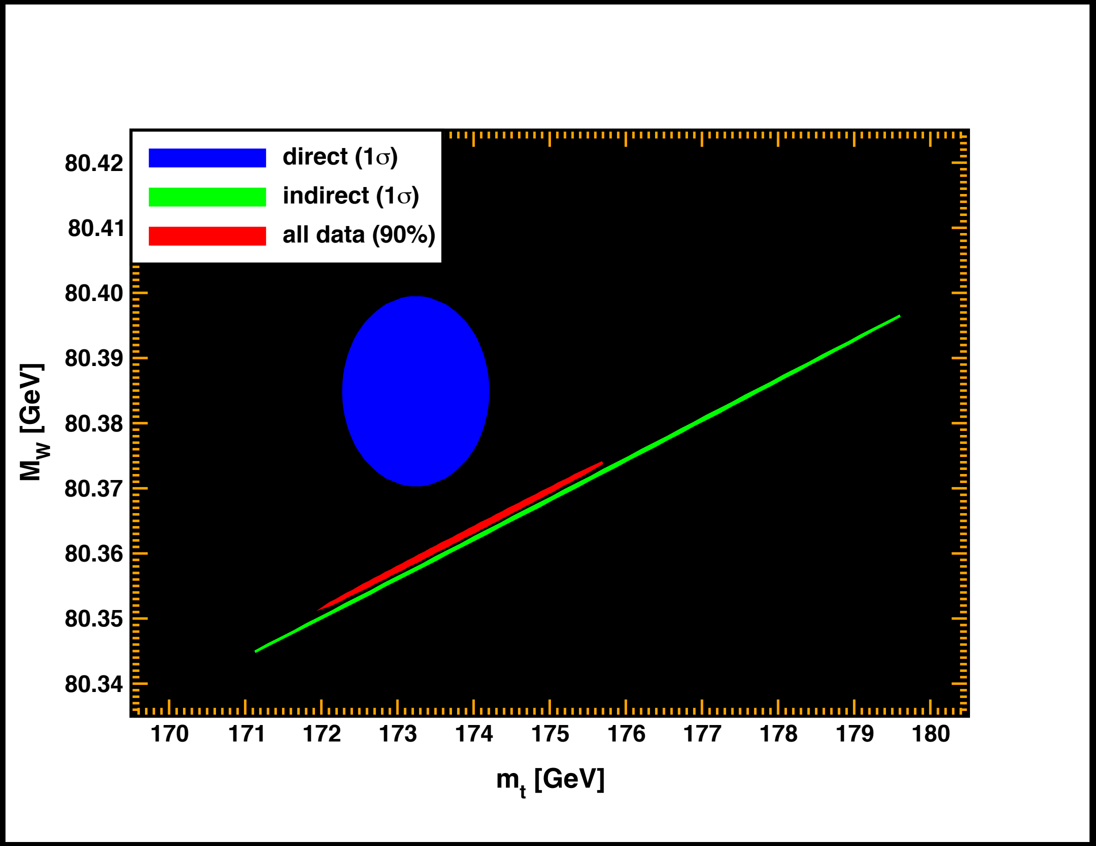
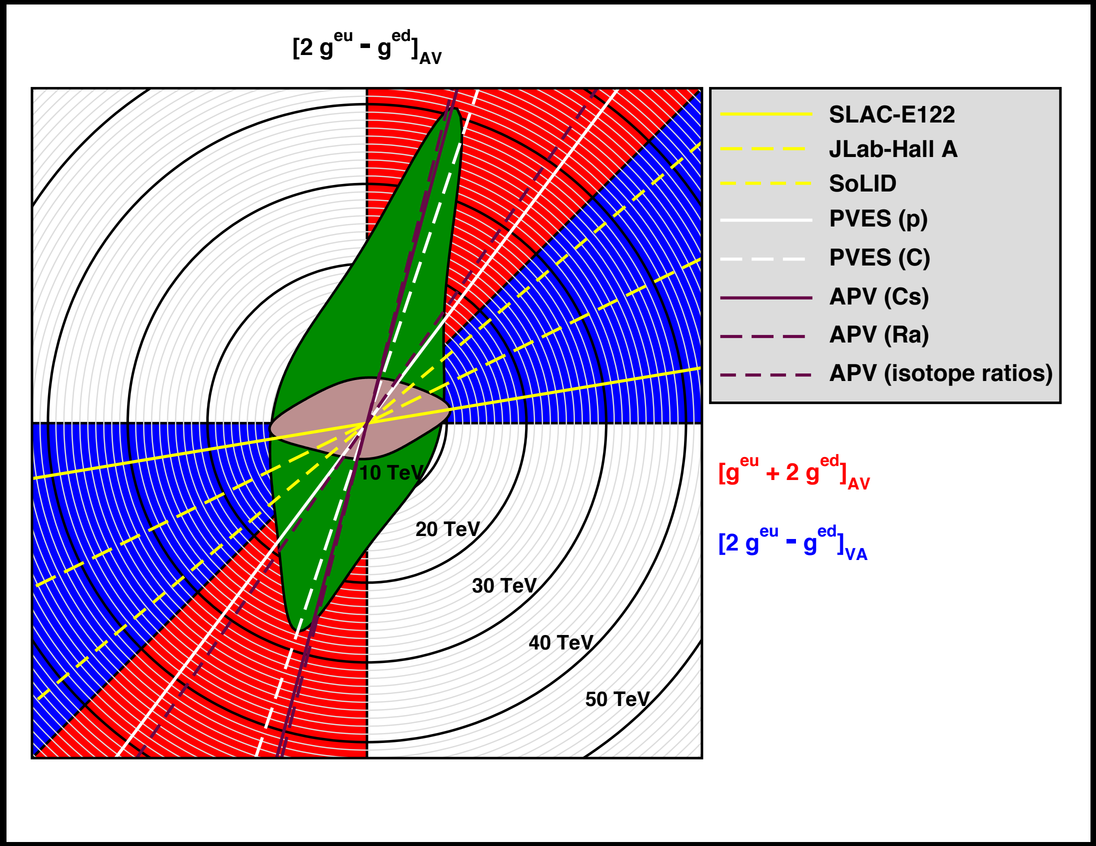
The Standard Model after the Higgs Discovery



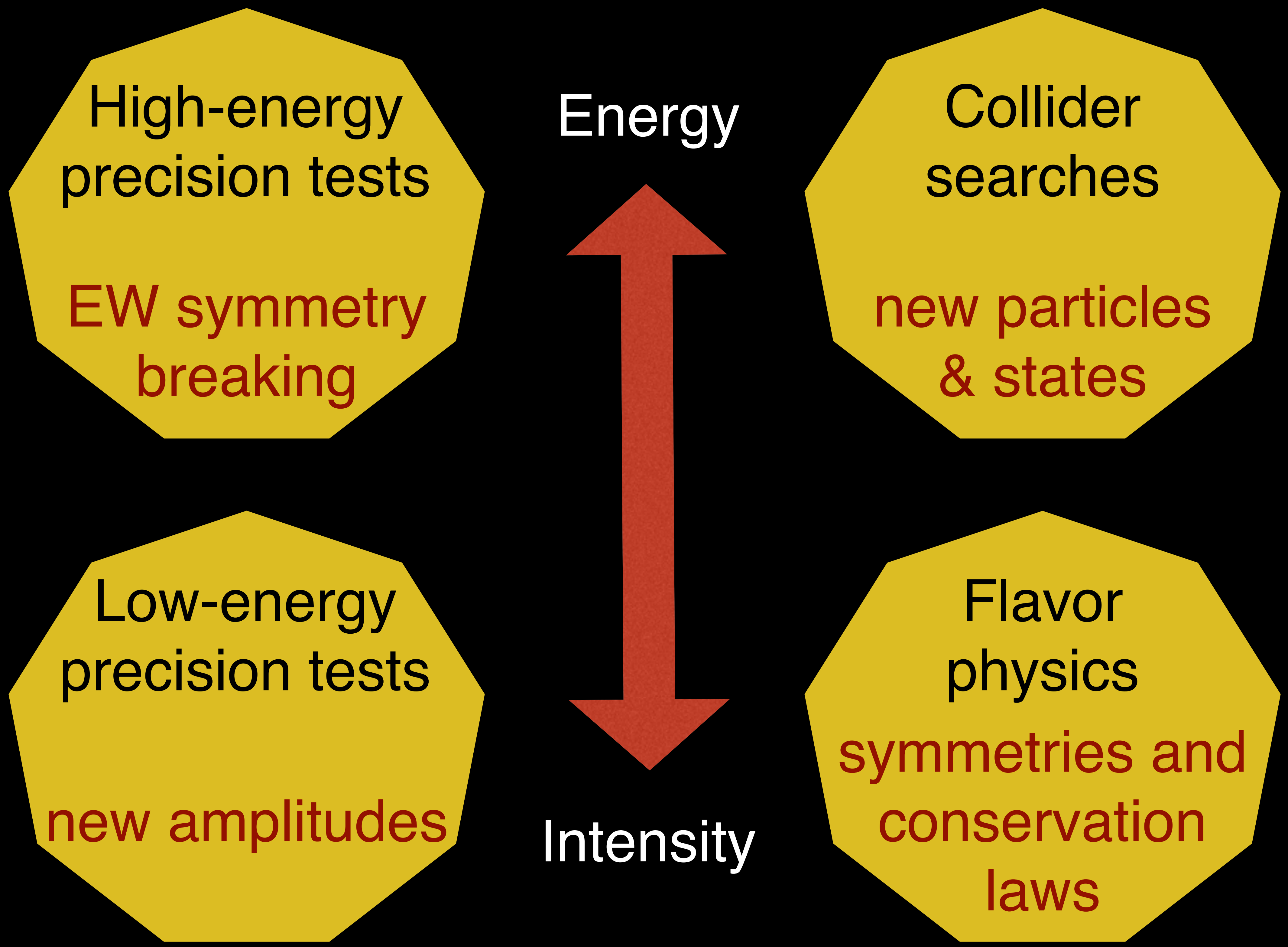


Jens Erler (IF-UNAM)

PHENO 2015

University of Pittsburgh, May 4, 2015

Complementary physics



Complementary tools

High-energy precision tests

EW symmetry breaking

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

Low-energy precision tests

new amplitudes

polarized e^- scattering
ν scattering
atomic parity violation

Complementary facilities

High-energy precision tests

EW symmetry breaking

High energy lepton and hadron colliders

LEP & SLC
Tevatron & LHC

Low-energy precision tests

new amplitudes

Medium energy accelerators & table-top

CEBAF (Jefferson Lab)
MESA (Mainz)

High Energy
Precision Tests

Strategy

- Consider fundamental SM relations like

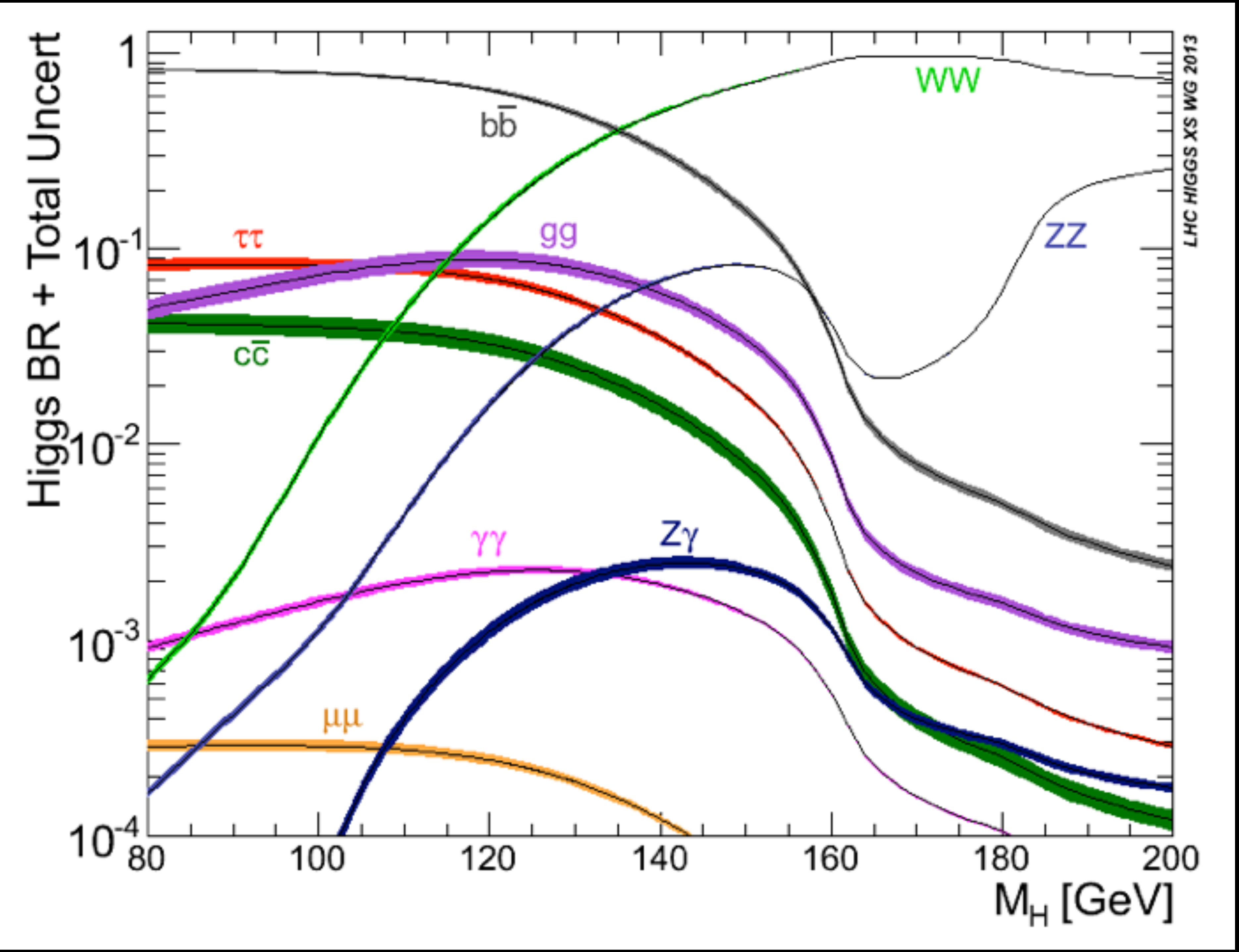
  $\sin^2\theta_W = g'^2/(g^2 + g'^2) = 1 - M_W^2/M_Z^2/(1 + \Delta\rho)$

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

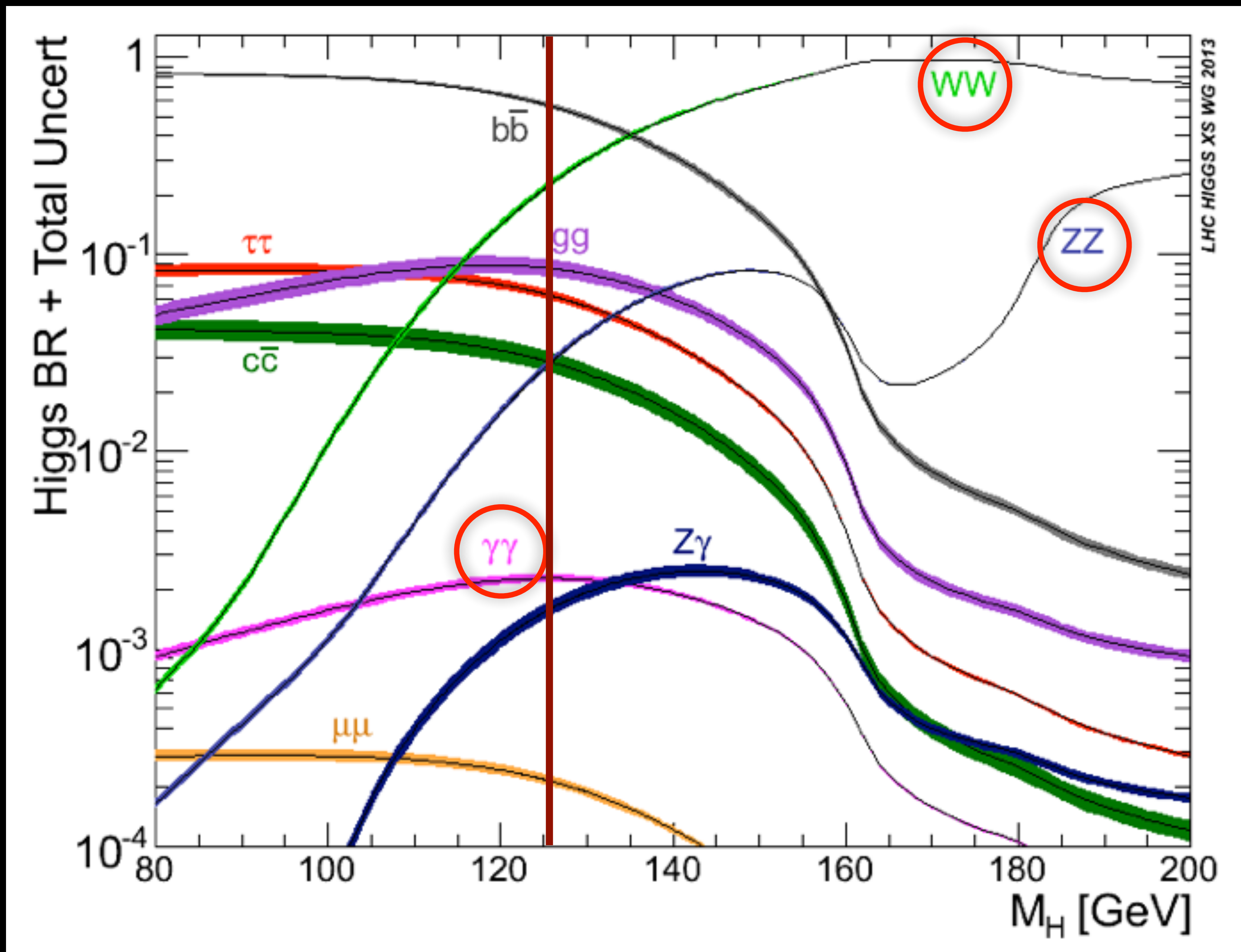
- Compute radiative correction parameters such as $\Delta\rho$ and Δr to very high (two-loop EW) accuracy
- These are functions of m_t, M_H, M_Z, …, as well as M_W and $\sin^2\theta_W$ themselves (needs numerical iterations)
- Compare with experimental $\Delta\rho$ and Δr to test SM and look for deviations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

M_H

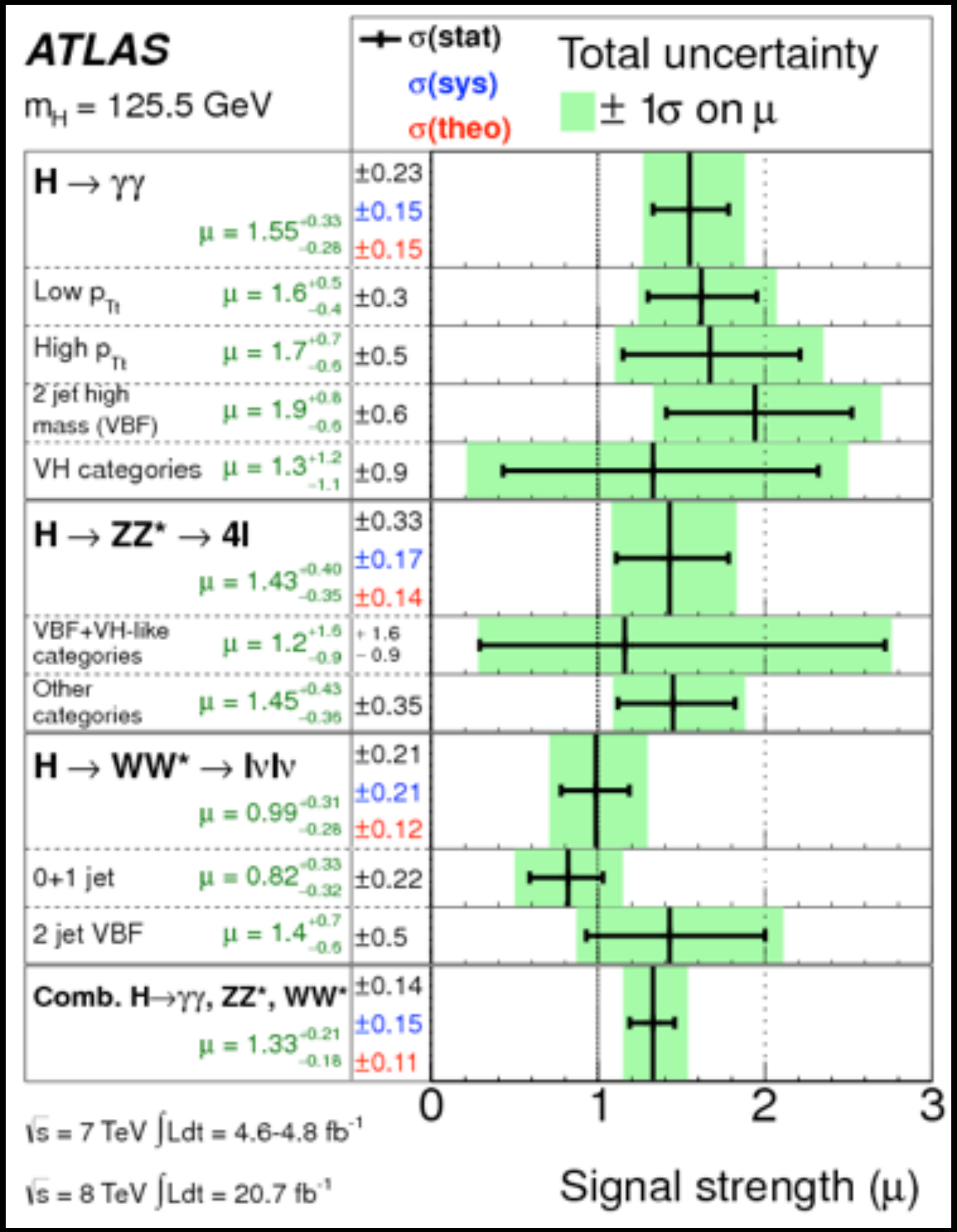
M_H from Higgs branching ratios?

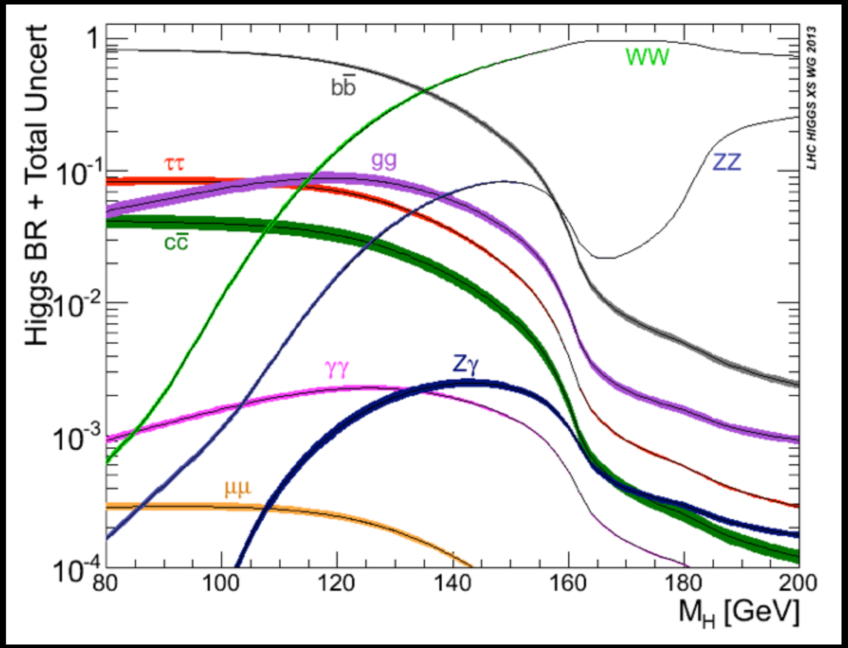


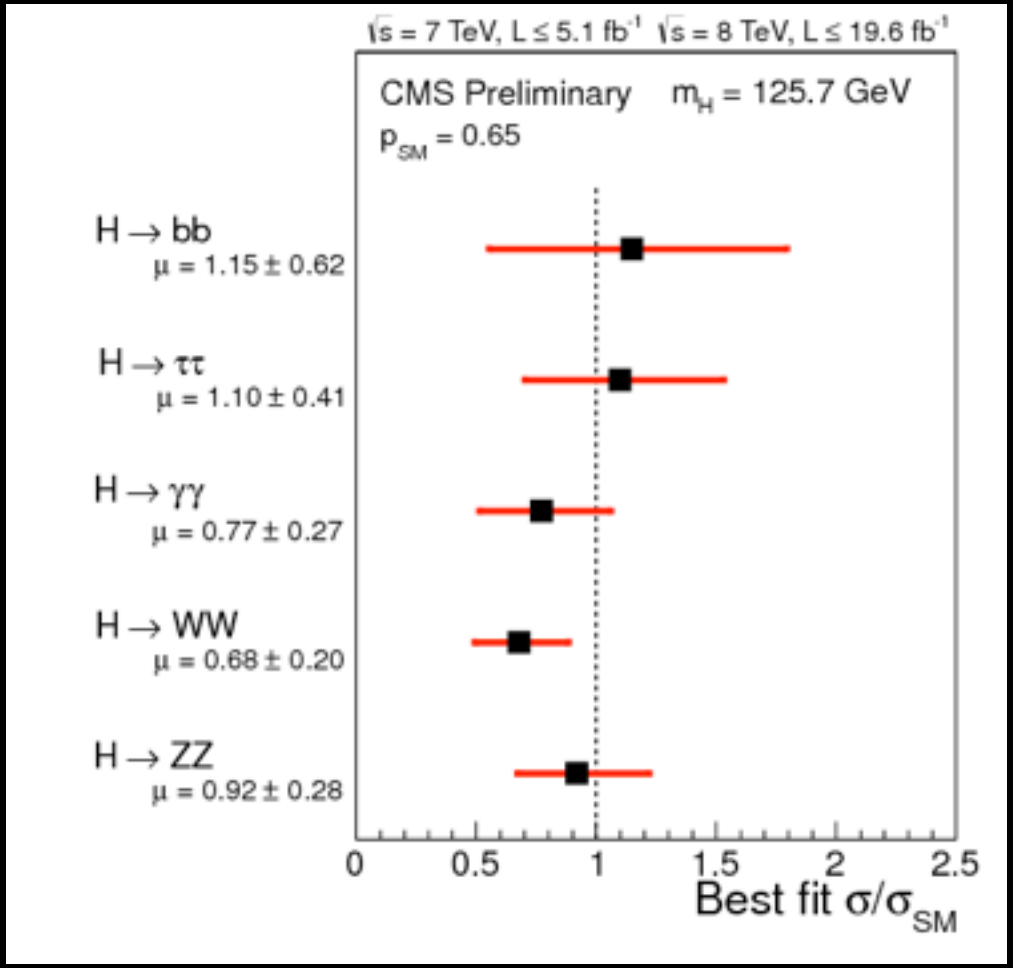
M_H from Higgs branching ratios?



Compare with results on coupling strength





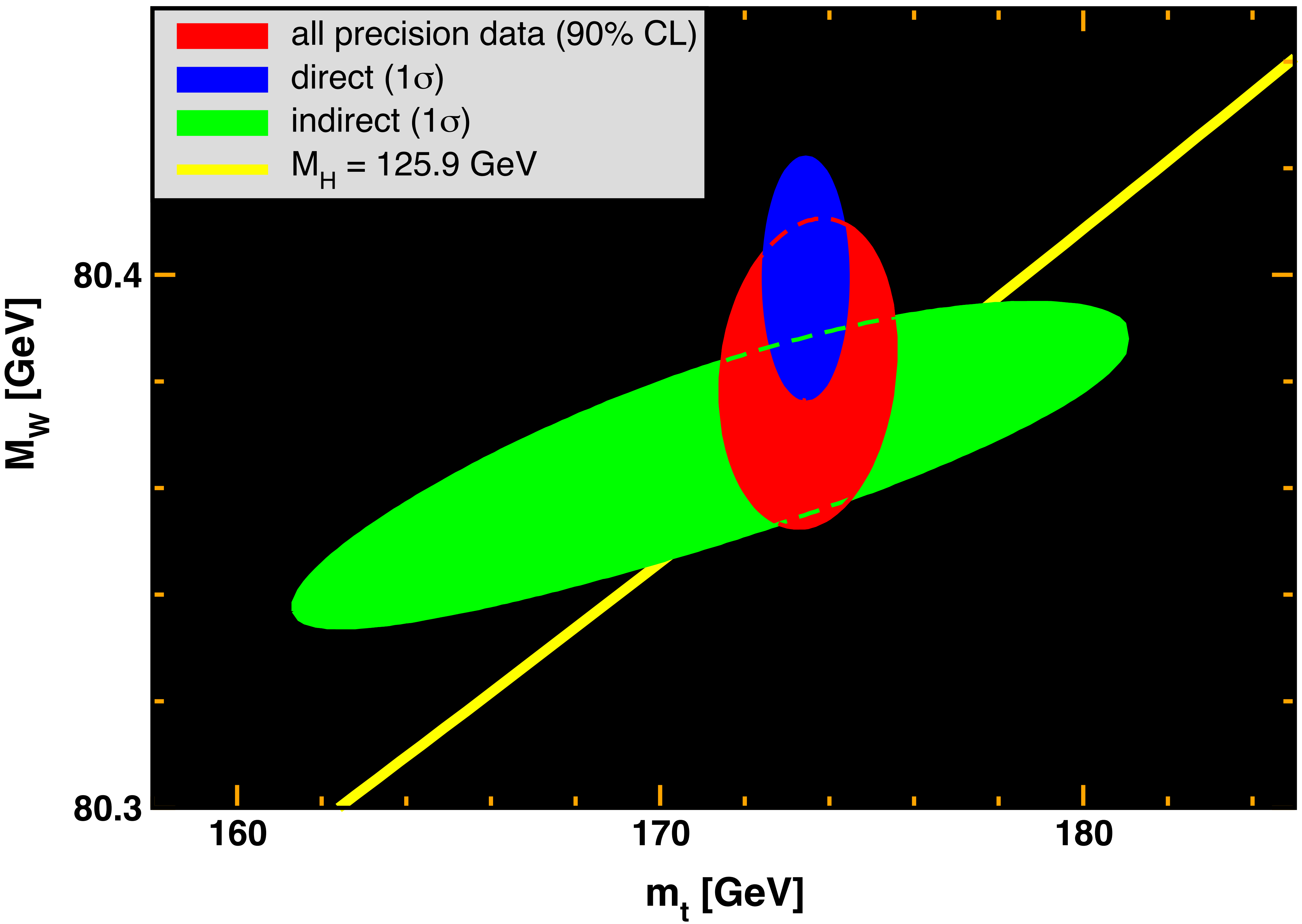


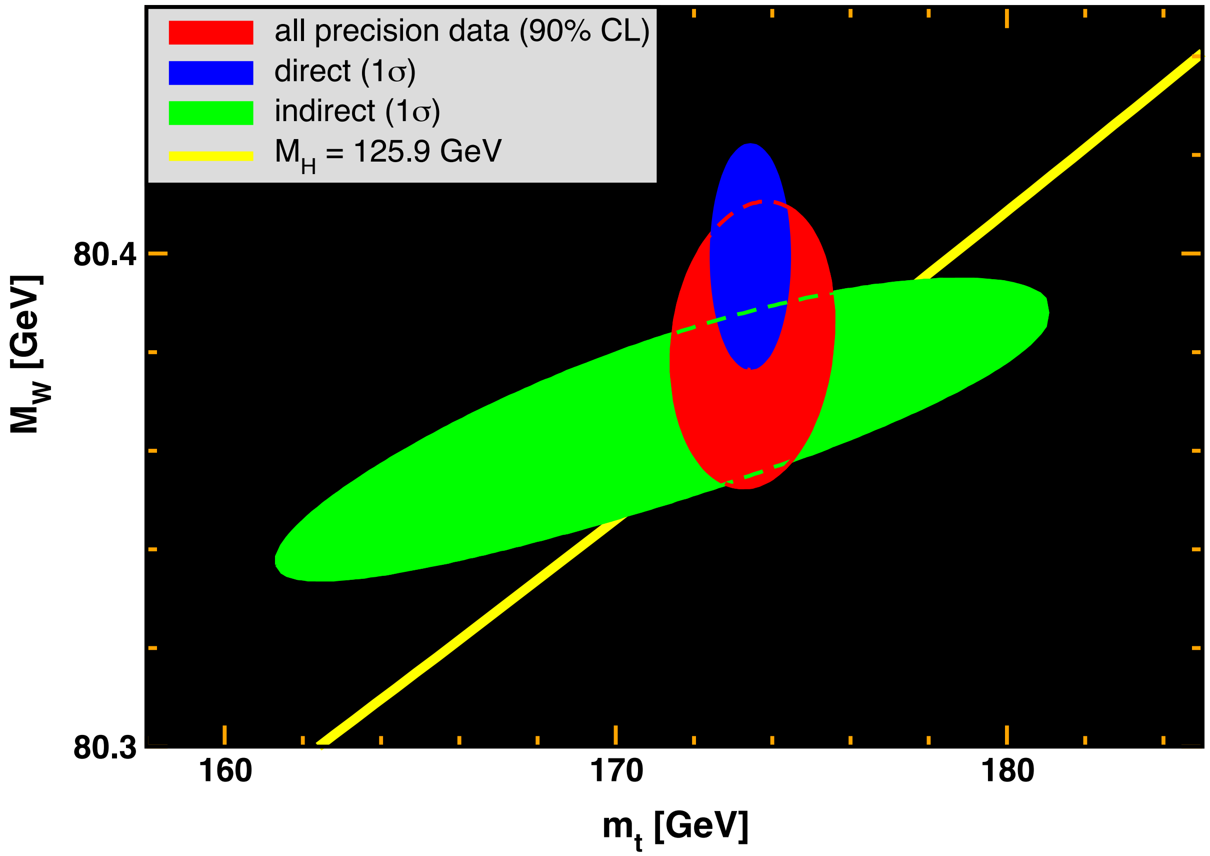
M_H [GeV]

source	M	uncertainty
radiative corrections	89	$^{+22}$
LHC	123.7	2.3
ATLAS	125.5	0.6
CMS	125.7	0.4
global fit	125.5	0.4

JE, Freitas 2013
PDG 2014

M_w


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
M_W [GeV]
80.4
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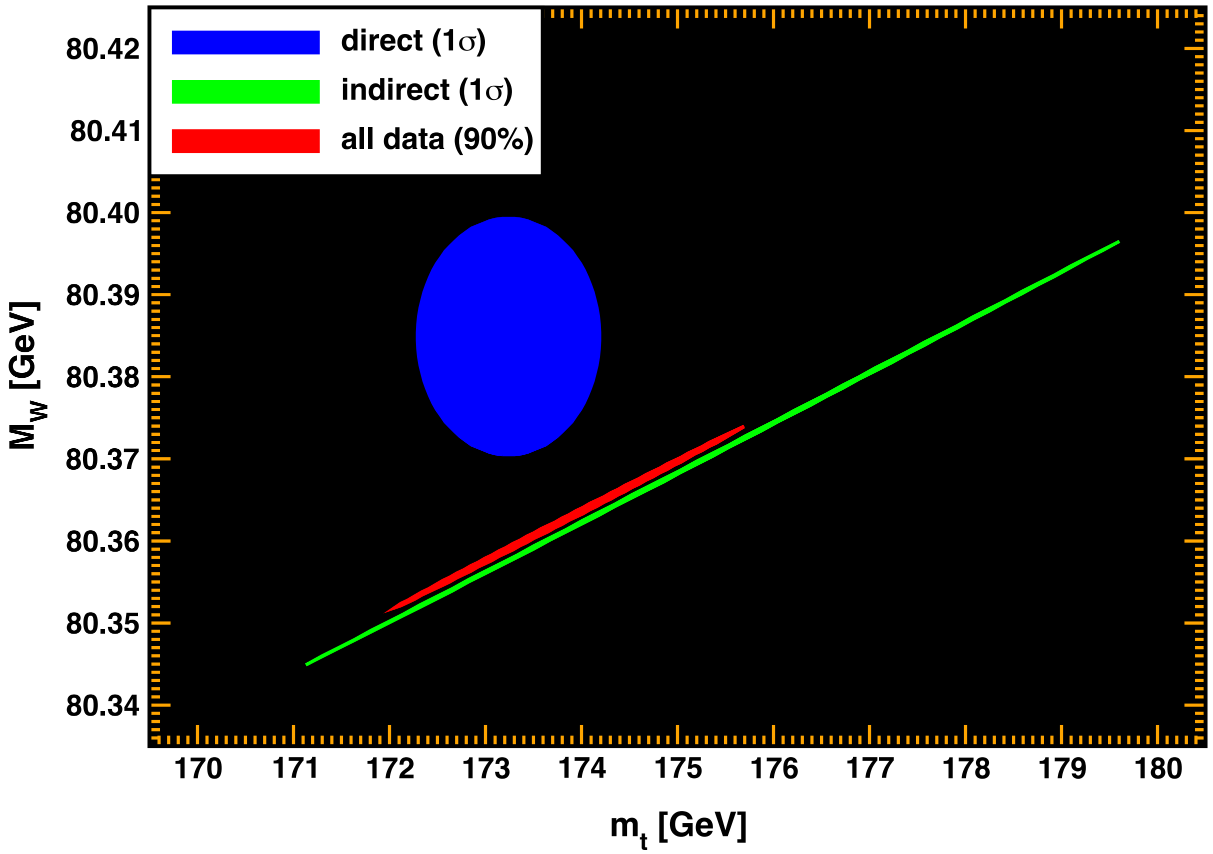
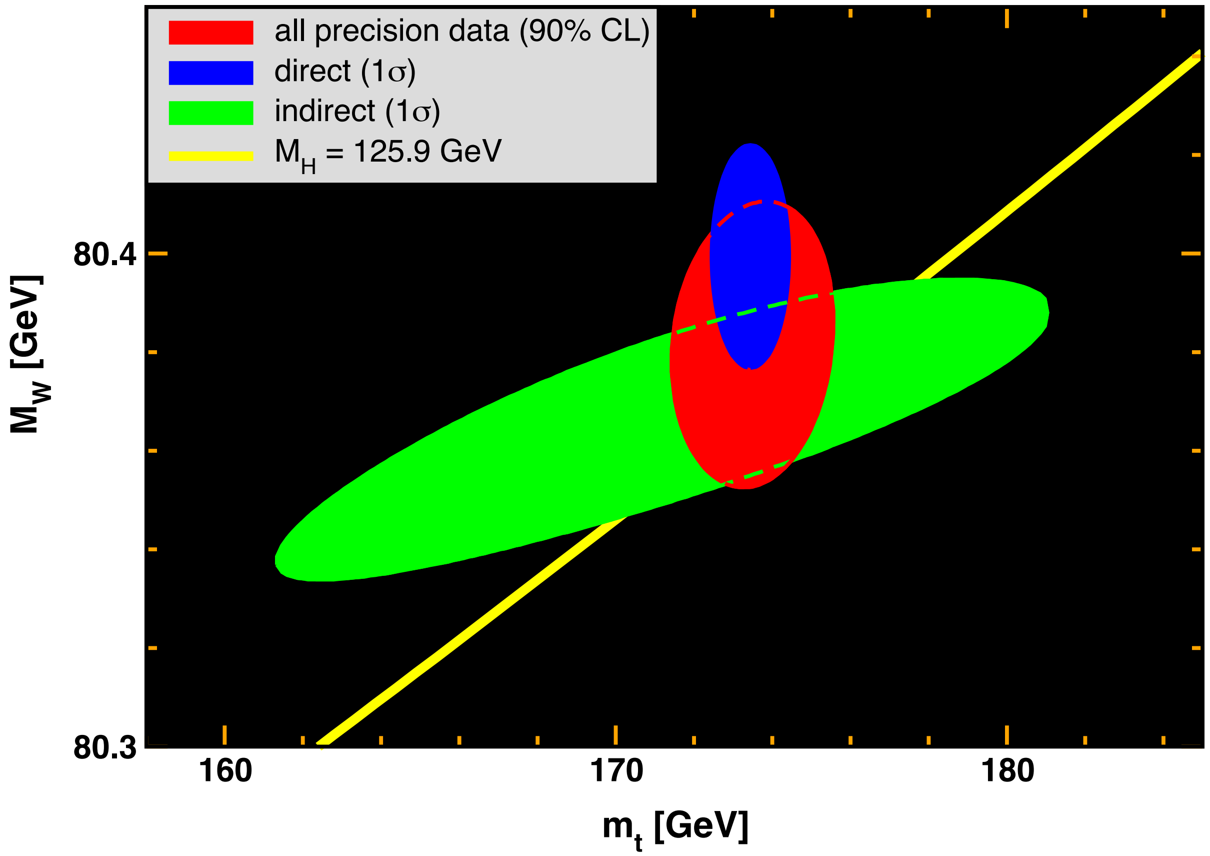
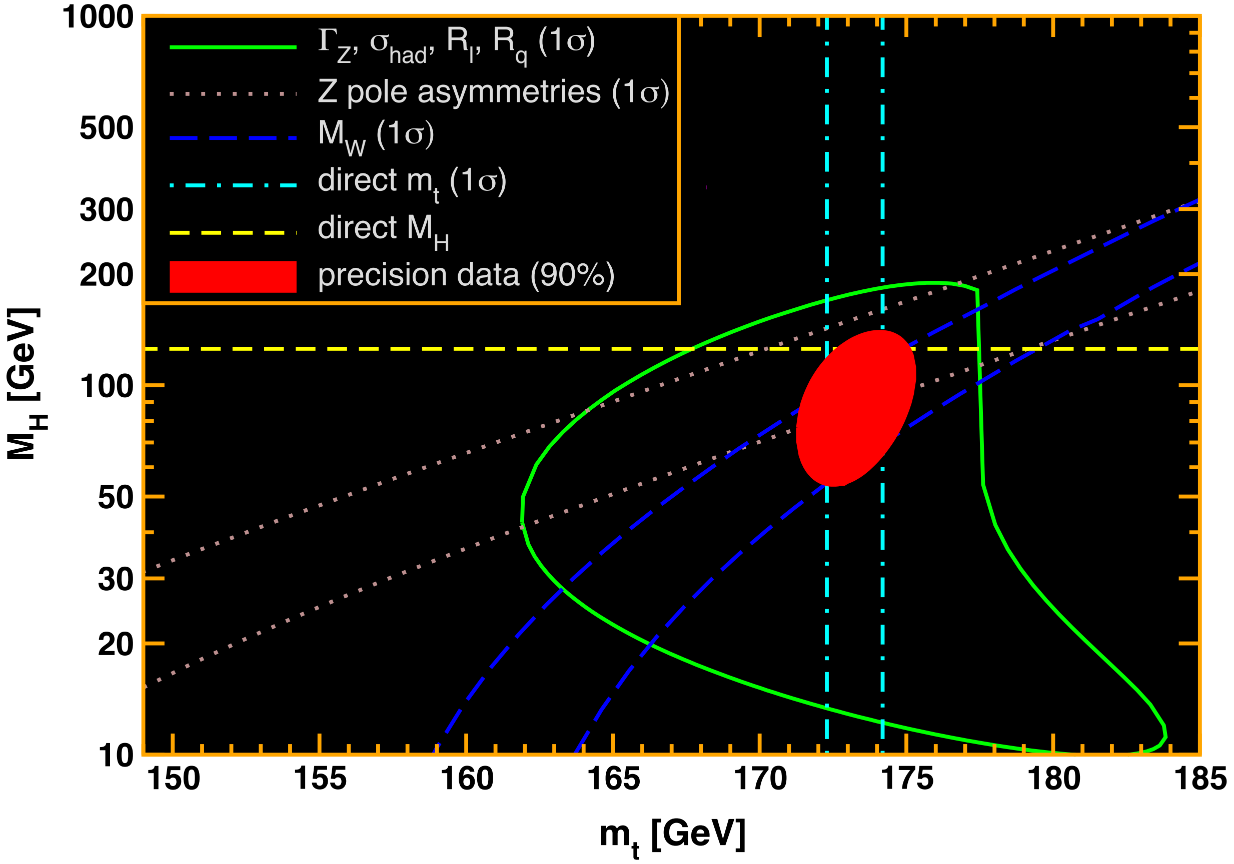
170
180
m_t [GeV]

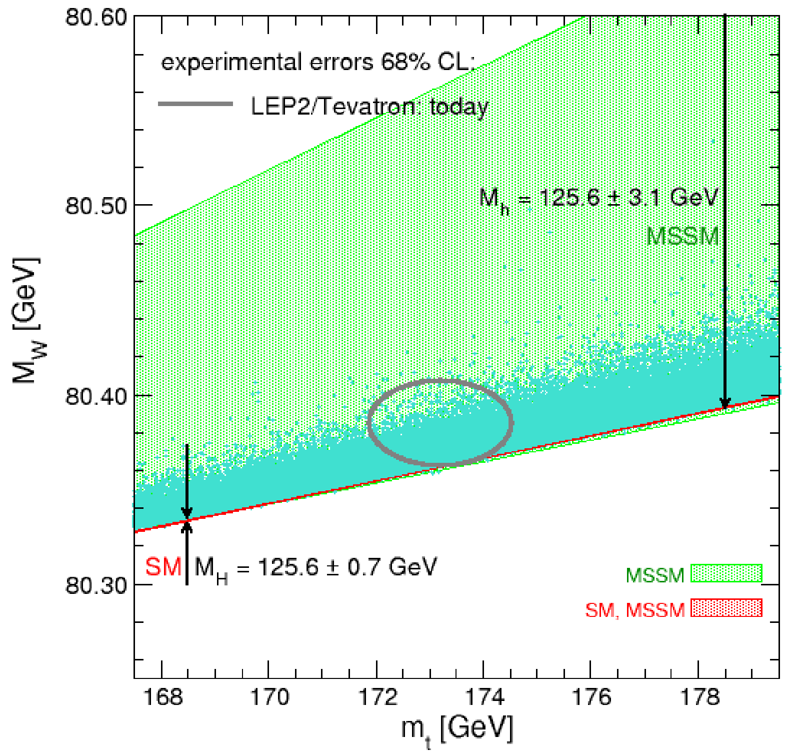

direct (1σ)
indirect (1σ)
all data (90%)
M_W [GeV]
80.42
80.41
80.40
80.39
80.38
80.37
80.36
80.35
80.34
170
171
172
173
174
175
176
177
178
179
180
m_t [GeV]

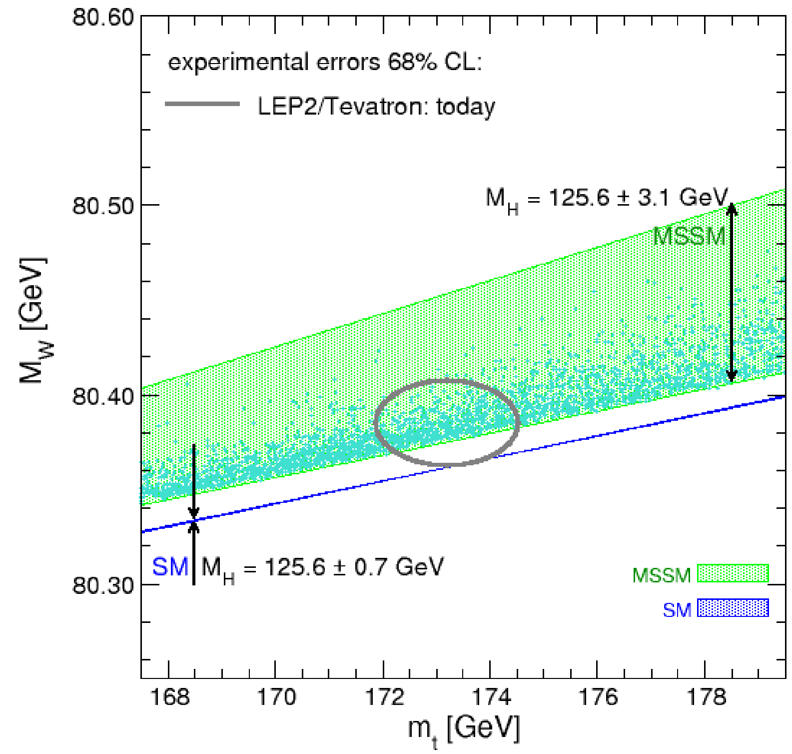


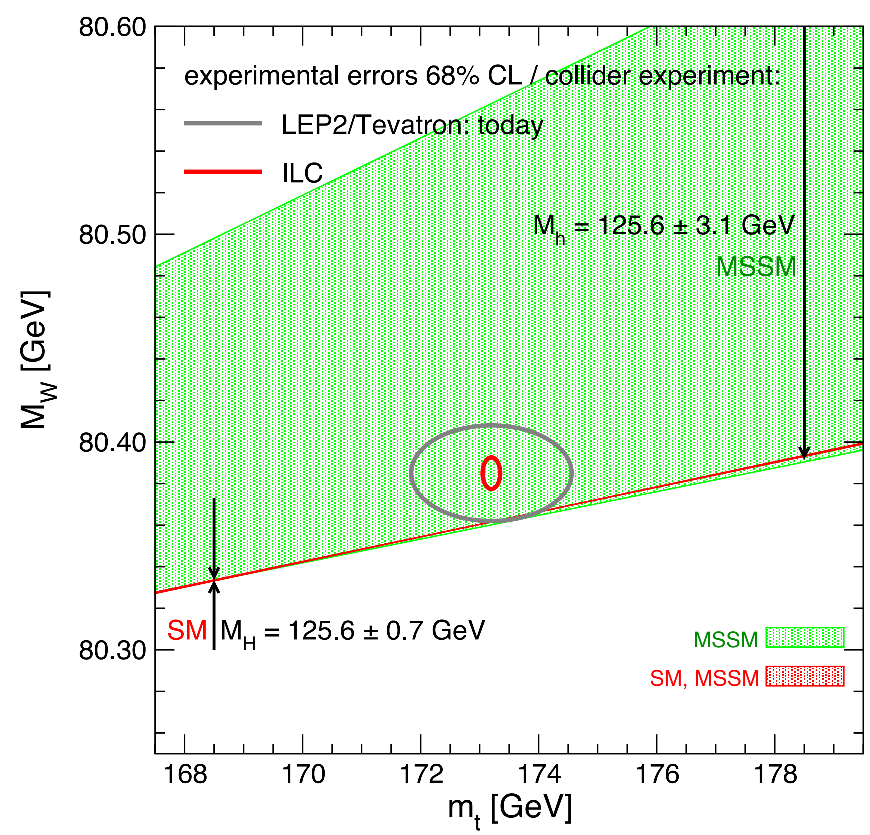
all precision data (90% CL)
direct (1σ)
indirect (1σ)
M_H = 125.9 GeV
80.4
80.3
M_W [GeV]
160
170
180
m_t [GeV]



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

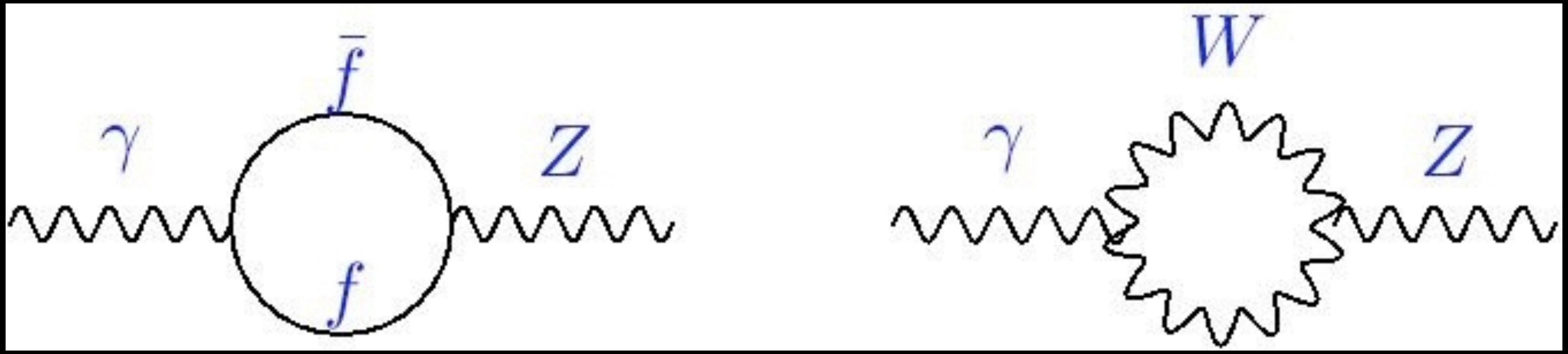
$\sin^2\theta_W$

$\sin^2\theta_W$

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

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

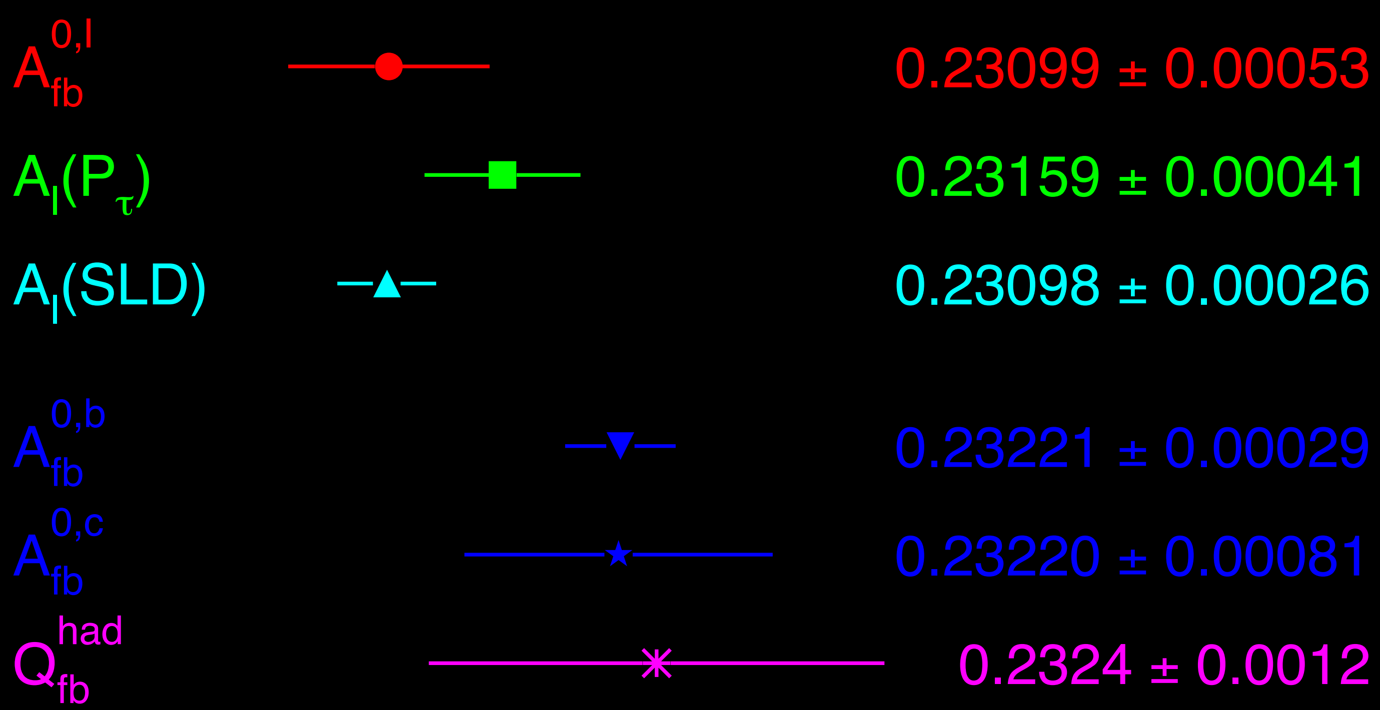
$$A = \sin\theta_W W^3 + \cos\theta_W B$$



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

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

Z-pole Asymmetries



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

Tevatron Average: 0.23176 ± 0.00060

LHC Average: 0.2297 ± 0.0010

Grand Average: 0.23150 ± 0.00016 χ^2/d.o.f. = 20.2/14

Standard Model: 0.23155 ± 0.000047

Parametric uncertainty in prediction

LEP/SLC Average: 0.23153 ± 0.00016 $\chi^2/\mathrm{d.o.f.} = 16.8/12$

Tevatron Average: 0.23176 ± 0.00060

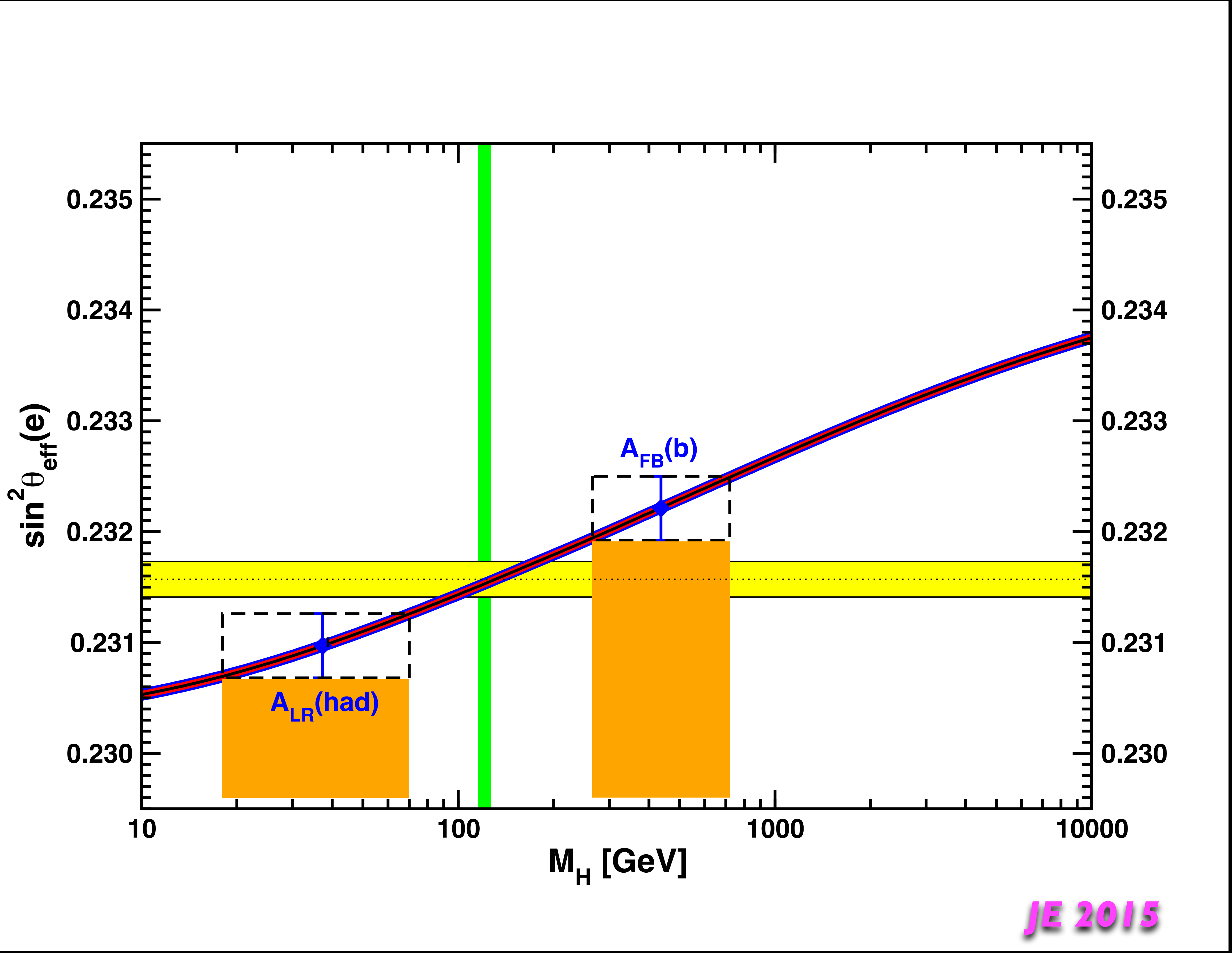
LHC Average: 0.2297 ± 0.0010

Grand Average: 0.23150 ± 0.00016 $\chi^2/\mathrm{d.o.f.} = 20.2/14$

Standard Model: 0.23155 ± 0.000047

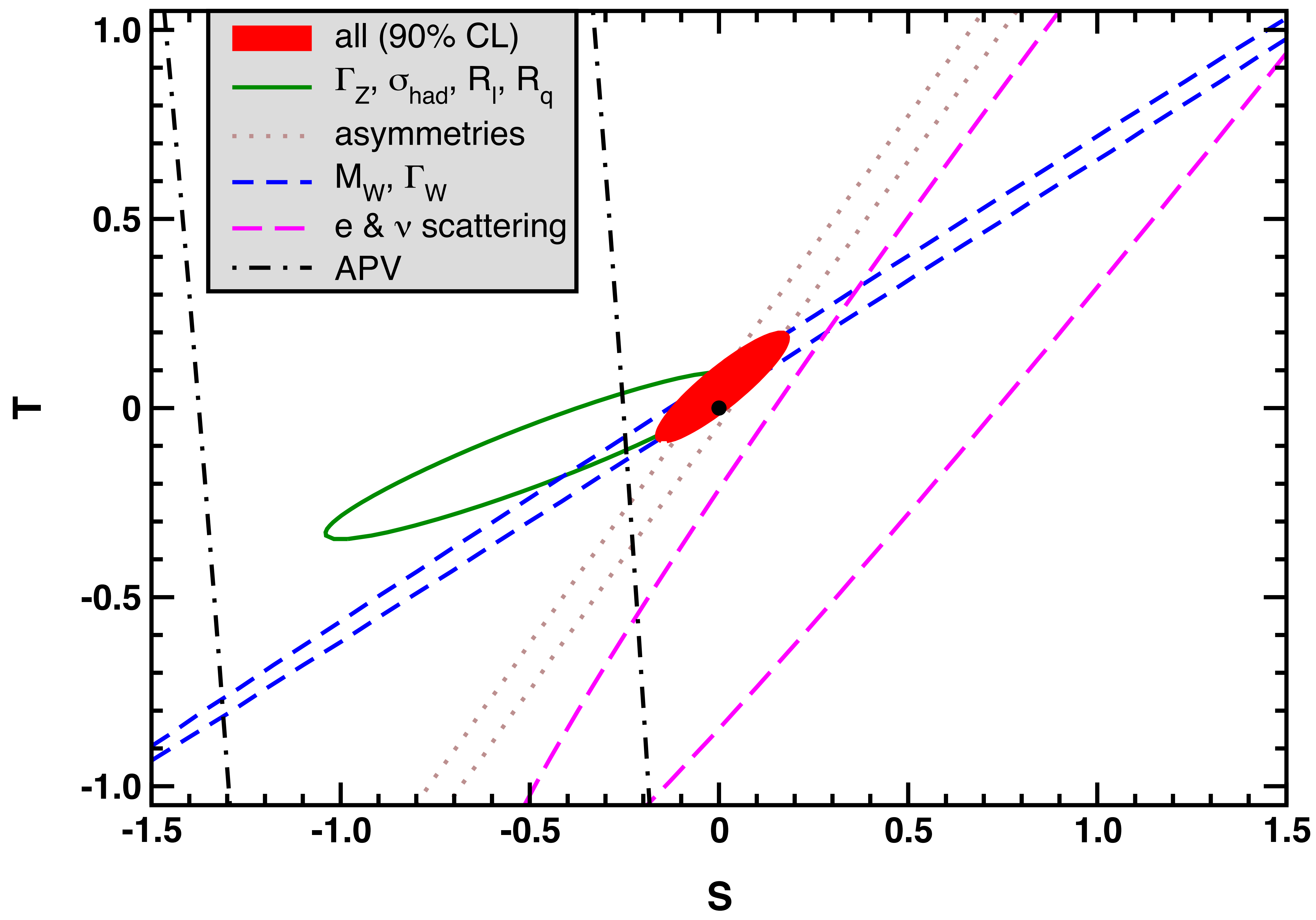
theory uncertainty also ± 0.00005 (conservative)

± 0.000047 (SM) =
± 0.000015 (M_Z)
± 0.000026 (m_t)
± 0.000020 (m_c)
± 0.000020 (α_s)
± 0.000023 (α_{had})

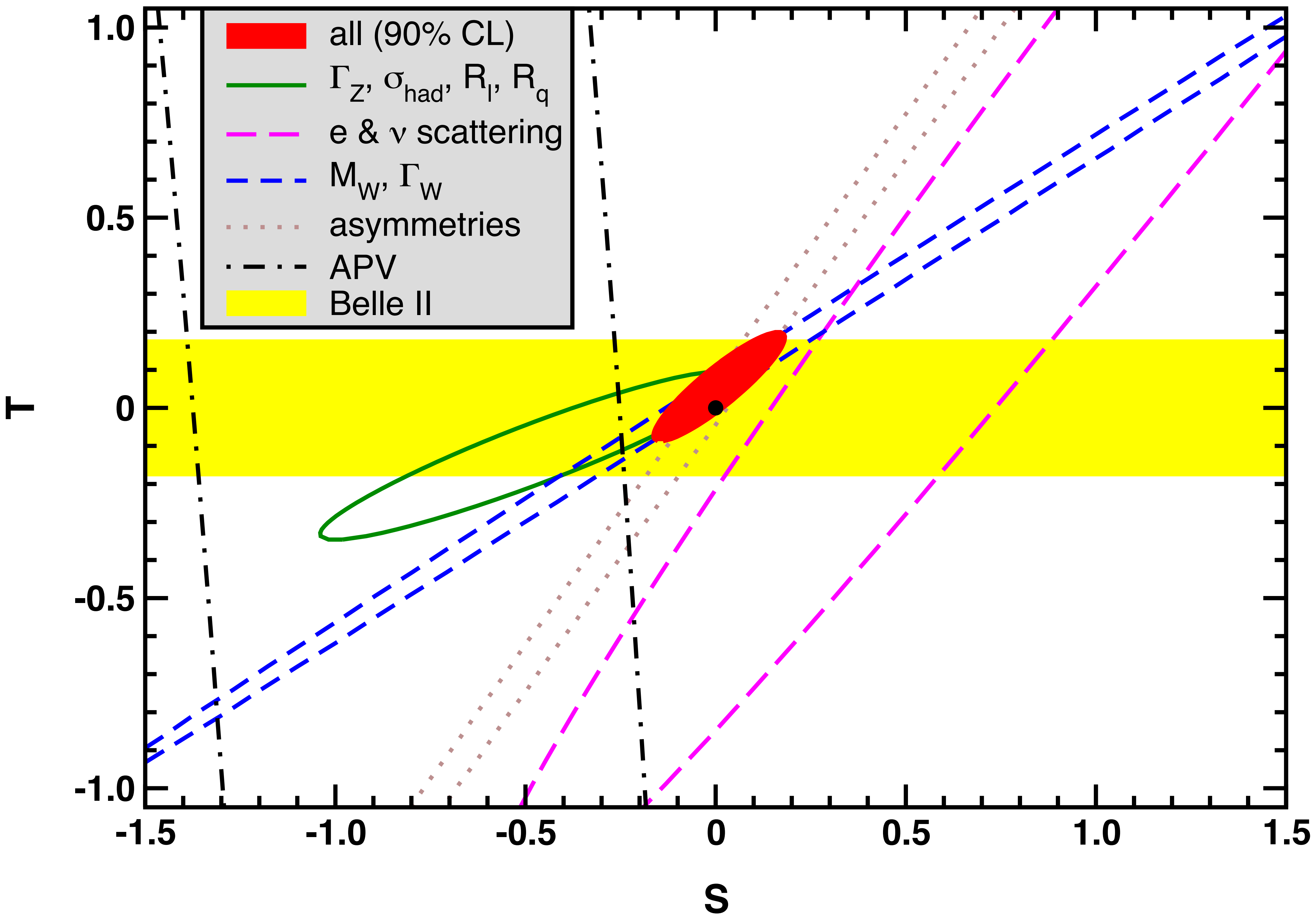


0.235
0.234
0.233
0.232
0.231
0.230
$\sin^2\theta_{eff}(e)$
$A_{FB}(b)$
$A_{LR}(had)$
10
100
1000
10000
M_H [GeV]
JE 2015

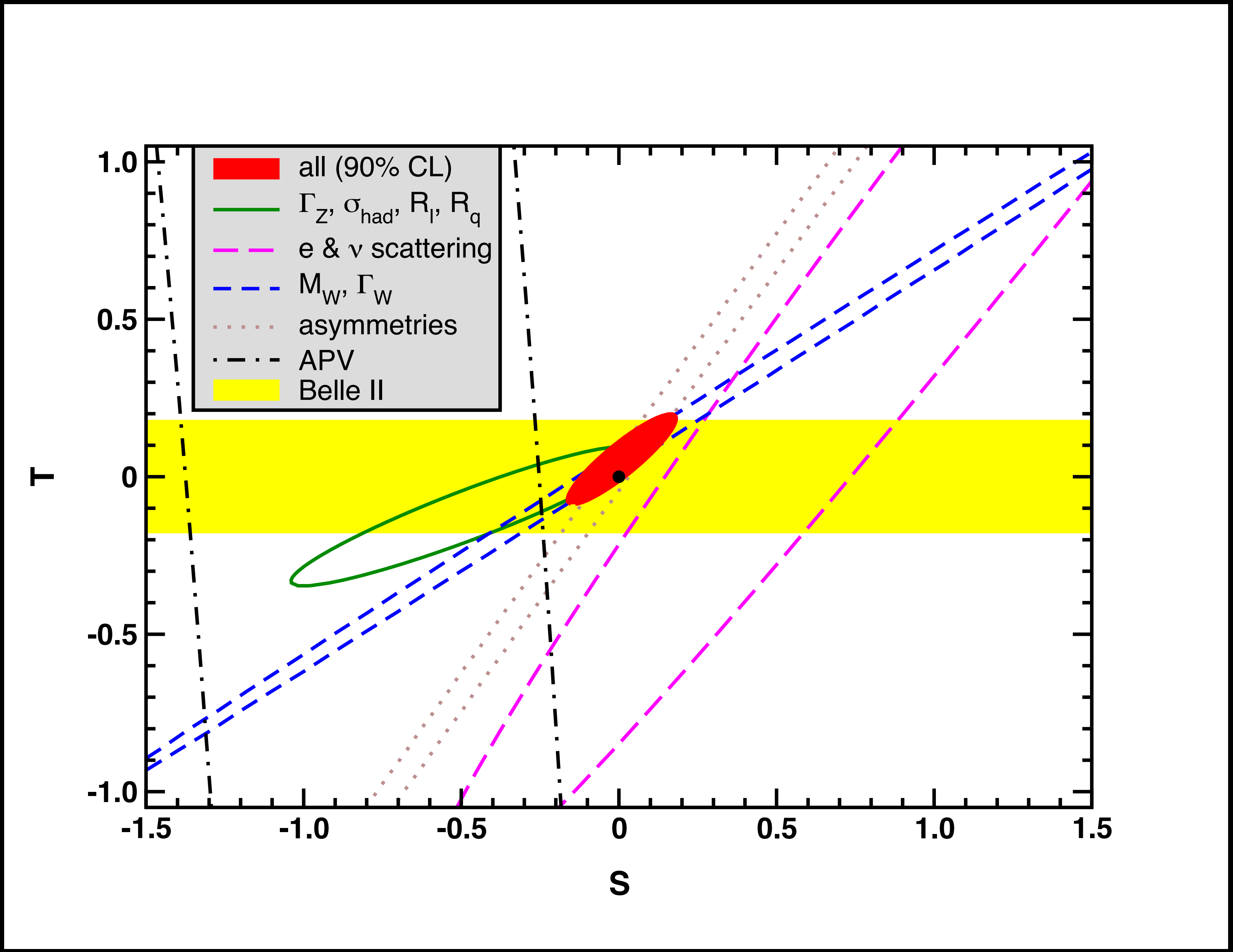
STU



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

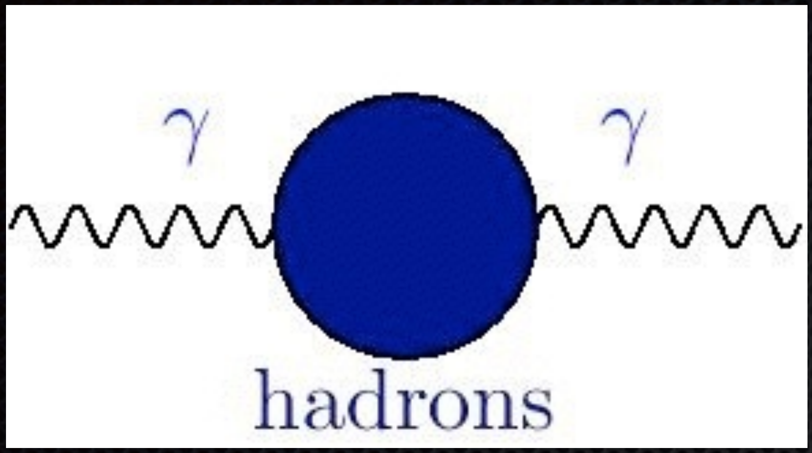


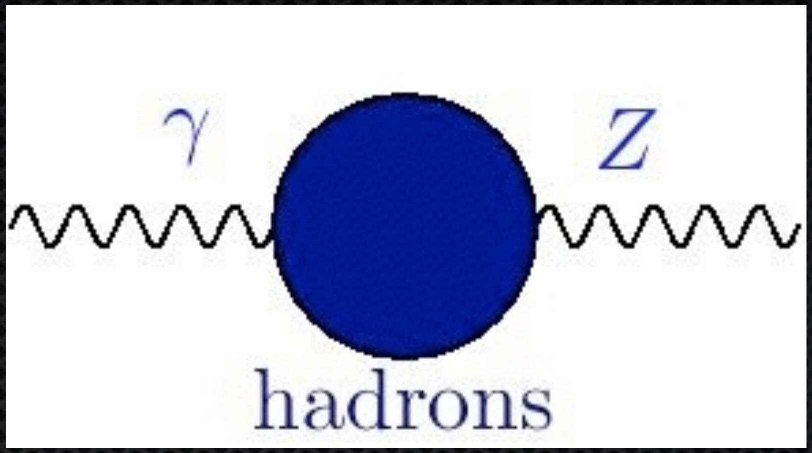
all (90% CL)
Γ_Z, σ_had, R_l, R_q
e & ν scattering
M_W, Γ_W
asymmetries
APV
Belle II
T
S
1.0
0.5
0
-0.5
-1.0
-1.5
-1.0
-0.5
0
0.5
1.0
1.5



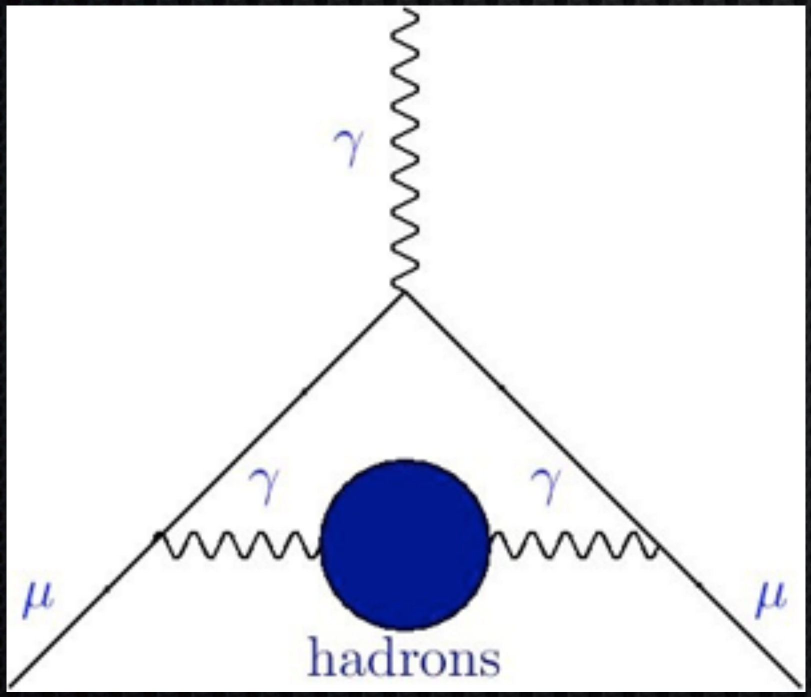
- T constraints mass splittings within SU(2) doublets
- Currently, $\sum_i C_i/3\ \Delta m_i^2 \leq (50\ \mathrm{GeV})^2$
- A_{FB} would give similar constraint (independent of S)

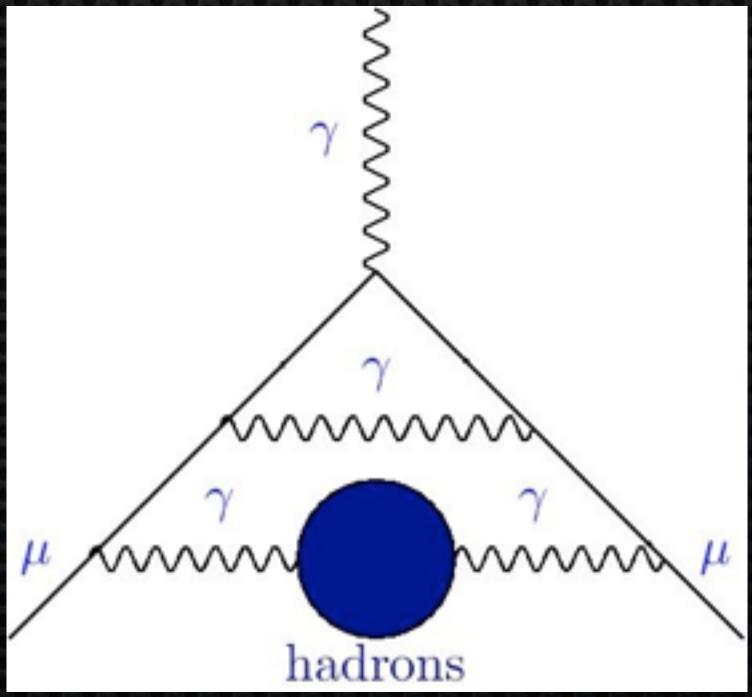
Low Energy
Precision Tests

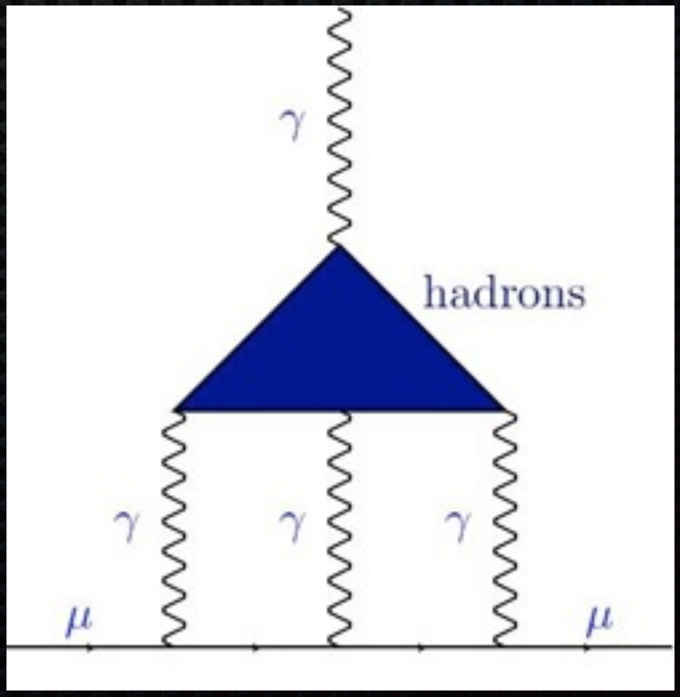




Hadronic effects

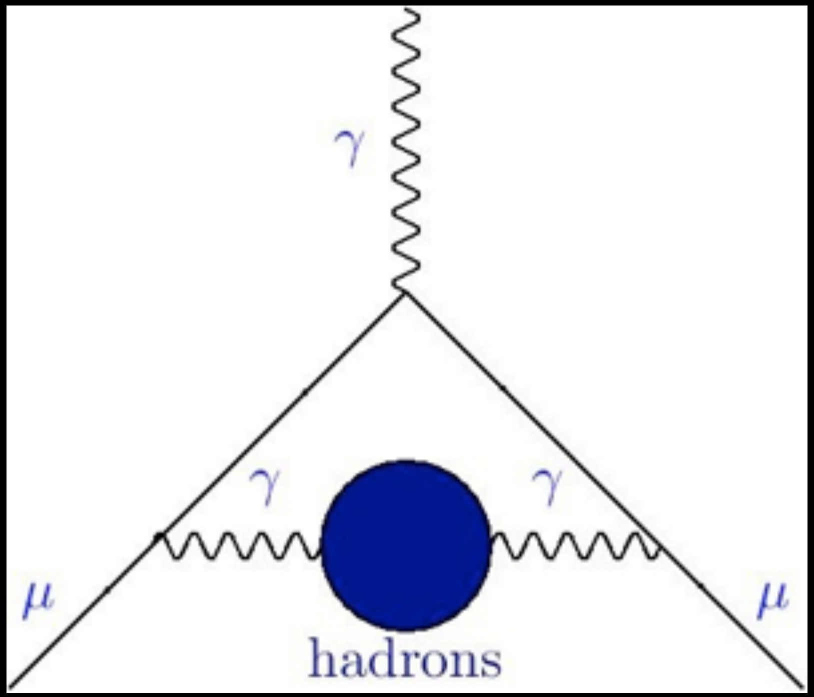


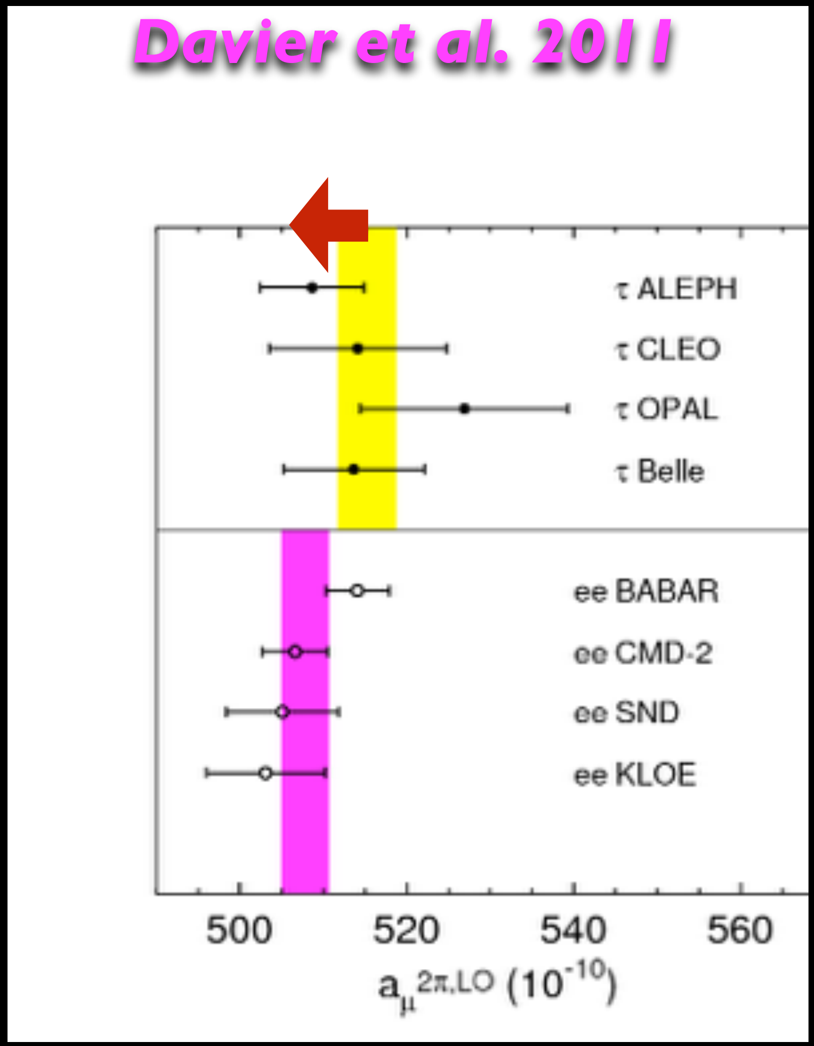




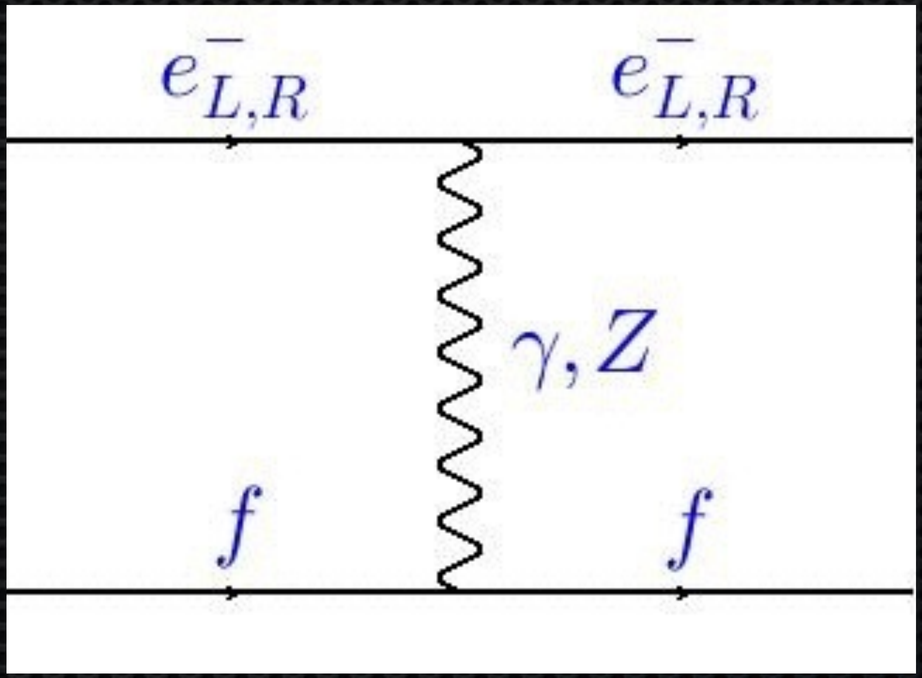
$g_\mu - 2$

- $a_\mu \equiv (1165920.80 \pm 0.63)\times 10^{-9}$ ***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*

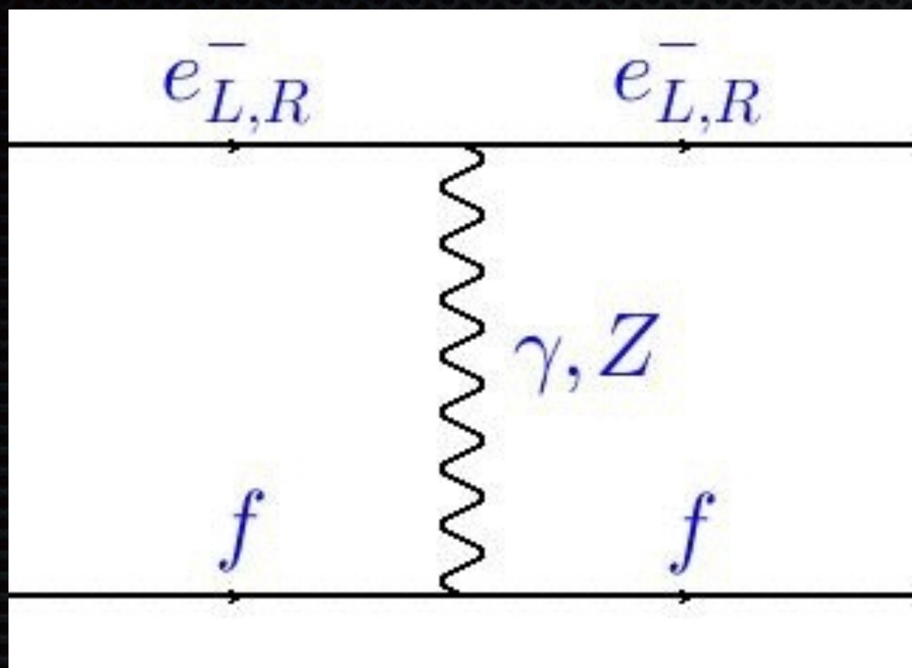


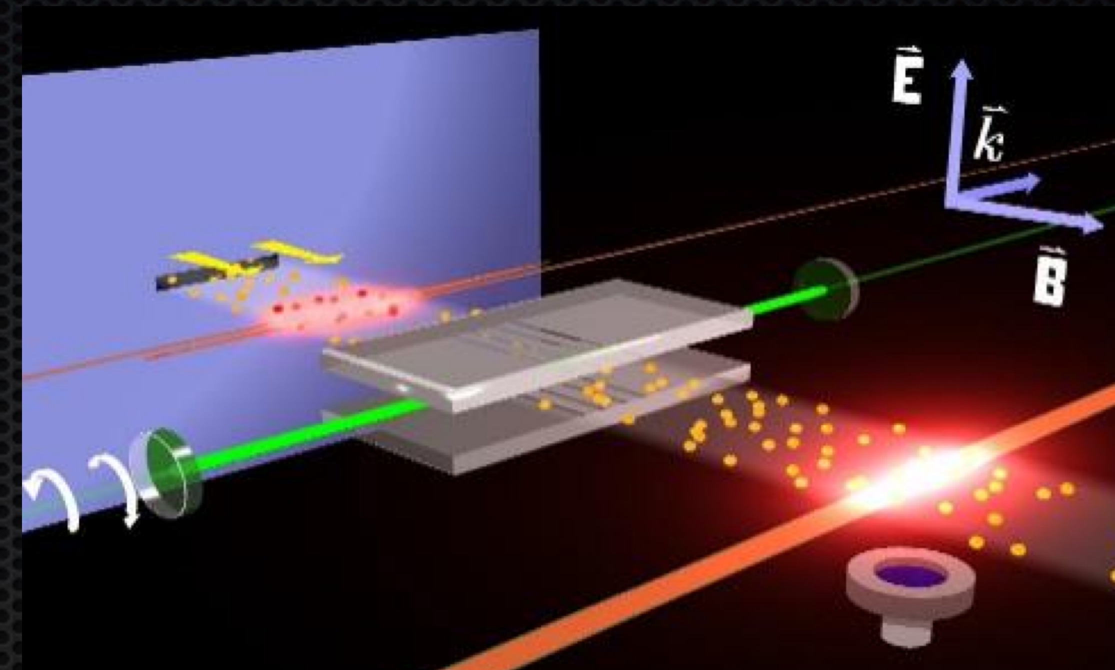


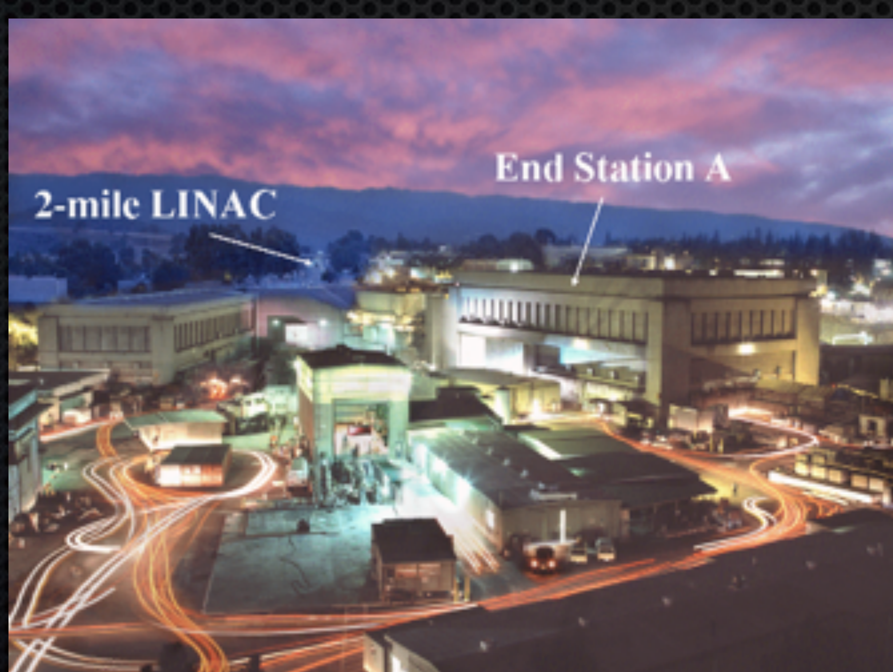
Parity Violation
– interference –



Parity Violation
– interference –



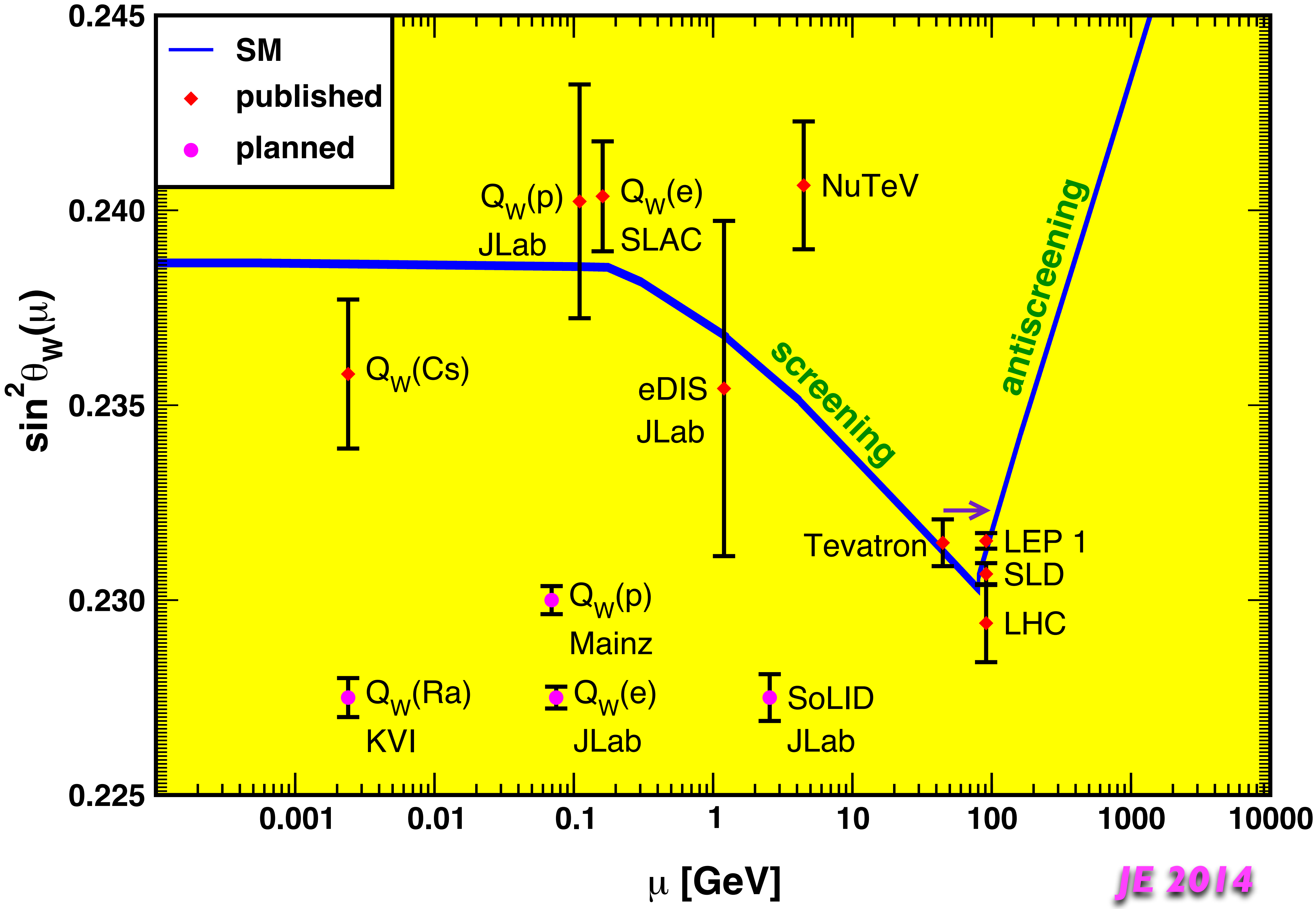




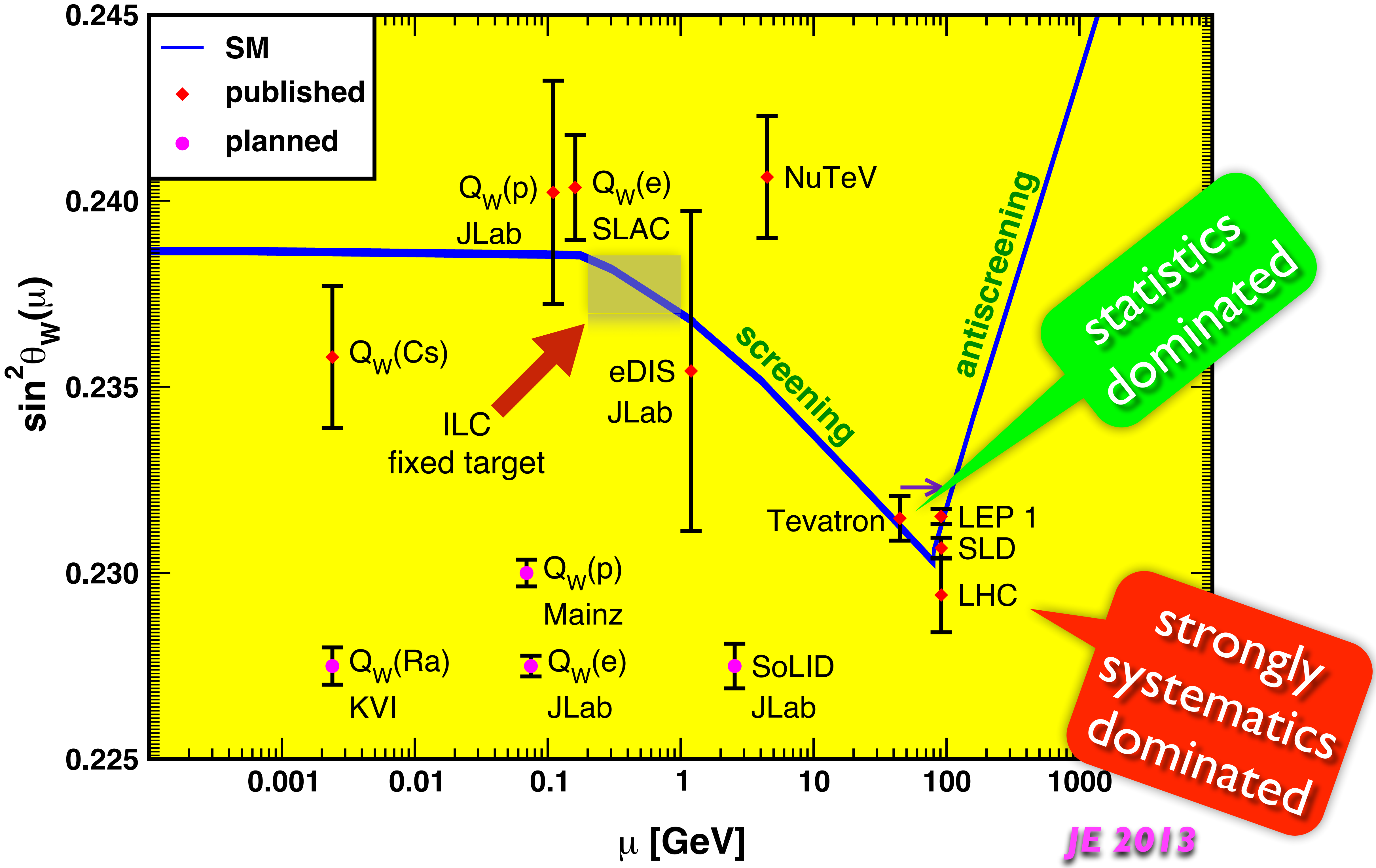
JG|U
JOHANNES GUTENBERG UNIVERSITÄT MAINZ

Jefferson Lab
Thomas Jefferson National Accelerator Facility

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

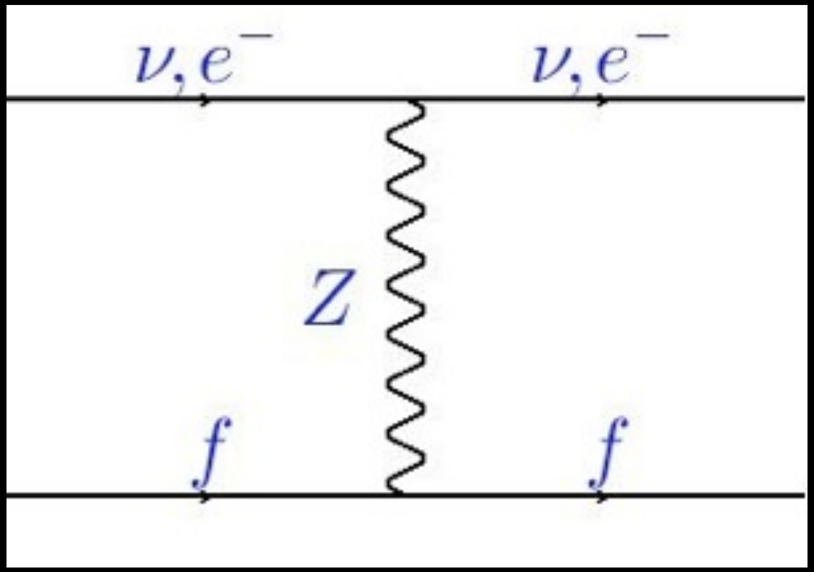


$\overline{\text{MS}}$-scheme



Contact Interactions

Effective couplings

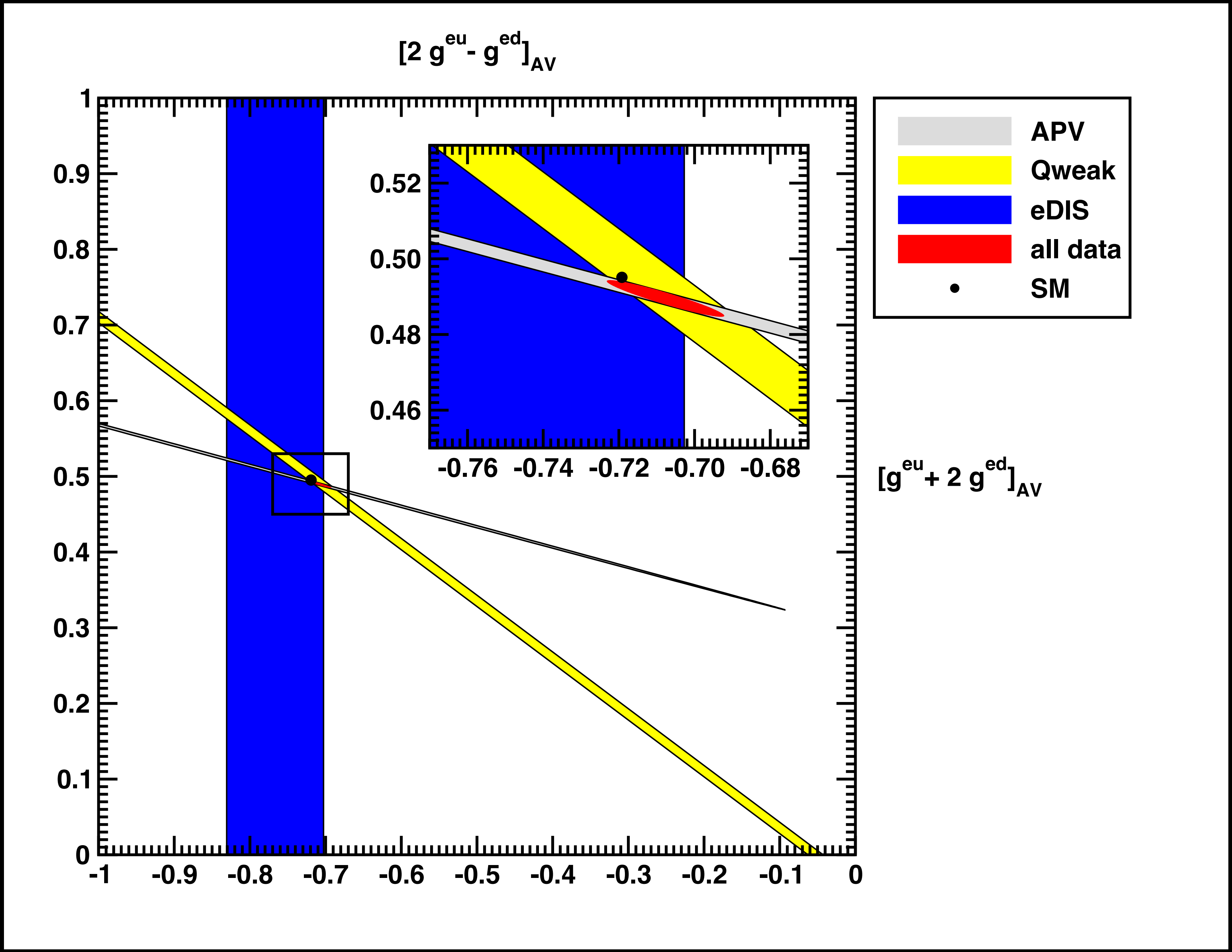


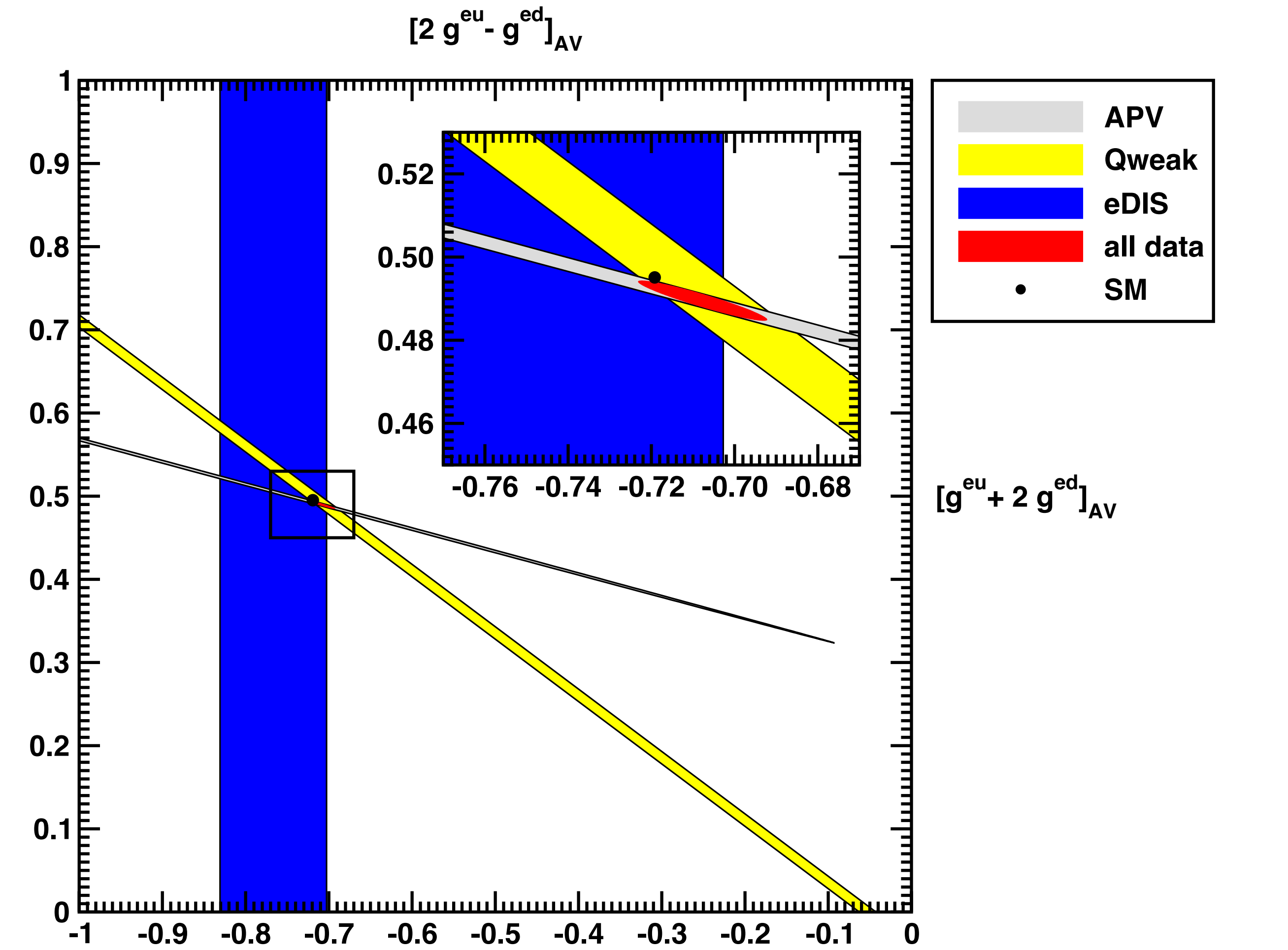
- Normalized so that $g_{LLLL} = 1$ (μ-decay)
- NC couplings: $g^{ef}_{AV}\ \bar{e}\gamma^{\mu}\gamma^{5} e\ \bar{f}\gamma_{\mu} f$ $\qquad g^{ef}_{VA}\ \bar{e}\gamma^{\mu} e\ \bar{f}\gamma_{\mu}\gamma^{5} f$
- $|g^{ef}_{AV}| = \frac{1}{2} - 2\,|Q_f|\,\sin^2\theta_W$ $\qquad |g^{ef}_{VA}| = \frac{1}{2}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

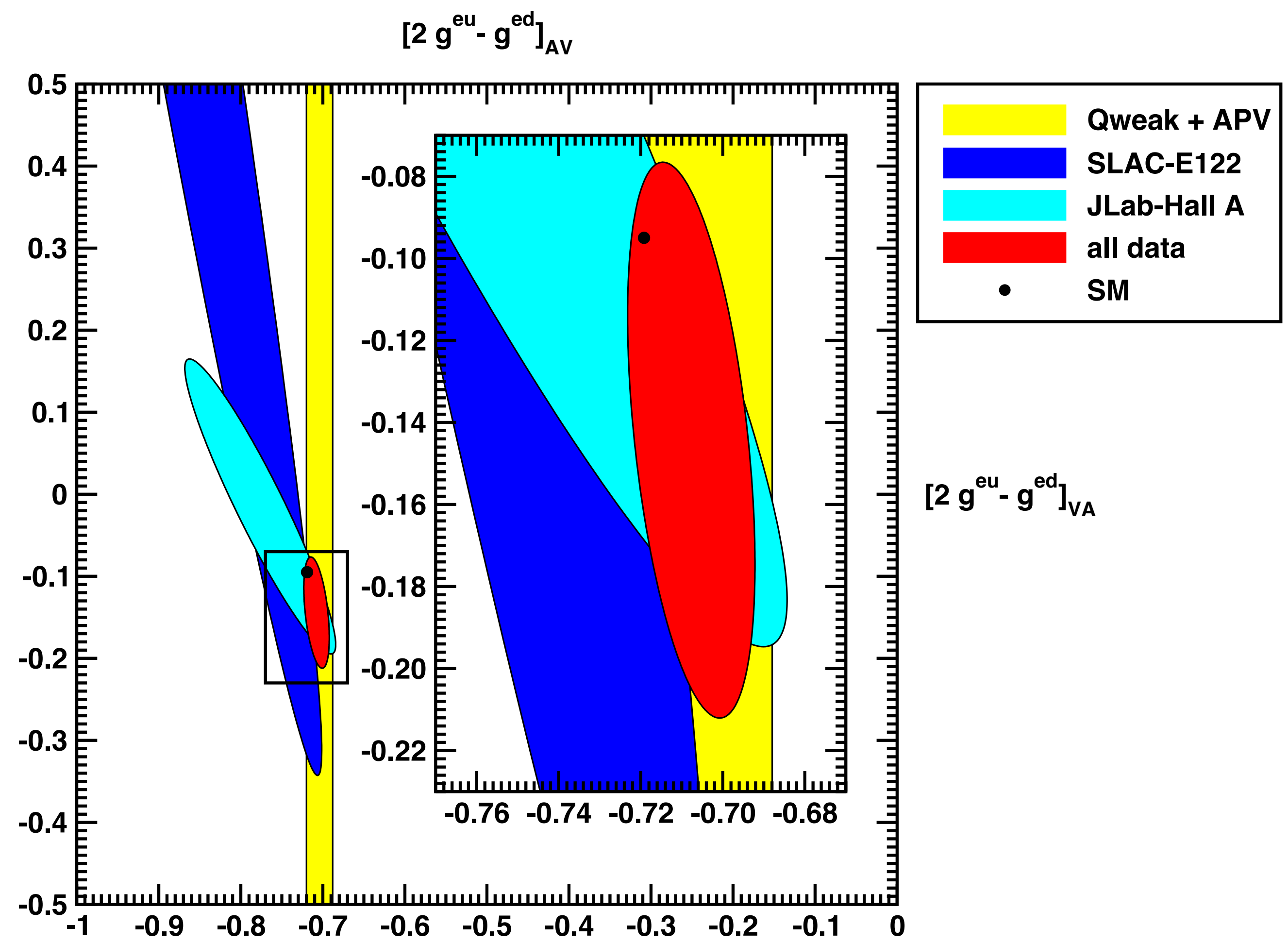
Asymmetries

- 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 / Belle II: $\chi \sim Q^2\, G_F \ll 1 \Longrightarrow$
  - $a_e\, v_f$ (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 $\sin^2\theta_W$)

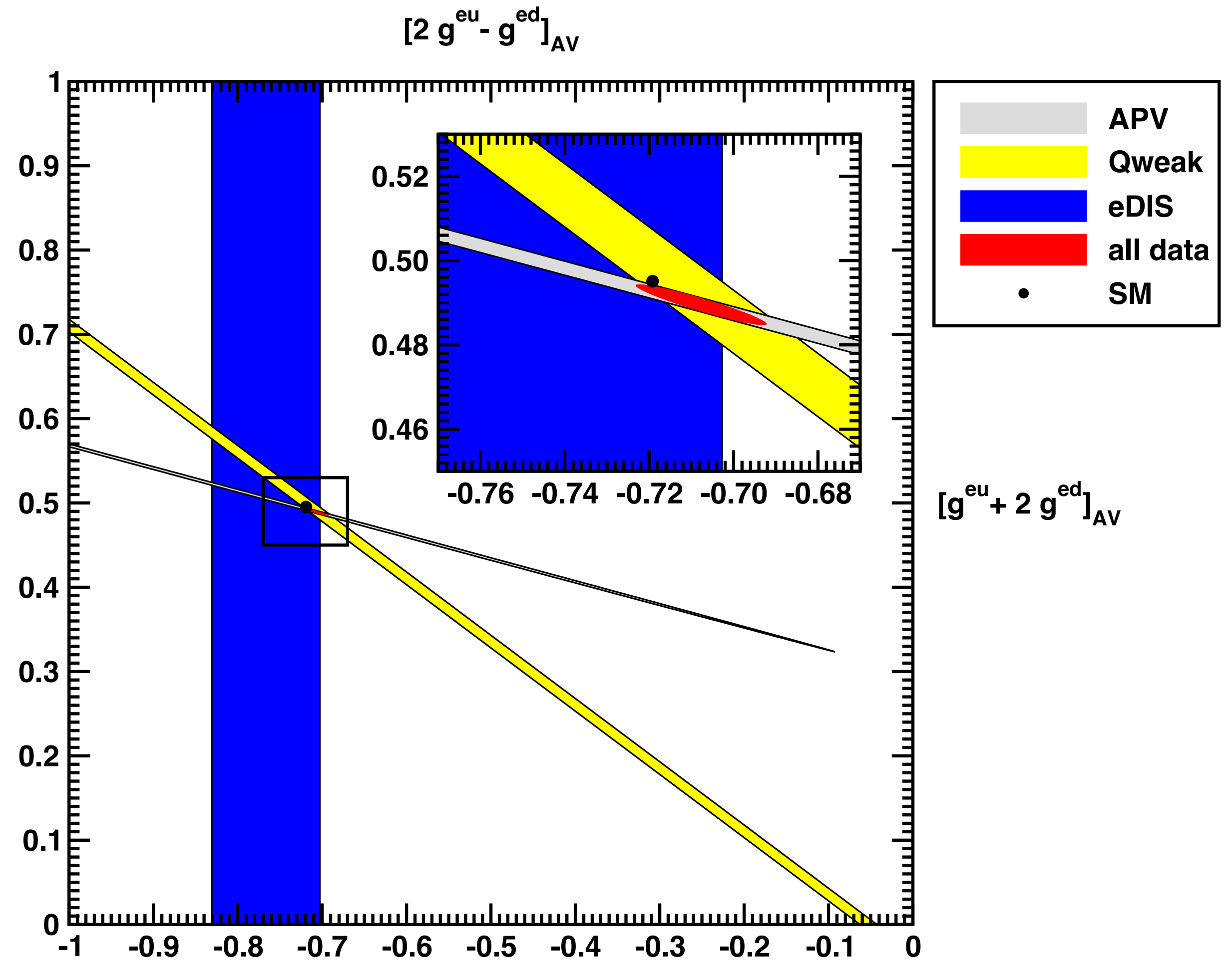
PV (axial)-electron (vector)-quark couplings

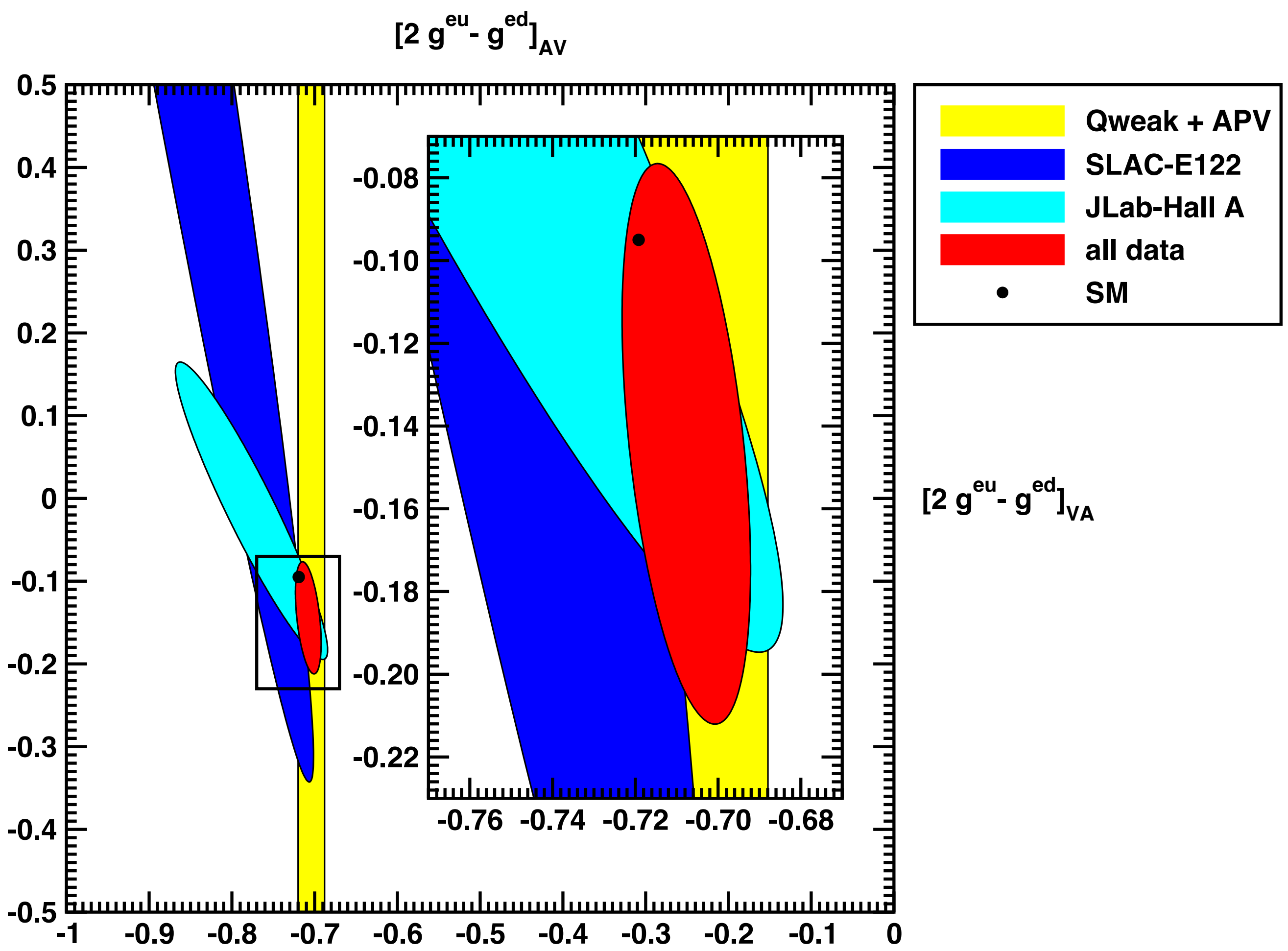


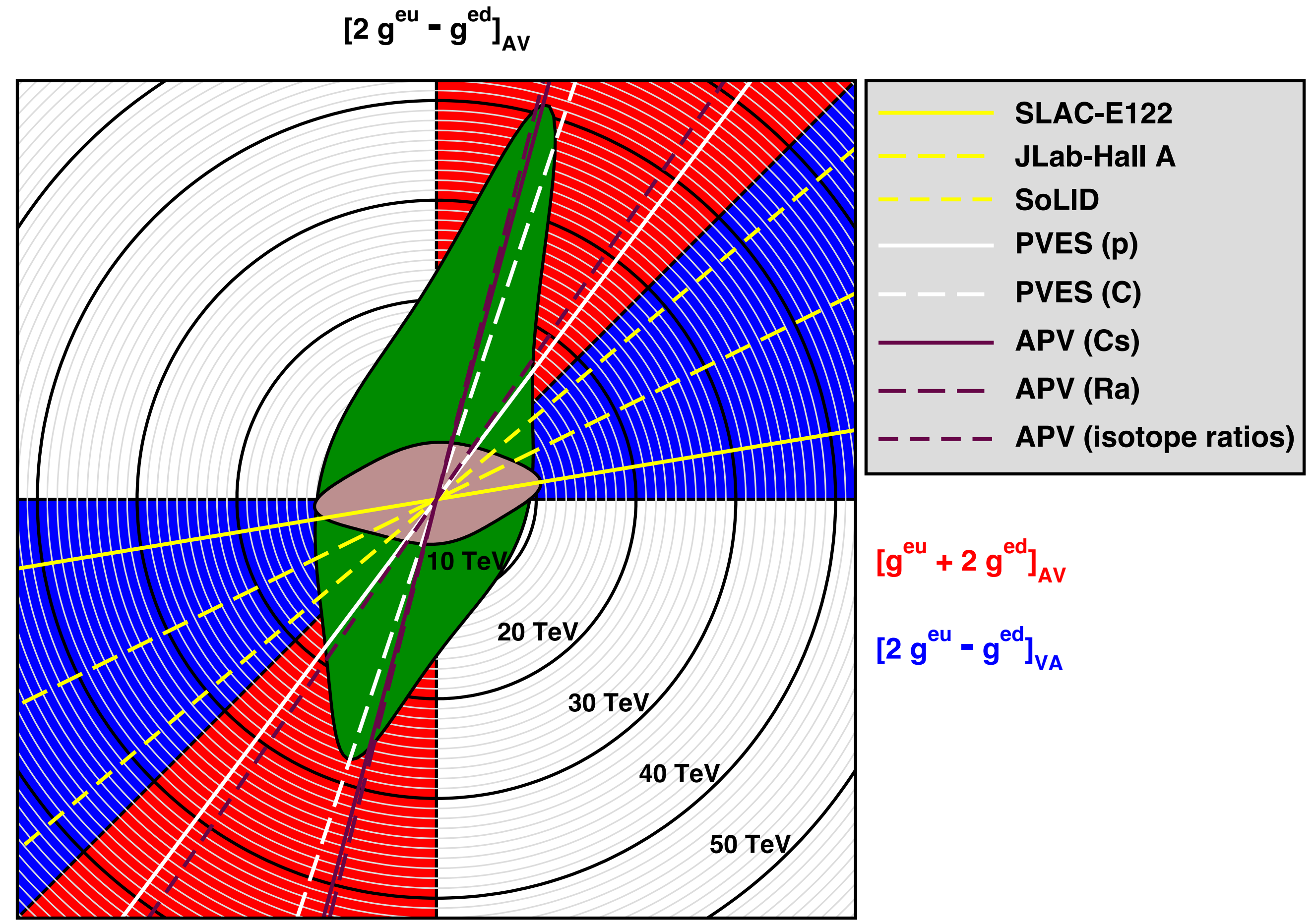

[2 g^eu - g^ed]_AV
[g^eu + 2 g^ed]_AV
APV
Qweak
eDIS
all data
SM
-1
-0.9
-0.8
-0.7
-0.6
-0.5
-0.4
-0.3
-0.2
-0.1
0
0.1
0.2
0.3
0.4
0.5
0.6
0.7
0.8
0.9
1
-0.76
-0.74
-0.72
-0.70
-0.68
0.46
0.48
0.50
0.52

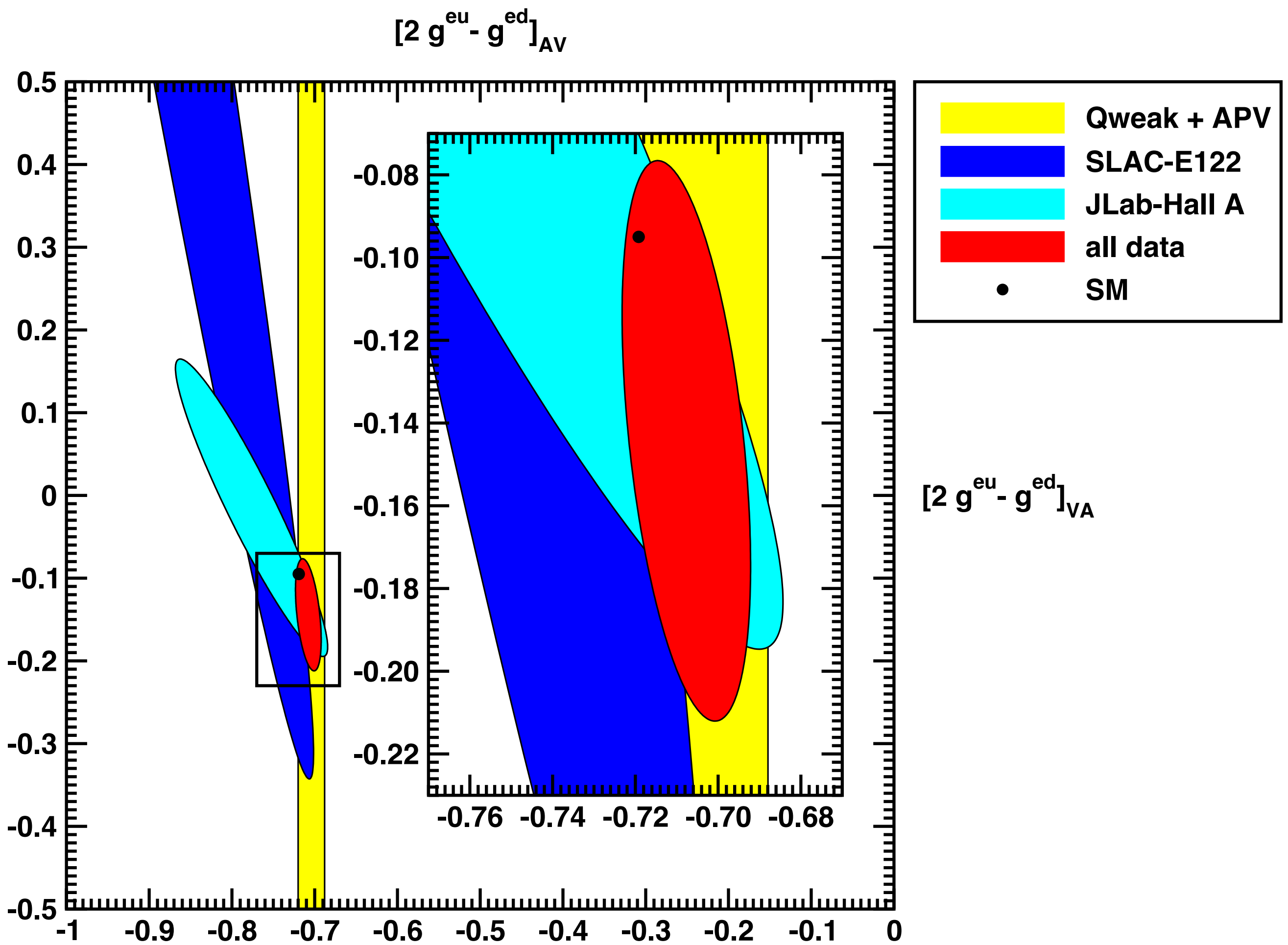

[2 g^eu - g^ed]_AV
[2 g^eu - g^ed]_VA
Qweak + APV
SLAC-E122
JLab-Hall A
all data
SM
-1
-0.9
-0.8
-0.7
-0.6
-0.5
-0.4
-0.3
-0.2
-0.1
0
-0.5
-0.4
-0.3
-0.2
-0.1
0
0.1
0.2
0.3
0.4
0.5
-0.76
-0.74
-0.72
-0.70
-0.68
-0.08
-0.10
-0.12
-0.14
-0.16
-0.18
-0.20
-0.22

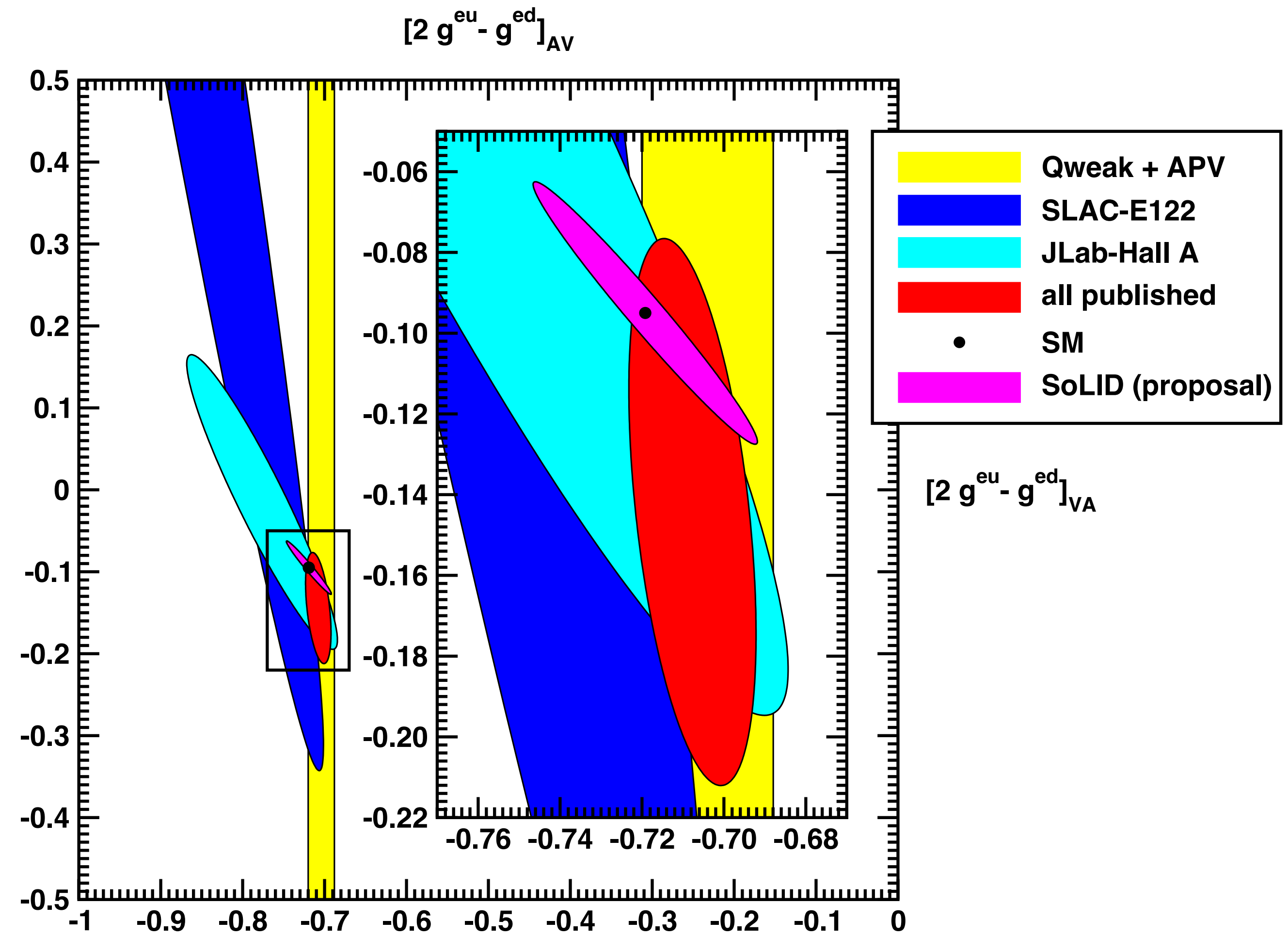
Compositeness Scales





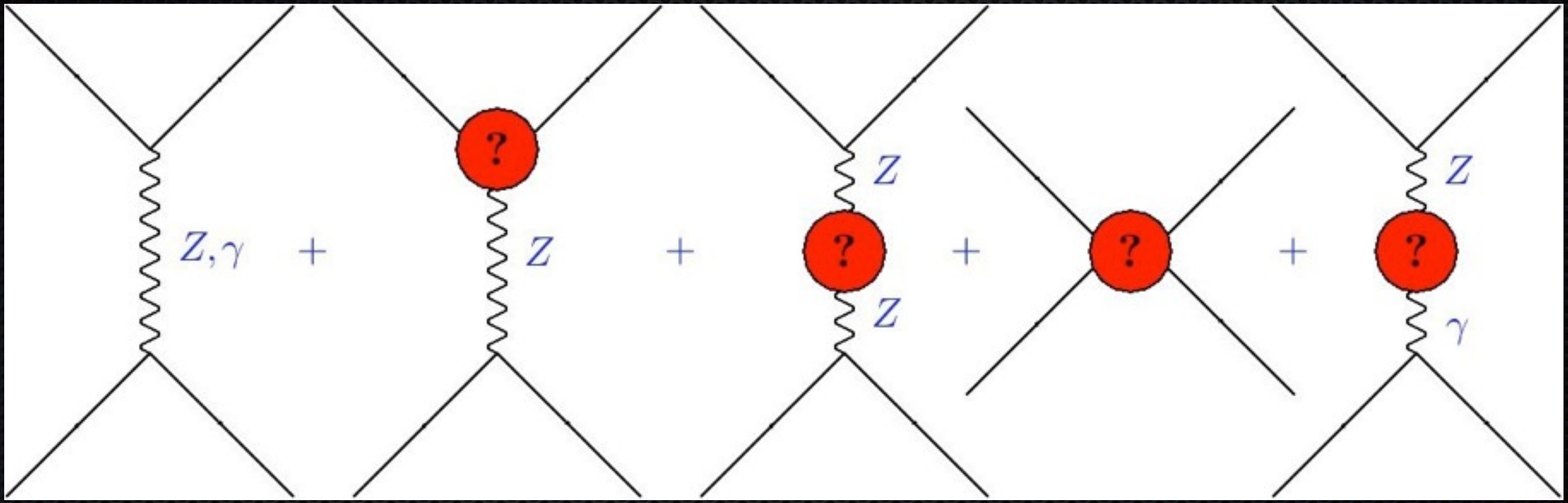



[2 g^eu - g^ed]_AV
[2 g^eu - g^ed]_VA
Qweak + APV
SLAC-E122
JLab-Hall A
all data
SM


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

	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

Separating New Physics



Z-pole

M_W, Γ_Z,
A_{FB}@Belle II

ZH-threshold
PVES

APV

Conclusions

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}
- Amusing: revival of APV anomaly?
- emergence of M_W anomaly? (small, but M_W is special)
- Low-energy:
  - next generation experiments set to reach *LEP* precision
  - model-independent couplings: multi-TeV scale

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

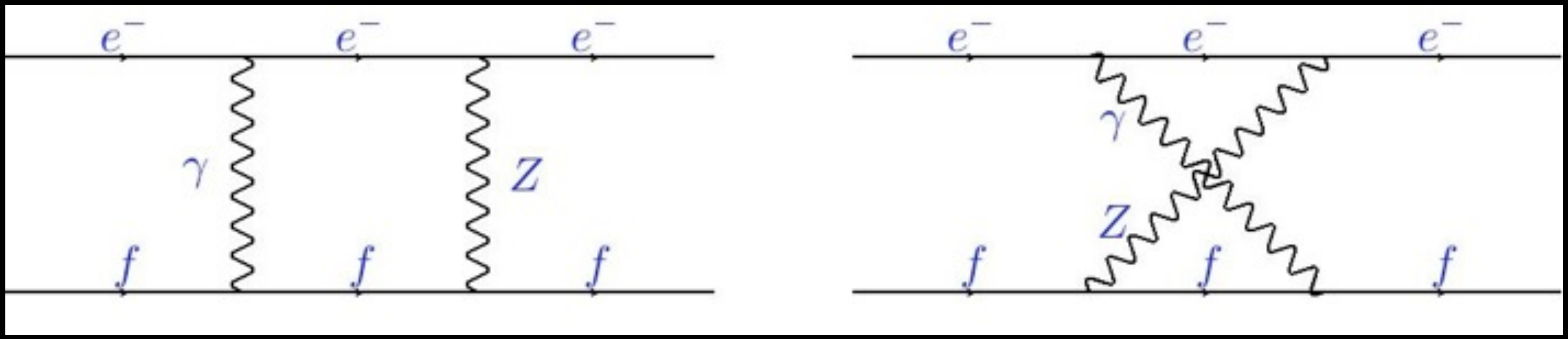
Particle Data Group (2014)

Jens Erler, Charles Horowitz, Sonny Mantry and Paul Souder

Annu. Rev. Nucl. Part. Sci. (2014)

If there is time…

γ-Z boxes

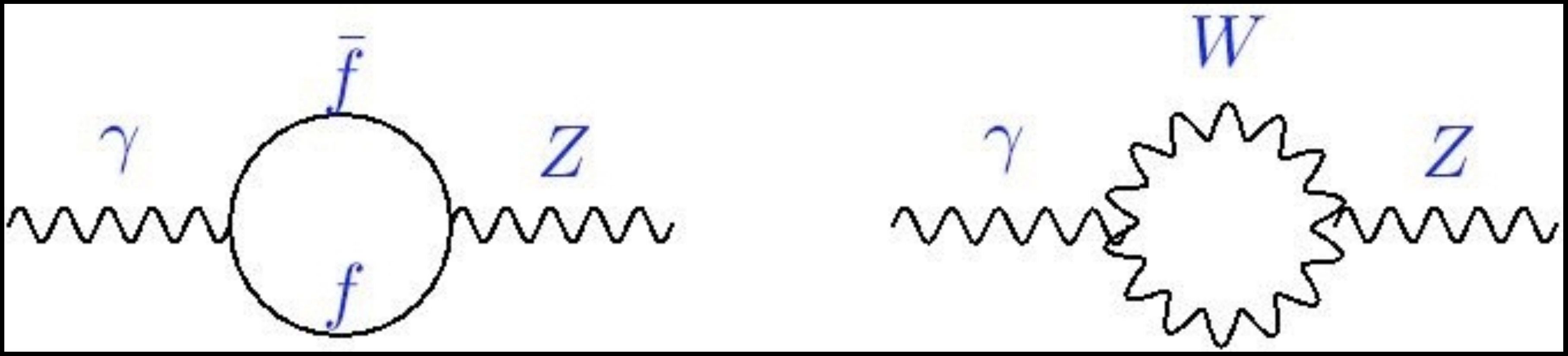


- generate large EW logs regulated in the IR by uncertain hadronic scale
  (similarly for charge radius correction to g_{VA}^{eq})
- for APV ($E_e \approx 0, Q^2 \approx 0$) effect for g_{AV}^{eq} is $\propto$ g_{VA}^{eq} and vice versa
- for elastic scattering $E_e \neq 0$, mixing in opposite chirality structure

➡ strong point for *P2 (Mainz)*

- much activity recently:
  - g_{VA}^{eq} large error ***Gorchtein, Horowitz 2009; Sibirtsev, Blunden, Melnitchouk, Thomas 2010; Gorchtein, Horowitz, Ramsey-Musolf 2011; Rislow, Carlson 2011; Hall et al. 2013***
  - g_{AV}^{eq} for PVES ***Blunden, Melnitchouk, Thomas 2011; Rislow, Carlson 2013***
  - g_{AV}^{eq} for APV $(1 - 4\sin^2\theta_W)$-suppressed ***Blunden, Melnitchouk, Thomas 2012***

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



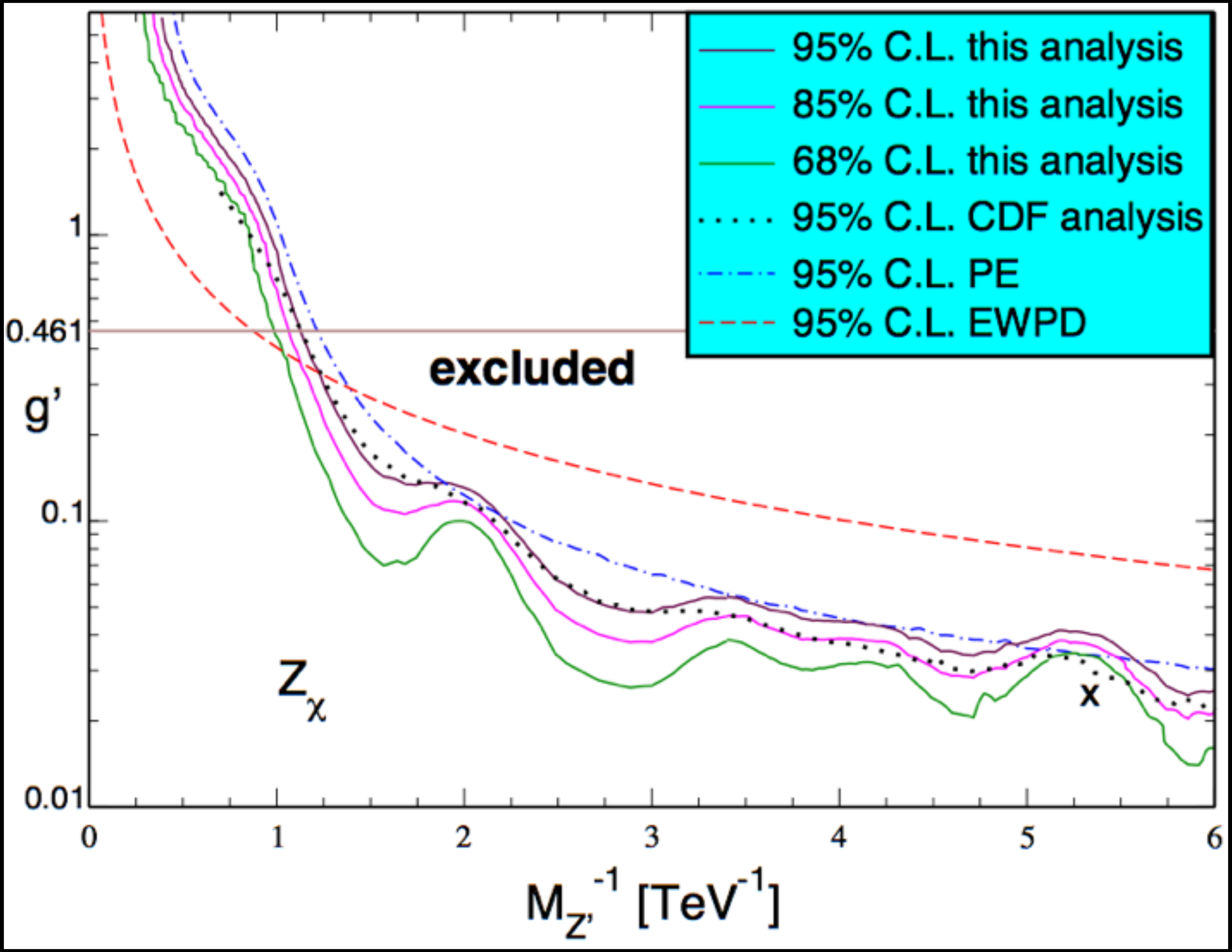
- Define in $\overline{MS}$-scheme: $\sin^2\overline{\theta}_W(\mu) \equiv \overline{g}'^2(\mu)/[\overline{g}^2(\mu) + \overline{g}'^2(\mu)]$
- RGE for $\overline{\alpha}$: $\mu^2\, d\bar{\alpha}/d\mu^2 \equiv \bar{\alpha}/24\pi \sum_k N_C^k \gamma^k (Q^k)^2$
- RGE for $\overline{v}_i$: $\overline{X}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

➡ running of $\bar{\alpha}$ (e^+e^- and/or τ data) $\Longrightarrow$ running of $\sin^2\overline{\theta}_W$ if

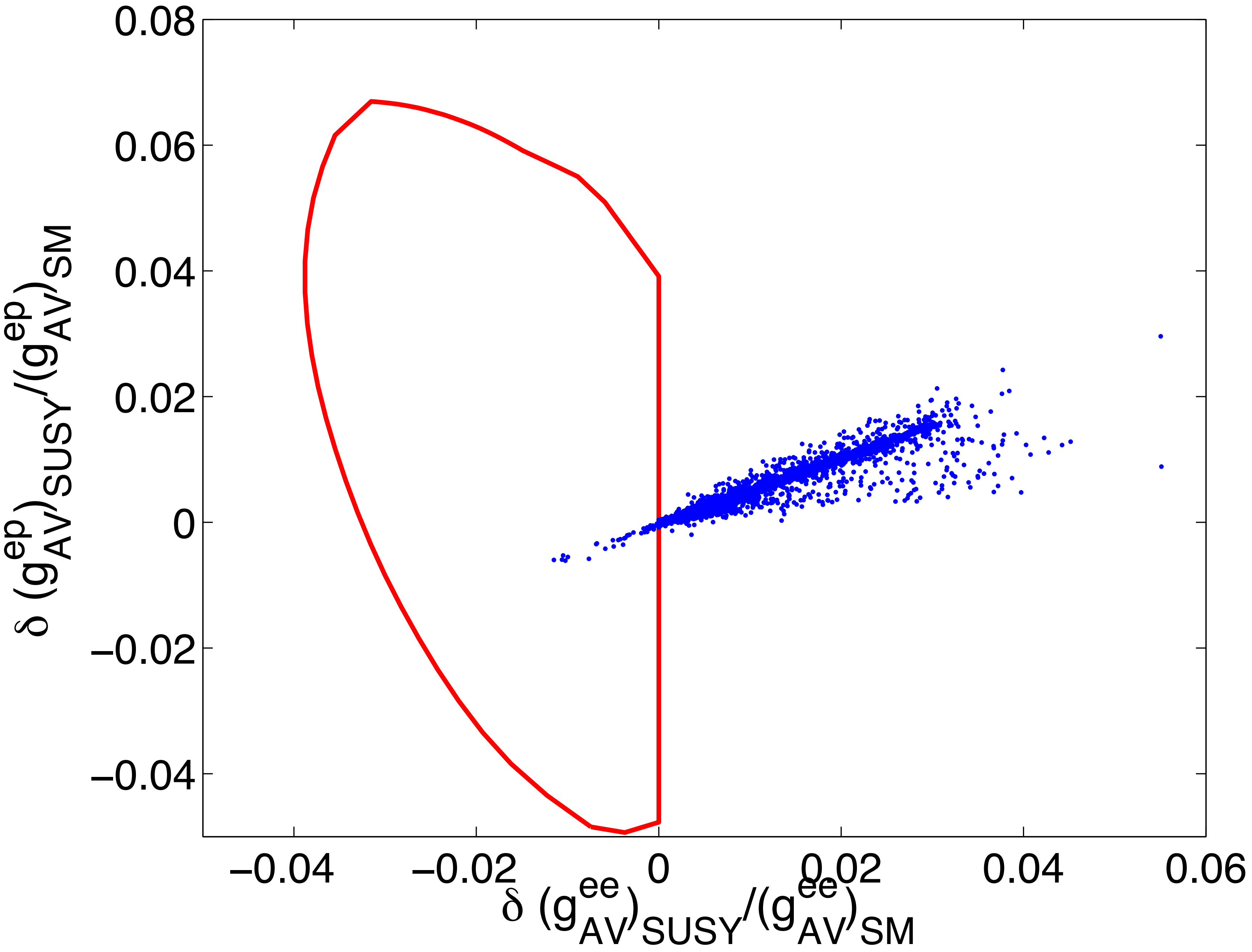
- either no mass threshold is crossed
- or perturbation theory applies ($W^\pm$, leptons, b & c quarks)
- or all coefficient are equal (RGE factorizes) like for (d,s)
- or there is a symmetry like $SU(3)_F$

Backups

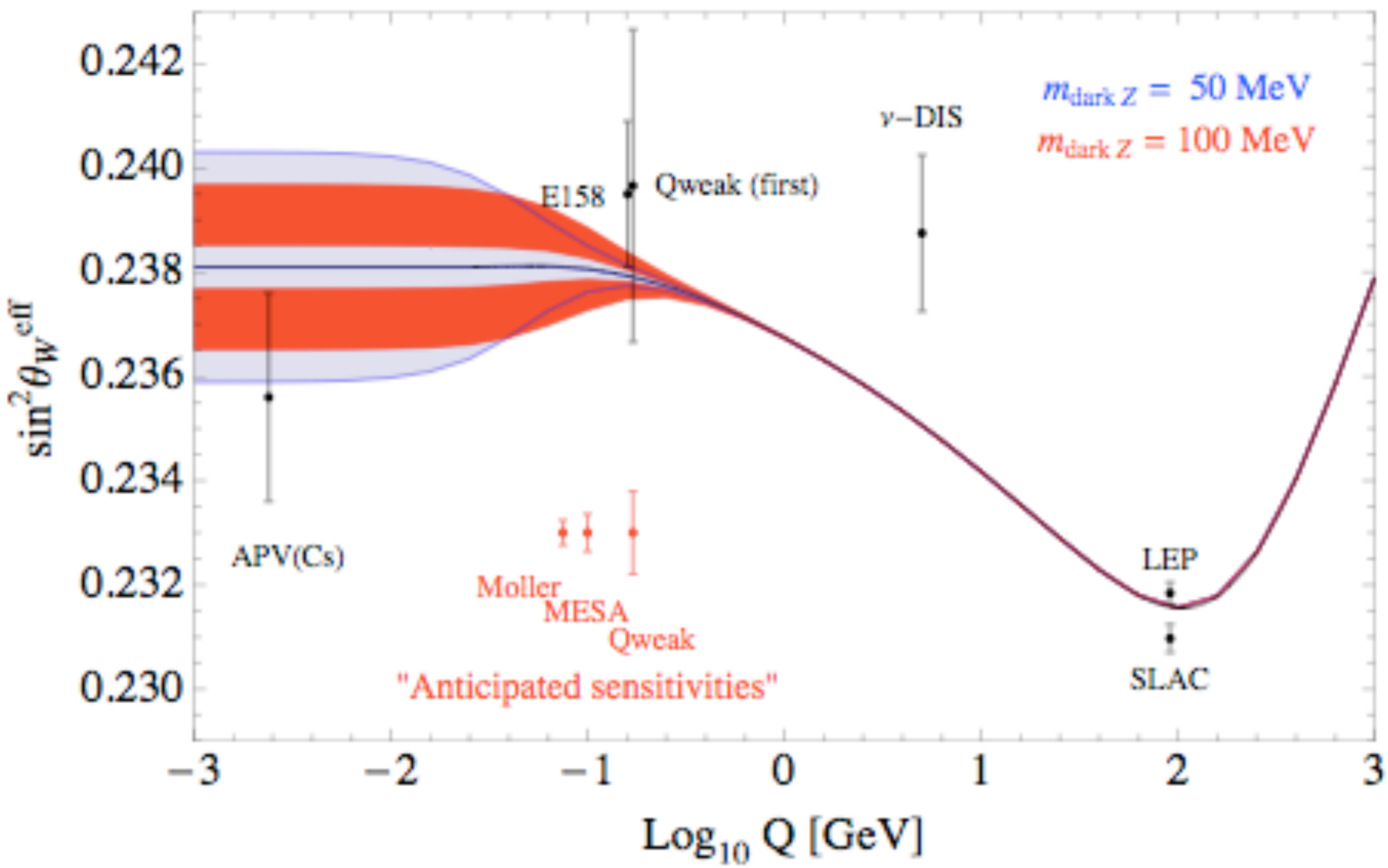
Energy-Intensity Complementarity



PVES and SUSY



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



Marciano 2013