Measurement of proton spin structure g_1^p and its moments from CLAS EG4 data

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June 20, 2019

- Physics motivation
- EG4 run overview
- Event selection
- Data analysis
- Results and status

Other "core" "most recent" "analyzers": Alexandre Deur, Sebastian Kuhn, Mikhail Osipenko, Marco Ripani, Jixie Zhang

Acknowledgment:

EG4 spokespeople: M. Battaglieri, R. De Vita, A. Deur, G. Dodge, M. Ripani, K. Slifer

EG4 students: K. Adhikari (inclusive ND3), H. Kang (inclusive NH3), K. Li-Kovacs (target)

UVa group Funded by DOE

Physics Motivation for Measurement of Spin Structure Functions and Their Moments

- Spin observables provide a testing ground for QCD and our understanding of the nucleon structure
- The Q^2 dependence allow us to study "How hadrons arise from quark and gluon degrees of freedom"?
- At very low Q^2/ long distance regime:
  - Perturbative QCD does not apply
  - Testing effective field theories that deal with non-perturbative regime

(Some) Moments and Sum Rules

- Quark spin contribution to the nucleon spin: $\sum_f \Delta q_f$
- Bjorken Sum Rule: (current algebra, isospin symmetry)

$$\int (g_1^p - g_1^n)\, dx = \frac{1}{6} g_A \left(1 + \frac{\alpha_S(Q^2)}{\pi} + \ldots\right) + \text{non-pertubative corrections (higher twist)}$$

axial charge

- GDH Sum Rule (real photon):

anomalous magnetic moment

(unitarity)

$$\int_{\nu_{th}}^{\infty} (\sigma^{1/2} - \sigma^{3/2}) \frac{d\nu}{\nu} = -\frac{2\alpha\pi^2\kappa^2}{M^2}$$

- GDH Sum Rule (virtual photon):

$$\boxed{I_{TT}(Q^2)} = \frac{M^2}{8\pi^2\alpha} \int_{\nu_{th}}^{\infty} \frac{K}{\nu} \frac{\sigma_{TT}}{\nu} d\nu = \frac{2M^2}{Q^2} \int_0^{x_{th}} A_1 F_1\, dx \xrightarrow[Q^2 \to 0]{} -\frac{2\alpha\pi^2\kappa^2}{M^2}$$

$$\frac{16\alpha\pi^2}{Q^2} \boxed{\int_0^1 g_1\, dx} = 2\alpha\pi^2 S_1$$

spin dependent DDVCS amplitude: low-to-intermediate Q^2: chiral PT, OPE

Higher Moments - Spin Polarizabilities

- Generalized forward spin polarizability:

$$\boxed{\gamma_0} = \frac{16\alpha M^2}{\pi Q^6}\int_0^{x_0} x^2\left[g_1 - \frac{4M^2}{Q^2}x^2 g_2\right]dx = \frac{16\alpha M^2}{\pi Q^6}\int_0^{x_0} x^2\left[A_1 F_1\right]dx$$

- Longitudinal-Transverse polarizability:

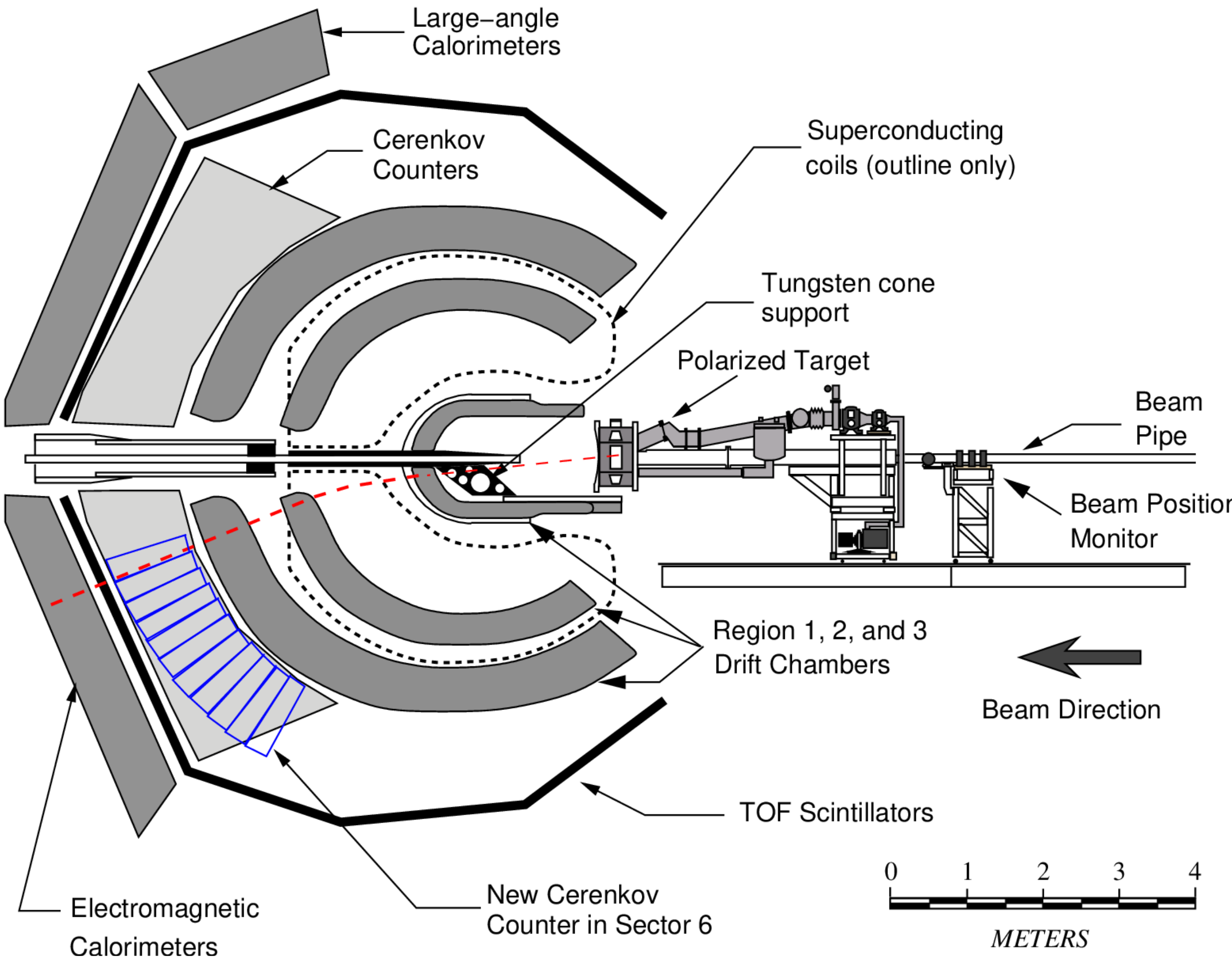
$$\delta_{LT} = \frac{16\alpha M^2}{\pi Q^6}\int_0^{x_0} x^2\left[g_1 + g_2\right]dx$$

- Twist-3 term d_2:

$$d_2(Q^2) = \int_0^1 x^2\left[2g_1(x,Q^2) + 3g_2(x,Q^2)\right]dx = 3\int_0^1 x^2\left[g_2(x,Q^2) - g_2^{WW}(x,Q^2)\right]dx$$

Calculations exist or possible from lattice QCD, Dyson-Schwinger Equations, or Chiral PT

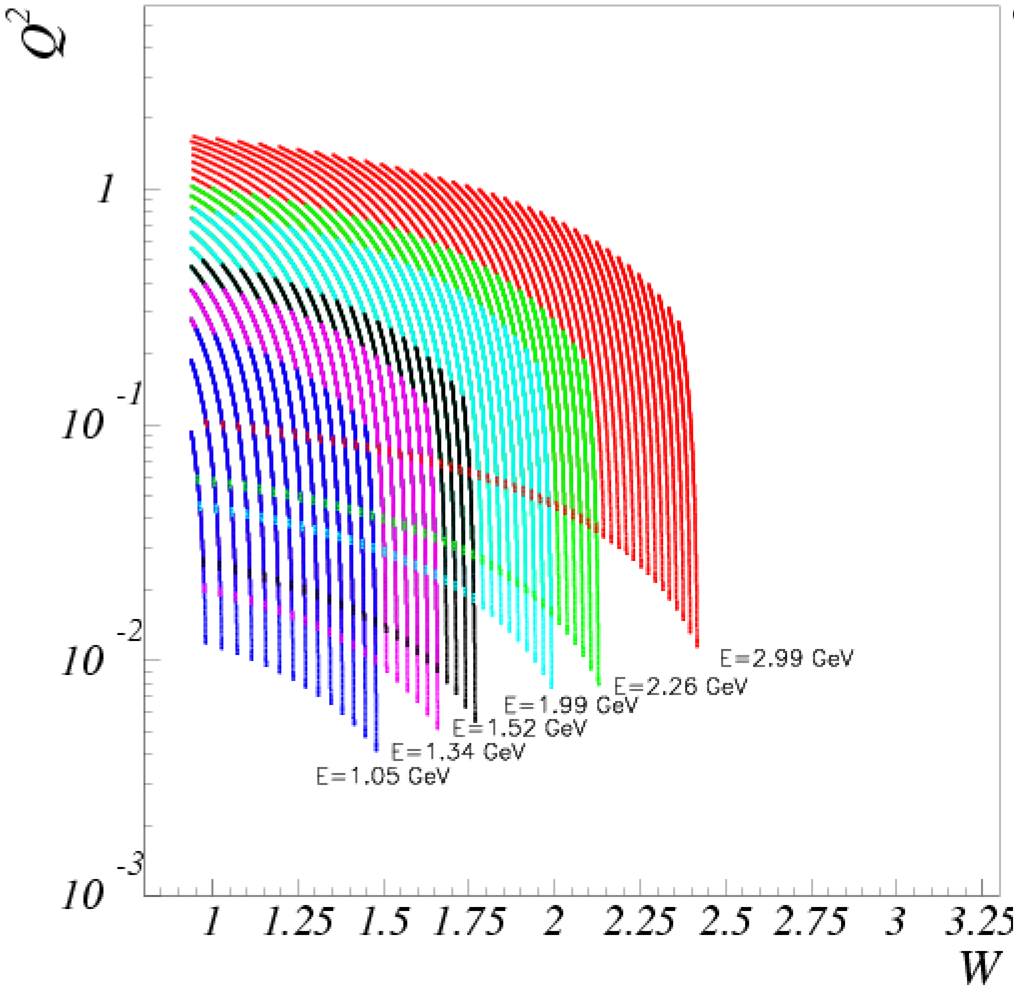
EG4 Overview



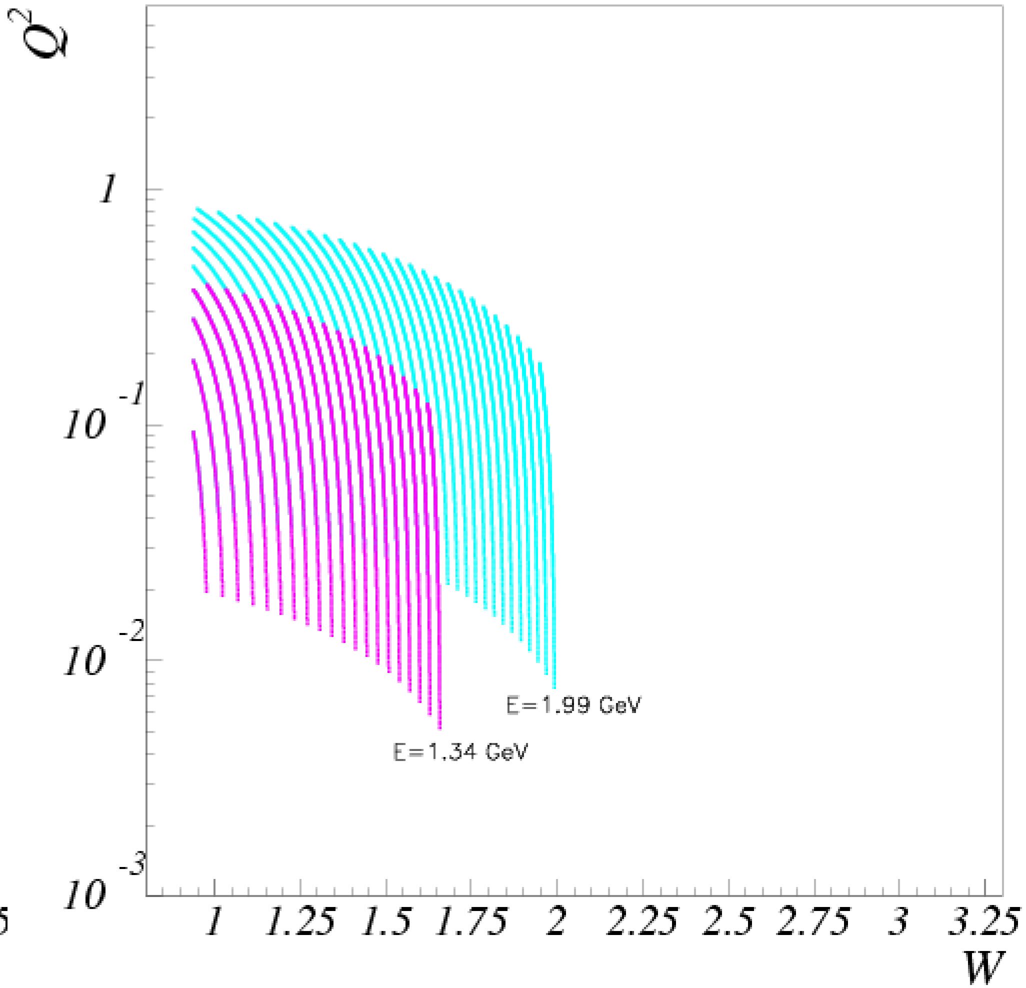
- Ran in Feb-Apr.2006
- Polarized target installed at ~1m upstream of CLAS center
- New CC in sector 6 reached 6° scattering angle (outbending); allowed measurement of g_1 at very low Q^2
- Both NH3 and ND3 targets
- Main trigger: CC+EC, calibration runs used EC only.
- At present, ND3 (deuteron) g1 results published, exclusive pion production channel asymmetries published

EG4 Kinematic Coverage

NH$_3$ target

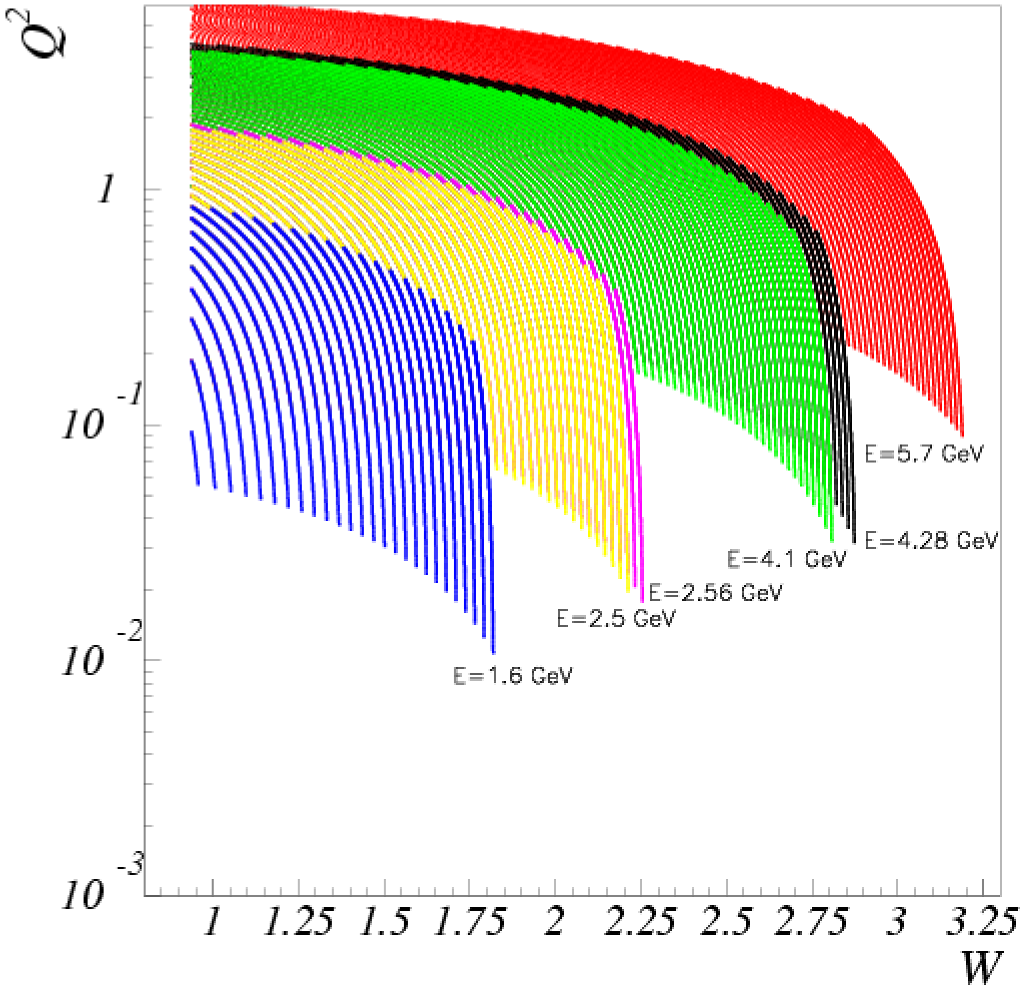


ND$_3$ target



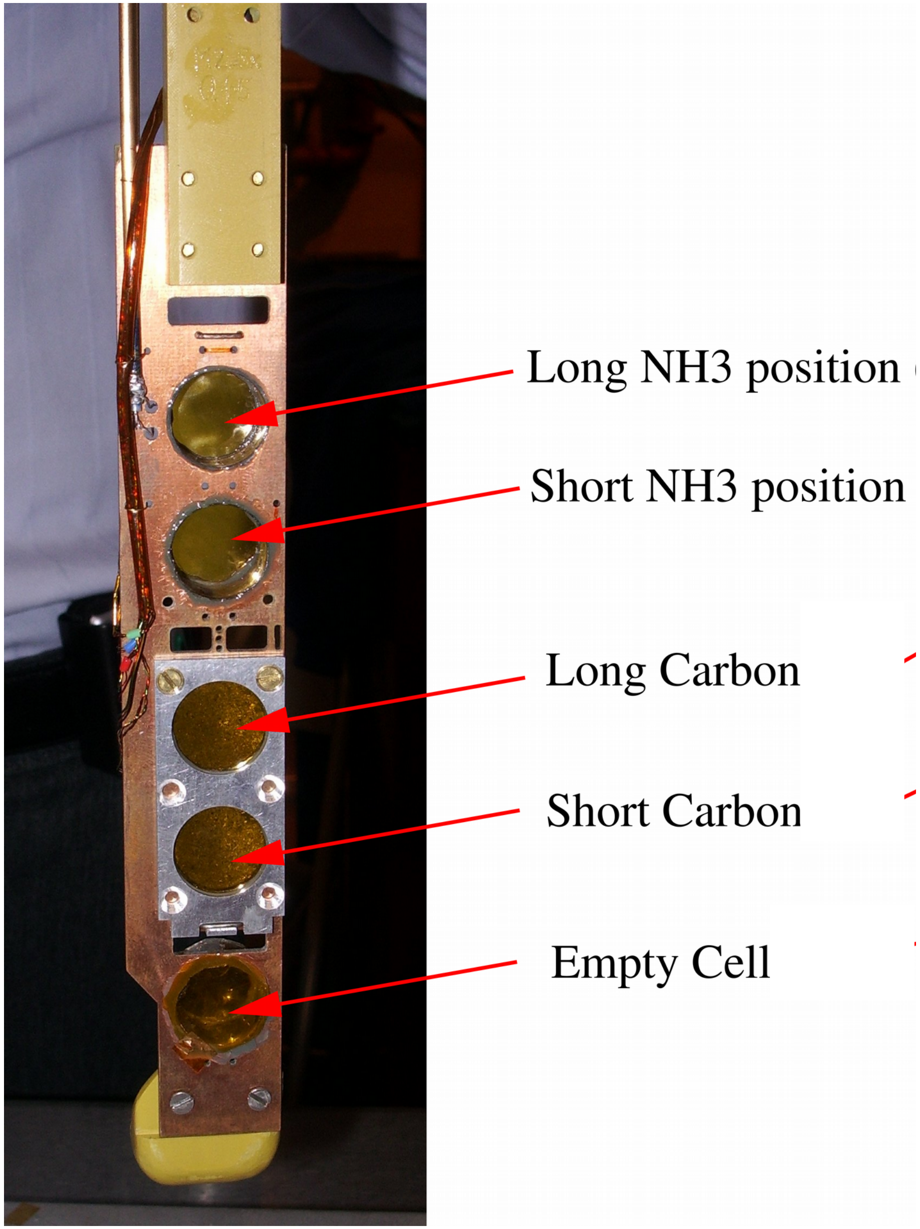
EG4 Kinematic Coverage

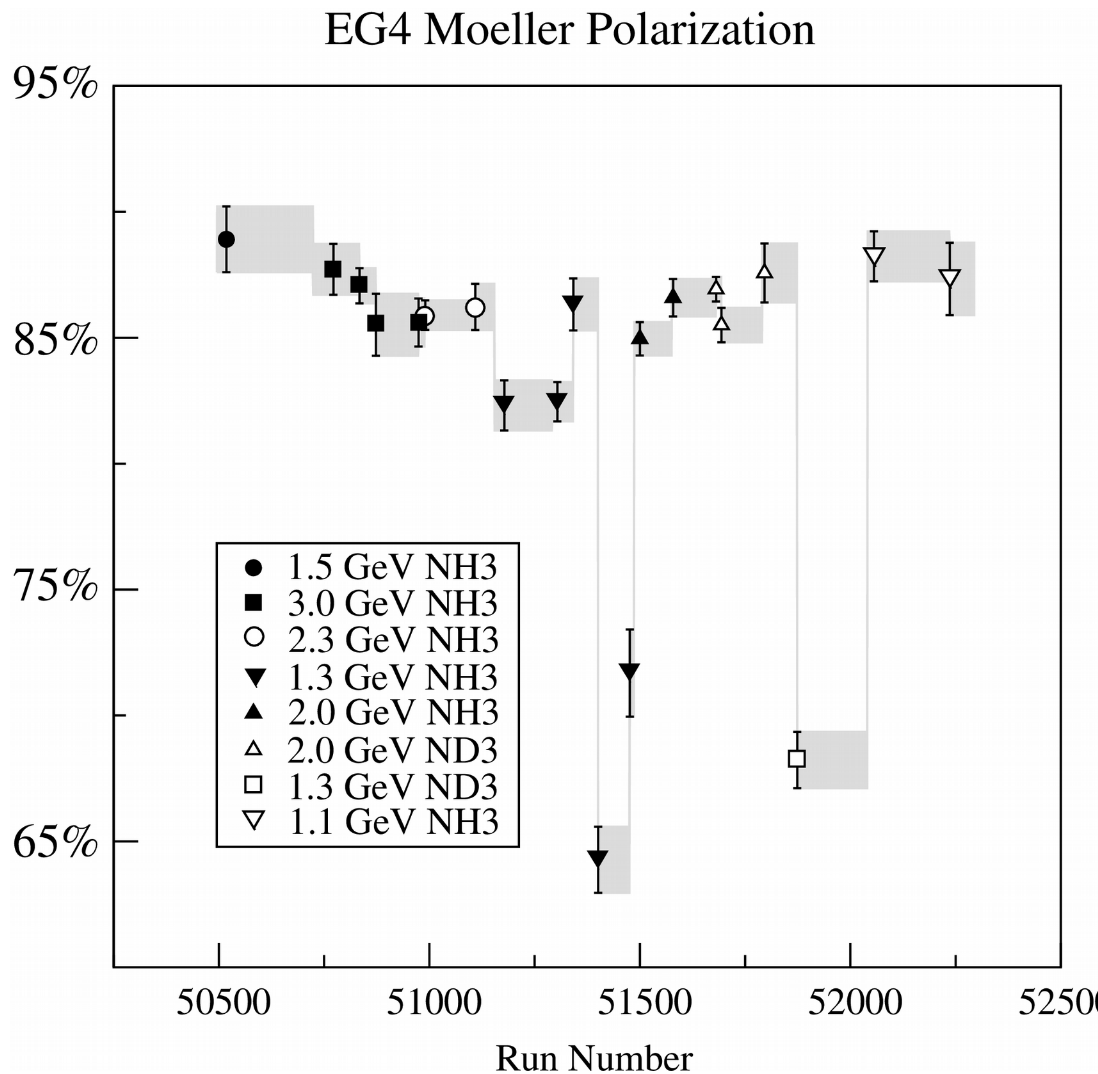
eg1b coverage: (for comparison)



Lowest Eb: 1.6 GeV

EG4 Target Insert and Beam Polarization





NH3 Target Inclusive Channel Statistics

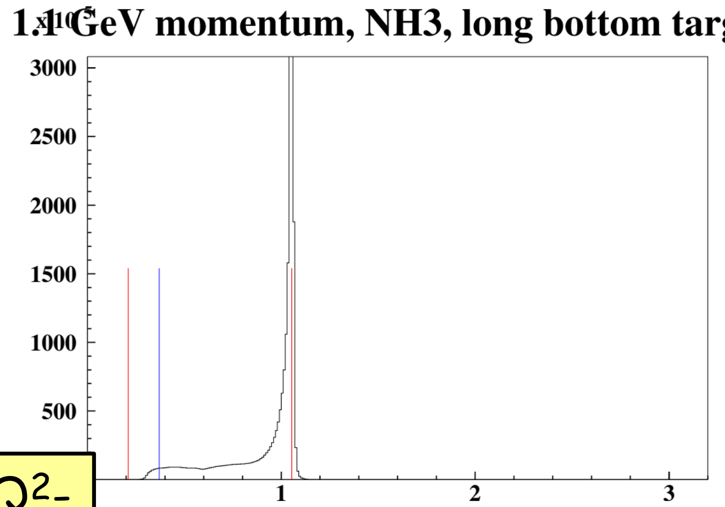
E_{beam} (GeV)	NH_3 target	#incl events for (target, beam) (1,0)	(1,1)	(-1,0)	(-1,1)	Q^2coverage (GeV^2)
1.1	long bottom	409M	411M	241M	241M	(0.011,0.156)
1.3	long top	160M	159M	135M	136M	(0.0223,0.223)
	long bottom	210M	209M	36M	36M	
	short	153M	152M	0	0	
2.0	long top	95.5M	96.2M	40.5M	40.1M	(0.0452,0.452)
	long bottom	5.8M	5.8M	0	0	
2.3	long top	36.7M	36.4M	25.8M	25.9M	(0.0919,0.645)
	short	34.6M	34.4M	24.1M	24.2M	
3.0	long top	57.9M	58.3M	33.8M	33.7M	(0.187,1.10)

Use of the short target provides check of radiative corrections

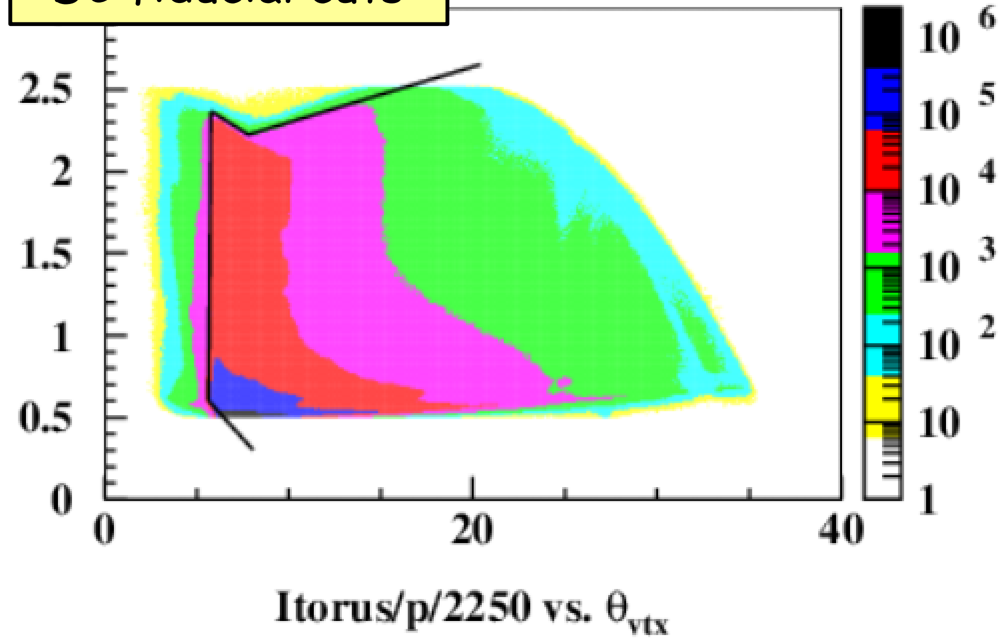
EG4 Proton Inclusive Channel Analysis

- Most of technique established in ND3 and exclusive-channel analysis. This includes: detector calibrations, beam charge analysis, PID, CC efficiency, kinematic corrections, kinematic and fiducial cuts;
- Vertex Z, EC signal, and DC and CC fiducial cuts fine-tuned for NH3 data.
- CC efficiency analyzed for NH3 data
- Extracted polarized yield differences
- Simulation was done on polarized yield differences using latest StrucFunc fits, multiple versions were generated, main sets are "standard fits", and "non-standard fits" where A1 is changed by +/-0.1.
- Extracted g_1 and A_1F_1 by comparing polarized yield differences between data and the two sets of simulations, factors such as PbPt and target thickness cancel through normalizing elastic simulation to data.
- Formed moments $\Gamma_{1,}\,\gamma_0$ and I_{TT} at low Q^2 (down to 0.012 GeV^2). Integration ranges not covered by data used latest S.F. fits to form the integrand.

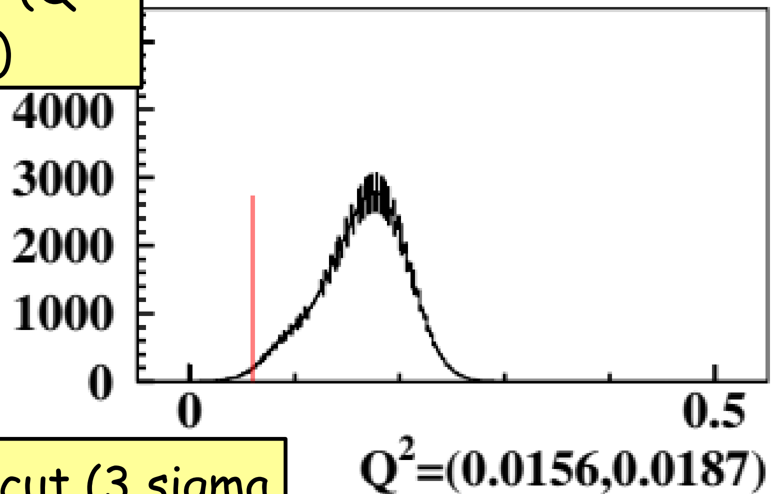
p cut



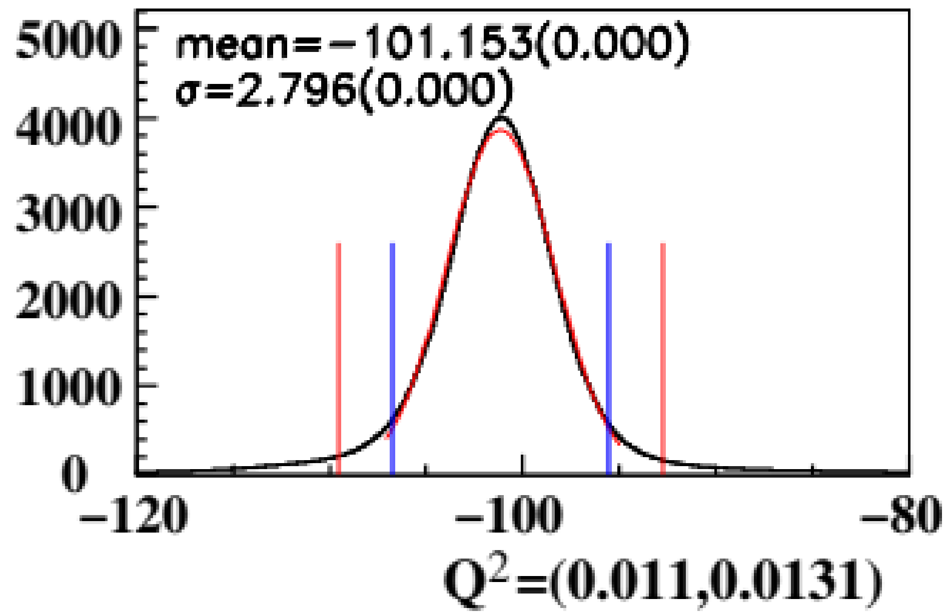
DC fiducial cuts



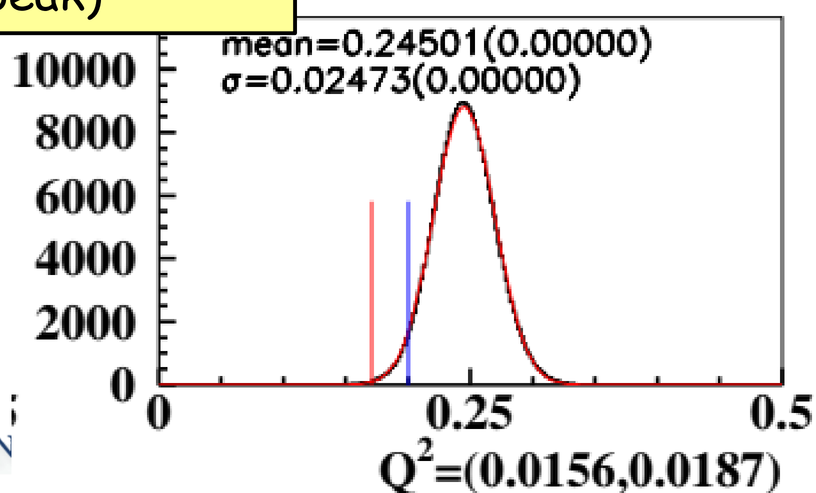
Ein cut (Q^2-binned)

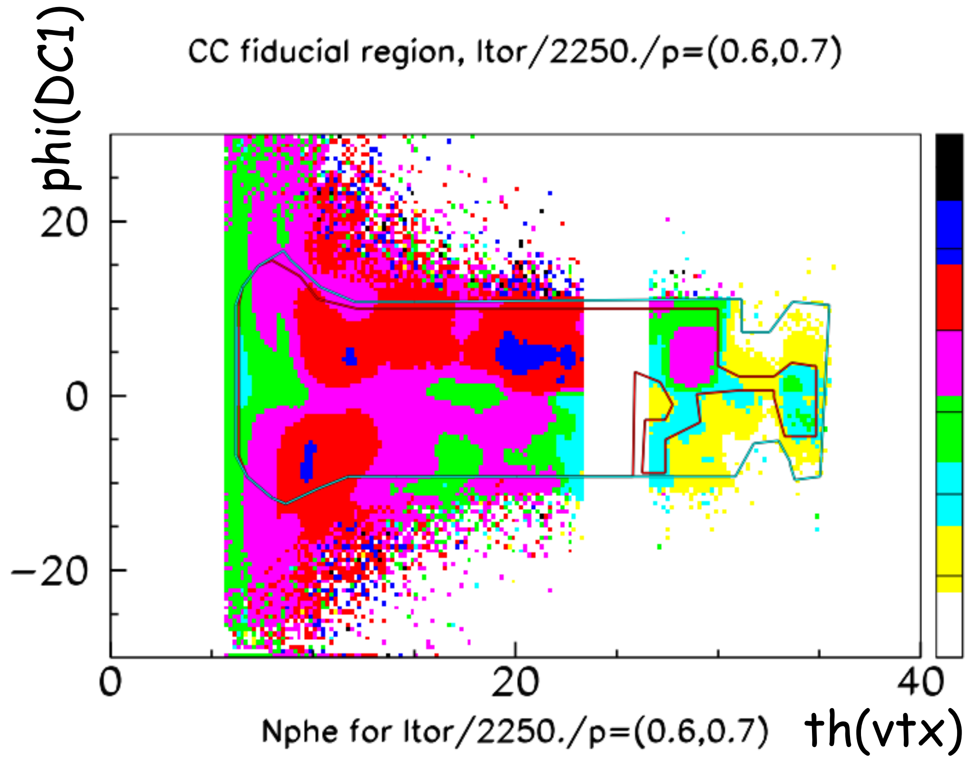


Zvertex cuts (Q2-binned, cut at 3, 2, or 1sigma)

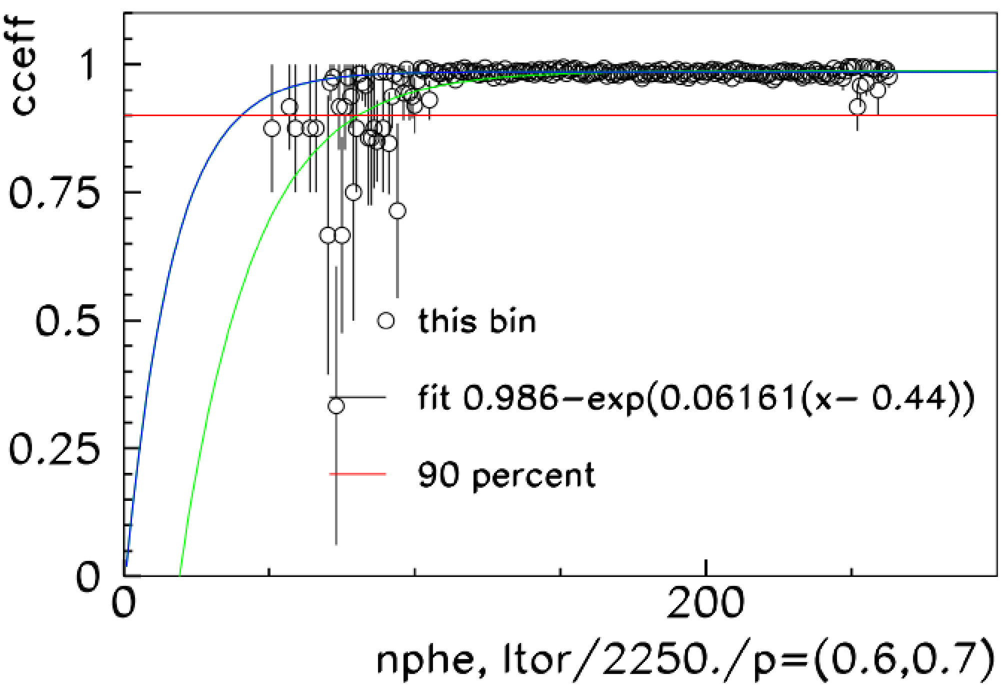


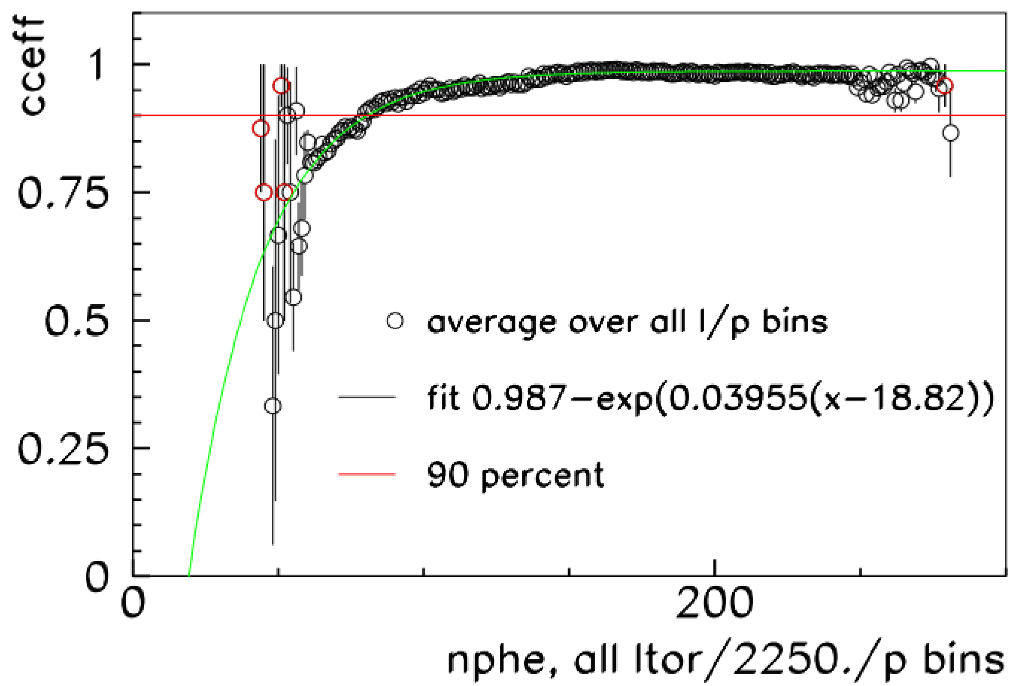
Etot/p cut (3 sigma below peak)





- CC: fiducial cuts determined for each Eb and Itor/p case;
- efficiency extracted for each phi(DC1) vs theta(vtx) bin using EC only calibration runs
- Poisson function used to fit efficiency vs. Npe, both Itor/p binned and total;
- The un-Itor/p-binned fit is used for the simulation (but different for beam energy/target combinations)
- data cut at Npe>2(or 20)





Analysis Procedure

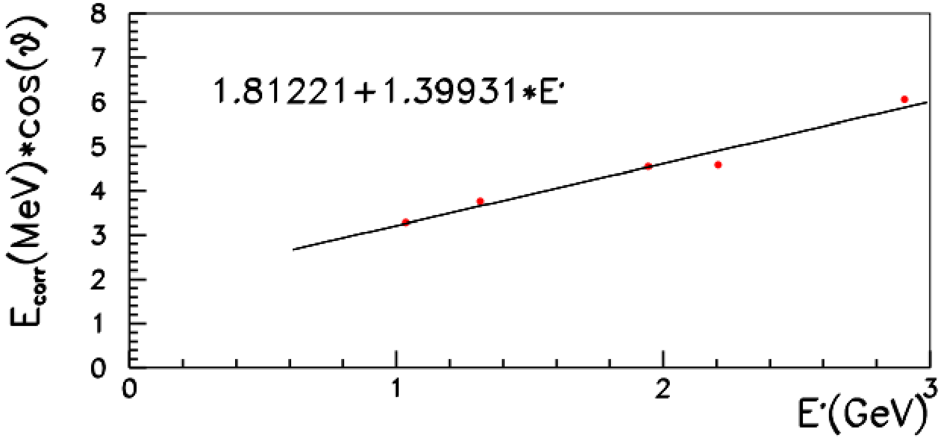
- Extraction of polarized yield differences
- Simulation of polarized yield differences
  - – elastic simulation using INFN generator + GSIM + …
  - – elastic peak normalization (to data) and fine-tuning
  - – inelastic simulation using RCSLACPOL + GSIM + …
  - – merging of two, extensive check of radiative tails
- Extraction of g1 and A1F1 from data
- Forming integrals of g1, A1F1, and A1F1x2

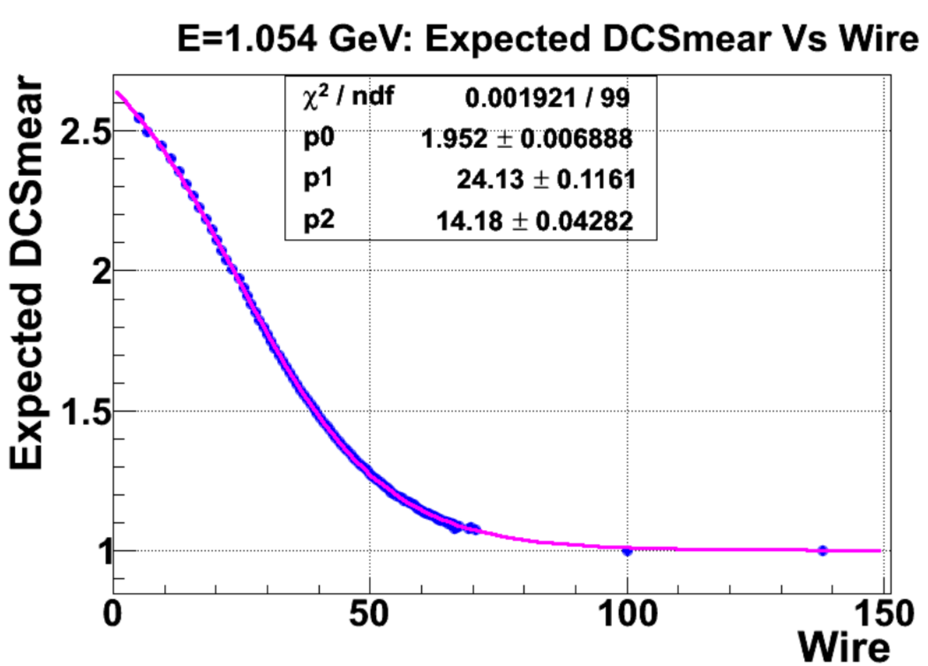
Elastic Simulation Details

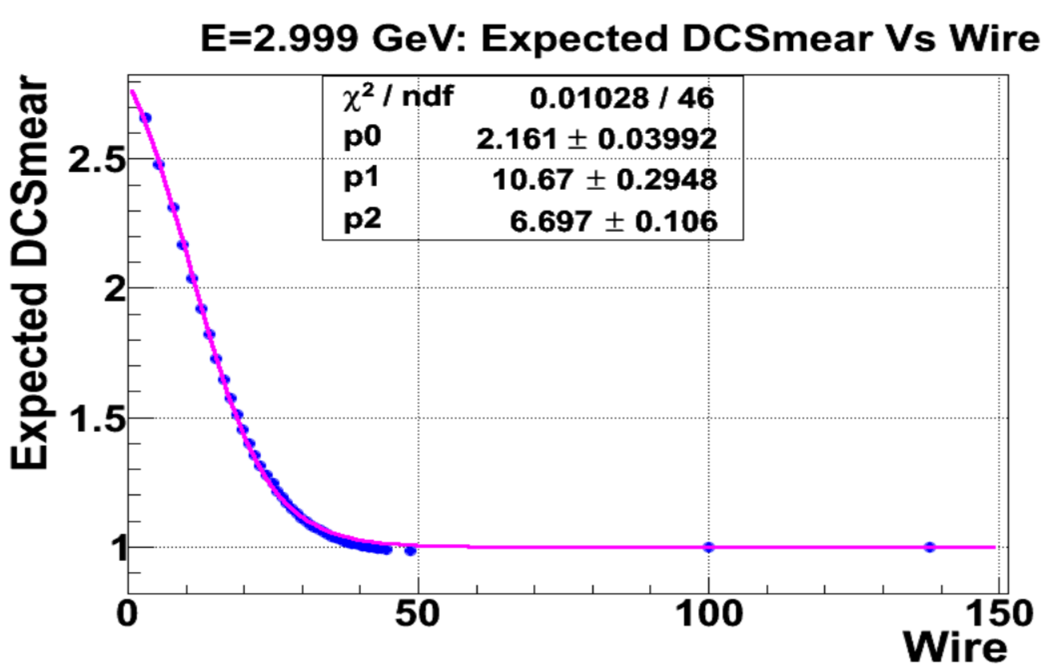
- INFN elastic event generator → GSIM → GPP → RECSIS
- Elastic peak comparison between data and simulation determined:

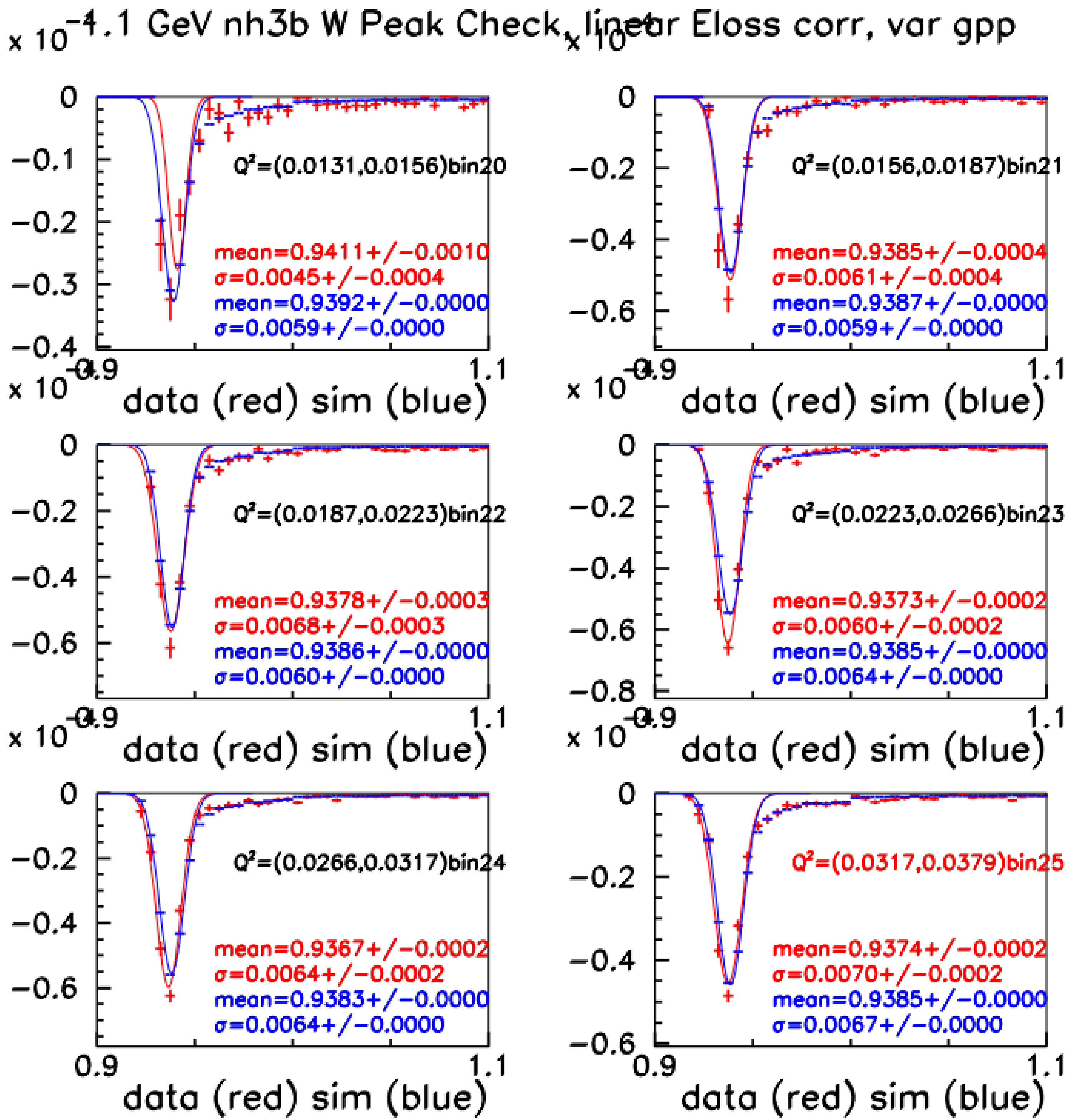
  – E′ correction for elastic events in the simulation to account for energy loss

  – GPP DC smearing (wire-number -dependent) to match elastic peak width with data





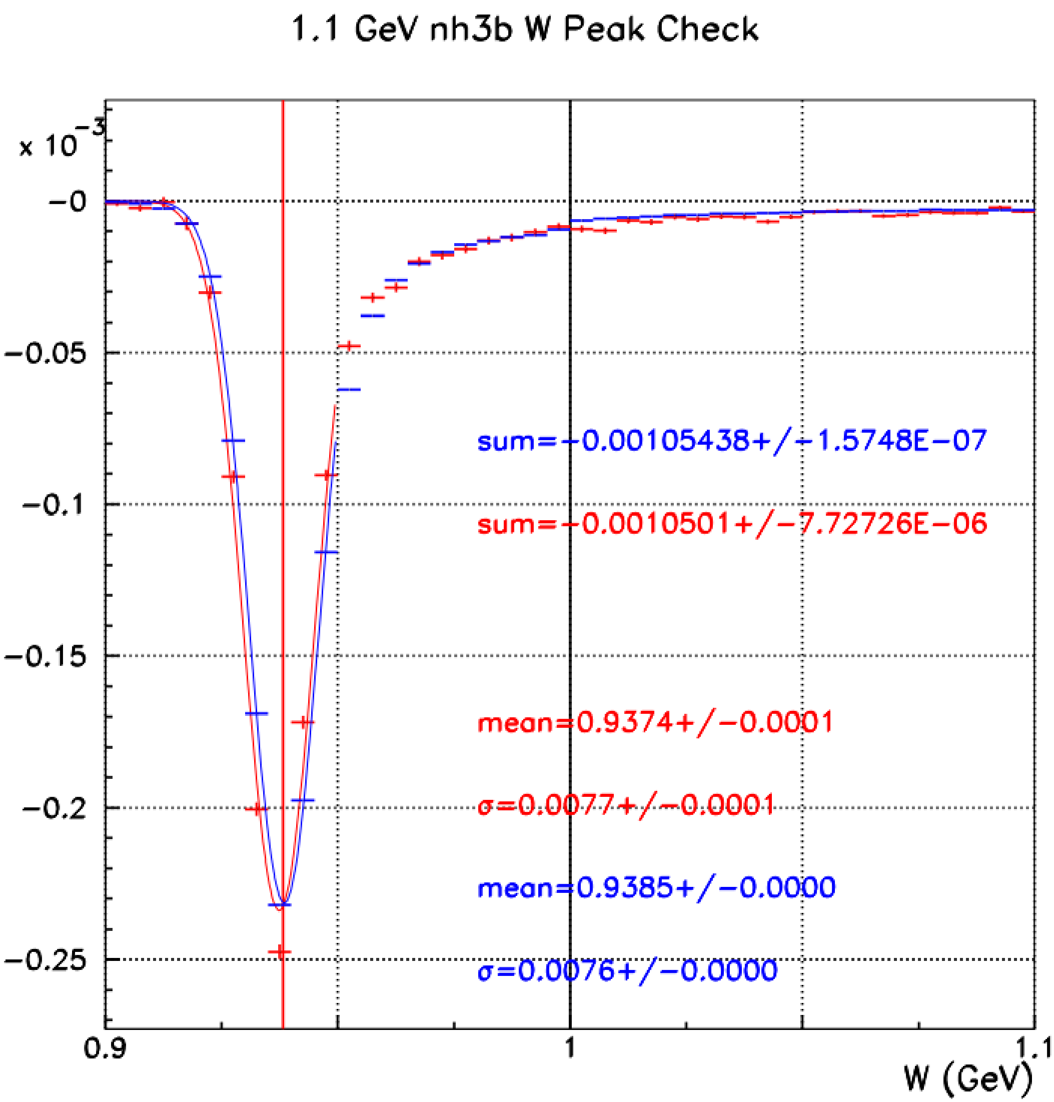




(sign of peak is arbitrary here)

– Q2-binned comparison provides a check for how good the simulation is.

Elastic Normalization Details



– Final normalization is done by summing all "good" Q2 bins;
– iterates until disagreement in peak area ("sum") reaches <2E-3

– Taken into further analysis:
(a) "normalization": stat uncertainty of data peak, 2E-3, and uncertainty in elastic FF

(b) "reconstruction": peak position discrepancy

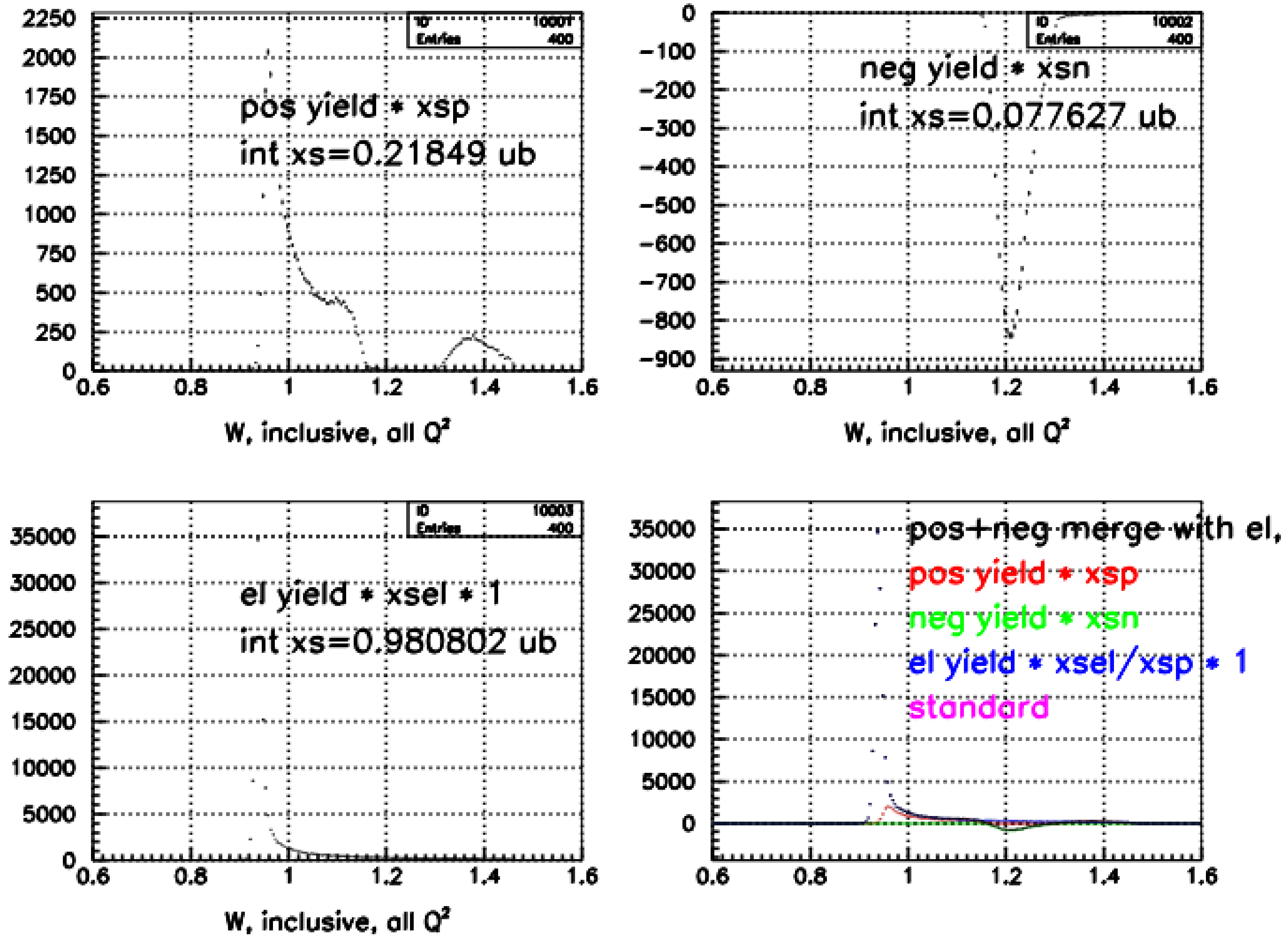
Inelastic Simulation Details

– based on RCSLACPOL
– generates two cross-section maps: One for positive, one for negative polarized x-sec
– Events are generated separated for the two maps and then combined

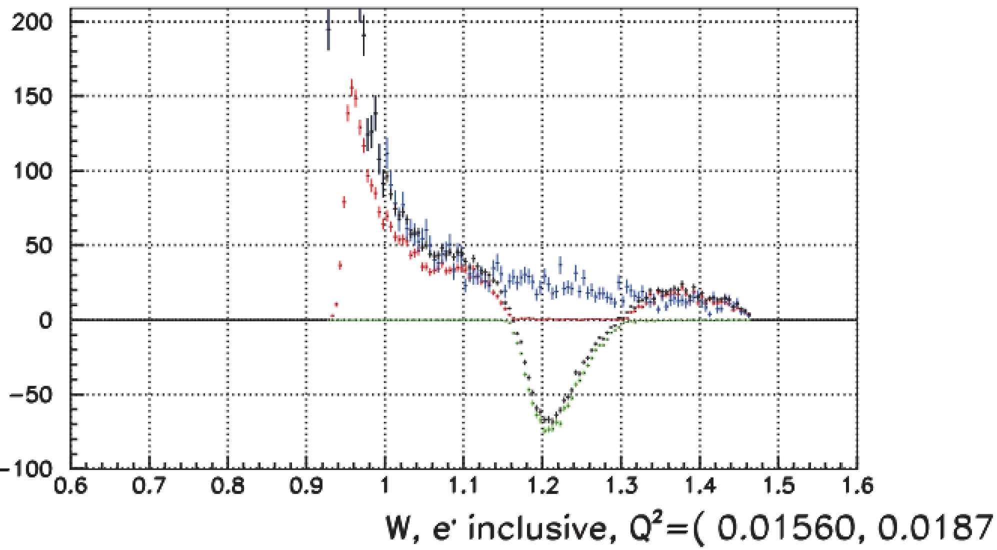
Merging of two simulations:
– Below W=1.0 GeV, take elastic simulation

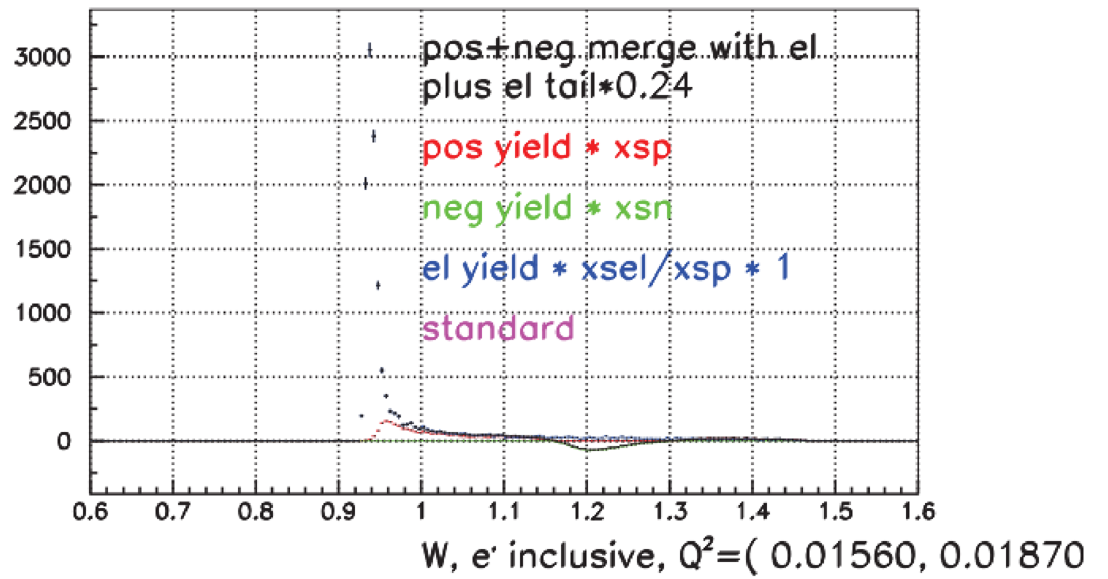
– Above W=1.0 GeV, take inelastic simulation, but see details of tail matching ...

1.1 GeV simulation, SF=20



1.1 GeV simulation, SF=20



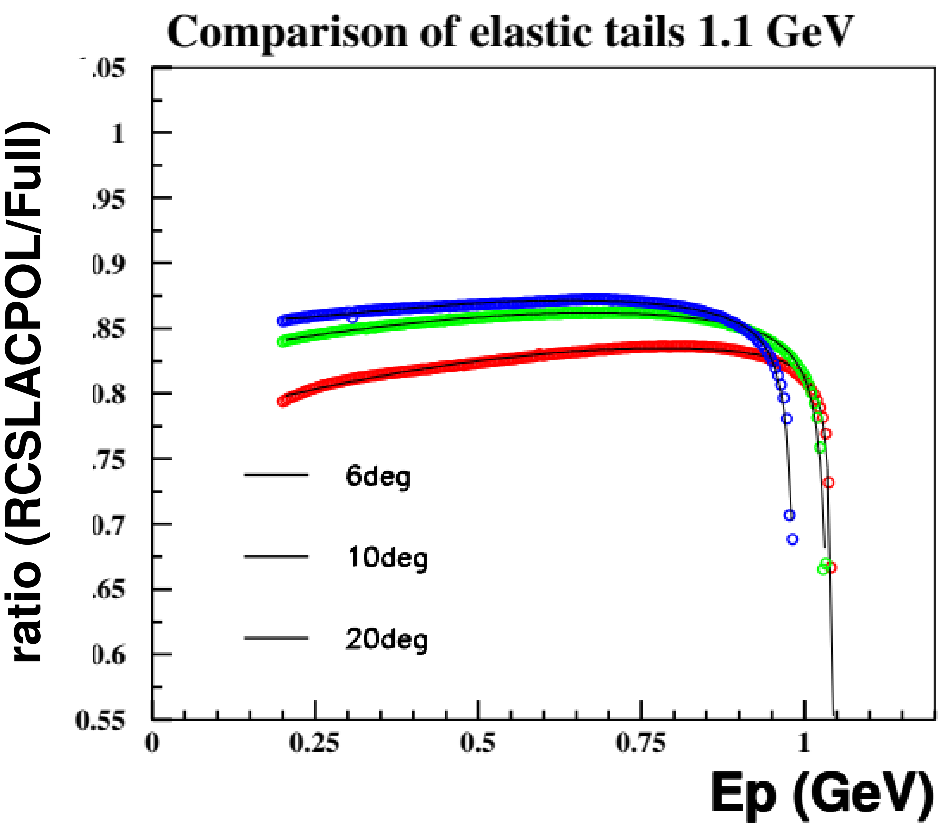


Inelastic Simulation Details

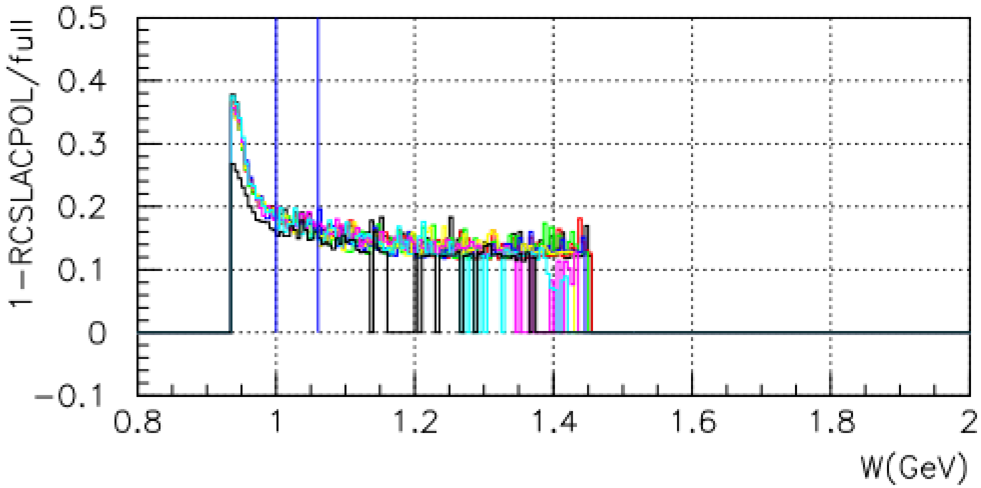
– Includes: full internal radiative tail of the elastic peak, and external radiation of the internally radiated tail of elastic peak.
– Only caveat: Does not include external radiative tail of elastic peak

Merging of two simulations:
– Below W=1.0 GeV, take elastic simulation
– Above W=1.0 GeV, adding fraction of elastic simulation (tail) to inelastic simulation
– "Fraction" determined by comparing the radiative tails of two codes (INFN vs. RCSLACPOL), and propagates through GSIM+GPP+RECSIS
– "Fraction" checked by data in the "tail region" $1.0 < W < 1.06$ GeV

– "Fraction" determined by comparing the radiative tails of two codes (INFN vs. RCSLACPOL),



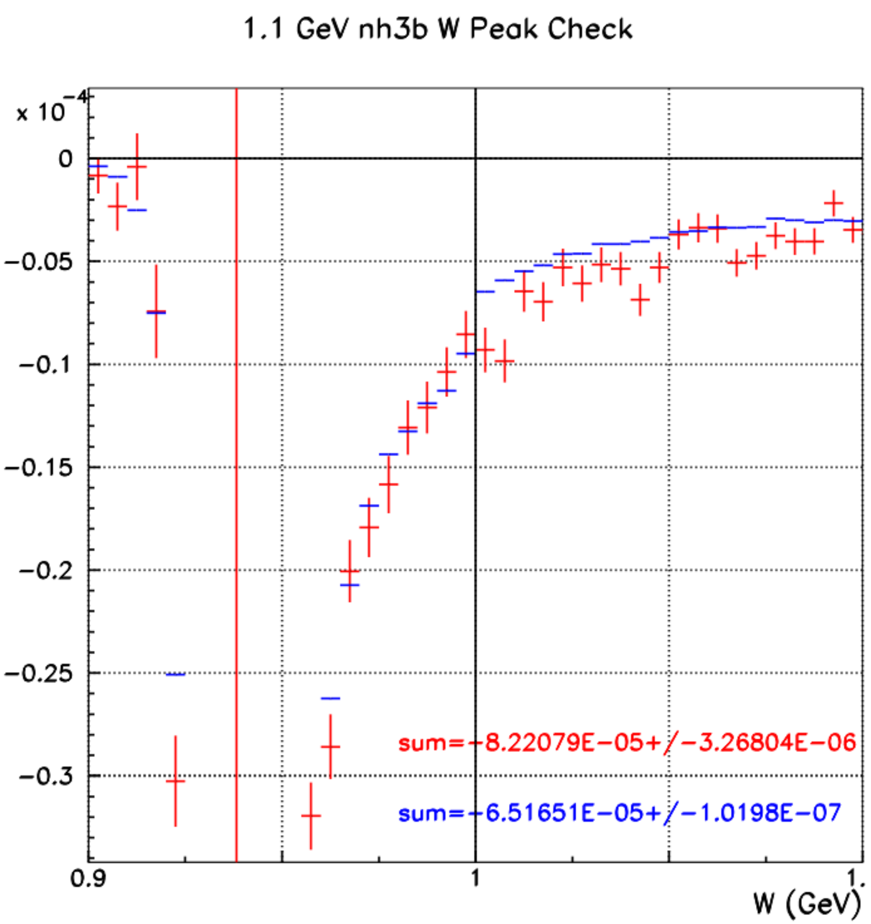
and propagates through GSIM+GPP+RECSIS

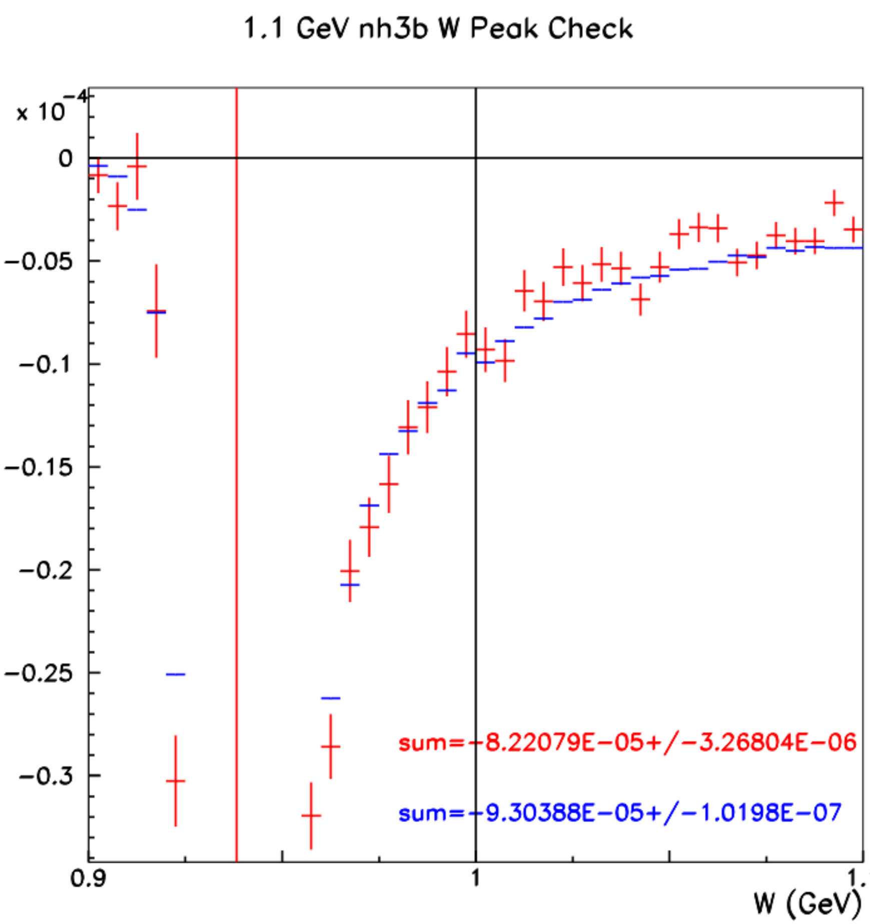


From above plot:

– extracted "missing tail" fraction for the tail region 1.0<W<1.06 (see next slide)

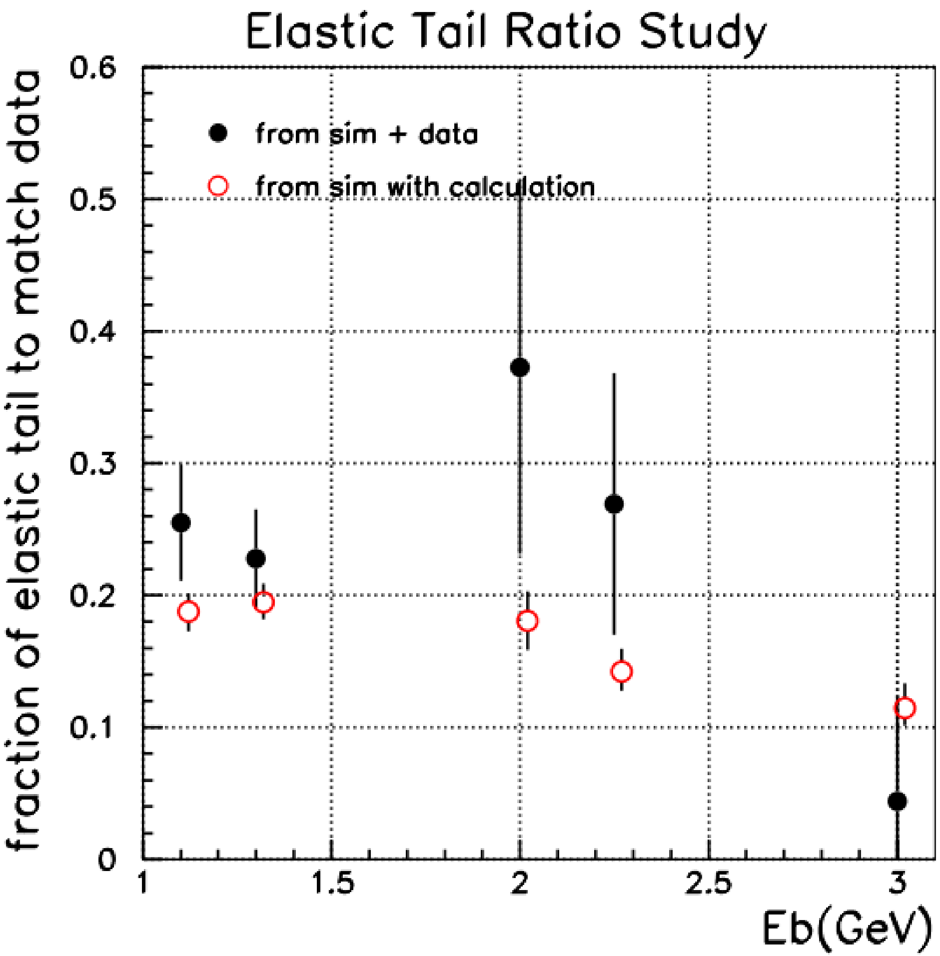
– “Fraction” checked by data in the “tail region” 1.0<W<1.06 GeV – step 1

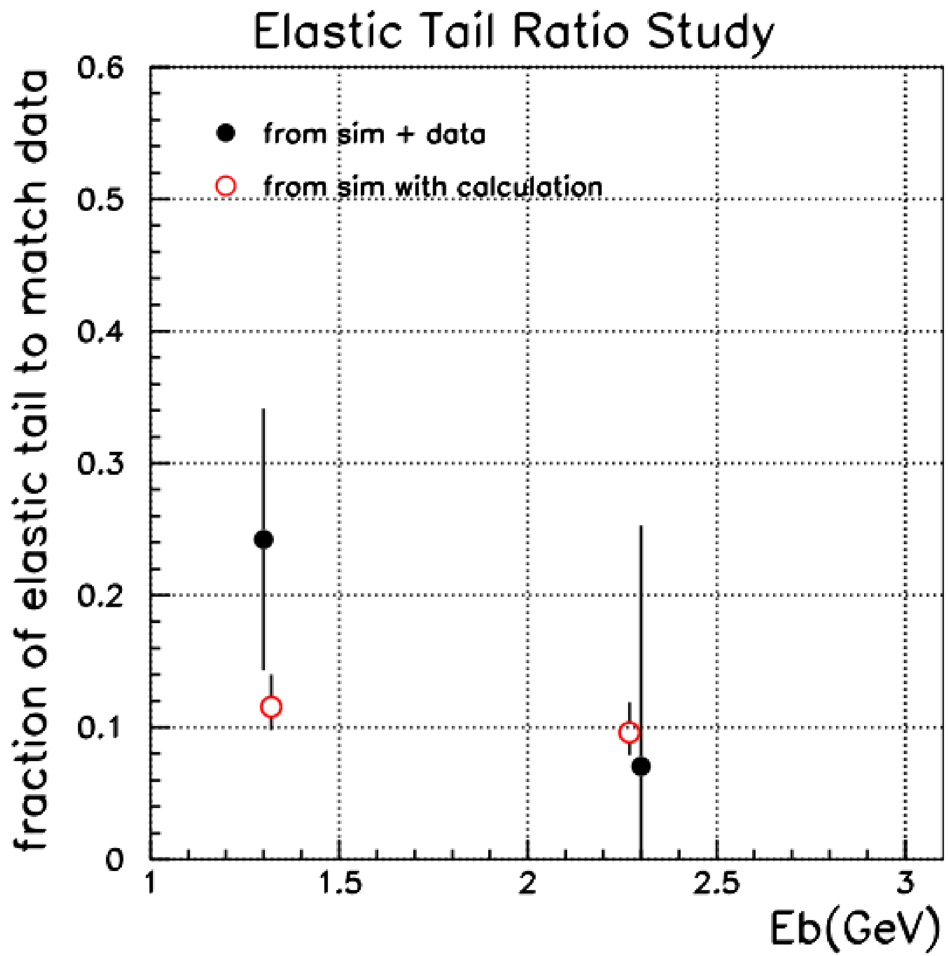




Above: adding 0% (left) and 40% (right) of elastic tail from elastic simulation to inelastic simulation, and compare with data (red) → interpolation gives us the “perfect” fraction of elastic tail to be added.

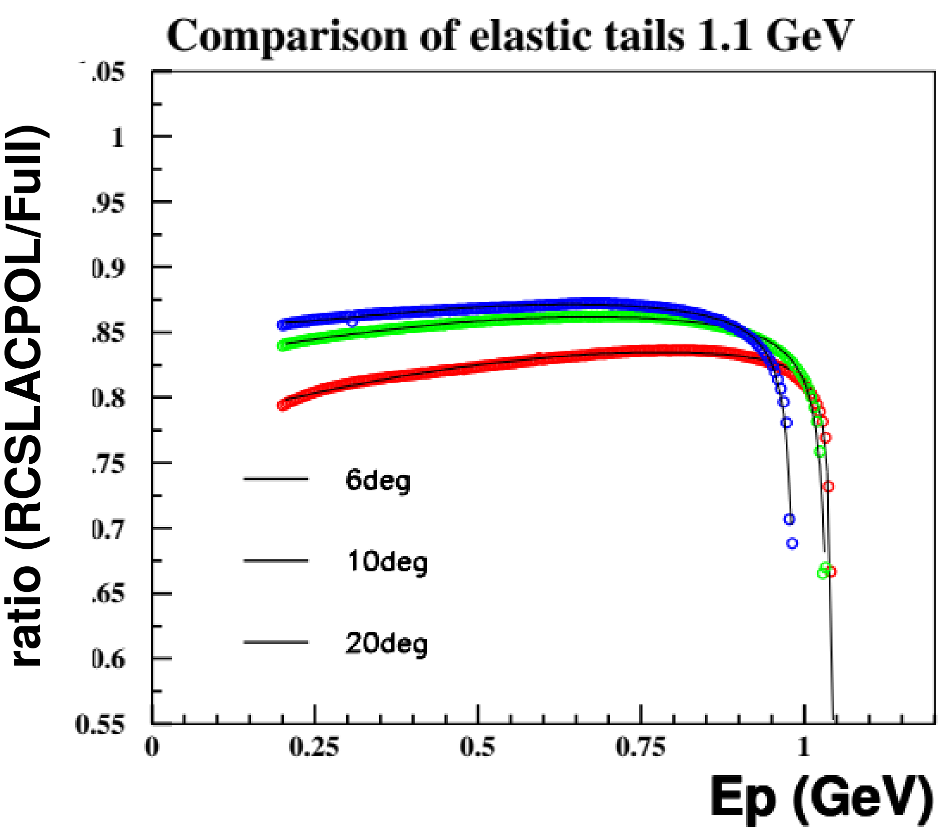
– “Fraction” checked by data in the “tail region” 1.0<W<1.06 GeV – step 2

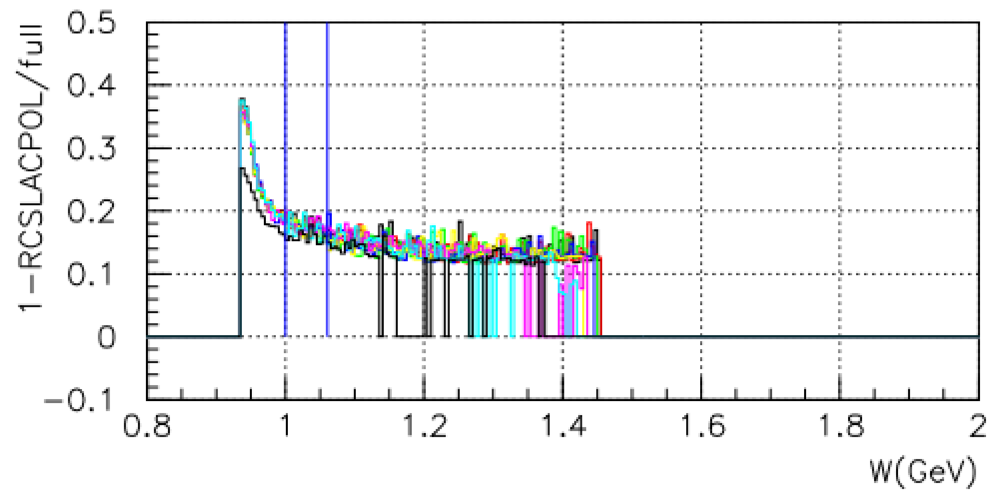




– “Fraction” determined by comparing the radiative tails of two codes (INFN vs. RCSLACPOL),

and propagates through GSIM+GPP+RECSIS





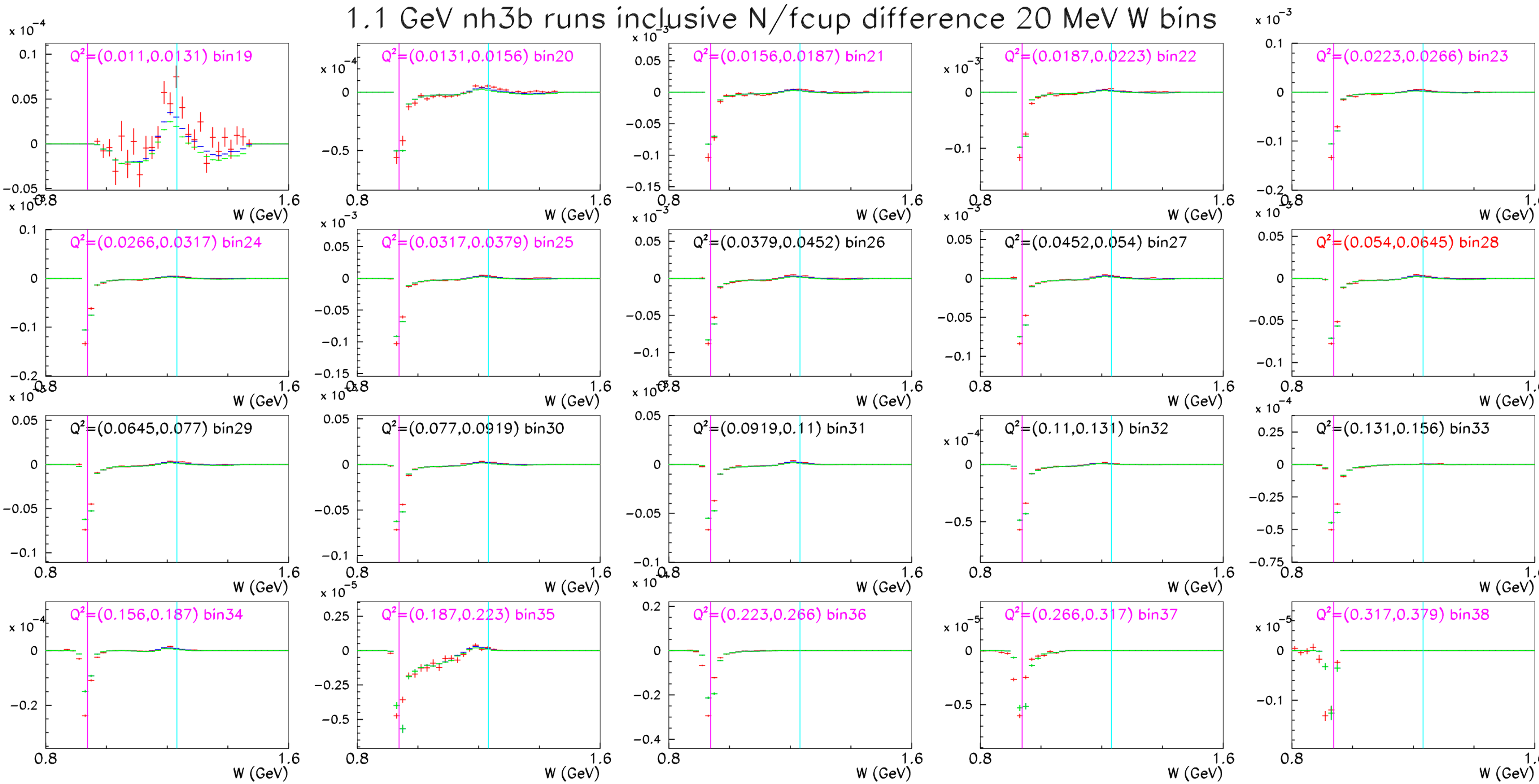
From above plot:

– extracted “missing tail” fraction for the tail region 1.0<W<1.06, found they agree with what we observe from data

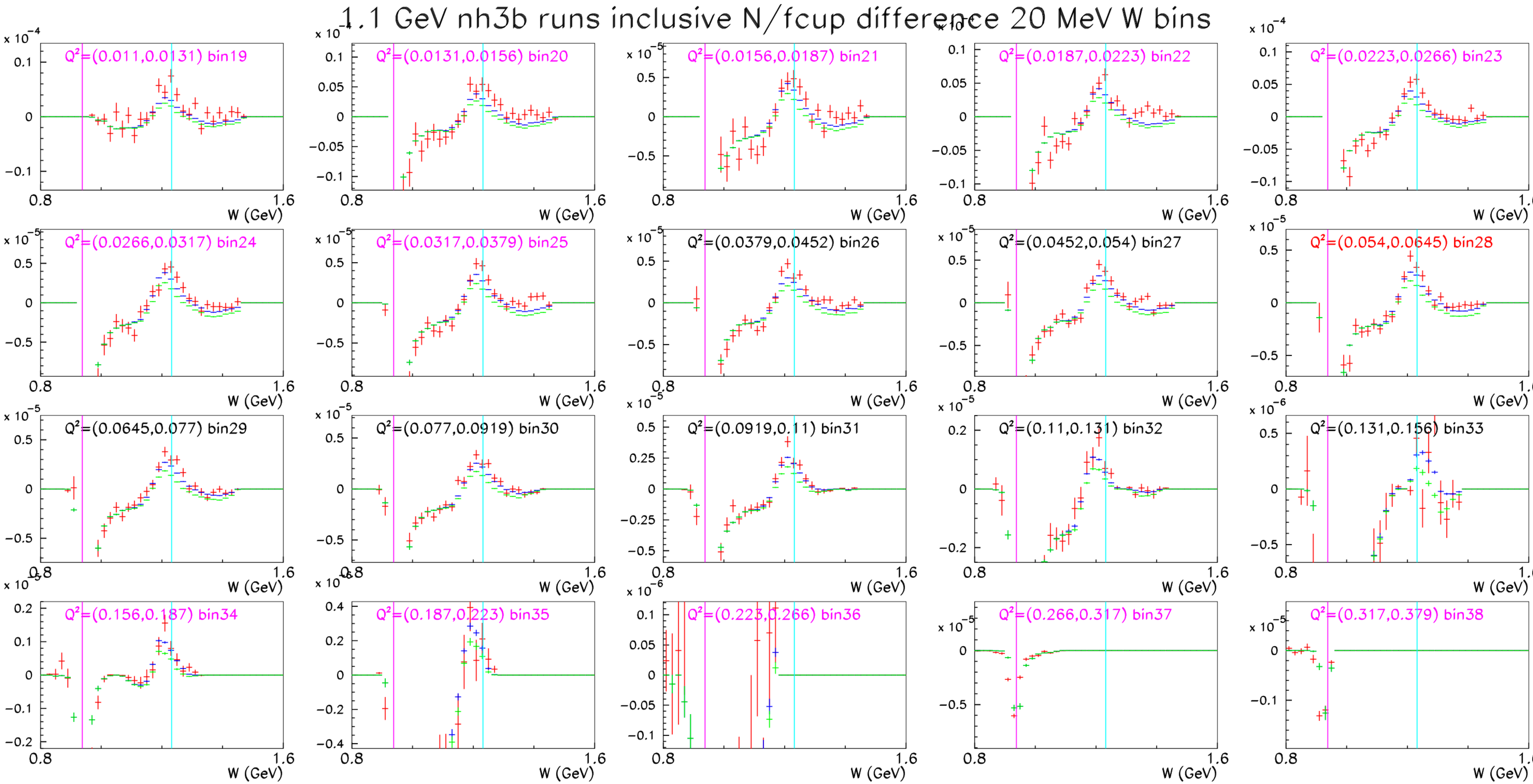
method 1: extracted “missing tail” fraction – mean, min, max – for the inelastic region W>1.15 GeV. These are used to calculate the final value of SSFs and to determine tail uncertainty

method 2: use the calculation to perform a W and Q2-dependent missing tail fraction correction to the simulation.

Polarized Yield - Data vs. Sim



Polarized Yield - Data vs. Sim



Extraction of g1 and A1F1

Two sets of inelastic simulations were performed in order to extract g1 or A1F1:
"standard" simulation using latest strucfunc, and the values of g1 used
"non-std" sim using latest strucfunc but with A1 changed +0.1, and the values of g1 used

Excluding region where Delta-n is insensitive to the change in g1 (such as W<1.15 GeV, or gaps in DC, or high W edge of acceptance):

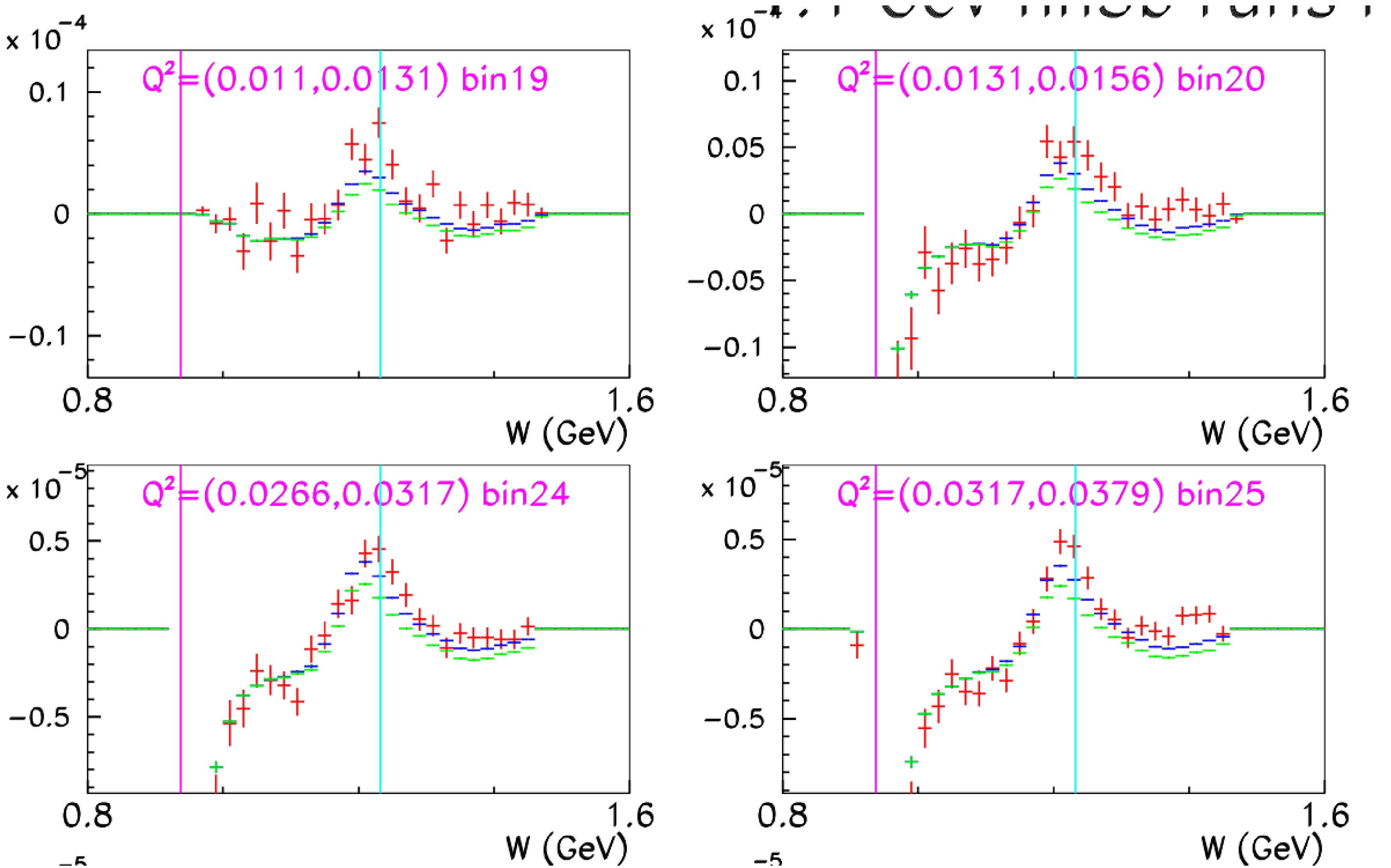
$$
\begin{aligned}
g_1^{\text{data}} &= g_1^{\text{sim0}} + (g_1^{\text{sim1}} - g_1^{\text{sim0}}) \frac{\Delta n^{\text{data}} - \Delta n^{\text{sim0}}}{\Delta n^{\text{sim1}} - \Delta n^{\text{sim0}}} \\
&= g_1^{\text{sim0}} + (g_1^{\text{sim1}} - g_1^{\text{sim0}}) \frac{\Delta n^{\text{data}} - \Delta n^{\text{sim0}}}{\Delta n^{\text{diff}}} .
\end{aligned}
$$

the value for $A_1 F_1$ is extracted as:

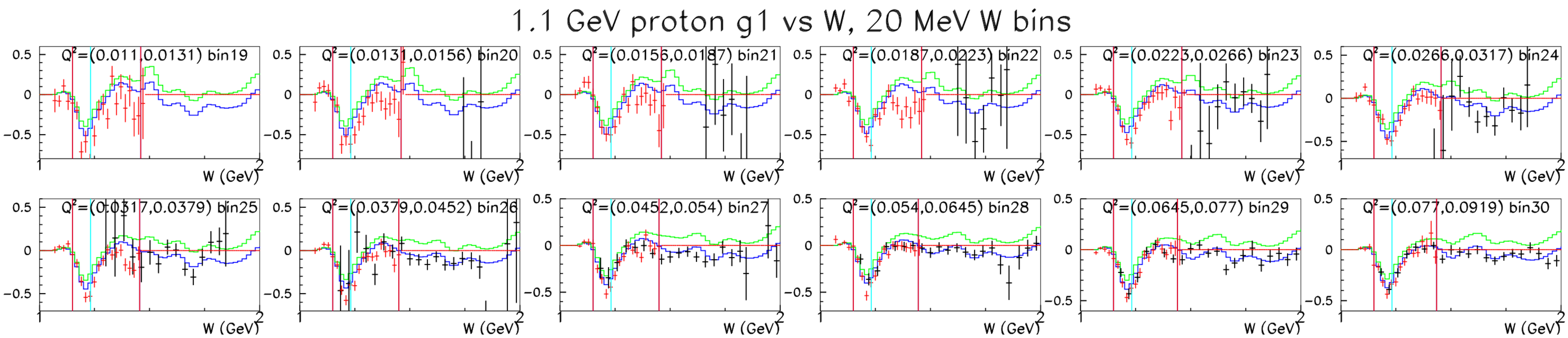
$$
(A_1F_1)^{\text{data}} = (A_1F_1)^{\text{sim0}} + \left[(A_1F_1)^{\text{sim1}} - (A_1F_1)^{\text{sim0}}\right] \frac{\Delta n^{\text{data}} - \Delta n^{\text{sim0}}}{\Delta n^{\text{diff}}} .
$$

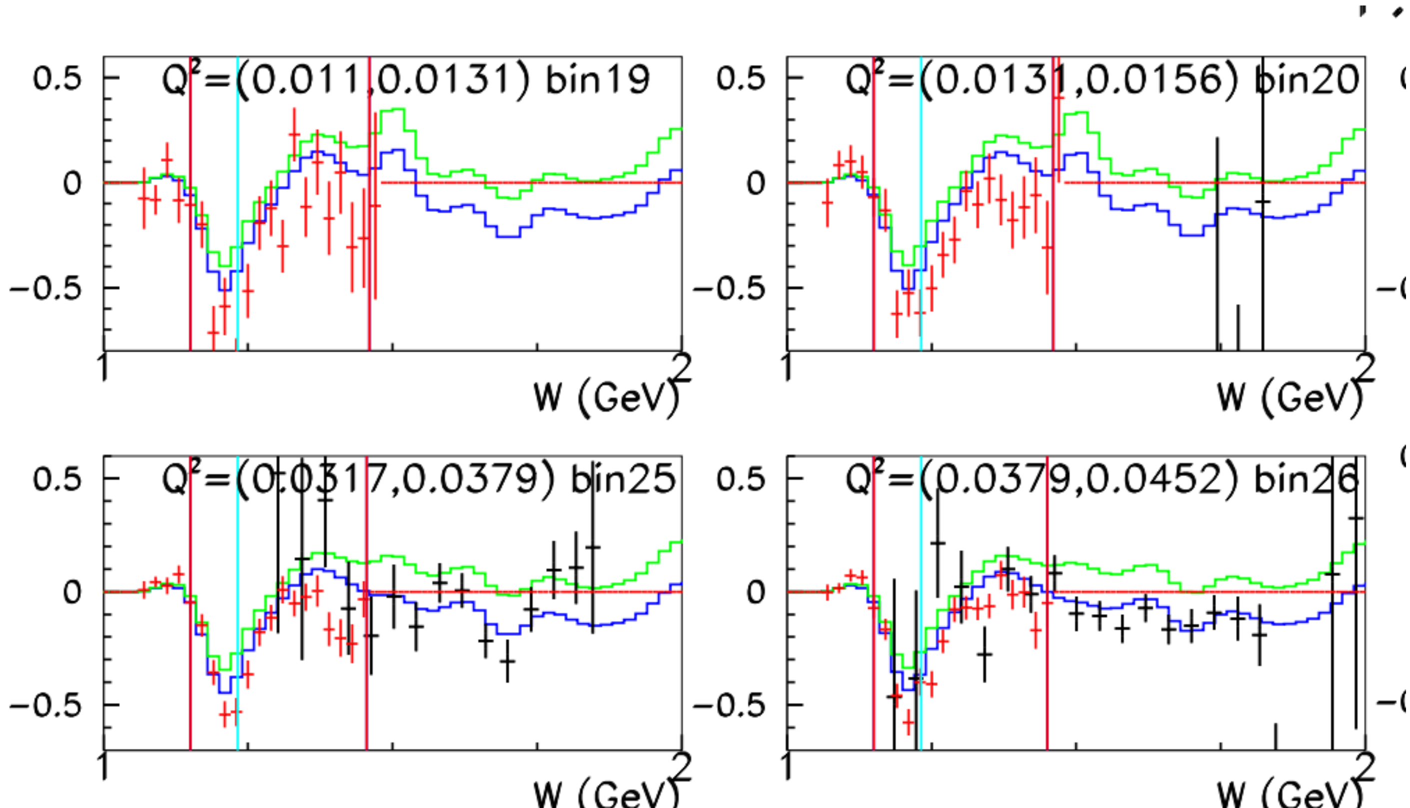
Extraction of g1 and A1F1

Two sets of inelastic simulations were performed in order to extract g1 or A1F1:
“standard” simulation using latest strucfunc, and the values of g1 used
“non-std” sim using latest strucfunc but with A1 changed +0.1, and the values of g1 used



Extraction was done for different “missing tail” factors. Here are extraction plots for the simulation with “calculation-based missing tail correction”:



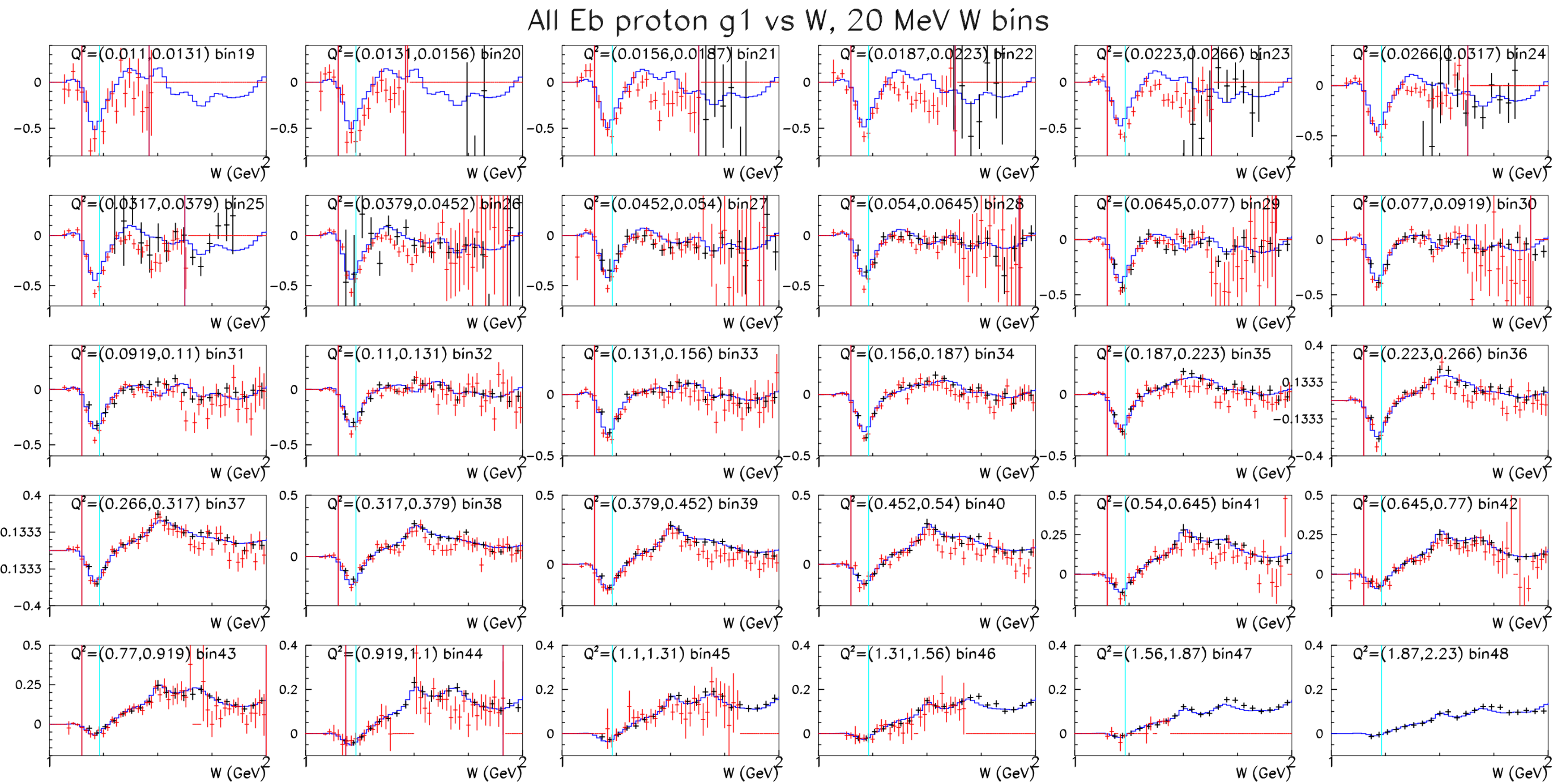


Final Results on g1 or A1F1

Final value on g1 is

(1) calculated using two “missing tail ratio value” (12% and 24%) extractions, and interpolate to the best estimate for the missing tail ratio (which is between 12% and 24%)

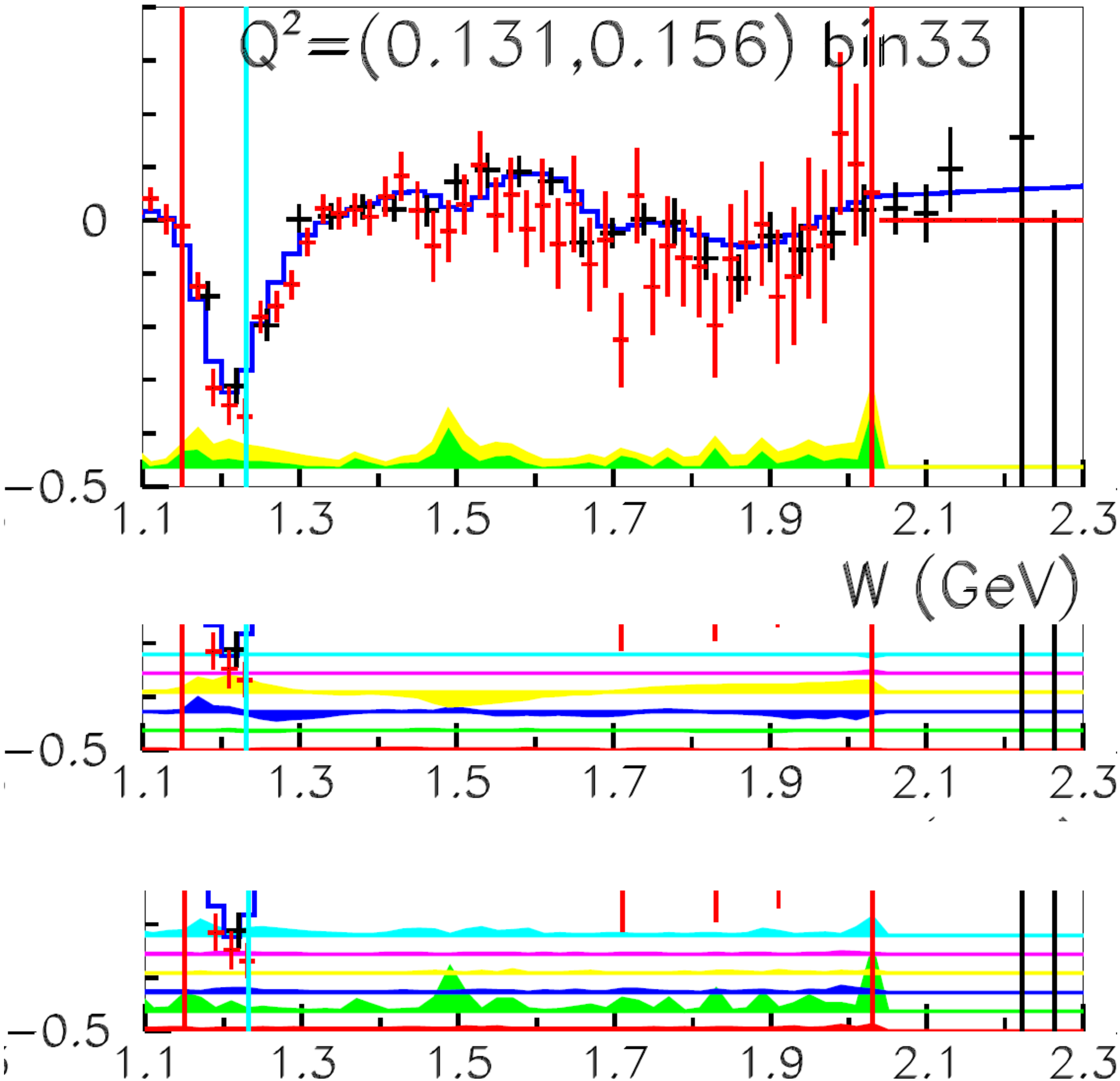
(2) combined over all five beam energies and all target types



Systematic Uncertainties (bucket list)

- Radiative tail
- Target packing fraction – by repeating simulation → extraction
- CC efficiency – by repeating extraction using CC-uncorrected simulation
- Elastic normalization – by changing normalization → repeating extraction
  - – statistical uncertainty
  - – disagreement between data and simulated peak area (<2E-3)
  - – elastic F.F. – 1%+1%*Eb in GeV
- Background: – similar to normalization
  - – pion and pair production background: <1% in polarized yield
  - – ^{15}N: 0.7% to inelastic polarized yield
  - – (^{15}N elastic: low Q2 bins excluded from elastic normalization
- Reconstruction (shift in W) – by shifting W → repeating extraction

- Model uncertainties: studied by varying inelastic simulation six times (F1,2; R; A1 res; A2 res, A1 DIS; A2 DIS) → repeating extraction



Q²=(0.131,0.156) bin33
0
−0.5
1.1
1.3
1.5
1.7
1.9
2.1
2.3
W (GeV)
−0.5
1.1
1.3
1.5
1.7
1.9
2.1
2.3
−0.5
1.1
1.3
1.5
1.7
1.9
2.1
2.3

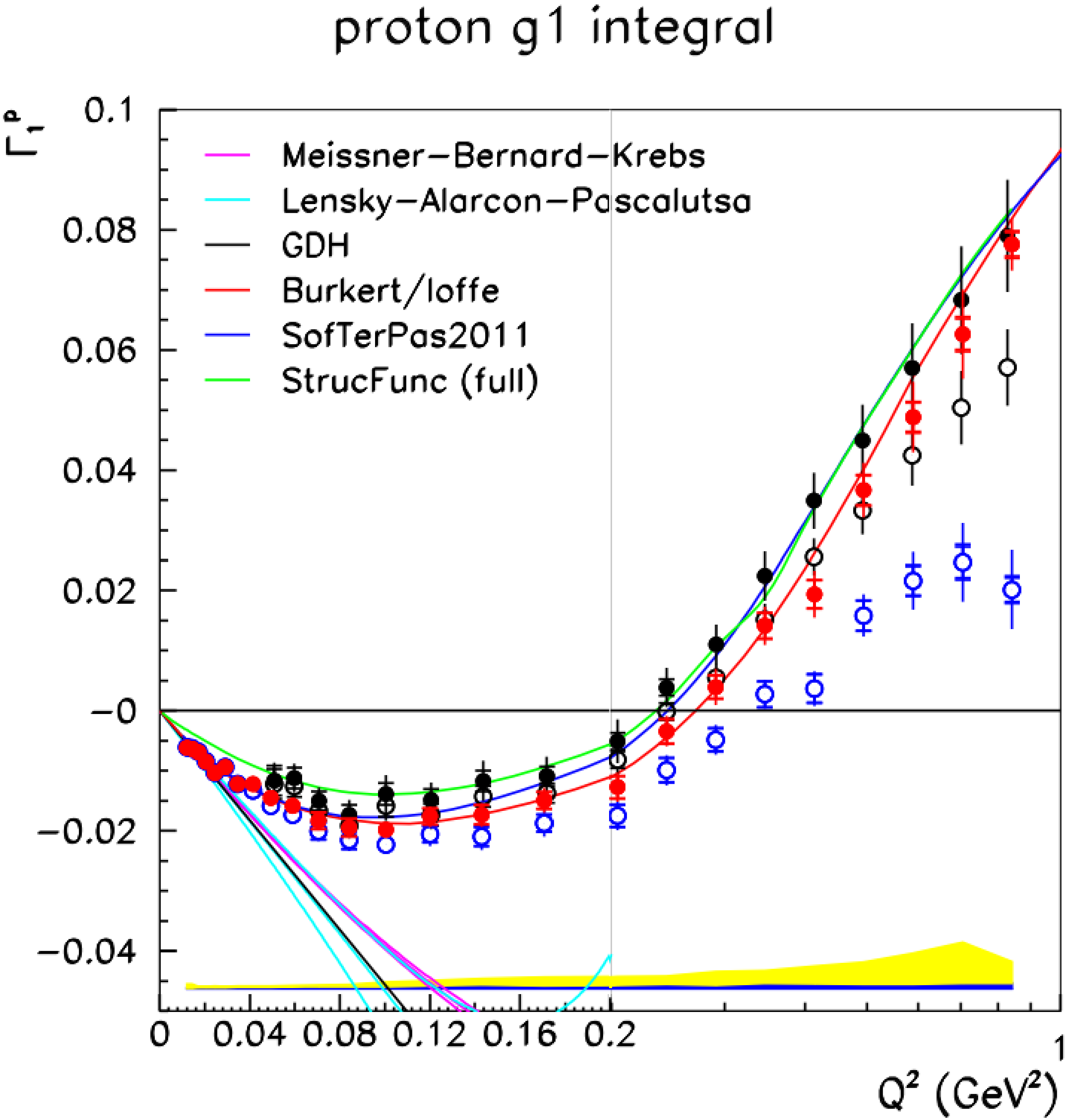
Results on Moments

$$\Gamma_1(Q^2) = \int_{0.001}^{x_{\rm lo}} g_1^{\rm mod}(x,Q^2)dx + \int_{x_{\rm lo}}^{x_{\rm hi}} g_1^{\rm EG4\ data}(x,Q^2)dx + \int_{x_{\rm hi}}^{x_{th}} g_1^{\rm mod}(x,Q^2)dx + \int_{\rm gaps\ (when\ applicable)} g_1^{\rm mod}(x,Q^2)dx \ ,$$

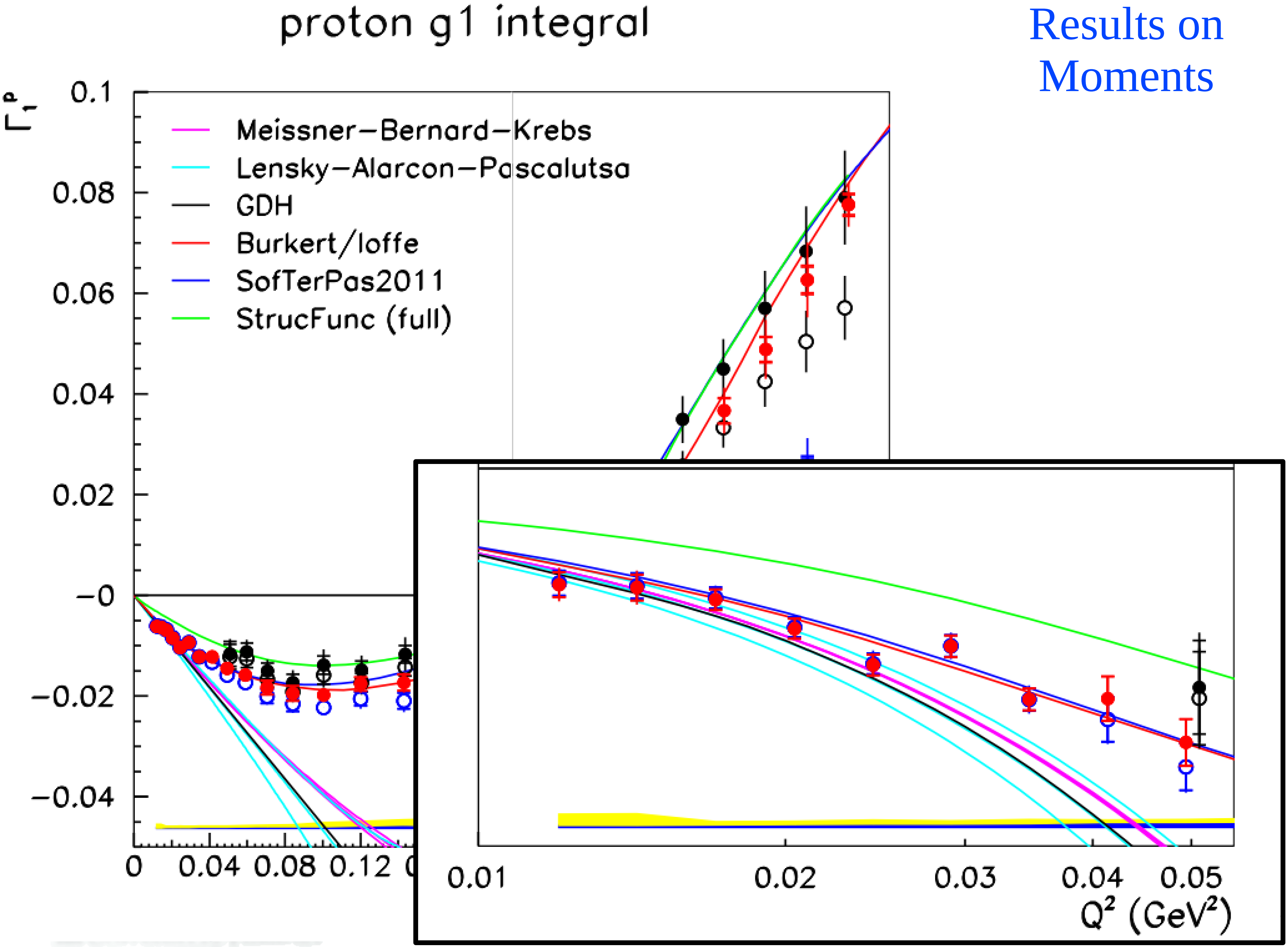
Model integration done with dx=0.00001

Model uncertainty evaluated the same way as for SSF

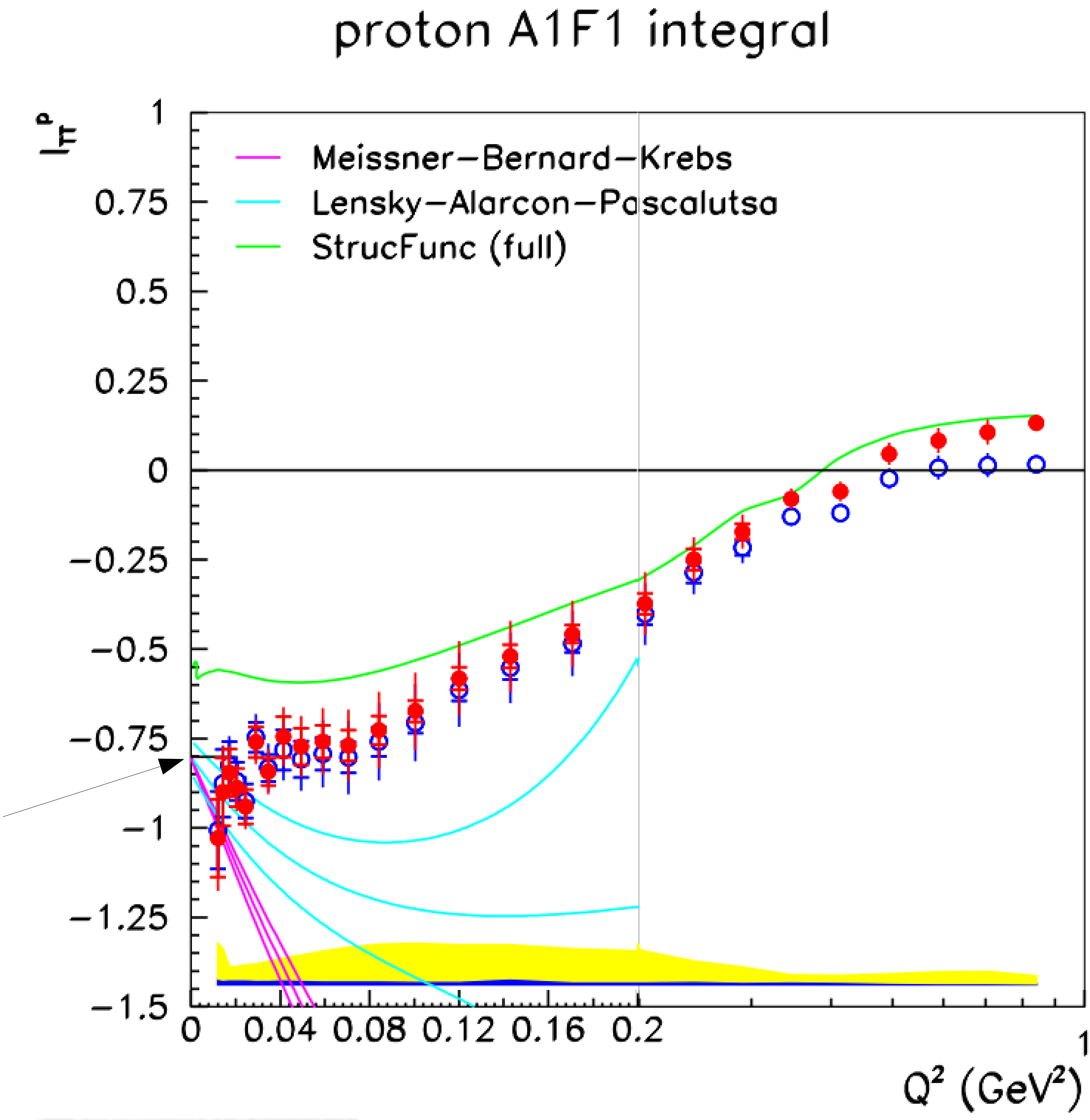
Results on Moments



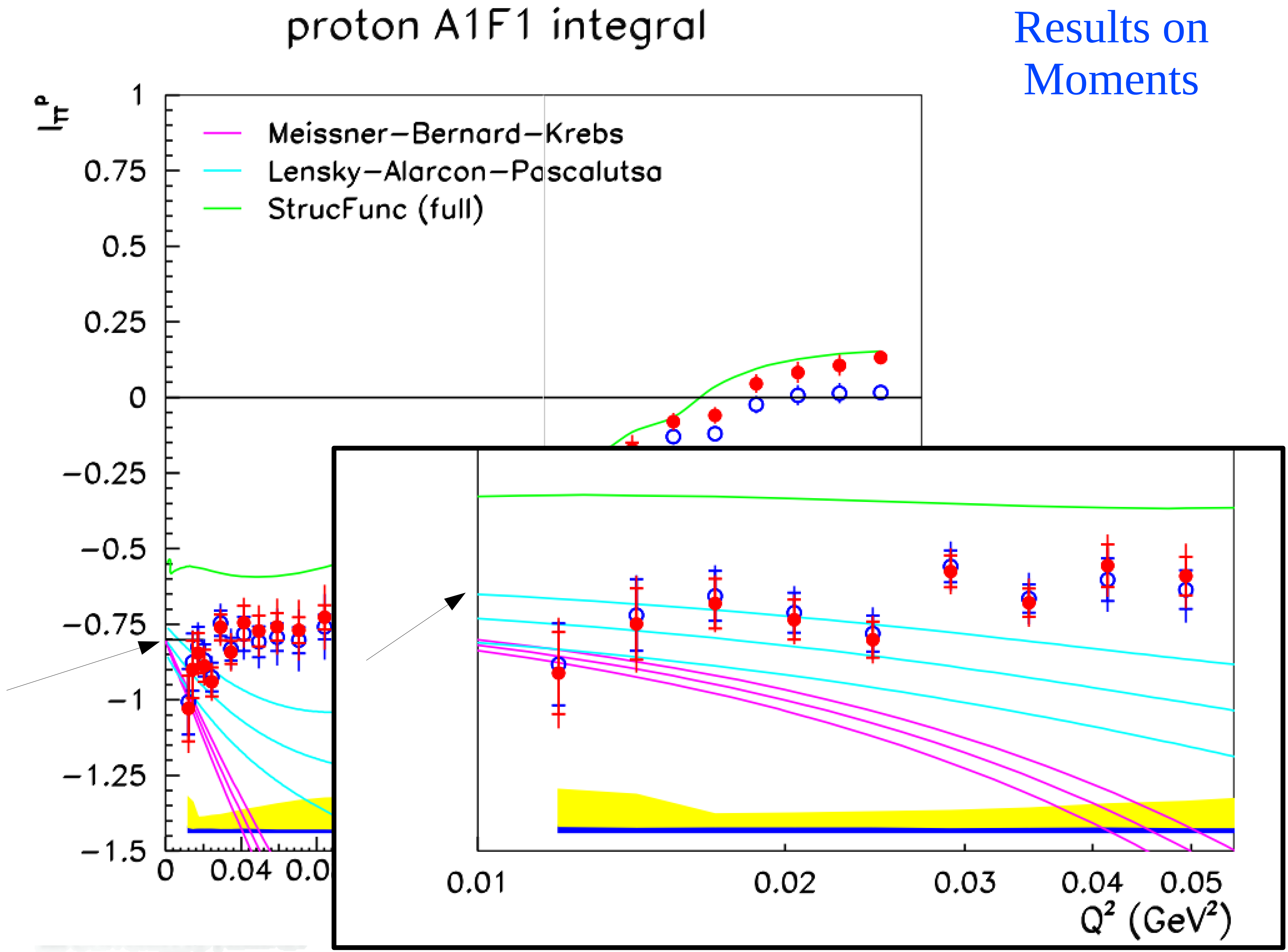
Results on Moments



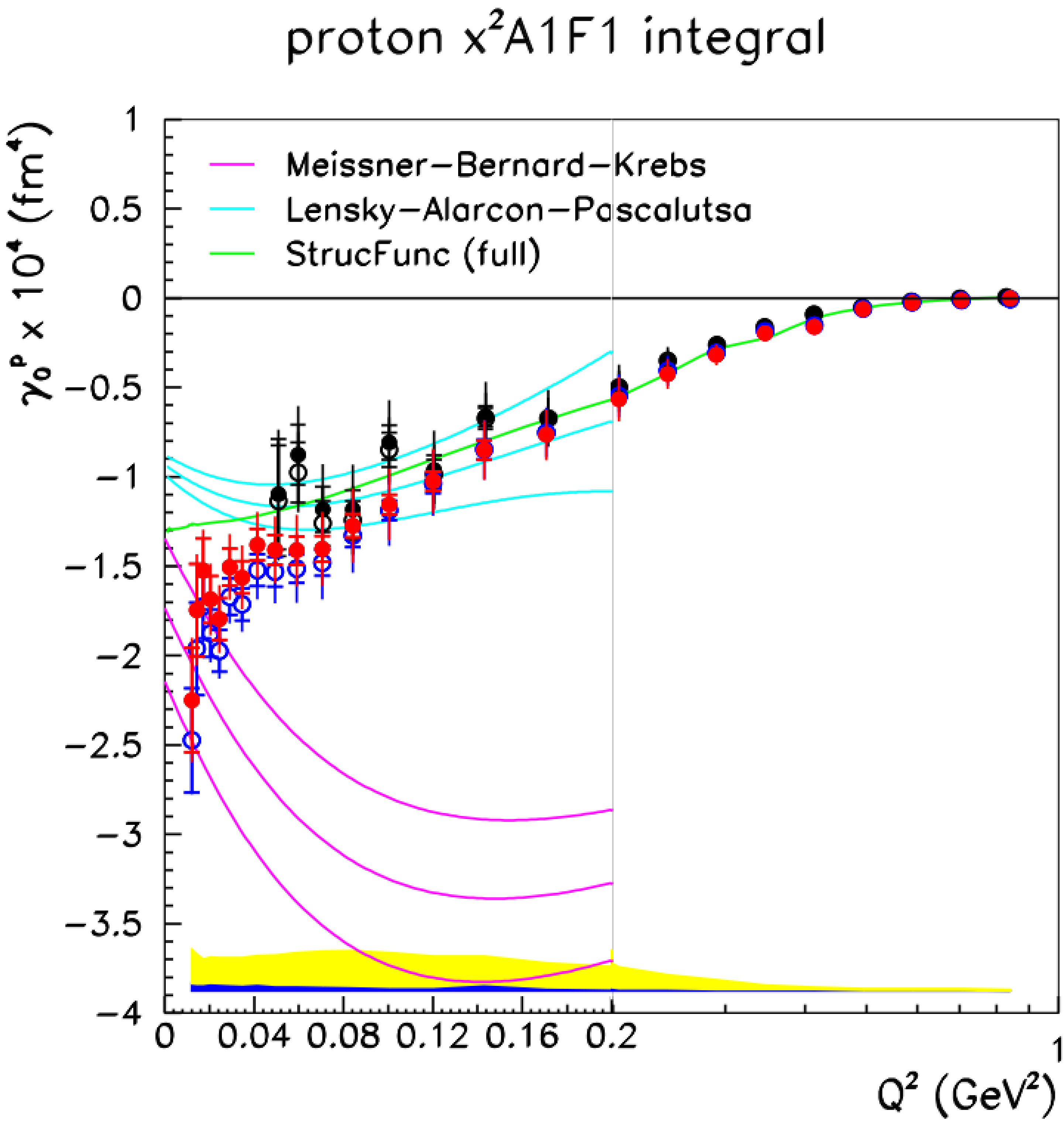
Results on Moments



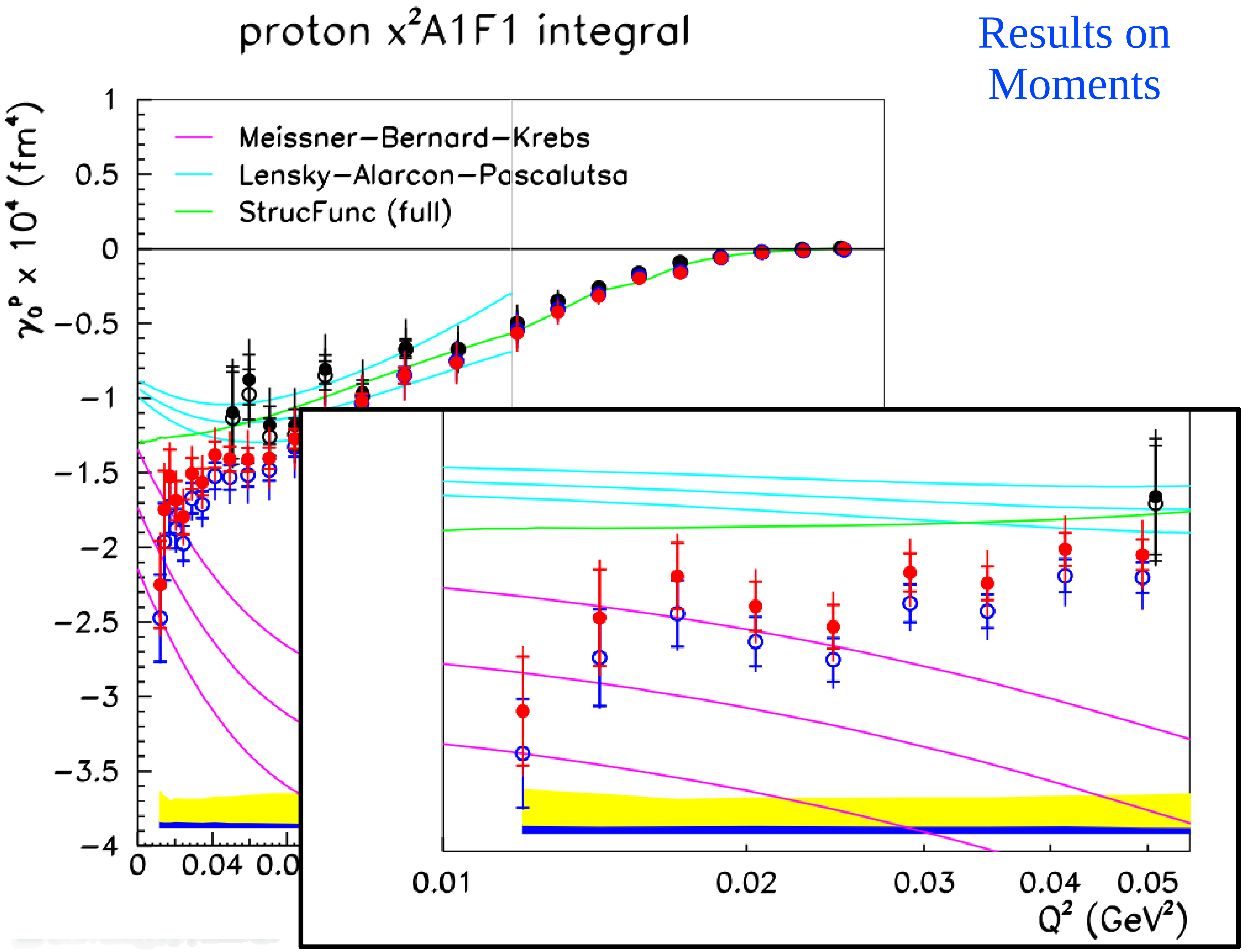
Results on Moments



Results on Moments

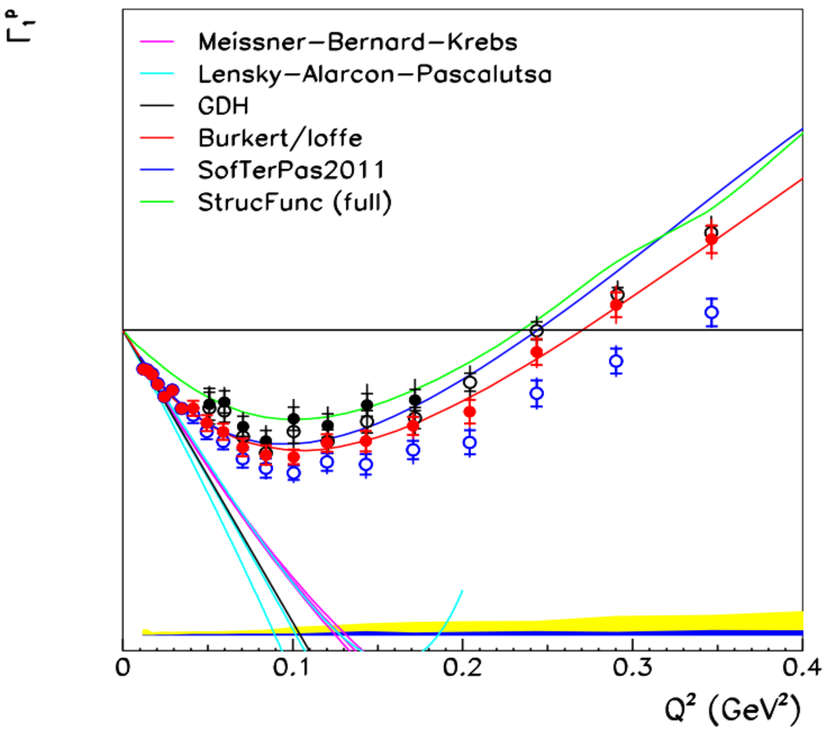


Results on Moments

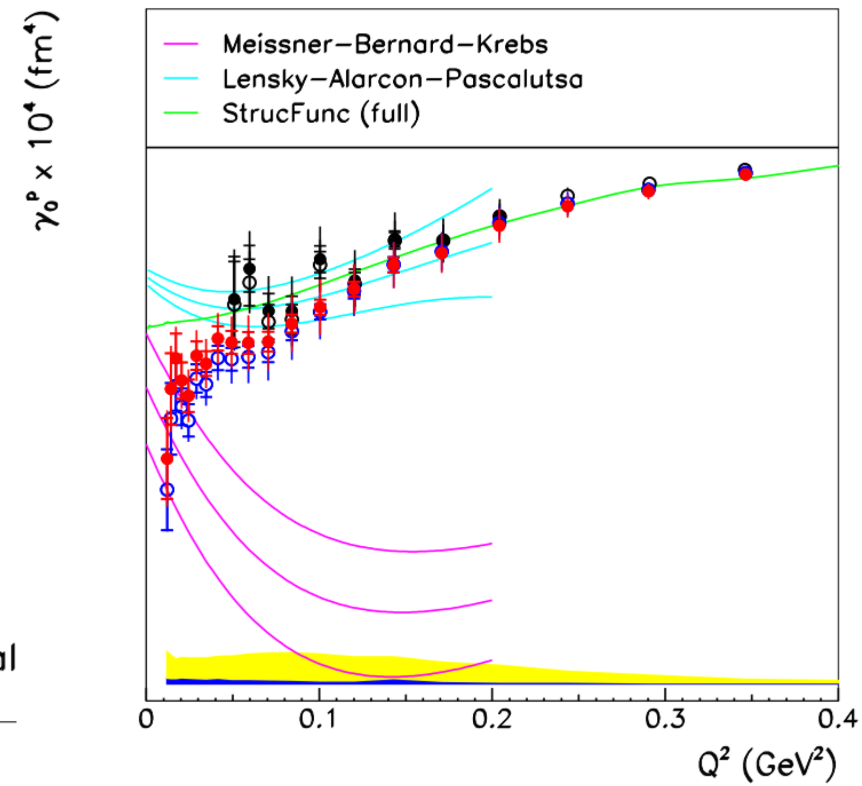


Backup Slides

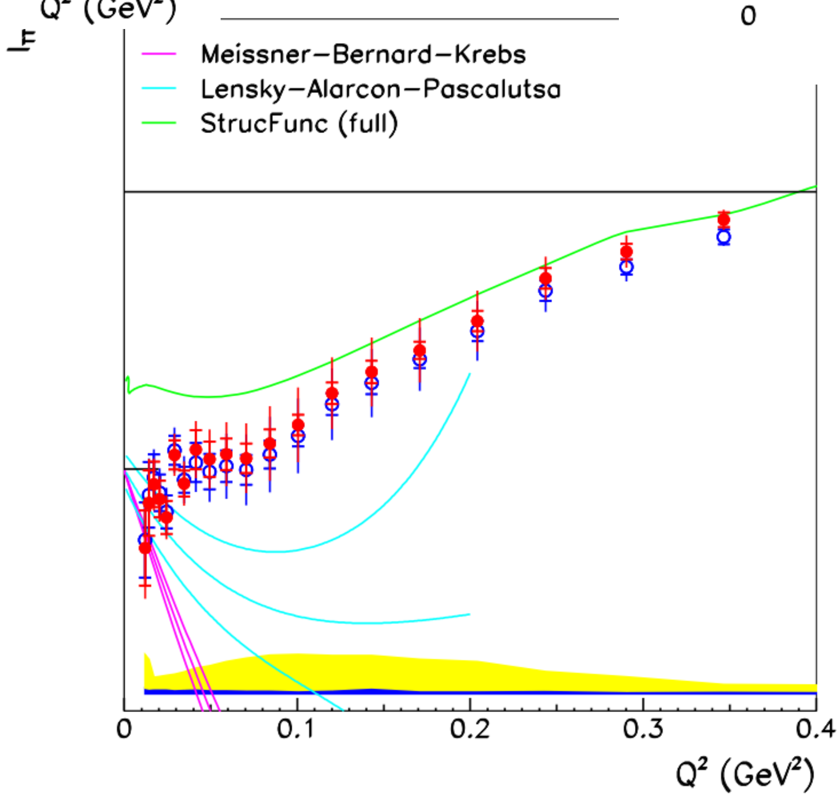
proton g1 integral

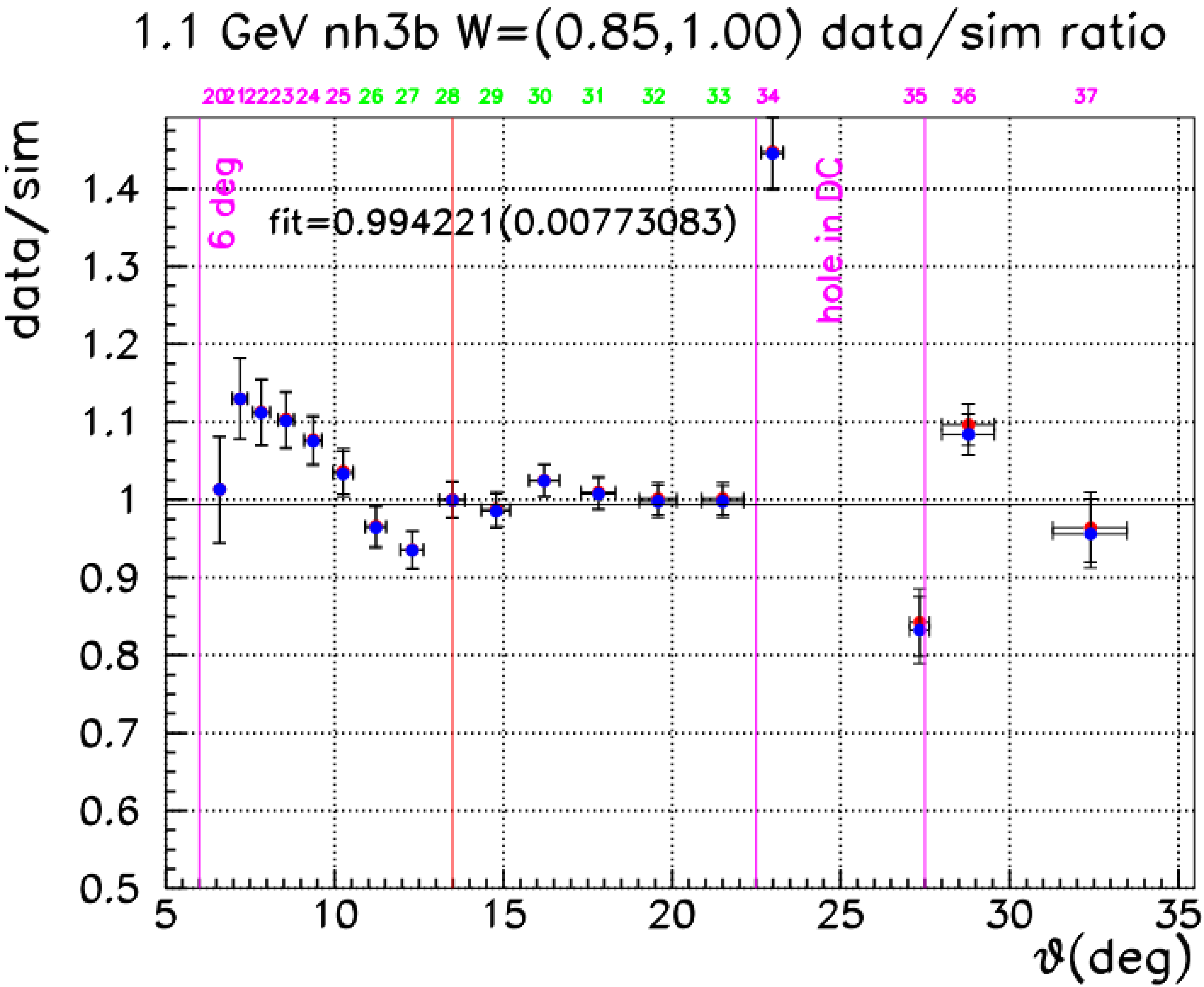


proton x^2A1F1 integral

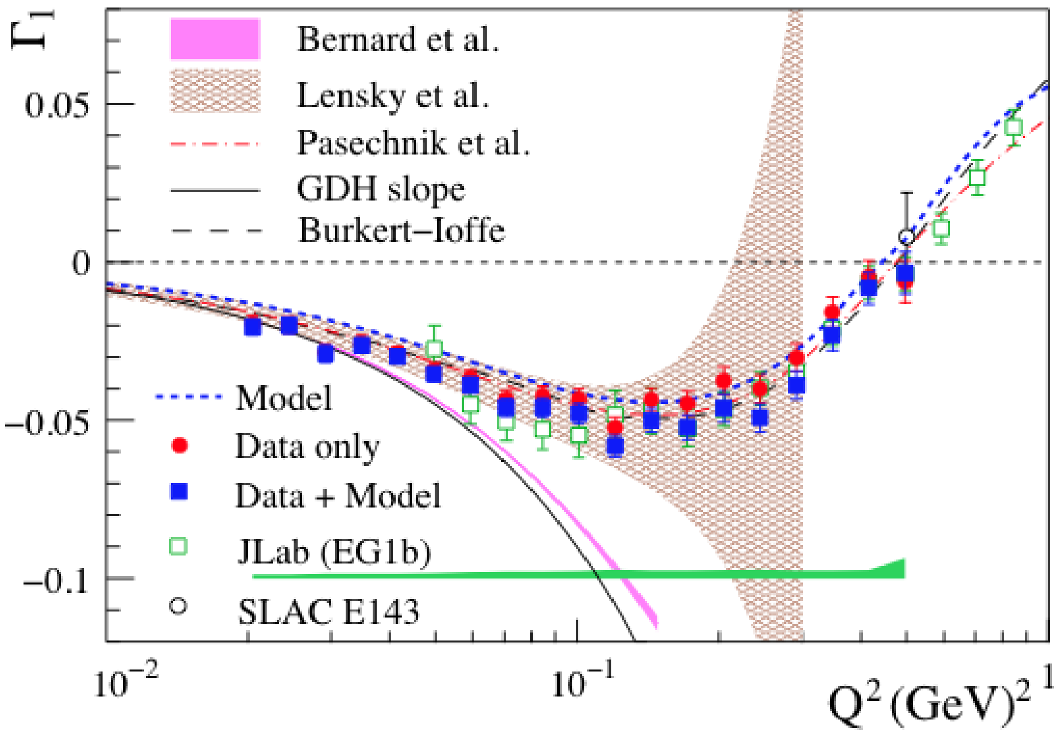


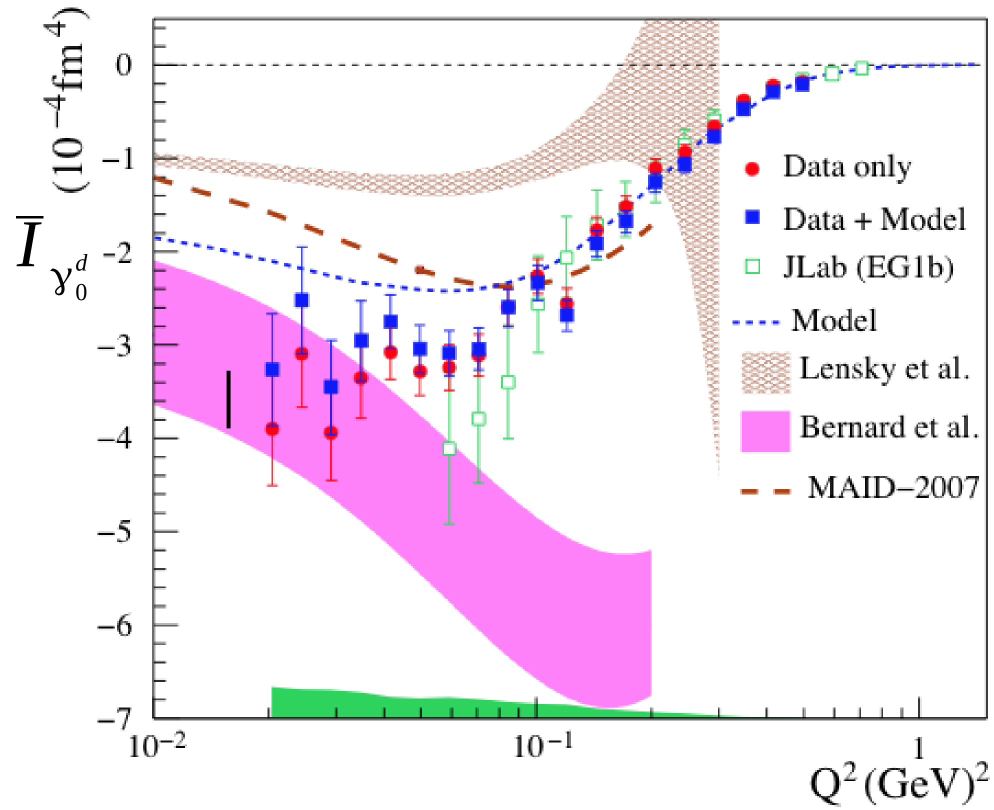
proton A1F1 integral




1.1 GeV nh3b W=(0.85,1.00) data/sim ratio
20 21 22 23 24 25 26 27 28 29 30 31 32 33 34 35 36 37
6 deg
fit=0.994221(0.00773083)
hole in DC
data/sim
1.4
1.3
1.2
1.1
1
0.9
0.8
0.7
0.6
0.5
5
10
15
20
25
30
35
ϑ(deg)

New deuteron results from EG4 (Hall B)





Just Published.

Adhikari et al. PRL 120, 062501 (2018)

Raster and Momentum Corrections