The Next Revolution in Particle Physics: Prospects for New Phenomena at the LHC

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CPS Seminar

28 November 2001

- Where We Stand
  - Standard Model
  - Higgs boson
  - Unification & hierarchy problems
- Beyond the Standard Model
  - Supersymmetry
  - Extra dimensions (large/small)
- Large Hadron Collider
  - Accelerator & experiments
  - Simulations
- Conclusions/Remarks

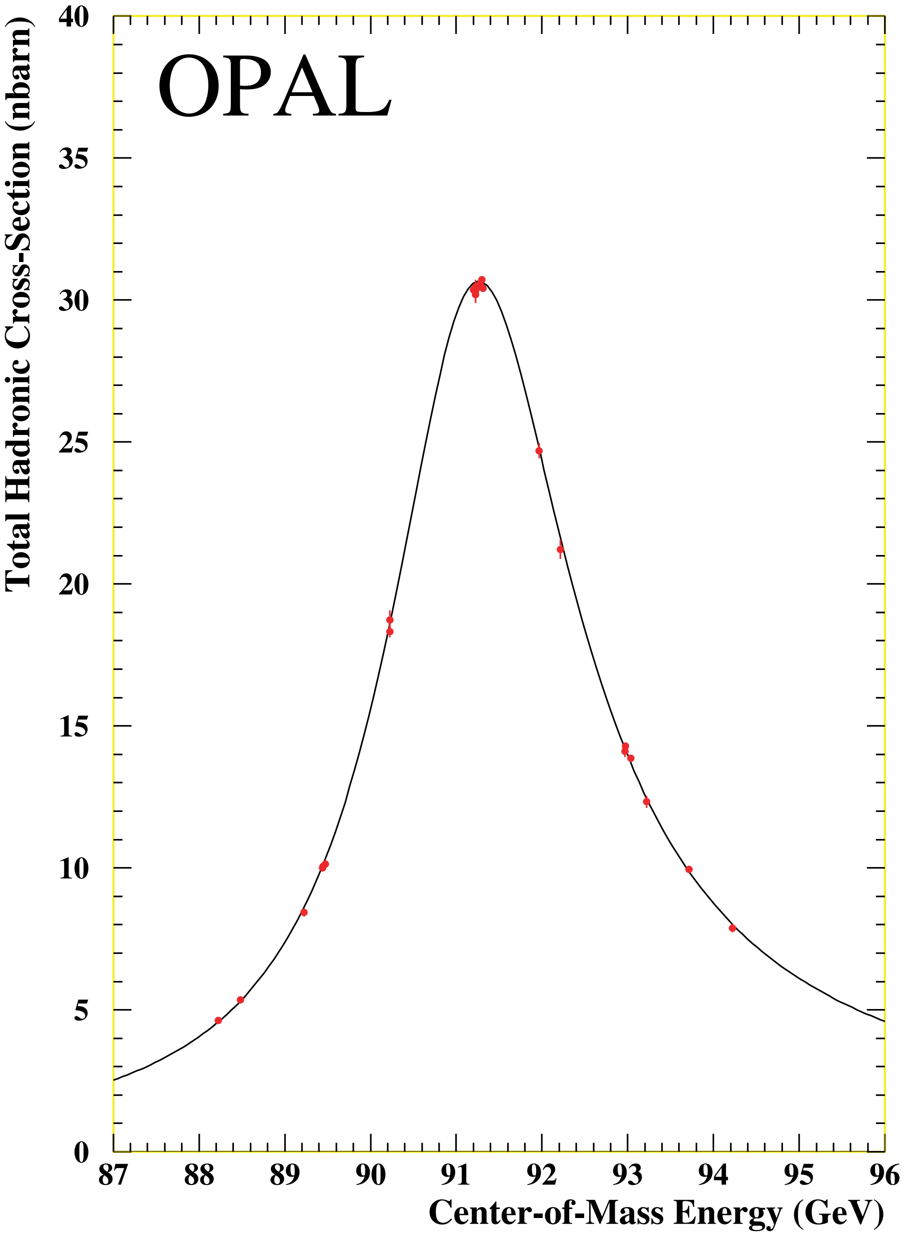
The Standard Model

- SU(3)×SU(2)×U(1) gauge field theory
  - SU(3) = quantum chromodynamics, unbroken "colour" symmetry of strong interactions
  - SU(2) = electroweak isospin (I) symmetry, spontaneously broken by vacuum
  - U(1) = electroweak hypercharge (Y), also spontaneously broken
- Unbroken residual $U_{em}(1)$ gauge symmetry = electromagnetism ($Q = I_3 + Y$)
- Chiral gauge theory (R≠L) ⇒ particles can get mass only through gauge symmetry breaking
- Symmetry breaking is due to non-zero vacuum expectation value of $I = \frac{1}{2}$ complex scalar Higgs field (4 d.o.f.)
  - 3 d.o.f. of Higgs field are "eaten" by electroweak gauge bosons (W^+, W^-, Z^0) to give them mass
- Only undiscovered SM particle is Higgs boson H^0, the quantum of remaining d.o.f. of Higgs field

The Standard Model

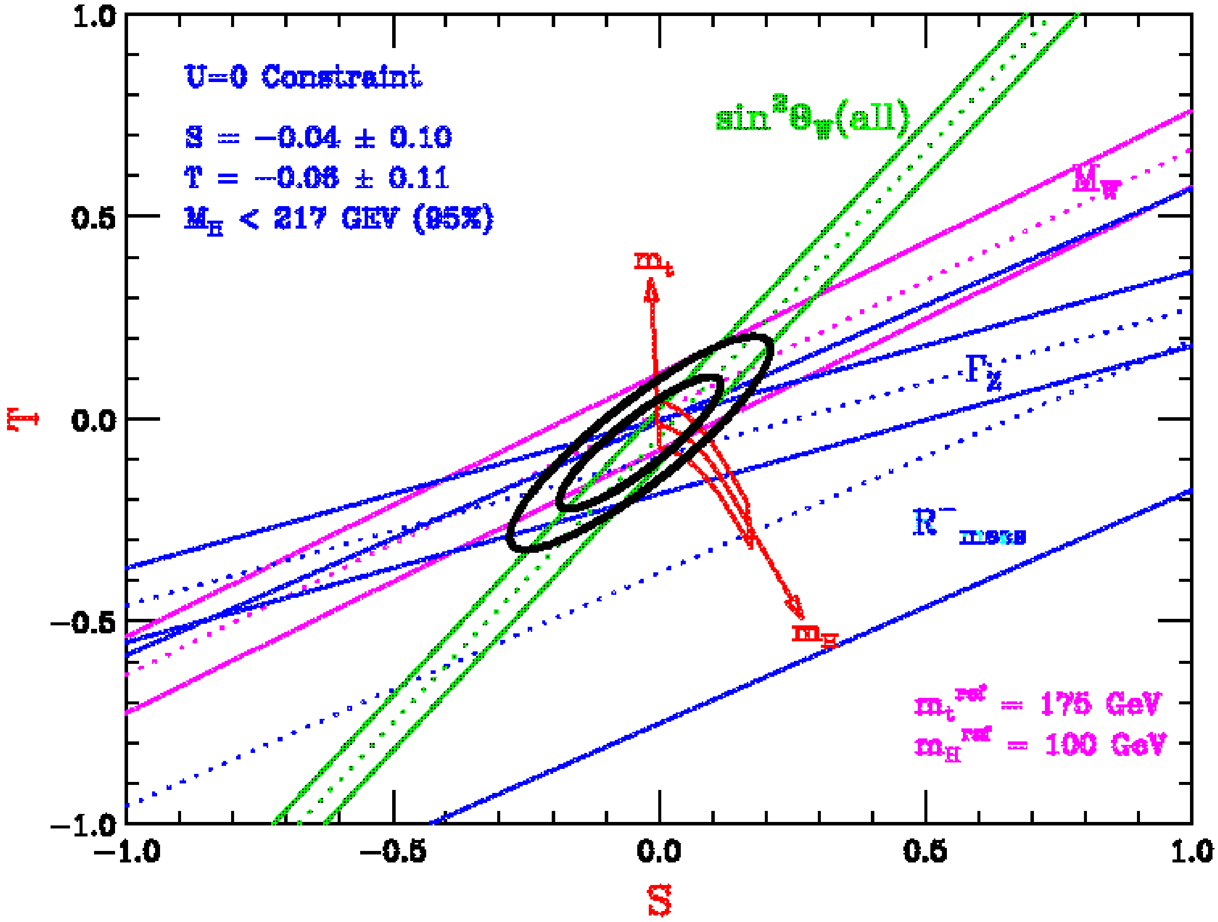
	SPIN 0	SPIN 1/2	SPIN 1
MATTER		QUARKS u,d,s,c,b,t LEPTONS $e, \nu, \mu, \nu, \tau, \nu$	
FORCES			GAUGE BOSONS γ, W,Z, g
MASS	HIGGS BOSON H^0		

- Electroweak sector verified to high precision ($\sim 10^{-5}$)



$$M_Z = 91.1882 \pm 0.0022 \text{ GeV}$$
$$\Gamma_Z = 2.4952 \pm 0.0026 \text{ GeV}$$

- Electroweak radiative corrections are tightly constrained around SM values

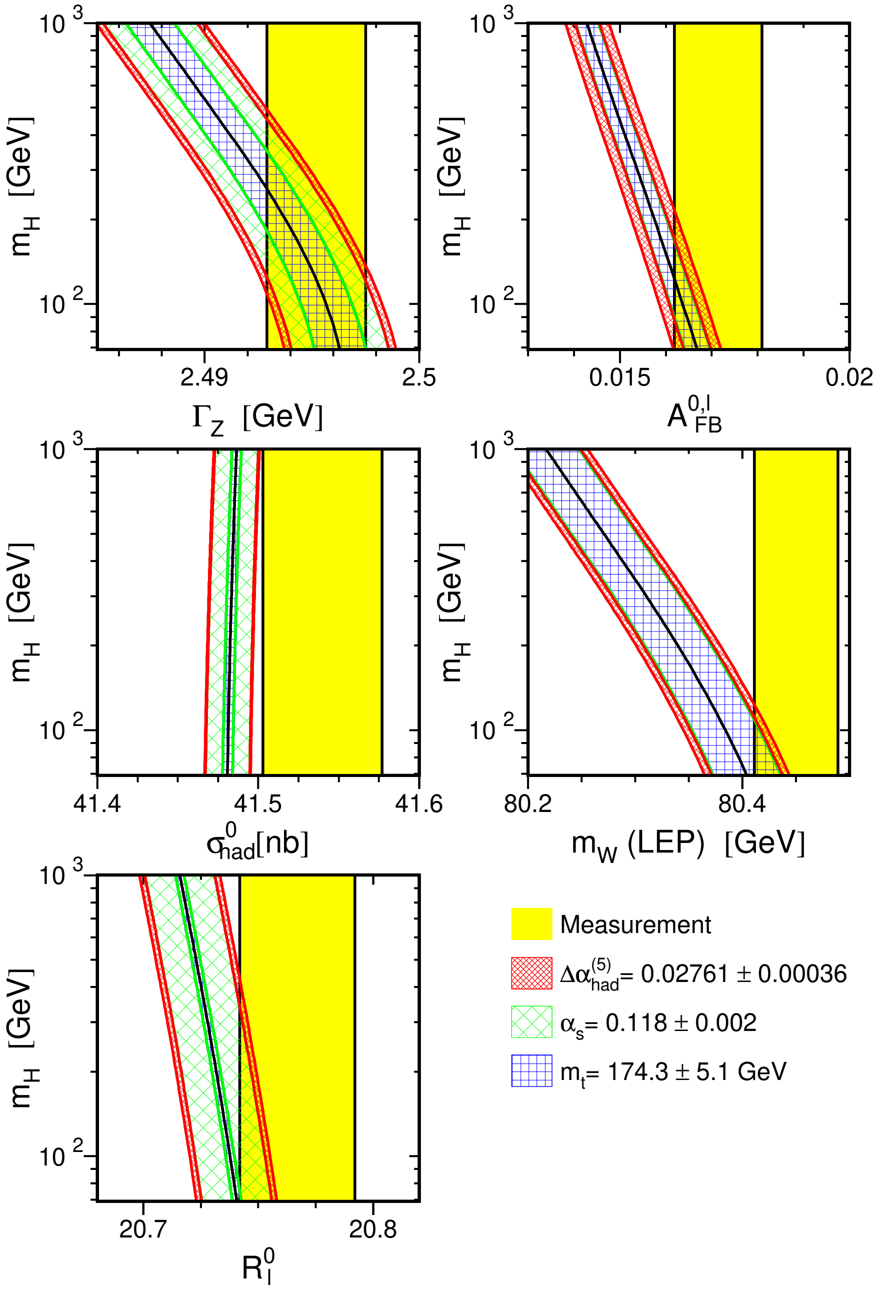


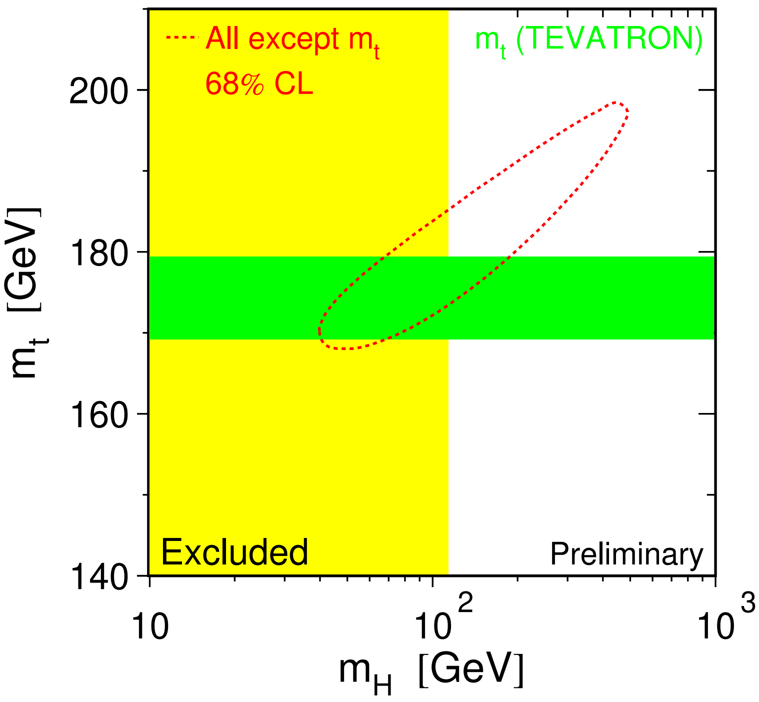
- In particular composite models of SM particles are practically excluded.

The Higgs Boson

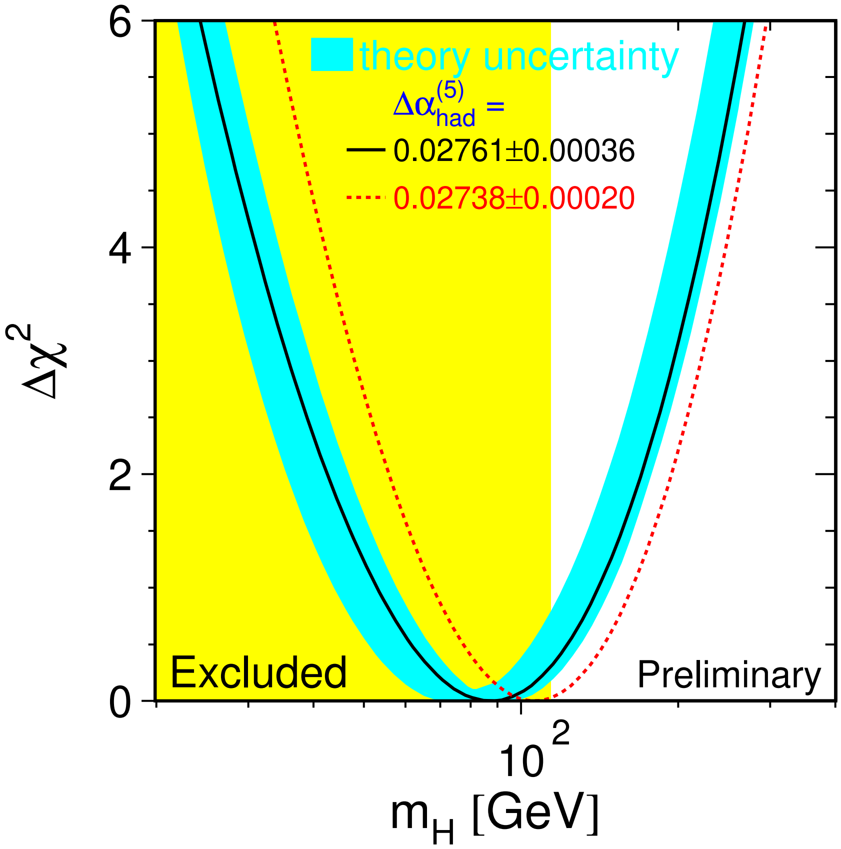
- Data are in excellent agreement with SM hypothesis that electroweak symmetry breaking is due to a single elementary Higgs doublet.

  - Higgs mass must be low.





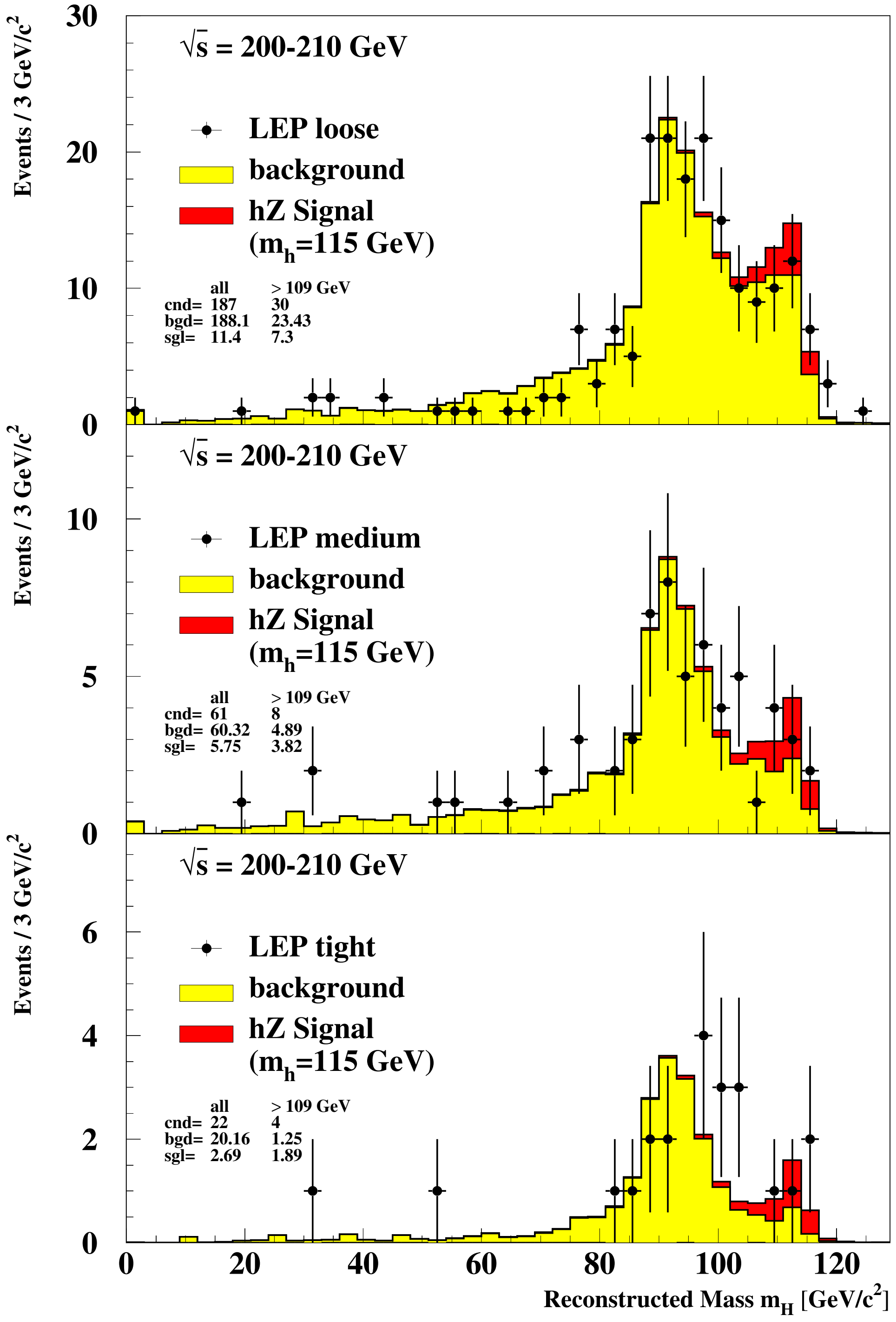
All except m_t
68% CL
m_t (TEVATRON)
200
180
160
140
m_t [GeV]
Excluded
Preliminary
10
10^2
10^3
m_H [GeV]



theory uncertainty
$\Delta\alpha^{(5)}_{had}$ =
0.02761±0.00036
0.02738±0.00020
6
4
2
0
$\Delta\chi^2$
Excluded
Preliminary
10^2
m_H [GeV]

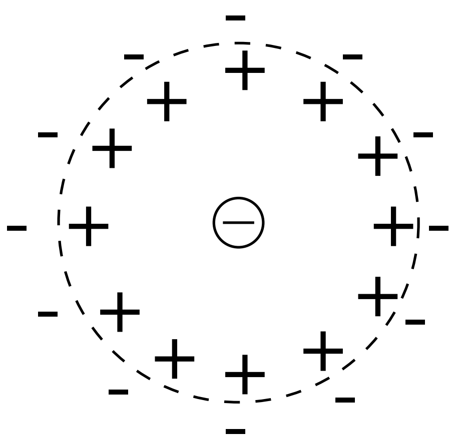
- There are (weak) indications that $m_H \sim 115$ GeV.

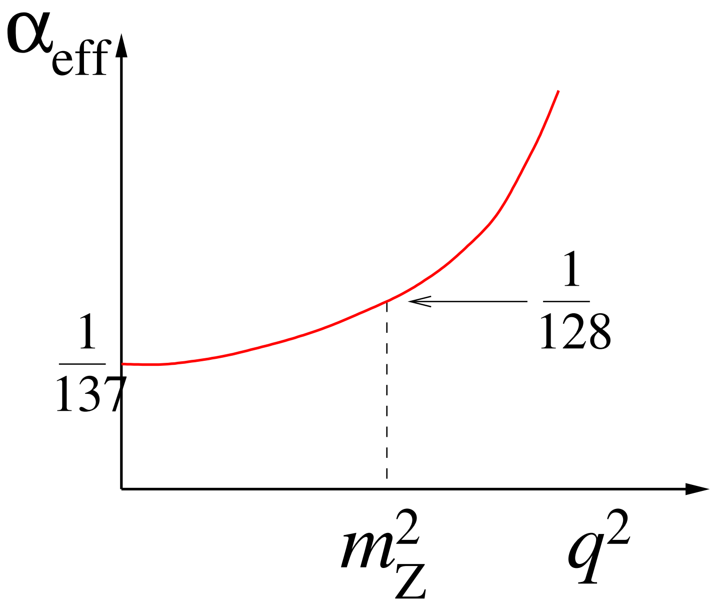
Reconstructed mass distributions



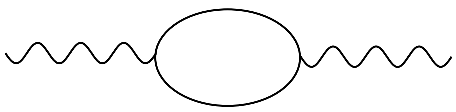
Running Couplings

- In QED the observed electron charge is distance-dependent ($\Rightarrow$ momentum transfer dependent) due to vacuum polarization:





- The one-loop vacuum polarization diagram



gives

$$q^2 \frac{d\alpha}{dq^2} = \frac{\alpha^2}{3\pi} > 0$$

Therefore $\alpha \to \infty$ at large q^2 (short distances).

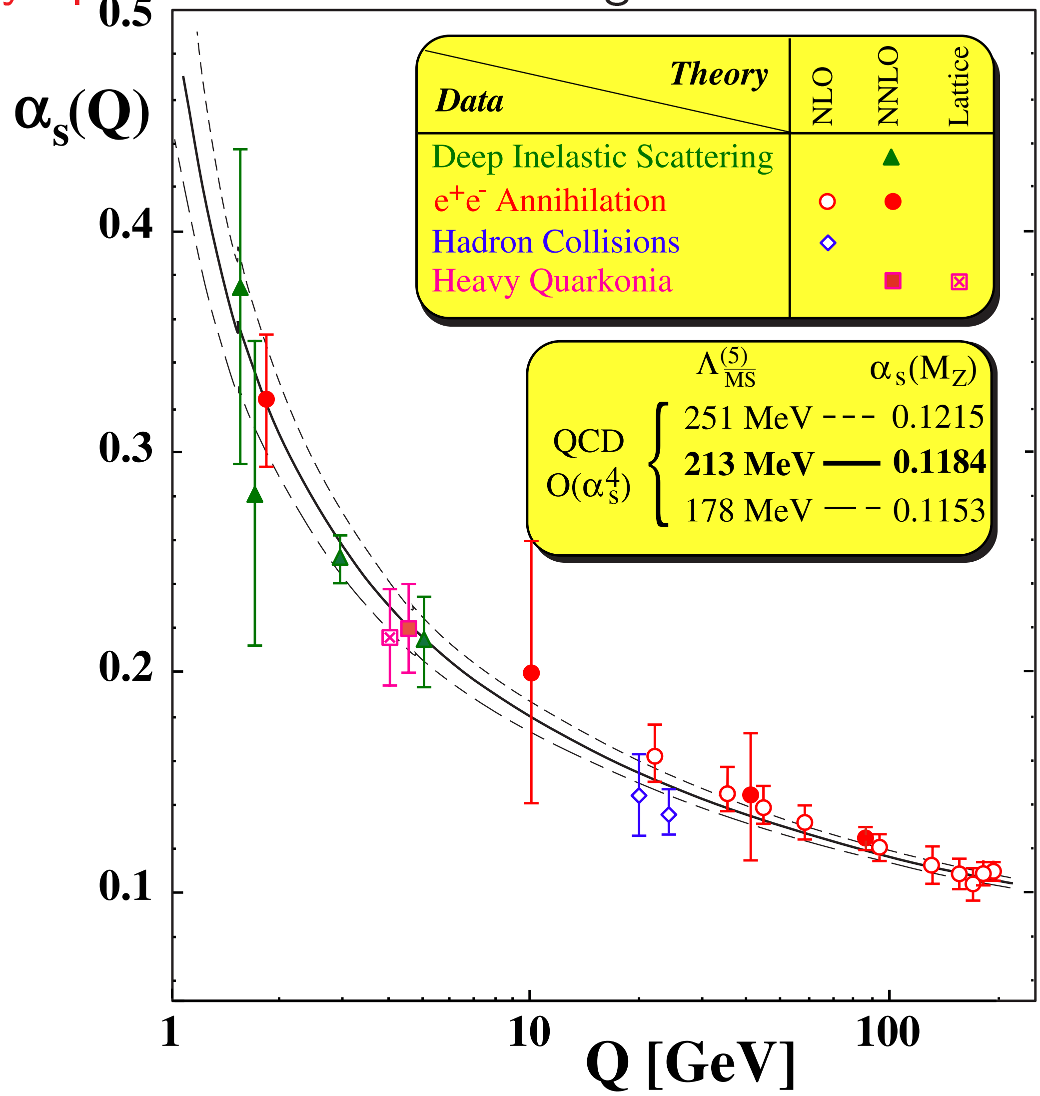
- More generally, contribution from particles of spin S is

$$q^2\frac{d\alpha}{dq^2} = -\frac{\beta_0}{2\pi}\alpha^2$$

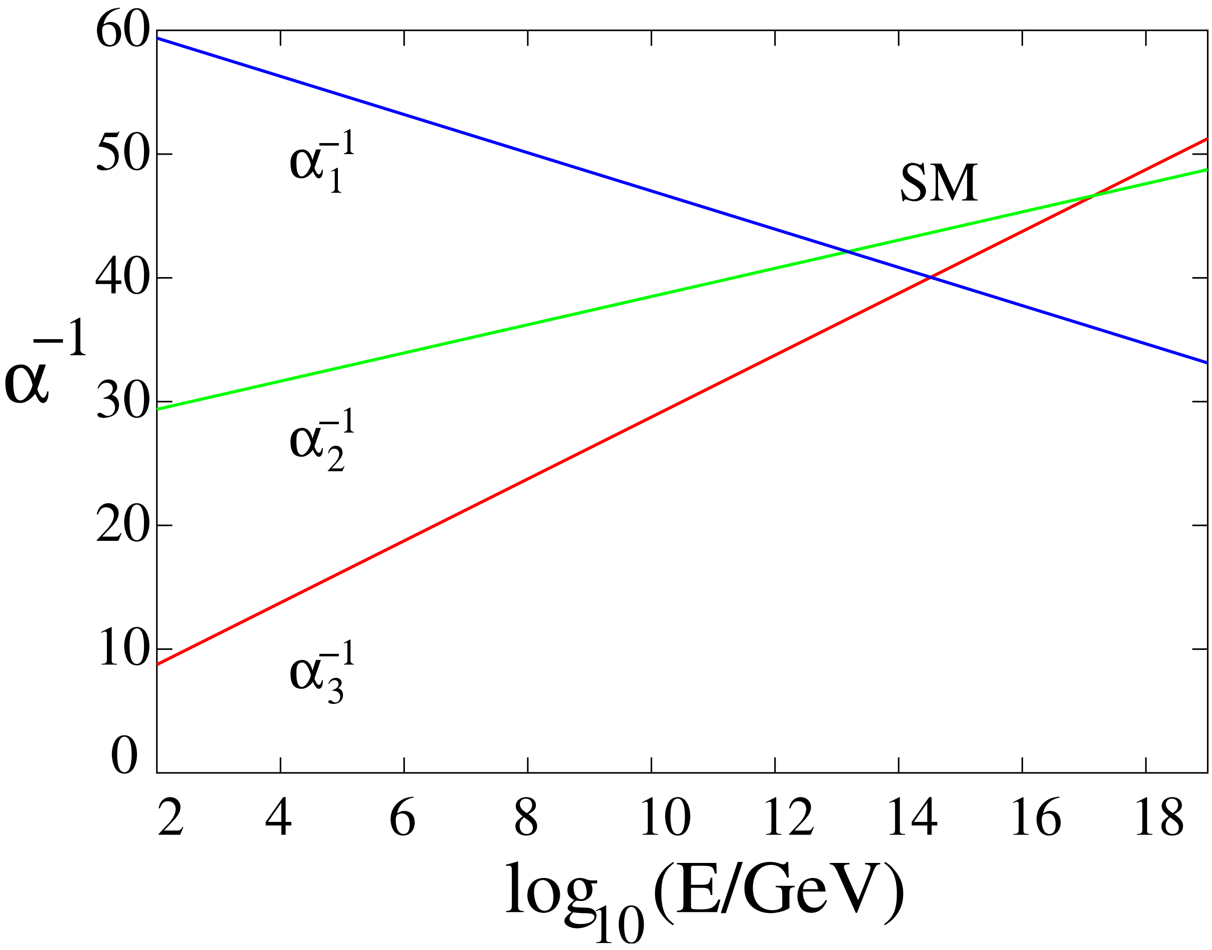
$$\beta_0 = (-1)^{2S}\left[(2S)^2-\frac{1}{3}\right]$$

$$= -\frac{1}{3}\,,\quad -\frac{2}{3}\,,\quad +\frac{11}{3}\quad \text{for } S=0\,,\ \frac{1}{2}\,,\ 1\,.$$

- SU(3) gets large contributions from gauge boson loops $\Rightarrow$ asymptotic freedom of strong interaction.

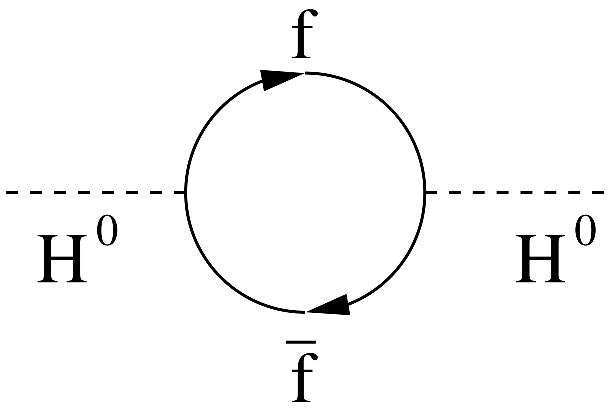


- SU(2) also asymptotically free in SM $\Rightarrow$ (not quite) high-scale unification.



The Hierarchy Problem

- Higgs mass receives large quantum corrections



$\Rightarrow$ need to introduce ultraviolet cutoff Λ to regularize loop integral

$$\delta M^2_{H\,f} = \frac{|g_f|^2}{16\pi^2}\left[-2\Lambda^2 + 6m_f^2 \ln\left(\Lambda/m_f\right)\right]$$

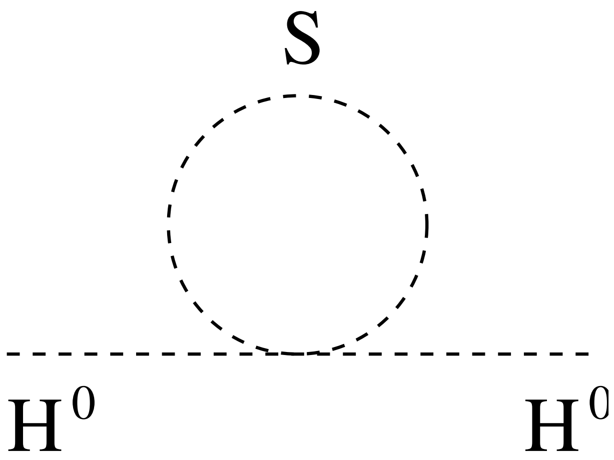
$\Rightarrow$ either the Higgs mass is at the GUT/Planck scale or there is a cancellation

$$M_H^2 = M^2_{H\,\mathrm{bare}} + \delta M_H^2,$$

of over 30 orders of magnitude for a light Higgs boson (or else $\Lambda \lesssim$ TeV without spoiling SM)

Supersymmetry

- A scalar loop contribution to the Higgs propagator



would give a contribution to the Higgs mass

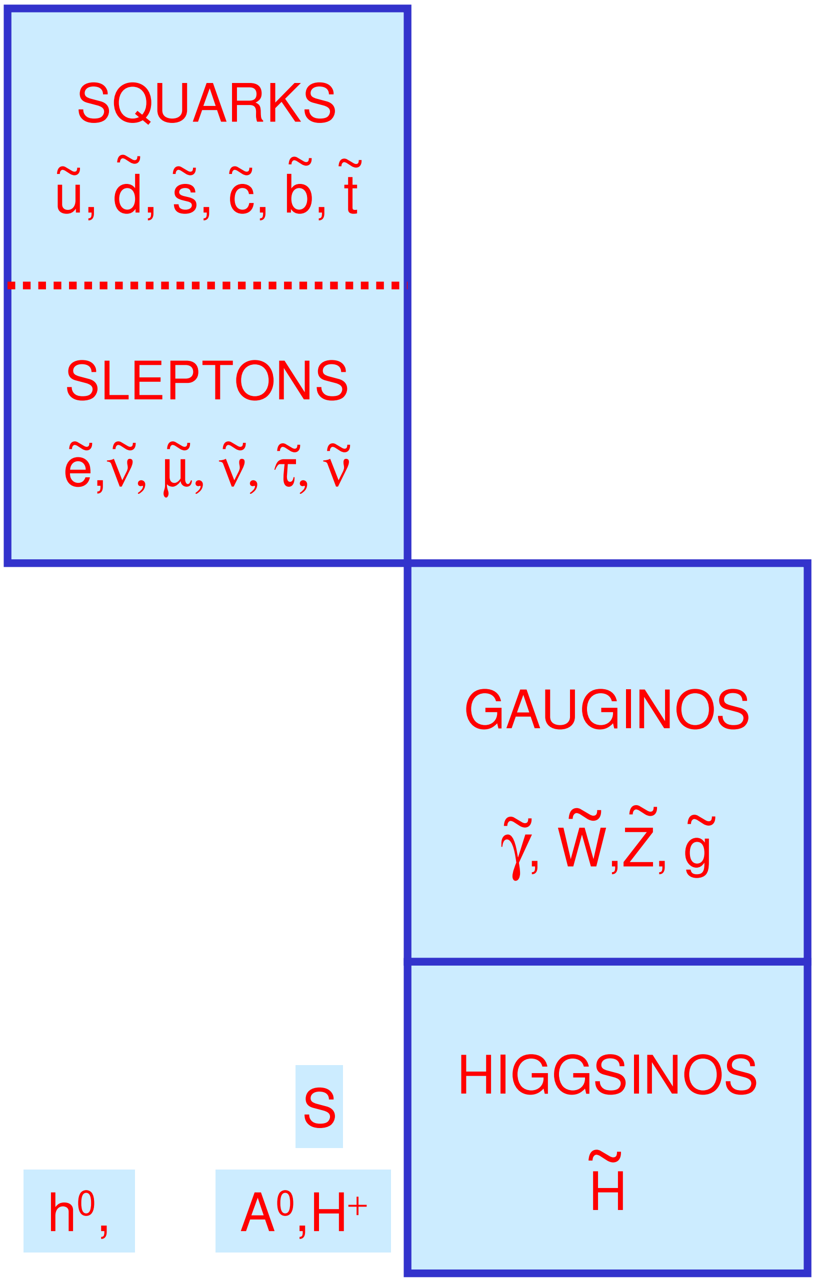
$$\delta M_{H\,S}^2 = \frac{\lambda_s}{16\pi^2}\left[\Lambda^2 - 2M_S^2 \ln\left(\Lambda/M_S\right]\right)$$

- So if there are two scalar particles for every fermion, with coupling $\lambda_s = |g_f|^2$, the quadratic dependence cancels.

- This is natural in theories with supersymmetry (SUSY).
  - Sleptons & squarks not seen $\Rightarrow$ SUSY broken
  - Scalars can get mass without breaking gauge symmetries $\Rightarrow$ SUSY breaking is "natural".
  - Similarly for fermionic gauginos.
  - But superpartners must not be too heavy ($\lesssim$ 1 TeV?).

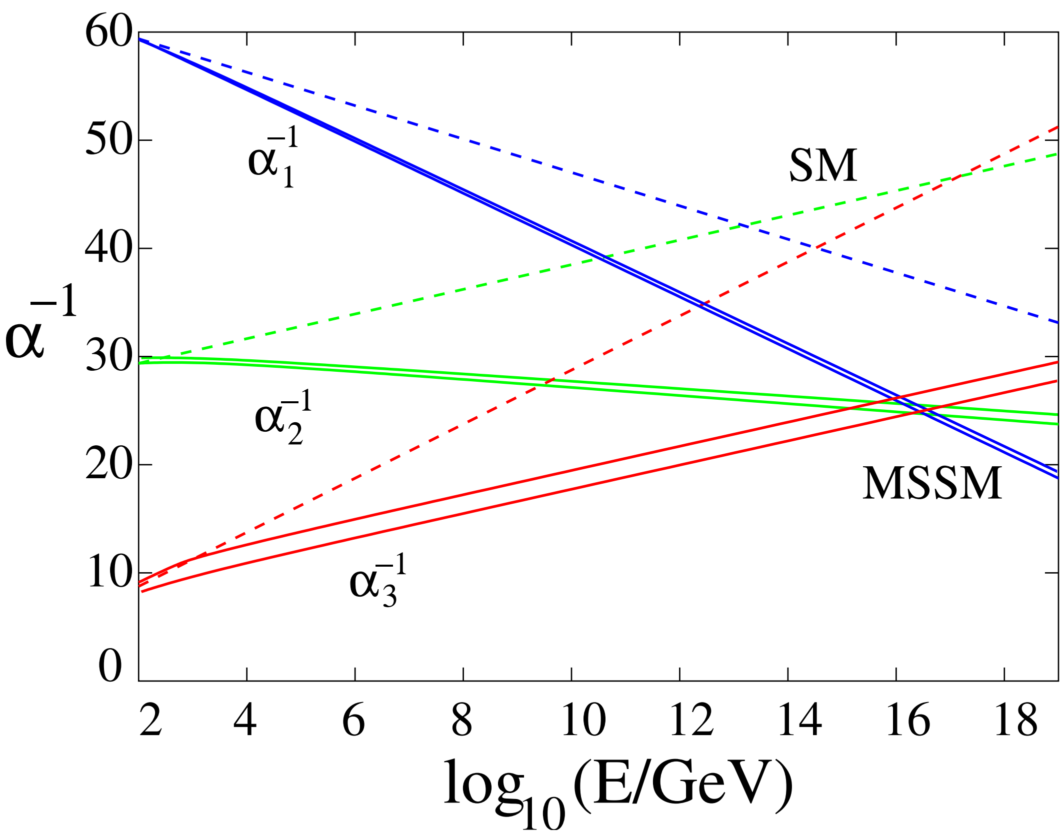
supersymmetric

Λ



Arguments for Supersymmetry

- Coupling constant unification at $\sim 10^{16}$ GeV



- Higgs mass: $m_H \ll \Lambda$; typically $m_H < 150$ GeV

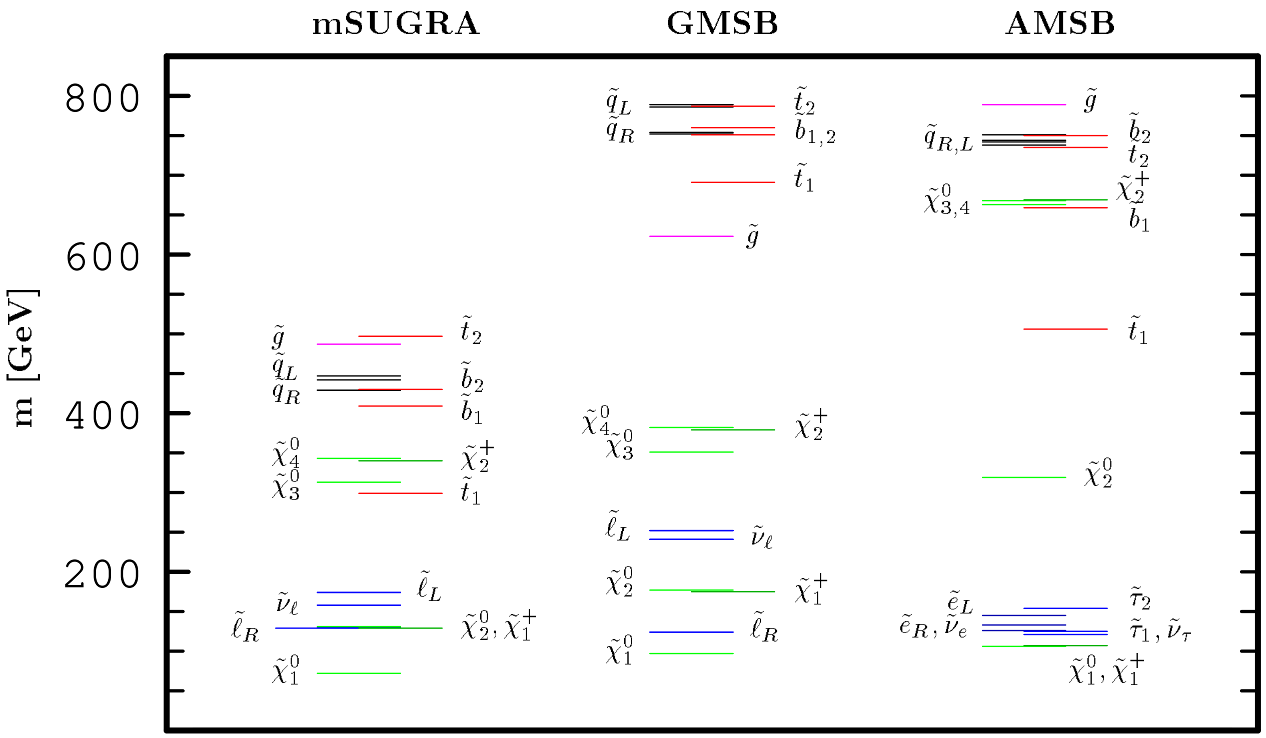
- Other good features:
  - No great radiative corrections at LEP
  - Lightest SUSY particle (LSP) = dark matter candidate
  - Neutrino mass "natural"

$$m_\nu \sim m_t^2/M_{\text{GUT}} \sim 175^2/10^{16}\ \text{GeV}\ \sim\ \text{few meV}$$

  - Radiative electroweak symmetry breaking
  - $(g-2)_\mu$ consistent with data

Spectrum of SUSY particles

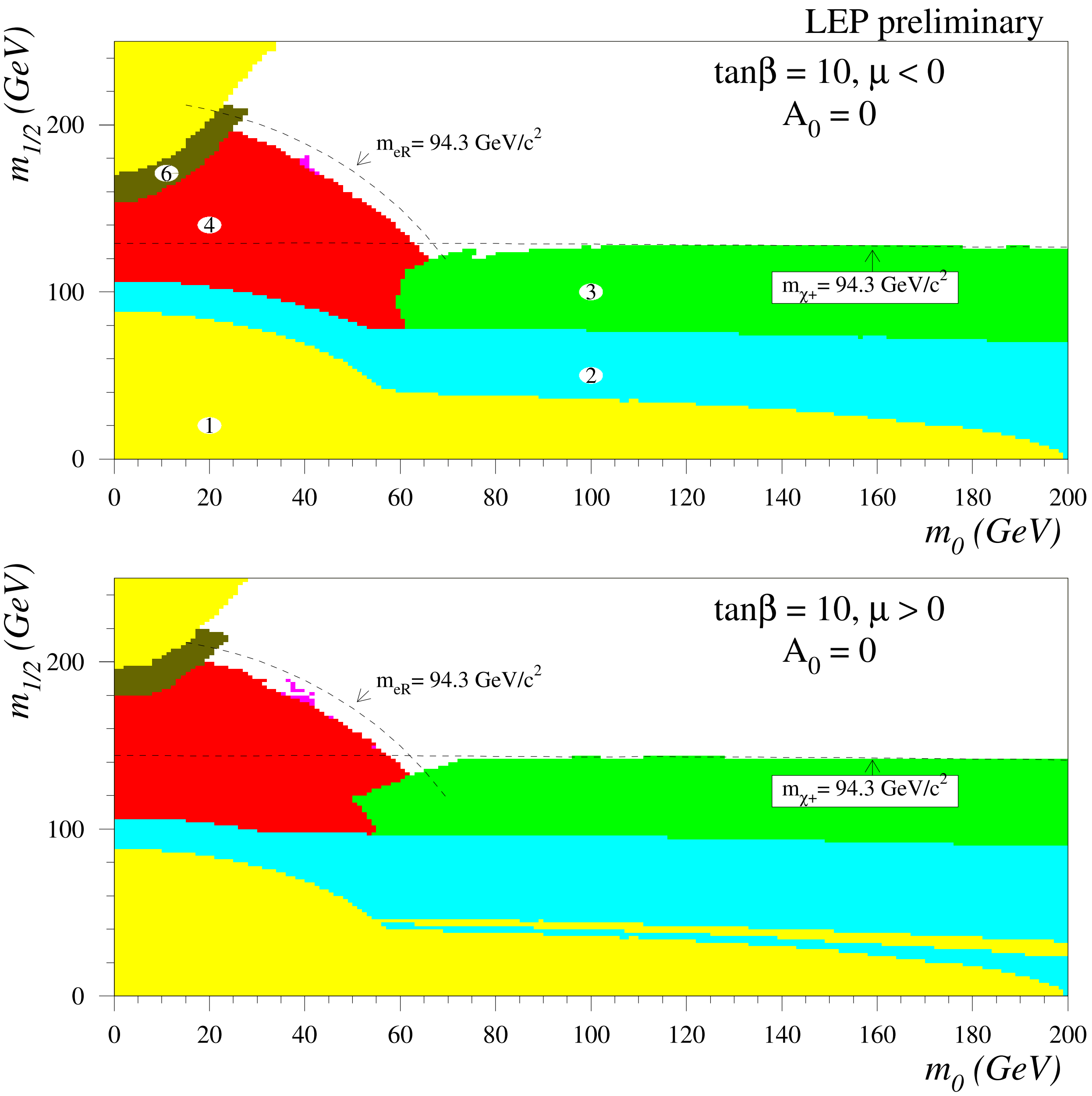
- Need 2 Higgs doublets $\Rightarrow$ extra Higgs bosons
- Higgsinos mix with electroweak gauginos $\Rightarrow$ neutralinos $\tilde{\chi}^0_{1,2,3,4}$ and charginos $\tilde{\chi}^\pm_{1,2}$
- Lightest neutralino $\tilde{\chi}^0_1$ is often stable LSP
- Further details depend on model for SUSY breaking



- SUGRA (gravity-mediated) model has universal scalar and gaugino mass parameters $(m_0, m_{1/2})$ at GUT scale.

- LEP limits in this model:

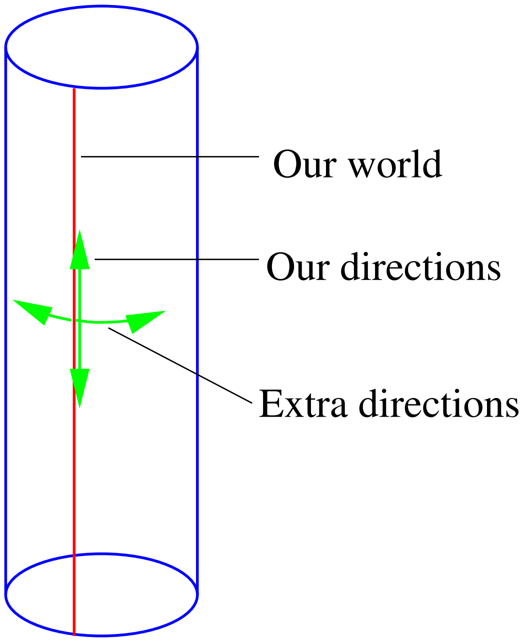
$$m(\tilde{\chi}_1^\pm) \sim 2\, m(\tilde{\chi}_1^0) \gtrsim 100 \text{ GeV}$$



Extra Dimensions

- Suppose space has n extra dimensions, only detectable at short distances/high energies.

  - Standard Model forces act only in our 3+1D world
  - Gravity must act in all directions $\Rightarrow$ looks weaker
  - Extra dimensions "curled up" $\Rightarrow$ classical tests unaffected
  - (1+1) dimensional analogy:



$$V(r) = \left(\frac{\hbar}{M_0 c}\right)^n \frac{m_1 m_2}{M_0^2} \frac{\hbar c}{r^{n+1}} \quad \text{for } r \ll R$$

$$\to \quad \left(\frac{\hbar}{M_0 c}\right)^n \frac{m_1 m_2}{M_0^2} \frac{\hbar c}{R^n r} = \frac{m_1 m_2}{M_{\mathsf{Pl}}^2} \frac{\hbar c}{r} \quad \text{for } r \gg R$$

where R = size of extra dimensions, M_0 = fundamental mass scale, M_{Pl} = Planck scale $\sim 10^{19}$ GeV.

- $M_0 \sim$ TeV would "solve" hierarchy problem. Then

$$\begin{aligned} R &= \frac{\hbar}{M_0 c}\left(\frac{M_{\mathsf{Pl}}}{M_0}\right)^{\frac{2}{n}} \\ &= 10^{13}\,,\ 10^{-3}\,,\ 10^{-9}\ \mathrm{m} \quad \text{for } n = 1\,,\ 2\,,\ 3 \end{aligned}$$

- This is "large extra dimension" (ADD) scenario.
  - Energy hierarchy replaced by size hierarchy.
- In "warped (small) extra dimension" (RS) models,

$$R \sim e^A \frac{\hbar}{M_{\mathsf{Pl}} c}$$

  - Warp factor $A \sim 40$ solves hierarchy problem.
- Particle collisions can excite resonances of gravitational field in extra directions.
  - Resonant frequencies $\Rightarrow$ size of extra dimension
  - Quanta of excitation are new particles, partners of the graviton (massless quantum of gravitational field), but with interactions and masses on Standard Model scale.

The Large Hadron Collider

- The largest machine ever built
  - 27 km (existing) tunnel
  - 7 TeV proton beams ($8000 \times mc^2$)
  - Total beam energy = 200 ton train at 200 km/hr
  - Beam spot size 30 μm
  - 1158 superconducting 15 metre 8.4 Tesla magnets
  - 700,000 litres liquid helium
  - First collisions April 2006
  - Luminosity 10^{34} cm^{-2}s^{-1}
    - $\sigma = 1$ fb $\Rightarrow$ 100 events/yr

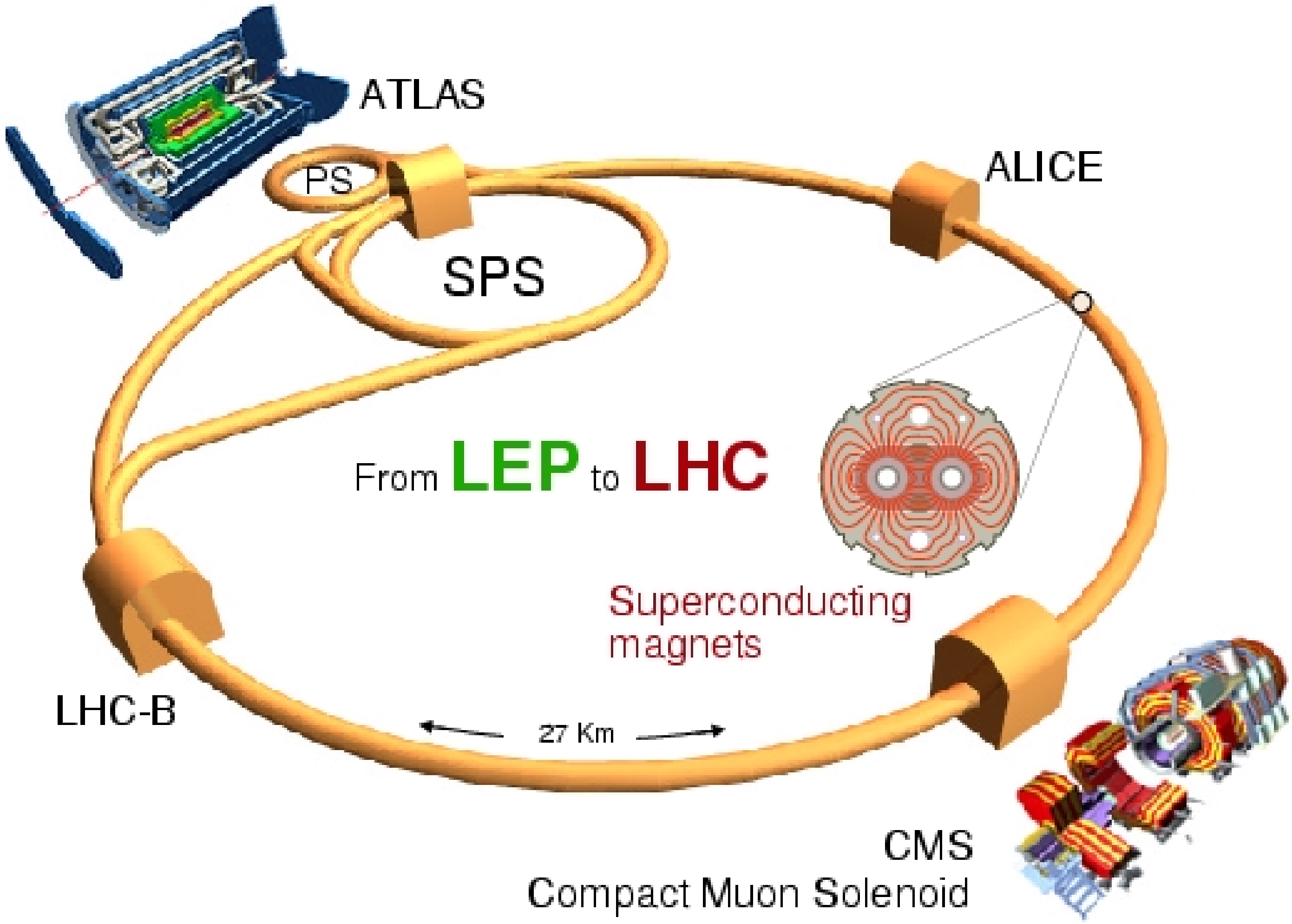
- What are we doing meanwhile?
  - Given any theory, what should happen at LHC?
  - Full event simulations, both SM and BeyondSM
  - Use these to refine theory, detector and analysis

The Large Hadron Collider (LHC)

(2006)

- New proton-proton collider being constructed inside LEP tunnel at CERN

  7 TeV + 7 TeV : $\sqrt{s} = 14$ TeV



- Two large general purpose detectors: ATLAS and CMS

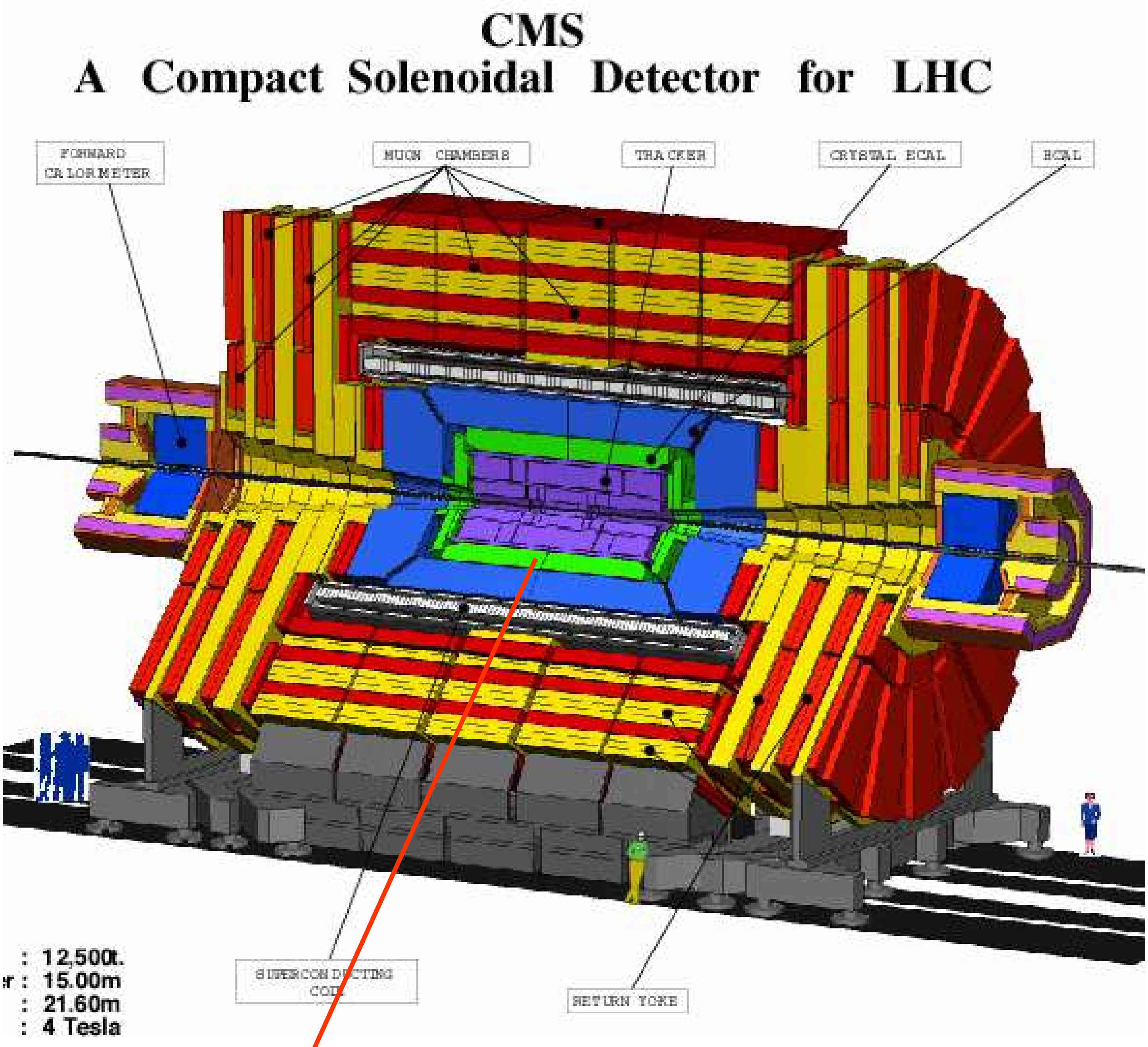
  plus CP violation expt: LHCb

  ($\sim 10^{12}$ B hadrons per year)

  plus quark-gluon plasma expt: ALICE

  (collide heavy ions, e.g. Au+Au)

The CMS Detector



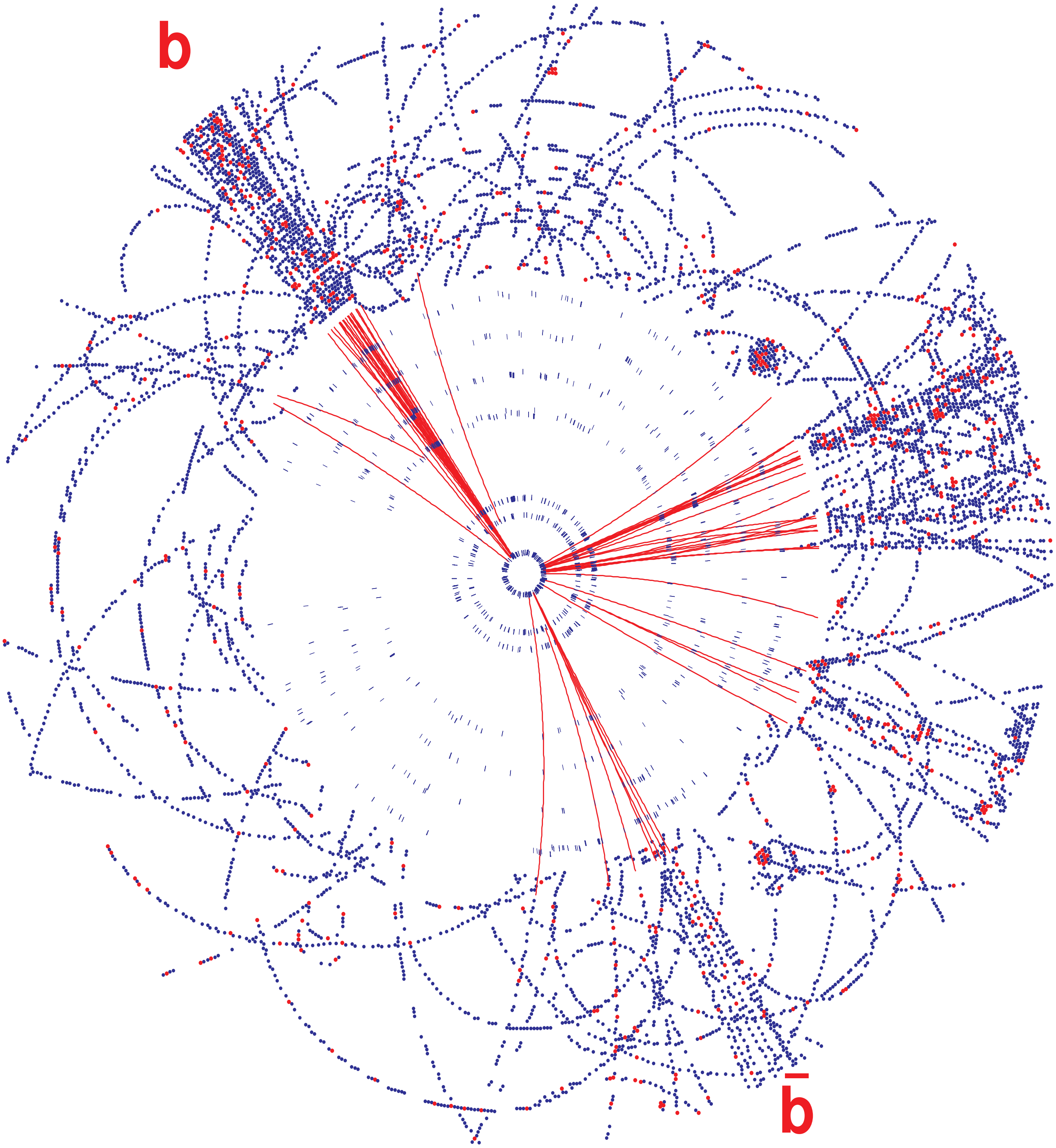
e.g. EM calorimeter:

80000 lead tungstate ($PbWO_4$) crystals

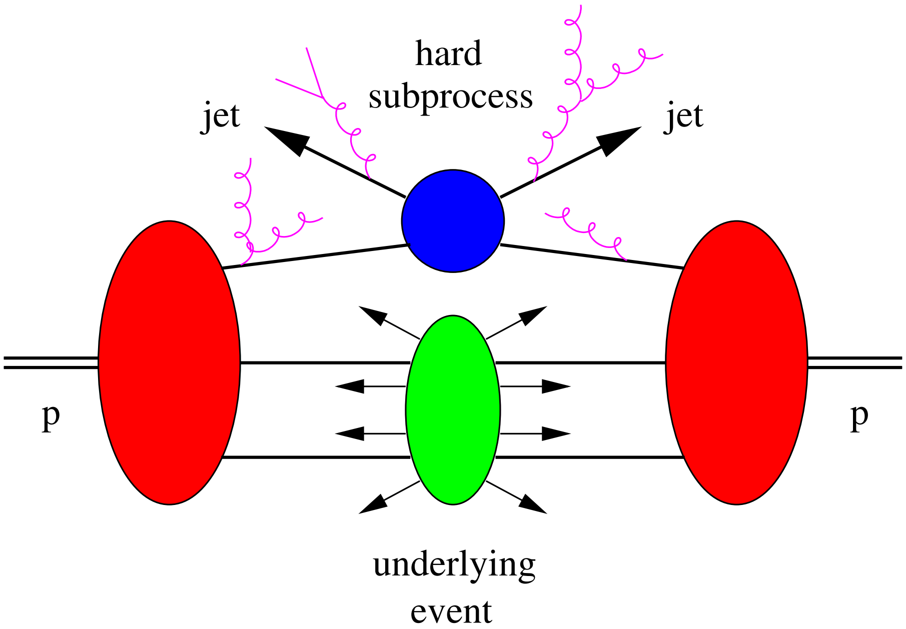
$\sigma(E)/E \sim 0.5\%$ $(H \to \gamma\gamma)$

ATLAS Barrel Inner Detector

H→b$\bar{b}$



LHC Event Simulation

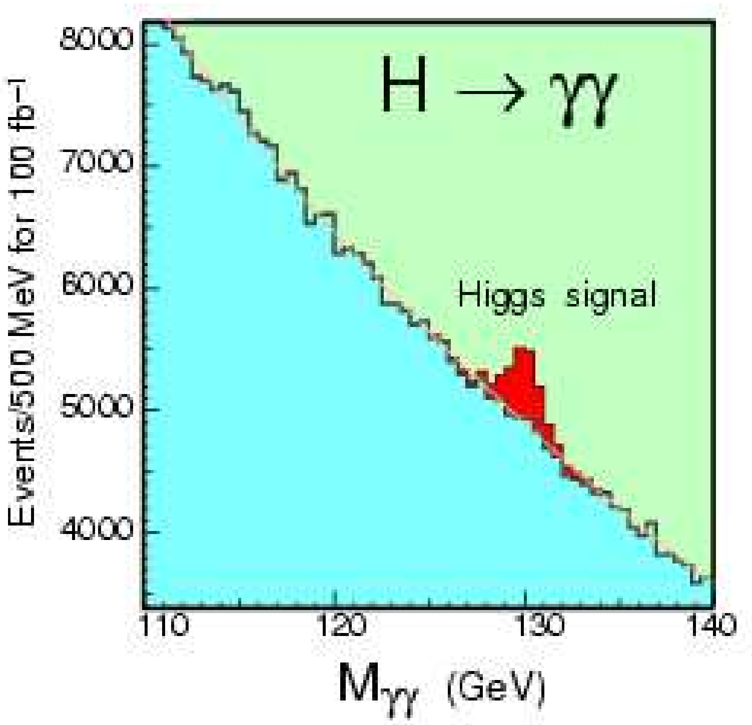


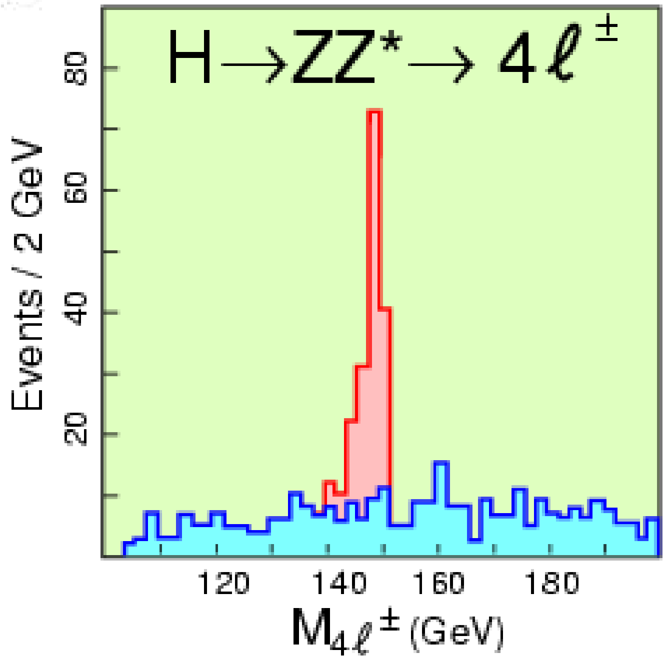
- Each collision event has several components:

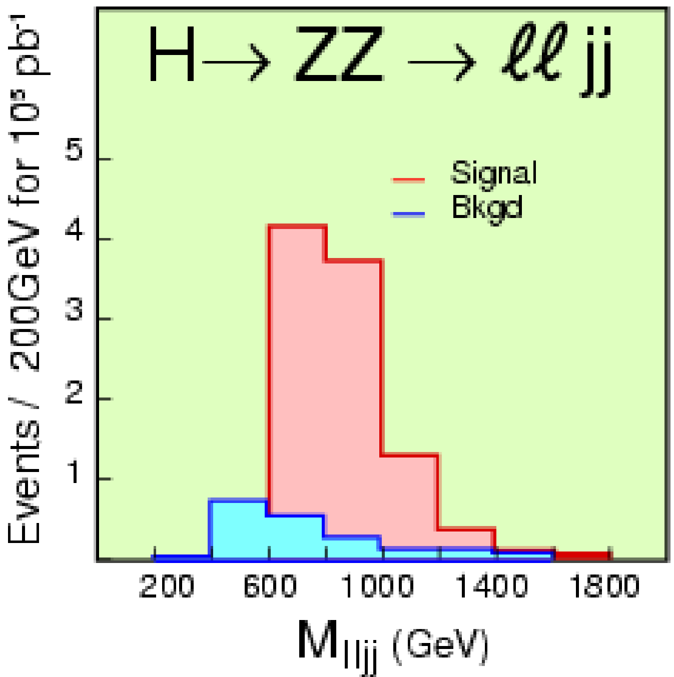
  - Constituent distributions: quarks, antiquarks, gluons
  - Hard subprocess: collision between constituents
  - Quark/gluon showering on incoming/outgoing constituents
  - Underlying event due to proton remnants
  - Hadronization: confinement of quarks and gluons.

- Hard subprocess is where new BSM physics should occur.

Future Higgs signals in CMS ?

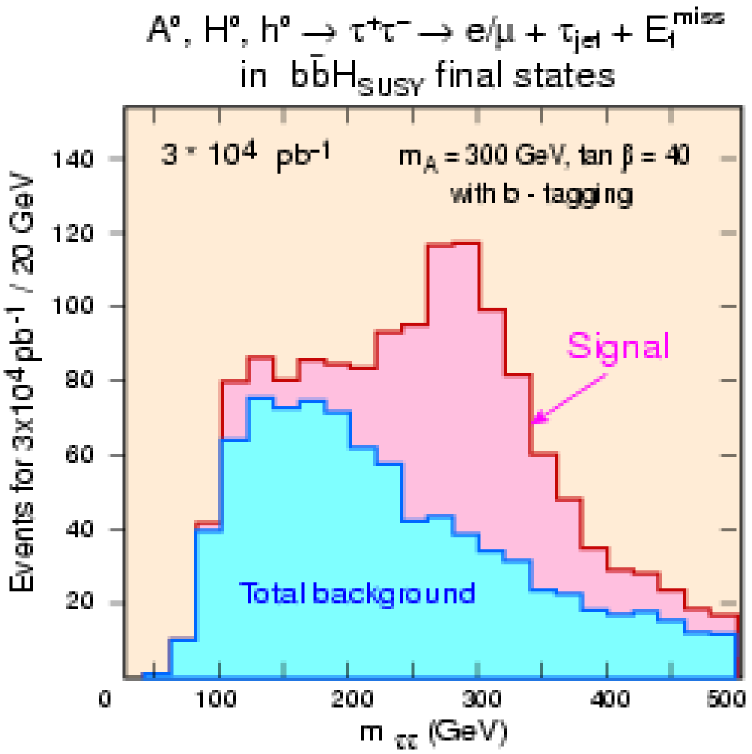


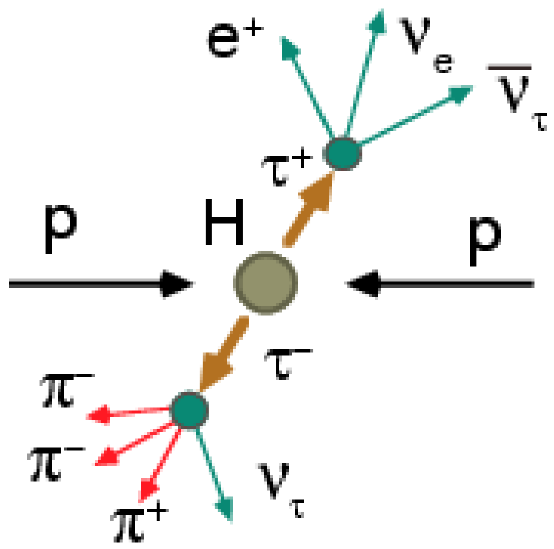




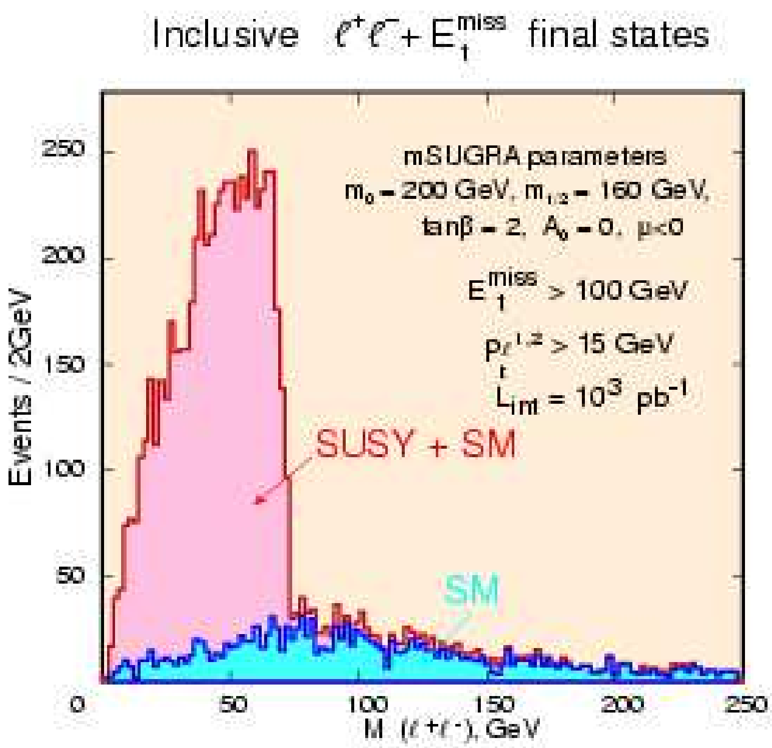
Future SUSY signals in CMS ?

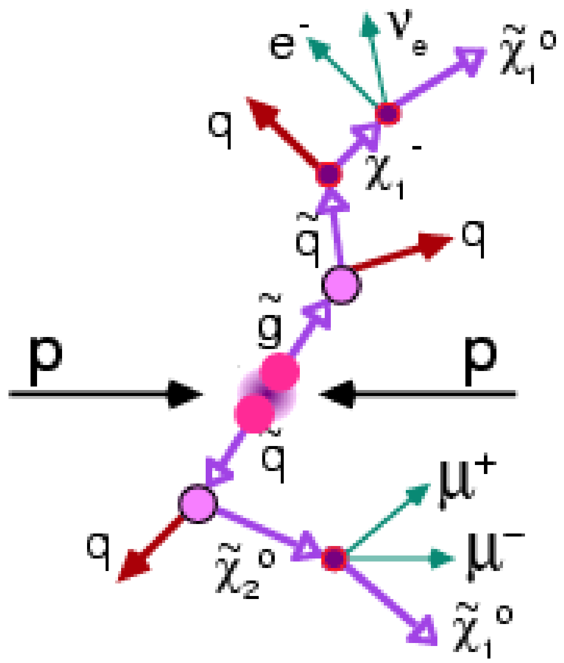
- e.g. a ~300 GeV SUSY Higgs to $\tau^+\tau^-$:





- e.g. SUSY giving missing energy plus l^+l^- :

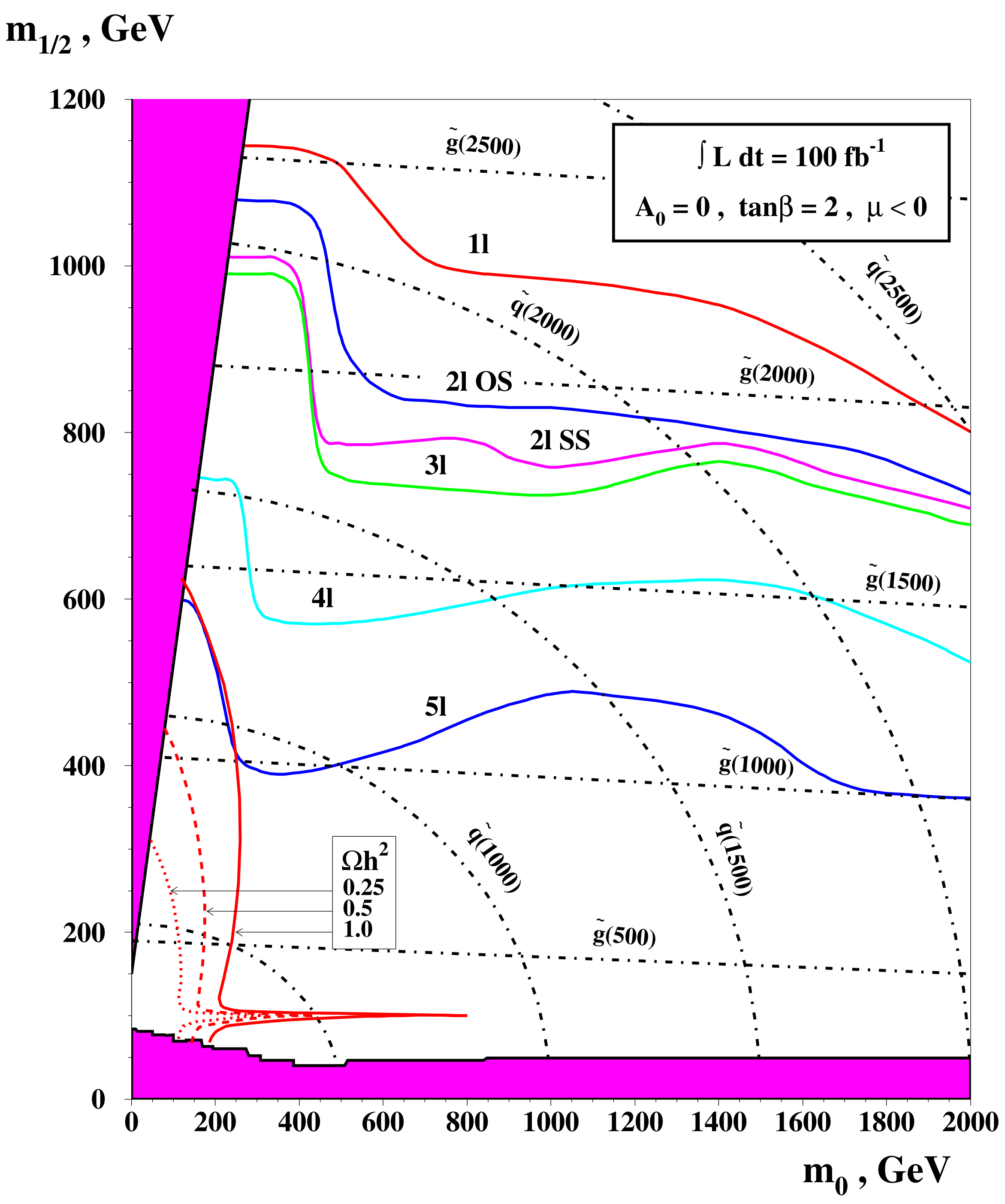




($\tilde{\chi}_1^0$ has negligible interaction cross section in detector)

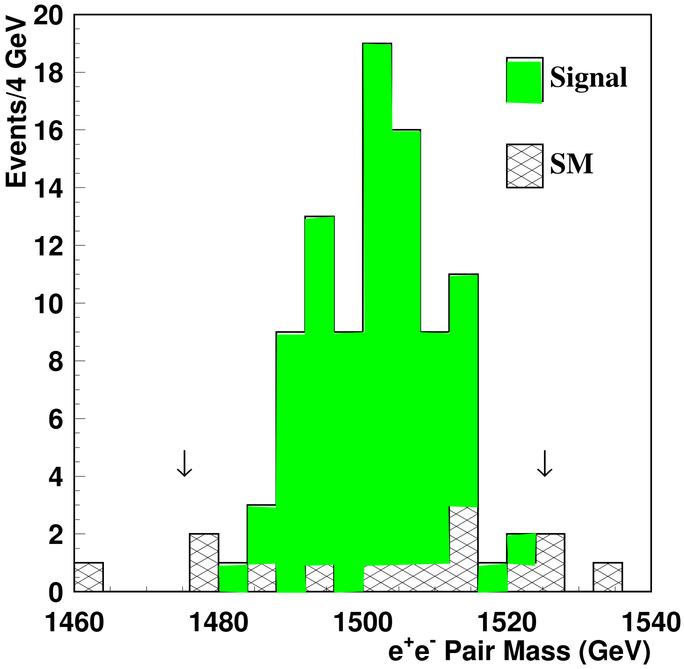
- 5σ discovery limits based on

n leptons $+ \geq 2$ jets $+$ missing energy



Graviton Resonance Production

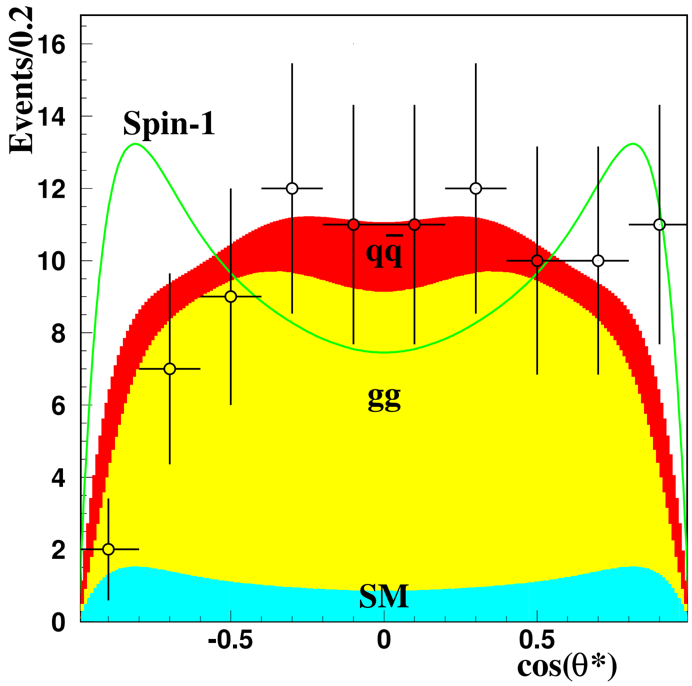
- What to look for?
  - SM interaction strength $\Rightarrow$ easily produced above energy threshold but decays promptly to SM particles
  - Interacts directly with energy-momentum $\Rightarrow$ decays "democratically" to all types of particles
  - Electrons easiest to measure $\Rightarrow$ look for resonance peak in electron-positron pairs:



  - Hatched boxes show background from SM processes
  - Width of peak is due to detector resolution.

Identifying a Graviton Resonance

- How would we know it's not e.g. a gauge boson (Z')?
  - "Democratic" interactions $\Rightarrow$ other decays, e.g. $\gamma\gamma$
  - Gravitons have spin 2 $\Rightarrow$ decay angular distribution:



  - Protons contain quarks (q), antiquarks ($\overline{q}$), gluons (g). Graviton produced only in $q\overline{q}$ and gg collisions, with characteristic decay distributions.

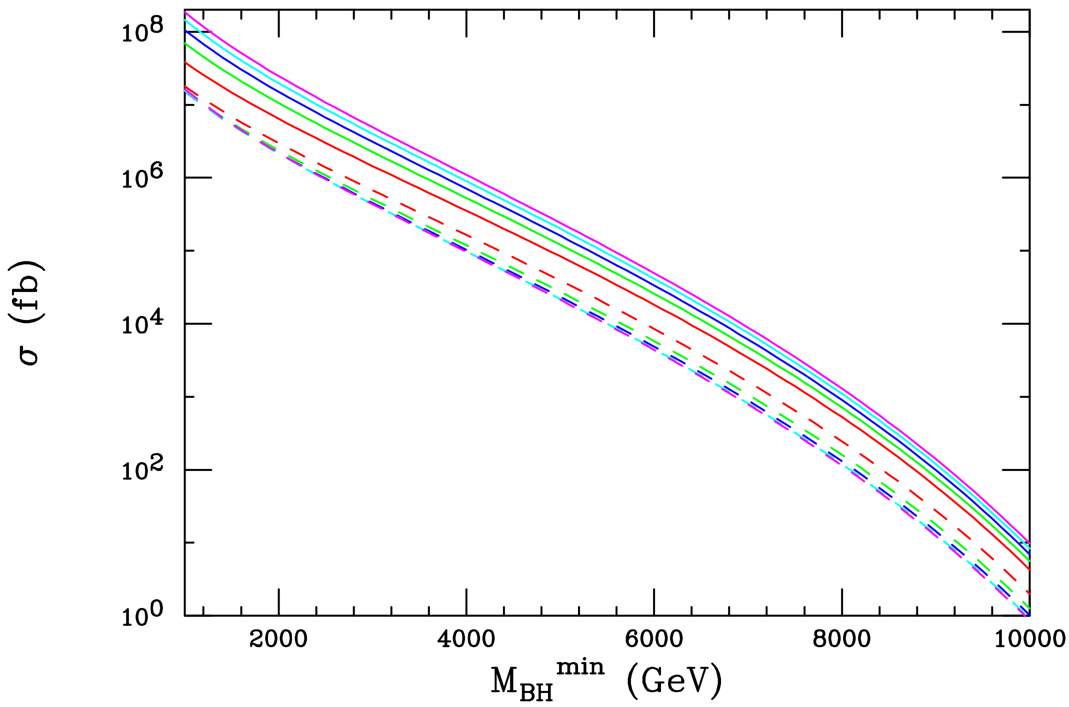
Black Hole Production

- Black hole radius (assuming $r_h \ll R$)

$$V(r_h) = \left(\frac{\hbar}{M_0 c}\right)^n \frac{m_h^2}{M_0^2}\frac{\hbar c}{r^{n+1}} \sim m_h c^2$$

$$\Rightarrow \quad r_h \sim \frac{\hbar}{M_0 c}\left(\frac{m_h}{M_0}\right)^{\frac{1}{n+1}}$$

- Classical approximation for cross section (somewhat controversial!) $\sigma_{\rm BH} \sim \pi r_h^2$ implies copious production (for $n = 2 \ldots 6$ extra dimensions):



- Decay (safely!) by Hawking radiation

- No event simulations yet

Conclusions/Remarks

- Standard Model is in beautiful agreement with data provided a light ($\lesssim$ 200 GeV) Higgs boson exists
  - LHC experiments can find it
- A light Higgs boson suggests TeV-scale physics beyond the Standard Model
  - Supersymmetry: is space-time really fermionic?
  - Extra dimensions: . . . and/or multi-dimensional?
  - Something completely different?
- Any of these could lead to spectacular new phenomena at LHC
  - Superpartners
  - Graviton resonances
  - Black holes
- The range of possibilities has increased in recent years
  - New mechanisms for supersymmetry breaking
  - Many models with extra dimensions
  - Latter need to confront existing data more seriously
- We need those LHC data!

Acknowledgments

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