The Qweak Experiment at Jefferson Lab

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for the Qweak Collaboration
Elba XII, June 2012

Qweak: measurement of the weak charge of the proton

Commissioning June - August, 2010
(LH2 target, QTOR spectrometer + 9000 A power supply, tracking detectors, scanner...)

"Engineering" runs October 2010

"25% run" (run 1): November 2010 - May 2011

"4% run" (run 2): November 2011 - May 2012

Data analysis continues!

May 18, 2012: JLab director pulls the plug on 6 GeV running

CEBAF down now for 2 years for upgrade to 12 GeV
Qweak running has truly ended !

Qweak Objectives

Measure elastic e-p parity-violating analyzing power:

- to 2% at $Q^2 = 0.026\ (GeV/c)^2$

→ weak charge of proton, Q_W, to 4%

→ $\sin^2\theta_W$ to 0.3% (10σ offset relative to Z-pole)

Evidence of physics beyond the Standard Model?

- To what extent can "new physics" be ruled out?

Ancillary measurements:

- Background asymmetry from Al windows of target
- e-p at 3.36 GeV to check γZ box correction to Q_W ($A_L \sim 8$ ppm)
- e-p inelastic analyzing power including to Δ(1232)
- Low Q^2 non-resonant inelastic asymmetries
- Transverse spin analyzing power on p, Al and C

Weak Charge

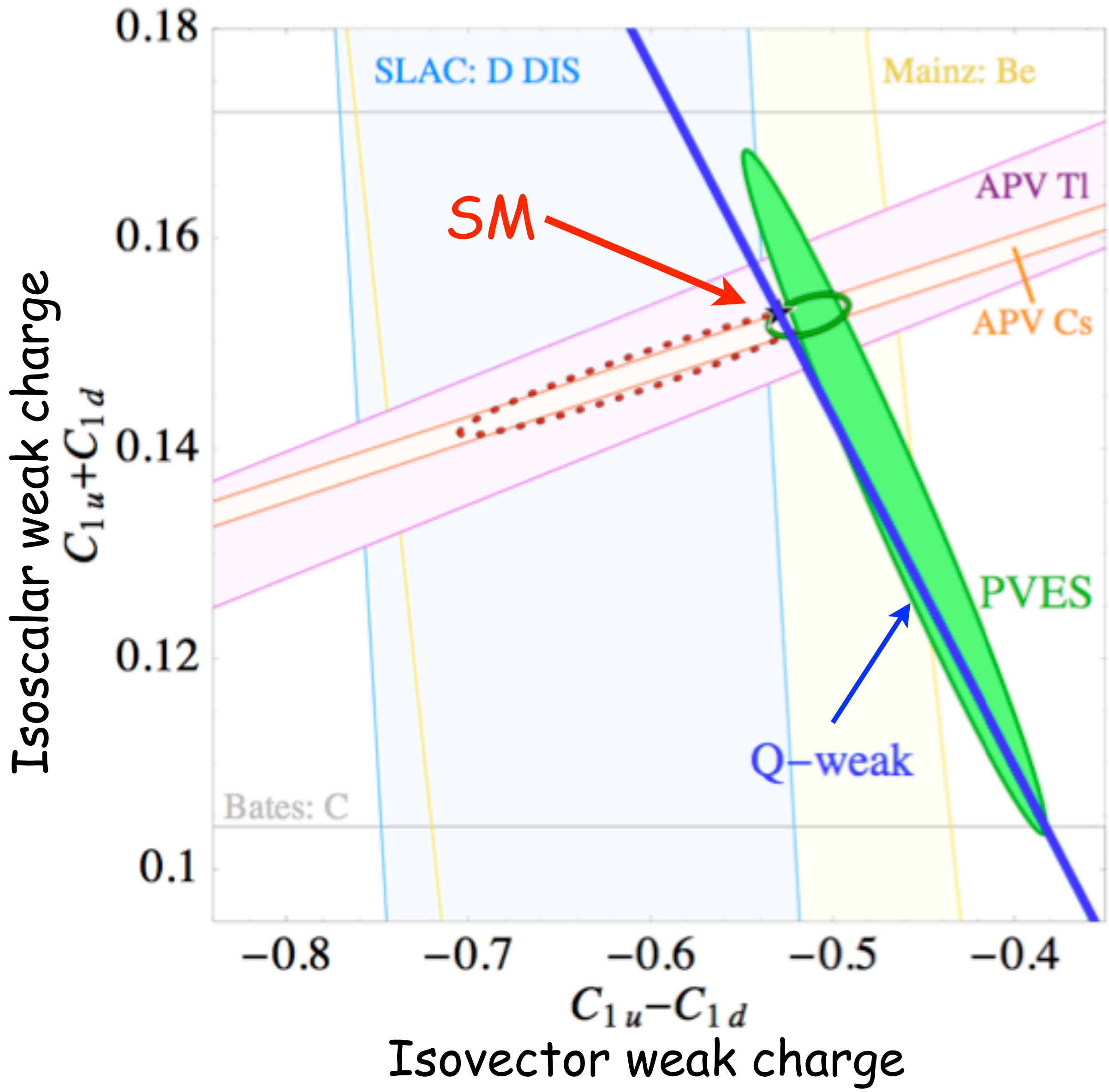
Parity-violating electron scattering couplings

- Weak vector coupling: $C_{1q} = 2g_A^e g_V^q$
- Weak axial coupling: $C_{2q} = 2g_V^e g_A^q$

Particle	**Electric charge**	**Weak charge** $(\sin^2\theta_W \simeq 1/4)$
u	$+2/3$	$-2C_{1u} = +1 - \frac{8}{3}\sin^2\theta_W \simeq +1/3$
d	$-1/3$	$-2C_{1d} = -1 + \frac{4}{3}\sin^2\theta_W \simeq -2/3$
p(uud)	$+1$	$Q_W^p = +1 - 4\sin^2\theta_W \simeq 0.07$
n(udd)	0	$Q_W^n = -1$

Suppression of the proton and electron weak charges in the standard model - easier to see an asymmetry outside of SM

Constraints on *C1q* couplings



Global PVES fit of R. Young, *et al.* (PRL **99**, 122003) reduces the 95% CL region by about a factor of 5 compared to the PDG2008

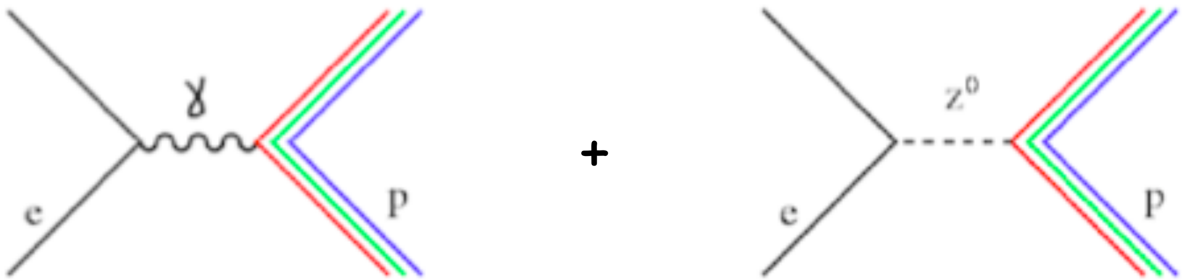
Constraints from Qweak would reduce the 95% CL region by a further factor of 5

Bands & PVES contour are 1σ; other contours are 95% CL

*Figure from R. Young, et al. (PRL **99**, 122003)*

What we measure: parity-violating analyzing power

Interference of photon and weak boson exchange



$$\mathcal{M}^{EM} \propto \frac{1}{Q^2} \qquad \mathcal{M}^{NC}_{PV} \propto \frac{1}{M_Z^2 + Q^2}$$

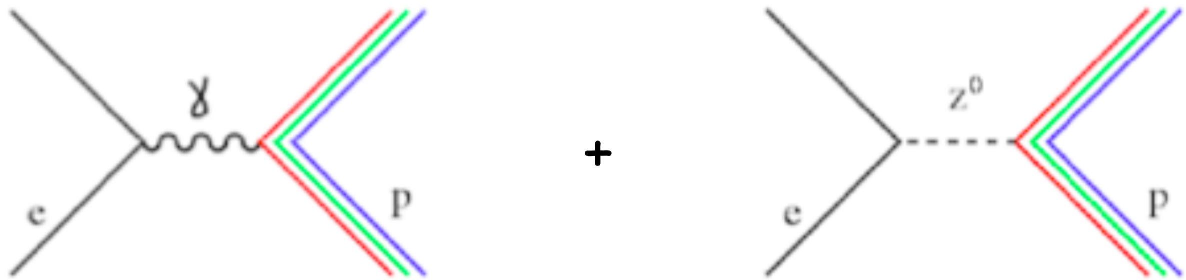
$$\sigma = |\mathcal{M}^{EM}|^2 + 2\mathcal{M}^{EM}\mathcal{M}^{NC}_{PV} + |\mathcal{M}^{NC}_{PV}|^2$$

Very small asymmetry between left and right helicity

$$A_{PV}(p) = \frac{\sigma_R - \sigma_L}{\sigma_R + \sigma_L} \propto \frac{\mathcal{M}^{NC}_{PV}}{\mathcal{M}^{EM}} \propto \frac{Q^2}{M_Z^2} \quad \text{when } Q^2 \ll M_Z^2$$

Parity-violating e-p analyzing power

Interference of photon and weak boson exchange



Asymmetry between left and right helicity in nucleons

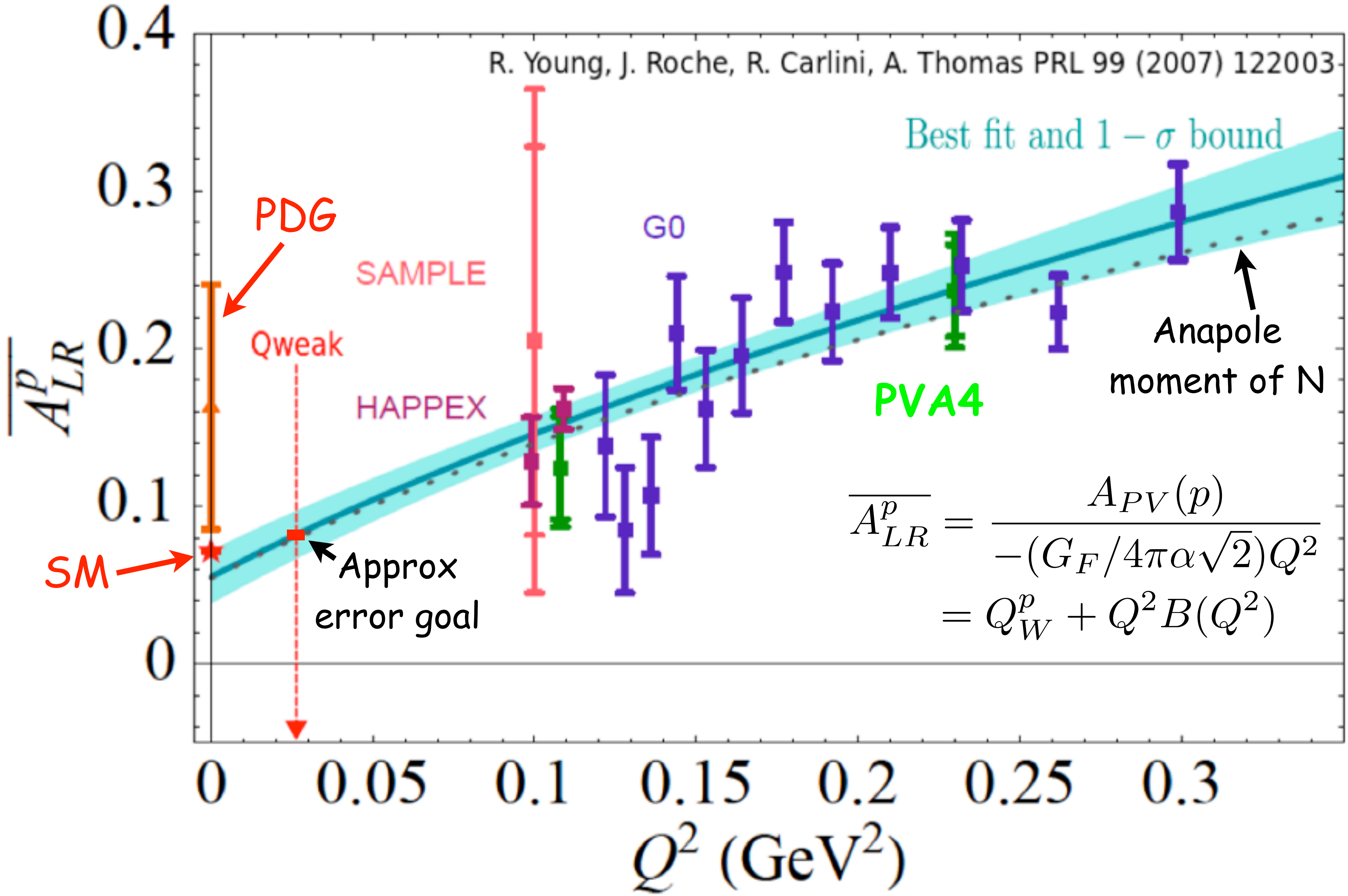
$$A_{PV}(p) = \frac{-G_F Q^2}{4\pi\alpha\sqrt{2}} \left[\frac{\epsilon G_E G_E^Z + \tau G_M G_M^Z - (1 - 4\sin^2\theta_W)\epsilon' G_M G_A^Z}{\epsilon (G_E)^2 + \tau (G_M)^2} \right]$$

In the forward elastic limit $Q^2 \to 0$, $\theta \to 0$ (plane wave)

$$A_{PV}(p) \xrightarrow{Q^2 \to 0} \frac{-G_F Q^2}{4\pi\alpha\sqrt{2}} \left[Q_W^p + Q^2 \cdot B(Q^2) \right] \approx 230\,\mathrm{ppb}$$

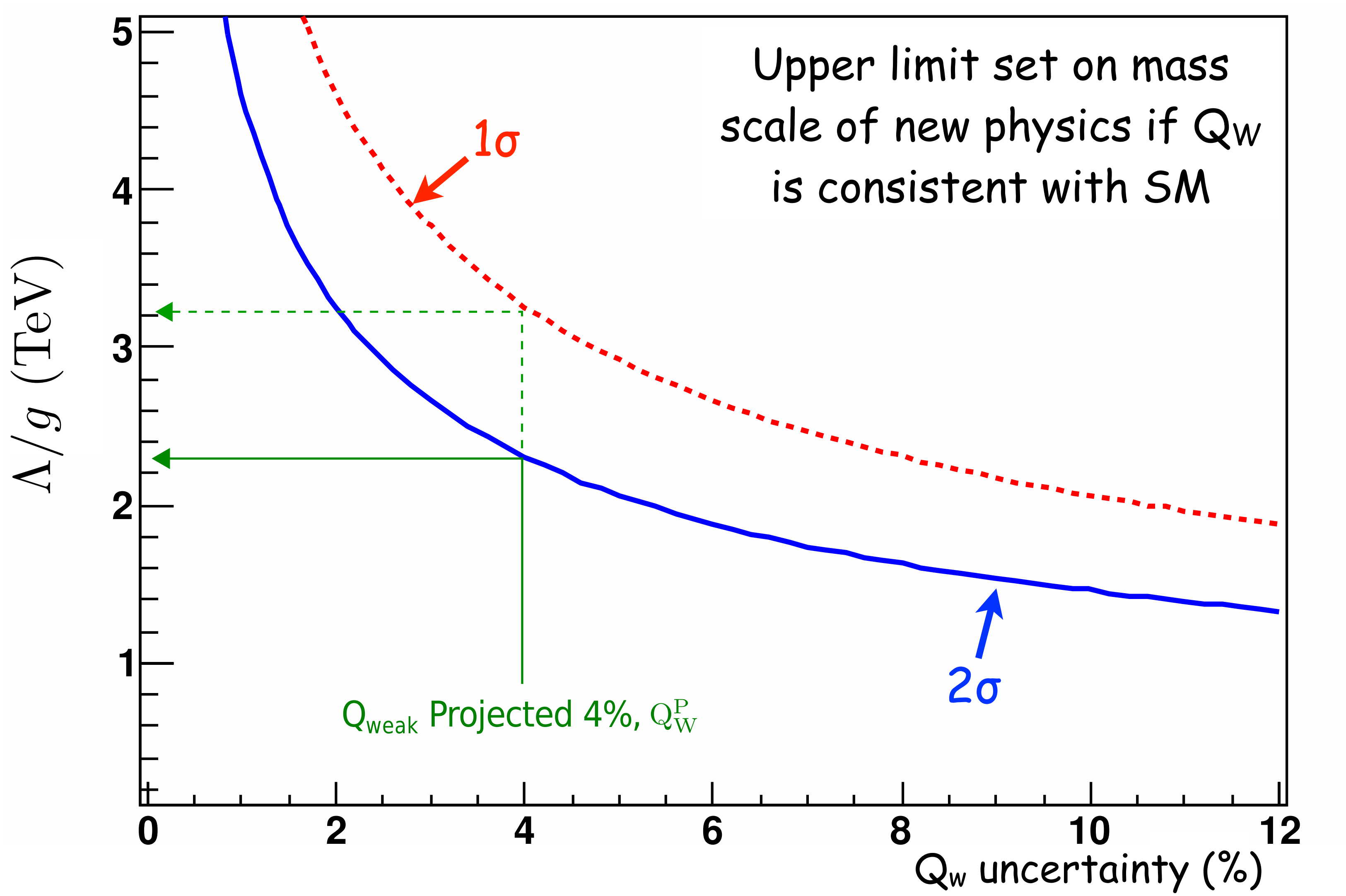
Hadronic corrections

Q_W from extrapolation to $Q^2 = 0$



Model-Independent Constraints on New Physics

$$L_{eff}^{PV} = \underbrace{-\frac{G_F}{\sqrt{2}}\bar{e}\gamma_\mu\gamma_5 e \sum_q C_{1q}\bar{q}\gamma^\mu q}_{L_{SM}^{PV}} + \underbrace{\frac{g^2}{4\Lambda^2}\bar{e}\gamma_\mu\gamma_5 e \sum_q h_V^q\bar{q}\gamma^\mu q}_{L_{\text{new}}^{PV}}$$



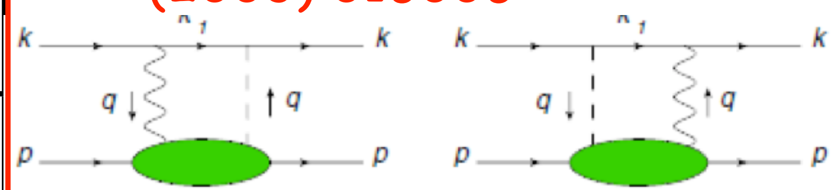
Radiative Corrections

Q_W^p Standard Model ($Q^2 = 0$) 0.0713 ± 0.0008

Q_W^p Experimental precision goal ± 0.003

Source	Q_W^p Uncertainty
$\Delta\sin\theta_W(M_Z)$	±0.0006
γZ box	±0.0005
$\Delta\sin\theta_W(Q)_{hadronic}$	±0.0003
WW, ZZ box - pQCD	±0.0001
Charge symmetry	0
Total	**±0.0008**

Erler et al., PRD 68 (2003) 016006



New calculations: γZ box: 8% correction with ~1% uncertainty. Verification in "DIS" region (Qweak data at 3.36 GeV), following calculation by Melnitchouk

Requirements for the experiment

Measure A_L(e-p) parity-violating analyzing power to relative error of ~2%, i.e. to ~5×10^{-9}

Need:

- high beam current and event rate
- precision polarimetry
- accurate measurement of Q^2
- control of systematic errors
- control of backgrounds

Qweak Error Budget - preliminary analysis

Source of Error	Contribution to $\Delta A_{PV}/A_{PV}$	Contribution to $\Delta Q_W/Q_W$
Counting statistics	**2.1%** (1.8%)	**3.2%** (2.9%)
Beam polarimetry	1.0% (1.0%)	1.5% (1.6%)
Backgrounds	0.7% (0.5%)	1.0% (0.8%)
Helicity-correlated beam properties	0.5% (0.5%)	0.8% (0.8%)
Absolute Q^2	0.5% (0.5%)	1.0% (1.1%)
Hadronic corrections	-	1.5% (1.9%)
Total Systematic	**1.4%** (1.3%)	**2.7%** (2.9%)
Total	**2.5%** (2.2%)	**4.2%** (4.1%)

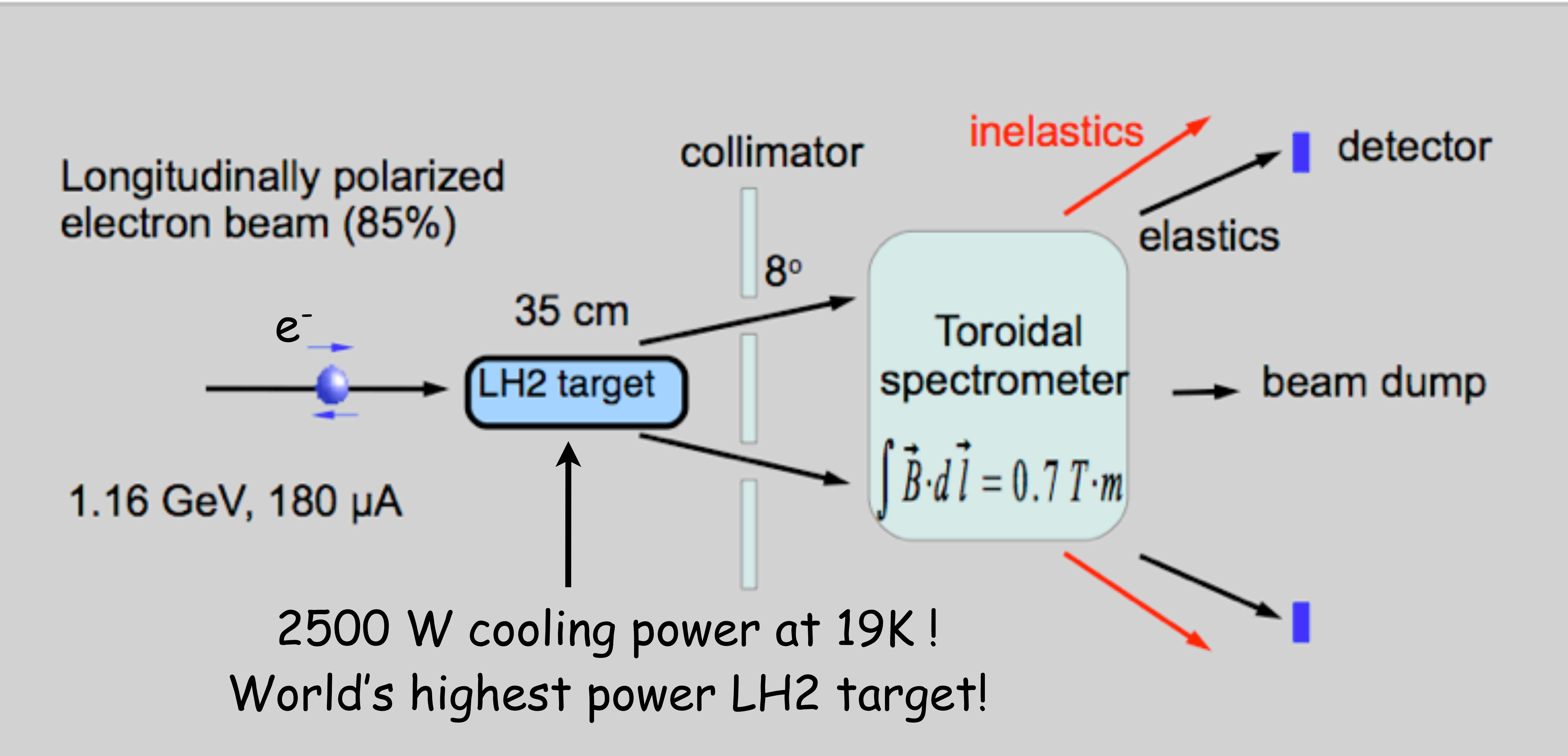
4.2% on $Q_W \rightarrow$ 0.3% on $\sin^2\theta_W$

Proposal: in red

Limits on Helicity-Correlated Beam Properties

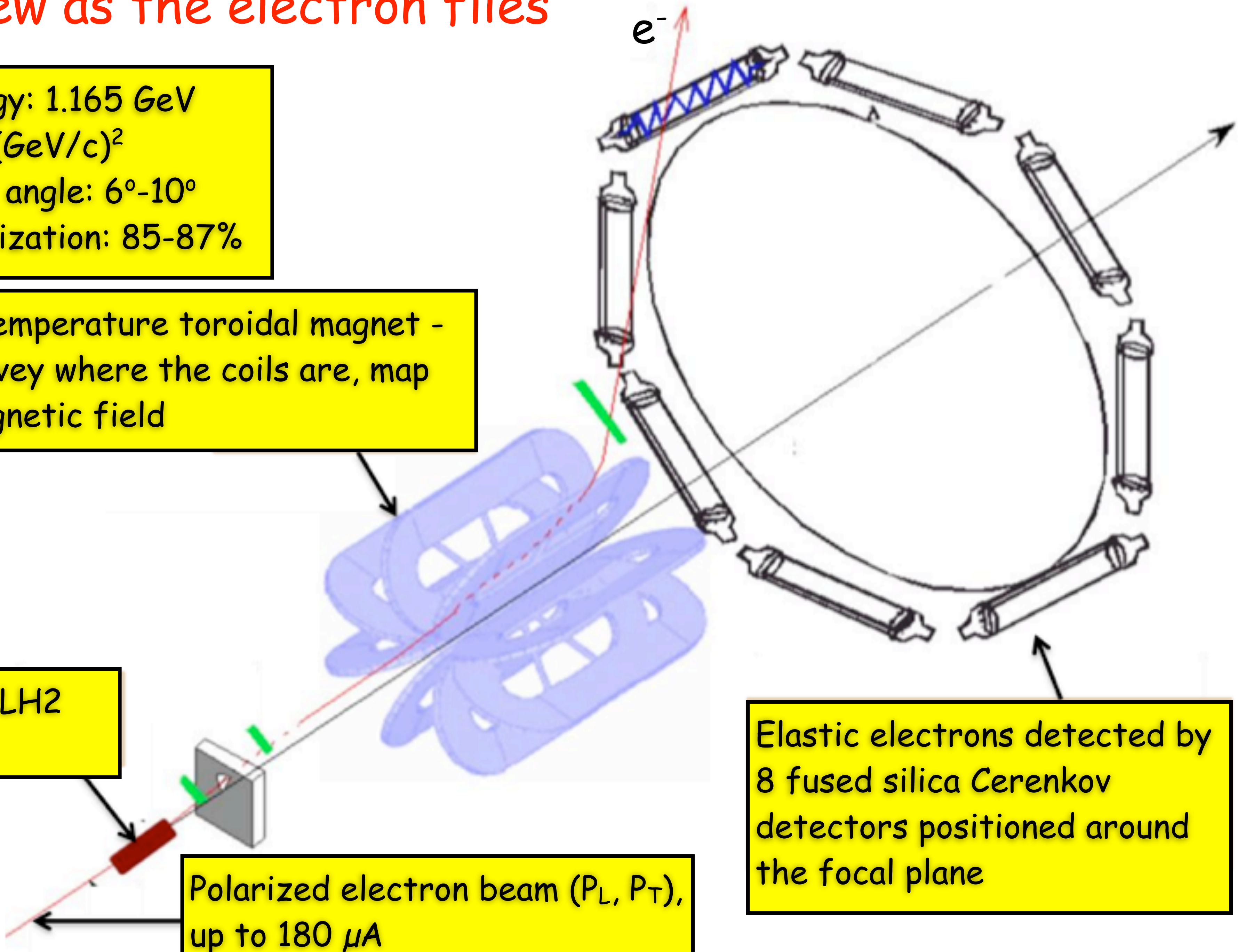
		Achieved	
Beam value	Requirement	Run I	Run II
X-position at target [nm]	<2	3.6 +/- 0.39	-0.95 +/- 0.06
Y-position at target [nm]	<2	-6.9 +/- 0.39	-0.24 +/- 0.28
X-angle at target [nrad]	<30	-0.22 +/- 0.012	-0.07 +/- 0.017
Y-angle at target [nrad]	<30	-0.18 +- 0.015	-0.06 +/- 0.011
Position at dispersion (3c12X)[nm]	-	-13.6 +/- 0.23	-0.83 +/- 0.30
Energy dE/E [ppb]	<1	<3.8 +/- 0.06	<0.23 +/- 0.08

Qweak: overview of the experiment



$$A_{PV}(p) = \frac{\sigma_R - \sigma_L}{\sigma_R + \sigma_L}$$

Overview as the electron flies



Beam energy: 1.165 GeV
Q^2: 0.026 $(GeV/c)^2$
Scattering angle: 6°-10°
Beam polarization: 85-87%

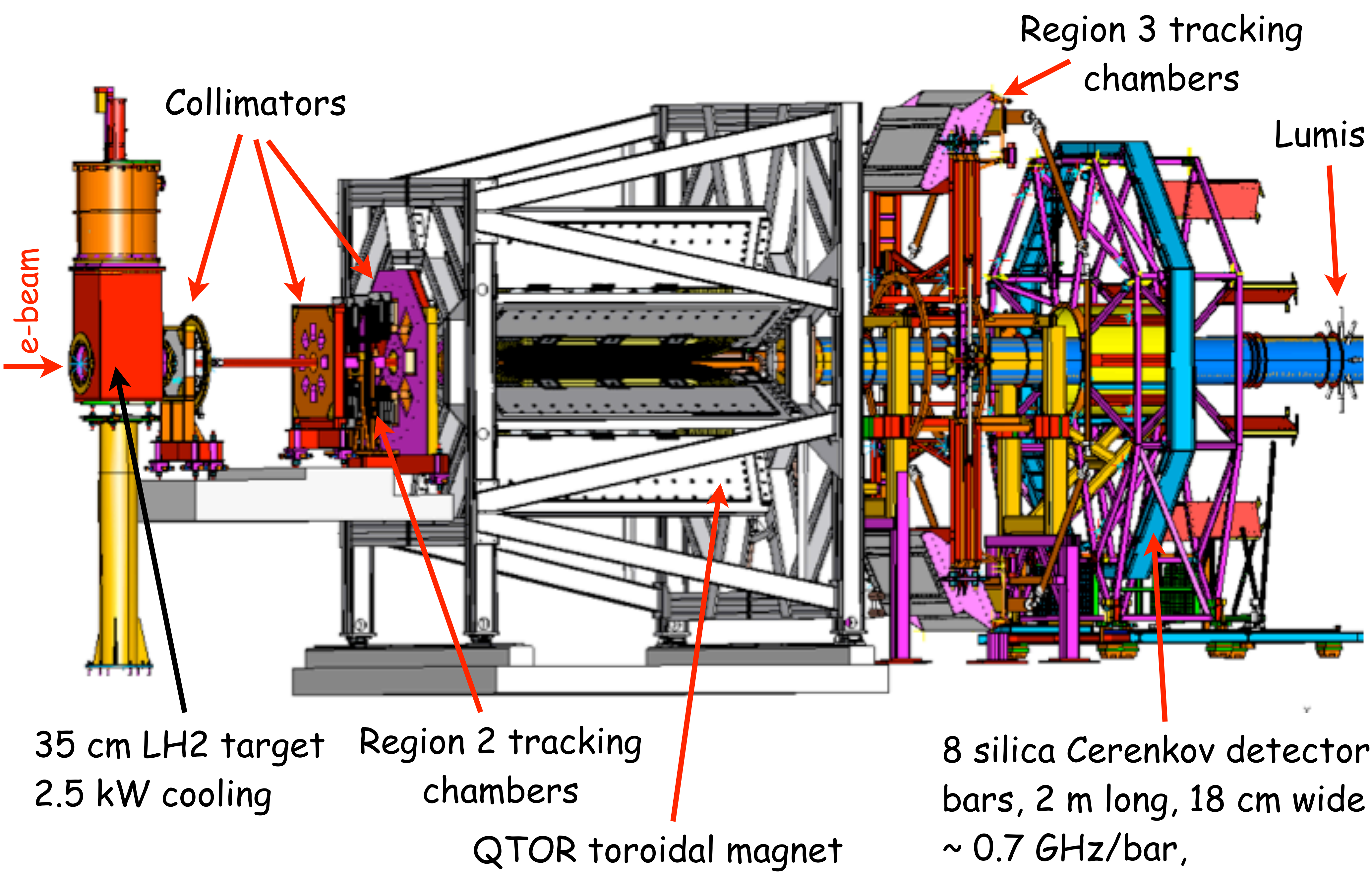
Room temperature toroidal magnet - can survey where the coils are, map the magnetic field

Unpolarized LH2 target

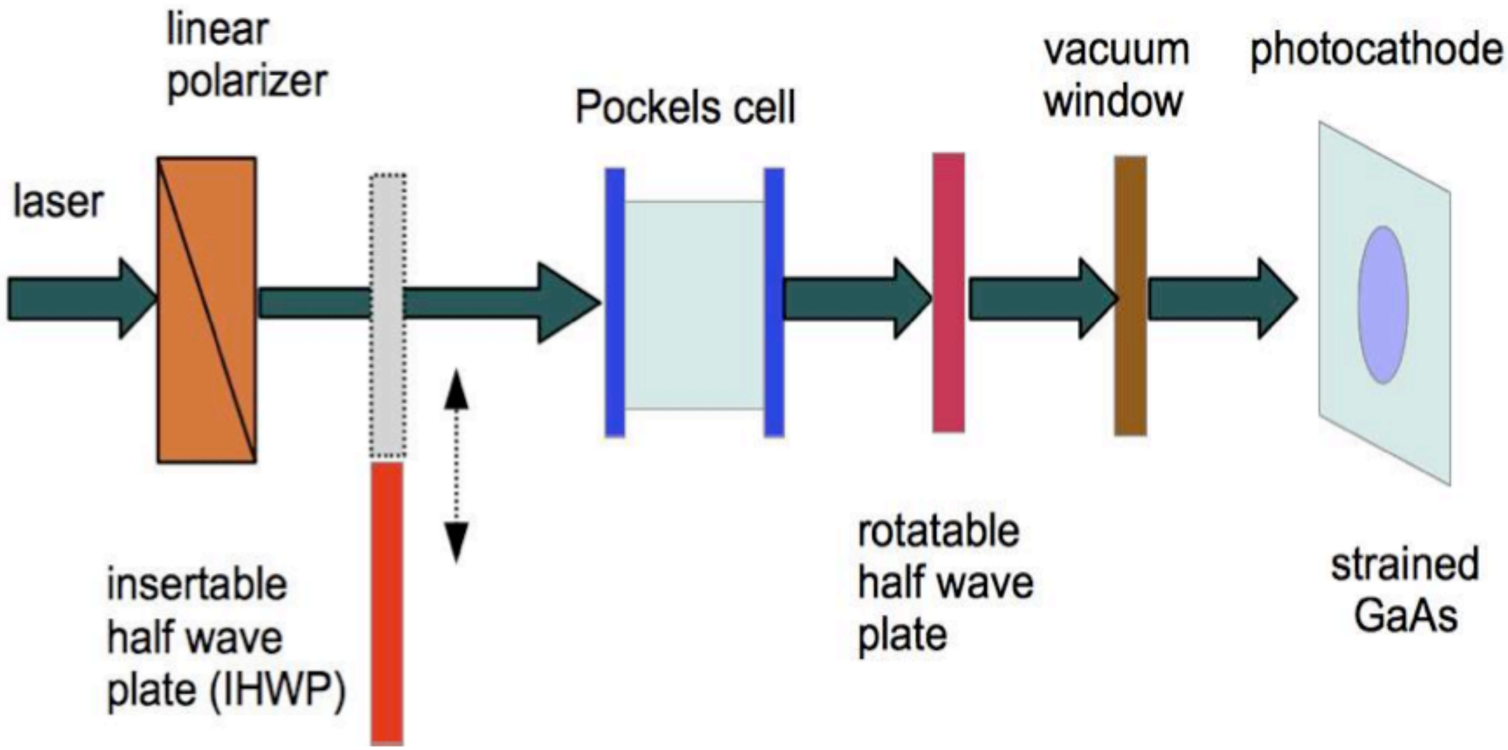
Polarized electron beam (P_L, P_T), up to 180 μA

Elastic electrons detected by 8 fused silica Cerenkov detectors positioned around the focal plane

Skeleton View of Qweak Apparatus

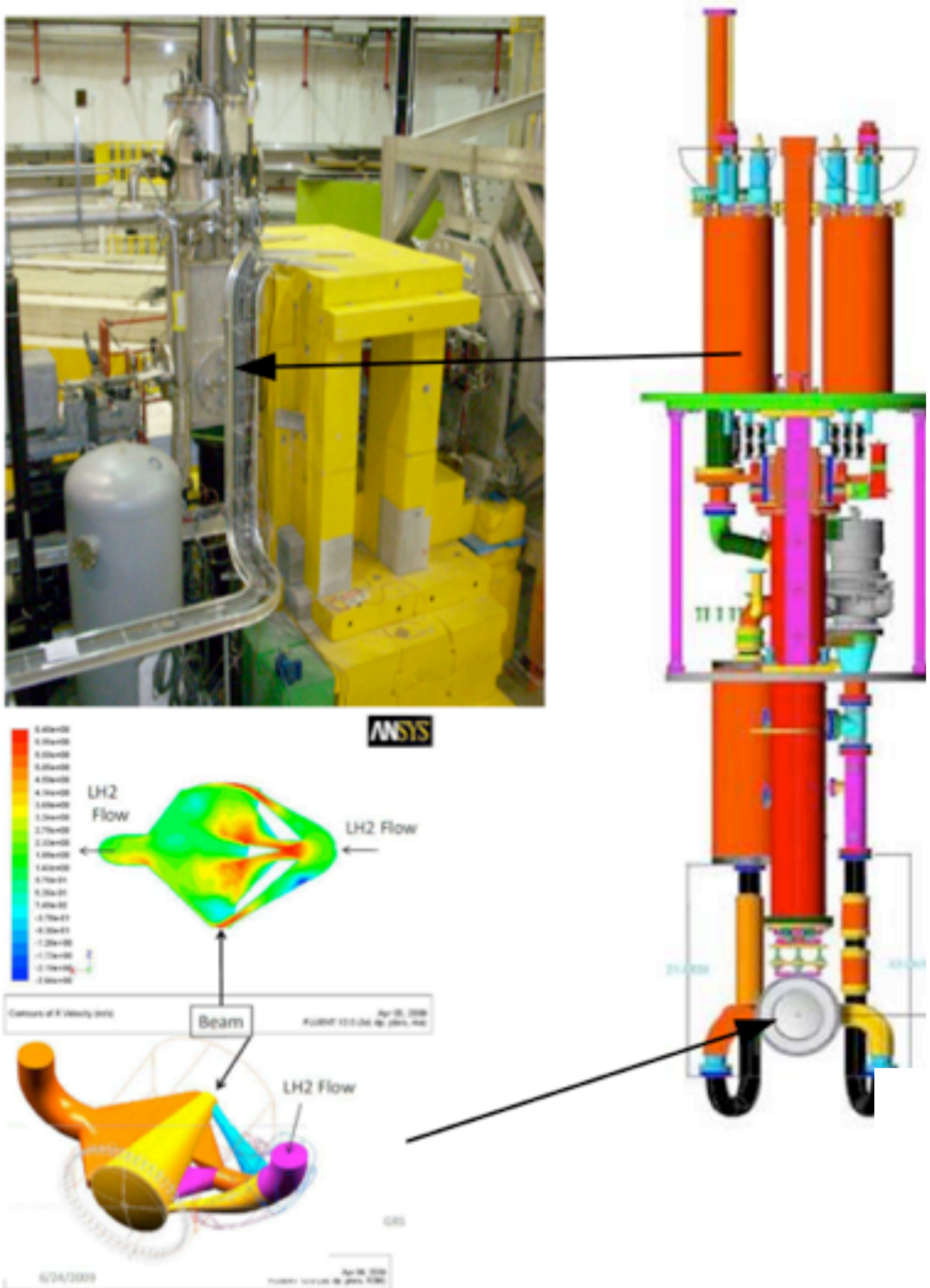


Polarized Source



- **Pockels cell** for fast helicity reversal
- **Helicity reversal frequency**: 960 Hz (to "freeze" bubble motion in the target)
- **Helicity pattern**: pseudo-random "quartets" (+--+ or -++-, asymmetry calculated for each quartet)
- **Insertable Half-Wave Plate**: for "slow reversal" of helicity to check systematic effects and cancel certain false asymmetries. Less frequently, by Wien filter.

Liquid Hydrogen Target

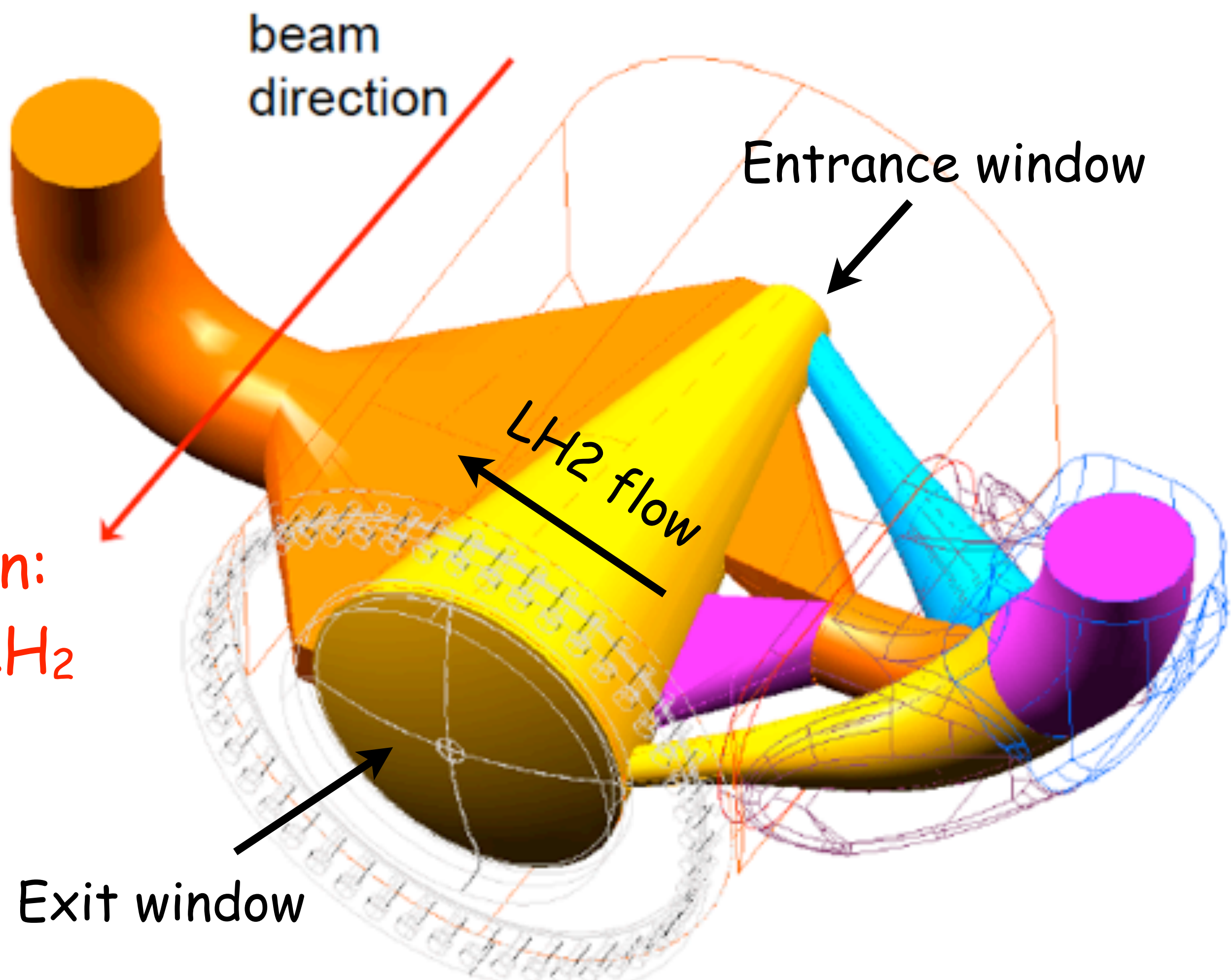


- The world's highest power LH2 target (~2.5 kW cooling power)
- Computational fluid dynamics used in design
- 35 cm long
- LH2 transverse flow at 2.8 m/s
- Density fluctuations < 5×10^{-5} at 15 Hz, run at 960 Hz to reduce further
- High power heater responds rapidly to changing beam power (H_2 liquid only 14-20 K !) to prevent freezing or boil-off

Qweak LH2 target

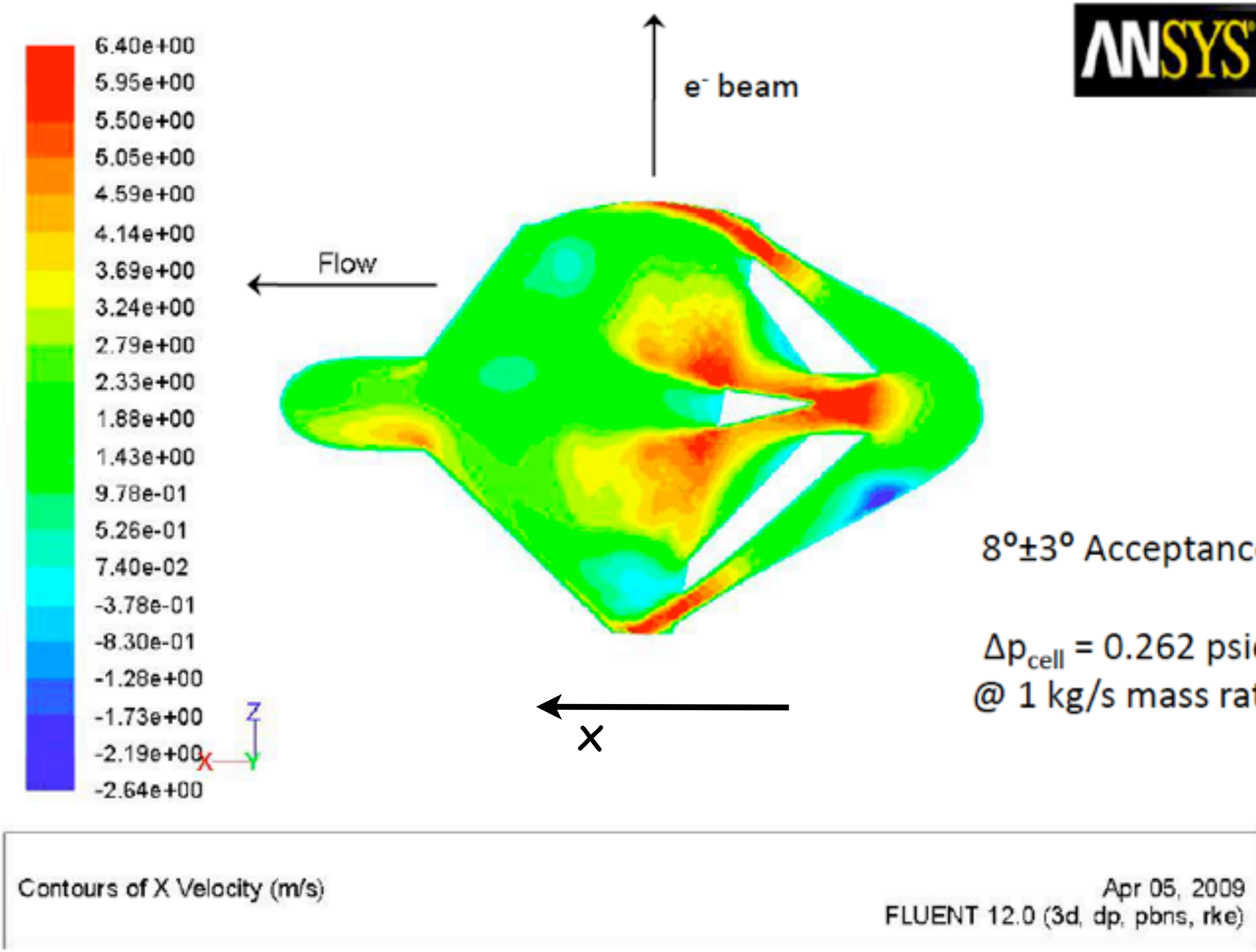
Design principle: minimize density induced noise

Entrance and exit windows: Al, 0.127 mm thick in beam



Initial concern: formation of LH_2 bubbles on windows

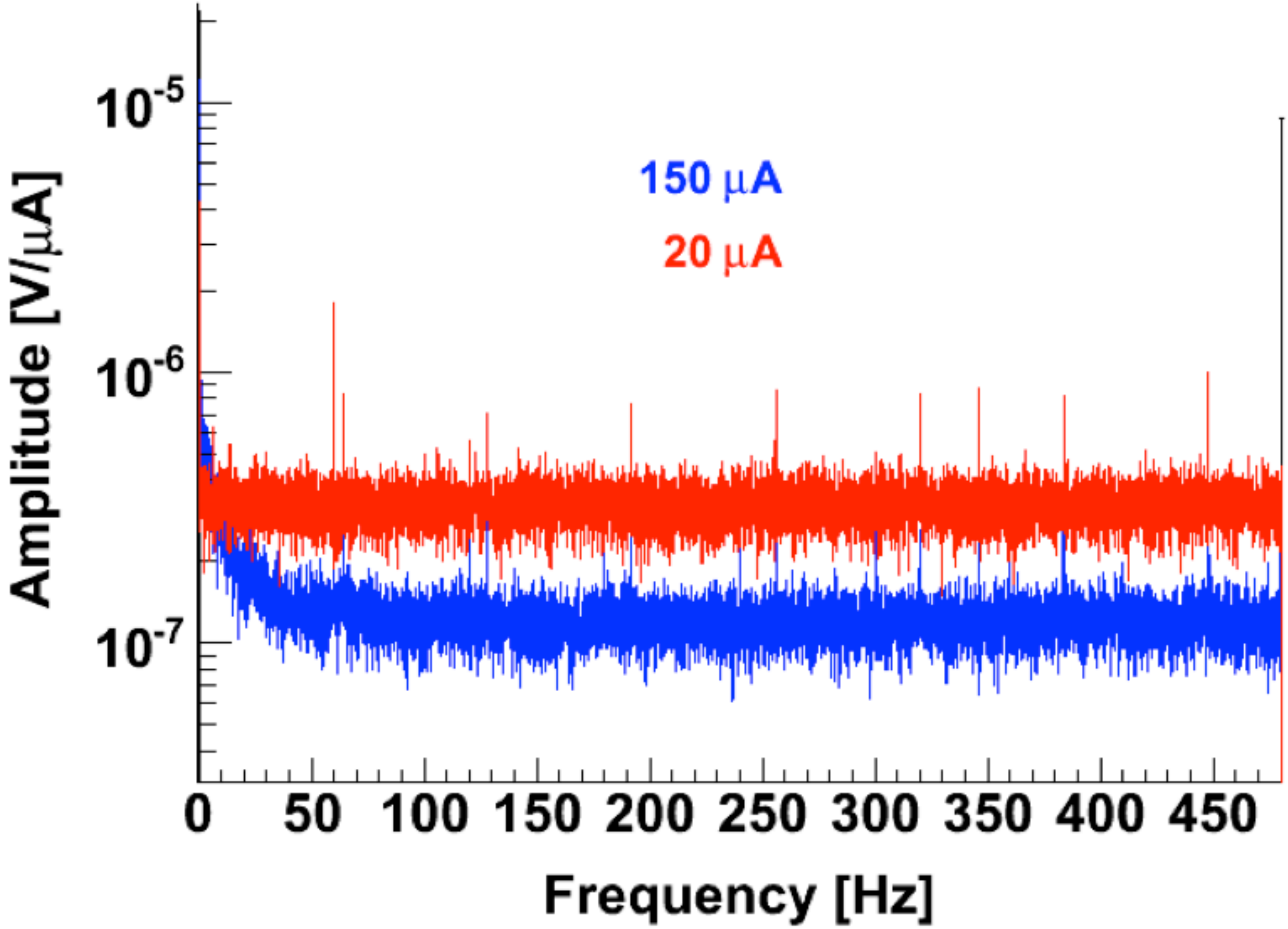
Computational Fluid Dynamics: liquid flow in LH2 target
Contours of constant v_x



8°±3° Acceptance

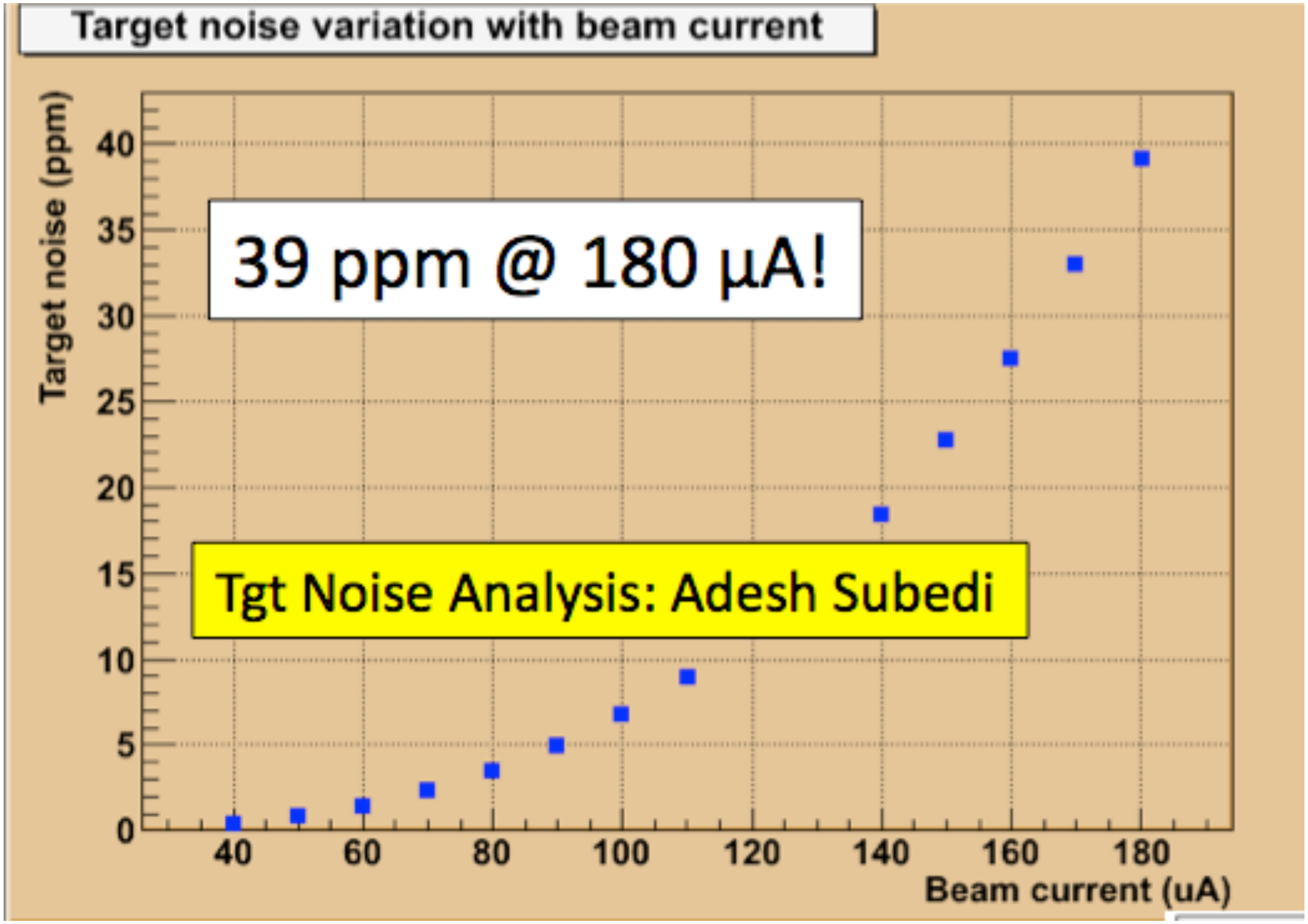
Δp_{cell} = 0.262 psid
@ 1 kg/s mass rate

Noise seen on detector signal



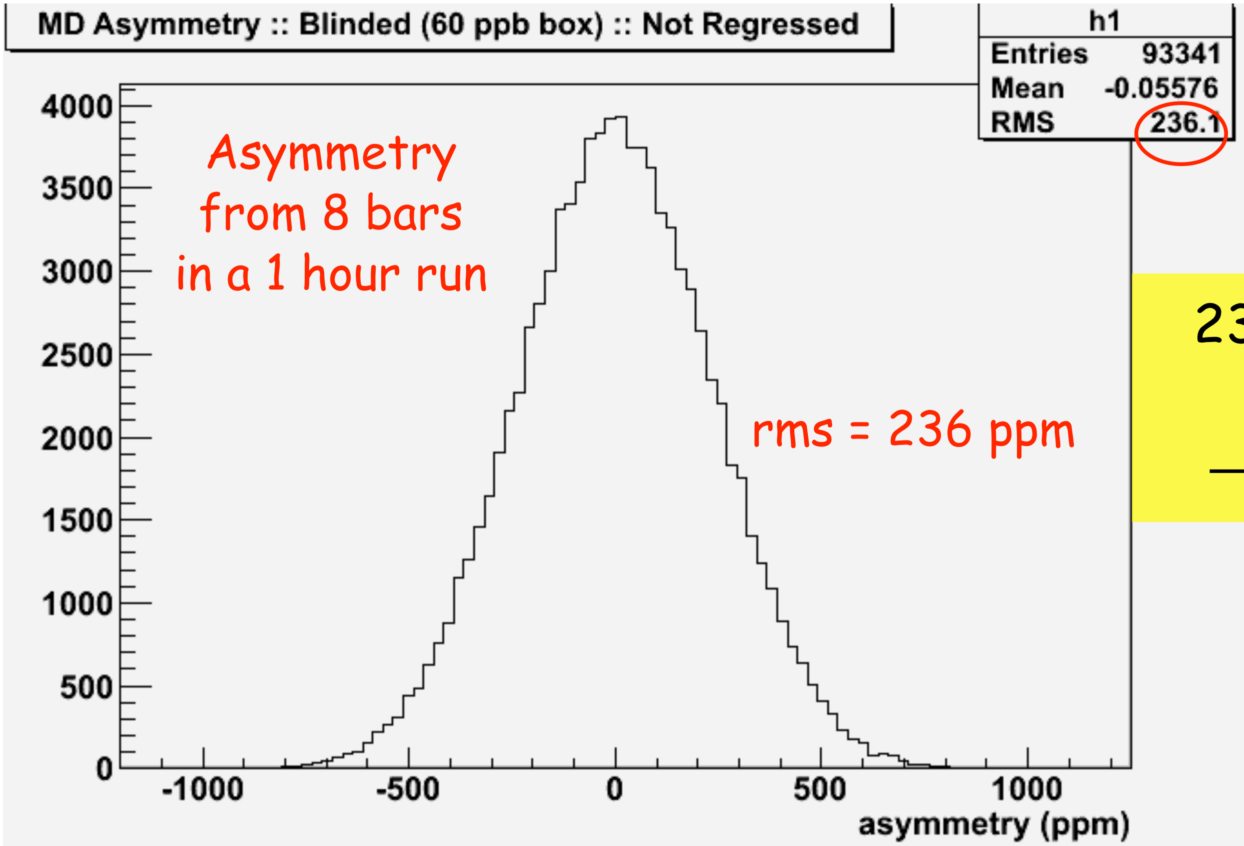
Target density fluctuations apparent at low frequency and high beam current → use 960 Hz spin flip rate (240 Hz rate for quartets)

Noise on detector asymmetry due to target boiling at 960 Hz spin flip rate



Increase in running time due to target noise ~3 %
Goal was < 5 %

Qweak Data Quality



236 ppm in a ~4 ms spin quartet @ 165 μA
→ 1 ppm in ~4 minutes

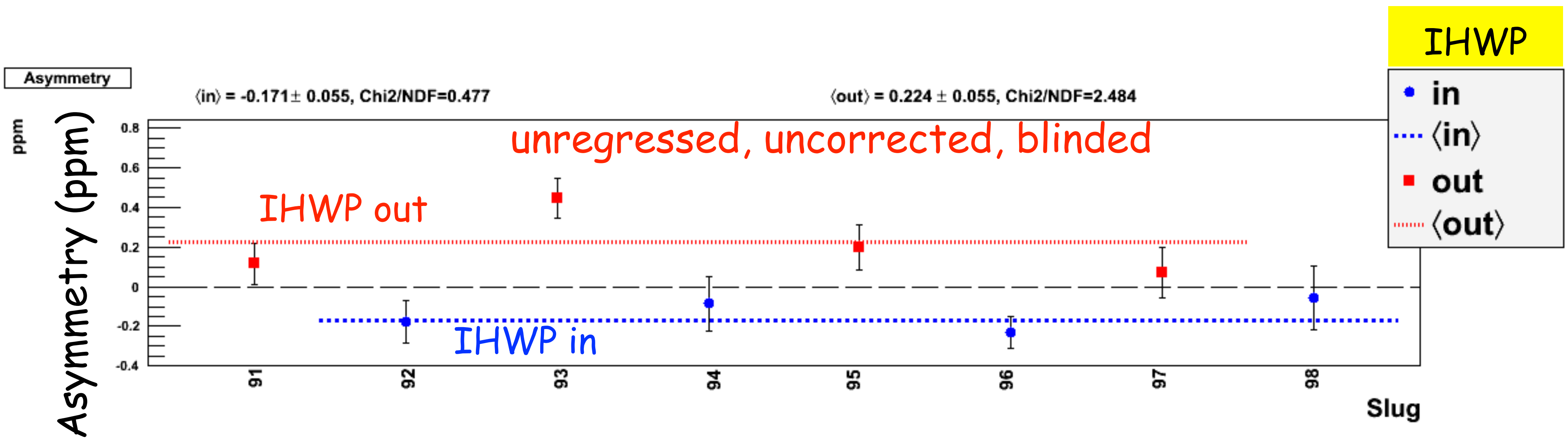
At 165 μA, total detected rate is 5.83 GHz (integrating mode)

- Pure counting statistics: 215 ppm @ 93% helicity reversal live time
- With detector shower fluctuations: 232 ppm
- With current normalization and target boiling: 235 ppm
- Very close to counting statistics!

Qweak Data Quality

"Slow reversal": the Insertable Half Wave Plate (IHWP) optically flips the spin polarity before every 8 hour "slug".

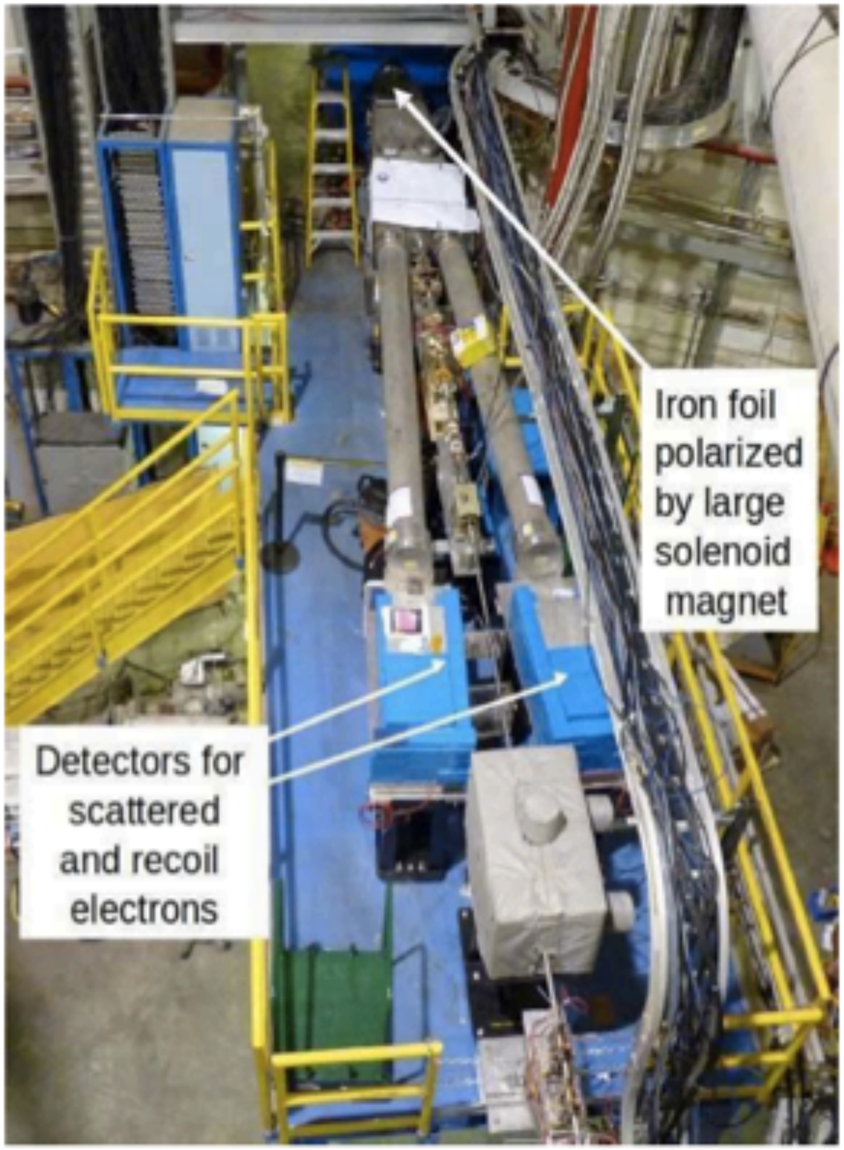
The signal must reverse sign...



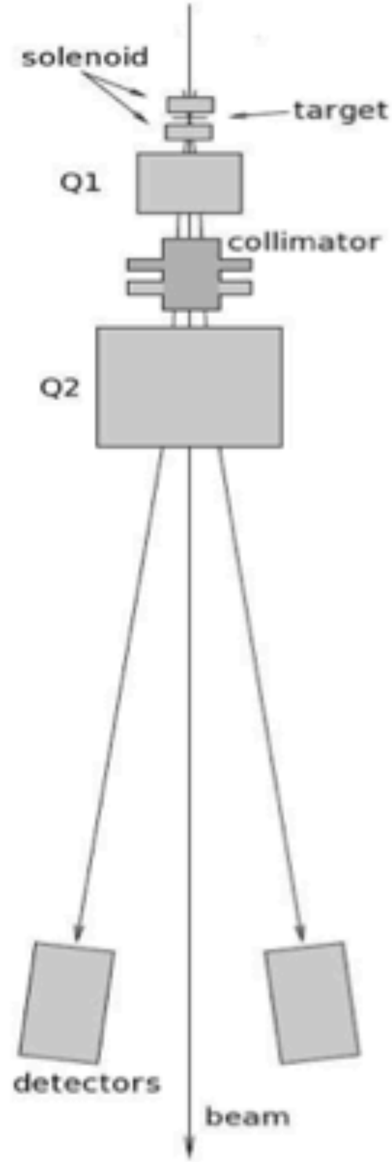
Looks good!

This is a selection out of a few hundred slugs

Hall C Moller Polarimeter

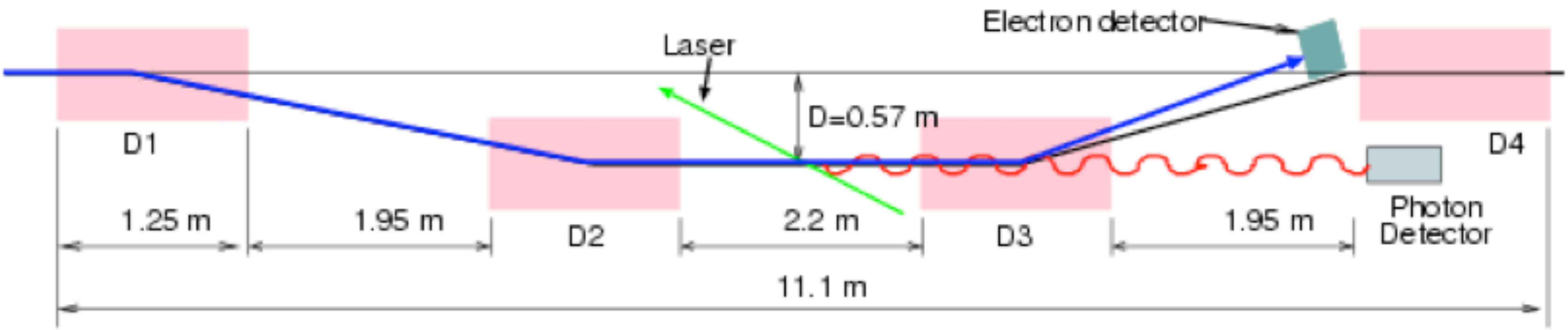


Top View – Moller Polarimeter



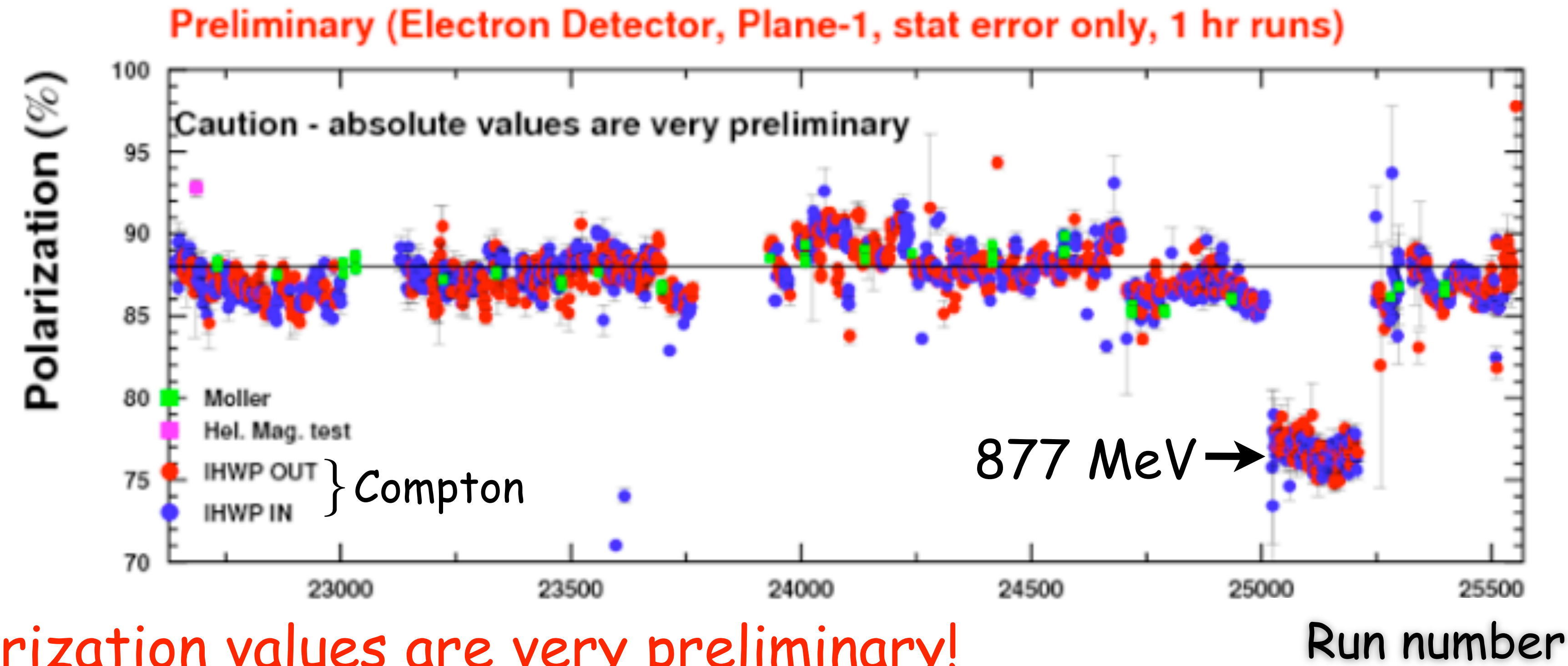
- Hall C Moller polarimeter has been refurbished
- Electrons are scattered from a magnetized Fe foil
- Beam polarization determined from scattering asymmetry
- One measurement every 3 - 4 days at ~2 μA

New Hall C Compton Polarimeter



- Operation: continuous at full beam current for Qweak (180 μA)
- Beam: directed along a chicane 57 cm below the undeflected line
- Laser system:
    - 532 nm green laser
    - 10 W CW laser with low gain cavity
- Photon detection: $PbWO_4$ scintillator in integrating mode
- Electron detection: Rad-hard diamond strips with 20 μm pitch
- Early results available for electron detector

Qweak: Polarimetry to 1%



Polarization values are very preliminary!

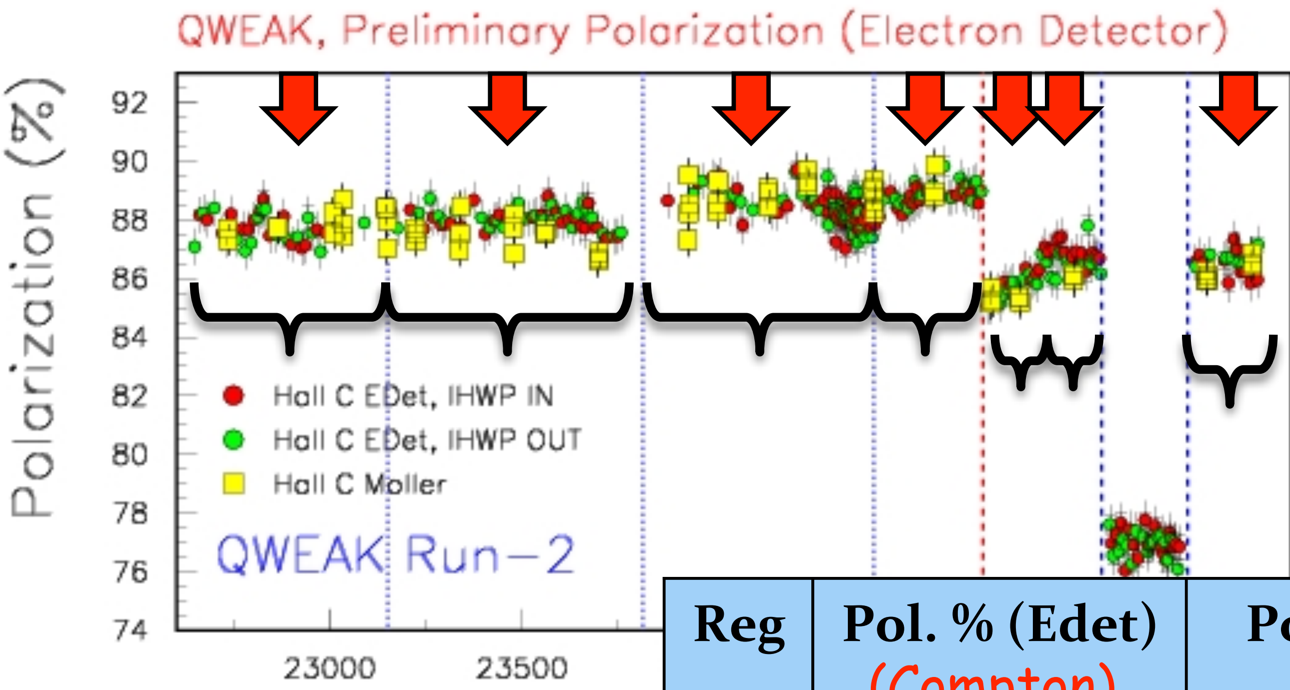
Møller polarimetry

- New beamline, refurbished
- Invasive measurements
- Polarization larger than anticipated: 86% to 88%

Compton polarimetry

- Excellent performance
- Continuous measurements
- Operates at full 180 μA
- Great statistical precision

Comparison of Moller and Compton Polarimeters



Data (Run 2) have been divided into 7 regions (between spot changes, re-activation, beam energy changes) in order to compare with results from the Moller experiment.

(Preliminary)

Reg.	Pol. % (Edet) (Compton)	Pol. % (Moller)	Diff (%)
1	87.658 +/- 0.060	87.799 +/- 0.181	– 0.141
2	88.011 +/- 0.047	87.510 +/- 0.124	0.501
3	88.380 +/- 0.041	88.780 +/- 0.129	–0.400
4	88.783 +/- 0.053	89.174 +/- 0.321	– 0.391
5	85.518 +/- 0.091	85.320 +/- 0.230	0.198
6	86.559 +/- 0.056	86.040 +/- 0.329	0.519
7	86.506 +/- 0.075	86.218 +/- 0.191	0.288

4

Only stat. errors and preliminary "p2p" syst. errors from Edet and Moller are used in the fits.

(V. Tvaskis)

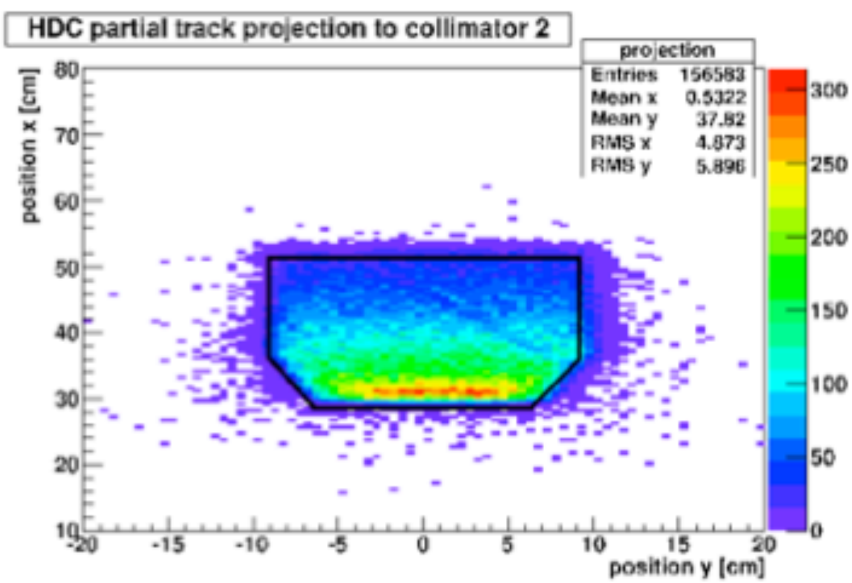
Tracking Mode: to determine Q^2 to 0.5%

Region 2

Horizontal drift chambers

- 32 wires in 0.5 m wide planes
- 12 planes per octant
- 2 instrumented octants
- Constructed at Va Tech

Projected to collimator 2

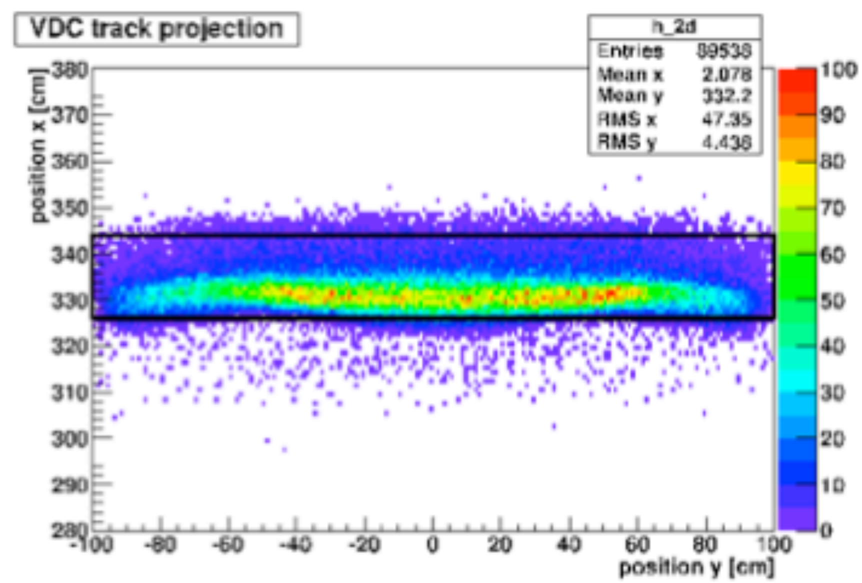


Region 3

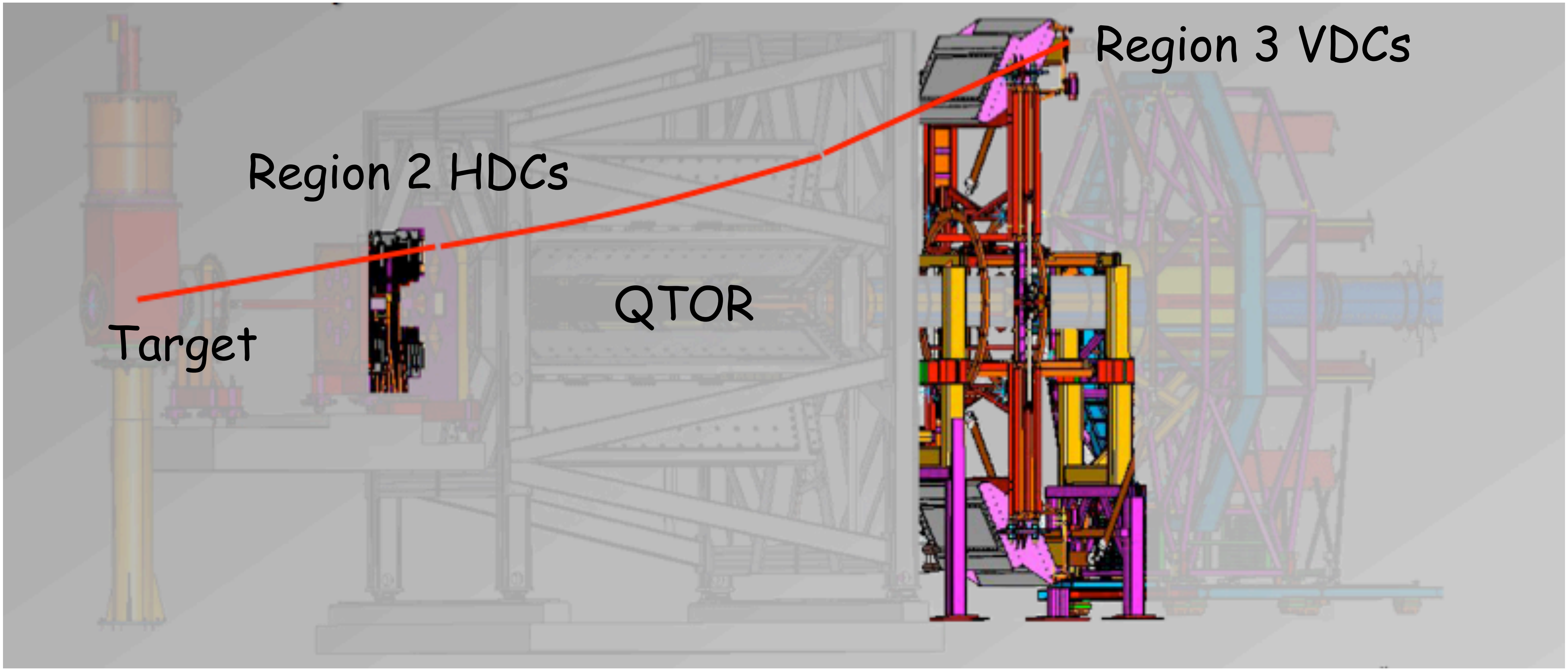
Vertical drift chambers

- 181 wires in 2 m long planes
- 4 planes per octant (65° tilt)
- 2 instrumented octants
- Constructed at W&M

Projected to Cerenkov bar



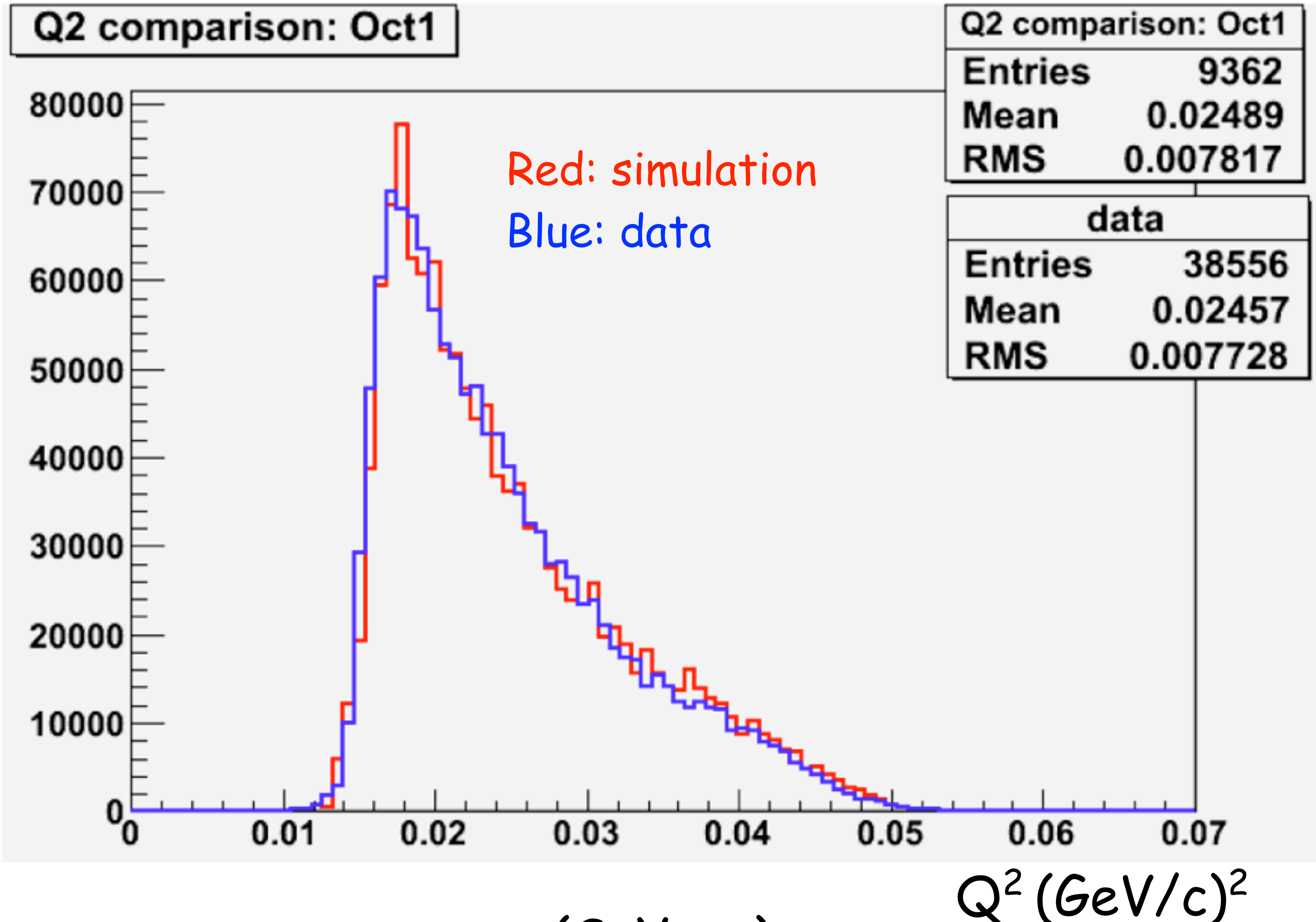
Q^2 measurement



Need momentum and scattering angle + energy loss to vertex:

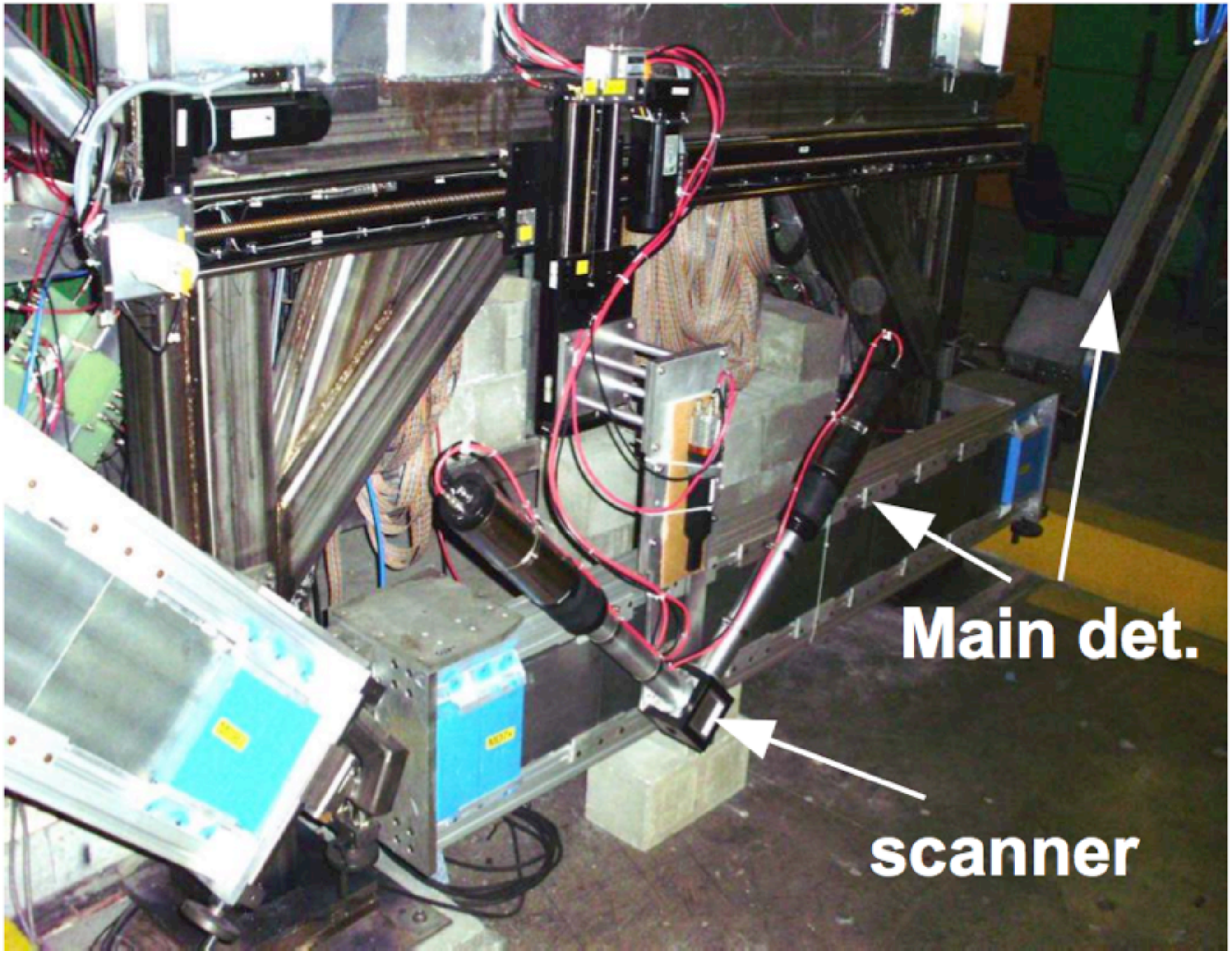
- Region 2 HDCs → scattering angle and vertex in target
- Region 3 VDCs → partial track from QTOR exit to detector
- Find momentum by "swimming" electrons through the QTOR magnetic field to match partial tracks
- Map out main detector's light response for single track to determine light-weighted $\langle Q^2 \rangle$

Sample tracking result (preliminary)



(S. Yang)

Scanner

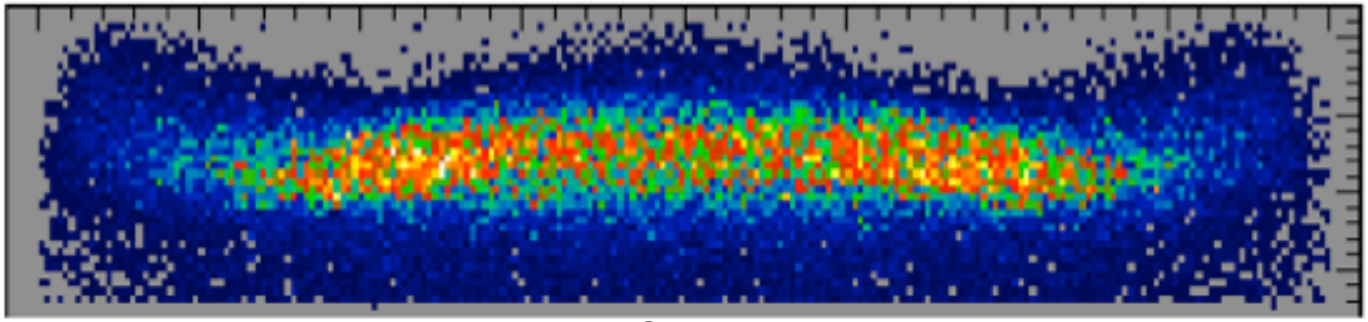


- Verifies event distributions the same at low current (Q^2 measurement) and for high current parity running
- Follows a raster pattern to map out event distribution along a Cerenkov bar

Tracking Mode

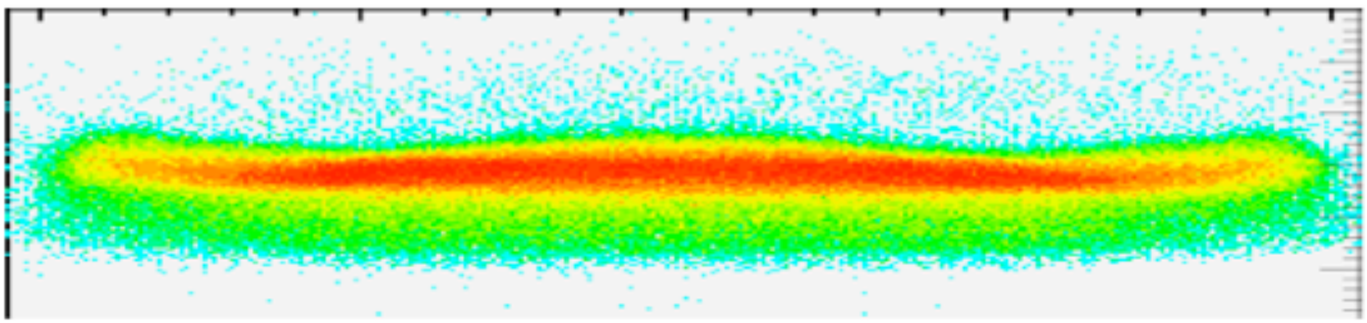
Simulation of electrons hitting main detector bar

18 cm

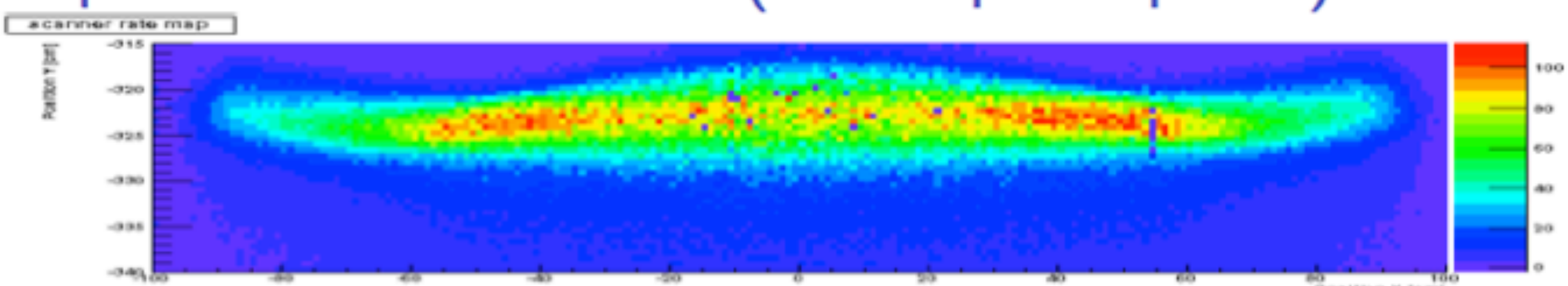


2 m

Projection of reconstructed tracks to detector bar



Focal plane scanner detector (1 cm square quartz)



Backgrounds

Largest component from Al windows of LH2 target:

$$A_{PV} = \frac{-G_F Q^2}{4\pi\alpha\sqrt{2}} \left[Q_W^p + \frac{N}{Z} Q_W^n \right]$$

(Approx. for N ≠ Z: T. Donnelly, Prog. Part. & Nucl. Phys. 24, 179 (1990))

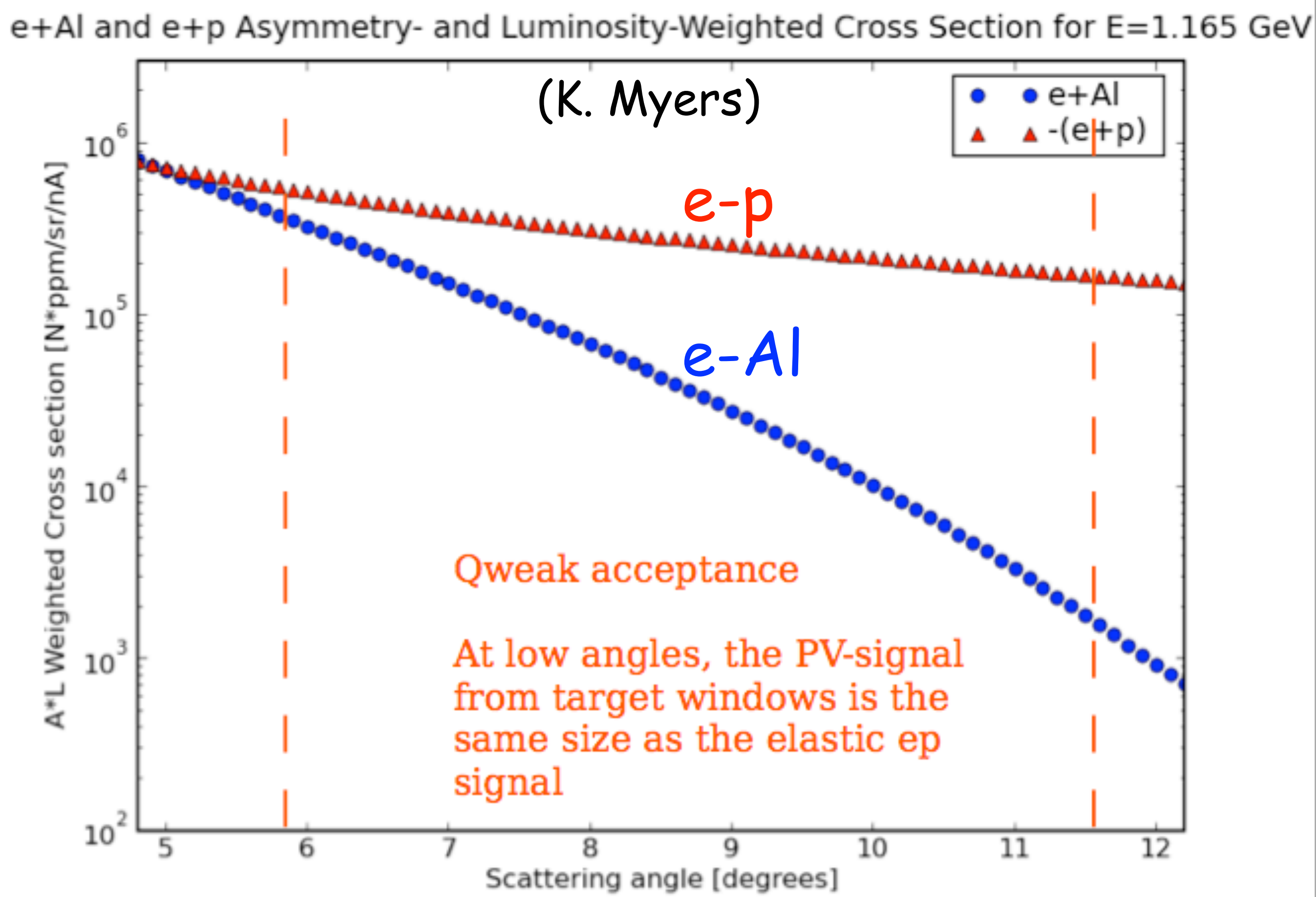
~0.07

Weak charge of neutron = -1

A_{ep} ~ -0.2 ppm

A_{Al} ~ 2 ppm !

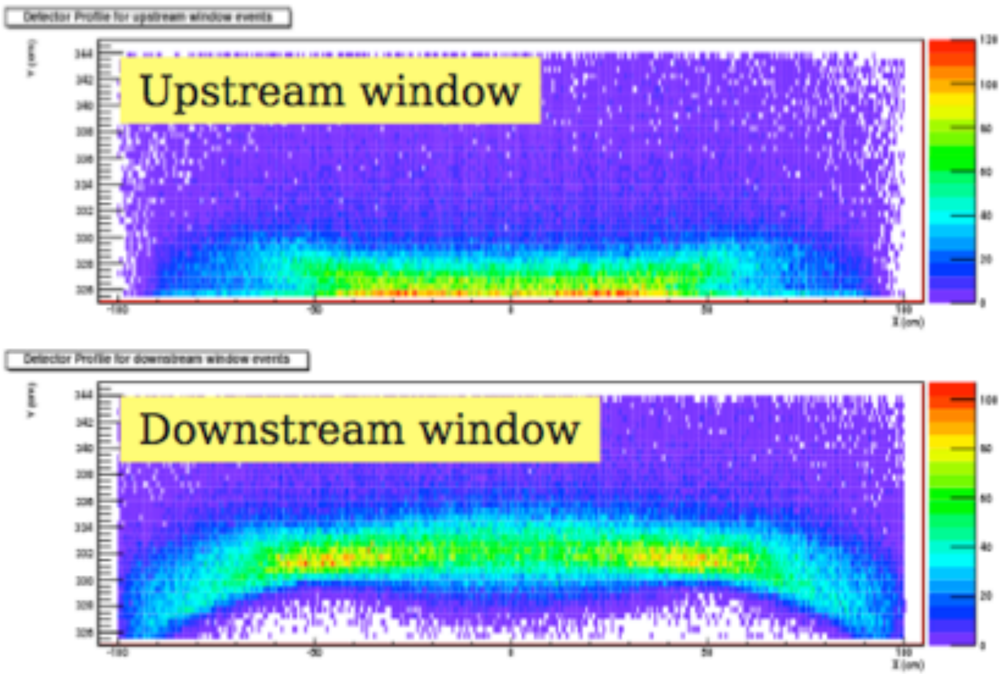
"Dilution": fraction of Cerenkov bar signal due to Al windows, f_{Al} ~3.5%



Aluminum Background

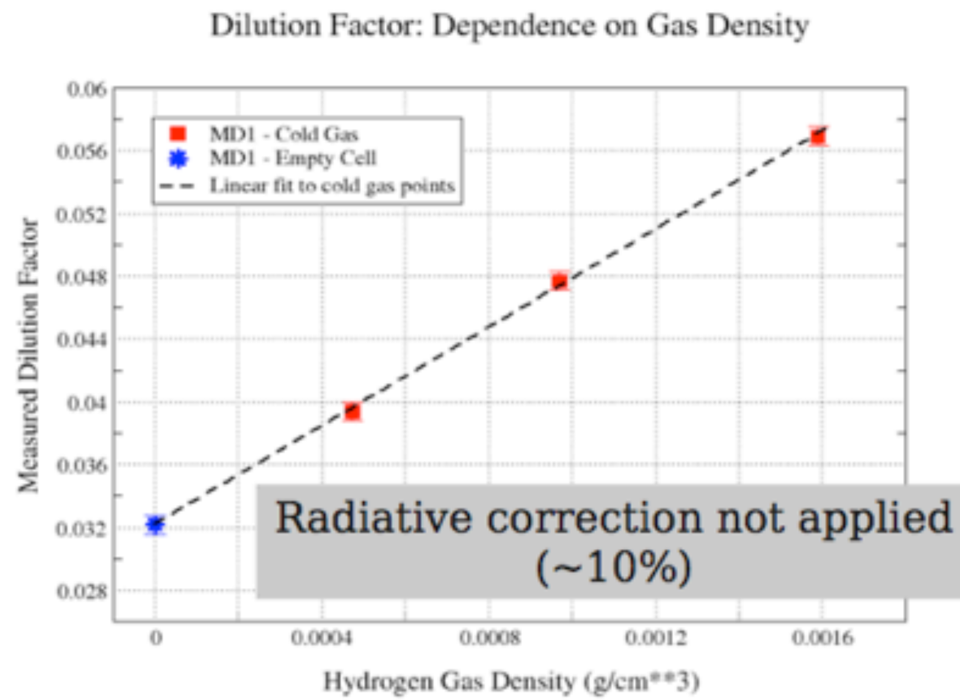
- Dilution Factor:
  - Effect from long target on acceptance:

Simulated elastic e- profile at detector:



Simulation predicts dilution of ~3.5%

- Measurement:
  - Evacuated target or low pressure (cold) gas



Recall:

$$\left(\frac{dA_{ep}}{A_{ep}}\right)_f \simeq df\,\frac{A_{bkgd}}{A_{ep}}$$

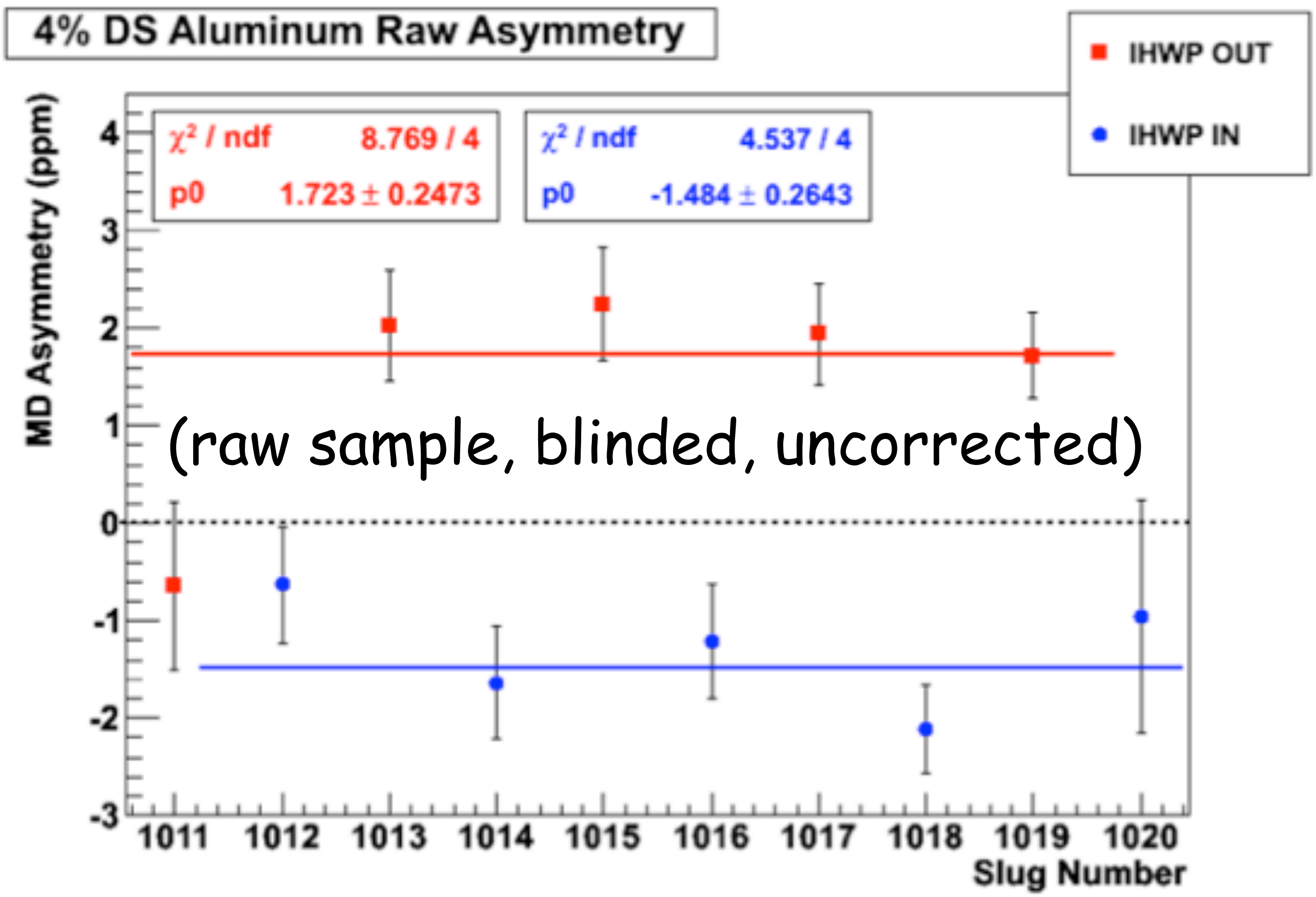
→ Measure f_{Al} to ~1%!!

(K. Myers)

Inelastics: f_{Al} ~ 0.02% - not as critical

Aluminum Background

- Measure asymmetry on thick dummy target



(Simulation: elastic A_{Al} ~ 2 ppm)

(K. Myers)

Raw asymmetry from a subset of data

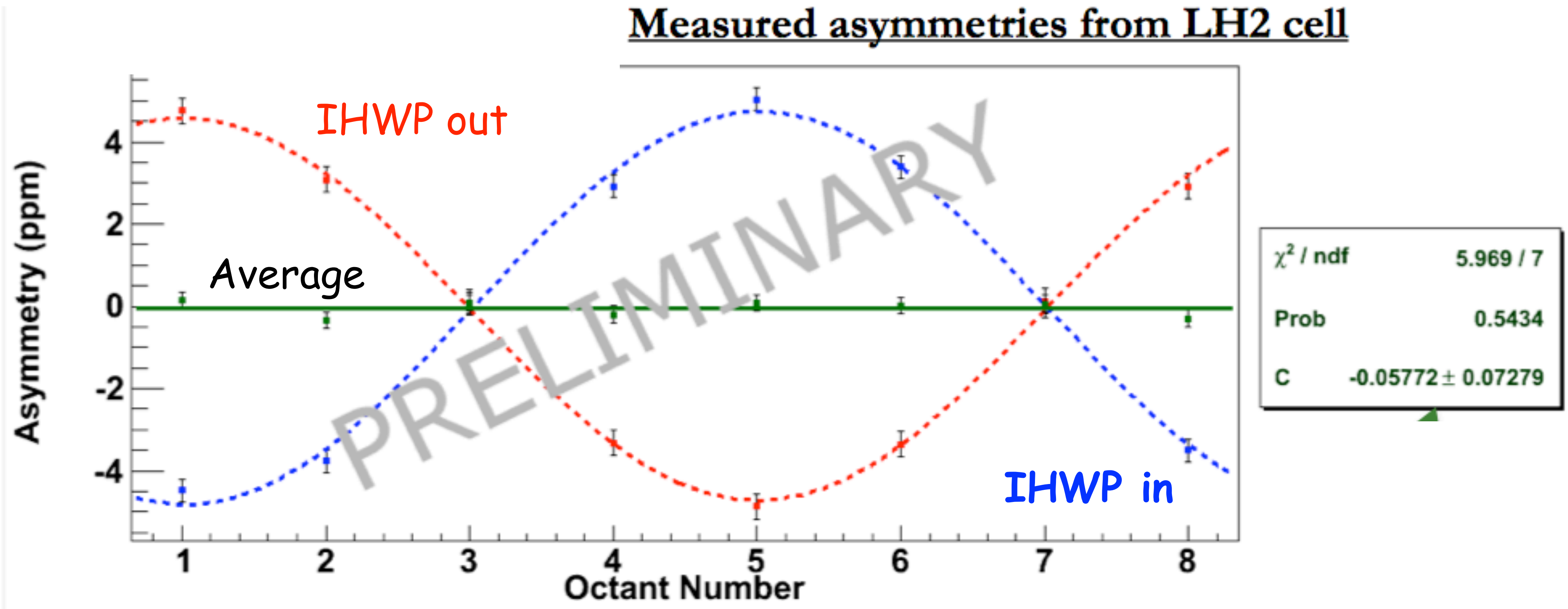
Measured on target 30x's thicker than windows

Target made of same Al alloy as windows

(Not corrected for: false asymmetry or beam polarization)

Ran ~10% of our time on Aluminum dummy target!

Detector Asymmetries with Transverse Polarized Beam



- Relative Uncertainties

$B_n = A_T$ = analyzing power for transverse polarized beam

Error source	Preliminary (dB/B)	Anticipated(dB/B)
Polarization	2.2 %	~1.0%
Statistics	1.3%	~1.3%
Q^2 acceptance	1.2%	~0.5%
Non-linearity	1.0%	~0.2%
Regression	0.9%	~0.9%
Backgrounds	0.3%	~0.3%

Impact of B_n (i.e., A_T) on Qweak

- **B_n leakage due to symmetry breaking:** (due to imperfect symmetry of the parity detectors)
  - 100% transverse polarization → leakage $\leq$ 64 ppb
  - Typical residual transverse polarization in the beam is 2-3%
    - leakage into PV asymmetry $\leq$ 2 ppb. Acceptable!

- **To keep the B_n leakage small, Qweak used the measured B_n asymmetry and the main detectors to monitor the amount of residual transverse polarization in the beam.**
  - Residual transverse polarization is known to a ± 3% at the injector.
  - Using main detectors, can control that to a level of better than ± 1% (transverse graduate-student feedback).

Preliminary result: A_T = -5.27 ± 0.07 (stat) ± 0.14 (syst) ppm

Relative Precisions of other Qweak B_n measurements.

- Analysis not complete.
- However, the relative precision of the measurements looks good.
- Good candidates to test model predictions!

Target	Relative Precisions
Inelastic Measurements with delta final state	
LH2 cell	~ 3%
Aluminum	~ 5%
Carbon	~ 3%
Elastic Measurements	
Aluminum	~4%
Carbon	~7%

Summary

- The experimental phase of Qweak has ended
- Key components worked very well
- Beam quality mostly very high
- Main detector asymmetry width close to counting statistics and excess understood
- Many systematics measurements taken
- Ancillary measurements at 0.877 and 3.3 GeV (Al, C)

- First preliminary result: transverse asymmetry on hydrogen -
  A_T = -5.27 ± 0.07 (stat) ± 0.14 (syst) ppm

- Release of further results in the next couple of years
  - Inelastic $N \rightarrow \Delta$
  - Aluminum asymmetry
  - Weak charge Q_W: 25% this year, followed by 8%, 4%...

Extra Slides

The Qweak Collaboration

The Qweak Collaboration

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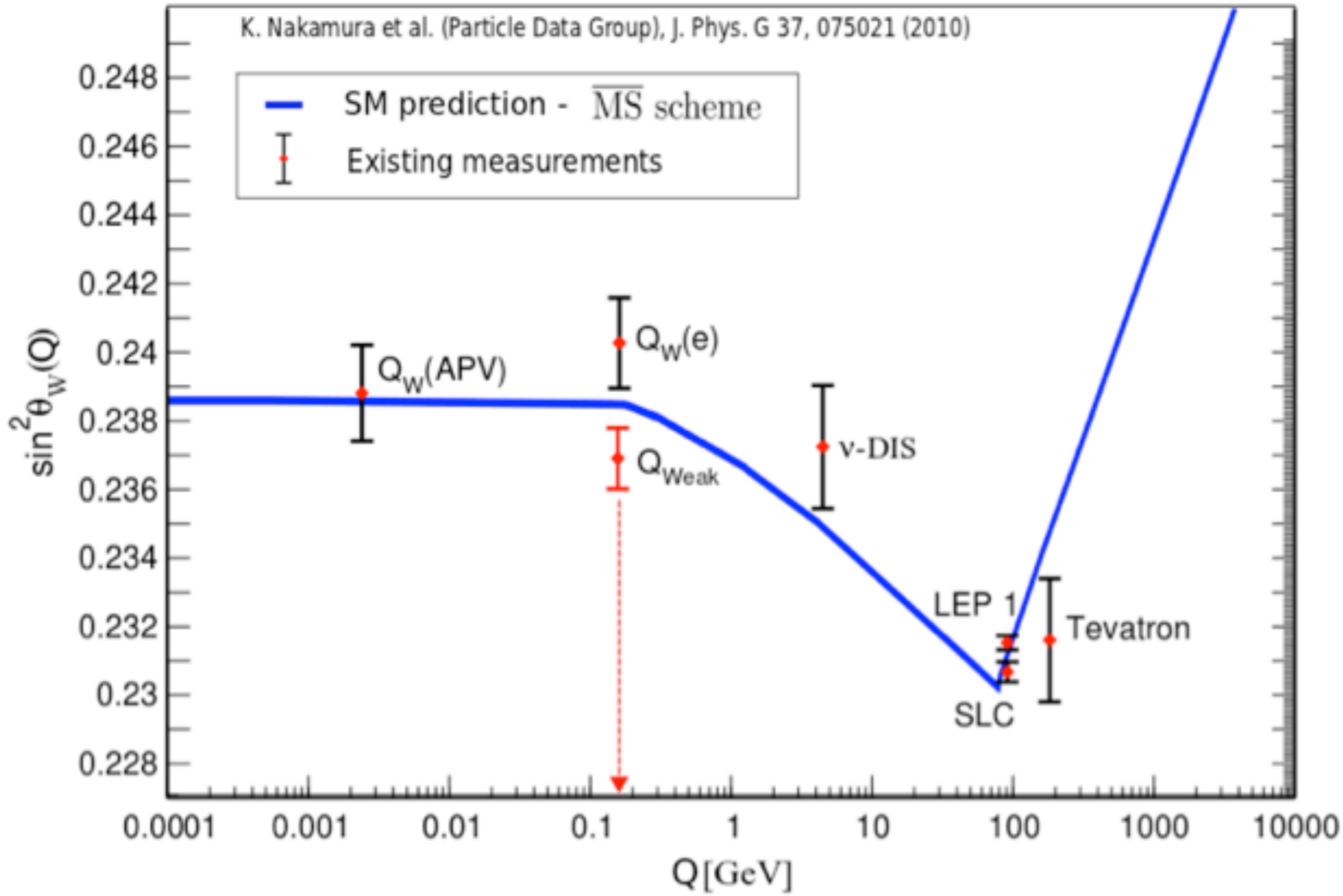
Running of $\sin^2\theta_W$

scale dependence of weak mixing angle in $\overline{\text{MS}}$ scheme

Qweak decreasing

$$\sin^2\theta_W = \frac{1}{4}\left(1 - Q_W^p\right)$$

Qweak increasing



far close

Figure from: K. Nakamura et al. (Particle Data Group), J. Phys. G 37, 075021 (2010) and 2011 partial update for the 2012 edition.

Sensitivity to New Physics

Lower bound on new physics (95% CL)

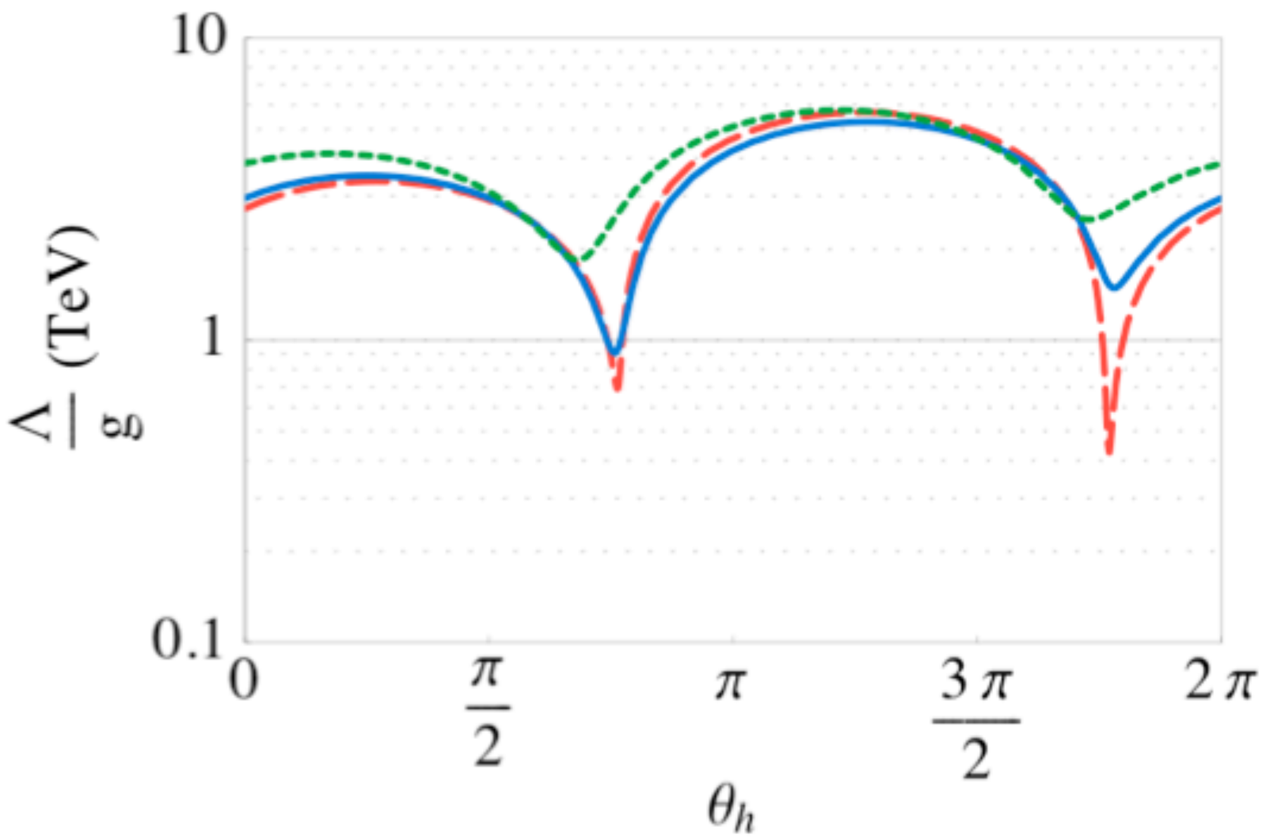


Figure: Young, Carlini, Thomas, Roche (2007)

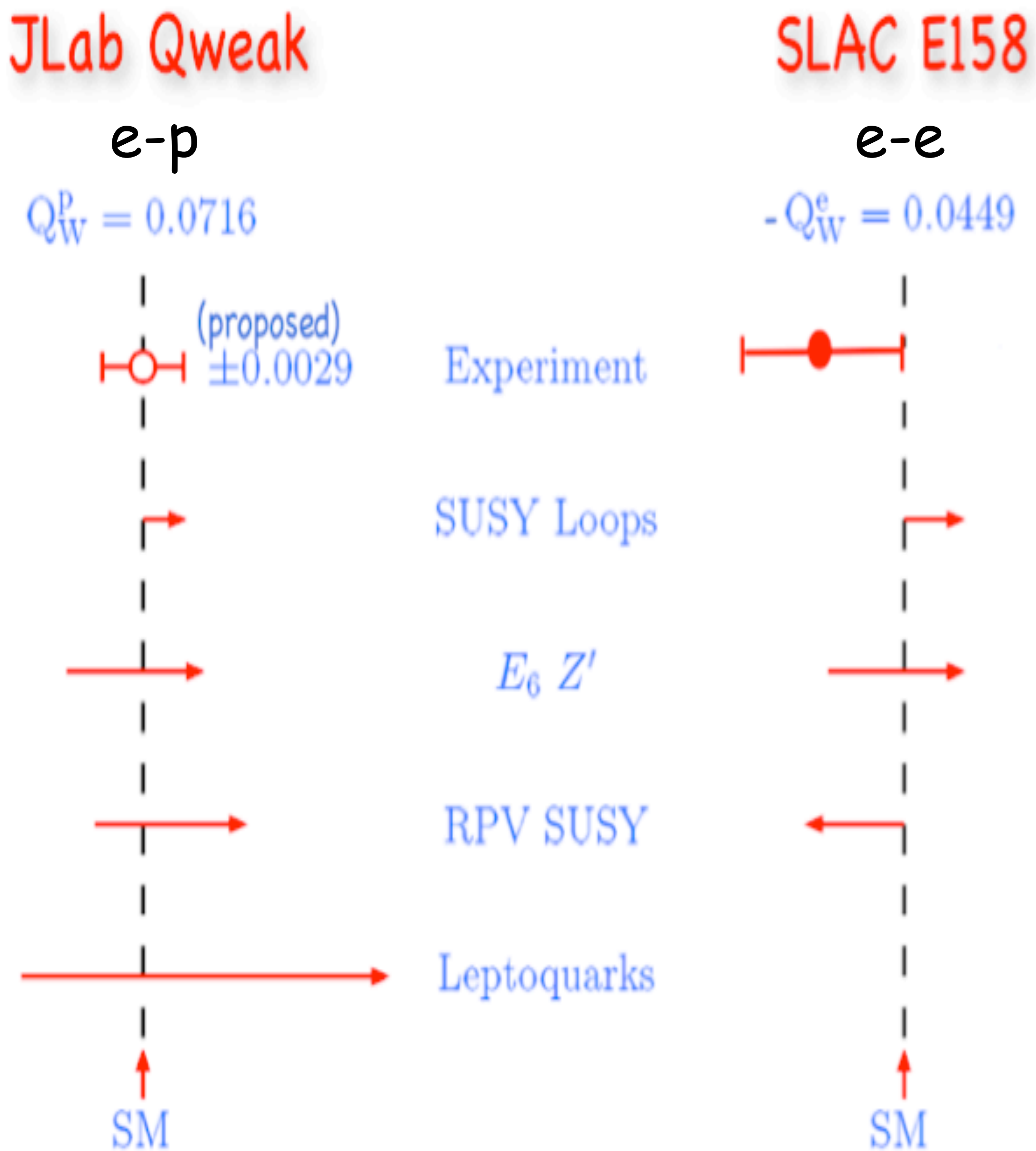
Constraints from

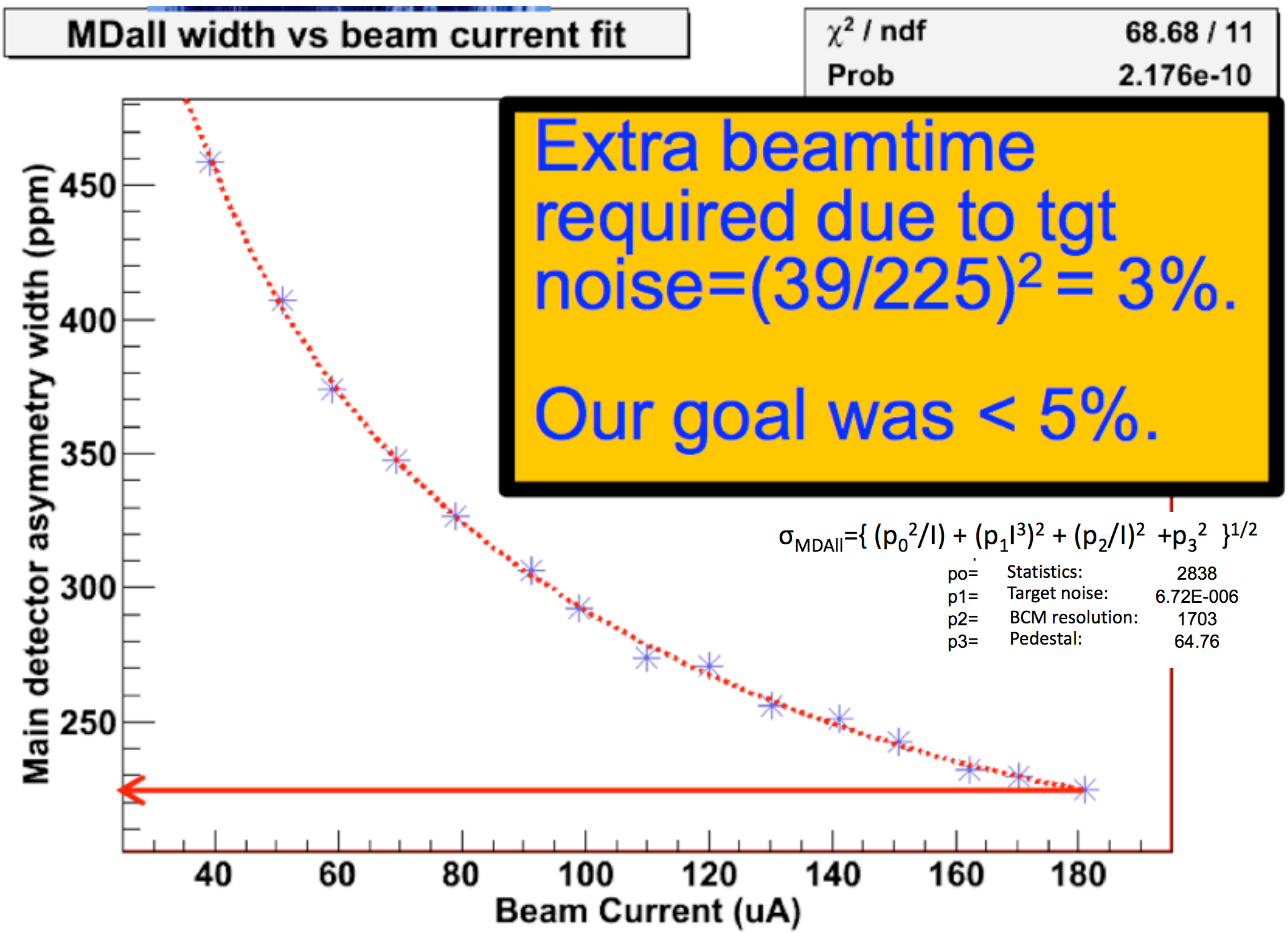
- Atomic PV: $\frac{\Lambda}{g} > 0.4$ *TeV*
- PV electron scattering: $\frac{\Lambda}{g} > 0.9$ *TeV*

Projection Q_{Weak}

- $\frac{\Lambda}{g} > 2$ *TeV*
- 4% precision

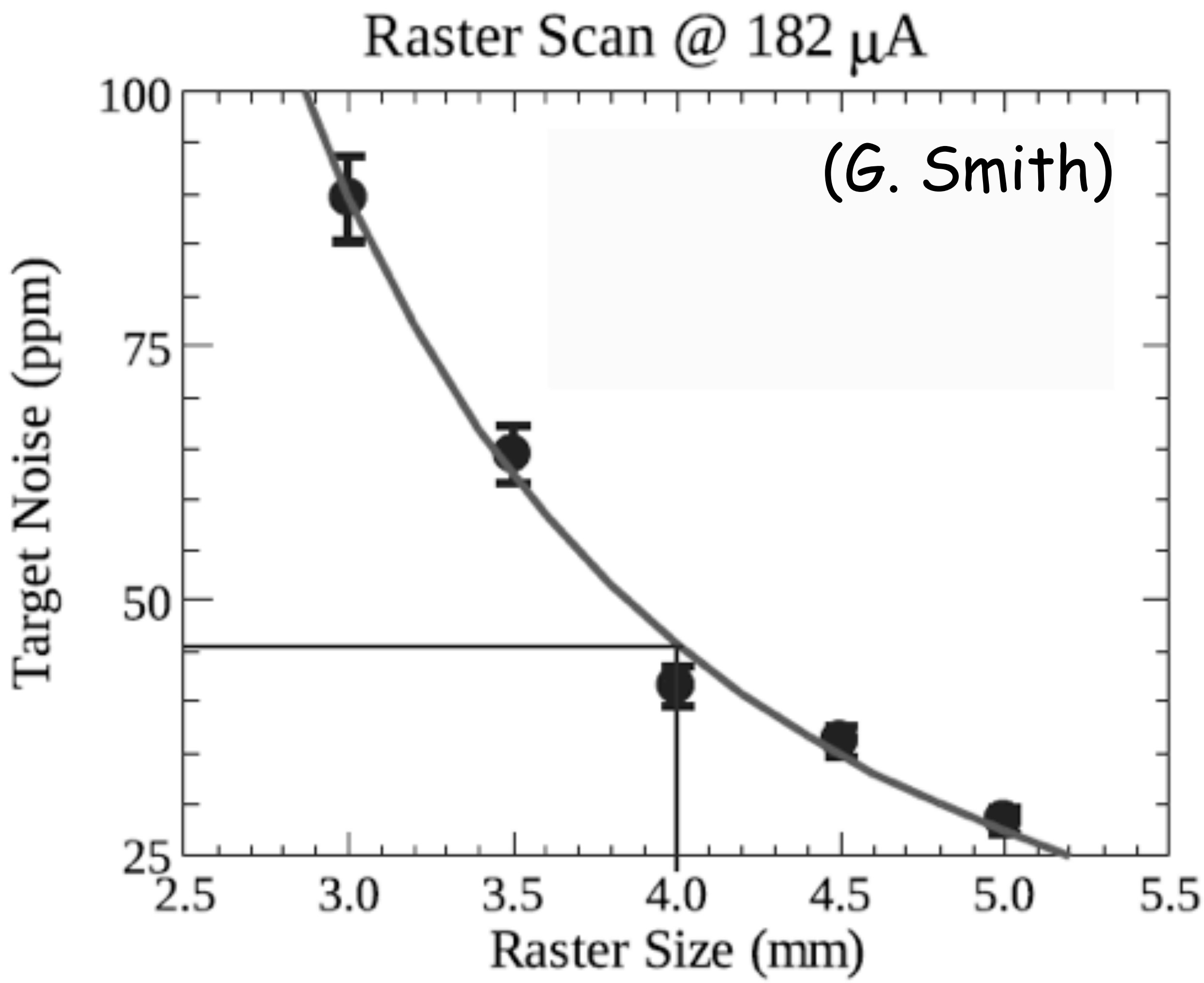
Possible deviations from the Standard Model allowed by fits to existing data





MDall width vs beam current fit
χ^2 / ndf 68.68 / 11
Prob 2.176e-10
Extra beamtime required due to tgt noise=$(39/225)^2$ = 3%.
Our goal was < 5%.
$\sigma_{MDAll}=\{ (p_0^2/I) + (p_1 I^3)^2 + (p_2/I)^2 + p_3^2 \}^{1/2}$
po= Statistics: 2838
p1= Target noise: 6.72E-006
p2= BCM resolution: 1703
p3= Pedestal: 64.76
Main detector asymmetry width (ppm)
450
400
350
300
250
40
60
80
100
120
140
160
180
Beam Current (uA)

Target noise vs raster size



Target noise extracted from main detector asymmetry width.