Electroweak Precision Data and New Gauge Bosons

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- for collaboration on Z' bosons
  - Paul Langacker (IAS)
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Outline

- The High Energy Frontier
  - constraining the Standard Model Higgs boson
  - constraining the W-Z-Z′ interdependence
- The Precision Frontier
  - constraining the Z′ mediated amplitude
- The Intensity Frontier
  - constraining non-universal Z′ bosons
- Conclusions

The High Energy Frontier:

SM Higgs boson and W-Z-Z′ interdependence

SM global fit: formalism

- μ-lifetime ⇒ $(\sqrt{2}\, G_F)^{-1/2} = 246.2209\ (5)$ GeV
- electron g−2 ⇒ $\alpha^{-1} = 137.035\ 999\ 679\ (94)$
- Z lineshape ⇒ $M_Z = 91.1876\ (21)$ GeV

➡ $\bar{\rho}\, \sin^2\bar{\theta}_W \cos^2\bar{\theta}_W\, (1 - \Delta\bar{r}) = 0.167\ 145\ (8) =$

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

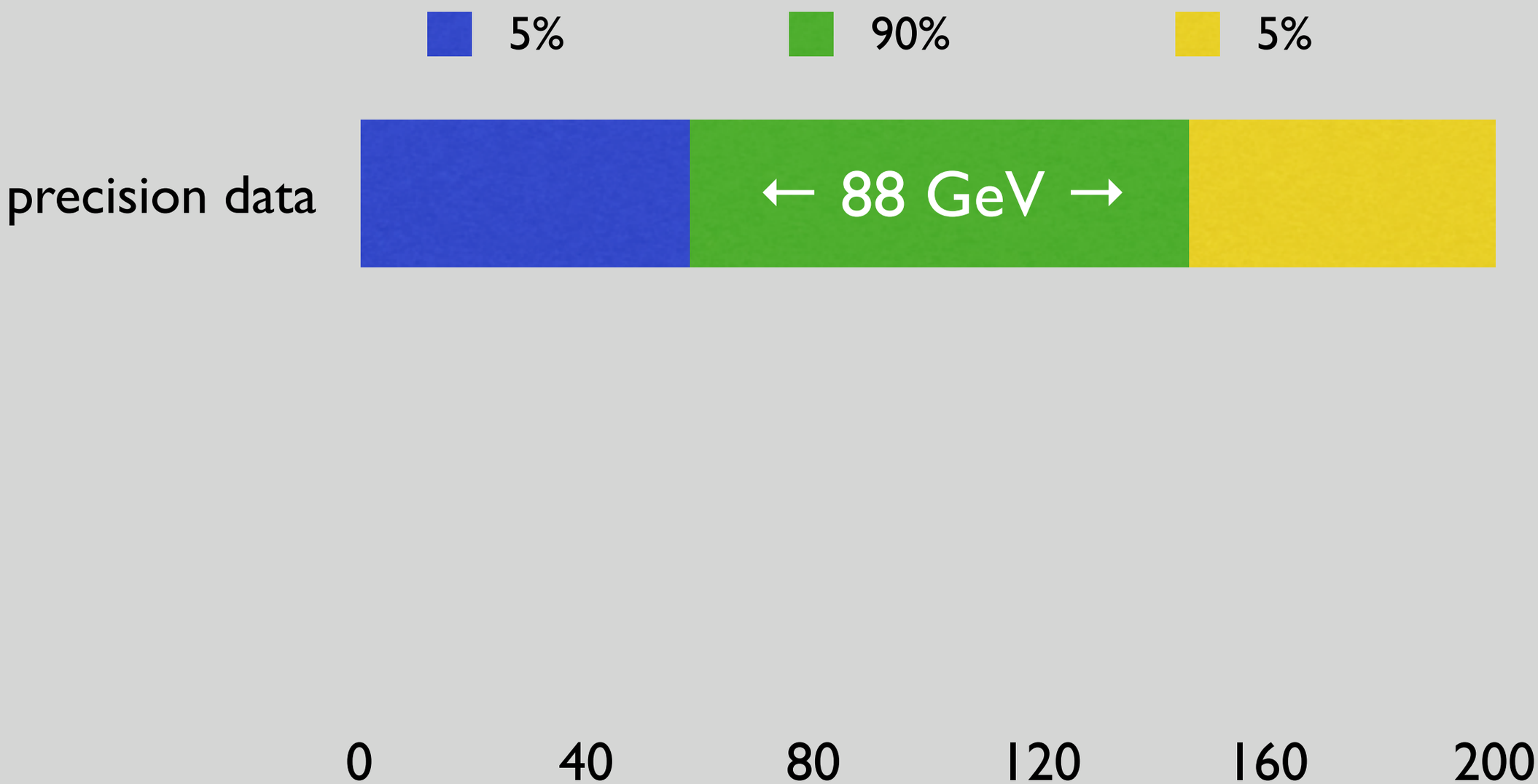
- two equations, one unknown: M_H (in $\bar{\rho}$ and Δr)
- there is additional M_H-dependence in Γ_Z & the low energy neutral current (ρ) and the $Z\bar{b}b$-vertex

SM global fit: results

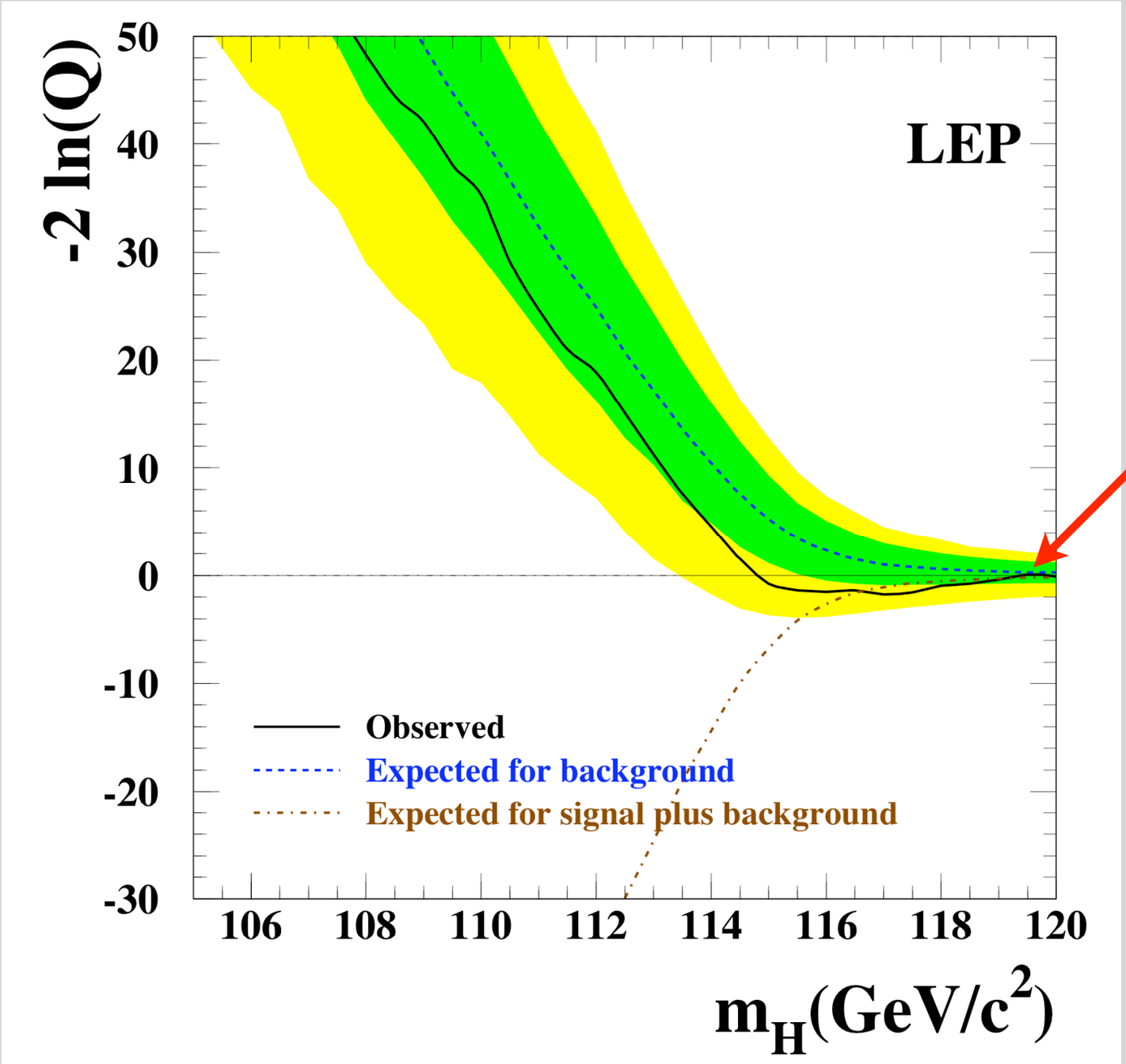
	global fit	dominated by
m_t [GeV]	173.1 ± 1.4	CDF & D0
M_W [GeV]	80.380 (15)	LEP 2, CDF & D0
M_Z [GeV]	91.1874 (21)	LEP I
$\sin^2\bar{\theta}_W(M_Z)$	0.23119 (13)	$A_{FB}(b)$ & A_{LR}
M_H [GeV]	96^{+29}_{-25}	$\sin^2\bar{\theta}_W(M_Z)$ & M_W
$\alpha_s(M_Z)$	0.1185 (16)	Z-lineshape & τ-decays
χ^2/d.o.f.	48.0/45 (35%)	muon g−2

SM: Higgs boson mass

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



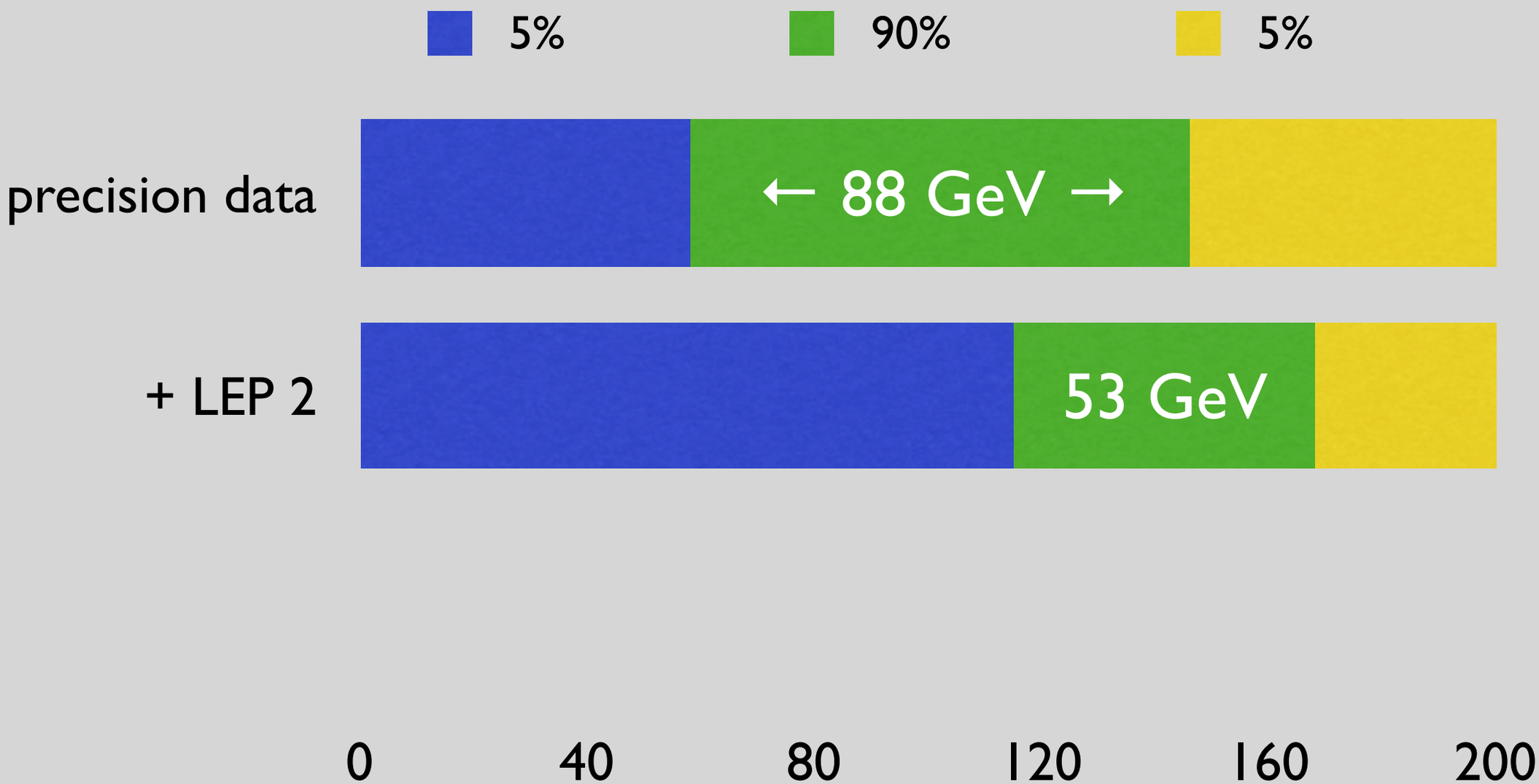
LEP 2 Higgs searches



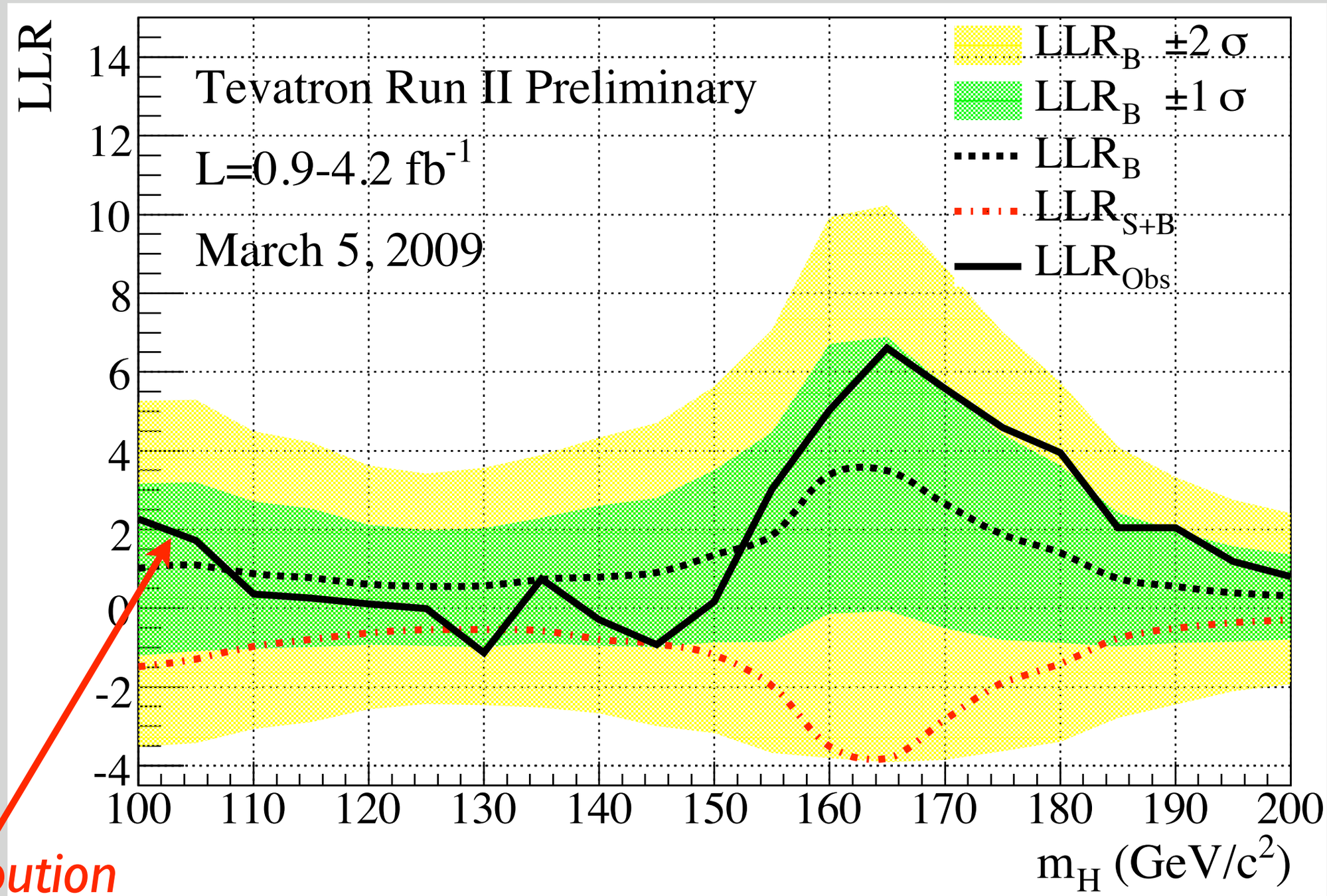
Contribution to likelihood

SM: Higgs boson mass

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



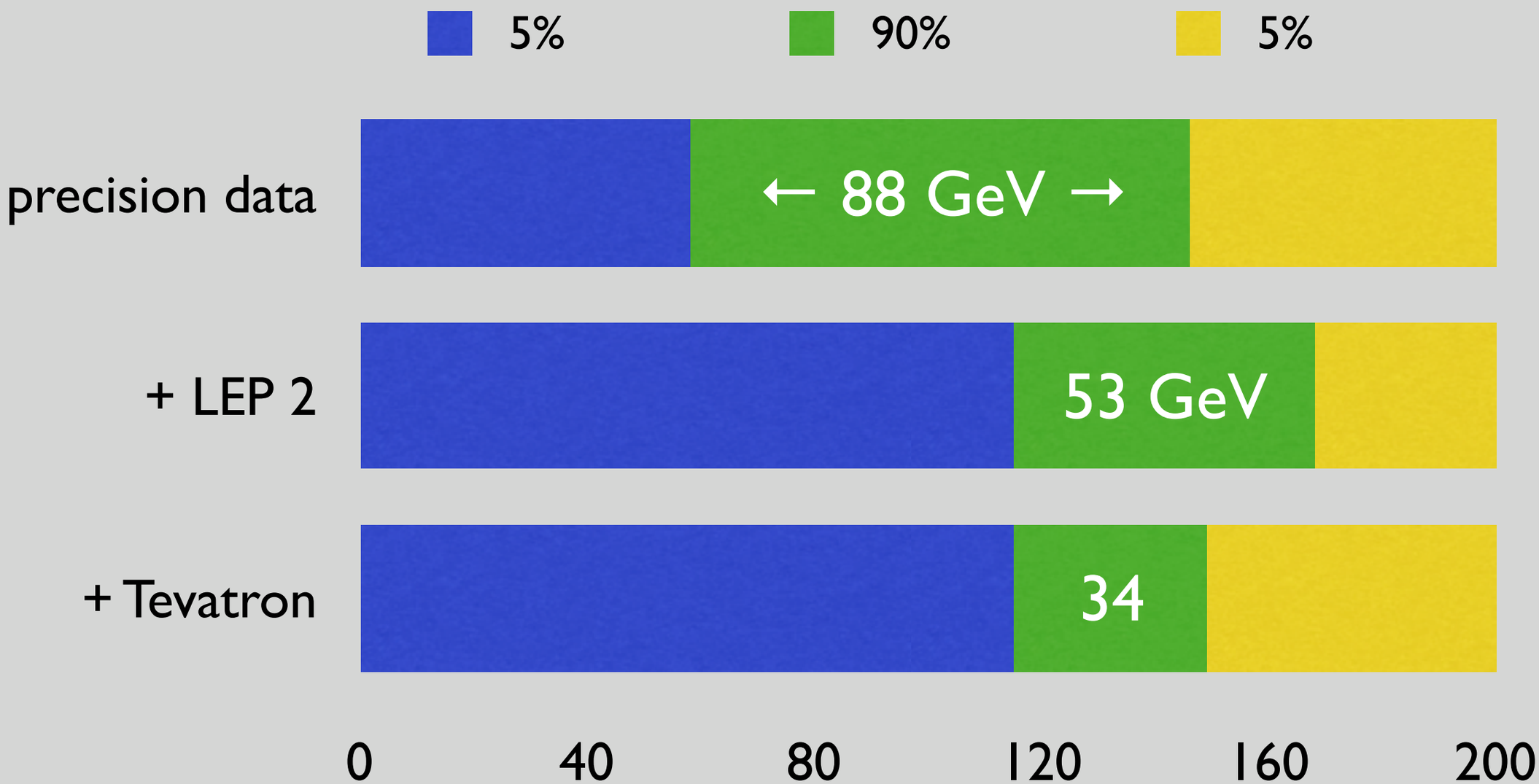
Tevatron Higgs searches



Contribution to likelihood

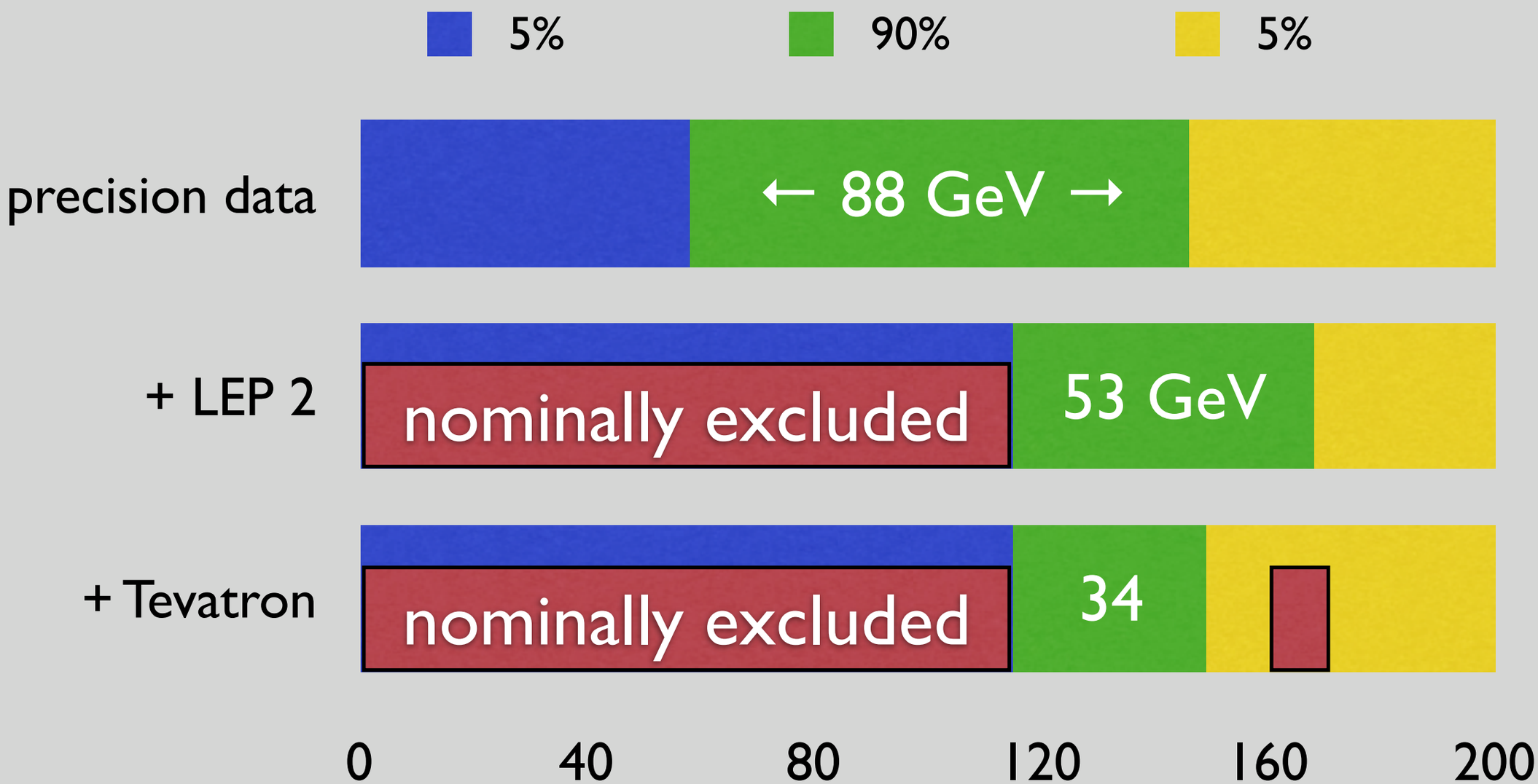
SM: Higgs boson mass

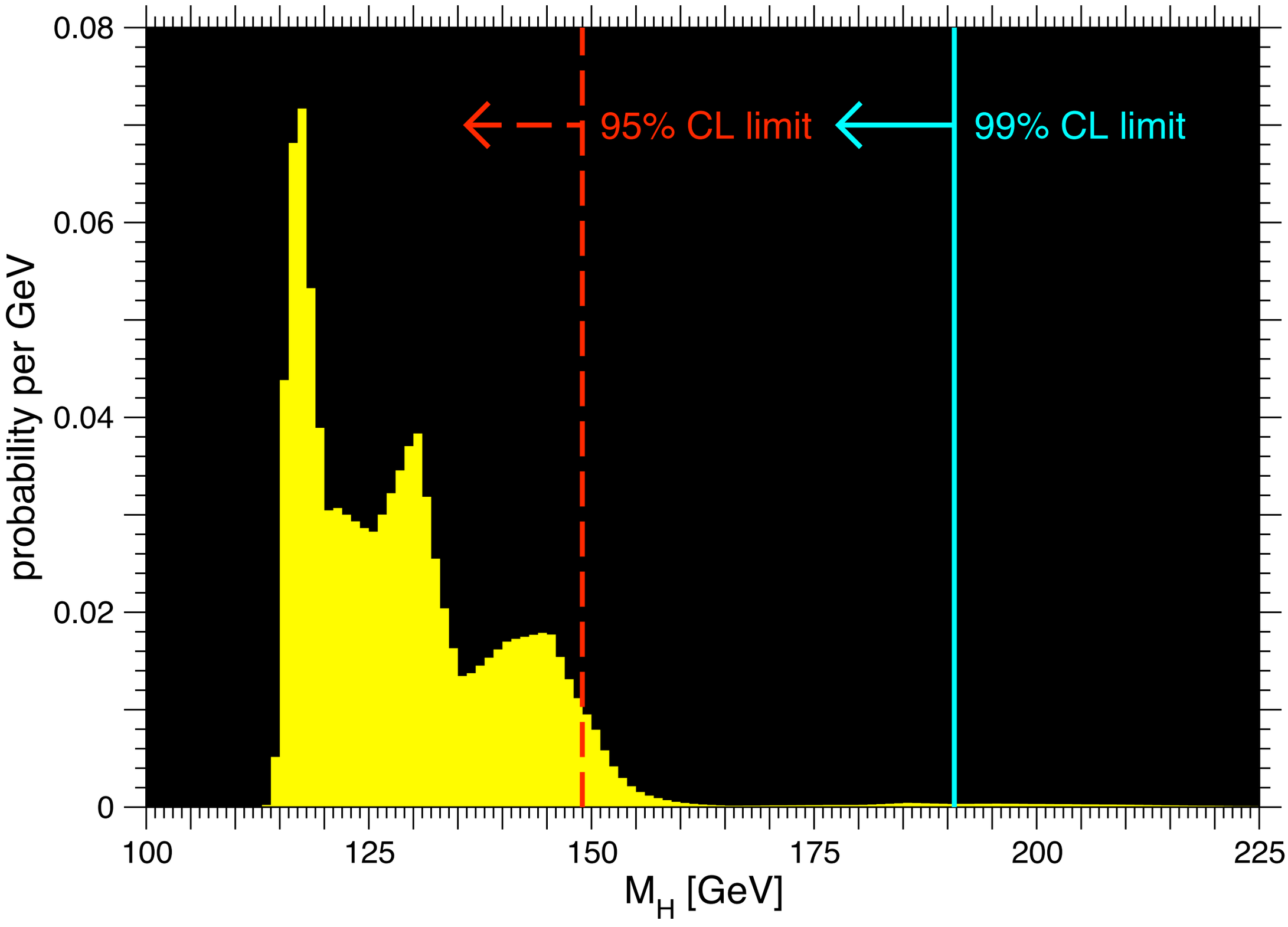
115 GeV < M_H < 149 GeV (90% CL)



SM: Higgs boson mass

115 GeV < M_H < 149 GeV (90% CL)




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]

Universal Z′ bosons: formalism

- consider only effects of Z′ (not exotic fermions)
- in this case Z′ decouples (unlike 4th family)
- $\tan^2\theta = [M_0^2 - M_Z^2]/[M_{Z'}^2 - M_0^2]$,
  with $\cos\theta_W = M_W/M_0$ (Langacker 1984)
- can allow $T \neq 0$ (Higgs triplets, exotics in loops)
- $\theta = C\, g_2/g_1\, M_Z^2/M_{Z'}^2$, with C a function of the U(1)′ charges and VEVs of the Higgs sector
- $\sin\theta = 0 \Rightarrow$ high energy data virtually blind to Z′
- conversely: high energy data $\Rightarrow \sin\theta \lesssim \mathcal{O}(10^{-3})$

Universal Z′ bosons: examples

- Z_χ: SO(10) → SU(5)×U(1) (GUTs)
- Z_ψ: E_6 → SO(10)×U(1) (GUTs)
- Z_η: $\sqrt{3/8}\, Z_\chi - \sqrt{5/8}\, Z_\psi$ (heterotic string)
- Z_{LR}: $SU(2)_R \times U(1)_{B-L} \to U(1)_Y \times U(1)'$ (LR model)
- Z_R: 3rd component of $SU(2)_R$ (best fit to data)
- sequential Z′: excited Z or from extra dimensions
- Z_X: model motivated by seesaw ν-masses (Adhikari, Ma, JE 2008)

The Precision Frontier:

Z′ mediated amplitude

CKM first row unitarity

- superallowed $0^+ \to 0^+$ β-decays (Hardy, Towner):
  $|V_{ud}| = 0.97424\ (8)\ (10)\ (18) = 0.97424 \pm 0.00022$
- K_{l3} decays: $|V_{us}| = 0.22478 \pm 0.00124$ (KLOE)
- K_{l2} decays: $|V_{us}/V_{ud}| = 0.23216 \pm 0.00145$ (KLOE)
- $|V_{ud}|^2 + |V_{us}|^2 + |V_{ub}|^2 - 1 = 0.0000 \pm 0.0006$
  $\propto e_L\,(e_L - q_L)\,\ln(M_{Z'}/M_W)/(M_{Z'}^2/M_W^2 - 1)$
  from 1-loop W-Z′ box (Marciano, Sirlin 1987)
- $\Rightarrow M_X \geq 265$ GeV at 95% CL ($\Delta\chi^2 \leq 3.84$)

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

Atomic parity violation

- Nuclear spin independent PV sensitive to q-vector e^--axial-vector couplings (C_{1i}, $Q_W \propto A^3$)
- most precise measurement: $Q_W(^{133}Cs)$ (Boulder)
- also needs precise atomic structure calculation ⇒

  $Q_W(^{133}Cs) = -73.17 \pm 0.29$ (exp.) ± 0.20 (theory)
  (Derevianko 2008)
- SM: $Q_W(Cs) = 188\, Q_W(u) + 211\, Q_W(d) = -73.15$
- $\Delta Q_W(q) \propto (e_L - e_R)\,(q_L + q_R)\, M_Z^2 / M_{Z'}^2$ ($\sin\theta = 0$)
- ⇒ $M_X \geq 0.89$ TeV (95% CL) (Z_ψ: $q_L + q_R = 0$)

Polarized Møller scattering

- SLAC E-158: $E = 45$ & 48 GeV, $P \simeq 89 \pm 4$ %
  $\Rightarrow Q^2 \simeq m\,E \simeq 0.026$ GeV^2 (high energy, low Q^2)

- $A_{RL} = -\,(1.31 \pm 0.14 \pm 0.10)\times 10^{-7} \propto Q_W(e)$
  $\Rightarrow Q_W(e) = -0.0403 \pm 0.0053$

- SM: $Q_W(e) = \rho\,(-1 + 4\,\kappa \sin^2\theta_W[\sqrt{Q^2}]) = -0.0472$

- $\Delta Q_W(e) \propto (e_L - e_R)\,(e_L + e_R)\,M_Z^2/M_{Z'}^2$ ($\sin\theta=0$)
  (manifestly complementary to Tevatron and LEP 2)

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

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:

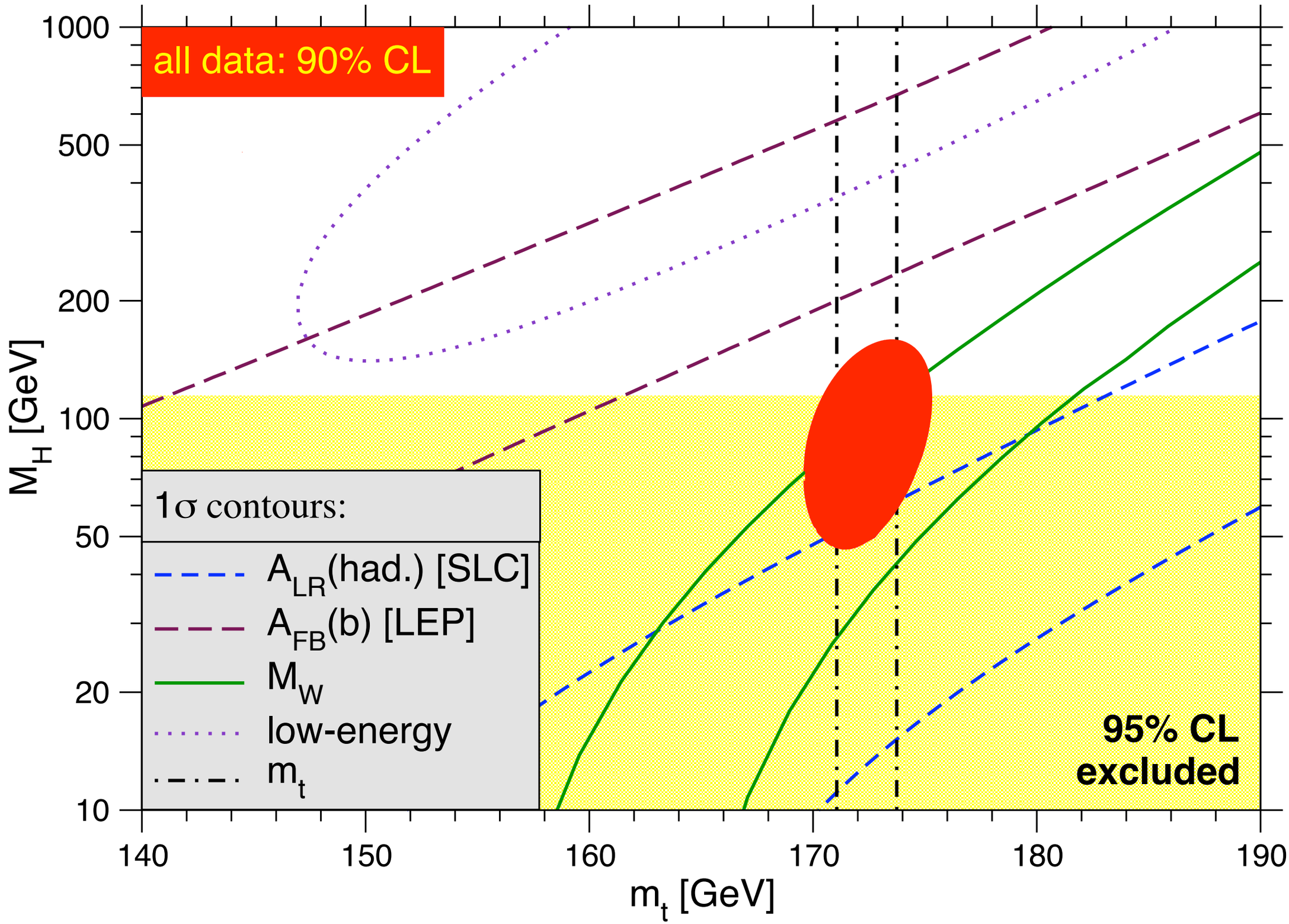
  $(2\, C_{1u} - C_{1d}) + 0.84\, (2\, C_{2u} - C_{2d}) = \pm 0.0049 \Rightarrow$

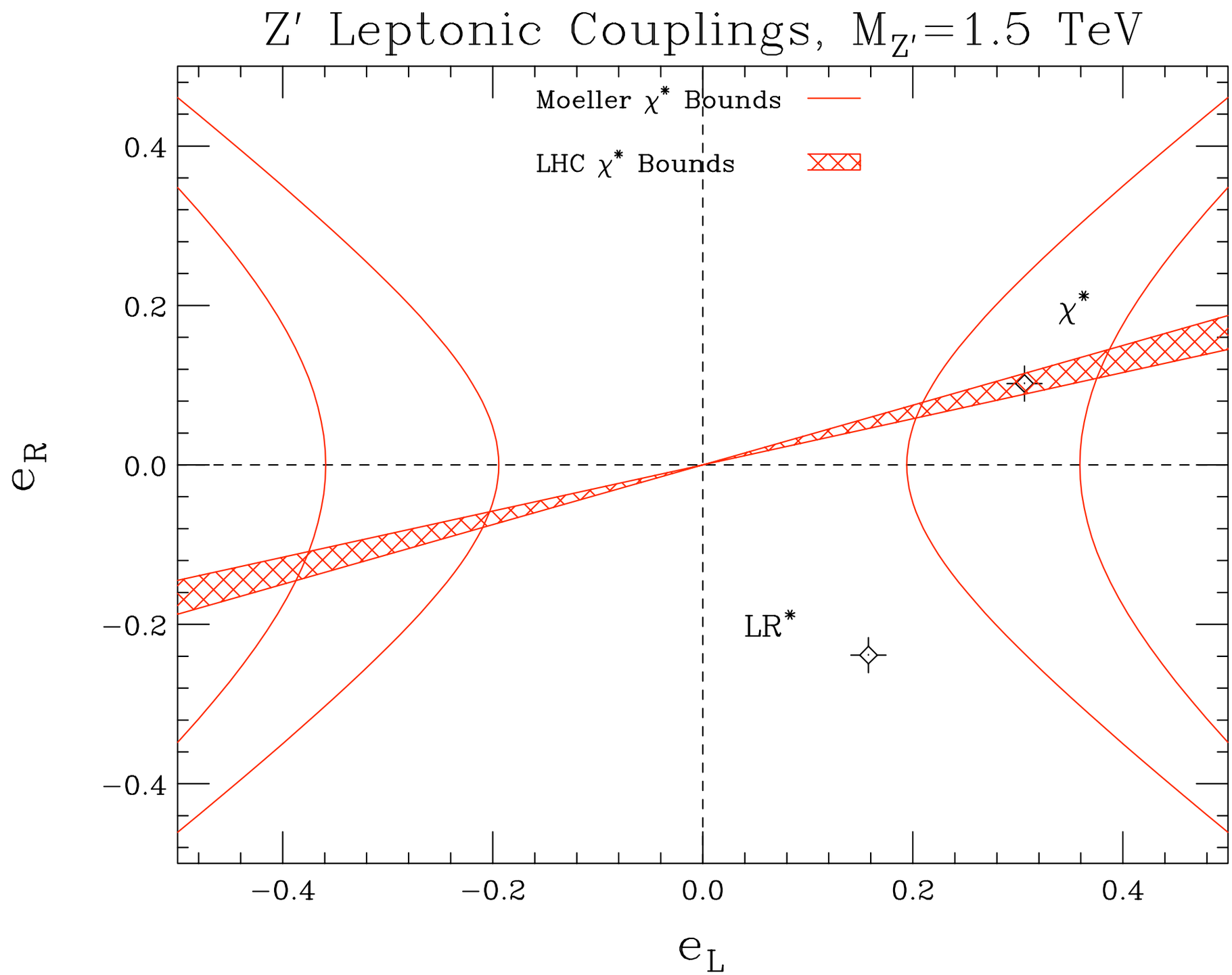
  $M_X \geq 0.45$ TeV (Z_ψ: $q_L + q_R = e_L + e_R = 0$) or

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

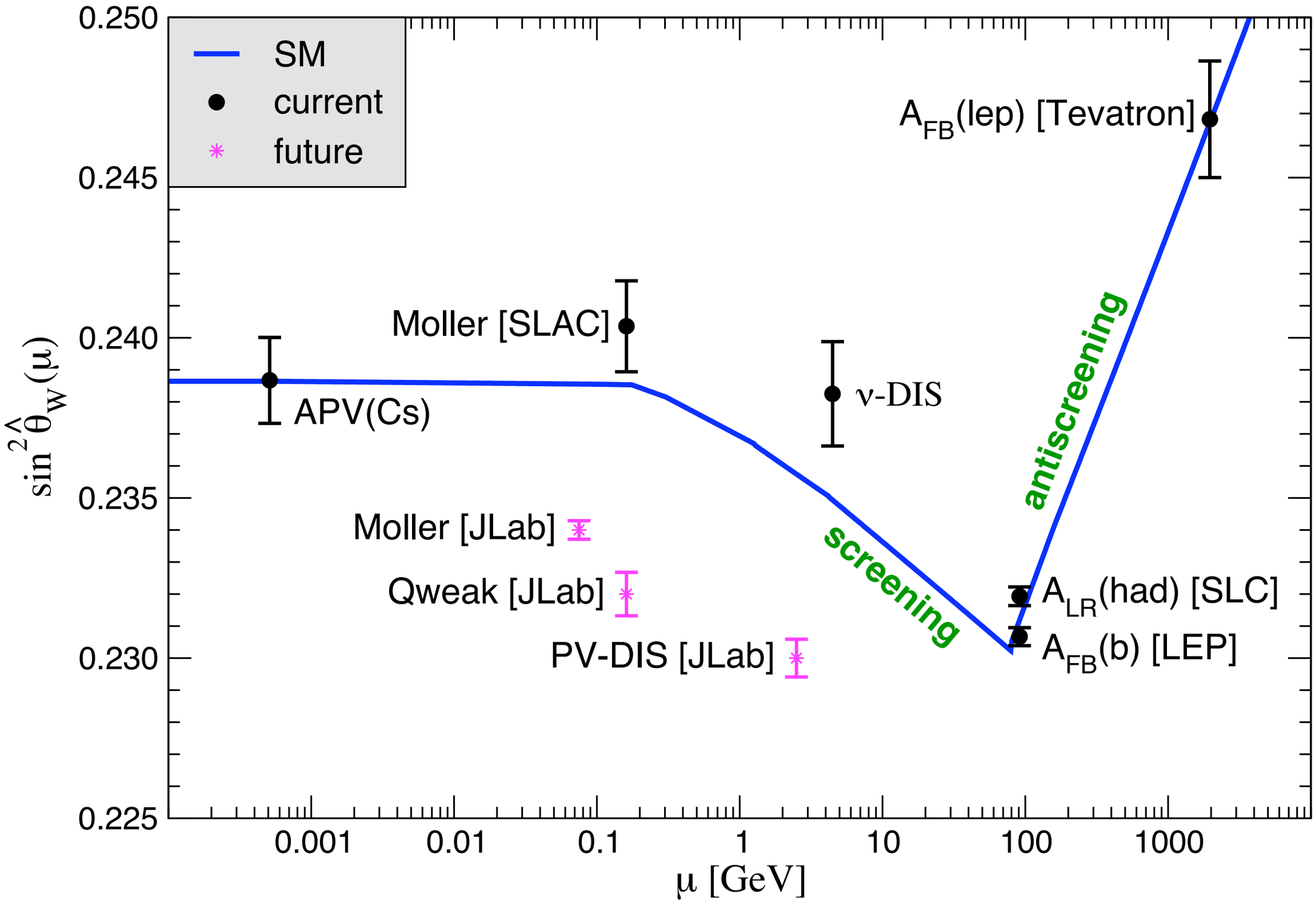
- e2ePV @ 12 GeV CEBAF: $\Delta Q_W(e) = \pm 0.0011 \Rightarrow$

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


all data: 90% CL
1σ contours:
A_LR(had.) [SLC]
A_FB(b) [LEP]
M_W
low-energy
m_t
95% CL
excluded
M_H [GeV]
m_t [GeV]
1000
500
200
100
50
20
10
140
150
160
170
180
190



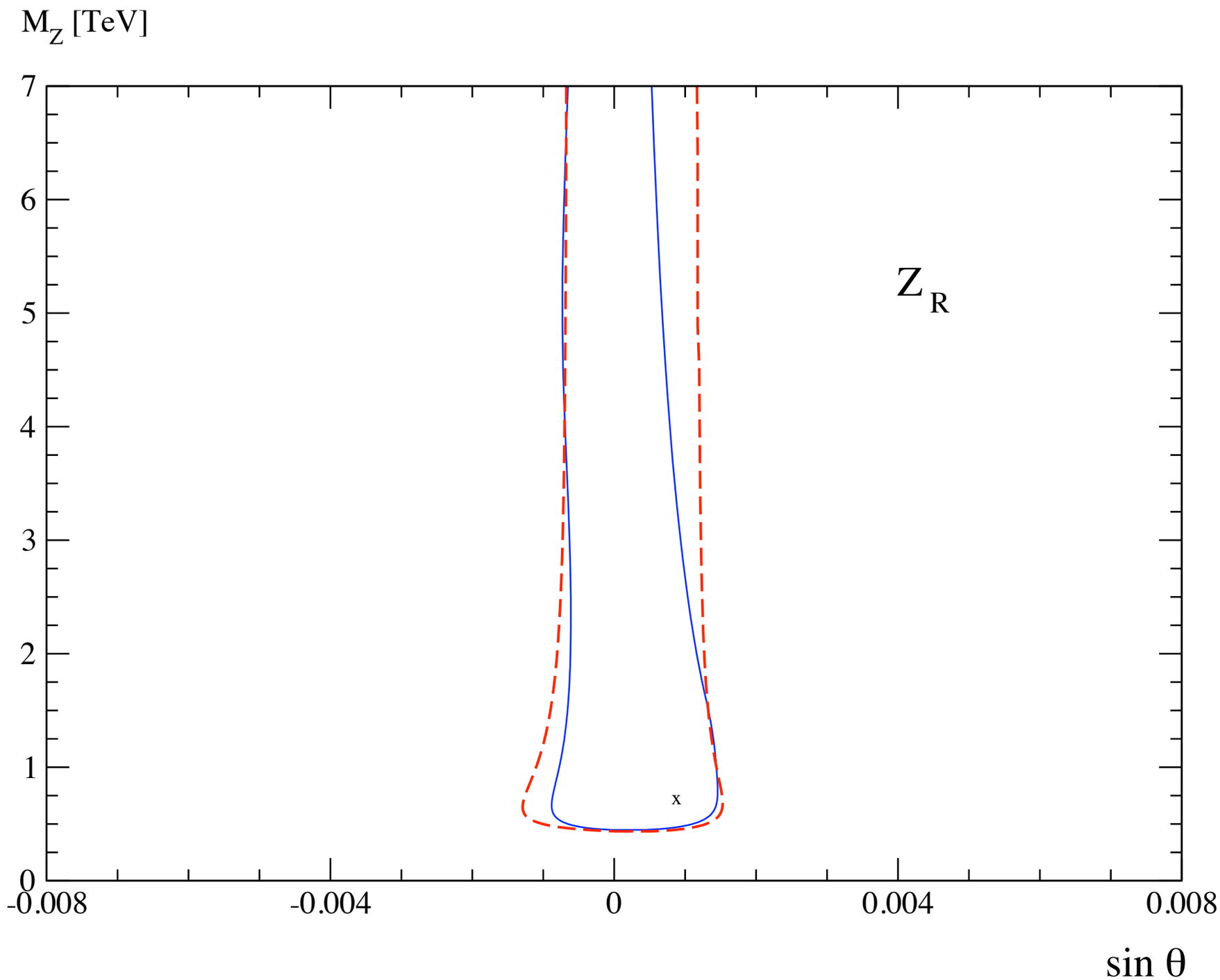
(Petriello, Quackenbush, 2008)


SM
current
future
0.250
0.245
0.240
0.235
0.230
0.225
$\sin^2\hat{\theta}_W(\mu)$
0.001
0.01
0.1
1
10
100
1000
μ [GeV]
A_{FB}(lep) [Tevatron]
Moller [SLAC]
APV(Cs)
ν-DIS
antiscreening
screening
Moller [JLab]
Qweak [JLab]
PV-DIS [JLab]
A_{LR}(had) [SLC]
A_{FB}(b) [LEP]

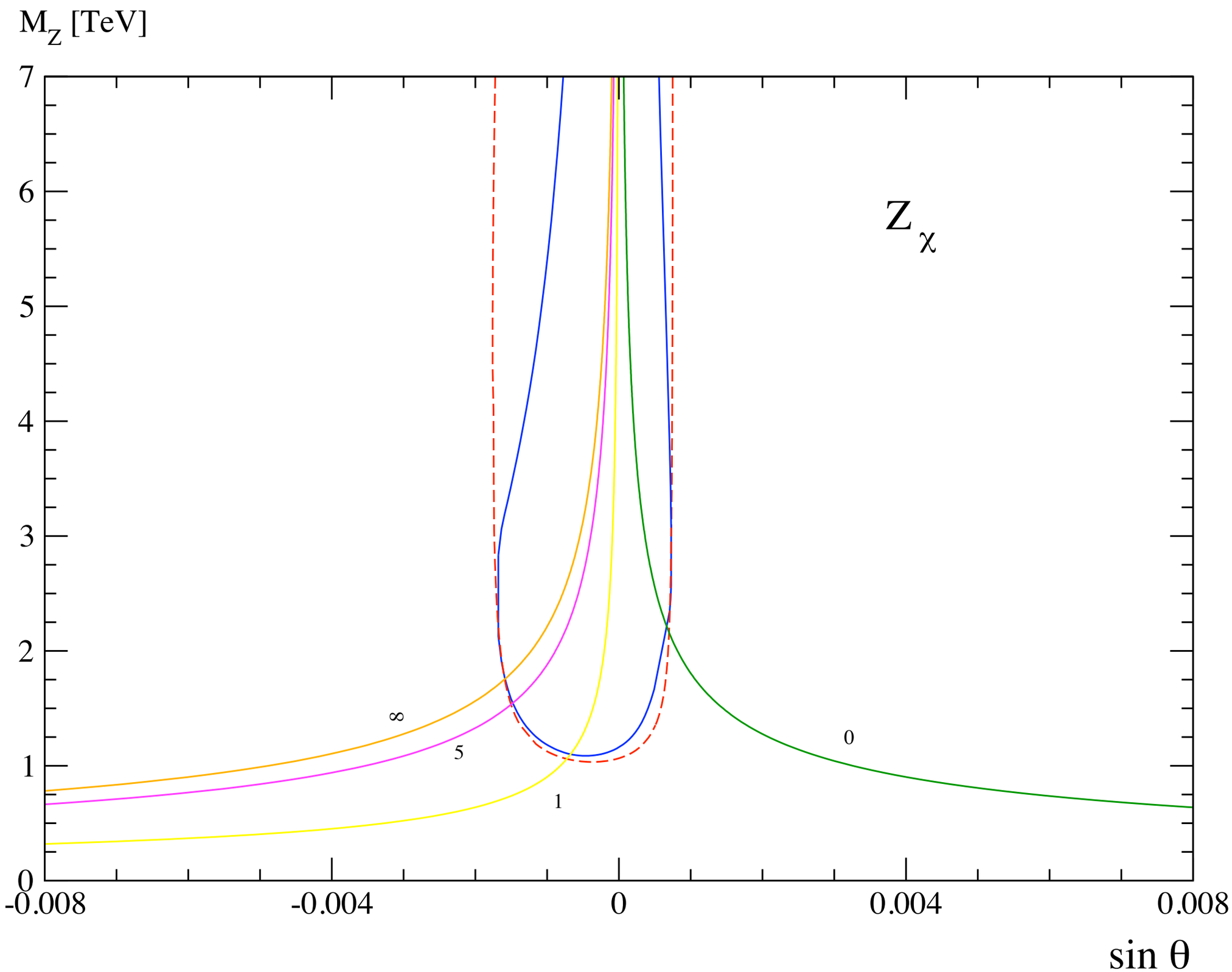
Universal Z′ bosons: results

95% CL lower limits [GeV]	precision data	CDF	LEP 2
Z_χ	1,140	892	781 (OPAL)
Z_ψ	147	878	481 (2f-WG)
Z_η	419	904	515 (OPAL)
Z_{LR}	976	630	804 (2f-WG)
sequential Z'	1,387	1,030	1,787 (2f-WG)

- precision data assume $T = 0$ ($\rho = 1$)
- CDF assumes no exotic or SUSY decay channels
- LEP 2 assumes $\sin\theta = 0$



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


M_Z [TeV]
7
6
5
4
3
2
1
0
-0.008
-0.004
0
0.004
0.008
sin θ
Z_χ
∞
5
1
0

The Intensity Frontier:
non-universal Z' bosons

Non-universal Z′ bosons

- CLFV, new FCNCs & CPV can be induced through
  - intergenerational couplings (charges) of the Z′
  - fermion mass matrices even if Z′ is diagonal
  - the ordinary Z if $\sin\theta \neq 0$
  - mixing of ordinary fermions & exotics (Z & Z′)
- ⇒ effects difficult to quantify even within a model

- comprehensive analysis: Langacker, Plümacher 2000
- non-univeral fit to EW data: Erler, Langacker 2000

Flavor change

- $B(K \to \mu\, e) < 4.7 \times 10^{-12}$ (BNL) $\Rightarrow \Lambda > 450$ TeV
- $B(\mu \to 3e) < 1.0 \times 10^{-12}$ (SINDRUM) $\Rightarrow \Lambda > 250$ TeV
- $B(\mu \to e\, \gamma) < 1.2 \times 10^{-11}$ (MEGA) $\Rightarrow \Lambda > 240$ TeV
- $R(\mu^- Ti \to e^- Ti) = \Gamma(\mu^- Ti \to e^- Ti) / \Gamma(\mu^- Ti \to \nu\, Sc) < 6.1 \times 10^{-13}$ (SINDRUM II) $\Rightarrow \Lambda > 280$ TeV
- $B(K^+ \to \pi^+ \nu\, \bar{\nu}) = (1.73 \pm 1.1) \times 10^{-10} \Rightarrow \Lambda \gtrsim 76$ TeV
- $[m(B_H) - m(B_L)] / [m(B_H) + m(B_L)] = 3.160(31) \times 10^{-14}$ (BaBar, Belle, CDF, D0, LEP) $\Rightarrow \Lambda \gtrsim 3$ PeV (theory!)

CP violation

- $|\varepsilon_K|\,[m(K_L) - m(K_S)]/[2\,m(K_0)] =$
  $(7.801 \pm 0.042)\times 10^{-18}$ (PDG) $\Rightarrow \Lambda \gtrsim 140$ PeV

- ε' $\Rightarrow \Lambda \gtrsim 800$ PeV, even with 100% SM uncertainty (cancellations between EW and QCD penguins)

- EDMs (need many different ones to discriminate between new physics scenarios)
  - eEDM, μEDM, nEDM, pEDM, dEDM
  - paramagnetic (eEDM) and diamagnetic (nuclear Schiff moment) atoms

Conclusions

Conclusions

- Higgs searches + EW precision data restricts Higgs mass to 30 GeV window (in SM)
- Z′ constraints from EW precision data competitive with LEP 2 and Tevatron
- 2σ problems in APV and CKM first row unitarity disappeared entirely
- CLFV, FCNCs & CPV effects typically off the charts
- B & B_S-mixing & CPV (K-system) typically too large even for equal U(1)′ charges of first two families