The MOLLER Experiment

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Indiana University
JLUO Meeting June 28, 2023

MOLLER Collaboration: ~ 160 authors, 37 institutions, 6 countries

Spokesperson: K. Kumar, UMass, Amherst

Executive Board Chair and Deputy Spokesperson: M. Pitt, Virginia Tech

Other Executive Board Members

D. Armstrong (William & Mary), J. Fast (JLab), C. Keppel (JLab), F. Maas (Mainz), J. Mammei (Manitoba), K. Paschke (UVa), P. Souder (Syracuse U.)

MOLLER Working Groups

Polarized Source
Beam Instrumentation
Hydrogen Target
Spectrometer
Integrating Detectors
Tracking Detectors
Hall Integration
Polarimetry
Electronics/DAQ/Offline
Simulations
Physics Extraction

Technical Board

MOLLER Project Personnel

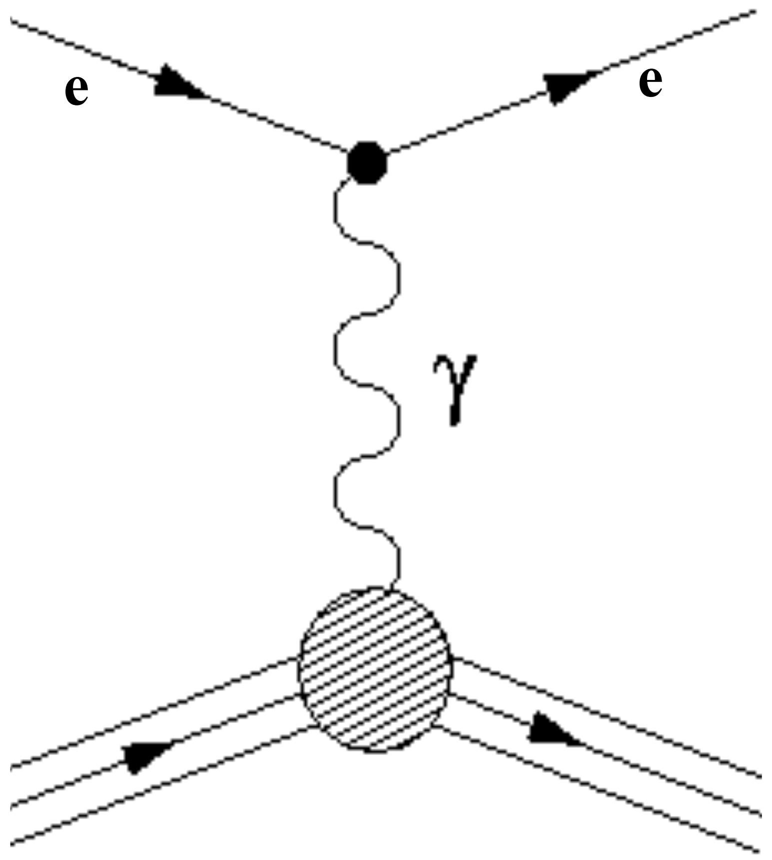
J. Fast, MOLLER Project Manager

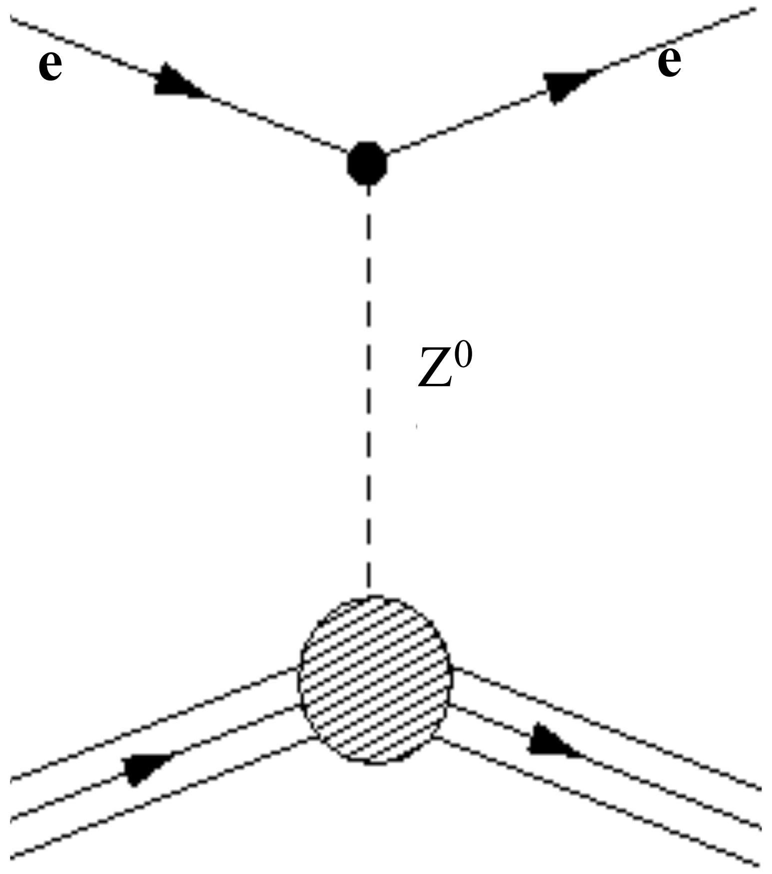
Project Leads

Control Account Managers

Technical Leads

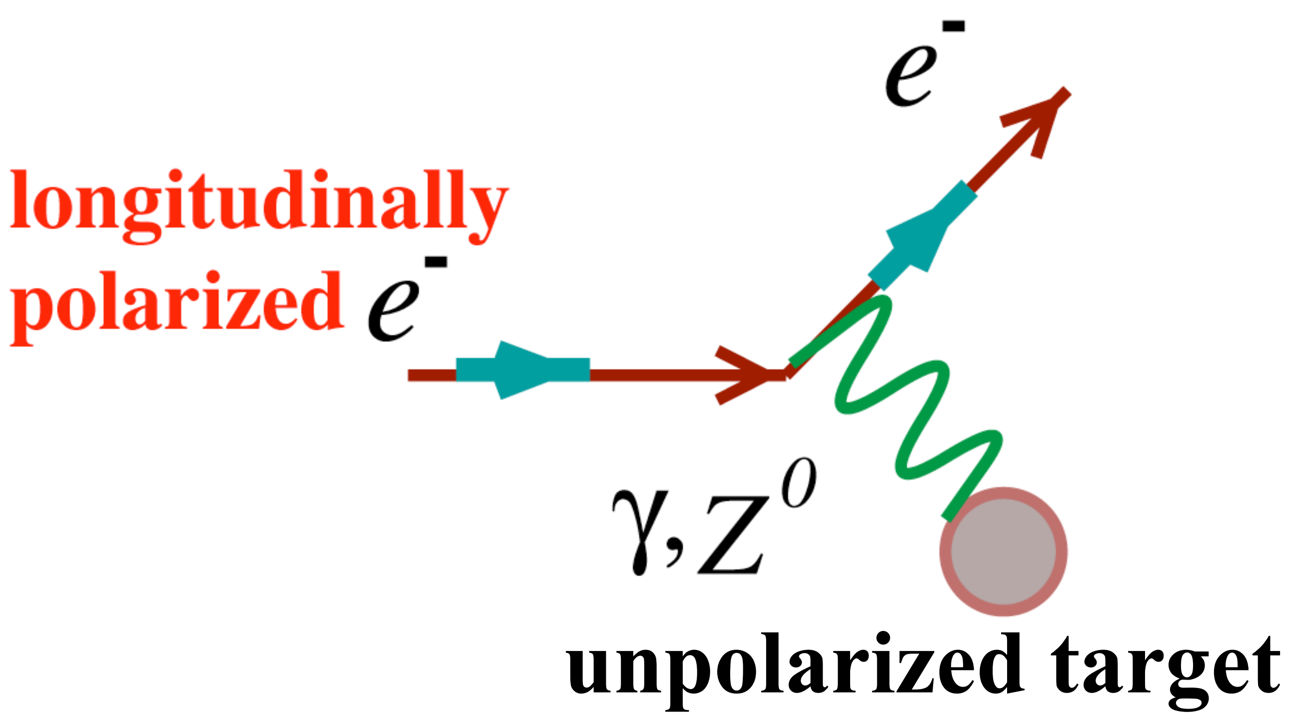
Parity-Violating Electron Scattering





$$\sigma \propto |M_\gamma + M_{weak}|^2$$
$$\sim |M_\gamma|^2 + 2M_\gamma (M_{weak})^* + \ldots$$

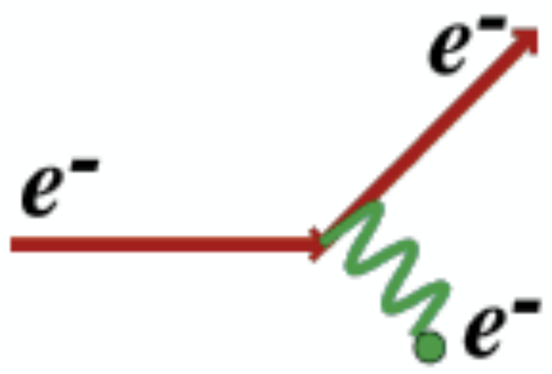
$$A_{PV} = \frac{\sigma_R - \sigma_L}{\sigma_R + \sigma_L} \propto \frac{M_\gamma^* M_W}{M_\gamma^2}$$



PVES measures Apv

- **Incident beam is longitudinally polarized**
- **Change sign of longitudinal polarization**
- **Measure fractional rate difference**

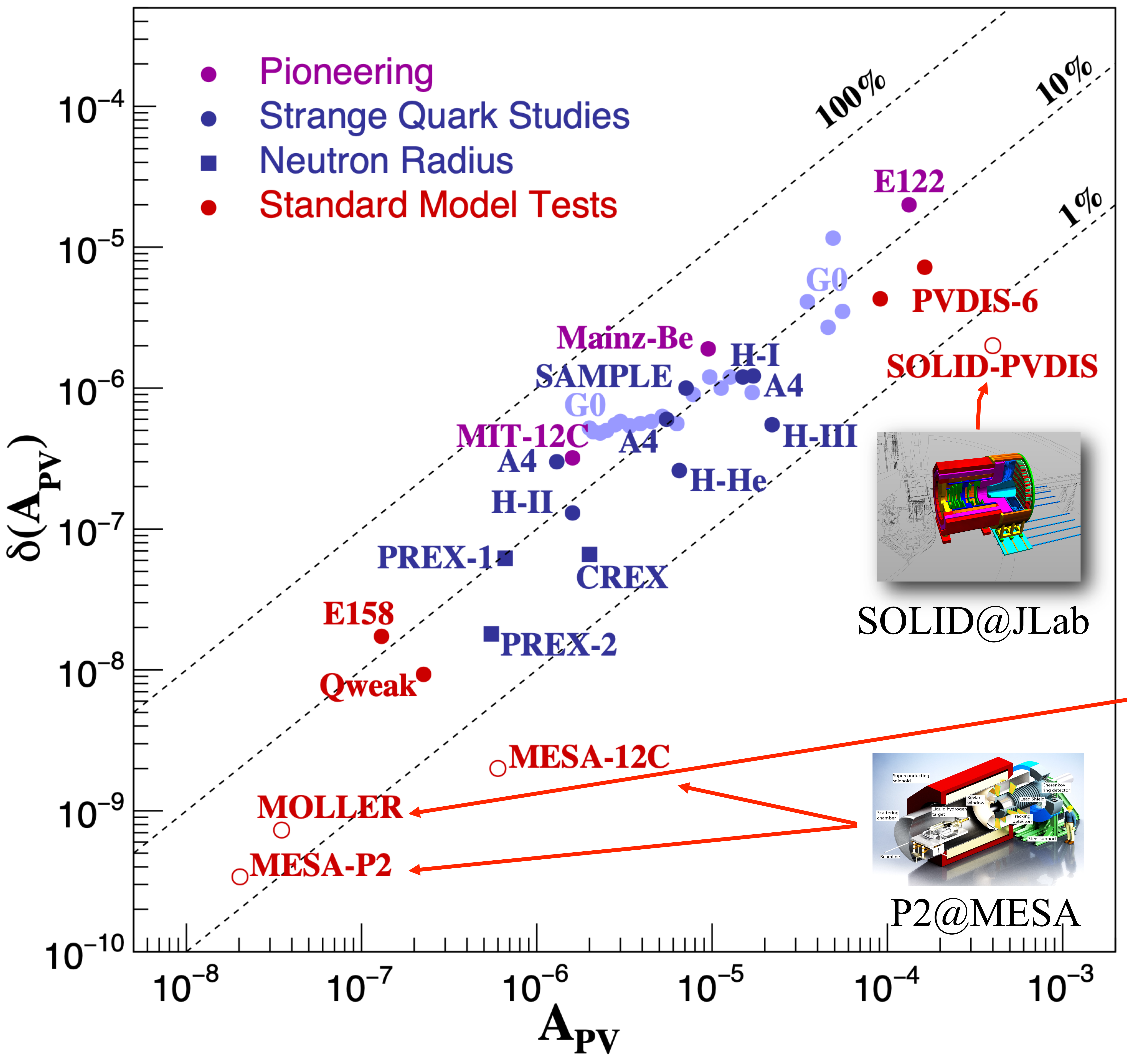
- **New physics:** measure fundamental coupling constants to test completeness of standard model



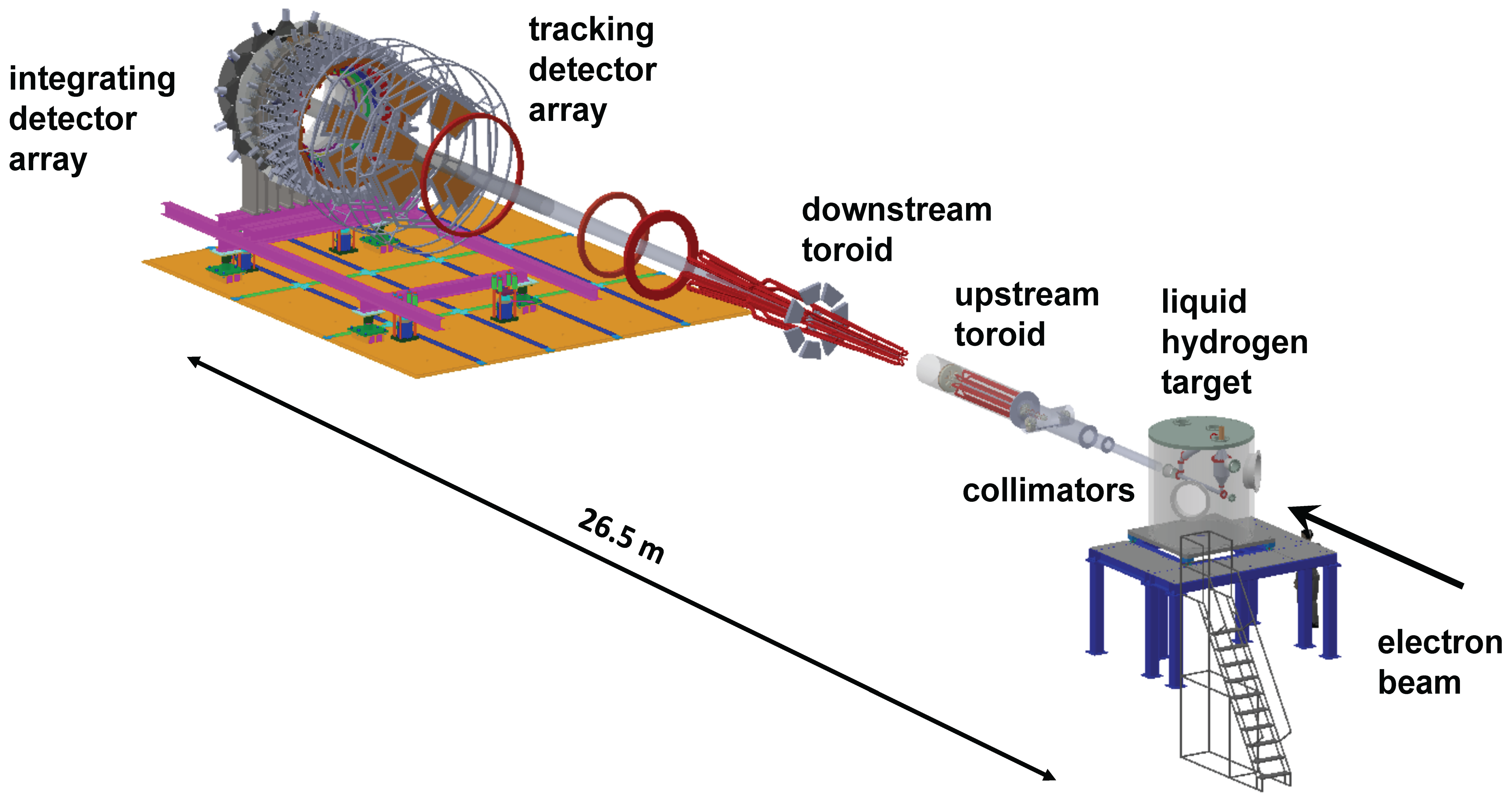
- **MOLLER:** measure fundamental constant Cee in electron-electron scattering

Next-generation Experiments will provide precise BSM probe

Broad program studying the structure of protons and nuclei, and searching for new (beyond Standard Model) physics



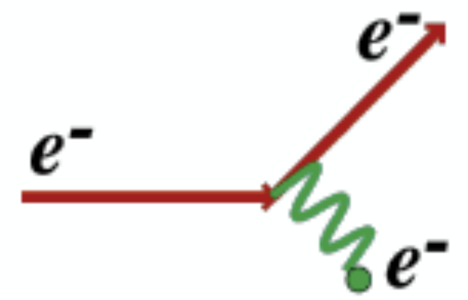
Experiments measure increasingly smaller Apv



MOLLER@JLab

Searches for New Neutral Currents

Møller (*ee*) scattering : Weak charge of the electron

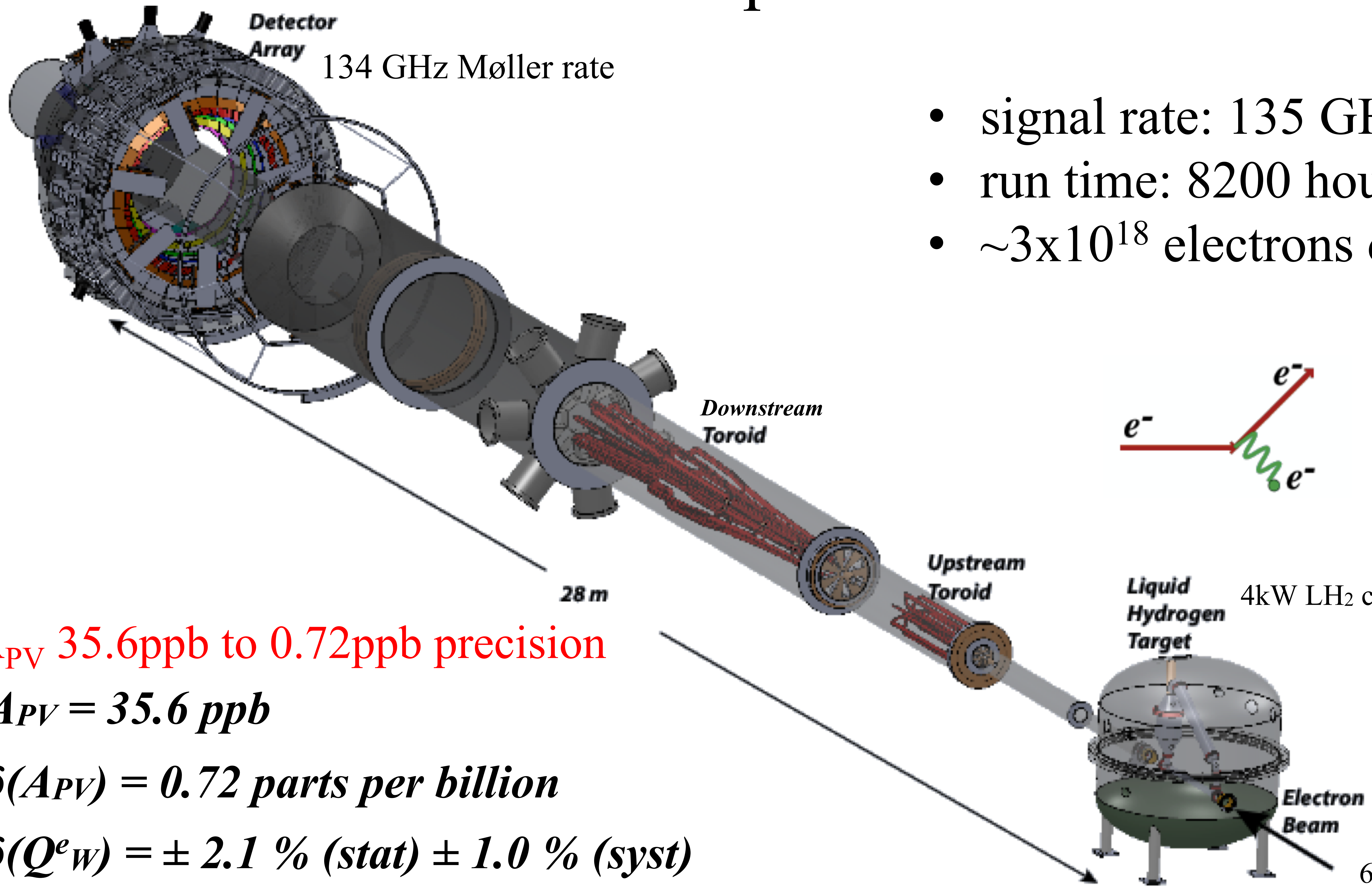


SLAC-E158 1997-2004

MOLLER

	APV	δ(APV)	δ(APV)/APV
MOLLER	35 ppb	0.8 ppb	2.2%

Moller Experiment Overview



- signal rate: 135 GHz
- run time: 8200 hours
- ~3x10^{18} electrons detected

A_{PV} 35.6ppb to 0.72ppb precision

$A_{PV} = 35.6$ *ppb*

$\delta(A_{PV}) = 0.72$ *parts per billion*

$\delta(Q^e_W) = \pm\ 2.1\ \%\ (stat) \pm\ 1.0\ \%\ (syst)$

MOLLER Purpose

- *Measure the **weak charge of the electron** to extremely high precision*
- *Constrains coupling coefficient Cee*
- *Extend the reach of new physics beyond the Standard Model*

Interference term between the electro-magnetic and weak amplitudes gives rise to parity-violating asymmetry,

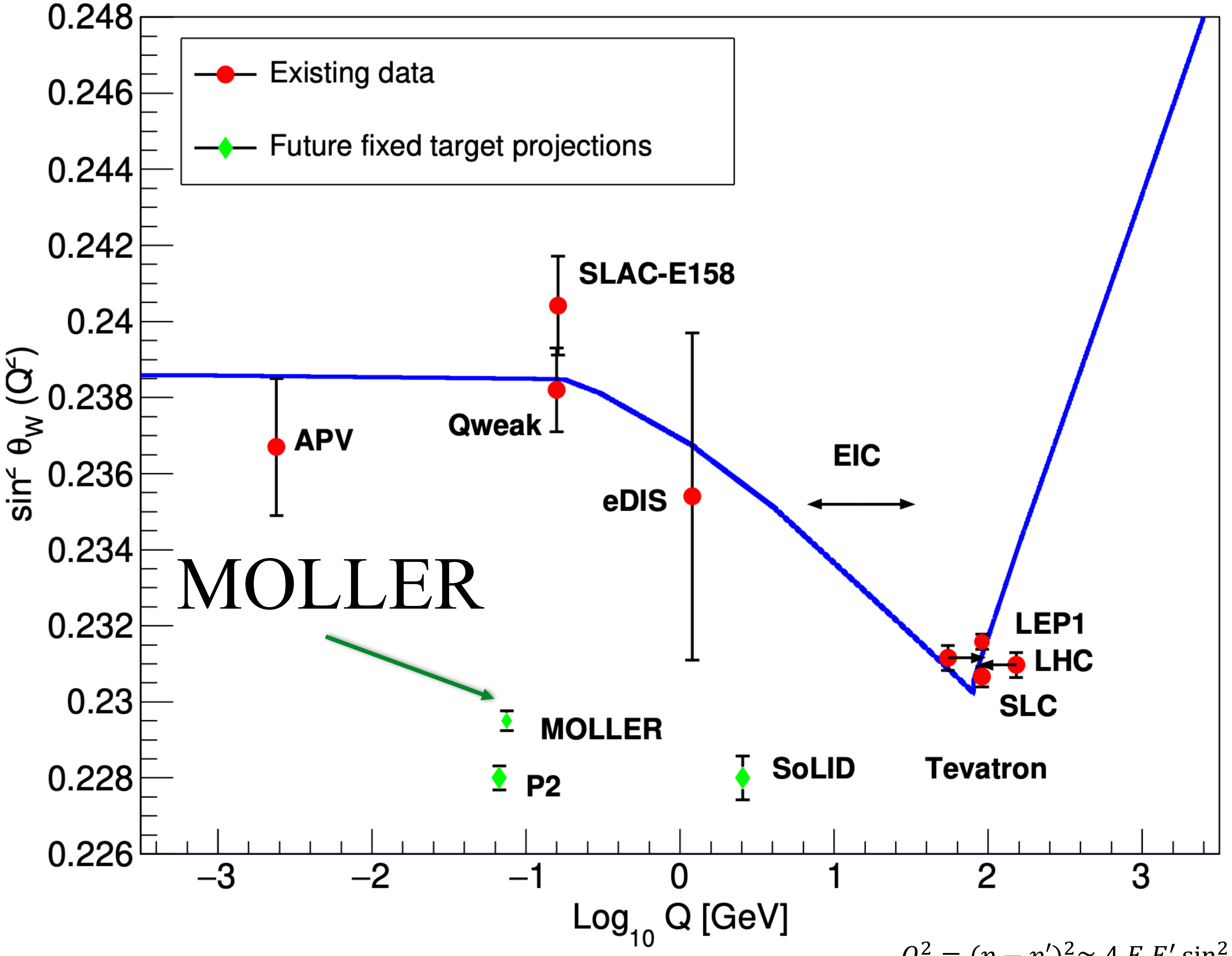
$$A_{PV} \Rightarrow Q_W^e \Rightarrow sin^2\theta_W \Rightarrow C_{ee}$$

$$Q_W^e = 1 - 4 \sin^2\theta_W = -2C_{ee}$$

which relates directly to the electron weak charge, weak mixing angle, and ee coupling coefficient

$\delta(Q^e{}_W) = \pm$ 2.1 % (stat) $\pm$ 1.0 % (syst)

$sin^2\theta_W$:±0.00026(stat) ±0.00013(syst)



$Q^2 = (p - p')^2 \approx 4\,E\,E' \sin^2(\theta/2)$

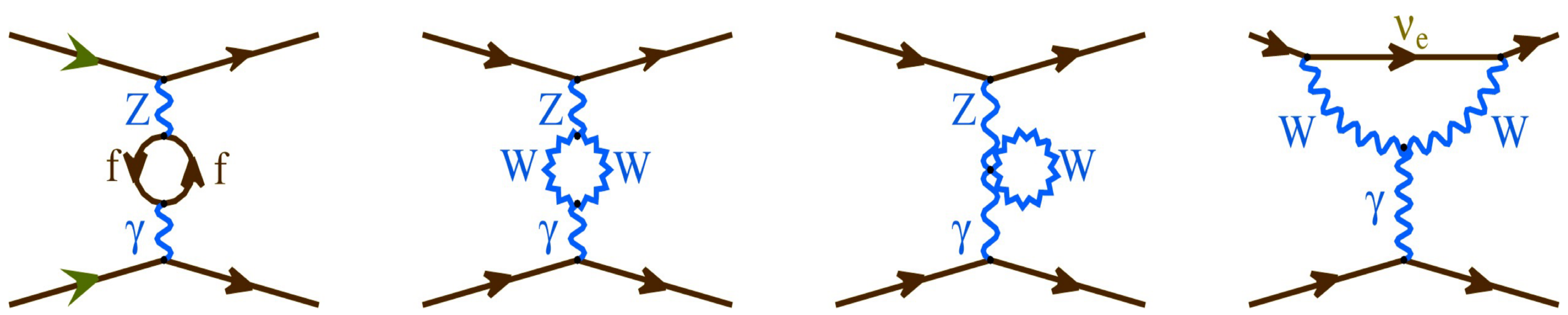
Ultra-precise measurement sensitive to new parity-violating interactions

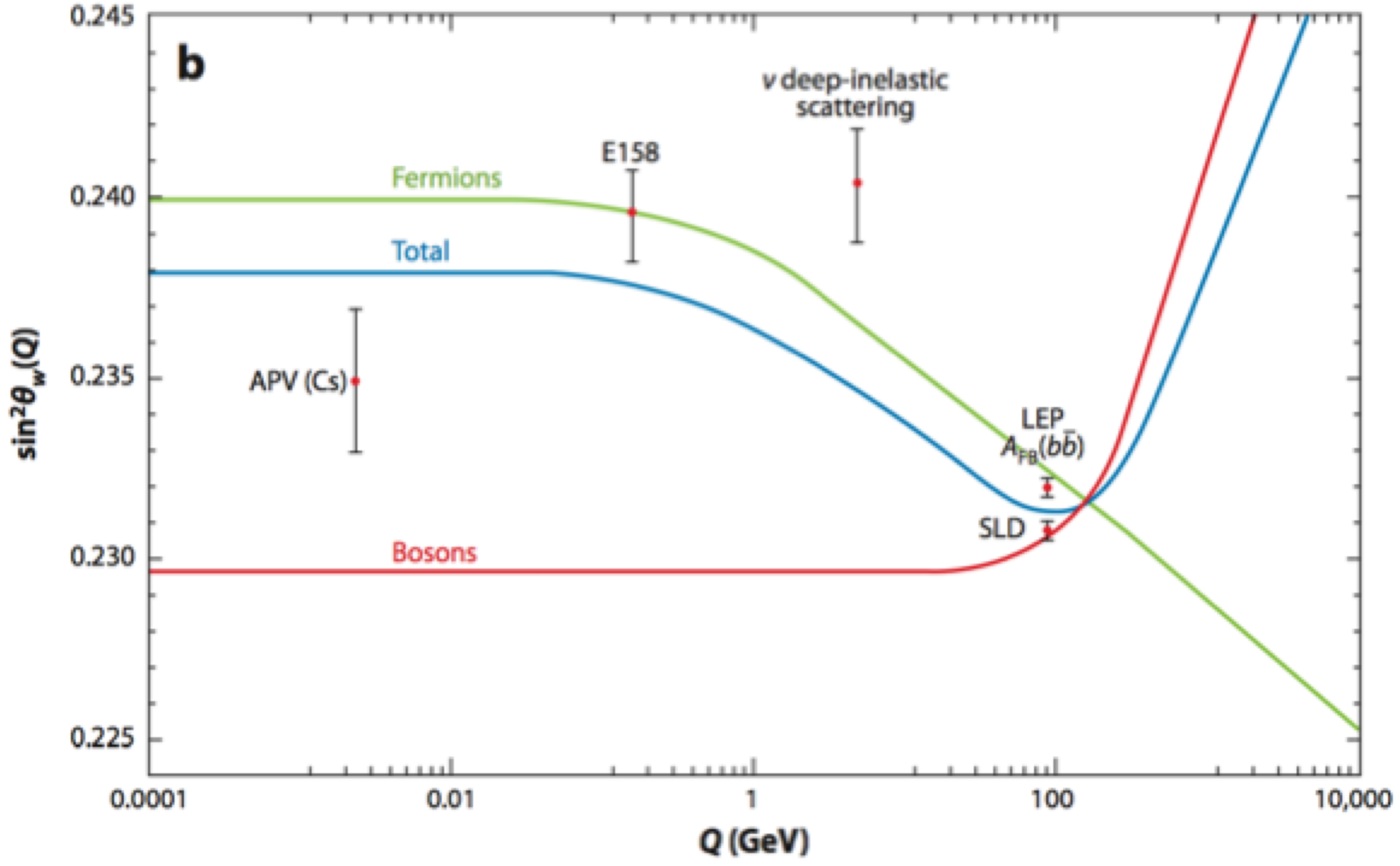
The Standard Model Prediction: Remarkably Well-Known

Theory: Standard Model prediction is tight and MOLLER measurement will constrain BSM theories

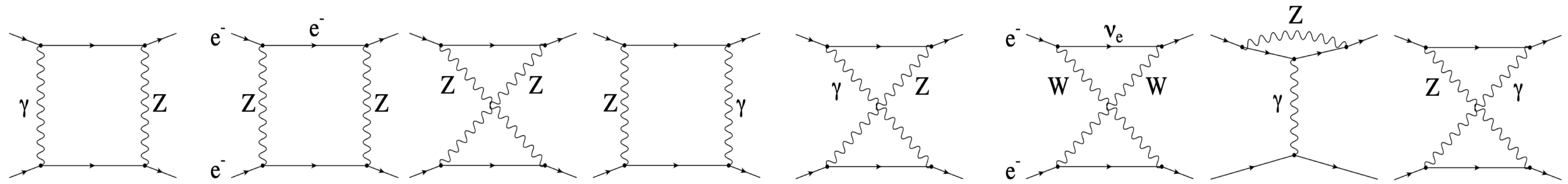
Radiative Corrections

Czarnecki and Marciano (1995)

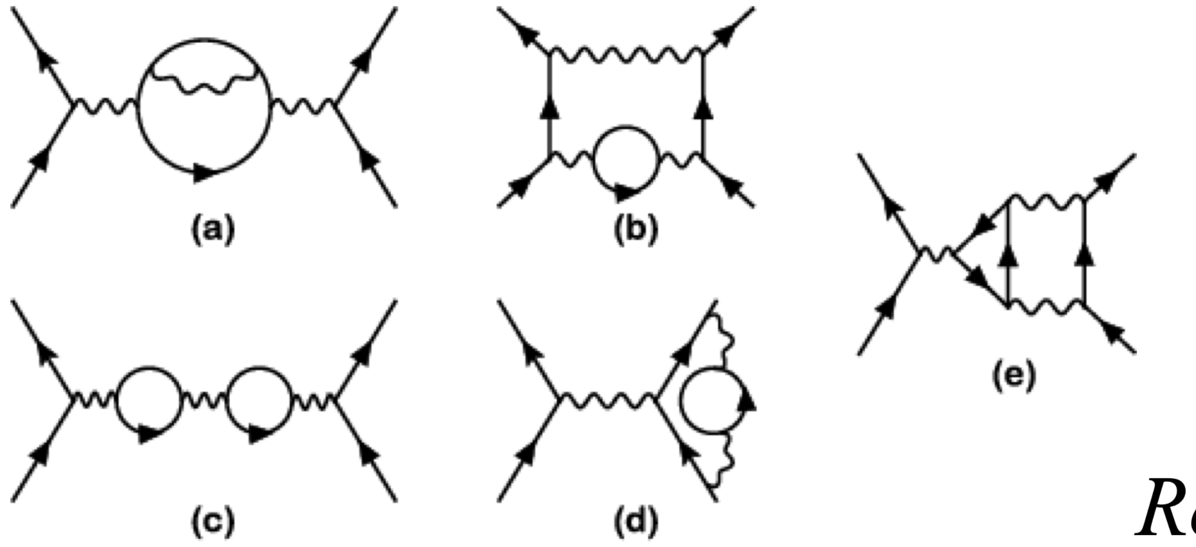




2-loop Calculations



2 groups working on 2-loop Calculations



Aleksejevs and Barkanova

Series of publications

Du, Freitas, Patel and Ramsey-Musolf

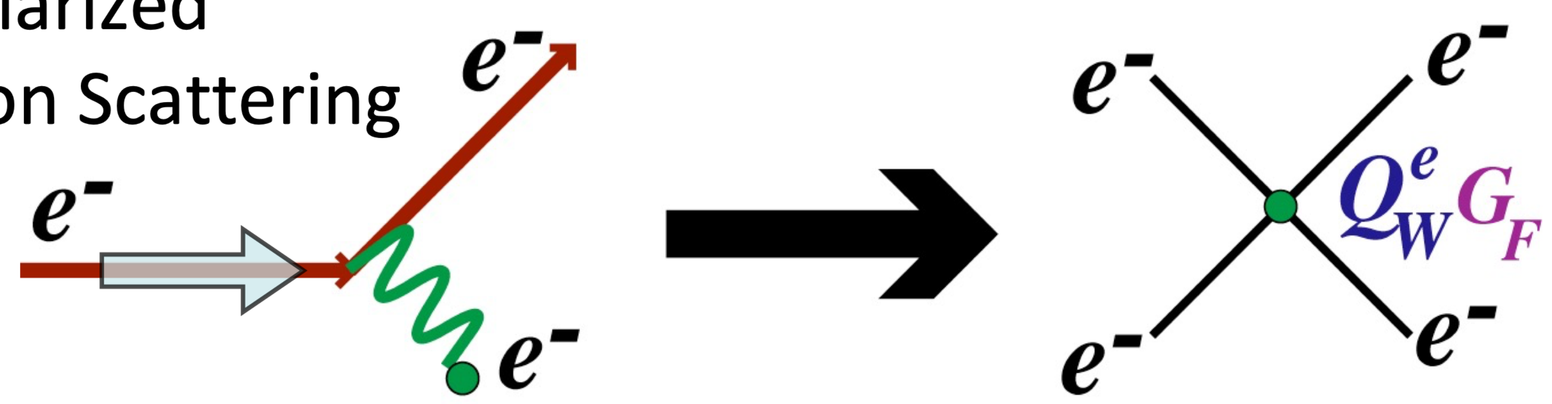
Recent closed-fermion loops: arXiv:1912

SM: **$\delta(Q^e{}_W) \lesssim 0.4\%$** ⇔ *MOLLER: $\delta(Q^e{}_W) = \pm$ 2.1 % (stat.) $\pm$ 1.1 % (syst.)*

Quantifying Discovery Potential: Mass Reach

Low energy WNC interactions ($Q^2 << M_Z^2$)

Fixed Target Polarized Electron-Electron Scattering



Heavy mediators = contact interactions

Measurements test for small deviations from precisely calculated SM processes $\longrightarrow$ new possible couplings

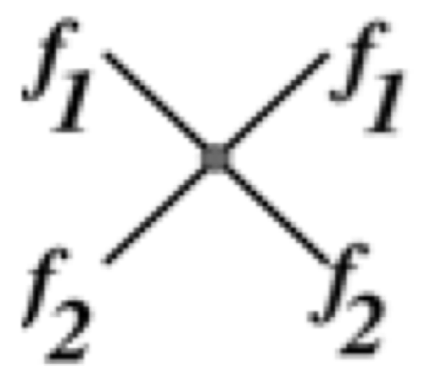
Consider $f_1 f_1 \to f_2 f_2$ or $f_1 f_2 \to f_1 f_2$ $\quad A_{PV,X} \sim \frac{1}{Q^2 - M_X^2} \sim \frac{4\pi}{\Lambda^2}$

Eichten, Lane and Peskin, PRL50 (1983)

$$\mathcal{L}_{f_1 f_2} = \sum_{i,j=L,R} \frac{(g_{ij}^{12})^2}{\Lambda_{ij}^2} \bar{f}_{1i}\gamma_\mu f_{1i} \bar{f}_{2j}\gamma_\mu f_{2j}$$

mass scale Λ, coupling g

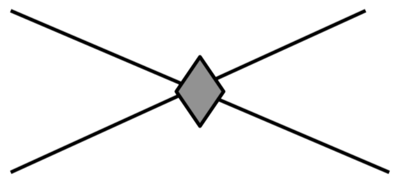
for **each fermion** and **handedness** combination



higher dimensional operators can be systematically classified

$$\mathcal{L} = \mathcal{L}_{SM} + \frac{1}{\Lambda}\mathcal{L}_5 + \frac{1}{\Lambda^2}\mathcal{L}_6 + \cdots$$

$$\mathbf{Q_W^e = 1 - 4\sin^2\theta_W \sim 0.075}$$

+  $\frac{1}{\Lambda^2}\mathcal{L}_6$ New Physics

$$\mathcal{L}_{e_1 e_2} = \sum_{i,j=L,R} \frac{g_{ij}^2}{2\Lambda^2} \bar{e}_i\gamma_\mu e_i \bar{e}_j \gamma^\mu e_j$$

$\delta(Q^e{}_W) = 2.3\%$

$$\frac{\Lambda}{\sqrt{|g_{RR}^2 - g_{LL}^2|}} = \frac{1}{\sqrt{\sqrt{2}G_F|\Delta Q_W^e|}}$$

$$\simeq \frac{246.22\ \text{GeV}}{\sqrt{0.023 Q_W^e}} = 7.5\ \text{TeV}.$$

Conventional Collider Contact Interaction Analysis: ➡ $|g_{RR}^2 - g_{LL}^2| = 4\pi$

Mass Reach scale ~ 38TeV Erler *et al*., Ann.Rev.Nucl.Part.Sci. 64 (2014)

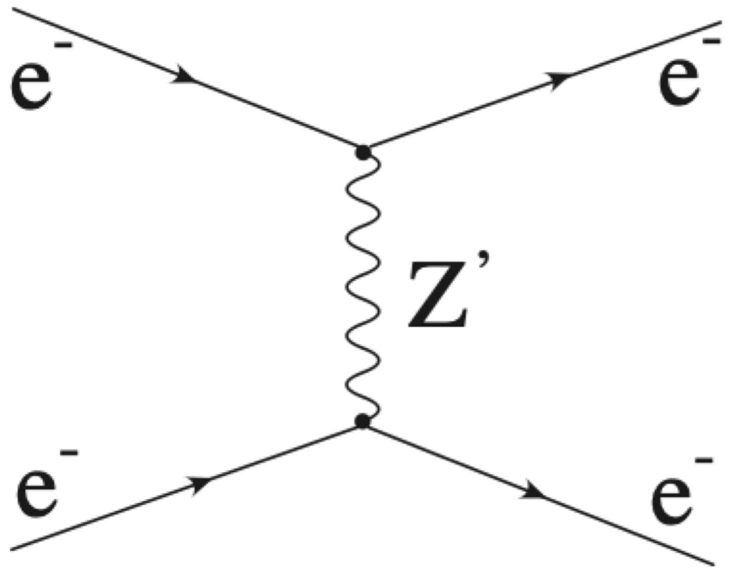
$\sqrt{|g_{RR}{}^2 - g_{LL}{}^2|} = 2\pi$ ⇨ Λ = up to 47 TeV

MOLLER is accessing discovery space that cannot be reached until the advent of a new lepton collider

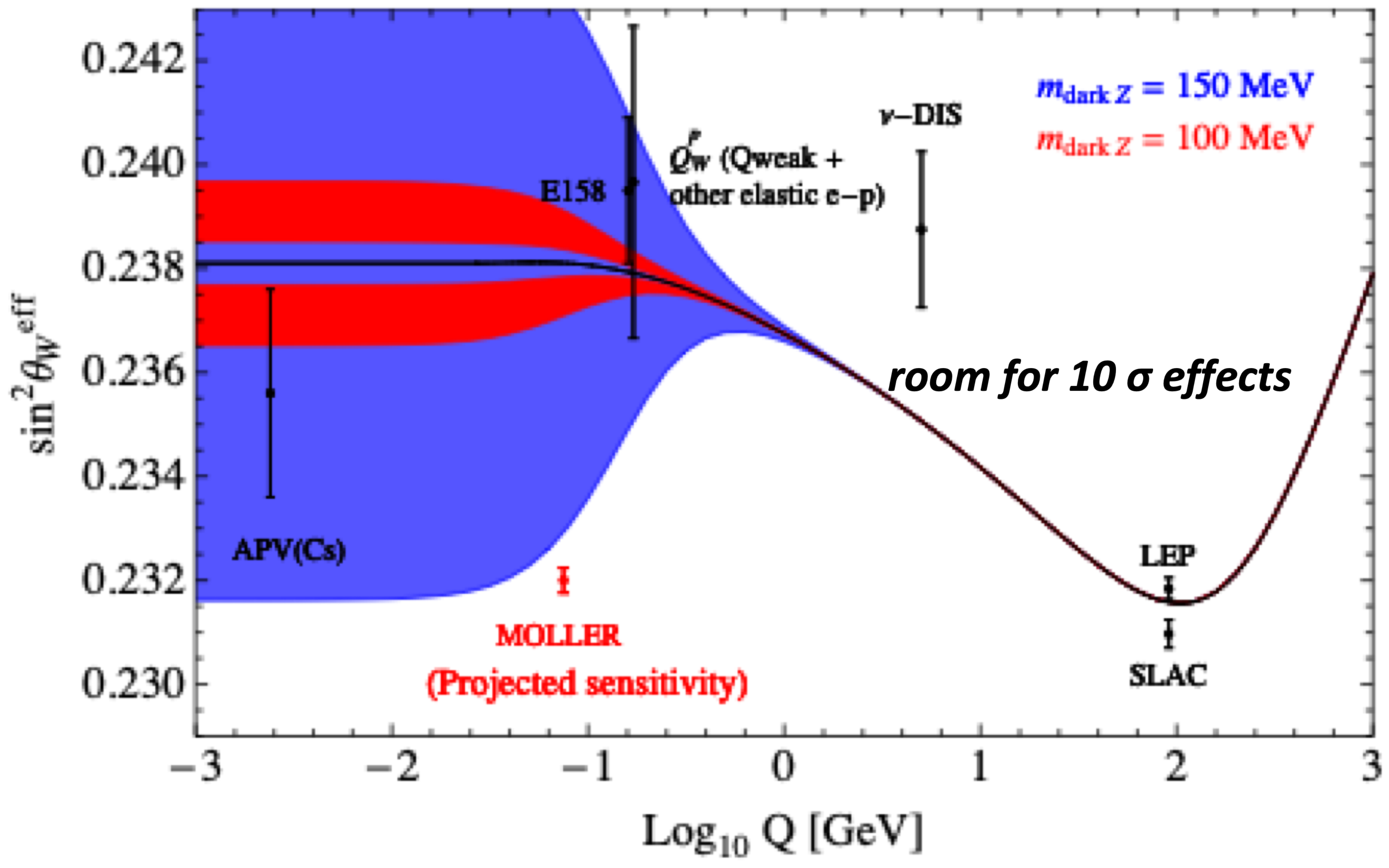
Quantifying Discovery Potential: Weak mixing angle precision

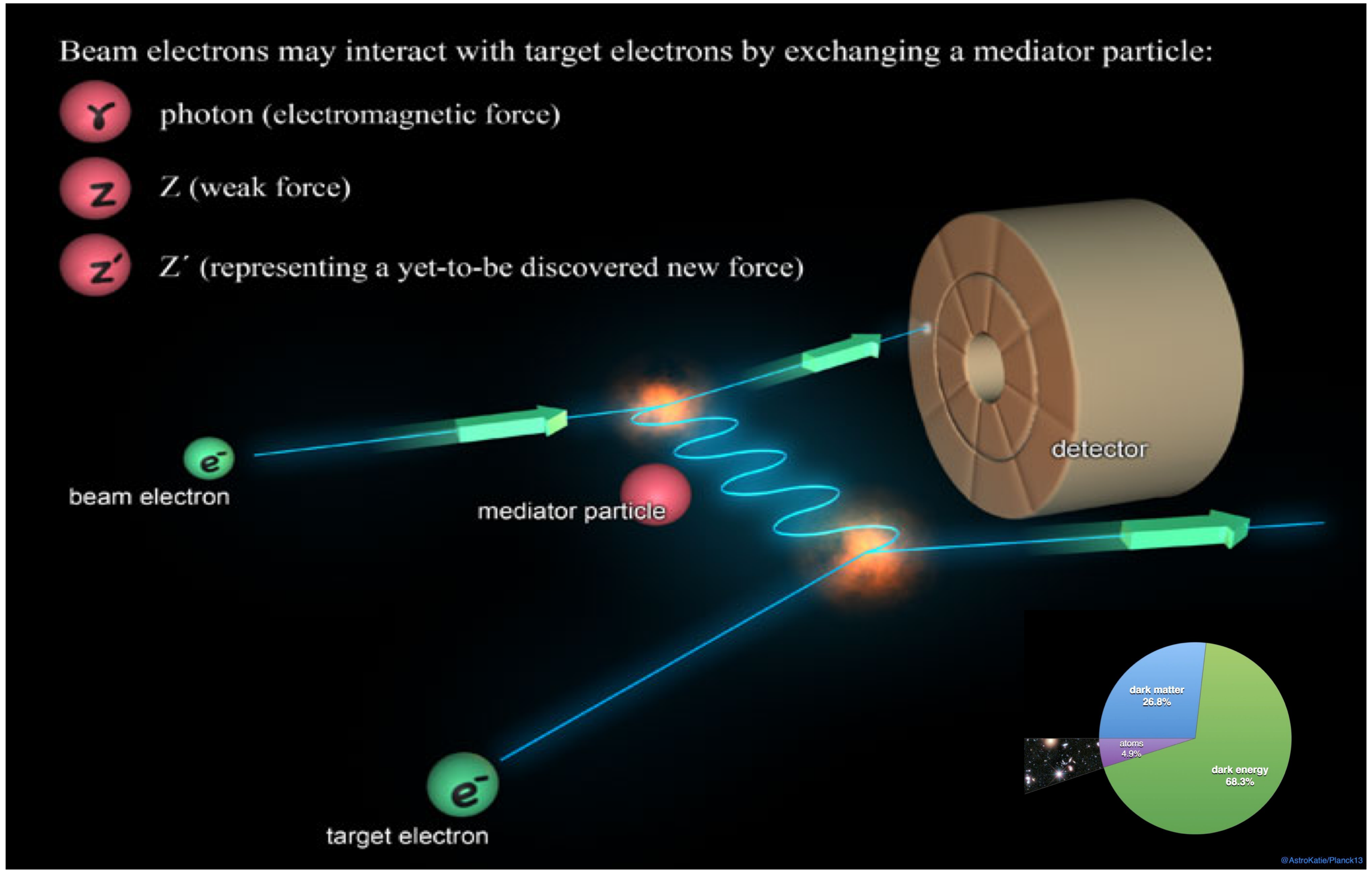
BSM: The Dark Z

Heavy Photons
(A' mixed with Z_0):
The Dark Z



H. Davoudiasl, H-S. Lee and W. Marciano



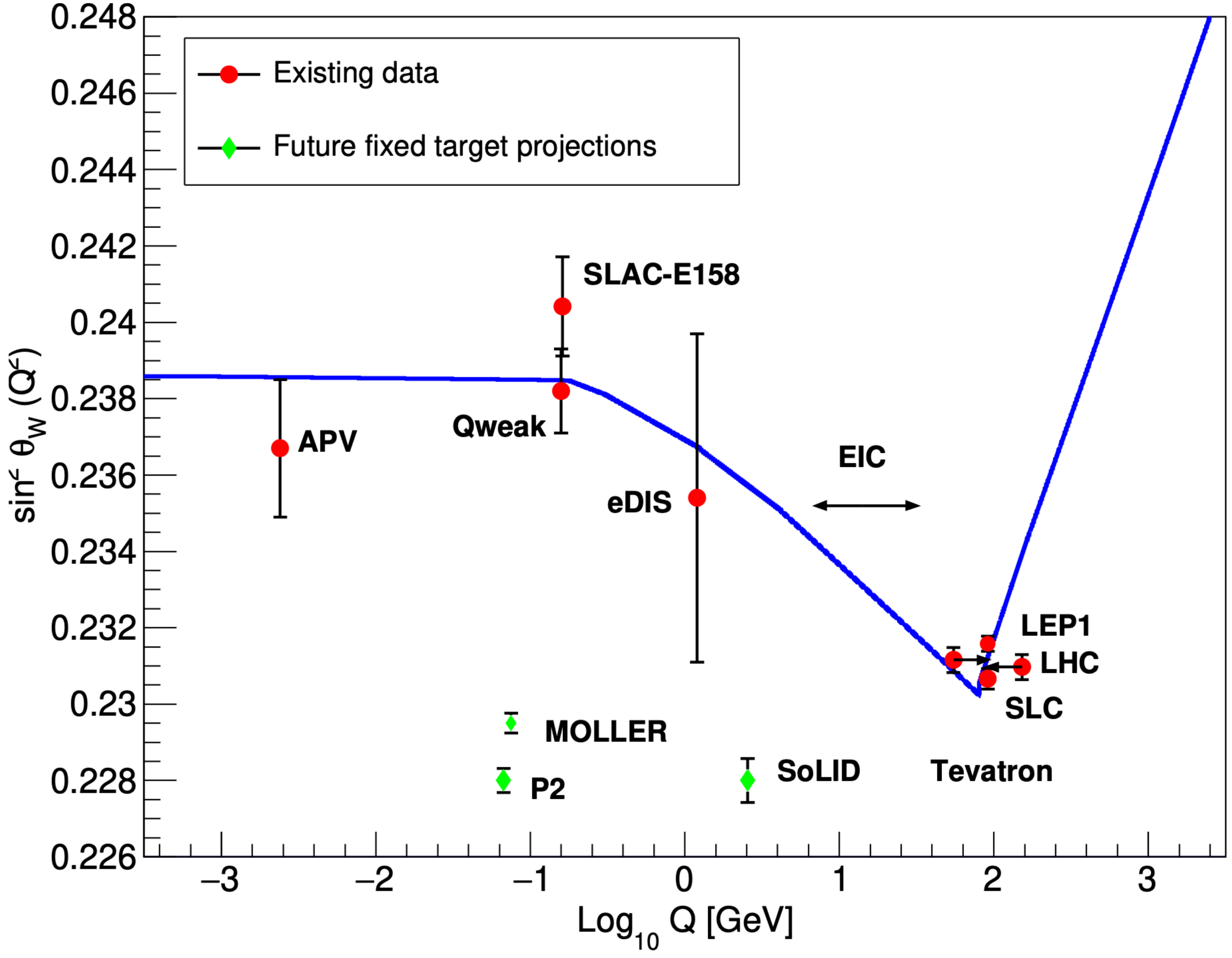


$$Q_W^e \Rightarrow \sin^2\theta_W$$

Interpreting each result as an independent measure of $\sin^2\theta_W$ provides a quick way to put these all one one plot, but:

- interference in precision PVES measurements away from the Z resonance enhances new physics sensitivity
- Room for 10sigma discovery potential
- But additionally…

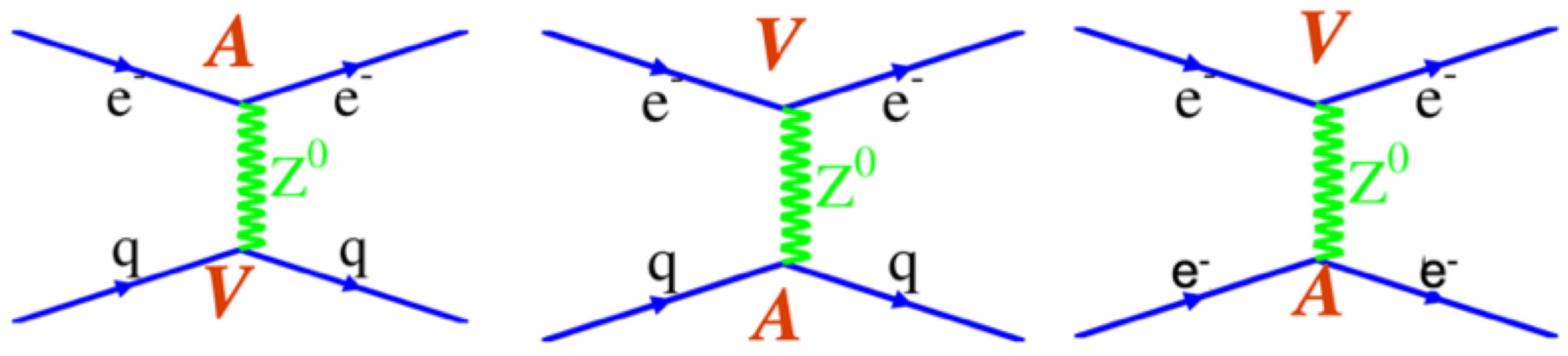
Quantifying Discovery Potential : Coupling coefficients phase space



- ee and ep elastic and e-D DIS are all unique phase space - the precision on $\sin^2\theta_W$ is not the story
- Constraining the space of BSM physics is the story

MOLLER	C_{ee}
Qweak, P2	$2C_{1u} + C_{1d}$
SoLID	$2C_{1u} - C_{1d}$, $2C_{2u} - C_{2d}$

Standard model PV *e-q* or *e-e* couplings



$g_{AV}^{eq} \equiv 2g_A^e g_V^q$ $\quad g_{VA}^{eq} \equiv 2g_V^e g_A^q$ $\quad g_{AV}^{ee} \equiv 2g_A^e g_V^e$

C_{1q} $\quad C_{2q}$ $\quad C_{ee}$

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

$C_{1q} \propto (g_{RR}^{eq})^2 + (g_{RL}^{eq})^2 - (g_{LR}^{eq})^2 - (g_{LL}^{eq})^2$ ⇨ ***PV elastic e-N scattering, Atomic parity violation***

$C_{2q} \propto (g_{RR}^{eq})^2 - (g_{RL}^{eq})^2 + (g_{LR}^{eq})^2 - (g_{LL}^{eq})^2$ ⇨ ***PV deep inelastic scattering***

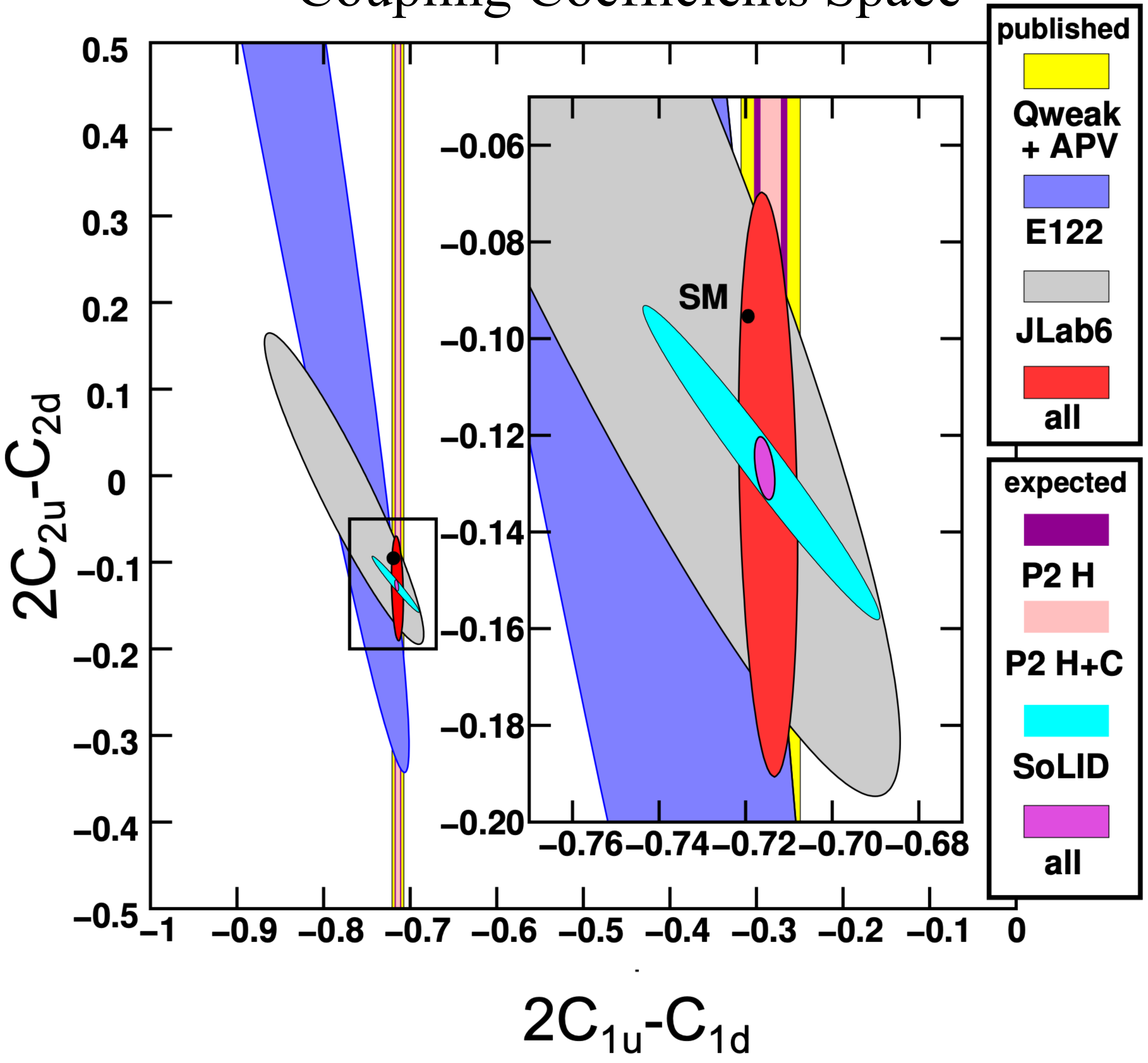
$C_{ee} \propto (g_{RR}^{ee})^2 - (g_{LL}^{ee})^2$ ⇨ ***PV Møller scattering***

Constraining the space of BSM physics: Complimentary Measurements

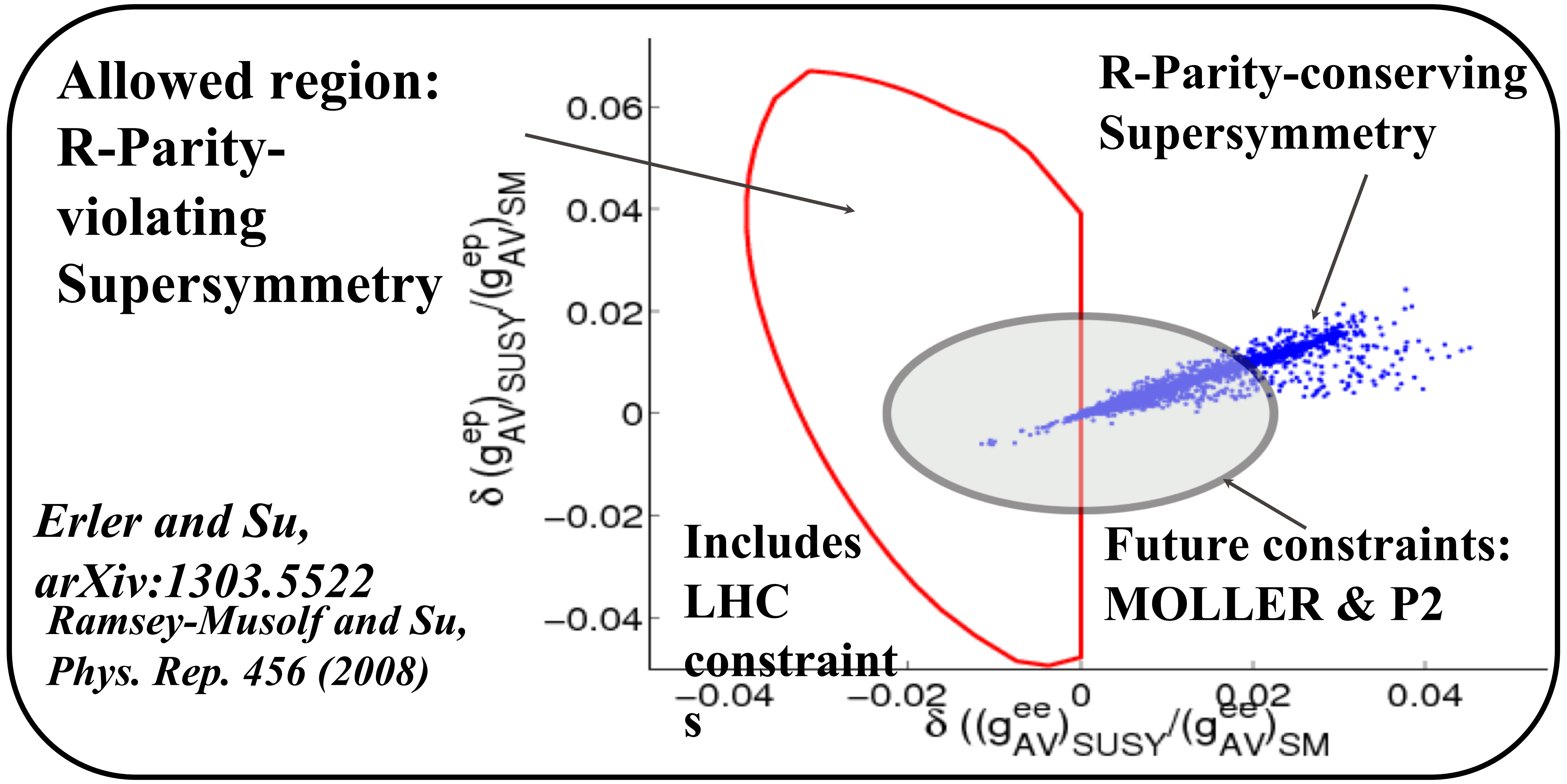
Many new physics models give rise to new neutral current interactions

Heavy Z's and neutrinos, technicolor, compositeness, extra dimensions, SUSY…

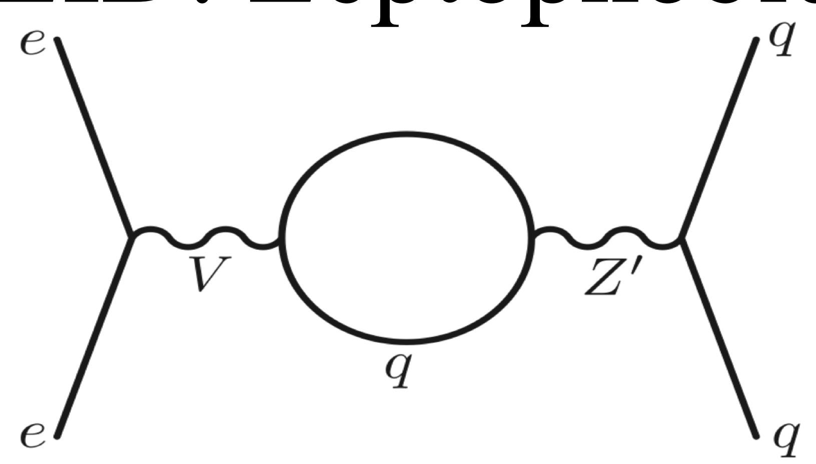
Coupling Coefficients Space



SUSY: – RPV and RPC



SOLID: Leptophobic Z'



SOLID: 100-200 GeV range

Buckley and Ramsey-Musolf Phys.Lett. B712 (2012) 261-265

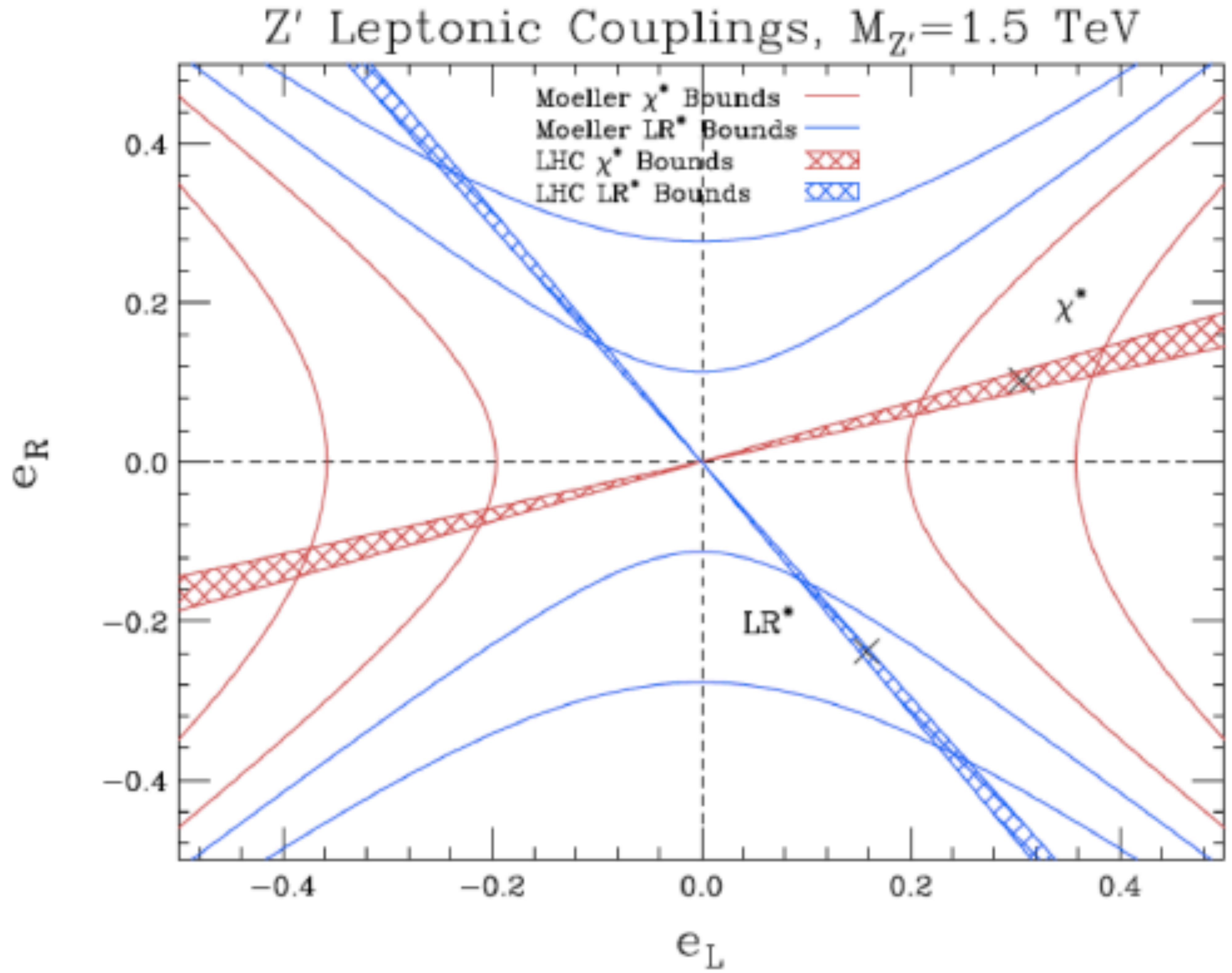
MOLLER: BSM and Sensitivity to New Physics

Complimentary Measurement with LHC

LHC observes an anomaly

MOLLER will help provide constraints to choose between various BSM theories

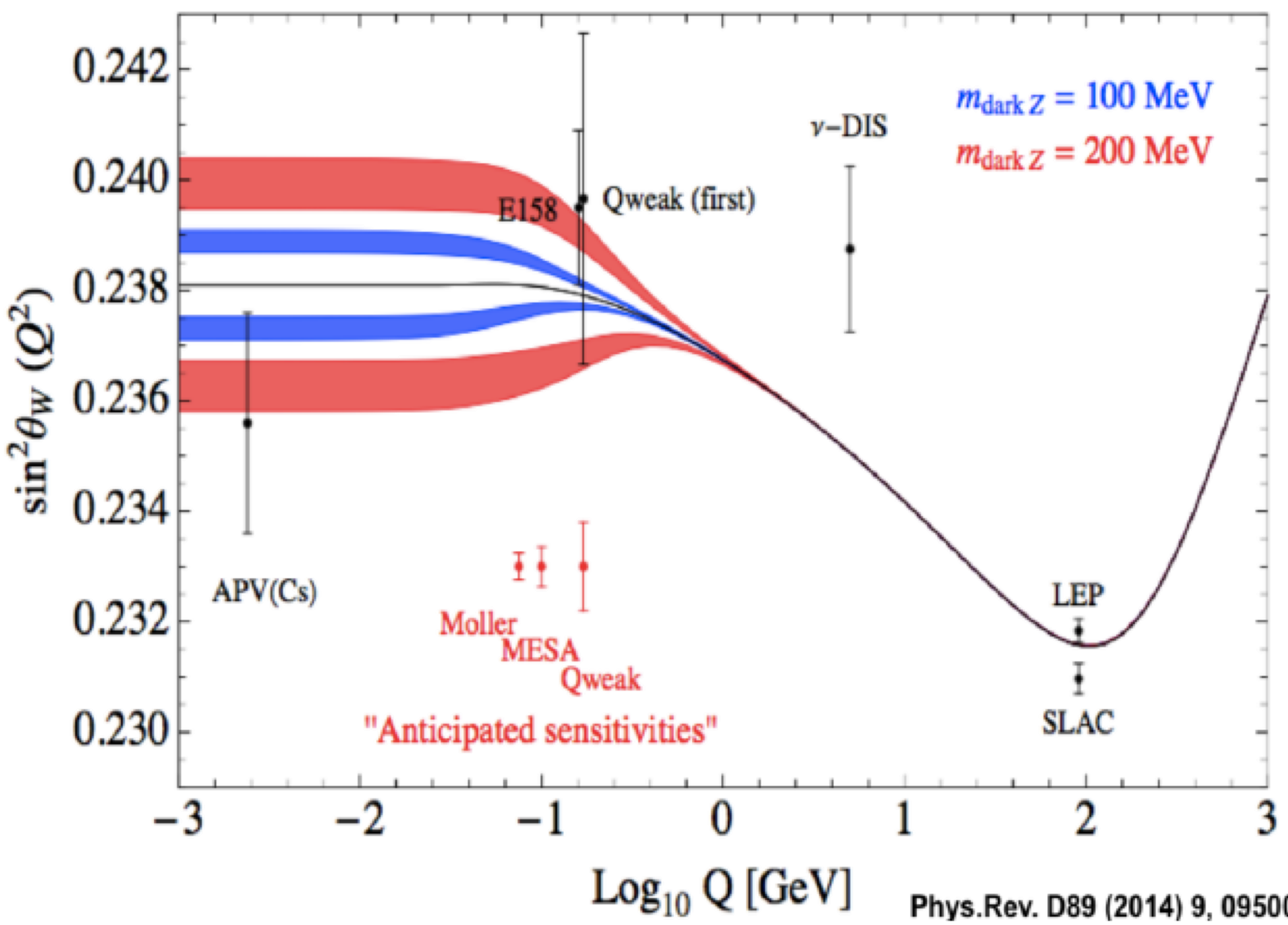
- ex) TeV scale Z'bosons



LHC agrees with the Standard Model to 14TeV

MOLLER: provide access to hidden weak scale BSM physics scenarios that could escape LHC detection

- ex) MeV-scale "Dark" Z^0_d



Phys.Rev. D89 (2014) 9, 095006

MOLLER: BSM and Sensitivity to New Physics

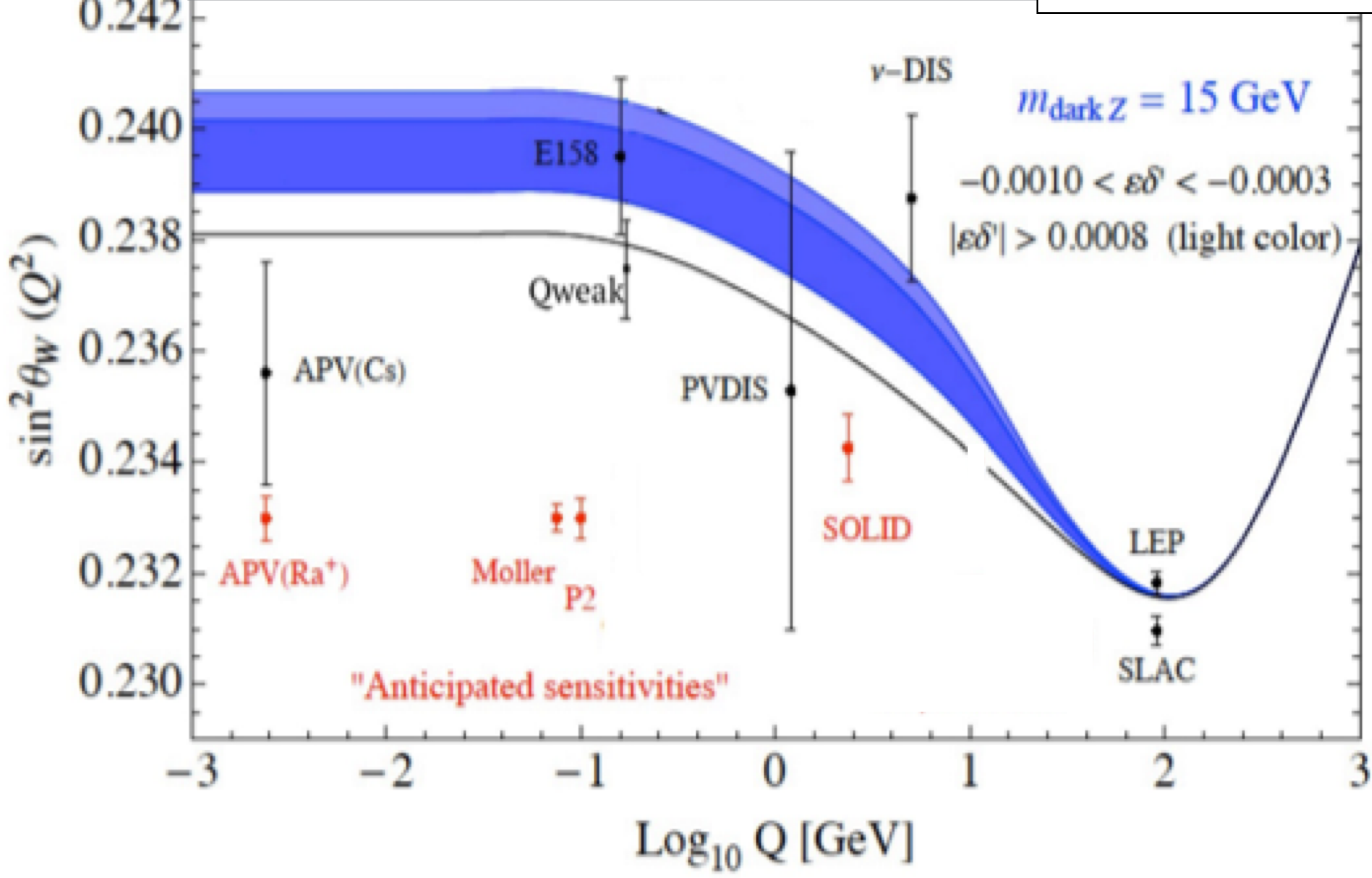
Many new physics models give rise to new neutral current interactions

Heavy Z's and neutrinos, technicolor, compositeness, extra dimensions, **SUSY, dark Z**…

Dark Z

dark Z: mass mixing with Z^0

Davoudiasl, Lee, Marciano
PRD89 (2014), 095006
PRD92 (2015) 055005

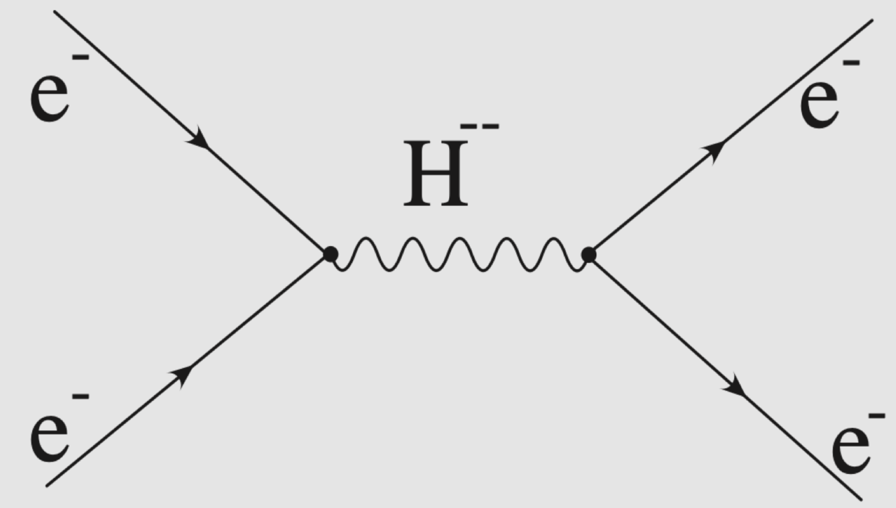


Doubly Charged Scalars

MOLLER: e^-e^- scattering

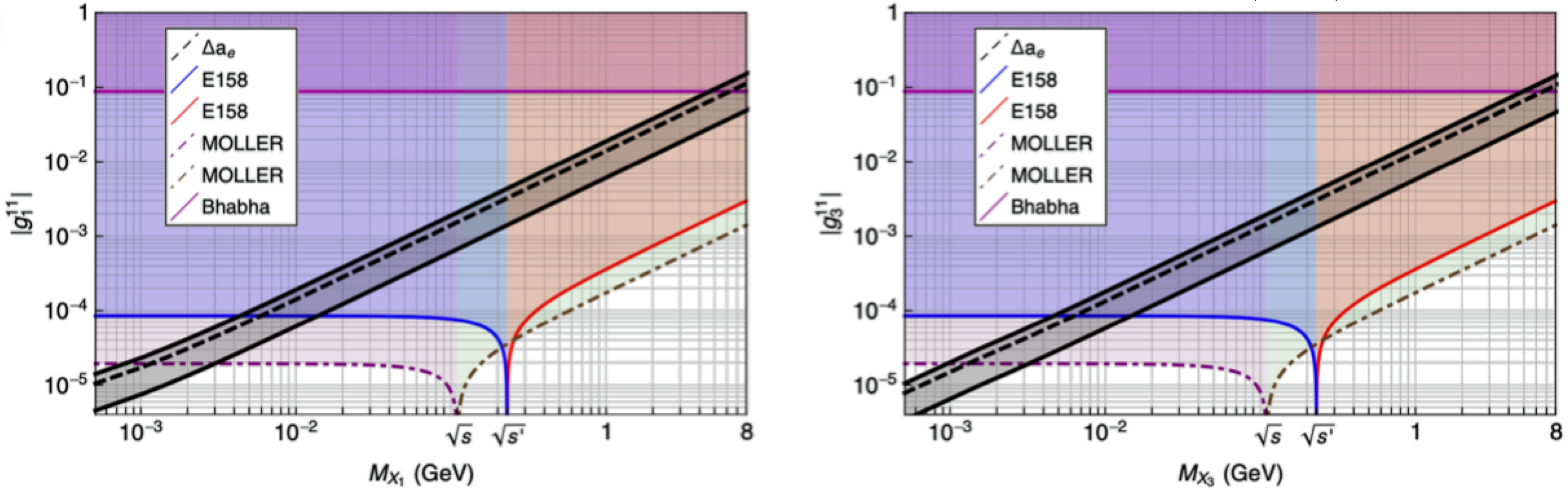
Lepton Number Violation

Λ > 5 TeV
Doubly-
Charged
Scalars

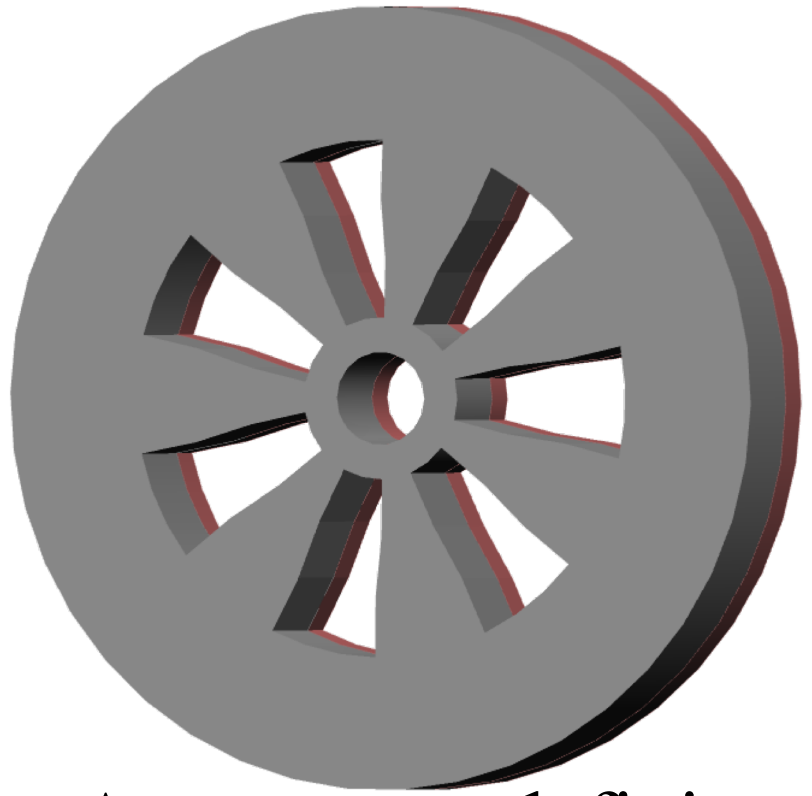


Significant reach beyond LEP-200

Susan Gardner and Xinshuai Yan,PHYSICAL REVIEW D (2020)

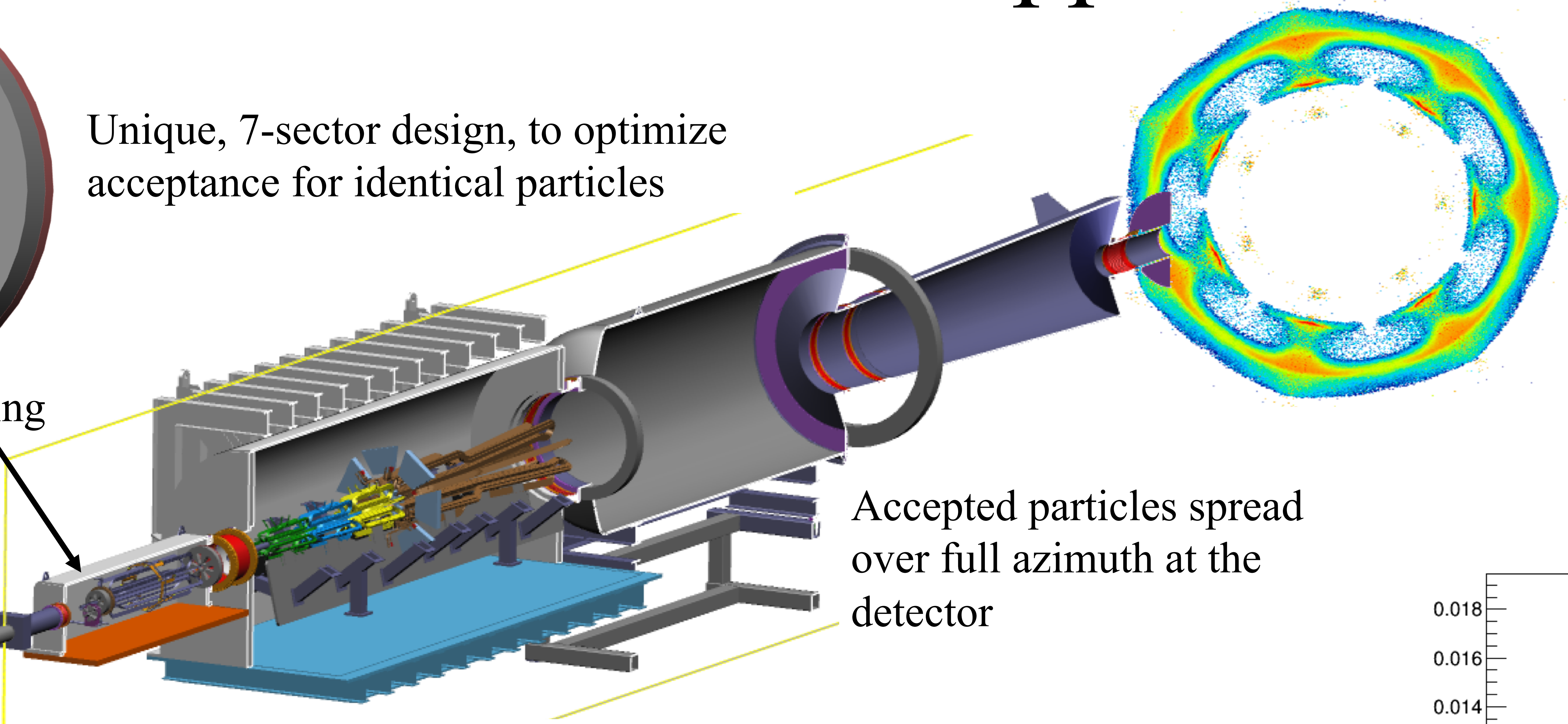


MOLLER Apparatus



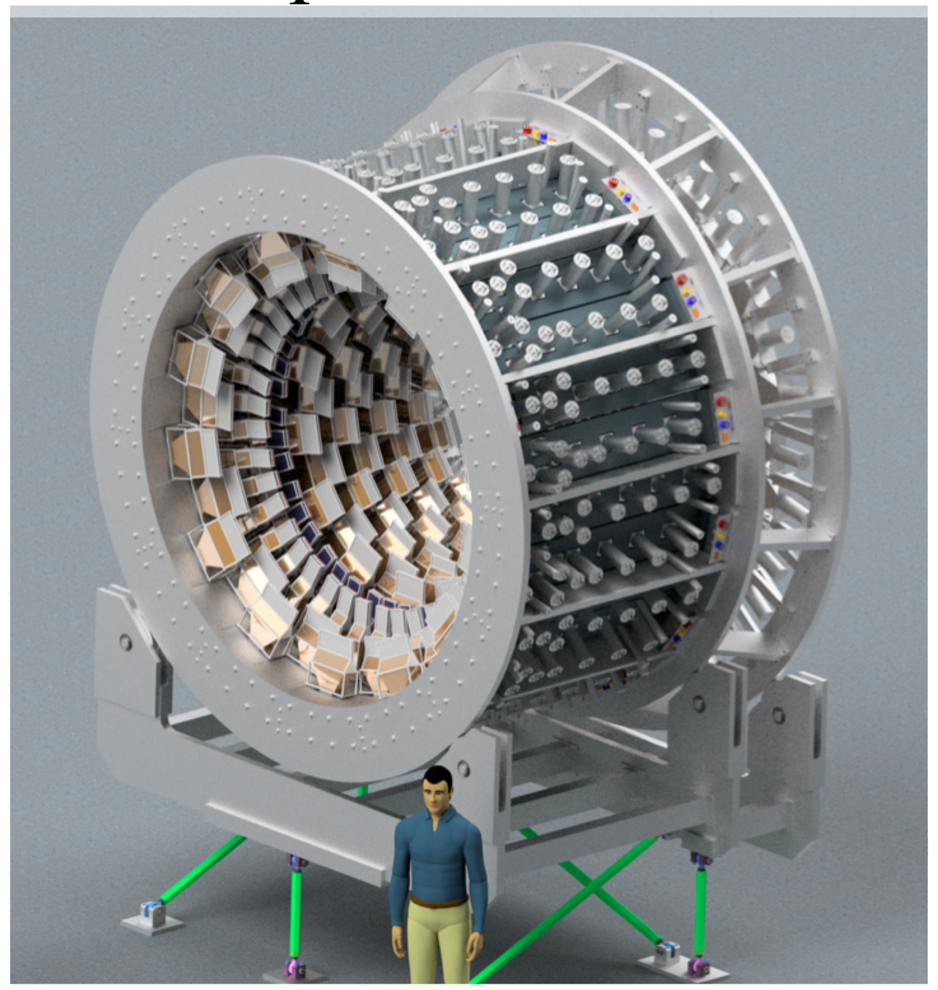
Acceptance-defining collimator

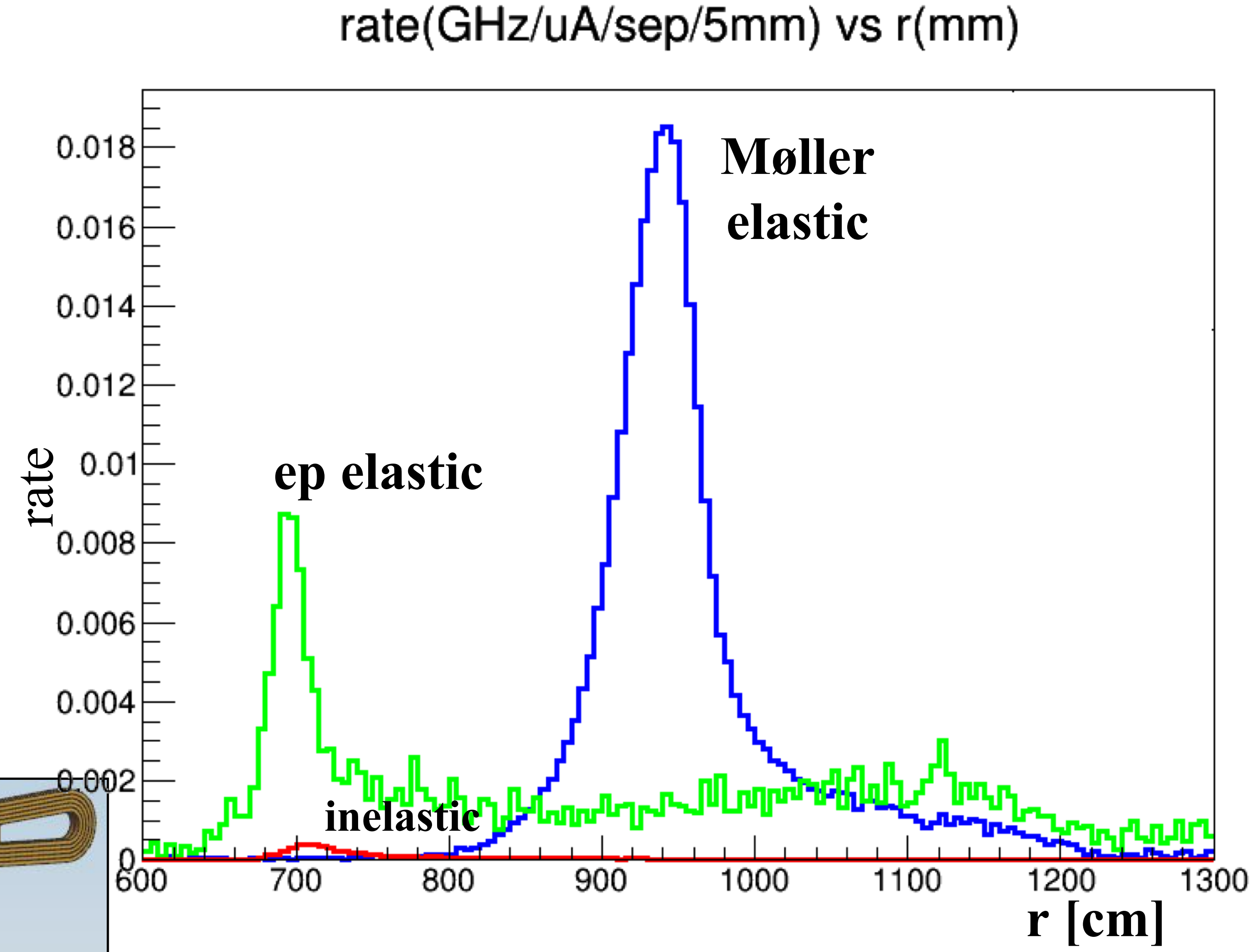
Unique, 7-sector design, to optimize acceptance for identical particles



Accepted particles spread over full azimuth at the detector

Focal plane instrumented with array of thin quartz detectors

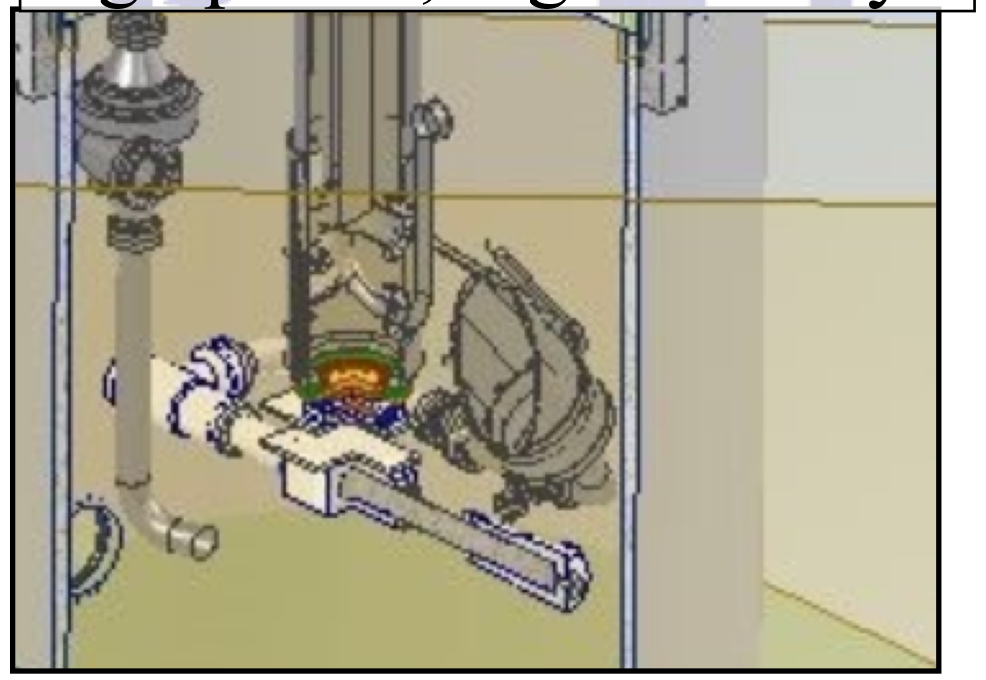




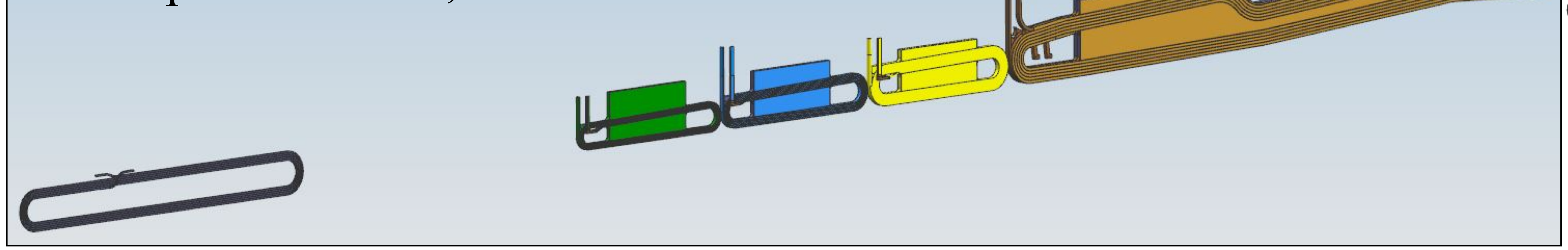
Møller scattered electrons localized at a radial distance, separated from ep elastic, photons

- θ_{lab} ~ 5-18 mrad, E’ = 2-8 GeV
- 134 GHz Møller rate
- Low noise beam with 1nm control of average beam position on target

4kW LH_2 cryotarget
high power, high stability



Five separate toroids, no iron



Moller Uncertainty Requirements

65uA, ~90% polarization, 344 PAC days

2 kHz helicity flip rate with 10 μs settle time (past: 1 kHz, 60 μs T_{settle})

35ppb Apv

Error Source	Fractional Error (%)	
	Run 1	Ultimate
Statistical	**11.4**	**2.1**
Absolute Norm. of the Kinematic Factor	3	0.5
Beam (second moment)	2	0.4
Beam polarization	1	0.4
$e + p(+\gamma) \to e + X(+\gamma)$	2	0.4
Beam (position, angle, energy)	2	0.4
Beam (intensity)	1	0.3
$e + p(+\gamma) \to e + p(+\gamma)$	0.6	0.3
$\gamma^{(*)} + p \to (\pi, \mu, K) + X$	1.5	0.3
$e + Al(+\gamma) \to e + Al(+\gamma)$	0.3	0.15
Transverse polarization	2	0.2
Neutral background (soft photons, neutrons)	0.5	0.1
Linearity	0.1	0.1
Total systematic	**5.5**	**1.1**

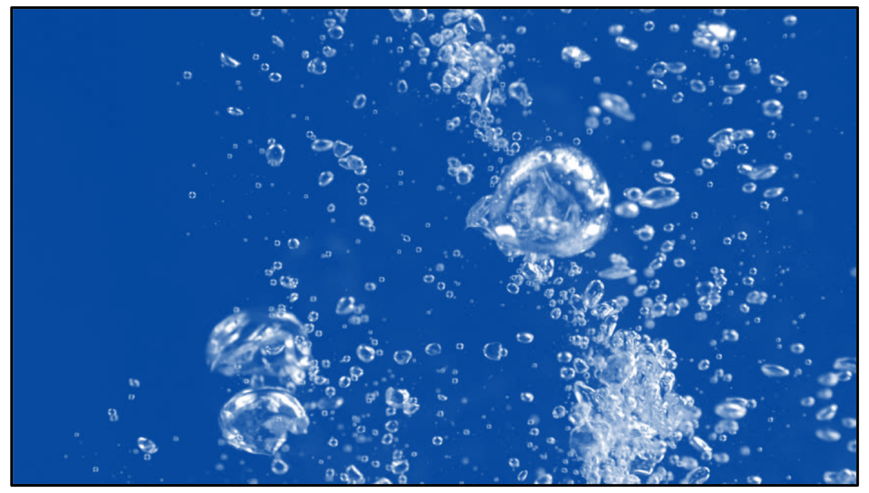
Stringent Uncertainty Goals

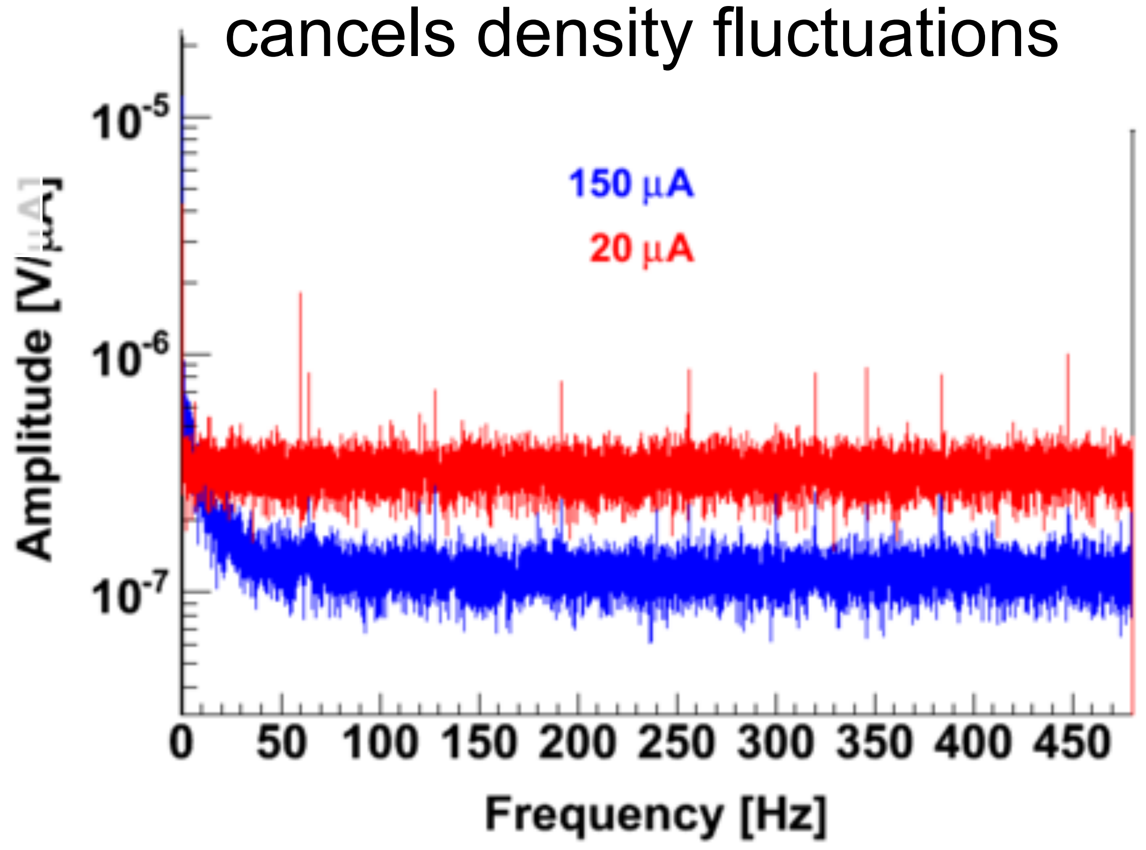
- Statistical goal is <1ppb !
- Total Systematic <0.5ppb!
- Each indiv. systematic is <1% of Apv
- Minimal Beam Asymmetries
- Well measured & controlled polarization
- Minimal and well characterized backgrounds

Measuring this small asymmetry

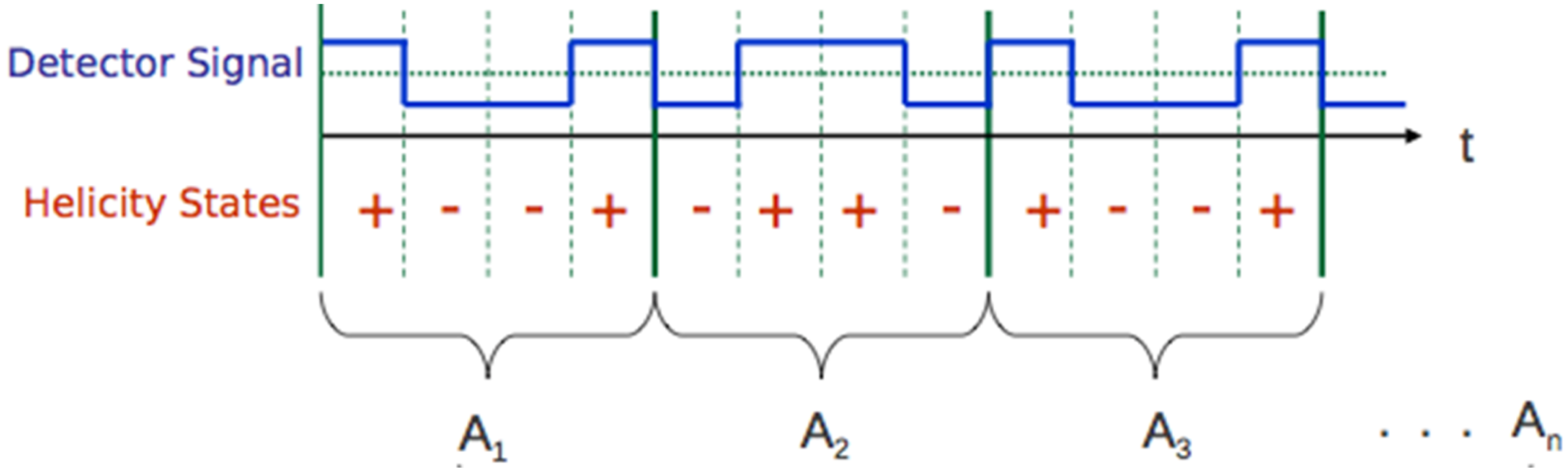
Target Boiling

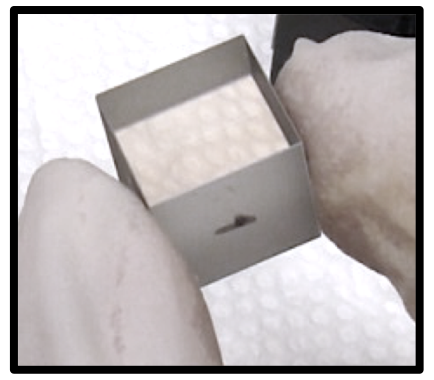
4kW LH_2 cryotarget
high power – Bubbles!





Rapid (2kHz) helicity reversals

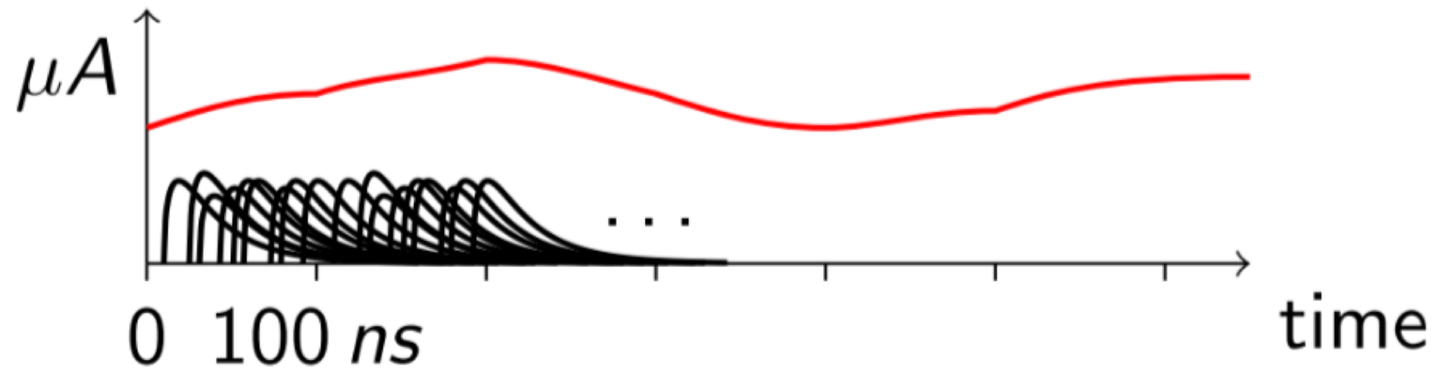




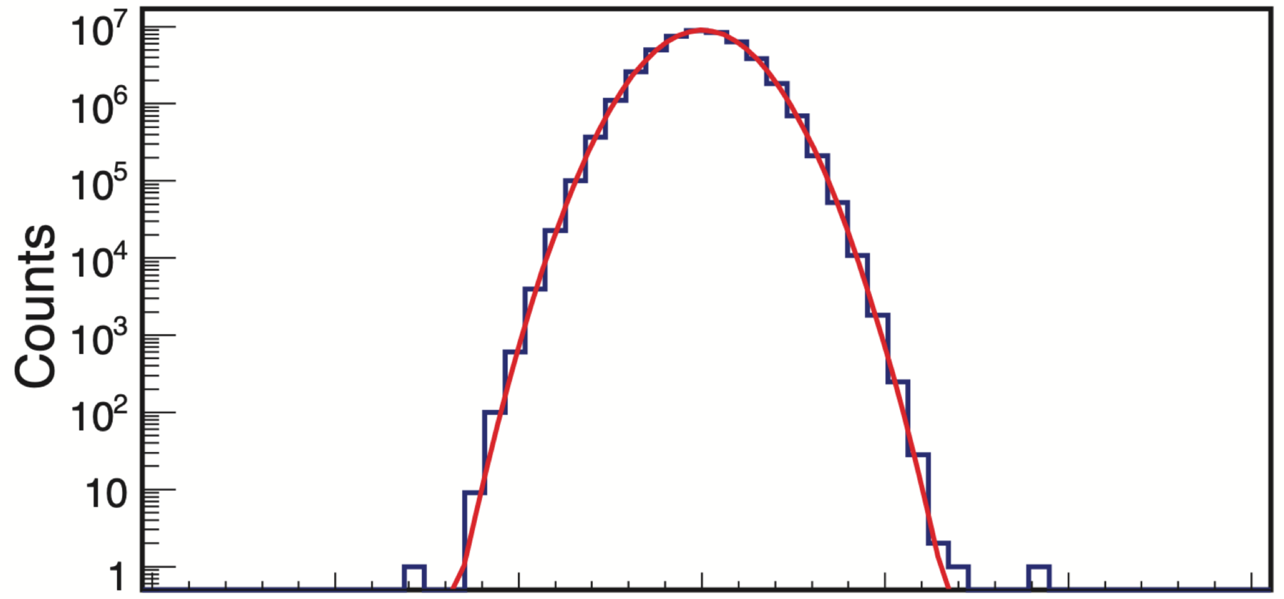
RTP Pockels Cell (Rubidium Titanyle Phosphate) currently in operation in Cebaf capable of fast ~10us switching for 2kHz

Place a detector where it sees the Møller scattered electron

Analog integrate detector current



Form an asymmetry over the helicity reversal



Measure to 0.01% at 1 kHz, repeat for a year straight

Specialized experimental techniques

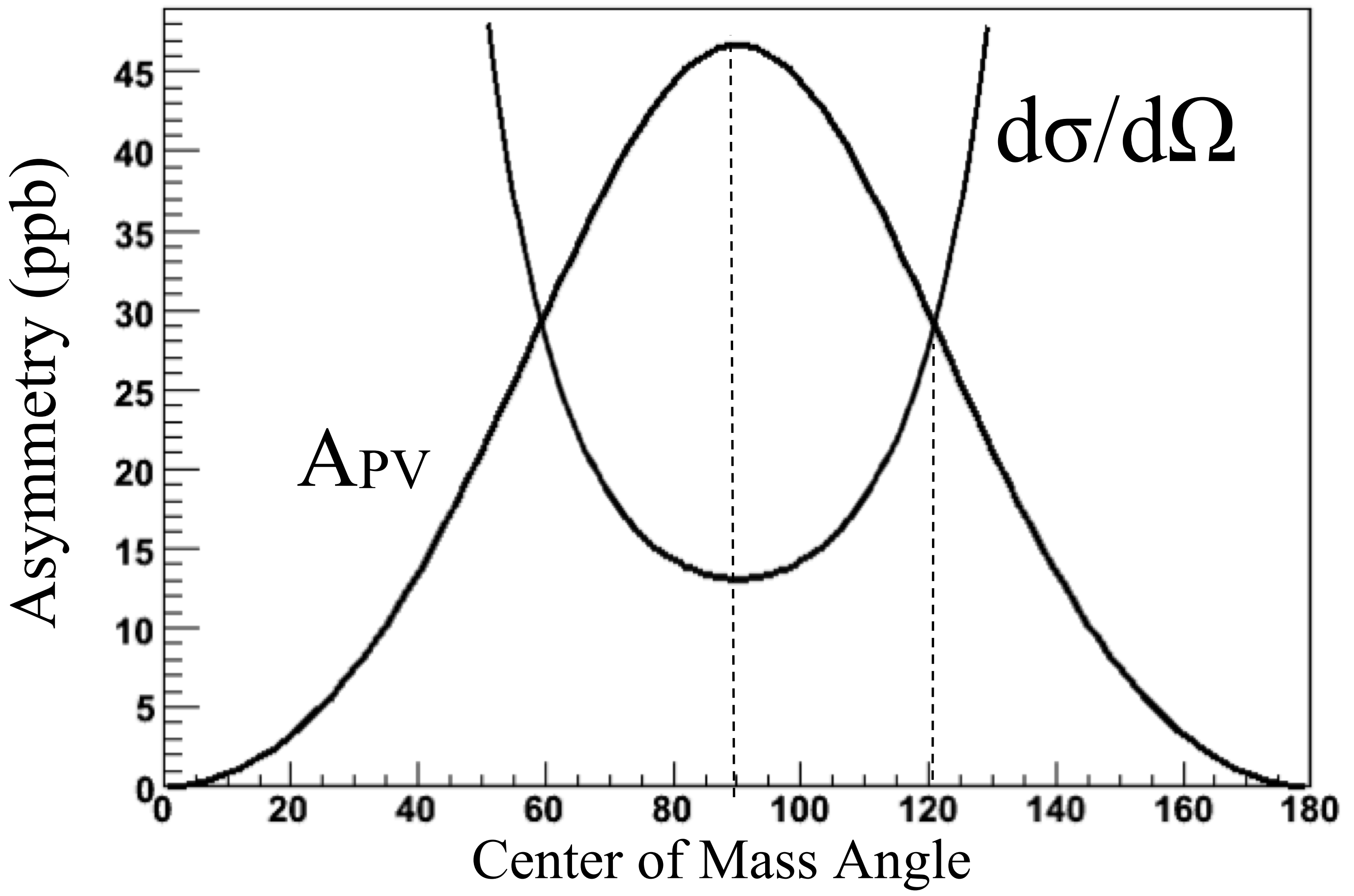
- Precise spectrometer to separate signal
- Low noise electronics
- Precise beam control and measurement
- …

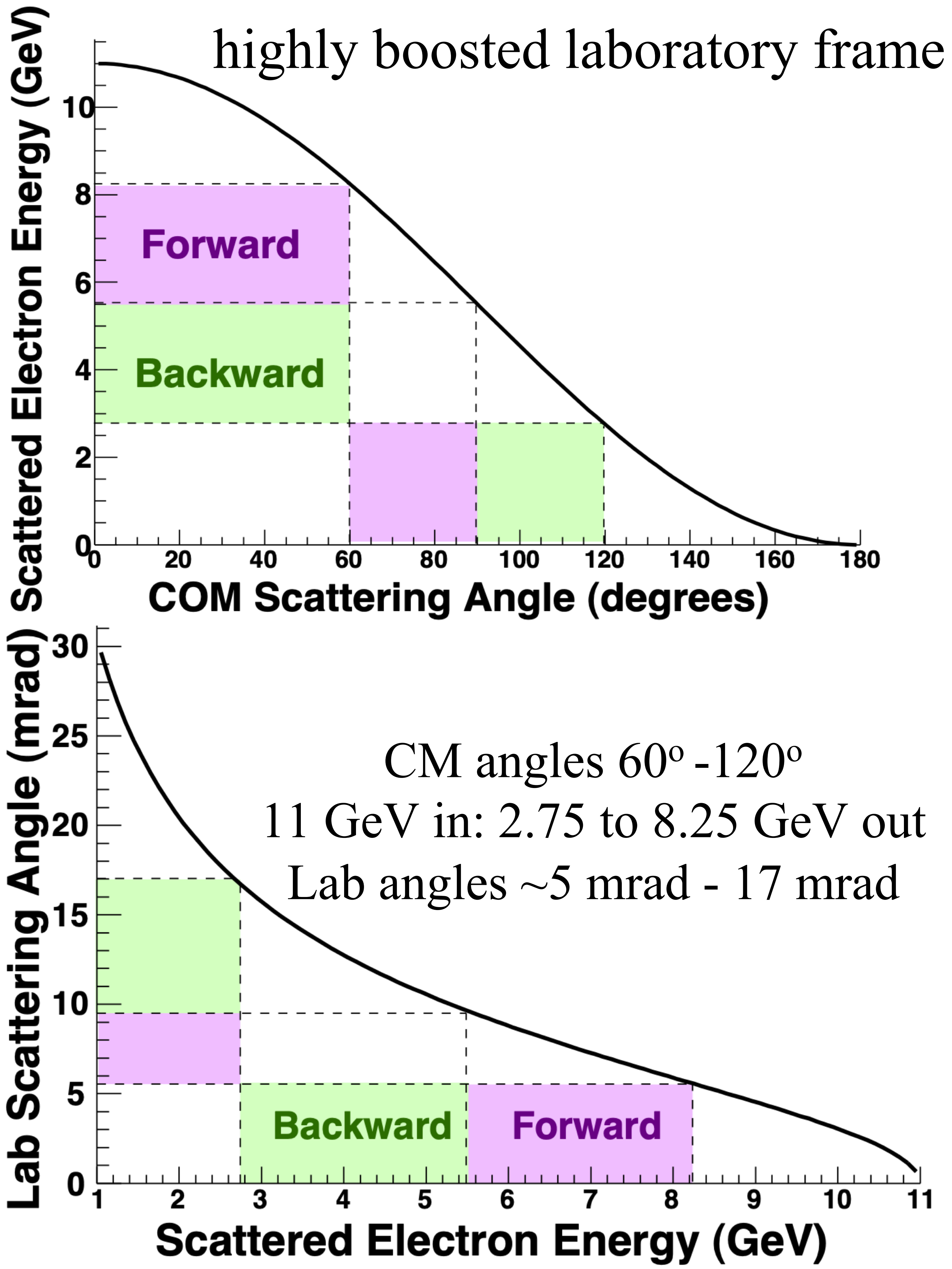
Full Azimuthal Coverage: Identical Particles

Since you only need either the forward or the backward scatter, accept forward+backward for half the azimuth

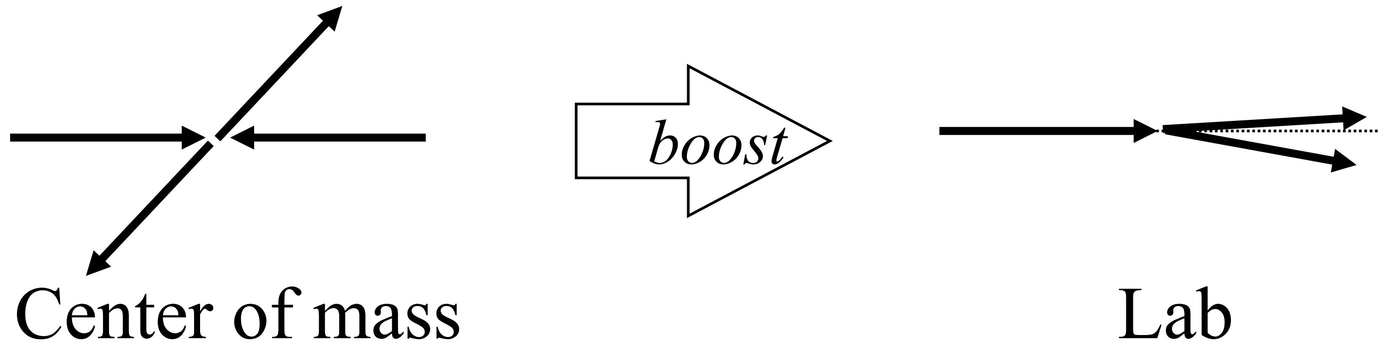
$$A_{PV} = \frac{\sigma_R - \sigma_L}{\sigma_R + \sigma_L} = mE\frac{G_F}{\sqrt{2}\pi\alpha}\frac{4\sin^2\theta}{(3+\cos^2\theta)^2}Q_W^e$$

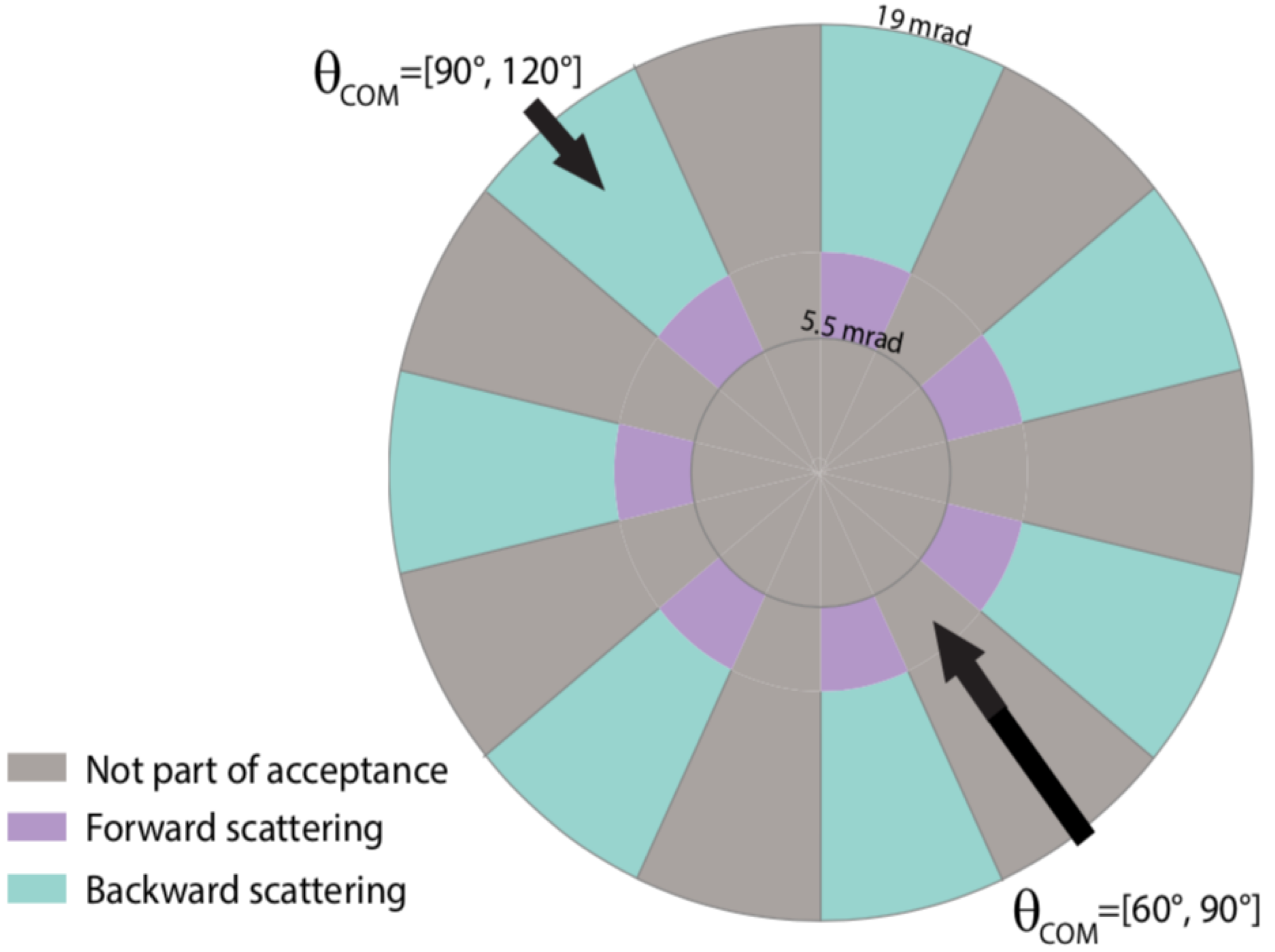
Highest figure of merit at $\theta_{CM} = 90^o$





Identical particles.
Measure either forward or backward scattering.





Unique concept allows for full azimuthal acceptance (effectively) even leaving space for coils but makes for a challenging design

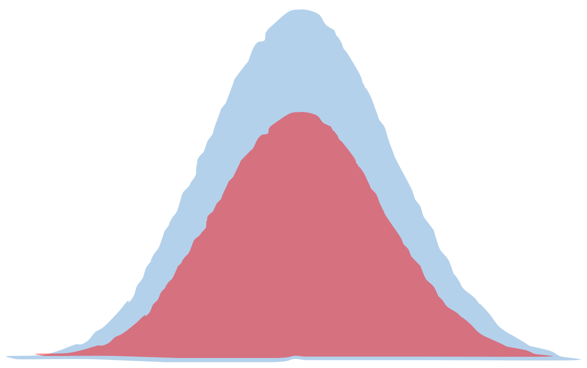
Types of HCBA that contribute to PVES systematics

Achieving HCBA goals all depends on the laser and Pockels Cell

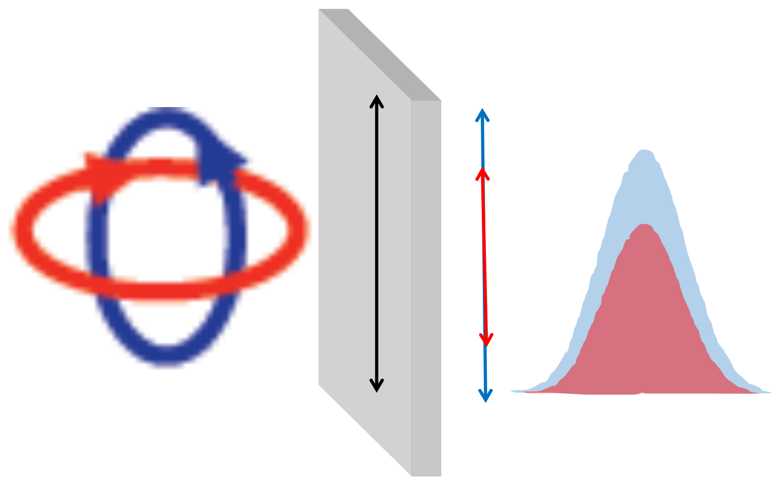
Any change in the polarized beam, correlated to helicity reversal, can be a potential source for a false asymmetry

$$A_{raw} = A_{det} - A_Q + \alpha\Delta_E + \Sigma\beta_i\Delta x_i$$

Intensity Asymmetry

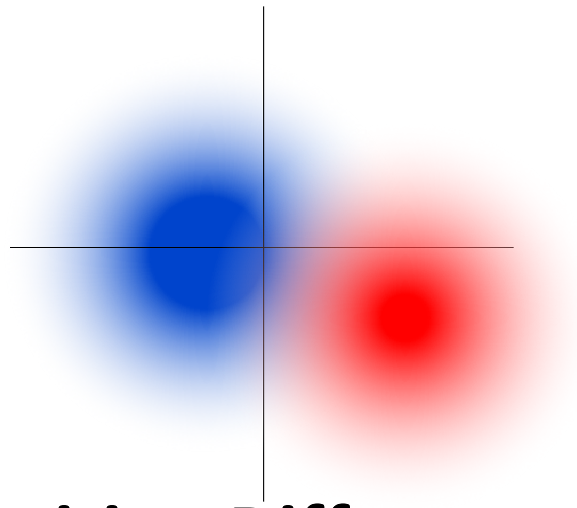


Intensity Asymmetry from Laser Polarization Asymmetry

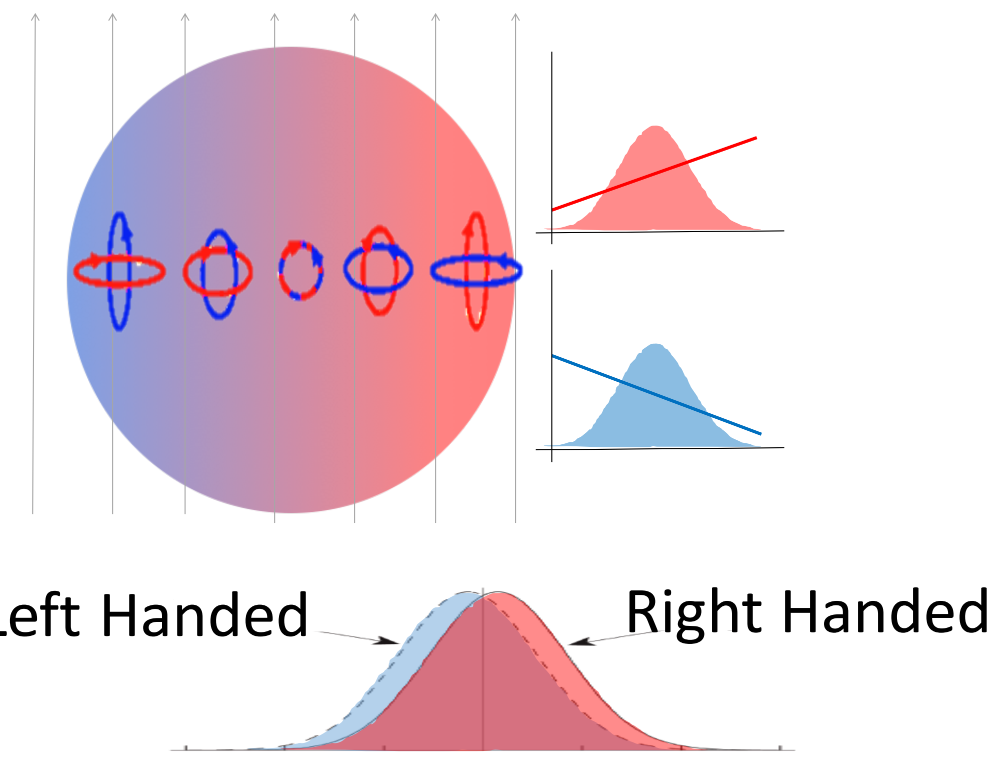


Polarizing element (i.e. photocathode)

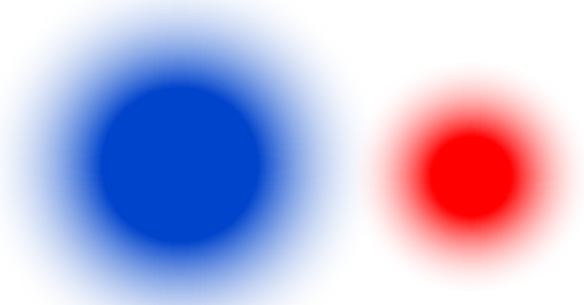
Position Difference



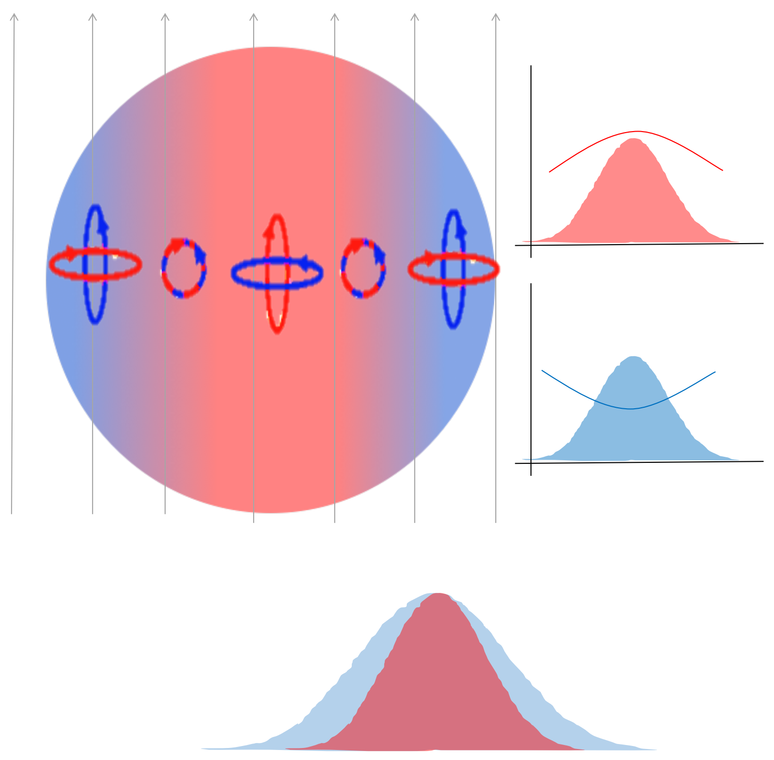
Position Difference from Polarization Gradient



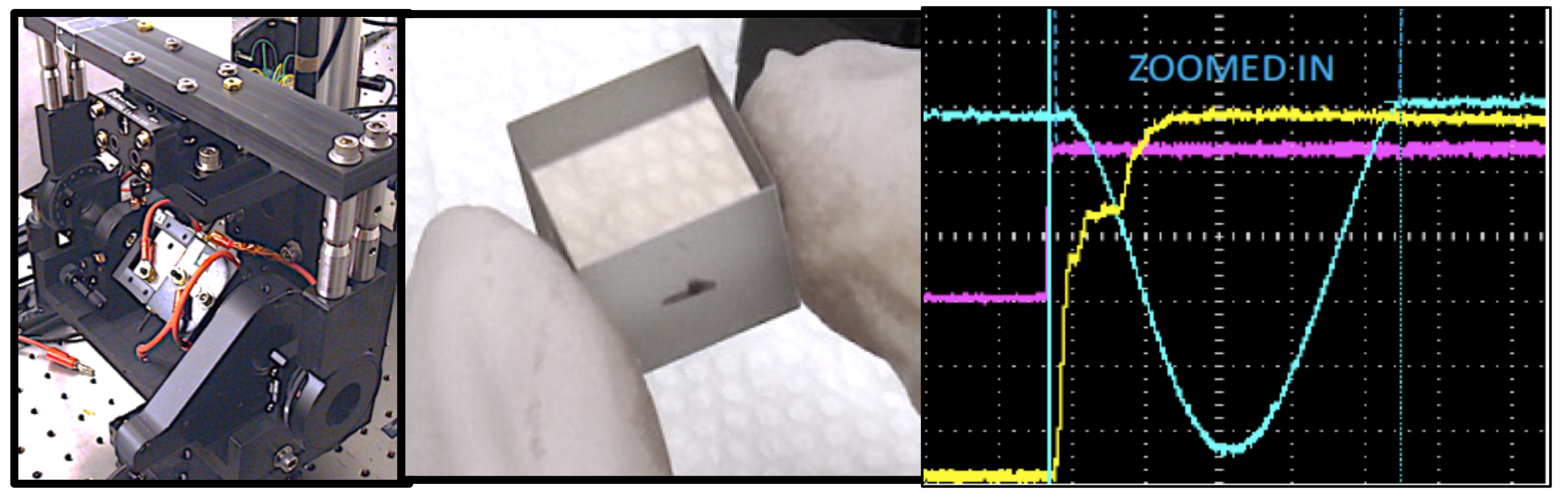
Spot-size *Asymmetry*



Spot-size Asymmetries from 2^{nd} moment Polarization Gradient



Polarized Beam Source
RTP Cell fast switching for 2kHz
(Rubidium Titanyle Phosphate)



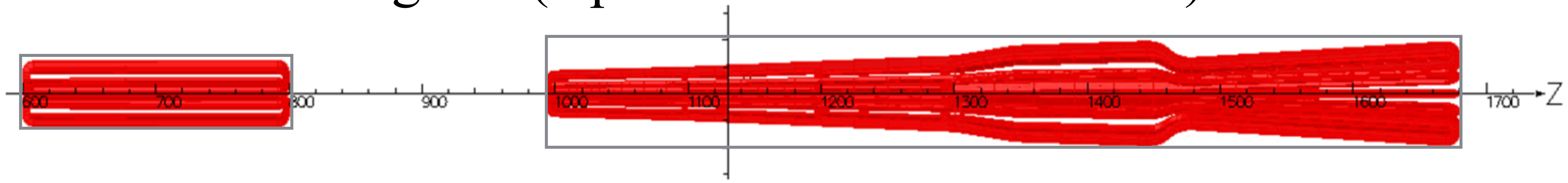
HCBA contributions

	Error
Systematic	0.2ppb
Intensity	0.1ppb
Position, E, angle	0.1ppb
Spot-size	0.12ppb

- The electron beam must be very **symmetric** to make this comparison, both forwards and backwards facing electron beams must have the same intensity and the same direction, position, and spot-size.

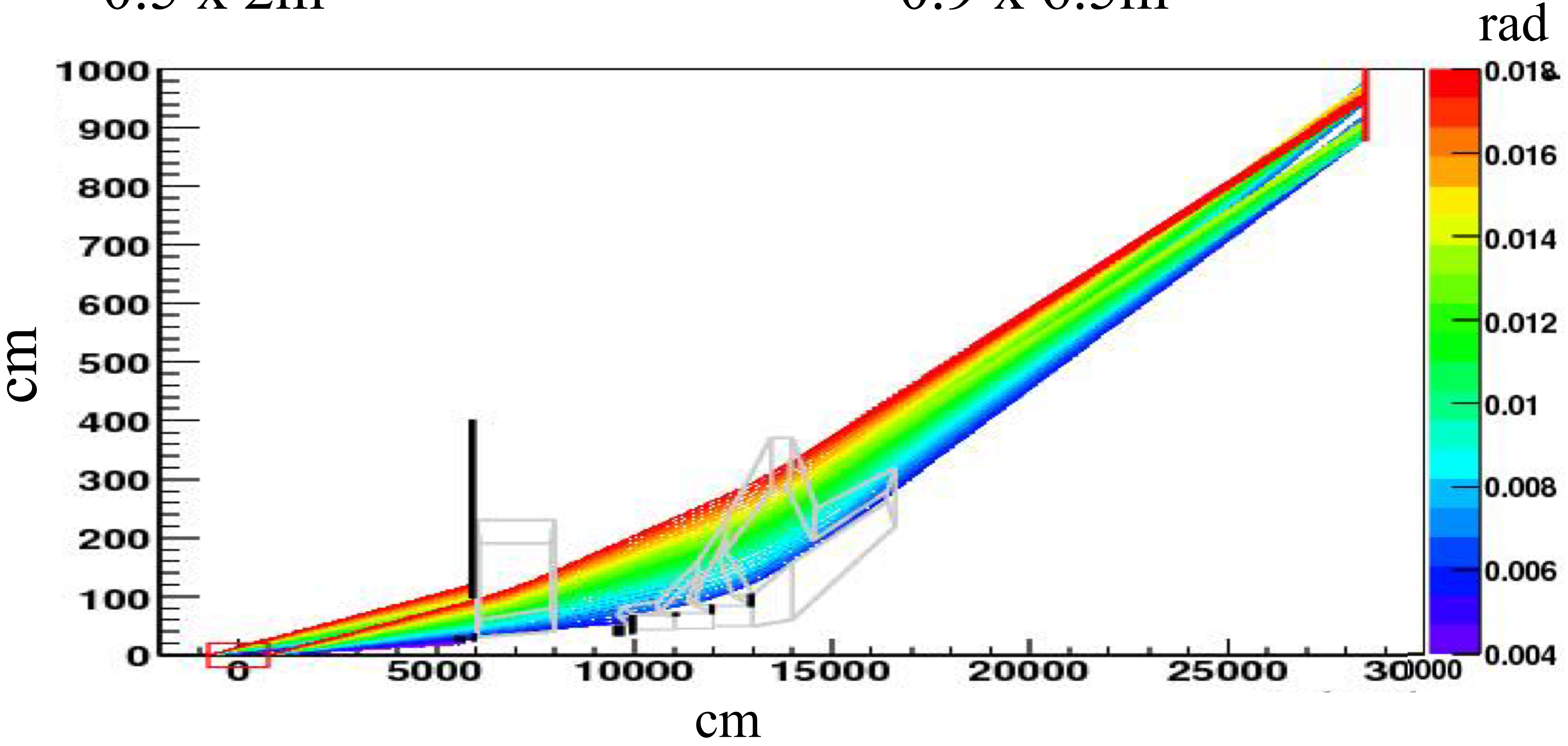
Magnet Concept

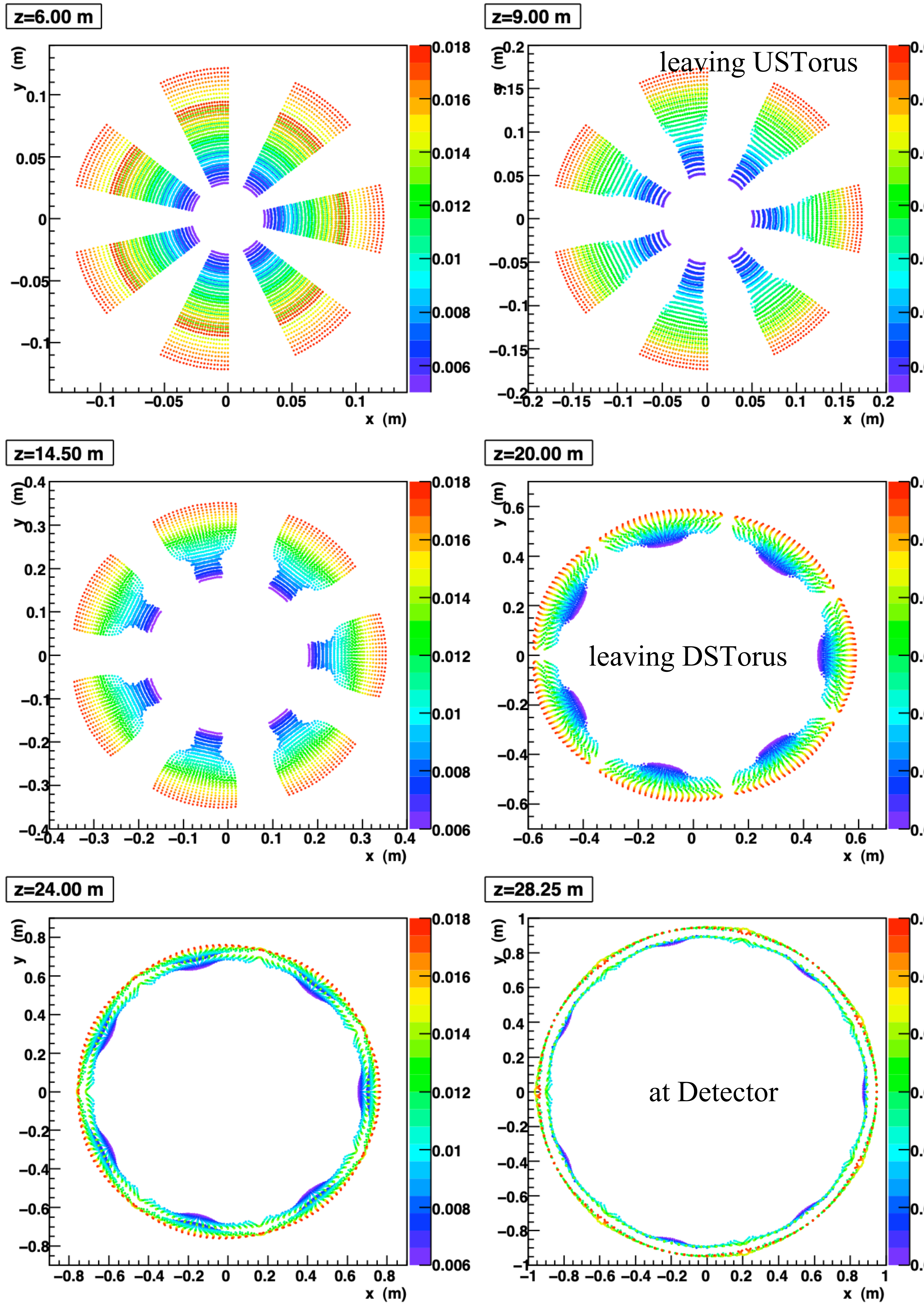
- long and skinny
- Bend scattered particles, separate ee from ep and photons
- Small angles and high beam power
- Large energy range (3-8 GeV)
- Focus both back & forward scattered electrons
- Two toroidal magnets (Upstream and Downstream)



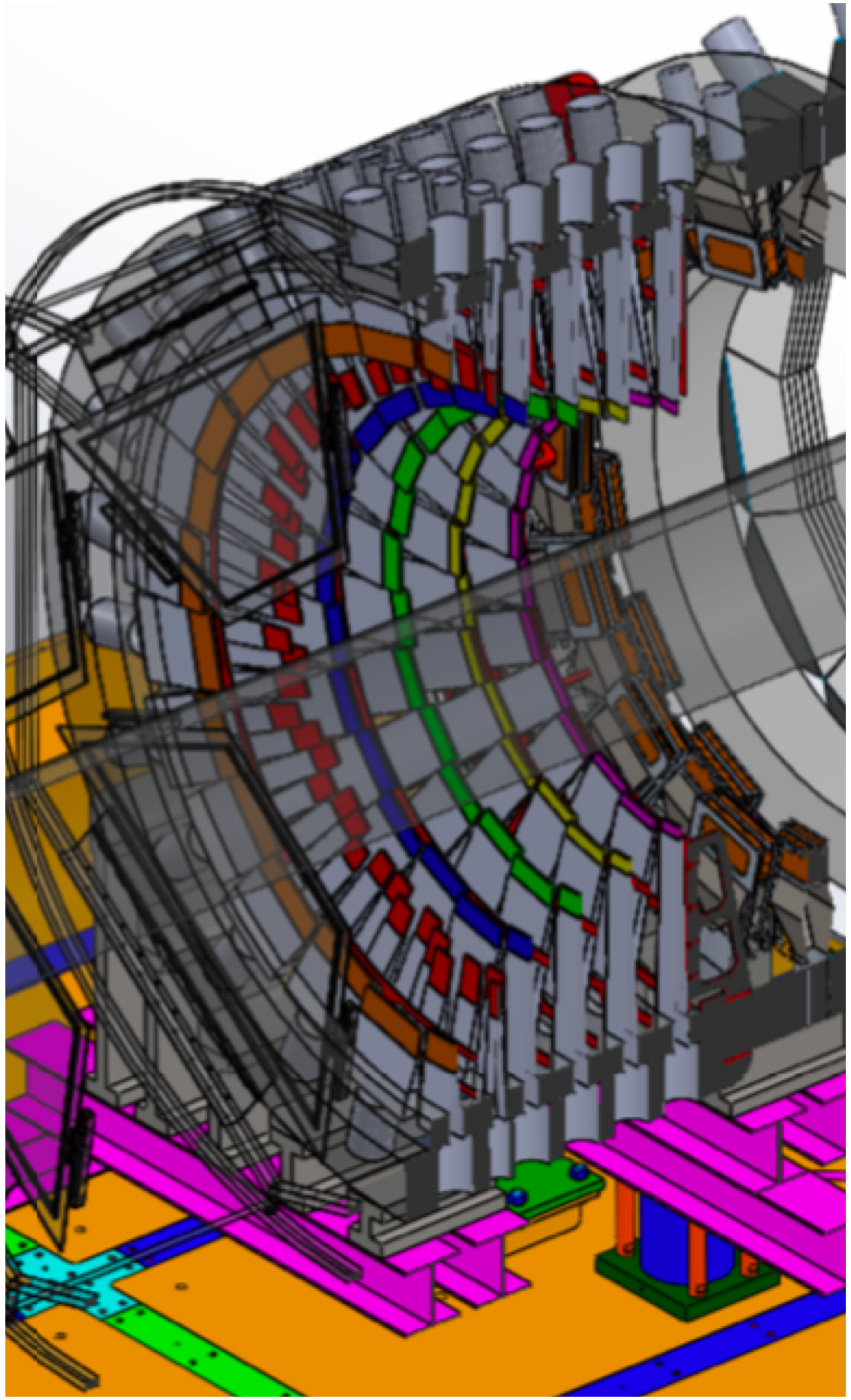
0.5 x 2m

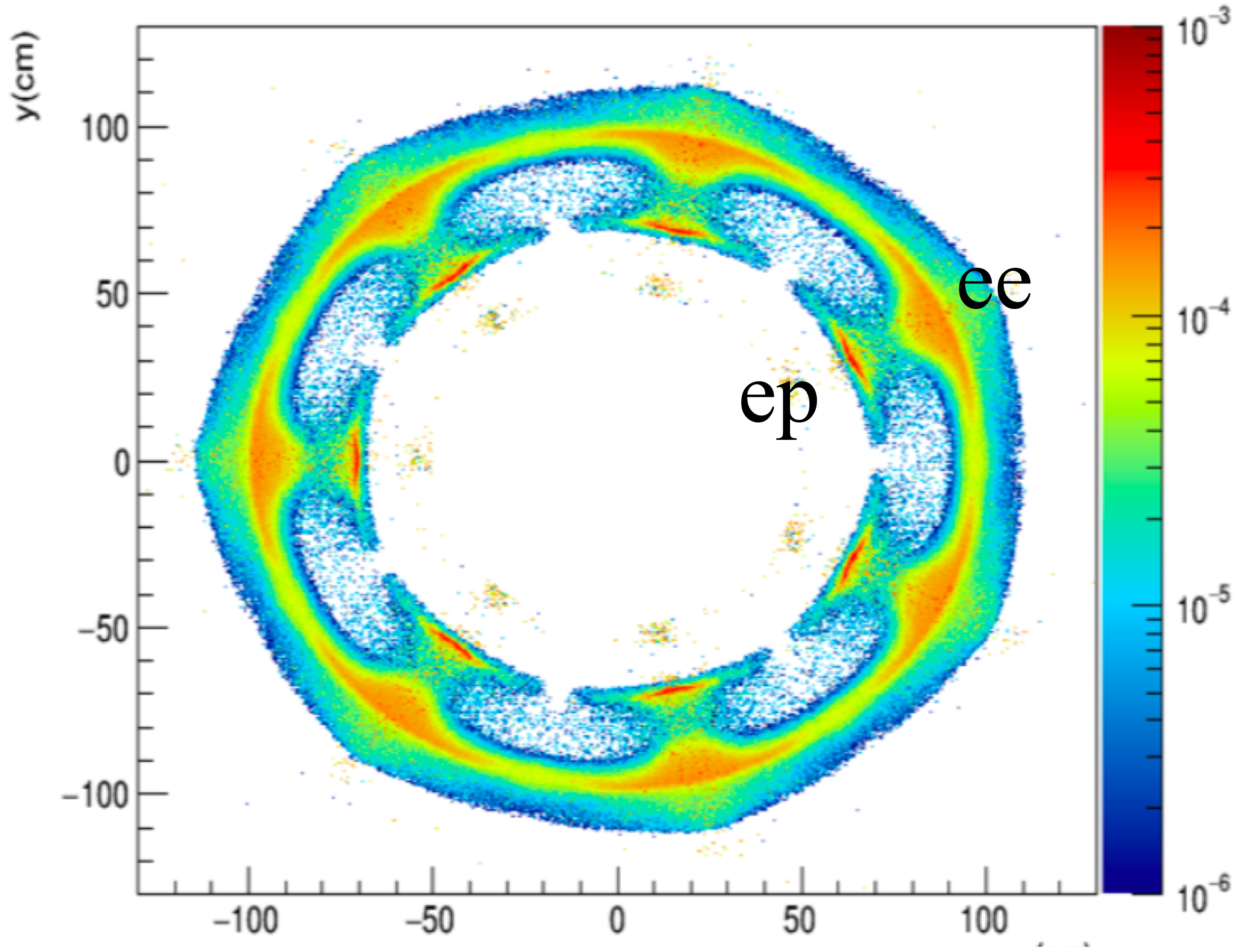
0.9 x 6.5m

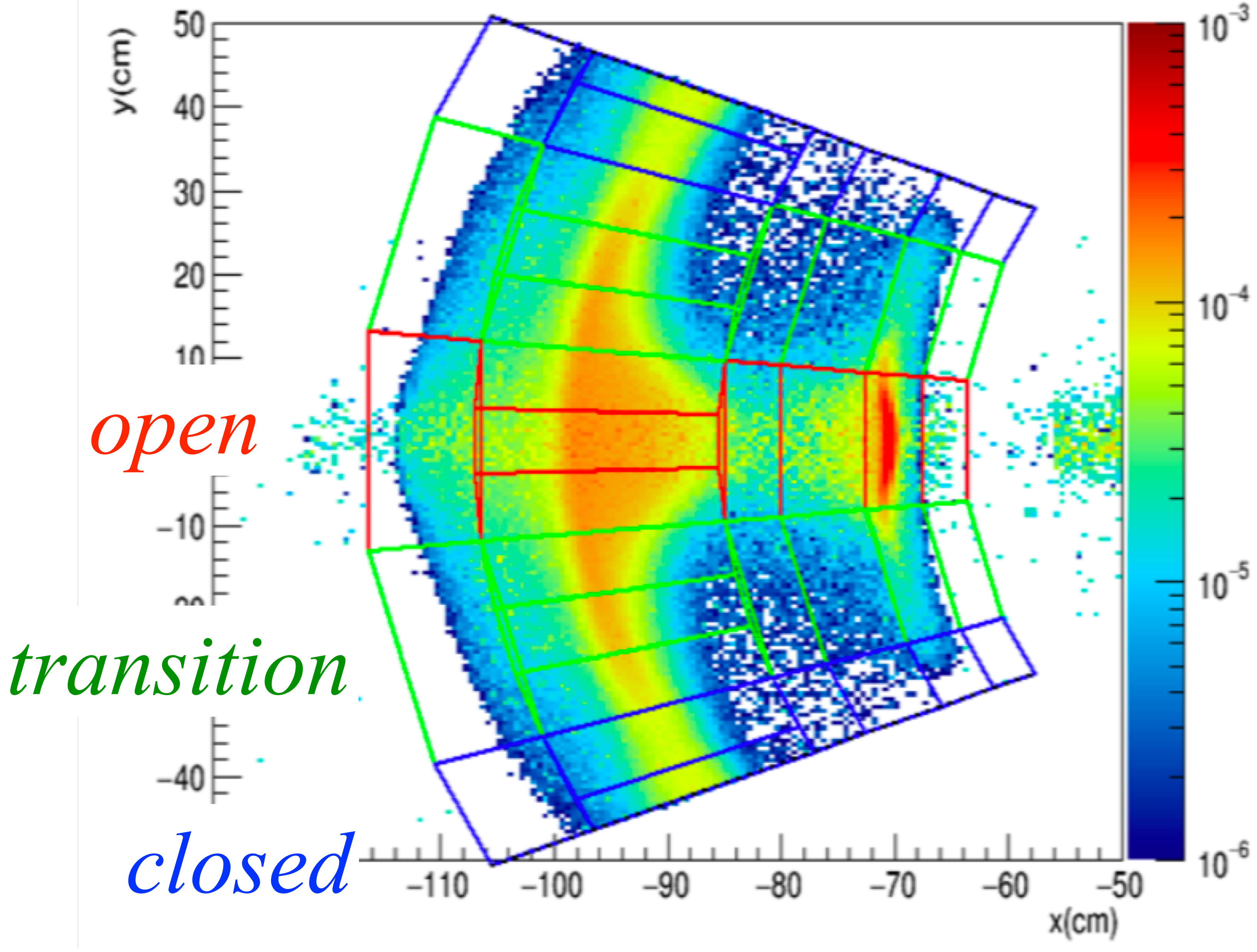


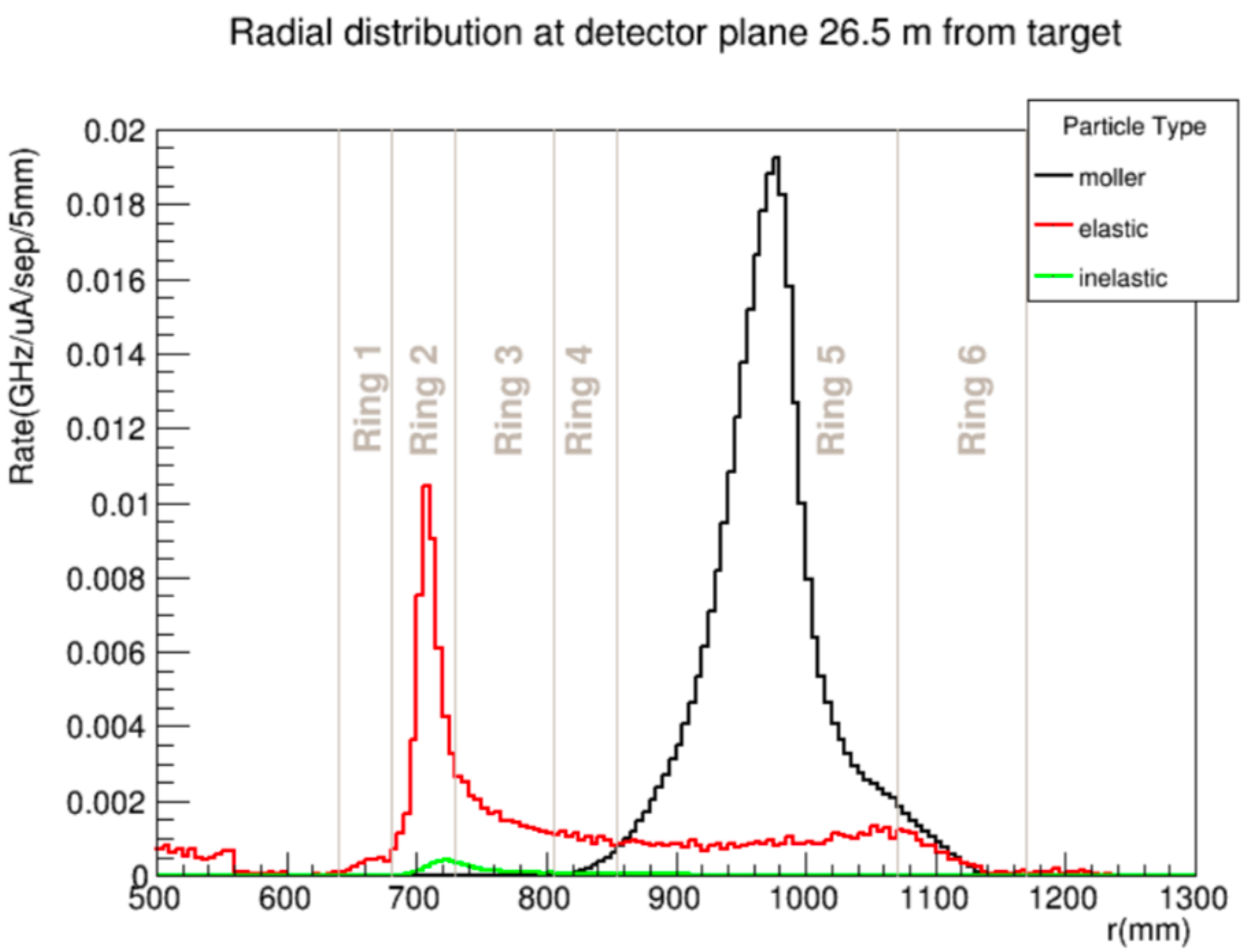


Main Detector



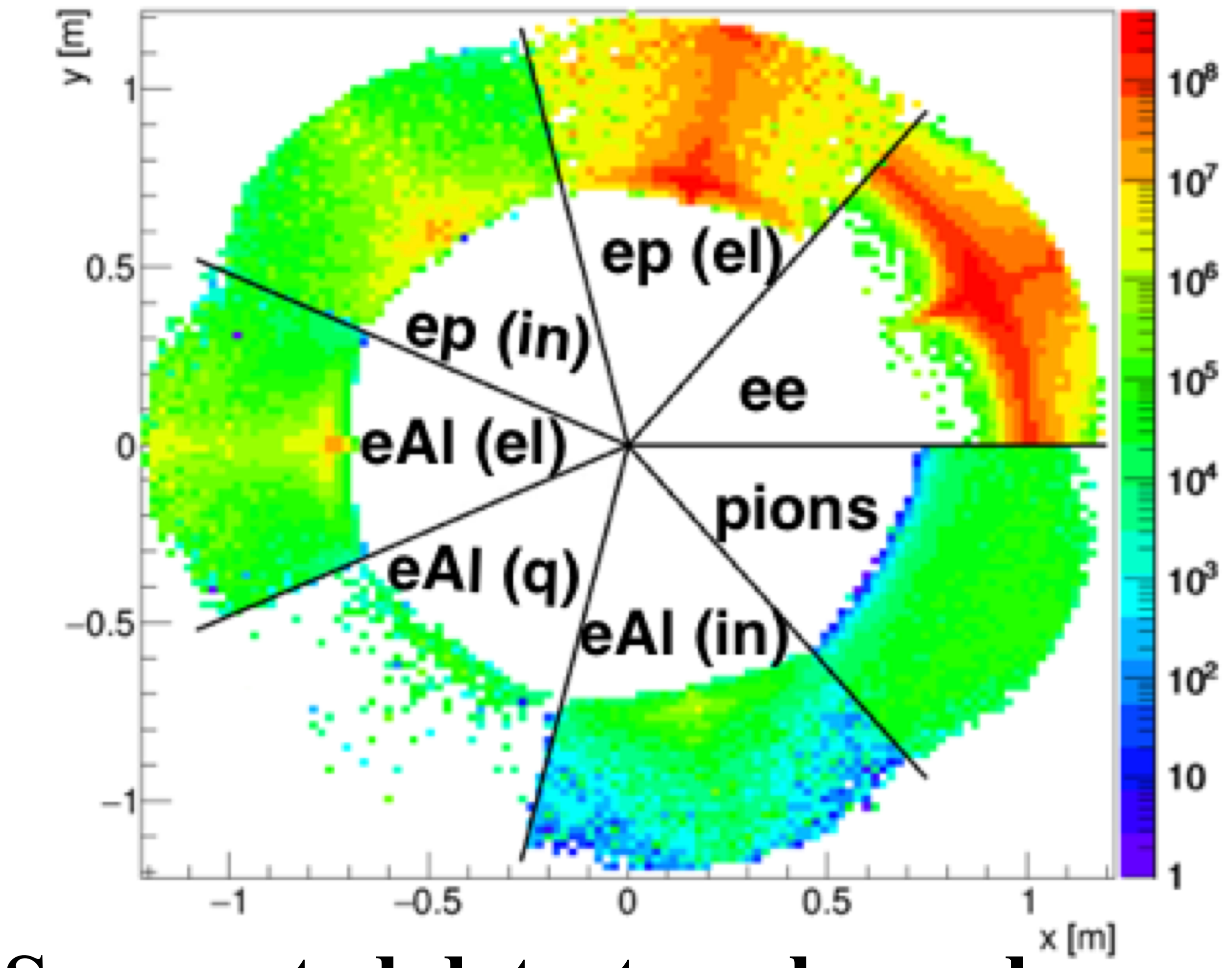






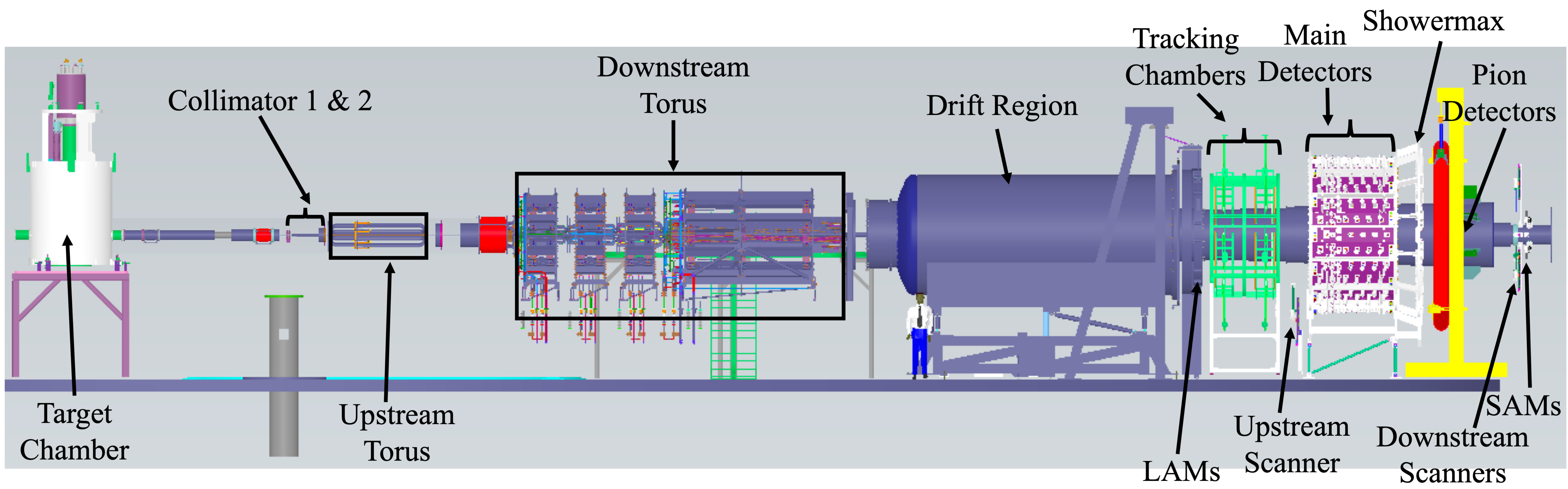
ep *ee*

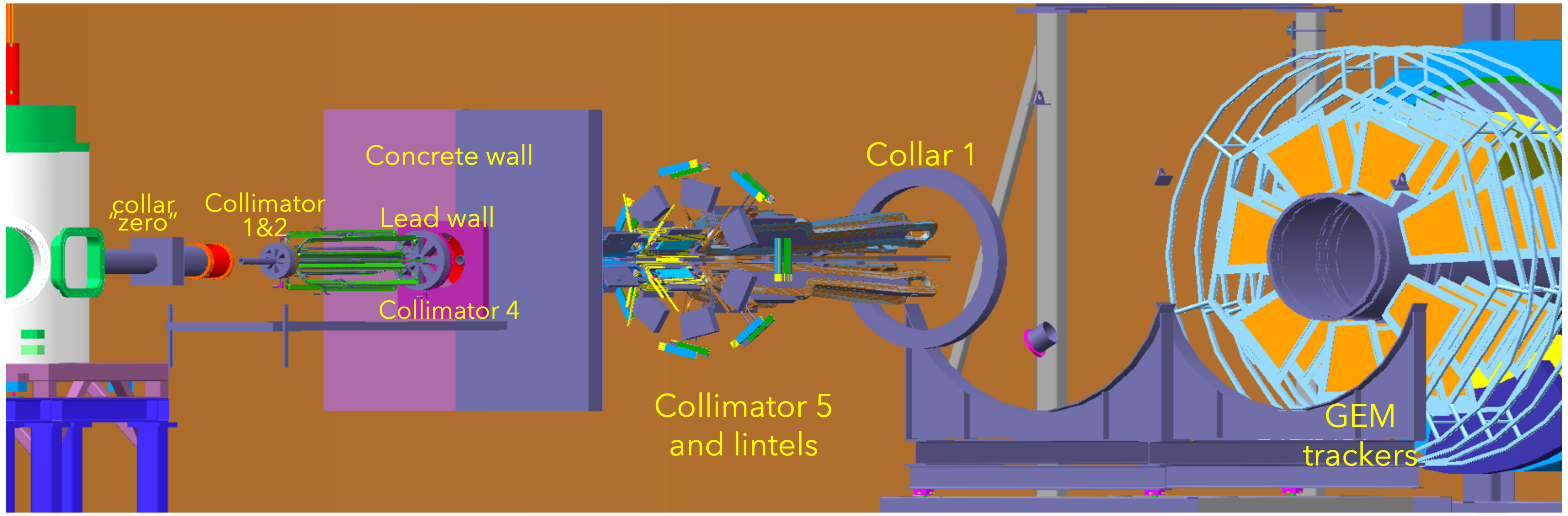
Illustration with each septant a different fundamental background

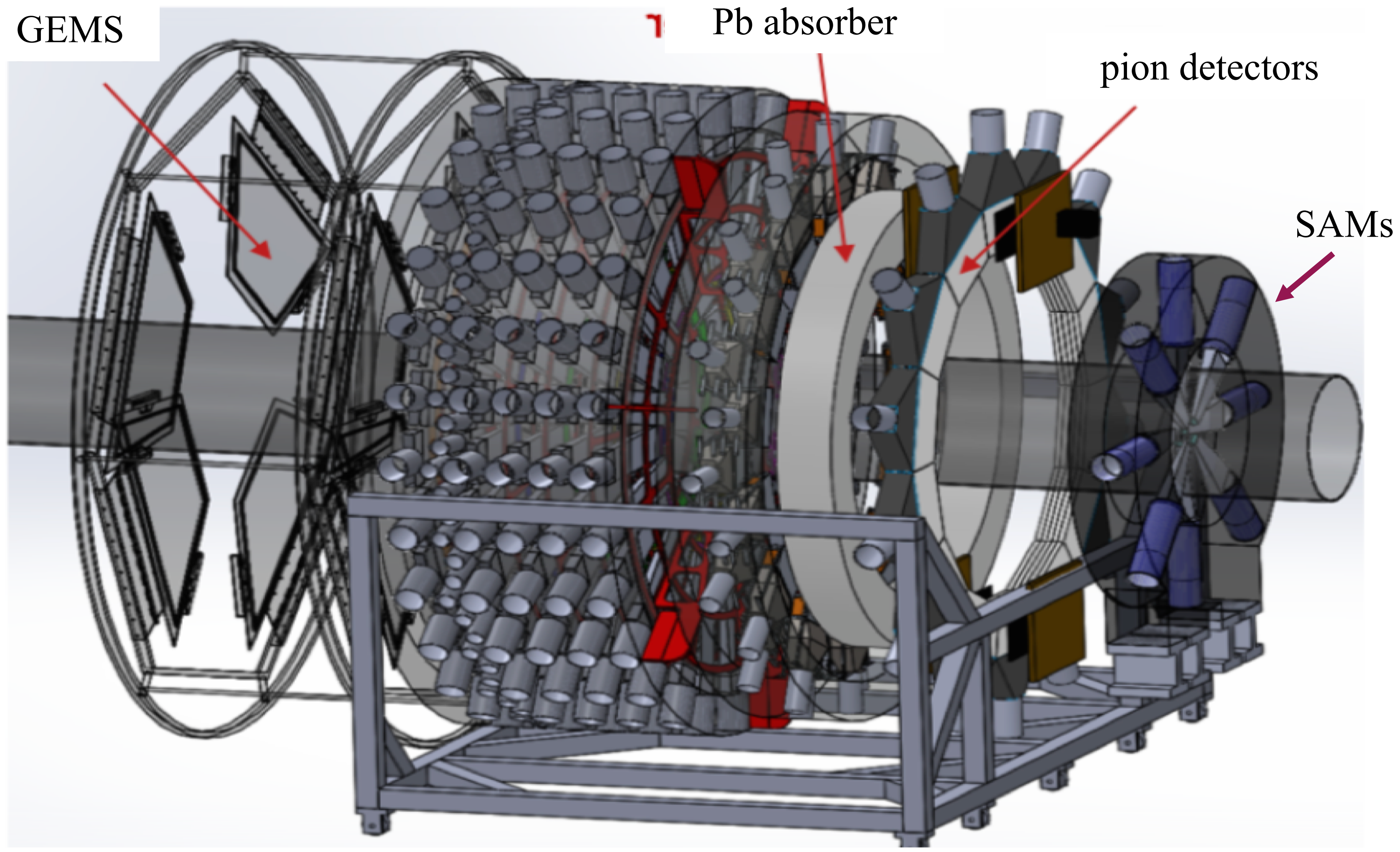


Segmented detector plane deconvolutes signal from backgrounds

Collimation & More Detectors







Collimator 1: long snout, collimates primary beam so what remains can go to the dump. ~3200 W

Collimator 2: wedges define the acceptance of the 7 septants

Walls, collars, and lintels supplement the collimation

MOLLER status

Prototyping/construction/installation (2022-25)

- Final Design Reviews now complete
- Plan for Fall 2023 CD-2/3 review followed by approval
- Technically driven schedule is then ~15 months construction and ~18 months installation
- Now fully funded!
- Project currently on track to be ready to start installation as early as Fall 2024/Q1 2025 or when the hall becomes available

*(*details beyond that depend on performance of CEBAF and delivery of luminosity to SBS program)*

- Project itself currently on track to be ready to start commissioning as early as Spring 2026 subject to scheduling/installation start date

MOLLER Collaboration

~ 160 authors, 37 institutions, 6 countries

K. Kumar: Contact
J. Fast: Project Manager

Includes experience from E158, PREX, Qweak, PVDIS, HAPPEX, G-Zero

MOLLER MIE Project Schedule

MOLLER MIE CD-3a Schedule			2023				2024				2025				2026				2027				2028			
	Start	End	FQ1	FQ2	FQ3	FQ4	FQ1	FQ2	FQ3	FQ4	FQ1	FQ2	FQ3	FQ4	FQ1	FQ2	FQ3	FQ4	FQ1	FQ2	FQ3	FQ4	FQ1	FQ2	FQ3	FQ4
CD-3a Authorization	3/16/23	3/16/23																								
Magnet Coil, Collimator Procurements	1/13/23	7/10/24																								
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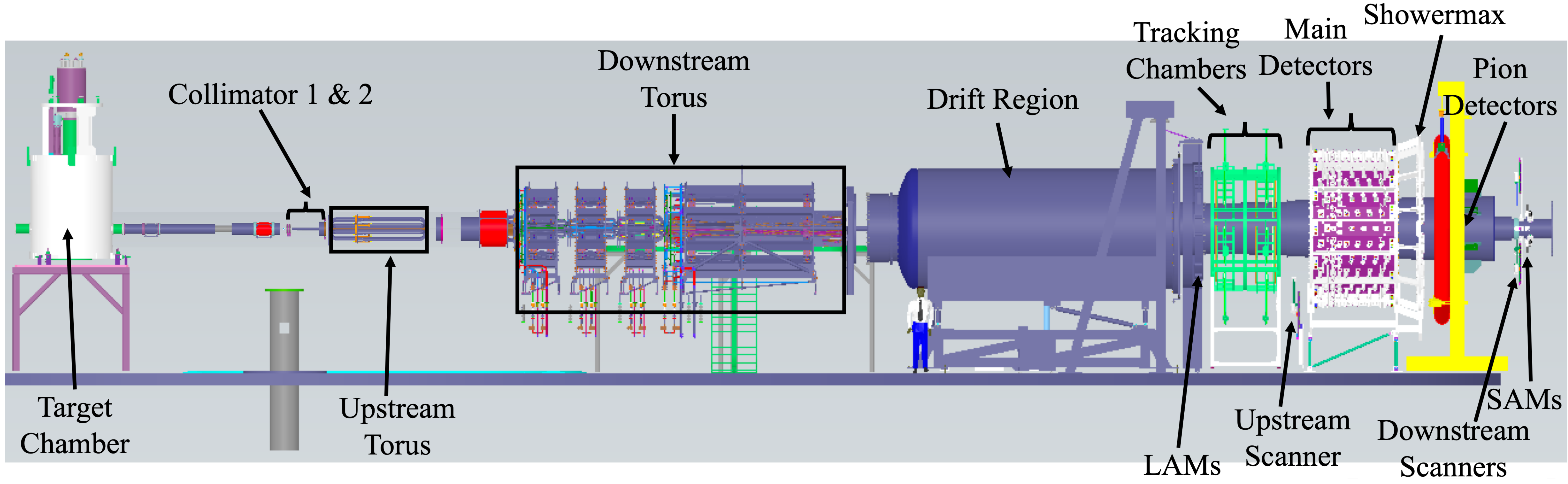
CD-3a Scope Complete (L3 Milestone)	7/19/24	7/19/24																								
Procurement/Fabrication/Assembly	1/5/24	11/6/24																								
Assembly in Hall A	2/10/25	1/13/26																								
Commissioning/KPP validation	1/13/26	3/5/26																								
Ready for CD-4 (L3 milestone)	3/5/26	3/5/26																								
CD-2/3 (L1 Milestone)	6/10/24	6/10/24																								
CD-3a Scope Complete (L2 Milestone)	7/2/25	7/3/25																								
All Equip Ready for Hall (L2 Milestone)	12/18/25	12/18/25																								
CD-4 (L1 Milestone)	3/3/28	3/3/28																								

Summary

- Thank you collaboration, Jlab staff, engineers, project team!
- MOLLER represents an outstanding opportunity to take advantage of the unique instrument (11 GeV CEBAF beam) enabled by the 12 GeV upgrade
- Electroweak physics with PVES are a powerful component of the low energy fundamental symmetries program
- The science case remains compelling and the plan is to run physics at about the time that precision results from high luminosity phases of 14 TeV LHC are becoming available
- MOLLER will search for new interactions with reach into new physics phase space that cannot otherwise be accessed
- Now we just have to do is build it and do it (construction and execution of MOLLER)



Backup

Outline

1. Collaboration
2. PVES measure Apv
3. Next-generation Experiments will provide precise BSM probe – experiments measure increasingly smaller Apv
4. MOLLER experiment Design
5. MOLLER is precise and measures Qwe and constrains Cee
6. Theory: Standard Model prediction is tight and MOLLER measurement will constrain BSM theories
7. Quantifying Discovery Potential: Mass Reach Scale
8. Quantifying Discovery Potential : sin2thetaW precision
9. Quantifying Discovery Potential : Coupling coefficients phase space
10. New Physics Complementarity
11. MOLLER Apparatus
12. MOLLER measuring the asymmetry – integration at 2kHz
13. MOLLER full azimuthal coverage
14. MOLLER complex magnets/collimation
15. MOLLER Main detector: segmented for backgrounds
16. MOLLER Beam Control??
17. MOLLER Uncertainty Requirements
18. MOLLER Status
19. Conclusion

MOLLER status

DOE MIE (Office of Nuclear Physics)

Prototyping/construction/installation (2022-25)

- Final Design Reviews now complete
- Plan for Fall 2023 CD-2/3 approval
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*(*details beyond that depend on performance of CEBAF and delivery of luminosity to SBS program)*

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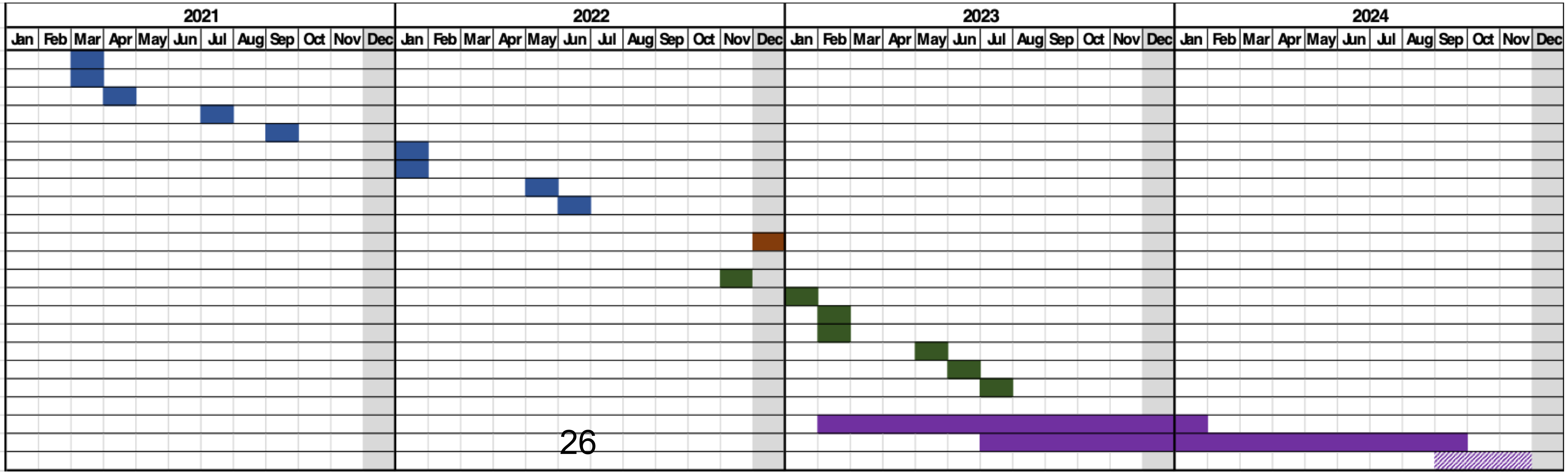
MOLLER MIE Project Schedule

MOLLER Schedule		
Review	Start	End
PDR - Downsteam Toroid	3/29/21	3/29/21
PDR - Trigger and DAQ	3/18/21	3/18/21
PDR - Magnet Power Supplies, Leads, Jumpers	4/30/21	4/30/21
PDR - Beam Pipes, Bellows and Windows	7/12/21	7/12/21
PDR - GEM Modules	9/14/21	9/14/21
PDR - Detector Systems (except GEMs)	1/12/22	1/14/22
PDR - Hydrogen Target	1/20/22	1/20/22
PDR - Spectrometers	5/23/22	5/24/22
PDR - Shielding and Utilties	6/1/22	6/1/22
FDR - All Systems	12/5/22	12/8/22
CD-3a Directors Review	11/15/22	11/17/22
CD-3a Independent Project Review	1/10/23	1/12/23
CD-3a Approval	2/12/23	2/12/23
Independent Final Design Review	2/6/23	2/9/23
CD-2/CD-3 Directors Review	5/9/23	5/13/23
CD-2/CD-3 Independent Project Review	6/27/23	6/30/23
CD-2/CD-3 ESAAB Approval	7/20/23	7/20/23
Long-Lead procurements	2/13/23	1/29/24
Construction	7/21/23	9/3/24
Installation	9/4/24	12/15/25



MOLLER schedule – CD-3a and beyond

- Working on completing final procurement packages for CD-3a scope
  - Intent is to have all requisitions in motion by July
- Completing planning (Performance Measurement Baseline) for CD-2/3
  - Data freeze in May – no changes until we set baseline at end of CY2023
- Plan remains to complete fabrication/assembly/test outside Hall A by end of Q1 FY25
  - Details beyond that depend on performance of CEBAF and delivery of luminosity to SBS program

MOLLER MIE CD-3a Schedule			2023				2024				2025				2026				2027				2028			
	Start	End	FQ1	FQ2	FQ3	FQ4	FQ1	FQ2	FQ3	FQ4	FQ1	FQ2	FQ3	FQ4	FQ1	FQ2	FQ3	FQ4	FQ1	FQ2	FQ3	FQ4	FQ1	FQ2	FQ3	FQ4
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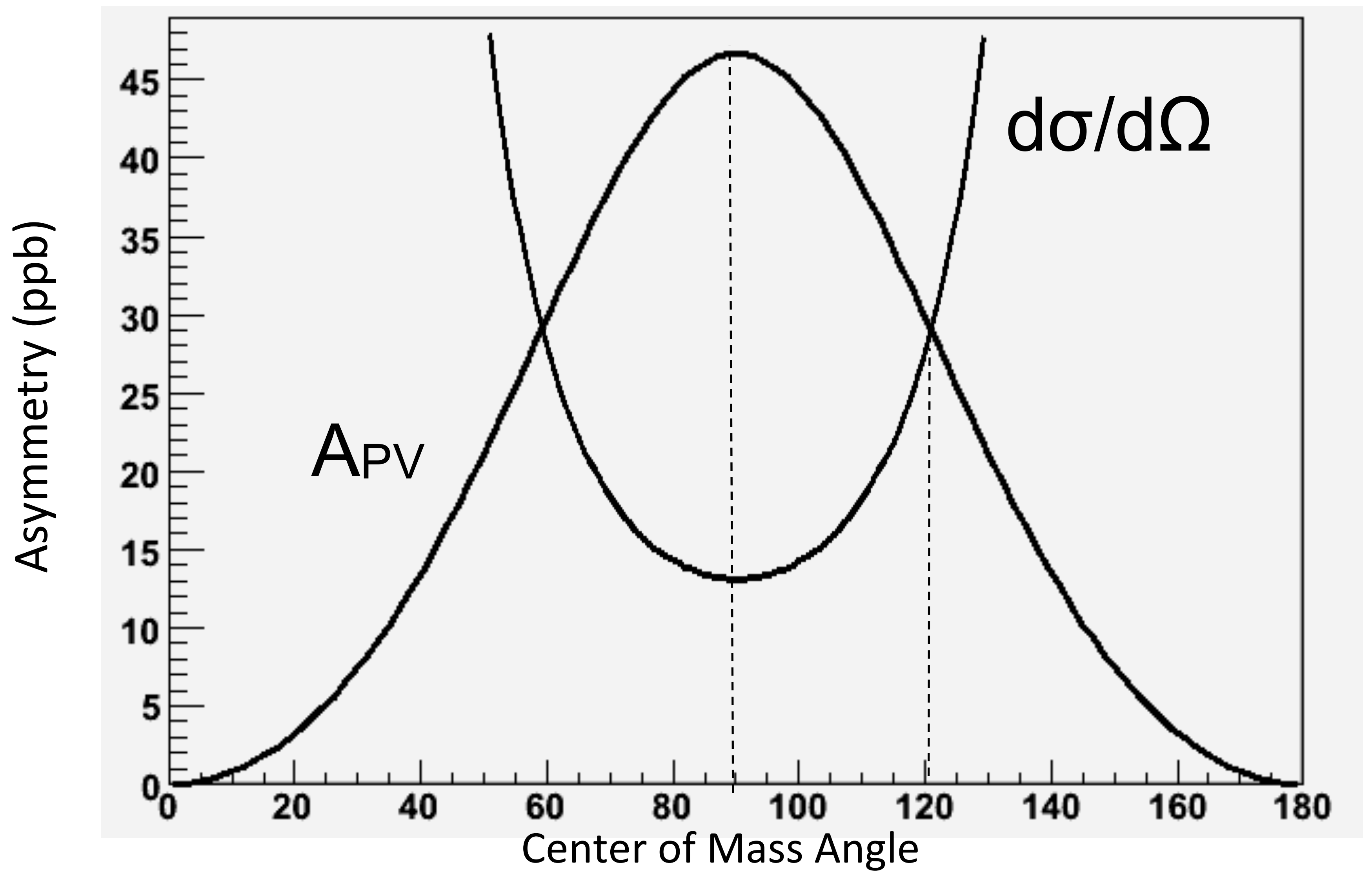
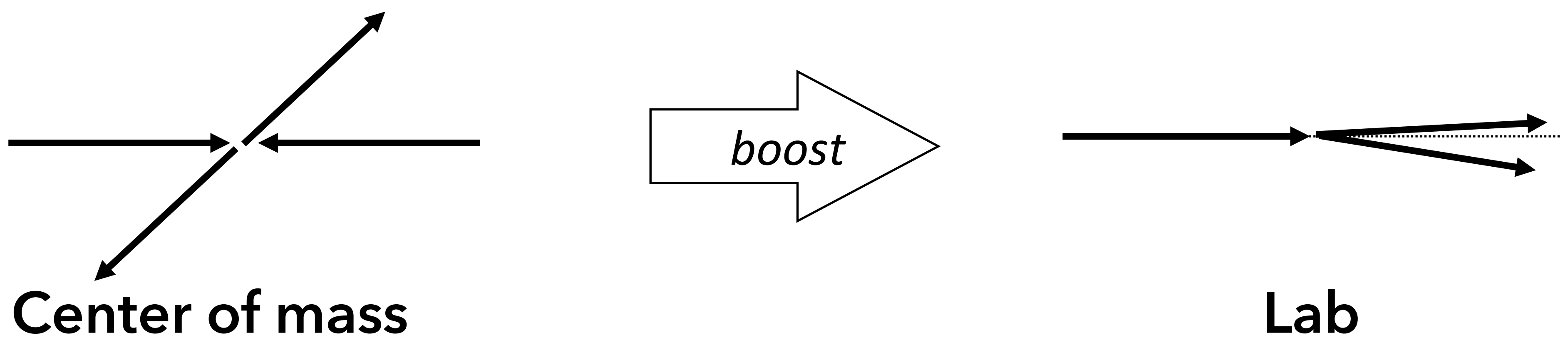
CD-4 (L1 Milestone)	3/3/28	3/3/28																								

Figure of Merit

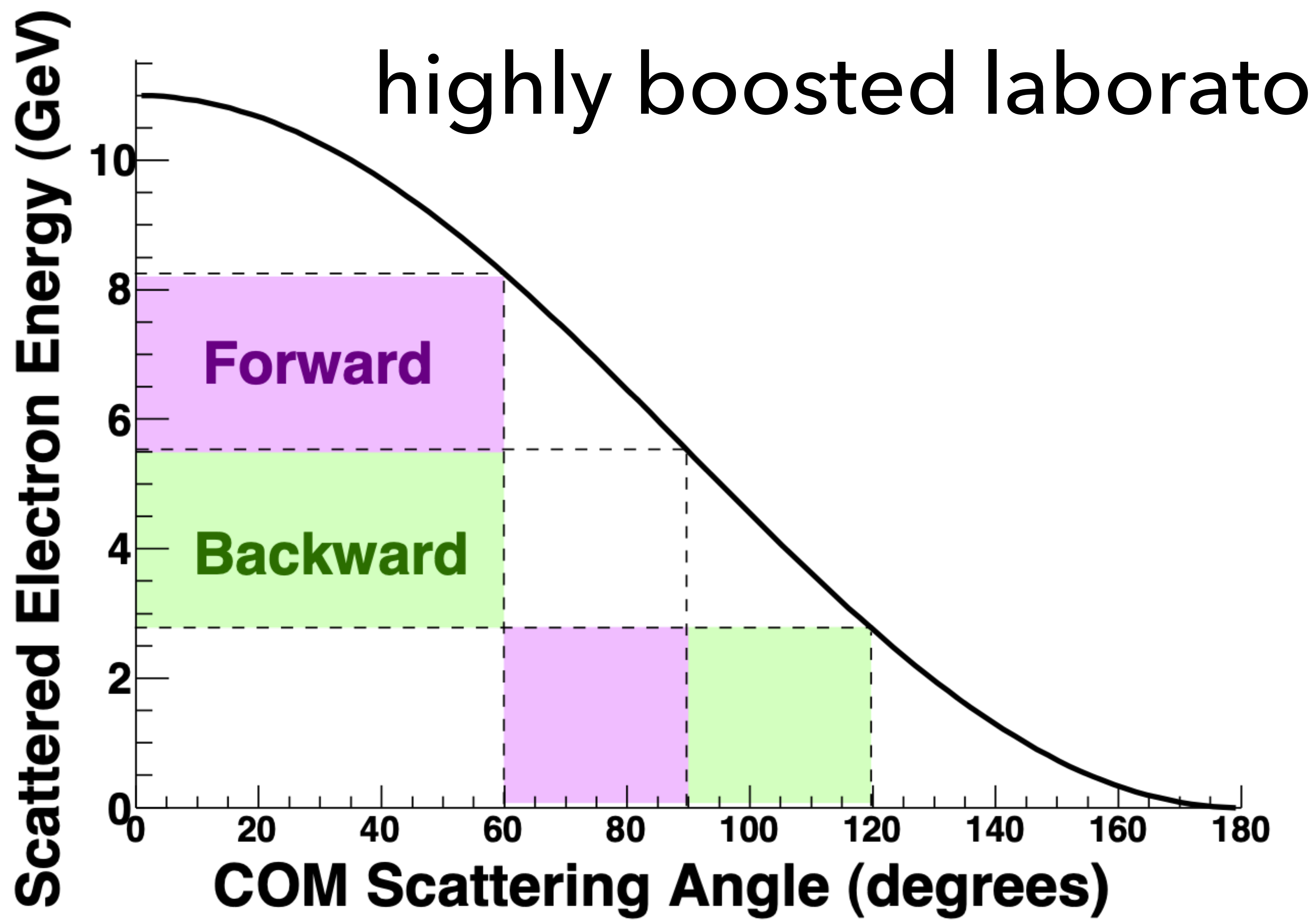
$$A_{PV} = \frac{\sigma_R - \sigma_L}{\sigma_R + \sigma_L} = mE\frac{G_F}{\sqrt{2}\pi\alpha}\frac{4\sin^2\theta}{(3+\cos^2\theta)^2}Q_W^e$$

Highest figure of merit at θ_{CM} = 90°

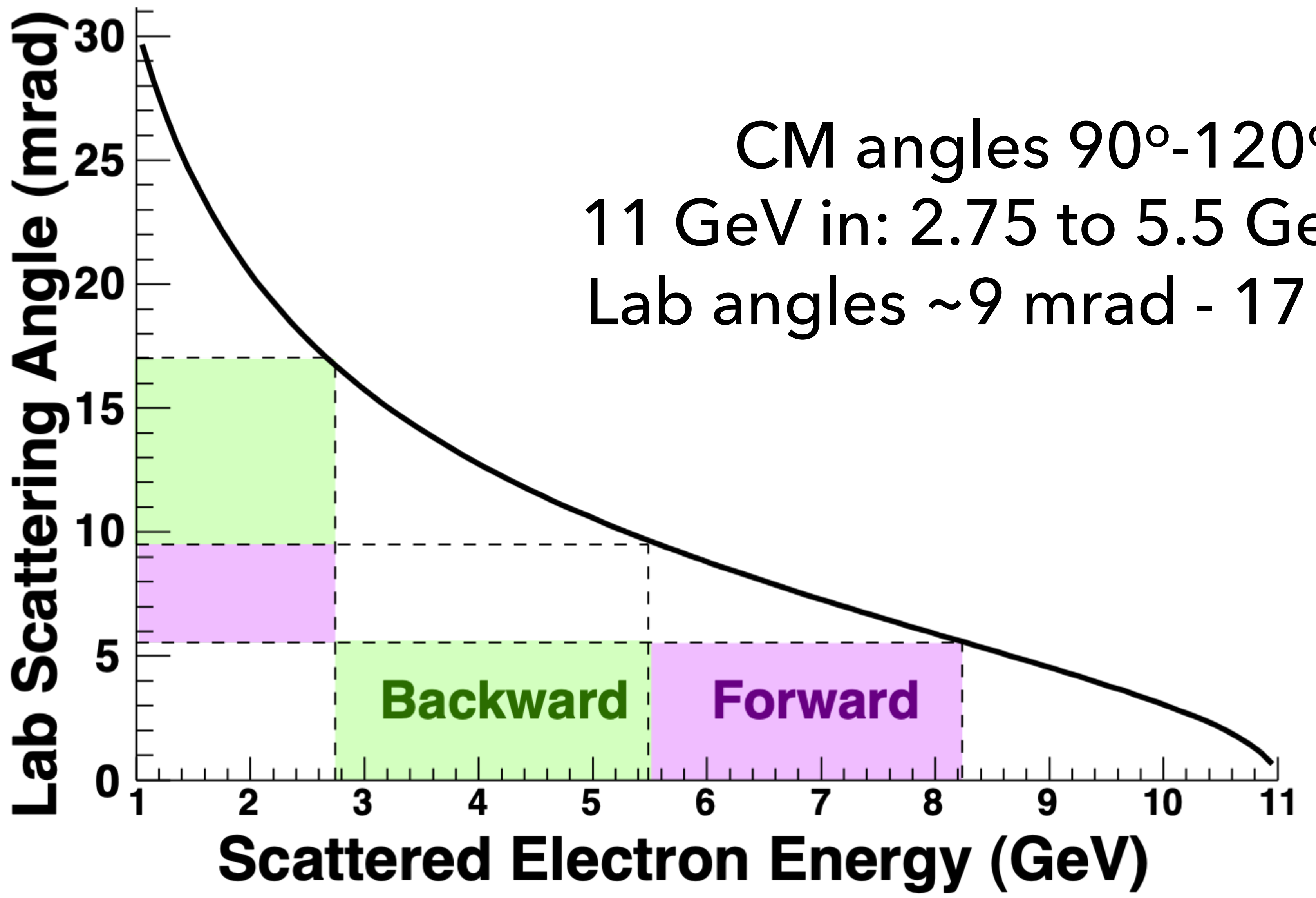




Identical particles.
Measure either forward or backward scattering.

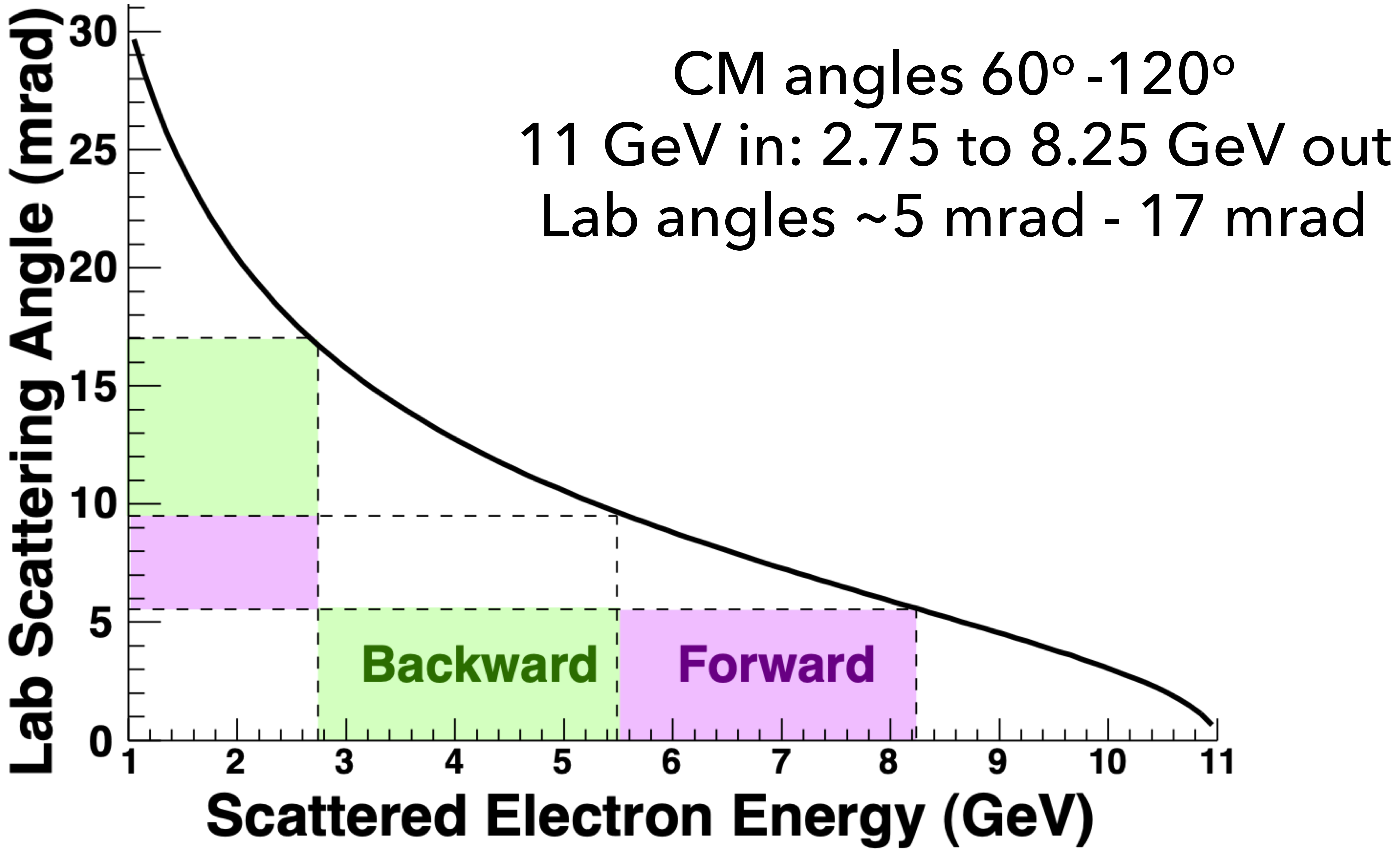


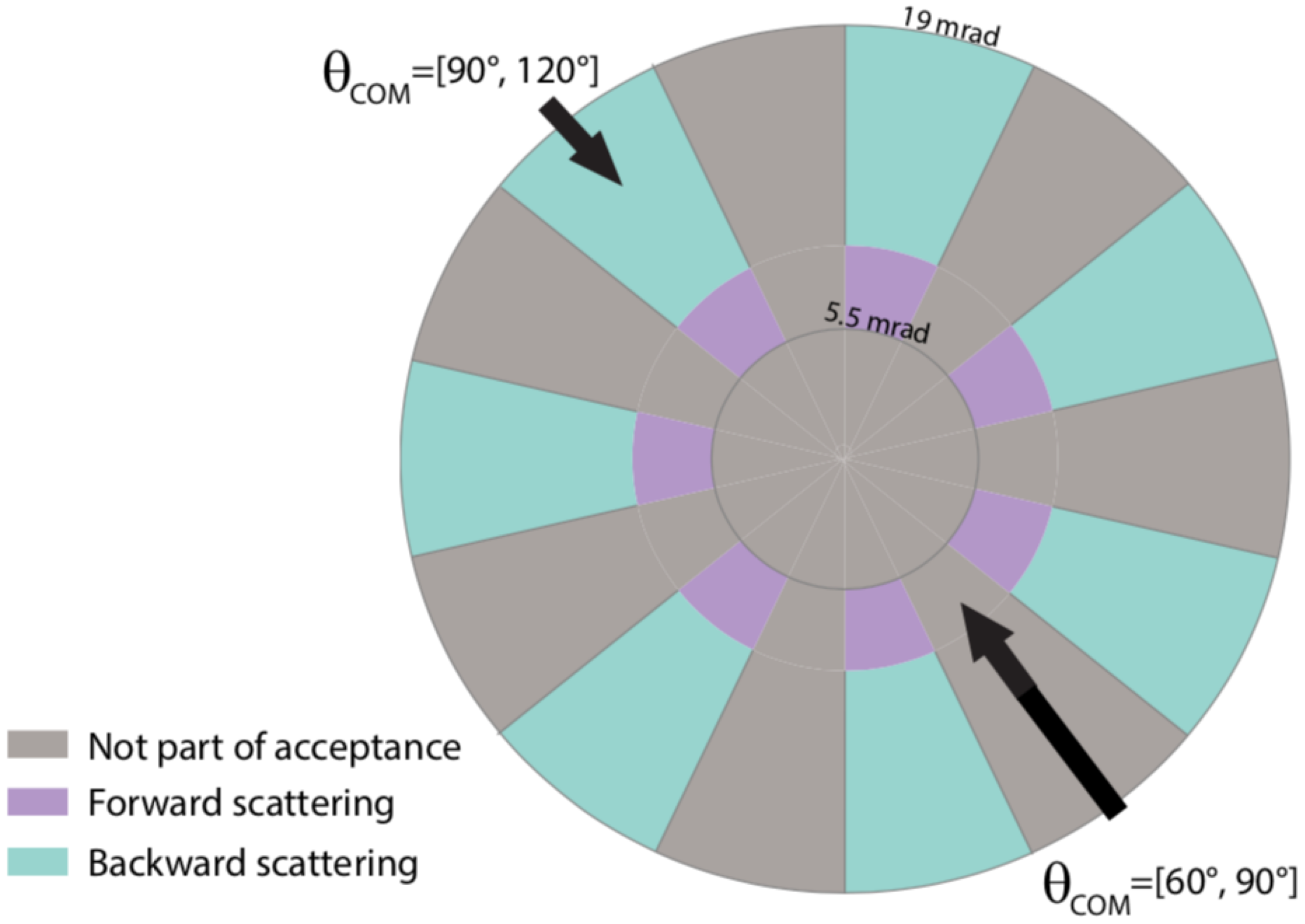
CM angles 90°-120°
11 GeV in: 2.75 to 5.5 GeV out
Lab angles ~9 mrad - 17 mrad



Identical Particles

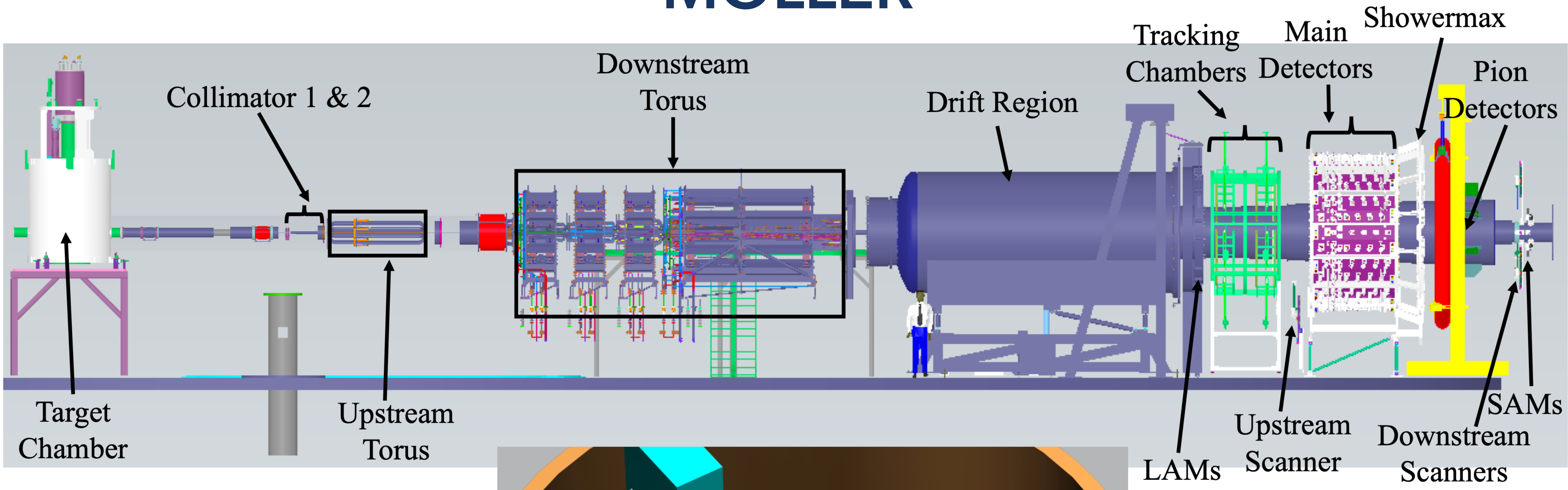
Since you only need either the forward or the backward scatter, accept forward+backward for half the azimuth



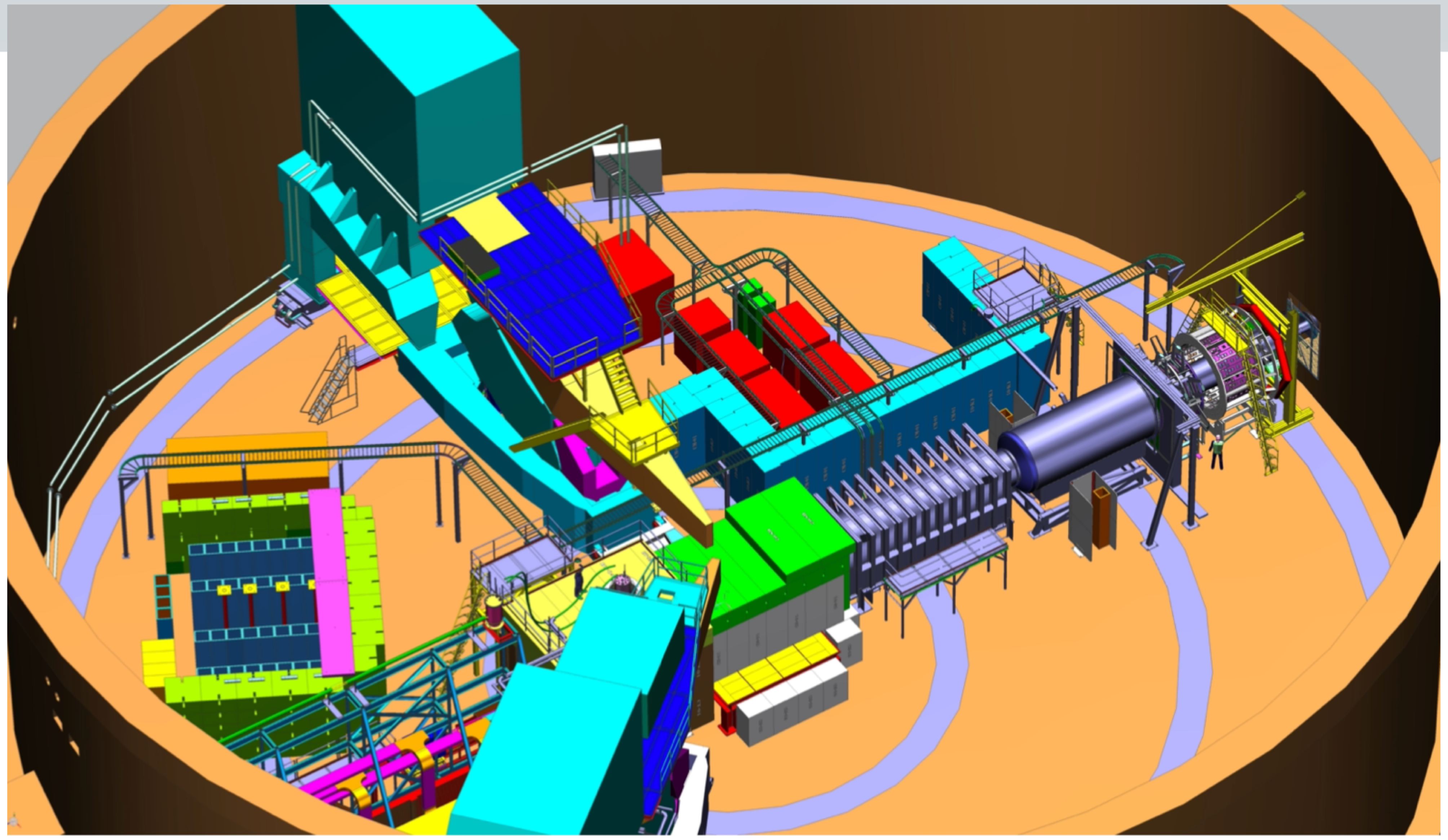


Unique concept allows for full azimuthal acceptance (effectively) even leaving space for coils but makes for a challenging design

MOLLER

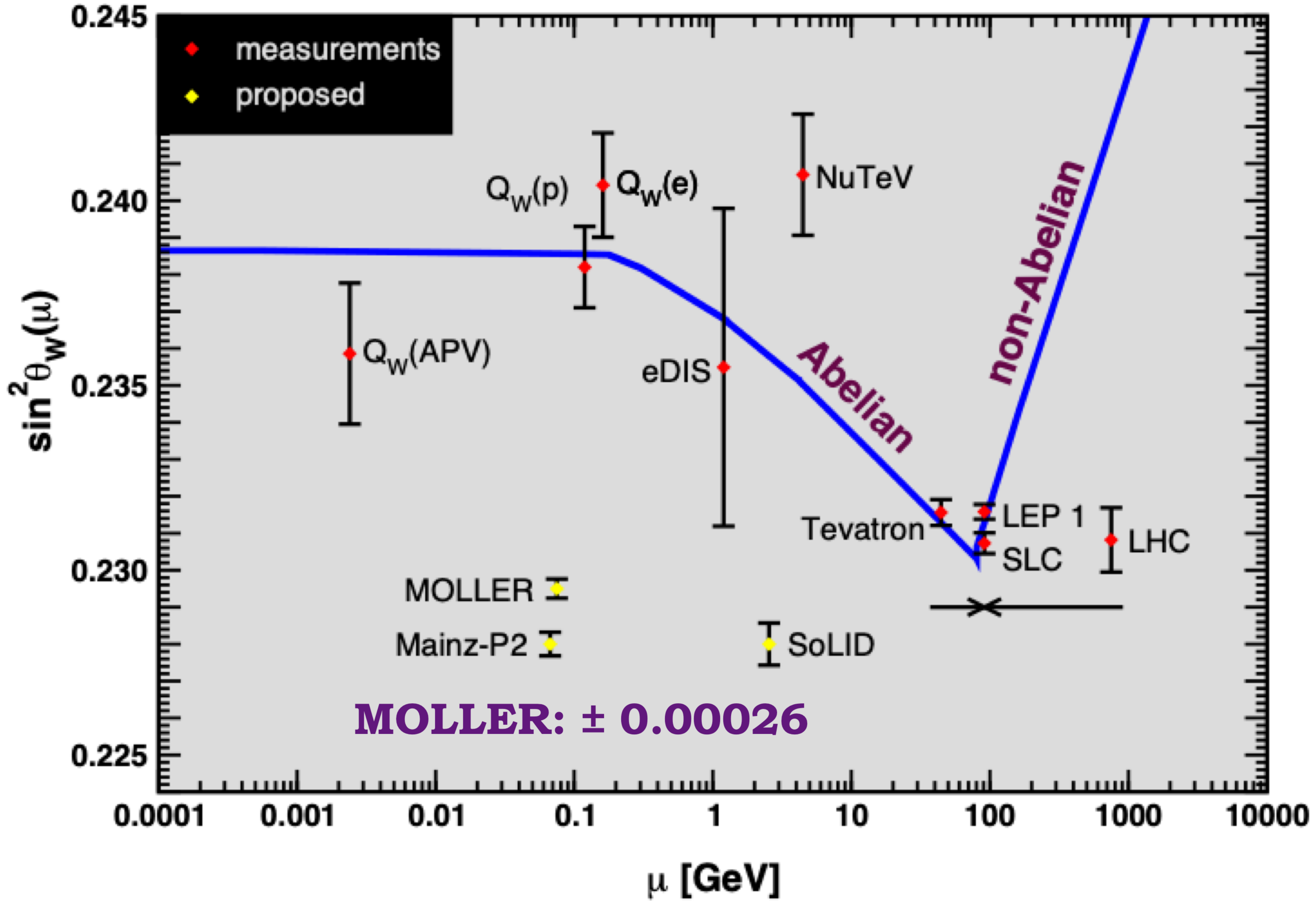


Collimator 1 & 2
Downstream
Torus
Drift Region
Tracking
Chambers
Main
Detectors
Showermax
Pion
Detectors
Target
Chamber
Upstream
Torus
LAMs
Upstream
Scanner
SAMs
Downstream
Scanners



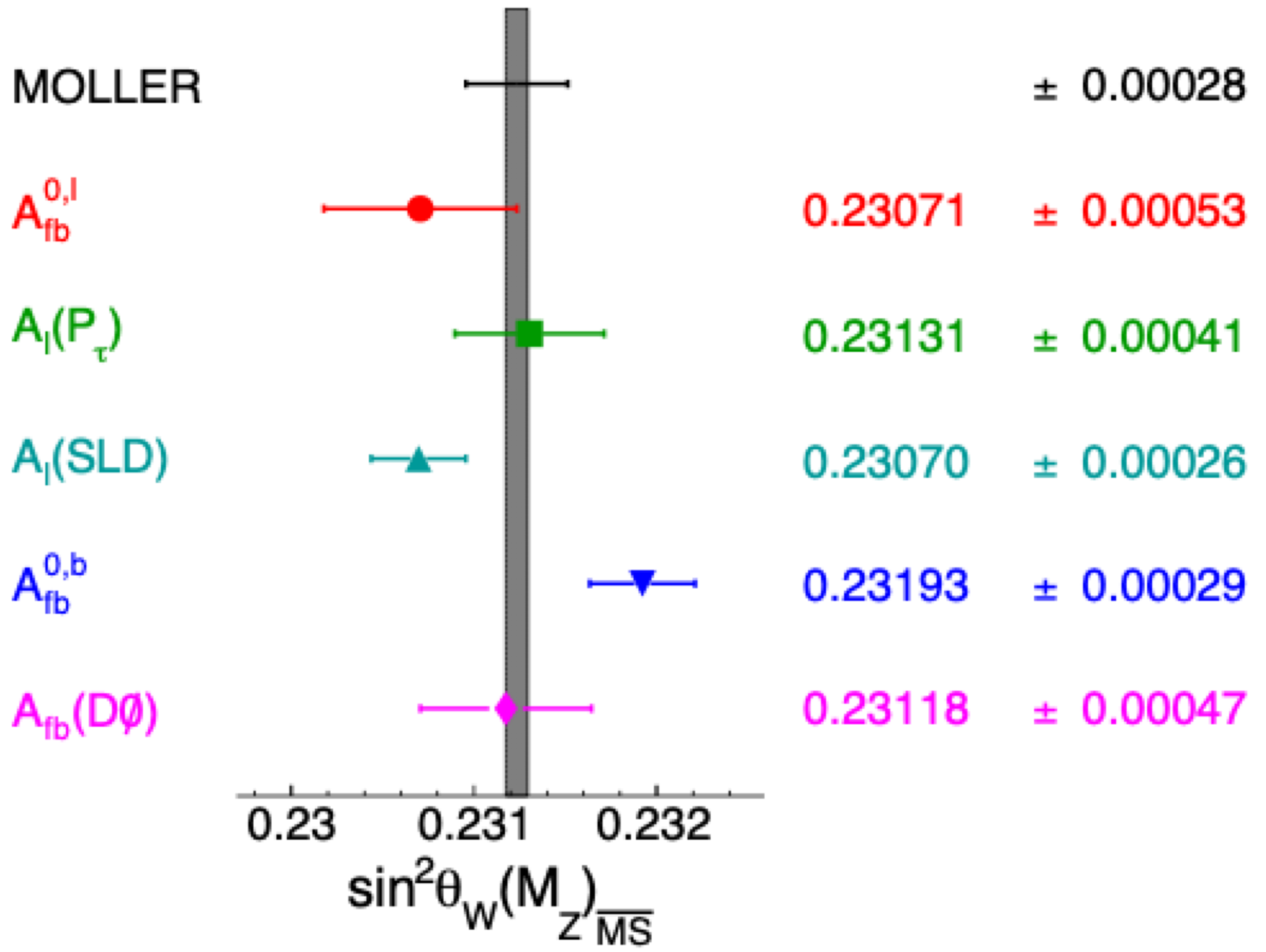
The Weak Mixing Angle

MOLLER Projection: $\delta(\sin^2\theta_W) = \pm\ 0.00023\ (stat.) \pm\ 0.00012\ (syst.)$



± 10σ discovery potential at $Q^2 \ll M_Z^2$

Z resonance measurements:
no interference term



Tevatron: 0.00033 (combined)

Mainz P2: 0.00031 (projected)

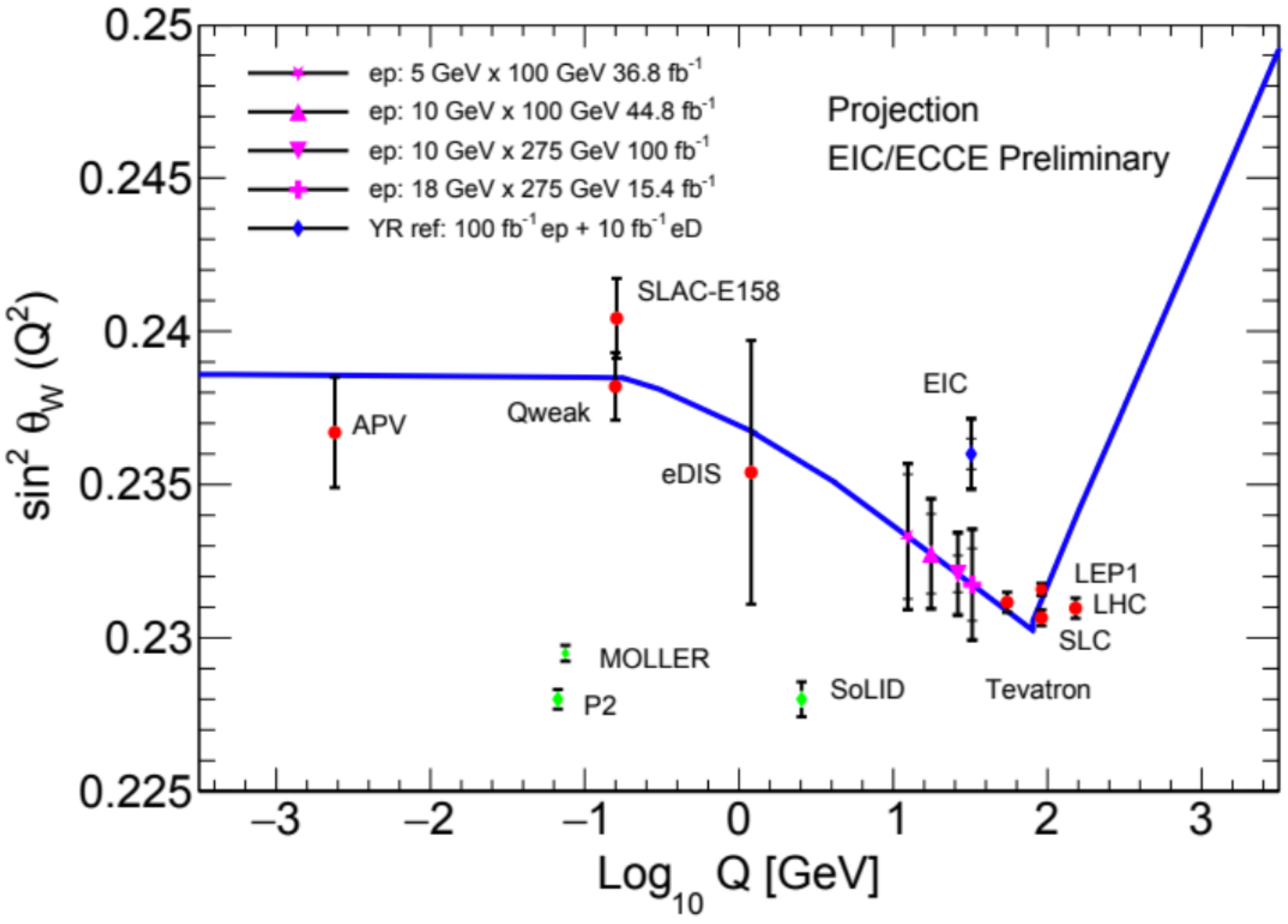
LHC (combined) : ~ 0.00036
systematics-dominated (pdf uncertainties)

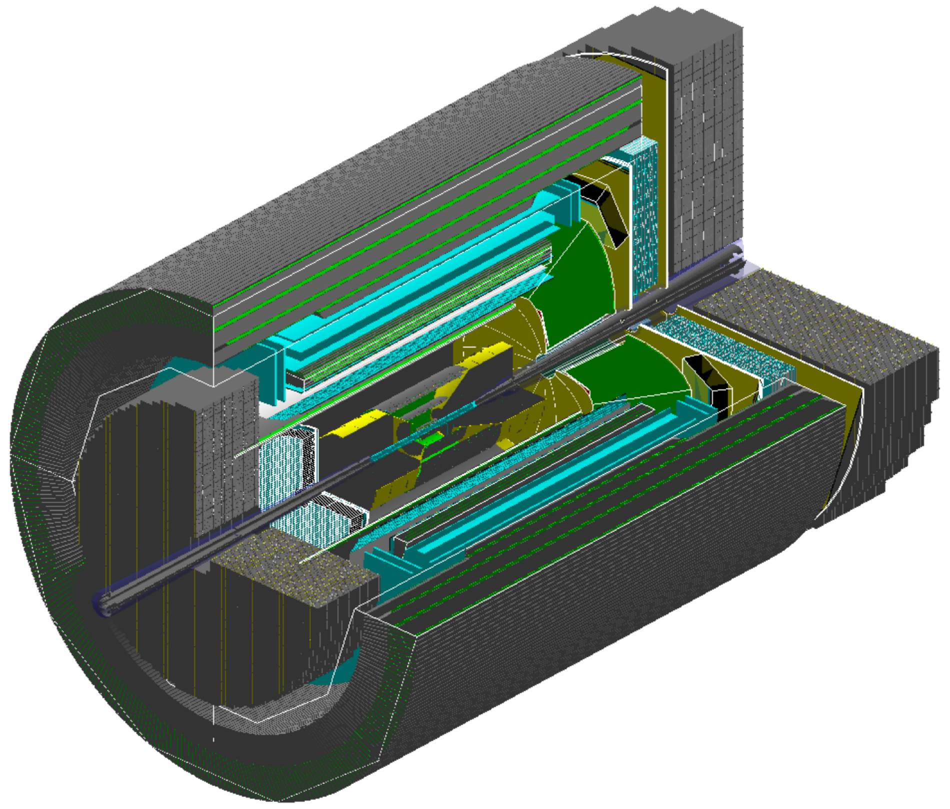
LHC (combined) and MOLLER/P2 (combined) will provide two combinations with uncertainties ~ 0.0002 in late-2020's

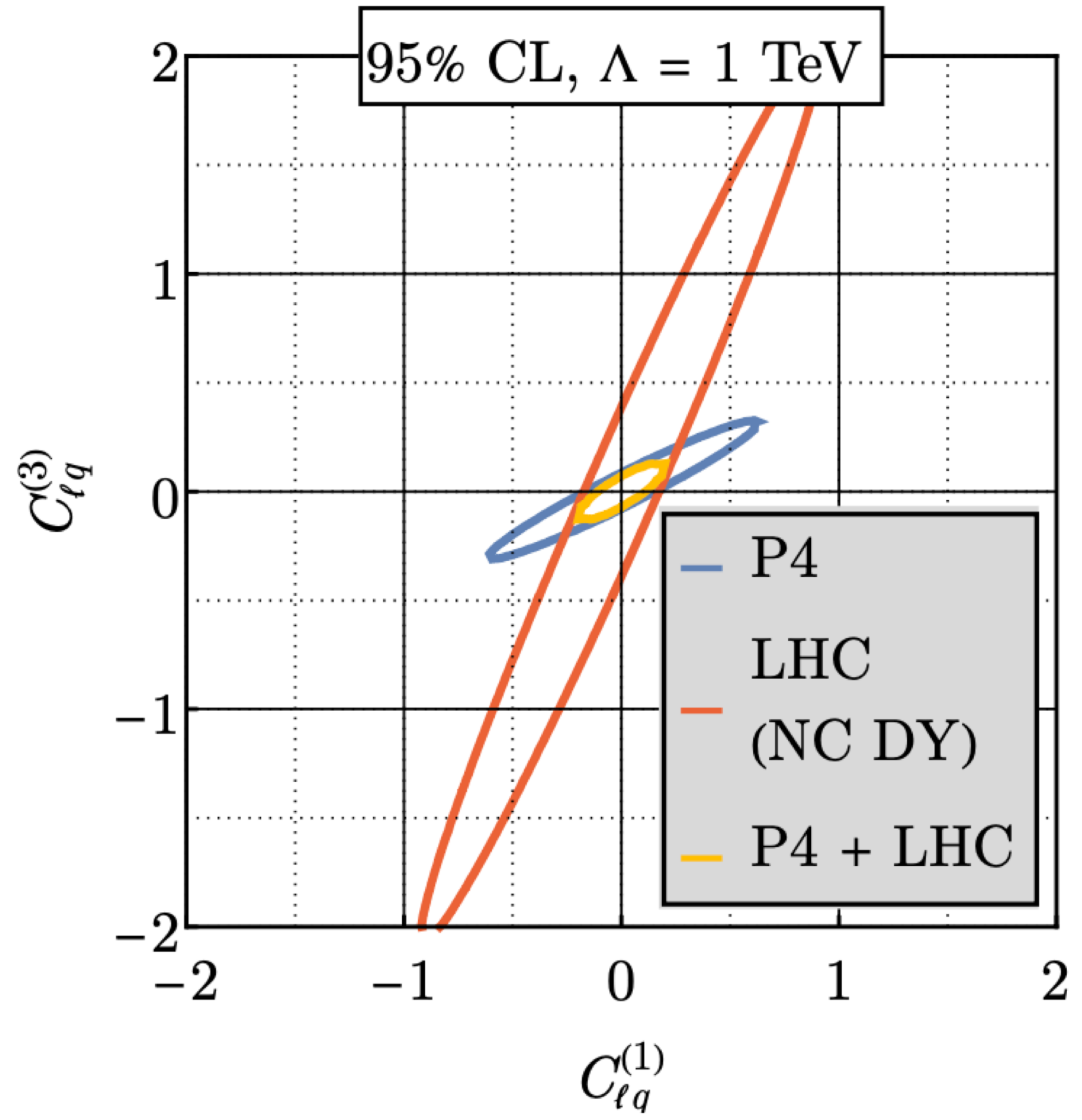
PV-DIS at EIC

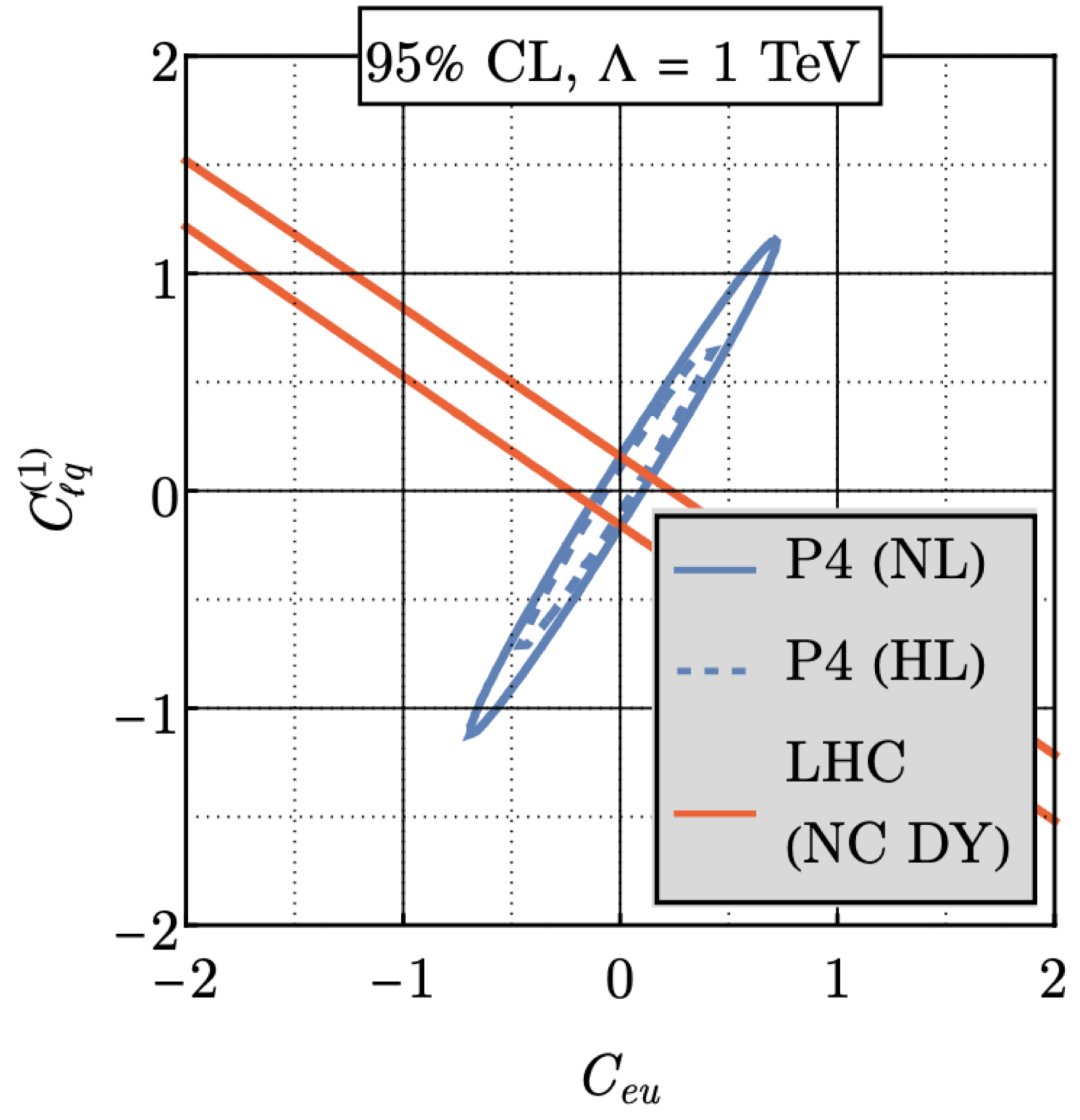
Measurement of A_{PV}^{DIS} modeled with ECCE detector

- Proton or deuterium, PDF uncertainty is under control
- Average over nuclear polarization
- 1% precision of e-beam polarimetry competes with statistics
- Int. Lumi. ~100 fb^{-1} (~1yr@10^{35})









Sensitivity to 4-Lepton Contact Interactions from Low Energy and Colliders

$$\frac{\Lambda}{\sqrt{|g_{RR}^2 - g_{LL}^2|}} = \frac{1}{\sqrt{\sqrt{2}G_F|\Delta Q_W^e|}}$$

$$\simeq \frac{246.22\ \text{GeV}}{\sqrt{0.023 Q_W^e}} = 7.5\ \text{TeV}.$$

Model	η_{LL}^f	η_{RR}^f	η_{LR}^f	η_{RL}^f
$LL^\pm$	±1	0	0	0
$RR^\pm$	0	±1	0	0
$LR^\pm$	0	0	±1	0
$RL^\pm$	0	0	0	±1
$VV^\pm$	±1	±1	±1	±1
$AA^\pm$	±1	±1	∓1	∓1
$VA^\pm$	±1	∓1	±1	∓1

Conventional Collider Contact Interaction Analysis: → $|g_{RR}^2 - g_{LL}^2| = 4\pi$

Simultaneous fits to cross-sections and angular distributions

LEP200

95% C.L. Limits

$\Lambda_{\rm LL}^{\rm ee} \sim \mathbf{8.3}$ TeV $\qquad \Lambda_{\rm LL}^{\rm ll} \sim \mathbf{12.8}$ TeV

$\Lambda_{\rm RR}^{\rm ee} \sim \mathbf{8.2}$ TeV $\qquad \Lambda_{\rm RR}^{\rm ll} \sim \mathbf{12.2}$ TeV

$\Lambda_{\rm VV}^{\rm ee} \sim \mathbf{17.7}$ TeV $\qquad \Lambda_{\rm VV}^{\rm ll} \sim \mathbf{22.2}$ TeV

E158 Reach (actual limits asymmetric)

$\Lambda_{\rm LL}^{\rm ee} \sim \mathbf{12}$ TeV $\qquad \Lambda_{\rm RR-LL}^{\rm ee} \sim \mathbf{17}$ TeV

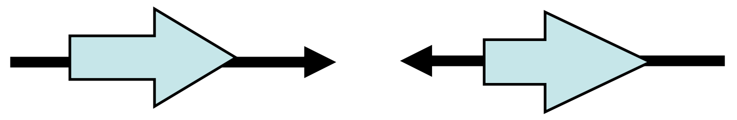
LEP-200 insensitive

MOLLER Reach

$\Lambda_{\rm LL}^{\rm ee} \sim \mathbf{27}$ TeV $\qquad \Lambda_{\rm RR-LL}^{\rm ee} \sim \mathbf{38}$ TeV

MOLLER is accessing discovery space that cannot be reached until the advent of a new lepton collider

Electroweak Structure Functions

e^-  $^1H,\ ^2H,\ ^3He$

***polarized* electron, *unpolarized* hadron**

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

***unpolarized* electron, *polarized* hadron**

$$A_{TPV} = \frac{G_F Q^2}{2\sqrt{2}\pi\alpha}\left[g_V \frac{g_5^{\gamma Z}}{F_1^{\gamma}} + g_A f(y)\frac{g_1^{\gamma Z}}{F_1^{\gamma}}\right]$$

proton

$$F_1^{\gamma Z} \propto u + d + s$$
$$F_3^{\gamma Z} \propto 2u_v + d_v$$
$$g_1^{\gamma Z} \propto \Delta u + \Delta d + \Delta s$$
$$g_5^{\gamma Z} \propto 2\Delta u_v + \Delta d_v$$

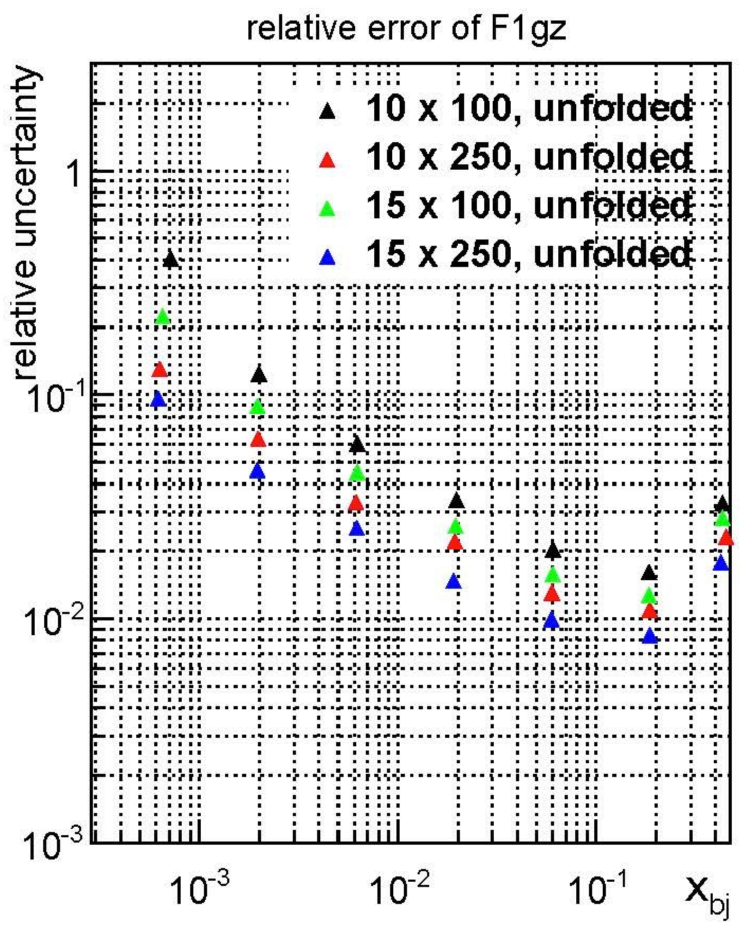
deuteron

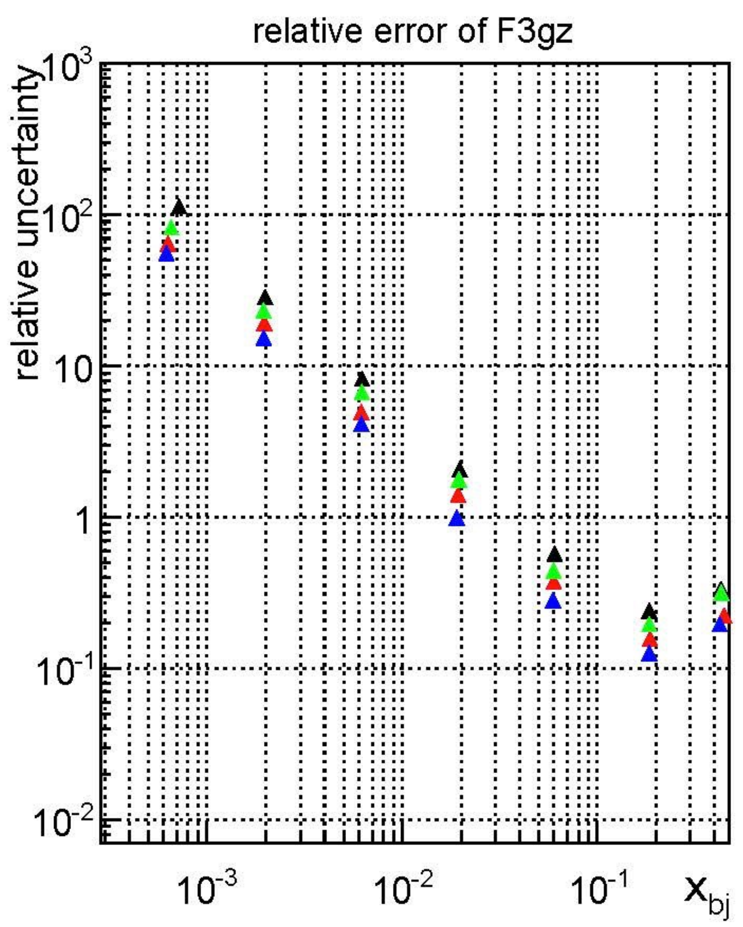
$$F_1^{\gamma Z} \propto u + d + 2s$$
$$F_3^{\gamma Z} \propto u_v + d_v$$
$$g_1^{\gamma Z} \propto \Delta u + \Delta d + \Delta s$$
$$g_5^{\gamma Z} \propto \Delta u_v + \Delta d_v$$

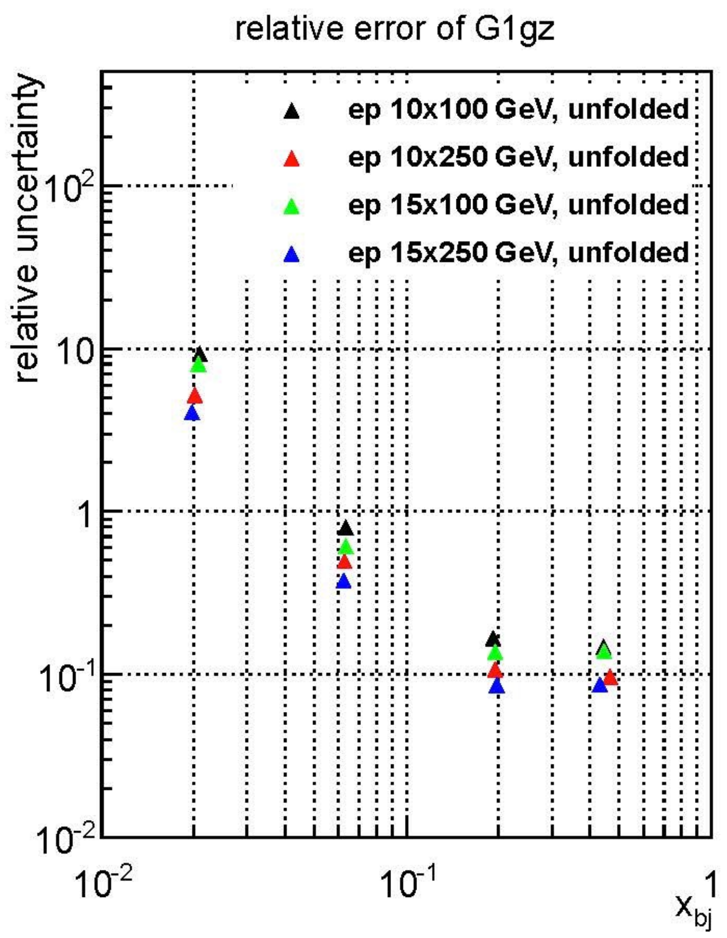
Assuming integrated luminosity ~500 fb^{-1}

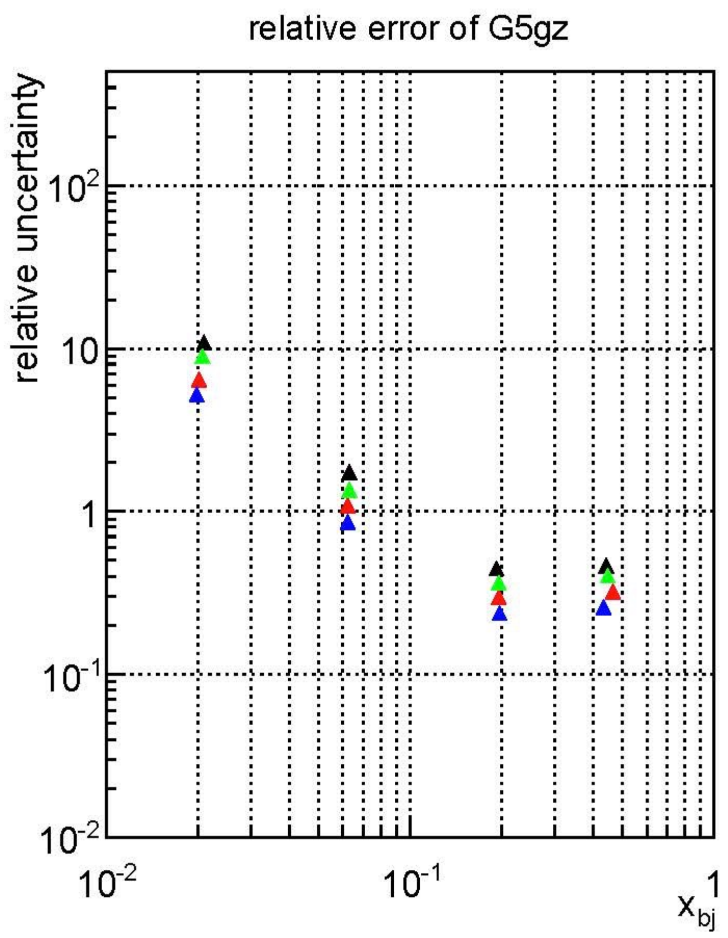
"Non-small x"

- few % on $F_1^{\gamma Z}$
- 10% on $g_1^{\gamma Z}$







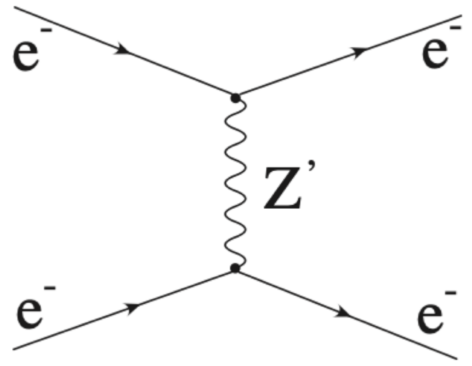


Simulations from Yuxiang Zhao, SBU

New (Low Energy) Physics Examples

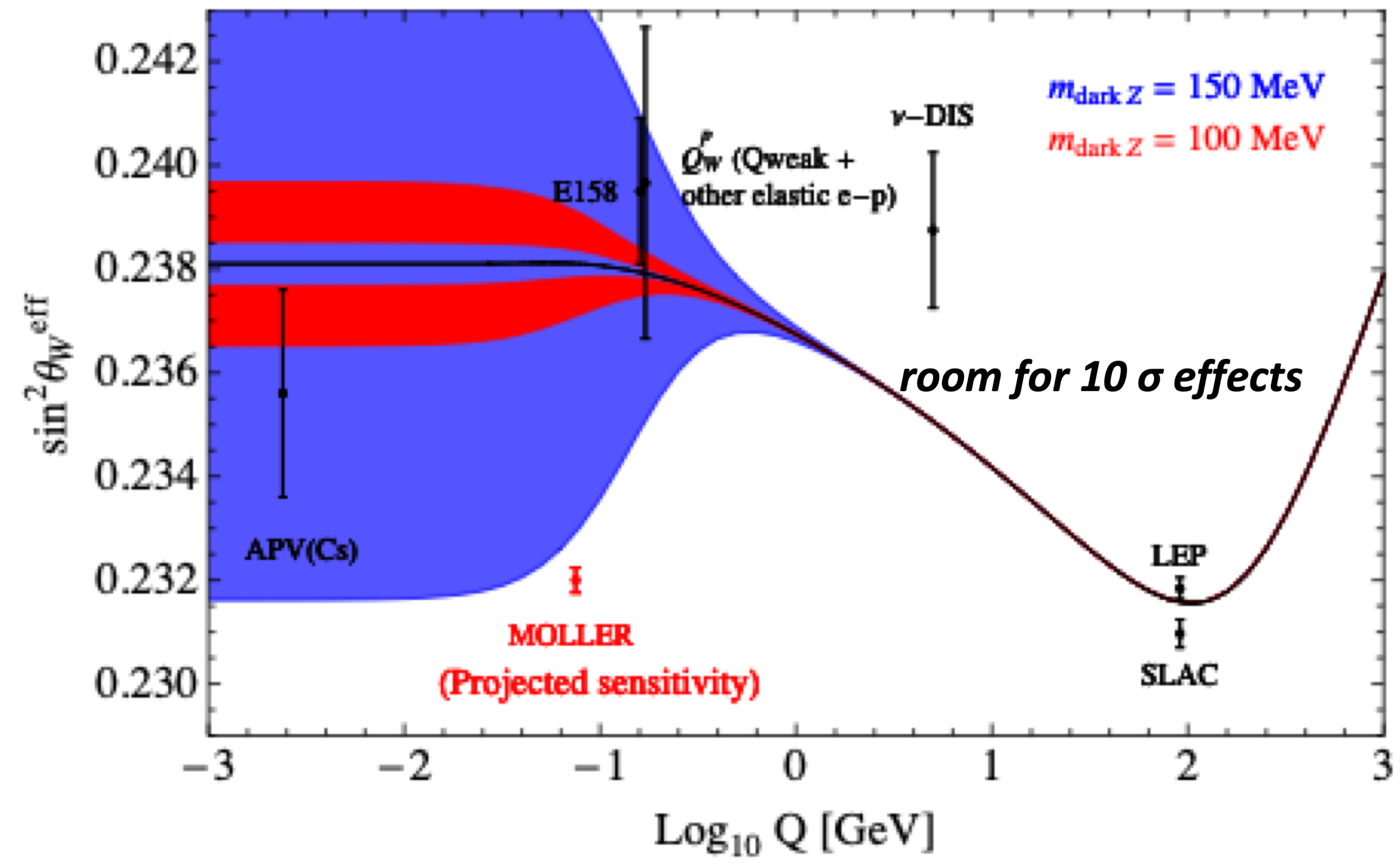
Unique Opportunity: Purely Leptonic Reaction at $Q^2 << M_Z^2$

Many different scenarios give rise to effective 4-electron contact interaction amplitudes: significant discovery potential



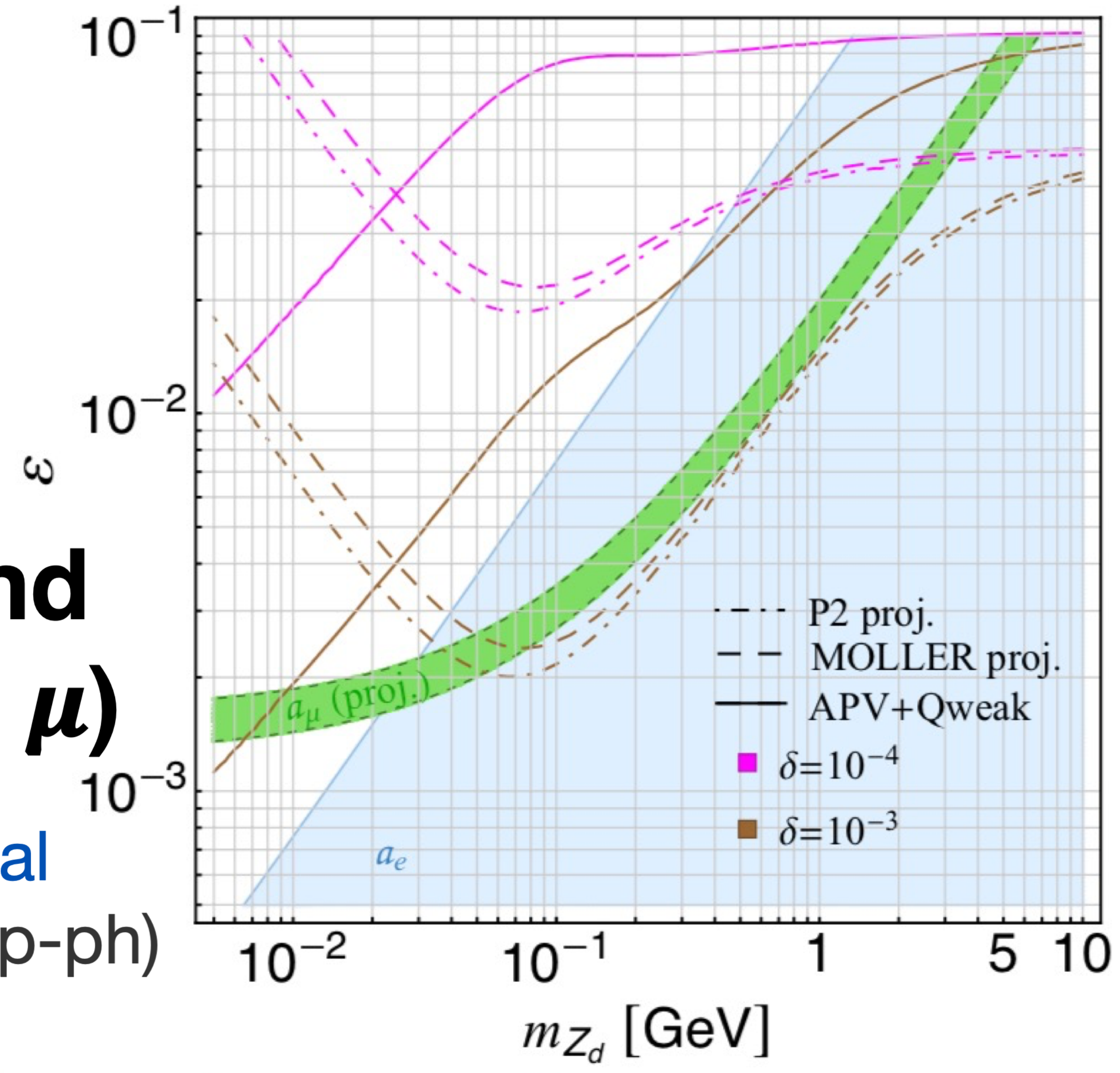
Heavy Photons (A' mixed with Z_0): The Dark Z

H. Davoudiasl, H-S. Lee and W. Marciano

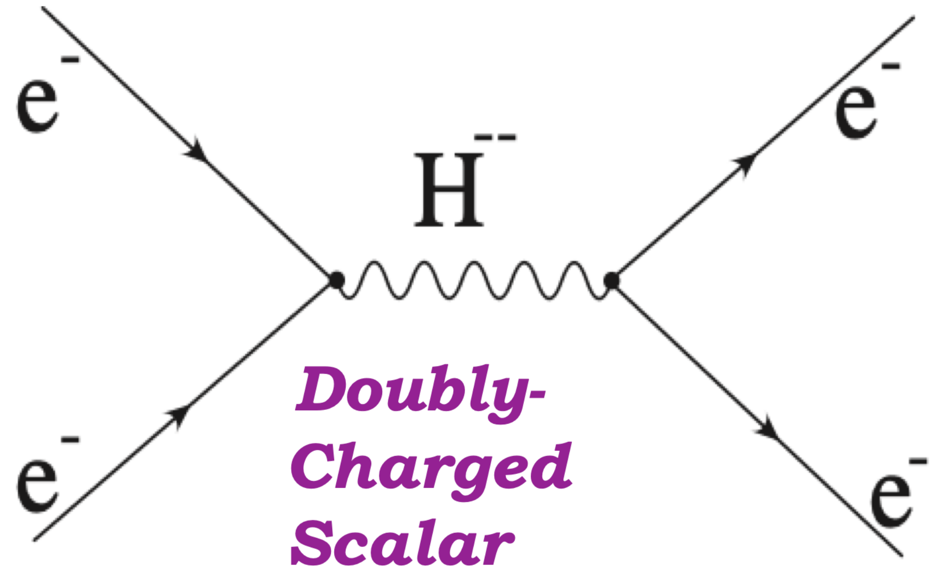


Specific Scenario folding in Cs APV and g-2 (e and μ)

M. Caddedu et al
2104.03280 (hep-ph)



Lepton Number Violation



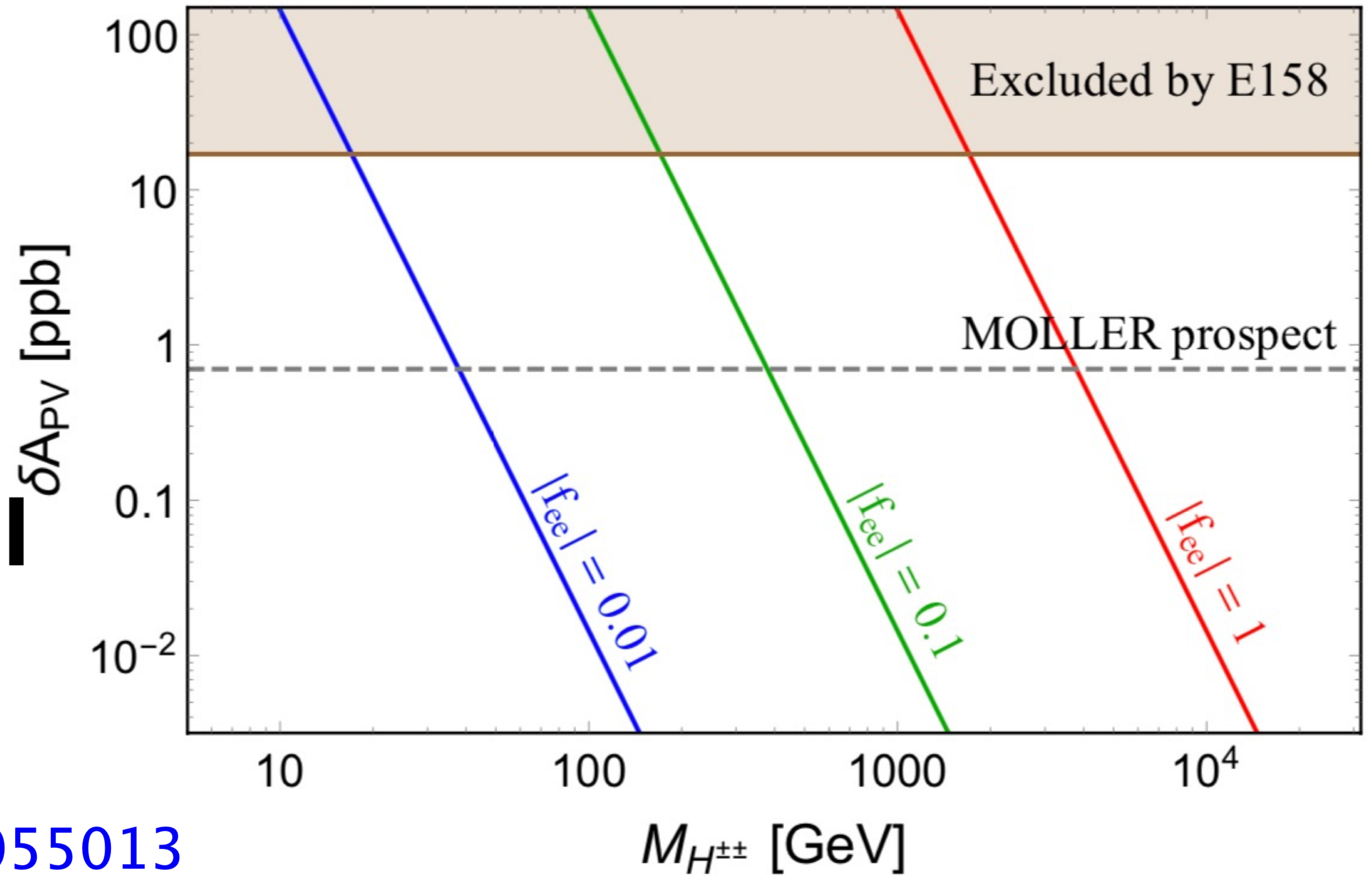
$$\left|\frac{\Delta Q_W^e}{Q_W^e}\right| = 0.14\frac{|h_{ee}|^2}{(M_\Delta/1\ \text{TeV})^2}$$

Cirigliano et al
Phys.Rev. D70 (2004) 075007

5 σ for h_{ee} ~ 1 and M_Δ ~ 1 TeV

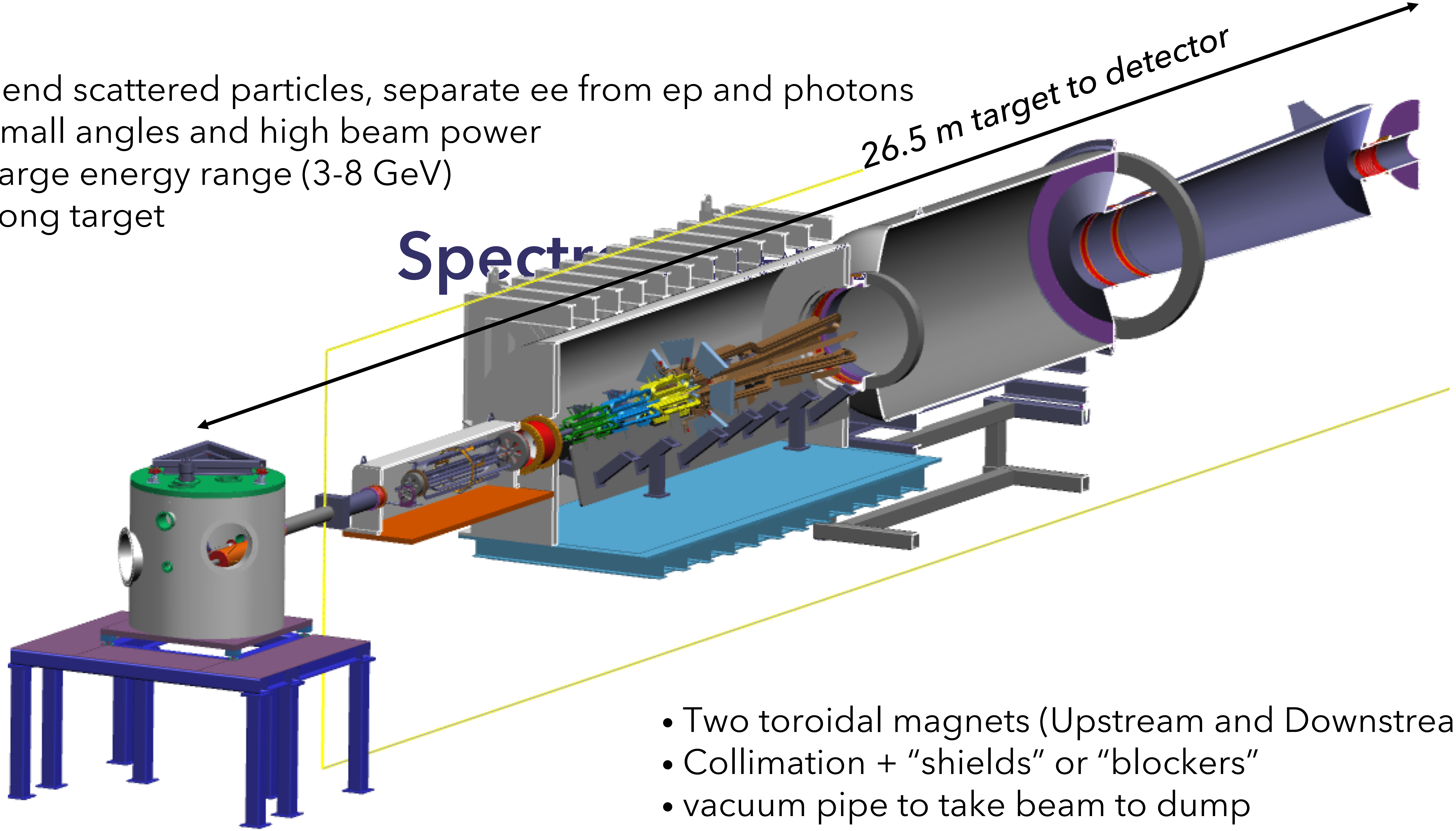
Specific Scenario for Type-II SeeSaw

B. Dev et al
PhysRevD.98.055013

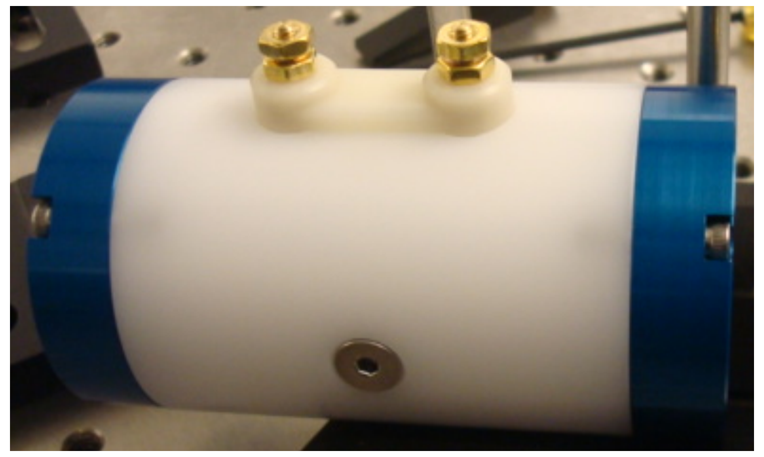


- Bend scattered particles, separate ee from ep and photons
- Small angles and high beam power
- Large energy range (3-8 GeV)
- Long target

Spectr



- Two toroidal magnets (Upstream and Downstream)
- Collimation + "shields" or "blockers"
- vacuum pipe to take beam to dump

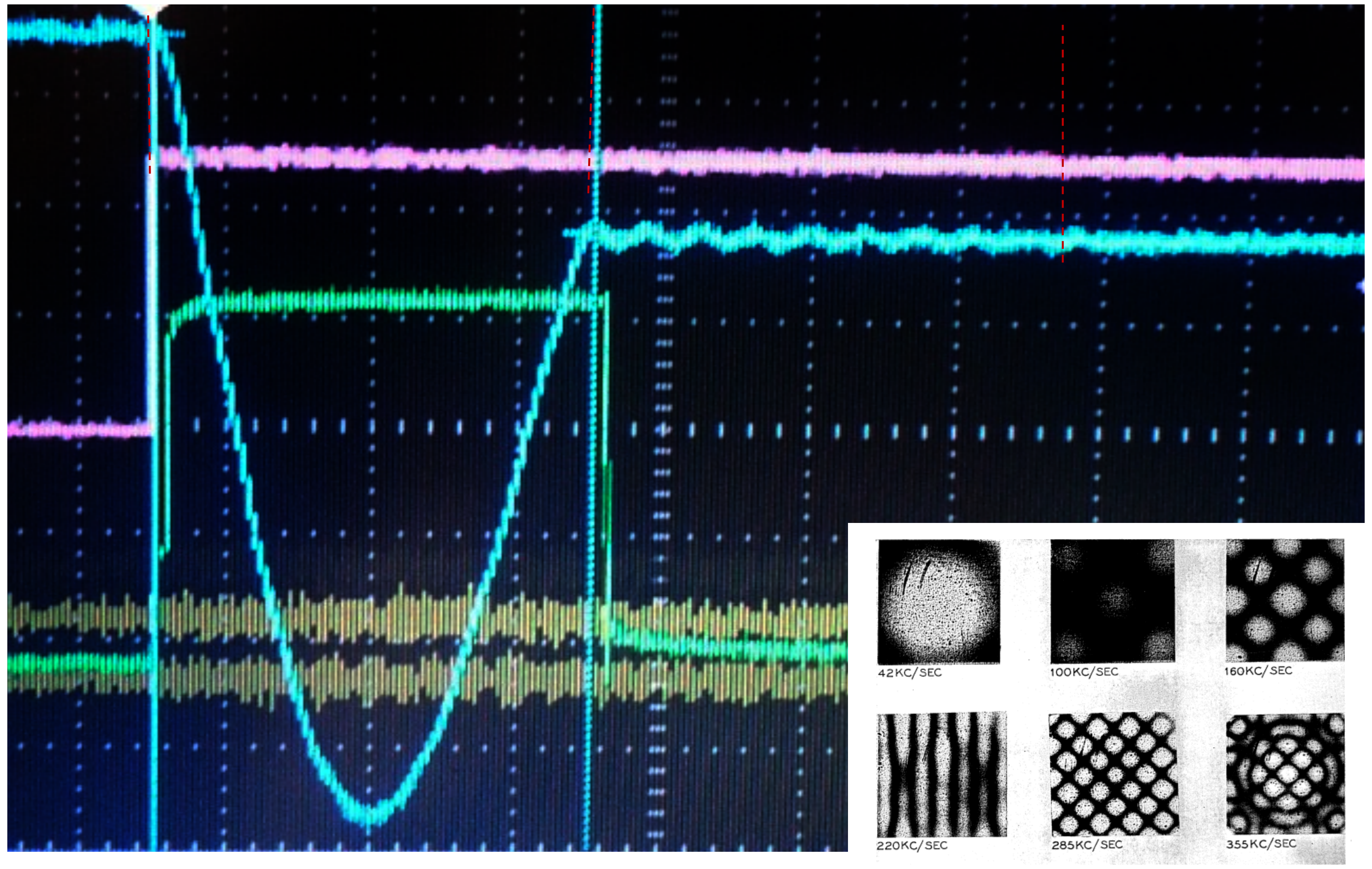


Switching faster – Use New Crystal

- KD*P Cell

(Potassium Dideuterium Phosphate)

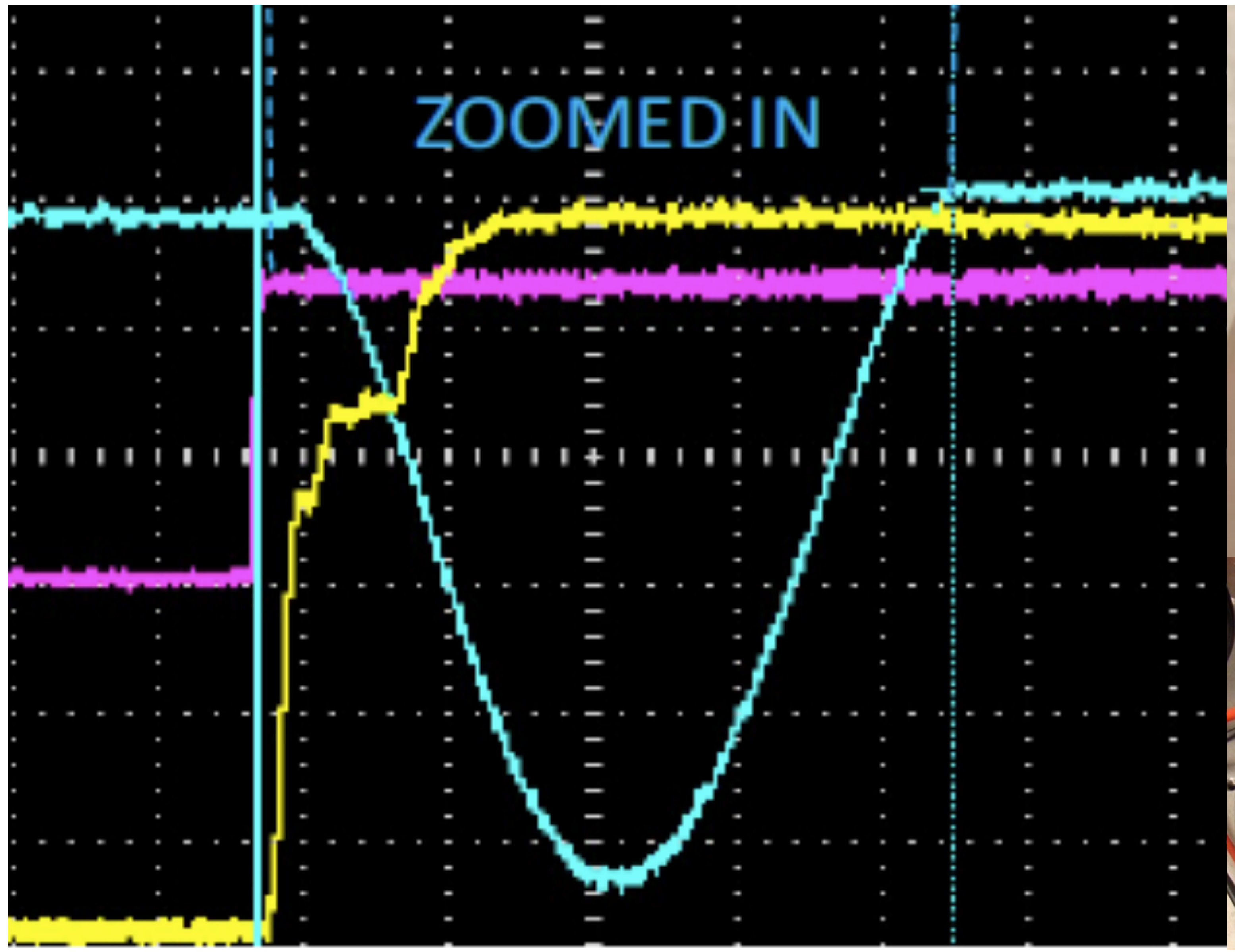
transition + ringing ~ 100μs

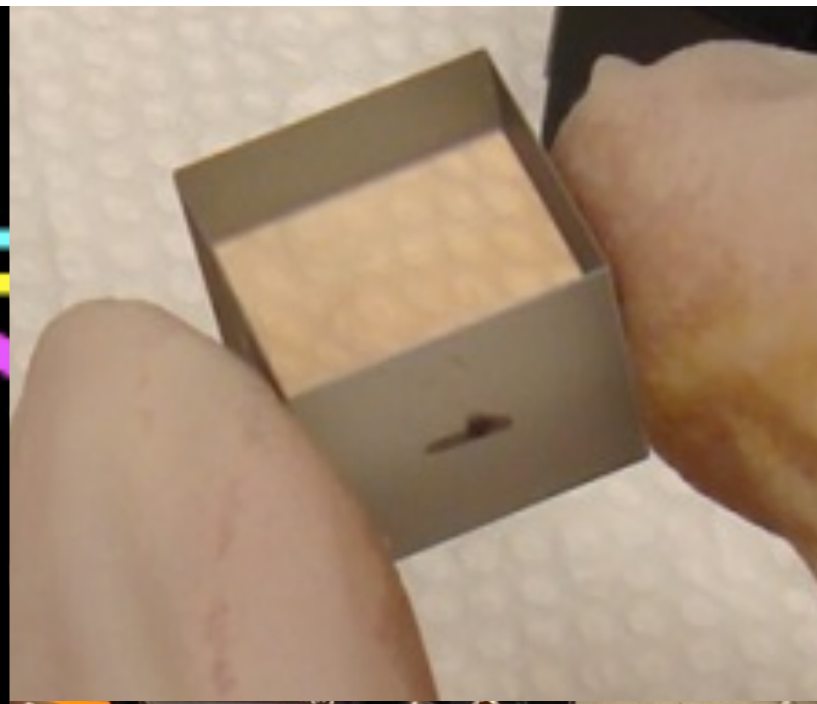


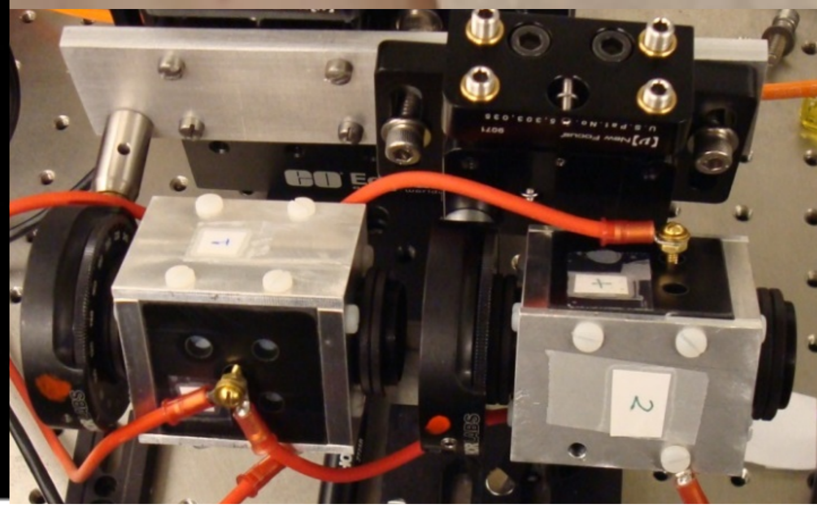
- RTP Cell

(Rubidium Titanyle Phosphate)

transition ~ 12μs



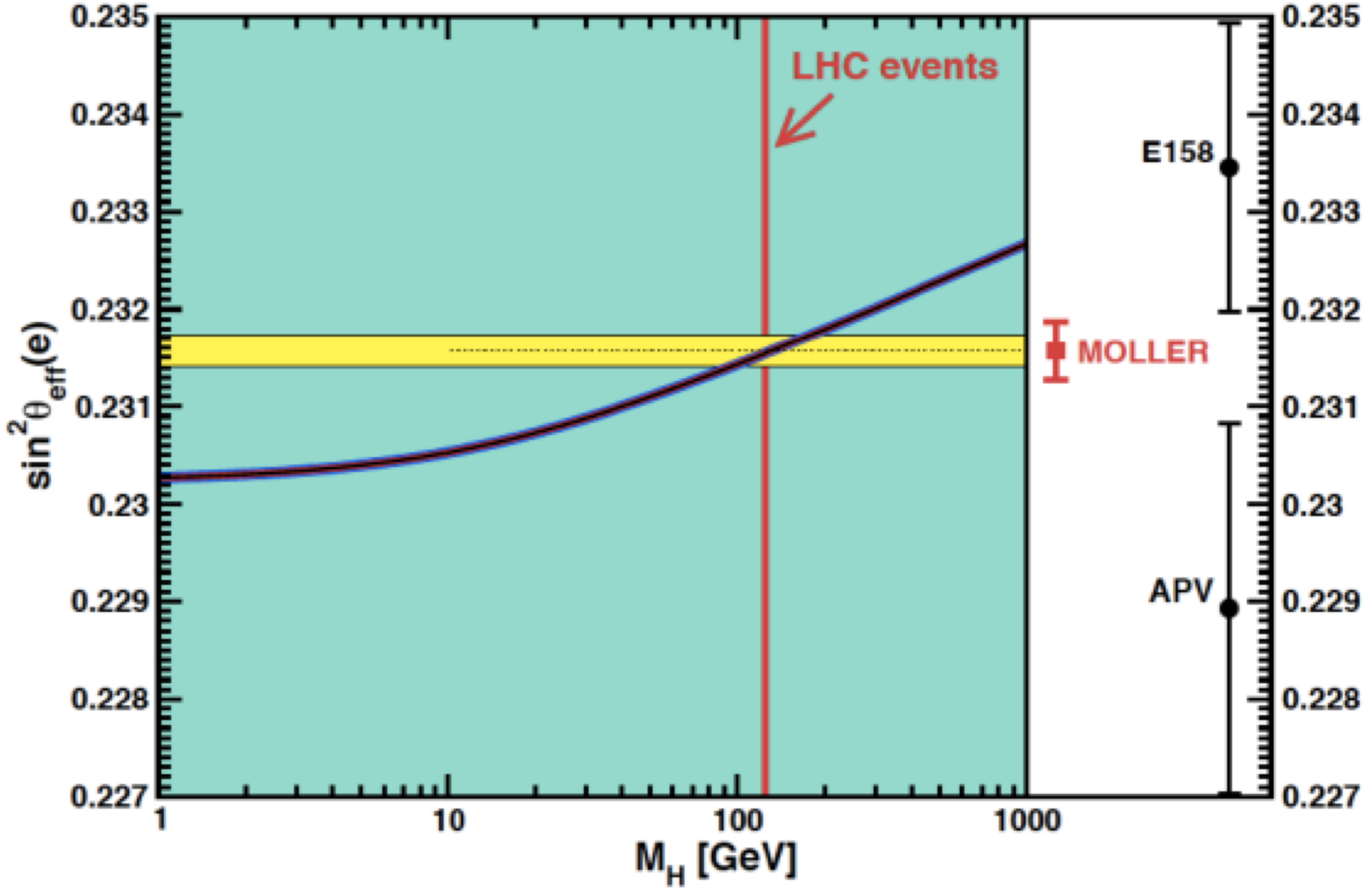


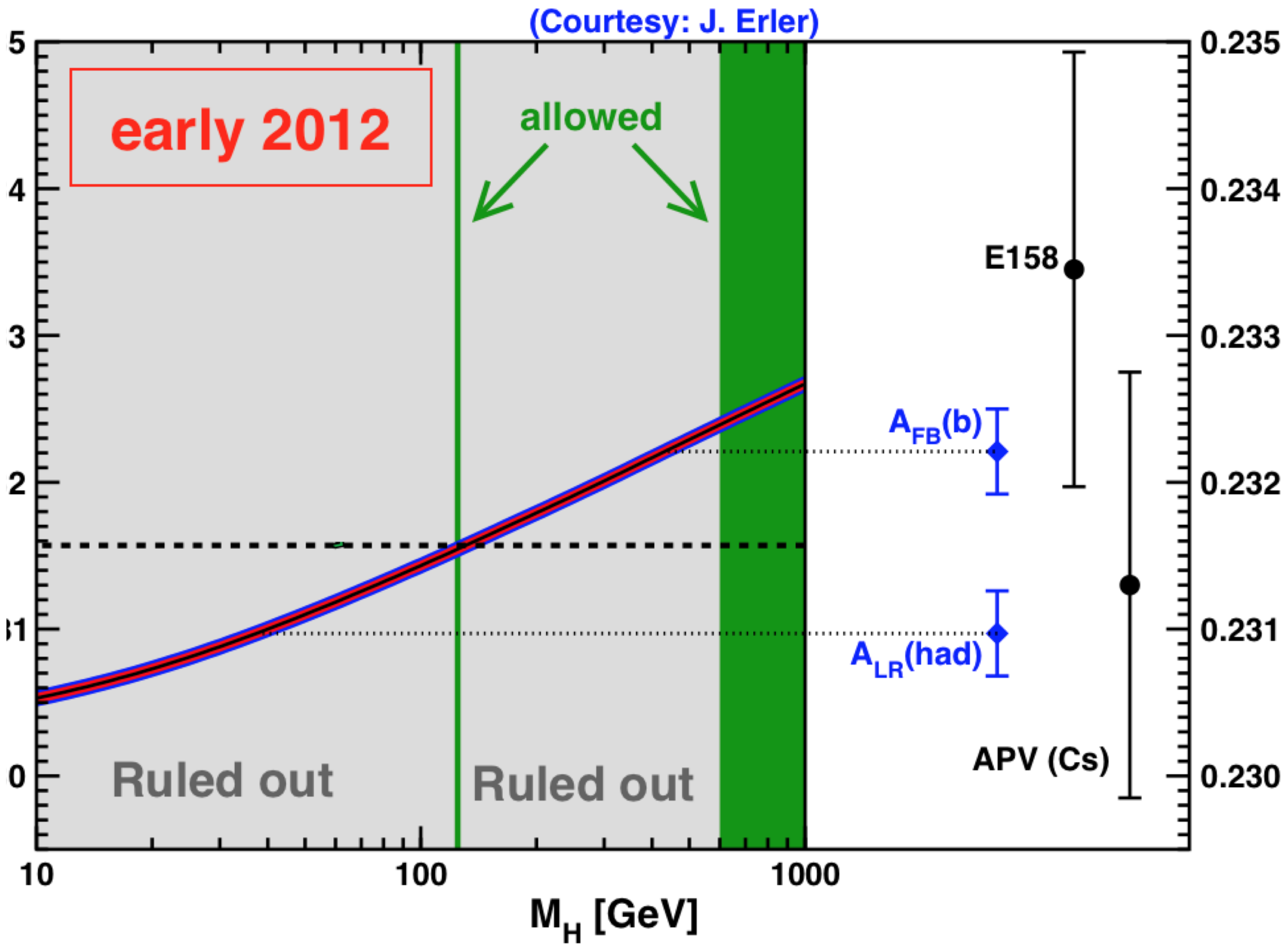


- Suffers from piezoelectric ringing
  - At 2kHz helicity switching,

70-100μs deadtime is <u>20% loss of data</u>

- No piezoelectric ringing up to 100kHz
- At 2kHz helicity switching, 12μs transition,
- <u>Deadtime reduced by ~10x</u>





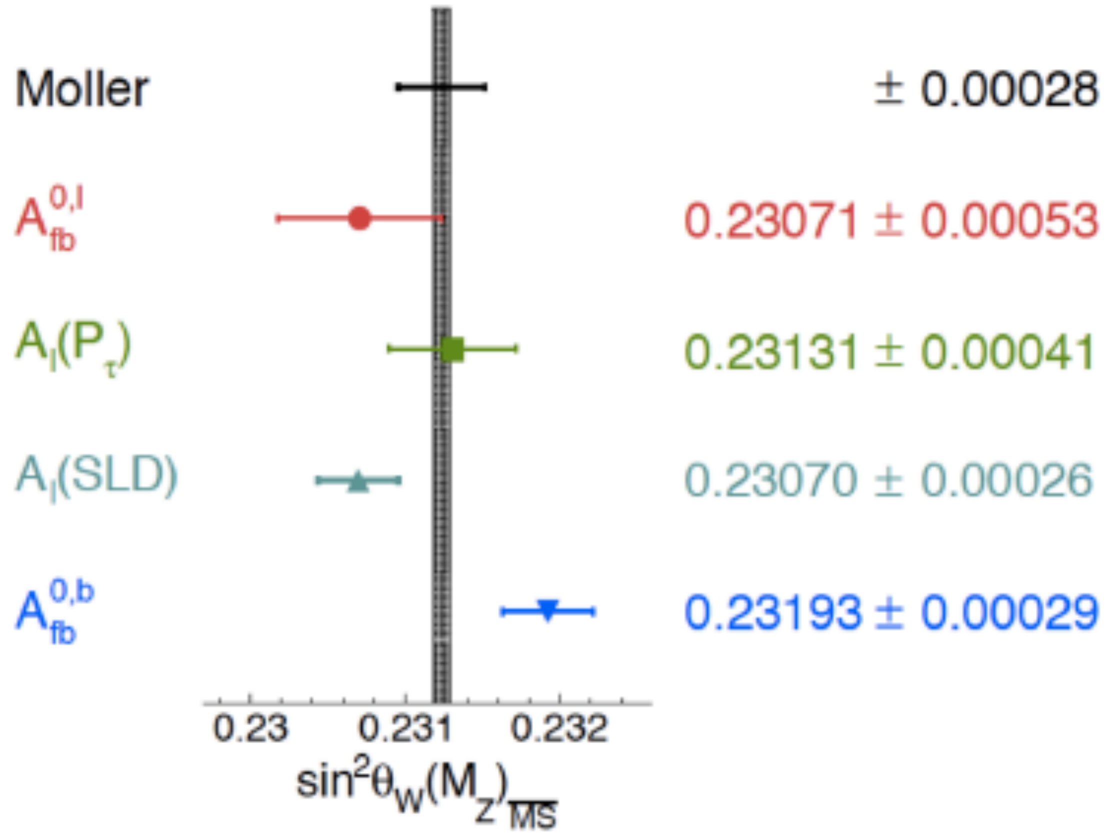
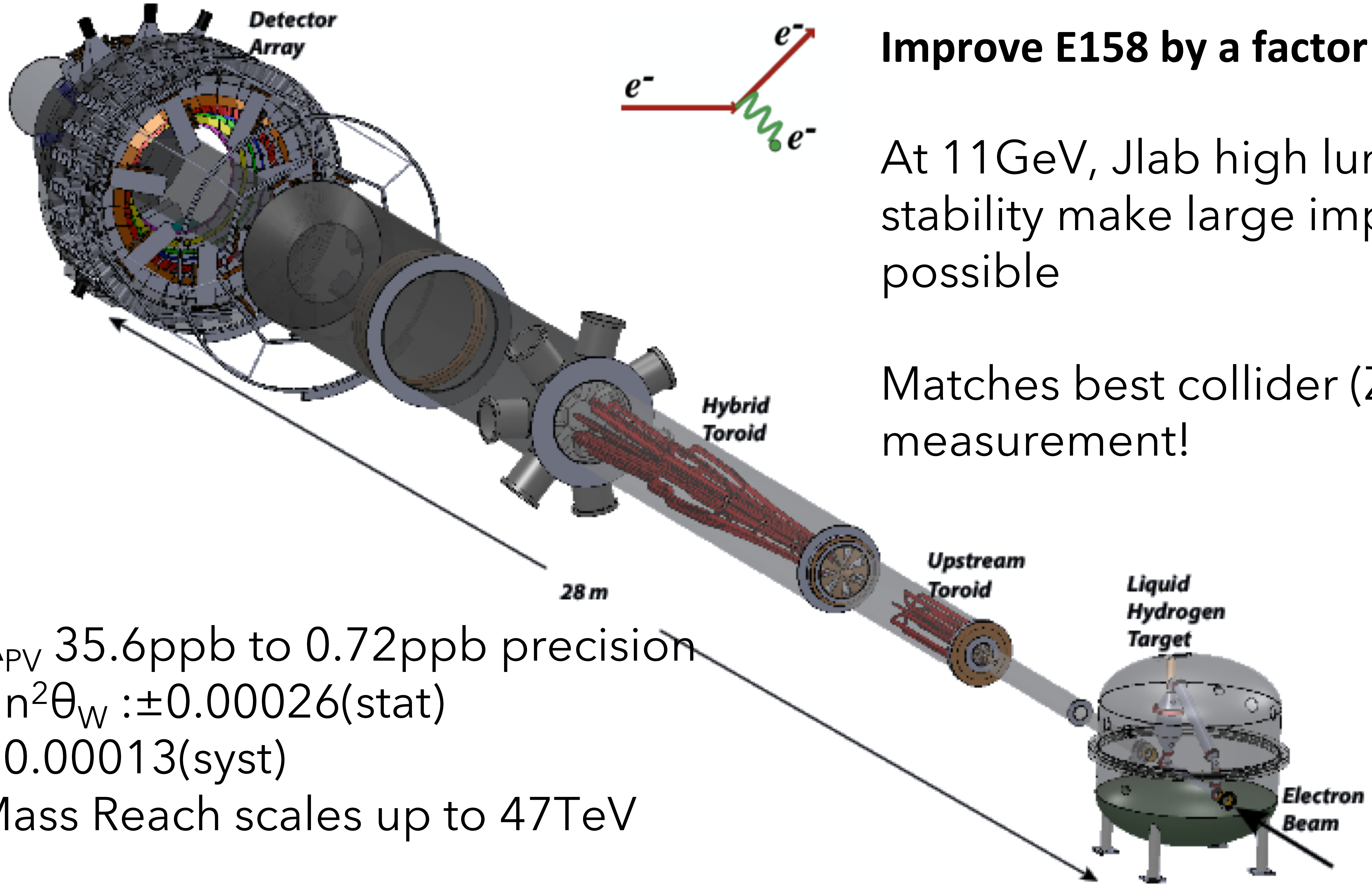


Figure 2-7: The four best $\sin^2\theta_W$ measurements and the projected error of the MOLLER proposal. The black band represents the theoretical prediction for $m_H = 126\ GeV$ (Measured value $m_H = 124.98 \pm 0.28\ GeV$ [28]).[1]

Design for Moller experiment



Improve E158 by a factor of 5

At 11GeV, Jlab high luminosity and stability make large improvement possible

Matches best collider (Z-pole) measurement!

A_{PV} 35.6ppb to 0.72ppb precision
$\sin^2\theta_W$:±0.00026(stat) ±0.00013(syst)
Mass Reach scales up to 47TeV

HCBA contributions

	Error
Systematic	0.39ppb
Intensity	0.1ppb
Position	0.14ppb
Spot-size	0.14ppb

Mass Reach is ~600X the mass of the W mediator, ~400X the Higgs Mass

Theory Prediction and Radiative Corrections

The Standard Model Prediction: Remarkably Well-Known

$$A_{PV} = \frac{\rho G_F Q^2}{\sqrt{2}\pi\alpha} \frac{1-y}{1+y^4+(1-y)^4} \{1 - 4\kappa(0)\sin^2\theta_W(m_Z)_{\overline{MS}} + \frac{\alpha(m_Z)}{4\pi\hat{s}^2} - \frac{3\alpha(m_Z)}{32\pi\hat{s}^2\hat{c}^2}(1-4\hat{s}^2)[1+(1-4\hat{s}^2)^2] + F_1(y,Q^2) + F_2(y,Q^2)\}$$

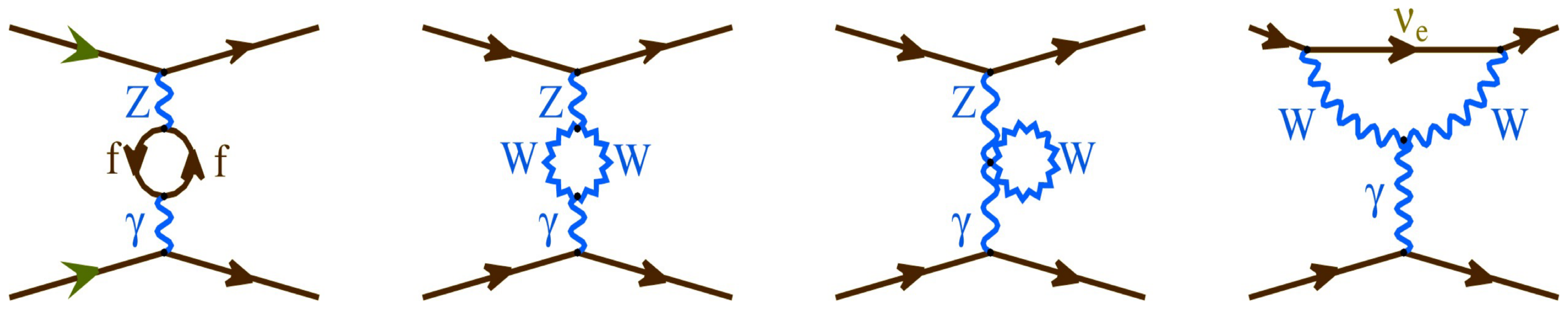
κ(0) known to 1% of itself
Erler and Ferro-Hernandez (2018)

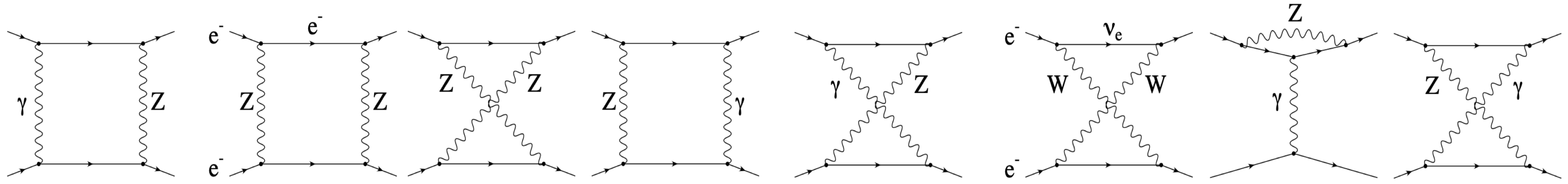
$$\mathbf{Q^e_W = 1 - 4\sin^2\theta_W \sim 0.075 \Longrightarrow 0.045}$$

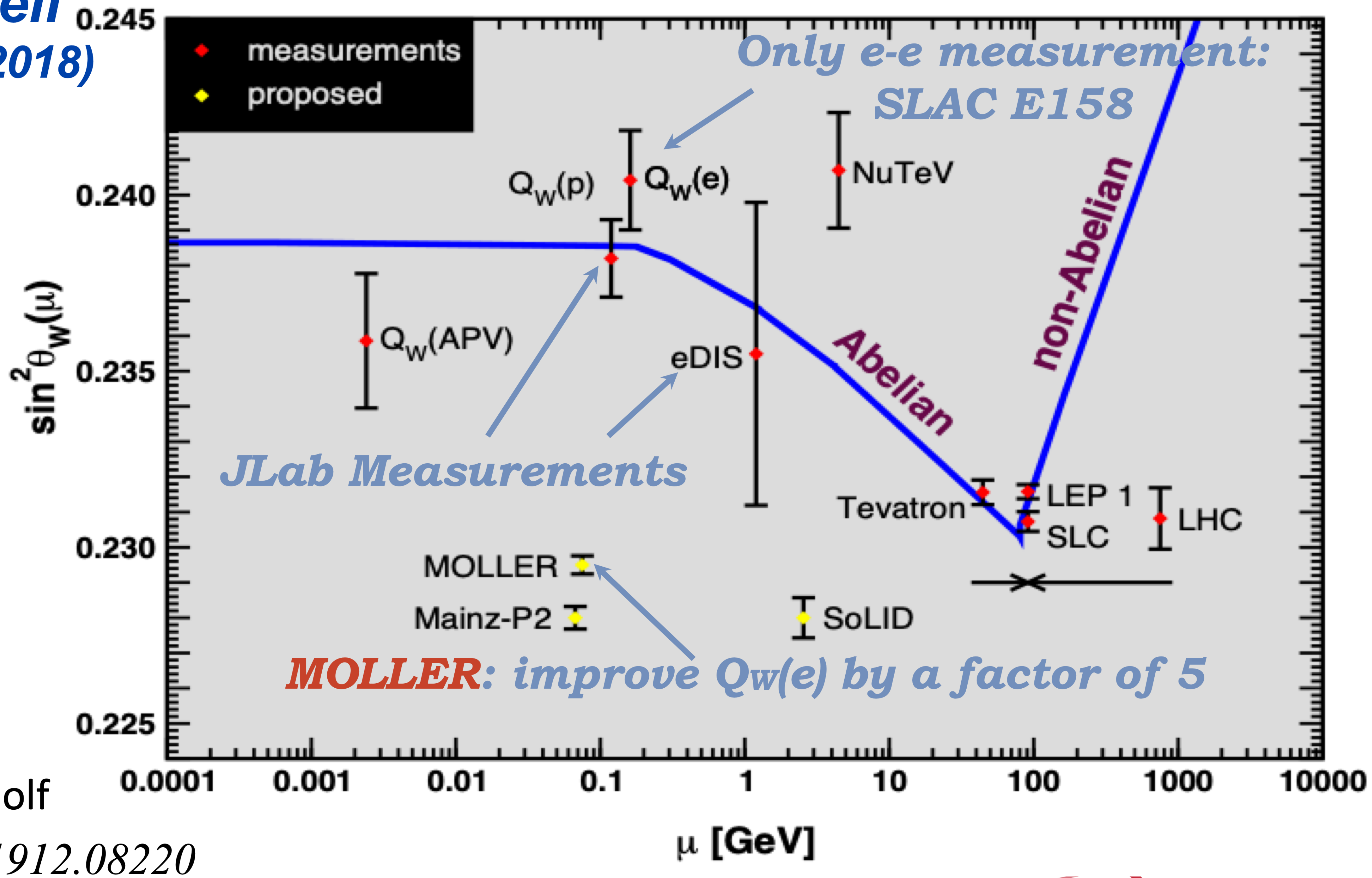
$$\frac{\delta(Q_W)}{Q_W} \sim 10\% \Longrightarrow \frac{\delta(\sin^2\theta_W)}{\sin^2\theta_W} \sim 0.5\%$$

δ(Q^e_W) ≲ 0.4%

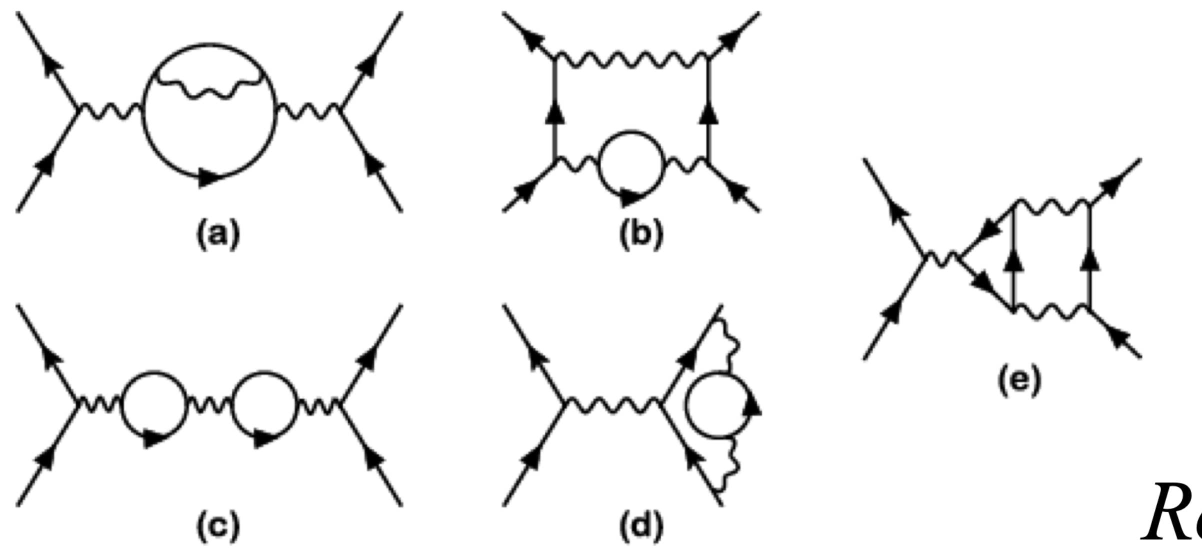
Czarnecki and Marciano (1995)







2 groups working on 2-loop Calculations

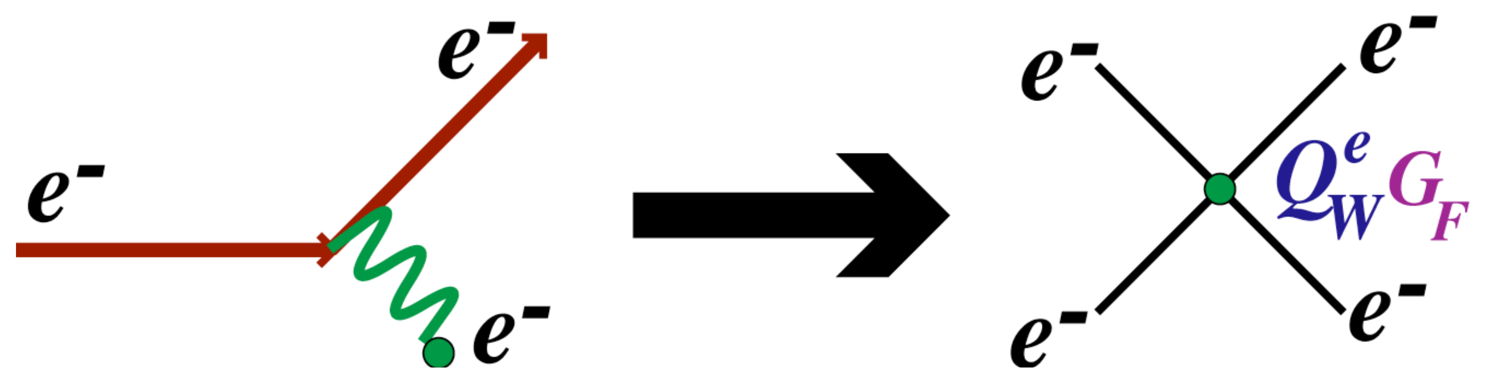


Aleksejevs and Barkanova
Series of publications

Du, Freitas, Patel and Ramsey-Musolf
Recent closed-fermion loops: arXiv:1912.08220

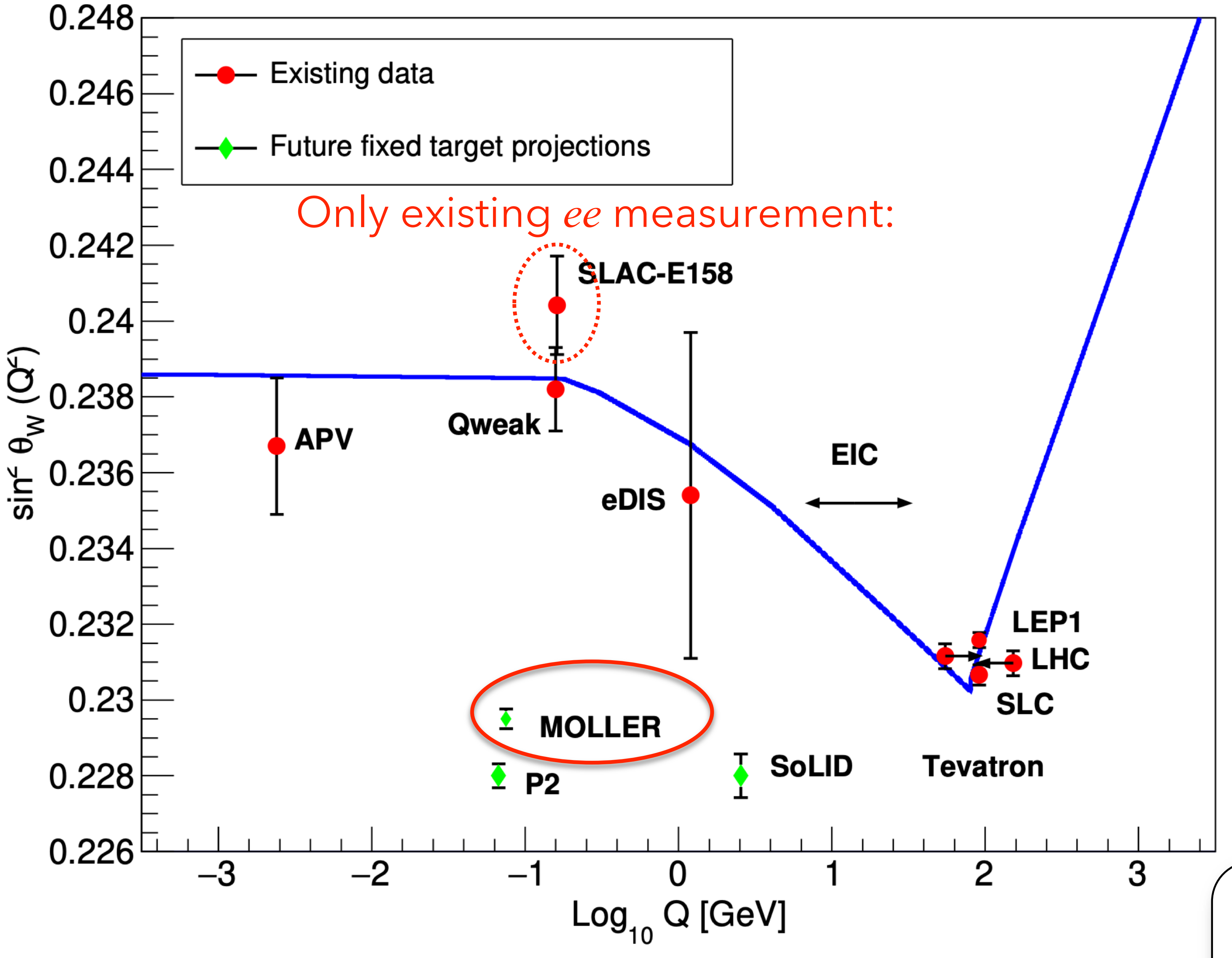
MOLLER at JLab

Elastic *ee* (Møller) scattering



Search for new flavor diagonal neutral currents

Unique (purely leptonic) new physics reach



Improve Q_W^e by a factor of 5

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

A_{PV} ~ 32 ppb $\delta(A_{PV})$ ~ 0.8 ppb

$\delta(Q^e_W) = \pm$ 2.1 % (stat.) $\pm$ 1.1 % (syst.)

$\delta(\sin^2\theta_W) = \pm$ 0.00024 (stat.) $\pm$ 0.00013 (syst.) $\Rightarrow$ ~ 0.1%

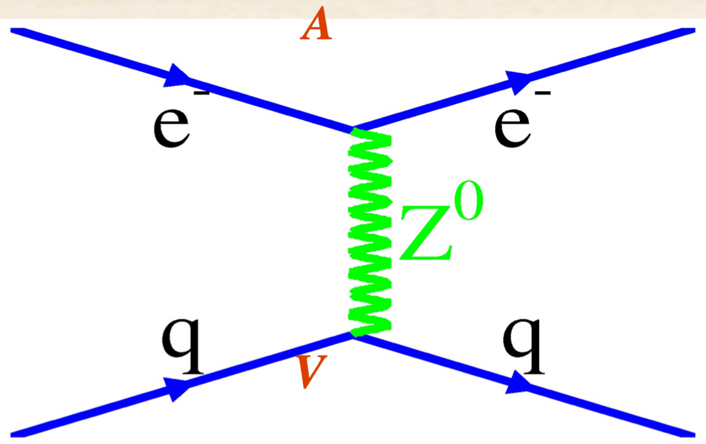
Matches best collider (Z-pole) measurement!

MOLLER Reach $\quad \Lambda^{ee}_{RR-LL} \sim \mathbf{38}$ TeV

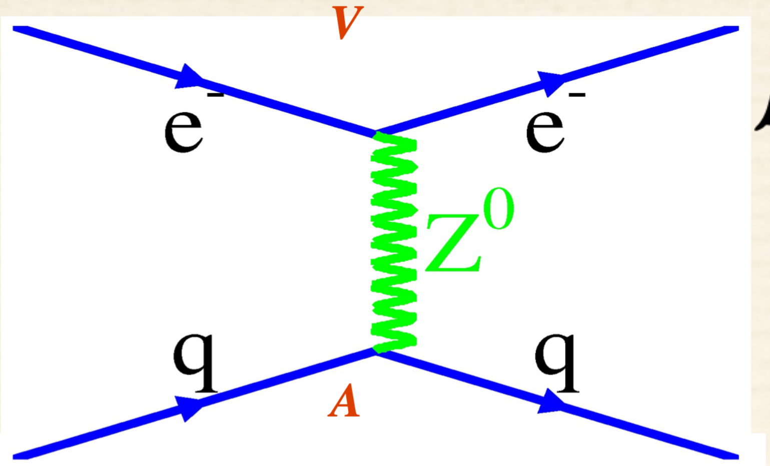
best contact interaction reach for leptons at low OR high energy

To do better for a 4-lepton contact interaction would require:
Giga-Z factory, linear collider, neutrino factory or muon collider

Weak Neutral Current (WNC) Couplings



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



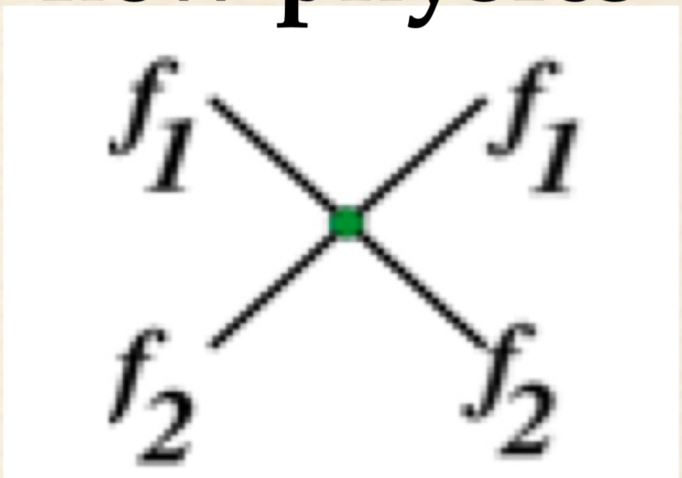
$C_{2i} \equiv 2g_V^e g_A^i$

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

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

+

new physics

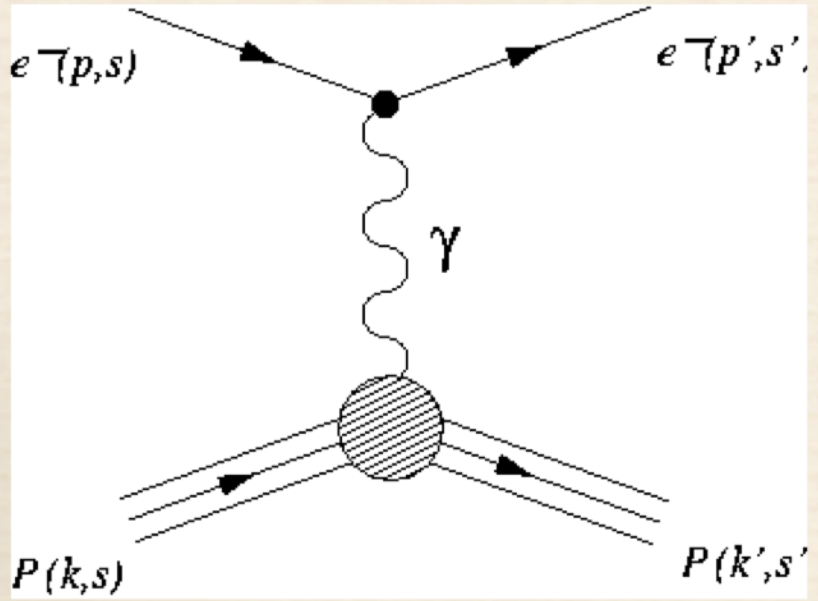


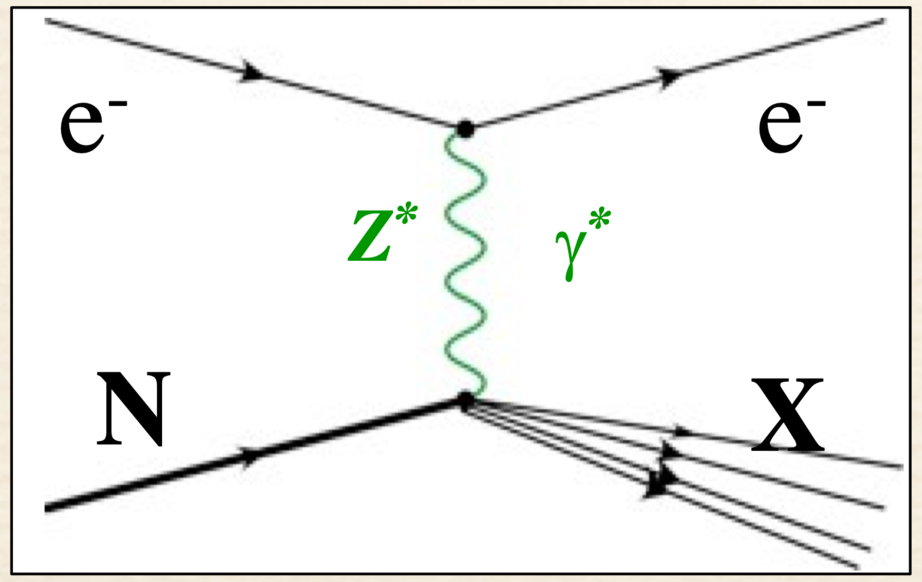
$C_{1q} \propto (g_{RR}^{eq})^2 + (g_{RL}^{eq})^2 - (g_{LR}^{eq})^2 - (g_{LL}^{eq})^2$ ⇒ ***PV elastic e-N scattering, Atomic parity violation***

$C_{2q} \propto (g_{RR}^{eq})^2 - (g_{RL}^{eq})^2 + (g_{LR}^{eq})^2 - (g_{LL}^{eq})^2$ ⇒ ***PV deep inelastic scattering***

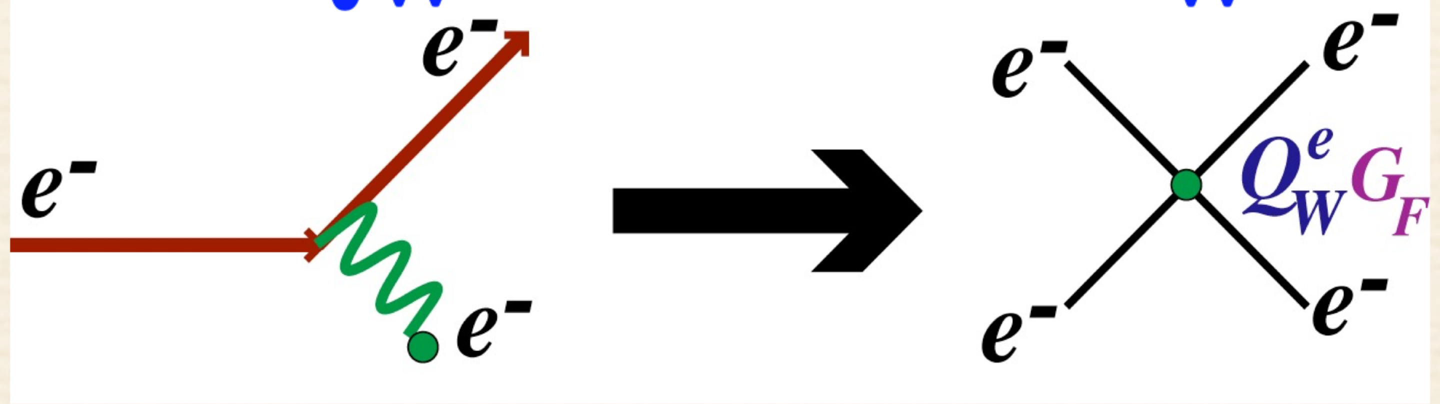
$C_{ee} \propto (g_{RR}^{ee})^2 - (g_{LL}^{ee})^2$ ⇒ ***PV Møller scattering***

$$\mathcal{L}_{f_1 f_2} = \sum_{i,j=L,R} \frac{(g_{ij}^{12})^2}{\Lambda_{ij}^2}\bar{f}_{1i}\gamma_\mu f_{1i}\bar{f}_{2j}\gamma_\mu f_{2j}$$





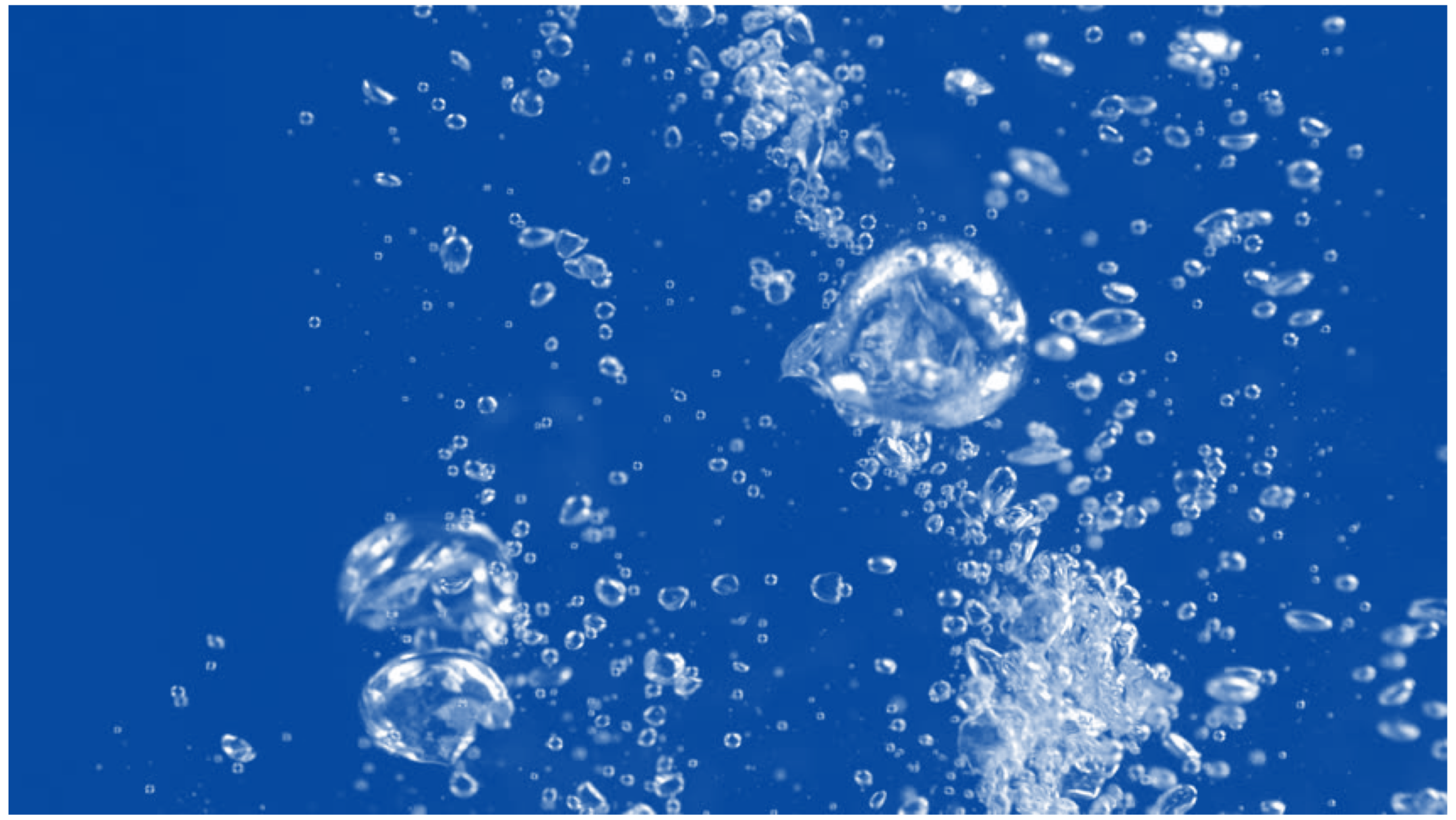
$\mathbf{Q_W = 1 - 4\sin^2\theta_W}$



Target

MOLLER goal: up to 85 A on 150 cm LHw - 5 kW power

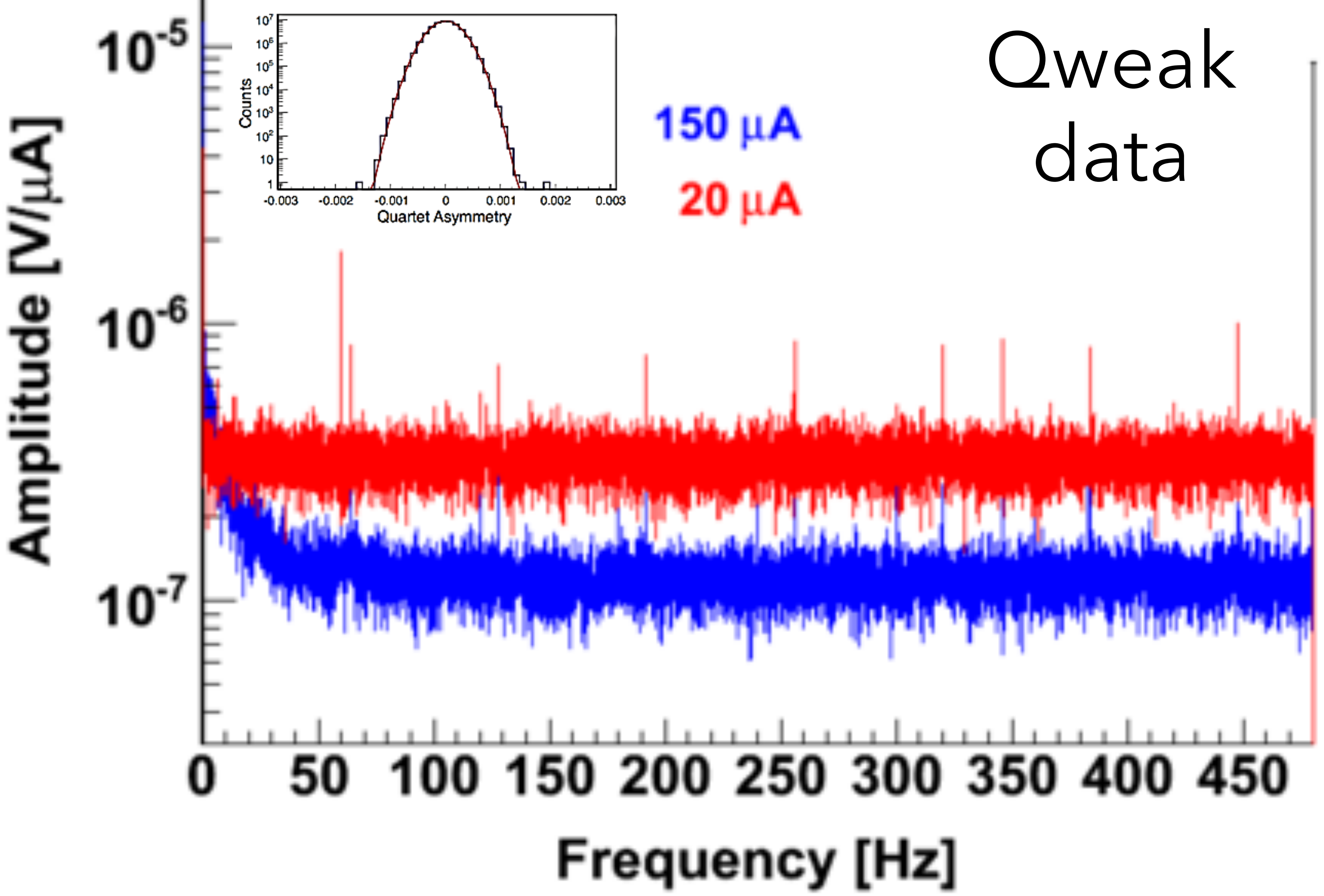
Target Boiling



Fast helicity flipping = high speed camera

Target boiling is a noise source that can't be filtered out using correlations with beam monitors, it must be suppressed by taking data faster than the bubbles form

Fast helicity reversal (1 ms) cancels density fluctuations



Moller is designed around a flip rate of at least 2 kHz

- The electron beam must **switch** back and forth very **quickly** between helicity states