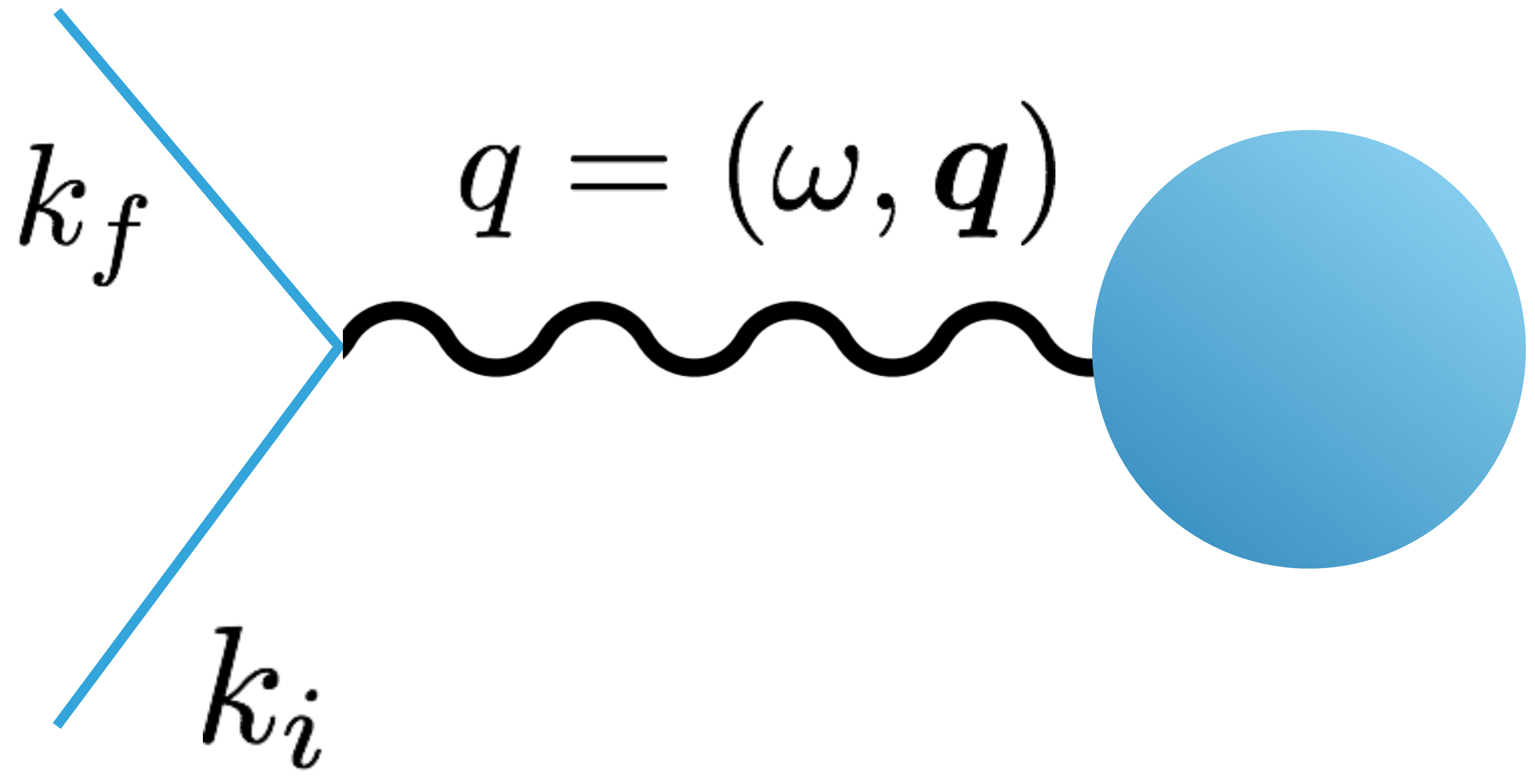
MICHAEL PAOLONE

NEW MEXICO STATE UNIVERSITY

FOR THE E05-110 COLLABORATION.

THE COULOMB SUM RULE IN NUCLEI

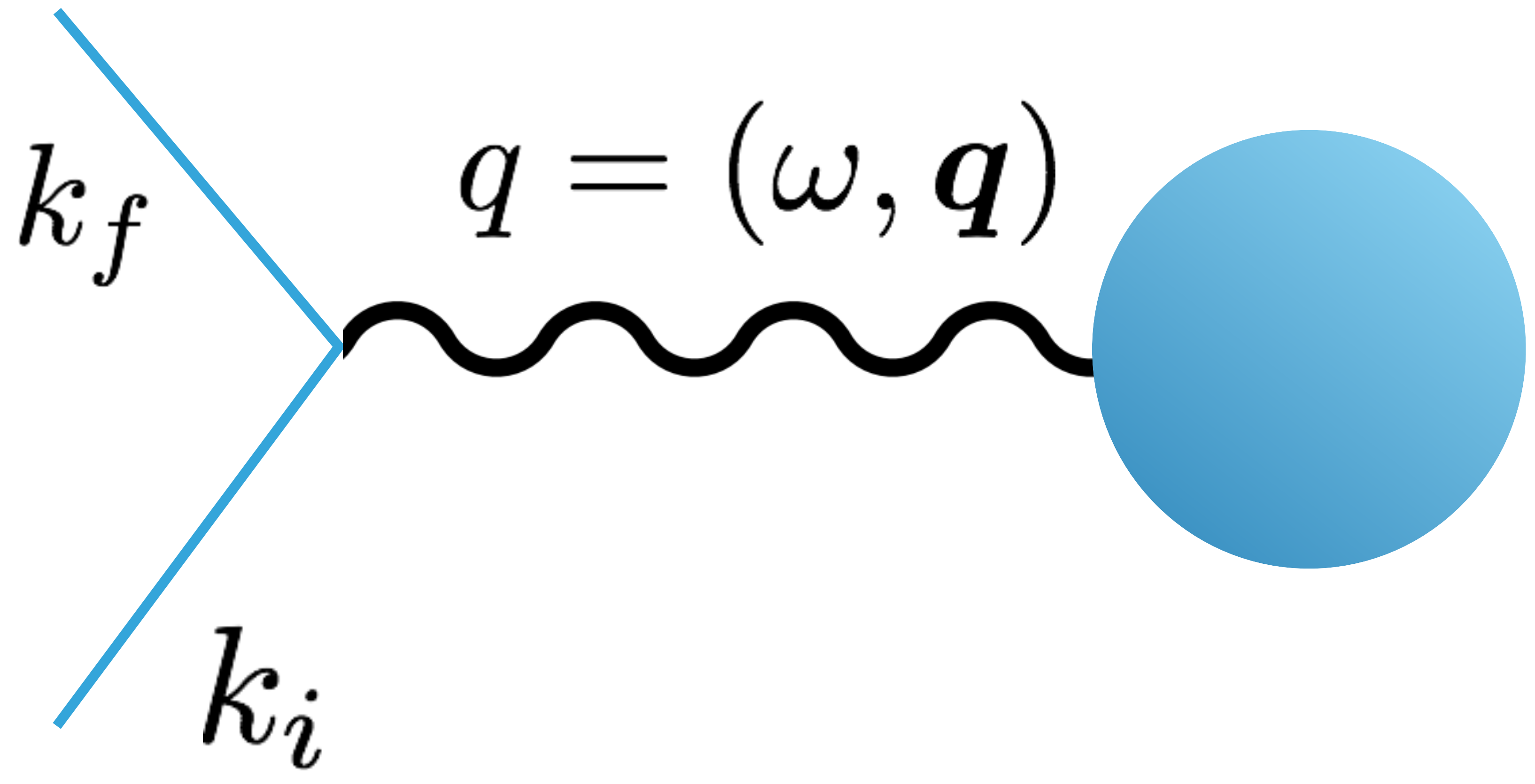
COULOMB SUM RULE



Inclusive electron scattering cross-section:

$$\frac{d^2\sigma}{d\Omega d\omega} = \sigma_{\text{Mott}} \left[\frac{q^4}{|\boldsymbol{q}|^4} R_L(\omega, |\boldsymbol{q}|) + \left(\frac{q^2}{2|\boldsymbol{q}|^2} + \tan^2\frac{\theta}{2} \right) R_T(\omega, |\boldsymbol{q}|) \right]$$

COULOMB SUM RULE



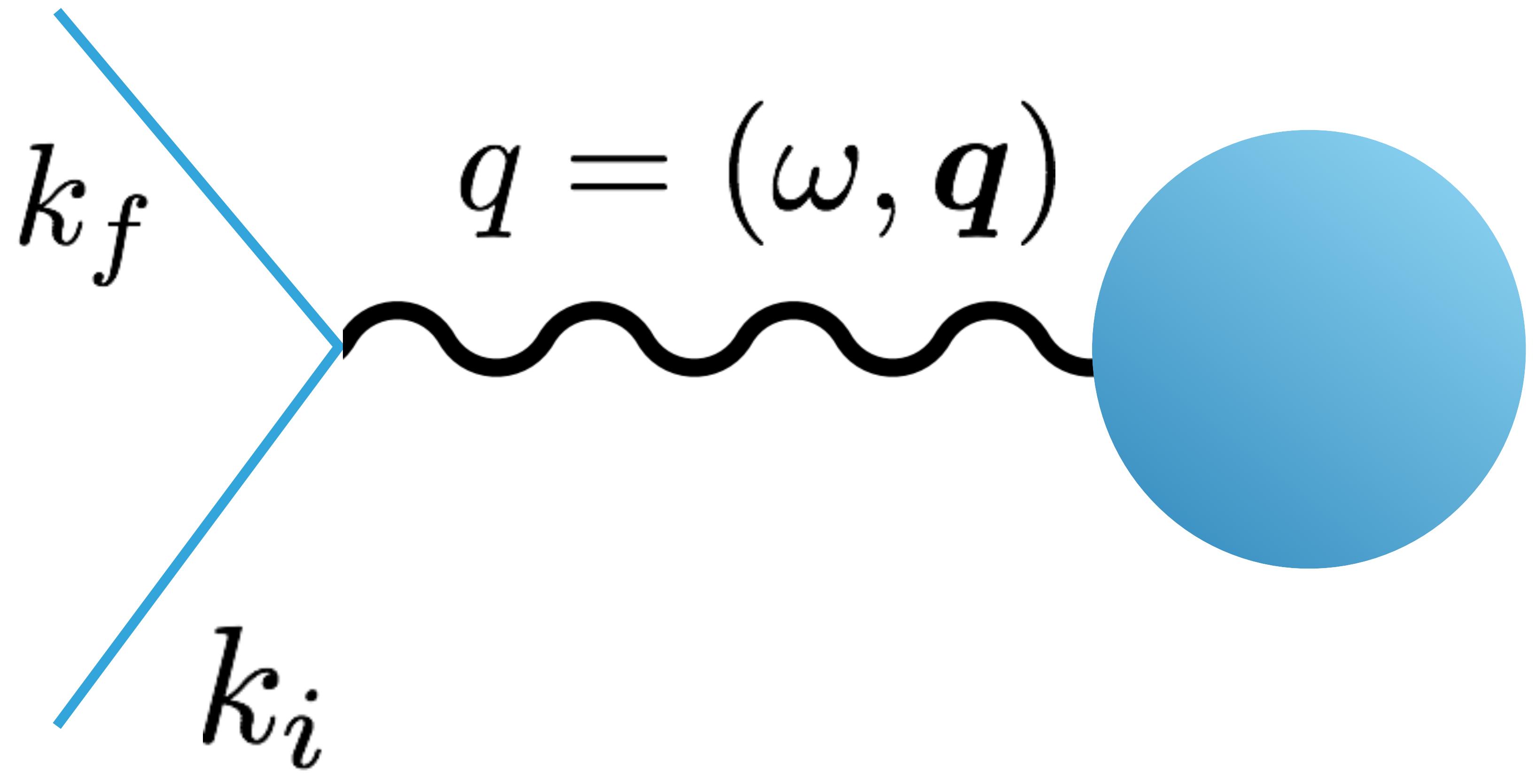
Inclusive electron scattering cross-section:

$$\frac{d^2\sigma}{d\Omega d\omega} = \sigma_{\mathrm{Mott}} \left[\frac{q^4}{|\boldsymbol{q}|^4} R_L(\omega, |\boldsymbol{q}|) + \left(\frac{q^2}{2|\boldsymbol{q}|^2} + \tan^2\frac{\theta}{2} \right) R_T(\omega, |\boldsymbol{q}|) \right]$$

Scattering response due to **charge** properties

Scattering response due to **magnetic** properties

COULOMB SUM RULE



Inclusive electron scattering cross-section:

$$\frac{d^2\sigma}{d\Omega d\omega} = \sigma_{\mathrm{Mott}} \left[\frac{q^4}{|\boldsymbol{q}|^4} R_L(\omega, |\boldsymbol{q}|) + \left(\frac{q^2}{2|\boldsymbol{q}|^2} + \tan^2\frac{\theta}{2} \right) R_T(\omega, |\boldsymbol{q}|) \right]$$

Scattering response due to **charge** properties (R_L)

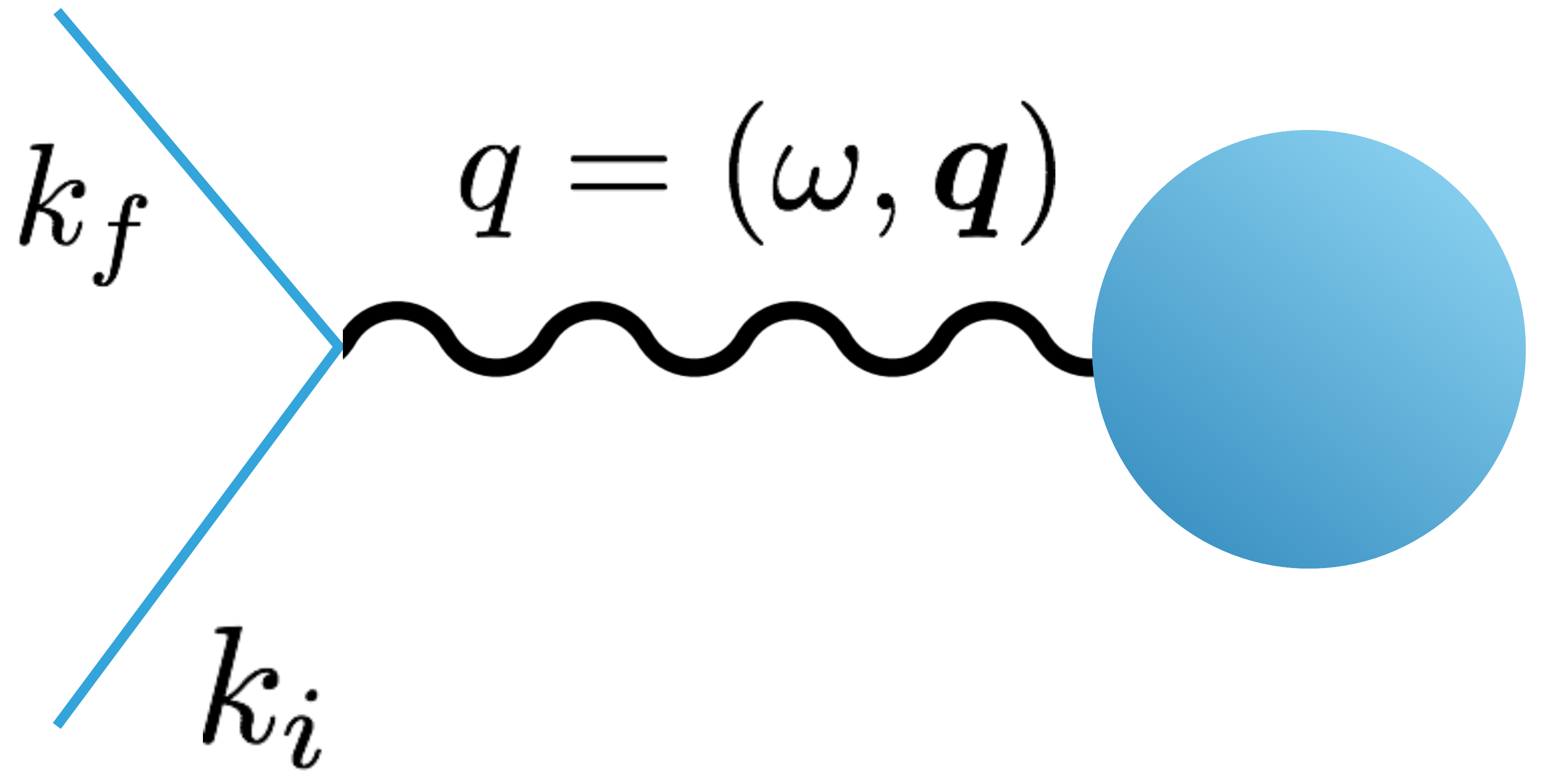
Scattering response due to **magnetic** properties (R_T)

Coulomb Sum Rule definition:

$$S_L(|\boldsymbol{q}|) = \int_{\omega^+}^{|\boldsymbol{q}|} d\omega \frac{R_L(\omega, |\boldsymbol{q}|)}{Z\tilde{G}^2_{Ep}(Q^2) + N\tilde{G}^2_{En}(Q^2)}$$

If one integrates the charge response divided by the total charge form factor over all available virtual photon energies, naively one might expect the integral to go to unity.

COULOMB SUM RULE



Inclusive electron scattering cross-section:

$$\frac{d^2\sigma}{d\Omega d\omega} = \sigma_{\mathrm{Mott}} \left[\frac{q^4}{|\boldsymbol{q}|^4} R_L(\omega, |\boldsymbol{q}|) + \left(\frac{q^2}{2|\boldsymbol{q}|^2} + \tan^2\frac{\theta}{2} \right) R_T(\omega, |\boldsymbol{q}|) \right]$$

Scattering response due to **charge** properties

Scattering response due to **magnetic** properties

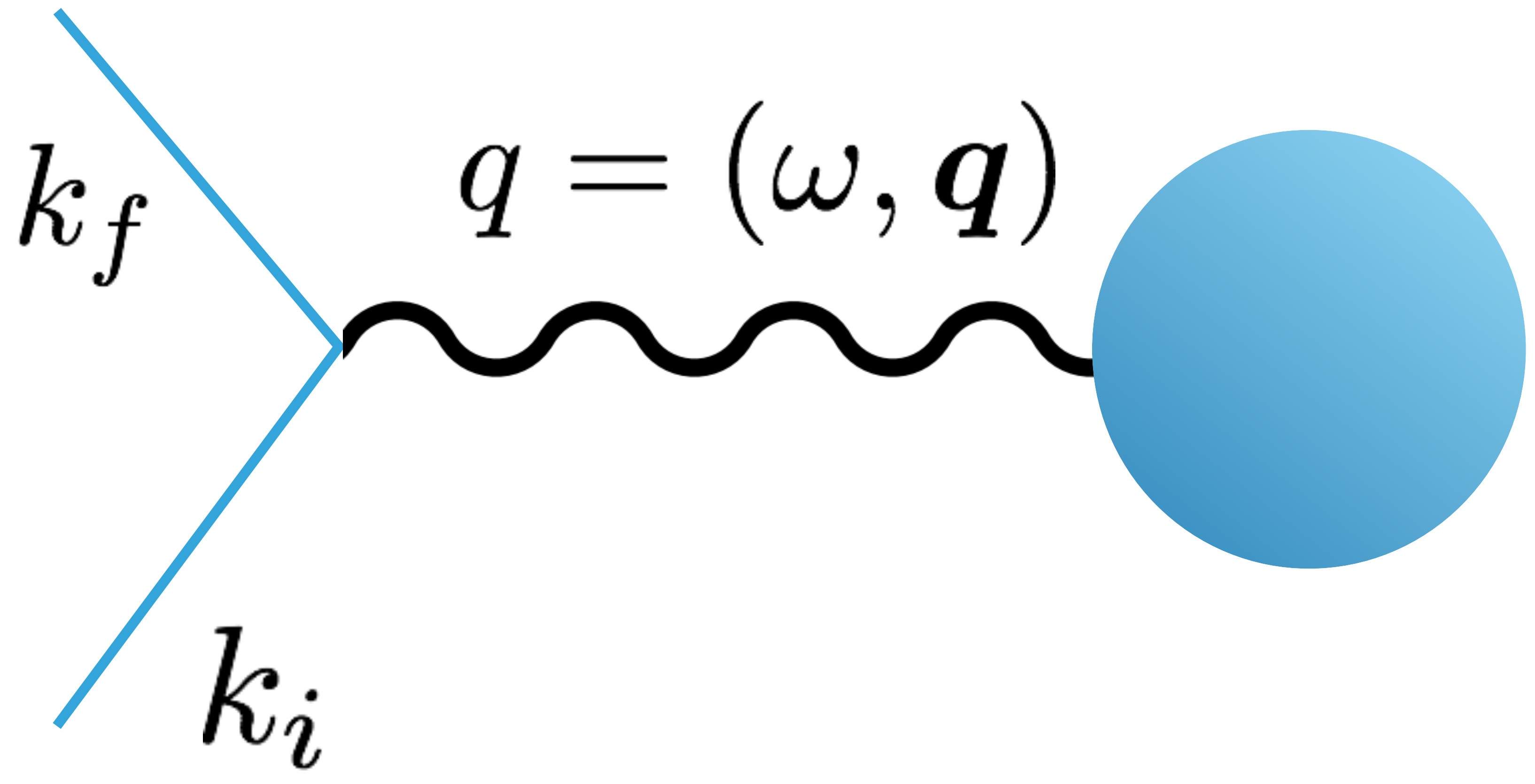
Coulomb Sum Rule definition:

$$S_L(|\boldsymbol{q}|) = \int_{\omega^+}^{|\boldsymbol{q}|} d\omega \frac{R_L(\omega, |\boldsymbol{q}|)}{Z\tilde{G}^2_{Ep}(Q^2) + N\tilde{G}^2_{En}(Q^2)}$$

At small |**q**| , S_L will deviate from unity due to long range nuclear effects, Pauli blocking. (directly calculable, well understood).

If one integrates the charge response divided by the total charge form factor over all available virtual photon energies, naively one might expect the integral to go to unity.

COULOMB SUM RULE



Inclusive electron scattering cross-section:

$$\frac{d^2\sigma}{d\Omega d\omega} = \sigma_{\text{Mott}} \left[\frac{q^4}{|\boldsymbol{q}|^4} R_L(\omega, |\boldsymbol{q}|) + \left(\frac{q^2}{2|\boldsymbol{q}|^2} + \tan^2\frac{\theta}{2} \right) R_T(\omega, |\boldsymbol{q}|) \right]$$

Scattering response due to **charge** properties

Scattering response due to **magnetic** properties

Coulomb Sum Rule definition:

$$S_L(|\boldsymbol{q}|) = \int_{\omega^+}^{|\boldsymbol{q}|} d\omega \frac{R_L(\omega, |\boldsymbol{q}|)}{Z\tilde{G}^2_{Ep}(Q^2) + N\tilde{G}^2_{En}(Q^2)}$$

If one integrates the charge response divided by the total charge form factor over all available virtual photon energies, naively one might expect the integral to go to unity.

At small |**q**| , S_L will deviate from unity due to long range nuclear effects, Pauli blocking. (directly calculable, well understood).

At large |q| >> $2k_f$, S_L should go to 1. Any significant* deviation from this would be an indication of relativistic or medium effects distorting the nucleon form factor!

*Short range correlations will also quench S_L, but only by < 10%

COULOMB SUM RULE

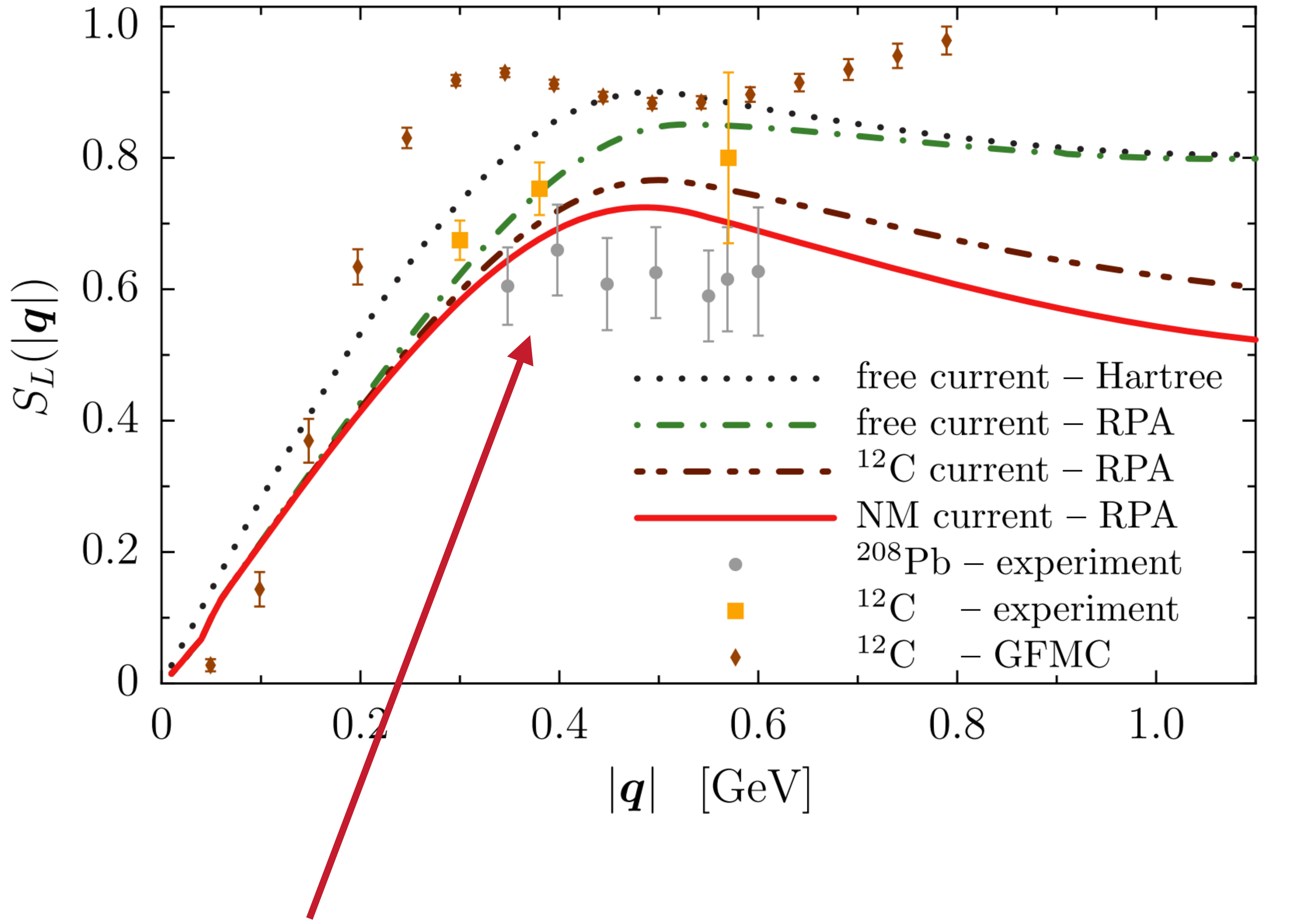
- Long standing issue with many years of theoretical interest.
- Even most state-of the-art models cannot predict existing data.
- New precise data at larger |q| would provide crucial insight and constraints to modern calculations.

$$S_L(|\boldsymbol{q}|) = \int_{\omega^+}^{|\boldsymbol{q}|} d\omega \frac{R_L(\omega, |\boldsymbol{q}|)}{Z\tilde{G}^2_{Ep}(Q^2) + N\tilde{G}^2_{En}(Q^2)}$$

PRL **116,** 032701 (2016) PHYSICAL REVIEW LETTERS week ending 22 JANUARY 2016

Relativistic and Nuclear Medium Effects on the Coulomb Sum Rule

Ian C. Cloët,[1] Wolfgang Bentz,[2] and Anthony W. Thomas[3]
[1]*Physics Division, Argonne National Laboratory, Argonne, Illinois 60439, USA*
[2]*Department of Physics, School of Science, Tokai University, Hiratsuka-shi, Kanagawa 259-1292, Japan*
[3]*CSSM and ARC Centre of Excellence for Particle Physics at the Terascale, Department of Physics, University of Adelaide, Adelaide South Australia 5005, Australia*
(Received 23 June 2015; published 19 January 2016)



At large |q| >> 2k$_f$, S$_L$ should go to 1. Any significant* deviation from this would be an indication of relativistic or medium effects distorting the nucleon form factor!

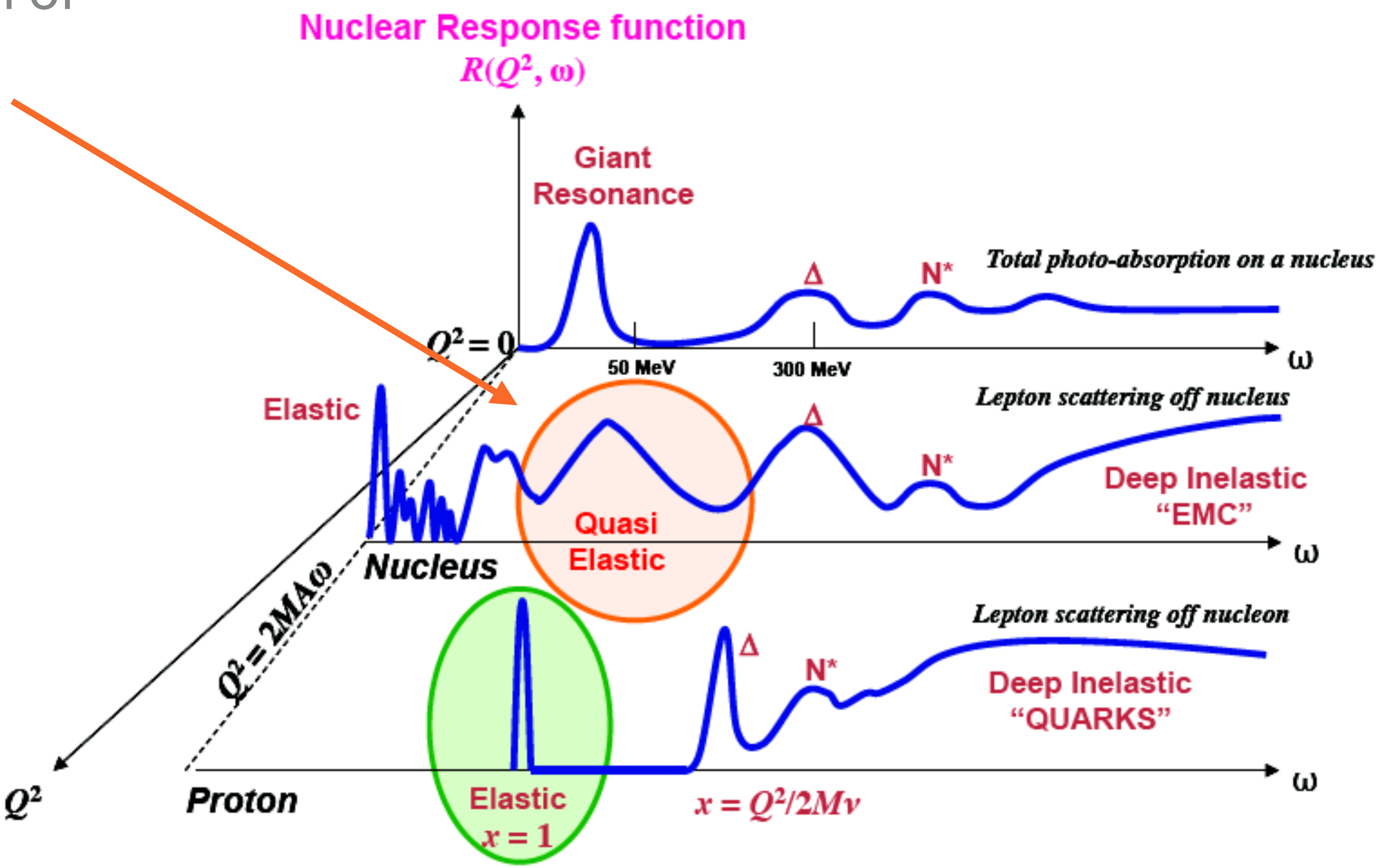
*Short range correlations will also quench S_L, but only by < 10%

QUASI-ELASTIC SCATTERING

$$S_L(|\boldsymbol{q}|) = \int_{\omega^+}^{|\boldsymbol{q}|} d\omega \frac{R_L(\omega, |\boldsymbol{q}|)}{Z\tilde{G}^2_{Ep}(Q^2) + N\tilde{G}^2_{En}(Q^2)}$$

We want to integrate above the coherent elastic peak:
Quasi-elastic is "elastic" scattering on constituent nucleons inside nucleus.

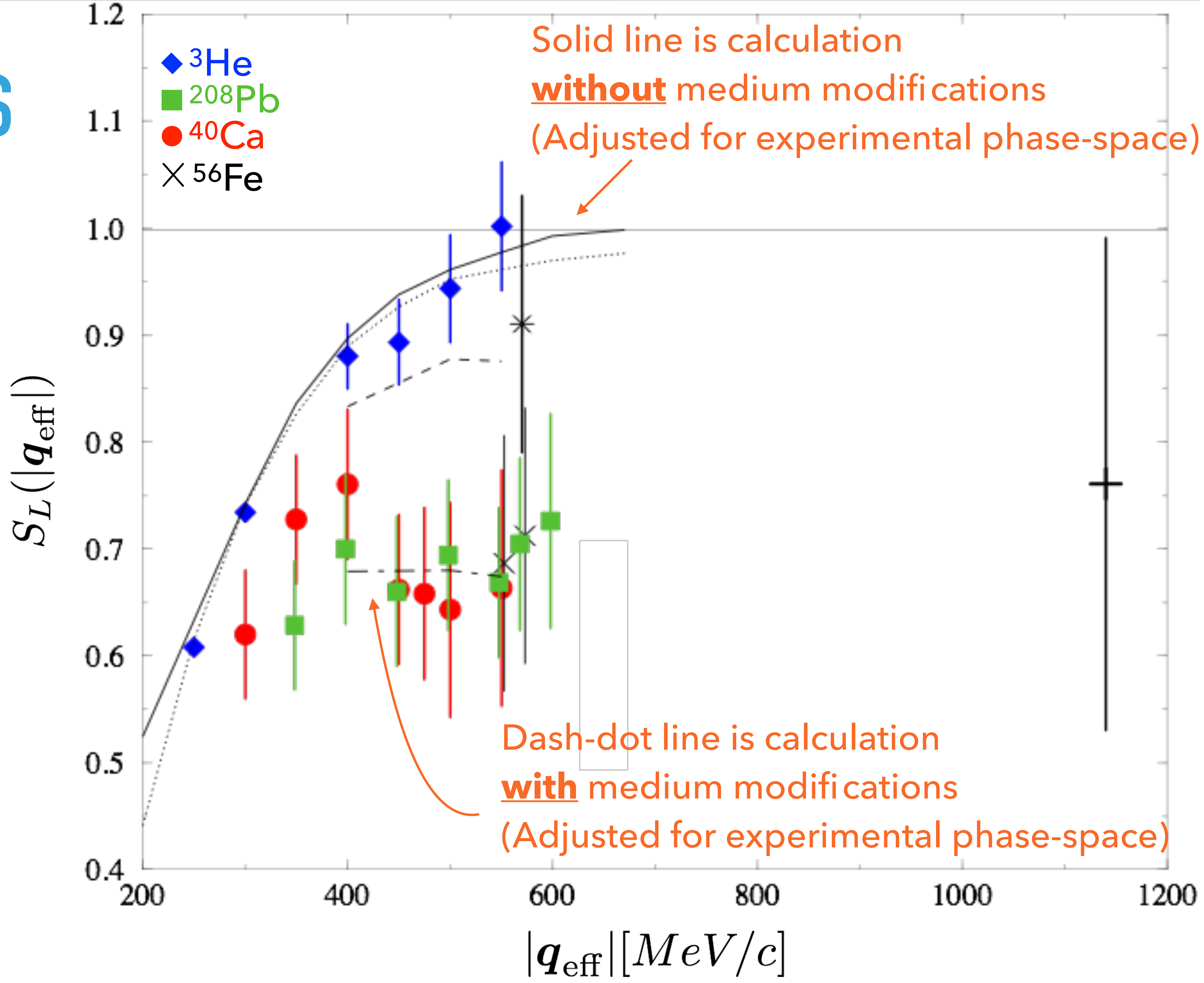
- Quasi-elastic scattering at intermediate Q^2 is the region of interest for our experiment:
  - Nuclei investigated:
    - ^{4}He
    - ^{12}C
    - ^{56}Fe
    - ^{208}Pb



PUBLISHED EXPERIMENTAL RESULTS

- First group of experiments from Saclay, Bates, and SLAC show a quenching of S_L consistent with medium modified form-factors.

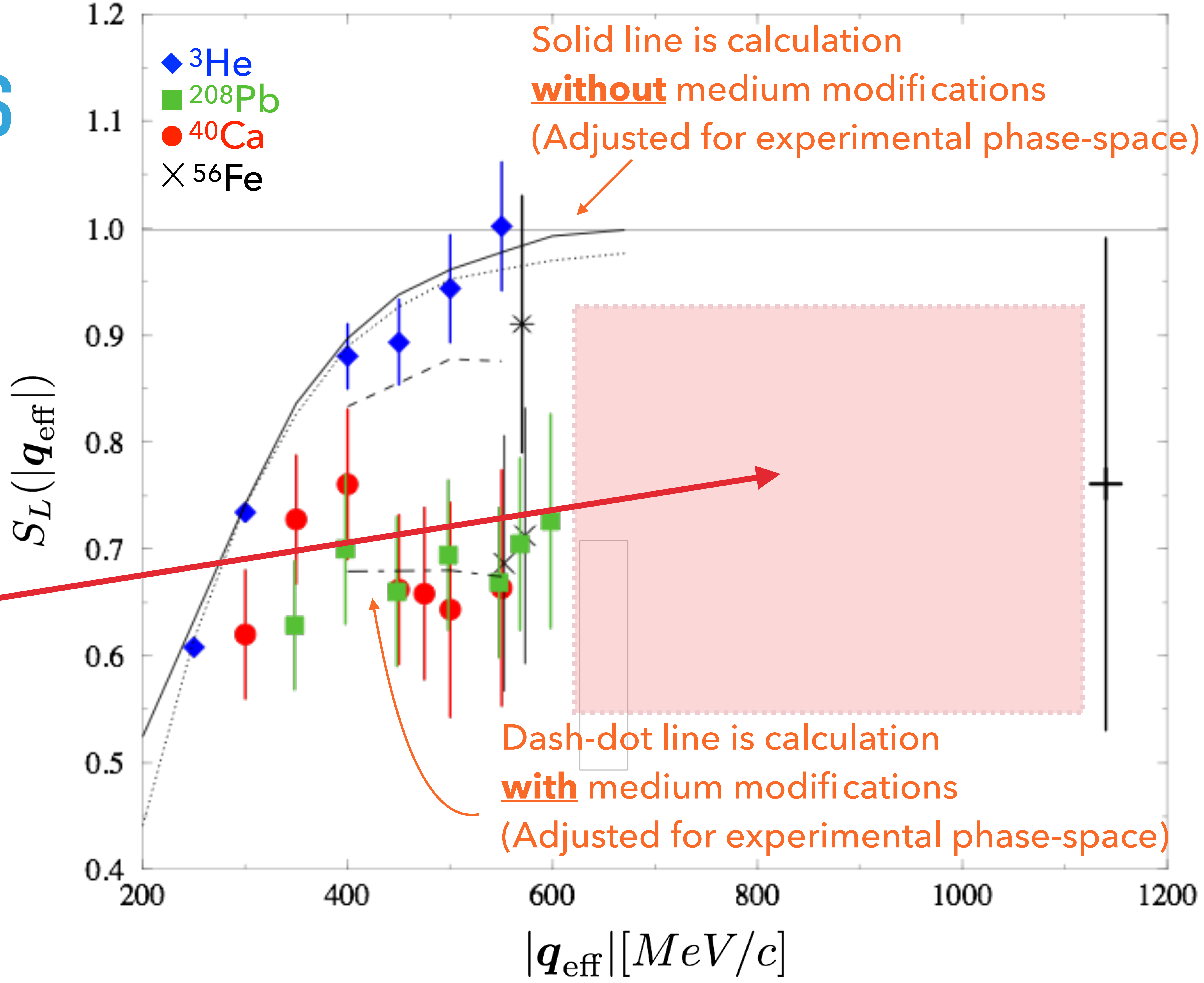
$$S_L(|\boldsymbol{q}|) = \int_{\omega^+}^{|\boldsymbol{q}|} d\omega \frac{R_L(\omega, |\boldsymbol{q}|)}{Z\tilde{G}^2_{Ep}(Q^2) + N\tilde{G}^2_{En}(Q^2)}$$



$|\boldsymbol{q}_{\text{eff}}|$ is $|\boldsymbol{q}|$ corrected for a nuclei dependent mean coulomb potential. Methodology agreed on by Andreas Aste, Steve Wallace and John Tjon.

PUBLISHED EXPERIMENTAL RESULTS

- First group of experiments from Saclay, Bates, and SLAC show a quenching of S_L consistent with medium modified form-factors.
- Very little data above |**q**| of 600 MeV/c, where the cleanest signal of medium effects should exist!
  - Saclay, Bates limited in beam energy reach up to 800 MeV.
  - SLAC limited in kinematic coverage of scattered electron at |q| below 1150 MeV/c.



|$\mathbf{q}_{\rm eff}$| is |**q**| corrected for a nuclei dependent mean coulomb potential. Methodology agreed on by Andreas Aste, Steve Wallace and John Tjon.

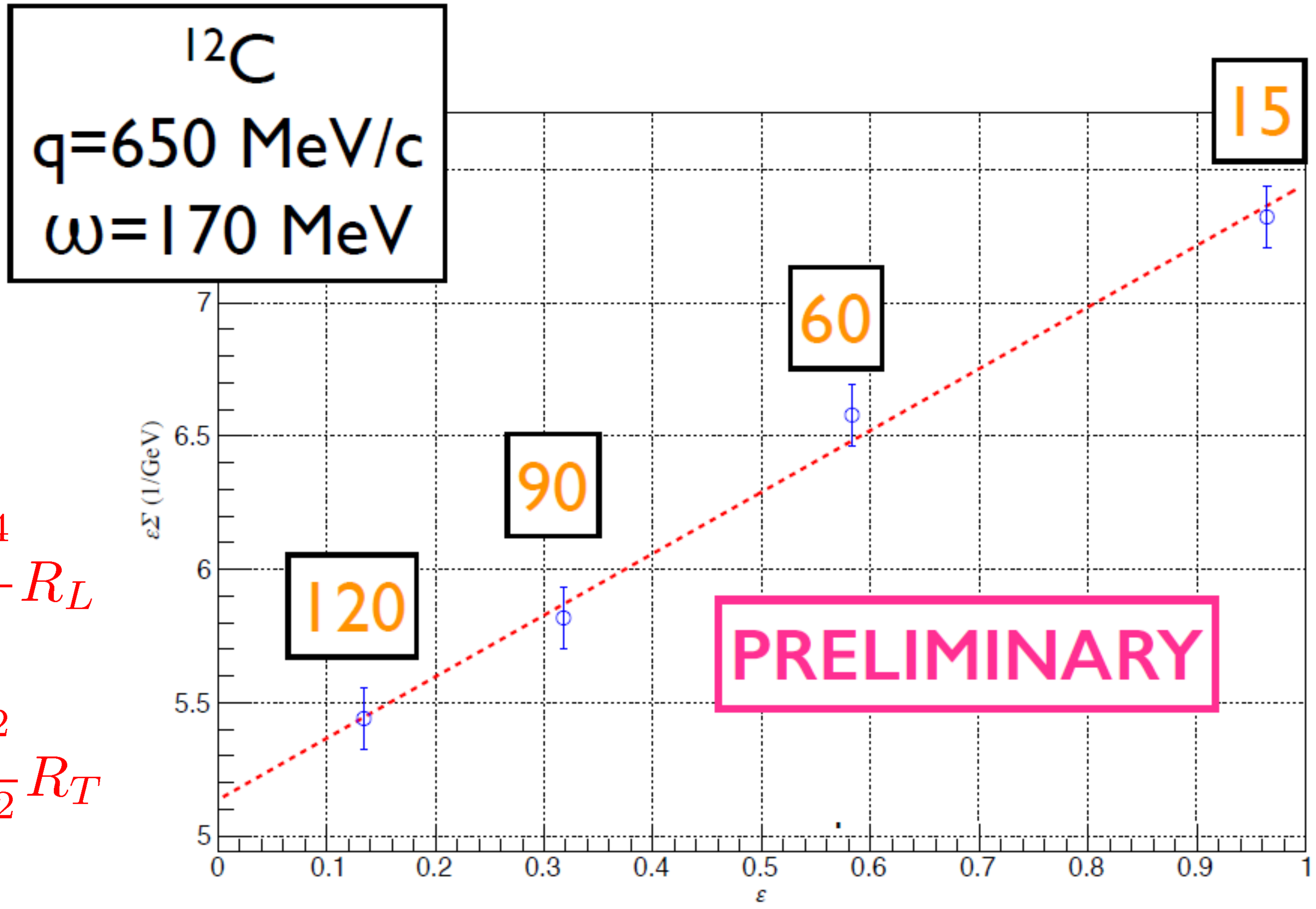
EXPERIMENTAL DESIGN

- Need R_L ⟶ Use Rosenbluth separation!

$$S_L(|\boldsymbol{q}|) = \int_{\omega^+}^{|\boldsymbol{q}|} d\omega \frac{R_L(\omega, |\boldsymbol{q}|)}{Z\tilde{G}^2_{Ep}(Q^2) + N\tilde{G}^2_{En}(Q^2)}$$

Slope = $\frac{Q^4}{\vec{q}^4} R_L$

Intercept = $\frac{Q^2}{2\vec{q}^2} R_T$



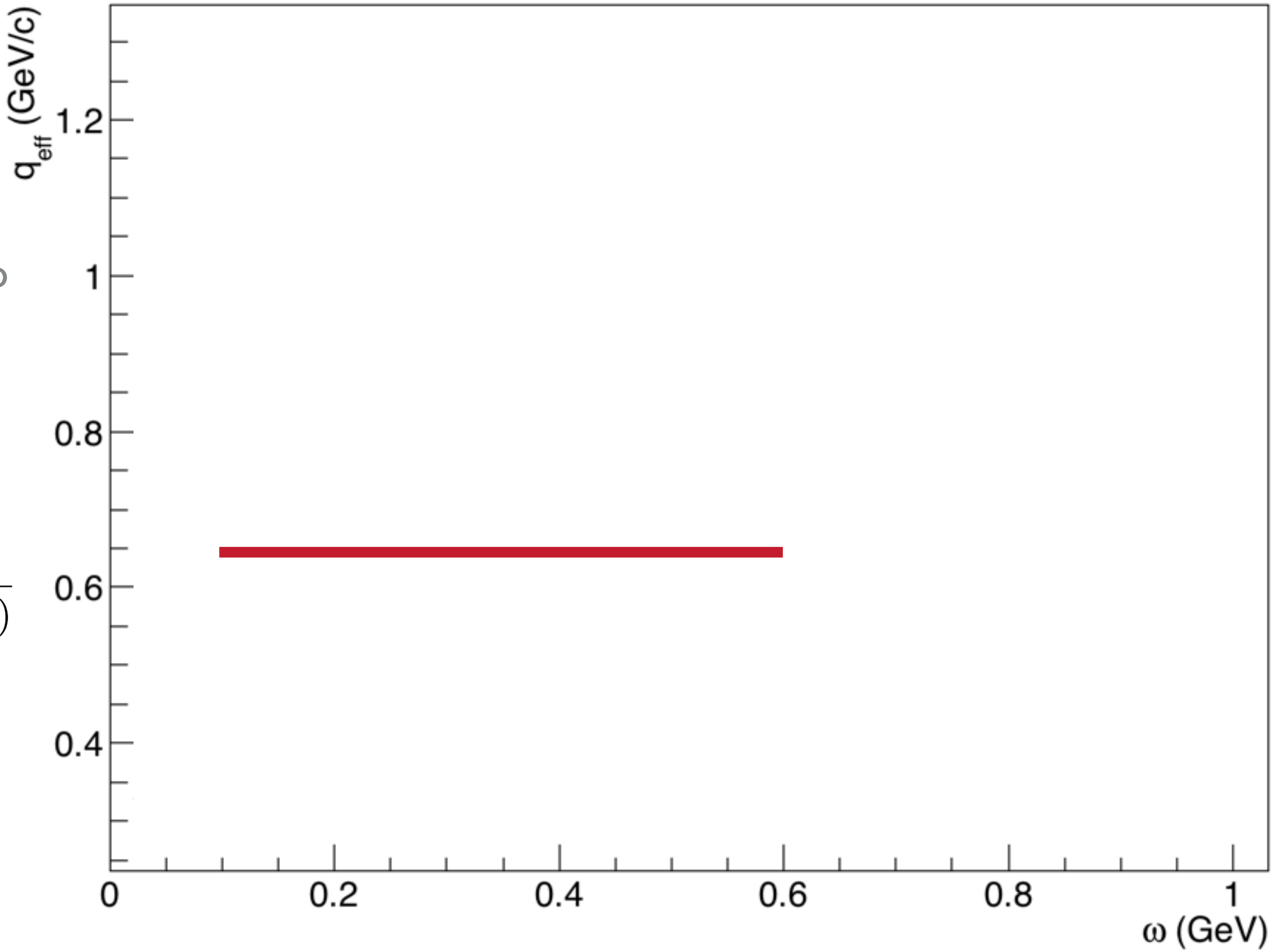
  - Experiment run at 4 angles per target: 15, 60, 90, 120 degs. Very large lever arm for precise calculation of R_L!
- Need data for each angle at a constant |q| over an ω range starting above the elastic peak up to |q|.
  - When running a single arm experiment with fixed beam energy and scattering angle, |q| is NOT constant over your momentum acceptance.
    - Need to take data at varying beam energies, and “map-out” |q| and ω space.

EXPERIMENTAL DESIGN

- If one wants to measure from 100 to 600 MeV ω at constant |q| = 650 MeV/c

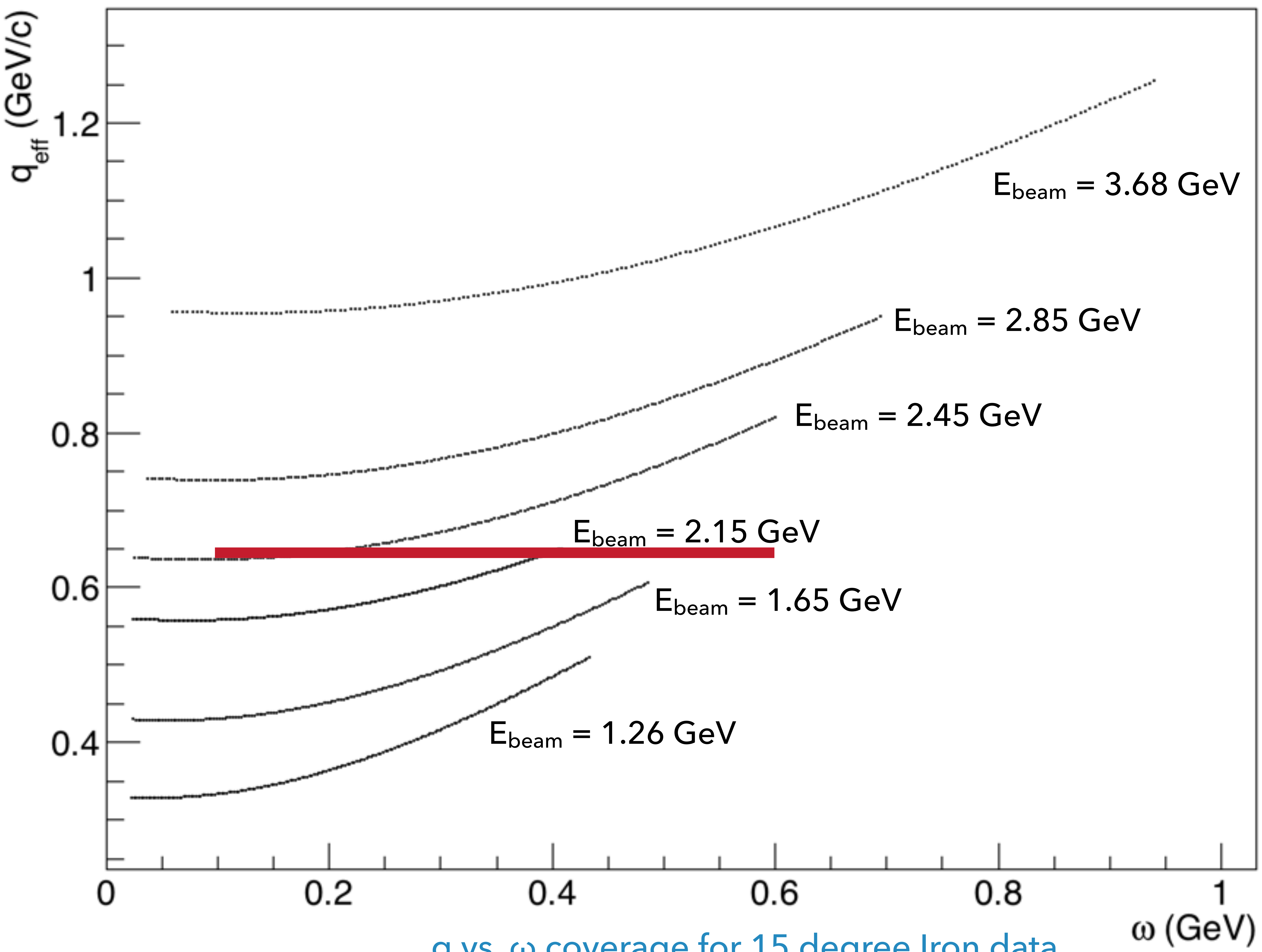
CSR calculated at constant |**q**| !!

$$S_L(|\boldsymbol{q}|) = \int_{\omega^+}^{|\boldsymbol{q}|} d\omega \frac{R_L(\omega, |\boldsymbol{q}|)}{Z\tilde{G}^2_{Ep}(Q^2) + N\tilde{G}^2_{En}(Q^2)}$$



EXPERIMENTAL DESIGN

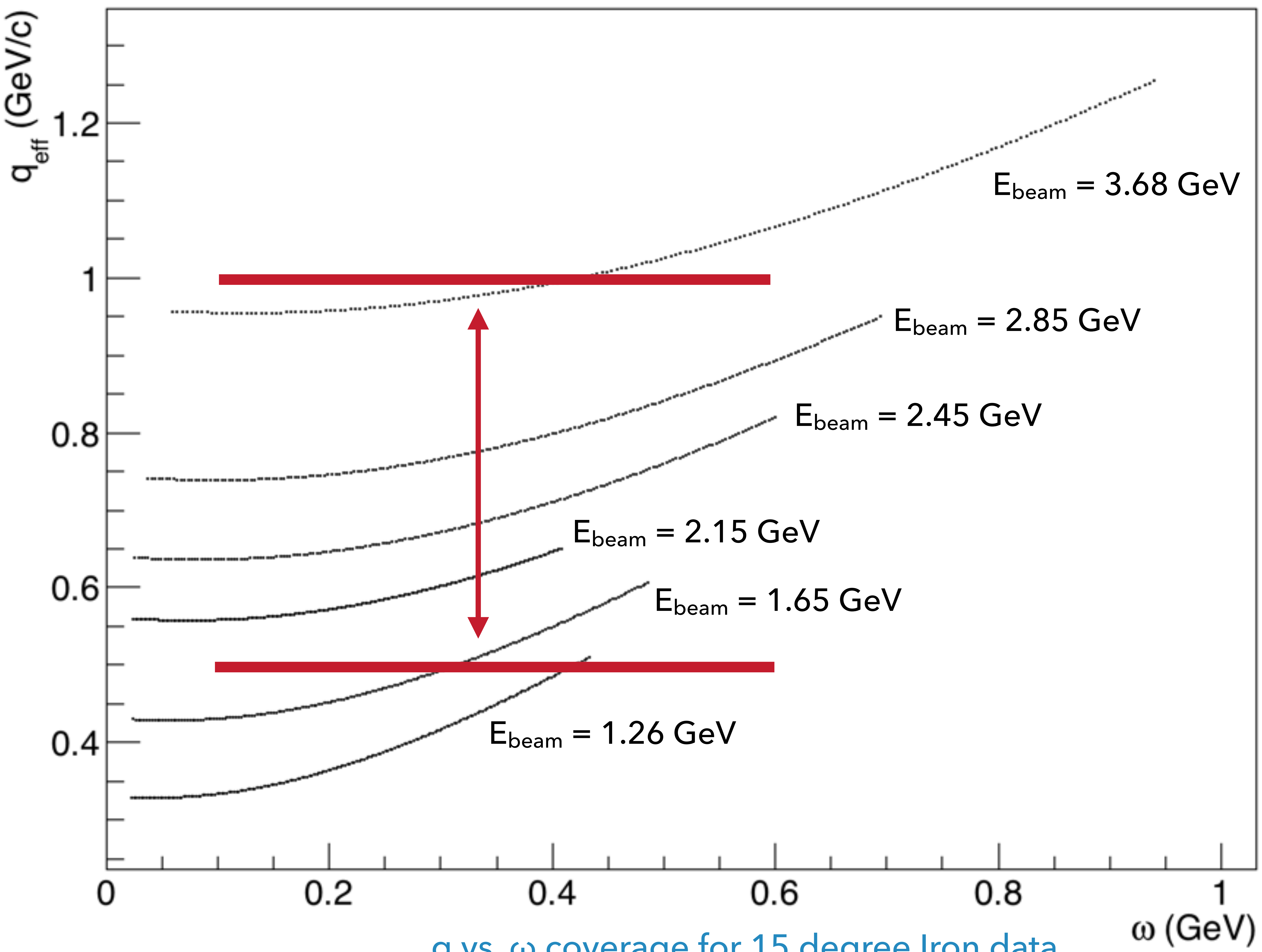
- If one wants to measure from 100 to 600 MeV ω at constant |q| = 650 MeV/c
  - Take data at different beam energies, and interpolate to determine cross-section at constant |q|.



q vs. ω coverage for 15 degree Iron data

EXPERIMENTAL DESIGN

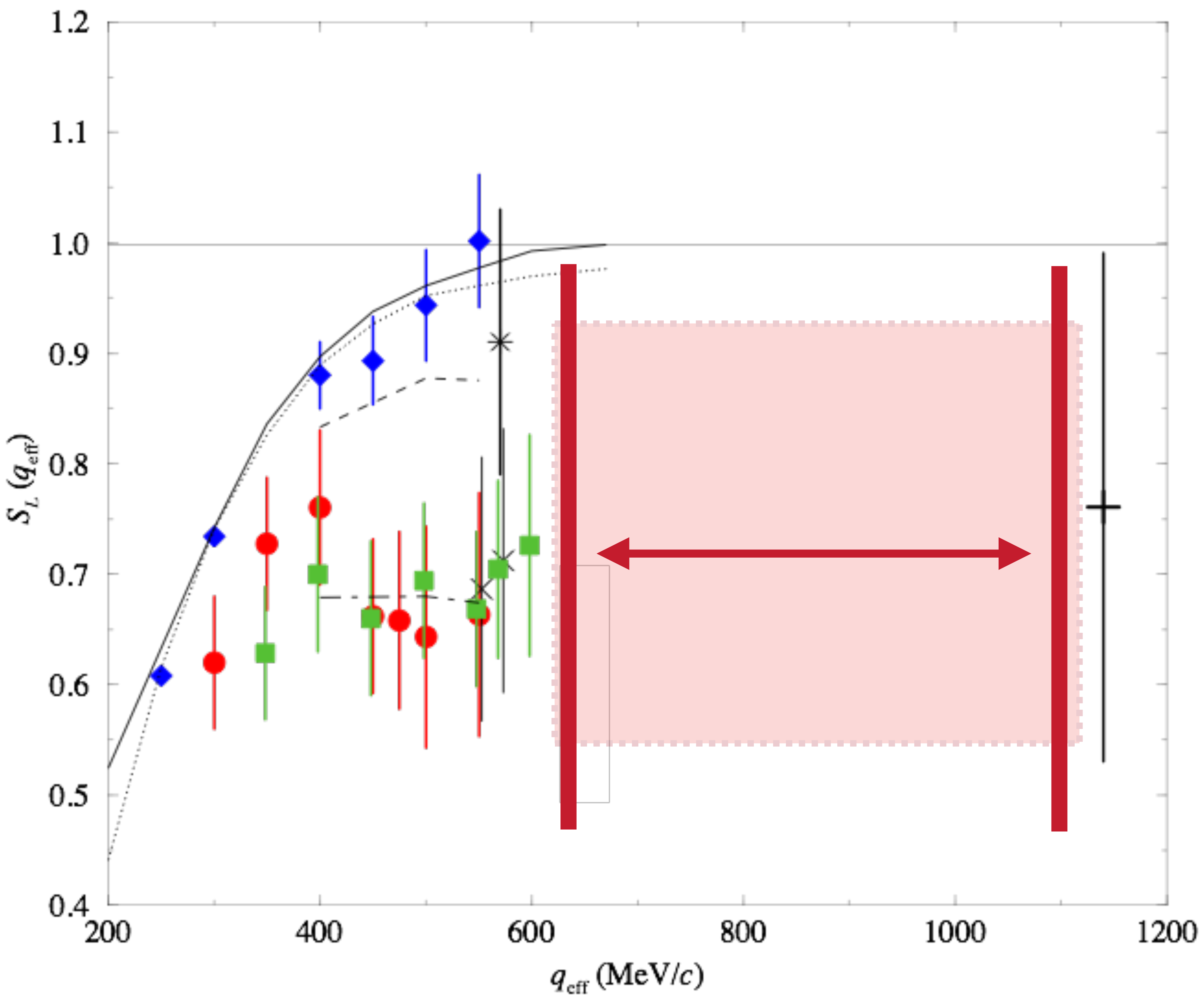
- If one wants to measure from 100 to 600 MeV ω at constant |q| = 650 MeV/c
  - Take data at different beam energies, and interpolate to determine cross-section at constant |q|.
  - |q| can be selected between 550 and 1000 MeV/c

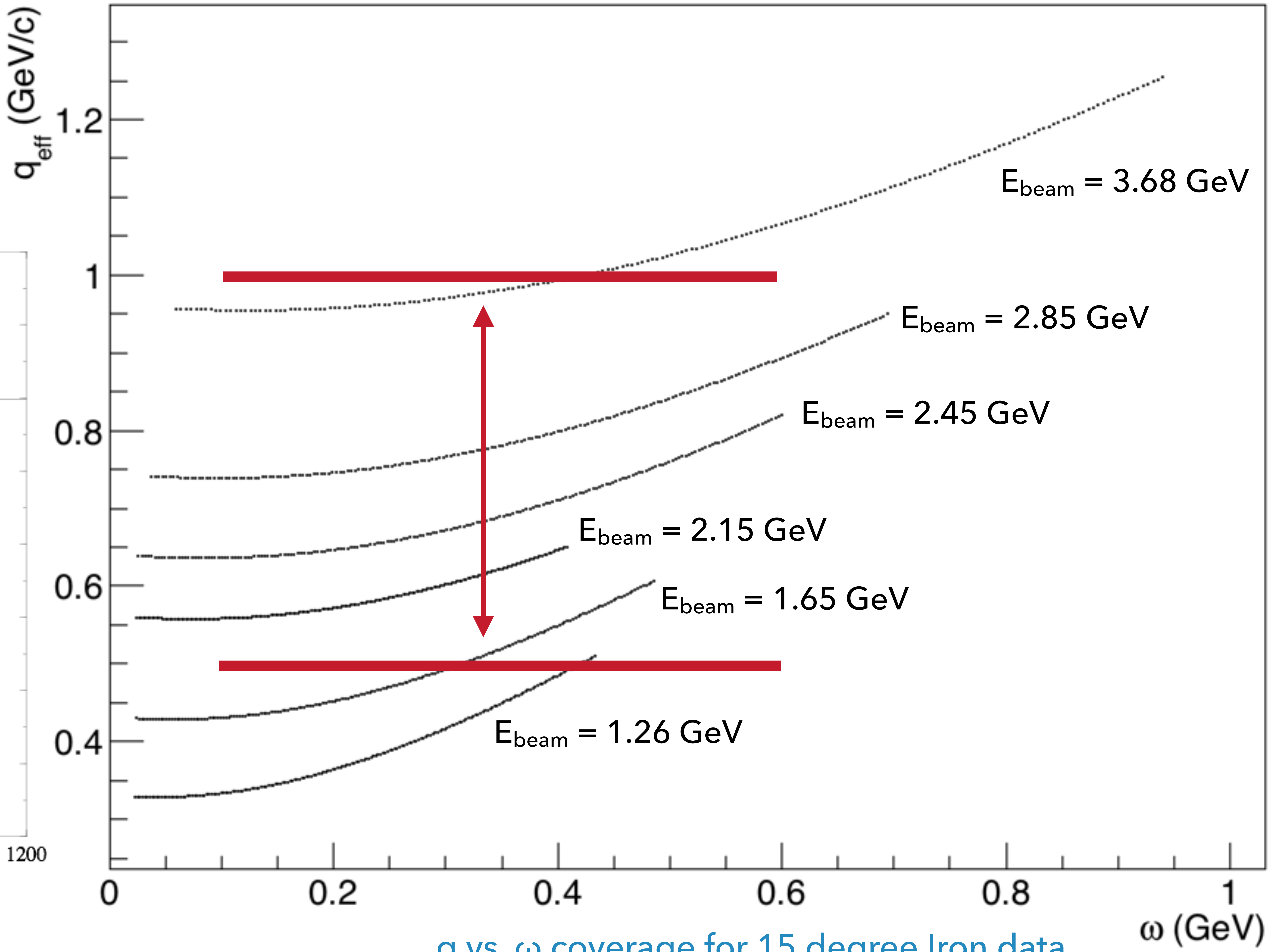


q vs. ω coverage for 15 degree Iron data

Repeat this "mapping" for 60, 90, and 120 degree spectrometer central angles.

EXPERIMENTAL DESIGN



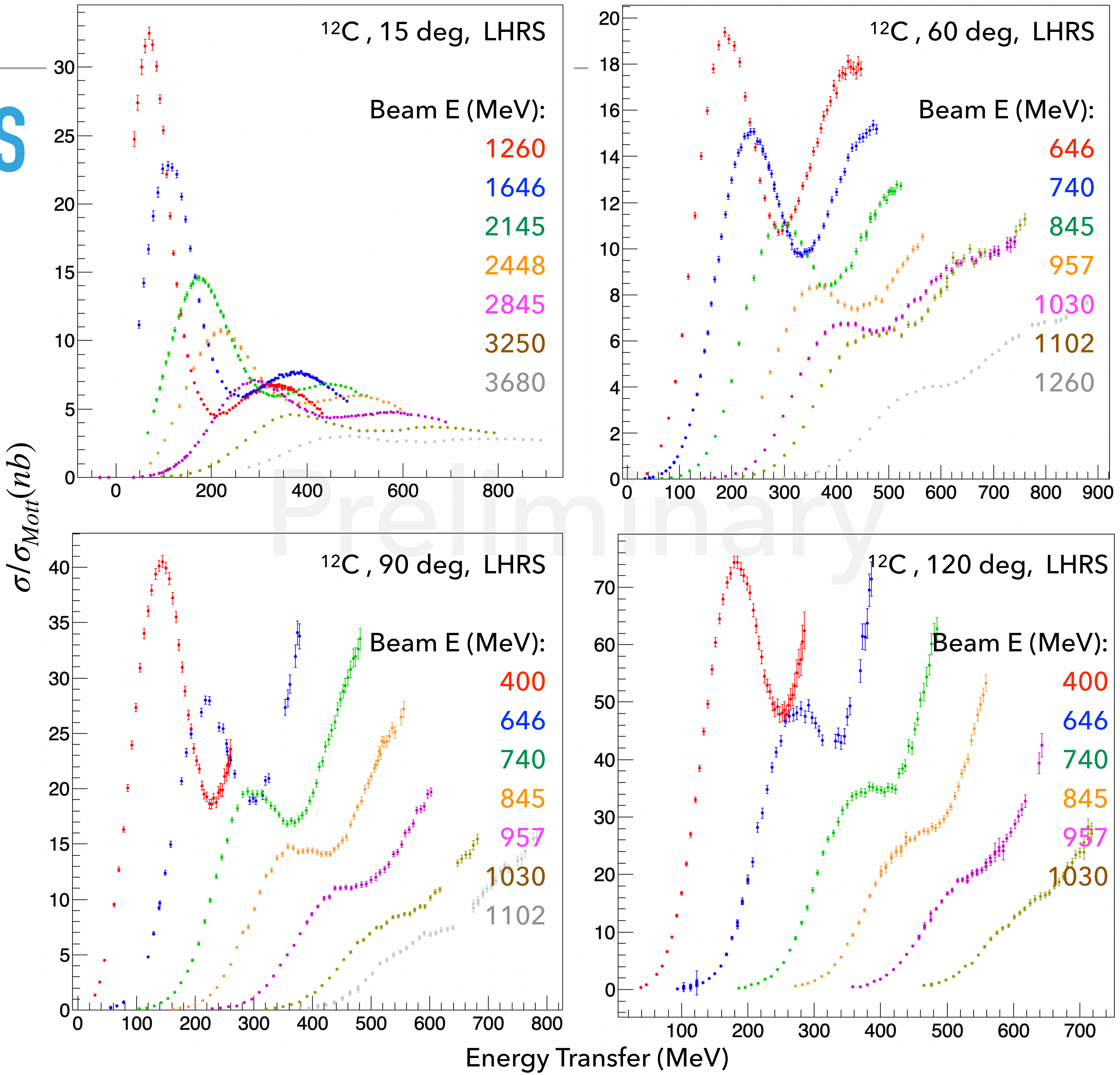


Repeat this "mapping" for 60, 90, and 120 degree spectrometer central angles.

q vs. ω coverage for 15 degree Iron data

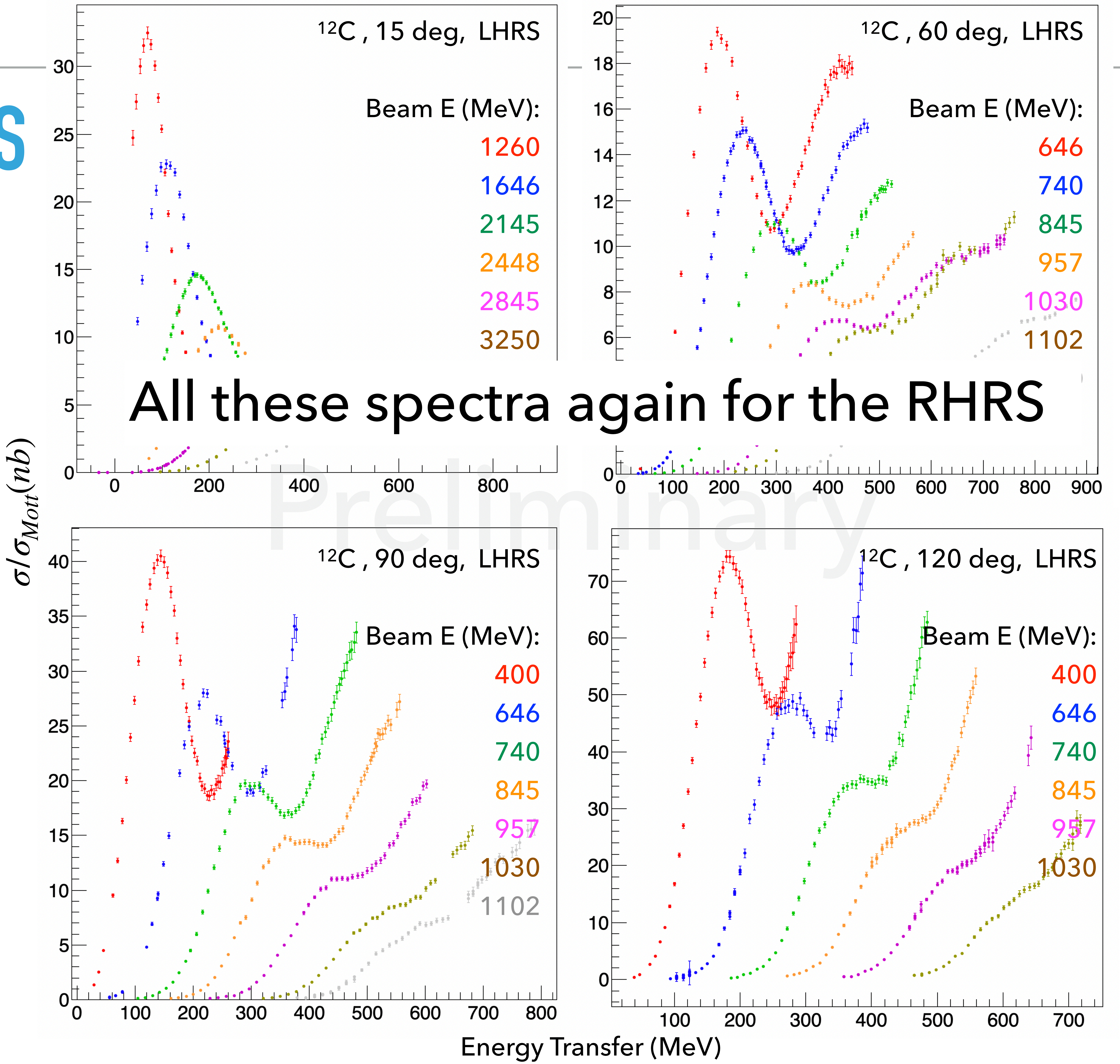
EXPERIMENTAL SPECIFICS

- E05-110:
  - Data taken from October 23rd 2007 to January 16th 2008
  - 4 central angle settings: 15, 60, 90, 120 degs.
  - Many beam energy settings: 0.4 to 4.0 GeV
  - Many central momentum settings: 0.1 to 4.0 GeV
  - LHRS and RHRS independent (redundant) measurements for most settings
  - 4 targets: ^{4}He, ^{12}C, ^{56}Fe, ^{208}Pb.



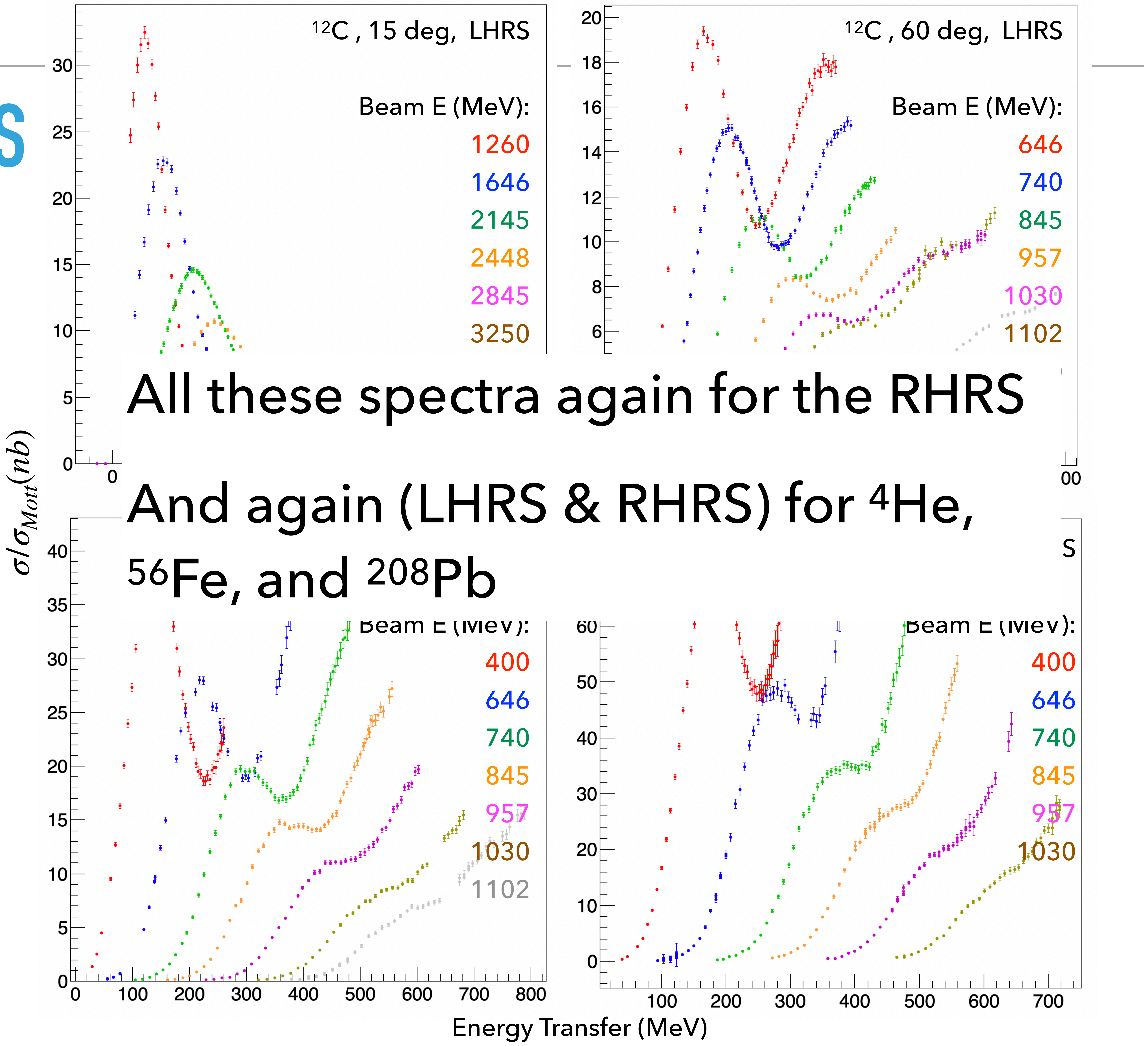
EXPERIMENTAL SPECIFICS

- E05-110:
  - Data taken from October 23rd 2007 to January 16th 2008
  - 4 central angle settings: 15, 60, 90, 120 degs.
  - Many beam energy settings: 0.4 to 4.0 GeV
  - Many central momentum settings: 0.1 to 4.0 GeV
  - LHRS and RHRS independent (redundant) measurements for most settings
  - 4 targets: ^{4}He, ^{12}C, ^{56}Fe, ^{208}Pb.



EXPERIMENTAL SPECIFICS

- E05-110:
  - Data taken from October 23rd 2007 to January 16th 2008
  - 4 central angle settings: 15, 60, 90, 120 degs.
  - Many beam energy settings: 0.4 to 4.0 GeV
  - Many central momentum settings: 0.1 to 4.0 GeV
  - LHRS and RHRS independent (redundant) measurements for most settings
  - 4 targets: ^{4}He, ^{12}C, ^{56}Fe, ^{208}Pb.

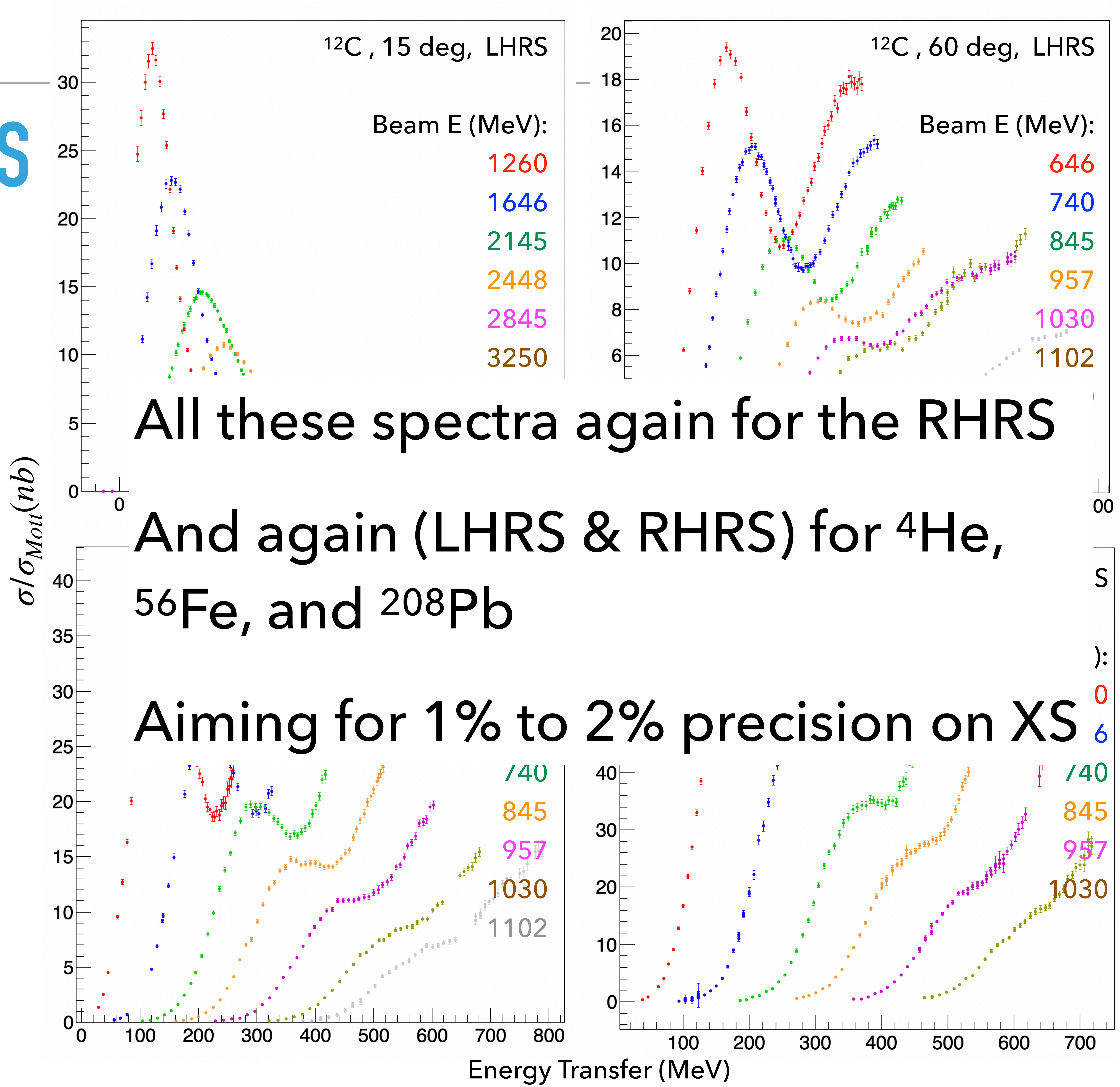


All these spectra again for the RHRS

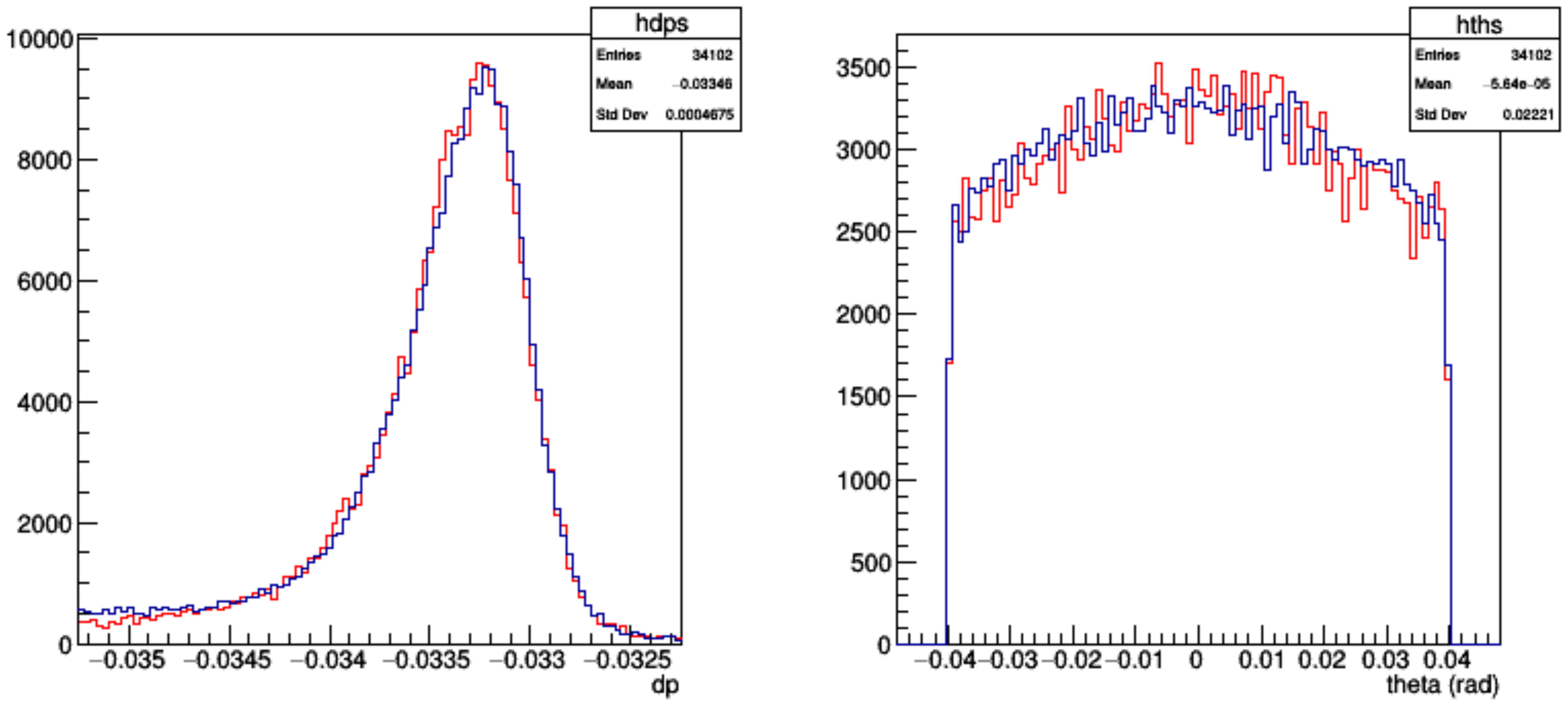
And again (LHRS & RHRS) for ^{4}He, ^{56}Fe, and ^{208}Pb

EXPERIMENTAL SPECIFICS

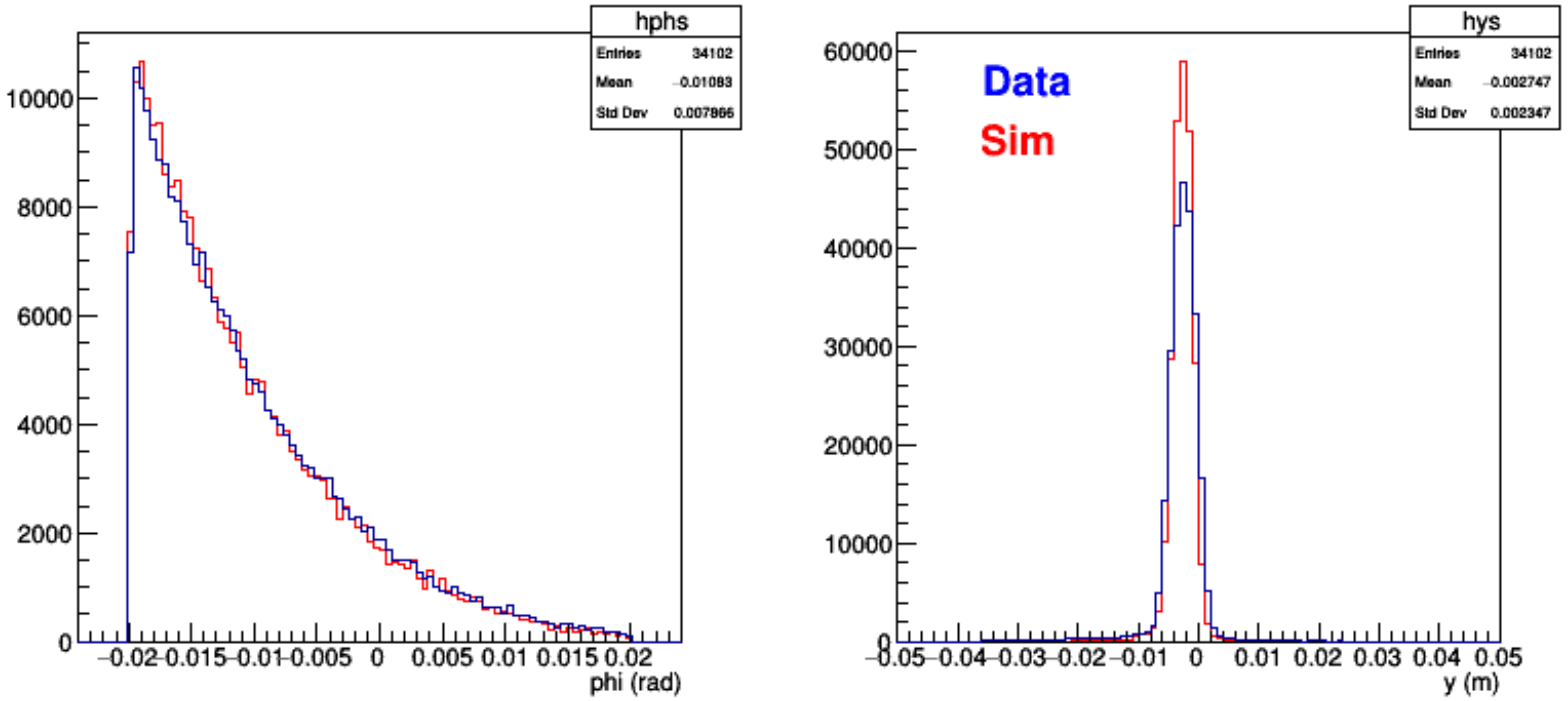
- E05-110:
  - Data taken from October 23rd 2007 to January 16th 2008
  - 4 central angle settings: 15, 60, 90, 120 degs.
  - Many beam energy settings: 0.4 to 4.0 GeV
  - Many central momentum settings: 0.1 to 4.0 GeV
  - LHRS and RHRS independent (redundant) measurements for most settings
  - 4 targets: ^{4}He, ^{12}C, ^{56}Fe, ^{208}Pb.



ELASTIC XS CALCULATIONS, AND ELASTIC TAIL CORRECTIONS

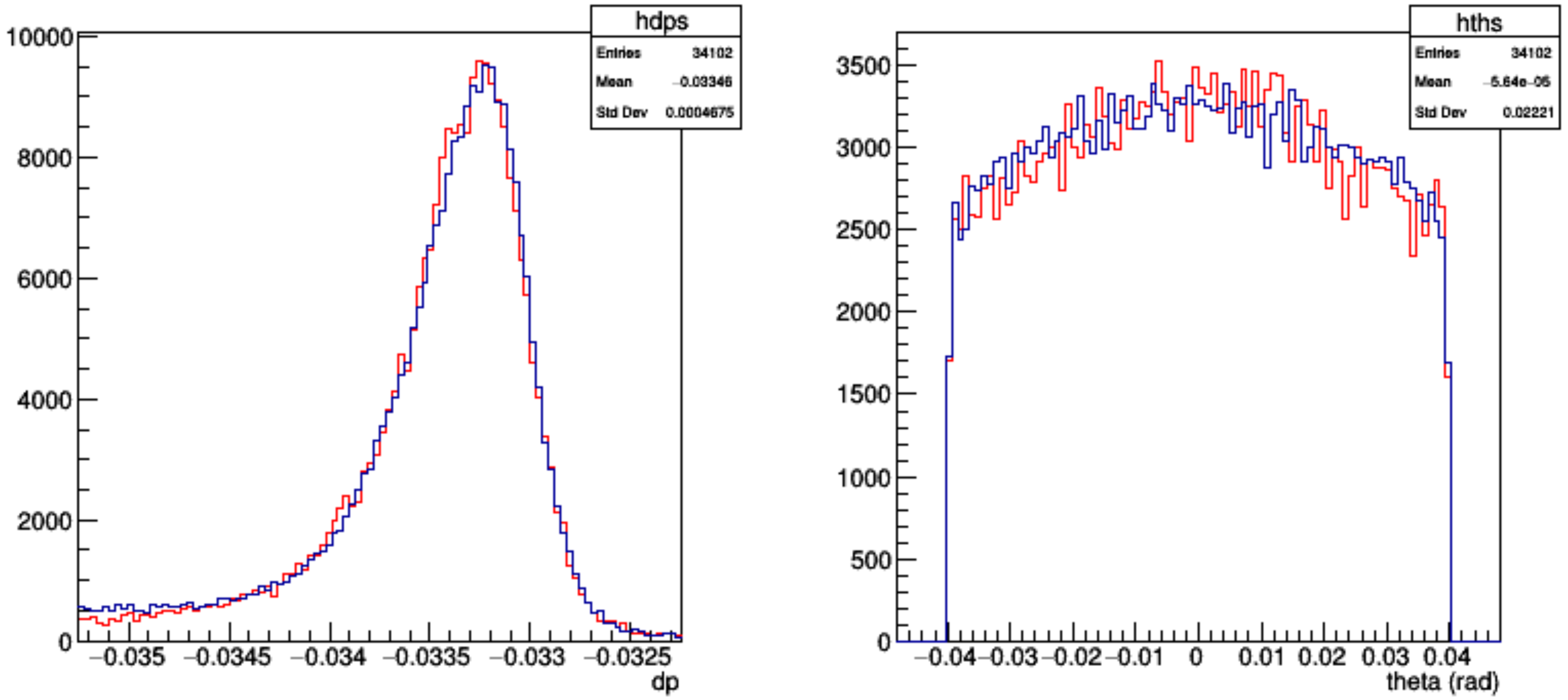


^{12}C elastic XS at 1260 MeV, 15 degrees

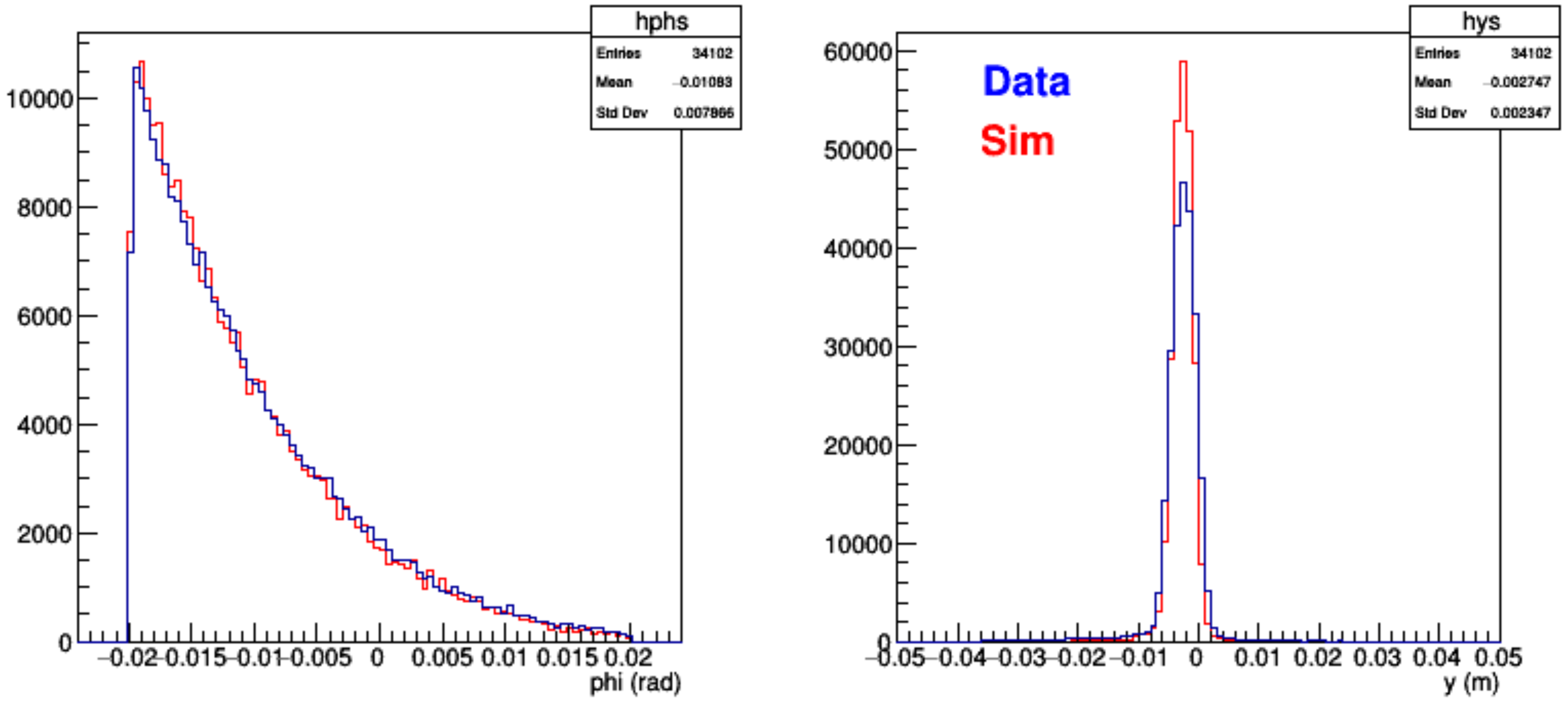


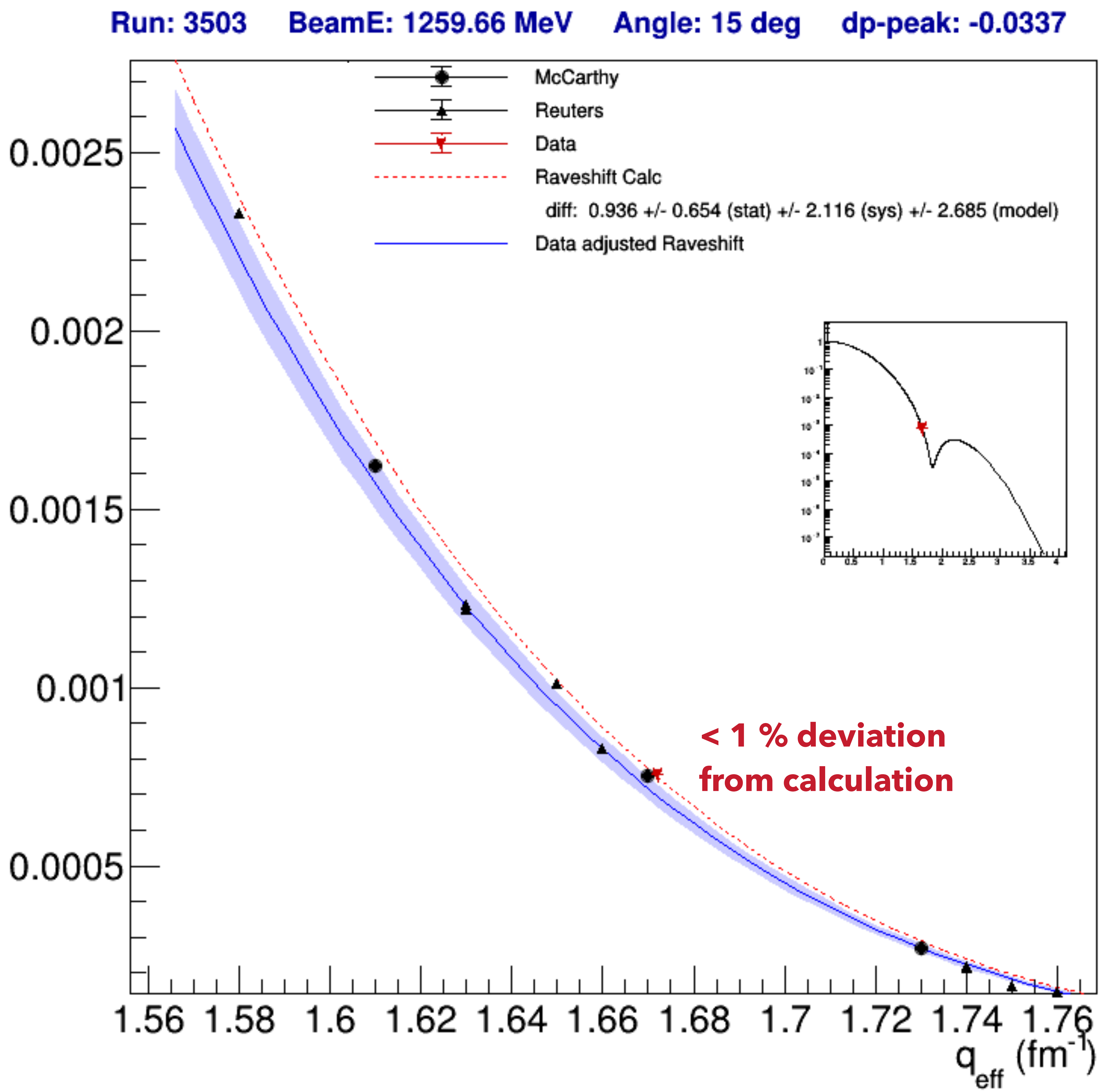
- Blue histograms are reconstructed data.
- Red histograms are monte-carlo:
  - Event sample generated from expected XS calculations (Fourier-Bessel fit to world data)
  - Radiative effects (internal, external, vertex) are handled, including exact bremsstrahlung distributions.
  - Resolution effects are applied by calculating the expected material effects of tracks passing through the VDC chamber materials.

ELASTIC XS CALCULATIONS, AND ELASTIC TAIL CORRECTIONS

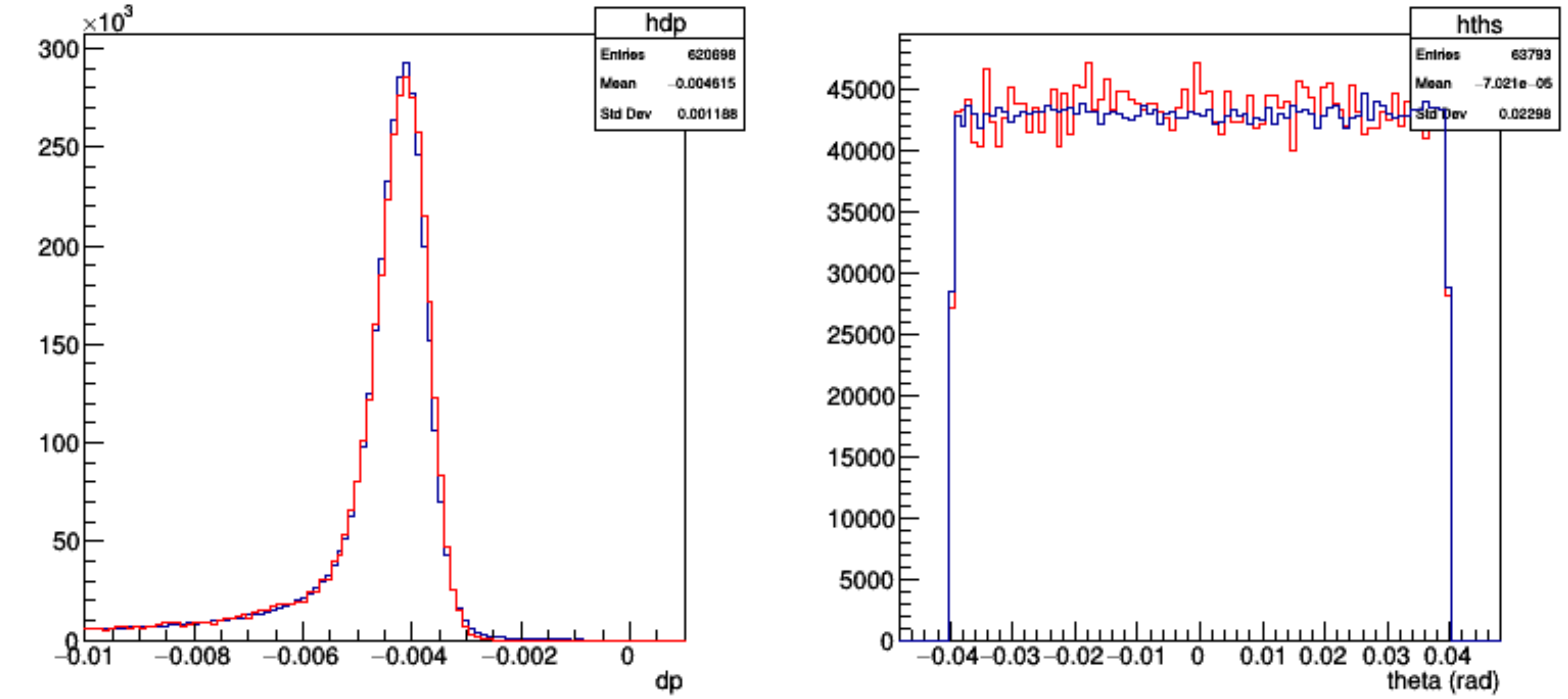


^{12}C elastic XS at 1260 MeV, 15 degrees

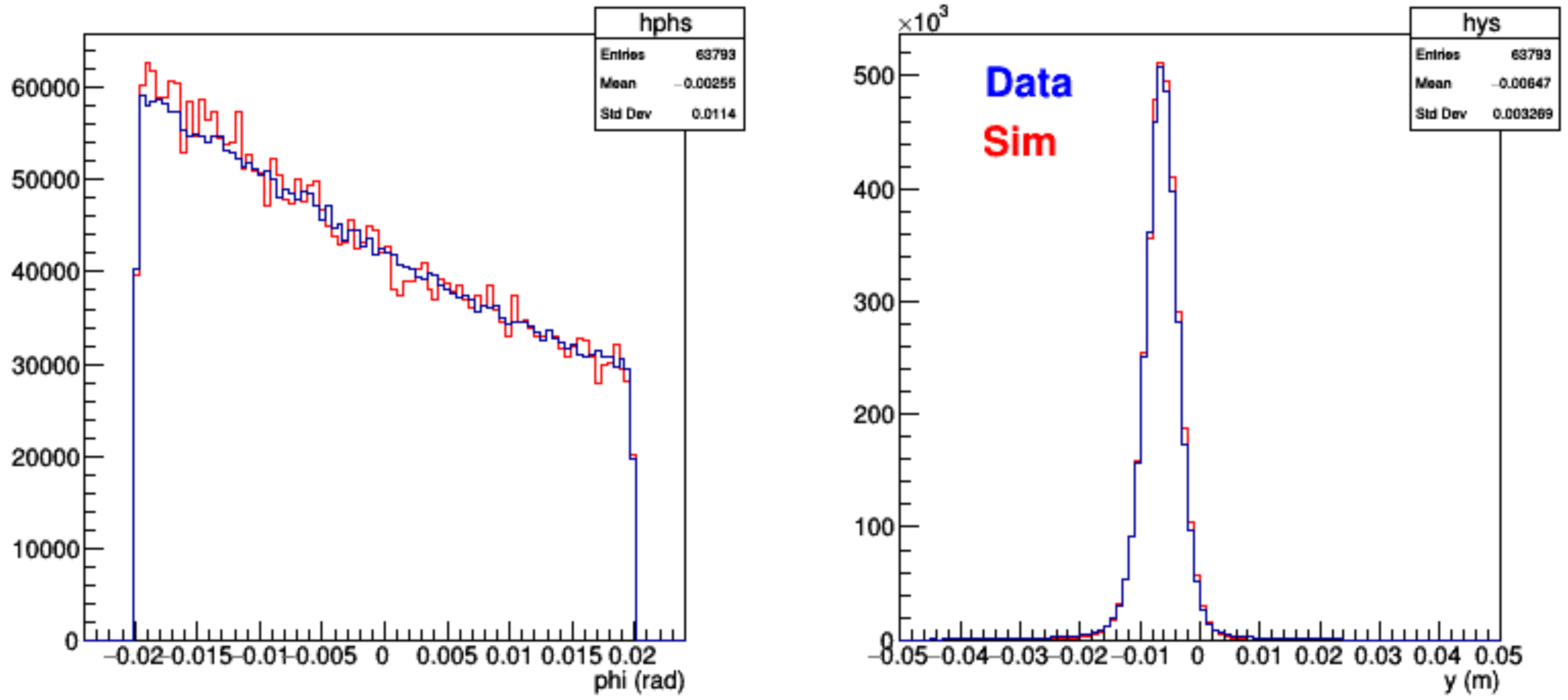


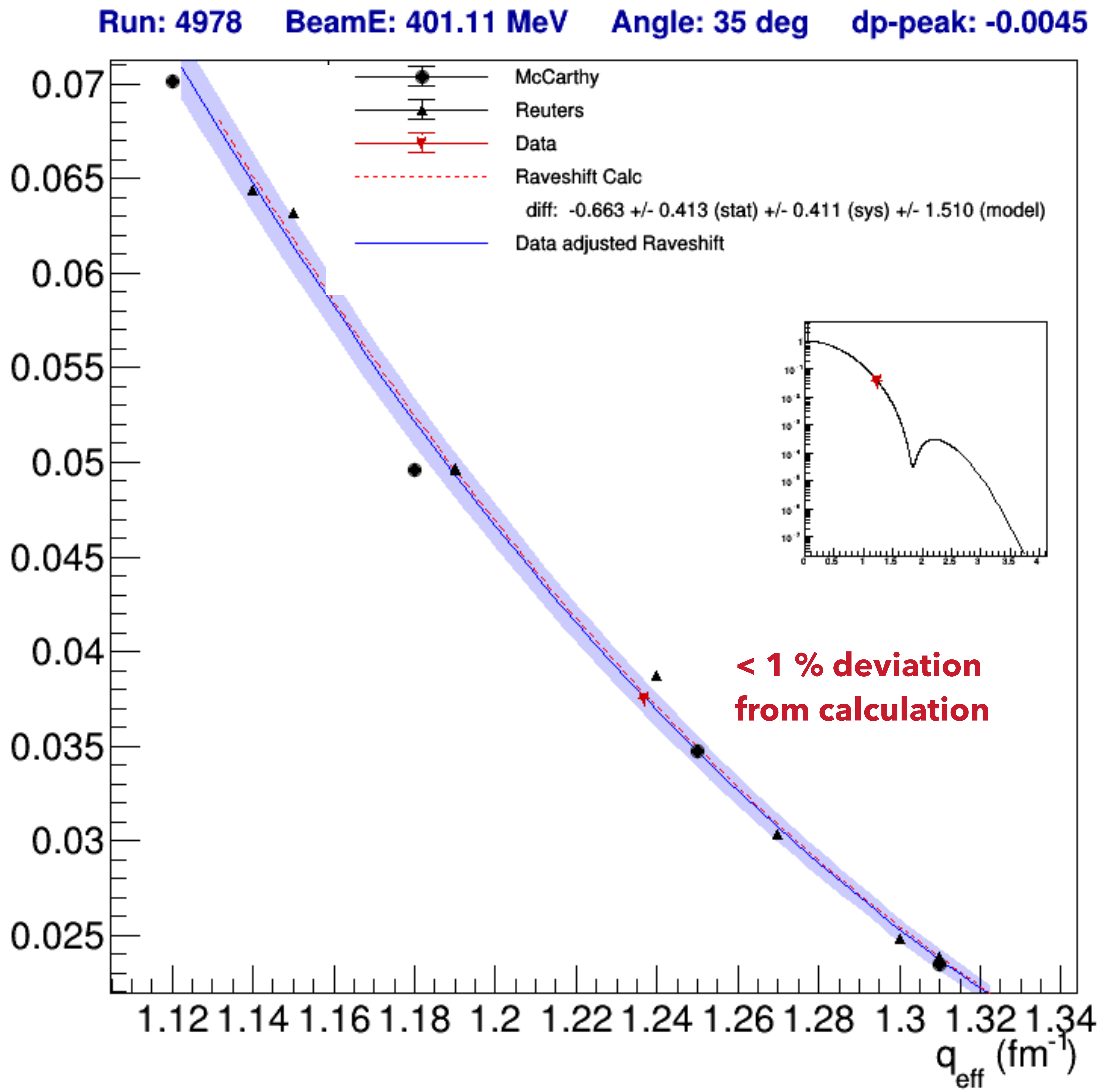


ELASTIC XS CALCULATIONS, AND ELASTIC TAIL CORRECTIONS

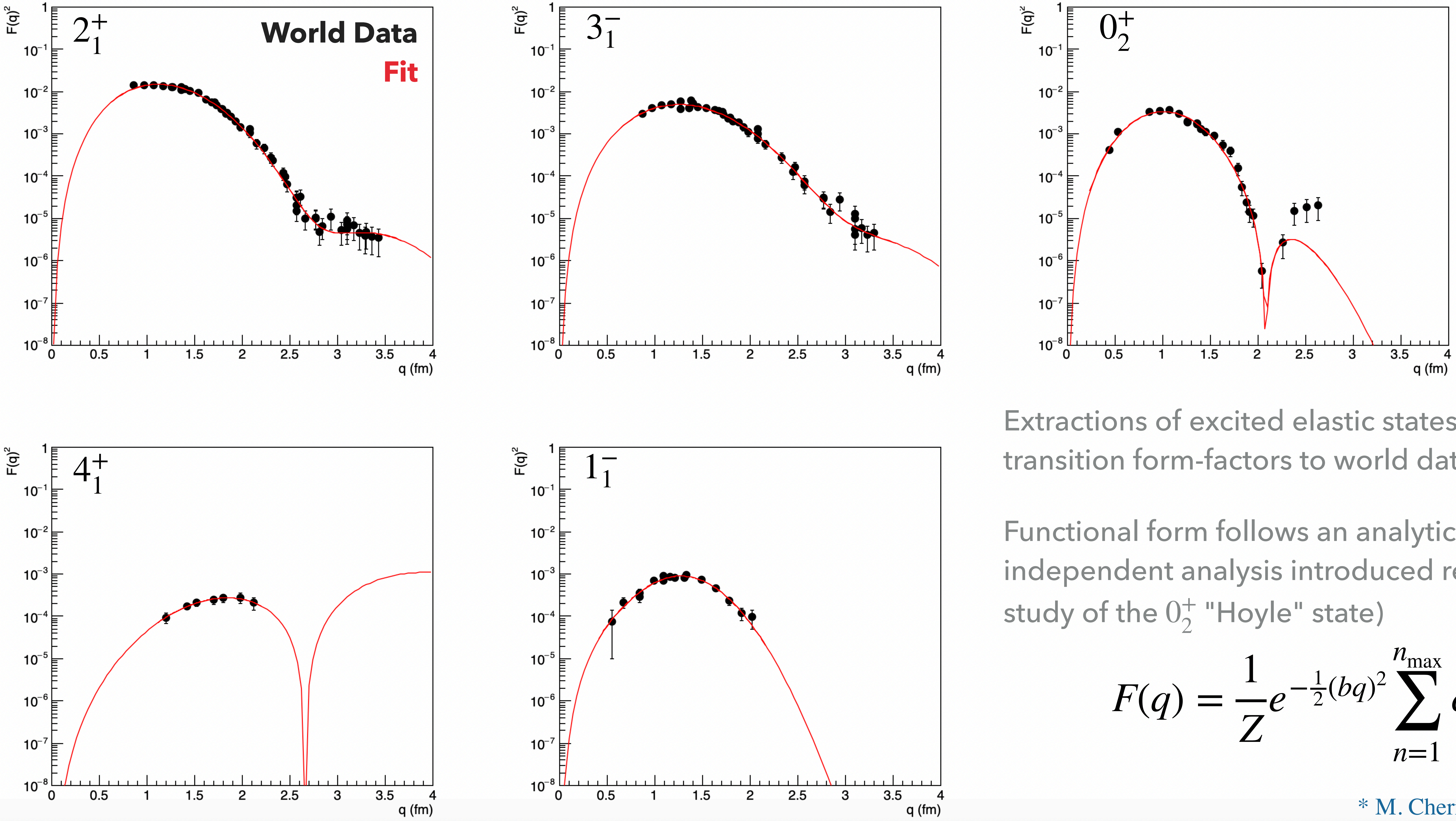


^{12}C elastic XS at 400 MeV, 35 degrees





EXCITED ELASTIC STATES



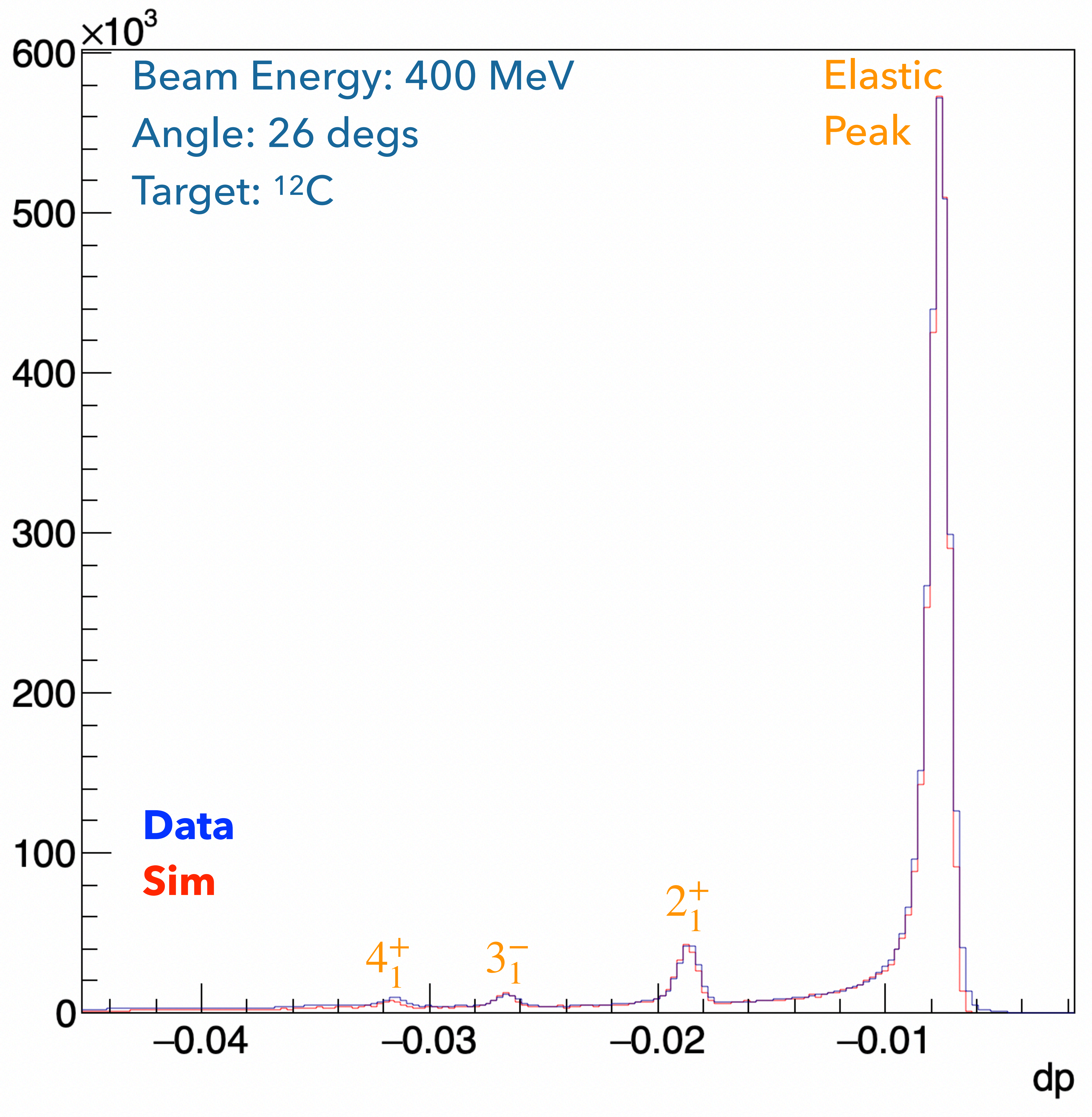
Extractions of excited elastic states based on fit of transition form-factors to world data.

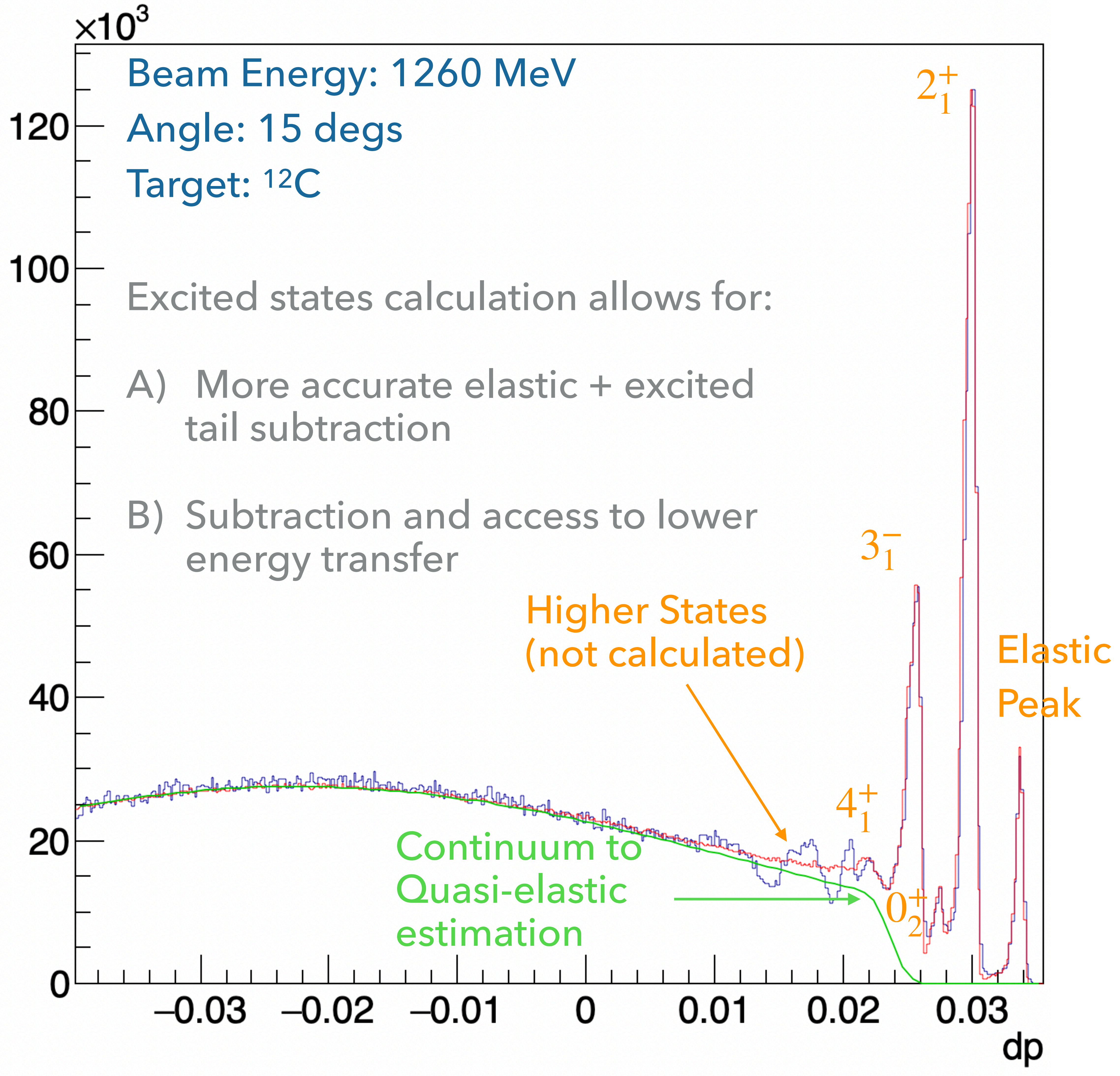
Functional form follows an analytic, global, and model-independent analysis introduced recently* (mostly in the study of the 0_2^+ "Hoyle" state)

$$F(q) = \frac{1}{Z} e^{-\frac{1}{2}(bq)^2} \sum_{n=1}^{n_{\max}} c_n (bq)^{2n}$$

* M. Chernykh, *et al*. Phys. Rev. Lett. 105

EXCITED ELASTIC STATES

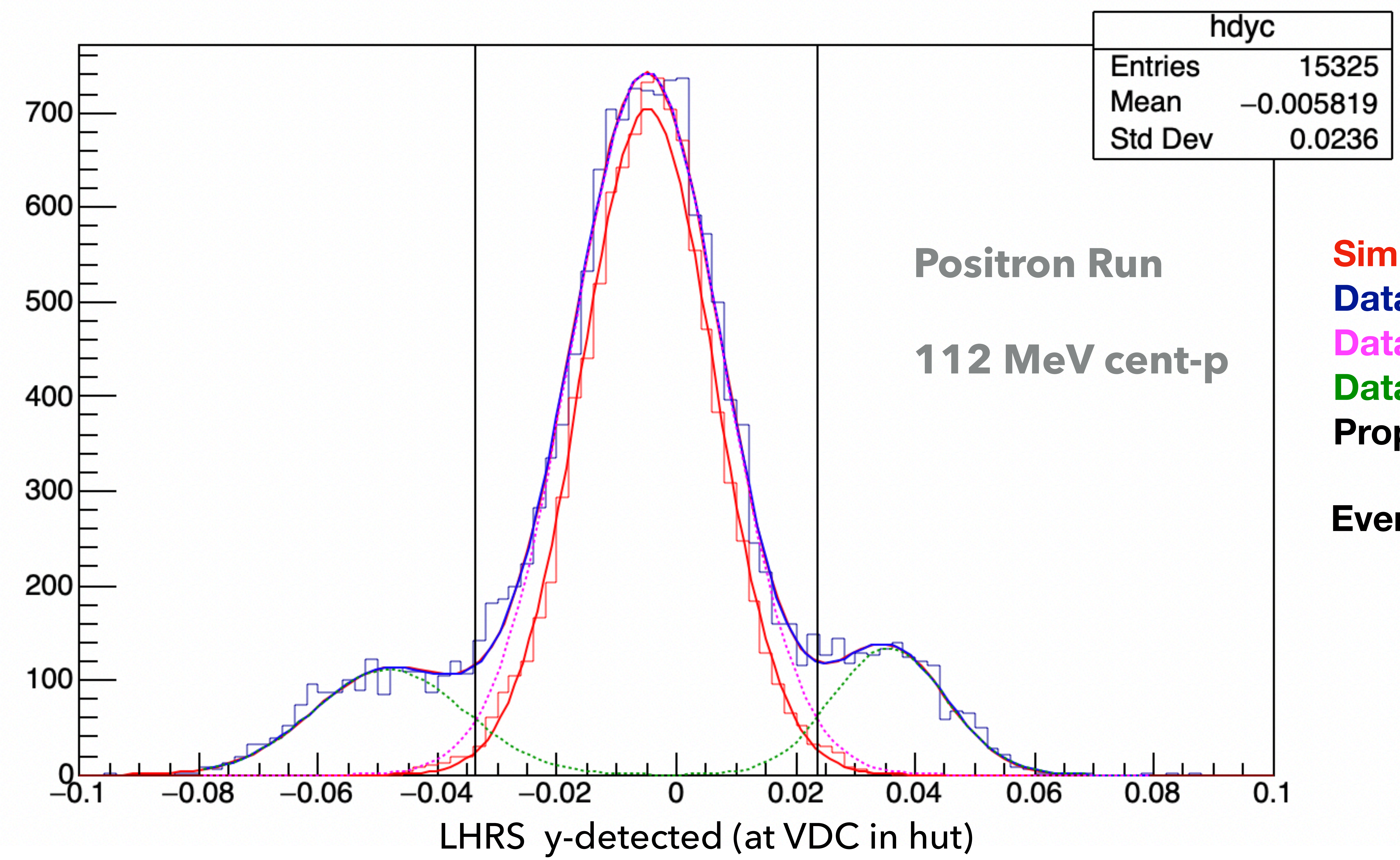




* M. Chernykh, *et al*. Phys. Rev. Lett. 105

MAGNET RESCATTERING

- At low central momentum, magnet-rescattered events may be present.

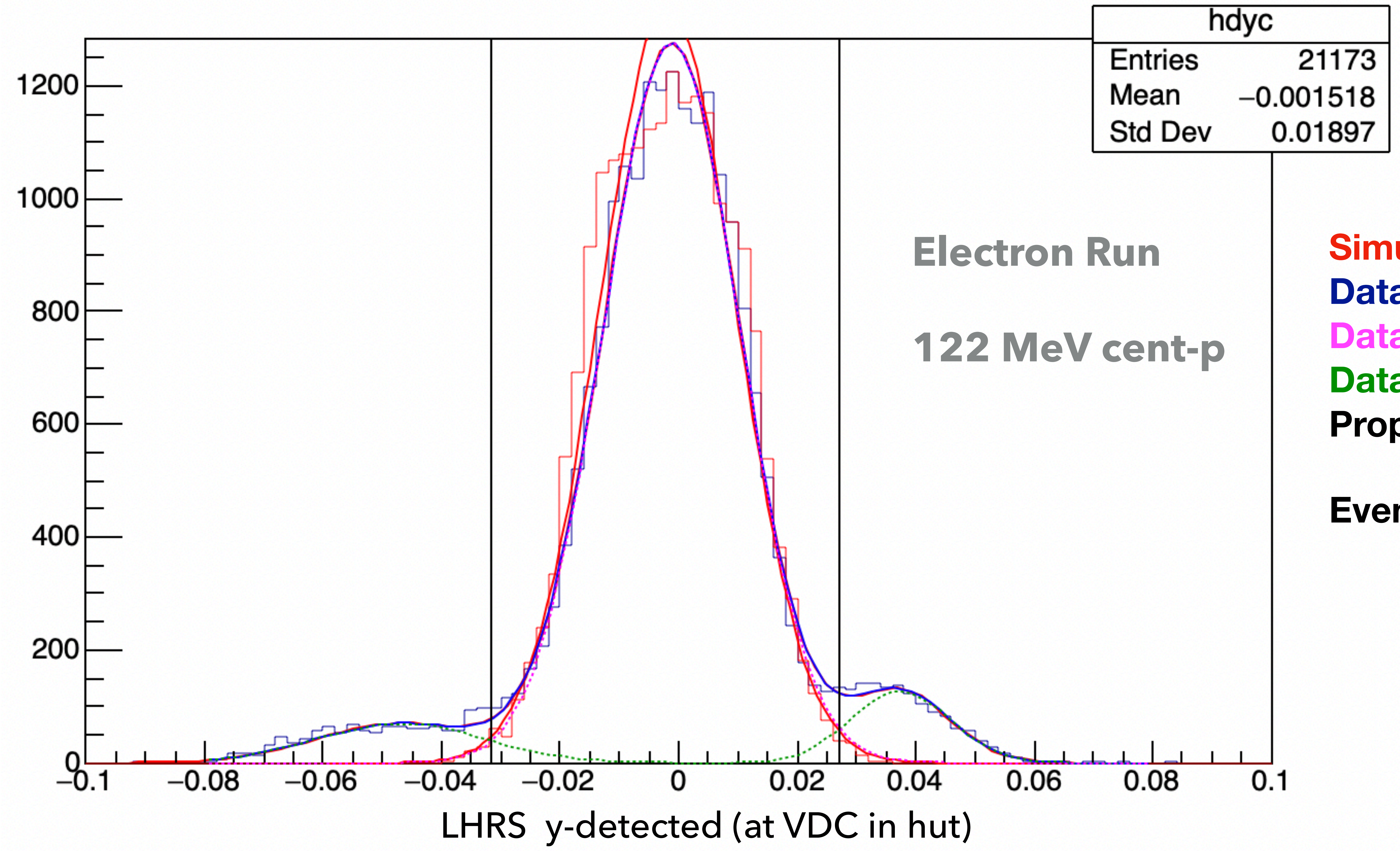


Simulation + Gaussian Fit
Data + 3 Gaussian Fit
Data central gaussian
Data outer 2 gaussian
Proposed cut line

Events cut / Total = 0.22

MAGNET RESCATTERING

- At low central momentum, magnet-rescattered events may be present.



Simulation + Gaussian Fit

Data + 3 Gaussian Fit

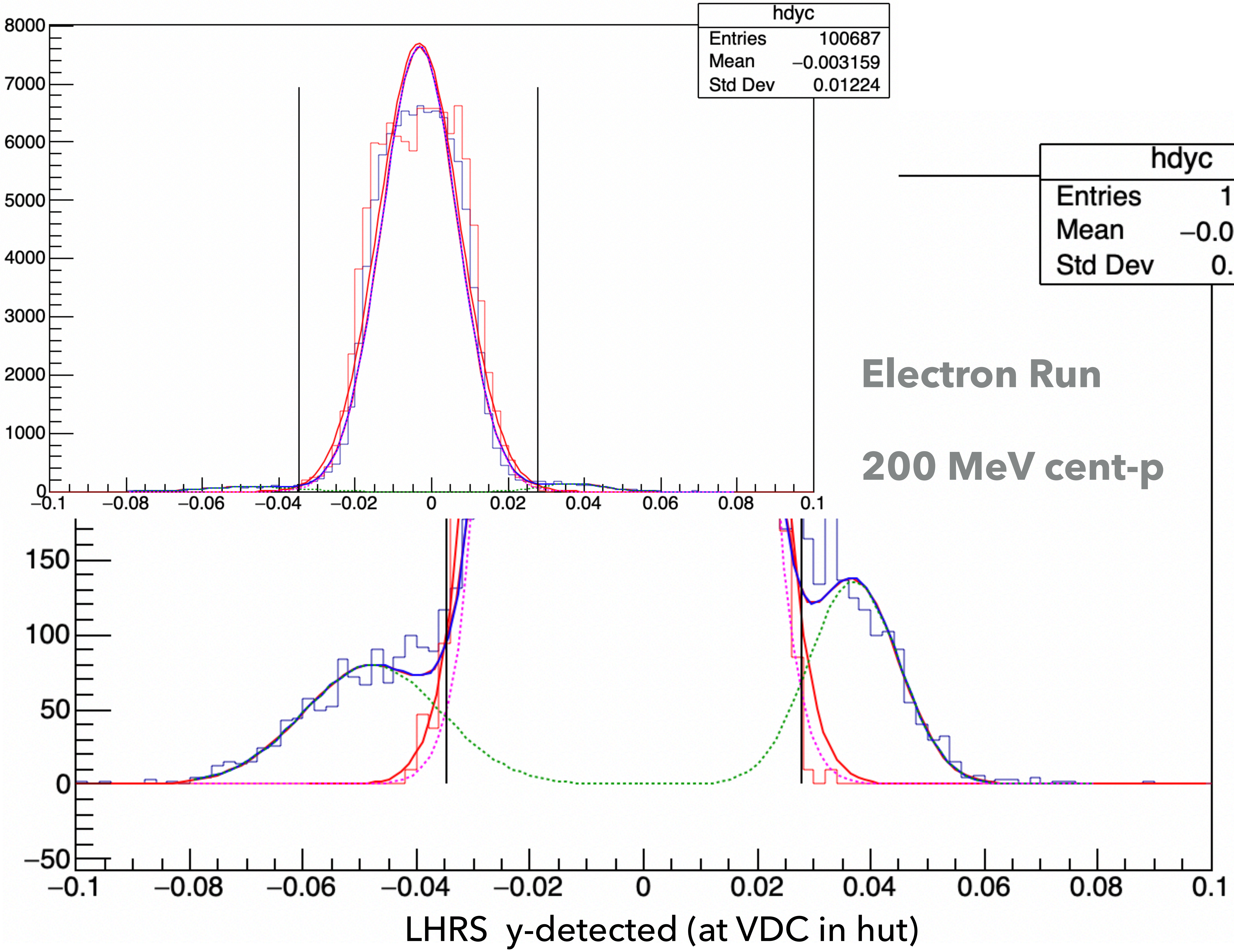
Data central gaussian

Data outer 2 gaussian

Proposed cut line

Events cut / Total = 0.13

MAGNET RESCATTERING



Electron Run

200 MeV cent-p

Simulation + Gaussian Fit
Data + 3 Gaussian Fit
Data central gaussian
Data outer 2 gaussian
Proposed cut line

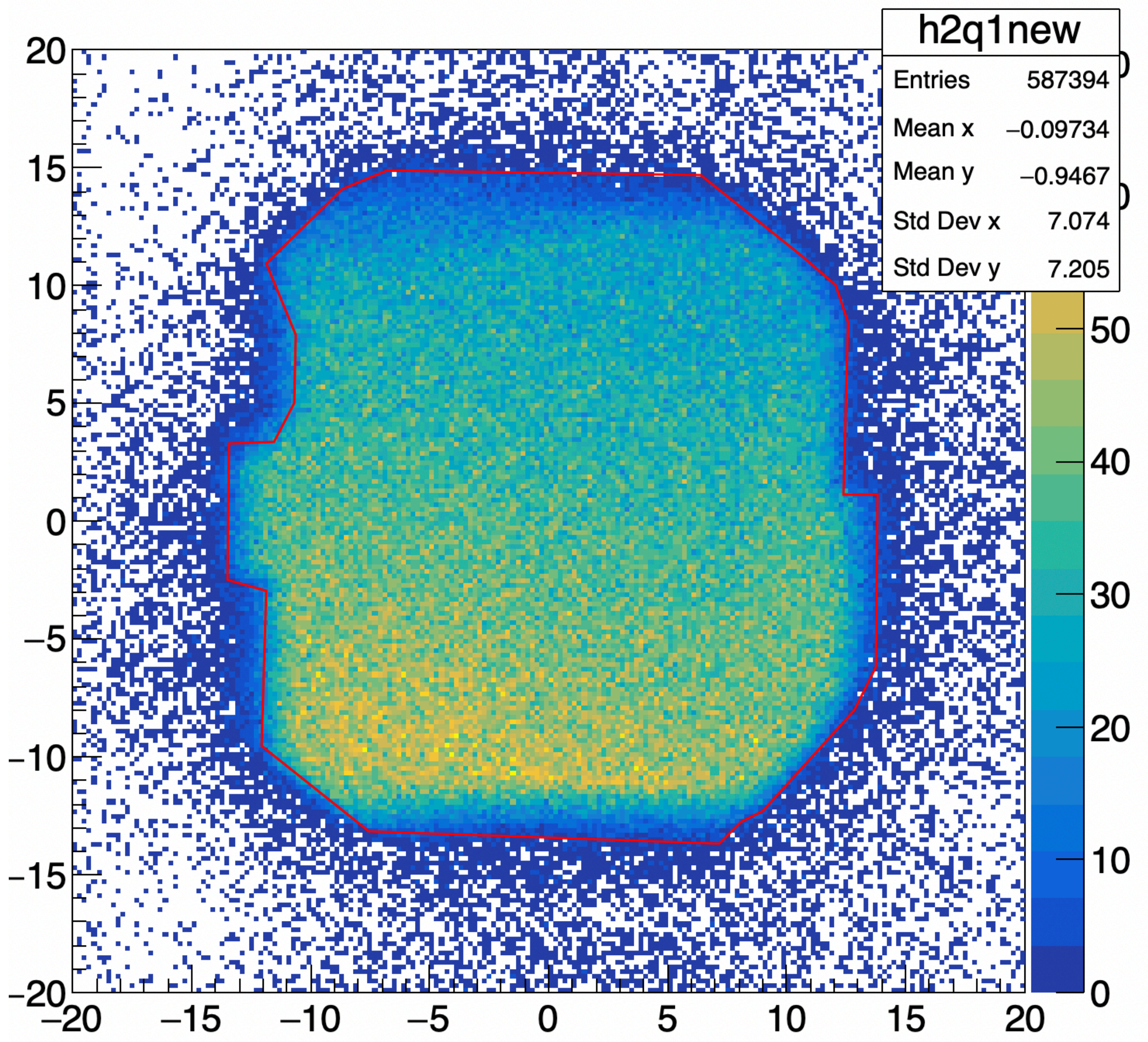
Events cut / Total = 0.025

- We can use LeRose's transport functions to estimate the distributions at the Q1 and Q3 exit.

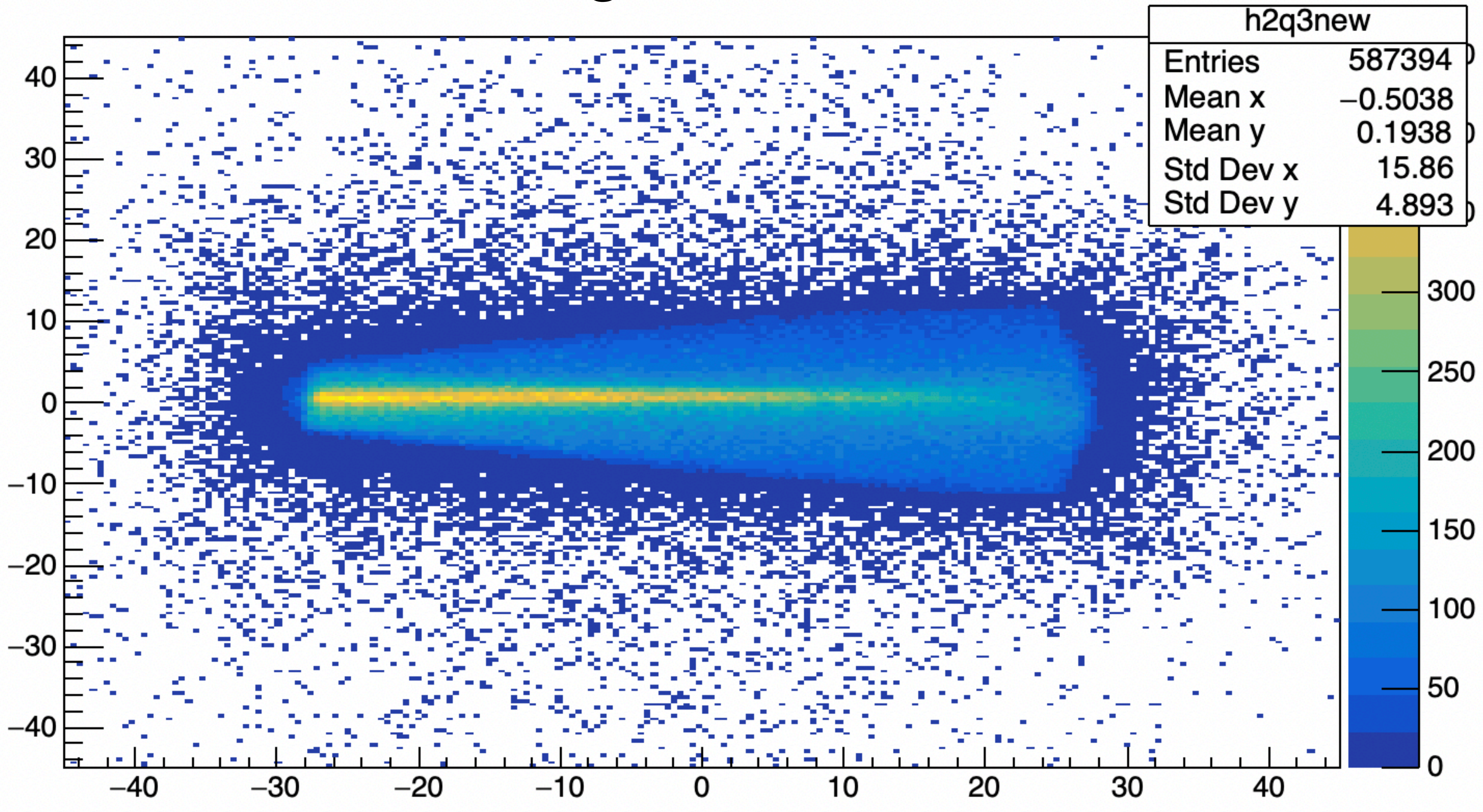
DATA is e- LHRS 930 MeV cent-p with NO SPECTROMETER CUTS

DATA is propagated through LeRose functions (from target variables)

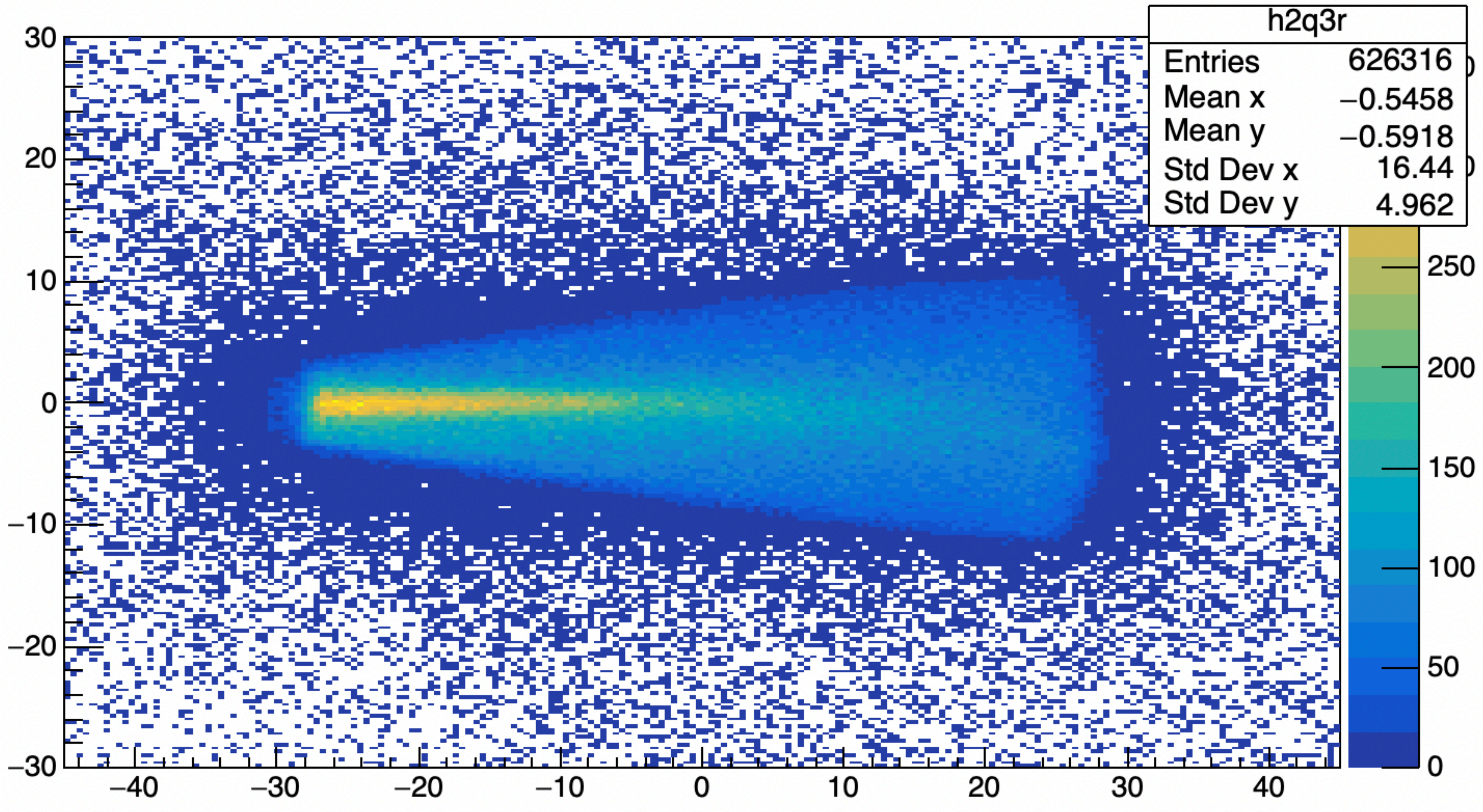
DATA is linearly extrapolated from FP variables to Q3 exit to compare LeRose vs pure DATA



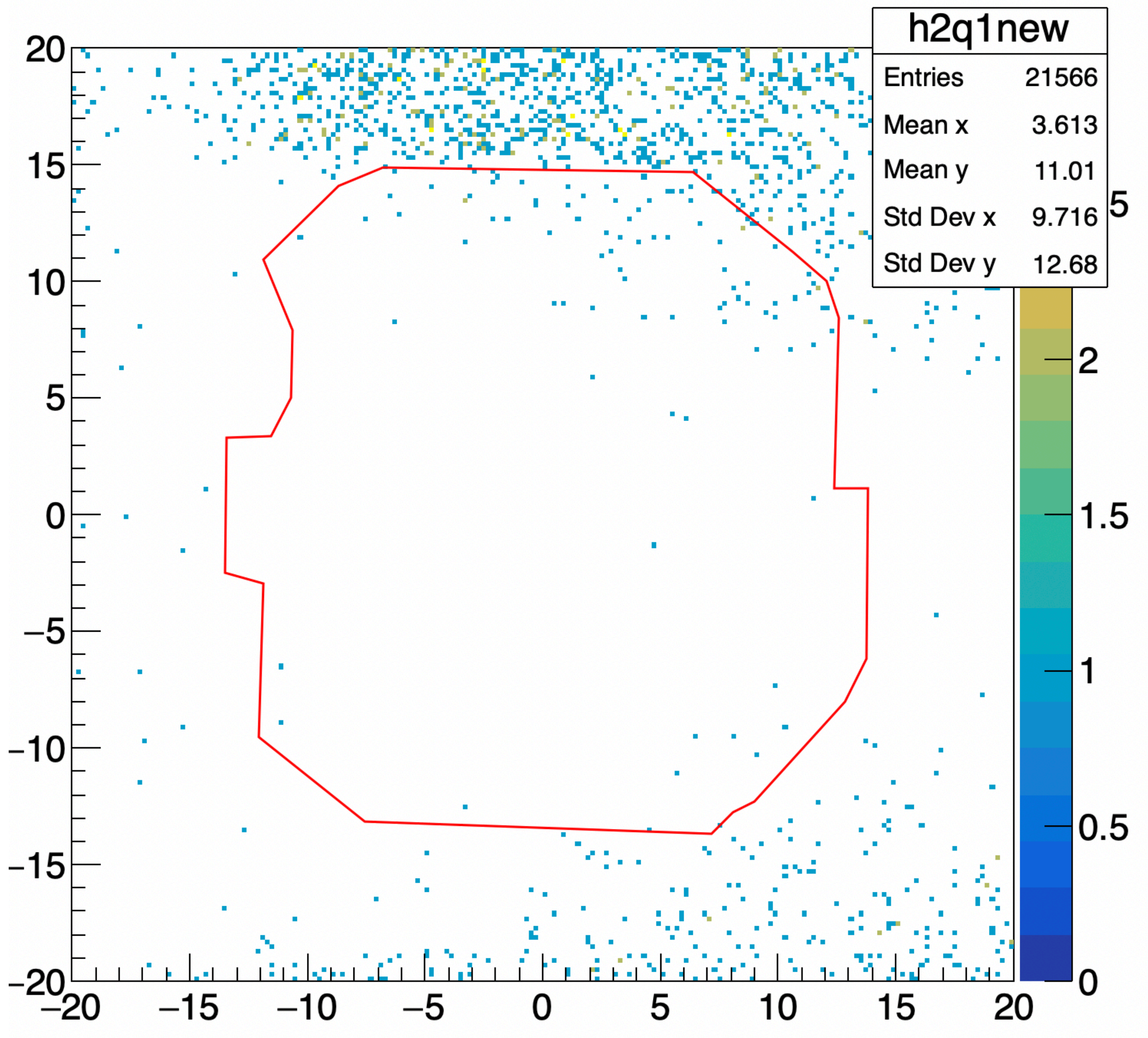
Q1 exit from tgt variables & LeRose function



Q3 exit from tgt variables & LeRose function



Q3 exit from fp variables (linear extrapolation)



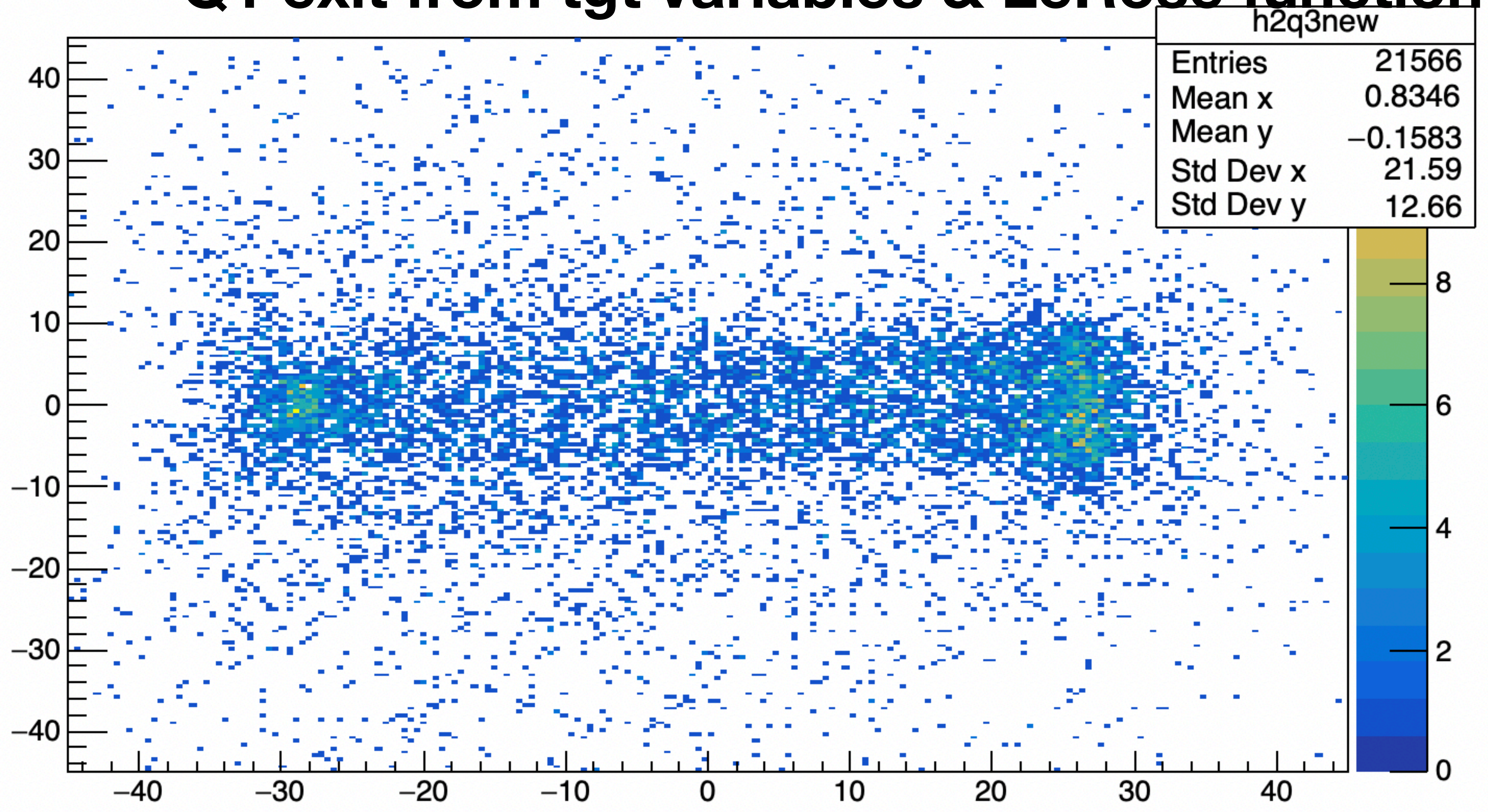
- We can use LeRose's transport functions to estimate the distributions at the Q1 and Q3 exit.

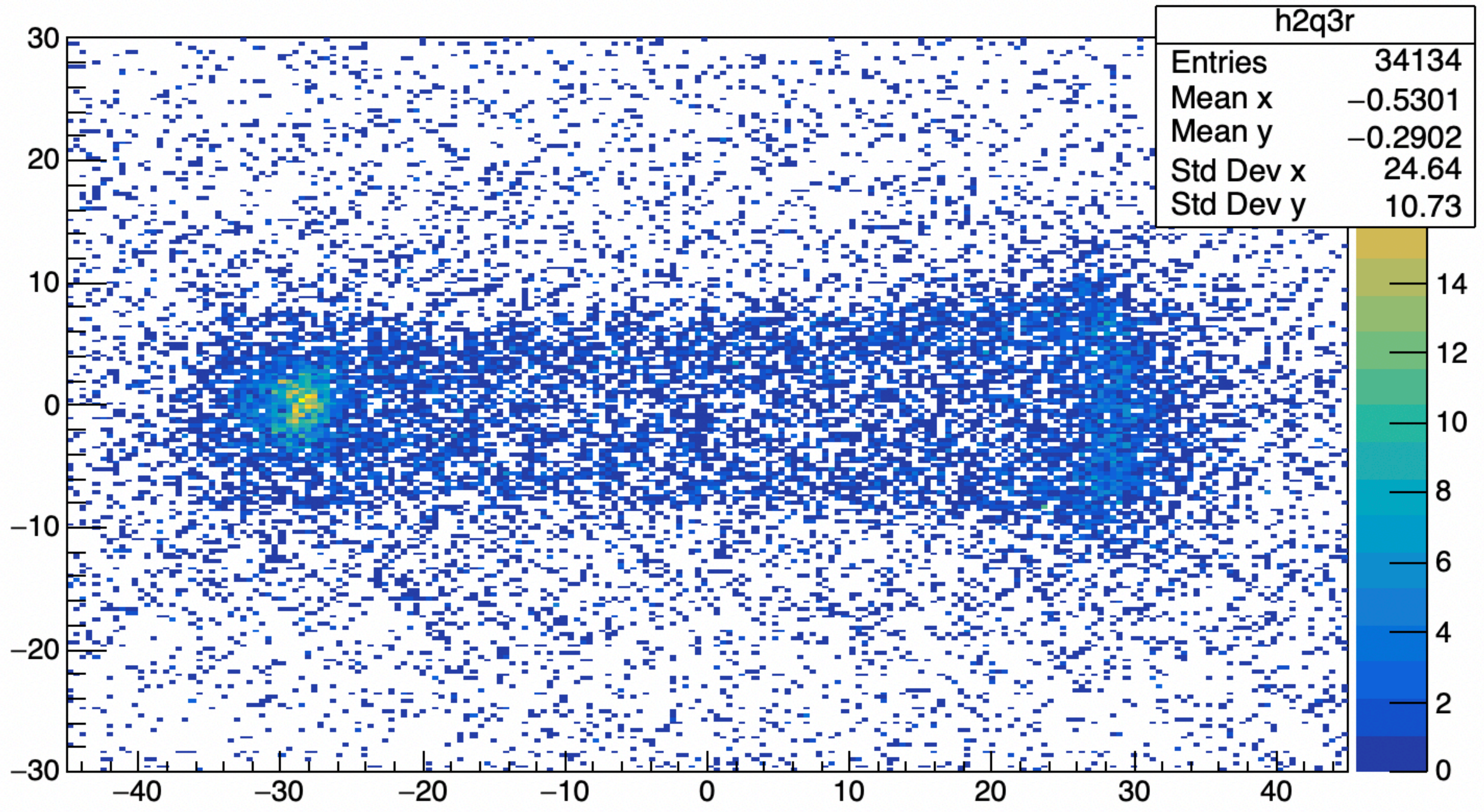
DATA is e- LHRS 930 MeV cent-p with Y-DETECTED TAILS CUT

DATA is propagated through LeRose functions (from target variables)

DATA is linearly extrapolated from FP variables to Q3 exit to compare LeRose vs pure DATA

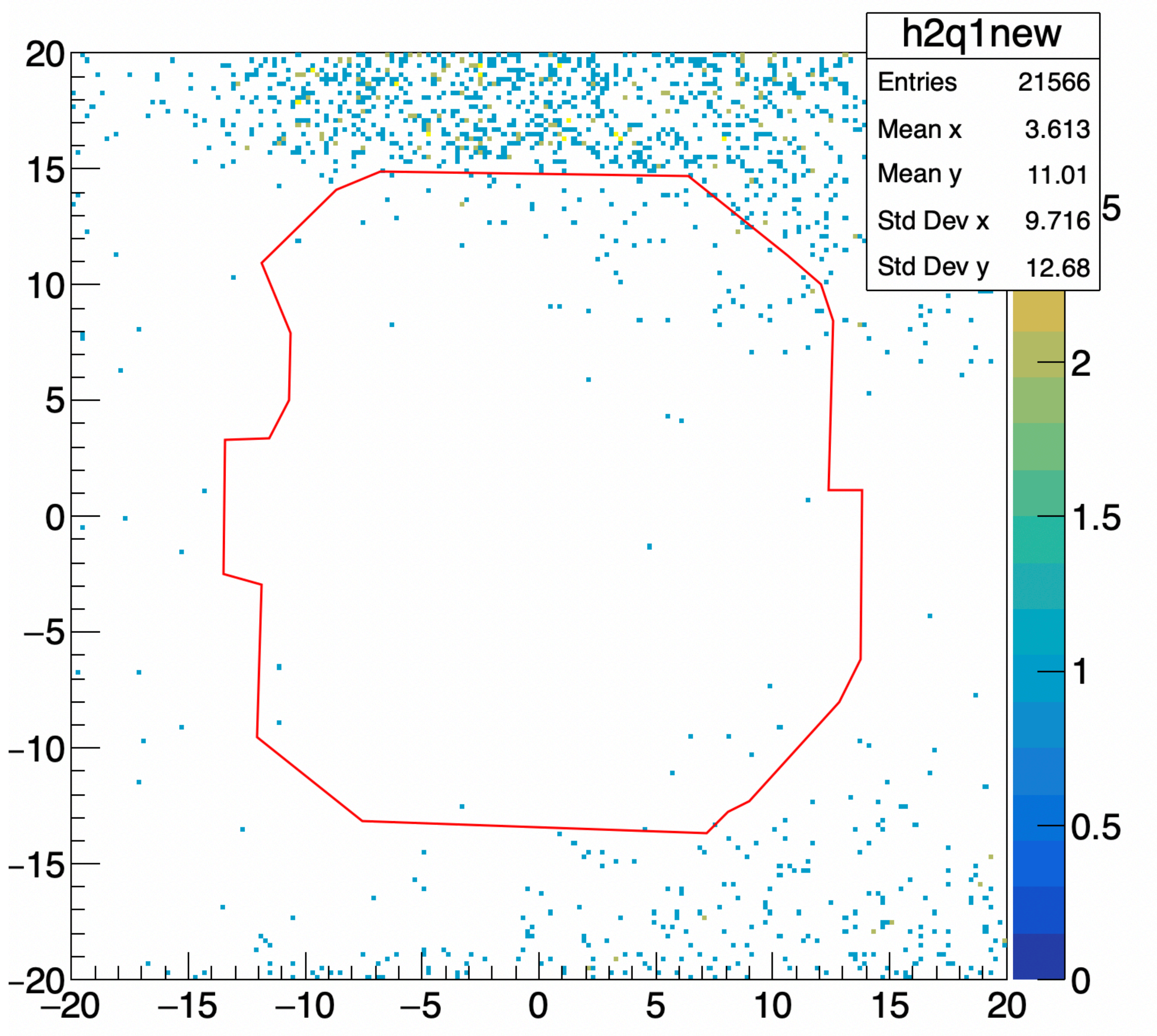
Q1 exit from tgt variables & LeRose function





Q3 exit from tgt variables & LeRose function

Q3 exit from fp variables (linear extrapolation)



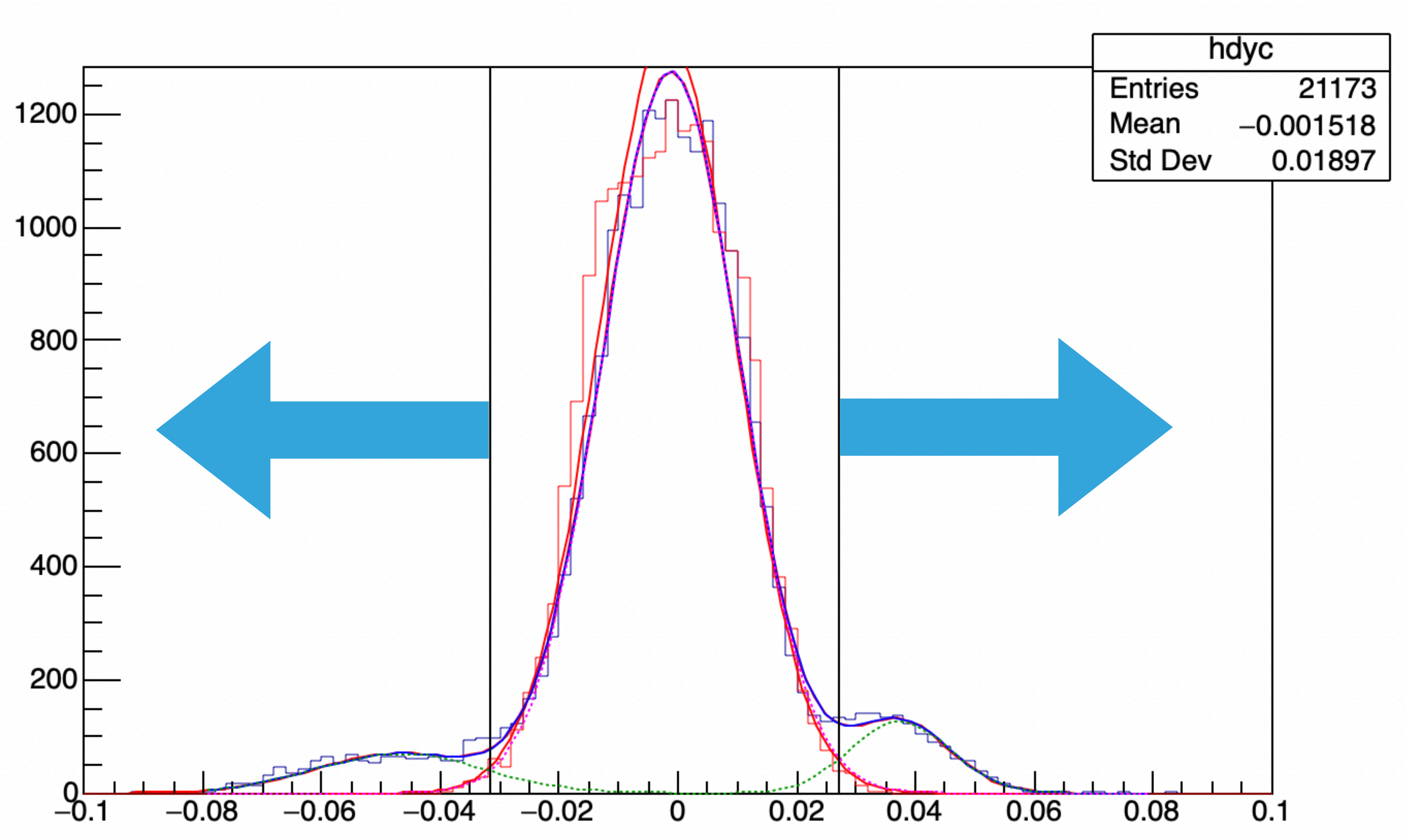
Q1 exit from tgt variables & LeRose function

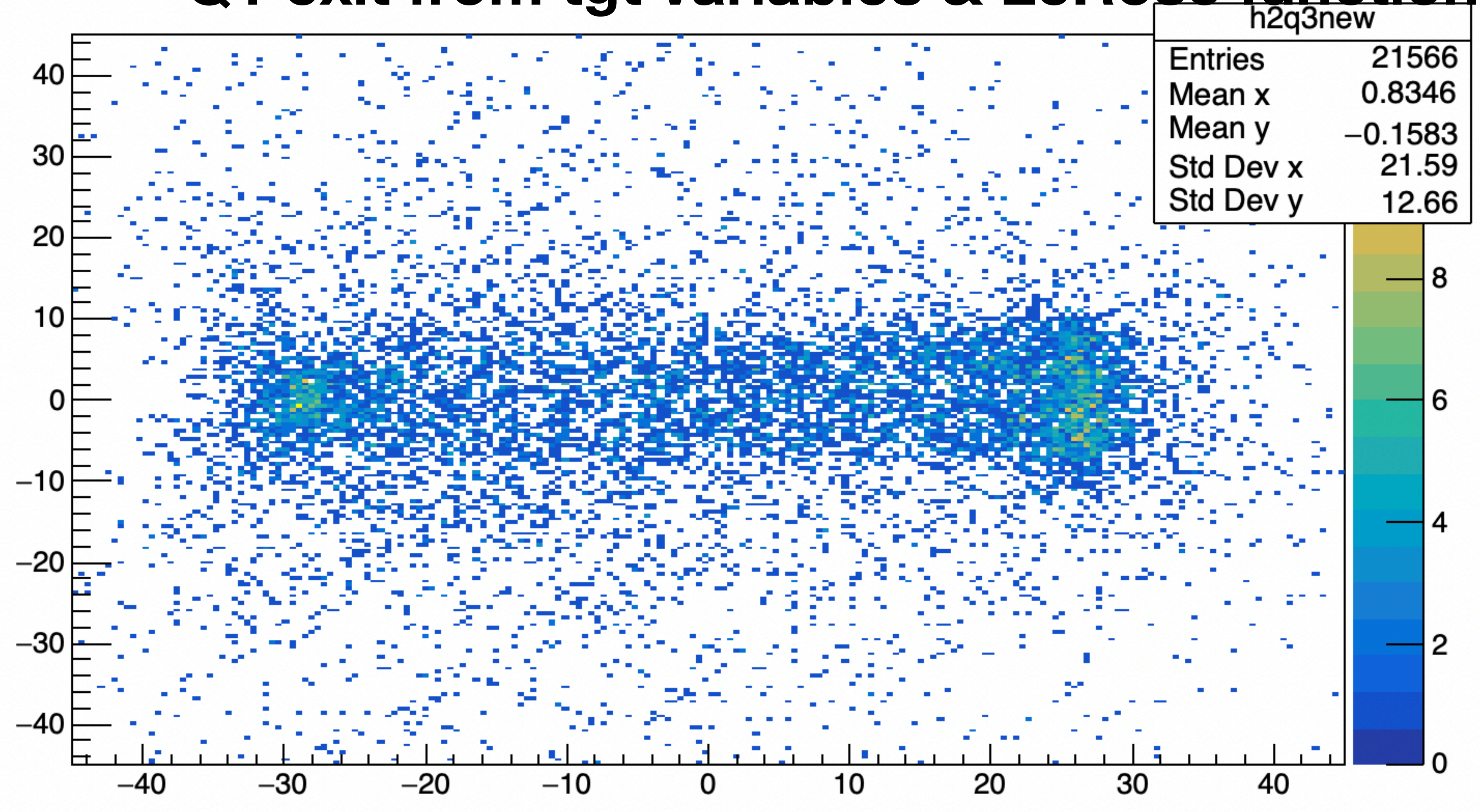
- We ca… the distrib…

D… S CUT

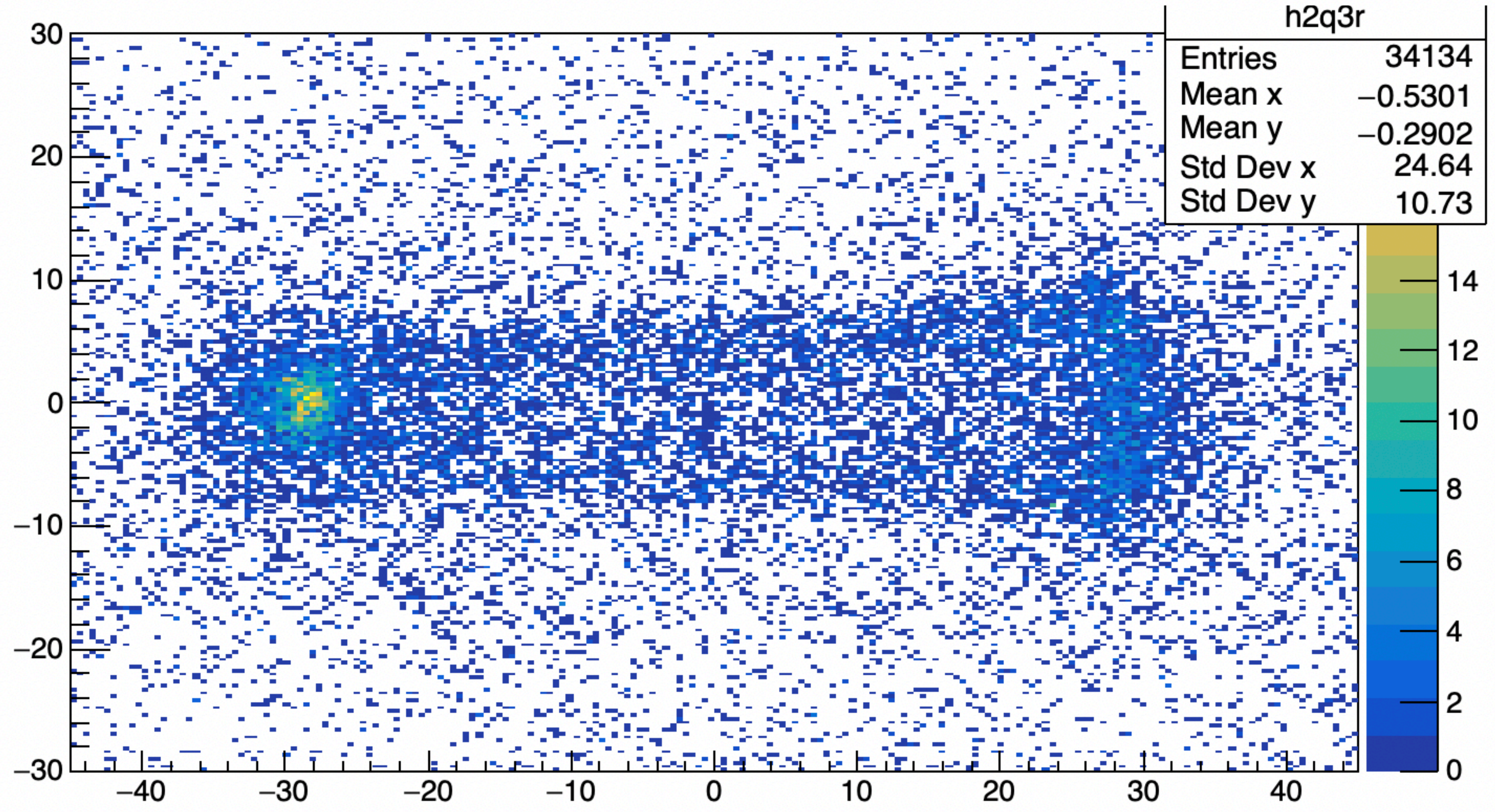
DAT… variables)

DAT… compare





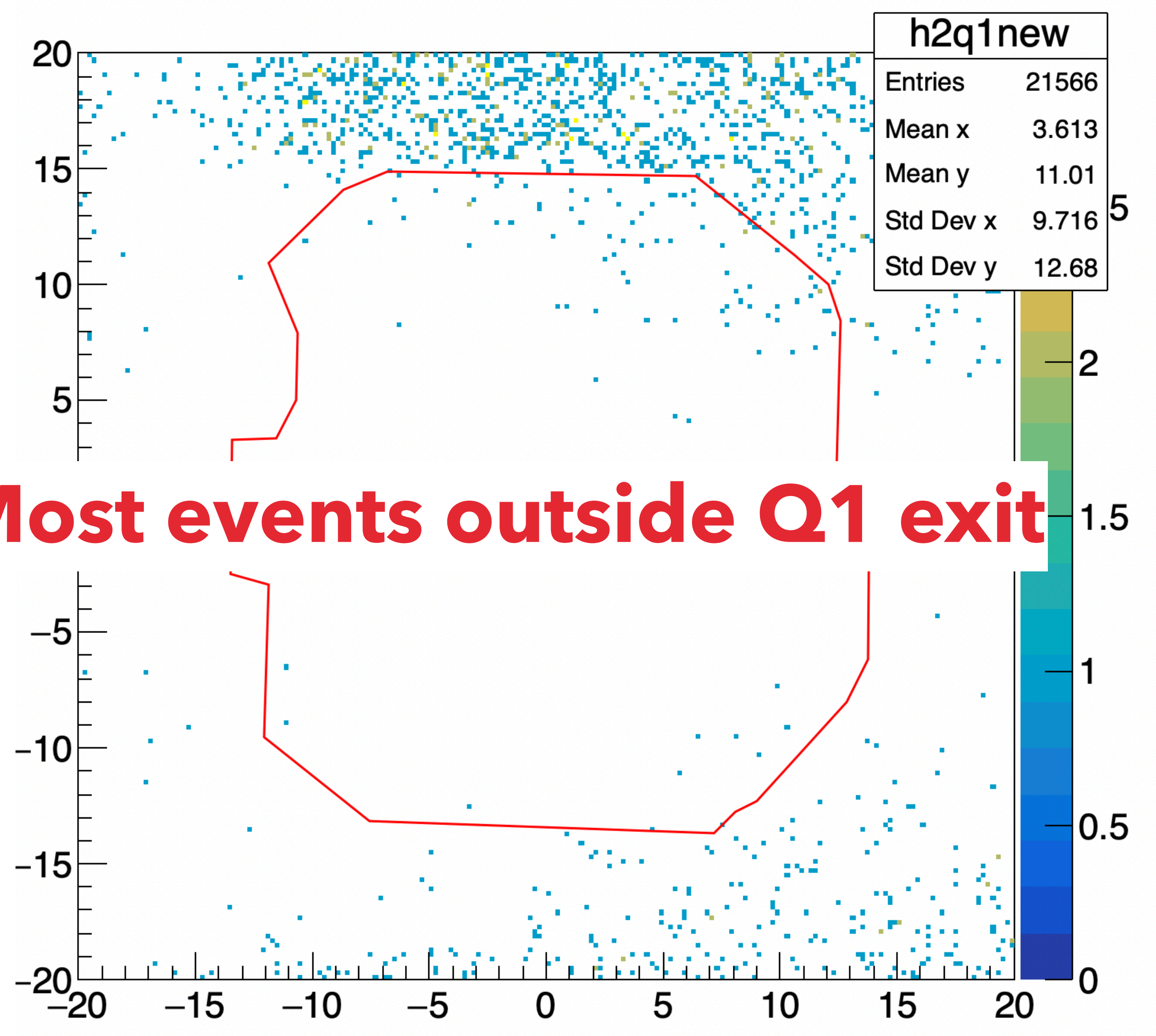
Q3 exit from tgt variables & LeRose function



Q3 exit from fp variables (linear extrapolation)

- We can use LeRose's transport functions to estimate the distributions at the Q1 and Q3 exit.

DATA is e- LHRS 930 MeV cent-p with Y-DETECTED TAILS CUT

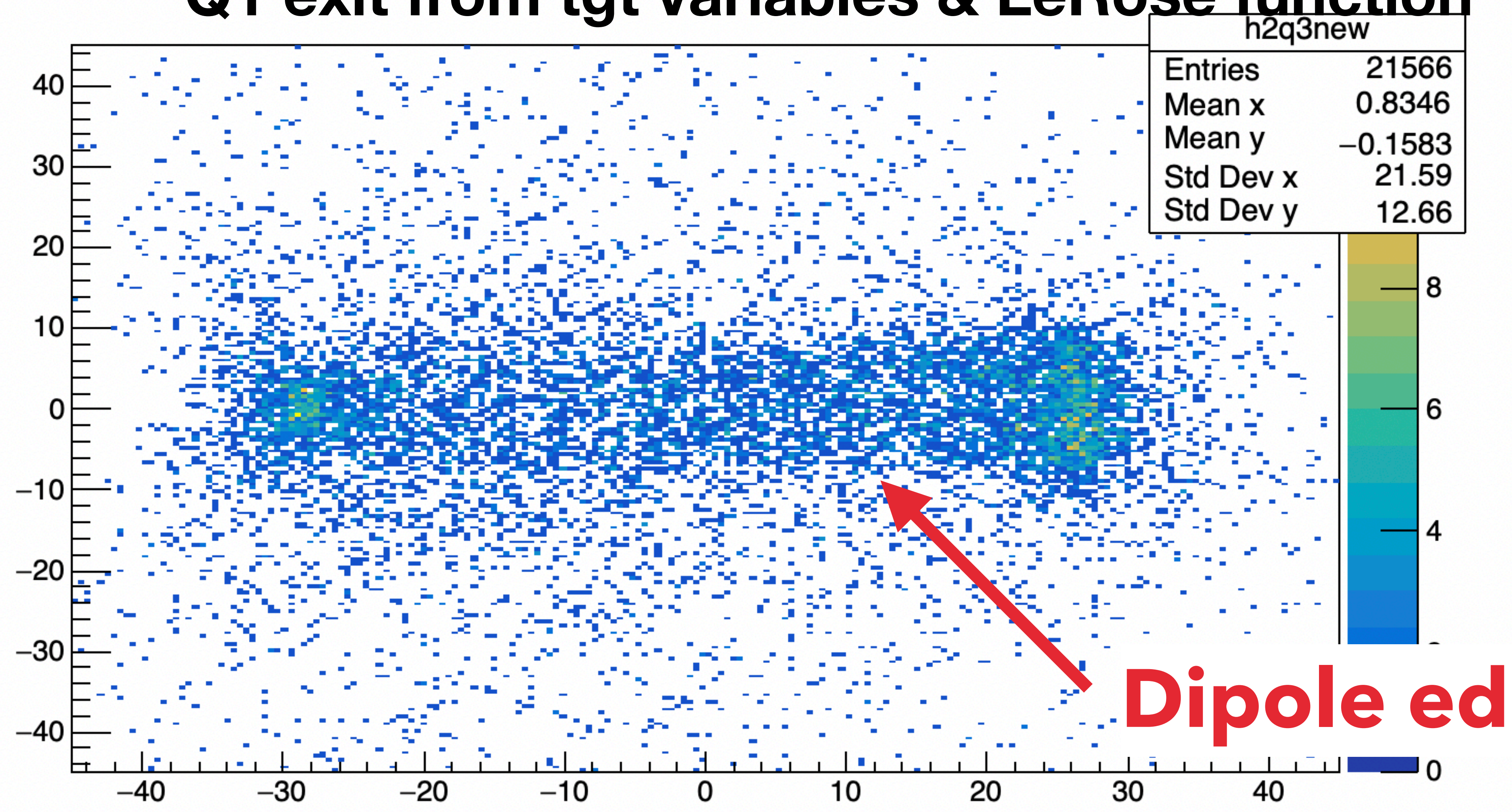


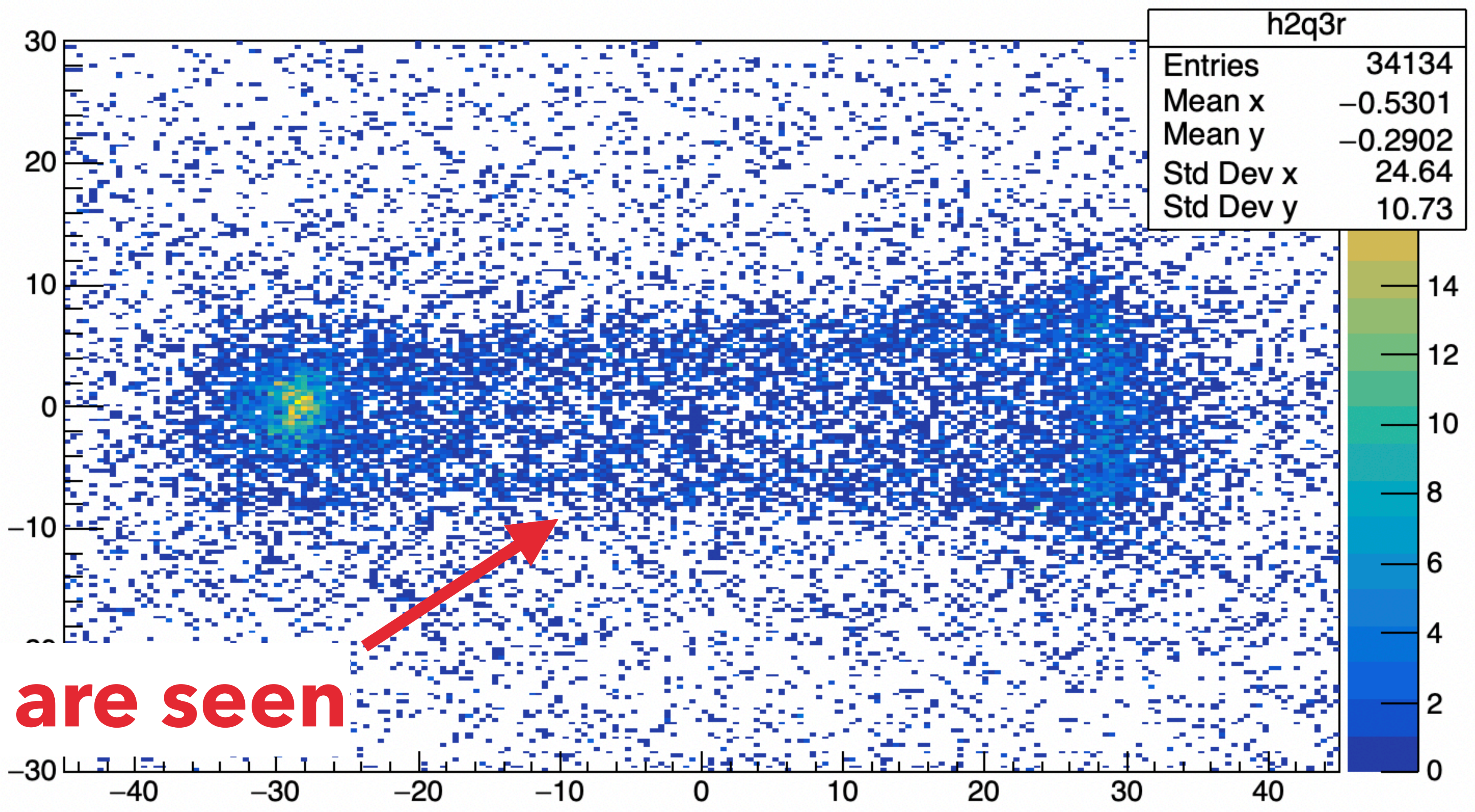
Most events outside Q1 exit

DATA is propagated through LeRose functions (from target variables)

DATA is linearly extrapolated from FP variables to Q3 exit to compare LeRose vs pure DATA

Q1 exit from tgt variables & LeRose function





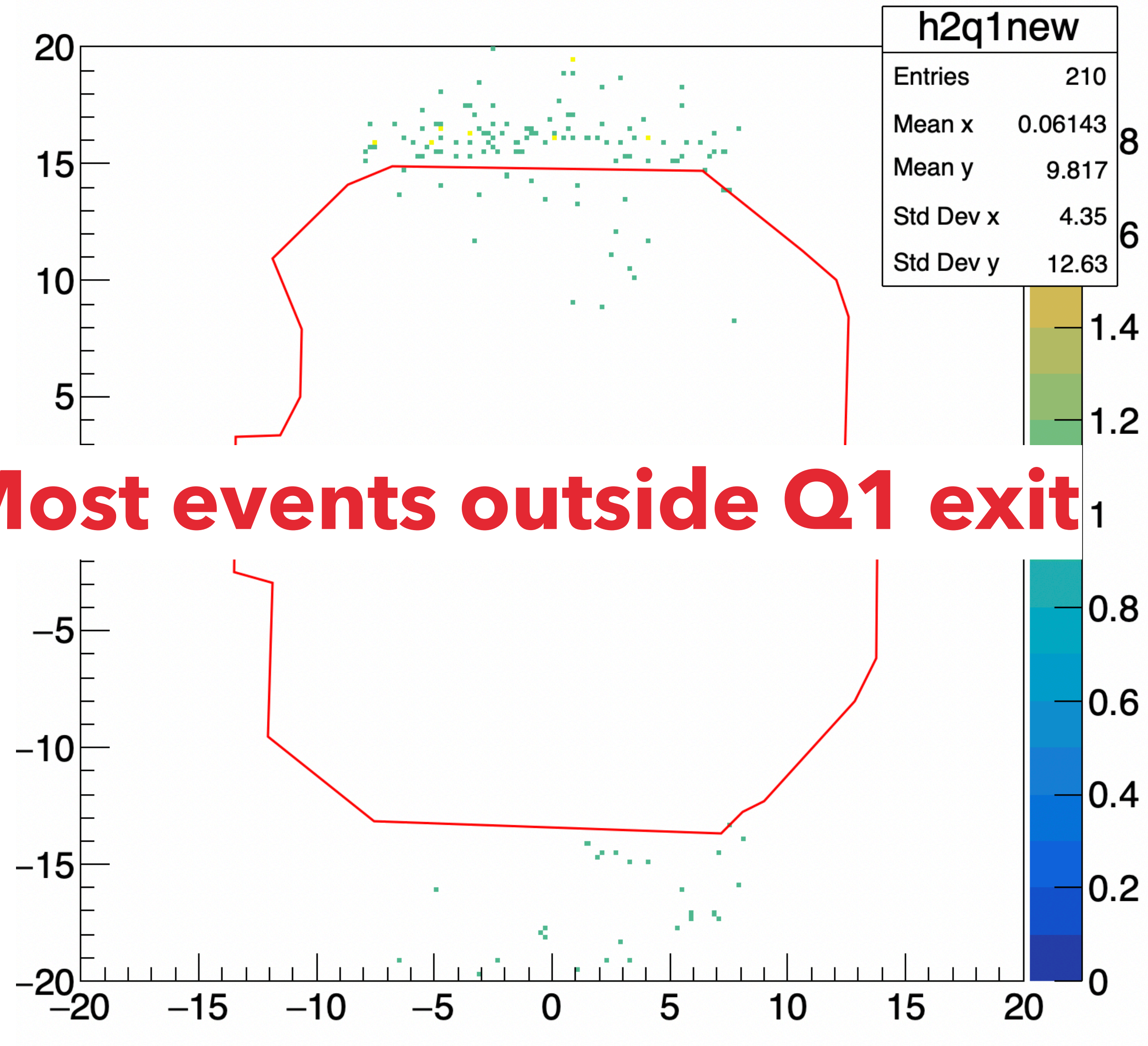
Dipole edges are seen

Q3 exit from tgt variables & LeRose function

Q3 exit from fp variables (linear extrapolation)

- We can use LeRose's transport functions to estimate the distributions at the Q1 and Q3 exit.

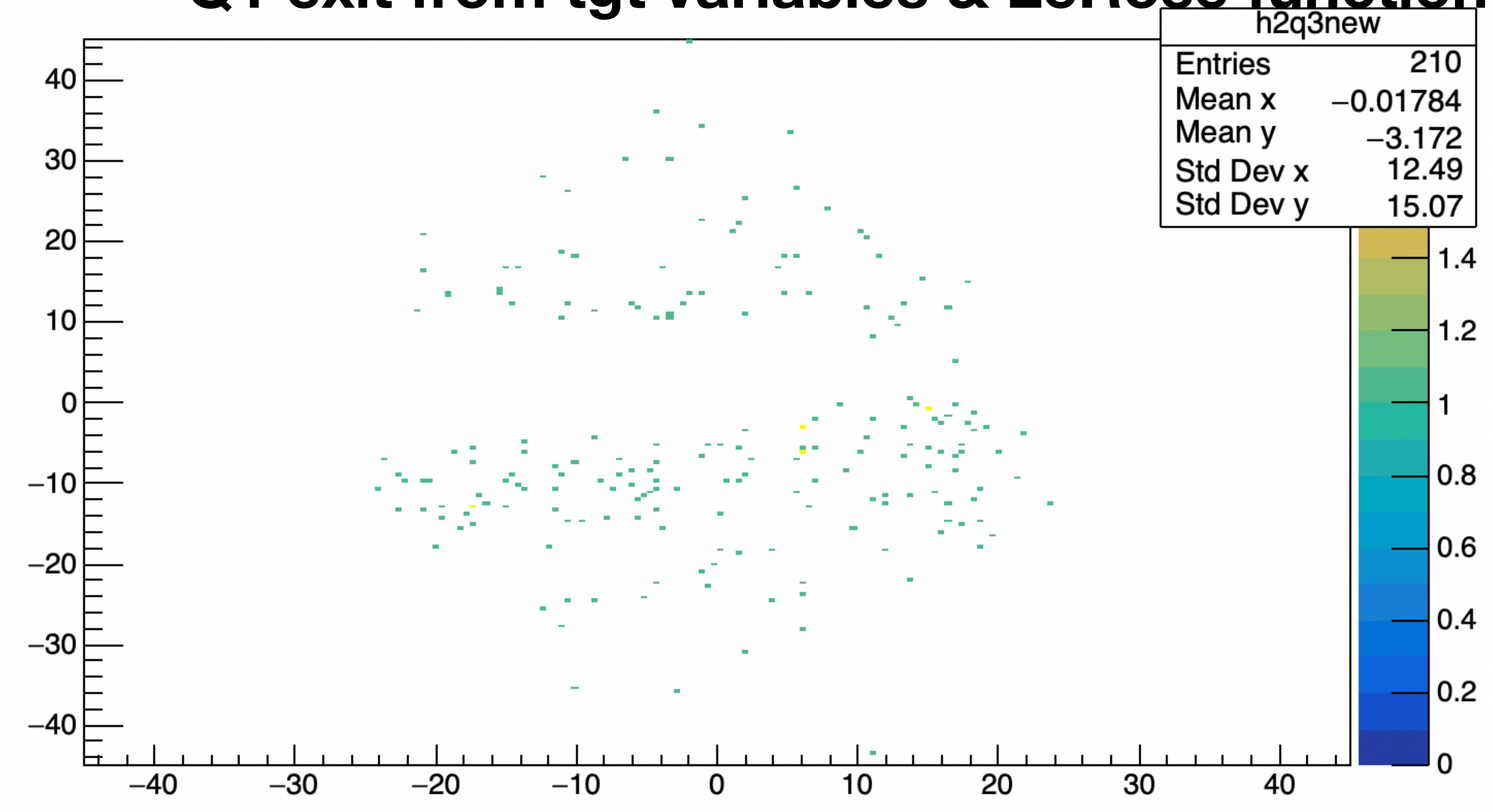
DATA is e- LHRS 930 MeV cent-p with Y-DETECTED TAILS CUT && STANDARD SPECTROMETER CUTS



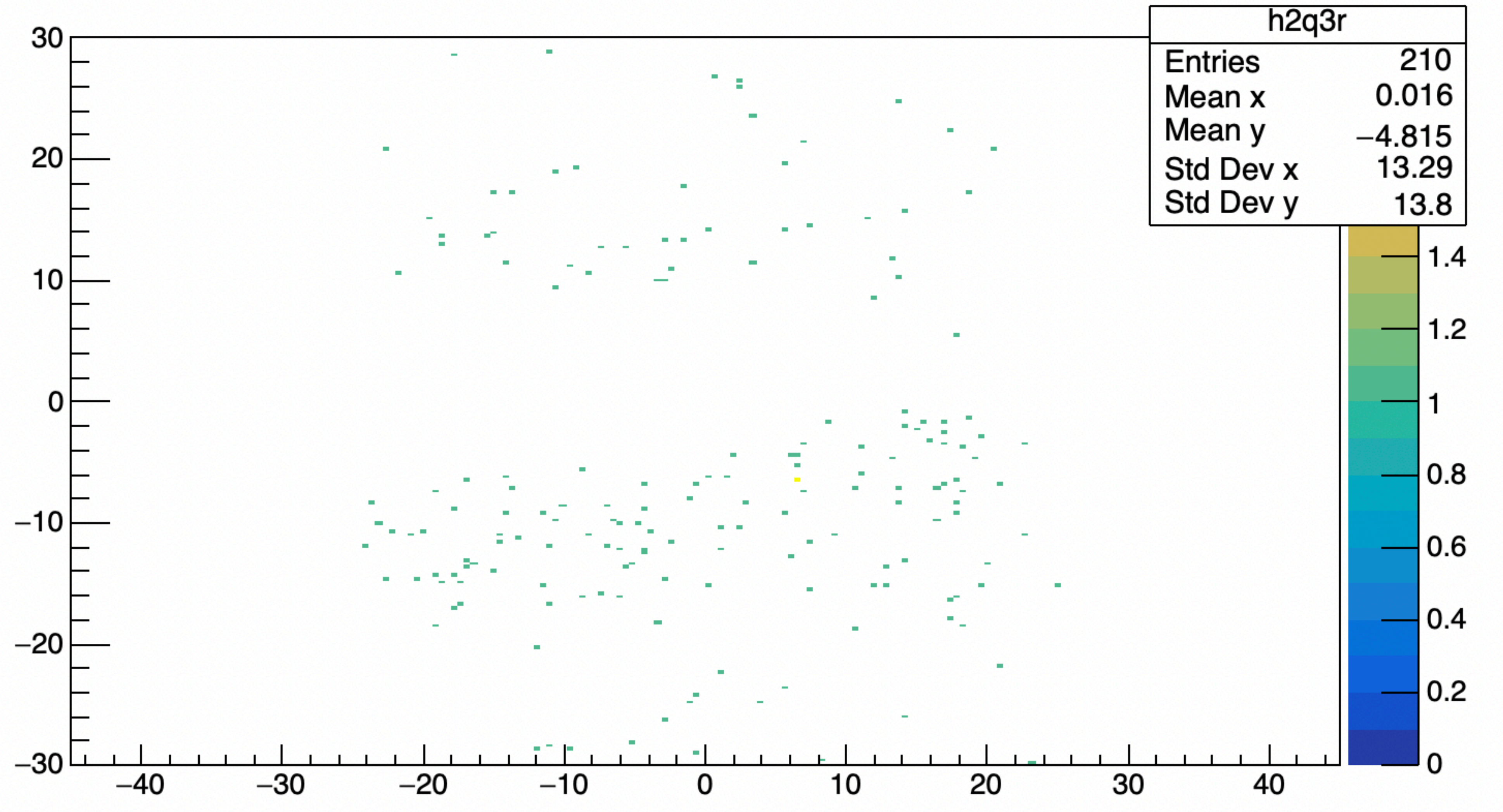
Q1 exit from tgt variables & LeRose function

DATA is propagated through LeRose functions (from target variables)

DATA is linearly extrapolated from FP variables to Q3 exit to compare LeRose vs pure DATA

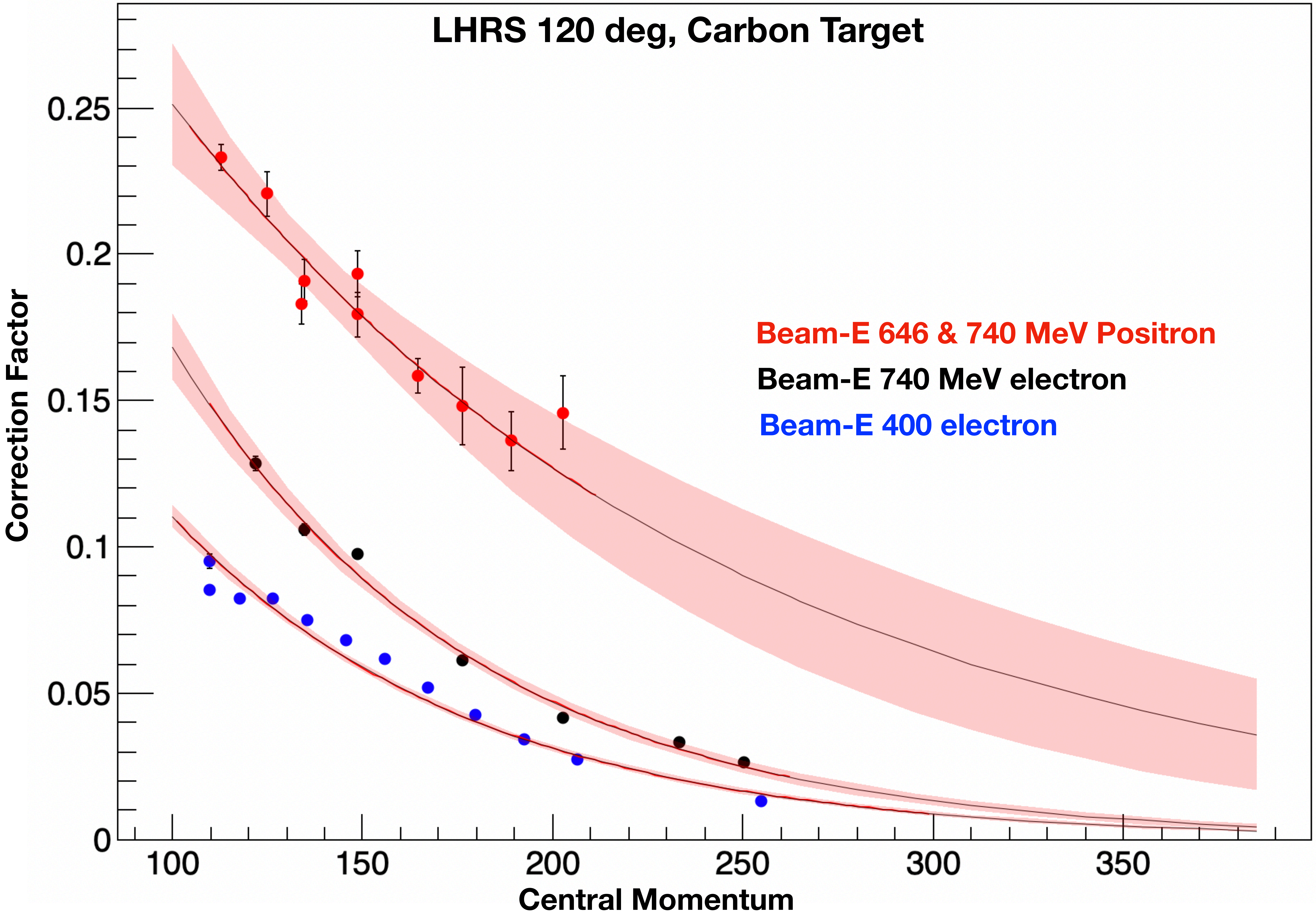


Q3 exit from tgt variables & LeRose function



Q3 exit from fp variables (linear extrapolation)

- Background seems more prevalent in positron data.
- Background looks to be topology dependent.



SUMMARY / LOOKING AHEAD

- Recent efforts:
  - Updated bin-centering correction
  - A magnet-rescattering background study is under way:
    - Needs to be evaluated for all angles, beam-energies, and targets.
- Up next:
  - A careful evaluation of the relativistic corrections.
  - Full systematic studies
  - Publish

THANK YOU!!!

Kalyan Allada, Korand Aniol, Jon Arrington, **Hamza Atac**, Todd Averett, Herat Bandara, Werner Boeglin, Alexandre Camsonne, Mustafa Canan, **Jian-Ping Chen**, Wei Chen, Khem Chirapatpimol, **Seonho Choi**, Eugene Chudakov, Evaristo Cisbani, Francesco Cusanno, Rafelle De Leo, Chiranjib Dutta, Cesar Fernandez-Ramirez, David Flay, Salvatore Frullani, Haiyan Gao, Franco Garibaldi, Ronald Gilman, Oleksandr Glamazdin, Brian Hahn, Ole Hansen, Douglas Higinbotham, Tim Holmstrom, Bitao Hu, Jin Huang, Yan Huang, Florian Itard, Liyang Jiang, Xiaodong Jiang, **Kai Jin**, Hoyoung Kang, Joe Katich, Mina Katramatou, Aidan Kelleher, Elena Khrosinkova, Gerfried Kumbartzki, John LeRose, Xiaomei Li, Richard Lindgren, Nilanga Liyanage, Joaquin Lopez Herraiz, Lagamba Luigi, Alexandre Lukhanin, Michael Paolone, Maria Martinez Perez, Dustin McNulty, **Zein-Eddine Meziani**, Robert Michaels, Miha Mihovilovic, Joseph Morgenstern, Blaine Norum, **Yoomin Oh**, Michael Olson, Makis Petratos, Milan Potokar, Xin Qian, **Yi Qiang, Arun Saha, Brad Sawatzky**, **Elaine Schulte,** Mitra Shabestari, Simon Sirca, Patricia Solvignon, Jeongseog Song, **Nikolaos Sparveris, Ramesh Subedi, Vincent Sulkosky,** Jose Udias, Javier Vignote, Eric Voutier, Youcai Wang, John Watson, Yunxiu Ye , Xinhu Yan, **Huan Yao**, **Xinhu Yan** Zhihong Ye, Xiaohui Zhan, Yi Zhang, Xiaochao Zheng, Lingyan Zhu

PEOPLE

and
Hall-A collaboration

PhD Students **Spokespersons** **Run Coordinators**