Spin Beyond Standard Model: Theory

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18th International Spin Physics Symposium (Spin 2008)
October 6–11, 2008
University of Virginia, Charlottesville, VA

Introduction

Introduction

- *Required to define spin: Lorentz-invariance and QM.*
- *Not required: causality (Lorentz invariance of the S-matrix) and cluster decomposition principle.*
- *⇒ Spin can be considered even outside the framework of a QFT (but not conversely).*
- *→ Spin can serve as an organizing principle for the many types of physics beyond the SM that have been suggested, including extra dimensions and strings.*
- *Tests: see talks by Bill Marciano (g-2, CKM unitarity), Yannis Semertzidis (EDMs, μ → e conversion), Krishna Kumar (polarized scattering).*

Relativistic Quantum Mechanics (Wigner)

p^2	p_0	standard k^β	little group	comments
> 0	> 0	$(M,0,0,0)$	$SO(3)$	massive particle
> 0	< 0	$(-M,0,0,0)$	$SO(3)$	$E < 0$ (unphysical)
$= 0$	> 0	$(k,k,0,0)$	$ISO(2)$	massless particle
$= 0$	$= 0$	$(0,0,0,0)$	$SO(3,1)$	vacuum (no particles)
$= 0$	< 0	$(-k,k,0,0)$	$ISO(2)$	$E < 0$ (unphysical)
< 0	any	$(0,M,0,0)$	$SO(2,1)$	tachyon ($\lvert v\rvert > c$)

- *spin of massive particle: algebra as in QM.*
- *helicity of massless particle: topology of $SO(3,1) = SL(2,\mathbb{C})/Z_2$ is that $\mathbb{R}^3 \times S^3/Z_2$ and is doubly connected.*

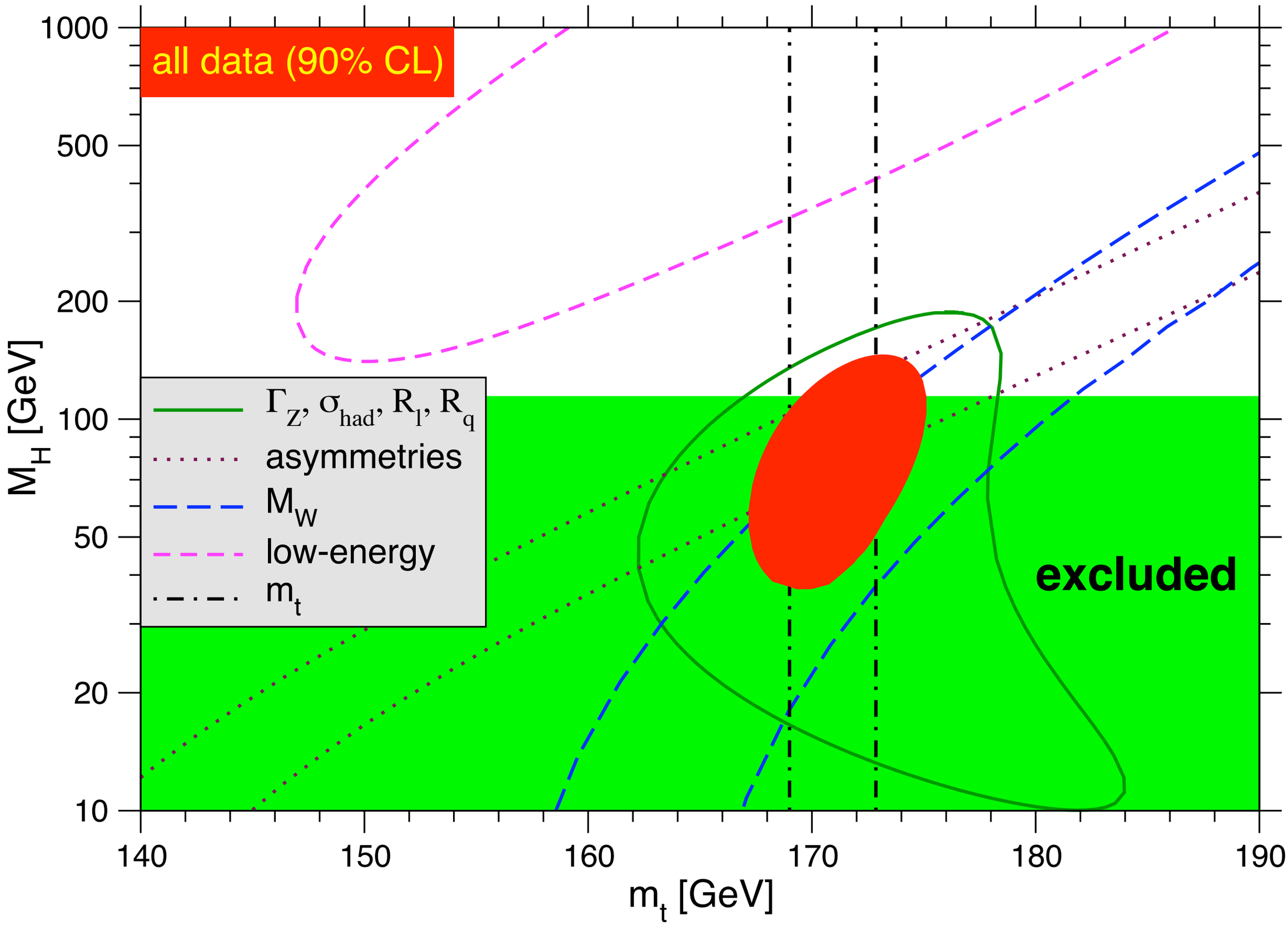
Overview

- *Spin 0: Higgs, familon ($\not{F}$), Majoron ($\not{L}$), axions ($\not{P}Q$), radion (graviscalar), dilaton, moduli, inflaton, scalar leptoquarks (LQ), sfermions*
- *Spin 1/2: 4th family, ν^R, exotics, techniquarks, X-inos*
- *Spin 1: Z′, W′, vector LQs (e.g. GUTs).*
- *Spin 2: graviton (predicted by string & M-theory), KK excitations (gravity in extra dimensions).*
- *Spin > 2: trivial S-matrix, massive string states*
- *Spin 3/2: gravitino (supergravity)*

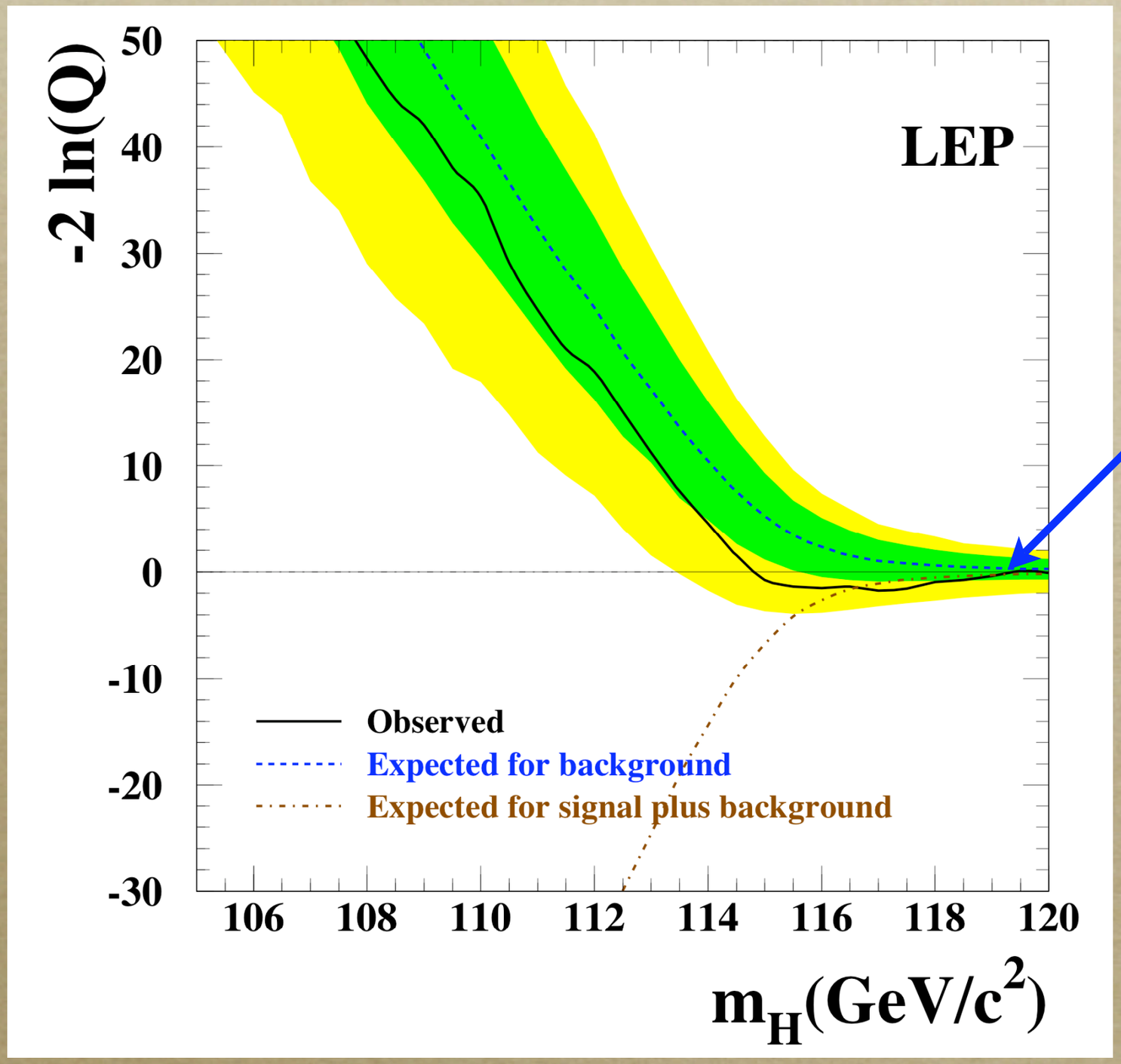
Spin 0

Spin 0 in the SM: Global Fit

	all data	*indirect only*
$M_H[GeV]$	89^{+29}_{-22}	*117 (fixed)*
$M_t[GeV]$	*172.4 ± 1.3*	*175.6 ± 3.0*
$\hat{\alpha}_s(M_Z)$	*0.1185 ± 0.0016*	*0.1185 ± 0.0016*
χ^2/d.o.f.	*49.1 / 43 (24%)*	*49.1 / 43 (24%)*

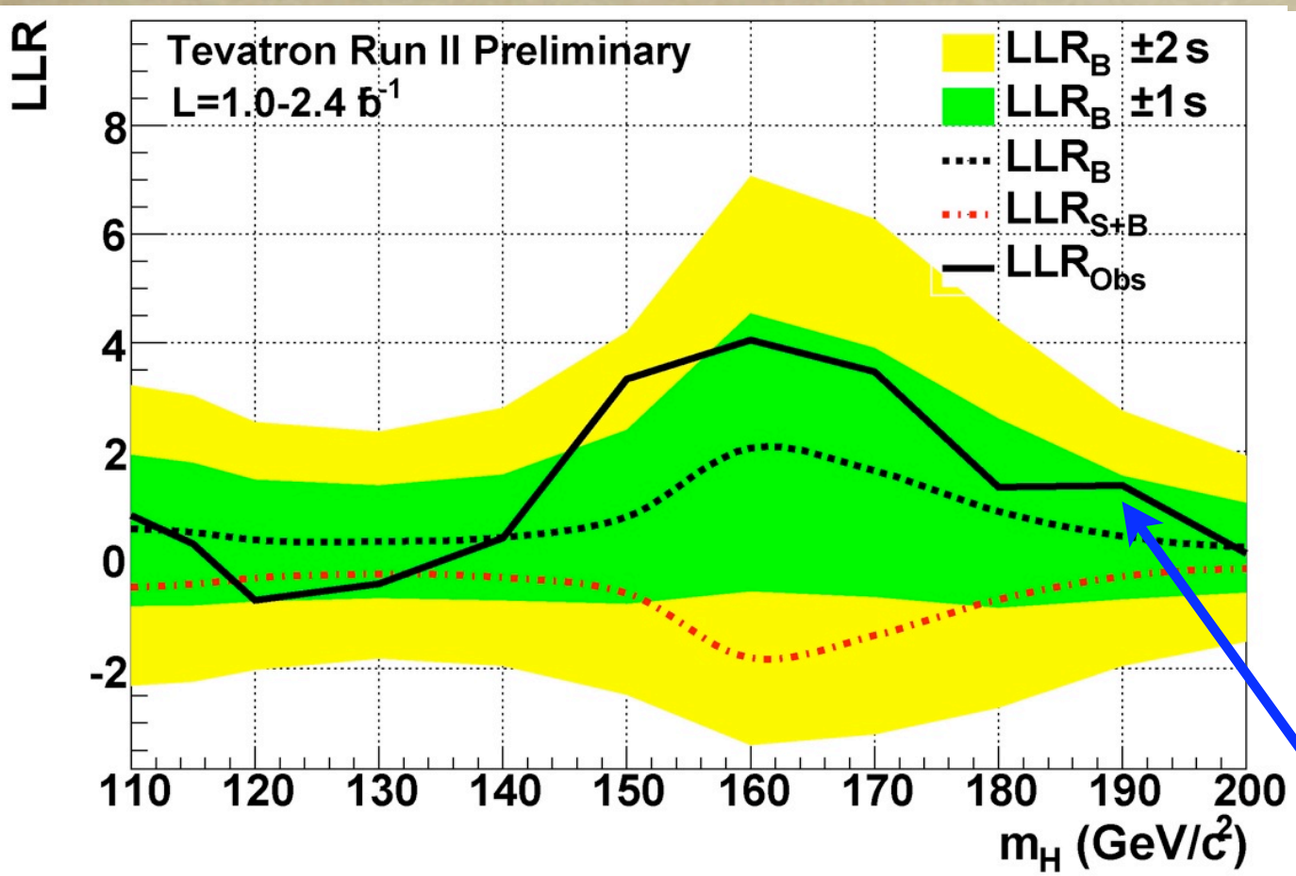

all data (90% CL)
Γ_Z, σ_{had}, R_l, R_q
asymmetries
M_W
low-energy
m_t
excluded
M_H [GeV]
m_t [GeV]
1000
500
200
100
50
20
10
140
150
160
170
180
190

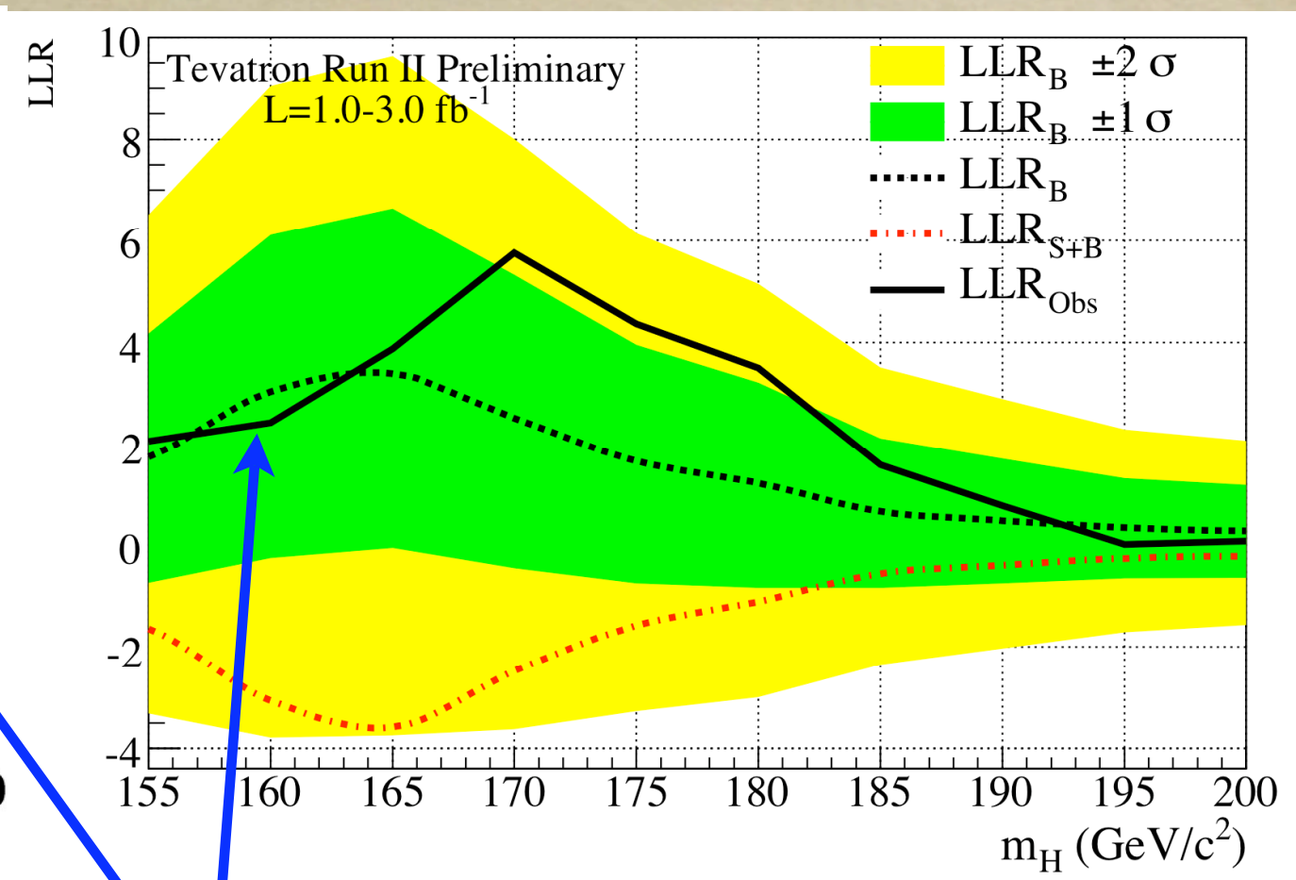
LEP 2 Higgs Searches



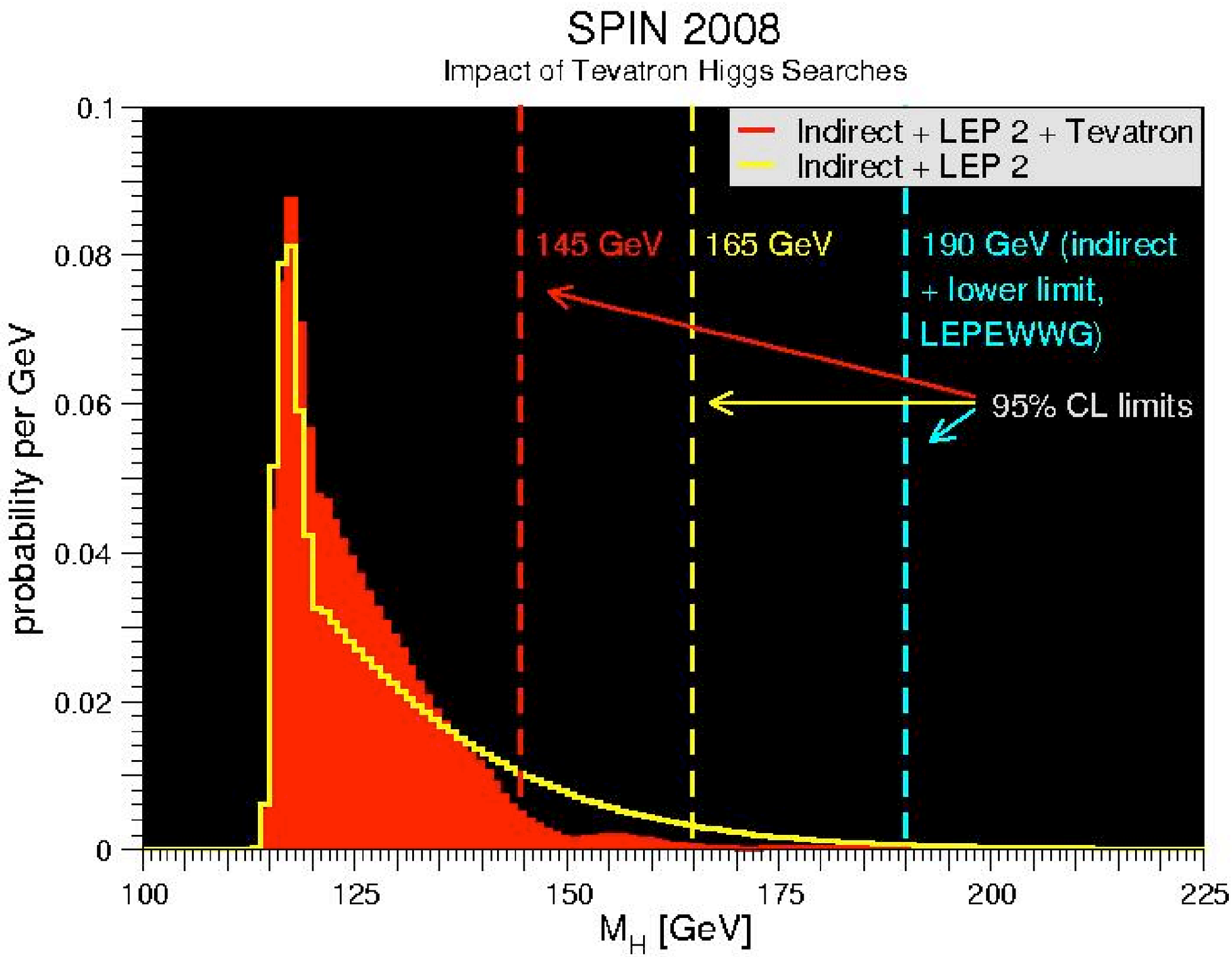
Contribution to likelihood

Tevatron Higgs Searches





Contribution to likelihood


SPIN 2008
Impact of Tevatron Higgs Searches
Indirect + LEP 2 + Tevatron
Indirect + LEP 2
145 GeV
165 GeV
190 GeV (indirect
+ lower limit,
LEPEWWG)
95% CL limits
probability per GeV
0.1
0.08
0.06
0.04
0.02
0
100
125
150
175
200
225
M_H [GeV]

Higgs Boson

- *Perturbativity to* M^P *(Planck scale)* $\Rightarrow M^H \lesssim 180$ *GeV.*
- *Vacuum (meta) stability to* $M^P \Rightarrow M^H \gtrsim 130\ (115)$ *GeV.*
- $(M^H)^2 = (M^H{}_0)^2 + \alpha/\pi\ (M^P)^2 \sim (M^W)^2$
  (*hierarchy problem*).
- *LHC mission: find Higgs boson(s) and solution to the hierarchy problem (ideally) explaining also*
  - *why precision data appear consistent with SM;*
  - *dark matter;*
  - *Baryon Asymmetry of the Universe (BAU).*

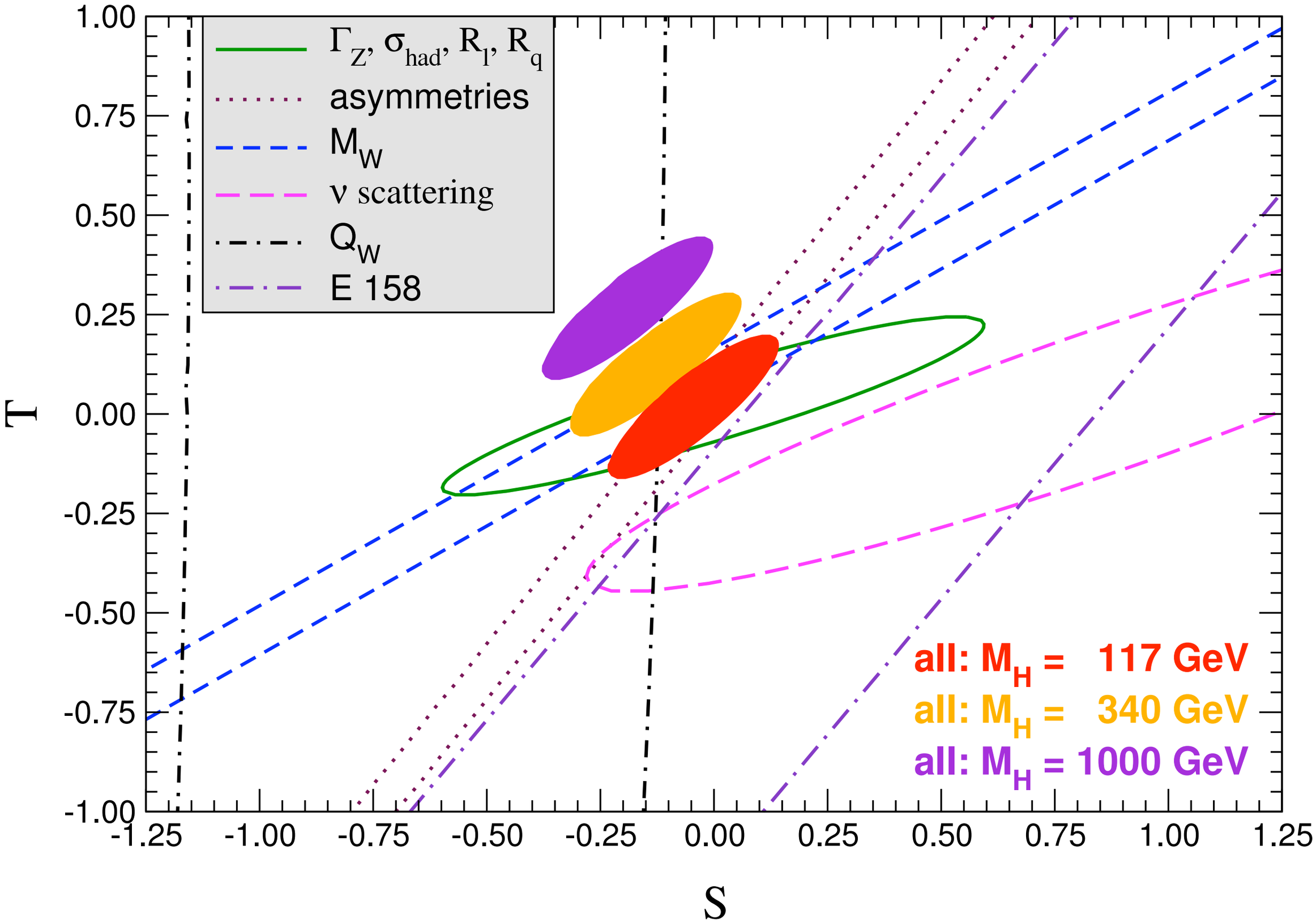
Spin 1/2

Technicolor (TC)

- *Weinberg, Susskind, 1979 ($\Lambda \sim 1$ TeV).*
- *Fermion masses* $\Rightarrow$ *extended technicolor.*
- *FCNC* $\Rightarrow$ *walking techniclor* ($\Lambda \sim 100$-1000 TeV).
- *Large top quark mass* $\longrightarrow$ *top quark condensation.*
- *Predicted* $M^{\top}$ *too large* $\Rightarrow$ *topcolor-assisted TC.*
- *No bottom condensation* $\Rightarrow$ *extra strong* $U(1)$ (Z')
- *Alternative: top quark seesaw model.*

Compositeness

- *Higgs Compositeness:*
  Kaplan, Georgi, Dimopoulos, 1983; Banks, 1984.
- *Reincarnation (Arkani-Hamed, Cohen, Georgi, 2001):*
  Little Higgs Theory ($\Lambda \sim$ 5-10 TeV).
- *Introduce Higgs as pseudo-Goldstone boson.*
- *Postpone quadratically divergent contributions to M^H by one (in some models two) loop order.*
- *Quark and Lepton Compositeness: Contact interaction scale $\Lambda \gtrsim \mathcal{O}$(10 TeV) (LEP); q* mass > 775 GeV (D0).*


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
-0.50
-0.25
0.00
0.25
0.50
0.75
1.00
1.25

Extra Fermion Generation

- *If degenerate* ($T = U = 0$) $\Rightarrow$ $\Delta S = 2/3\pi = 0.21$; *excluded at the* 6σ *level* ($N^G = 2.71 \pm 0.22$).
- *Complementary to* $N^G = 2.991 \pm 0.007$ *from Z-width.*
- *Allowing* $T \Rightarrow$ $T = 0.232 \pm 0.045$, *but* $\Delta\chi^2 = 6.8$ *relative to SM* ($M^H = 117$ *GeV*): *excluded at 99% CL.*
- *Designer splitting of extra doublets:* $m(\nu_4) = 100$ *GeV,* $m(l_4) = 155$ *GeV,* $m(u_4) = 400$ *GeV,* $m(d_4) = 350$ *GeV* $\Rightarrow (S,T) \approx (0.15,0.19)$ *for* $M^H = 115$ *GeV (Kribs, Plehn, Spannowsky, Tait,* 2007).
- *Used approximation:* $S \approx N(1-4Y \ln m^u/m^d)/6\pi$.

Spin 1

Gauge Theories

- *Lorentz invariance, quantum mechanics, the cluster decomposition principle, and $1/r^2$-forces (long-range) helicity = ± 1 particles ⇒ gauge invariance (Weinberg, 1965).*

- *Extra Z' bosons: e.g., from $E_6 \rightarrow SO(10)\times U(1) \rightarrow SU(5)\times U(1)^2$, $SU(2)^L\times SU(2)^R\times U(1) \rightarrow SU(2)^L\times U(1)^2$, it could be the techni-ρ, topcolor-Z', a KK state or the extra U(1)' may solve a problem in some other model.*

- *Z': mass > 1305 GeV (sequential, DELPHI), > 630 to 891 GeV (E_6, CDF); mixing < $O(10^{-2})$ (electroweak).*

- *W': mass > 1000 GeV (D0); mixing < 0.12 (OPAL).*

Spin 2

Gravity

- *Lorentz invariance, quantum mechanics, the cluster decomposition principle, and $1/r^2$-forces (long-range) for helicity = ± 2 particles ⇒ invariance under general coordinate transformations (Weinberg, 1965).*
- *UV completion: embed into string or M-theory.*
- *Growing # of vacua: string landscape (anything goes).*

  ⇒ *revival of anthropic reasoning: the multiverse (Hall, Nomura, 2008).*

Gravity in Large Extra Dimensions (LEDs)

- *Arkani-Hamed, Dimopoulos, Dvali (ADD, 1998).*
- *Factorized space:* $\mathbb{R}^4 \times M^{D-4}$, *where M is a flat space with volume* $V^{D-4} = (2\pi R)^{D-4}$.
- $\mathcal{O}(M_Z) = \kappa_D \gg R^{-1} = \kappa_D \left(\kappa_D/\kappa_4\right)^{2/(D-4)}$.
- *D = 4 + 1 excluded from macroscopic Newton's law.*
- *Colliders* ($e^+e^- \longrightarrow \gamma + \not{E}$, *etc.*) $\Longrightarrow \kappa^D > \mathcal{O}(1\ \text{TeV})$.
- *4-Fermi operators* ($e^+e^- \longrightarrow l^+l^-$, *etc.*): $\Lambda \gtrsim \mathcal{O}(10\ \text{TeV})$.
- *Astrophysics* (γ*-rays from n-stars, pulsar luminosities, etc.*): $\kappa^D \gtrsim \mathcal{O}(100\ \text{TeV})$, *but can be avoided in models.*

SM Fields in Flat Extra Dimension

- *TeV-scale compactification (Antoniadis, 1990): gauge fields in the bulk ($R^{-1} \gtrsim 7$ TeV, from $e^+e^- \to f\bar{f}$, etc.).*
- *Universal Extra Dimensions (UEDs; Appelquist, Cheng, Dobrescu, 2001): all SM particles in the bulk; KK-parity $\Rightarrow$ weaker limits ($R^{-1} \gtrsim 300$ TeV); lightest KK state: $B^{(1)} \to$ dark matter candidate if ~ 600 GeV.*
- *Gauge-Higgs Unification (Manton, 1979): weak scale protection by defining Higgs as gauge field component.*
- *Grand Unification in extra dimensions: $R^{-1} = M(\mathrm{Unif})$: can solve doublet-triplet problem of SUSY-GUTs.*

Warped Extra Dimensions

- *Randall, Sundrum (RS, 1999).*
- *Warped space:* $ds^2 = e^{-yk}\eta_{\mu\nu}dx^\mu dx^\nu - dy^2$, *where k is the AdS curvature and* $0 \leq y \leq \pi R$ *the 5th coordinate.*
- $\mathcal{O}(M_Z) = \Lambda_{IR} = \Lambda_{UV}e^{-\pi kR} = \kappa_4 e^{-\pi kR}$.
- *Colliders probe interaction scale of KK-gravitons with matter* (l^+l^-, $\gamma\gamma$ *invariant mass spectra*) $\Rightarrow$ $kR \gtrsim 11$.

SM Fields in Warped Extra Dimensions

- *Hierarchy problem ⇒ Higgs remains on the IR brane.*
- *Models can be viewed as dual description of walking TC by virtue of the AdS/CFT correspondence.*
- *No fully realistic model, yet (precision data, $M^{\dagger}$).*
- *Higgsless models (Csaki, Grojean, Murayama, Pilo, Terning, 2003).*
  - *Gauge symmetry breaking by boundary conditions of gauge fields living in warped extra dimensions.*
  - *KK vector bosons (too light without warping) postpone unitarity breakdown to ~ 15 TeV.*

Spin 3/2

Supersymmetry (SUSY)

- *Lorentz invariance, quantum mechanics, the cluster decomposition principle, and $1/r^2$-forces (long-range) for helicity = ± 3/2 particles ⇒ local SUSY (Weinberg, 1965).*
- *Unique non-trivial extention of the Poincaré group.*
- *Solves technical aspect of hierarchy problem.*
- *Radiative electroweak symmetry breaking (top-quark).*
- *MSSM consistent with gauge coupling unification.*
- *MSSM* $\Rightarrow M^{\mathrm{H}} \lesssim 135$ *GeV (lightest CP-even Higgs).*

Muon g−2: Issues

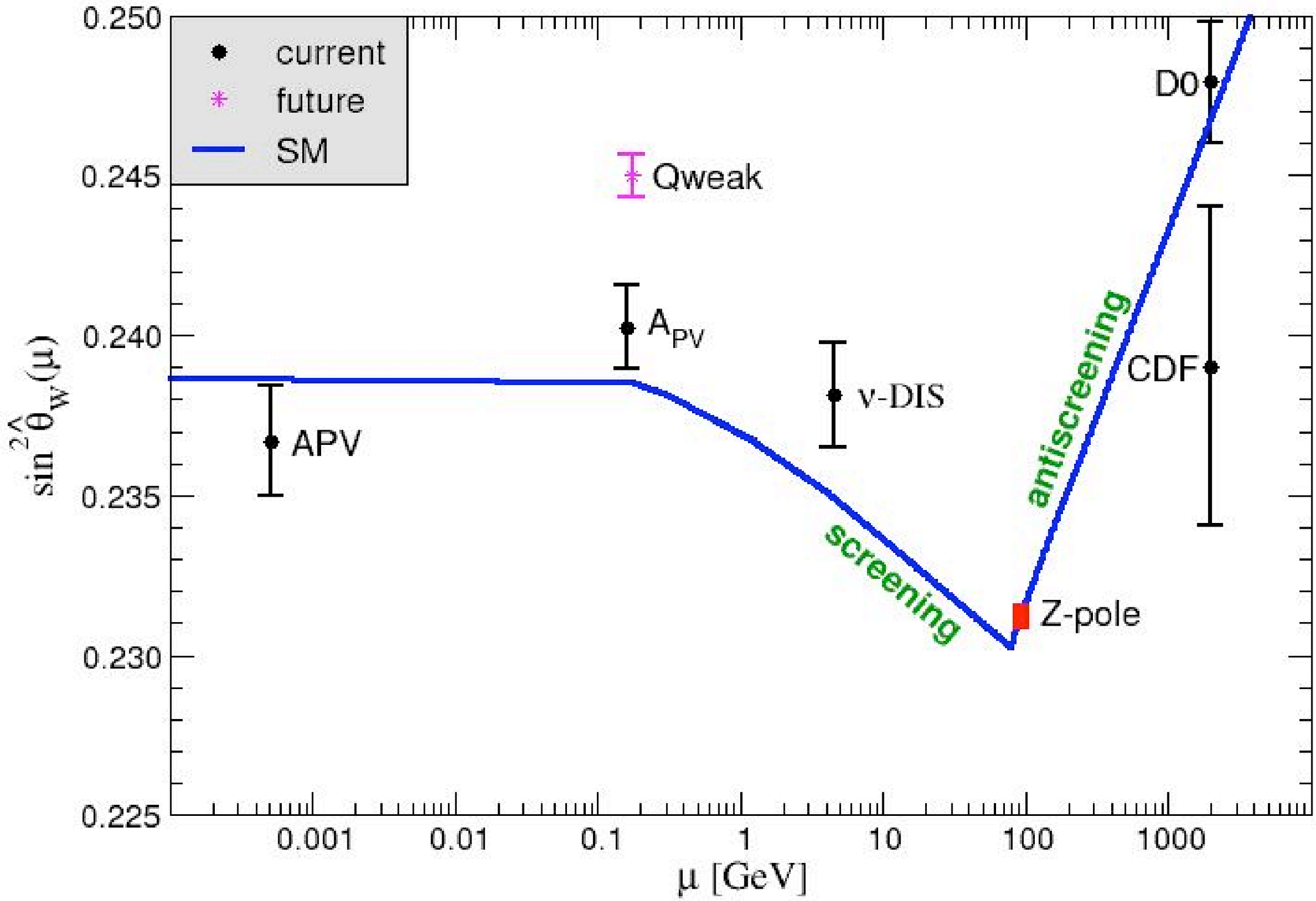
- *1.7–2.7 σ deviation from SM ⇒ supersymmetry?*
- *2-loop vacuum polarization contribution: need optical theorem and same spectral functions as for running α and $\sin^2\theta^W$ (see also Passera, Marciano, Sirlin, 2008).*
  - *τ decay and e^+e^- data (CMD & SND) inconsistent.*
  - *e^+e^- shapes (s-channel vs. KLOE) inconsistent.*
  - *Radiative returns (KLOE & BaBar) inconsistent.*
- *3-loop light-by-light contribution: only models & χPT.*
  - *Quark level estimate (JE, G. Toledo, 2006): $a^{LBL}(\mu, had) < 1.59 \times 10^{-9}$.*

Conclusions

- *SM still standing.*
- *Only small number of insignificant deviations.*
- *Searches at the Tevatron Run II and the LHC likely to yield discovery of new physics (SUSY, TC, LEDs, etc.).*
- *Electroweak precision measurements both at colliders and low-energy will give guidance and discriminatory power as to what will have benn discovered.*
- *However: anthropic arguments weaken the case for new physics at the TeV scale.*

Backup: NuTeV (νN and $\bar{\nu} N$-scattering)

- *2.0 σ deviation from SM ⇒ new physics?*
- *Was 2.7 σ before inclusion of $\int dx\, x\, (S - \bar{S}) = 0.0020 \pm 0.0014$ (NuTeV now agrees with CTEQ).*
- *New QED radiative corrections (Diener, Dittmaier, Hollik) but not yet included by NuTeV collaboration.*
- *Valence parton Charge Symmetry Violation (CSV) due to "quark model" and "QED splitting effects" each predict removal of 1 σ; phenomenological parton CSV PDFs can remove or double the effect (MRST).*
- *Nuclear effects: different for NC and CC; 20% of effect, both signs possible (Brodsky, Schmidt, Yang).*


current
future
SM
Qweak
A_{PV}
APV
ν-DIS
D0
CDF
Z-pole
screening
antiscreening
$\sin^2\hat{\theta}_W(\mu)$
μ [GeV]
0.250
0.245
0.240
0.235
0.230
0.225
0.001
0.01
0.1
1
10
100
1000