Parton Distribution Functions via Parity Violation

Mark Dalton for the PVPDF collaboration

Jefferson Lab

The Parity Violation Parton Distribution Function (PVPDF) Experiment: a new experimental constraint on PDFs

Proposal to JLab PAC 45

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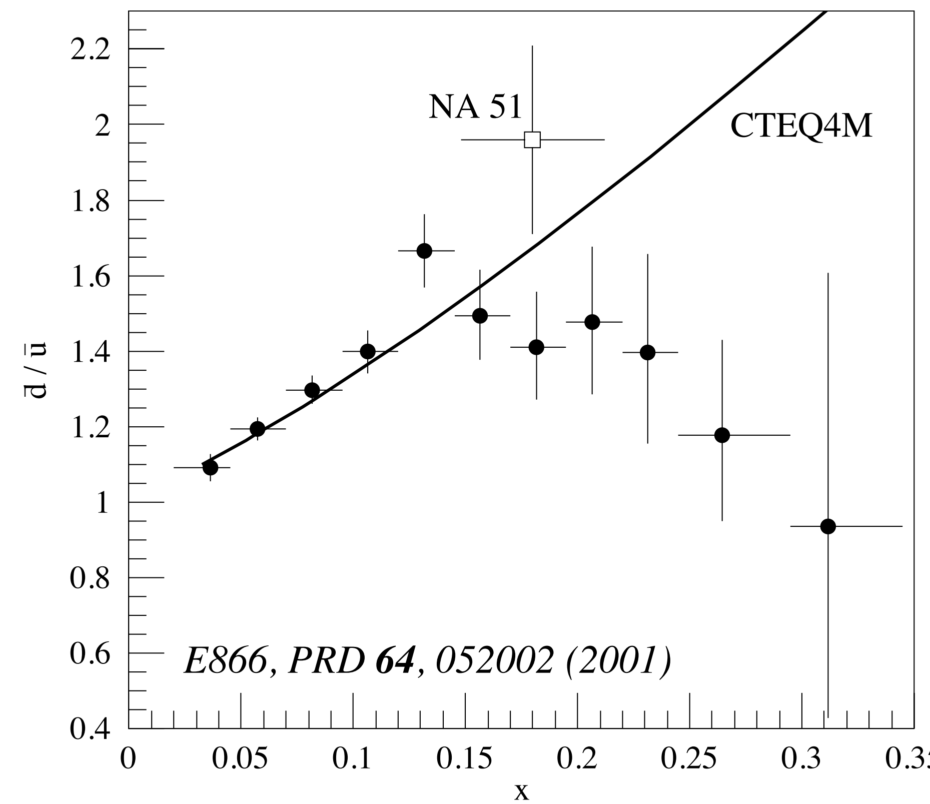
Importance of Strange Quarks

- Fundamental interest, is the sea SU(3) symmetric?

- What is the origin of the non-perturbative sea?
  non-zero $\bar{d} - \bar{u}$ cannot be generated perturbatively from gluon radiation
    chiral symmetry breaking?
    hadronic fluctuations (pion, kaon cloud)?
  Knowledge of the strange distributions is a vital component of understanding the effect.



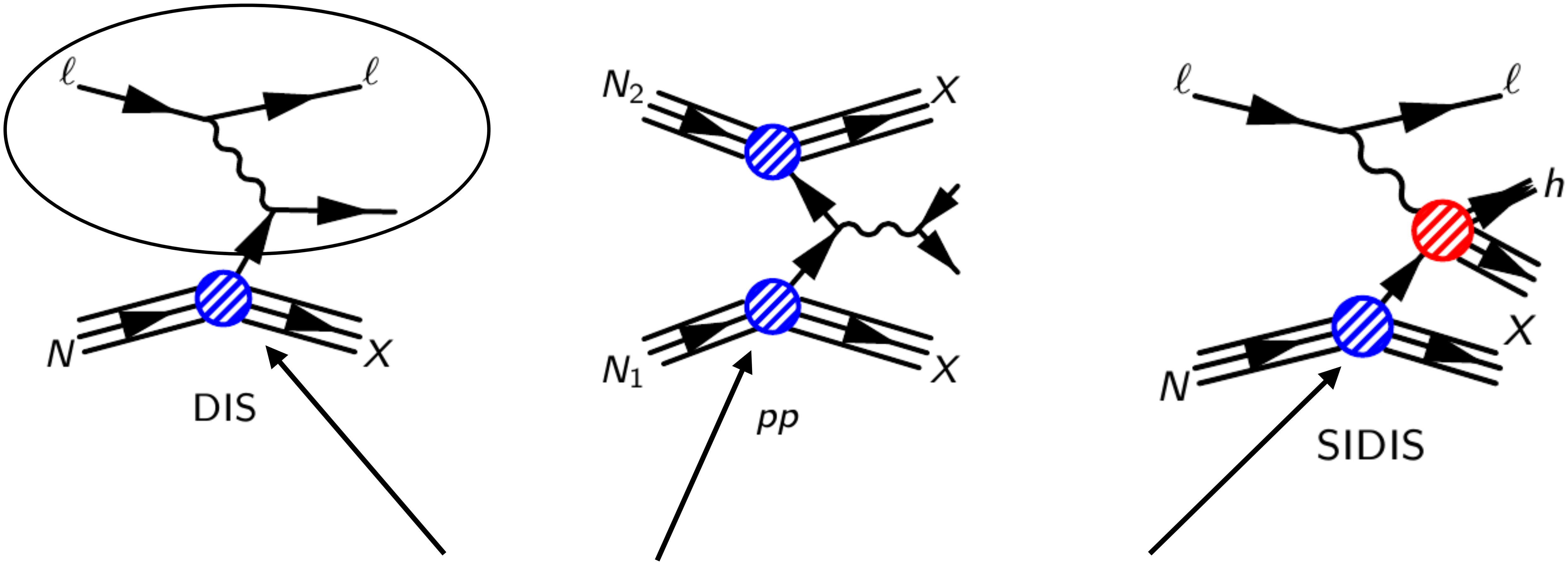
- Proton spin puzzle: a large negative contribution made by strange quarks?
  The polarized strange distribution (largely still unknown) constrained by the strange distribution.

$$|\Delta f(x, Q^2)| < f(x, Q^2)$$

- TMDs: Theoretical descriptions of transverse momentum distributions, central to the JLab 12 program, require precise input of the sea distribution.

Factorization

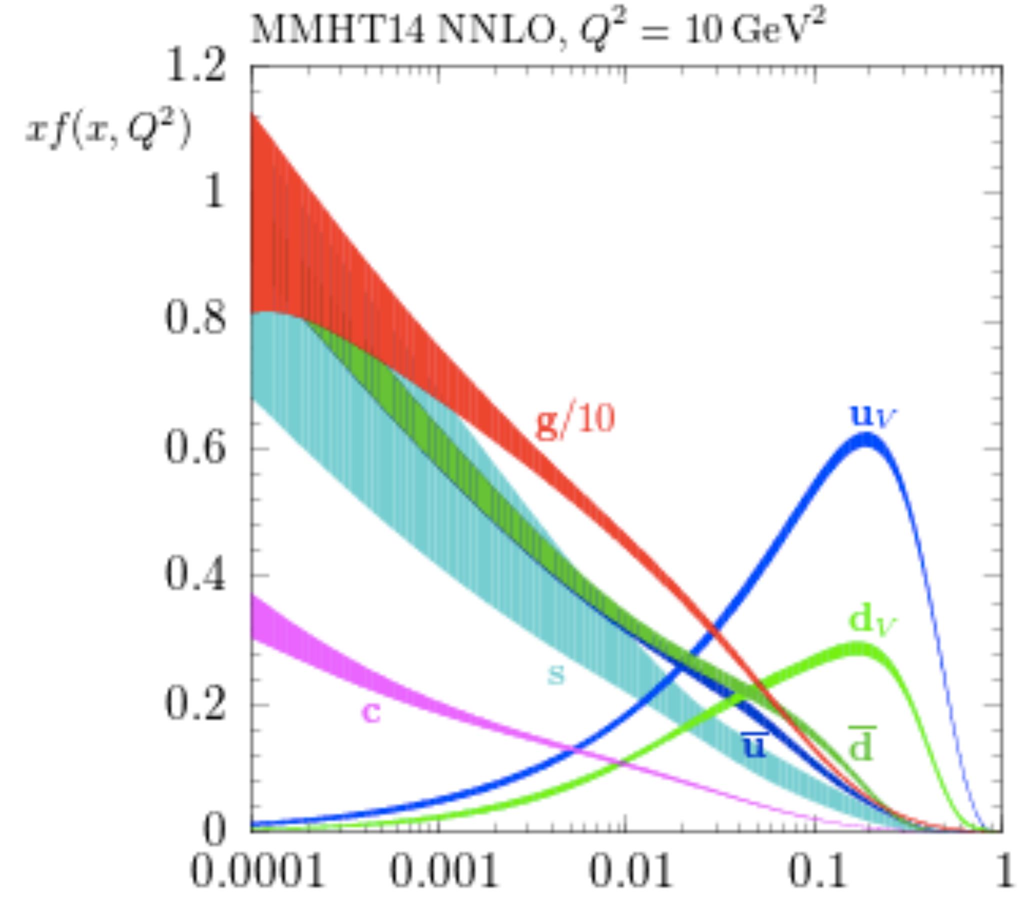
hard, calculable part



process-independent non-perturbative part, "universal" PDF

different processes probe different parts of the distributions

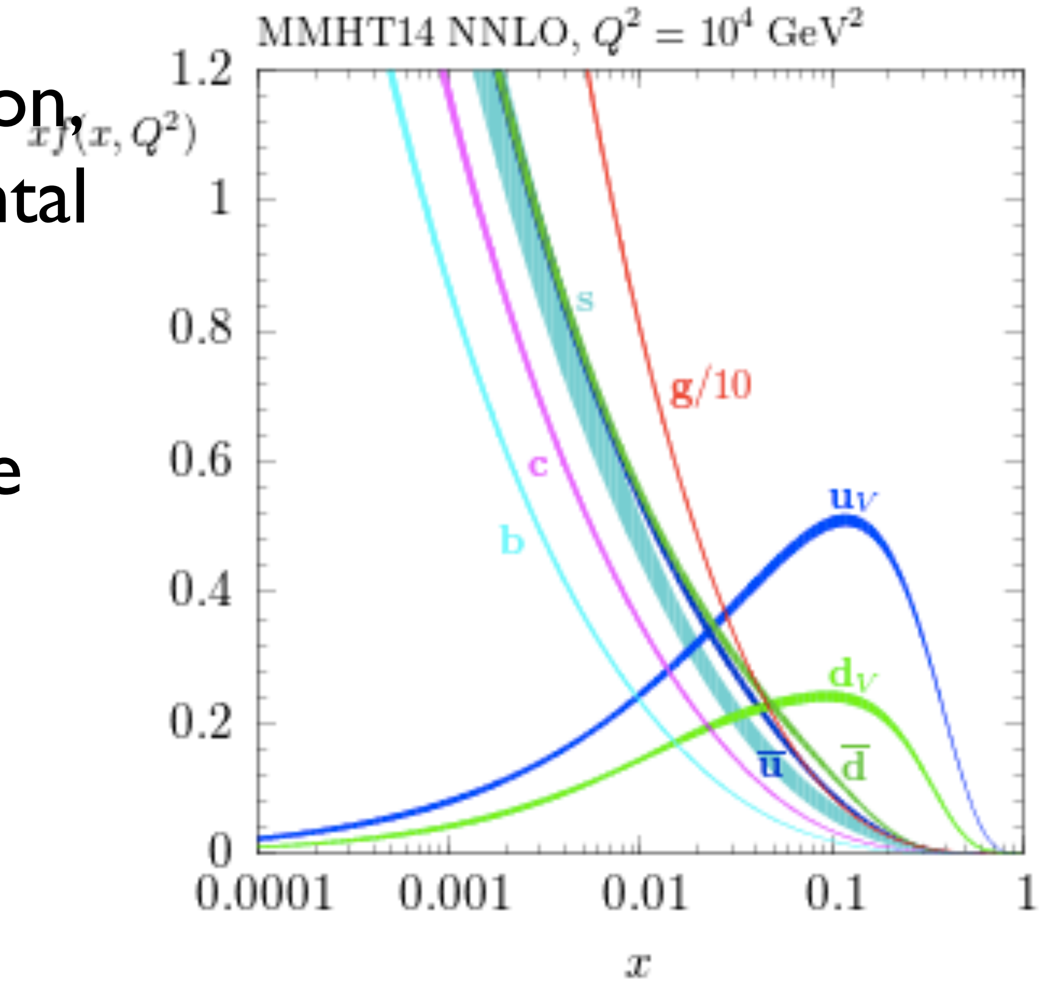
PDF Global Analysis



PDF: probability densities of the longitudinal momentum fraction x of quarks and gluons relative to their parent hadron momentum

- Experimental data (~ 4k data points)
- QCD factorization: PDF (same for PPDF, FF)
- Global analysis

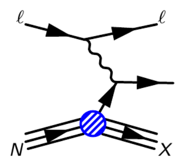
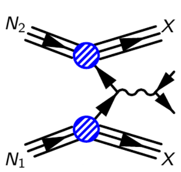
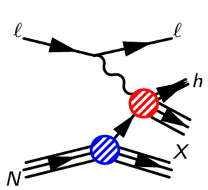
global analyses differ in: input data, parameterization, treatment of heavy quarks, value of αs, experimental errors treatment, theoretical error estimation.



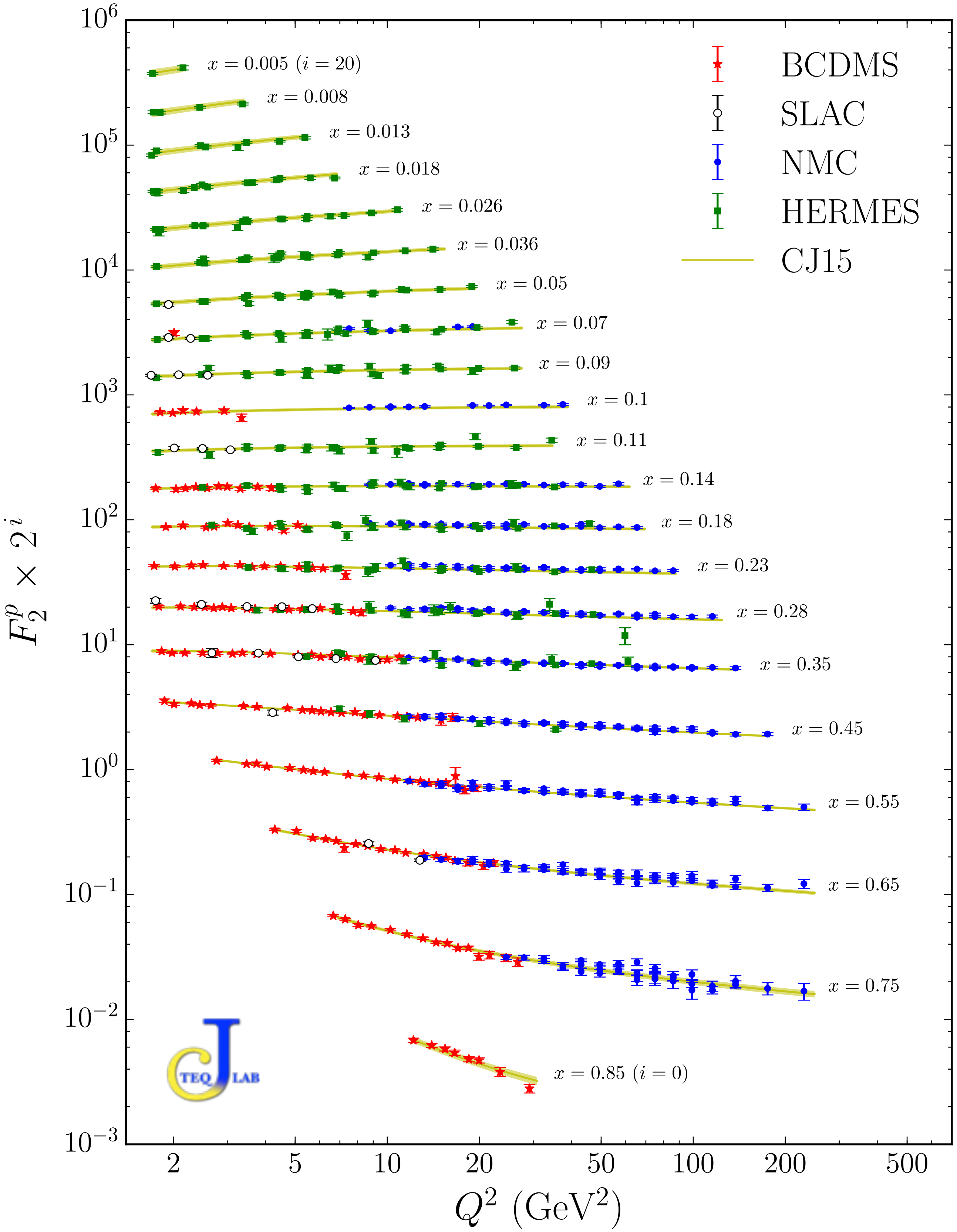
Fits have been done for 3 decades but the strange remains poorly determined

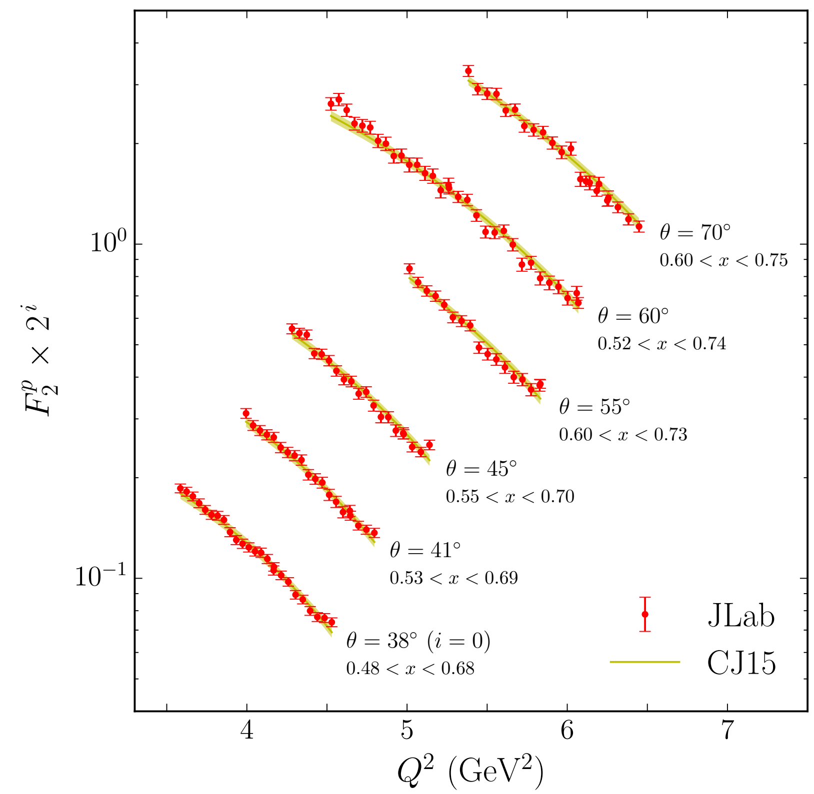
Momentum sum rule is important constraint

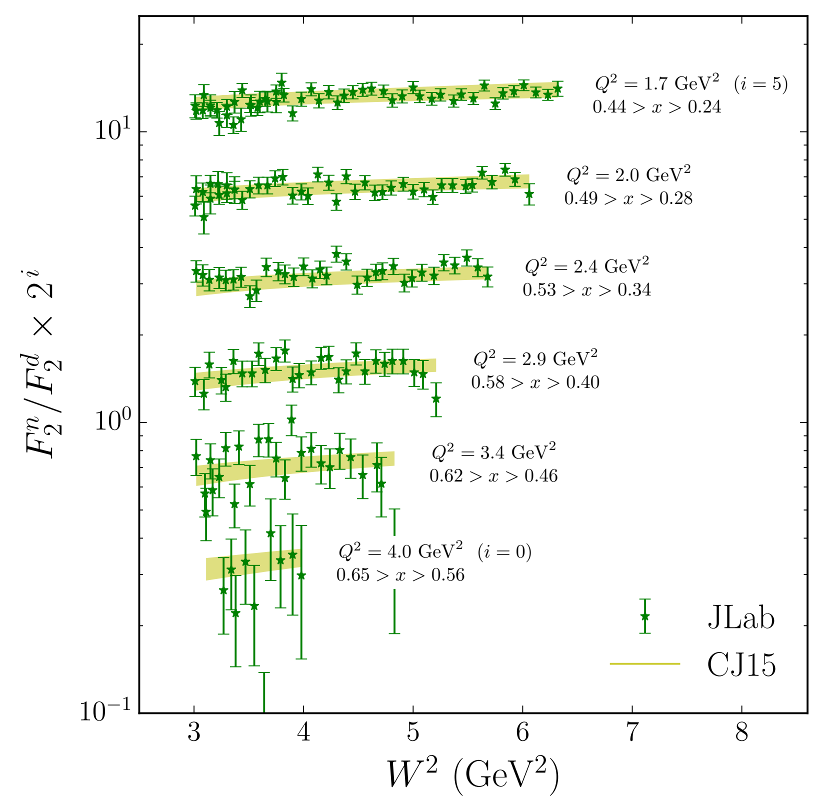
Nucleons in the initial state: Parton Distribution Functions

Process	Reaction	Subprocess	PDFs probed	x
	$\ell^\pm\{p,n\}\to\ell^\pm+X$	$\gamma^*q\to q$	$q,\bar q,g$	$x\gtrsim 0.01$
	$\ell^\pm n/p\to\ell^\pm+X$	$\gamma^* d/u\to d/u$	d/u	$x\gtrsim 0.01$
	$\nu(\bar\nu)N\to\mu^-(\mu^+)+X$	$W^*q\to q'$	$q,\bar q$	$0.01\lesssim x\lesssim 0.5$
 DIS	$\nu N\to\mu^-\mu^++X$	$W^*s\to c$	s	$0.01\lesssim x\lesssim 0.2$
	$\bar\nu N\to\mu^+\mu^-+X$	$W^*\bar s\to\bar c$	$\bar s$	$0.01\lesssim x\lesssim 0.2$
	$e^\pm p\to e^\pm+X$	$\gamma^*q\to q$	$g,q,\bar q$	$0.0001\lesssim x\lesssim 0.1$
	$e^+p\to\bar\nu+X$	$W^+\{d,s\}\to\{u,c\}$	d,s	$x\gtrsim 0.01$
	$e^\pm p\to e^\pm c\bar c+X$	$\gamma^*c\to c,\gamma^*g\to c\bar c$	c,g	$0.0001\lesssim x\lesssim 0.1$
	$e^\pm p\to jet(s)+X$	$\gamma^*g\to q\bar q$	g	$0.01\lesssim x\lesssim 0.1$
	$\vec\ell^\pm\{\vec p,\vec d,\vec n\}\to\ell^\pm+X$	$\gamma^*q\to q$	$\Delta q+\Delta\bar q,\Delta g$	$0.003\lesssim x\lesssim 0.8$
	$pp\to\mu^+\mu^-+X$	$u\bar u,d\bar d\to\gamma^*$	$\bar q$	$0.015\lesssim x\lesssim 0.35$
	$pn/pp\to\mu^+\mu^-+X$	$(u\bar d)/(u\bar u)\to\gamma^*$	$\bar d/\bar u$	$0.015\lesssim x\lesssim 0.35$
	$p\bar p(pp)\to jet(s)+X$	$gg,qg,qq\to 2jets$	g,q	$0.005\lesssim x\lesssim 0.5$
	$p\bar p\to(W^\pm\to\ell^\pm\nu)+X$	$ud\to W^+,\bar u\bar d\to W^-$	$u,d,\bar u,\bar d$	$x\gtrsim 0.05$
 pp	$pp\to(W^\pm\to\ell^\pm\nu)+X$	$u\bar d\to W^+,d\bar u\to W^-$	$u,d,\bar u,\bar d,(g)$	$x\gtrsim 0.001$
	$p\bar p(pp)\to(Z\to\ell^+\ell^-)+X$	$uu,dd(u\bar u,d\bar d)\to Z$	$u,d(g)$	$x\gtrsim 0.001$
	$pp\to(W+c)+X$	$gs\to W^-c,g\bar s\to W^+\bar c$	$s,\bar s$	$x\sim 0.01$
	$pp\to t\bar t+X$	$gg\to t\bar t$	g	$x\sim 0.01$
	$\vec p p\to W^\pm+X$	$u_L\bar d_R\to W^+,d_L\bar u_R\to W^-$	$\Delta u\ \Delta\bar u\ \Delta d\ \Delta\bar d$	$0.05\lesssim x\lesssim 0.4$
	$\vec p\vec p\to\pi+X$	$gg\to qg,qg\to qg$	Δg	$0.05\lesssim x\lesssim 0.4$
 SIDIS	$\vec\ell^\pm\{\vec p,\vec d\}\to\ell^\pm h+X$	$\gamma^*q\to q$	$\Delta u\ \Delta\bar u\ \Delta d\ \Delta\bar d$ Δg	$0.005\lesssim x\lesssim 0.5$
	$\vec\ell^\pm\{\vec p,\vec d\}\to\ell^\pm D+X$	$\gamma^*g\to c\bar c$	Δg	$0.06\lesssim x\lesssim 0.2$

Proton F_2







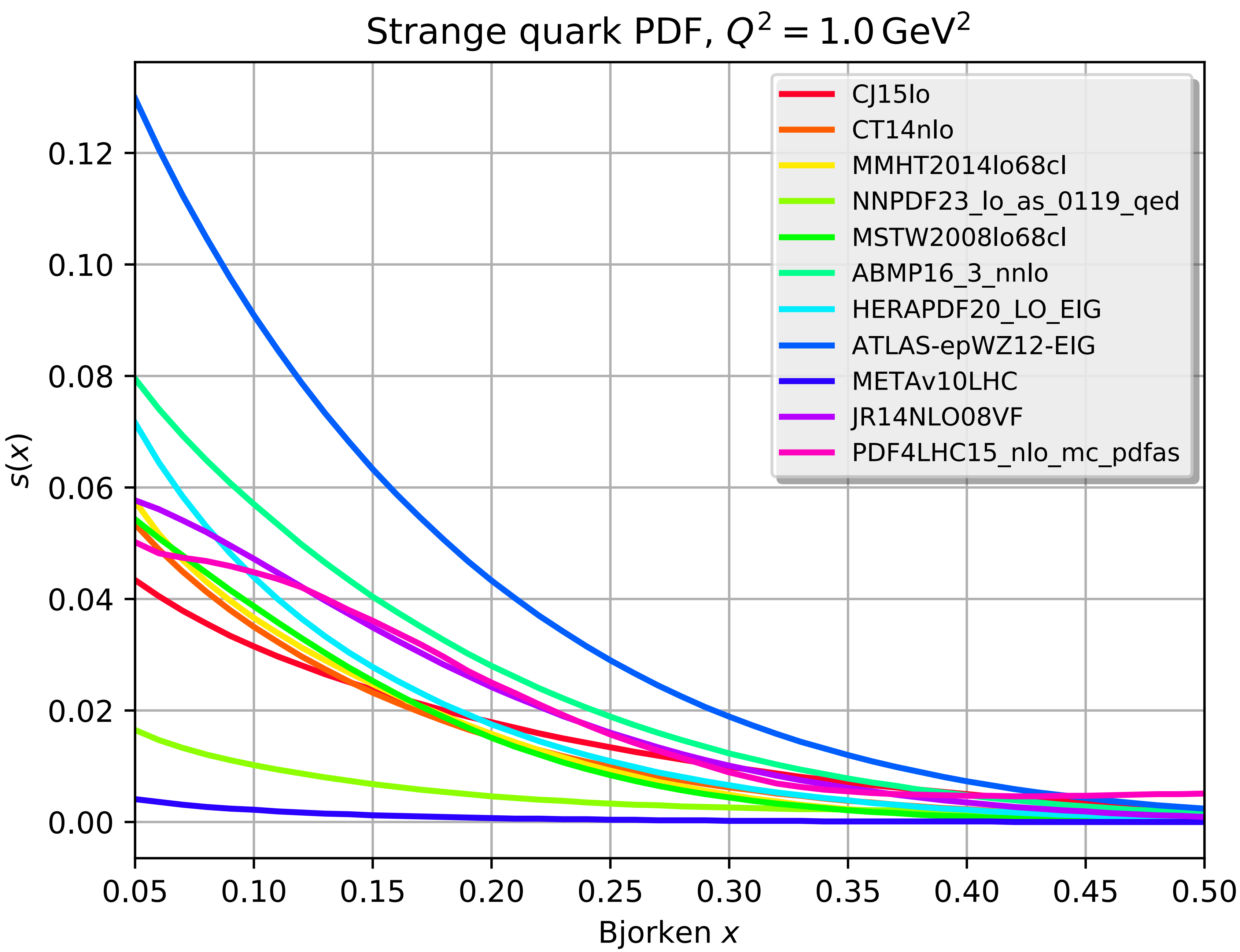
Excellent description over orders of magnitude in x and Q^2

PhysRevD.93.114017 (2016)

Strange PDF

Various extractions differ by more than and order of magnitude
Many fits not focusing on strange contribution

Results depend on parameterizations and assumptions in global fit.



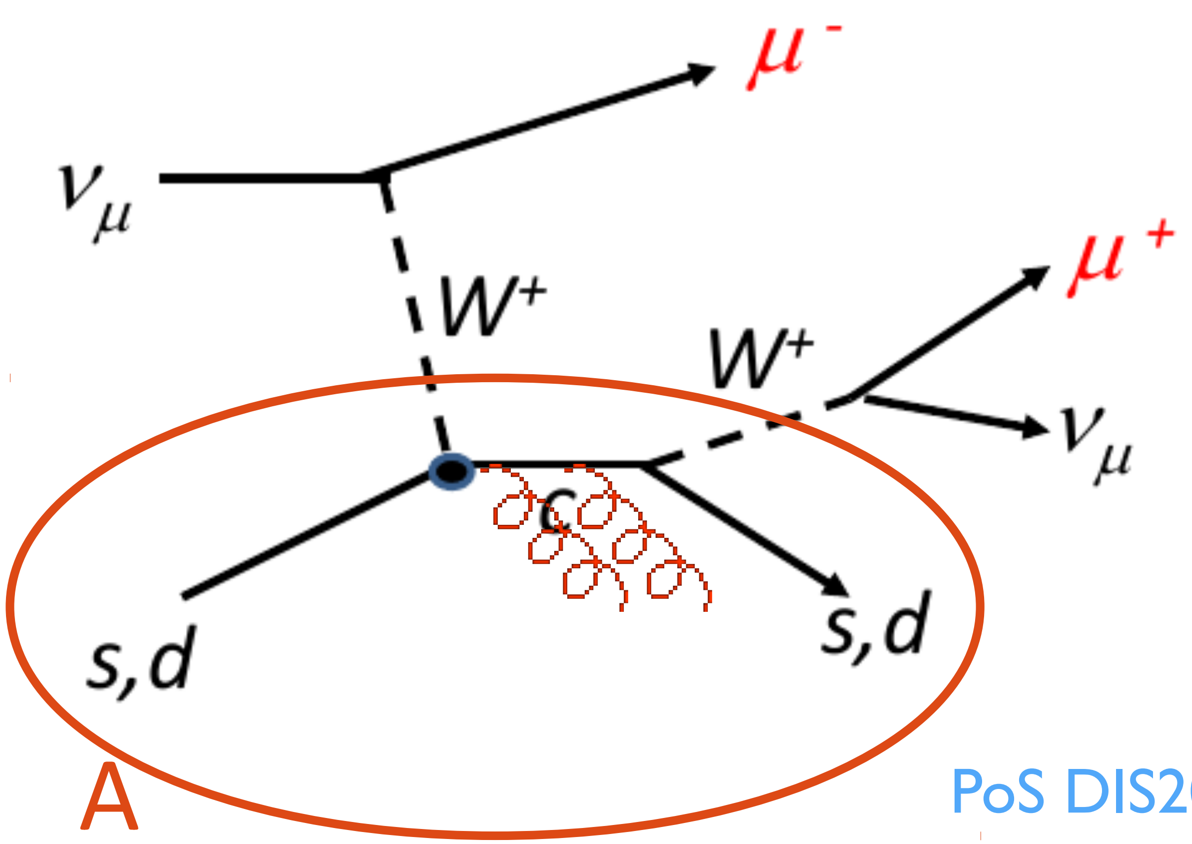
Accessing Strange Quarks

• di-muon production in neutrino-nucleus scattering	$0.01 < x < 0.2$
• W and Z rapidity distributions	$x >\sim 0.001$
• LHC W+c production	$x \sim 0.01$
• Semi-inclusive K production: not included in global fits (fragmentation)	$0.02 < x < 0.6$
• Parity Violating electron scattering	$0.1 < x < 0.5$

It's still not clear whether the strange sea is as big as the up and down sea (k ~ 1) or half as big (k ~ 0.5)

$$k = \frac{2s}{(\bar{u} + \bar{d})}$$

Neutrino nucleus



PoS DIS2015 (2015) 001

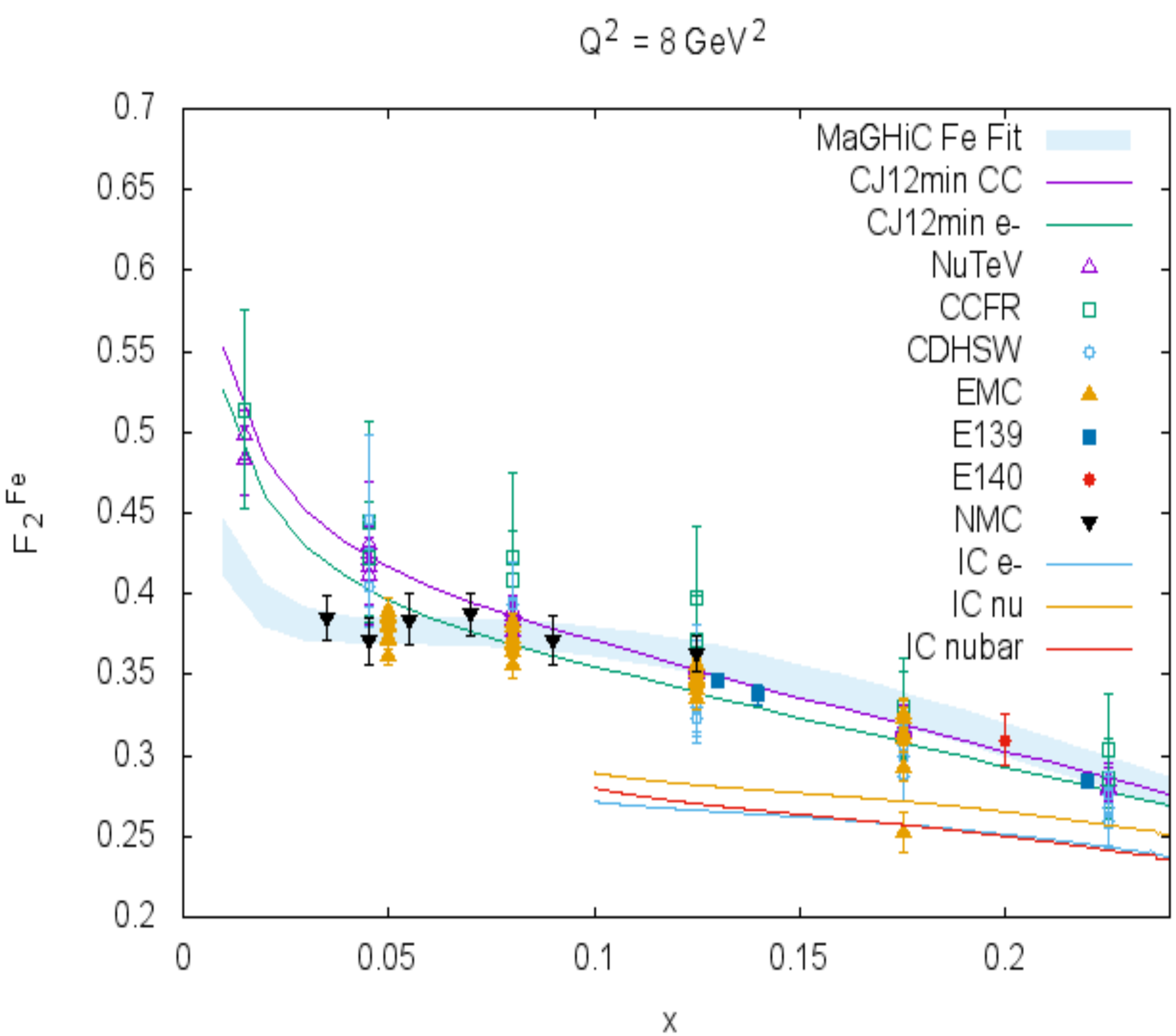
di-muon production in neutrino-nucleus scattering tags strangeness

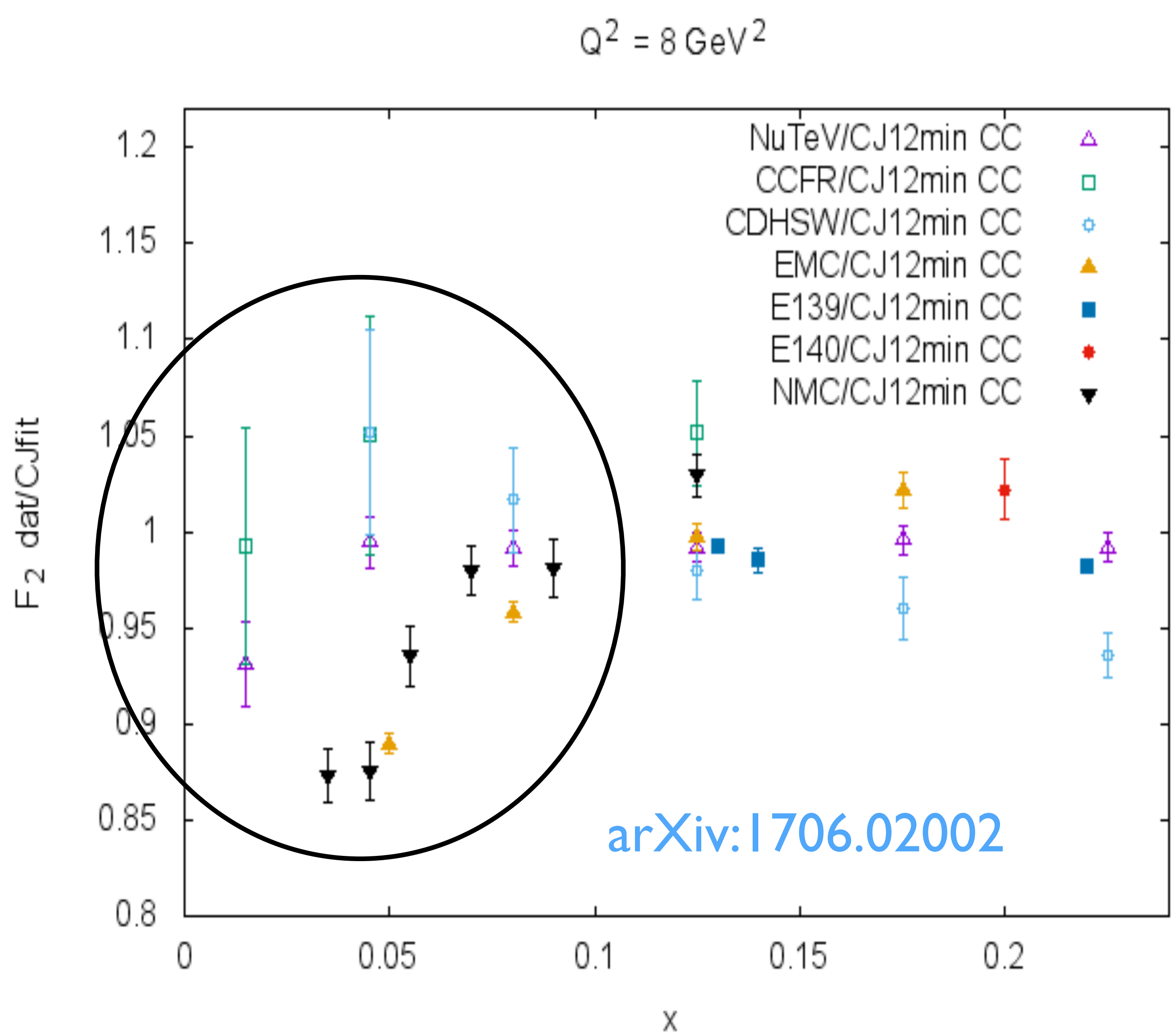
k ≈ 0.4

- initial state nuclear modifications of the PDFs themselves (partly under control—nuclear PDF fits)
- final state interactions
  - medium-induced gluon bremsstrahlung;
  - final state suppression of charm production (measured at RHIC significantly larger than perturbative calculations for QGP)

Neutrino nucleus

Neutrino and electron scattering data
from iron do not agree below x~0.1
Sensitive to different nuclear effects?

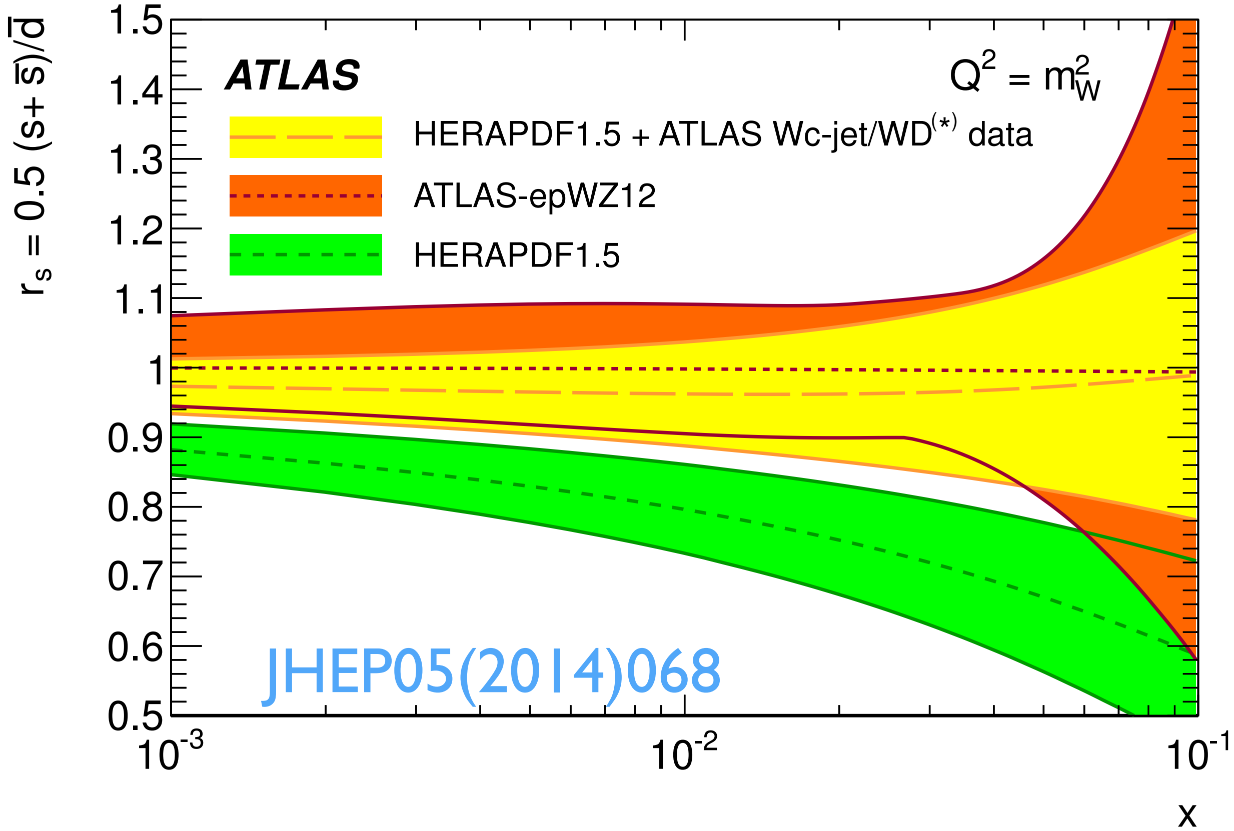




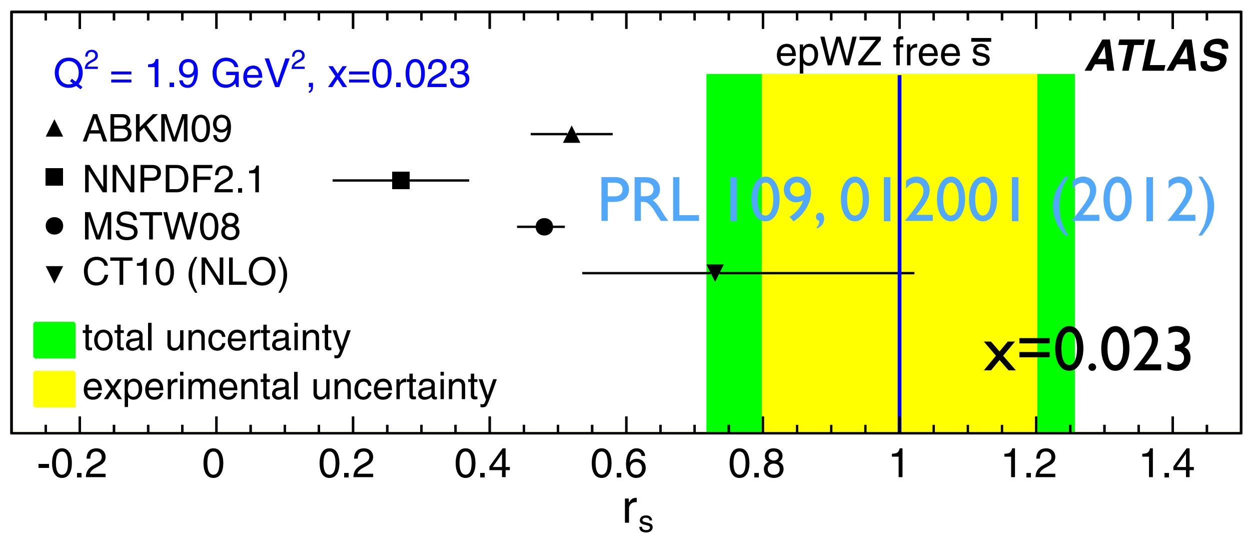
Proton—proton

ATLAS fits get k≈1 using collider only data

$$pp \to (W + c) + X$$

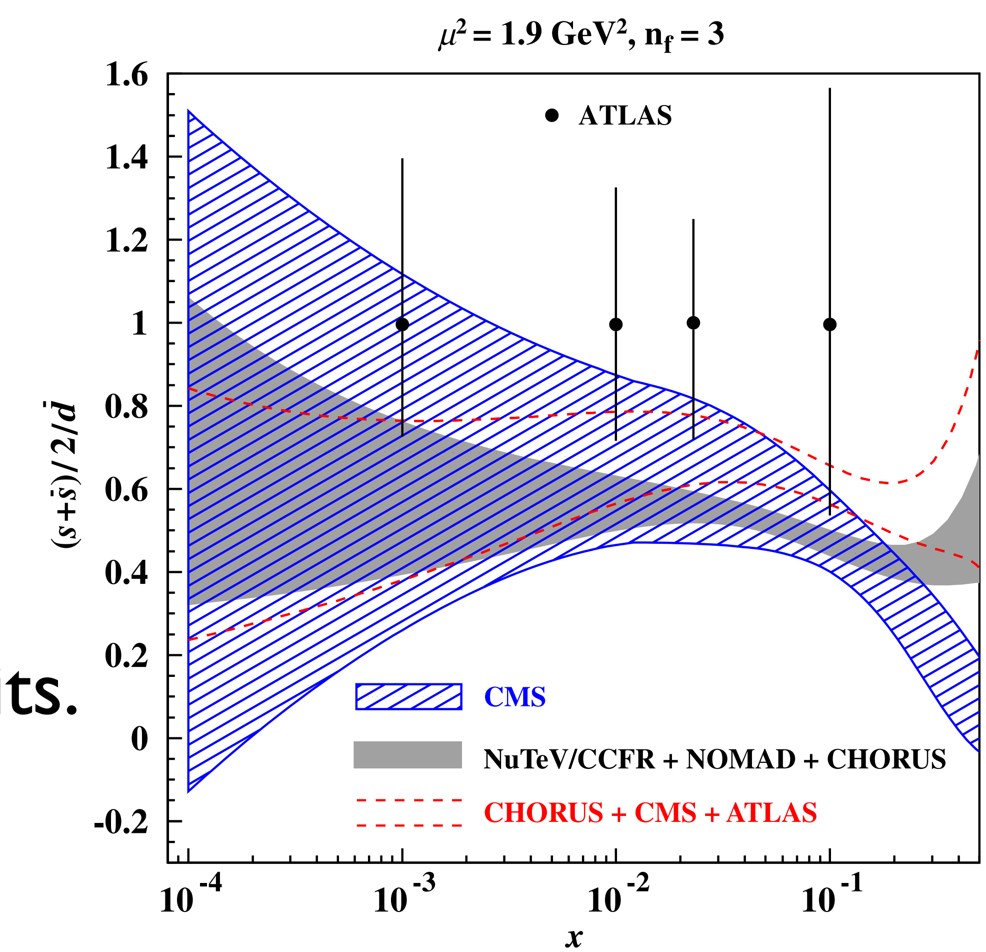


$$pp \to (W^\pm \to l^\pm + \nu, Z \to l^+ l^-) + X$$



Quoted uncertainties depend on assumptions

$$r_s = \frac{s + \bar{s}}{2\bar{d}}$$



Tension with neutrino nucleus

Down might be underestimate in collider-only fits.

Comparing data will expose final state effects

Parity violating electron scattering

very small

$$A_{PV} = \frac{G_F Q^2}{4\sqrt{2}\pi\alpha_{\mathrm{em}}}\left[a_2(x) + \frac{1-(1-y)^2}{1+(1-y)^2}a_3(x)\right]$$

$$a_2(x) = -2\,g_A^e\,\frac{F_2^{\gamma Z}(x)}{F_2^{\gamma}(x)} = \frac{2\sum_q e_q\,g_V^q\,q^+(x)}{\sum_q e_q^2\;q^+(x)}$$

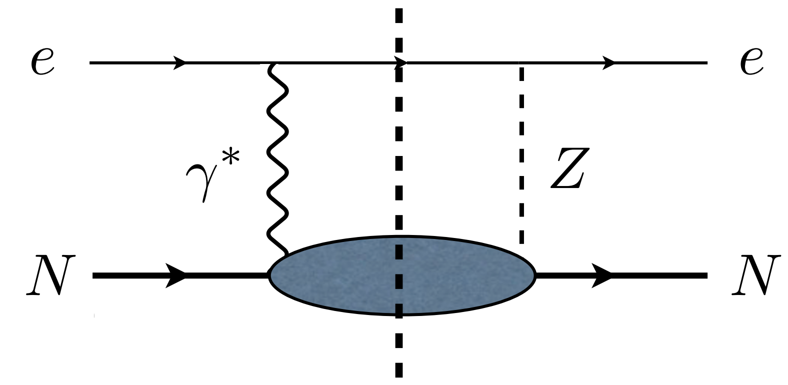
$$a_3(x) = -2\,g_V^e\,\frac{F_3^{\gamma Z}(x)}{F_2^{\gamma}(x)} = -4\,g_V^e\,\frac{\sum_q e_q\,g_A^q\,q^-(x)}{\sum_q e_q^2\;q^+(x)}$$

$$g_V^u = \tfrac{1}{2} - \tfrac{4}{3}\sin^2\theta_W$$
$$g_V^d = -\tfrac{1}{2} + \tfrac{2}{3}\sin^2\theta_W$$
$$g_A^e = -\tfrac{1}{2}$$
$$g_V^e = -\tfrac{1}{2} + 2\sin^2\theta_W$$
$$g_A^u = -g_A^d = \tfrac{1}{2}$$
$$q^+(x) = q(x) + \bar{q}(x)$$
$$q^-(x) = q(x) - \bar{q}(x)$$

Isolating strange

Parity-violating DIS allows strange contribution to be isolated, when combined with e.m. p and n DIS data at low/intermediate x

→ at leading order



$$F_2^{\gamma p} = \frac{4}{9}x(u+\bar{u}) + \frac{1}{9}x(d+\bar{d}+s+\bar{s}) + \cdots$$

$$F_2^{\gamma n} = \frac{4}{9}x(d+\bar{d}) + \frac{1}{9}x(u+\bar{u}+s+\bar{s}) + \cdots$$

$$F_2^{\gamma Z,p} = \left(\frac{1}{3} - \frac{8}{9}\sin^2\theta_W\right) x(u+\bar{u}) + \left(\frac{1}{6} - \frac{2}{9}\sin^2\theta_W\right)(d+\bar{d}+s+\bar{s}) + \cdots$$

$$\approx \frac{1}{9}x(u+\bar{u}+d+\bar{d}+s+\bar{s}) + \cdots \quad \text{for } \sin^2\theta_W \approx 1/4$$

3 equations with 3 unknowns

$$s+\bar{s} \approx 3(5F_2^{\gamma Zp} - F_2^{\gamma p} - F_2^{\gamma n})$$

Not a new idea!

SLAC-PROPOSAL E149 *bis*
May 4, 1993

DIS-PARITY

Parity Violation in Deep Inelastic Electron Scattering

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ABSTRACT

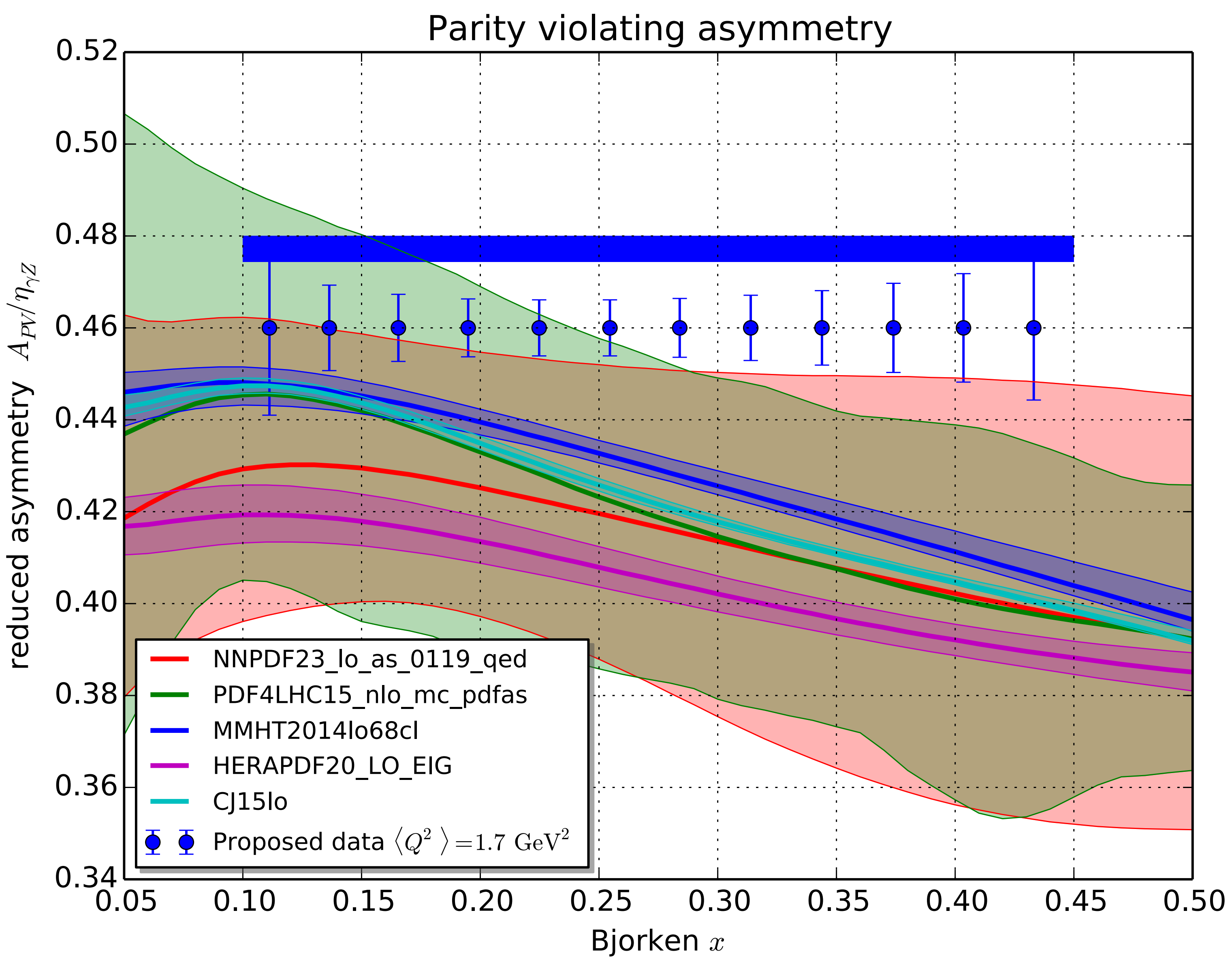
We propose to measure the parity-violating interference between electromagnetic and weak coupling in deep-inelastic electron scattering from hydrogen and deuterium. The primary physics goals are to test the electro-weak Standard Model and to determine the flavor content of the quark sea. The experiment will determine the $Z-$quark coupling to an equivalent precision in $\sin^2(\theta_w)$ of approximately 0.003 (1.2%), and will be quite sensitive to the possible existence of certain types of new physics beyond the Standard Model. The experiment will also measure two new combinations of quark distribution functions with errors of about 0.05. The deuterium case is particularly interesting because it directly isolates the strange sea quark contributions.

The experiment consists of scattering polarized electrons from long liquid hydrogen and deuterium targets in End Station A. The scattered electrons are detected in two large solid angle magnetic spectrometers centered around scattering angles of 4.25 and 6.5 degrees for an incident beam energy of 29.1 GeV. At E = 48.6 GeV, the 6.5° spectrometer is moved to 2.75°. The spectrometers are entirely made up of existing magnets. The detectors consist primarily of lead glass arrays that can be made from the surplus ASP pieces. The beam is required to have a polarization of 80% or more, and high current (4×10^{11} e^- per beam pulse at 120 Hz non-SLED, 2×10^{11} SLED). The combination of higher beam polarization, higher beam energy, and larger spectrometer solid angle provides a factor of eight greater sensitivity than the original SLAC experiment on deuterium. The addition of hydrogen allows more sensitive studies of the flavor content of the quark sea.

A total of twelve weeks of running time is requested for an initial run at 29.1 GeV, of which one third will be used for checkout, calibrations, and background studies, and two thirds for data taking. A subsequent run of ten weeks at 48.6 GeV is also requested. In a relatively modest running time, this experiment will provide significantly improved precision on electroweak physics at low Q^2 and on the flavor content of the quark sea. We emphasize that this experiment can only be undertaken at SLAC.

Predicted asymmetry

Curves from LO equations at Q^2=1 GeV2



Large spread in central values

Corrections and Interpretation

Target Mass Corrections

$$\propto \frac{M^2}{Q^2}$$

Under control in CJ15 (+ NNPDF3.0 …), for cross section observables.

Higher Twist Corrections

non-pert. parton correlations

$$\propto \frac{\Lambda^2}{Q^2} \qquad \Lambda \sim 0.1 - 1\mathrm{GeV}$$

Under control in CJ15, for cross-section observables.
Flavor dependence?

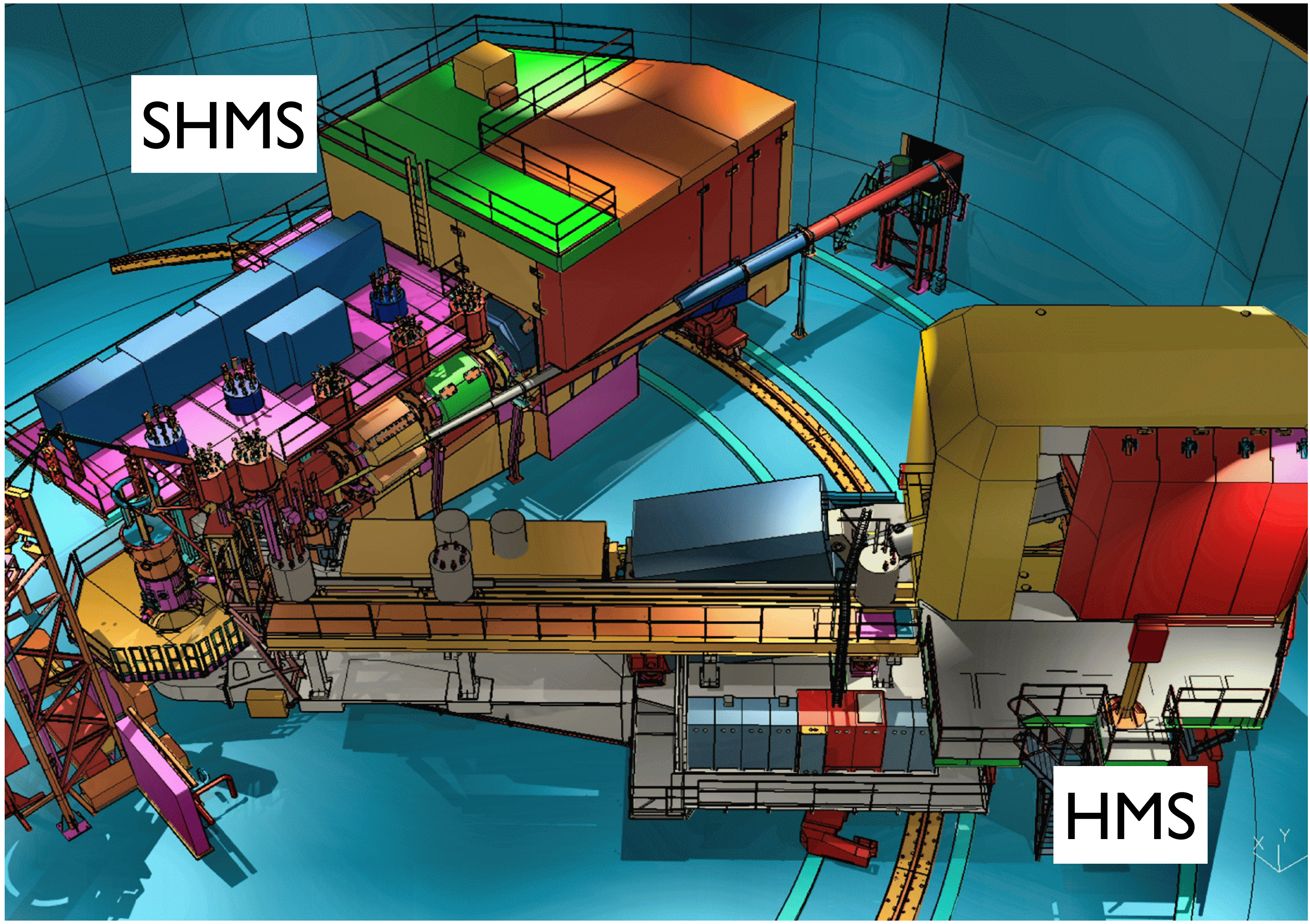
~~**Nuclear Corrections**~~

~~binding, Fermi motion, off-shellness~~
~~calculations are largely model-dependent~~

~~Under control in CJ15 (+ MMHT14 …)~~

Experimental Overview

- Beam: 70 uA, maximum energy, minimized transverse polarization.
- 20 cm, GMP-style, liquid-hydrogen target
- Helicity flip rate 240 Hz, delayed reporting
- Charge feedback + Insertable Half-Wave Plate + Helicity magnets
- Qweak-level polarimetry
- Full tracking for kinematics
- Asymmetry measurement using lead glass calorimeters and Heavy Gas Cherenkov detectors.

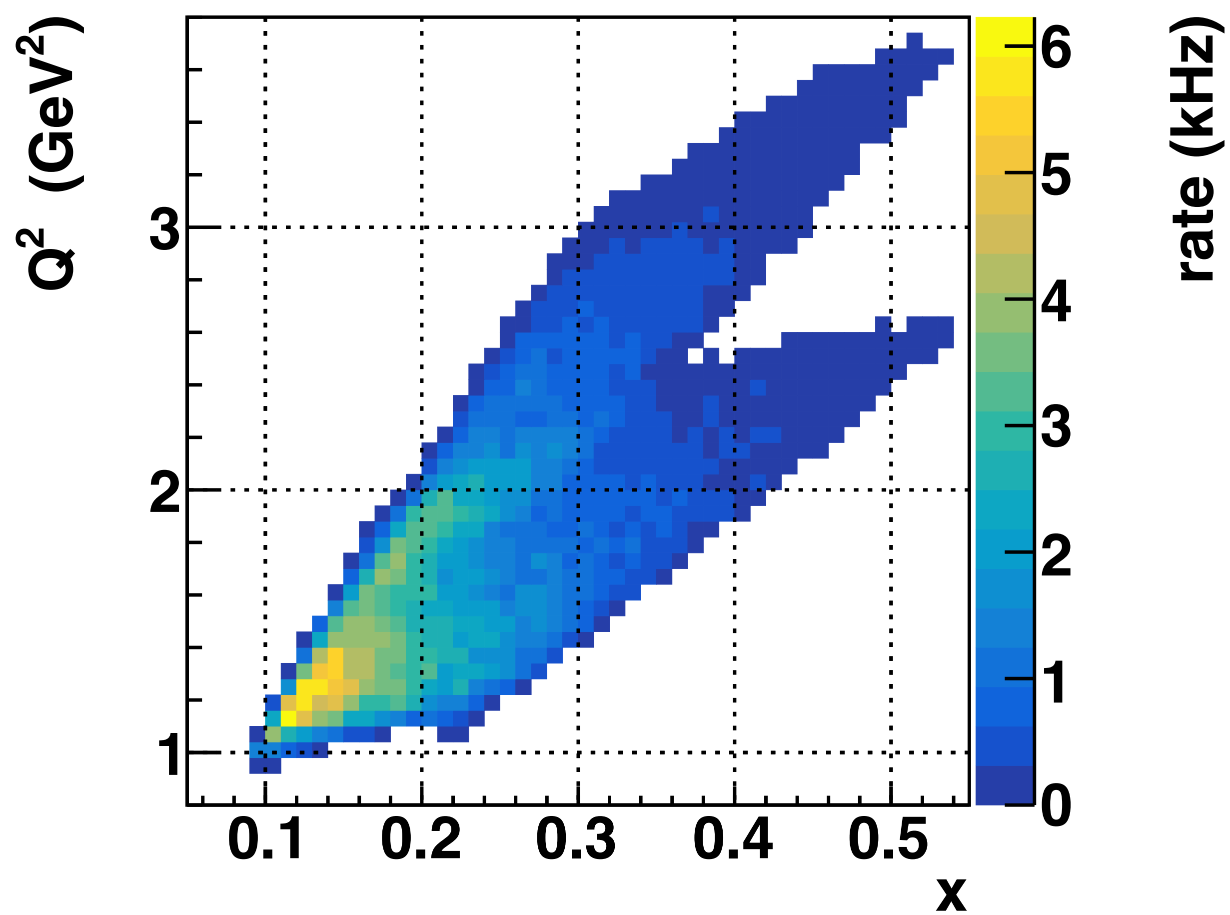


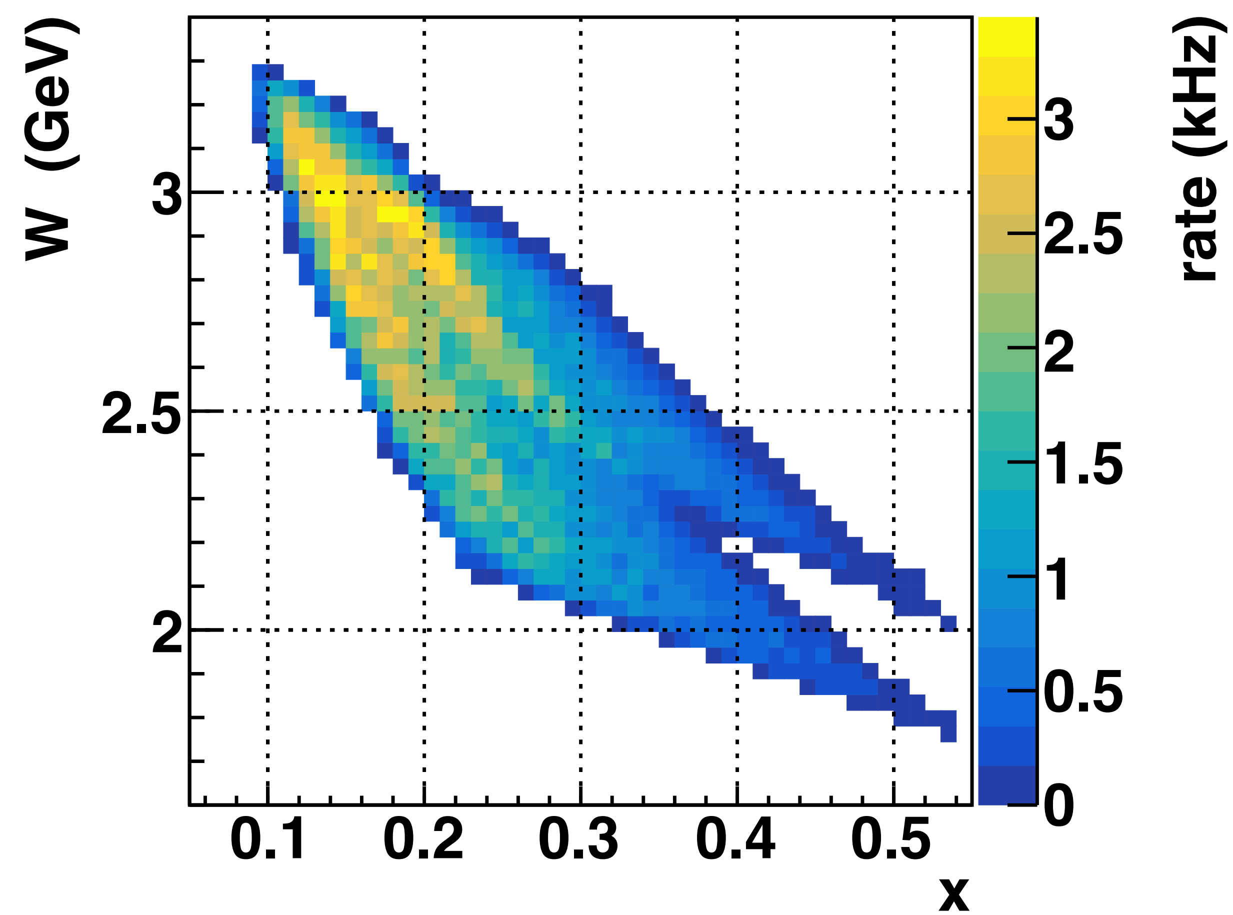
High rate, basic idea already pioneered modern technology will make it easier pushing systematic uncertainty

Spectrometer Kinematics

Spectrometer	$P_{\rm cent}$ (GeV/c)	$\theta_{\rm cent}$ (deg)	$\langle Q^2 \rangle$ (GeV^2/c^2)	$\langle x \rangle$	$\langle W \rangle$ (GeV)	$\langle A_{\rm PV} \rangle$ (ppm)
HMS	6.4	10.5	2.31	0.275	2.66	185
SHMS	6.5	8.5	1.53	0.209	2.64	122

Push to low x keeping $Q^2 > 1$ GeV^2





High Rate

rate from simulation
using Mo and Tsai,
asymmetry from
Standard Model
$\delta A/A \sim 0.22\%$

reverse
spectrometer
polarity
$\delta A/A \sim 0.2\%$

High total rate
custom DAQ

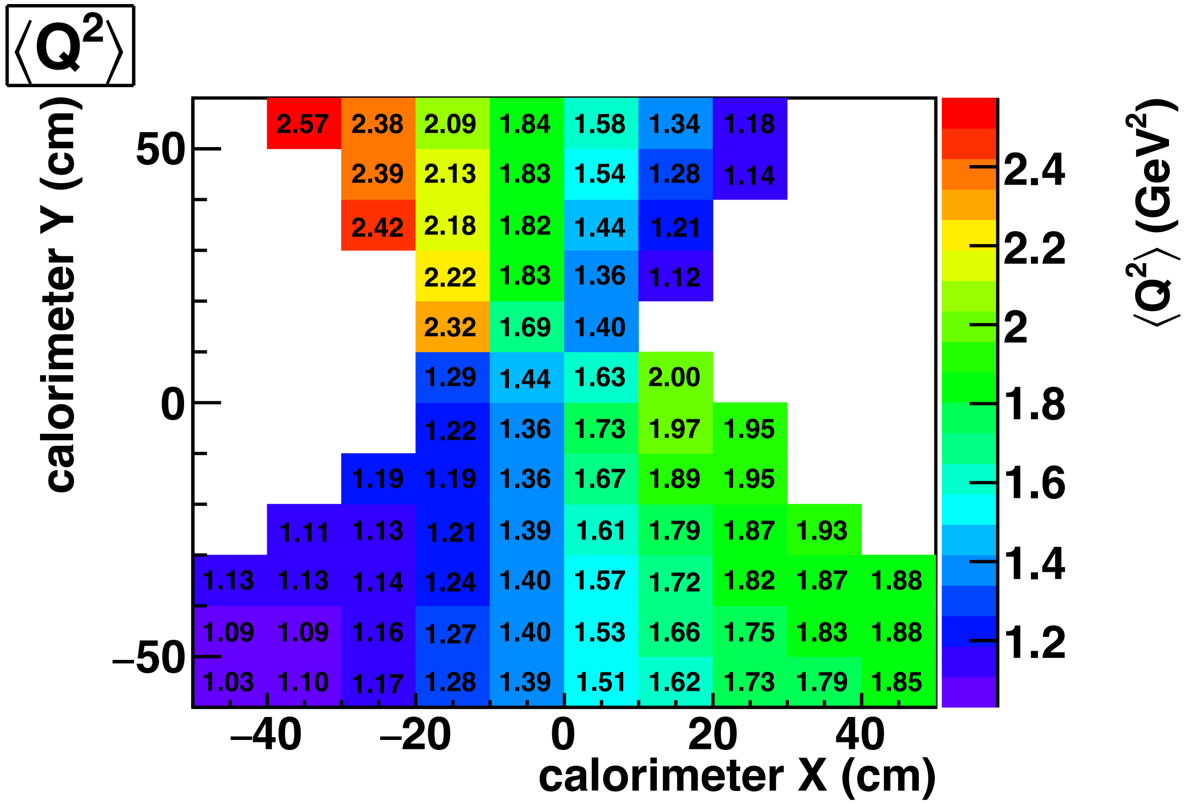
Spectrometer Rate (kHz)	DIS	elastic tail	π^-	charge symm.	Al windows	total
HMS	173.9	2.8	73.0	1.0	7.3	258.1
SHMS	608.1	17.6	344.0	5.0	26.1	1000.8

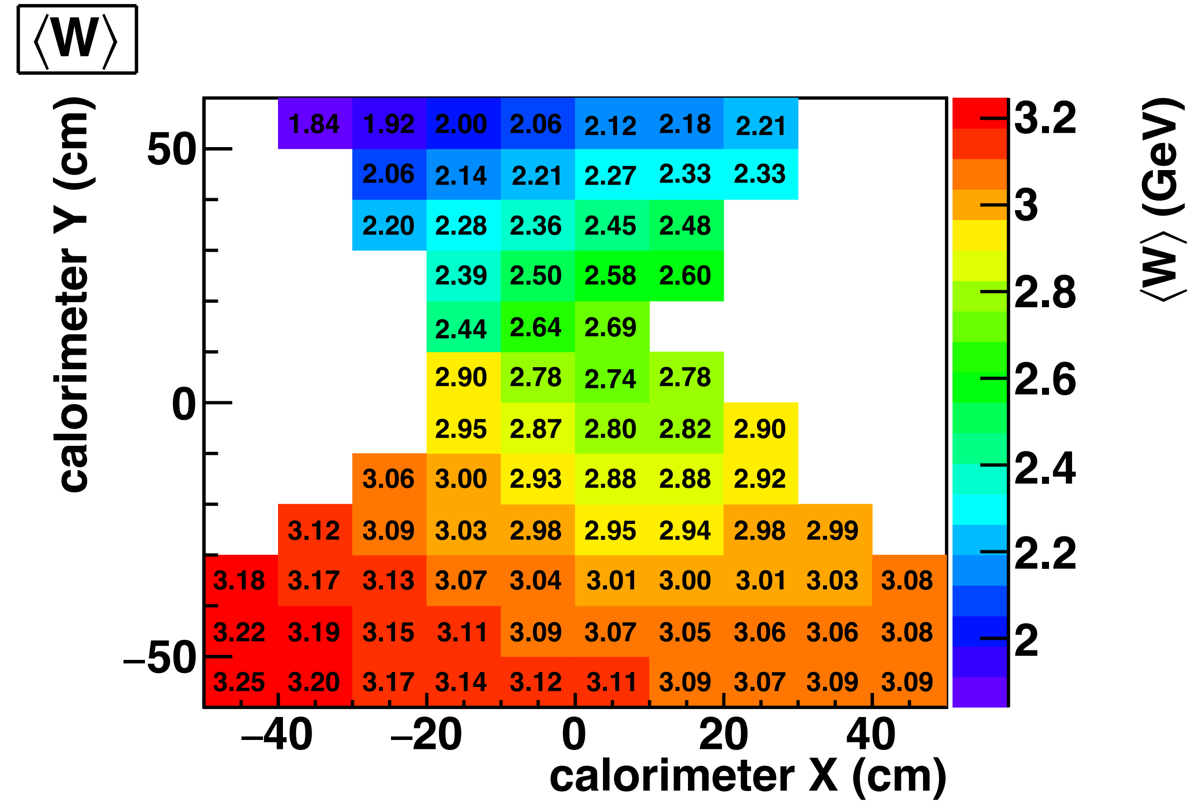
pi/e ~0.6
modest online PID requirement
$\delta A/A \sim 0.08\%$

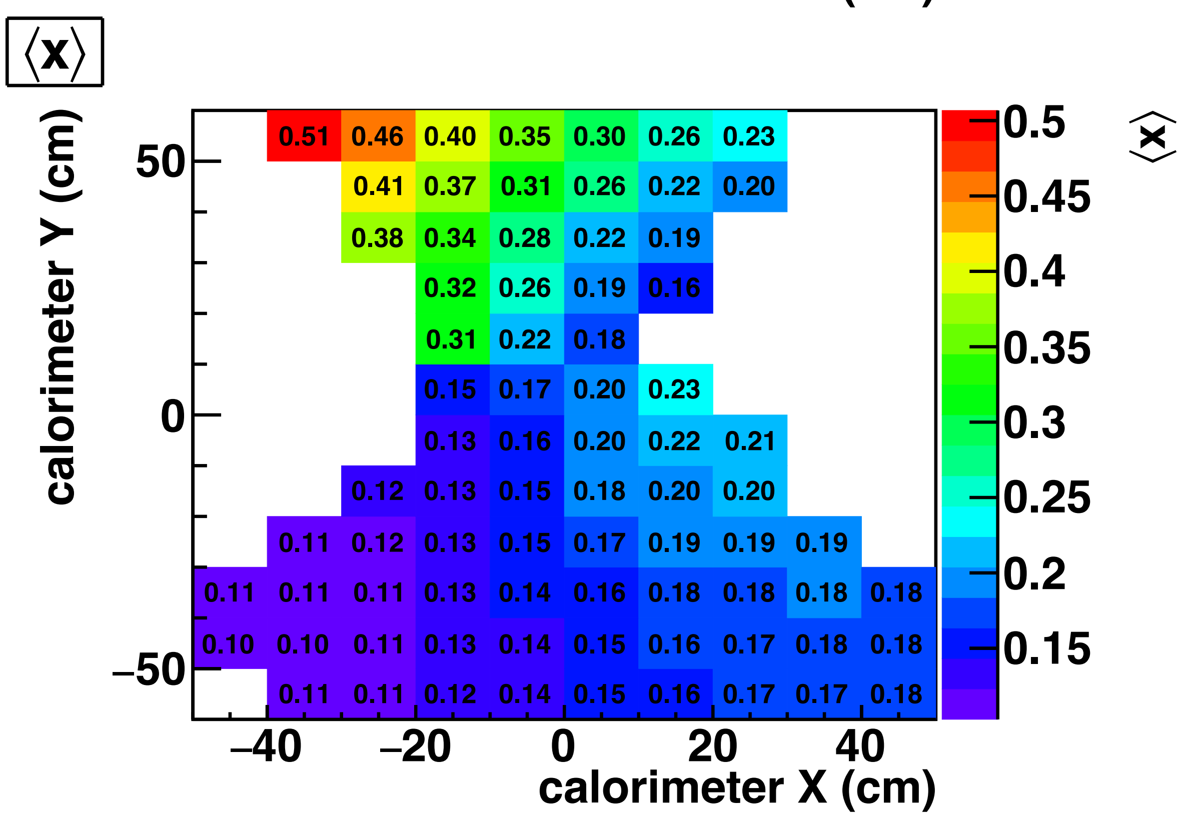
dedicated asymmetry
measurement on
dummy aluminum target
$\delta A/A \sim 0.2\%$

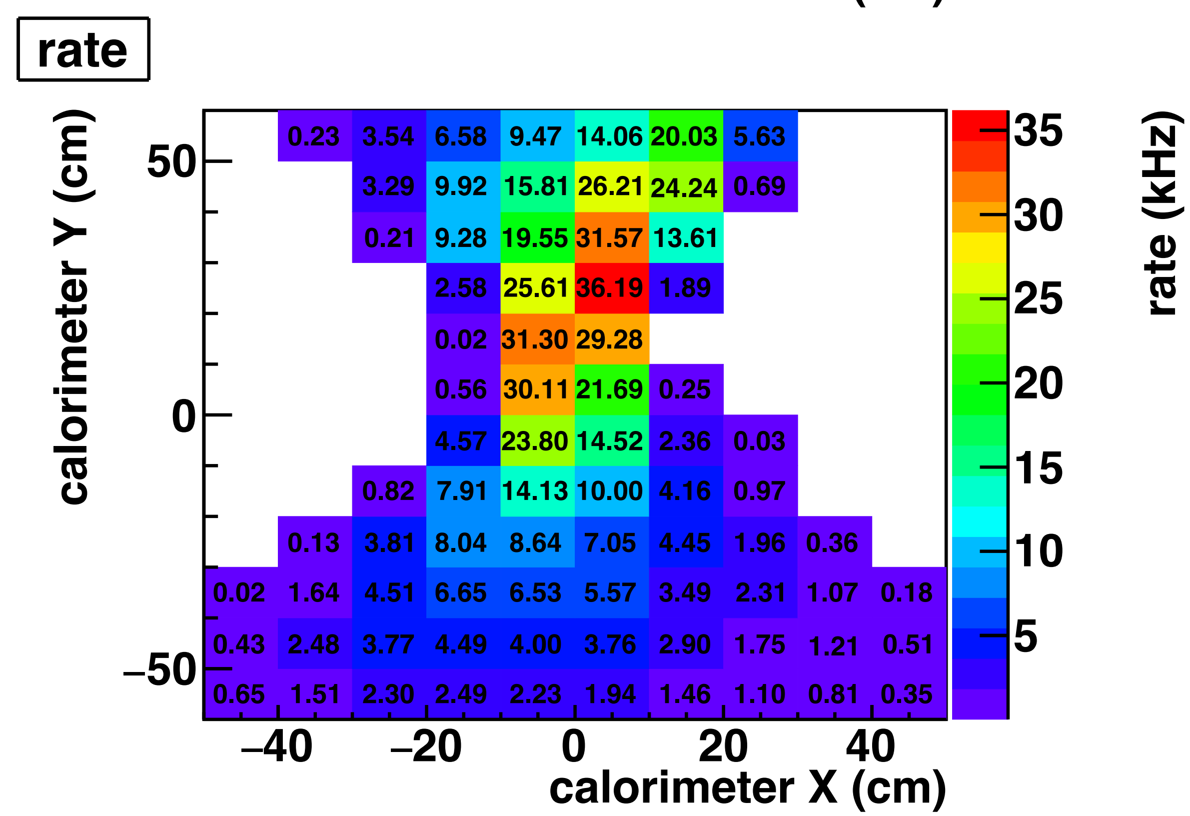
Binning SHMS

Position on calorimeter separates events by kinematics









Data Acquisition

High rate PID and counting, basic principles already pioneered in PVDIS experiment, more modern technology will make it easier.

- Assume 50 ns recovery time for Cherenkov, 1 MHz => 5 % pile up
- The existing readout system in Hall C is fully-pipeline capable
- VXS Trigger Processor (VTP) is the heart of the DAQ
  - 4 MB fast memory
  - run algorithms to detect pulses, determine geometrical center in the calorimeter, determine PID from Cherenkov and calorimeter
  - 2 histograms ~1 MB each—one filled while the other is read out
    - 16 bit depth (65536 counts) to be 26 bins in 4 dimensions
  - Maximum 240 MB/s rate to to tape
  - Custom firmware produced by JLab Fast Electronics group
- Dead time monitored by injecting pulses
- Dedicated data runs reading out full waveforms
- Beam current scans, threshold scans and charge asymmetry scans—to study nonlinearities in dead-time and other rate-dependent effects
- Measure dead time to 5% ⇒ ~0.25% uncertainty

Tracking and Q^2

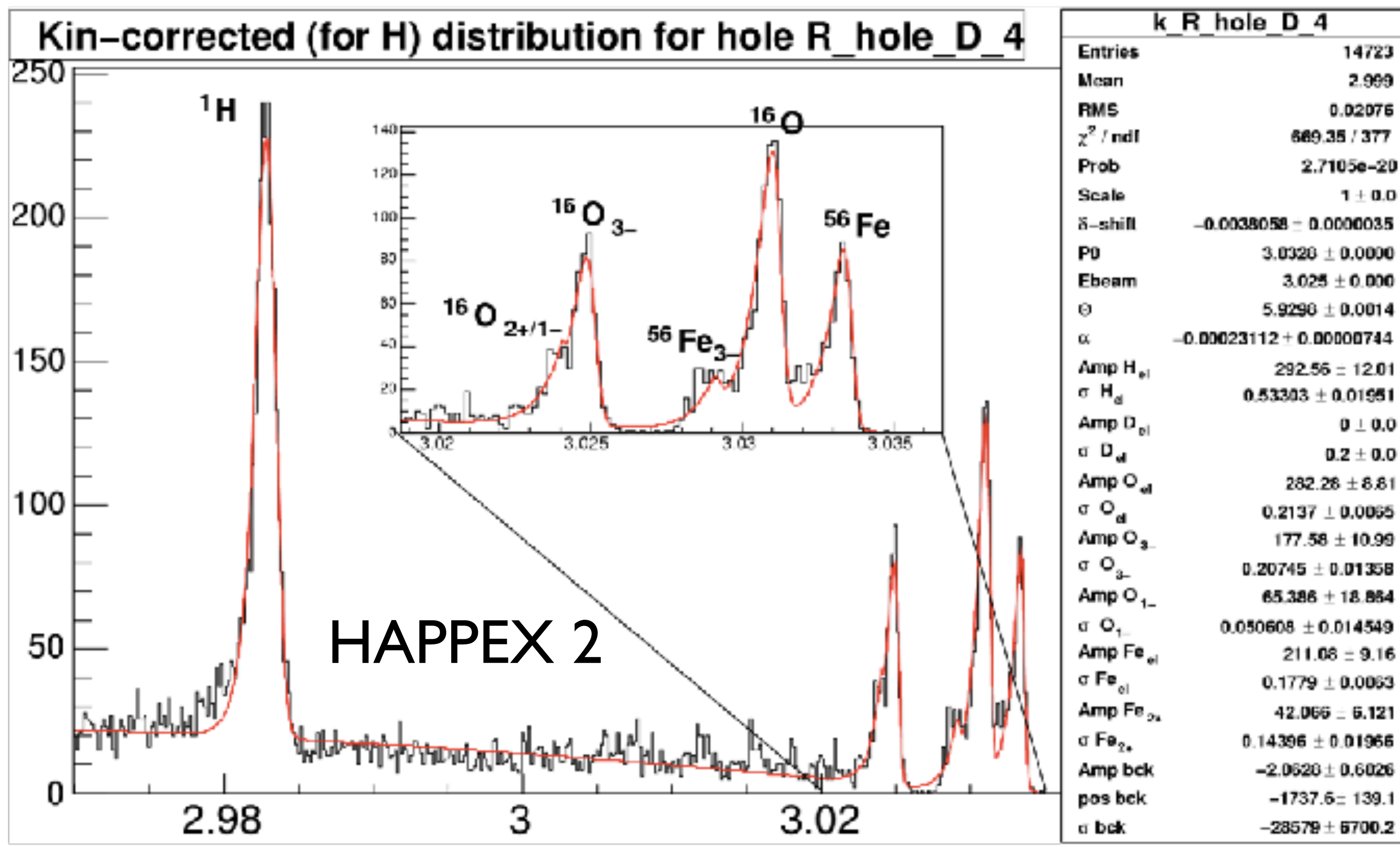
Largest systematic

Assuming level of uncertainty achieved during 6 GeV era

Small angle, large sensitivity

Beam energy	0.1 %
Scattered momentum	0.1 %
Scattering angle (0.5 mrad)	0.71 %
Q^2 determination	0.72 %

- extensive survey
- water target

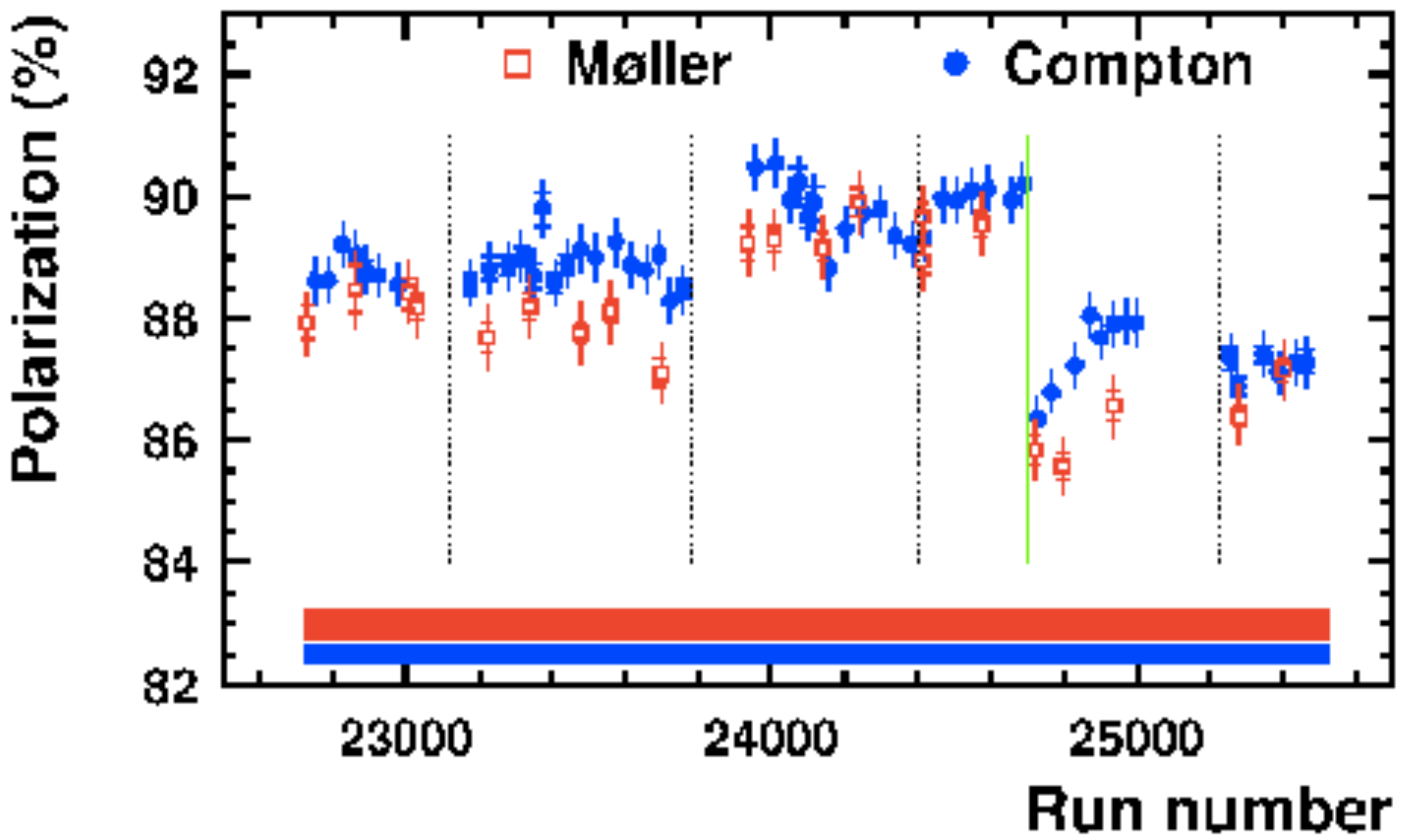


Polarimetry

Second largest systematic

Same strategy as Qweak:
combined Moller and Compton measurements.

Revive high-precision techniques before the run.



Compton asymmetry significantly larger at higher energy.
Existing electron detector will capture half of the spectrum.
Largest source of uncertainty can be reduced with new firmware.

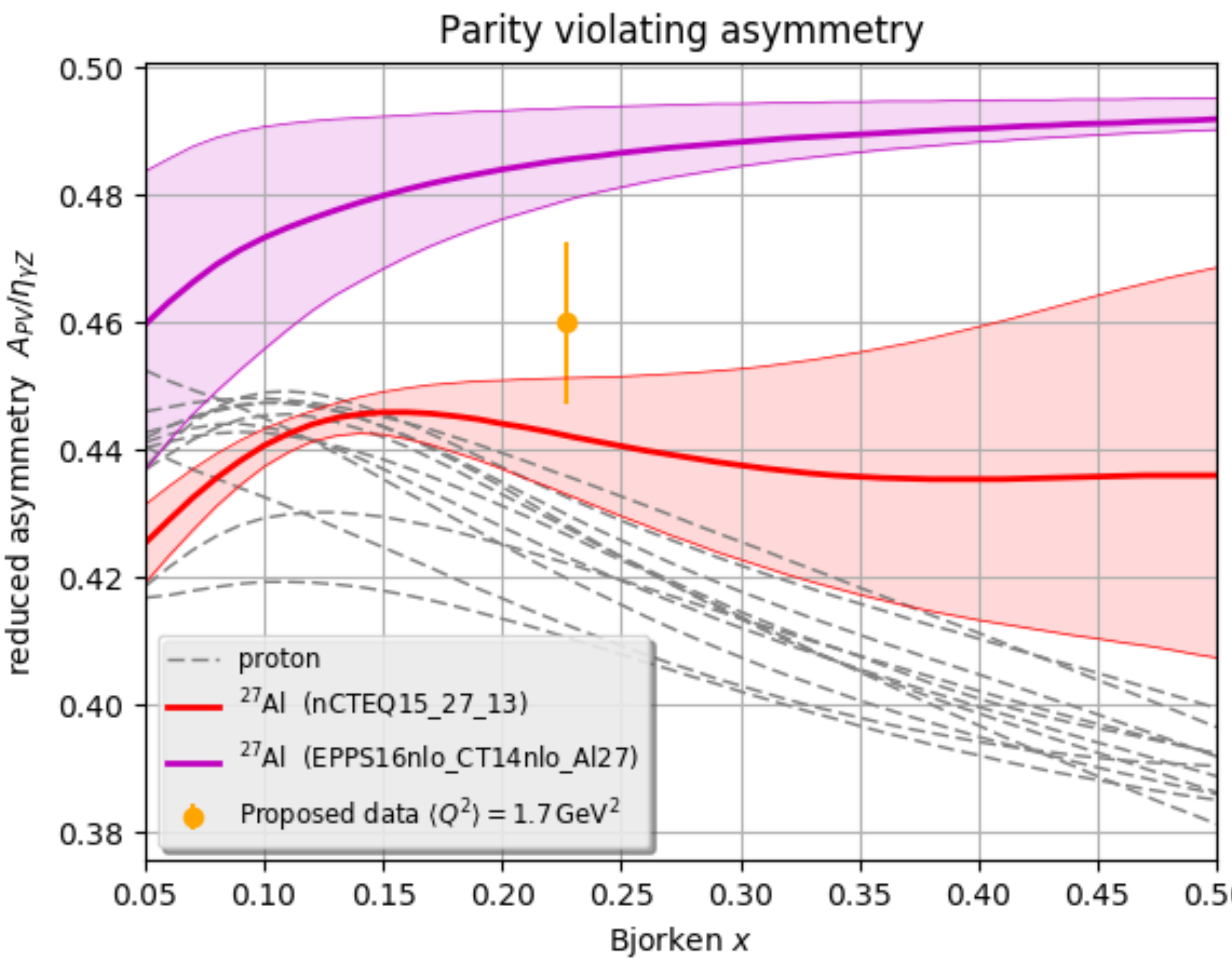
Compton 0.59% Phys. Rev. X6 no. 1, (2016) 011013

Moller simulations predict 0.74% uncertainty at 11 GeV.
Measurements every 3 days, ~4 hours.

Aluminum Background

5 Mil thick windows < 3% of rate
Asymmetry up to 10% larger than hydrogen

Opportunity to make a contribution to nuclear PDFs



EPPS
Q^2_{min} = 1.7 GeV^2

nCTEQ no neutrino data,
Q^2_{min} = 2 GeV^2

Systematic Uncertainties

Q^2 determination	0.72 %
Polarization measurement	0.60 %
Residual transverse beam polarization	0.40 %
Dead-time corrections	0.25 %
Elastic radiative tail	0.22 %
Pair-symmetric background	0.20 %
Aluminum endcaps	0.20 %
Beam asymmetries	0.10 %
Pion contamination	0.08 %
Total	1.12 %

Beam Time Request

	days	8 hour shifts
Optics and tracking		6
Moller measurements		5
Aluminum target		3
Compton commissioning		3
Pileup monitoring		2.5
Vertical polarization		1
Spectrometer re-scattering		1
Reverse polarity		1
Polarization setup		1
Target fluctuation studies		0.5
Total commissioning and systematics	8	24
Total production	30	
Total	38	

Summary

Parity violation experiment using the standard equipment in Hall C

Will provide new information on nucleon Parton Distribution Functions

- unique sensitivity to strange

Small spectrometer angles allow access down to $x \sim 0.1$

- strange quarks expected to rise rapidly
- not covered by any non-nuclear data

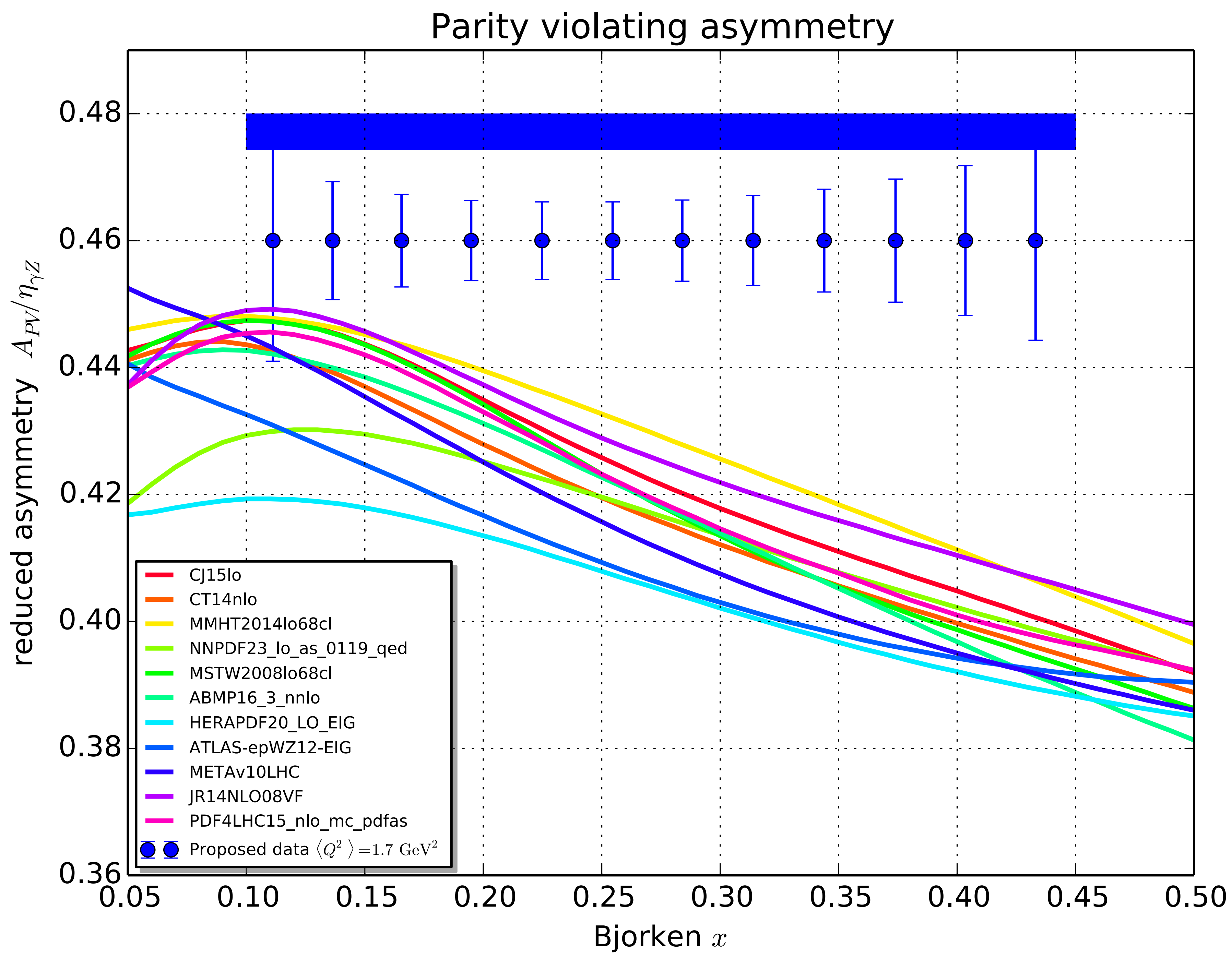
DAQ is the most non-standard item

Can only be done at CEBAF with small angle spectrometers


EXTRA!!

Asymmetry

PDFs without uncertainty



Transverse asymmetry leakage

Left-Right asymmetry

Vertical polarization:
0.0% ± 2.0% (1.15 degrees)

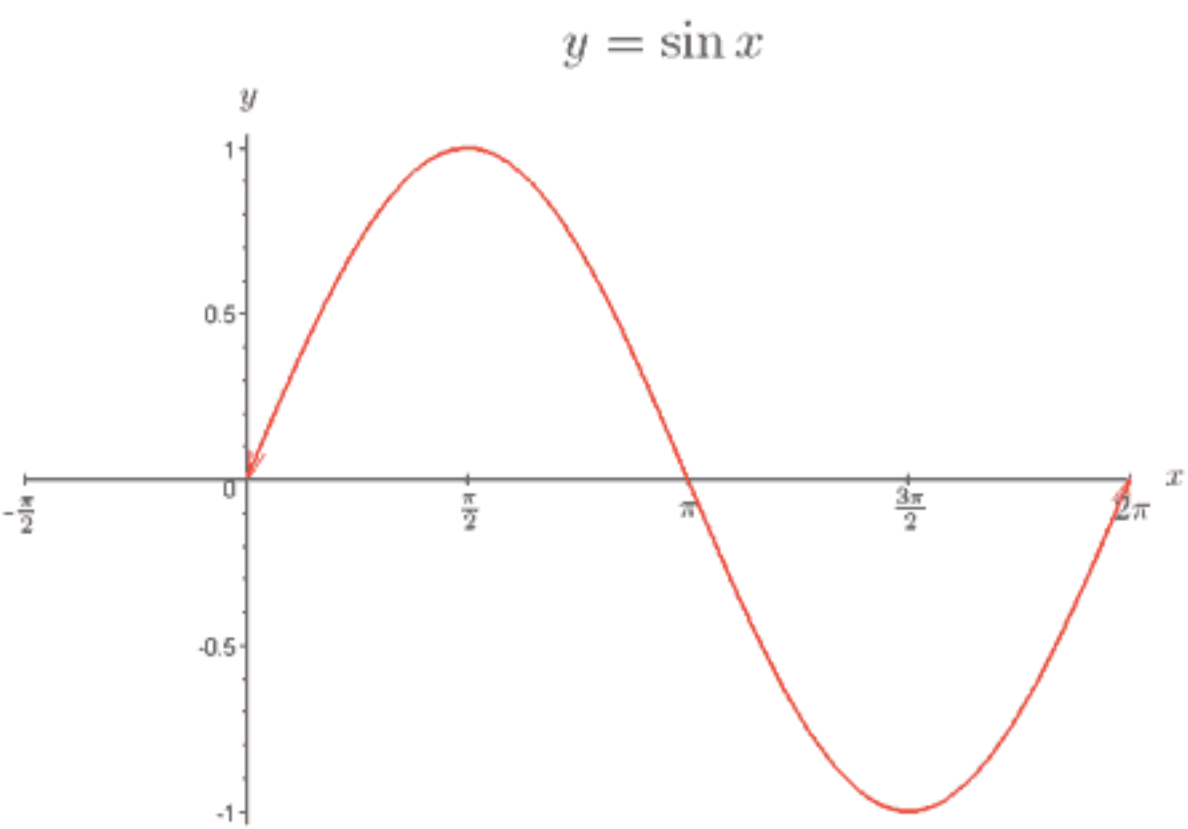
SHMS and HMS will have opposite central angles and similar momenta. Some degree of first order cancellation.

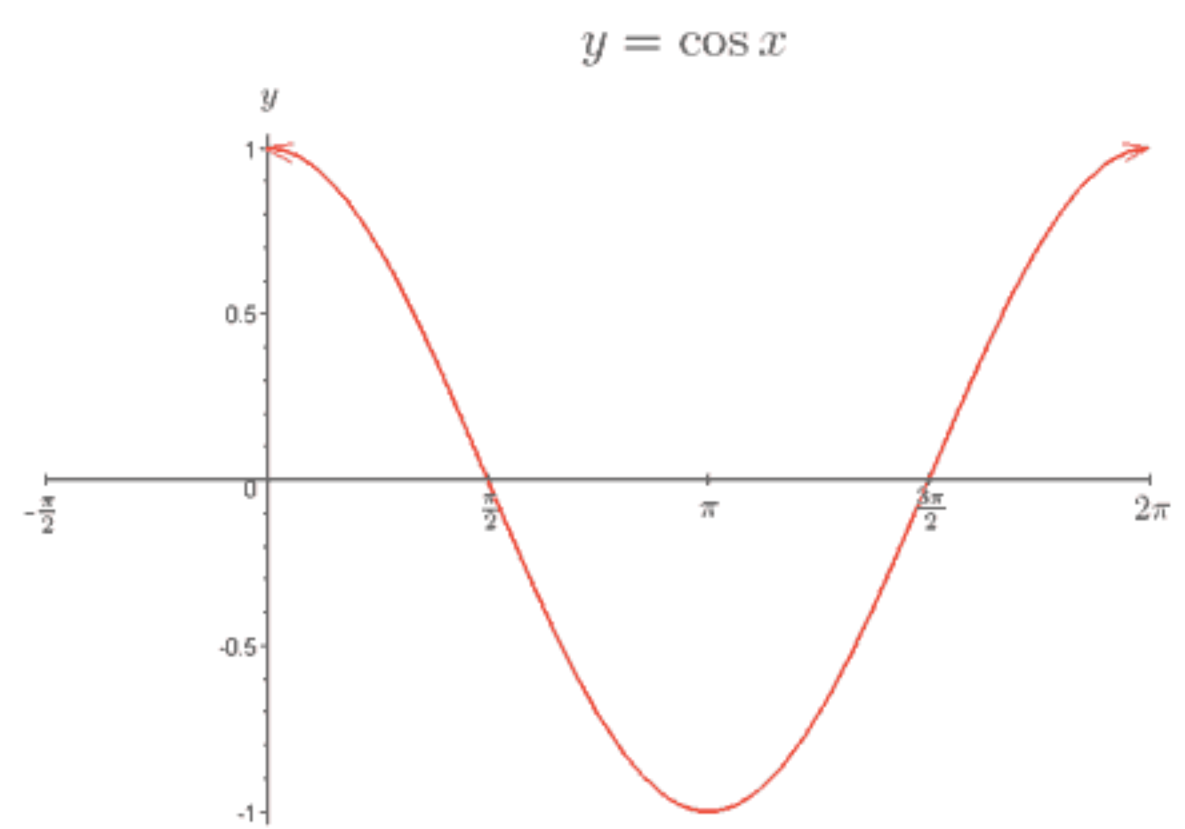
Up-Down asymmetry

Horizontal polarization: ± 4.0% (2.3 degrees)
acceptance around horizontal: -10% to 10%

Acceptance might map to different kinematics, potential non-cancellation must be studied, assume 50%.

50 ppm*4%*10%*50%=0.02 ppm





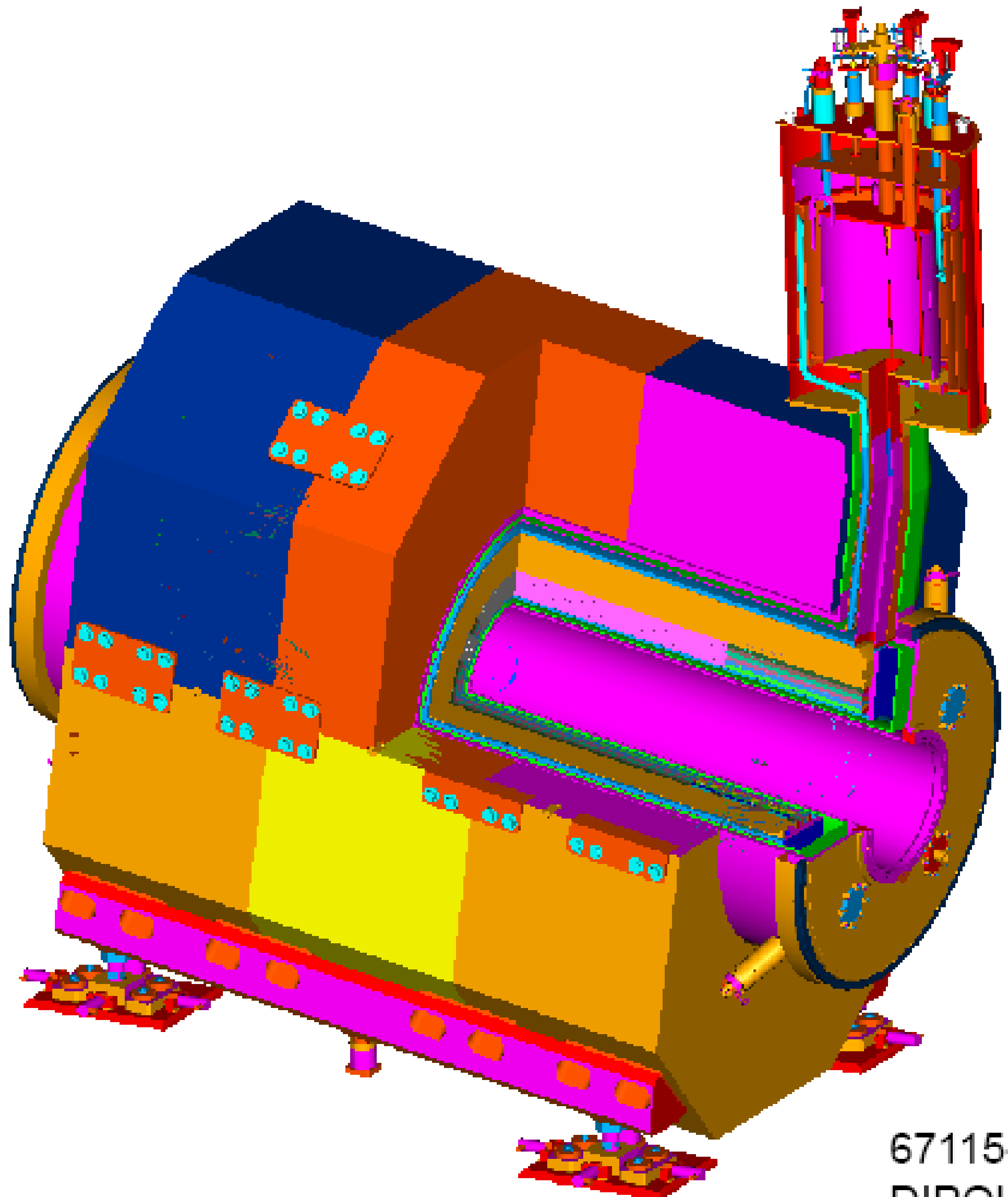
Spectrometer Backgrounds

Re-scattering within the spectrometer may cause background with unknown asymmetry in the acceptance.

No large asymmetry processes contribute.

Unlike HRS dipoles in Hall A there are no magnetized iron "pole tips" to scatter off.

Bounded using a full simulation the spectrometer and tracking data from early 12 GeV experiments. Specific beam based studies might be necessary.



Target density fluctuations

Adds additional noise

Compare to statistical width—this experiment large

Experiment	I_{beam}	Raster	Reversal	Width
G0	40 uA	2x2 mm	30 Hz	238 ppm
PVDIS	100 uA	4x4 mm	30 Hz	569 ppm
HAPPEX 3	100 uA		30 Hz	1000 ppm
GMP	60 uA	2x2 mm	30 Hz	536 ppm

We will use a GMP-style target
mitigated by increasing flip rate and raster size

$$\left(\frac{4\text{mm}^2}{16\text{mm}^2}\right)\left(\frac{70\mu A}{60\mu A}\right)^3\left(\frac{20\text{cm}}{15\text{cm}}\right)^3 536\text{ ppm} = 504\text{ ppm}.$$

Electron rate	Reversal rate	Statistical width	Assumed target width	Relative width increase
800 kHz	30 Hz	4330 ppm	1000 ppm	2.6 %
800 kHz	240 Hz	12250 ppm	1000 ppm	0.3 %
800 kHz	240 Hz	12250 ppm	504 ppm	0.08 %

Helicity Correlated Differences

- moderate sensitivity to differences
- feedback on charge in the source
- beam differences off the photocathode minimized in source setup
- helicity magnets in the injector will be used to further diminish the position and angle differences.
- regular IHWP to help cancel the remaining differences
- modulation of the beam position and energy to extract sensitivity

Sensitivity	Difference	Correction
$\partial R/\partial x \sim 22$ ppb/nm	< 20 nm	< 440 ppb
$\partial R/\partial \theta \sim 34$ ppb/nrad	< 4 nrad	< 136 ppb
$\partial R/\partial E \sim 0.23$ ppb/ppb	< 100 ppb	< 23 ppb

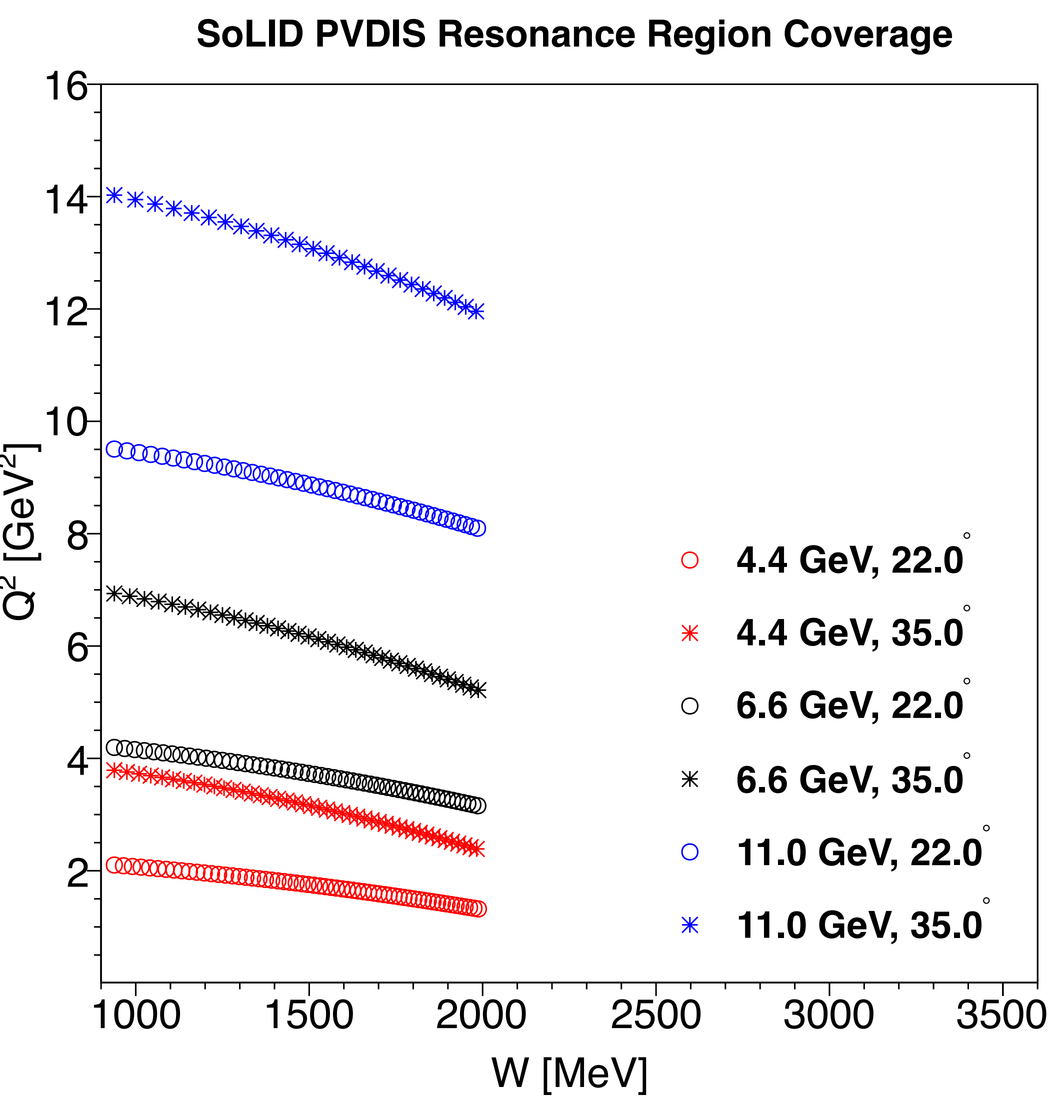
All HAPPEX experiments and Qweak exceeded these difference specs.

Assume 20% uncertainty on corrections $\Rightarrow$ 0.1% overall uncertainty

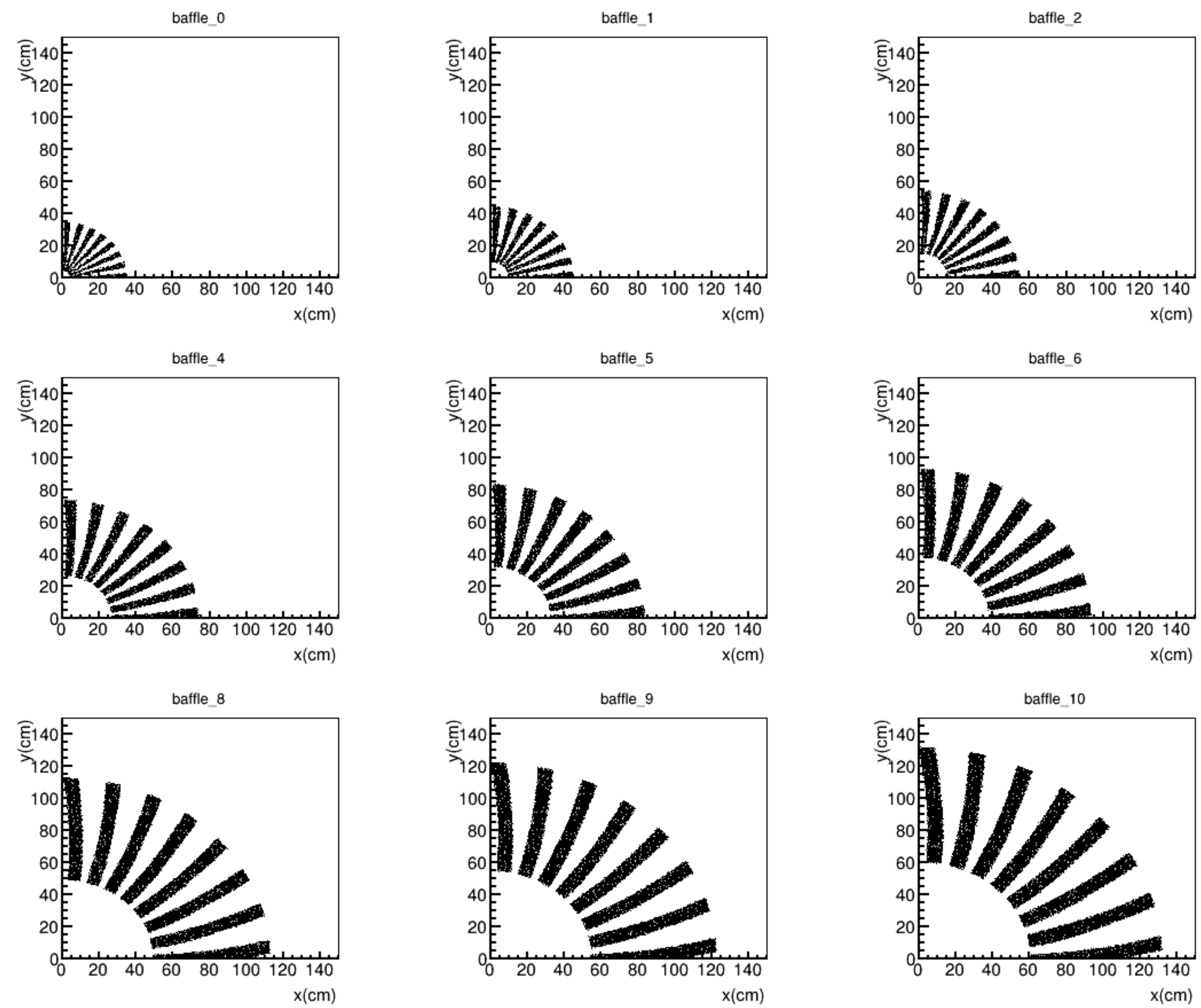
Relationship to SOLID

Low Q^2, resonance-region studies are not possible in SOLID

Minimum angle is 22 degrees.

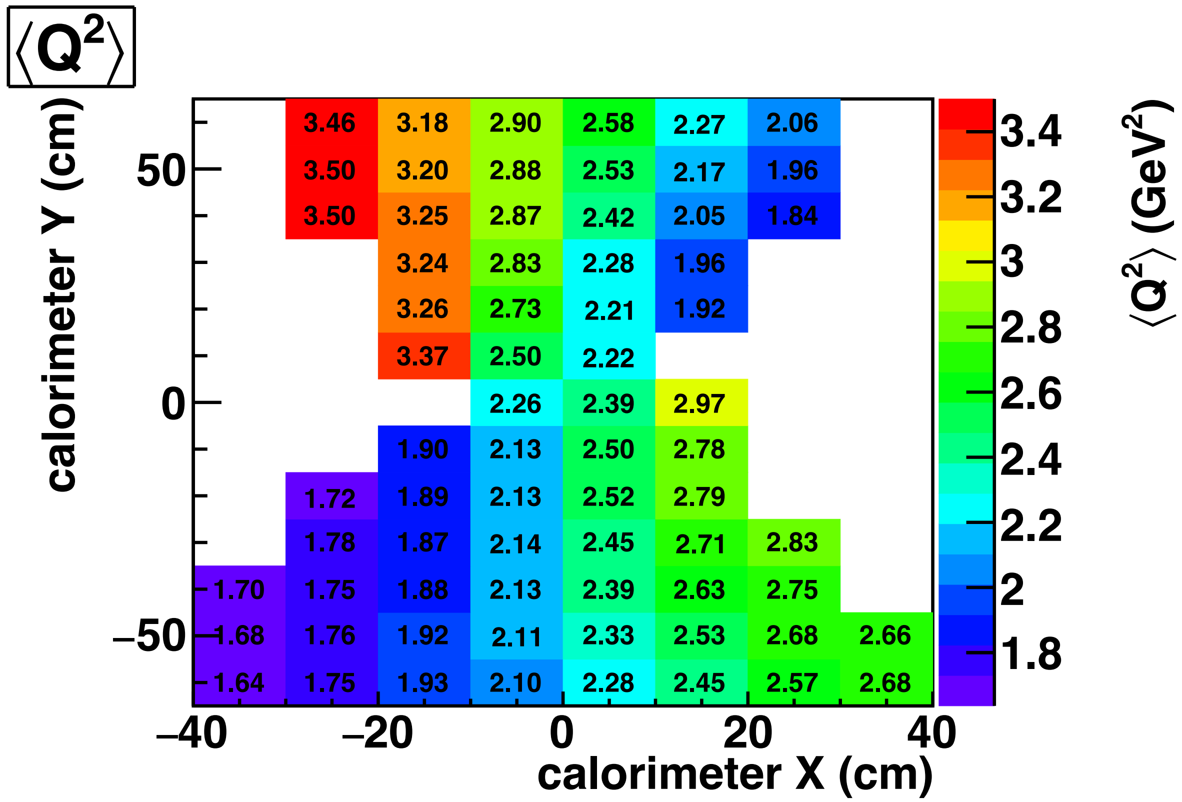


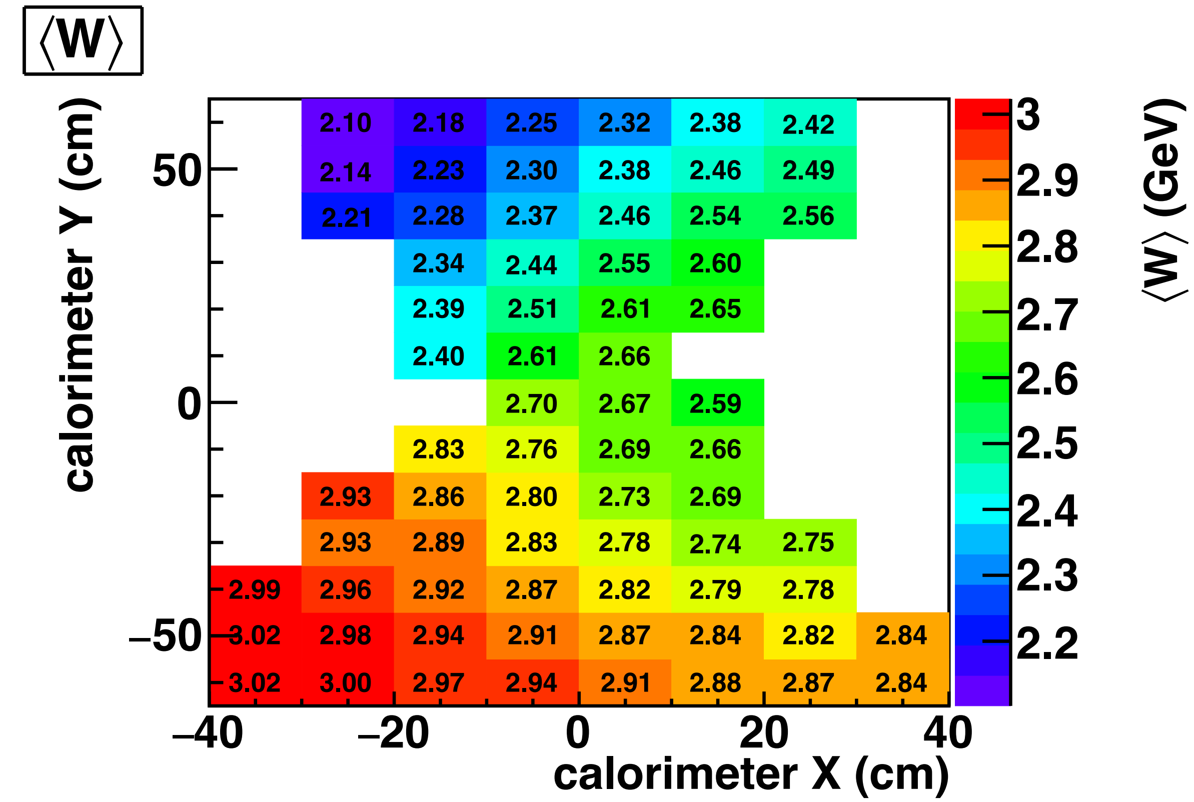
Baffles designed to block low momentum particles

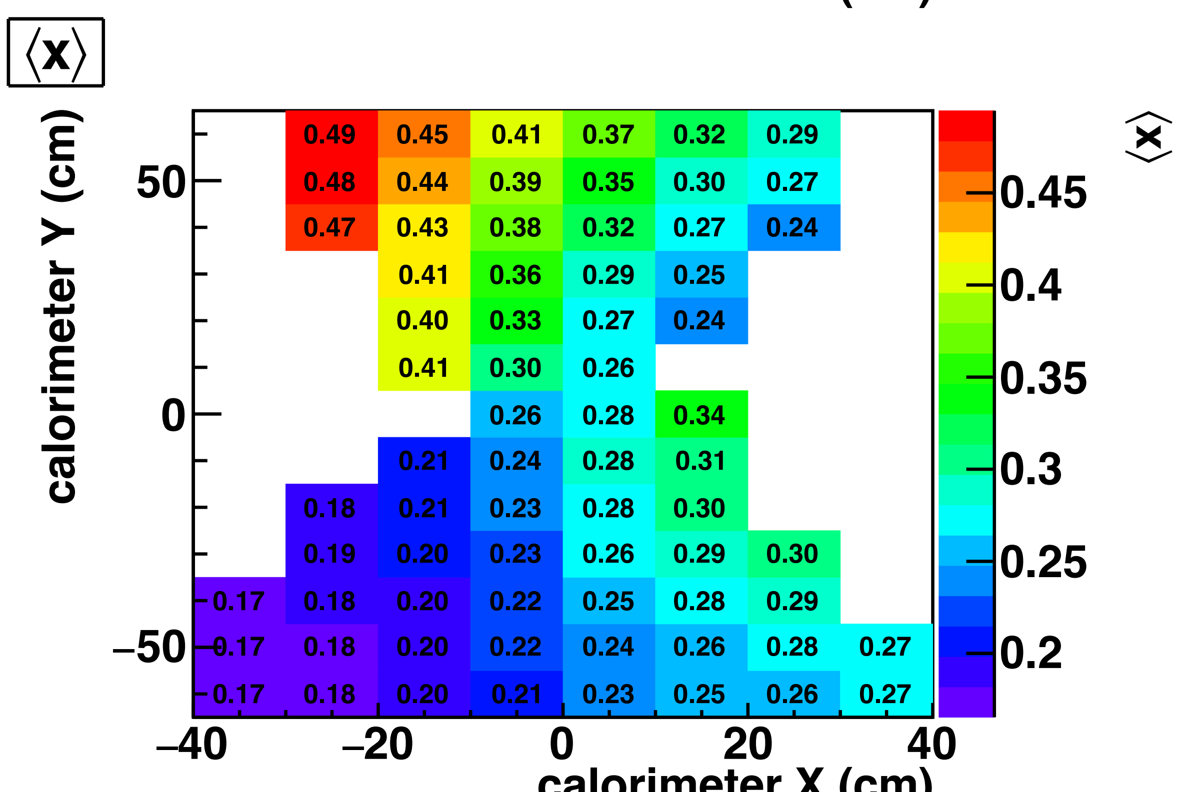


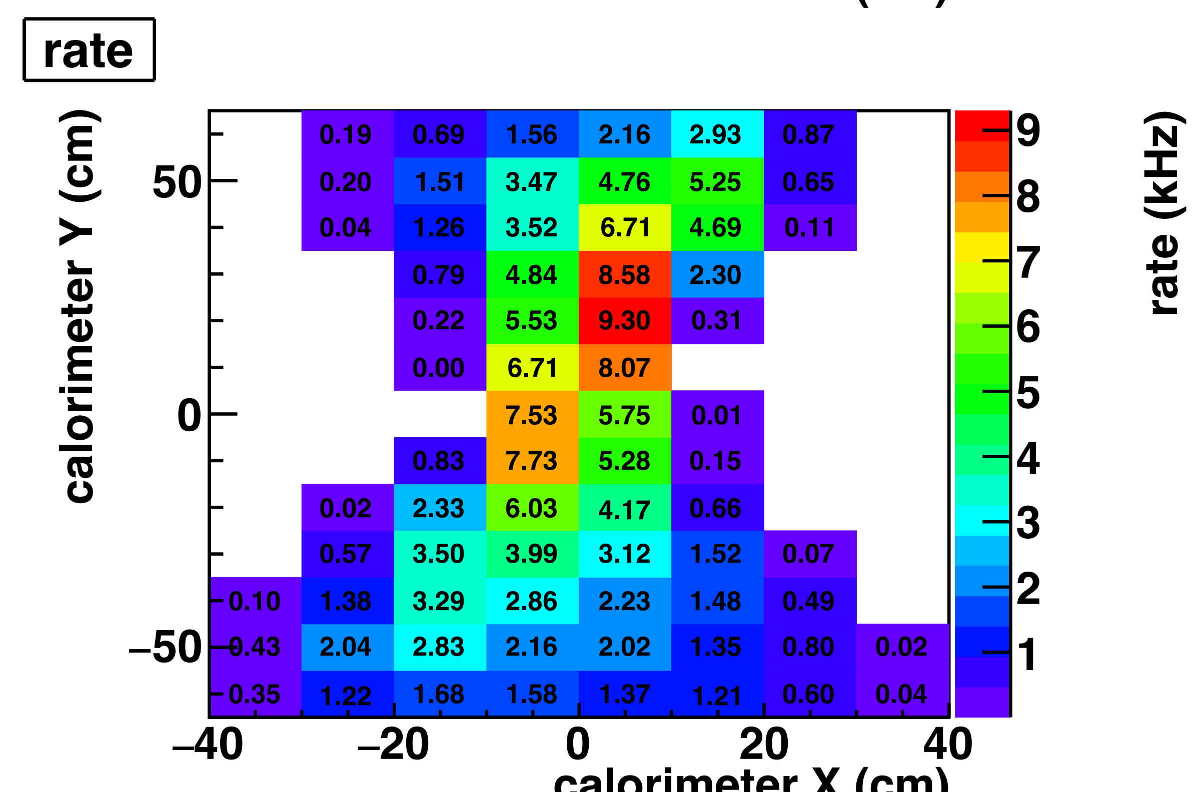
Binning HMS

Position on calorimeter separates events by kinematics

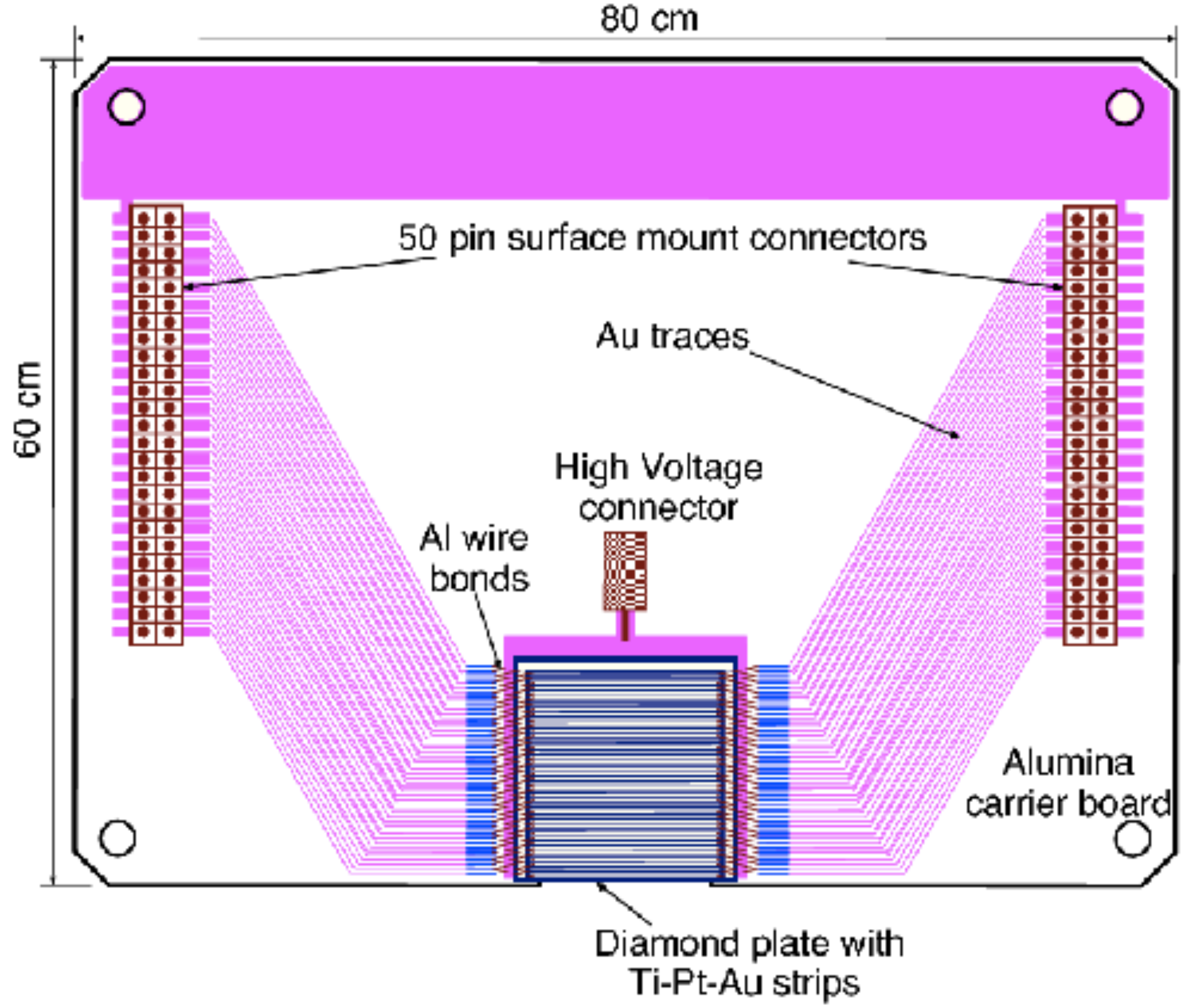


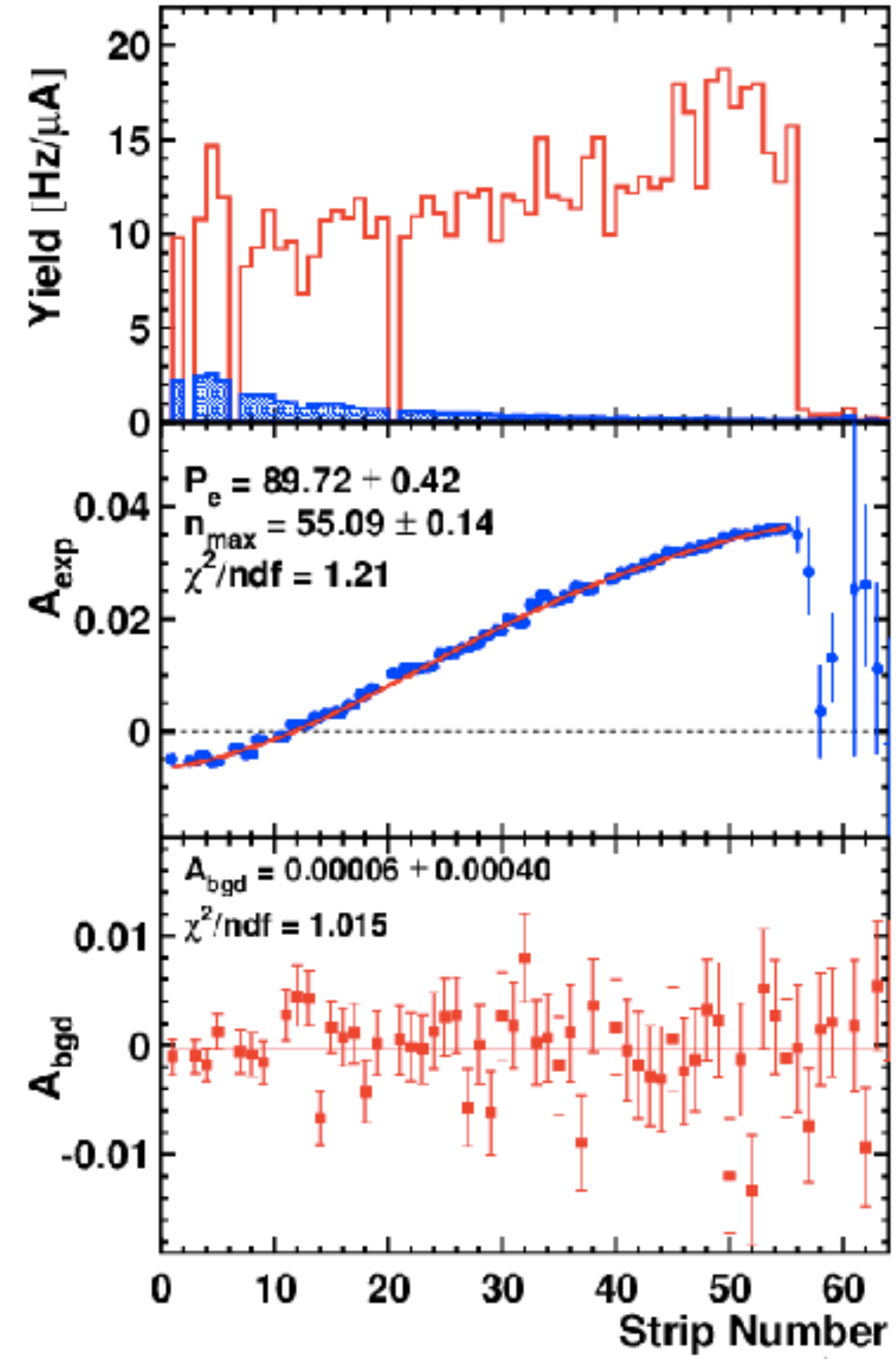


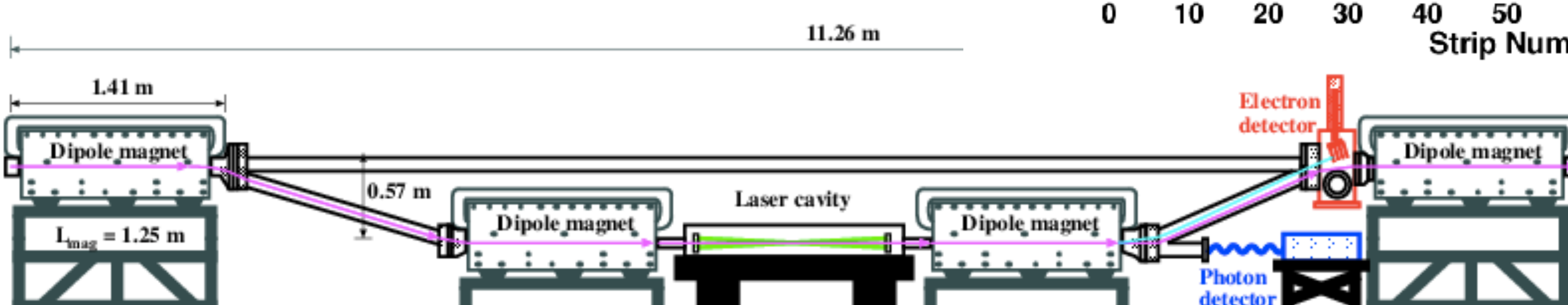




Compton Polarimetry



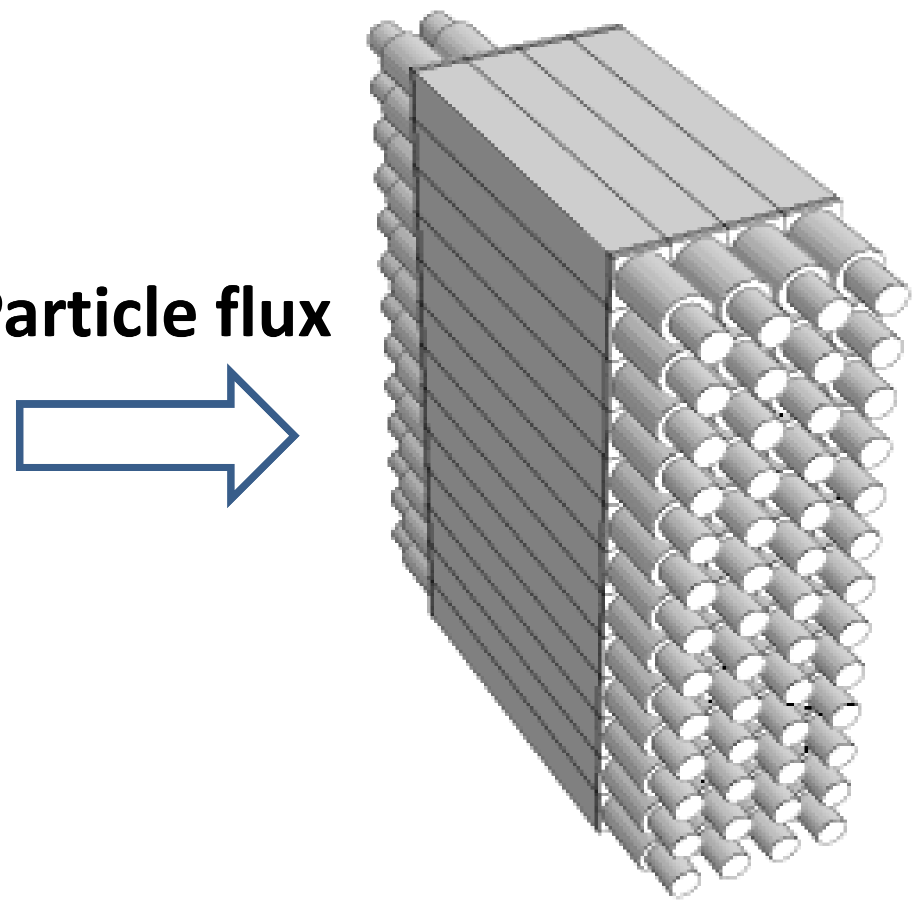




HMS & SOS calorimeters' construction

HMS calorimeter

Particle flux



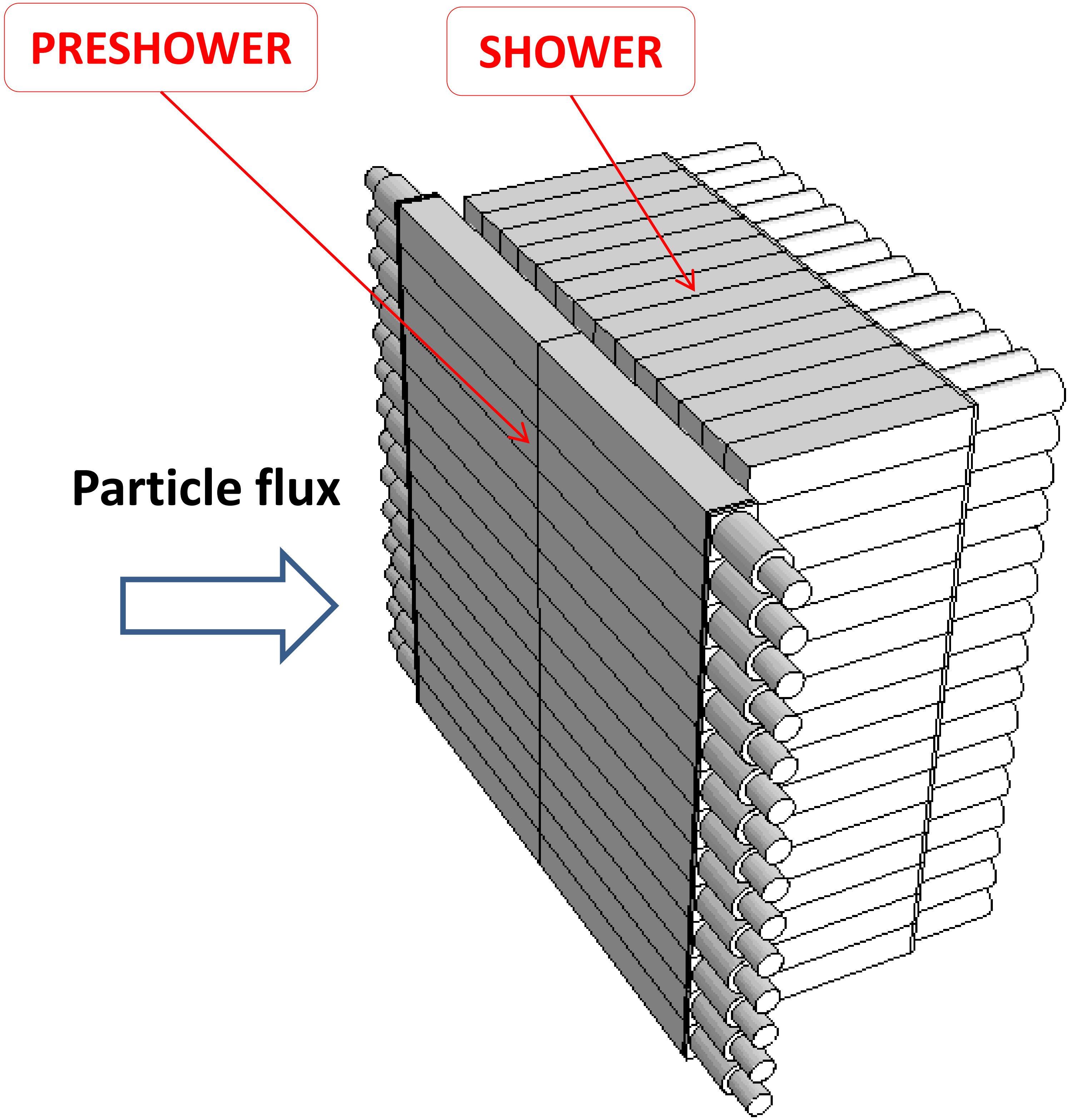
Thickness14.6 rad.length	
Effective area	60×120 cm^2
# of modules	52
# of channels	78
Arrangement	4×13
Block sizes	10×10×70 cm^3
Radiator	TF-1 lead glass
Light detector	XP3462B PMT
In operation	1995 - present

- HMS and SOS calorimeters have similar design.
- Blocks are arranged in four planes.
- Each block is a lead glass optically isolated with aluminized Mylar and black Tedlar film.
- The total thickness of material along the particle direction is about

14.6 rad.length which is enough to absorb the major part of electrons energy.

Mariana Khachatryan HUGS 2012 6

Design construction of SHMS calorimeter



CALORIMETER:

Number of channels	252
Effective Area (cm^2)	116x134
Thickness (Rad.L.)	21.6

PRESHOWER:

Number of blocks	28
Blocks & PMTs from	SOS
Block size (cm^3)	10x10x70
Lead Glass type	TF-1
Thickness (Rad.L.)	3.6

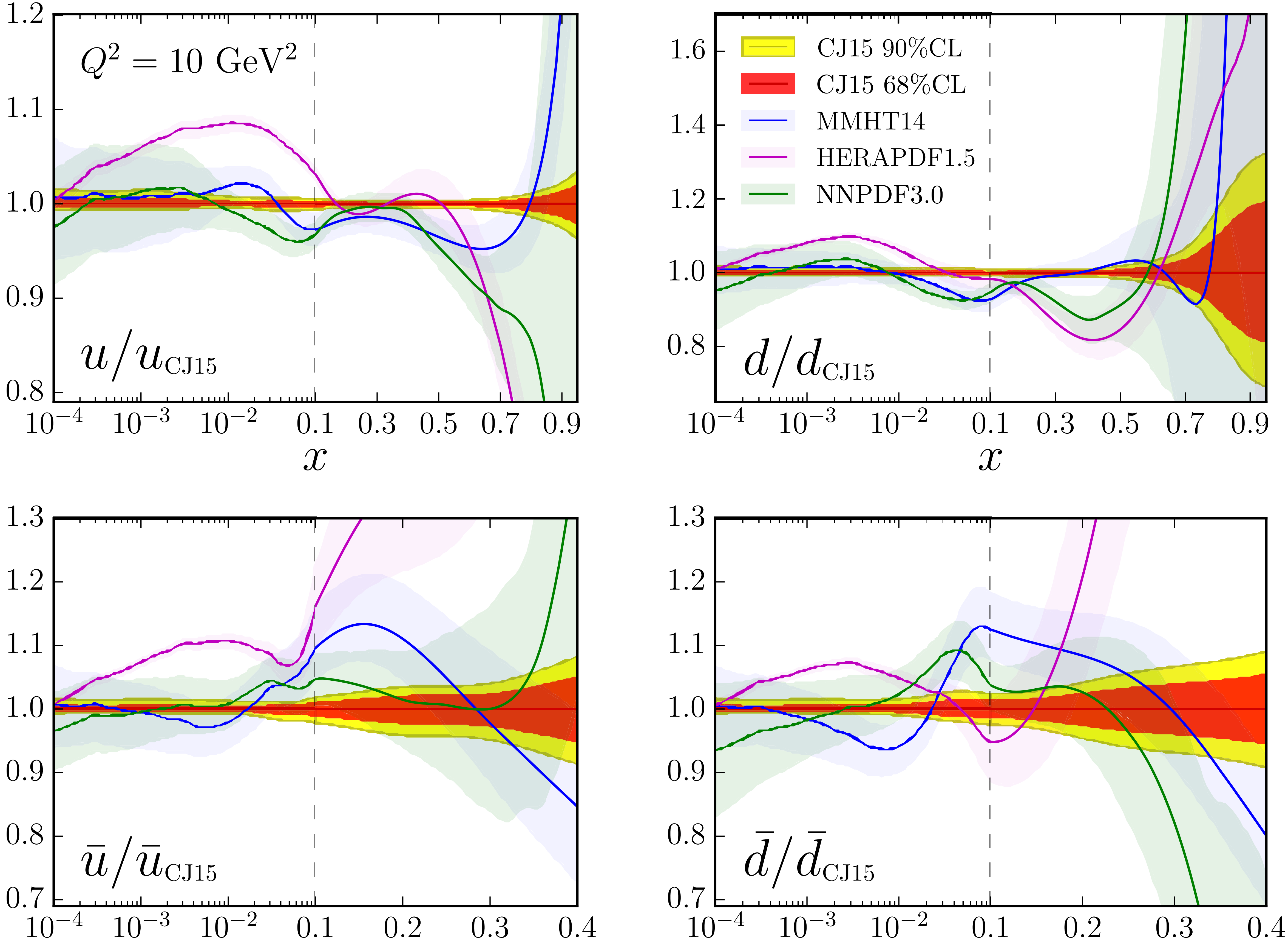
SHOWER:

Number of blocks	224
Modules from	HERMES
Block size (cm^3)	9x9x50
Lead Glass type	F-101
Thickness (Rad.L.)	18.0

Radiators:

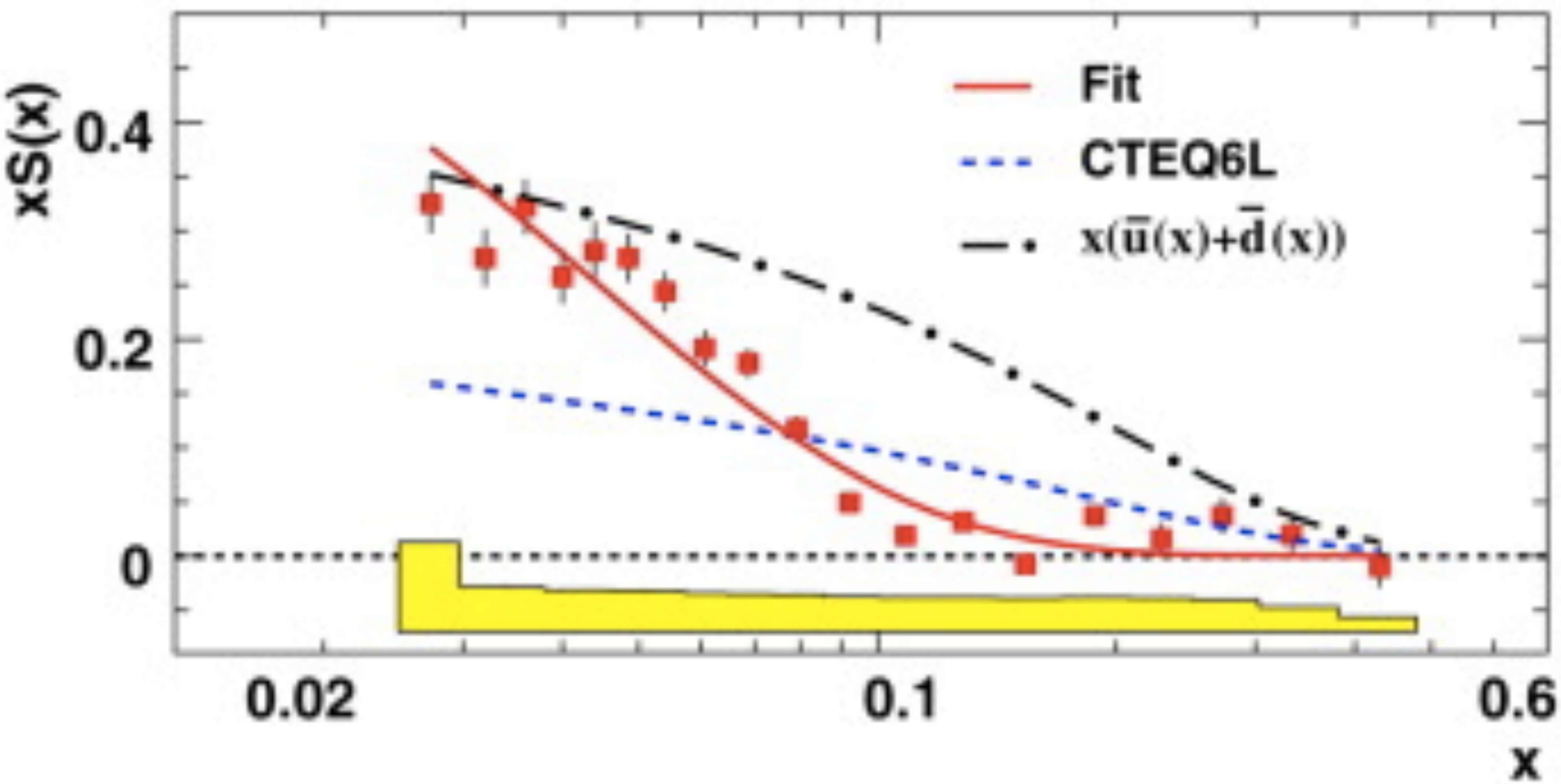
TF-1 Rad.L.(cm)	2.74
F-1 Rad.L.(cm)	2.78
Density (g/cm^3)	3.86
Refractive Index	1.65

Up and Down quarks



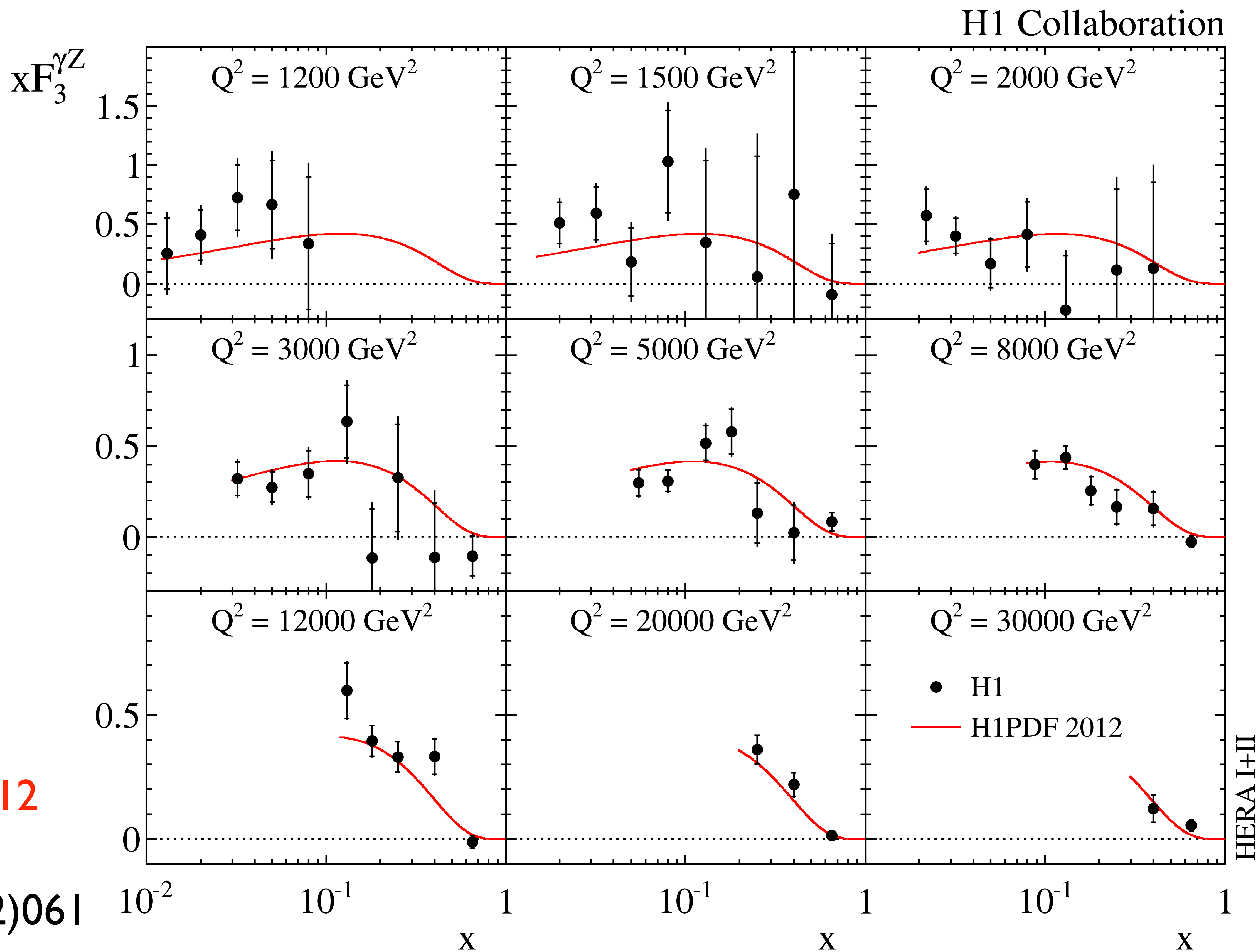
HERMES semi inclusive K production

Highly precise data compared uncertainty in strange
Can't use this data in global fits due to uncertainty in fragmentation
Different shape from results using neutrino data.



HERA $xF_3^{\gamma Z}$

60 < Q2 < 50000 GeV2
0.0008 < x< 0.65.



H1PDF2012

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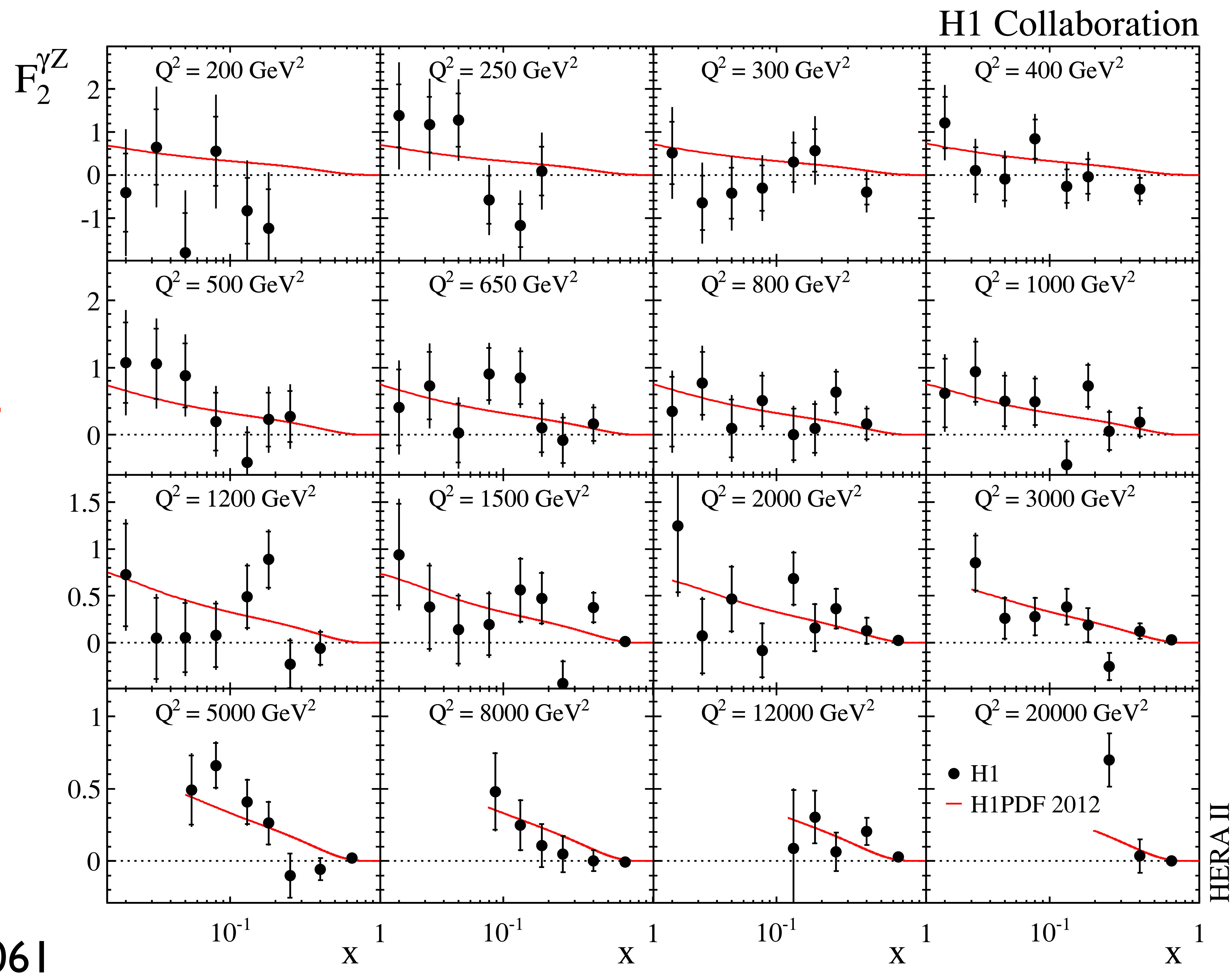
HERA $F_2^{\gamma Z}$

H1PDF2012



JHEP09(2012)061