Precision study of Z pole observables in SMEFT framework

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Outlook

- Motivation
- Introduction to SMEFT
- Electroweak Precision observables(EWPO)
- SMEFT correction to EWPO
- Summary

Motivation

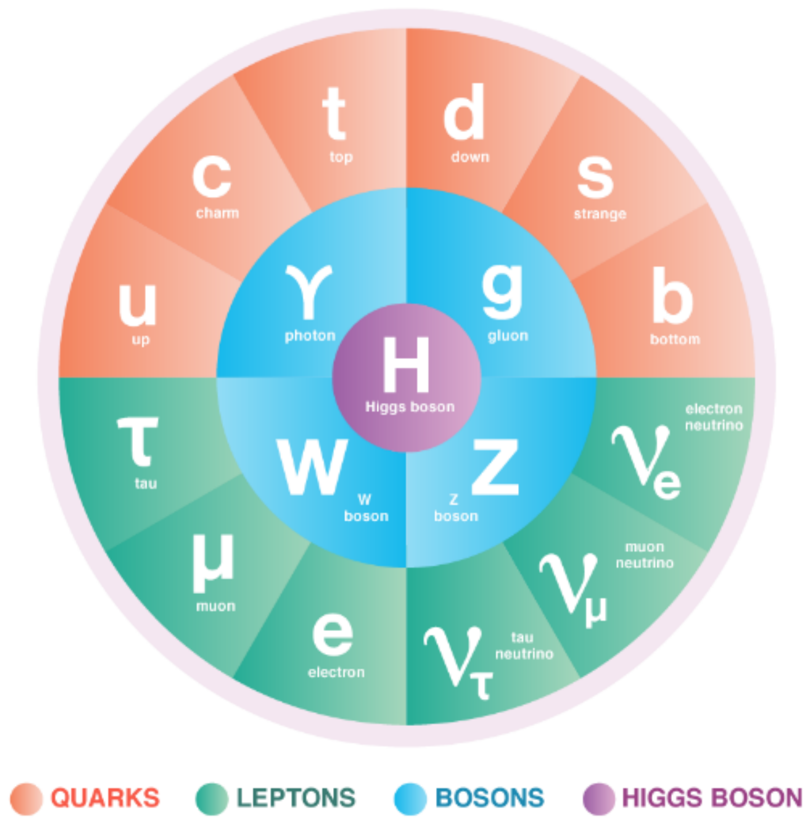


Image courtesy: Symmetry magazine, a joint Fermilab/SLAC publication.

- **S**tandard **M**odel(SM): Over constrained and tested to high precision

- Why Beyond SM?: Neutrino mass, Dark matter/energy,….

Direct signal

Indirect:
Reveal itself as deviation from SM

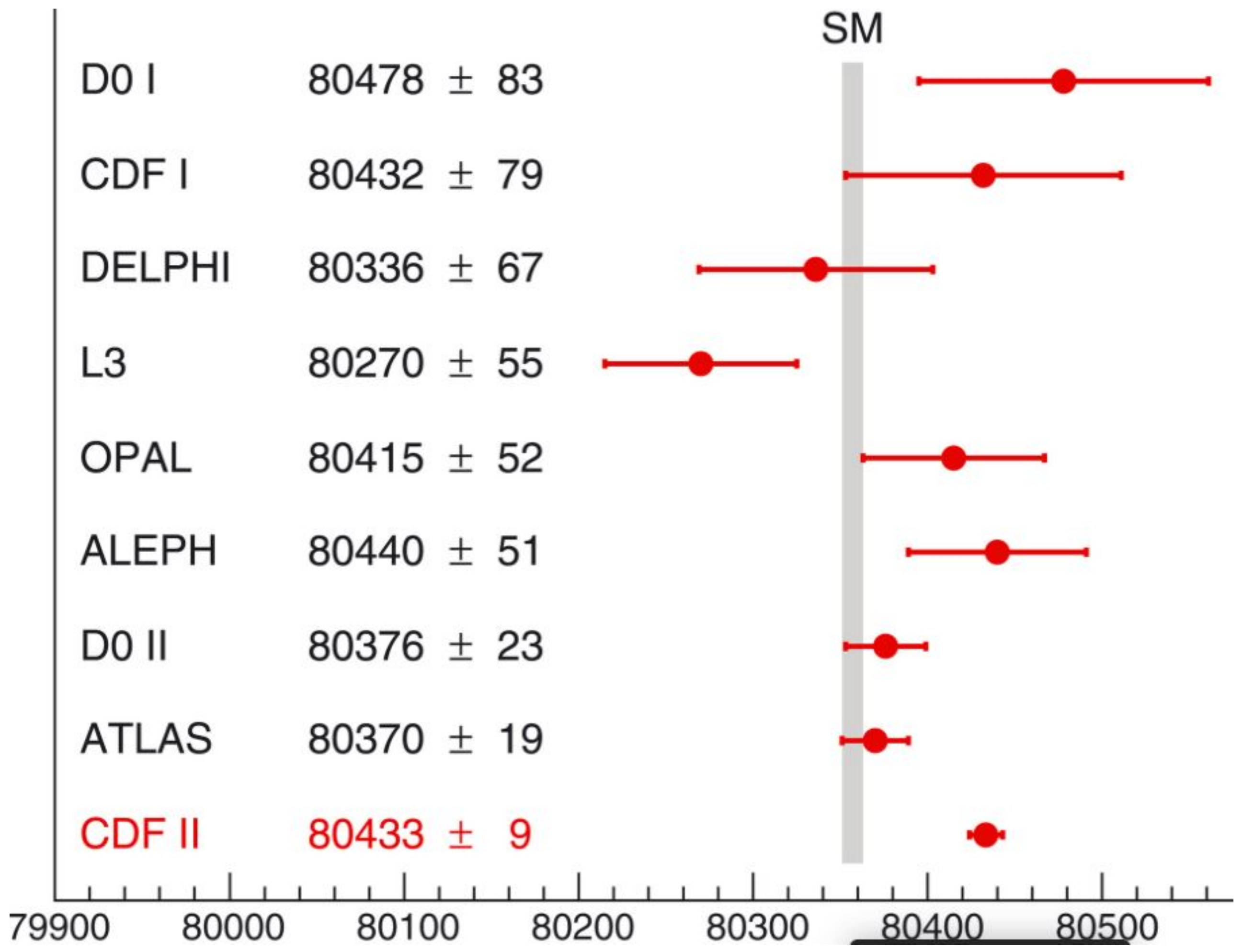
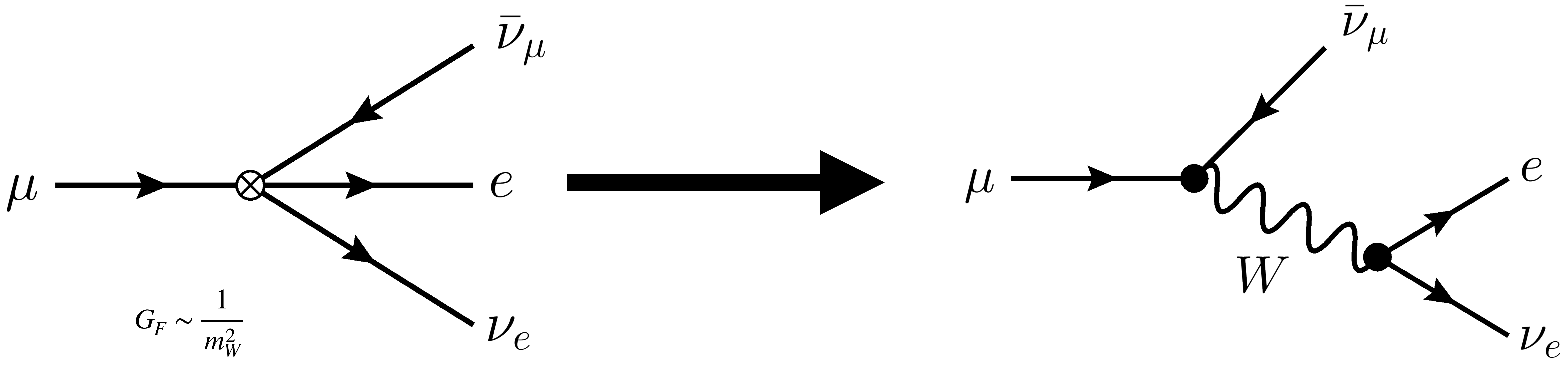


Image courtesy: science 2.0

- **S**tandard **M**odel **E**ffective **F**ield **T**heory (SMEFT): Model-independent way to parametrize the deviation

Motivation

Example: Muon decay ($\mu \to e\bar{\nu}_e\nu_\mu$)



Effective Fermi theory

UV theory(Standard Model)

G_F : hints about electroweak scale

Standard Model Effective Field Theory (SMEFT)

Standard Model Effective Field Theory

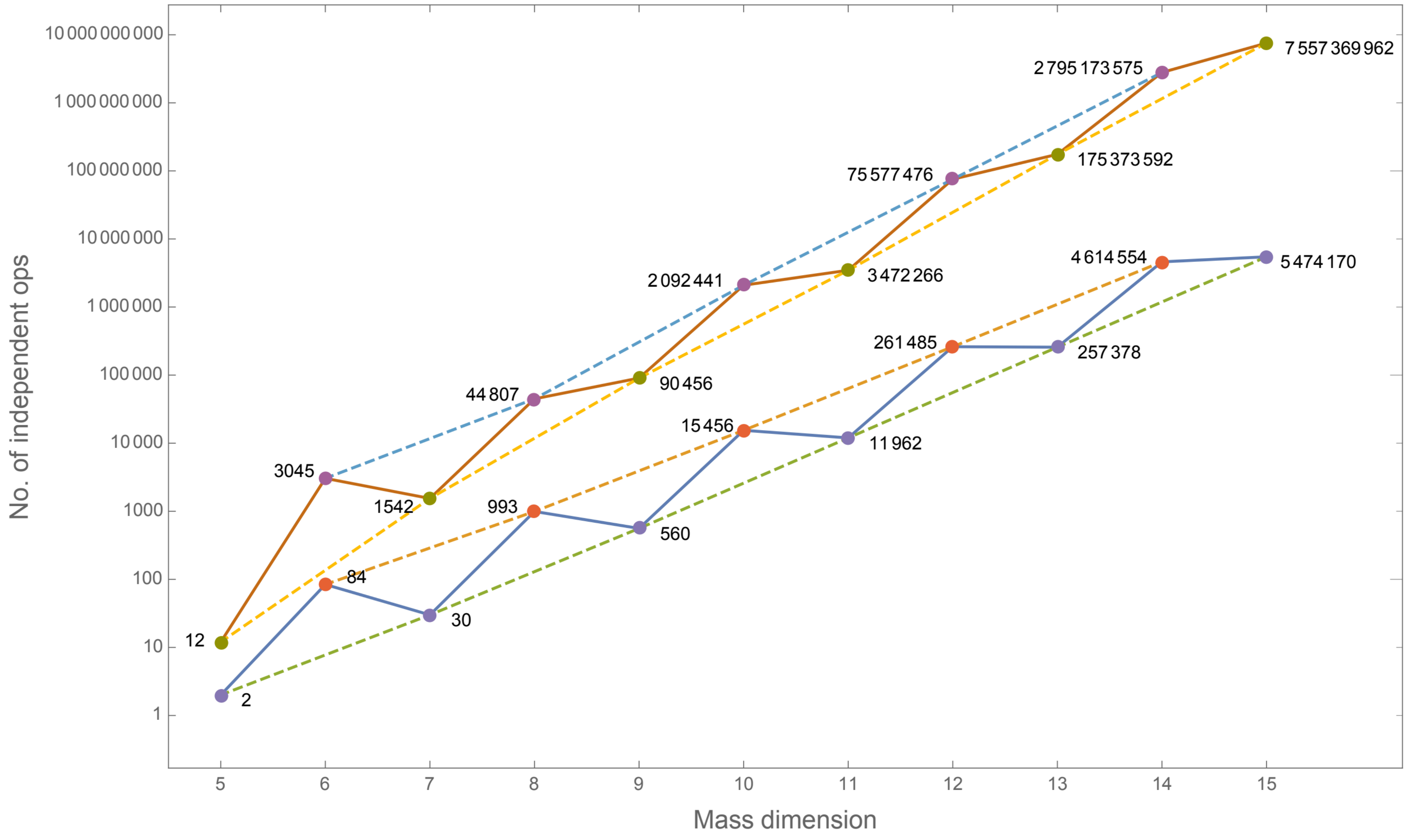
- Bottom-up EFT, UV physics is unknown
- No light BSM

$$\mathscr{L}_{\text{SMEFT}} = \mathscr{L}_{\text{SM}} + \sum_{D>4} \frac{1}{\Lambda^{D-4}} \sum_i C_i^{(D)} \mathcal{O}_i^{(D)}$$

Λ- New physics scale ($v \gg \Lambda$)

$C_i^{(D)}$- Wilson coefficients(constrained by measurements)

$\mathcal{O}_i^{(D)}$-Operators (built out of SM field and gauge group)



Brian Henning et al, arXiv:1512.03433

Warsaw Basis

1)W. Buchmüller and D. Wyler, Nucl. Phys. B 268 (1986) 621W. Buchmüller and D. Wyler, Nucl. Phys. B 268 (1986) 621
2)B. Grzadkowski, M. Iskrzyński, M. Misiak and J. Rosiek[1008.4884]

Bosonic-15 | Yukawa-54

X^3		φ^6 and $\varphi^4 D^2$		$\psi^2\varphi^3$	
Q_G	$f^{ABC} G_\mu^{A\nu} G_\nu^{B\rho} G_\rho^{C\mu}$	Q_φ	$(\varphi^\dagger\varphi)^3$	$Q_{e\varphi}$	$(\varphi^\dagger\varphi)(\bar l_p e_r \varphi)$
$Q_{\widetilde G}$	$f^{ABC} \widetilde G_\mu^{A\nu} G_\nu^{B\rho} G_\rho^{C\mu}$	$Q_{\varphi\Box}$	$(\varphi^\dagger\varphi)\Box(\varphi^\dagger\varphi)$	$Q_{u\varphi}$	$(\varphi^\dagger\varphi)(\bar q_p u_r \widetilde\varphi)$
Q_W	$\varepsilon^{IJK} W_\mu^{I\nu} W_\nu^{J\rho} W_\rho^{K\mu}$	$Q_{\varphi D}$	$\left(\varphi^\dagger D^\mu\varphi\right)^\star \left(\varphi^\dagger D_\mu\varphi\right)$	$Q_{d\varphi}$	$(\varphi^\dagger\varphi)(\bar q_p d_r \varphi)$
$Q_{\widetilde W}$	$\varepsilon^{IJK} \widetilde W_\mu^{I\nu} W_\nu^{J\rho} W_\rho^{K\mu}$				

$X^2\varphi^2$		$\psi^2 X\varphi$		$\psi^2\varphi^2 D$	
$Q_{\varphi G}$	$\varphi^\dagger \varphi\, G^A_{\mu\nu} G^{A\mu\nu}$	Q_{eW}	$(\bar l_p \sigma^{\mu\nu} e_r) \tau^I \varphi W^I_{\mu\nu}$	$Q_{\varphi l}^{(1)}$	$(\varphi^\dagger i\overleftrightarrow{D}_\mu \varphi)(\bar l_p \gamma^\mu l_r)$
$Q_{\varphi\widetilde G}$	$\varphi^\dagger \varphi\, \widetilde G^A_{\mu\nu} G^{A\mu\nu}$	Q_{eB}	$(\bar l_p \sigma^{\mu\nu} e_r) \varphi B_{\mu\nu}$	$Q_{\varphi l}^{(3)}$	$(\varphi^\dagger i\overleftrightarrow{D}^I_\mu \varphi)(\bar l_p \tau^I \gamma^\mu l_r)$
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$Q_{\varphi WB}$	$\varphi^\dagger \tau^I \varphi\, W^I_{\mu\nu} B^{\mu\nu}$	Q_{dW}	$(\bar q_p \sigma^{\mu\nu} d_r) \tau^I \varphi\, W^I_{\mu\nu}$	$Q_{\varphi d}$	$(\varphi^\dagger i\overleftrightarrow{D}_\mu \varphi)(\bar d_p \gamma^\mu d_r)$
$Q_{\varphi\widetilde WB}$	$\varphi^\dagger \tau^I \varphi\, \widetilde W^I_{\mu\nu} B^{\mu\nu}$	Q_{dB}	$(\bar q_p \sigma^{\mu\nu} d_r) \varphi\, B_{\mu\nu}$	$Q_{\varphi ud}$	$i(\widetilde\varphi^\dagger D_\mu \varphi)(\bar u_p \gamma^\mu d_r)$

dipole-144 | Current-81

4 fermion–2751

$(\bar LL)(\bar LL)$		$(\bar RR)(\bar RR)$		$(\bar LL)(\bar RR)$	
Q_{ll}	$(\bar l_p \gamma_\mu l_r)(\bar l_s \gamma^\mu l_t)$	Q_{ee}	$(\bar e_p \gamma_\mu e_r)(\bar e_s \gamma^\mu e_t)$	Q_{le}	$(\bar l_p \gamma_\mu l_r)(\bar e_s \gamma^\mu e_t)$
$Q_{qq}^{(1)}$	$(\bar q_p \gamma_\mu q_r)(\bar q_s \gamma^\mu q_t)$	Q_{uu}	$(\bar u_p \gamma_\mu u_r)(\bar u_s \gamma^\mu u_t)$	Q_{lu}	$(\bar l_p \gamma_\mu l_r)(\bar u_s \gamma^\mu u_t)$
$Q_{qq}^{(3)}$	$(\bar q_p \gamma_\mu \tau^I q_r)(\bar q_s \gamma^\mu \tau^I q_t)$	Q_{dd}	$(\bar d_p \gamma_\mu d_r)(\bar d_s \gamma^\mu d_t)$	Q_{ld}	$(\bar l_p \gamma_\mu l_r)(\bar d_s \gamma^\mu d_t)$
$Q_{lq}^{(1)}$	$(\bar l_p \gamma_\mu l_r)(\bar q_s \gamma^\mu q_t)$	Q_{eu}	$(\bar e_p \gamma_\mu e_r)(\bar u_s \gamma^\mu u_t)$	Q_{qe}	$(\bar q_p \gamma_\mu q_r)(\bar e_s \gamma^\mu e_t)$
$Q_{lq}^{(3)}$	$(\bar l_p \gamma_\mu \tau^I l_r)(\bar q_s \gamma^\mu \tau^I q_t)$	Q_{ed}	$(\bar e_p \gamma_\mu e_r)(\bar d_s \gamma^\mu d_t)$	$Q_{qu}^{(1)}$	$(\bar q_p \gamma_\mu q_r)(\bar u_s \gamma^\mu u_t)$
		$Q_{ud}^{(1)}$	$(\bar u_p \gamma_\mu u_r)(\bar d_s \gamma^\mu d_t)$	$Q_{qu}^{(8)}$	$(\bar q_p \gamma_\mu T^A q_r)(\bar u_s \gamma^\mu T^A u_t)$
		$Q_{ud}^{(8)}$	$(\bar u_p \gamma_\mu T^A u_r)(\bar d_s \gamma^\mu T^A d_t)$	$Q_{qd}^{(1)}$	$(\bar q_p \gamma_\mu q_r)(\bar d_s \gamma^\mu d_t)$
				$Q_{qd}^{(8)}$	$(\bar q_p \gamma_\mu T^A q_r)(\bar d_s \gamma^\mu T^A d_t)$

$(\bar LR)(\bar RL)$ and $(\bar LR)(\bar LR)$		B-violating	
Q_{ledq}	$(\bar l_p^j e_r)(\bar d_s q_t^j)$	Q_{duq}	$\varepsilon^{\alpha\beta\gamma}\varepsilon_{jk}\left[(d_p^\alpha)^T C u_r^\beta\right]\left[(q_s^{\gamma j})^T C l_t^k\right]$
$Q_{quqd}^{(1)}$	$(\bar q_p^j u_r)\varepsilon_{jk}(\bar q_s^k d_t)$	Q_{qqu}	$\varepsilon^{\alpha\beta\gamma}\varepsilon_{jk}\left[(q_p^{\alpha j})^T C q_r^{\beta k}\right]\left[(u_s^\gamma)^T C e_t\right]$
$Q_{quqd}^{(8)}$	$(\bar q_p^j T^A u_r)\varepsilon_{jk}(\bar q_s^k T^A d_t)$	Q_{qqq}	$\varepsilon^{\alpha\beta\gamma}\varepsilon_{jn}\varepsilon_{km}\left[(q_p^{\alpha j})^T C q_r^{\beta k}\right]\left[(q_s^{\gamma m})^T C l_t^n\right]$
$Q_{lequ}^{(1)}$	$(\bar l_p^j e_r)\varepsilon_{jk}(\bar q_s^k u_t)$	Q_{duu}	$\varepsilon^{\alpha\beta\gamma}\left[(d_p^\alpha)^T C u_r^\beta\right]\left[(u_s^\gamma)^T C e_t\right]$
$Q_{lequ}^{(3)}$	$(\bar l_p^j \sigma_{\mu\nu} e_r)\varepsilon_{jk}(\bar q_s^k \sigma^{\mu\nu} u_t)$		

- 59(+4) [omitting flavour indices]
- 2499(+546) [with flavour indices]

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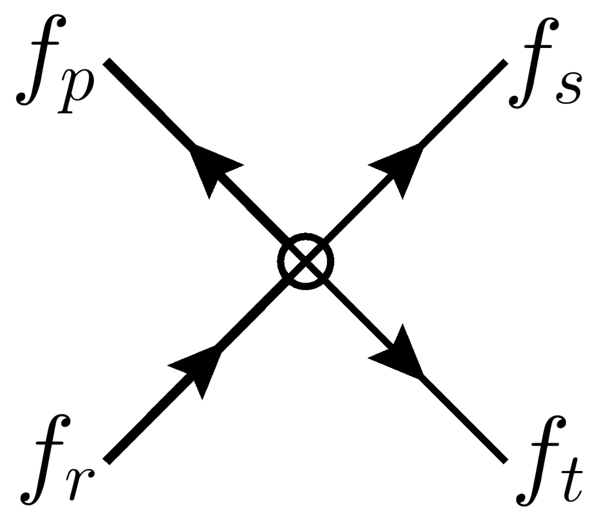
Contact interaction,



Rare process:
- Proton decay
- $\mu \to 3e$

Precsion observables:
- Parity violation
- Z pole

- 59(+4) [omitting flavour indices]
- 2499(+546) [with flavour indices]

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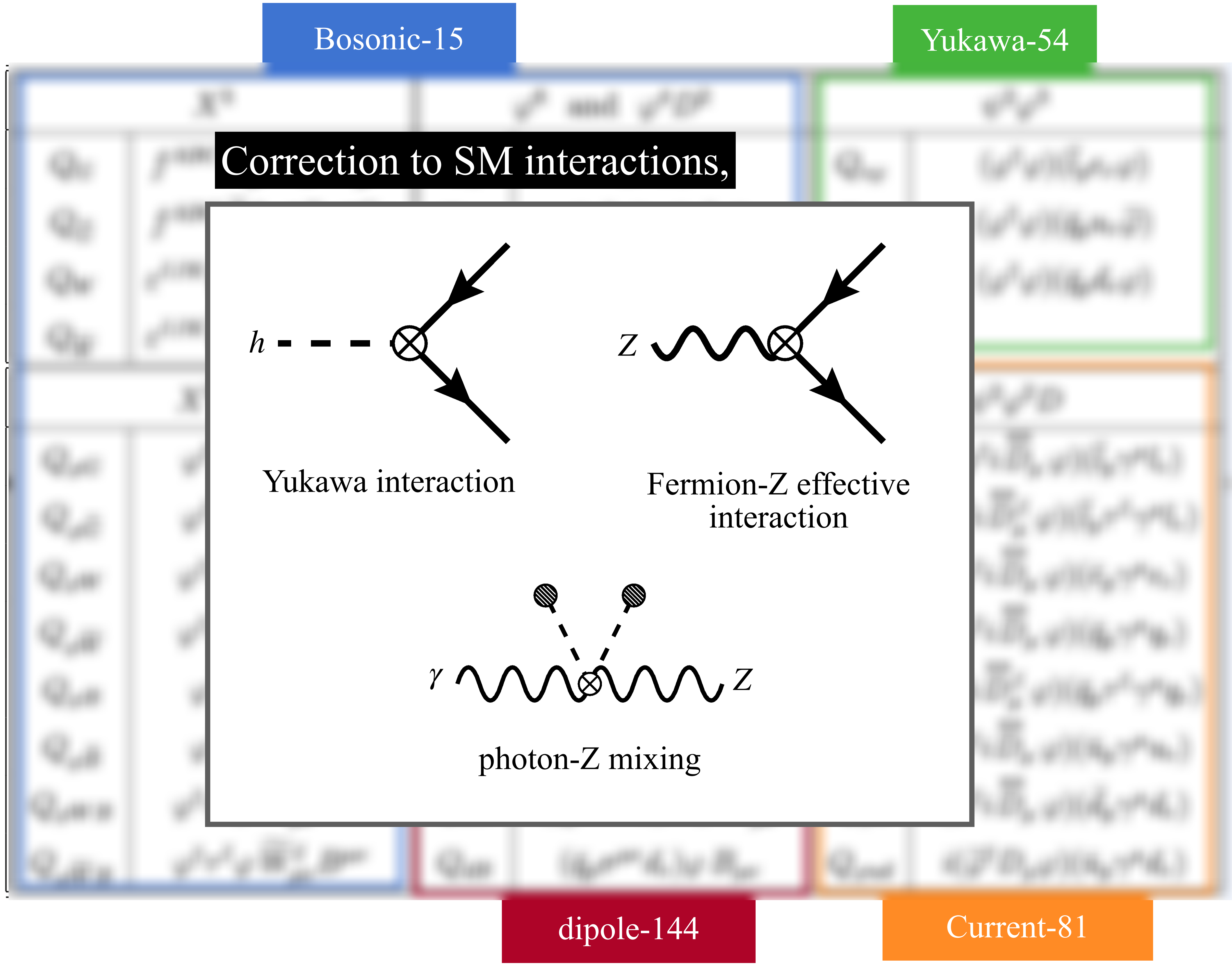

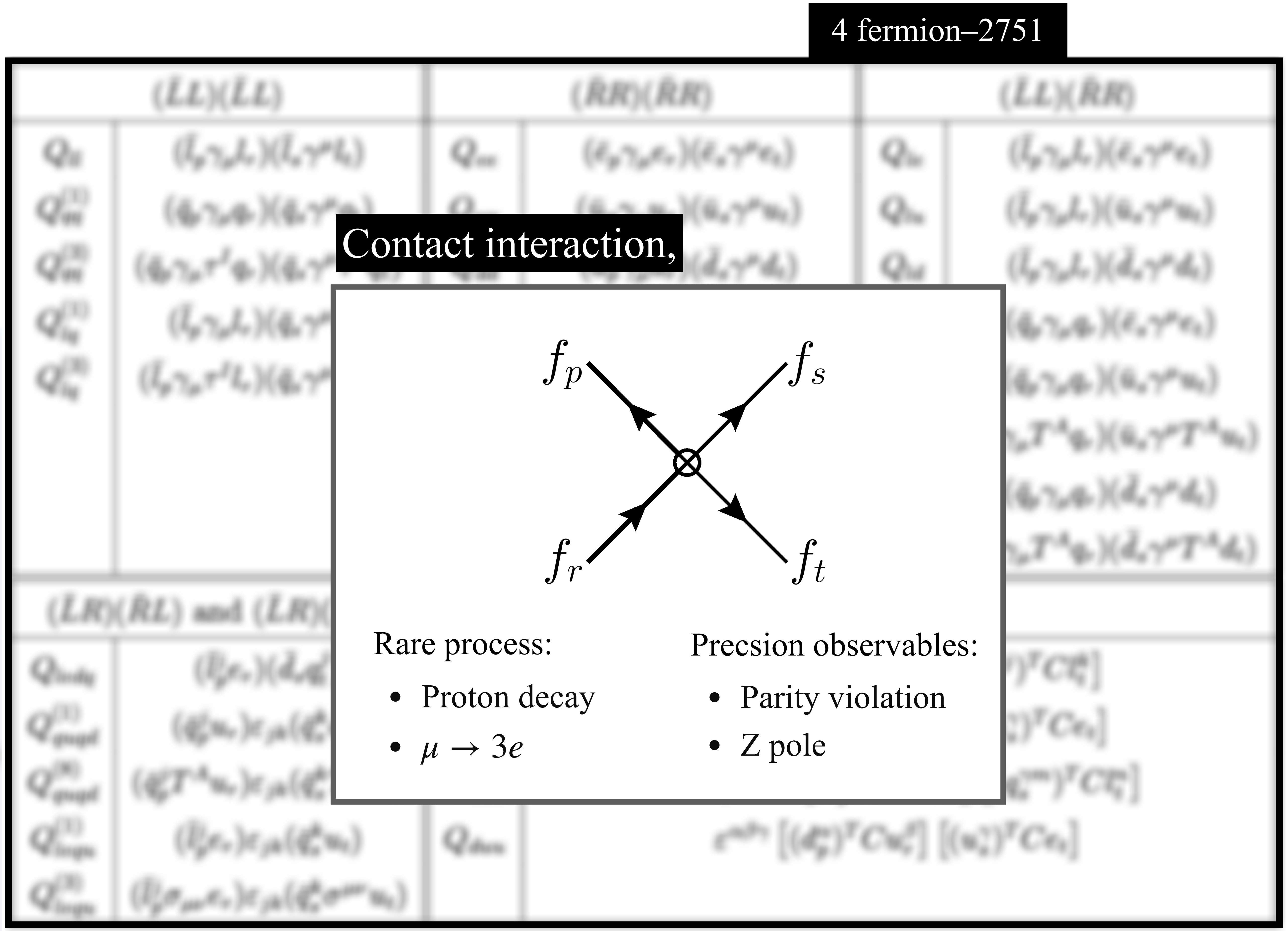

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Leading effect from D=6 operator

$$\mathcal{O} \sim \left| \mathcal{M}^{(4)}_{SM} + \sum_k \mathcal{M}^{(6)}_{k,LO} \right|^2 = \underbrace{\left| \mathcal{M}^{(4)}_{SM} \right|^2}_{\text{SM}} + \underbrace{2Re\left(\sum_k \mathcal{M}^{(4)*}_{SM} \mathcal{M}^{(6)}_{k,LO} \right)}_{\mathcal{O}\left(\Lambda^{-2}\right)} + \underbrace{\left| \mathcal{M}^{(6)}_{k,LO} \right|^2}_{\mathcal{O}\left(\Lambda^{-4}\right)}$$

$\mathcal{O}\left(\Lambda^{-2}\right)$ term → Precision observable

$\mathcal{O}\left(\Lambda^{-4}\right)$ term → SM forbidden process

Semi-leptonic/leptonic observables : Crucial for precision physics

<u>Example:</u>

- High energy: Hadronic cross-section (LEP),Drell-Yan process (Tevatron, LHC)
- Low energy: Parity violating process (PVES, PVDIS), β decay, CEνNS

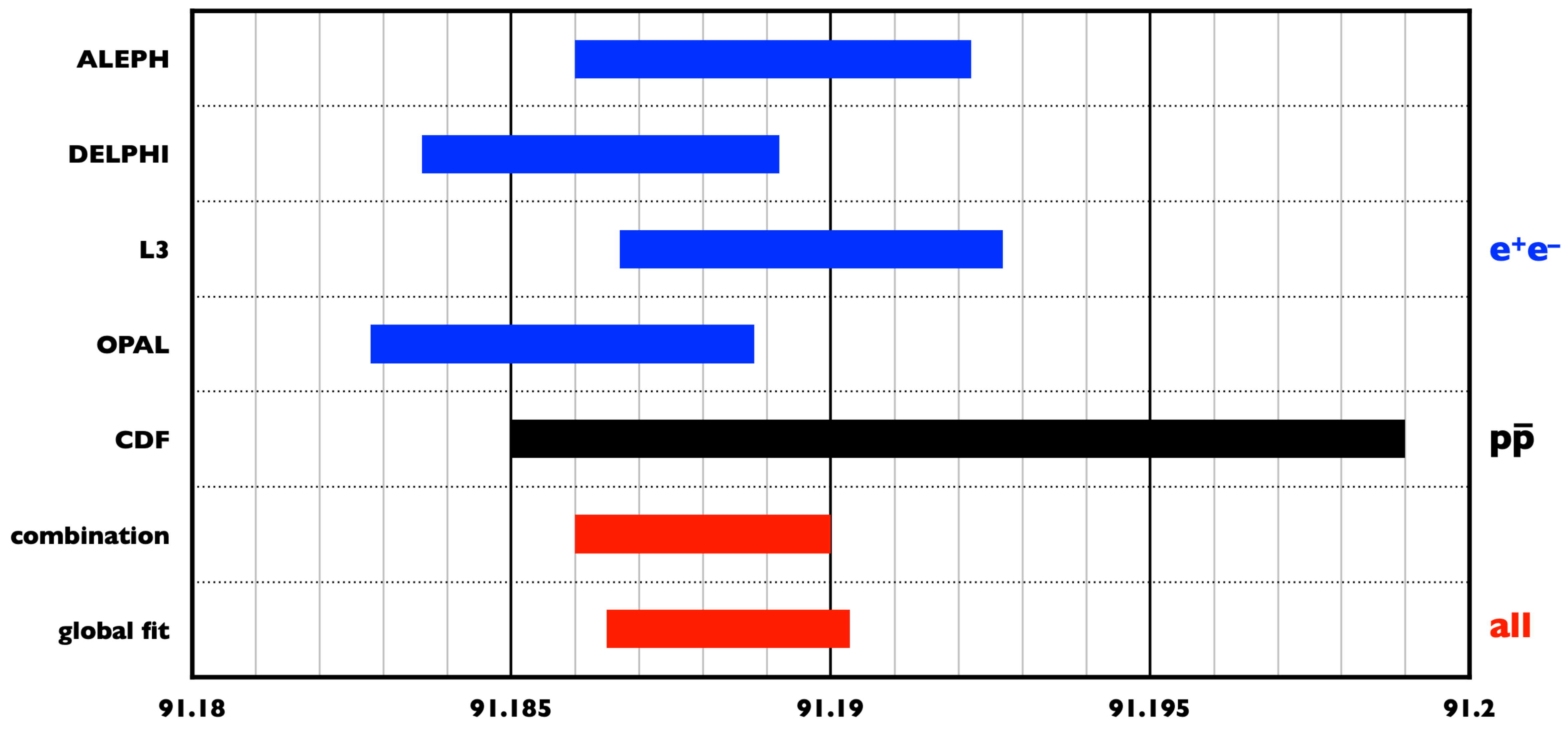
Z pole observables

LEP-1

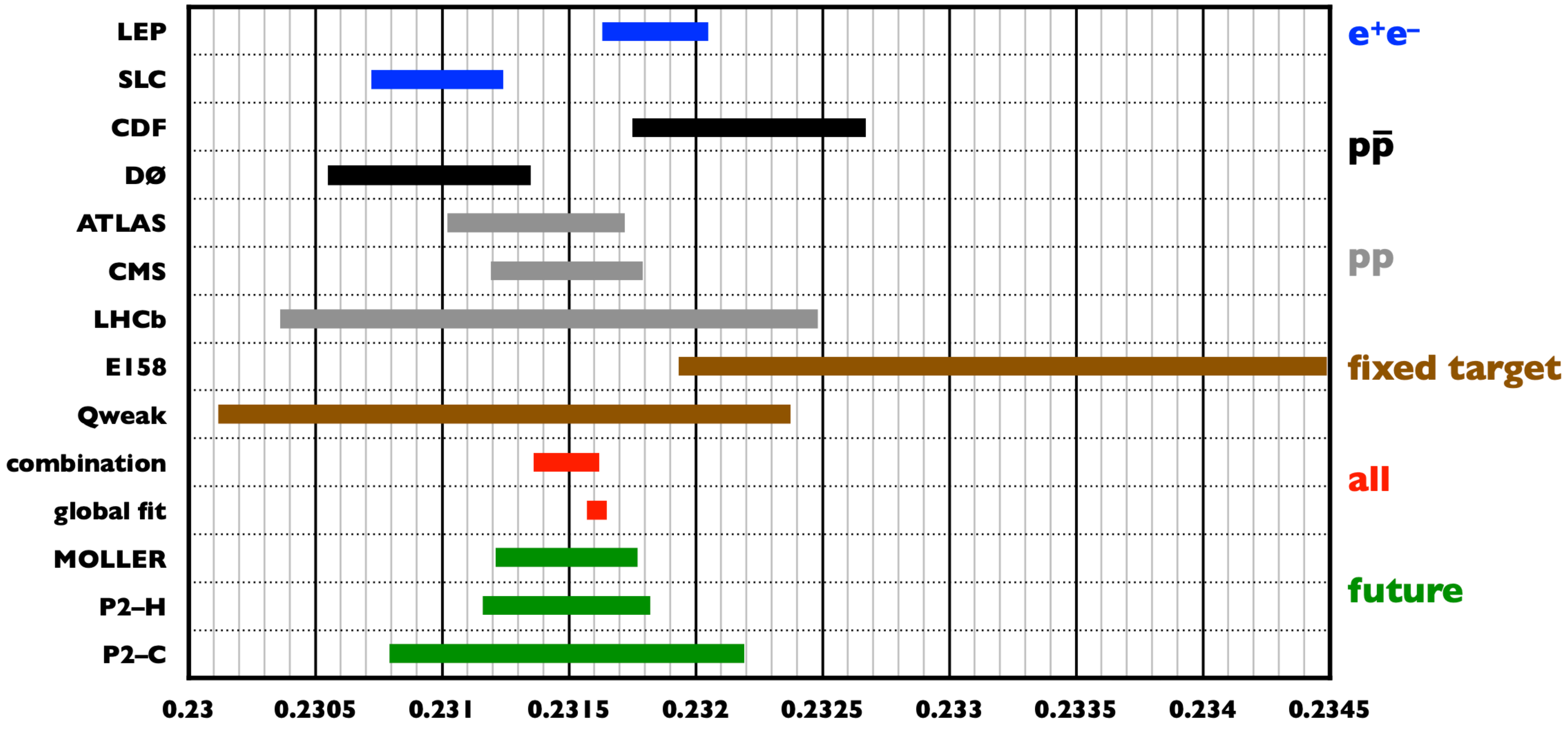
- Electron-positron collider to study Z pole observable $\left(E_{cm} \sim M_Z\right)$
- Observed 17 Million Z decays
- Precisely measured the Z parameters $(M_Z, \Gamma_Z, g_{Xf}, \sin^2\theta_W)$

Jens Erler [arXiv: 2505.03457]

Mass of Z boson



$\sin^2\theta_W$



Note: M_Z acts as a fixed point in SM

LEP measurements

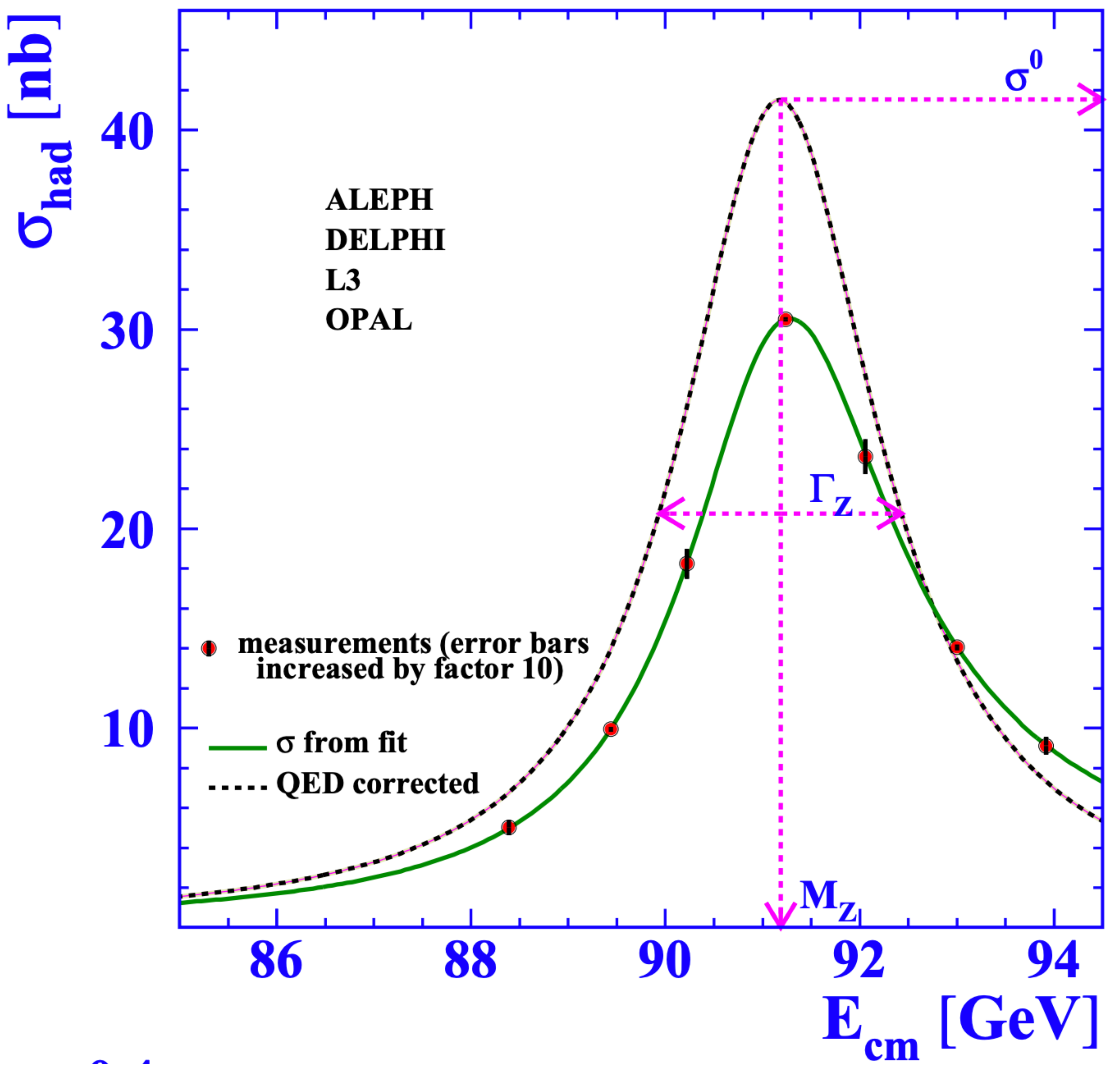
LEP Report: Phys.Rept.427:257-454,2006

- LEP measures σ_{had}, $\sigma_{e,\mu,\tau}$ and $A_{FB}^{e,\mu,\tau}$
- The measured cross-section/ asymmetry around the Z-pole,

$$\sigma(\mathrm{s}) = \int_{4\mathrm{m_f^2/s}}^{1} \mathrm{dz}\ \mathrm{H_{QED}^{tot}}(\mathrm{z,s}) \underbrace{\sigma_{\mathrm{ew}}(\mathrm{z,s})}$$

Electroweak kernel

QED deconvoluted,
- 36% larger
- 100 MeV shift in peak position



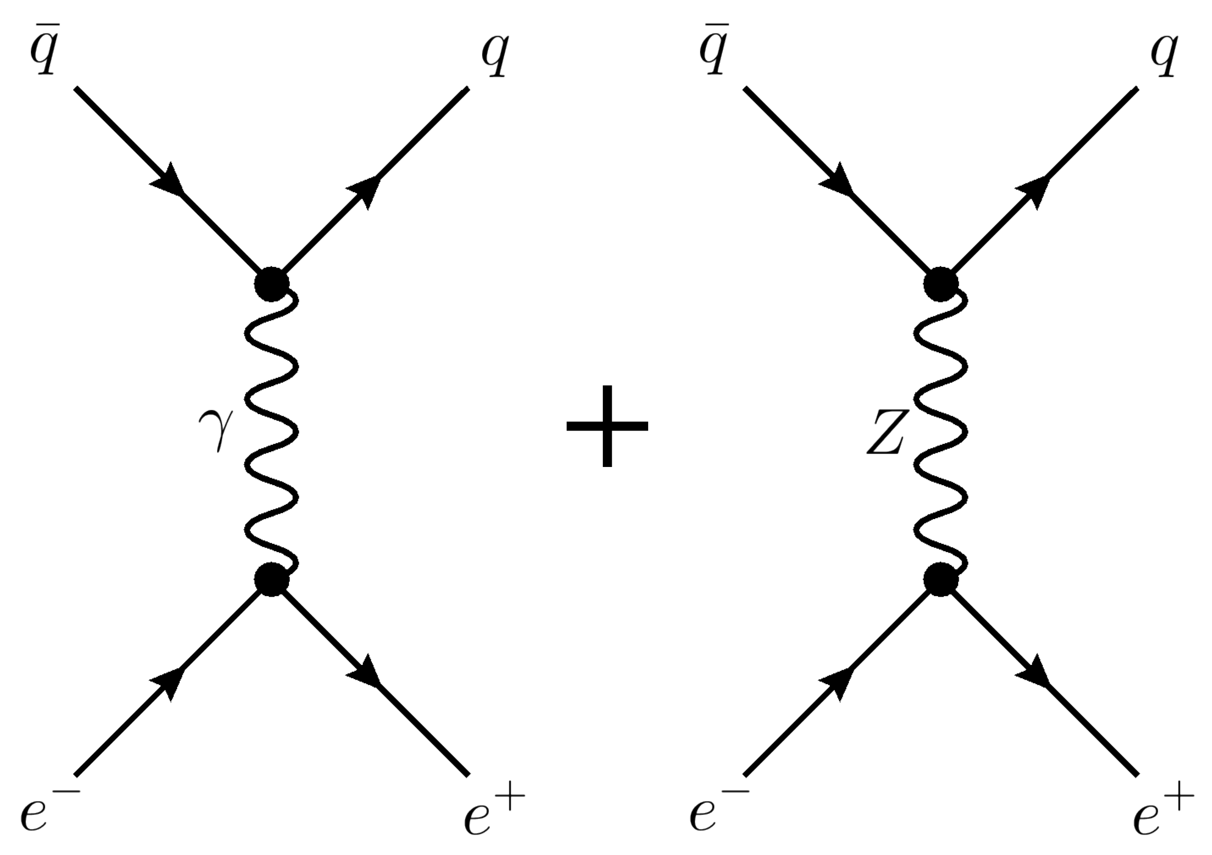
- Z resonance parameters are extracted after correcting for the QED effects

$$\sigma_{\mathrm{had}} = \sum_{\mathrm{q}\neq\mathrm{t}} \sigma_{\mathrm{ew}}^{\mathrm{q\bar{q}}}$$

Electroweak Kernel σ_{ew}

- In SM, electroweak cross-section, $\sigma_{\text{ew}} \sim \left| \mathcal{M}^{(4)}_{\text{SM}} \right|^2$

$\mathcal{M}^{(4)}_{\text{SM}} = \mathcal{M}_\gamma + \mathcal{M}_Z =$



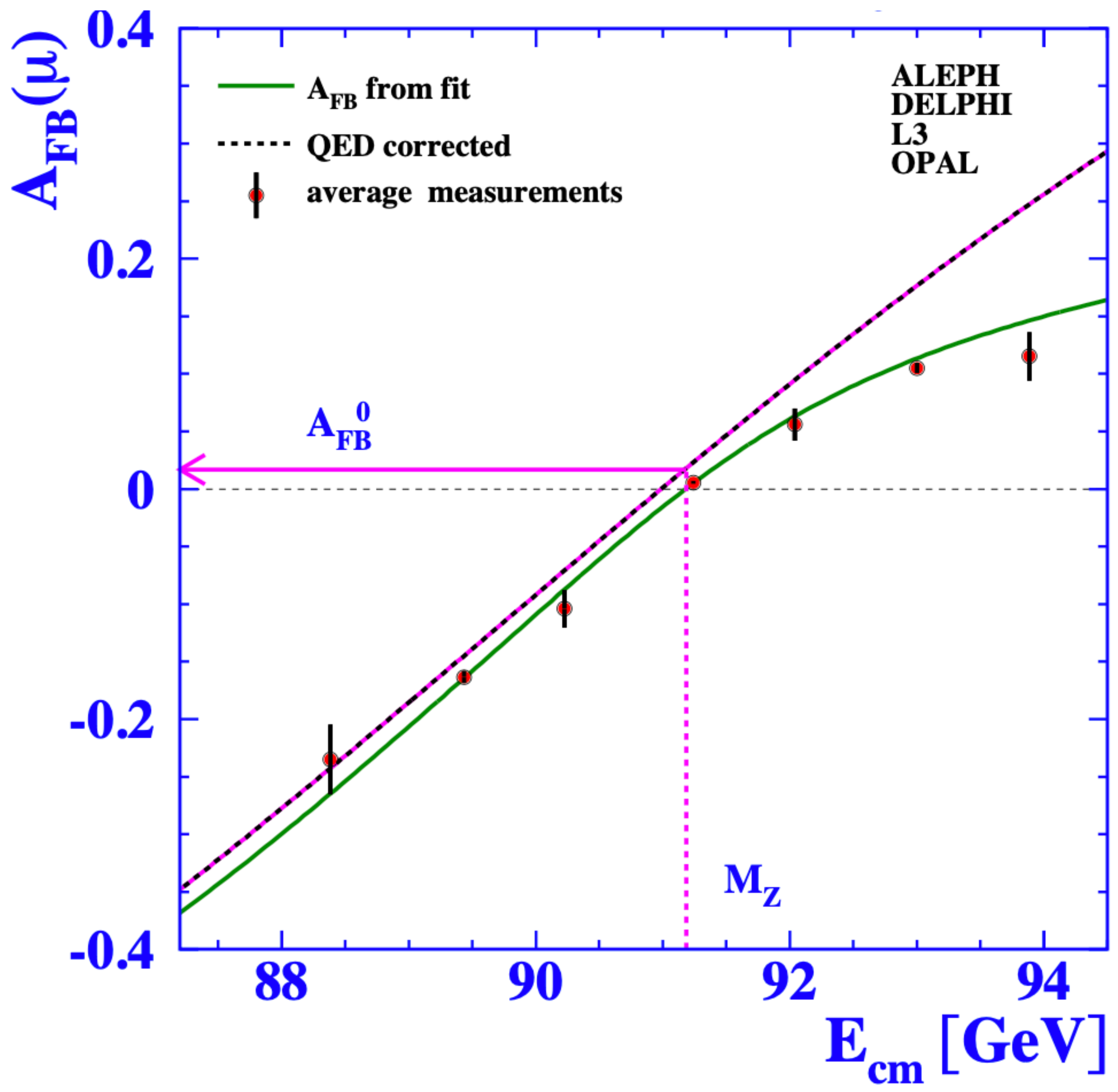
- Cross-section is parametrised based on a **Breit-Wigner shape**,

$$\sigma^{\bar{f}f}_{\text{ew}}(s) = \underbrace{\sigma^{\bar{f}f}_0 \frac{1}{1+\delta_{\text{QED}}} \frac{s\Gamma_Z^2}{(s-M_Z^2)^2 + \frac{s^2\Gamma_Z^2}{M_Z^2}}}_{\sigma_Z} + \sigma_\gamma + \sigma_{\gamma Z}$$

$\sigma_Z =$ ... Dominating at LEP 1

$\sigma_\gamma + \sigma_{\gamma Z}$: $< 1\,\%$ in SM

- Similarly forward-backward asymmetry, $A_{FB} = \dfrac{\sigma_F - \sigma_B}{\sigma_F + \sigma_B} = A^Z_{FB} + A^{\gamma Z}_{FB}$



LEP Report: Phys.Rept.427:257-454,2006

Electroweak Pseudo Observables (EWPO)

From Z pole measurements

$\sigma_{had}, \sigma_{e,\mu,\tau}, A_{FB}^{e,\mu,\tau}$

radiator function

+

fixing γ and γZ

9 EWPO's are extracted

Z parameters, $M_Z, \Gamma_Z, \sigma^0_{had}$

Peak cross-section ratio, $R^0_l = \frac{\sigma^0_{had}}{\sigma^0_l}$

Peak asymmetry, $A^{0,l}_{FB} = \frac{\sigma_F - \sigma_B}{\sigma_F + \sigma_B}$

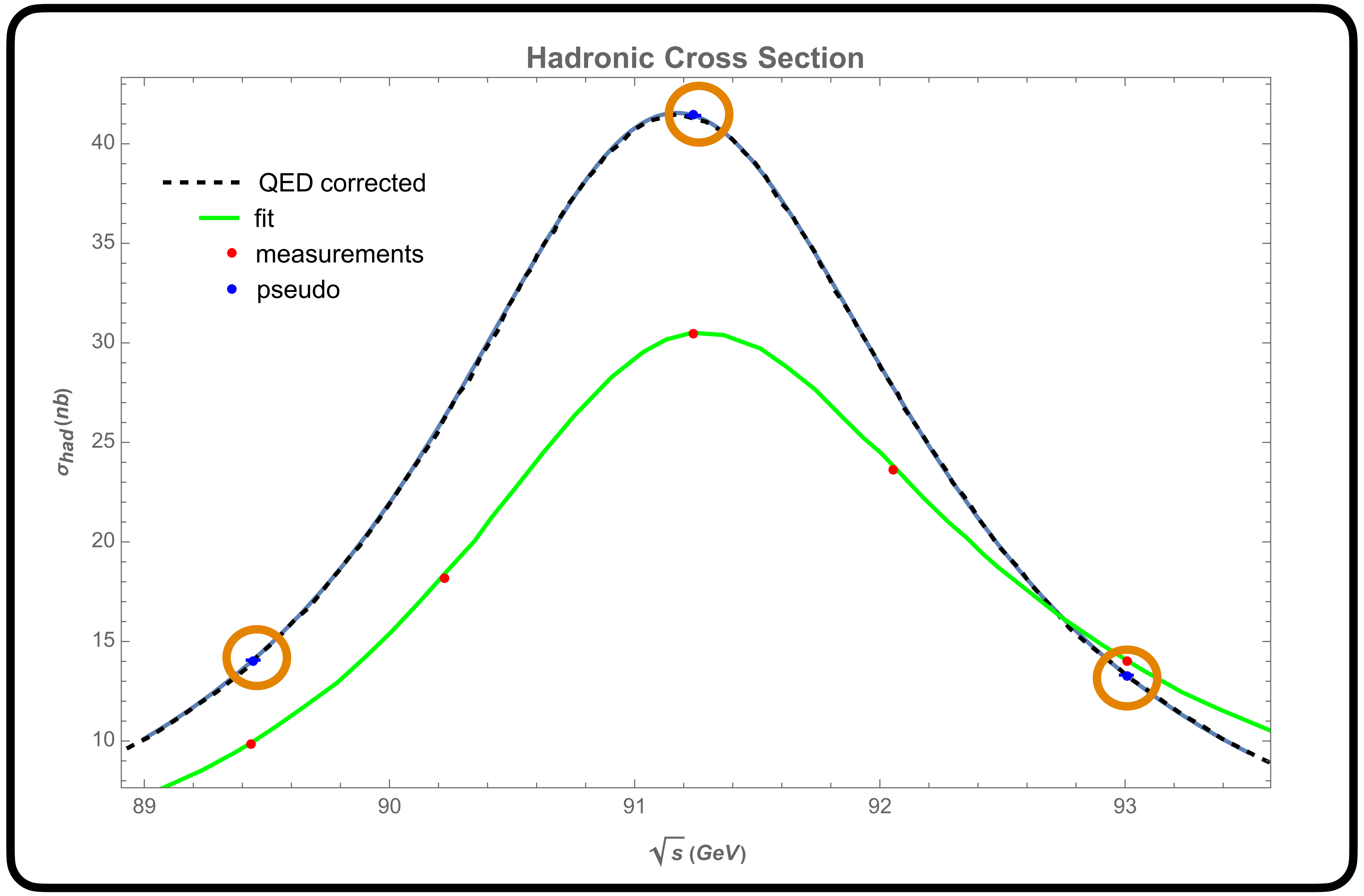
Without lepton universality	
$\chi^2/\mathrm{dof} = 32.6/27$	
m_Z [GeV]	91.1876 ± 0.0021
Γ_Z [GeV]	2.4952 ± 0.0023
σ^0_{had} [nb]	41.541 ± 0.037
R^0_e	20.804 ± 0.050
R^0_μ	20.785 ± 0.033
R^0_τ	20.764 ± 0.045
$A^{0,e}_{FB}$	0.0145 ± 0.0025
$A^{0,\mu}_{FB}$	0.0169 ± 0.0013
$A^{0,\tau}_{FB}$	0.0188 ± 0.0017

LEP Report: Phys.Rept.427:257-454,2006

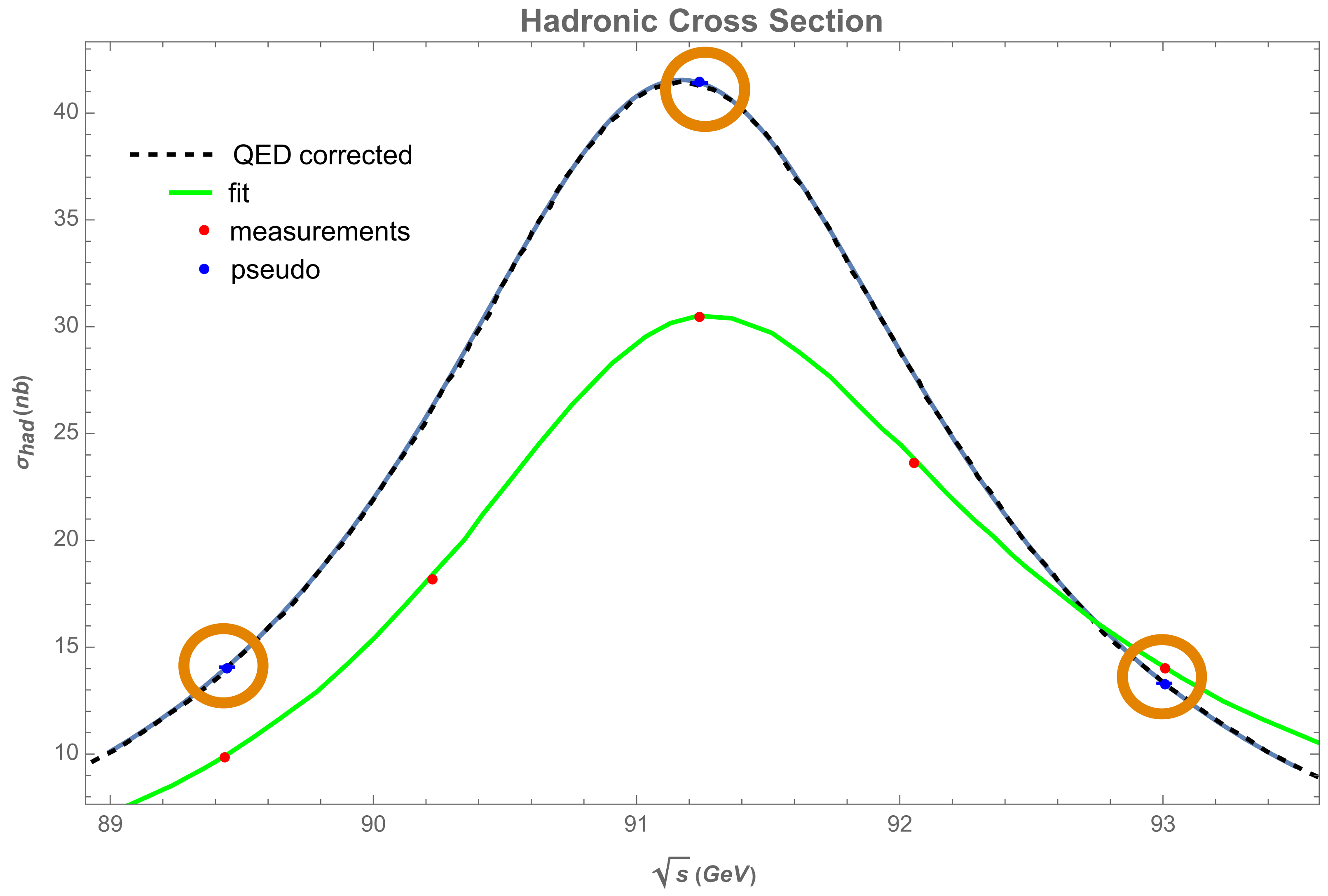
Z-line shape

- Z line shape → determines M_Z and Γ_Z
- Branching farction for Z to hadrons, neutrinos and leptons are 70%, 20% and 10%
- Hadronic cross-section at 89.4, 91.2 and 93.0 GeV

	Values	**Correlations**		
		M_Z	Γ_Z	σ^0_{had}
M_Z [GeV]	91.1876 ± 0.0021	1		
Γ_Z [GeV]	2.4952 ± 0.0023	-0.024	1	
σ^0_{had} [nb]	41.541 ± 0.037	-0.044	-0.297	1

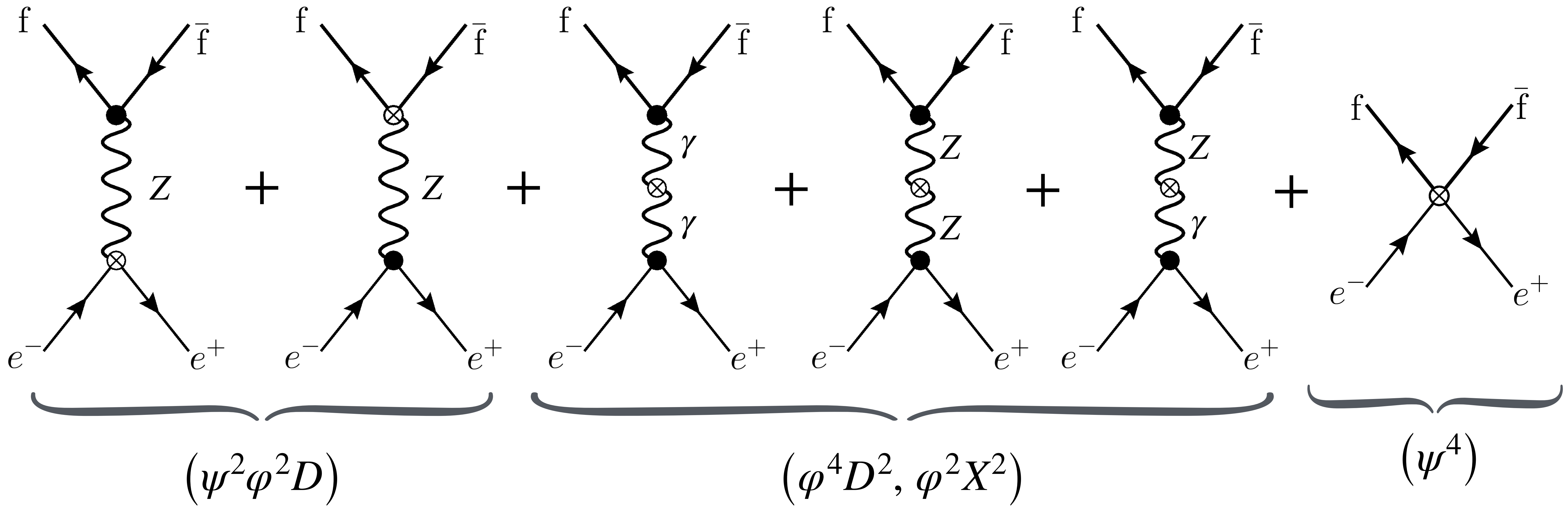


Hadronic cross-section



- Cross-section upto $\mathcal{O}(1/\Lambda^2)$, $\sigma_{\rm ew} \sim \left|\mathcal{M}^{(4)}_{\rm SM}\right|^2 + 2{\rm Re}\left(\sum_{\rm k} \mathcal{M}^{(4)*}_{\rm SM}\mathcal{M}^{(6)}_{\rm k,LO}\right)$
- Amplitudes from dim.6 operator,

$\mathcal{M}^{(6)} =$



- Total: 37 operators
- Family universal: 18 operators

Hadronic cross-section in SMEFT

$$\sigma_{ew}^{had}(s) = \sigma_0^{had}\frac{1}{1+\delta_{QED}}\frac{s\Gamma_Z^2}{(s-M_Z^2)^2+\frac{s^2\Gamma_Z^2}{M_Z^2}} + \sigma_\gamma^{had} + \sigma_{\gamma Z}^{had} + \sigma_{(6)}^{had}$$

SM input values

$\sin^2\hat{\theta}_W\left(\mu = M_Z\right) = 0.23129$
$M_Z = 91.1876 \pm 0.0021$ GeV
$\Gamma_Z = 2.4952 \pm 0.0023$ GeV
$\alpha_{em} = 1/127.951$
$G_F = 1.1663788\ 10^{-5}\text{GeV}^{-2}$

Linear combination of Wilson coefficient constrained by σ_{ew}^{had},

$$\sigma_{had}^{SM,89.4} + \frac{10^6}{\Lambda^2}\left(-12.86\, C_{\varphi B} + \ldots.\right) + \frac{10^6}{\Lambda^2}\left(1.68\ \left[C_{\varphi l}^{(1)}\right]_{11} + \ldots..\right) + \frac{10^3}{\Lambda^2}\left(3.46\ \left[C_{lq}^{(1)}\right]_{1111} + \ldots.\right) = 14.065(30)\text{nb}$$

$$\sigma_{had}^{SM,91.2} + \frac{10^6}{\Lambda^2}\left(+1.76\, C_{\varphi B} + \ldots.\right) + \frac{10^6}{\Lambda^2}\left(5.19\ \left[C_{\varphi l}^{(1)}\right]_{11} + \ldots.\right) + \frac{10^3}{\Lambda^2}\left(0.23\ \left[C_{lq}^{(1)}\right]_{1111} + \ldots.\right) = 41.417(37)\text{nb}$$

$$\sigma_{had}^{SM,93.0} + \frac{10^6}{\Lambda^2}\left(+12.45\, C_{\varphi B} \ldots.\right) + \frac{10^6}{\Lambda^2}\left(1.74\ \left[C_{\varphi l}^{(1)}\right]_{11} + \ldots.\right) + \frac{10^3}{\Lambda^2}\left(-2.62\ \left[C_{lq}^{(1)}\right]_{1111} + \ldots.\right) = 13.310(26)\text{nb}$$

Hadronic cross-section in SMEFT

Linear combination of Wilson coefficient constrained by σ_{ew}^{had},

$$\sigma_{had}^{SM,89.4} + \frac{10^6}{\Lambda^2}\left(-12.86\, C_{\varphi B} + \ldots.\right) + \frac{10^6}{\Lambda^2}\left(1.68\, \left[C_{\varphi l}^{(1)}\right]_{11} + \ldots..\right) + \frac{10^3}{\Lambda^2}\left(3.46\, \left[C_{lq}^{(1)}\right]_{1111} + \ldots.\right) = 14.065(30)\text{nb}$$

$$\sigma_{had}^{SM,91.2} + \frac{10^6}{\Lambda^2}\left(+1.76\, C_{\varphi B} + \ldots.\right) + \frac{10^6}{\Lambda^2}\left(5.19\, \left[C_{\varphi l}^{(1)}\right]_{11} + \ldots.\right) + \frac{10^3}{\Lambda^2}\left(0.23\, \left[C_{lq}^{(1)}\right]_{1111} + \ldots.\right) = 41.417(37)\text{nb}$$

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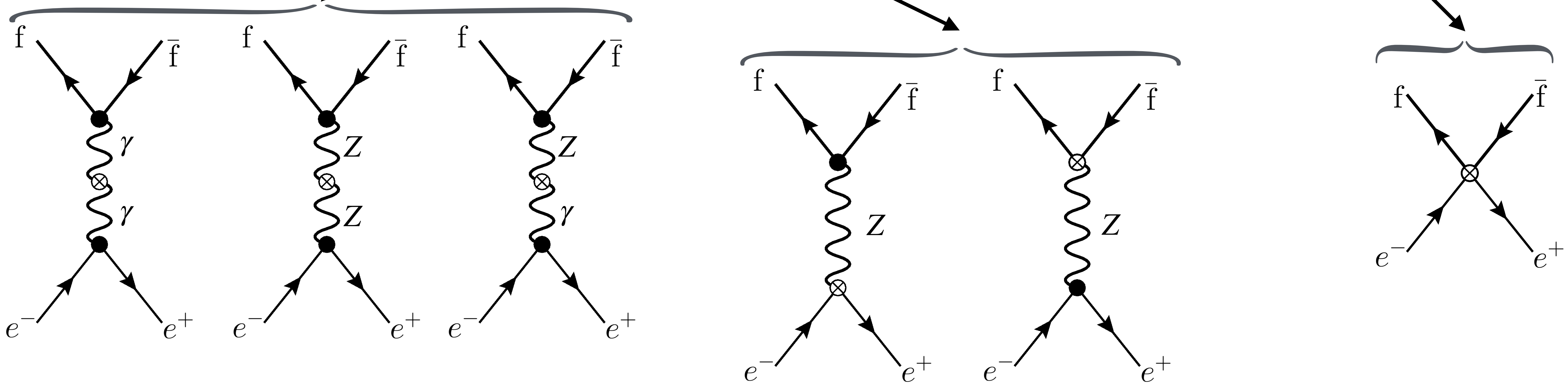
Bosonic opeartor   Current opeartor   Four fermion



Interference effect (Preliminary)

Current precision — Future Z pole

	LEP1	CEPC & FCCee
ΔMz[MeV]	2.1	0.1
ΔΓz[MeV]	2.3	0. 025
$\Delta\sigma^0_{had}$[nb]	0. 37	0. 002

arXiv: 1811.10545

$$\sigma^{had}_{ew}(s) = \sigma^{had}_0 \frac{1}{1+\delta_{QED}} \frac{s\Gamma_Z^2}{(s-M_Z^2)^2 + \frac{s^2\Gamma_Z^2}{M_Z^2}} + \sigma^{had}_{\gamma} + \sigma^{had}_{\gamma Z} + \underbrace{\sigma^{had}_{(6)}}$$

In presence of the four fermion operator

- $C^{(3)}_{lq} = \mathcal{O}(1),\ \Lambda = \ 5$ TeV

EWPO	LEP 1	FCCee
Z mass [GeV]	0.13 σ	2.8 σ
Z decay width[GeV]	0.03 σ	2.5 σ
Pole cross-section [nb]	0.02 σ	0.4 σ

EWPO are blind to these non-resonant effects

Summary

- EWPO don’t capture all BSM effects around the Z pole
- Interference effect can affect the extracted Z parameters
- Without falvour assumption 37 operators contribute to the hadronic cross-section

- Study the significace of dim.6 operators on off peak leptonic cross-section in Z pole
- Include Low energy PV observables (sensitive to four fermion operators)

Thank you.

Back up

Four fermion operator effects on EWPO

Assumption:

- $U(3)^5$ symmetry: $\left[C_{lq}^{(3)}\right]_{1111} = \left[C_{lq}^{(3)}\right]_{1122} = \left[C_{lq}^{(3)}\right]_{1133} = C_{lq}^{(3)}$
- $C_{lq}^{(3)} = \mathcal{O}(1)$
- $\Lambda = 1$ TeV, 5 TeV

EWPO	C=0(SM)	Λ=1TeV	Λ=5TeV
Z mass [GeV]	91.1876 ±0.0021	91.1951 ±0.0021 (2.5σ)	91.1879 ±0.0021 (0.1σ)
Z decay width[GeV]	2.4952±0.0023	2.4969±0.0023 (0.5σ)	2.4953±0.0023 (0.03σ)
Pole cross-section [nb]	41.541±0.037	41.525±0.037 (0.3σ)	41.540±0.037 (0.02σ)

Future projection CEPC & FCCee

ΔMz	0.1 MeV
ΔΓz	0.025 MeV
$\Delta\sigma_{had}^{0}$	0.002 nb

arXiv: 1811.10545

Four fermion operator effects on EWPO

EWPO	SM	C3Hq	C3lq
Mz [GeV]	91.1876(21)	91.1876(21) (0σ)	91.1879 ±0.0021 GeV (0.1σ)
Z decay width[GeV]	2.4952(23)	2.4952(23) (0σ)	2.4953±0.0023 GeV (0.03σ)
Pole Cross section [nb]	41.541(37)	41.452(37) (1.7σ)	41.540±0.037 GeV (0.02σ)

Future projection CEPC & FCCee

ΔMz	0.1 MeV
ΔΓz	0.025 MeV
Δσhad0	0.002 nb

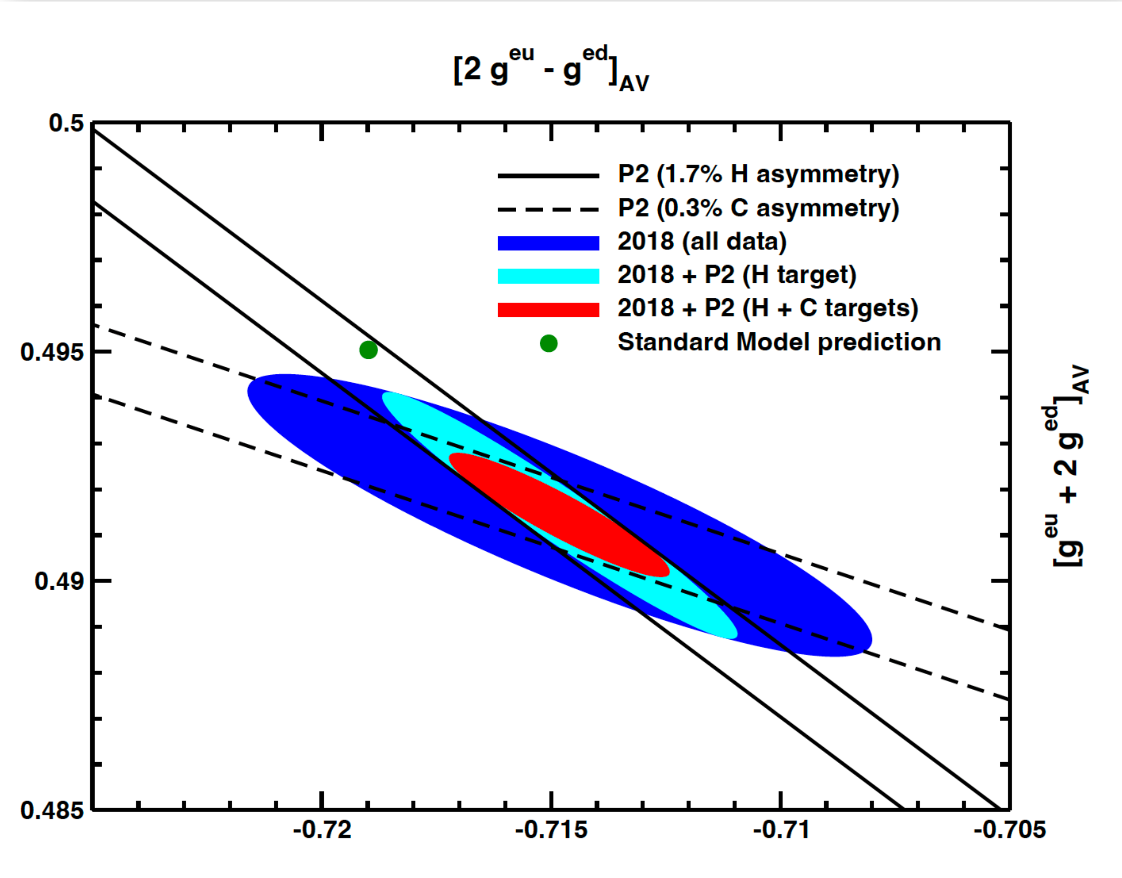
Parity Violating Electron Scattering

e-P scattering	
Parity asymmetry	$A_{PV} = -\frac{G_F Q^2}{4\pi\alpha_{em}\sqrt{2}}\left[Q_W(P) - F(E_i, Q^2)\right]$
Weak charge	$Q_W(P) = 2\left(2C_{1u} + C_{1d}\right) = 1 - 4s_W^2$
Hadronic/ Nuclear	$F(E_i, Q^2) = F^{EM}(E_i, Q^2) + F^A(E_i, Q^2) + F^S(E_i, Q^2)$

e-C scattering	
Parity asymmetry	$A_{PV} = -\frac{G_F Q^2}{4\pi\alpha_{em}\sqrt{2}}\frac{Q_W(^{12}C)}{Z}(1+\Delta)$
Weak charge	$Q_W(^{12}C) = 36\left(C_{1u} + C_{1d}\right) = -24s_W^2$
Hadronic/ Nuclear	$\Delta = \frac{F_{wk}(Q^2)}{F_{ch}(Q^2)} - 1$

Oleksandr Koshchii et.al. [2005.00479v2]

Dominik Becker et.al. [1802.04759v2]



Current Experimental constraints

1) Weak collaboration[1905.08283]
2)P.A. Souder, R. Holmes, D.H. Kim, Krishna S. Kumar et.al.

Process	$Q^2[\mathrm{GeV}^2]$	$A_{PV}[\mathrm{ppm}]$	Combination	Exp.	SM
e-P	0.0248	-0.2265 ±0.0073(st) ±0.0058(sy)	$2C_{1u} + C_{1d}$	0.0719±0.0045	0.0711±0.0002
e-C	0.0225	-0.60 ±0.14(st) ±0.02(sy)	$C_{1u} + C_{1d}$	0.138±0.034	0.1528

$$C_{1q} = C_{1q}^{\mathrm{SM}} + \delta C_{1q}$$

- C_{1q}^{SM} is SM contribution
- δC_{1q} is leading BSM contribution from dim.6 operators

Deep inelastic scattering process

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

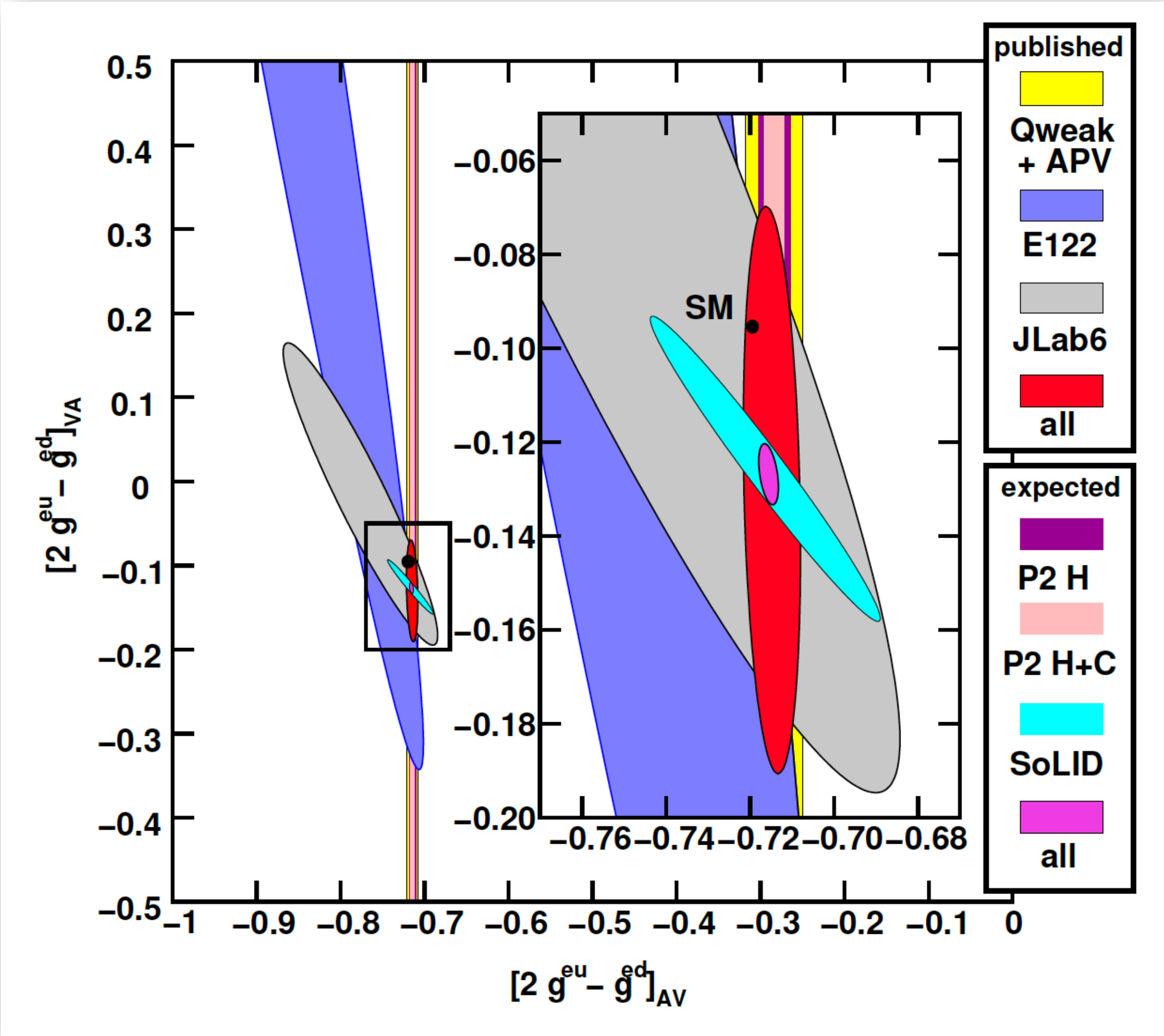
Parity asymmetry	$A_{PV}^{SM} = -\frac{G_F Q^2}{4\pi\alpha_{em}\sqrt{2}}\left[a_1 + a_3\frac{1-(1-y)^2}{1+(1-y)^2}\right]$	
	Axial-vector	Vector-axial
SM contribution	$a_1 = \frac{6}{5}(2C_{1u} - C_{1d})$	$a_3 = \frac{6}{5}(2C_{2u} - C_{2d})$

$$y = \frac{Q^2}{2M_N x E_1}$$

x is Bjorken scale

M_N is mass of nucleons

J. Arrington et.al.[2209.13357v1]



Current Experimental constraints

The Jefferson Lab PVDIS Collaboration [doi:10.1038/nature12964]

	$Q^2[\mathrm{GeV}^2]$	x	$A_{PV}[\mathrm{ppm}]$	Combination	Exp.	SM
e-D	1.085	0. 241	-91.1±3.1(st)±3.0(sy)	$2C_{1u} - C_{1d}$	-0.7165±0.0068	-0.7193
	1.901	0. 295	-160.8±6.4(st)±3.1(sy)	$2C_{2u} - C_{2d}$	-0.13±0.06	-0.0950

Linear combinations

Process	Linear combination
e-P	$2\delta C_{1u} + \delta C_{1d} = 0.01 \pm 0.0045$
e-C	$\delta C_{1u} + \delta C_{1d} = 0.015 \pm 0.034$
e-D	$2\delta C_{1u} - \delta C_{1d} = 0.0028 \pm 0.006$
	$2\delta C_{2u} - \delta C_{2d} = -0.035 \pm 0.06$

Correction to fermion-Z vertices

$(\varphi^\dagger i \overleftrightarrow{D}_\mu \varphi)(\bar{l}_p \gamma^\mu l_r)$

$(\varphi^\dagger i \overleftrightarrow{D}^I_\mu \varphi)(\bar{l}_p \tau^I \gamma^\mu l_r)$

$(\varphi^\dagger i \overleftrightarrow{D}_\mu \varphi)(\bar{e}_p \gamma^\mu e_r)$

$(\varphi^\dagger i \overleftrightarrow{D}_\mu \varphi)(\bar{q}_p \gamma^\mu q_r)$

$(\varphi^\dagger i \overleftrightarrow{D}^I_\mu \varphi)(\bar{q}_p \tau^I \gamma^\mu q_r)$

$(\varphi^\dagger i \overleftrightarrow{D}_\mu \varphi)(\bar{u}_p \gamma^\mu u_r)$

$(\varphi^\dagger i \overleftrightarrow{D}_\mu \varphi)(\bar{d}_p \gamma^\mu d_r)$

4 fermione operators

$(\bar{l}_p \gamma_\mu l_r)(\bar{u}_s \gamma^\mu u_t)$

$(\bar{l}_p \gamma_\mu l_r)(\bar{d}_s \gamma^\mu d_t)$

$(\bar{q}_p \gamma_\mu q_r)(\bar{e}_s \gamma^\mu e_t)$

$(\bar{e}_p \gamma_\mu e_r)(\bar{u}_s \gamma^\mu u_t)$

$(\bar{e}_p \gamma_\mu e_r)(\bar{d}_s \gamma^\mu d_t)$

$(\bar{l}_p \gamma_\mu l_r)(\bar{q}_s \gamma^\mu q_t)$

$(\bar{l}_p \gamma_\mu \tau^I l_r)(\bar{q}_s \gamma^\mu \tau^I q_t)$

$l1 = \begin{pmatrix} \nu_L \\ e_L \end{pmatrix}$	$e1 = e_R$
$q1 = \begin{pmatrix} u_L \\ d_L \end{pmatrix}$	$d1 = d_R$ $u1 = u_R$

In total 14 dim.6 operators contribute to the Parity violating process

$$\delta C_{1u} = \hat{g}^e_A \left[-C_{\varphi u1} + \left(-C^{(1)}_{\varphi q1} + C^{(3)}_{\varphi q1} \right) \right] \frac{v^2}{\Lambda^2} + \hat{g}^u_V \left[-C_{\varphi e1} - \left(-C^{(1)}_{\varphi l1} - C^{(3)}_{\varphi l1} \right) \right] \frac{v^2}{\Lambda^2} + \left[C_{e1u1} + C_{q1e1} - C_{l1u1} - \left(C^{(1)}_{l1q1} - C^{(3)}_{l1q1} \right) \right] \frac{v^2}{2\Lambda^2}$$

$$\delta C_{1d} = \hat{g}^e_A \left[-C_{\varphi d1} + \left(-C^{(1)}_{\varphi q1} - C^{(3)}_{\varphi q1}] \right) \right] \frac{v^2}{\Lambda^2} + \hat{g}^d_V \left[-C_{\varphi e1} - \left(-C^{(1)}_{\varphi l1} - C^{(3)}_{\varphi l1} \right) \right] \frac{v^2}{\Lambda^2} + \left[C_{e1d1} + C_{q1e1} - C_{l1d1} - \left(C^{(1)}_{l1q1} + C^{(3)}_{l1q1} \right) \right] \frac{v^2}{2\Lambda^2}$$

$$\delta C_{2u} = \hat{g}^e_V \left[-C_{\varphi u1} - \left(-C^{(1)}_{\varphi q1} + C^{(3)}_{\varphi q1} \right) \right] \frac{v^2}{\Lambda^2} + \hat{g}^u_A \left[-C_{\varphi e1} + \left(-C^{(1)}_{\varphi l1} - C^{(3)}_{\varphi l1} \right) \right] \frac{v^2}{\Lambda^2} + \left[C_{e1u1} - C_{q1e1} + C_{l1u1} - \left(C^{(1)}_{l1q1} - C^{(3)}_{l1q1} \right) \right] \frac{v^2}{2\Lambda^2}$$

$$\delta C_{2d} = \hat{g}^e_V \left[-C_{\varphi d1} - \left(-C^{(1)}_{\varphi q1} - C^{(3)}_{\varphi q1} \right) \right] \frac{v^2}{\Lambda^2} + \hat{g}^d_A \left[-C_{\varphi e1} + \left(-C^{(1)}_{\varphi l1} - C^{(3)}_{\varphi l1} \right) \right] \frac{v^2}{\Lambda^2} + \left[C_{e1d1} - C_{q1e1} + C_{l1d1} - \left(C^{(1)}_{l1q1} + C^{(3)}_{l1q1} \right) \right] \frac{v^2}{2\Lambda^2}$$