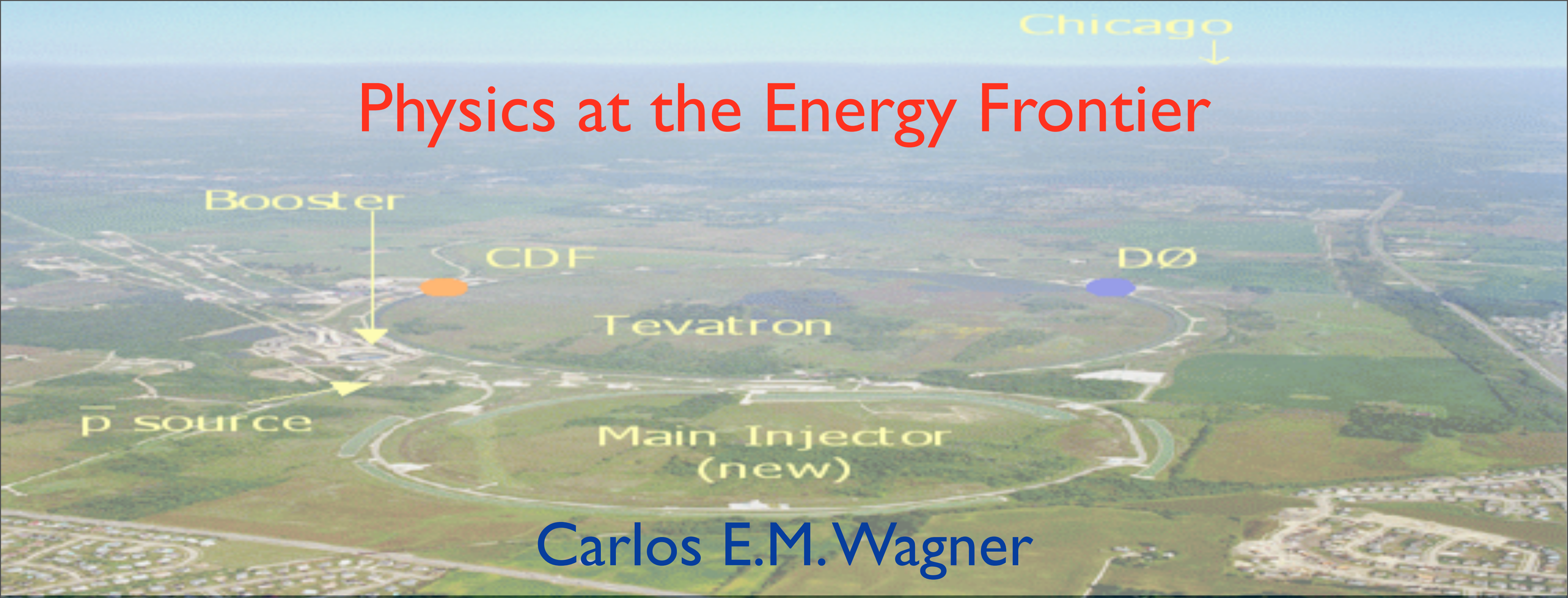
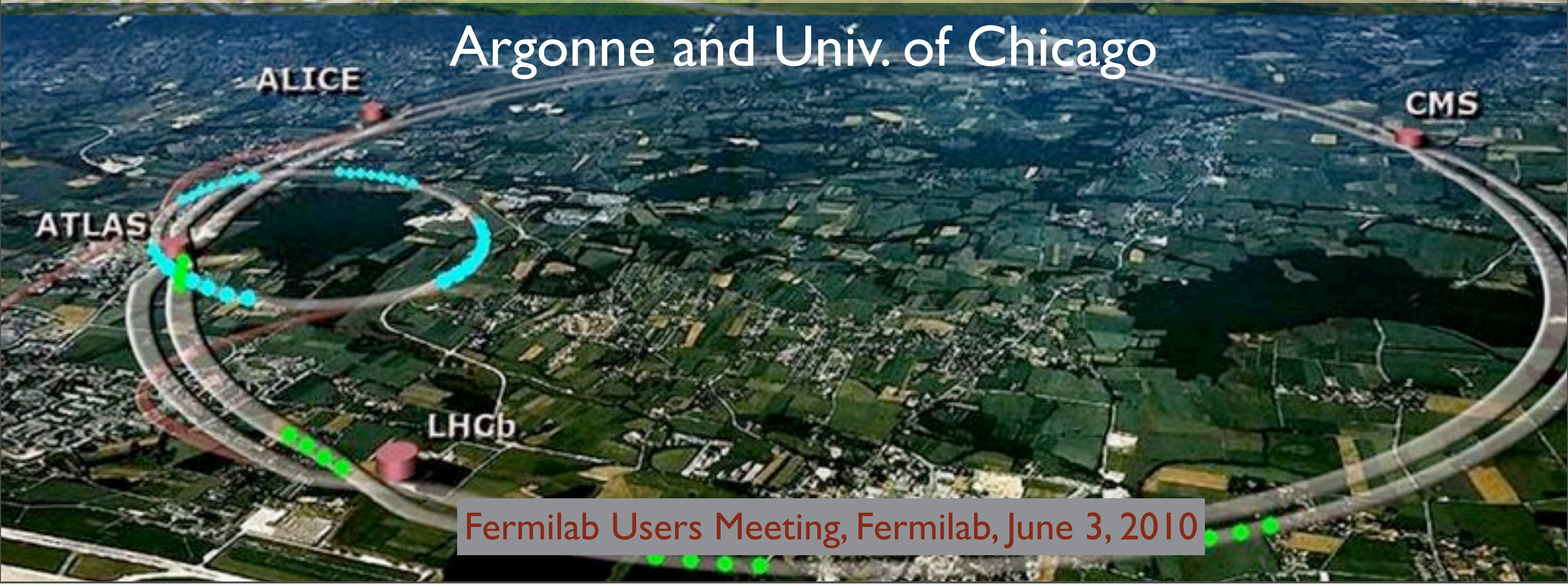
Physics at the Energy Frontier



Carlos E.M. Wagner

Argonne and Univ. of Chicago



Fermilab Users Meeting, Fermilab, June 3, 2010

Standard Model Particles

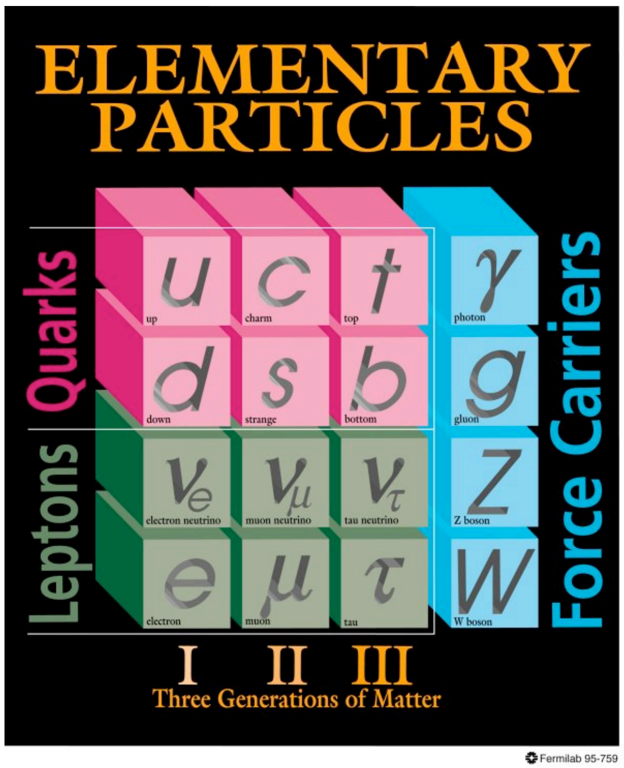
There are 12 fundamental gauge fields:

8 gluons, 3 W_μ's and B_μ

and 3 gauge couplings g_1, g_2, g_3

The matter fields:

3 families of quarks and leptons with same quantum numbers under gauge groups



But very different masses!

m_3/m_2 and $m_2/m_1 \simeq$ a few tens or hundreds

$m_e = 0.5\ 10^{-3}$ GeV, $\frac{m_\mu}{m_e} \simeq 200$, $\frac{m_\tau}{m_\mu} \simeq 20$

Largest hierarchies

$m_t \simeq 175$ GeV $\qquad m_t/m_e \propto 10^5$

neutrino masses smaller than as 10^{-9} GeV!

FERMIONS matter constituents spin = 1/2, 3/2, 5/2, ...

Leptons spin = 1/2			
Flavor		Mass GeV/c^2	Electric charge
ν_e	electron neutrino	$<1\times10^{-8}$	0
e	electron	0.000511	−1
ν_μ	muon neutrino	<0.0002	0
μ	muon	0.106	−1
ν_τ	tau neutrino	<0.02	0
τ	tau	1.7771	−1

Quarks spin = 1/2			
Flavor		Approx. Mass GeV/c^2	Electric charge
u	up	0.003	2/3
d	down	0.006	−1/3
c	charm	1.3	2/3
s	strange	0.1	−1/3
t	top	175	2/3
b	bottom	4.3	−1/3

Only left handed fermions transform under the weak SM gauge group

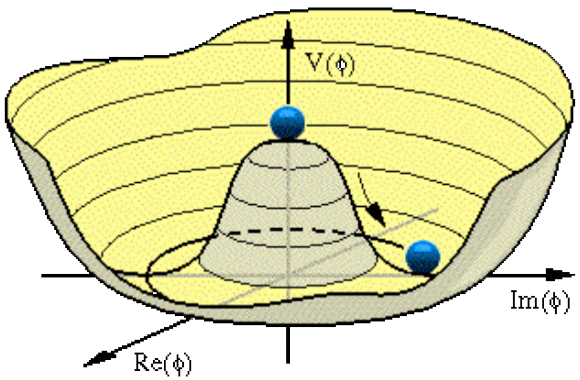
$SU(3) \times SU(2)_L \times U(1)_Y$

Fermion and gauge boson masses forbidden by symmetry

In the Standard Model, explicit masses are forbidden by symmetry

The Higgs Mechanism and the Origin of Mass

A scalar (Higgs) field is introduced. The Higgs field acquires a nonzero value to minimize its energy



Spontaneous Breakdown of the symmetry : $SU(2)_L \times U(1)_Y \to U(1)_{\rm em}$

Vacuum becomes a source of energy = a source of mass

$$\langle H^0 \rangle = \mathrm{v}$$

A physical state (Higgs boson) appear associated to fluctuations in the radial direction . Goldstone modes: Longitudinal component of massive Gauge fields.

Masses of fermions and gauge bosons proportional to their couplings to the Higgs field:

$$\mathbf{M_W = g_{W,Z}\, v} \qquad \mathrm{m_{top} = h_{top}\, v} \qquad \mathrm{m_H^2 = \lambda\, v^2}$$

$$\mathcal{L} = \sum_i i\bar{\Psi}^i_{L,R}\mathcal{D}^\mu\gamma_\mu\Psi^i_{L,R} - \sum_{i,j}\left(\bar{\Psi}^i_L h^d_{ij} H d^j_R + \bar{\Psi}^i_L h^u_{ij}(i\sigma_2 H^*)u^j_R + h.c.\right)$$

Discovering the Higgs will put the final piece of the Standard Model in place

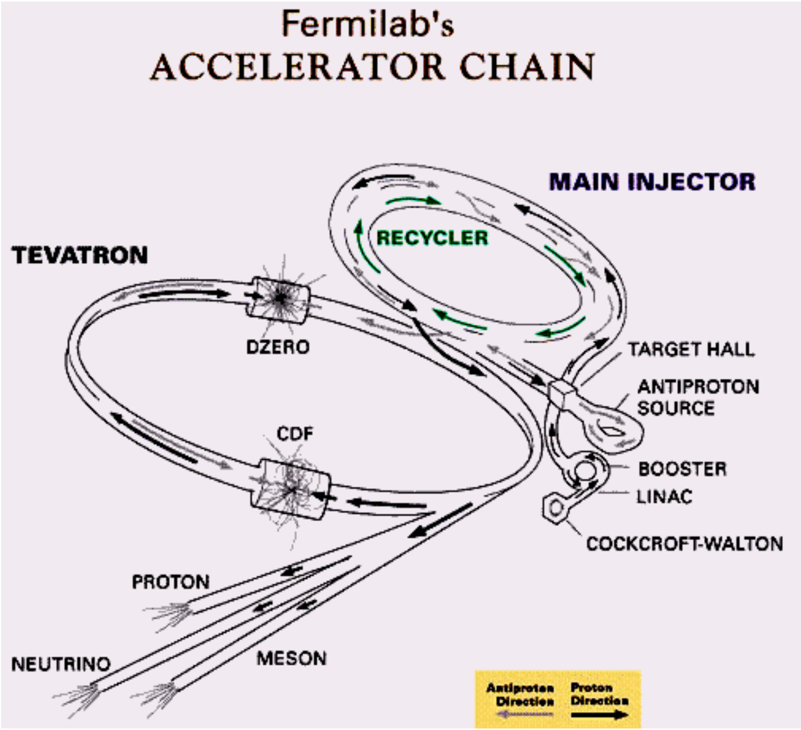
It will prove that our simplest explanation for the origin of mass is indeed correct.

How do we search for the Higgs?

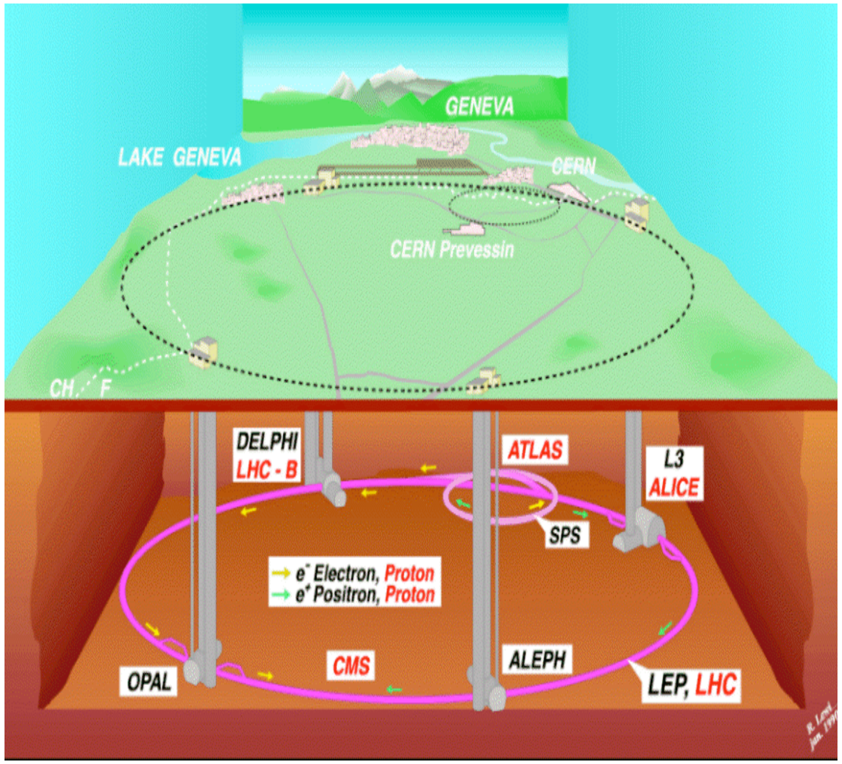
Colliding particles at High Energy Accelarators:

LEP, the Tevatron, the LHC

$p\bar{p}$ at $\sqrt{s}$ = 1.96 TeV



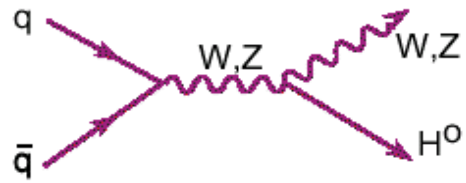
e^+e^- at $\sqrt{s}$ = 210 GeV and pp at $\sqrt{s}$ = 14 TeV



Direct Higgs searches at the Tevatron

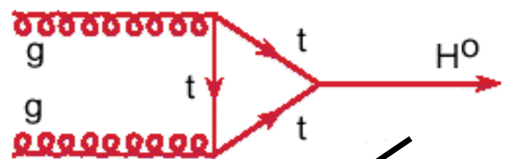
Tevatron can search for the Higgs in all the mass range preferred by precision data

Many Possible production Processes



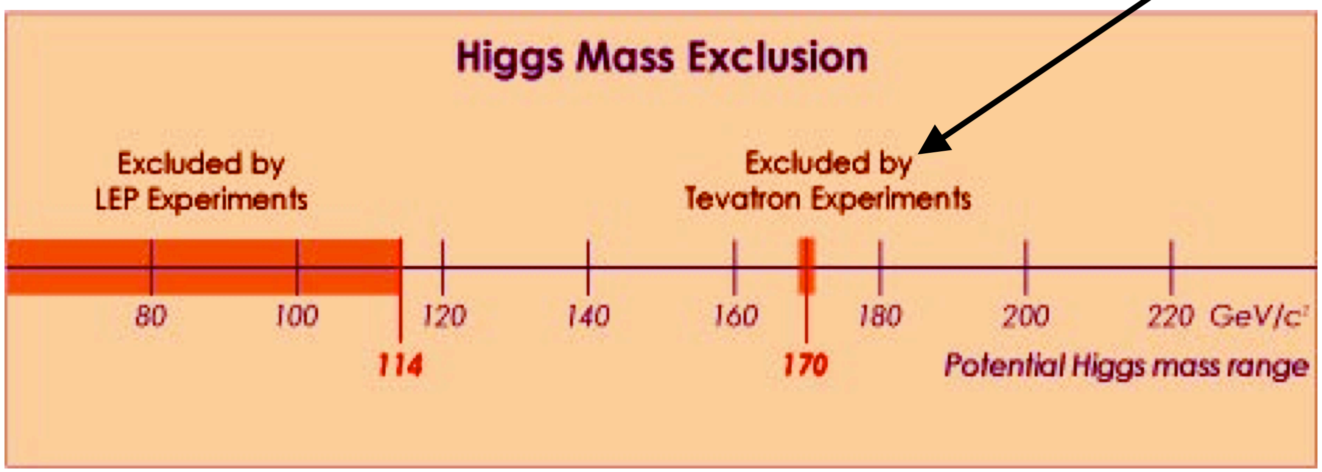
W, Z bremsstrahlung

with $H \to b\bar{b}$, WW



g g fusion

with $H \to WW$



Press release: 9/08

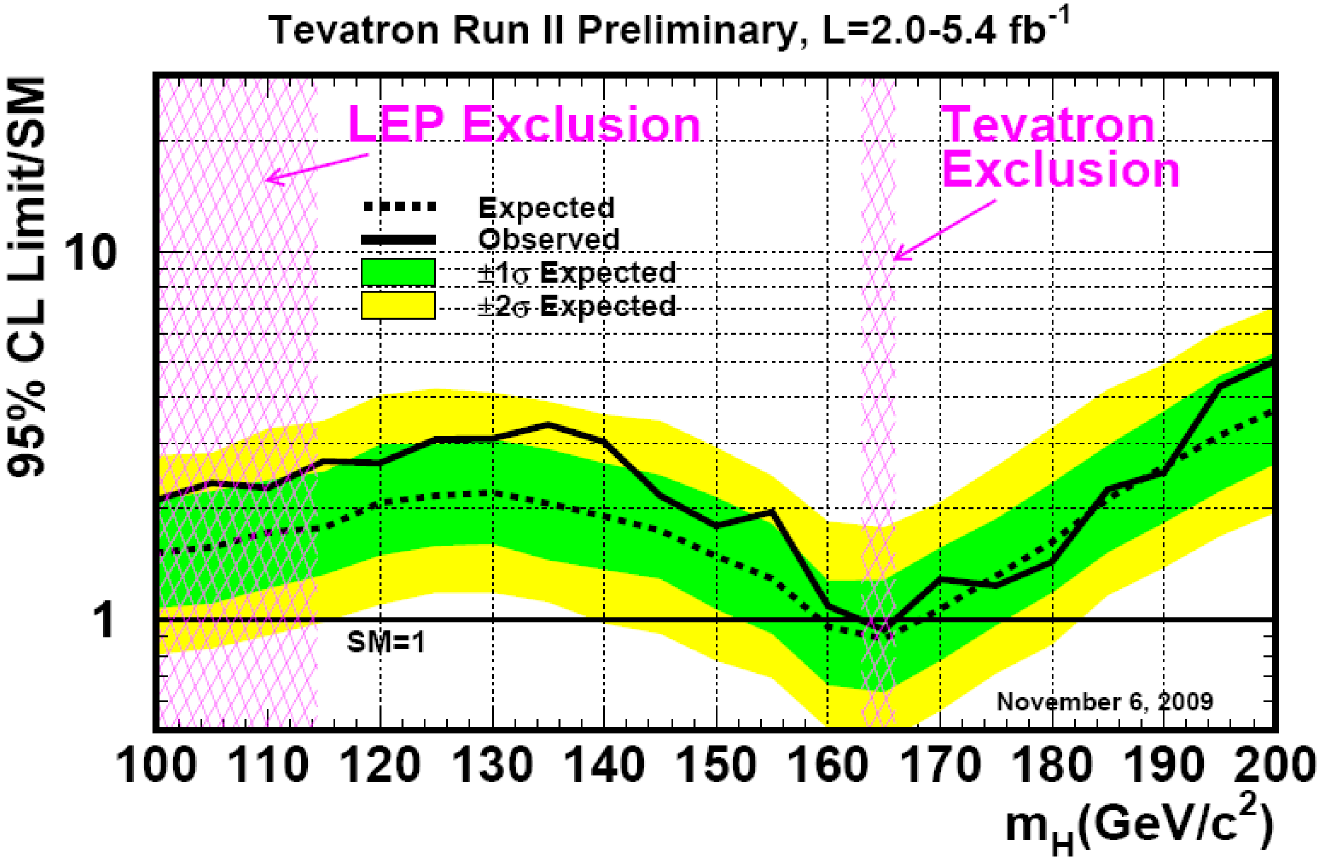
Tevatron achieves sensitivity to exclude a Higgs with mass 170 GeV

Higgs Searches at the Tevatron

See J. Dittmann's talk

- Higgs searches at the Tevatron collider are reaching maturity, both in the high mass as well as in the low mass region.
- By the end of next year, the luminosity will be high enough to probe the existence of the Standard Model Higgs boson on a large range of masses.
- The question is what is that range and what kind of sensitivity improvement will that demand
- Moreover, what would that imply for well motivated models like the MSSM ?
- The LHC will eventually surpass the Tevatron capabilities, but in the meantime, we should be able to make use of the available data and profit from the information we can extract from it.
- Also, the Tevatron is searching for the Higgs in bottom quark decays, something that the LHC may be only able to do applying sophisticated methods.
- This also raises the question : Is it worth to continue running the Tevatron after its planned shutdown at the end of 2011 ?

The Tevatron can see evidence of a Higgs



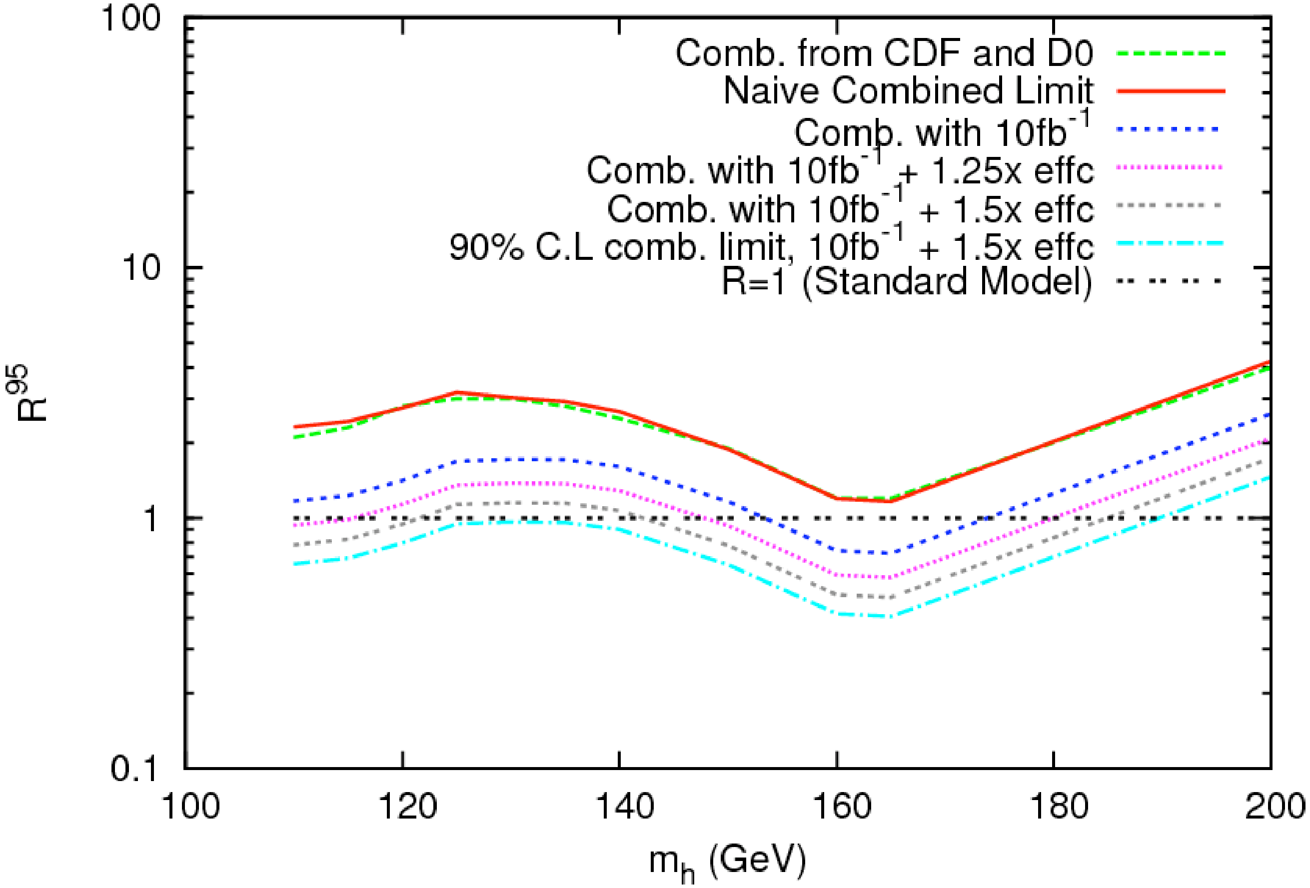
At m_H=165GeV:
Exp 0.89xSM, Obs 0.94xSM

At m_H =115GeV:
Exp 1.8xSM, Obs 2.7xSM

Interesting enough, if a Higgs were there, one would expect, in average $R_{\rm obs} = R_{\rm exp} + 1$.
The excess statistical significance is, however, $2/R_{\rm exp}$

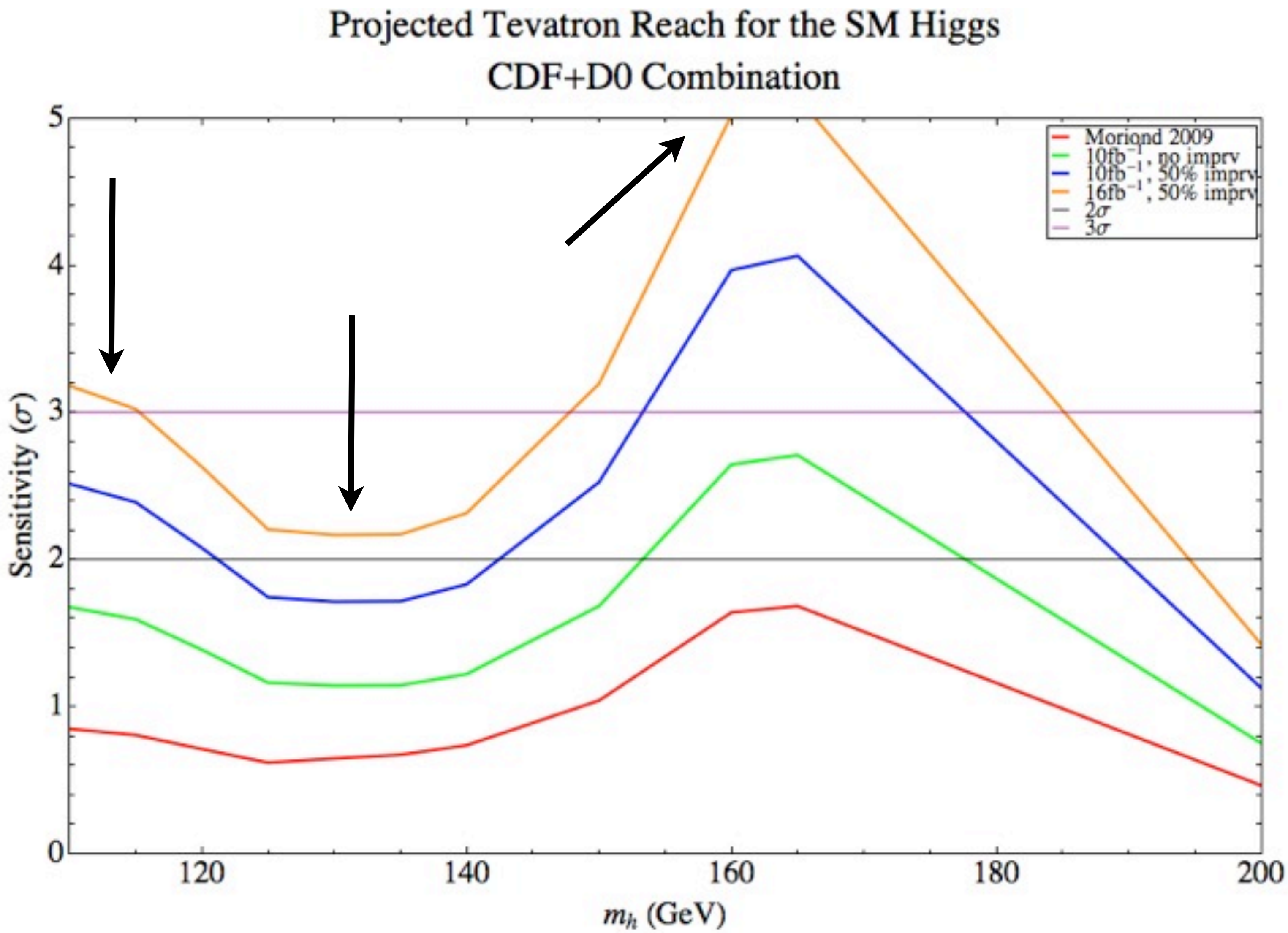
Prospects for Higgs Searches at the Tevatron

P. Draper, T. Liu and C. Wagner'09



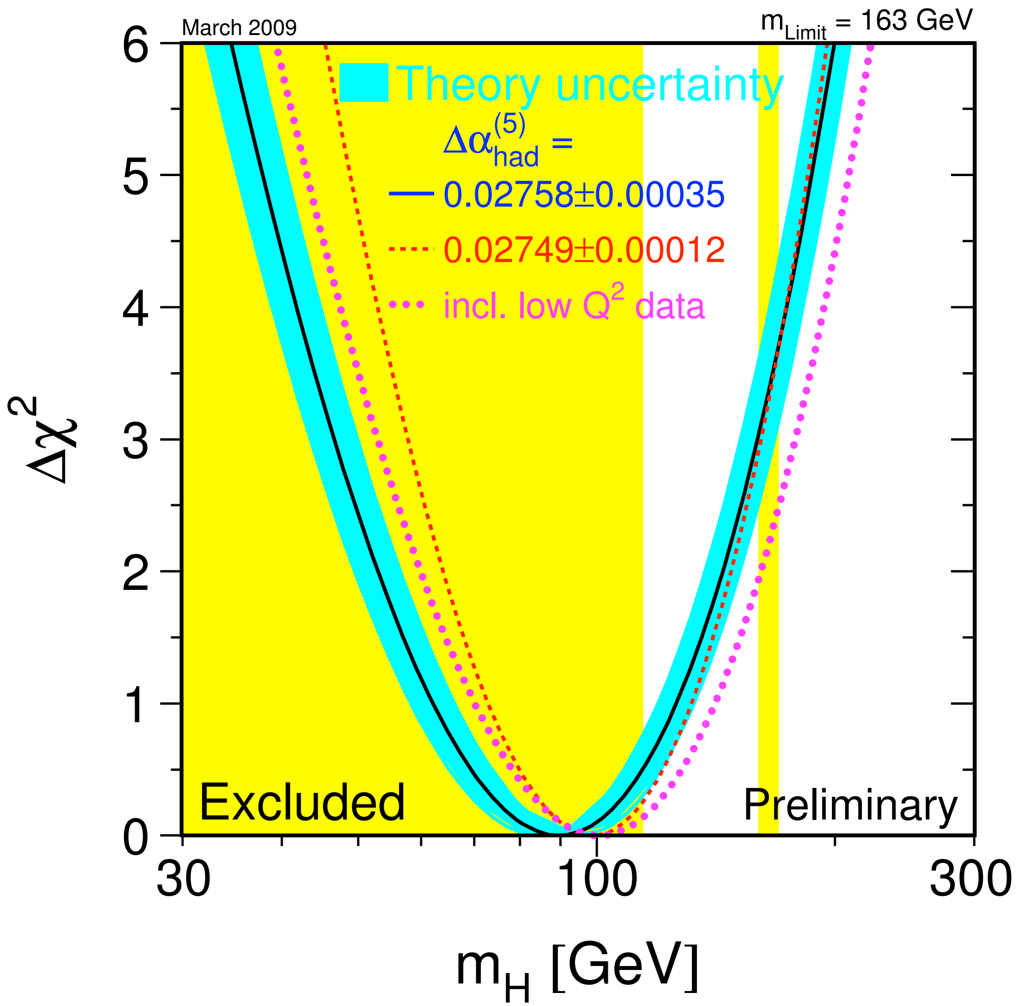
Running for two years more, the Tevatron should collect more than 10 fb^{-1}
With expected detector/analysis performance, $m_H < 185$ GeV may be probed.

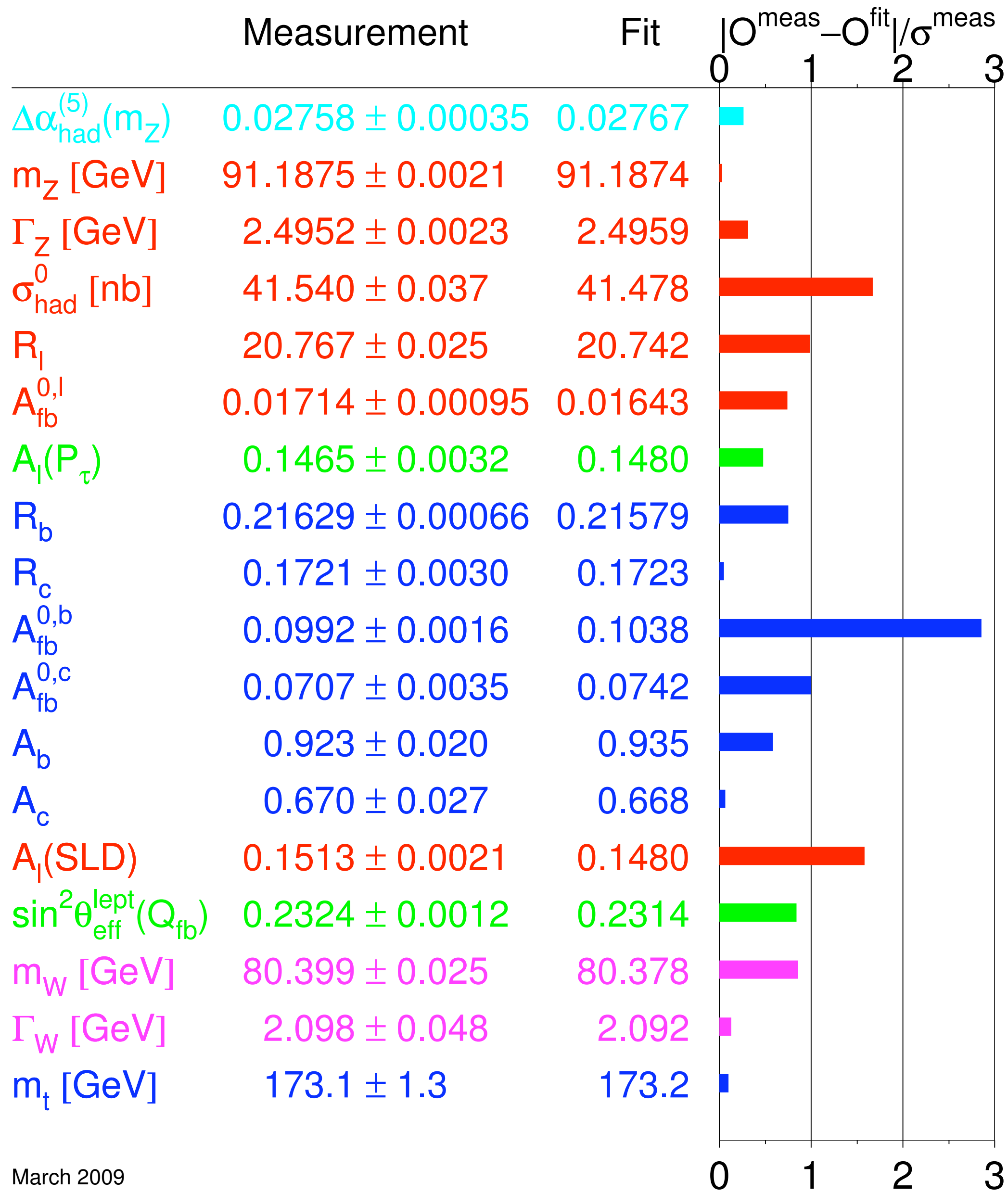
Prospects for SM Higgs Searches at the Tevatron



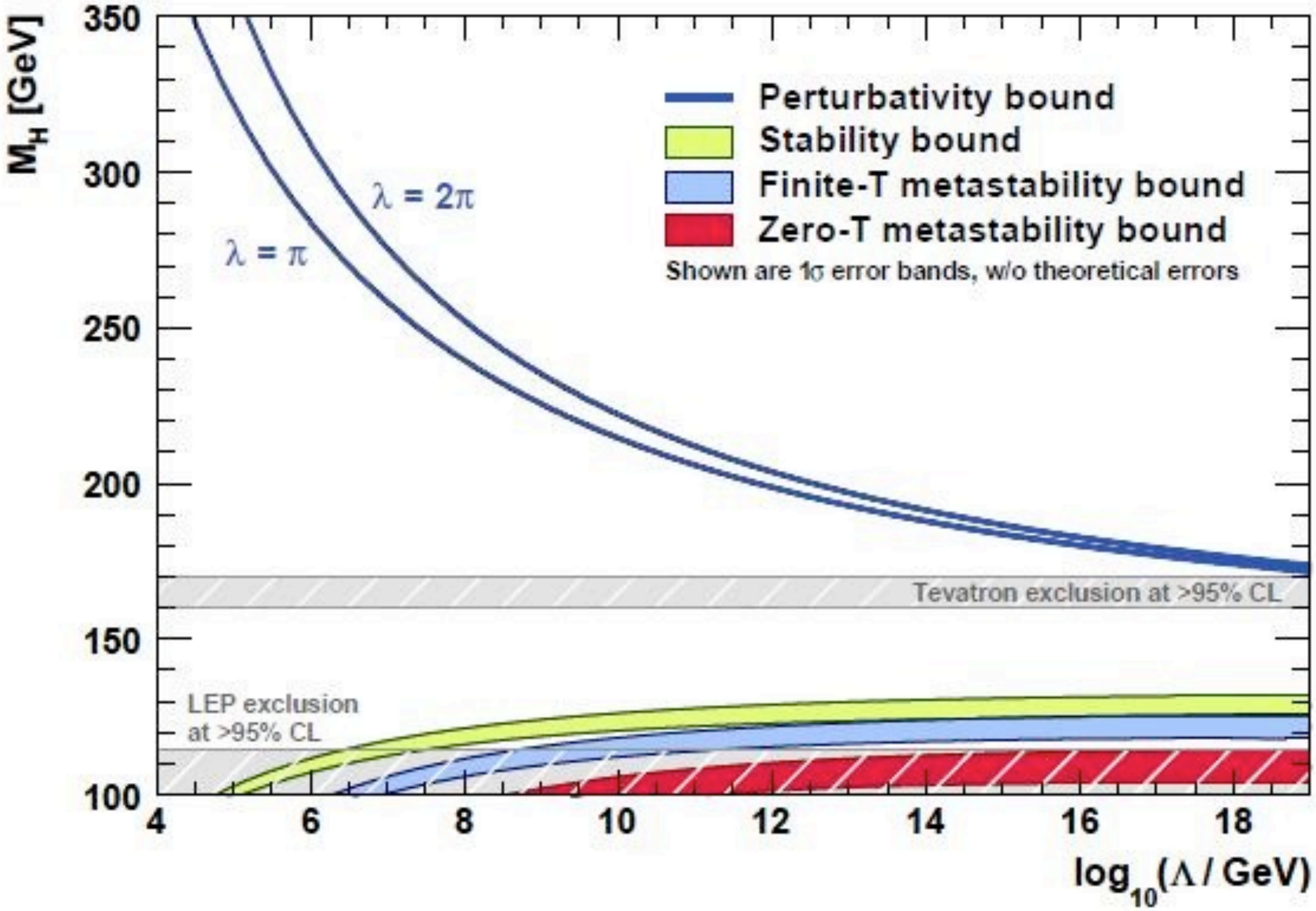
CDF+D0 multi-channel combination. WH->bb dominates at 115 GeV, gg->H->WW dominates at 160 GeV. Both contribute in intermediate range.

Tevatron testing the region preferred by SM Precision Electroweak Data





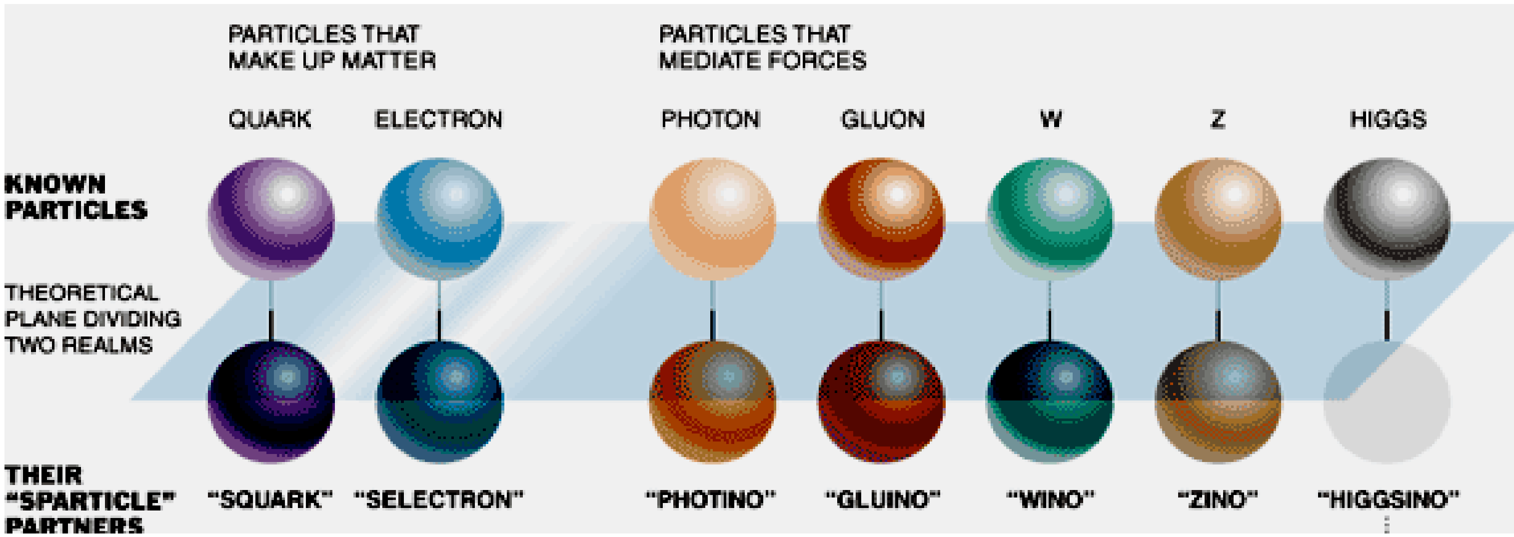
Tevatron also testing region of Higgs Masses consistent with SM extrapolation until high scales



Supersymmetry

Supersymmetry

fermions bosons



Photino, Zino and Neutral Higgsino: Neutralinos

Charged Wino, charged Higgsino: Charginos

Particles and Sparticles share the same couplings to the Higgs. Two superpartners of the two quarks (one for each chirality) couple strongly to the Higgs with a Yukawa coupling of order one (same as the top-quark Yukawa coupling)

$$\text{Two Higgs doublets necessary} \rightarrow \tan\beta = \frac{v_2}{v_1}$$

Why Supersymmetry ?

- Helps to stabilize the weak scale—Planck scale hierarchy: $\delta\, m_H^2 \approx (-1)^{2S_i} \dfrac{n_i\, g_i^2}{16\pi^2} \Lambda^2$

- Supersymmetry algebra contains the generator of space-time translations.
  Possible ingredient of theory of quantum gravity.

- Minimal supersymmetric extension of the SM :
  Leads to Unification of gauge couplings.

- Starting from positive masses at high energies, electroweak symmetry breaking is induced radiatively.

- If discrete symmetry, P = $(-1)^{3B+L+2S}$ is imposed, lightest SUSY particle neutral and stable: Excellent candidate for cold Dark Matter.

Mass of the SM-like Higgs h

- Most important corrections come from the stop sector,

$$M_{\tilde{t}}^2 = \begin{pmatrix} m_Q^2 + m_t^2 + D_L & m_t X_t \\ m_t X_t & m_U^2 + m_t^2 + D_R \end{pmatrix}$$

where the off-diagonal term depends on the stop-Higgs trilinear couplings, $X_t = A_t - \mu^* / \tan\beta$

- For large CP-odd Higgs boson masses, and with $M_S = m_Q = m_U$ dominant one-loop corrections are given by,

$$m_h^2 \approx M_Z^2 \cos^2 2\beta + \frac{3 m_t^4}{4\pi^2 v^2}\left(\log\left(\frac{M_S^2}{m_t^2} \right) + \frac{X_t^2}{M_S^2}\left(1 - \frac{X_t^2}{12 M_S^2}\right) \right)$$

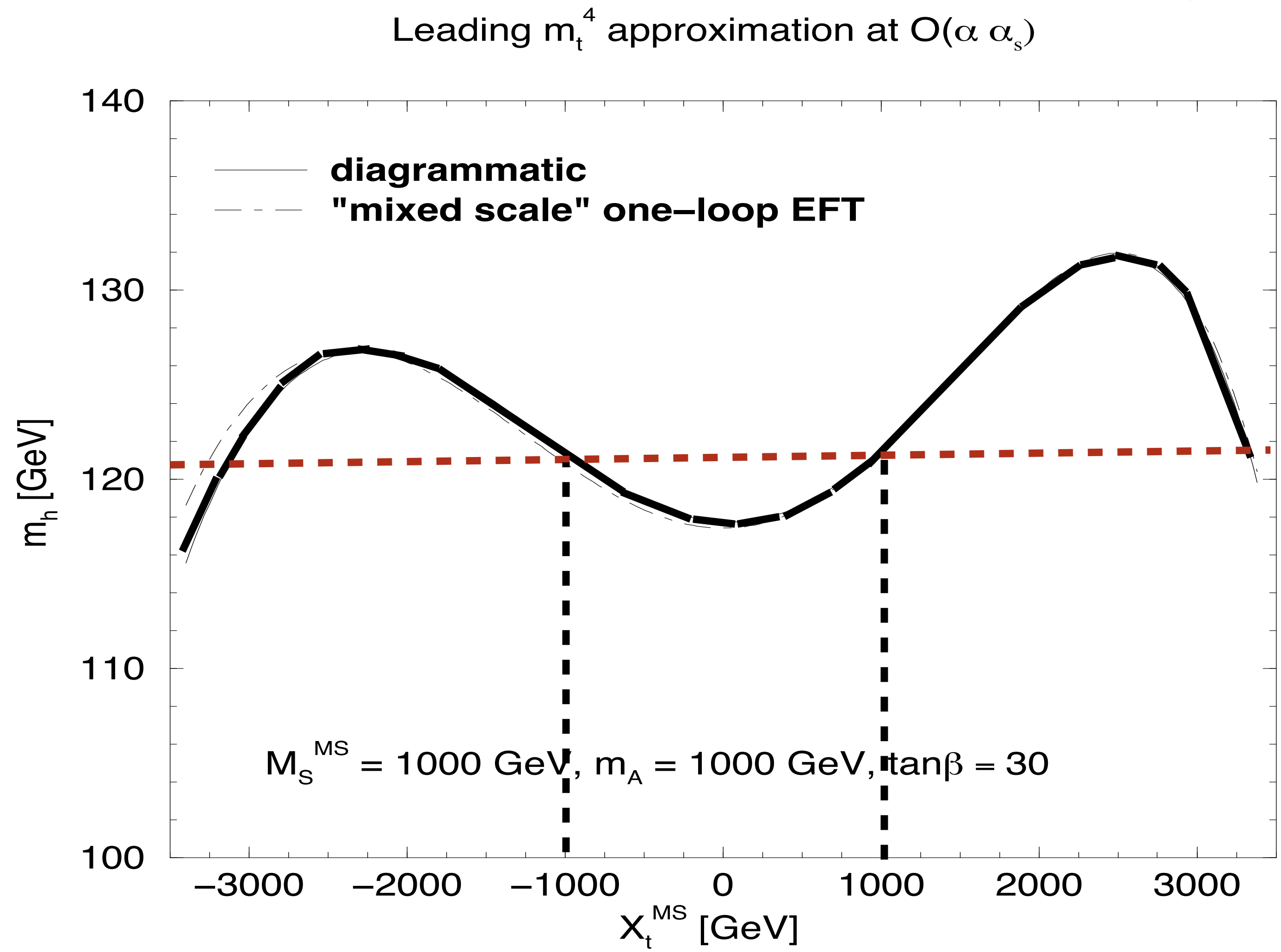
- After two-loop corrections:

M.Carena, J.R. Espinosa, M. Quiros, C.W. '95
M. Carena, M. Quiros, C.W.'95

Standard Model-like Higgs Mass

Long list of two-loop computations: Carena, Degrassi, Ellis, Espinosa, Haber, Harlander, Heinemeyer, Hempfling, Hoang, Hollik, Hahn, Martin, Pilaftsis, Quiros, Ridolfi, Rzehak, Slavich, C.W., Weiglein, Zhang, Zwirner

Carena, Haber, Heinemeyer, Hollik, Weiglein, C.W.'00

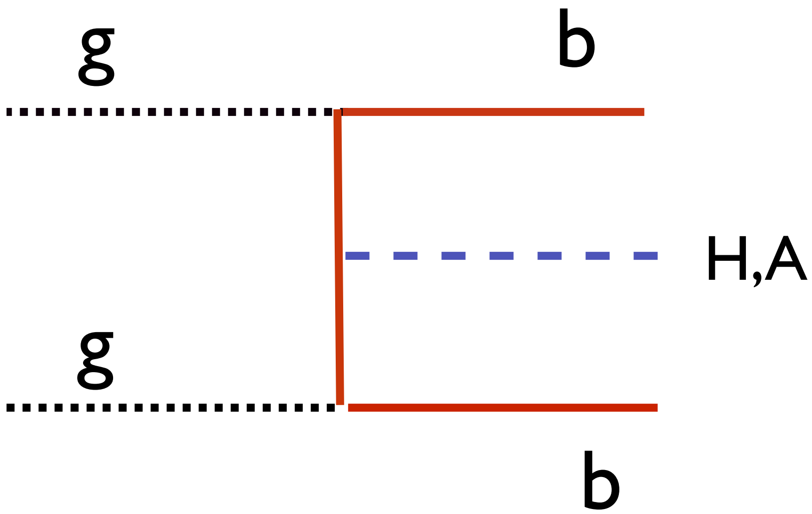


For natural values of the stop mixing, the Higgs remains lighter than 120 GeV

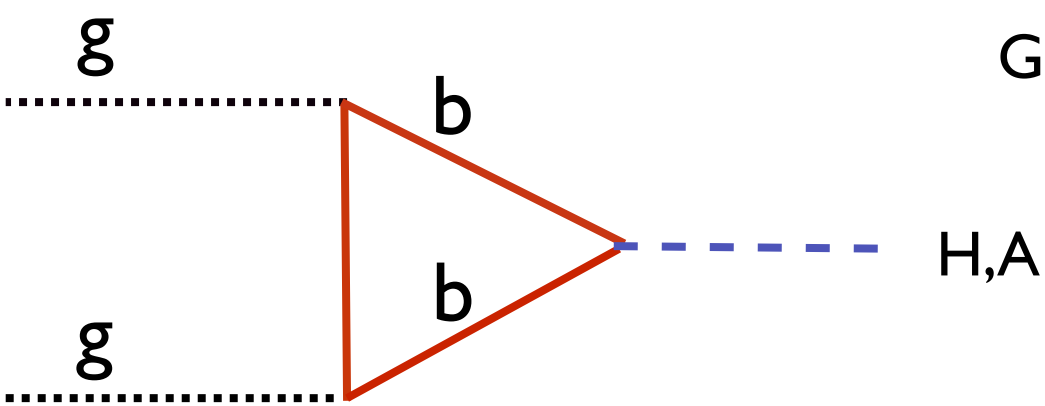
$$X_t = A_t - \mu/\tan\beta, \qquad X_t = 0 : \text{ No mixing}; \qquad X_t = \sqrt{6} M_S : \text{ Max. Mixing}$$

Non-Standard Higgs Production

QCD: S. Dawson, C.B. Jackson, L. Reina, D.Wackeroth, hep-ph/0603112



Associated Production



Gluon Fusion

$$g_{Abb} \simeq g_{Hbb} \simeq \frac{m_b \tan\beta}{(1+\Delta_b)v}, \qquad g_{A\tau\tau} \simeq g_{H\tau\tau} \simeq \frac{m_\tau \tan\beta}{v}$$

Searches for non-standard Higgs bosons

M. Carena, S. Heinemeyer, G.Weiglein, C.W, EJPC'06

- Searches at the Tevatron and the LHC are induced by production channels associated with the large bottom Yukawa coupling.

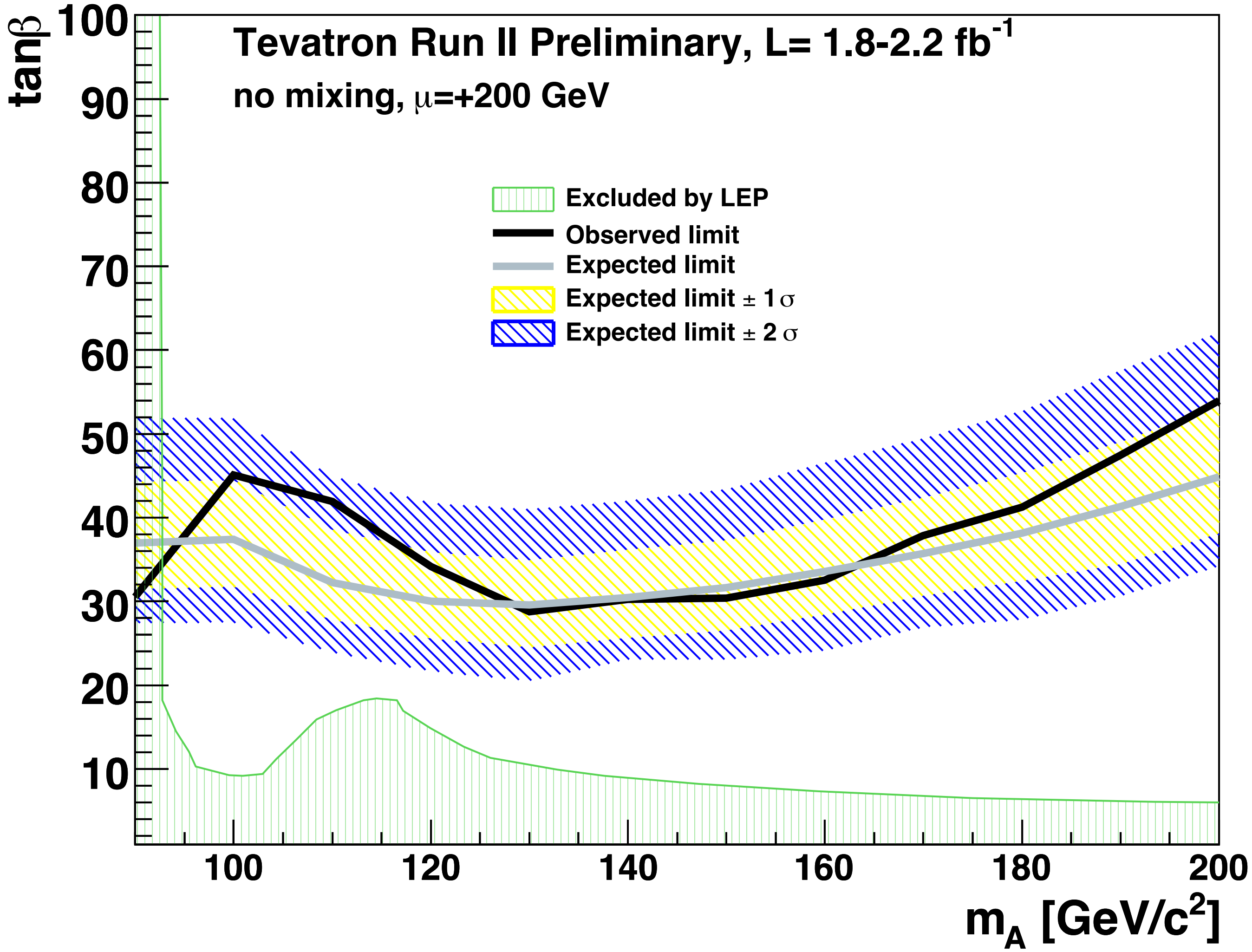
$$\sigma(b\bar{b}A) \times BR(A \to b\bar{b}) \simeq \sigma(b\bar{b}A)_{\rm SM} \frac{\tan^2\beta}{(1+\Delta_b)^2} \times \frac{9}{(1+\Delta_b)^2 + 9}$$

$$\sigma(b\bar{b}, gg \to A) \times BR(A \to \tau\tau) \simeq \sigma(b\bar{b}, gg \to A)_{\rm SM} \frac{\tan^2\beta}{(1+\Delta_b)^2 + 9}$$

- There may be a strong dependence on the parameters in the bb search channel, which is strongly reduced in the tau tau mode.

Validity of this approximation confirmed by NLO computation by
D. North and M. Spira, arXiv:0808.0087
Further work by Mhulleitner, Rzehak and Spira, 0812.3815

Combination of CDF and D0 Non-Standard Higgs Searches

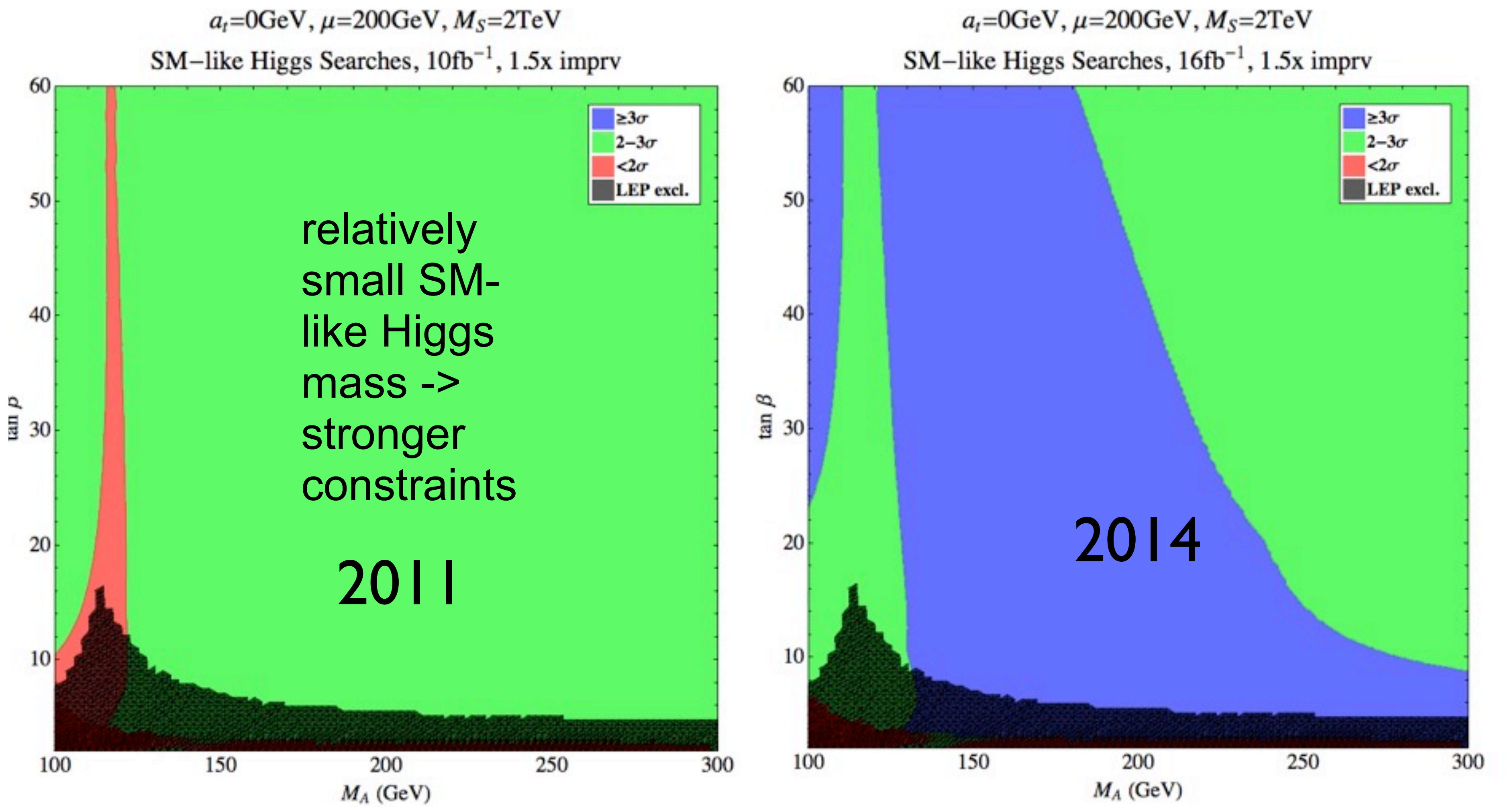


Relevance of Combination of Channels

- As we have seen, the Tevatron has the potential to probe the Standard Model in all the allowed region of the lightest MSSM CP-even Higgs mass.
- There are regions of parameter space, however, where this Higgs boson present significant departures from the SM behavior
- In particular either the production cross section or the branching ratio into bottom quarks can be suppressed
- When this happens, there tend to be other light Higgs bosons which can give significant signatures, or alternatively, additional decay channels of the same Higgs boson, like the $\tau\tau$ or W^+W^- modes
- In this talk, I will combine in quadrature the significance of different channels for the SM-like Higgs. At some point, we will combine it also with non-standard sources, even when coming from different Higgs boson sources. I show the relevance of these combinations.

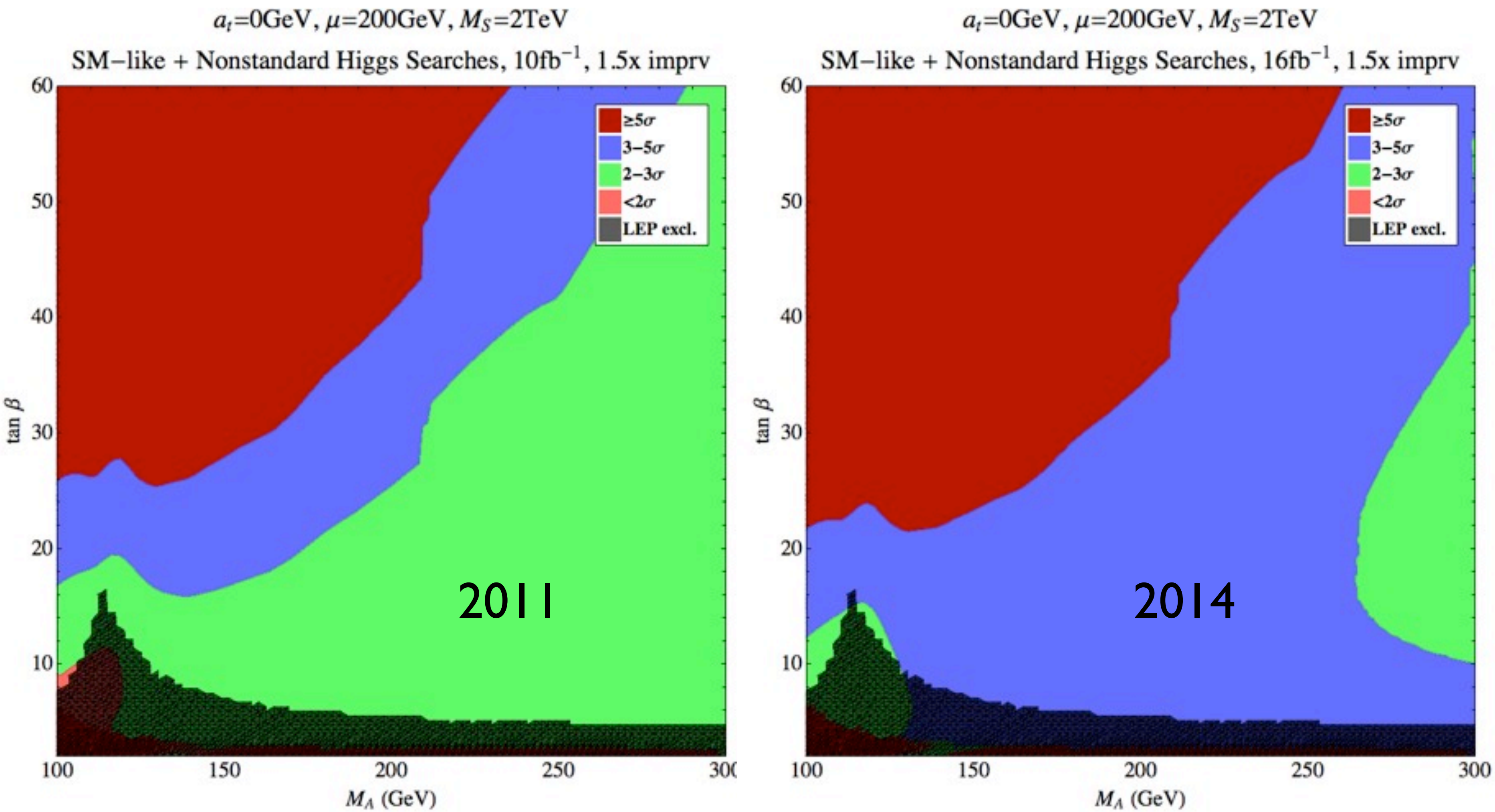
Minimal Mixing Scenario (SM-like Higgs mass below 120 GeV)

P. Draper, T. Liu and C.W. '09 + M. Carena'10



Even with only SM channels and 2011 run, 2 sigma sensitivity is achieved in most parameter space. Evidence may be achieved with further running.

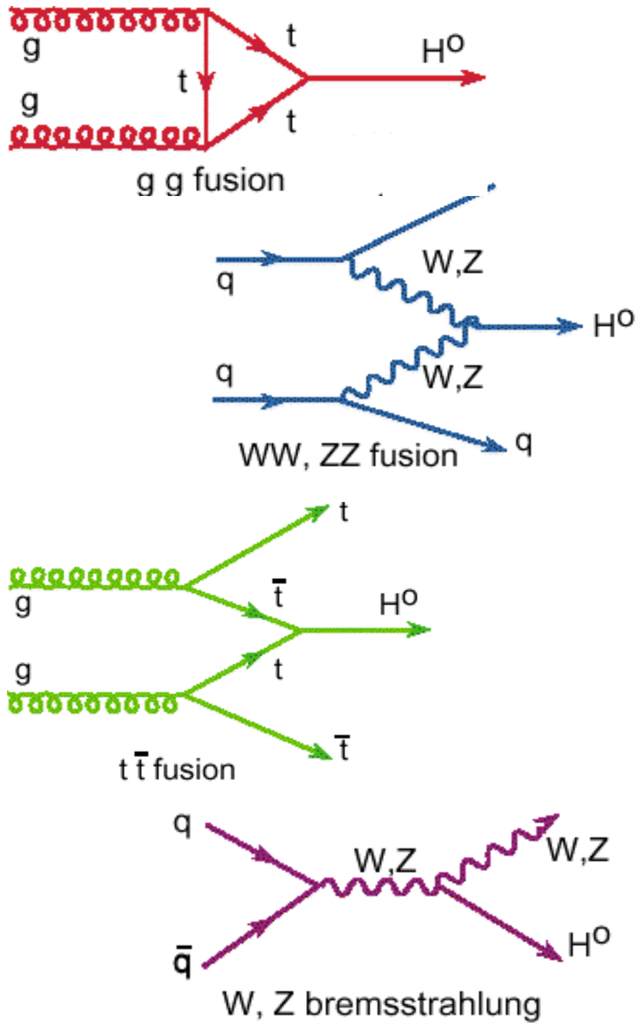
Combination with Non-Standard Higgs channels



Combination enlarges the region where evidence may be achieved in a considerable way

LHC Higgs Searches

The search for the Standard Model Higgs at the LHC

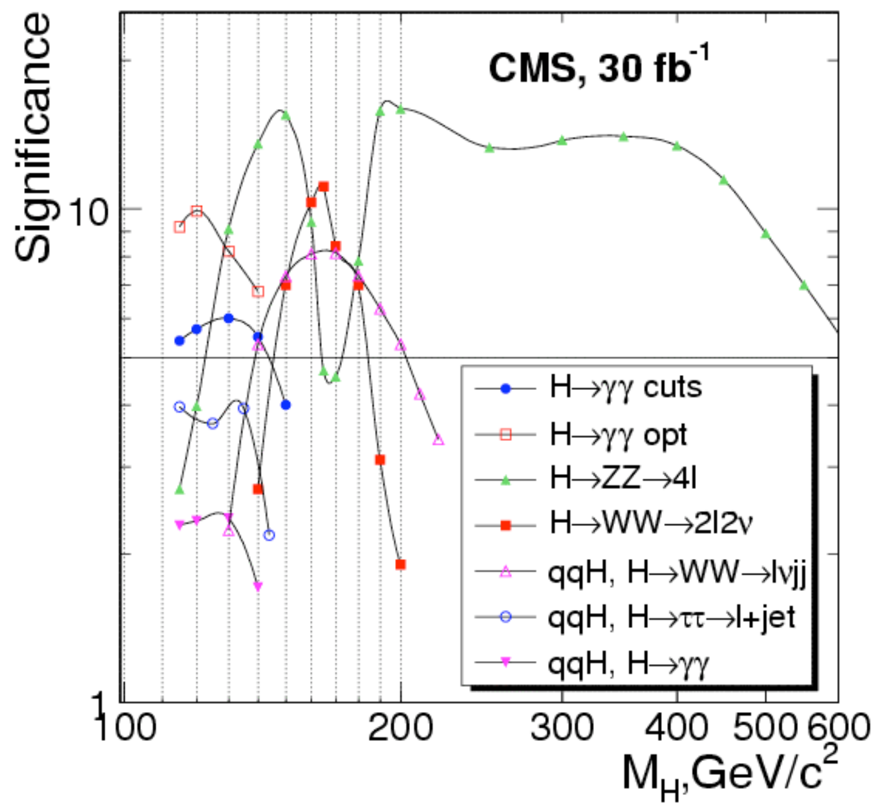


- **Low mass range** $m_{H_{SM}} < 200$ GeV

$$H \to \gamma\gamma, \tau\tau, bb, WW, ZZ$$

- **High mass range** $m_{H_{SM}} > 200$ GeV

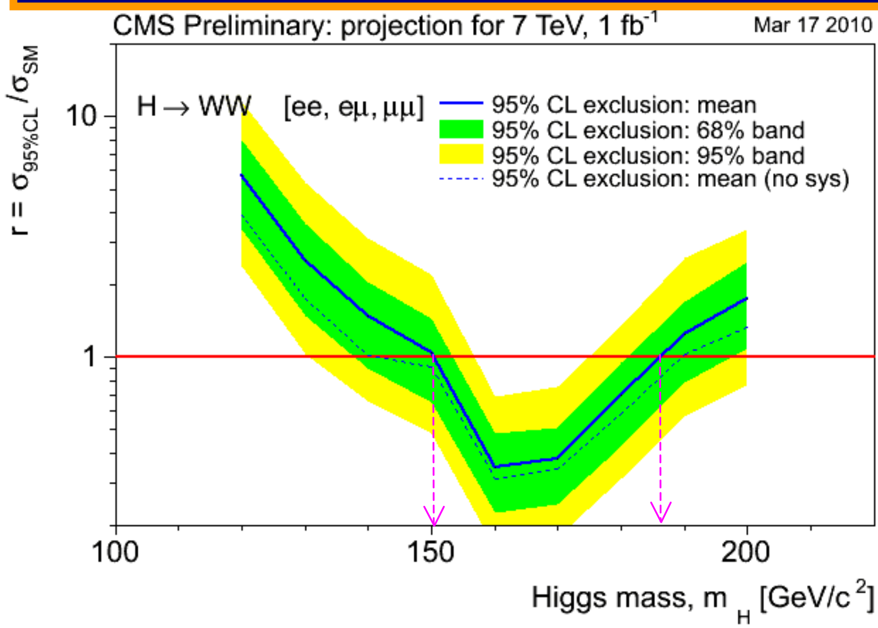
$$H \to WW,\ ZZ$$

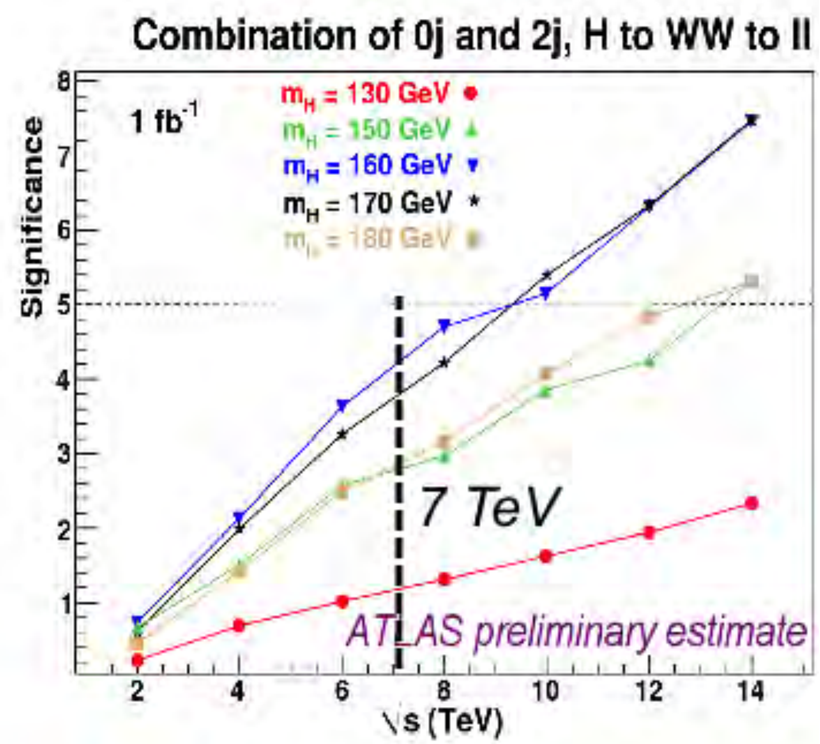


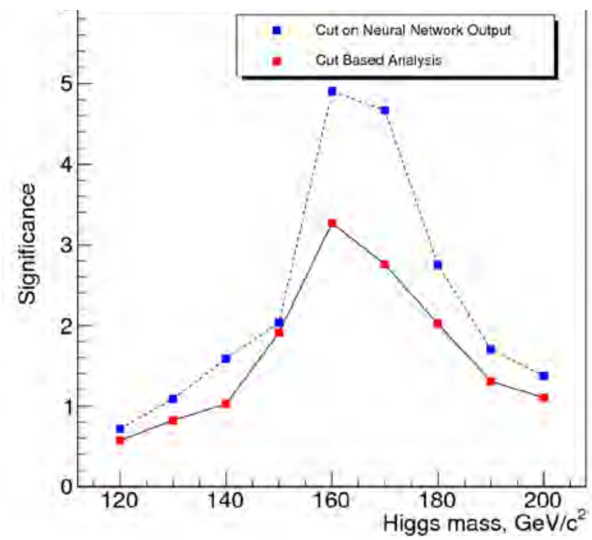
If there is a Higgs boson, with properties similar to those predicted in the Standard Model, the high energy/luminosity LHC will find it.

Early LHC Searches

SM H→WW→2l2ν







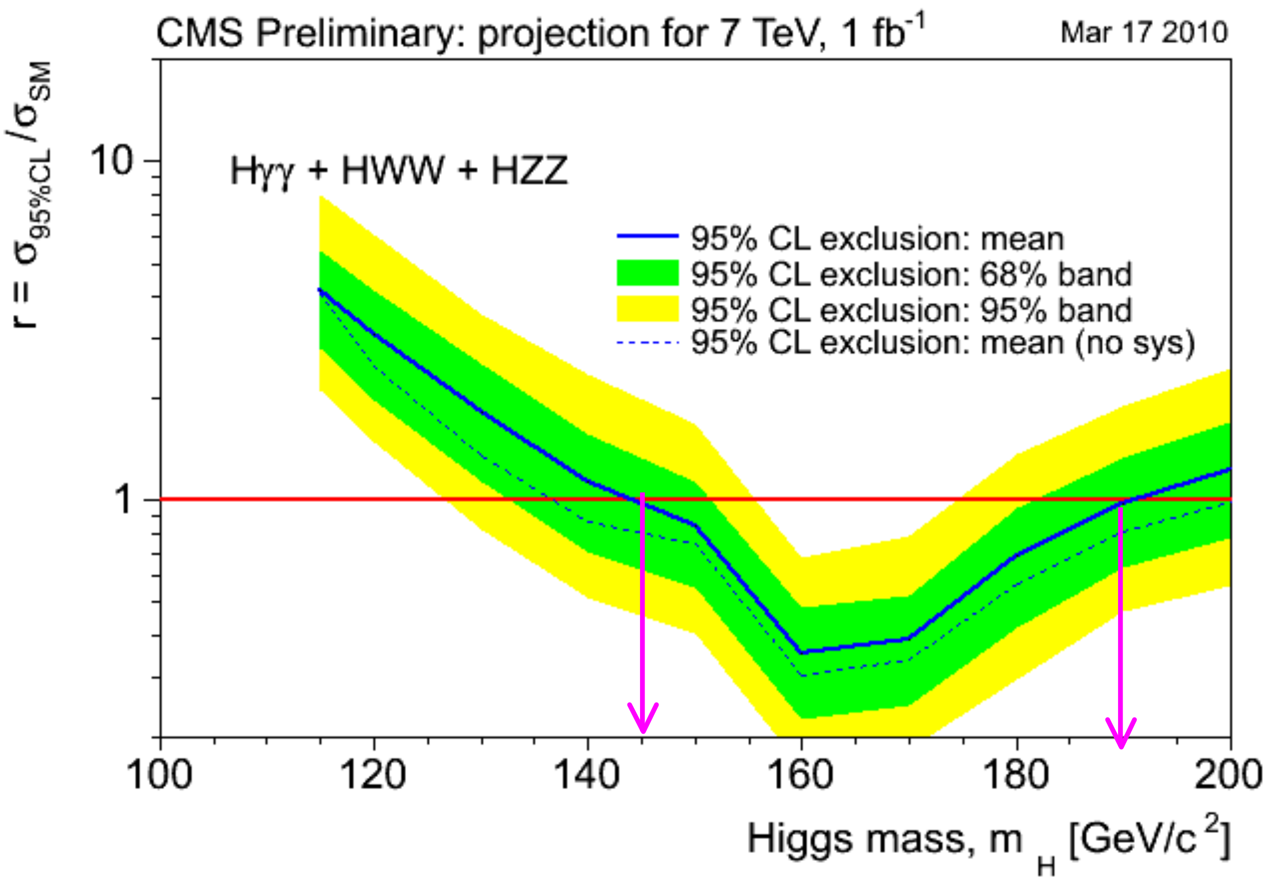
CMS expected exclusion range :[150-185]
ATLAS expected exclusion range : [140-185]

CMS discovery 3-5σ sensitivity : near 160 GeV

9

V. Sharma '10
See also E. Berger et al. '10

CMS: All Modes Combined

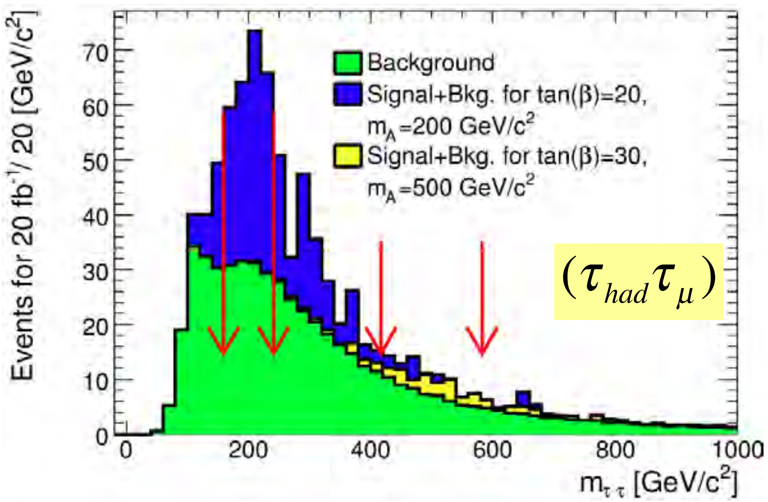


SM Higgs expected excluded range: **145-190 GeV**

SM Higgs with 4 fermion generations: **< ≈ 420 GeV**

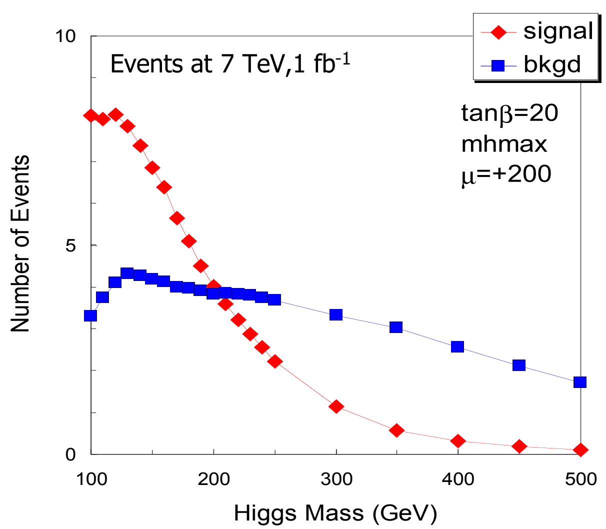
V. Sharma '10

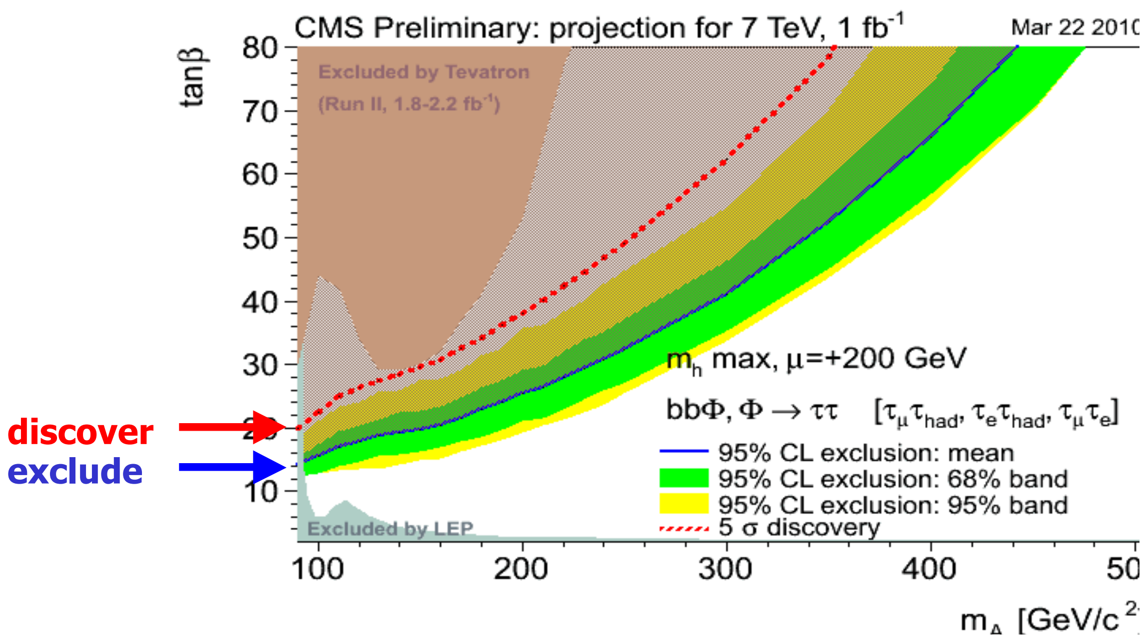
MSSM Higgs In pp→bbΦ; Φ→ $\tau^+ \tau^-$



- – Isolated pairs of $(\tau_{had}\tau_\mu),(\tau_{had}\tau_e),(\tau_\mu\tau_e)$
- – With MET, 1 tagged bjet, veto extra jets
- – Build $\tau\tau$-mass using collinear approx
- – Count events in sliding $\tau\tau$-mass window
- – Dominant backgrounds: $t\bar{t}$, Z+$b\bar{b}$ & Z+$c\bar{c}$

  -- assessed from data





V. Sharma ’10

Comparison of Tevatron and Early LHC Higgs Searches

- The Tevatron remains superior than the 7 TeV machine in the low Higgs mass searches
- It also remains competitive in the high mass Higgs searches, with mass in the range 140 GeV -- 190 GeV
- Moreover, the Tevatron will probe most of the region consistent with an eventual non-standard Higgs signature at the LHC
- Running the Tevatron for a few more years, until the LHC acquires its full capabilities makes scientific sense

Comparison of Tevatron and LHC Cross Sections

Cross sections in most channels become significantly larger at the 7 TeV LHC

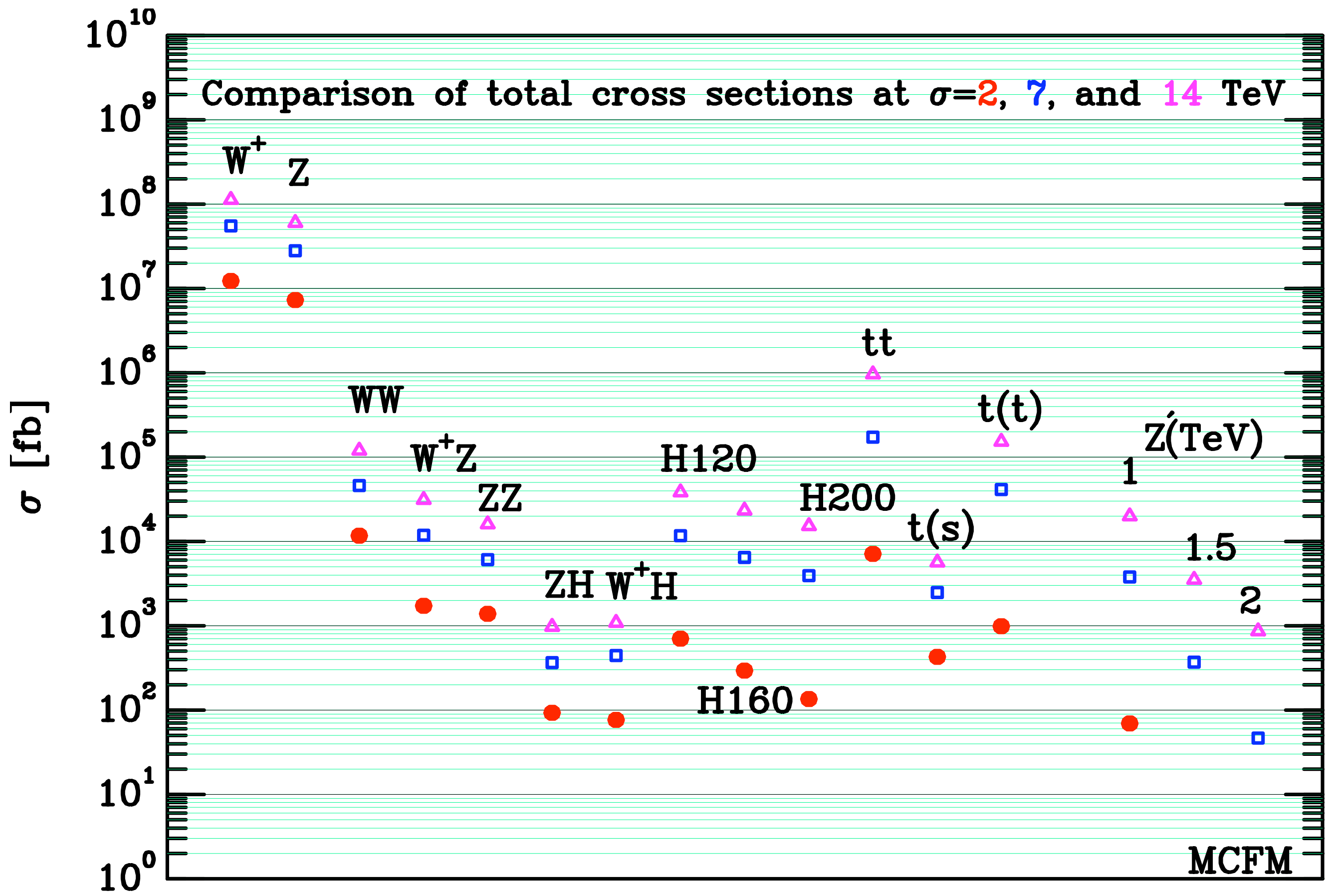
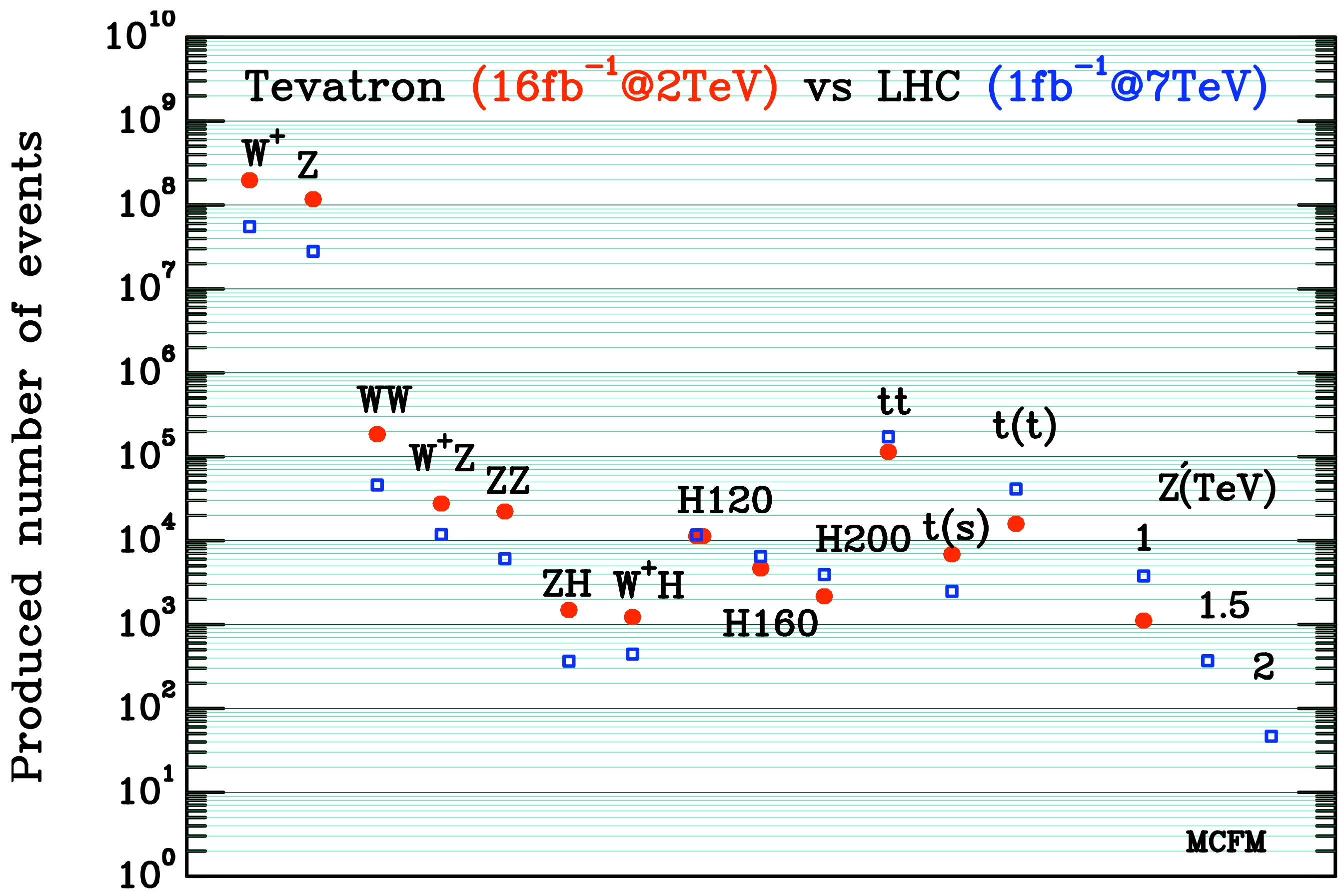


Figure 4: Comparison of total cross section comparison between Tevatron and LHC.

K. Ellis, 2010

Higher Luminosities compensate for smaller cross sections

Comparison of Number of Events at the Tevatron and Early LHC



K. Ellis, 2010

Figure 5: Comparison of Tevatron Run III and LHC at 1 fb^{-1} and 7 TeV in the cms.

It is clear that low mass Higgs Searches become more difficult at the Early LHC than at the Tevatron.

Beyond the SM Physics

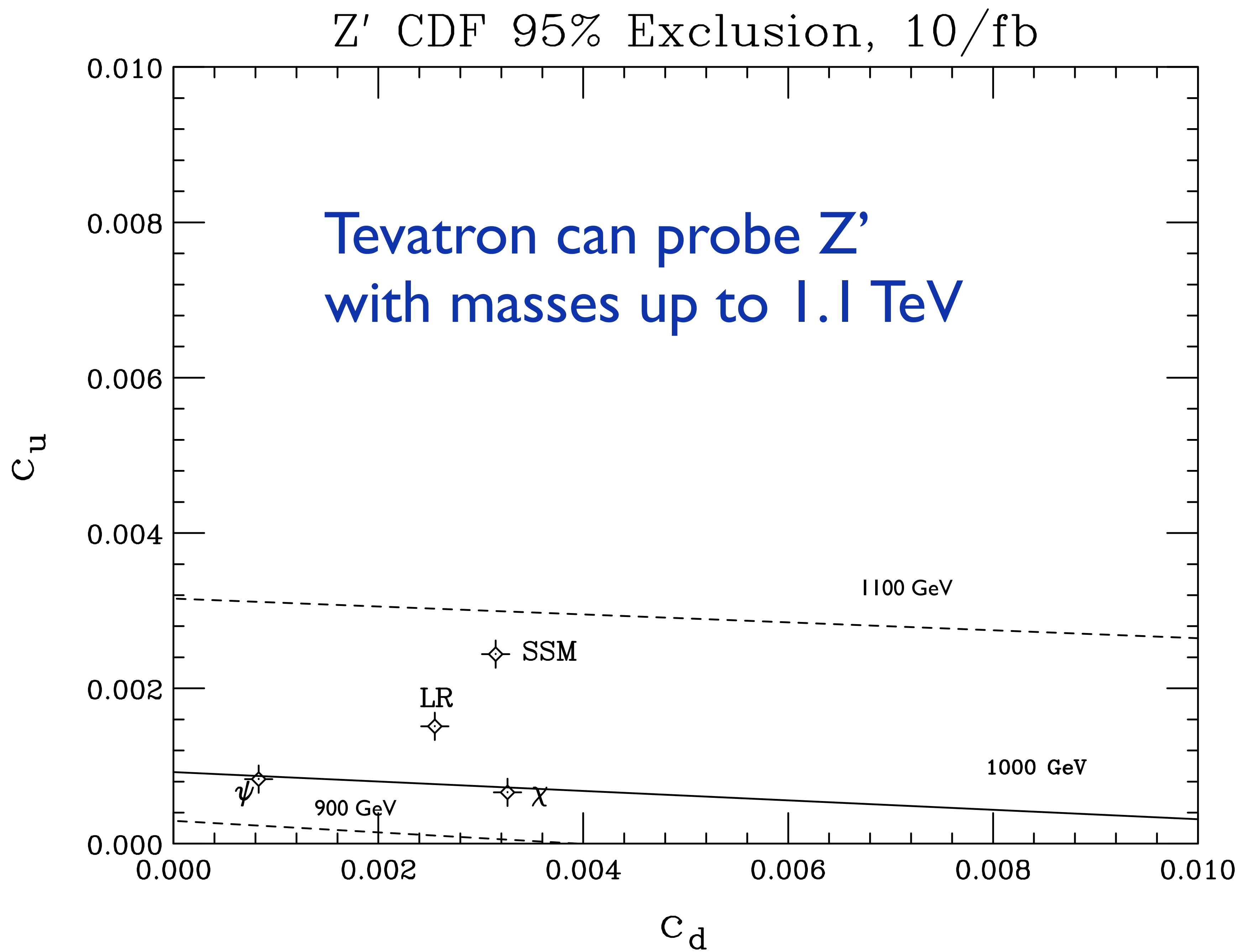
LHC is the new Energy Frontier

New particles could appear that are beyond the Energy Threshold at the Tevatron

A Z' particle is the most natural new particle, since it appears in most gauge extensions of the SM.

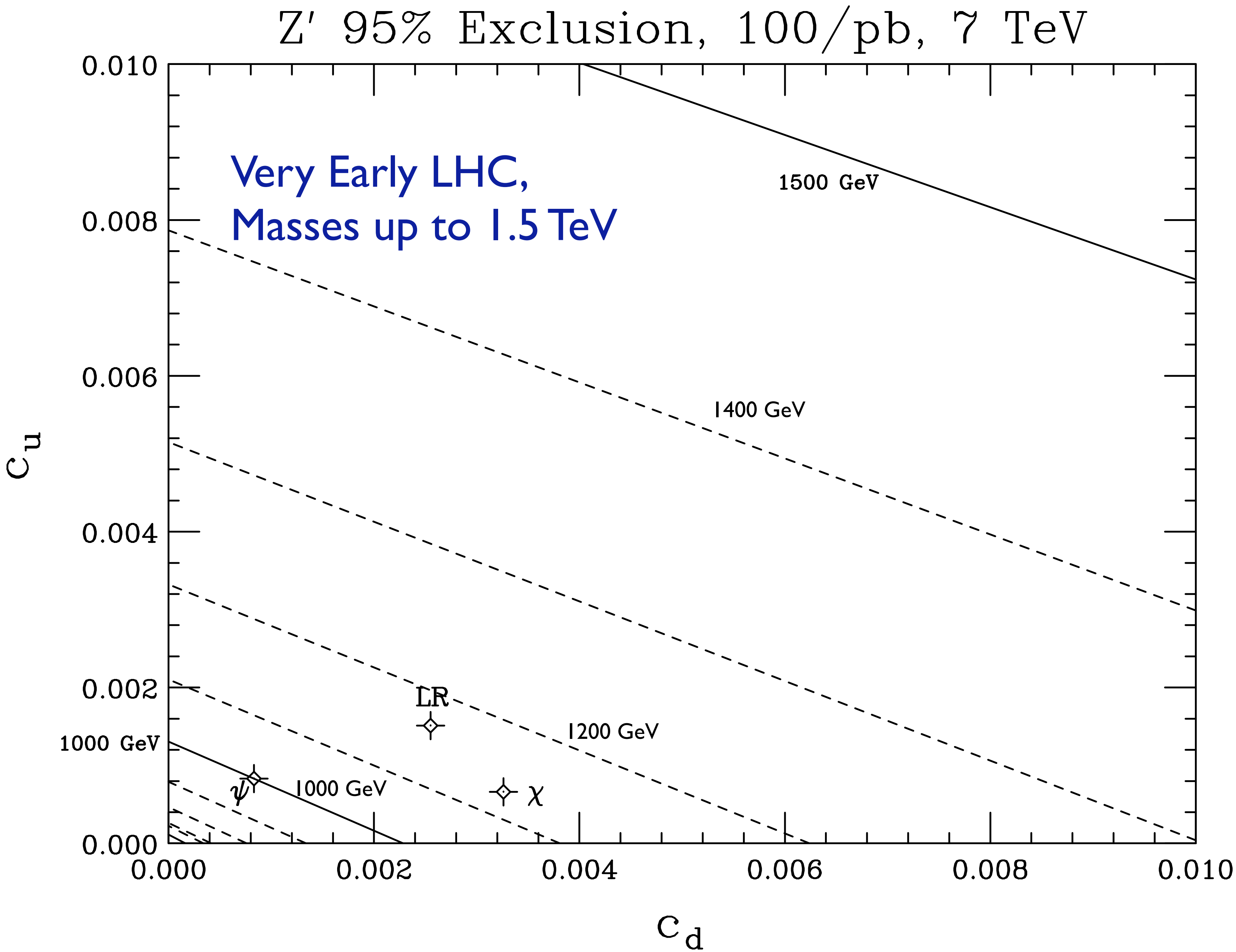
Could a Z' resonance be seen within the current Tevatron limits ?

Yes, but the reach will depend on the final LHC luminosity



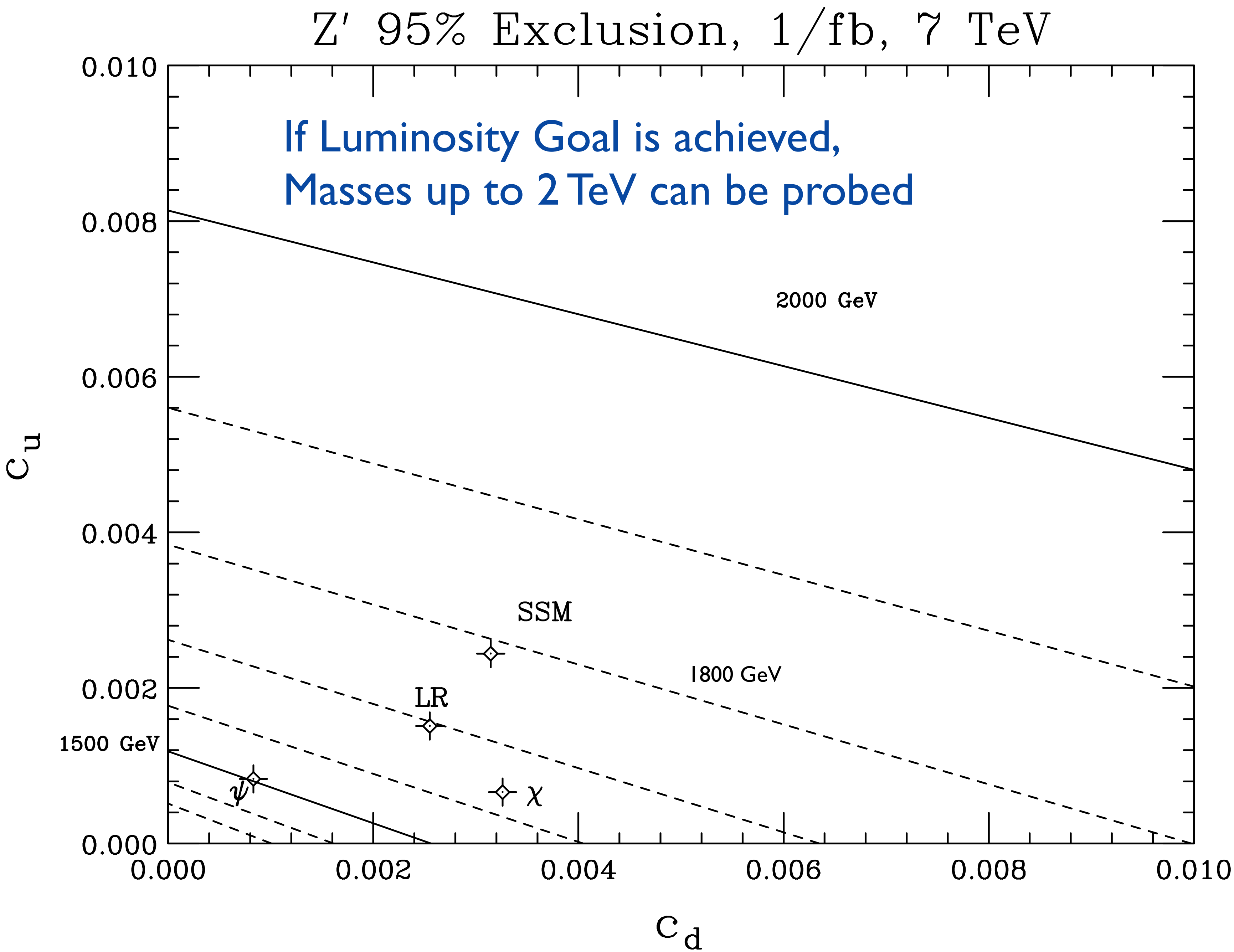
c_q = (q_R^2 + q_L^2) Br(Z' -> ll)

S. Quackenbush’10



c_q = (q_R^2 + q_L^2) Br(Z' -> ll)

S. Quackenbush'10



c_q = (q_R^2 + q_L^2) Br(Z' -> ll)

S. Quackenbush'10

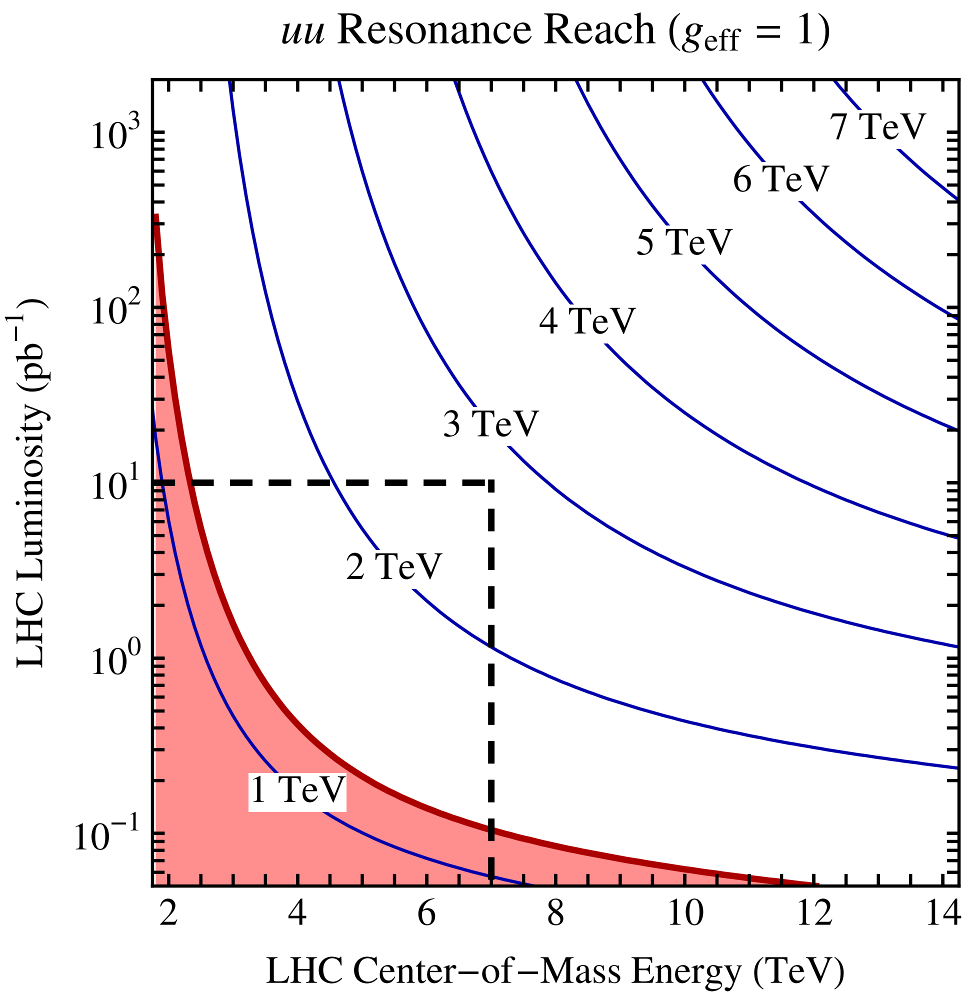
LHC is a proton-pronton collider

- In a proton, quarks are prominent at large values of the momentum fraction x, while antiquarks are absent
- Similarly, in an anti-proton, antiquarks are prominent at large x, while quarks are absent
- To produce a heavy resonant, large values of x of each colliding parton is necessary. Indeed,

$$s_{parton} \simeq S x_1 x_2$$

- Hence, a heavy di-quark resonance may be produced at the LHC with very little constraints from the Tevatron.
- Di-quark resonances up to 2.5 TeV in mass may be detected with as little as 10/pb of luminosity at the 7 TeV LHC.

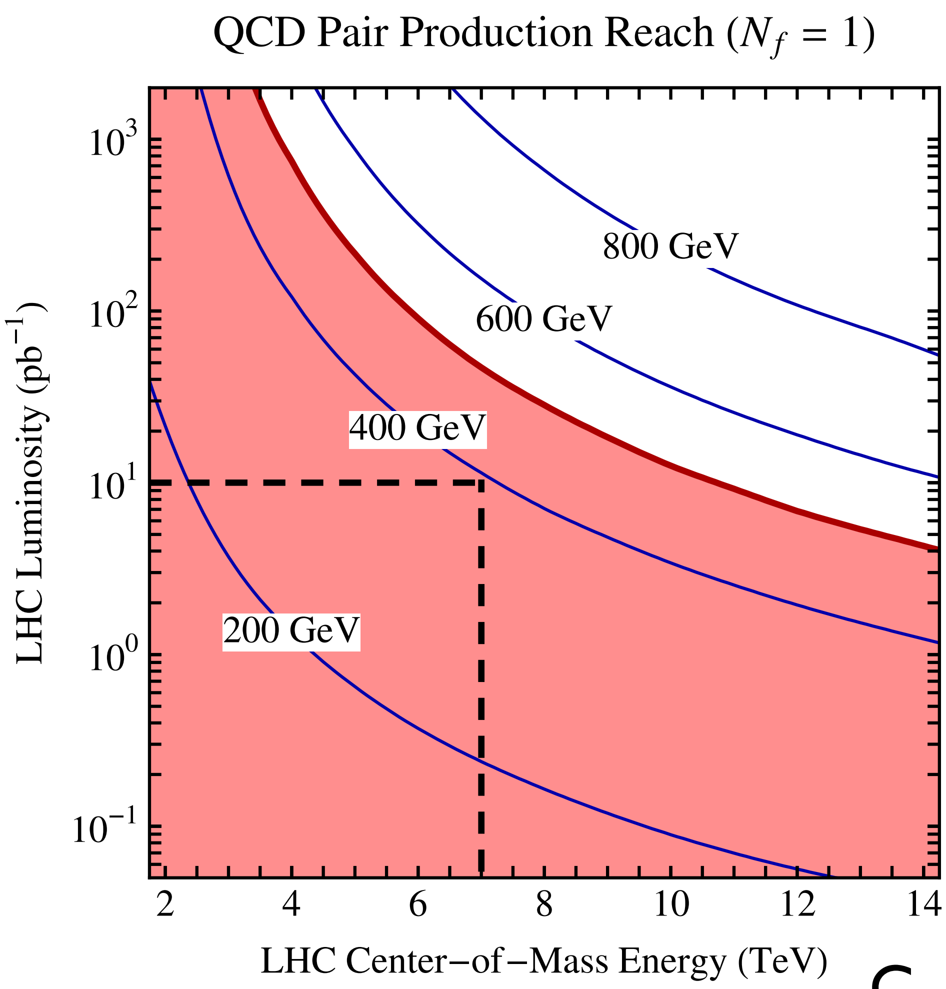
LHC reach (dashed) compared to Tevatron Exclusion (red)



C. Bauer et al'10

The reach for QCD produced heavy quarks is, instead, not enhanced. Full 1/fb necessary

Tevatron reach (red) compare to early LHC reach (dashed)



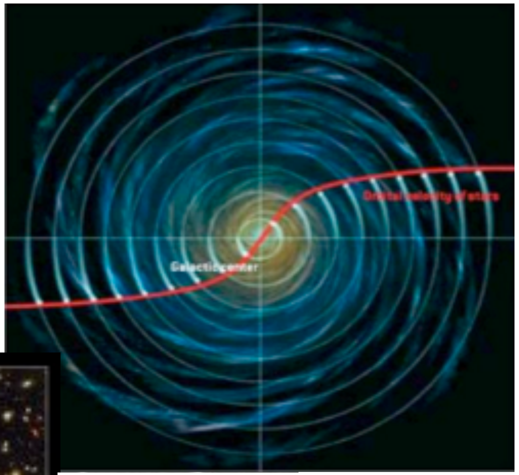
C. Bauer et al'10

Dark Matter and Electroweak Symmetry Breaking

Physics Beyond the SM ? Dark Matter

- Cosmological measurements provided "precision tests" of the Universe energy density composition, making the case for Dark Matter quite compelling.
- Today we know that Dark Matter makes most of the matter of the Universe and there are experiments looking for its direct (and indirect) detection.
- The detection of Dark Matter may just be the tip of the Iceberg of a whole new world of additional particles
- High Energy Physics experiments could provide clues toward the understanding of the nature of these particles: This will depend on their energy range and interaction strength with SM particles.

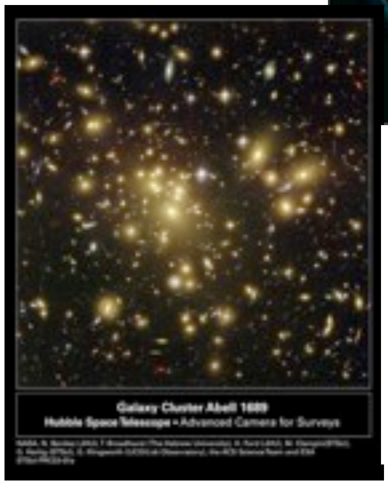
The Mystery of Dark Matter



- Rotation curves from Galaxies.

  Luminous disk → not enough mass to explain rotational velocities of galaxies → Dark Matter halo around the galaxies

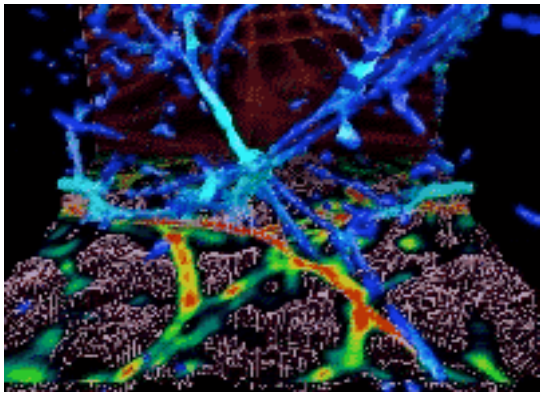
- Gravitational lensing effects

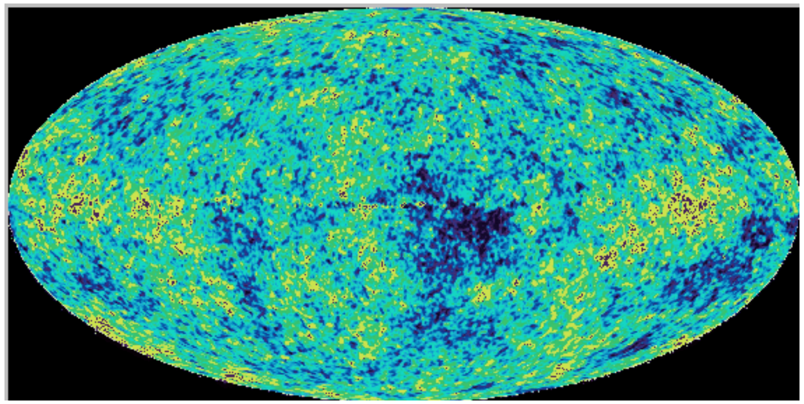


Measuring the deformations of images of a large number of galaxies, it is possible to infer the quantity of Dark Matter hidden between us and the observed galaxies

- Structure formation:

Large scale structure and CMB Anisotropies





The manner in which structure grows depends on the amount and type of dark matter present.
All viable models are dominated by cold dark matter.

Bullet Cluster

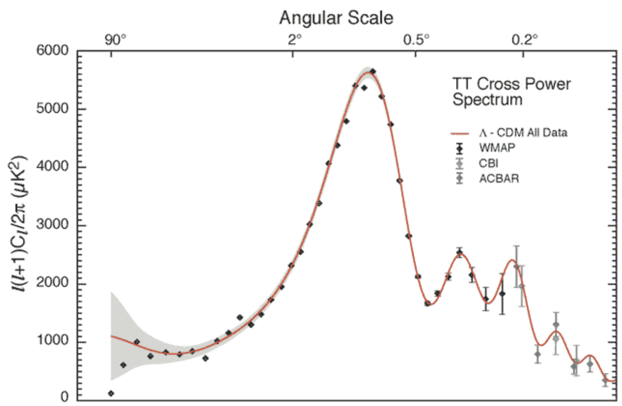
Position of X-ray emitting hot gas (red) different from main mass concentration detected by lensing (blue) after collision of two clusters of galaxies. Clear separation between the "dark matter" and the gas clouds is considered one of the best evidences that dark matter exists.

Results from WMAP

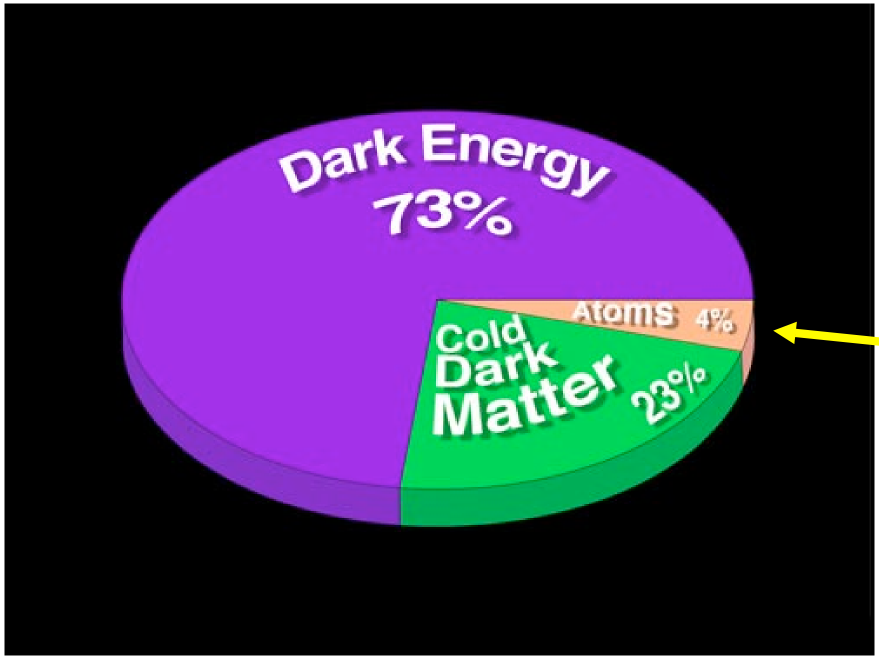
Ω_i : Fraction of critical density

Universe density $\Omega_0 = 1.02 \pm 0.02$
Dark energy density $\Omega_\Lambda = 0.73 \pm 0.04$
Total matter density $\Omega_M = 0.27 \pm 0.05$
Baryon matter density $\Omega_b = 0.044 \pm 0.004$

$\longrightarrow$ Dark matter is non-baryonic



Our Universe:



us

Why do we think that Dark Matter may be accessible at high energy physics experiments ?

- Dark Matter is most likely associated with new particles
- Many dark matter candidates have been proposed. They differ in mass and in the range of interaction with SM particles.
- However, if the relic density proceeds from the primordial thermal bath, there are reasons to believe that it must be part of the dynamics leading to an explanation of electroweak symmetry breaking.
- It is likely to interact with (annihilate into) ordinary matter at an observable rate
- The relic density depends on this annihilation rate

Dark Matter Annihilation Rate

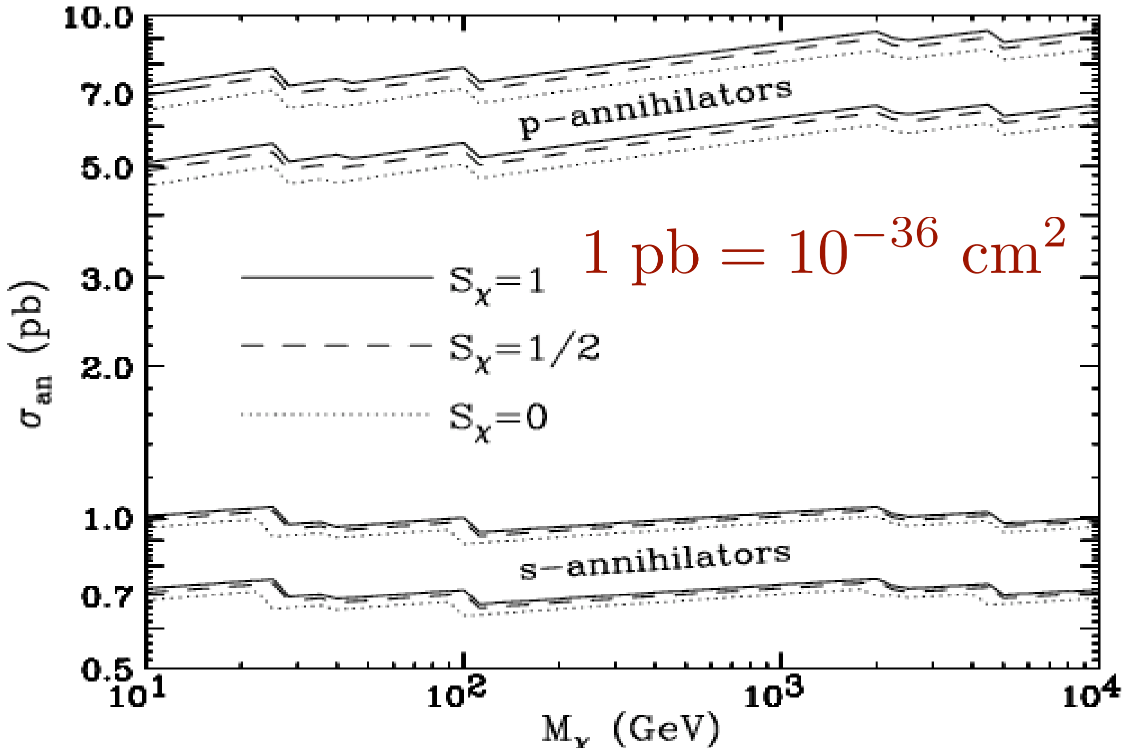
- The main reason why we think there is a chance of observing dark matter at colliders is that, when we compute the annihilation rate to get the proper relic density, we get a cross section

$$\sigma_{\rm ann.}(\text{DM DM} \to \text{SM SM}) \simeq 1 \text{ pb}$$

- This is approximately

$$\sigma_{\rm ann.} \simeq \frac{\alpha_W^2}{\text{TeV}^2}$$

This suggests that it is probably mediated by weakly interacting particles with weak scale masses



$$1 \text{ pb} = 10^{-36} \text{ cm}^2$$

(A.B., K. Matchev and M. Perelstein, PRD 70:077701, 2004)

- Connection of Thermal Dark Matter to the weak scale and to the mechanism of electroweak symmetry breaking

Missing Energy at Colliders

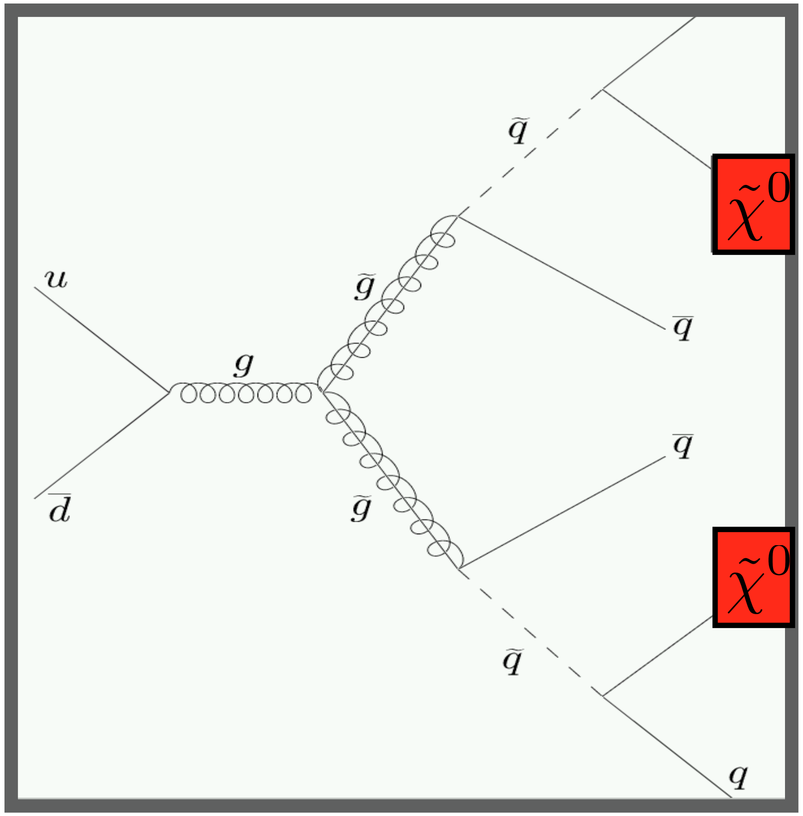
- In general, if the dark matter particle is neutral and weakly interacting, it will not be detected at current lepton and hadron colliders.
- Just like when the neutrino was discovered, evidence of the production of such a particle will come from an apparent lack of conservation of the energy and momentum in the process.
- Missing Energy and (transverse) momentum signatures, beyond the ones expected in the Standard Model, should be sizable and will be the characteristic signatures of theories with a thermal WIMP as a Dark Matter Candidate.

Supersymmetry at colliders

Gluino production and decay: Missing Energy Signature

Supersymmetric Particles tend to be heavier if they carry color charges.

Charge-less particles tend to be the lightest ones.



Lightest Supersymmetric Particle: Excellent cold dark matter candidate

Other WIMP candidates

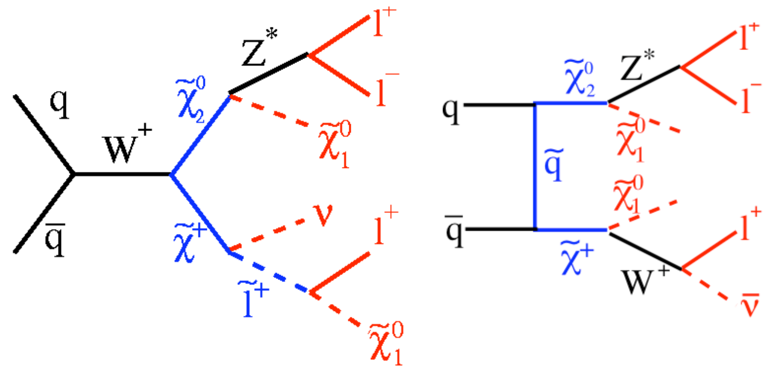
- For most electroweak symmetry breaking models proposed, a possible dark matter candidate has been found. These include
- The Lightest KK particle (LKP) in Universal Extra Dimensions
- The lightest T-odd Particle in little Higgs models
- Lightest mirror KK particle in warped extra dimensional models
- Lightest neutral particle in inert doublet models
- The game is quite simple. If a discrete symmetry exists that ensures the stability of a light neutral weakly interacting particle of the model, then the numbers will probably work well in certain region of parameter space of such a model.

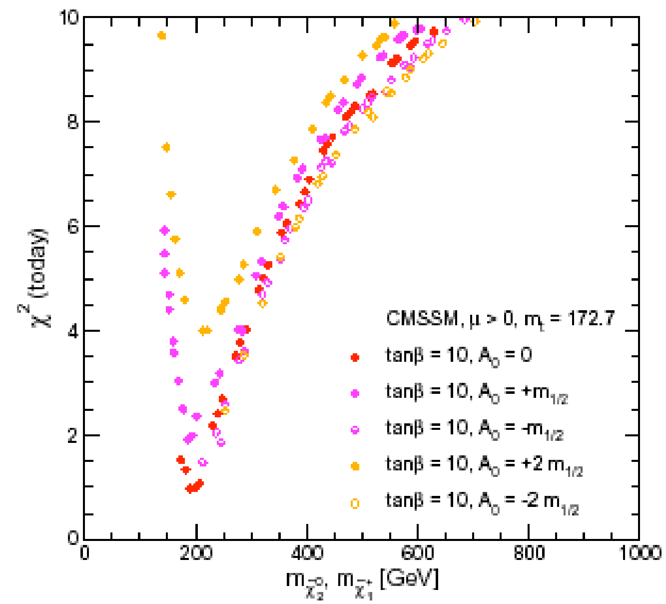
Searches at Colliders


Chicago
Booster
CDF
DØ
Tevatron
$\bar{p}$ source
Main Injector
(new)

Searches at the Tevatron: Trileptons

- **“Golden” Trilepton Signature**
  - **Chargino–neutralino production**
  - **Low SM backgrounds**
- **3 leptons and large Missing E_T:**
  - **Neutralino χ^0_1 is LSP**
- **Recent analysis of electroweak precision and WMAP data** (J. Ellis, S. Heinemeyer, K. Olive, G. Weiglein: hep-ph/0411216)
  - **Preference for “light SUSY”**
  - **Chargino mass around 200 GeV/c²**
- **Current DØ analysis:**
  - **2 l (l=e,μ,τ) + isolated track or $\mu^\pm\mu^\pm$**
  - **$\not{E}_t$ +topological cuts**
  - **Analysis most sensitive at low tanβ**
  - **BG expectation: 2.9±0.8 events**
  - **Observed: 3 events**





M(chargino)

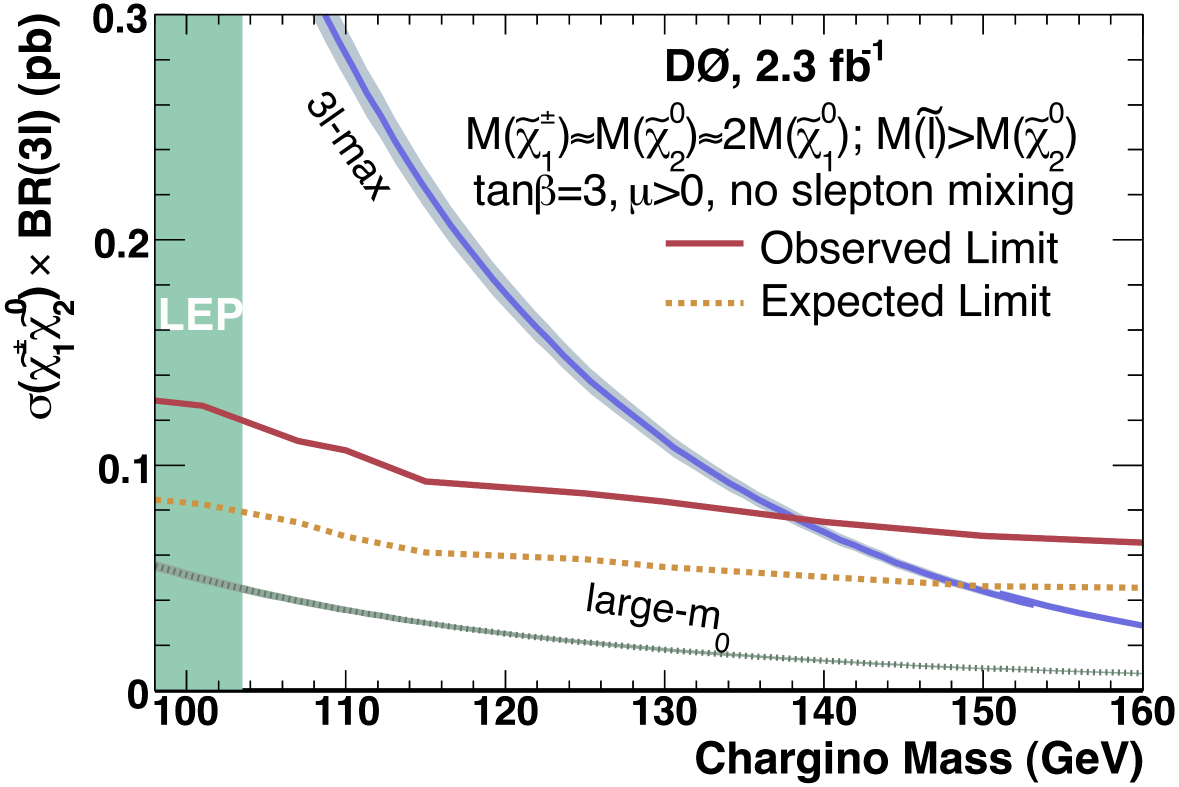
Comment: Preferred region strongly depends on muon anomalous magnetic moment, that as we will explain, slightly differs from SM prediction

Result

- No evidence for SUSY observed
  - Set limit on production cross sections times branching ratio $\sigma \times BR(3\ell)$
  - 3ℓ–max scenario
    - $m_{\tilde{\chi}_1^\pm} \approx m_{\tilde{\chi}_2^0} \approx 2m_{\tilde{\chi}_1^0}$ and $m_{\tilde{\ell}}$ slightly heavier than $m_{\tilde{\chi}_2^0}$
    - Maximized branching ratio into three leptons

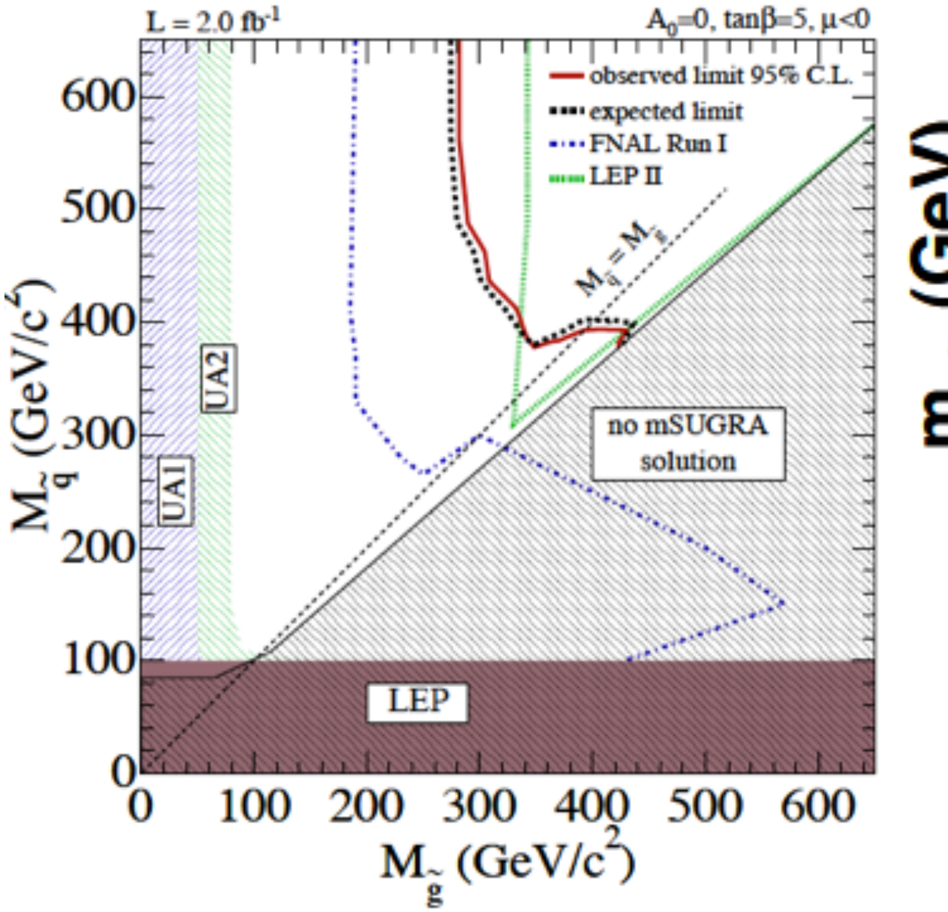
- Cross section limit $\sigma \times BR(3\ell)$
  - Observed: 0.06–0.12 pb
  - Expected: 0.04–0.08 pb

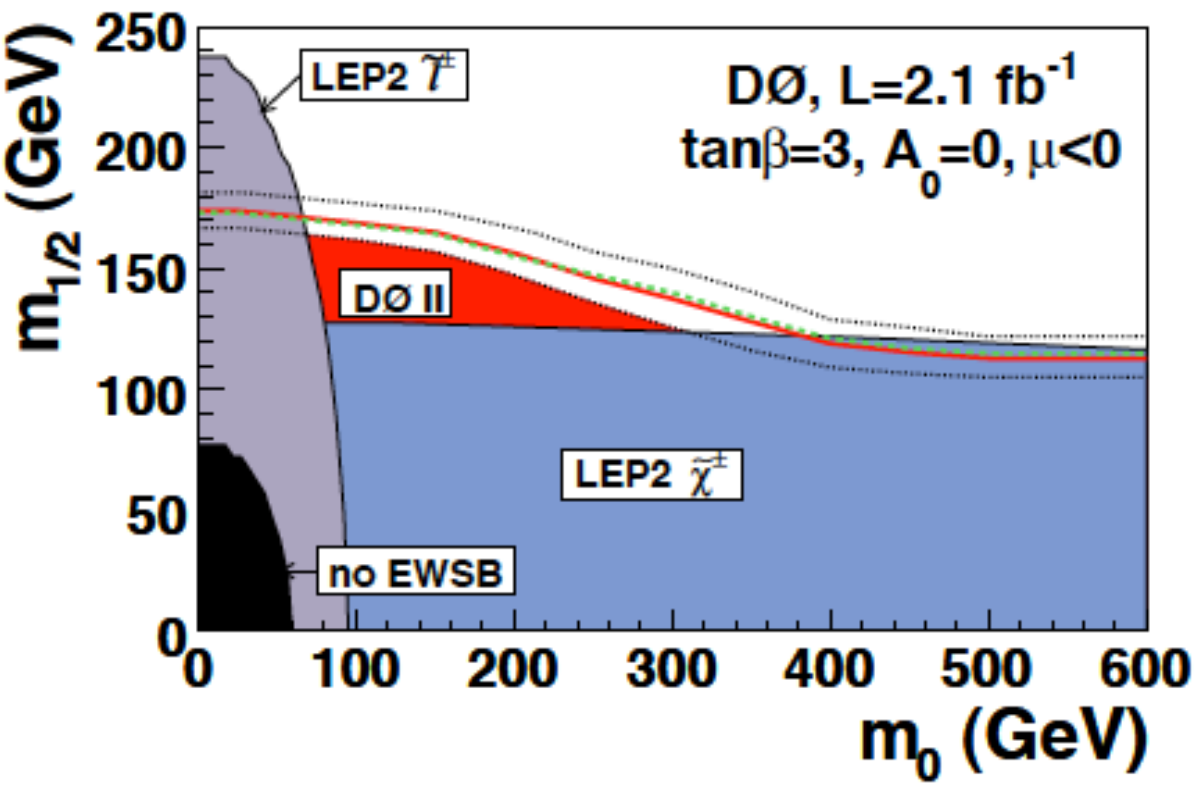
- Mass limits for $m_{\tilde{\chi}_1^\pm}$
  - Observed: 138 GeV
  - Expected: 148 GeV

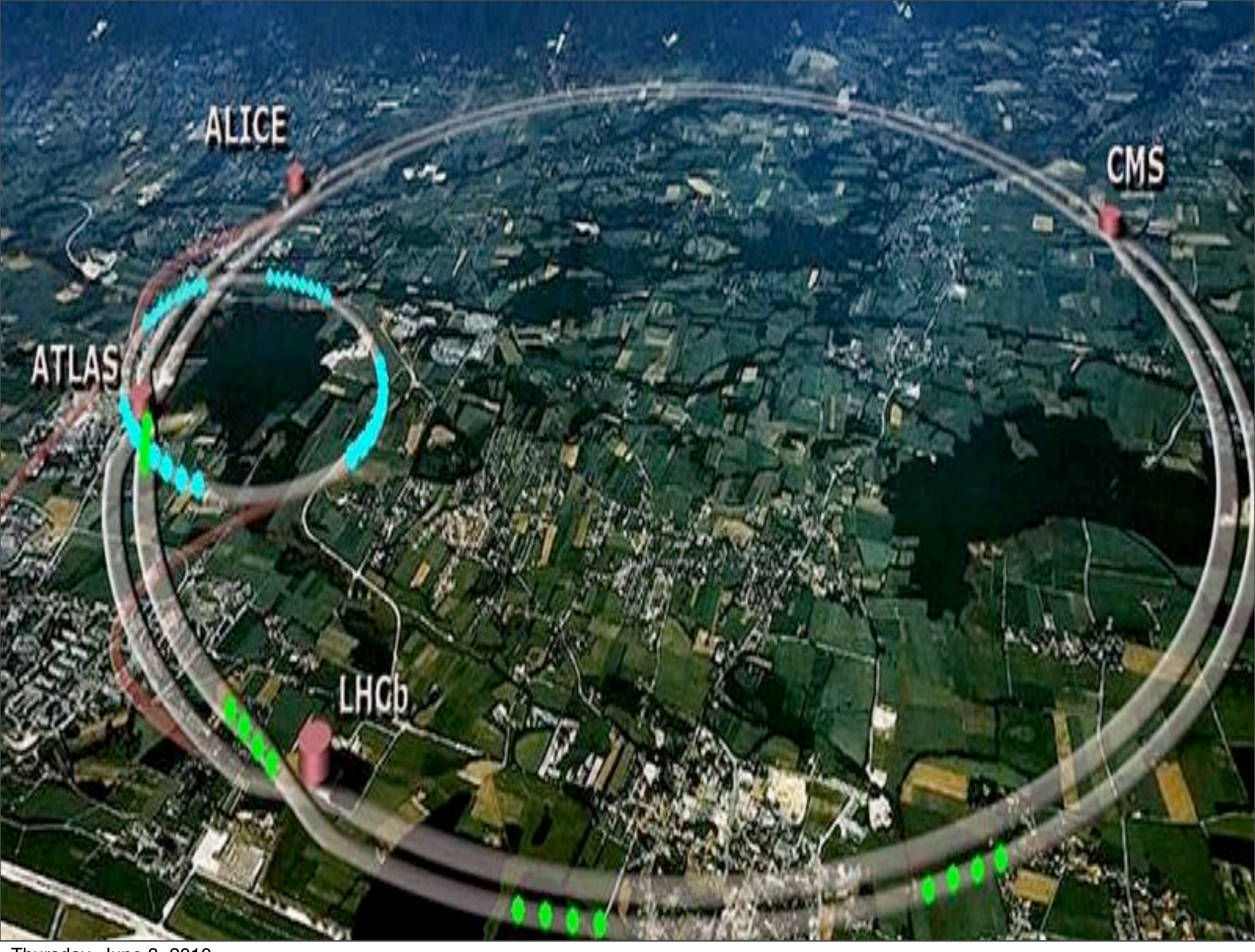


Squark and Gluino Limits at the Tevatron (jets plus miss. E)

Masses up to about 400 GeV have been probed



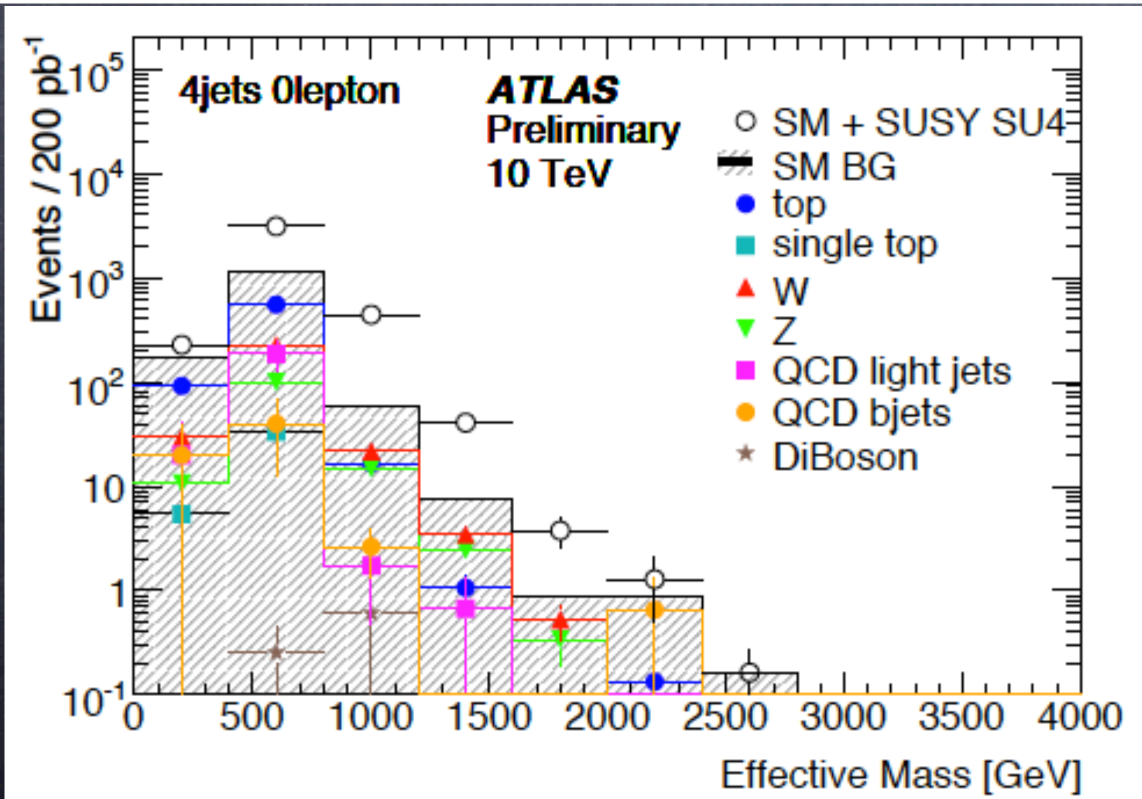


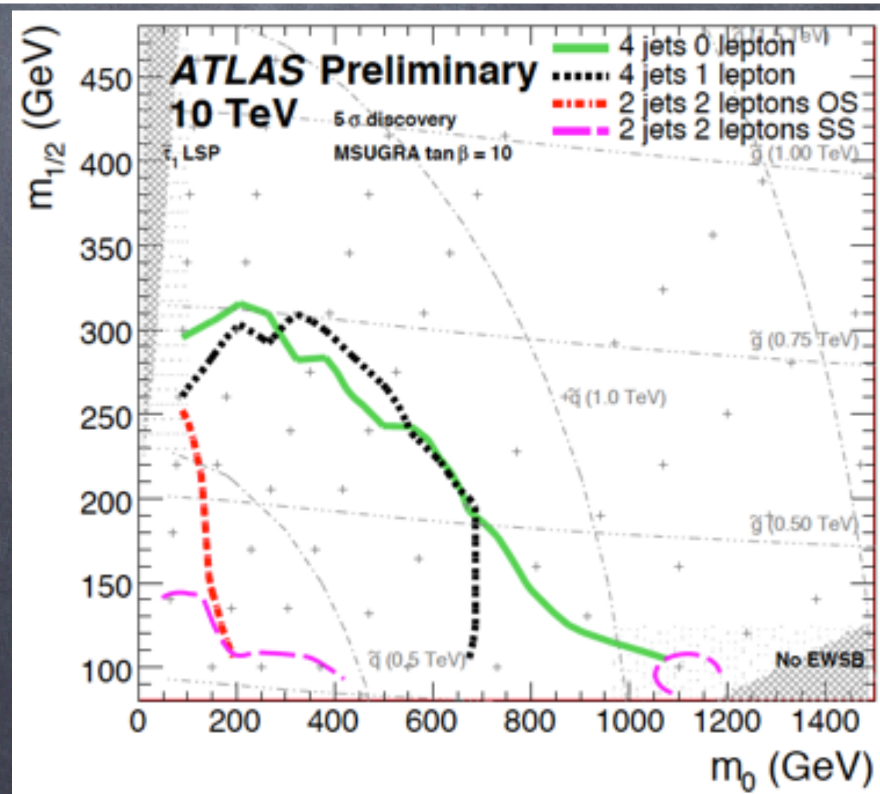

ALICE
CMS
ATLAS
LHCb

ATLAS Study of SUSY reach for 10 TeV and 200/pb

Expected reach very similar to 7 TeV and 1/fb

Quark and Gluino Masses up to 750 GeV can be probed



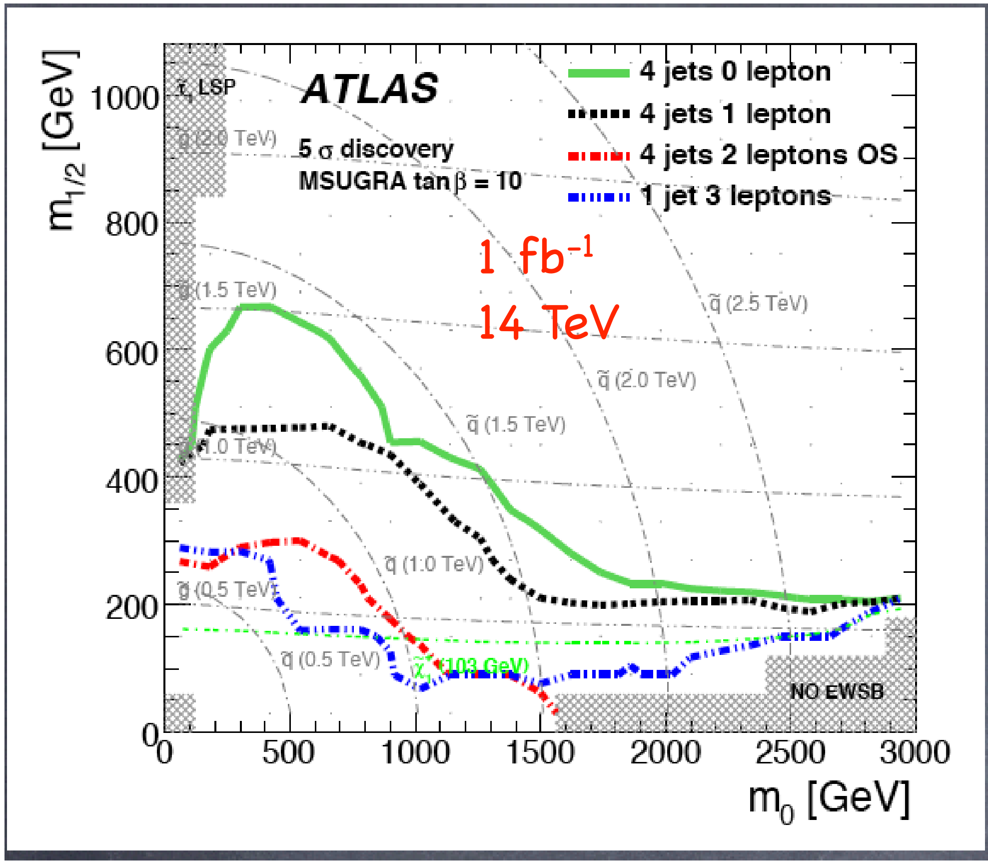


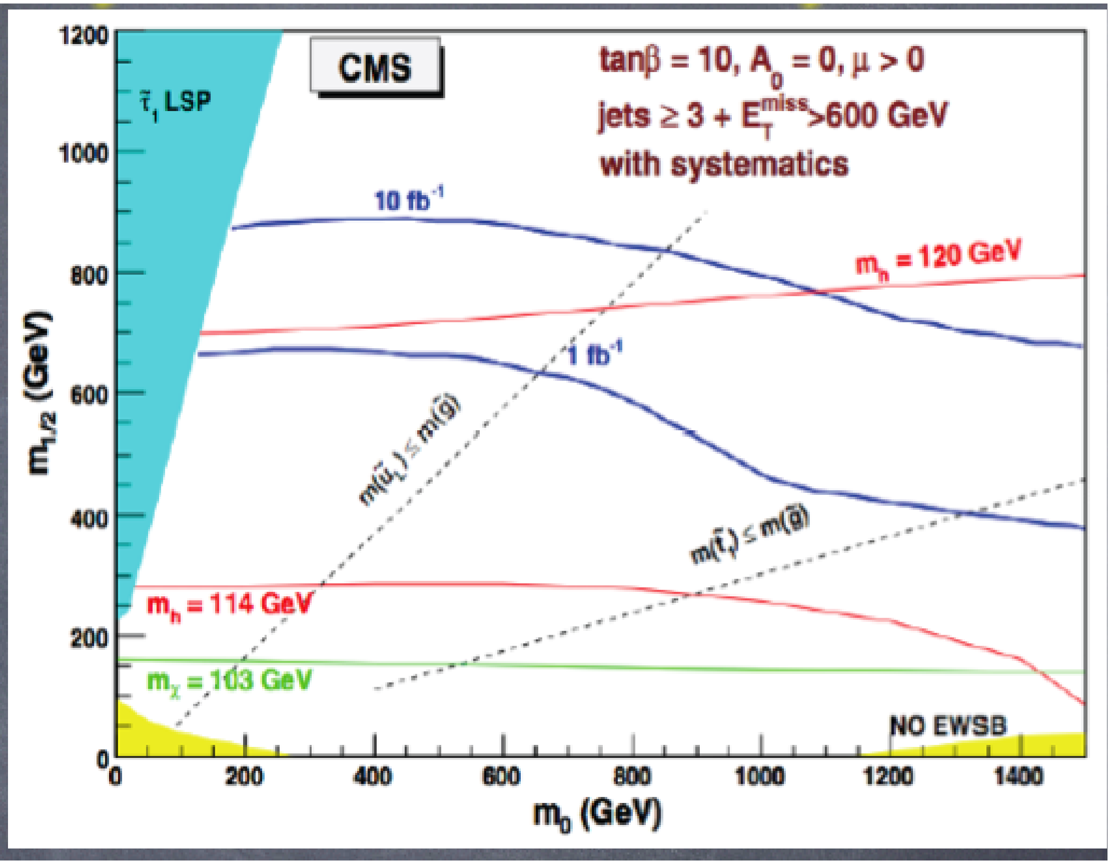
Particle	SU1	SU2	SU3	SU4	SU6	SU8.1	SU9
$\tilde{d}_L$	764.90	3564.13	636.27	419.84	870.79	801.16	956.07
$\tilde{u}_L$	760.42	3563.24	631.51	412.25	866.84	797.09	952.47
$\tilde{b}_1$	697.90	2924.80	575.23	358.49	716.83	690.31	868.06
$\tilde{t}_1$	572.96	2131.11	424.12	206.04	641.61	603.65	725.03
$\tilde{d}_R$	733.53	3576.13	610.69	406.22	840.21	771.91	920.83
$\tilde{u}_R$	735.41	3574.18	611.81	404.92	842.16	773.69	923.49
$\tilde{b}_2$	722.87	3500.55	610.73	399.18	779.42	743.09	910.76
$\tilde{t}_2$	749.46	2935.36	650.50	445.00	797.99	766.21	911.20
$\tilde{e}_L$	255.13	3547.50	230.45	231.94	411.89	325.44	417.21
$\tilde{\nu}_e$	238.31	3546.32	216.96	217.92	401.89	315.29	407.91
$\tilde{\tau}_1$	146.50	3519.62	149.99	200.50	181.31	151.90	320.22
$\tilde{\nu}_\tau$	237.56	3532.27	216.29	215.53	358.26	296.98	401.08
$\tilde{e}_R$	154.06	3547.46	155.45	212.88	351.10	253.35	340.86
$\tilde{\tau}_2$	256.98	3533.69	232.17	236.04	392.58	331.34	416.43
$\tilde{g}$	832.33	856.59	717.46	413.37	894.70	856.45	999.30
$\tilde{\chi}_1^0$	136.98	103.35	117.91	59.84	149.57	142.45	173.31
$\tilde{\chi}_2^0$	263.64	160.37	218.60	113.48	287.97	273.95	325.39
$\tilde{\chi}_3^0$	466.44	179.76	463.99	308.94	477.23	463.55	520.62
$\tilde{\chi}_4^0$	483.30	294.90	480.59	327.76	492.23	479.01	536.89
$\tilde{\chi}_1^+$	262.06	149.42	218.33	113.22	288.29	274.30	326.00
$\tilde{\chi}_2^+$	483.62	286.81	480.16	326.59	492.42	479.22	536.81
h^0	115.81	119.01	114.83	113.98	116.85	116.69	114.45
H^0	515.99	3529.74	512.86	370.47	388.92	430.49	632.77
A^0	512.39	3506.62	511.53	368.18	386.47	427.74	628.60
H^+	521.90	3530.61	518.15	378.90	401.15	440.23	638.88
t	175.00	175.00	175.00	175.00	175.00	175.00	175.00

Observe that, as anticipated Higgs mass is always small

SUSY LHC Reach at 14 TeV and 1/fb

Squark and Gluino Masses up to 1.5 TeV

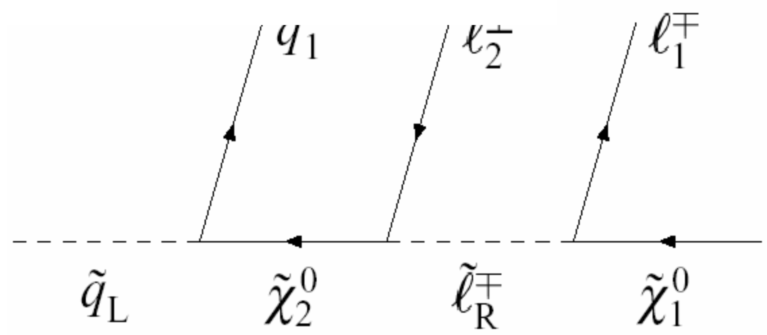




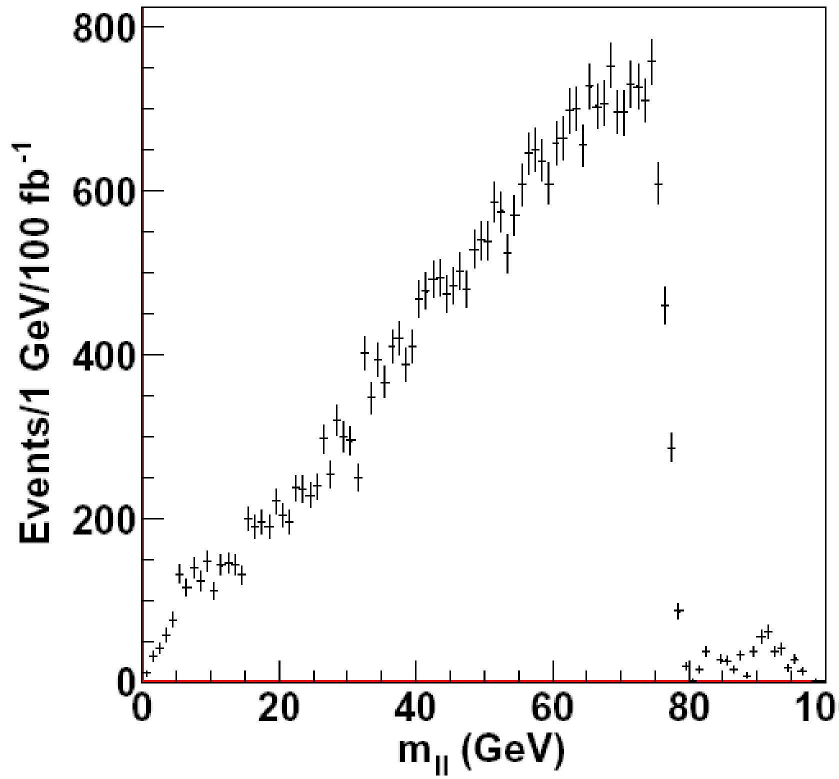
Searches at the LHC

New particle searches at the LHC are induced by the cascade decay of strongly interacting particles.

By studying the kinematic distributions of the decay products one can determine the masses of produced particles, including the LSP.



$$
\begin{aligned}
(m^2_{ll})^{\text{edge}} &= \frac{(m^2_{\tilde{\chi}^0_2} - m^2_{\tilde{l}_R})(m^2_{\tilde{l}_R} - m^2_{\tilde{\chi}^0_1})}{m^2_{\tilde{l}_R}} \\
(m^2_{qll})^{\text{edge}} &= \frac{(m^2_{\tilde{q}_L} - m^2_{\tilde{\chi}^0_2})(m^2_{\tilde{\chi}^0_2} - m^2_{\tilde{\chi}^0_1})}{m^2_{\tilde{\chi}^0_2}} \\
(m^2_{ql})^{\text{edge}}_{\text{min}} &= \frac{(m^2_{\tilde{q}_L} - m^2_{\tilde{\chi}^0_2})(m^2_{\tilde{\chi}^0_2} - m^2_{\tilde{l}_R})}{m^2_{\tilde{\chi}^0_2}} \\
(m^2_{ql})^{\text{edge}}_{\text{max}} &= \frac{(m^2_{\tilde{q}_L} - m^2_{\tilde{\chi}^0_2})(m^2_{\tilde{l}_R} - m^2_{\tilde{\chi}^0_1})}{m^2_{\tilde{l}_R}} \\
(m^2_{qll})^{\text{thres}} &= [(m^2_{\tilde{q}_L} + m^2_{\tilde{\chi}^0_2})(m^2_{\tilde{\chi}^0_2} - m^2_{\tilde{l}_R})(m^2_{\tilde{l}_R} - m^2_{\tilde{\chi}^0_1}) \\
&\quad -(m^2_{\tilde{q}_L} - m^2_{\tilde{\chi}^0_2})\sqrt{(m^2_{\tilde{\chi}^0_2} + m^2_{\tilde{l}_R})^2(m^2_{\tilde{l}_R} + m^2_{\tilde{\chi}^0_1})^2 - 16 m^2_{\tilde{\chi}^0_2} m^4_{\tilde{l}_R} m^2_{\tilde{\chi}^0_1}} \\
&\quad +2m^2_{\tilde{l}_R}(m^2_{\tilde{q}_L} - m^2_{\tilde{\chi}^0_2})(m^2_{\tilde{\chi}^0_2} - m^2_{\tilde{\chi}^0_1})]/(4m^2_{\tilde{l}_R} m^2_{\tilde{\chi}^0_2})
\end{aligned}
$$



Weiglein et al. (2004)

Are there any Hints of New Physics

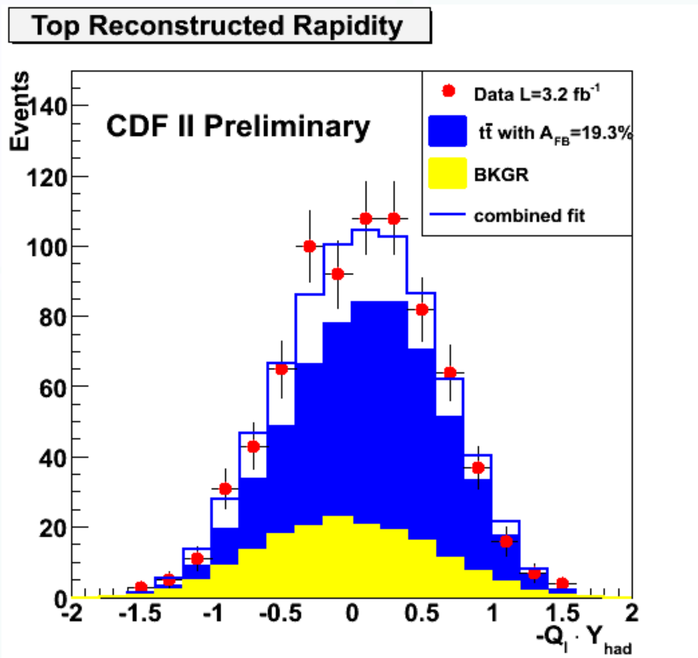
Beyond the ones coming from Astrophysics and Cosmology ?

Some weak scale anomalies

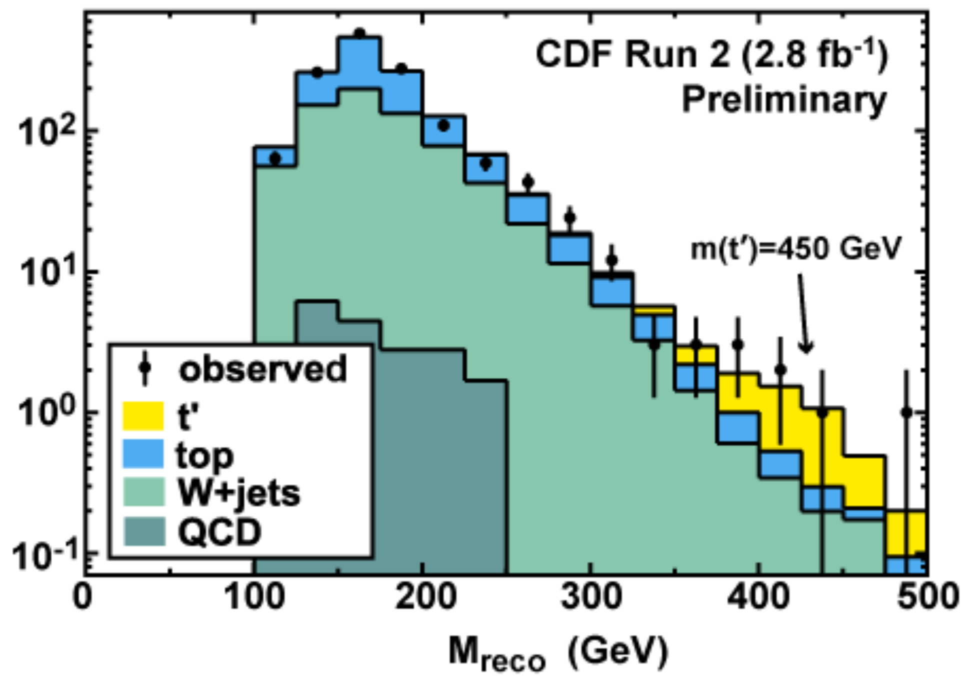
Signals which are two to three standard deviations away from the expected SM predictions.

- 100 GeV Higgs signal excess. Rate about one tenth of the corresponding SM Higgs one.
- 115 GeV Higgs signal, seen only by Aleph experiment at LEP.
- DAMA/LIBRA annual modulation signal, direct DM detection searches (sodium iodide NaI scintillation crystal). COGENT experiment sees an compatible excess, disputed by XENON
- Anomalous magnetic moment of the muon.
- Forward-backward asymmetry of the bottom quark at LEP.
- Forward-backward asymmetry of the top quark at the Tevatron.
- Apparent heavy quark events, with mass about 450 GeV.
- CP-violation in the Bs mixing seen by D0 and CDF. Related dimuon charge asymmetry at D0
- Anomalies observed in $B \to K\pi, \;\; B \to \tau\nu \;\; \text{and} \;\; B \to K l^+ l^-$ transitions
- Apparent 214 MeV muon pair resonance in the decay $\Sigma \to p\, \mu^+ \mu^-$
- Apparent 250 GeV electron pair resonance at CDF

Top Forward Backward Asymmetry and New Heavy, Top-like Quarks



A_{fb} = 19.3% +/- 6.5% (stat) +/- 2.4% (syst)



Production cross section larger than pure QCD one

Possible Explanations analyzed, for example, in Q.H. Cao et al'10, arXiv:1003.3461

See, for example
B. Dobrescu et al, **arXiv:0902.0792**

Most anomalies will be fully tested in the LHC ERA

- The current decade will see the completion of the Tevatron and the full development of the LHC program, which will provide detailed information of physics at the TeV scale.
- Origin of fermion and gauge boson masses (electroweak symmetry breaking dynamics) expected to be revealed by these experiments.
- Missing energy signatures at the LHC may reveal the presence of a dark matter candidate which may be the first evidence of a world of new particles.
- LHCb and super B-factories will provide accurate information on flavor physics, leading possibly to complementary information on new physics.
- Search for charged lepton number violation and neutrino double beta decay experiments could reveal nature of neutrinos, and new dynamics at the TeV scale. Neutrino oscillation experiments may lead to the observation of CP-violation or other surprises.
- Direct and indirect Dark Matter detection experiments will reach maturity. The equation of state of the Dark Energy component is expected to be determined.
- The next years can mark the termination of the Standard Model Dictatorship and the beginning of a genuine new era in physics, similar to the one that led to the successful SMs of particle physics and cosmology, which arguably started about 100 years ago.

New Physics may appear at the LHC within the Next Year !

- It will demand good performance of the detectors and a faster luminosity increase
- As I showed, it will also demand some help from Nature
- If that happens, we will celebrate it in the Next Users Meeting
- It may appear just before the SUSY11 Conference, to be held at Fermilab in the Summer of 2011

Let me conclude by insisting on that the Tevatron can still add very interesting information on Higgs searches, both in SM as well as in non-standard channels.

There is a clear complementarity with early LHC searches in both the high mass region as in non-standard Higgs boson searches. It remains superior to the early LHC in the low mass region, where the Higgs presence is most likely

An extended Tevatron run, until 2014 will further strengthen these capabilities, leading to possibilities of discoveries before the LHC developes its full potential.

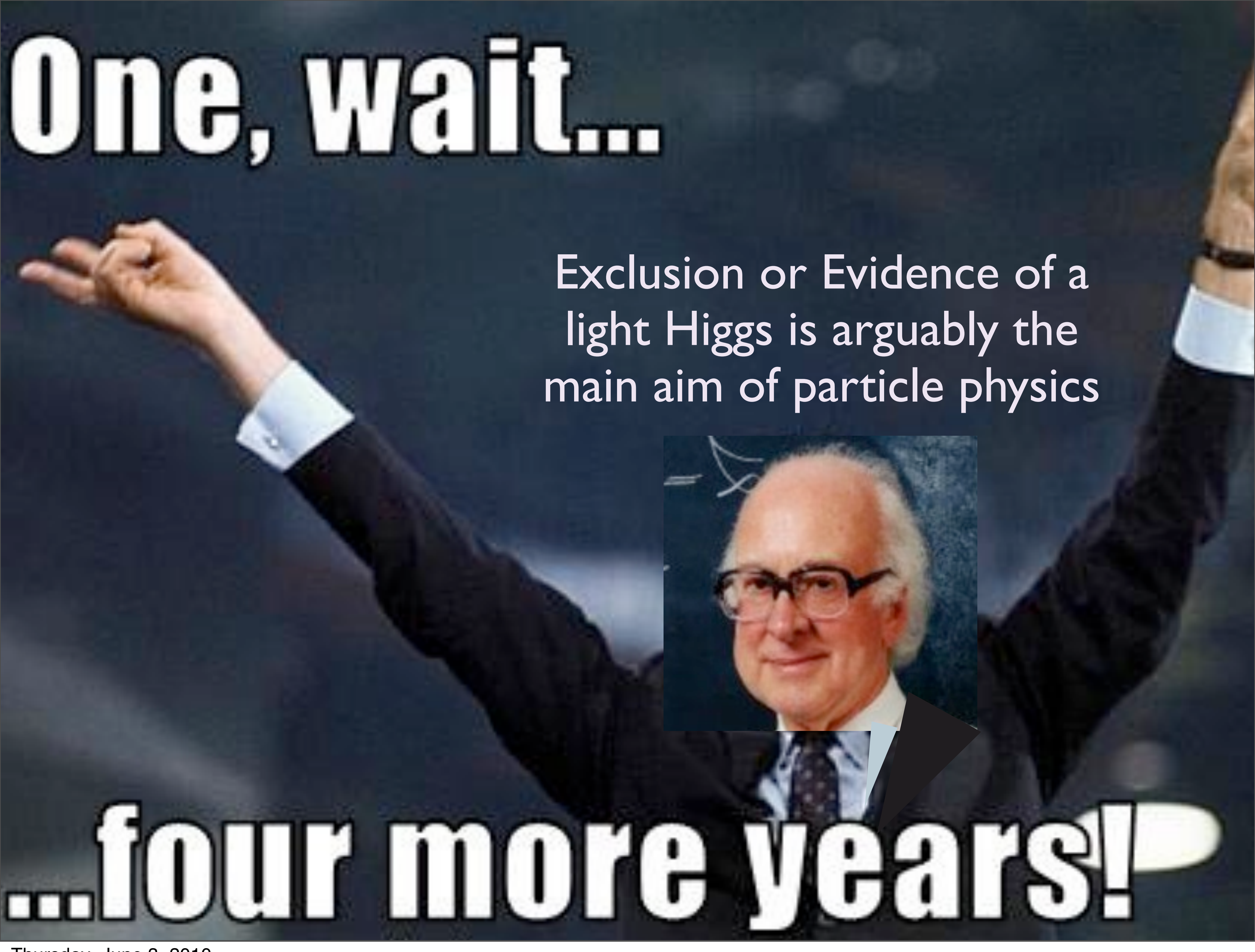
The Higgs is not yet another particle. It is the "mother" of them all.

There is also the fact that the Tevatron will remain sensitive to many other search channels, beyond the Higgs

After all,

Life is what happens to you while you are busy making other plans

J. Lennon


One, wait...
Exclusion or Evidence of a light Higgs is arguably the main aim of particle physics
...four more years!

Solution to Anomalies

- Solution to all anomalies have been proposed
- They are solved by postulating new particles
- Difficult to explain more than one anomaly with the same particle
- Theory that explain all anomalies is probably (or necessarily) wrong
- Is there any historic precedent for this situation ?

Reasons for Proposal and Later Solutions to 4 Puzzles (1932)

- 1) Klein Paradox --apparent violation of unitarity (solution:positron existence- pair production possible)
- 2) Wrong Statistics in Nuclei--N-14 nucleus appeared to be bosonic--(solution: neutron not a proton-electron bound state)
- 3) Beta Ray Emission-apparent Energy non conservation (solution:neutrino)
- 4) Energy Generation in Stars (solution: nuclear forces, pep chain, carbon cycle etc.----pion)

G. Segre'10

The New York Times on the Web

UPDATED FRIDAY, MARCH 18, 2005 8:05 PM ET | Personalize Your Weather

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About NYTDigital
Jobs at NYTDigital
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Black Hole at RHIC

By ABBY GOODNOUGH and MARIA NEWMAN 7:01 PM ET

Scientists at the RHIC atom smasher, located at Brookhaven National Lab on Long Island, created a black hole in a gold-gold particle collision. The black hole is not sucking the Earth in, yet.

- Video: The Times's Adam Liptak
- Text: The Schiavo Case (*Findlaw.com*)

In Lebanon, Factions Deadlocked in Talks for New Government

By DEXTER FILKINS 6:22 PM ET

Allies of the pro-Syrian government and the opposition said the two sides disagreed on a number of important issues, which raises the possibility that elections may be postponed.

- Explosion Rocks Beirut Suburb

Wal-Mart Settles Illegal Immigrant Case

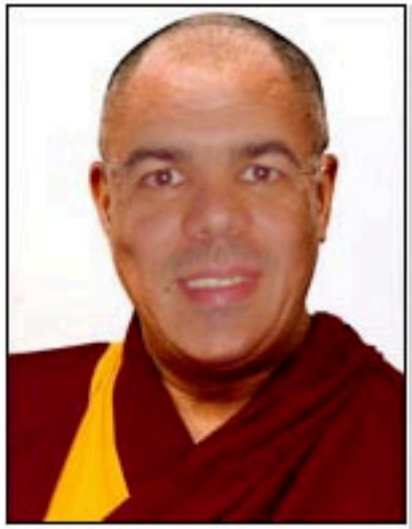
By TERENCE NEILAN 1:12 PM ET

Wal-Mart Stores has agreed to pay $11 million to settle federal allegations it used illegal immigrants to clean its stores.

In Blow to Bush, Senators Reject Cuts to Medicaid

By SHERYL GAY STOLBERG

The vote, a rebuke to both the White House and the Senate leadership, put the House and Senate on a collision course.



Wagner becomes monk

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Constraints on SUSY Breaking Models

M. Carena, P. Draper, T. Liu, C. Wagner and G. Weiglein, in preparation

- Behavior in specific models are governed, by the scale of squark masses, the relative values of A_t and μ, as well as by the value of $\tan\beta$
- In the CMSSM, for instance

Carena, Pokorski, Olechowsi, C.W. '93

$$
\begin{aligned}
A_t &\simeq A_0\left(1 - y_t^2\right) - 2M_{1/2} \\
m_Q^2 &\simeq m_0^2\left(1 - y_t^2/2\right) + 5.5M_{1/2}^2 \\
m_U^2 &\simeq m_0^2\left(1 - y_t^2\right) + 5M_{1/2}^2 \\
m_{H_u}^2 &\simeq m_0^2\left(1 - 3y_t^2/2\right) - 3M_{1/2}^2
\end{aligned}
$$

- Closer to minimal than to maximal mixing unless A_0 is large.

- Here the top Yukawa factor refers to the ratio with respect to its IR fixed point, of order 2/3. Additional bottom Yukawa factors appear at large $\tan\beta$. In addition, μ is not small and m_A diminish for large values of $\tan\beta$

$$
\begin{aligned}
\mu^2 &\simeq -M_Z^2/2 - m_{H_u}^2 \\
m_A^2 &\simeq -M_Z^2 + (m_{H_d}^2 - m_{H_u}^2)
\end{aligned}
$$

Scans in High-Scale Models: CMSSM & GMSB

Constrained MSSM: Scan over GUT-scale values for common soft scalar mass m_0, gaugino mass $m_{1/2}$, trilinear coupling A_0, and tan beta.

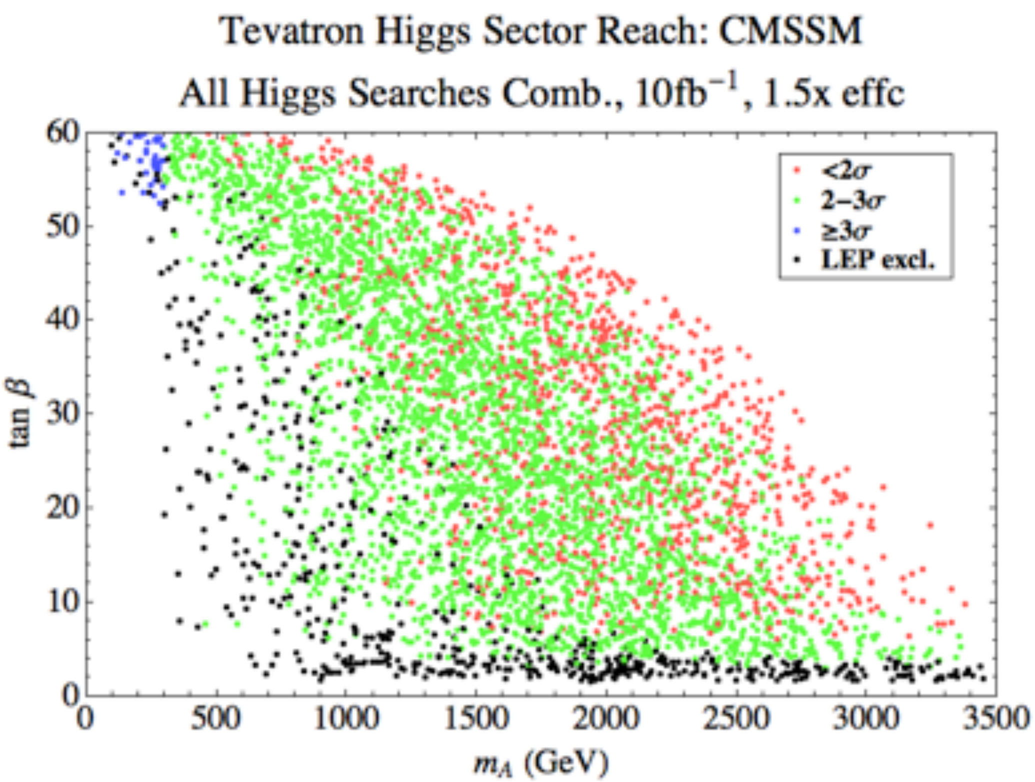
$$50 \text{ GeV} < m_0 < 2 \text{ TeV}$$
$$50 \text{ GeV} < m_{1/2} < 2 \text{ TeV}$$
$$-3 \text{ TeV} < A_0 < 3 \text{ TeV}$$
$$1.5 < \tan\beta < 60$$

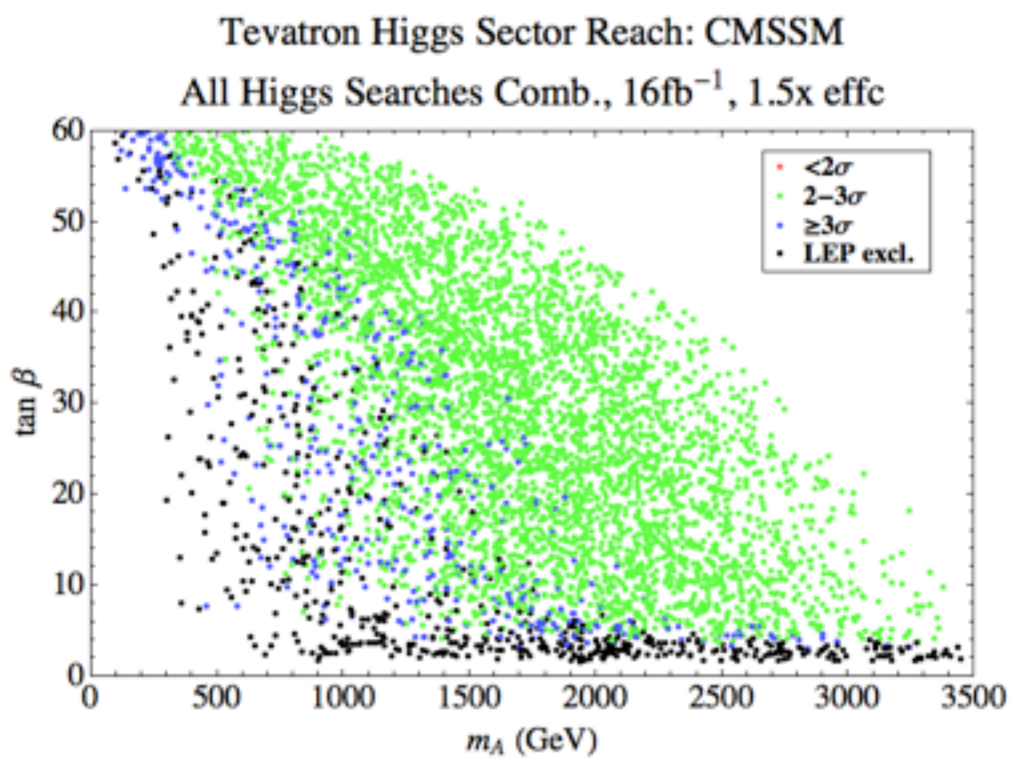
Minimal Gauge Mediation: Scan over...
-messenger scale M_{mess} where SUSY-breaking is communicated to the MSSM
-SUSY-breaking vev scale $\Lambda \sim \langle F \rangle / \langle S \rangle$ (soft masses $\sim \alpha\Lambda/4\pi$)
-number of messengers N_{mess} in complete SU(5) $5+\bar{5}$ reps
-tan beta

$$10^4 \text{ GeV} < \Lambda < 2\times 10^5 \text{ GeV}$$
$$\Lambda < M_{mess} < 10^4 \times \Lambda$$
$$1 \le N_{mess} \le 8$$
$$1.5 < \tan\beta < 60$$

CMSSM

M. Carena, P. Draper, S. Heinemeyer, T. Liu, G. Weiglein, C.W. '10

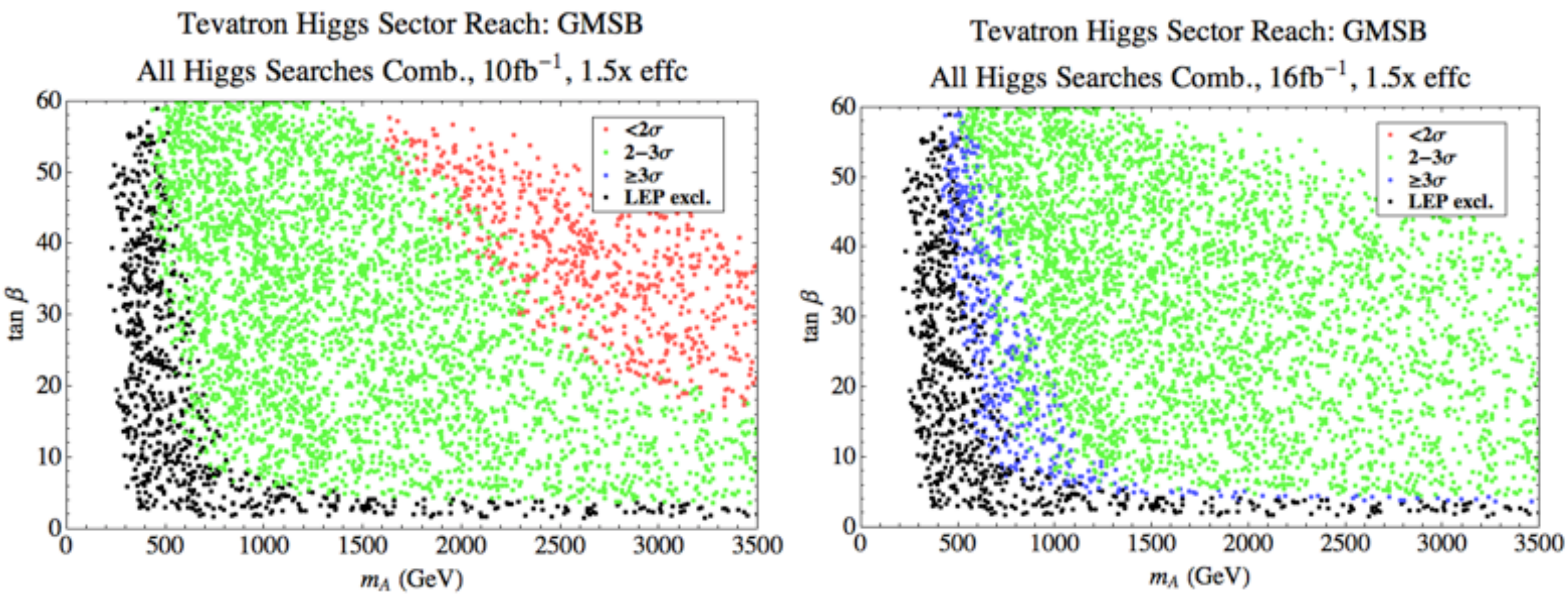




Even for very large values of the squark masses, combining all Higgs search channels, the CMSSM may be probed if Tevatron continues running. Evidence found in large regions of parameters

Minimal Gauge Mediation

M. Carena, P. Draper, S. Heinemeyer, T. Liu, G. Weiglein, C.W. '10



Results in Minimal Gauge Mediation similar to the case of the MSSM. Complete coverage at the 2 sigma level for the case of continuous Tevatron running.

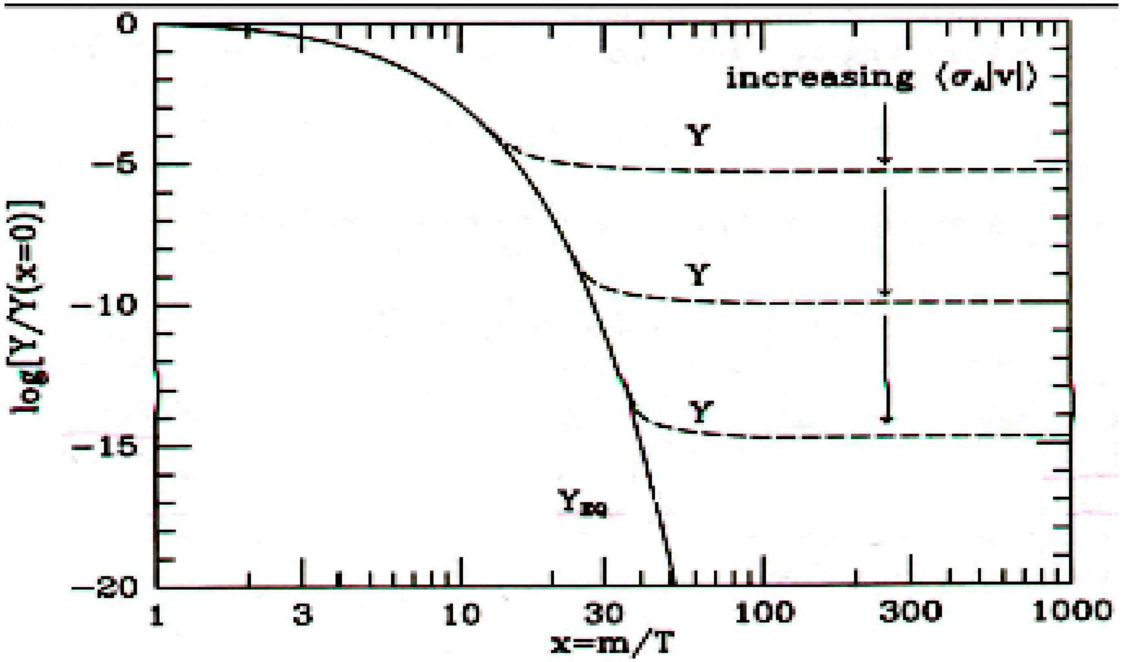
Evolution of Dark Matter Density

$$\frac{dn}{dt} = -3Hn - \langle \sigma_{eff} v \rangle (n^2 - n_{eq}^2), \qquad n_{eq} \approx \exp(-m/T)$$

$\langle \sigma_{eff} v \rangle$ Thermal average of (co-)annihilation cross section

$$Y = \frac{n}{s}$$

$$s \approx g_* T^3$$



$$\Omega \simeq \frac{2\ 10^{-10}\mathrm{GeV}^{-2}}{\sigma_{\rm eff} v}$$