Stony Brook University

Electroweak physics at an EIC

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Spin2016 at UIUC

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Outline

- Electroweak physics at an EIC
  - Nucleon spin structure
    - Measurements in e-p(n) DIS processes in the past decades
    - Weak neutral currents at an EIC offer a new opportunity
  - The weak mixing angle $\sin^2\Theta_w$
- Simulations and projections
  - Generator and detector smearing
  - Projections on unpolarized/polarized structure functions and $\sin^2\Theta_w$
- Summary

Spin structure study Before EIC
---Structure functions and PDFs in e-p(n) DIS processes

Experimental observables

Unpolarized cross section

Unpolarized structure functions

F_1^γ F_2^γ

A_{LL} A_{LT}

Polarized structure functions

g_1^γ g_2^γ

~50%

Quark-Parton Model
QPM

~30%
Spin
crisis

PDFs

Unpolarized pdfs:

f(x)=q↑(x) + q↓(x)

$$F_2(x) = x \sum_q e_q^2 (f_1^q(x) + f_1^{\bar{q}}(x))$$

$$F_2(x) = 2x F_1(x)$$

Polarized pdfs:

Helicity distribution Δq=q↑(x) - q↓(x)

$$g_1(x) = \frac{1}{2} \sum_q e_q^2 \Delta q(x)$$

No g_2 interpretation in QPM

SIDIS to access TMDs, DVCS to access GPDs … 3D era … ongoing efforts

EIC offers new opportunities with weak neutral currents

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

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

$$\frac{d^2\sigma_{nc}^{\ell N}}{dx\,dy}(\lambda, S = S_L) = 4\pi m_N E y \frac{\alpha^2}{Q^4}\sum_i \eta^i C^i \times \Big\{2xy F_1^i + \frac{2}{y}\Big(1 - y - \frac{xym_N}{2E}\Big)(F_2^i + g_3^i) - 2\lambda x\Big(1-\frac{y}{2}\Big)F_3^i - 2\lambda x\Big(2 - y - \frac{xym_N}{E}\Big)g_1^i + 4\lambda\frac{x^2 m_N}{E}g_2^i - \frac{2}{y}\Big(1+\frac{xm_N}{E}\Big)\Big(1 - y - \frac{xym_N}{2E}\Big)g_4^i + 2xy\Big(1+\frac{xm_N}{E}\Big)g_5^i\Big\},$$

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

Inclusive electron measurements

pol. electron & unpol. nucleon:

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

unpol. electron & pol. nucleon:

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

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

pol. electron & unpol. nucleon:

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

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

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

unpol. electron & pol. nucleon:

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

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

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

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

pol. electron & unpol. nucleon:

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

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

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

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

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

unpol. electron & pol. nucleon:

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

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

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

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

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

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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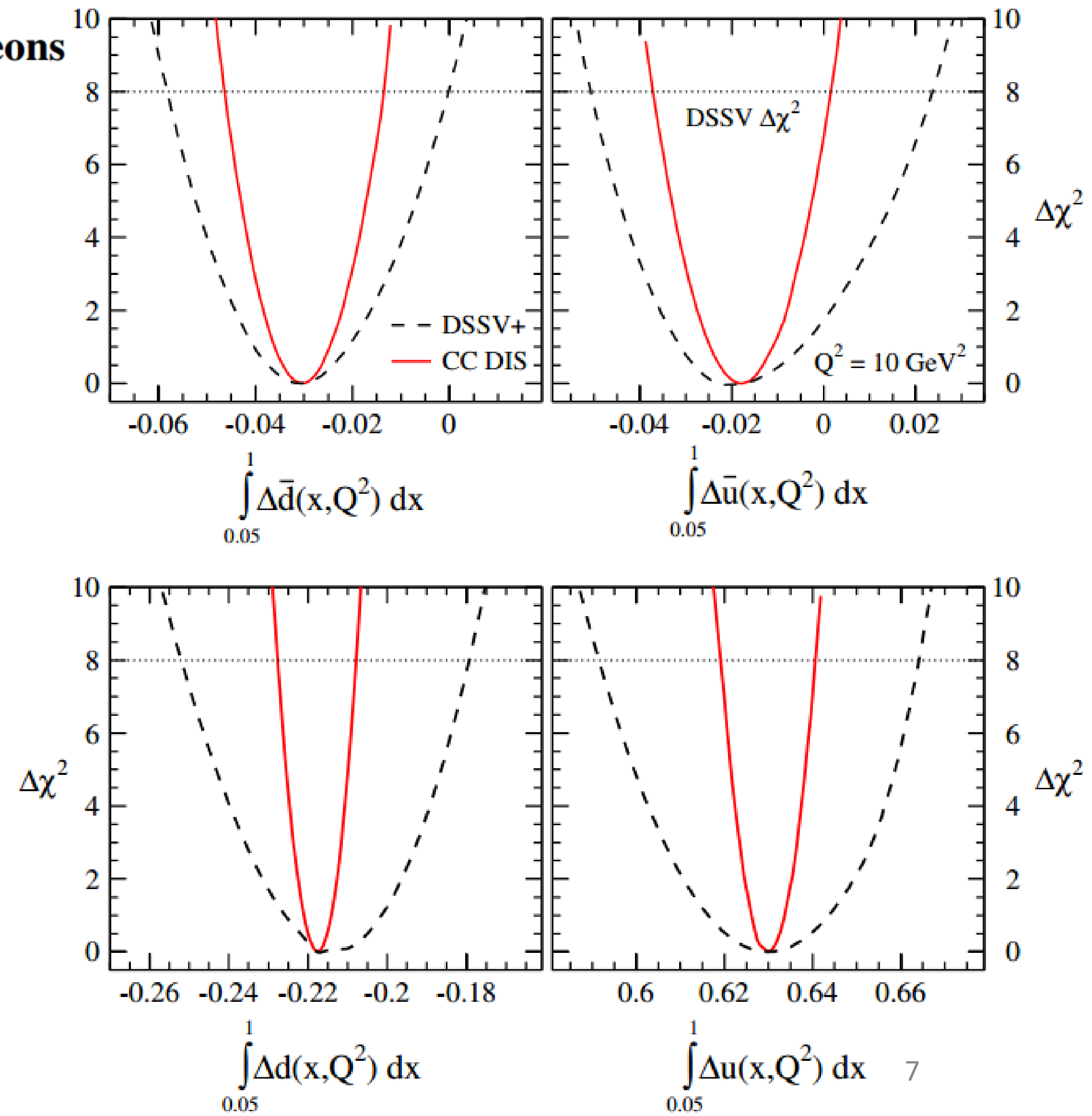
(Received 23 September 2013; published 9 December 2013)

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

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

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

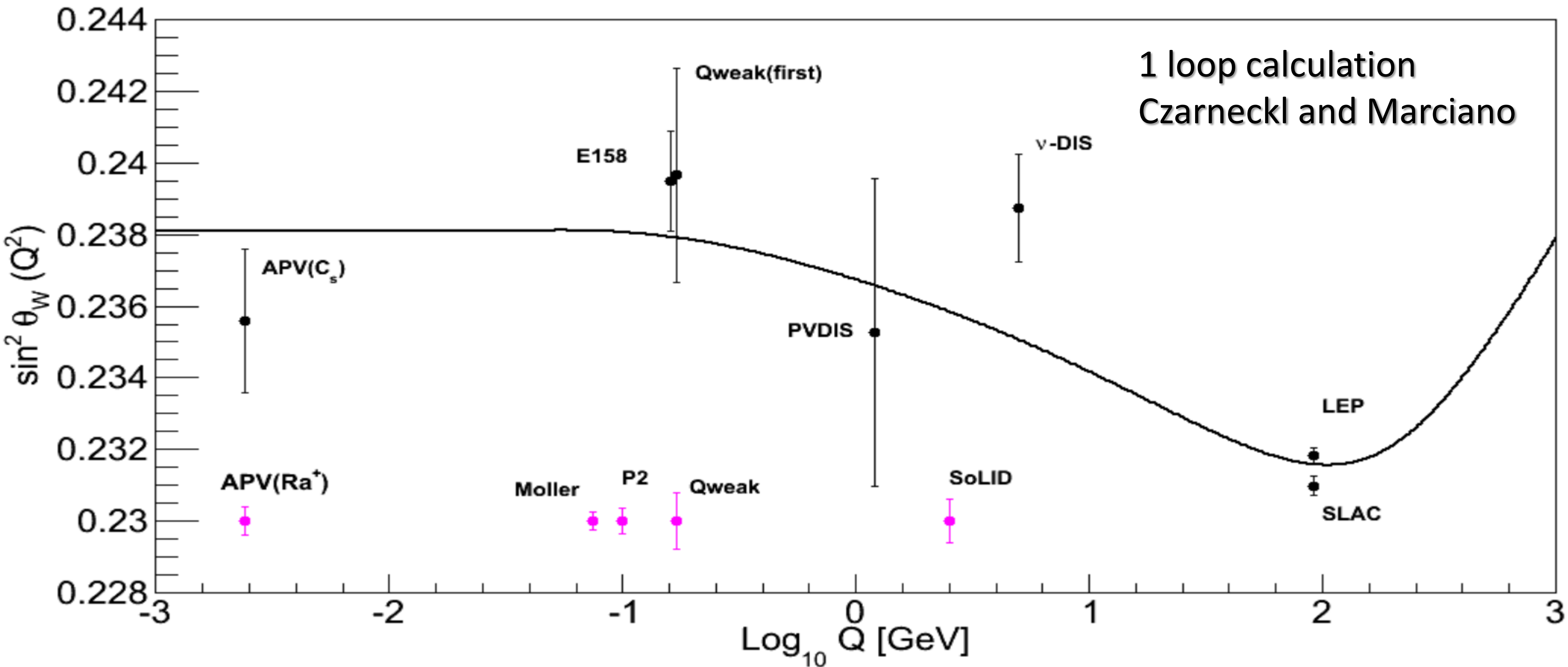
$$g_5^{W^+,p}(x) = \Delta\bar{u}(x) - \Delta d(x) + \Delta\bar{c}(x) - \Delta s(x)$$



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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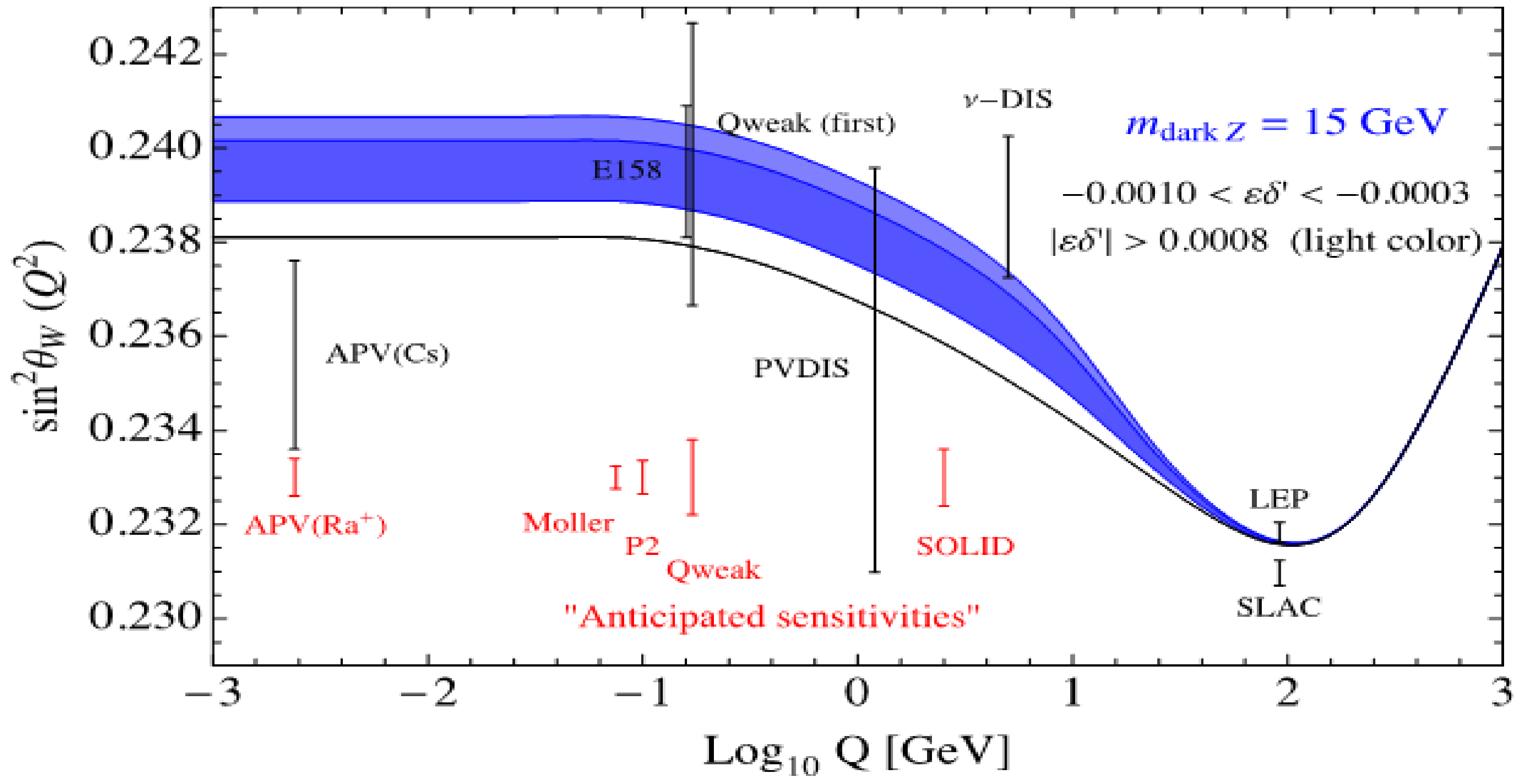
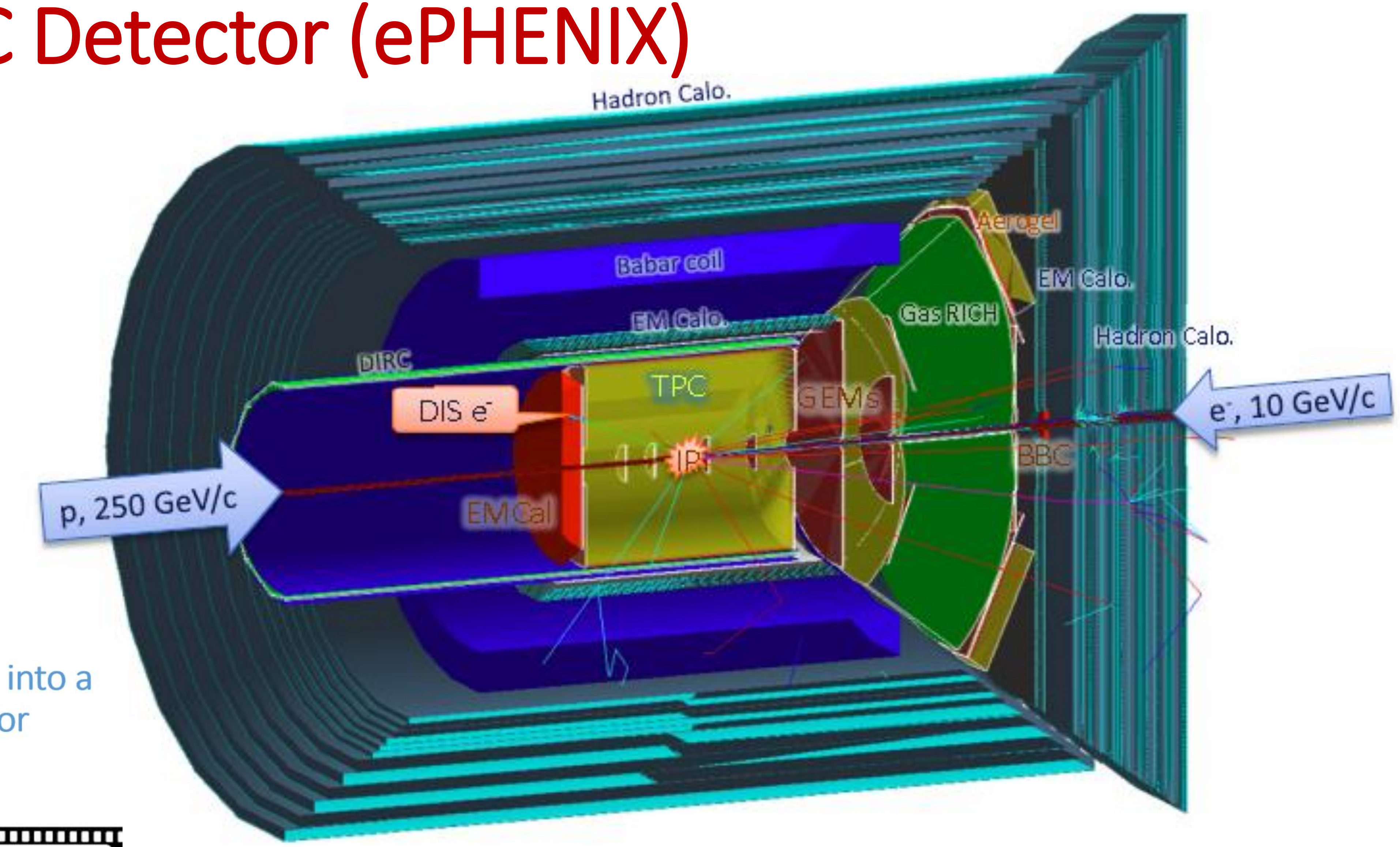
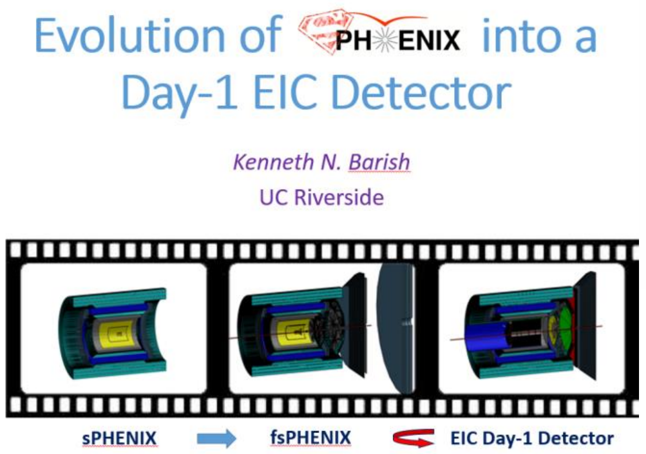


Simulations

- 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 projections:
  - ✓ 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 $\sin^2\Theta_w$ projections
  - ✓ Unfolding for kinematical migration due to radiation and finite detector resolution

Day-1 EIC Detector (ePHENIX)





Please refer to ePHENIX LOI for the details

Detector smearing

		Barrel (-1.1< η <1.1)	electron going direction
Tracking	θ (mrad)	10	1
	ϕ (mrad)	0.3	0.3
	$\frac{dp_T}{p_T}$	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)

e-p collisions	10x100, 10x250, 15x100, 15x250
Run time luminosity	10^{34} /cm^2/s
Detector efficiency	70%
Beam efficiency	70%
Beam time for running	2.5 years 5 months per year = 12.5 months
luminosity after all efficiencies	40 fb^{-1} per month
Integrated luminosity	**500 fb^{-1}**
Proton (electron) beam polarization	70% (80%)
Uncertainty of proton (electron) beam polarization	5% (2%)

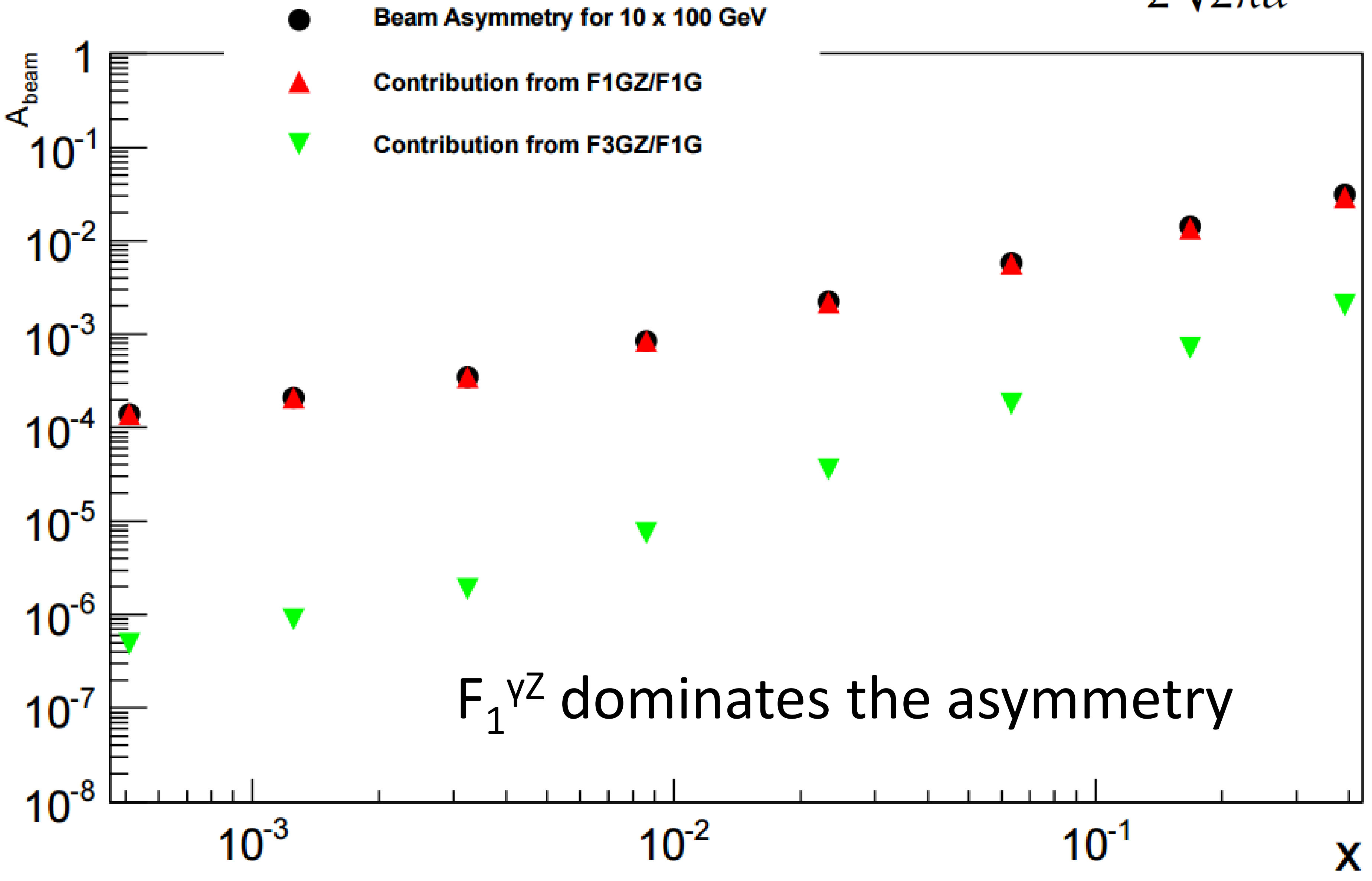
Luminosity and polarization table (e-D collisions)

e-D collisions	10x100,10x250,15x100,15x250,20x250
Run time luminosity (per nucleon)	10^{34} /cm^2/s
Detector efficiency	70%
Beam efficiency	70%
Beam time for running	200 days
luminosity after all efficiencies	40 fb^{-1} per month
Integrated luminosity	**267 fb^{-1}**
Electron beam polarization	80%
Uncertainty of electron beam polarization	2%

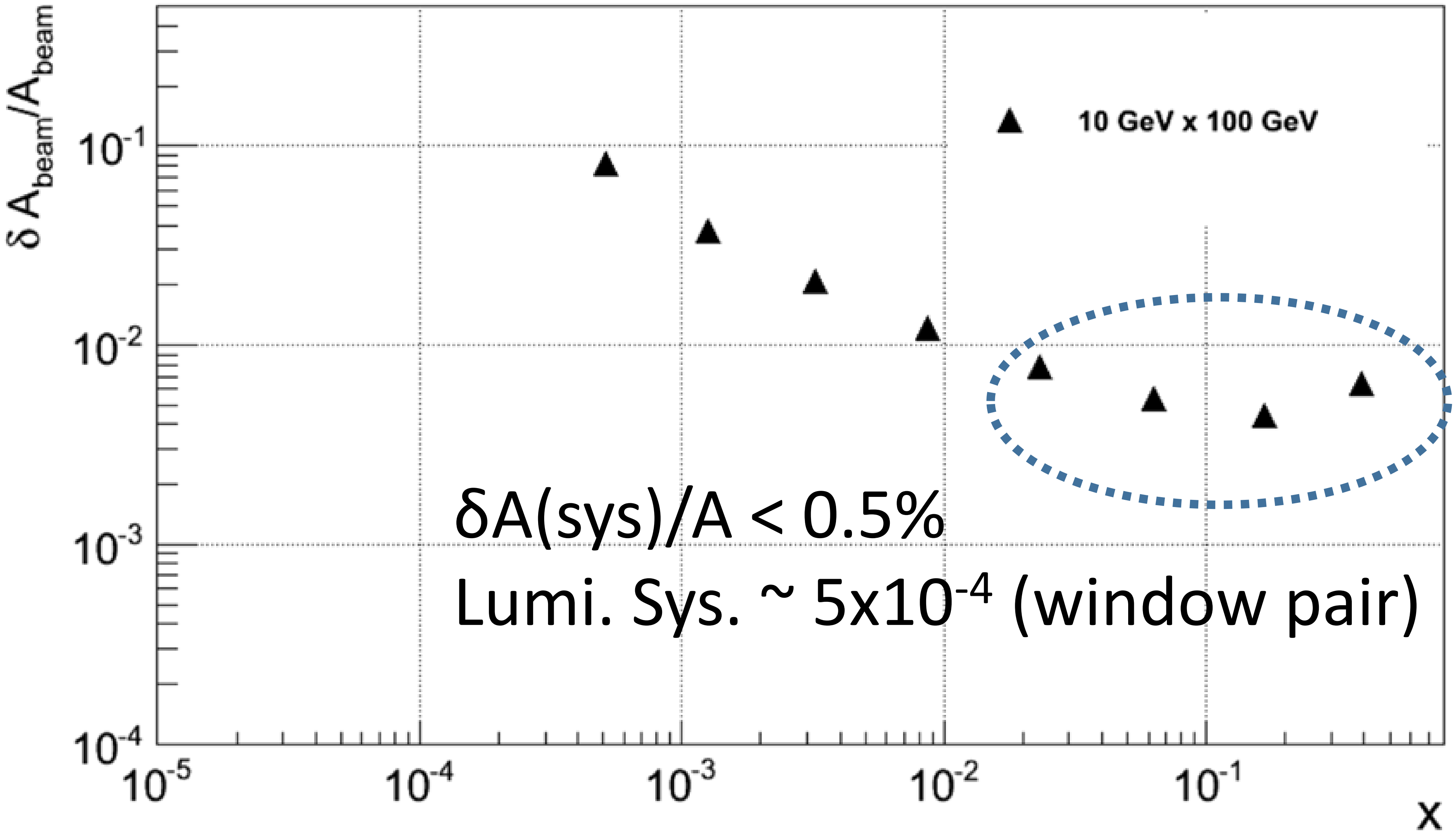
- Unpolarized structure functions
  - e-p collisions
  - electron: longitudinally polarized
  - proton: unpolarized
  - Integrated luminosity: 500 fb^{-1}

Predicted asymmetries

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



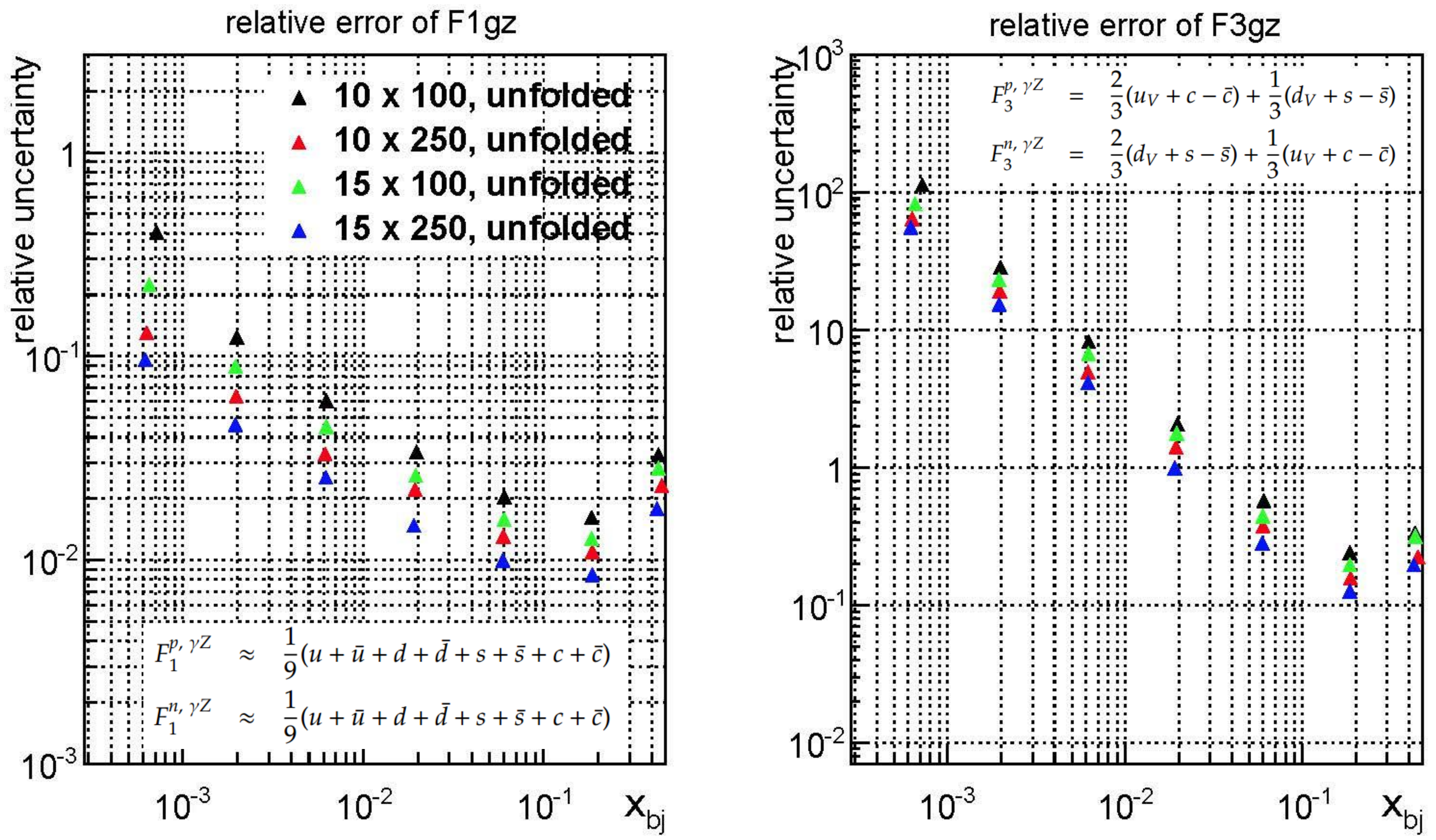
δA/A as a function of x



δA(sys)/A < 0.5%

Lumi. Sys. ~ 5x10^{-4} (window pair)

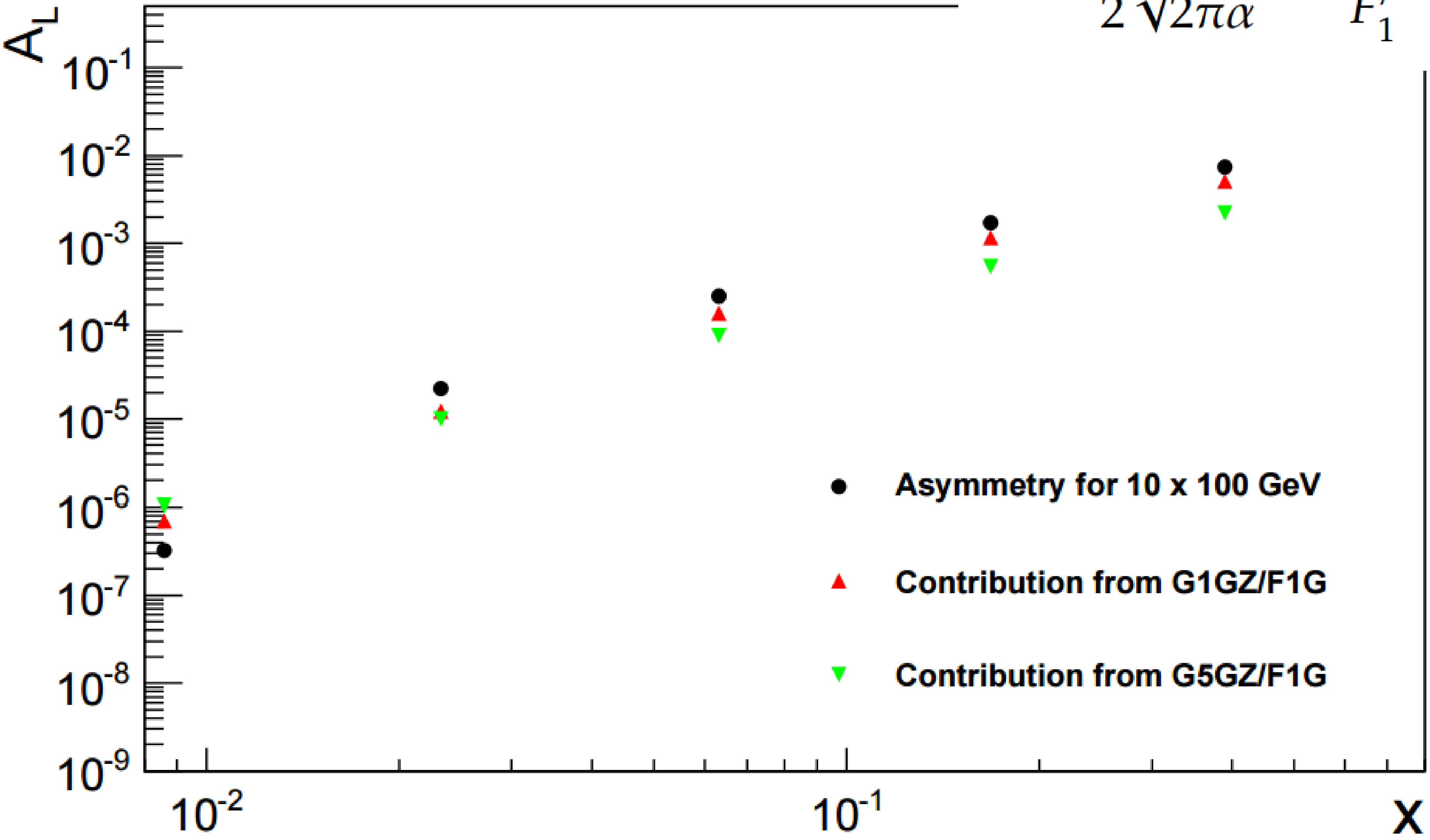
Unpol. SFs projections after unfolding



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

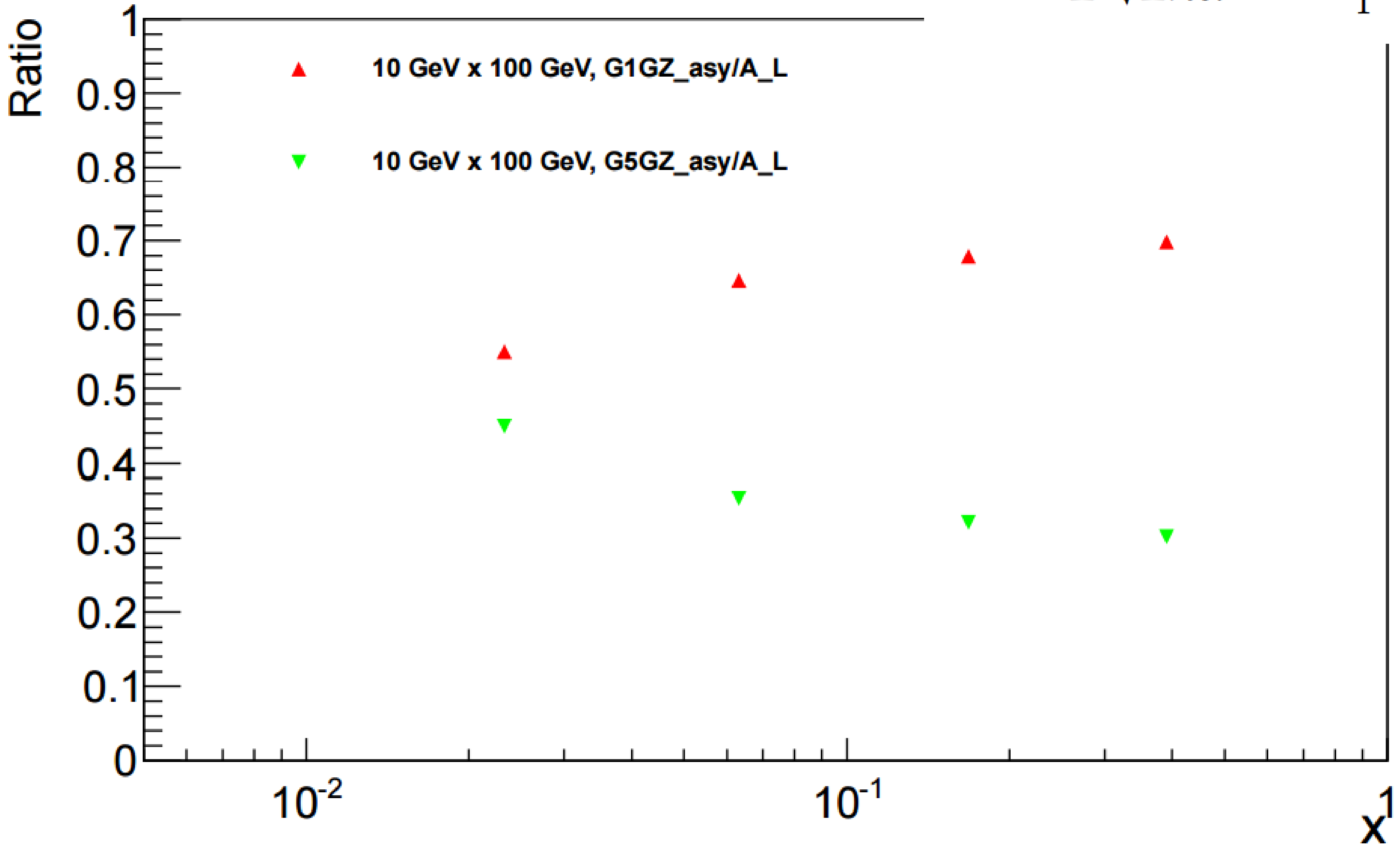
Predicted asymmetries

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

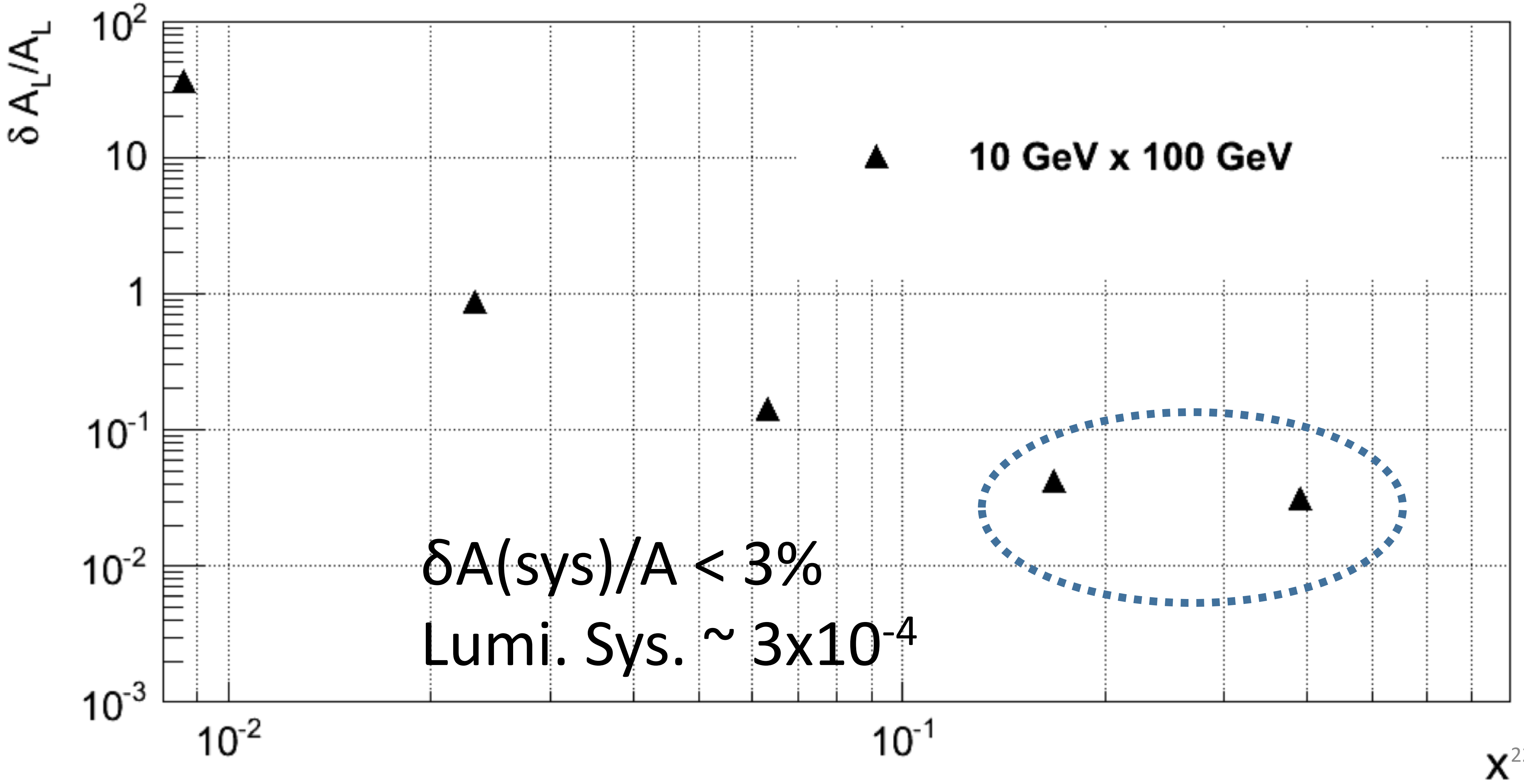


Predicted asymmetries

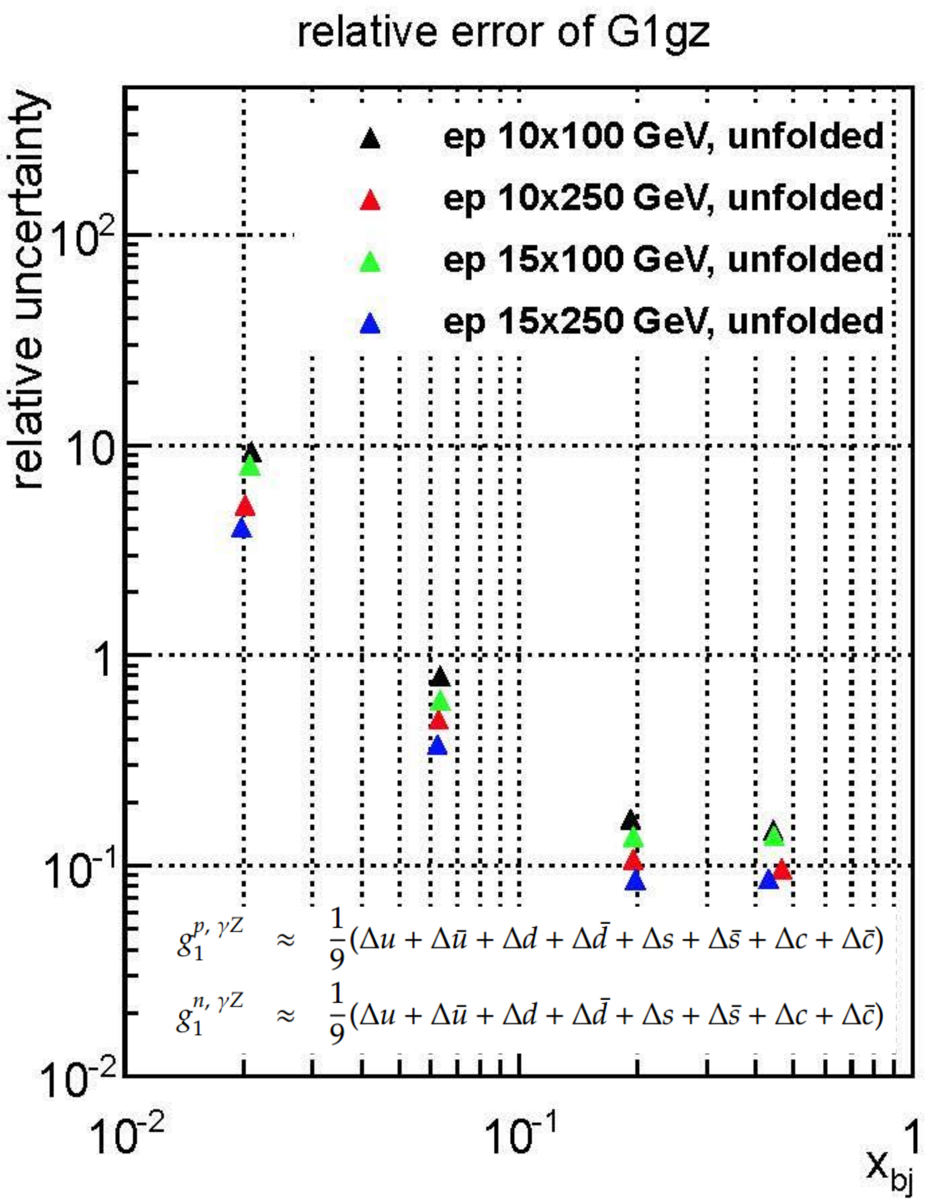
$$A_L = \frac{G_F Q^2}{2\sqrt{2}\pi\alpha}\left[g_V^e \frac{g_5^{\gamma Z}}{F_1^\gamma} + g_A^e \frac{Y_-}{Y_+}\frac{g_1^{\gamma Z}}{F_1^\gamma}\right]$$

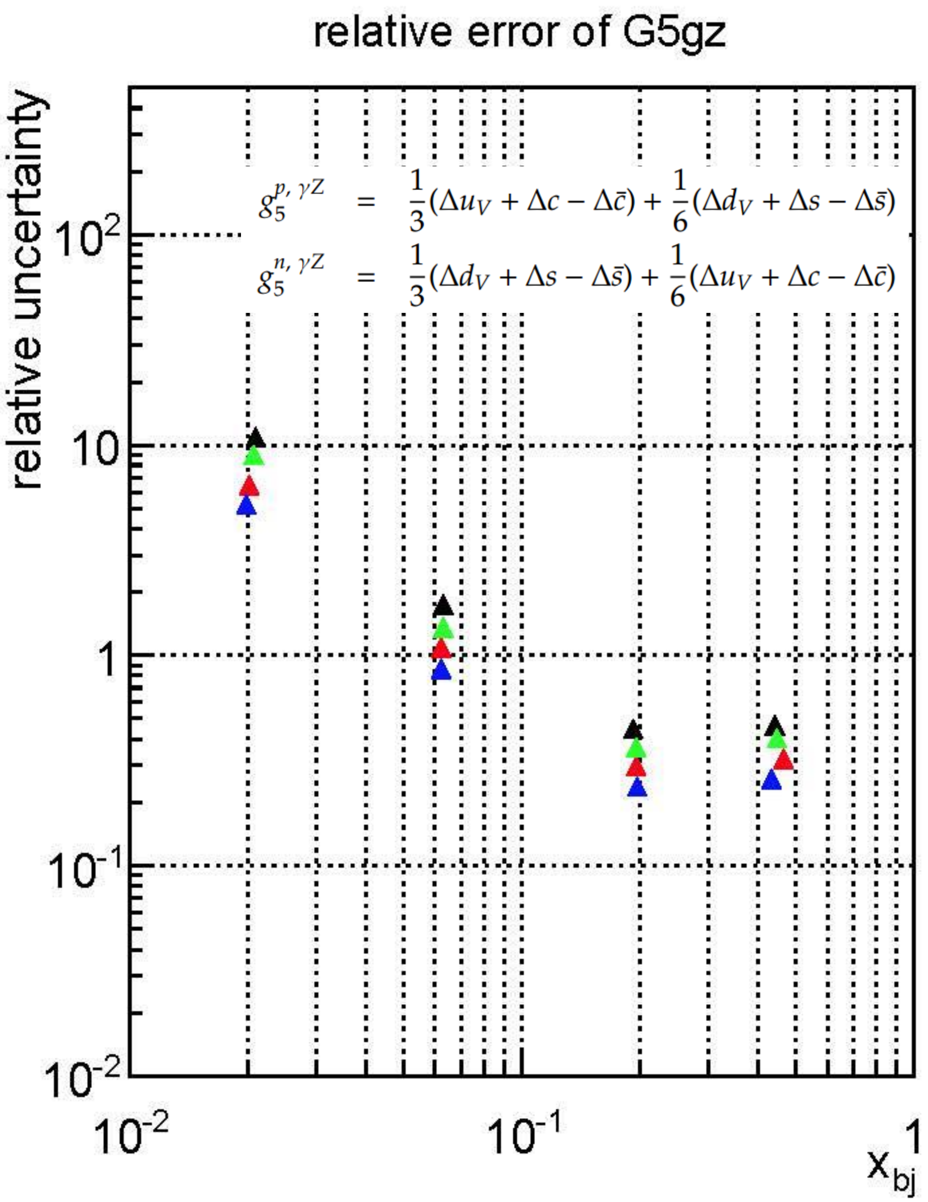


δA/A as a function of x



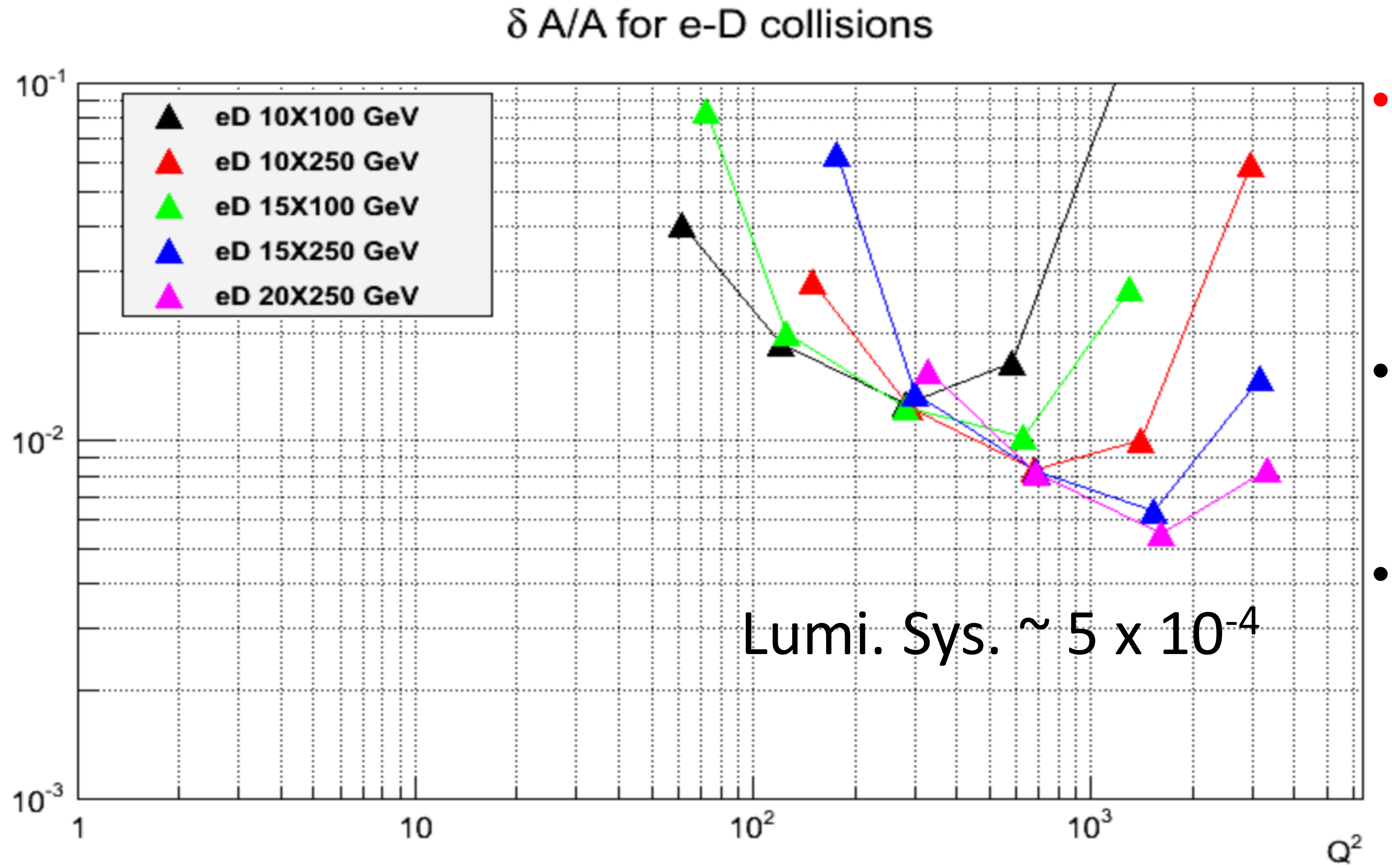
Pol. SFs projections after unfolding





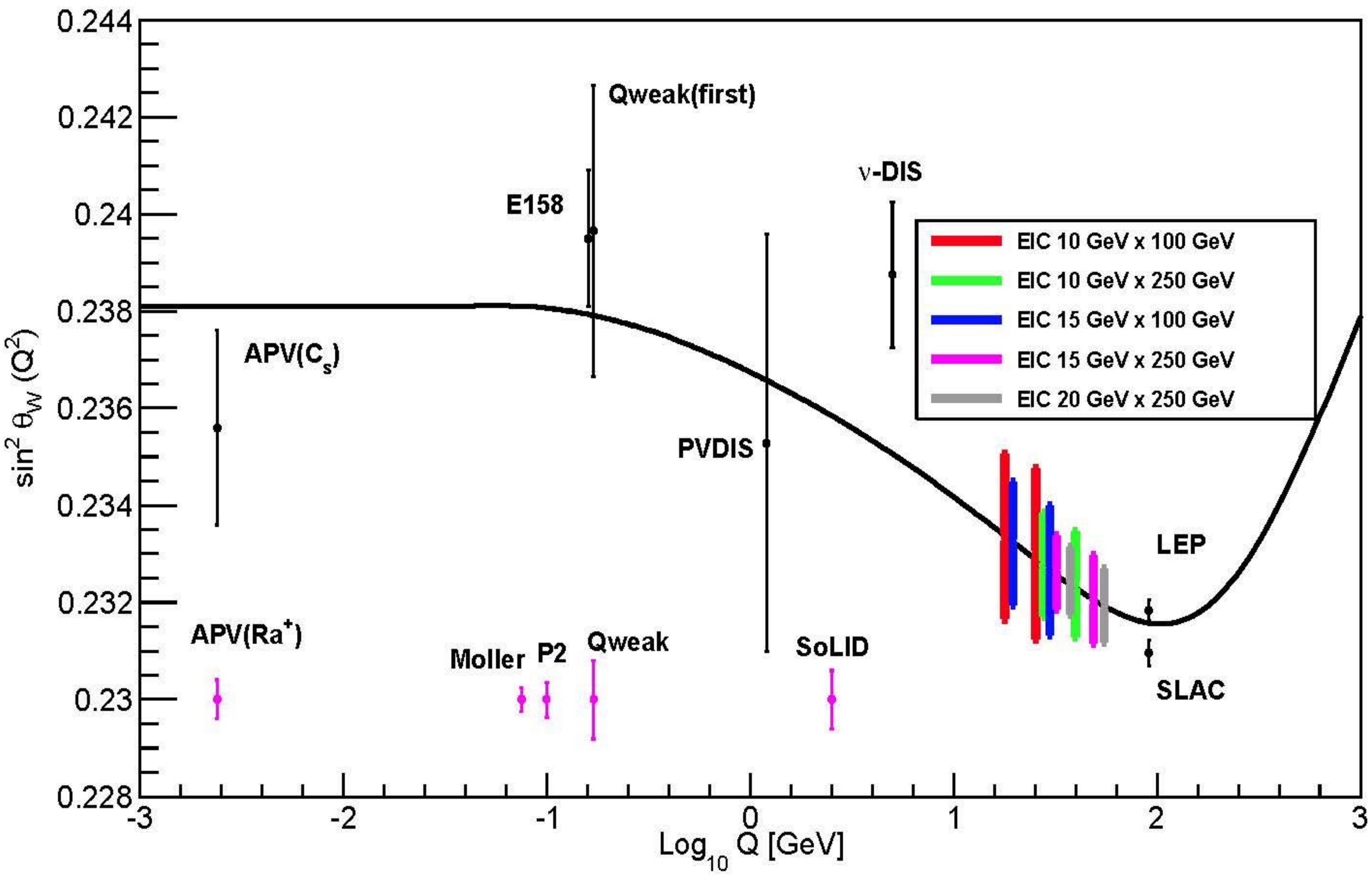
- **Weak mixing angle**
  - ❑ e-D collisions
  - ❑ e: longitudinally polarized
  - ❑ D: unpolarized
  - ❑ Integrated luminosity: 267 fb^{-1} (200 days)

δA/A for e-D collisions



- Polarimetry ~1% at the beginning and then 0.5% for higher energy and higher luminosity
- R&D proposal :
  target at 1% in the first stage
- Experience:
  Parity experiments drive the precision frontier of electron polarimetry: SLAC, PREX/CREX, MOLLER, SoLID

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



- 200 days of dedicated run
- Can reach similar precision to SoLID measurement
- Interesting Q^2 region never been measured or planned

Summary

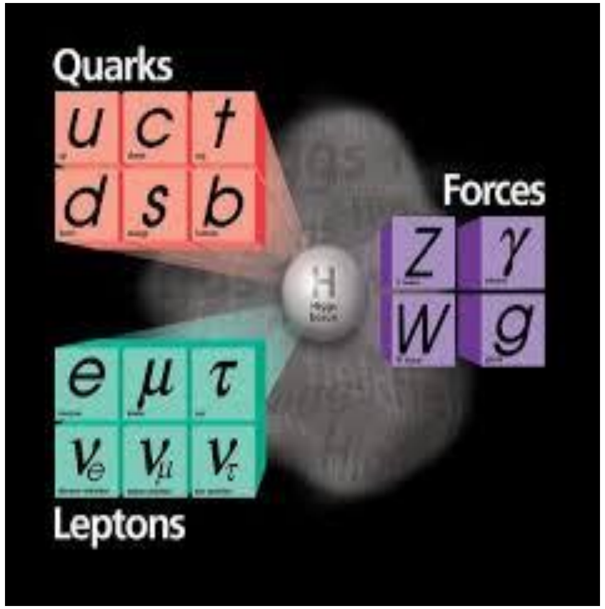
- Presented the projections of new unpol./pol. structure functions
  - ❑Unique combinations of PDFs
  - ❑Brand new, never been measured before
  - ❑Independ inputs to the world data with high precision
- Presented the projections of weak mixing angle
  - ❑Dedicated 200 days of beam time
  - ❑Reach relative high precision in an interesting Q^2 region
- Ongoing efforts…
  - ❑Investigating the impact of the measurements of these structure functions on PDF fits
    - ❖Almost done with pol-PDF impact study using DSSV re-fit
    - ❖Unpol-PDF: HERA code to do re-fit
  - ❑Systematic uncertainties

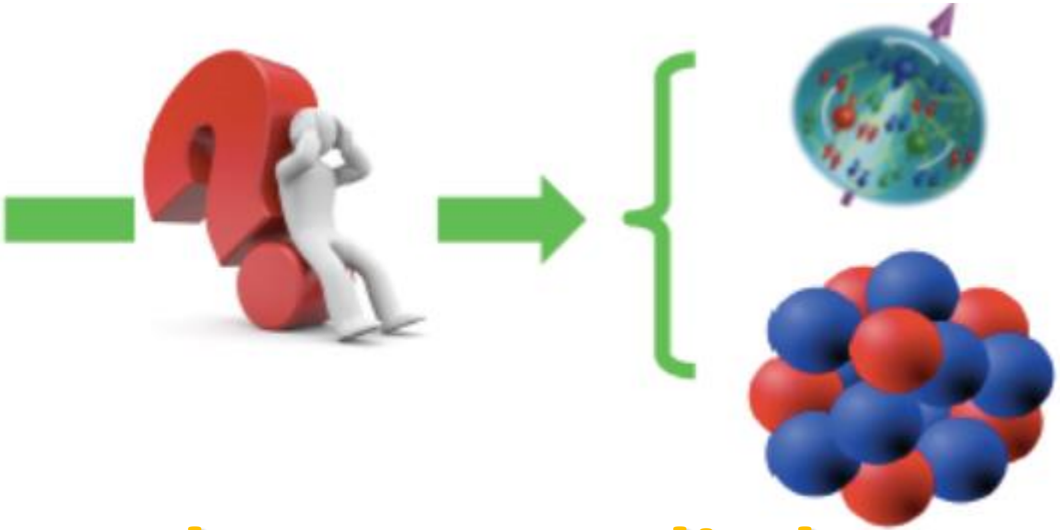
Backups

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**

What holds/glues hadrons together

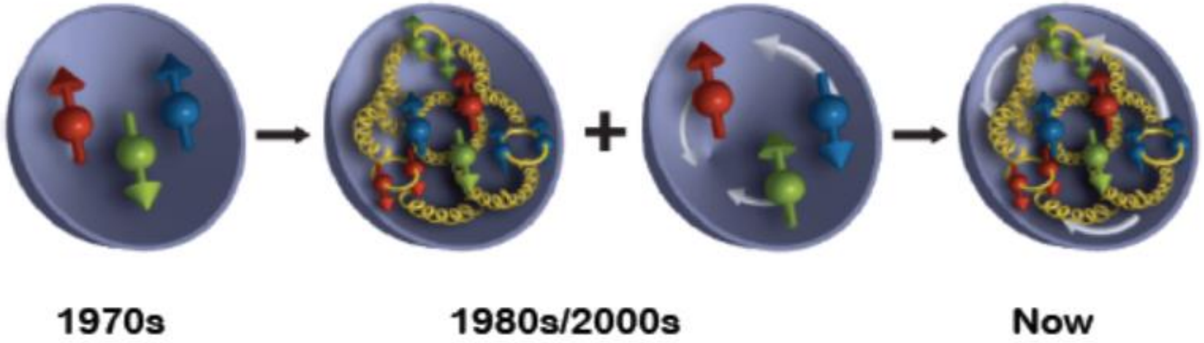




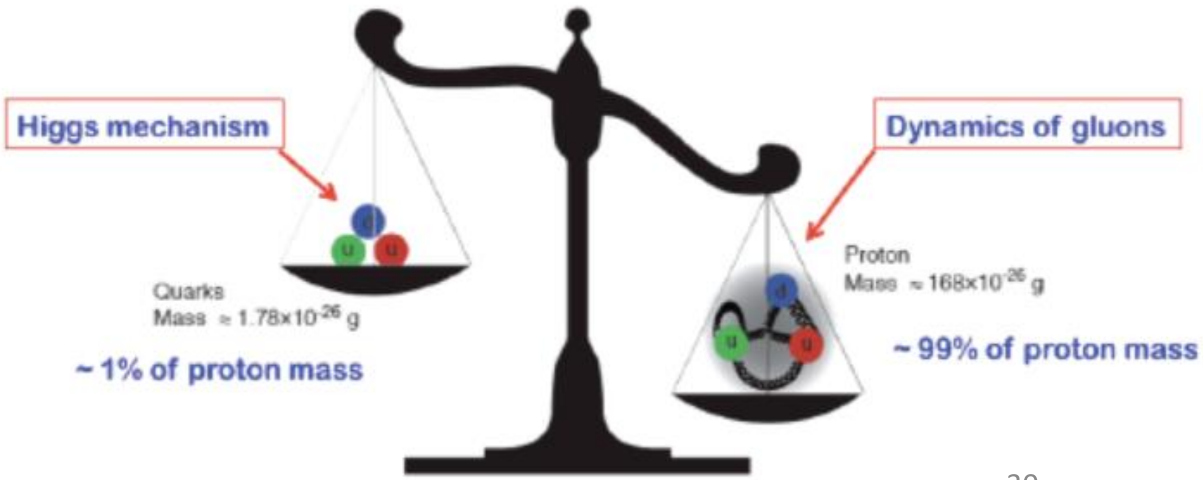
Spin structure

Mass structure

We know very little ...



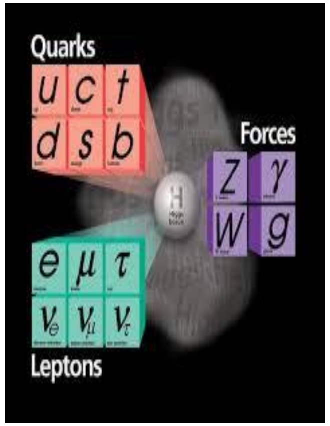
$$\frac{1}{2} = \left[\frac{1}{2}\Delta\Sigma + L_Q\right] + [\Delta g + L_G]$$

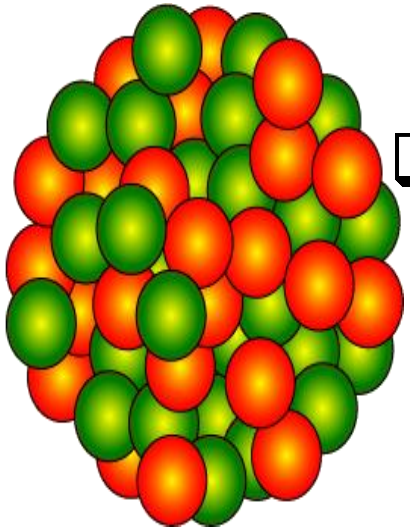


A newly proposed Facility, Electron Ion Collider

With

- ❑a versatile range of kinematics
- ❑beam polarizations
- ❑high luminosity
- ❑different beam species





TO

- ❑***precisely image*** *the sea quarks and gluons in nucleons and **nuclei***
- ❑explore the new QCD frontier of strong color fields in nuclei
- ❑resolve outstanding issues in understanding nucleons and nuclei in terms of fundamental building blocks of QCD

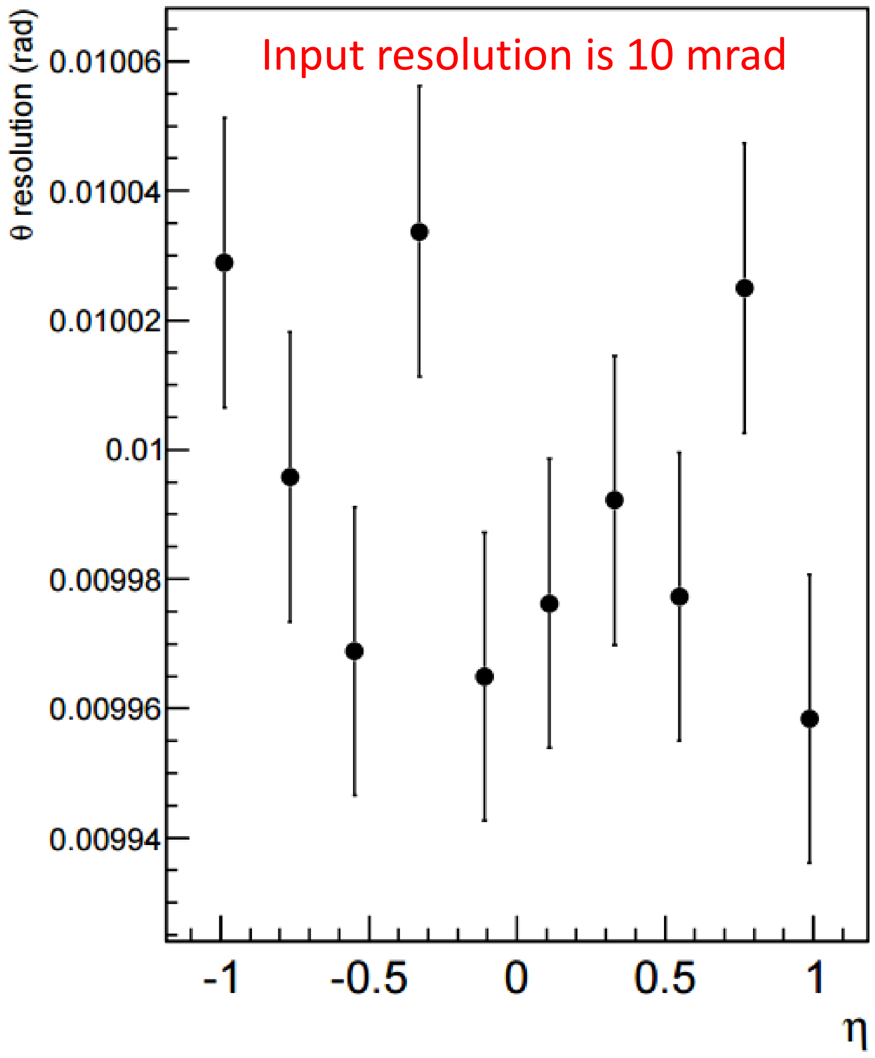
EIC: the world wide interests

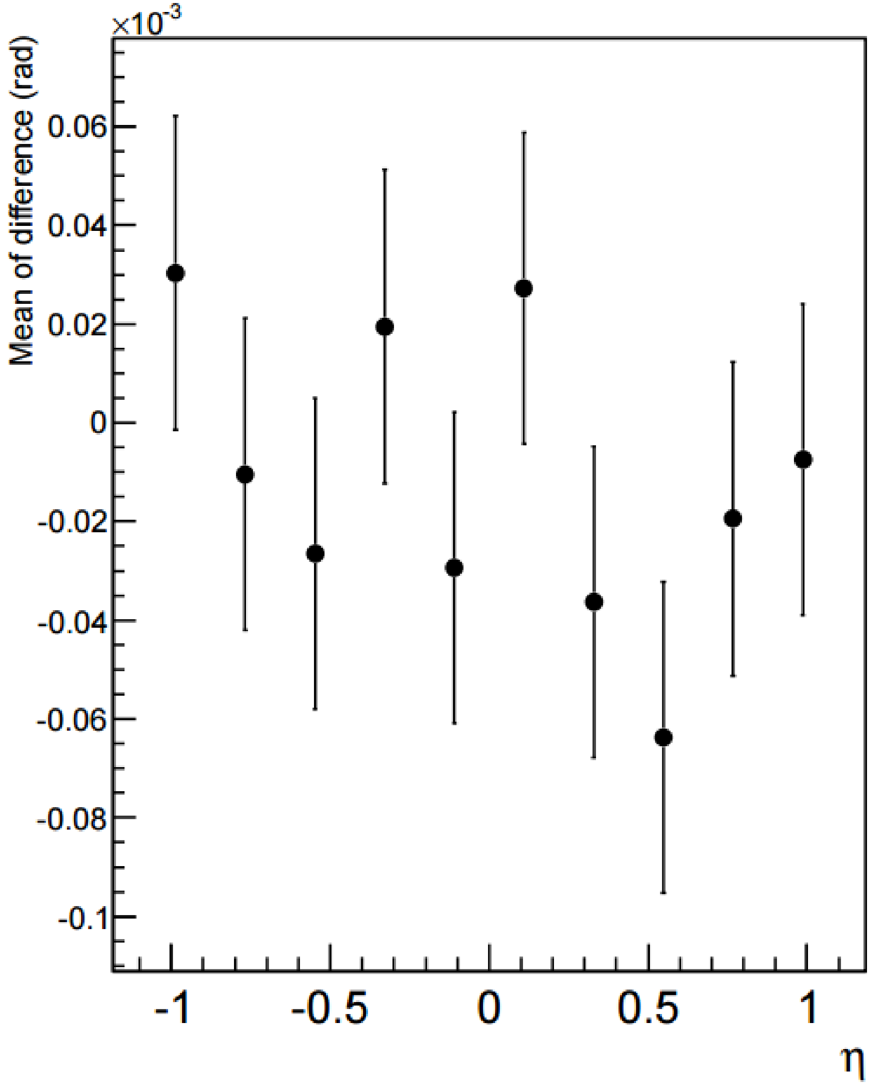
	HERA@DESY	LHeC@CERN	eRHIC@BNL	JLEIC@JLab	HIAF@CAS	ENC@GSI
E_{CM} (GeV)	320	800-1300	45-175	12-140	12 → 65	14
proton x_{min}	1×10^{-5}	5×10^{-7}	3×10^{-5}	5×10^{-5}	$7 \times 10^{-3} \rightarrow 3 \times 10^{-4}$	5×10^{-3}
ion	p	p to Pb	p to U	p to Pb	p to U	p to ~ ^{40}Ca
polarization	-	-	p, ^3He	p, d, ^3He (^6Li)	p, d, ^3He	p,d
L [cm^{-2} s^{-1}]	2×10^{31}	10^{33}	$10^{33\text{-}34}$	$10^{33\text{-}34}$	$10^{32\text{-}33} \rightarrow 10^{35}$	10^{32}
IP	2	1	2+	2+	1	1
Year	1992-2007	2022 (?)	2022	Post-12 GeV	2019 → 2030	upgrade to FAIR

Germany CERN US China Germany

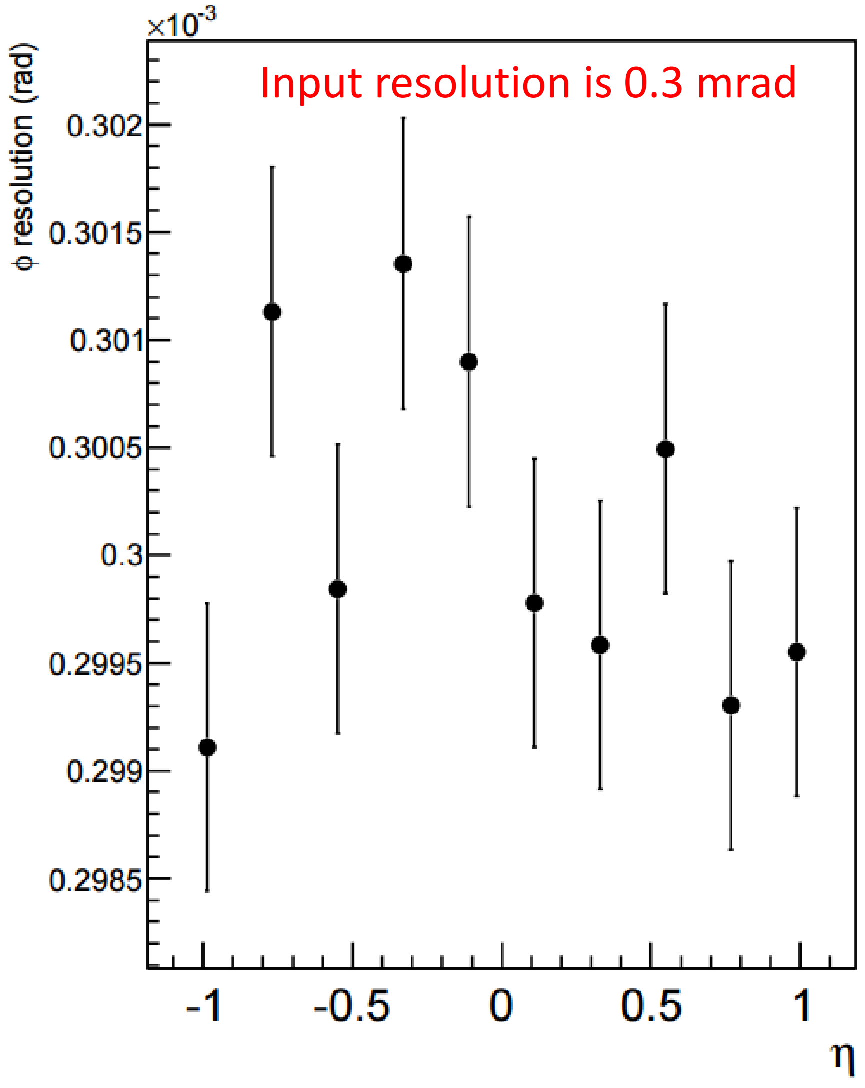
The past **Possible future**

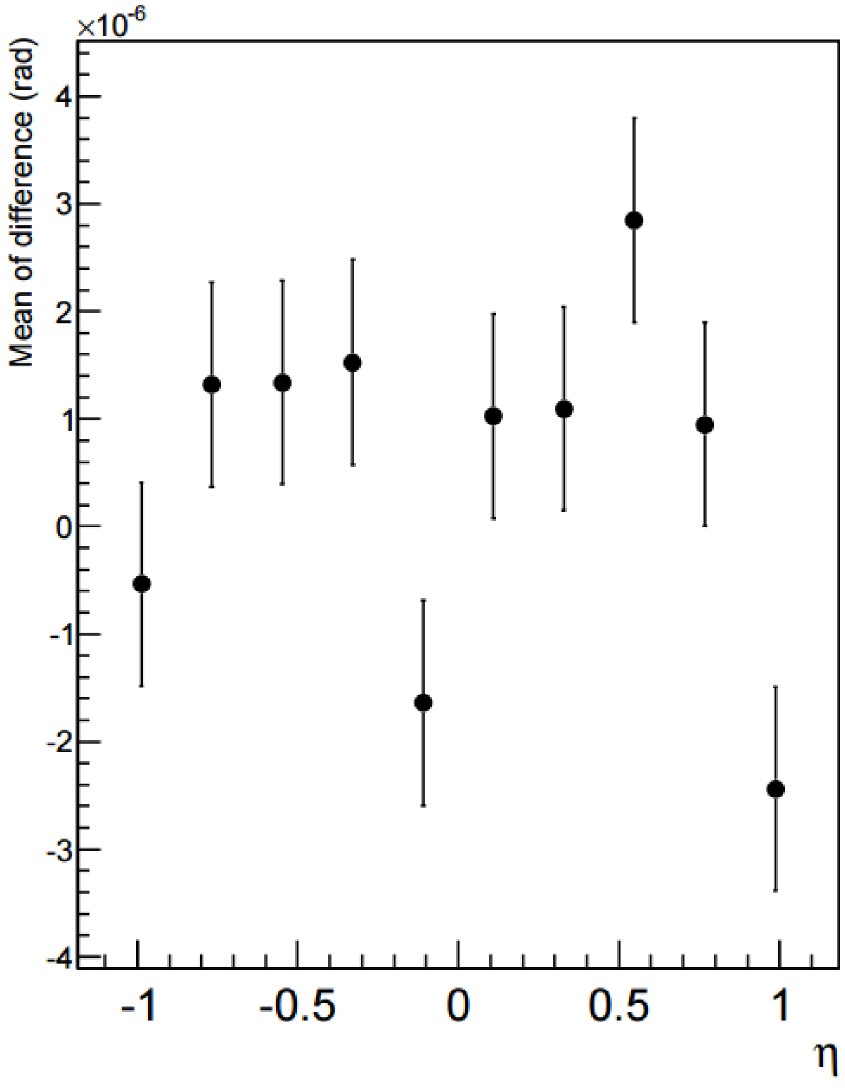
Check of detector smearing ---theta





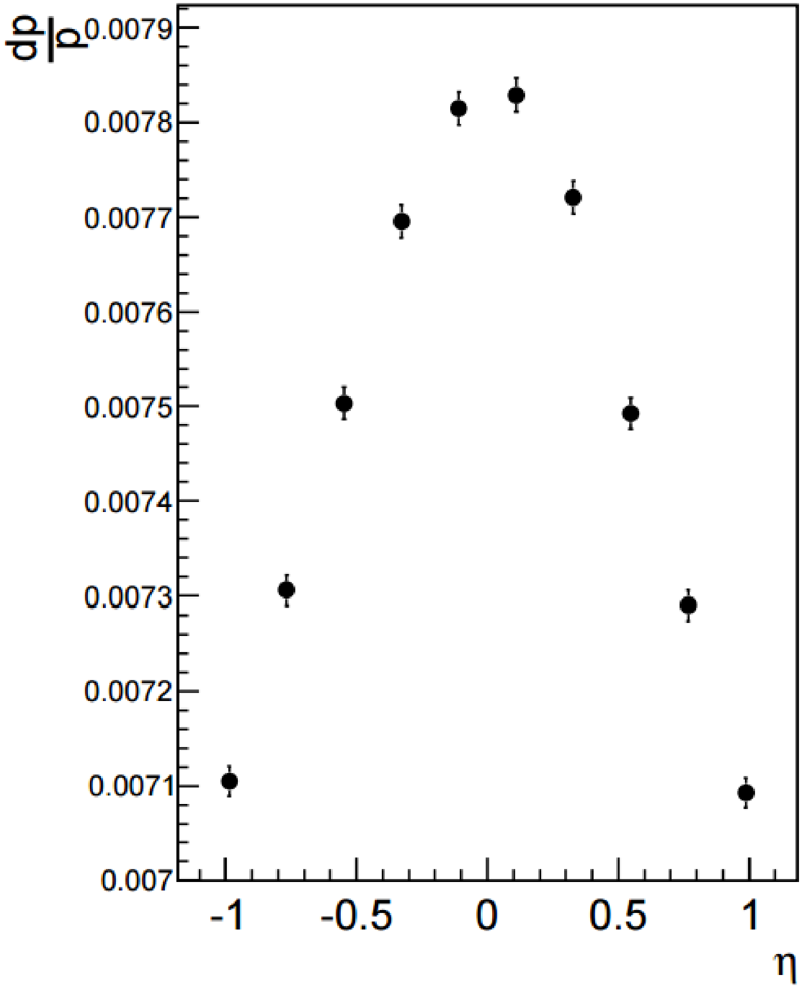
Check of detector smearing ---phi

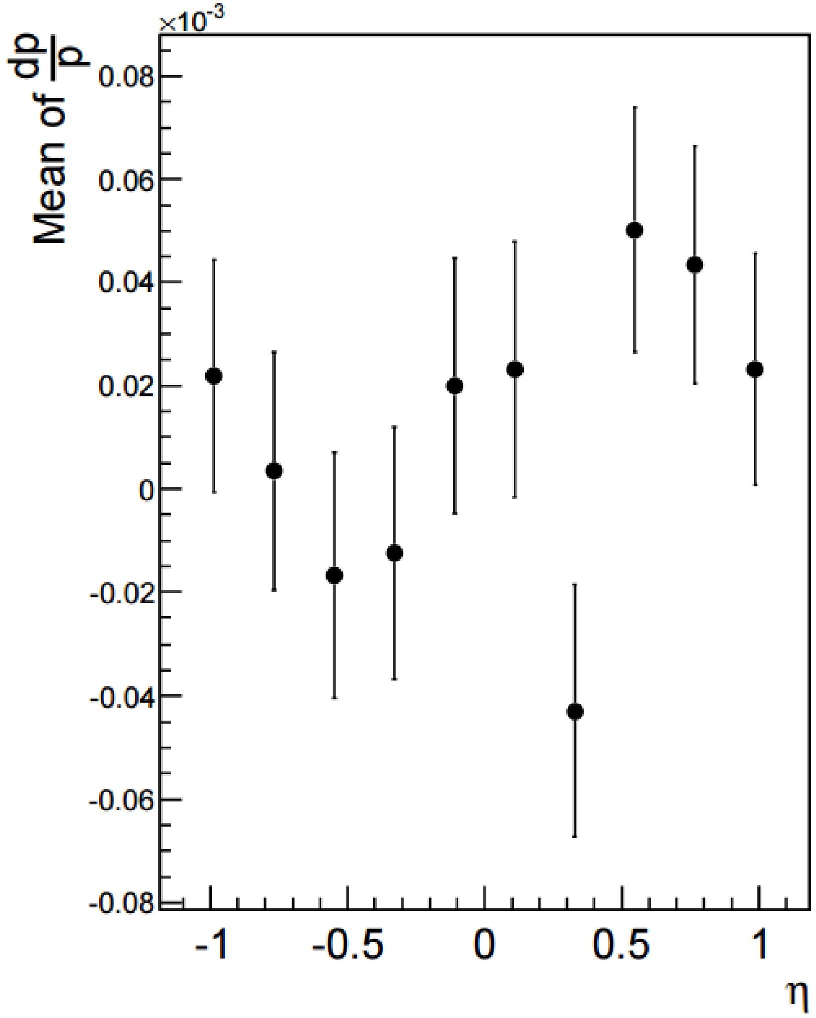




Check of detector smearing ---dp/p (for 5 +/- 0.1 GeV particles)

For 5 GeV electrons at θ = 90 degree, $\frac{dp}{p}$=0.79% and $\frac{dE}{E}$=6%.





Parametrized detection resolutions for inclusive electrons

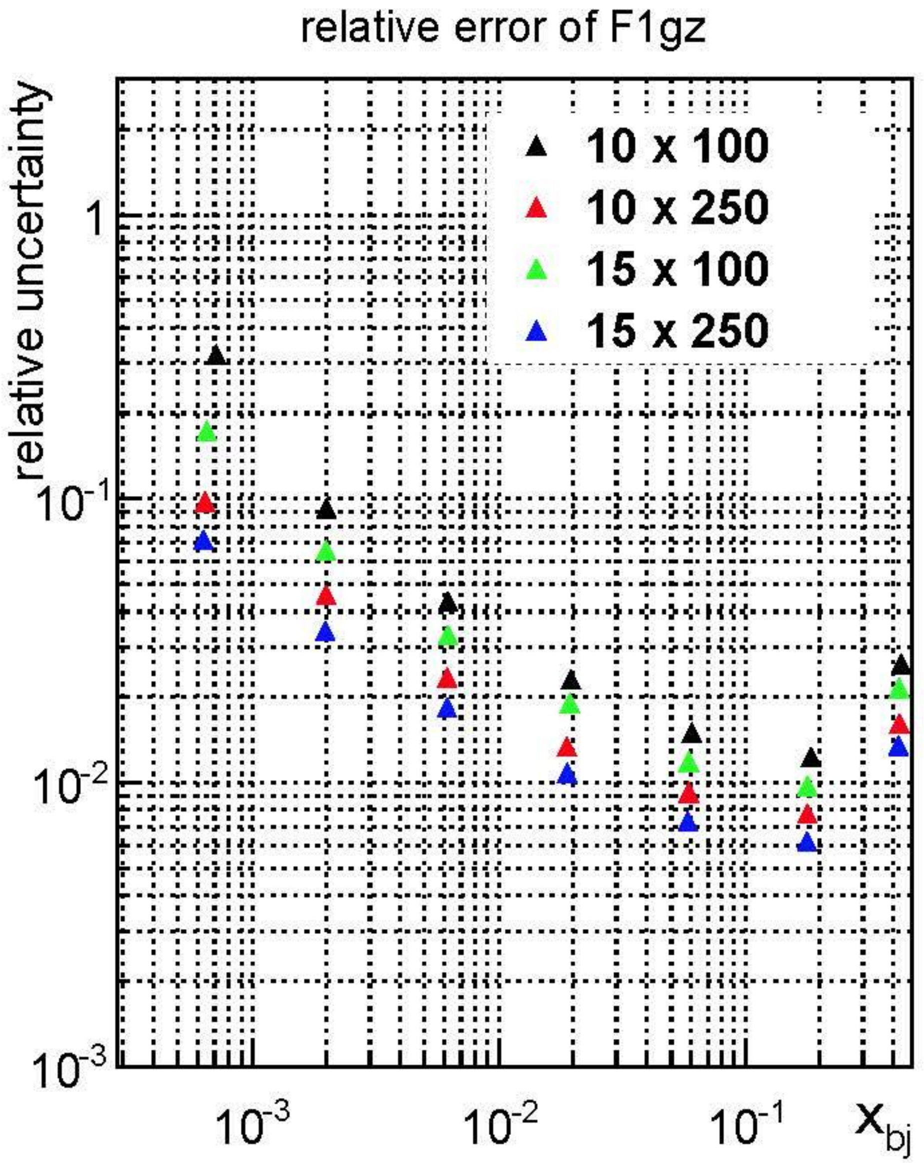
```
------Barrel: -1.1<eta<+1.1

  Tracking:

        dpT/pT = 0.65% (+) 0.09%*pT,  [2] Fig 4.32

        dTheta ~ 10 mrad

        dPhi  ~ 0.3mrad

  EMCal:

        dE/E = 3.0% (+) 11.7%/Sqrt(E). [2] Fig 5.23
```

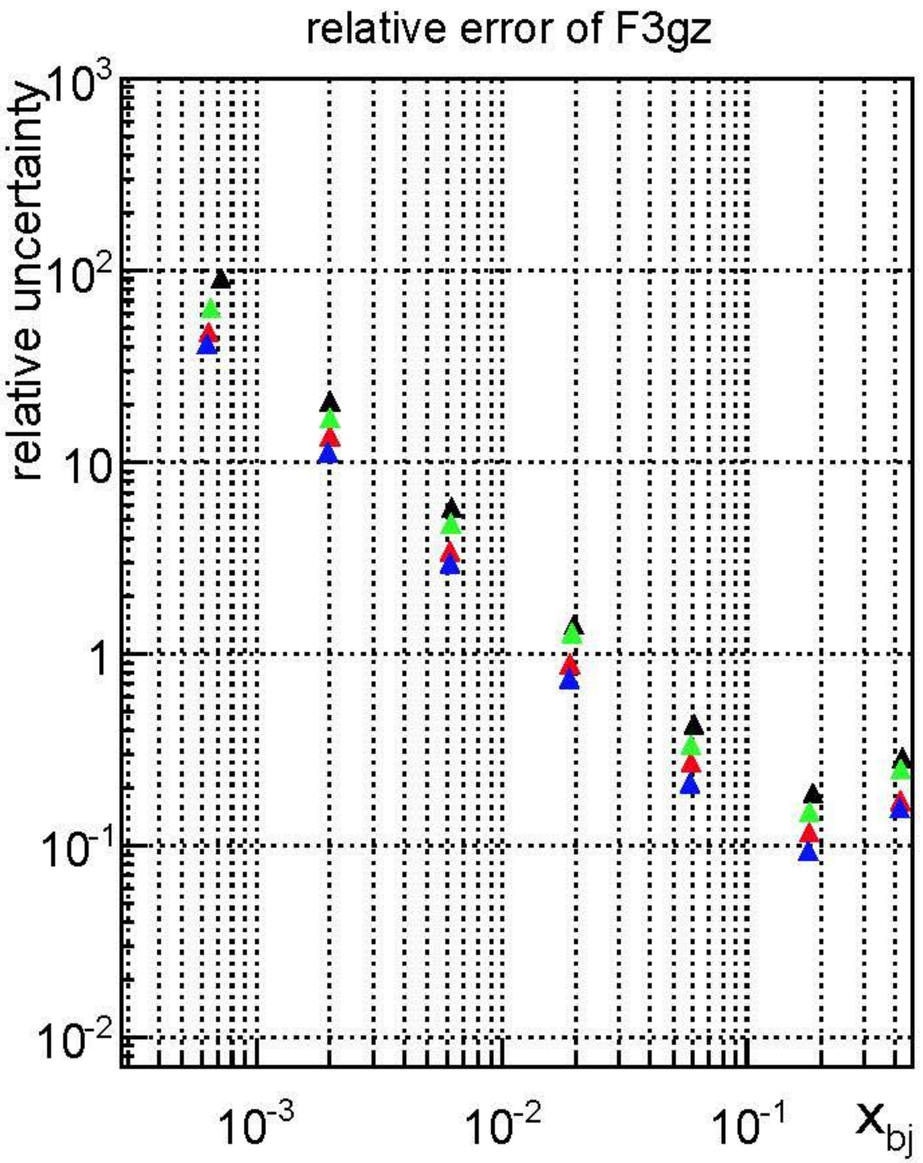
```
------Forward: eta > 1.1  (in my simulation using DJANGOH, electron going direction is the positive direction)

  Tracking:

        dpT/pT ~ 0.65% (+) 1%*pT,  [1] Fig 3.4

        dTheta ~ 1 mrad

        dPhi  ~ 0.3mrad

  EMCal:
        dE/E = 1.0% (+) 2.5%/Sqrt(E). [1] Sec 3.3.1
```


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

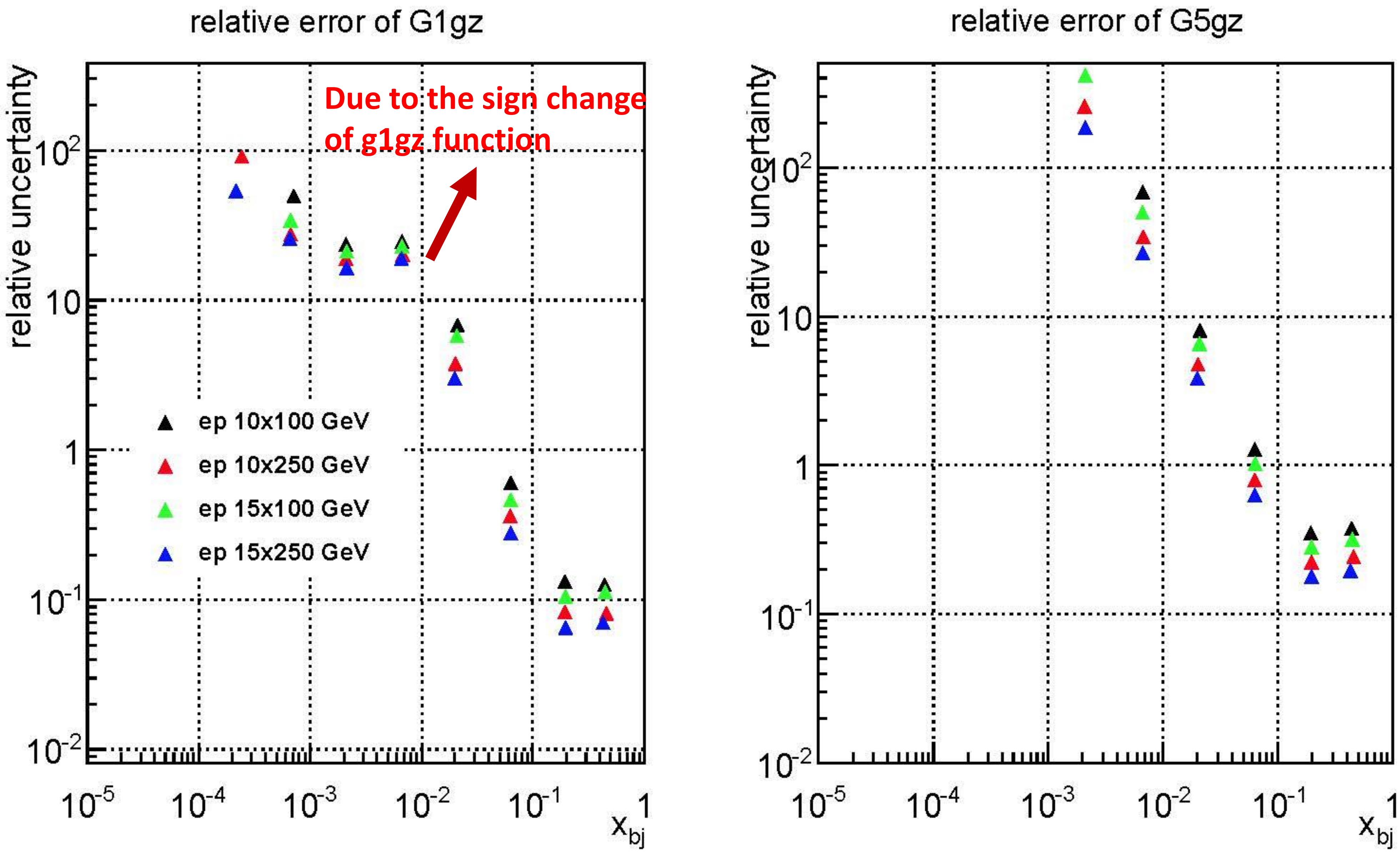
Reference [2] sPHENIX pre-CDR design report: https://indico.bnl.gov/conferenceDisplay.py?confId=1483

Projections on the measured yield (before unfolding)

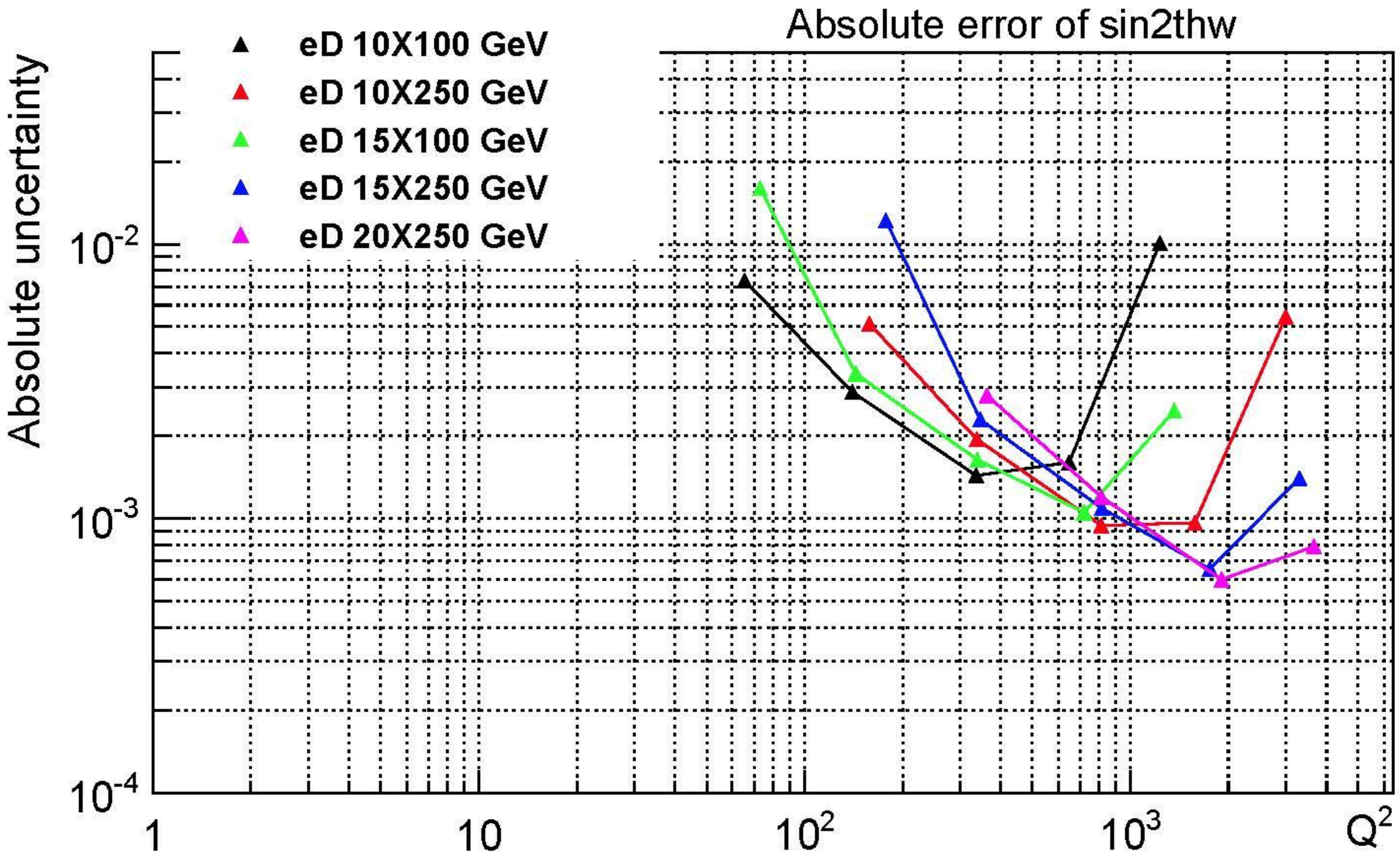




Projections on the measured yield (before unfolding)



Projections on measured yield



Projections considering bin migration