NEUTRAL PION MULTIPLICITY STUDIES AT CLAS12

MARSHALL B. C. SCOTT

HTTPS://WWW.LINKEDIN.COM/IN/MARSHALL-SCOTT-PH-D-17AB191B9

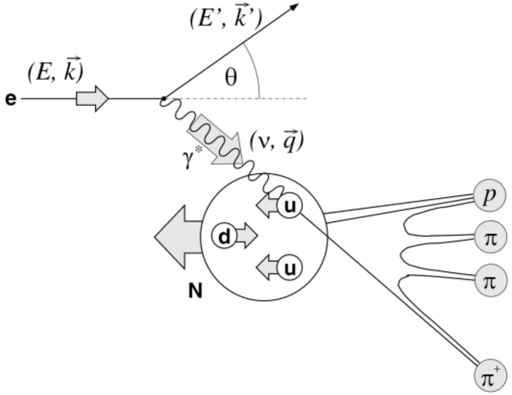
U.S. DEPARTMENT OF ENERGY

Argonne National Laboratory is a U.S. Department of Energy laboratory managed by UChicago Argonne, LLC.

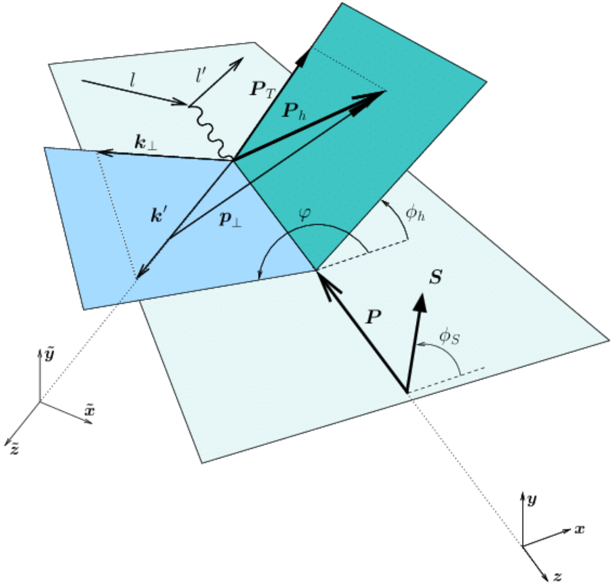
This work is supported in part by the U.S. Department of Energy, Office of Nuclear Physics under contract No. DE-AC02-06CH11357.

SEMI-INCLUSIVE DEEP INELASTIC SCATTERING

- Our analysis is centered on the study of neutral pion hadronization.
- The SIDIS channel of interest involves the detection of the scattered electron and photons coming from neutral pion decays.
- **SIDIS variables of interest**
  - $Q^2 = -q^2 = -(l' - l)^2$: the square of the momentum transferred from the electron to the parton
  - $x_B = Q^2/2P \cdot q$: the fraction of target momentum the struck parton contained
  - $z = P \cdot P_h / P \cdot q$: the fraction of transferred momentum the resultant hadron contained
  - p_T : the transverse hadron momentum
  - $\varphi_h = \arccos[(q \times l) \cdot (q \times P_h)/(|q \times l| \cdot |q \times P_h|)]$: angle between the lepton scattering plane and the hadron plane



https://doi.org/10.1103/PhysRevD.71.012003



https://doi.org/10.1103/PhysRevD.75.054032

SIDIS Multiplicities

- **Goal**
  - Measure neutral pion multiplicities

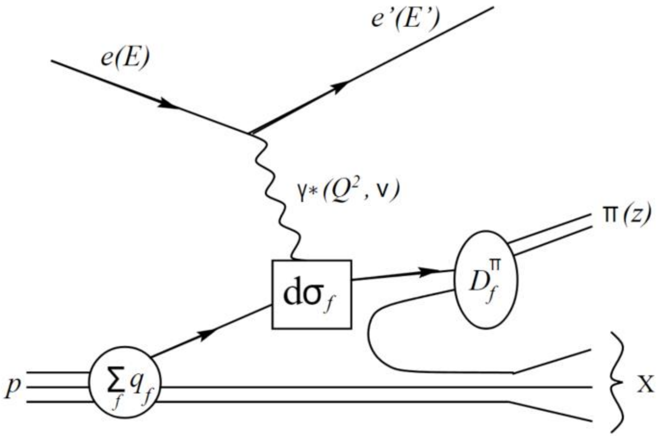
$$M_h = \frac{d\sigma^h}{dxdQ^2dzdp_T^2} \Big/ \frac{d\sigma^{DIS}}{dxdQ^2}$$

  - Related to the non-perturbative proton structure, i.e., PDFs and FFs

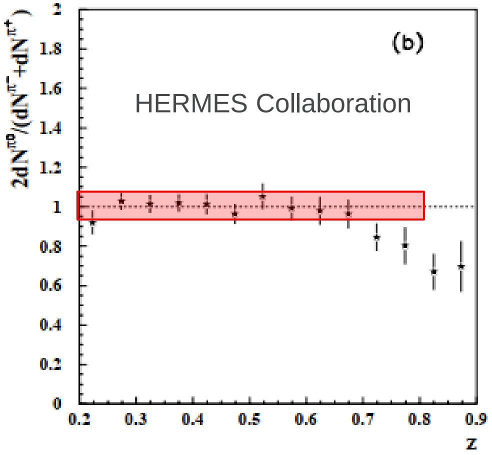
$$\sigma^{\pi^0} \approx \sigma^{DIS} \otimes f^p(x, Q^2) \otimes D^{p\to\pi^0}(z, Q^2)$$

  - Connected to charged pion multiplicities

$$D_1^{\pi^0/q} = \frac{1}{2}\left(D_1^{\pi^+/q} + D_1^{\pi^-/q}\right)$$



https://doi.org/10.1007/s100520100765

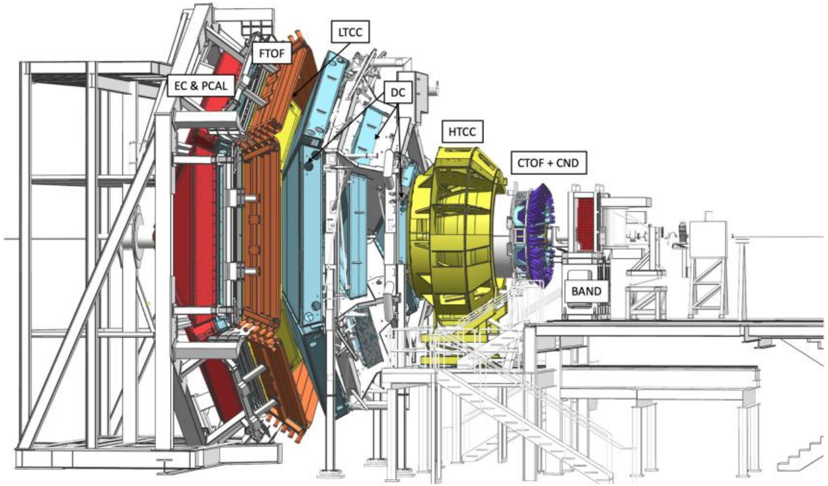


https://doi.org/10.1007/s100520100765

CEBAF Large Acceptance Spectrometer for 12 GeV (CLAS12)

- CLAS12 is a fixed target experiment housed at Hall B in Jefferson Lab.
- The spectrometer is divided into 6 sectors providing full azimuthal coverage with two main detector systems.
- **Forward detector (FD)**
  – Polar angle coverage : 5 – 40º
  – 7 m from target
  – Torus, Drift chambers, Low Threshold Cherenkov Counter (LTCC), Forward Time of Flight (FTOF)
- **Central detector (CD)**
  – Polar angle coverage : 35 – 135º
  – 0.5 m from target
  – Solenoid, Silicon Vertex Tracker (SVT), Central Time of Flight (CTOF)

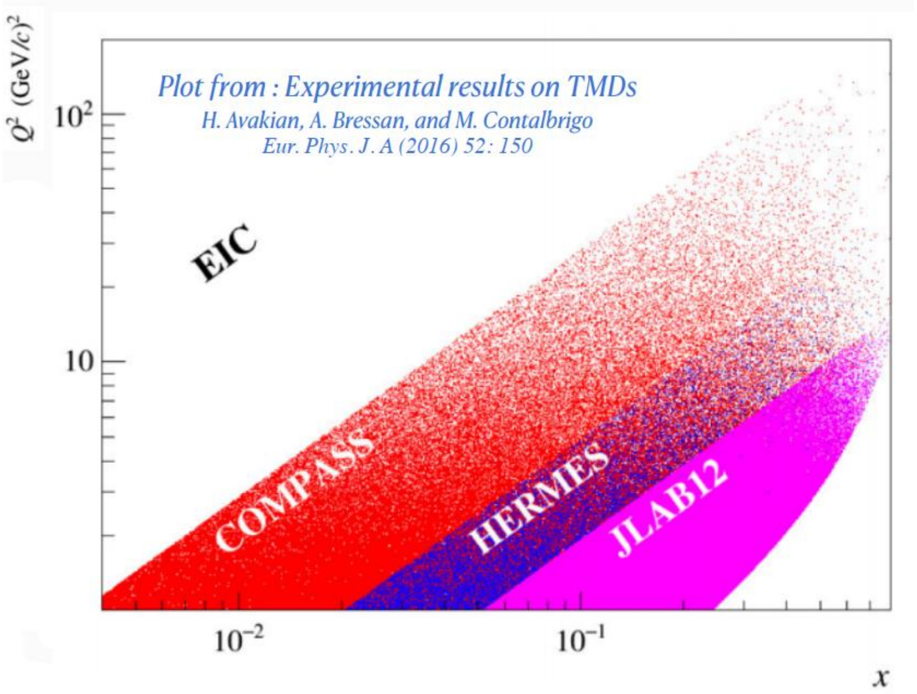
https://www.jlab.org/Hall-B/int-web/welcome.html



https://doi.org/10.1016/j.nima.2020.163419

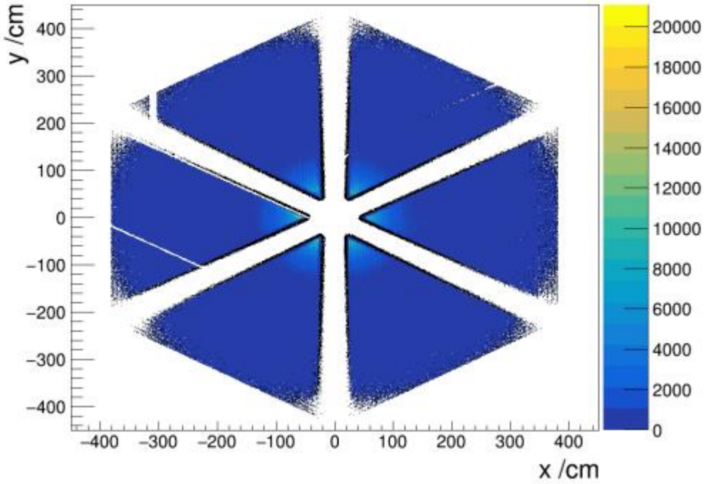
Previous SIDIS Multiplicity Kinematic Coverage

- Previous SIDIS multiplicity studies have been done at COMPASS and HERMES.
- COMPASS published charged pion multiplicities at low x_B.
- HERMES published charged and neutral pion multiplicities with an average x_B less than 0.1.
- CLAS12's coverage overlaps with HERMES', but is positioned to expand the SIDIS neutral pion multiplicity data to higher x_B as the mean x_B is greater than 0.3.
- The plot to the right depicts the x_B-Q^2 kinematic phase spaces of the three experiments.



Data Selection

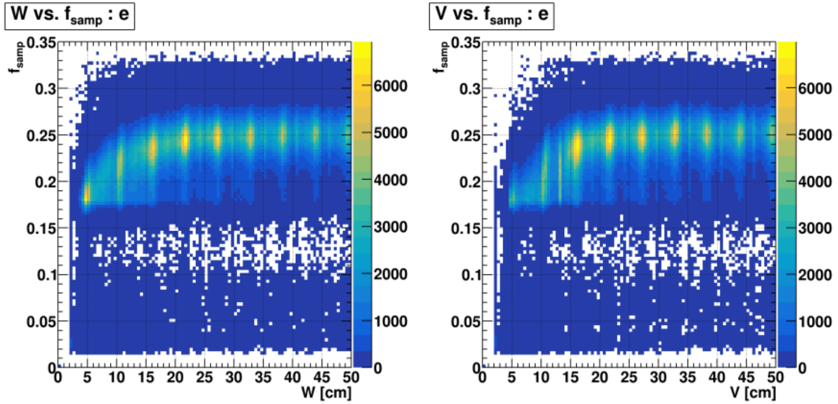
- Fall 2018 data taking period, which used a 10.6 GeV polarized election beam scattering off an unpolarized liquid hydrogen target.
- Zero net electron polarization over this run period.
- **General quality cuts**
  - – Data quality cuts
  - – Fiducial cuts for better data-mc agreement
  - – Exactly 1 electron in Forward Detector
  - – At least 2 photons in Forward Detector

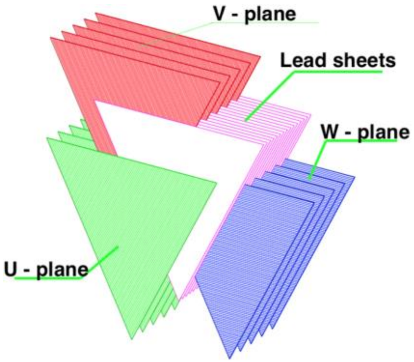


Preshower Calorimeter (PCAL) hit plane for electrons. Black points show hits before fiducial cuts were made and the overlayed colored points show the surviving hits after the cut (Internal Documentation : RG-A Analysis note).

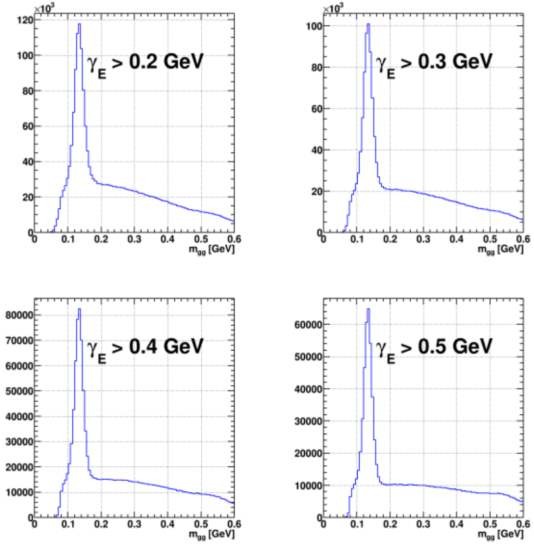
Selection Cuts for Electrons and Photons

- **Electron**
  - $2 < p_e < 8$ GeV
  - $Q^2 > 2$ GeV^2
  - $W > 2$ GeV [$W = |q + P|$]
  - $y < 0.75$ [$y = q \bullet P / l \bullet P$] : remove events with large radiative effects
  - l_v & l_w > 9 cm (constant sampling fraction region)
- **Photon**
  - $E_\gamma > 0.5$ GeV : background removal
  - e-γ opening angle > 8 deg : remove radiative γs
  - $0.9 < \beta < 1.1$: γs with $\beta > 1.1$ are not associated with π^0s
  - l_v & l_w > 15 cm (constant sampling fraction region)



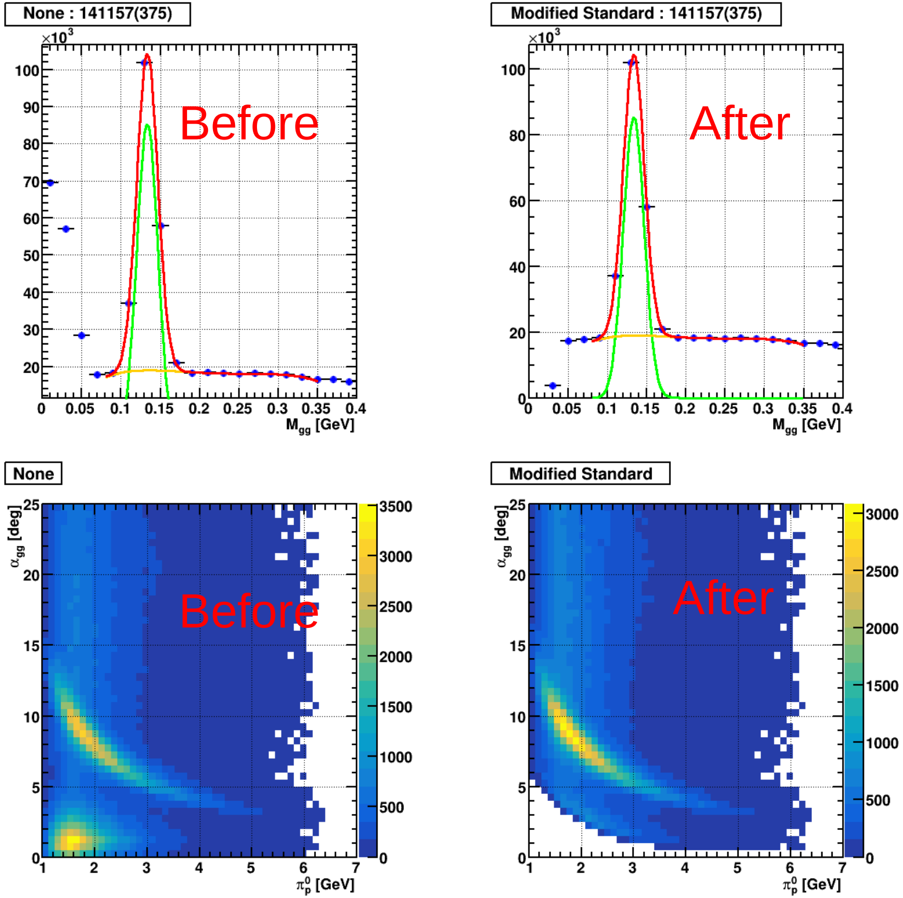


https://www.sciencedirect.com/science/article/pii/S0168900220300309



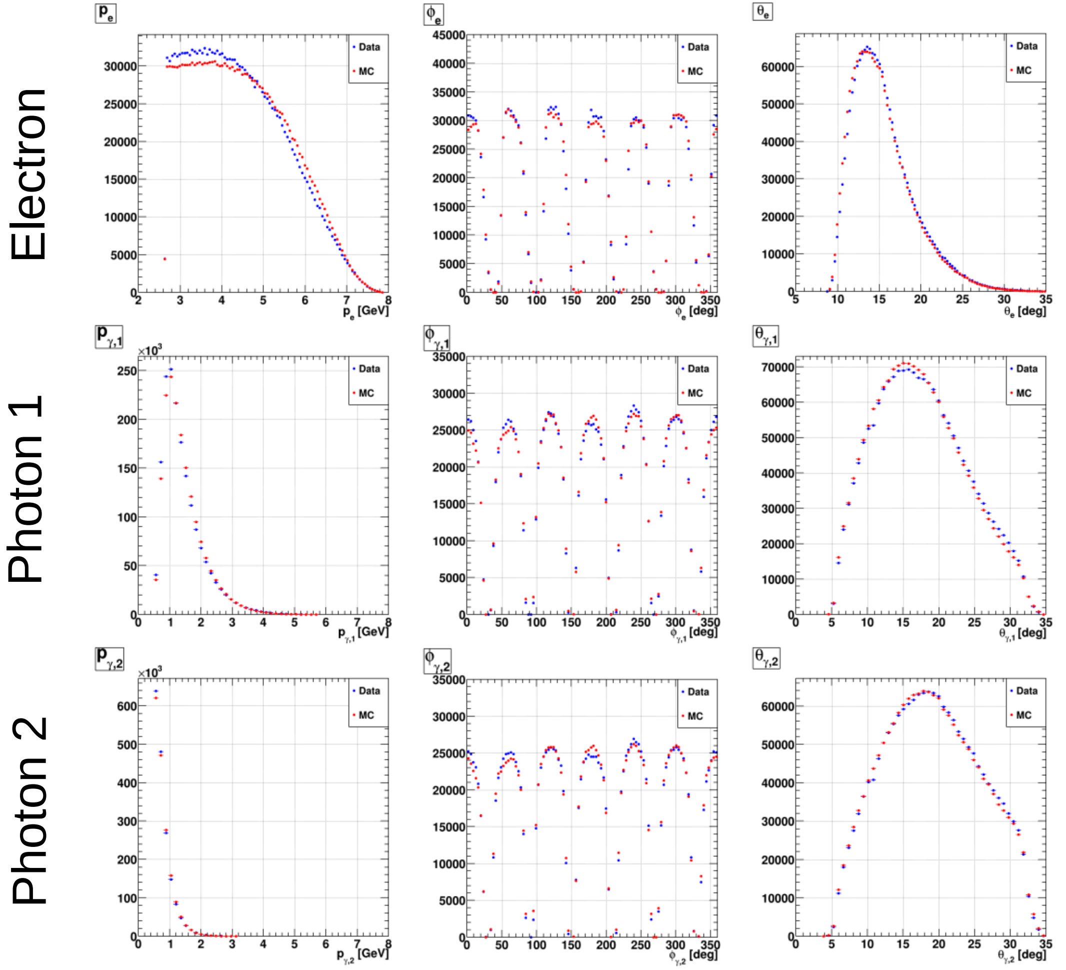
Selection Cuts for Neutral Pions

- π^0 candidates are reconstructed from photon pairs.
- The resulting invariant mass distribution shows a characteristic peak around the π^0 mass of 0.135 GeV.
- **Cuts**
  - $x_F > 0$ [$x_F = 2P_{h,L}/\sqrt{s}$] : current fragmentation region
  - $M_x > 1.5$ GeV [$M_x = |q + P - P_h|$] : remove exclusive events
  - $\alpha_{\gamma\gamma} > 6 \cdot \mathrm{Exp}(1 - p_\pi) + 0.5$ deg : background removal



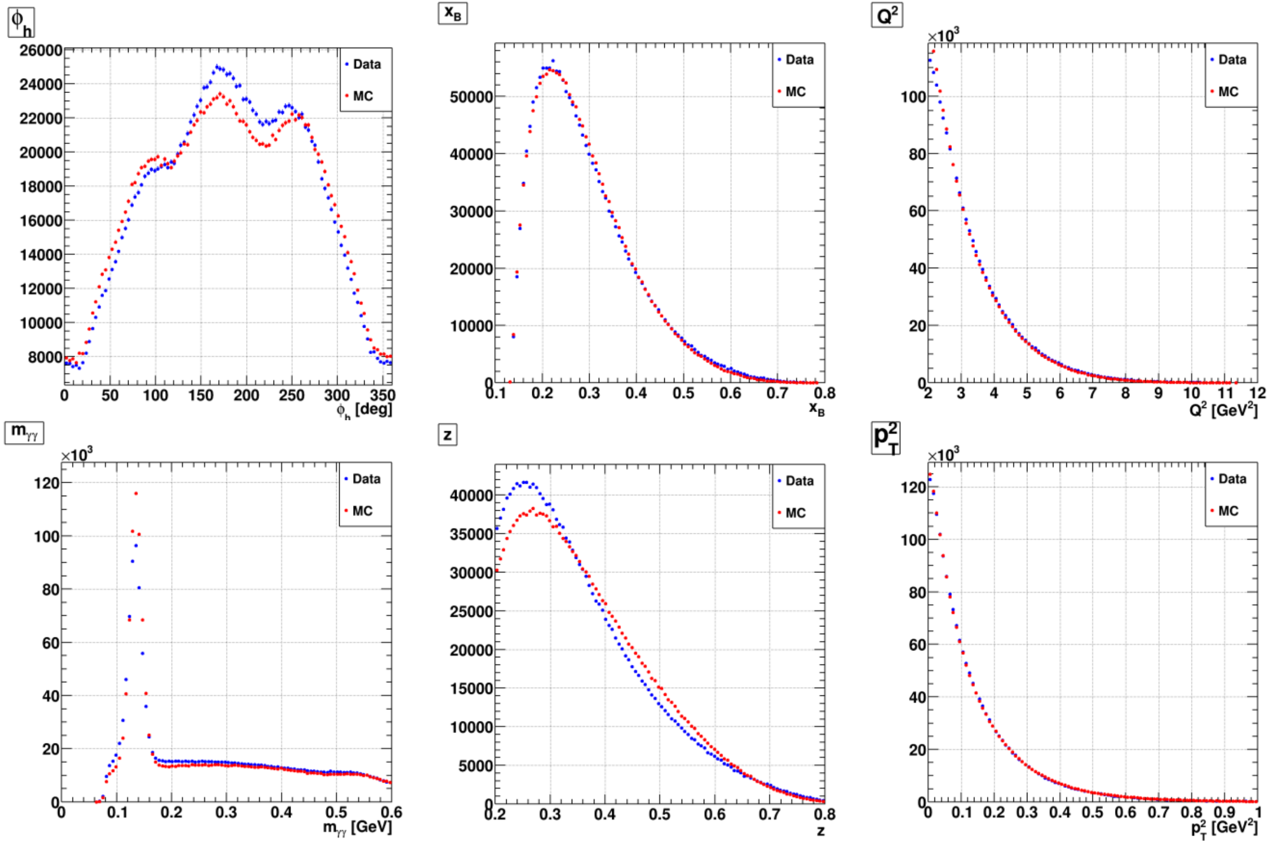
Data & Monte Carlo

- The monte carlo is created from a SIDIS generator based on LEPTO.
- The momenta, θ, and φ distributions of the electron and the two photons between the data and monte carlo agree well.



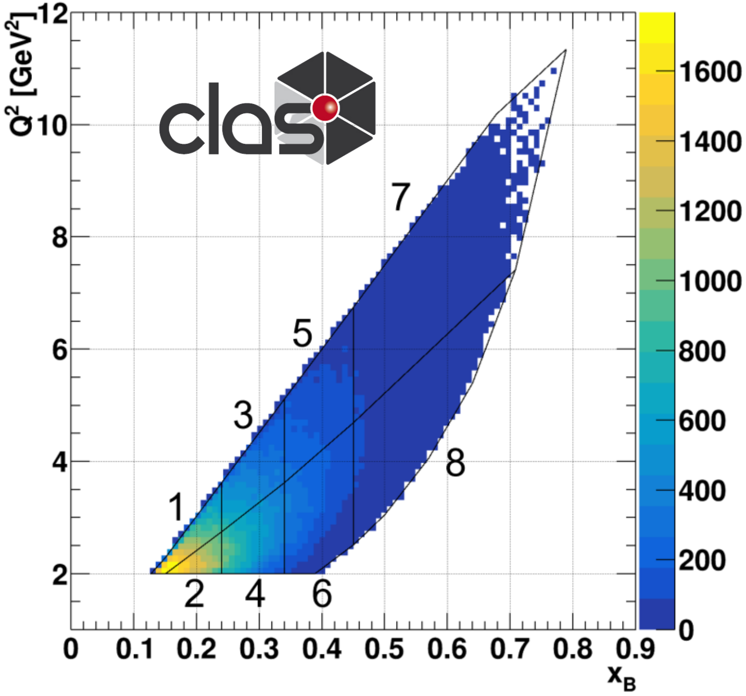
DATA & MONTE CARLO

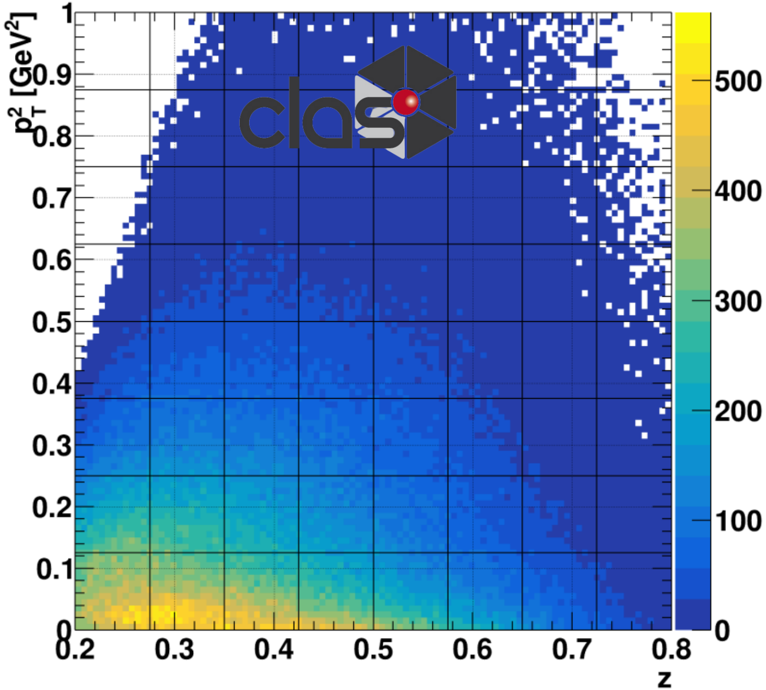
- The data and monte carlo also show agreement in the x_B, Q^2, z, p_T^2, φ_h, and $m_{\gamma\gamma}$ distributions.



PHASE SPACE
8 z bins & 8 p_T^2 bins ∈ 8 x_B-Q^2 bins ; Integration over φ_h

- Integration over φ_h





Multiplicities

- 5D multiplicity

$$M_h = \frac{d\sigma}{dxQ^2dzdp_T^2d\phi_h} / \frac{d\sigma}{dxdQ^2}$$
$$= A(1 + Bcos(\phi_h) + Ccos(2\phi_h)) / \frac{d\sigma}{dxdQ^2}$$

- For the results in this presentation, φ_h was averaged over, so the 4D multiplicity was measured, which is the ratio of the neutral pion production to the DIS cross section :

$$M_h = \frac{d\sigma}{dxQ^2dzdp_T^2} / \frac{d\sigma}{dxdQ^2}$$

Raw Multiplicities and Acceptance

- Raw multiplicity

$$M_{h,raw} = \frac{dN^{\pi^0}}{dxQ^2dzdp_T^2} \Big/ \frac{dN^{DIS}}{dxdQ^2}$$

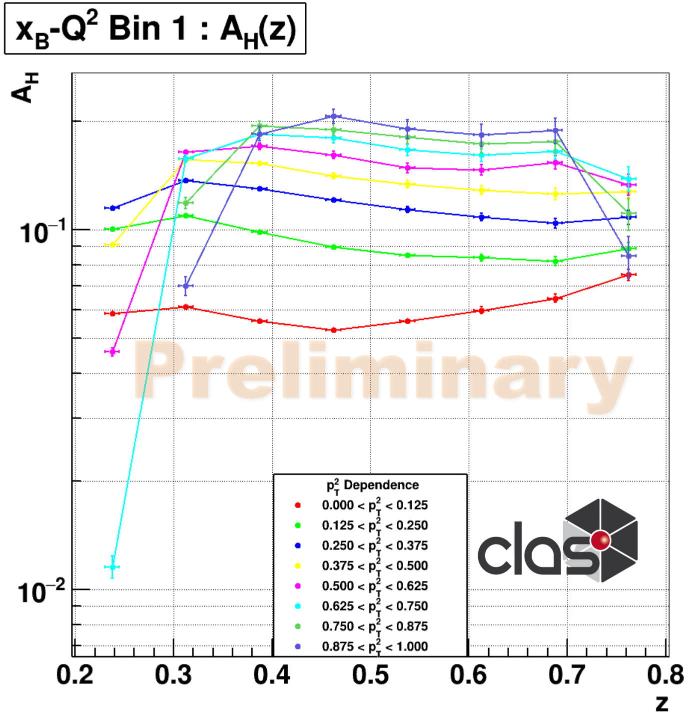
- For the bin-by-bin acceptance*efficiency we divide the reconstructed mc by the generated mc, with the understanding that the generated mc stemmed from an event where the reconstructed electron passed all the DIS cuts.

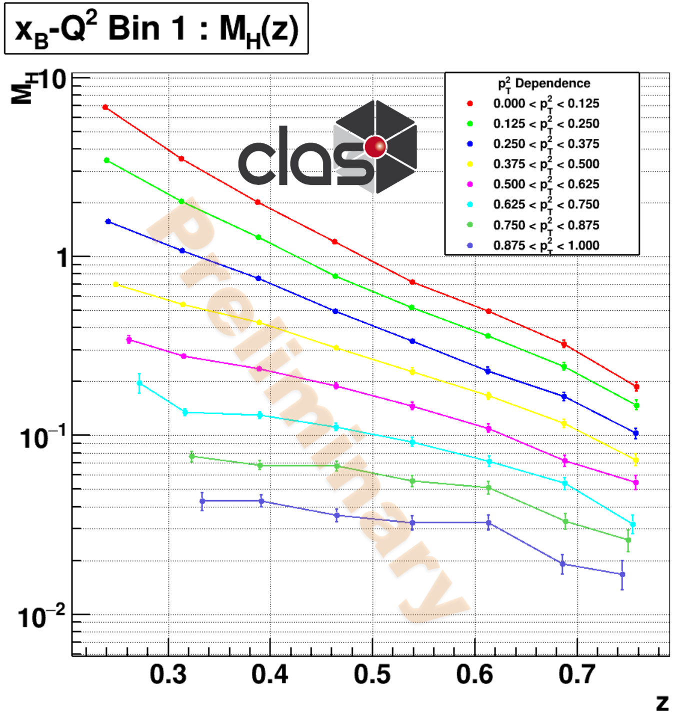
$$A_h = \frac{dN^{\pi^0}_{rec}}{dxdQ^2dzdp_T^2} \Big/ \frac{dN^{\pi^0}_{gen}}{dxdQ^2dzdp_T^2}$$

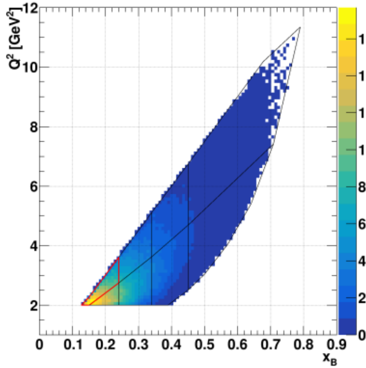
- The final multiplicity is the raw multiplicity divided by the acceptance.

$$M_h = M_{h,raw}/A_h$$

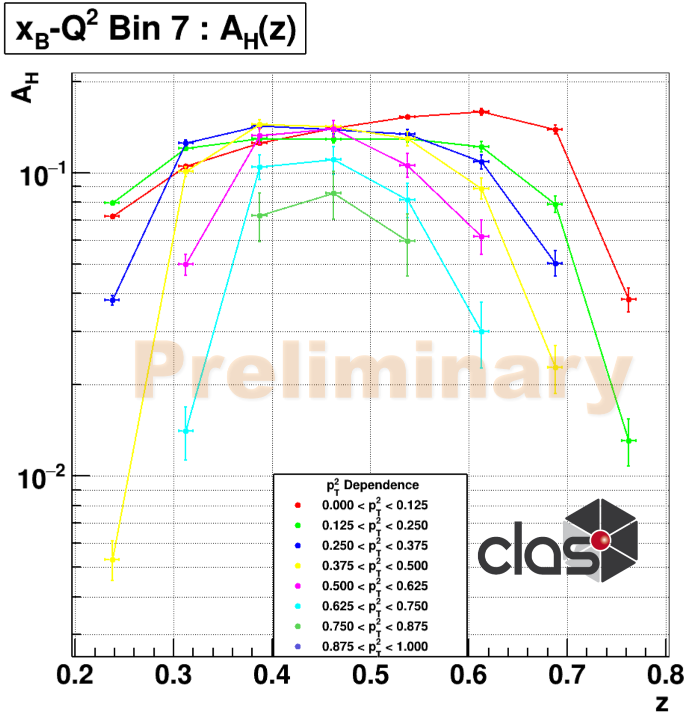
Multiplicities and Acceptances for x_B-Q^2 Bin 1

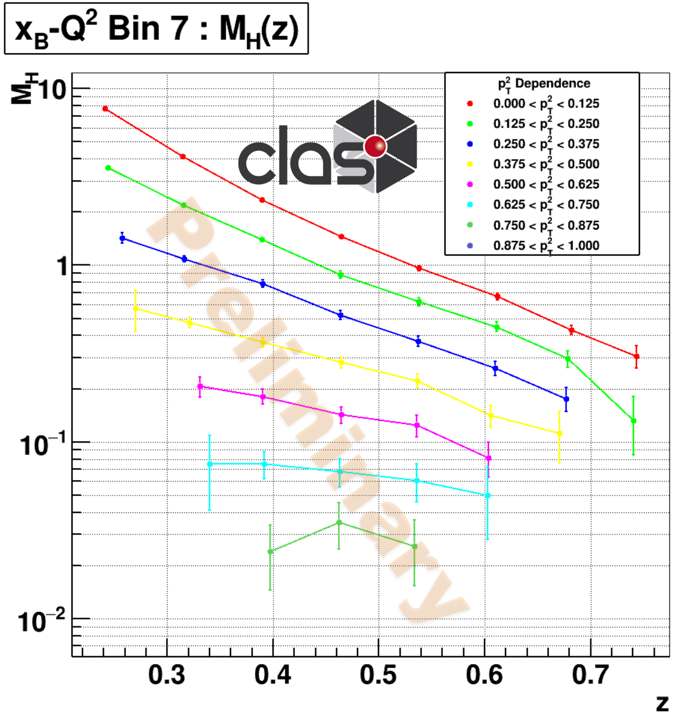


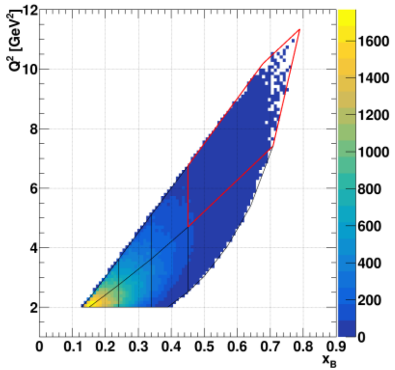




Multiplicities and Acceptances for x_B-Q^2 Bin 7



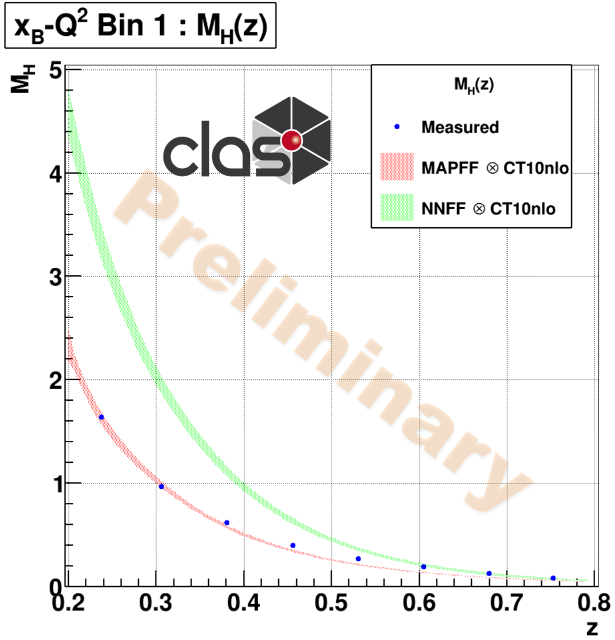


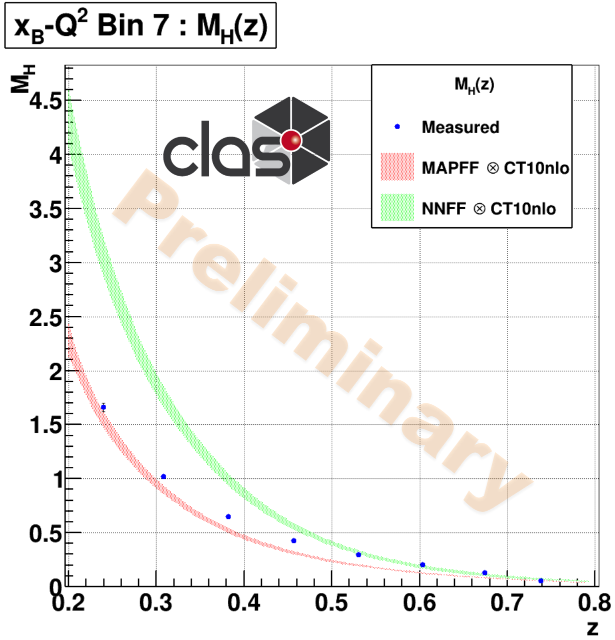


P_T^2 Integrated M_H and Leading Order Theoretical predictions

- The LO predictions used the MAPFF (https://doi.org/10.1103/PhysRevD.104.034007) and NNFF (https://doi.org/10.1140/epjc/s10052-017-5088-y) FFs and the CT10nlo PDF sets.
- The FF plots are drawn with 1σ error bands.
- NNFF only contains e^+e^- annihilation data, whereas MAPFF contains annihilation data and multiplicity data.

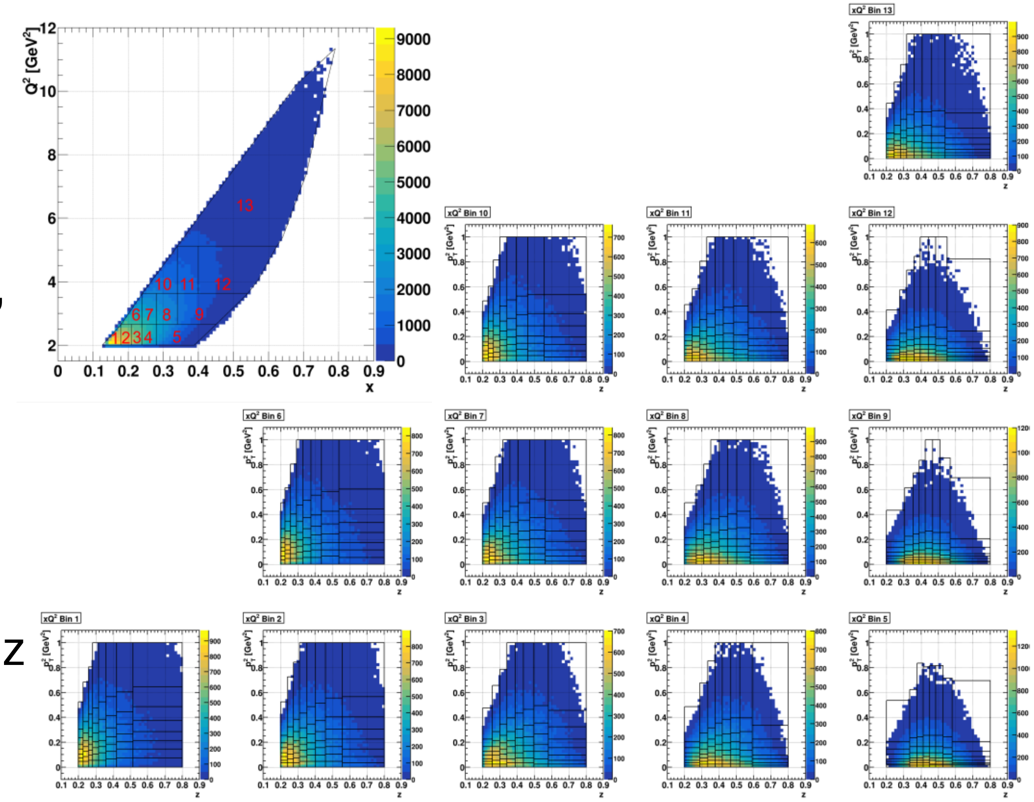
$$M_h = \frac{\sum_q e_q^2 f_q(x) D_q(z)}{\sum_q e_q^2 f_q(x)}$$





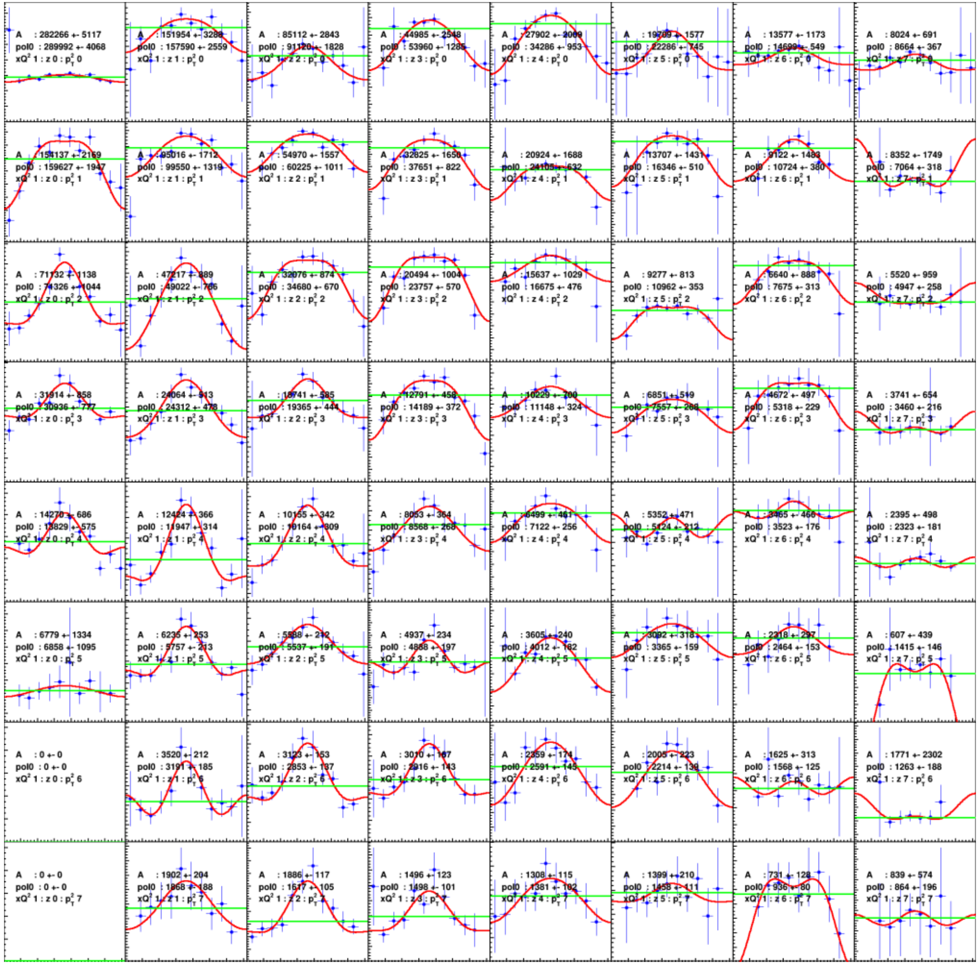
CURRENT WORK

- Current work is devoted to three prongs : using the migration matrix, SVD unfolding and Bayesian unfolding for acceptance corrections, incorporating a new binning scheme, and ϕ_h fitting.
- The new binning scheme is depicted to the right.
  - 13 x_B-Q^2 bins
  - 8 z bins and 8 p_T^2 bins within each z bin (equi-statistics)
  - Improved ϕ_h coverage



Current work

- Instead of averaging over the φ_h bins, now the number of pions is fit within each φ_h bin, and that distribution is then fit with $A(1 + B\cos(\varphi_h) + C\cos(2\varphi_h))$.
- The resultant number of pions is then the extracted A term.
- The plots to the right show the a preliminary φ_h distribution in the old binning scheme with the $A(1 + B\cos(\varphi_h) + C\cos(2\varphi_h))$ fit in red along with a pol0 fit in green.
- They are within error of each other for most bins.



Conclusion

- Using the invariant mass distributions of photon pairs, the number of neutral pions has been extracted from the Fall 2018 data taking period at CLAS12.
- From these distributions, correcting for acceptance and efficiency, the neutral pion multiplicities was measured in the x_B-Q^2-z-p_T^2, four-dimensional kinematic phase space, thereby increasing the SIDIS multiplicity data to higher x_B.
- The p_T^2 integrated multiplicities have also been extracted and shown to be inline with the LO theory predictions using the MAPFF$\otimes$CT10nlo.
- Ongoing work is using the new binning scheme, fitting the ϕ_h distributions for pion extraction, and utilizing the migration matrix along with Bayesian and SVD unfolding for acceptance corrections.
- Future work is studying radiative effects.

THANK YOU FOR YOUR ATTENTION

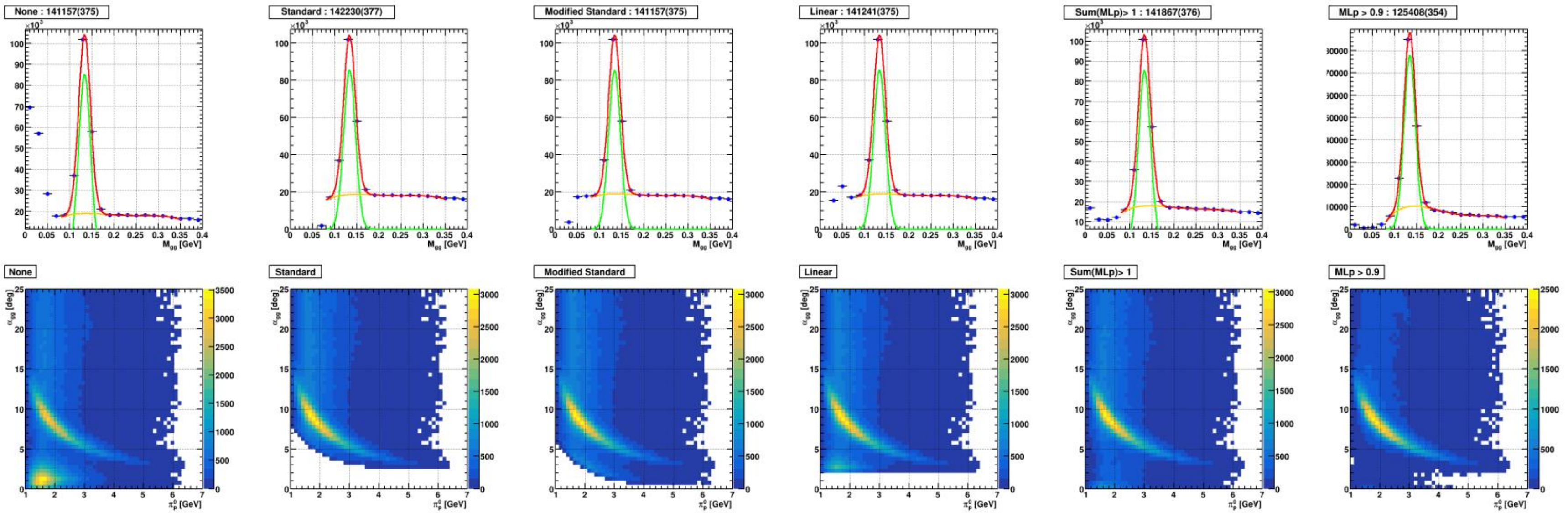
BACKUP SLIDES

- SIDIS CROSS SECTION
- ACCEPTANCES AND MULTIPLICITIES FOR ALL X_B-Q^2 BINS
- P_T^2 INTEGRATED MULTIPLICITIES FOR ALL X_B-Q^2 BINS

Opening angle Cut

ML was studied, but modifying the $\alpha_{\gamma\gamma}$ cut worked best

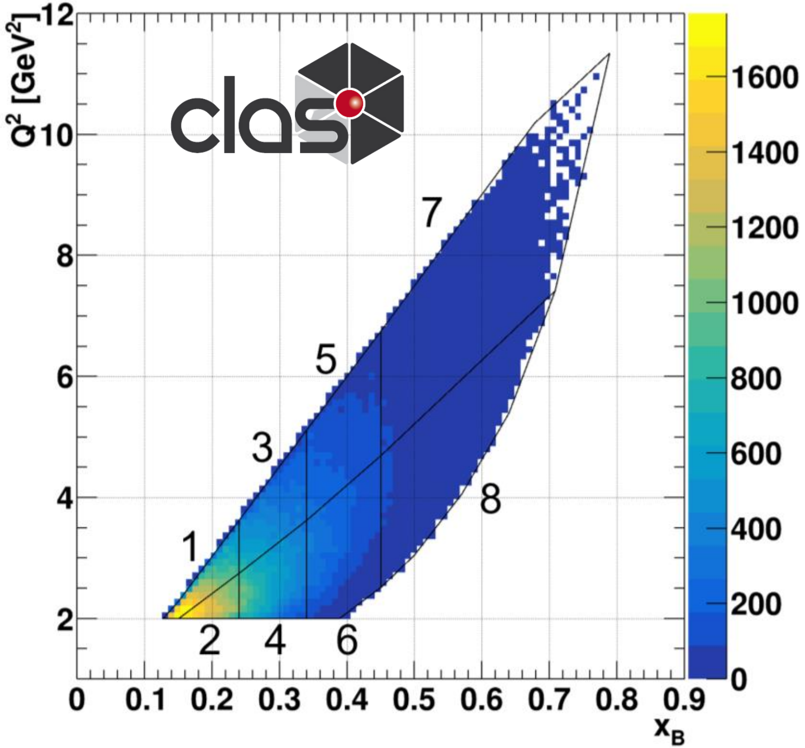
- Below is a comparison between different cuts and how these cuts affect the mass distribution. The small number of bins, 20, is used to reflect the $m_{\gamma\gamma}$ distributions in the eventual 5D space.
- Standard : $\alpha_{\gamma\gamma} > 6*\mathrm{Exp}(1 - p_{\pi}) + 2.5$ | Modified Standard : $\alpha_{\gamma\gamma} > 6*\mathrm{Exp}(1 - p_{\pi}) + 0.5$
- Linear : $\alpha_{\gamma\gamma} > 2.25$ | Sum(MLp) : $MLp_1 + MLp_2 > 1$ | MLp > 0.9 : MLp_1 , $MLp_2 > 0.9$



Kinematic Phase space

8 x_B-Q^2 bins ; Integration over ϕ_h

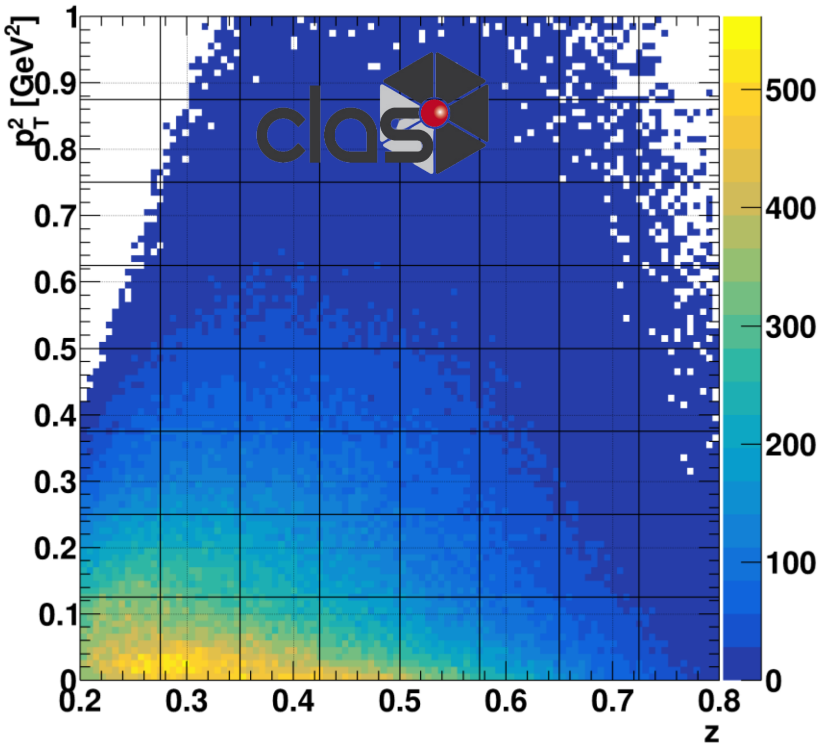
- The x_B-Q^2 phase space is divided into 8 bins as depicted to the right.
- Kinematic ranges
  – x_B : $0.1 < x_B < 0.8$
  – Q^2 : $2 < Q^2 < 12$ GeV^2
  – $\langle x_B \rangle = 0.311$
  – $\langle Q^2 \rangle = 3.13$ GeV^2



Kinematic Phase space

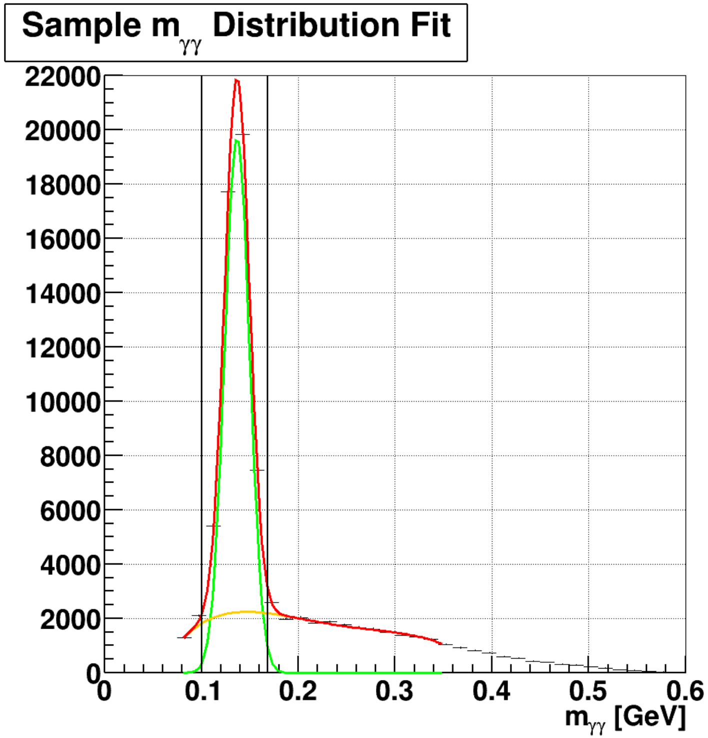
8 z bins & 8 p_T^2 bins ∈ 8 x_B-Q^2 bins ; Integration over φ_h

- Within each x_B-Q^2 bin, the z-p_T^2 phase space is divided into 64 bins as depicted to the right.
- Kinematic ranges
  – z : $0.1 < z < 0.8$
  – p_T^2 : $0 < p_T^2 < 1$ GeV^2
  – $\langle z \rangle = 0.362$
  – $\langle p_T^2 \rangle = 0.176$ GeV^2



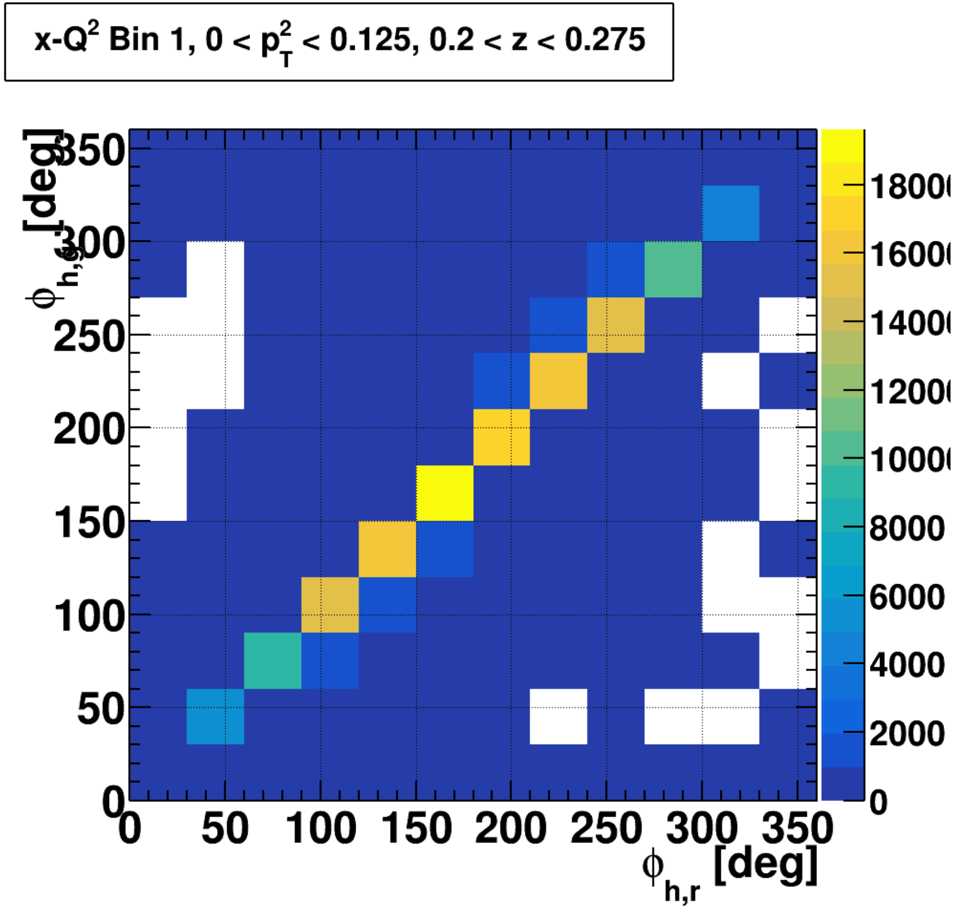
π^0 Extraction

- All photons within an event are combined into unique pairs, which become our neutral pion candidates.
- The resulting invariant mass distributions are fit, and the number of pions is extracted.
- **π^0 extraction**
  – 40 bins : 0 – 0.6 GeV
  – Fit range : 0.08 – 0.35 GeV
  – Fit function : Gaussian + 4th degree polynomial
  – Signal range (≈2σ) : 0.1 – 0.168 GeV



Current work : Unfolding

- Current acceptance work is using Singular Value Decomposition (SVD), Bayesian unfolding, and the migration matrix for acceptance corrections in all bins.
- The plot to the right is a portion of the x_B-Q^2 Bin 1(old binning scheme) 3D migration matrix showing φ_h migration in the first x_B-Q^2 -z-$p_T{}^2$ bin.



P_T^2 Integrated M_H and Leading Order Theoretical predictions

- The results for all x_B-Q^2 bins are in the back up slides, and from what has been shown the results favor the MAPFF$\otimes$CT10nlo LO fits.
- We more neutral pion multiplicity data in the higher x_B range than HERMES (HERMES $\langle x_B \rangle = 0.082$ vs. 0.311 for this work) and at an average higher Q^2 ($\langle Q^2 \rangle = 2.5$ GeV^2 vs $\langle Q^2 \rangle = 3.11$).

SIDIS Cross Section

$$\frac{d\sigma}{dxQ^2dzdP_{hT}^2d\phi_h} = \frac{\pi\alpha_e^2}{xQ^4}\frac{y^2}{(1-\varepsilon)}\left(1+\frac{\gamma^2}{2x}\right)\times \left\{F_{UU,T} + \varepsilon F_{UU,L} + \sqrt{2\varepsilon(1+\varepsilon)}cos(\phi_h)F_{UU}^{cos(\phi_h)} + \varepsilon cos(2\phi_h)F_{UU}^{cos(2\phi_h)}\right\}$$

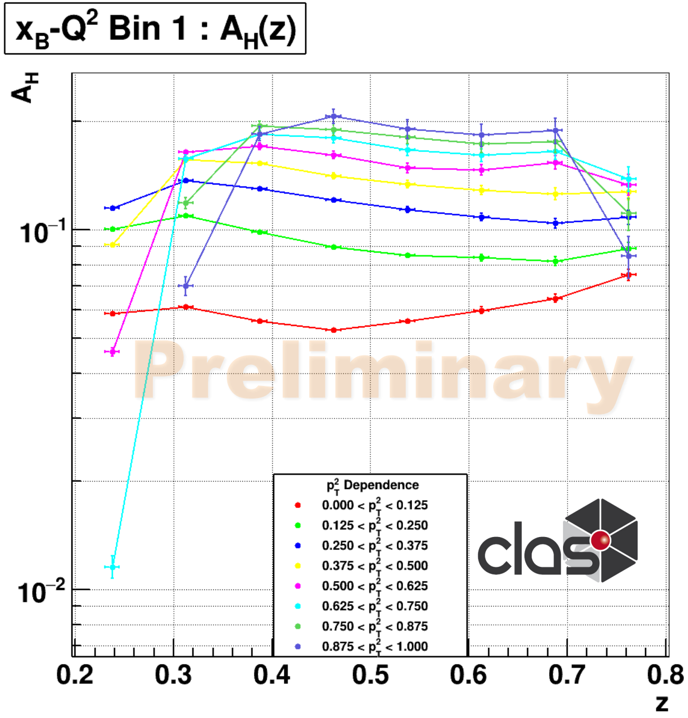
$$\frac{d\sigma}{dxQ^2dzdP_{hT}^2d\phi_h} = A\left(1 + Bcos(\phi_h) + Ccos(2\phi_h)\right)$$

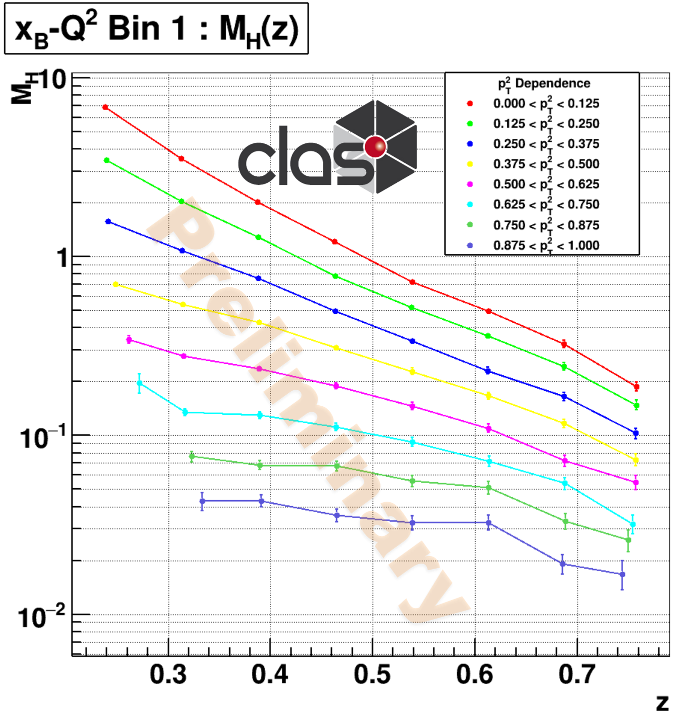
$$A = \frac{\pi\alpha_e^2}{xQ^4}\frac{y^2}{(1-\varepsilon)}\left(1+\frac{\gamma^2}{2x}\right)\left(F_{UU,T} + \varepsilon F_{UU,L}\right),$$

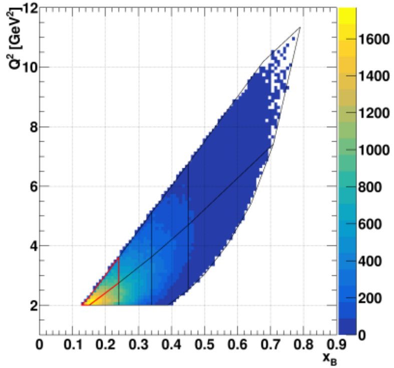
$$B = \frac{\sqrt{2\varepsilon(1+\varepsilon)}F_{UU}^{cos(\phi_h)}}{F_{UU,T} + \varepsilon F_{UU,L}}, and$$

$$C = \frac{\varepsilon cos(2\phi_h)F_{UU}^{cos(2\phi_h)}}{F_{UU,T} + \varepsilon F_{UU,L}}.$$

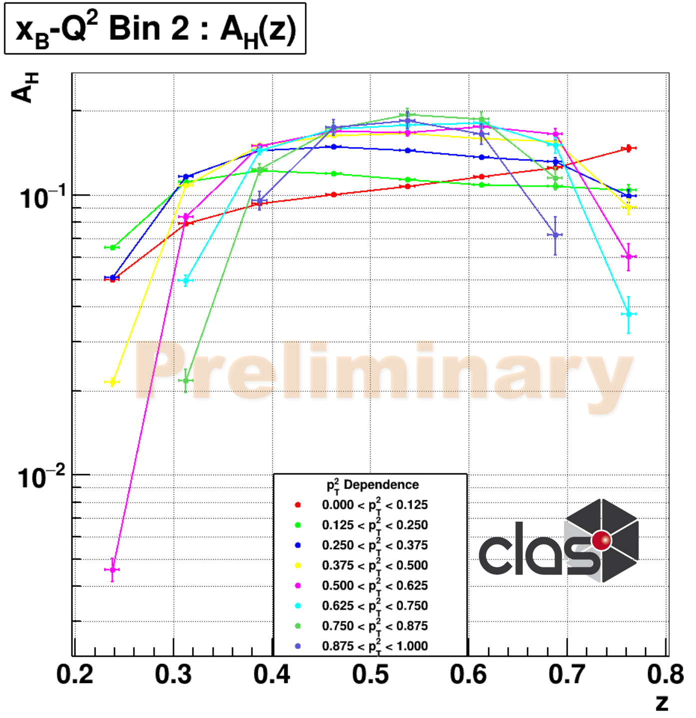
Multiplicities and Acceptances for x_B-Q^2 Bin 1

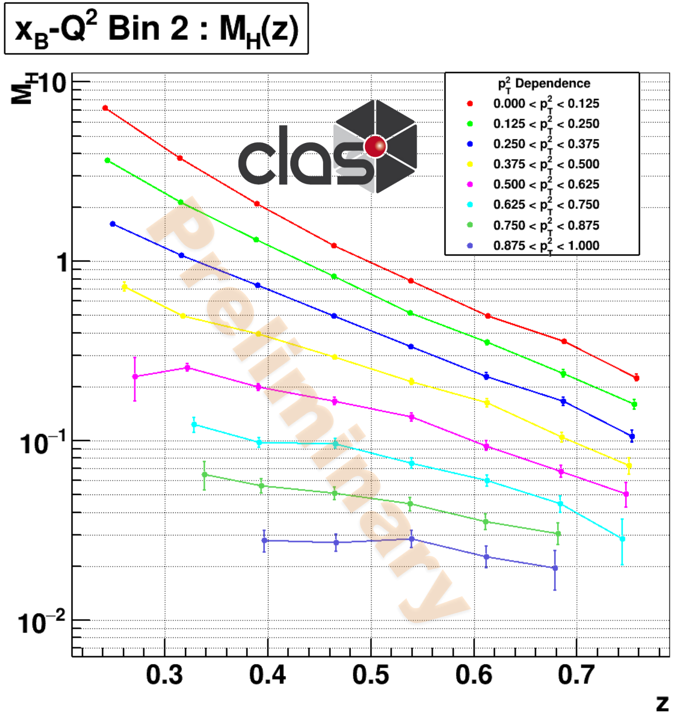


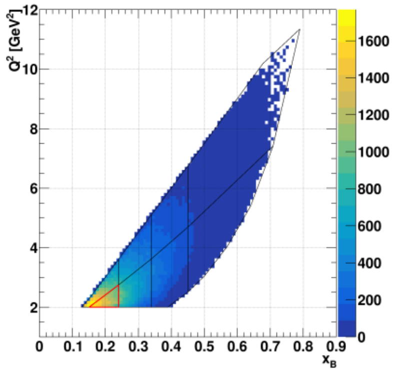




MULTIPLICITIES AND ACCEPTANCES FOR x_B-Q^2 BIN 2

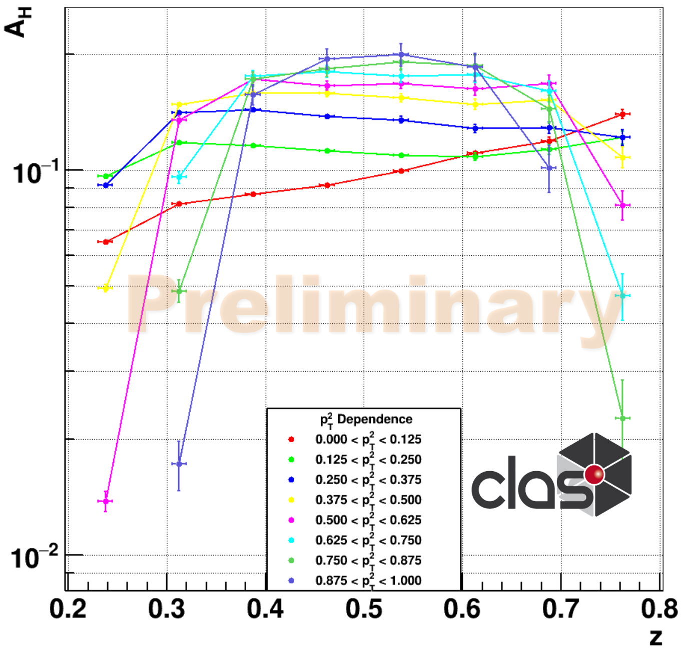




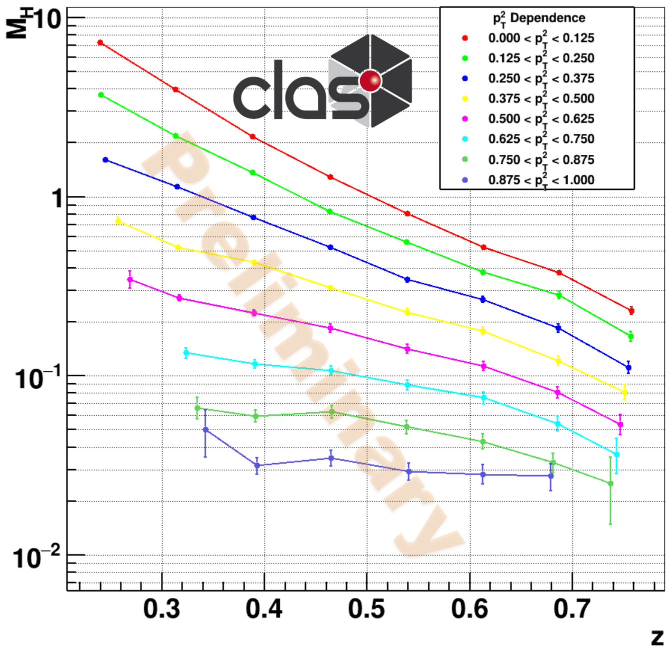


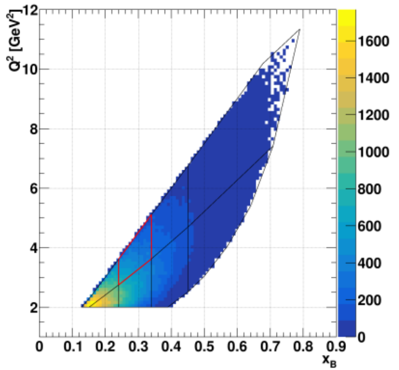
Multiplicities and Acceptances for x_B-Q^2 Bin 3

x_B-Q^2 Bin 3 : $A_H(z)$



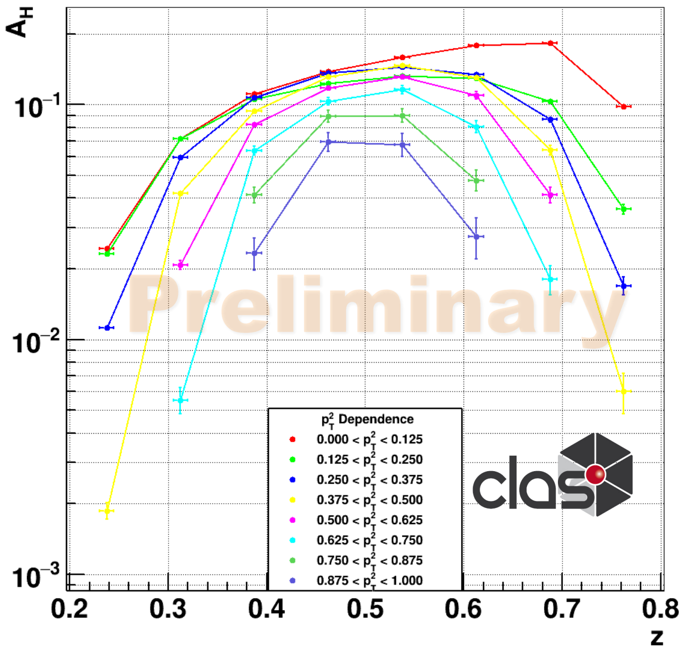
x_B-Q^2 Bin 3 : $M_H(z)$



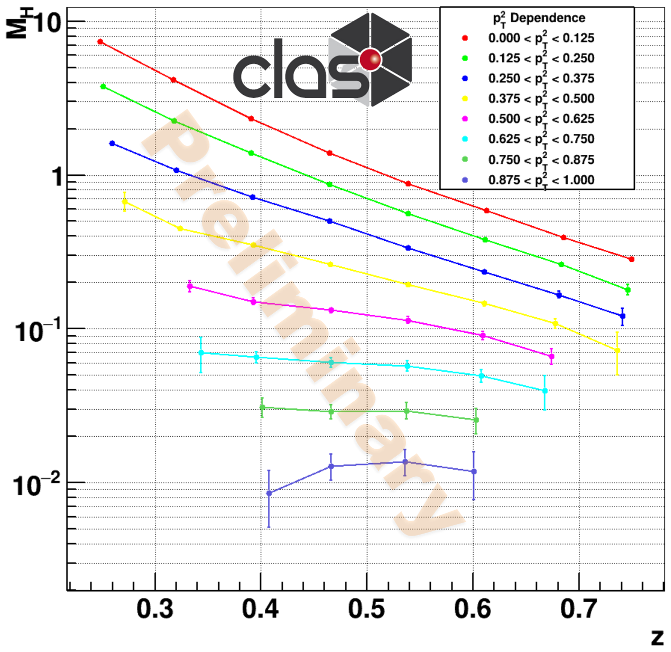


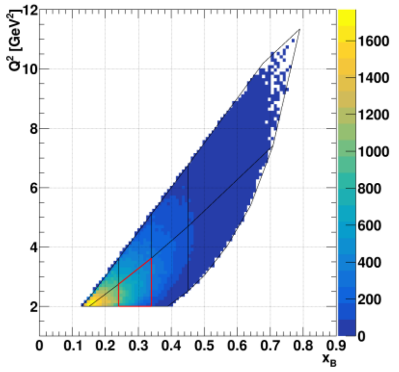
Multiplicities and Acceptances for x_B-Q^2 Bin 4

x_B-Q^2 Bin 4 : $A_H(z)$

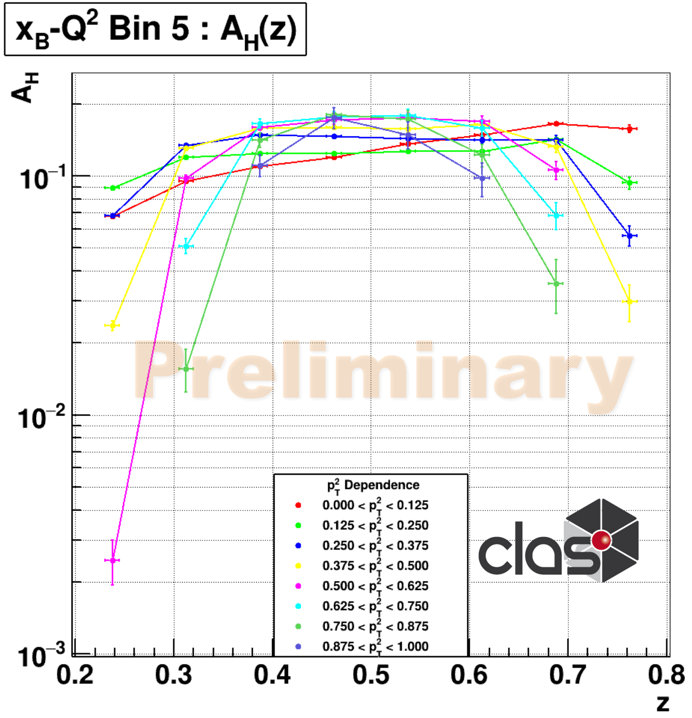


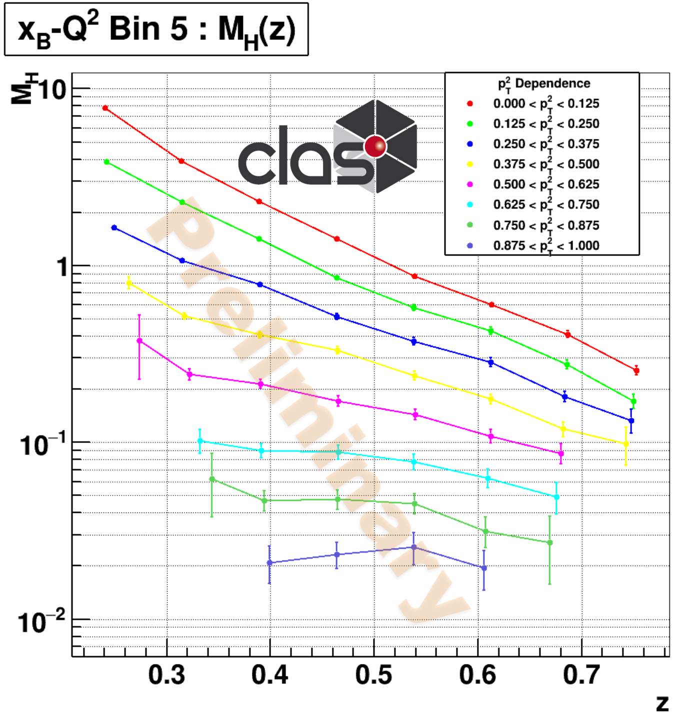
x_B-Q^2 Bin 4 : $M_H(z)$

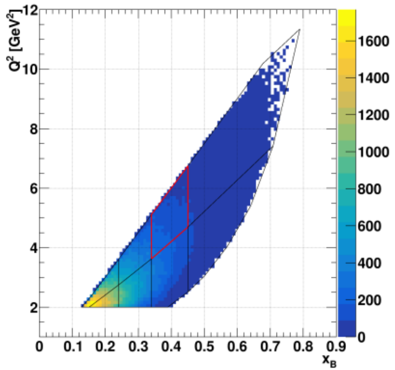




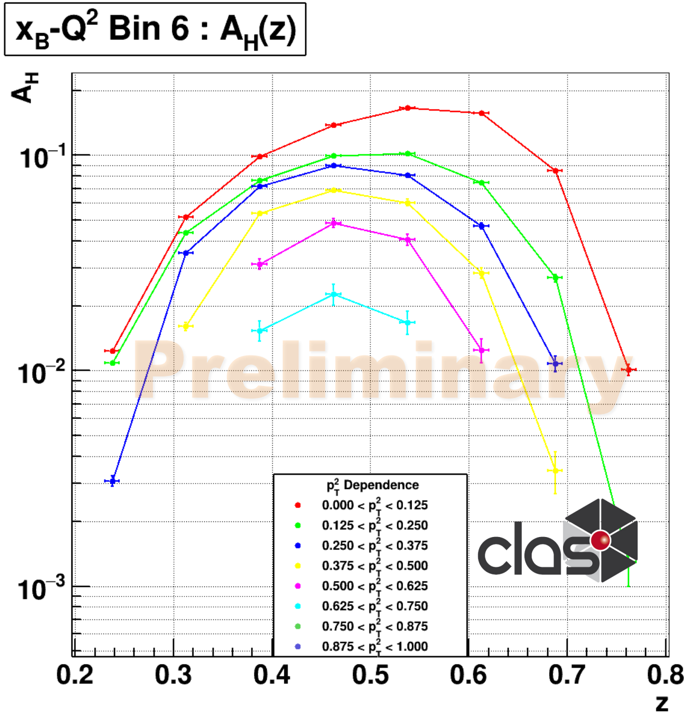
MULTIPLICITIES AND ACCEPTANCES FOR x_B-Q^2 BIN 5

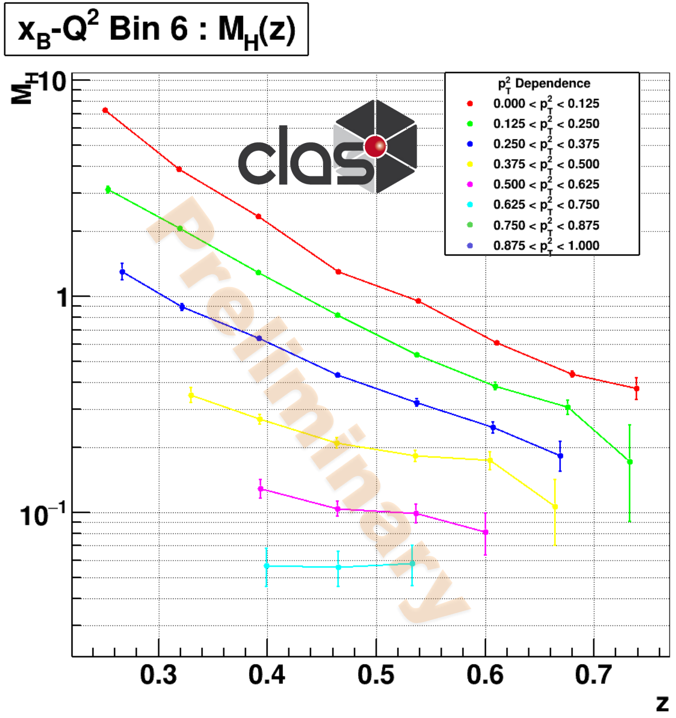


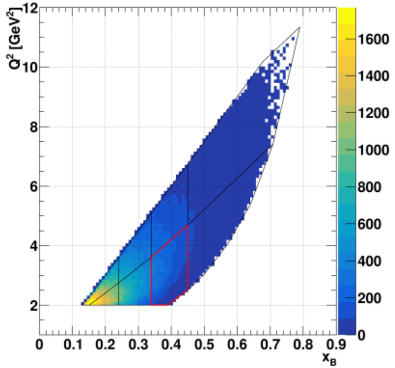




Multiplicities and Acceptances for x_B-Q^2 Bin 6

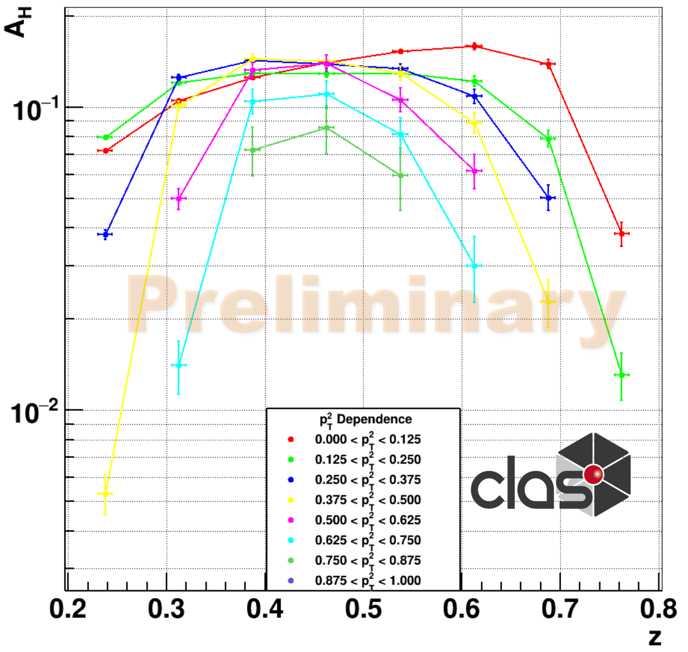




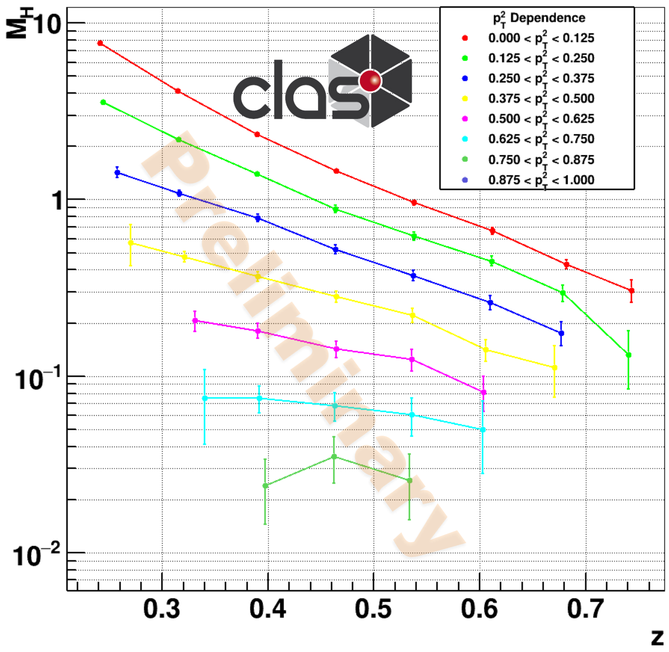


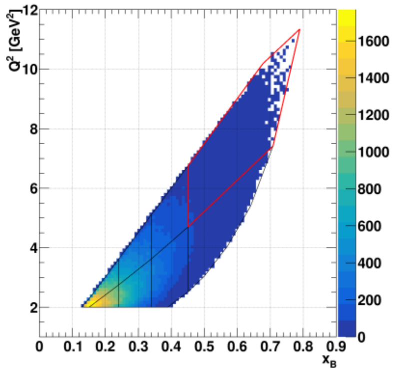
Multiplicities and Acceptances for x_B-Q^2 Bin 7

x_B-Q^2 Bin 7 : $A_H(z)$

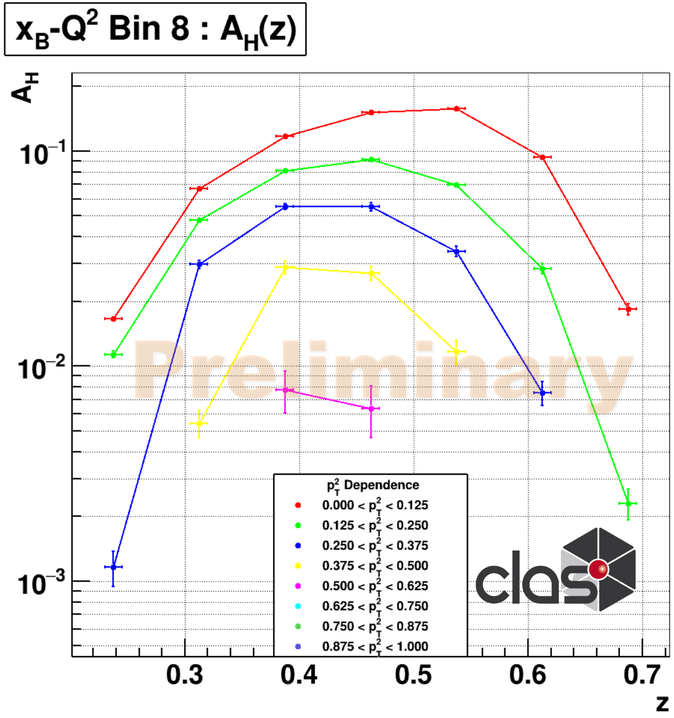


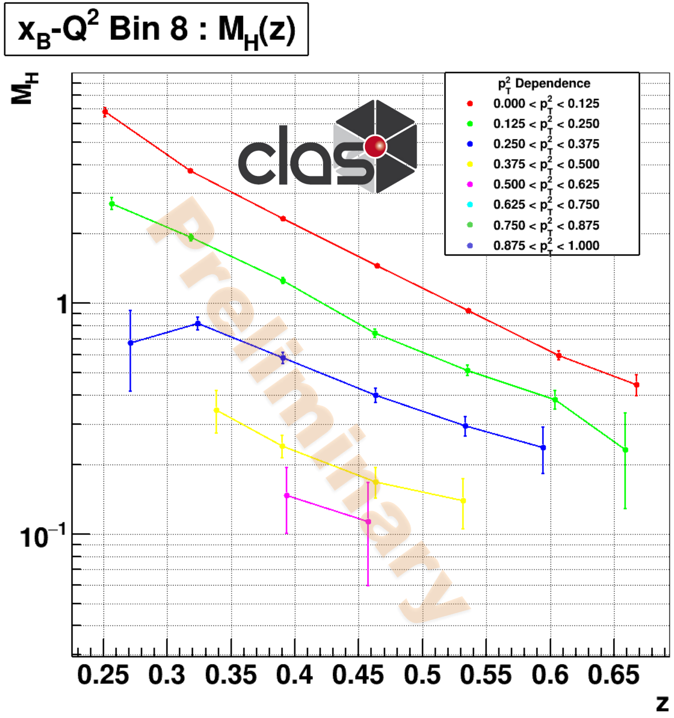
x_B-Q^2 Bin 7 : $M_H(z)$

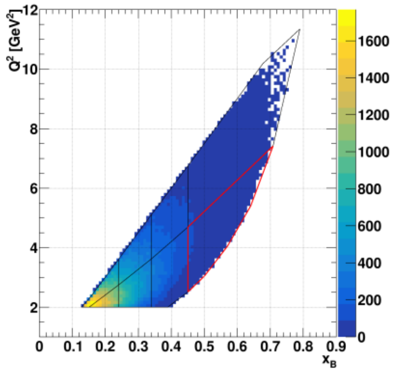




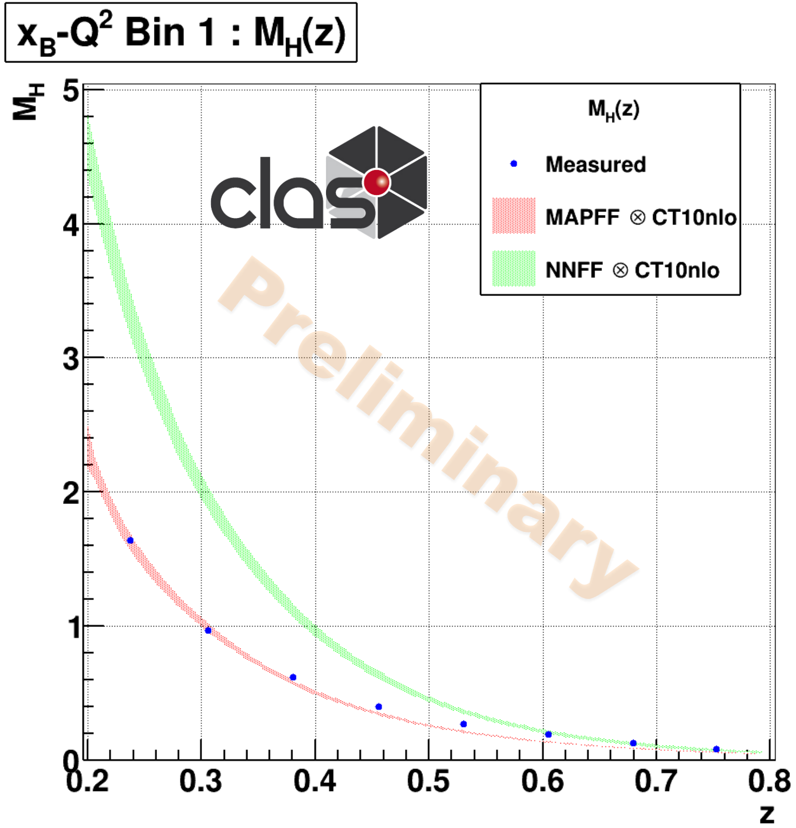
MULTIPLICITIES AND ACCEPTANCES FOR x_B-Q^2 BIN 8

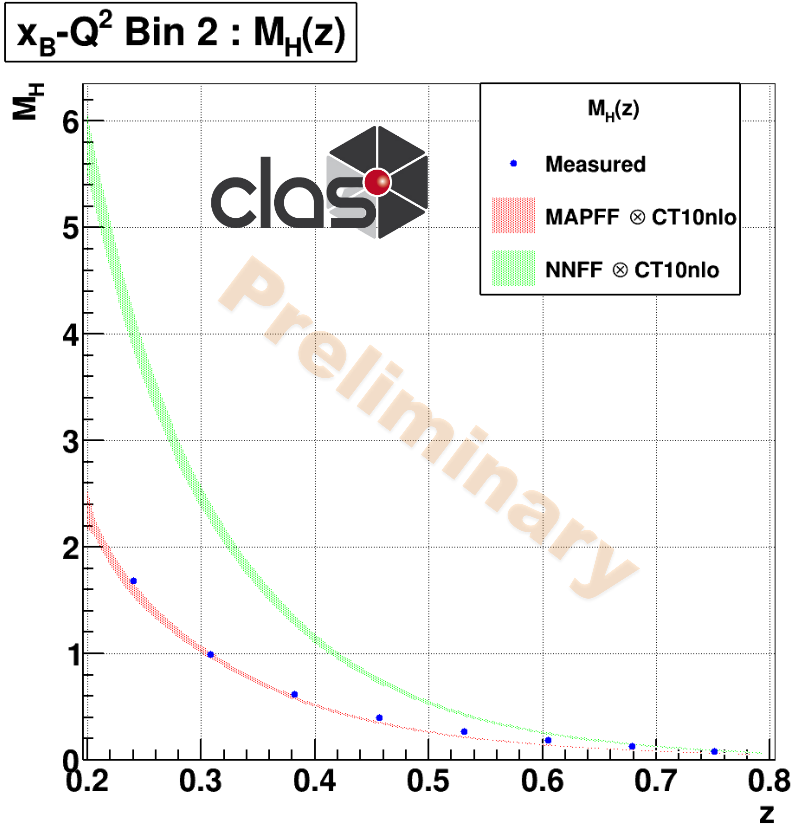




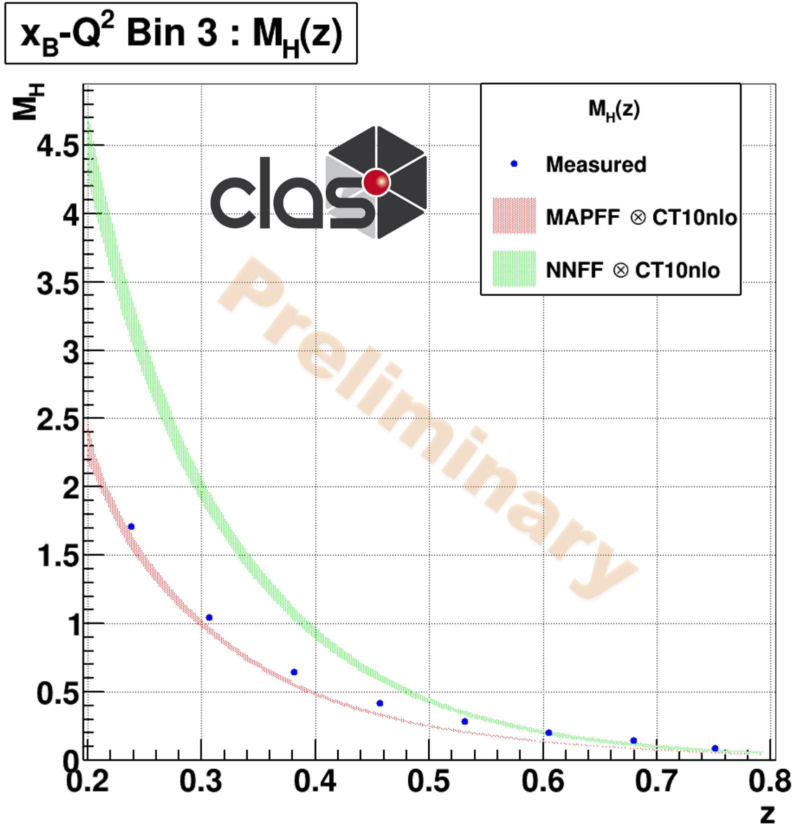


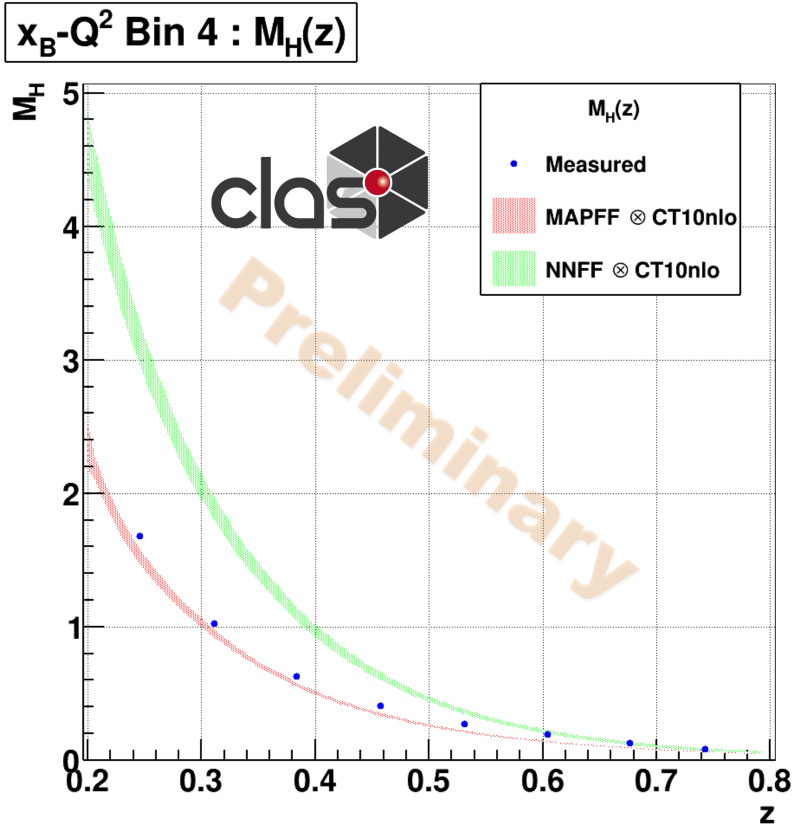
M_H with LO Theory Predictions for x_B-Q^2 Bins 1 & 2





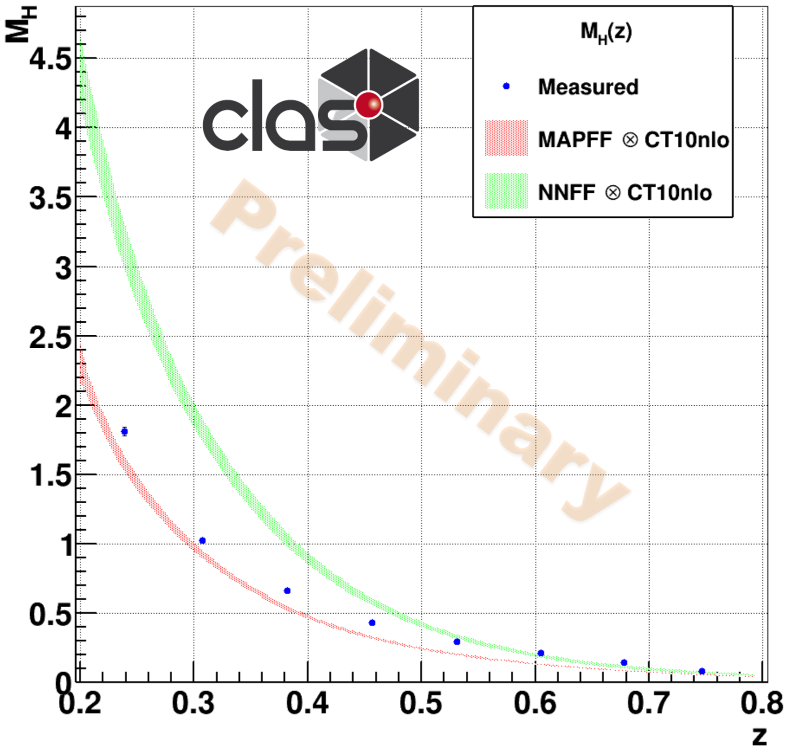
M_H with LO Theory Predictions for x_B-Q^2 Bins 3 & 4



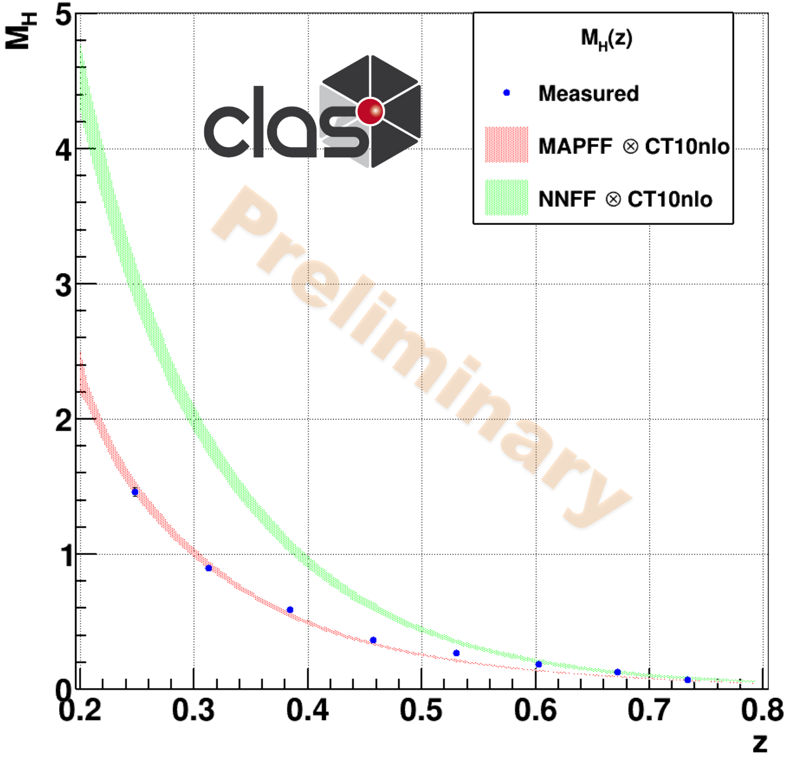


M_H with LO Theory Predictions for x_B-Q^2 Bins 5 & 6

x_B-Q^2 Bin 5 : $M_H(z)$

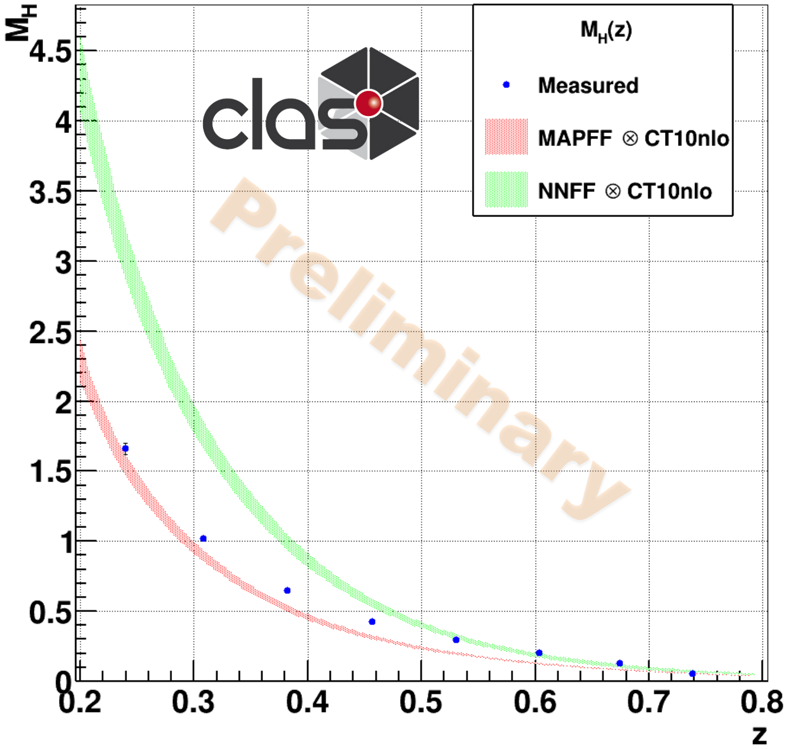


x_B-Q^2 Bin 6 : $M_H(z)$



M_H with LO Theory Predictions for x_B-Q^2 Bins 7 & 8

x_B-Q^2 Bin 7 : $M_H(z)$



x_B-Q^2 Bin 8 : $M_H(z)$