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Neutral-Current Weak Interactions at an EIC

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Outline

- Introduction of electroweak interactions in electron scatterings
- Electroweak physics study at an EIC
  - Nucleon spin structure
  - The weak mixing angle $\sin^2\theta_w$
- Summary

Discovery of Parity Violation

Symmetries play a central role in physics. Parity, Time Reversal, Charge Conjugation, …, were naturally assumed to be conserved until

T.D. Lee and C.N. Yang first suggested parity violation. Awarded Nobel Prize 1957 after experimental confirmation.

Tsung-Dao Lee

Chen-Ning Yang

"for their penetrating investigation of the so-called parity laws which has led to important discoveries regarding the elementary particles"

C. S. Wu led the experiment confirmed parity violation in nuclear β-decay

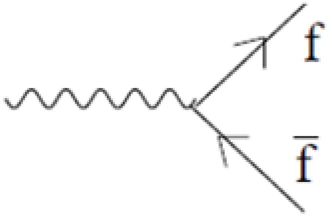
Chien-Shiung Wu

Glashow-Weinberg-Salam (GWS) theory yields the unification of electroweak interaction and predicts Z boson

Electro-weak interactions

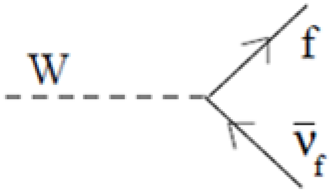
Spin-1/2 particles carry two types of couplings: Axial and Vector
Axial: difference of strength for left/right handed states
Vector: Average of the two

γ $\quad -iQ\gamma^\mu$



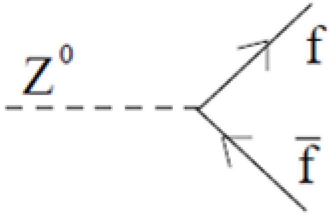
No difference for left/right particle
Vector coupling = Q

$W^\pm$ $\quad -i\frac{g}{\sqrt{2}}\gamma^\mu\frac{1}{2}\left(1-\gamma^5\right)$



Only interact with left-handed fermions

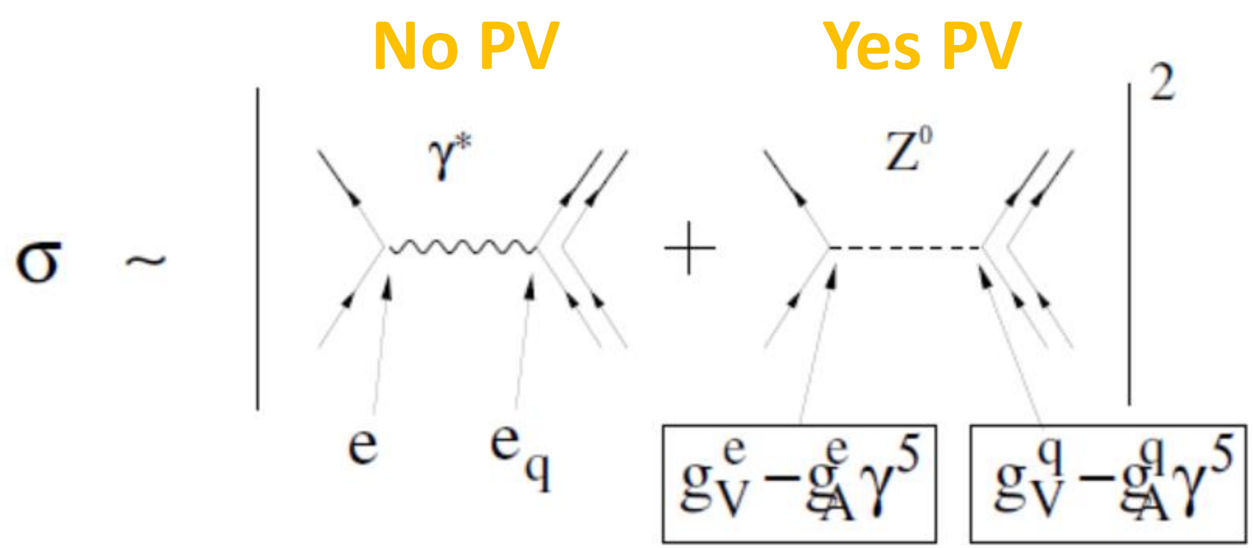
Z^0 $\quad -i\frac{g}{\cos\theta_W}\gamma^\mu\frac{1}{2}\left(g_V^e - g_A^e\gamma^5\right)$



Interact with both left and right handed fermions

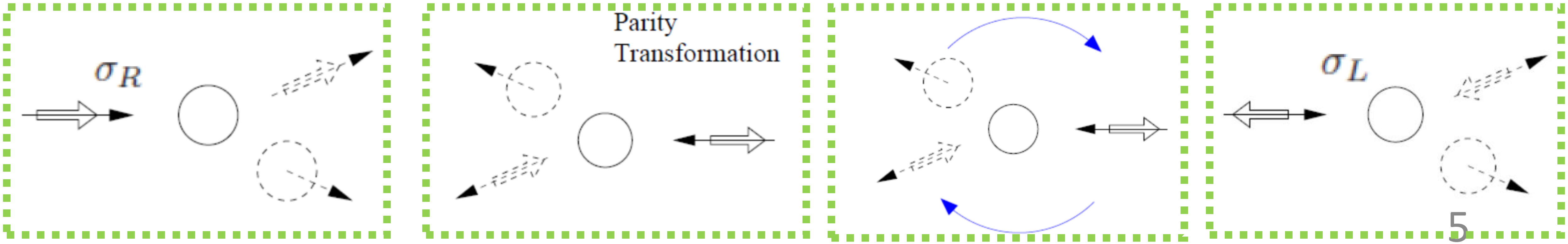
$$g_A^e = -\frac{1}{2} \qquad g_V^e = -\frac{1}{2} + 2\sin^2\theta_W = -0.036$$

Parity Violating in Electron Scatterings
--- Neutral current

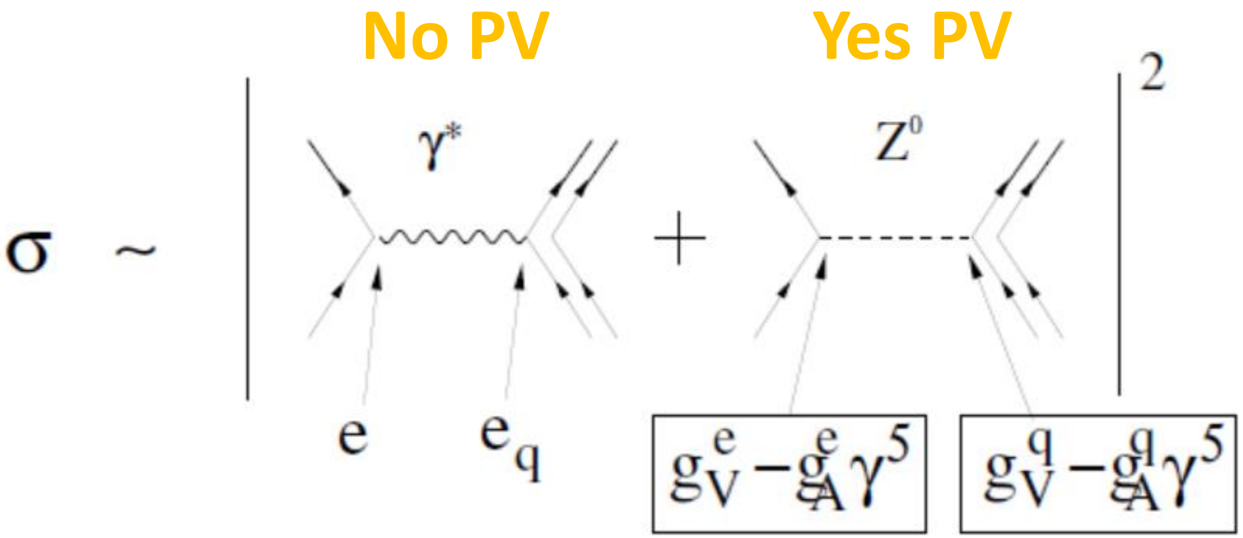


In context of SM
Tree level…

To detect PV : **long. pol. Electron + unpol. Nucl.**



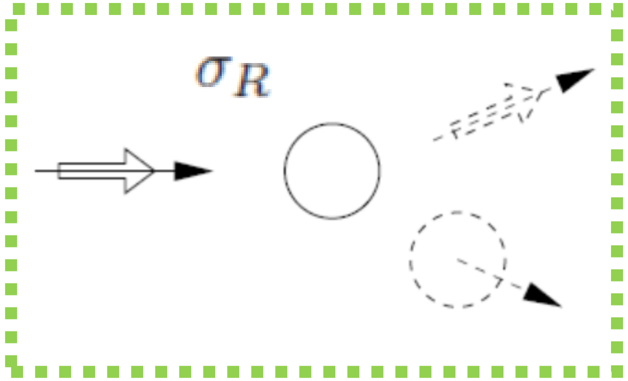
Parity Violating in Electron Scattering
--- Neutral current

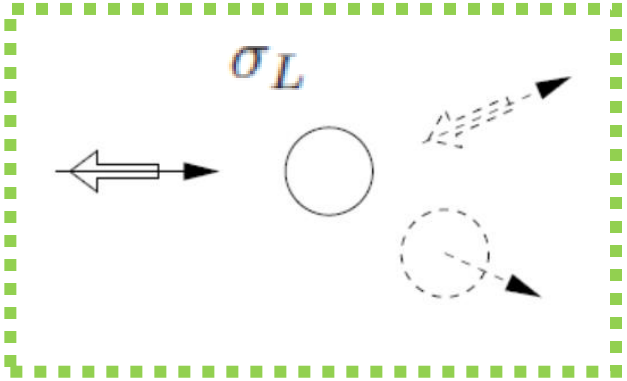


In context of SM
Tree level…

To detect PV : **long. pol. Electron + unpol. Nucl.**

$$A_{PV} \equiv \frac{\sigma_R - \sigma_L}{\sigma_R + \sigma_L}$$





Flavor Decompositions
--- an example for polarized case

- With pure γ exchange in inclusive DIS:

$$g_1^P = \frac{1}{2}\left(\frac{4}{9}(\Delta u + \Delta\bar{u}) + \frac{1}{9}(\Delta d + \Delta\bar{d}) + \frac{1}{9}(\Delta s + \Delta\bar{s})\right)$$
$$g_1^n = \frac{1}{2}\left(\frac{1}{9}(\Delta u + \Delta\bar{u}) + \frac{4}{9}(\Delta d + \Delta\bar{d}) + \frac{1}{9}(\Delta s + \Delta\bar{s})\right)$$

Hmm … No third kind of nucleon … No…

- Assumption: SU(3) flavor symmetry
  - ✓ Additional inputs from β-decay of neutron and hyperons

    $\Delta u + \Delta d - 2\,\Delta s$ $\qquad\qquad$ $\Delta u + \Delta d$
  - ✓ SIDIS measurements also provide information with quark flavors, fragmentation functions provide different weights

Electroweak interactions in DIS region at an EIC can have new inputs…

EIC offers new opportunities with weak neutral currents

Anselmino, Efremov, Leader, Ji …
Phys. Rep. 216 (1995)

$$\frac{d^2\sigma_{nc}^{\ell N}}{d\Omega dE'} = \frac{1}{2m_N(4\pi)^2}\frac{E'}{E}\times|M_\gamma + M_Z|^2$$

$$\frac{d^2\sigma_{nc}^{\ell N}}{dx\,dy}(\lambda, S=S_L) = 4\pi m_N E y\frac{\alpha^2}{Q^4}\sum_i \eta^i C^i$$

$$\times\left\{2xy F_1^i + \frac{2}{y}\left(1-y-\frac{xym_N}{2E}\right)(F_2^i + g_3^i)\right.$$

$$- 2\lambda x\left(1-\frac{y}{2}\right)F_3^i - 2\lambda x\left(2-y-\frac{xym_N}{E}\right)g_1^i$$

$$+ 4\lambda\frac{x^2m_N}{E}g_2^i - \frac{2}{y}\left(1+\frac{xm_N}{E}\right)\left(1-y-\frac{xym_N}{2E}\right)g_4^i$$

$$\left. + 2xy\left(1+\frac{xm_N}{E}\right)g_5^i\right\},$$

With parity violation and $Q^2 << Z^2$

Inclusive electron measurements

pol. electron & unpol. nucleon:

$$A_{beam} = \frac{G_F Q^2}{2\sqrt{2}\pi\alpha}\left[g_A^e\frac{F_1^{\gamma Z}}{F_1^\gamma} + g_V^e\frac{Y_-}{2Y_+}\frac{F_3^{\gamma Z}}{F_1^\gamma}\right]$$

unpol. electron & pol. nucleon:

$$A_L = \frac{G_F Q^2}{2\sqrt{2}\pi\alpha}\left[g_V^e\frac{g_5^{\gamma Z}}{F_1^\gamma} + g_A^e\frac{Y_-}{Y_+}\frac{g_1^{\gamma Z}}{F_1^\gamma}\right]$$

New structure functions
---γ-Z interference structure functions

pol. electron & unpol. nucleon:

$$A_{beam} = \frac{G_F Q^2}{2\sqrt{2}\pi\alpha}\left[g_A^e \frac{F_1^{\gamma Z}}{F_1^{\gamma}} + g_V^e \frac{Y_-}{2Y_+}\frac{F_3^{\gamma Z}}{F_1^{\gamma}}\right]$$

$$F_1^{\gamma Z} = \sum_f e_{q_f}(g_V)_{q_f}(q_f + \bar{q}_f)$$

$$F_3^{\gamma Z} = 2\sum_f e_{q_f}(g_A)_{q_f}(q_f - \bar{q}_f)$$

unpol. electron & pol. nucleon:

$$A_L = \frac{G_F Q^2}{2\sqrt{2}\pi\alpha}\left[g_V^e \frac{g_5^{\gamma Z}}{F_1^{\gamma}} + g_A^e \frac{Y_-}{Y_+}\frac{g_1^{\gamma Z}}{F_1^{\gamma}}\right]$$

$$g_1^{\gamma Z} = \sum_f e_{q_f}(g_V)_{q_f}(\Delta q_f + \Delta\bar{q}_f)$$

$$g_5^{\gamma Z} = \sum_f e_{q_f}(g_A)_{q_f}(\Delta q_f - \Delta\bar{q}_f)$$

New and unique combinations of individual PDFs

New structure functions
---γ-Z interference structure functions

pol. electron & unpol. nucleon:

$$A_{beam} = \frac{G_F Q^2}{2\sqrt{2}\pi\alpha}\left[g_A^e \frac{F_1^{\gamma Z}}{F_1^\gamma} + g_V^e \frac{Y_-}{2Y_+}\frac{F_3^{\gamma Z}}{F_1^\gamma}\right]$$

$$F_1^{p,\gamma Z} \approx \frac{1}{9}(u + \bar{u} + d + \bar{d} + s + \bar{s} + c + \bar{c})$$

$$F_1^{n,\gamma Z} \approx \frac{1}{9}(u + \bar{u} + d + \bar{d} + s + \bar{s} + c + \bar{c})$$

$$F_3^{p,\gamma Z} = \frac{2}{3}(u_V + c - \bar{c}) + \frac{1}{3}(d_V + s - \bar{s})$$

$$F_3^{n,\gamma Z} = \frac{2}{3}(d_V + s - \bar{s}) + \frac{1}{3}(u_V + c - \bar{c})$$

unpol. electron & pol. nucleon:

$$A_L = \frac{G_F Q^2}{2\sqrt{2}\pi\alpha}\left[g_V^e \frac{g_5^{\gamma Z}}{F_1^\gamma} + g_A^e \frac{Y_-}{Y_+}\frac{g_1^{\gamma Z}}{F_1^\gamma}\right]$$

$$g_1^{p,\gamma Z} \approx \frac{1}{9}(\Delta u + \Delta\bar{u} + \Delta d + \Delta\bar{d} + \Delta s + \Delta\bar{s} + \Delta c + \Delta\bar{c})$$

$$g_1^{n,\gamma Z} \approx \frac{1}{9}(\Delta u + \Delta\bar{u} + \Delta d + \Delta\bar{d} + \Delta s + \Delta\bar{s} + \Delta c + \Delta\bar{c})$$

$$g_5^{p,\gamma Z} = \frac{1}{3}(\Delta u_V + \Delta c - \Delta\bar{c}) + \frac{1}{6}(\Delta d_V + \Delta s - \Delta\bar{s})$$

$$g_5^{n,\gamma Z} = \frac{1}{3}(\Delta d_V + \Delta s - \Delta\bar{s}) + \frac{1}{6}(\Delta u_V + \Delta c - \Delta\bar{c})$$

W exchange in DIS region

PHYSICAL REVIEW D **88,** 114025 (2013)

Prospects for charged current deep-inelastic scattering off polarized nucleons at a future electron-ion collider

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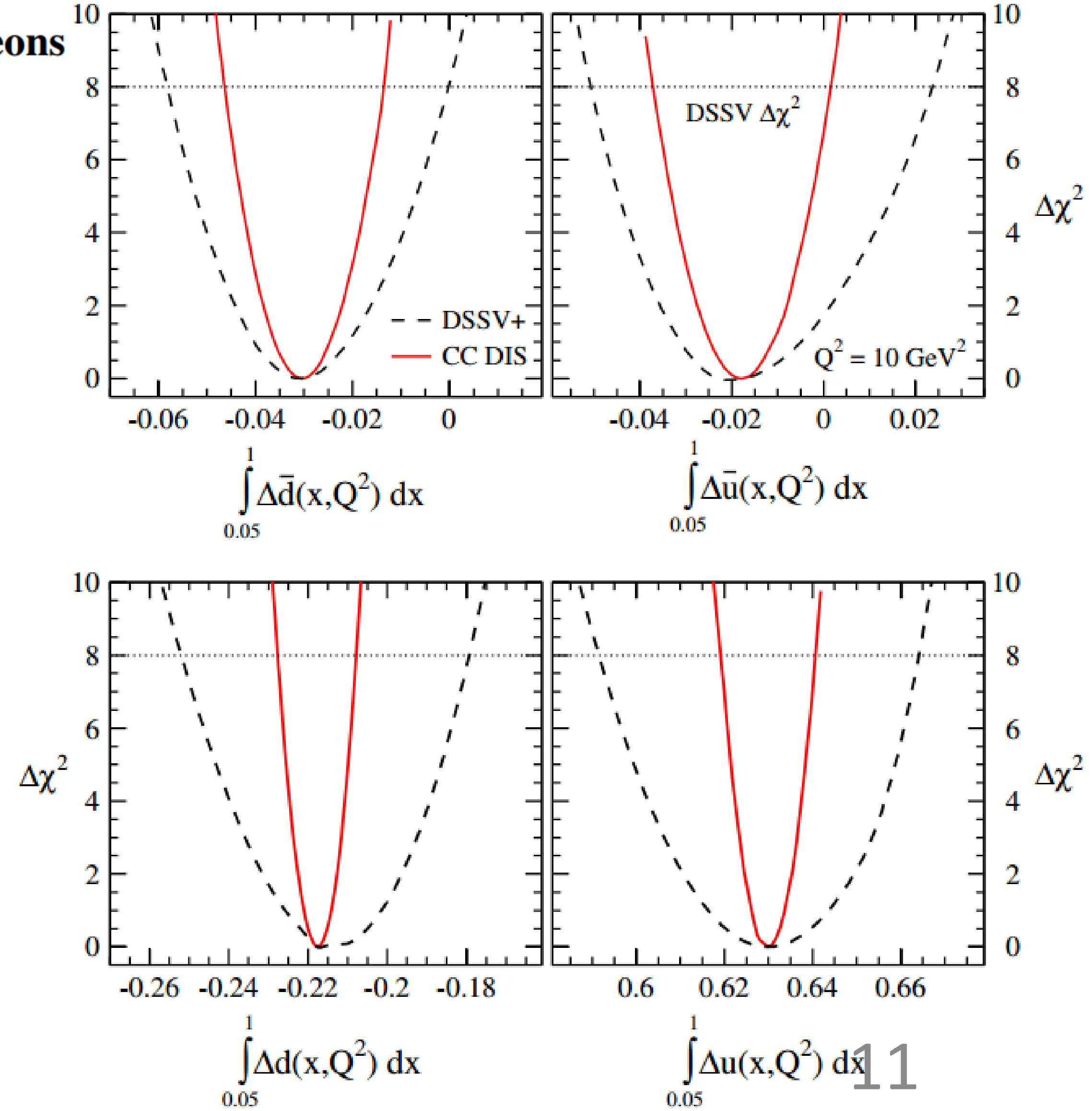
(Received 23 September 2013; published 9 December 2013)

$$g_1^{W^-,p}(x) = \Delta u(x) + \Delta\bar{d}(x) + \Delta c(x) + \Delta\bar{s}(x),$$

$$g_5^{W^-,p}(x) = -\Delta u(x) + \Delta\bar{d}(x) - \Delta c(x) + \Delta\bar{s}(x)$$

$$g_1^{W^+,p}(x) = \Delta\bar{u}(x) + \Delta d(x) + \Delta\bar{c}(x) + \Delta s(x),$$

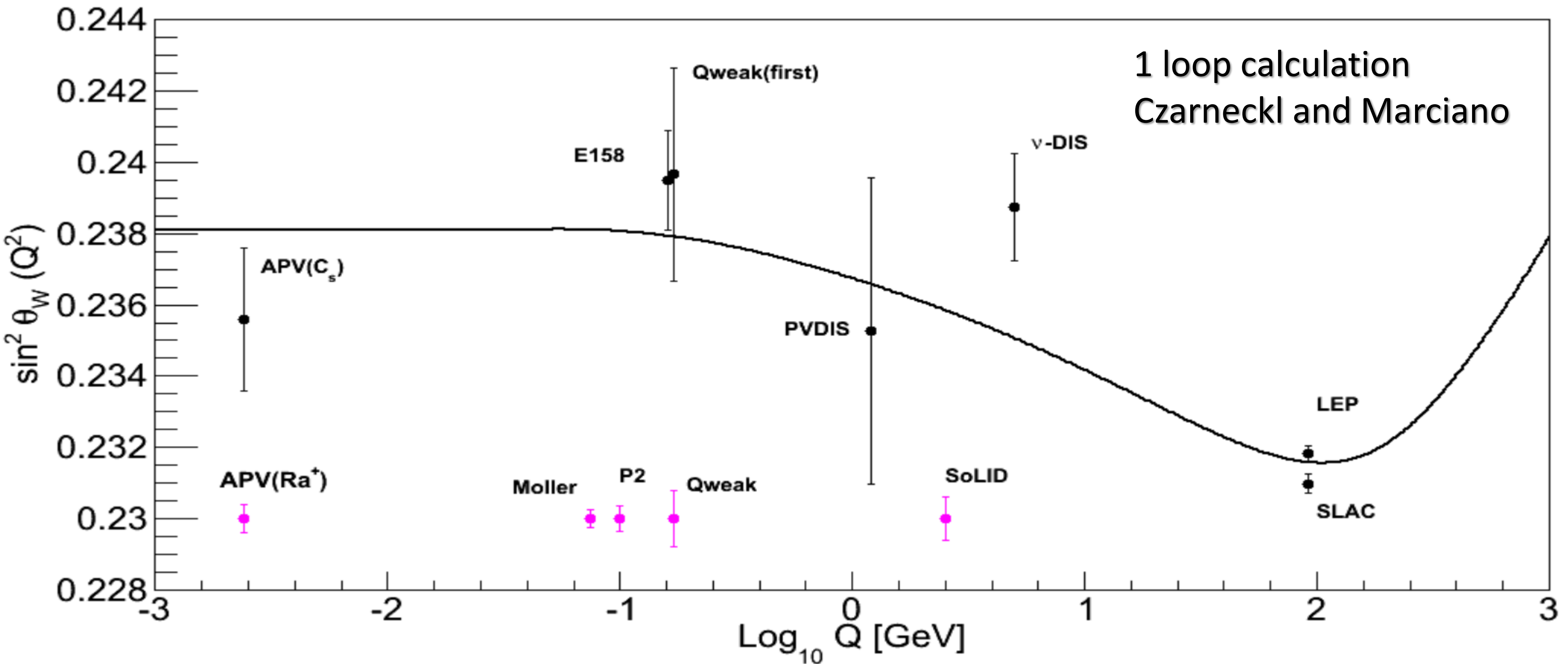
$$g_5^{W^+,p}(x) = \Delta\bar{u}(x) - \Delta d(x) + \Delta\bar{c}(x) - \Delta s(x)$$



Parity-violating asymmetries in e-D collisions

- Deuteron has same amount of u and d in x>0.2 region
- APV ~ 20/3 $\sin^2\Theta_w$ -1
- Fundamental quantity in SM, constraints on new physics, such as new Z boson etc.

$$A_{beam} = \frac{G_F Q^2}{2\sqrt{2}\pi\alpha}\left[g_A^e \frac{F_1^{\gamma Z}}{F_1^{\gamma}} + g_V^e \frac{Y_-}{2Y_+}\frac{F_3^{\gamma Z}}{F_1^{\gamma}}\right]$$



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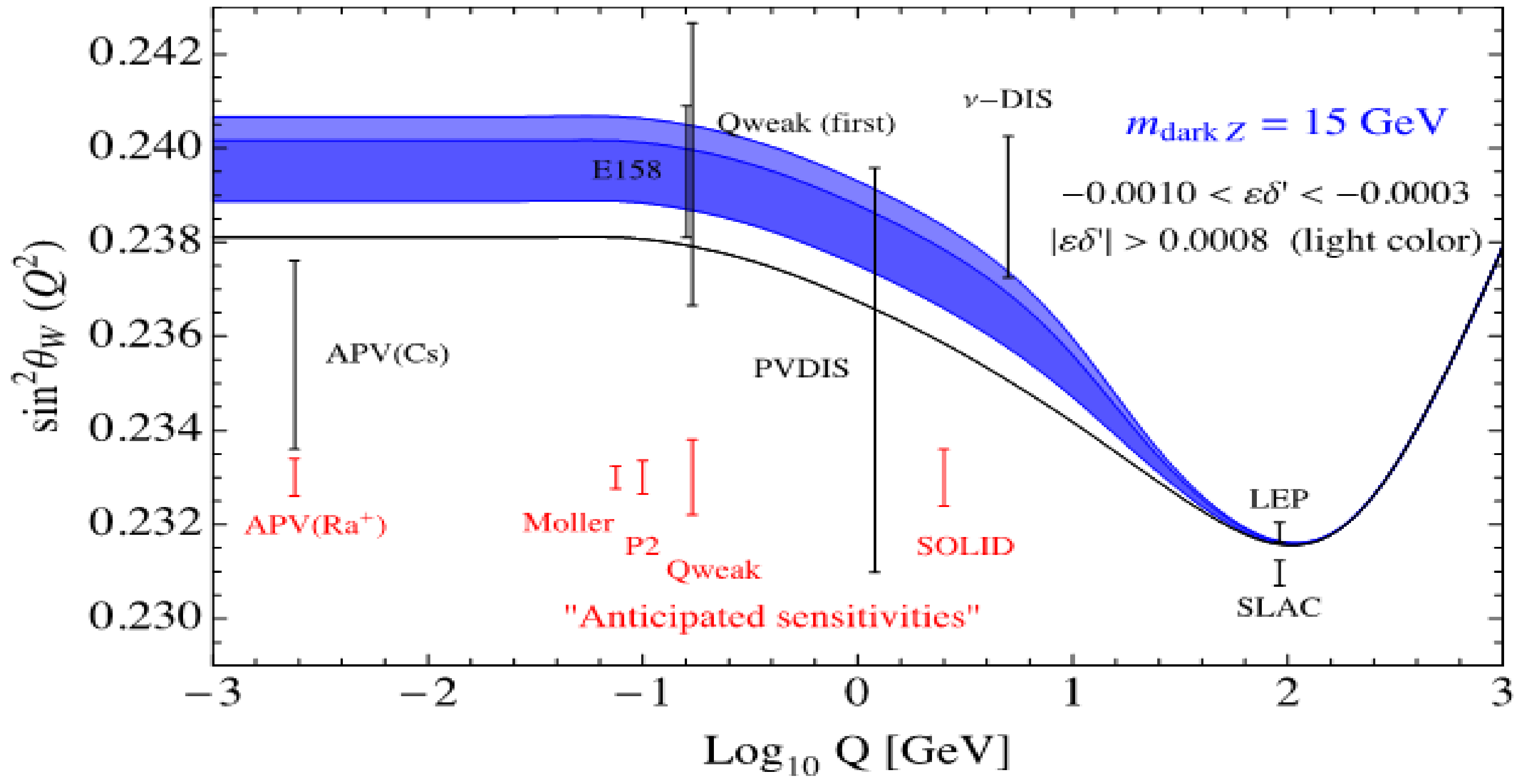
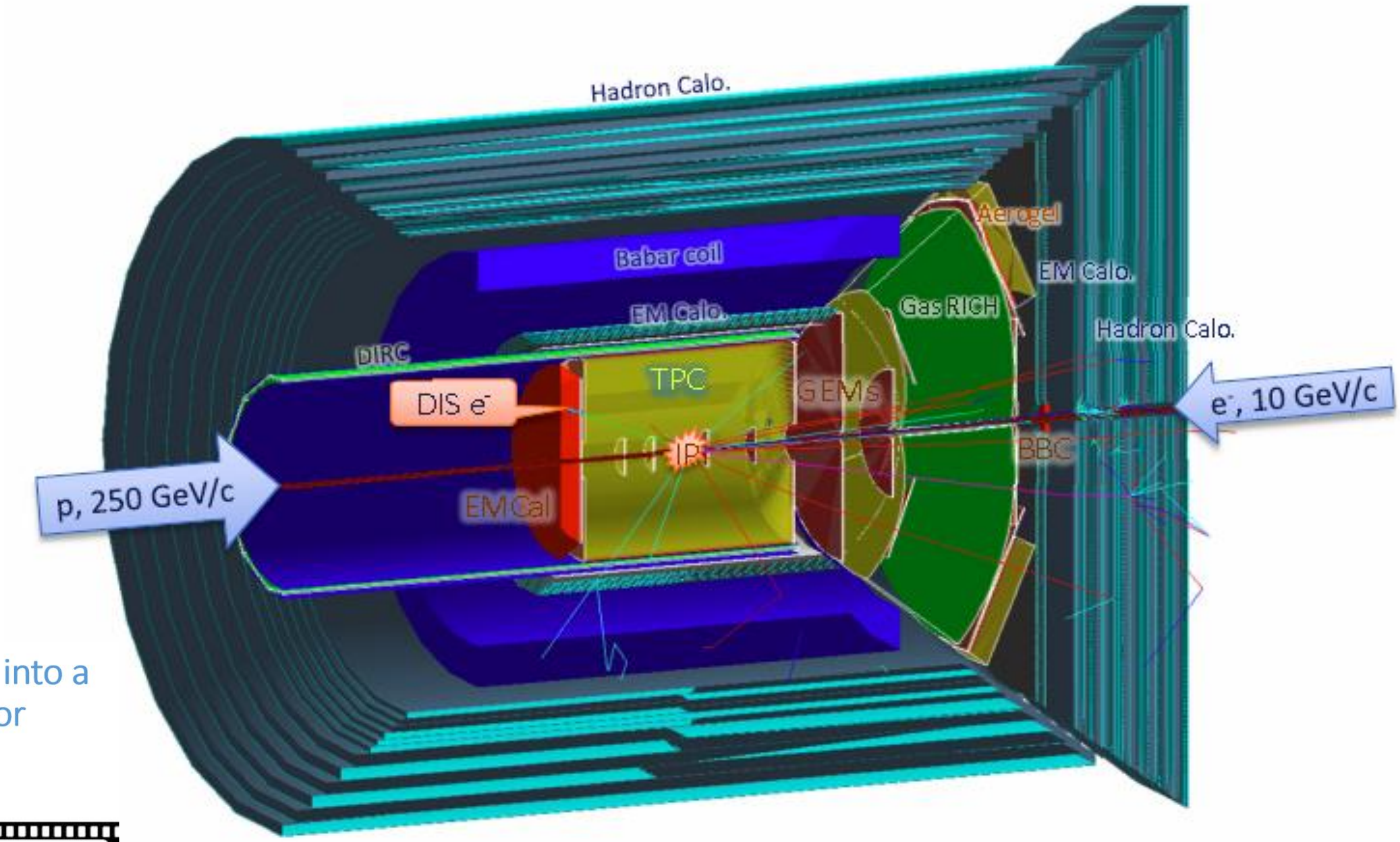
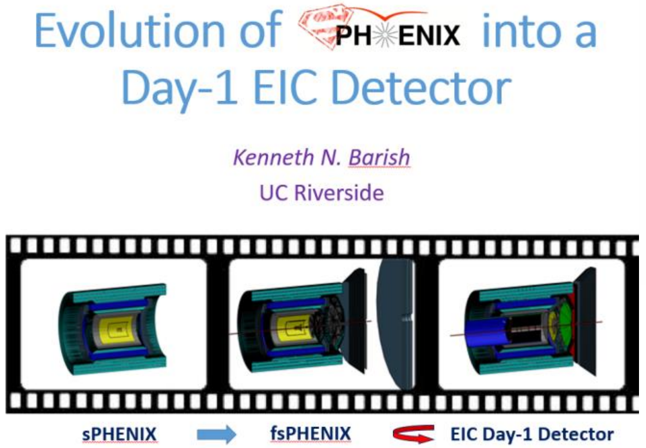


Simulations

- DJANGOH generator simulates DIS processes including QED and QCD radiation
  - ✓ Developed by Hubert Spiesberger and used at BNL for the EIC Charged Current study
- Electron-proton collisions to study new structure functions
  - ✓ The data is binned in (x, Q^2) two dimensions
  - ✓ Doing Y dependent fit to extract projections on $F_1^{\gamma Z}$, $F_3^{\gamma Z}$, $g_1^{\gamma Z}$, $g_5^{\gamma Z}$
- $\sin^2\Theta_w$ projections are from electron beam asymmetries in e-D collisions
- Highlights of the study:
  - ✓ Cuts:
    - ❑ $Q^2 > 1$ GeV^2, $W_h > 2$ GeV, $y > 0.1$, p cut for structure function studies
    - ❑ $Q^2 < 6400$ GeV^2 and $x > 0.2$ in addition for $\sin^2\Theta_w$ studies
  - ✓ Unfolding for kinematical migration due to radiation and finite detector resolution

ePHENIX





Please refer to ePHENIX LOI for the details

Detector resolutions for inclusive electrons

	sPHENIX Barrel ($-1.1 < \eta < 1.1$)	ePHENIX electron going direction
Tracking: θ (mrad)	10	1
Tracking: ϕ (mrad)	0.3	0.3
Tracking: $\frac{dp_T}{p_T}$	0.65% (+) 0.09% * p_T	0.65% (+) 1% * p_T
EMCal: $\frac{dE}{E}$	3% (+) 11.7%/ $\sqrt{E}$	1% (+) 2.5%/ $\sqrt{E}$

Reference [2]   Reference [1]

Reference [1] ePHENIX letter of intent: http://arxiv.org/abs/1402.1209

Reference [2] sPHENIX pre-CDR design report: https://indico.bnl.gov/conferenceDisplay.py?confId=1483

Luminosity and polarization table

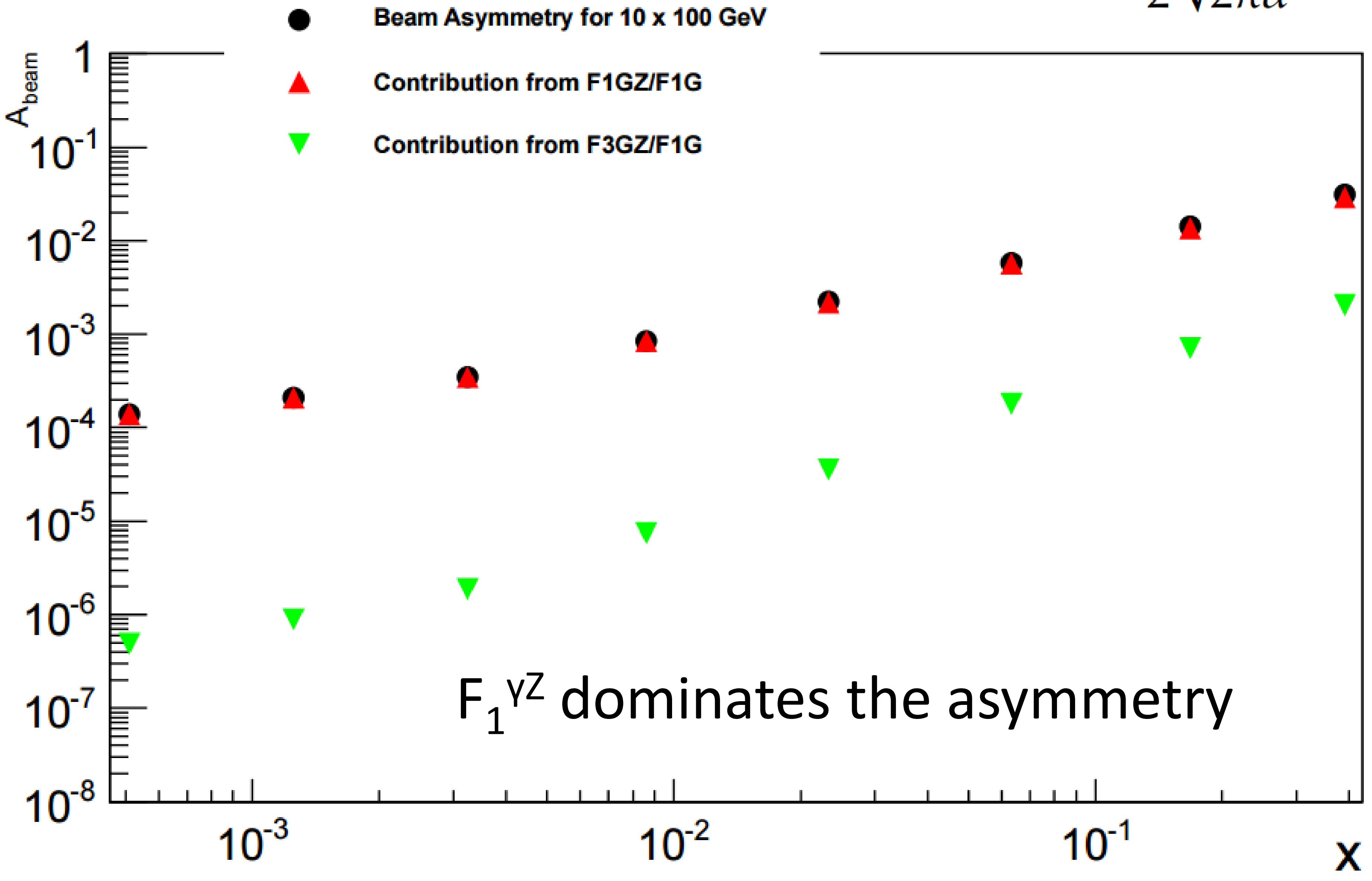
e-p collisions	10x100, 10x250, 15x100, 15x250
Integrated luminosity	**500 fb^{-1}**
Proton (electron) beam polarization	70% (80%)

e-D collisions	10x50,10x125,15x50,15x125,20x125 GeV/u
Integrated luminosity	**267 fb^{-1}**
Electron beam polarization	80%

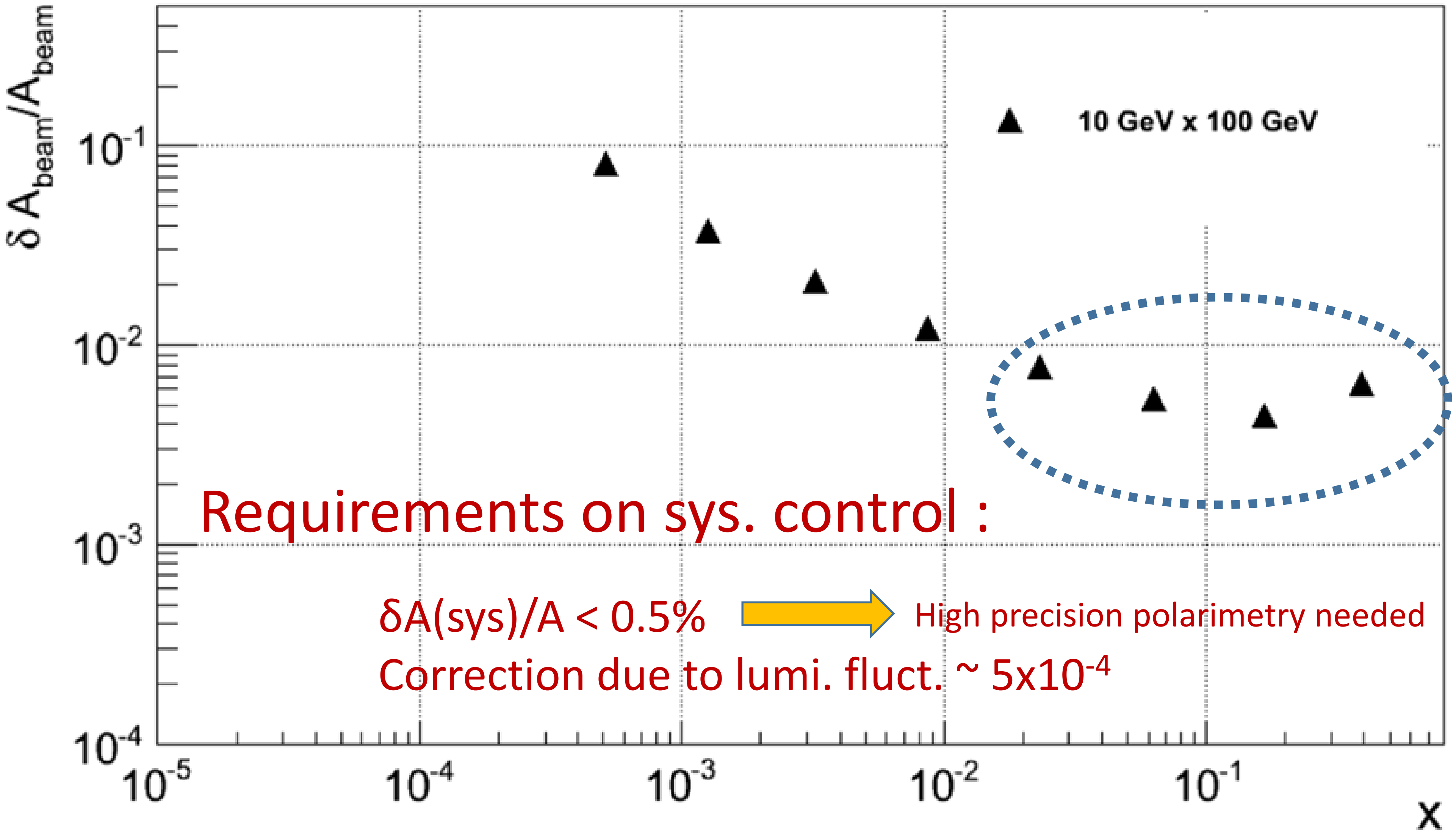
- **Unpolarized structure functions**
  - **e-p collisions**
  - **electron: longitudinally polarized**
  - **proton: unpolarized**
  - **Integrated luminosity: 500 fb^{-1}**

Predicted asymmetries

$$A_{beam} = \frac{G_F Q^2}{2\sqrt{2}\pi\alpha}\left[g_A^e \frac{F_1^{\gamma Z}}{F_1^{\gamma}} + g_V^e \frac{Y_-}{2Y_+}\frac{F_3^{\gamma Z}}{F_1^{\gamma}}\right]$$



δA/A as a function of x

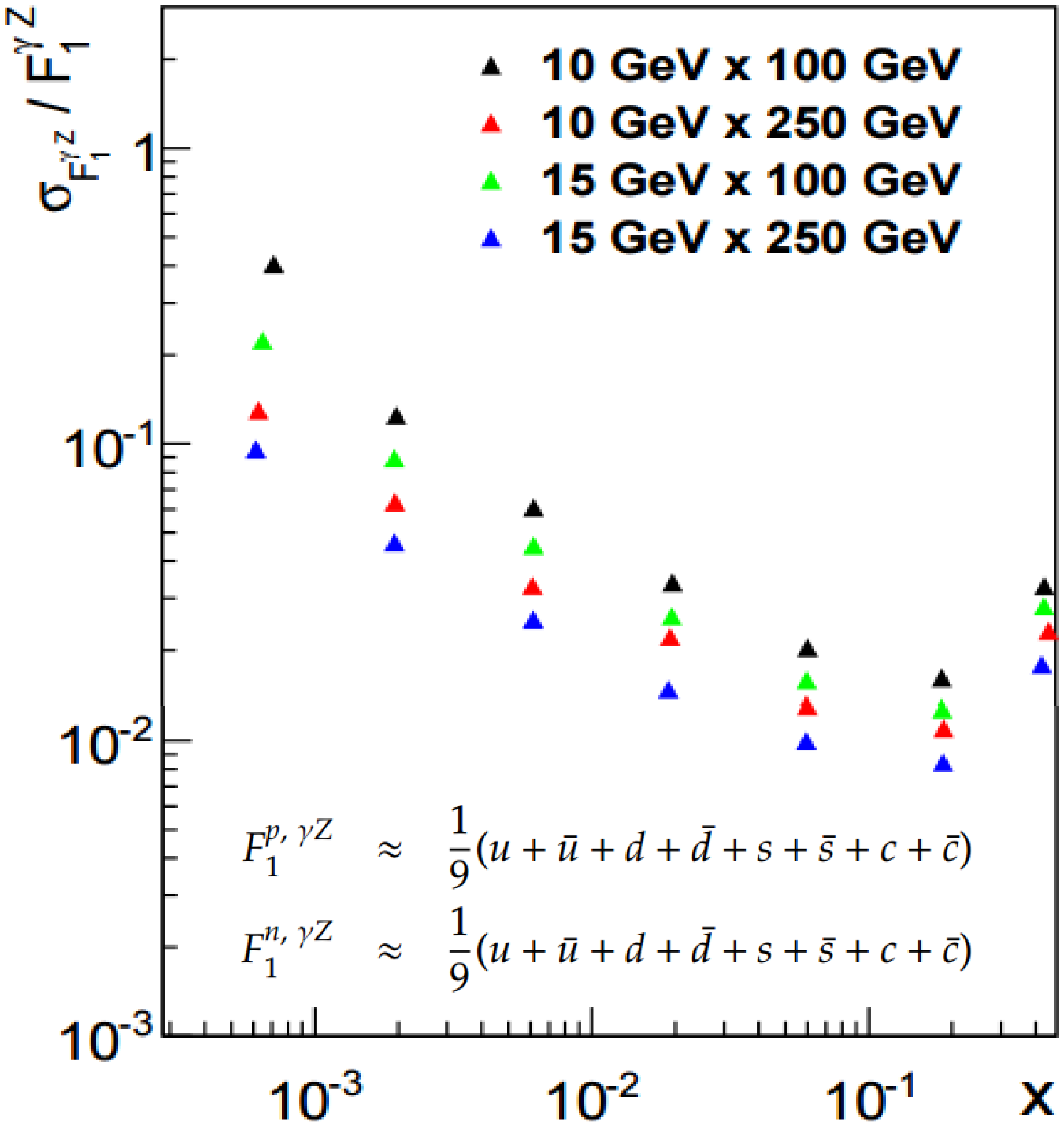


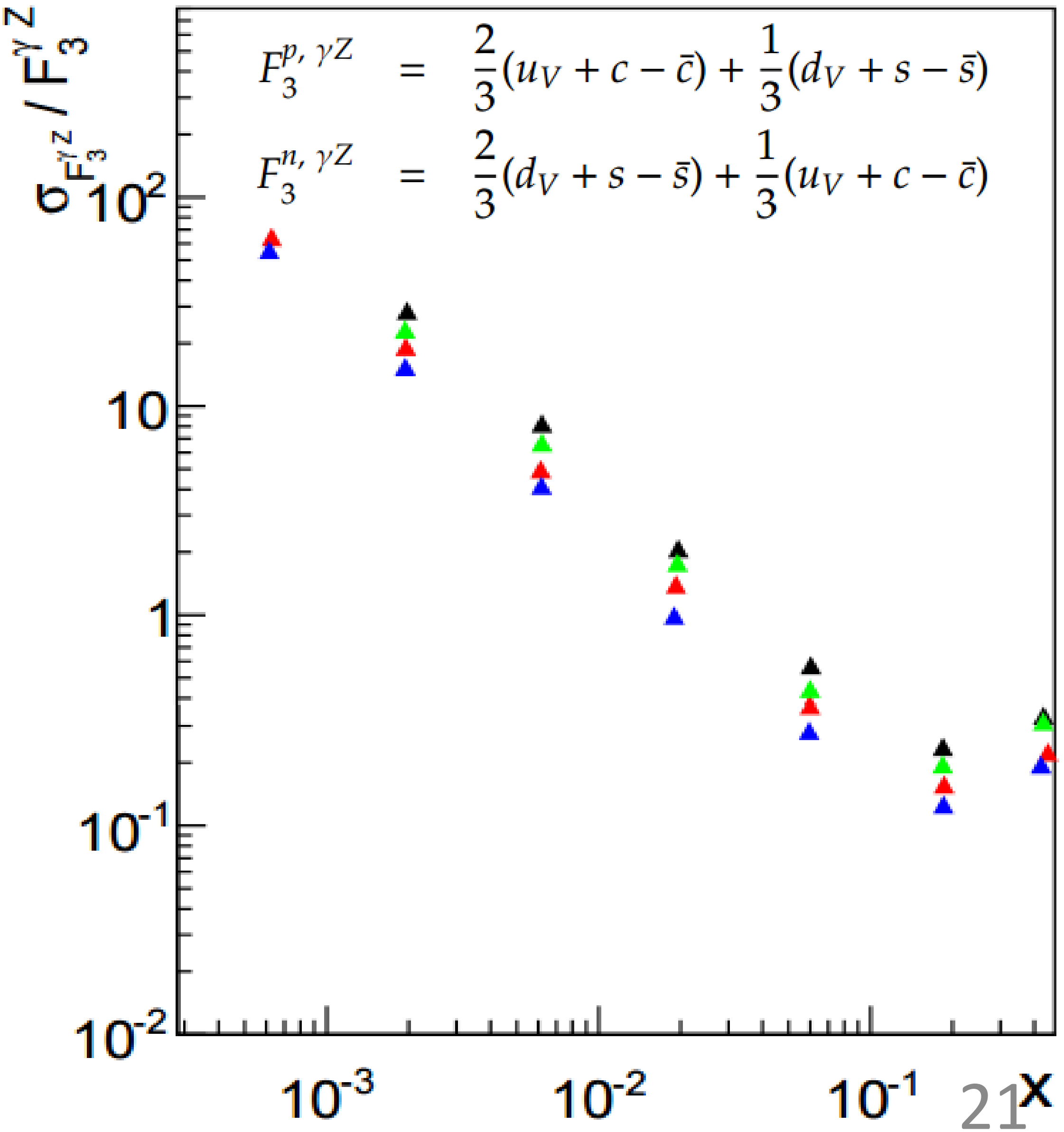
Requirements on sys. control :

δA(sys)/A < 0.5% → High precision polarimetry needed

Correction due to lumi. fluct. ~ $5\text{x}10^{-4}$

Unpol. SFs projections after unfolding

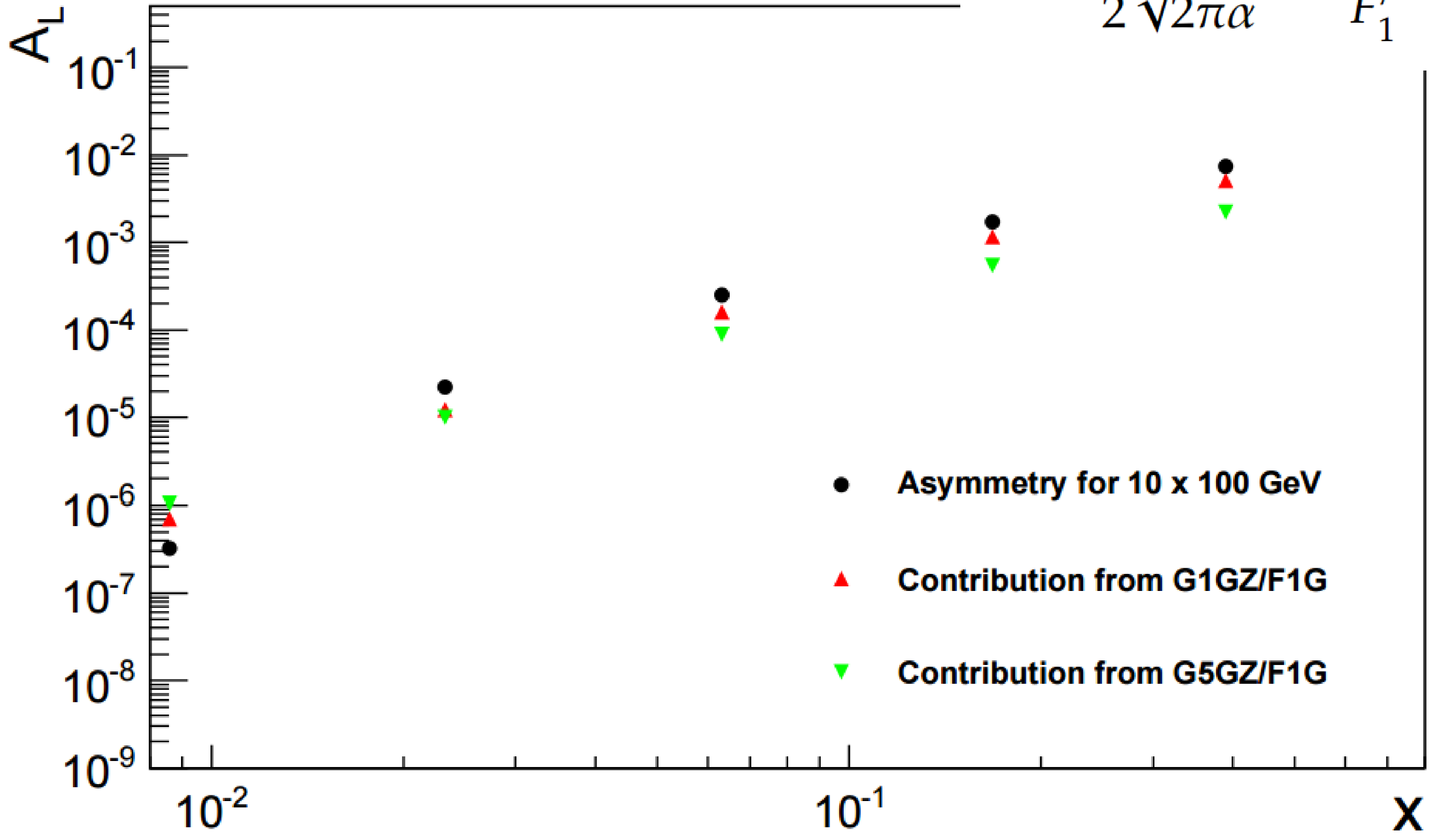




- Polarized structure functions
  - e-p collisions
  - e: unpolarized
  - p: longitudinally polarized
  - Integrated luminosity: 500 fb^{-1}

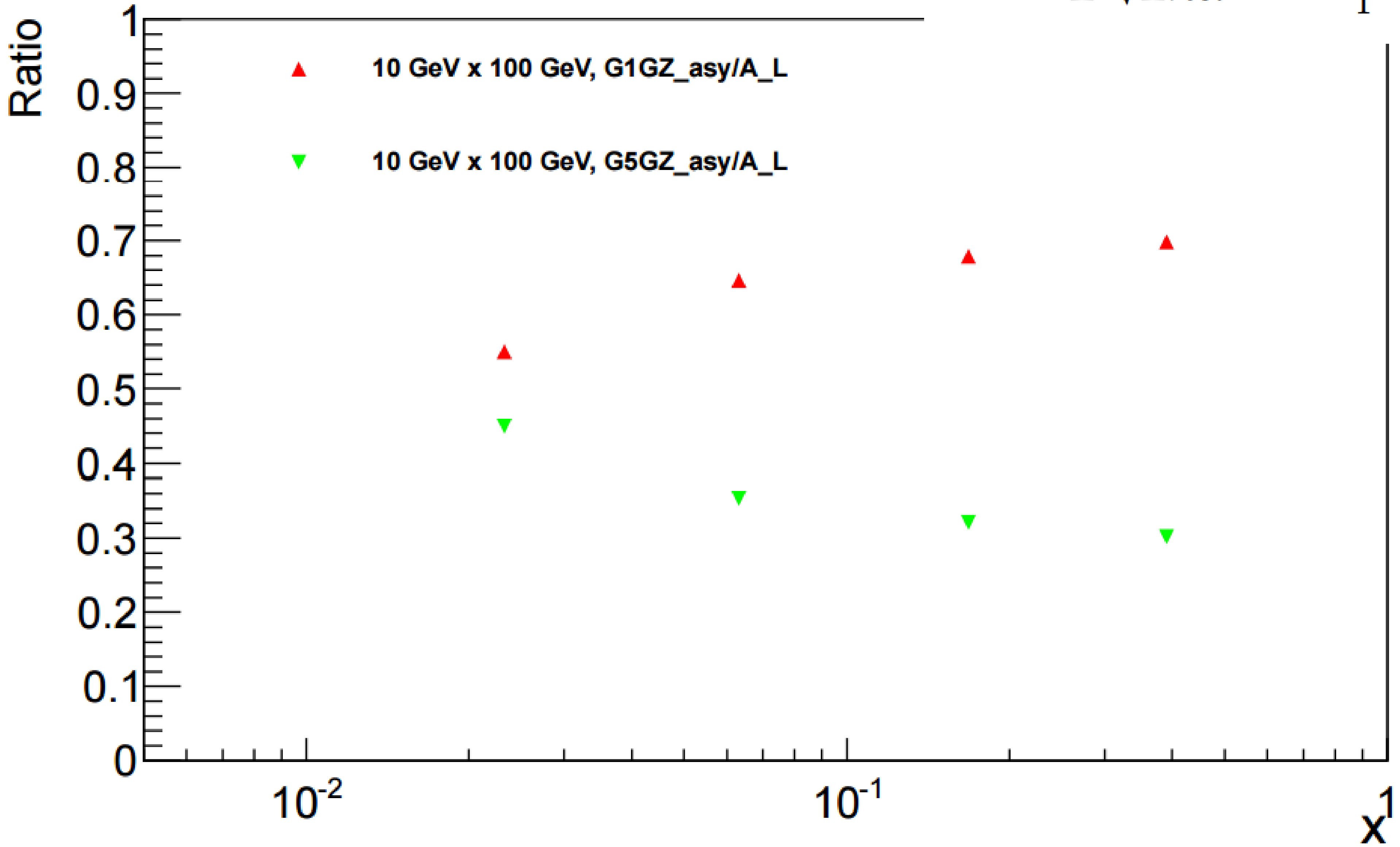
Predicted asymmetries

$$A_L = \frac{G_F Q^2}{2\sqrt{2}\pi\alpha}\left[g_V^e \frac{g_5^{\gamma Z}}{F_1^\gamma} + g_A^e \frac{Y_-}{Y_+}\frac{g_1^{\gamma Z}}{F_1^\gamma}\right]$$

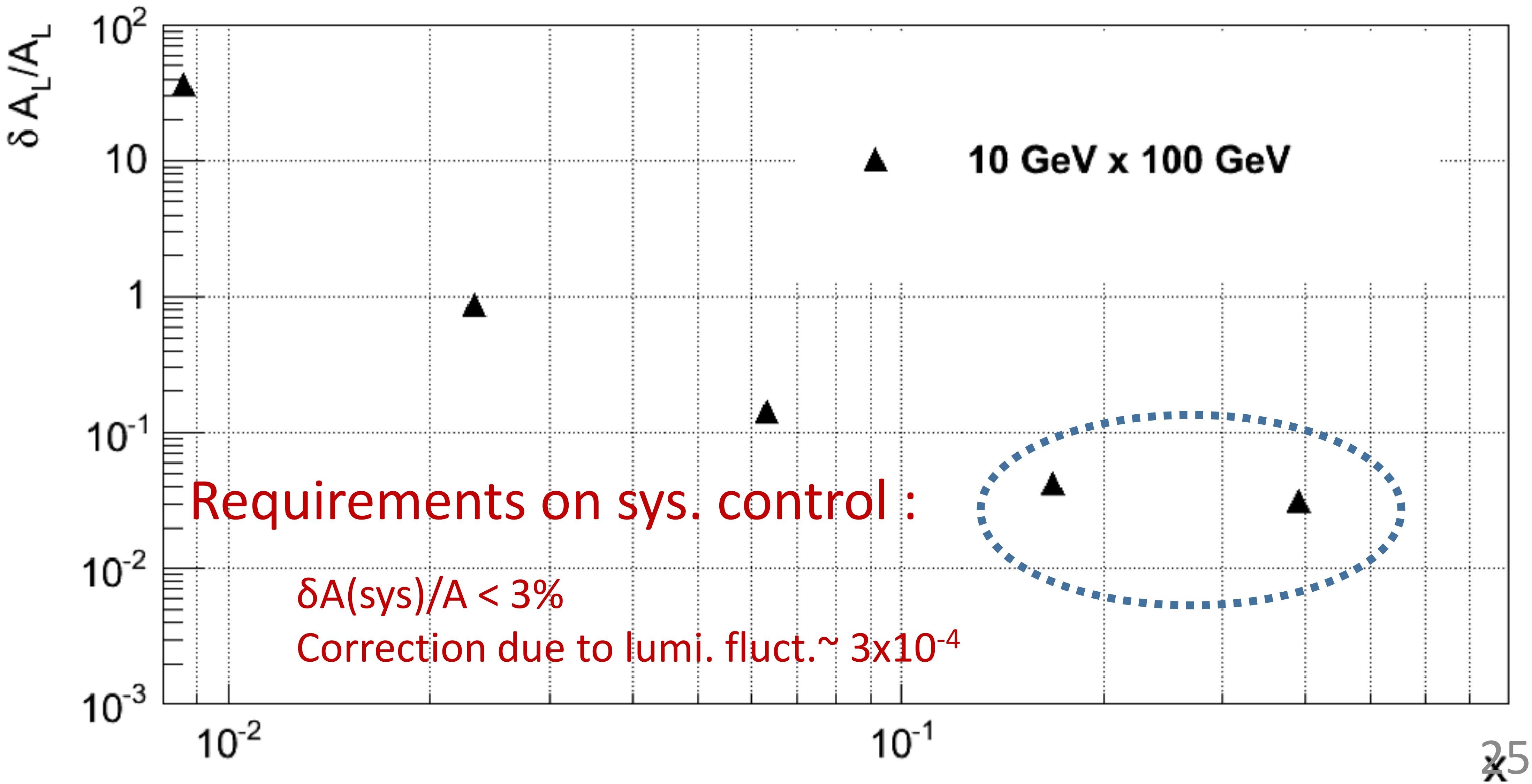


Predicted asymmetries

$$A_L = \frac{G_F Q^2}{2\sqrt{2}\pi\alpha}\left[g_V^e \frac{g_5^{\gamma Z}}{F_1^\gamma} + g_A^e \frac{Y_-}{Y_+}\frac{g_1^{\gamma Z}}{F_1^\gamma}\right]$$



δA/A as a function of x

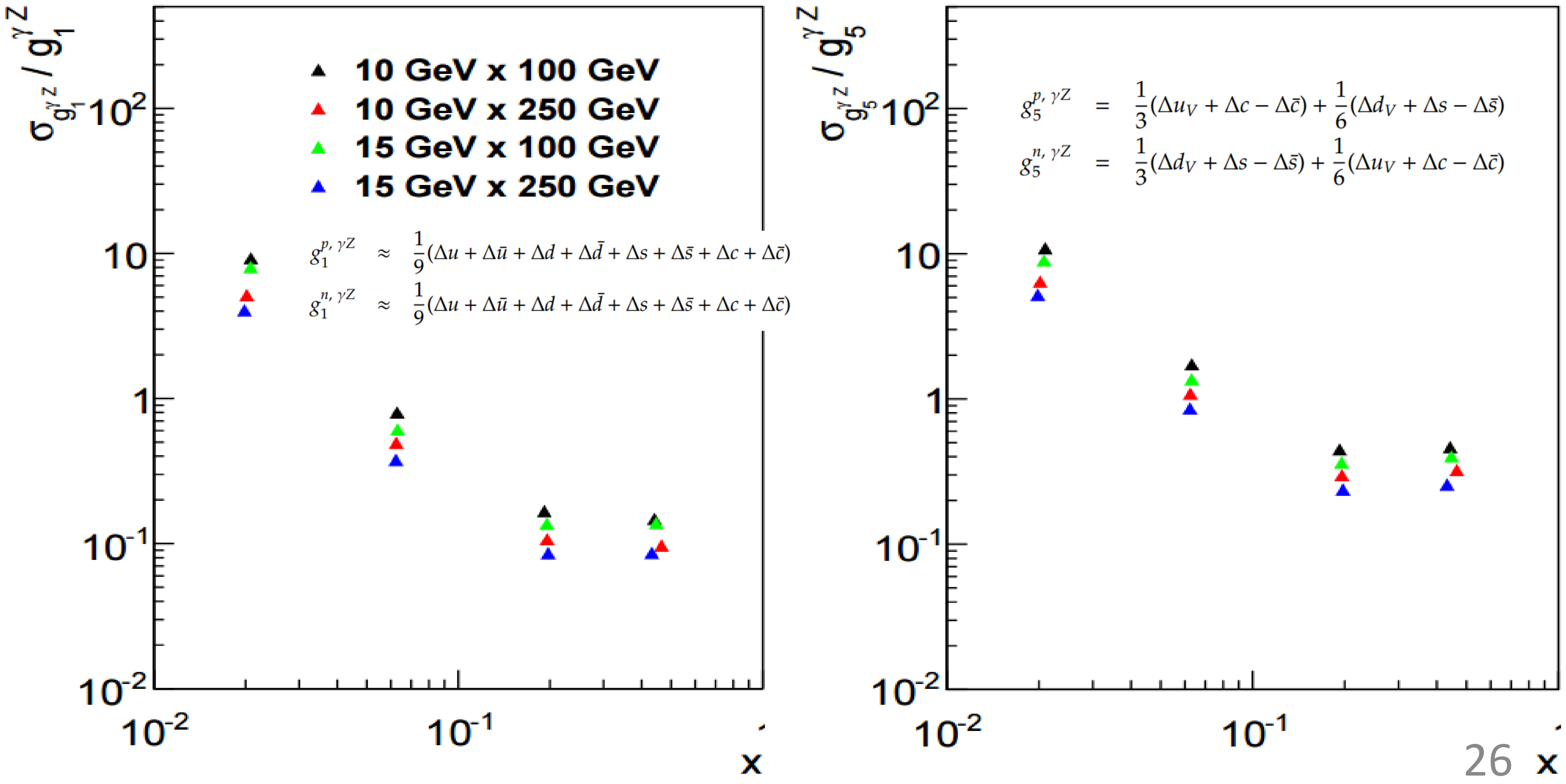


Requirements on sys. control :

δA(sys)/A < 3%

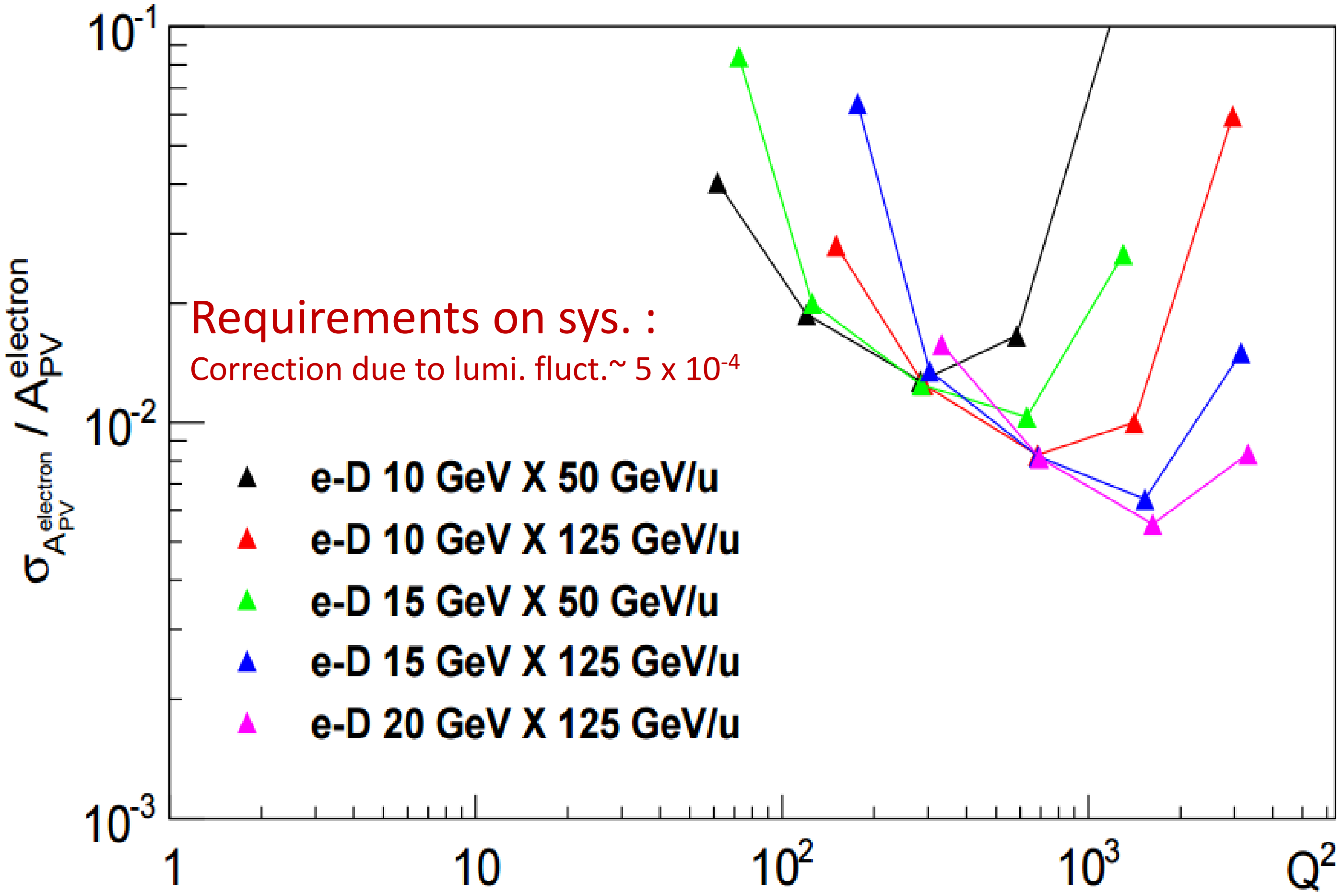
Correction due to lumi. fluct.~ 3×10^{-4}

Pol. SFs projections after unfolding



- **Weak mixing angle**
  - ❑ e-D collisions
  - ❑ e: longitudinally polarized
  - ❑ D: unpolarized
  - ❑ Integrated luminosity: **267 fb^{-1}**

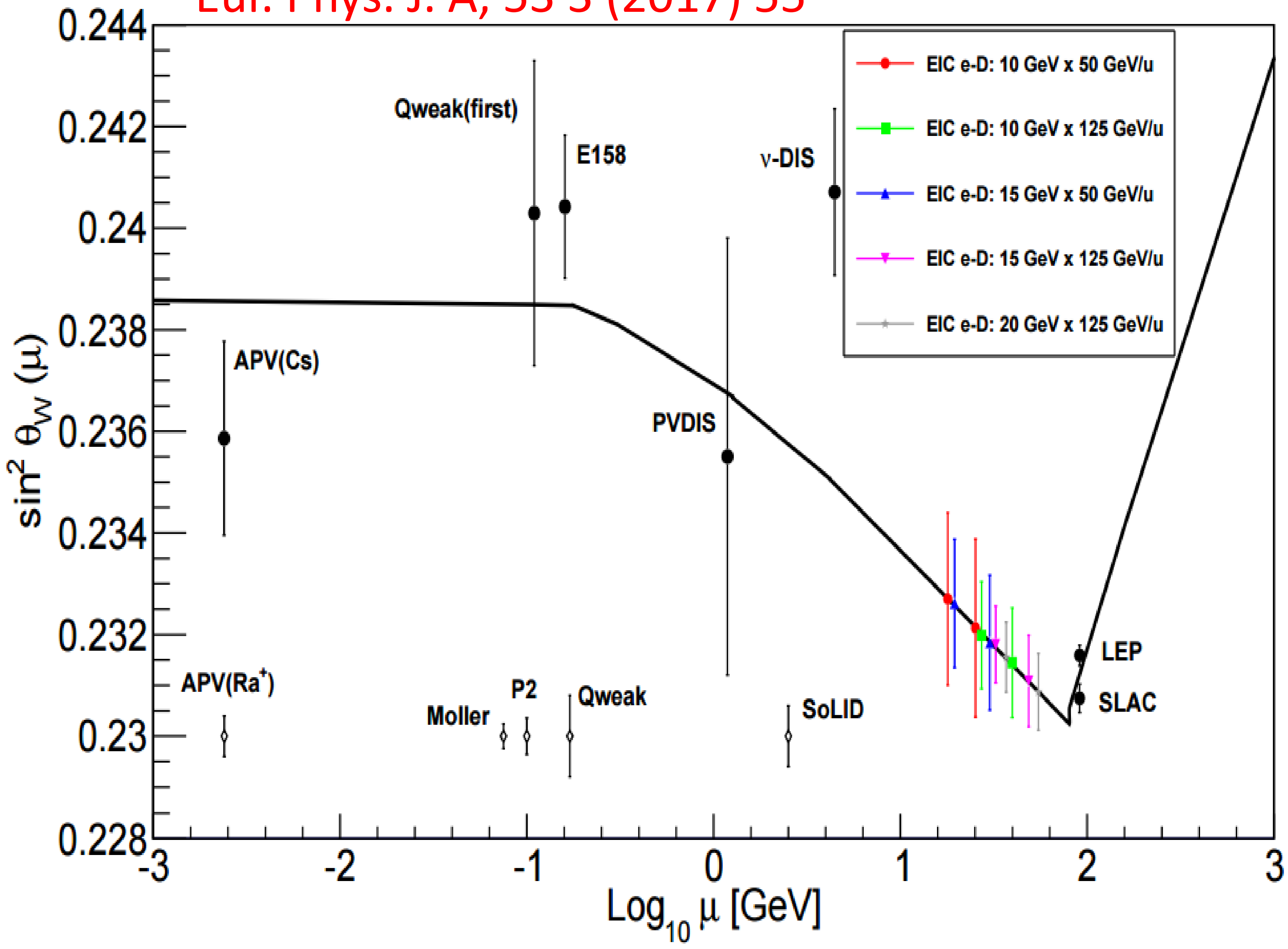
δA/A for e-D collisions



- A challenge for electron polarimetry
- Polarimetry ~1% at the beginning and then 0.5% for higher energy and higher luminosity

World data of $\sin^2\Theta_W$ including EIC projections

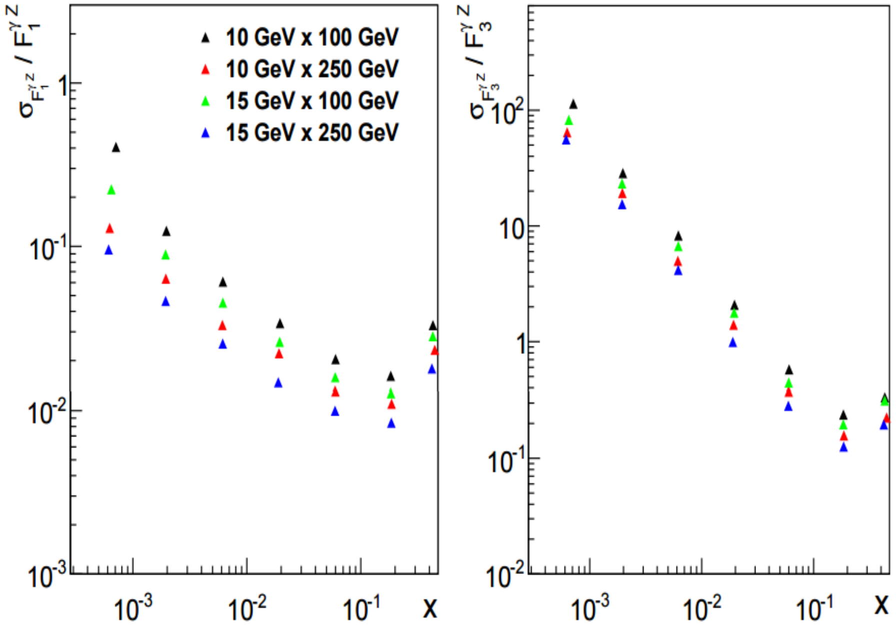
Eur. Phys. J. A, 53 3 (2017) 55



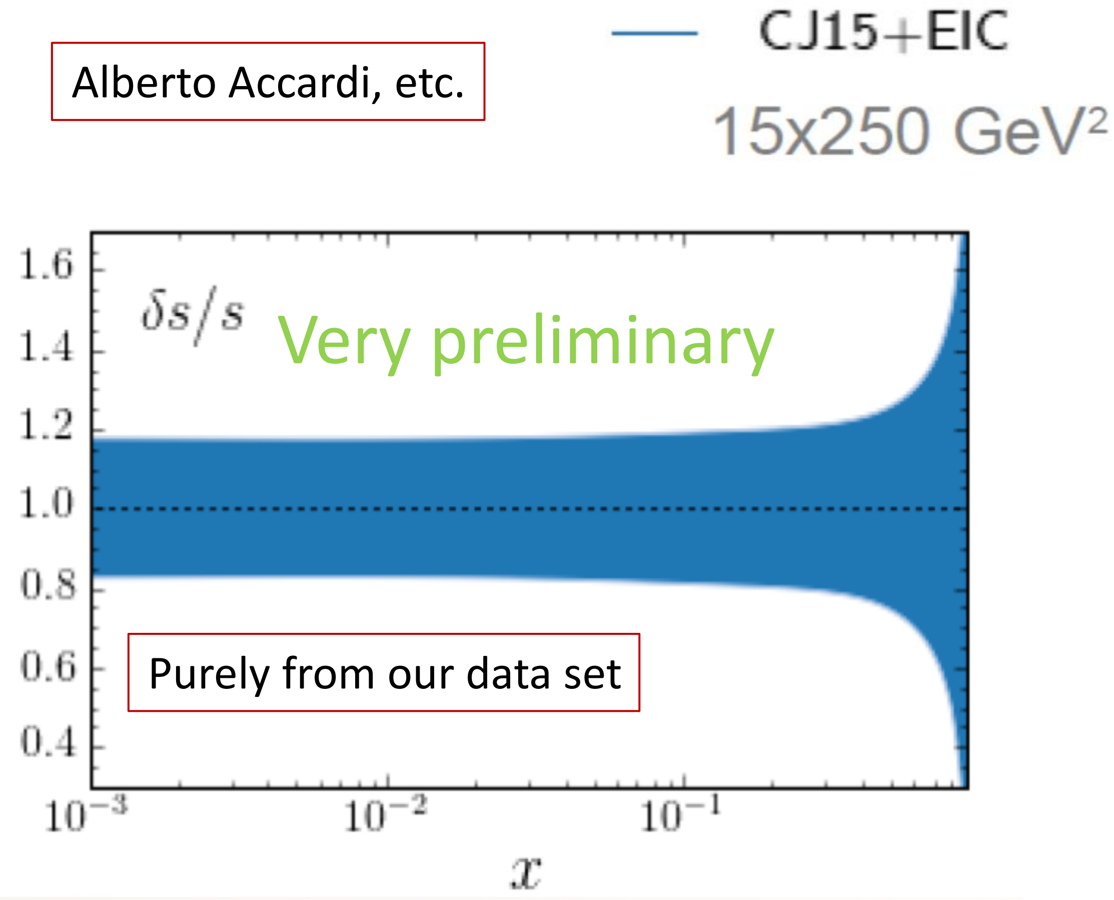
- Can reach similar precision to SoLID measurement
- Interesting Q^2 region

Frist trial of unpolarized PDF fit

$$A_{beam} = \frac{G_F Q^2}{2\sqrt{2}\pi\alpha}\left[g_A^e \frac{F_1^{\gamma Z}}{F_1^{\gamma}} + g_V^e \frac{Y_-}{2Y_+}\frac{F_3^{\gamma Z}}{F_1^{\gamma}}\right]$$



Alberto Accardi, etc.



To study the impact of these new structure functions → require fitting program to include electroweak physics

Summary

- new unpolarized/polarized structure functions
  - ✓Clean access to s and Δs PDFs
- weak mixing angle
  - ✓Reach relative high precision in an interesting Q^2 region
- Eur. Phys. J. A, 53 3 (2017) 55 for more details

- Detector requirements:
  - ✓<1% polarimetry for electron beam
  - ✓<3% polarimetry for proton beam

Backups

Center-of-mass table

Beam energy configuration (e x p, GeV)	Center of Mass (GeV)
10 x 100	63
10 x 250	100
15 x 100	77
15 x 250	122
20 x 250	141