Electroweak Physics: Present and Future

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Mazatlan, November 5, 2015

Outline

- Preliminaries / introduction
- Weak boson masses
- The weak mixing angle
- Oblique parameters (STU)
- Low energy precision tests
- Parity violation
- Contact interactions
- Conclusions

Introduction

Recent reviews

Krishna Kumar, Sonny Mantry, William Marciano and Paul Souder

Annu. Rev. Nucl. Part. Sci. 63 (2013) 237–67

Jens Erler and Shufang Su

Prog. Part. Nucl. Phys. 71 (2013) 119–149

Jens Erler and Ayres Freitas

Particle Data Group (2014)

Jens Erler, Charles Horowitz, Sonny Mantry and Paul Souder

Annu. Rev. Nucl. Part. Sci. 64 (2014) 269–298

Introduction

ν	τ	τ	t	t	t				b	b	b	$\bar{b}$	$\bar{b}$	$\bar{b}$
s=½	s=½	s=½	s=½	s=½	s=½	s=½	s=½	s=½	s=½	s=½	s=½	s=½	s=½	s=½
ν	μ	μ	c	c	c	$\bar{c}$	$\bar{c}$	$\bar{c}$	s	s	s	$\bar{s}$	$\bar{s}$	$\bar{s}$
s=½	s=½	s=½	s=½	s=½	s=½	s=½	s=½	s=½	s=½	s=½	s=½	s=½	s=½	s=½
ν	e	e	u	u	u	$\bar{u}$	$\bar{u}$	$\bar{u}$	d	d	d	$\bar{d}$	$\bar{d}$	$\bar{d}$
s=½	s=½	s=½	s=½	s=½	s=½	s=½	s=½	s=½	s=½	s=½	s=½	s=½	s=½	s=½
H	H	Z	W	W	g	g	g	g	g	g	g	g	γ	G
s=0	s=0	s=1	s=1	s=1	s=1	s=1	s=1	s=1	s=1	s=1	s=1	s=1	s=1	s=2

(before electroweak symmetry breaking)

Key SM Parameters

- 4 parameters from bosonic sector: g, g'

$$\mathcal{L}_\phi = (D^\mu \phi)^\dagger D_\mu \phi - \mu^2 \phi^\dagger \phi - \frac{\lambda^2}{2} (\phi^\dagger \phi)^2$$

- h / m_{Rb}: $\alpha \equiv g^2 \sin^2\theta_W / 4\pi$ ($\pm$ 6.6 × 10^{-10})
- $g_e - 2$: $\alpha \equiv g^2 \sin^2\theta_W / 4\pi$ ($\pm$ 8 × 10^{-13}) [derived]
- PSI: $G_F \equiv 1/(\sqrt{2}\, v^2)$ ($\pm$ 5 × 10^{-7}) [v = 246.22 GeV]
- LEP 1: $M_Z \equiv M_W / \cos\theta_W$ ($\pm$ 2 × 10^{-5})
- Tevatron: $M_W \equiv g\, v/2$ ($\pm$ 2 × 10^{-4}) [derived]
- Z pole: $\sin^2\theta_W \equiv g'^2/(g^2 + g'^2)$ ($\pm$ 7 × 10^{-4}) [derived]
- LHC: $M_H \equiv \lambda\, v = \sqrt{(-2\, \mu^2)}$ ($\pm$ 3 × 10^{-3})
- LHC / Tevatron: $m_t(m_t) \equiv \lambda_t\, v$ ($\pm$ 6 × 10^{-3})

History

- 1950s: development of fundamental ideas underlying the SM (Yang-Mills theory, parity violation, V−A, intermediate vector bosons)
- 1960s: construction of the SM (gauge group, Cabbibo-universality, Higgs mechanism, model of leptons)
- 1970s: discovery of key predictions of the SM (neutral currents, APV, ν-scattering, polarized DIS)
- 1980s: establishment of basic structure of the SM (discovery of W & Z, mutually consistent values of $\sin^2\theta_W = g'^2/(g^2 + g'^2)$ from many different processes)
- 1990s (LEP, SLC): confirmation of the SM at the loop level ⇒ new physics at most a perturbation
- 2000s (Tevatron): ultra-high precision in m_t (0.5%) and M_W (0.02%) ⇒ (most of) new physics seperated by at least a little hierarchy (or else conspiracy or very weak coupling)
- 2010s (LHC, intensity frontier): EW symmetry breaking sector (Higgs & BSM)

Complementary physics

High-energy precision tests

EW symmetry breaking

Energy

Collider searches

new particles & states

Low-energy precision tests

new amplitudes

Intensity

Flavor physics

symmetries and conservation laws

Complementary tools

High-energy precision tests

EW symmetry breaking

M_W
$\sin^2\theta_W$
Z & H properties
top quark properties

Low-energy precision tests

new amplitudes

polarized e^- scattering
ν scattering
atomic parity violation
lepton properties

Complementary facilities

High-energy precision tests

EW symmetry breaking

High energy lepton and hadron colliders

LEP & SLC
Tevatron & LHC
ILC, CEPC (SppC) & FCC

Low-energy precision tests

new amplitudes

Medium energy accelerators & table-top

CEBAF (Jefferon Lab)
MESA (Mainz)
flavor physics facilities

Weak boson masses

M_H from radiative corrections

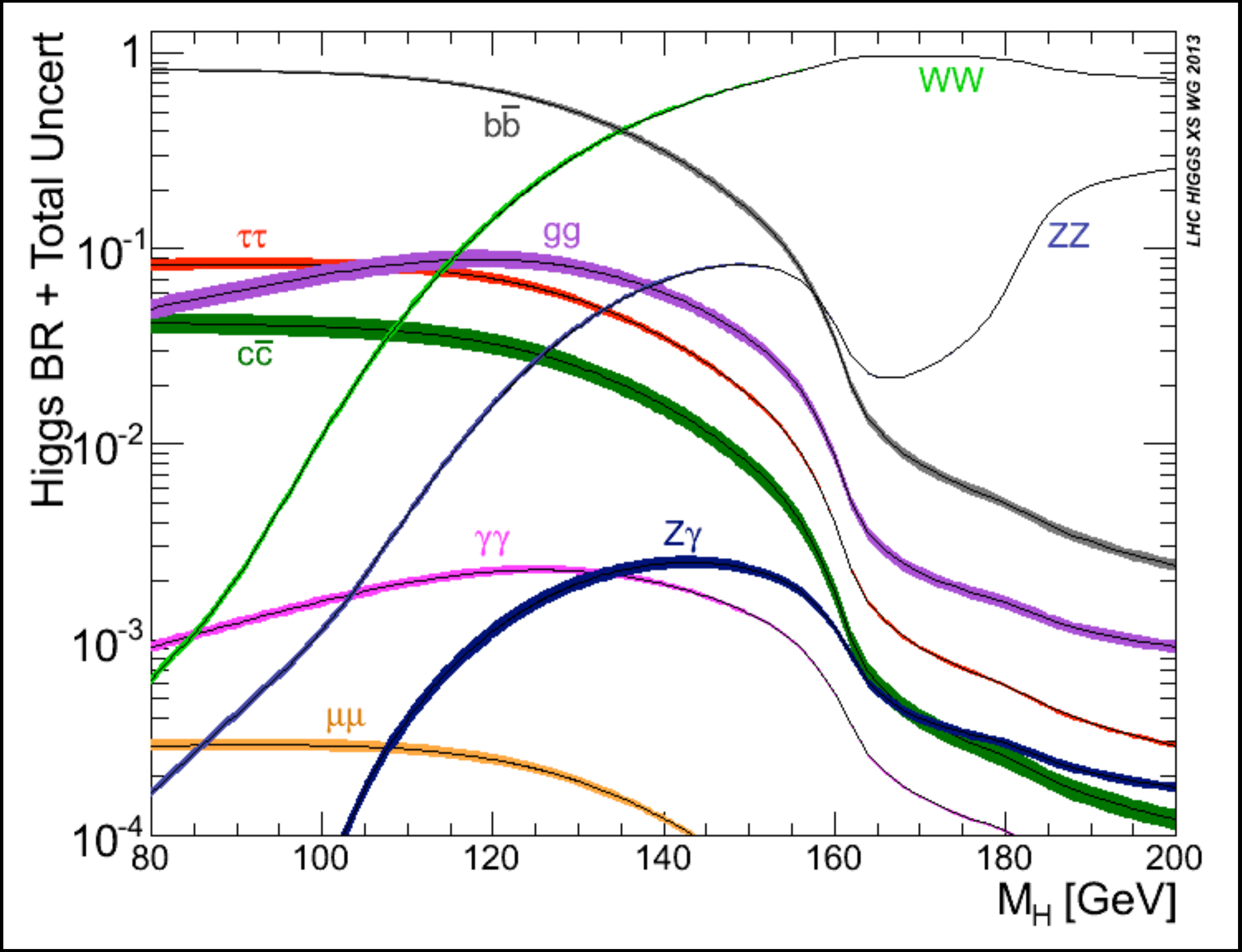
- Consider fundamental SM relations like

  $\sin^2\theta_W = g'^2/(g^2 + g'^2) = 1 - M_W^2/M_Z^2/(1 + \Delta\rho)$

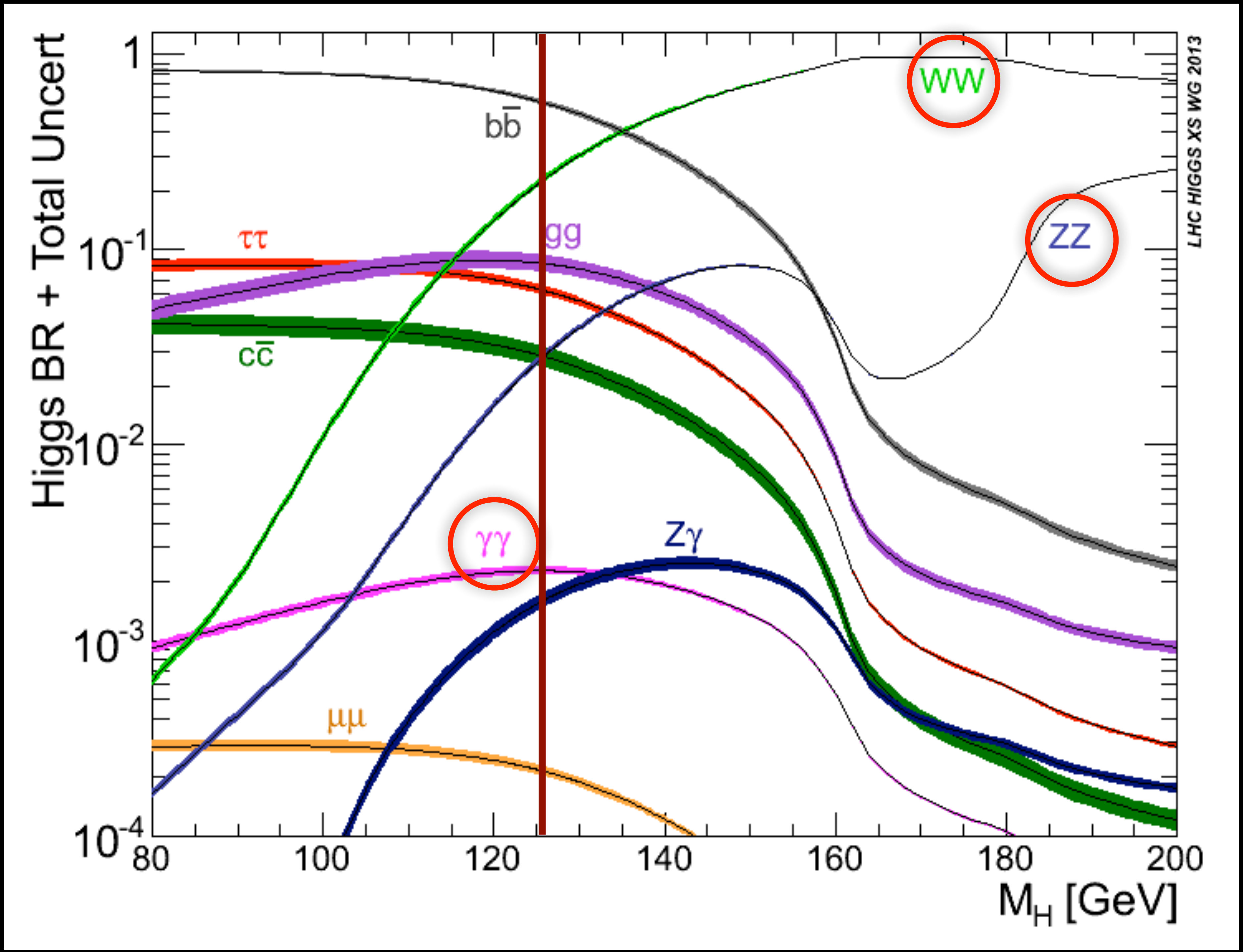
  or $\sqrt{2}\, G_F\, (1 - \Delta r) = e^2\, /(4 \sin^2\theta_W\, M_W^2)$

- Compute radiative correction parameters such as $\Delta\rho$ and Δr to very high (two-loop EW) accuracy
- These are functions of m_t, M_H, M_Z, …, as well as M_W and $\sin^2\theta_W$ themselves (needs numerical iterations)
- Compare with experimental $\Delta\rho$ and Δr to test SM and look for deviations (new physics)

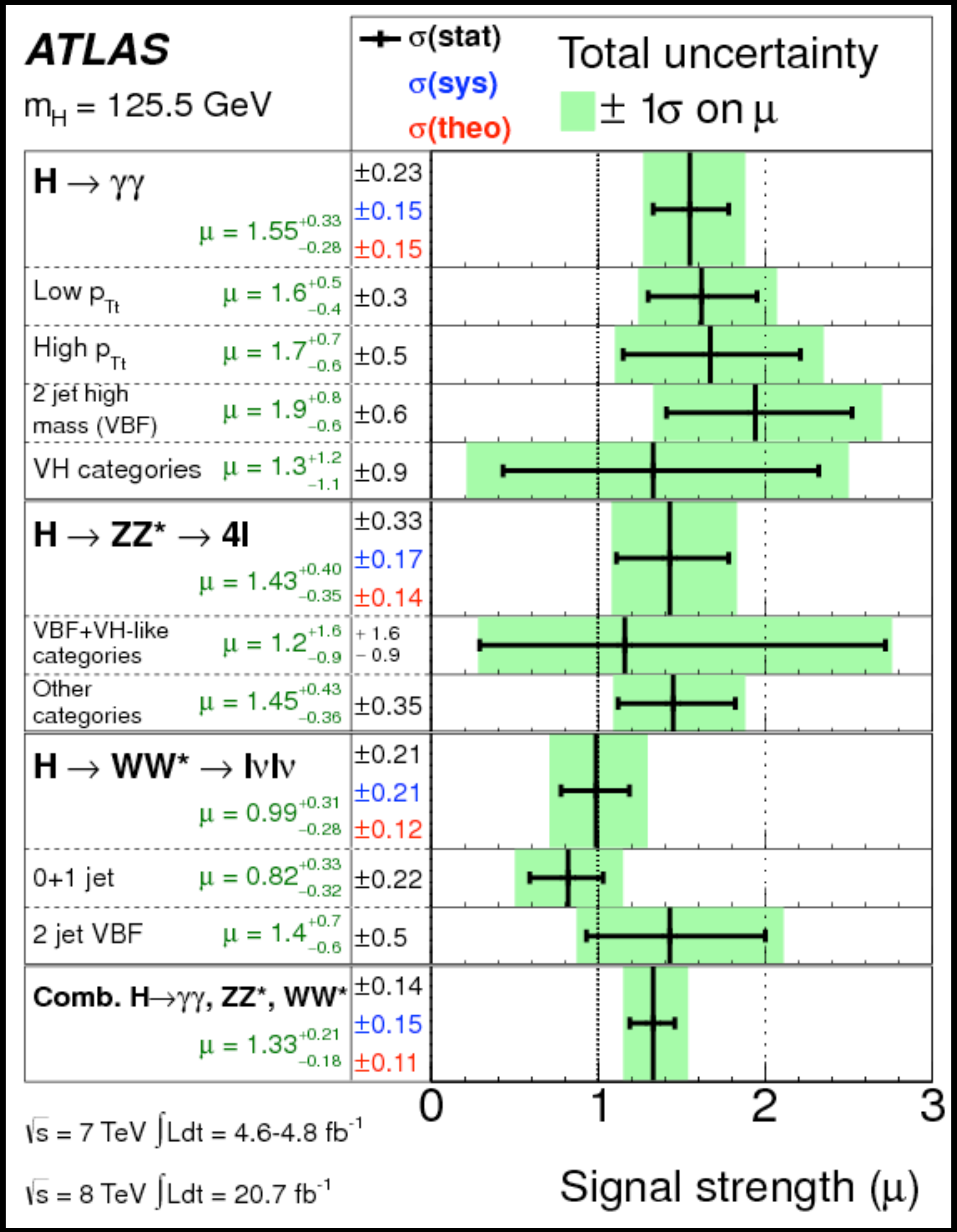
M_H from Higgs branching ratios?

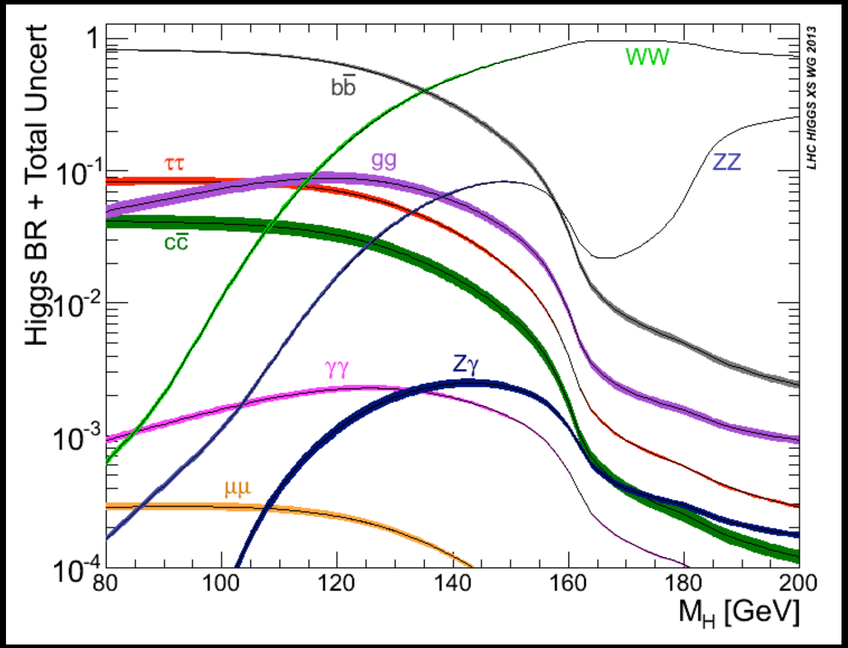


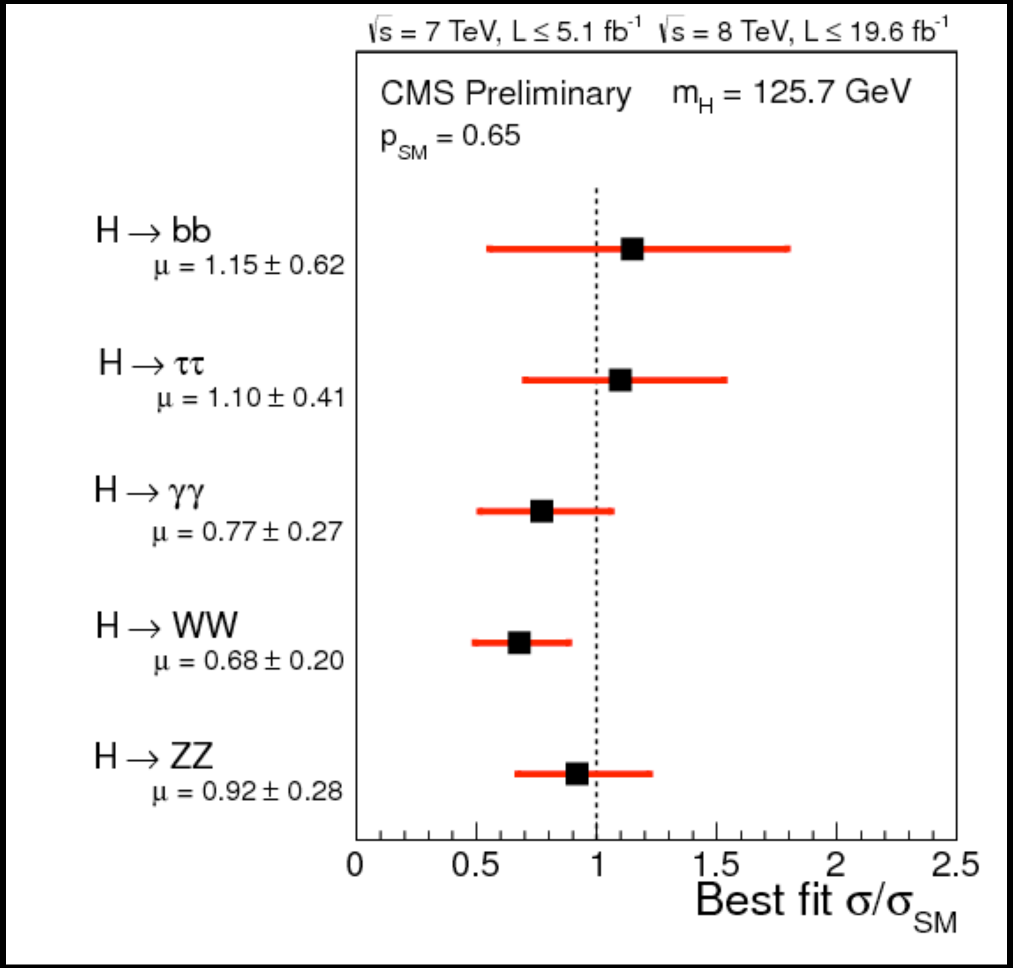
M_H from Higgs branching ratios?



Compare with results on coupling strength



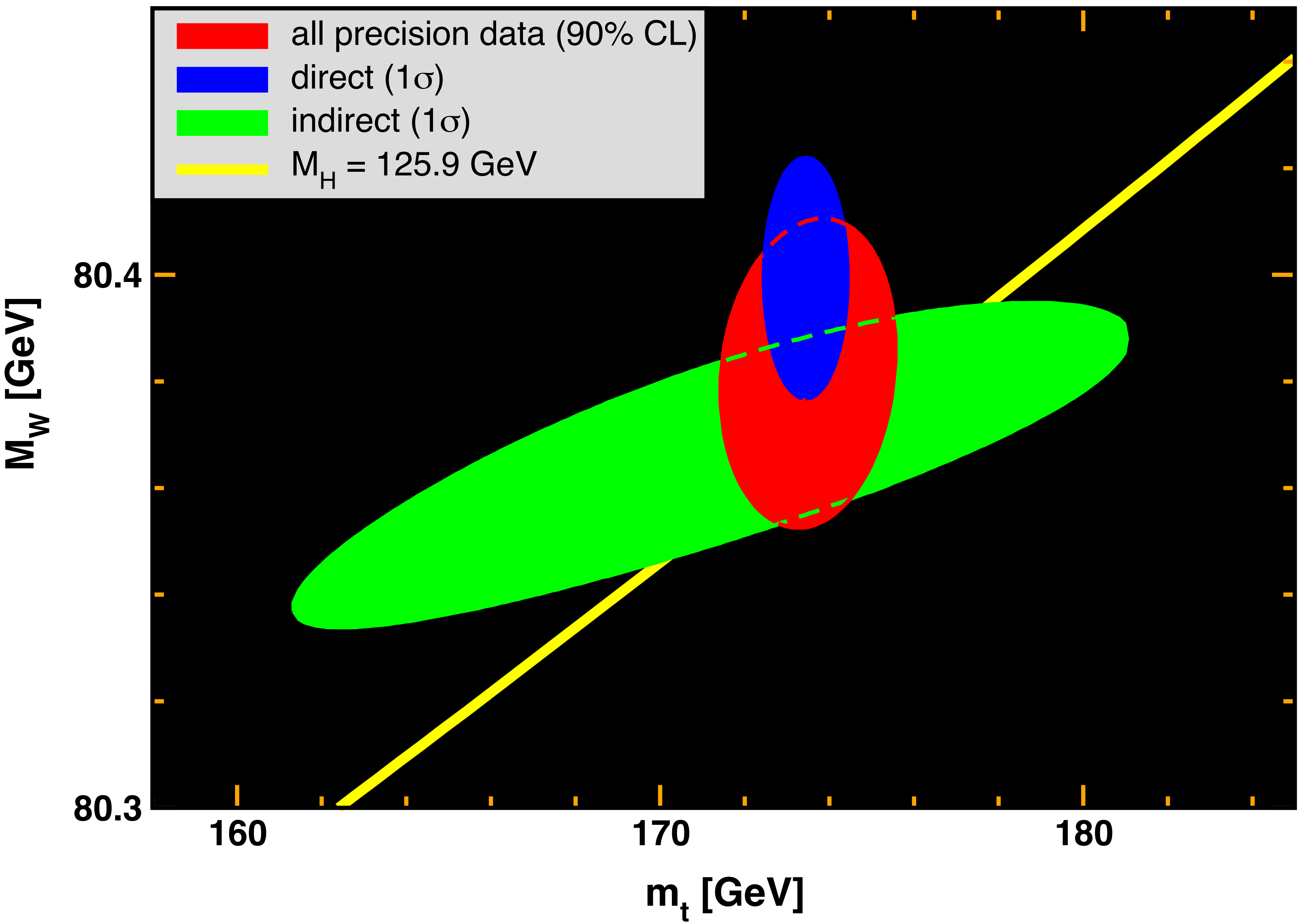




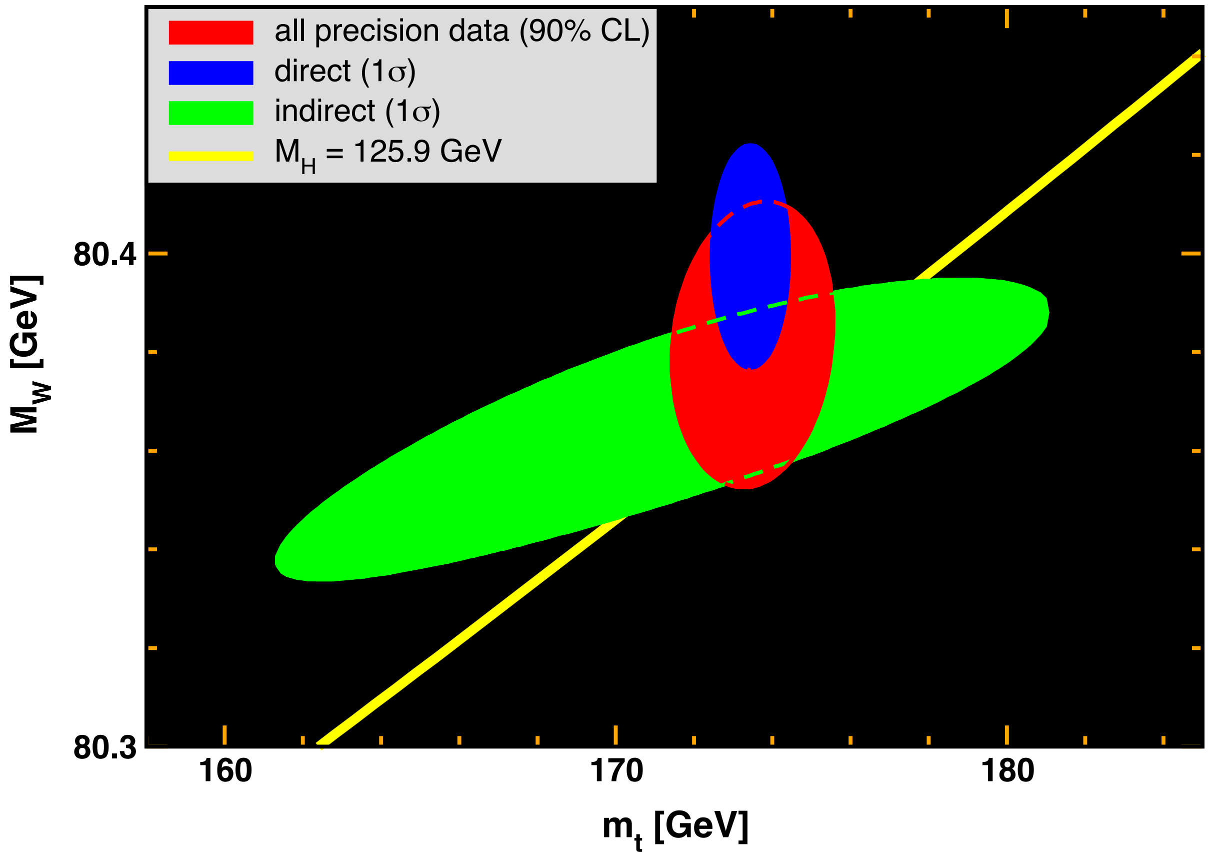
M_H [GeV]

source	M(H)	uncertainty
radiative corrections	89	$^{+22}_{-18}$
LHC Higgs branching ratios	123.7	±2.3
ATLAS & CMS (combination 2015)	125.09	±0.24

JE, Freitas 2013
PDG 2014



all precision data (90% CL)
direct (1σ)
indirect (1σ)
M_H = 125.9 GeV
80.4
80.3
M_W [GeV]
160
170
180
m_t [GeV]


all precision data (90% CL)
direct (1σ)
indirect (1σ)
M_H = 125.9 GeV
80.4
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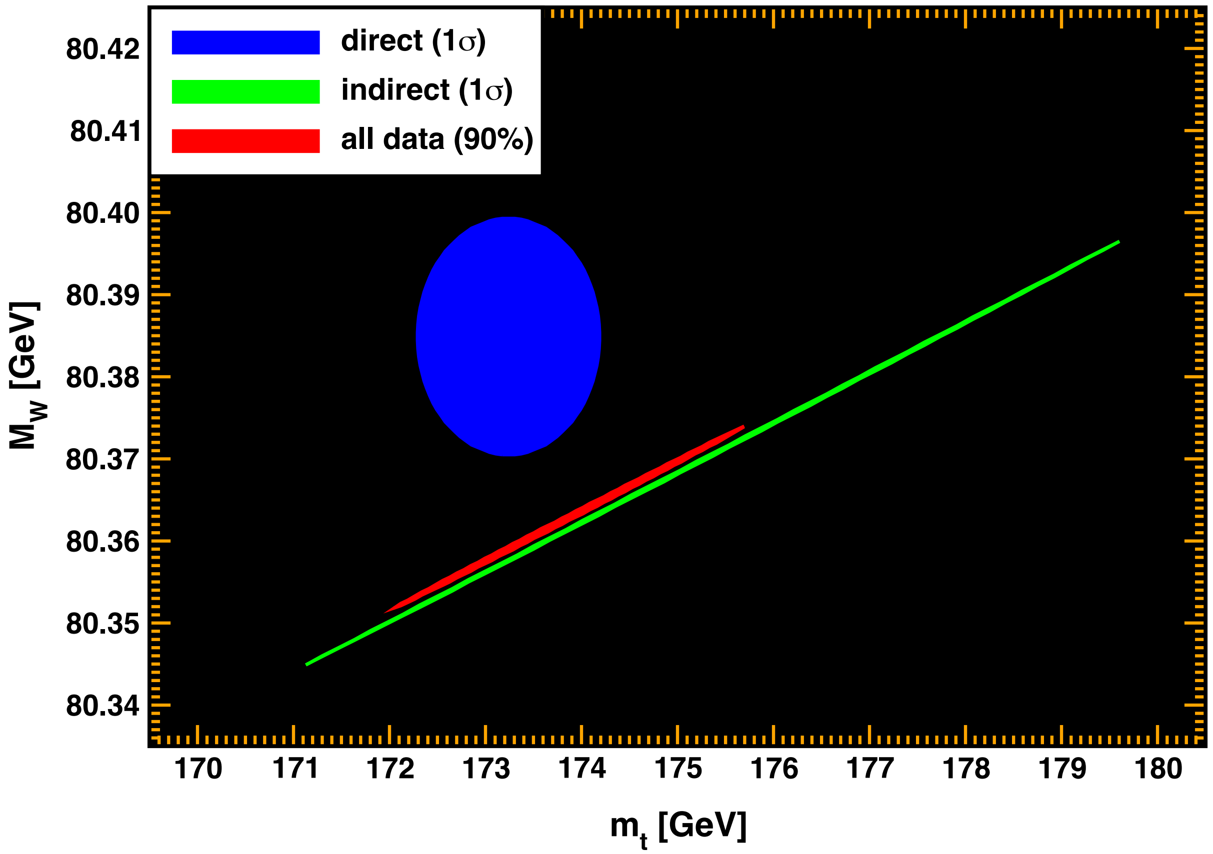
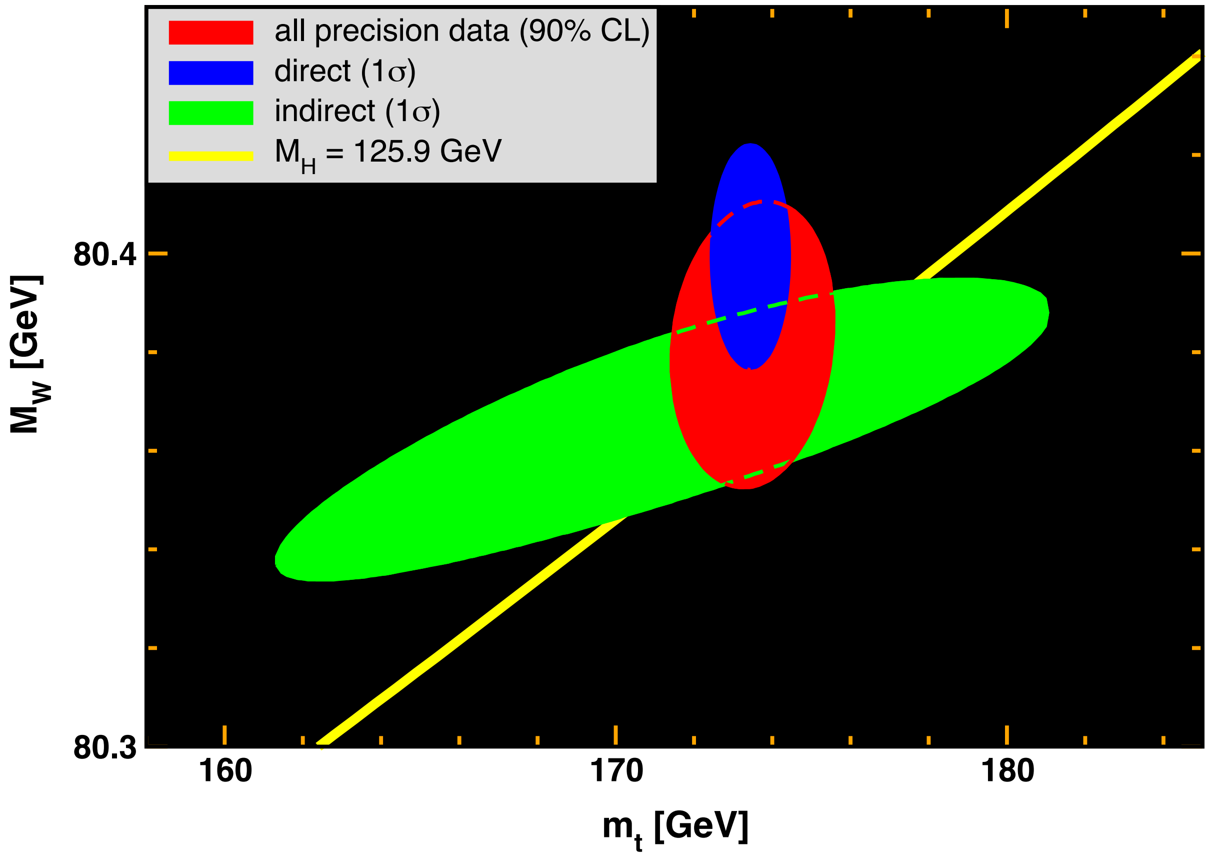
160
170
180
m_t [GeV]
M_W [GeV]


direct (1σ)
indirect (1σ)
all data (90%)
80.42
80.41
80.40
80.39
80.38
80.37
80.36
80.35
80.34
170
171
172
173
174
175
176
177
178
179
180
m_t [GeV]
M_W [GeV]



all precision data (90% CL)
direct (1σ)
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170
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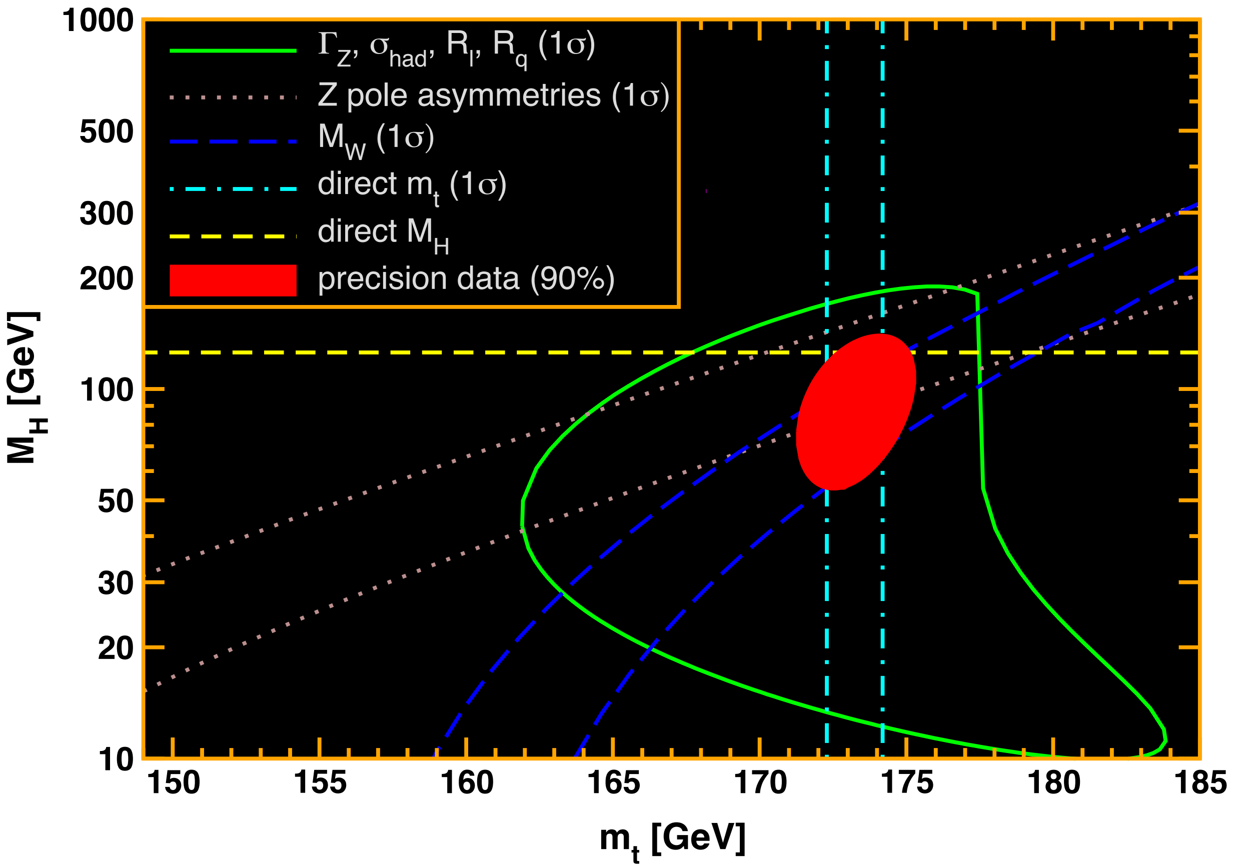
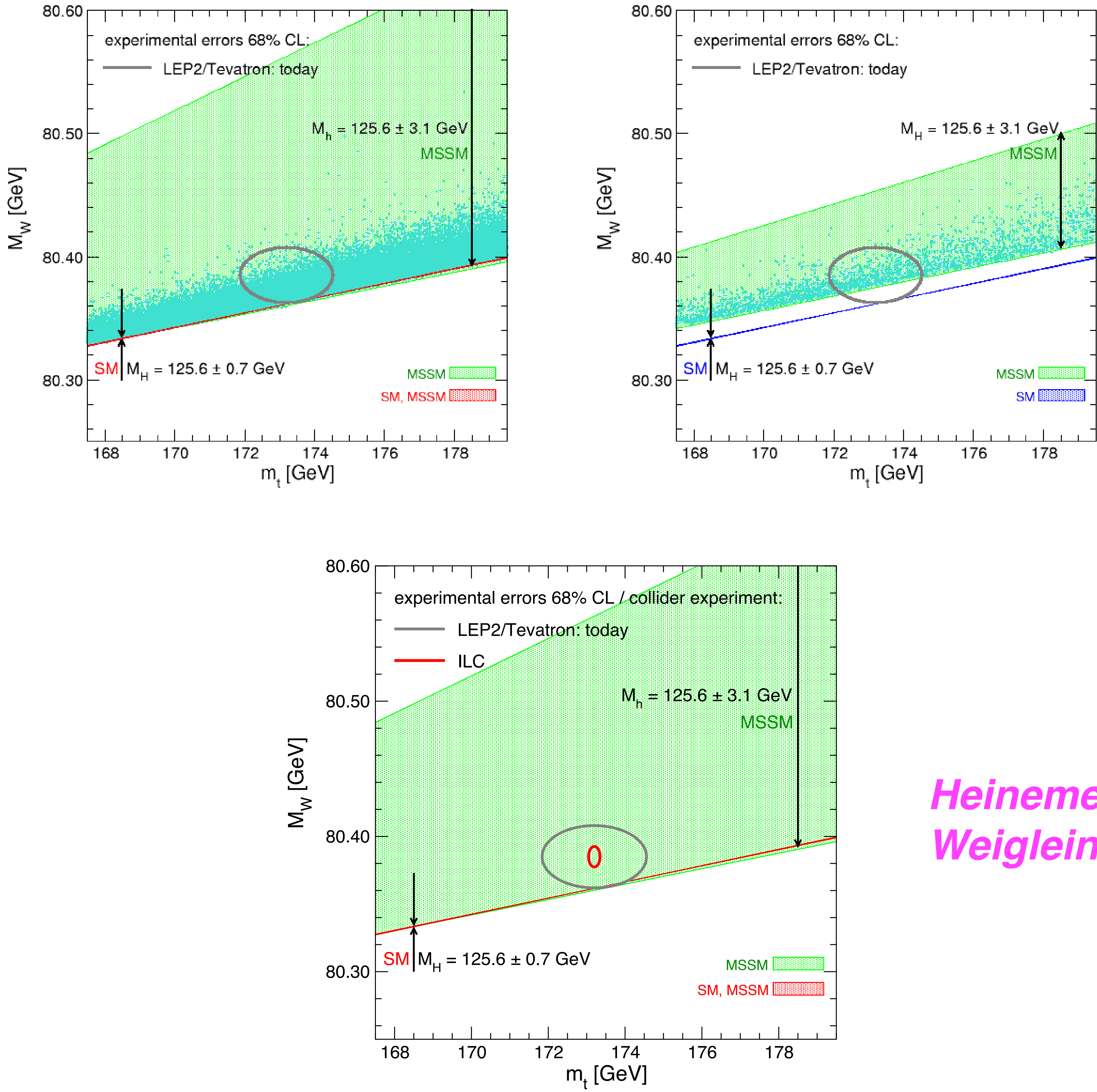


Γ_Z, σ_{had}, R_l, R_q (1σ)
Z pole asymmetries (1σ)
M_W (1σ)
direct m_t (1σ)
direct M_H
precision data (90%)
1000
500
300
200
100
50
30
20
10
M_H [GeV]
150
155
160
165
170
175
180
185
m_t [GeV]



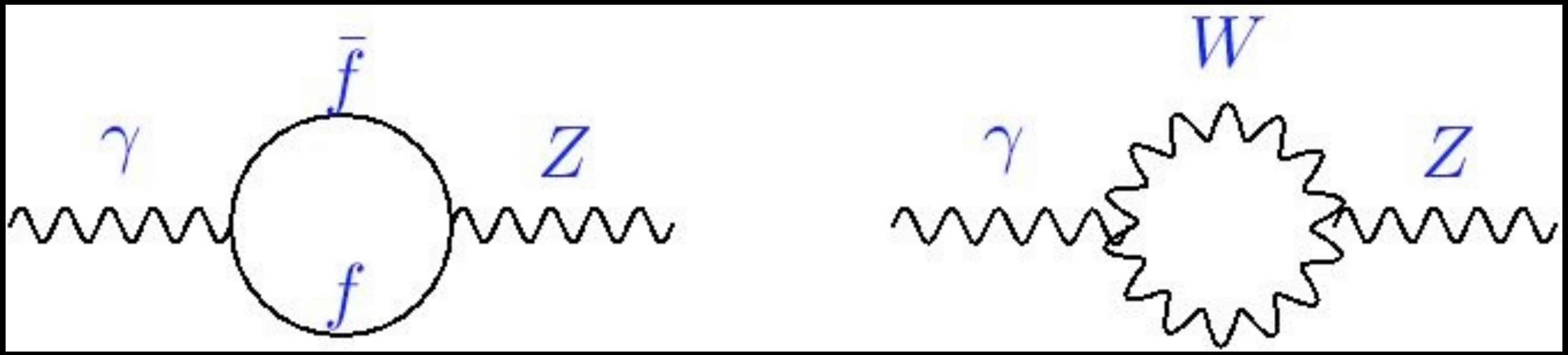
Heinemeyer, Hollik, Weiglein, Zeune 2013

The weak mixing angle

$W^{\pm} = (W^1 \mp i\,W^2)/\sqrt{2}$

$Z^0 = \cos\theta_W\, W^3 - \sin\theta_W\, B$

$A = \sin\theta_W\, W^3 + \cos\theta_W\, B$



$M_W = \frac{1}{2}\, g\, v = \cos\theta_W\, M_Z$

$\sin^2\theta_W = g'^2/(g^2 + g'^2) = 1 - M_W^2/M_Z^2$

Renormalization schemes

Many different schemes and definitions. Most commonly used:

- $\overline{\text{MS}}$-scheme: $\sin^2\overline{\theta}_W(\mu) \equiv \overline{g}'^2 / (\overline{g}^2 + \overline{g}'^2)$ (theorist's definition)
  - ideal for gauge coupling unifcation (analogous to $\overline{\alpha}_s$ in QCD)
- effective weak mixing angle in terms of vector ($g_V \propto 1 - 4\, Q^f \sin^2\theta_W$) and axial-vector couplings g_A (experimentalist's definition)

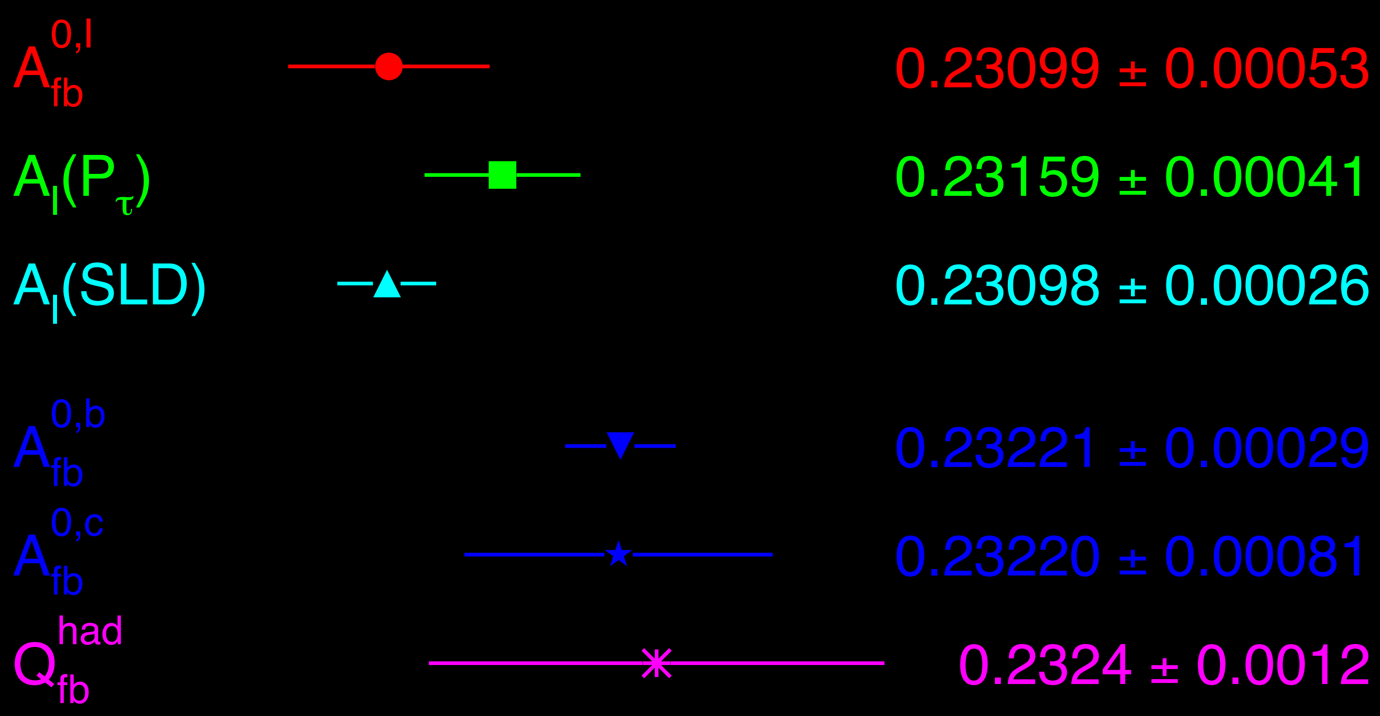
$$A^f \equiv \frac{2 g_V^f g_A^f}{(g_V^f)^2 + (g_A^f)^2} \qquad \sin^2\theta^\ell_{\text{eff}} \equiv \frac{1}{4}\left[1 - \frac{g_V^\ell}{g_A^\ell}\right] = \sin^2\hat{\theta}_W(M_Z) + 0.00029$$

  - numerically close to $\sin^2\overline{\theta}_W(M_Z)$
- on-shell definition: $\sin^2\theta_W \equiv 1 - M_W^2 / M_Z^2$
  - induces spurious m_t^2-dependence (enhances higher order contributions)

Asymmetries

- Z-pole: $\chi \sim M_Z/\Gamma_Z \gg 1 \Longrightarrow$ [with $A_f = 2\, v_e\, a_e\, /\, (v_e^2 + a_e^2)$]
  - $A_e\, A_\mu$ (A_{FB}) *LEP*
  - A_τ (final state A_{pol}) *LEP*
  - A_e (A_{LR}) *SLD*
  - A_μ (A_{FB}^{LR}) *SLD*
- PVES / $e^+\, e^-$ annihilation: $\chi \sim Q^2\, G_F \ll 1 \Longrightarrow$
  - $a_e\, v_f$ (A_{LR} in forward direction) *SLAC-E122 & E158, Qweak, MOLLER, P2*
  - $v_e\, a_q$ (A_{LR} at larger scattering angles) *PVDIS, SoLID*
  - $a_e\, a_\mu$ (A_{FB}) *Belle II* (independent of $\sin^2\theta_W$)

Z-pole asymmetries

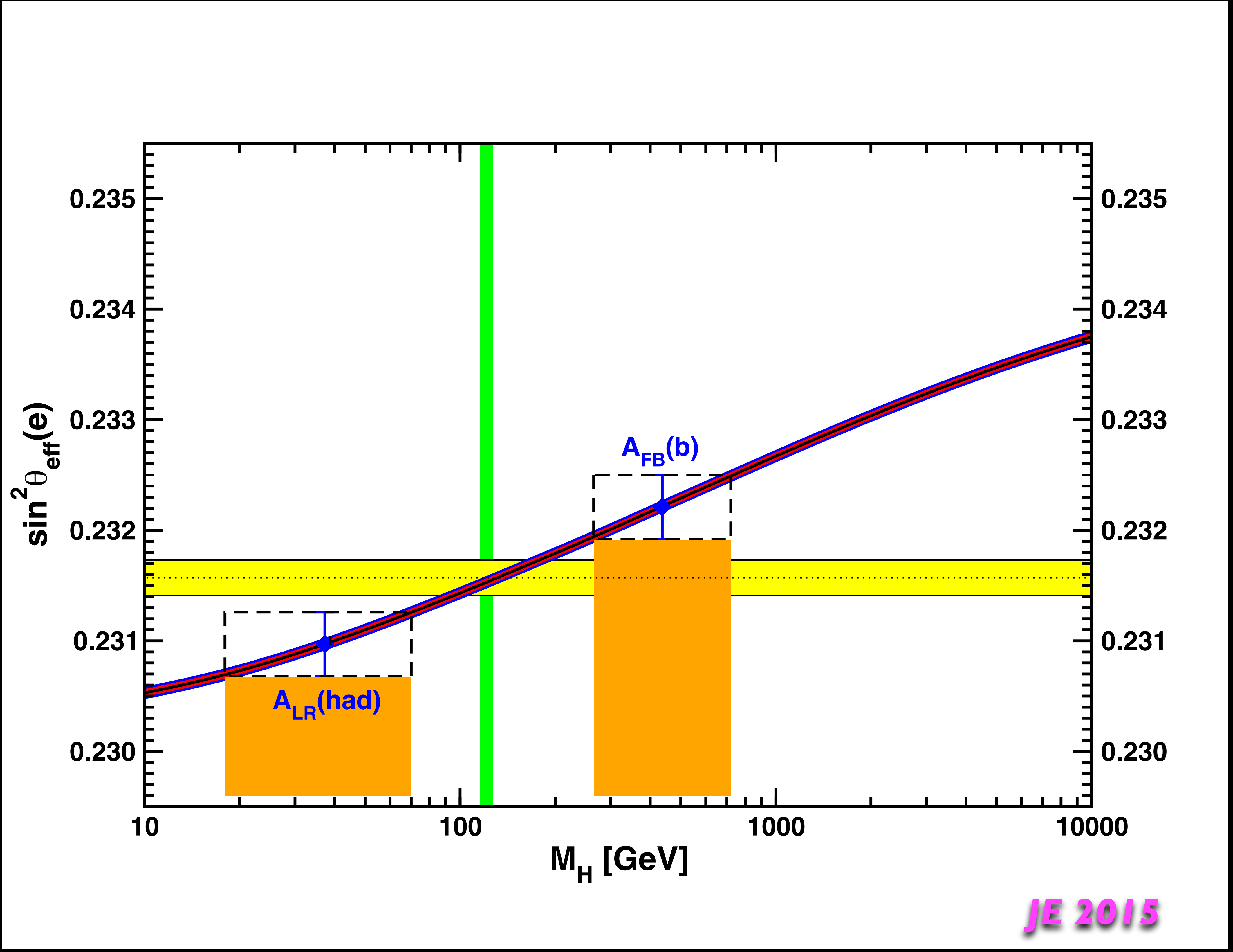


LEP/SLC Average: 0.23153 ± 0.00016 χ^2/d.o.f. = 16.8/12

CDF: 0.2315 ± 0.0010
DO: 0.23146 ± 0.00047
ATLAS: 0.2308 ± 0.0012

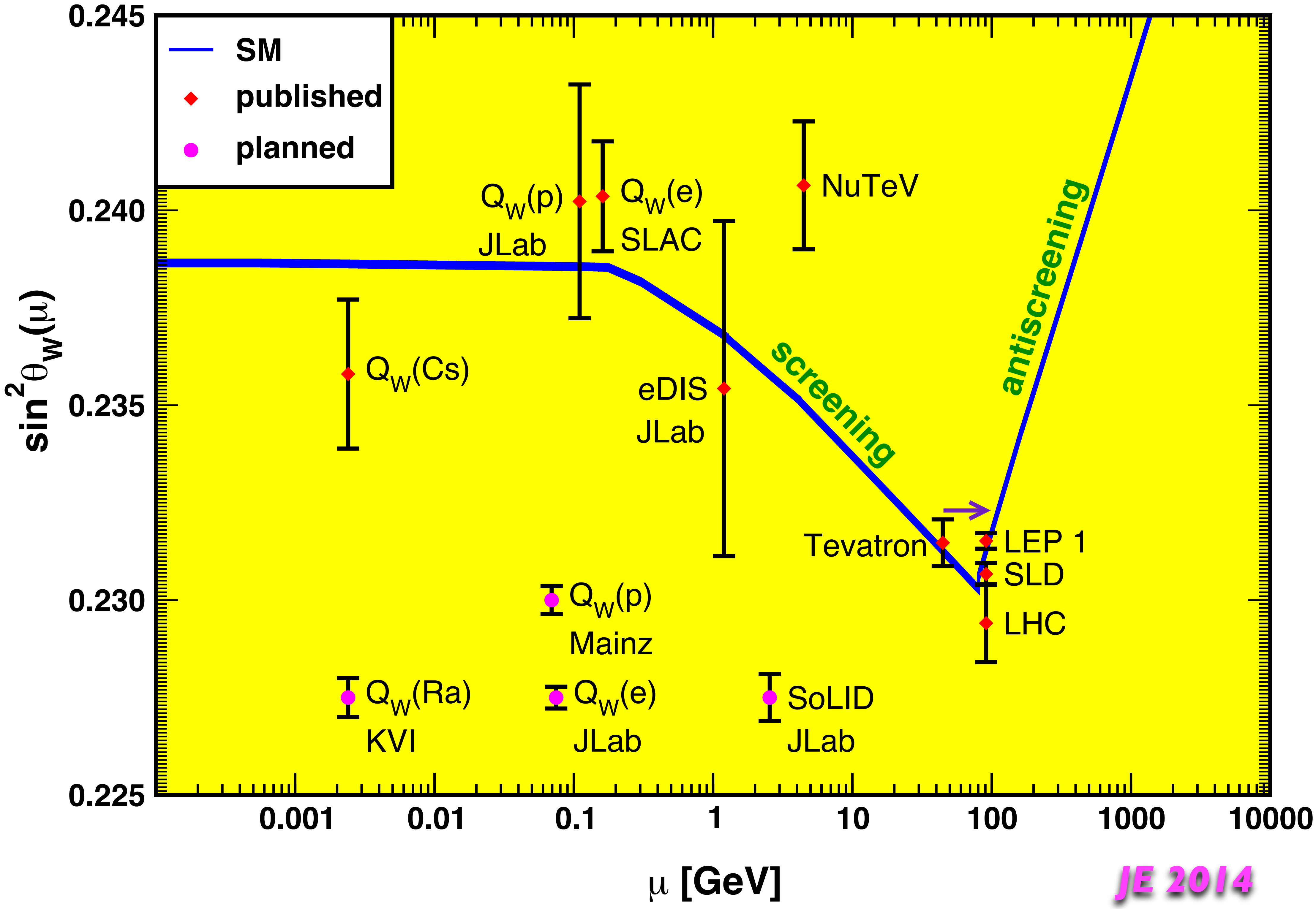
Grand Average: 0.23151 ± 0.00015

Standard Model: 0.23155 ± 0.00005

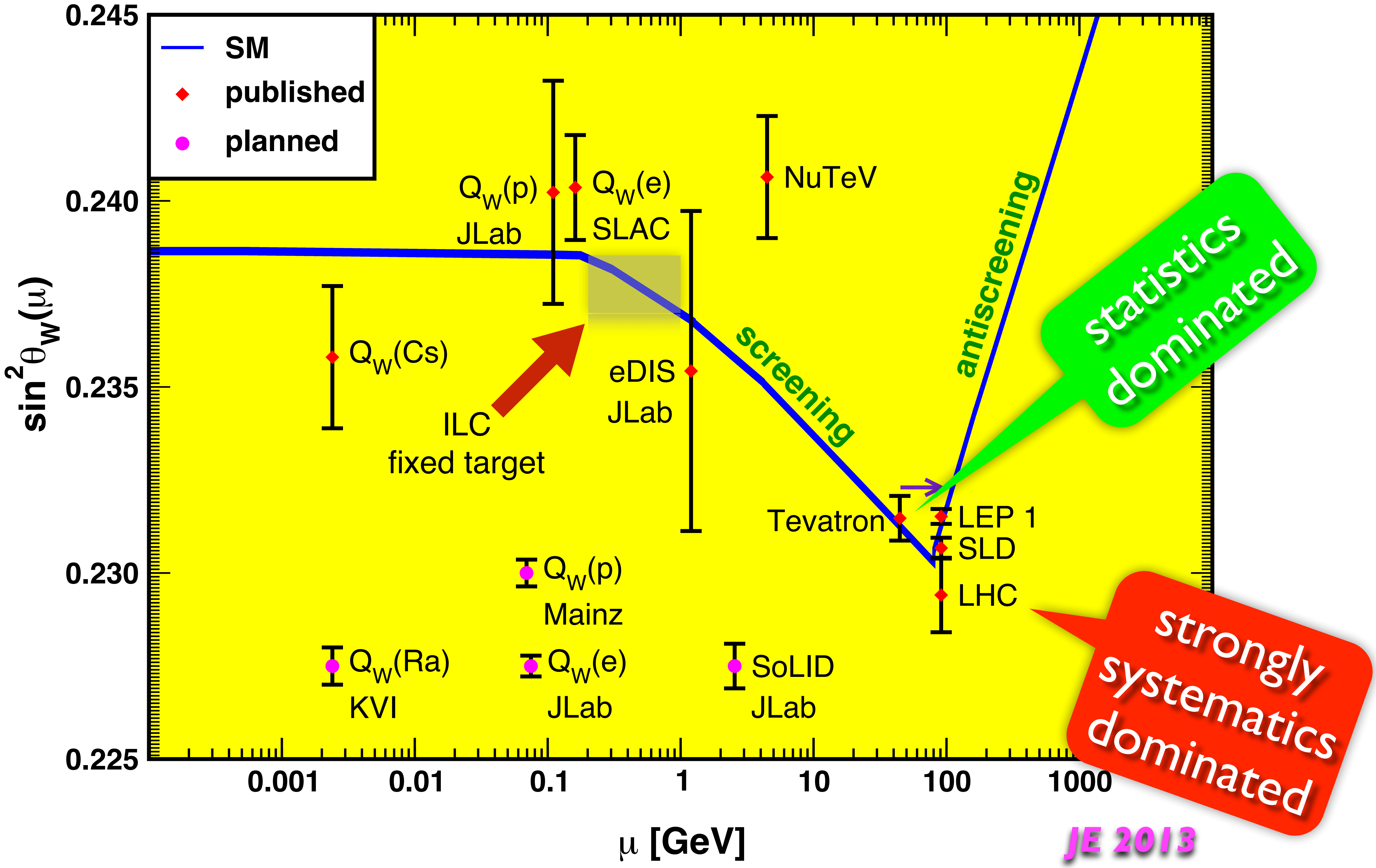


0.235
0.234
0.233
0.232
0.231
0.230
$\sin^2\theta_{eff}(e)$
$A_{FB}(b)$
$A_{LR}(had)$
10
100
1000
10000
M_H [GeV]
JE 2015

$\overline{\text{MS}}$-scheme



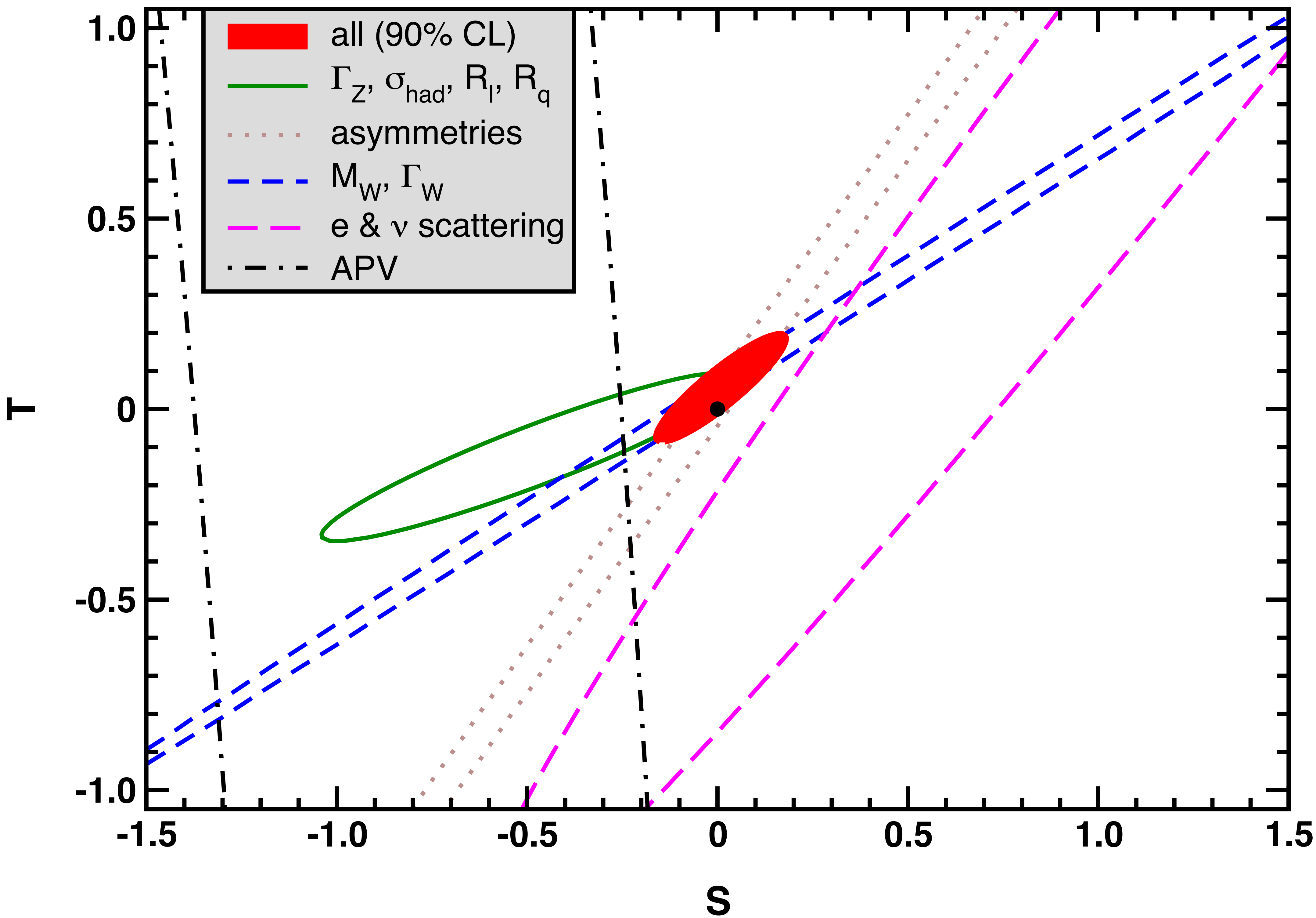
$\overline{\text{MS}}$-scheme

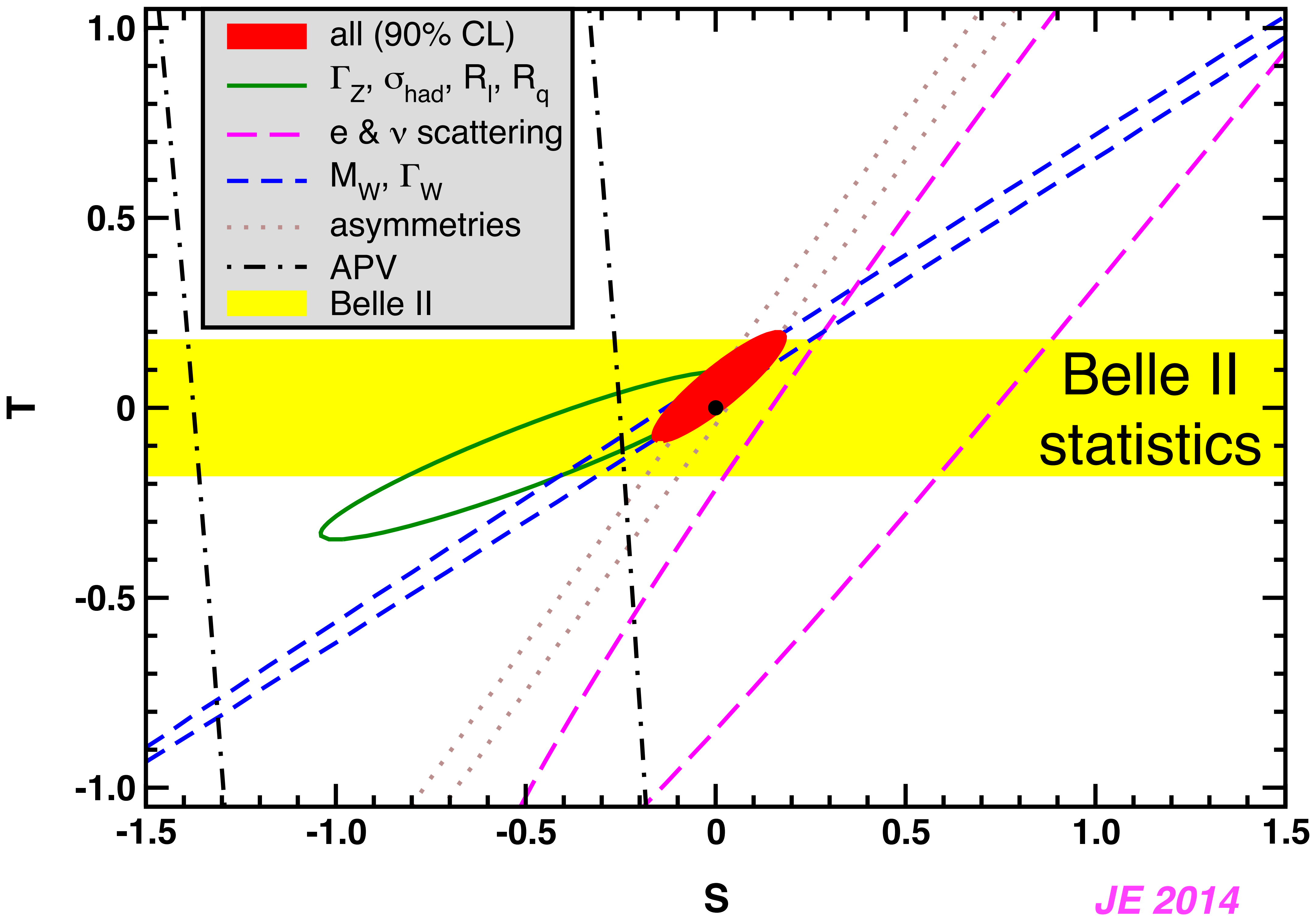


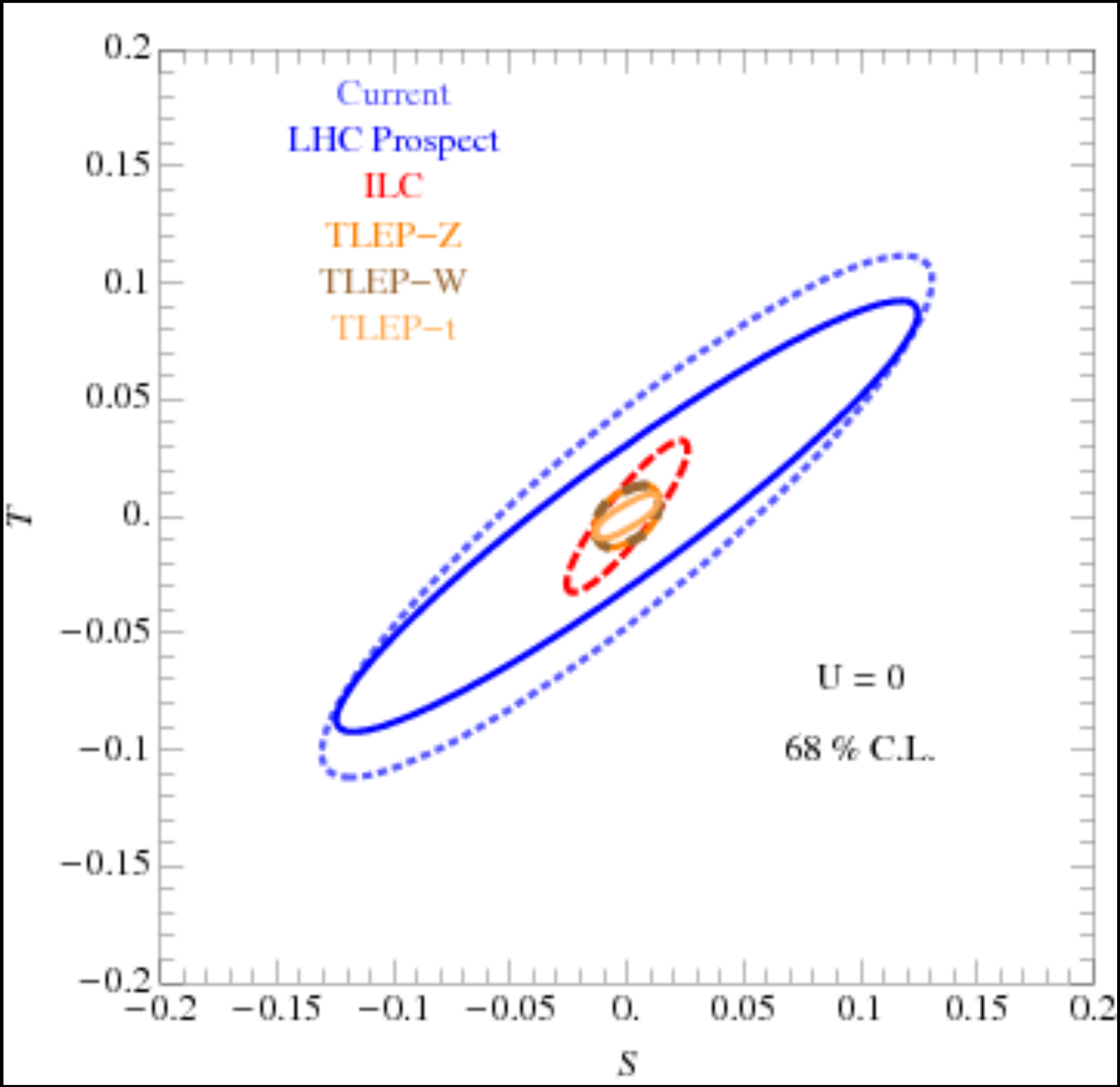
Oblique parameters (STU)

Oblique physics beyond the SM

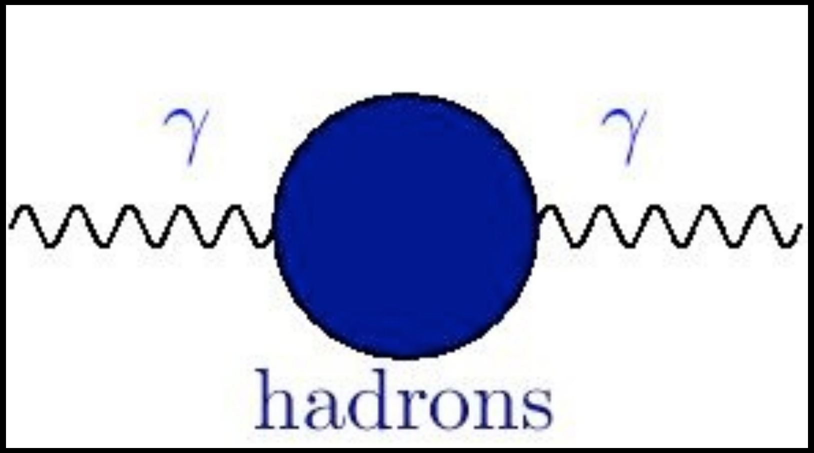
- STU describe corrections to gauge-boson self-energies
- T breaks custodial SO(4)
- a non-degenerate $SU(2)_L$ doublet contributes
  $\Delta T \approx \Delta m^2/(264\ \mathrm{GeV})^2$
- Currently: $\sum_i C_i/3\ \Delta m_i^2 \leq (50\ \mathrm{GeV})^2$
- a multiplet of heavy degenerate chiral fermions contributes
  $\Delta S = N_C/3\pi \sum_i [t_{3L}{}^i - t_{3R}{}^i]^2$
- extra degenerate fermion family yields $\Delta S = 2/3\pi \approx 0.21$
- S and T (U) correspond to dimension 6 (8) operators

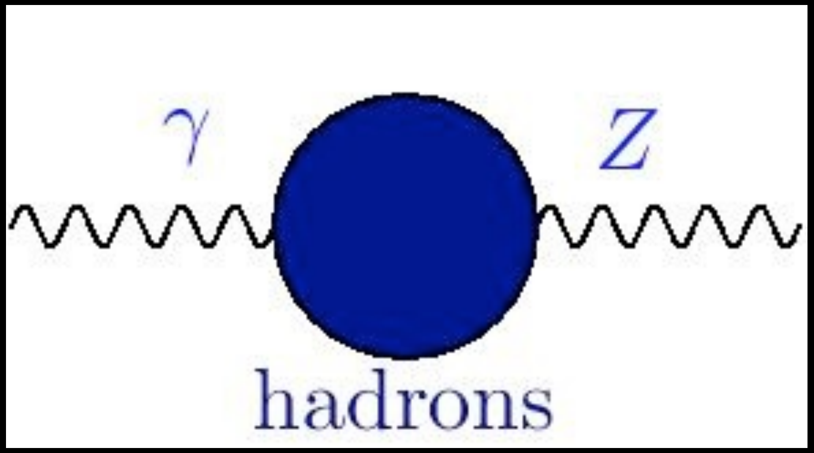

all (90% CL)
Γ_Z, σ_{had}, R_l, R_q
asymmetries
M_W, Γ_W
e & ν scattering
APV
T
S
1.0
0.5
0
-0.5
-1.0
-1.5
-1.0
-0.5
0
0.5
1.0
1.5


all (90% CL)
Γ_Z, σ_had, R_l, R_q
e & ν scattering
M_W, Γ_W
asymmetries
APV
Belle II
Belle II statistics
T
S
1.0
0.5
0
-0.5
-1.0
-1.5
-1.0
-0.5
0
0.5
1.0
1.5
JE 2014

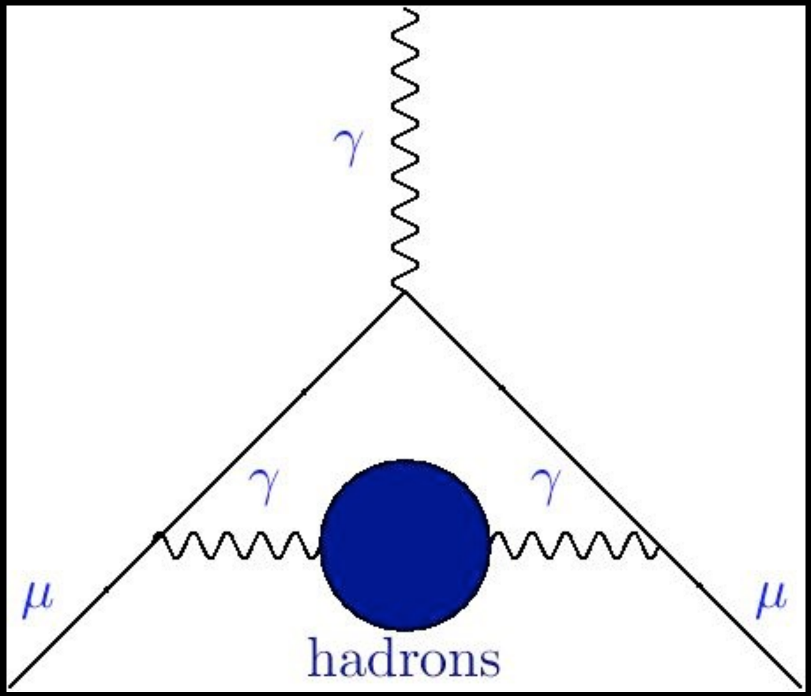


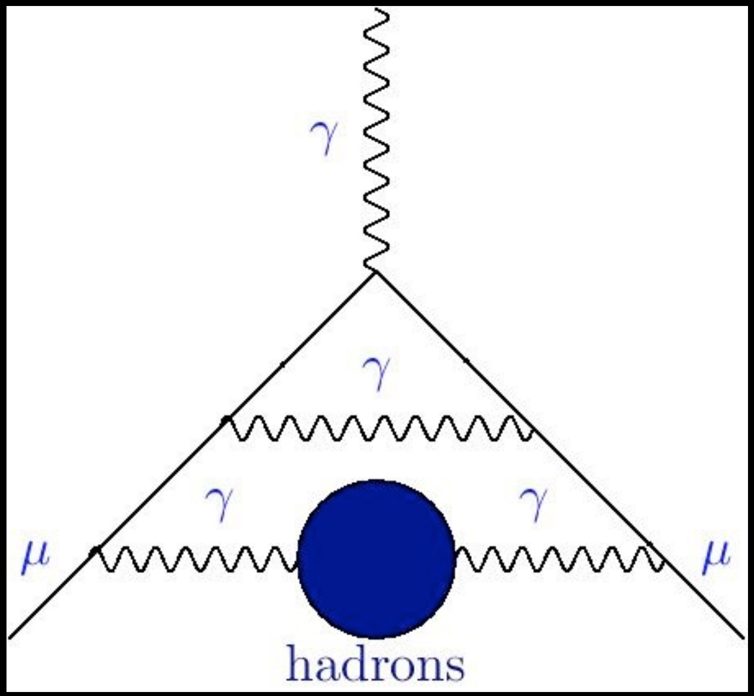
Fan, Reece, Wang 2014

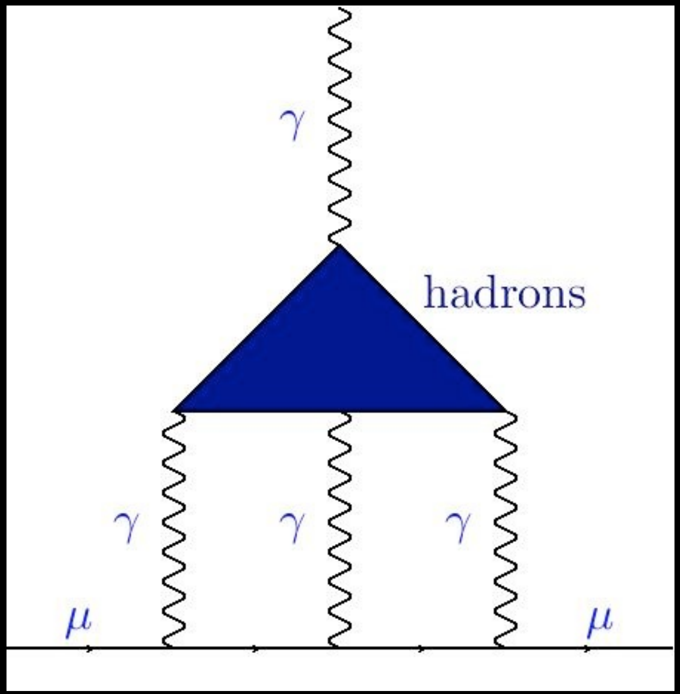




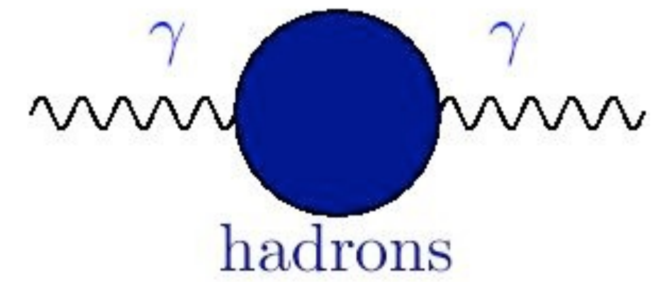
Low energy precision tests





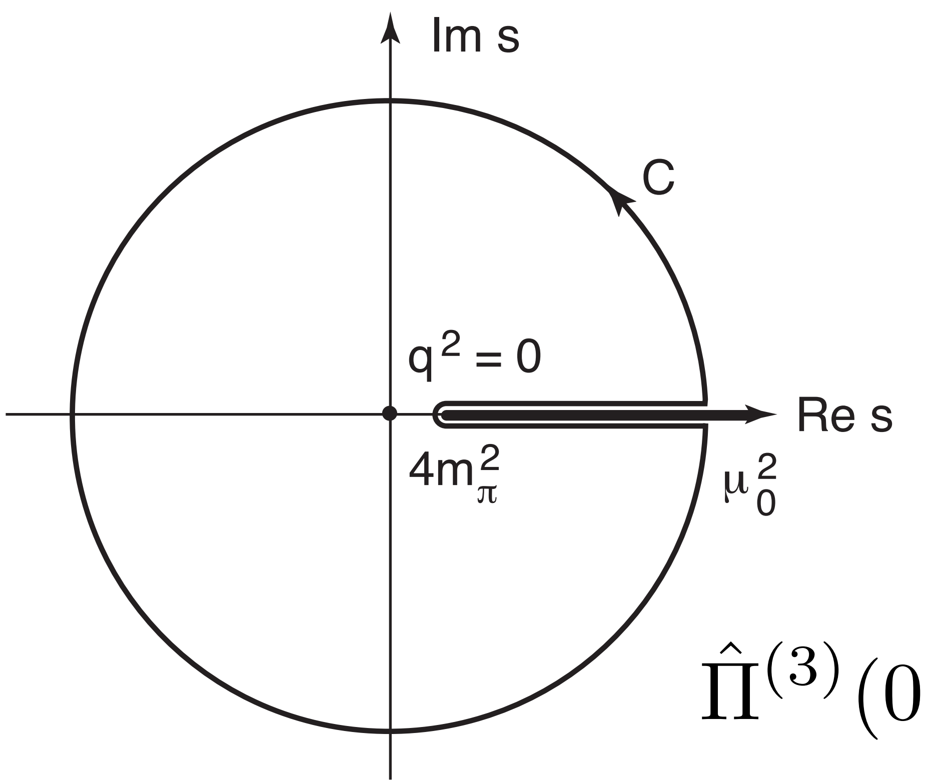


Δα



$$\hat{\Pi}^{(h)}(0) = \frac{Q_h^2}{4\pi^2}\left\{L + \frac{\hat{\alpha}_s}{\pi}\left[\frac{13}{12} - L\right] + \frac{\hat{\alpha}_s^2}{\pi^2}\left[\frac{655}{144}\zeta(3) - \frac{3847}{864} - \frac{5}{6}L - \frac{11}{8}L^2 + n_q\left(\frac{361}{1296} - \frac{L}{18} + \frac{L^2}{12}\right)\right]\right\},$$

JE 1998

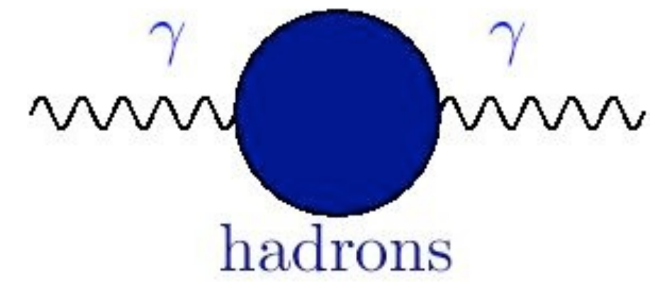


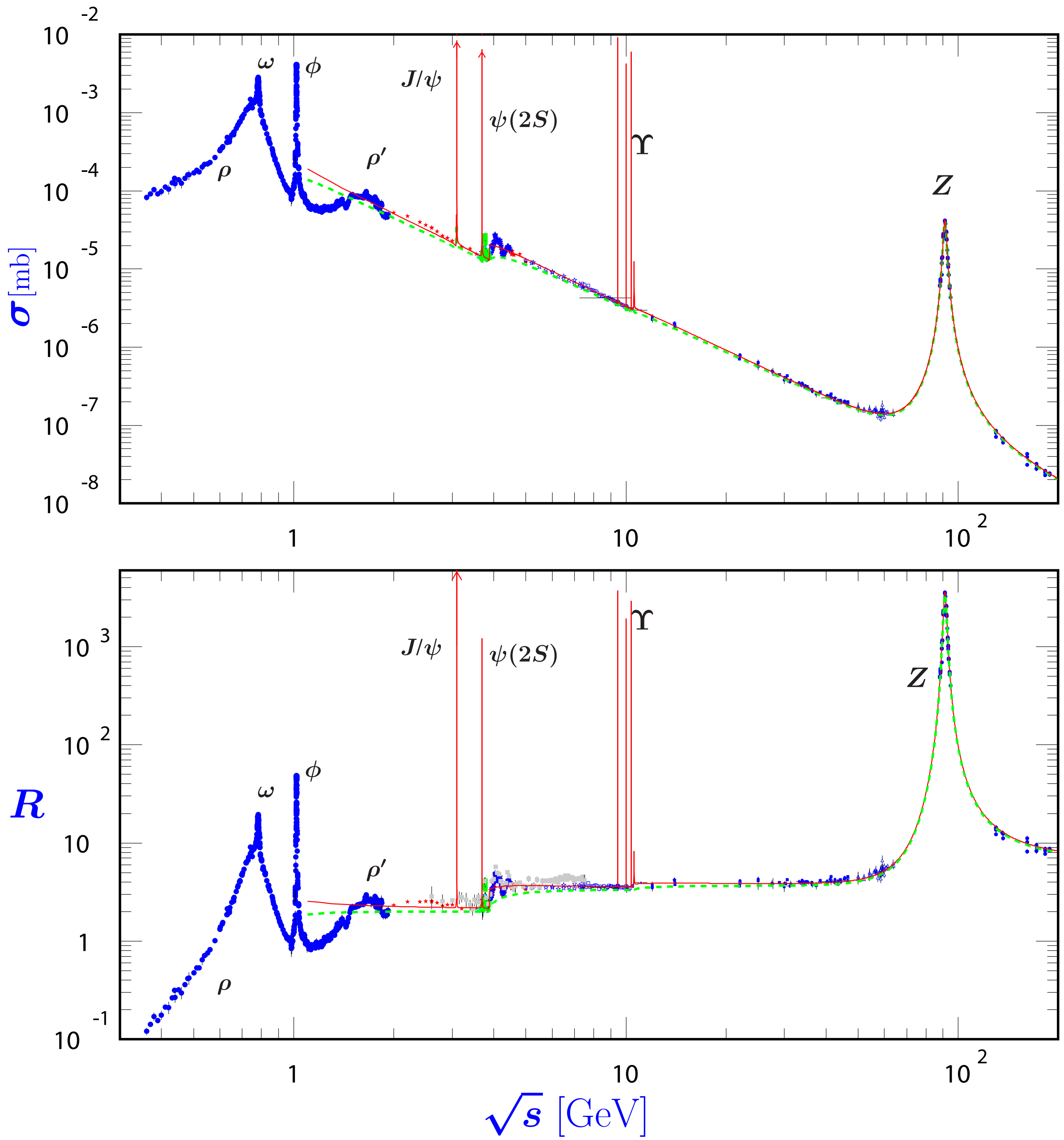
matching

RGE

$$\hat{\Pi}^{(3)}(0) = \frac{1}{12\pi^2}\int_{4m_\pi^2}^{\mu_0^2}\frac{ds}{s - i\epsilon}R(s) + \frac{1}{2\pi}\int_0^{2\pi} d\theta\, \hat{\Pi}^{(3)}(\theta).$$

R(s)





$$R(s) = 12\pi \, \mathrm{Im}\, \hat{\Pi}^{(\mathrm{had})}(s)$$

$$= \frac{\sigma_{\mathrm{hadrons}}}{\sigma_{\mu^+\mu^-}}$$

PDG 2012

Δα and μ anomalous magnetic moment (a_μ)

$\hat{\alpha}(\mu) = \frac{\alpha}{1-4\pi\alpha\hat{\Pi}(0)}$ ($\overline{\text{MS}}$)

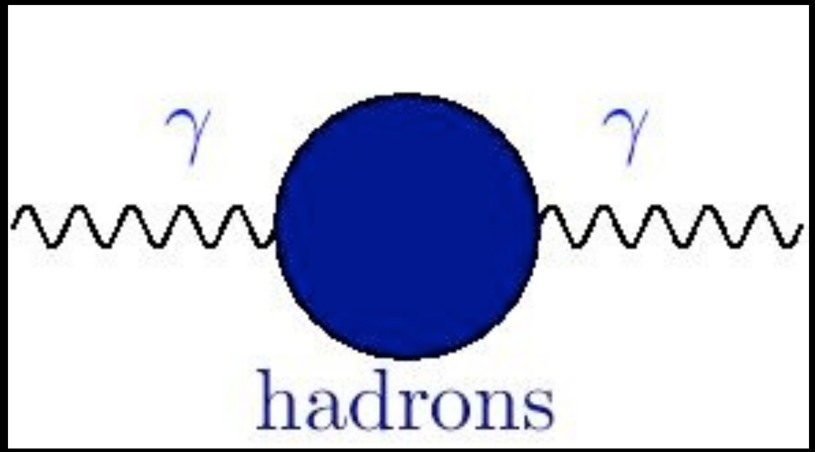
$\alpha(s) = \frac{\alpha}{1-\Delta\alpha_{\text{lep}}(s)-\Delta\alpha_{\text{had}}(s)}$ (on-shell)

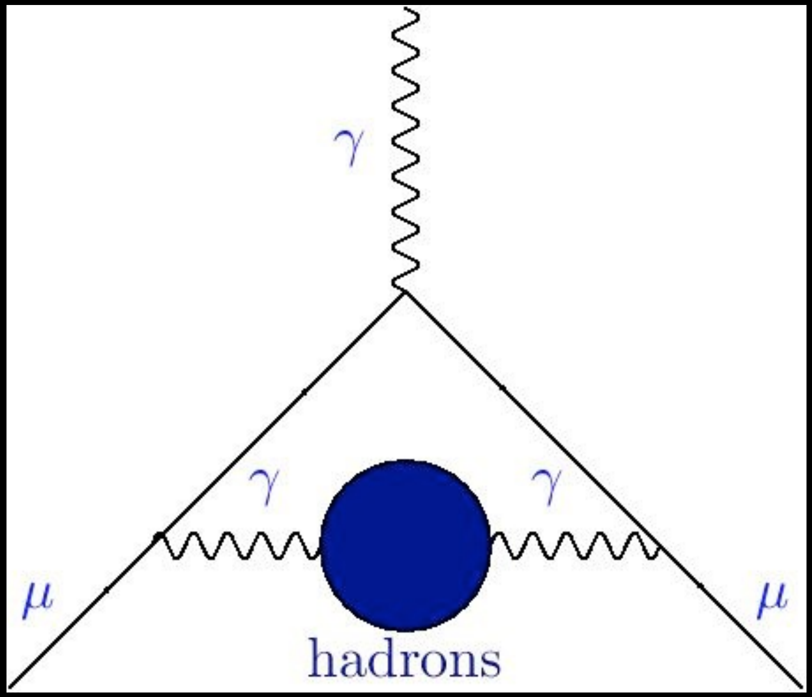
$\Delta\alpha_{\text{had}}(s) = -\frac{\alpha}{3\pi}\text{Re}\int_{4m_\pi^2}^{\infty} ds' \frac{sR(s')}{s'(s'-s-i\epsilon)}$

$a_\mu \equiv \frac{g_\mu - 2}{2}$

$a_\mu^{\text{had,2-loop}} = \frac{\alpha^2}{3\pi^2}\int_{4m_\pi^2}^{\infty} ds\, \frac{K(s)}{s} R(s)$

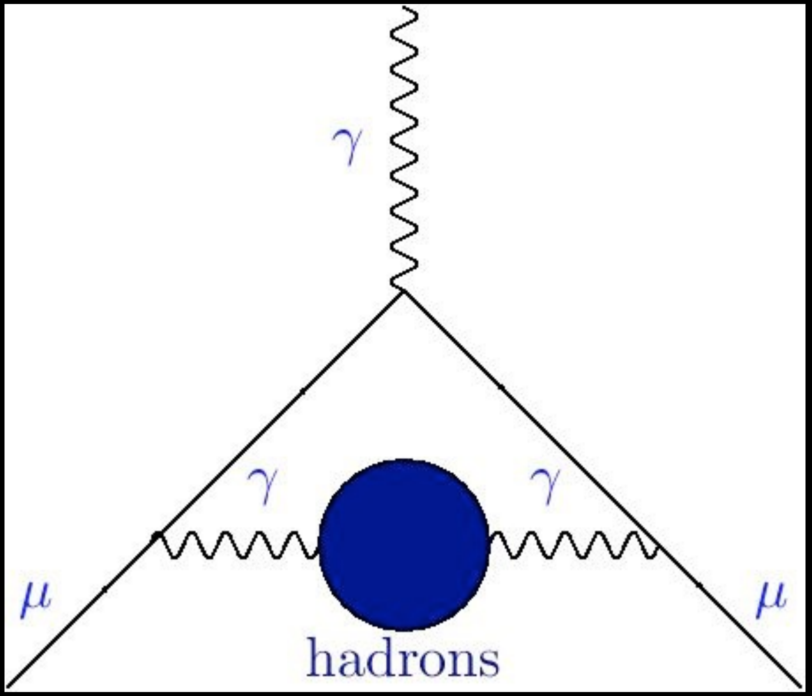
$K(s)$: known kernel function



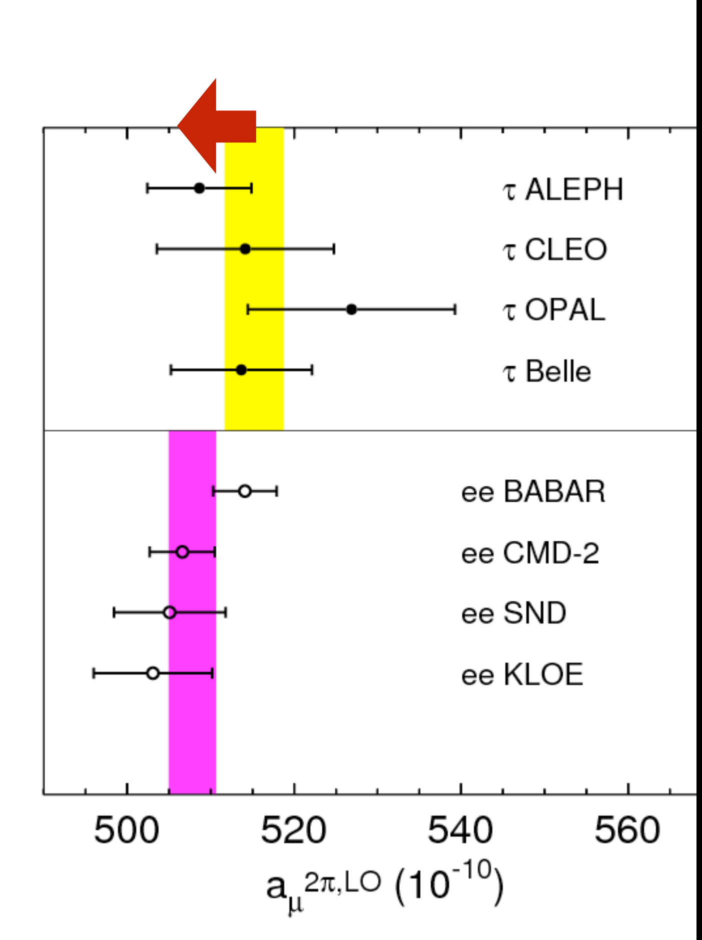


$g_\mu - 2$

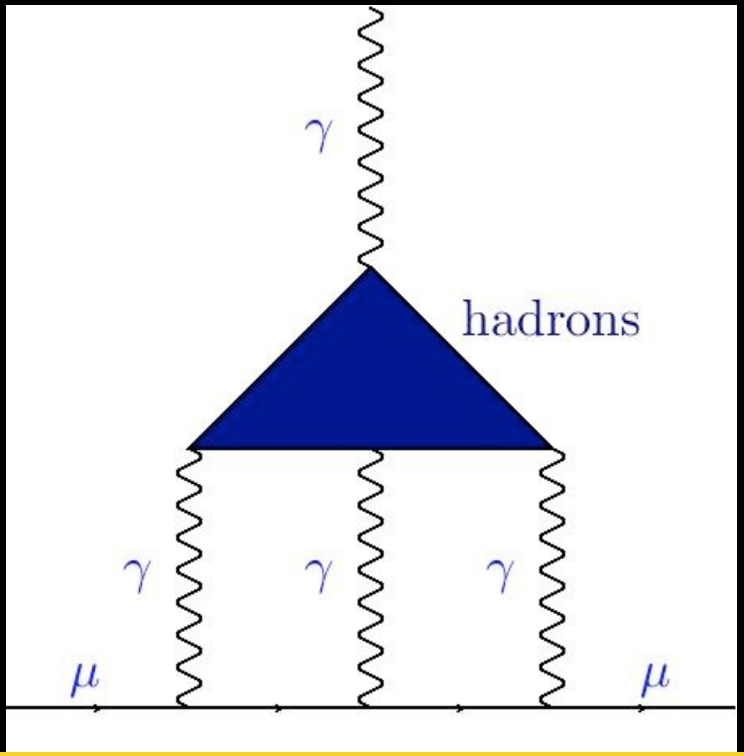
- $a_\mu \equiv (1165920.80 \pm 0.63)\times 10^{-9}$ ***BNL-E821 2004***
- goal of *FNAL-E989 (New g−2 Collaboration)*: $\pm\, 0.16 \times 10^{-9}$
- SM: $a_\mu = (1165918.21 \pm 0.48)\times 10^{-9}$
- 3.3 σ deviation (includes e^+e^- & τ-decay data)
- 2 and 3-loop hadronic vacuum polarization:
  - consistency between exp. $B(\tau^- \to \nu\, \pi^0 \pi^-)$ and prediction from e^+e^- and CVC after accounting for γ-ρ mixing ***Jegerlehner, Szafron 2011***
  - 1.9 σ conflict between *KLOE* and *BaBar*



Davier et al. 2011



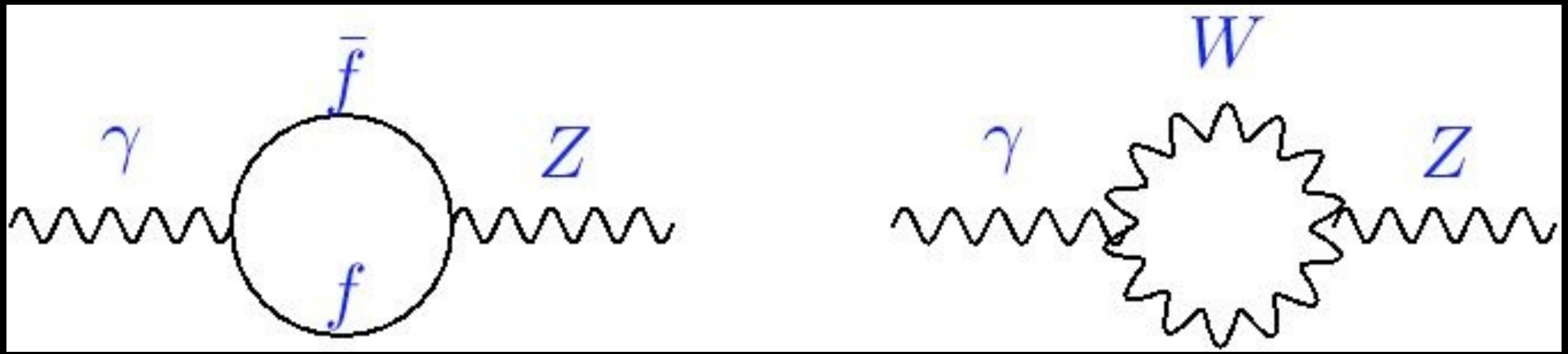
$g_\mu-2$: other contributions



talk by Adolfo Guevara

- 4-loop and leading 5-loop QED corrections
  Aoyama, Hayakawa, Kinoshita, Nio 2012
- electroweak corrections: 1-loop (W, Z, H)
  Czarnecki, Krause, Marciano 1995
  - 2-loop, leading 3-loop ***Degrassi, Giudice 1998; Czarnecki, Krause, Marciano 1996; Czarnecki, Marciano, Vainshtein 1996***
- $\gamma\times\gamma$: $(1.1 \pm 0.3)\times10^{-9}$ ***Prades, de Rafael, Vainshtein 2009***
  - $< 1.6\times10^{-9}$ ***JE, Toledo 2006***
- SUSY? $M_{SUSY} \simeq + 71^{+14}_{-9}$ GeV $\sqrt{\tan\beta}$ ***Arnowitt, Chamsedine, Nath 1984***
- dark photon? ***Fayet 2004; Finkbeiner, Weiner 2007; Arkani-Hamed, Finkbeiner, Slatyer, Weiner 2008***
- dark Z? ***Davoudiasl, Lee, Marciano 2012***

Running $\sin^2\overline{\theta}_W$



- Define in $\overline{\mathrm{MS}}$-scheme: $\sin^2\overline{\theta}_W(\mu) \equiv \overline{g}'^2(\mu)/[\overline{g}^2(\mu) + \overline{g}'^2(\mu)]$
- RGE for $\bar{\alpha}$: $\mu^2\, d\bar{\alpha}/d\mu^2 \equiv \bar{\alpha}/24\pi \sum_k N_C^k\, \gamma^k\, (Q^k)^2$
- RGE for $\overline{v}_i$: $\overline{X} \equiv \sum_i N_C^i\, \gamma^i\, \overline{v}^i\, Q^i \Longrightarrow d\overline{X}/\overline{X} = d\bar{\alpha}/\alpha$
- running of $\bar{\alpha}$ (e^+e^- and/or τ data) $\Rightarrow$ running of $\sin^2\overline{\theta}_W$ if

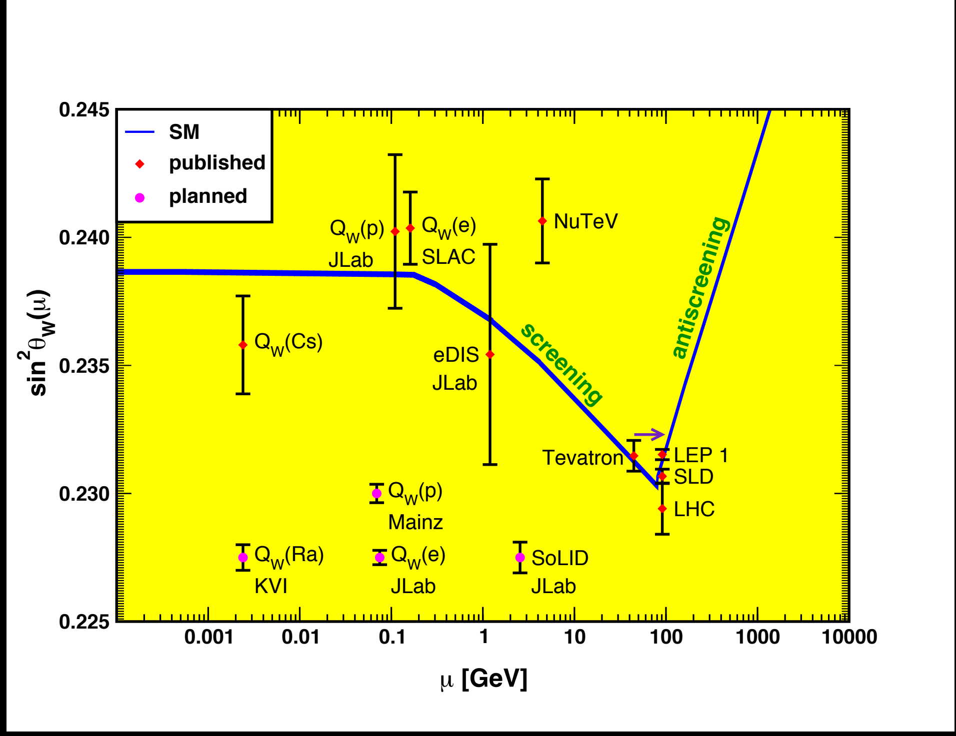
    either no mass threshold is crossed

    or perturbation theory applies ($W^\pm$, leptons, b & c quarks)

    or all coefficient are equal (RGE factorizes) like for (d,s)

    or there is a symmetry like $SU(3)_F$

Flavor separation and threshold mass trick



only problem area: u vs. (d,s) or s vs. (u,d) ($m_s \neq m_d \approx m_u$)

strategy: define threshold masses, $\bar{m}_q = \frac{1}{2}\, \xi_q\, M_{1S}$ ($0 \leq \xi_q \leq 1$)

expect: $\xi_b > \xi_c > \xi_s > \xi_d > \xi_u$

compute $\bar{m}_b$ = 3.995 GeV and $\bar{m}_c$ = 1.176 GeV in perturbative QCD $\Longrightarrow$ $\xi_b = 0.845 > \xi_c = 0.759$ (✓)

heavy quark limit for $\bar{m}_s$: $\xi_s \rightarrow \xi_c \Longrightarrow \bar{m}_s < 387$ MeV

SU(3)$_F$ limit: $\xi_s \rightarrow \xi_d \approx \xi_u$ + dispersion result for $\Delta\bar{\alpha}^{(3)}(\bar{m}_c)$

$\Rightarrow$ $\bar{m}_s > 240$ MeV ***JE, Ramsey-Musolf 2005***

OZI rule violation

QCD annihilation ("singlet") type diagrams

$Q_u + Q_d + Q_s = 0 \Rightarrow$ no OZI rule violation in $SU(3)_F$ limit

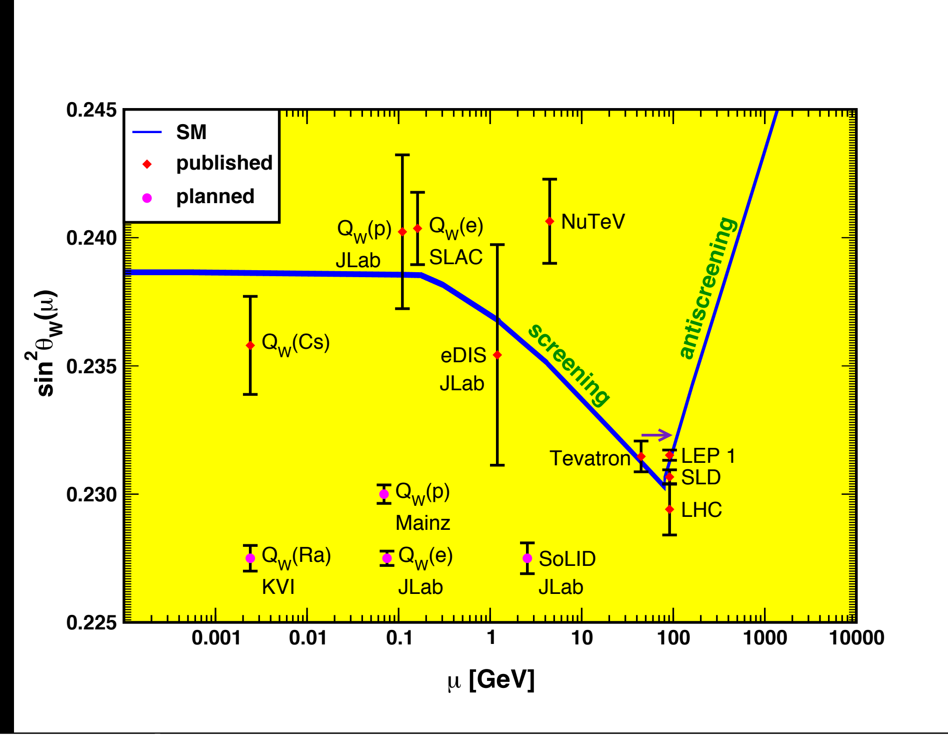
$T_u + T_d = 0 \Rightarrow$ only "induced" OZI rule violation

assuming that the leading order perturbative coefficient is of typical size (not accidentally small) $\Rightarrow \delta_{OZI} \sin^2\theta_W \sim 10^{-6}$

not assuming this $\Rightarrow \delta_{OZI} \sin^2\theta_W \sim \alpha / 90\pi \sim 2.6 \times 10^{-5}$ from N_C counting and considering EFT with strange quarks integrated out

10^{-6} estimate in line with small ω-Φ mixing angle ~ 0.055, but we use the very conservative 3×10^{-5} *JE, Ramsey-Musolf 2005*

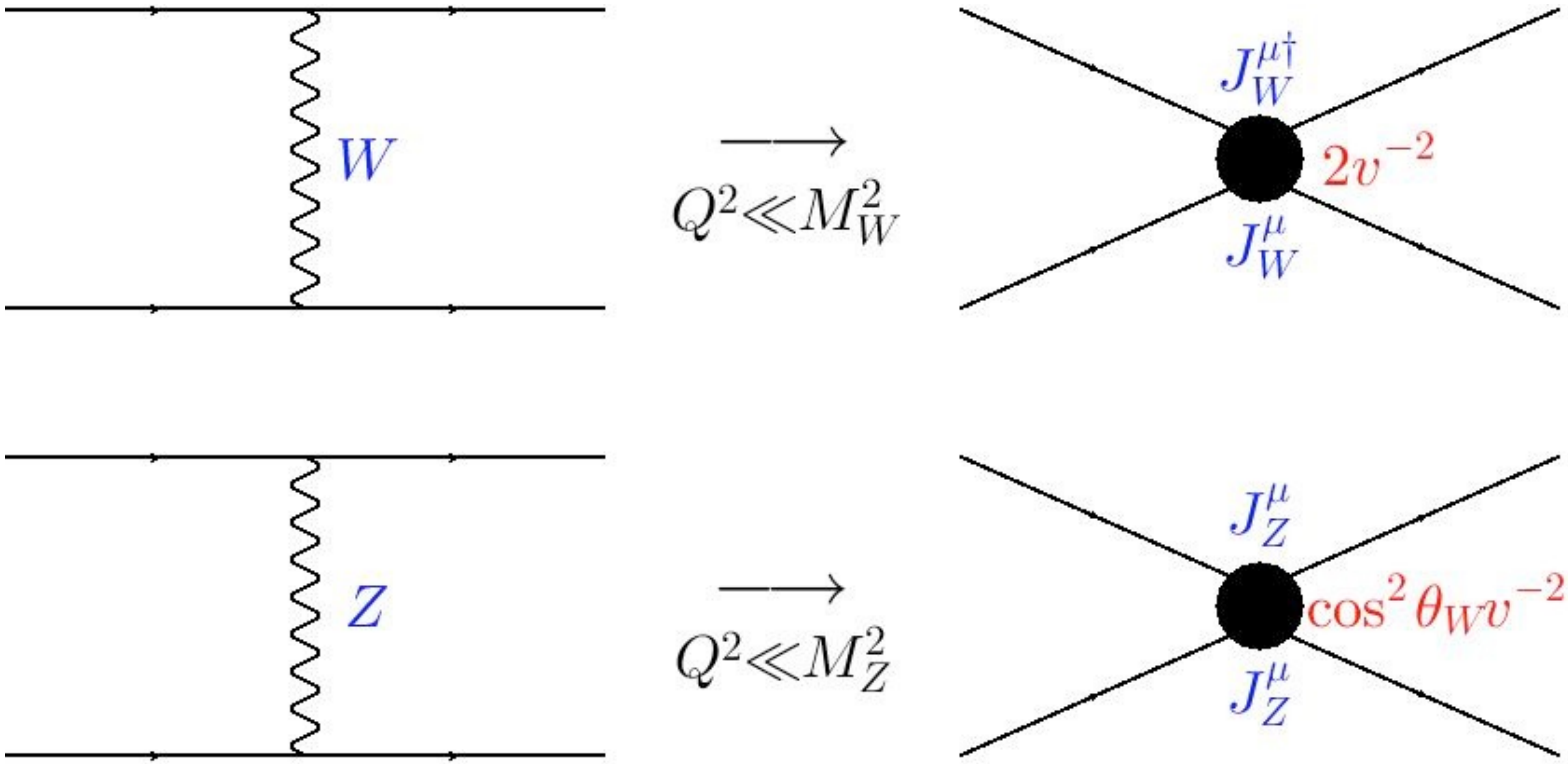
Uncertainties



JE, Ramsey-Musolf 2005

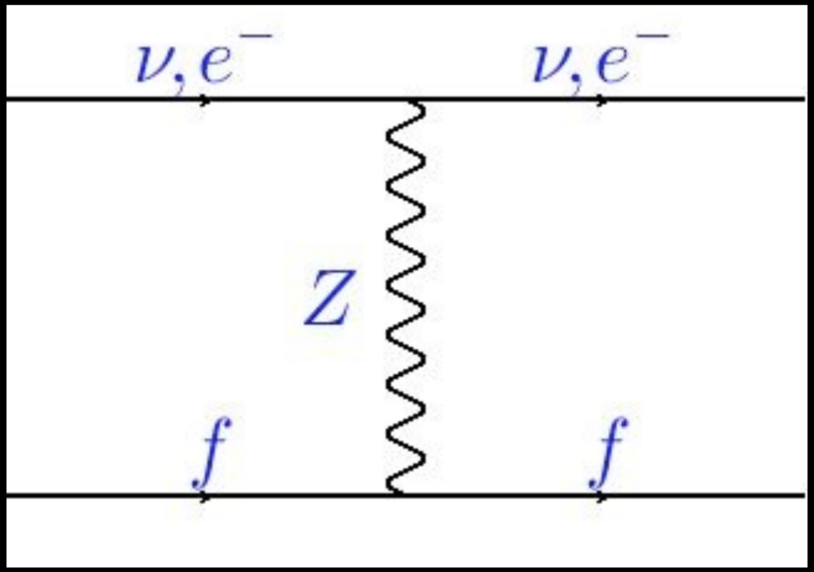
source	comment	uncertainty
δΔα	e	3 × 10
m	flavor separation	5 × 10
m	isospin breaking	1 × 10
singlet contributions	OZI rule violation	3 × 10
$\bar{m}$	QCD sum rules	4 × 10
$\bar{\alpha}$	Z and τ-decays	4 × 10
TOTAL	incl. (excl.) parametric	9 (7) × 10

The low-energy (Fermi) limit



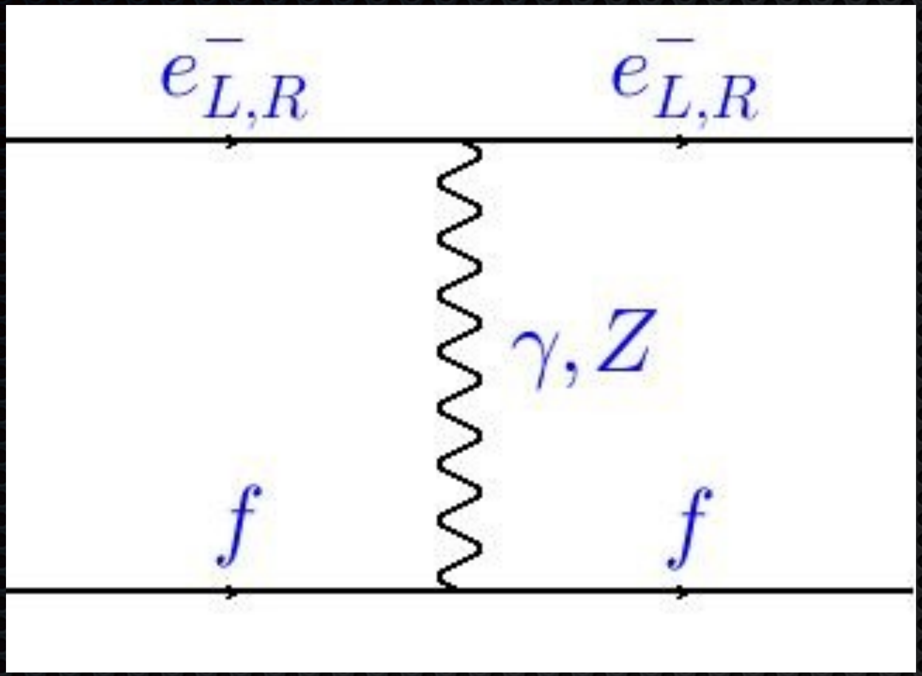
$$\mathcal{L}_{\text{eff.}} = -\frac{2}{v^2}\left(J_W^{\mu\,\dagger} J_{W\mu} + \cos^2\theta_W \,\frac{J_Z^\mu J_{Z\mu}}{2} \right)$$

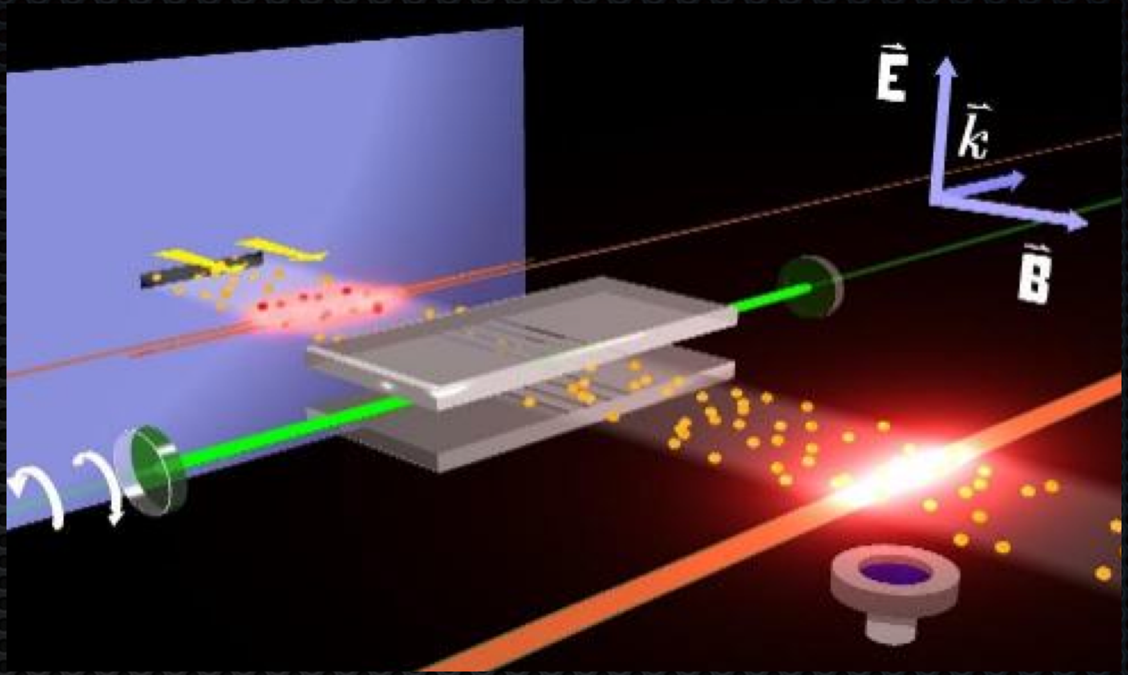
Effective couplings

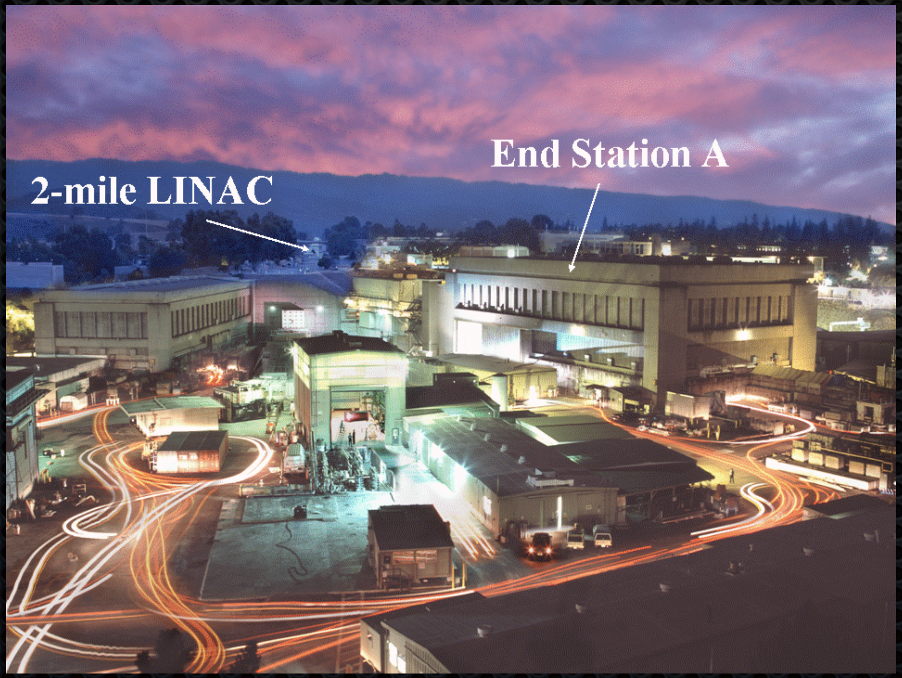


- Normalized so that $g_{LLLL} = 1$ (μ-decay)
- NC couplings: $g^{ef}_{AV}\, \bar{e}\gamma^{\mu}\gamma^{5} e\, \bar{f}\gamma_{\mu} f$ $\quad g^{ef}_{VA}\, \bar{e}\gamma^{\mu} e\, \bar{f}\gamma_{\mu}\gamma^{5} f$
- $|g^{ef}_{AV}| = ½ - 2\,|Q_f|\,\sin^2\theta_W$ $\quad |g^{ef}_{VA}| = ½ - 2\,\sin^2\theta_W$
- $f = e \rightarrow |g^{ee}_{AV}| = ½ - 2\,\sin^2\theta_W \ll 1$
  - in SM: enhanced sensitivity to $\sin^2\theta_W$ (compete with Z-pole)
  - BSM: enhanced sensitivity to Λ_{new}

Parity violation
– interference –







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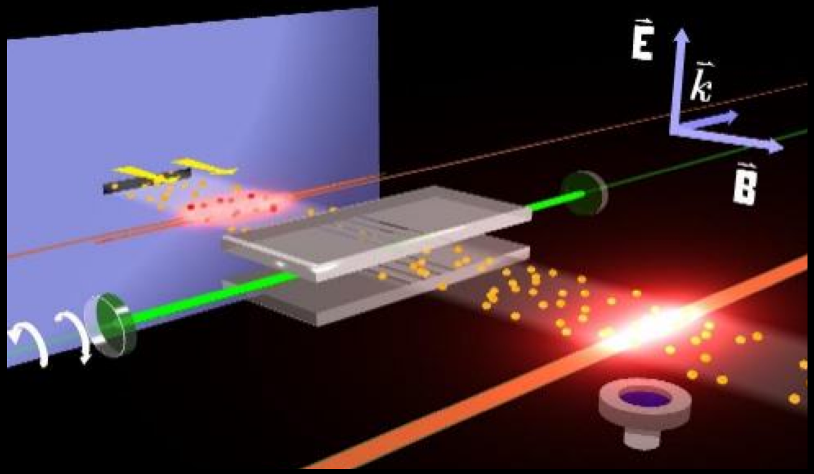
Jefferson Lab
Thomas Jefferson National Accelerator Facility

Atomic parity violation



- effects tiny and ~ Z^3 → seen only in heavy atoms
- g_{AV} (C_{1q}) add up coherently → nuclear spin-independent interaction
- spin-dependent g_{VA} (C_{2q}) clouded by dominant nuclear anapole moment (~ $Z^{2/3}$)
- separate g_{AV} and g_{VA} by measuring different hyperfine transitions
- Future: take ratios of PV in different isotopes ***Rosner 1996***
- single trapped Ra ions are promising due to much larger PV effect ***Wansbeek et al 2012***

Elastic scattering

Q-weak A Search for New Physics

- Scattering from proton as a whole →

  $g_{VA}^{ep} \equiv 2\, g_{VA}^{eu} + g_{VA}^{ed} = -\tfrac{1}{2} + 2 \sin^2\theta_W$

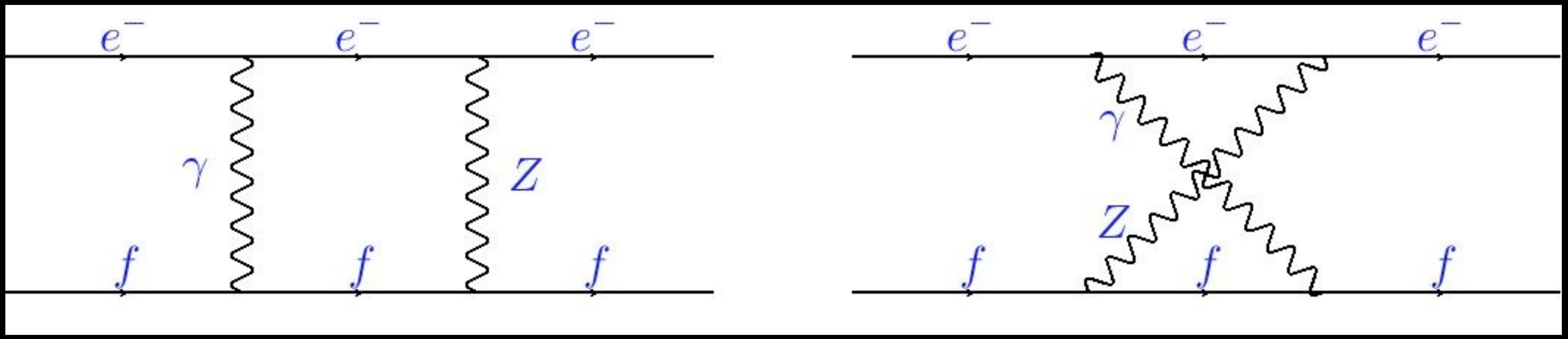
- *JLAB-Qweak Collaboration* completed data taking to determine g_{VA}^{ep} from

$$A_{LR}^{ep} \equiv \frac{d\sigma_L - d\sigma_R}{d\sigma_L + d\sigma_R} = -\frac{m_p(2E_e + m_p)}{v^2} \frac{g_{AV}^{ep}}{4\pi\alpha} \mathcal{F}^{ep}$$

$$\mathcal{F}^{ep} = \left[y + \mathcal{O}(y^2)\right] \mathcal{F}_{\rm QED}^{ep}(Q^2, y)$$

- Small $Q^2 = 0.025$ GeV^2 and $y \equiv 1 - E'/E = 0.0082$ important to keep y^2-term and associated hadronic uncertainties below experimental error.
- extrapolation to $y \to 0$ using other A_{LR}^{ep} measurements at higher Q^2
- can extract weak charge of proton $Q_W^p \approx -2\, g_{AV}^{ep}$ (4%) and $\sin^2\theta_W$ (0.3%)

γ-Z boxes (PVES-p)



- generate large EW logs regulated in the IR by uncertain hadronic scale

  (similarly for charge radius correction to g_{VA}^{eq})

- for APV ($E_e \approx 0$, $Q^2 \approx 0$) effect for g_{AV}^{eq} is $\propto$ g_{VA}^{eq} and vice versa

- for elastic scattering $E_e \neq 0$, mixing in opposite chirality structure

- strong point for *P2 (Mainz)*

Elastic scattering future (*P2*)

- order y^2-term significant at *Qweak* (⅓; no $1 - 4\sin^2\theta_W$ suppression)
  - 1.5% theory uncertainty
  - go to even lower y
- New experiment (*P2*) planned at *MESA* (Mainz) at $Q^2 = 0.0048\ \text{GeV}^2$ and $y = 0.0038$
- γ-Z box correction will also be smaller at lower Q^2
  - auxiliary *JLab* and *Mainz* experiments will help to better constrain γ-Z box
- *P2* goal of 2% in g_{AV}^{ep} or Q_W^p and ±0.00036 in $\sin^2\theta_W$ or better

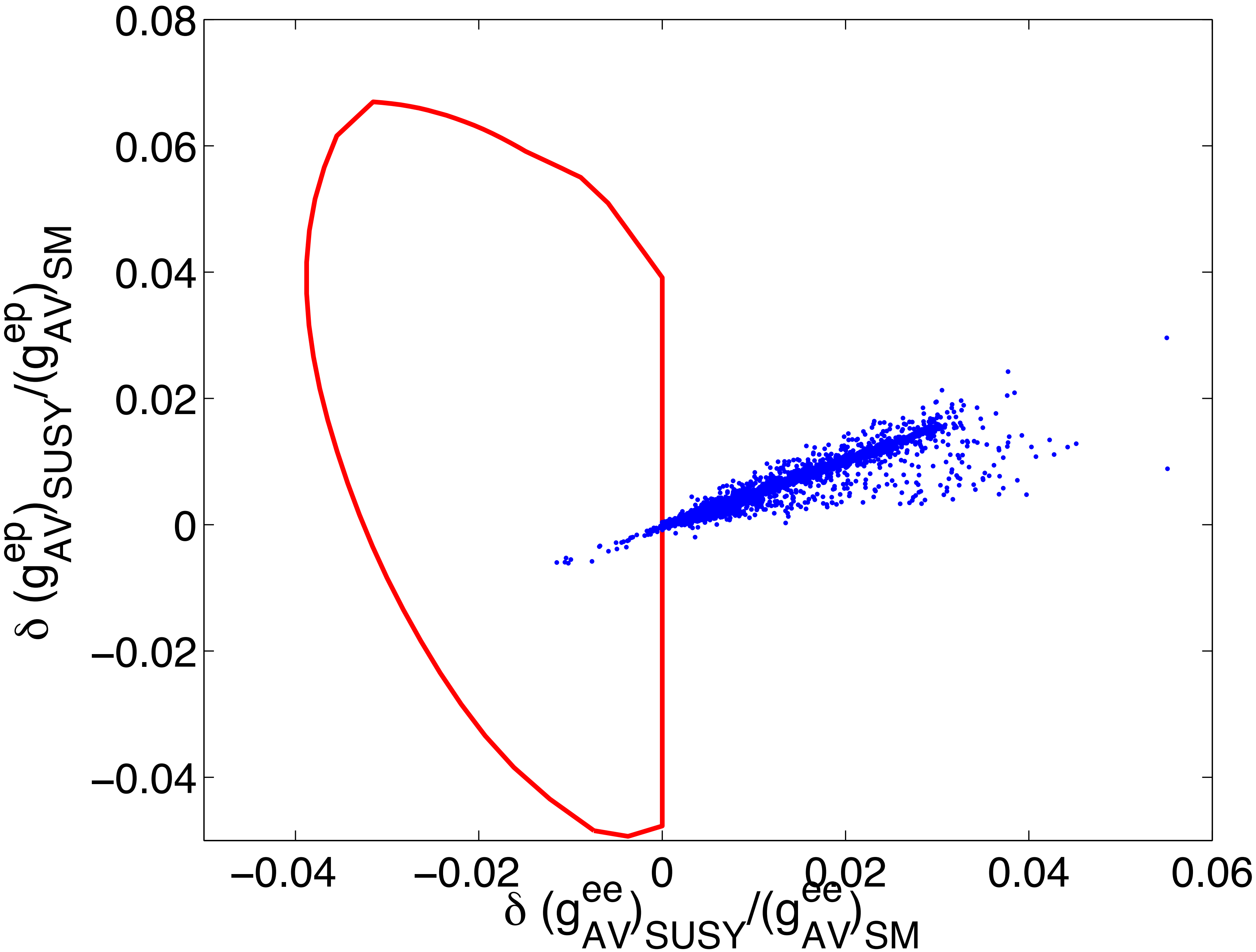
g_{VA}^{eu} and g_{VA}^{ed} (DIS)

- problematic at very low energies (elastic or quasi-elastic)
- charge weighted combination from (in valence quark approximation)

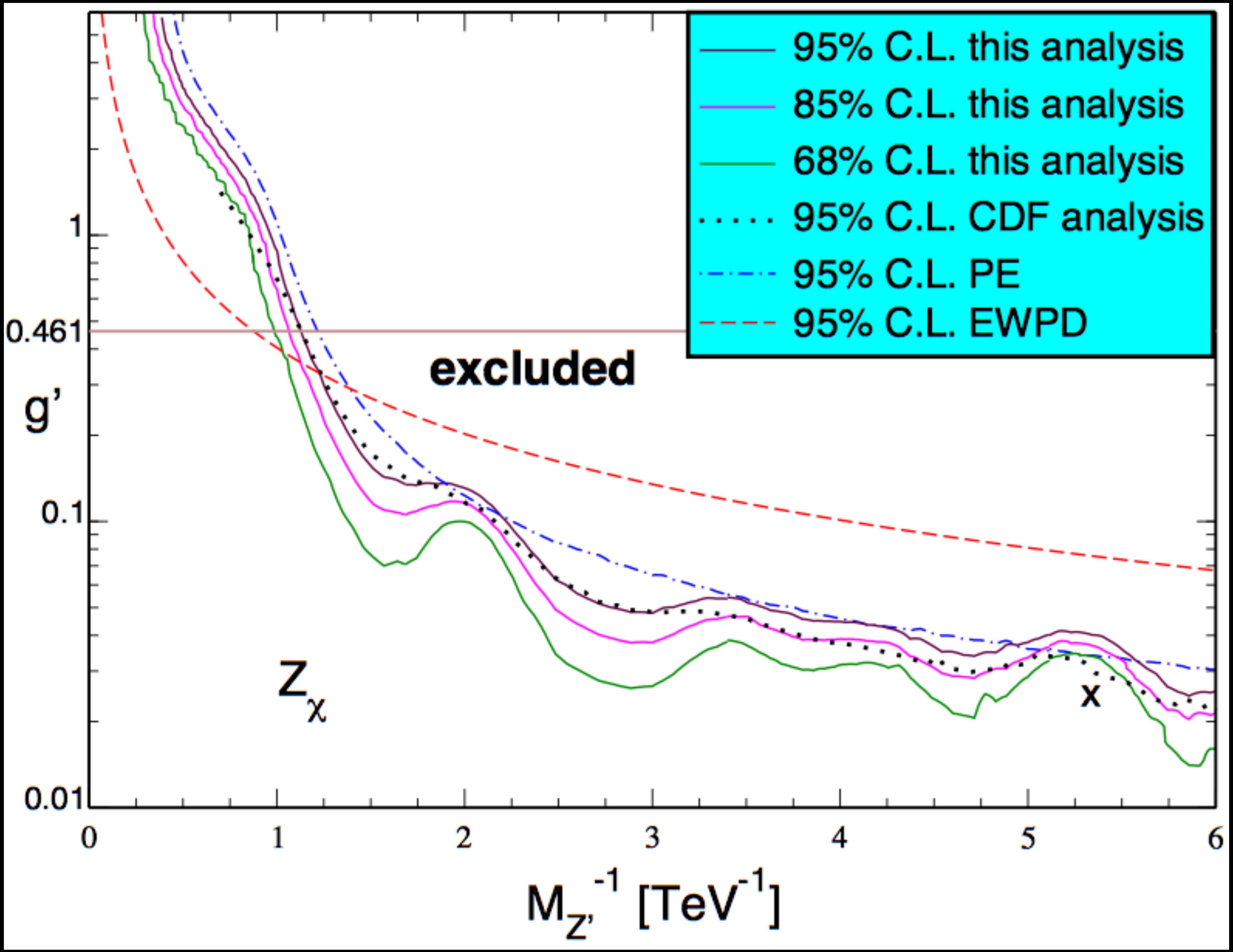
$$A_{LR}^{\rm eDIS} = -\frac{3}{20\pi\alpha}\frac{Q^2}{v^2}\left[\left(2g_{AV}^{eu} - g_{AV}^{ed}\right) + \left(2g_{VA}^{eu} - g_{VA}^{ed}\right)\frac{1-(1-y)^2}{1+(1-y)^2}\right]$$

  - eDIS asymmetries much larger ($\gtrsim 10^{-4}$) than in elastic scattering
  - measured to ~ 10% at *SLAC* for $0.92\ \mathrm{GeV}^2 < Q^2 < 1.96\ \mathrm{GeV}^2$
    Prescott et al 1979
  - 2 further points at $Q^2 = 1.1$ and $1.9\ \mathrm{GeV}^2$ to 4.5% by *JLab-Hall A Collaboration 2014*
  - approved *SOLID* experiment will measure large array of kinematic points up to $9.5\ \mathrm{GeV}^2$ (0.5% precision in coupling combination)

PVES and SUSY



Energy-intensity complementarity



Contact interactions

Model independent new physics sensitivity

$$\mathcal{L}_{eq} = \left[\frac{G_F}{\sqrt{2}} g_{VA}^{eq}(\mathrm{SM}) + \frac{g^2}{\Lambda^2}\right] \bar{e}\gamma_\mu e\, \bar{q}\gamma^\mu\gamma^5 q$$

$$\frac{g^2}{\Lambda^2} = \frac{4\pi}{\Lambda^2} = \frac{\bar{g}_{VA}^{eq} - g_{VA}^{eq}(\mathrm{SM})}{2v^2}$$

$g^2 = 4\pi$ (convention)

Customary to quote one-sided limits on Λ!

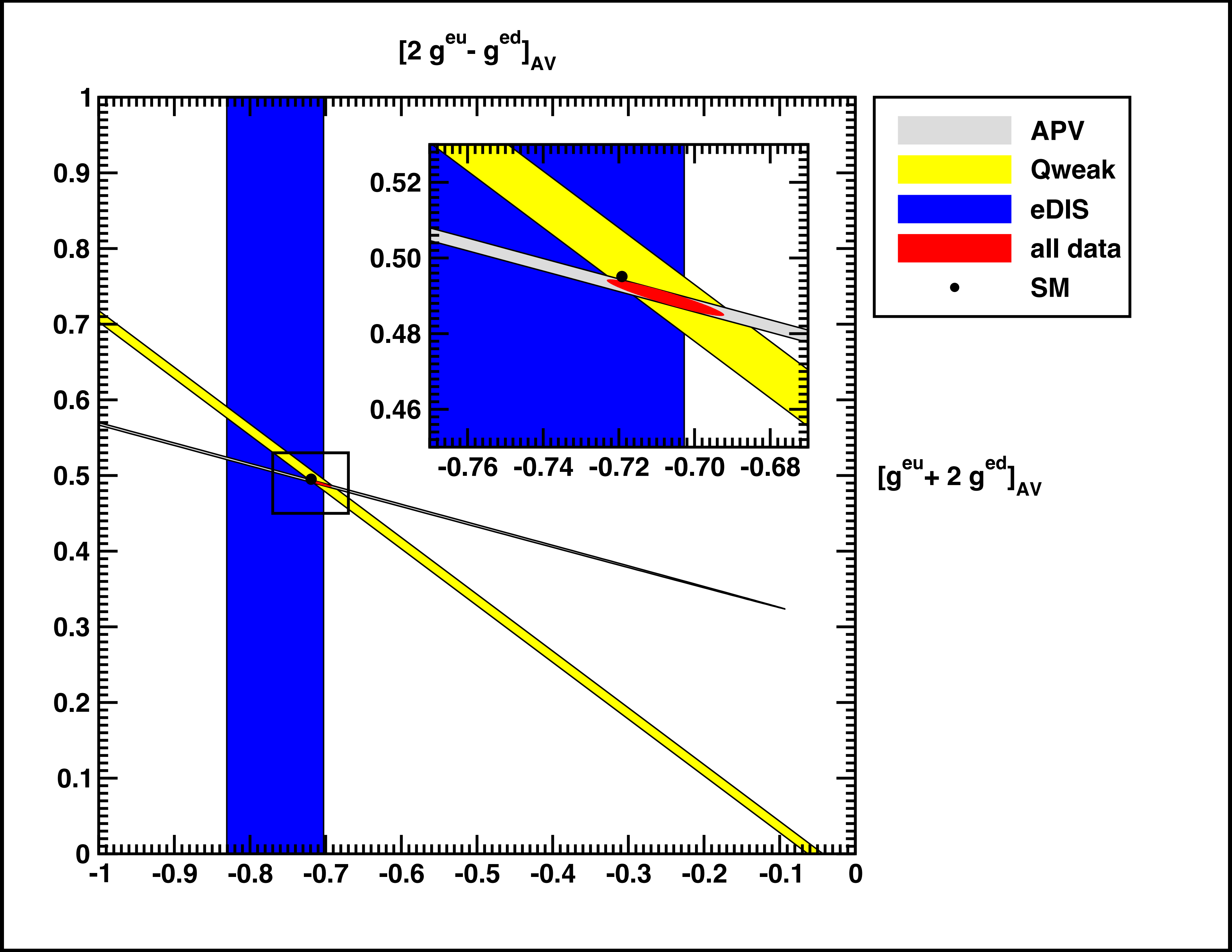
important metric:
generalization to other types of operators?

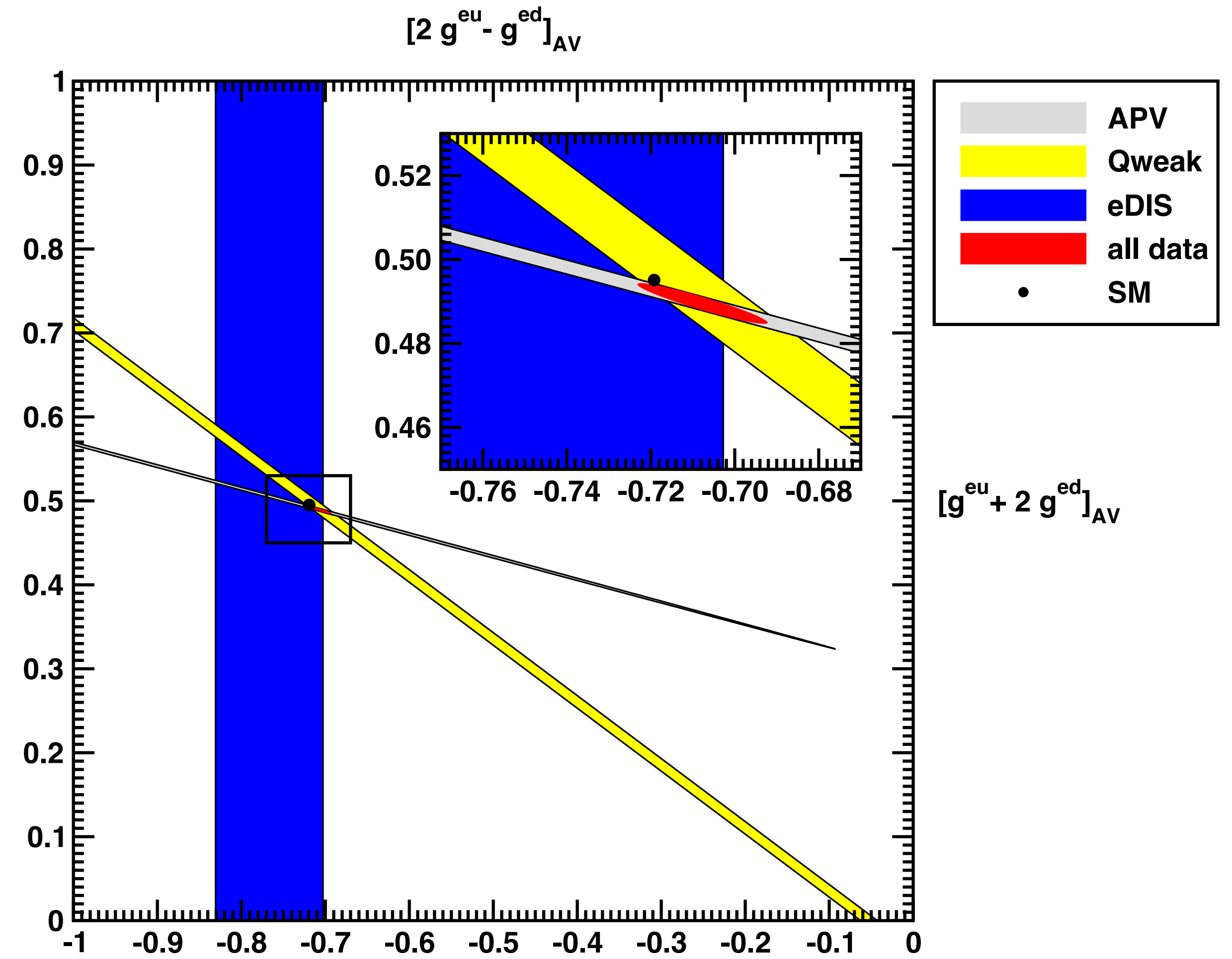
	precision	Δ	Λ
APV	0.58 %	0.0019	32.3 TeV
E158	14 %	0.0013	17.0 TeV
Qweak I	19 %	0.0030	17.0 TeV
PVDIS	4.5 %	0.0051	7.6 TeV
Qweak final	4.5 %	0.0008	33 TeV
SoLID	0.6 %	0.00057	22 TeV
MOLLER	2.3 %	0.00026	39 TeV
P2	2.0 %	0.00036	49 TeV
PVES	0.3 %	0.0007	49 TeV
APV	0.5 %	0.0018	34 TeV
APV	0.1 %	0.0037	16 TeV
Belle II	0.14 %	—	33 TeV
CEPC / FCC	?	?	?

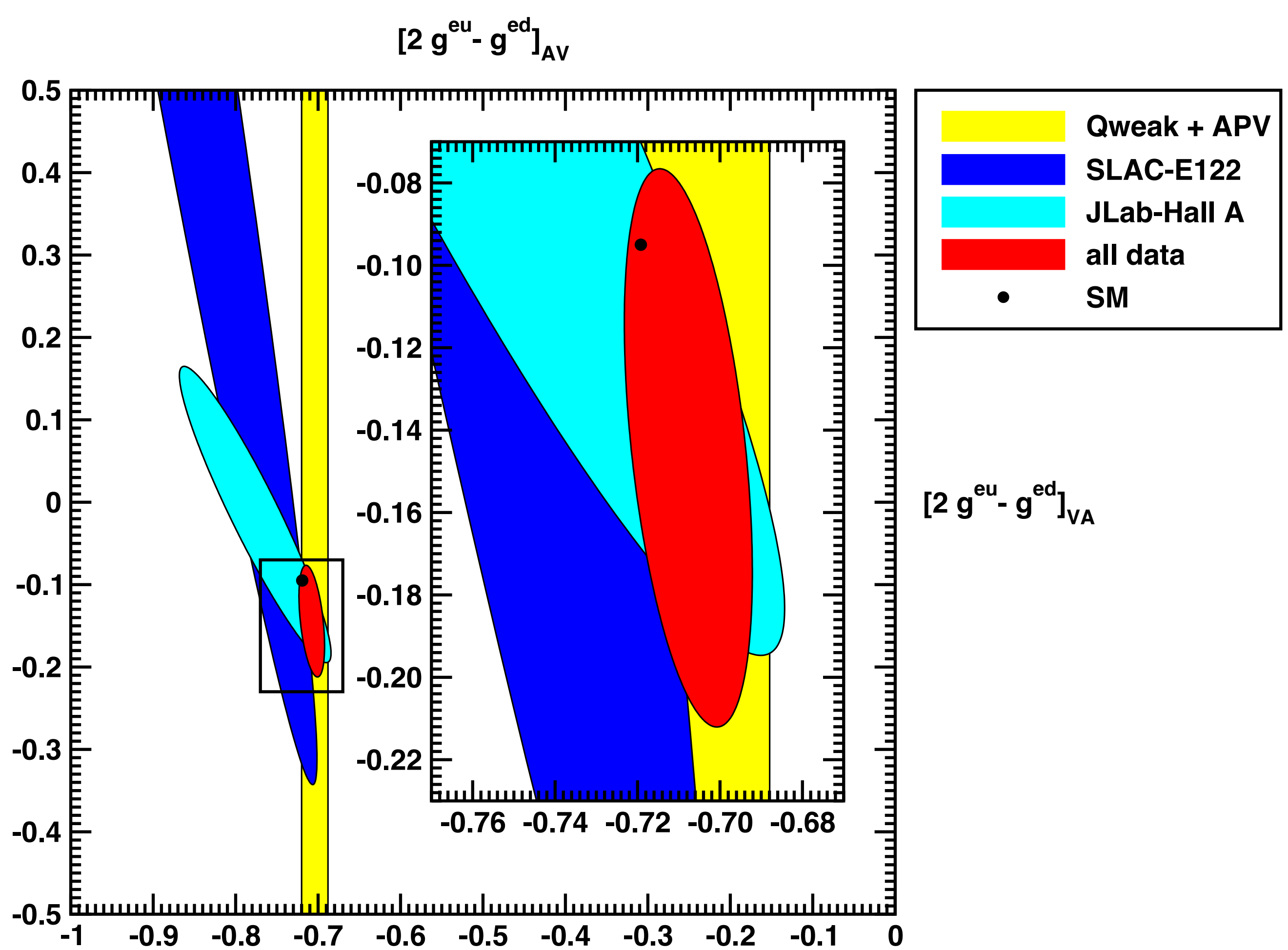
CepC-SppC

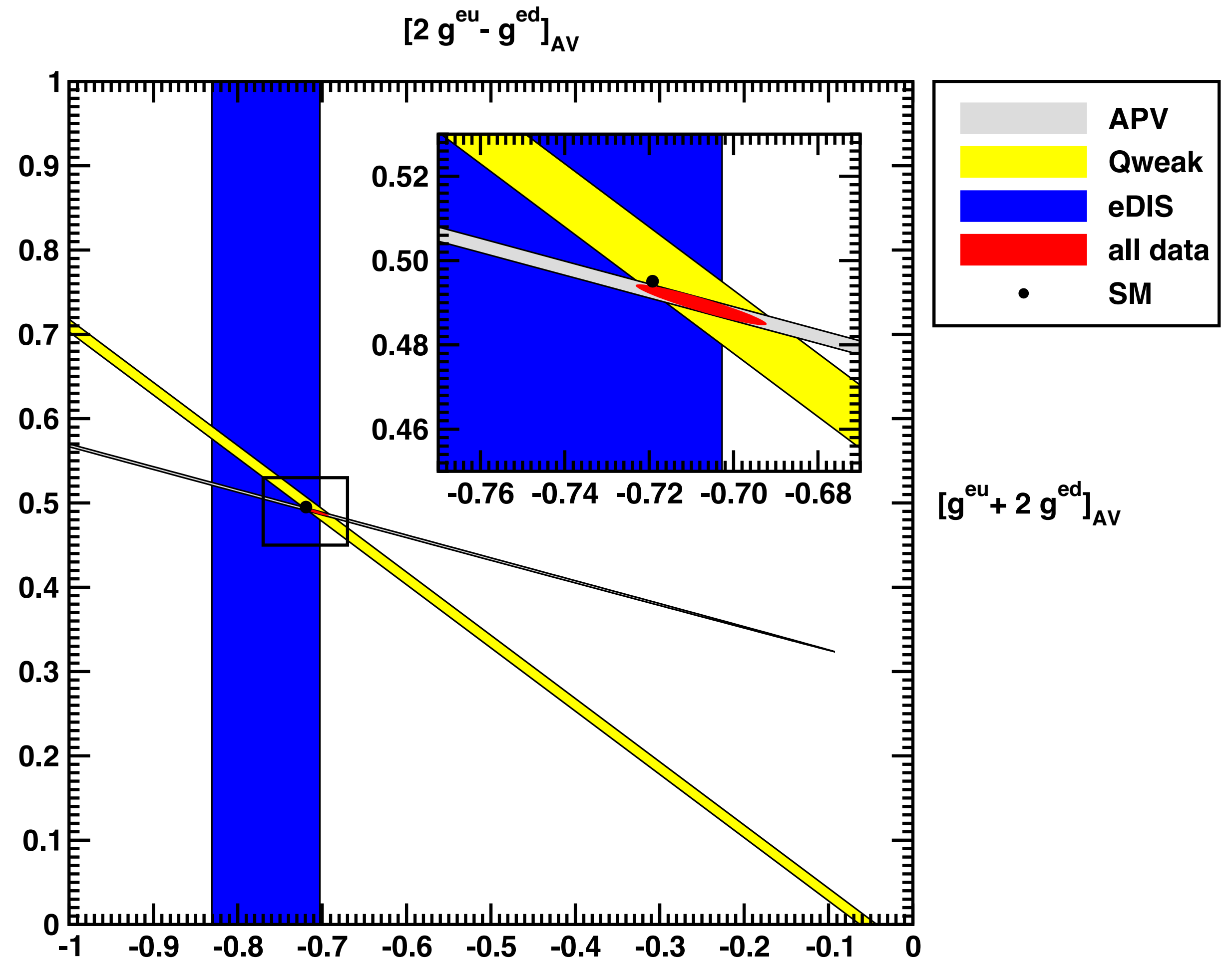
- 240 GeV $e^+ e^-$ collider
- Can significantly increase precision of many EW observables over LEP even when no advances regarding systematics.
- Contact interactions from ZH threshold (poor statistics @LEP)
- Can obtain good measurements of M_W and Γ_W from WW threshold without beam polarization but very high rates?
  - Γ_W can determine α_s with very small theory error and is less sensitive to new physics (invisible decays) than Γ_Z and provides a CKM matrix unitarity check.

PV (axial)-electron (vector)-quark couplings

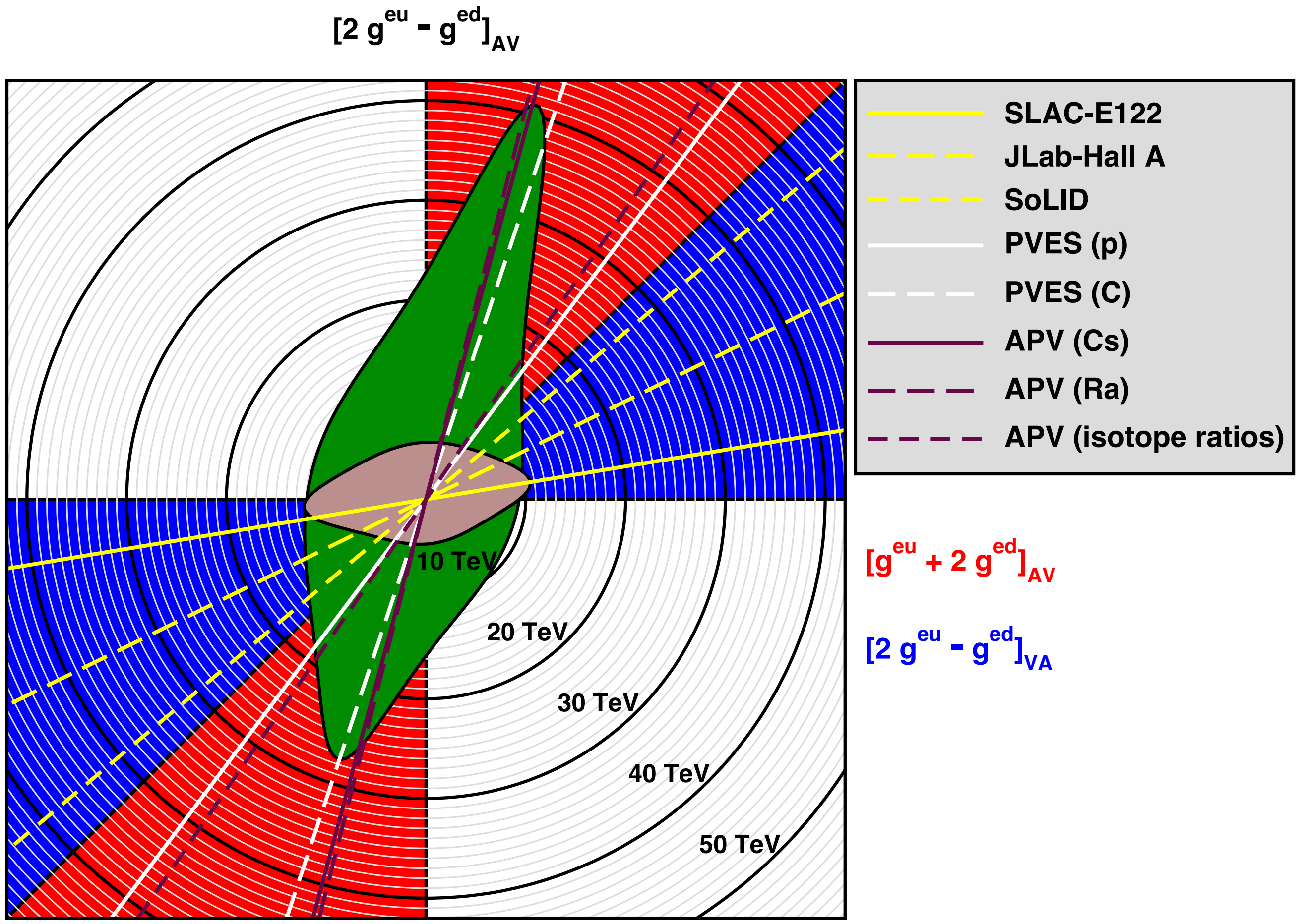


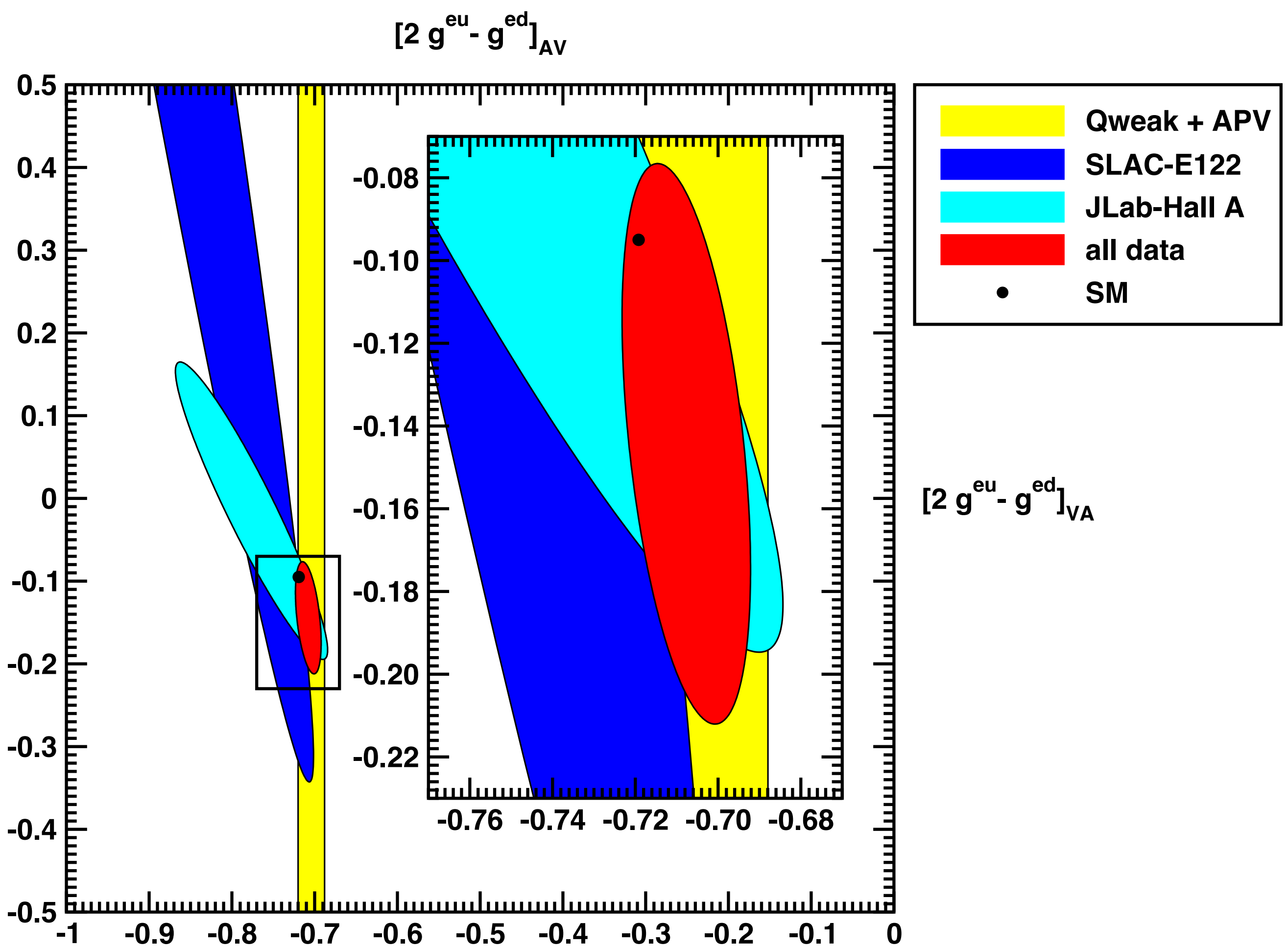

[2 g^eu - g^ed]_AV
[g^eu + 2 g^ed]_AV
APV
Qweak
eDIS
all data
SM

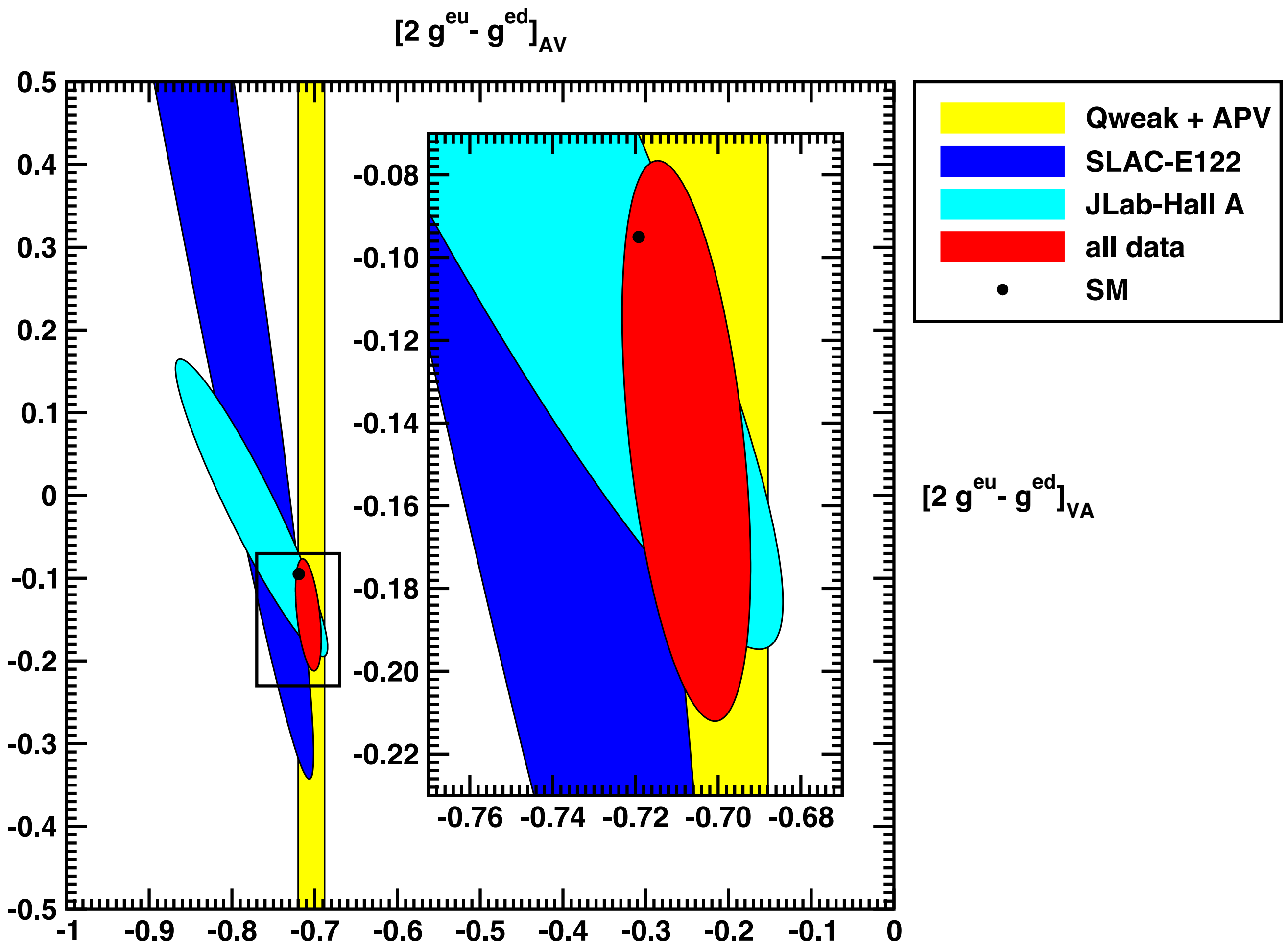

[2 g^eu - g^ed]_AV
[2 g^eu - g^ed]_VA
Qweak + APV
SLAC-E122
JLab-Hall A
all data
SM

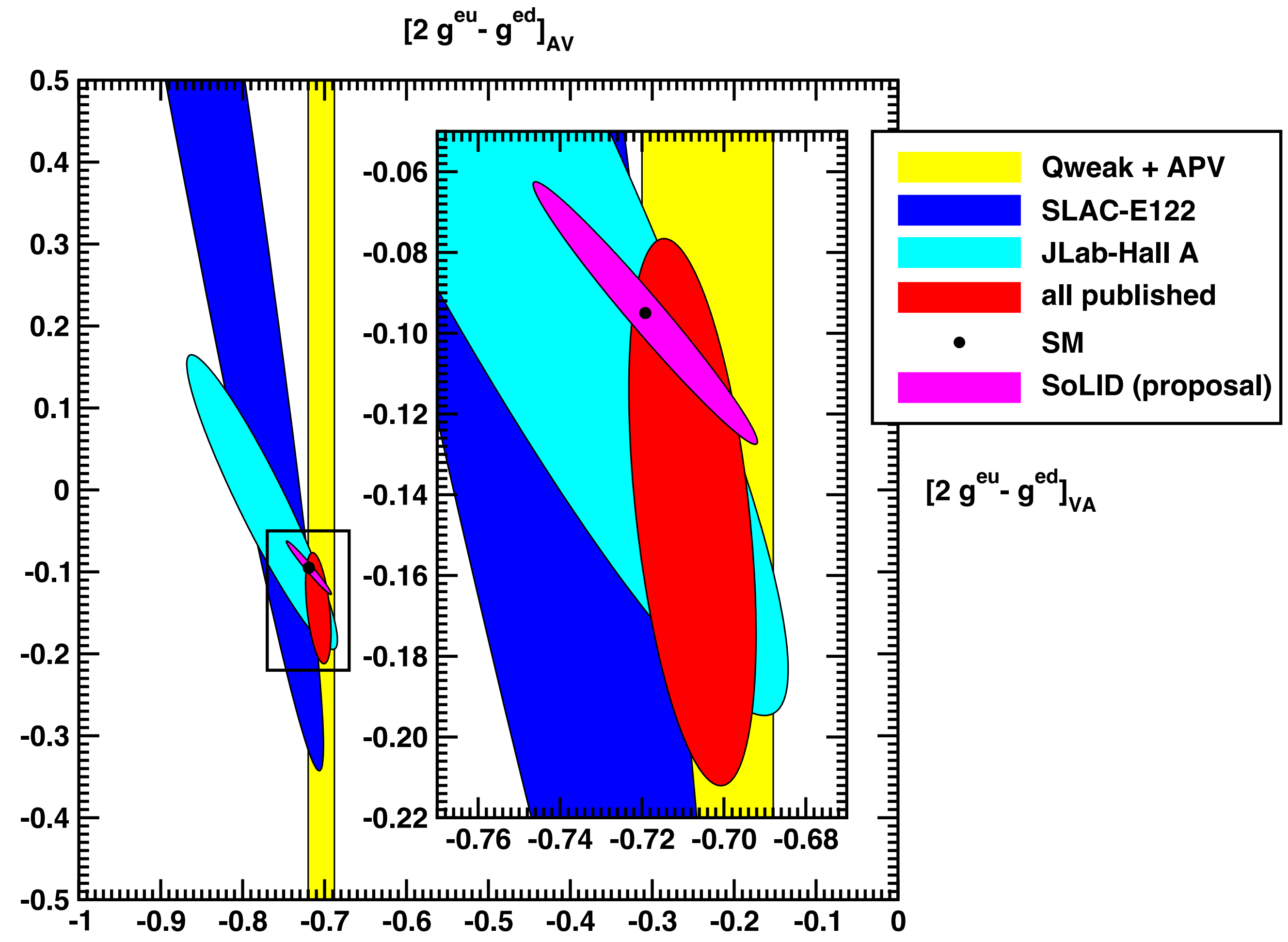


Compositeness scales

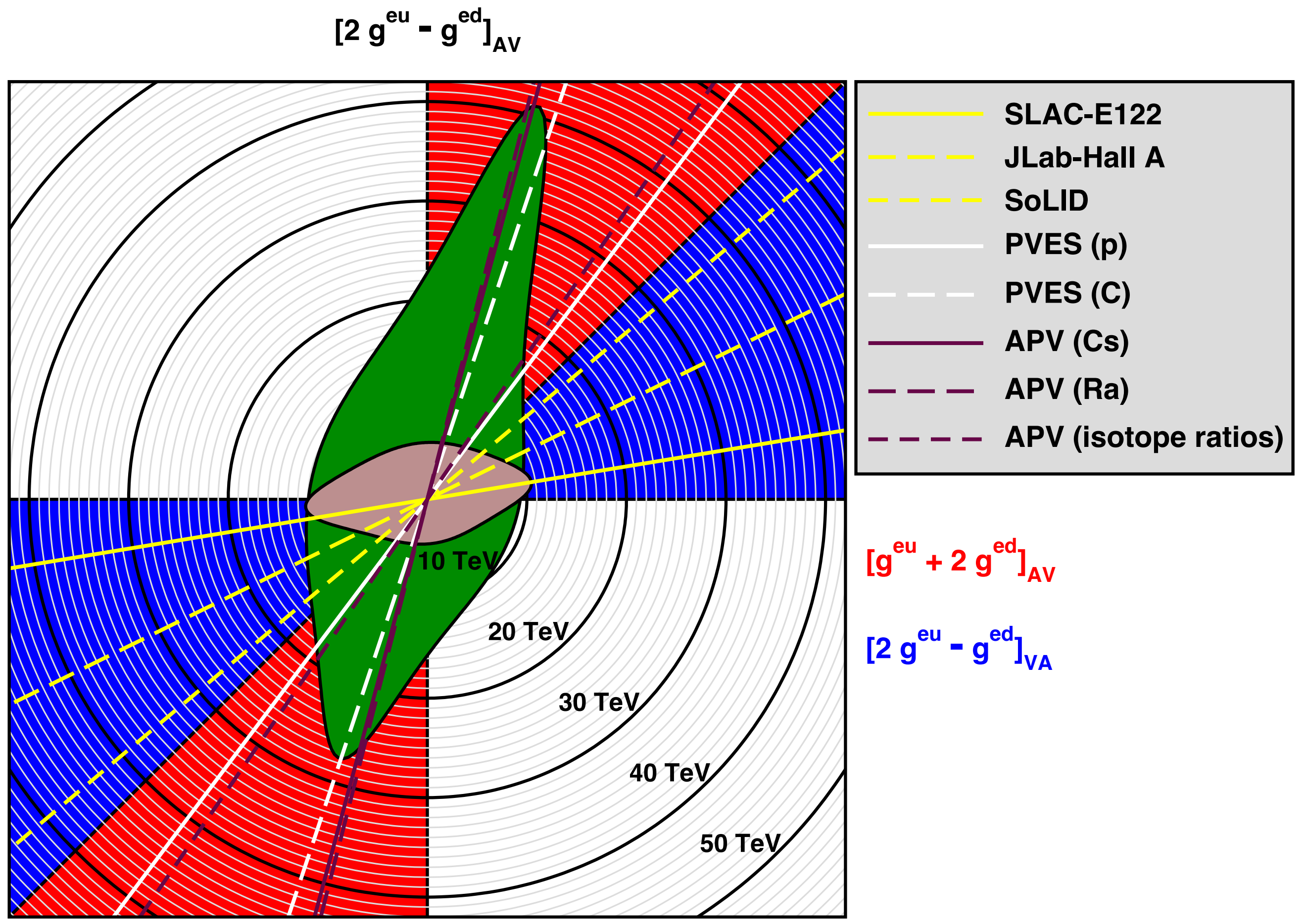


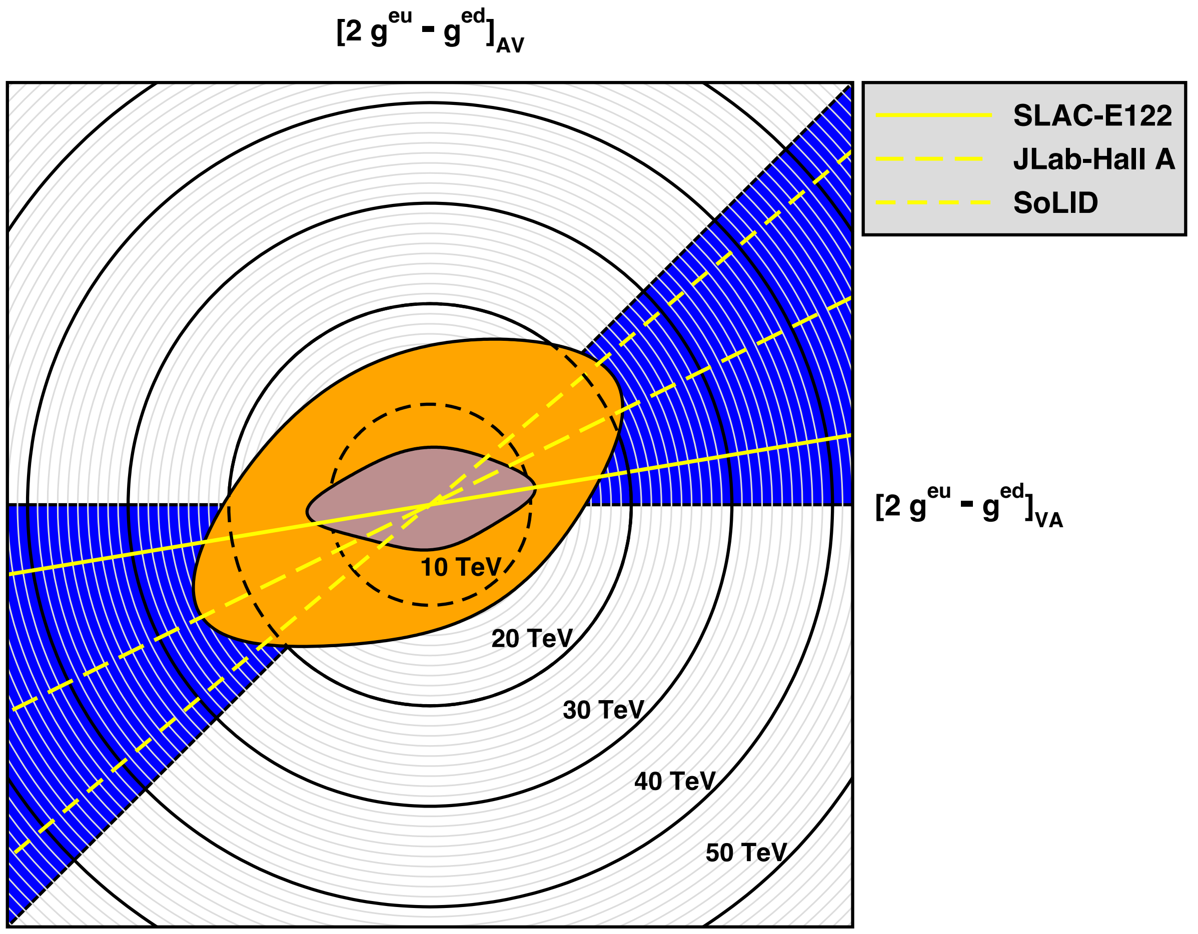



[2 g^eu - g^ed]_AV
[2 g^eu - g^ed]_VA
Qweak + APV
SLAC-E122
JLab-Hall A
all data
SM


[2 g^eu - g^ed]_AV
[2 g^eu - g^ed]_VA
Qweak + APV
SLAC-E122
JLab-Hall A
all published
SM
SoLID (proposal)

Compositeness scales



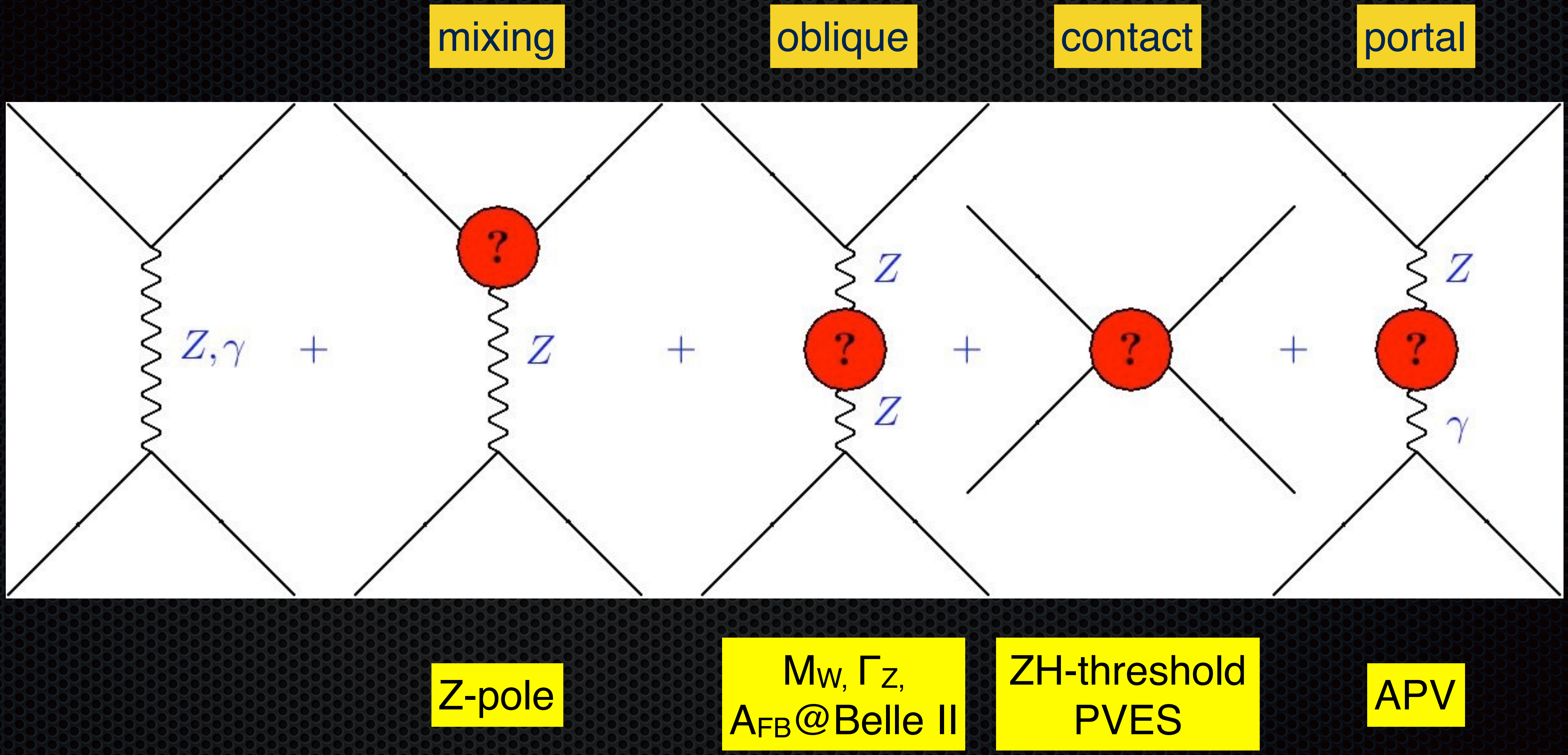


present

future

Conclusions

Synopsis: separating new physics

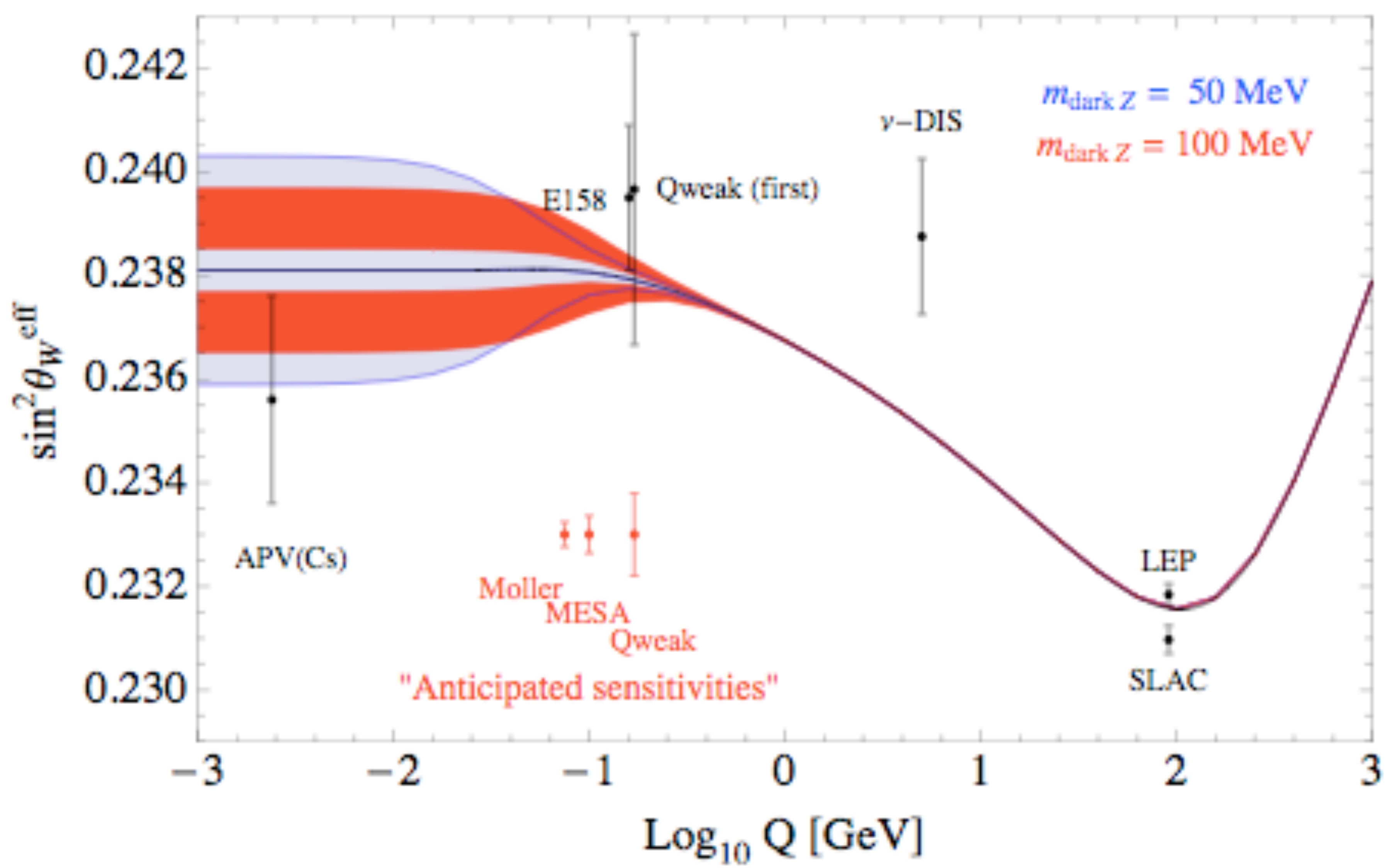


Conclusions

- Precision tests generally in excellent agreement with SM
- Three independent determinations of M_H agree very well
- Persistent: $g_\mu - 2$ (3.3 σ) and $A_{FB}(b)$ vs. A_{LR}
- Emergence of M_W anomaly? (small, but M_W is special)
- Consistent with what the *LHC* has not seen, there appears to be at least a little hierarchy between M_H and Λ_{new}
- Low-energy:
    - next generation experiments set to reach *LEP* precision
    - model-independent couplings: multi-TeV scale (stay tuned)

If there is time…

Running $\sin^2\theta_W$ and Dark Parity Violation



Marciano 2013

Backups

Cs APV

- good understanding of atomic structure crucial → Cs (Tl)
- moving history of most precise measurement (Cs) by Boulder group
- initially agreement with SM ***Wood et al 1997***
- direct measurement of ratio of off-diagonal hyperfine amplitude to polarizability reduced overall error → 2.5 σ deficit ***Bennett, Wieman 1999***
- reevaluation of Breit interaction → 1.2 σ ***Derevianko 2000***
- reevaluation of other effects canceled each other → 1 σ
  Dzuba, Flambaum, Ginges; Johnson; Milstein, Sushkov; Kuchiev, Flambaum; Derevianko; Milstein, Sushkov, Terekhov 2002; Sapirstein 2003; Shabaev 2005
- state-of-the-art many body calculation → 0.1 σ ***Porsev, Beloy, Derevianko 2009***
- corrections to two non-dominating terms → 1.5 σ ***Dzuba, Berengut, Flambaum, Roberts 2012***

APV Future

- take ratios of PV in different isotopes ***Rosner 1996***
  - reduces atomic theory uncertainty ***Bouchiat, Pottier 1986***
  - but effect also partly cancels → higher precision needed
  - also new uncertainty from poorly known neutron radius ***Pollock, Fortson, Wilets 1992***
    - JLab experiments such as *PREX* and *CREX* will help
  - mostly constrains $g_{AV}^{ep} \equiv 2\, g_{AV}^{eu} + g_{AV}^{ed}$ ***Ramsey-Musolf 1999***
    - but different γ-Z box than *Qweak* experiment (see later)
  - ideally one would measure APV in H and D ***Dunford, Holt 2007***
- single trapped Ra ions are promising due to much larger PV effect ***Wansbeek et al 2012***

NuTeV

- $\sin^2\theta_W^{\text{on-shell}} \equiv 1 - M_W^2/M_Z^2 = 0.2277 \pm 0.0016$
- SM: $\sin^2\theta_W = 0.22296 \pm 0.00028$ ($3.0\ \sigma$ deviation)
  - deviation sits in g_L^2 ($2.7\ \sigma$)
  - various SM effects have been suggested:

    asymmetric strange sea

    isospin violation (QED splitting effects ***Glück, Jimenez-Delgado, Reya 2005*** and PDFs ***Sather 1992; Rodionov, Thomas, Londergan 1994; Martin et al. 2004***)

    nuclear effects (e.g., isovector EMC effect ***Cloët, Bentz, Thomas 2009***)

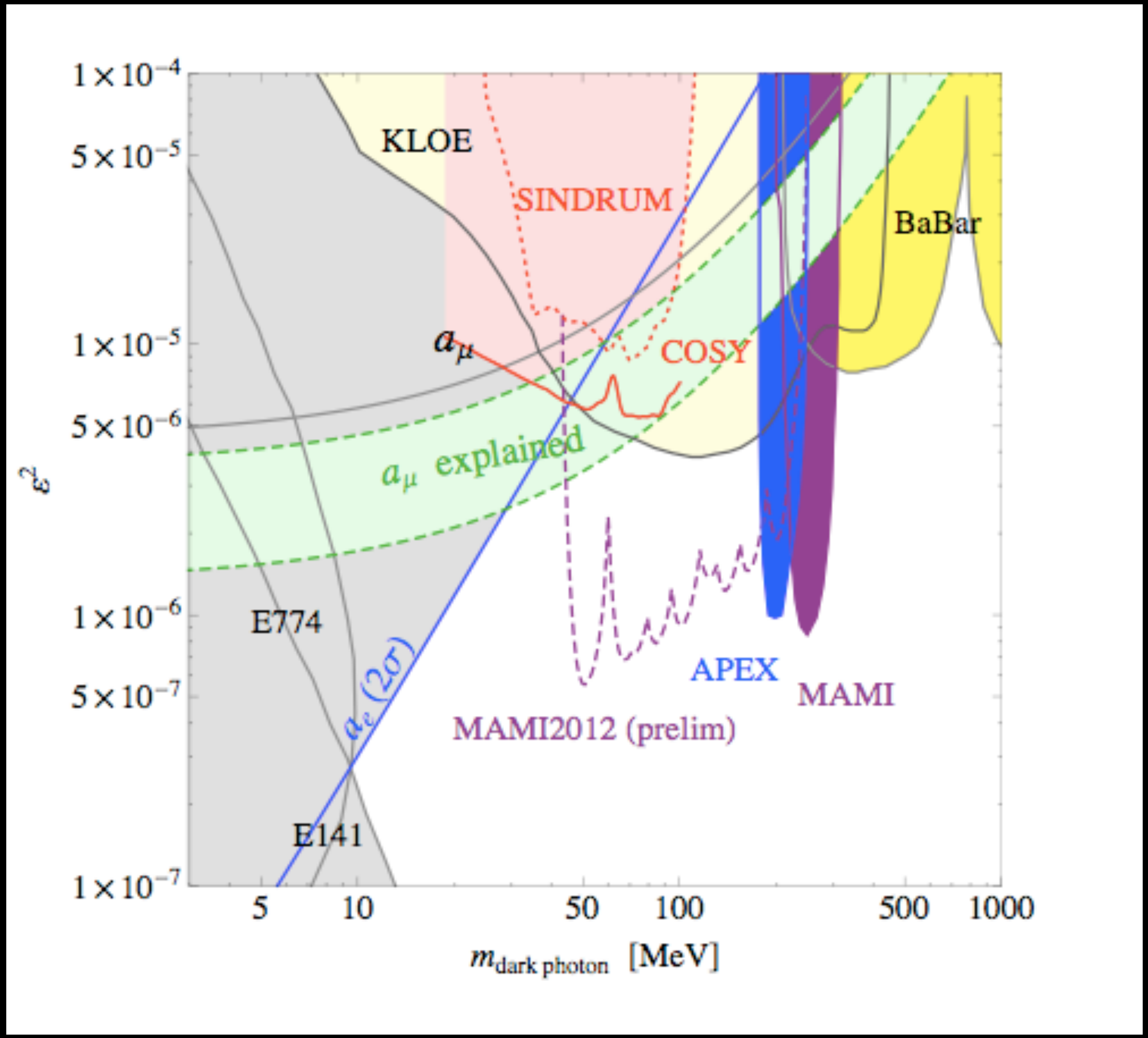
    QED ***Arbuzov, Bardin, Kalinovskaya 2005; Park, Baur, Wackeroth 2009, Diener, Dittmaier, Hollik 2004*** QCD ***Dobrescu, Ellis 2004*** & EW ***Diener, Dittmaier, Hollik 2005*** radiative corrections
  - situation not conclusive: collaboration working on update
  - new physics: difficult to explain full effect

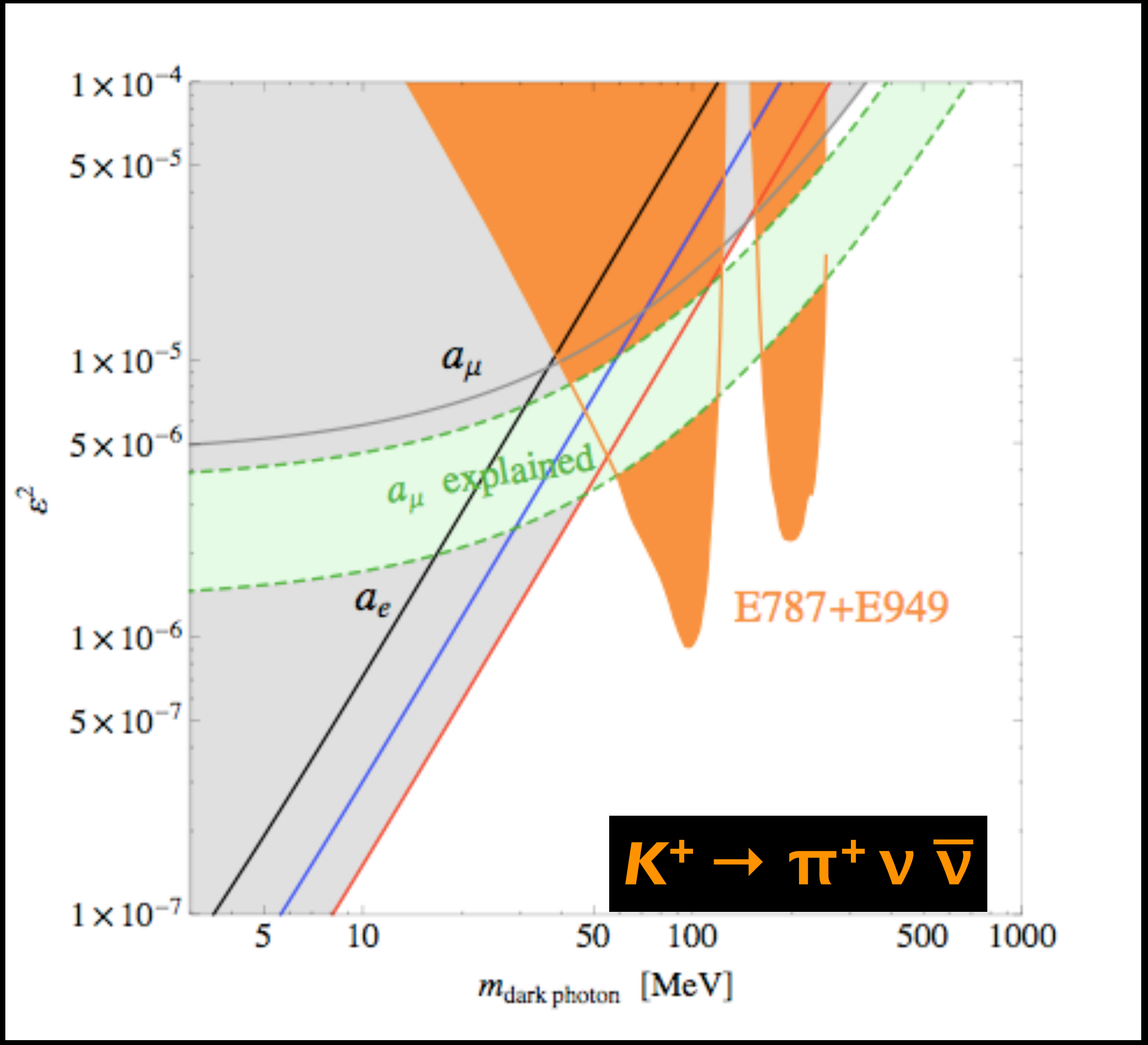
Portals to New Physics

- neutrino portal: $H\ L\ S$
- Higgs portal: $|H|^2\ |H|^2$
- U(1) portal: $F_{\mu\nu}\ F^{\mu\nu}$

Running $\sin^2\theta_W$ and Dark Parity Violation

Davoudiasl, Lee, Marciano 2012; Marciano 2013





$Br(Z_d \to e^+ e^-) \approx 1$

$Br(Z_d \to e^+ e^-) \approx 0$

Hypothetical Data

	current	CEPC	TLEP	low-energy
M	± 2.1	± 0.6	± 0.1	
Γ	± 2.3	± 0.6	± 0.1	
σ	± 0.037	± 0.01	± 0.01	
R	± 0.024	± 0.0007	± 0.0015	
R	± 0.00066	± 0.00018	± 0.00006	
A	± 0.0022		± 2 × 10	
M	± 15	± 3	± 0.6	
A	± 0.0016	± 0.00015		
m	± 950		± 16	
Δα	± 7.8 × 10			± 4 × 10
m	± 30			± 3
m	± 29			± 4
α				± 0.0001

STU

	current	CEPC	CEPC + am	CEPC + mm	TLEP	TLEP + am
S	± 0.101	± 0.025	± 0.023	± 0.023	± 0.012	± 0.006
T	± 0.117	± 0.032	± 0.031	± 0.030	± 0.008	± 0.006
U	± 0.096	± 0.024	± 0.023	± 0.023	± 0.007	± 0.005
S	± 0.081	± 0.018	± 0.014	± 0.013 (10)	± 0.012	± 0.005
T	± 0.068	± 0.019	± 0.017	± 0.013 (6)	± 0.004	± 0.003
T	± 0.030	± 0.014	± 0.010	± 0.006	± 0.002	± 0.002