Timelike Compton Scattering with CLAS12 at Jefferson Lab

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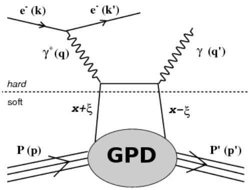
Outline

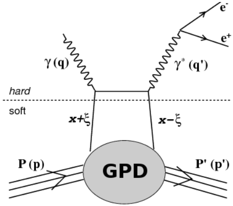
- Current status of the TCS analysis
- Pion/Positron separation above 4.9 GeV: multivariate analysis approach

From DeeplyVirtualComptonScattering to TimelikeComptonScattering

DVCS ($\gamma^* p \to \gamma p$)



TCS ($\gamma p \to \gamma^* p$)



Compton Form Factors (CFF)

$$\mathcal{H} = \sum_q e_q^2 \left\{ \mathcal{P} \int_{-1}^{1} dx H^q(x,\xi,t) \left[\frac{1}{\xi - x} - \frac{1}{\xi + x} \right] + i\pi \left[H^q(\xi,\xi,t) - H^q(-\xi,\xi,t) \right] \right\}$$

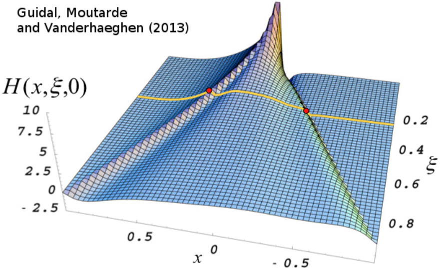
Imaginary part

- Measured in DVCS asymmetries
- Accessible in TCS photon polarization asymmetry

Real part

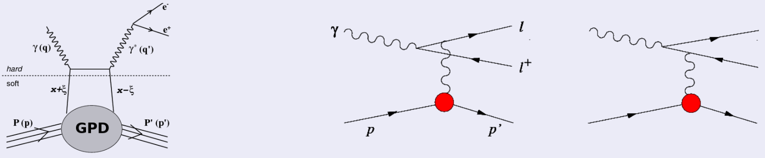
- Accessible in DVCS cross section
- Accessible in TCS in cross section angular modulation

Guidal, Moutarde and Vanderhaeghen (2013)



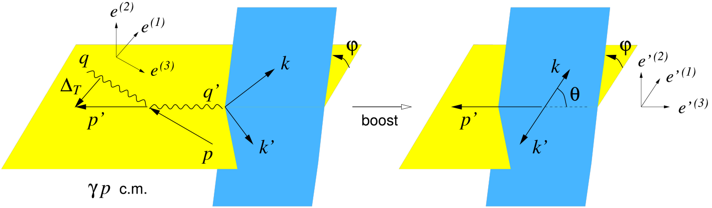
TCS, Bethe-Heitler and some kinematics

$\gamma p \to e^+ e^- p$



TCS

Bethe-Heitler



$Q'^2 = (k + k')^2 \qquad t = (p' - p)^2 \qquad L = \frac{(Q'^2 - t)^2 - b^2}{4} \qquad L_0 = \frac{Q'^4 sin^2\theta}{4}$

$b = 2(k - k')(p - p') \qquad \tau = \frac{Q'^2}{2p\cdot q} = \frac{Q'^2}{s - M^2} \qquad \xi = \frac{\tau}{2-\tau} \qquad s = (p + q)^2 \qquad t_0 = -\frac{4\xi^2 M^2}{(1-\xi^2)}$

$\gamma p \to e^+ e^- p$ Cross section and CFFs

Interference cross section

$$\frac{d^4\sigma_{INT}}{dQ'^2 dt d\Omega} = -\frac{\alpha_{em}^3}{4\pi s^2}\frac{1}{-t}\frac{m_p}{Q'}\frac{1}{\tau\sqrt{1-\tau}}\frac{L_0}{L}\left[\cos(\phi)\frac{1+\cos^2(\theta)}{\sin(\theta)} Re\ \tilde{M}^{--} + \ldots\right]$$

$$\to \tilde{M}^{--} = \frac{2\sqrt{t_0 - t}}{M}\frac{1-\xi}{1+\xi}\left[F_1\mathcal{H} - \xi(F_1+F_2)\tilde{\mathcal{H}} - \frac{t}{4M^2}F_2\mathcal{E}\right]$$

BH cross section

$$\frac{d^4\sigma_{BH}}{dQ'^2 dt d\Omega} \approx -\frac{\alpha_{em}^3}{2\pi s^2}\frac{1}{-t}\frac{1+\cos^2(\theta)}{\sin^2(\theta)}\left[(F_1^2 - \frac{t}{4M^2}F_2^2)\frac{2}{\tau^2}\frac{\Delta_T^2}{-t} + (F_1+F_2)^2\right]$$

BH cross section diverges at $\theta \approx 0^\circ$ and 180°

Weighted cross section ratio

$$R(\sqrt{s}, Q'^2, t) = \frac{\int_0^{2\pi} d\phi\ \cos(\phi)\ \frac{dS}{dQ'^2 dt d\phi}}{\int_0^{2\pi} d\phi \frac{dS}{dQ'^2 dt d\phi}} \qquad \frac{dS}{dQ'^2 dt d\phi} = \int_{\pi/4}^{3\pi/4} d\theta \frac{L}{L_0}\frac{d\sigma}{dQ'^2 dt d\phi d\theta}$$

Data analysis

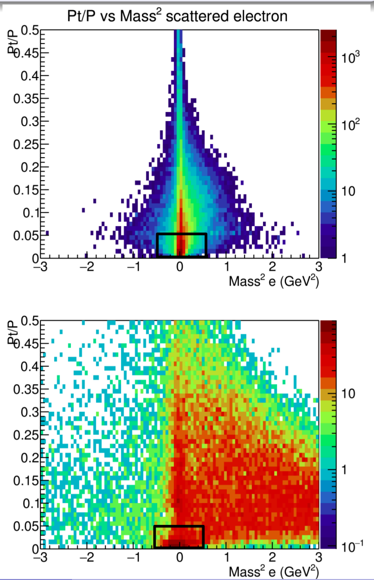
$$ep \rightarrow e'\gamma p \rightarrow (e')e^+e^-p'$$

Final state

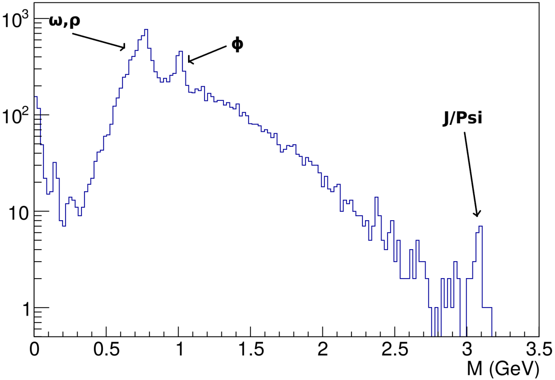
- Use the CLAS12 reconstruction software PID
- Events with exactly one e^+,one e^- and one proton are selected

Scattered electron

- Cut on scattered electron missing mass
- Cut on missing transverse momentum
- These cuts constrain the virtuality of the photon $Q^2 \propto cos(\Theta_{scattered})$



Lepton-pair spectrum



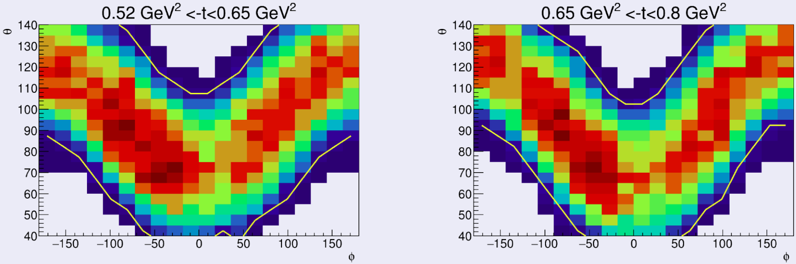
- Whole inbending data set available (64 runs)
- 22 J/Psi (Analysis by J.Newton)
- The mass region between 2 *GeV* and 3 *GeV* is resonance-free and will be used for the final analysis. We are investigating the possibility of using data down to 1.5 GeV (Discussion with M.Guidal and M.Vanderhaeghen).

Acceptance estimation

Experimental cross section ϕ modulation ratio

$$R = \frac{\int_0^{2\pi} d\phi \;\; cos(\phi) \;\; \frac{dS}{dQ'^2 dtd\phi}}{\int_0^{2\pi} d\phi \frac{dS}{dQ'^2 dtd\phi}} \quad \rightarrow \quad R' = \frac{\sum_\phi cos(\phi) Y_\phi}{\sum_\phi Y_\phi} \text{ where } Y_\phi = \sum_{event \;\; in \;\; \phi \;\; bin} \frac{L}{L_0} \frac{1}{A_\theta^\phi}$$

Estimate of CLAS12 acceptance with BH simulation

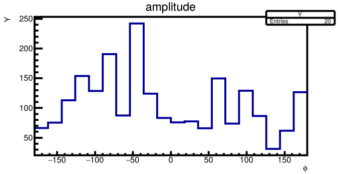


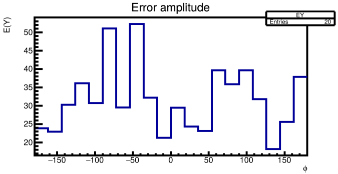
Acceptance in the θ/ϕ plane ($A_\theta^\phi = \frac{N_{REC}}{N_{GEN}}$)

→ Yellow lines are CLAS12 acceptance limits (Limits set at first bin with acceptance higher than 5%)

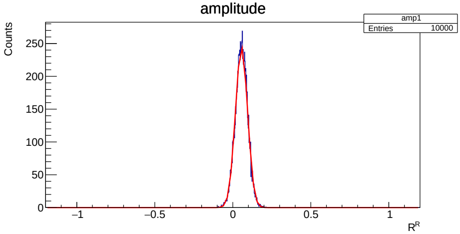
Statistical error estimation using Monte Carlo

$$R' = \frac{\sum_{\phi} cos(\phi) Y_{\phi}}{\sum_{\phi} Y_{\phi}} \text{ where } Y_{\phi} = \sum_{event\ in\ \phi\ bin} \frac{L}{L_0}\frac{1}{A_{\theta}^{\phi}} \text{ and } E(Y_{\phi})^2 = \sum_{event\ in\ \phi\ bin} \left(\frac{L}{L_0}\frac{1}{A_{\theta}^{\phi}}\right)^2$$





- For each ϕ bin, a random value Y_{ϕ}^{R} is generated from a gaussian with mean Y_{ϕ} and sigma $E(Y_{\phi})$
- $R'^{R} = \frac{\sum_{\phi} cos(\phi) Y_{\phi}^{R}}{\sum_{\phi} Y_{\phi}^{R}}$ is calculated. This process is repeated many times (10000 times)



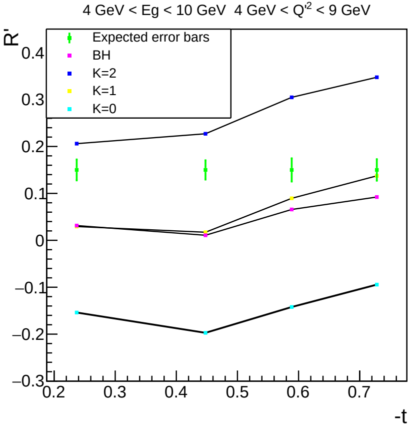
- σ of the gaussian fit is the statistical error

Projected results (2-3 GeV region)

Generator developed by R. Paremuzyan at Jefferson Lab.

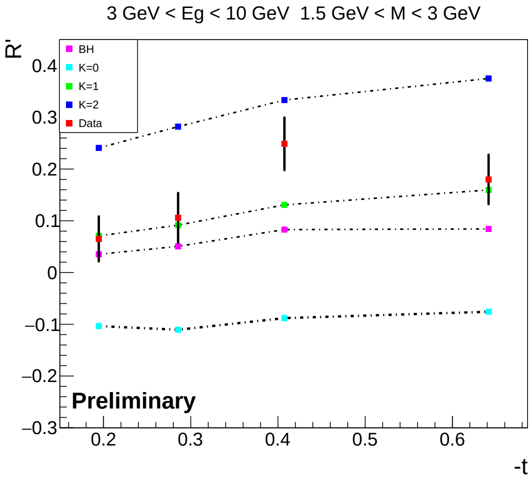
→ Double distribution GPD parametrization

$$H(x,\xi,t) = H_{DD}(x,\xi,t) + \kappa \frac{1}{N_f}\Theta(\xi - |x|)D(\frac{x}{\xi},t)$$



- R' is sensitive to D-term strength within CLAS12 acceptance.
- Full data set (≈4000 events) will provide enough statistics to give insight on D-term in the 2-3 GeV mass region(green points and associated error bars).

Preliminary results (1.5-3 GeV region)

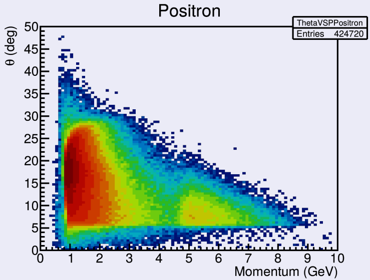


- ≈1000 events
- No Fiducial cuts, no further pid cuts yet included (EB only)
- Central efficiency for protons to be corrected using ($ep \rightarrow ep\pi^+\pi^-$) (In progress)

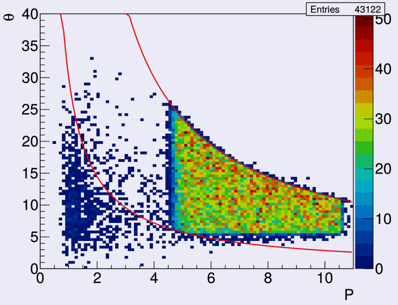
Positron/Pion Separation at high momentum (>4.9 GeV)

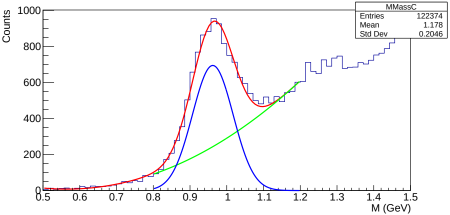
Clear Pion contamination in PID -11

Data: clear increase in the number of positron above 4.9 GeV



Simu.: mis-identified pions above 4.9 GeV

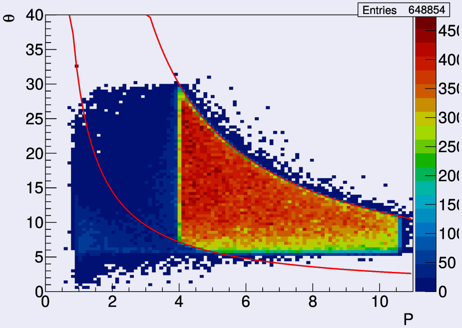




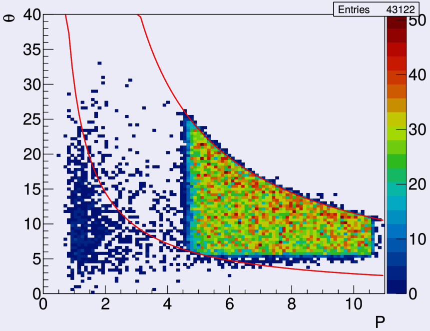
- Skim events with electron in FD and P<4.4 GeV, "positron" (ID -11) in FD and P>4.4 GeV
- Assign m_π to positron, and look for the missing particle $e^- p \rightarrow e^- \pi^+_{PID\ -11} X$
- Clear neutron peak

Simulation of e^+ and π^+

Generated e^+/ Reconstructed e^+:



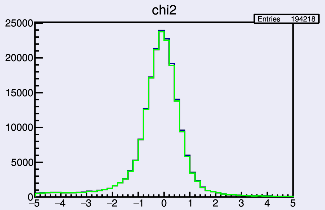
Generated π^+/reconstructed e^+:



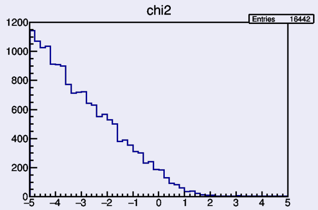
- Momentum between 4 and 10.6 GeV
- Pt between 0.5 and 2 GeV (≈ CLAS12 FD acceptance)

Simple approaches: Chi2 and sampling fractions cuts (from simu.)

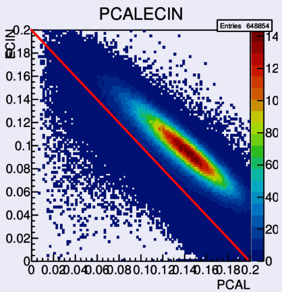
True positron:

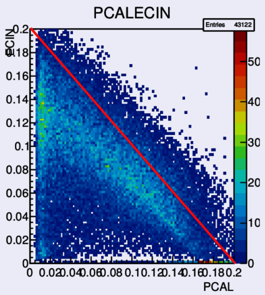


Fake positron:



ECIN SF vs PCAL SF





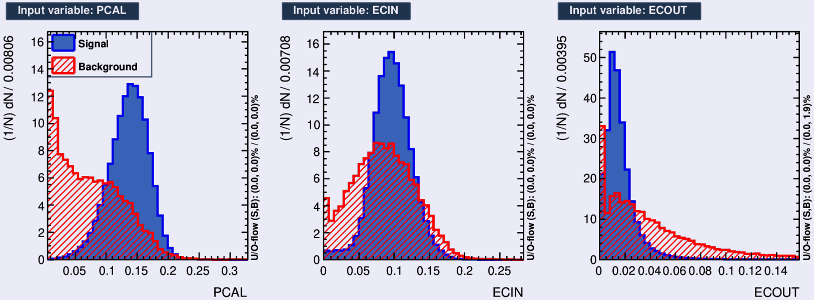
Multivariate analysis approach

- Positron/Pion separation above HTCC threshold is a typical multivariate problem : sampling fraction (total, PCAL, ECin, ECout), shower profile , shower skewness ,...
- Use of the Root/TMVA package https://root.cern.ch/tmva

How does it work ?

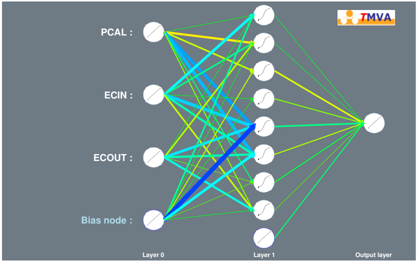
- Give "signal" and "background" trees
- Training and testing of the selected method performed by the package
- "Weights" produced for later applications

TMVA application on Sampling Fraction (from simulation)

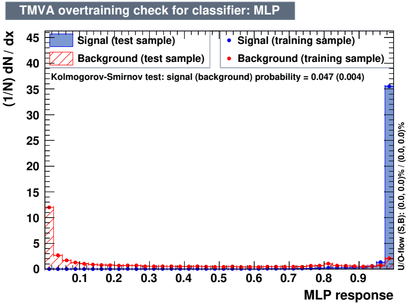


One example of MVA: **Multilayer perceptron**

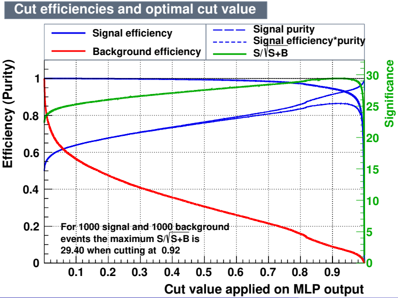
MLP architecture



Output

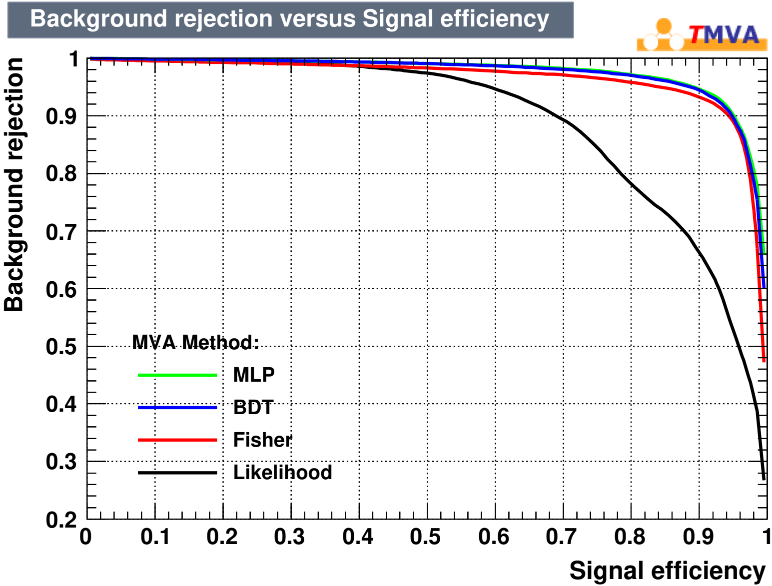


Efficiency



- Plots provided by TMVA package
- Assess efficiency of method and gives best value for cut

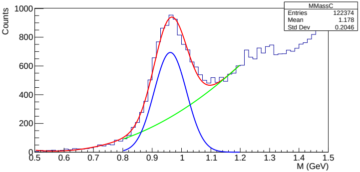
Comparison of different methods on simulation: ROC curve



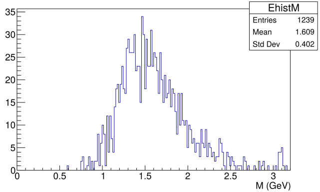
Comparison of different methods on data

- $e^- p \rightarrow e^- \pi^+_{PID\ -11} X$ provides good estimation of mis-identified pion ("background")
- "Signal+Background" →number of lepton pair photoproduction events with $P_{e^+} > 4\ GeV$ (TCS exclusivity cuts).
- For each selected method measure "signal" and "background" for multiple values of cut → Plot "signal+background" strength VS "background" strength (≈ ROC curve).

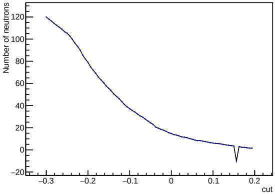
No cut BK

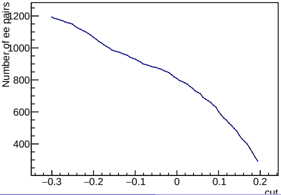


No cut lepton pairs

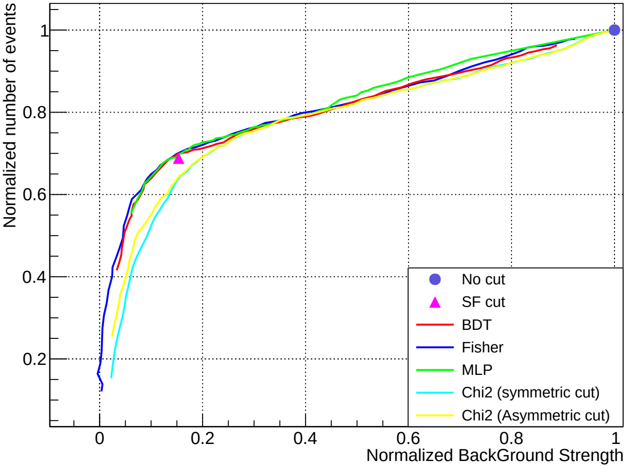


BDT cut





3D VS 1D/2D Positron/Pion separation

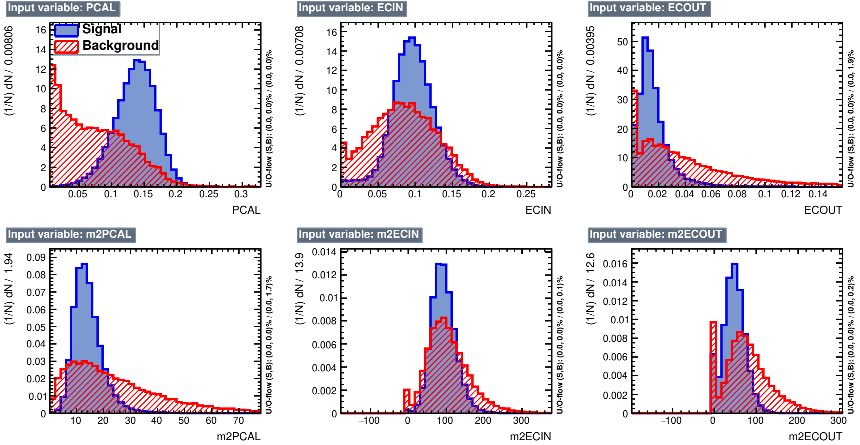


- Chi2 is not optimal.
- Common Linear behaviour at high Background strength: validation of the procedure
- Cut on the ECINsf/PCALsf is compatible with multivariate methods although less flexible.

6D Positron/Pion separation

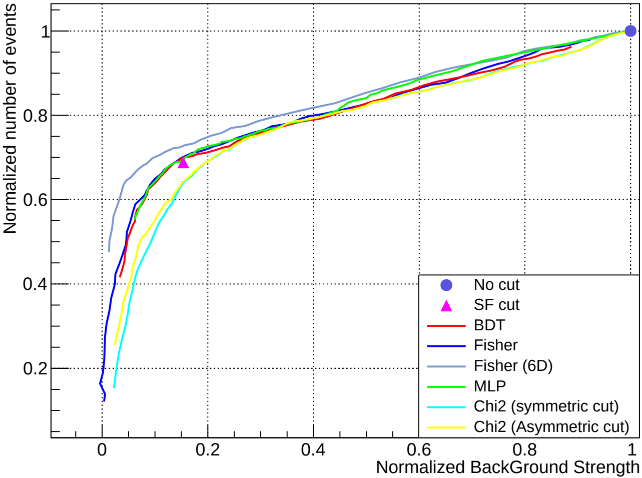
Shower width M^2

$$D = \frac{\sum_{strip} x \cdot ln(E)}{\sum_{strip} ln(E)} \qquad M_2 = \frac{\sum_{strip} (x-D)^2 \cdot ln(E)}{\sum_{strip} ln(E)}$$



From simulation

6D Positron/Pion separation



Adding the shower profile to the discriminating variables reduces contamination by a factor of ≈2

Conclusion

TCS analysis

- Timelike Compton Scattering allows to investigate the real part of CFFs.
- Projected statistic will allow insight on the strength of the D-term.
- The analysis procedure leading to R' is fully
- Extension of the mass range down to 1.5 GeV being investigated; developed.

Positron/Pion Separation

- Contamination of Pion in PID -11 is important
- MVA tools applied to this issue leads to good reduction of background.
- These results will be added to the TCS analysis code soon.

Back up

Physics Motivations

- The CFFs dispersion relation at leading-order and leading twist :

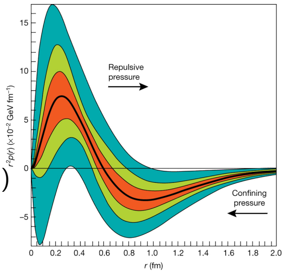
$$Re\mathcal{H}(\xi,t) = \mathcal{P}\int_{-1}^{1} dx\left(\frac{1}{\xi - x} - \frac{1}{\xi + x}\right) Im\mathcal{H}(\xi,t) + D(t)$$

- D-term expansion

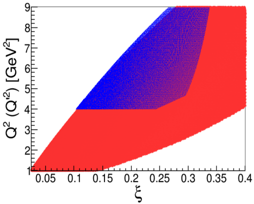
$$D(t) = \frac{1}{2}\int_{-1}^{1} dz \frac{D(z,t)}{1-z}$$

$$D(z,t) = (1-z^2)[d_1(t)C_1^{3/2}(z) + ...]$$

- $d_1(t)$ is directly related to the pressure distribution in the nucleon.
- Measurement of photon polarization asymmetry will provide a test of universality of GPDs.



Nature (2018) Burkert, Elouadrhiri, Girod



DVCS phase space

TCS phase space

Boër, Guidal, Vanderhaeghen (2015)

Projected results

- R' is sensitive to D-term strength BUT also depends on acceptance limits $\rightarrow$ difficulties to compare measurement with theoretical models
- Possibility to restore θ dependence of the interference cross-section

We want to access the ϕ moment of the cross section. We can measure :

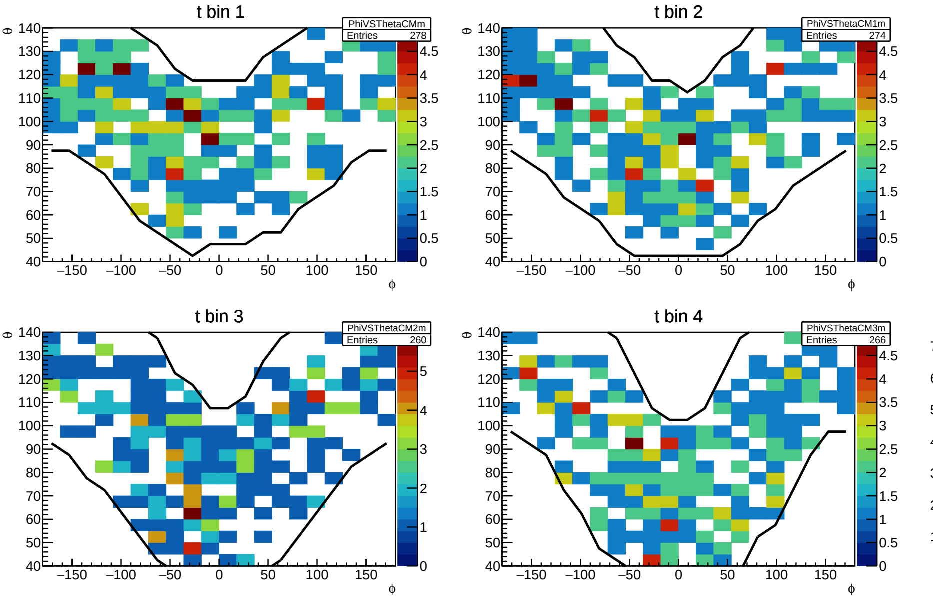
$$\frac{dS_{TOT}}{dQ'^2 dt d\phi} = \int_{b(\phi)}^{a(\phi)} d\theta \frac{d^4\sigma_{TOT}}{dQ'^2 dt d\Omega} \frac{L}{L_0} = \frac{dS_{BH}}{dQ'^2 dt d\phi} + \frac{dS_{INT}}{dQ'^2 dt d\phi}$$

- $\frac{dS_{BH}}{dQ'^2 dt d\phi}$ is calculable from form factors.
- The θ/ϕ dependance of the interference term is fully known :

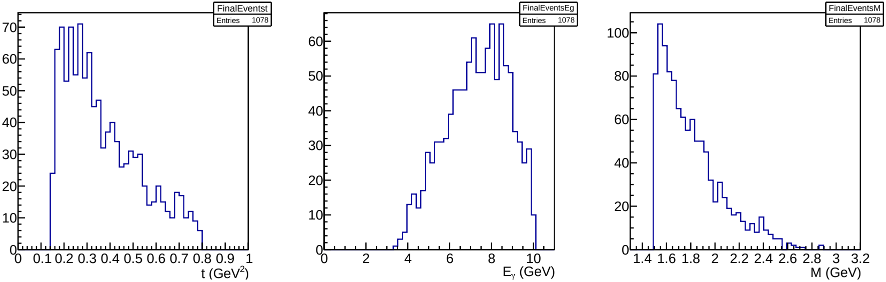
$$\frac{dS_{INT}}{dQ'^2 dt d\phi} = -\frac{\alpha_{em}^3}{4\pi s^2} \frac{1}{-t} \frac{m_p}{Q'} \frac{1}{\tau\sqrt{1-\tau}} [cos(\phi) \int_{b(\phi)}^{a(\phi)} (1 + cos^2(\theta)) d\theta \cdot Re\ \tilde{M}^{--} + ...]$$

This method will be implemented at a later stage of the analysis, as it requires good accumulated luminosity estimation.

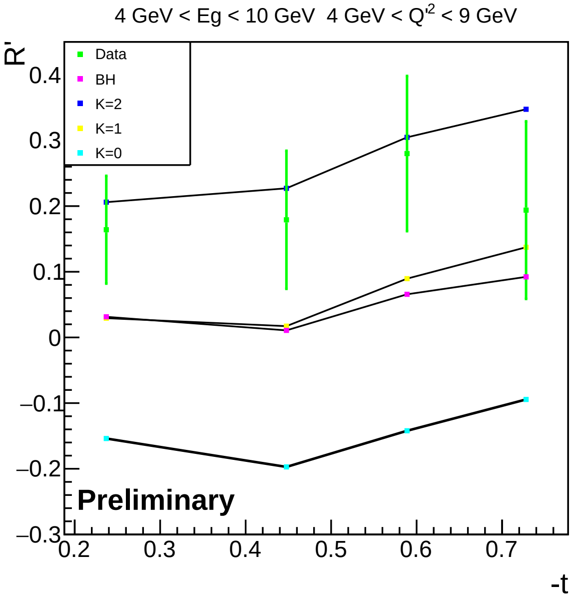
1.5 - 3 GeV event kinematics (1)



1.5 - 3 GeV event kinematics (2)

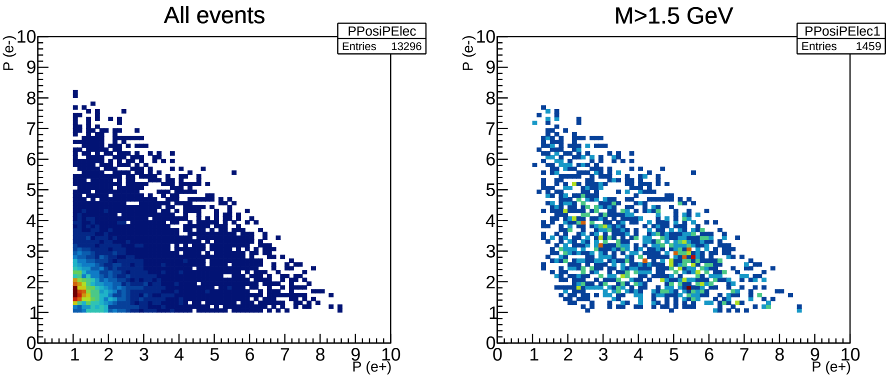


2 - 3 GeV

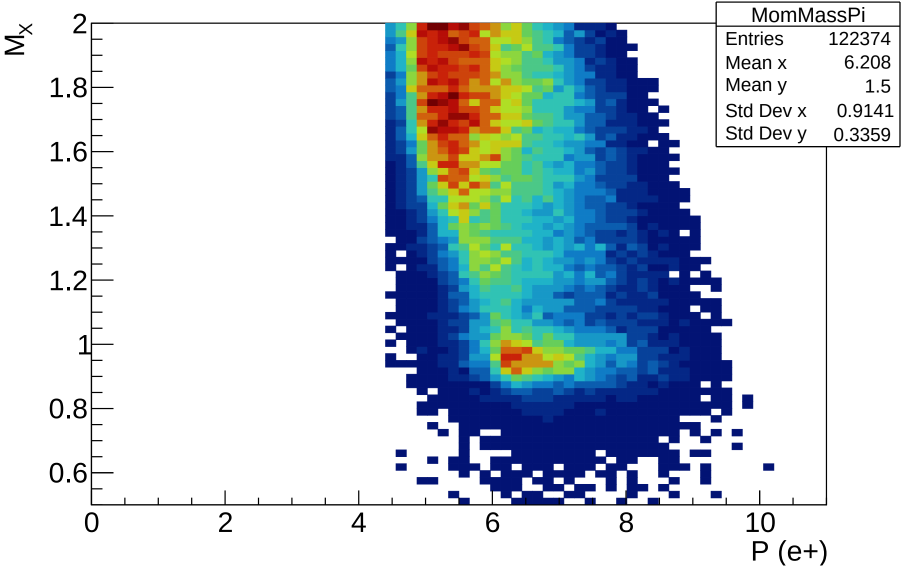


4 GeV < Eg < 10 GeV 4 GeV < Q'2 < 9 GeV
R'
Data
BH
K=2
K=1
K=0
Preliminary
0.4
0.3
0.2
0.1
0
–0.1
–0.2
–0.3
0.2
0.3
0.4
0.5
0.6
0.7
-t

Lepton Pair momentum



Mis-ID Pion



MomMassPi
Entries 122374
Mean x 6.208
Mean y 1.5
Std Dev x 0.9141
Std Dev y 0.3359
M_X
P (e+)
0.6
0.8
1
1.2
1.4
1.6
1.8
2
0
2
4
6
8
10