Electroweak Precision Physics

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LoopFest VIII

University of Wisconsin at Madison May 7–9, 2009

Outline

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- Introduction:
  probes of the SM and beyond

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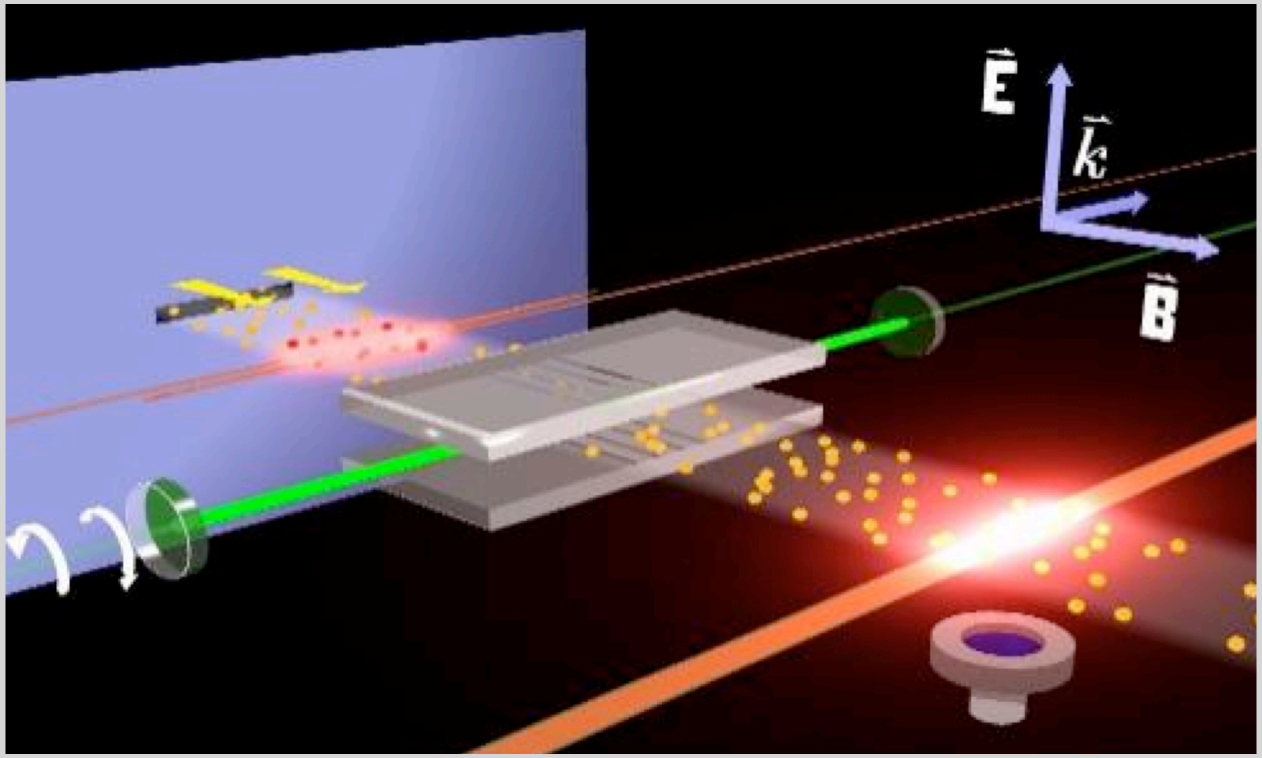
- Physics beyond the SM:
  Z' bosons and 4th fermion generation
- Conclusions

Introduction

probes of the SM and beyond

Low energy probes

- ν: scattering, oscillations, magnetic moments
- e: polarization asymmetries, g−2, EDM
- μ: lifetime, decay parameters, g−2, LFV, EDM
- τ: lifetime, BRs, spectral functions, LFV
- atoms, ions, molecules, solids: PNC, EDMs
- muonic atoms, muonium: LFV

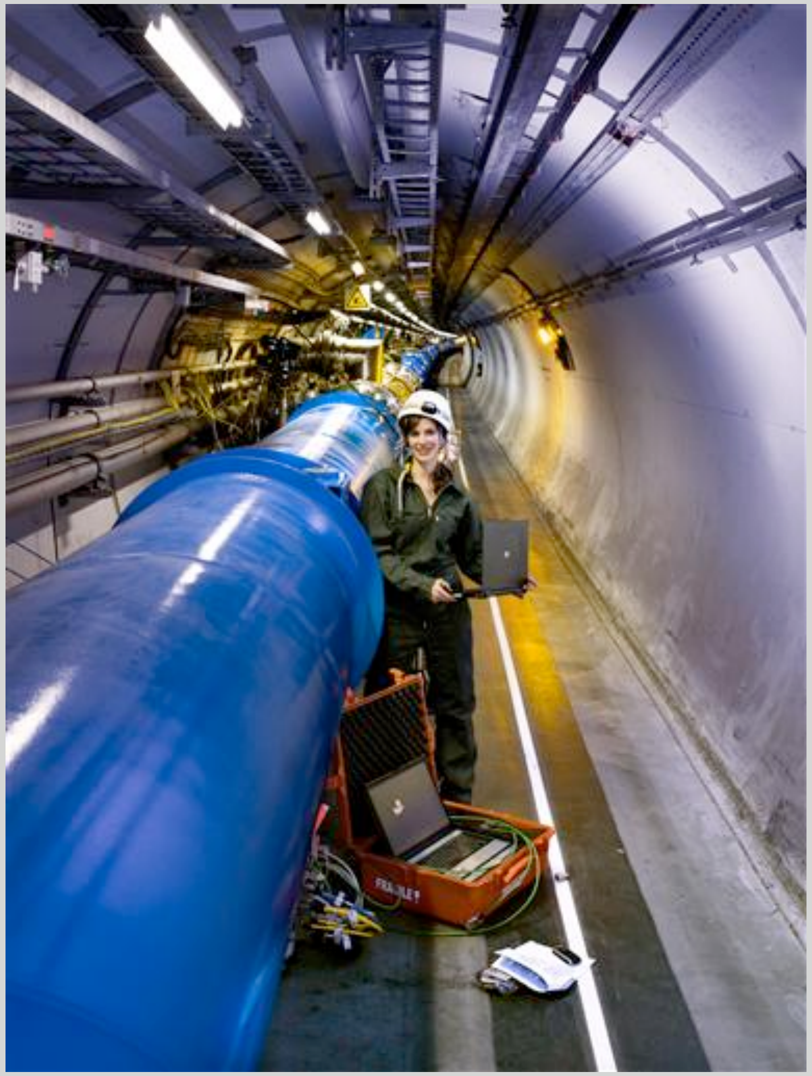


Hadronic and nuclear probes

- Mesons: weak decays, mixings
- $c\bar{c}$, $b\bar{b}$: resonance parameters, production X-section
- p: lifetime, EDM
- n: lifetime, decay parameters, EDM, n-$\bar{n}$ oscillation
- ^{2}H: EDM
- ^{3}H: ordinary β-decay
- nuclei (10 < A< 74): superallowed $0^{+} \to 0^{+}$ β-decays
- heavy nuclei: $0\nu\beta\beta$-decay

High energy probes

- t: pair decays, single (EW) production X-section
- W: mass, width, BRs, anomalous gauge couplings
- Z: lineshape parameters, BRs, asymmetries
- H: collider searches



SM global fit

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$\sin^2\theta_W \cos^2\theta_W\ (1 - \Delta r)$, with $\cos\theta_W = M_W / M_Z$

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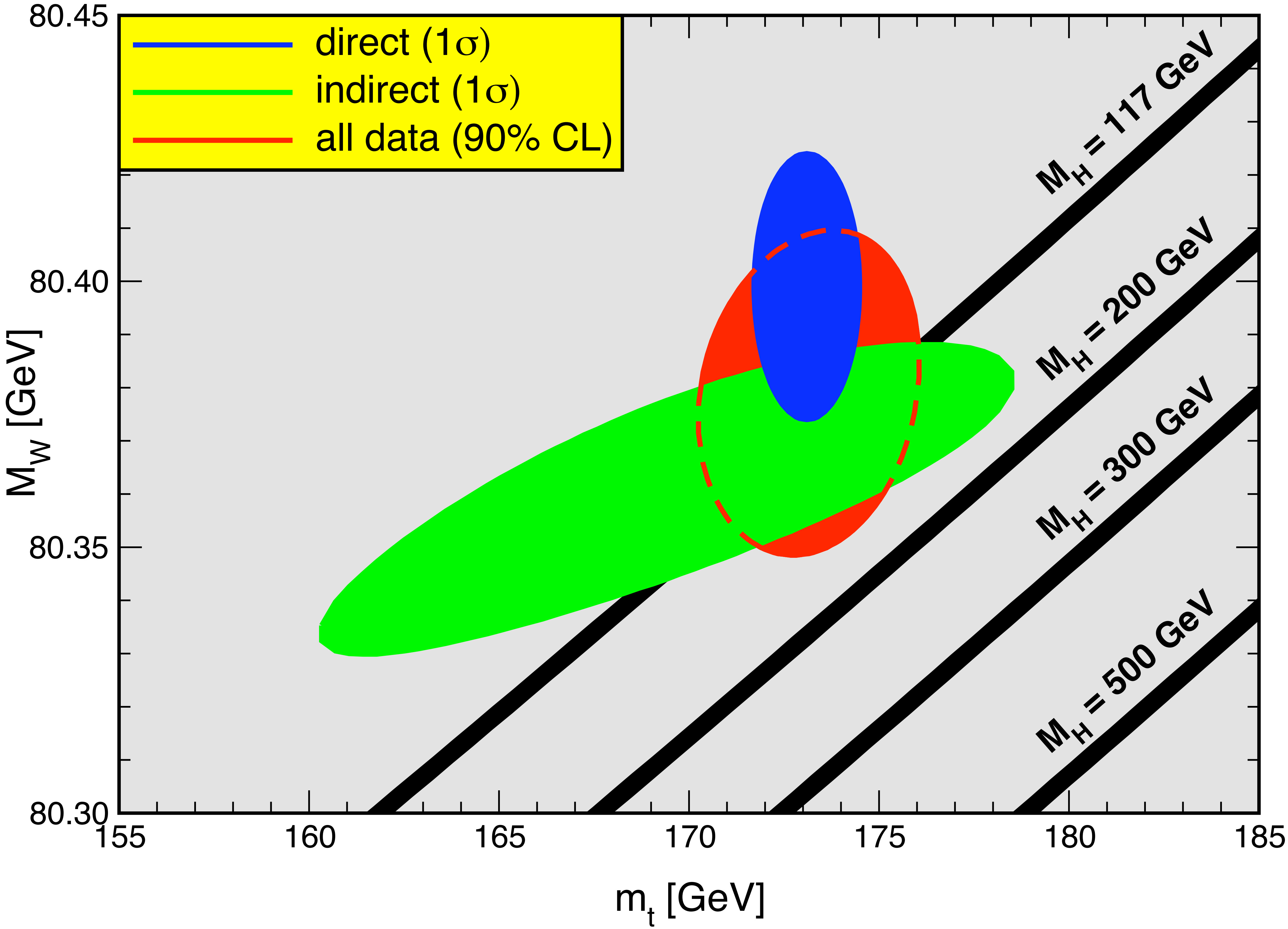
- two equations, one unknown: M_H (in $\bar{\rho}$, Δr & $\Delta\bar{r}$)
- there is independent M_H-dependence in Γ_Z & the low energy neutral current (ρ) and the $Zb\bar{b}$-vertex


direct (1σ)
indirect (1σ)
all data (90% CL)
M_H = 117 GeV
M_H = 200 GeV
M_H = 300 GeV
M_H = 500 GeV
80.45
80.40
80.35
80.30
M_W [GeV]
155
160
165
170
175
180
185
m_t [GeV]

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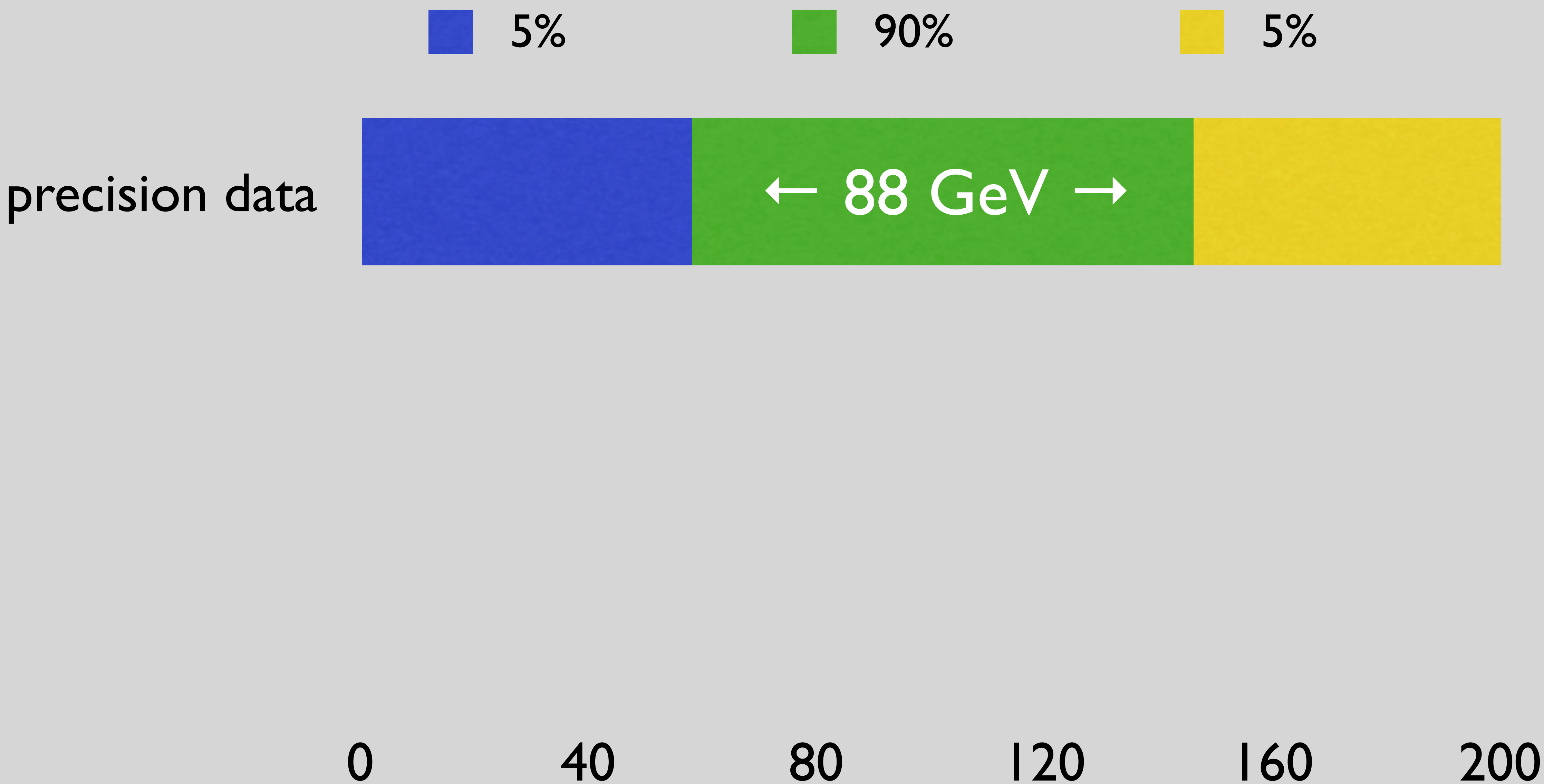
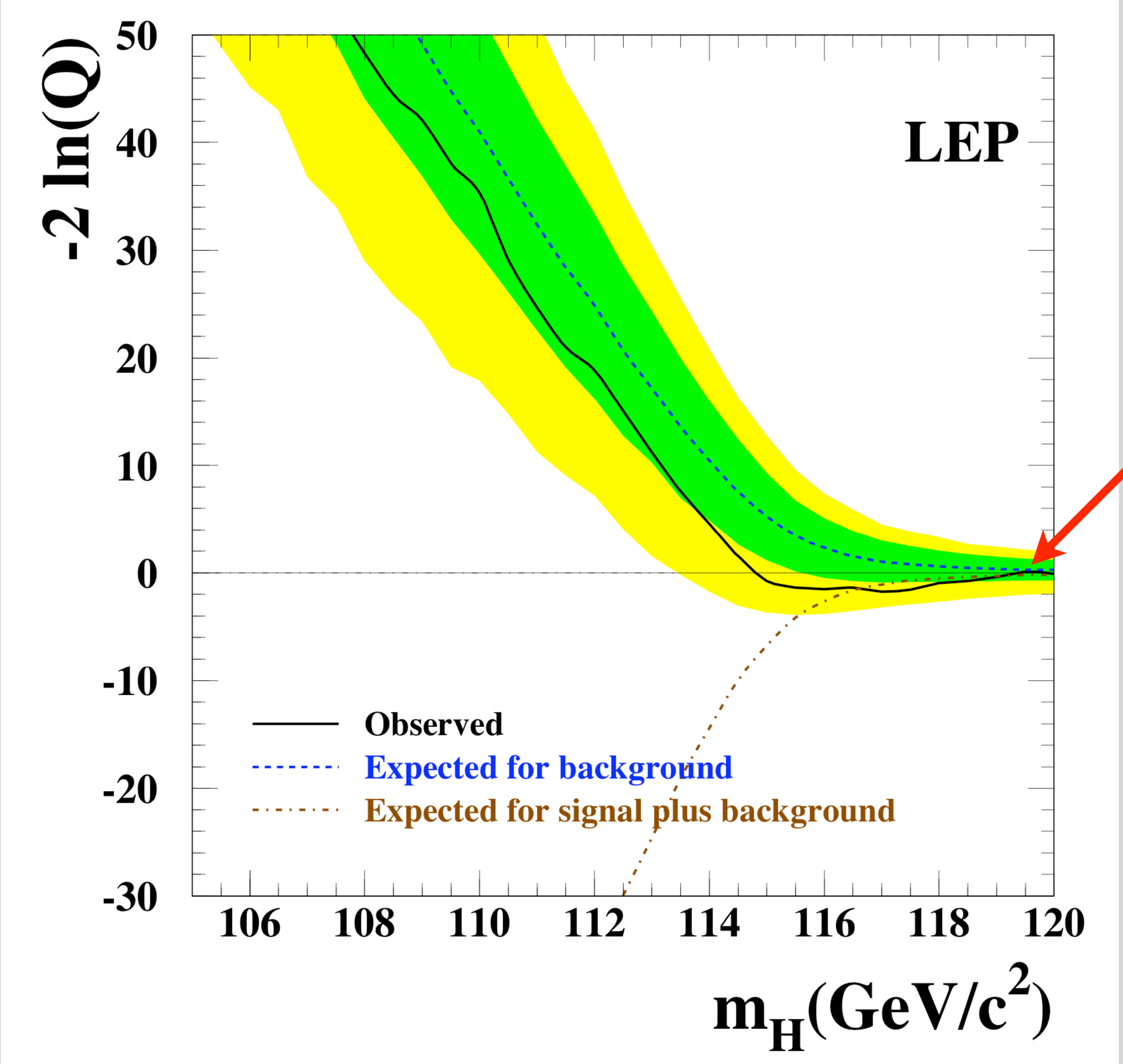
χ^2/d.o.f.	48.0/45 (35%)	muon g−2

SM: Higgs boson mass

58 GeV < M_H < 146 GeV (90% CL)



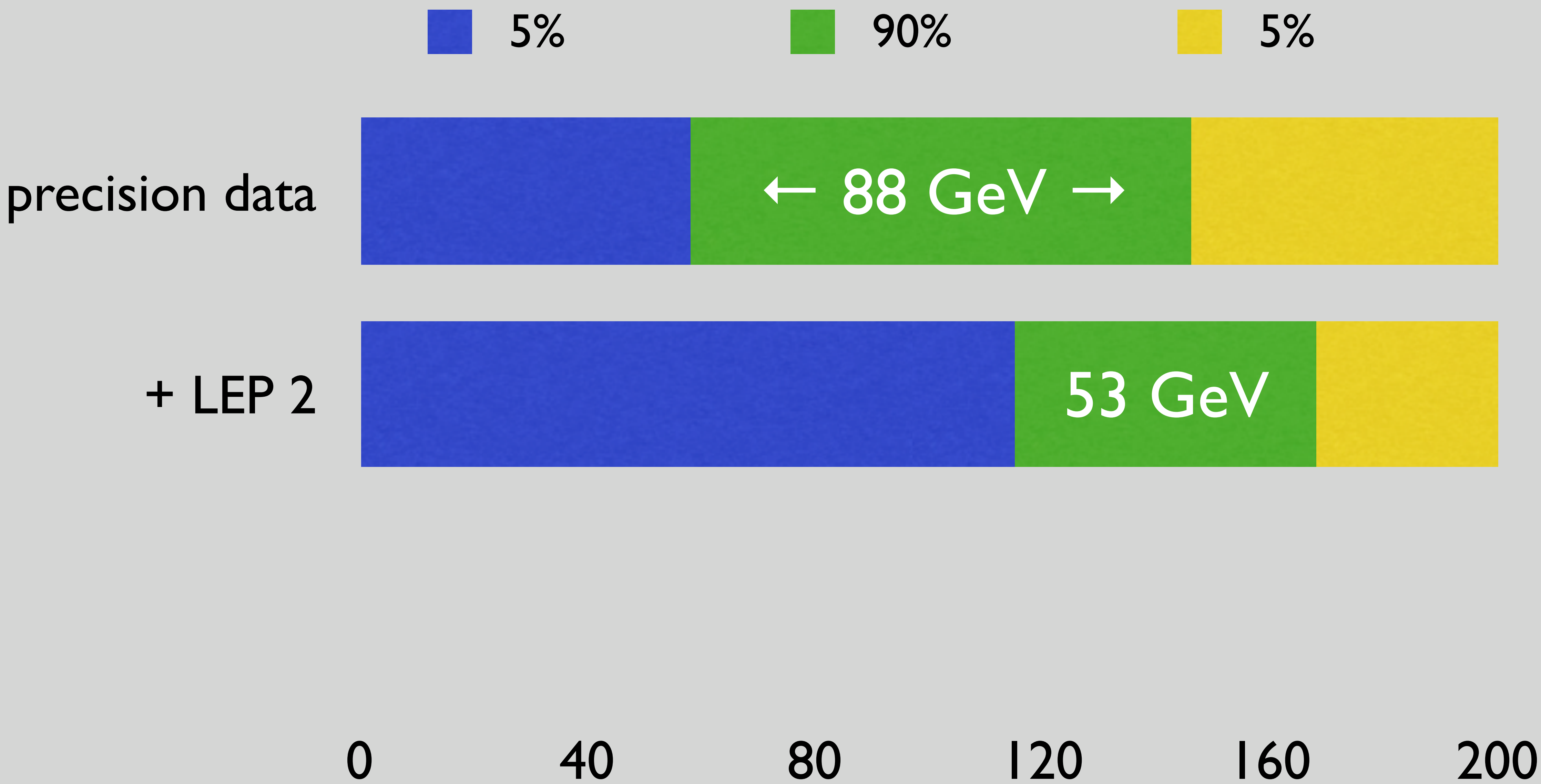
LEP 2 Higgs searches



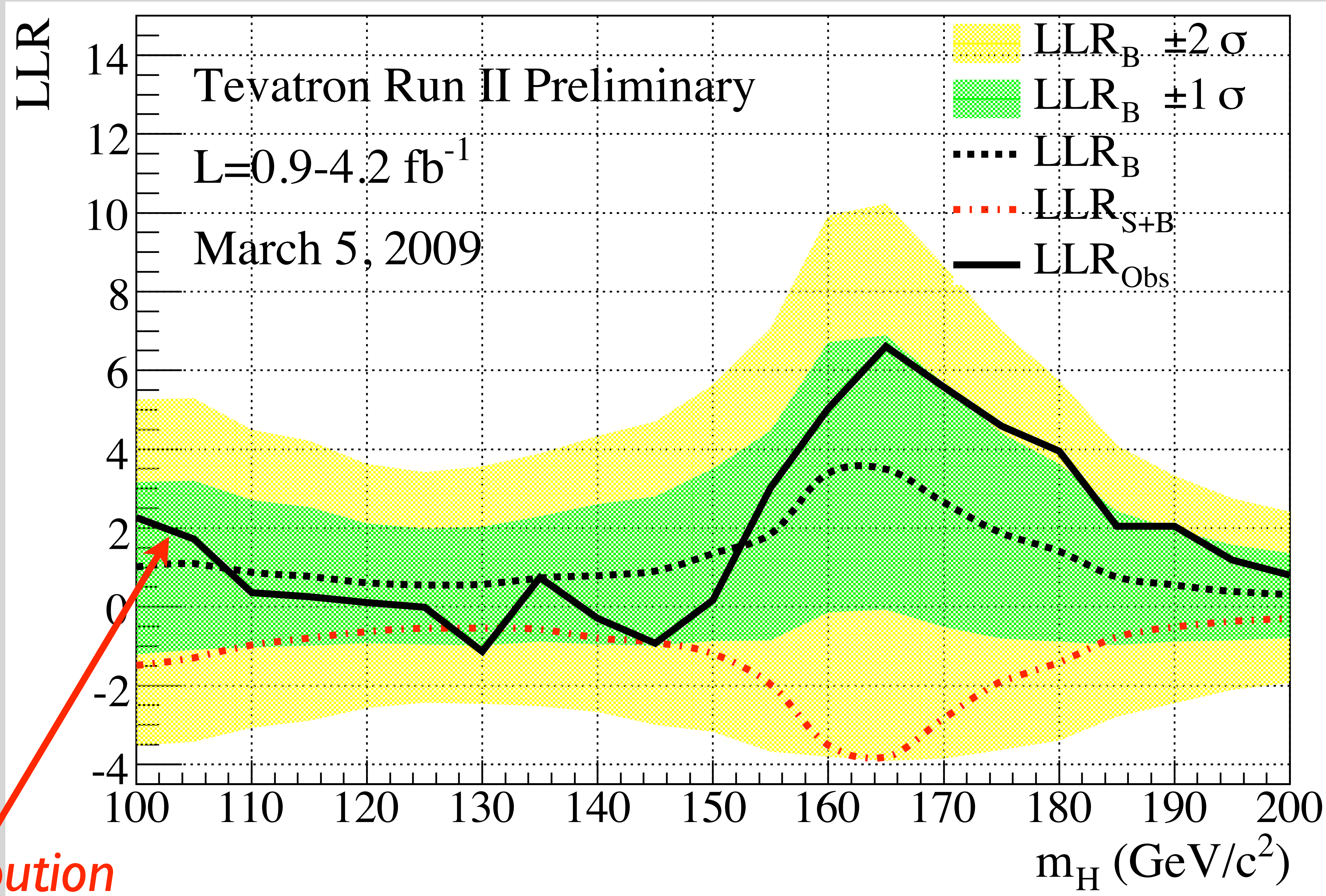
Contribution to likelihood

SM: Higgs boson mass

115 GeV < M_H < 168 GeV (90% CL)



Tevatron Higgs searches



Contribution to likelihood

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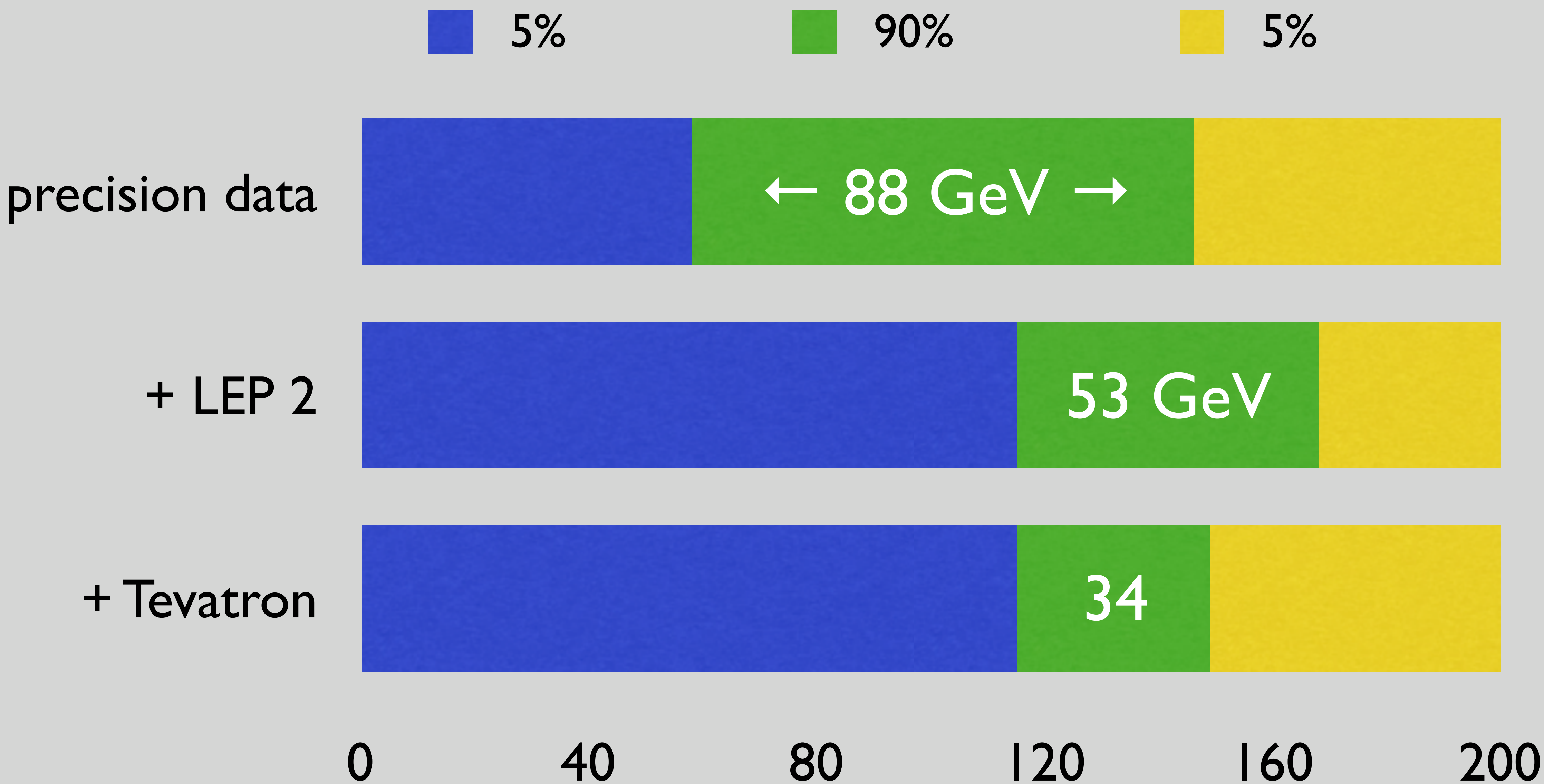

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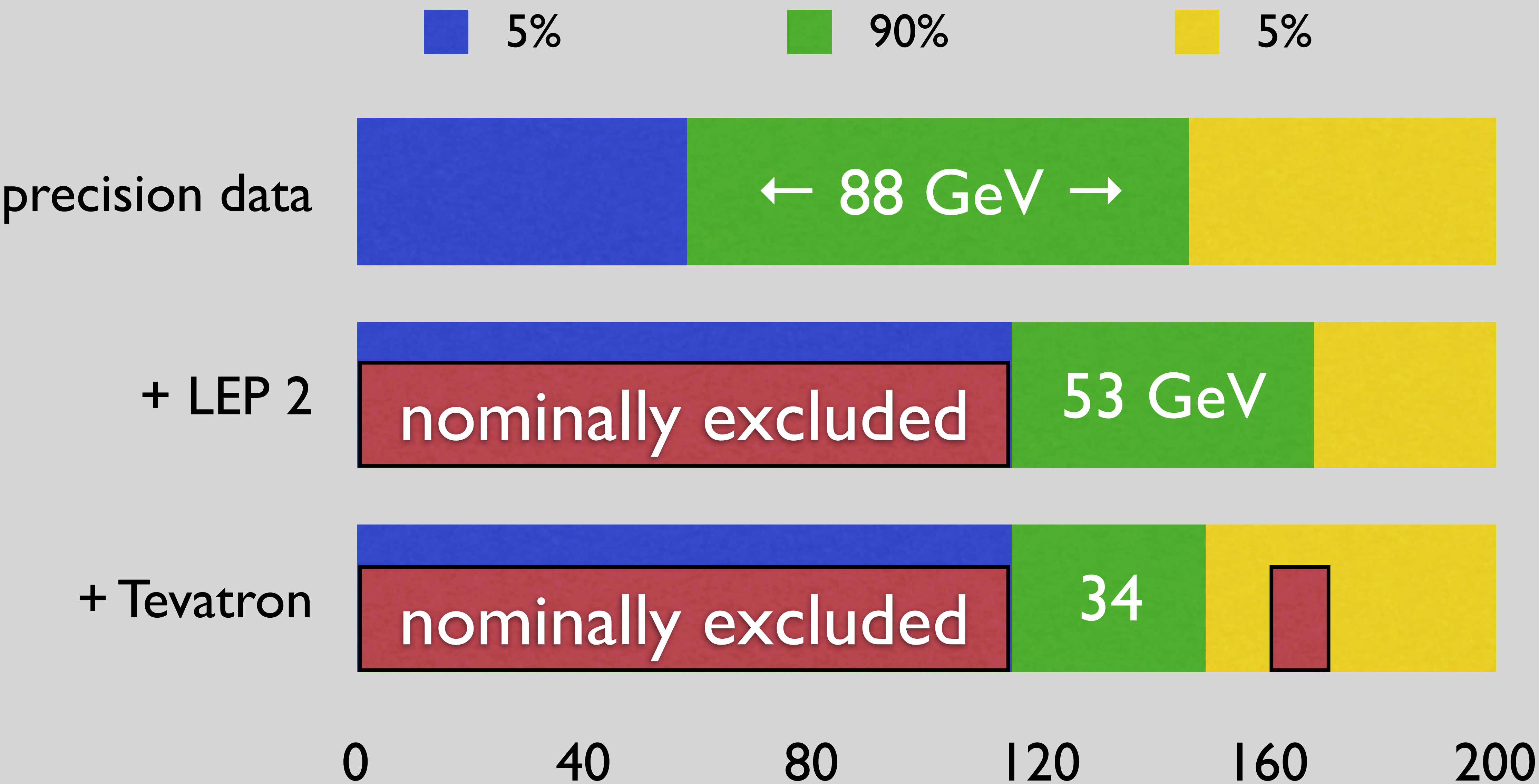

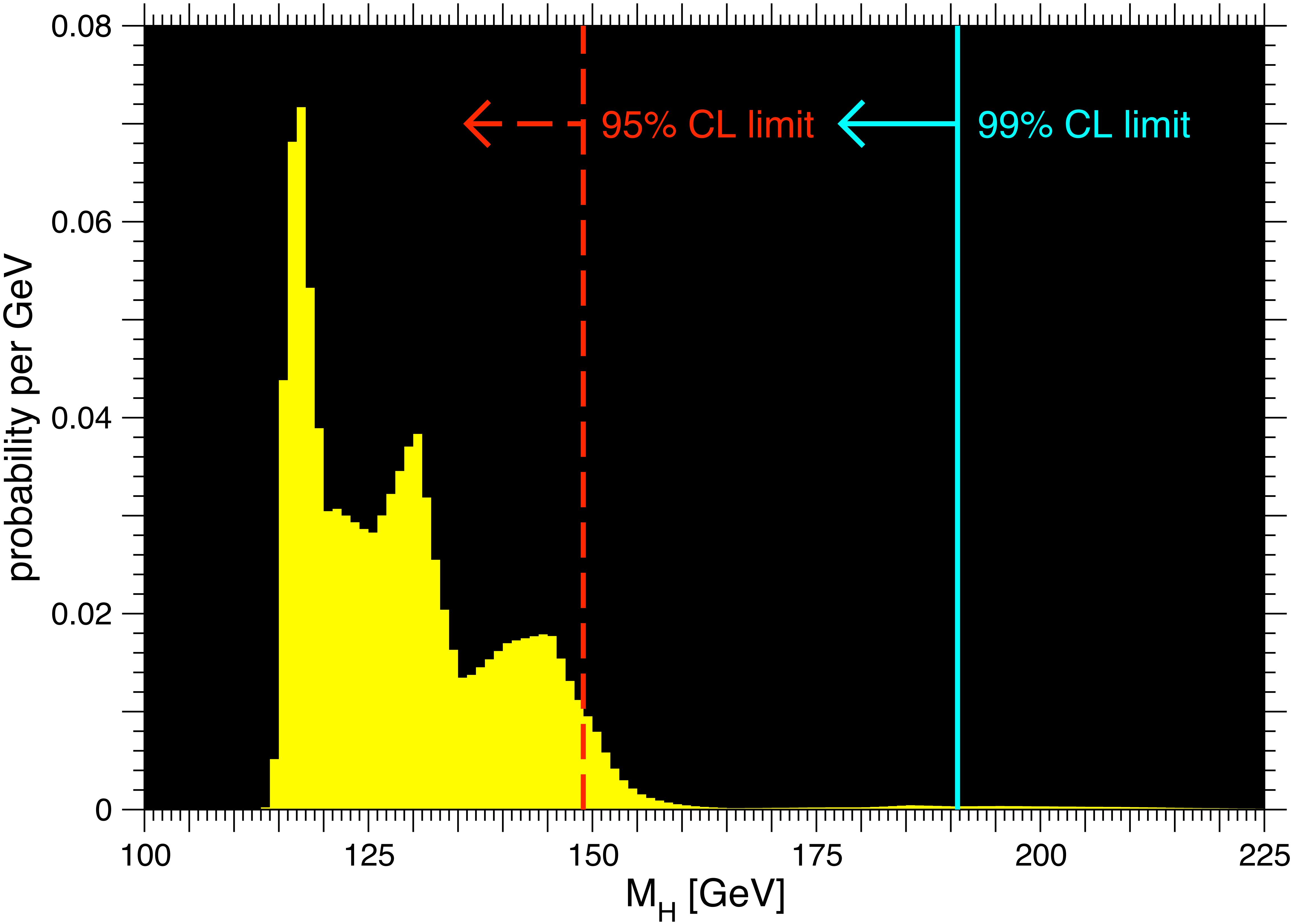

95% CL limit
99% CL limit
probability per GeV
0.08
0.06
0.04
0.02
0
100
125
150
175
200
225
M_H [GeV]

Physics beyond the SM

Z′ bosons and 4th fermion generation

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- conversely: high energy data $\Rightarrow \sin\theta \lesssim \mathcal{O}(10^{-3})$

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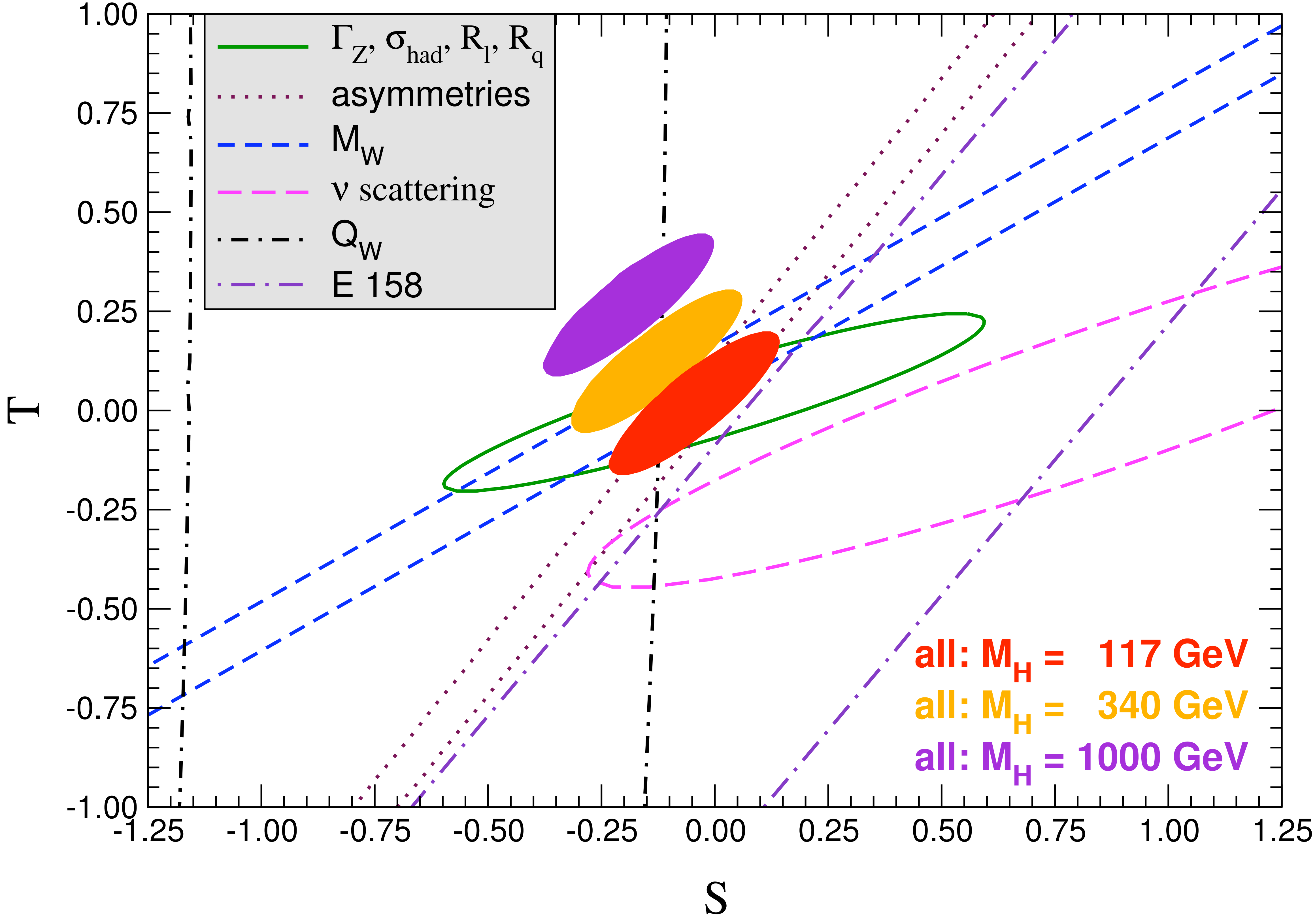
- ⇒ $M_X \geq 0.89$ TeV (95% CL) (Z_ψ: $q_L + q_R = 0$)

PDG 2008



Γ_Z, σ_{had}, R_l, R_q
asymmetries
M_W
ν scattering
Q_W
E 158
all: M_H = 117 GeV
all: M_H = 340 GeV
all: M_H = 1000 GeV
T
S
1.00
0.75
0.50
0.25
0.00
-0.25
-0.50
-0.75
-1.00
-1.25
-1.00
-0.75
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- T parameter free: $T = 0.21 \pm 0.04$ ($M_H = 117$ GeV) but $\Delta\chi^2 = 5.2$ relative to SM (excluded at 98% CL)
- Designer splittings ($\Delta m \approx 50$ GeV) of doublets: (He, Polonsky, Su 2001; Bulanov et al. 2003; Novikov, Rozanov, Vysotsky 2009)
  $(m_{t'}, m_{\nu'}) = (400, 100)$ GeV $\Rightarrow S = 0.15, T = 0.19$
  (Kribs et al. 2007): $\Delta\chi^2 = 2.8$ (marginal at 90% CL)

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- $|V_{ud}|^2 + |V_{us}|^2 + |V_{ub}|^2 - 1 = 0.0000 \pm 0.0006$
  $\propto e_L\ (e_L - q_L)\ \ln(M_{Z'}/M_W)/(M_{Z'}^2/M_W^2 - 1)$
  from 1-loop W-Z′ box (Marciano, Sirlin 1987)

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  from 1-loop W-Z′ box (Marciano, Sirlin 1987)
- $\Rightarrow M_X \geq 265$ GeV at 95% CL ($\Delta\chi^2 \leq 3.84$)

  (no constraint on Z_ψ, since $e_L = q_L$)

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- $\Rightarrow M_X \geq 0.67$ TeV (95% CL) (Z_ψ: $e_L + e_R = 0$)

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- PV-DIS @ 6 and 12 GeV CEBAF:

  $(2\ C_{1u} - C_{1d}) + 0.84\ (2\ C_{2u} - C_{2d}) = \pm\ 0.0049 \Rightarrow$

  $M_X \geq 0.45$ TeV (Z_ψ: $q_L + q_R = e_L + e_R = 0$) or

  PDFs: higher twist (CSV) go with Q^2 (x)

Polarized e^- scattering: future

- Qweak @ 6 GeV CEBAF: $\Delta Q_W(p) = \pm 0.0029 \Rightarrow$

  $M_X \geq 0.67$ TeV (expected 95% CL limit)

- PV-DIS @ 6 and 12 GeV CEBAF:

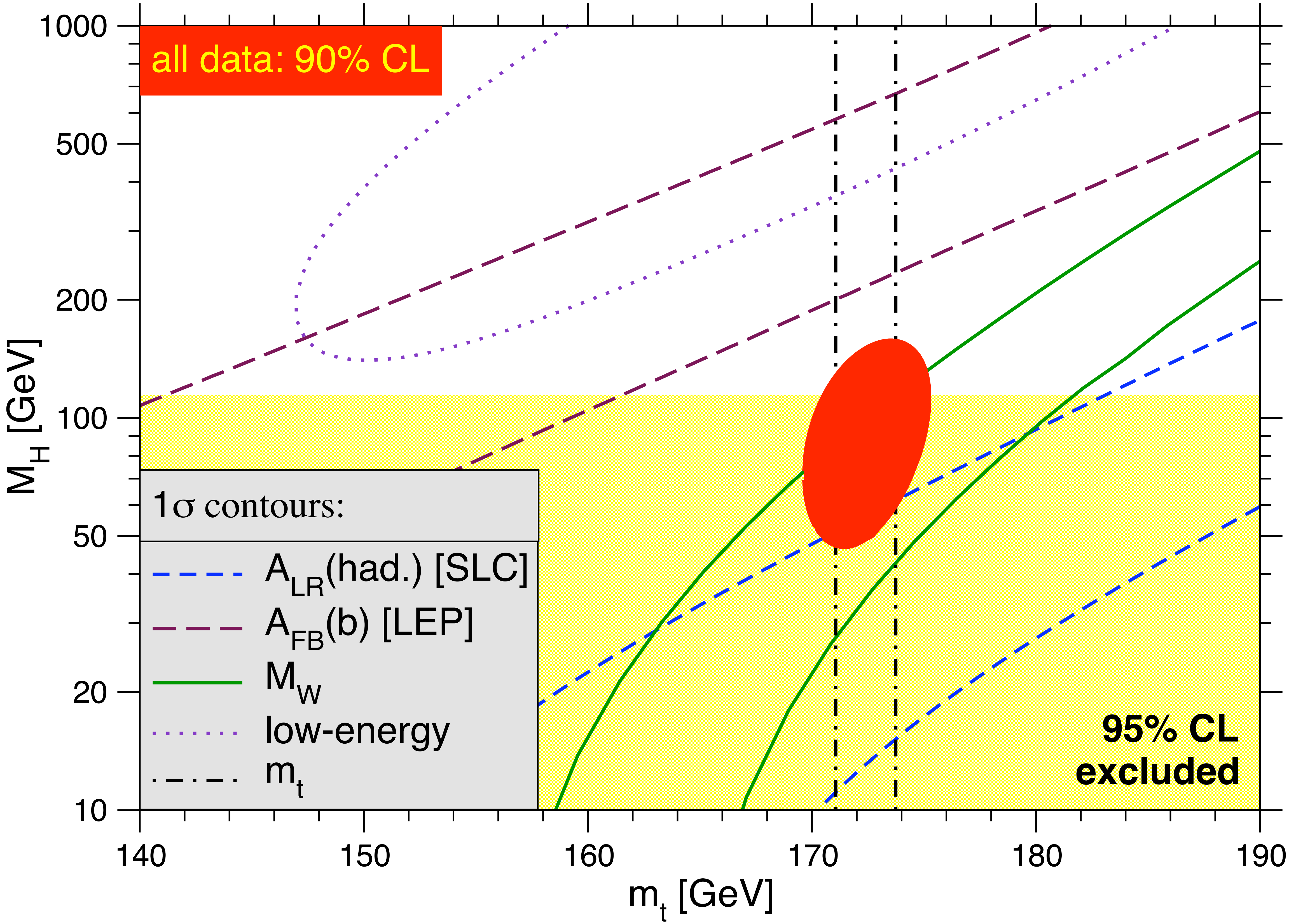
  $(2\, C_{1u} - C_{1d}) + 0.84\, (2\, C_{2u} - C_{2d}) = \pm 0.0049 \Rightarrow$

  $M_X \geq 0.45$ TeV (Z_ψ: $q_L + q_R = e_L + e_R = 0$) or

  PDFs: higher twist (CSV) go with Q^2 (x)

- e2ePV @ 12 GeV CEBAF: $\Delta Q_W(e) = \pm 0.0011 \Rightarrow$

  $M_X \geq 1.07$ TeV or $\Delta \sin^2\theta_W = \pm 0.00029$


all data: 90% CL
1000
500
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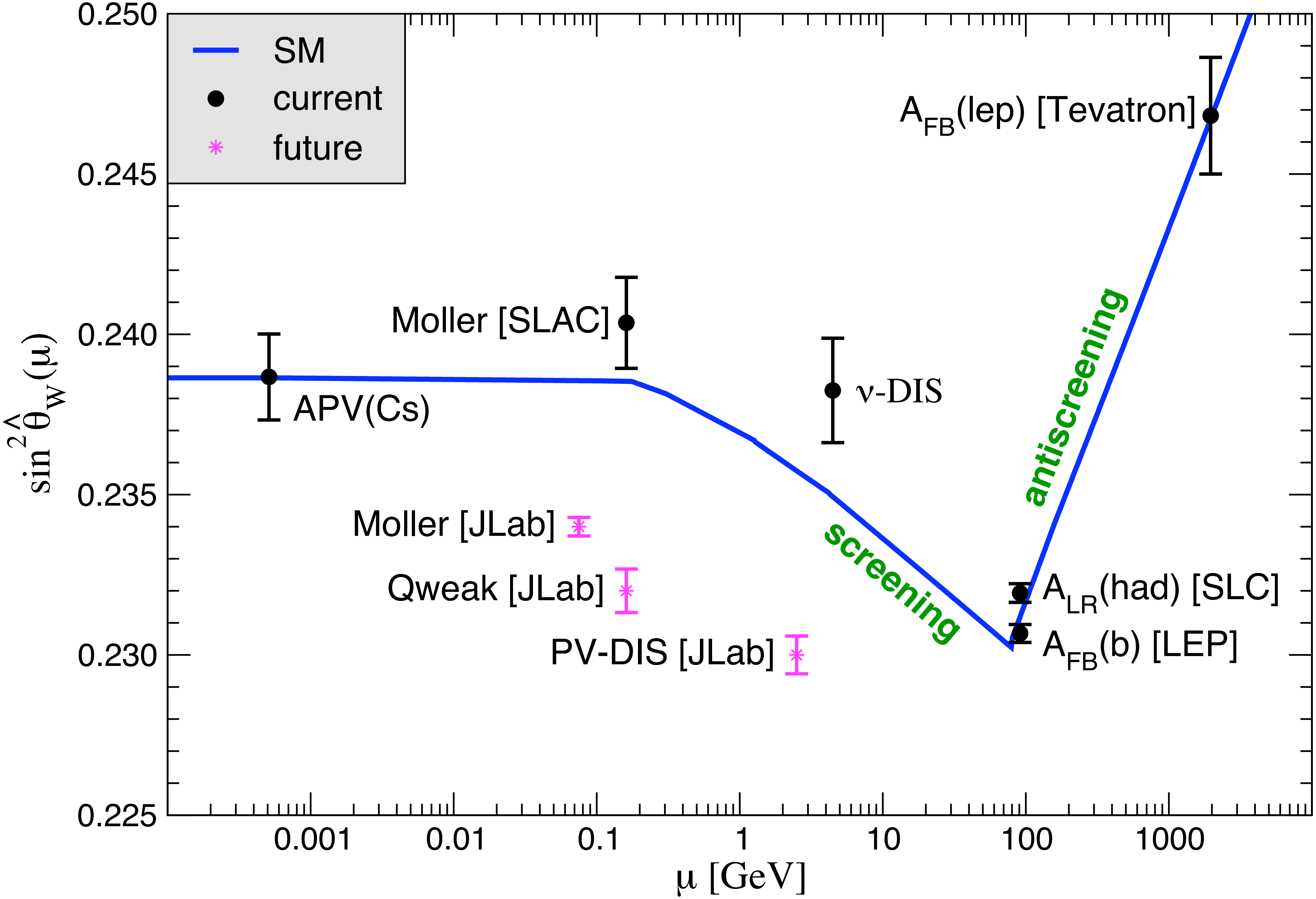
10
M_H [GeV]
140
150
160
170
180
190
m_t [GeV]
1σ contours:
A_{LR}(had.) [SLC]
A_{FB}(b) [LEP]
M_W
low-energy
m_t
95% CL
excluded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100
1000
μ [GeV]
sin²θ̂_W(μ)
APV(Cs)
Moller [SLAC]
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- absorb higher order QCD corrections into effective "threshold masses", $\bar{m}_q$
  - $\bar{m}_c$ and $\bar{m}_b$: from QCD sum rules (S resonances)
  - $\bar{m}_u$ and $\bar{m}_d$ ($E < 1.8$ GeV): use dispersive result and approximate isospin symmetry, $\bar{m}_u = \bar{m}_d$
  - $\bar{m}_s$: difficult to determine independently of $\bar{m}_d$

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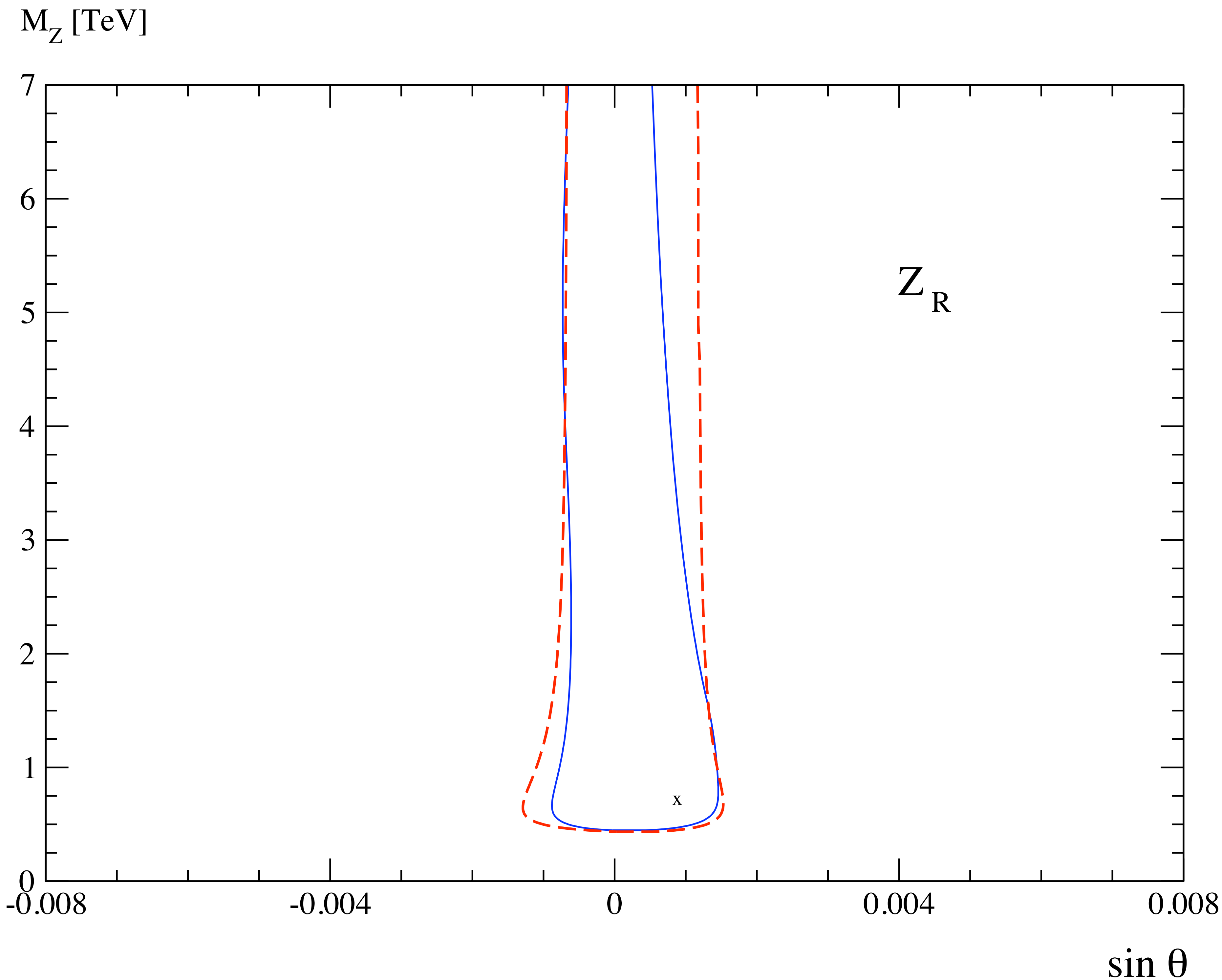

$0.46\ \text{TeV} < M_{Z'} < 29\ \text{TeV}$ (90% CL)

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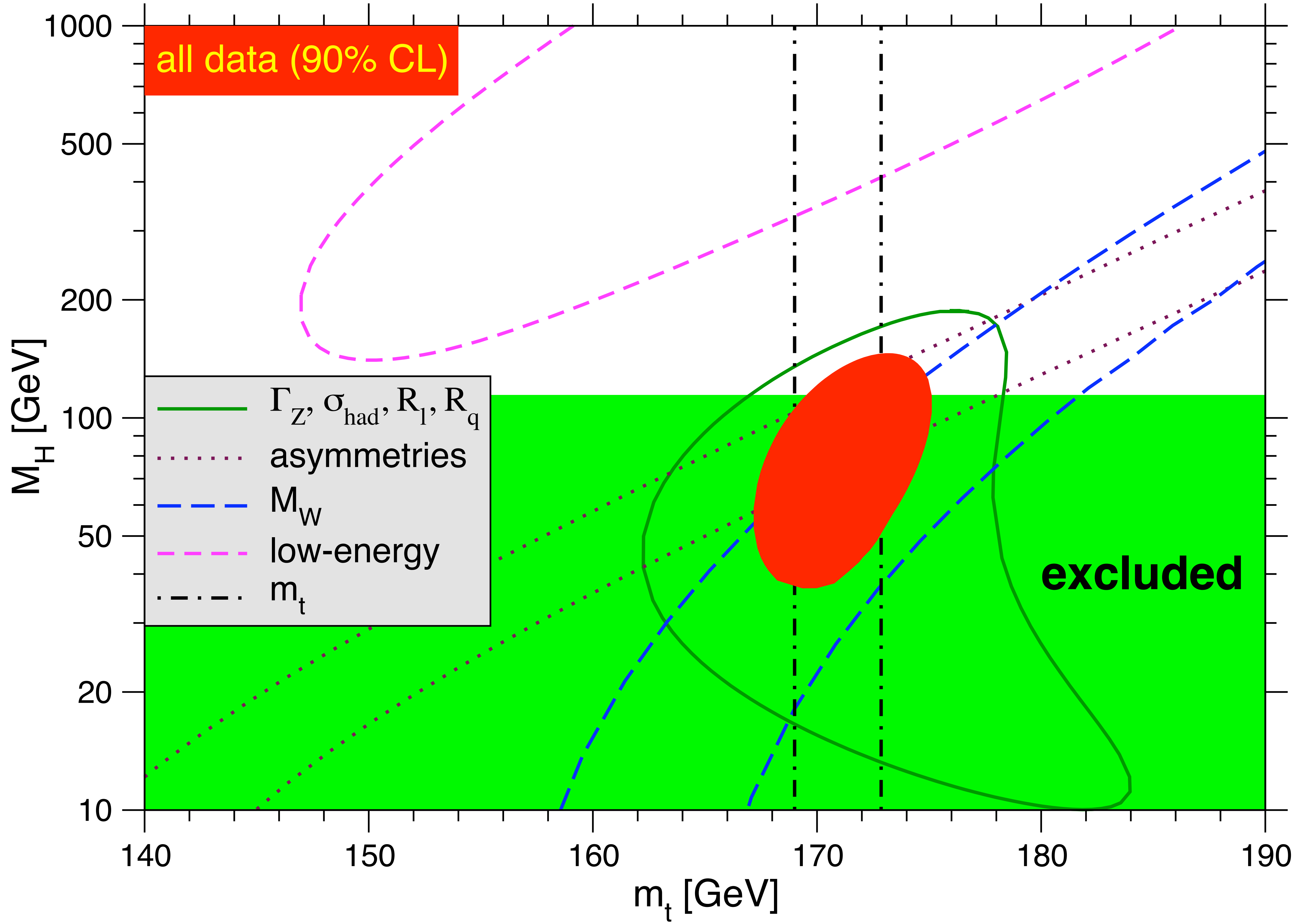
- 2σ problems in CKM 1st row unitarity & APV disappeared entirely (4th family constraints somewhat weaker)

Backup slides


all data (90% CL)
1000
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✓ LHC (Hoang, Stewart, 2008): $m_t \equiv \mathbb{M}_t$ (MSR mass), $\mathbb{M}_t(\mathbb{M}_t) = \overline{m}_t(\overline{m}_t)$; $\mathscr{M}_t = \mathbb{M}_t(3^{+6}{}_{-2}$ GeV) at large p_T

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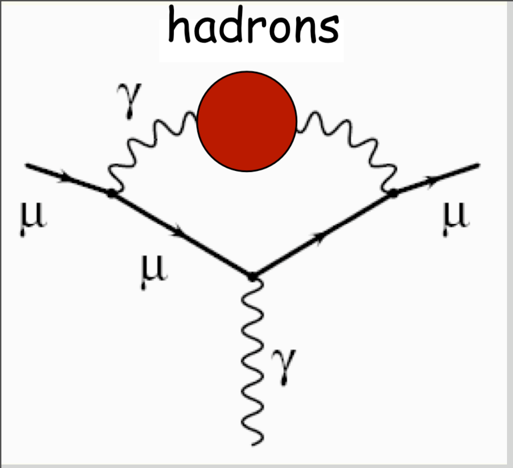
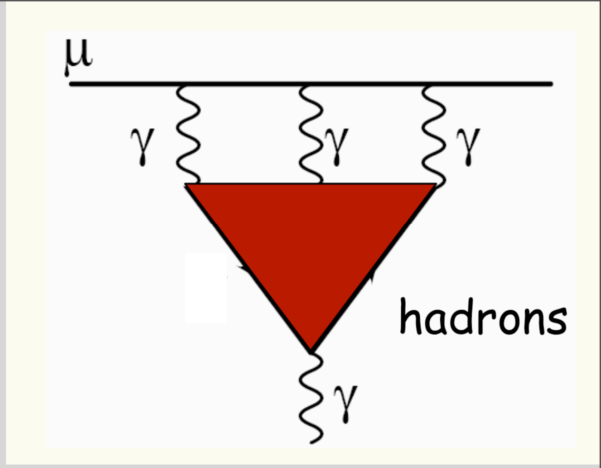
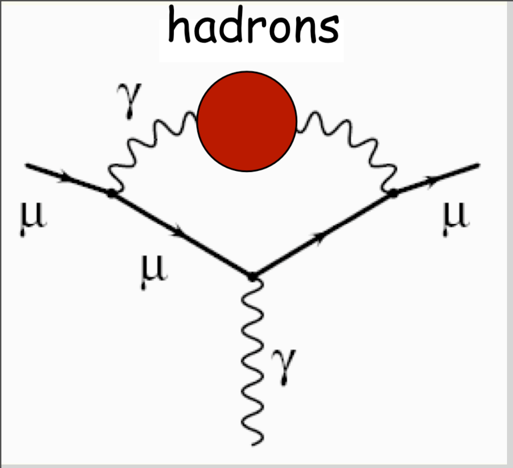
- nuclear effects: different for NC and CC; 20% of effect, both signs possible (Brodsky, Schmidt, Yang)



Muon g−2 (BNL)





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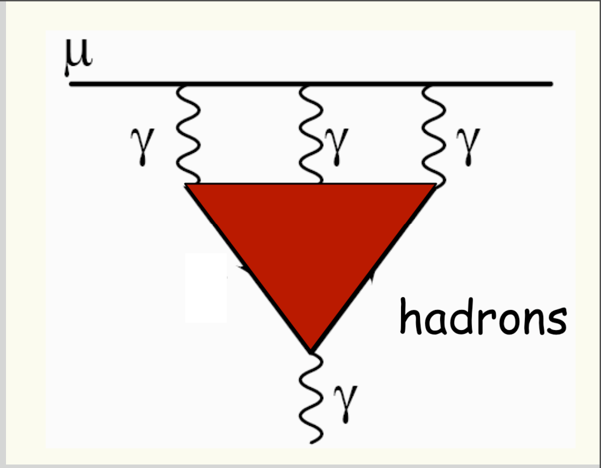

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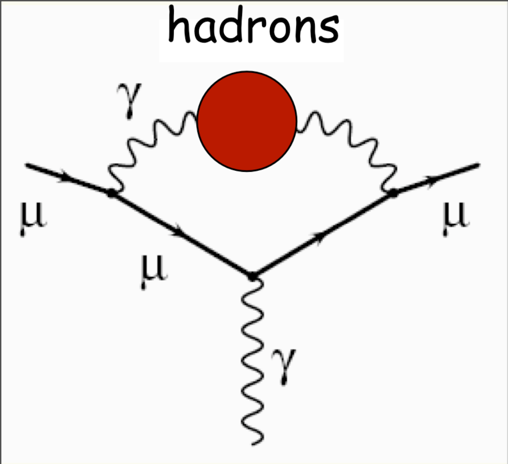

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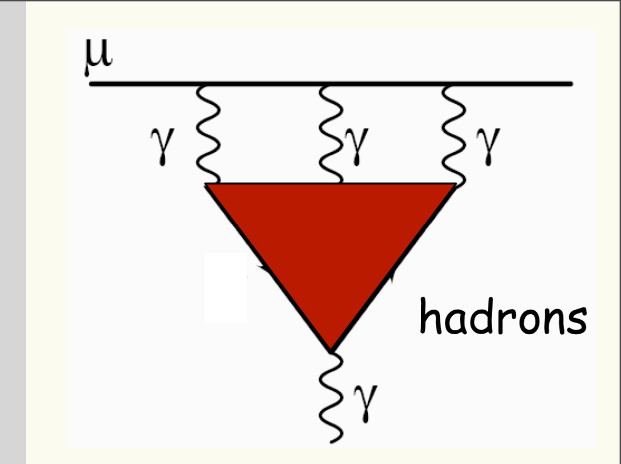

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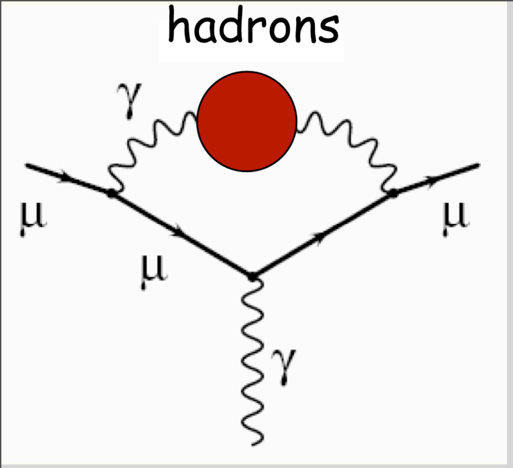

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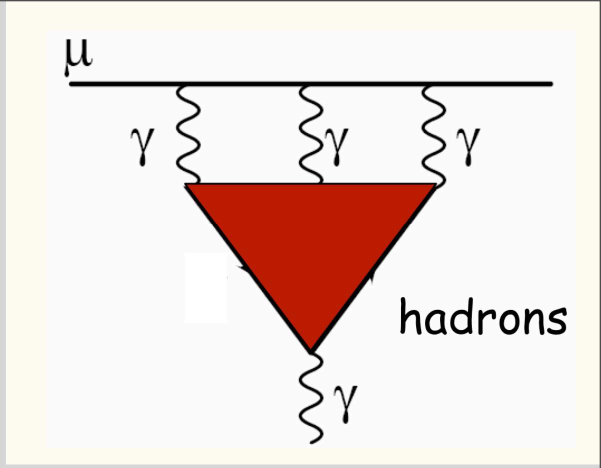

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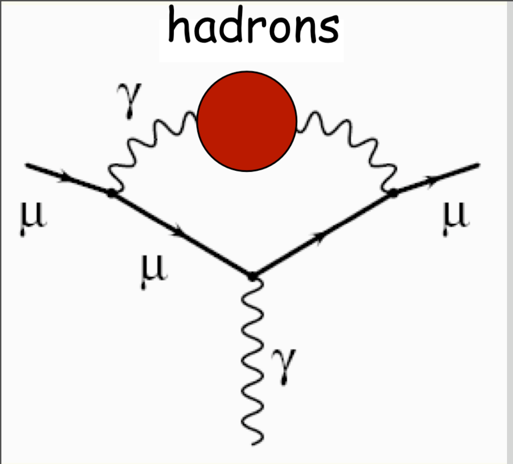

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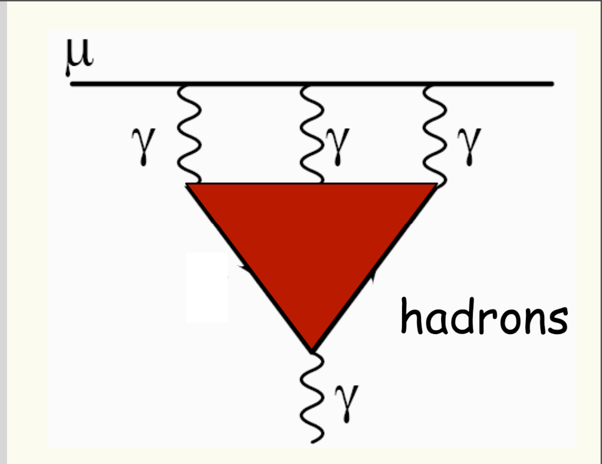

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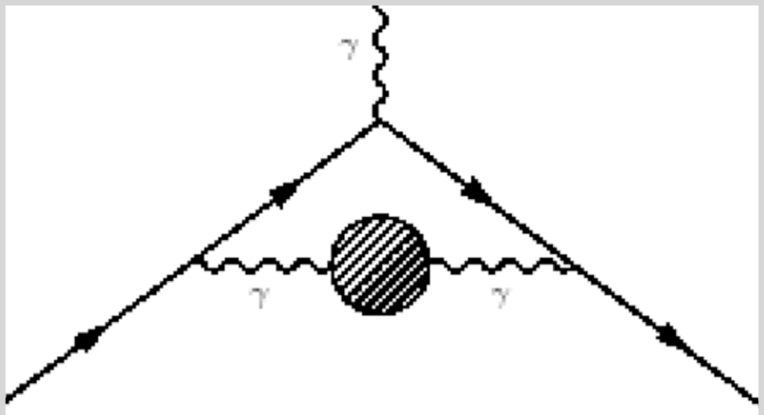
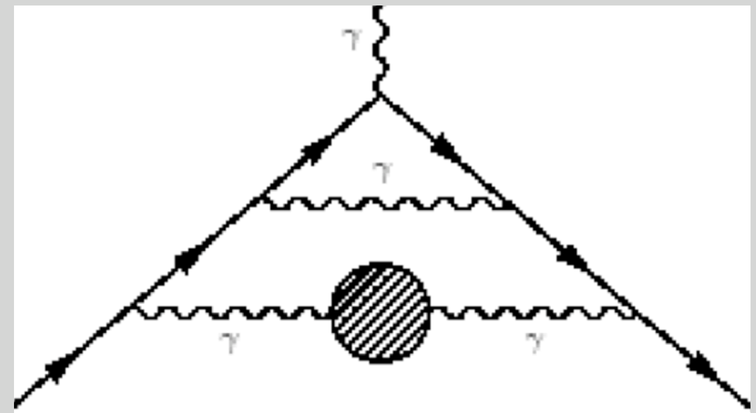
- 3-loop γ × γ (not first principles calculations!): π^0 + VMD: $(1.16 \pm 0.40)\times10^{-9}$ (Nyffeler 2009) free quarks: $< 1.59\times10^{-9}$ (Toledo, JE 2006)

g−2: vacuum polarization



(1)



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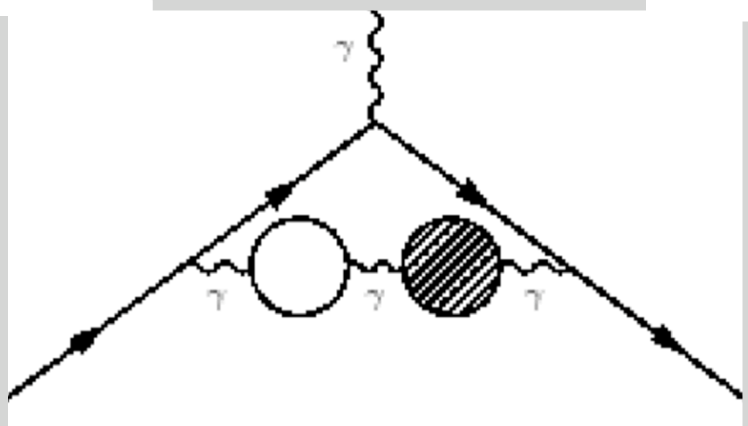
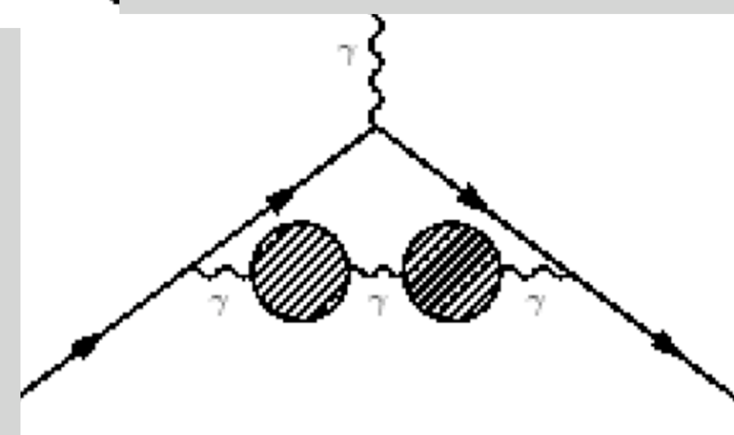
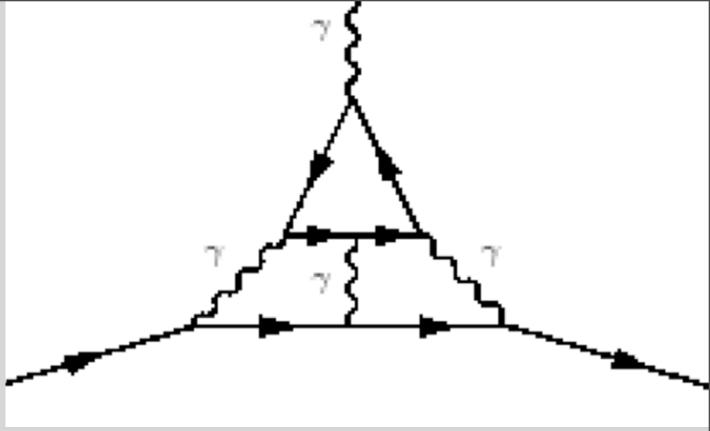


(2b)



(2c)

kernel	free quarks	data	deviation
$K^{(1)}$	+65.1	+70.3	8%
$K^{(2a)}$	-211.00	-182.00	14%
$K^{(2b)}$	+1.07	+0.99	7%
$K^{(2c)}$	+0.027	+0.028	4%



g−2: light × light

- free quark estimate (using quark masses for running α)
- exact for infinitely heavy quarks (short distance ok)
- overestimate in chiral limit with m_μ/m_π fixed (charged pointlike pions contribute negatively)
- VMD::$(1.36 \pm 0.25) \times 10^{-9}$ (error: "rough guess"; μ ~ 0.6 GeV) Melnikov, Vainshtein (2004)
- Toledo, JE (2006):

$$\text{free quarks} \begin{cases} (1.37^{-0.27}_{+0.15}) \times 10^{-9} \\ < 1.59 \times 10^{-9} (\text{ } 95\% \text{ CL}) \end{cases}$$