Parton Distribution Functions from Parity Violation (PVPDF)

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for the PVPDF collaboration

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Jefferson Lab

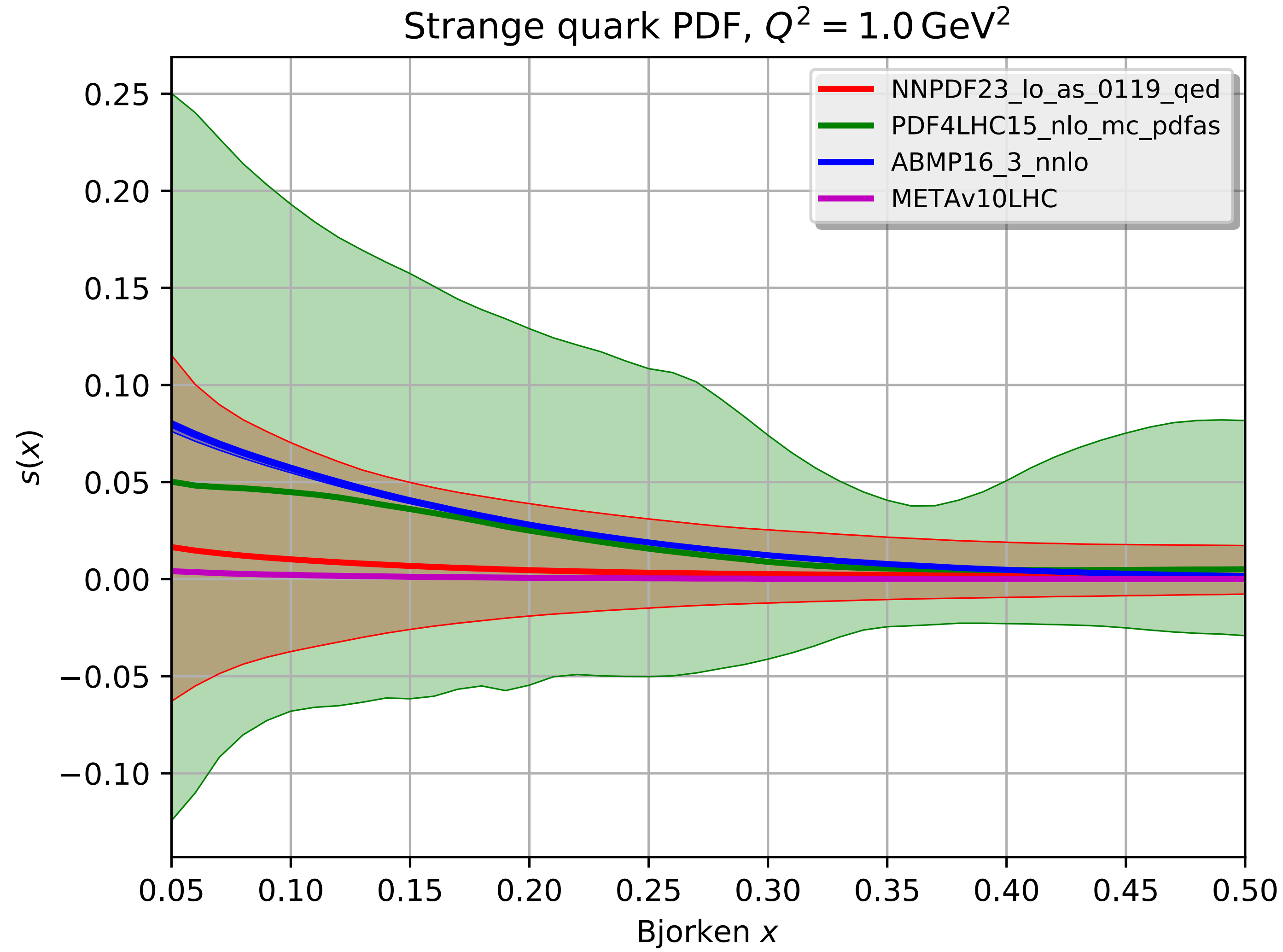
Introduction

We request 38 days of beam for commissioning and data taking.

Hall C standard spectrometers

Measure the parity violating asymmetry in Deep Inelastic Scattering (DIS), ($F_2^{\gamma Z,p}$ structure function) from which new information on the strange quark PDF will be extracted.

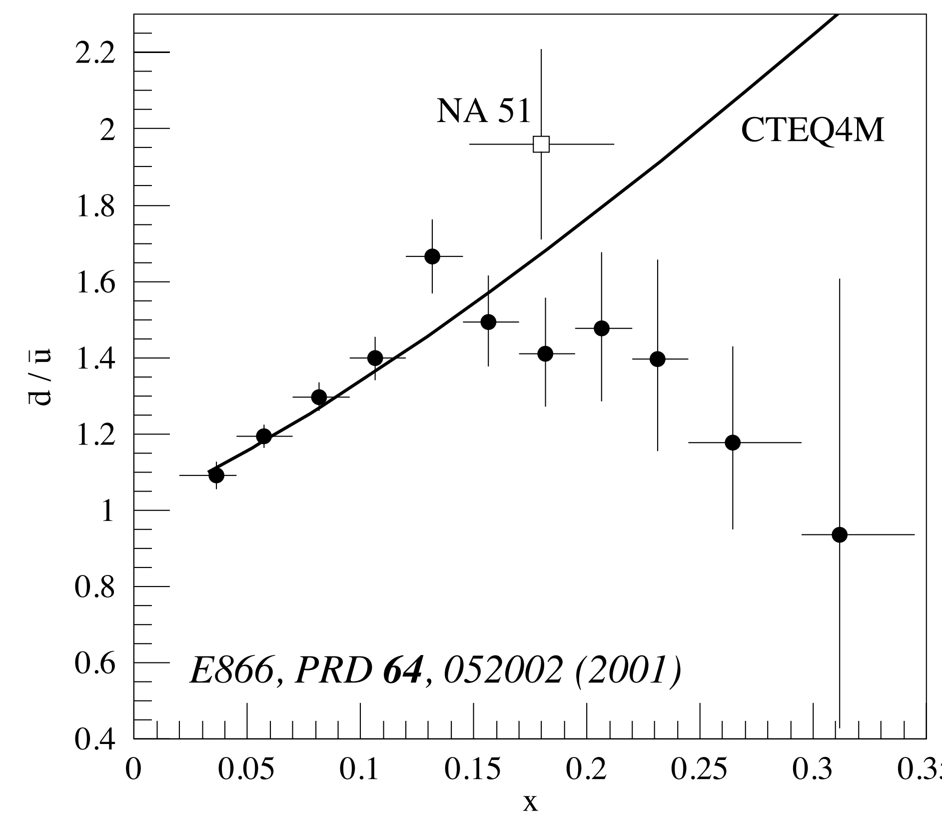
Strange quark PDF is essentially completely unknown.



Importance of Strange Quark PDF

- Fundamental component of nucleon structure
- essentially unknown—is the sea SU(3) symmetric?
- the few measurements available conflict, or are subject to unknown corrections
  - nuclear corrections for neutrino targets
  - fragmentation functions

- 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.



PDF Global Analysis

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

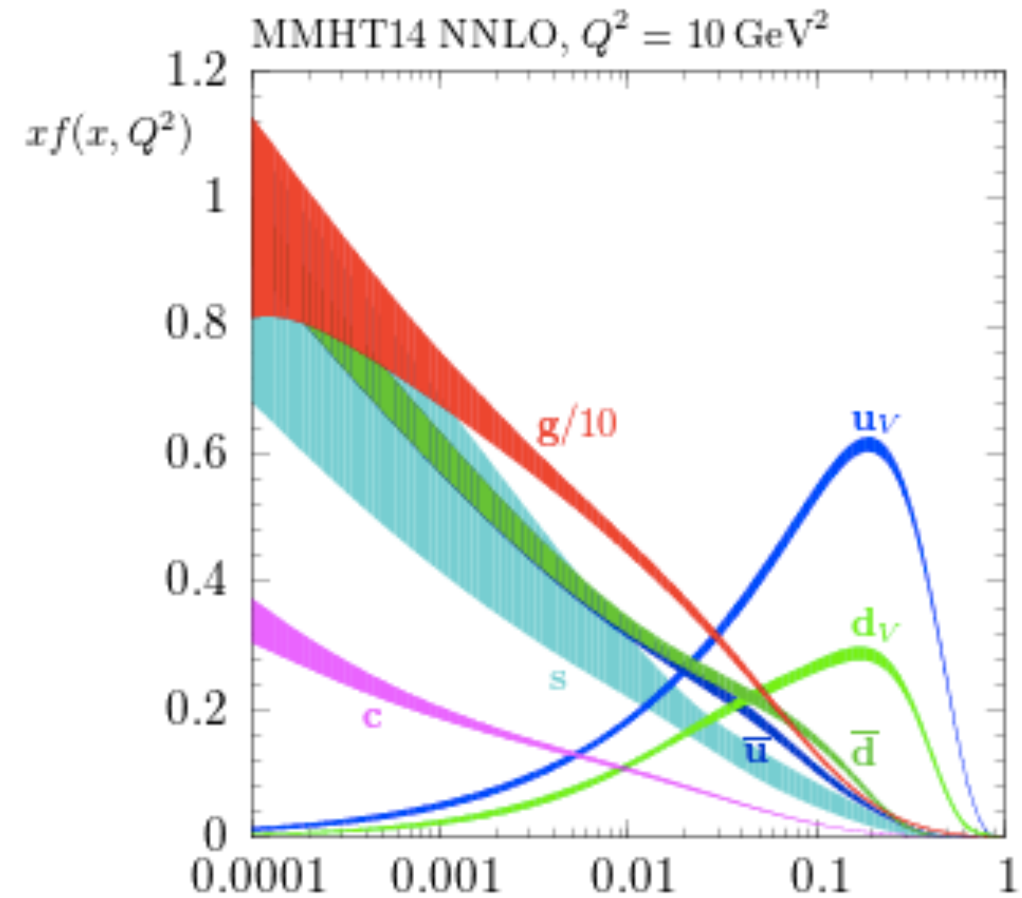
- Experimental data (~ 4k data points)
- QCD factorization: PDF (same for PPDF, FF)
- Global analysis

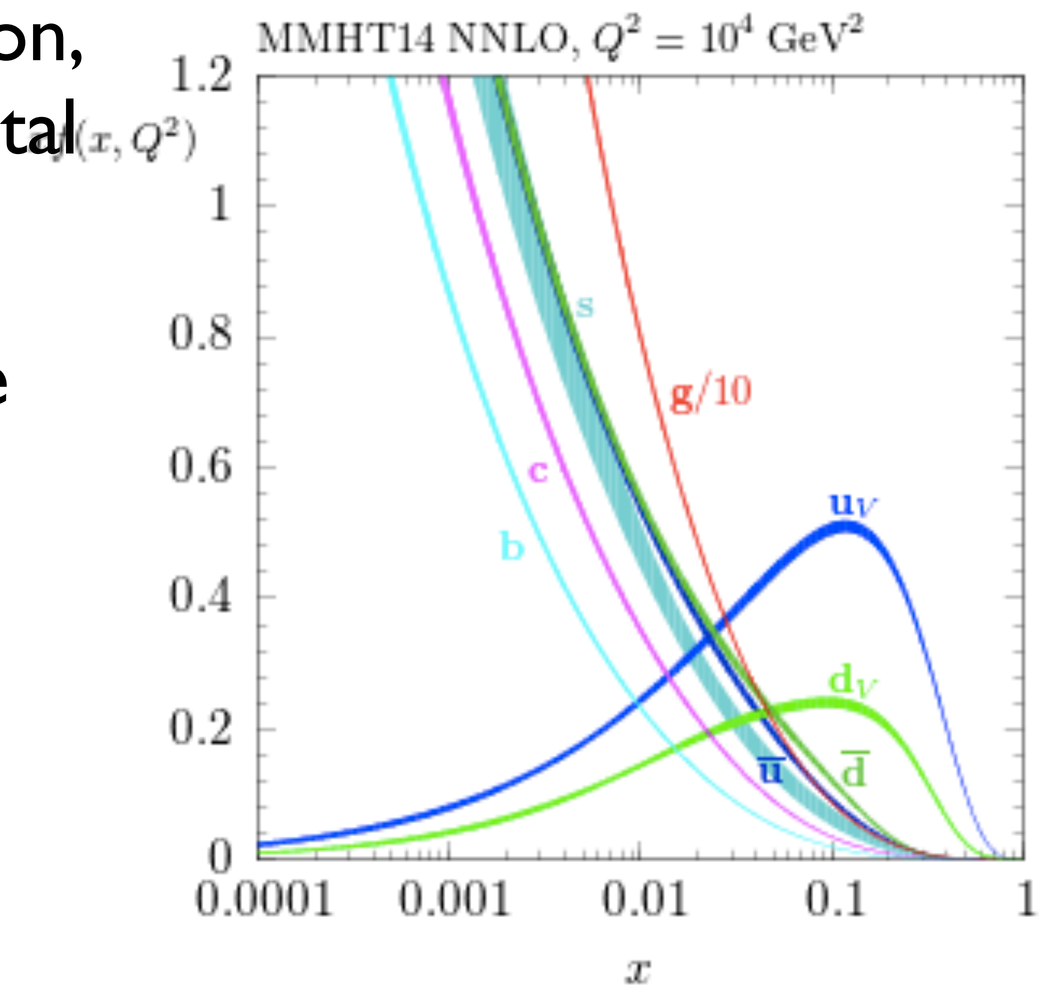
global analyses differ in: input data, parameterization, treatment of heavy quarks, value of α_s, experimental errors treatment, theoretical error estimation.

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

Data to isolate strange still elusive

Both the magnitude and the shape of the strange pdf are essentially unknown.

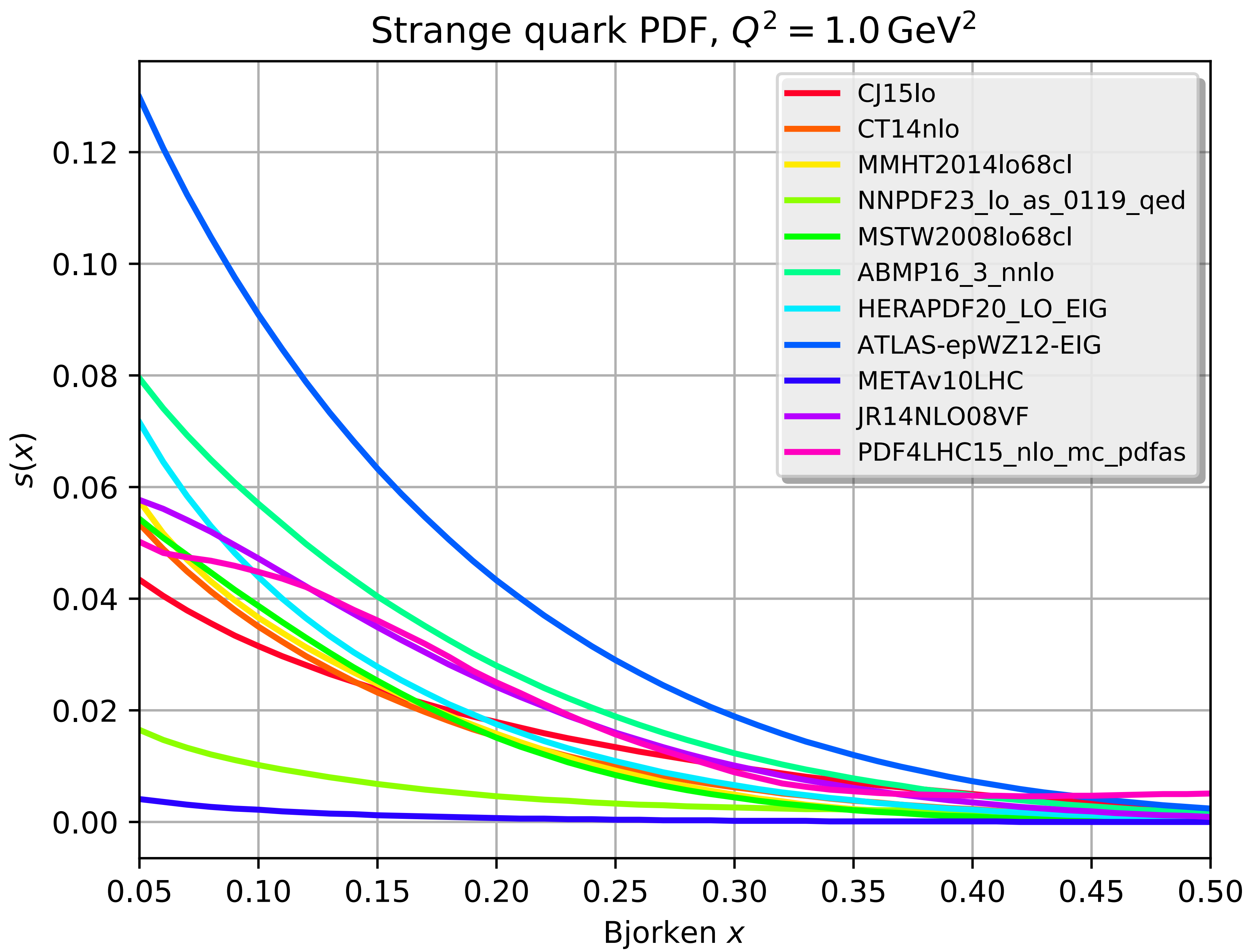




Strange PDF

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.



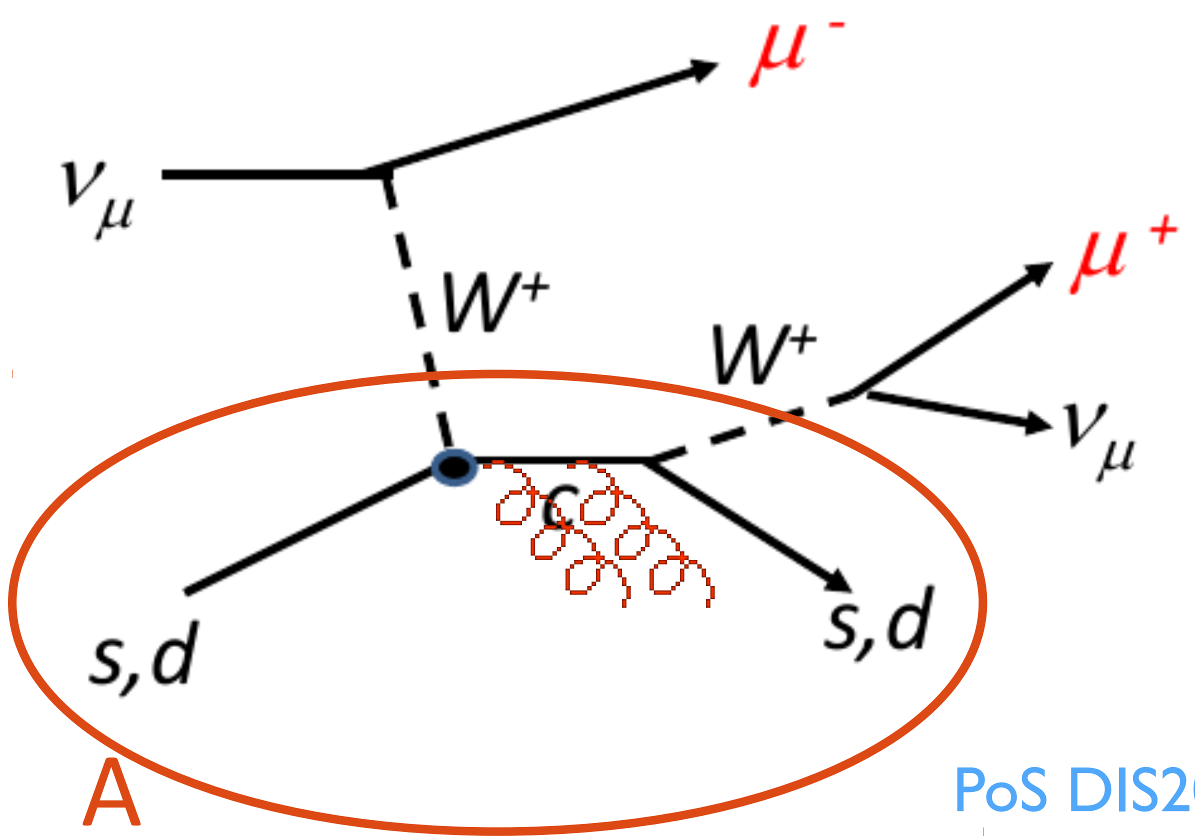
Accessing Strange Quarks

• di-muon production in neutrino-nucleus scattering	$0.01 < x < 0.2$
• W and Z rapidity distributions	$x >\sim 0.001$
• 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



di-muon production in neutrino-nucleus scattering tags strangeness

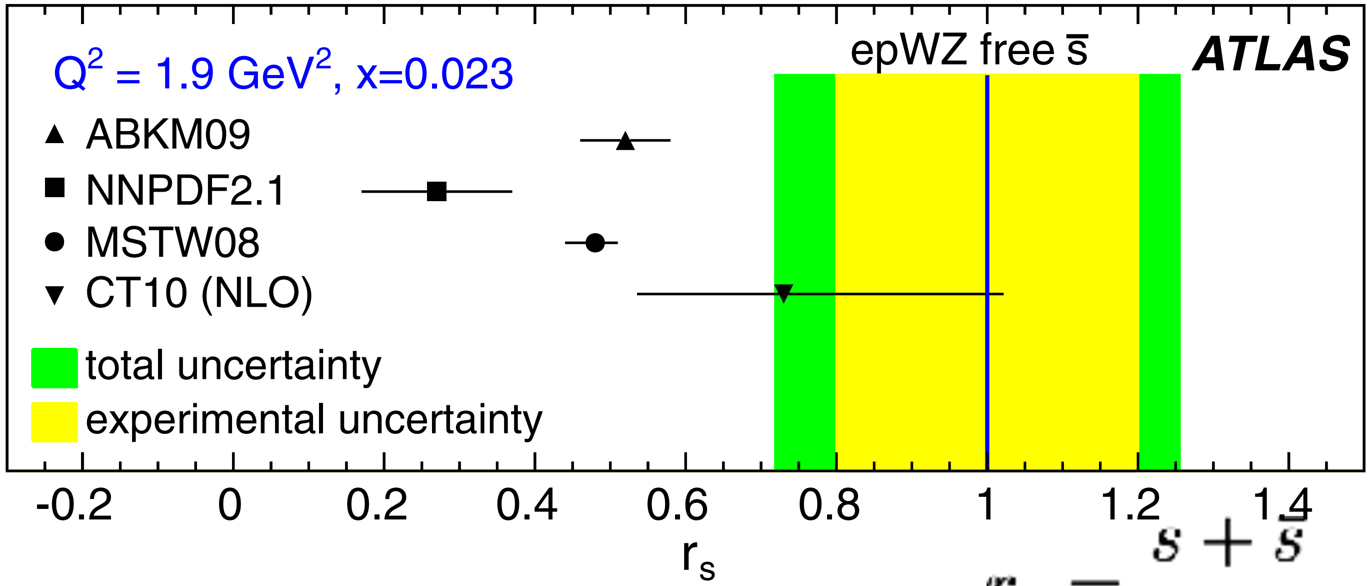
PoS DIS2015 (2015) 001

- 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)
- Using these data tends to give **k ≈ 0.5**

Proton—proton at high energy

ATLAS fits get **k≈1** using collider only data

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



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

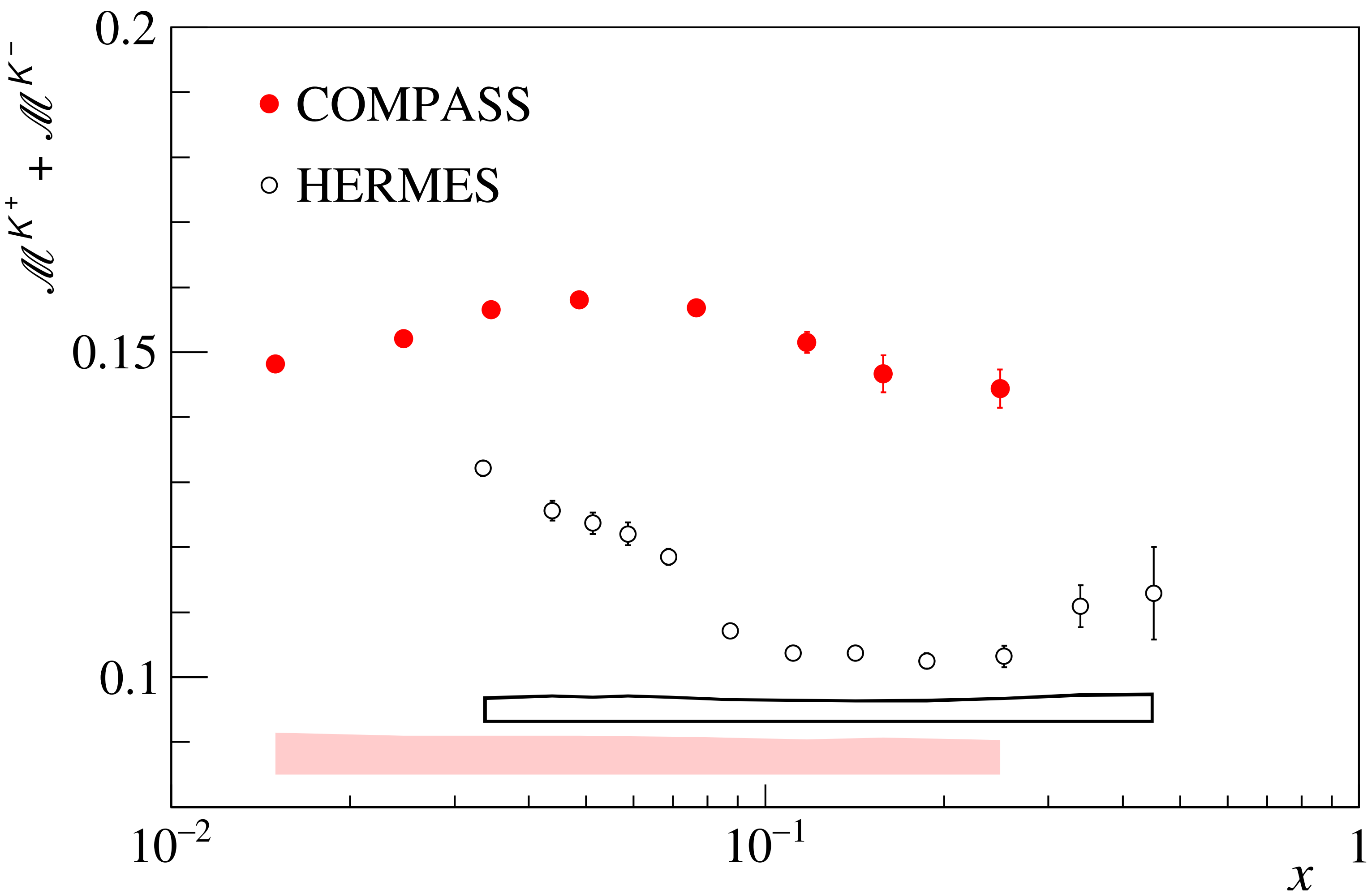
PRL 109, 012001 (2012)

Similar results from $pp \to (W + c) + X$ JHEP05(2014)068

Data at high Q^2, strange mainly comes from gluon radiation

Evolution works most effectively from low Q^2 to high Q^2

Semi-inclusive K production

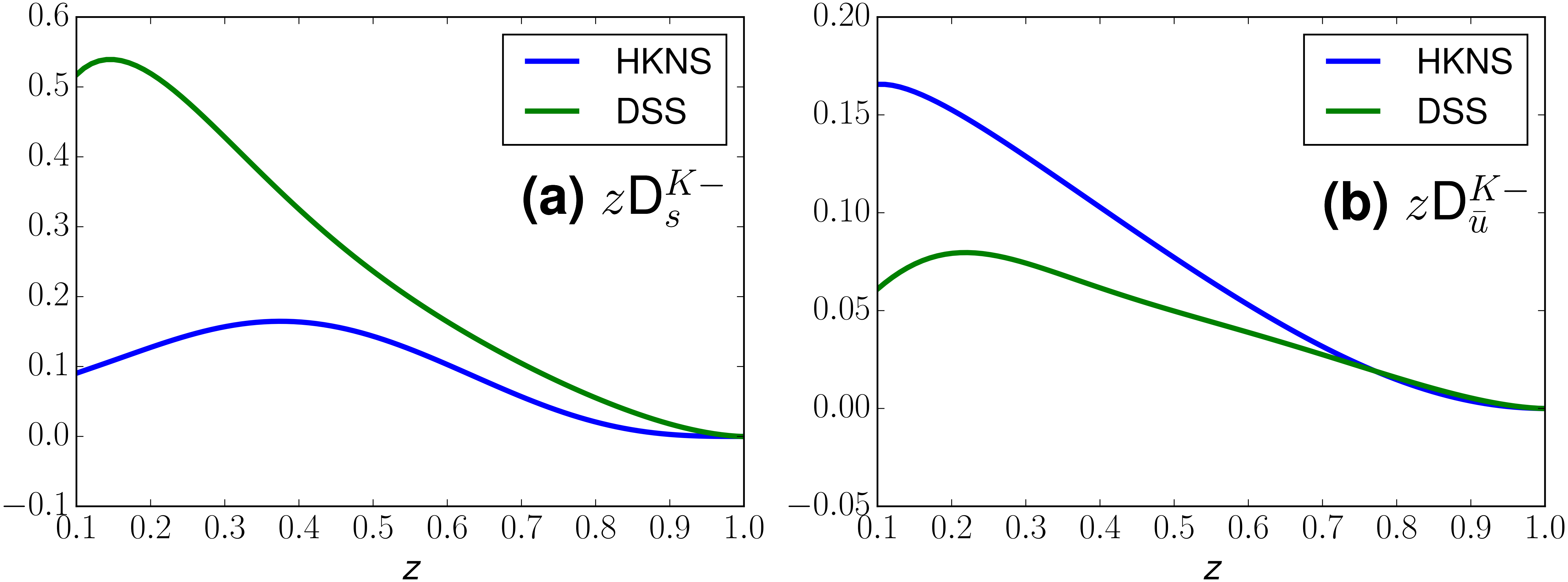


HERMES and COMPASS data on kaon multiplicities from SIDIS

- Depend on 2 non-perturbative inputs:
  - strange PDF
  - kaon fragmentation functions
- Do not agree in shape or magnitude
  - problem with factorization assumption?

Kaon fragmentation functions

Fragmentation function to kaons not well constrained



Parity Violating Deep Inelastic Scattering (DIS)

small

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

Dominates

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

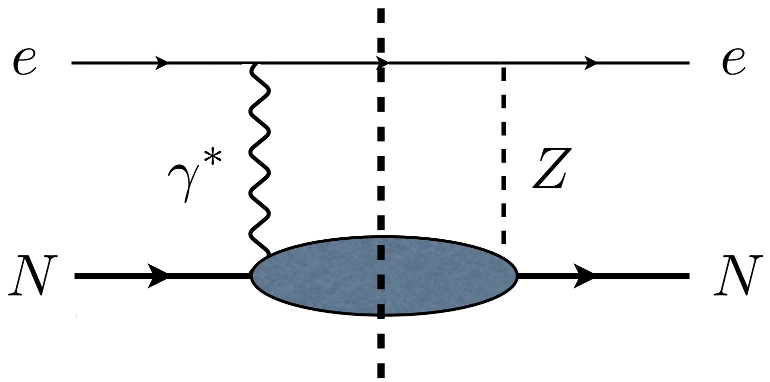
$$a_3(x) = -2\,g_V^e\,\frac{F_3^{\gamma Z}(x)}{F_2^{\gamma}(x)} = -4\,g_V^e\,\frac{\sum_q e_q\,g_A^q\,q^-(x)}{\sum_q e_q^2\;q^+(x)}$$

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

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

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

$F_2^{\gamma Z,p}$ is 5 times more sensitive to strange

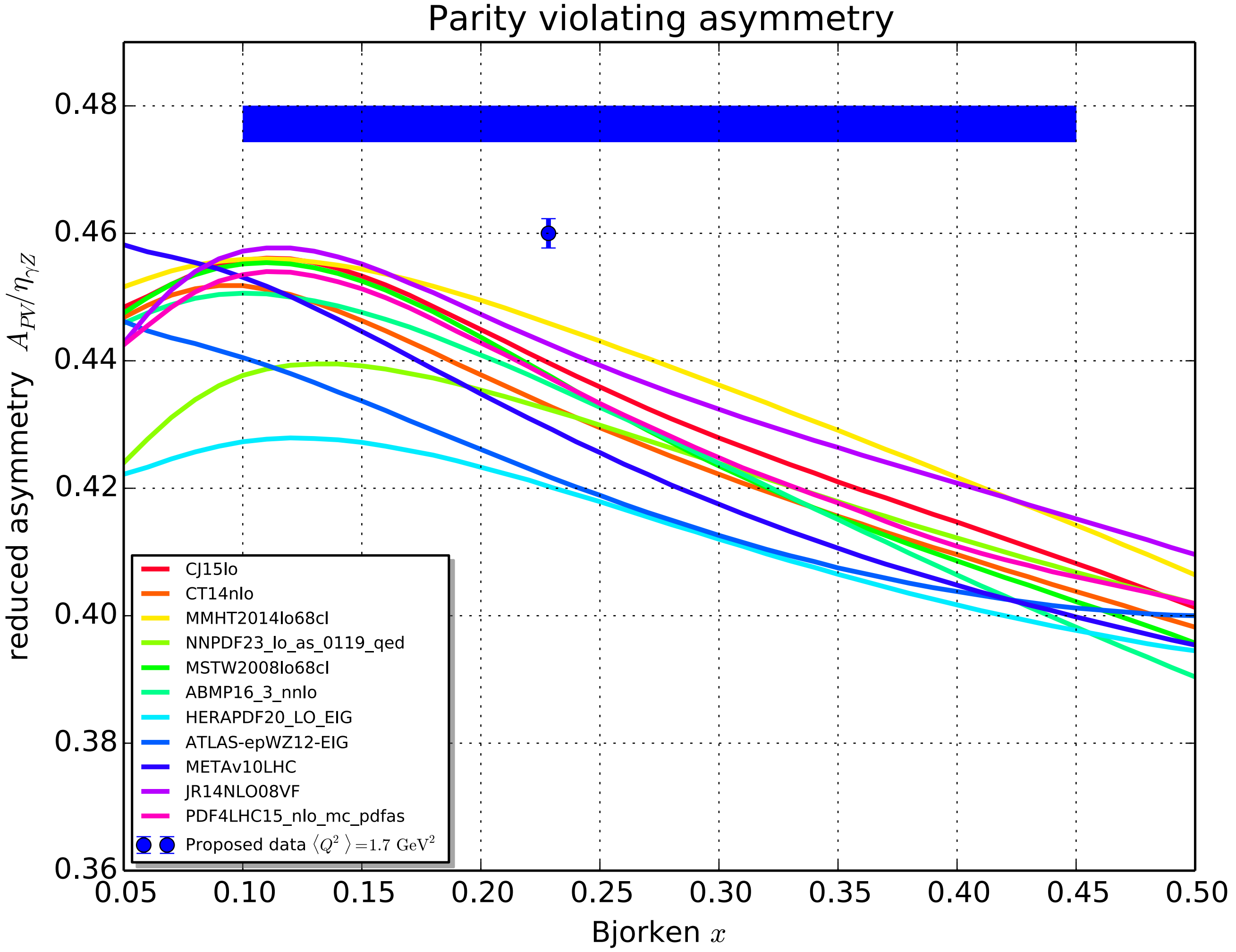
Predicted asymmetry

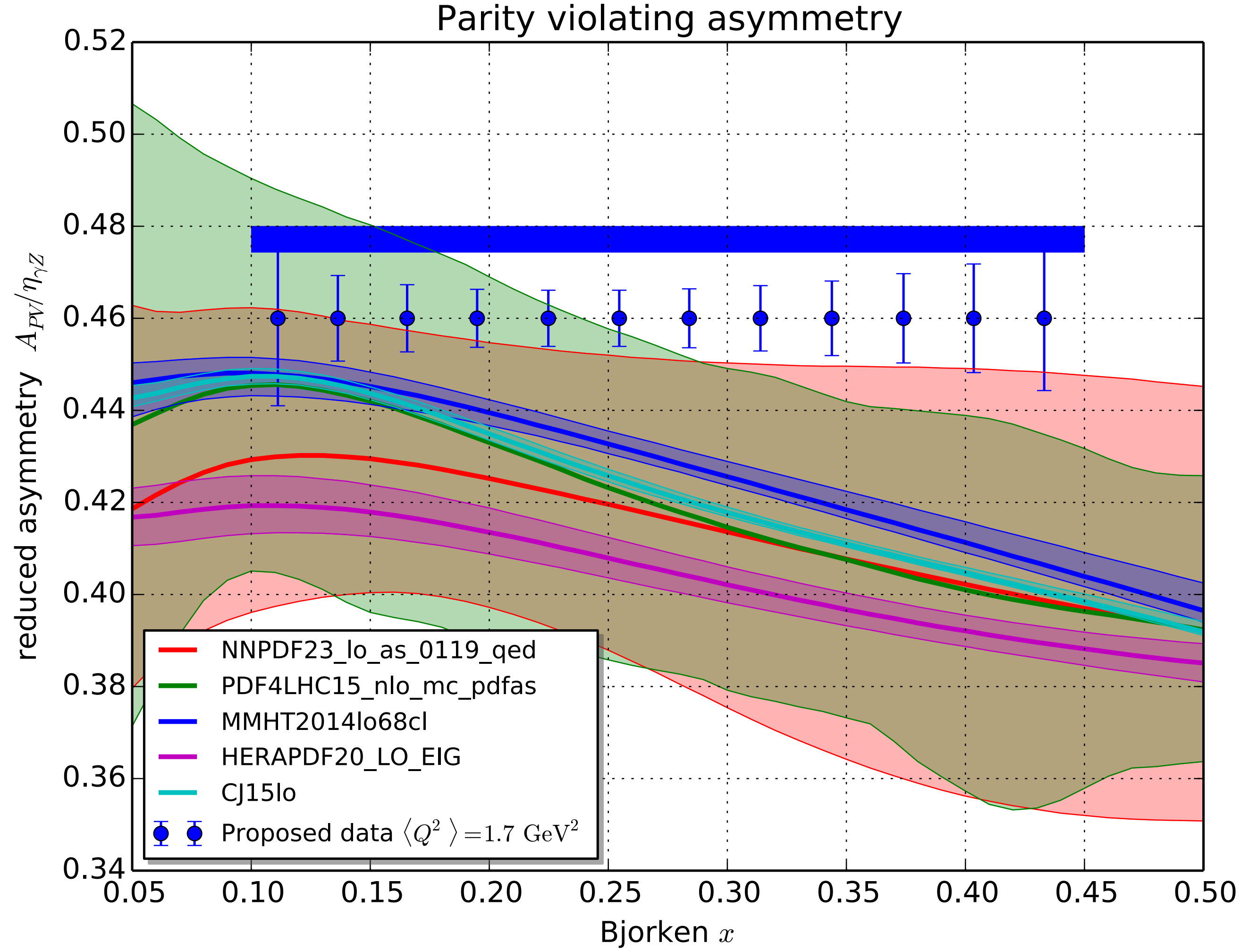
Large spread in central values

Data in single bin to indicate overall statistical precision.

Large quoted theoretical uncertainties

Data in multiple bins to indicate ability to measure shape.

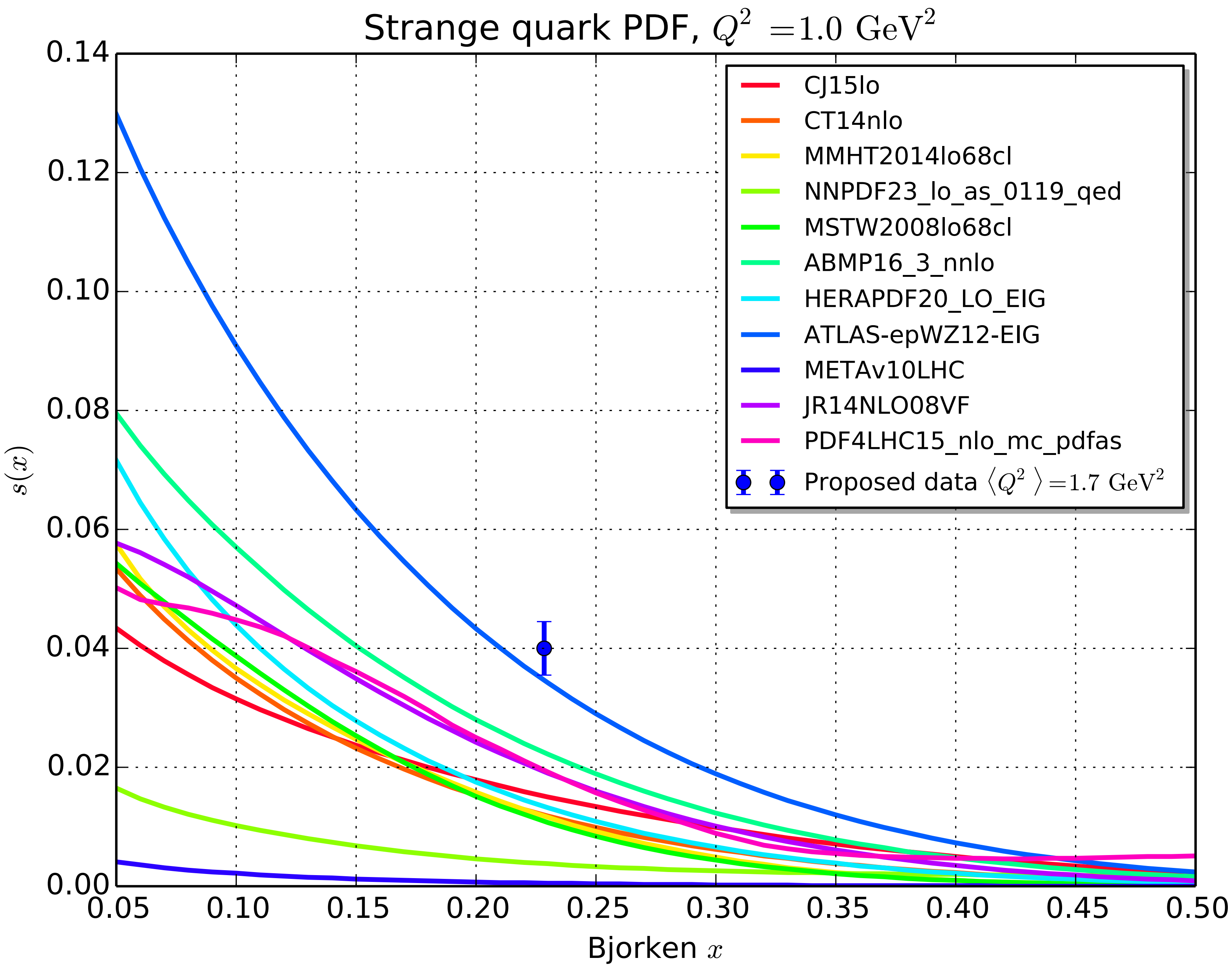




$$\frac{A_{PV}}{\eta_{\gamma Z}} \approx a_2(x)$$

Curves from LO equations at Q^2=1 GeV^2

Impact on s-PDF

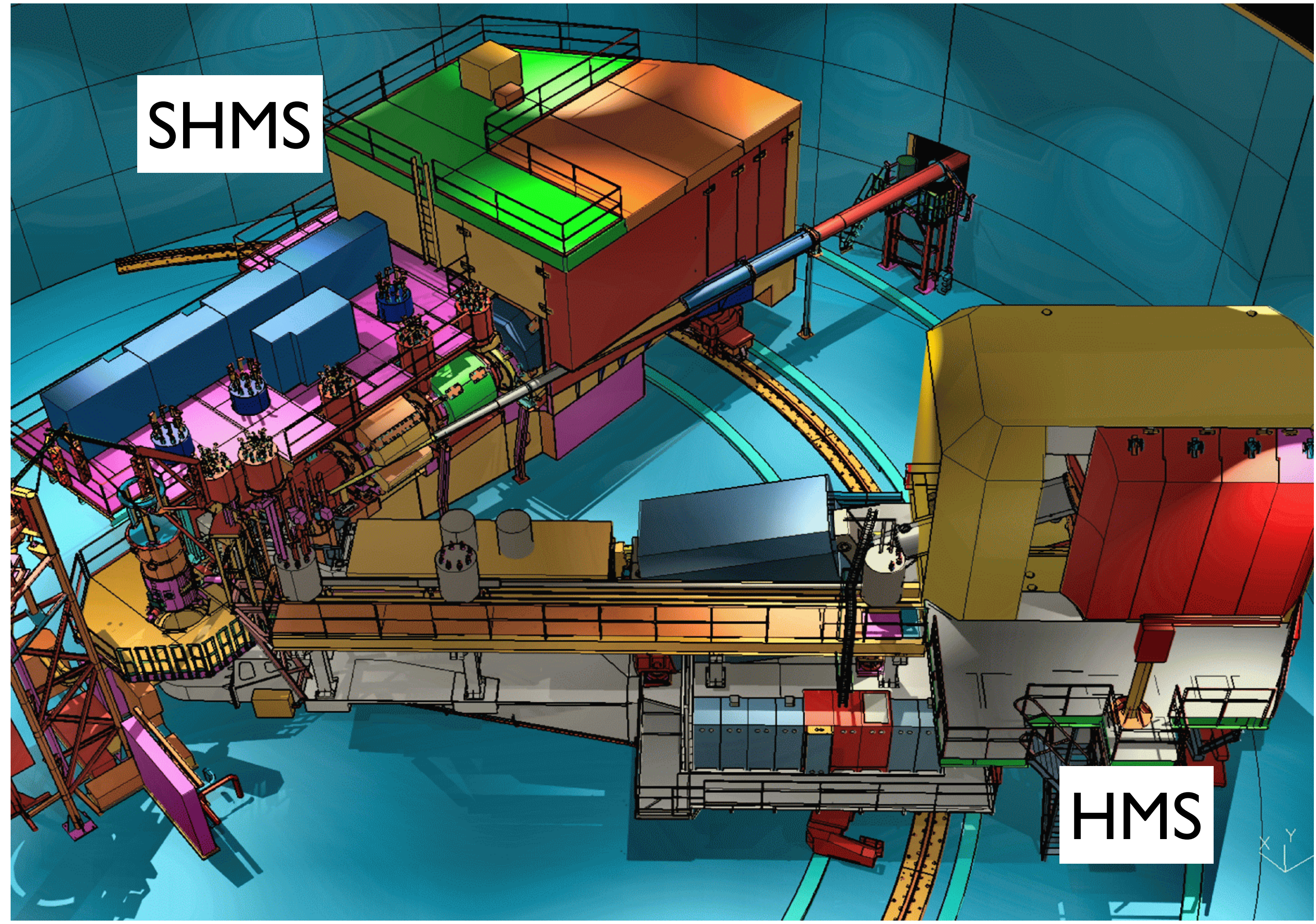


Total precision on the s-PDF with uncertainty only from A_{PV} (assuming all other components of the structure function are known)

Proposed data will significantly help establish the strange PDF magnitude and x shape.

Experimental Overview

- Beam: 70 uA, maximum energy, minimized transverse polarization.
- 20 cm, "standard" liquid-hydrogen target (as used in GMP)
- Helicity flip rate 240 Hz
- Parity level beam control
- Qweak-level polarimetry
- Full tracking for calibration
- Counting mode asymmetry measurement (same as PVDIS in Hall A)
- Asymmetry measurement using lead glass calorimeters and Heavy Gas Cherenkov detectors.

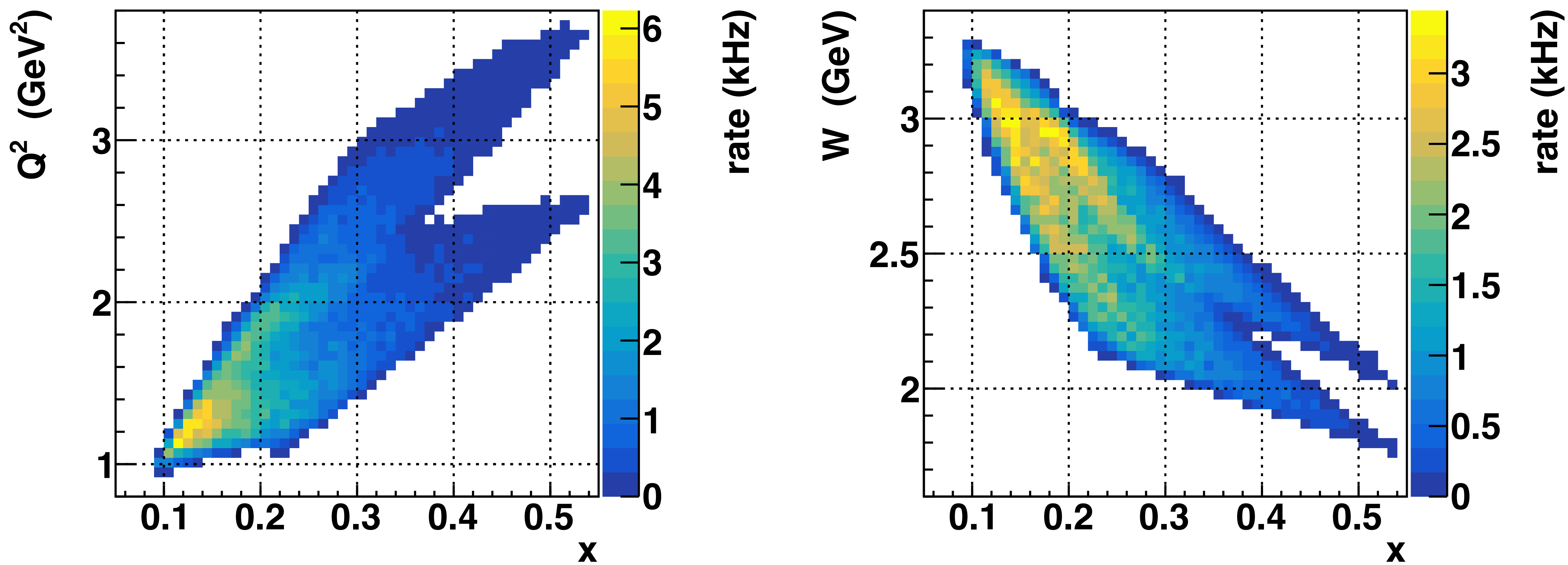


High rate DAQ—basic idea already pioneered modern technology will make it easier

Spectrometer Kinematics

Spectrometer	P_{cent} (GeV/c)	θ_{cent} (deg)	$\langle Q^2 \rangle$ (GeV^2/c^2)	$\langle x \rangle$	$\langle W \rangle$ (GeV)	$\langle A_{PV} \rangle$ (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



Rate Breakdown

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

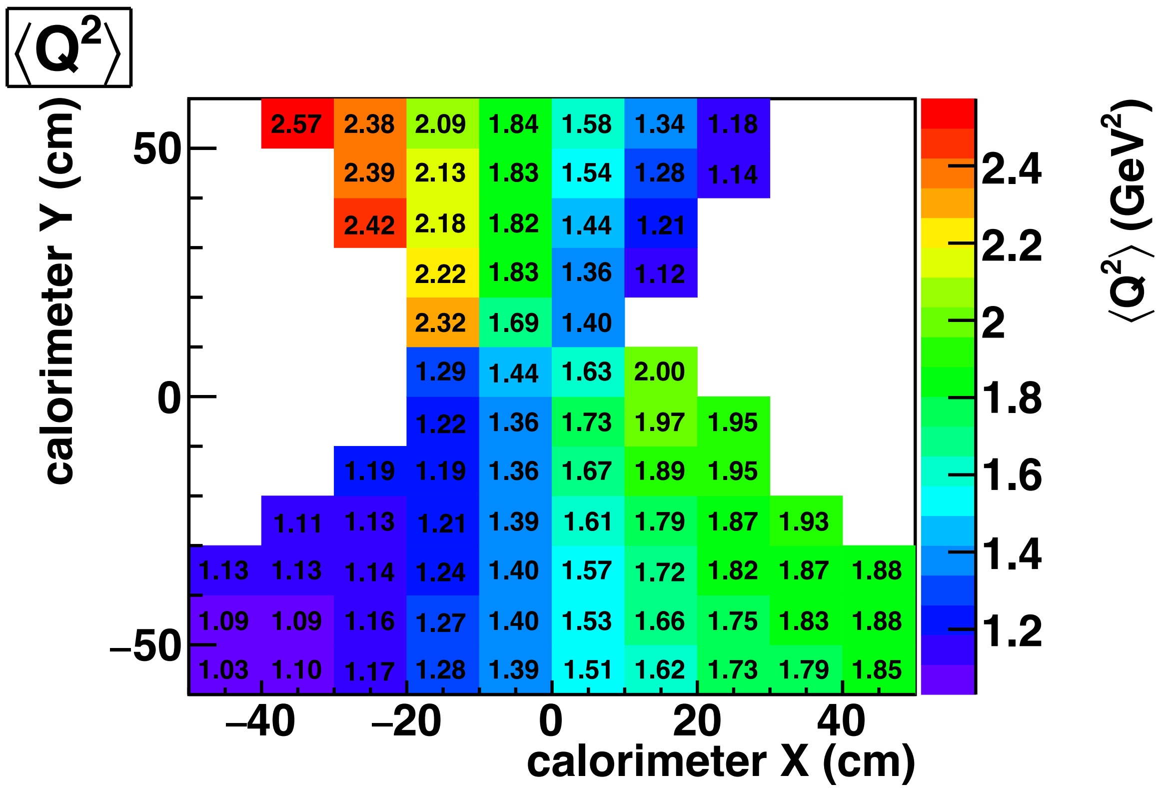
Spectrometer Rate (kHz)	DIS	elastic tail	π^-	charge symm.	Al windows	total
HMS	173.9	2.8	73.0	1.0	7.3	258.1
SHMS	608.1	17.6	344.0	5.0	26.1	1000.8

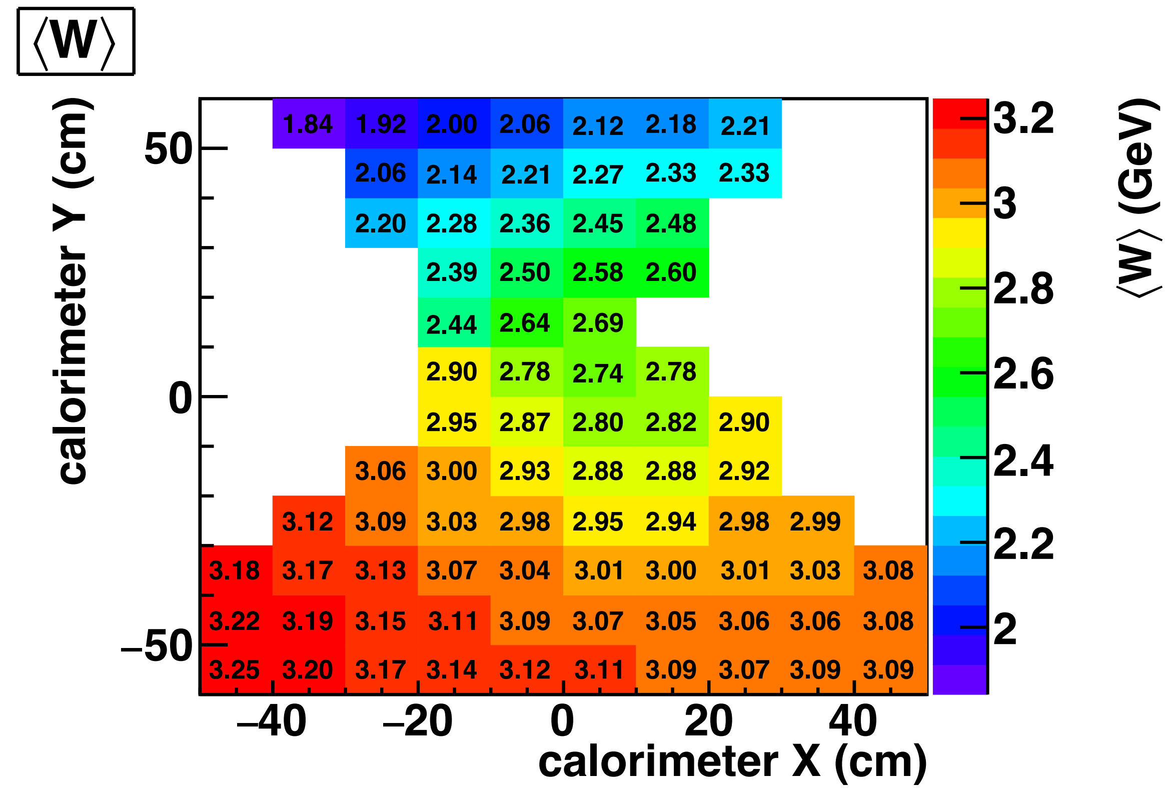
pi/e ~0.6
modest online PID requirement
$\delta A/A \sim 0.08\%$

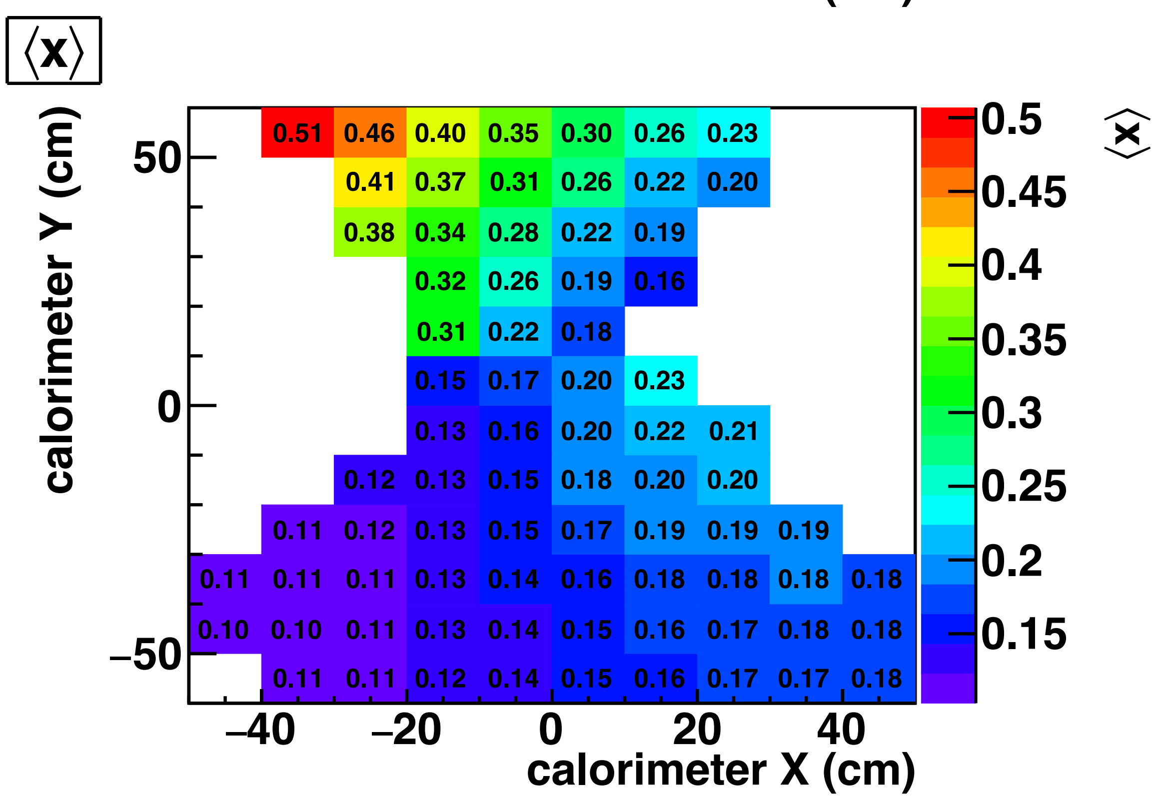
dedicated asymmetry measurement on dummy aluminum target
$\delta A/A \sim 0.2\%$

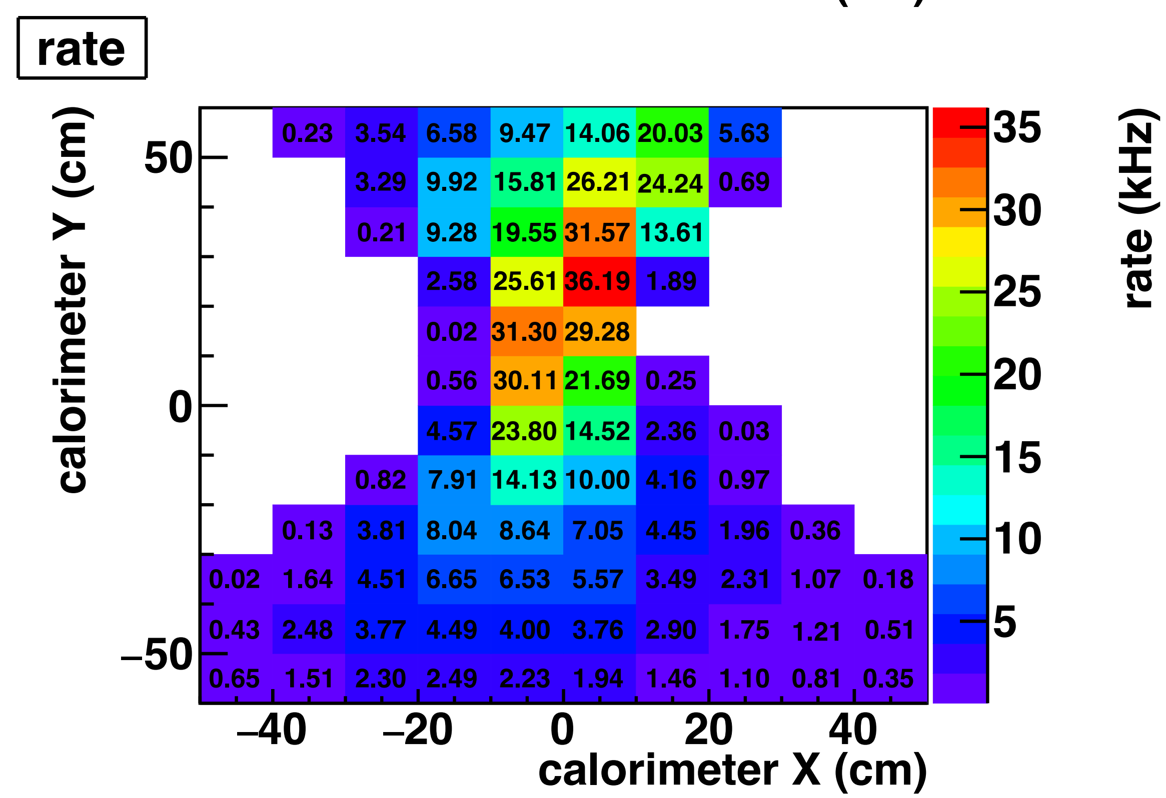
Segmentation of SHMS calorimeter

Kinematics determined from position on calorimeter









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

DAQ is the most novel item

Tracking and Q^2

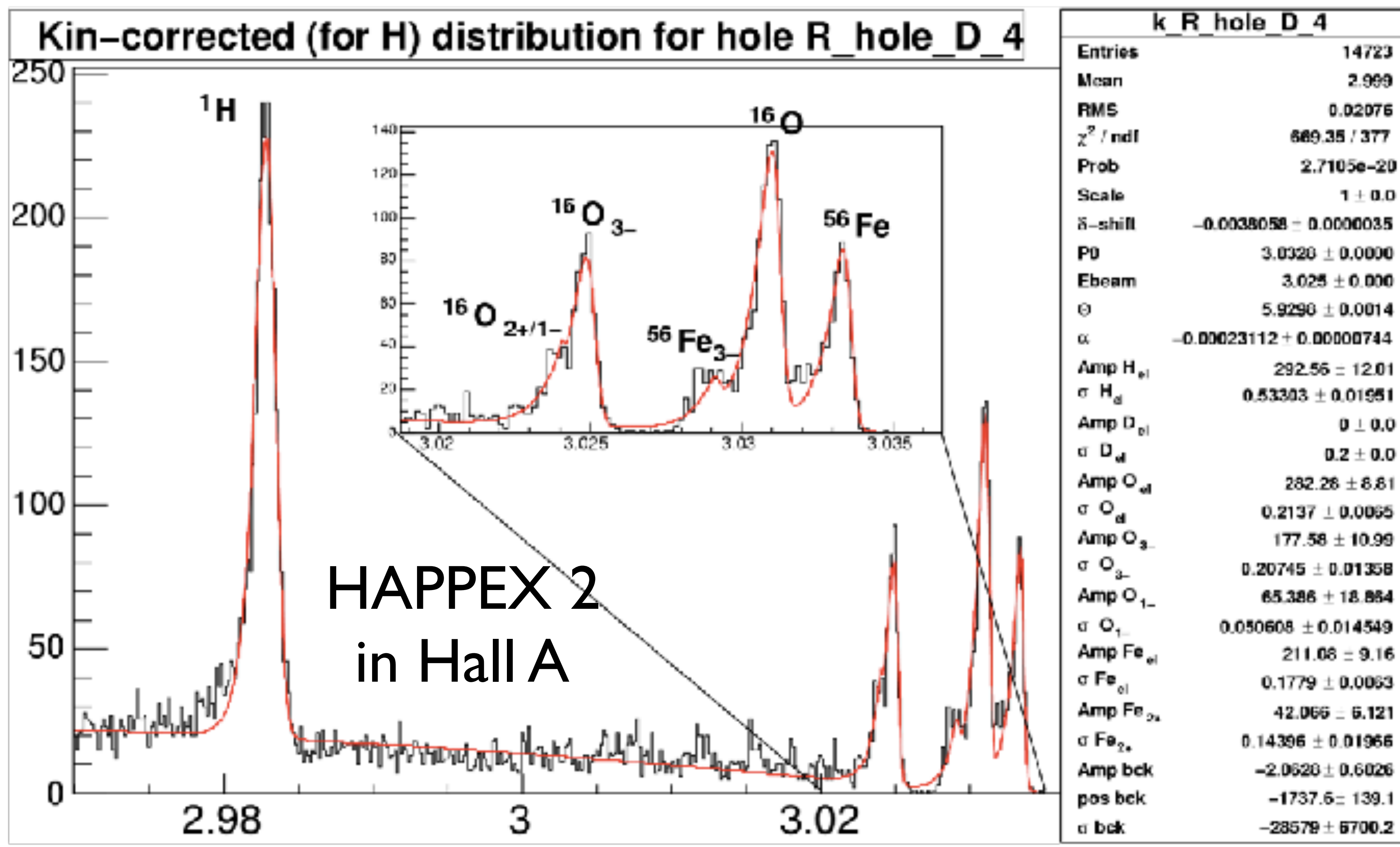
Largest systematic

Assuming level of uncertainty achieved during 6 GeV era

Small angle, large sensitivity to angle

- extensive survey
- water target
  1 pass beam

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

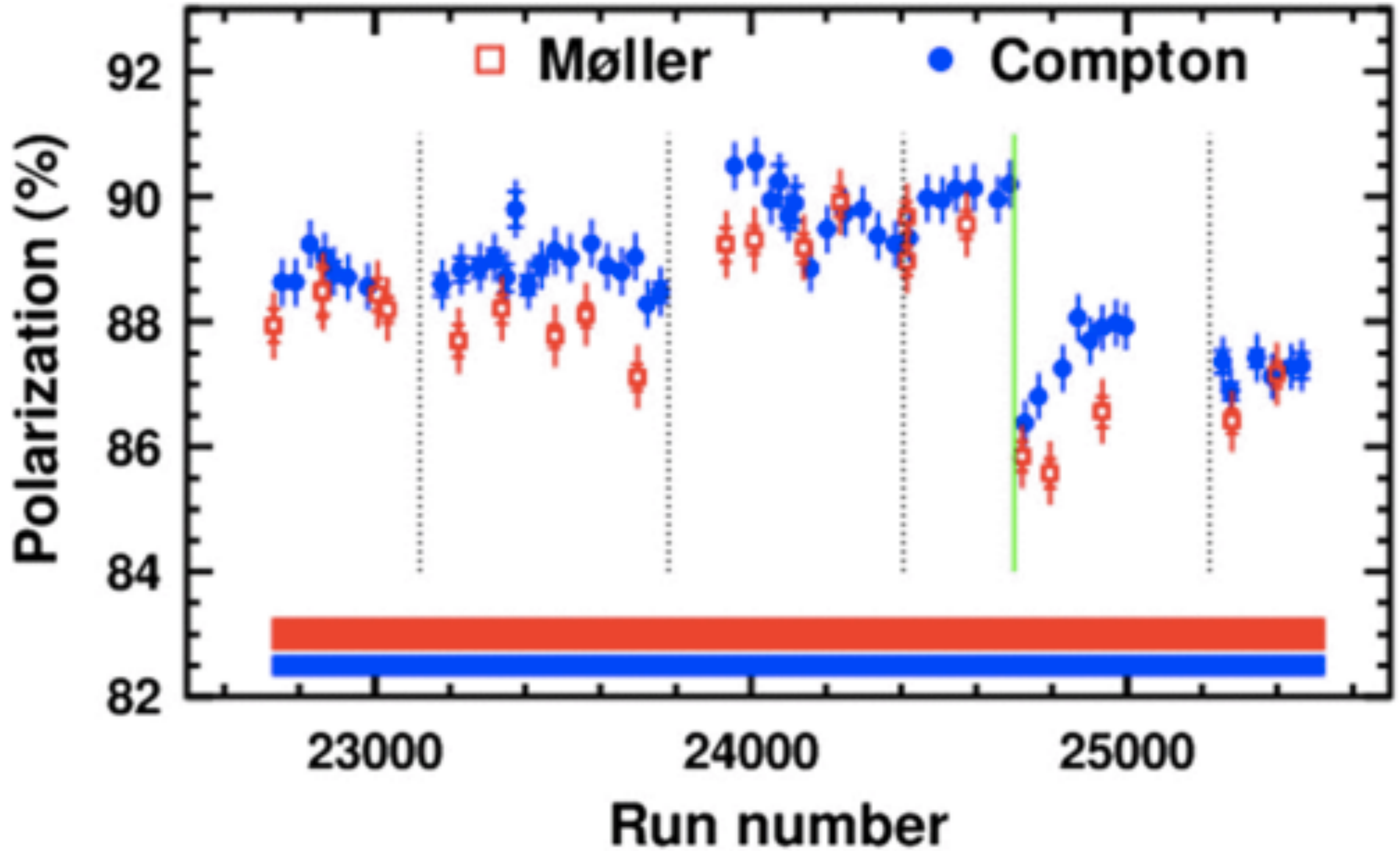


Polarimetry

Second largest systematic

Same strategy as Qweak: combined Moller and Compton measurements.

Revive high-precision techniques before the run.



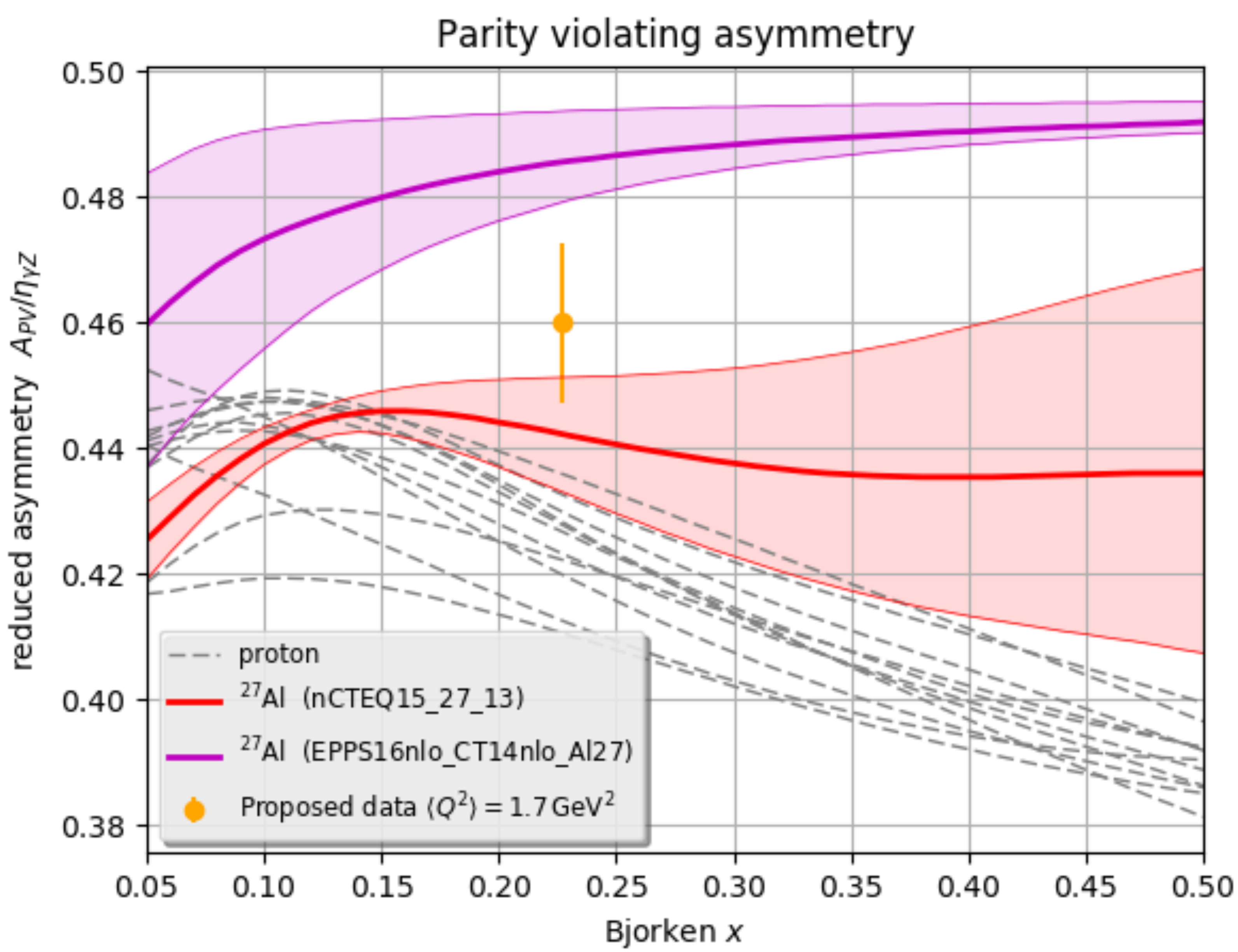
Compton asymmetry significantly larger at higher energy.
Existing electron detector will capture half of the spectrum.
Largest source of uncertainty can be reduced with new firmware.
Compton 0.59% Phys. Rev. X6 no. 1, (2016) 011013

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 20% 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

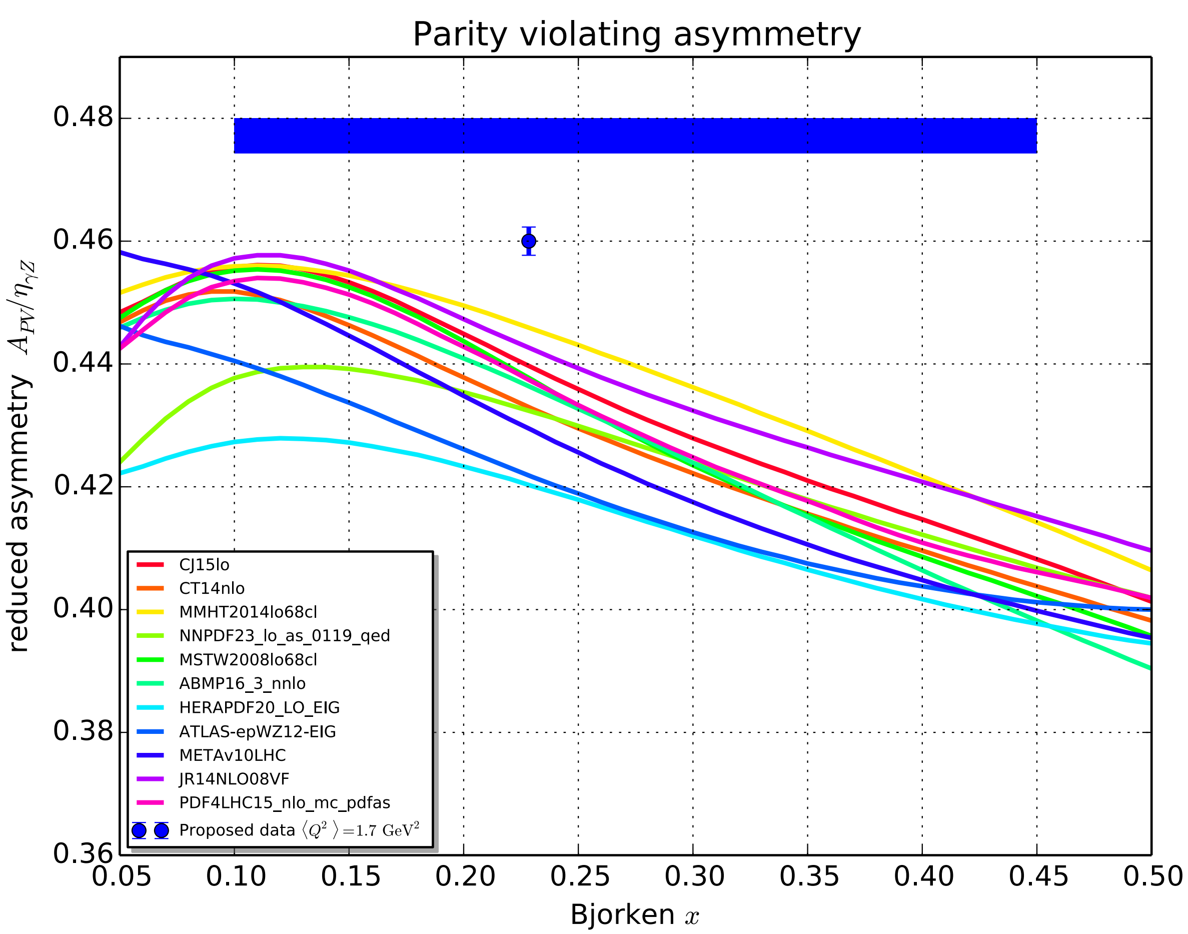
Q^2 determination	0.72 %
Polarization measurement	0.60 %
Residual transverse beam polarization	0.40 %
Dead-time corrections	0.25 %
Elastic radiative tail	0.22 %
Pair-symmetric background	0.20 %
Aluminum endcaps	0.20 %
Beam asymmetries	0.10 %
Pion contamination	0.08 %
Total	1.12 %

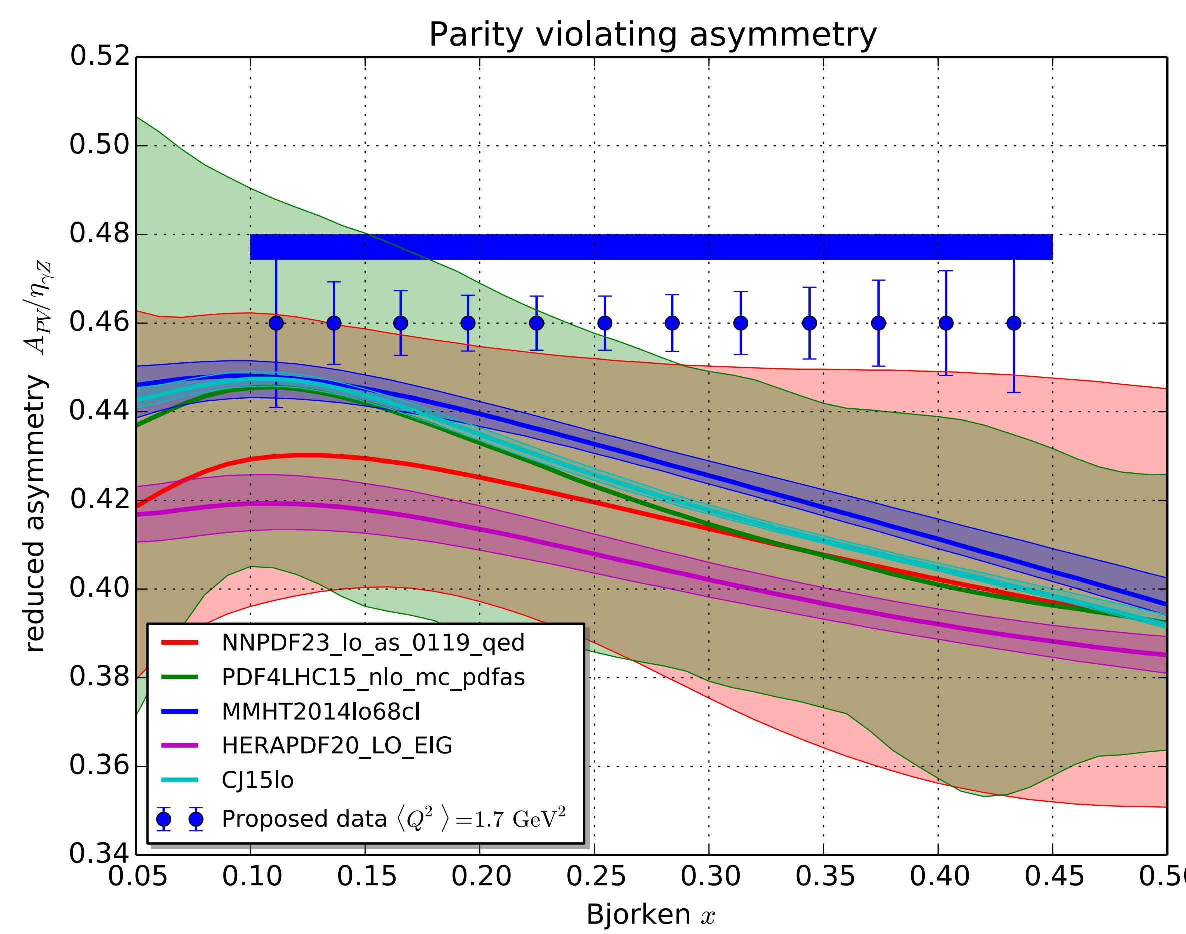
Beam Time Request

	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
  - gives precision measurement of $F_2^{\gamma Z,p}$
  - First model independent constraint on strange PDF in valence regime
- can only be done at CEBAF with small angle spectrometers
  - allow access down to x ~ 0.1 where strange quark PDF rises rapidly
  - not covered by any non-nuclear data






EXTRA!!

The Parity Violation Parton Distribution Function (PVPDF) Experiment: a new experimental constraint on PDFs
Proposal to JLab PAC 45

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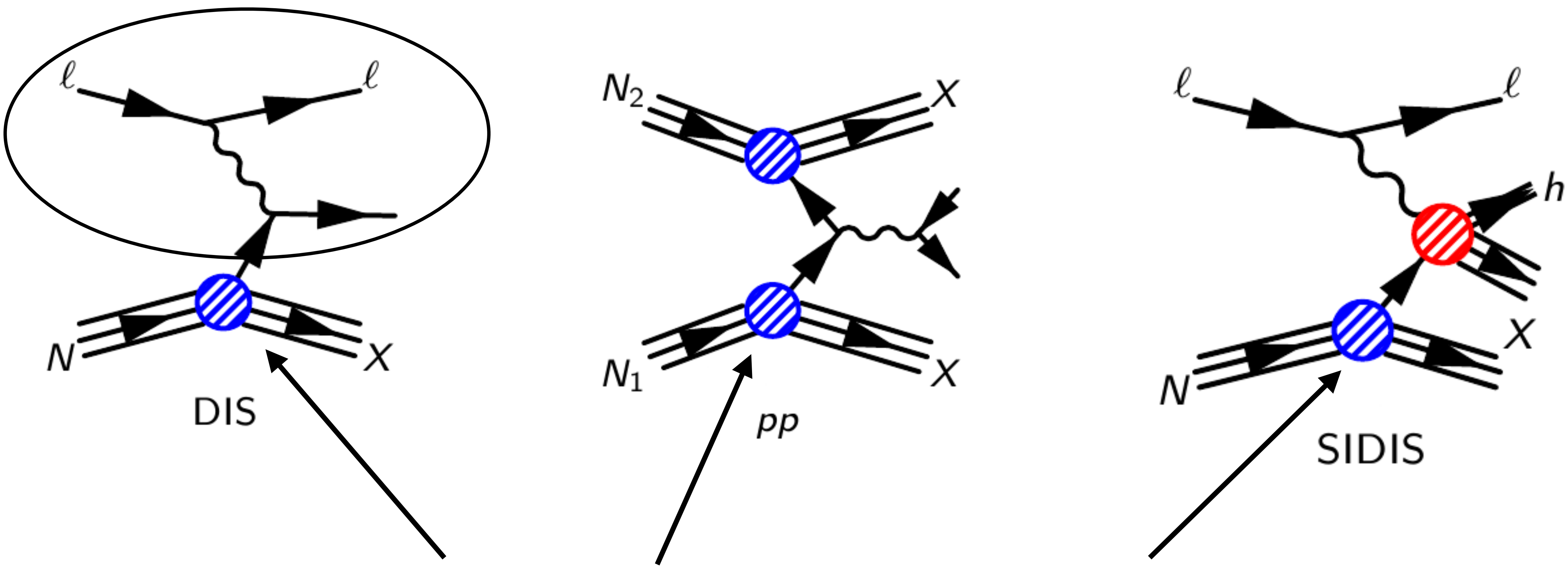
Factorization

hard, calculable part



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

different processes probe different parts of the distributions

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

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

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 ⇒ 0.1% overall uncertainty

Transverse asymmetry leakage

Left-Right asymmetry

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

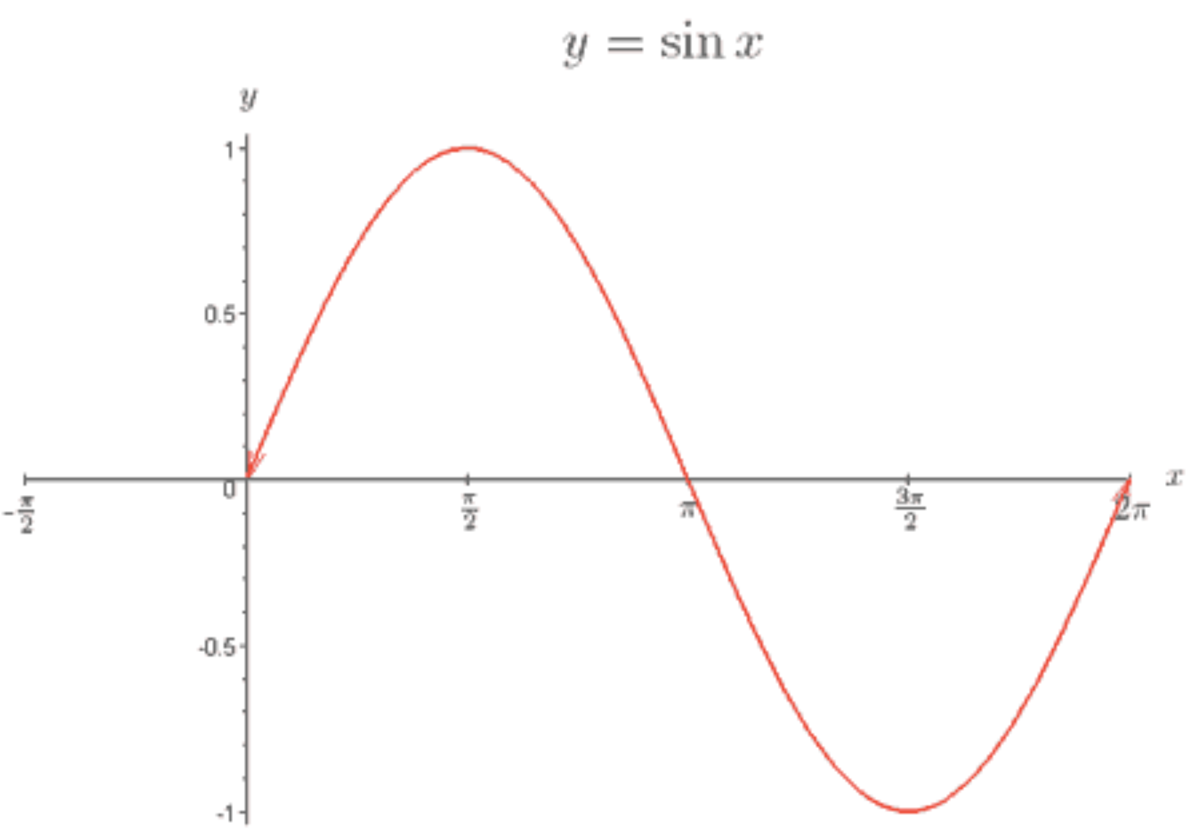
25 ppm*2%=0.5 ppm

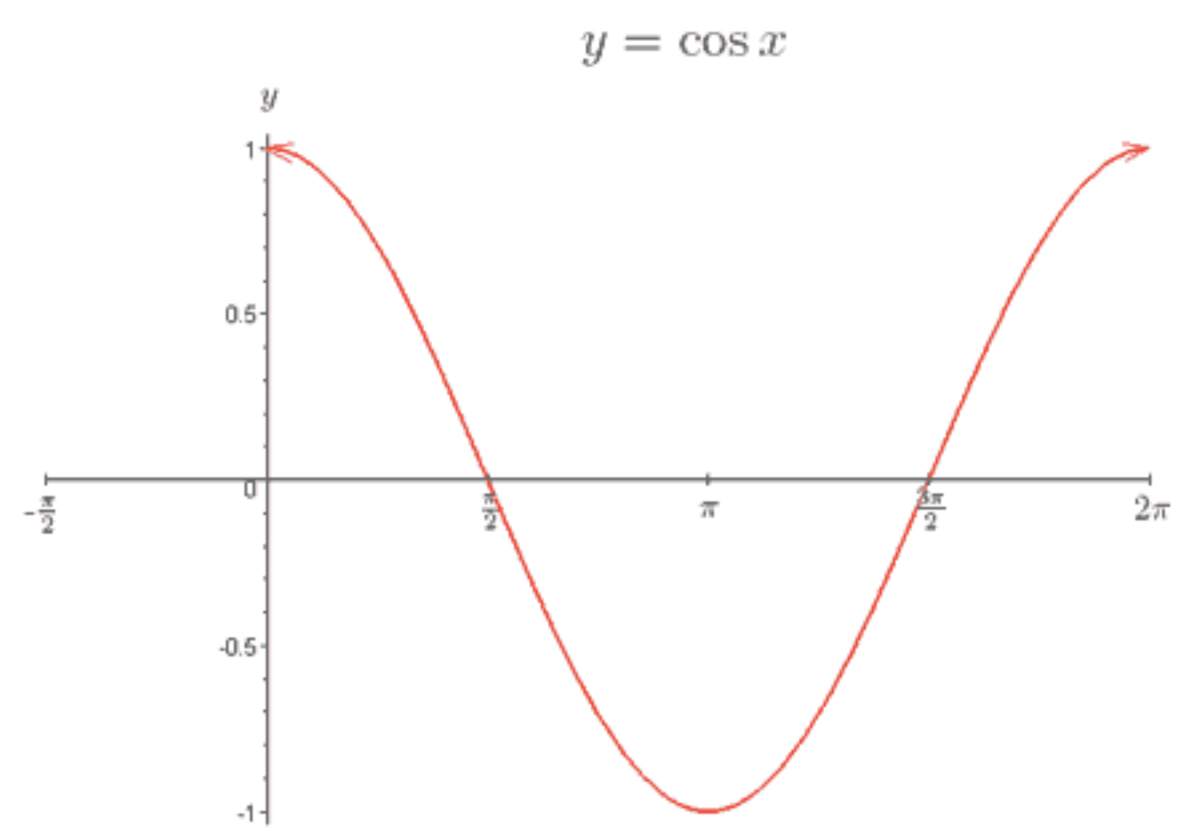
Up-Down asymmetry

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 10% residual.

25 ppm*4%*10%*10%=0.01 ppm





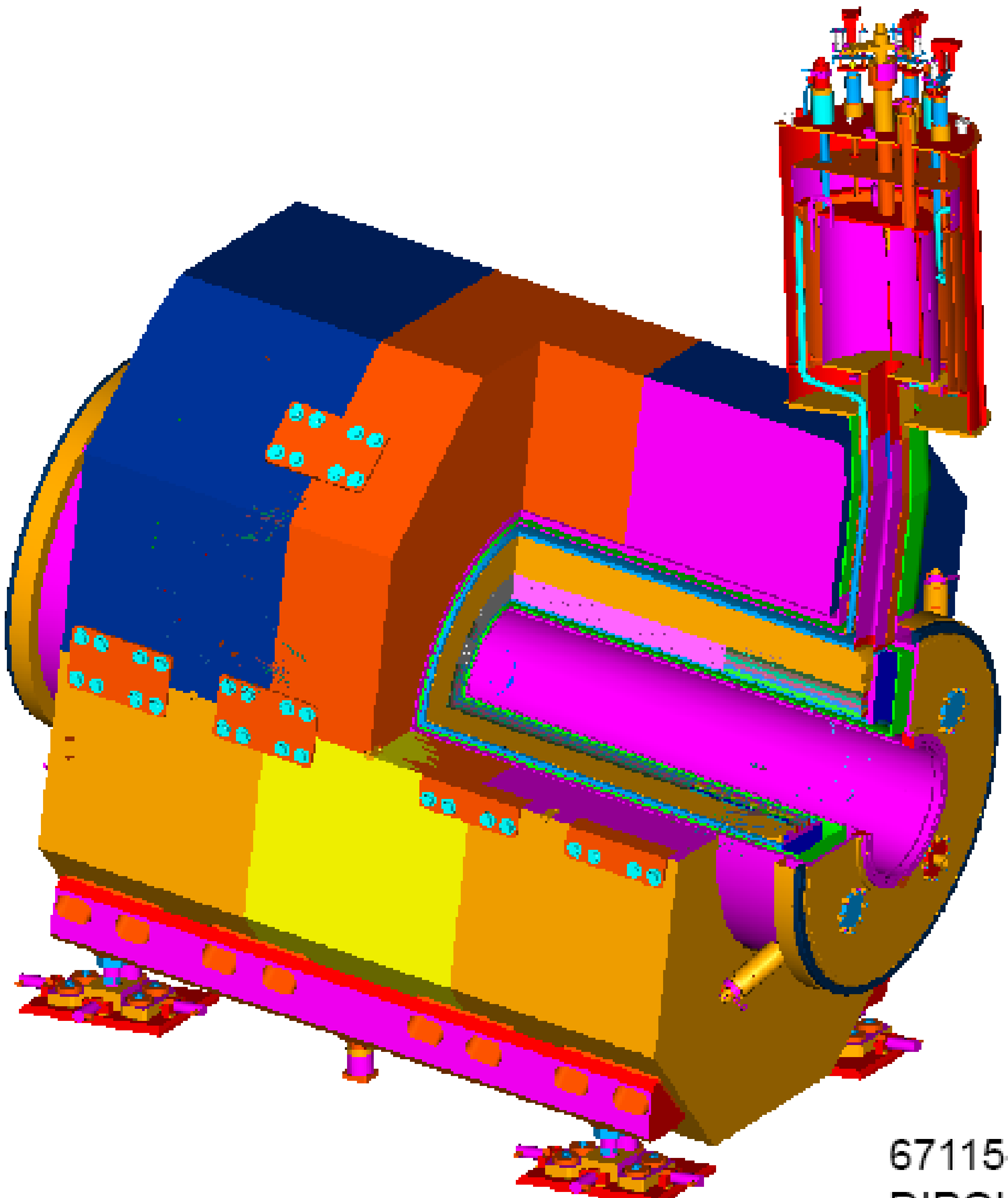
Spectrometer Backgrounds

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

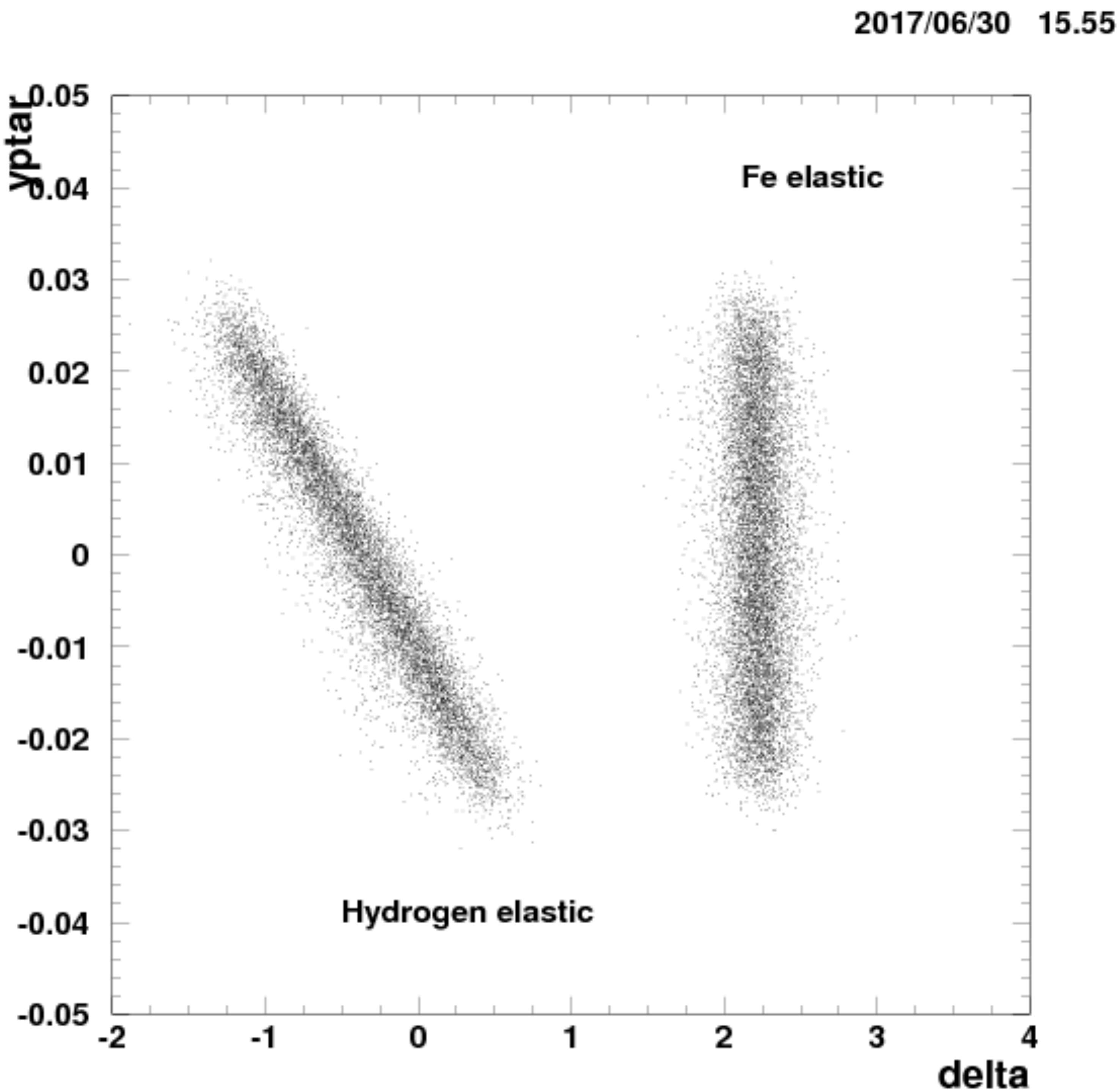
No large asymmetry processes contribute.

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.



Water Target Resolution



SHMS

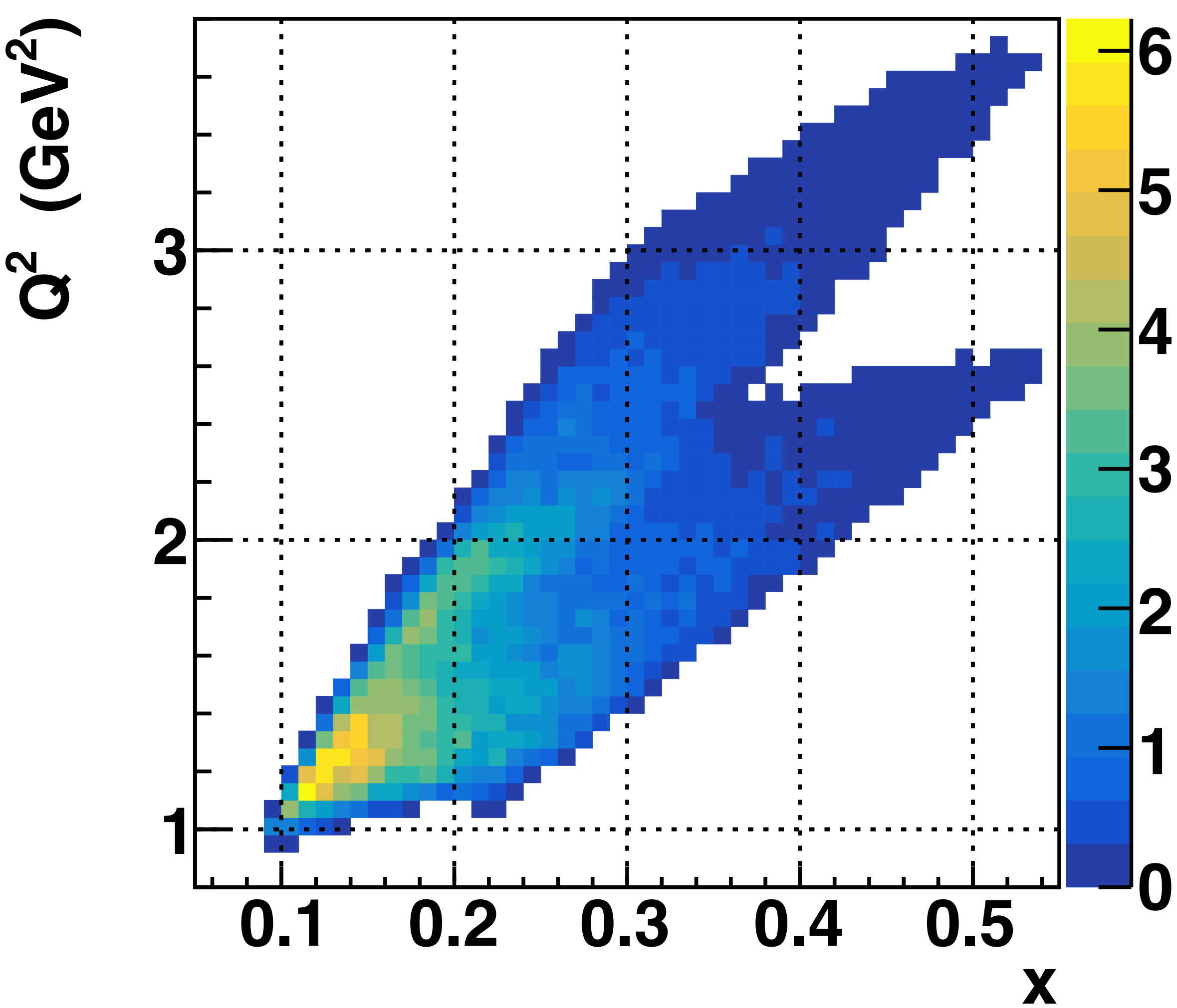
E_{beam} = 2.2 GeV

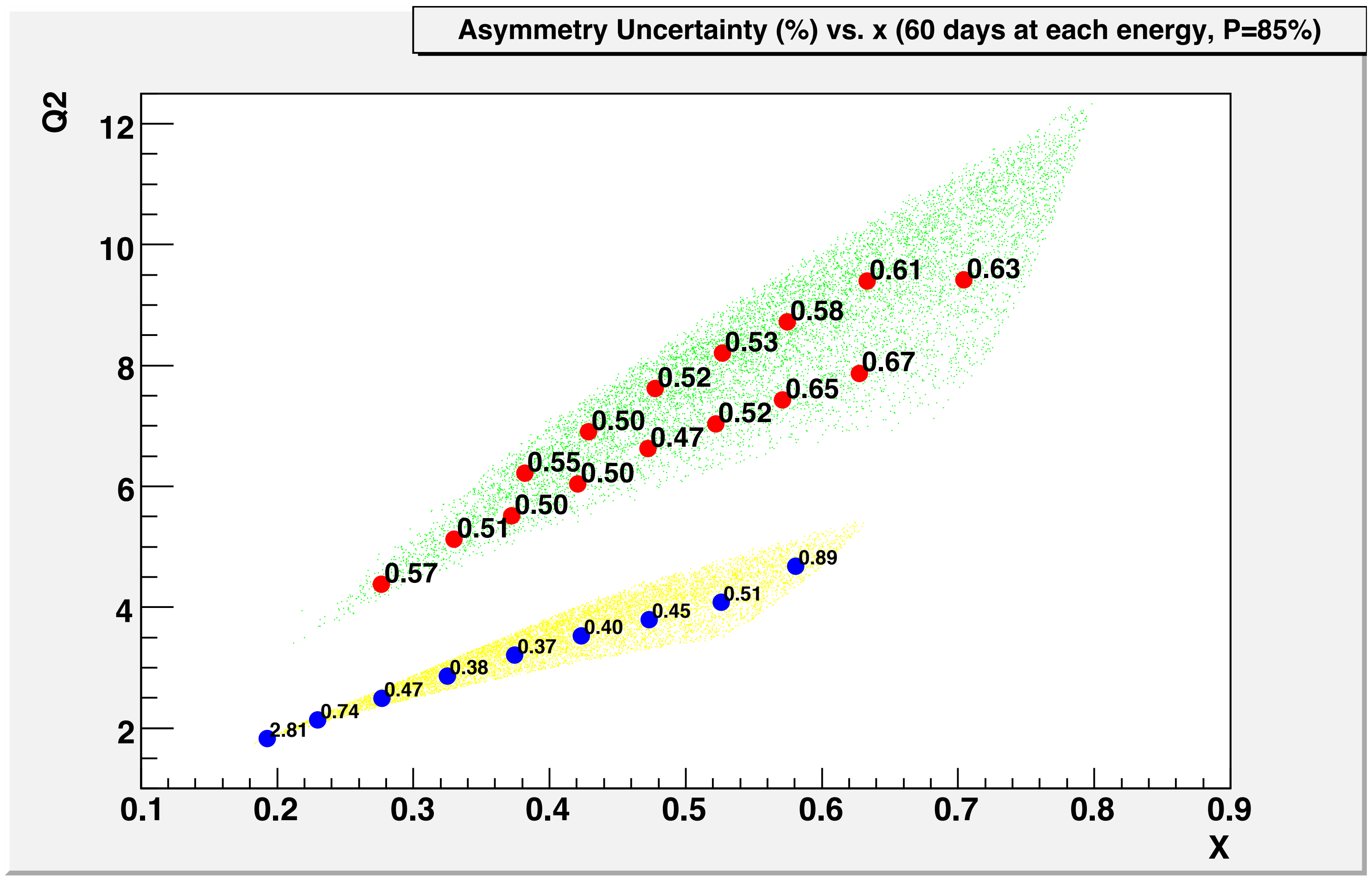
theta = 8.5 deg

P_{SHMS} = 2.15 GeV

Comparison to SOLID kinematics

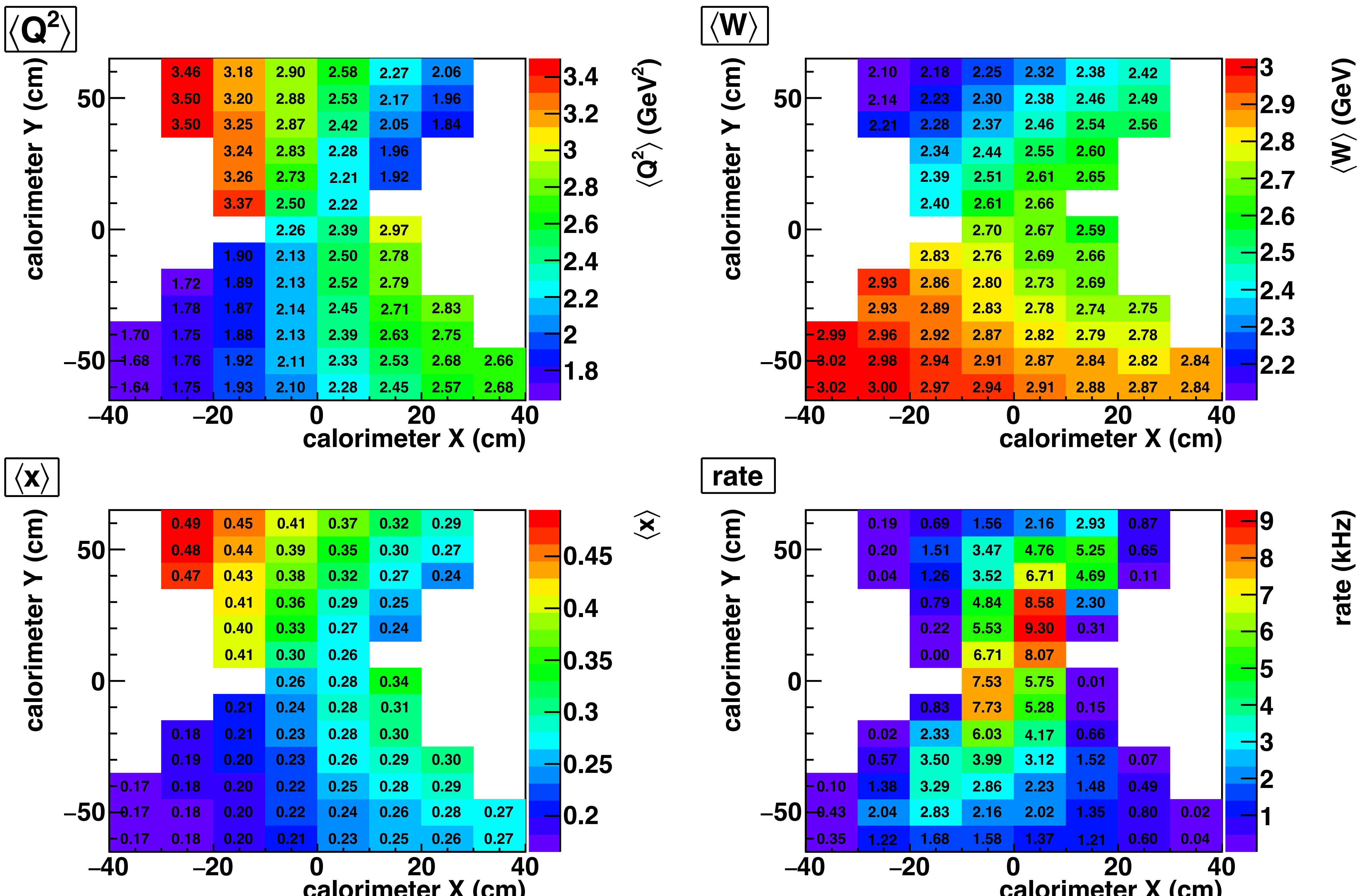
PVPDF at lower x where the s-PDF fits diverge the most
Accessed through small angle capability in Hall C



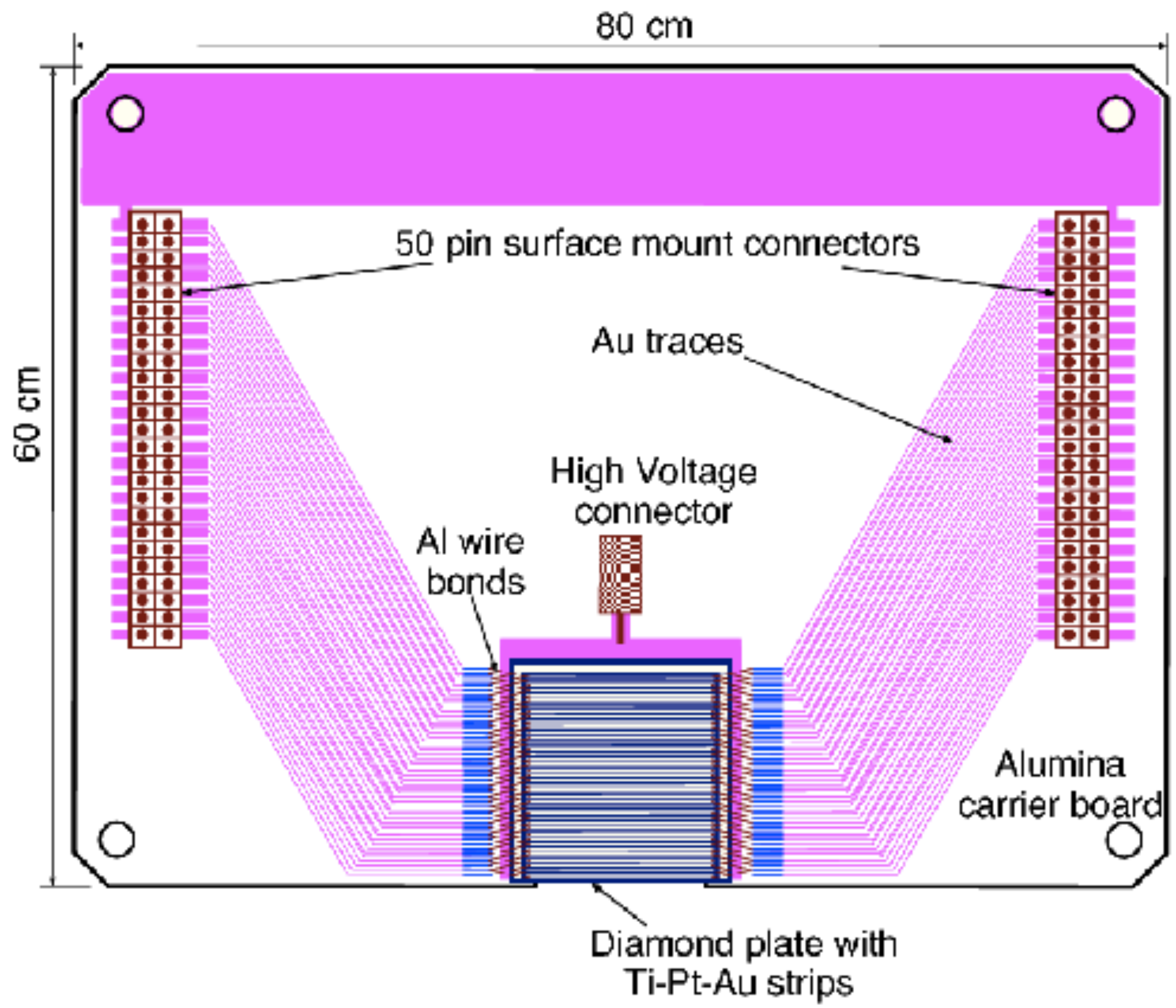


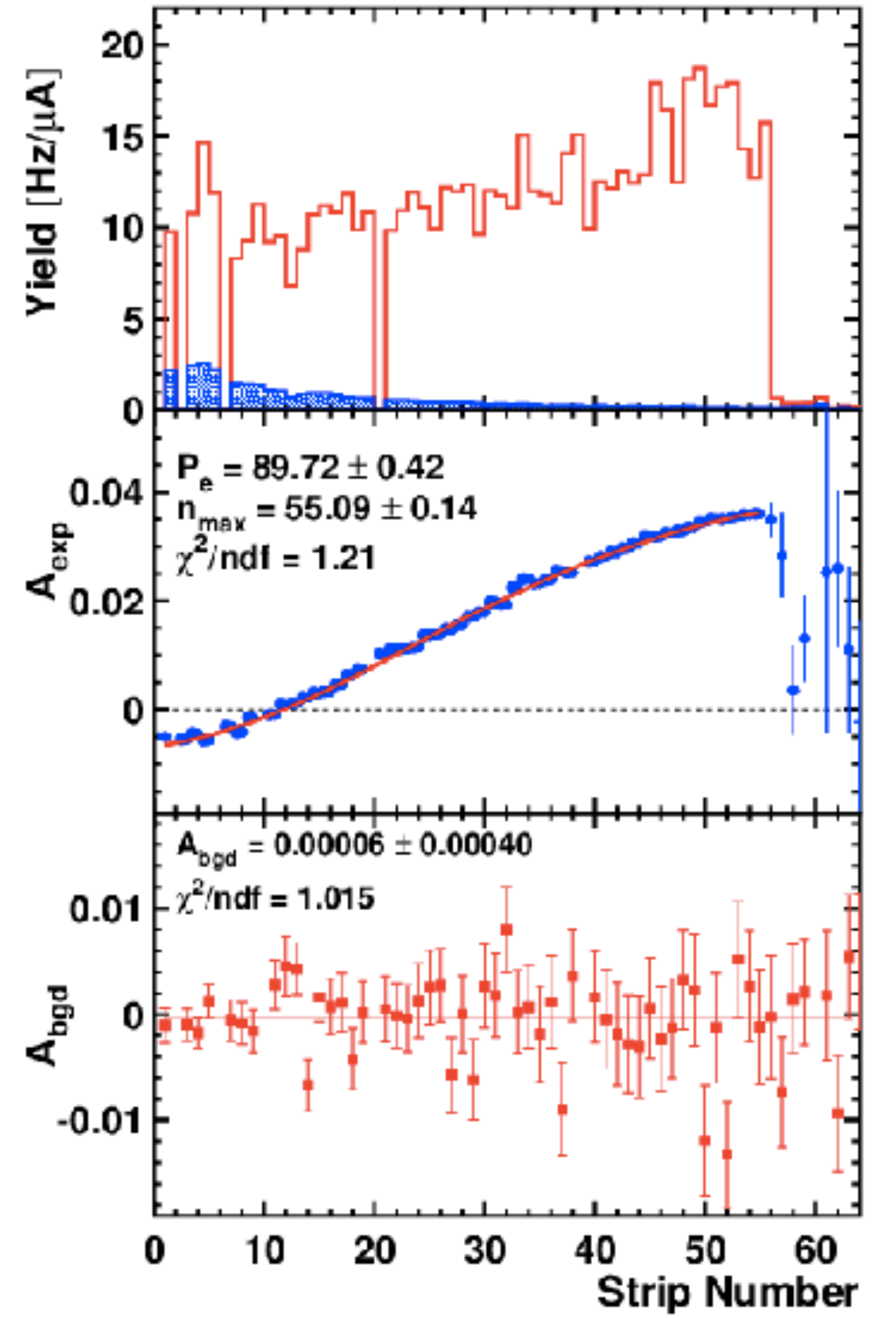
Segmentation of HMS calorimeter

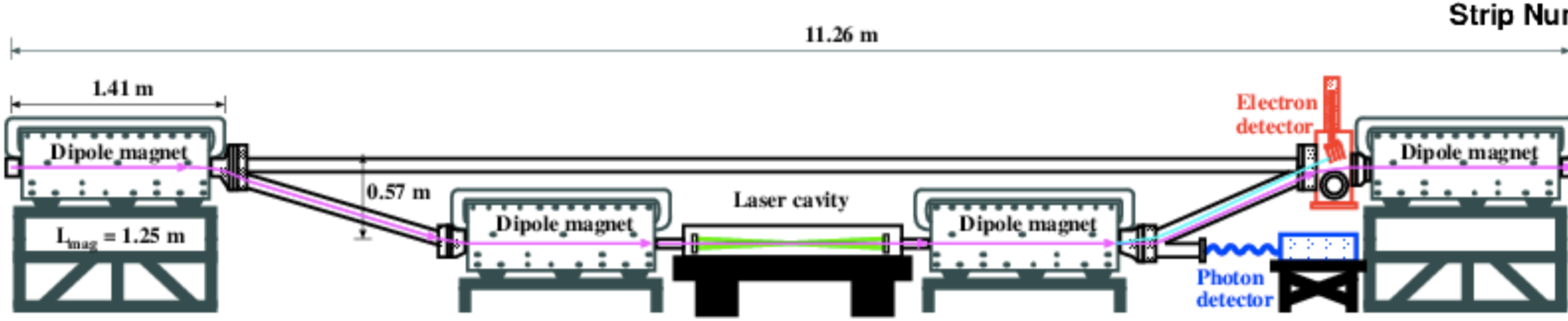
Kinematics determined from position on calorimeter



Qweak Compton Polarimetry



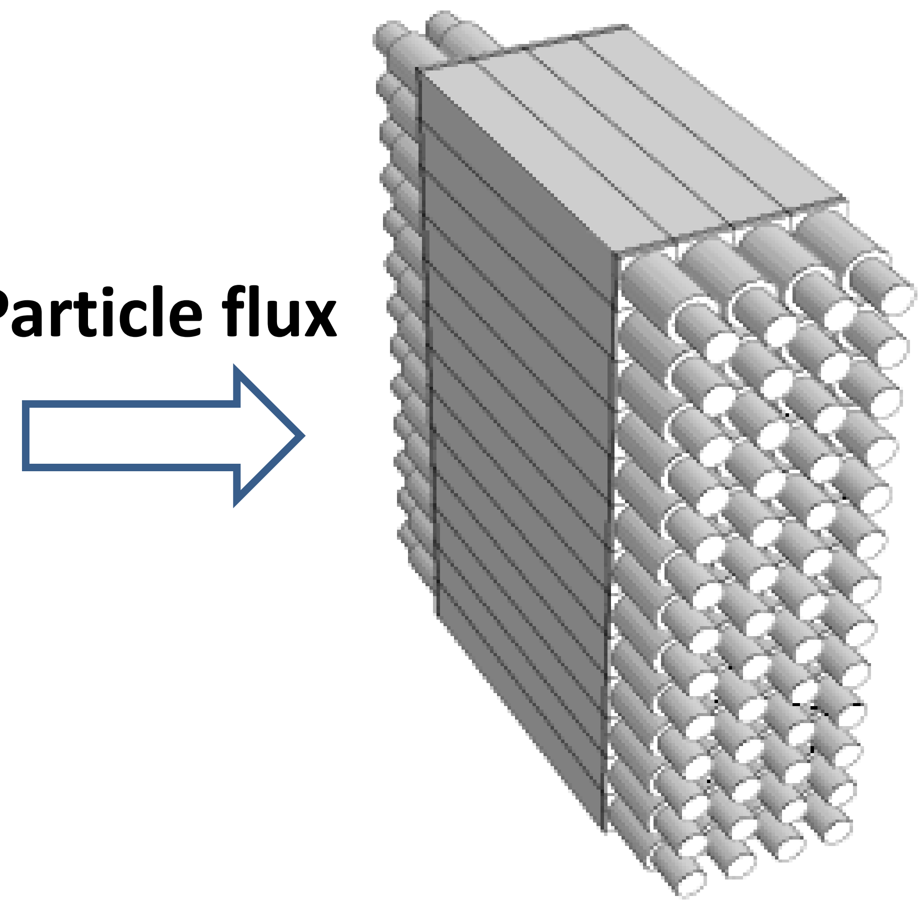




HMS & SOS calorimeters' construction

HMS calorimeter

Particle flux

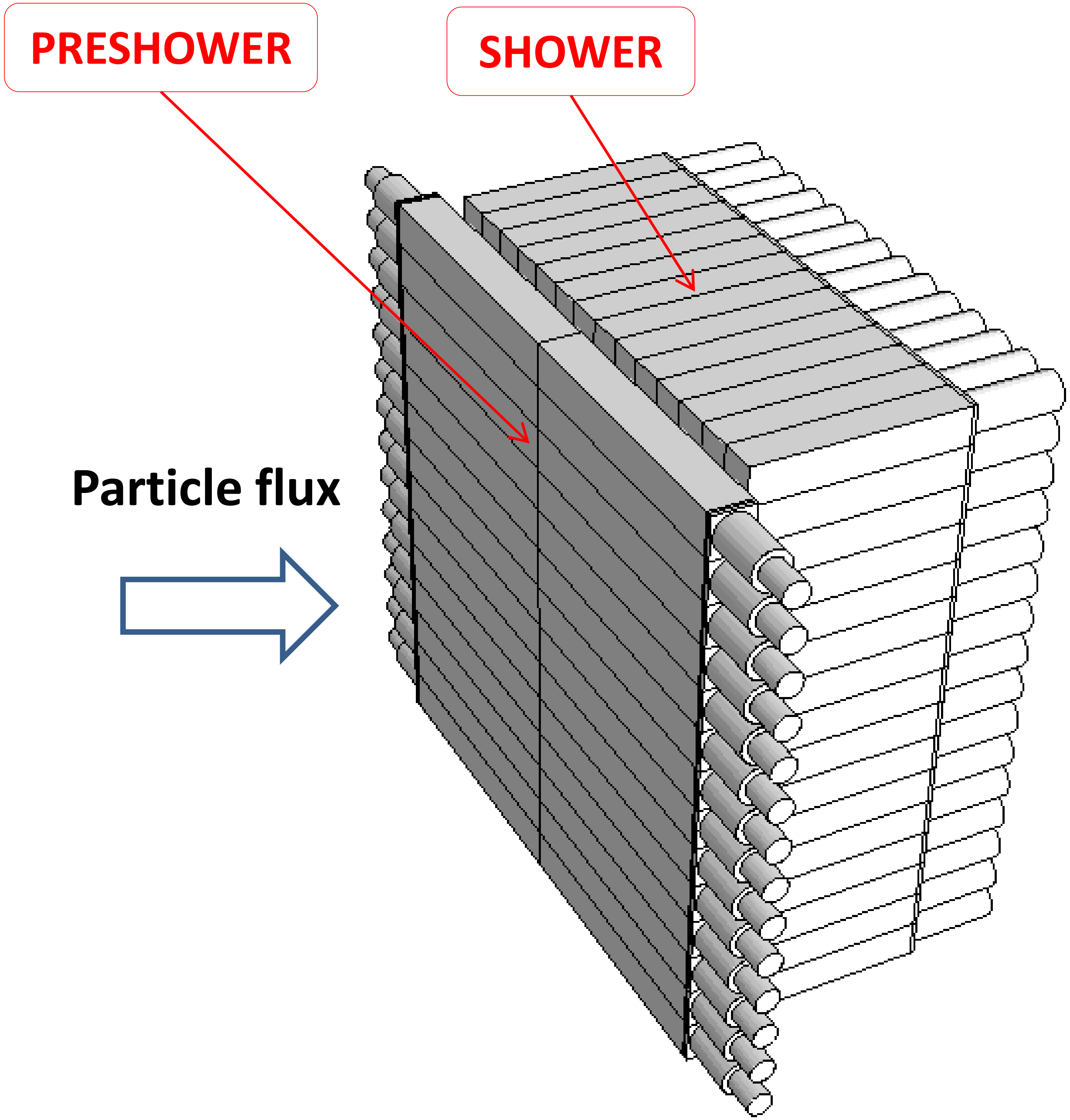


Thickness14.6 rad.length	
Effective area	60×120 cm^2
# of modules	52
# of channels	78
Arrangement	4×13
Block sizes	10×10×70 cm^3
Radiator	TF-1 lead glass
Light detector	XP3462B PMT
In operation	1995 - present

- 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.

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