Timelike Compton Scattering with CLAS12

CLAS Collaboration meeting - July 2020

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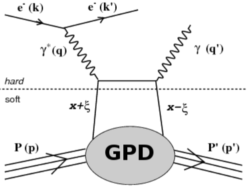
Outline

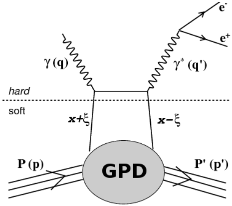
- Physics motivations
- Event selection and Positron identification
- Proton efficiency and momentum corrections
- Ratio R and Forward/Backward asymmetry preliminary results and systematics

From DeeplyVirtualComptonScattering to TimelikeComptonScattering

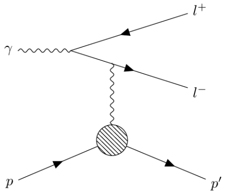
DVCS ($\gamma^* p \rightarrow \gamma p$)



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



Bethe-Heitler



Compton Form Factors (CFF)

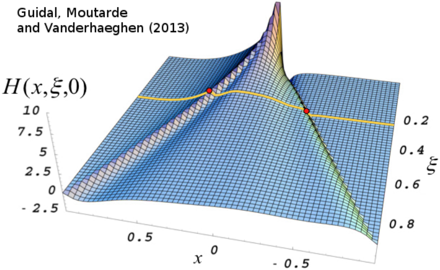
$$\mathcal{H} = \sum_q e_q^2 \left\{ \mathcal{P} \int_{-1}^{1} dx H^q(x,\xi,t) \left[\frac{1}{\xi - x} - \frac{1}{\xi + x} \right] + i\pi \left[H^q(\xi,\xi,t) - H^q(-\xi,\xi,t) \right] \right\}$$

Imaginary part

- Measured in DVCS asymmetries
- TCS γ polarization asymmetry

Real part

- Accessible in DVCS cross section
- Charge asymmetry (E. Voutier talk)
- TCS cross section angular modulation (R and F/B asymmetry)



Physics motivations

1 **Nucleon D-term**

- 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

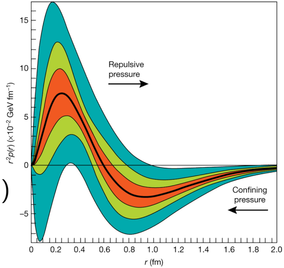
$$D(t) = \frac{1}{2}\int_{-1}^{1} dz \frac{D(z,t)}{1-z}$$

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

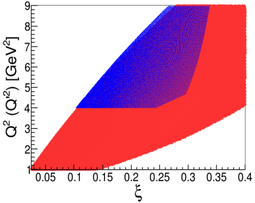
- $d_1(t)$ is directly related to the pressure distribution in the nucleon.

2 **Test of universality of GPDs**

- Photon polarization asymmetry sensitive to $Im\mathcal{H}$



Nature (2018) Burkert, Elouadrhiri, Girod

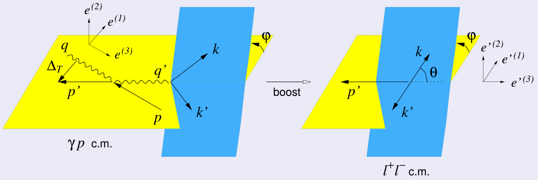


DVCS phase space

TCS phase space

Boër, Guidal, Vanderhaeghen (2015)

$\gamma p \to e^+ e^- p$ cross section and observables (1)



$$Q'^2 = (k + k')^2 \qquad t = (p' - p)^2$$

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

$$b = 2(k - k')(p - p')$$

$$\tau = \frac{Q'^2}{2p \cdot q} \qquad s = (p + q)^2$$

$$\xi = \frac{\tau}{2 - \tau} \qquad t_0 = -\frac{4\xi^2 M^2}{(1 - \xi^2)}$$

Interference cross section

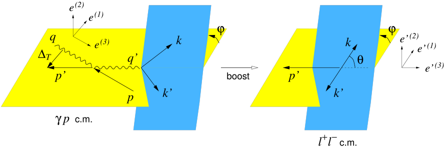
$$\frac{d^4\sigma_{INT}}{dQ'^2 dt d\Omega} = -\frac{\alpha_{em}^3}{4\pi s^2} \frac{1}{-t} \frac{m_p}{Q'} \frac{1}{\tau\sqrt{1-\tau}} \frac{L_0}{L} [\cos(\phi) \frac{1 + \cos^2(\theta)}{\sin(\theta)} Re\ \tilde{M}^{--} \quad + \quad ...]$$

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

1st observable: Weighted cross section ratio (Berger, Diehl and Pire, 2002)

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

$\gamma p \to e^+e^-p$ cross section and observables (2)



Unpol. cross section

$$\frac{d^4\sigma_{INT}}{dQ'^2dtd\Omega} \propto -\frac{L_0}{L}\cos(\phi)\frac{1+\cos^2(\theta)}{\sin(\theta)} Re\ \tilde{M}^{--}$$

2nd observable: Forward-Backward Asymmetry

Concept explored for J/Ψ production [Gryniuk and Vanderhaeghen(2016)].
No predictions for TCS have been published yet.

$$A_{FB}(\theta_0, \phi_0) = \frac{d\sigma(\theta_0, \phi_0) - d\sigma(180^\circ - \theta_0, 180^\circ + \phi_0)}{d\sigma(\theta_0, \phi_0) + d\sigma(180^\circ - \theta_0, 180^\circ + \phi_0)} \propto Re\tilde{M}^{--}$$

$\rightarrow$ Access to the real part of the CFFs with no integration over angles (removes large dependencies on angular acceptance)

Event selection

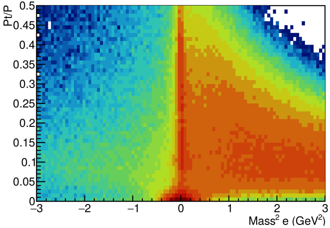
$$ep \to e'\gamma p \to (e')e^+e^-p'$$

Final state selection

- Use the CLAS12 reconstruction software PID
- Additional positron pid (see further slides)
- Events with exactly one e^+,one e^- and one proton are selected

Exclusivity cuts

- Cut on scattered electron missing mass and missing transverse momentum
- Put a constraint on the virtuality of the photon $Q^2 \propto 1 - cos(\Theta_{scattered})$



Exclusivity cuts

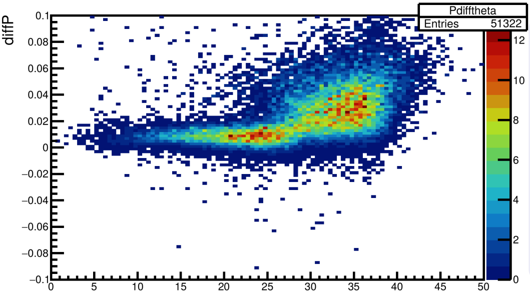
$$\frac{Pt}{P} < 0.05$$

$$Mass^2 < 0.4\ GeV^2$$

$$P_{lepton} > 1\ GeV$$

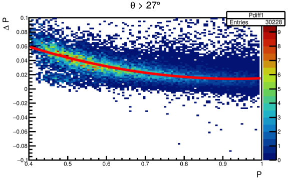
Exclusivity cuts are performed after all momentum corrections detailed in the following.

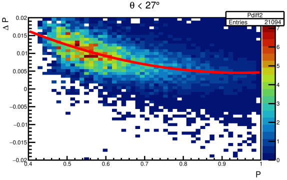
Proton Momentum Corrections: MC corrections

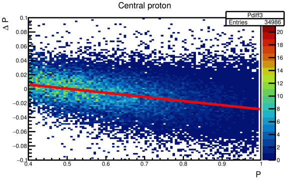


ΔP versus θ for proton in the FD. theta

- Generated events are passed through the full chain simulation.
- Generated and reconstructed momenta for protons are compared.
- 3 regions are considered: FD $\theta < 27^\circ$, FD $\theta > 27^\circ$ and CD.

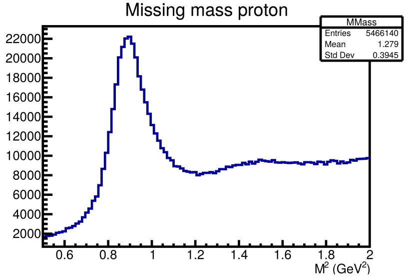


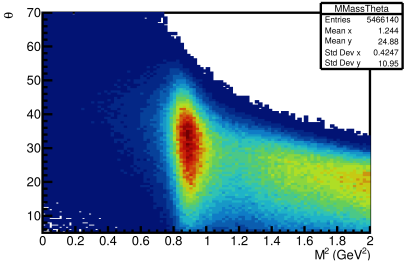




Momentum correction is parameterized as a function of P and corrected in simulation and data.

Proton Momentum Corrections: Central corrections (1)

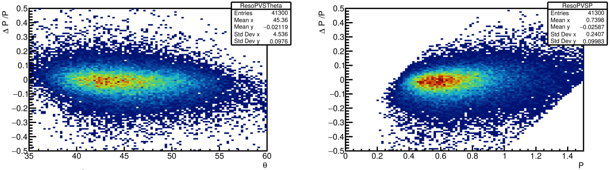




Missing proton mass spectrum; as a function of the missing particle θ angle.

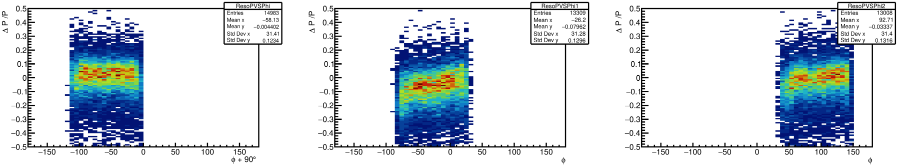
- Use $ep \rightarrow ep'\rho \rightarrow e(p')\pi^+\pi^-$ reaction, where the missing proton goes in the CD. Compare missing proton kinematics with reconstructed ones.
- At $\theta > 37^\circ$, there is very low background $\rightarrow$ clean one-to-one matching

Proton Momentum Corrections: Central corrections (2)



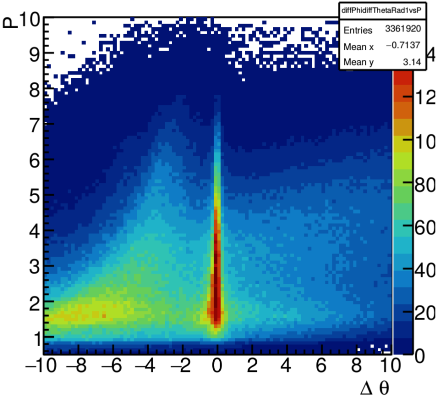
$\Delta P/P$ versus θ and momentum for proton in the CD.

- Issues with momentum reconstruction in the CVT.
- No large shift seen in the θ and momentum dependence.

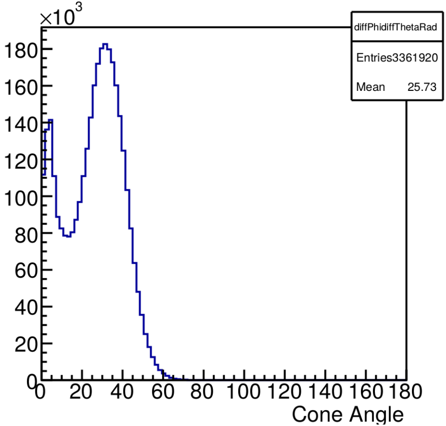


- Correction applied for each of the three regions, only for data.
- $\frac{\Delta P}{P}$ is parametrized as a function of the local ϕ angle of the last layer of the CVT

Lepton Momentum Corrections: Detected Photon "radiative corrections"



$\Delta\theta_{e^-/\gamma}$ versus P_{e^-}

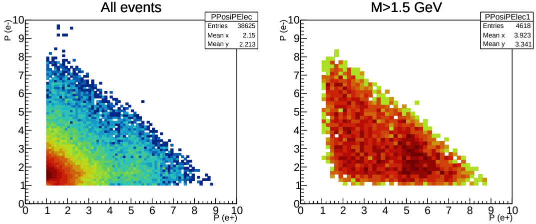


Cone angle between electrons and photons.

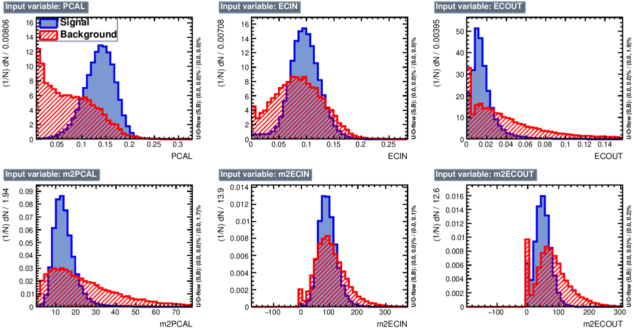
At the vertex, some photons are produced very close to leptons. γ momenta is added to the lepton momentum within $-1.5^\circ < \Delta\theta < 1.5^\circ$ and *Cone angle* $< 10^\circ$. Applied in both simulation and data. (see Joseph talk tomorrow)

Positron identification (1)

Clear π^+ contamination above HTCC threshold



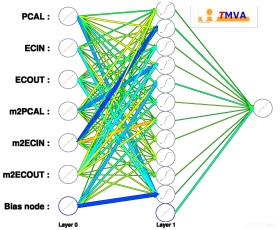
Training of Multivariate Analysis methods on simulation

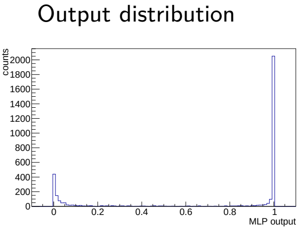


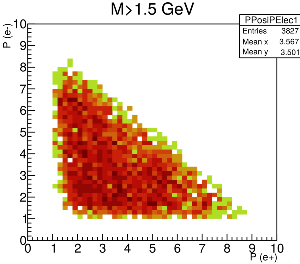
- Use e^+ and π^+ simulation samples
- Train MVAs on reconstructed e^+
- Use SFs and second shower moment (averaged over U,V,W)
- Test on data

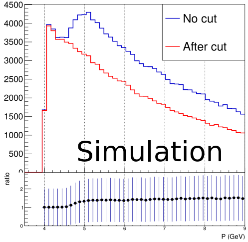
Positrons identification (2)

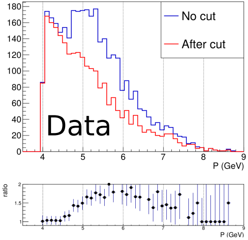
Applying neural network pid









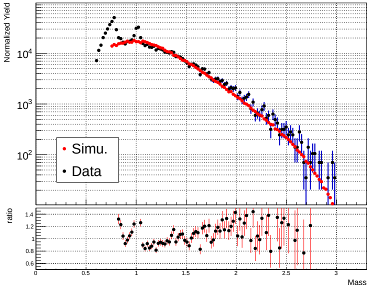


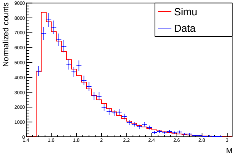
When applied to data and simulation, the pion contamination is removed.
The ratio B/S is reduced from 50% to 5% using the neural network approach (see Back-Up slides for details).

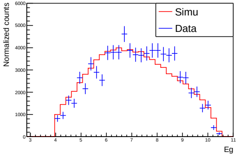
Data/Simulation comparison

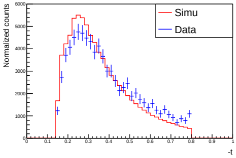
Complete RG-A inbending data set, after momentum corrections, fiducial cuts, positron PID and exclusivity cuts.

Fiducial cuts on V and W strips of PCAL included.







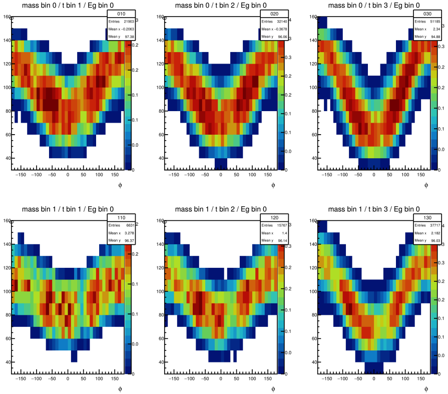


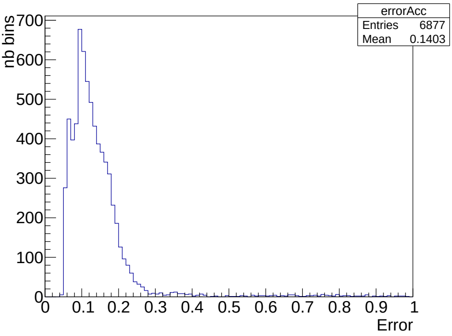
Data/BH simulation comparison in the high mass region $4\ GeV < E_\gamma < 10\ GeV$
$0.15\ GeV < -t < 0.8\ GeV$
No evident vector meson background

Acceptance

$$Acc_{\Omega=(E_\gamma, Q'^2, -t, \phi, \theta)} = \frac{N_{REC\ \Omega}}{N_{GEN\ \Omega}}$$

4 bins in $-t$ and Q'^2, 3 bins in E_γ, 10° x 10° bins in the ϕ/θ plane. Bins with $\frac{\Delta Acc}{Acc} > 0.5$ and $Acc < 0.05$ are discarded (ΔAcc is statistical error).





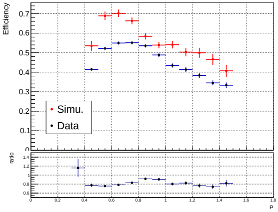
20M generated events simulation set

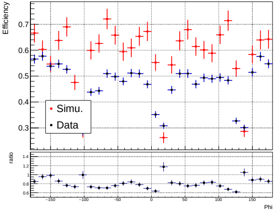
$4\ GeV < E_\gamma < 10\ GeV \quad 1.5\ GeV < m_{e^+e^-} < 3\ GeV \quad 0.15\ GeV^2 < -t < 0.8\ GeV^2$

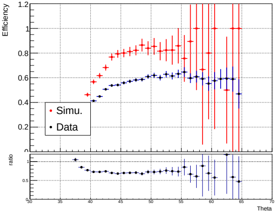
Proton efficiency correction: in the CD

Use $e(p')\pi^+\pi^-$ reaction, where the missing proton goes in the CD. All the efficiency analysis is done using kinematic variables of the missing proton.

Data set: $e\pi^+\pi^-(X)$, cut on the ρ mass in the $m_{\pi^+\pi^-}$ spectrum
Simulation set: Events generated with genev, $ep\rho$





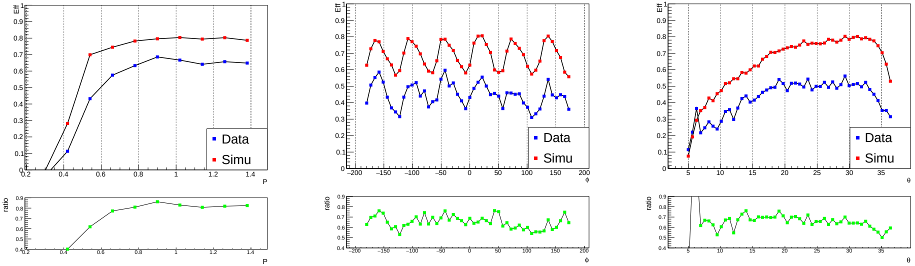


$$Eff_{DATA} = \frac{N_{REC}}{N_{Missing}} \qquad Eff_{SIMU} = \frac{N_{REC}}{N_{Missing}} \qquad Eff_{Corr} = \frac{Eff_{DATA}}{Eff_{SIMU}}$$

4 bins in momentum, 2 bins in θ, 30 in ϕ

Proton efficiency correction: in the FD

- Use $e(p')\pi^+\pi^-$ reaction, where the missing proton goes in the FD.
- Each bin is fitted with Gaussian + linear background



1-dimension correction: 9 bins in momentum

Change in the acceptance calculation

$$Acc = \frac{\sum_{REC} Eff_{Corr}}{N_{Gen}}$$

R' ratio measurement

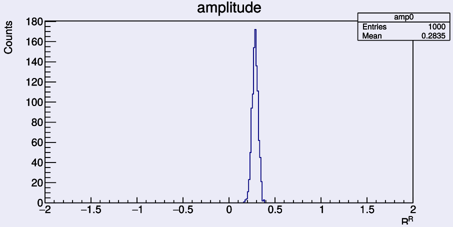
Weighted cross section ratio

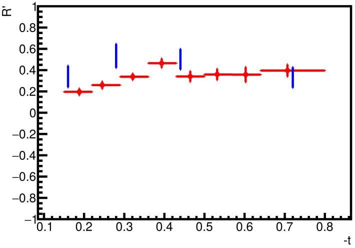
$$R = \frac{\sum_\phi Y_\phi \cdot cos(\phi)}{\sum_\phi Y_\phi},$$

$$Y_\phi = \sum_{\theta \in [\frac{\pi}{4}, \frac{3\pi}{4}]} \frac{L}{L_0} \frac{1}{Acc},$$

$$\delta Y_\phi = \sum_{\theta \in [\frac{\pi}{4}, \frac{3\pi}{4}]} \left(\frac{L}{L_0} \frac{1}{Acc} \right)^2.$$

Statistical error calculation with MC method (R calculated 1000 times with Y_ϕ within error bars)

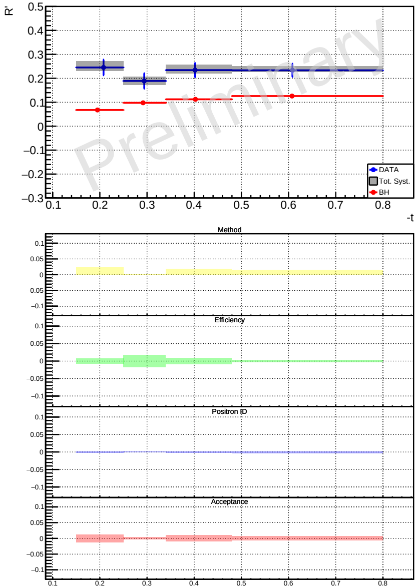




Comparison with CLAS results (Rafayel Paremuzyan thesis results)

- $1.1\ GeV < M_{ee} < 1.7\ GeV$
- $2\ GeV < E_\gamma < 5\ GeV$
- No specific acceptance study was done. The lowest M_{ee}/E_γ bin of the CLAS12 acceptance is used.

Results (R' ratio) and Systematics



Method

- Calculate observable in CLAS12 acceptance for generated BH events, and full-chain simulated events. Difference is assigned as Method Systematic.

Efficiency

- Calculate observable with/without proton efficiency

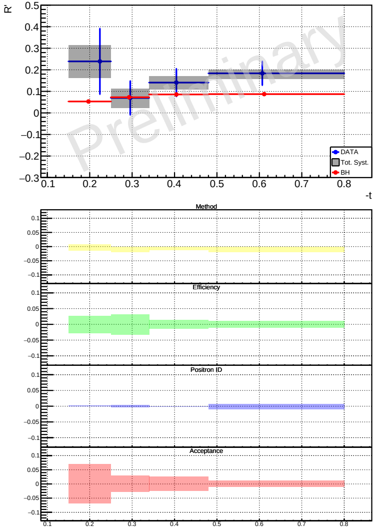
Positron Identification

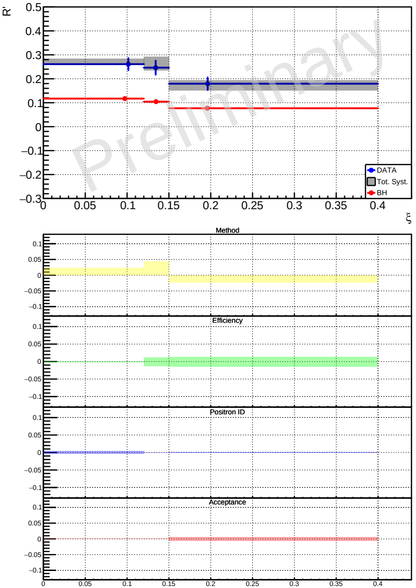
- Vary the positron ID cut. 0.5 ± 0.1 are used.

Acceptance

- Calculate observable with acceptance file produced using BH-weighted events (TCSGen) and independent generator (GRAPE).

Results (R' ratio)





Lepton pair mass in 2 − 3 GeV range (resonance free region).

A_{FB} measurement

- Forward direction: Integration range $\mathcal{I}_F$, $\phi \in [-50^\circ, 50^\circ]$ and $\theta \in [50^\circ, 70^\circ]$.
- Backward direction: Integration range $\mathcal{I}_B$, $\phi < -130^\circ$ *or* $\phi > 130^\circ$ and $\theta \in [110^\circ, 130^\circ]$.

Bin Volume correction

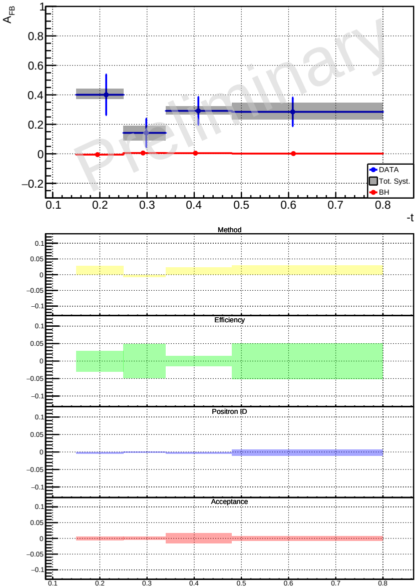
- Some $E_\gamma/Q'^2/t$ acceptance bin do not cover the whole integration range.
- Additional correction to take into account the "hole" in acceptance.
- The volume covered by the acceptance Vol_{Acc} in the forward and backward direction is calculated.
- Correction factor is given: $Vol_{corr} = Vol_{Acc}/Vol_{\mathcal{I}}$.
- 2 sets of volume correction factors for each $E_\gamma/Q'^2/t$ acceptance bin.

- Each event is weighted by $\frac{1}{Acc \cdot Vol_{corr}}$ / Error bars given by propagating $\delta\sigma \propto \sqrt{\sum(1/Acc \cdot Vol_{corr})^2}$

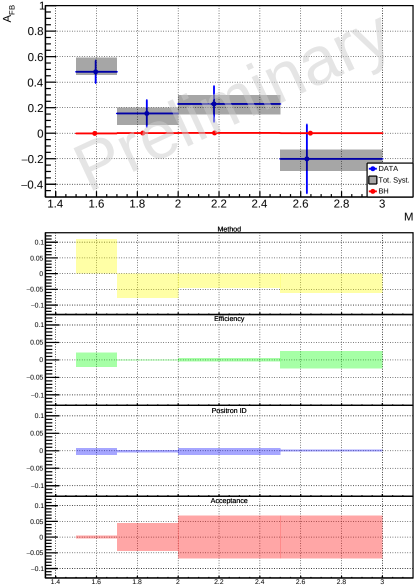
Method systematics

- Calculate A_{FB} for generated BH events (without acceptance cuts), and full-chain simulated events. Difference is assigned as Method Systematic.

Results (A_{FB})



A_FB
-t
Preliminary
DATA
Tot. Syst.
BH
Method
Efficiency
Positron ID
Acceptance



A_FB
M
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DATA
Tot. Syst.
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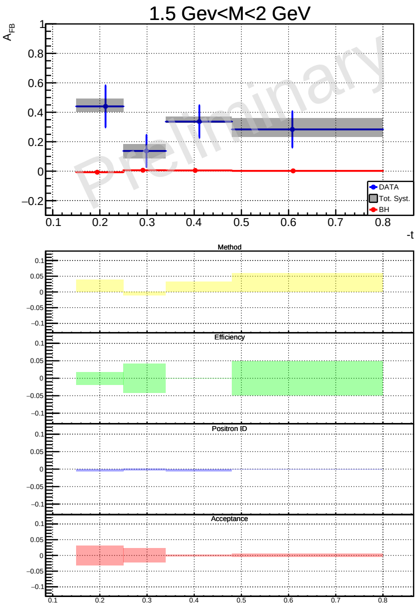
Results (A_{FB})



1.5 Gev<M<2 GeV
A_{FB}
Preliminary
DATA
Tot. Syst.
BH
-t
Method
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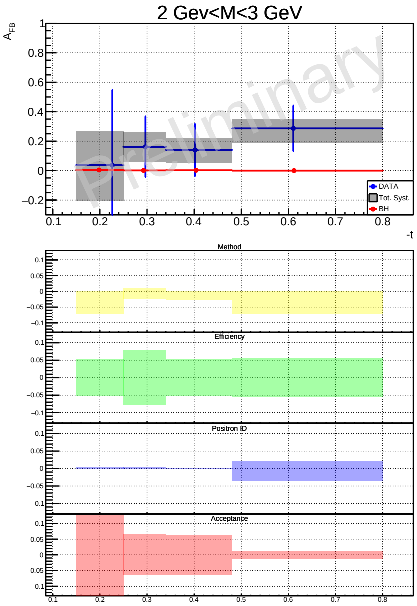
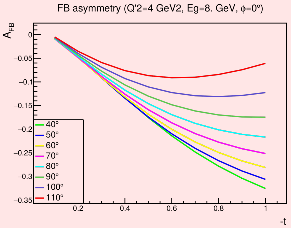
Positron ID
Acceptance

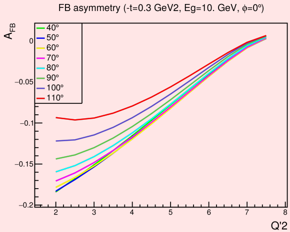


2 Gev<M<3 GeV
A_{FB}
Preliminary
DATA
Tot. Syst.
BH
-t
Method
Efficiency
Positron ID
Acceptance

A_{FB} predictions

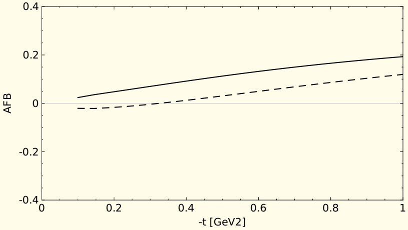
Projections from VGG ($b_{val} = b_{sea} = 1$, no D-term)





These predictions have been cross-checked by Marc Vanderhaeghen.

Predictions from PARTONS. Courtesy of Pawel Sznajder.



GK model for GPDs
Dashed: LO
Plain: NLO

- Sign discrepancies between VGG code and PARTONS
- Issue being investigated

Summary

- Preliminary R' ratio and A_{FB} extracted.
- Systematics investigated, still need for exclusivity cuts checks.
- Models comparison is under way.
- Analysis note is also under way (2 more weeks).

Bibliography

Oleksii Gryniuk and Marc Vanderhaeghen.
Accessing the real part of the forward $j/\psi - p$ scattering amplitude from j/ψ photoproduction on protons around threshold.
Phys. Rev. D, 94:074001, Oct 2016.
doi: 10.1103/PhysRevD.94.074001.
URL https://link.aps.org/doi/10.1103/PhysRevD.94.074001.

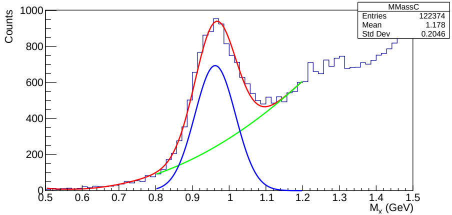
Back-up slides

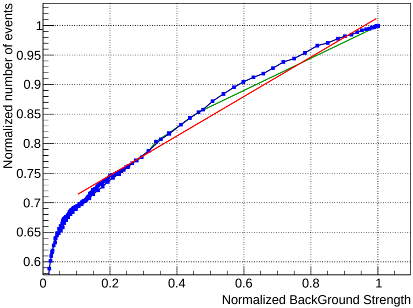
Estimation of the absolute contamination of π^+ in the TCS sample

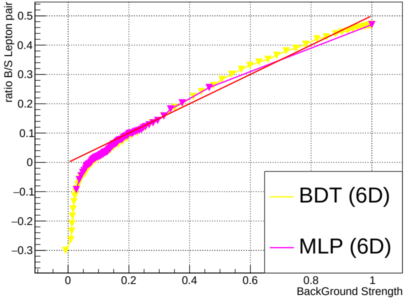
- Use pure uncorrelated background sample :

$$ep \rightarrow ee^+_{m_\pi}(n)$$

- Compare effect of cut on the NN output on both samples







$\rightarrow$ This method reduces B/S from 0.5 to 0.05

Absolute contamination from ROC curve

$$y(x) = \frac{S(x) + x \cdot \beta}{S(1) + \beta} \tag{1}$$

extrapolated it to $x = 0$:

$$y(0) = \frac{S(0)}{S(1) + \beta} \tag{2}$$

The *Normalized number of TCS events* is:

$$y(x_0) = \frac{S(x_0) + x_0 \cdot \beta}{S(1) + \beta} \tag{3}$$

For a given x_0, $\frac{y(x_0)}{y(0)} - 1$ gives a good estimate of the ratio $\frac{B(x_0)}{S(x_0)}$:

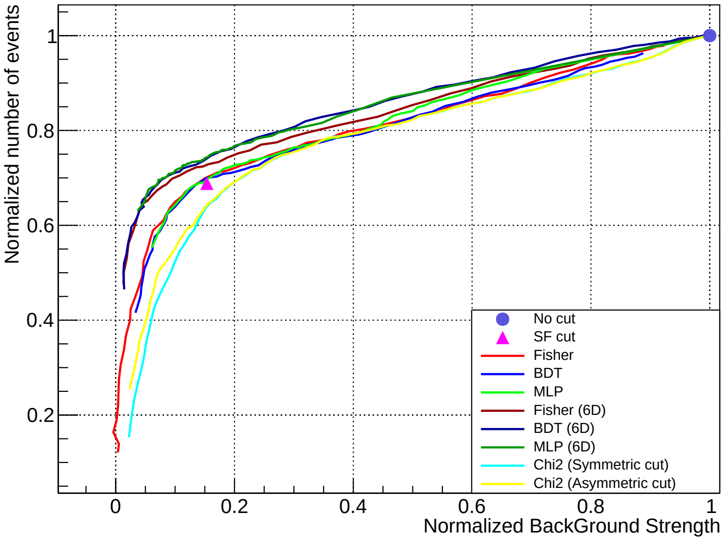
$$\frac{y(x_0)}{y(0)} - 1 = \frac{S(x_0) + x_0 \cdot \beta}{S(0)} - 1 \tag{4}$$

and

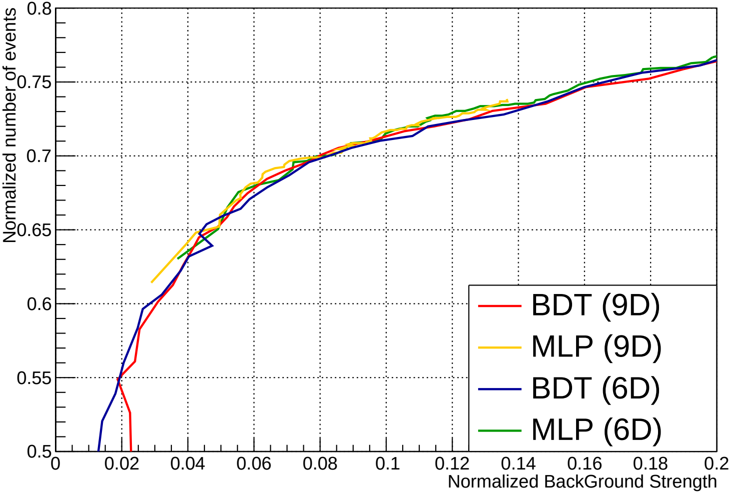
$$\frac{y(x_0)}{y(0)} - 1 = \frac{S(x_0)}{S(0)} \left(1 + \frac{x_0 \cdot \beta}{S(x_0)}\right) - 1 \tag{5}$$

$$\frac{y(x_0)}{y(0)} - 1 \simeq \frac{B(x_0)}{S(x_0)} \tag{6}$$

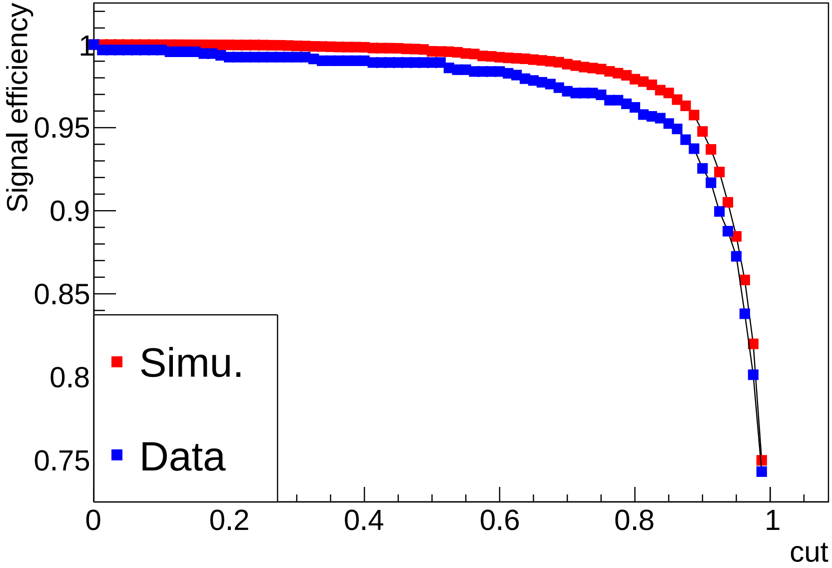
MVA comparison (1)



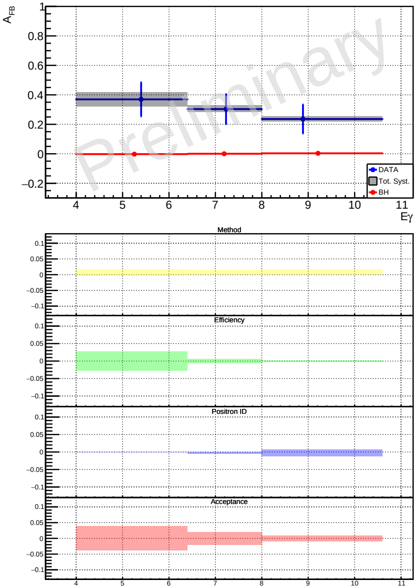
MVA comparison (2)

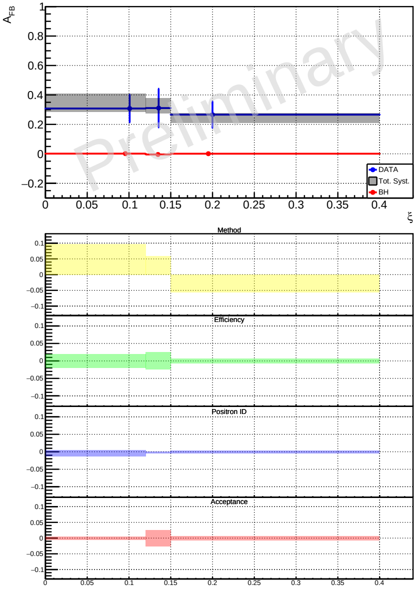


NN on electron

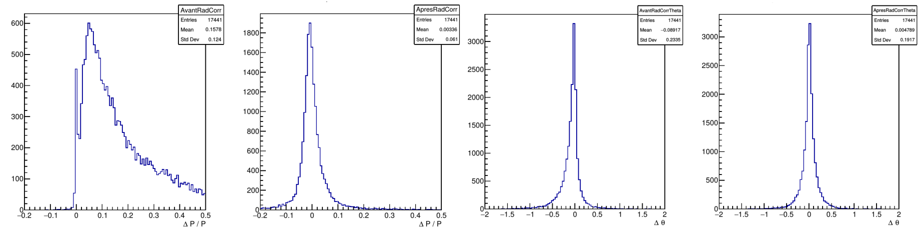


Results (AFB) (3)





Correction to lepton momenta



Same effects on positron momenta