CLAS Collaboration Meeting
Deep Processes Working Group

# Deep Virtual Production of Pion Pairs

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# Project

- We are mainly considering two reactions, Charged and Neutral Pion Pairs
  - $ep \rightarrow e'p'\pi^{+}\pi^{-}$
    - Isospin I=1, angular momentum J=1
      - $\boldsymbol{\rho(770)}$
    - Isospin I=0, angular momentum J=0
      - $\boldsymbol{f_0(500) = \sigma, f_0(980)}$
  - $ep \rightarrow e'p'\pi^{0}\ \pi^{0}$
    - Isospin zero, spin zero channel (I:J=0:0)
      - $\boldsymbol{f_0(500) = \sigma, \quad f_0(980)}$

# Deep exclusive two pion production

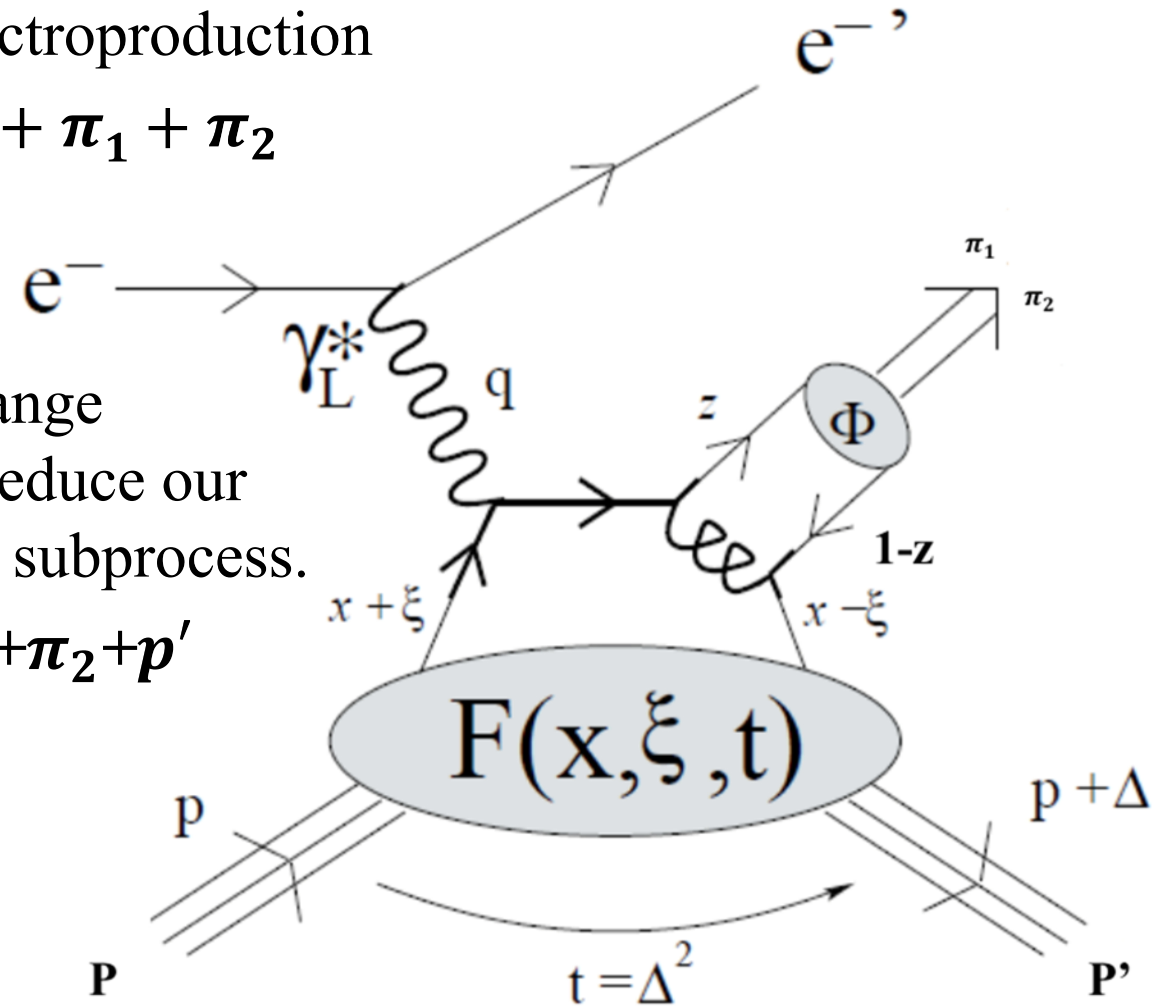


- Exclusive two-pion electroproduction

$$e + p \rightarrow e' + p' + \pi_1 + \pi_2$$

- In the one-photon exchange approximation we can reduce our analysis to the hadronic subprocess.

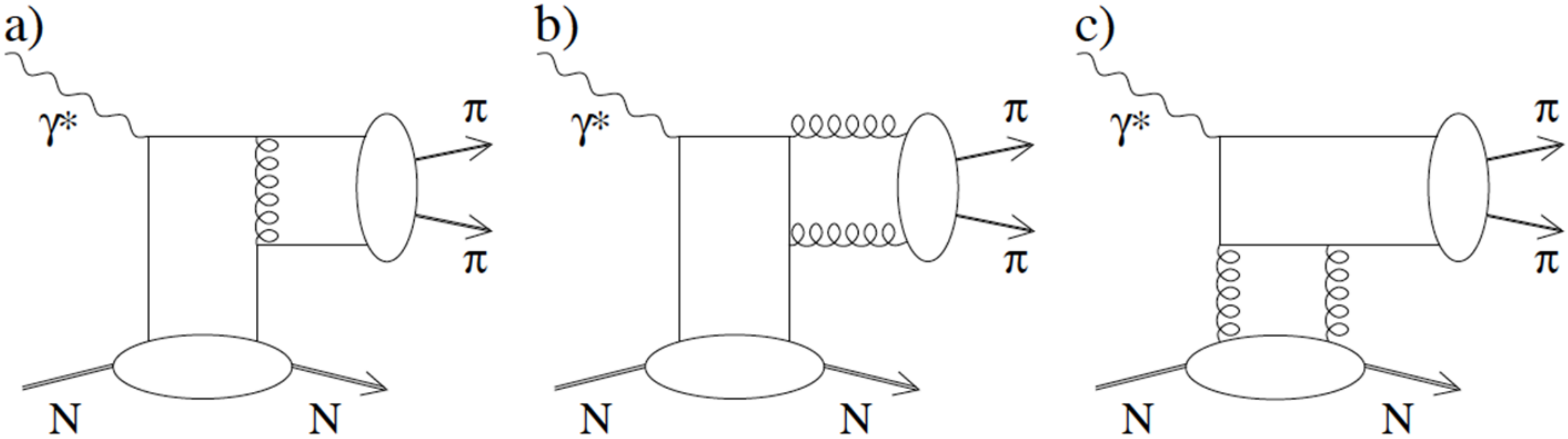
$$\gamma^* + p \rightarrow \pi_1 + \pi_2 + p'$$



# Deep Virtual Factorization



- Leading order diagrams for exclusive deep virtual production of two pions




B. Lehmann-Dronke *et al.*, Phys Lett B **475** (2000) 147

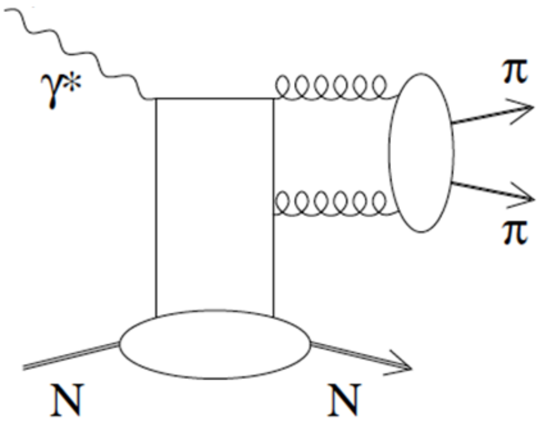
B. Lehmann-Dronke *et al.*, Phys Rev D, **63** (2001) 114001

Neutral mesonic final state: $\pi^+\pi^-$ *or* $\pi^0\pi^0$

a) [Flavor-Diagonal quark-GPD] ⊗ [$q\bar{q}$ -Two-Pion Distribution Amplitude (DA)]
b) [Flavor-Diagonal quark-GPD] ⊗ [gluon-Two-Pion Distribution Amplitude(DA)]
c) [Gluon-GPD] ⊗ [$q\bar{q}$ -Two-Pion Distribution Amplitude (DA)]

# Deep sigma

- σ-meson Asymptotic Distribution Amplitudes:
  - $\phi_{gluon} = 2\,\phi_{qq}$




- σ-meson: $f_0(500)$ well established.
  - ***Pole = (450±20)MeV – i(275±12) MeV)***

- Microscopic structure of $f_0(500)$ not well understood.
  - $q\bar{q}$ : $^3P_0$
  - Tetraquark
  - $\pi\pi$ -molecule
  - Glueball
  - Superposition of all of the above

- Deep sigma-production offers intriguing evidence for gluonic content of $f_0(500)$.

# Deep virtual $\pi\pi$ Production Amplitude



- **Deep Virtual $\pi\pi$ Production Amplitude**

$$\mathscr{M} = \sum_{\substack{I \\ \lambda_N,\lambda_\pi \in (q\bar{q},g)}} \int d\tau dz \mathrm{GPD}_{\lambda_N}(\tau,\xi,t) \odot S_{\lambda_N,\lambda_\pi}(\tau,z,\xi) \odot \mathrm{DA}^I_{\lambda_\pi}(z,\zeta; m_{\pi\pi} : \theta^*)$$

$$\mathscr{M} = \sum_{\substack{J^\pi : I \\ \lambda_N,\lambda_\pi \in (q\bar{q},g)}} \int d\tau dz \mathrm{GPD}_{\lambda_N}(\tau,\xi,t) \odot S_{\lambda_N,\lambda_\pi}(\tau,z,\xi) \odot \mathrm{DA}^I_{\lambda_\pi}(z,\zeta) P_J(\cos(\theta^*)\Omega_{J:I}(m_{\pi\pi})$$

- **Kinematics**

$$\xi \sim \frac{x_B}{2 - x_B}$$

$$t = (q - p_{\pi\pi})^2 = (P'_p - P_p)^2$$

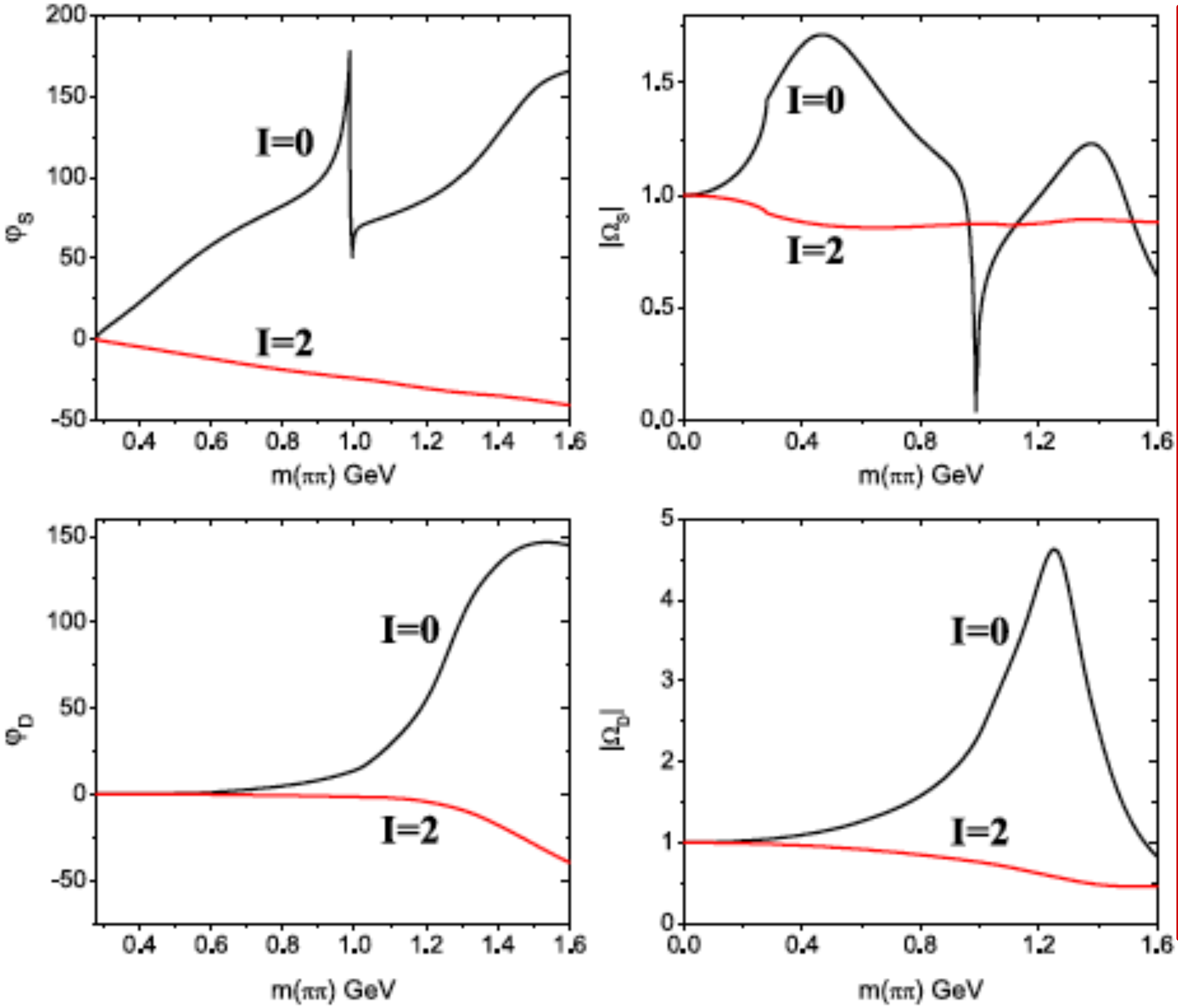
$$\zeta,\ (1-\zeta) = \frac{1}{2}[1 \pm \beta^* \cos\theta^*] = \text{ pion lightcone momentum fractions}$$

$$\beta^* = \text{ pion velocity in } \pi\pi \text{ rest frame}$$

$$\theta^* = \text{ pion polar angle in } \pi\pi \text{ rest frame}$$

- **Dynamics**
  - $S(\tau,z;\xi)$ = Hard scattering amplitude (quark-gluon propagators)
  - $\Omega_{J;I}$ = Omnès-function, derived from $\pi\pi$ phase shifts
  - $\tau$ = average momentum fraction of parton in nucleon
  - $z$ = momentum fraction of parton in $\pi\pi$ DA

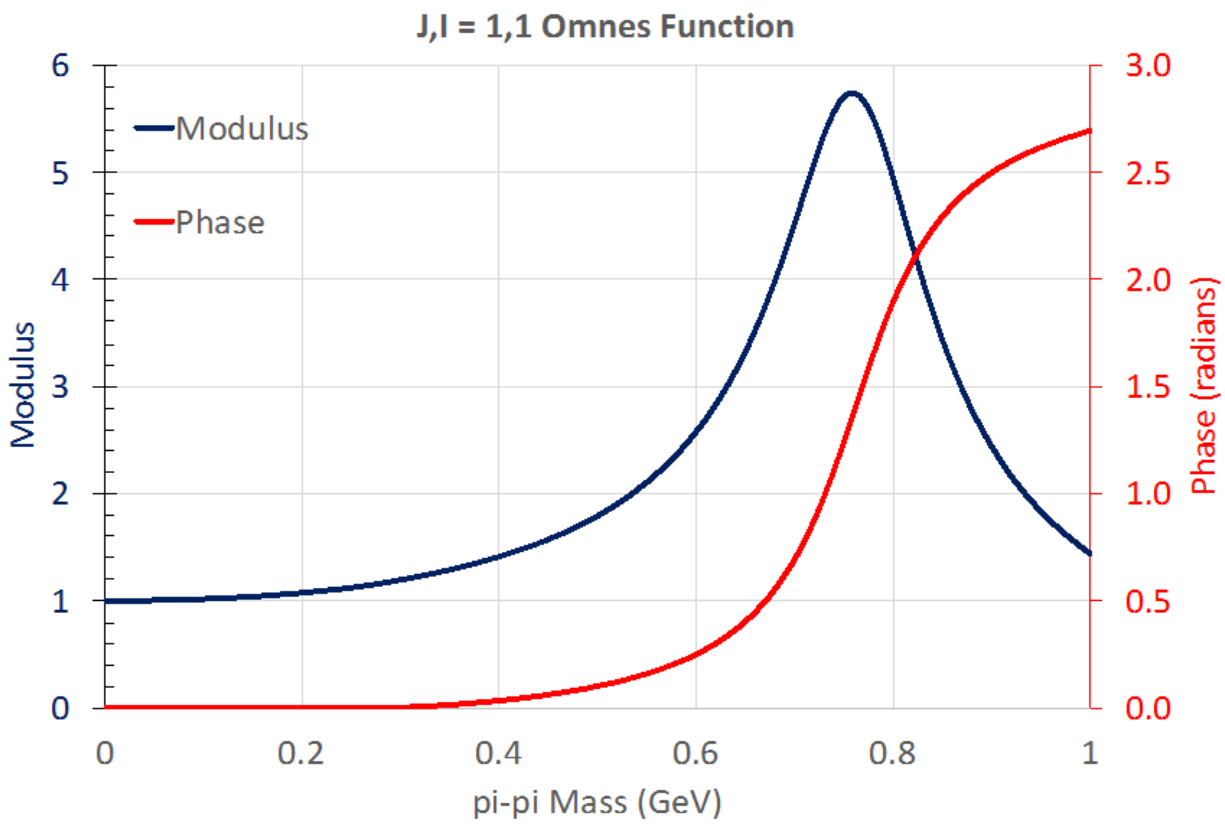
# $\pi\pi$ Mass Distribution (Omnès F'n)




- L.Dai, M.Pennington, Phys Rev D **90** 036004 (2014)
- L=0
  - *$f_0$(500)*
  - *$f_0$(980)*
  - *Small I=2 non-resonant*
- L=2
  - $f_2$(1270)
  - *Small I=2 non-resonant*

# $\pi\pi$ Omnès F'n I;J = 1;1 ($\rho$-meson)






- L.Dai, M.Pennington, Phys Rev D **90** 036004 (2014)

$$\Omega_l^I(m_{\pi\pi}) = \exp\left\{ i\delta_l^I(m_{\pi\pi}) + \frac{m_{\pi\pi}^2}{\pi}\Re\mathrm{e}\left[\int_{4m_\pi^2}^{\infty} ds \frac{\delta_l^I(s)}{s(s-m_{\pi\pi}^2-i\epsilon)}\right]\right\}$$

# Simulation : Event Generation



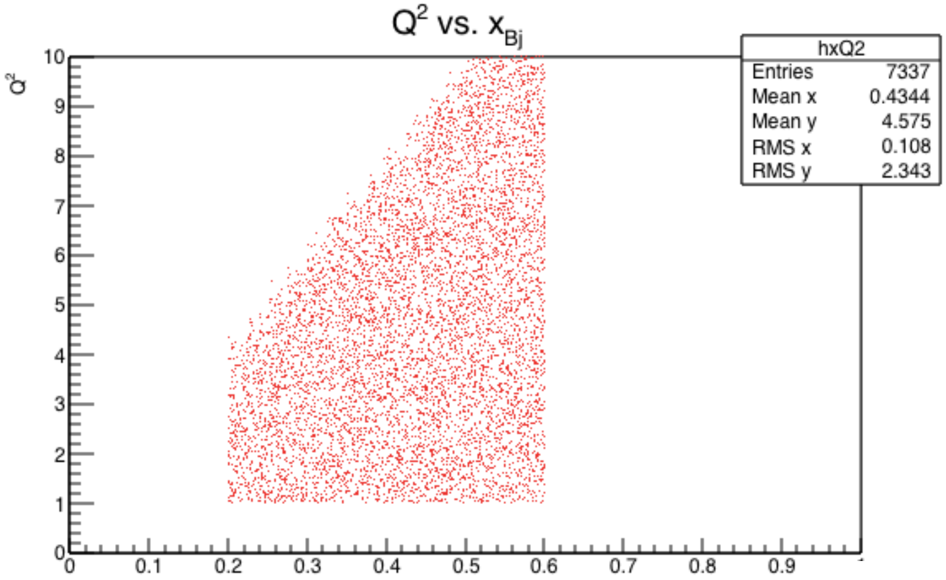
- **Monte-Carlo Generation of Phase Space Variables**
  - There are eight independent kinematic variables in the final state of the $ep \rightarrow e'p'\pi\pi$ reaction.

| Total kinematic variables in final state (four 4-vectors) | 16 |
|---|---|
| Mass constraint of the four final state particles | -4 |
| Four-Momentum Conservation, initial to final state | -4 |
| Total number of independent variables in final state | 8 |

- These are,
  - $Q^2, x_B, \phi_e, M^2_{1,2}, t, \phi^*_{1,2}, cos\theta_{\sigma\_Rest}, \phi_{\sigma\_Rest}$

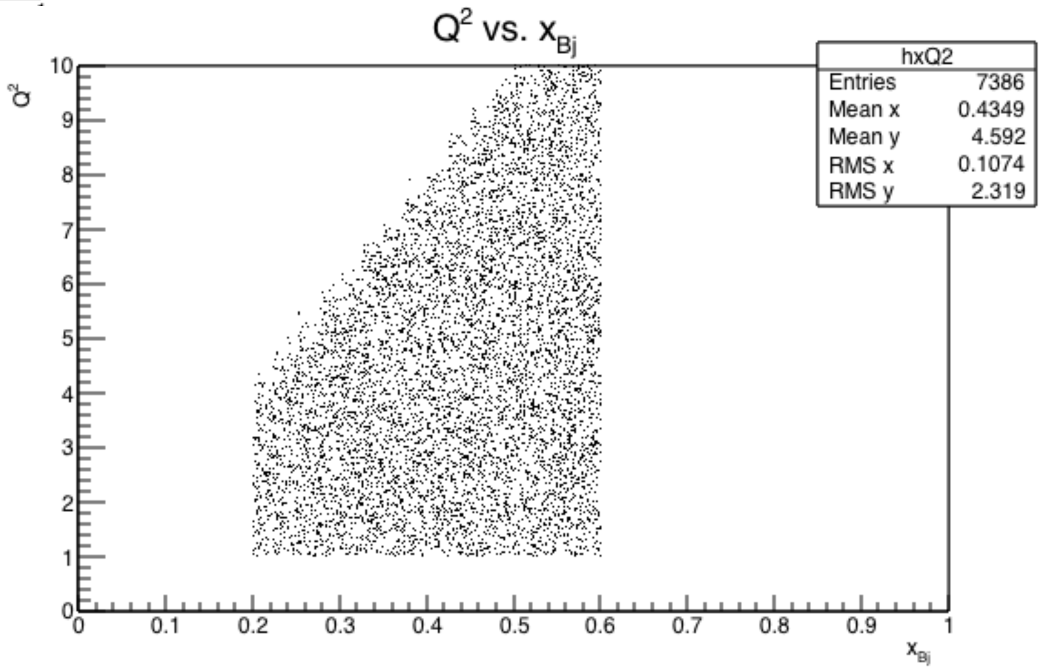
# Event Generator Results






$$ep \rightarrow e'p'\pi^+\pi^-$$

$$ep \rightarrow e'p'\pi^0\pi^0$$



# Reactions

1. First consider the reaction $\boldsymbol{e} + \boldsymbol{p} \rightarrow \boldsymbol{e}' + \boldsymbol{p}' + \boldsymbol{\pi}^{+} + \boldsymbol{\pi}^{-}$

    - Four Particles in final state

2. Secondly consider the reaction $\boldsymbol{e} + \boldsymbol{p} \rightarrow \boldsymbol{e}' + \boldsymbol{p}' + \boldsymbol{\pi}^{\mathbf{0}} + \boldsymbol{\pi}^{\mathbf{0}}$,

    its primary mode of decay is $\boldsymbol{\pi}^{\mathbf{0}} \rightarrow \boldsymbol{\gamma}\,\boldsymbol{\gamma}$

    6 particles in final state

    - Scattered electron
    - Recoil Proton
    - Two $\boldsymbol{\pi}^{\mathbf{0}}$ s $\Rrightarrow$ Four gamma-rays

# Simulation and Reconstruction



- For my simulation and reconstruction, I used

  **GEMC version 4a.2.1**

  **COATJAVA version 4a.8.2**

**Steps :**

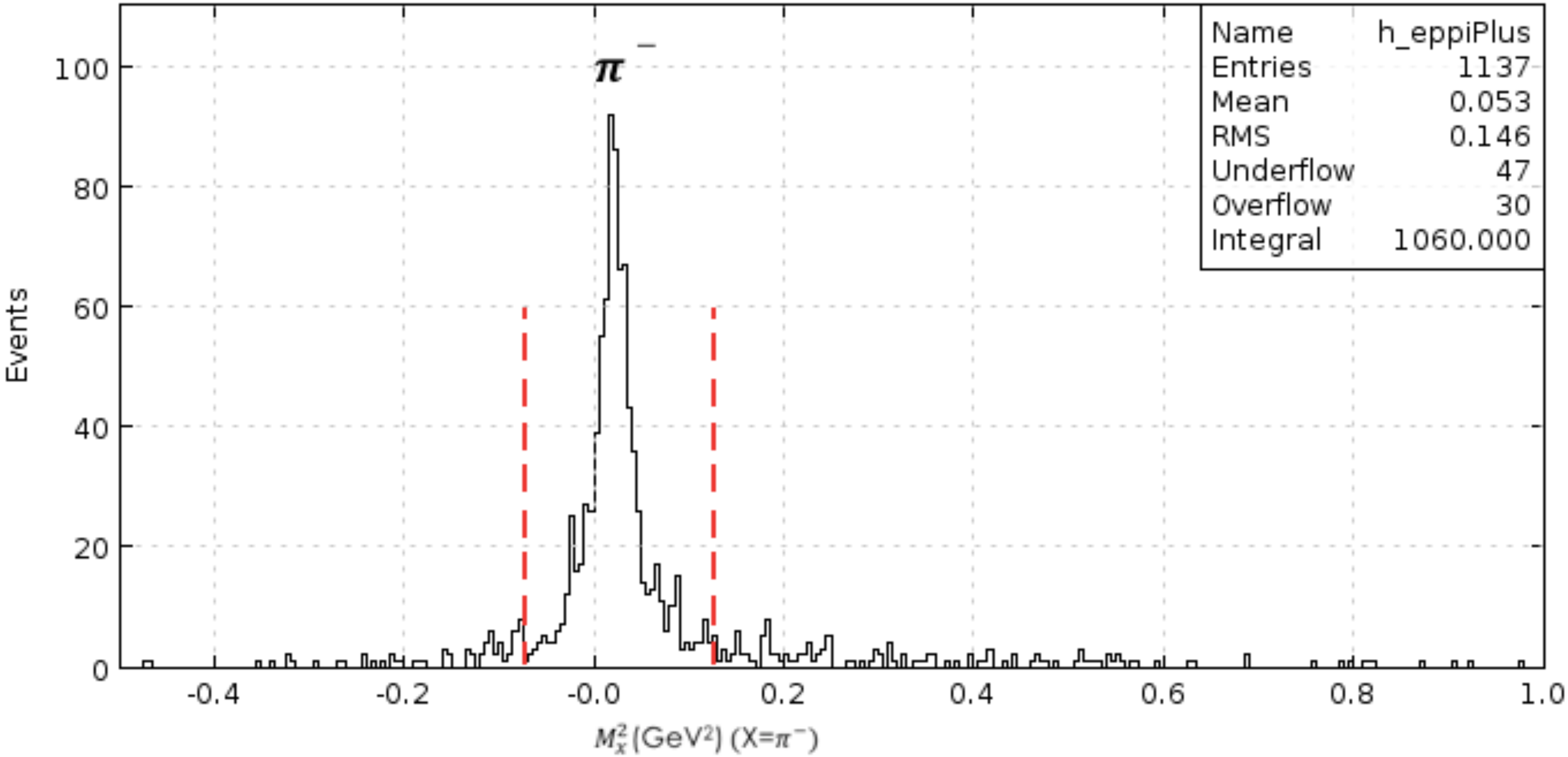
- After generation monte-carlo data is passed through the GEMC in the form of LUND format.
- Reconstruction is done with coatjava.

- CLAS12 analyses are done with **groovy** scripts (java).

- This method ties well with the coatjava framework and provides standard tools for reading EVIO files and reconstructed banks.

# Missing mass for $ep \to e\ p\ \pi^+ X$

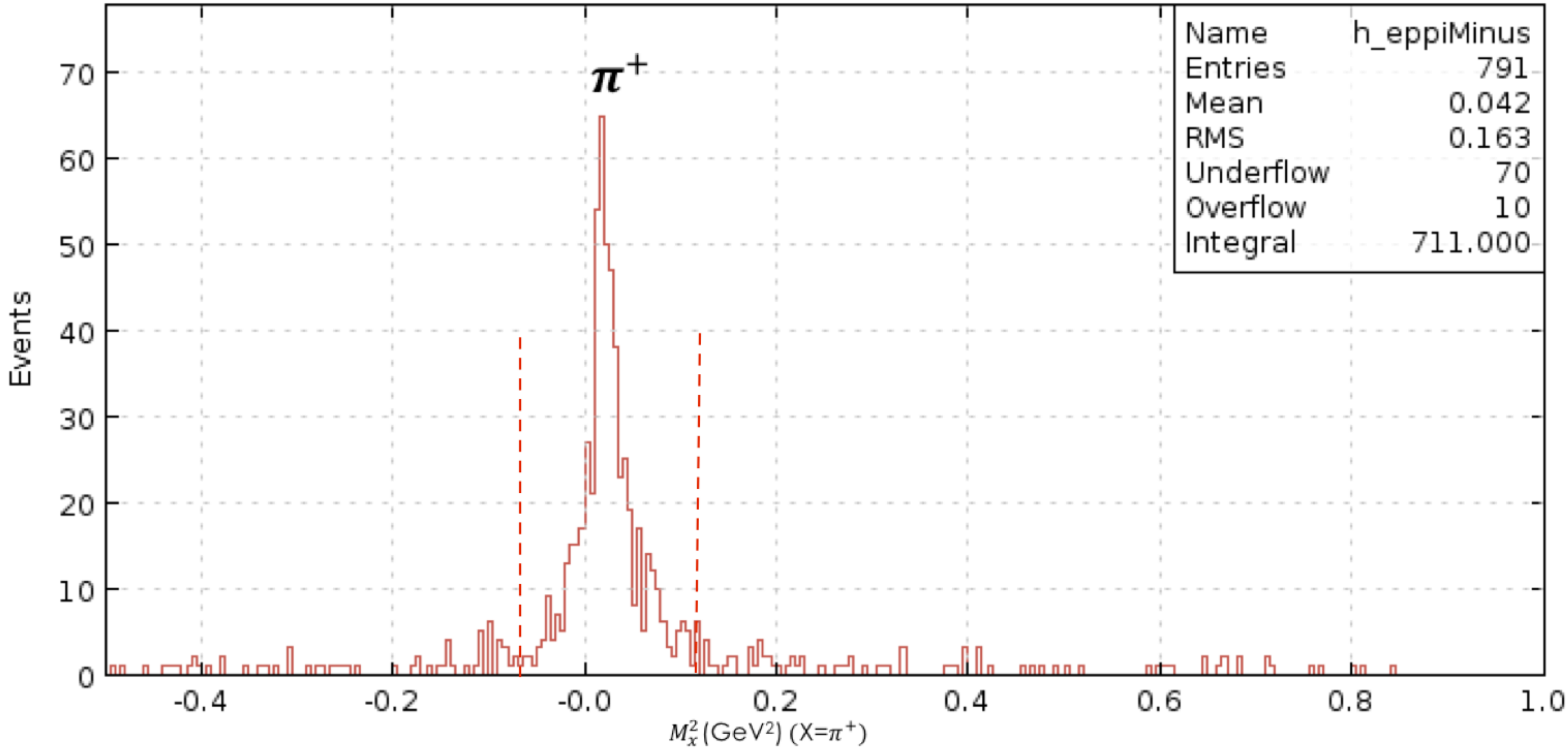
- Missing mass square of $\mathrm{H}(e, e'p\,\pi^+)\mathbf{X}, \quad \mathbf{X} = \boldsymbol{\pi}^-$




**Detection ⊗ reconstruction efficiency ≈ 14%**

# Missing mass for $ep \rightarrow e\ p\ \pi^-\ X$

- Missing mass square of $\pi^+$

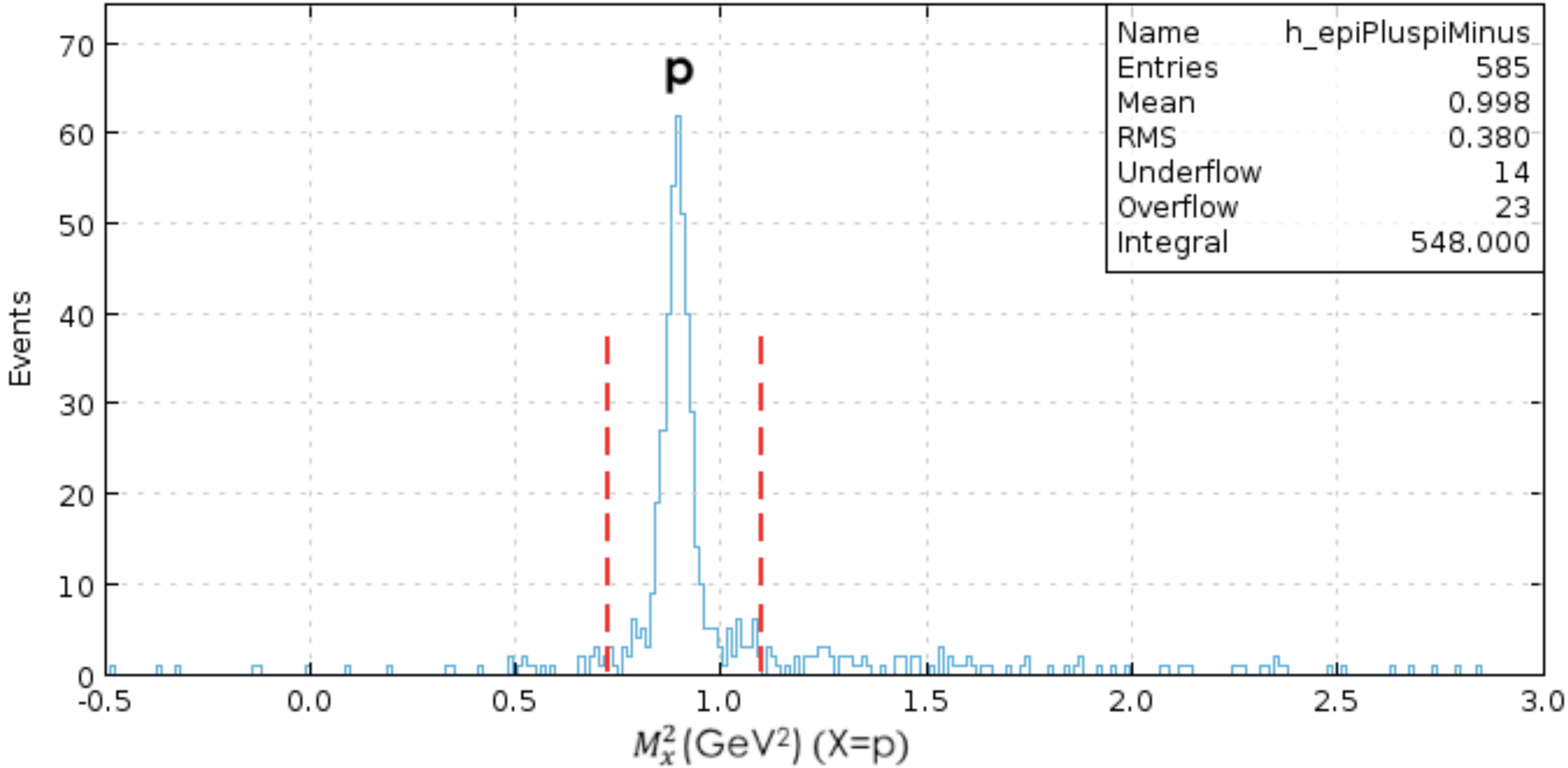



**Detection ⊗ reconstruction efficiency ≈ 11%**

# Missing mass for $ep \to e\ \pi^+\ \pi^-$



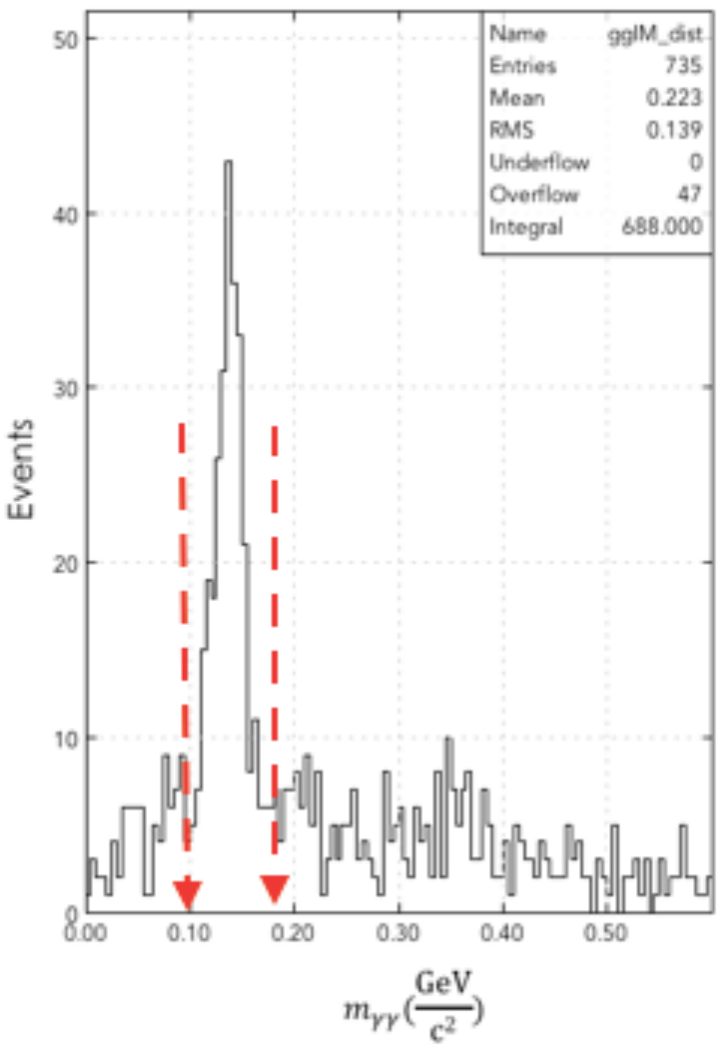
- Missing mass square of *proton*




**Detection ⊗ reconstruction efficiency ≈ 8%**

# Invariant mass for $ep \rightarrow e' p' \pi^0 \pi^0$

- Secondly, consider the reaction, $ep \rightarrow e'p'\pi^0\ \pi^0$, and $\pi^0$ decays into two gammas ($\pi^0 \rightarrow \gamma\gamma$).
- Expected two photon invariant mass peak

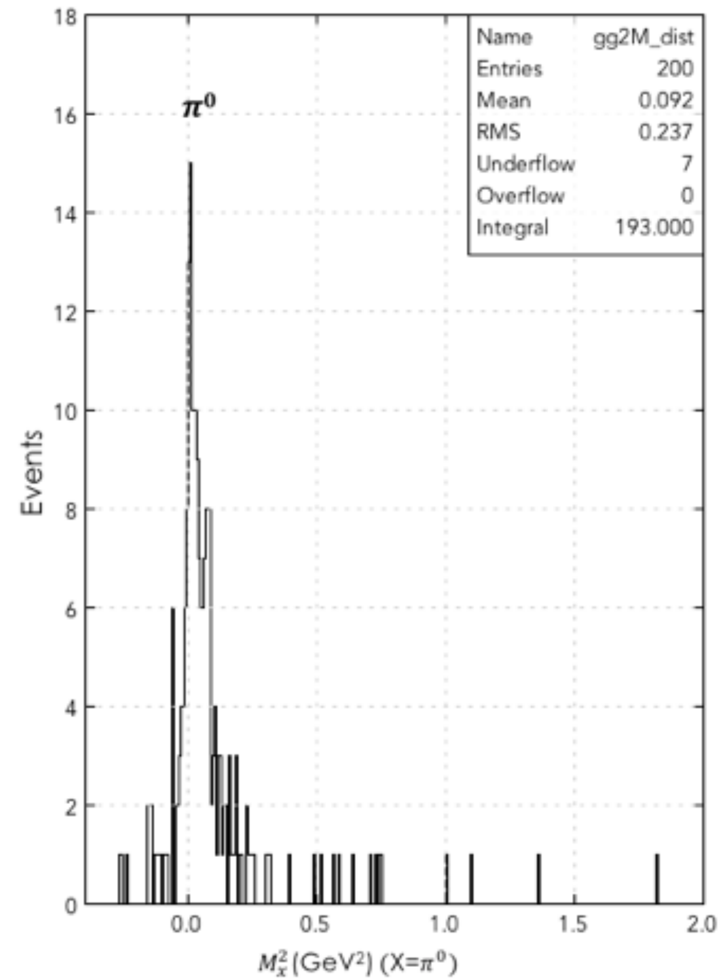


# Missing mass for $ep \rightarrow e'p'\pi^0X$



- Applied a cut on invariant mass : around $0.10 < m_{\gamma\gamma}^2 < 0.17\ GeV$

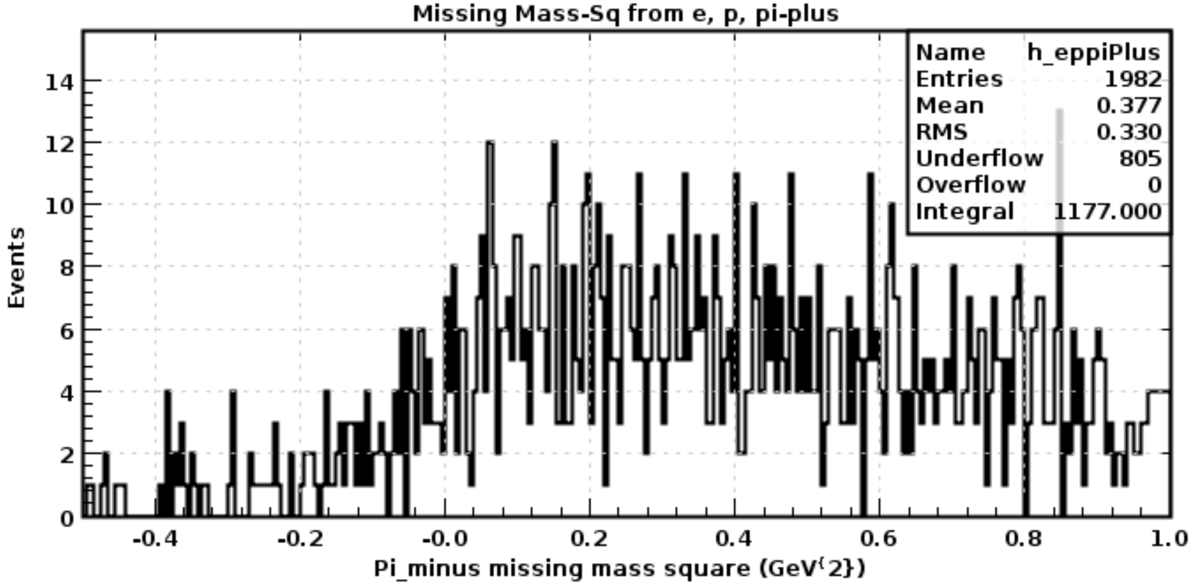
- *Peak around 0.02 GeV²*



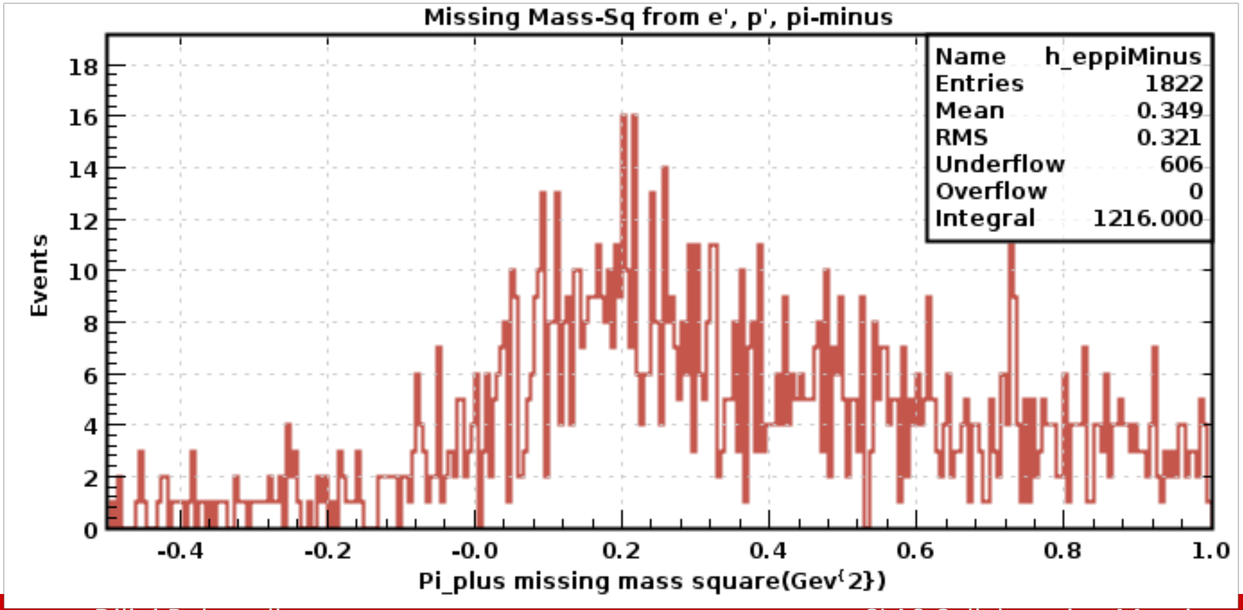

**Detection ⊗ reconstruction efficiency ≈ 2%**

# Real Data Analysis (same analysis scripts)

- Run Number 3050(6.4GeV)



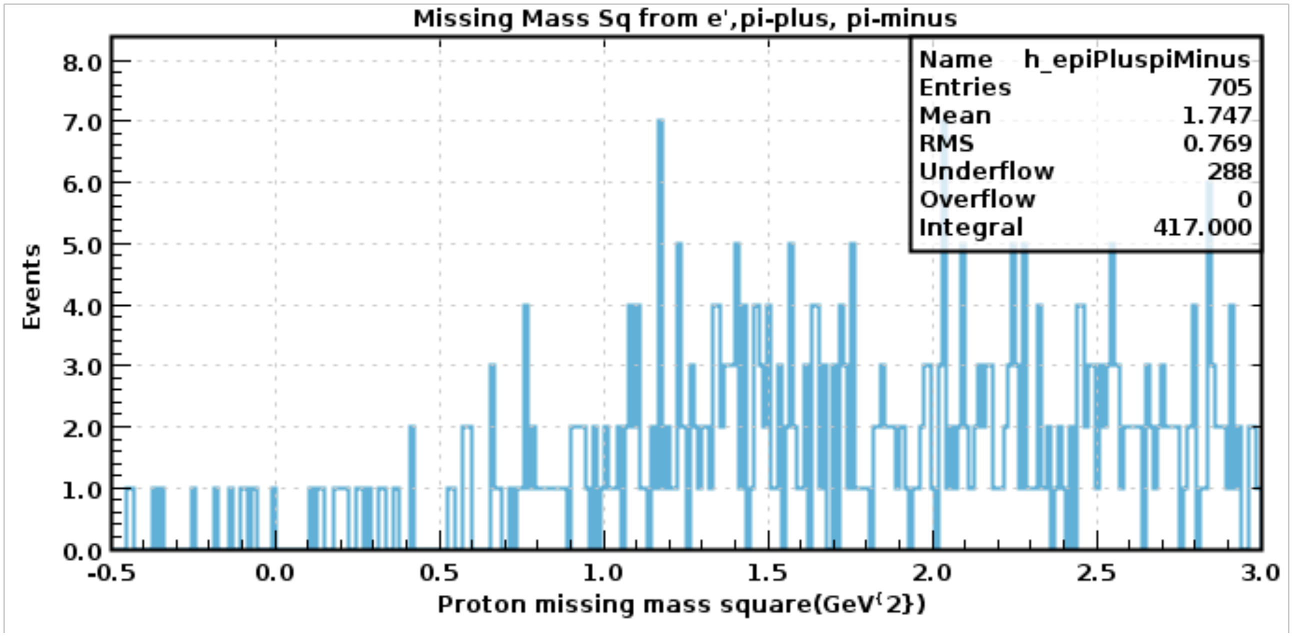

- Missing mass square of $\pi^-$




- Missing mass square of $\pi^+$

# Real Data Analysis

- Run_Number 3050(6.4GeV)




- Missing mass square of Proton

Thresholds look physical, but no sign of an exclusive peak in any of the three channels

- Particle ID?
- Momentum Calibrations?

# Conclusion



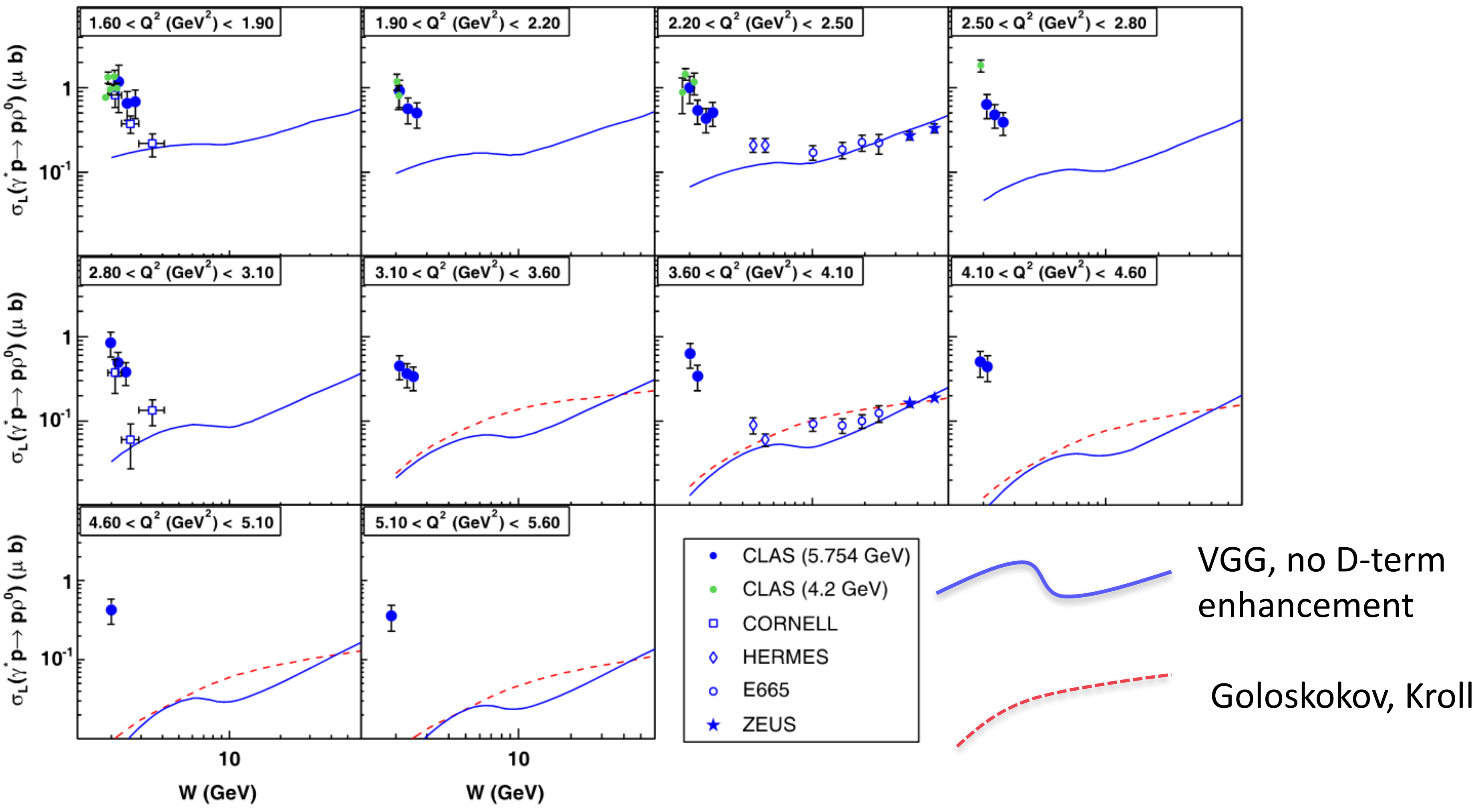
- Preparing a run group proposal
  - Working on full cross section model
- Continue with 10.6 GeV data analysis

# Back Up Slides

- Deep $\rho$ is a background to deep $\sigma$ in $\pi^{+}\pi^{-}$ channel
  - Theory work on deep $\rho$
    - G-K Transversity
    - C.Weiss: Instanton dynamics study in progress.
- Detecting deep σ in the $\pi^0\pi^0$ channel is challenging in CLAS12.

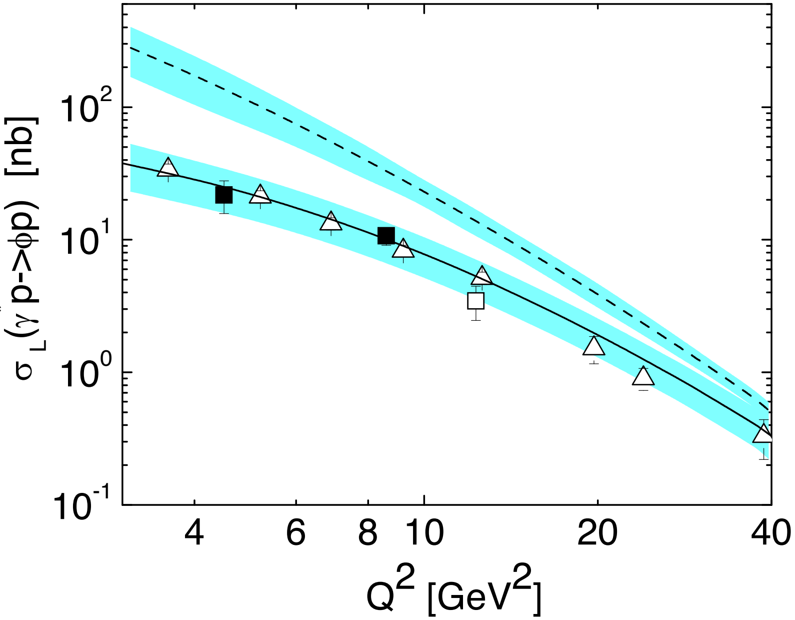
# Deep $\rho$ meson Problem

- S-channel helicity conservation violated
- Cross section is anomalously large at low W

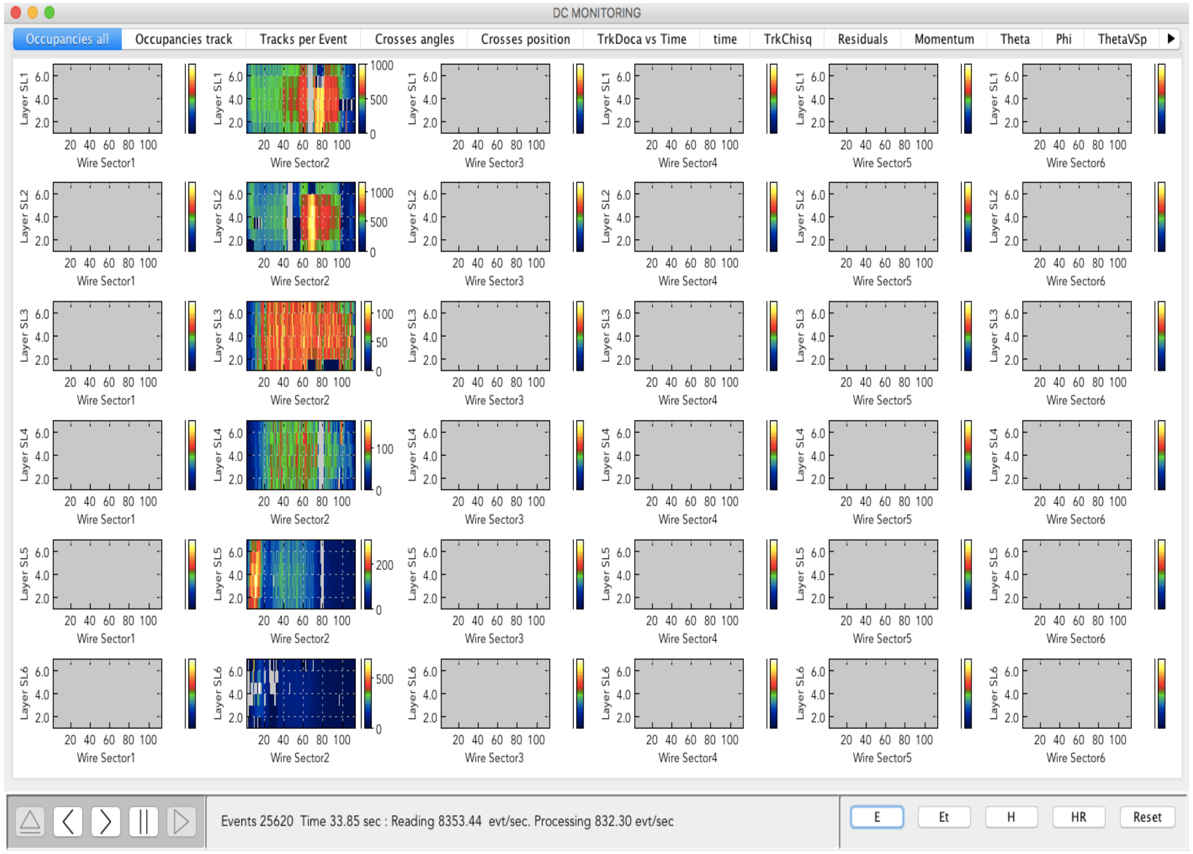


# The Deep $\phi$-meson

- Corrections up to factor of 10 to leading-order factorization at Jlab kinematics
- Successful phenomenology with finite-size/$\chi$SB in $\gamma \rightarrow$meson amplitud and kinematic higher twist in proton GPD.
  - Deep $\pi^0$, η: $\chi$SB Twist-3 DA⊗$GPD_T$
    - $d\sigma_T >> d\sigma_L$
    - (Recent Hall A and CLAS results)
- Deep $\phi$ : Sudakov form factor (finite-size) suppression:
  - CLAS/HERMES/HERA data ➔



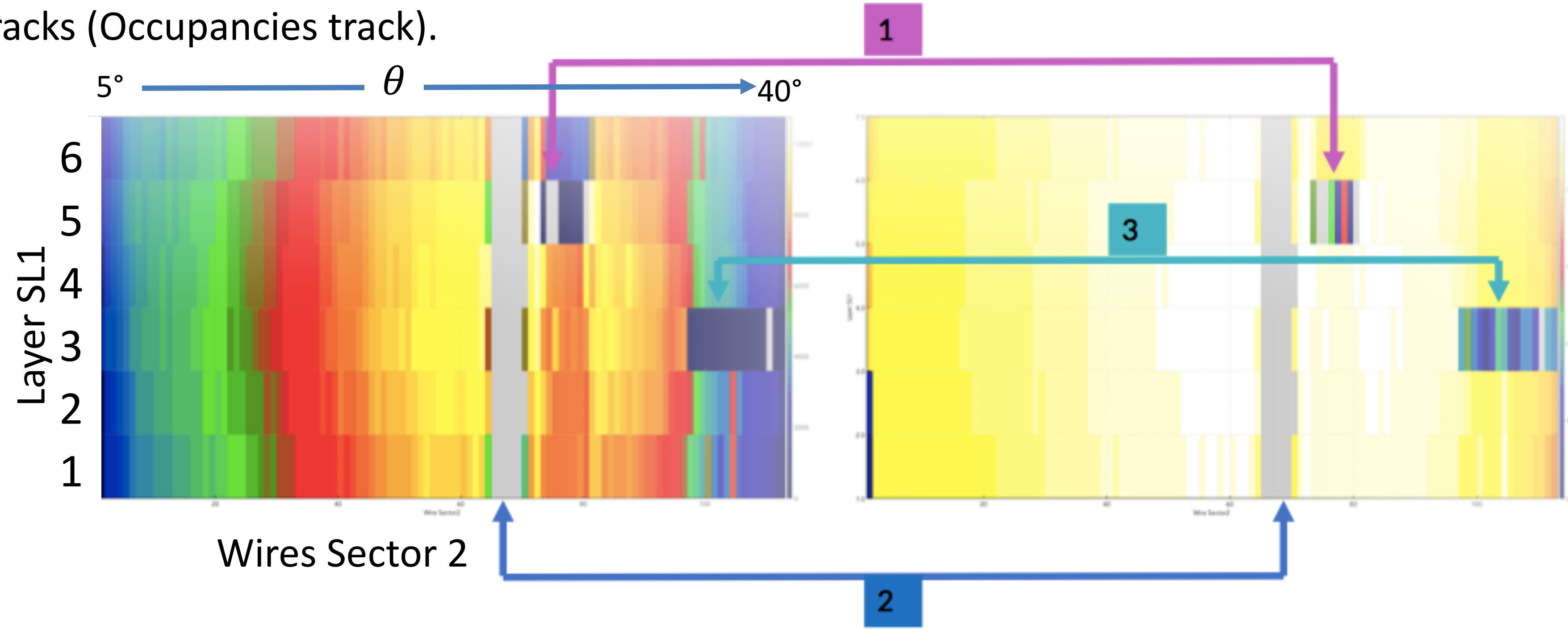
# Service Project : DC Monitoring




- Occupancy Plots
- Track per Event
- Time
- Track DOCA vs Time
- Residual
- $\Delta t$ *Plot*
- Hits per track
- Residual vs Track DOCA
- Crosses angles
- Crosses Position

# Service Project : Occupancy Plots

**Occupancy Plots**: it displays plots of layer versus wire for all the hits (Occupancy Raw) in the DC::TDC bank, for all the hits in the TBHits bank (Occupancies all) and for the hits used only in tracks (Occupancies track).



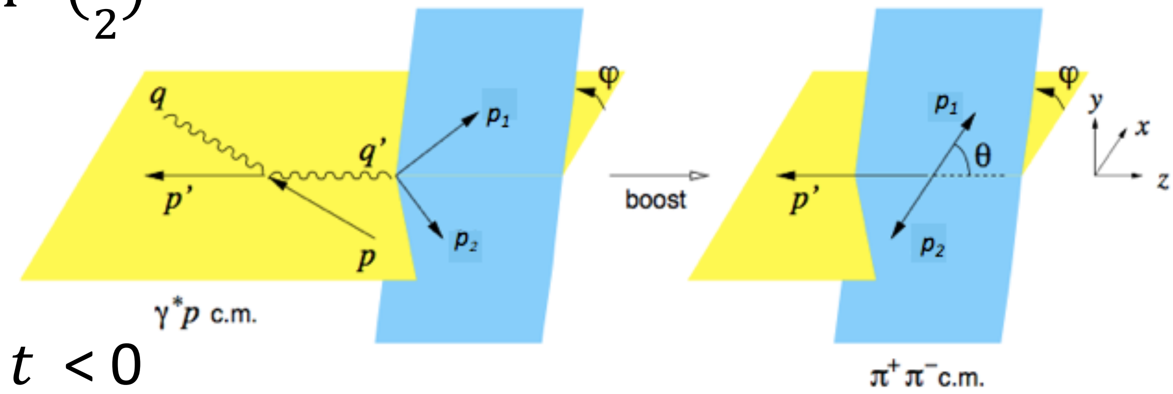

| Anomaly | How to spot it |
|---|---|
| Individual dead wire | A single hole |
| Individual hot wire | A single hot spot |
| Unplugged Signal connector | 16 wires: Vertical stripe, 6 layers high by 2 or 3 wires wide |
| Blown lv fuse | 32 wires: Vertical stripe, 6 layers high by 5-6 wires wide |
| Unplugged hv pin, sense wire | Horizontal stripe, 1 layer high by 8 wires wide (or 16 if past wire 80) |
| 2 Unplugged hv pin, sense wire | Horizontal stripe, 2 layer high by 8 wires wide (or 16 if past wire 80) **almost no counts** |
| Unplugged hv pin, field wire | Horizontal stripe, 2 layer high by 8 wires wide (or 16 if past wire 80) **only depleted** |
| Tripped hv supply channel or rarely a malfunction signal board | Rectangular hole: 6 layer high by 8 wires wide (wire 1-48); 16 wires wide (wire 49 - 80); and 32 wires wide (wires 81 - 112) |

# Basic Kinematics and Observables

- Here are the exclusive two-pion electroproduction kinematics on a proton using the following momentum variables:

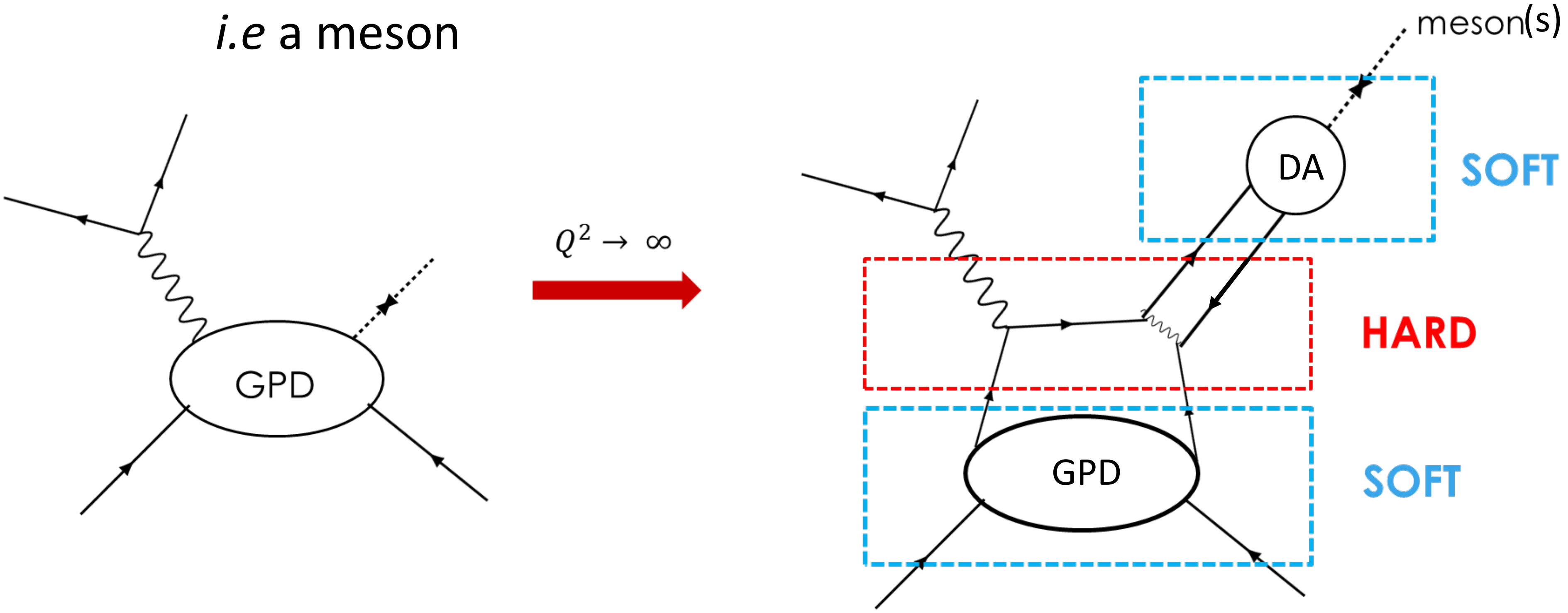
$$\boldsymbol{e(k) + P(P) \rightarrow e(k') + \pi_1(p_1) + \pi_2(p_2) + P(P')} \,.$$

- $q = k - k'$
- $q^2 = -Q^2 = 4EE' \sin^2\left(\frac{\theta}{2}\right)$
- $\nu = E - E'$
- $W^2 = (P + q)^2$
- $x_{\mathrm{B}} = \boldsymbol{\frac{Q^2}{2P.q}}$
- $\Delta = P' - P$ and $\Delta^2 = t < 0$
- $(p_1 + p_2)^2 = m_{\pi\pi}{}^2$
- $q' = p_1 + p_2$ (e.g. σ or ρ meson)



# Deep Virtual Exclusive Scattering (DVES)

- $ep \rightarrow e'p'h$ where h is the hadronic system *i.e* a meson




- The interaction of the scattered electron with a parton (HARD), calculable through perturbative QCD, and the parton interaction with the proton (SOFT), described in terms of GPDs and another soft part describes the meson production.

# GPD

Traditionally, elastic form factors and parton distribution functions (PDFs) were considered totally unrelated:

Elastic form factors give information on the charge and magnetization distributions in the transverse plane;

PDFs describe the distribution of partons in the longitudinal direction.

Generalized Parton Distributions encode information on the distribution of partons both in the transverse plane and in the longitudinal direction

→ natural extension and continuation of studies of the hadron structure.

# Leading Order Amplitudes

$$\langle B_2(p'),\pi^a\pi^b(q')|J^{\mathrm{e.m.}}\cdot\varepsilon_L|B_1(p)\rangle$$

$$= -(e4\pi\alpha_s)\frac{N_c^2-1}{N_c^2}\frac{1}{4Q}\int_{-1}^{1}d\tau\int_0^1 dz$$

$$\times\Bigg[\sum_{f,f'}F_{ff'}(\tau,\xi)\Phi_{f'f}^{ab}(z,\zeta,m_{\pi\pi})$$

$$\times\left\{\frac{e_{f'}}{z(\tau+\xi)-i0}+\frac{e_f}{(1-z)(\tau-\xi)+i0}\right\}$$

$$-\frac{2N_c}{N_c^2-1}\sum_f e_f F_{ff}(\tau,\xi)\Phi_G^{ab}(z,\zeta,m_{\pi\pi})$$

$$\times\frac{1}{z(1-z)}\left\{\frac{1}{(\tau+\xi)-i0}-\frac{1}{(\tau-\xi)+i0}\right\}$$

$$+\frac{4N_c}{N_c^2-1}\sum_f e_f\tau F_G(\tau,\xi)\Phi_{ff}^{ab}(z,\zeta,m_{\pi\pi})$$

$$\times\frac{1}{z(1-z)}\frac{1}{[\tau+\xi-i0][\tau-\xi+i0]}\Bigg]. \qquad (4)$$

$e_f$ is the charge of a quark of flavor f=u,d,s in units of the proton charge.

$\xi$ is the skewness parameter

*$\zeta$ is the longitudinal momentum fraction carried by the pion.*

The function $F_{ff'}(\tau,\xi)$ is a skewed quark distribution defined as:

$$F_{ff'}(\tau,\xi)=\int\frac{d\lambda}{2\pi}e^{i\lambda\tau}\langle B_2(p')|T\{\bar{\psi}_{f'}(-\lambda n/2)$$
$$\times\hat{n}\psi_f(\lambda n/2)\}|B_1(p)\rangle, \qquad (6)$$

The quark two-pion distribution amplitude $\Phi_{f'f}^{ab}(z,\zeta)$ is defined as:

$$\Phi_{f'f}^{ab}(z,\zeta)=\int\frac{d\lambda}{2\pi}e^{-i\lambda z(q'\cdot n^*)}\langle\pi^a\pi^b|T\{\bar{\psi}_f(\lambda n^*)$$

and the two-pion gluon distribution amplitude $\Phi_G^{ab}(z,\zeta)$ as:

$$\Phi_G^{ab}(z,\zeta,m_{\pi\pi}^2)=\frac{1}{n^*\cdot q'}\int\frac{d\lambda}{2\pi}e^{-i\lambda z(q'\cdot n^*)}$$
$$\times\langle\pi^a\pi^b|\{n^{*\mu}n^{*\nu}G^A_{\alpha\mu}(\lambda n^*)$$
$$\times G_\nu^{A\alpha}(0)\}|0\rangle, \qquad (9)$$

– $\pi^+\pi^-$ *production:*

$$\Phi_{\pi^+\pi^-}^{f'f}(z,\zeta,m_{\pi\pi}) = \delta^{f'f}\Phi^{I=0}(z,\zeta,m_{\pi\pi}) + \tau_3^{f'f}\Phi^{I=1}(z,\zeta,m_{\pi\pi}), \quad (13)$$

$$\Phi_G^{\pi^+\pi^-}(z,\zeta,m_{\pi\pi}) = \Phi^G(z,\zeta,m_{\pi\pi}), \quad (14)$$

– $\pi^0\pi^0$ *production:*

$$\Phi_{\pi^0\pi^0}^{f'f}(z,\zeta,m_{\pi\pi}) = \delta^{f'f}\Phi^{I=0}(z,\zeta,m_{\pi\pi}), \quad (15)$$

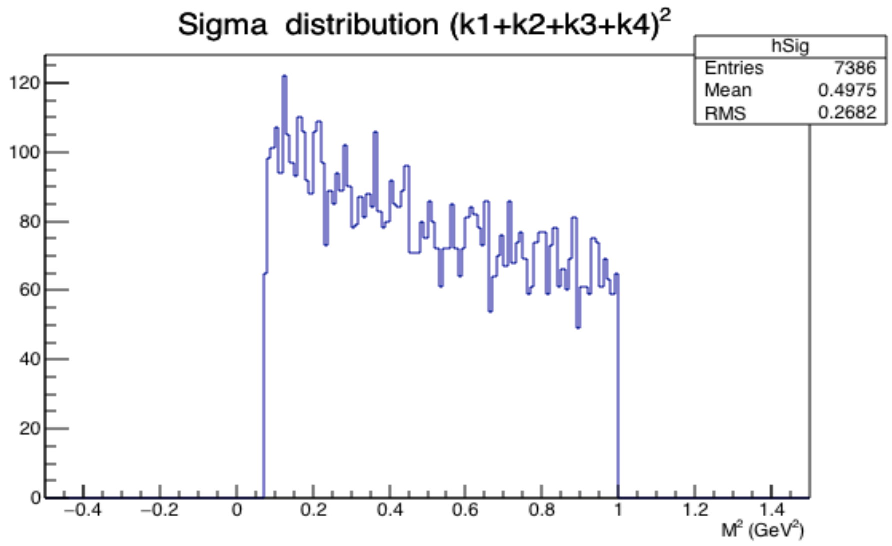
$$\Phi_G^{\pi^0\pi^0}(z,\zeta,m_{\pi\pi}) = \Phi^G(z,\zeta,m_{\pi\pi}), \quad (16)$$

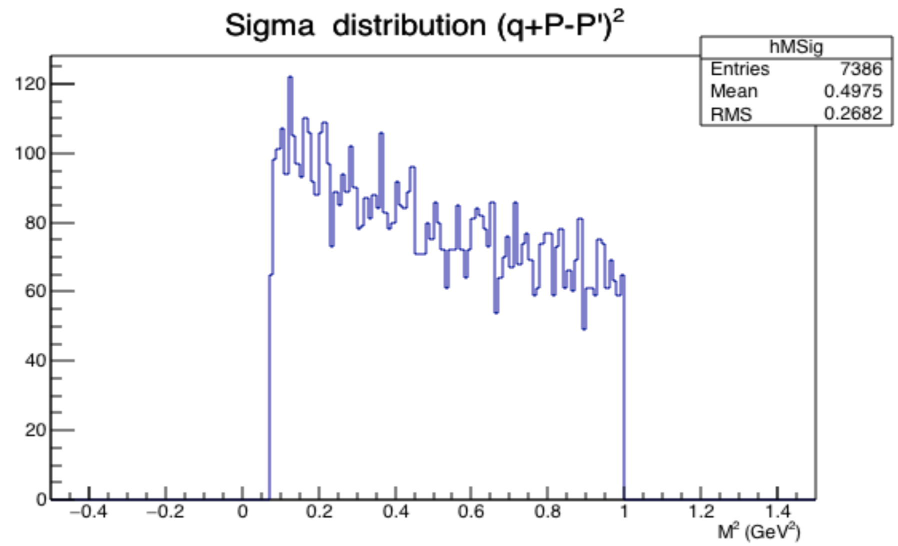
# CLAS12 Detector

HTCC- Detection with charged pions with momentum above 5 GeV/c
LTCC- Charged pion identification for p>3GeV/c
FTOF- for precise time-of-flight measurements for charged particle identification
FT-measures the small angle scattered electrons using a lead tungsten inner calorimeter
CTOF- particle identification is achieved with the central time of flight scintillator array, CTOF array allows for particle identification in momentum range upto 1.2GeV/c, 0.65 GeV/c for pi/p and pi/k separation
EC-To detect showering particles
IC-(Inner Calorimeter) High energy resolution photon detector
Cherenkov Counter- e/pi seperation
RICH- π/K and p/K separation
Micromegas-moderate magnetic field
SVT-very little thing,around target. take tracking information. Silican tracker is great for locating a vertex

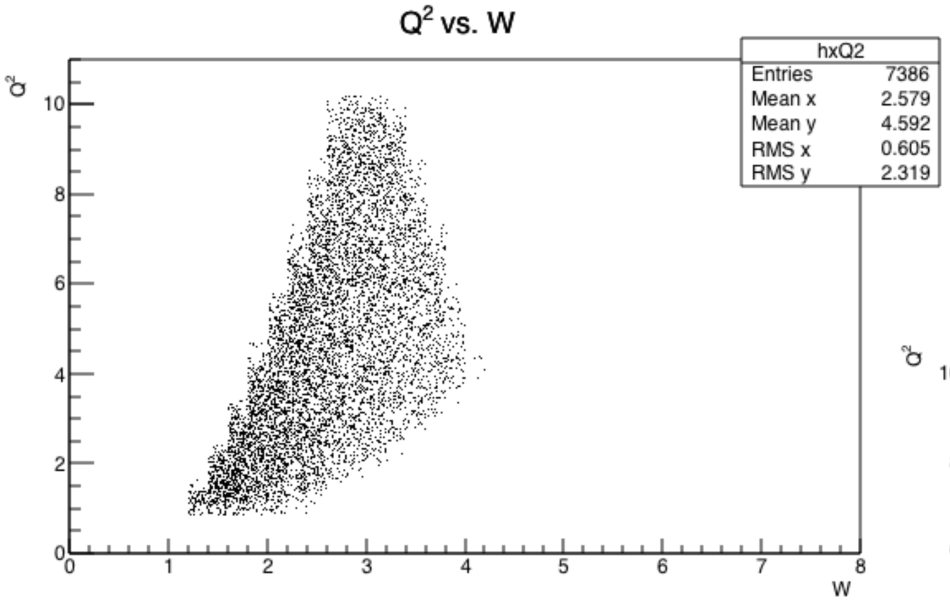
# Event Generation

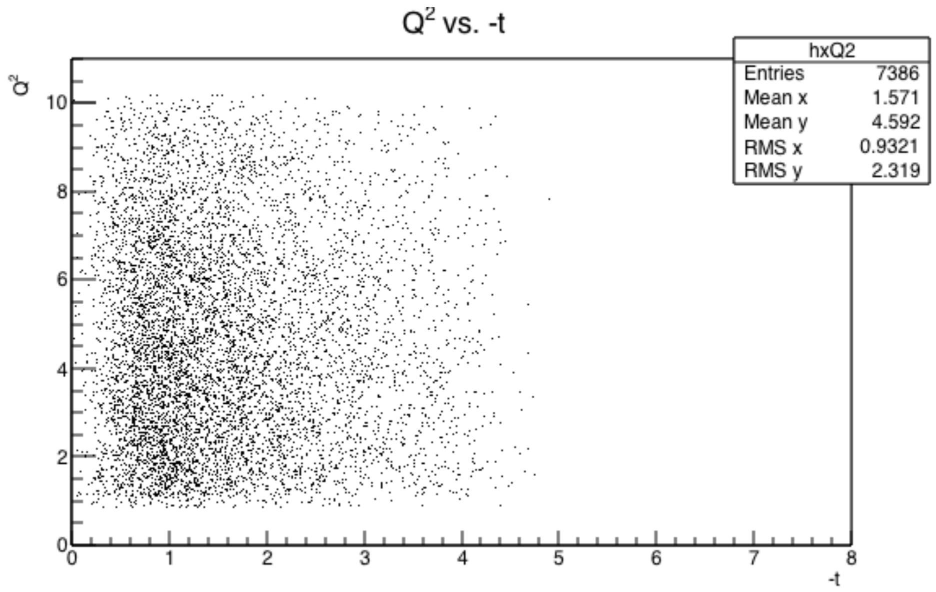
- From **ep → ep'$\boldsymbol{\pi^0}$ $\boldsymbol{\pi^0}$,** $\pi^0$ decays into two gammas **($\boldsymbol{\pi^0 \rightarrow \gamma\, \gamma}$ )**
- Now we have 4 gammas. We can check Sigma Distribution in two ways
  - $(k_1 + k_2 + k_3 + k_4)^2$
  - $(q + p - p')^2$



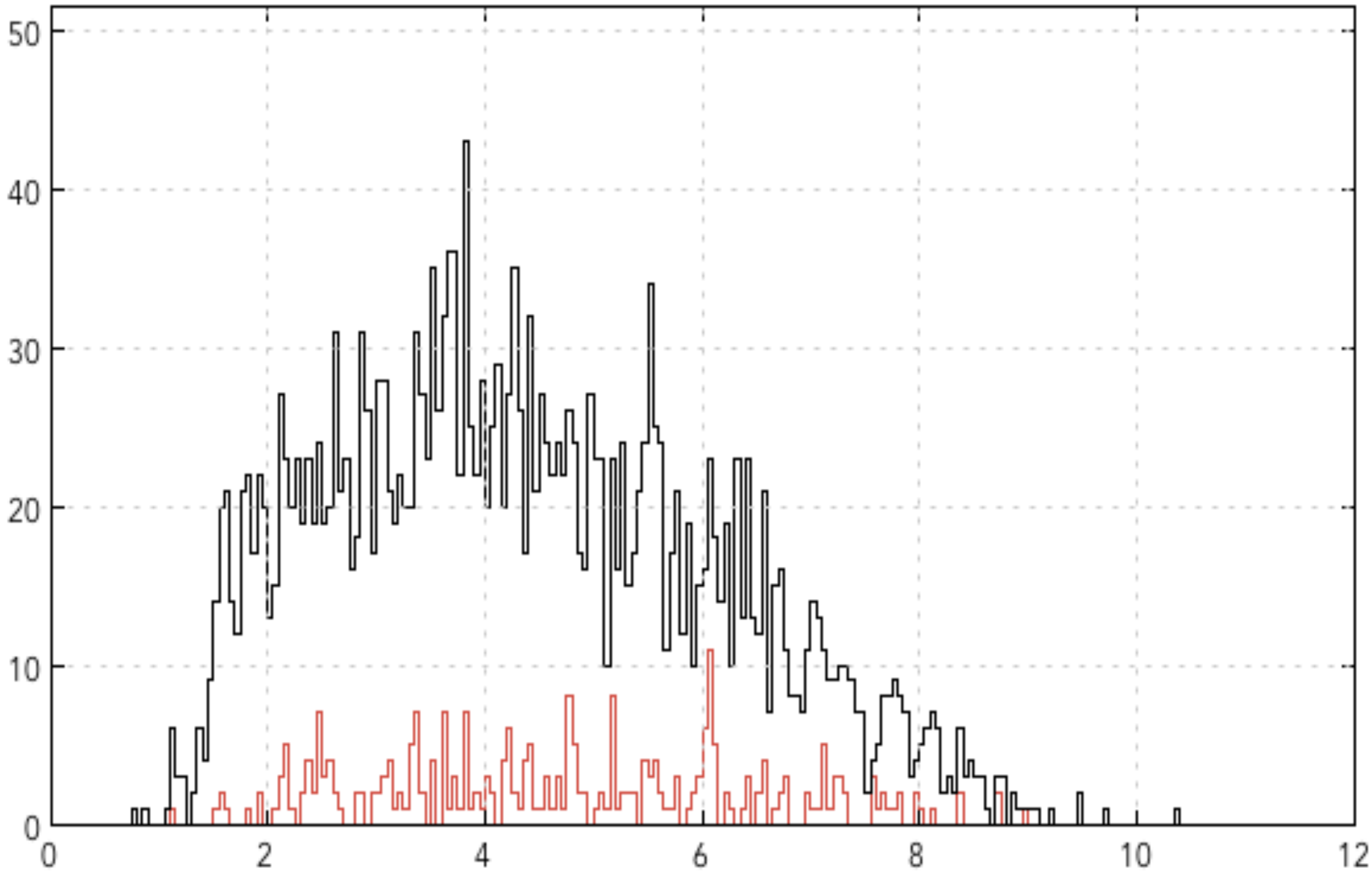



# Event Generation



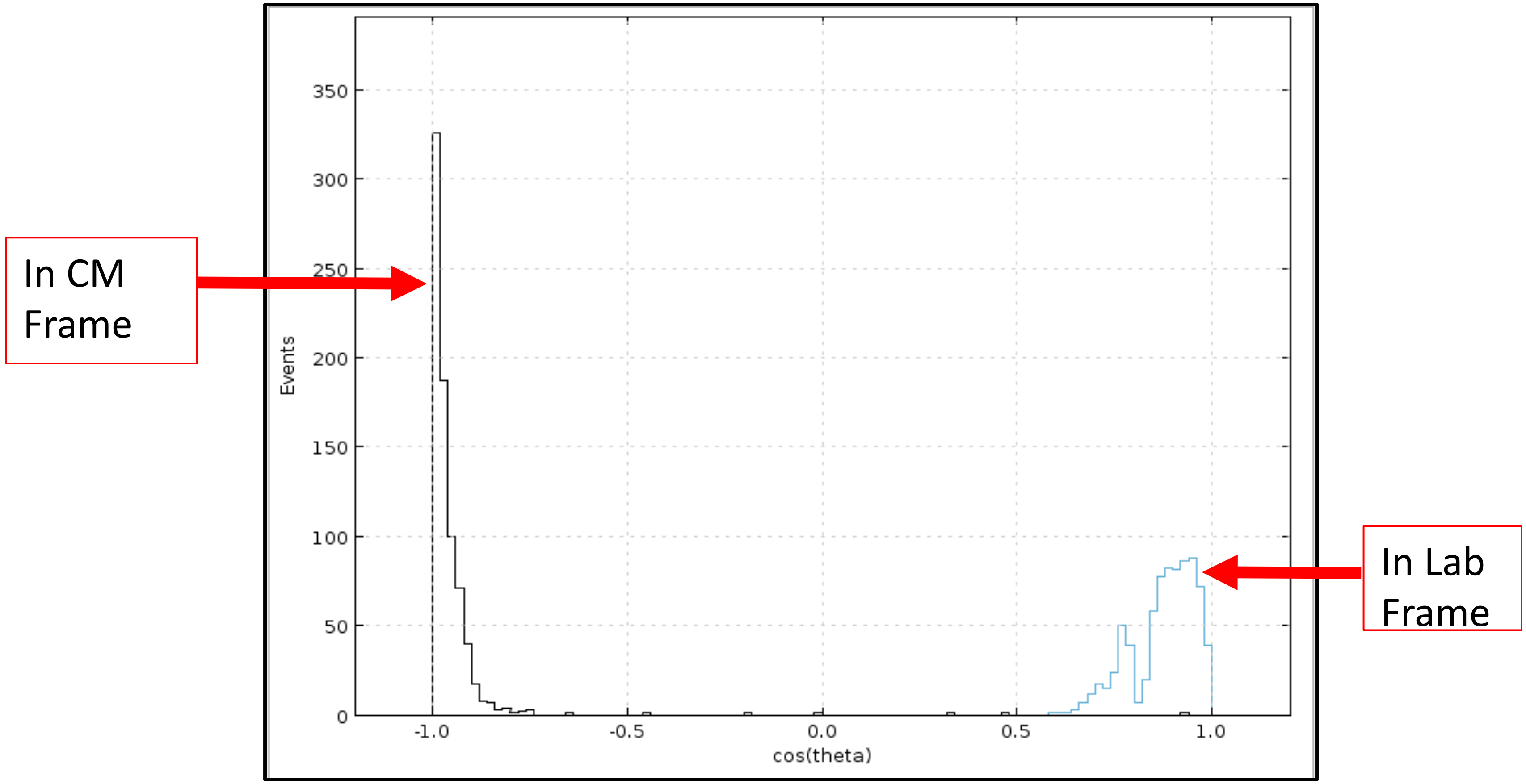



# Analysis



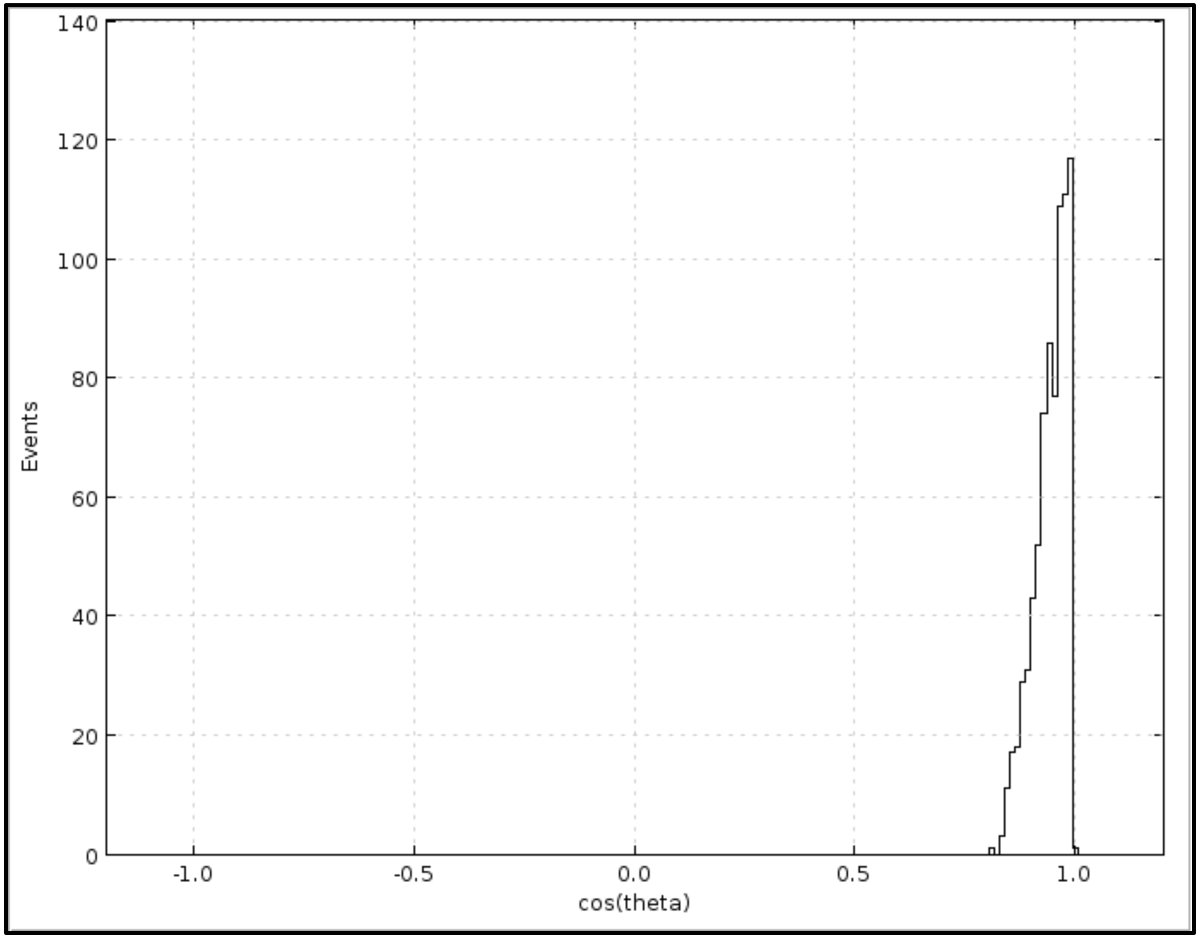
# Analysis

- Here is the proton cosine distribution in both lab frame and CM frame
- Protons are forward direction in the Lab frame
- But in the CM frame they are100% backward

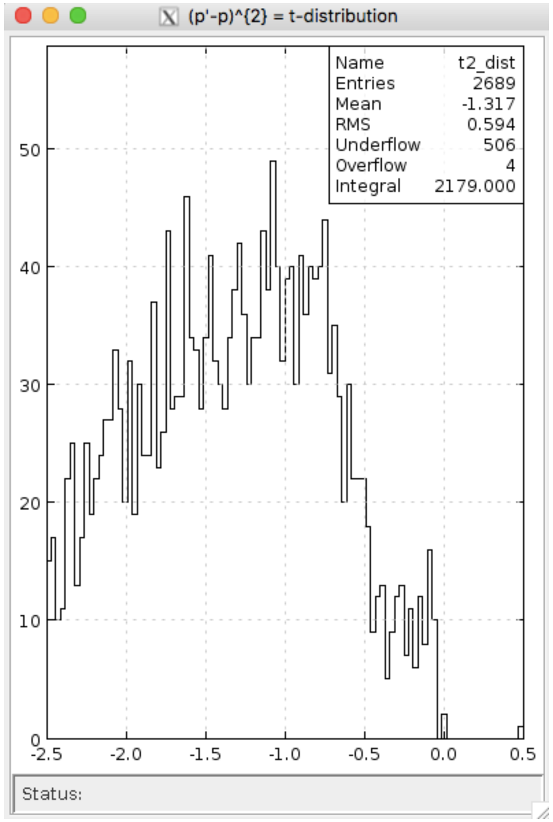


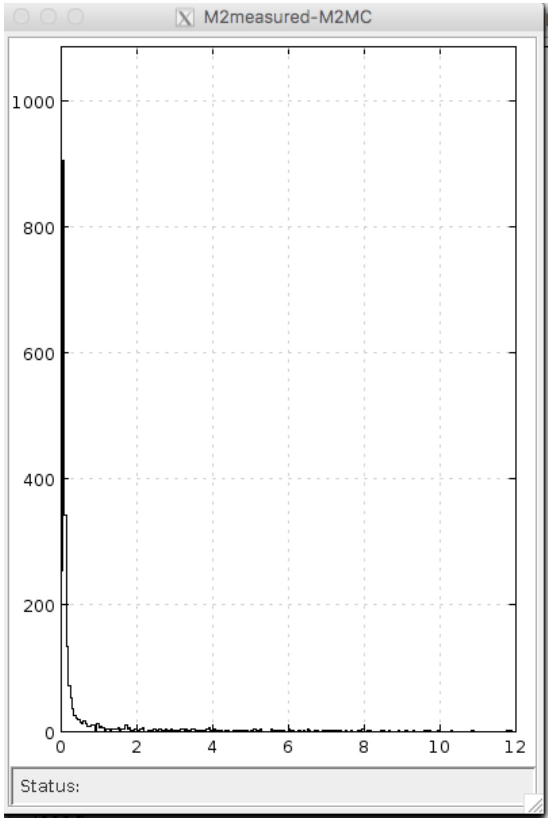
# Analysis

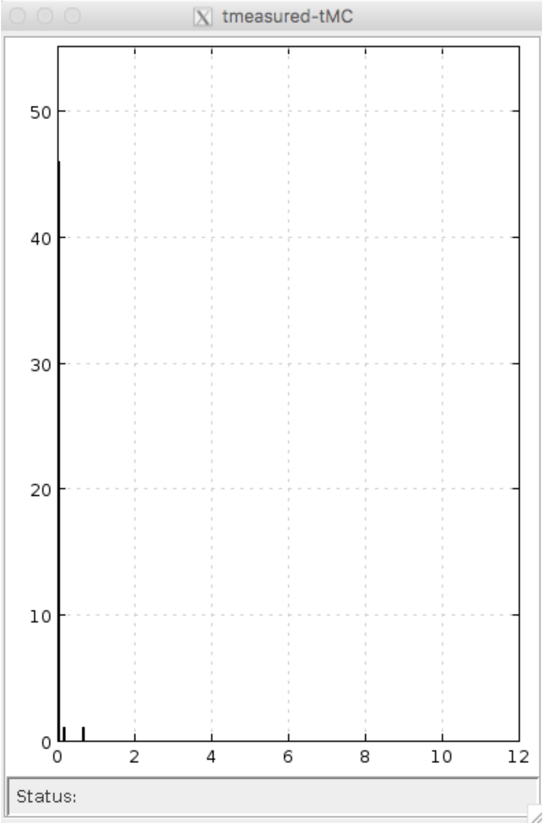
- Treat pi-minus as "missing" even if detected
- Here is the cosine distribution in rest frame
- This said that, piplus is always forward.

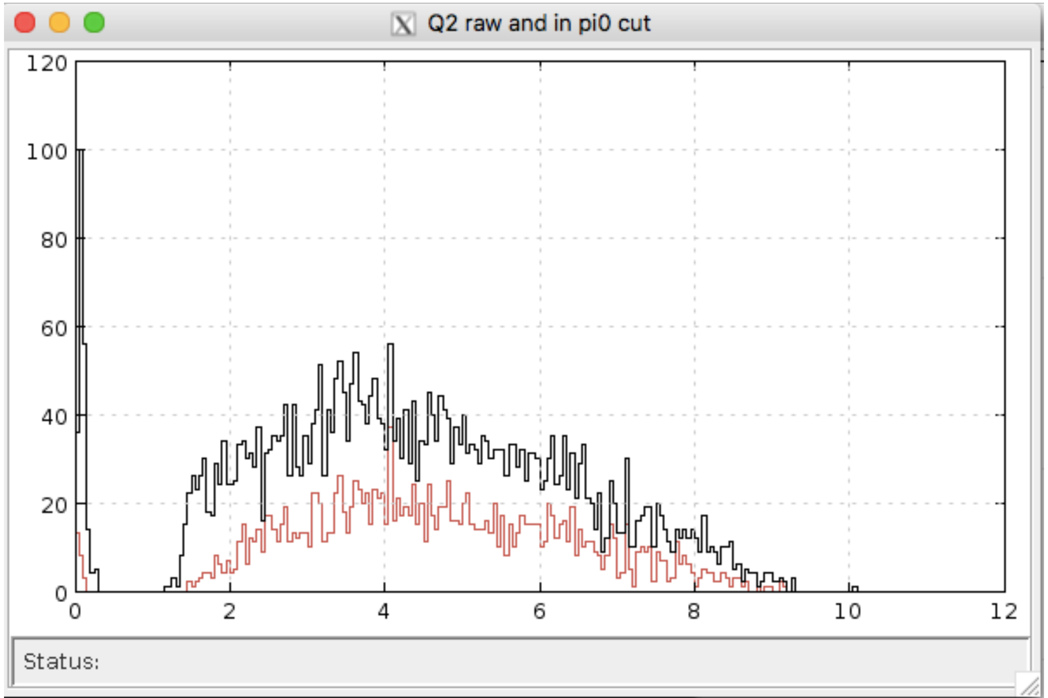


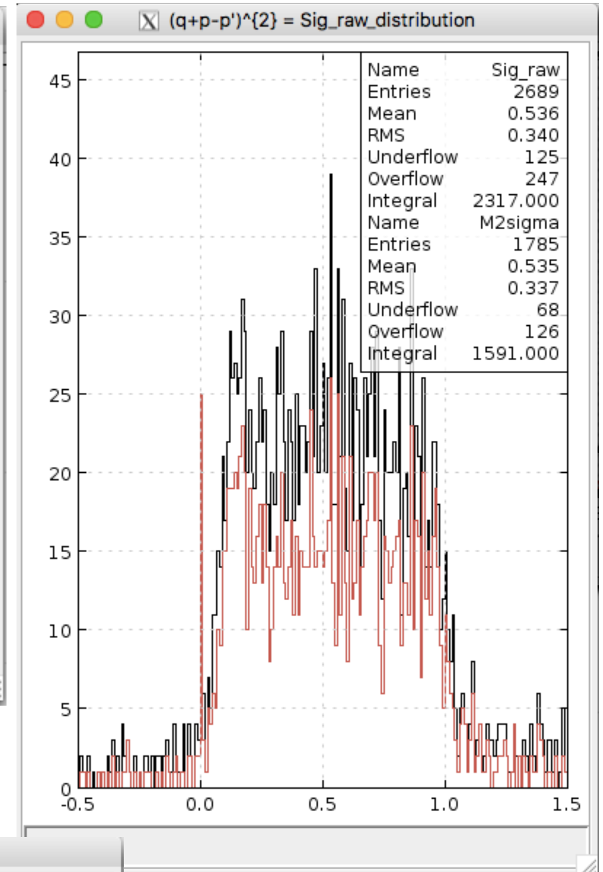
# Analysis

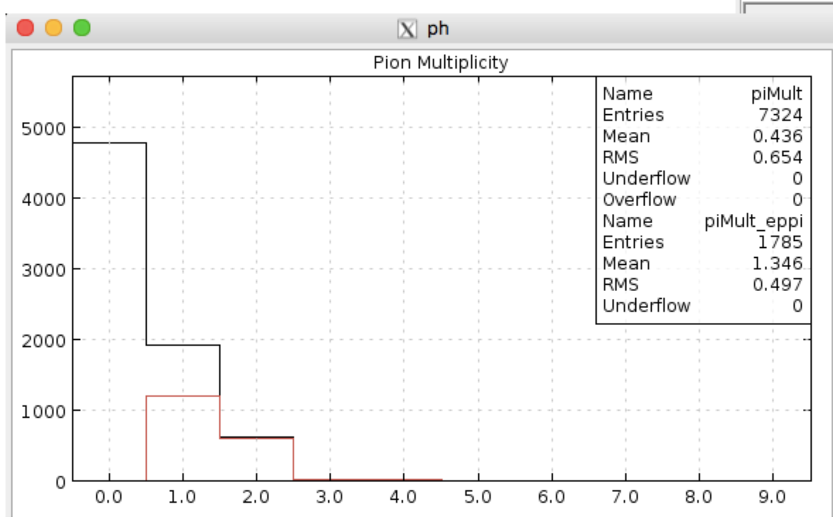

(p'-p)^{2} = t-distribution
Name t2_dist
Entries 2689
Mean -1.317
RMS 0.594
Underflow 506
Overflow 4
Integral 2179.000
Status:

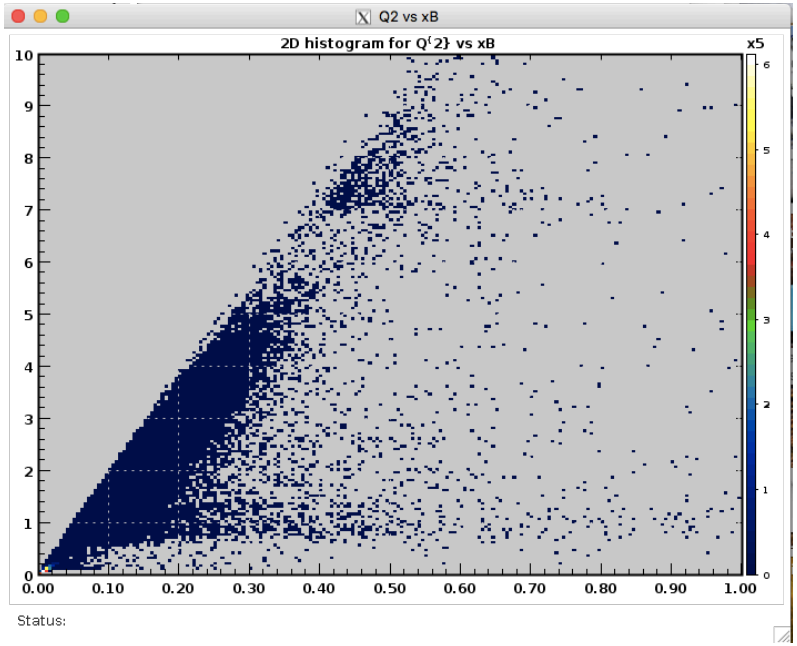

M2measured-M2MC
Status:


tmeasured-tMC
Status:

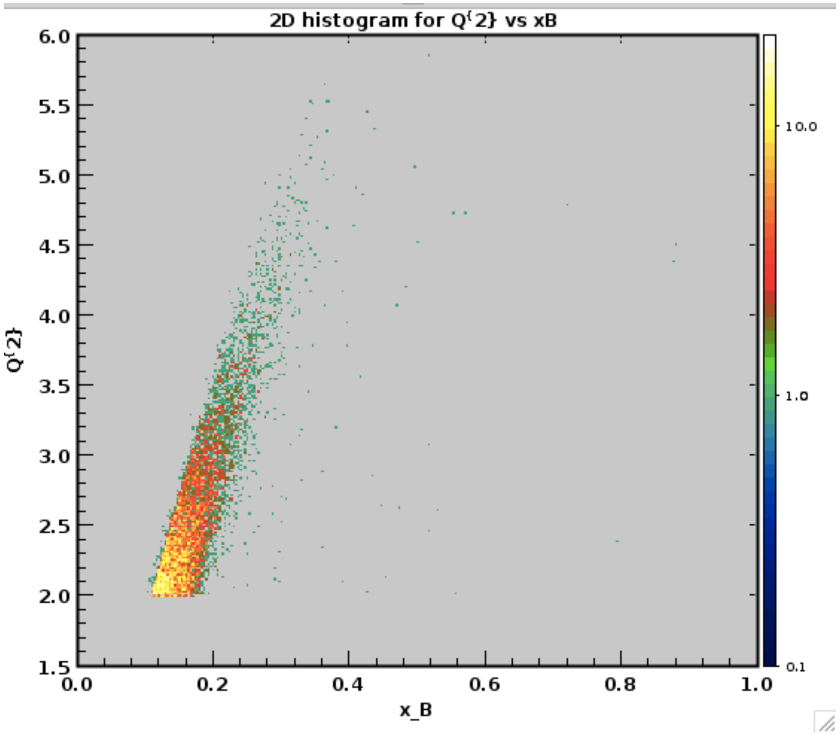

Q2 raw and in pi0 cut
120
100
80
60
40
20
0
0
2
4
6
8
10
12
Status:

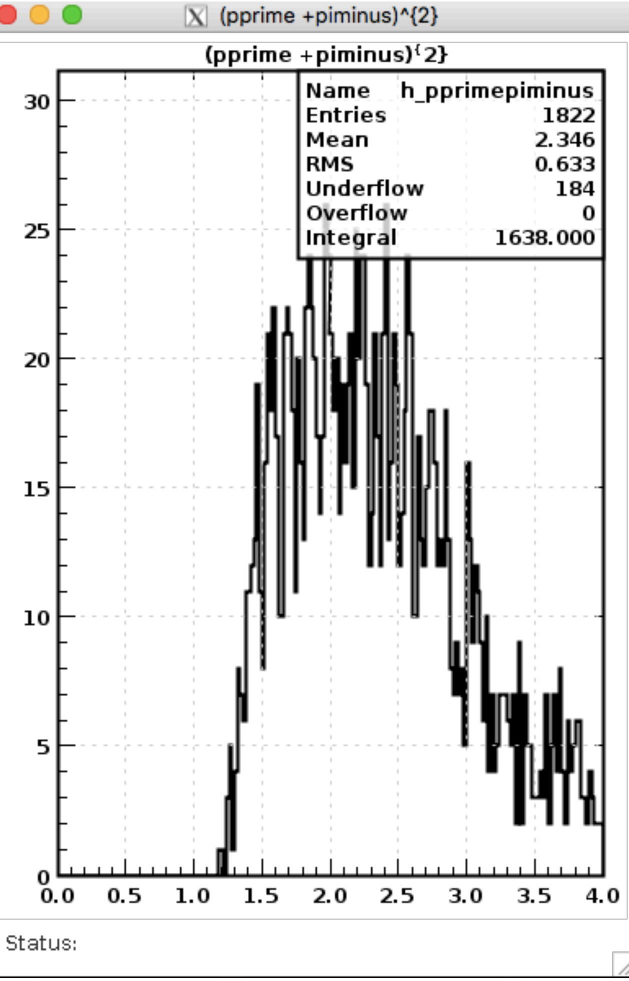

(q+p-p')^{2} = Sig_raw_distribution
Name Sig_raw
Entries 2689
Mean 0.536
RMS 0.340
Underflow 125
Overflow 247
Integral 2317.000
Name M2sigma
Entries 1785
Mean 0.535
RMS 0.337
Underflow 68
Overflow 126
Integral 1591.000
45
40
35
30
25
20
15
10
5
0
-0.5
0.0
0.5
1.0
1.5

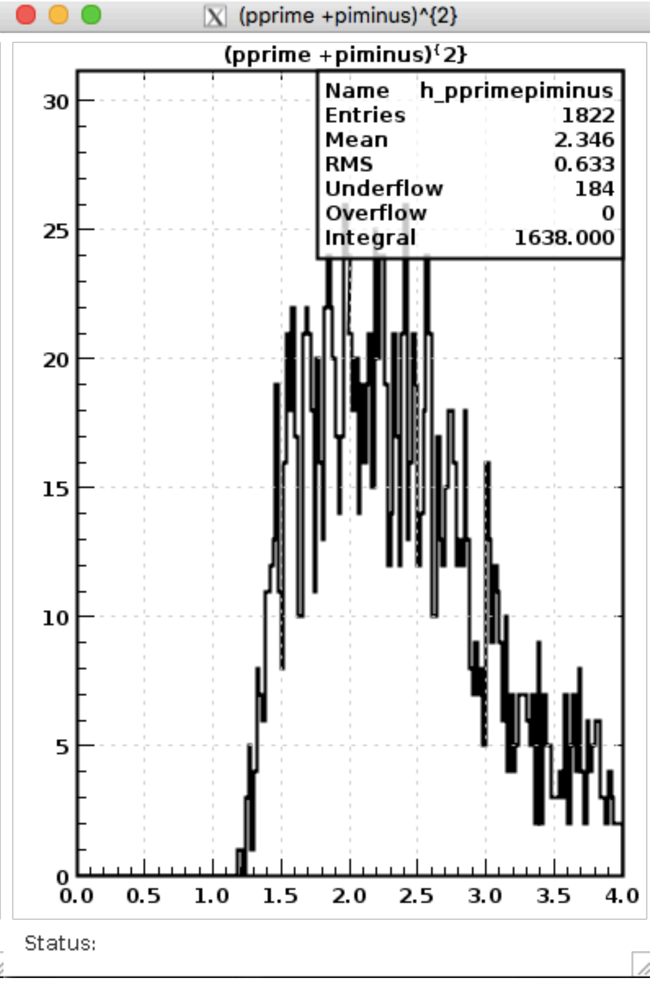

ph
Pion Multiplicity
Name piMult
Entries 7324
Mean 0.436
RMS 0.654
Underflow 0
Overflow 0
Name piMult_eppi
Entries 1785
Mean 1.346
RMS 0.497
Underflow 0
5000
4000
3000
2000
1000
0
0.0
1.0
2.0
3.0
4.0
5.0
6.0
7.0
8.0
9.0

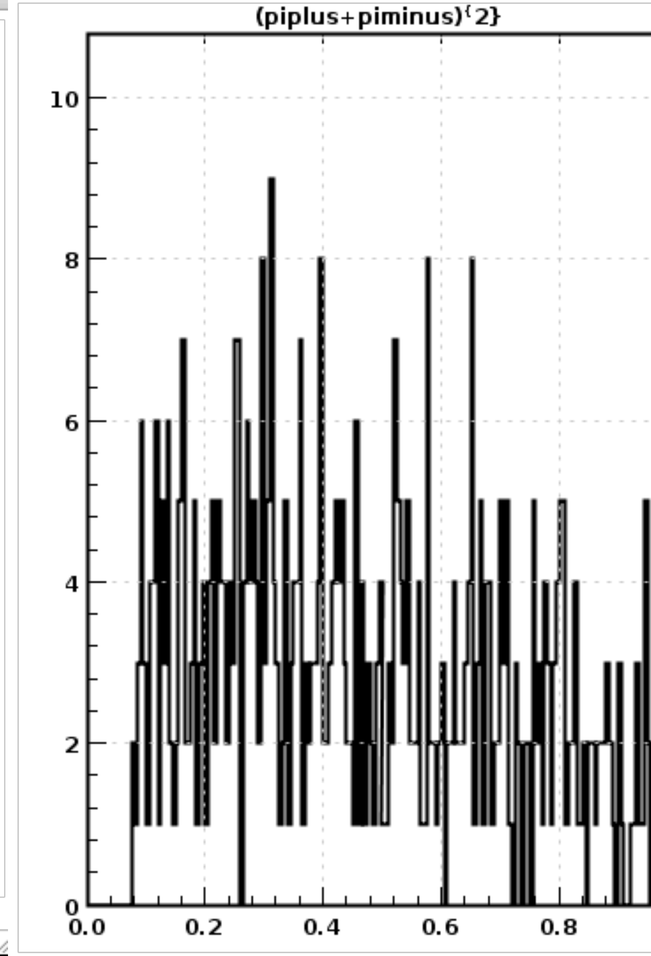



After cut
Q^{2}>2
log plot




(pprime +piminus)^{2}
(pprime +piminus)^{2}
Name h_pprimepiminus
Entries 1822
Mean 2.346
RMS 0.633
Underflow 184
Overflow 0
Integral 1638.000
Status:


(pprime +piminus)^{2}
(pprime +piminus)^{2}
Name h_pprimepiminus
Entries 1822
Mean 2.346
RMS 0.633
Underflow 184
Overflow 0
Integral 1638.000
Status:


(piplus+piminus)^{2}