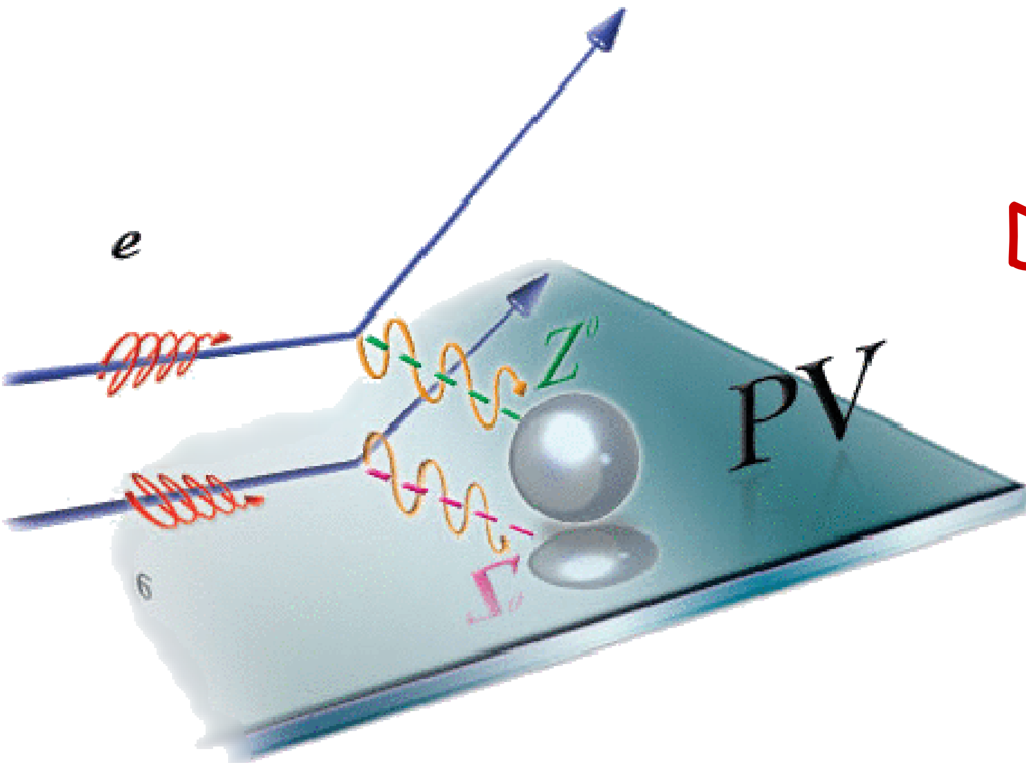
The 12 GeV Parity Violation Program



David S. Armstrong

College of William & Mary

Jlab User Group Meeting June 9 2009

The College of WILLIAM & MARY

Jefferson Lab

Outline

- Precision tests of Standard Model
- Parity-violation in electron scattering

    Early work: SLAC E122 *etc.*
- Weak Charges & Physics Reach
- 6 GeV: Qweak, PVDIS-6
- PVDIS with Base Equipment
- PVDIS with SoLID
- Moller at 11 GeV
- Conclusions

Precision Tests of the Standard Model

- Received Wisdom: *Standard Model is the effective low-energy theory of underlying more fundamental physics*

- Finding new physics: Two complementary approaches:
  - Energy Frontier (direct) : *eg.* Tevatron, LHC
  - Precision Frontier (indirect) : *(aka Intensity Frontier)*

    eg.
    - μ(g-2) , EDM, $\beta\beta$ decay, $\mu \to e\,\gamma$, $\mu A \to eA$, $K^+ \to \pi^+ \nu\nu$, *etc.*
    - *ν - oscillations*
    - *Atomic Parity violation*
    - *Parity-violating electron scattering*

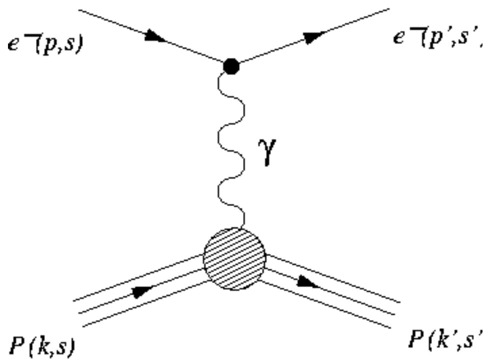
Often at modest or low energy…

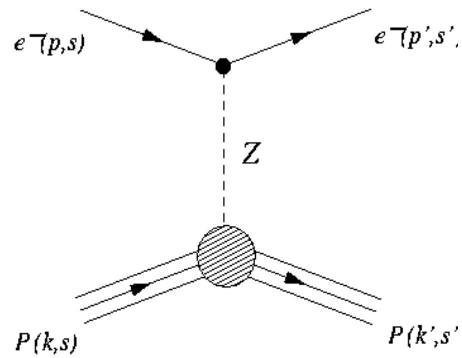
Hallmark of Precision Frontier:

choose observables that are *zero* or *suppressed* in Standard Model

When new physics found in direct measurements, precision measurements useful to determine e.g. couplings…

Parity Violating Electron Scattering:
Weak Neutral Current Amplitudes





$$M^{EM} = \frac{4\pi\alpha}{Q^2} Q_\ell \, \ell^\mu J_\mu^{EM} \qquad M_{PV}^{NC} = \frac{G_F}{2\sqrt{2}} \left[g_A \ell^{\mu 5} J_\mu^{NC} + g_V \ell^\mu J_{\mu 5}^{NC} \right]$$

Interference: $\sigma \sim |M^{EM}|^2 + |M^{NC}|^2 + 2Re(M^{EM*})M^{NC}$

scatter electrons of opposite helicities from unpolarized target

Interference with EM amplitude makes Neutral Current (NC) amplitude accessible ⇨

$$A_{PV} = \frac{\sigma_R - \sigma_L}{\sigma_R + \sigma_L} \sim \frac{|M_{PV}^{NC}|}{|M^{EM}|} \sim \frac{Q^2}{(M_Z)^2}$$

First discussed: Ya. B Zel'dovich JETP **36** (1959)

PARITY NON-CONSERVATION IN INELASTIC ELECTRON SCATTERING☆

C.Y. PRESCOTT, W.B. ATWOOD, R.L.A. COTTRELL, H. DeSTAEBLER, Edward L. GARWIN, A. GONIDEC [1], R.H. MILLER, L.S. ROCHESTER, T. SATO [2], D.J. SHERDEN, C.K. SINCLAIR, S. STEIN and R.E. TAYLOR
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Phys. Lett. 77B (1978)

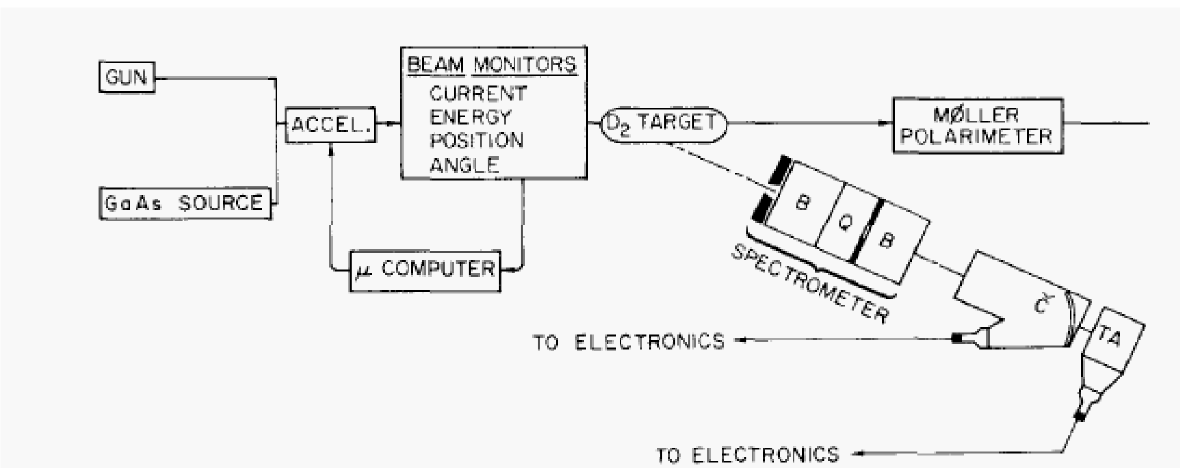
Received 14 July 1978

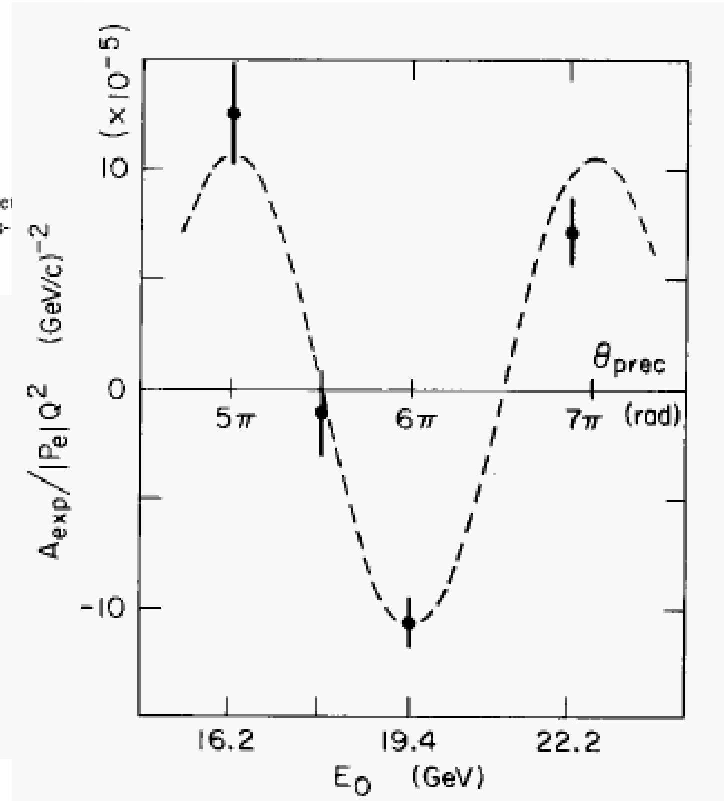
Pioneering Experiment

SLAC E122

We have measured parity violating asymmetries in the inelastic scattering of longitudinally polarized electrons from deuterium and hydrogen. For deuterium near $Q^2 = 1.6$ (GeV/c)^2 the asymmetry is $(-9.5 \times 10^{-5})Q^2$ with statistical and systematic uncertainties each about 10%.

Deep-inelastic scattering from isoscalar target





Textbook Physics: High Energy Physics (D.H. Perkins); Quarks and Leptons (Halzen & Martin)

SLAC E122 *cont'd*

Also critical test of parton model

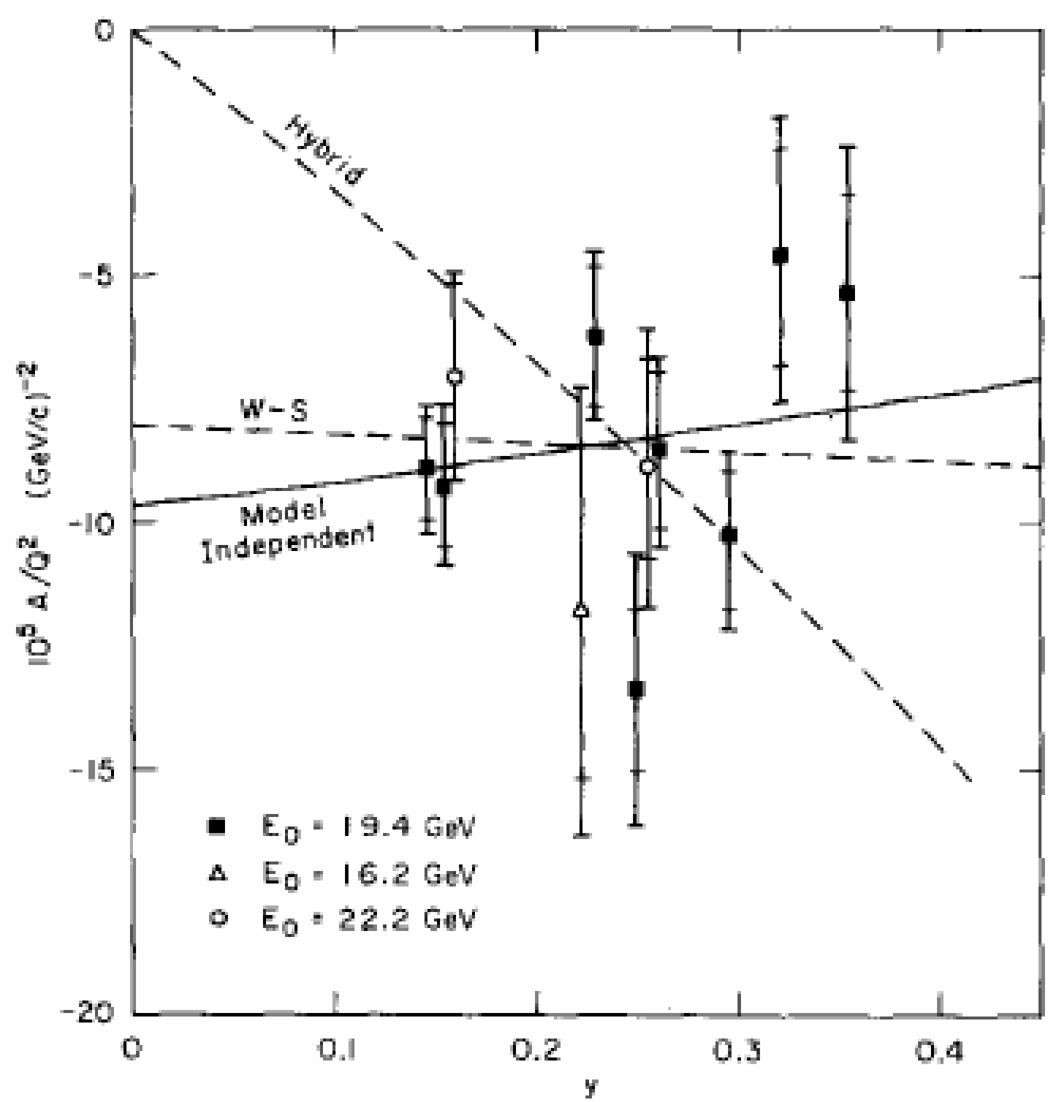
Pivotal to establishing Weinberg-Salam-Glashow SU(2)×U(1) gauge theory

Techniques

Optically pumped electron source: rapid helicity reversal

integrate scattered flux

monitoring & feedback to control electron beam fluctuations



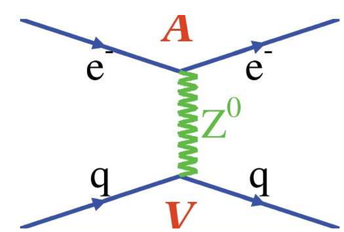
Followed by:

1989: Mainz ^9Be
W. Heil et al.

1990: MIT/Bates ^{12}C
P.A. Souder et al.

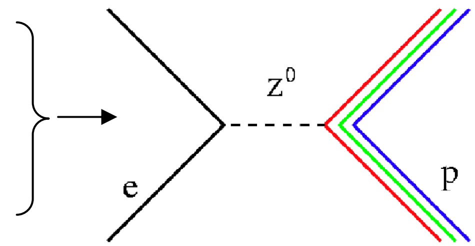
Weak Charges: Vector

Govern strength of neutral current interaction with fermion



$$C_{1i} = 2 g_A^e g_V^i$$

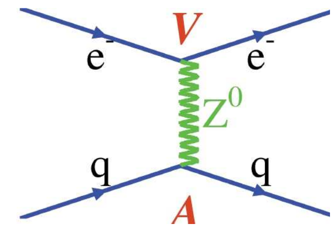
Charge / Particle	Electric	Weak (vector)
u	+2/3	$C_{1u} = -1/2 + 4/3 \sin^2\theta_W$
d	-1/3	$C_{1d} = 1/2 - 2/3 \sin^2\theta_W$
Proton uud	+1	$Q_w^p = 1 - 4 \sin^2\theta_W \approx 0.06$
Electron e	-1	$Q_w^e = 1 - 4 \sin^2\theta_W \approx 0.06$



Note "accidental" suppression of Q_w^p , Q_w^e $\rightarrow$

sensitivity to new physics

Weak Charges: Axial



$$C_{2i} = 2 g_V^e g_A^i$$

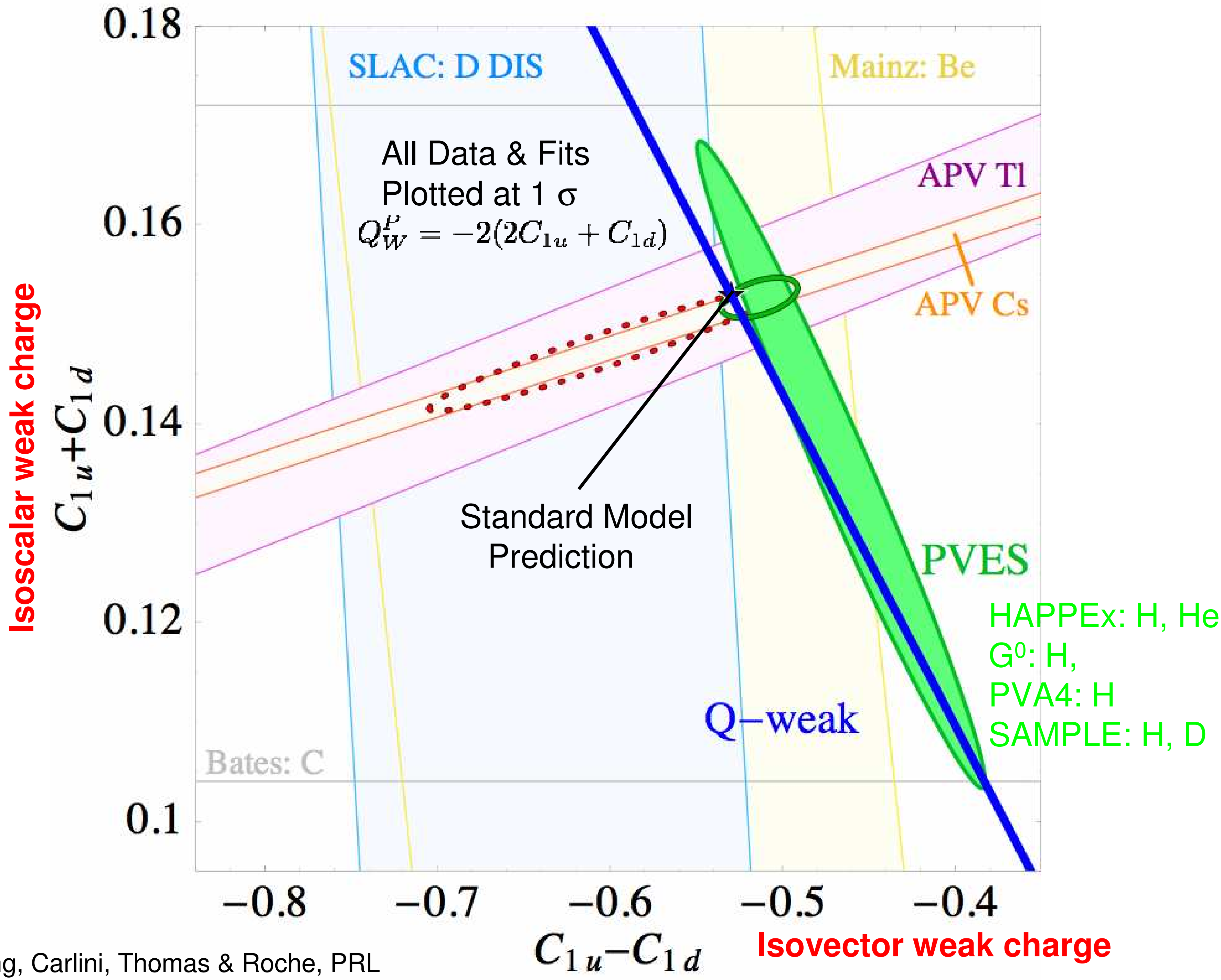
Particle \ Charge	Electric	Weak (axial)
u	+2/3	$C_{2u} = -1/2 + 2\sin^2\theta_W$
d	-1/3	$C_{2d} = +1/2 - 2\sin^2\theta_W$

$$C_{2u} = -C_{2u} \approx -0.04$$

Note : weak axial charge of proton is not "protected" from hadronic effects via current conservation, unlike vector case (CVC)

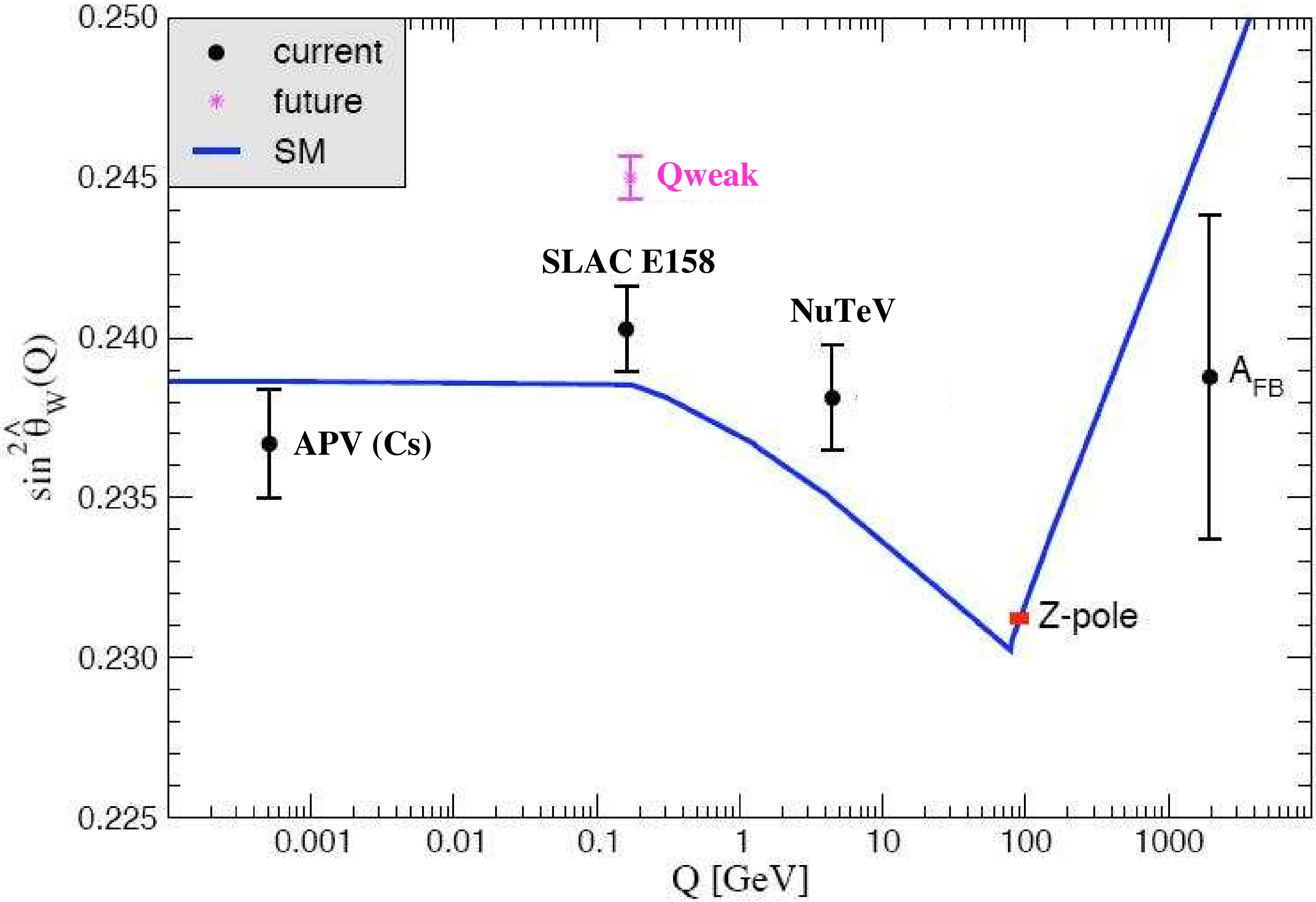
$\rightarrow$ *no clean Standard Model prediction*

Access C_{2u} and C_{2d} via parity-violating Deep Inelastic Scattering (PVDIS)



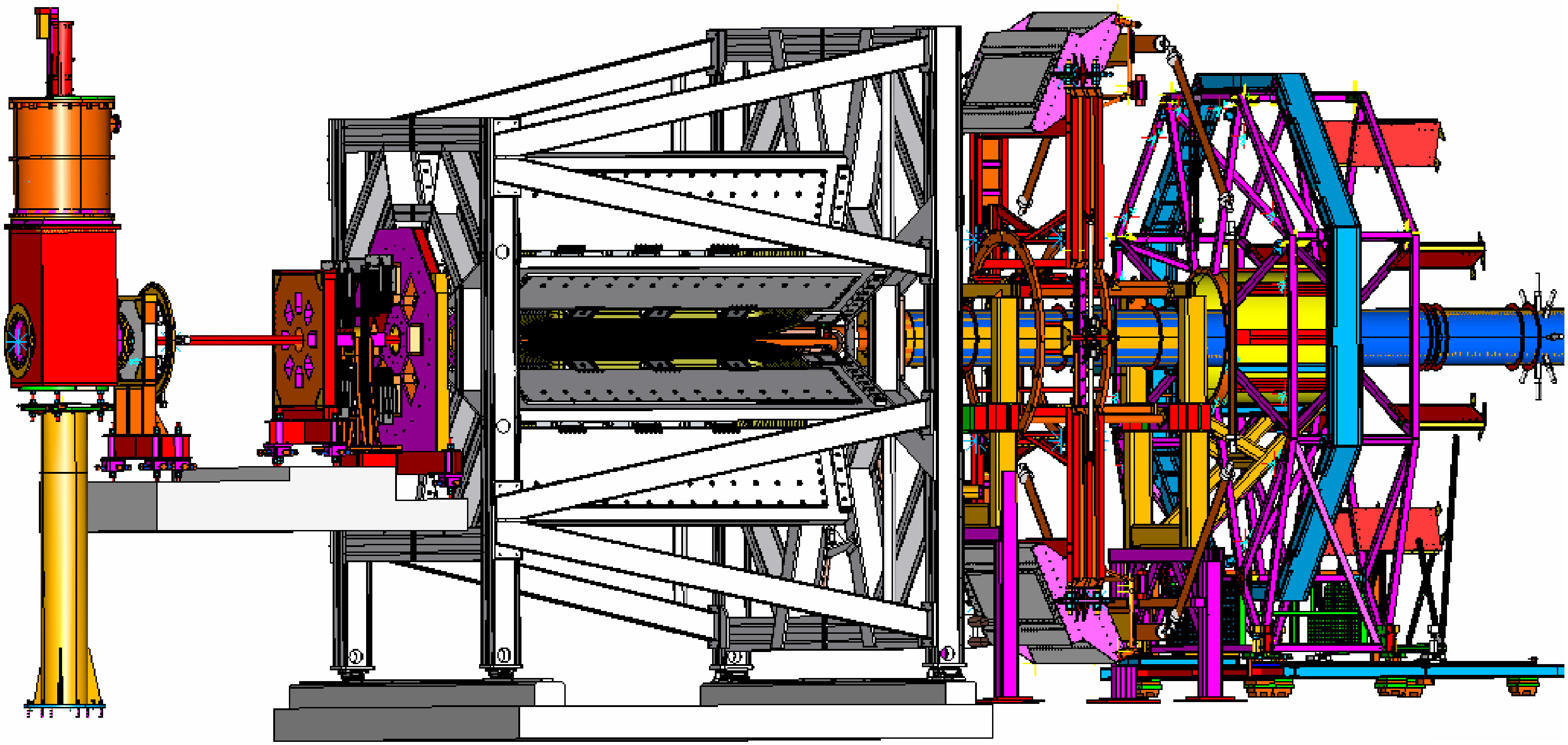
Young, Carlini, Thomas & Roche, PRL

Running of $\sin^2\theta_W$



PDG 2008 Review: “Electroweak and constraints on New Physics Model”
J. Erler & P. Langacker

QWeak (proton)



- Forward-angle elastic scattering 1.16 GeV e's from proton at 8°

  $Q^2 = 0.026\ (GeV/c)^2$
- Expected Asymmetry: 234 parts per billion
- Installation begins November 2009
- Runs June 2010 to May 2012
  - Final expt. in Hall C before 12 GeV upgrade

Running of $\sin^2\theta_W$: recent developments

1) Atomic Parity Violation (^{133}Cs): W.G. Porsev, K. Beloy, A. Derevianko
arXiv:0902.00335 hep-ph Feb 2009

New calculation of many-body atomic theory (up to triple excitations)
in $6S_{1/2} \rightarrow 7S_{1/2}$ transition (100 Gb basis set)

$Q_W(^{133}Cs)^{exp}$: $-73.25 \pm 0.29 \pm 0.20$

$Q_W(^{133}Cs)^{SM}$: -73.16 ± 0.03

2) NuTeV anomaly: originally quoted 3σ violation of Standard Model

- Erler & Langacker: include corrections due to asymmetry in strange quark PDFs (from NuTeV and CTEQ)
- Charge Symmetry violations (*eg* Londergan & Thomas PL B 558(2003)132)
  (u/d quark mass difference) account for 1σ
- I.C. Cloet, W. Bentz, A.W. Thomas arXiv:0901.3359 nucl-th Jan 2009

$\rightarrow$ vector mean fields in nucleus modifies in-medium PDFs

claim: entire anomaly accounted for

Energy Scale of an Indirect Search

- Estimate sensitivity to new physics Mass/Coupling ratio
  $\rightarrow$ add new contact term to the electron-quark Lagrangian:

Erler et al. PRD 68, 016006 (2003)

$$
\begin{aligned}
\mathcal{L}_{e-q}^{PV} &= \mathcal{L}_{SM}^{PV} + \mathcal{L}_{New}^{PV} \\
&= -\frac{G_F}{\sqrt{2}} \bar{e}\gamma_\mu\gamma_5 e \sum_q C_{1q} \bar{q}\gamma^\mu q + \frac{g^2}{4\Lambda^2} \bar{e}\gamma_\mu\gamma_5 e \sum_q h_V^q \bar{q}\gamma^\mu q
\end{aligned}
$$

Λ = mass g = coupling

$$
\frac{\Lambda}{g} = \frac{1}{\sqrt{\sqrt{2}G_F}} \cdot \frac{1}{\sqrt{\Delta Q_W(p)}}
$$

Few to 10's of TeV scale can be reached with PV electron scattering at JLab

New Physics: Examples

- Extra neutral gauge bosons: *Z'* *eg.* *E6* $\to$ SO(10)$\times$U(1)ψ GUT, SUSY, left/right symmetric models, technicolor, string theories…
- Composite fermions
- Leptoquarks (scalar LQs can arise in R-parity violating SUSY)

New physics can show up differently in Q_W^e , Q_W^p, vector vs. axial couplings…
$\to$ *complementarity*

M.J. Ramsey-Musolf PRC 60(1999)015501; PRD62(2000)056009

J. Erler, A. Kurylov, M.J. Ramsey-Musolf PRD 68(2003)016006

Direct search at Tevatron : $M_{Z'_\psi} > 0.82$ TeV
CDF PRL 99 (2007)171802

Electroweak Global Fit

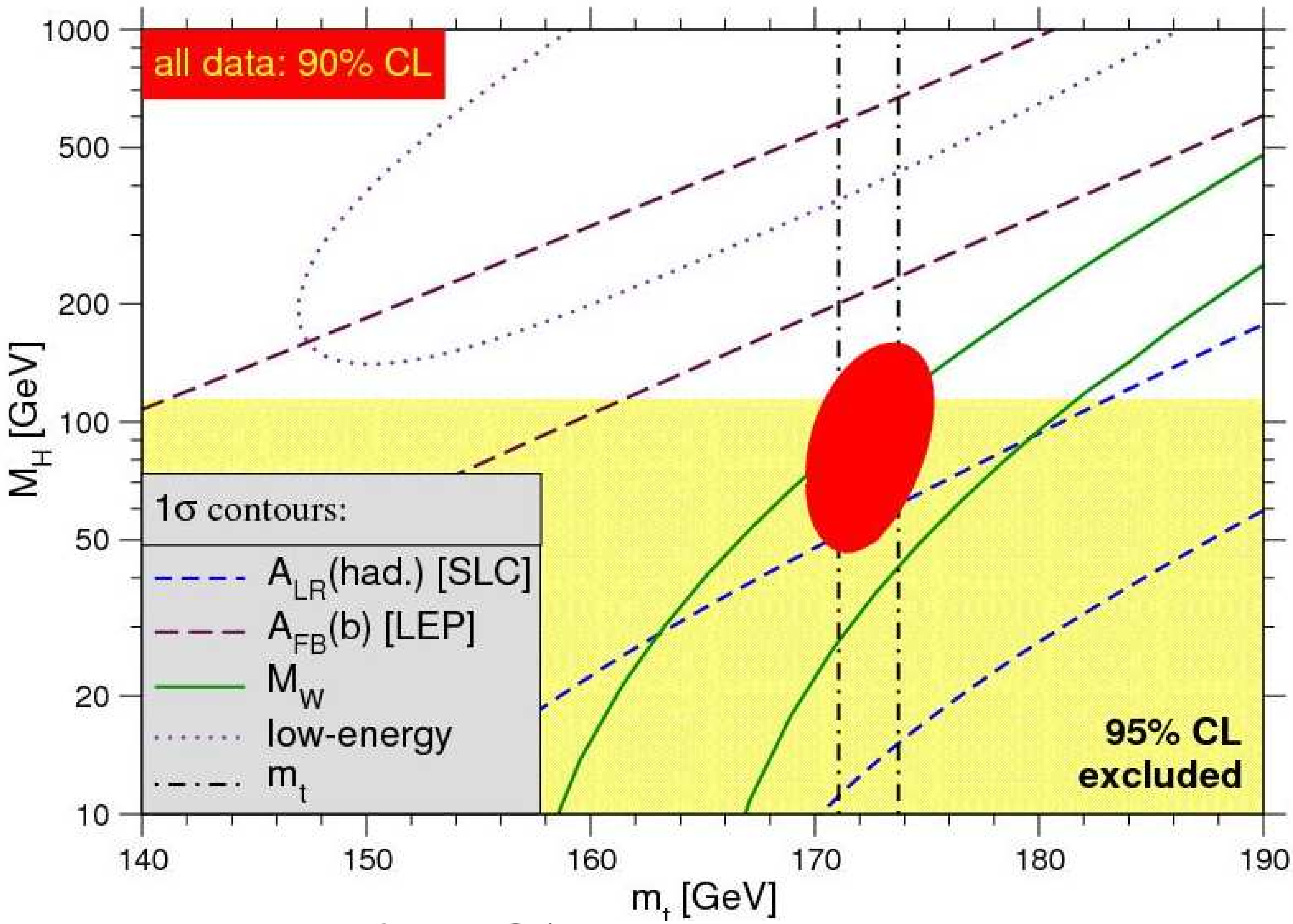


Figure courtesy of Jens Erler

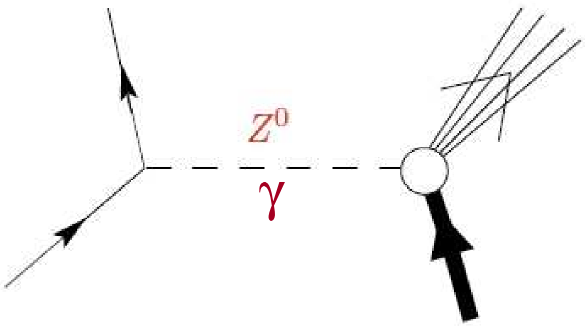
Parity-violating DIS

Goal: C_{2u} and C_{2d}

$$A_d = -\left(\frac{3G_F Q^2}{\pi\alpha 2\sqrt{2}}\right)\frac{(2C_{1u}-C_{1d})\left[1+R_s(x)\right]+Y(2C_{2u}-C_{2d})R_v}{5+R_s(x)}.$$

Y = kinematic variable (with R_{LT})

$$R_s(x) = \frac{s(x)+\bar{s}(x)}{u(x)+\bar{u}(x)+d(x)+\bar{d}(x)}$$



$W^2 > 4\ \mathrm{GeV}^2$
$Q^2 > 1\ \mathrm{GeV}^2$

$$R_v(x) = \frac{u_v(x)+d_v(x)}{u(x)+\bar{u}(x)+d(x)+\bar{d}(x)}$$

1. PVDIS-6 GeV – this Fall
2. PVDIS-12 GeV - Hall C SHMS/HMS (approved)
3. SoLID: Large Acceptance Solenoid Spectrometer (cond. approved)

Caveat : hadron structure…

Hadronic Structure and PV DIS

- PDFs, R_{LT} : under sufficient control at moderate x

- Higher-twist: different Q^2 dependence than DGLAP
  effects on asymmetry of order 1% seem plausible
  $\rightarrow$ PVDIS may provide unique window into higher-twist

- Charge Symmetry Violation (CSV): $u^p(x) \neq d^n(x)$ etc.
  $\rightarrow$ effect expected to grow with x

- [d/u ratio at high x for proton
  $\rightarrow$ PVDIS can access with hydrogen target]

•Standard Model tests require robust understanding of nucleon structure effects

•Untangling structure effects: kinematic range

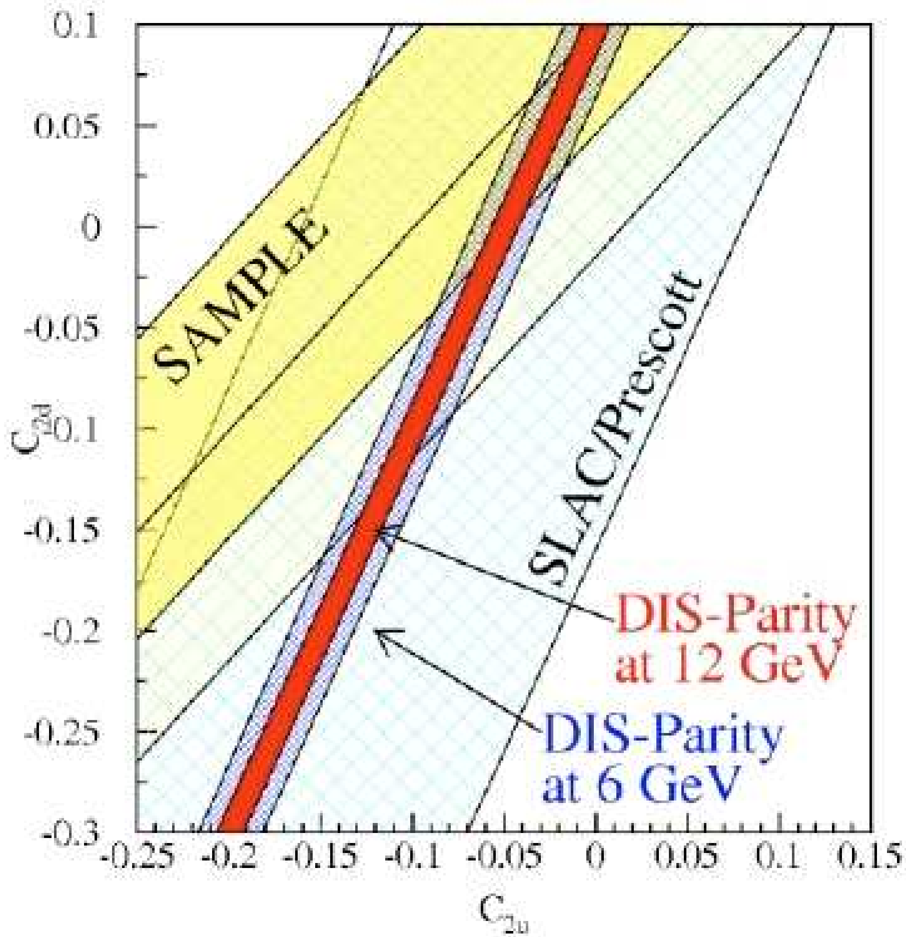
PVDIS - approved program

- 6 GeV E08-011

  (Q^2,x) =

  (1.1 GeV^2, 0.25) & (1.9 GeV^2, 0.3)

  - use HRS in Hall A, custom fast DAQ
  - study Q^2 evolution (higher twist)
  - 3% (stat) precision on A_d

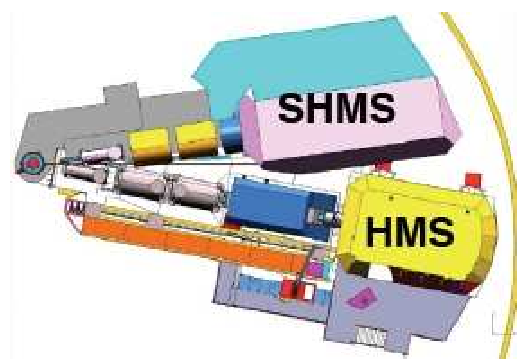


11 GeV PR12-07-012

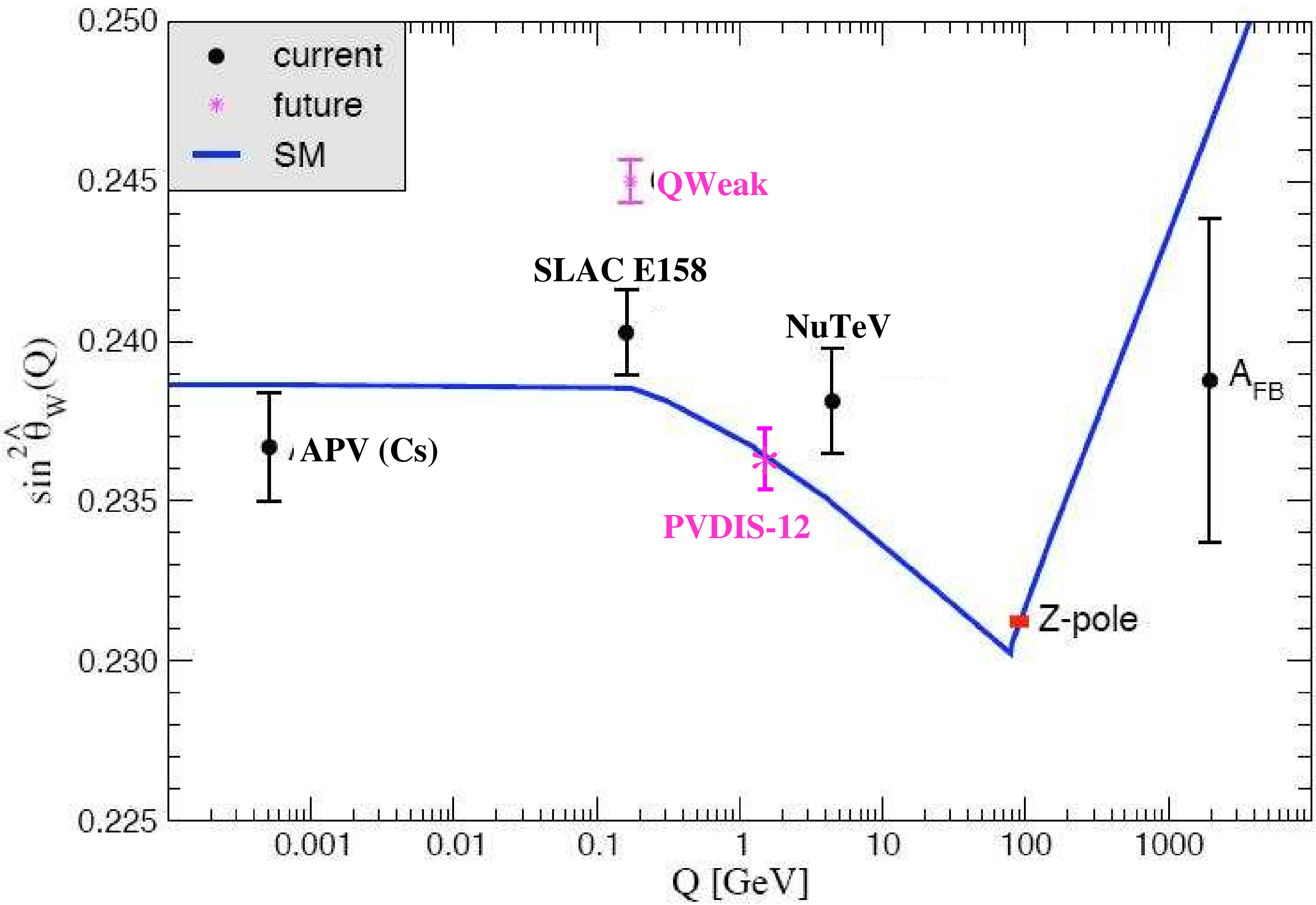
Detect DIS e's in SHMS, HMS at 13.5°

- custom fast DAQ (240 kHz)
- 85 μA on 40 cm lD_2 target
- (Q^2,x,W) = (3.3 GeV^2, 0.25, 7.3 GeV^2)
- 0.5% stats on A_d in 670 hrs
- 0.7% systematics goal
- expected A_d: 285 ppm
- $\sin^2\theta_W$ to ± 0.45%

(*if* one assumes CSV and higher-twist under control)

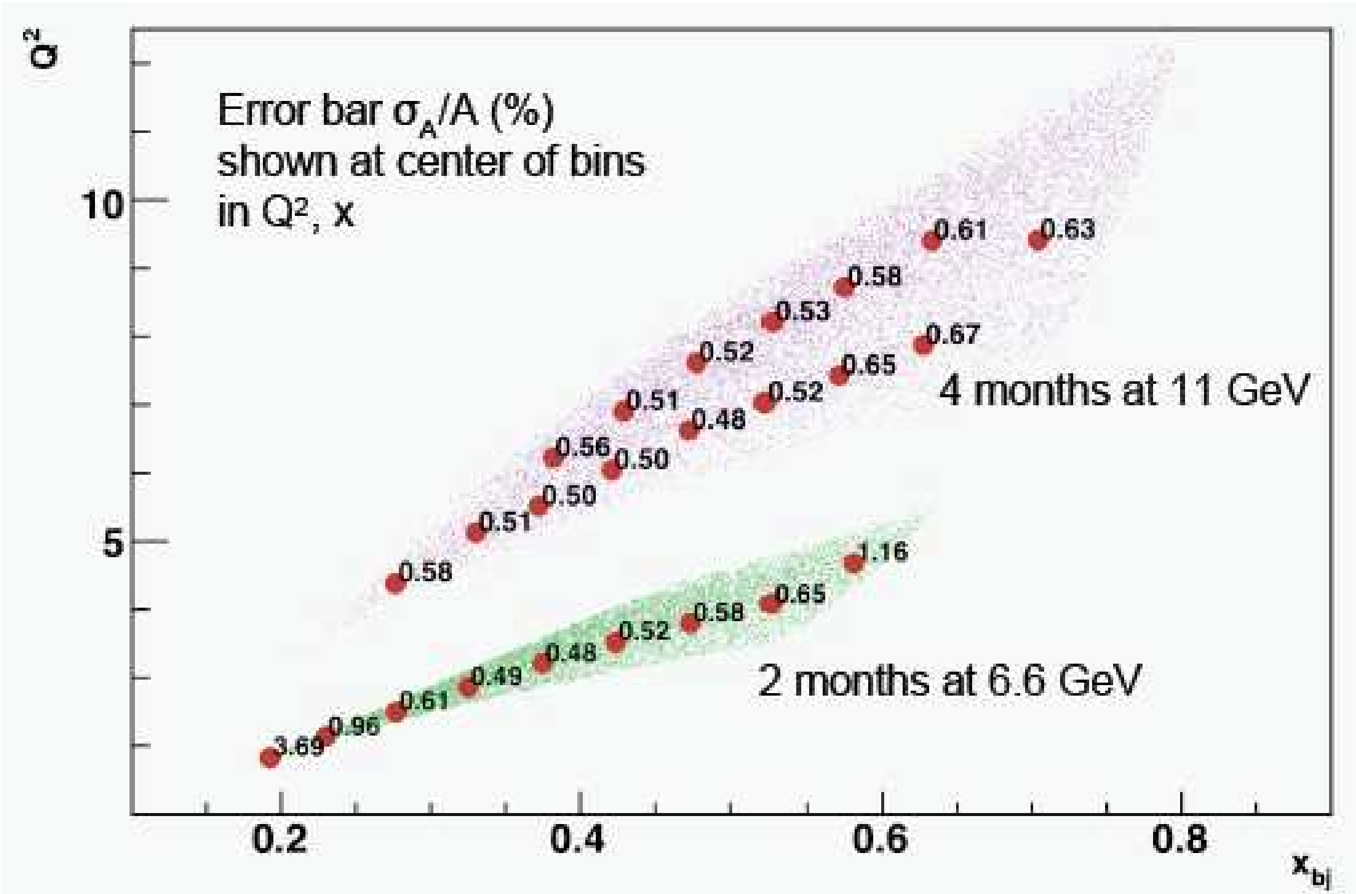


Running of $\sin^2\theta_W$



PVDIS with SoLID (PR12-09-12)

Goal: Measure A_d over large kinematic range
$\rightarrow$ disentangle New Physics from hadron structure

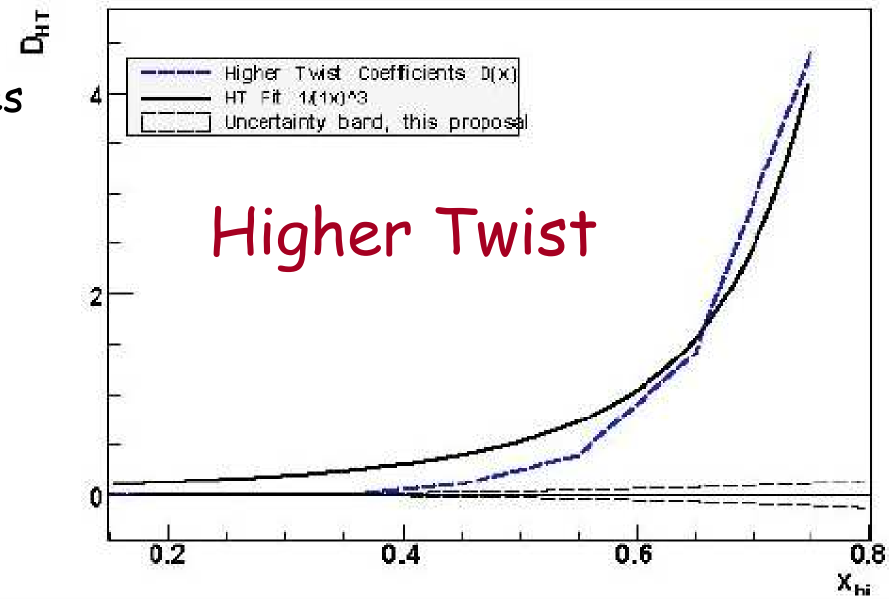


Factor of 2 in Q^2 for each x; $W^2 > 4$ GeV^2

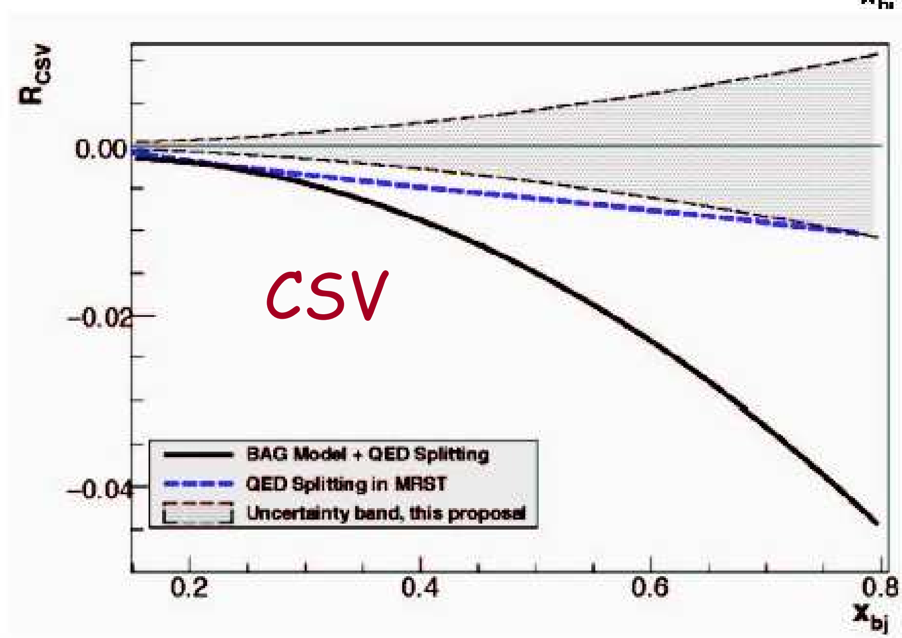
SoLID : Hadronic effects

Disentangle via x, Q^2 and y $(=\nu/E)$ dependences

$$A = A\left[1 + \beta_{HT}\frac{1}{(1-x)^3 Q^2} + \beta_{CSV}x^2\right]$$



	x	Q^2	y
Higher Twist	➡	➡	
CSV	➡		
New Physics			➡



SoLID : spectrometer

Solenoid: BaBar, CDF, or CLEO-II

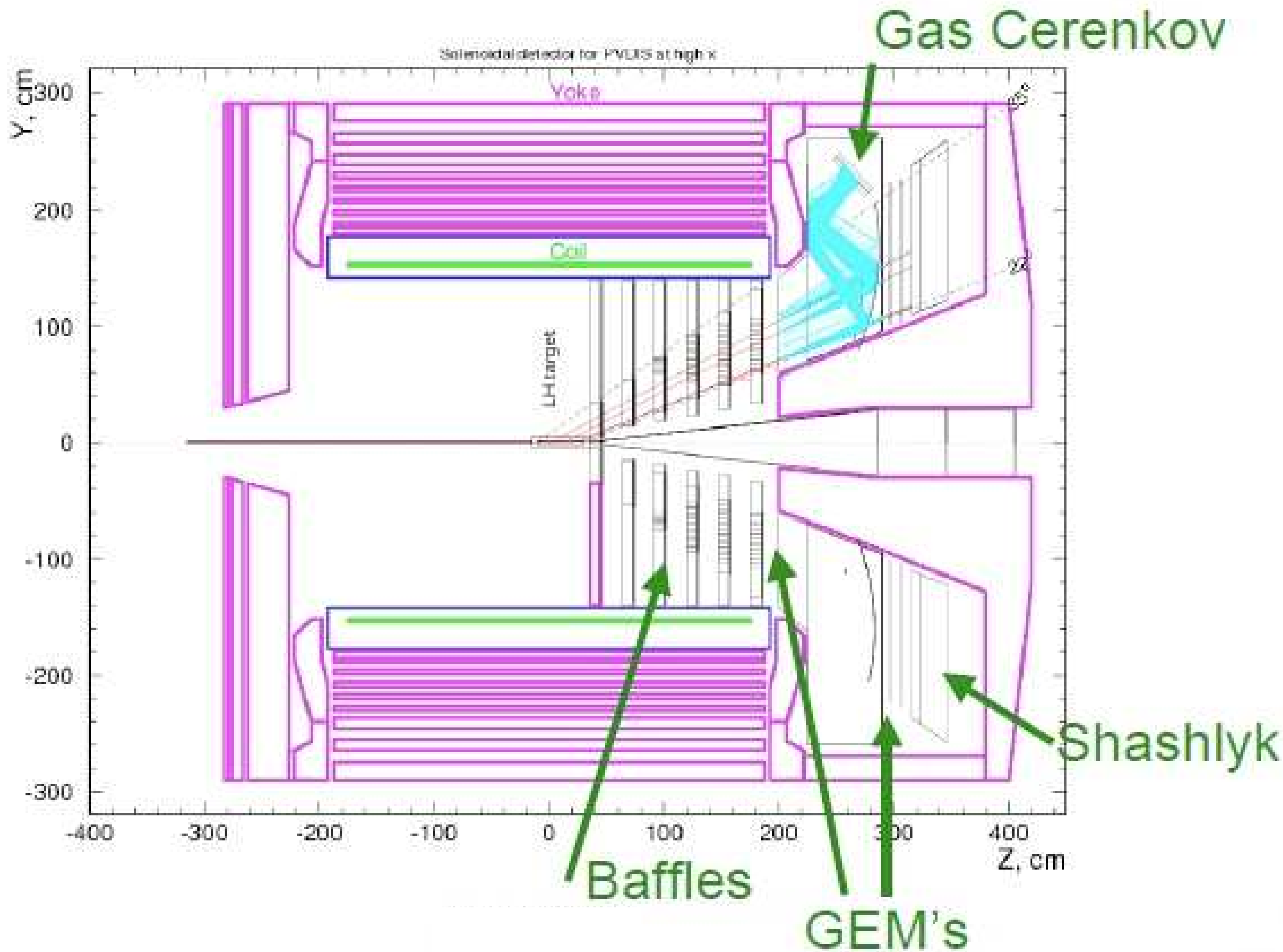
Fast tracking, particle ID, calorimetry, pipeline electronics

Measure tracks after baffles: suppress low-energy backgrounds (Moller, π's…)

> 200 msr

Resolution < 2%

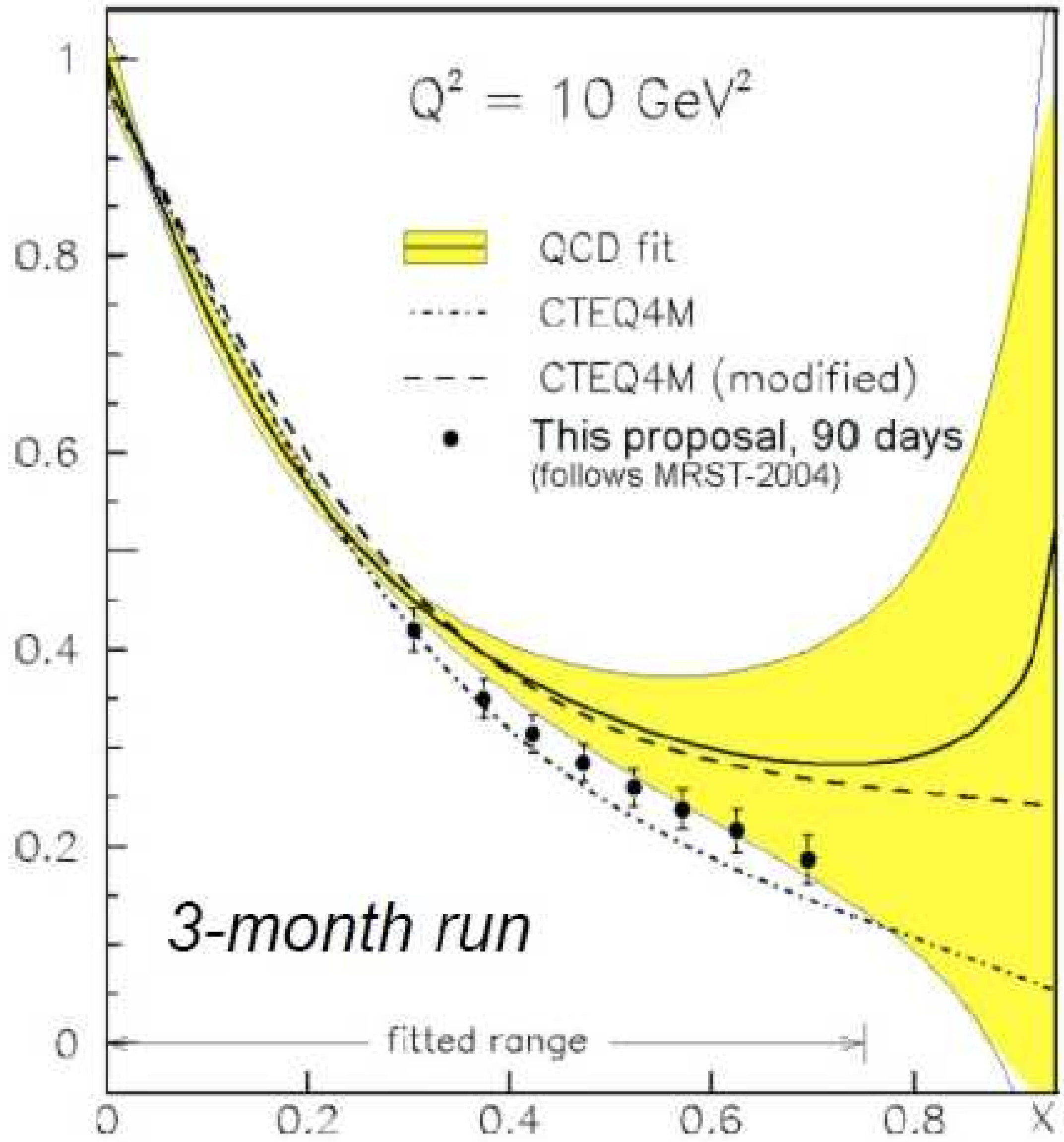
100 kHz



d/u at high x with SoLID

Switch to hydrogen target:

$$a^P(x) \approx \frac{u(x) + 0.91d(x)}{u(x) + 0.25d(x)}$$

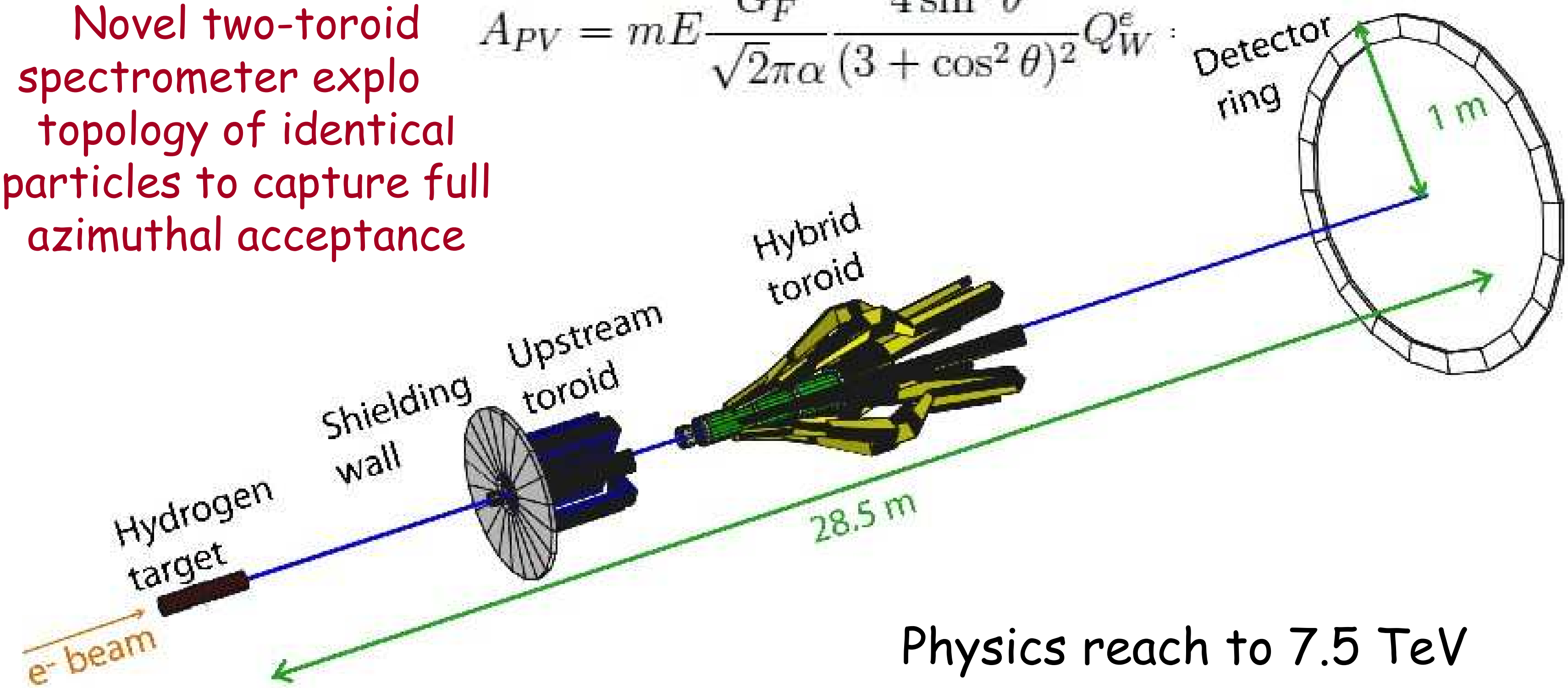


Parity-violating Moller at 11 GeV

Goal: measure 36 ppb asymmetry with 0.7 ppb error
Would determine Q^e_{weak} to 2.3%
$\sin^2\theta_W$ to ± 0.00026(stat) ± 0.00013(syst)

Novel two-toroid spectrometer explo topology of identical particles to capture full azimuthal acceptance

$$A_{PV} = mE\frac{G_F}{\sqrt{2}\pi\alpha}\frac{4\sin^2\theta}{(3+\cos^2\theta)^2}Q^e_W$$



Physics reach to 7.5 TeV

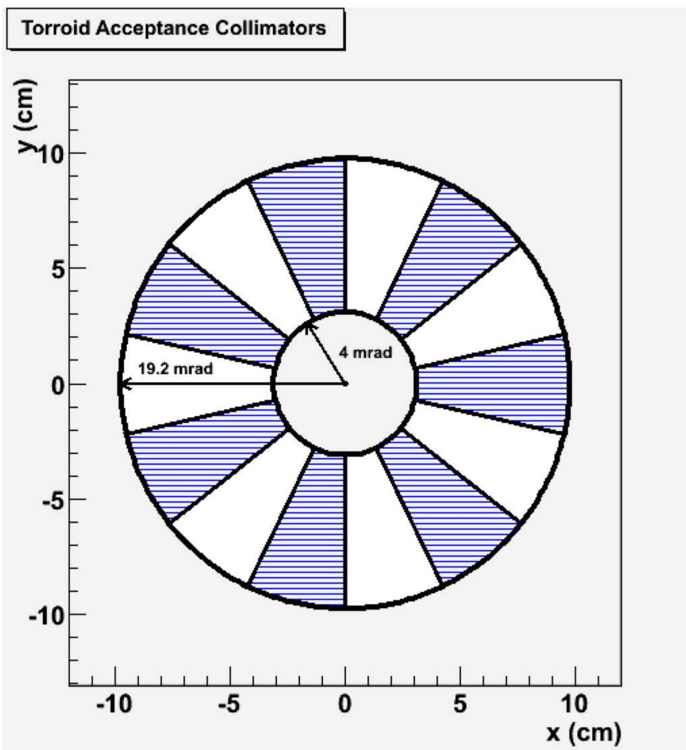
Moller: spectrometer concept

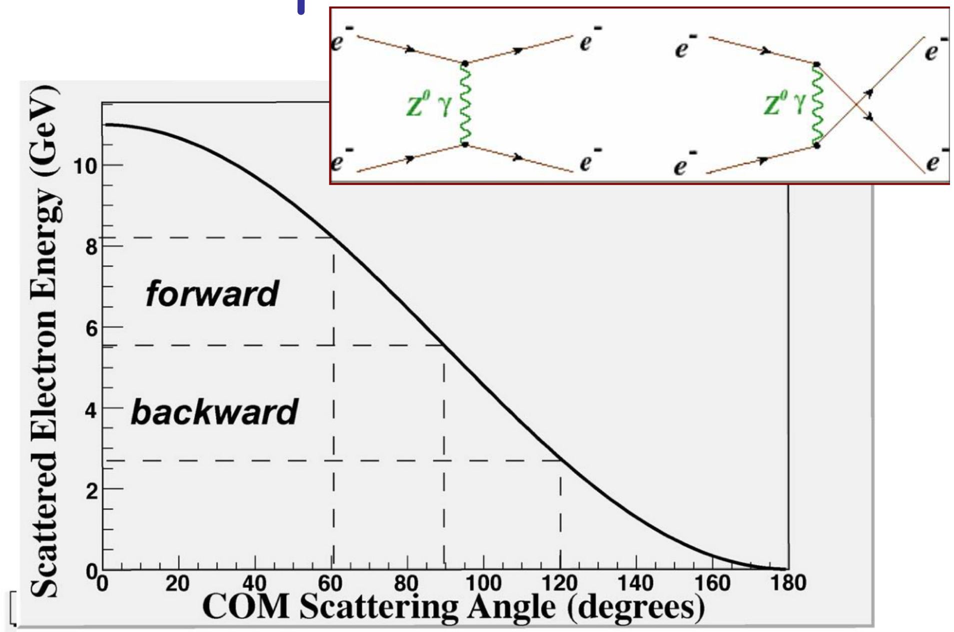
Identical particles: avoid double-counting, only take forward or backward in c-o-m.

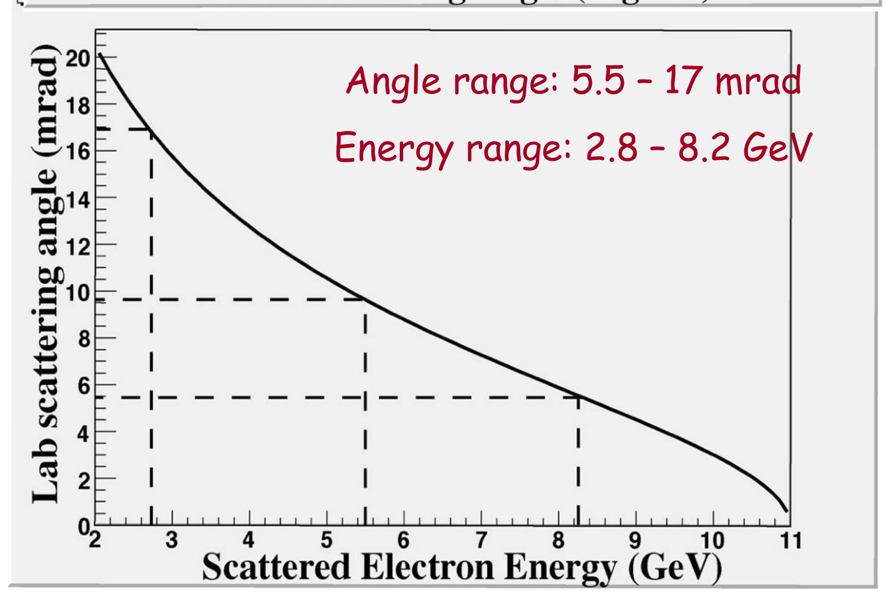
select backward θ_{CM}

Exploit to gain full azimuthal acceptance: odd-sectored toroid

Lost $\theta_{CM} > 90^\circ$ electrons in one sector detected via partner ($\theta_{CM} < 90^\circ$) in opposing sector!





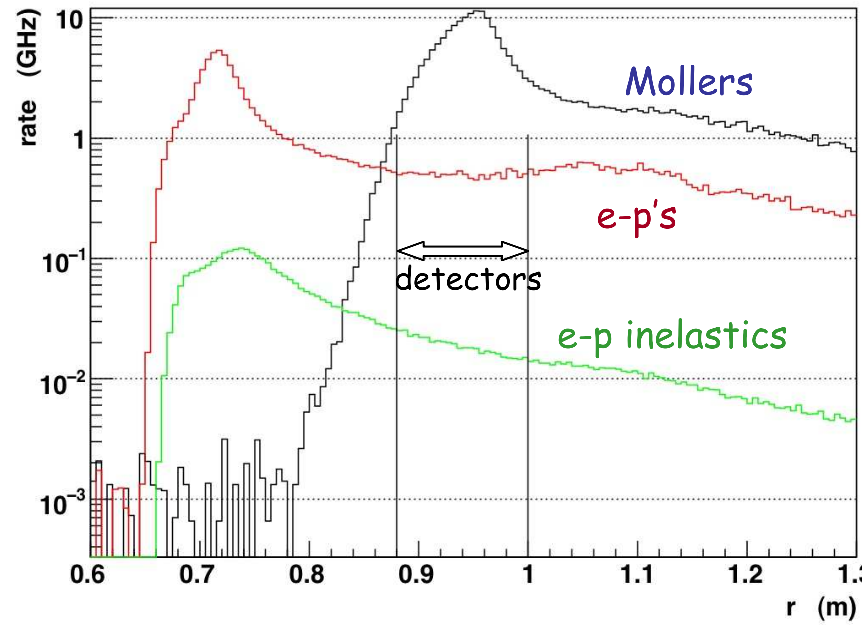


Moller: some details

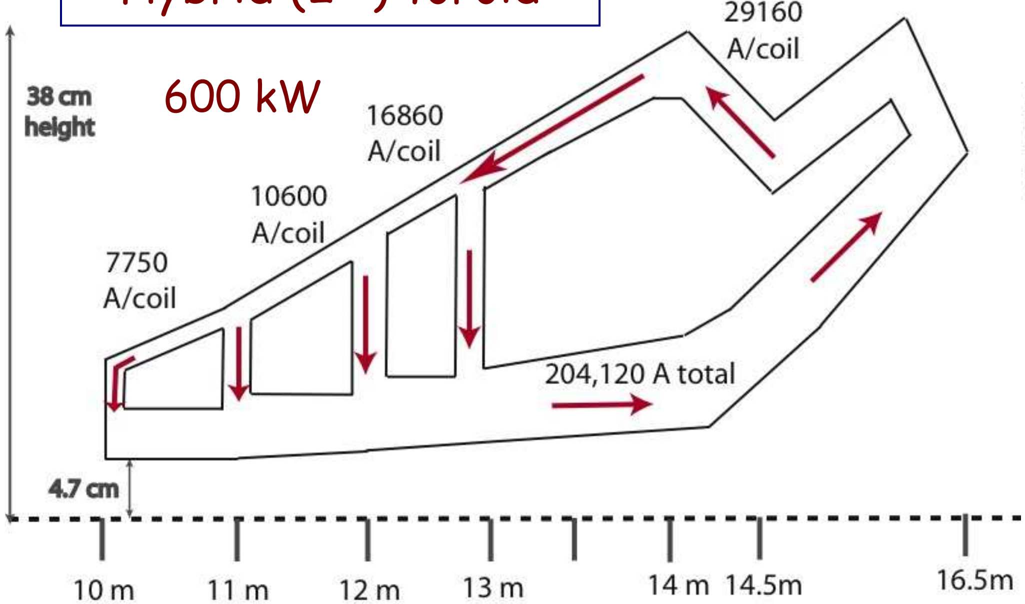
- 85 μA   150 cm lH2 target: 5 kW
- 150 GHz rate (integrating DAQ)
- 5040 hours

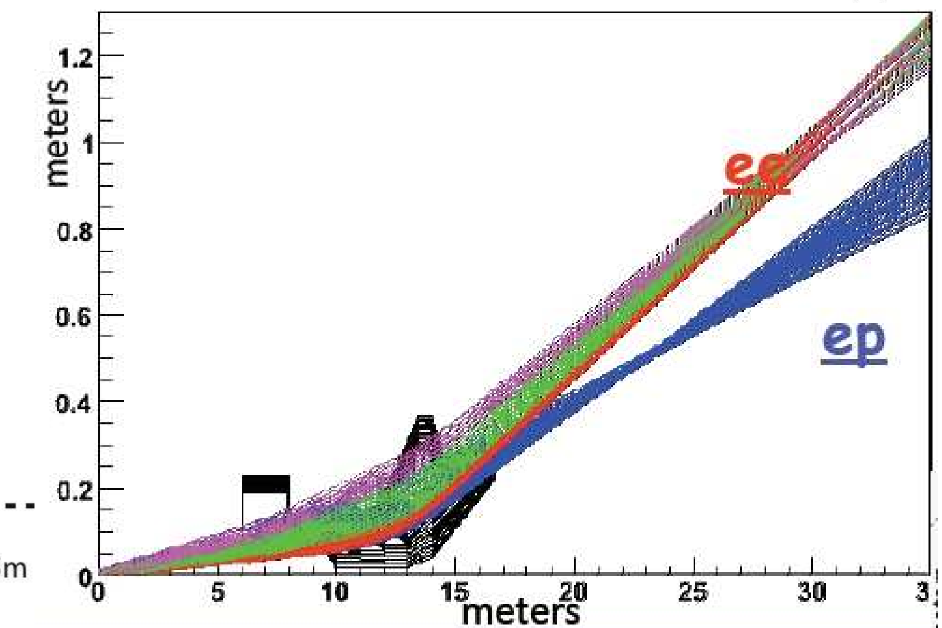
- azimuthal defocusing – full φ population at focal plane; complex hybrid toroid

- background discrimination: r, φ

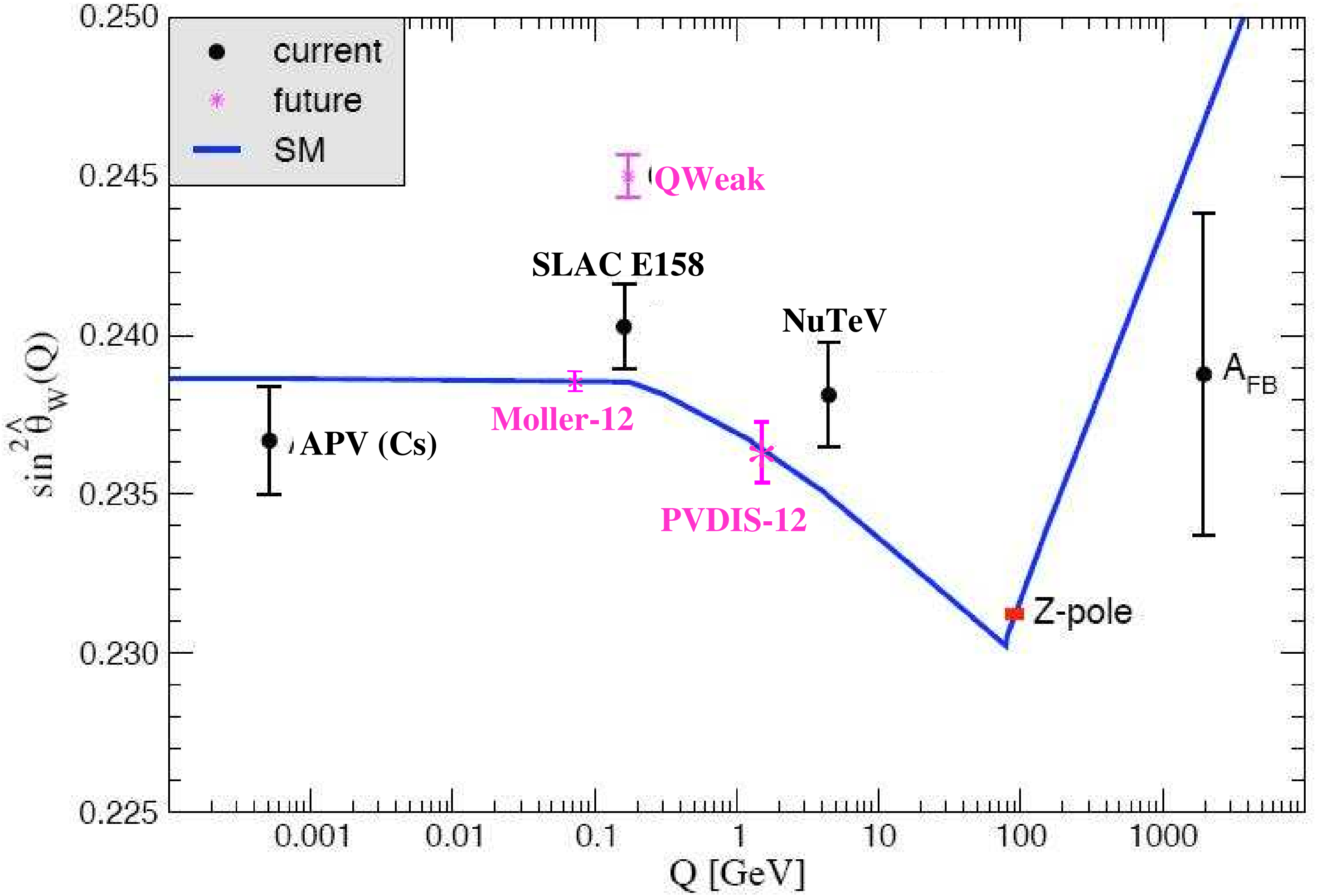


Hybrid (2nd) toroid



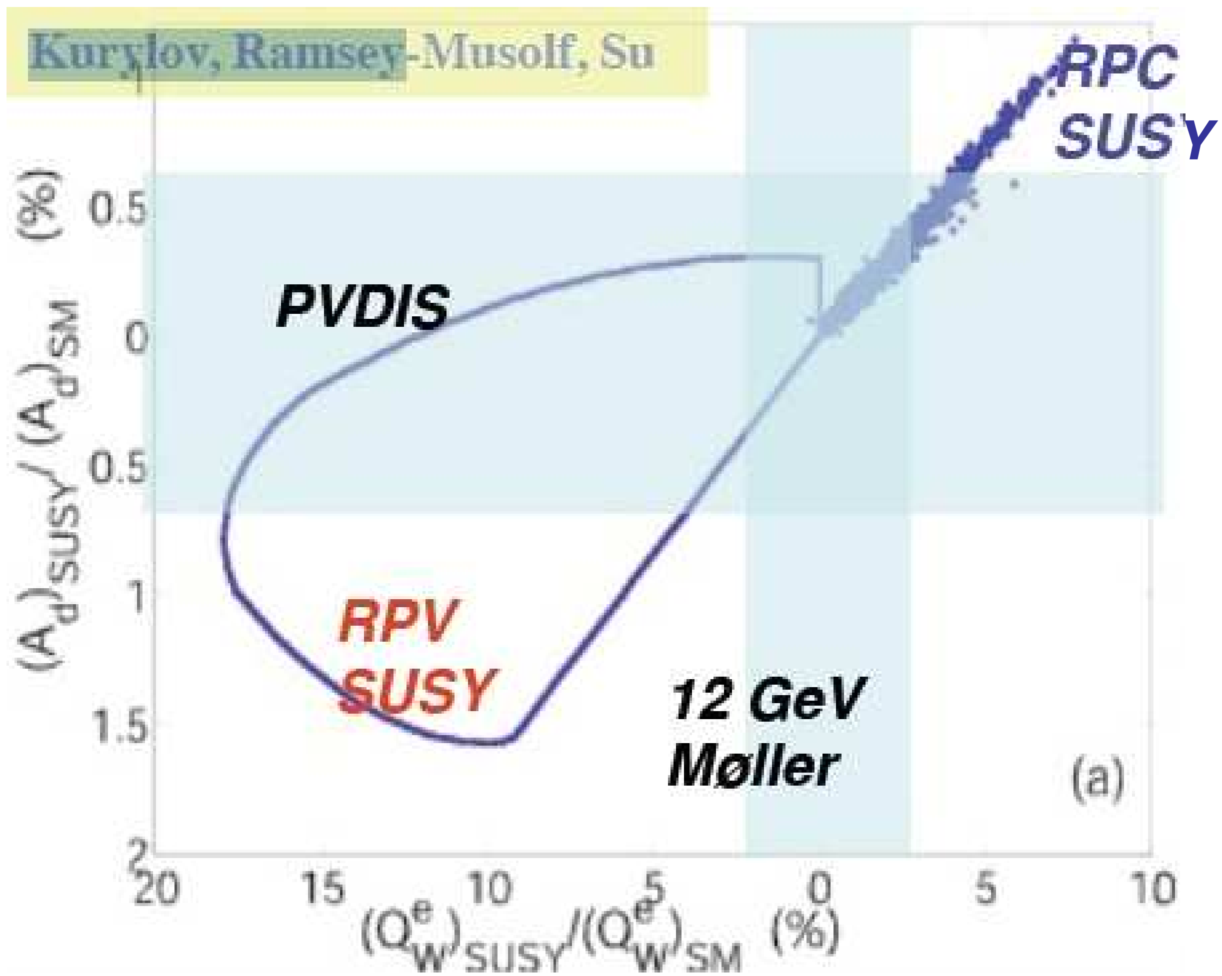


Running of $\sin^2\theta_W$



Moller-12: competitive with most precise collider data at Z-pole

Complementarity: an example



Precision on $\sin^2\theta_W$

Experiment	$\delta \sin^2\theta_w$ (10^{-4})
APV (Cs)	11
NuTeV	16
SLAC E158	15
PVDIS - 6	18
Qweak	7
PVDIS -12	11
Moller - 12	3

Caveat: not all theoretical errors on equal basis

Timeline/status: SoLID and Moller-12

Moller-12

- PAC 34 - full approval – strong endorsement:

"The proposed physics reach is outstanding and capable of making this effort a flagship experiment at JLab." "The PAC believes the mission of this experiment… is so important that the Laboratory should make every effort to support the securing of the resources required"

- Working with lab management to prepare funding request (DOE nuclear, +…)
- Goals: CD-0 Spring 2010 construction 2012-2015
- First review (JLab-initiated): late this year

SoLID

- PAC 34 - conditional approval. Issues: clarify hadronic issues, esp. higher-twist; portability of apparatus (effect on other experiments)
- Plan to resubmit to next PAC
- Theory workshop last week at UW Madison (M. Ramsey-Musolf). Focus: higher twist in PVDIS
- Securing engineering help on mechanical design/portability of detector package

Summary

- Precision Parity-Violation experiments at JLab will probe new physics at the TeV scale

- May provide critical information for interpretation of “Beyond the Standard Model physics at the LHC

- PVDIS experiments also can address topical issues in hadron structure: higher-twist, charge symmetry violation, u/d at high-x

- finis -