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π^0 SIDIS MULTIPLICITIES: GAMMA DETECTION EFFICIENCY AT CLAS12

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U.S. DEPARTMENT OF ENERGY
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MULTIPLICITY

What do we extract?

Radiative Corrections

Raw Event Yield

Background

Corrected SIDIS yield

$$N^{h,\mathrm{corr}}_{ijmn} = C^{h}_{\mathrm{rad}\,ijmn} \sum_{k} \frac{N^{h,\mathrm{raw}}_{ijmn} - N^{h,\mathrm{bkg}}_{ijmn}}{A^{h}_{ijmnk}}$$

k is φ bin

Acceptance and Efficiency Correction

$$M^{h}_{ijmn} = \frac{1}{\Delta z_m \, \Delta P^2_{T,n}} \frac{N^{h,\mathrm{corr}}_{ijmn}}{N^{\mathrm{DIS,\,corr}}_{ij}}, \quad (i,j,m,n) \equiv (x_B\text{-bin},\ Q^2\text{-bin},\ z\text{-bin},\ P_T^2\text{-bin})$$

z-P_T^2 bin size

Radiative Corrections

Raw Event Yield

Corrected DIS yield

$$N^{\mathrm{DIS,\,corr}}_{ij} = C^{\mathrm{DIS}}_{\mathrm{rad}\ ij} \frac{N^{e,\mathrm{raw}}_{ij}}{A^{e}_{ij}}$$

Acceptance and Efficiency Correction

- Electron-side efficiencies partially cancel out in the ratio

STATUS OF THE ANALYSIS

Updated:

- γ/π^0 Efficiency MC/Data studies

To do:

- Estimate systematic uncertainties
- VM contamination studies

Completed:

- Particle ID
- Smearing
- Acceptance Corrections
- Radiative corrections

On the way:

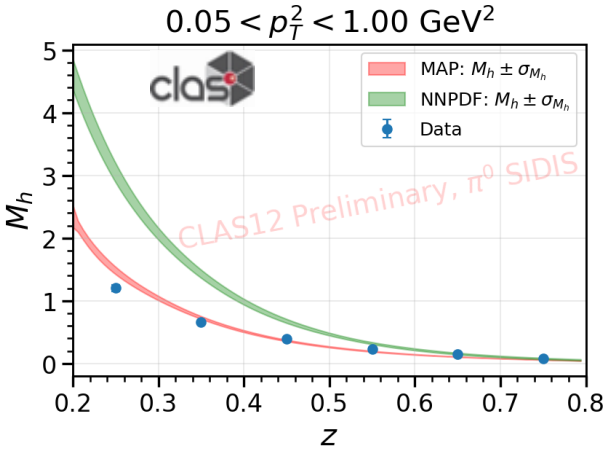
- Theory predictions with NLO MAP22 model + NN-based global Fit

RESULTS

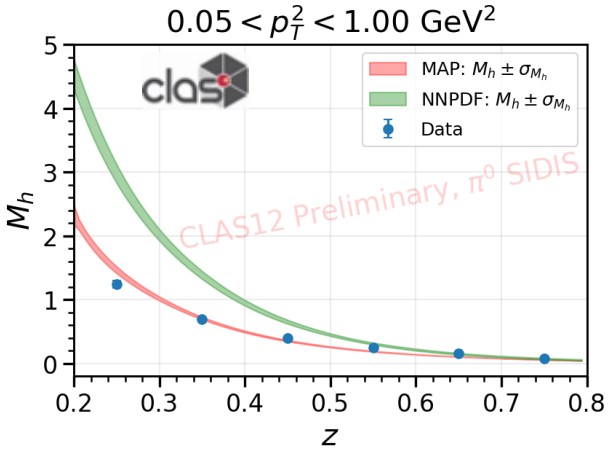
$M_h(z)$ integrated over P_T^2 for selected x-Q^2 bins

P_T^2 integrated multiplicity:

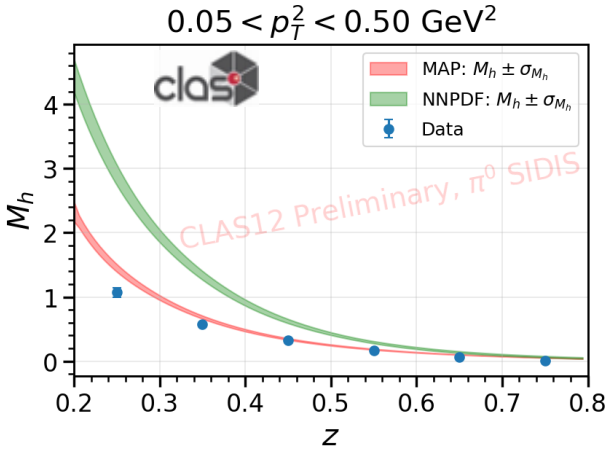
$$M_h = \frac{\sum_q e_q^2 f_q(x) D_q(z)}{\sum_q e_q^2 f_q(x)}$$



$0.18 < x < 0.21$, $2.0 < Q^2 < 2.66$ GeV^2



$0.24 < x < 0.28$, $2.66 < Q^2 < 3.63$ GeV^2



$0.39 < x < 0.62$, $3.63 < Q^2 < 5.12$ GeV^2

- M_h was integrated over the P_T^2 range that preserves full z coverage
- The theoretical curves were computed with CT10nlo PDFs using two fragmentation-function sets:
  - **NNFF**, fitted only to single-inclusive hadron production in e^+e^- annihilation
  - **MAPFF**, which additionally includes charged-hadron multiplicity data from HERMES and COMPASS
- After integrating over P_T^2, **multiplicities** vs. z follow the trend of LO predictions using MAPFF FF and CT10nlo PDFs

GAMMA DETECTION EFFICIENCY

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PROCEDURE

Correction factor

1. Objective is to have photon detection efficiency as a function of P, Θ and ϕ
2. Select $ep \rightarrow ep\gamma X$ using Event Builder
3. Use exclusivity cuts to isolate events consistent with $ep \rightarrow ep\pi^0$ topology
4. Reconstruct the missing photon momentum from conservation laws (X in $ep \rightarrow ep\gamma X$)
5. Search for the missing photon in the $ep \rightarrow ep\gamma\gamma$ topology (subset of $ep \rightarrow ep\gamma X$)
6. Determine the reconstruction rate using a 3σ cut on ΔP:

Detected photons ⋯▶ $\dfrac{ep \rightarrow ep\gamma\gamma}{ep \rightarrow ep\gamma X}$

Expected photons ⋯▶

7. Repeat the study for both MC and data
8. Extract the photon efficiency correction from the data/MC ratio

$$\text{Eff} = \frac{\text{Data}(\#ep\gamma\gamma)}{\text{Data}(\#ep\gamma X)} \cdot \frac{\text{MC}(\#ep\gamma X)}{\text{MC}(\#ep\gamma\gamma)}$$

SAMPLES PREPARATION

- Realistic efficiency estimates require realistic MC simulations
- MC samples:
  1. Exclusive topology ($ep \rightarrow ep\pi^0$): **AAO_noRad**
  2. SIDIS background: **CLASDIS** with generated-level cut
  3. DVCS background: **DVCSgen**

- Momentum corrections used:
  1. Electron Task Force Group Corrections
  2. Additional Pierre corrections from the (J/psi) analysis

- Smearing:
  - Electron smearing from Richard Capobianco's charged-pion SIDIS study
  - Proton smearing developed from MC resolution studies

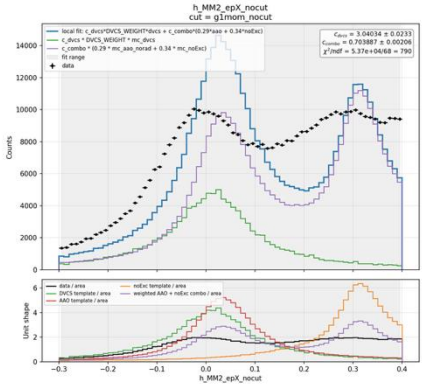
- Normalization:
  - Template fits

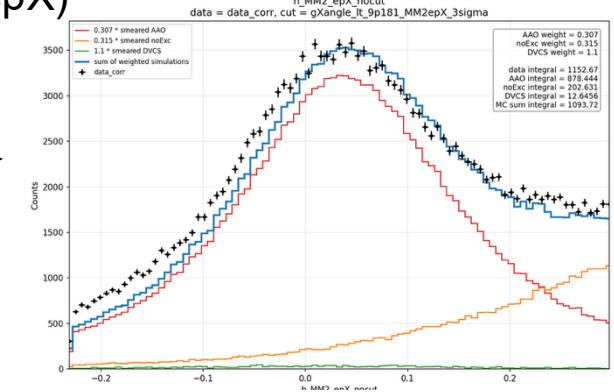
SMEARING AND MOMENTUM CORRECTIONS

- Momentum corrections follow Pierre's J/psi analysis
- Smearing is based on MC resolution
- dP(rec-gen) was fit in theta bins to estimate MC resolution
- The smearing factor was tuned to match data and MC
- Momentum smearing was applied as follows:

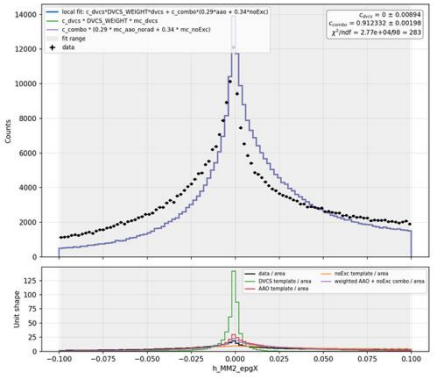
$$P_{new} = P_{rec} + F * gaus(0,1) * \sigma(\Theta)$$

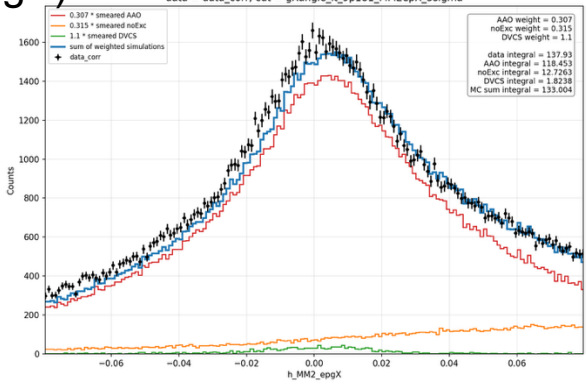
$MM^2(epX)$





$MM^2(epgX)$

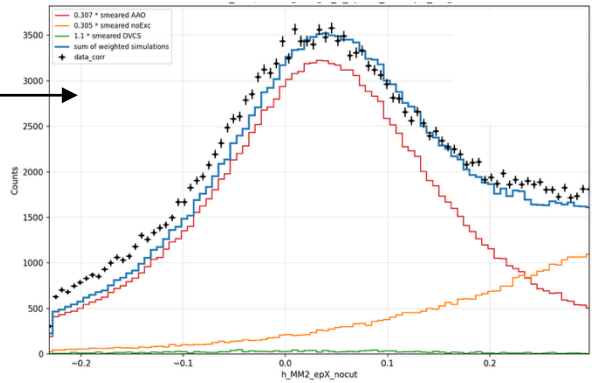




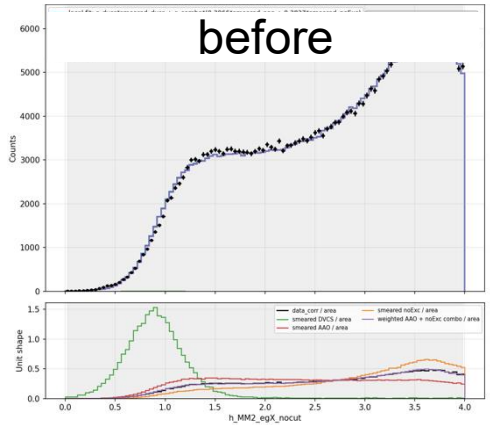
EXCLUSIVITY CUTS

- $-0.231 < MM^2(epX) < 0.309\ GeV^2$
- $MM^2(e\gamma X) > 1.4\ GeV^2$
- $-5.7 < \Delta\varphi(p,\gamma) < 5.7$
- Angle(e,X) < 9.2°

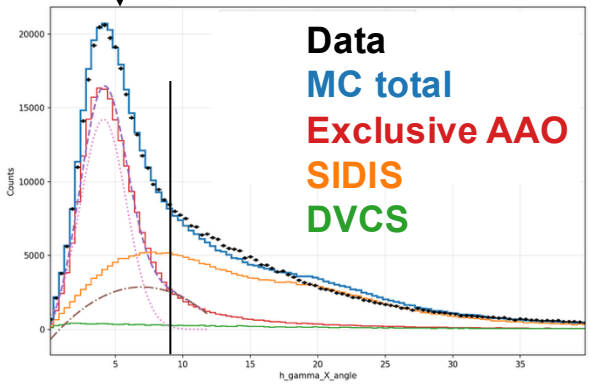
$MM^2(epX)$



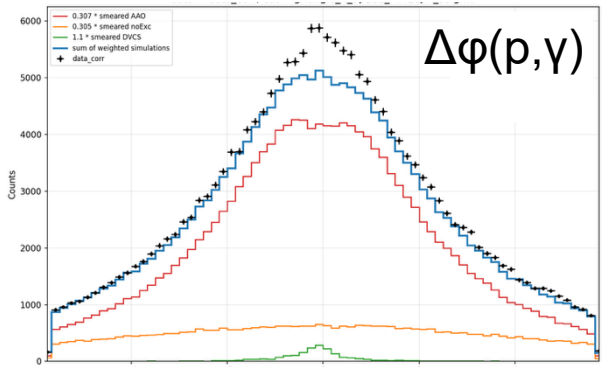
$MM^2(e\gamma X) > 1.4\ GeV^2$

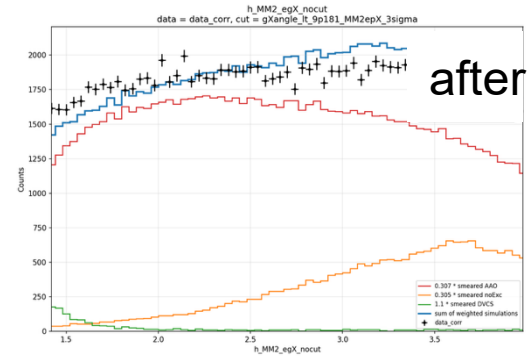


Angle(e,X)



$\Delta\varphi(p,\gamma)$





NORMALIZATION

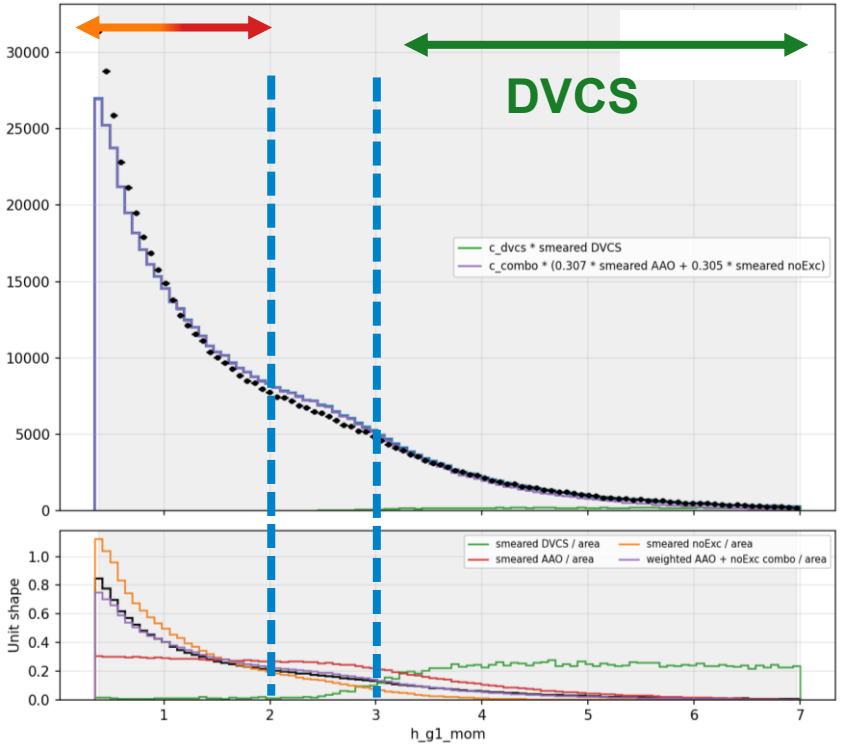
Exclusive and SIDIS normalization

- Energy of **DVCS photons** > 2 GeV , which allows us to separate regions dominated by **Exclusive**/**SIDIS** form **DVCS**

- Normalize the **exclusive** and **SIDIS** contributions at E_γ < 2 GeV where **DVCS** can be ignored.

- After fixing the **exclusive** and **SIDIS** normalization **DVCS** can be normalized at E_γ > 3 GeV

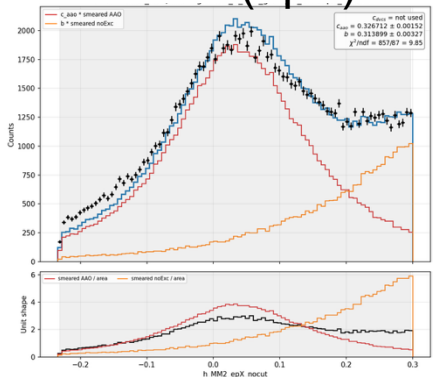
Photon energy



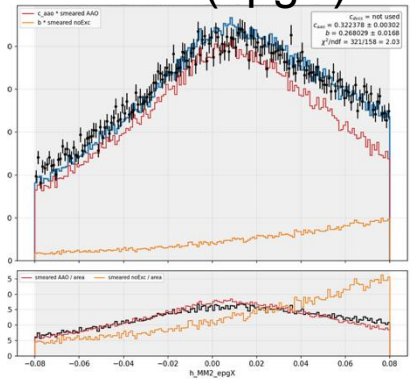
NORMALIZATION

Exclusive and SIDIS normalization

MM^2(epX)



MM^2(epgX)

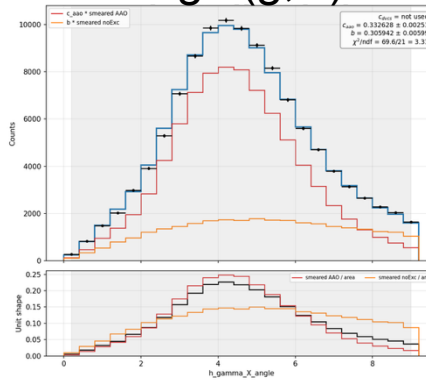


Rows used: 7
Average c_aao_average = 0.30676279676513735
Average b_average = 0.3153468624617621

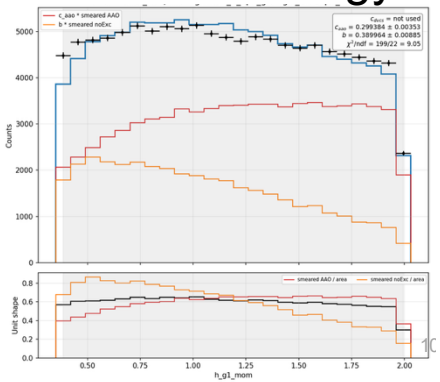
[2]:

	group	c_aao_average	b_average
4	h_MM2_egX_nocut	0.254706	0.304619
6	h_MM2_epX_nocut	0.326712	0.313899
7	h_MM2_epgX	0.322378	0.268029
11	h_g1_mom	0.299384	0.389964
12	h_gX_v4_invMass2	0.326712	0.313899
13	h_gamma_X_angle	0.332628	0.305942
15	h_total_miss_E_nocut	0.284819	0.311075

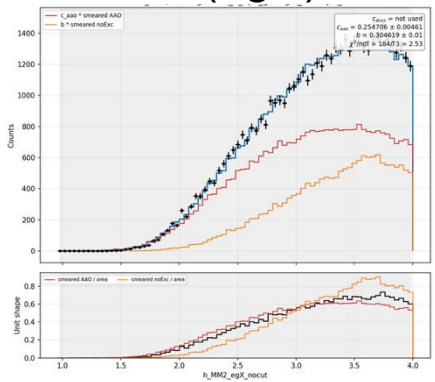
Angle(g,X)



Photon energy



MM^2(egX)



AAO: 0.25 - 0.33
SIDIS: 0.27 – 0.39

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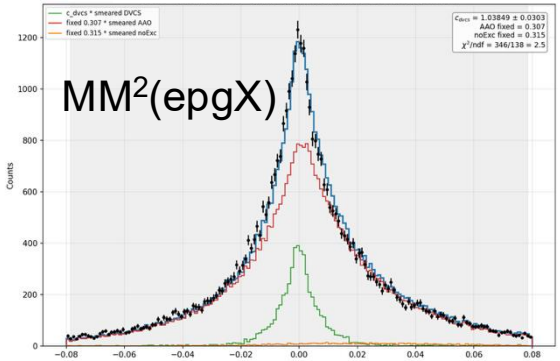
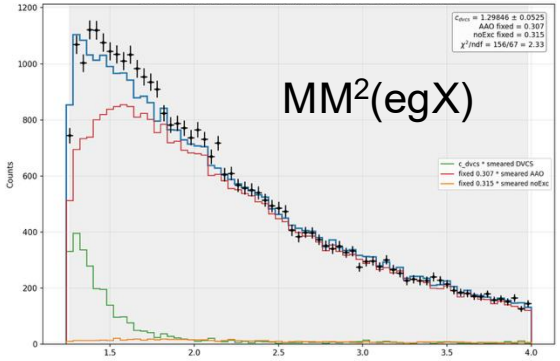
NORMALIZATION

DVCS normalization

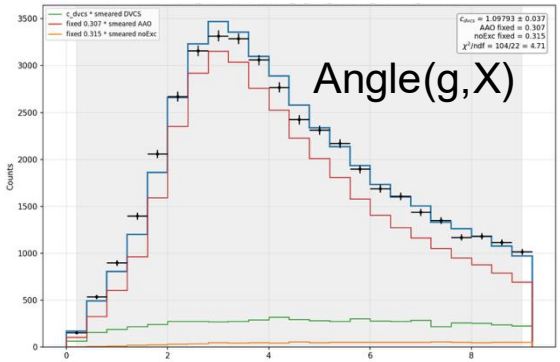
DVCS: 1.1
Range: 1.0 – 1.2

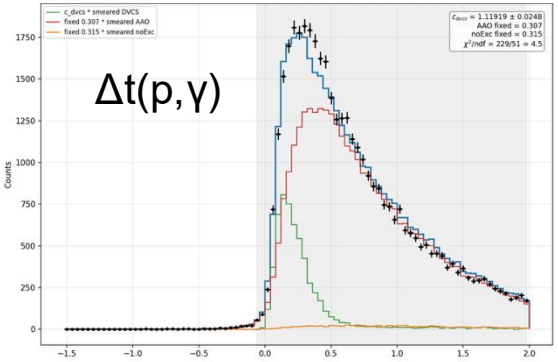


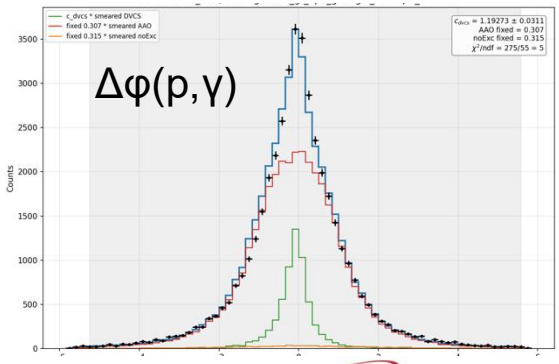


hist_name	c_dvcs
h_MM2_epgX	1.038495
h_MM2_epX_nocut	1.048711
h_MM2_egX_gt_1p25	1.298460
h_gamma_X_angle	1.097931
h_gX_v4_invMass2	1.048711
h_g1_mom	1.001221
h_delta_Phi	1.192727
h_delta_t_photon_nocut	1.119190

N selected = 8
Average c_dvcs = 1.1056806





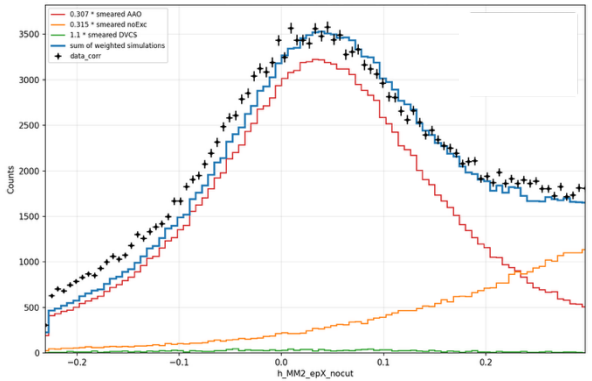


NORMALIZATION

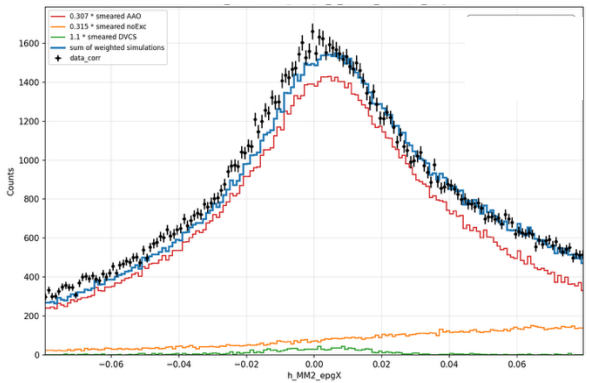
Final Normalization

- Reasonable agreement between Data and MC was achieved in $ep \rightarrow ep\gamma X$ topology
- The efficiency was calculated using both average normalization factors and the most deviated correction factors
- The difference was assigned as the systematic uncertainty

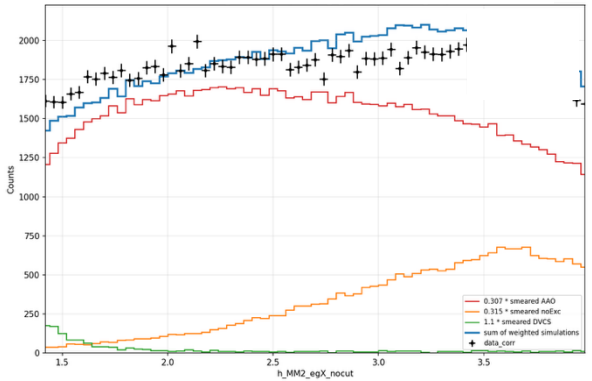
$MM^2(epX)$



$MM^2(epgX)$



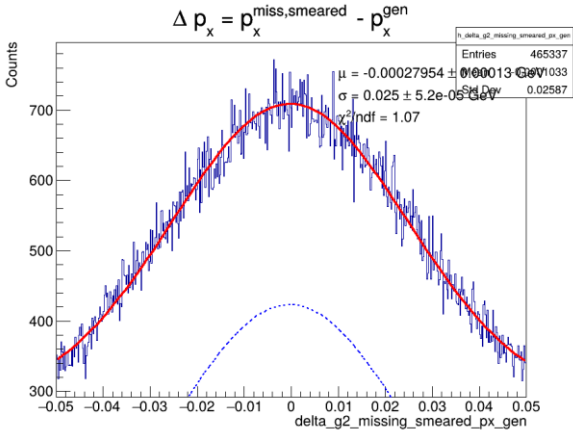
$MM^2(egX)$

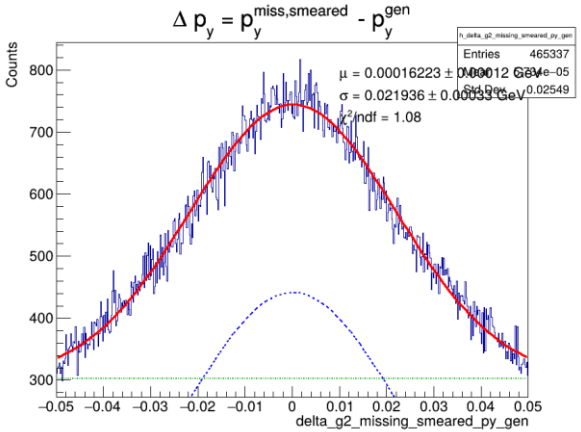


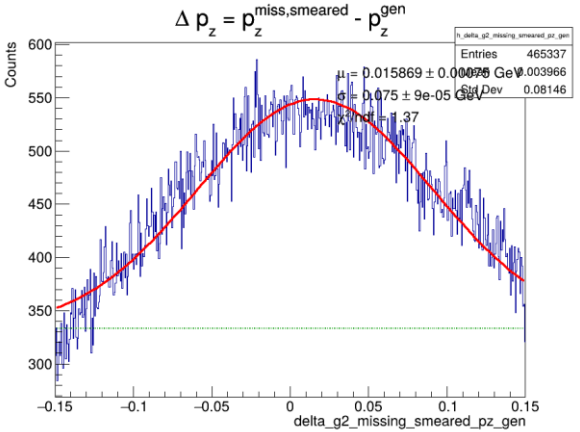
RESOLUTION

Photon matching

- Resolution estimated as ΔP between missing photon X from $ep \rightarrow ep\gamma X$ and true photon
- Exclusive AAO sample is used
- Electron and proton smearing was applied
- Resolution: 25 MeV for P_X and P_Y and 75 MeV for P_Z
- 3σ cut: : 75 MeV for P_X and P_Y and 225 MeV for P_Z





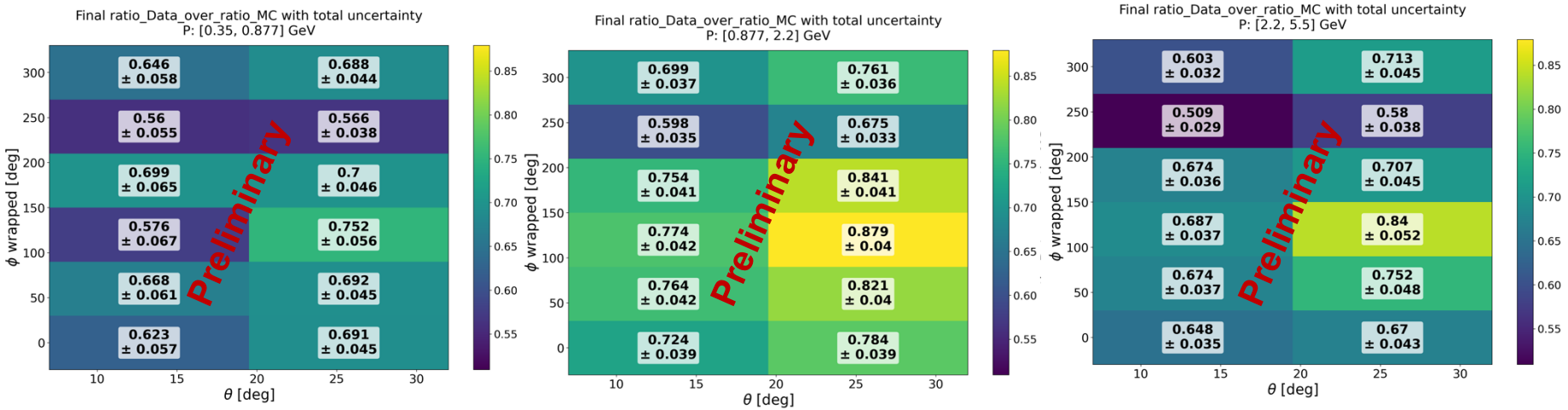


GAMMA DETECTION EFFICIENCY

Data/MC ratio

$$\text{Eff} = \frac{\text{Data}(\#ep\gamma\gamma)}{\text{Data}(\#ep\gamma X)} \cdot \frac{\text{MC}(\#ep\gamma X)}{\text{MC}(\#ep\gamma\gamma)}$$

- Efficiency was estimated in three momentum bins, two theta bins and for each sector
- The efficiency lays in rage of 60% - 85%
- Total uncertainty is less than 10%
- **The optimal X-γ matching method is still under investigation.**



CROSS CHECK

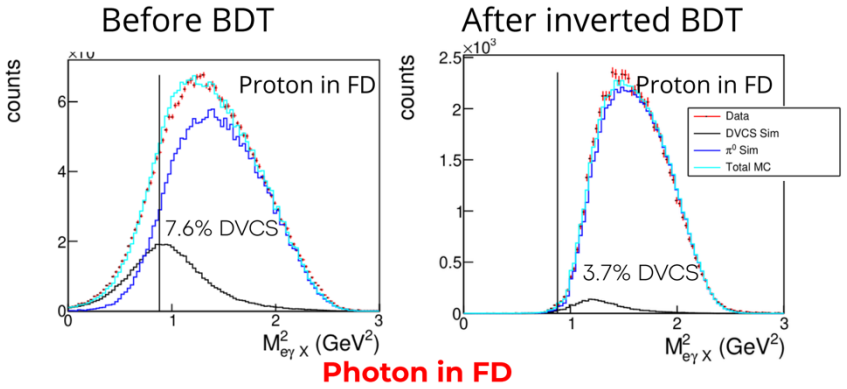
Previous estimations

By inverting the BDT cut

- we select exclusive π^0 events with one photon detection
- We can compute the direction of the missing photon

- If two photons in FD
  - Proton in the FD
  - Photon1 > 2 GeV in FD
    - Similar to DVCS selection
  - Photon2 >0.35 GeV
    - Within CLAS12 detection threshold

$ep \rightarrow ep\pi^0 \rightarrow ep\,\gamma(\gamma)$



Photon in FD

Subsystem	ϵ (%)
FD Sector 1	(79.04 ± 0.86 (stat) ± 1.93 (sys))%
FD Sector 2	(77.84 ± 0.84 (stat) ± 0.71 (sys))%
FD Sector 3	(78.11 ± 0.81 (stat) ± 0.01 (sys))%
FD Sector 4	(75.62 ± 0.81 (stat) ± 1.14 (sys))%
FD Sector 5	(81.68 ± 0.88 (stat) ± 0.74 (sys))%
FD Sector 6	(77.37 ± 0.94 (stat) ± 1.74 (sys))%
FT	(120.79 ± 1.46 (stat) ± 5.91 (sys)) %

By Juan Sebastian Alvarado: presentation

CROSS CHECK

Simplified estimation

- Detected photon energy > 2 GeV in: $ep \rightarrow ep\gamma X$
- Momentum of X > 0.35 GeV
- No SIDIS background
- New normalization factors for DVCS and Exclusive contributions
- Only statistical uncertainty is shown
- Both approaches agree within systematical uncertainty

Subsystem	ϵ (%)
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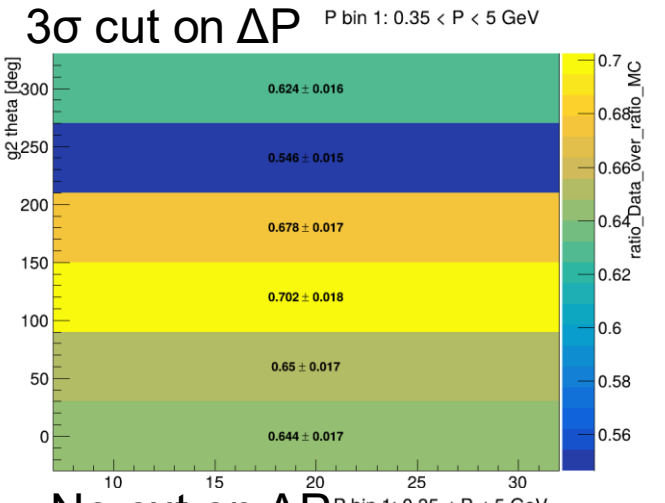
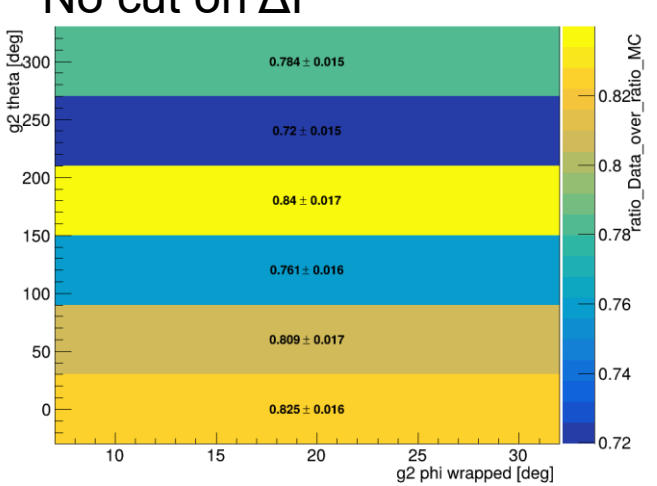
3σ cut on ΔP



No cut on ΔP



CONCLUSIONS AND OUTLOOK

Results:

- Photon detection efficiency was estimated
- Preliminary Neutral pion SIDIS Multiplicities (x_B, Q^2, z, P_T^2) at CLAS12 are available
- After integrating over P_T^2 , multiplicities vs. z follow the trend of LO predictions using MAPFF fragmentation functions and CT10nlo PDFs
- The data will provide new constraints on unpolarized TMD PDFs and fragmentation functions (FFs) and enabling tests of isospin symmetry in FFs

In progress:

- Finalize systematic uncertainties
- VM contamination studies

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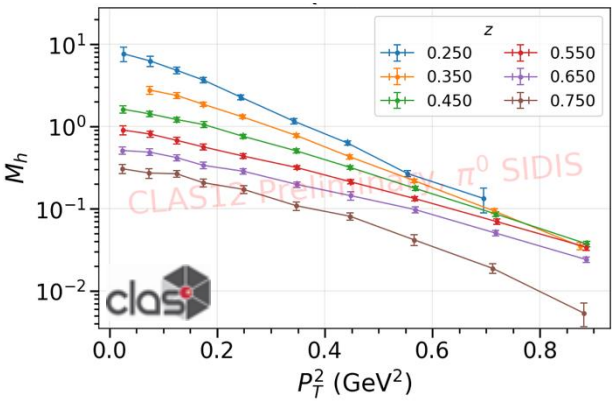
BACK UP SLIDES

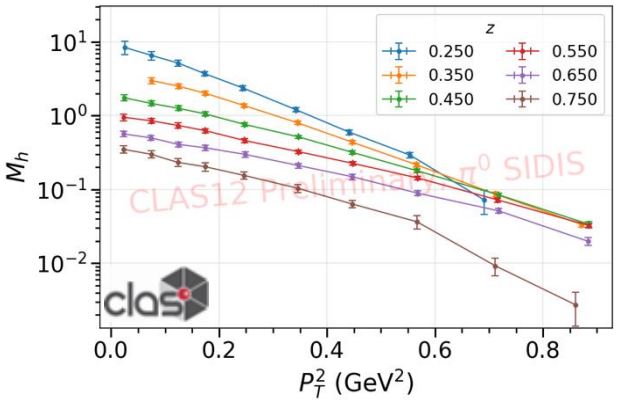
RESULTS

$M_h(p_T^2)$ for selected x-Q^2 bins

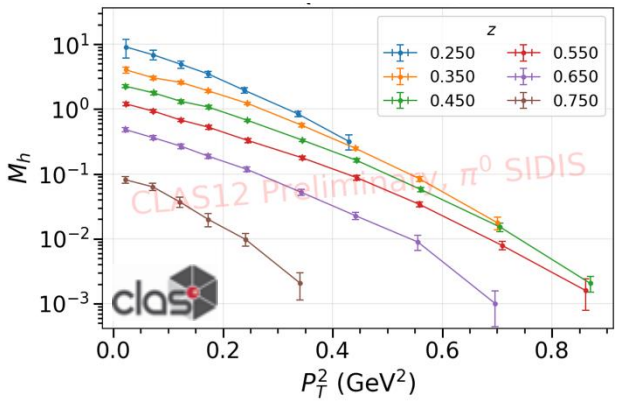
0.18 < x < 0.21, 2.0 < Q^2 < 2.66 GeV^2



0.24 < x < 0.28, 2.66 < Q^2 < 3.63 GeV^2



0.39 < x < 0.62, 3.63 < Q^2 < 5.12 GeV^2



- LO, gaussian approximation:

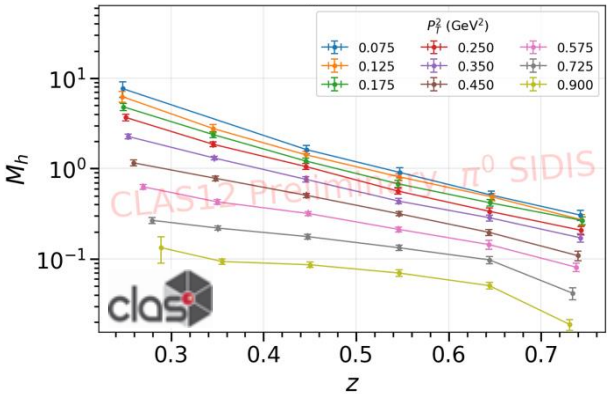
$$\frac{\mathrm{d}^2 M^h}{\mathrm{d}z\,\mathrm{d}P_T^2} = \left(\frac{\mathrm{d}^4\sigma}{\mathrm{d}x\,\mathrm{d}Q^2\,\mathrm{d}z\,\mathrm{d}P_T^2}\right) \Big/ \left(\frac{\mathrm{d}^2\sigma^{\mathrm{DIS}}}{\mathrm{d}x\,\mathrm{d}Q^2}\right) = \frac{N}{\pi\langle P_T^2\rangle} \exp\left(-\frac{P_T^2}{\langle P_T^2\rangle}\right)$$

- The behavior is consistent with an LO Gaussian model, except for a high-P_T^2 downturn attributable to the phase-space restriction $M_x > 1.5$ GeV
- Only statistical uncertainties are shown

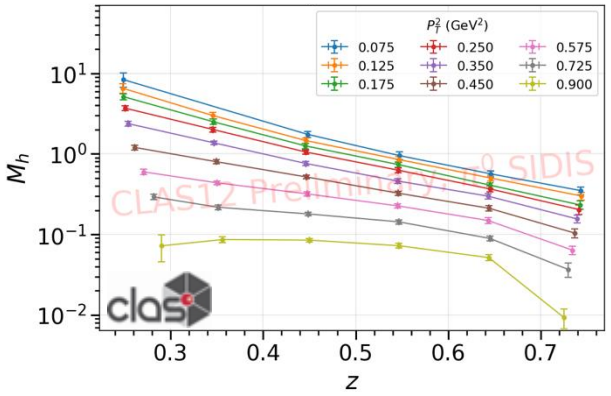
RESULTS

$M_h(z)$ for selected x-Q^2 bins

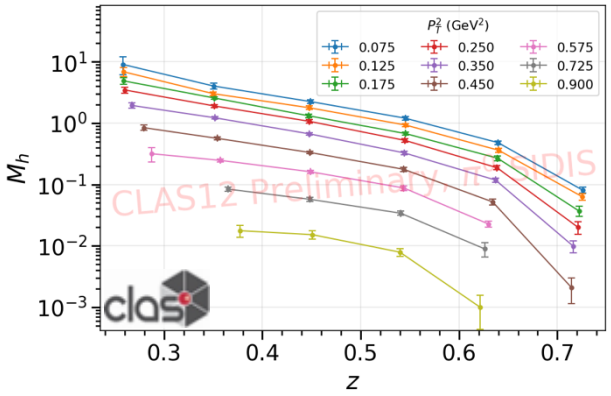
$0.18 < x < 0.21,\ 2.0 < Q^2 < 2.66\ \text{GeV}^2$



$0.24 < x < 0.28,\ 2.66 < Q^2 < 3.63\ \text{GeV}^2$



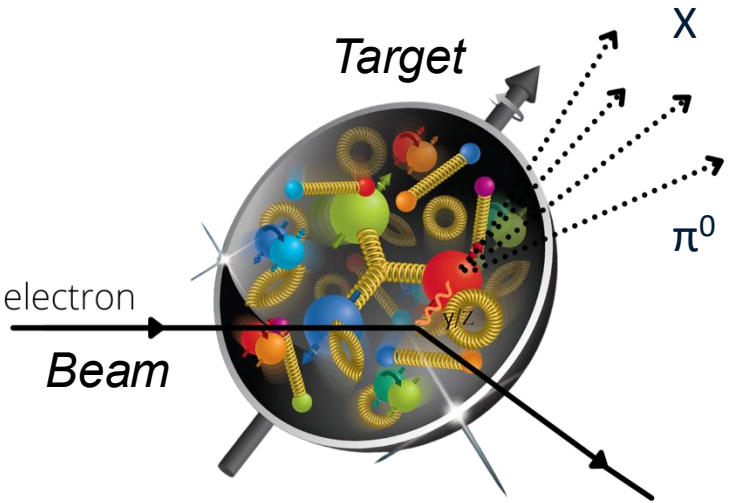
$0.39 < x < 0.62,\ 3.63 < Q^2 < 5.12\ \text{GeV}^2$



- $\ln(M_h(z))$ is approximately linear, but drops at large z due to the $M_x > 1.5$ phase-space cut
- Only statistical uncertainties are shown

MOTIVATION

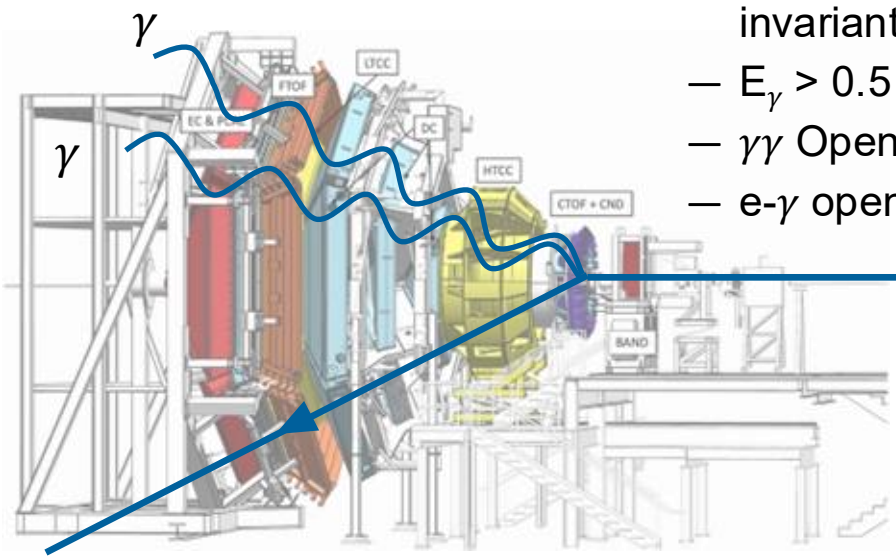
- Neutral pion Semi-Inclusive Deep Inelastic Scattering Multiplicities measure the probability of producing a hadron (π^0) per DIS event
- Multiplicity measurements uniquely link hadronization with the proton's internal transverse motion, advancing both FF determinations and our 3D understanding of proton structure
- The **z** - dependence constrains **fragmentation functions (FFs):** how colored partons turn into color-neutral hadrons
- The $\boldsymbol{P_T^2}$ **-** dependence directly probes the unpolarized **TMD PDFs** revealing the proton's intrinsic transverse momentum dynamics
- It also allows to study isospin invariance as the neutral pion fragmentation function is thought to be dependent on the charged pion fragmentation functions



$$\frac{d^2M_h}{dz\,dP_T^2}(x_B, Q^2, z, P_T^2) = \frac{\int_0^{2\pi} d\phi_h \frac{d\sigma^{SIDIS}}{dx\,dQ^2\,dz\,dP_T^2\,d\phi_h}}{\frac{d\sigma^{DIS}}{dx\,dQ^2}}$$

CLAS12

Selection of the ep → eπ^{0}X reaction with Forward Detector



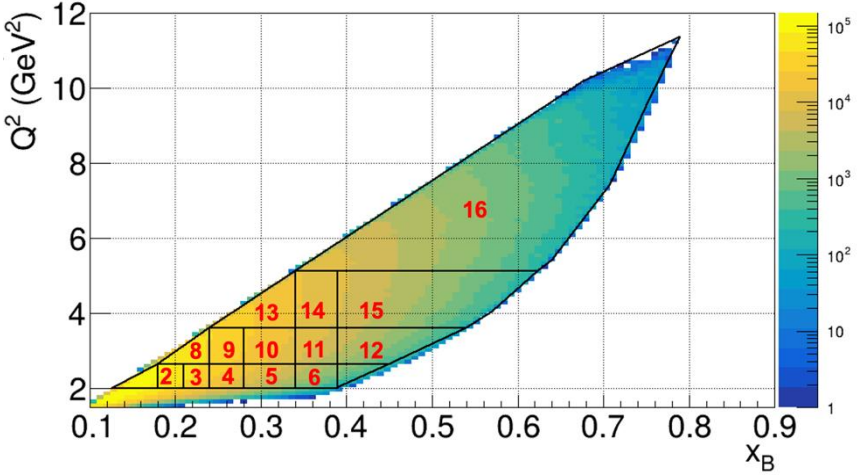
- **π^0 candidates** are reconstructed from photon pairs invariant mass (registered in Calorimeters)
- E_γ > 0.5 GeV
- $\gamma\gamma$ Opening angle vs momentum cut
- e-γ opening angle > 8 deg

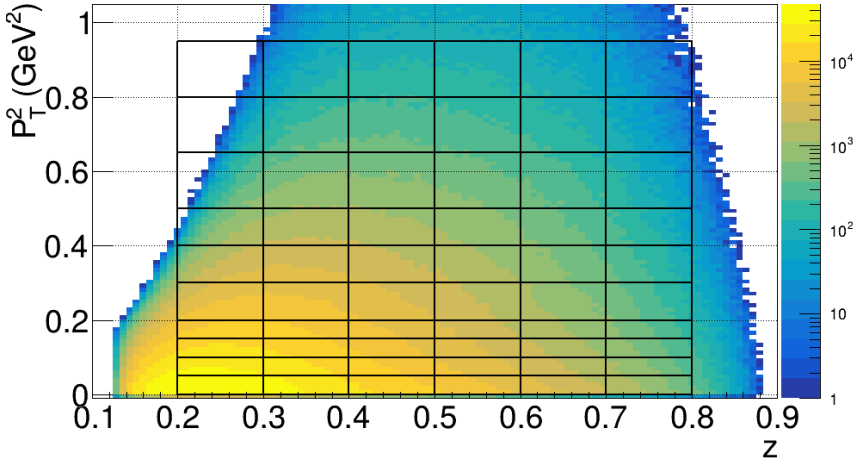
10.6 GeV electron beam, LH_2 5-cm long hydrogen target

The detector subsystems used for **electron identification**:

- Drift Chambers (track)
- Calorimeters (EM shower)
- Time of Flight (PID)
- Cherenkov counters (PID)

KINEMATICS AND BINNING





— Large CLAS12 acceptance together with large statistics allow for multidimensional binning

— Semi-Inclusive DIS events selected with following kinematic cuts:

- $W > 2$ GeV
- $Q^2 > 2$ GeV^2
- $y < 0.75$

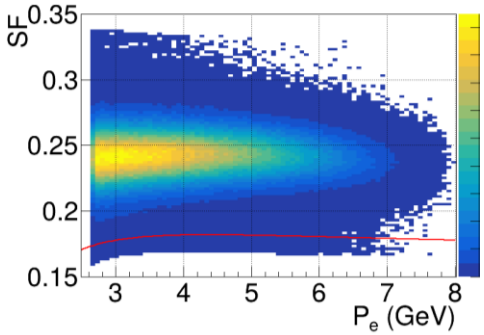
- $x_F > 0$ [$x_F = 2P_{h,L}/\sqrt{s}$] : current fragmentation region
- $M_x > 1.5$ GeV

Number of bins:
- X-Q^2 - 16
- Z – 6
- P_T^2- 9
- Φ_h - 8

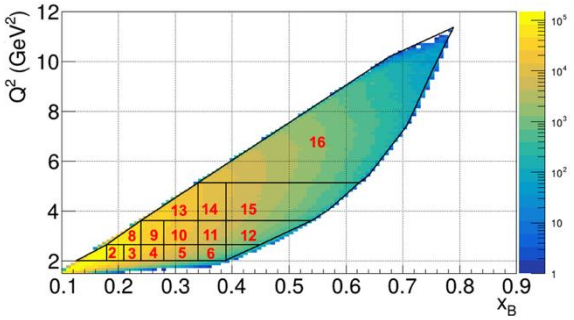
PID AND EVENT SELECTION

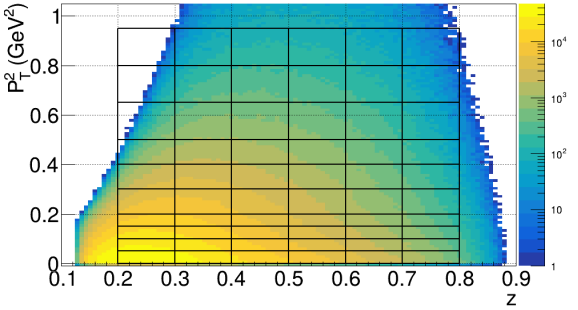
Starts with CLAS12 reconstruction algorithm

- Electron
  - $2 < p_e < 8$ GeV
  - $y < 0.75$
  - Z-Vertex cut
  - DC and PCAL fiducial
  - Sampling Fraction



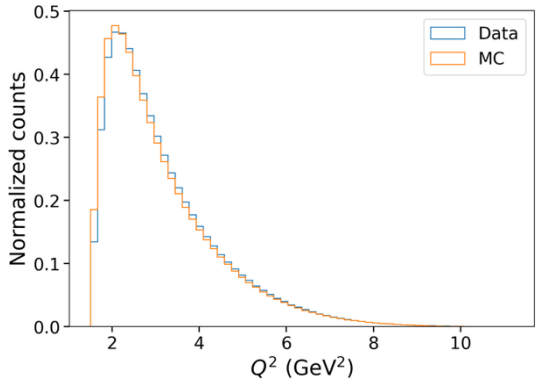
- Photon
  - $E_\gamma > 0.5$ GeV
  - e-γ opening angle > 8 deg
  - $0.9 < \beta < 1.1$
- π^0
  - Candidates are reconstructed from photon pairs
  - $x_F > 0$ [$x_F = 2P_{h,L}/\sqrt{s}$] : current fragmentation region
  - $M_x > 1.5$ GeV
  - $\alpha_{\gamma\gamma} > 6 \cdot \mathrm{Exp}(1 - p_\pi) + 0.5$ deg



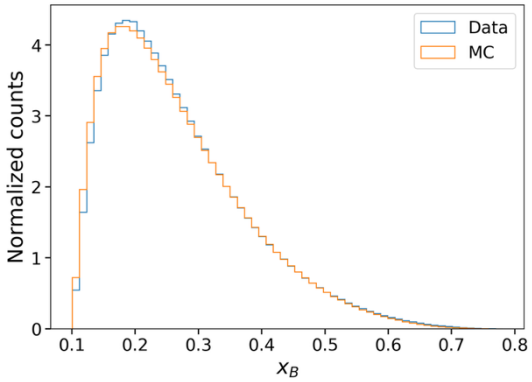


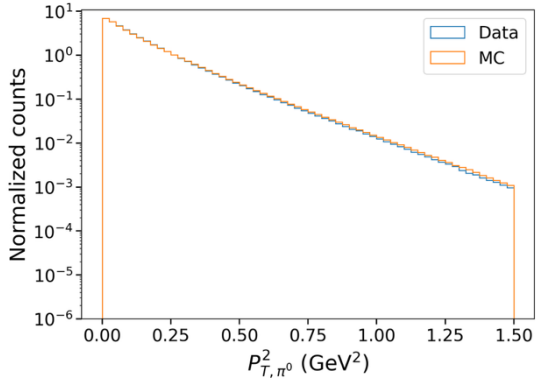
MONTE CARLO

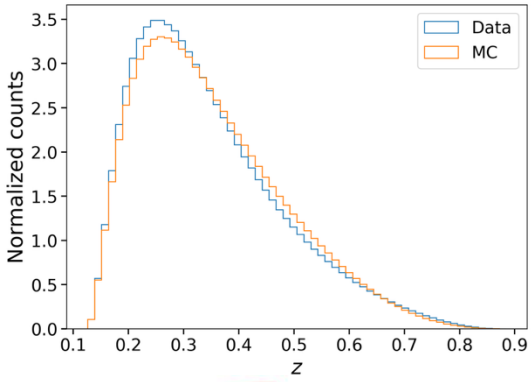
Event Generator used for the Acceptance



- CLASDIS-EG built on LEPTO
- Lund string model as in PYTHIA/JETSET
- LO electroweak DIS (arbitrary lepton polarization); O(α) matrix elements for boson–gluon fusion and gluon radiation; higher-order QCD via parton showers
- QED radiation is not included in the current MC sample
- Hadronization parameters tuned to CLAS12 semi-inclusive data ($Q^2 > 1$ GeV^2, $W > 2$ GeV)







histograms normalized to unit area