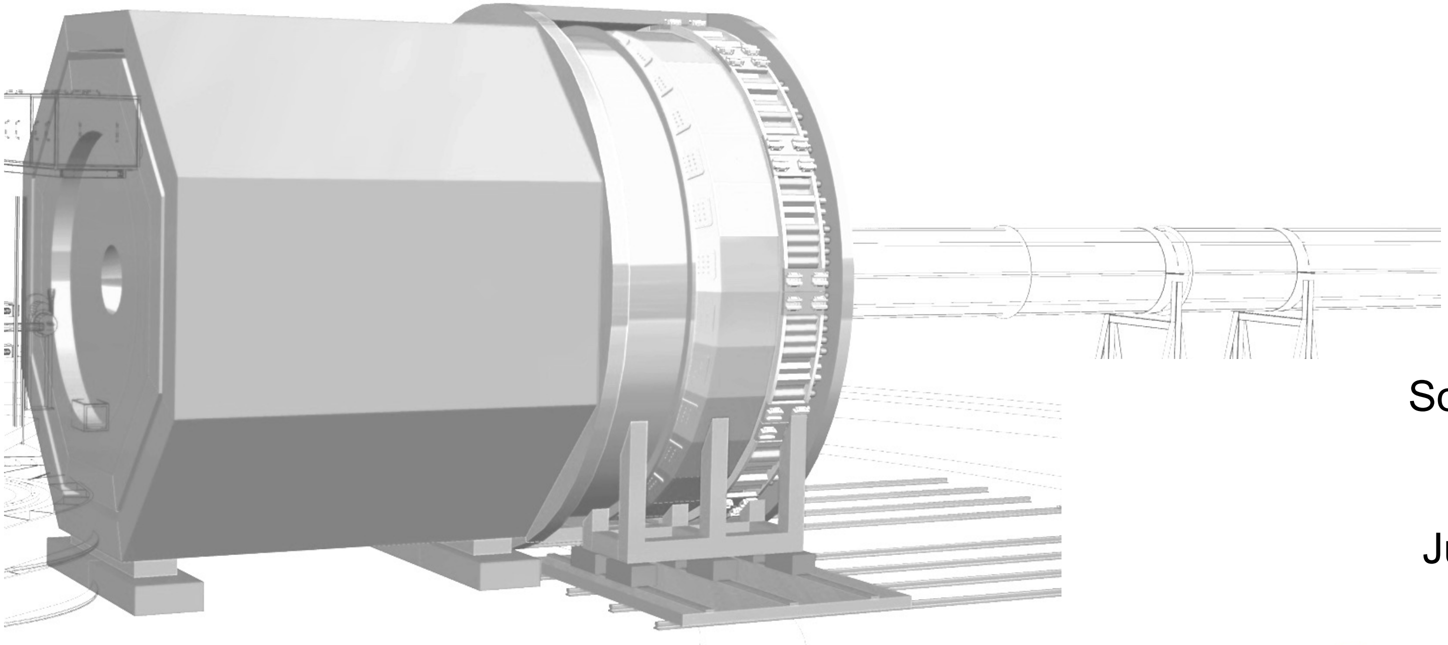
SoLID PVDIS Program



SoLID Status

June 2022

SOLENOIDAL LARGE INTENSITY DEVICE

Paul Souder

Syracuse University

Outline

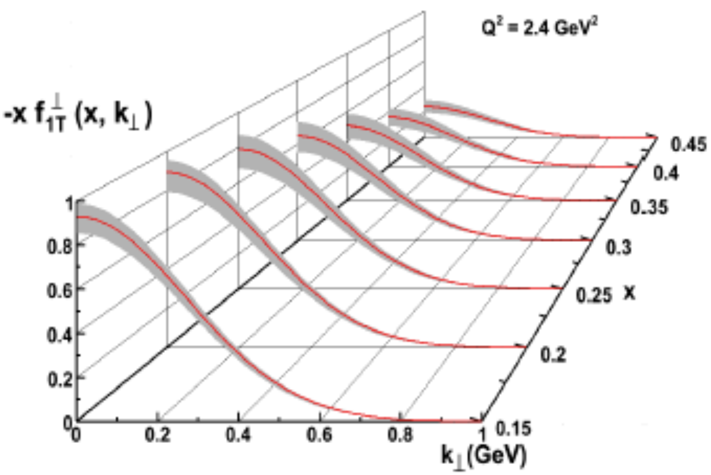
- The SoLID Spectrometer: Physics Program and Status
- PVDIS BSM Motivation
- Hadronic Physics with PVDIS
- Experimental and Theory Uncertainties

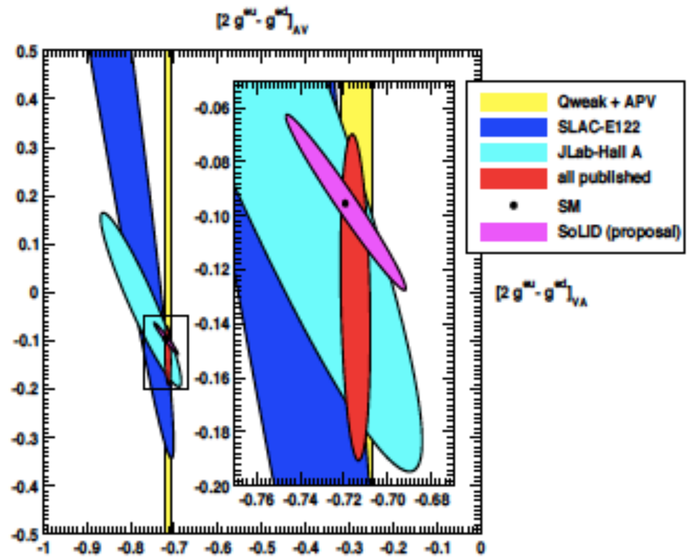
SoLID Physics Overview

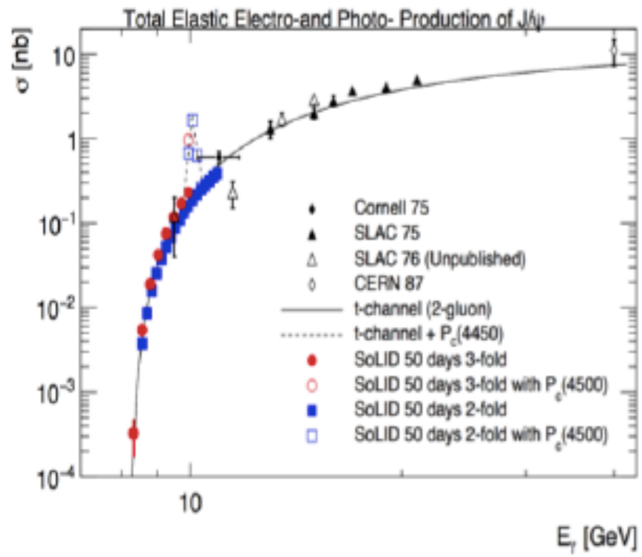
- **Full exploitation of JLab 12 GeV Upgrade to maximize scientific return**

A Large Acceptance Detector AND Can Handle High Luminosity (10^{37}-10^{39})

- SIDIS - reaching ultimate precision for tomography of the nucleon (E12-10-006, E12-11-007, E12-11-108)
- PVDIS in high-x region - providing sensitivity to new physics at 10-20 TeV (E12-10-007)
- Threshold J/ψ - probing strong color fields in the nucleon and the origin of its mass (trace anomaly) (E12-12-006)







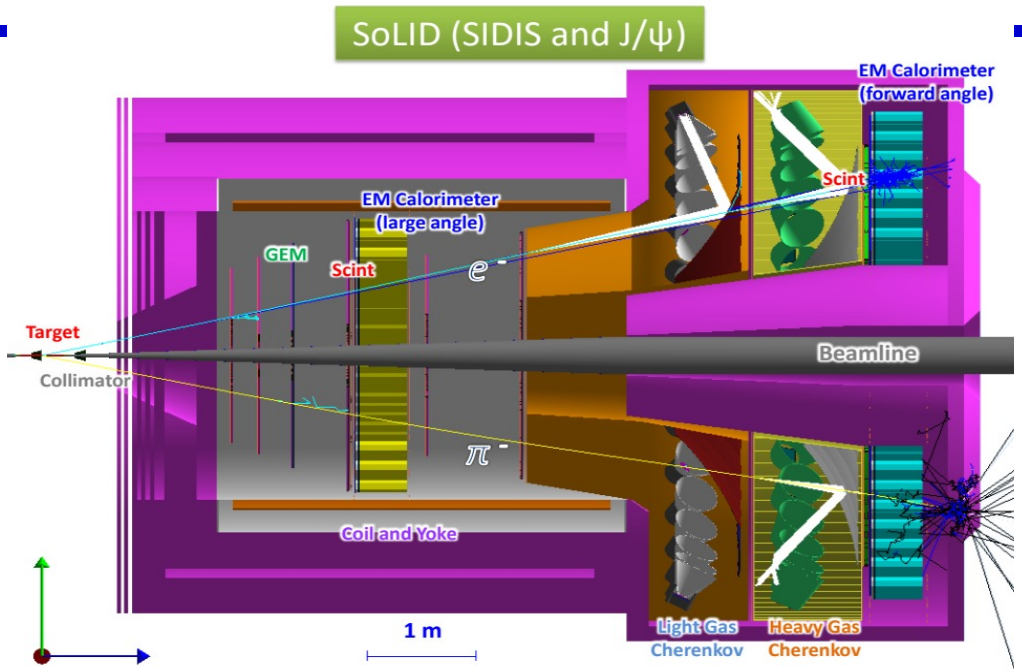
- **2015 LRP recommendation IV**

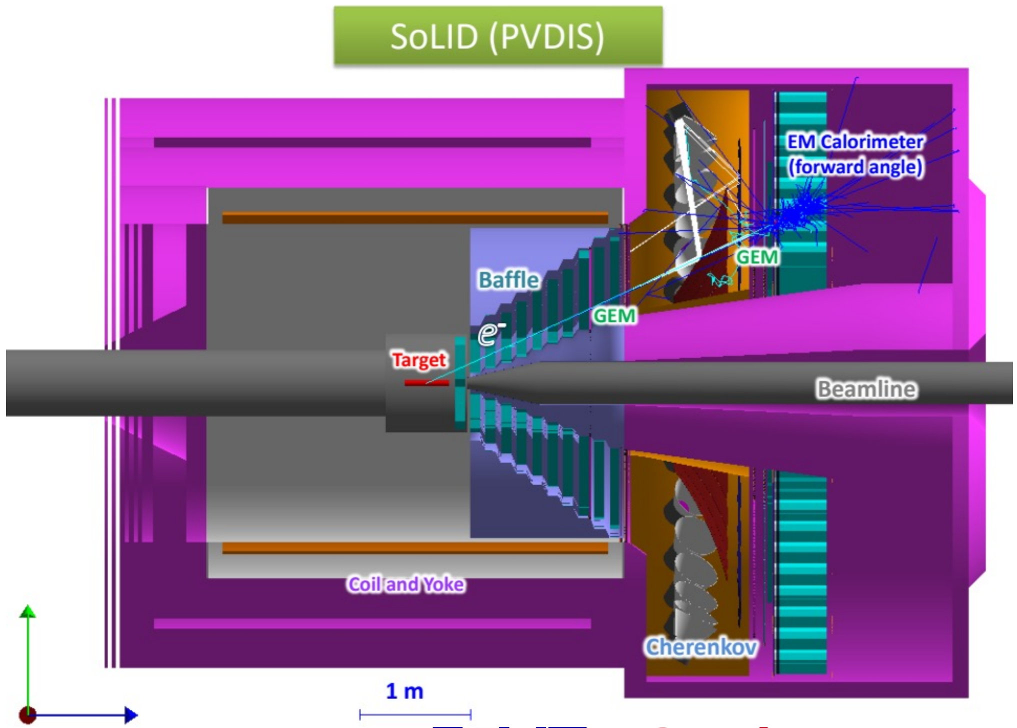
- We recommend increasing investment in small-scale and mid-scale projects and initiatives that enable forefront research at universities and laboratories – **SoLID – mid-scale project**

SoLID Apparatus

Requirements are Challenging

- High Luminosity (10^{37}-10^{39})
- High data rate
- High background
- Low systematics
- High Radiation
- Large scale (Like RHIC)
- New Technologies
  - GEM's
  - Shashlyk Ecal
  - Pipeline DAQ



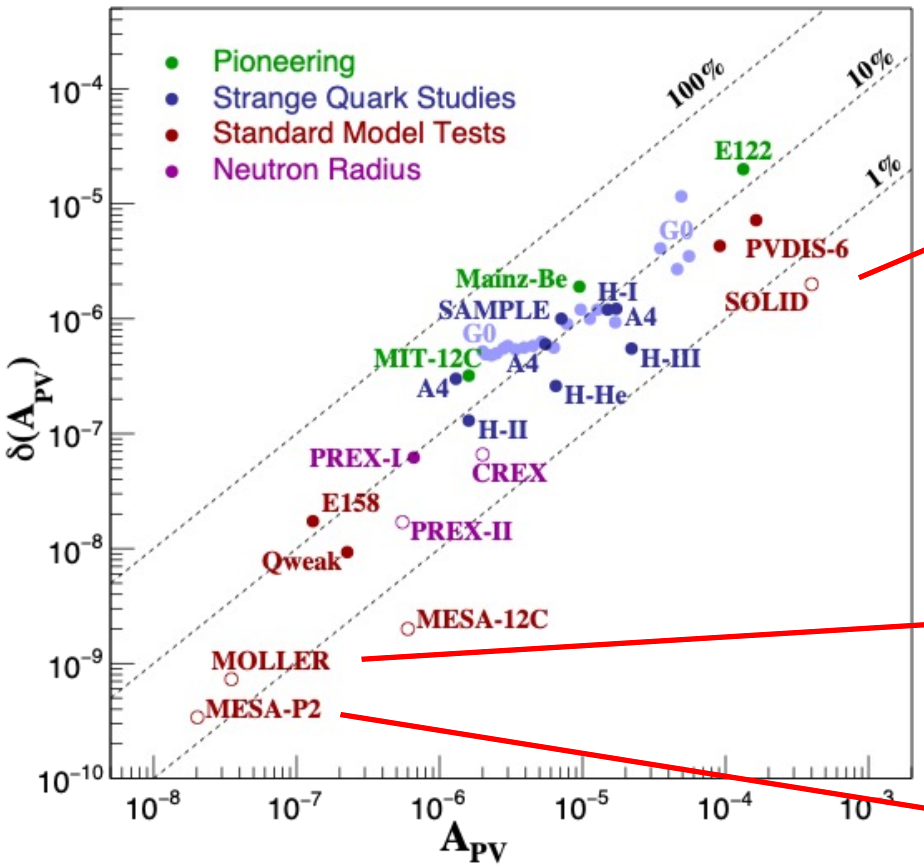


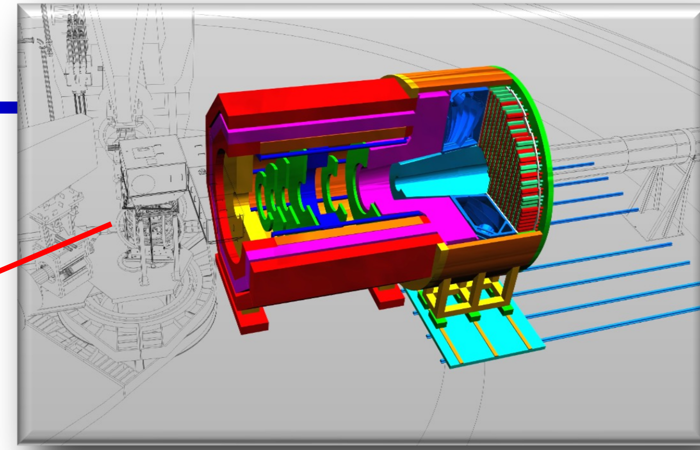
SoLID Progress Timeline and Present Status

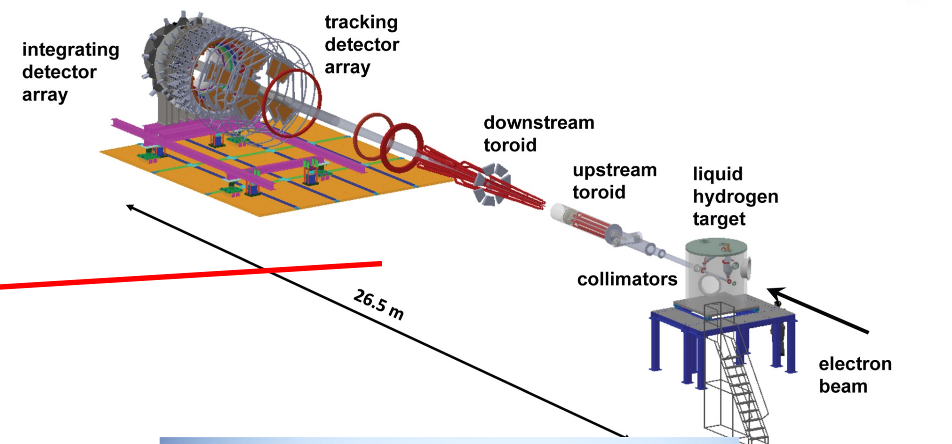
- Since 2010: Five SoLID experiments approved by PAC with high rating
  3 SIDIS with polarized ^{3}He/p target, 1 PVDIS, 1 threshold J/ψ
  Five run-group experiments approved
- 2013: CLEO-II magnet requested, agreed, arrived at JLab 2016
- 2014: pCDR submitted to Jlab with cost estimation and proposed schedule
  estimation based on Hall D and CLAS12 experience
- 2015: Director's Review, positive with many recommendations
- 2017: Updated pCDR submitted to JLab with responses to the recommendations
- 7/2018: DOE NP visit and discussion:
- 9/2019: Director's Review 9/9-9/11 with WBS structure and proposed cost and schedule
- 11/2019 Pre-R&D Plan Funded
- 12/2019 pCDR reviewed by JLab and submitted to the DOE
- 3/2021 DOE Science Review; Make CD0 decision
- 7/2022 JLab PAC Jeopardy Review
- 9/2022 Defend SoLID for the NP Long Range Plan

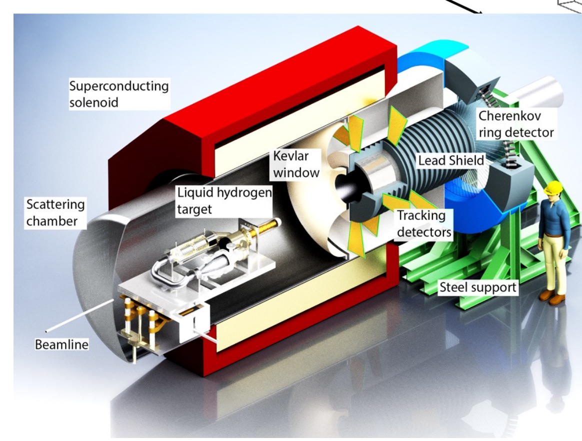
Present Status: No new DOE Projects this year.
Encouraging Comments: "If the Science Review were negative, we would have heard by now." "It is not an issue of if, but when".

BSM PVES Experiments









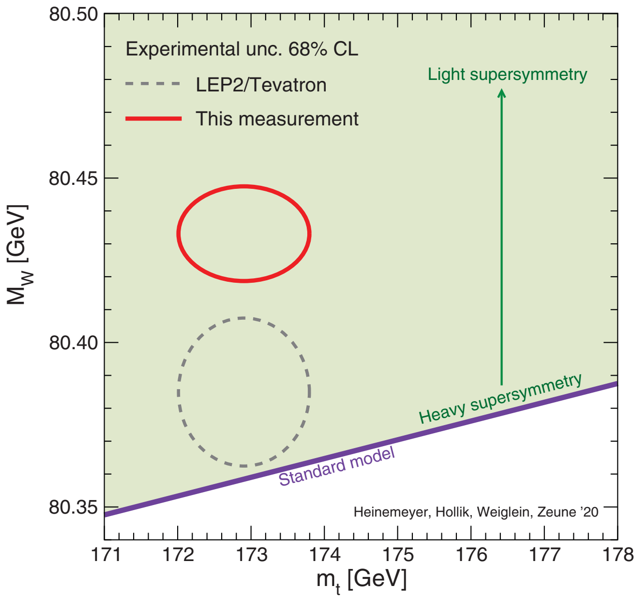
	A	δA	δA/A(%)
SoLID	500 ppm	3 ppm	0.6
MOLLER	0.035 ppm	0.0008 ppm	2.2
P2	0.020 ppm	0.0004 ppm	2.0

MOLLER, SoLID, and P2 all improve precision

Status of Anomalies in Standard Model Tests

Clues for BSM Physics??

1. W mass from CDF
2. g-2
3. Lack of μ-e universality in B decays



"Although these extensions could reconcile the SM with the larger W-boson mass, getting them to do so without causing inconsistencies with other predictions may prove nontrivial."

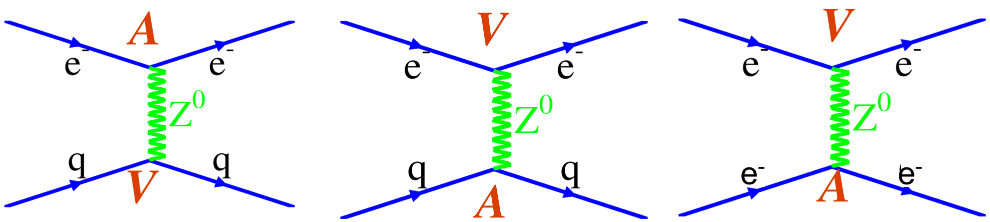
H .Hill, Physics Today

Should we use the ideas behind the Standard Model to exclude BMS models?

BSM Physics Talks: Updating our Physics Case

- Dark Z and New Parity Violating Processes
  - Hooman Davoudiasi
- SMEFT Projections using EIC PVDIS Asymmetries
  - Kagan Simsek
- Dark Photons and PVES
  - Anthony Thomas
- The P2/MREX Experiment
  - Malte Wilfert

PVES Lagrangian



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

$$\mathcal{L}^{PV} = \frac{G_F}{\sqrt{2}}[\bar{e}\gamma^\mu\gamma_5 e(C_{1u}\bar{u}\gamma_\mu u + C_{1d}\bar{d}\gamma_\mu d)$$
$$+\bar{e}\gamma^\mu e(C_{2u}\bar{u}\gamma_\mu\gamma_5 u + C_{2d}\bar{d}\gamma_\mu\gamma_5 d)$$

$$\begin{aligned}
C_{1u} &= -\tfrac{1}{2}+\tfrac{4}{3}\sin^2\theta_W \approx -0.19\\
C_{1d} &= \tfrac{1}{2}-\tfrac{2}{3}\sin^2\theta_W \approx 0.35\\
C_{2u} &= -\tfrac{1}{2}+2\sin^2\theta_W \approx -0.04\\
C_{2d} &= \tfrac{1}{2}-2\sin^2\theta_W \approx 0.04
\end{aligned}$$

$C_{ij}=C_{ij}^{SM}+C_{ij}^{BSM}$ ← Tree only

Renormalized

SMEFT: C_{ij}^{BSM}: are linear combinations of the $C^{ij}{}_6$

$$\mathcal{L} = \sum_d \sum_{ij} \frac{C_d^{ij}}{\Lambda^{4-d}}\mathcal{O}_d^{ij}$$

$$\mathcal{O}_d^{ij} = \bar{e}_i\gamma_\mu e_i \bar{f}_j\gamma^\mu f_j$$

$$e_{L/R} = \frac{1}{2}(1\mp\gamma^5)\psi_e$$

$$\mathcal{O}_d^{ij} = LL_f,\ LR_f,\ RL_f,\ RR_f$$

SMEFT: Useful for Global analysis.

Goals of SoLID, MOLLER, and P2

$$A_{PV} = Q_W^e \frac{Q^2 G_F}{\sqrt{2}\pi} \left(\frac{1-y}{1+y^4+(1-y)^4} \right)$$

Moller (Simple formula)

$$A_{PV} = \frac{G_F Q^2}{\pi \sqrt{2}} (Q_W^p + A_M + A_s + A_A)$$

P2: eP (Simple formula at low E and θ)

$$A^{PV} = \left(\frac{G_F Q^2}{4\sqrt{2}\pi} \right) (Y_1 a_1 + Y_3 a_3)$$

SoLID PVDIS (Simple for d at large E and θ, only way to get C_2's)

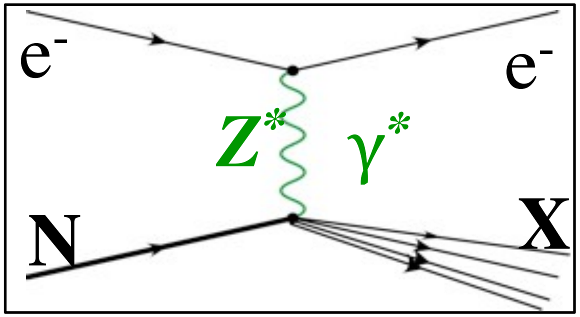
$$a_1^d = \frac{6}{5}(2C_{1u} - C_{1d}); \quad a_3^d = \frac{6}{5}(2\underline{C_{2u}} - \underline{C_{2d}})$$

$$Q_W(Z,N) = -2[\underline{C_{1u}}(2Z+N) + \underline{C_{1d}}(Z+2N)]$$

$$Q_W(e) = -2\underline{C_{2e}}$$

Measure all the C's as precisely as possible

PVDIS for eD Scattering



$$A_{PV} = \frac{G_F Q^2}{2\sqrt{2}\pi\alpha}\left[g_A \frac{F_1^{\gamma Z}}{F_1^{\gamma}} + g_V \frac{f(y)}{2}\frac{F_3^{\gamma Z}}{F_1^{\gamma}}\right]$$

$x \equiv x_{Bjorken}$

$y \equiv 1 - E'/E$

$Q^2 >> 1\ GeV^2$, $W^2 >> 4\ GeV^2$

$$A_{PV} = \frac{G_F Q^2}{\sqrt{2}\pi\alpha}\left[a(x) + f(y) b(x)\right]$$

$$A_{\rm iso} = \frac{\sigma^l - \sigma^r}{\sigma^l + \sigma^r} = -\left(\frac{3G_F Q^2}{\pi\alpha 2\sqrt{2}}\right)\frac{2C_{1u} - C_{1d}(1+R_s) + Y(2C_{2u} - C_{2d})R_v}{5 + R_s}$$

$$R_s(x) = \frac{2S(x)}{U(x)+D(x)} \xrightarrow{\text{Large } x} 0$$

$$R_v(x) = \frac{u_v(x)+d_v(x)}{U(x)+D(x)} \xrightarrow{\text{Large } x} 1$$

At high x, A_{iso} becomes independent of pdfs, x & W, with well-defined SM prediction for Q^2 and y

Standard Model Effective Field Theory (SMEFT)

$$\mathcal{L} = \sum_d \sum_{ij} \frac{C_d^{ij}}{\Lambda^{4-d}} \mathcal{O}_d^{ij}$$

$$\mathcal{O}_d^{ij} = \bar{e}_i \gamma_\mu e_i \bar{f}_j \gamma^\mu f_j$$

$$e_{L/R} = \frac{1}{2}(1 \mp \gamma^5)\psi_e$$

$$\mathcal{O}_d^{ij} = LL_f,\ LR_f,\ RL_f,\ RR_f$$

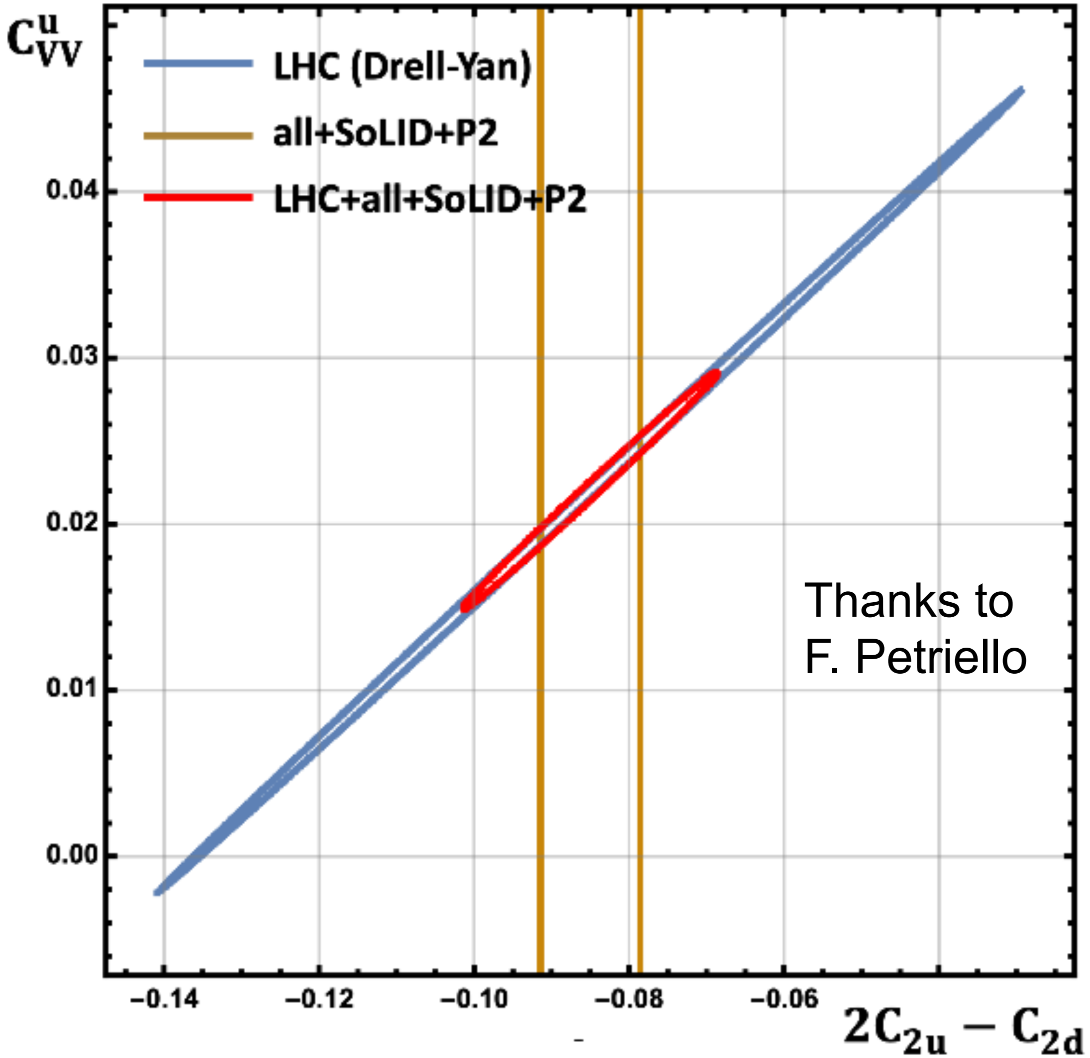
SMEFT analysis identifies all possible BSM physics

84 d=6; 993 d=8 independent couplings

Goal: Measure each C_d^{ij} as precisely as possible (Nobody really knows where the new physics is.)

SMEFT also identifies regions of exclusion from world data sets

SMEFT Analysis with LHC Drell-Yan and SoLID



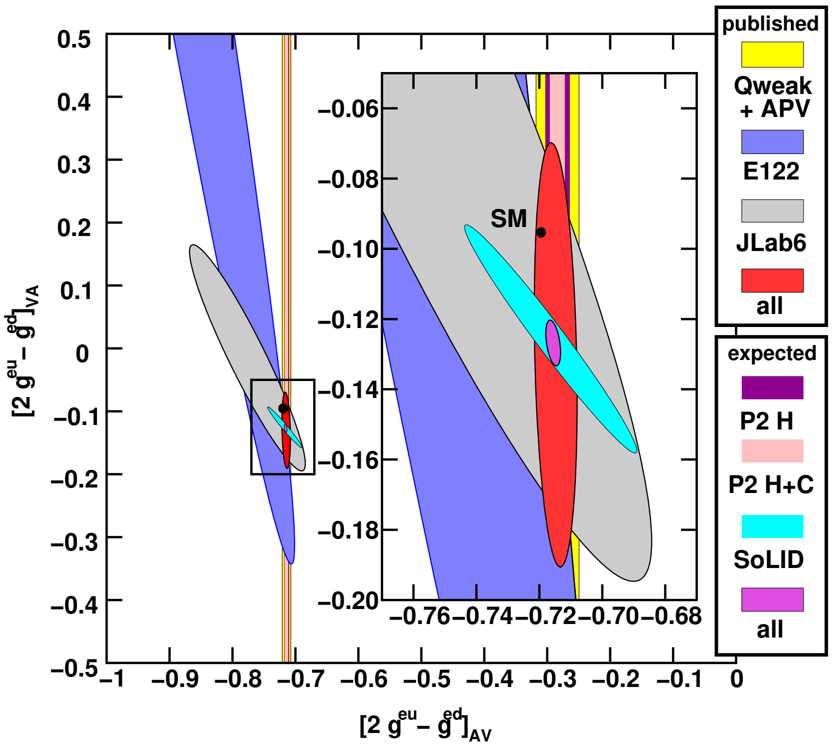
Shows complementarity of LHC and SoLID data.
Would like a model-independent fit with no assumptions.

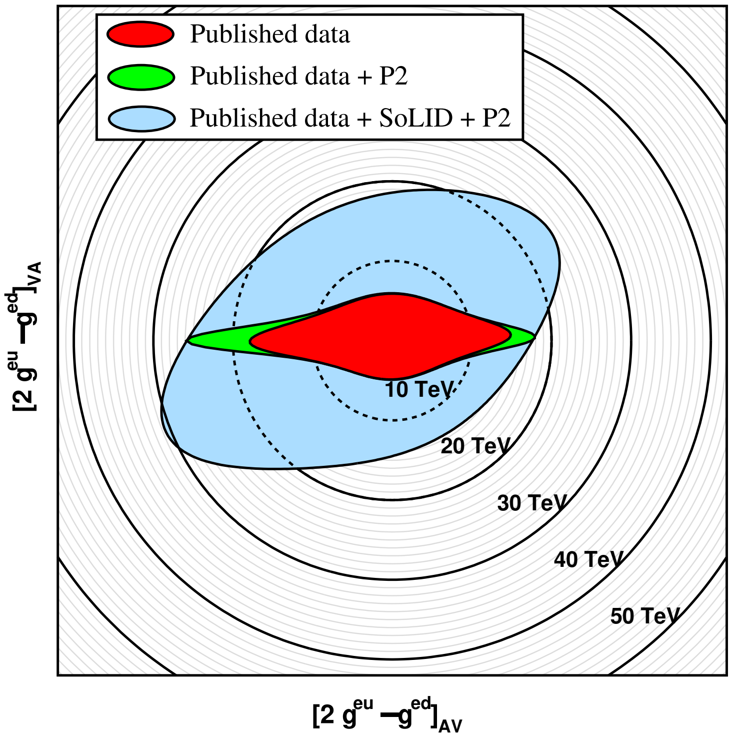
Projected Results

With this precision,
SoLID makes a unique contribution
to the SMEFT program.

Improvement in couplings

Improvement in energy reach for electron-nucleon couplings





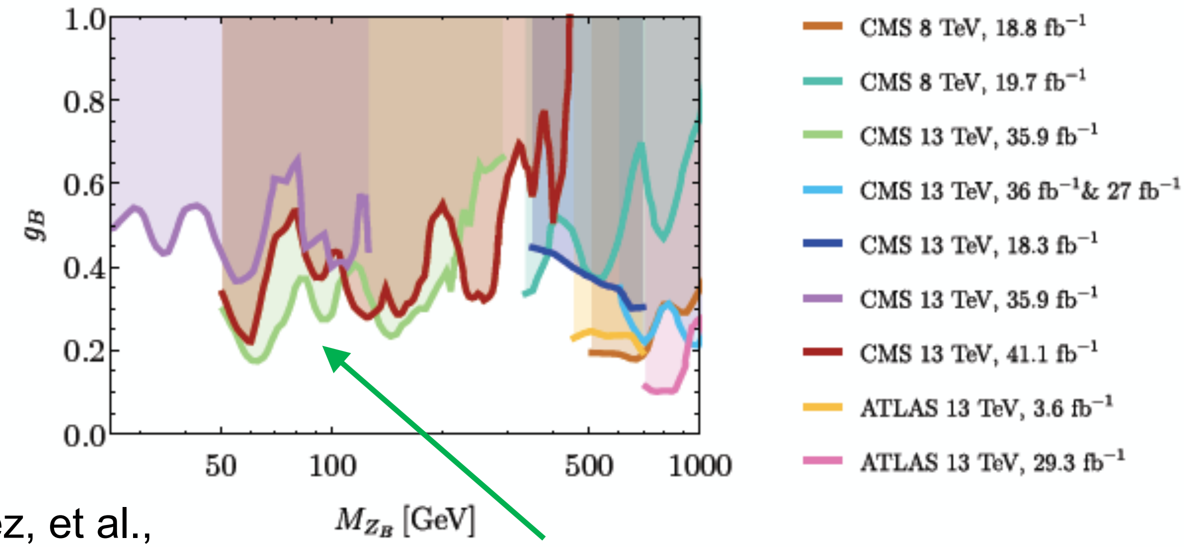
Possible Lepto-Phobic Z'; Example at lower energy

Motivation for introducing new particle:

$$A \sim \frac{(gB)2}{(M_{Z'})^2}$$

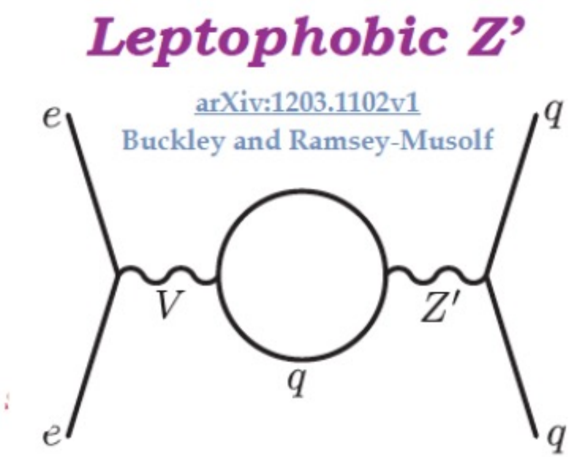
Baryon number is a global symmetry in the SM (bad).
Theories of local baryon number symmetry are attractive.
They predict a lepto-phobic boson.
They also predict a dark matter candidate.

Perez, Phys. Rept. 597, (2015) 1-30



Perez, et al., *JHEP* 07 (2020) 087

Limits depend on branching ratios.

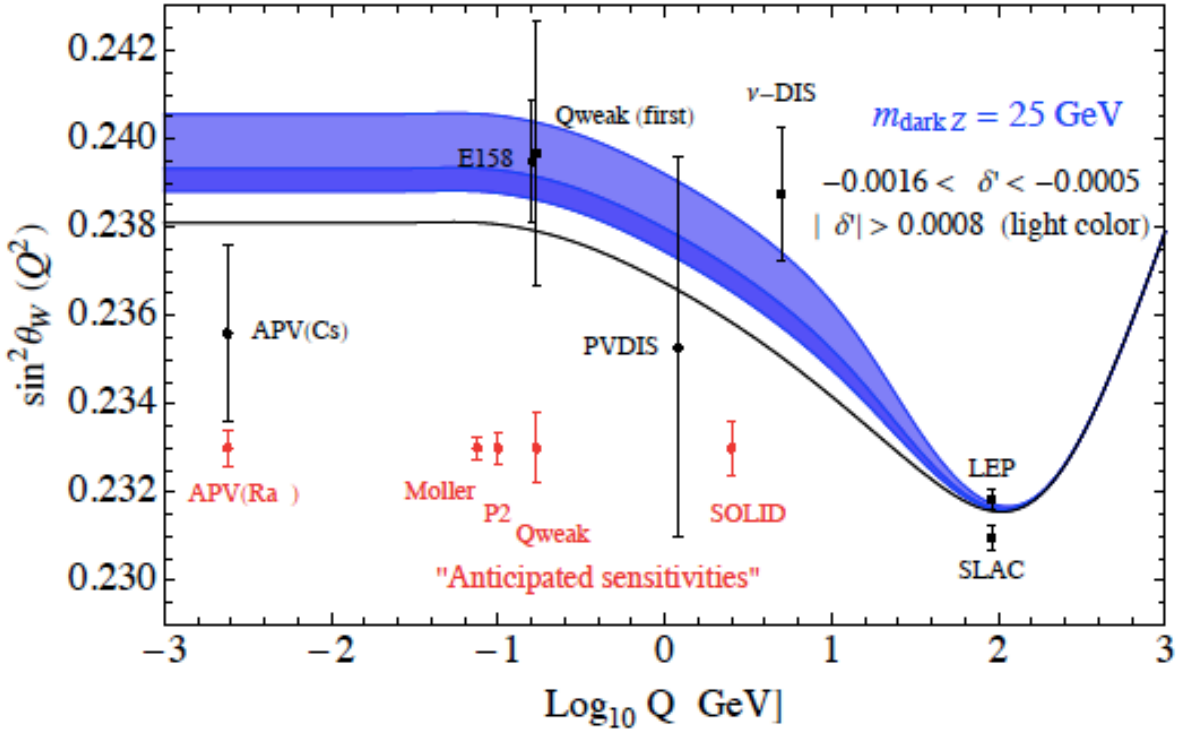


Modifies mainly C_2's in PVES

Question: Is this Z' a useful motivation since it is not known if it is possible to write a model consistent with all other electroweak data? (cf W mass)

Dark Boson Z_d and $\sin^2\theta_W$

- *Davoudiasl, et al. Phys.Rev.D* 92 (2015) 5, 055005



PVES is the only way to see Z_d if decay is dominated by invisible particles

Will the MOLLER experiment exclude this possibility?

Method:

1. Assume Standard Model
2. Treat C_i's as function of $\sin^2\theta_W$
3. Fit to one parameter
4. SoLID C_2 sensitivity irrelevant

Theory of Hadronic Physics

1. Charge Symmetry Violation
2. Higher Twist
3. PDF's: d/u for the Proton with no Nuclear Corrections

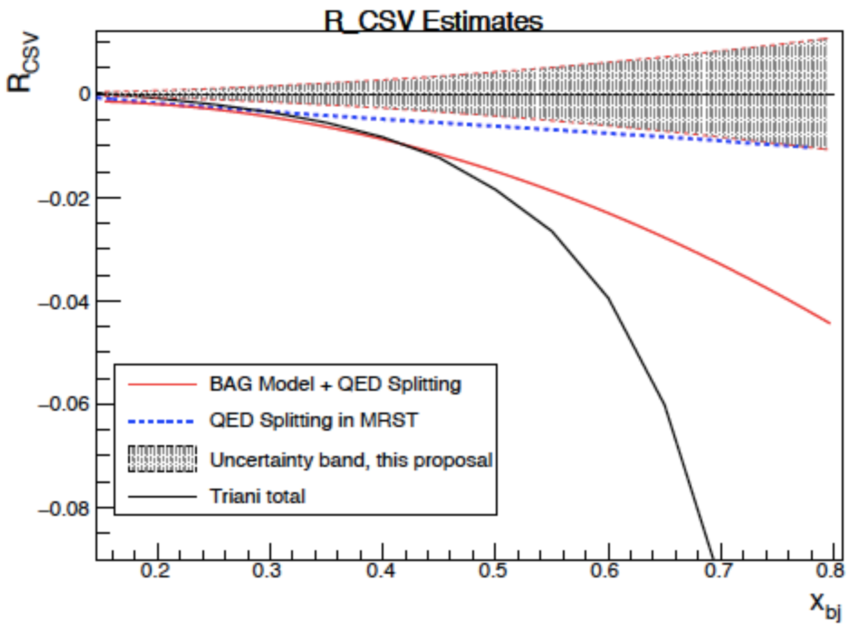
Hadronic Physics: Charge Symmetry Violation

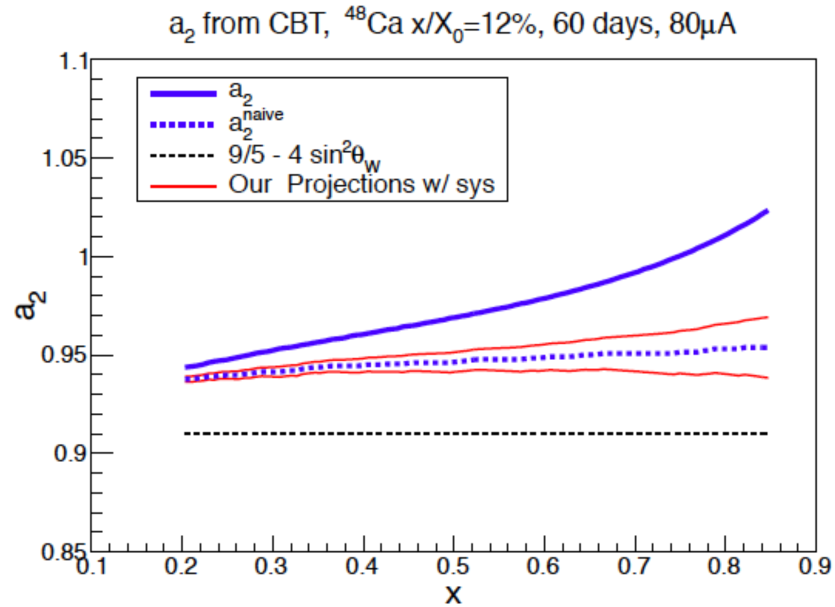
$$u^p(x) \stackrel{?}{=} d^n(x) \quad \Rightarrow \quad \delta u(x) \equiv u^p(x) - d^n(x)$$
$$d^p(x) \stackrel{?}{=} u^n(x) \quad \Rightarrow \quad \delta d(x) \equiv d^p(x) - u^n(x)$$

$$R_{CSV} = \frac{\delta A_{PV}}{A_{PV}} \approx 0.28 \frac{\delta u(x) - \delta d(x)}{u(x) + d(x)}$$

For A_{PV} in electron-^{2}H DIS

Additional contribution to NuTeV anomaly?





"The paper on PVDIS and the EMC effect highlights a way -- perhaps the best way -- to access the flavor dependence of the EMC effect using PVDIS." Ian Cloet

Unique Higher Twist Contribution

The observation of Higher Twist in PV-DIS would be exciting direct evidence for diquarks

following the approach of
Bjorken, PRD 18, 3239 (78),
Wolfenstein, NPB146, 477 (78)

$$V_\mu = \left(\bar{u}\gamma_\mu u - \bar{d}\gamma_\mu d\right) \Leftrightarrow S_\mu = \left(\bar{u}\gamma_\mu u + \bar{d}\gamma_\mu d\right)$$

$$\langle VV\rangle = l_{\mu\nu}\int \langle D|V^\mu(x)V^\nu(0)|D\rangle e^{iqx} d^4x$$

Isospin decomposition
before using PDF's

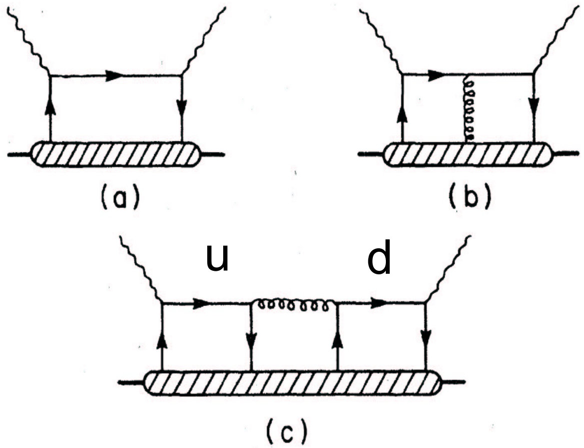
$$A_{PV} = \frac{G_F Q^2}{\sqrt{2}\pi\alpha}\left[a(x) + f(y)b(x)\right]$$

$$\delta = \frac{\langle VV\rangle - \langle SS\rangle}{\langle VV\rangle + \langle SS\rangle} \qquad a(x) \propto \frac{F_1^{\gamma Z}}{F_1^\gamma} \propto 1 - 0.3\delta$$

Higher-Twist valence quark-quark correlation

Zero in quark-parton model

$$\langle VV\rangle - \langle SS\rangle = \langle (V-S)(V+S)\rangle \propto l_{\mu\nu}\int \langle D|\bar{u}(x)\gamma_\mu u(x)\bar{d}(0)\gamma_\nu d(0)|D\rangle e^{iqx} d^4x$$



(c) type diagram is the only operator that can contribute to a(x) higher twist: theoretically very interesting!

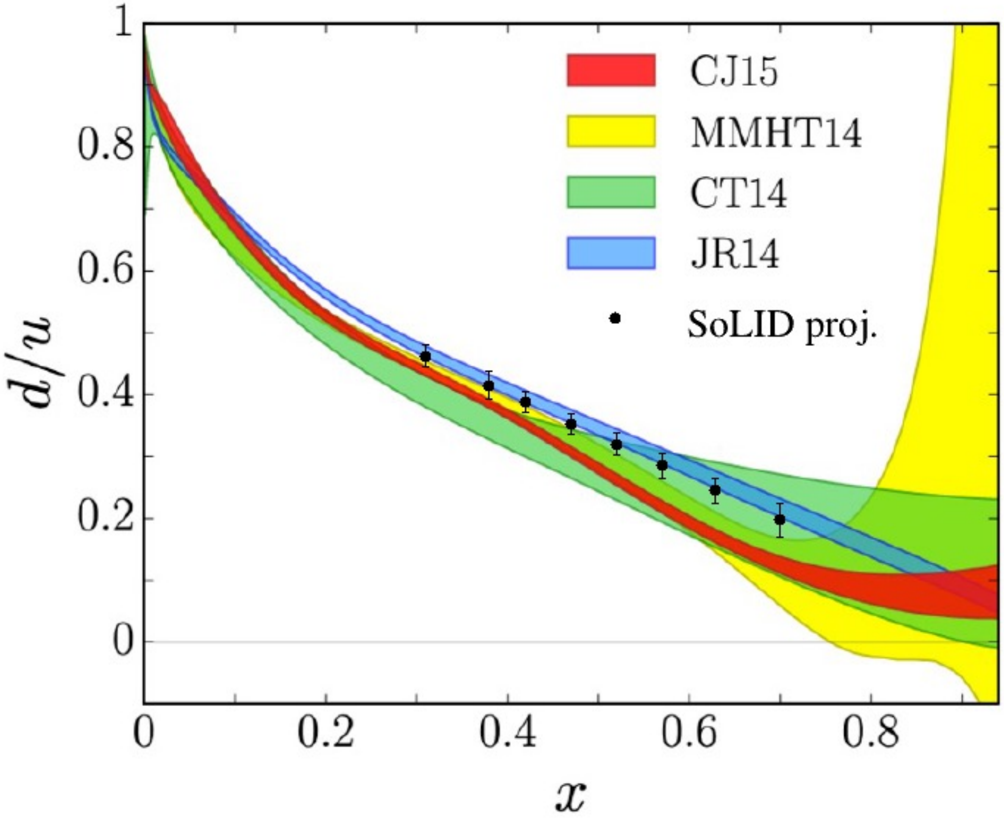
σ_L contributions cancel

Structure Function Ratio d/u for the Proton

$$A_{PV} = \frac{G_F Q^2}{\sqrt{2}\pi\alpha}\left[a(x) + f(y)b(x)\right]$$

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

Phys. Rev. D 87 (2013) 094012



PVDIS is complementary to the rest of the JLab d/u program.

PVDIS has no nuclear effects

Hadron Physics Talks: Can we update our Physics Case?

- Overview of d/u and SoLID Contribution Violating
  - Cynthia Keppel
- MARATHON experiment, d/u and Radiative Corrections
  - Hanjie Liu
- Parity-Violating Measurements of the Flavor Dependence of the EMC Effect
  - John Arrington
- The Role of Apv in Hadron Structure Studies
  - Nobuo Sato

PAC Jeopardy Question

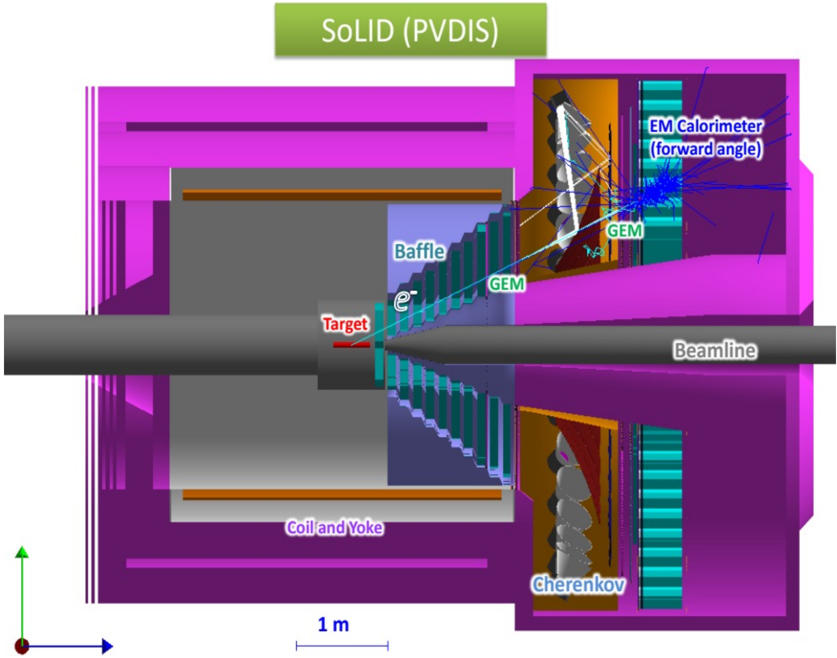
Is there any new information that would affect the scientific importance or impact of the Experiment since it was originally proposed?

- BSM tests with PVES: Still strong
  - Lack of SUSY helps
  - Lack of any BSM physics form the LHC is unfortunate
- CSV: more interest
- Nuclear effects in d/u: New data increases interest
  - Marathon
  - Bonus

SoLID Apparatus for PVDIS

Kinematic Requirements

- High Luminosity with E ~ 11 GeV
- Only electron is detected.
- Wide x-range: 0.25-0.75: untangle physics.
- W^2 > 4 GeV: Isolate DIS events.
- Large scattering angles ~22° < θ < ~35° : (for high x & y).
- Large azimuthal acceptance.
- Better than 1% statistical errors for small bins
- Q^2 range a factor of 2 for each x bin: Measure Higher Twist.
  - (Except at very high x)
- 2 GeV < E′< 6 GeV: Low background
- ~2% Momentum resolution

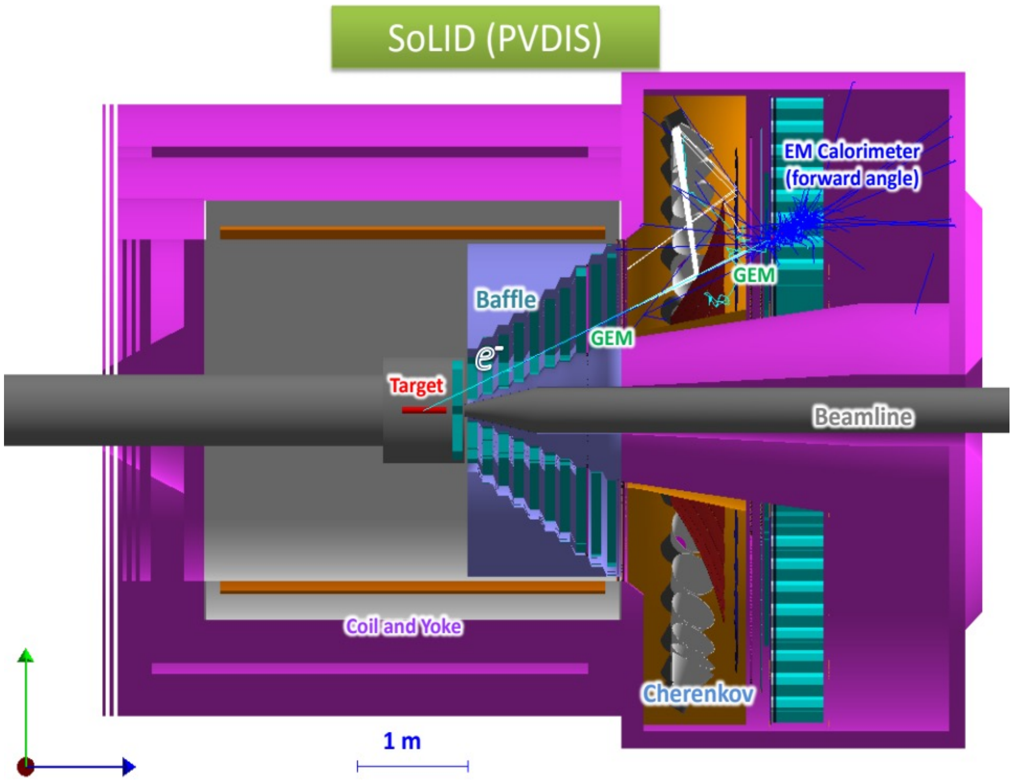


CLEO magnet with the LD_2 or LH_2 target in the center provides the desired acceptance.

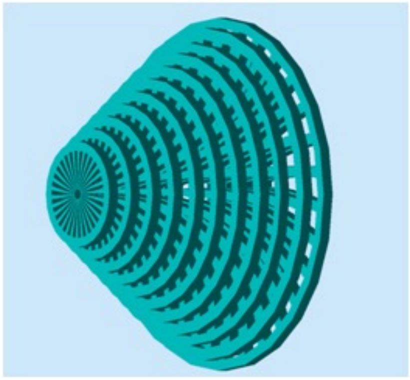
SoLID Apparatus

Achieving High Luminosity

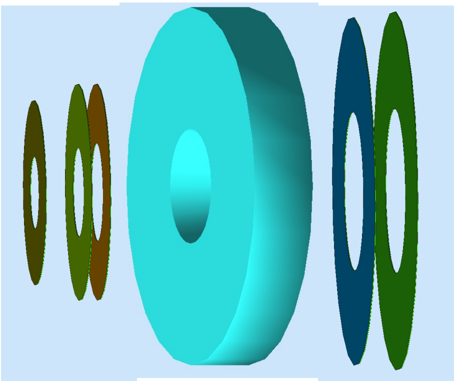
- 50 μA beam current.
- 40 cm LD_2 and target
- >30% azimuthal coverage with baffles which provide curved channels that block positive and neutral background particles
- Azimuthally symmetric.
- High-rate GEM tracking Chambers



Baffles



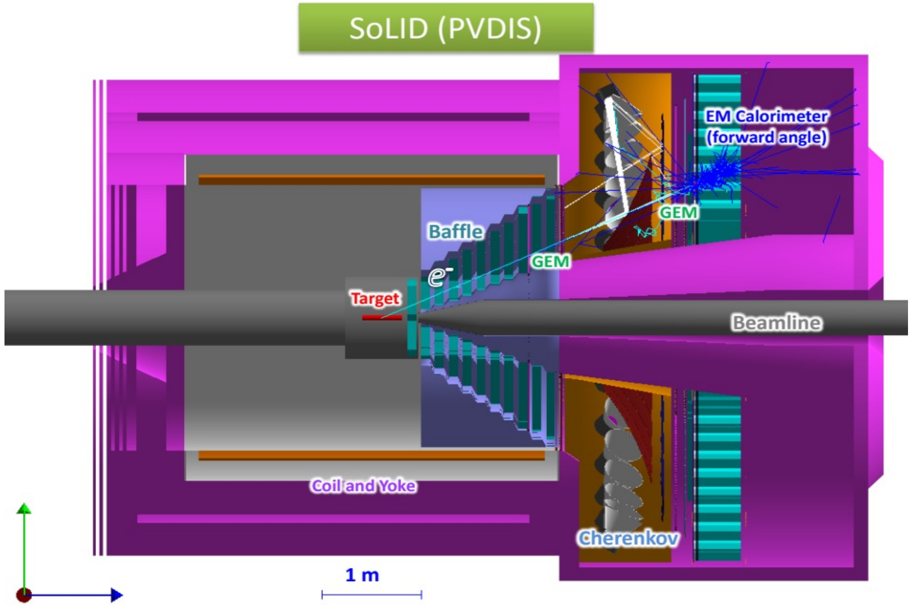
GEM Chambers

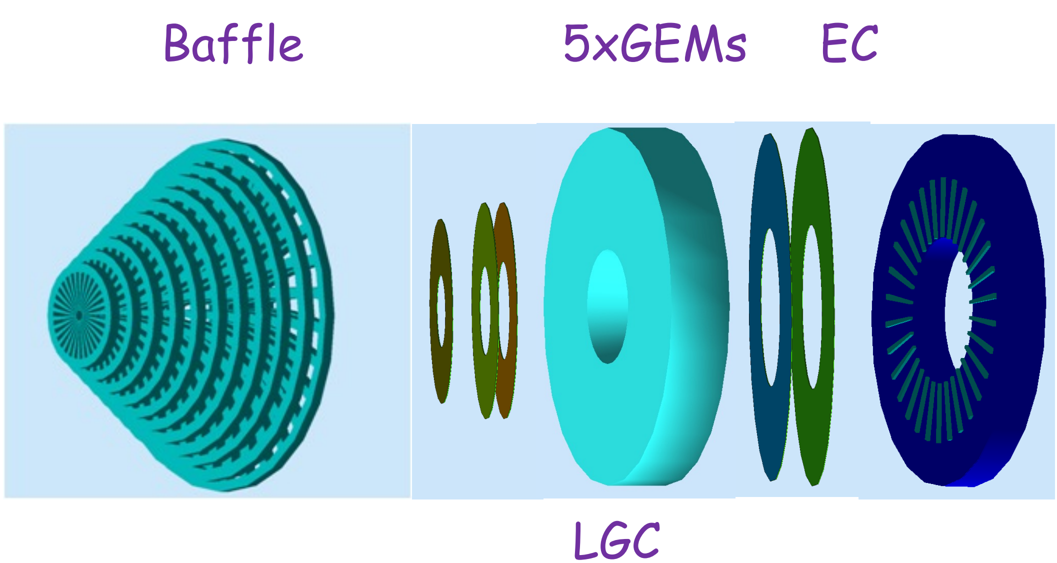


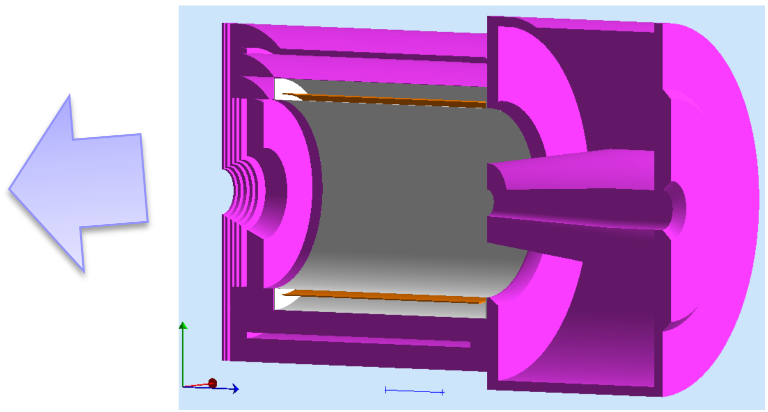
SoLID Apparatus

Requirements for Particle Identification and Trigger

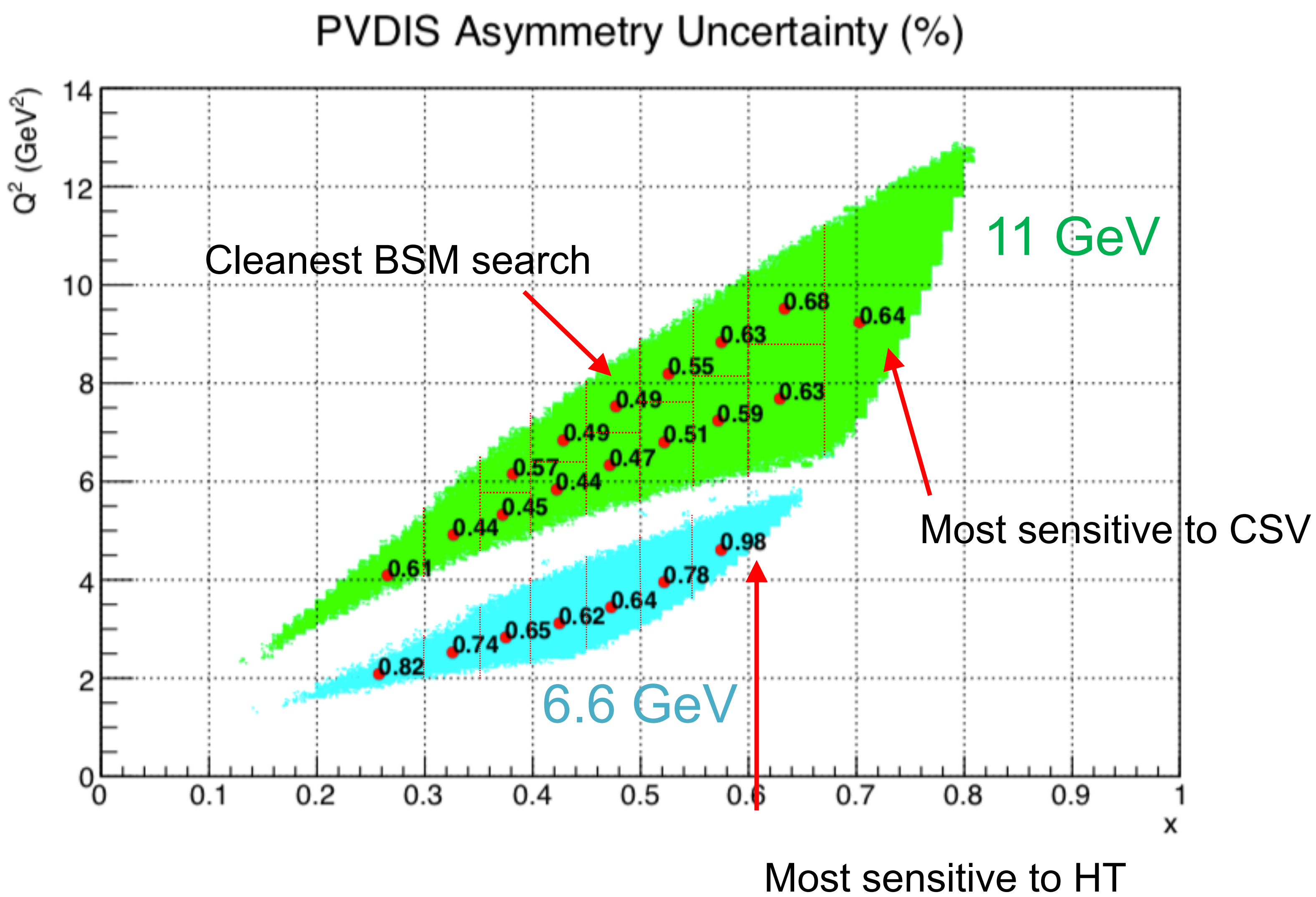
- Light Gas Cherekkov: identify electrons for trigger; reject pions.
- Shashlyk electromagnetic calorimeter (ECal) : coincident trigger and further particle identification.
- With tracking, tight E/p cuts reduce pion backgrounds.







Projected Statistical Precision



Untangling the Physics

Kinematic dependence of physics topics:

	x	Y	Q^2
New Physics	none	yes	small
CSV	yes	small	small
Higher Twist	large?	no	large

$$A_{\text{Meas.}} = A_{\text{SM}} \left[1 + \frac{\beta_{\text{HT}}}{(1-x)^3 Q^2} + \beta_{\text{CSV}} x^2 \right]$$

	A_{SM}	β_{HT}	β_{CSV}
A_{SM}	1	0.18	-0.67
β_{HT}	0.18	1	-0.81
β_{CSV}	-0.67	-0.81	1

Summary of Experimental Error Budget

Total	0.6
Polarimetry	0.4
Q2	0.2
Radiative Corrections	0.2
Event reconstruction	0.2
Statistics	0.3

Energy(GeV)	4.4	6.6	11	Test
Days(LD2)	18	60	120	27
Days(LH2)	9	-	90	14

169 Days are Approved

Plans for Radiative Corrections

- Start with DJANGOH Monte Carlo event generator
  - Includes complete one-loop electroweak corrections
  - Includes real radiation (radiative tails)
  - Developed for H1 and Zeus
  - Recently updated and used by COMPASS and for EIC studies
- Additional corrections needed for our lower Q^2 and W
  - Final state hadron in internal radiation are sometimes at low W
  - Gamma-Z and Gamma-Gamma boxes need QCD corrections
  - Etc.
- We would like input to develop a detailed plan with an estimate of the effort required for reaching our 0.2% precision goal for radiative corrections to A_{PV}

Talks on Radiative Corrections

- High-Precision Radiative Corrections
  - Hubert Spiesberger
- Box Diagrams for Elastic PVES and Relevance for DIS
  - Misha Gorchtein
- Radiative Correction Methods Used at Jlab
  - Xiaochao Zheng
- BNSSA DIS Measurement with SoLID
  - Michael Nycz
- TMD in Radiative Corrections and SSA Calculations
  - Andrei Afanasev
- The New Method of Radiative Corrections for PVDIS
  - Tianbo Liu

PDF Errors

- Error in $\sin^2\theta_W$ due to various PDF errors.

$$a_1(x) = \frac{6\left[2C_{1u}(1+R_C) - C_{1d}(1+R_S)\right]}{5+R_S+4R_C},$$
$$a_3(x) = \frac{6\left(2C_{2u} - C_{2d}\right)R_V}{5+R_S+4R_C},$$

Analysis led by X. Zheng

$$R_C \equiv \frac{2(c+\bar{c})}{u+\bar{u}+d+\bar{d}}, \quad R_S \equiv \frac{2(s+\bar{s})}{u+\bar{u}+d+\bar{d}}, \quad \text{and} \quad R_V \equiv \frac{u-\bar{u}+d-\bar{d}}{u+\bar{u}+d+\bar{d}}.$$

None	PDFLHC	JAM	CT18	NNPDF
0.00060	0.00063	0.00071	0.00077	0.00092

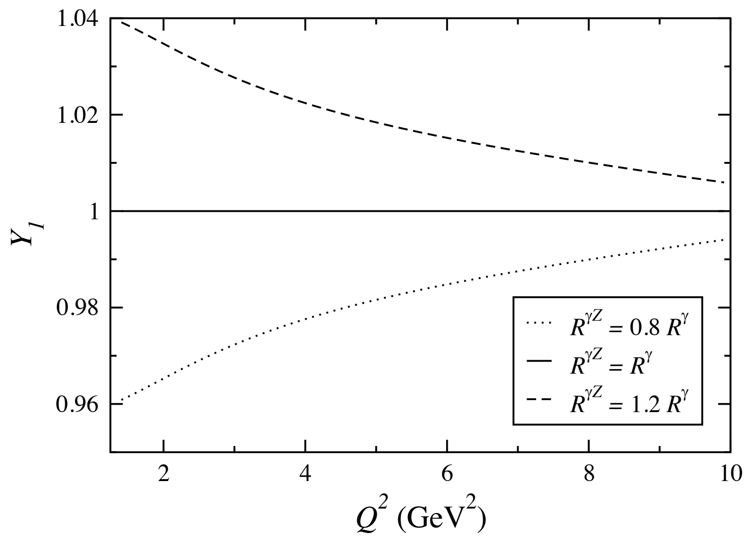
- Error estimates vary a lot, some estimates are comparable to statistical errors.
- Will SeaQuest cross section data help?
- Real question: what will PDF errors be when we publish?

Other Theory Errors Errors Such as $R_{\gamma Z}$

$$Y_1 = \left[\frac{1+R^{\gamma Z}}{1+R^{\gamma}}\right] \frac{1+(1-y)^2 - y^2\left[1-\frac{r^2}{1+R^{\gamma Z}}\right] - xy\frac{M}{E}}{1+(1-y)^2 - y^2\left[1-\frac{r^2}{1+R^{\gamma}}\right] - xy\frac{M}{E}}$$

From Hobbs and Melnitchouk, Phys. Rev. D77, (2008) 114023

$$Y_3 = \left[\frac{r^2}{1+R^{\gamma}}\right] \frac{1-(1-y)^2}{1+(1-y)^2 - y^2\left[1-\frac{r^2}{1+R^{\gamma}}\right] - xy\frac{M}{E}},$$



The consensus of previous workshops on SoLID PVDIS was that although uncertain, it is unlikely that these theoretical errors will be dominant.

Higher Twist and target mass corrections are other issues

Talks Theory Errors

- CTEQ PDF Updates
  - Tim Hobbs
- CJ PDF Updates
  - Alberto Accardi; Shujie Li
- Recent Measurements on Light Sea Quark Asymmetry from SeaQuest
  - Arun Tadepalli
- PDF4LHC21 Updates
  - Tom Cridge
- Neutrino Physics and F3gammaZ Structure Function
  - Bryan Ramson
- The New Method of Radiative Corrections for PVDIS
  - Tianbo Liu

Summary

- The SoLID Spectrometer, which is awaiting CD0 approval, has an exciting physics program in PVDIS, SIDIS, and J/Ψ production.
- The goals for experimental precision for PVDIS are aggressive.
- How can we minimize theory uncertainties?

Backups