



## Measurement of Proton Beam Energy Loss Using the Fitting on Hypothetical Residual Range

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# ProtoDUNE-SP : Pion Beam Study

## Beam selection

- MC : true beam PDG = 211 or  $\pm 13$
- Data
  - No cosmic trigger
  - N(reco beam particle) = 1
  - At least one of “beam\_inst\_PDG\_candidates” should be 211 or  $\pm 13$

## Additional cuts on beam tracks

- Pandora slice cut : beam is reconstructed as track by the Pandora
- Calo size cut : at least one reconstructed hit in the collection plane
- Beam quality cut : cut on beam angle and entrance positions
  - $-3 < dz/\sigma_z < 3$ ,  $-1 < dxy/\sigma_{xy} < 3$ ,  $\cos\theta > 0.95$
- Beam XY cut : Heng-Ye's beam scraper cut
- Daughter Michel score  $< 0.55$ 
  - Hit charge weighted average of CNN Michel scores near vertex
- Pass proton veto cut
  - $\chi^2_{\text{proton}} > 80$

# Used Samples and Normalization Factors

## MC

- PDSPProd4a\_MC\_0.3GeV\_reco1\_sce\_datadriven\_v1\_ntuple\_v09\_41\_00\_03.root
- PDSPProd4a\_MC\_0.5GeV\_reco1\_sce\_datadriven\_v1\_ntuple\_v09\_41\_00\_04.root
- PDSPProd4a\_MC\_1GeV\_reco1\_sce\_datadriven\_v1\_ntuple\_v09\_41\_00\_03.root
- PDSPProd4a\_MC\_2GeV\_reco1\_sce\_datadriven\_v1\_ntuple\_v09\_41\_00\_03.root

## Data

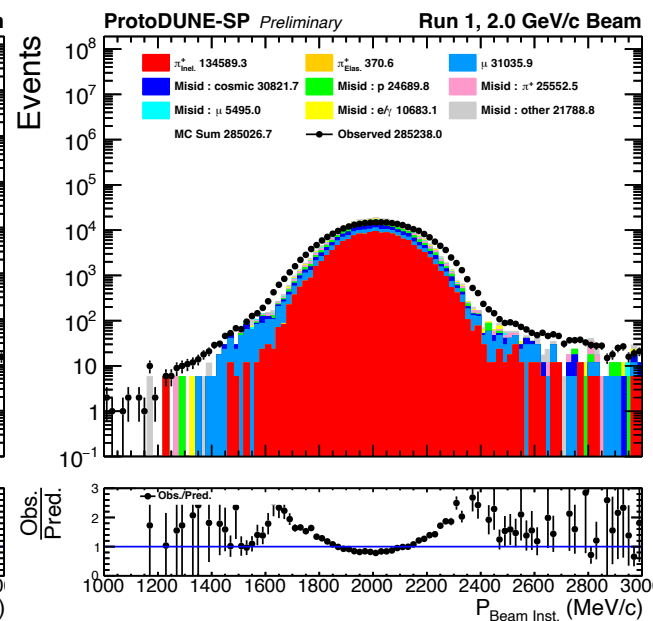
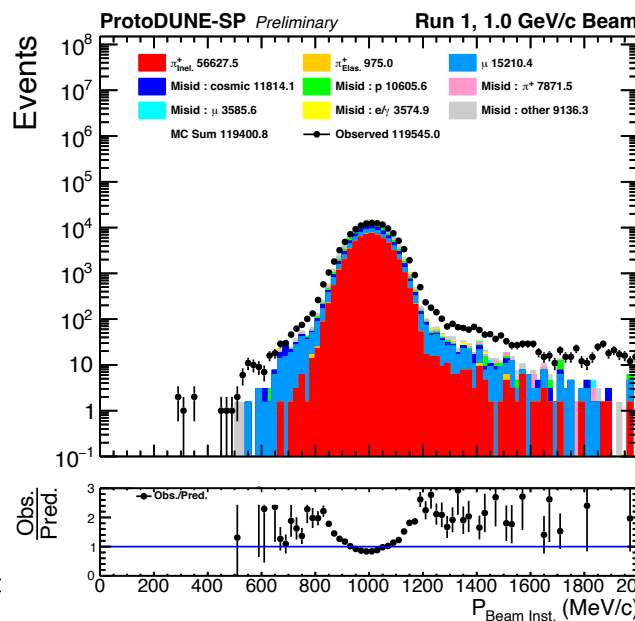
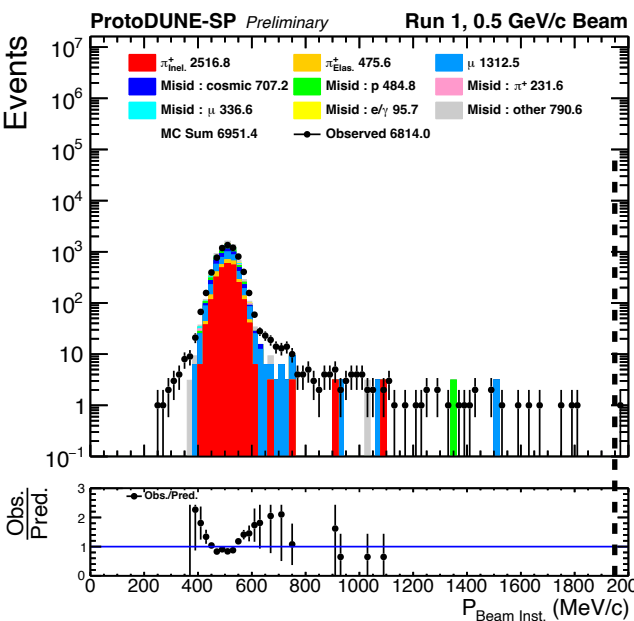
- PDSPProd4\_data\_0.3GeV\_reco2\_ntuple\_v09\_41\_00\_04.root
- PDSPProd4\_data\_0.5GeV\_reco2\_ntuple\_v09\_41\_00\_04.root
- PDSPProd4\_data\_1GeV\_reco2\_ntuple\_v09\_41\_00\_04.root
- PDSPProd4\_data\_2GeV\_reco2\_ntuple\_v09\_42\_03\_01.root

## Normalization factors for MC samples

- Using non-empty events, normalization scale factor =  $N_{\text{Data, Norm}} / N_{\text{MC, Norm}}$
- $N_{\text{Data, Norm}}$  : no cosmic trigger, at least on of beam\_inst\_PDG\_candidates should be 211 or  $\pm 13$
- $N_{\text{MC, Norm}}$  : true\_beam\_PDG should be 211 or  $\pm 13$

# Beam Momentum from the Beam Instrument

Data distributions show bigger sigma compared to MC distributions



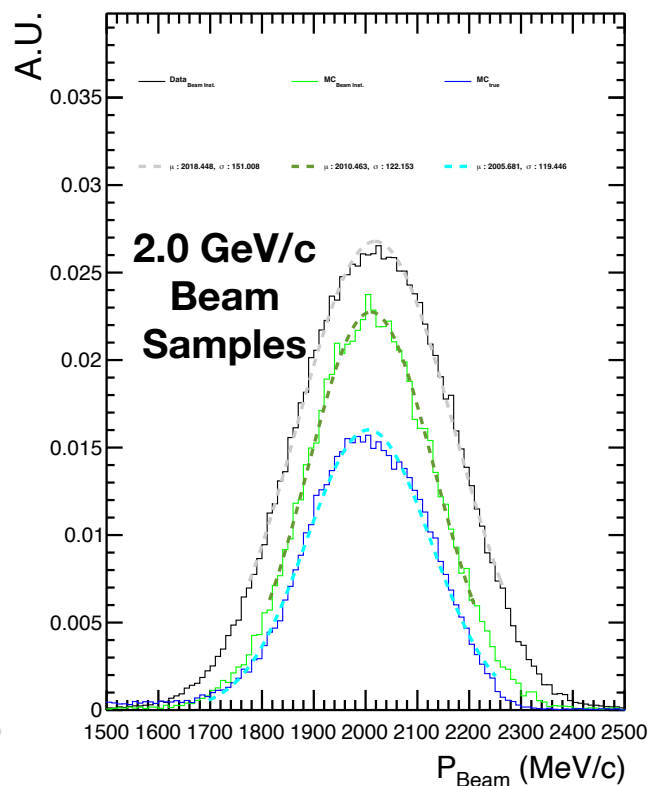
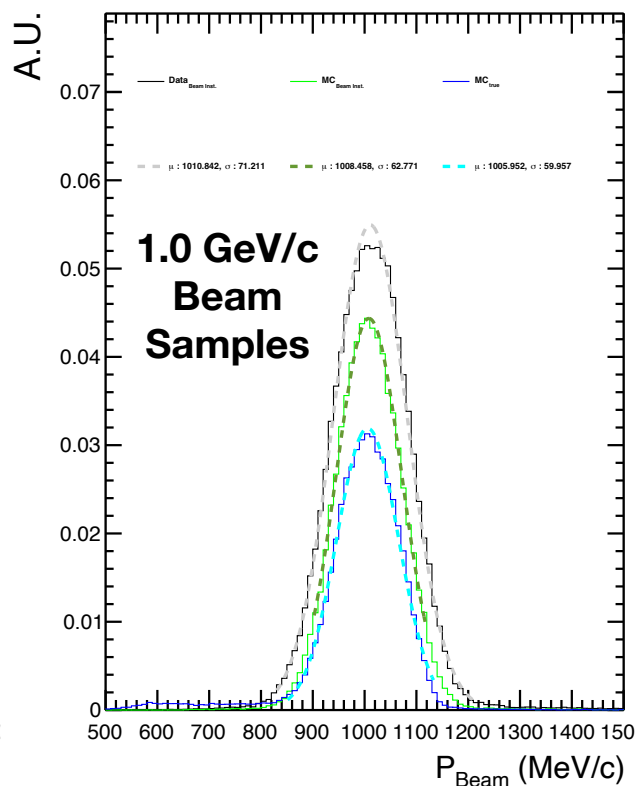
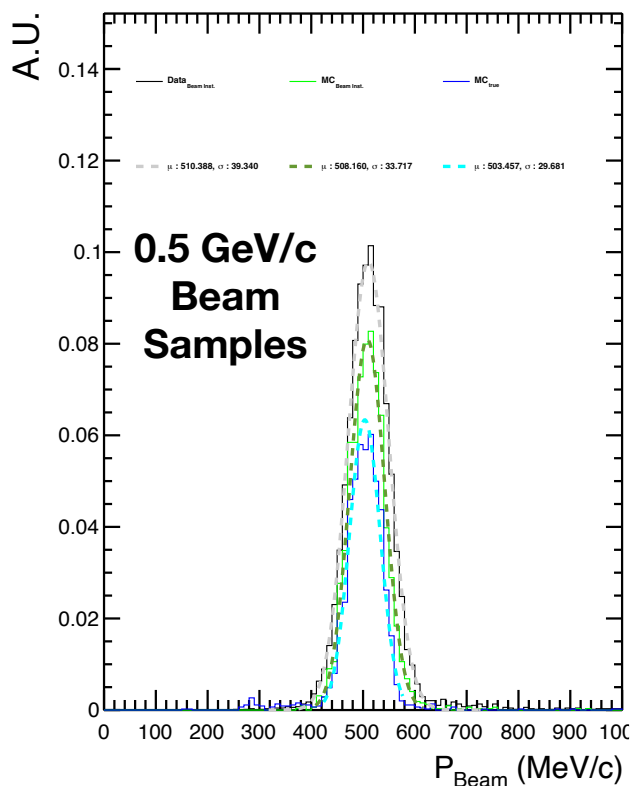
Beam |P| from  
the beam instrument  
0.5 GeV/c

Beam |P| from  
the beam instrument  
1.0 GeV/c

Beam |P| from  
the beam instrument  
2.0 GeV/c

# Beam Momentum from the Beam Instrument and Truth Level

Fitted using Gaussian



**Fitted  
( $\mu, \sigma$ )  
MeV**

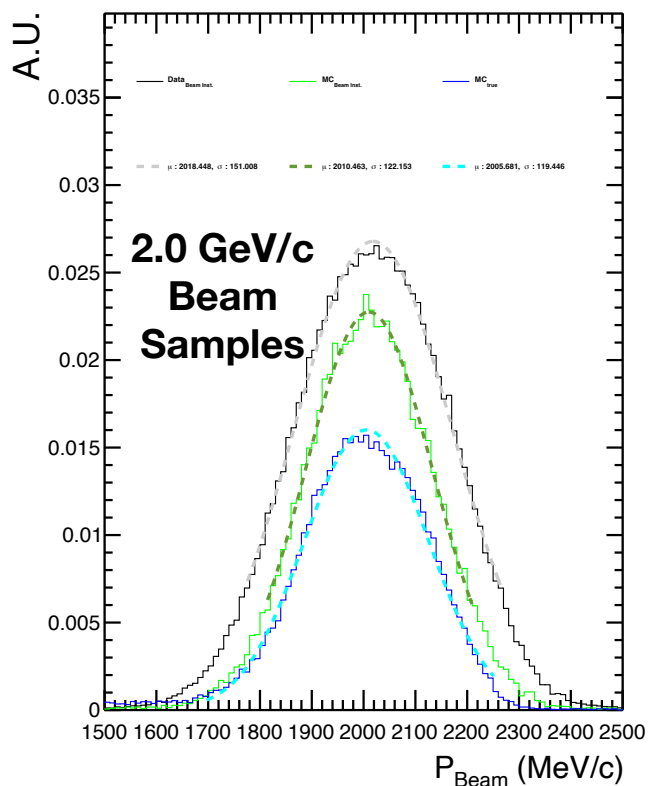
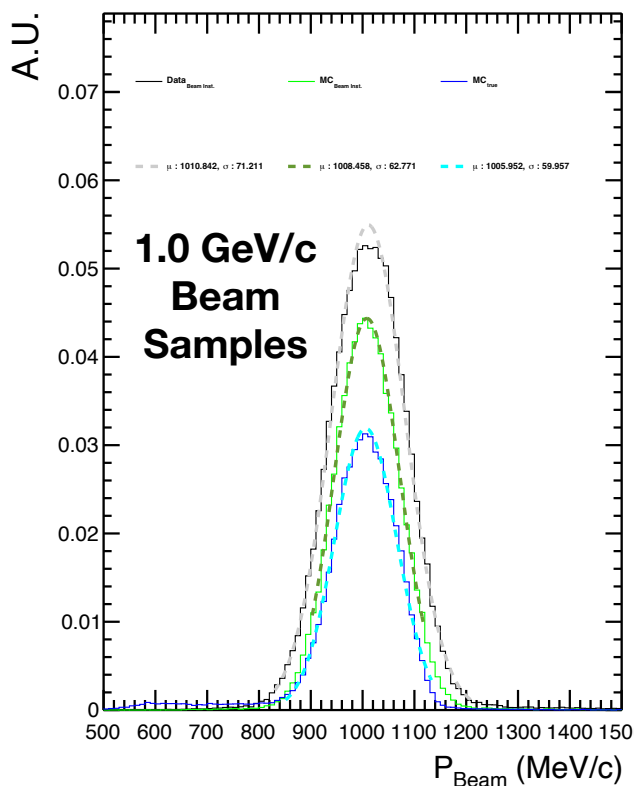
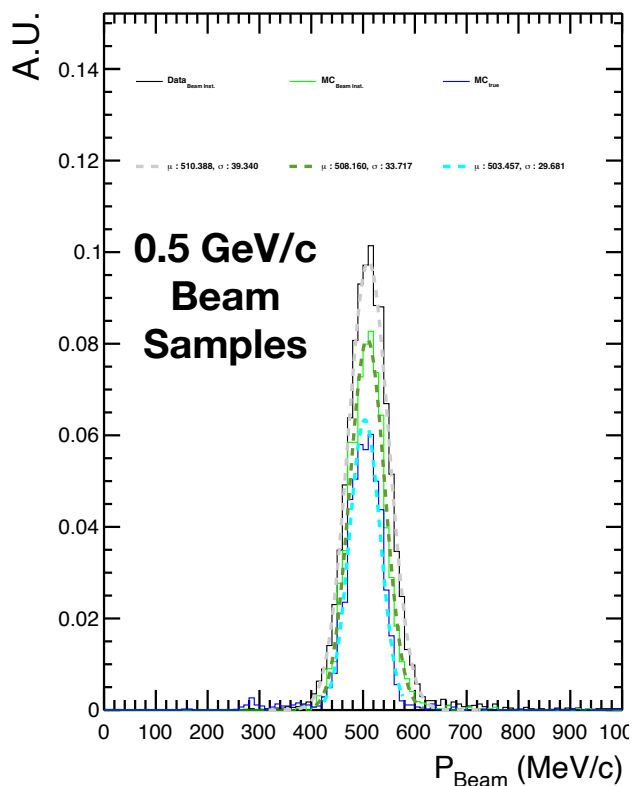
Data : (510.4, 39.3)  
 MC : (508.2, 33.7)  
 MC<sub>true</sub> : (503.5, 29.7)

Data : (1011, 71.2)  
 MC : (1008, 62.8)  
 MC<sub>true</sub> : (1006, 60.0)

Data : (2018, 151)  
 MC : (2010, 122)  
 MC<sub>true</sub> : (2006, 119)

# Beam Momentum from the Beam Instrument and Truth Level

Since Gaussian convolution of Gaussian is Gaussian with :  $\mu' = \mu_1 + \mu_2$  and  $\sigma'^2 = \sigma_1^2 + \sigma_2^2$



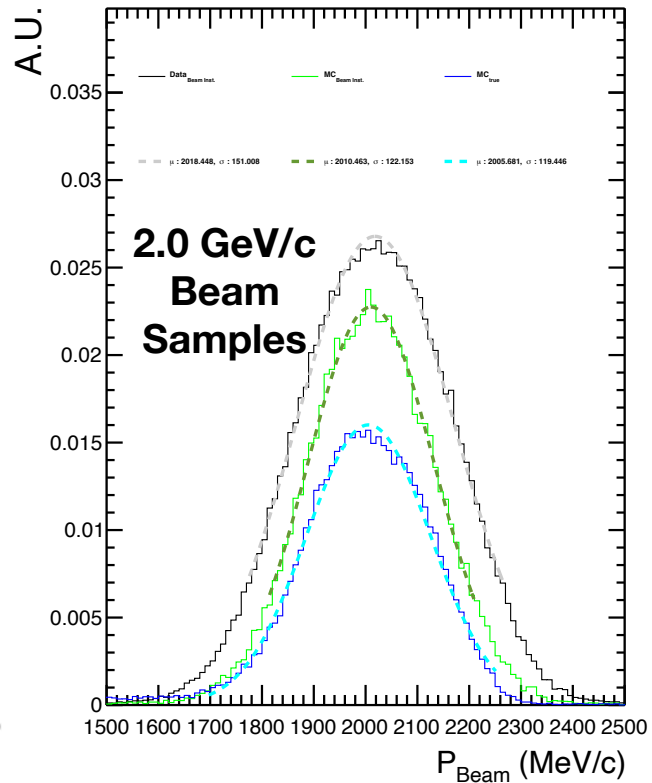
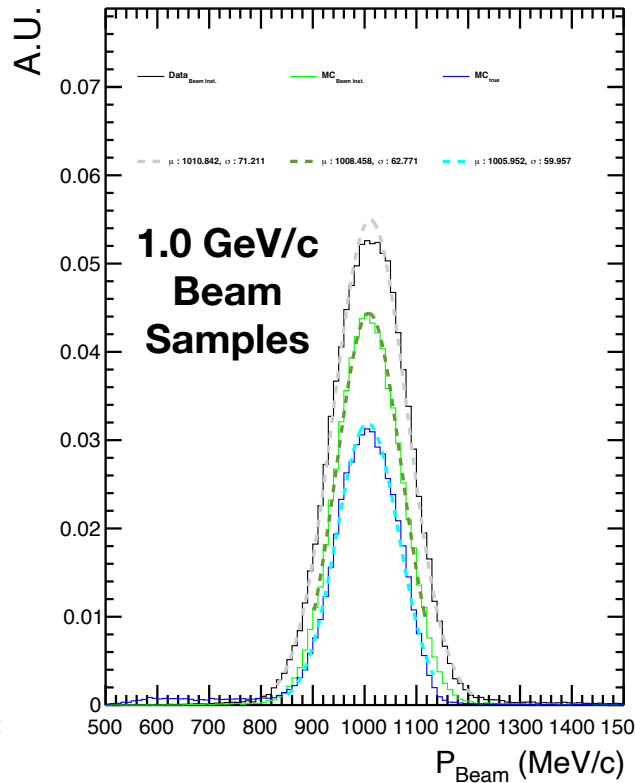
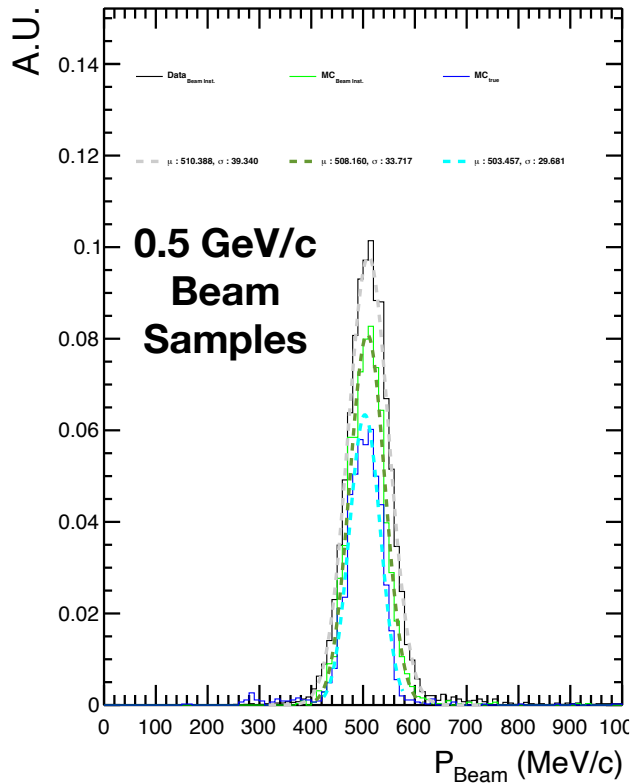
MC<sub>true</sub> → MC  
Required Gaussian Convolution  
( $\mu, \sigma$ ) = (4.70, 16.0) MeV  
 $\sigma / \langle P_{\text{true}} \rangle = 3.18 \%$

MC<sub>true</sub> → MC  
Required Gaussian Convolution  
( $\mu, \sigma$ ) = (2.51, 18.6) MeV  
 $\sigma / \langle P_{\text{true}} \rangle = 1.85 \%$

MC<sub>true</sub> → MC  
Required Gaussian Convolution  
( $\mu, \sigma$ ) = (4.78, 25.6) MeV  
 $\sigma / \langle P_{\text{true}} \rangle = 1.28 \%$

# Beam Momentum from the Beam Instrument and Truth Level

Since Gaussian convolution of Gaussian is Gaussian with :  $\mu' = \mu_1 + \mu_2$  and  $\sigma'^2 = \sigma_1^2 + \sigma_2^2$



MC<sub>true</sub> → Data

Required Gaussian Convolution

$(\mu, \sigma) = (6.93, 25.8)$  MeV

$\sigma / \langle P_{\text{true}} \rangle = 5.13 \%$

MC<sub>true</sub> → Data

Required Gaussian Convolution

$(\mu, \sigma) = (4.89, 38.4)$  MeV

$\sigma / \langle P_{\text{true}} \rangle = 3.82 \%$

MC<sub>true</sub> → Data

Required Gaussian Convolution

$(\mu, \sigma) = (12.8, 92.4)$  MeV

$\sigma / \langle P_{\text{true}} \rangle = 4.60 \%$

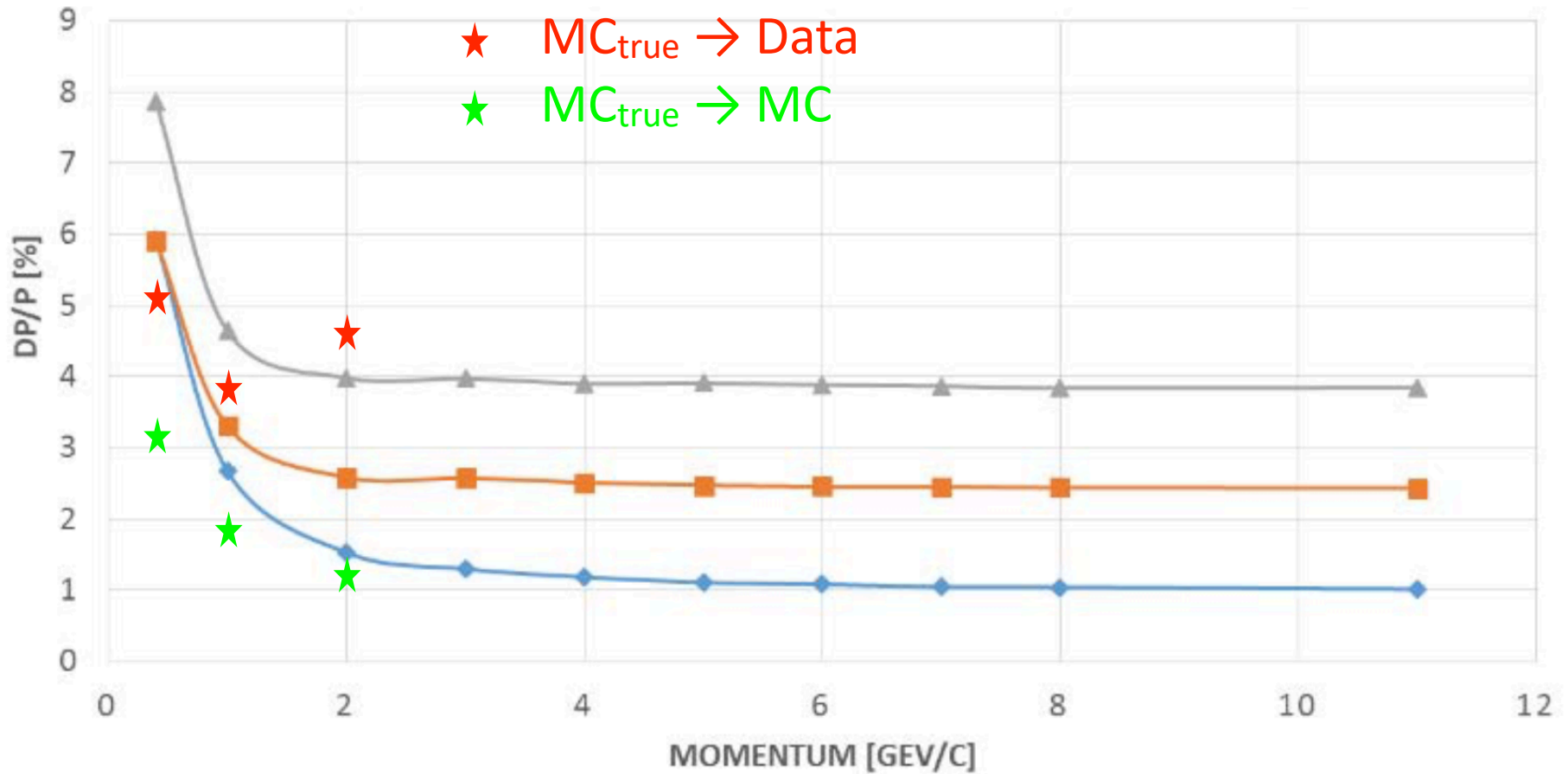
## Beam Momentum from the Beam Instrument and Truth Level

### MOMENTUM RESOLUTION FOR 3 POSITION RESOLUTIONS

—●—  $r=0.2\text{mm}$     —■—  $r=0.5\text{mm}$     —▲—  $r=0.8\text{mm}$

★  $\text{MC}_{\text{true}} \rightarrow \text{Data}$

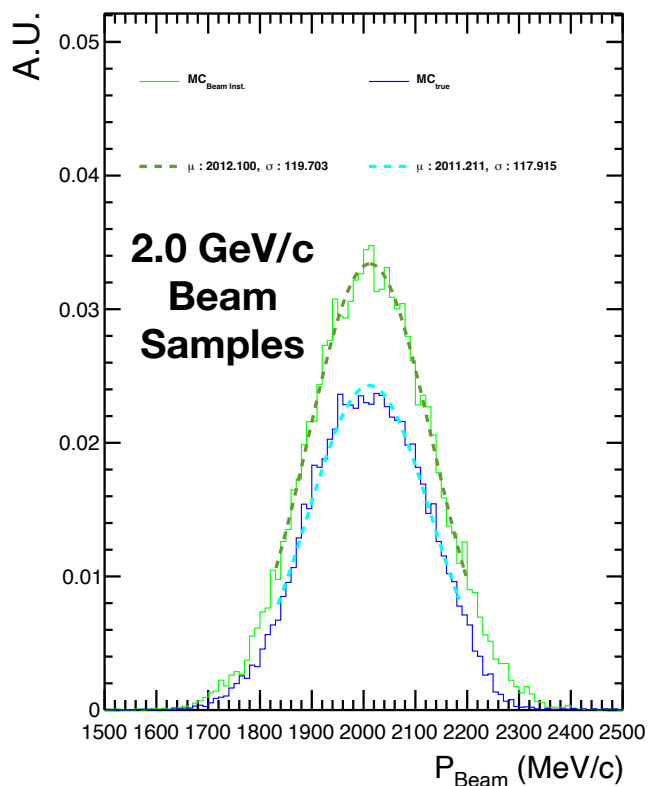
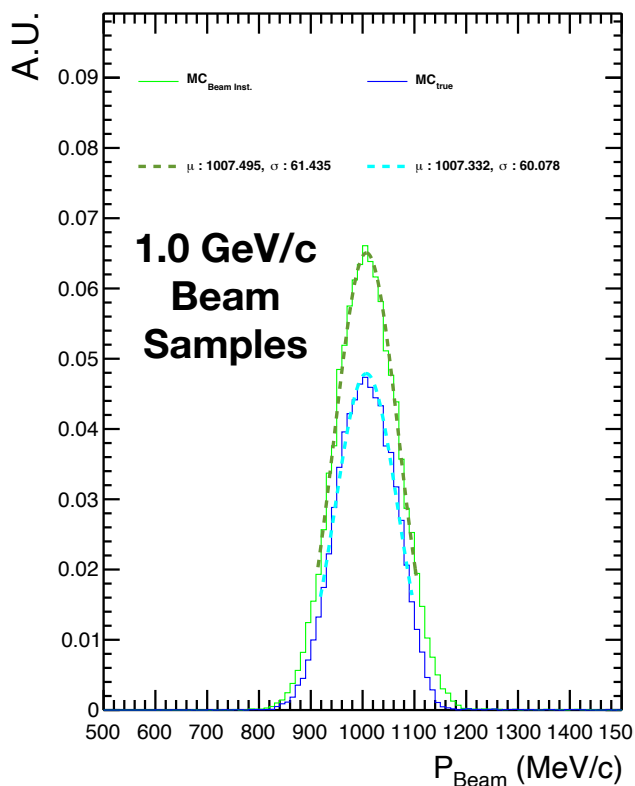
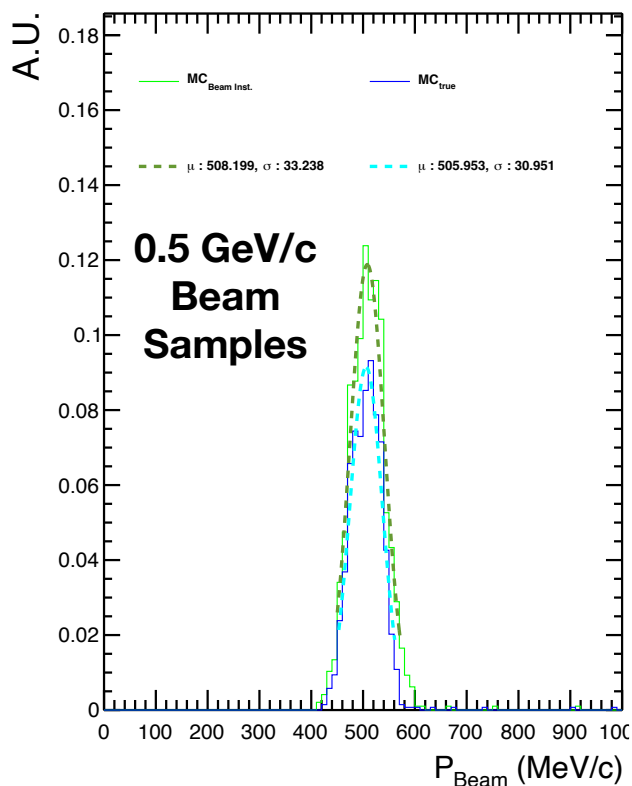
★  $\text{MC}_{\text{true}} \rightarrow \text{MC}$





# Beam Momentum from the Beam Instrument and Truth Level

Selected only pion beam particle : Pilnel II PiElas



**Fitted  
( $\mu, \sigma$ )  
MeV**

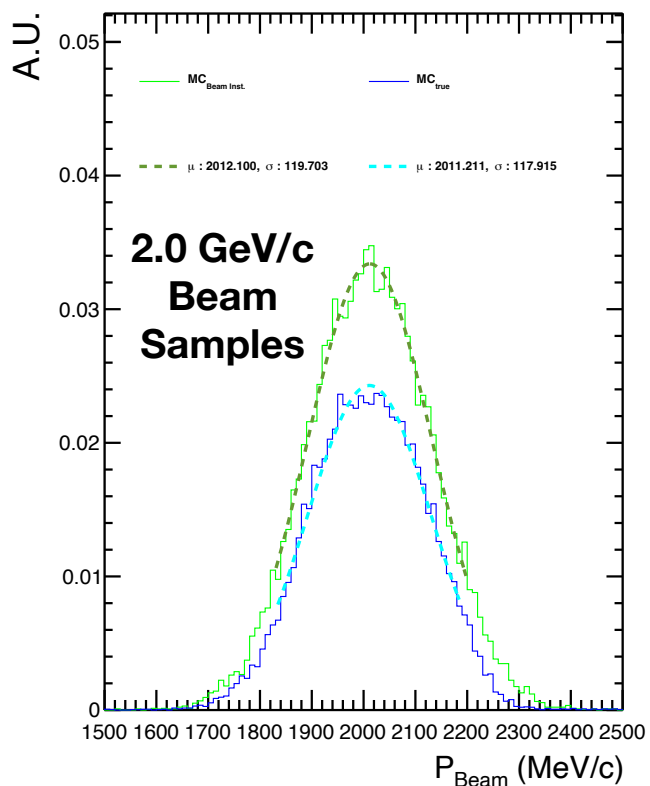
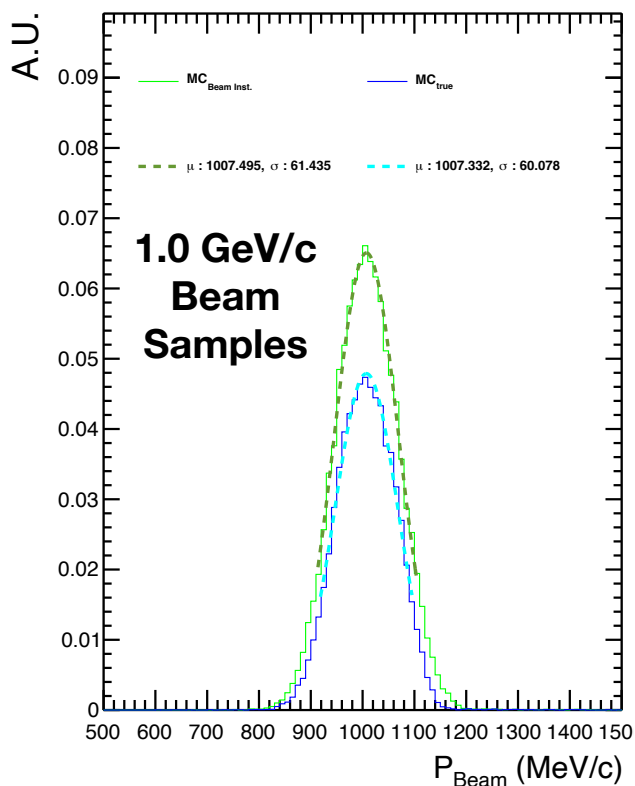
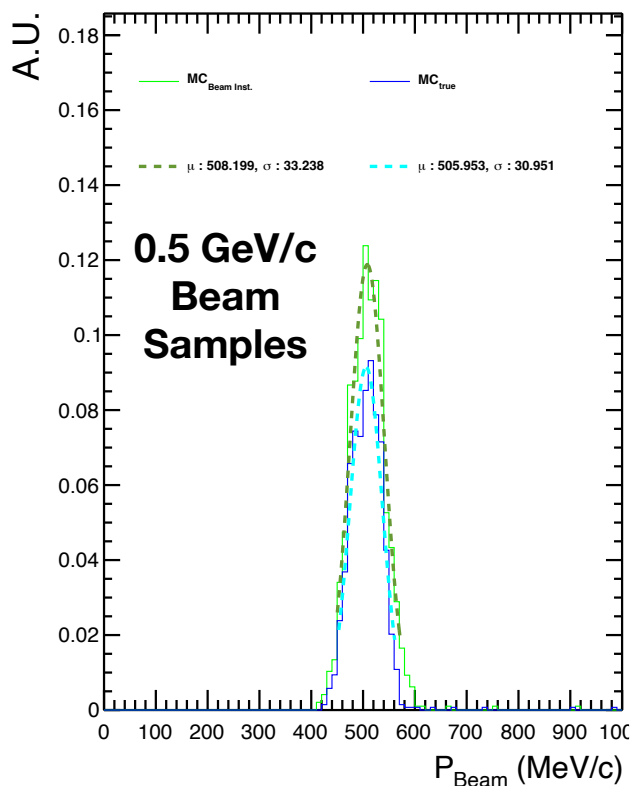
MC :  $(508.2, 33.2)$   
MC<sub>true</sub> :  $(506.0, 31.0)$

MC :  $(1007, 61.4)$   
MC<sub>true</sub> :  $(1007, 60.1)$

MC :  $(2012, 120)$   
MC<sub>true</sub> :  $(2011, 118)$

# Beam Momentum from the Beam Instrument and Truth Level

Selected only pion beam particle : Pilnel II PiElas



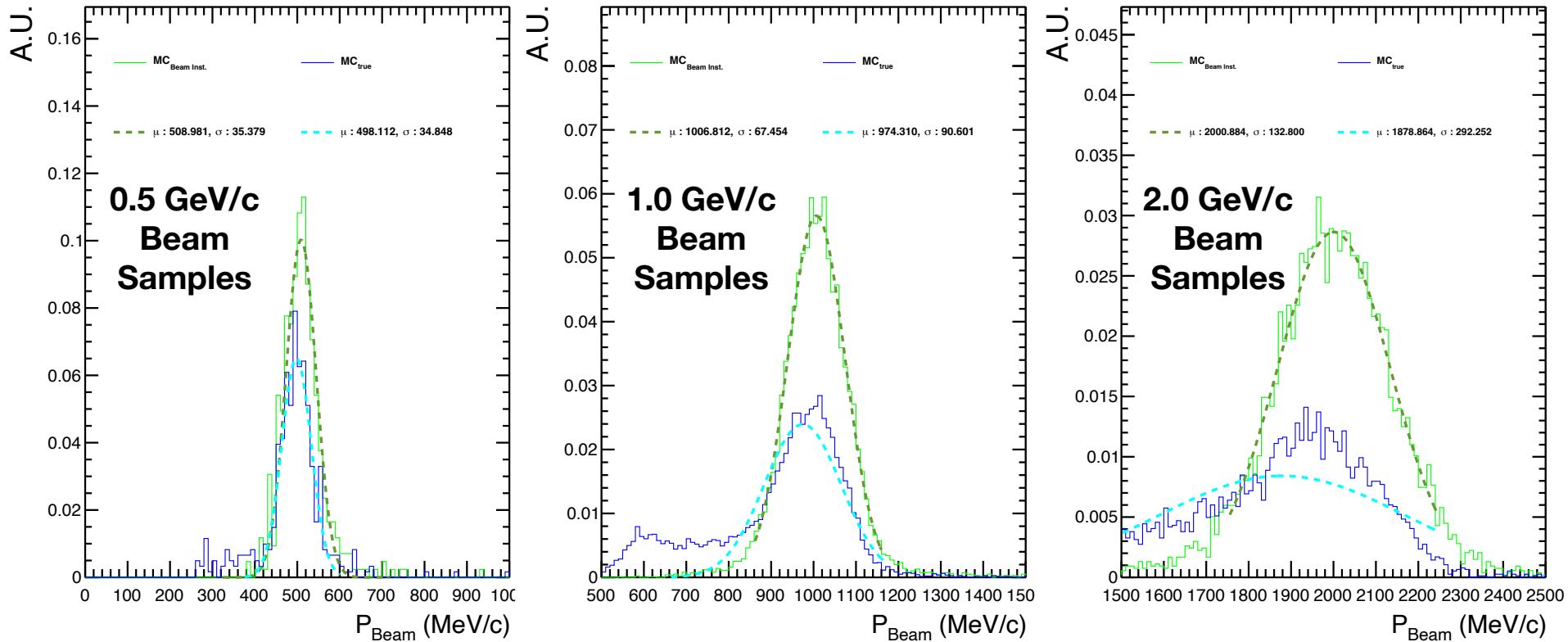
MC<sub>true</sub> → MC  
Required Gaussian Convolution  
 $(\mu, \sigma) = (2.25, 12.1)$  MeV  
 $\sigma / \langle P_{true} \rangle = 2.39 \%$

MC<sub>true</sub> → MC  
Required Gaussian Convolution  
 $(\mu, \sigma) = (0.16, 12.8)$  MeV  
 $\sigma / \langle P_{true} \rangle = 1.27 \%$

MC<sub>true</sub> → MC  
Required Gaussian Convolution  
 $(\mu, \sigma) = (0.89, 20.6)$  MeV  
 $\sigma / \langle P_{true} \rangle = 1.02 \%$

# Beam Momentum from the Beam Instrument and Truth Level

Selected only muon beam particle (not including misID:mu)



Strange  $P_{\text{true}}$  at starting point of the true beam particle for muons

- But, eventually,  $P_{\text{Beam Inst}}$  distributions show Gaussian-like shapes

# Beam Energy Loss at Between Front-face and Beam Instrument

Mean values for energy loss are similar for different beam energies, but widths are different much

