbending Data 10.6 GeV
Outbending Data 10.6 GeV
Inbending Data 10.2 GeV
P_3 [GeV]
P_{mm}[GeV]


a of Expected Neutron using Crystal Ball Function
Inbending Data 10.6 GeV
Outbending Data 10.6 GeV
Inbending Data 10.2 GeV
a [GeV]
P_{mm}[GeV]


a of Detected Neutron using Crystal Ball Function
Inbending Data 10.6 GeV
Outbending Data 10.6 GeV
Inbending Data 10.2 GeV
a [GeV]
P_{mm}[GeV]


Chi2 of Expected Neutron using Gaussian Function
Chi2
Inbending 10.6 GeV, < χ²/ν > = 2.63
Outbending 10.6 GeV, < χ²/ν > = 7.49
Inbending 10.2 GeV, < χ²/ν > = 5.94
P_mm[GeV]
Chi2 of Detected Neutron using Gaussian Function
Chi2
Inbending 10.6 GeV, < χ²/ν > = 2.42
Outbending 10.6 GeV, < χ²/ν > = 4.22
Inbending 10.2 GeV, < χ²/ν > = 2.31
P_mm[GeV]
Width of Expected Neutron using Gaussian Function
σ [GeV]
Inbending Data 10.6 GeV
Outbending Data 10.6 GeV
Inbending Data 10.2 GeV
P_mm[GeV]
Width of Detected Neutron using Gaussian Function
σ [GeV]
Inbending Data 10.6 GeV
Outbending Data 10.6 GeV
Inbending Data 10.2 GeV
P_mm[GeV]
Amp of Expected Neutron using Gaussian Function
Amp
×10³
Inbending Data 10.6 GeV
Outbending Data 10.6 GeV
Inbending Data 10.2 GeV
P_mm[GeV]
Amp of Detected Neutron using Gaussian Function
Amp
×10³
Inbending Data 10.6 GeV
Outbending Data 10.6 GeV
Inbending Data 10.2 GeV
P_mm[GeV]
P_0 of Expected Neutron using Gaussian Function
P_0 [GeV]
×10³
Inbending Data 10.6 GeV
Outbending Data 10.6 GeV
Inbending Data 10.2 GeV
P_mm[GeV]
P_0 of Detected Neutron using Gaussian Function
P_0 [GeV]
×10³
Inbending Data 10.6 GeV
Outbending Data 10.6 GeV
Inbending Data 10.2 GeV
P_mm[GeV]
Mean of Expected Neutron using Gaussian Function
Mean [GeV]
Inbending Data 10.6 GeV
Outbending Data 10.6 GeV
Inbending Data 10.2 GeV
P_mm[GeV]
Mean of Detected Neutron using Gaussian Function
Mean [GeV]
Inbending Data 10.6 GeV
Outbending Data 10.6 GeV
Inbending Data 10.2 GeV
P_mm[GeV]
P_1 of Expected Neutron using Gaussian Function
P_1 [GeV]
×10⁶
Inbending Data 10.6 GeV
Outbending Data 10.6 GeV
Inbending Data 10.2 GeV
P_mm[GeV]
P_1 of Detected Neutron using Gaussian Function
P_1 [GeV]
×10³
Inbending Data 10.6 GeV
Outbending Data 10.6 GeV
Inbending Data 10.2 GeV
P_mm[GeV]


P2 of Expected Neutron using Gaussian Function
P2 of Detected Neutron using Gaussian Function
P3 of Expected Neutron using Gaussian Function
P3 of Detected Neutron using Gaussian Function
P4 of Expected Neutron using Gaussian Function
P4 of Detected Neutron using Gaussian Function
Inbending Data 10.6 GeV
Outbending Data 10.6 GeV
Inbending Data 10.2 GeV
P2 [GeV]
P3 [GeV]
P4 [GeV]
Pmm[GeV]