JLAB CLAS results on pion production from nuclear target

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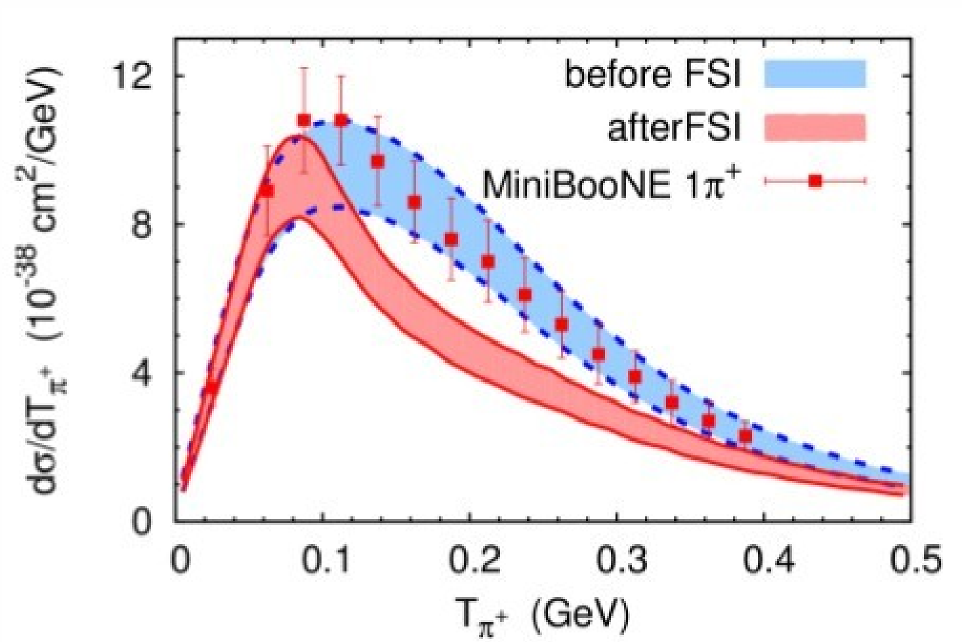
Representing the CLAS (EG-2) collaboration

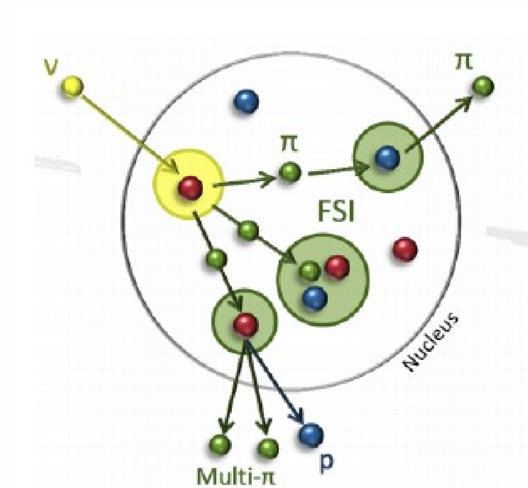
Why eA? – Goal of this work

- This work aims to produce high statistics, differential, charged pion production measurements on different nuclei that will be useful for learning about and tuning models for FSI.



Olga Lalakulich, NuInt2012

"Comparison of GiBUU calculations with MiniBooNE pion production data"

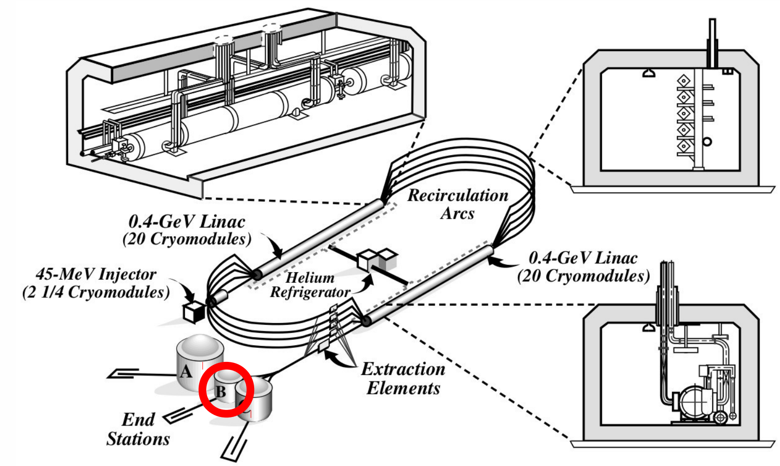


D. Schmitz,

The CLAS Detector

- CEBAF(Continuous Electron Beam Accelerator Facility) at JLAB

  - Up to 6 GeV e^- and γ beam (upgrading to 12 GeV).



- Hall B, CLAS detector

  - Liquid and/or solid target

  with e^- and γ beam

- CLAS Components in 6 sectors

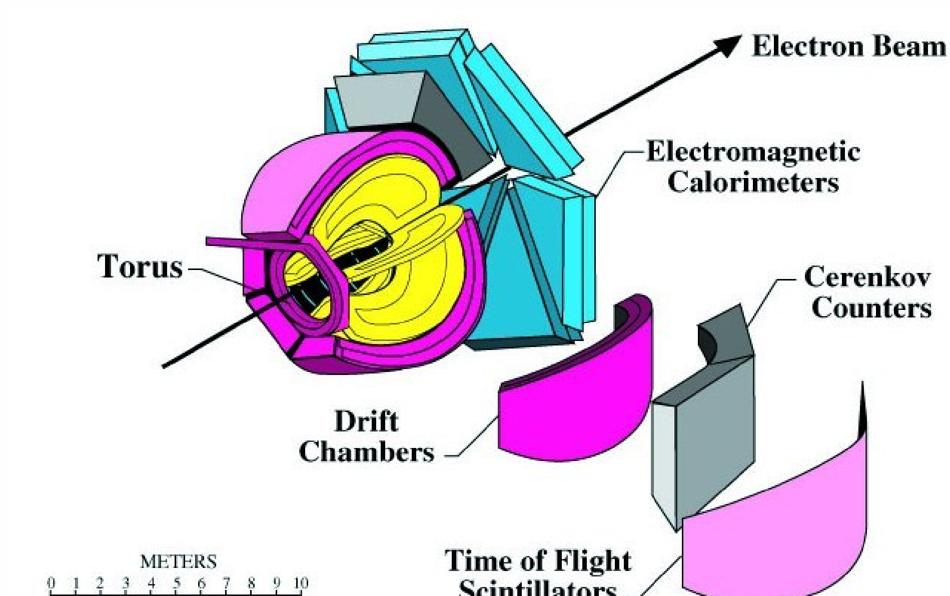
  - Super-conducting toroidal magnet

  - Drift chambers for particle tracking

  - Cerenkov counters for e^- identification

  - TOF Scintillators for particle identification

  - Calorimetry for e^- identification



EG2 Experiment

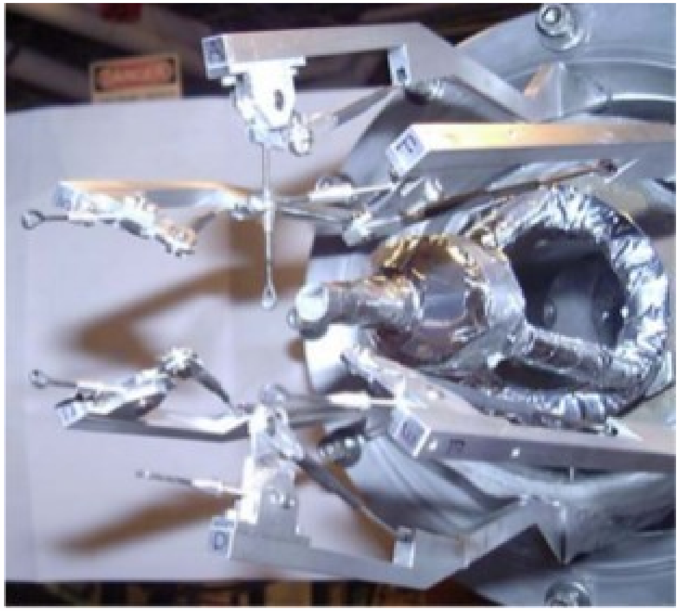
- 4 GeV, 5 GeV e^- beam. 2 targets(liquid & solid) in the beam simultaneously in CLAS.

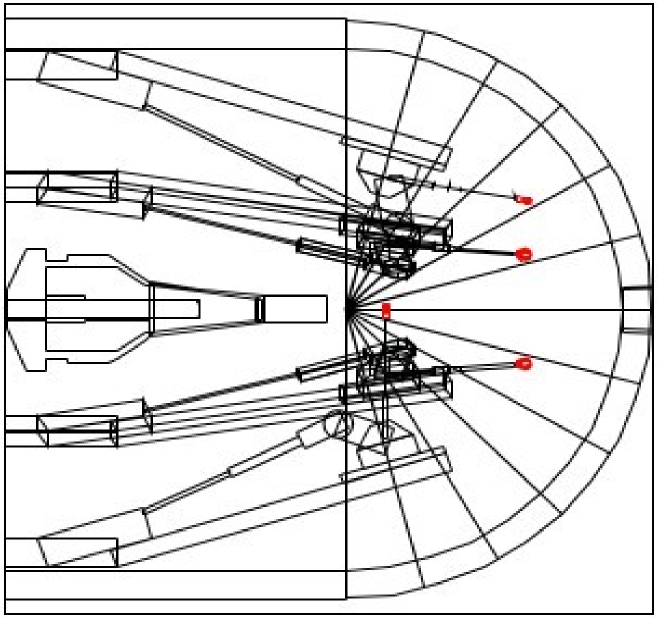
  - [LD_2, LH] + [C, Fe, Pb, Sn, Al(2 thicknesses)]

- 5 GeV Beam (EG2c) + (D_2, C, Fe, Pb) used for this study.

- Events with an electron and at least one detected charged pion were extracted for this study.

- In analysis, extract signal for one and only one charged pion.





Evolving Analysis

If you've been paying attention, we've been working on this for some time ...

- Early work - full 5-dimensional distributions in W, Q^2, p_π, θ_π, ±, inclusive
- Simplified to single pion production (hoping that it is simpler to analyze and interpret)
- Introduced new nuclear model(effective spectral functions)
- At NUINT 2014

  - Reported very preliminary distributions in W, Q^2, p_π, θ_π only about D and C targets with rough estimation of background.
- After NUINT 2014

  - Have struggled with background analysis. ← MC/data background shapes disagree

  - Have converged on technique to estimate background and will show semi-final results in this talk.

Semi-final? You ask. :-) Semi-final means we hope it is final but we need to go through collaboration approval process.

GENIE eA

Use GENIE version 2.8.0 in eA mode with $Q^2 > 0.5\ GeV^2$

Patched with effective spectral function for target momentum.

(hep/ph: 1405.0583)

C. Andreopoulos: GENIE eA mode is a "straightforward adaptation of the neutrino generator"

- Use charged lepton predictions of cross-section models: Rein-Sehgal, Bodek-Yang, etc.
- Transition region handled as in neutrino mode.
- Nuclear model (Bodek-Ritchie, Fermi-Gas) same as in neutrino mode.
- Intranuclear cascade (INTRANUKE/hA) same as in neutrino mode.
- Small modifications to take into account probe charge for hadronization model and resonance event generation.
- In-medium effects to hadronization same as in neutrino mode.

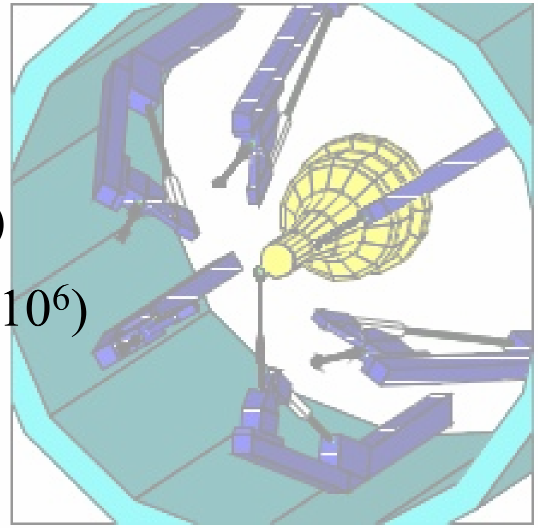
Samples

- EG2 data sample size

  - Deuterium + C/Fe/Pb raw events 1.1/2.2/1.5 ($\times 10^9$)

  - D/C/Fe/Pb events passing all cuts 2.4/0.6/0.4/0.2 ($\times 10^6$)

  → ½ of D-Fe data excluded due to stability issue.



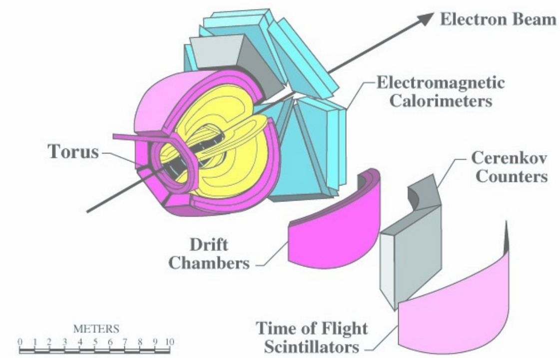
- Simulated sample size (Genie MC + detector simulation)

  - D/C/Fe/Pb generated events (4)$\times 1.0 \times 10^8$

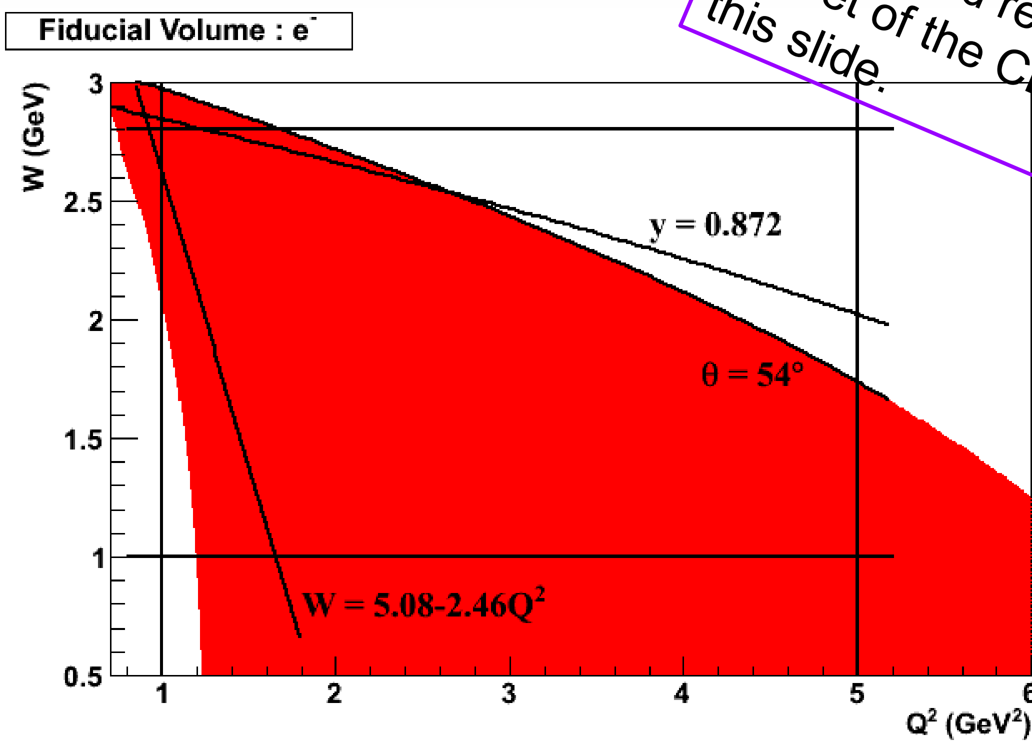
  - D/C/Fe/Pb events passing all cuts 8.8/8.0/6.5/4.5 ($\times 10^4$)

Variables and Fiducial Volume - Electron

- Electron
  - Q^2 : 1~5 GeV^2 → Detector cannot cover $\theta_e<8^o$, inefficiency at low Q^2
  - W : 1~2.8 GeV
  - $y<0.872$ ($p>0.64$ GeV) ← EC threshold
  - $\theta_e<54^o$ $W>5.08-2.46\times Q^2$



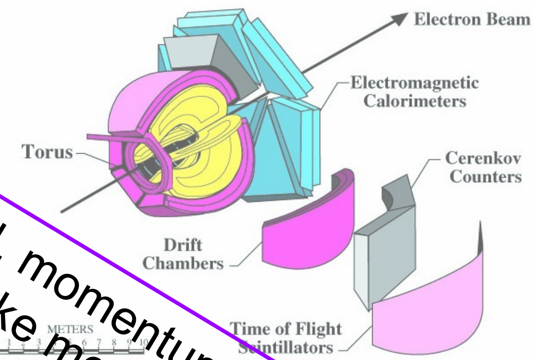
CLAS has complicated, momentum dependent acceptance. So, we make measurements in well-defined regions of phase space which are a subset of the CLAS acceptance. Defined on this slide.

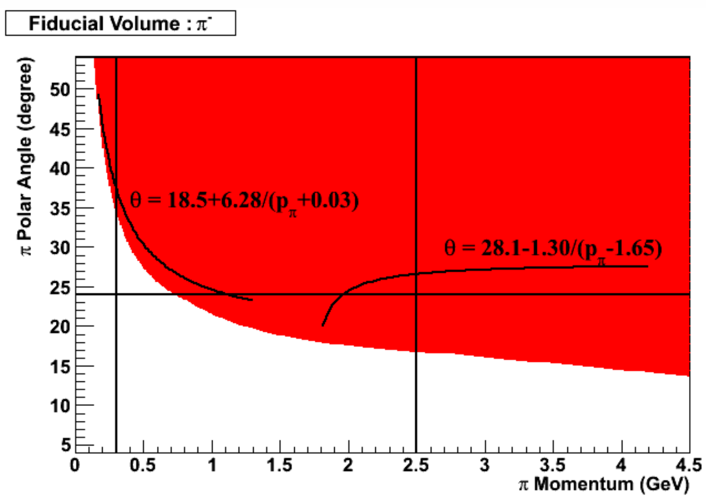


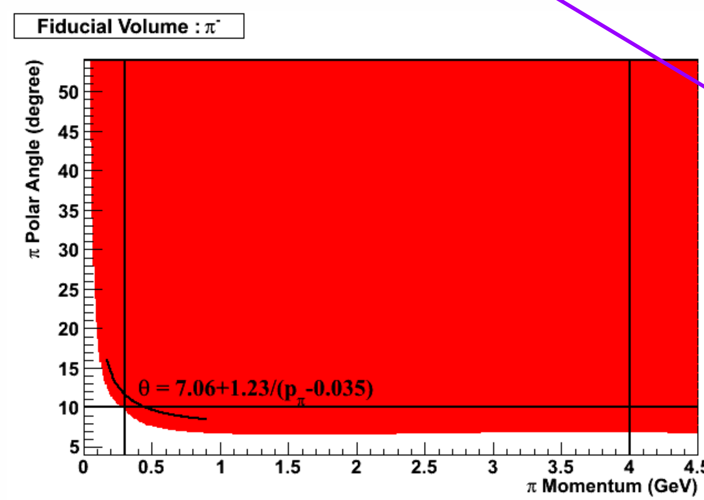
Variables and Fiducial Volume - π

- π^-
  - p_π : 0.3~2.5 GeV θ_π : 24~54°
  - $\theta_\pi > 18.5+6.28/(p_\pi+0.029)$,
  - $\theta_\pi > 28.1-1.30/(p_\pi-1.65)$
- π^+
  - p_π : 0.3~4 GeV, θ_π : 10~54°
  - $\theta_\pi > 7.06+1.23/(p_\pi-0.035)$
- π^-/π^+
  - They have different fiducial volume ← Magnetic field.

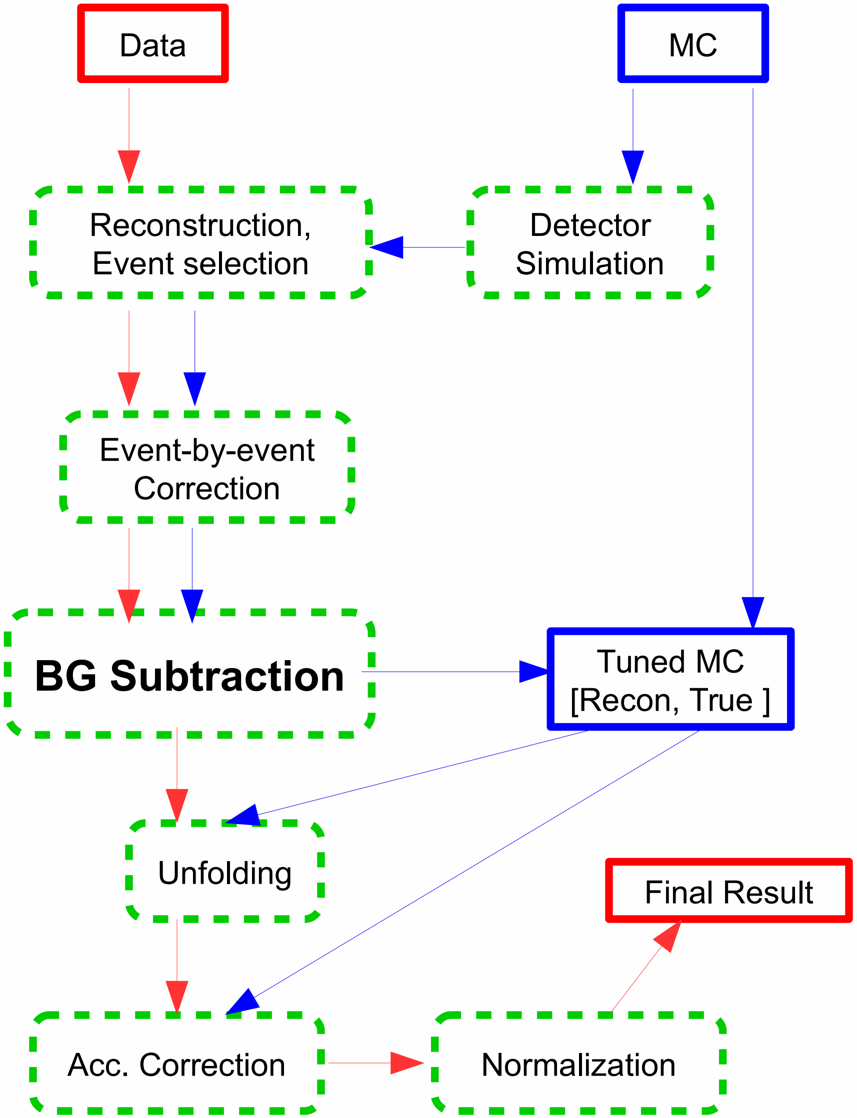
CLAS has complicated, momentum dependent acceptance. So, we make measurements in well-defined regions of phase space which are a subset of the CLAS acceptance. Defined on this slide.







Overall



- Data : eg2c (D, C, Fe, and Pb target)
- MC : GENIE 2.8.0 patched with effective spectral function for target momentum.
- Detector simulation : GSIM, GPP
- Reconstruction : Uana
- Event selection : Filter, PiEG2

  → One and only one charged pion.
- Event-by-event Correction

  - Fiducial volume correction

  - Radiative Correction :

    Externals_all(eg1-dvcs) and Haprad2
- Background subtraction
- Unfolding : RooUnfold (arXiv:1105.1160)

  - Bayesian method with 1 iteration
- Final result

  - 1D differential cross-section (Q^2, W, p_π, θ_π)

Missing Mass – Background Removal

- Background

  - Major source : Nπ (including π^0) due to detector inefficiency.

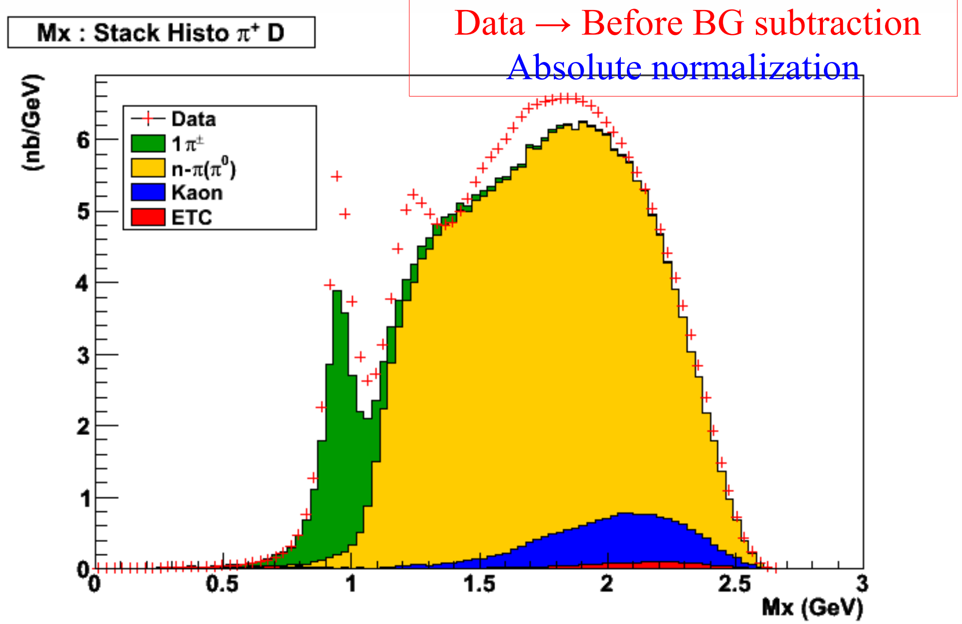
- Missing mass (Mx)

  - Use cut in Mx → Assume target nucleon is at rest.

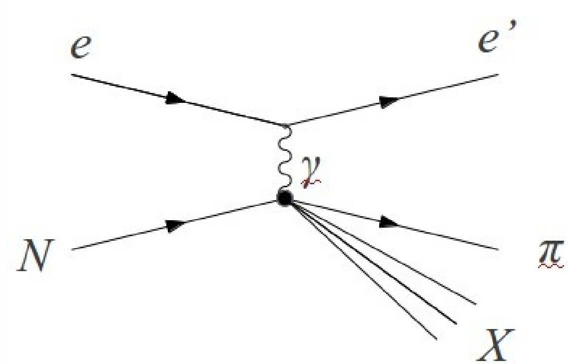
  - For signal(one and only one charged π production), expect the Mx distribution to peak around the target nucleon mass.

  - Use signal cut : 0.8<Mx<1.1 GeV for D, 0.7<Mx<1.2 GeV for solid target.

D target, π^+
Data → Before BG subtraction
Absolute normalization



$$M_X^2 = (p_\gamma + p_N - p_\pi)^2$$

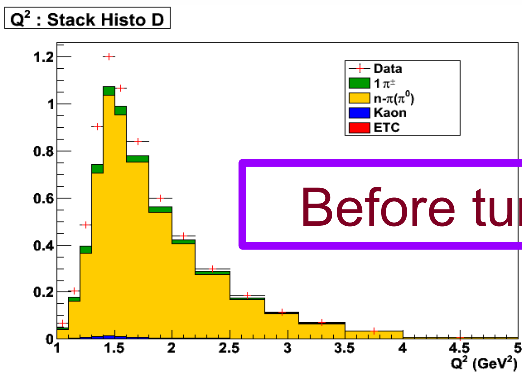


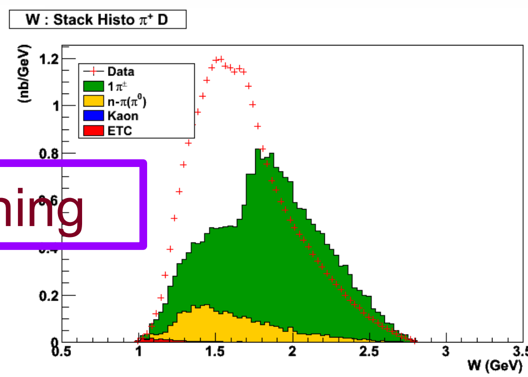
Background Removal – Sideband Tuning?

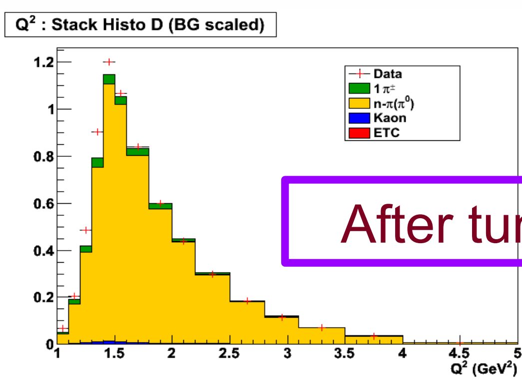
- Use Q^2 in sideband (1.2 <Mx<1.4 GeV) to get the scale factors for multi-pion background.
- MC significantly disagrees with data → Complications for background subtraction in signal region
  - Data/MC shape difference in W and π momentum distribution.
  - Total integrals of Data/MC distribution are very different.
- Sideband tuning method is problematic

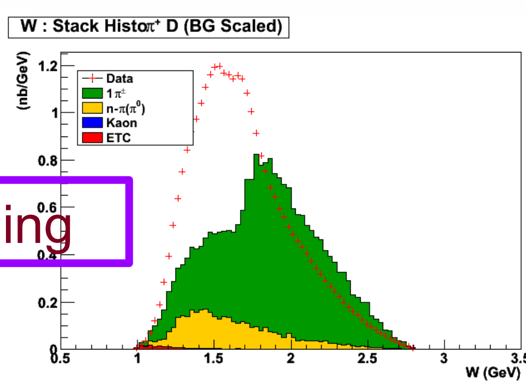
Q2 in sideband

W in signal region

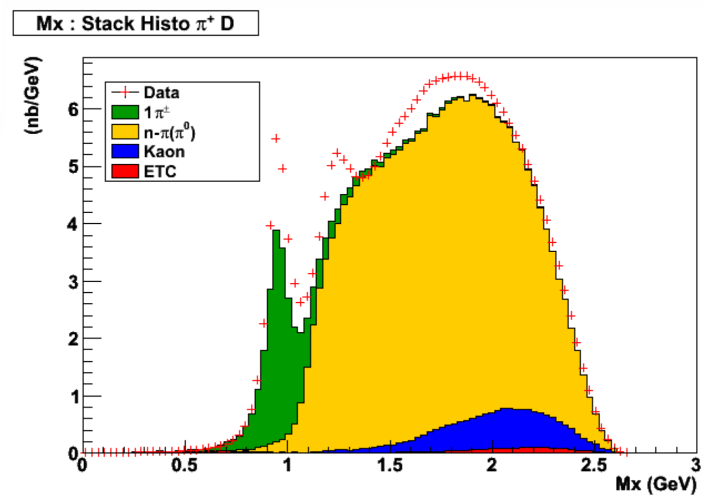








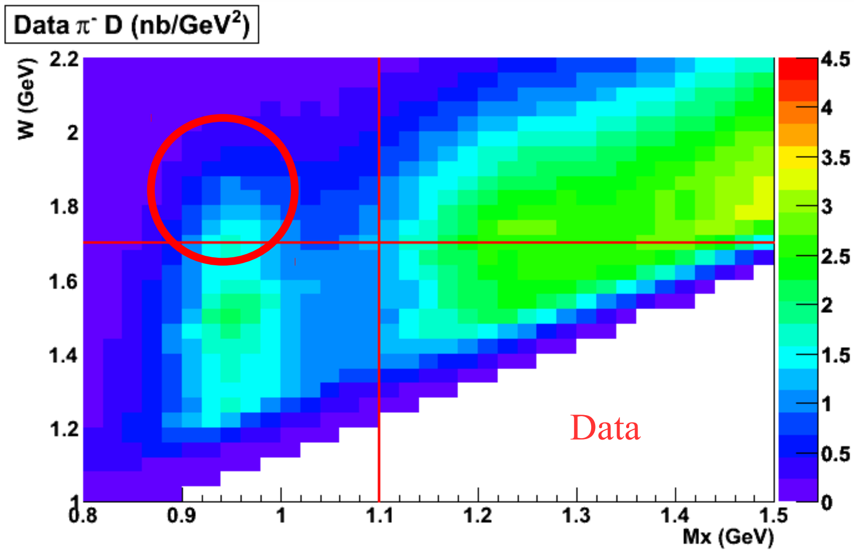
D target, π^+
Data → Before BG subtraction
Absolute normalization

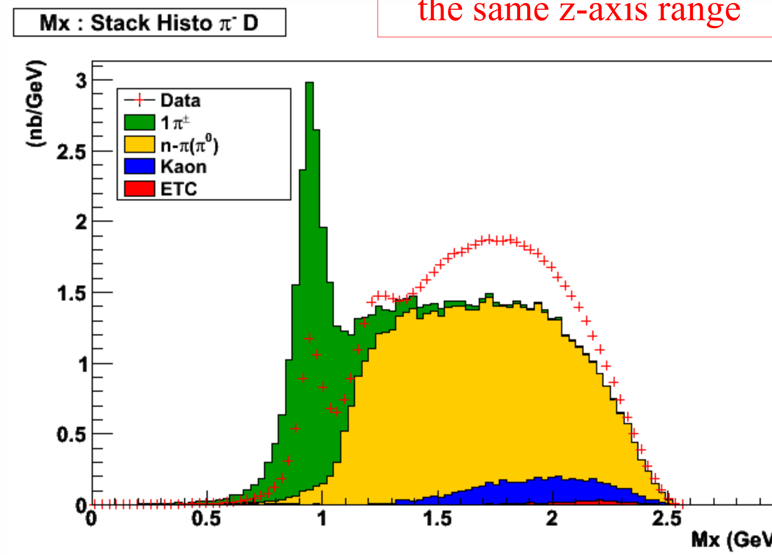


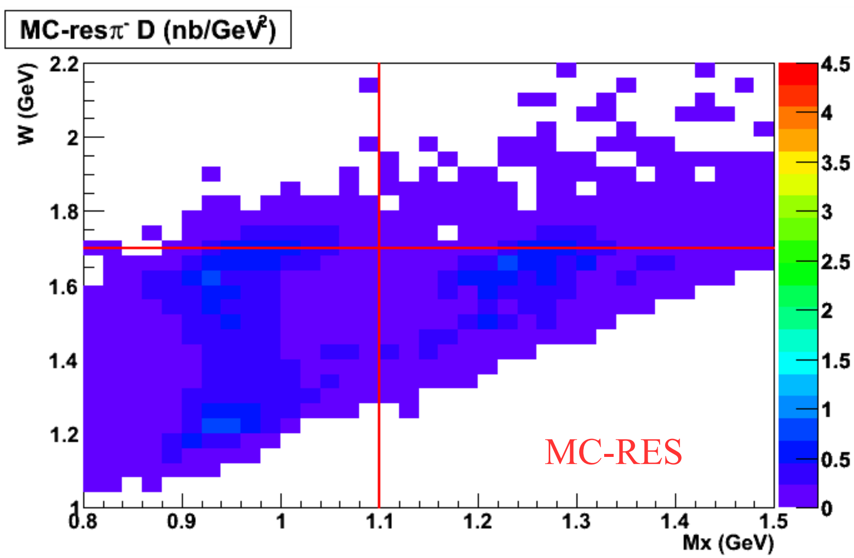
W vs. missing mass (Mx) [π⁻, D]

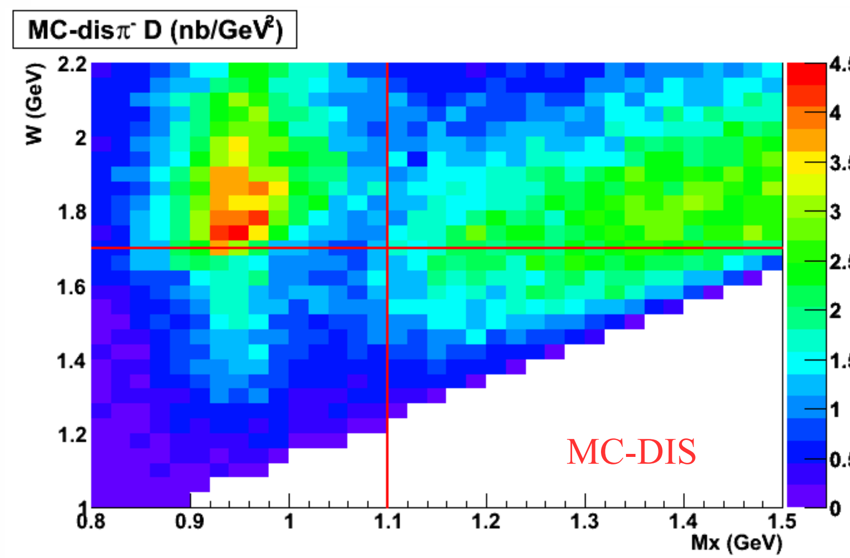
- Scaling down for DIS(W>1.7 GeV) process is needed.

D target, π⁻
!! All 2D plots have the same z-axis range





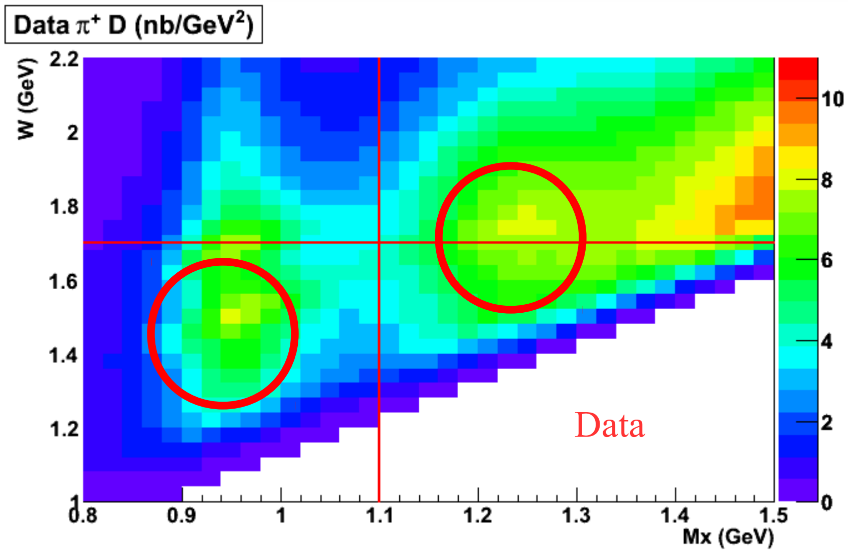


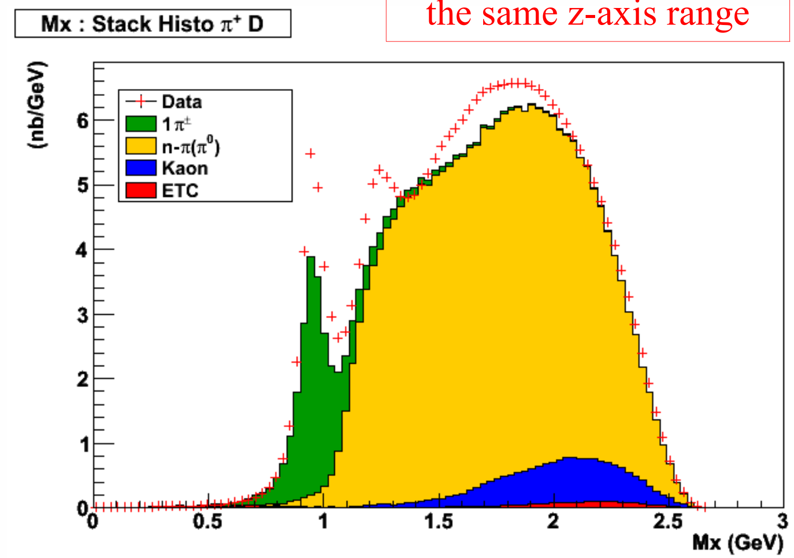


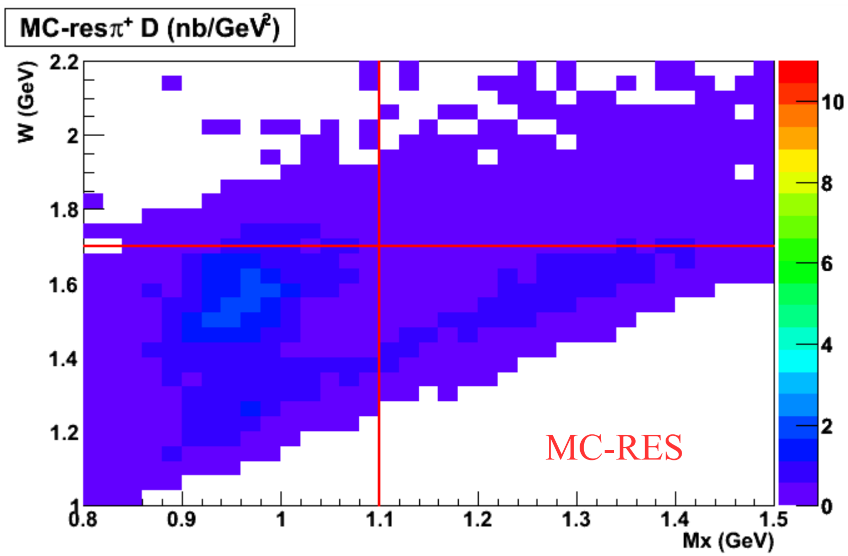
W vs. missing mass (Mx) [π^+, D]

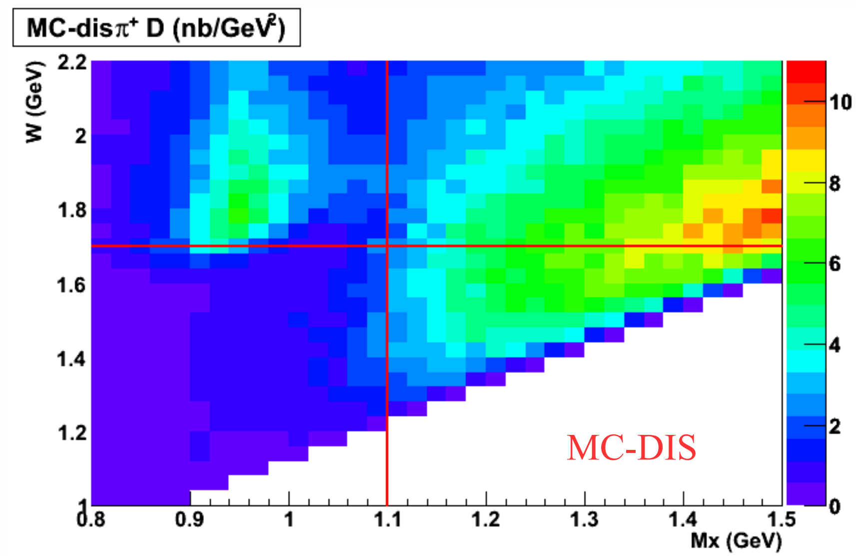
- At both signal and sideband region, data and MC disagree.
- Scaling up for resonance process is needed.

D target, π^+
!! All 2D plots have the same z-axis range









Background Removal – Tuning in Signal Region

- Sideband tuning will not work

- Look in signal region, work in GENIE "process" space rather than "signal-background" space

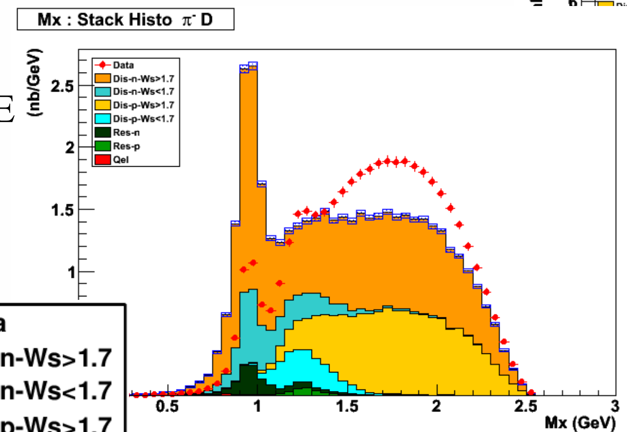
  - Resonance

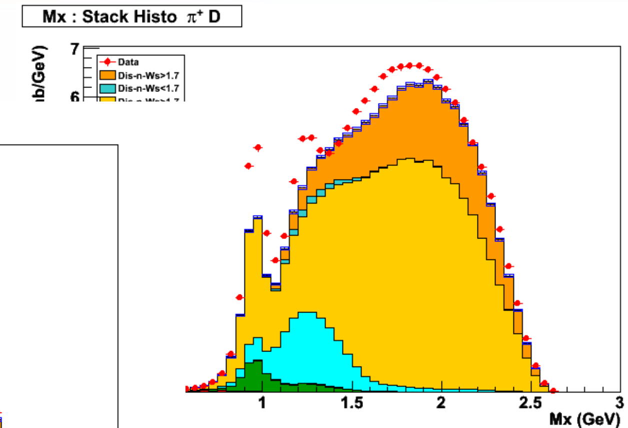
  - DIS (n target, W<1.7 GeV)

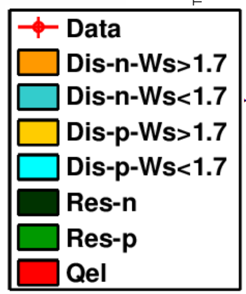
  - DIS (n target, W>1.7 GeV)

  - DIS (p target, W<1.7 GeV)

  - DIS (p target, W>1.7 GeV)







- Fit in Q^2 signal region, allow process scale factors to vary until data-MC shapes agree

  - Why Q^2? From the lepton, so not affected by Fermi motion and FSI

- After "tuning", subtract background in signal-background space

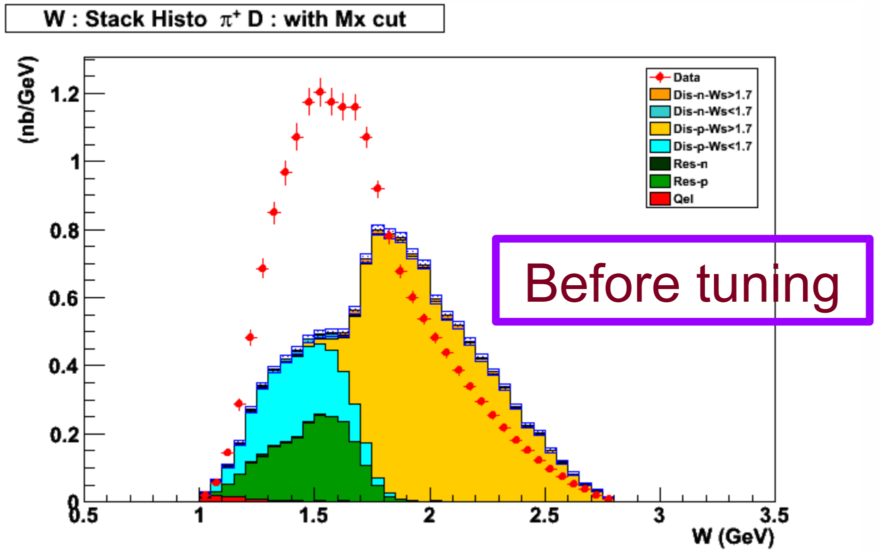
π-	D	C	Fe	Pb
Resonance	1.089	1.213	0.666	0.581
DIS-n-W<1.7	0.993	0.877	0.893	0.760
DIS-n-W>1.7	**0.070**	**0.147**	**0.129**	**0.091**
DIS-p-W<1.7	0.809	1.161	1.161	0.783
DIS-p-W>1.7	2.772	1.196	1.000	0.738

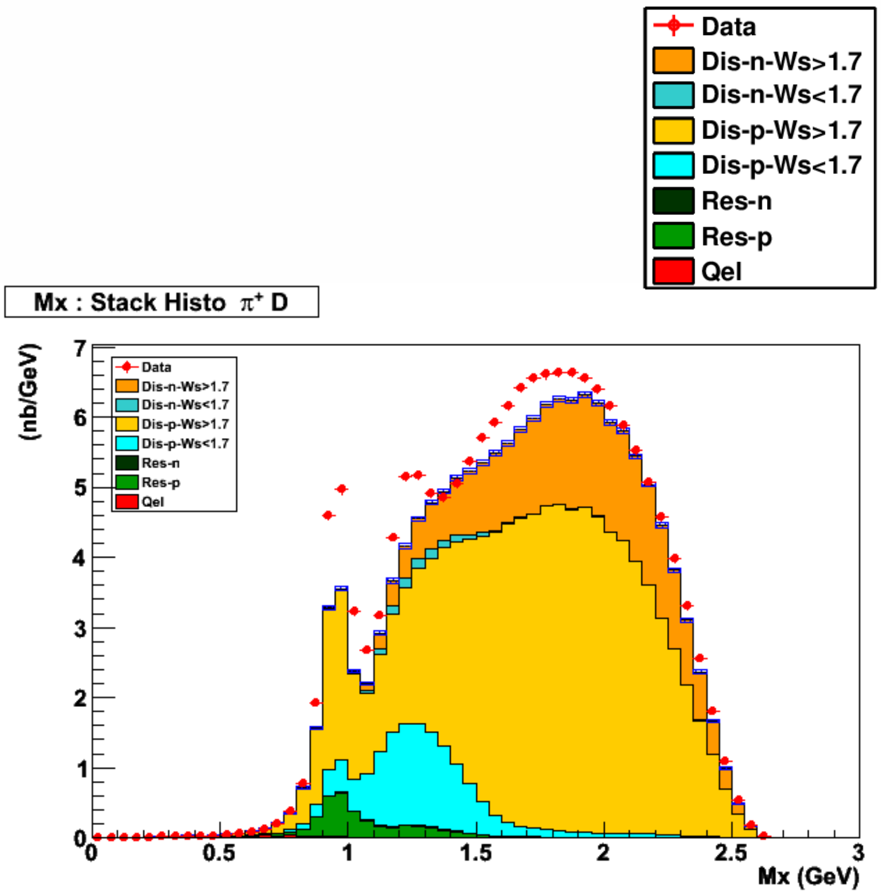
π+	D	C	Fe	Pb
Resonance	**3.564**	**3.644**	**2.651**	**1.635**
DIS-n-W<1.7	0.010	1.043	0.893	1.721
DIS-n-W>1.7	0.058	0.446	0.136	0.518
DIS-p-W<1.7	1.523	1.230	1.302	1.042
DIS-p-W>1.7	0.748	0.889	0.857	0.680

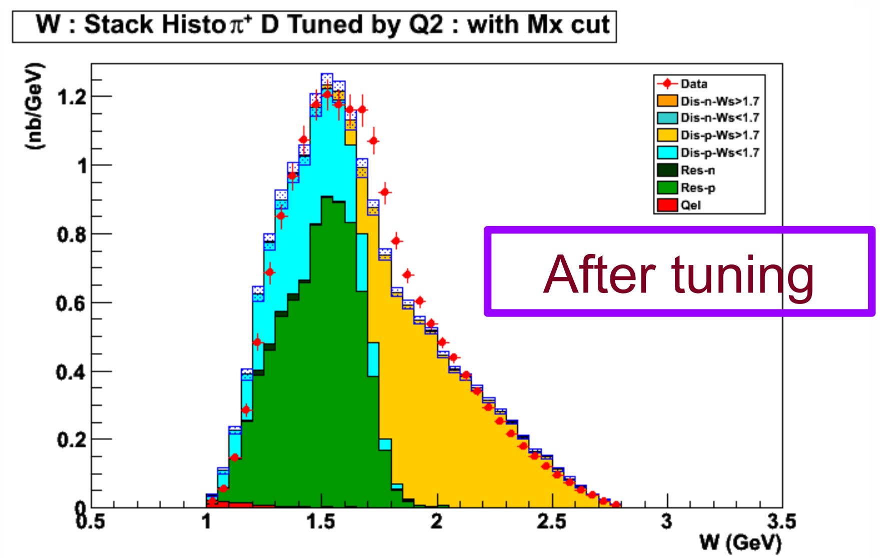
Tuning in Signal Region – W [π^+, D]

- An example of W distribution from D target, π^+ before and after MC tuning.
- Scale factors are chosen from Mx-Q^2 distribution, not from W!!!

W in signal region

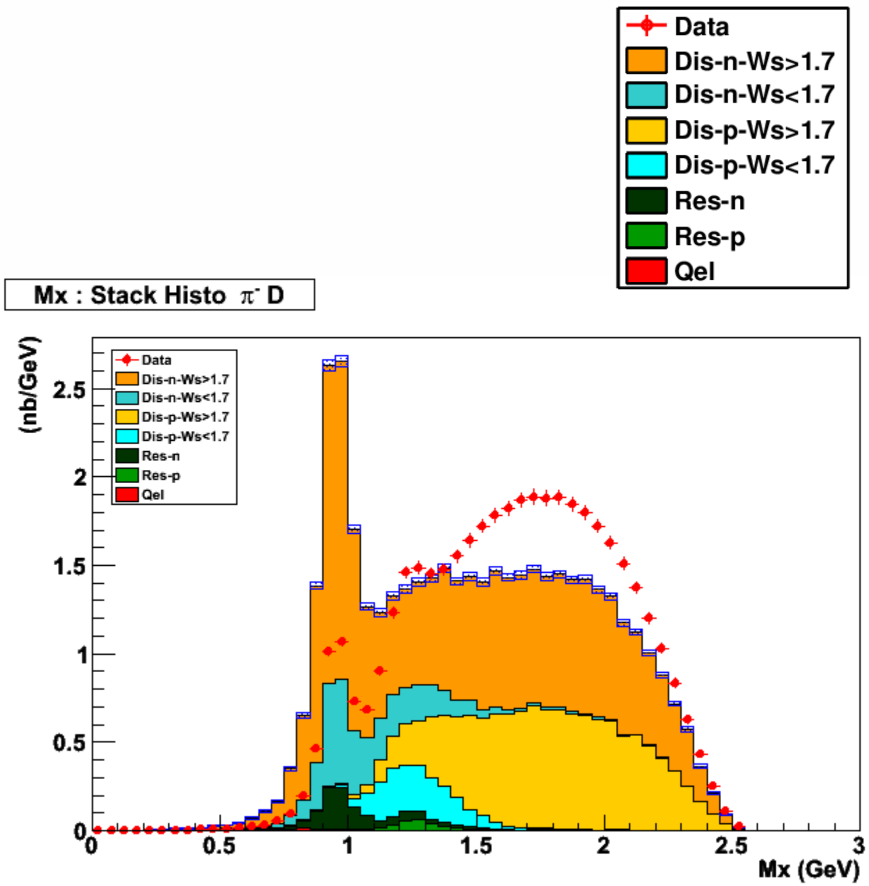




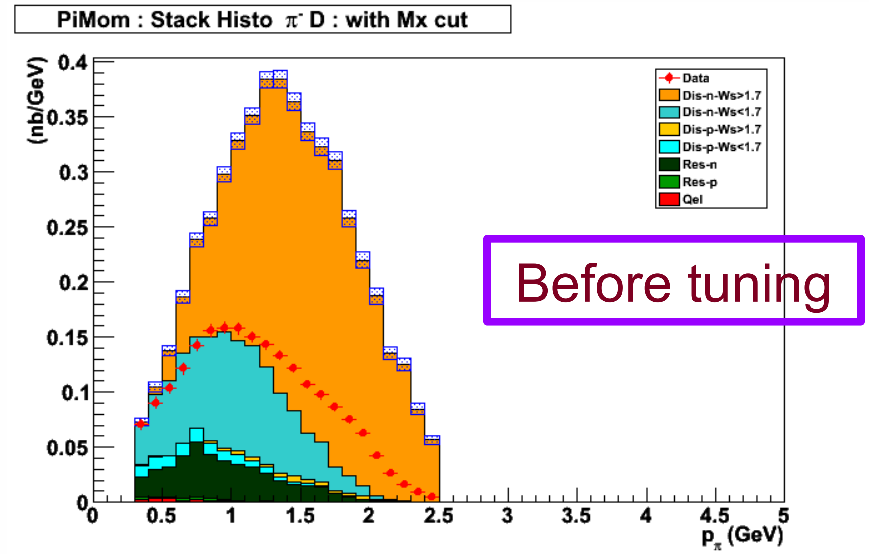


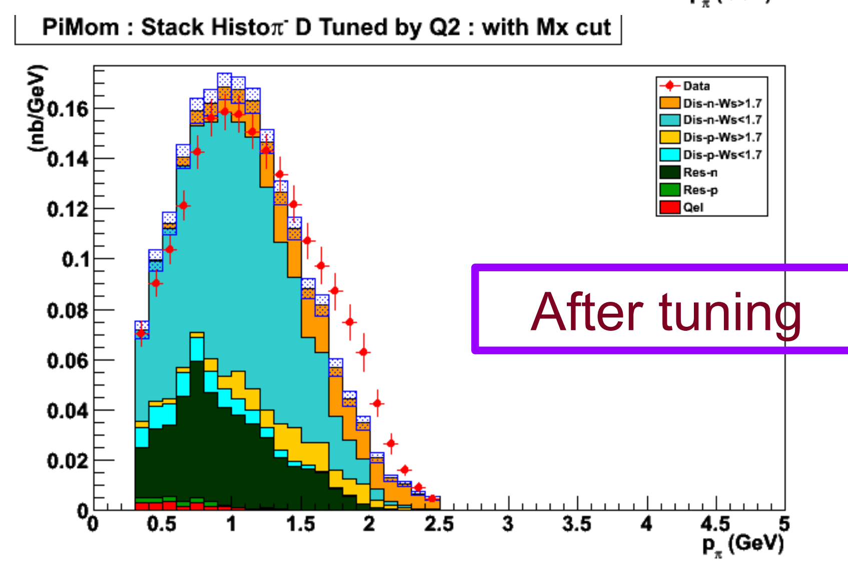
Tuning in Signal Region – π Momentum [π⁻, D]

- An example of π momentum distribution from D target, π^- before and after MC tuning.
- Scale factors are chosen from Mx-Q^2 distribution, not from π momentum!!!



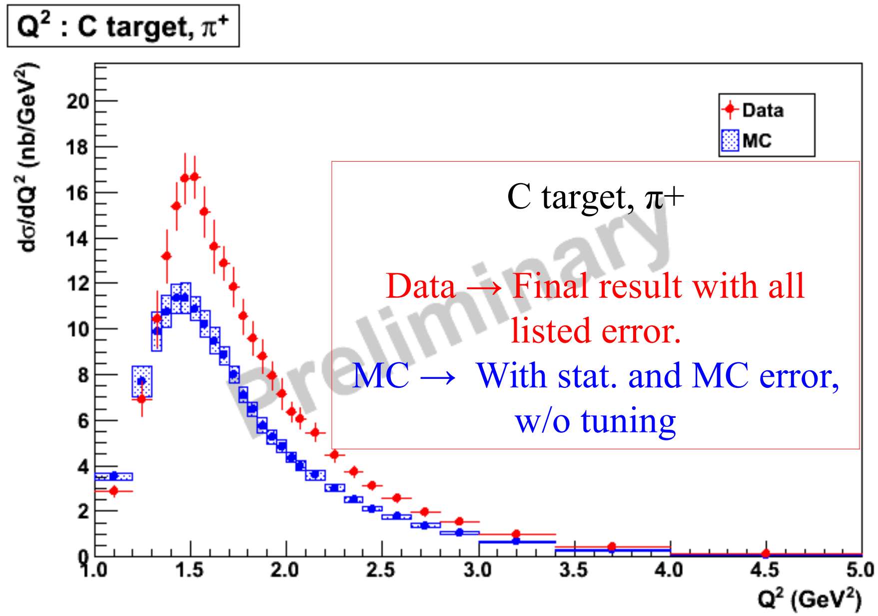
π momentum in signal region

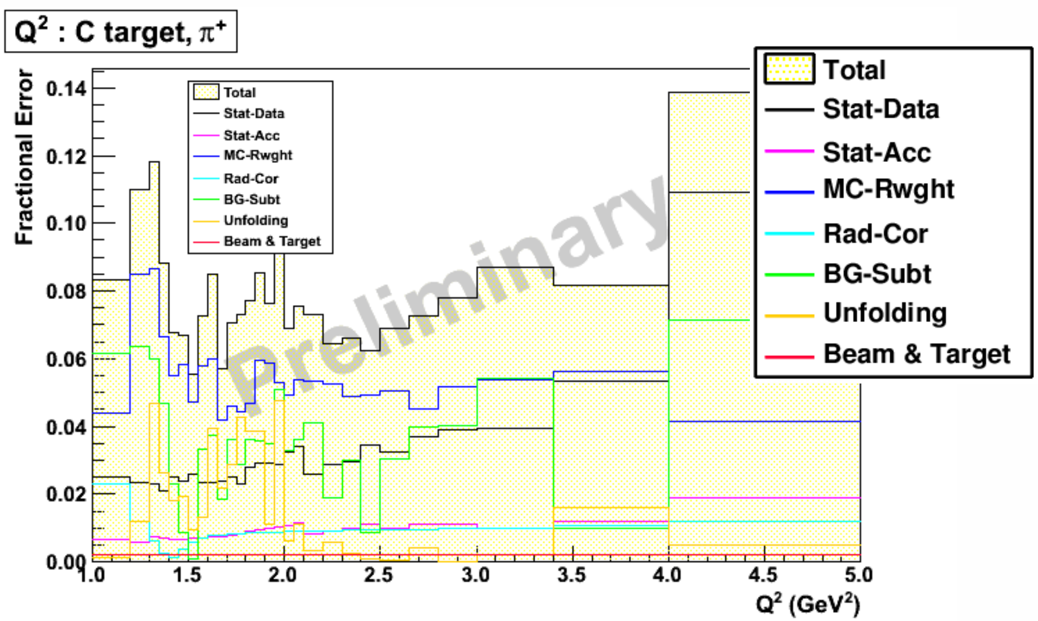




Errors

- Statistical error
  - Data : ~5%
  - Acceptance : ~1%
- Systematic error – Global(normalization)
  - Total beam Q : Faraday cup <1%
  - Target properties : Area density
    D/C/Fe/Pb → 1.0/0.2/0.3/0.7%
- Systematic error – Bin-by-bin
  - MC : Use GENIE reweighting ~8%
  - Background subtraction ~3.5%
  - Radiative correction ~1%
  - Unfolding ~ 3.5%
  - Detector geometry ← Only for θ_π ~4%
- Average total fractional error
  - $Q^2/W/p_\pi/\theta_\pi$ → 10/11/13/12 %





Caveats

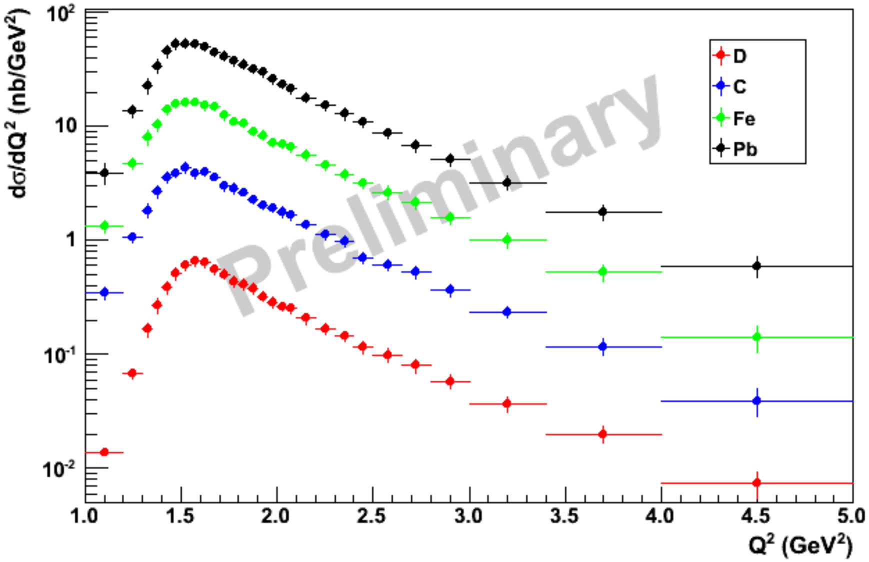
- All results shown here are preliminary

  - Currently writing documentation to get results reviewed/approved by CLAS

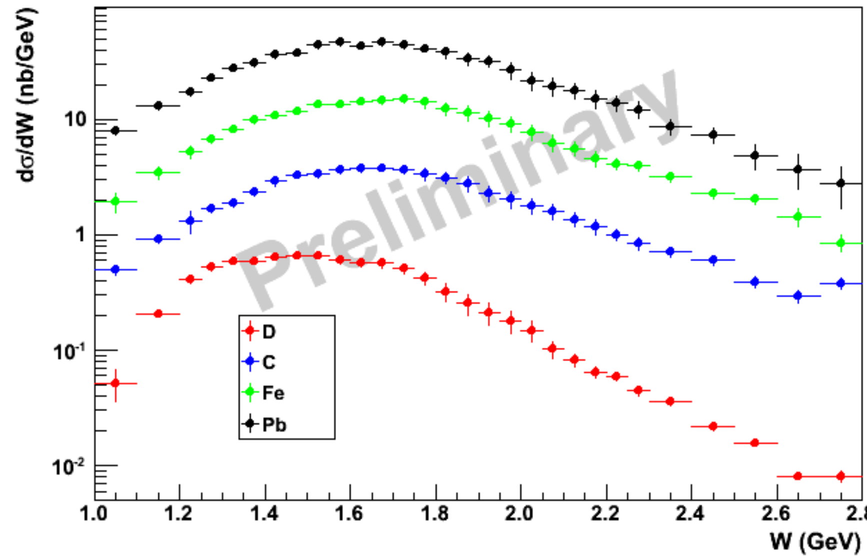
  - We believe the significant parts of the analysis are all in place and hope things will not change much before results are finalized.

Final Result : Differential X-section π^-

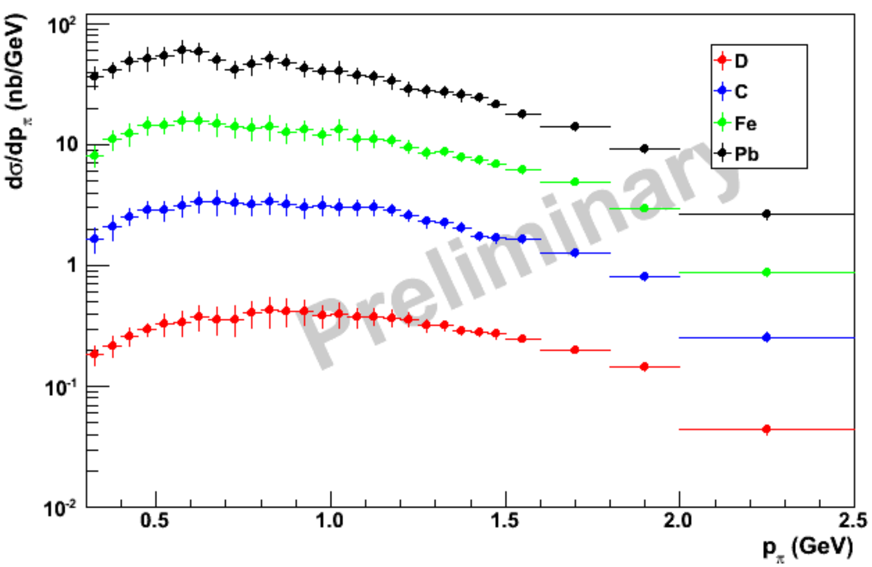
$Q^2 : \pi^-$



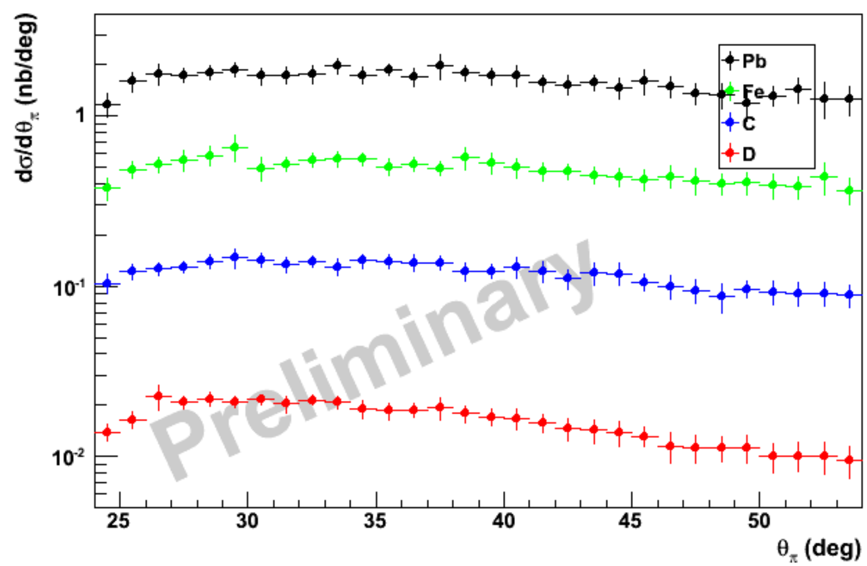
$W : \pi^-$



$P_\pi : \pi^-$

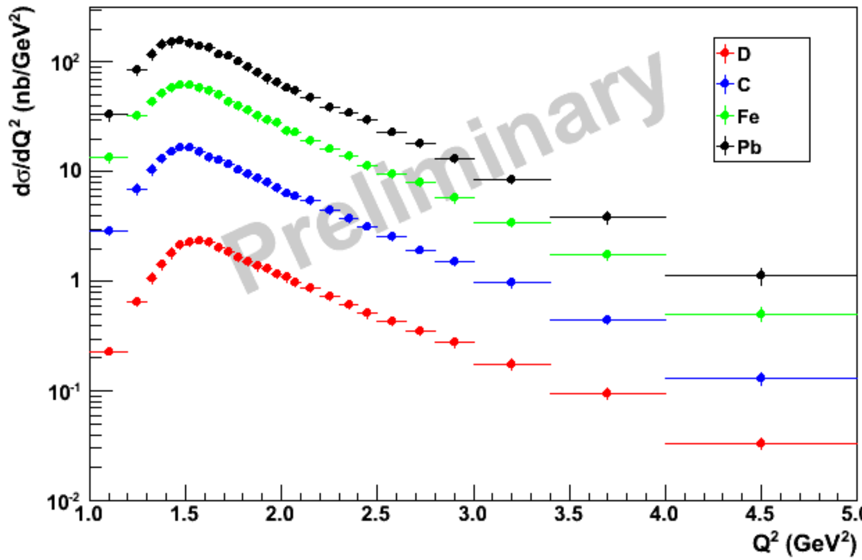


$\theta_\pi : \pi^-$

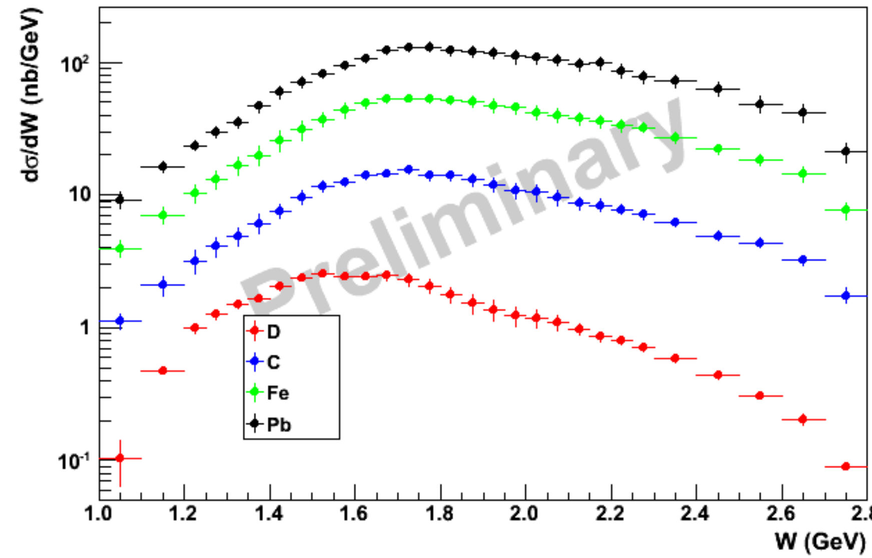


Final Result : Differential X-section π^+

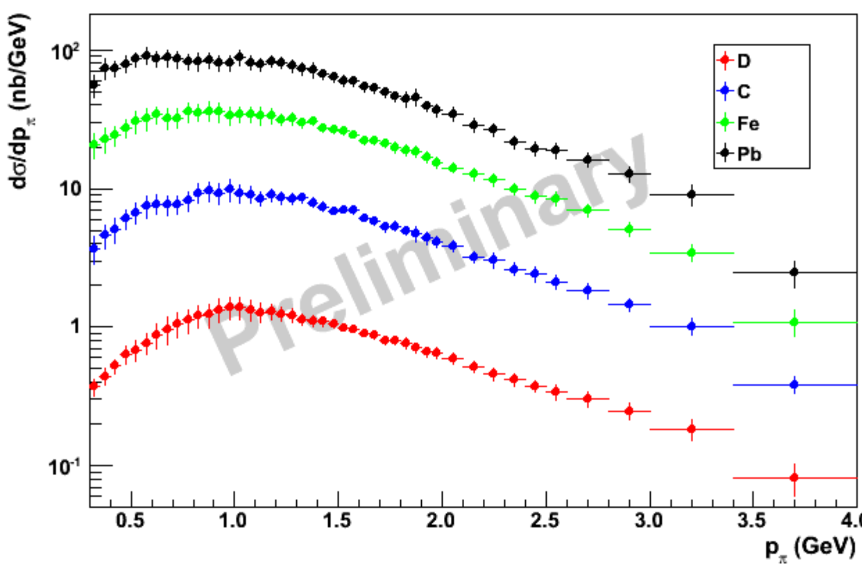
$Q^2 : \pi^+$



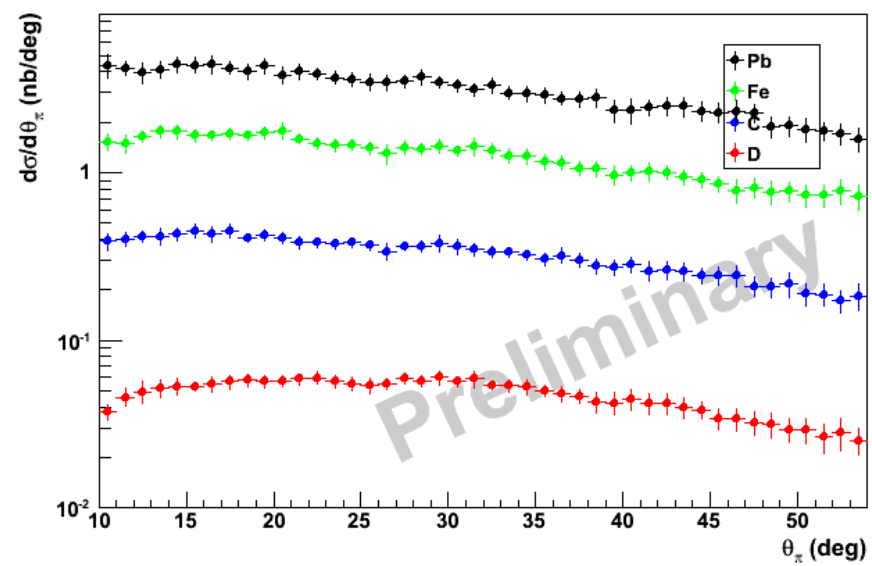
$W : \pi^+$



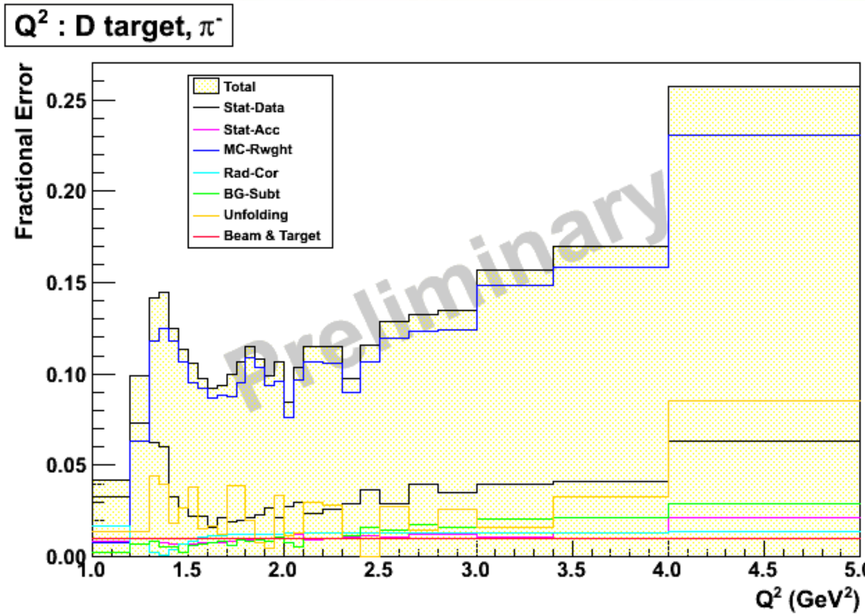
$P_\pi : \pi^+$

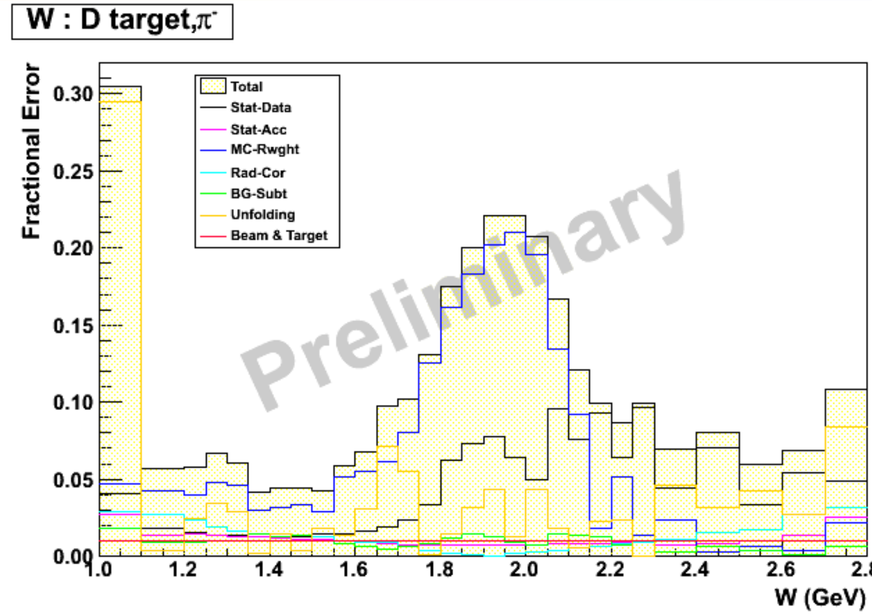


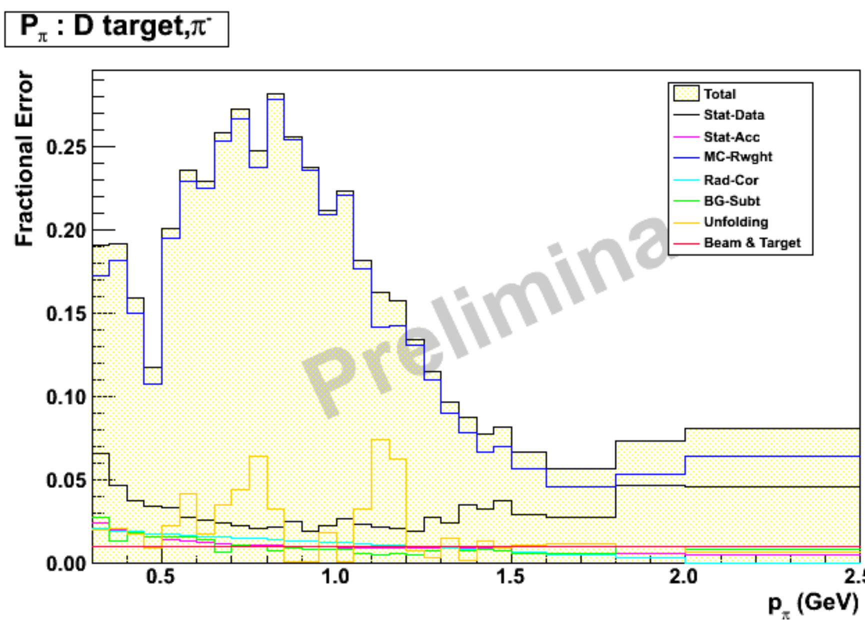
$\theta_\pi : \pi^+$

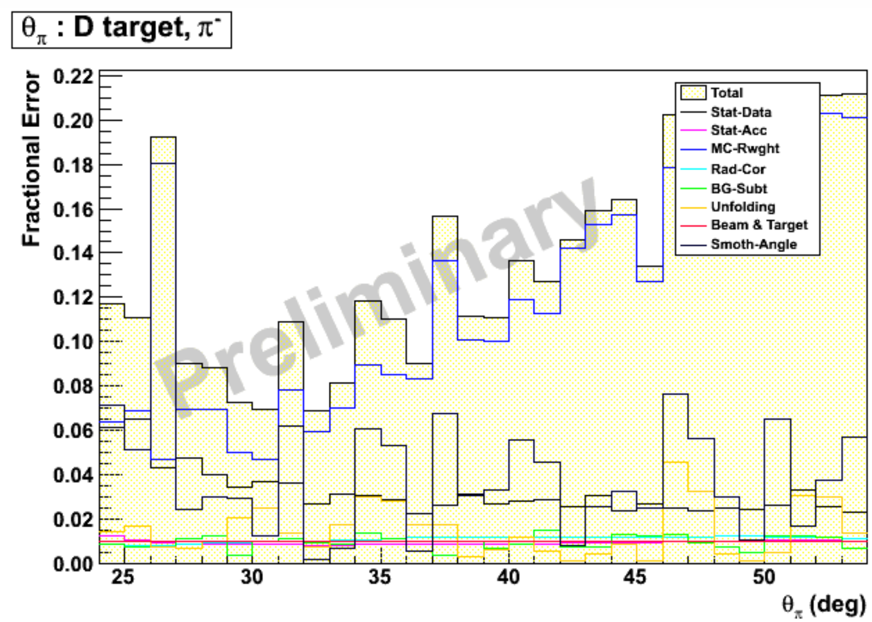


Error π⁻ D


Q² : D target, π⁻
Fractional Error
Q² (GeV²)
Total
Stat-Data
Stat-Acc
MC-Rwght
Rad-Cor
BG-Subt
Unfolding
Beam & Target
Preliminary

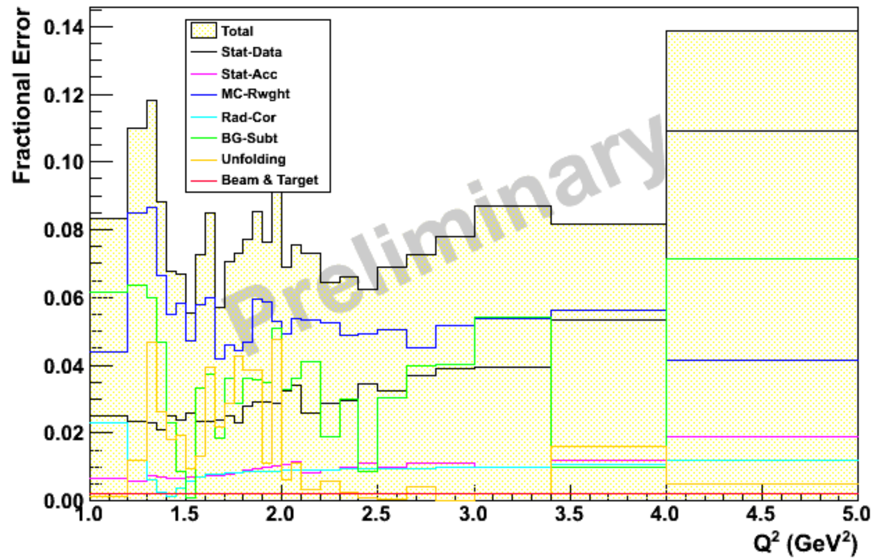

W : D target,π⁻
Fractional Error
W (GeV)
Total
Stat-Data
Stat-Acc
MC-Rwght
Rad-Cor
BG-Subt
Unfolding
Beam & Target
Preliminary


Pπ : D target,π⁻
Fractional Error
pπ (GeV)
Total
Stat-Data
Stat-Acc
MC-Rwght
Rad-Cor
BG-Subt
Unfolding
Beam & Target
Prelimina

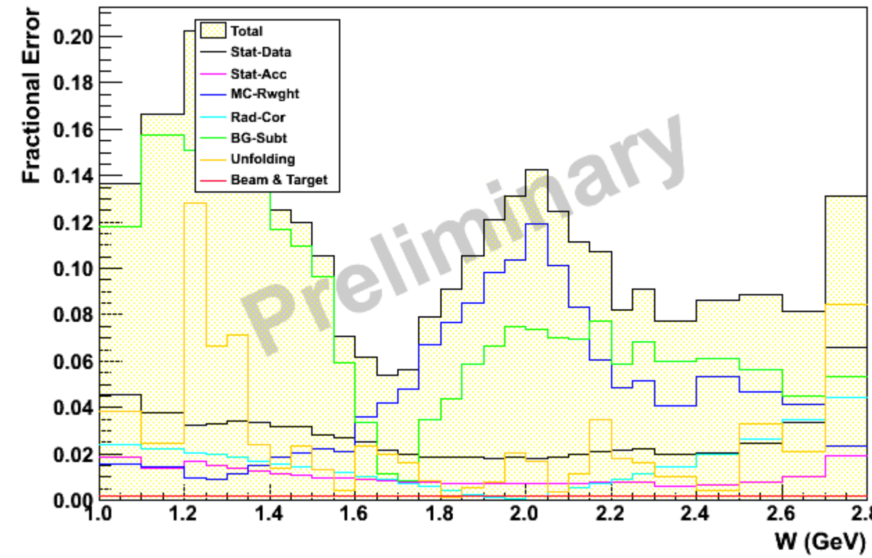

θπ : D target, π⁻
Fractional Error
θπ (deg)
Total
Stat-Data
Stat-Acc
MC-Rwght
Rad-Cor
BG-Subt
Unfolding
Beam & Target
Smoth-Angle
Preliminary

Error π⁺ C

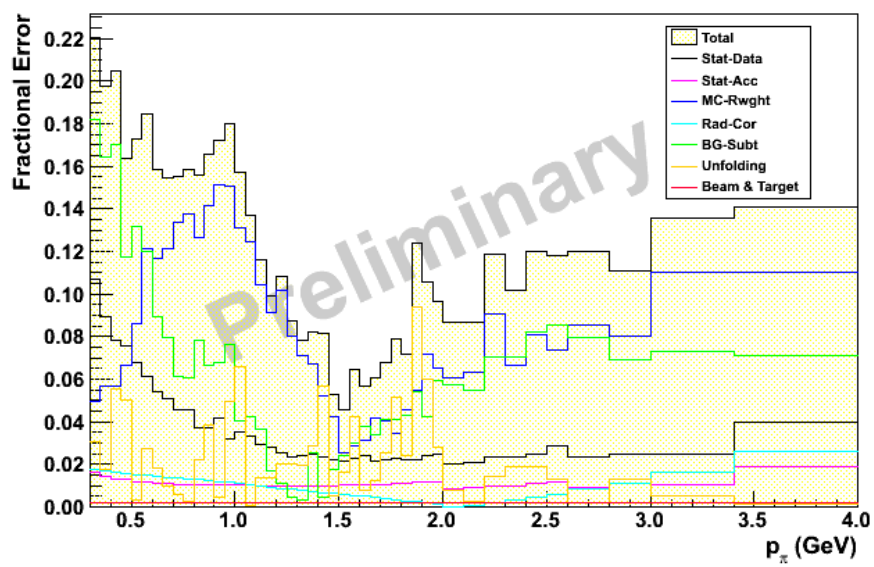
Q^2 : C target, π^+



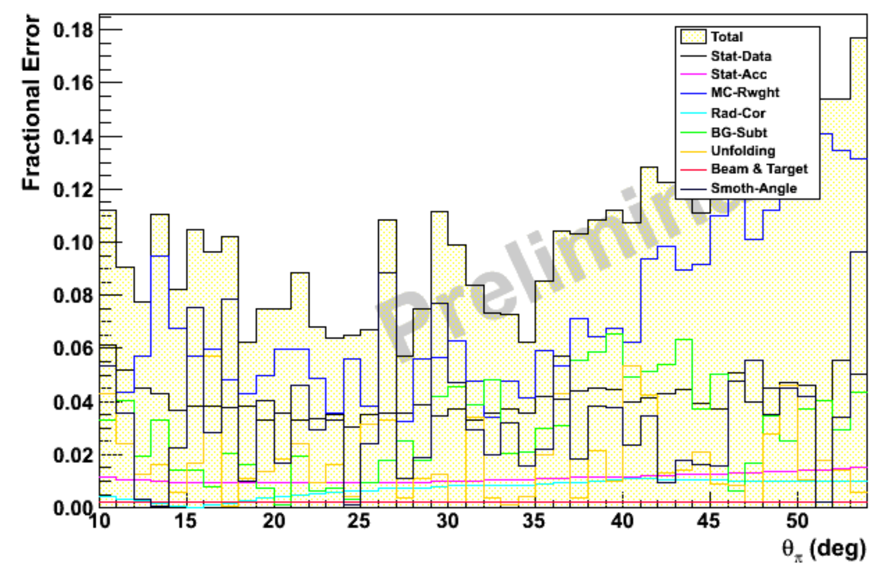
W : C target, π^+



P_π : C target, π^+



θ_π : C target, π^+



Finally...

- We (CLAS/EG2) are producing 1-$\pi^{\pm}$ production cross-sections on different nuclei (D, C, Fe, Pb) in a region of phase space relevant for the current precision neutrino physics program.

- Hope to publish final results in early 2016.

Backup

Pseudo-Fiducial Volume?

- Difficulties for theorists to use our results because of CLAS-optimized fiducial cuts(Function of momentum and 2 angles.)

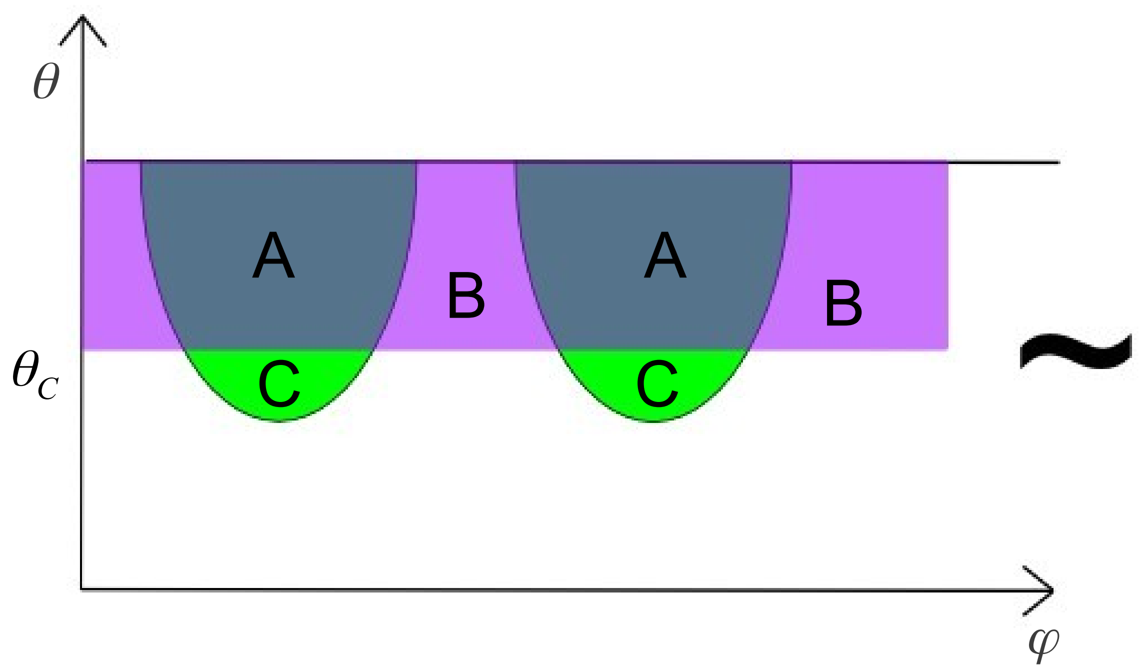
  → Changing analysis to use cuts that are more easily modeled for comparison to theory.

- Main idea → Assuming azimuthal symmetry, reduce a variable [azimuthal angle] in the function for fiducial cut.

  - Cut only on polar angle for fixed momentum(No cut for azimuthal angle).

  - The cut should be reasonably greater than the lower limit of polar angle in fiducial volume.

Pseudo-Fiducial Volume : Define



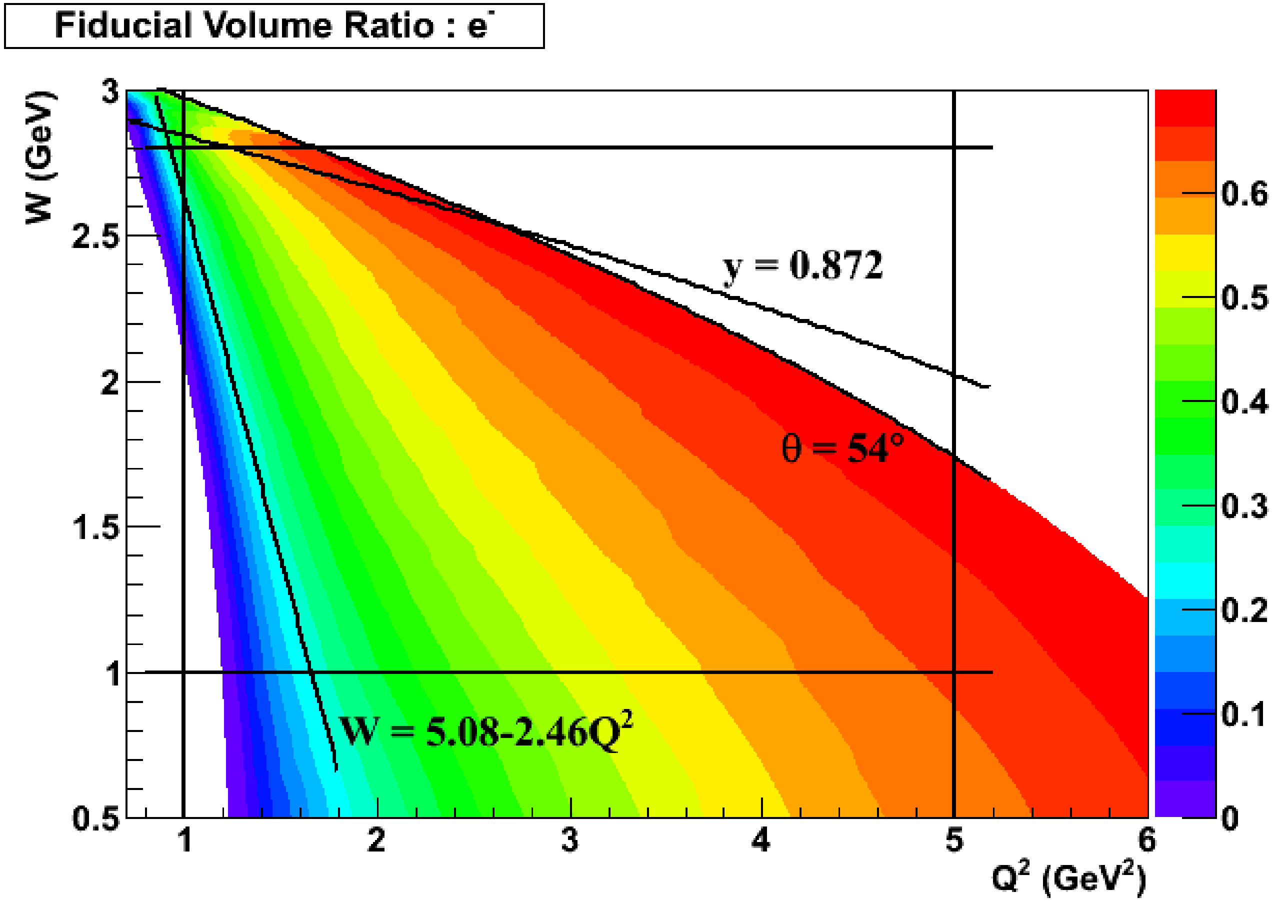
- Fiducial volume[FV] → A+C
- Pseudo-fiducial volume[PFV] → A+B

!!! FV is not a sub-volume of PFV

- Cut on angle where FV to PFV ratio greater than 25%.

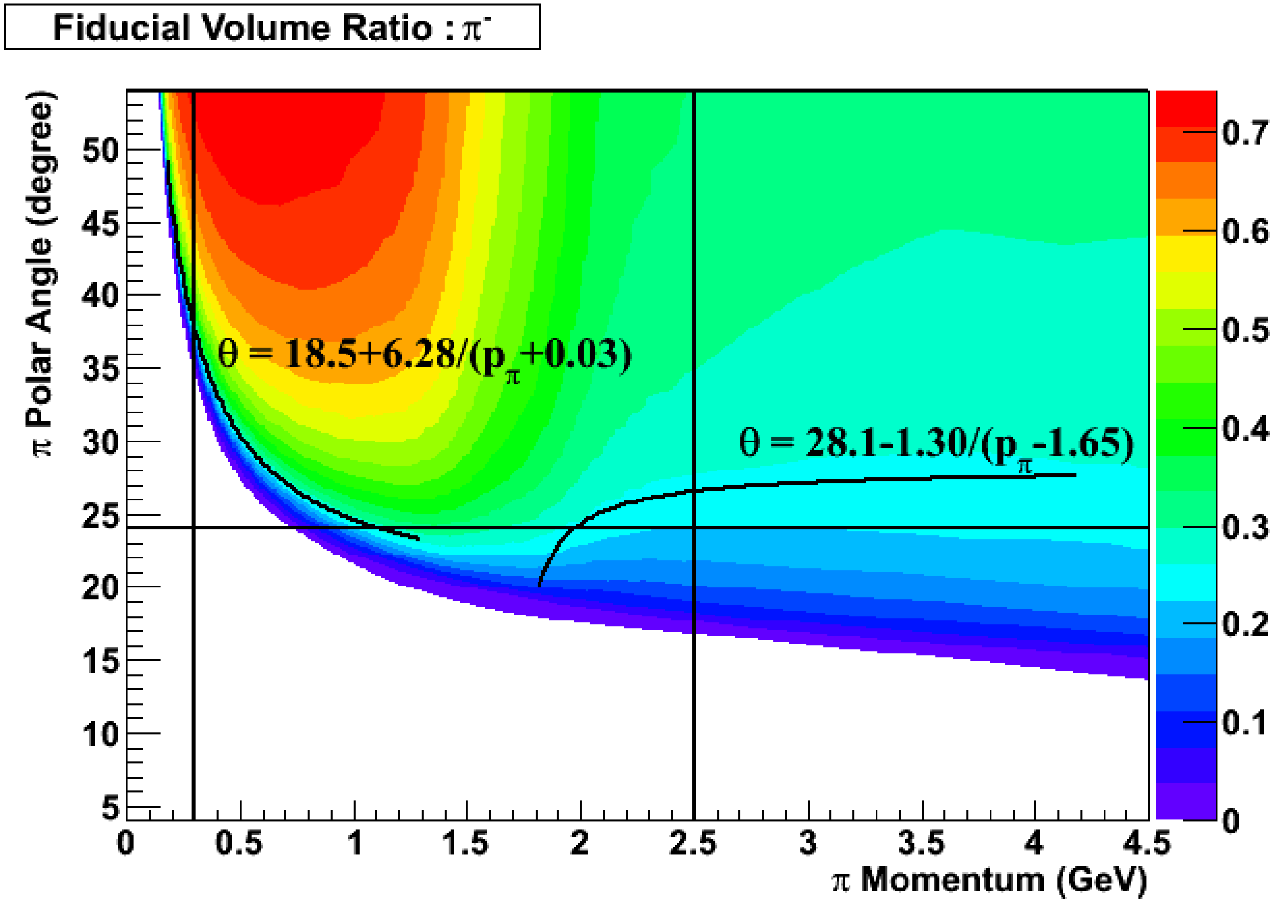
$$\frac{dA(\theta_C)}{dA(\theta_C)+dB(\theta_C)}=0.25$$

Pseudo-Fiducial Volume : Electron



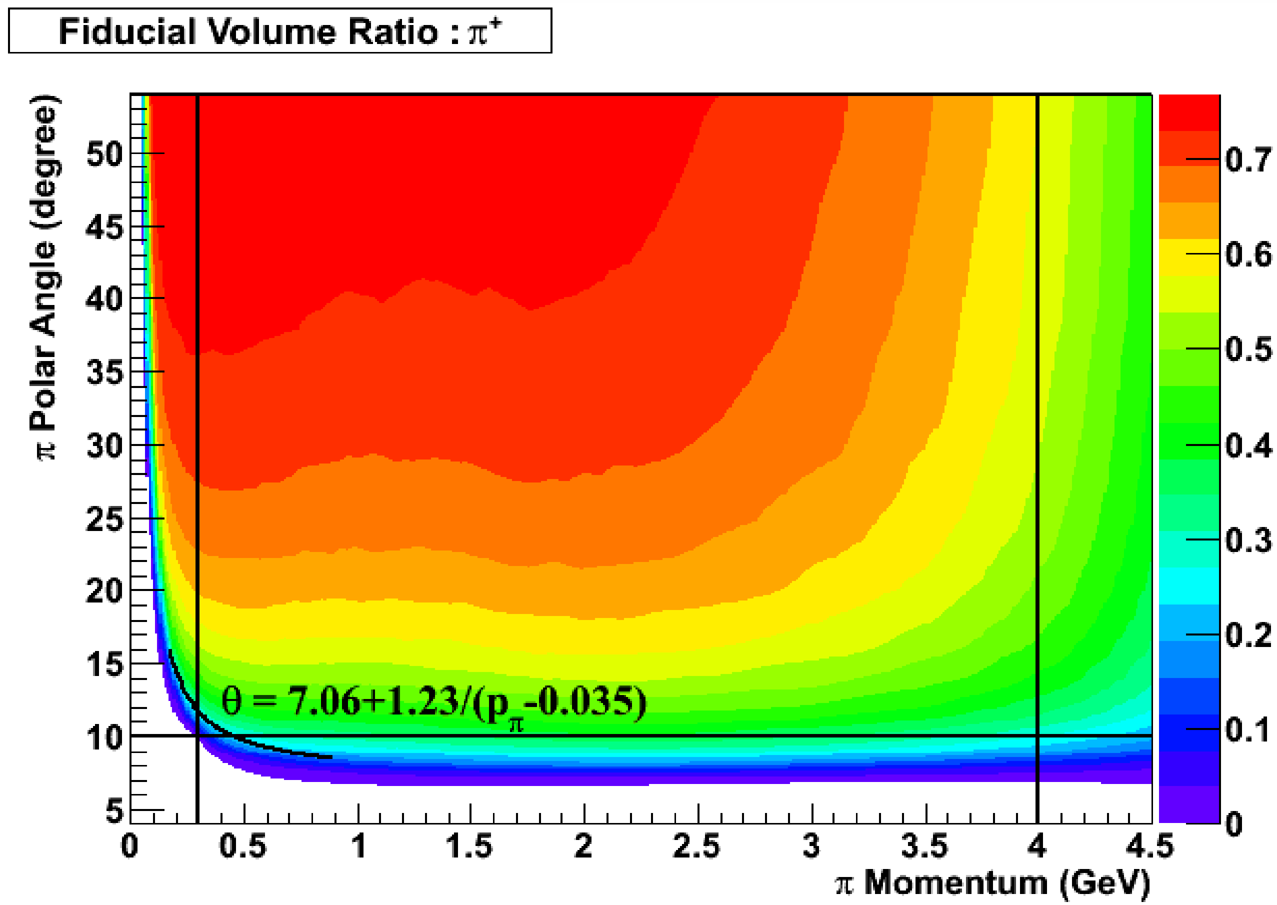
- Use Q^2 and W, instead of electron p_e and θ_e.
- Ratio → A/[A+B] at given Q^2 and W
- $\theta_e < 54$, $W > 5.08\text{-}2.46*Q^2$

Pseudo-Fiducial Volume : π^-



- Ratio → A/[A+B] at given p_π and θ_π.
- $24 < \theta_\pi < 54$, $\theta_\pi > 18.5+6.28/(p_\pi+0.029)$, $\theta_\pi > 28.1-1.30/(p_\pi-1.65)$

Pseudo-Fiducial Volume : π^+



- Ratio → A/[A+B] at given p_π and θ_π.
- $10 < \theta_\pi < 54$, $\theta_\pi > 7.06+1.23/(p_\pi-0.035)$

Radiative Corrections

- Externals_all

  - For RC calculation in the process of inclusive electron scattering.

  - It is designed for eg1-dvcs and being used for eg1 and eg4.

  - Need 2 leptonic variables with fixed beam energy : W, Q^2.

  - Calculate differential X-sections with/without QED radiative effects.

  - Contribution from (Quasi-)elastic parts are excluded for our study.

    ← We select events with pion(s).

  - Being used as our RC calculation for this talk.

Normalization

- Accumulated Charge

  Take all eg2c runs and accumulate all the charge which counted by faraday cup during DAQ-live time.

  D_2 : 14.7 mC C : 3.4 mC Fe : 6.0 mC Pb : 5.3 mC

- Mass Number of Target

  D_2 : 2.014   C : 12.011   Fe : 55.845   Pb : 207.2

- Thickness of Target

  D_2 : 2 cm C : 0.1723 cm Fe : 0.040 cm Pb : 0.014 cm

- Mass Density of Target

  Liquid D_2 : 0.162 g/cm^3

  C : 1.747 g/cm^3 Fe : 7.874 g/cm^3 Pb : 11.34 g/cm^3

GENIE eA Mode Processes

- “GENIE Physics and User Manual” from http://www.genie-mc.org/

- GENIE eA mode uses 3 event generators based on their cross section models.

- Quasi-Elastic Scattering (QEL)

  - Does not play a significant role in pion production.

- Baryon Resonance Production (RES)

  - Based on Rein-Sehgal model.

  - Covers only on “resonance-dominance" region where Ws(hadronic W) smaller than 1.7 GeV.

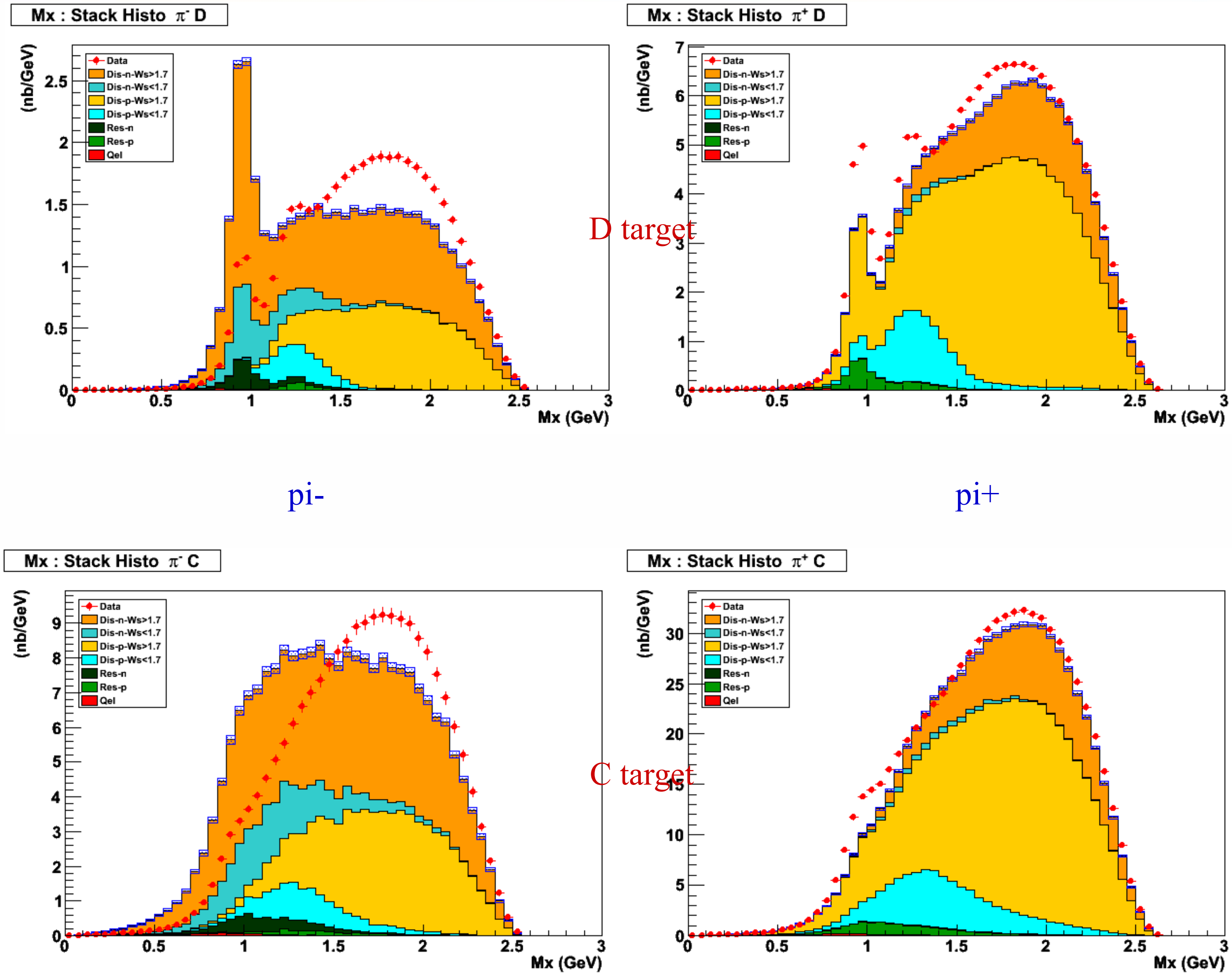
- Non-Resonance Inelastic Scattering (DIS)

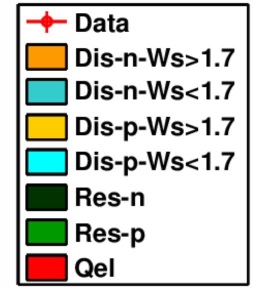
  - Deep (and not-so-deep) inelastic scattering → Not same as nuclear physics definition.

  - Based on Bodek and Yang model.

  - Covers resonance-dominance region(Ws < 1.7 GeV) also.

New Basis : Mx





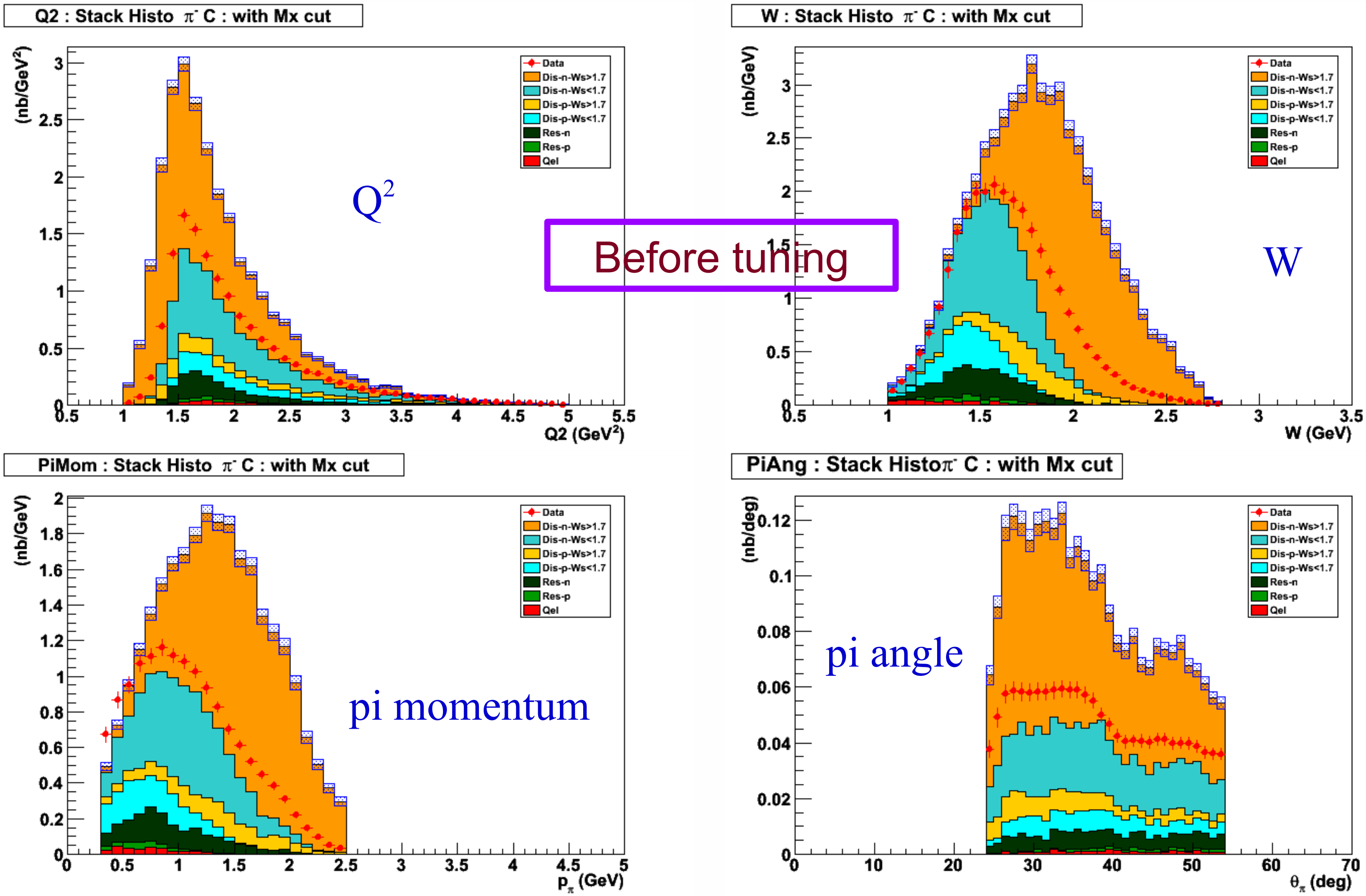
- Dark color : hitnuc → n
- Light color : hitnuc → p
- Orange : DIS, Ws>1.7

  Cyan : DIS, Ws<1.7

  Green : RES

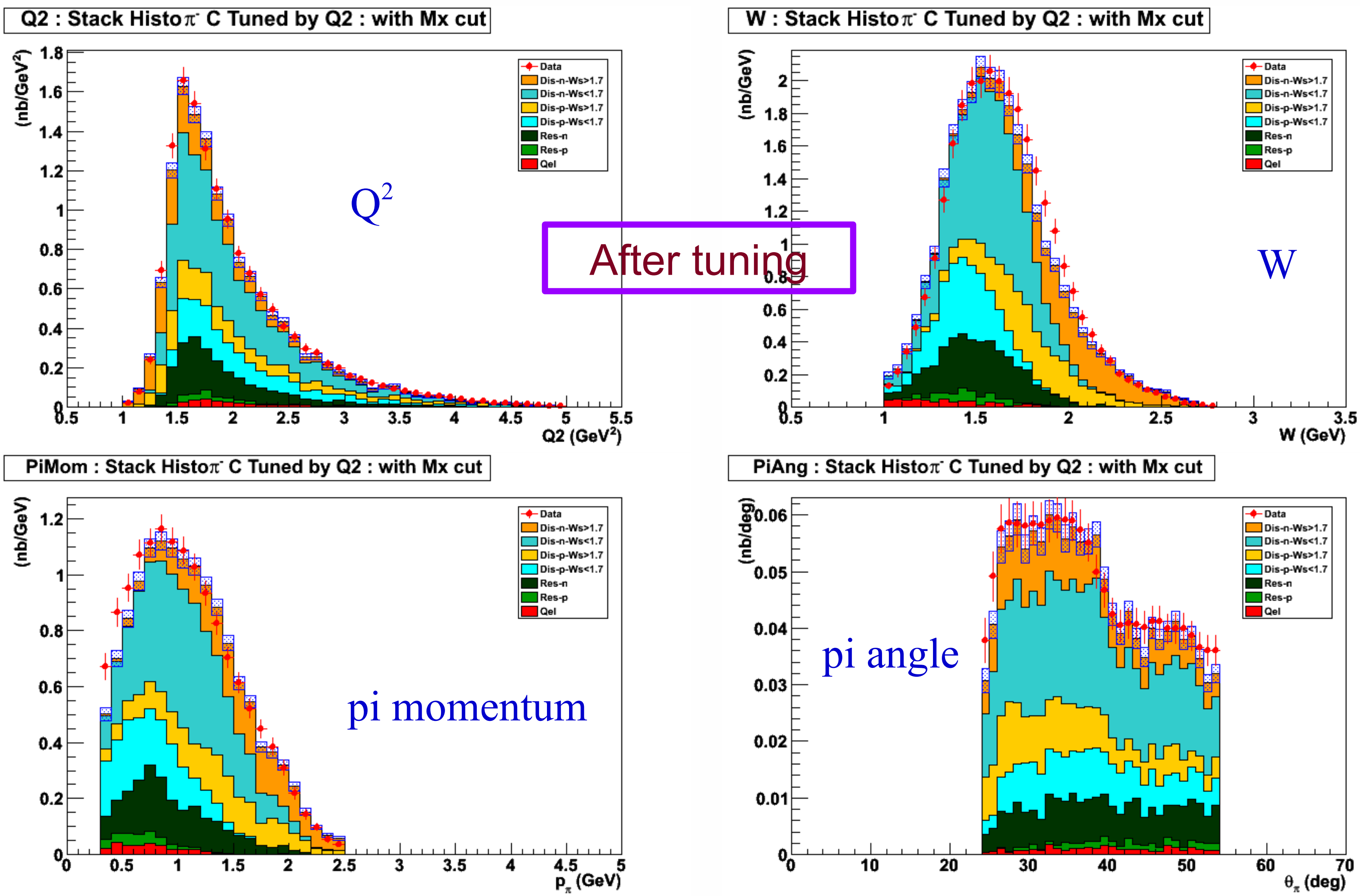
Before Tuning : [C, pi-]

- In signal region.



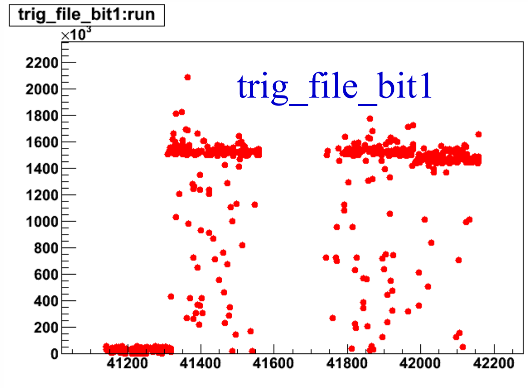
After Tuning : [C, pi-]

- Fit from Mx-Q2 In signal region.

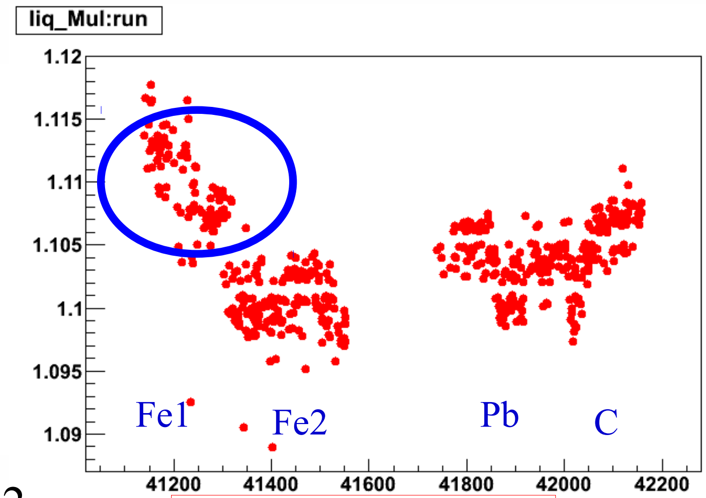


Systematic Error - Global

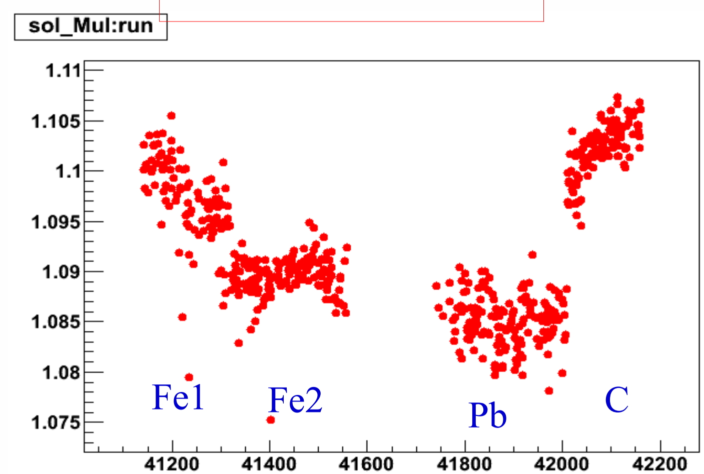
- Total Q – Gated Faraday cup
  - < 1%



- Target
  - Liquid(D2) : ~1.0%
  - Solid : 0.2~0.7%
  - X. Zheng, Cryogenic Target Thickness Study for EG2
    → EG2 internal note, May 2003
  - H. Hakobyan et al., NIM A 592 (2008) 218



π multiplicity
Up → Liquid target
Down → Solid target



- Stability
  - Problem at first half part of iron target.
  - We are finding absolute x-section.
    → Excluded

GENIE Reweighting

- Use reweighting tool on 18 physics parameters in GENIE which related to eA production.

  - Cross section model, hadronization, and intranuclear rescattering.

  - GENIE knob name

  "MFP_pi", "MFP_N", "FrCEx_pi", "FrElas_pi", "FrInel_pi", "FrAbs_pi", "FrPiProd_pi", "FrCEx_N", "FrElas_N", "FrInel_N", "FrAbs_N", "FrPiProd_N", "RDecBR1gamma", "RDecBR1eta", "AGKYxF1pi", "AGKYpT1pi", "AhtBYshape", "BhtBYshape"

- Tweak ±σ shifts for each parameter.

  - Go through the entire analysis chain and get the final x-section result bin-by-bin.

    → Differences with central value as its error.

  - Assume as they are independent.

    → Take square sum of them and use as total MC systematic error for each bin.

- AGKY hadronization model → Major source of error.

- Gives ~8% average fractional error.

[Background Subtraction], [Radiative Correction]

- Background Subtraction

  - Use error matrix of 5 fit parameters for MC tuning

  Make (100 universes)*(3 variables which is used for tuning)

  π angle is not used for tuning.

  Fit results from Q2 used as CV.

  - Average ~3.5% fractional error

- Radiative Correction

  - Use 2 different programs

  External_all(eg1-dvcs) : Only use electron information to get the corrections.(2 variables)

  Haprad2 : Include pion information (5 variables)

  → Phys.Lett.B672:35-44,2009

  - Take the difference between 2 as error.

  - Gives ~1% average fractional error.

Unfolding – Bin migration

- RooUnfold

  - Bayesian method with 1 iteration.

- Basic Idea

  - Bin migrations are related to detector performance and mostly independent on targets

  - Apply response matrices from other targets on MC reconstructed sample → Get unfolded sample and compare with MC truth sample.

  - For example... (→ Response matrix from Pb, MC recon and truth from D → A set of error on D target.)

  - Take mean of errors which are taken 3 possible combinations.

- Gives ~2.5% average fractional error.

Structure in π Angle Distribution

- Fiducial volume correction?

  Assuming azimuthal symmetry, reduce a variable[azimuthal angle] in the function for fiducial cut for simplicity. → Take the ratio inside fiducial region for fixed momentum and polar angle.

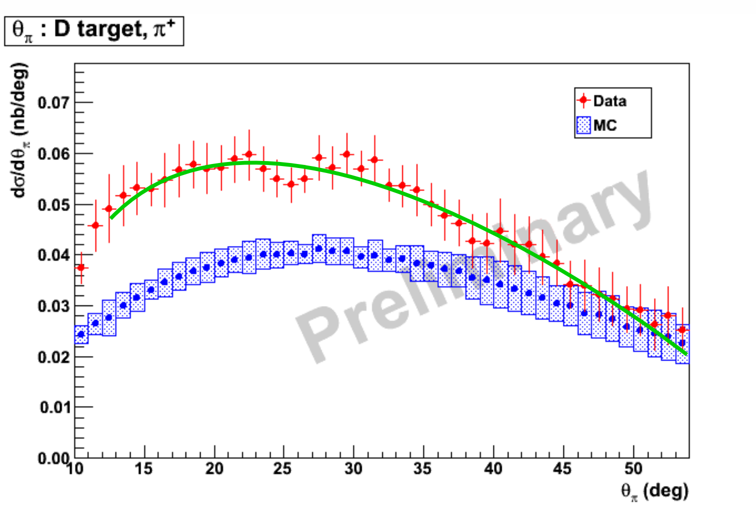
- This looks like the source of strange structure in pion angle distribution.

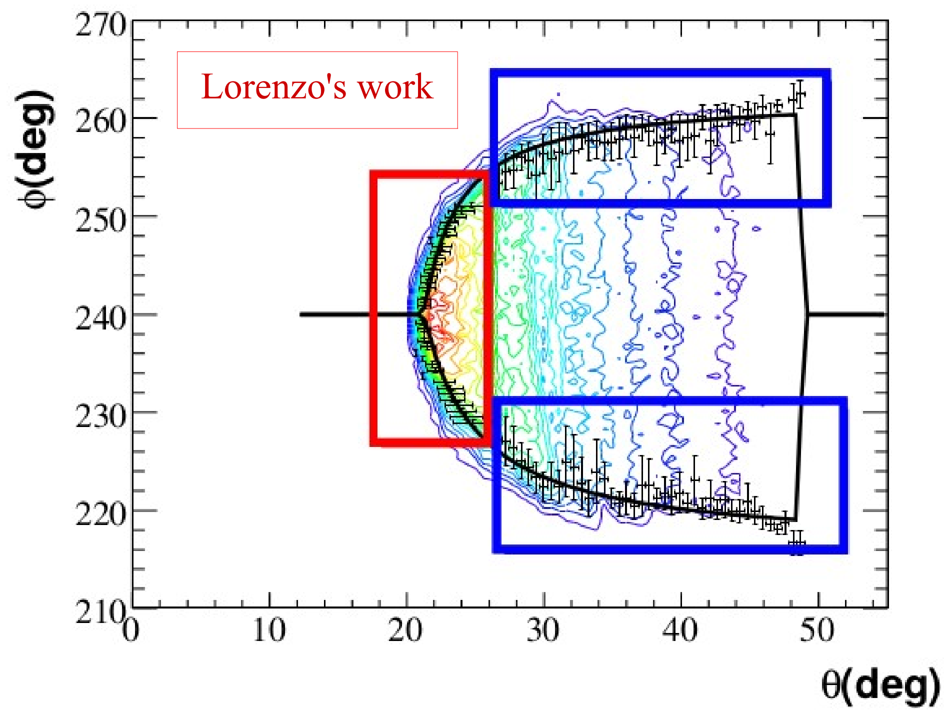
  - If there exist certain region where the fit function does not work well... → It's more likely with polar angle due to the detector geometry → Could give wrong corrections in that region.

- Error estimation?

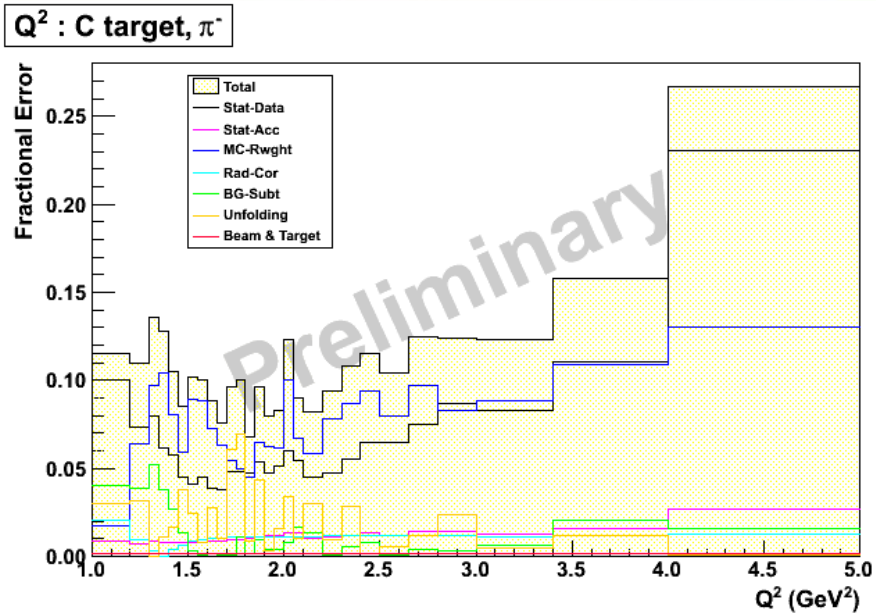
  - Making a smooth fit function on final distribution and take the difference as error.

  → Our current plan. Any other suggestion?

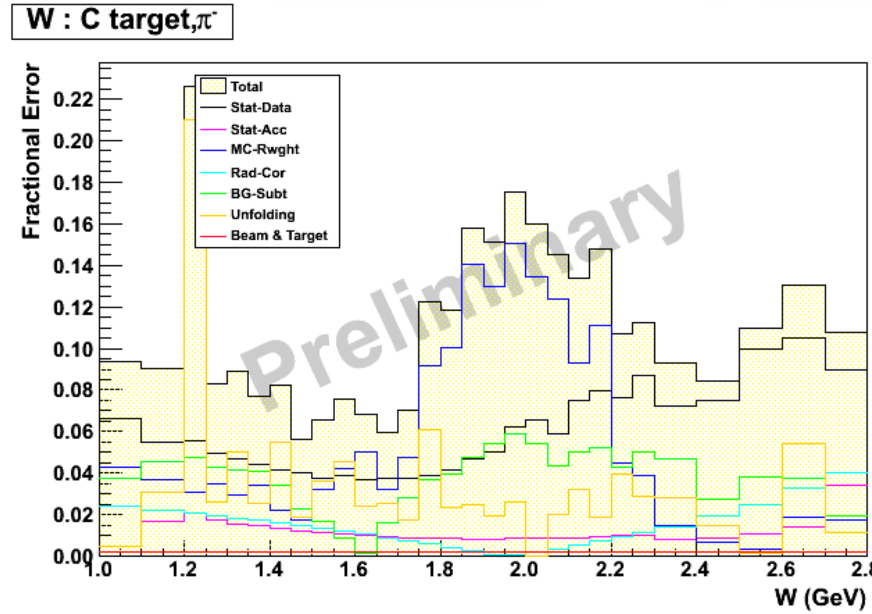




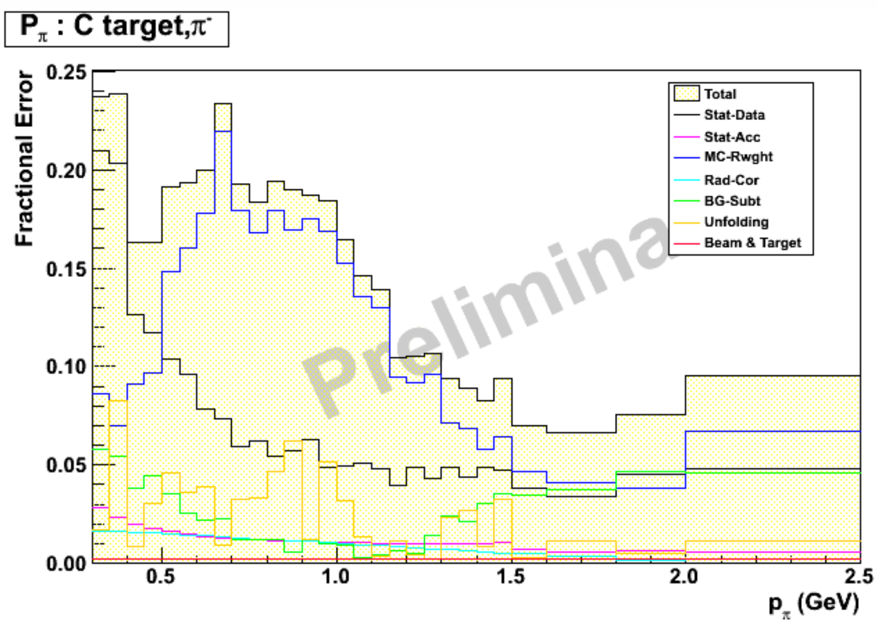
Error pim C



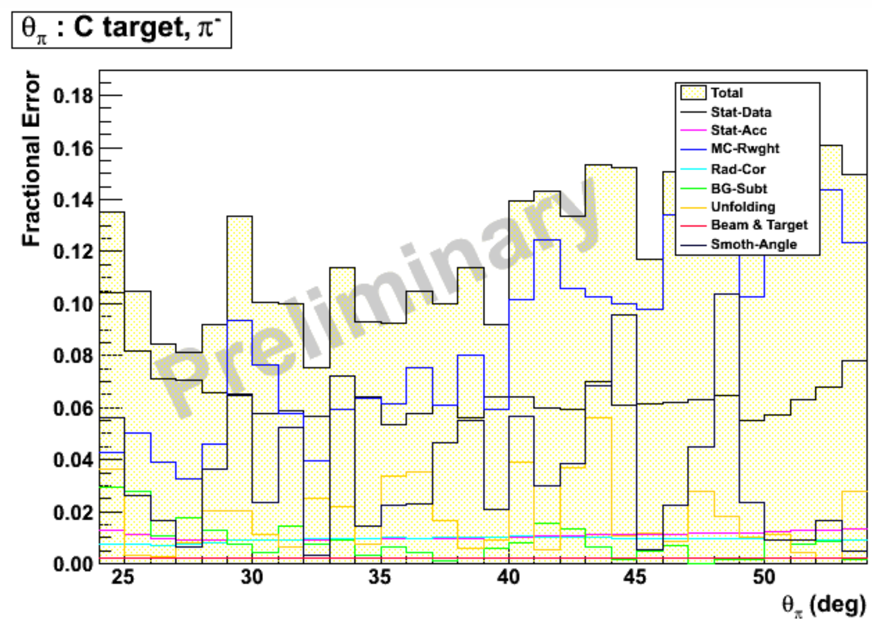
Q^2 : C target, π^-
Fractional Error
Total
Stat-Data
Stat-Acc
MC-Rwght
Rad-Cor
BG-Subt
Unfolding
Beam & Target
Preliminary
Q^2 (GeV^2)



W : C target,π^-
Fractional Error
Total
Stat-Data
Stat-Acc
MC-Rwght
Rad-Cor
BG-Subt
Unfolding
Beam & Target
Preliminary
W (GeV)

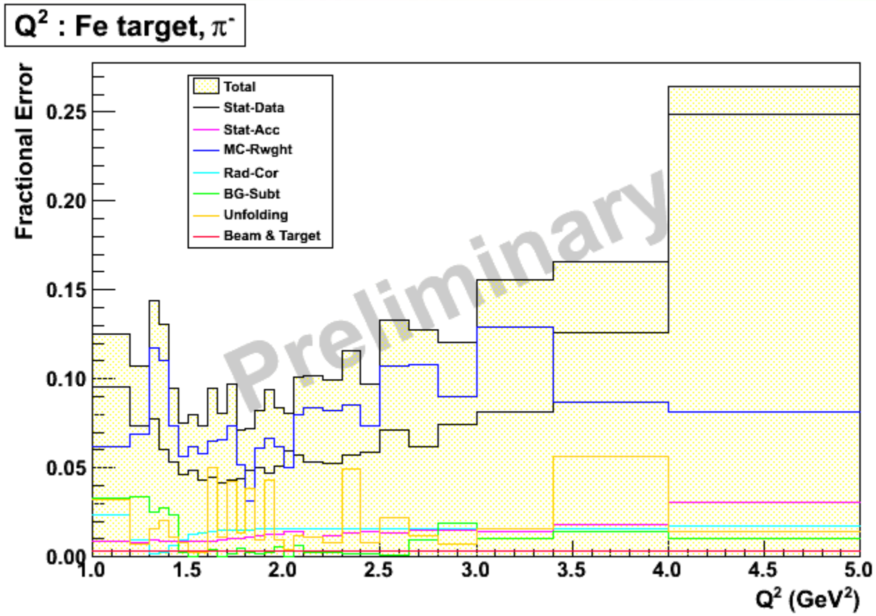


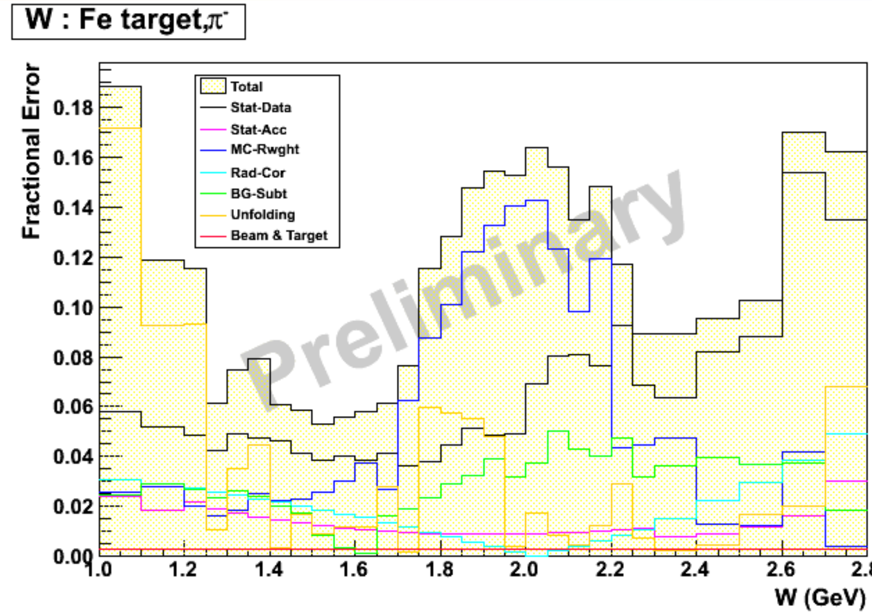
P$_\pi$: C target,π^-
Fractional Error
Total
Stat-Data
Stat-Acc
MC-Rwght
Rad-Cor
BG-Subt
Unfolding
Beam & Target
Prelimina
p$_\pi$ (GeV)

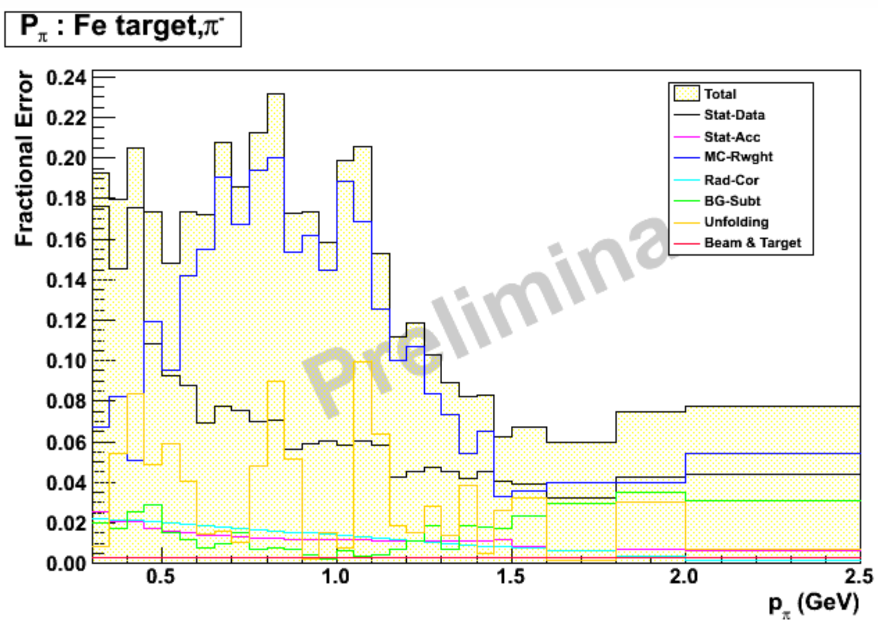


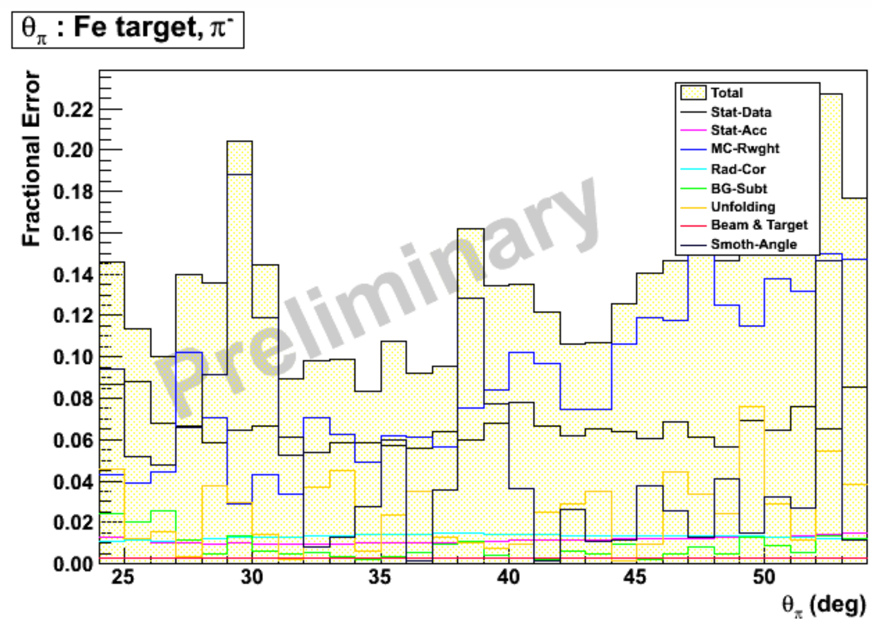
θ$_\pi$: C target, π^-
Fractional Error
Total
Stat-Data
Stat-Acc
MC-Rwght
Rad-Cor
BG-Subt
Unfolding
Beam & Target
Smoth-Angle
Preliminary
θ$_\pi$ (deg)

Error pim Fe


Q^2 : Fe target, π^-
Fractional Error
Total
Stat-Data
Stat-Acc
MC-Rwght
Rad-Cor
BG-Subt
Unfolding
Beam & Target
Preliminary
Q^2 (GeV^2)

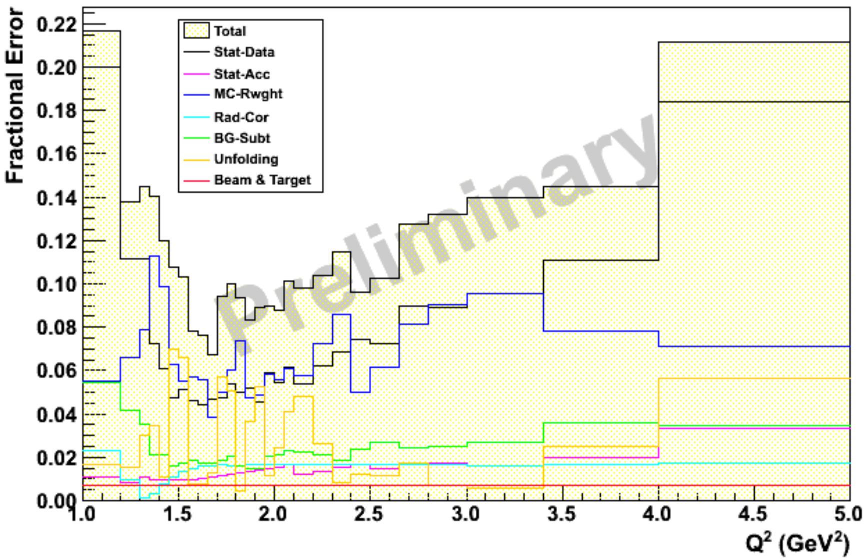

W : Fe target,π^-
Fractional Error
Total
Stat-Data
Stat-Acc
MC-Rwght
Rad-Cor
BG-Subt
Unfolding
Beam & Target
Preliminary
W (GeV)


P$_\pi$: Fe target,π^-
Fractional Error
Total
Stat-Data
Stat-Acc
MC-Rwght
Rad-Cor
BG-Subt
Unfolding
Beam & Target
Preliminary
p$_\pi$ (GeV)

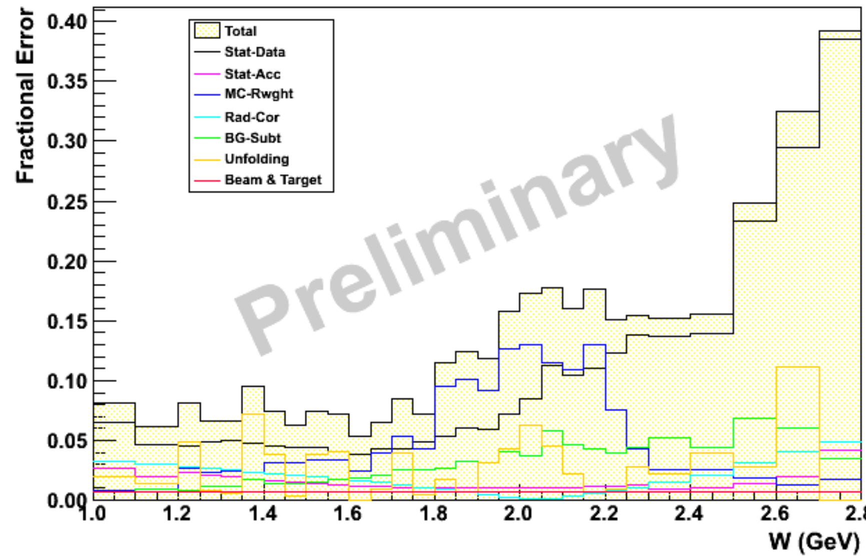

θ_π : Fe target, π^-
Fractional Error
Total
Stat-Data
Stat-Acc
MC-Rwght
Rad-Cor
BG-Subt
Unfolding
Beam & Target
Smoth-Angle
Preliminary
θ_π (deg)

Error pim Pb

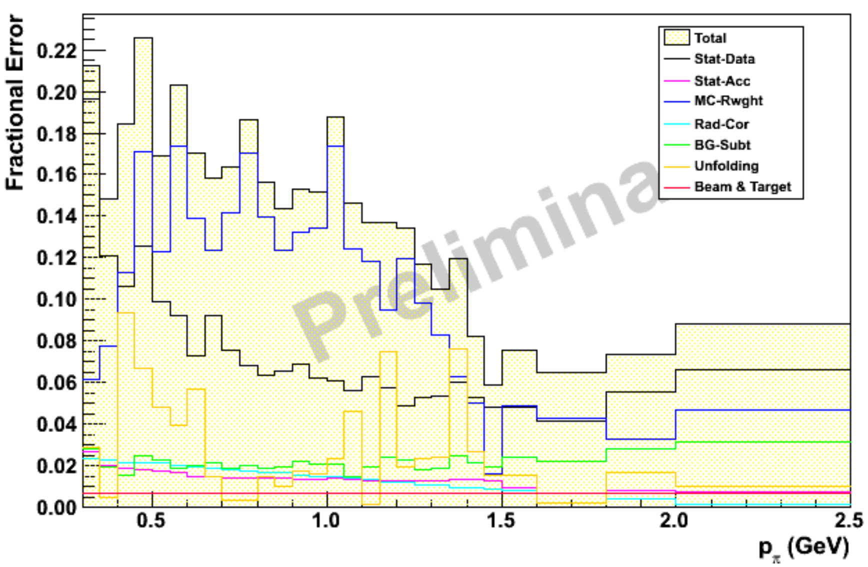
Q^2 : Pb target, π^-



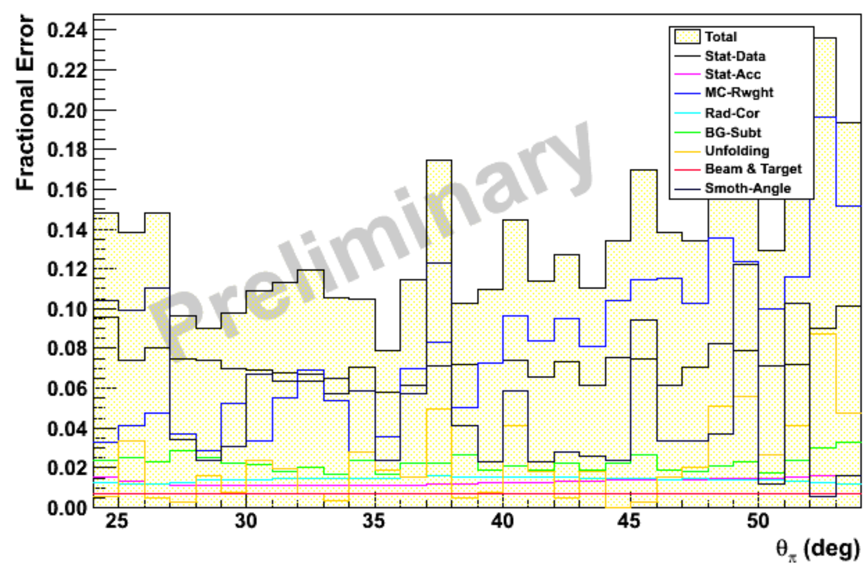
W : Pb target, π^-



P_π : Pb target, π^-

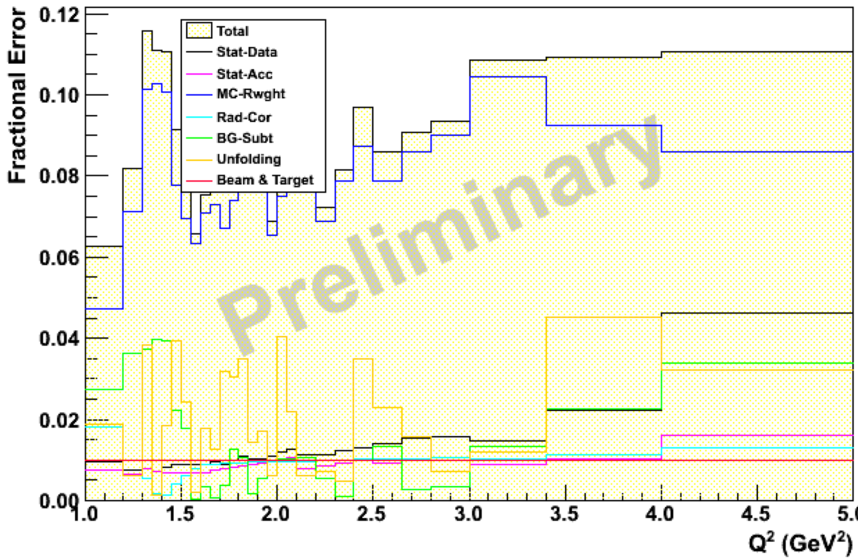


θ_π : Pb target, π^-

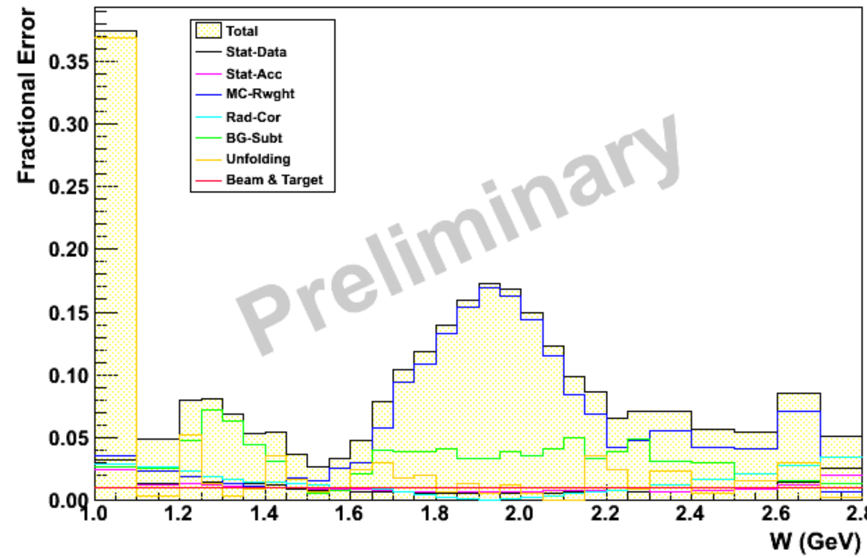


Error pip D

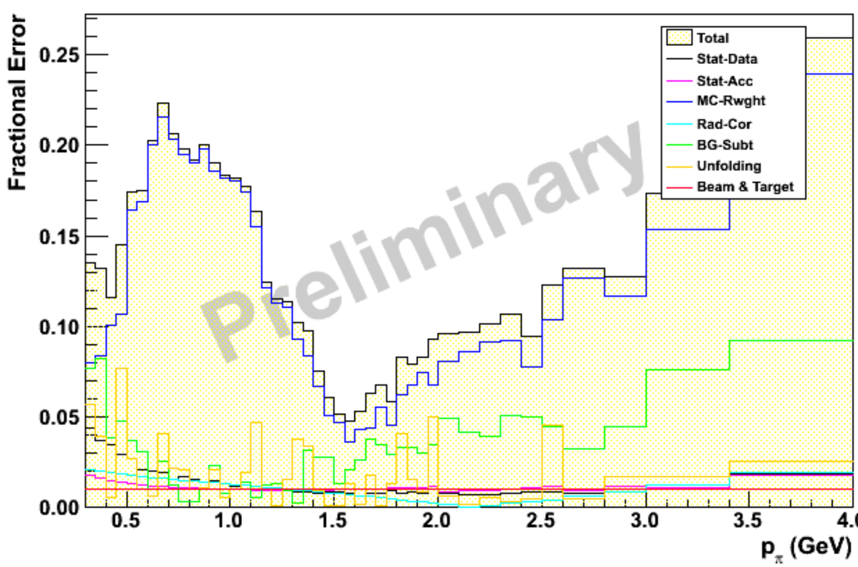
Q^2 : D target, π^+



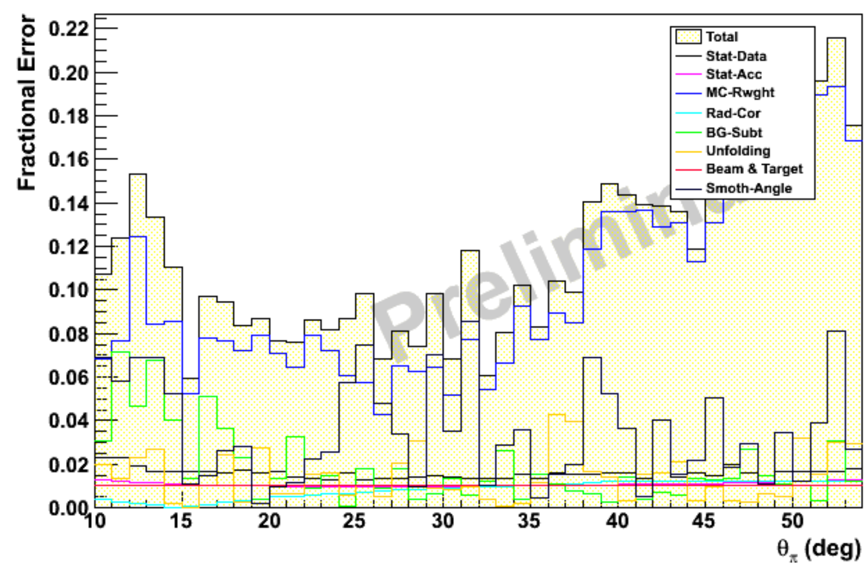
W : D target, π^+



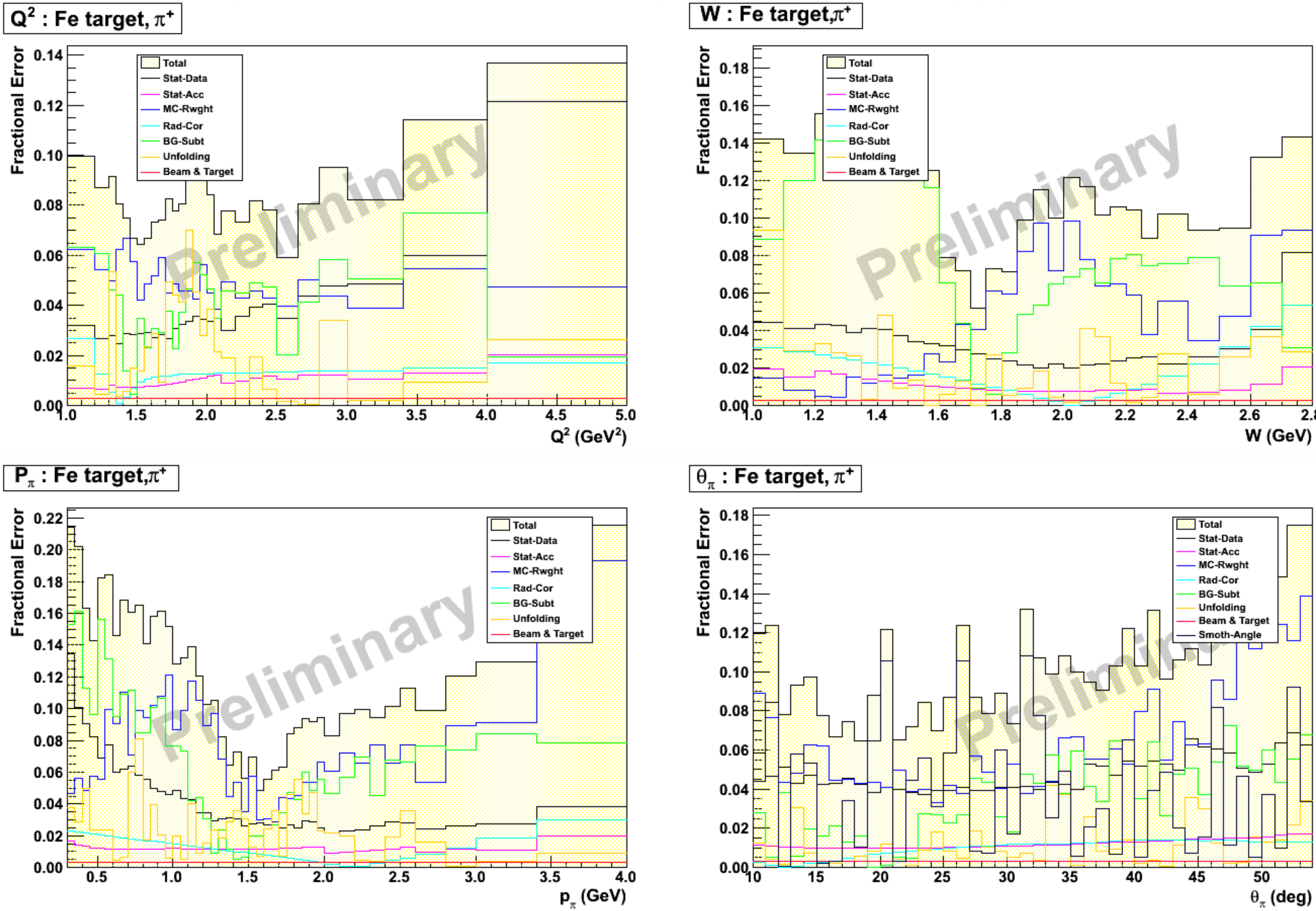
P_π : D target, π^+



θ_π : D target, π^+

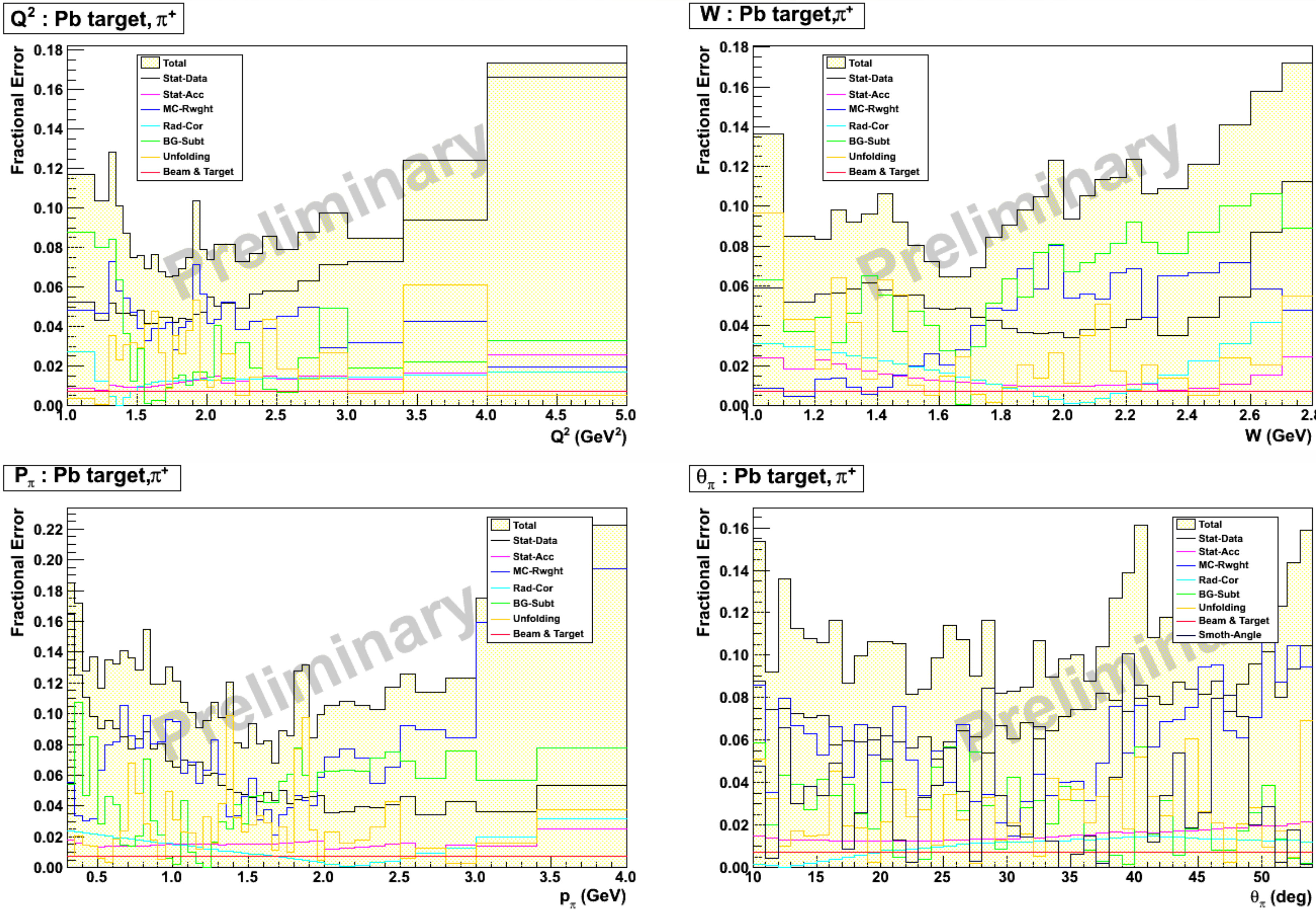


Error pip Fe



Q^2 : Fe target, π^+
Fractional Error
Total
Stat-Data
Stat-Acc
MC-Rwght
Rad-Cor
BG-Subt
Unfolding
Beam & Target
Preliminary
Q^2 (GeV^2)
W : Fe target,π^+
W (GeV)
P_π : Fe target,π^+
p_π (GeV)
θ_π : Fe target, π^+
Smoth-Angle
θ_π (deg)

Error pip Pb


Q² : Pb target, π⁺
W : Pb target,π⁺
Pπ : Pb target,π⁺
θπ : Pb target, π⁺
Fractional Error
Q² (GeV²)
W (GeV)
pπ (GeV)
θπ (deg)
Total
Stat-Data
Stat-Acc
MC-Rwght
Rad-Cor
BG-Subt
Unfolding
Beam & Target
Smoth-Angle
Preliminary