SFB 1044 THE LOW-ENERGY FRONTIER OF THE STANDARD MODEL FROM QUARKS AND GLUONS TO HADRONS AND NUCLEI

PRISMA

JOHANNES GUTENBERG UNIVERSITÄT MAINZ

Deutsche Forschungsgemeinschaft DFG

Long-range hadronic effects and precision tests of SM

Misha Gorshteyn

Marc Vanderhaghen,
Hubert Spiesberger,
Carl E. Carlson,
Chuck Horowitz,
Michael Ramsey-Musolf
Xavi Roca Maza

Workshop “Hadronic contributions to New Physics Searches” - Sep 26-30, 2016 - Tenerife

Outline

- Context: precise tests of SM with electron scattering
- Long-range effects from 2γ-box
  - Charge radius and beam normal spin asymmetry
- Long-range effects from PV2γ-box
  - Superconvergence relation in ChPT
  - Estimates for the PV2γ correction
- Conclusions

Test of SM with running of weak mixing angle

Weak mixing angle: very central role in the EW sector

$$\begin{pmatrix} \gamma \\ Z^0 \end{pmatrix} = \begin{pmatrix} \cos\theta_W & \sin\theta_W \\ -\sin\theta_W & \cos\theta_W \end{pmatrix} \begin{pmatrix} B^0 \\ W^0 \end{pmatrix}$$

Tree level: fixed by boson masses and SU(2)/U(1) couplings

$$\sin^2\theta_W = 1 - M_W^2/M_Z^2 = g'^2/(g^2 + g'^2)$$

Upon renormalization: weak mixing angle is scale-dependent

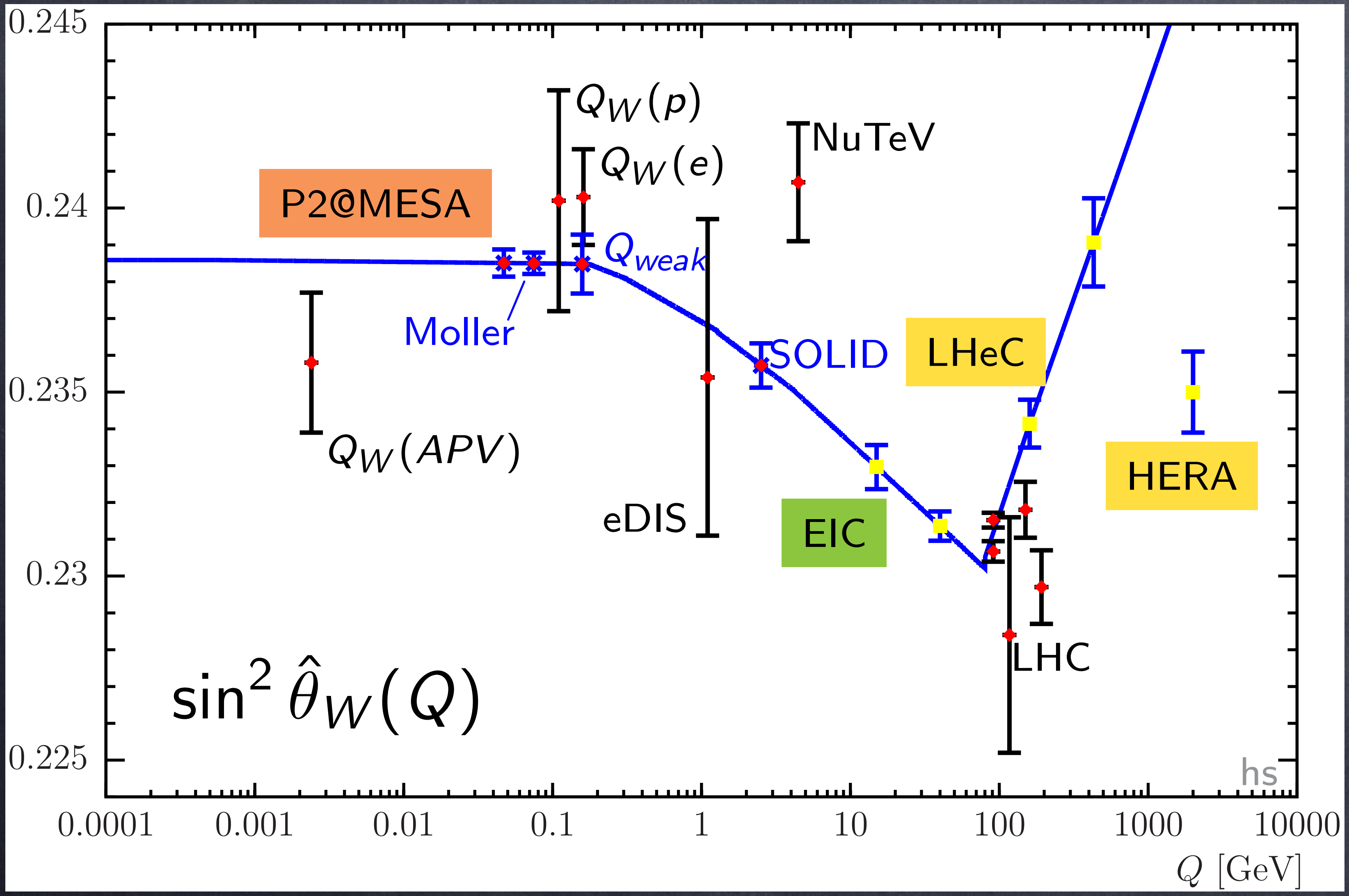
$$\sin^2\theta_W \rightarrow \sin^2\theta_{eff}(Q)$$

The running is a unique prediction of the SM;
A theory with a different content will predict a different running;
WMA - a good way to test the SM and New Physics

Test of SM with running of weak mixing angle

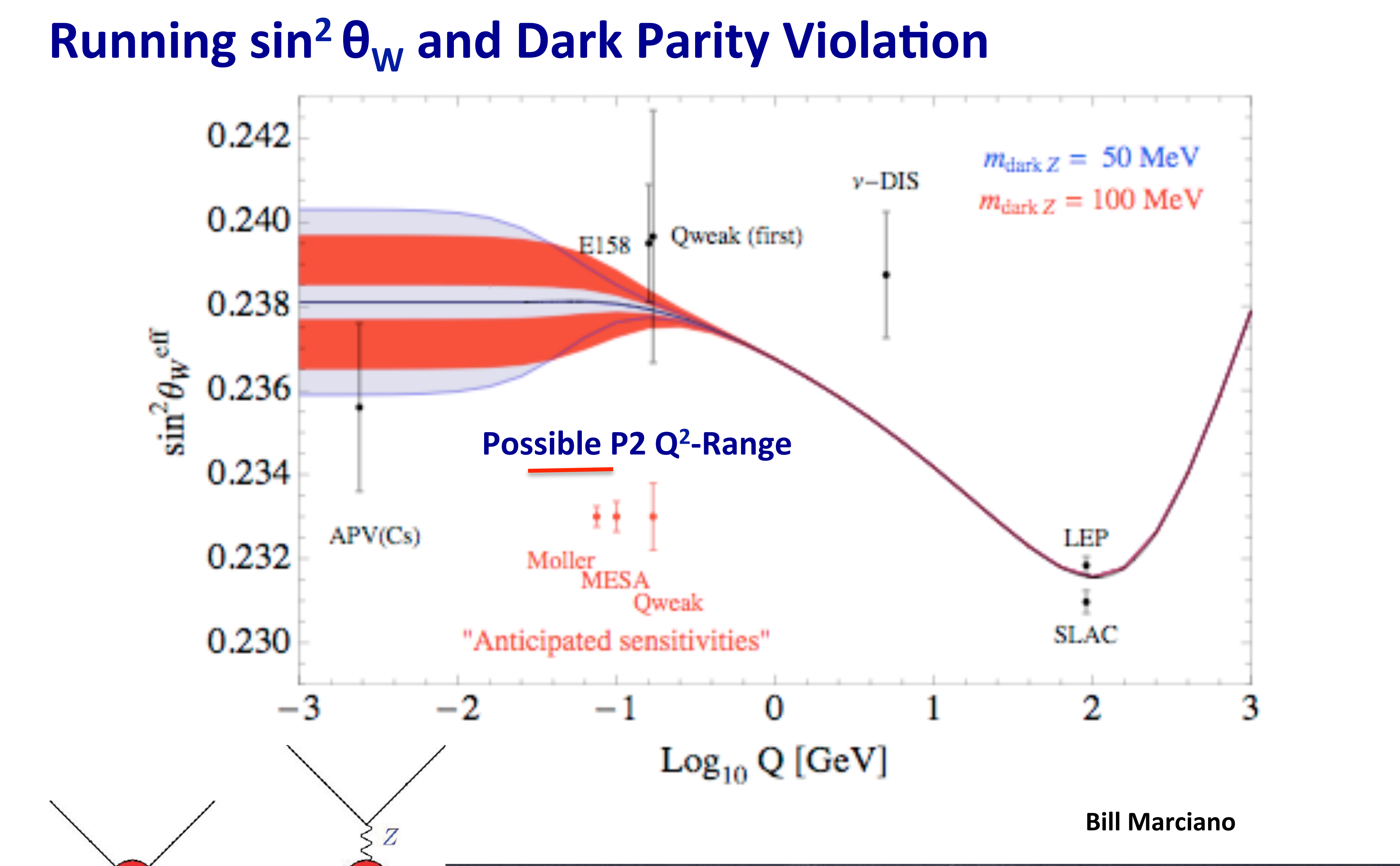
SM running: confirmed qualitatively (not yet quantitatively)

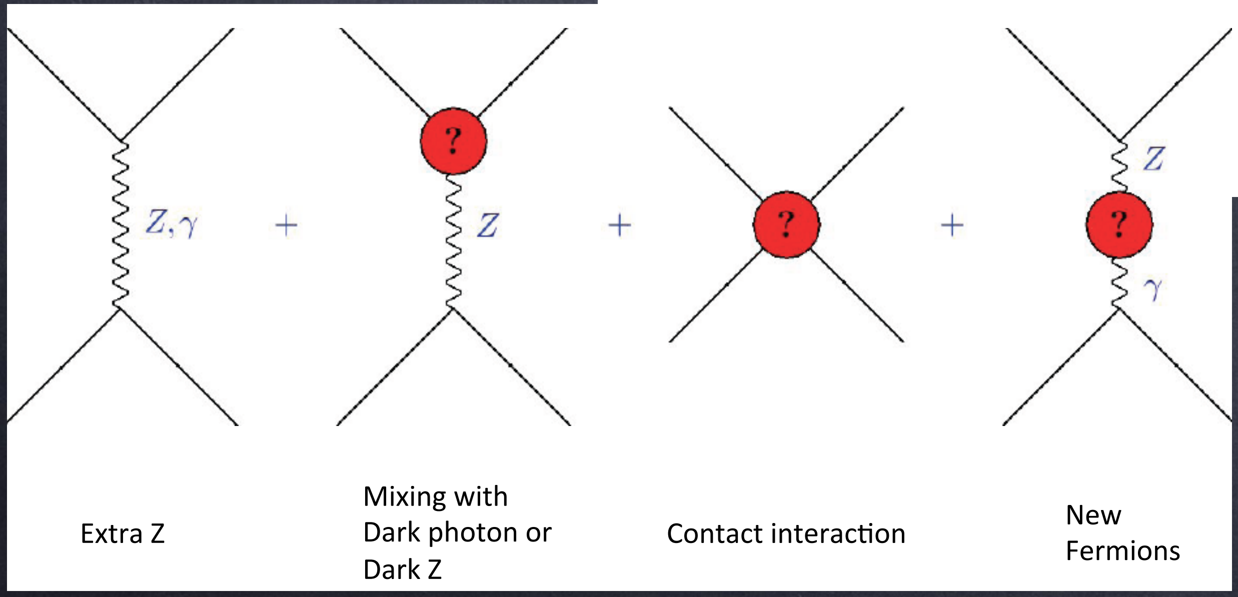
Existing and planned measurements



- Atomic PV (Cs)
- Neutrino scattering
- LEP and SLC (Z-pole)
- Møller scattering
- Q_{weak} (under analysis)
- ATLAS (under analysis)
- MOLLER (planned)
- MESA P2 (planned)
- MESA C12 (proposed)
- DIS SOLID (planned)
- APV with Yb, Dy (planned)
- Future colliders

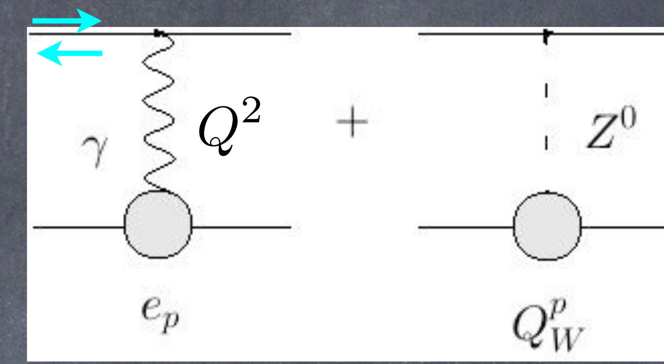
A theory with a different content will predict different running

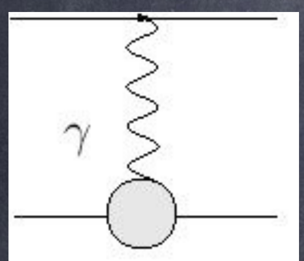




Weak Charge of the Proton from PVES

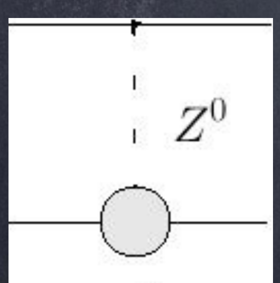
- Elastic e-p scattering with polarized e^- beam





$$\frac{e^2}{Q^2}[1 - \{R_p^2, \mu_p\}Q^2 + O(Q^4)]$$

Talk by Keith



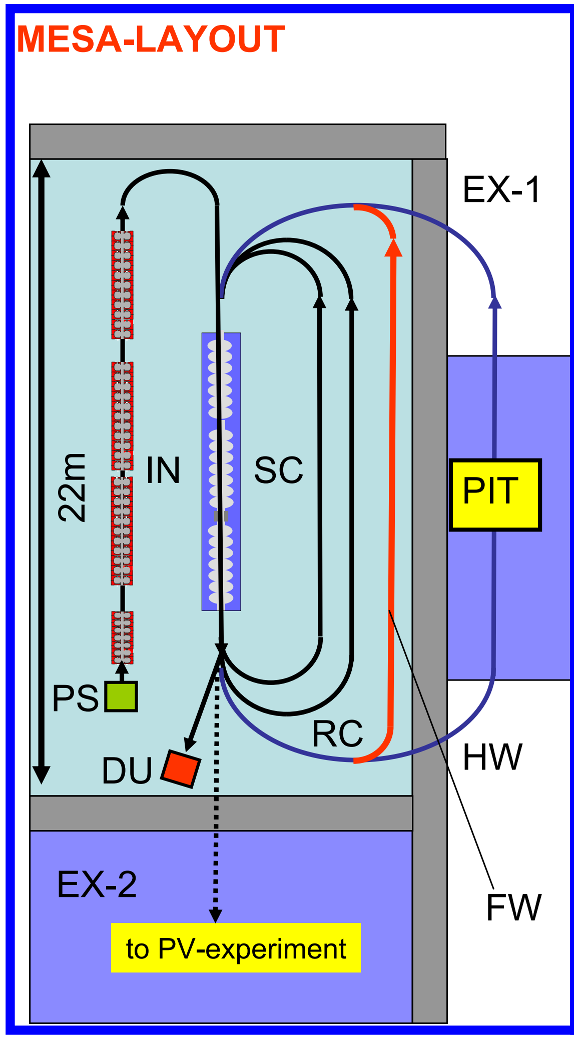
$$-\frac{G_F}{2\sqrt{2}}[Q_W^p + \{R_{p,n}^2, \mu_{p,n}, G_{E,M}^s, G_A\}Q^2 + O(Q^4)]$$

low Q^2, $\epsilon \to 1$

$$A^{PV}(\epsilon, Q^2) = -\frac{G_F Q^2}{4\sqrt{2}\pi\alpha}\left[Q_W^p + B(Q^2)Q^2\right]$$

Talk by Ross

WMA determination with MESA/P2



KEY:
PS: Photosource (polarized or unpolarized beam)
IN: 5MeV, 45kW beam loading injector (normal conducting)
SC: 3 Superconducting cavities in single Cryostat. Energy gain 33 MeV per pass.
RC: Beam recirculation (3 times)
HW: Third recirculation option 'half wave': Energy Recovery Linac (ERL-) Mode
FW: Third recirculation option: 'full wave' : External Beam (EB-) mode
PIT: Pseudo Internal target (ERL mode)
PV: Parity violation experiment (EB-mode)
DU: 5 MeV beam dump in ERL-mode
EX: Experimental areas 1 and 2
Existing walls: 2-3m thick shielding

EXPERIMENTAL BEAM PARAMETERS:
1.3 GHz c.w.
EB-mode: 150 μA, 137 MeV polarized beam (liquid Hydrogen target L~10^{39})
ERL-mode: 10mA, 104 MeV unpolarized beam (Pseudo-Internal Hydrogen Gas target, L~10^{35})

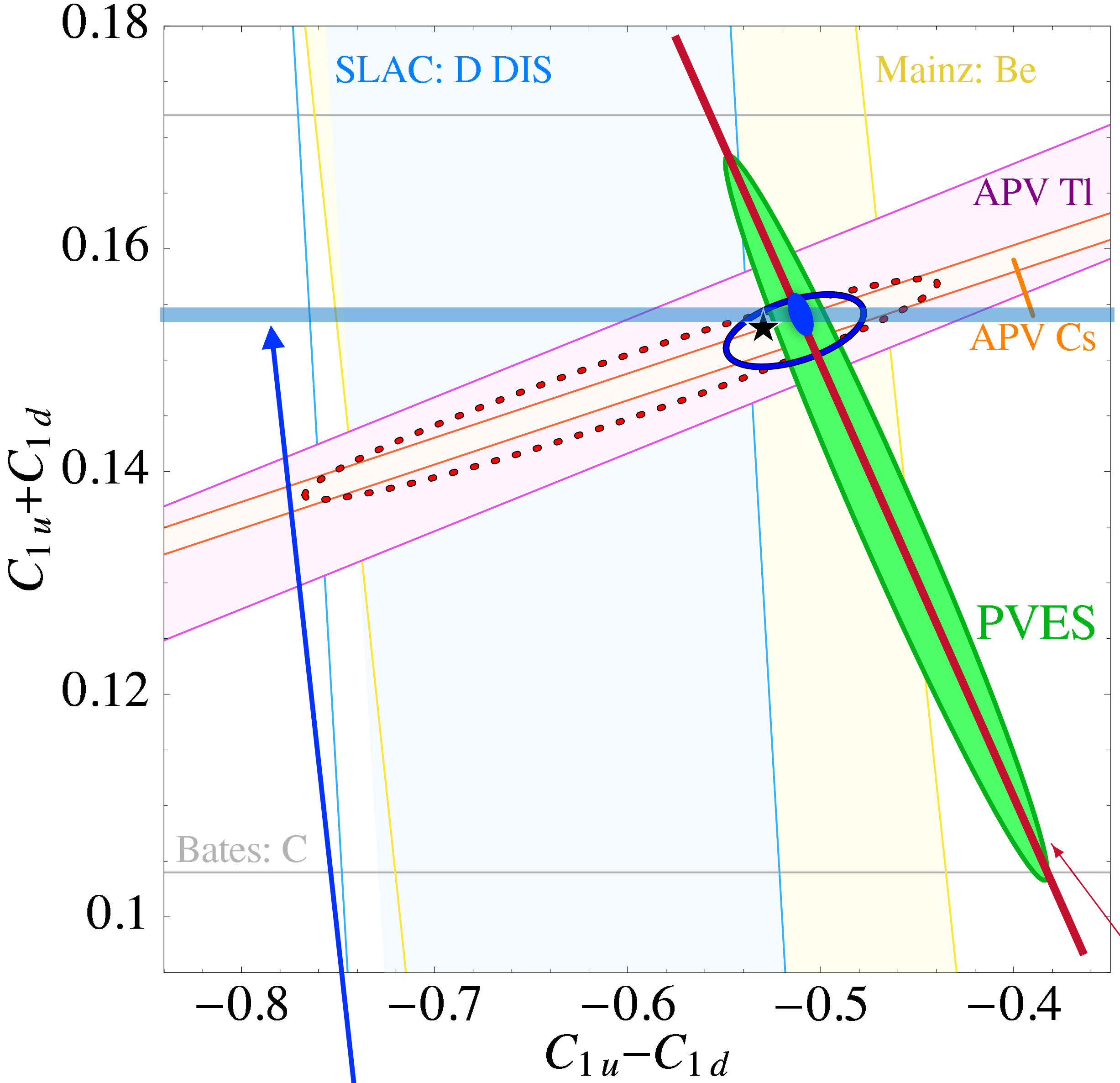
- E = 155 MeV, 150μA
- Scattering angle 20°±10°
- Q^2 = 0.0045 GeV^2
- Polarization (85±0.5)%
- Pol. flip few 1000/sec
- 60cm Liquid H target
- Asymmetry A = -29 ppb
- δA/A = 1.5%

Requirements to the beam:
1-2 o.o.m. improvement w.r.t. MAMI

Beam Quantity	Achieved at MAMI	Contribution to $\delta(A_{PV})$	Required for MESA
Energy	0.04 eV	$<$ 0.1 ppb	fulfilled
Position	3 nm	5 ppb	0.13 nm
Angle	0.5 nrad	3 ppb	0.06 nrad
Intensity	14 ppb	4 ppb	0.36 ppb

Timeline: Accelerator commissioning: 2018
Data taking: 2020

Impact of MESA (H and C12) on SM tests



A more general approach
for extensions of the Standard Model:

model independent coupling constants,
effective low-energy 4-fermion interaction

C_{1f}: $A_e \otimes V_f$, C_{2f}: $V_e \otimes A_f$

SM prediction (black star):

$C_{1f} = -I_f + 2Q_f \sin^2\theta_W$

$(C_{1u} - C_{1d} = -1 + 2\sin^2\theta_W,$

$C_{1u} + C_{1d} = \frac{2}{3}\sin^2\theta_W)$

$Q_W(p) = -2(2C_{1u} + C_{1d})$

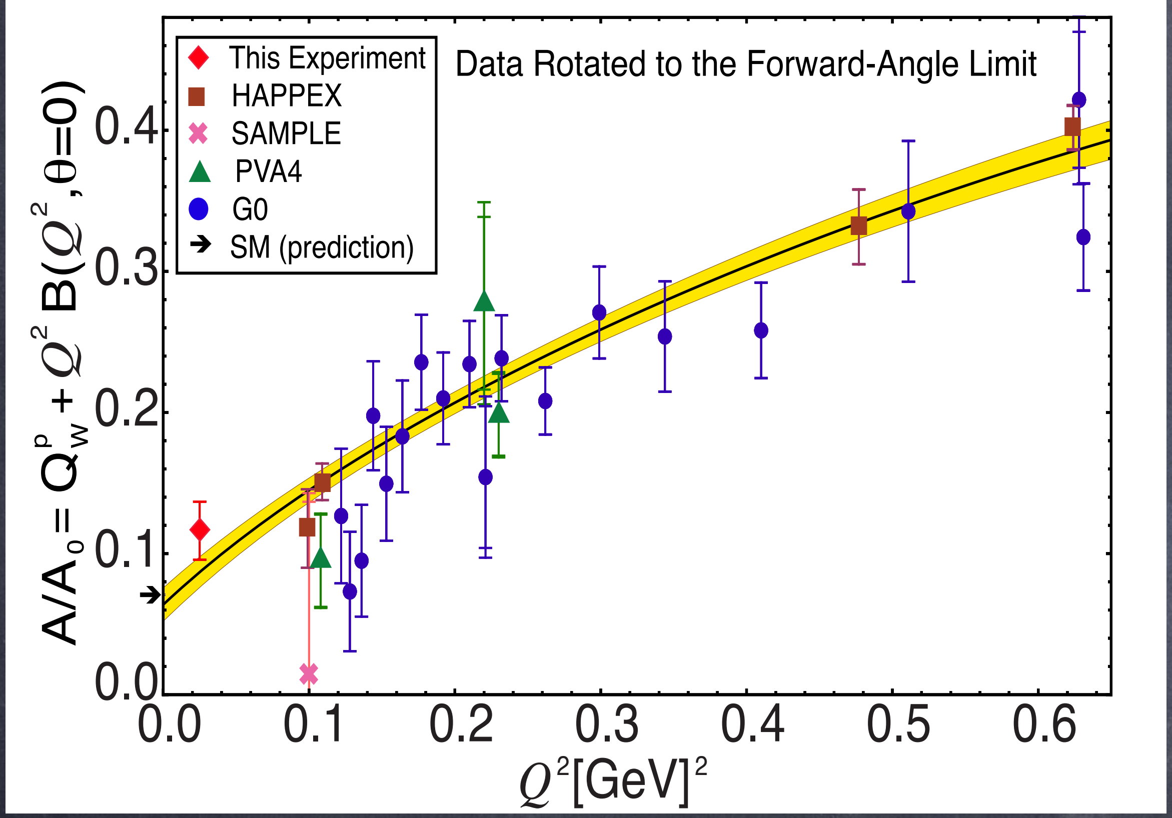
Mainz P2: $\Delta Q_W(p) = \pm 0.0097$ (2.1 %)

MESA C12: $\Delta Q_W(C12) = 18\Delta(C_{1u}+C_{1d}) = \pm 0.0086$ (0.3%)

Theory uncertainties

$$A^{PV}(\epsilon, Q^2) = -\frac{G_F Q^2}{4\sqrt{2}\pi\alpha}\left[Q_W^p + B(Q^2)Q^2\right]$$

- $B(Q^2)$ - take from somewhere else (PVES, lattice, ...)

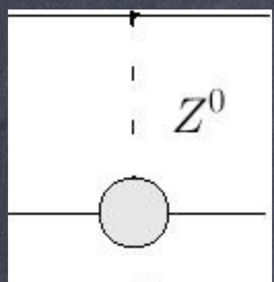


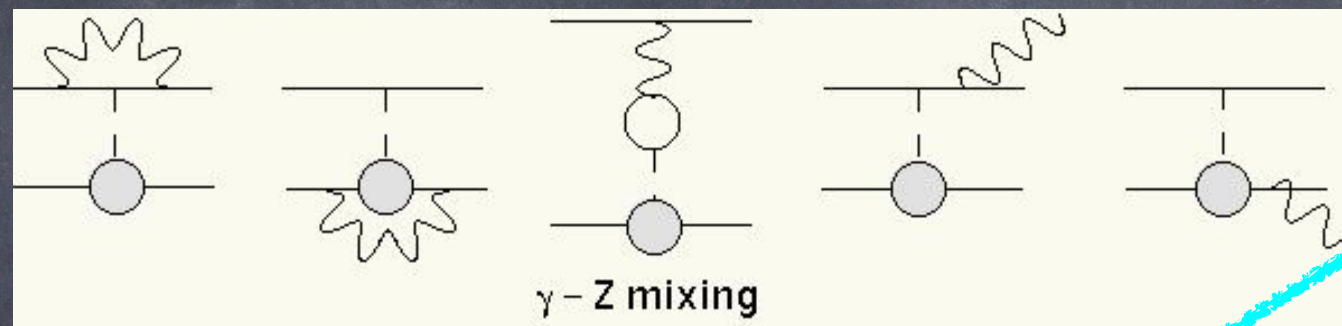
Young, Carlini, Thomas, Roche, PRL 2007;
Androic et al. [Qweak Coll.], PRL 2013

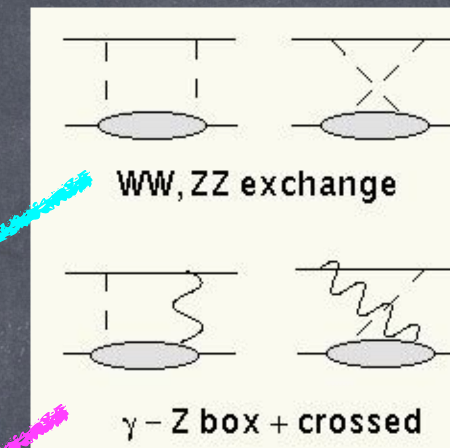
- Rationale: go to the lowest Q^2 - asymmetry directly measures the weak charge

How is this picture modified by the radiative corrections?

1-loop radiative corrections to Z-exchange







RGE

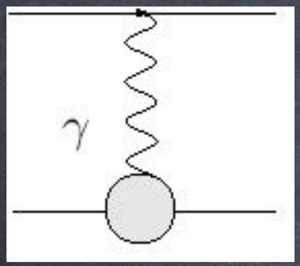
$$\longrightarrow \quad -\frac{G_F}{2\sqrt{2}}[Q_W^p + \delta Q_W^p(\mu) + \Box_{\gamma Z}(E) + O(Q^2)]$$

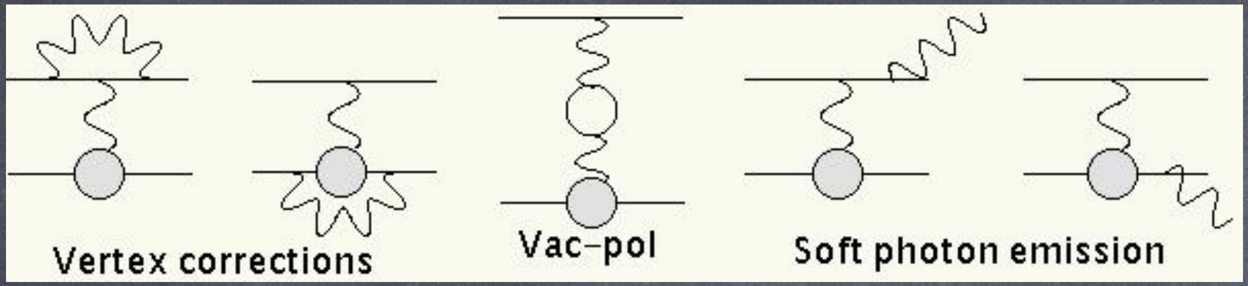
γZ-box: hadron structure- and energy dependent

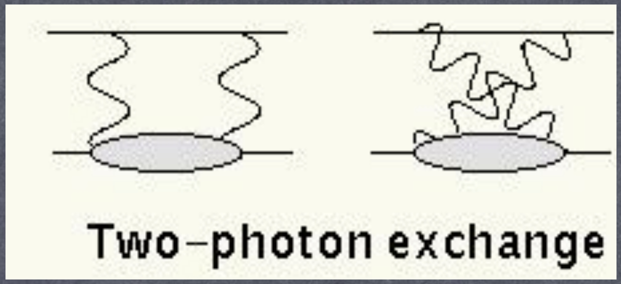
Marciano & Sirlin; Erler, Kurylov, Ramsey-Musolf; MG & Horowitz

In presence of 1-loop RC's the Z-exchange amplitude is not modified essentially as function of Q^2 (at low Q^2); γZ-box shifts the apparent value of the weak charge.

1-loop radiative corrections to γ-exchange







2γ-exchange: inclusive off-shell hadronic states, arbitrary kinematics

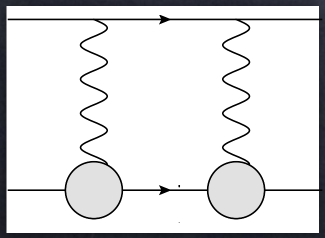
$$T_{2\gamma} = \int \frac{d^4q}{(2\pi)^4} \frac{\ell_{\mu\nu} W^{\mu\nu}}{q^2 q'^2 [(k-q)^2 - m_e^2]}$$

$$W^{\mu\nu} = \int dx\, e^{iqx} \langle N' | T[J^\nu(x) J^\mu(0)] | N \rangle$$

Two current correlator: can't calculate from first principles in QCD

Elastic box: IR divergent, UV finite, calculable with known form factors

$$W^{\mu\nu}_{el} \sim \langle N' | J^\nu | N \rangle \langle N | J^\mu | N \rangle$$



a long history in the literature:

Mo, Tsai; Maximon, Tjon; Feshbach, McKinley; Blunden, Melnitchouk, Tjon; Kobushkin, Borysiuk;Tomalak, Vanderhaeghen; …

Elastic box correction δ_{RC}^{el} is subtracted at the observables level

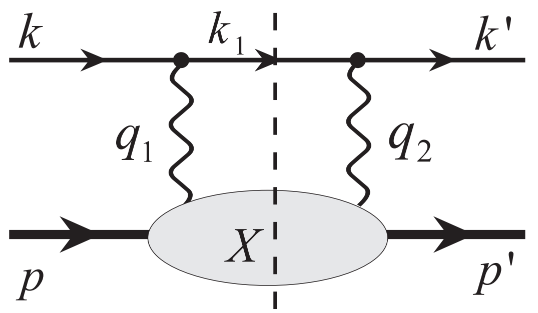
Inelastic 2γ-exchange

Cannot calculate in arbitrary kinematics!

In forward kinematics:
optical theorem + dispersion relation

$$W^{\mu\nu} \sim 2M\omega\,\sigma_{\gamma p}^{tot}(\omega)\,g^{\mu\nu} + \dots$$

$$2\mathrm{Im}T_{2\gamma} \;=\; e^4 \int \frac{d^3\vec{k}_1}{(2\pi)^3 2E_1}\,\frac{\ell_{\mu\nu}\cdot \mathrm{Im}W^{\mu\nu}}{(q_1^2+i\epsilon)(q_2^2+i\epsilon)}$$



Collinear log enhancement

Brown 1970; Gorchtein 2007, 2014

$$\frac{e^2}{Q^2}\left[1-\{R_p^2,\,\mu_p\}Q^2+\delta_{RC}^{elastic}+\frac{\alpha}{\pi}Q^2C_{2\gamma}(E)\ln\frac{4E^2}{Q^2}+O(Q^2)\right],$$

Sum rule for the coeff. $C_{2\gamma}$

$$C_{2\gamma}(E)=\frac{1}{4\pi^2\alpha}\int_{\nu_\pi}^{\infty}\frac{d\omega}{\omega}\sigma_{\gamma p}^{tot}(\omega)f(\omega,E)$$

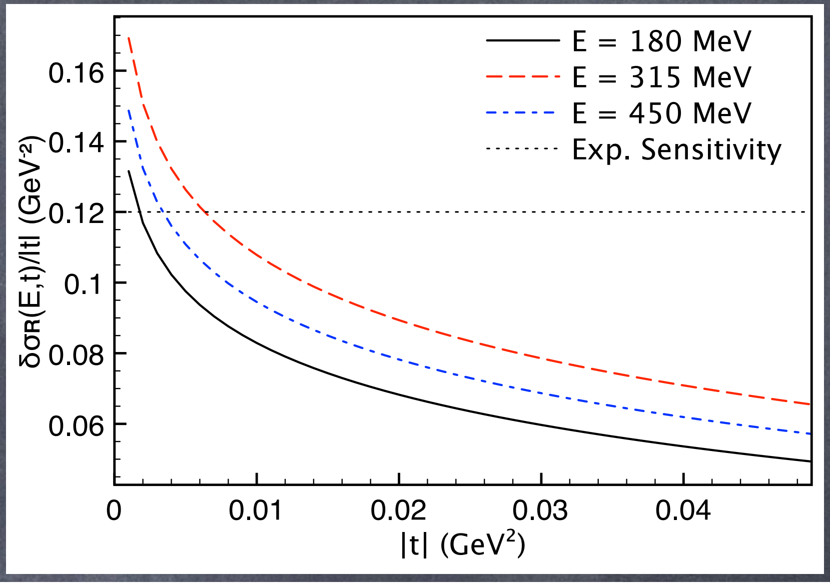
generates a long-range potential (shorter than Coulomb);
essentially modifies the low-Q^2 asymptotics!

Numerical impact for charge radius extraction

$$\sigma_R - \delta\sigma_{RC}^{el} = 1 - Q^2 R_p^2/3 + (\alpha/\pi) Q^2 C_{2\gamma}(E) \ln(4E^2/Q^2) + \ldots$$

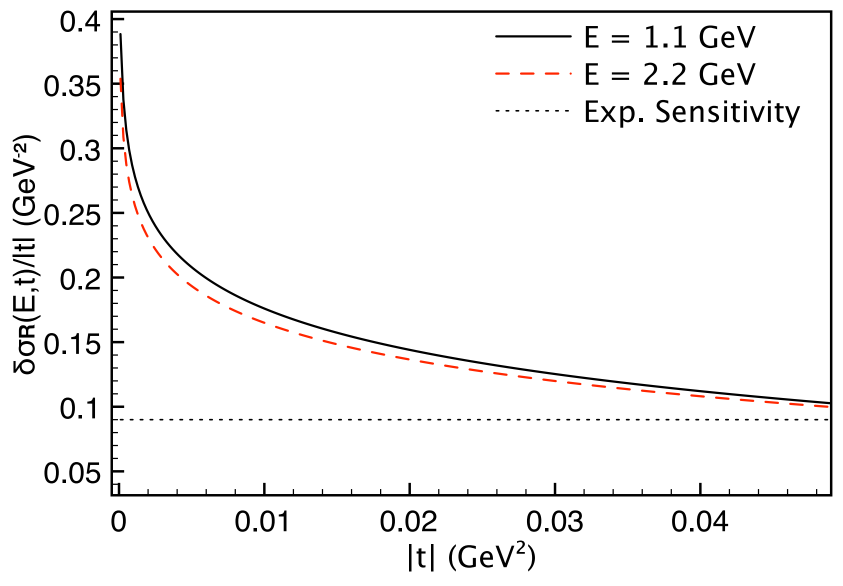
A1@MAMI: R_p = 0.879(8) fm

$$\frac{\sigma_R - 1}{Q^2} = -\frac{R_p^2}{3}(1 \pm 2\frac{\delta R_p}{R_p}) = -6.61(12)\,\mathrm{GeV}^{-2}$$



PRad@JLab: higher E, lower Q^2, R_p below 1%

$$\frac{\sigma_R - 1}{Q^2} = -\frac{R_p^2}{3}(1 \pm 2\frac{\delta R_p}{R_p}) = -6.61(9)\,\mathrm{GeV}^{-2}$$



Log Q^2 dependence affects the extraction of the radius;
But the log term is exactly calculable!

2γ-exchange correction to the weak charge

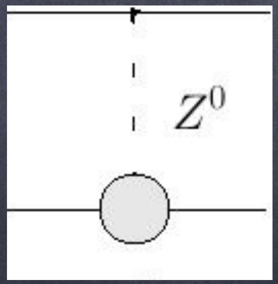
2γ-box ~ 1-3% of the charge radius; does it matter for the Q^p_W?

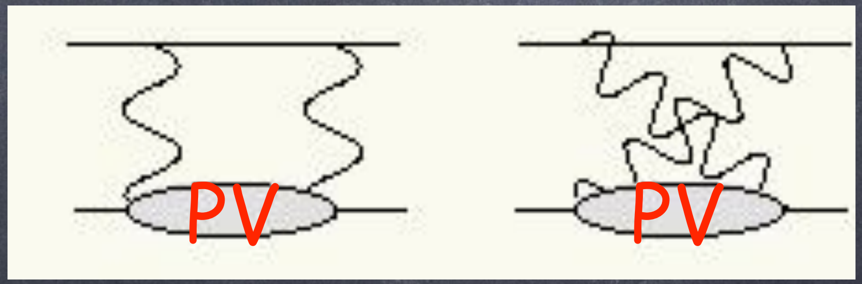
$$Q^p_W \to Q^p_W + Q^p_W \frac{\alpha}{\pi} Q^2 C_{2\gamma}(E) \ln \frac{4E^2}{Q^2}$$

part of the B(Q^2) term!

What if the 2γ-box contributed to the PV amplitude?

"Long-range parity-nonconserving interactions", Flambaum 1992
"PV-odd van der Waals forces", Khriplovich, Zhizhimov, 1982





$$-\frac{G_F}{2\sqrt{2}}[Q^p_W + \ldots] + \frac{e^2}{Q^2}\frac{\alpha}{\pi} Q^2 C^{PV}_{2\gamma} \ln \frac{4E^2}{Q^2}$$

Dangerous for the weak charge definition!

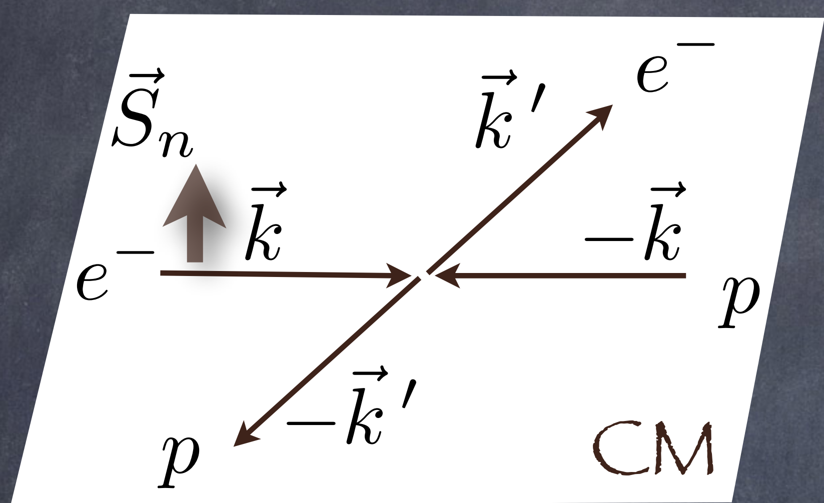
$$Q^p_W \to Q^p_W + \frac{4\sqrt{2}\alpha^2}{G_F} C^{PV}_{2\gamma}(E) \ln \frac{4E^2}{Q^2}$$

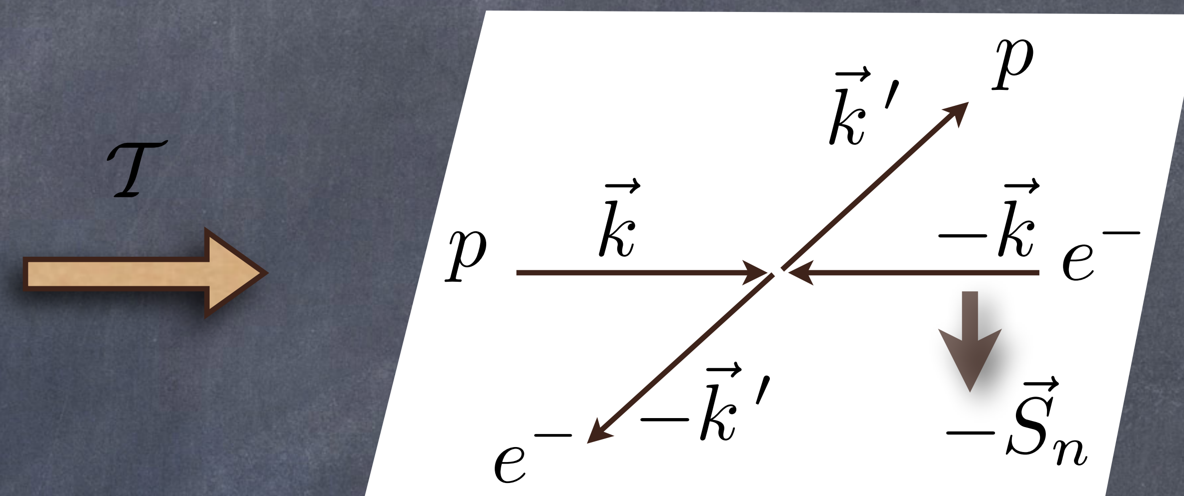
Two questions to ask:

1. are these collinear log calculations reliable?
2. is this catastrophic scenario for the weak charge realized?

How well do we understand these collinear logarithms?

Beam normal spin asymmetry:
collinear logs are measurable and dominate

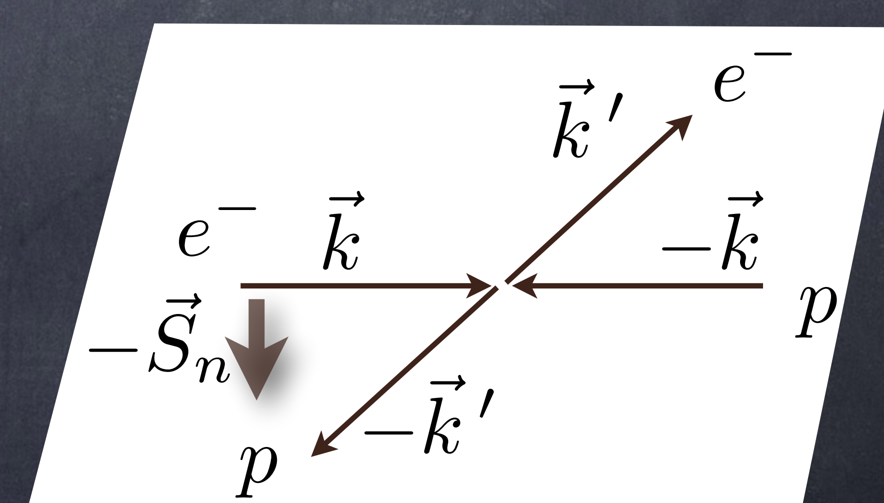




180° rotation around y-axis

$$T(S_n, \vec{k}, \vec{k}') \rightarrow \eta_1 T^*(-S_n, -\vec{k}, -\vec{k}') \rightarrow \eta_1 \eta_2 T^*(-S_n, \vec{k}, \vec{k}')$$

Mismatch between time-reversed states
is due to imaginary part of the amplitude
(in absence of CP- and CPT-violation)

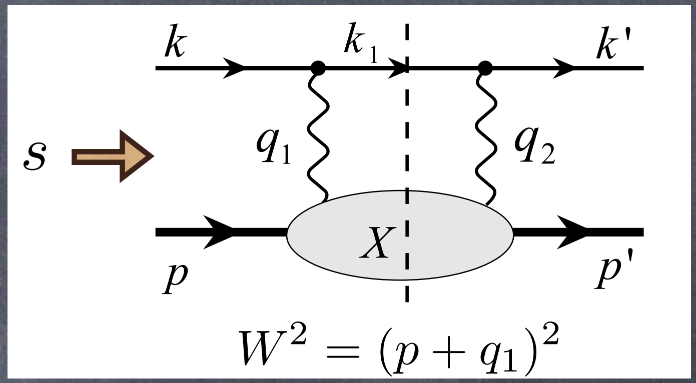


Elastic e-p scattering in presence of two-photon exchange

$$T_{ep} = T_{1\gamma} + T_{2\gamma} + \ldots$$

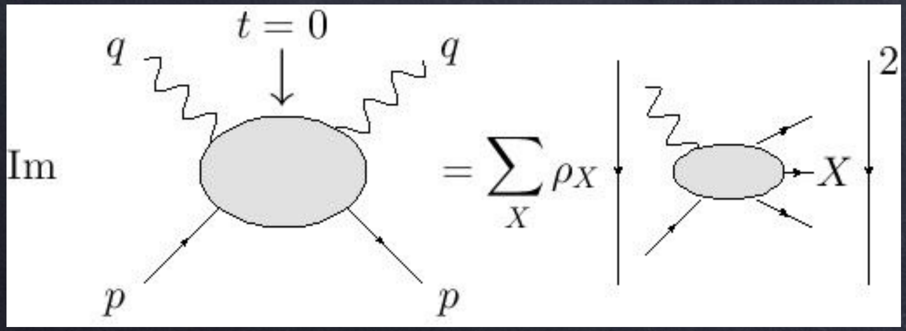
$$B_n = \frac{T_{1\gamma}^* \, 2\mathrm{Im} T_{2\gamma}}{|T_{1\gamma}|^2}$$

Bn in forward kinematics



$$\mathrm{Im} T_{2\gamma} = e^4 \int \frac{d^3\vec{k}_1}{2E_1 (2\pi)^3} \frac{\bar{u}(k')\gamma_\nu (\not{k}_1 + m_e)\gamma_\mu u(k)}{Q_1^2 Q_2^2} \mathrm{Im} W^{\mu\nu}(W^2, Q_1^2, Q_2^2, t)$$

Forward spin-independent Compton tensor - from Optical Theorem



$$W^{\mu\nu} = 2\pi \left[-g^{\mu\nu} F_1^{\gamma\gamma} + \frac{P^\mu P^\nu}{(P \cdot q_1)} F_2^{\gamma\gamma} \right]$$

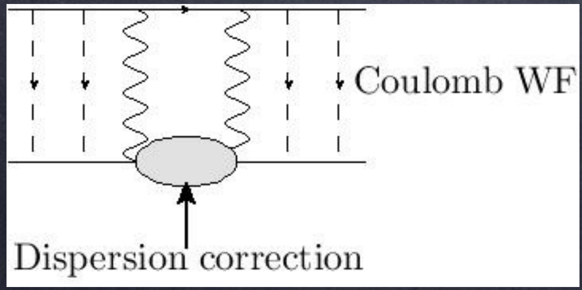
Bn features a large collinear log - $\ln(Q^2/m_e^2)$

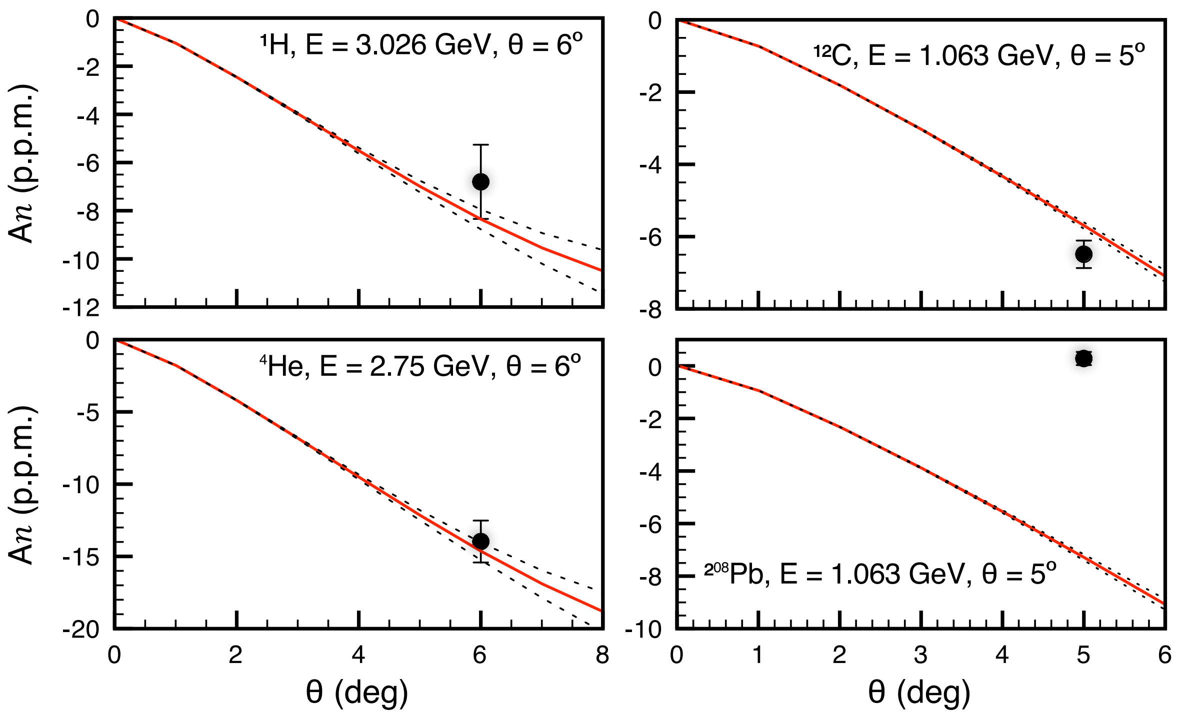
$$B_n \approx -\frac{1}{4\pi^2}\frac{m_e\sqrt{Q^2}}{E^2}\ln\left(\frac{Q^2}{m_e^2}\right)\frac{e^{-BQ^2}}{F_C(Q^2)}\int_{\omega_\pi}^{E} d\omega\omega\sigma_{\gamma N}^{tot}(\omega)$$

Good quality data on selected nuclei - HAPPEX & PREx

Excellent description for light nuclei and very forward angles

Fails for lead - two photons is not enough





Abrahamyan et al. [HAPPEX and PREx], 2012

Work in progress with Xavi Roca Maza

Collinear logs are under control at forward angles for light nuclei

To summarize:

forward collinear logs are a well-established feature;
measured and confirmed for B_n
(where two-photon exchange dominates over h.o. effects);
modify the low-Q^2 asymptotics of observables;

Need to be assessed more accurately for PVES!

Calculate the coefficient $C_{2\gamma}^{PV}(E)$ in the forward regime

PV2γ dispersive contribution to forward PVES

MG, H. Spieberger, arXiv: 1608.07484

$$\mathrm{Im}\, T^{PV}_{\gamma\gamma} = e^4 \int \frac{d^4 k_1}{(2\pi)^4} 2\pi\delta(k_1^2 - m_e^2) \frac{2\pi \tilde{W}^{\mu\nu}_{\gamma\gamma} \ell^{\gamma\gamma}_{\mu\nu}}{Q^4}$$

Proton spin-independent case $\qquad \tilde{W}^{\mu\nu}_{\gamma\gamma} = \frac{i\varepsilon^{\mu\nu\alpha\beta} p_\alpha q_\beta}{2(pq)} F_3^{\gamma\gamma}$

Identify the sought for coefficient:

$$C^{PV}_{2\gamma}(E) = \frac{1}{M} \int\limits_{E_\pi}^{\infty} \frac{d\omega}{\omega^2} F_3^{\gamma\gamma}(\omega) \left[\frac{\omega}{2E} \ln \left| \frac{E+\omega}{E-\omega} \right| + \frac{\omega^2}{4E^2} \ln \left| 1 - \frac{E^2}{\omega^2} \right| \right],$$

Does not vanish for E=0??? $\qquad C^{PV}_{2\gamma}(0) = \frac{3}{4M} \int_{\omega_\pi}^{\infty} \frac{d\omega}{\omega^2} F_3^{\gamma\gamma}(\omega)$

Compare to the PC case: $C_{2\gamma}(0) = 0$

Formal definition of the Q_W to remove $\Box_{\gamma Z}(E)$ - not viable??

$$-\lim_{E,Q^2 \to 0} \frac{4\pi\alpha\sqrt{2}}{G_F Q^2} A^{PV}_{exp}(E, Q^2) = Q_W^{p,\,1-loop} - \frac{4\sqrt{2}\alpha^2}{G_F} C^{PV}_{2\gamma}(0) \ln \frac{4E^2}{Q^2}$$

General properties of the PV Compton amplitude

Low-energy expansion + high energy behavior ->
superconvergence relation (SCR)

Lukaszuk, arXiv: nucl-th/0207038;
Kurek, Lukaszuk, arXiv: hep-ph/0402297

$$\int_{E_\pi}^{\infty} \frac{d\omega}{\omega^2} F_3^{\gamma\gamma}(\omega) = 0$$

SM: shown to hold for γ+e -> Z+e, γ+e -> W+ν

Altarelli, Cabibbo, Maiani 1972, ...

Check the SCR in ChPT

PV pion-nucleon coupling $\mathcal{L}_{\pi N}^{PV} = \frac{h_\pi^1}{\sqrt{2}} \bar{N} [\vec{\tau} \times \vec{\pi}]^3 N$

Donoghue, Desplanques, Holstein; Savage, Kaplan; ...

Heavy Baryon ChPT calculation of PV Compton amplitude

Cohen et al, arXiv: nucl-th/0009031

Result used by Kurek&Lukaszuk to check SCR: failed!

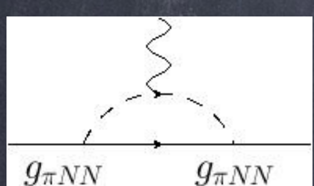
SCR important for the definition of Q_W^p - recheck!

Similar to the GDH sum rule proof to order $O(g_{\pi NN}^2)$

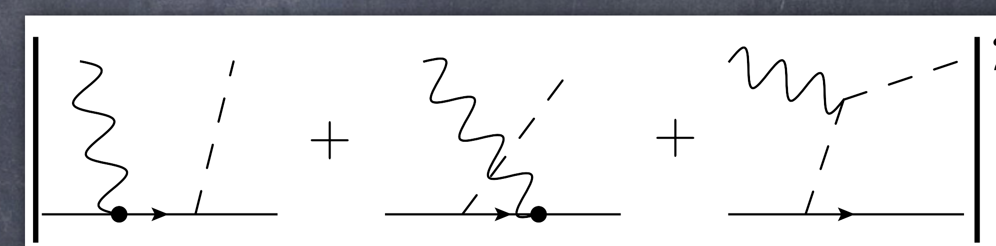
Holstein, Vanderhaeghen, Pascalutsa, 2005

Anomalous m.m. ⟷ Inelastic scattering of polarized photon on polarized proton w. helicities parallel (antiparallel)

1-loop level



$$\kappa_p^2 \sim \int_{E_\pi}^{\infty} d\omega \frac{\sigma_{\gamma p}^{3/2}(\omega) - \sigma_{\gamma p}^{1/2}(\omega)}{\omega}$$



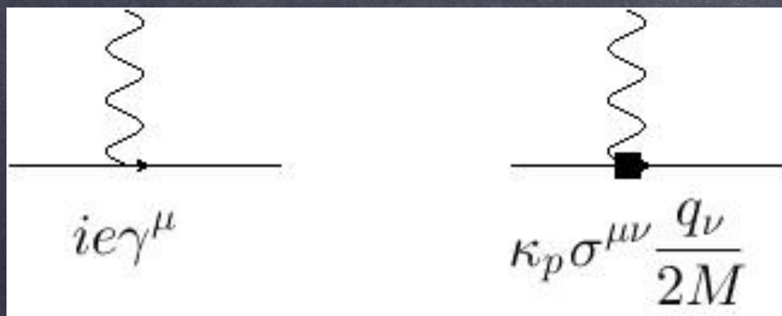
Scales as $g_{\pi NN}^4$

Scales as $g_{\pi NN}^2$

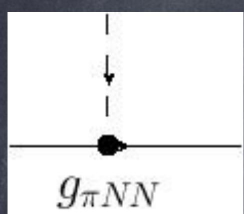
Holds in relativistic ChPT,
but not in heavy-baryon ChPT!

$$\int_{E_\pi}^{\infty} d\omega \frac{\sigma_{\gamma p}^{3/2}(\omega) - \sigma_{\gamma p}^{1/2}(\omega)}{\omega} \Bigg|_{\text{tree level}} = 0$$

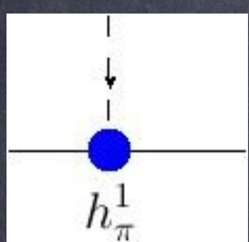
Prove SCR for PV Compton to order O($g_{\pi NN}\, h^1_\pi$)



Electromagnetic vertex

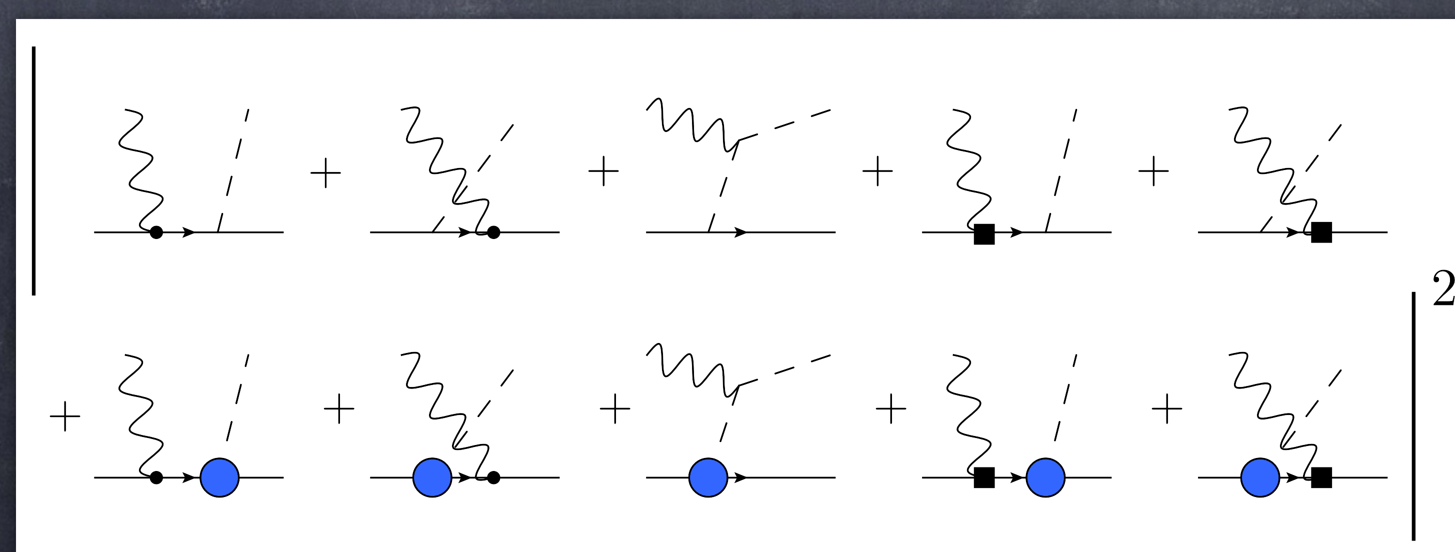


$$\mathcal{L}^{PC}_{\pi N} = \frac{g_A}{2f_\pi} \bar{N} \tau^a \,\partial\!\!\!/ \pi^a \gamma_5 N = -g_{\pi NN} \bar{N} \tau^a \gamma_5 N \pi^a$$



$$\mathcal{L}^{PV}_{\pi N} = \frac{h^1_\pi}{\sqrt{2}} \bar{N} [\vec{\tau} \times \vec{\pi}]^3 N = -i h^1_\pi (\bar{n} \pi^+ p - \bar{p} \pi^- n)$$

$F_3^{\gamma\gamma} \sim$



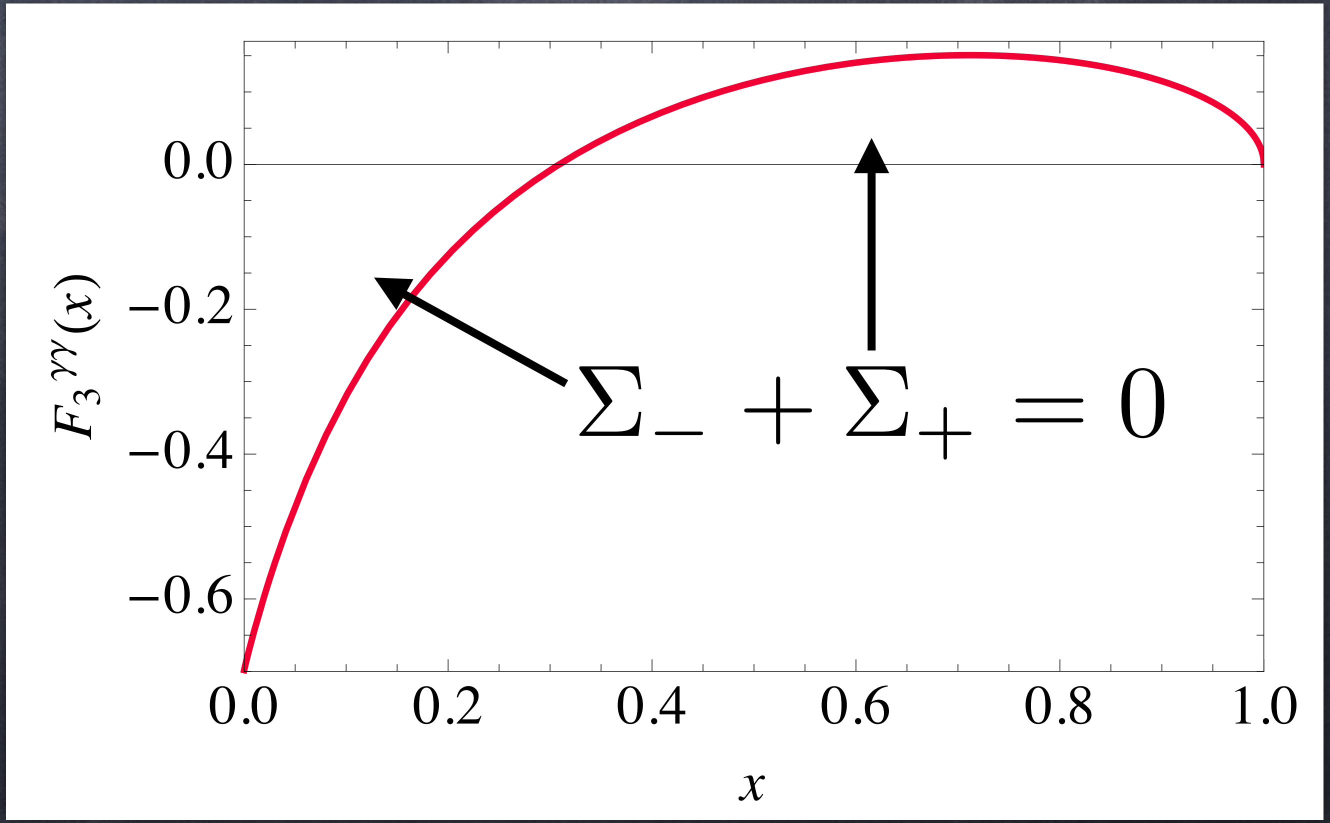
$$F_3^{\gamma\gamma}(\omega) = -\frac{g_{\pi NN}h_\pi^1 q_\pi}{2\sqrt{2}\pi^2\sqrt{s}}\left\{\mu^p\left[\frac{E'}{\sqrt{s}} - \frac{E_\pi}{q} + \frac{m_\pi^2}{2qq_\pi}\ln\frac{E_\pi+q_\pi}{E_\pi-q_\pi}\right]\right.$$
$$-\mu^n\left[-\frac{E}{q} + \frac{m_\pi^2}{2qq_\pi}\ln\frac{E_\pi+q_\pi}{E_\pi-q_\pi} + \frac{M^2}{2qq_\pi}\ln\frac{E'+q_\pi}{E'-q_\pi}\right]$$
$$\left.-\frac{qE'}{2M^2}\kappa^V\kappa^S + (\mu^n)^2\frac{s-M^2}{4M^2}\left[-\frac{E'}{q} + \frac{M^2}{2qq_\pi}\ln\frac{E'+q_\pi}{E'-q_\pi}\right]\right\},$$

Terms $O(\kappa^2)$ - too many derivatives, SCR diverges;
not surprising: at tree level $O(g^5_{\pi NN}\, h^1_\pi)$ incomplete

SCR - check numerically
up to terms linear in a.m.m.

Change variables $x = E_\pi/\omega$

$$\int_0^1 dx F_3^{\gamma\gamma}(E_\pi/x) = 0$$



Superconvergence relation for $F_3^{\gamma\gamma}$:

checked for the first time in relativistic field theory;

must be used as a basis for any reasonable estimate of the PV2γ correction to the weak charge

SCR ensures that the log term vanishes at E=0

$$C_{2\gamma}^{PV}(0) = \frac{3}{4M}\int_{\omega_\pi}^{\infty}\frac{d\omega}{\omega^2}F_3^{\gamma\gamma}(\omega)$$

The definition of the weak charge is still viable

$$Q_W^{p,\,1-\text{loop}} = -\lim_{E,Q^2\to 0}\frac{4\pi\alpha\sqrt{2}}{G_F Q^2}A_{exp}^{PV}(E,Q^2)$$

Numerical estimates: Input parameters

Origin: effective PV 4-quark operators

PV πNN coupling

$h^1_\pi = (1.1 \pm 1.0)\,10^{-6}$ De Vries et al, arXiv:1501.01832

$h^1_\pi = 3.8 \cdot 10^{-7}$ DDH, 1979

PV γNΔ coupling d_Δ $\mathcal{L}^{\gamma N \Delta}_{PV} = i\frac{e}{\Lambda_\chi}\left[d^+_\Delta \bar{\Delta}^+_\alpha \gamma_\beta\, p + d^-_\Delta \bar{\Delta}^-_\alpha \gamma_\beta\, n\right] F^{\alpha\beta}$

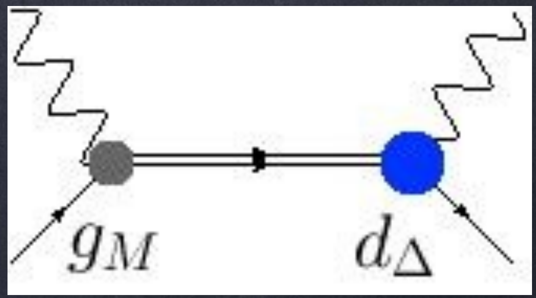
Early claim: may be 10-100 x h^1_π Zhu et al, arXiv:0106216

Not quite supported by exp. $|d^-_\Delta| = (0.31 \pm 0.91)\,10^{-6}$

Androic et al [G0], arXiv:1112.1720

Q_{weak} has taken data that may further constrain d_Δ

$$F^{\gamma\gamma}_{3\,\Delta}(\omega)|_{\Gamma_\Delta \to 0} = \sqrt{\frac{2}{3}}\frac{4M g_M(0) d^+_\Delta}{\Lambda_\chi (M + M_\Delta)}\omega^2_\Delta \delta(\omega - \omega_\Delta)$$



Δ contribution alone does not obey SCR

Supplement by a high energy Regge-like background

$$F_{3\,\mathrm{HE}}^{\gamma\gamma}(\omega) = C_\lambda(\Lambda)\,(\omega/\Lambda)^\lambda\,\Theta(\omega-\Lambda)$$

With Λ ≈ 1 GeV and λ < 1 (SCR integral converges)

Fix HE contribution by imposing SCR
$$\int_{\omega_\pi}^{\infty} \frac{d\omega}{\omega^2}\left[F_{3\,\Delta}^{\gamma\gamma}(\omega) + F_{3\,\mathrm{HE}}^{\gamma\gamma}(\omega)\right] = 0$$

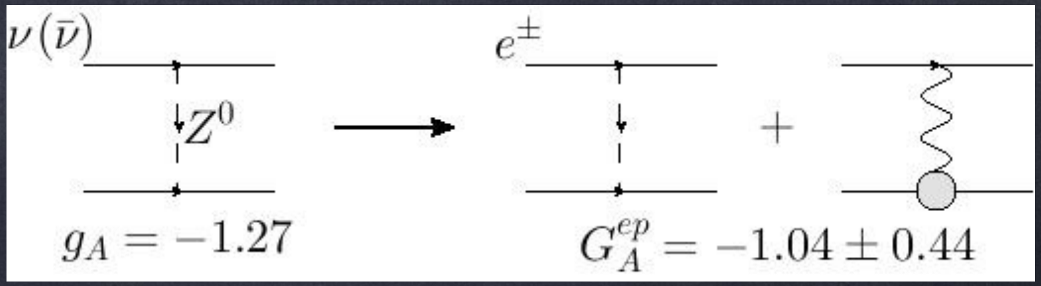
Normalization depends on λ
$$C_\lambda(\Lambda) = -\sqrt{\frac{2}{3}}\frac{4Mg_M d_\Delta^+ \Lambda}{\Lambda_\chi (M+M_\Delta)}(1-\lambda)$$

Explore $-1/2 < \lambda < 1/2$

Final ingredient (for completeness)
Anapole moment

$$\mathcal{L}_{PV} = ie\,a_0 \partial_\mu F^{\mu\nu}\,\bar{N}\gamma_\nu\gamma_5 N$$

Axial charge seen by charged leptons is not g_A!



Results for the kinematics of relevant experiments

Object of interest $$\delta Q_W^p(E,Q^2) = -\frac{4\sqrt{2}\alpha^2}{G_F} C_{2\gamma}^{PV}(E) \ln\frac{4E^2}{Q^2}$$

The SM expectation: $Q_W^p = 0.0713(8)$

	Contribution	P2@MESA	Qweak	MOLLER
δQ_W^p	Elastic	$-(1.0 \pm 2.0)\cdot 10^{-4}$	$-(1.2 \pm 2.2)\cdot 10^{-5}$	$-(3 \pm 5)\cdot 10^{-7}$
	π	$-(2.0 \pm 2.0)\cdot 10^{-5}$	$-(5.5 \pm 5.5)\cdot 10^{-5}$	$-(2.8 \pm 2.8)\cdot 10^{-5}$
	$\Delta +$ HE ($\lambda = 0.5$)	$-(0.67 \pm 2.0)\cdot 10^{-4}$	$-(1.3 \pm 3.8)\cdot 10^{-4}$	$-(1.1 \pm 3.3)\cdot 10^{-4}$
	$\Delta +$ HE ($\lambda = 0$)	$-(0.4 \pm 1.2)\cdot 10^{-4}$	$-(1.1 \pm 3.3)\cdot 10^{-4}$	$-(0.5 \pm 1.4)\cdot 10^{-4}$
	$\Delta +$ HE ($\lambda = -0.5$)	$-(0.32 \pm 0.93)\cdot 10^{-4}$	$-(1.1 \pm 3.3)\cdot 10^{-4}$	$-(0.2 \pm 0.6)\cdot 10^{-4}$
	Total	$-(1.7 \pm 0.3 \pm 2.5)\cdot 10^{-4}$	$-(1.9 \pm 0.1 \pm 3.6)\cdot 10^{-4}$	$-(0.9 \pm 0.5 \pm 1.8)\cdot 10^{-4}$

$\delta Q_W^p \leq 0.3\%$ $\delta Q_W^p \leq 0.53\%$

Cs-133 weak charge: $Q_W(^{113}Cs) = -72.58(29)_{exp}(32)_{th}$

$$\delta Q_W(^{113}Cs) \sim 113\delta Q_W^p(0) = -(2.0 \pm 3.9)\cdot 10^{-2}$$

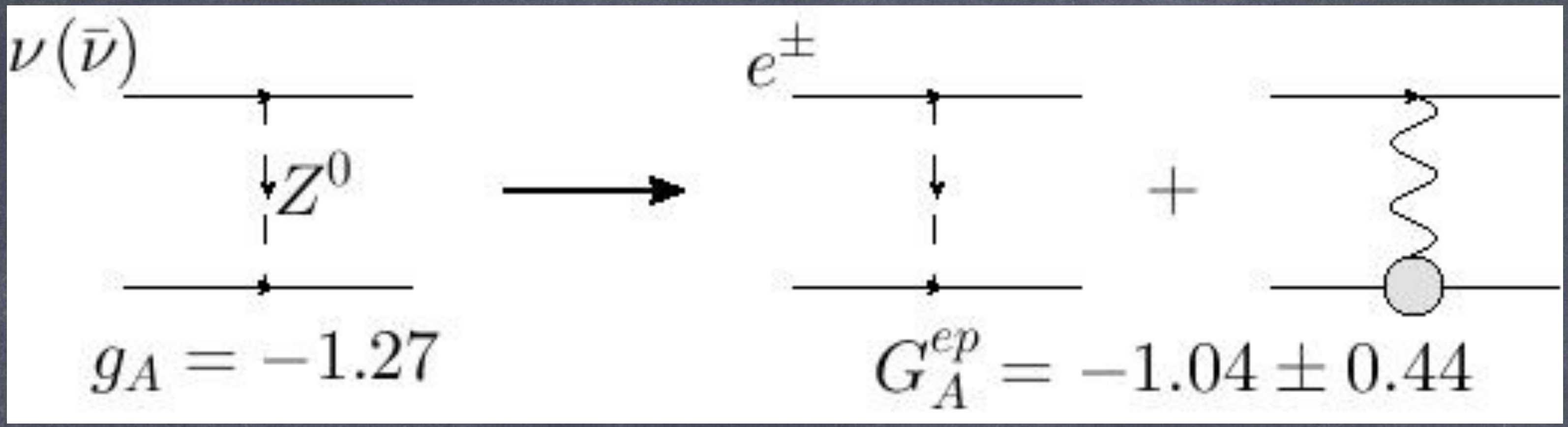
Summary

- 2γ-exchange induces a long-rang interaction that modifies the extraction of charge radius and weak charge from electron scattering
- Formal definition of $Q_W(p)$ protected by a superconvergence relation;
- The superconvergence relation proved in relativistic ChPT;
- 0.5% uncertainties due to d_Δ - Q-Weak data may further reduce it!
- High energy part needed to obey SCR - unknown; Very mild sensitivity for Q-Weak, may matter for MOLLER e-p if $\lambda > 1/2$
- Sensitivity to anapole moment: non-negligible for MESA, but the uncertainty of G_A will be reduced w. MESA by a factor of 4
- Further hadronic PV couplings may be also included
- Atomic PV: hadronic 2γ-box purely short-range, small; nuclear resonances may change this behavior - more work needed

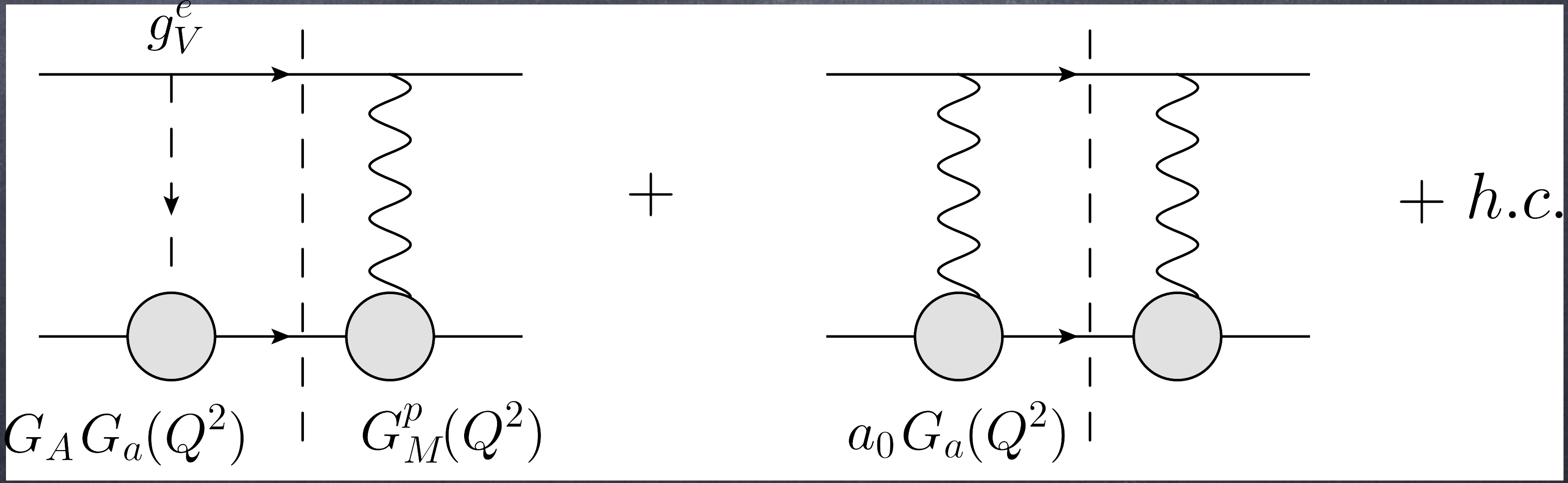
Backup slides

Anapole moment $\mathcal{L}_{PV} = ie\, a_0 \partial_\mu F^{\mu\nu} \bar{N} \gamma_\nu \gamma_5 N$

Axial charge seen by charge leptons is not g_A!



Update the axial box: include uncertainty due to anapole



Attn: elastic contribution not enhanced by collinear log: no anapole moment for real photons

Update the axial box: simply use G_A^{ep} instead of g_A

$$\delta(Q_W^p)^{el.} = \frac{\alpha g_V^e G_A^{ep}(0)}{ME} \int_0^\infty dQ^2 G_M(Q^2) G_a(Q^2) \left(\ln\left|\frac{E+E_Q}{E-E_Q}\right| + \frac{Q^2}{2ME} \ln\left|1 - \frac{E^2}{E_Q^2}\right| \right)$$

Some caveats here!

Blunden et al. included running of $\sin^2\theta_W$ -> g_V^e = 0.045;

they used g_A = -1.27;

We use:

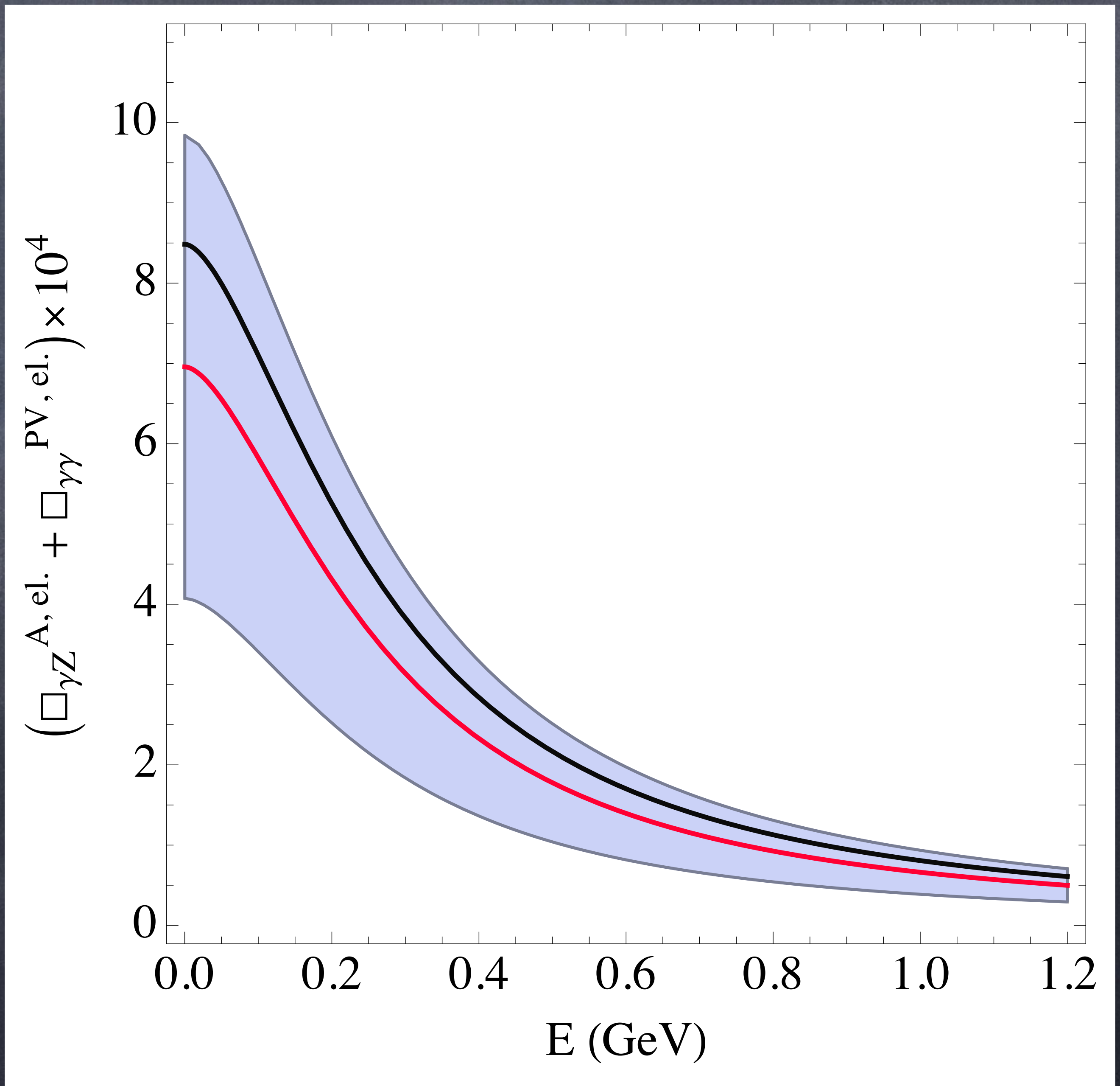
full one loop result -> g_V^e = 0.07,

and include RC in G_A^{ep} = -1.04(43)

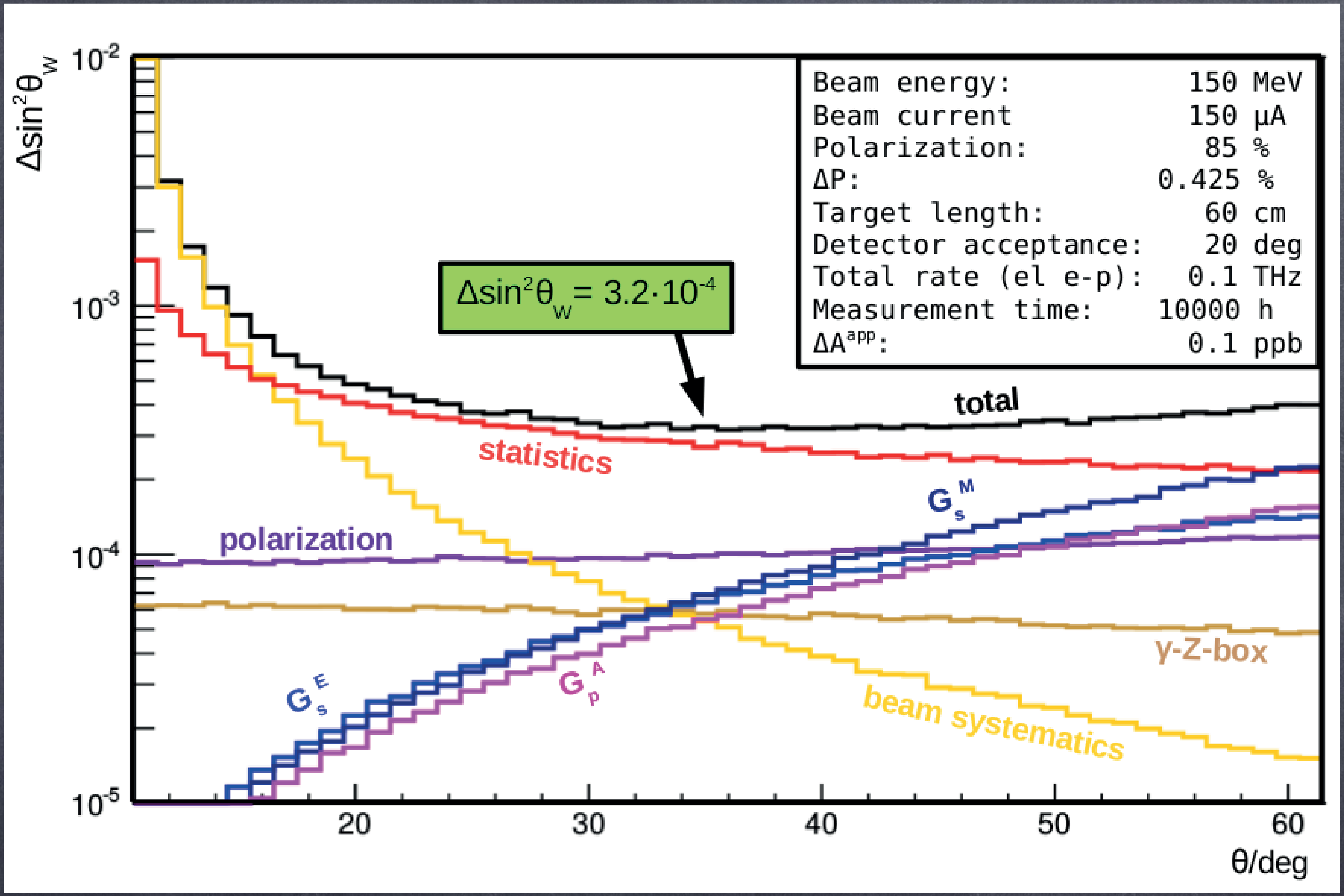
More natural from DR side

Central value almost identical;

Now can estimate an uncertainty!



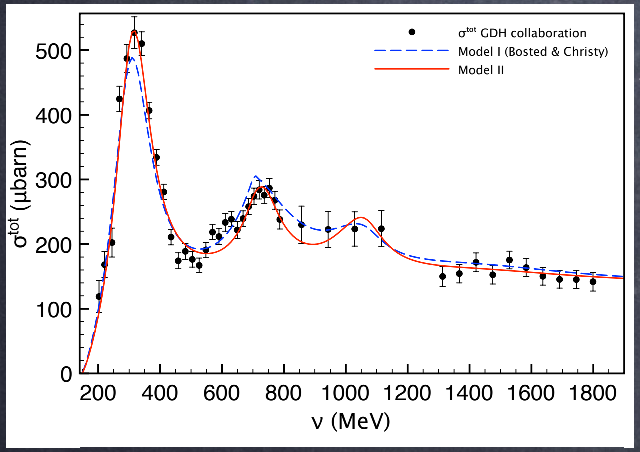
WMA determination with MESA/P2



- Strange nucleon FFs: from the lattice
- Axial FF: from an auxiliary backward measurement (will reduce the uncertainty on GA by factor ~4)

Model dependence of the γZ box

$\sigma^{\gamma^* p \to X}$



Model-dependent

Definite spin, flavor states

$M_{\gamma^* p \to H_{S,I}}$

Model-dependent

Weak Isospin (flavor) rotation

$M_{Z^* p \to H_{S,I}}$