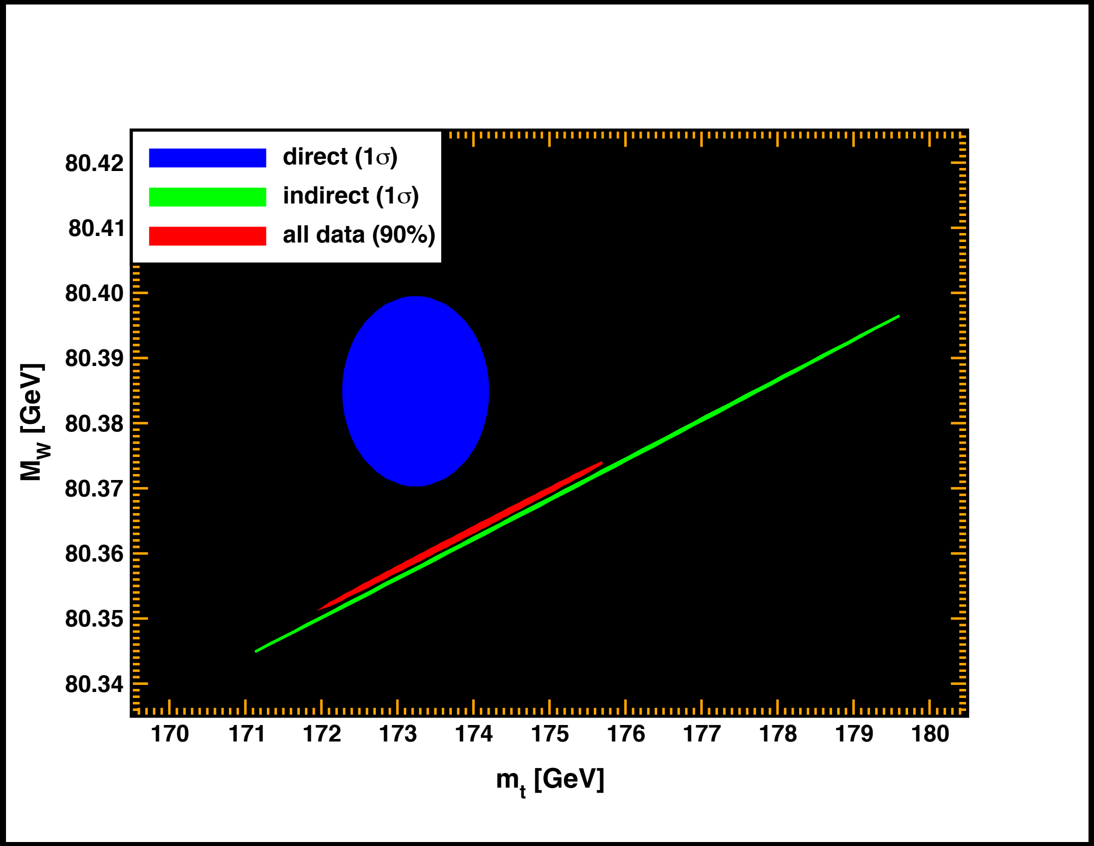
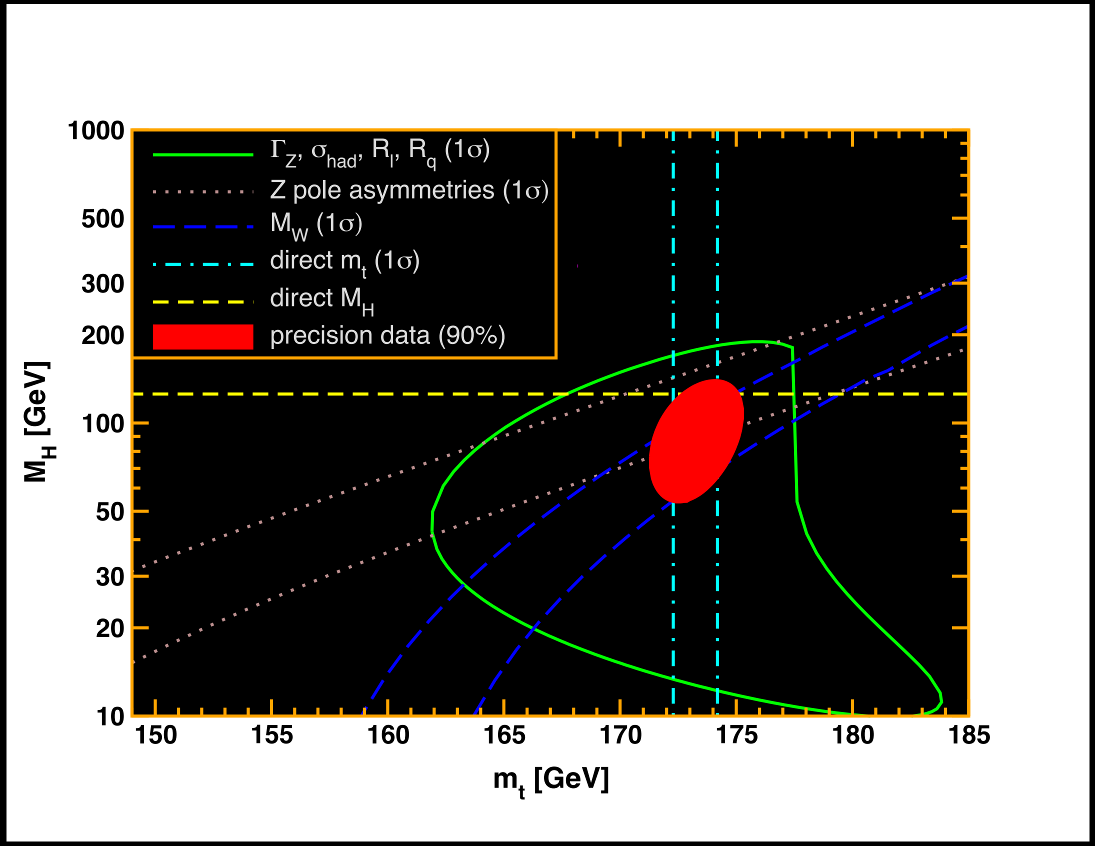
Status of the Electroweak Standard Model





Jens Erler (IF-UNAM & MITP)

Sommerfeld Theory Colloquium

LMU Munich, January 15, 2014

Outline

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- Introduction

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- Introduction
- The Weak Mixing Angle

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- Conclusions

Introduction

ν_τ	τ^-	τ^+	t	t	t	$\bar{t}$	$\bar{t}$	$\bar{t}$	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^-	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^-	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	$H^\pm$	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 [SU(2)$_L$], g′ [U(1)$_Y$], μ, λ

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

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

History

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- 2010s (LHC, intensity frontier): EW symmetry breaking sector (Higgs & BSM)

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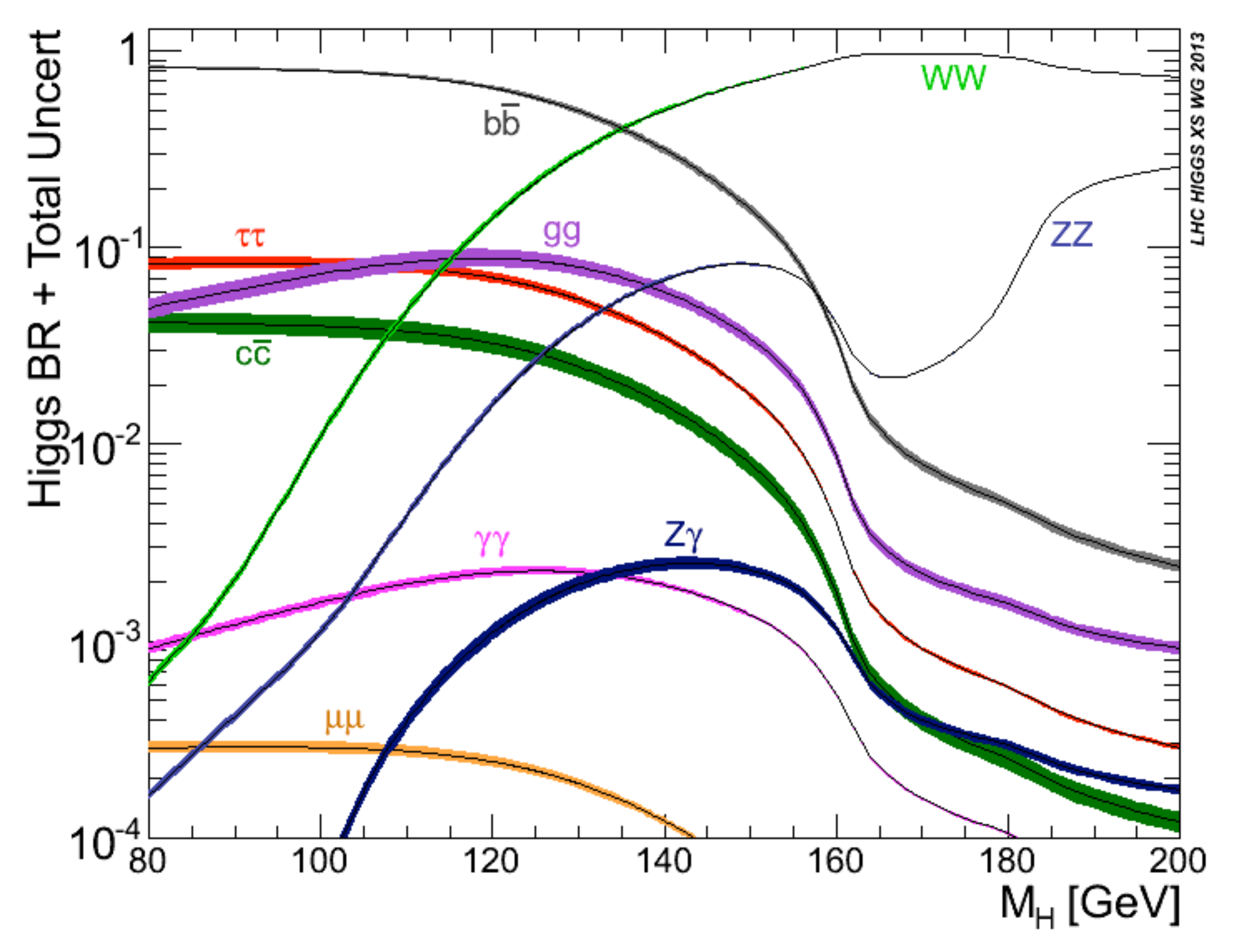
- consistent with $M_H = 125.6 \pm 0.4$ GeV ***ATLAS, CMS (CERN) 2012***

M_H from Higgs branching ratios?



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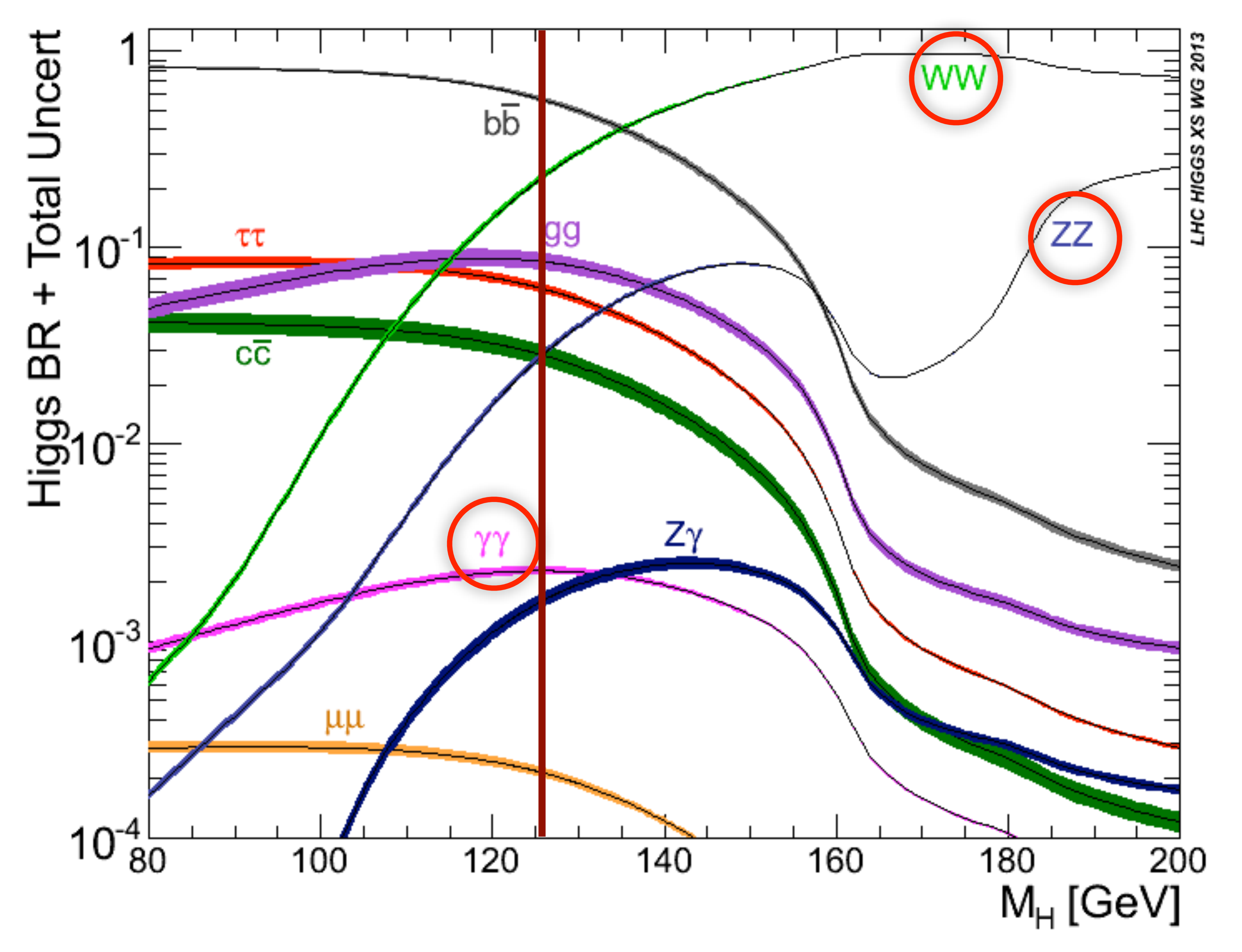
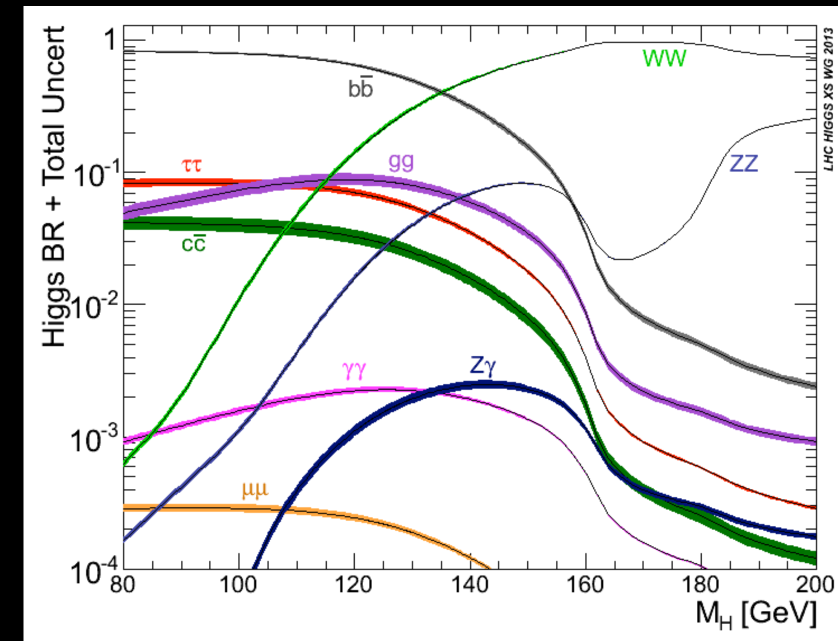
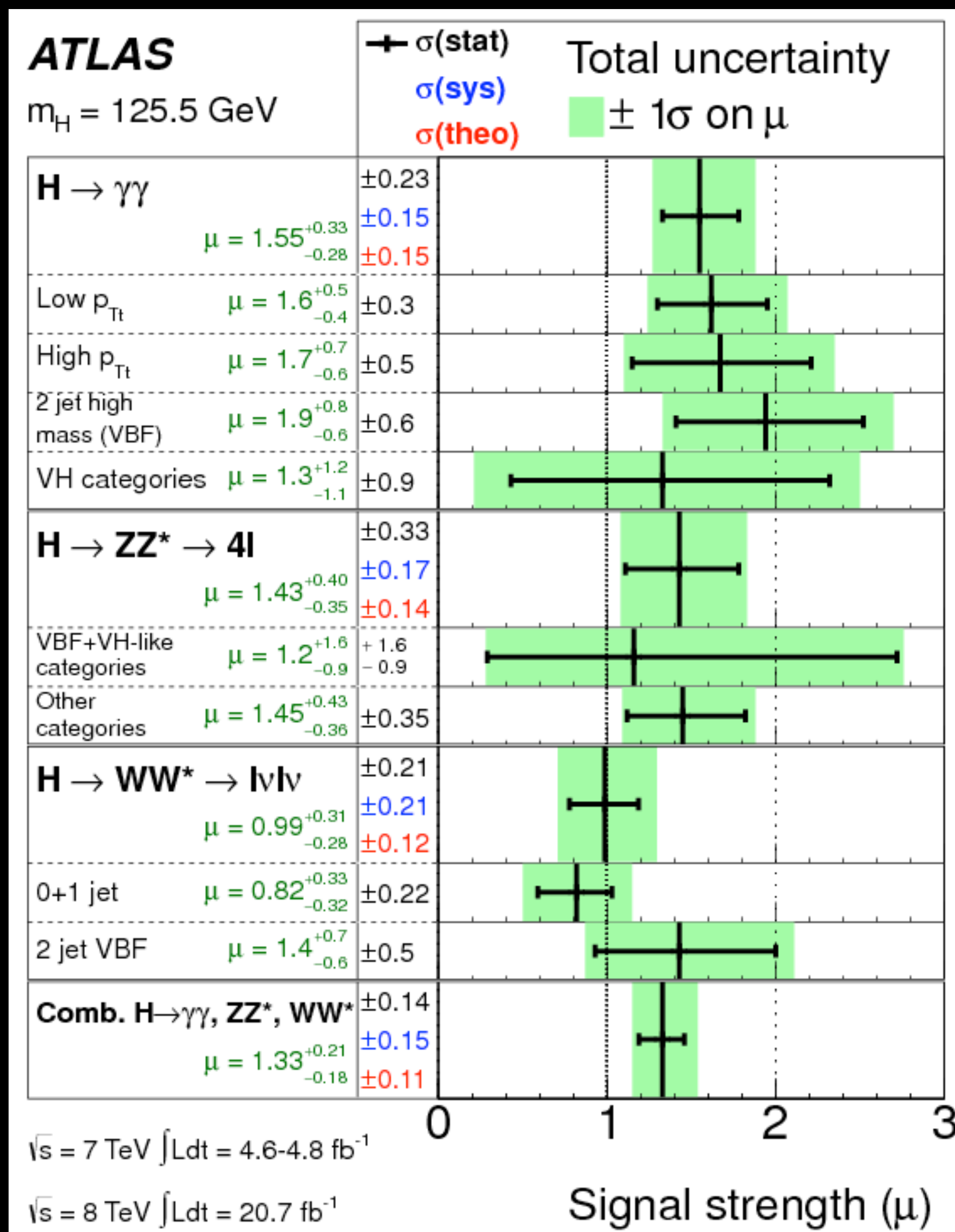
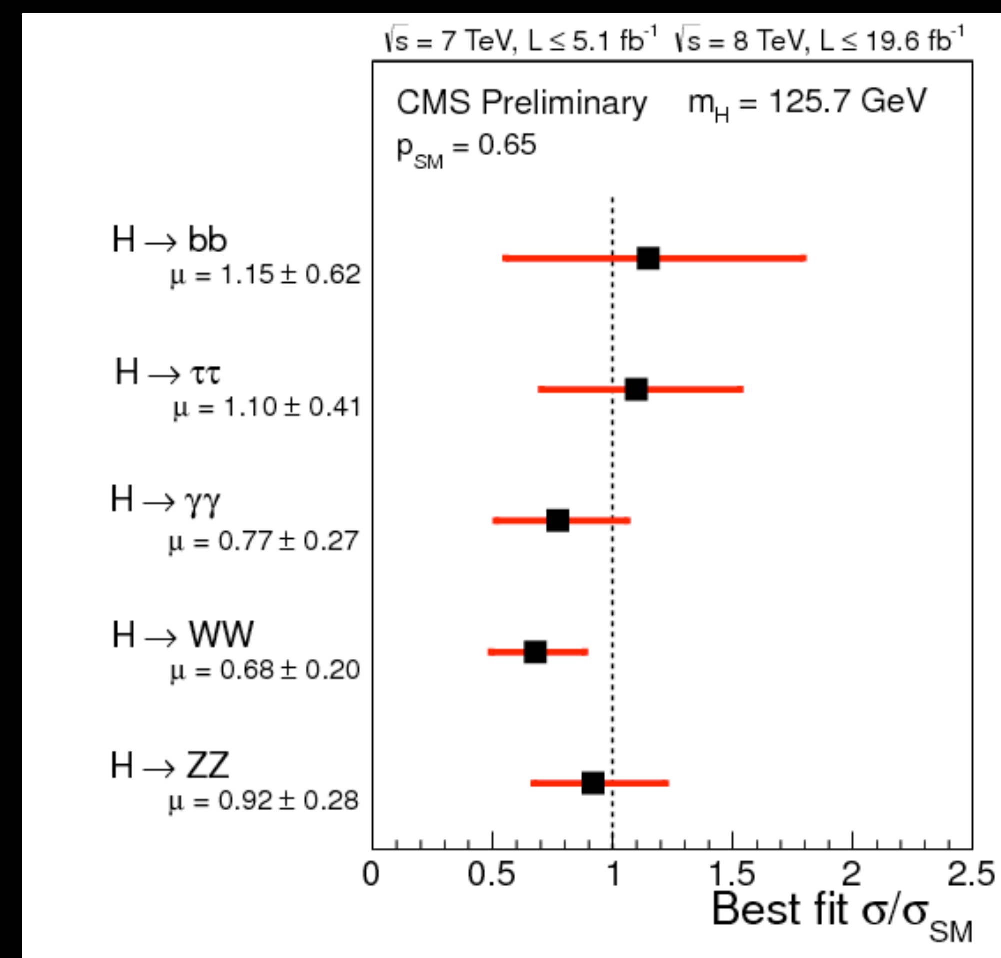


Compare with results on coupling strength



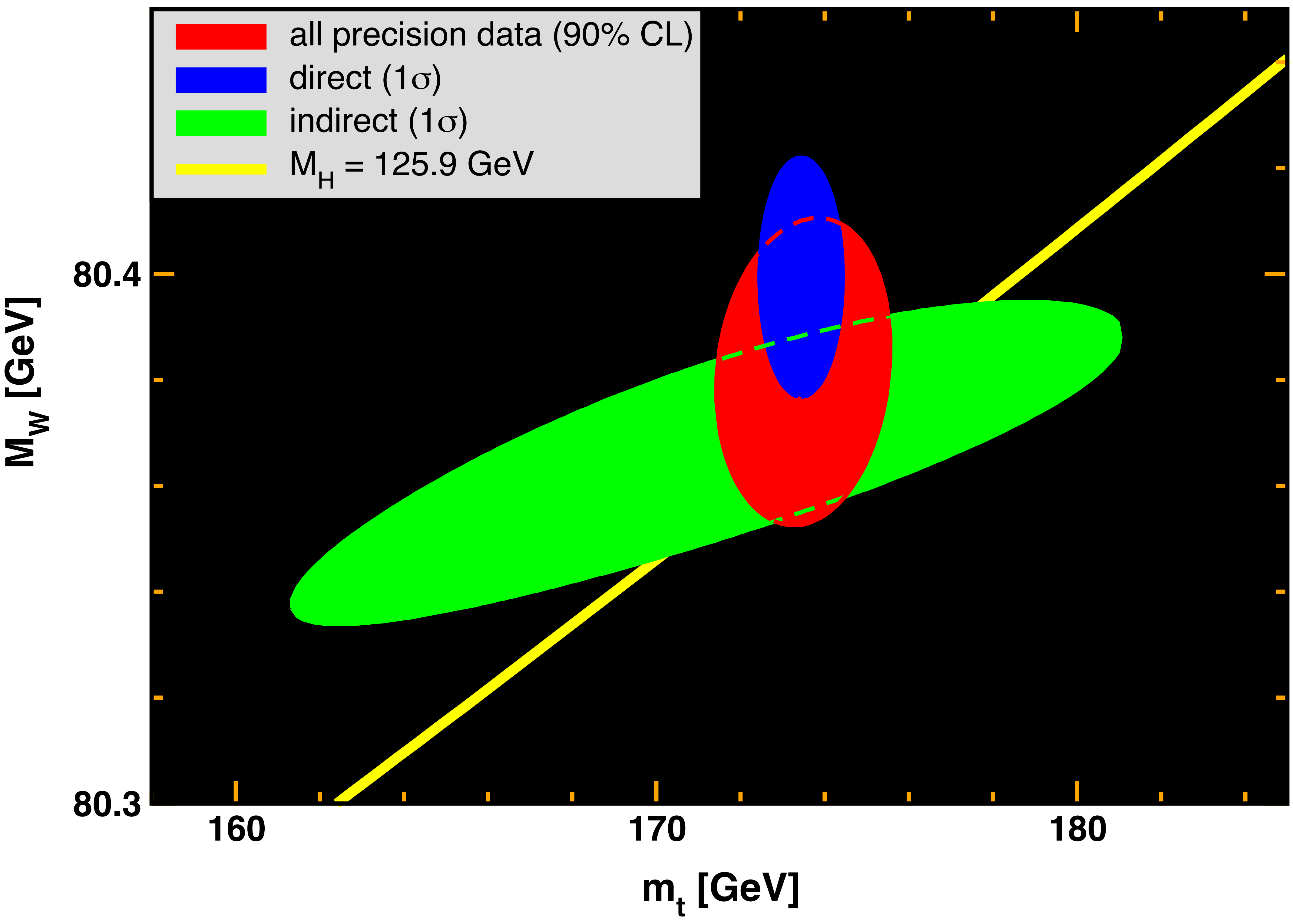




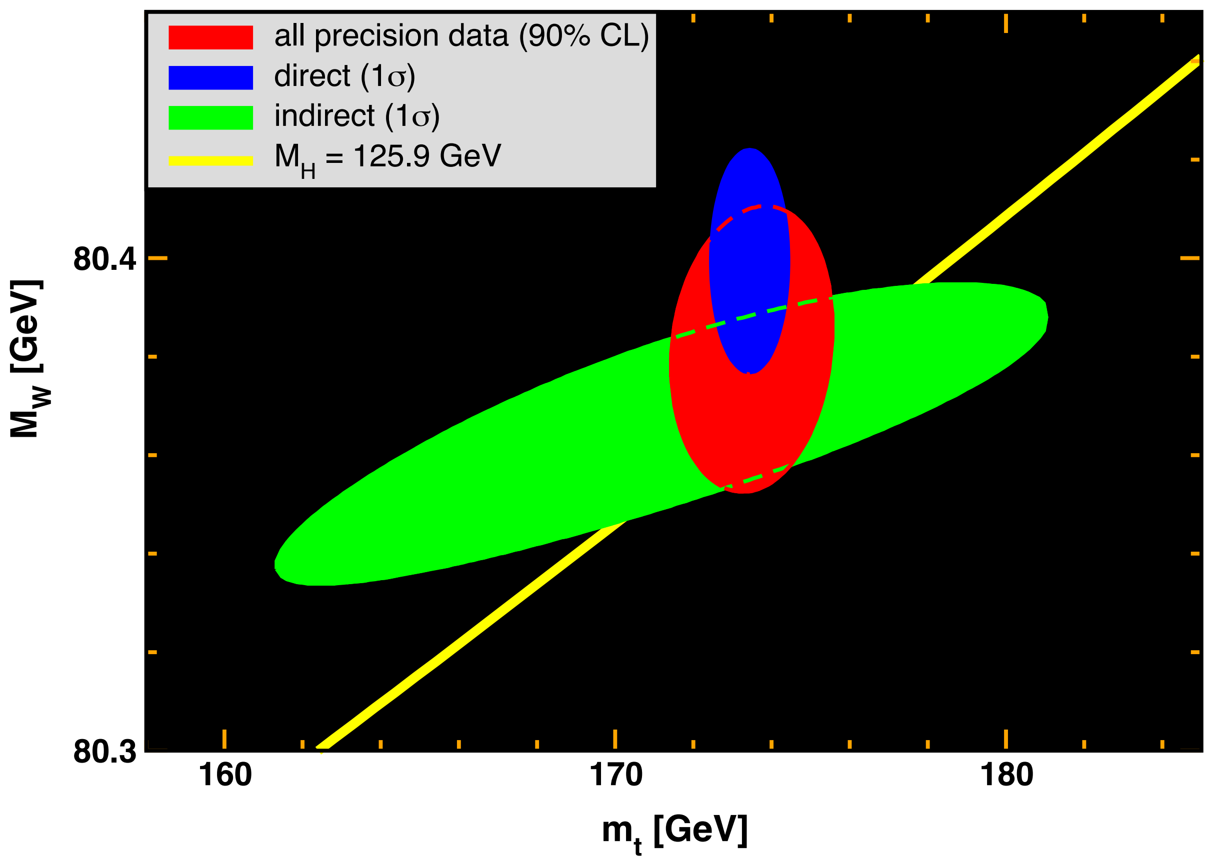
M_H [GeV]

source	M_H	uncertainty
radiative corrections	89	$^{+22}_{-18}$
LHC Higgs branching ratios	123.7	2.3
ATLAS direct	125.5	0.6
CMS direct	125.7	0.4
global fit	125.5	0.4

JE, Ayres 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]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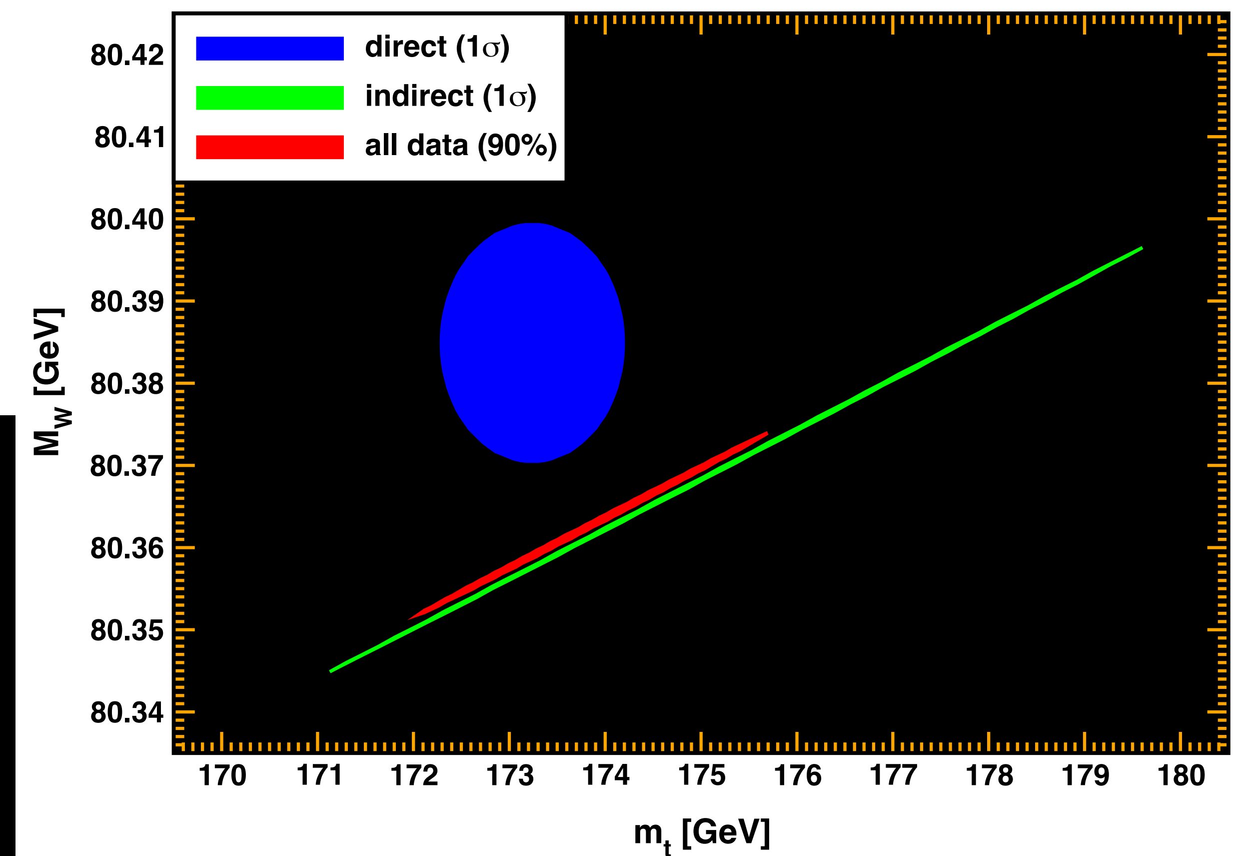
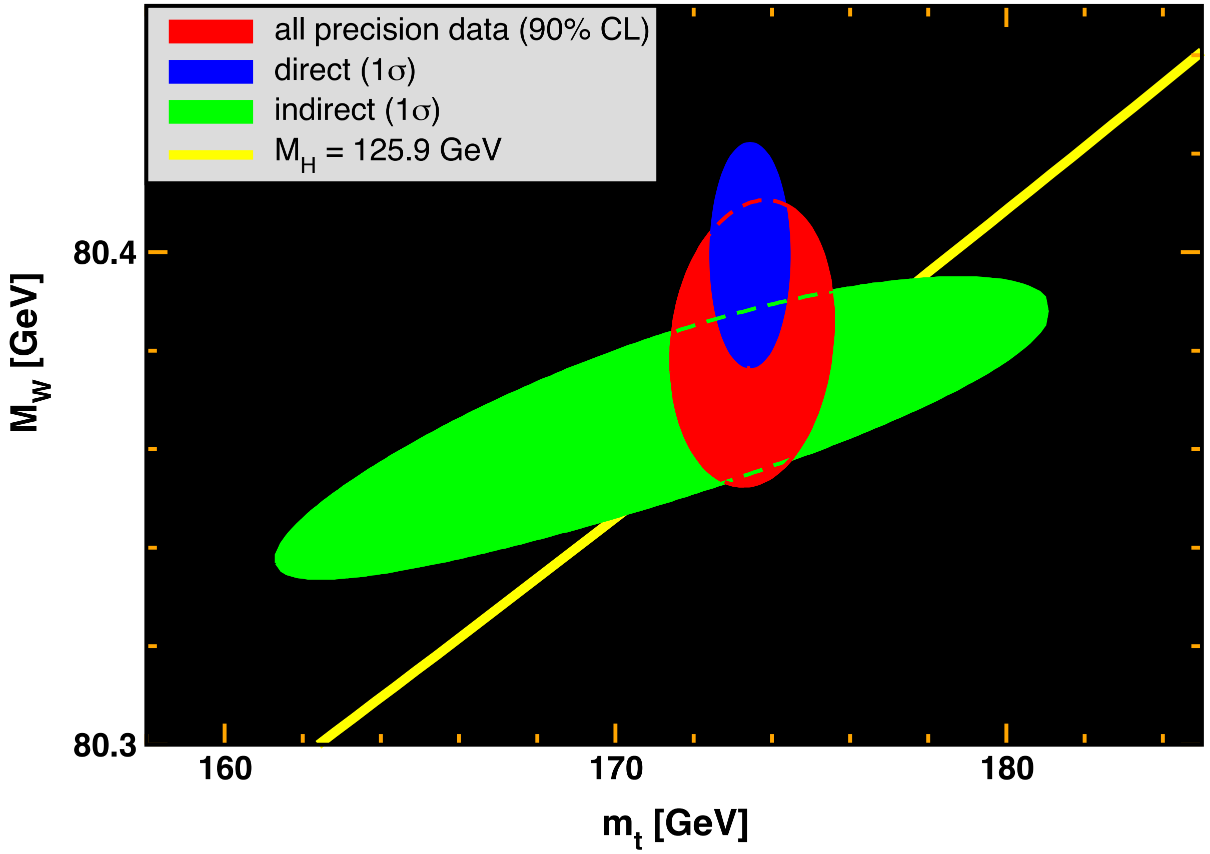

direct (1σ)
indirect (1σ)
all data (90%)
80.42
80.41
80.40
80.39
80.38
80.37
80.36
80.35
80.34
170
171
172
173
174
175
176
177
178
179
180
m_t [GeV]
M_W [GeV]


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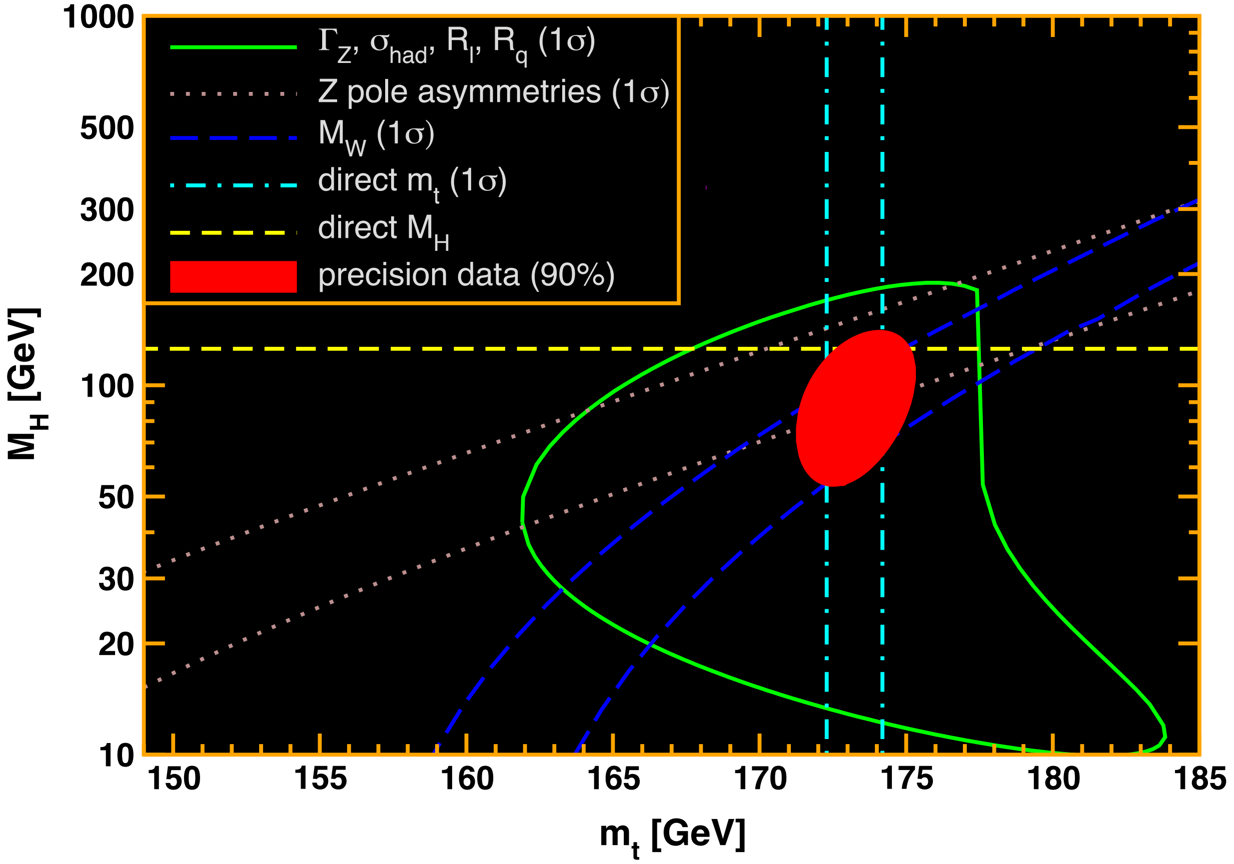
M_H = 125.9 GeV
80.4
80.3
160
170
180
M_W [GeV]
m_t [GeV]

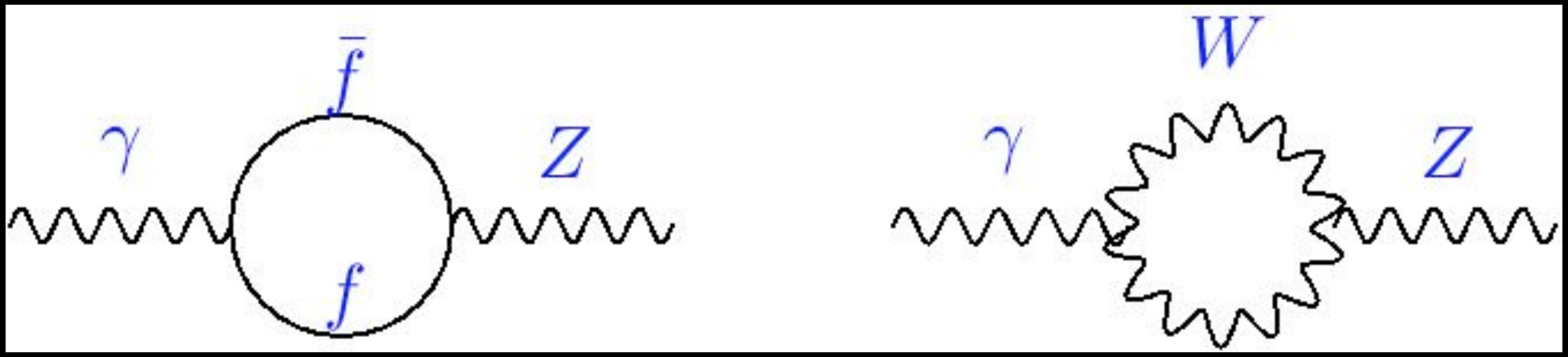

Γ_Z, σ_had, R_l, R_q (1σ)
Z pole asymmetries (1σ)
M_W (1σ)
direct m_t (1σ)
direct M_H
precision data (90%)
1000
500
300
200
100
50
30
20
10
150
155
160
165
170
175
180
185
M_H [GeV]
m_t [GeV]

The Weak Mixing Angle

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

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

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



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

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

Renormalization schemes

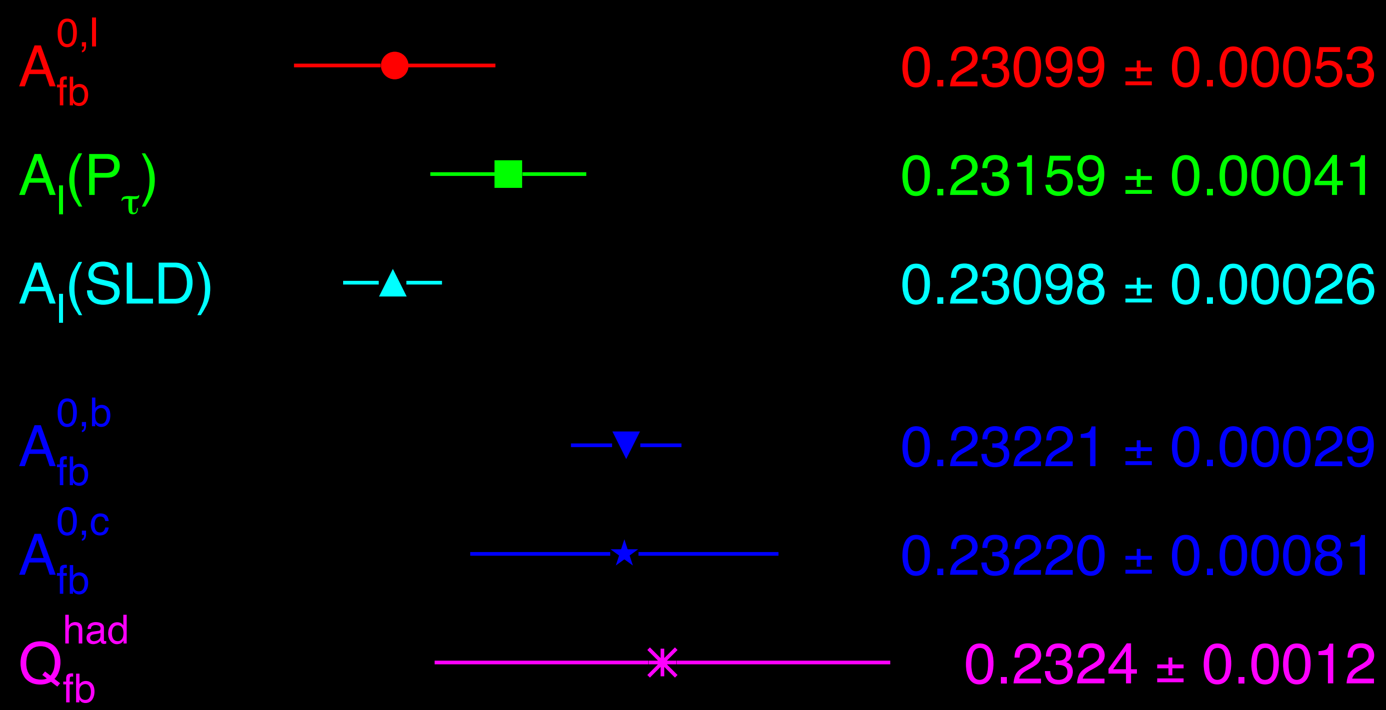
Many different schemes and definitions. Most commonly used:

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

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

  - numerically close to $\sin^2\overline{\theta}_W(M_Z)$ (analogous to α in QED)
- 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)

Z-pole Asymmetries



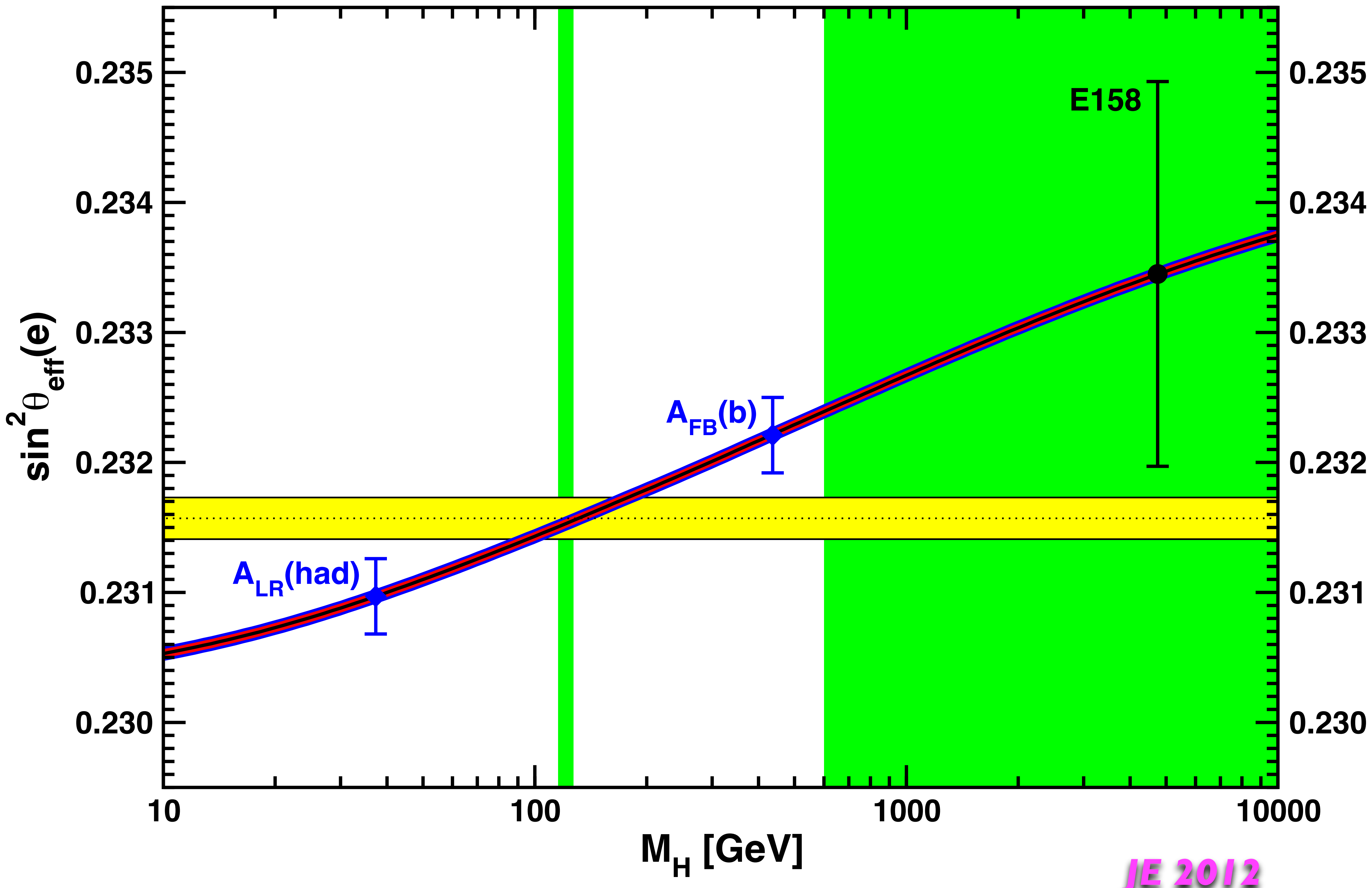
LEP/SLC Average: 0.23153 ± 0.00016 χ^2/d.o.f. = 16.8/12

Tevatron Average: 0.23176 ± 0.00060

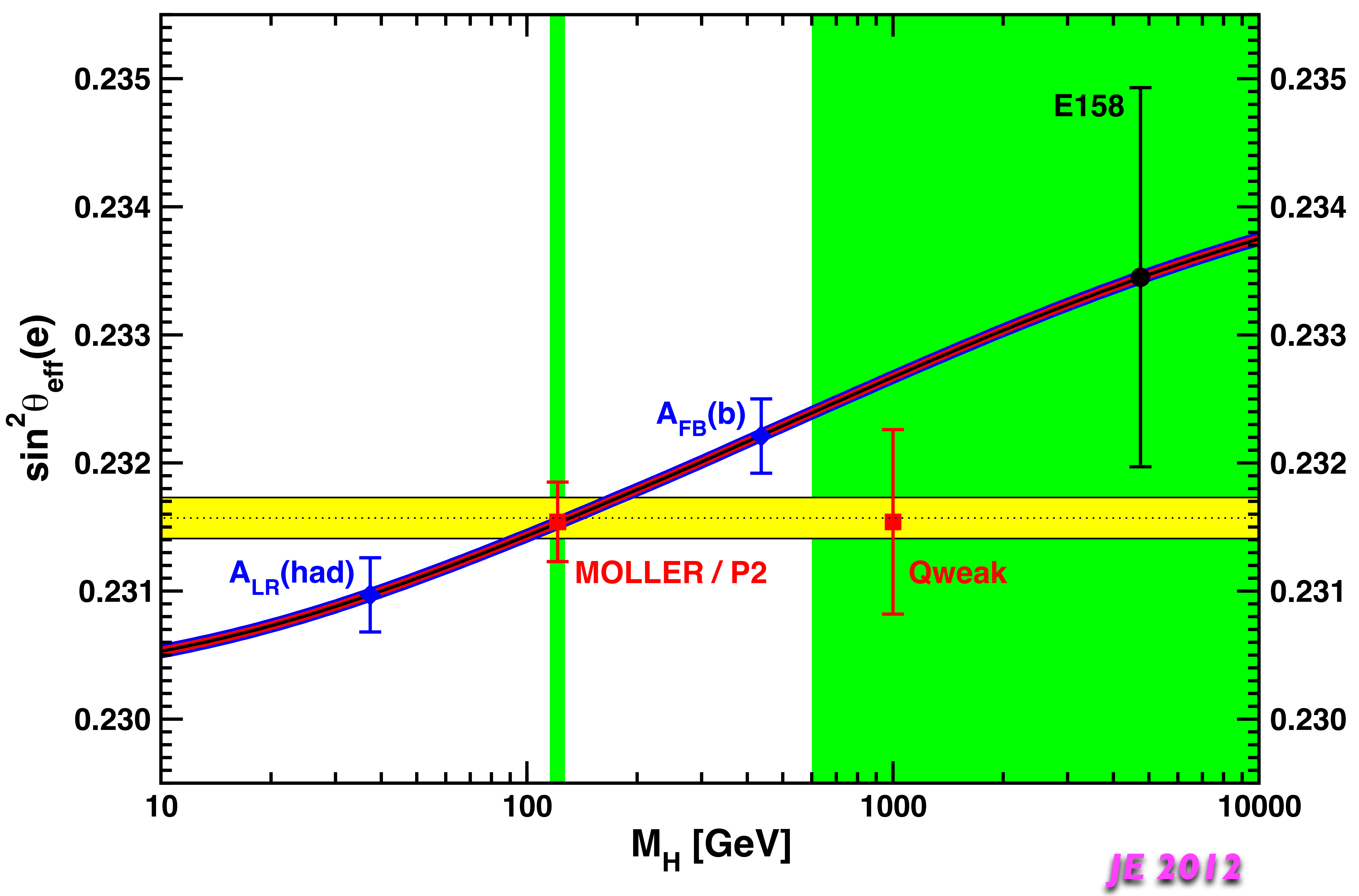
LHC Average: 0.2297 ± 0.0010

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

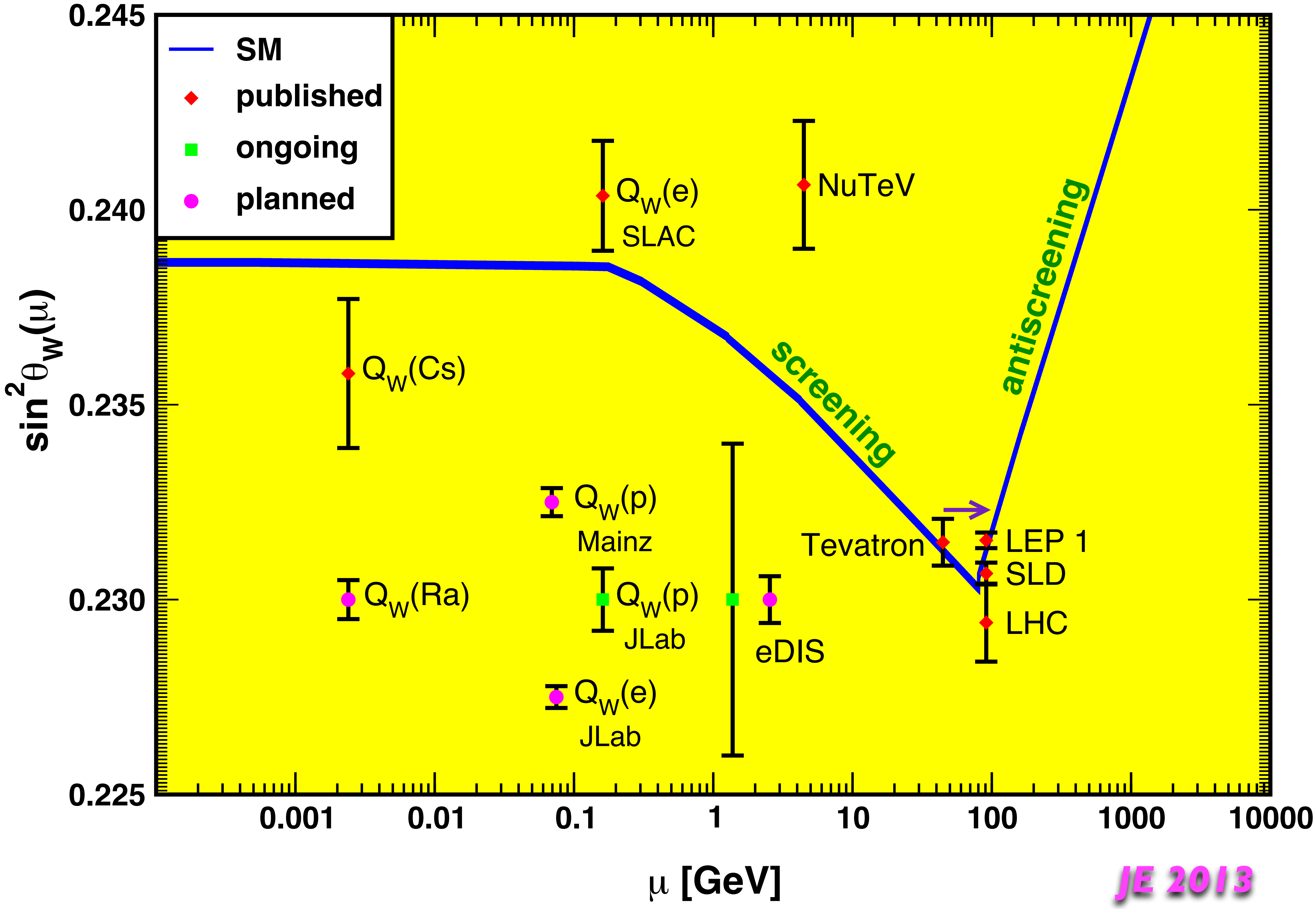
Standard Model: 0.23155 ± 0.00005



0.235
0.234
0.233
0.232
0.231
0.230
E158
A_FB(b)
A_LR(had)
sin²θ_eff(e)
10
100
1000
10000
M_H [GeV]
JE 2012

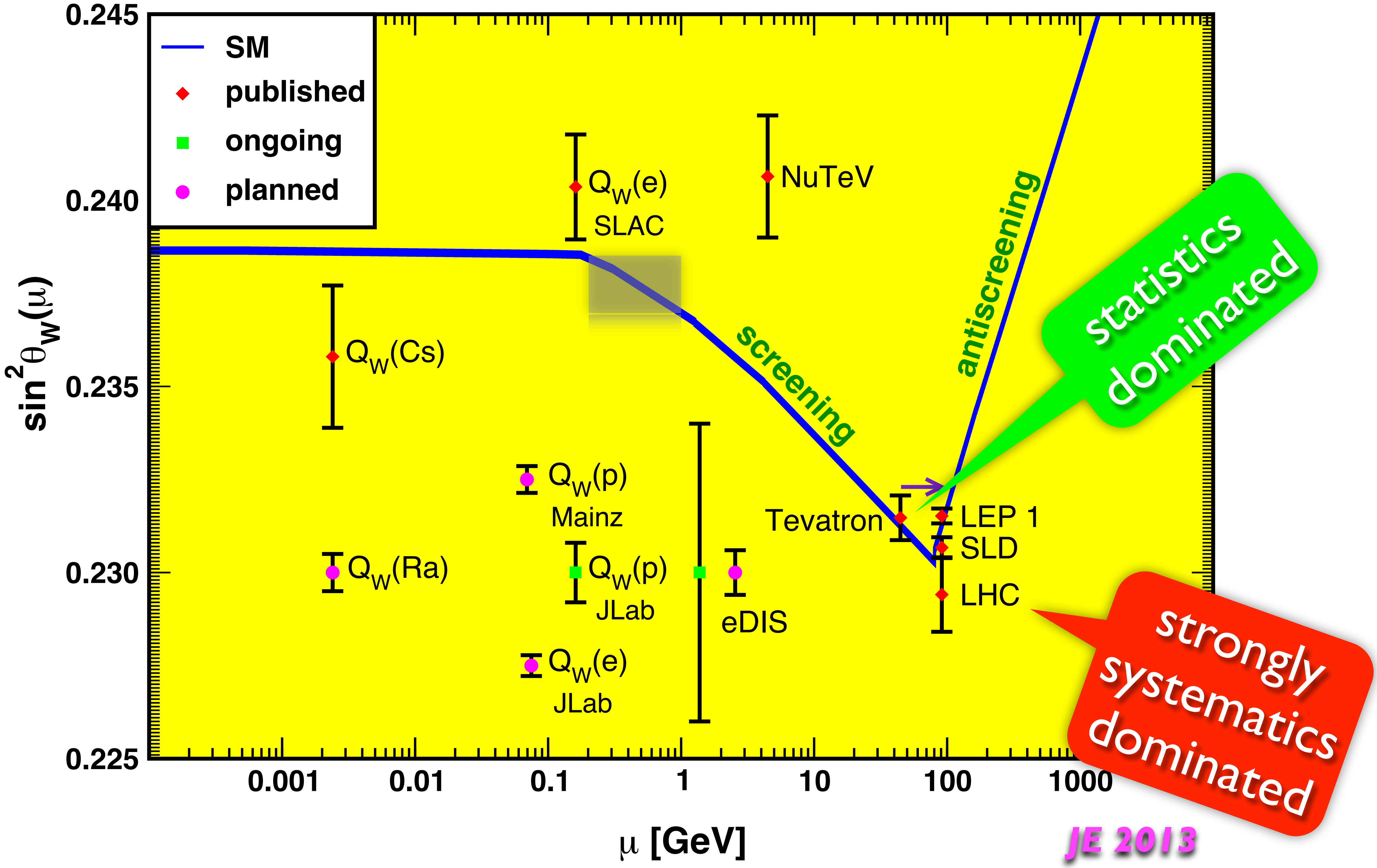


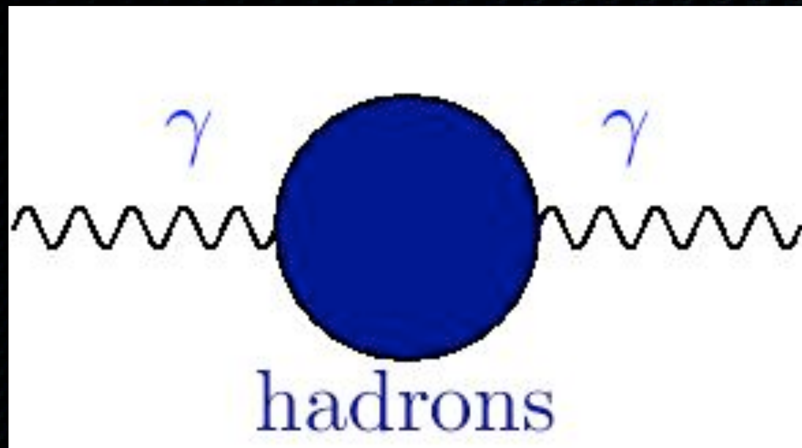
0.235
0.234
0.233
0.232
0.231
0.230
E158
$A_{FB}(b)$
$A_{LR}(had)$
MOLLER / P2
Qweak
$\sin^2\theta_{eff}(e)$
10
100
1000
10000
M_H [GeV]
JE 2012

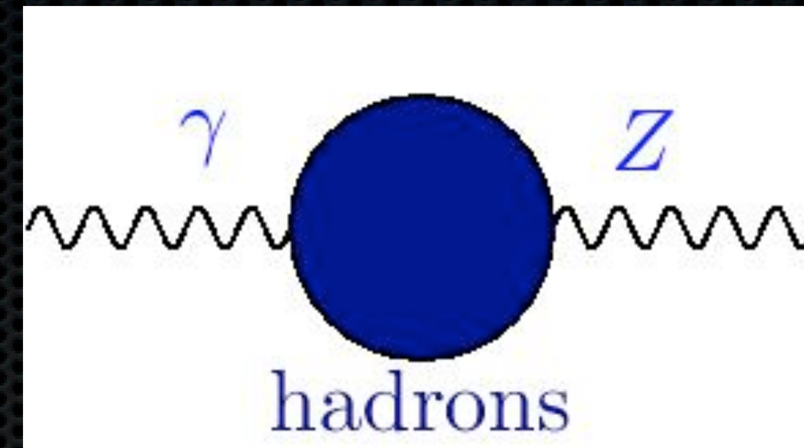


SM
published
ongoing
planned
0.245
0.240
0.235
0.230
0.225
$\sin^2\theta_W(\mu)$
$Q_W(e)$
SLAC
NuTeV
$Q_W(Cs)$
screening
antiscreening
$Q_W(p)$
Mainz
Tevatron
LEP 1
SLD
$Q_W(Ra)$
$Q_W(p)$
JLab
eDIS
LHC
$Q_W(e)$
JLab
0.001
0.01
0.1
1
10
100
1000
10000
μ [GeV]
JE 2013

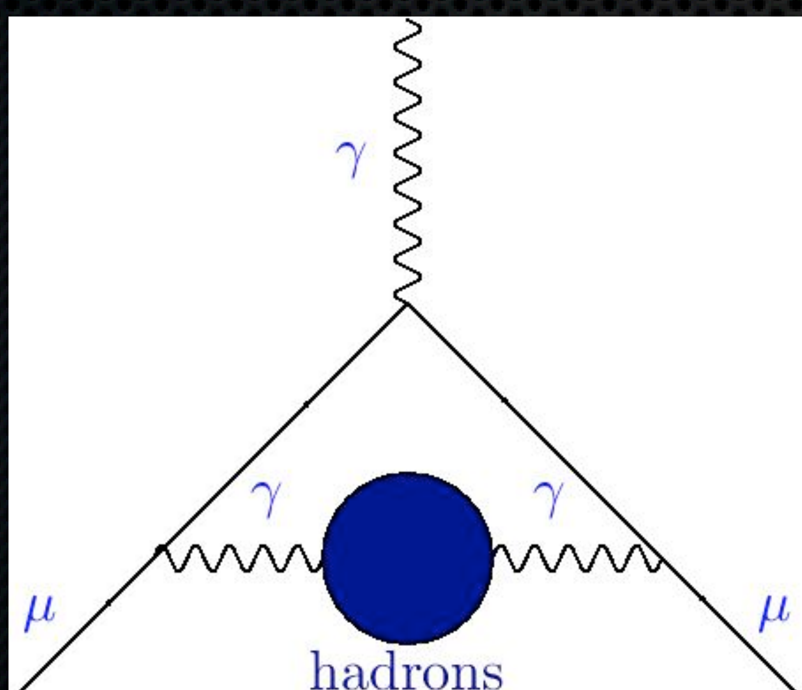
$\overline{MS}$-scheme

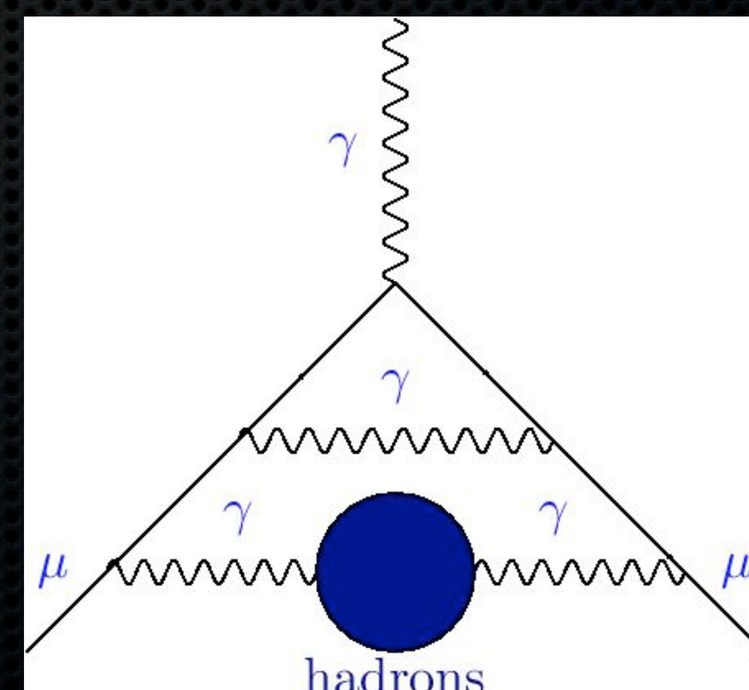






Lower Energies

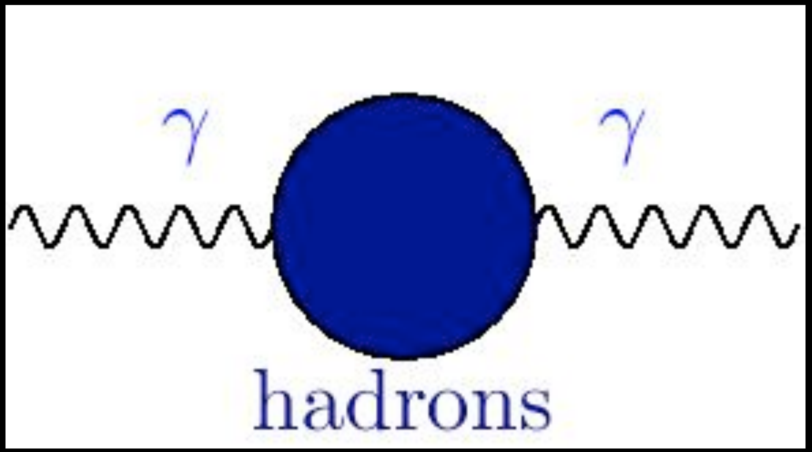




Δα and μ anomalous magnetic moment (a_μ)

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

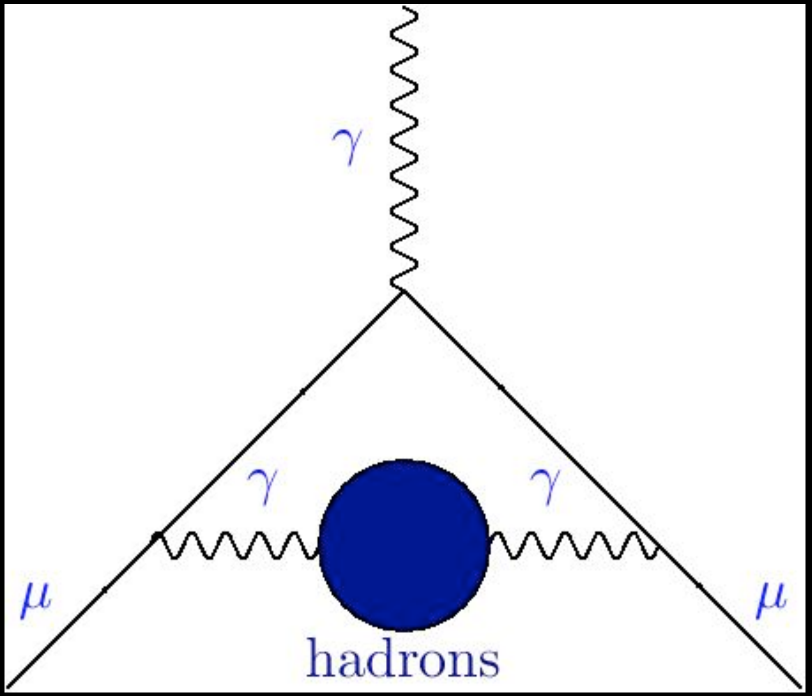
$$\alpha(s) = \frac{\alpha}{1-\Delta\alpha_{\text{lep}}(s)-\Delta\alpha_{\text{had}}(s)} \quad \text{(on-shell)}$$



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

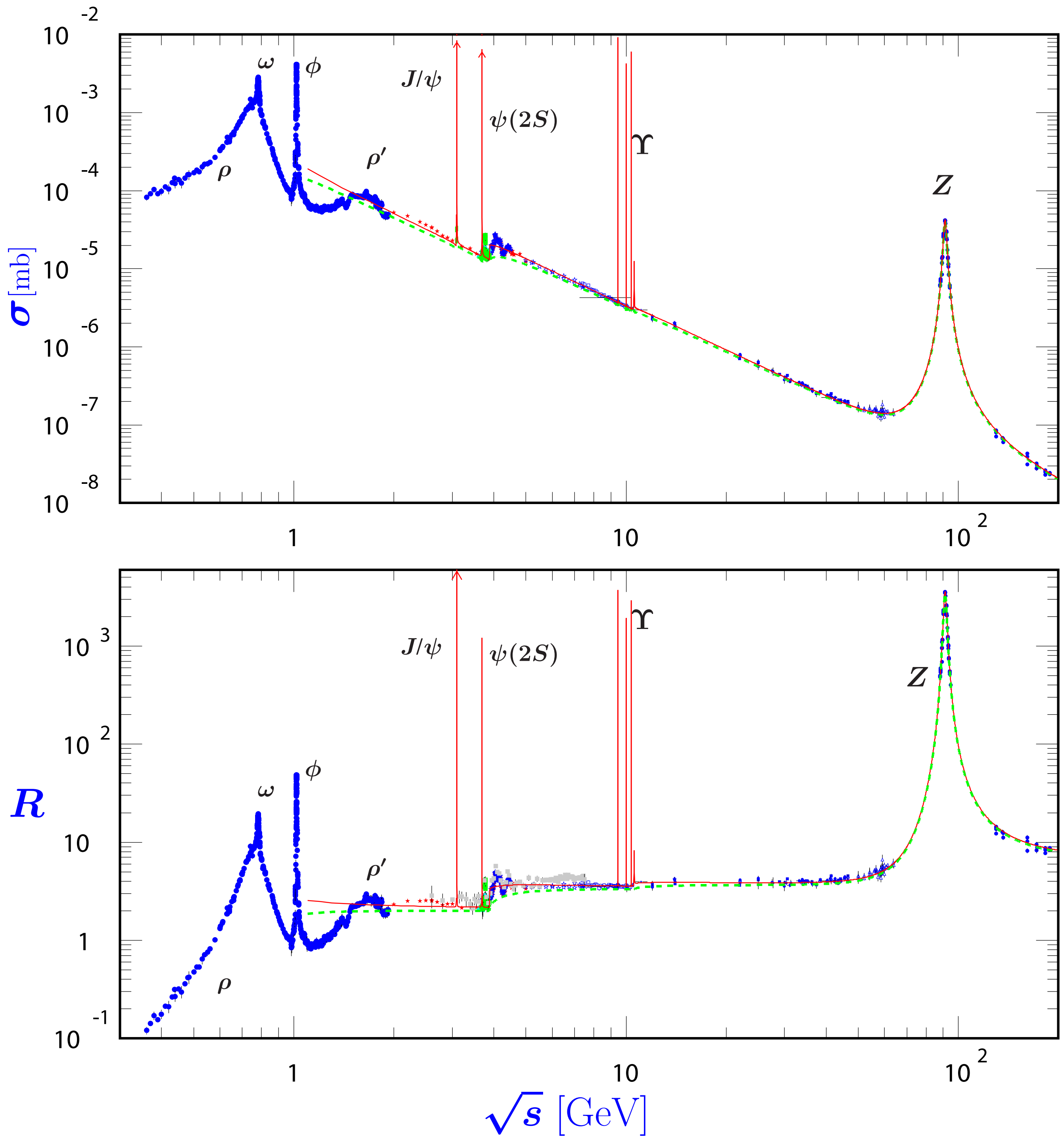
$$a_\mu \equiv \frac{g_\mu - 2}{2}$$

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



$K(s)$: known kernel function

R(s)

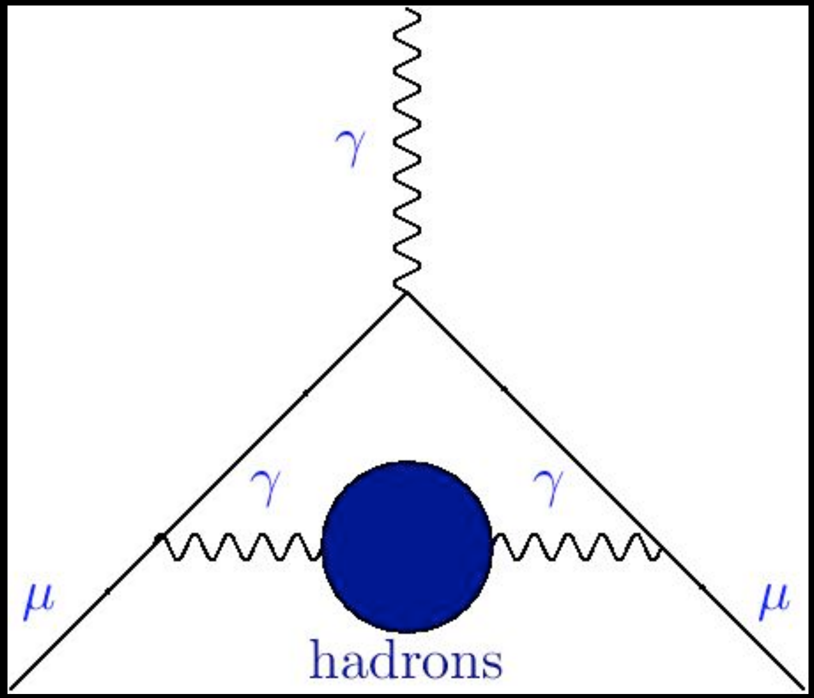


$$R(s) = 12\pi \, \mathrm{Im}\, \hat{\Pi}^{(\mathrm{had})}(s)$$

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

PDG 2012

$g_\mu - 2$



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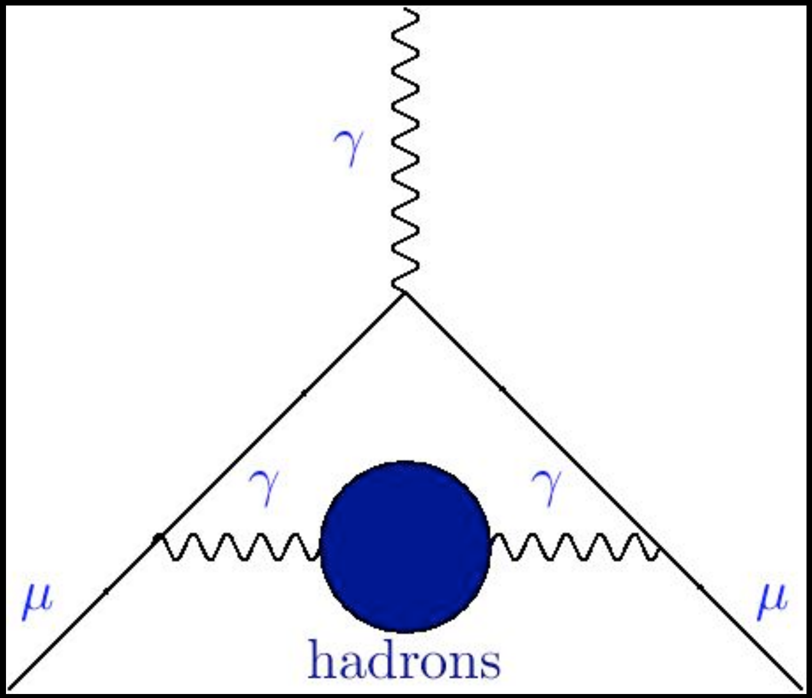

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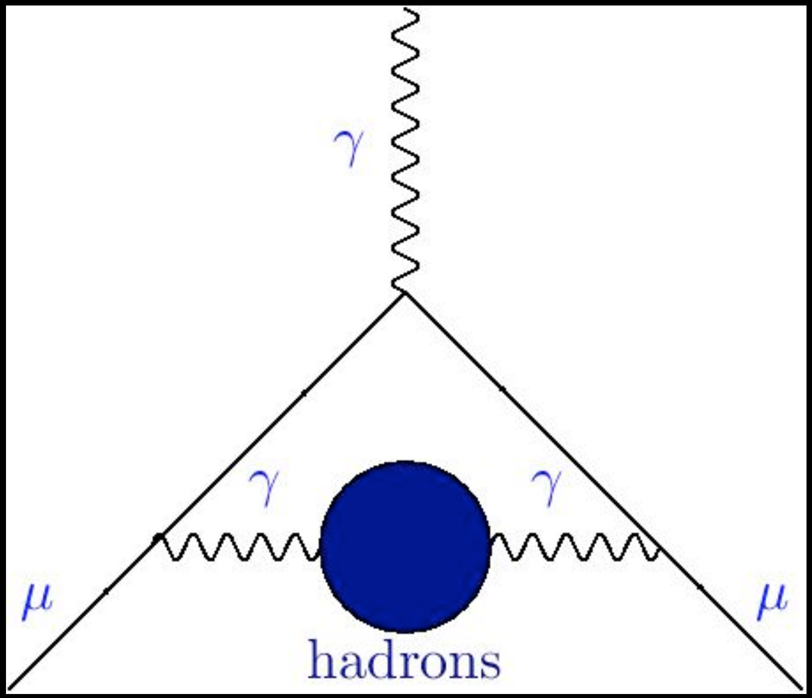

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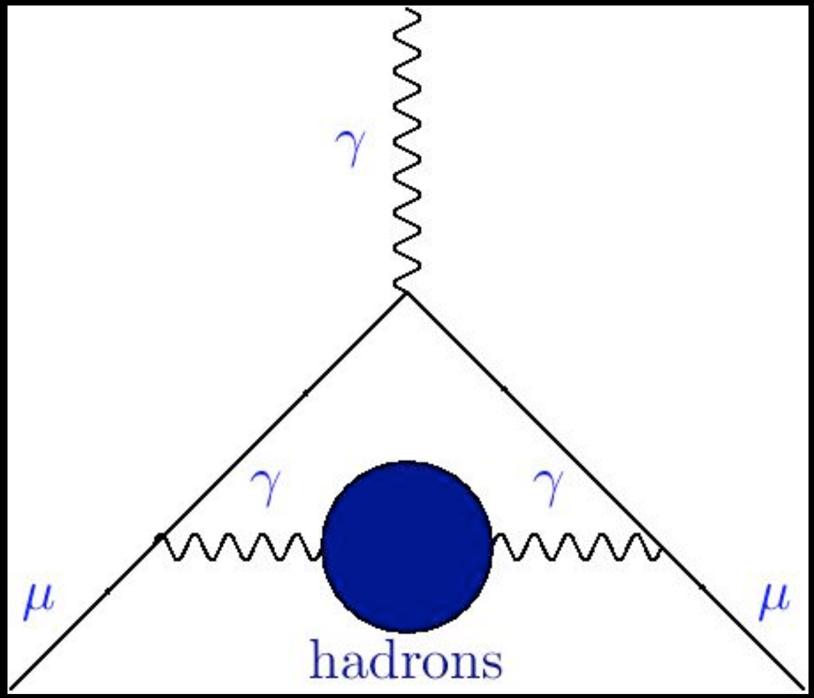

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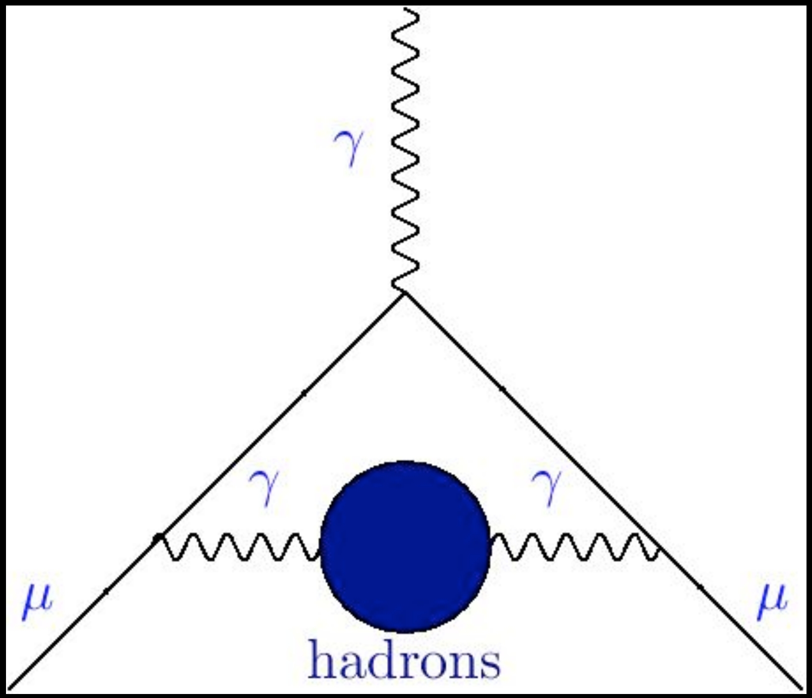

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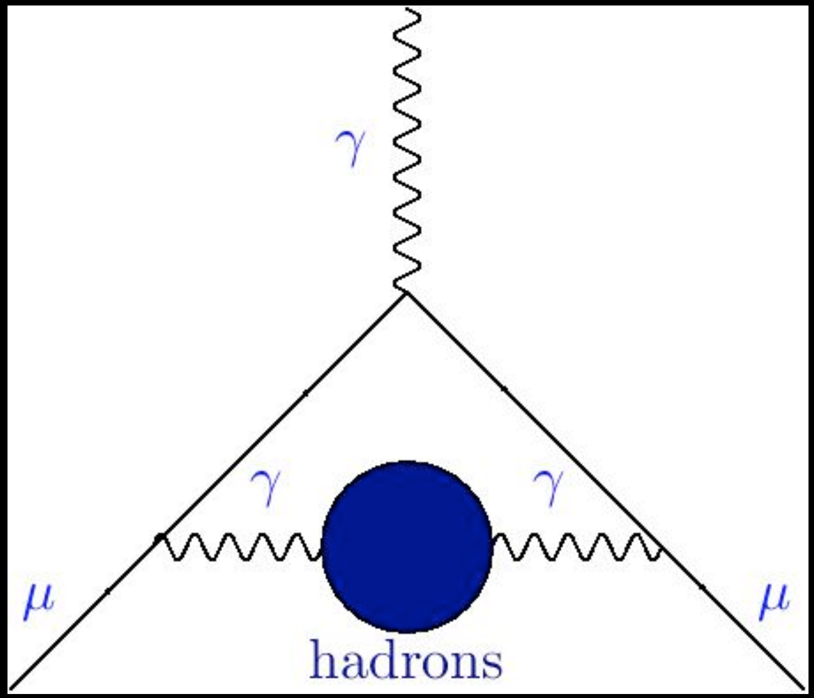

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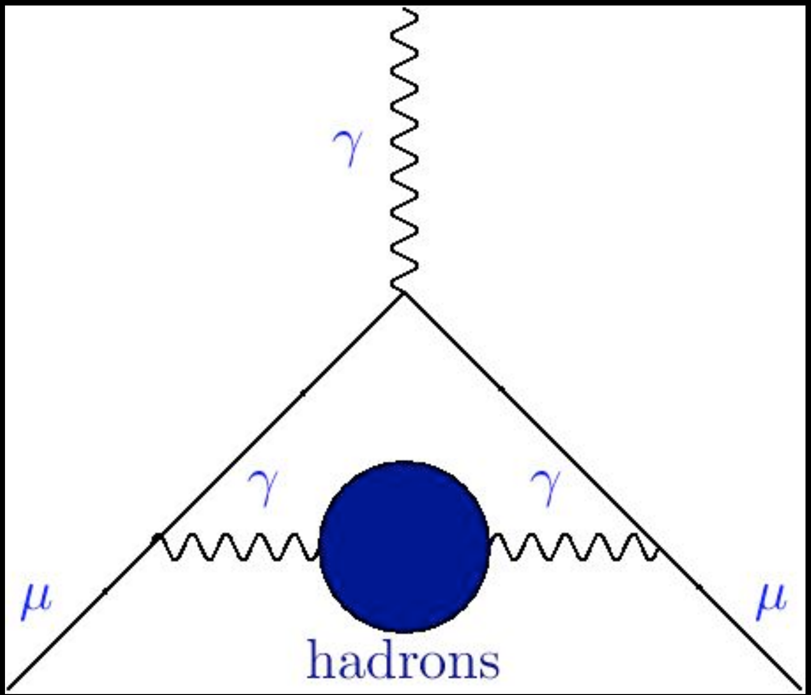

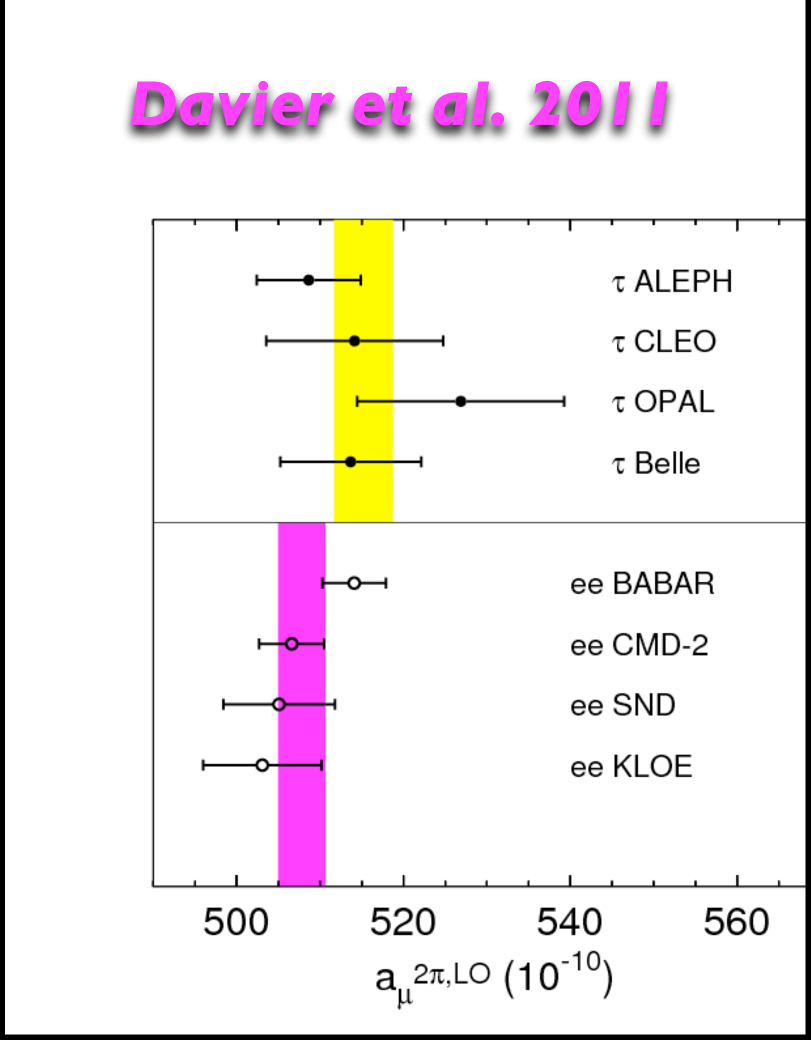

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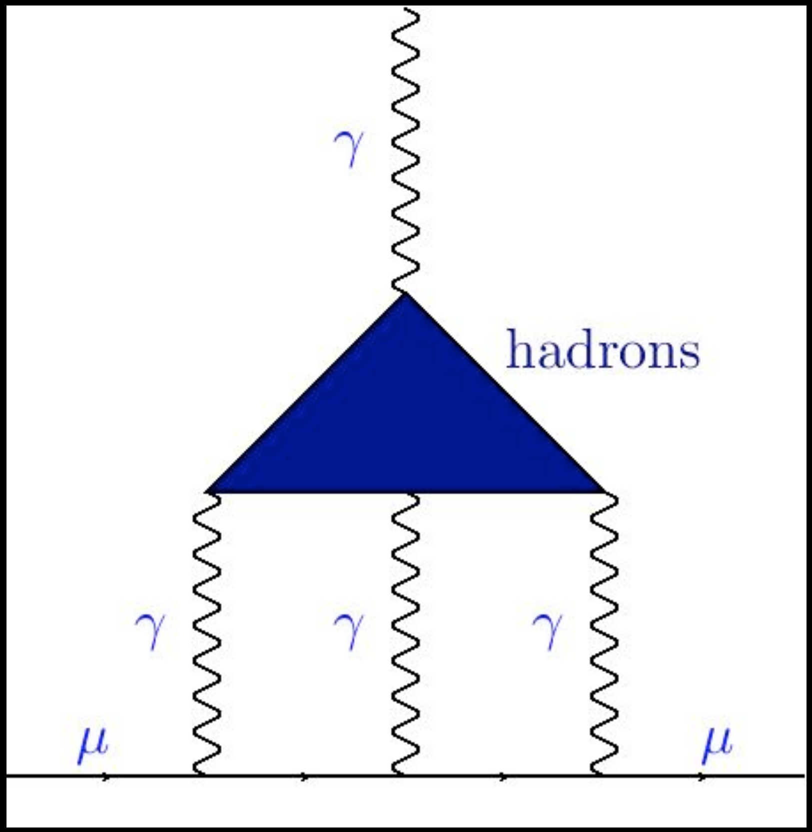

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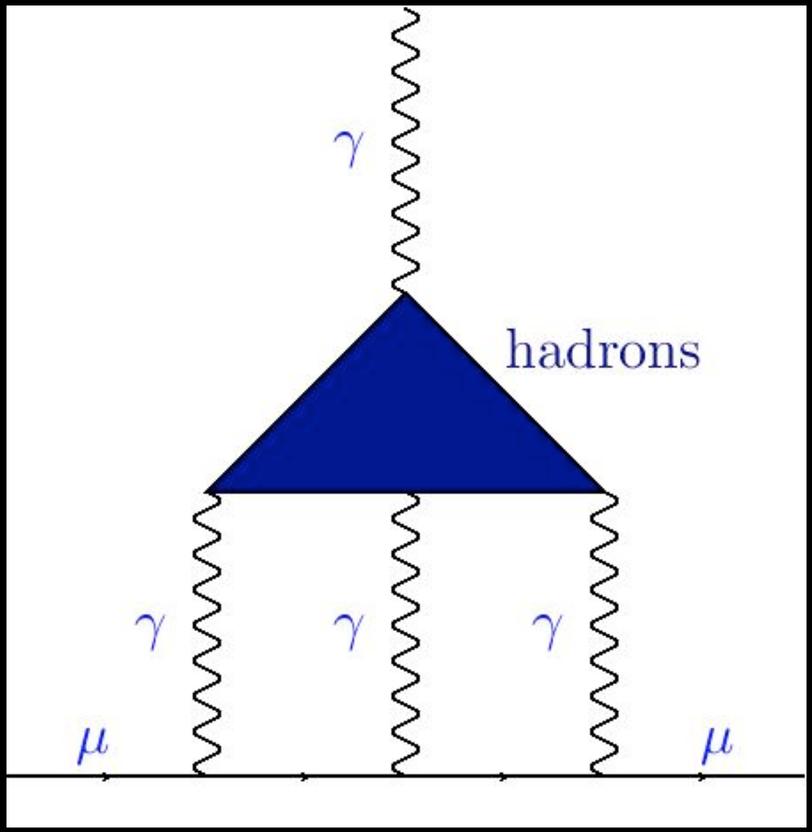

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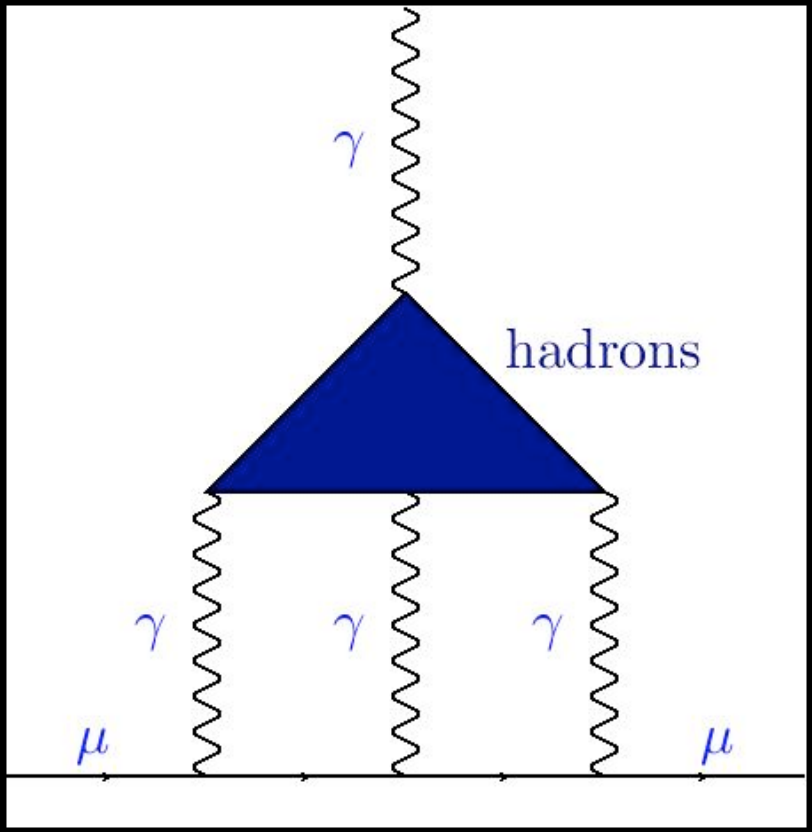

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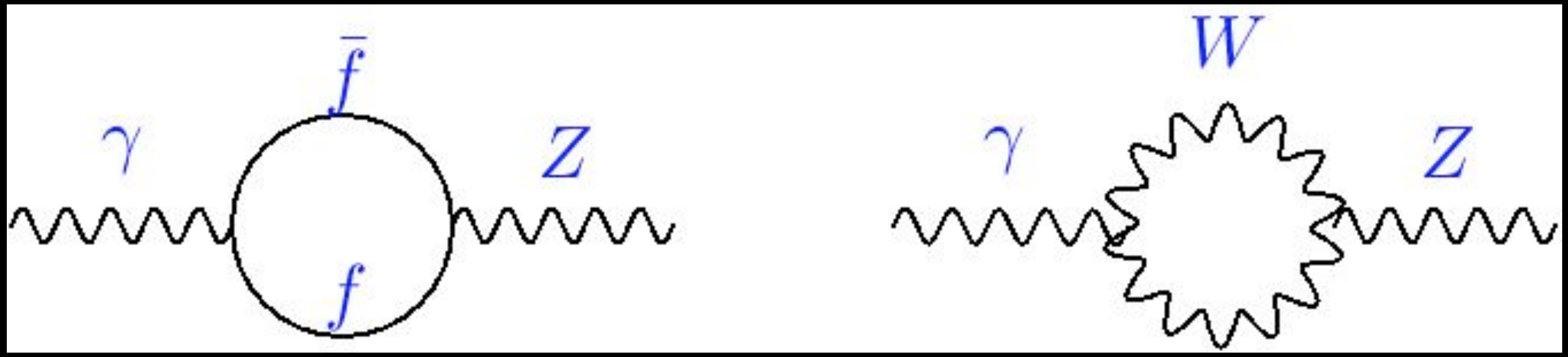
  Arnowitt, Chamsedine, Nath 1984

Uncertainties



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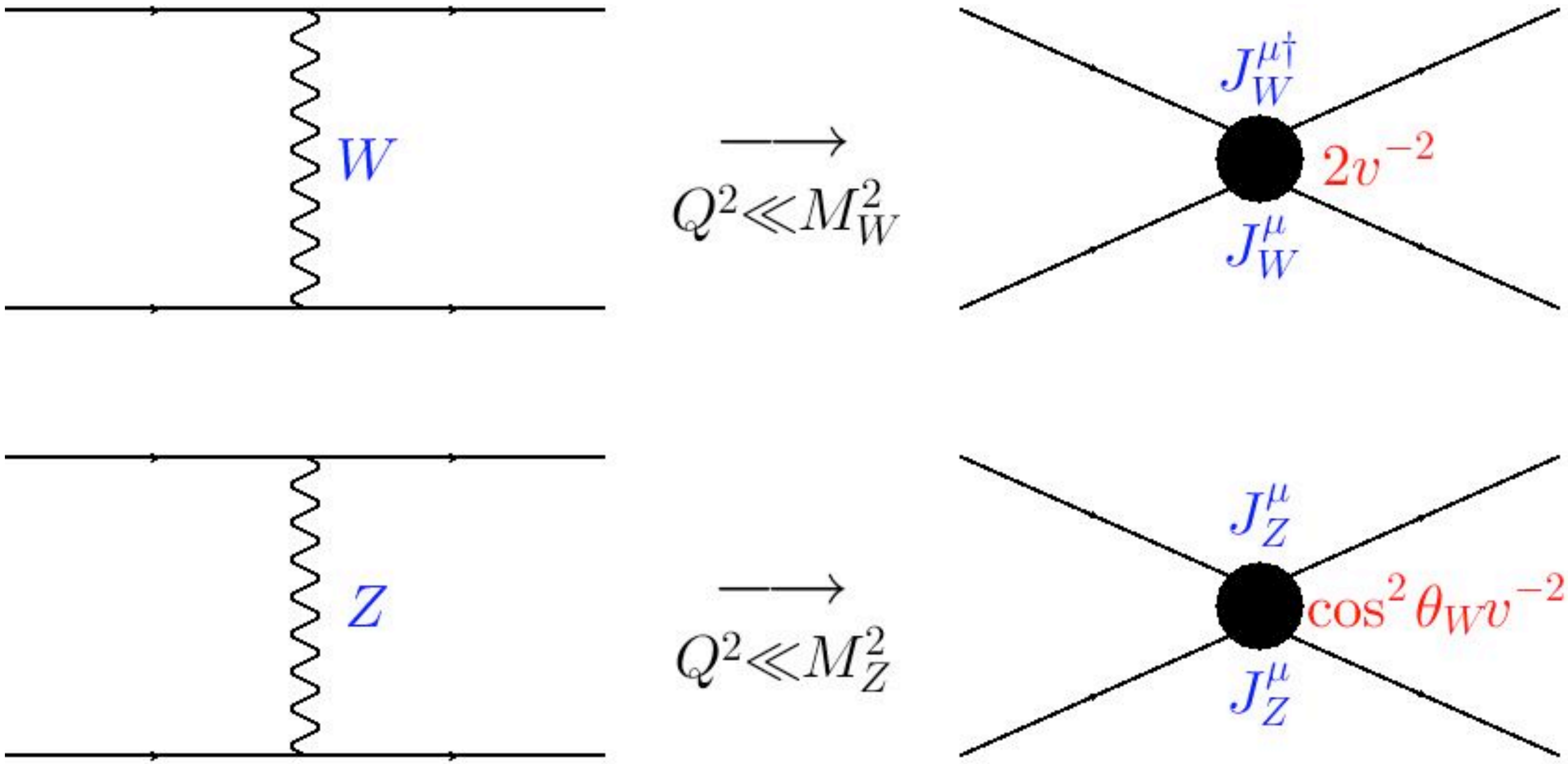
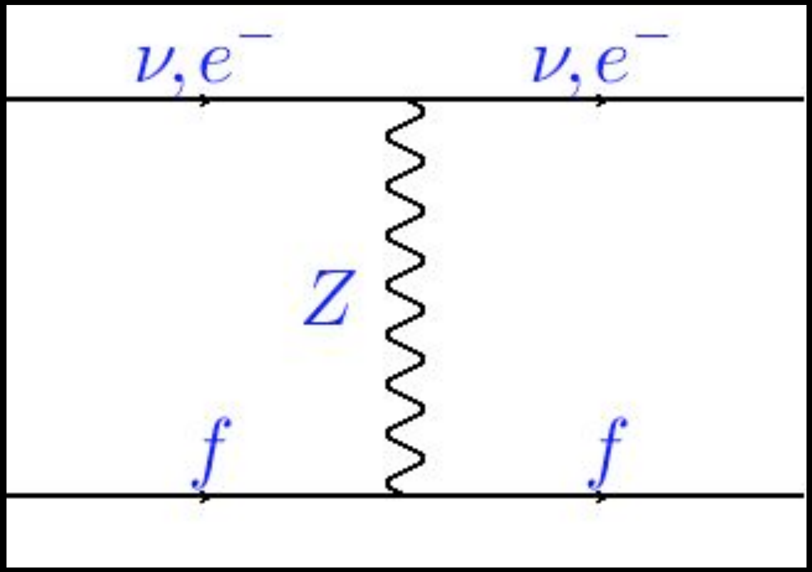
The Low-Energy (Fermi) Limit



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

Effective couplings



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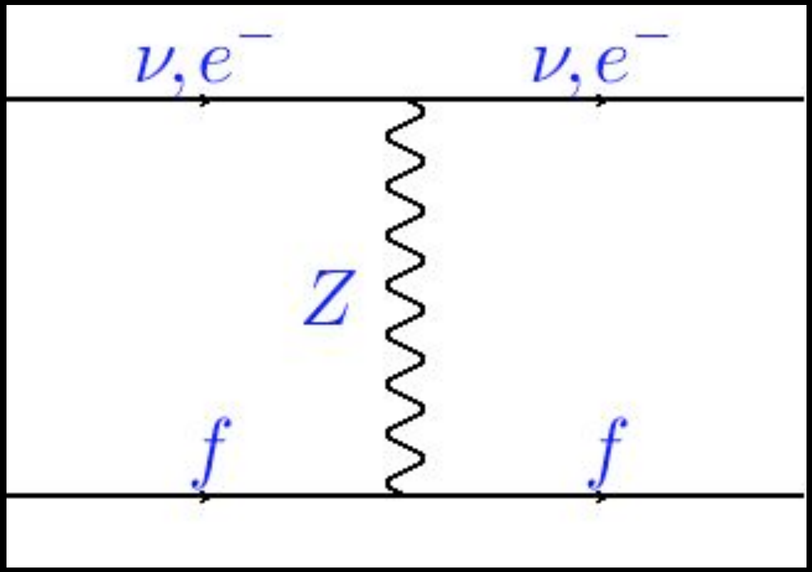

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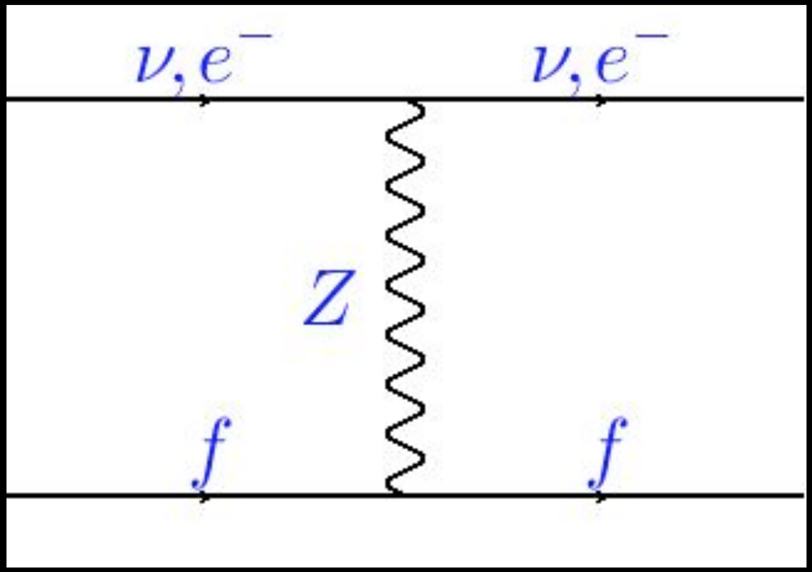

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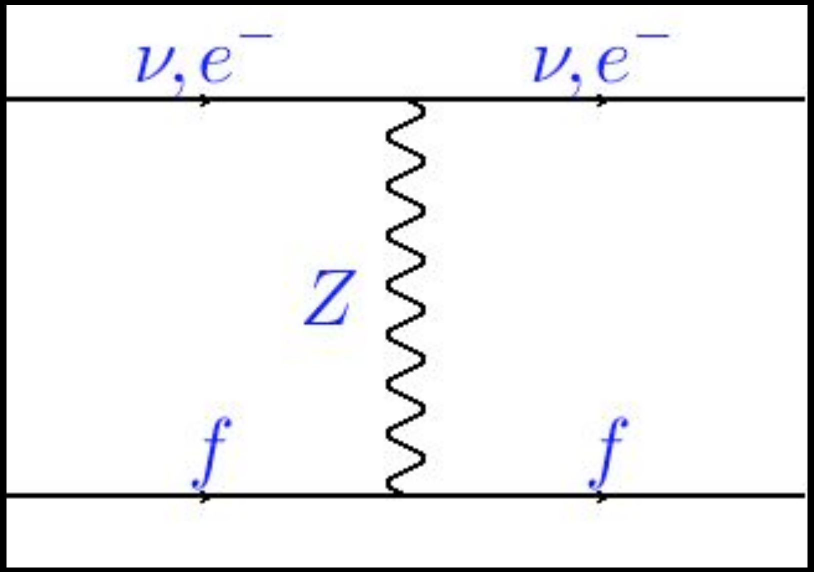

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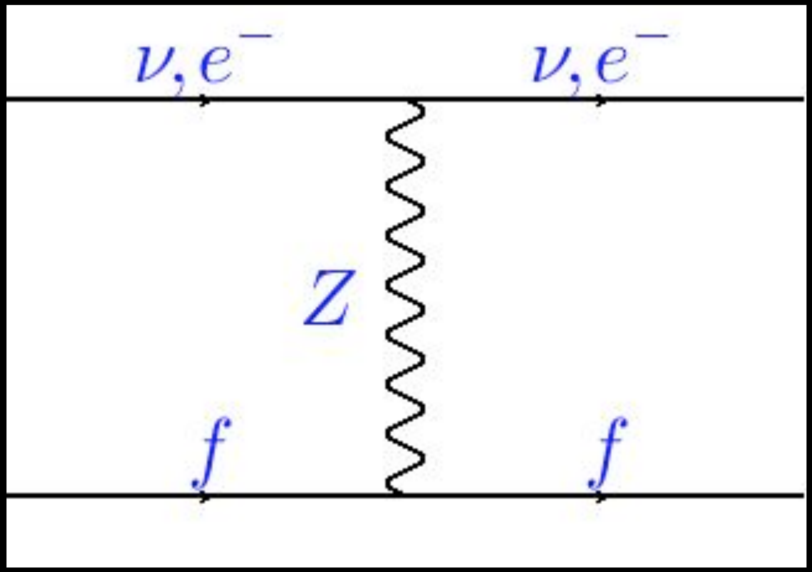

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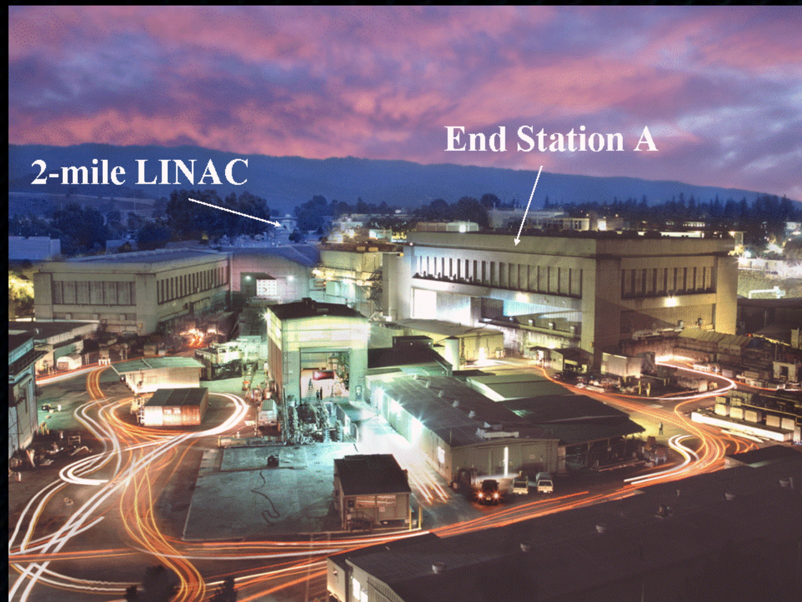
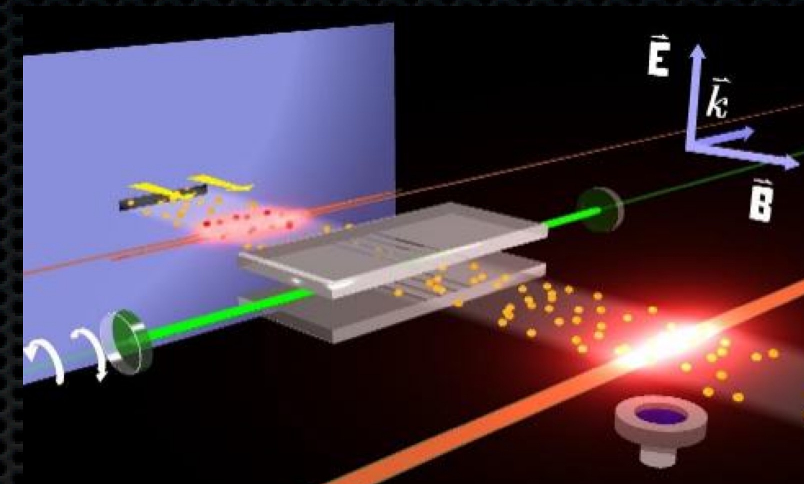
- $f = e \rightarrow |g^{ee}_{AV}| = ½ - 2\,\sin^2\theta_W \ll 1$
    - in SM: enhanced sensitivity to $\sin^2\theta_W$ (compete with Z-pole)
    - BSM: enhanced sensitivity to Λ_{new}



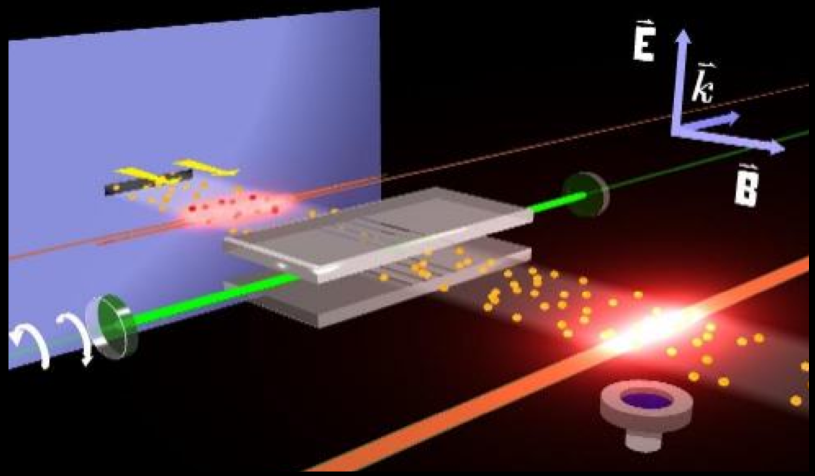


Parity Violation

Jefferson Lab
Thomas Jefferson National Accelerator Facility

JG|U
JOHANNES GUTENBERG UNIVERSITÄT MAINZ

Atomic Parity Violation



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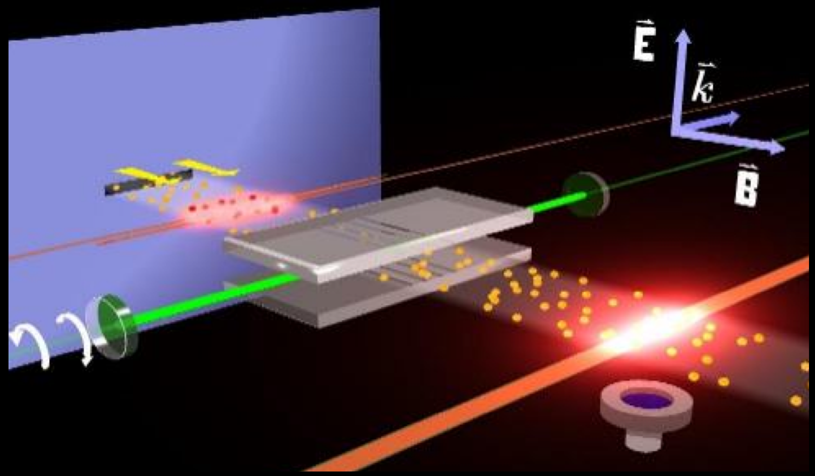

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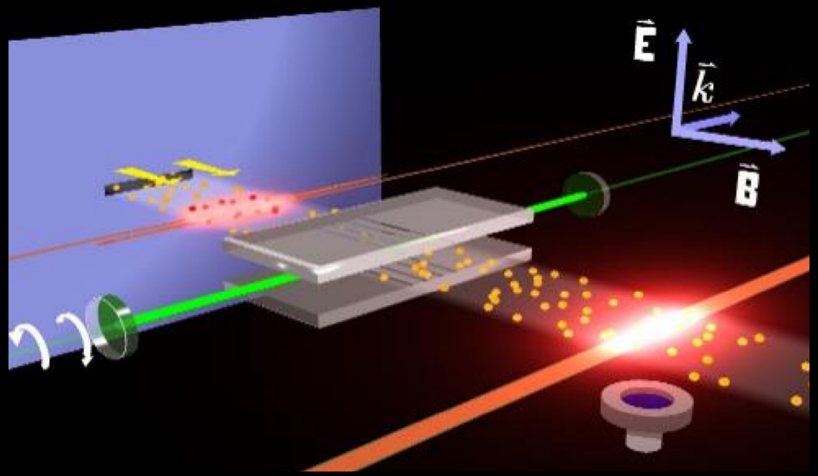

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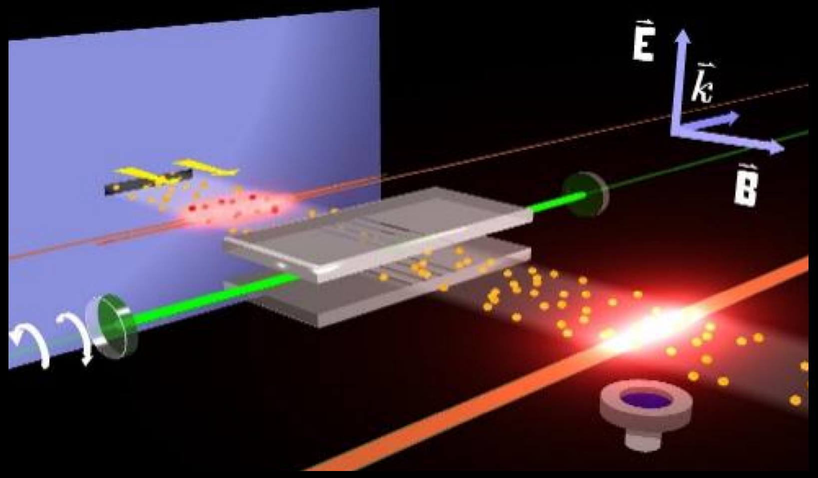

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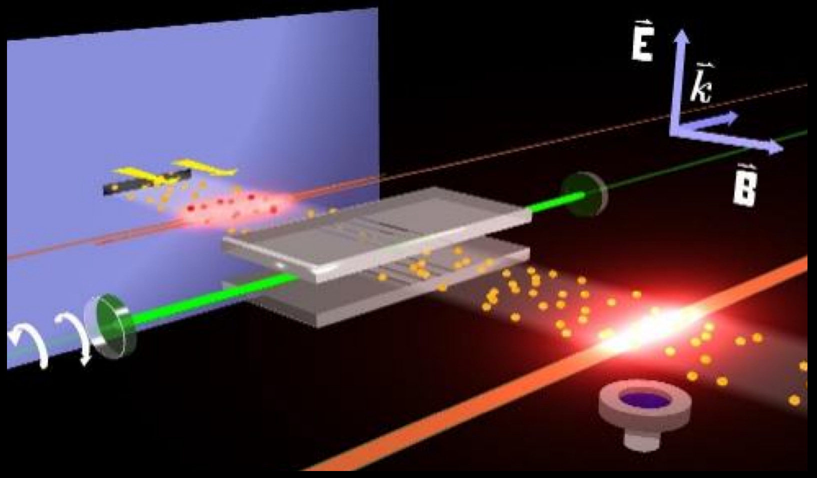

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- separate g_{AV} and g_{VA} by measuring different hyperfine transitions

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- 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 →

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

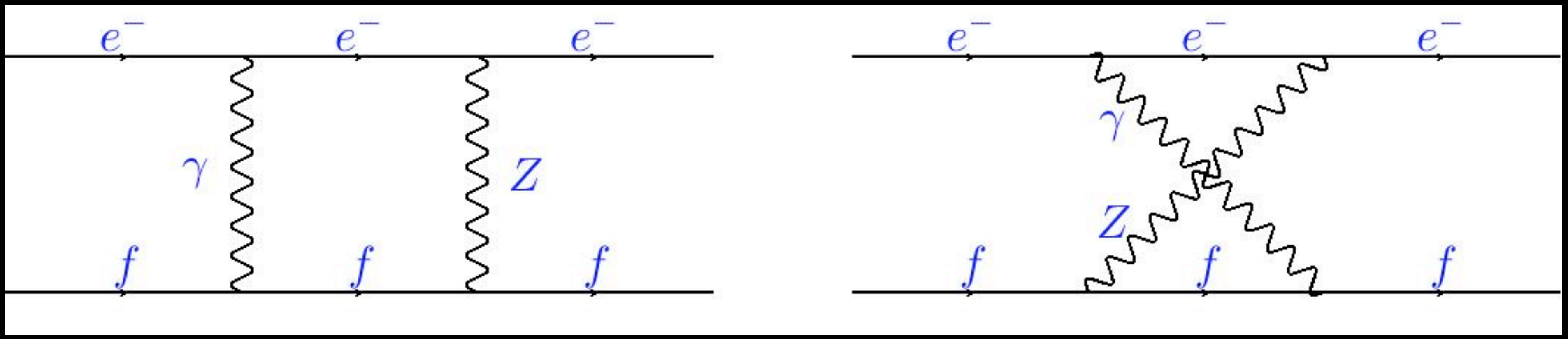
- *JLAB-Qweak Collaboration* completed data taking to determine g_{VA}^{ep} from

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

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

- 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



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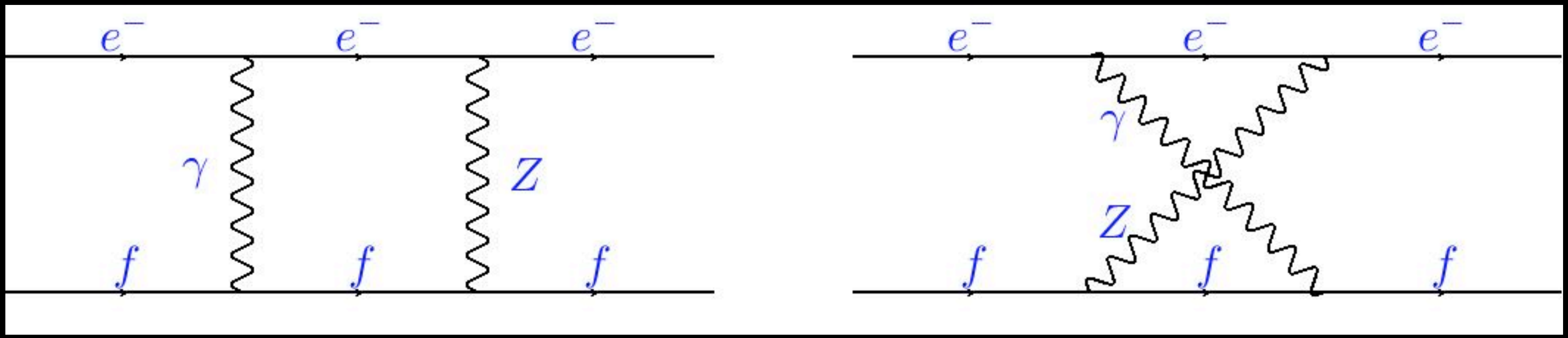

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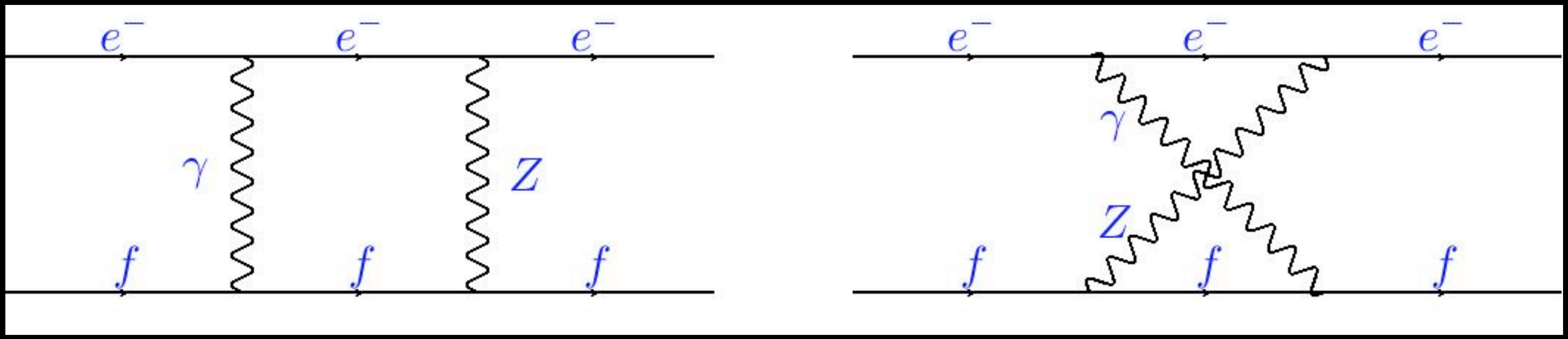

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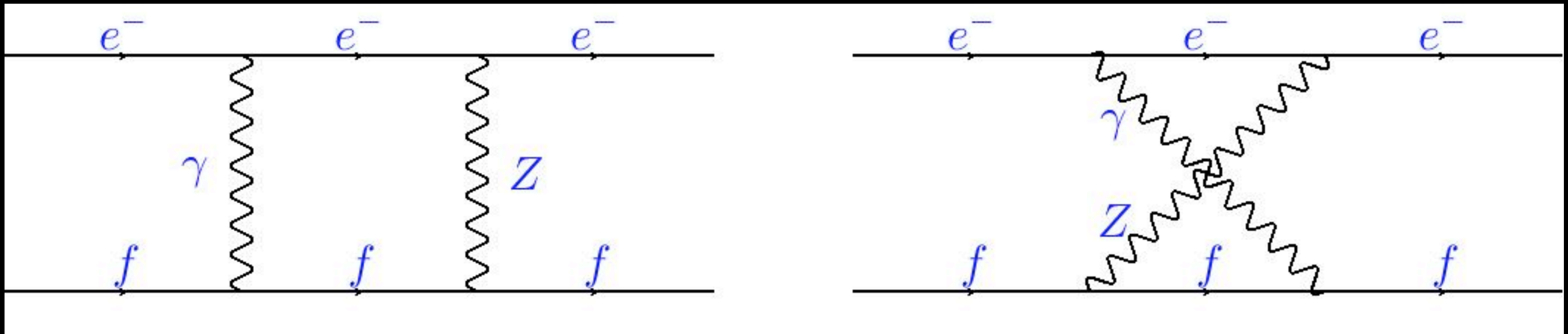

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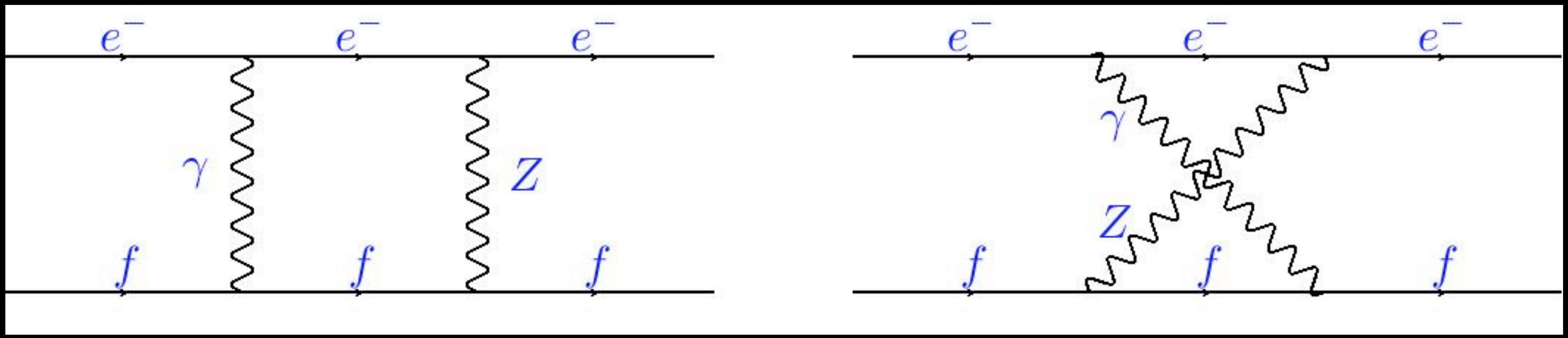

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➡ strong point for *P2 (Mainz)*

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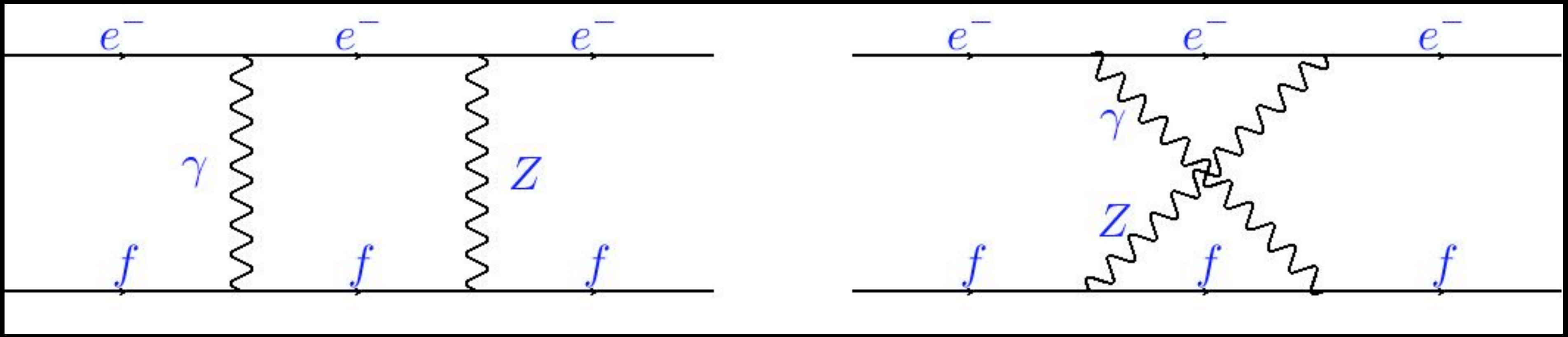

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- for APV ($E_e \approx 0, Q^2 \approx 0$) effect for g_{AV}^{eq} is $\propto$ g_{VA}^{eq} and vice versa
- for elastic scattering $E_e \neq 0$, mixing in opposite chirality structure

➡ 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***

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➡ *P2* goal of 2% in g_{AV}^{ep} or Q_W^p and ±0.00036 in $\sin^2\theta_W$ or better

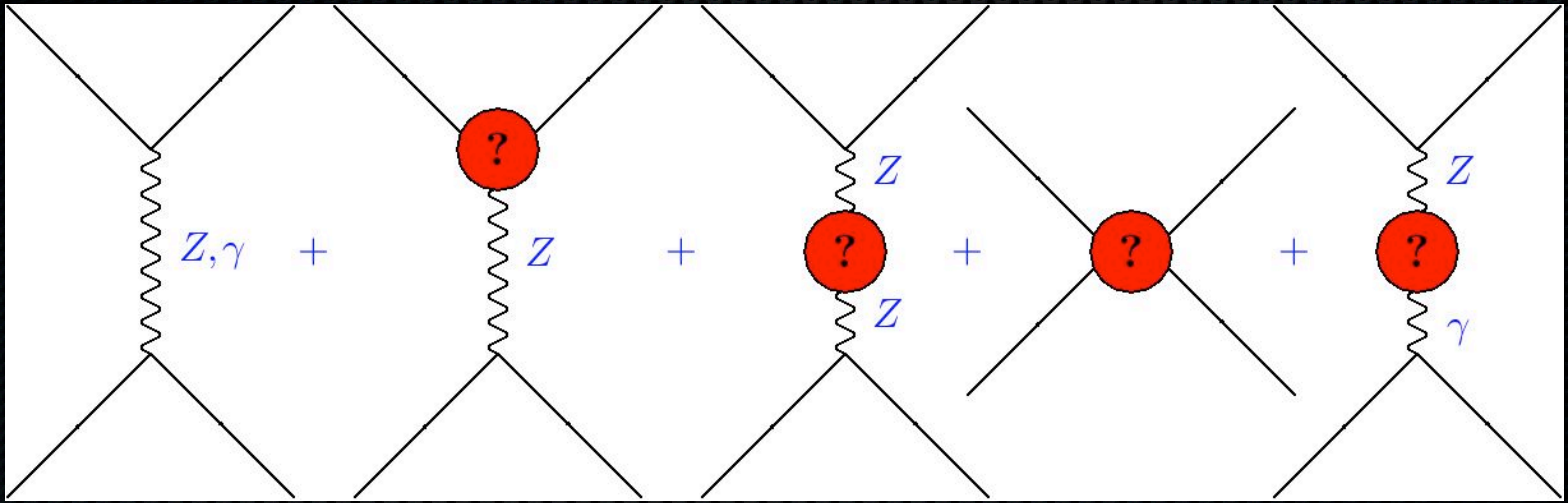
g_{VA}^{eu} and g_{VA}^{ed}

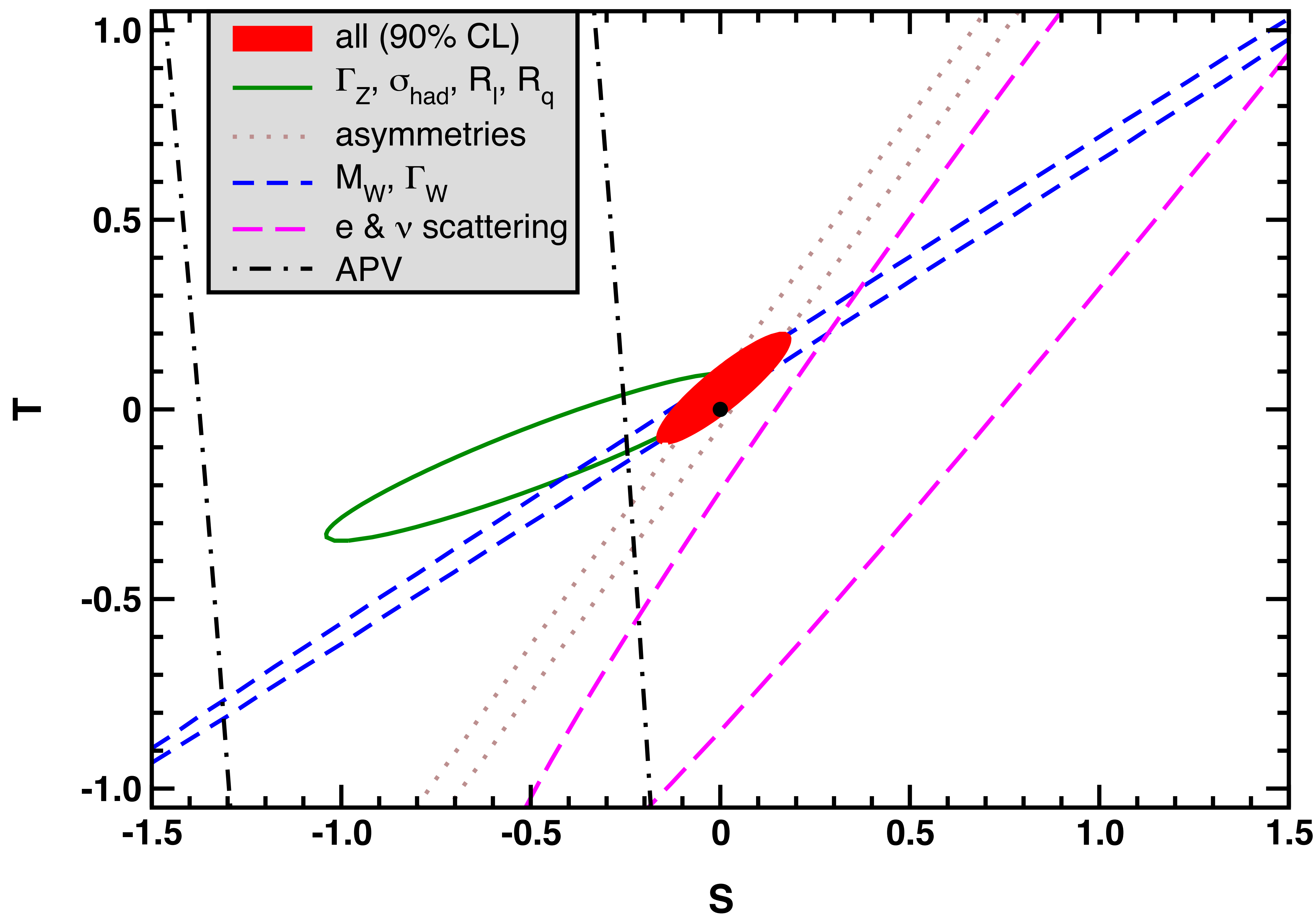
- problematic at low very energies (elastic or quasi-elastic)
- charge weighted combination from (in valence quark approximation)

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

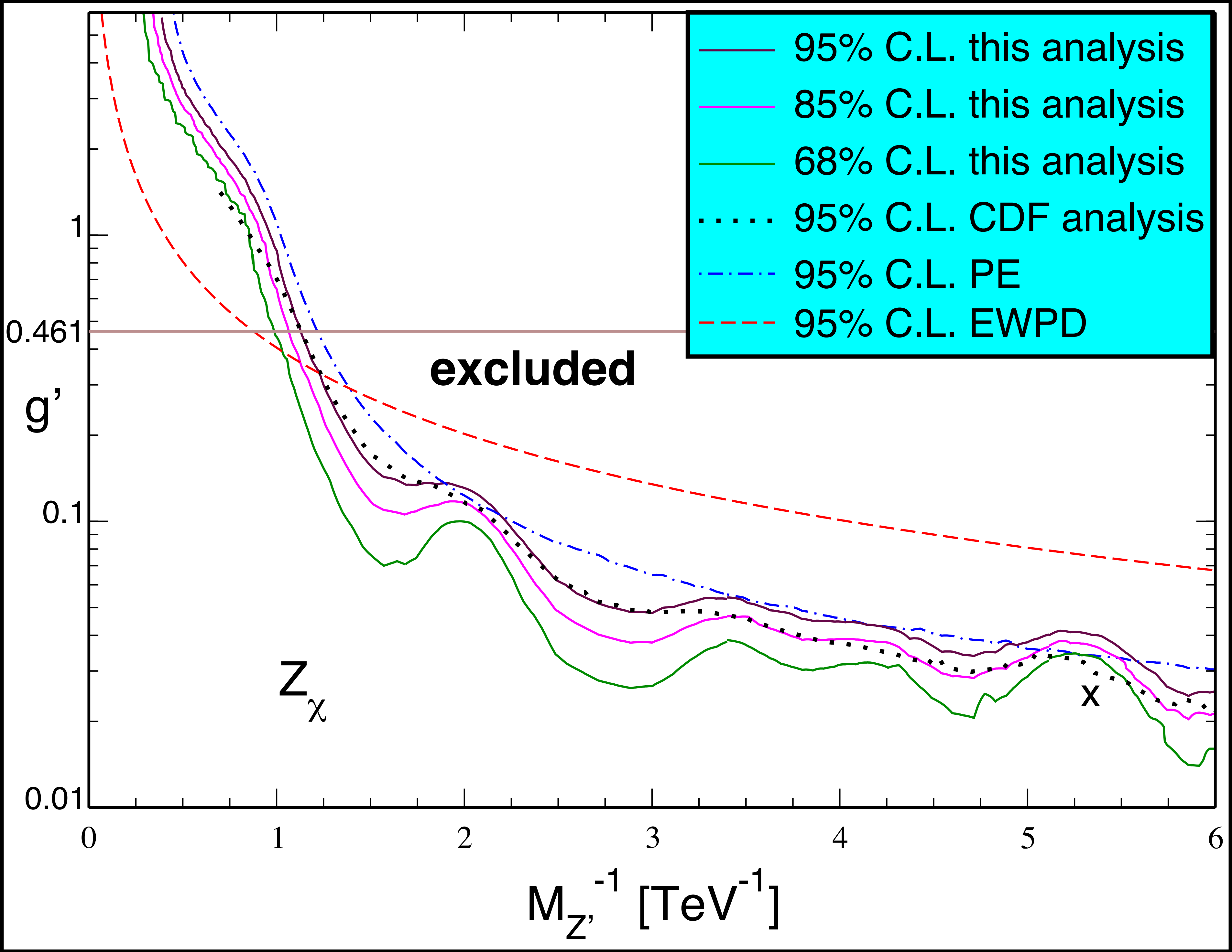
  - eDIS asymmetries much larger ($\gtrsim 10^{-4}$) than in elastic scattering
  - measured to ~ 10% at *SLAC* for 0.92 GeV^2 < Q^2 < 1.96 GeV^2
    Prescott et al 1979
  - 2 further points at Q^2 = 1.1 and 1.9 GeV^2 to 4.5% by *JLab-Hall A Collaboration*
  - approved *SOLID* experiment will measure large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

Implications for New Physics




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

Energy-Intensity Complementarity



New Physics Sensitivity

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

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

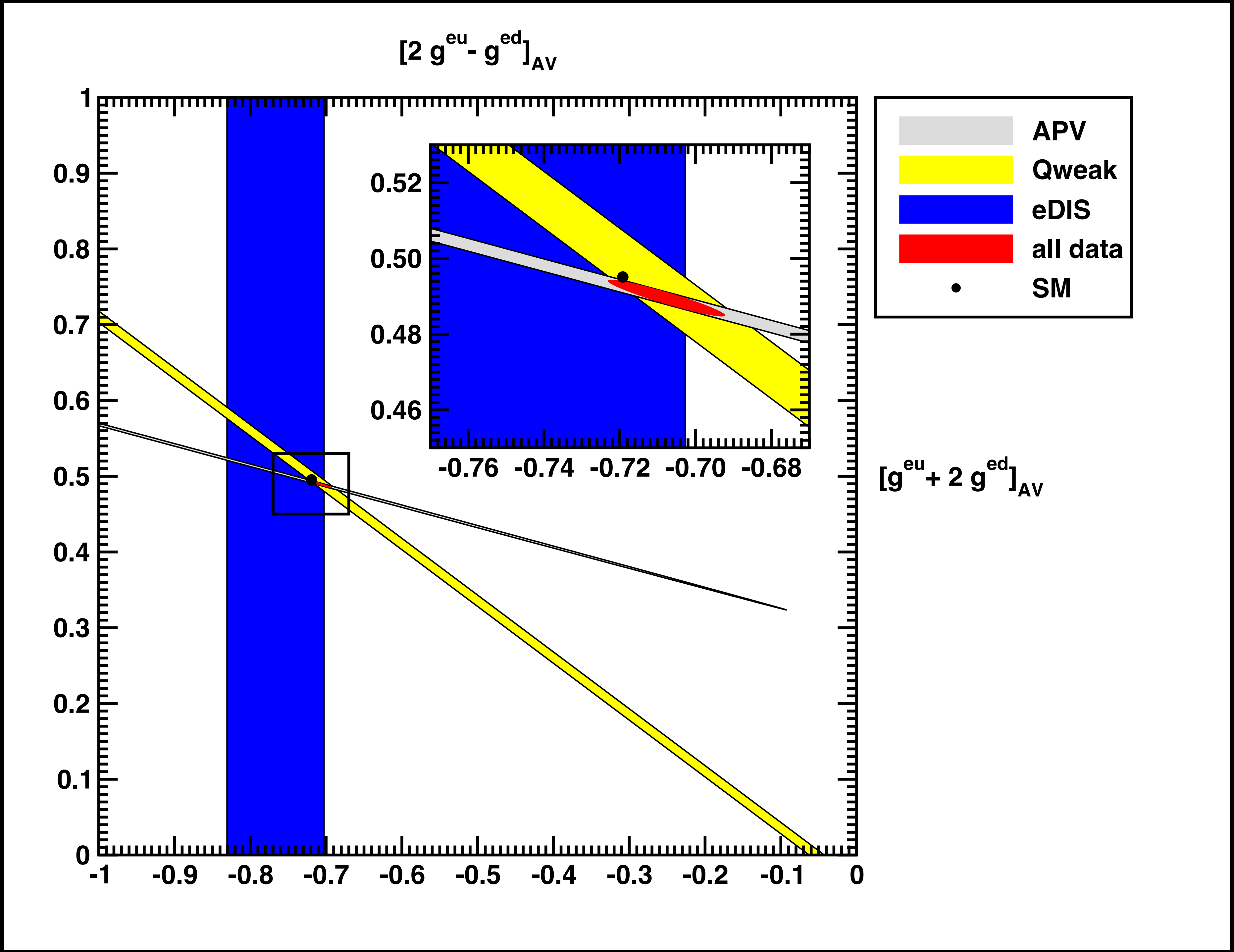
$g^2 = 4\pi$ (convention)

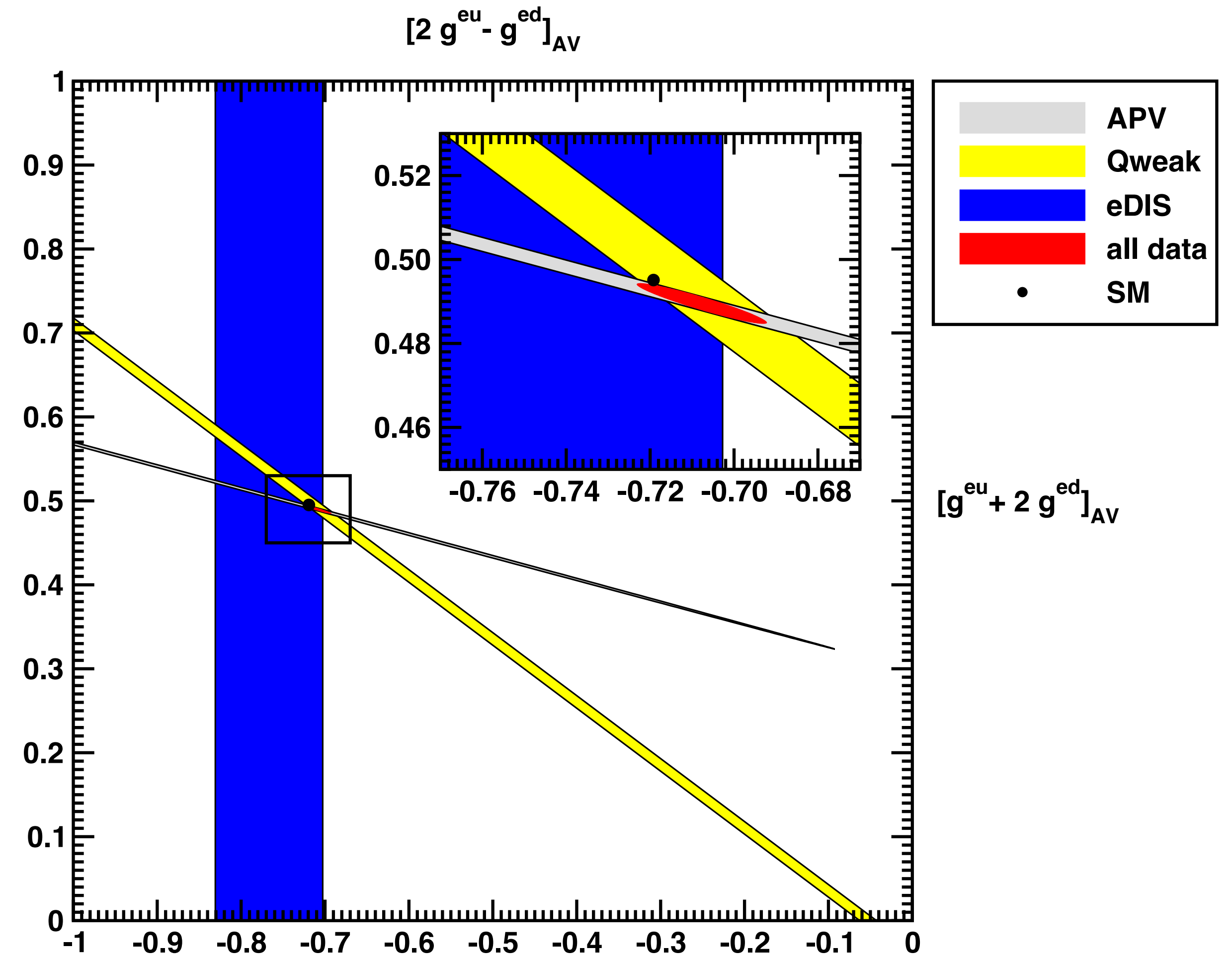
Customary to quote one-sided limits on Λ!

$\not{P}$-Experiments

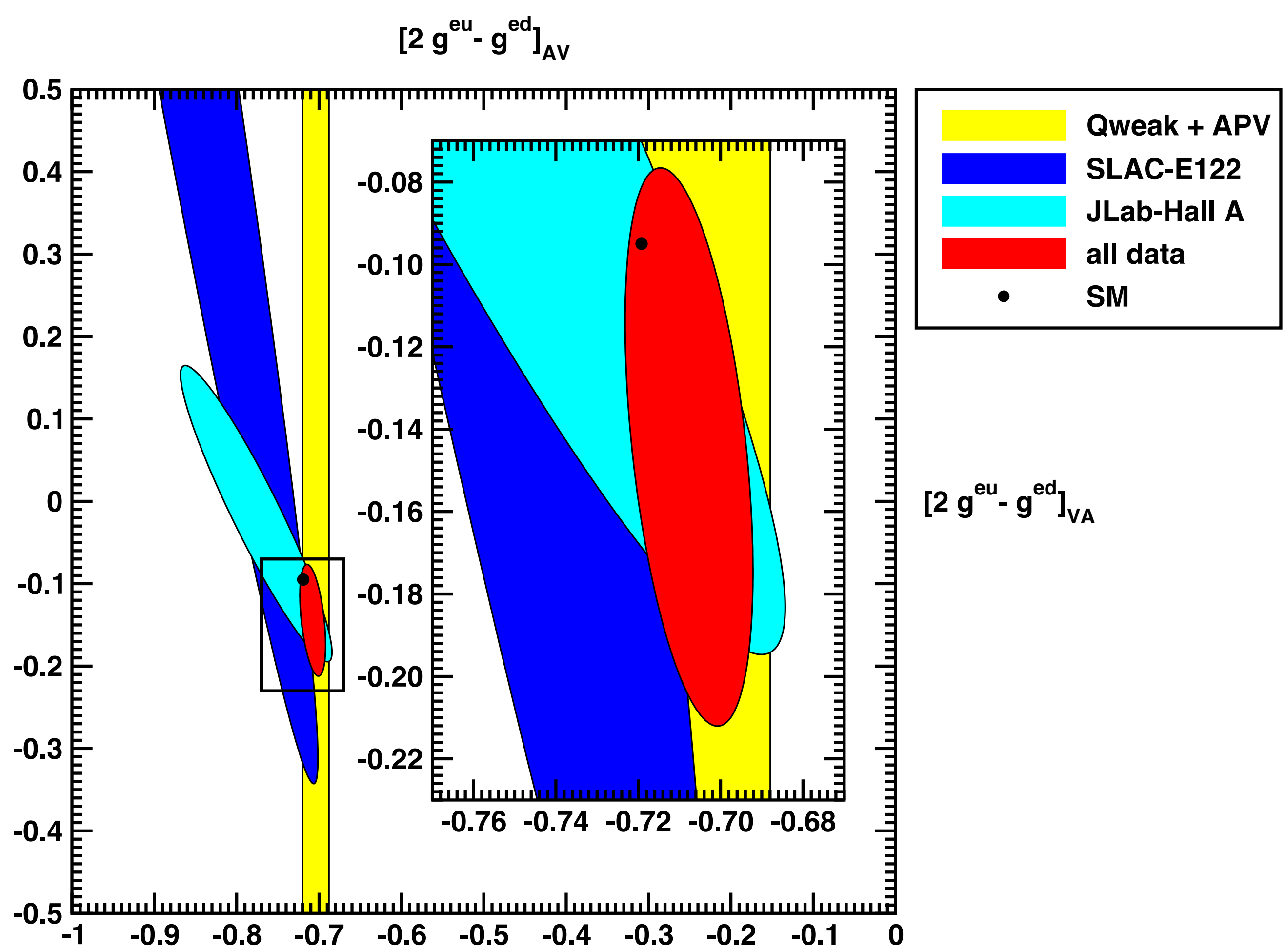
	precision	$\Delta \sin^2\overline{\theta}_W(0)$	Λ_{new} (expected)
APV ^{133}Cs	0.58 %	0.0019	32.3 TeV
E158	14 %	0.0013	17.0 TeV
Qweak I	19 %	0.0030	17.0 TeV
PVDIS	4.5 %	0.0051	7.6 TeV
Qweak final	4.5 %	0.0008	33 TeV
SoLID	0.6 %	0.00057	22 TeV
MOLLER	2.3 %	0.00026	39 TeV
P2	2.0 %	0.00036	49 TeV
PVES ^{12}C	0.3 %	0.0007	49 TeV
APV ^{225}Ra	0.5 %	0.0018	34 TeV
APV ^{213}Ra/^{225}Ra	0.1 %	0.0037	16 TeV

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



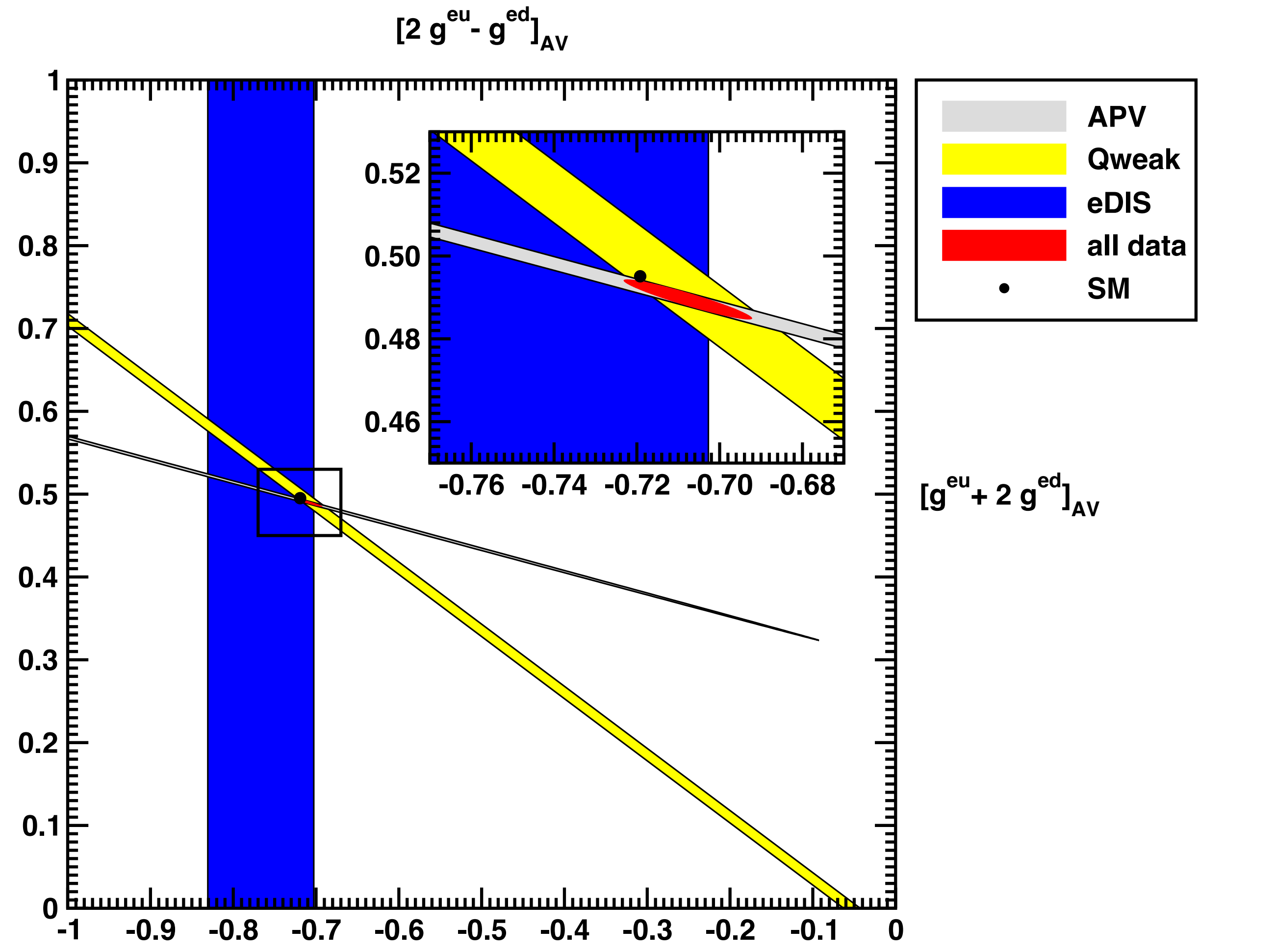


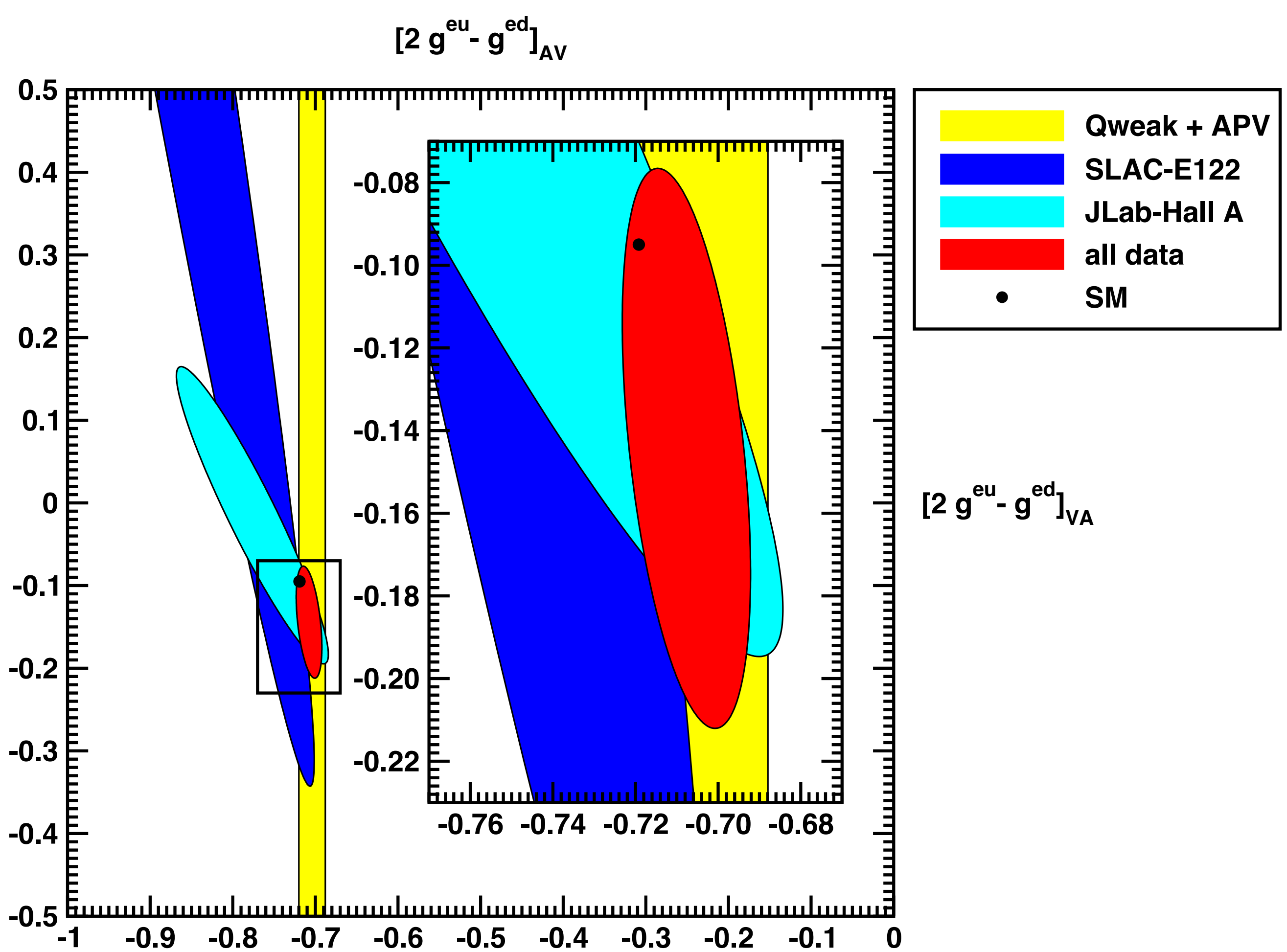
$[2\,g^{eu} - g^{ed}]_{AV}$
APV
Qweak
eDIS
all data
SM
$[g^{eu} + 2\,g^{ed}]_{AV}$

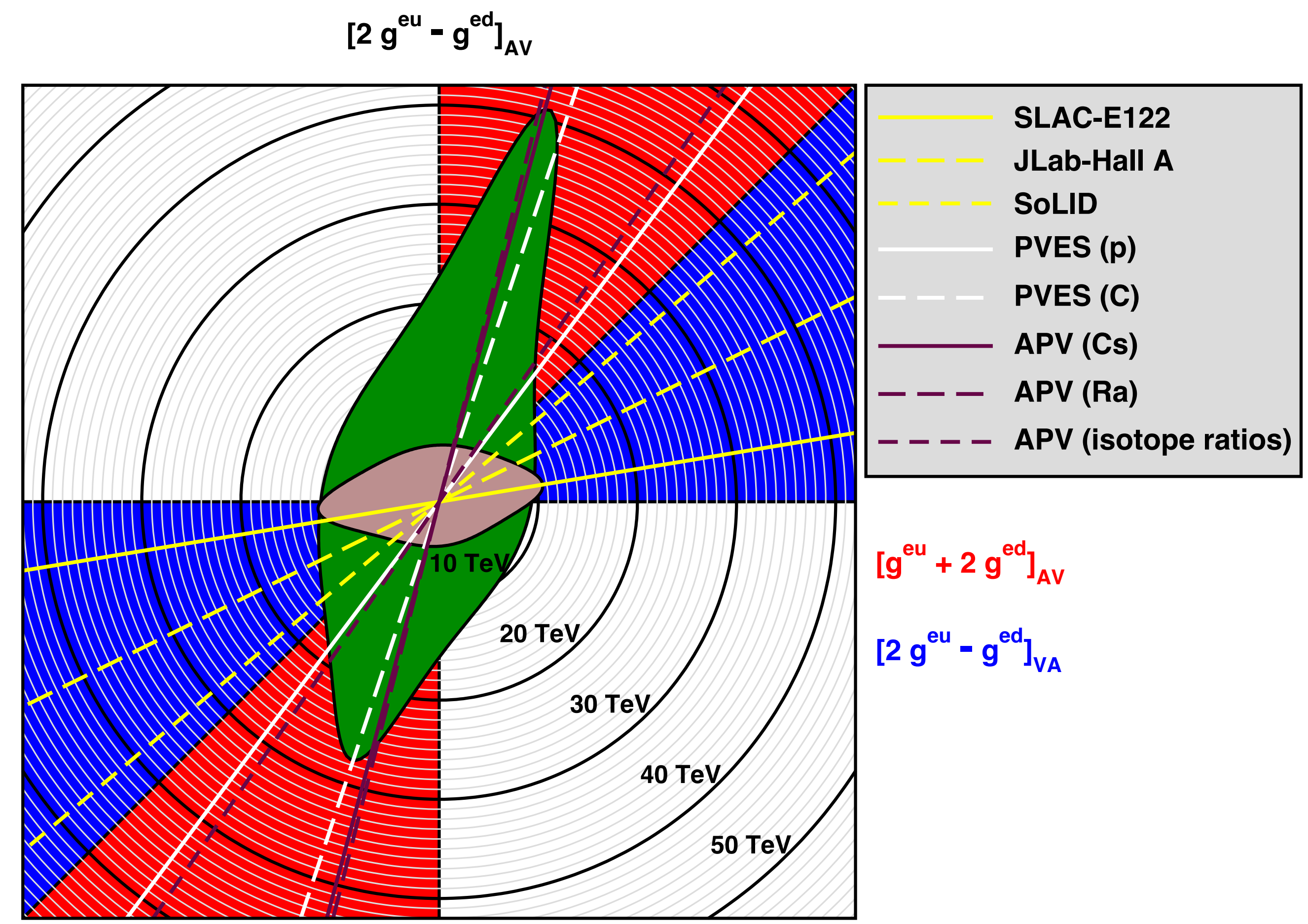


$[2\,g^{eu} - g^{ed}]_{AV}$
Qweak + APV
SLAC-E122
JLab-Hall A
all data
SM
$[2\,g^{eu} - g^{ed}]_{VA}$

Compositeness Scales







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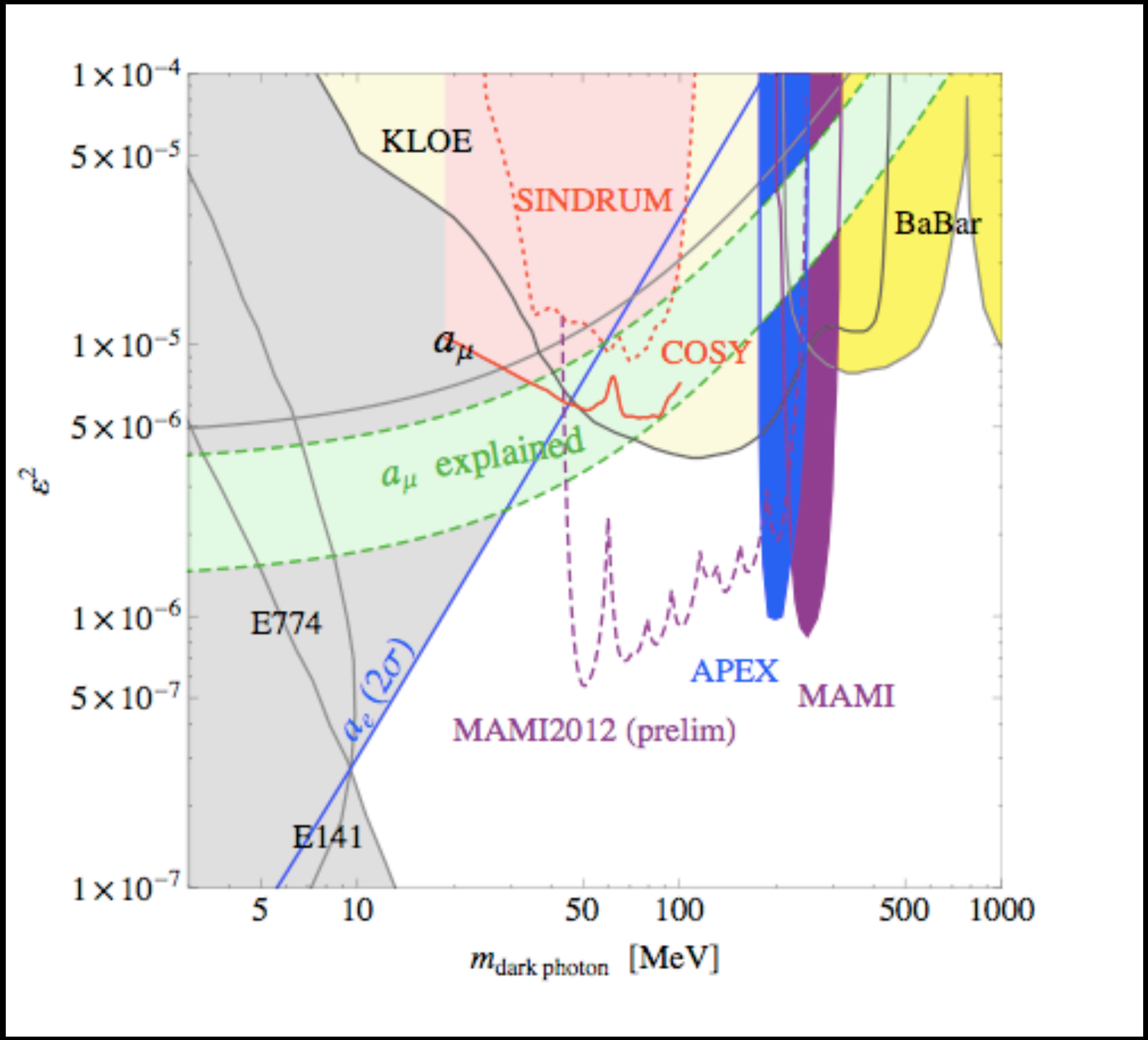
- U(1) portal: $F_{\mu\nu} \, F^{\mu\nu}$

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

Davoudiasl, Lee, Marciano 2012; Marciano 2013



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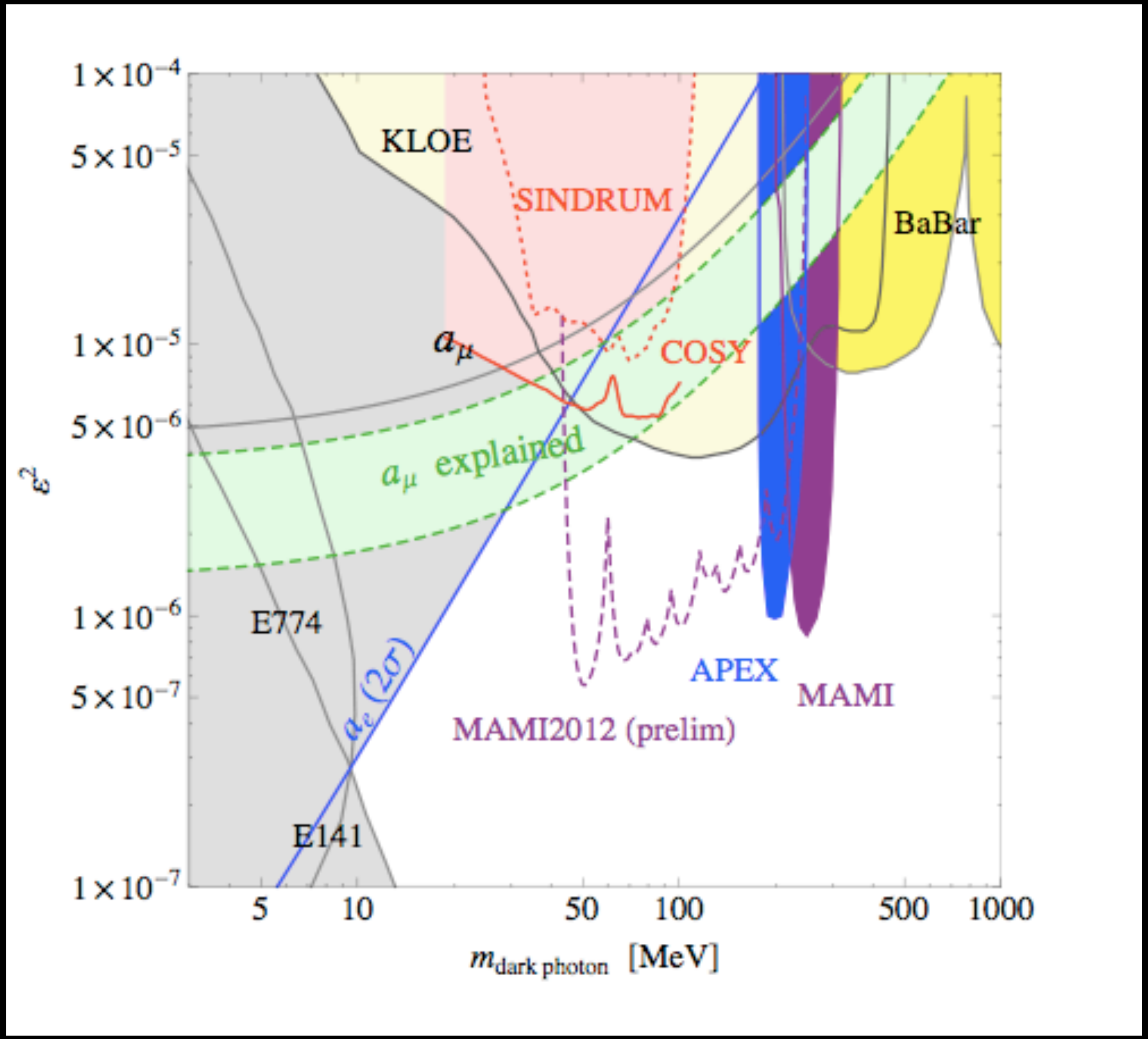

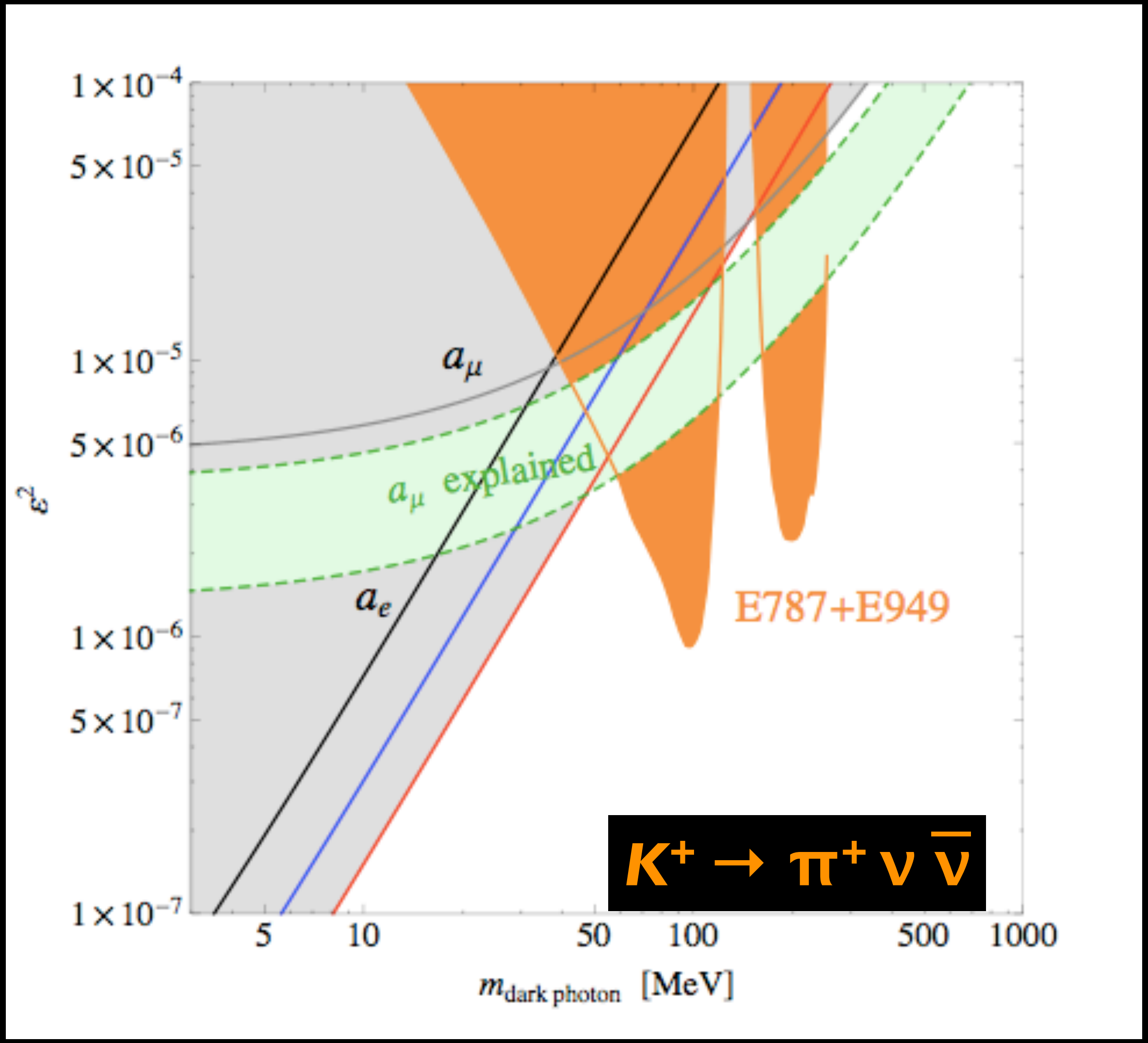

$Br(Z_d \to e^+ e^-) \approx 1$

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

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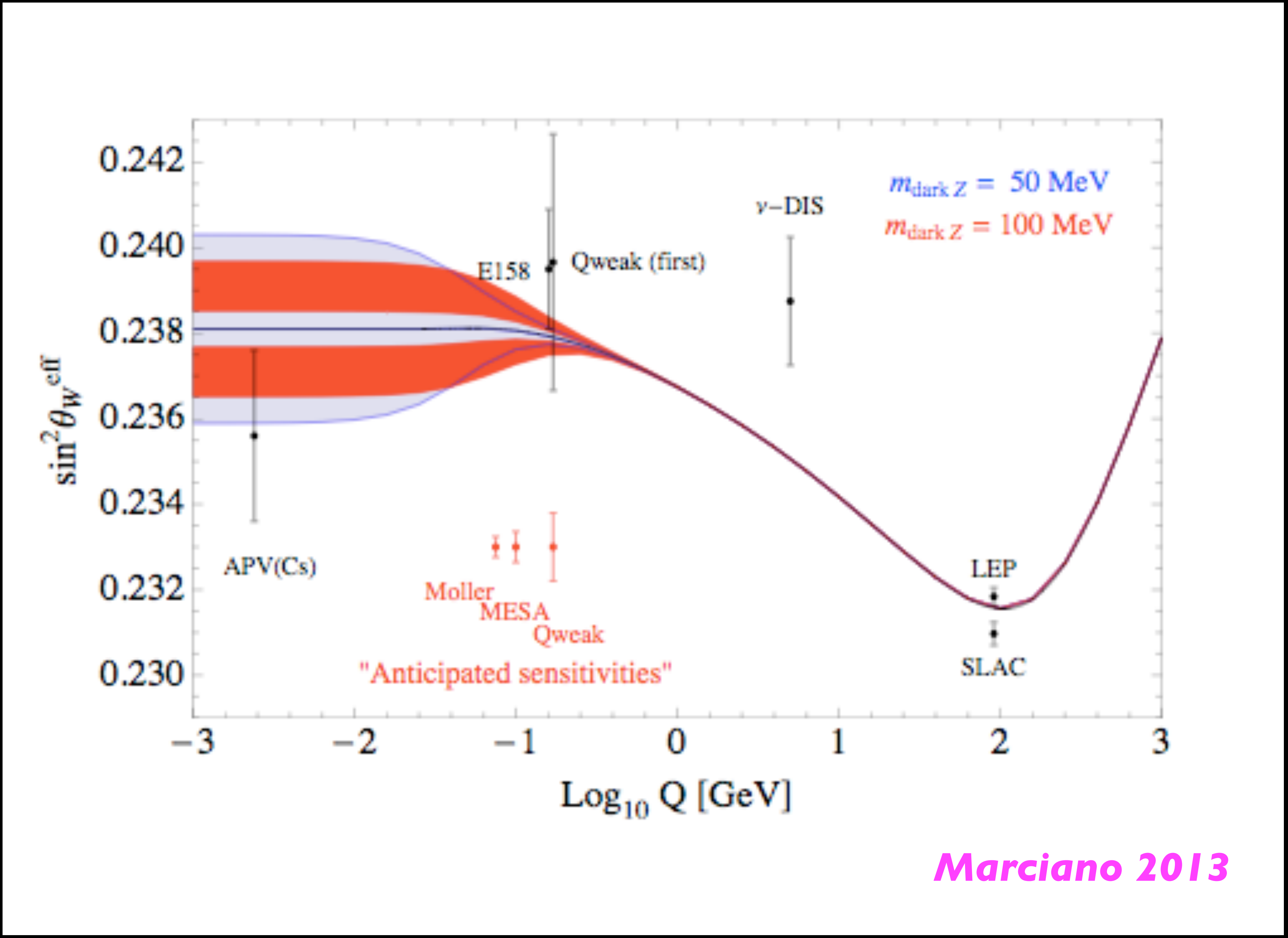

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  - is the dark sector messing with low-energy observables?

Recent and Upcoming 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)