The GEp-2γ Experiment at Jefferson Lab Hall-C

2011 HALL-C USERS MEETING

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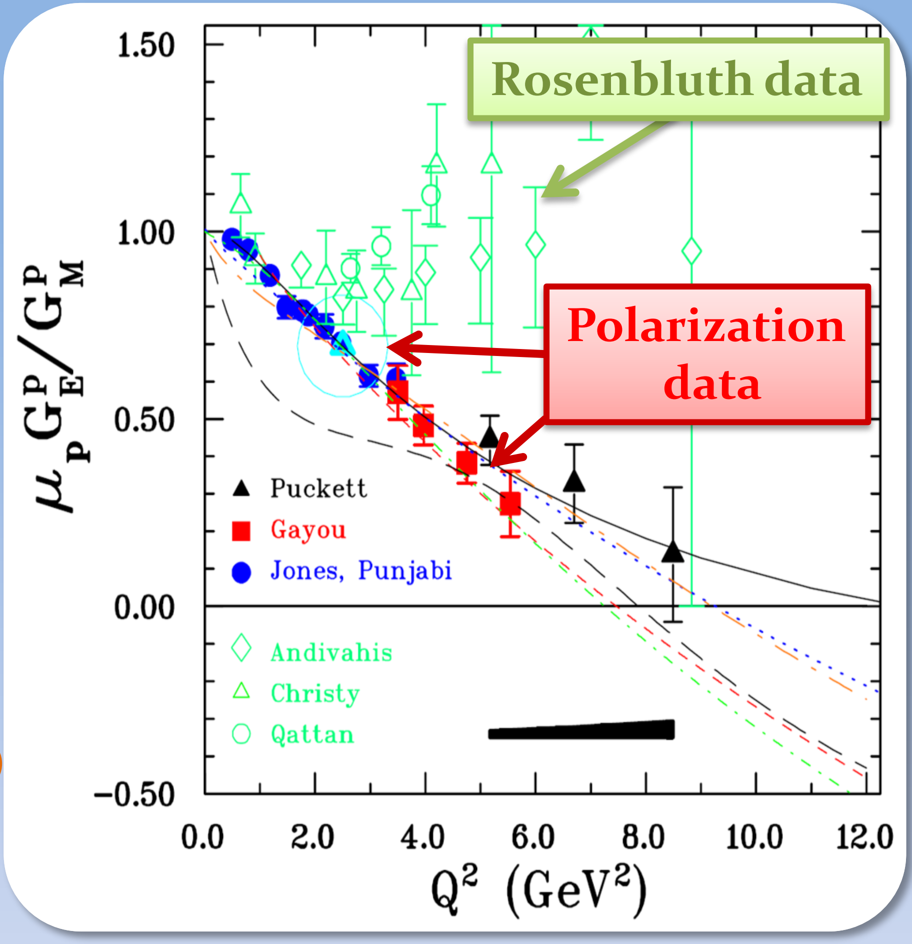
and the JLab GEp-2γ Collaboration

OUTLINE

- **Introduction**
- **Beyond the Born Approximation**
- **The GEp-2γ Experiment at Jlab:**
  - Goal
  - Analysis
  - Polarization Component Ratio and P_l quasi-final results
- **Determination of the 2γ amplitudes**
- **Conclusion**

Polarization/Rosenbluth data crisis

- Over the past decade both intensive theoretical and experimental effort have been done aiming at explaining the Rosenbluth/Polarization discrepancy.
- The difference between the two experimental ratios increases systematically with Q^2 for $Q^2 > 2$ GeV^2
- Two methods, two different results
  - ➢ Incomplete radiative corrections?
  - ➢ Something beyond the Born Approximation? (one photon exchange)
  - ➢ Possible Two-photon exchange effect? (TPEX)
- This experiment is a search for a kinematical dependence in P_t/P_ℓ vs ε



Jones *et al.*, Phys. Rev. Lett. 84, 1398 (2000);
Gayou *et al.*, Phys. Rev. Lett. 88, 092301 (2002);
Punjabi *et al.*, Phys. Rev. C 71, 055202 (2005);
Puckett *et al.*, Phys. Rev. Lett 104, 242301 (2010);

Beyond the Born-Approximation formalism

$$P_t = -\sqrt{\frac{2\varepsilon(1+\varepsilon)}{\tau}}\,\frac{1}{\sigma_r}\{G_E G_M\}$$

Transverse polarization.

$$P_l = \sqrt{1-\varepsilon^2}\,\frac{1}{\sigma_r}\{G_M^2\}$$

Longitudinal polarization.

$$\sigma_r = G_M^2 + \frac{\varepsilon}{\tau}G_E^2$$

Reduced cross section.

$$R = -\mu_p\sqrt{\frac{(1+\varepsilon)\tau}{2\varepsilon}}\,\frac{P_t}{P_l} = \mu_p\frac{G_E}{G_M}$$

Polarization component ratio.

Born Approx.

Beyond the Born-Approximation formalism

$$P_t = -\sqrt{\frac{2\varepsilon(1+\varepsilon)}{\tau}}\frac{1}{\sigma_r}\{G_E G_M + \boxed{G_E}\,\boxed{\mathrm{Re}(\delta\tilde{G}_M)} + \boxed{G_M}\,\boxed{\mathrm{Re}(\delta\tilde{G}_E + \frac{\upsilon}{M^2}\tilde{F}_3)\} + O(e^4)}$$

$$P_l = \sqrt{1-\varepsilon^2}\frac{1}{\sigma_r}\{G_M^2 + 2\,\boxed{G_M}\,\boxed{\mathrm{Re}(\delta\tilde{G}_M + \frac{\varepsilon}{1+\varepsilon}\frac{\upsilon}{M^2}\tilde{F}_3)\} + O(e^4)}$$

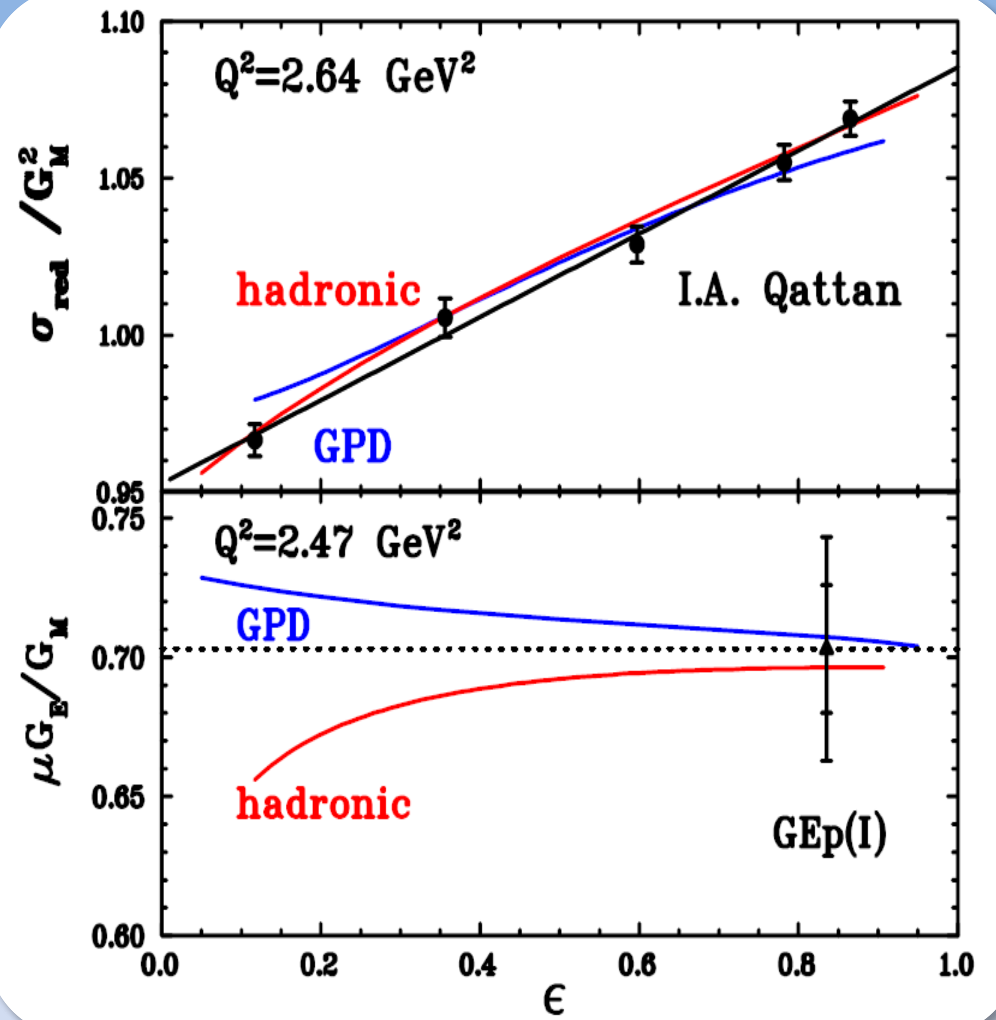
$$\sigma_r = G_M^2 + \frac{\varepsilon}{\tau}G_E^2 + 2\,\boxed{G_M}\,\boxed{\mathrm{Re}(\delta\tilde{G}_M + \varepsilon\frac{\upsilon}{M^2}\tilde{F}_3)} + 2\frac{\varepsilon}{\tau}\boxed{G_E}\,\boxed{\mathrm{Re}(\delta\tilde{G}_E + \frac{\upsilon}{M^2}\tilde{F}_3) + O(e^4)}$$

$$\boxed{\upsilon = \frac{s-u}{4M^2}}$$

$$R = -\mu_p\sqrt{\frac{(1+\varepsilon)\tau}{2\varepsilon}}\frac{P_t}{P_l} = \mu_p\frac{G_E}{G_M} + \mu_p\boxed{\frac{G_E}{G_M}}\,\boxed{\mathrm{Re}\{\frac{\delta\tilde{G}_E}{G_E} - \frac{\delta\tilde{G}_M}{G_M} + \frac{\upsilon}{M^2}\tilde{F}_3(\frac{1}{G_E} - \frac{2\varepsilon}{1+\varepsilon}\frac{1}{M^2}\frac{1}{G_M})\} + O(e^4)}$$

Born Approx. | Beyond Born Approx.

Theoretical Estimates



Hadronic (elastic)

Dominated by correction to $G_{M.}$

P.Blunden et al., Phys.Rev.C72: 034612 (2005)

Generalized Parton Distribution

Dominated by F_3 correction and correction to $G_{E.}$

A.Afanasev et al., Phys. Rev.D72:013008 (2005)

Born value calculated from the G_{Ep}/G_{Mp} fit of the polarization data

Both theories describe Rosenbluth data but have opposite prediction for $G_{Ep}/G_{Mp.}$

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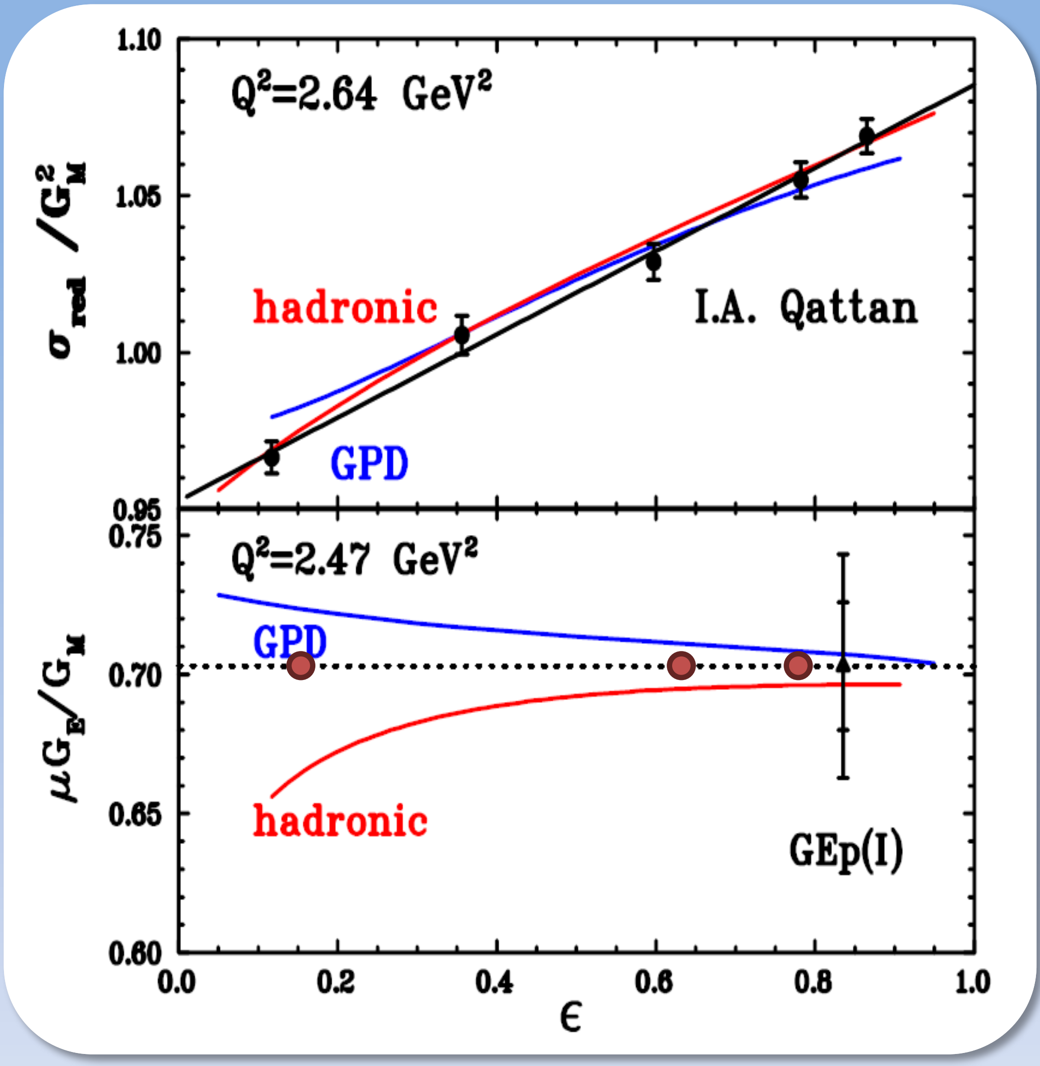

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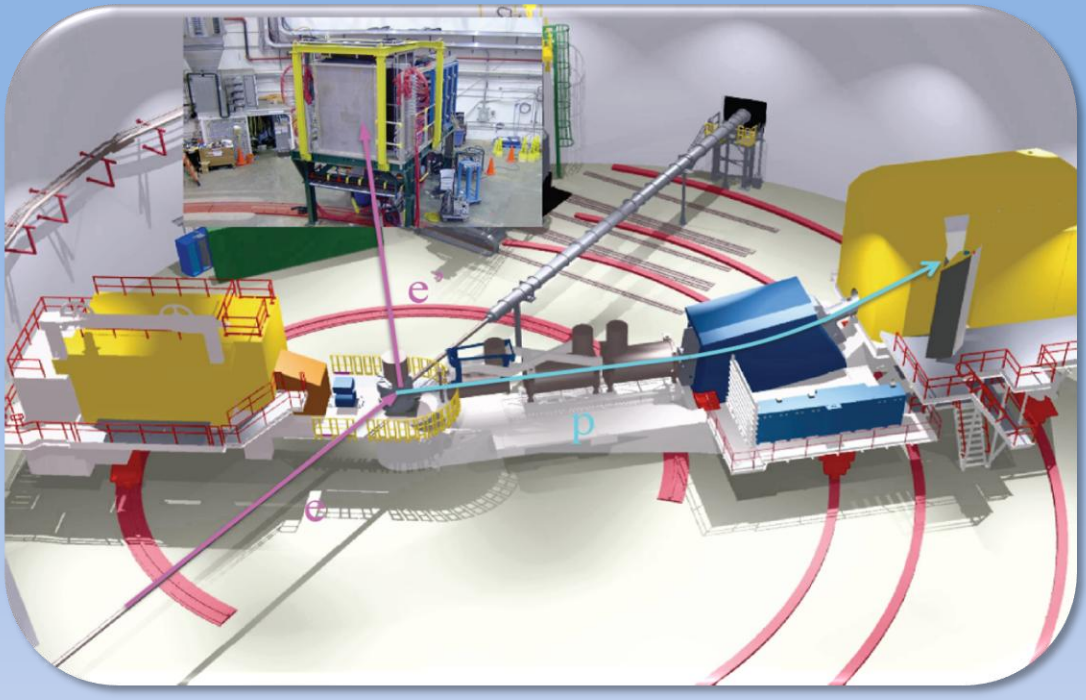
The GEp-2γ Experiment

•We look for a kinematical dependence of P_t/P_ℓ to detect a possible two-photon exchange effect in the ep-scattering.

Key idea:

- fixed Q^2.
- same spin transport. (spin precession fixed)
- same analyzing power. (P_p fixed)

precision limited only by statistics (~ 0.01 for a ratio value of 0.7)



unlike Rosenbluth, very small p.t.p systematics ≤0.006 : Ay , h cancel out in the P_t/P_l ratio.

80μA beam current.
85% pol.
20cm LH_2 target.

E_e, GeV	p_p	E_e'	θ_p, deg	θ_e	ε range	$\langle Q^2 \rangle$
1.867	2.068	0.527	14.13	106	.130-.160	2.49
2.839	2.068	1.507	30.76	45.3	.611-.647	2.49
3.549	2.068	2.207	35.39	32.9	.765-.786	2.49

Spin Precession Check

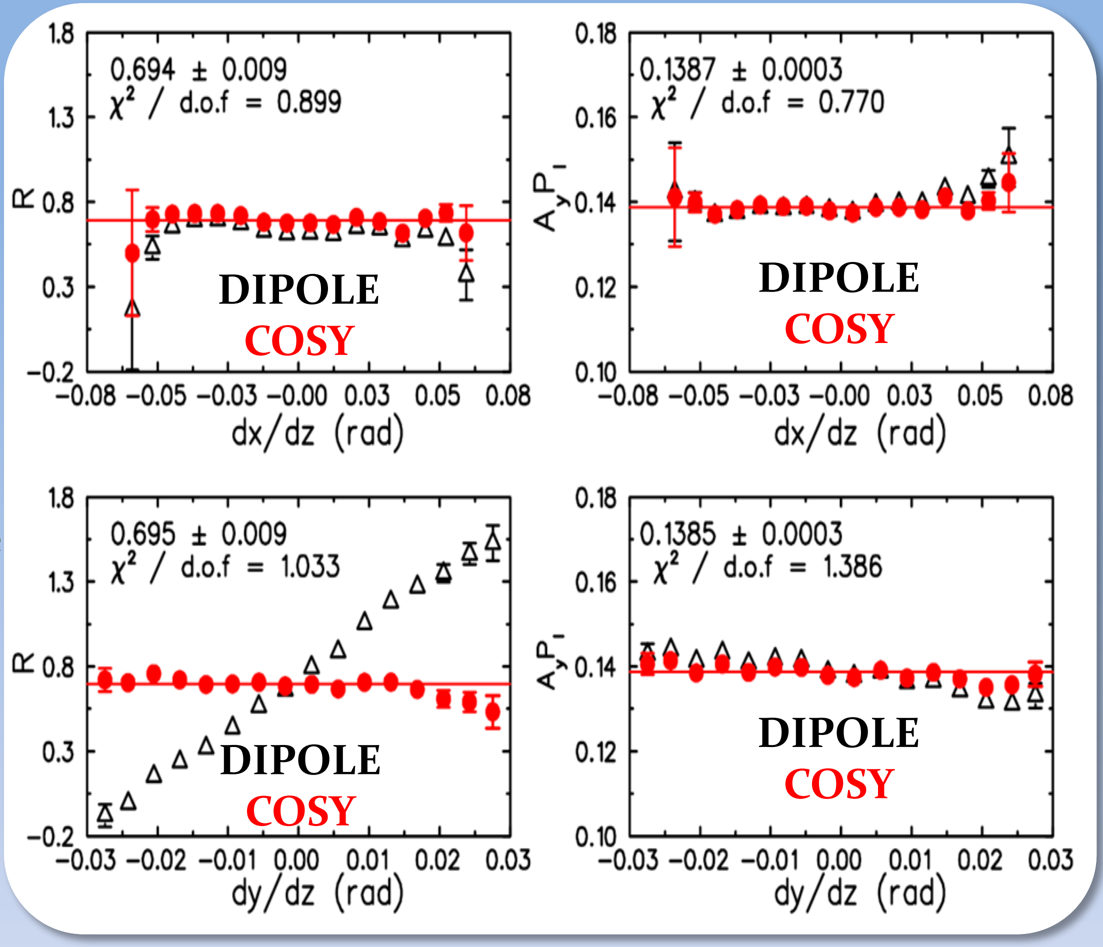
The polarization component ratio and $A_y P_l$ are independent of the reconstructed kinematics

dx/dz (dispersive, vertical) and dy/dz (non-dispersive, horizontal) are the slopes at the target.

In each panel, result integrated over the other kinematic variables: dx/dx, dy/dz, δ or y_{tgt} (target length seen from the spectrometer)

Good understanding of the spin precession calculation through the spectrometer magnets.

Good quality of the COSY Spin transport matrix.



$\varepsilon=0.15$, $Q^2=2.5$ GeV^2

Systematic Uncertainties on R

	$\varepsilon=0.152$	$\varepsilon=0.635$	$\varepsilon=0.785$
θ_{bend} (2 mrad)	0.0018	0.0018	0.0019
φ_{bend} (0.5 mrad)	0.0102	0.0061	0.0058
δ (0.1%)	0.0036	4.402E-05	0.0002
φ_{fpp} (0.14 mrad)	0.0039	0.0025	0.0024
E_{beam} (0.05%)	0.0015	0.0001	5.7876E-05
False Asymmetry	0.0059	0.0063	0.0059
TOTAL	0.0131	0.0093	0.0088

- Half of the false asymmetry correction as false asymmetry systematic uncertainty
- Systematics dominated by the uncertainty on φ_{bend} and the false asymmetry correction

Polarization Component Ratio

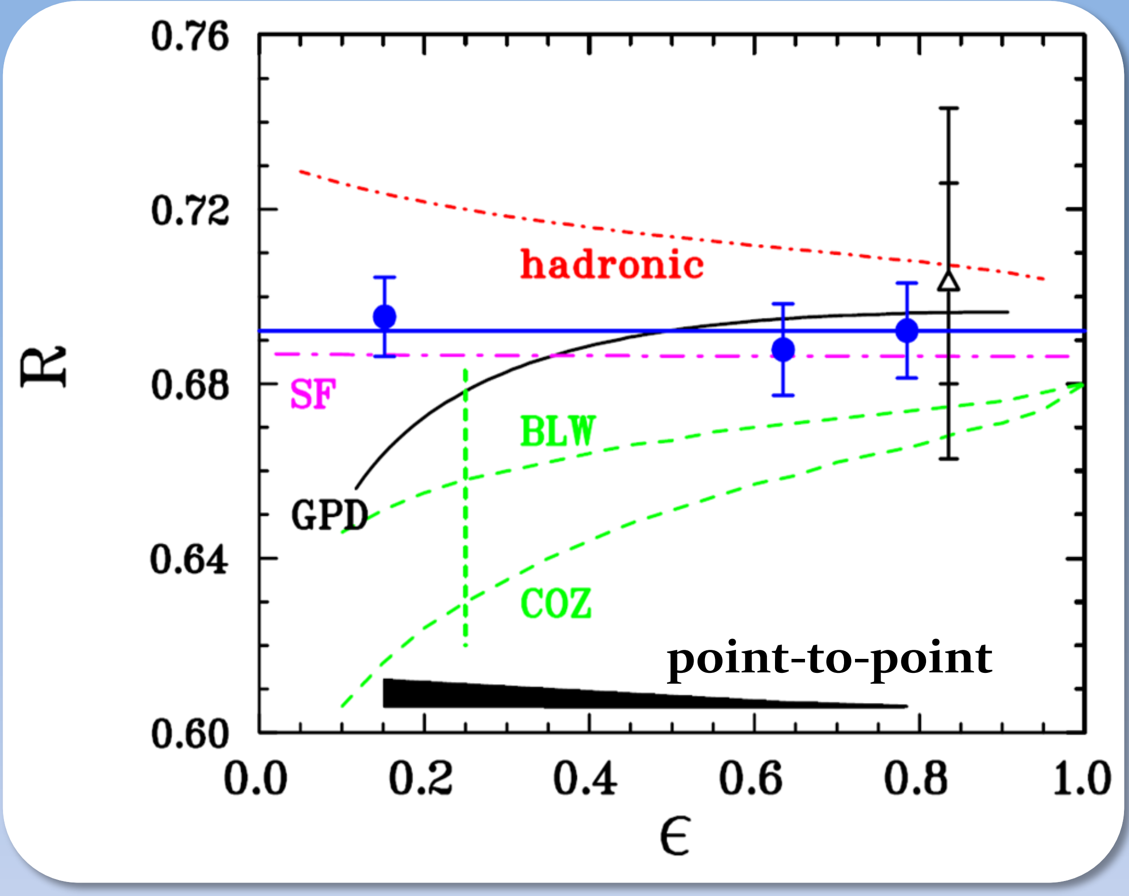
- No evidence of an epsilon dependence at a 0.01 level for a ratio of 0.7 in the polarization data at $Q^2 = 2.5$ GeV^2.

- Models predict a bigger correction (opposite sign) at small ε, not seen in the data.

- Theoretical predictions are with respect to the Born approximation. (calculated from the fit to the polarization data)

- Small point-to-point systematics

- Radiative corrections calculated with MASCARAD ~0.01-0.02% (*Afanasev et.al, Phys. Rev. D 64, 113009 (2001)*)



*P.Blunden et al., Phys.Rev.C**72**: 034612 (2005)*

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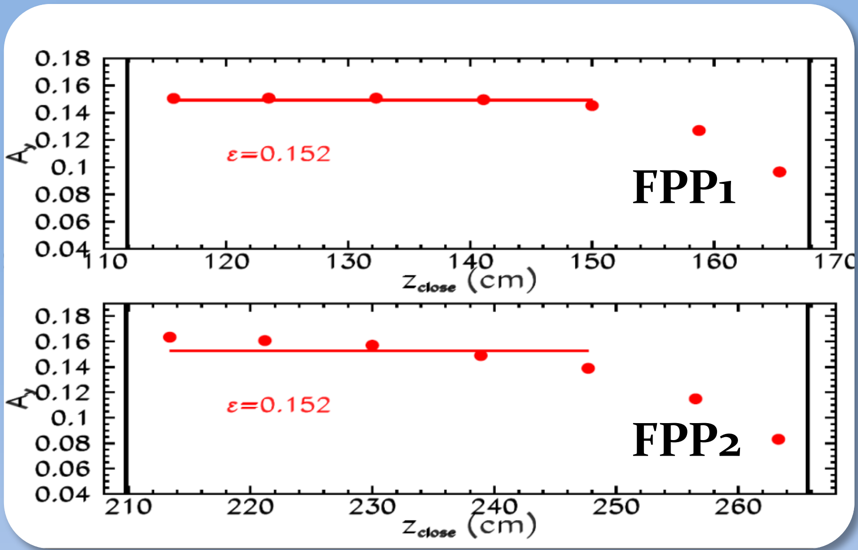
*N. Kivel and M. Vanderhaeghen Phys.Rev.Lett.**103**:092004 (2009)*

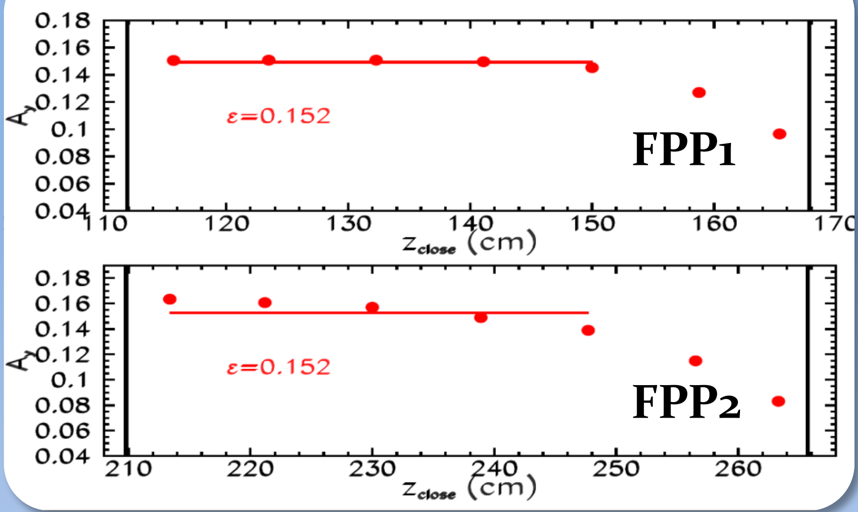
*Bystritskiy, Kuraev and Tomasi-Gustafsson, Phys.Rev.C**75**: 015207 (2007)*

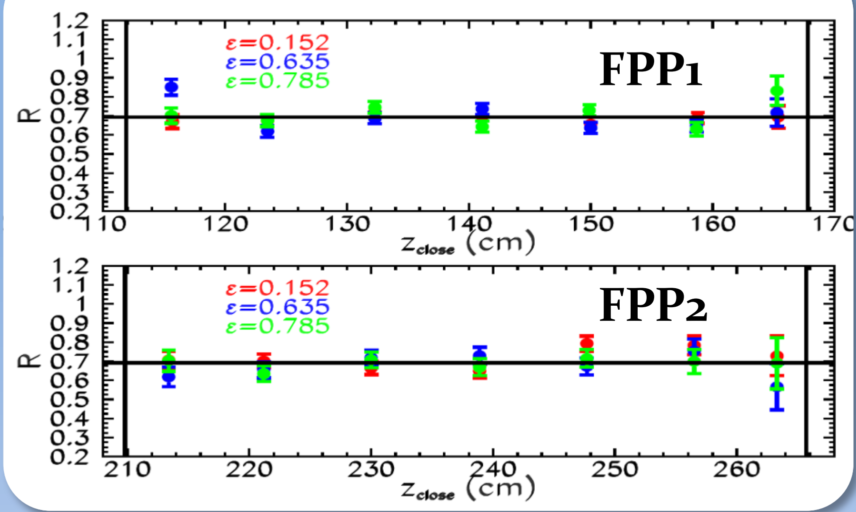
Zclose Dependence



- The analyzing power is not constant within the whole width of the analyzer.

Zclose Dependence





- The analyzing power is not constant within the whole width of the analyzer.
- The form factor ratio is constant within the analyzer for the 3 kinematics.

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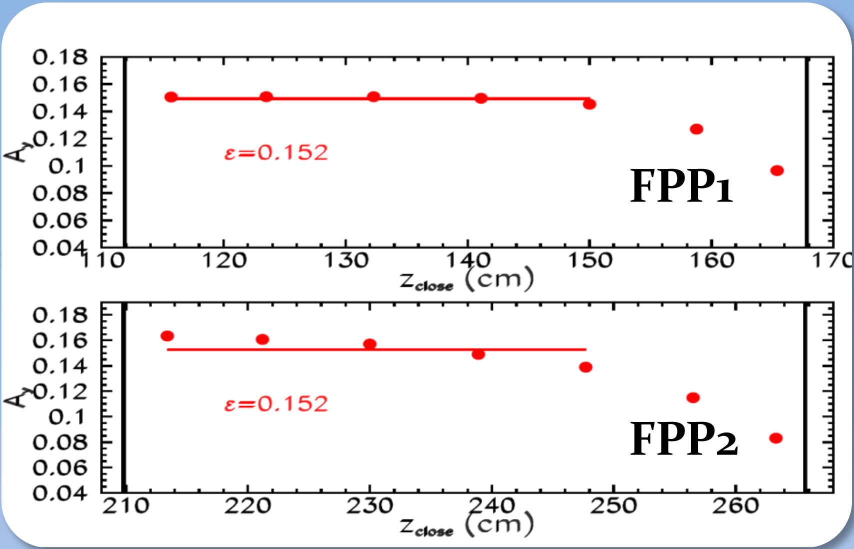
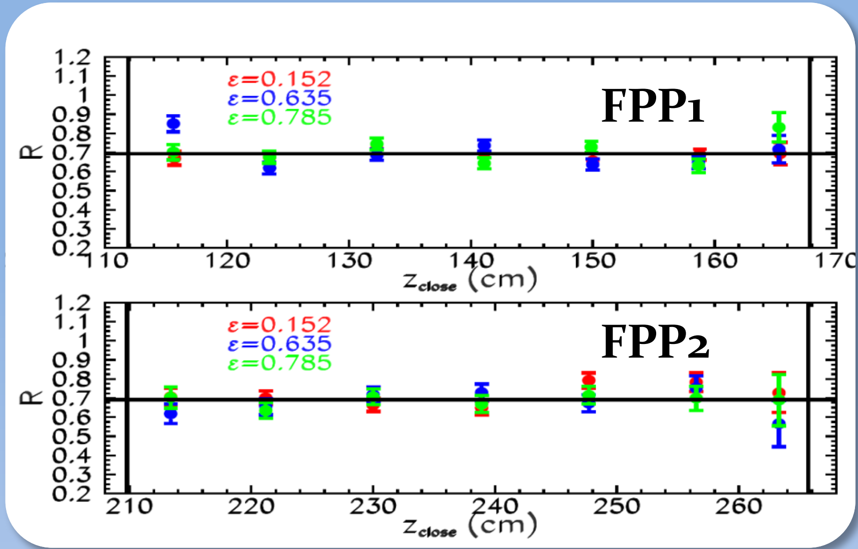
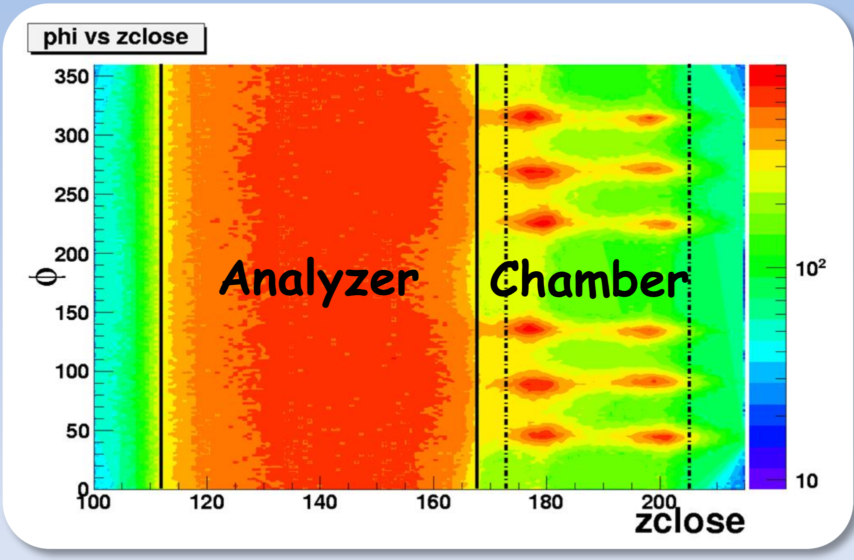
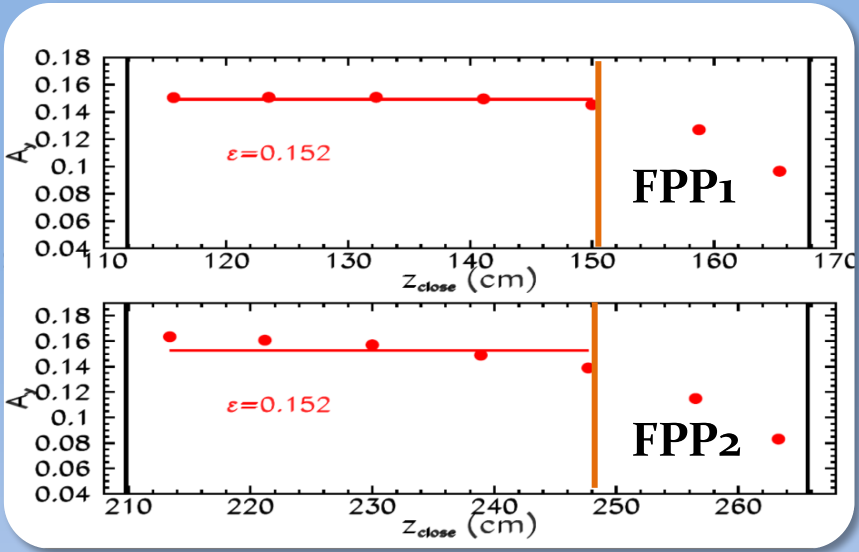


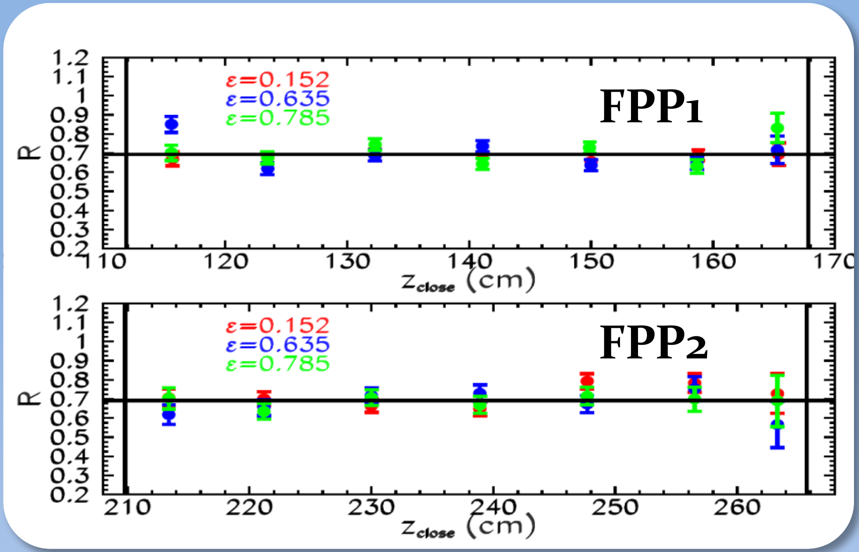


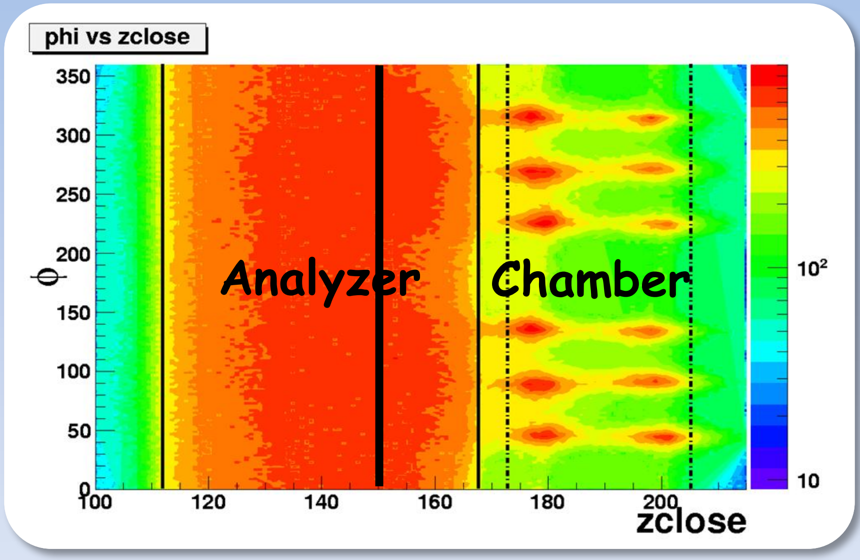


- The analyzing power is not constant within the whole width of the analyzer.
- The form factor ratio is constant within the analyzer for the 3 kinematics.
- Dilution of the analyzing power from bad reconstructed events.

Zclose Dependence







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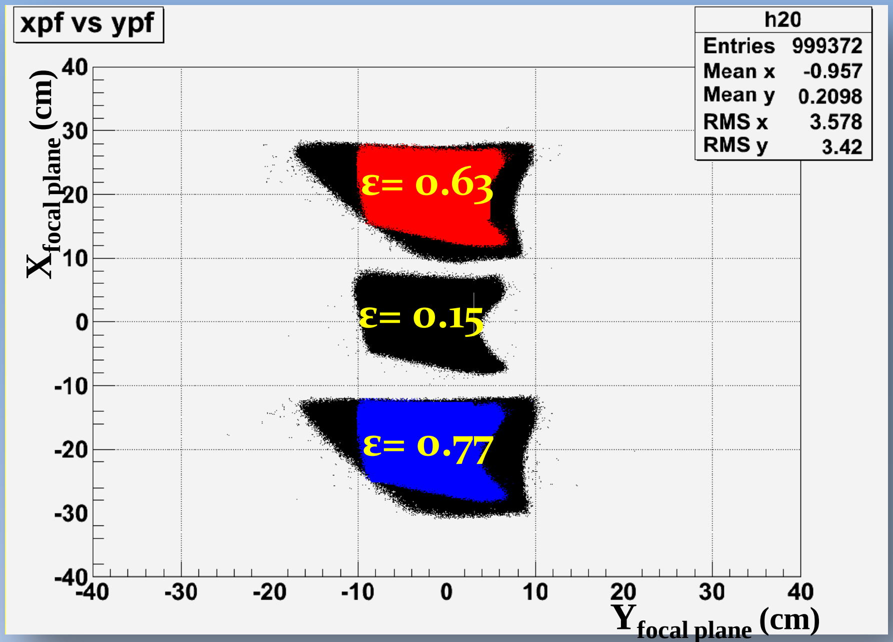
- Dilution of the analyzing power from bad reconstructed events.

⇒ Cut in Zclose .

Longitudinal Polarization I

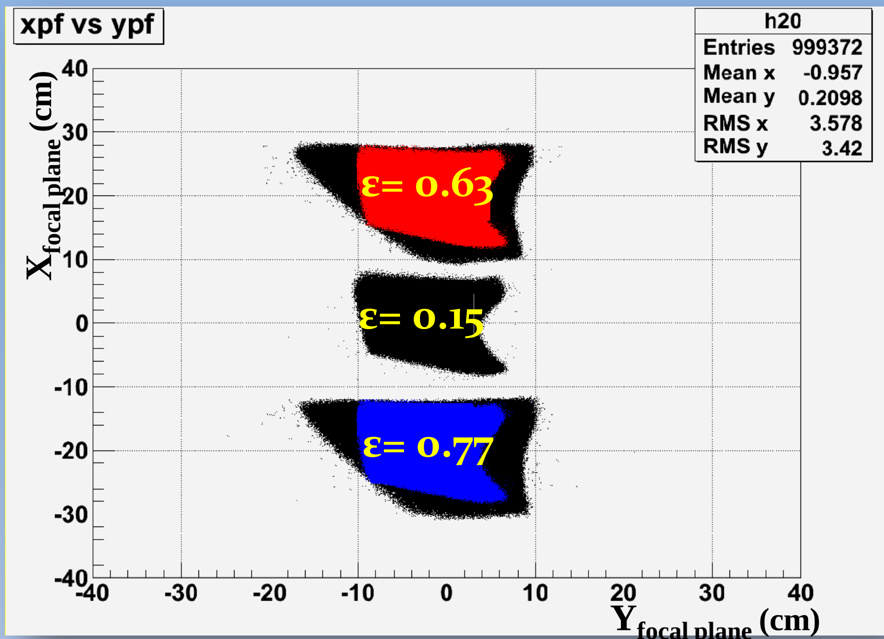


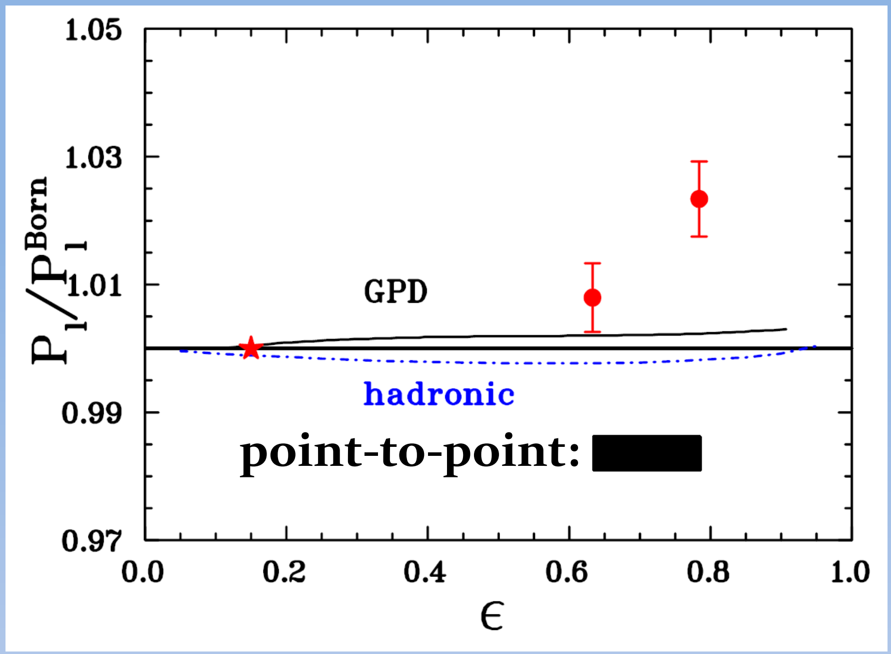
- Matching acceptance cut : cut to match the acceptance of the largest ε kinematic, to that of the ε=0.15 one.

  → Same spin transport, Same A_y to the 10^{-3} level

- Smallest ε kinematic determines the analyzing power.

Longitudinal Polarization I



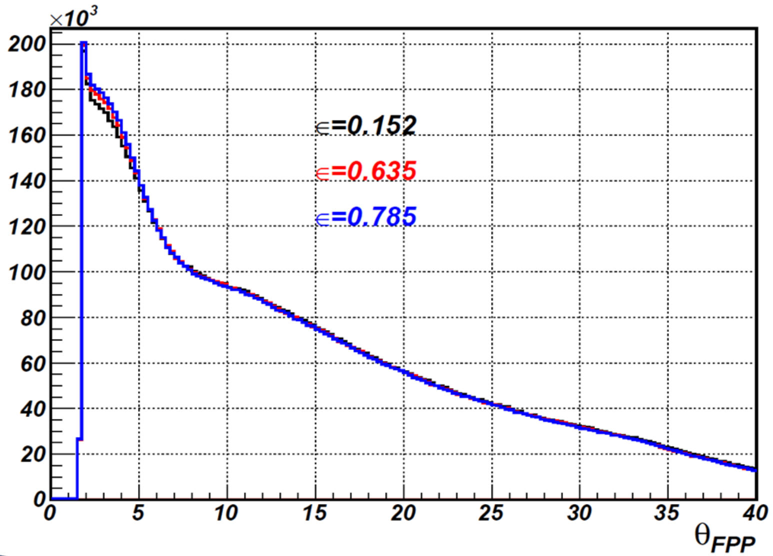


- Matching acceptance cut : cut to match the acceptance of the largest ε kinematic, to that of the ε=0.15 one.

  ⇨ Same spin transport, Same A_y to the 10^{-3} level

- Smallest ε kinematic determines the analyzing power: A_y^{ave}=0.15079 ±0.00038
- $P_{\ell\ Born}$ calculated from E_{beam}, the momentum p and the fitted ratio value from this experiment
- 1% absolute, 0.5% point-to-point systematic errors (Möller dominated)
- Radiative corrections smaller than polarization component ratio (*Afanasev et.al, Phys. Rev. D 64, 113009 (2001)*)

Longitudinal Polarization II



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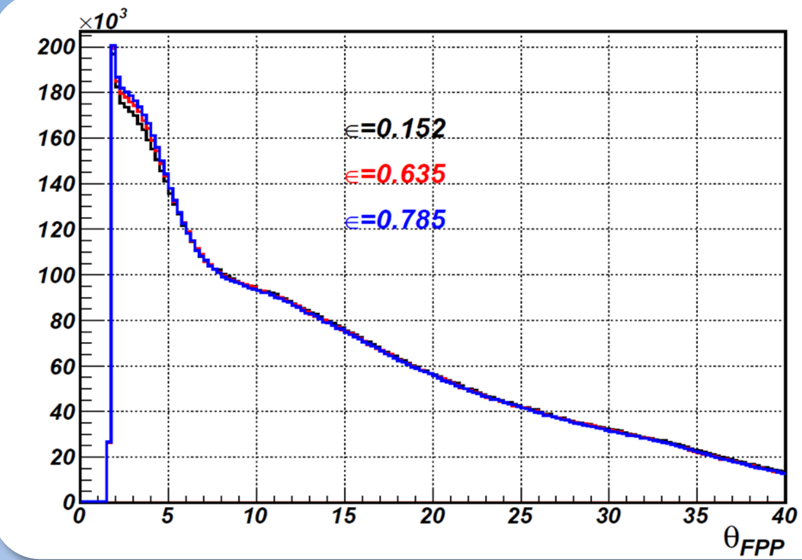

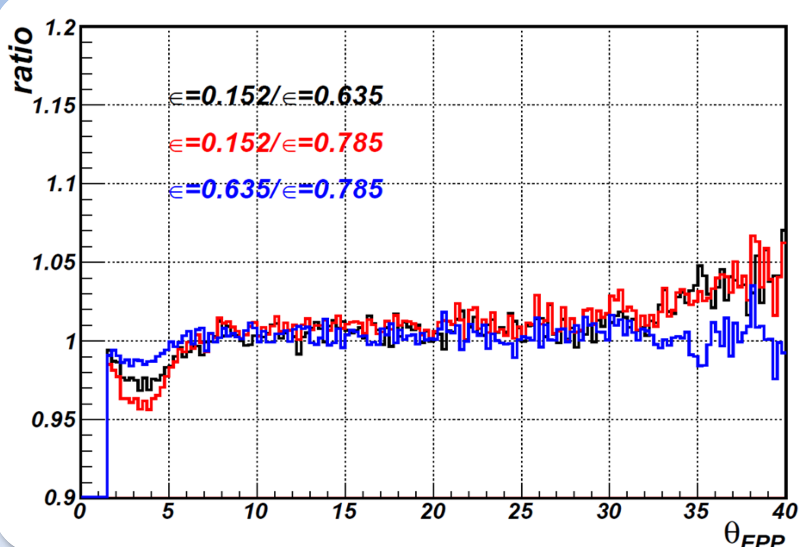

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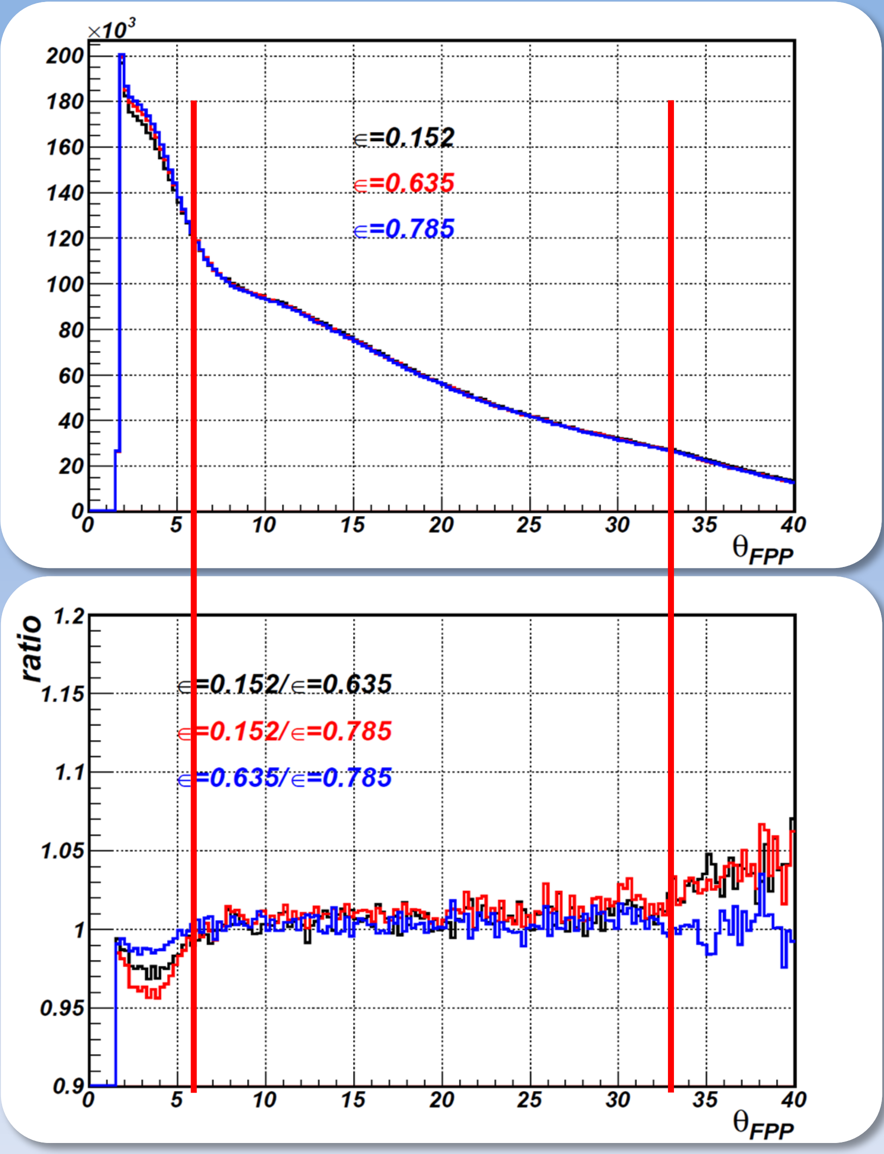

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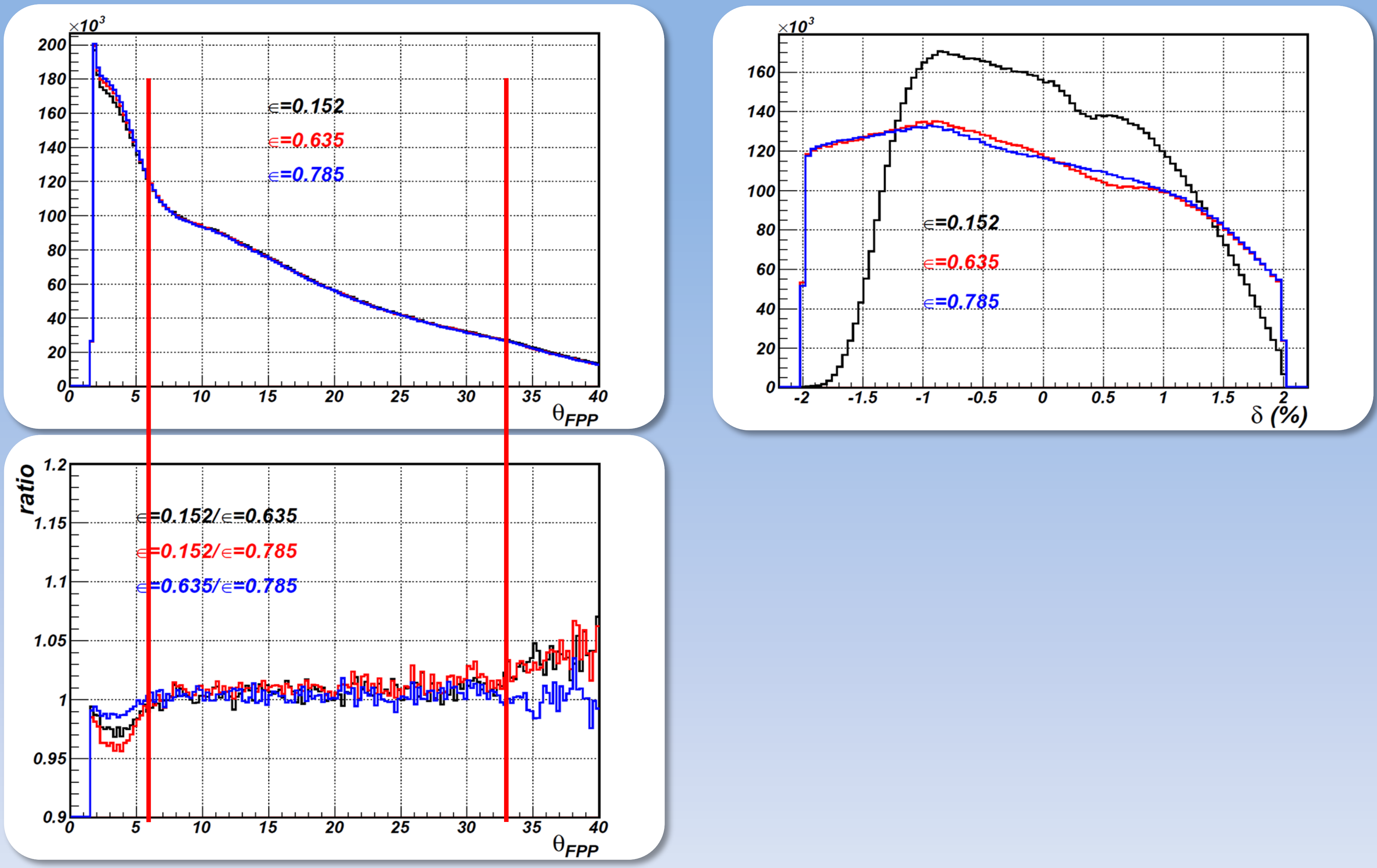

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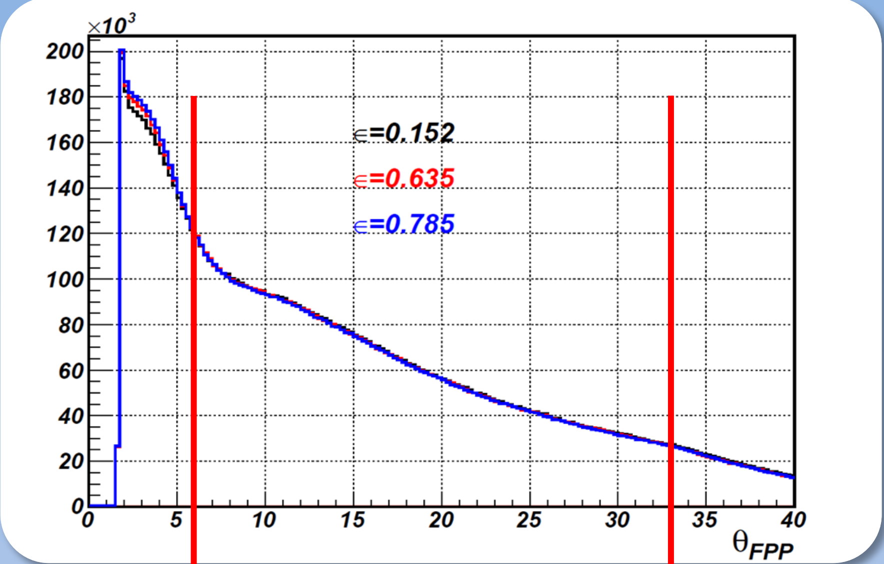

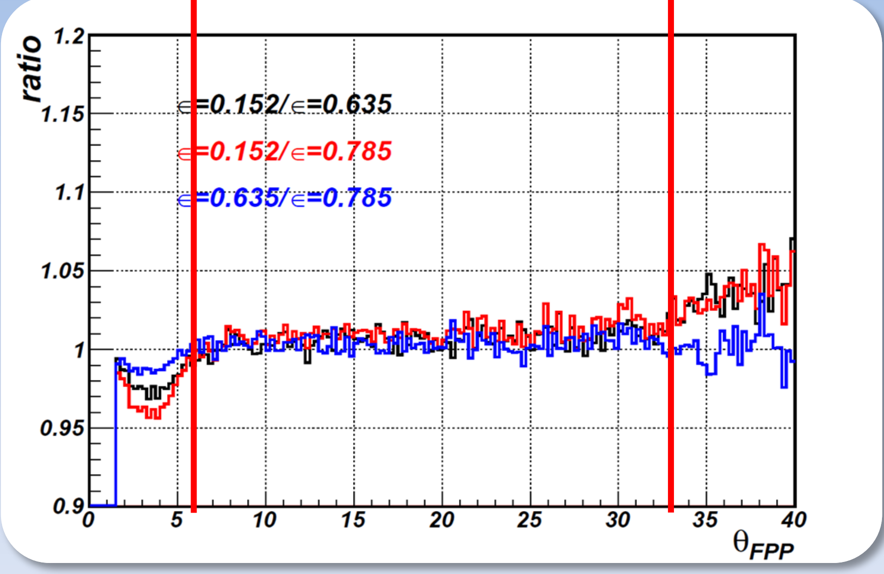

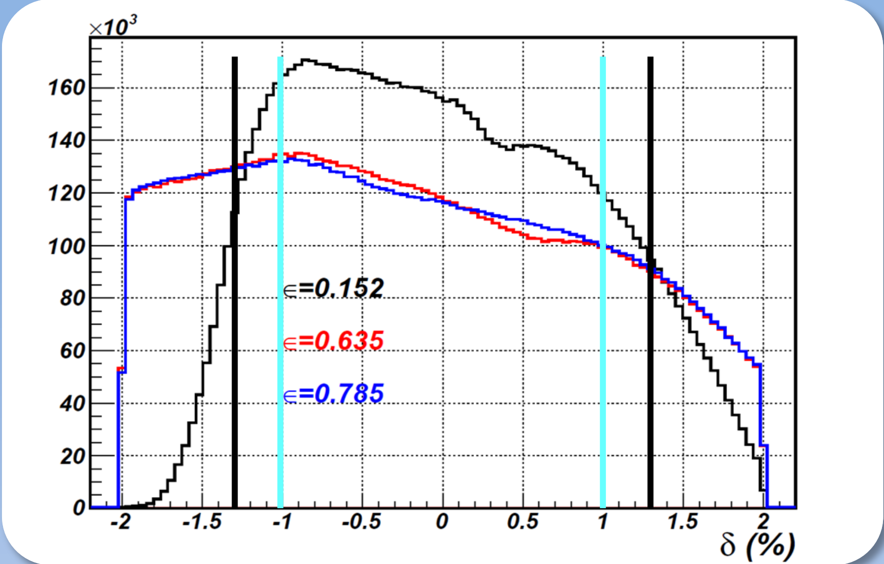

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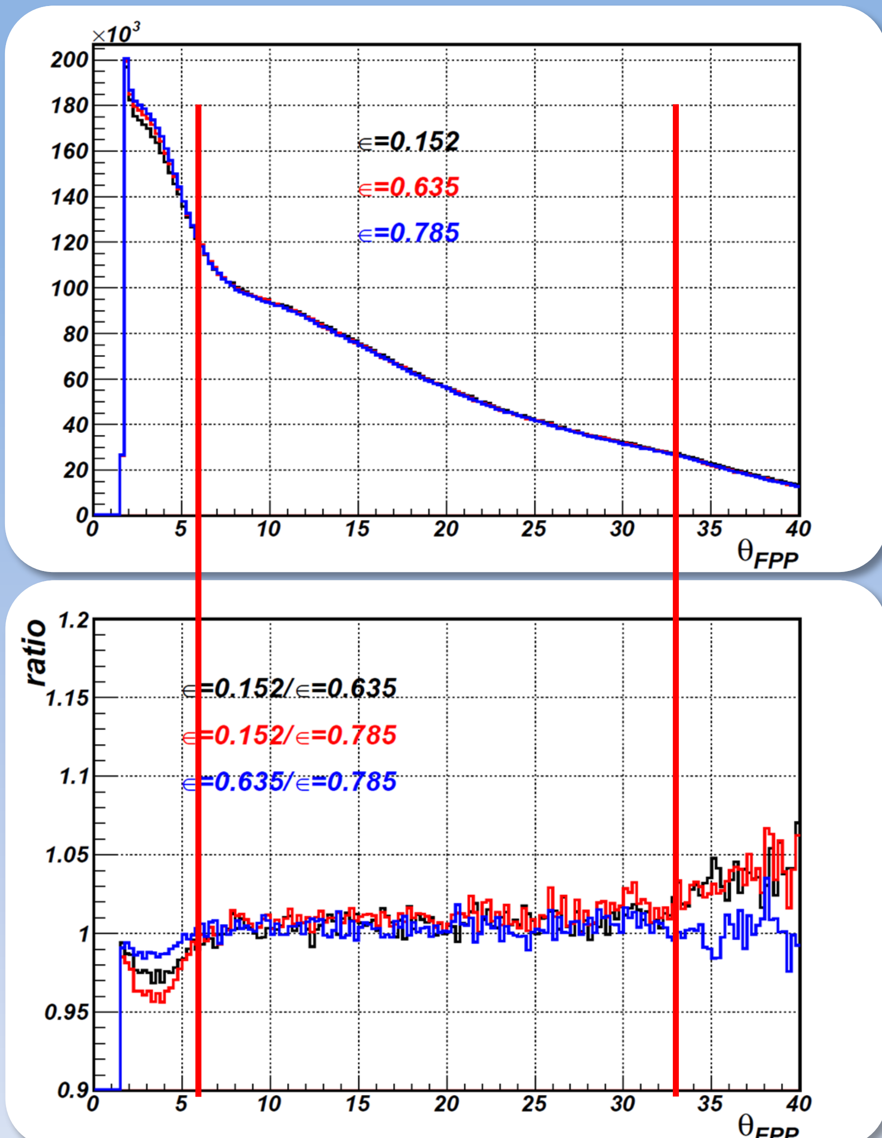

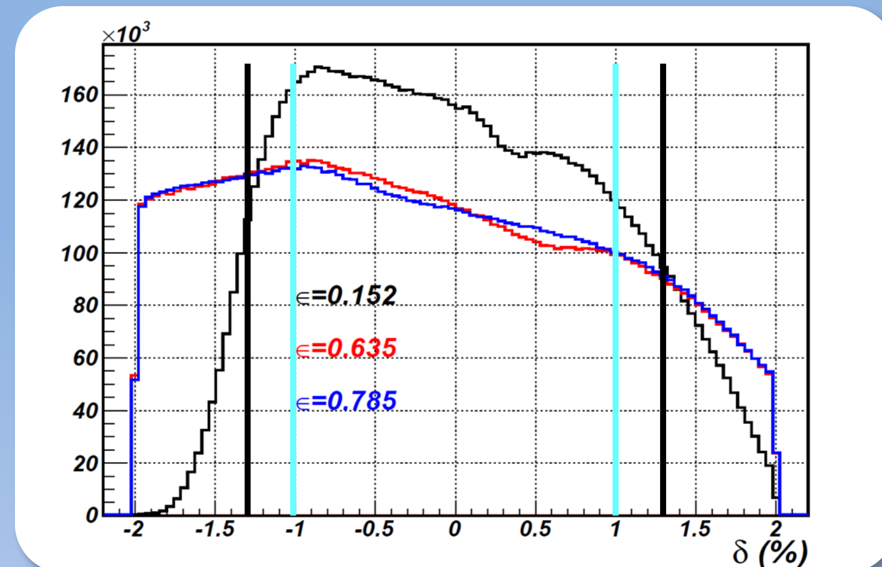

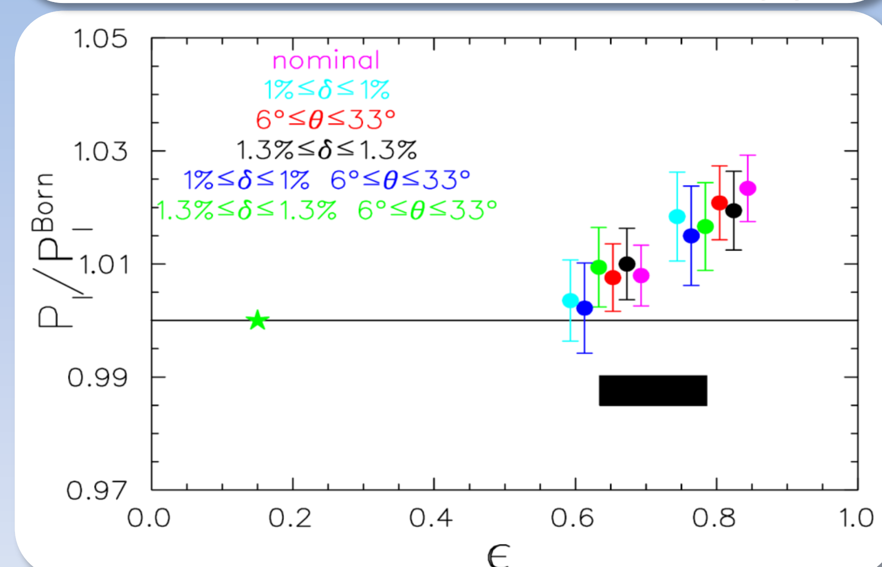

Empirical determination of TPEX amplitudes

- Fit the ratio $-\mu_p\sqrt{\frac{\tau(1+\varepsilon)}{2\varepsilon}}\frac{P_t}{P_\ell}$ $\left(= \mu_p \frac{G_E^p}{G_M^p}\right.$ in the OPEX$\left.\right)$ with a constant

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- Fit $\frac{P_\ell}{P_{\ell\ \mathrm{Born}}}$ with $1 + A\varepsilon^4 (1-\varepsilon)^{1/2}$

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- Fit $\frac{P_\ell}{P_{\ell\ \mathrm{Born}}}$ with $1 + A\varepsilon^4(1-\varepsilon)^{1/2}$
- Fit $\frac{\sigma_r}{\mu_p G_D}$ with a linear function in ε: $a + b\varepsilon$

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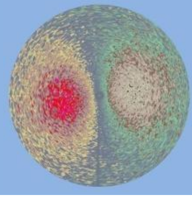

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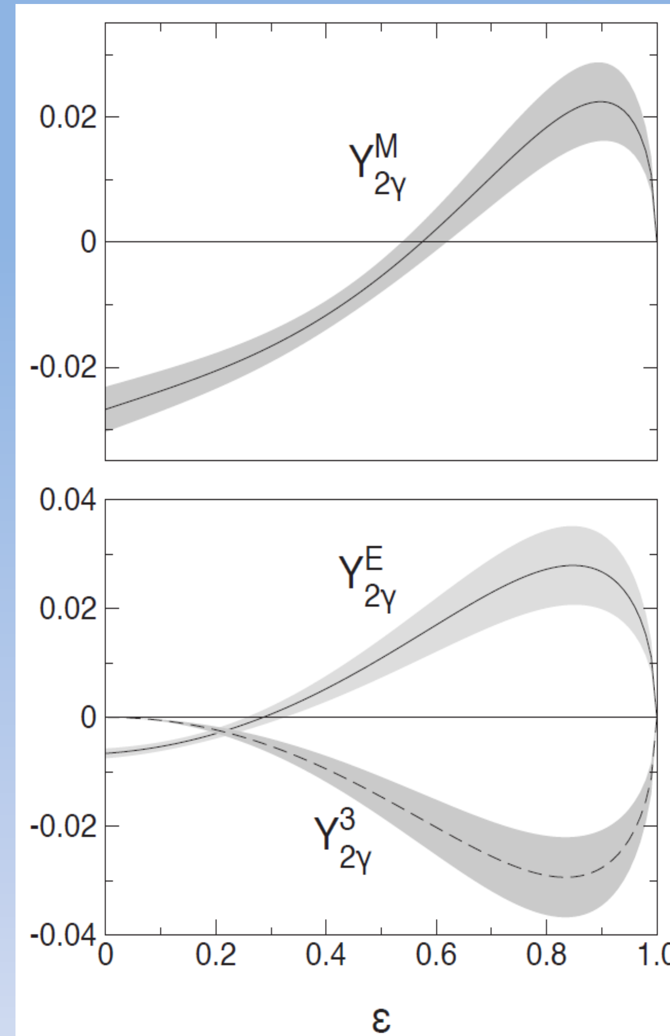
- Extract G_M^2 using the G_E^P / G_M^P value from P_t / P_ℓ fit and $a,\ b$

$Y_{2\gamma}^M = \mathrm{Re}(\delta\tilde{G}_M / G_M)$ best constrained

$Y_{2\gamma}^E = \mathrm{Re}(\delta\tilde{G}_E / G_M)$

$Y_{2\gamma}^3 = \mathrm{Re}(\delta\tilde{F}_3 / G_M)\nu/M^2$

are at the 3% level, opposite sign, cancel partially in the observables



Vanderhaeghen, Kivel, Guttmann, Meziane (submitted to PRL)

CONCLUSION

- The polarization component ratio is independent of the reconstructed kinematics.

- No evidence of an epsilon dependence at a 0.01 level for a polarization component ratio of 0.7 at Q^2 of 2.5 GeV^2.

- Results show an enhancement at small ε for the longitudinal polarization observable.

- PRL submitted for publication.

- Determination of the TPEX amplitudes is possible

- TPEX puzzle remains:

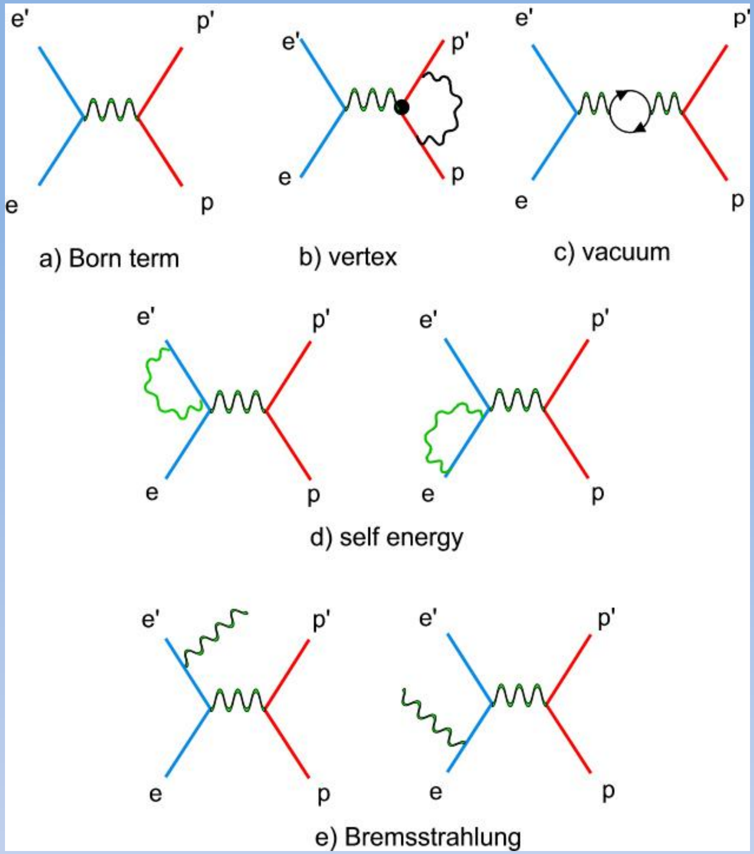
Need more experimental constrains:

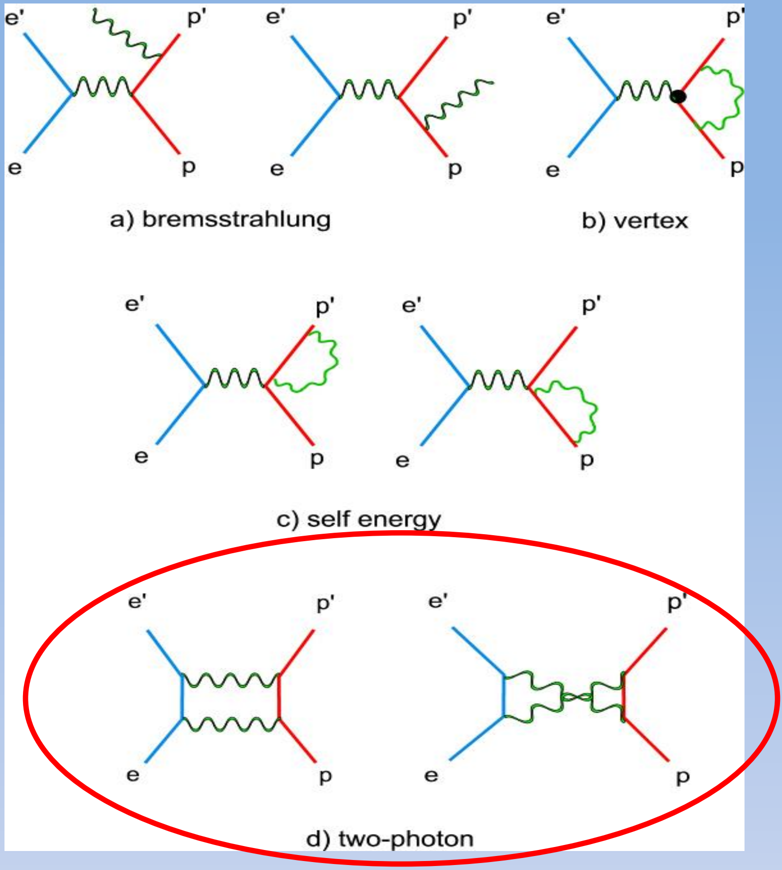
- Non linearity of the cross section.
- Single spin asymmetries.
- Ratio e^+/e^-.

To fully understand, quantify the TPEX.

BACK-UP SLIDES

“Standard” Radiative Corrections





Beyond the Born-Approximation

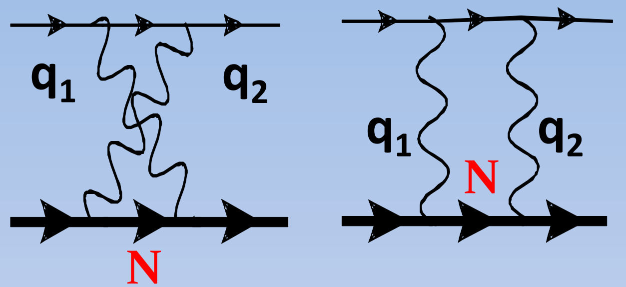
Parity, Wigner time reversal invariance and lepton helicity conservation give the following expansion of the hadronic vertex function (not unique):

(P.A.M Guichon, M. Vanderhaeghen, Phys. Rev. Lett. 91, 142303 (2003))

$$\Gamma^{\mu}(p,p') = \tilde{G}_M \gamma^{\mu} - \tilde{F}_2 \frac{P^{\mu}}{M} + \tilde{F}_3 \frac{\gamma . K P^{\mu}}{M^2}$$

Beyond the Born Approximation a third complex amplitude arises.

Born Approx.	Beyond Born Approx.
$G_M(Q^2), F_2(Q^2)$	$\tilde{G}_M(Q^2,\varepsilon), \tilde{F}_2(Q^2,\varepsilon)$
$\tilde{F}_3(Q^2,\varepsilon) = 0$	$\tilde{F}_3(Q^2,\varepsilon)$
real	complex



$$\tilde{G}_M(Q^2,\varepsilon) = G_M(Q^2) + \delta\tilde{G}_M(Q^2,\varepsilon)$$
$$\tilde{G}_E(Q^2,\varepsilon) = G_E(Q^2) + \delta\tilde{G}_E(Q^2,\varepsilon)$$

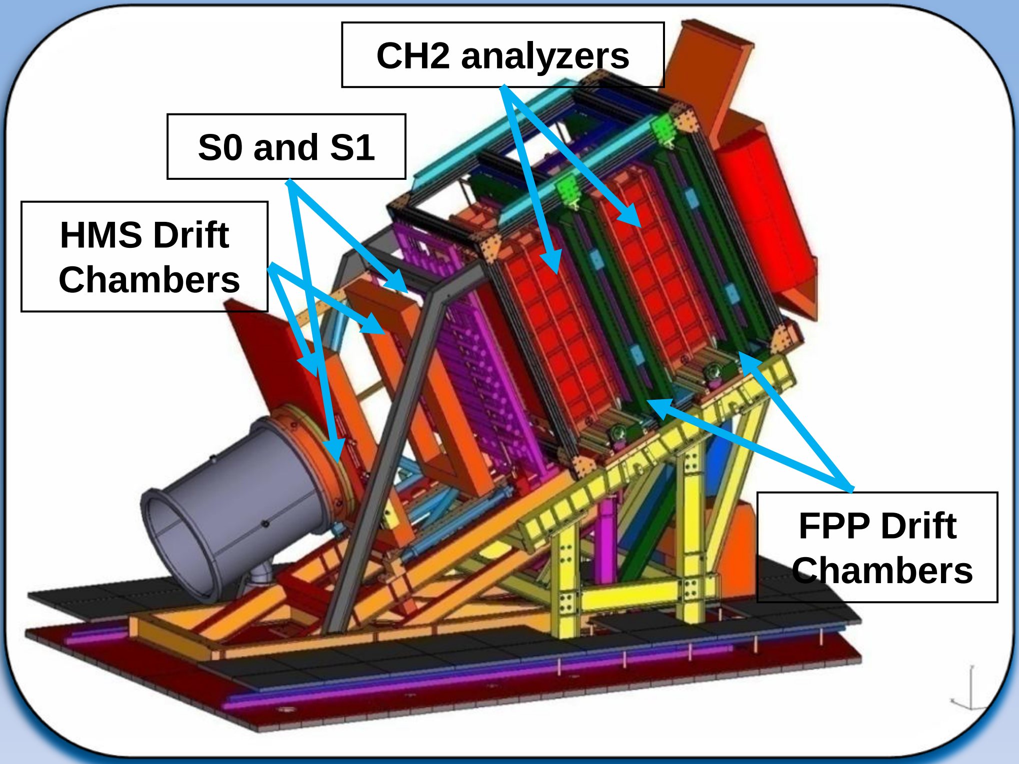
The kinematical parameter ε is: $\varepsilon = \dfrac{(s-u)^2 + t(4M^2 - t)}{(s-u)^2 - t(4M^2 - t)}$

HMS with Focal Plane Polarimeter

- Two HMS drift chambers for tracking--measure proton momentum and define incident trajectory for FPP.

- Scintillator hodoscopes S0 and S1 for trigger and timing.

- Focal Plane Polarimeter
  - Two CH_2 analyzers, 55 cm thick
  - Two sets of drift chambers track protons scattered in analyzer.

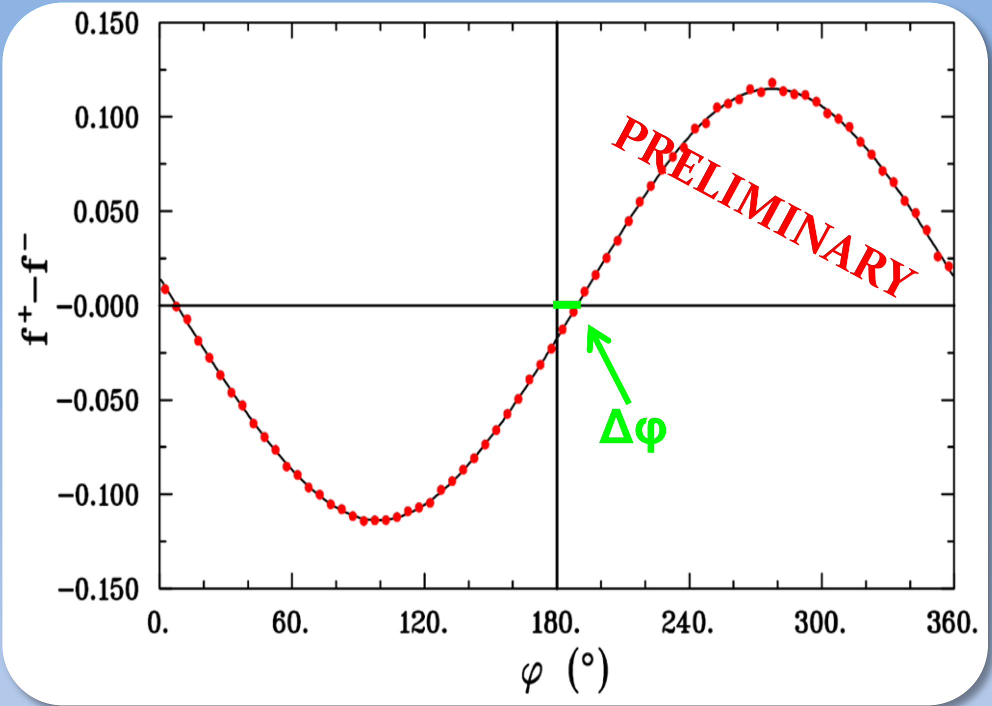


BigCal Calorimeter

- 1744 channels electromagnetic calorimeter
- Measure electron angles and energy
- Separate elastic from inelastic background
- From $\frac{6.8\%}{\sqrt{E}}$ to $\frac{23\%}{\sqrt{E}}$ energy resolution (E in GeV) due to radiation damage
- Position resolution not very sensitive to radiation damage ~5 mm

PHYSICAL ASYMMETRIES

Physical asymmetries (helicity dependent) are obtained by taking the difference between the angular distributions of events of the two helicity states: $f^{+}(\theta, \phi) - f^{-}(\theta, \phi)$



Focal plane asymmetry can be written as a sine function with a phase shift which is related to the polarization components ratio at the focal plane.

$$f^{+}(\theta - \varphi) - f(\theta - \varphi) = B\sin(\varphi + \Delta\varphi)$$

With the FPP, we measure the proton polarization after undergoing precession through the HMS magnets.

$$B = hA_y\sqrt{(P_t^{FPP})^2 + (P_n^{FPP})^2}$$

$$\tan\Delta\varphi = -\frac{P_t^{FPP}}{P_n^{FPP}}, \quad P_n^{FPP} \approx P_l^{Tgt}\sin\chi_\theta$$

FALSE ASYMMETRIES

- The angular distribution is given by:

$$N^{\pm}(p,\theta,\varphi) = N_0^{\pm}\frac{\varepsilon(p,\theta)}{2\pi}[1 + (c_1 \pm A_y P_y^{fpp})\cos\varphi + (s_1 \mp A_y P_x^{fpp})\sin\varphi + c_2\cos(2\varphi) + s_2\sin(2\varphi) + \ldots]$$

$N_0^{\pm}$ Number of incident proton with ± helicity state.

$\varepsilon(p,\theta)$ Fraction of proton with momentum p scattered with an angle θ.

$A_y(p,\theta)$ Analyzing power of the $\vec{p} + CH_2$ reaction.

P_x^{fpp}, P_y^{fpp} Polarization components at the focal plane.

$c_1, s_1, \ldots$ Fourier coefficients of helicity independent instrumental asymmetries. (sum of N^+ and N^-, *cancelled in first order)*

$$\Lambda_0 = \sum_i c_i\cos\varphi_i + s_i\sin\varphi_i$$

- Maximizing the Likelihood function: (S_{ij} COSY spin transport matrix elements)

$$L(P_t,P_l) = \prod_{i=1}^{N_{event}}[1 + h\varepsilon_i A_y^{(i)}(S_{yt}^{(i)}P_t + S_{yl}^{(i)}P_l)\cos\varphi_i - h\varepsilon_i A_y^{(i)}(S_{xt}^{(i)}P_t + S_{xl}^{(i)}P_l)\sin\varphi_i + \Lambda_0^{(i)}]$$

Small negative correction at the 2^{nd} order in the P.C. ratio for the 3 kin. : $|\Delta R| \approx 0.013$

Other determination of TPEX amplitudes

Based on:
- The linearity of the reduced cross section σ_r
- No ε -dependence of the polarization transfer ratio
- TPEX amplitudes vanish at ε=1

The reduced cross section gives information about the amplitude $\delta\tilde{G}_M$

$$\sigma_r = G_M^2\left\{\tau + \varepsilon R_0^2 + 2\tau\frac{\delta\tilde{G}_M}{G_M} + \cancel{2\varepsilon R_0^2\frac{\delta\tilde{G}_E}{G_E}}\right\}$$

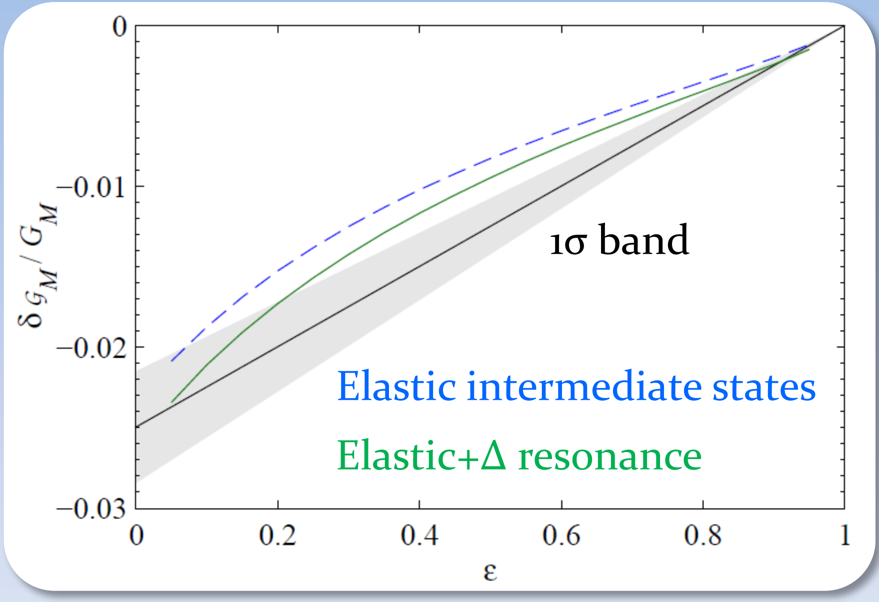
with

$$R_0 = \frac{G_E}{G_M}$$

- Neglect the last term (cross check afterward)

$$\Rightarrow \boxed{\frac{\delta\tilde{G}_M}{G_M} = a(1-\varepsilon)}$$

- a is determined by the slope of the reduced cross section



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Other determination of TPEX amplitudes

The polarization component ratio gives information about the amplitude $\delta\tilde{G}_E$

$$R = R_0\{1 + \frac{\delta\tilde{G}_E}{G_E} - \frac{\delta\tilde{G}_M}{G_M} - \cancel{\underbrace{\frac{\varepsilon(1-\varepsilon)}{1+\varepsilon}}_{<<1}\frac{\delta\tilde{G}_3}{G_M}}\}$$

with $\delta\tilde{G}_3 = \upsilon\tilde{F}_3 / 4M^2$

- Rough estimate of $\delta\tilde{G}_E$ $\Longrightarrow$ Need the determination of $\delta R = R - R_0$

The TPE correction to P_ℓ gives information about the amplitude $\delta\tilde{G}_3$

$$\delta P_\ell = -2P_\ell\varepsilon\{\cancel{\frac{R_0^2\delta R}{\varepsilon R_0^2 + \tau}} - \frac{\varepsilon}{1+\varepsilon}\frac{\delta\tilde{G}_3}{G_M}\}$$

- Two few data points

- $\delta\tilde{G}_3$ computed at the ε value of the data points

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