The Abdus Salam
International Centre for Theoretical Physics

United Nations Educational, Scientific and Cultural Organization

International Atomic Energy Agency

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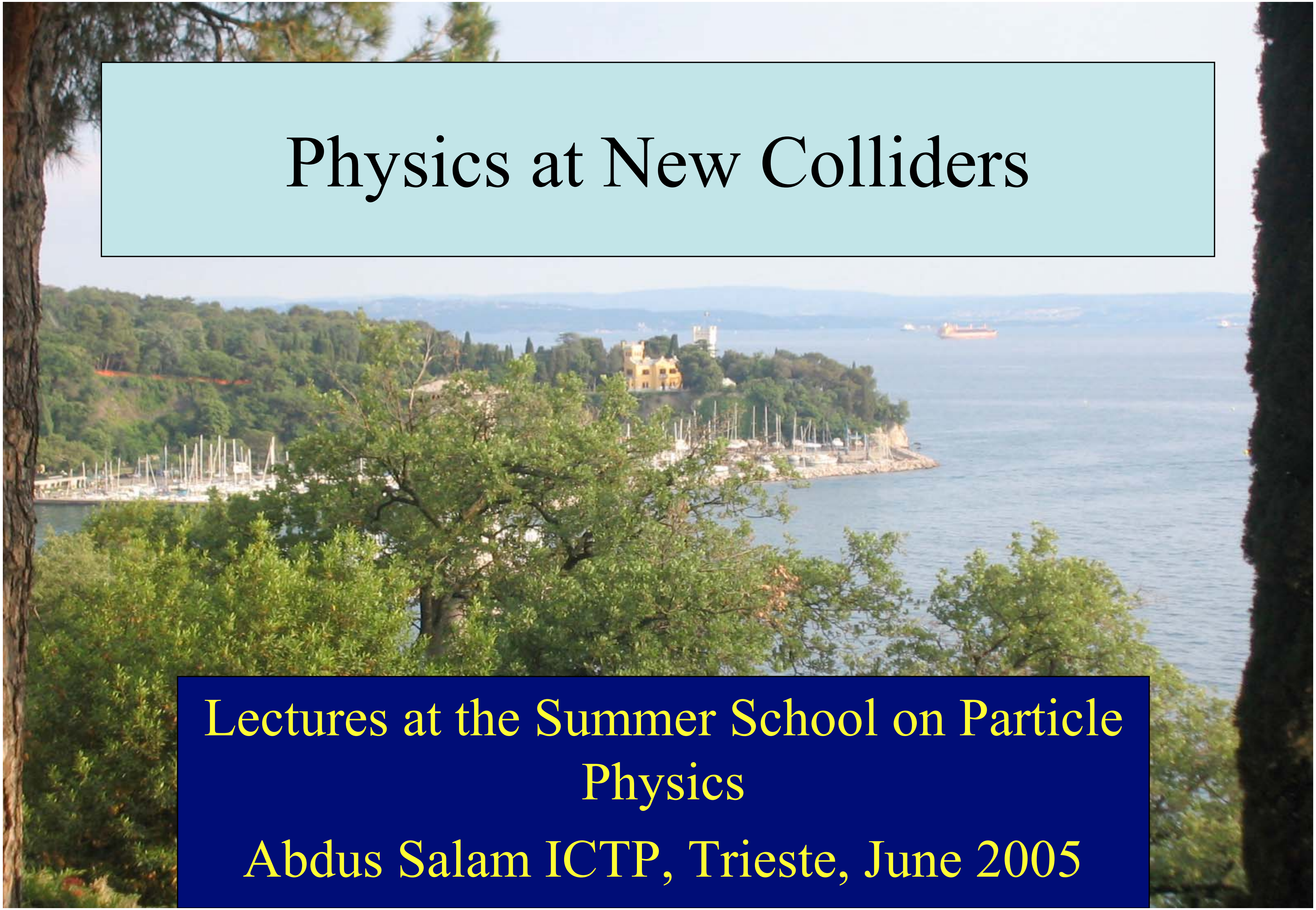
SUMMER SCHOOL ON PARTICLE PHYSICS

13 - 24 June 2005

Physics at New Colliders

J. ELLIS
C.E.R.N.
Theory Division
CH-1211 Geneva 23
SWITZERLAND

Physics at New Colliders



Lectures at the Summer School on Particle Physics

Abdus Salam ICTP, Trieste, June 2005

Plan of the Lectures

- Status of the Standard Model
- Open issues beyond the Standard Model
- Origin of particle masses
- Search for the Higgs boson
- Supersymmetry
- Searches for supersymmetry
- Possible other new physics at colliders

Summary of the Standard Model

- Particles and SU(3) X SU(2) X U(1) quantum numbers:

L_L E_R	$\begin{pmatrix}\nu_e\\ e^-\end{pmatrix}_L, \begin{pmatrix}\nu_\mu\\ \mu^-\end{pmatrix}_L, \begin{pmatrix}\nu_\tau\\ \tau^-\end{pmatrix}_L$ e_R^-, μ_R^-, τ_R^-	$(\mathbf{1},\mathbf{2},-1)$ $(\mathbf{1},\mathbf{1},-2)$
Q_L U_R D_R	$\begin{pmatrix}u\\ d\end{pmatrix}_L, \begin{pmatrix}c\\ s\end{pmatrix}_L, \begin{pmatrix}t\\ b\end{pmatrix}_L$ u_R, c_R, t_R d_R, s_R, b_R	$(\mathbf{3},\mathbf{2},+1/3)$ $(\mathbf{3},\mathbf{1},+4/3)$ $(\mathbf{3},\mathbf{1},-2/3)$

- Lagrangian:

$$\begin{aligned}\mathcal{L} &= -\frac{1}{4}F^a_{\mu\nu}F^{a\,\mu\nu} && \text{gauge interactions}\\ &+ i\bar{\psi}\,\not{D}\psi + h.c. && \text{matter fermions}\\ &+ \psi_i y_{ij}\psi_j\phi + h.c. && \text{Yukawa interactions}\\ &+ |D_\mu\phi|^2 - V(\phi) && \text{Higgs potential}\end{aligned}$$

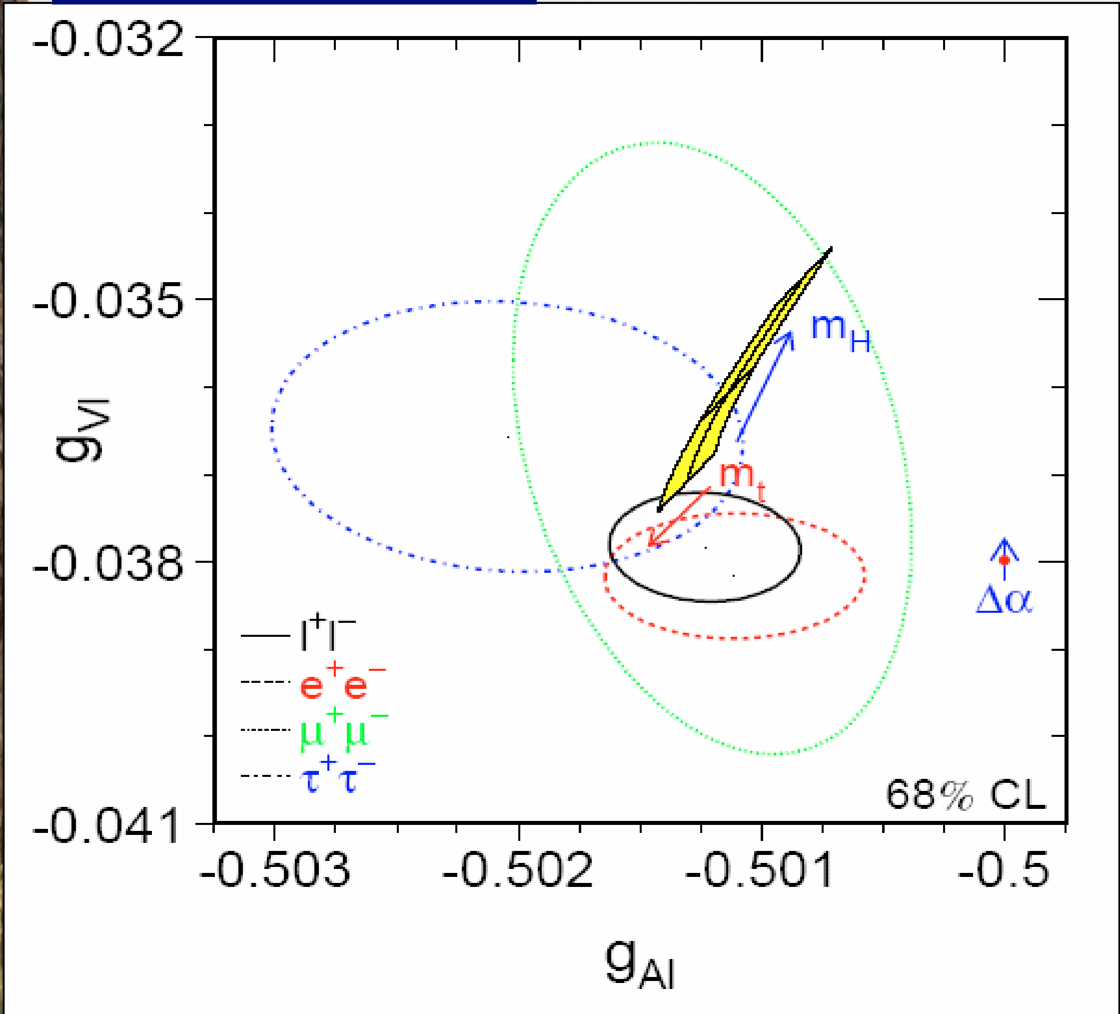
Status of the Standard Model

- Perfect agreement with all *confirmed* accelerator data
- Consistency with precision electroweak data (LEP et al) *only if there is a Higgs boson*
- Agreement seems to require *a relatively light Higgs boson* weighing < 300 GeV
- Raises many unanswered questions:

mass? flavour? unification?

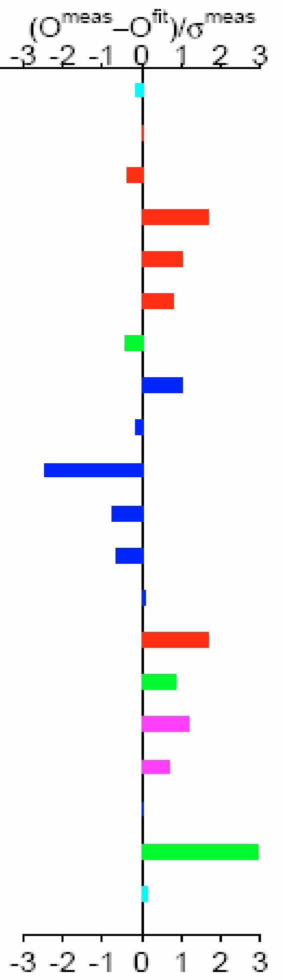
Precision Tests of the Standard Model

Lepton couplings



Pulls in global fit

	Measurement	Pull
$\Delta\alpha^{(5)}_{had}(m_Z)$	0.02761 ± 0.00036	-0.16
m_Z [GeV]	91.1875 ± 0.0021	0.02
Γ_Z [GeV]	2.4952 ± 0.0023	-0.36
σ^0_{had} [nb]	41.540 ± 0.037	1.67
R_l	20.767 ± 0.025	1.01
$A^{0,l}_{fb}$	0.01714 ± 0.00095	0.79
$A_l(P_\tau)$	0.1465 ± 0.0032	-0.42
R_b	0.21644 ± 0.00065	0.99
R_c	0.1718 ± 0.0031	-0.15
$A^{0,b}_{fb}$	0.0995 ± 0.0017	-2.43
$A^{0,c}_{fb}$	0.0713 ± 0.0036	-0.78
A_b	0.922 ± 0.020	-0.64
A_c	0.670 ± 0.026	0.07
A_l(SLD)	0.1513 ± 0.0021	1.67
$\sin^2\theta^{lept}_{eff}(Q_{fb})$	0.2324 ± 0.0012	0.82
m_W [GeV]	80.426 ± 0.034	1.17
Γ_W [GeV]	2.139 ± 0.069	0.67
m_t [GeV]	174.3 ± 5.1	0.05
$\sin^2\theta_W(\nu N)$	0.2277 ± 0.0016	2.94
Q_W(Cs)	-72.83 ± 0.49	0.12



Open Questions beyond the Standard Model

- What is the origin of particle masses?

  due to a Higgs boson? + other physics?

  solution at energy < 1 TeV (1000 GeV)

  Susy

- Why so many types of matter particles?

  matter-antimatter difference?

- Unification of the fundamental forces?

  at very high energy ~ 10^{16} GeV?

  probe directly via neutrino physics, indirectly via masses, couplings

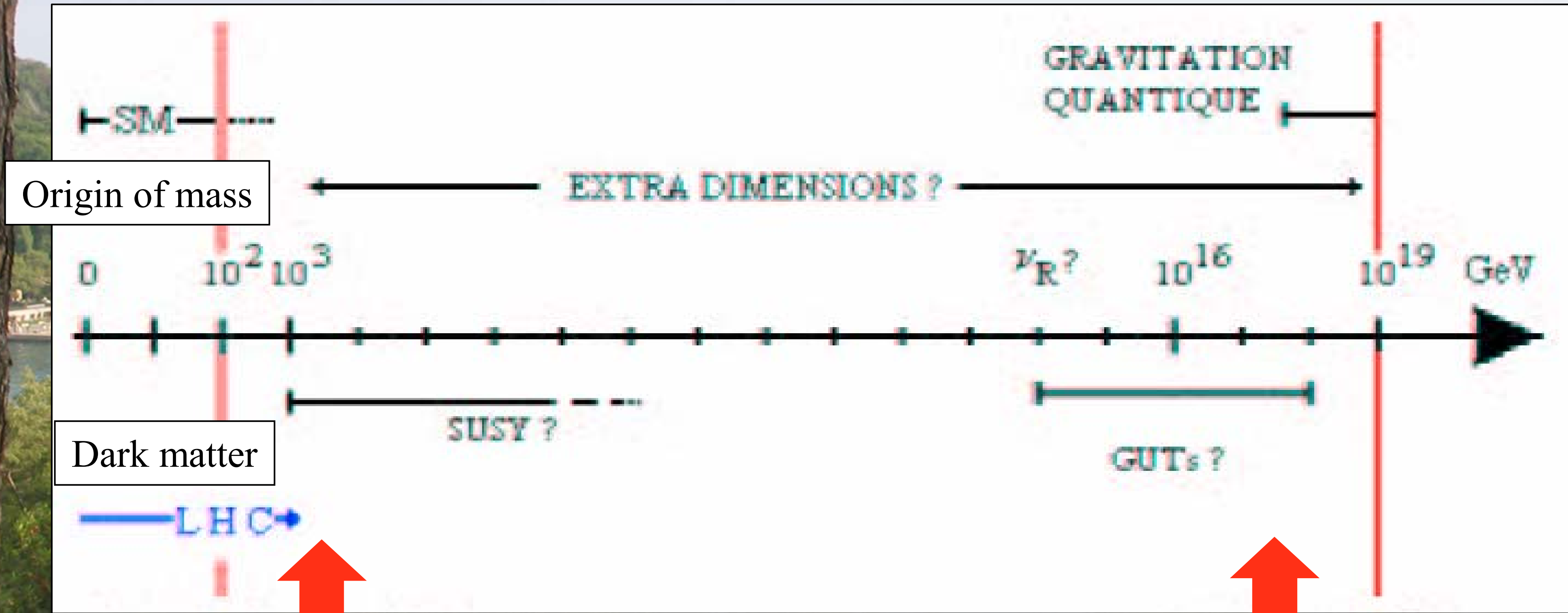
  Susy

- Quantum theory of gravity?

  (super)string theory: extra space-time dimensions?

  Susy

At what Energy is the New Physics?



A lot accessible
To the LHC, ILC

Some accessible
only indirectly

Some particles have mass, some do not

Where do the masses come from ?

Newton:

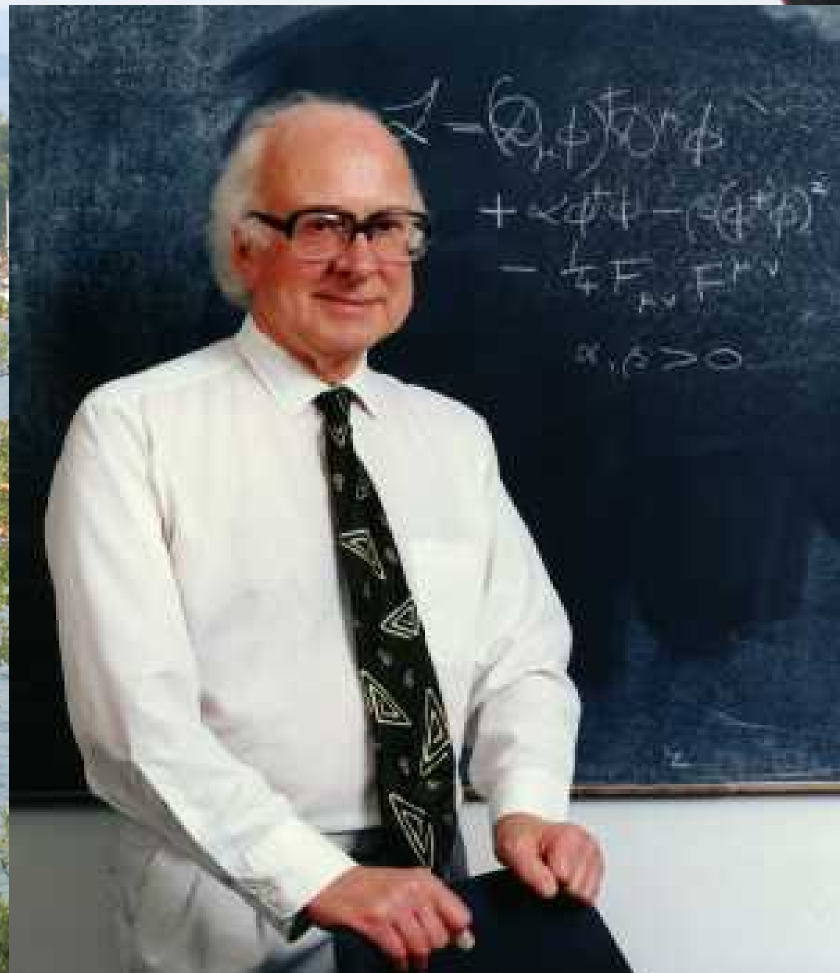
Weight proportional to Mass

Einstein:

Energy related to Mass

Neither explained origin of Mass

Are masses due to Higgs boson?
(yet another particle)



The Higgs Mechanism

- Postulated effective Higgs potential:

$$V[\phi] = -\mu^2\phi^\dagger\phi + \lambda(\phi^\dagger\phi)^2$$

- Minimum energy at non-zero value:

$$\phi_0 =< 0|\phi|0 >= \frac{1}{\sqrt{2}}\begin{pmatrix} 0 \\ +v \end{pmatrix} \quad v = \sqrt{\frac{\mu^2}{\lambda}}$$

- Non-zero masses: $M_f = y_f \frac{v}{\sqrt{2}}$ $M_W = \frac{g\,v}{2}$
- Components of Higgs field: $\phi(x) = \frac{1}{\sqrt{2}}(v + \sigma(x))e^{i\pi(x)}$
- π massless, σ massive: $m_H^2 = 2\mu^2 = 2\lambda v$

Constraints on Higgs Mass

- Electroweak observables sensitive via quantum loop corrections:

$$m_W^2 \sin^2\theta_W = m_Z^2 \cos^2\theta_W \sin^2\theta_W = \frac{\pi\alpha}{\sqrt{2}G_F}(1+\Delta r)$$

- Sensitivity to top, Higgs masses:

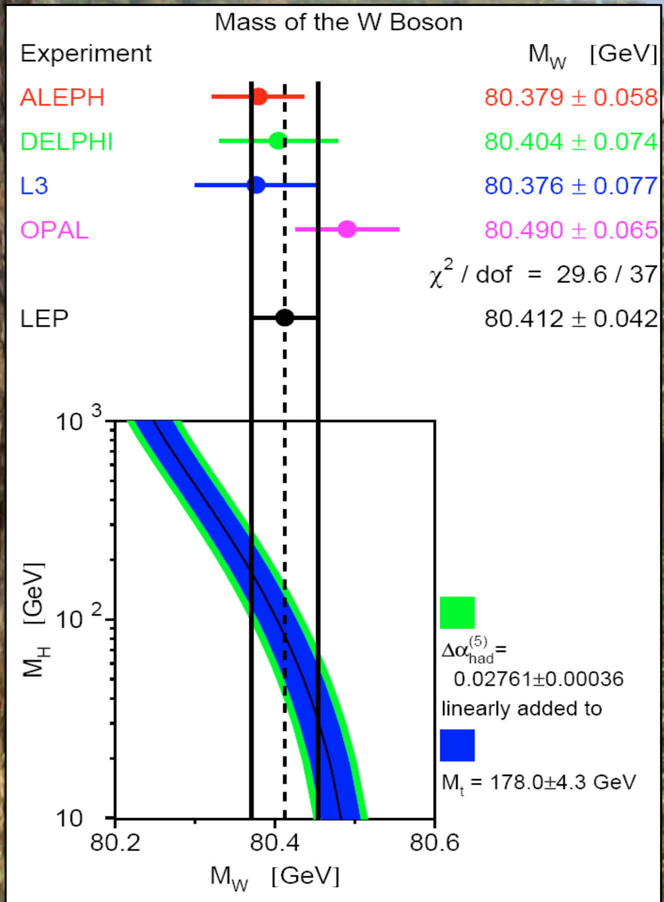
$$\frac{3G_F}{8\pi^2\sqrt{2}}m_t^2 \qquad \frac{\sqrt{2}G_F}{16\pi^2}m_W^2\left(\frac{11}{3}\ln\frac{M_H^2}{m_Z^2}+\ldots\right),\ M_H >> m_W$$

- Preferred Higgs mass: **$m_H \sim 126$ GeV**
- Compare with lower limit from direct searches:

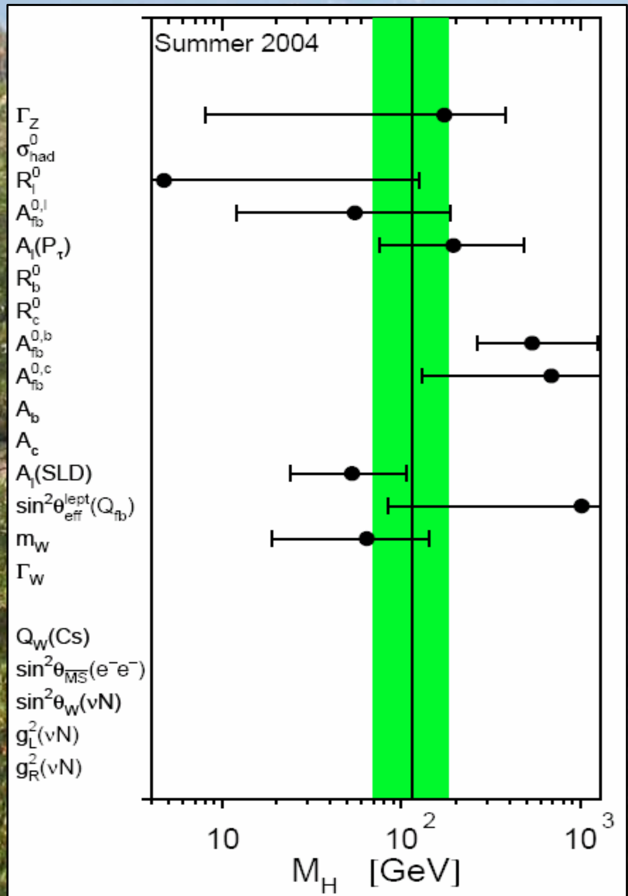
  $m_H > 114$ GeV

Indications on the Higgs Mass

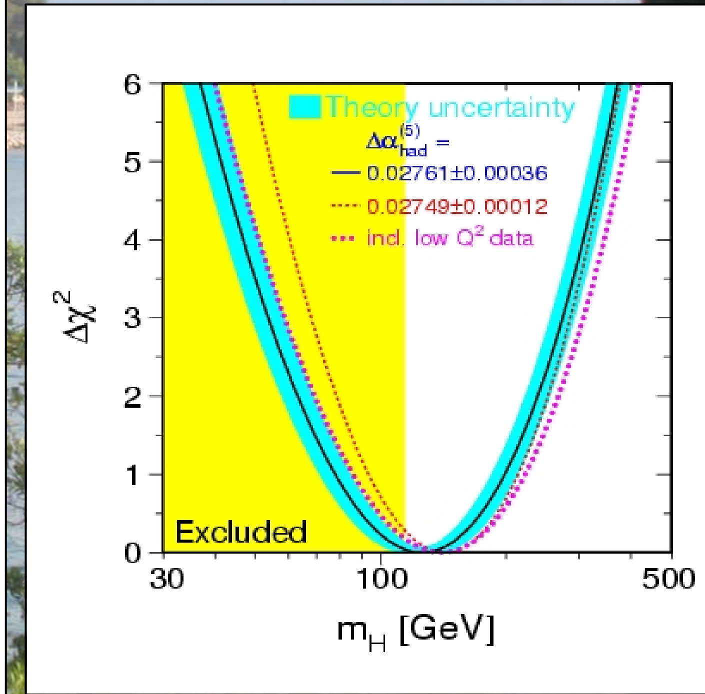
Sample observable: W mass @ LEP



Sensitivities of many observables

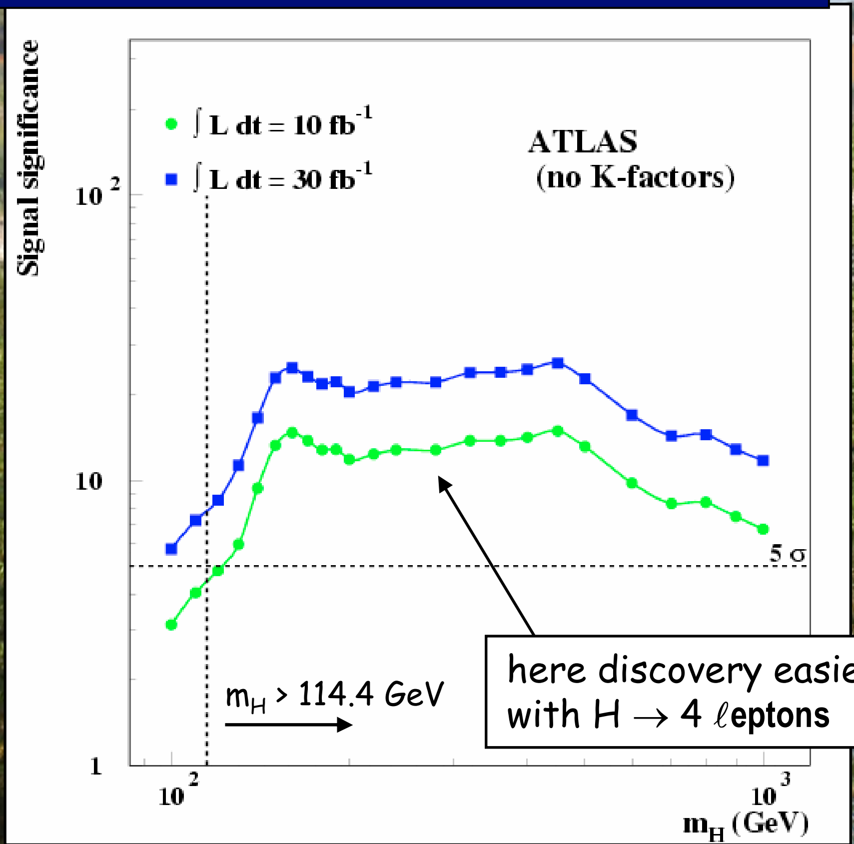


Combined information on Higgs mass



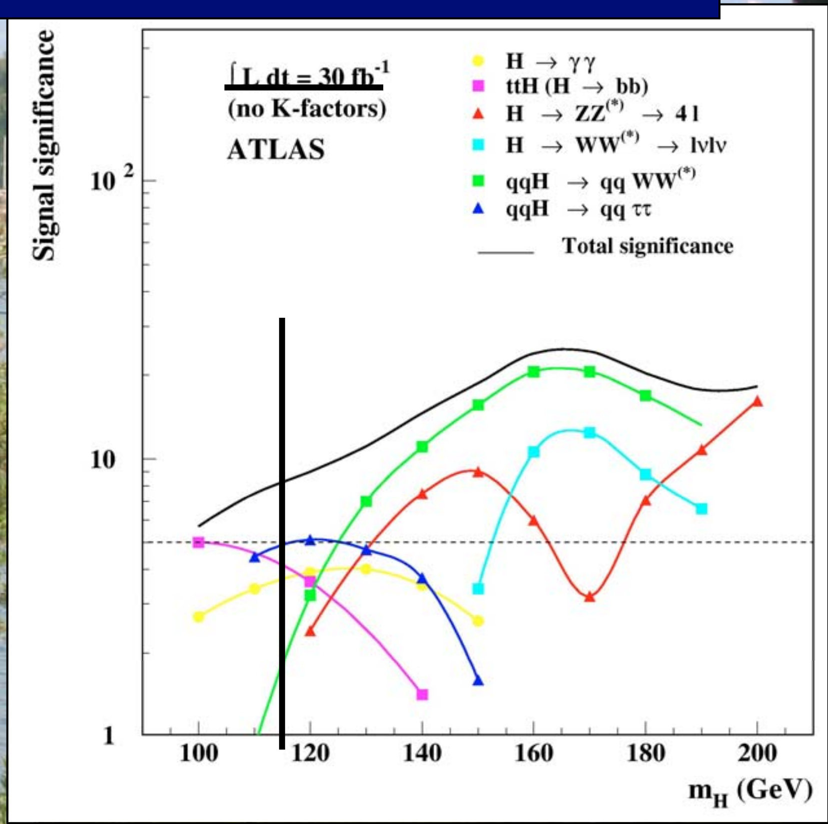
Higgs Detection at the LHC

The Higgs may be found quite quickly …



here discovery easier with H → 4 ℓeptons

… in several different channels

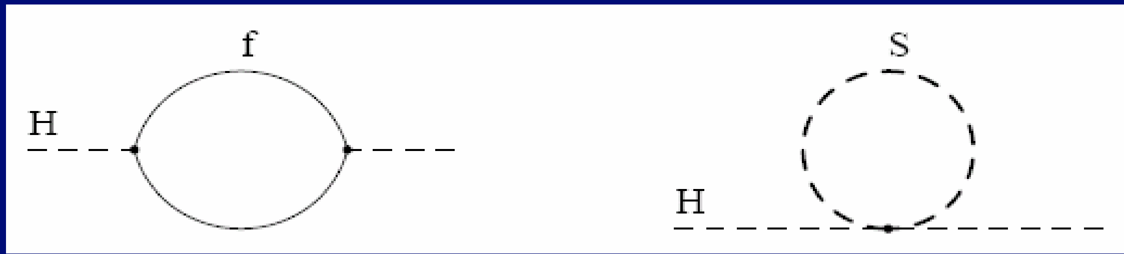


Theorists getting Cold Feet

- Composite Higgs model?
  conflicts with precision electroweak data
- Interpretation of EW data?
  consistency of measurements? Discard some?
- Higgs + higher-dimensional operators?
  corridors to higher Higgs masses?
- Little Higgs models?
  extra `Top’, gauge bosons, `Higgses’
- Higgsless models?
  strong WW scattering, extra D?

Loop Corrections to Higgs Mass^2

- Consider generic fermion and boson loops:



- Each is quadratically divergent: $\int^{\Lambda} d^4k/k^2$

$$\Delta m_H^2 = -\frac{y_f^2}{16\pi^2}[2\Lambda^2 + 6m_f^2 \ln(\Lambda/m_f) + \ldots]$$

$$\Delta m_H^2 = \frac{\lambda_S}{16\pi^2}[\Lambda^2 - 2m_S^2 \ln(\Lambda/m_S) + \ldots]$$

- Leading divergence cancelled if

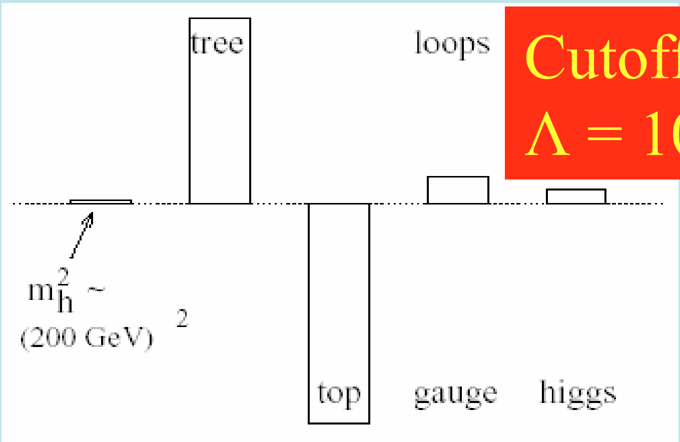
$$\lambda_S = y_f^2$$

Elementary Higgs or Composite?

- Higgs field:

  $\langle 0|H|0\rangle \neq 0$

- Quantum loop problems



Cutoff
$\Lambda = 10$ TeV

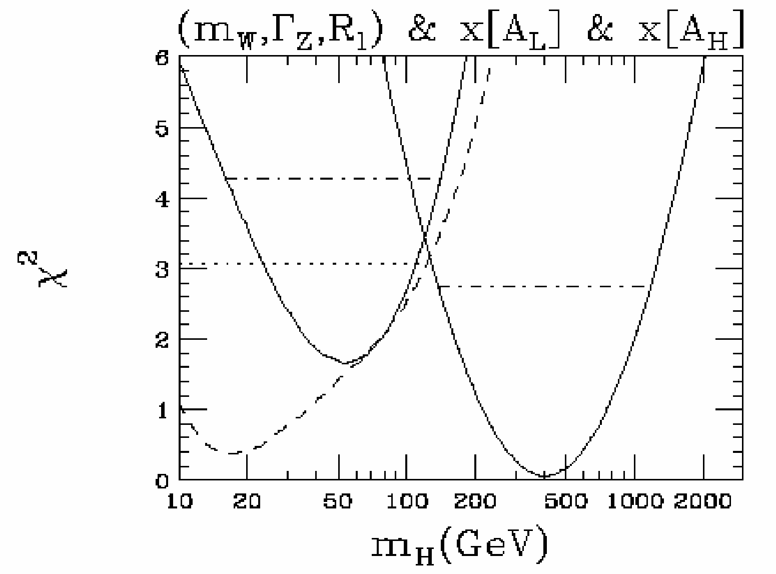
- Cut-off $\Lambda \sim 1$ TeV with Supersymmetry?

- Fermion-antifermion condensate
- Just like QCD, BCS superconductivity
- Top-antitop condensate? needed $m_t > 200$ GeV

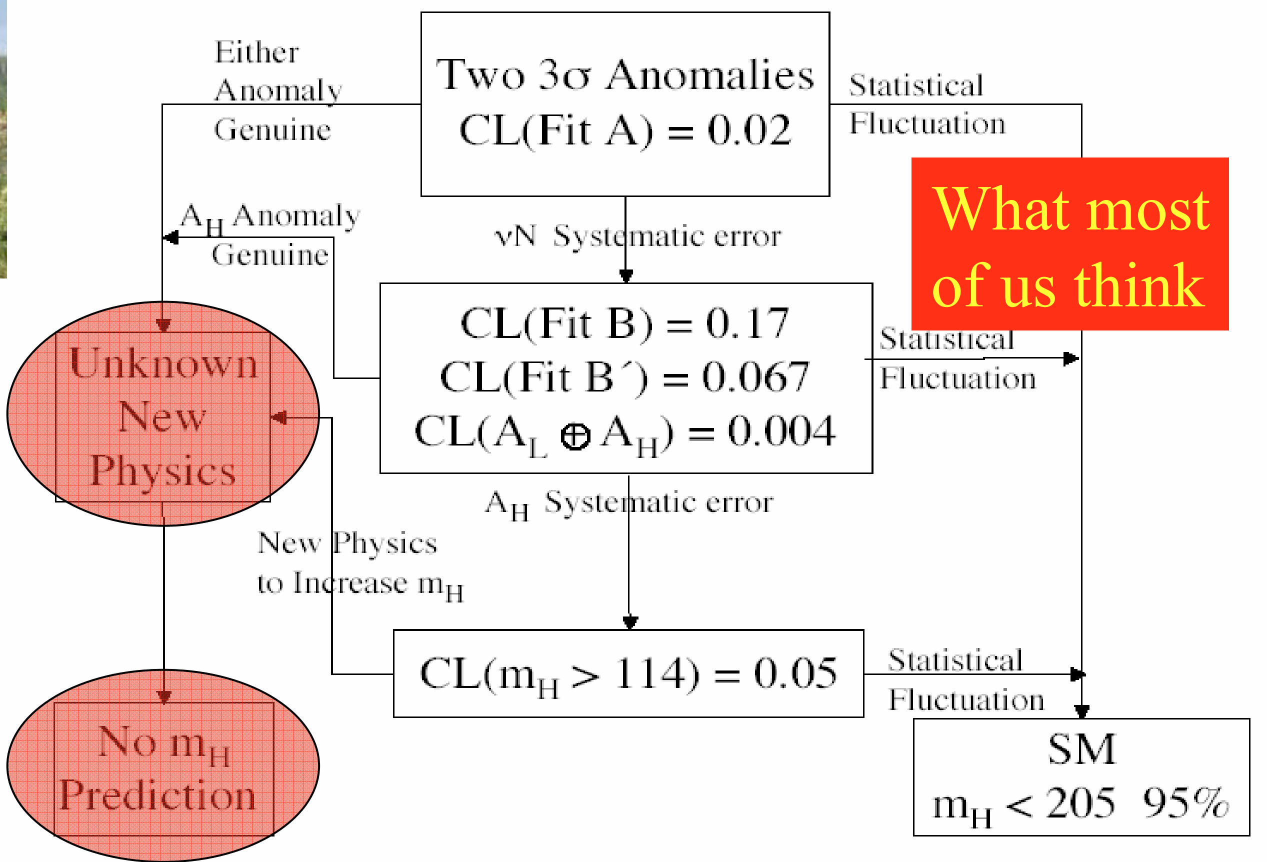
- New technicolour force? inconsistent with precision electroweak data?

Heretical Interpretation of EW Data

Do all the data tell the same story?
e.g., A_L vs A_H



What attitude towards LEP, NuTeV?



What most of us think

Higgs + Higher-Order Operators

$$\mathcal{L}_{\rm eff} = \mathcal{L}_{\rm SM} + \sum_i \frac{c_i}{\Lambda^p} \mathcal{O}_i^{(4+p)}$$

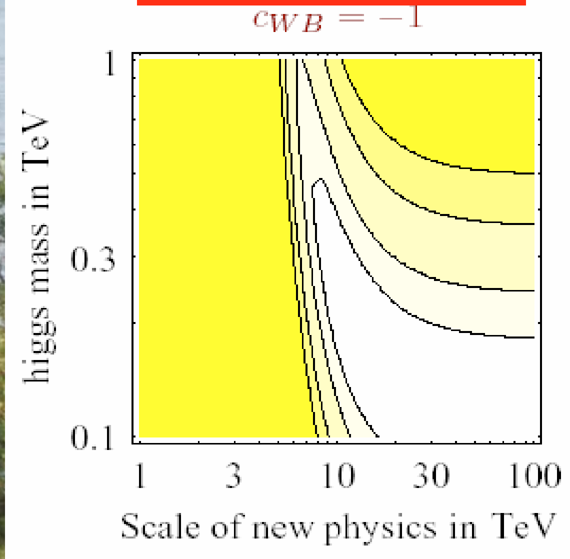
Precision EW data suggest they are small: why?

Dimension six operator	$c_i = -1$	$c_i = +1$
$\mathcal{O}_{WB} = (H^+ \sigma^a H) W^a_{\mu\nu} B_{\mu\nu}$	9.0	13
$\mathcal{O}_H = \|H^+ D_\mu H\|^2$	4.2	7.0
$\mathcal{O}_{LL} = \frac{1}{2}(\bar{L}\gamma_\mu \sigma^a L)^2$	8.2	8.8
$\mathcal{O}_{HL} = i(H^+ D_\mu H)(\bar{L}\gamma_\mu L)$	14	8.0

95% lower bounds on Λ/TeV

But conspiracies are possible: m_H could be large, even if believe EW data …?

Corridor to heavy Higgs?



Do not discard possibility of heavy Higgs

Little Higgs Models

- Embed SM in larger gauge group
- Higgs as pseudo-Goldstone boson
- Cancel top loop

$$\delta m^2_{H,top}(SM) \sim (115GeV)^2(\frac{\Lambda}{400GeV})^2$$

with new heavy T quark $m_T > 2\lambda_t f \sim 2f$ $f > 1$ TeV

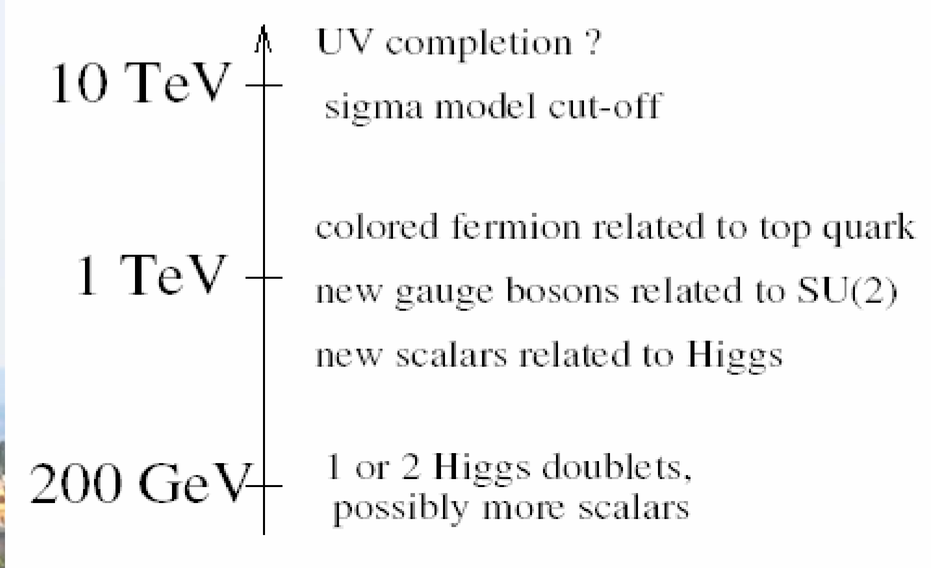
$$\delta m^2_{H,top}(LH) \sim \frac{6G_F m_t^2}{\sqrt{2}\pi^2} m_T^2 log\frac{\Lambda}{m_T} \gtrsim 1.2f^2$$

- New gauge bosons, Higgses
- Higgs light, other new physics heavy

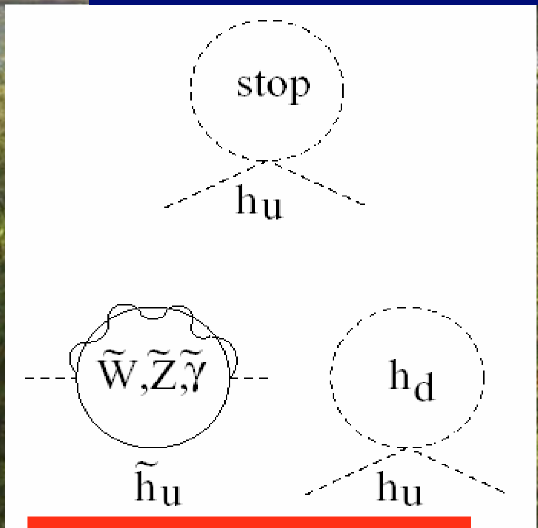
$M_T < 2$ TeV $(m_h / 200$ GeV$)^2$
$M_{W'} < 6$ TeV $(m_h / 200$ GeV$)^2$
$M_{H++} < 10$ TeV

Not as complete as susy: more physics > 10 TeV

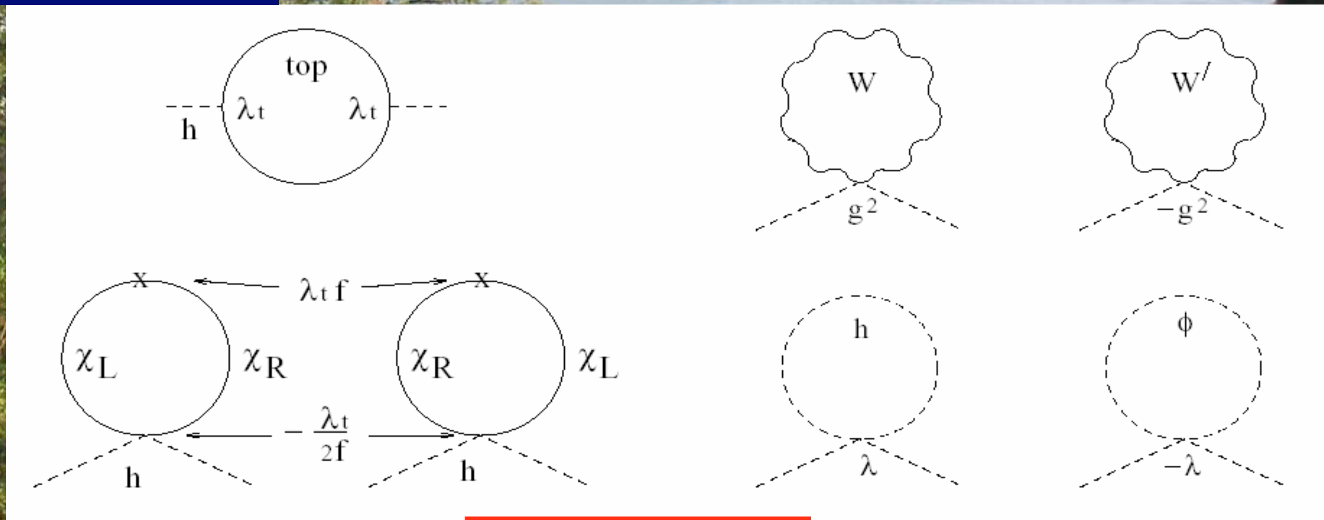
Generic Little Higgs Spectrum



Loop cancellation mechanisms



Supersymmetry



Little Higgs

Higgsless Models?

- Four-dimensional versions:

  Strong WW scattering @ TeV, incompatible with precision data?

- Break EW symmetry by boundary conditions in extra dimension:

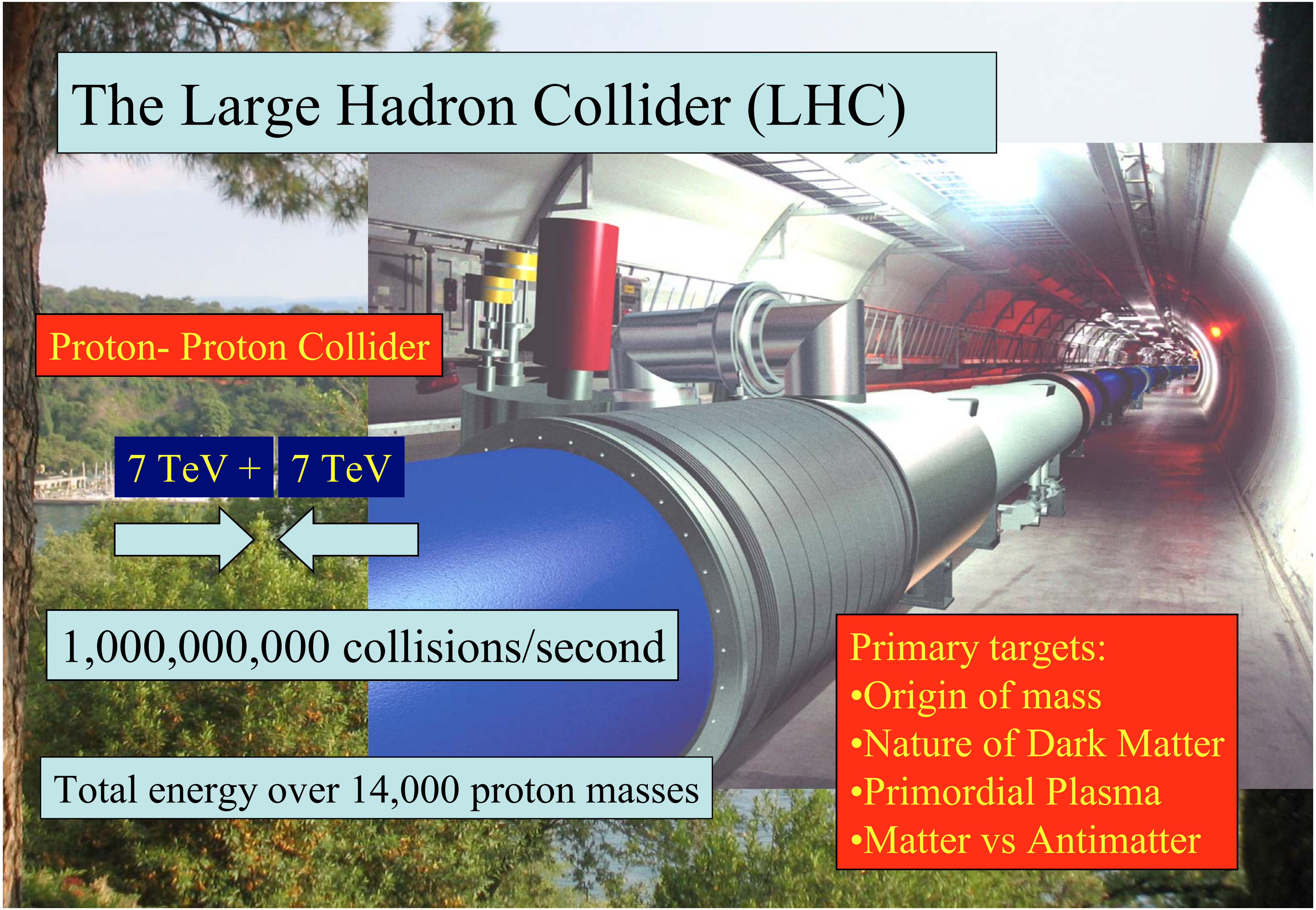
  delay strong WW scattering to ~ 10 TeV?

  Kaluza-Klein modes: m_{KK} > 300 GeV?

  compatibility with precision data?

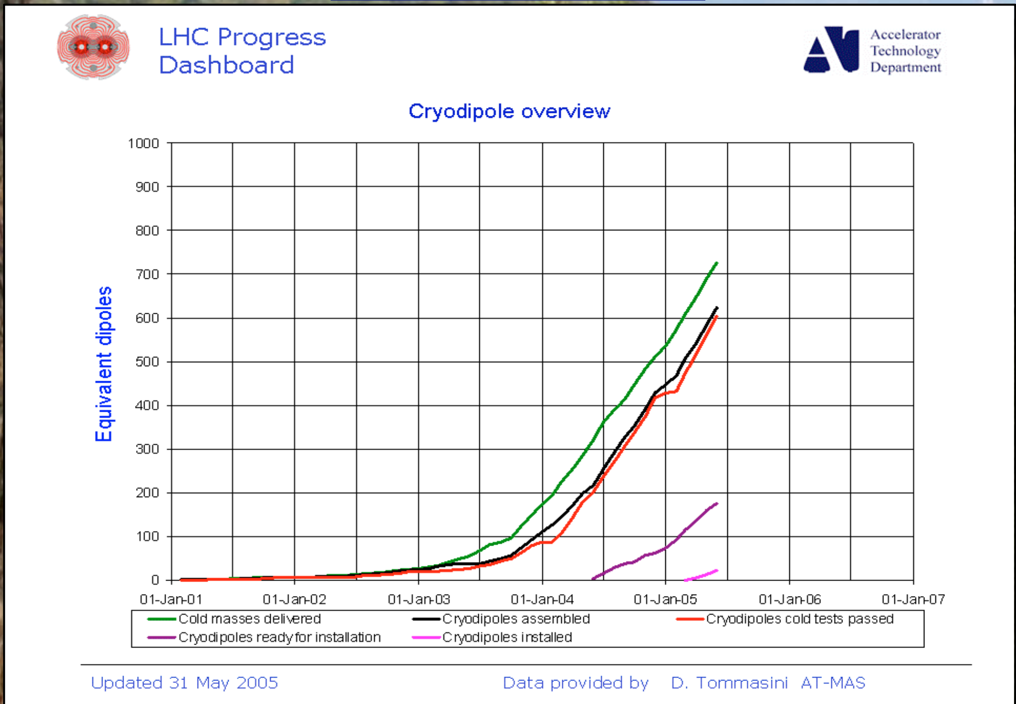
- Warped extra dimension + brane kinetic terms?

Lightest KK mode @ 300 GeV, strong WW @ 6-7 TeV

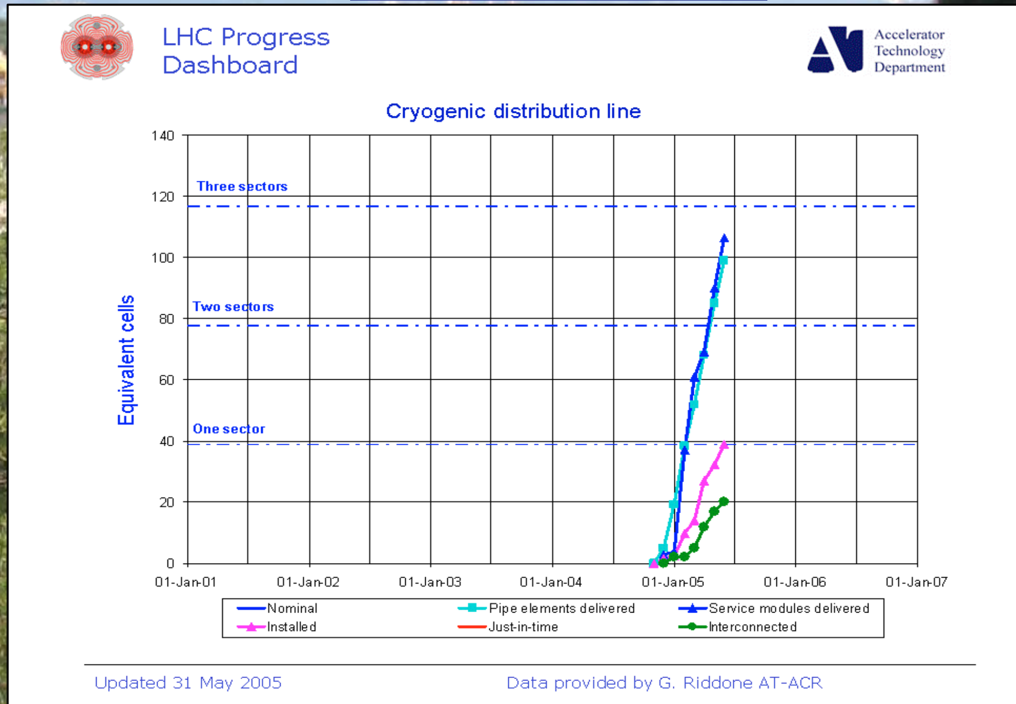

The Large Hadron Collider (LHC)
Proton- Proton Collider
7 TeV + 7 TeV
1,000,000,000 collisions/second
Total energy over 14,000 proton masses
Primary targets:
•Origin of mass
•Nature of Dark Matter
•Primordial Plasma
•Matter vs Antimatter

LHC Progress Dashboard

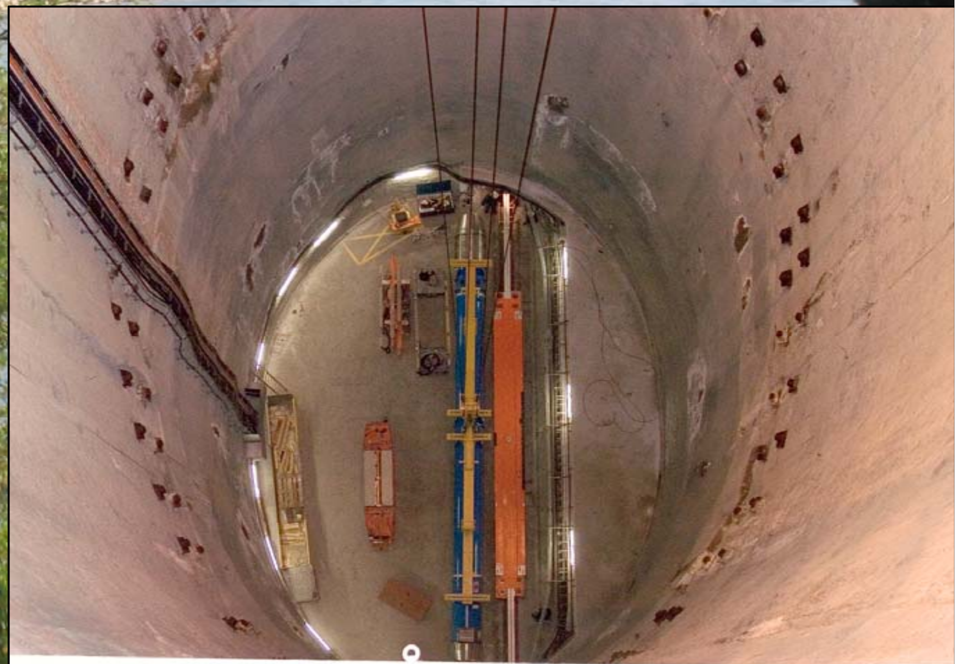
Main dipoles



Cryogenic line

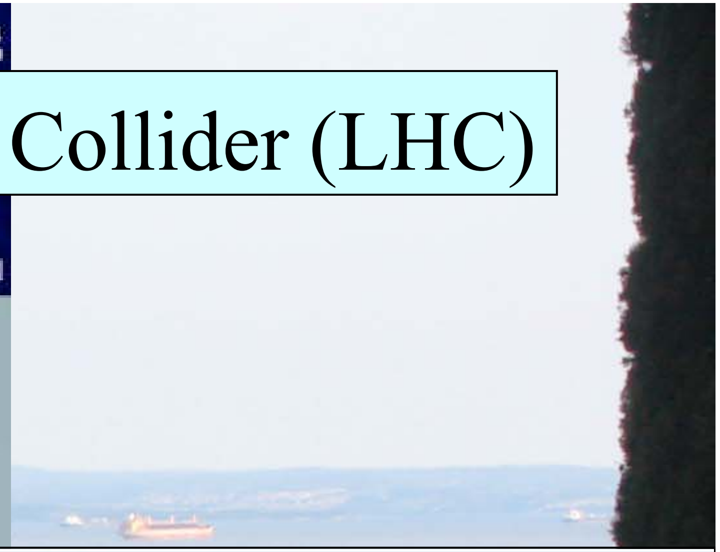


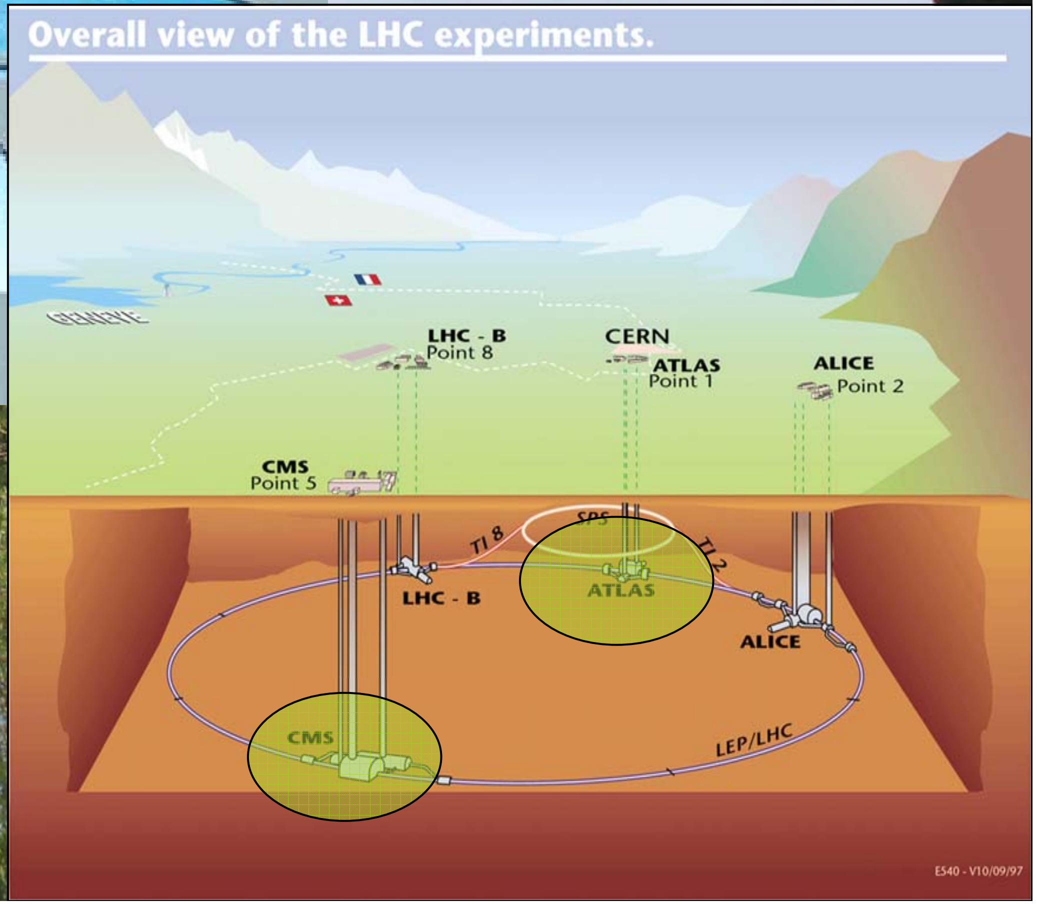
The First Magnets are in the Tunnel



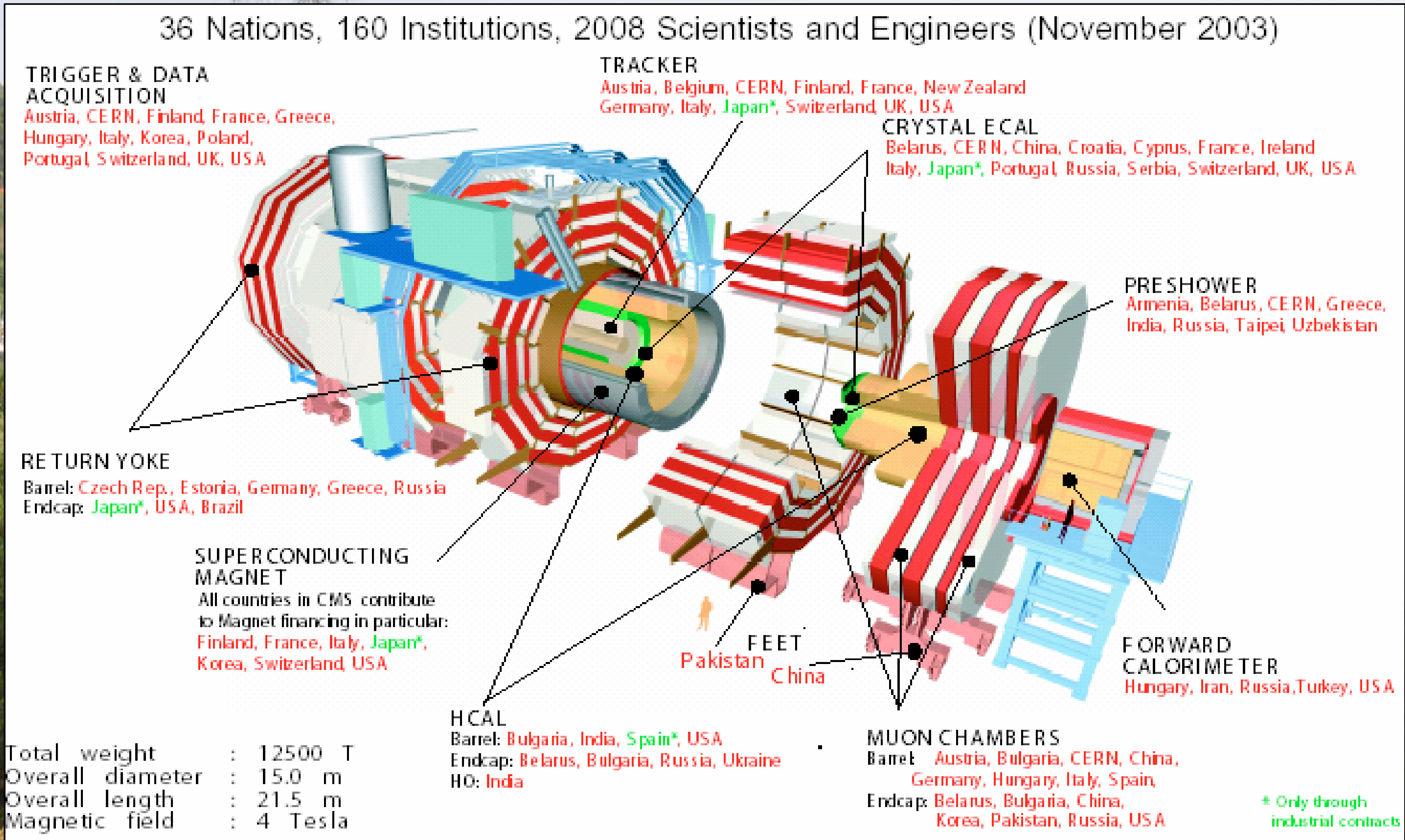
Installation of the First LHC Magnets

Overall View of the Large Hadron Collider (LHC)





CMS Experiment

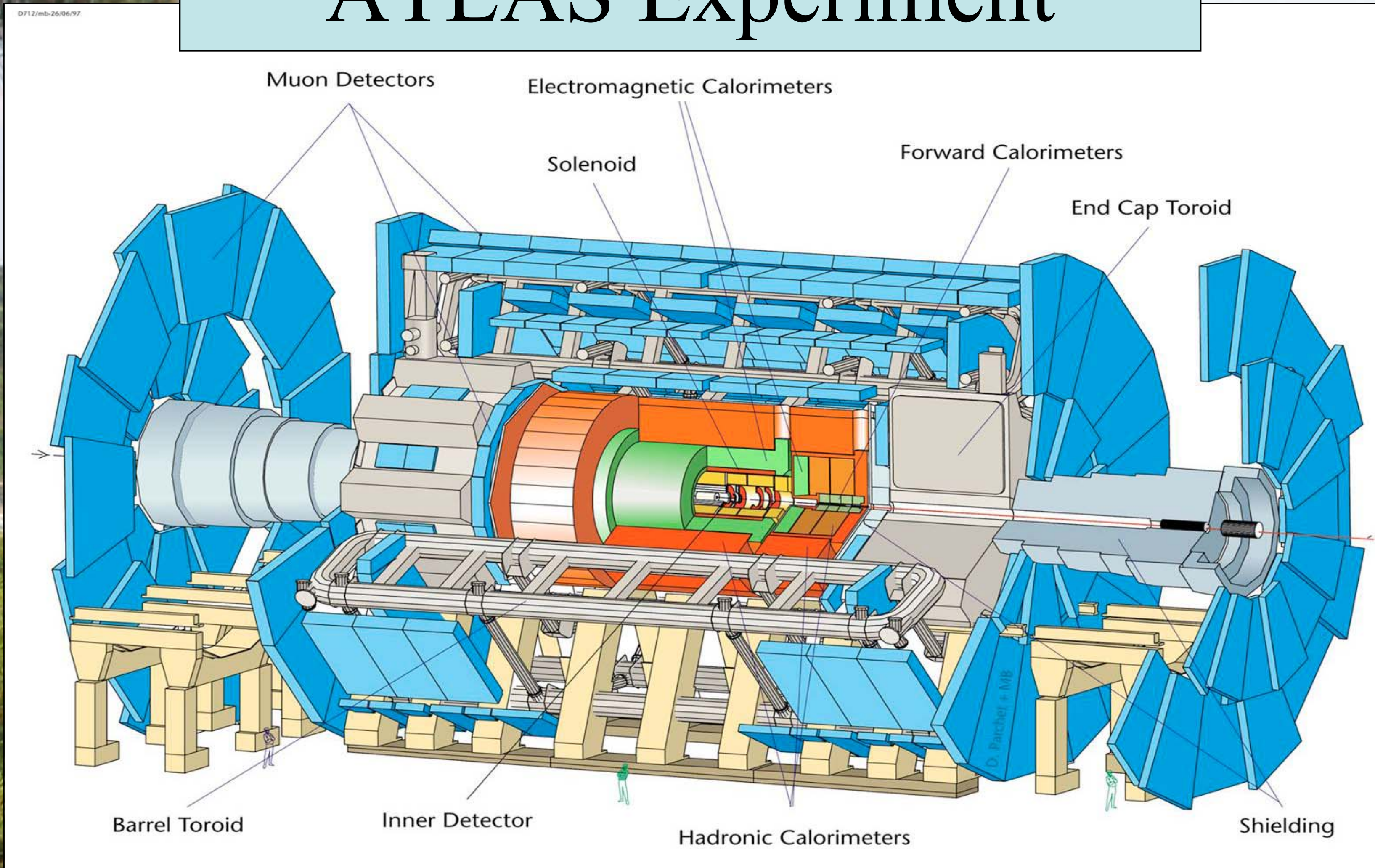


CMS Under Construction

Recycling Russian naval shells

to be completed in 2007

ATLAS Experiment



Diameter	***25 m***
Barrel toroid length	***26 m***
End-cap end-wall chamber span	***46 m***
Overall weight	***7000 Tons***

The ATLAS Cavern

Huge Statistics thanks to High Energy and Luminosity

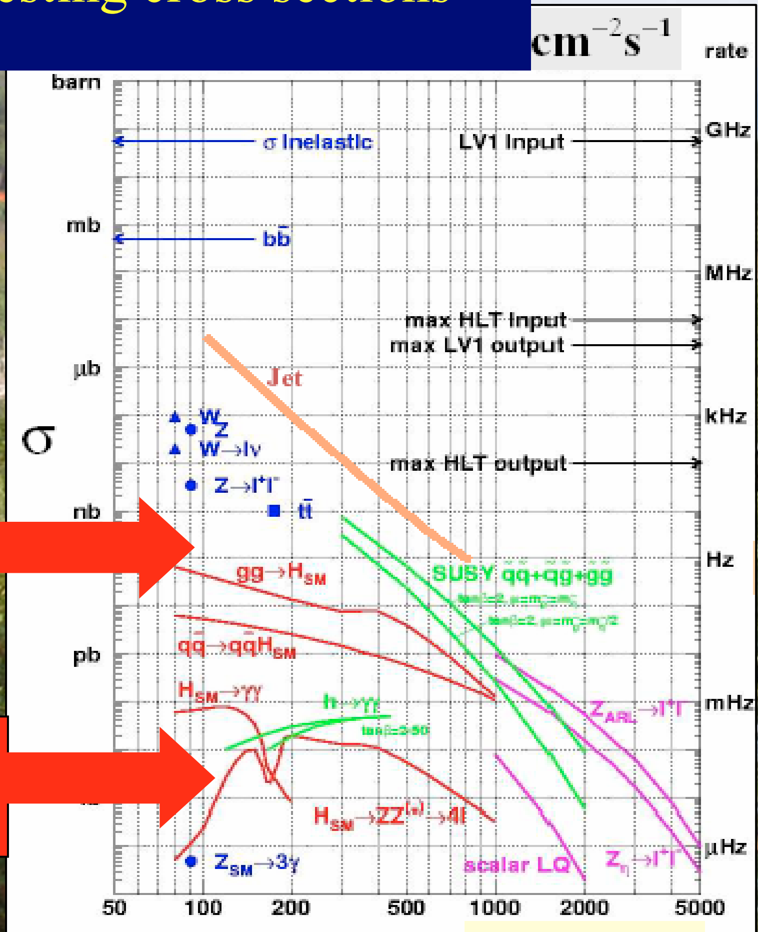
Event rates in ATLAS or CMS at $L = 10^{33}\ cm^{-2}\ s^{-1}$

Process	Events/s	Events per year	Total statistics collected at previous machines by 2007
$W \to e\nu$	15	10^8	10^4 LEP / 10^7 Tevatron
$Z \to ee$	1.5	10^7	10^7 LEP
$t\bar{t}$	1	10^7	10^4 Tevatron
$b\bar{b}$	10^6	10^{12} - 10^{13}	10^9 Belle/BaBar ?
H m=130 GeV	0.02	10^5	?
$\tilde{g}\tilde{g}$ m= 1 TeV	0.001	10^4	---
Black holes m > 3 TeV (M_D=3 TeV, n=4)	0.0001	10^3	---

LHC is a factory for anything: top, W/Z, Higgs, SUSY, etc….
mass reach for discovery of new particles up to m ~ 5 TeV

The LHC Physics Haystack(s)

Interesting cross sections

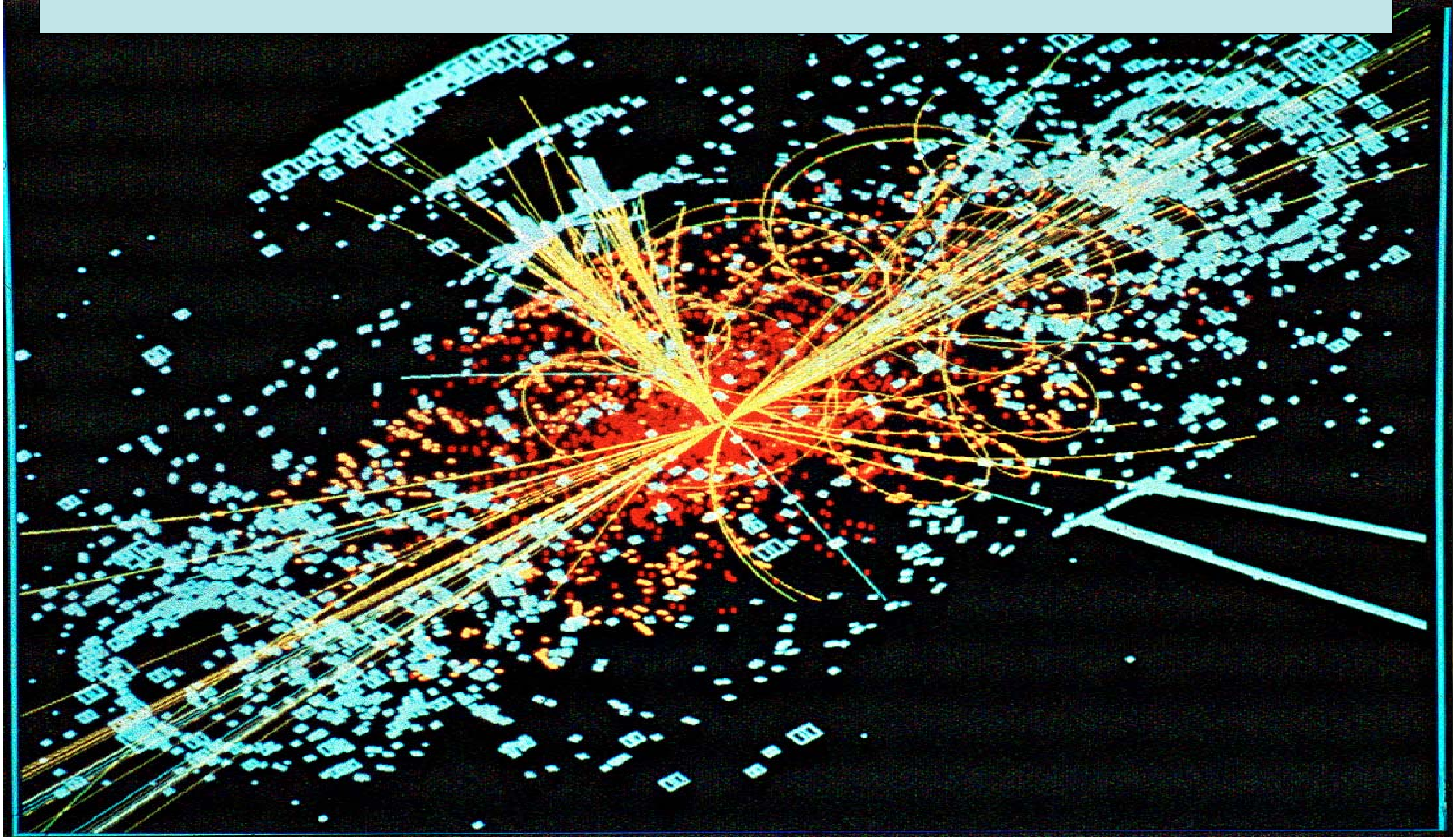


Susy

Higgs

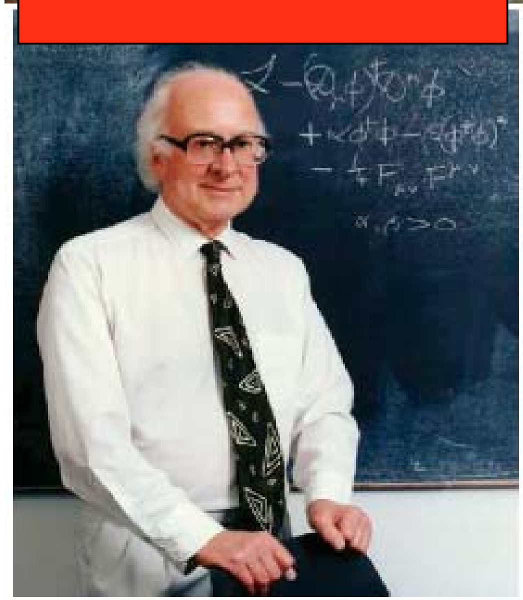
- Cross sections for heavy particles
  $\sim 1/(1\text{ TeV})^2$
- Most have small couplings $\sim \alpha^2$
- Compare with total cross section
  $\sim 1/(100\text{ MeV})^2$
- Fraction ~ 1/1,000,000,000,000
- Need ~ 1,000 events for signal
- Compare needle
  $\sim 1/100{,}000{,}000\text{ m}^3$
- Haystack $\sim 100\text{ m}^3$
- Must look in ~ 100,000 haystacks

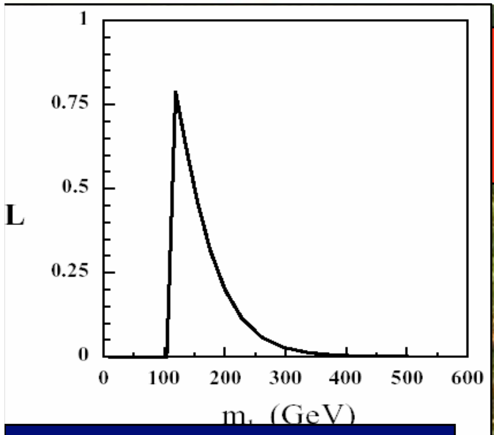
A Simulated Higgs Event in CMS

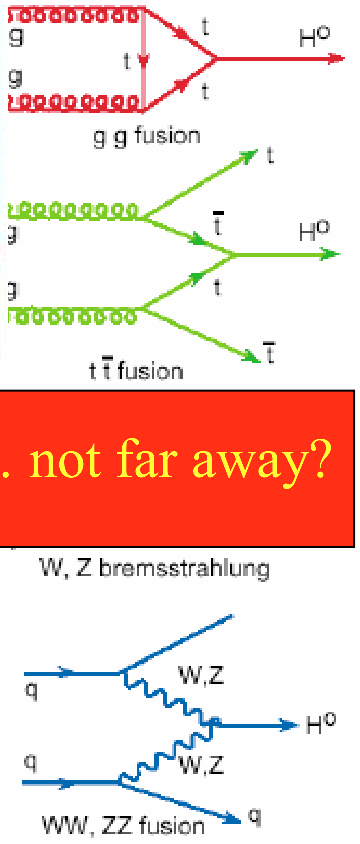


A la recherche du Higgs perdu …

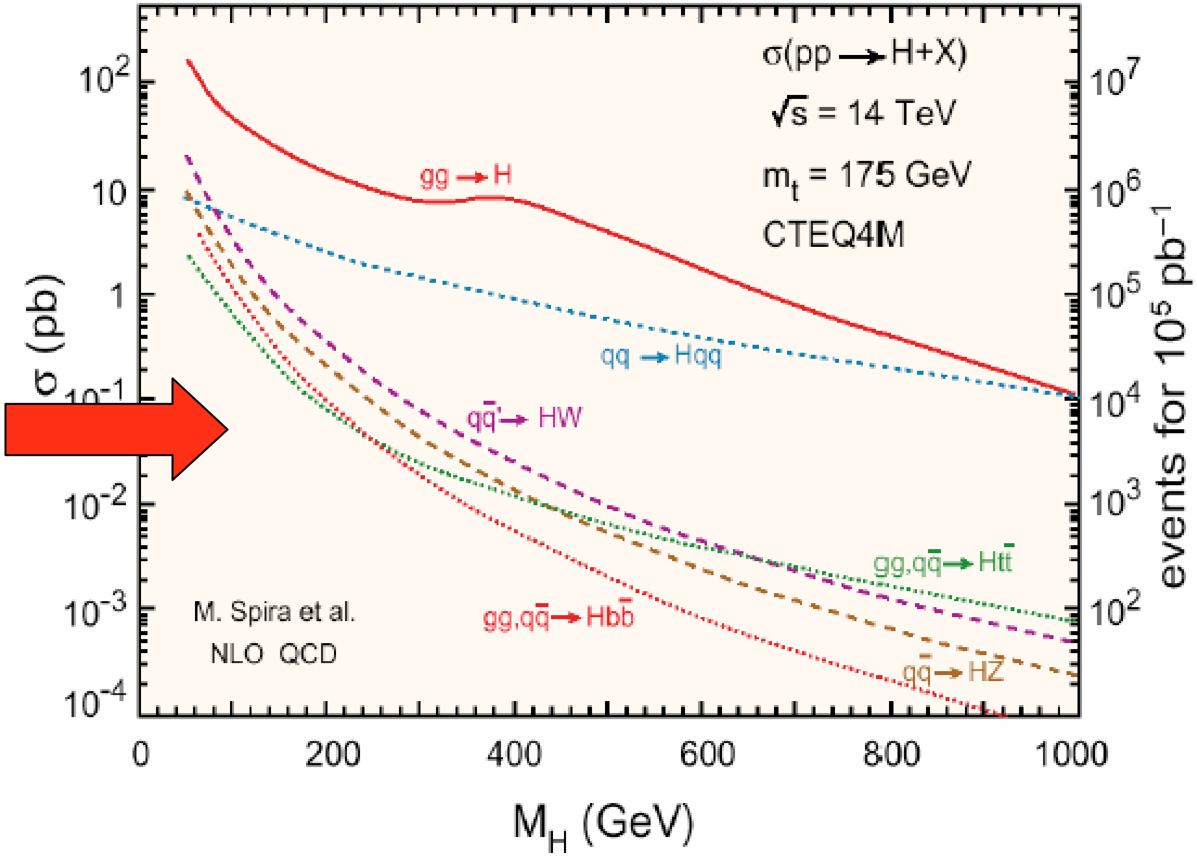
Higgs Production at the LHC





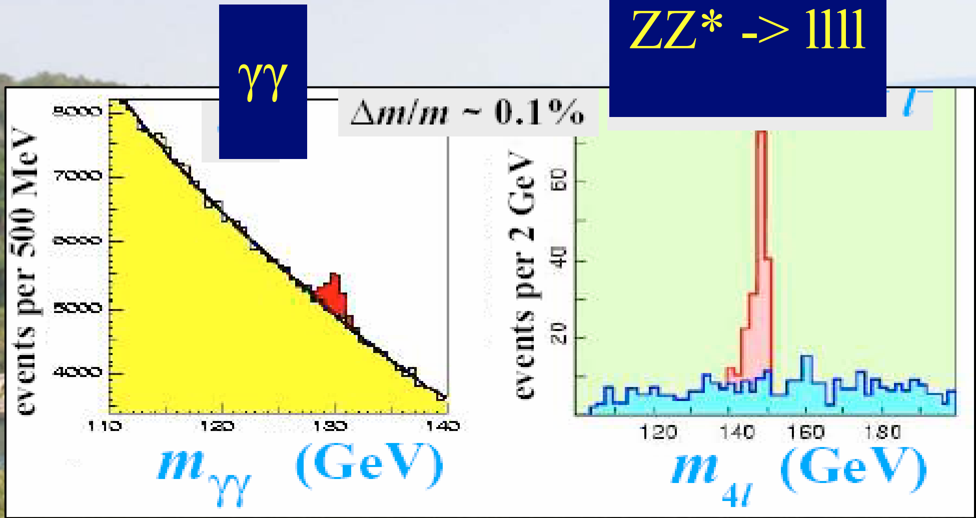


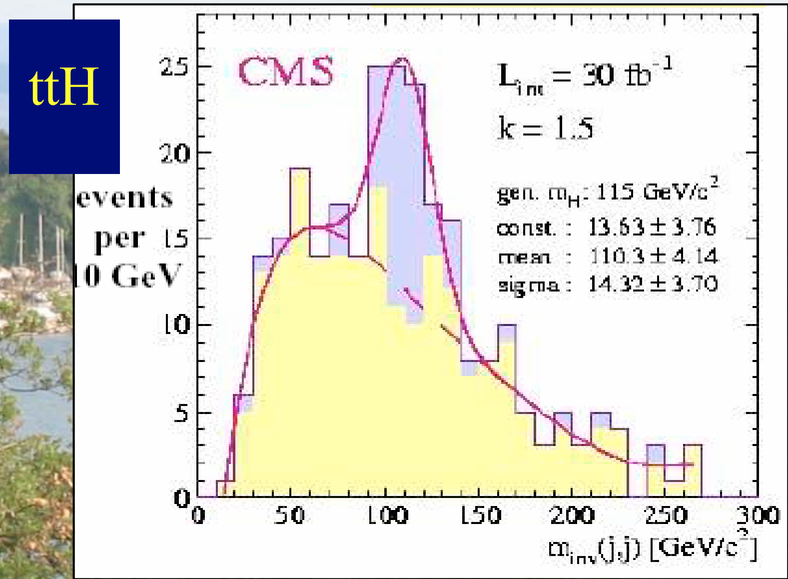
.. not far away?

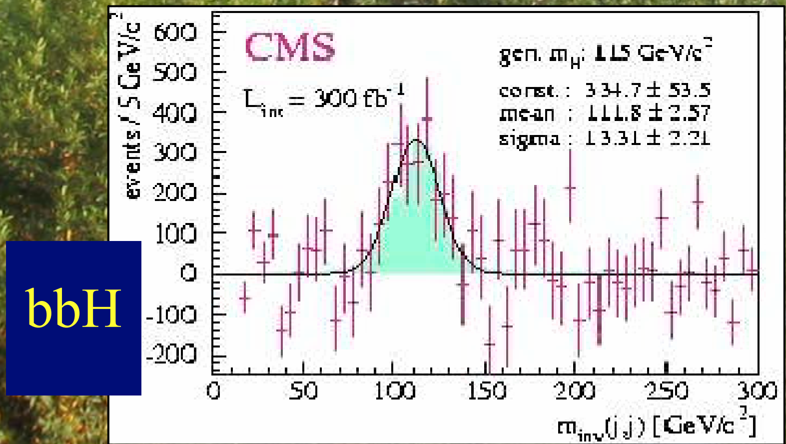


Combining direct, Indirect information

Some Sample Higgs Signals

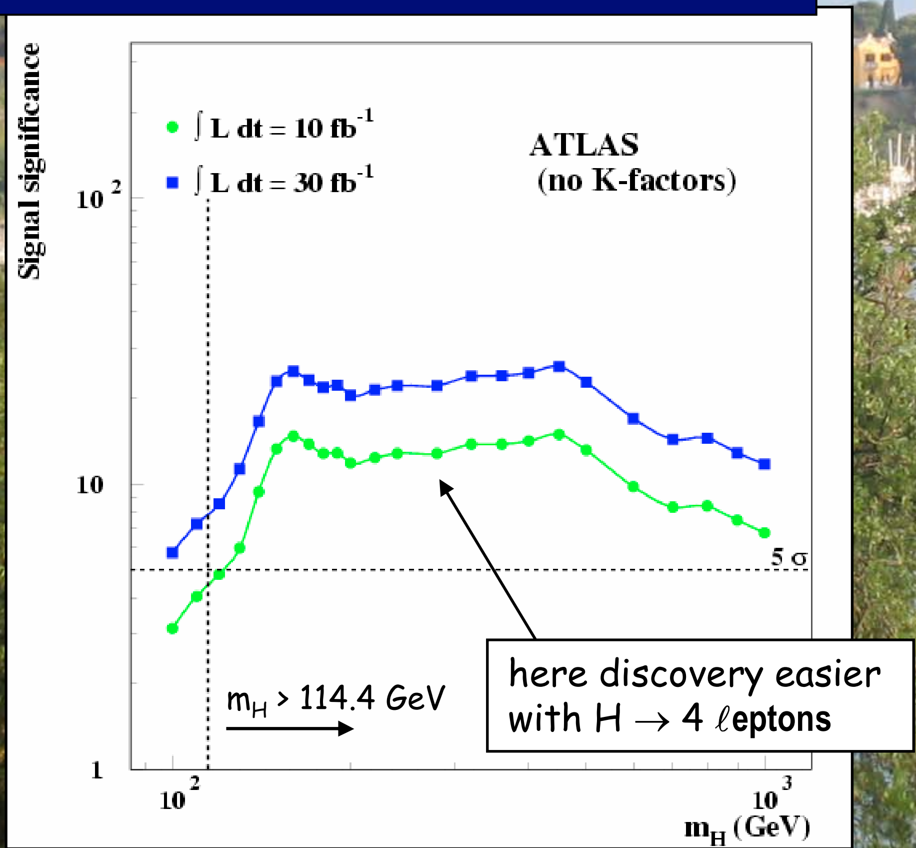




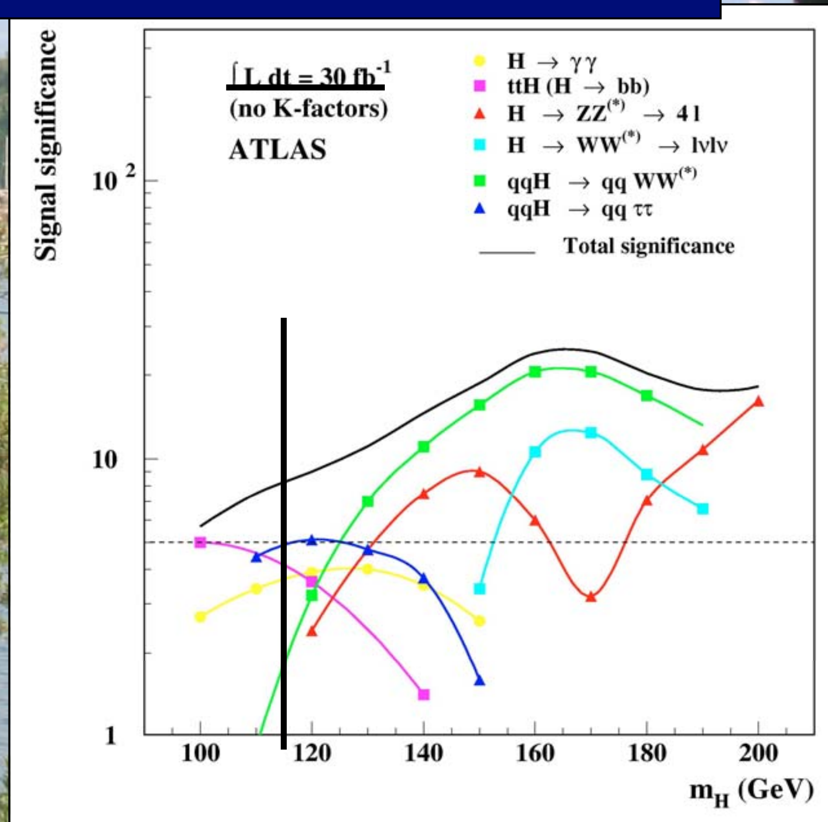


Higgs Detection at the LHC

The Higgs may be found quite quickly …

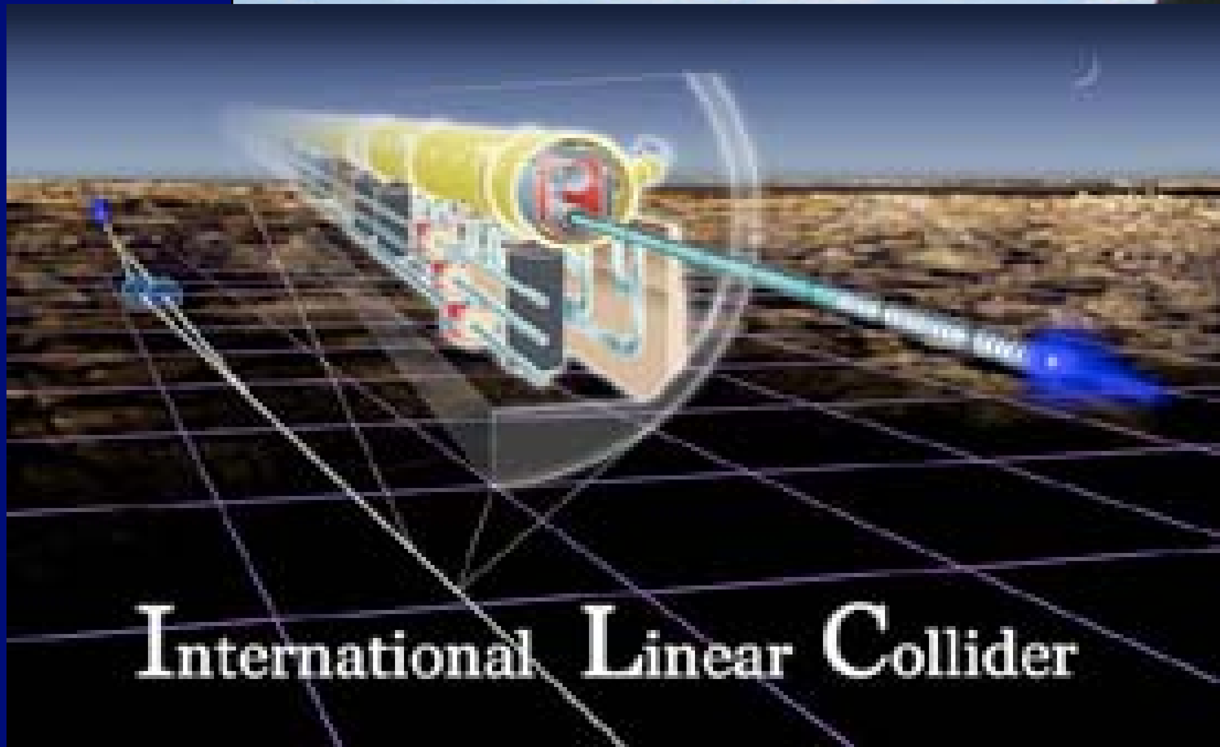


… in several different channels



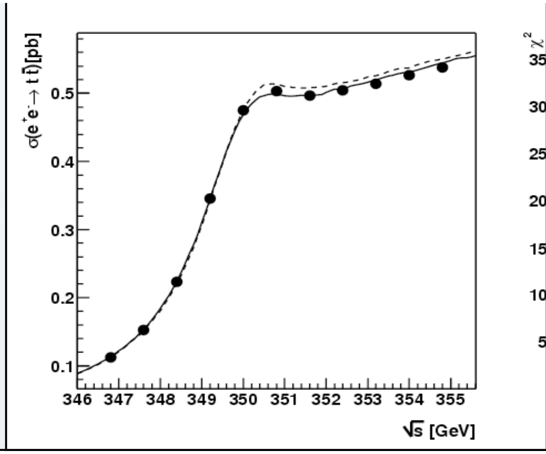
International Linear Collider

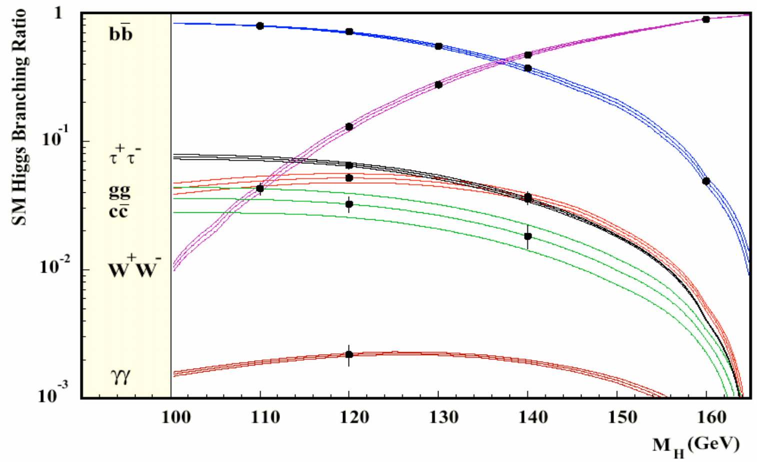
- e^+e^- collisions up to $E_{cm} = 1$ TeV
- Preferred choice for next collider
- Now subject of Global Design Effort
- Hope for decision 2010 – 2012
- To be constructed by 2015 – 2020?

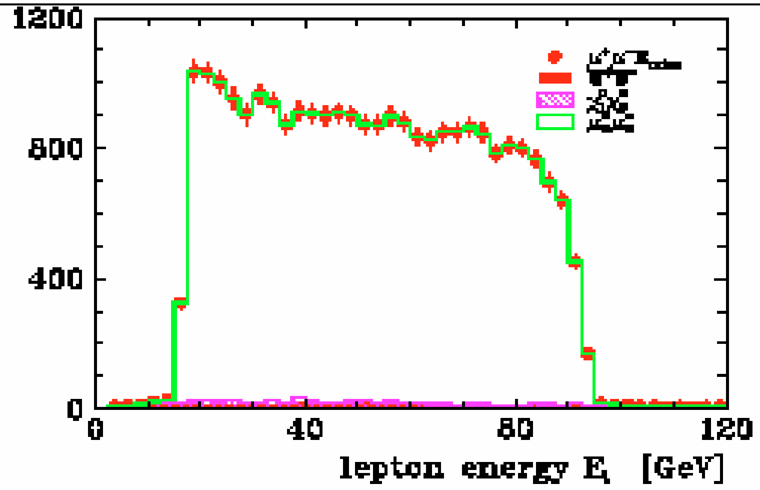


Tasks for the TeV ILC

- Measure m_t to < ± 100 MeV
- If there is a light Higgs of any kind, pin it down:
  - Does it have standard model couplings?
  - What is its precise mass?
- If there are extra light particles:
  - Measure mass and properties
- If LHC sees nothing new below ~ 500 GeV:
  - Look for indirect signatures



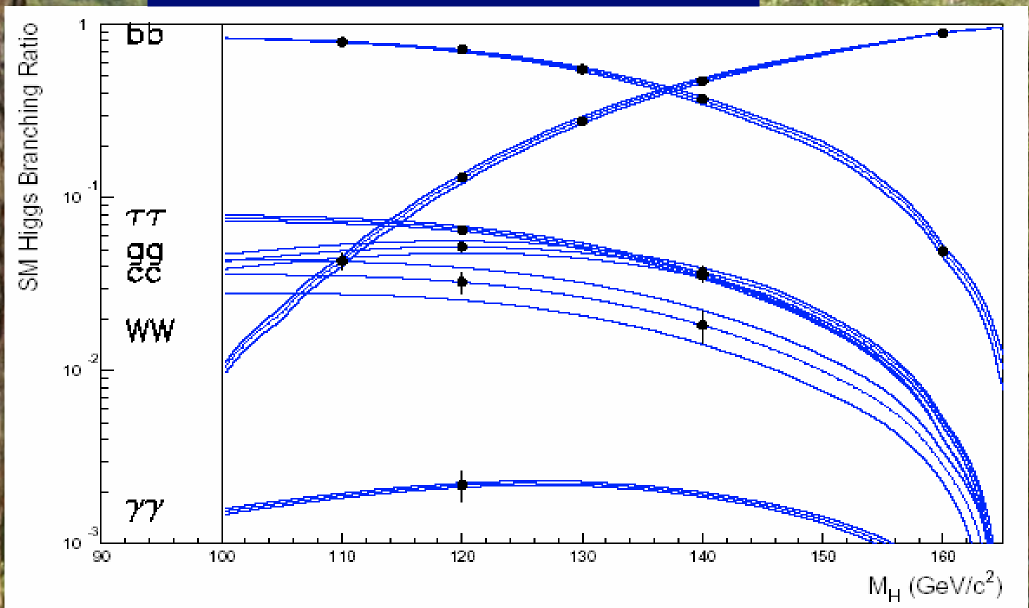




Measuring Properties of Light Higgs

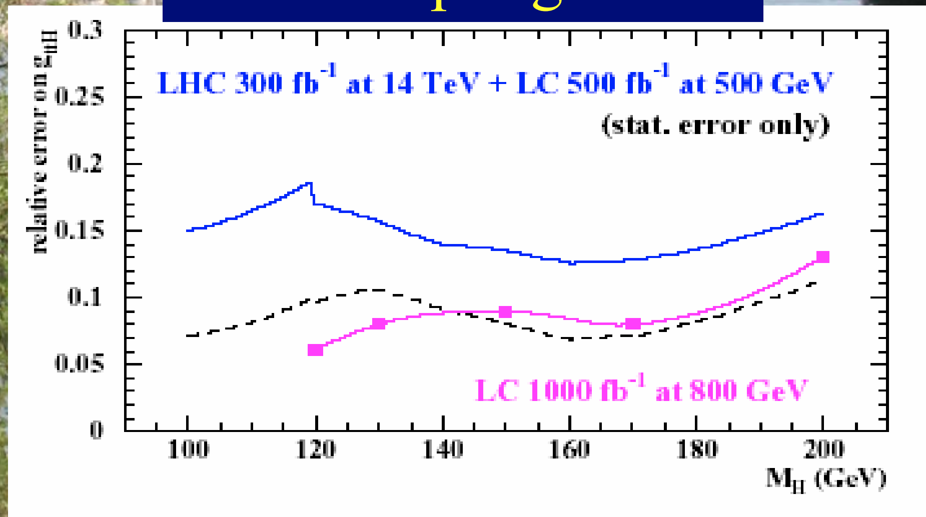
LC capabilities

bb, ττ, gg, cc, WW, γγ

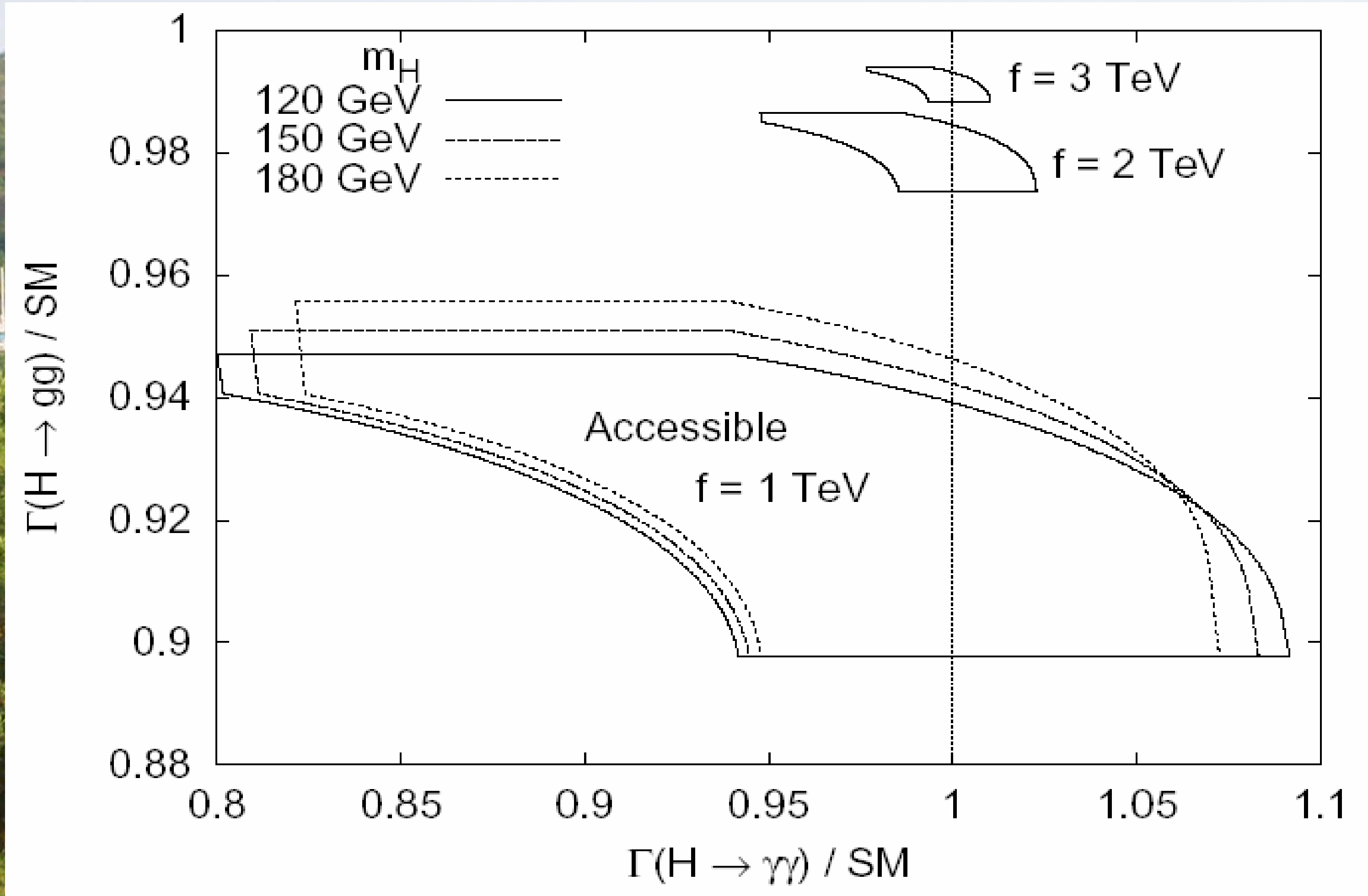


Some new studies …

Measuring top-Higgs couplings

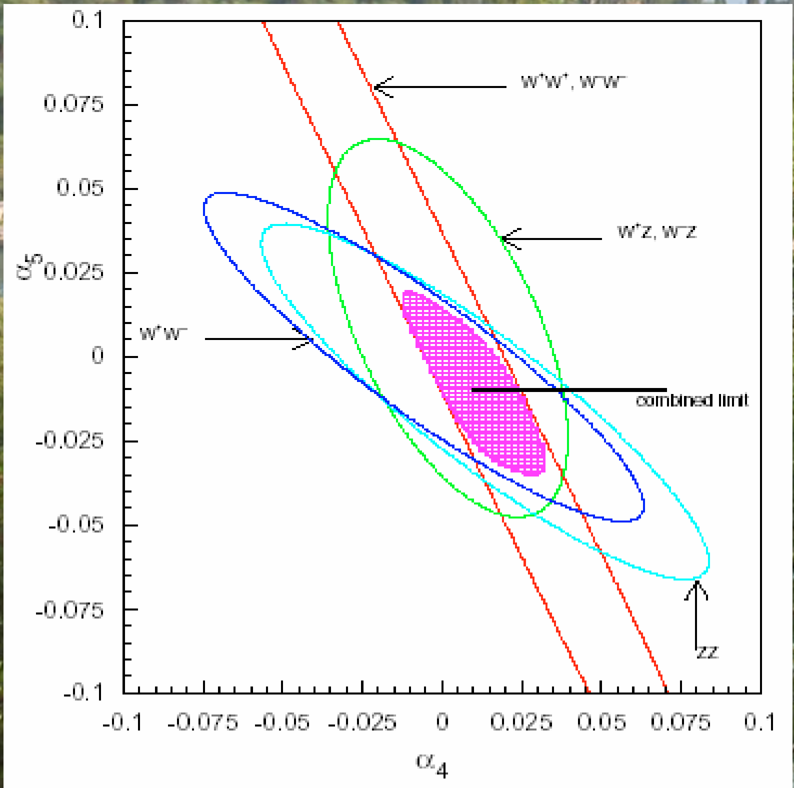


Measure Little Higgs Decays @ LC

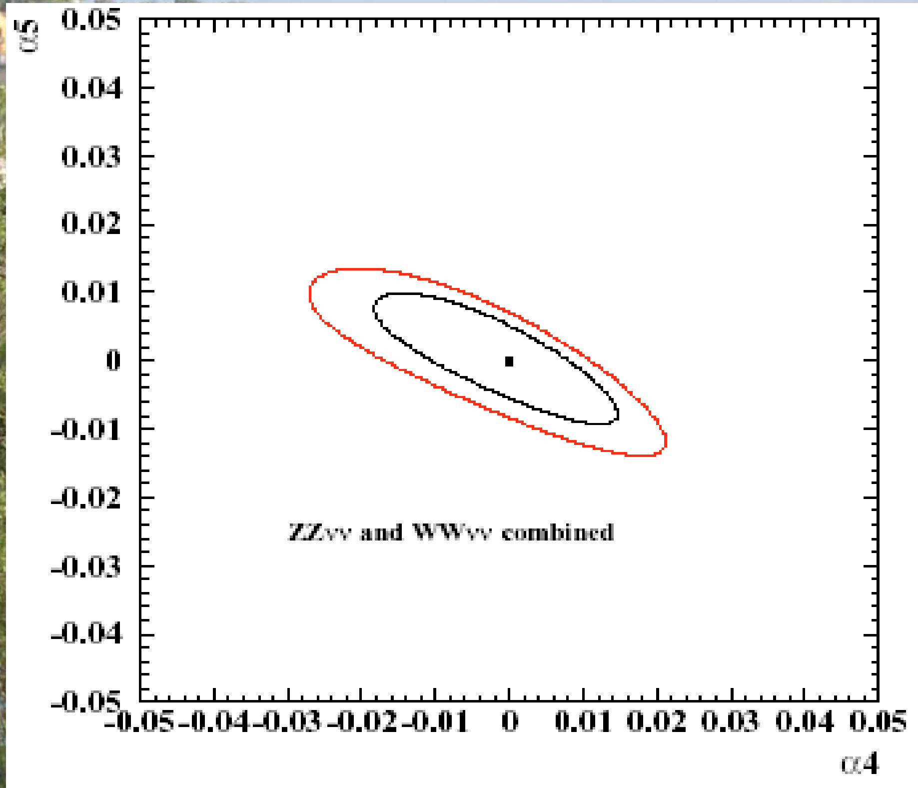


Sensitivity to Strong WW scattering

@ LHC



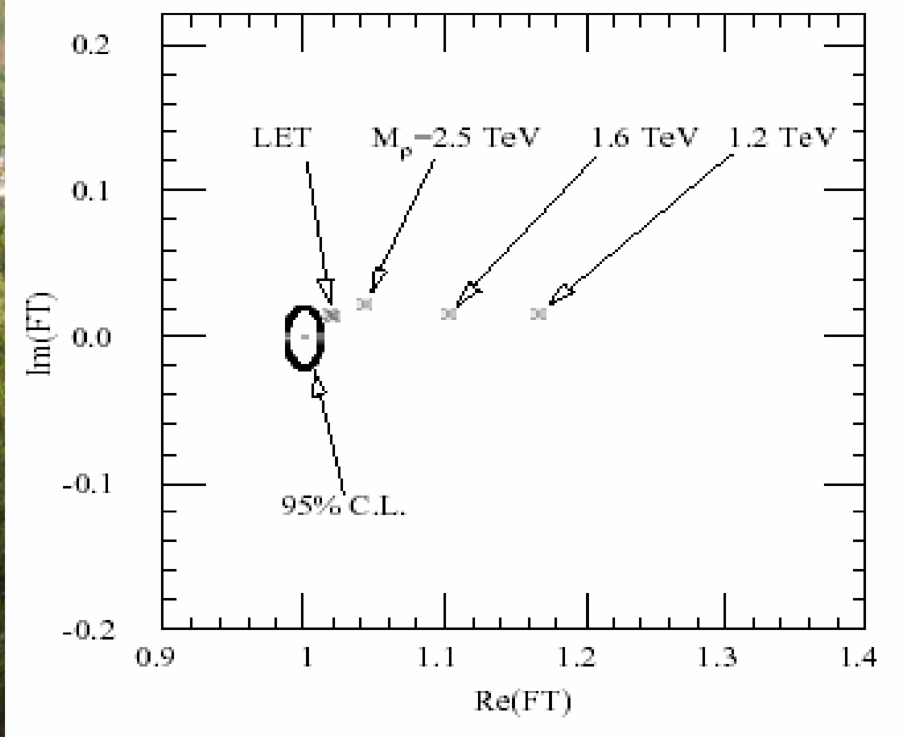
@ 800 GeV LC

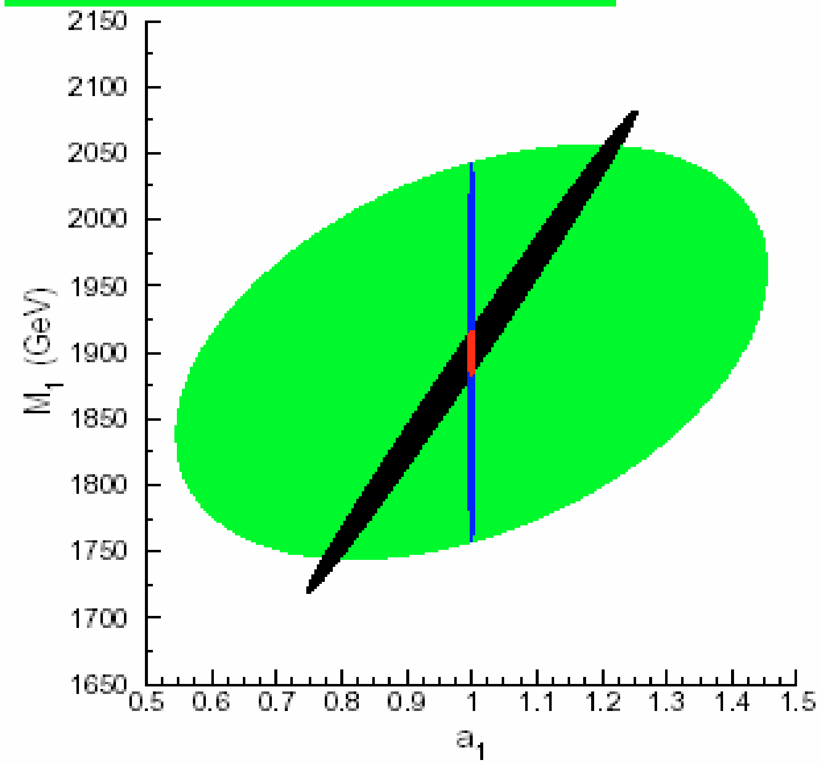


Measuring a WW Resonance

Form factor measurements @ 500 GeV LC

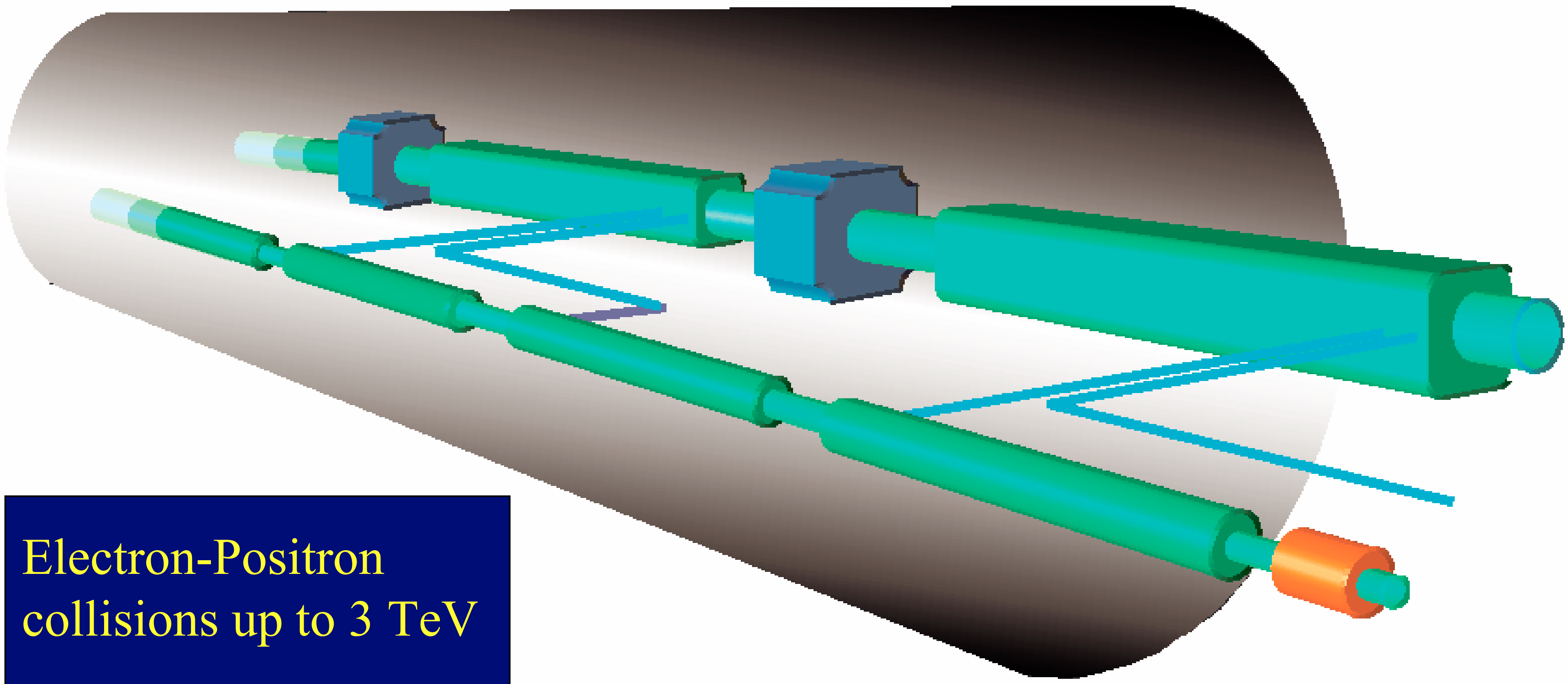
Resonance parameters @ LHC





Resonance parameters @ 500 GeV LC

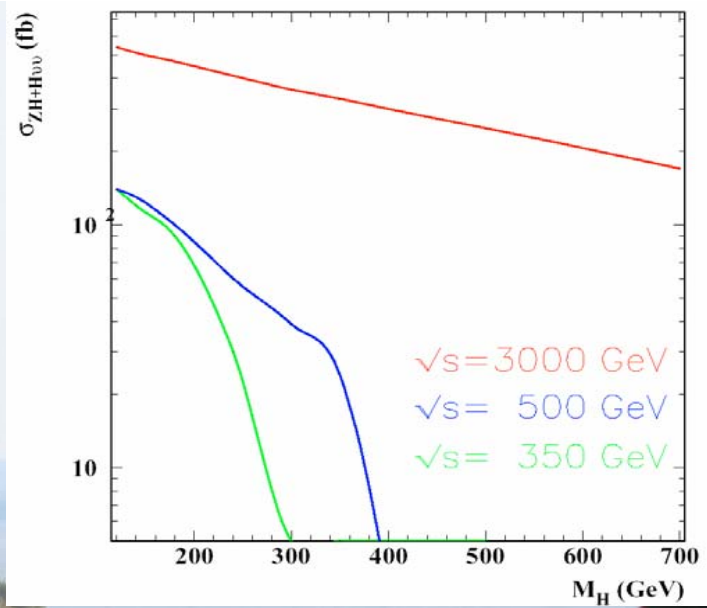
After LHC @ CERN - CLIC?

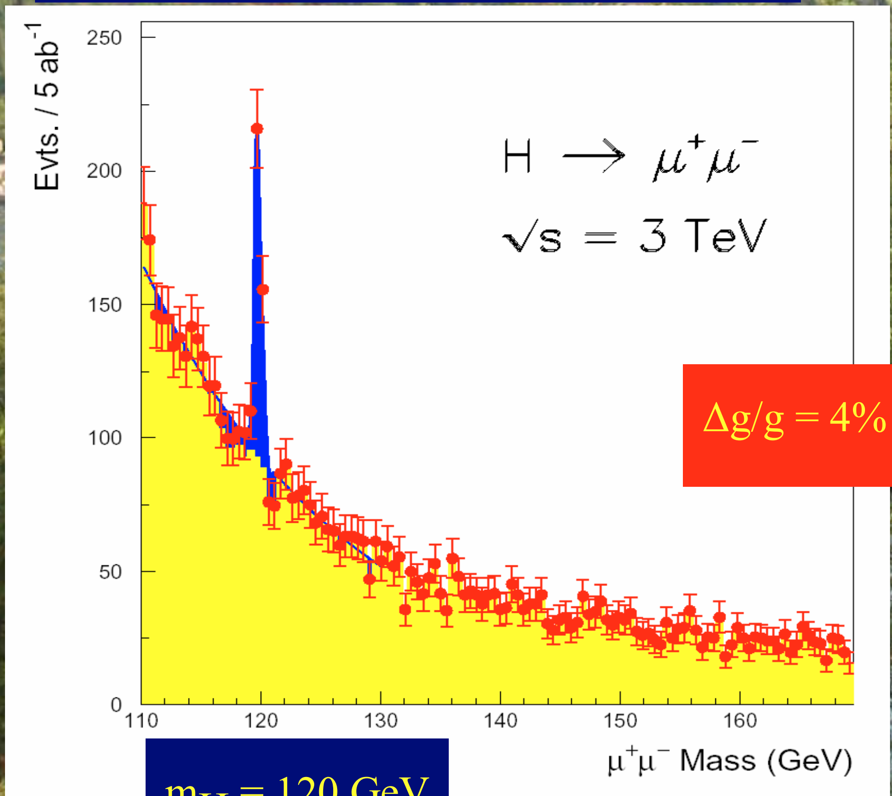


Electron-Positron
collisions up to 3 TeV

Advantages of Higher Energy LC

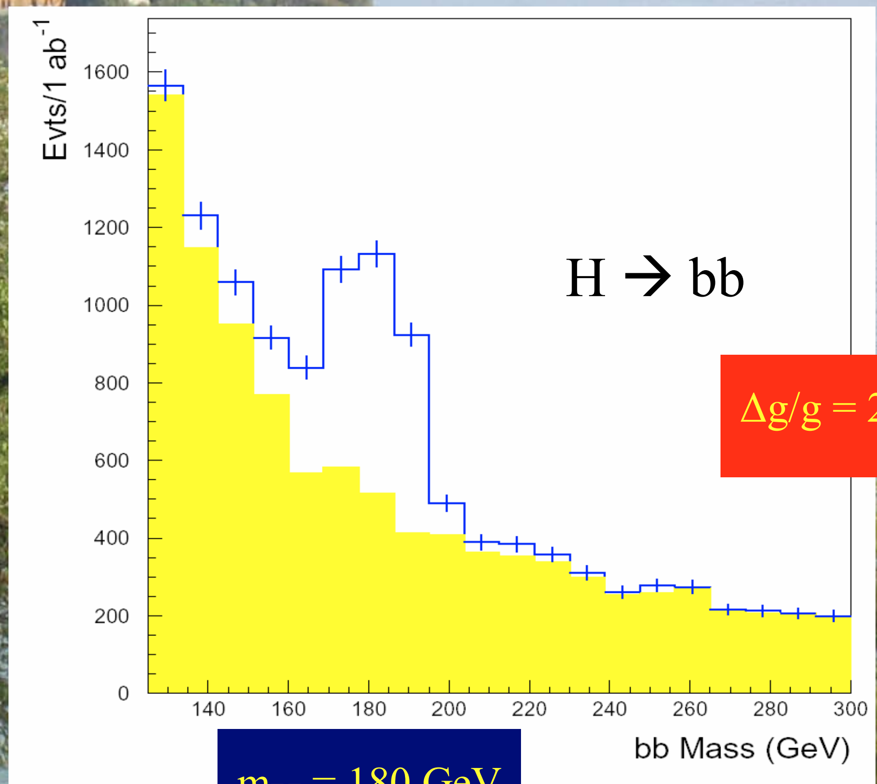
Larger cross section @ 3 TeV
can measure rare decay modes





$\Delta g/g = 4\%$

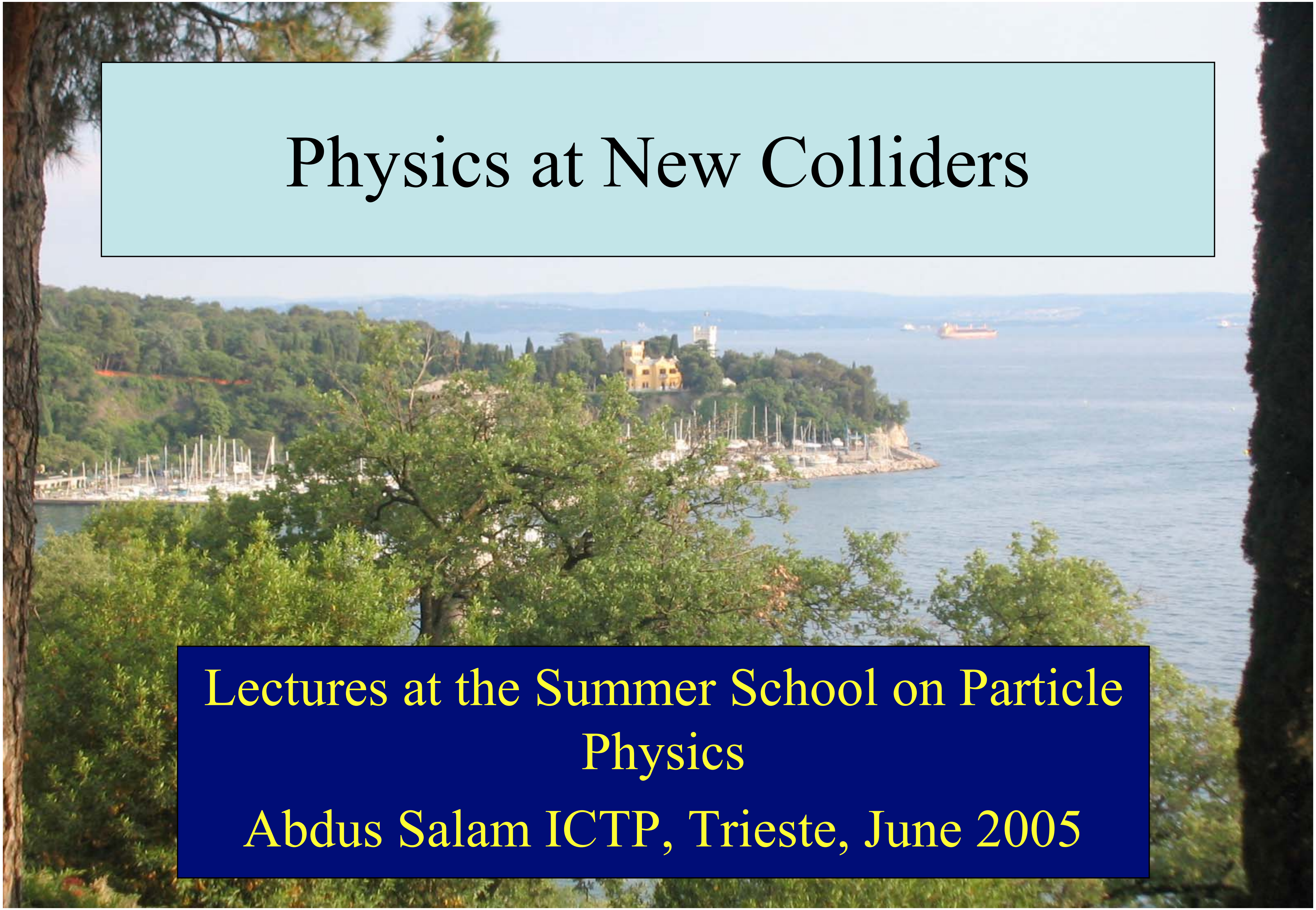
$m_H = 120$ GeV



$\Delta g/g = 2\%$

$m_H = 180$ GeV

Physics at New Colliders



Lectures at the Summer School on Particle Physics

Abdus Salam ICTP, Trieste, June 2005

Plan of the Lectures

- Status of the Standard Model
- Open issues beyond the Standard Model
- Origin of particle masses
- Search for the Higgs boson
- Supersymmetry
- Searches for supersymmetry
- Possible other new physics at colliders

What is Supersymmetry (Susy)?

- Unifies matter and force particles?
- Links fermions and bosons

  Exclusion principle vs laser coherence
- Relates particles of different spins

  0 - ½ - 1 - 3/2 - 2

  Higgs - Electron - Photon - Gravitino - Graviton
- Helps fix masses, unify fundamental forces

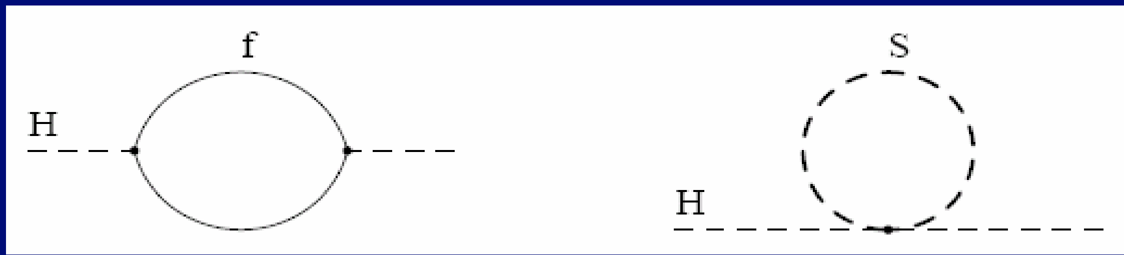
1973

Why Supersymmetry (Susy)?

- Hierarchy problem: why is $m_W << m_P$?
  ($m_P \sim 10^{19}$ GeV is scale of gravity)
- Alternatively, why is
  $G_F = 1/\, m_W^2 >> G_N = 1/m_P^2$?
- Or, why is
  $V_{Coulomb} >> V_{Newton}$? $e^2 >> G\, m^2 = m^2 / m_P^2$
- Set by hand? What about loop corrections?
  $\delta m_{H,W}^2 = O(\alpha/\pi)\, \Lambda^2$
- Cancel boson loops ⇔ fermions
- Need $|\, m_B^2 - m_F^2| < 1\ \text{TeV}^2$

Loop Corrections to Higgs Mass^2

- Consider generic fermion and boson loops:



- Each is quadratically divergent: $\int^{\Lambda} d^4k/k^2$

$$\Delta m_H^2 = -\frac{y_f^2}{16\pi^2}[2\Lambda^2 + 6m_f^2 \ln(\Lambda/m_f) + ...]$$

$$\Delta m_H^2 = \frac{\lambda_S}{16\pi^2}[\Lambda^2 - 2m_S^2 \ln(\Lambda/m_S) + ...]$$

- Leading divergence cancelled if

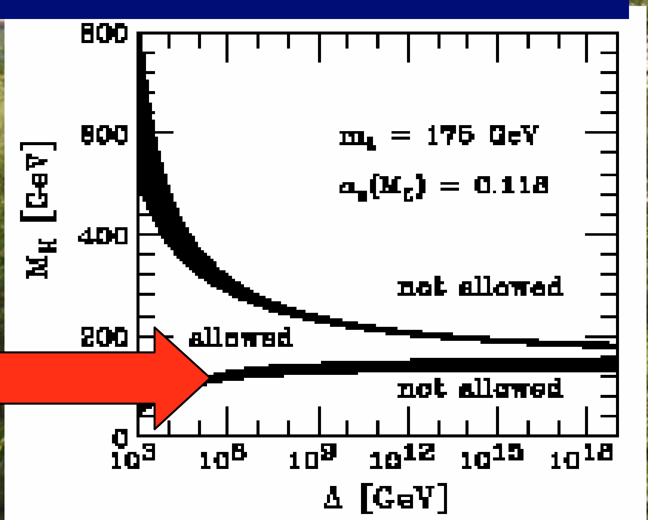
$$\lambda_S = y_f^2$$

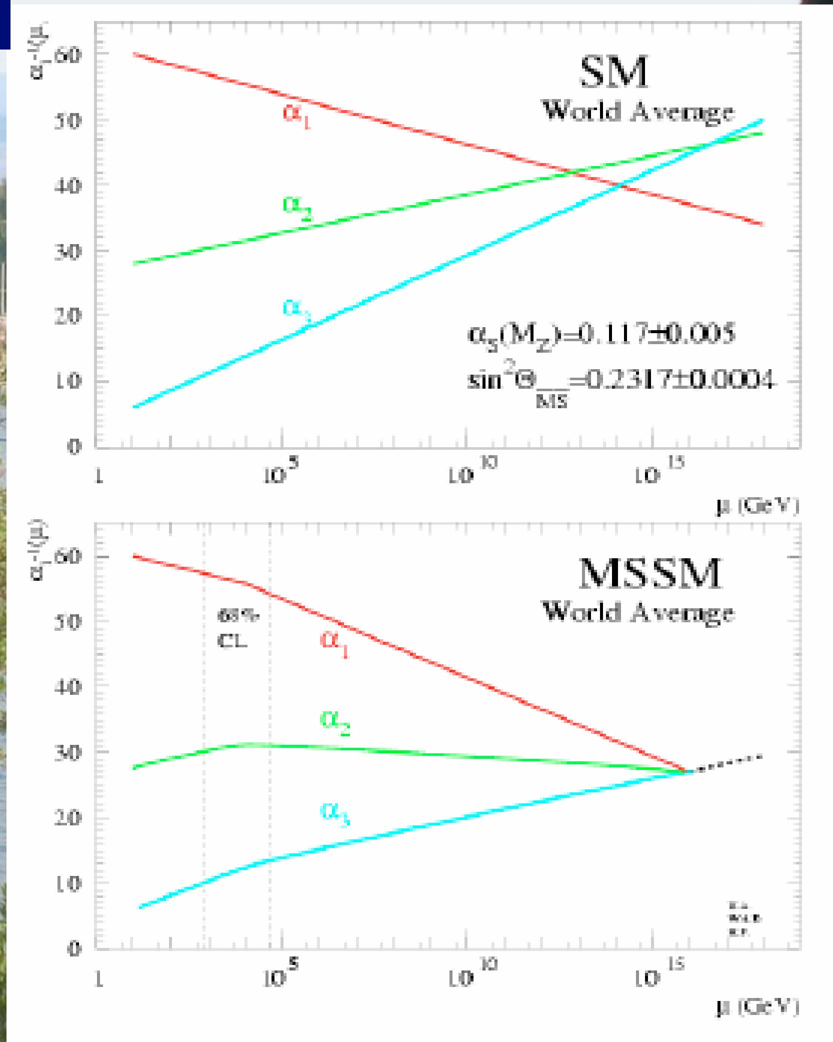
Other Reasons to like Susy

It enables the gauge couplings to unify

It predicts $m_H < 150$ GeV

It stabilizes the Higgs potential for low masses





Approved by Fabiola Gianotti

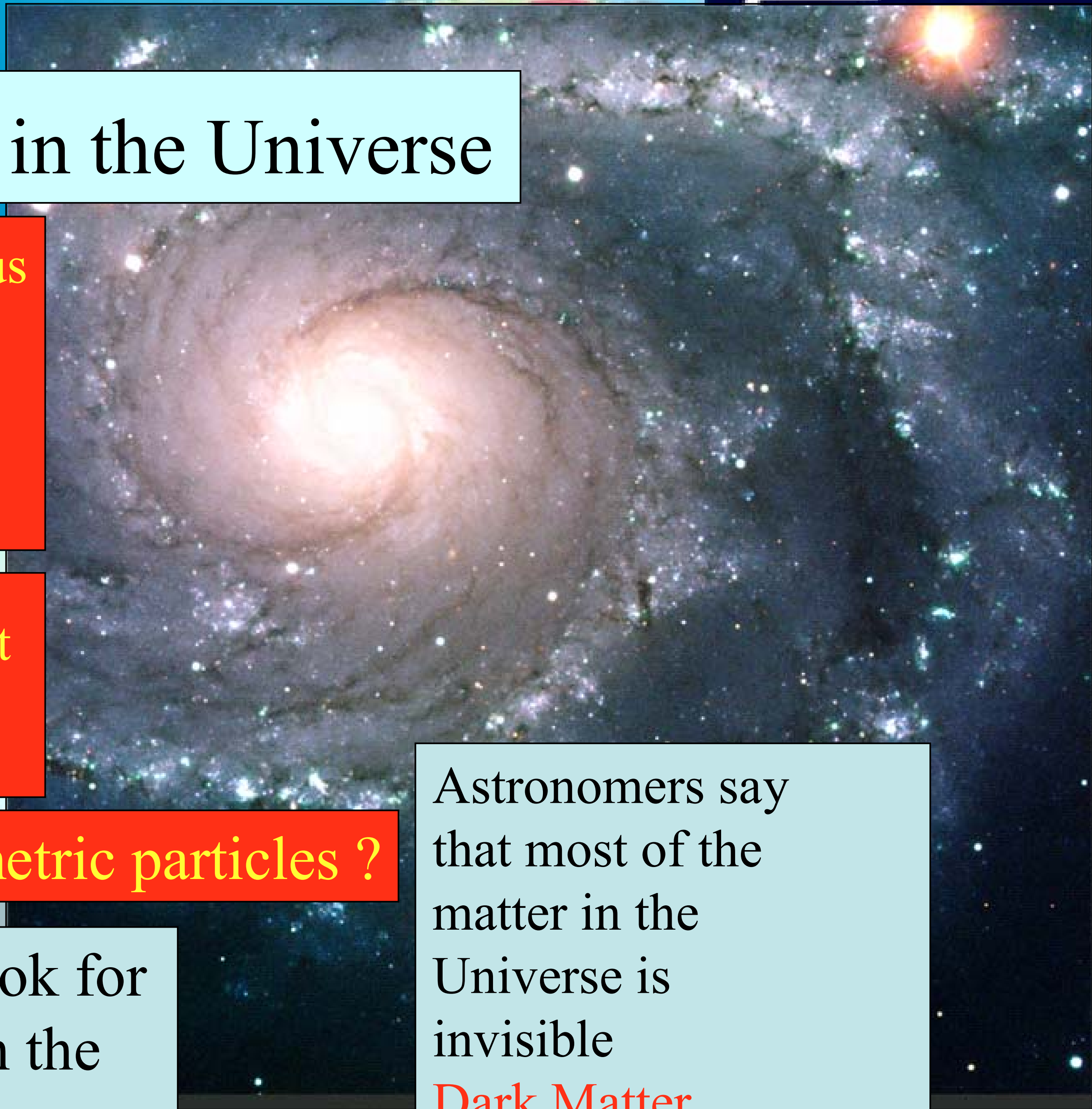
Dark Matter in the Universe

Astronomers tell us that most of the matter in the universe is invisible

We will look for it

with the LHC

Lightest Supersymmetric particles ?



Astronomers say that most of the matter in the Universe is invisible
Dark Matter

We shall look for them with the LHC

Supersymmetry Algebra

- Simply stated:

$$\begin{aligned} Q|Boson > &= |Fermion > \\ Q|Fermion > &= |Boson > \end{aligned}$$

- Spinorial charges obey algebra:

$$\begin{aligned} [P^\mu, Q_\alpha] &= 0 = [P^\mu, \bar{Q}^{\dot{\alpha}}] \\ \{Q_\alpha, \bar{Q}_{\dot{\beta}}\} &= 2(\sigma_\mu)_{\alpha\dot{\beta}} P^\mu \\ \{Q_\alpha, Q_\beta\} &= \{\bar{Q}^{\dot{\alpha}}, \bar{Q}^{\dot{\beta}}\} = 0 \end{aligned}$$

- Only possible symmetry of S-matrix that combines particles of different spins
- Supermultiplets: chiral (0, 1/2), vector (1/2, 1)

Simplest Supersymmetric Field Theory

- Free scalar boson and free spin-1/2 fermion:

$$S = \int d^4x \; \mathcal{L}_{scalaire} + \mathcal{L}_{fermion}$$
$$\mathcal{L}_{scalaire} = -\partial^\mu \phi \, \partial_\mu \phi^*$$
$$\mathcal{L}_{fermion} = -i\psi^\dagger \bar{\sigma}^\mu \, \partial_\mu \psi$$

- Transform boson to fermion:

$$\delta\phi = \epsilon^\alpha \psi_\alpha \quad \text{et} \quad \delta\phi^* = \bar{\epsilon}_{\dot{\alpha}} \, \bar{\psi}^{\dot{\alpha}}$$
$$\Rightarrow \delta\mathcal{L}_{scalaire} = -\epsilon^\alpha \left(\partial^\mu \psi_\alpha\right) \partial_\mu \phi^* - \partial^\mu \phi \, \bar{\epsilon}_{\dot{\alpha}} \left(\partial_\mu \bar{\psi}^{\dot{\alpha}}\right)$$

- Fermion to boson: $\delta\psi_\alpha = i(\sigma^\mu \epsilon^\dagger)_\alpha \, \partial_\mu \phi \quad \text{et} \quad \delta\bar{\psi}^{\dot{\alpha}} = -i(\epsilon \, \sigma^\mu)^{\dot{\alpha}} \, \partial_\mu \phi^*$
- Lagrangian changes by total derivative: action $A = \int d^4x \, L(x)$ invariant
- Supersymmetry: QQ = P $\quad \phi \to \psi \to \partial\phi, \quad \psi \to \partial\phi \to \partial\psi$

Supersymmetry with Interactions

- General form: $L = L_0 - V(\phi^i, \phi^*_j) - \frac{1}{2} M_{ij}(\phi, \phi^*) \bar{\psi}^{ci} \psi^j$
- Variation includes: $\frac{\partial M}{\partial \phi^*} \psi^* \bar{\psi}^c \psi$ $\frac{\partial M_{ij}}{\partial \phi^k} \bar{E} \psi^k \bar{\psi}^{ci} \psi^j$
- Cannot cancel, so $M = M(\phi)$ ymmetric $M_{ij} = \frac{\partial W}{\partial \phi^i \partial \phi^j}$
- Cancel variation in potential:

$$\frac{\partial V}{\partial \phi^i} \bar{E} \psi^I + (\mathrm{Herm.Conj.}) \rightarrow \quad V = \left| \frac{\partial W}{\partial \phi^i} \right|^2$$

- Final form:

$$L = i \bar{\psi}_i \gamma_\mu \partial^\mu \psi^i + |\partial_\mu \phi^i|^2 - \left| \frac{\partial W}{\partial \phi^i} \right|^2 - \frac{1}{2} \frac{\partial^2 W}{\partial \phi^i \partial^j} \bar{\psi}^{ci} \partial \psi^j + (\mathrm{Herm.Conj.})$$

- Simple case:

$$W = \frac{\lambda}{3} \phi^3 + \frac{m}{2} \phi^2 \qquad L = i \bar{\psi} \gamma_\mu \partial^\mu \psi + |\partial_\mu \phi|^2 - |m\phi + \lambda \phi^2|^2 - m \bar{\psi}^c \psi - \lambda \phi \bar{\psi}^c \psi.$$

More Supersymmetric Field Theories

- Gauge bosons + adjoint spin-1/2 fermions = supersymmetric gauge theory
- Effective potential fixed by Yukawa, gauge couplings: $V = g^2 \varphi^2 \varphi^{*2} + y^2 \varphi^2 \varphi^{*2}$

  → prediction for Higgs mass

  $m_h < m_Z$ at tree level, loops

$$\delta m_h^2 \propto \frac{m_t^4}{m_W^2} \ln\left(\frac{m_{\tilde{t}}^2}{m_t^2}\right) + \dots$$

- Graviton minimally coupled to spin-3/2 fermion = supergravity

Minimal Supersymmetric Extension of Standard Model (MSSM)

- Particles + spartners

$$\begin{pmatrix} \frac{1}{2} \\ 0 \end{pmatrix} \; e.g., \; \begin{pmatrix} \ell \; (lepton) \\ \tilde{\ell} \; (slepton) \end{pmatrix} \; or \; \begin{pmatrix} q \; (quark) \\ \tilde{q} \; (squark) \end{pmatrix} \begin{pmatrix} 1 \\ \frac{1}{2} \end{pmatrix} \; e.g., \; \begin{pmatrix} \gamma \; (photon) \\ \tilde{\gamma} \; (photino) \end{pmatrix} \; or \; \begin{pmatrix} g \; (gluon) \\ \tilde{g} \; (gluino) \end{pmatrix}$$

- 2 Higgs doublets, coupling μ, ratio of v.e.v.'s = $\tan\beta$
- Unknown supersymmetry-breaking parameters:
  - Scalar masses m_0, gaugino masses $m_{1/2}$,
  - trilinear soft couplings A_λ, bilinear soft coupling B_μ
- Often assume universality:
  - Single m_0, single $m_{1/2}$, single A_λ, B_μ: not string?
- Called constrained MSSM = CMSSM
- Gravitino mass? Minimal supergravity: not string?
  - $m_{3/2} = m_0$, $B_\mu = A_\lambda - m_0$

Lightest Supersymmetric Particle

- Stable in many models because of conservation of R parity:

  $R = (-1)^{2S - L + 3B}$

  where S = spin, L = lepton #, B = baryon #
- Particles have R = +1, sparticles R = -1:

  Sparticles produced in pairs

  Heavier sparticles → lighter sparticles
- Lightest supersymmetric particle (LSP) stable

Possible Nature of LSP

- No strong or electromagnetic interactions
  - Otherwise would bind to matter
  - Detectable as anomalous heavy nucleus
- Possible weakly-interacting scandidates
  - Sneutrino
    - (Excluded by LEP, direct searches)
  - Lightest neutralino χ
  - Gravitino
    - (nightmare for detection)

Constraints on Supersymmetry

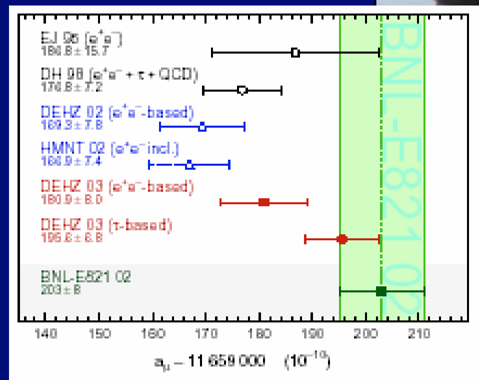
- Absence of sparticles at LEP, Tevatron

  selectron, chargino > 100 GeV

  squarks, gluino > 250 GeV

- Indirect constraints

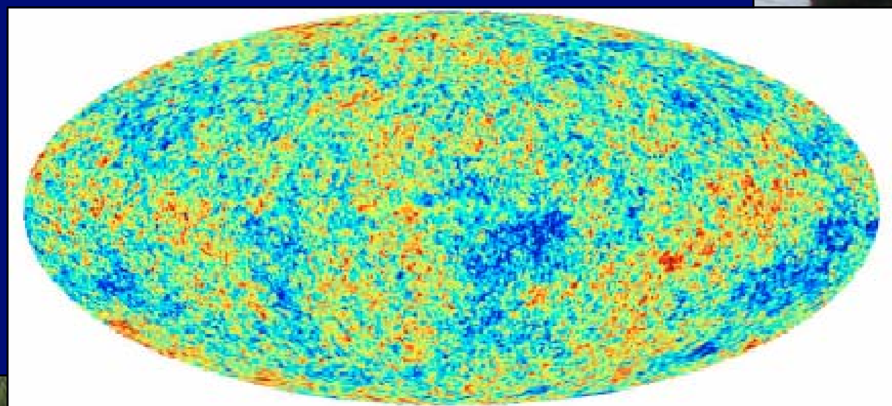
  Higgs > 114 GeV, b -> s γ $\quad$ g_μ - 2



- Density of dark matter

  lightest sparticle χ:

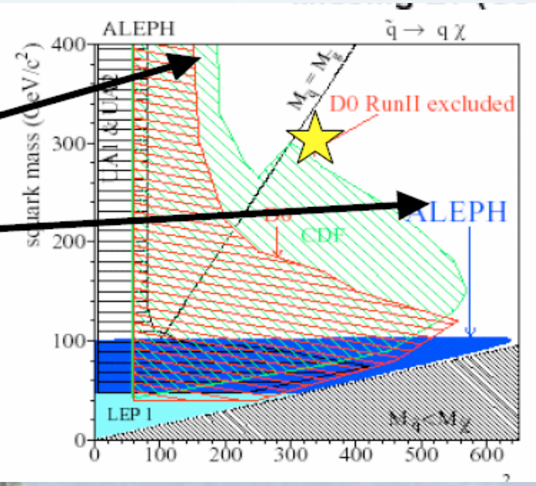
WMAP: $0.094 < \Omega_\chi h^2 < 0.124$



Squark & Gluino Searches @ FNAL

General Squarks & gluinos

- Exclude: $m(\tilde{q}/\tilde{g}) < 292/333$ GeV
- Gluino and Squark mass limits:
  - $M(q)>M(g)$: $\tilde{u},\tilde{d},\tilde{s},\tilde{c},\tilde{b}$ mass equal
  - $M(g)<M(q)$: $\tilde{u},\tilde{d},\tilde{s},\tilde{c}$ mass equal
- Improves Run I limits:
  - Include more data
  - Scan parameter space

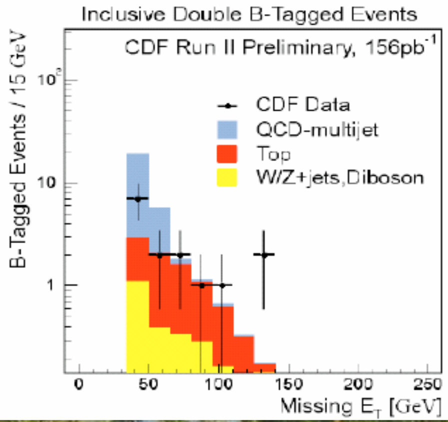


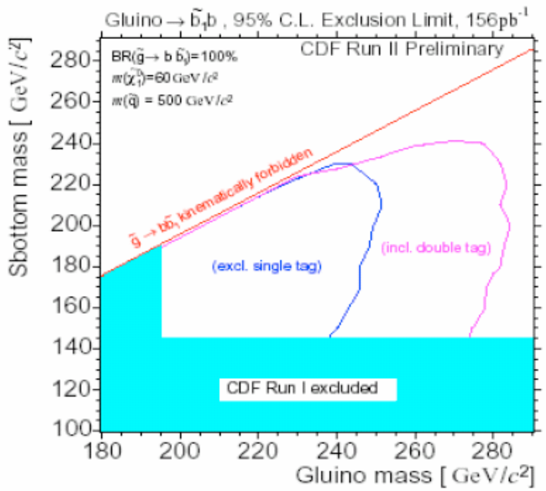
Specific search for light sbottom

- $BR(\tilde{g}\to\tilde{b}b)\sim100\%$ assumed
- Spectacular signature:
  - 4 b-quarks + $\not{E}_T$
- Require b-jets and $\not{E}_T>80$ GeV

Expect: 2.6±0.7

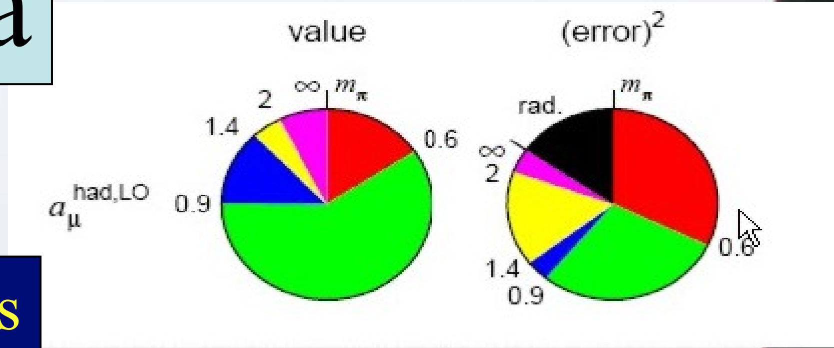
Observe: 4



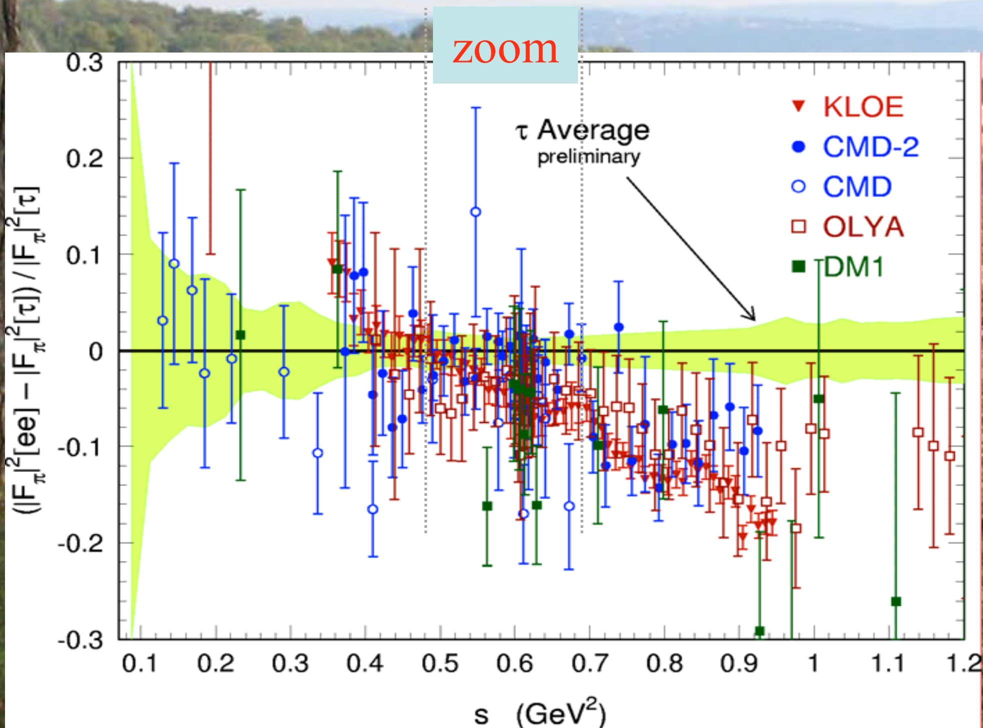


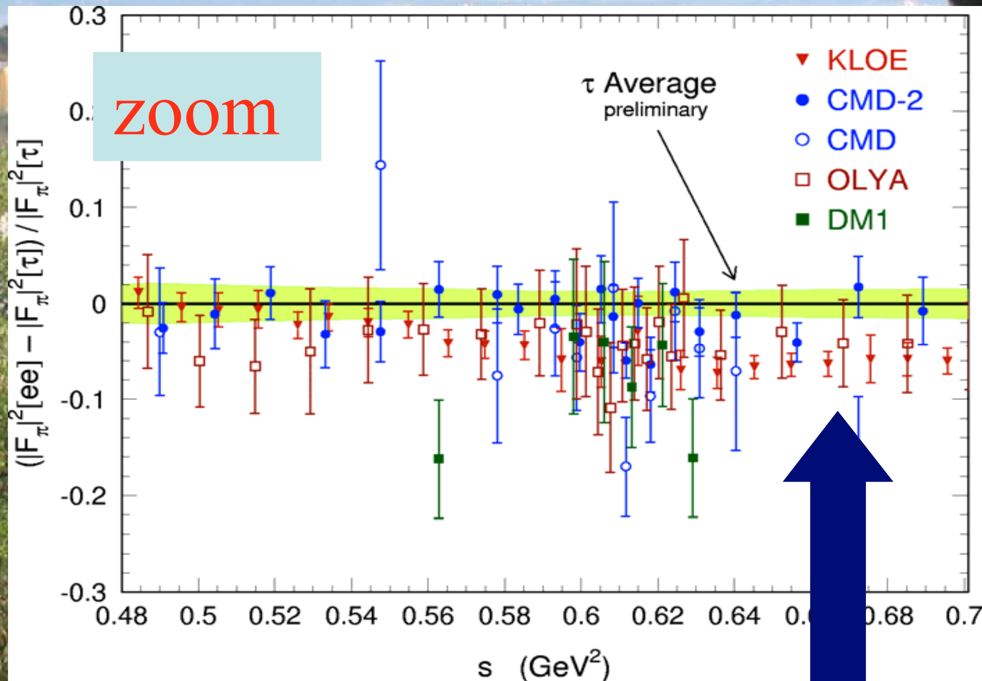
Exclude new parameter space in gluino vs. sbottom mass plane

g_μ - 2: e^+e^- Data vs τ Data



Largest contributions, errors from low energies





KLOE agrees with CMD-2: discard τ data

Why the 10%
τ - e^+e^- discrepancy
above ρ peak?

Updated Results for g_μ - 2

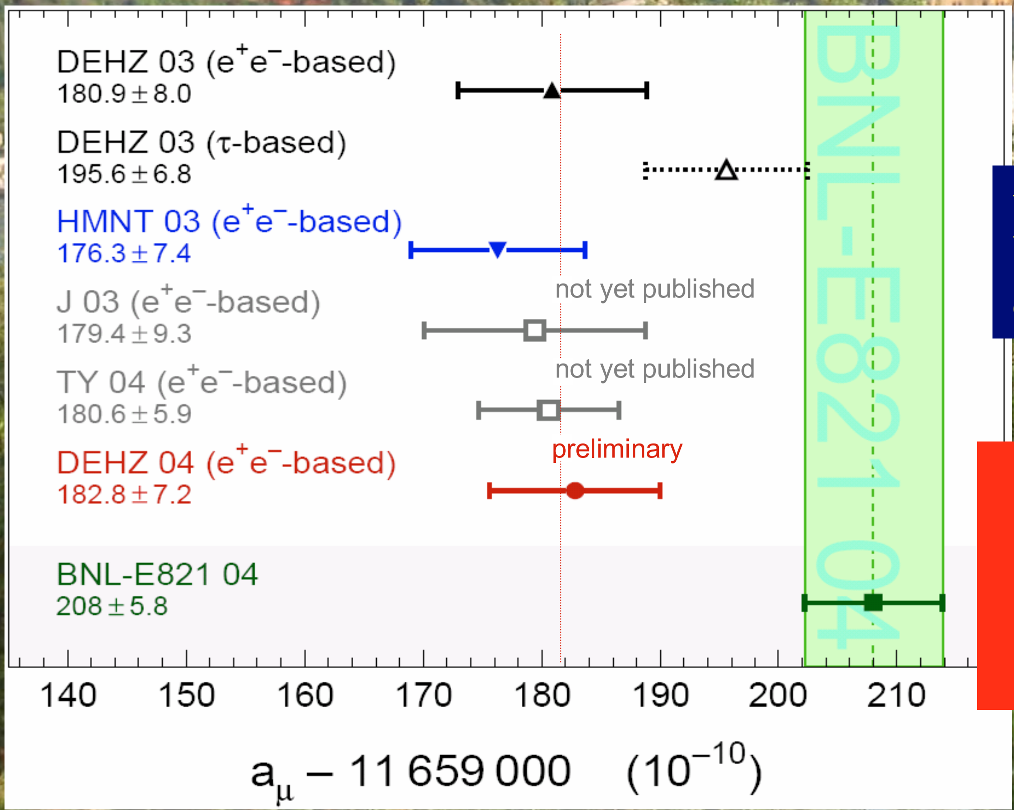
$a_\mu^{had}[e^+e^-] = (693.4 \pm 5.3 \pm 3.5) \times 10^{-10}$

$a_\mu^{SM}[e^+e^-] = (11\,659\,182.8 \pm 6.3_{had} \pm 3.5_{LBL} \pm 0.3_{QED+EW}) \times 10^{-10}$

Weak contribution : $a_\mu^{weak} = +(15.4 \pm 0.3) \times 10^{-10}$

Hadronic contribution from higher order : $a_\mu^{had}[(\alpha/\pi)^3] = -(10.0 \pm 0.6) \times 10^{-10}$

Hadronic contribution from LBL scattering: $a_\mu^{had}[LBL] = +(12.0 \pm 3.5) \times 10^{-10}$



BNL E821 (2004):

$a_\mu^{exp} = (11\,659\,208.0 \pm 5.8)\ 10^{-10}$

$a_\mu^{exp} - a_\mu^{SM} = (25.2 \pm 9.2) \times 10^{-10}$

➡ 2.7 standard deviations

Current Constraints on CMSSM

Assuming the lightest sparticle is a neutralino

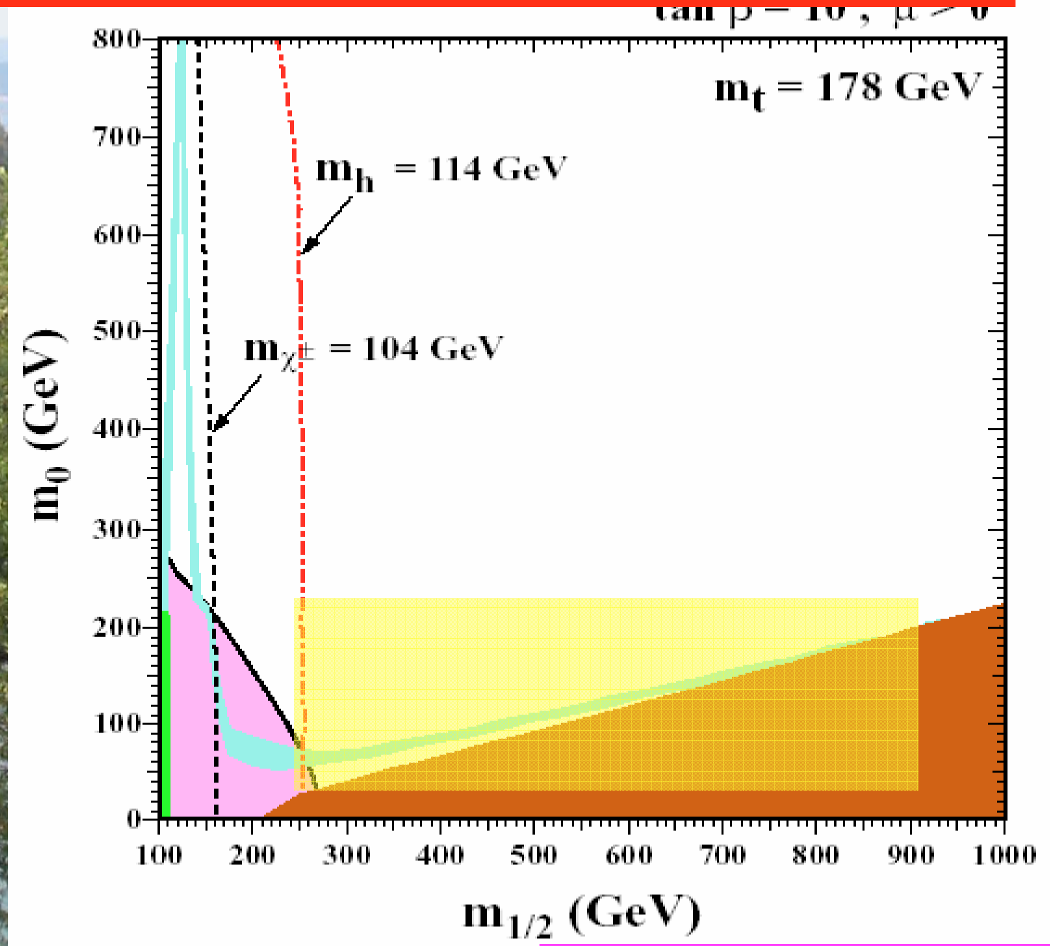
Focus-point region above 7 TeV for m_t = 178 GeV

Excluded because stau LSP

Excluded by $b \rightarrow s$ gamma

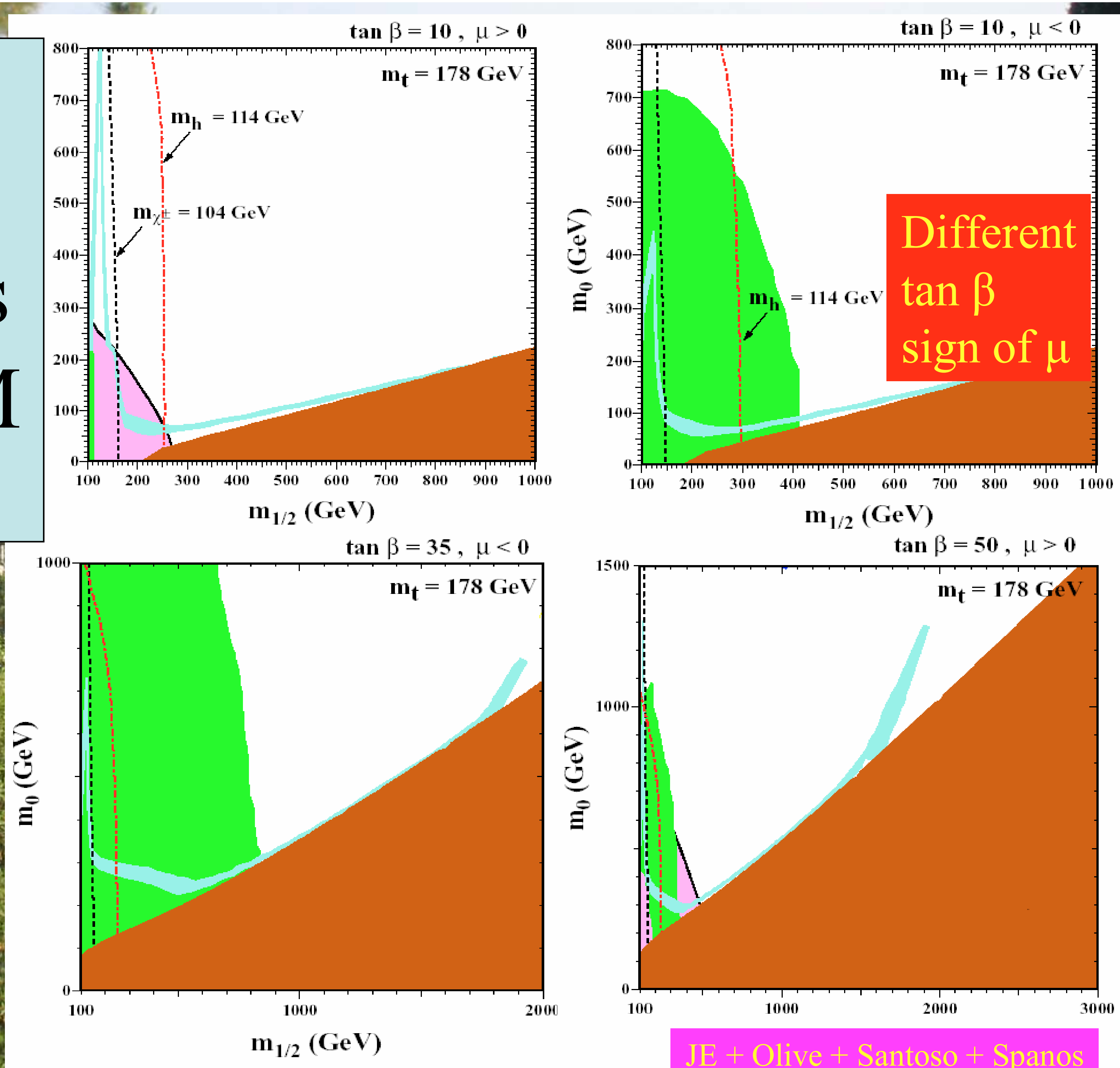
WMAP constraint on relic density

Excluded (?) by latest g - 2



JE + Olive + Santoso + Spanos

Current Constraints on CMSSM



Different $\tan\beta$
sign of μ

Impact of Higgs constraint reduced if larger m_t

Focus-point region far up

JE + Olive + Santoso + Spanos

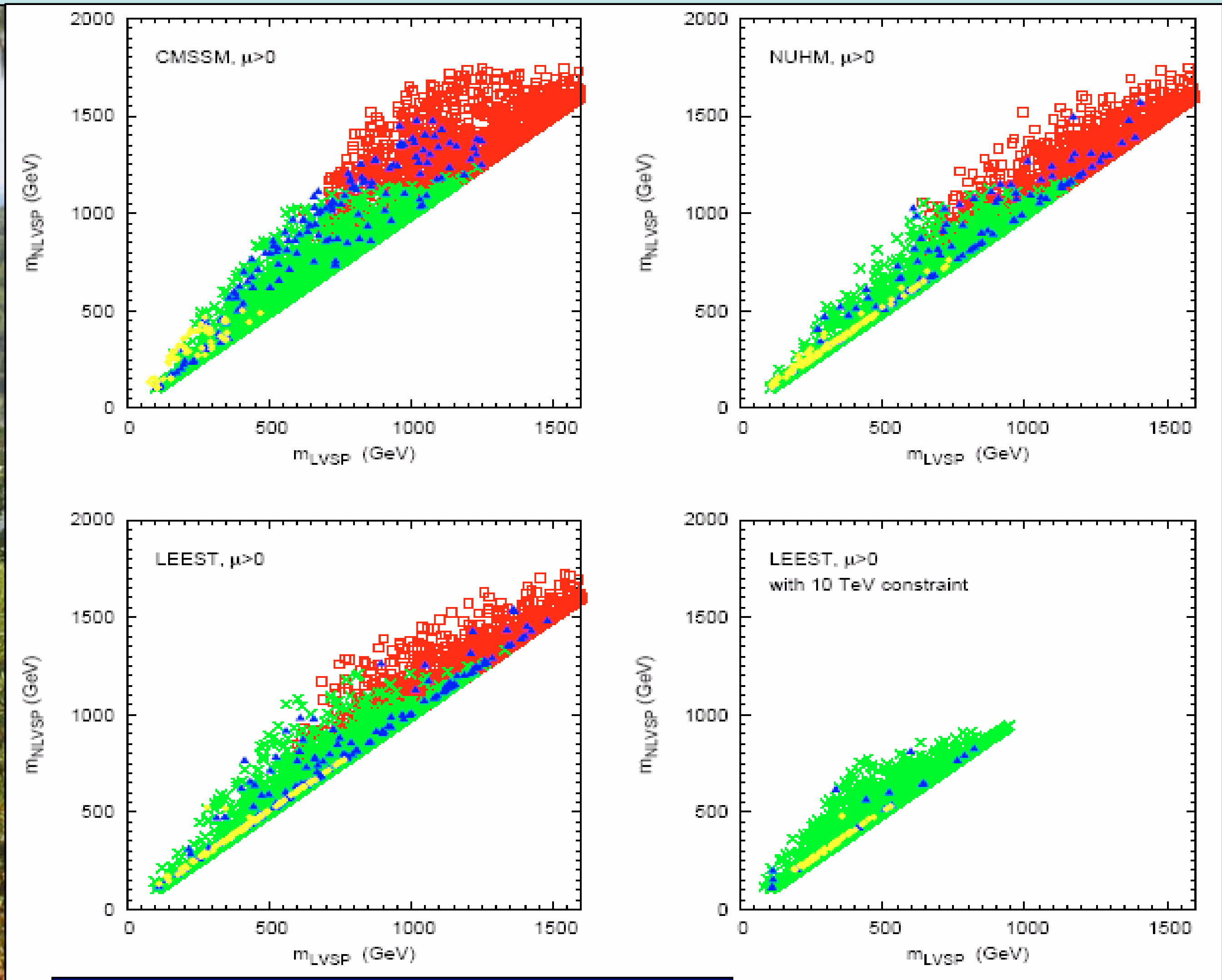
Sparticles may not be very light

Full Model samples

Detectable @ LHC

Provide Dark Matter

Dark Matter Detectable Directly



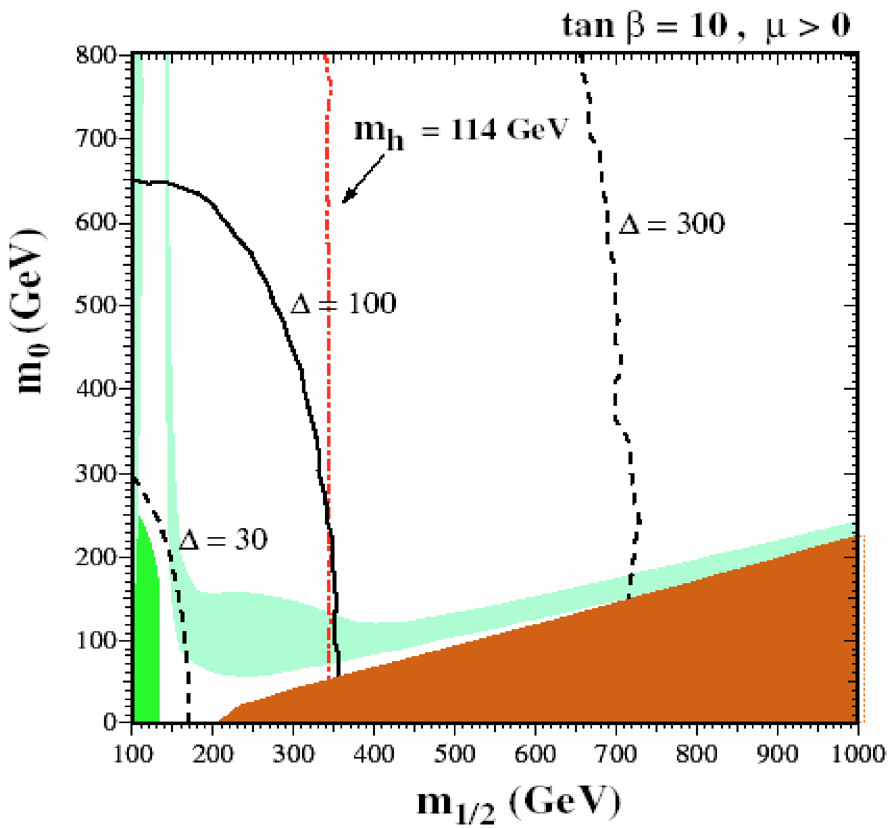
← Second lightest visible particle

Lightest visible sparticle →

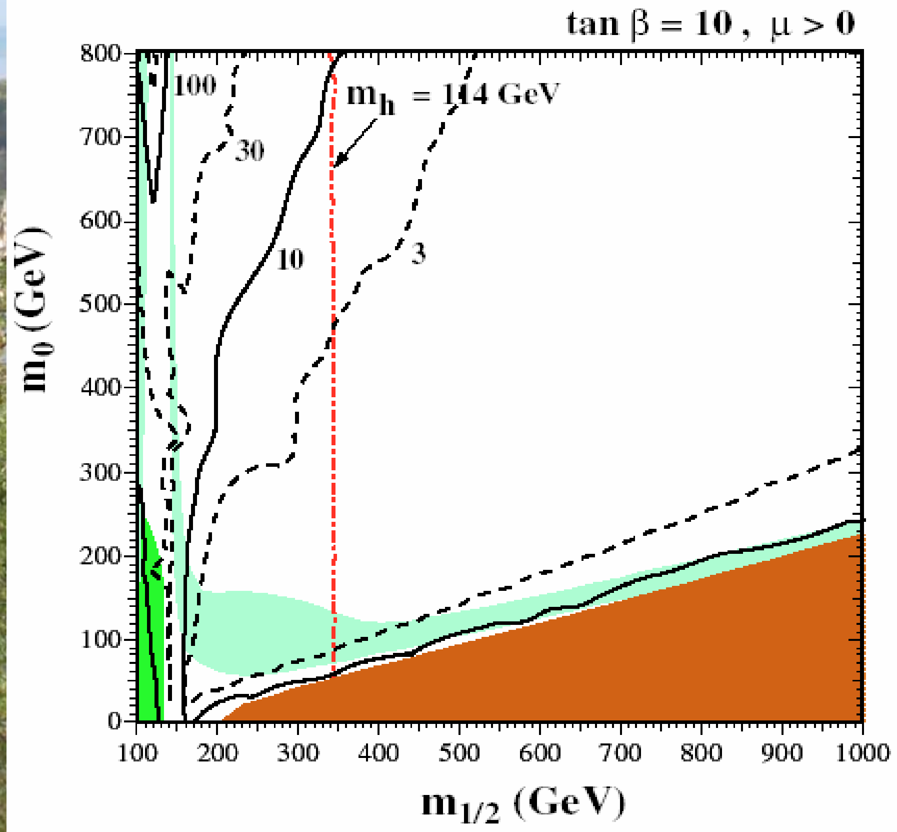
JE + Olive + Santoso + Spanos

How ‘Likely’ are Heavy Sparticles?

Fine-tuning of EW scale



Fine-tuning of relic density

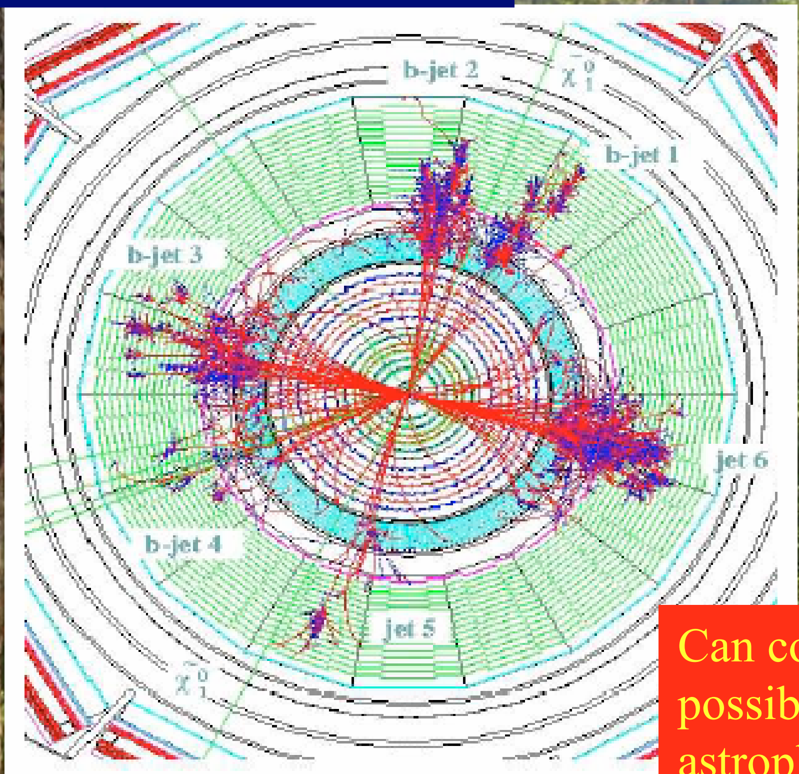


Larger masses require more fine-tuning: but how much is too much?

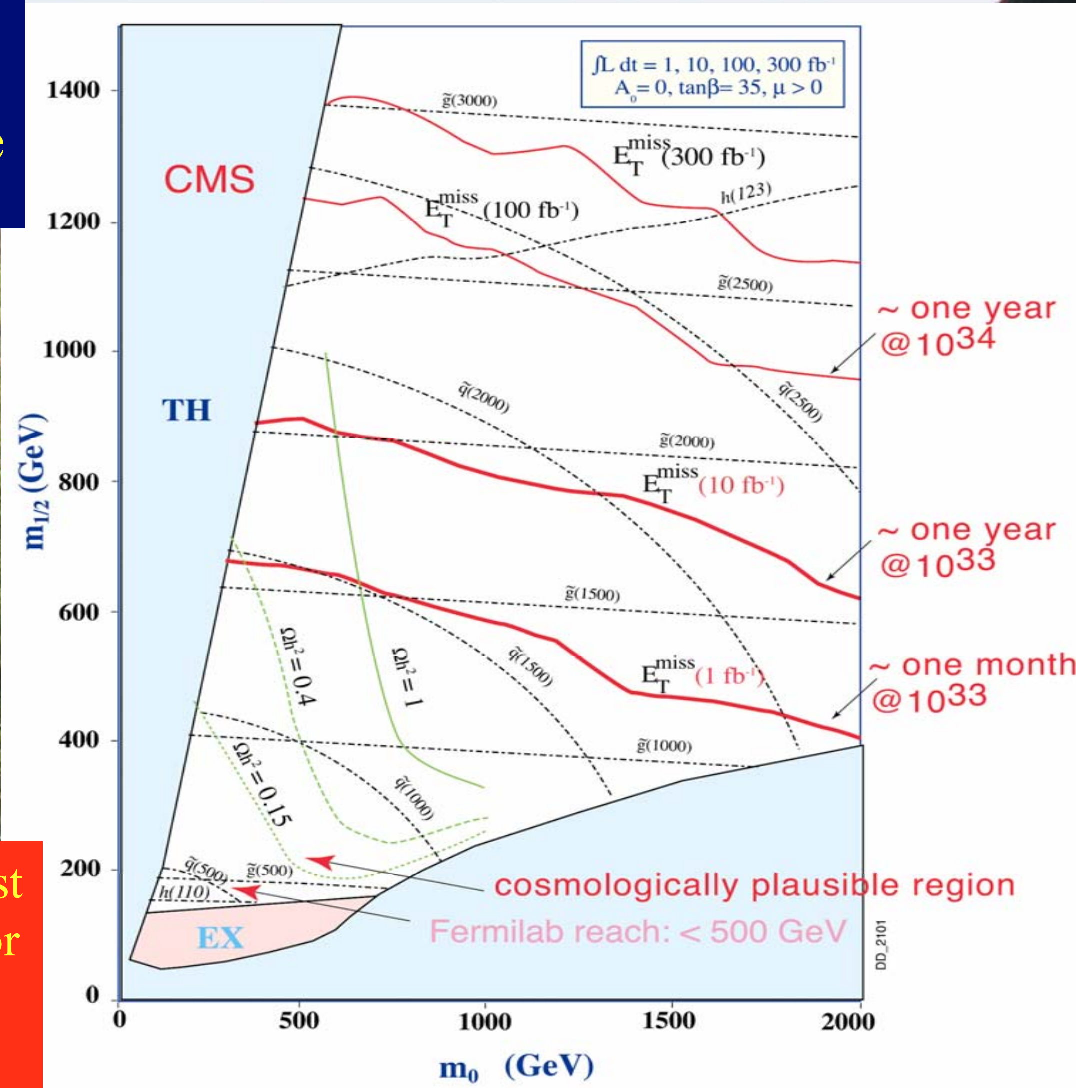
Supersymmetry Searches at LHC

`Typical' supersymmetric Event at the LHC

LHC reach in supersymmetric parameter space

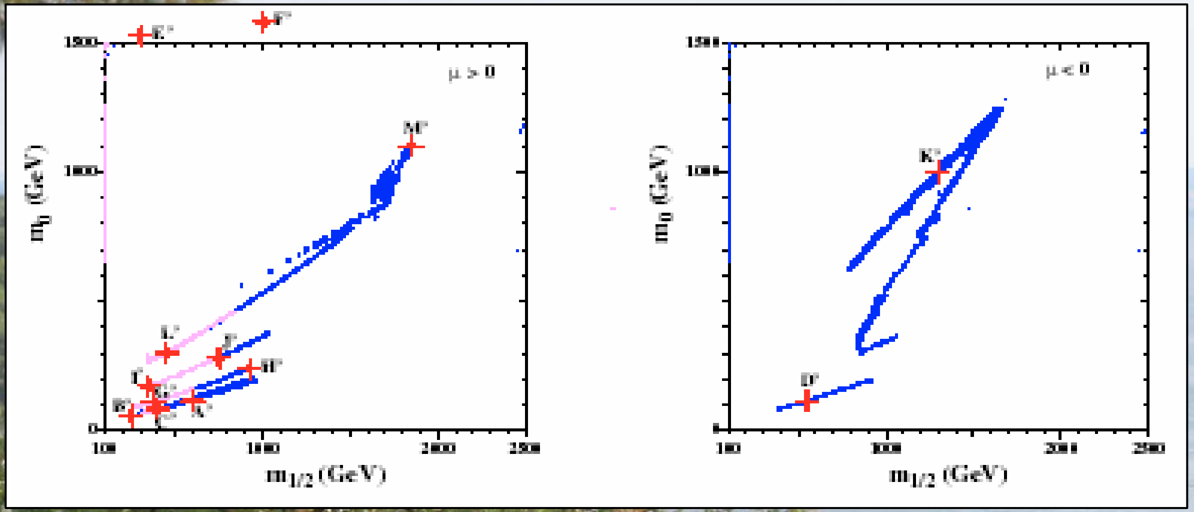


Can cover most possibilities for astrophysical dark matter



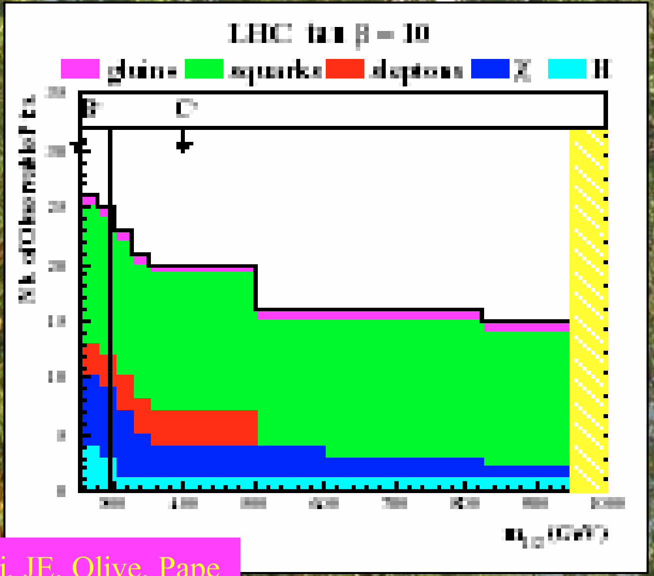
Supersymmetric Benchmark Studies

Lines in susy space allowed by accelerators, WMAP data

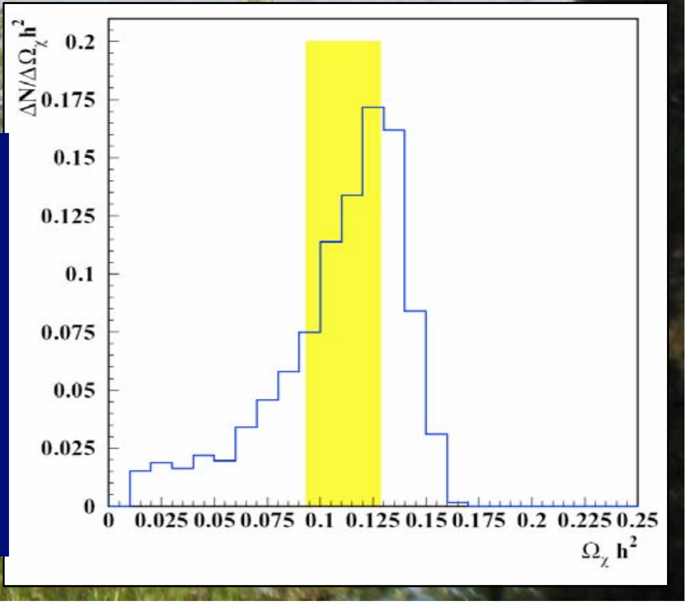


Specific benchmark Points along WMAP lines

Sparticle detectability Along one WMAP line

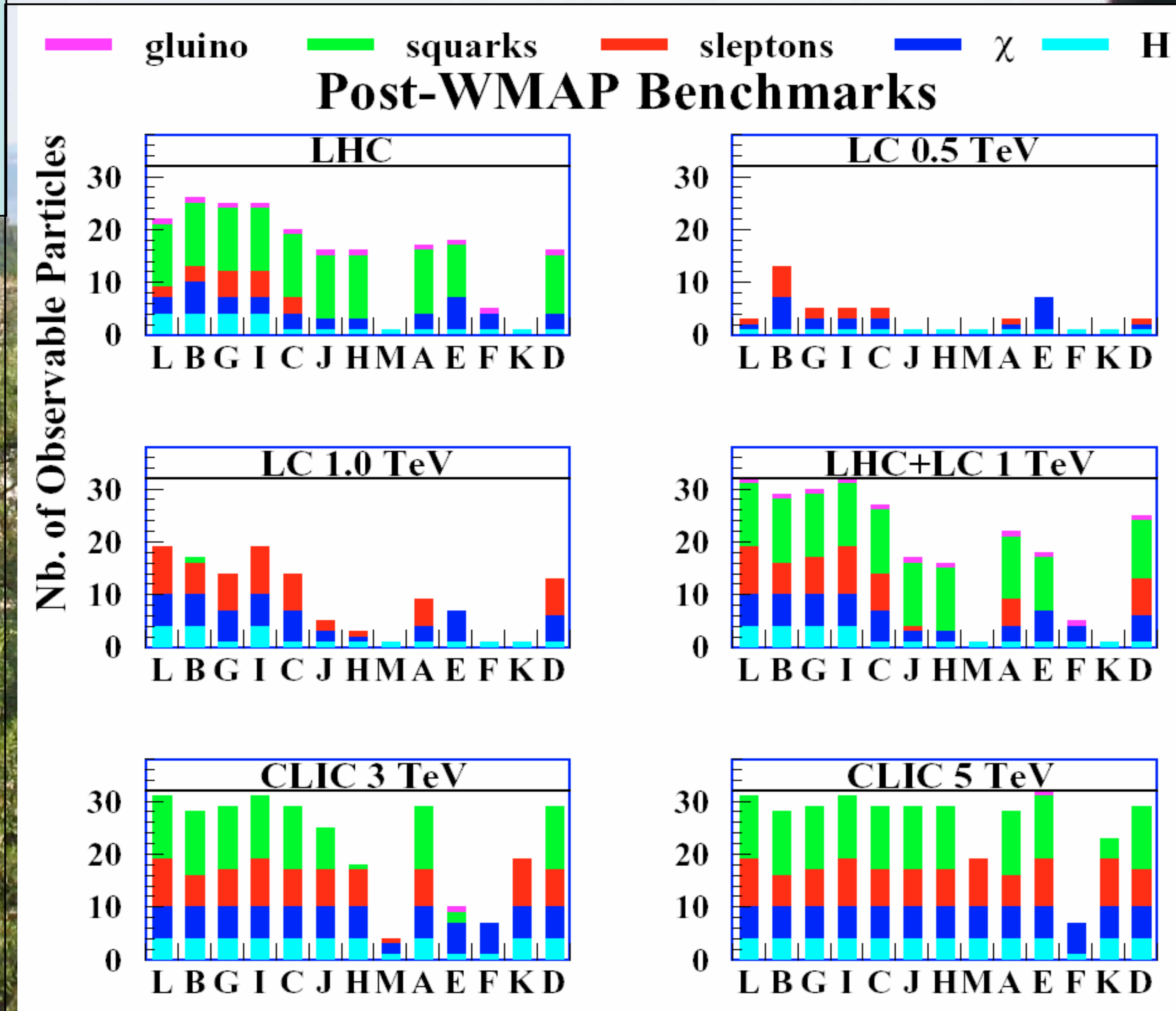


Calculation of relic density at a benchmark point



Battaglia, De Roeck, Gianotti, JE, Olive, Pape

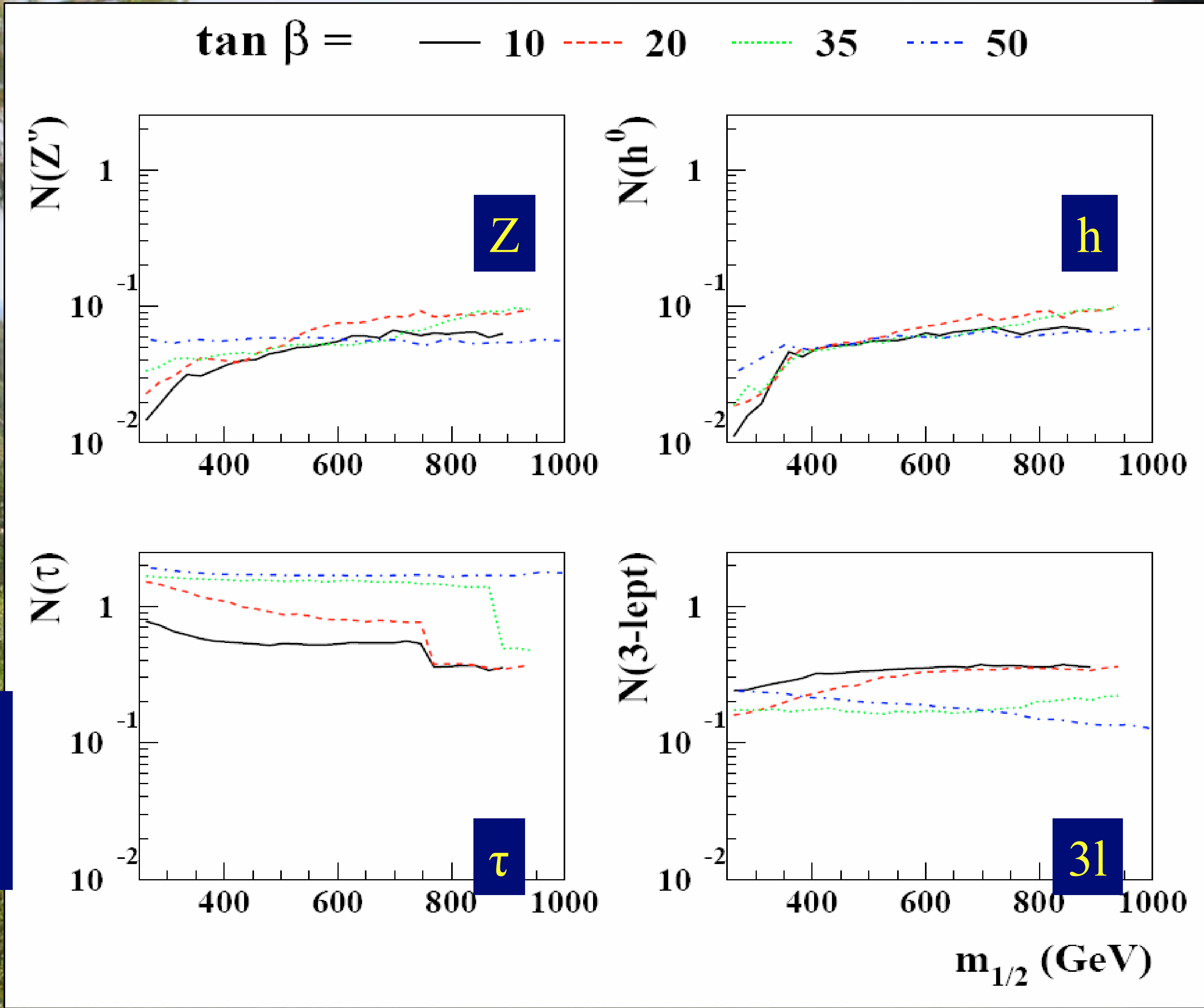
Summary of LHC Scapabilities … and Other Accelerators



LHC almost
`guaranteed'
to discover
supersymmetry
if it is relevant
to the mass problem

Battaglia, De Roeck, Gianotti, JE, Olive, Pape

Sparticle Signatures along WMAP lines

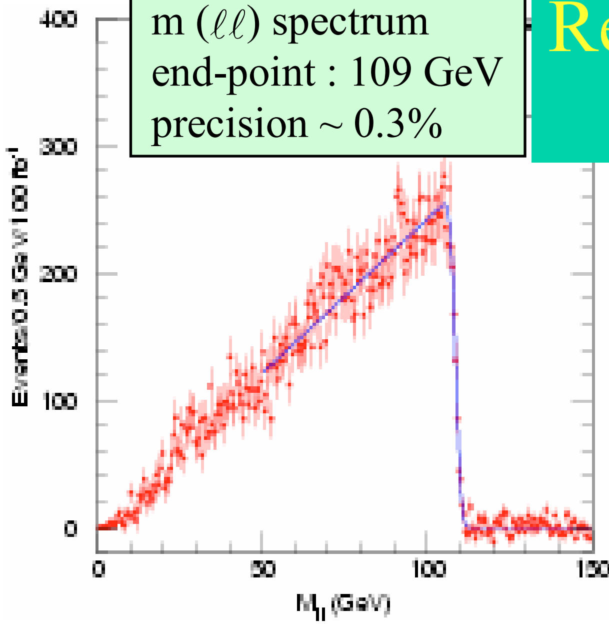


Average numbers of particles per sparticle event

Battaglia, De Roeck, Gianotti, JE, Olive, Pape

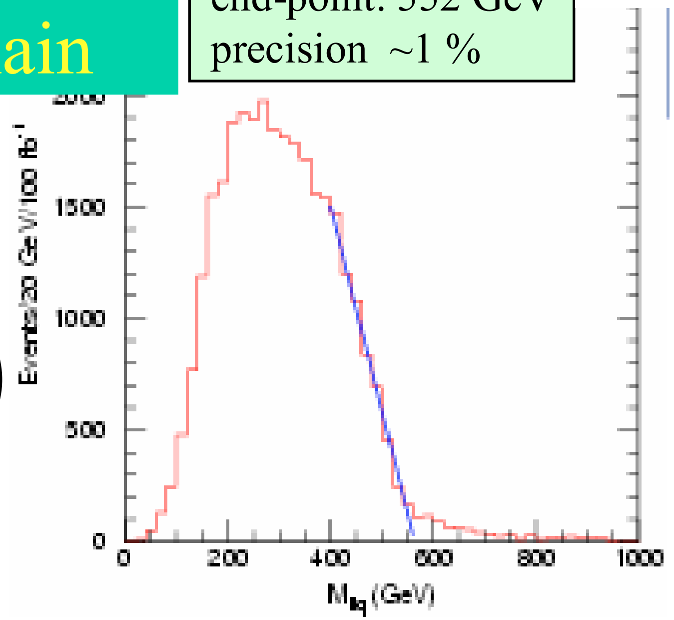
Reconstruction of `Typical' Sparticle Decay Chain

m ($\ell\ell$) spectrum
end-point : 109 GeV
precision ~ 0.3%

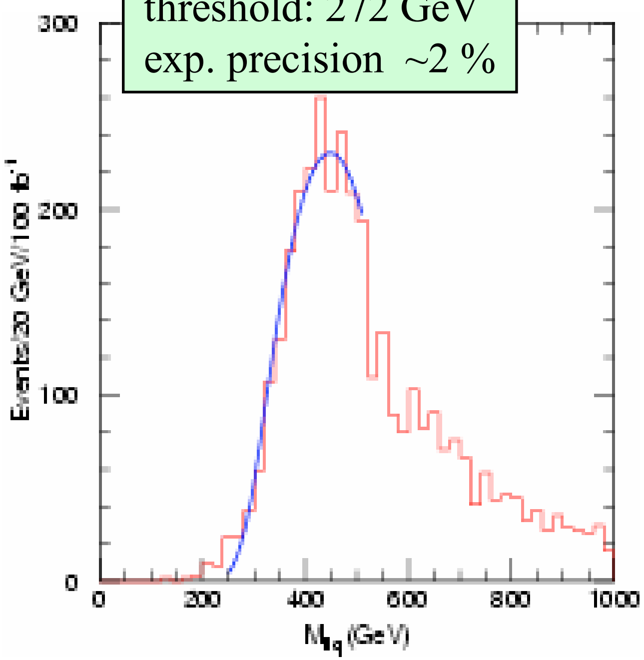


$\tilde{q}_L \rightarrow q\, \chi^0_2$
$\hookrightarrow \tilde{\ell}_R\, \ell$
$\hookrightarrow \ell\, \chi^0_1$

m ($\ell\ell$j)^{min} spectrum
end-point: 552 GeV
precision ~1 %

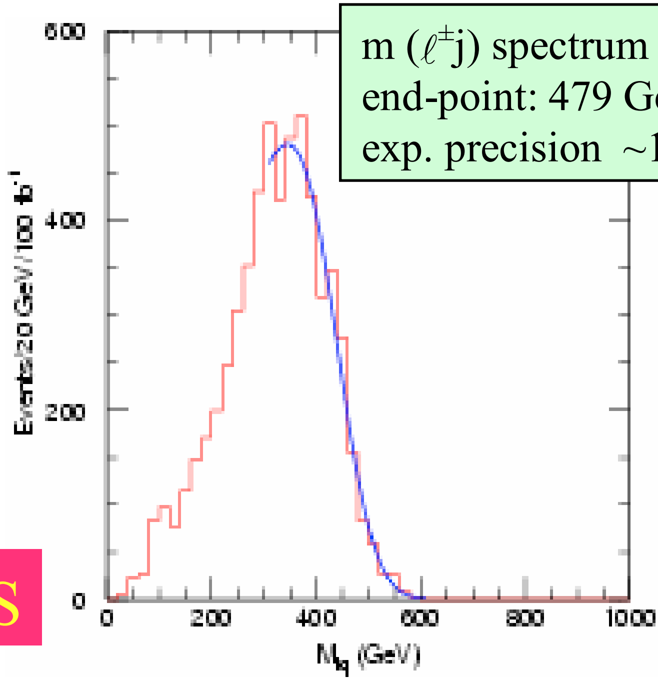


m ($\ell\ell$j)^{max} spectrum
threshold: 272 GeV
exp. precision ~2 %



$M_{squark} = 690$
$M_{\chi'} = 232$
$M_{slepton} = 157$
$M_{\chi} = 121$
(GeV)

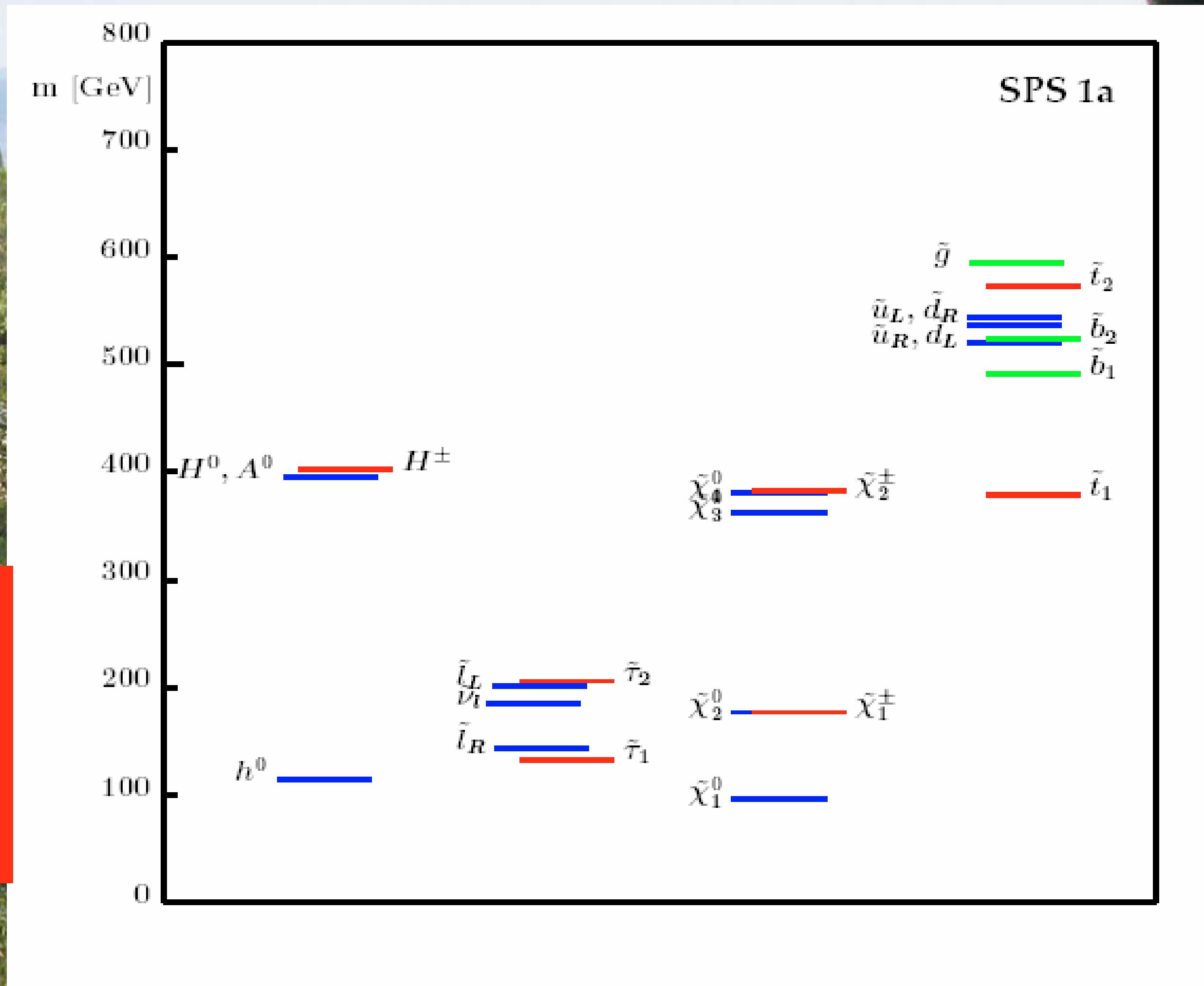
m ($\ell^{\pm}$j) spectrum
end-point: 479 GeV
exp. precision ~1 %



ATLAS

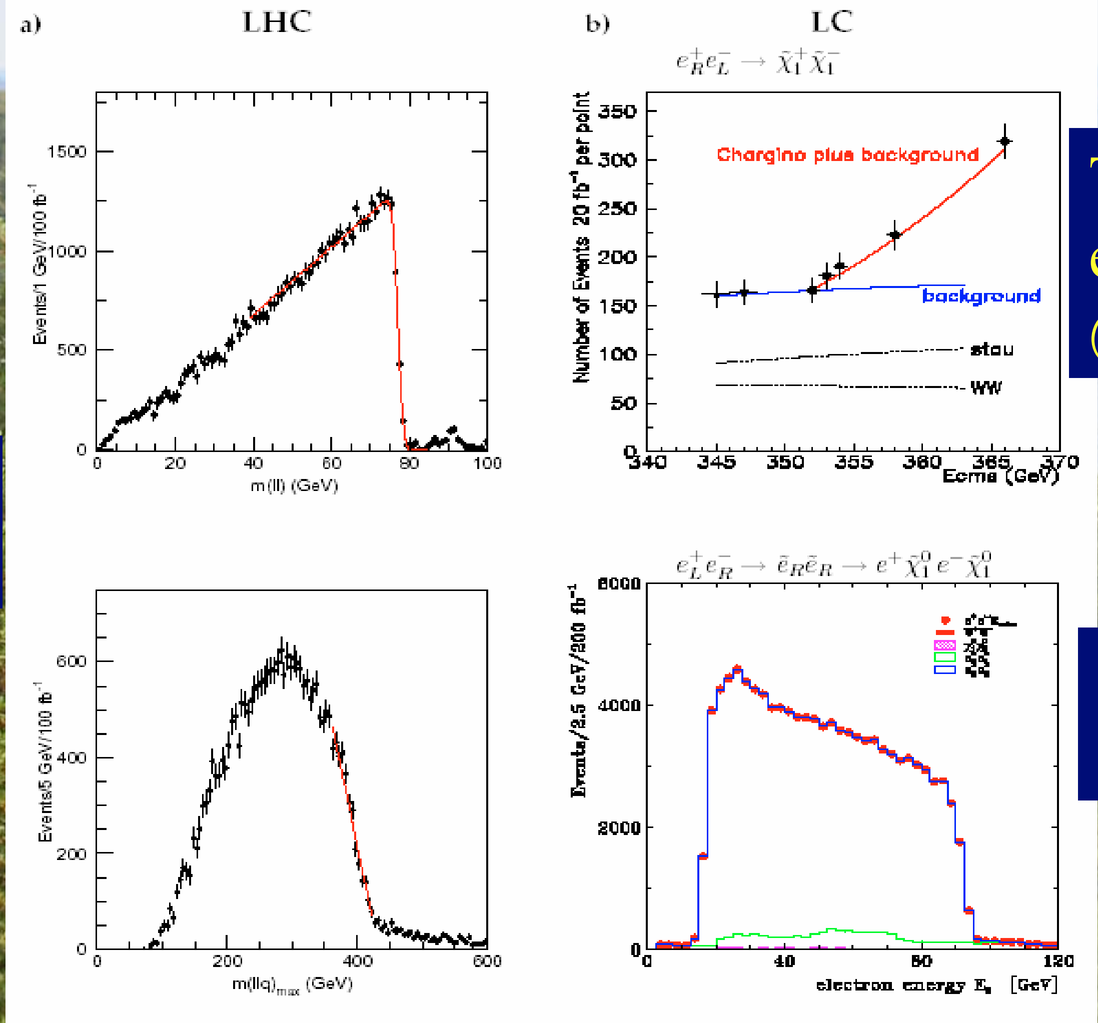
Example of Benchmark Point

Spectrum of Benchmark SPS1a ~ Point B of *Battaglia et al*



Several sparticles at 500 GeV LC, more at 1000 GeV, some need higher E

Examples of Sparticle Measurements



Threshold excitation @ LC

Spectrum edges @ LHC

Spectra @ LC

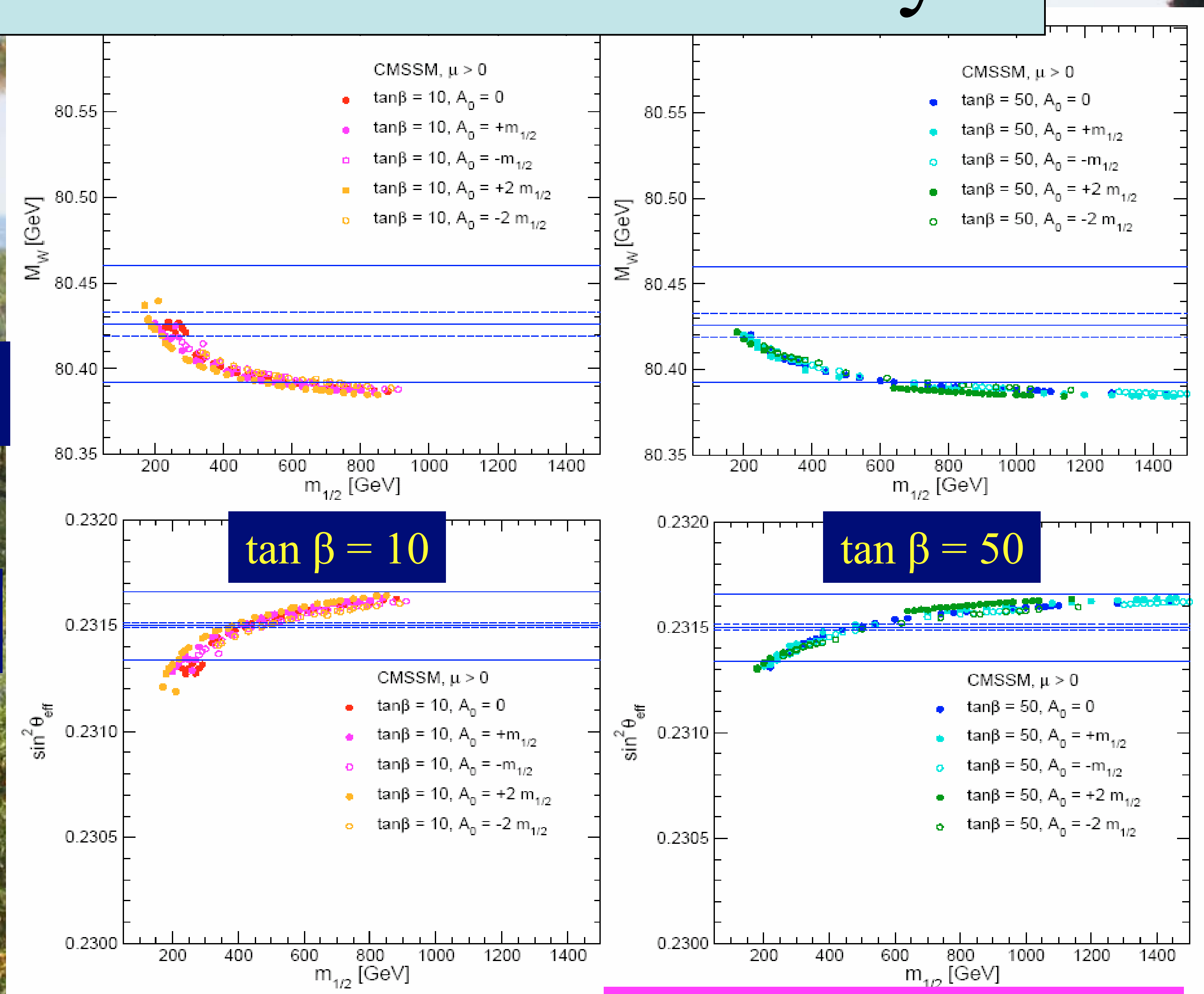
Can one estimate the scale of supersymmetry?

Precision Observables in Susy

Sensitivity to $m_{1/2}$
in CMSSM
along WMAP lines
for different A

m_W

$\sin^2\theta_W$

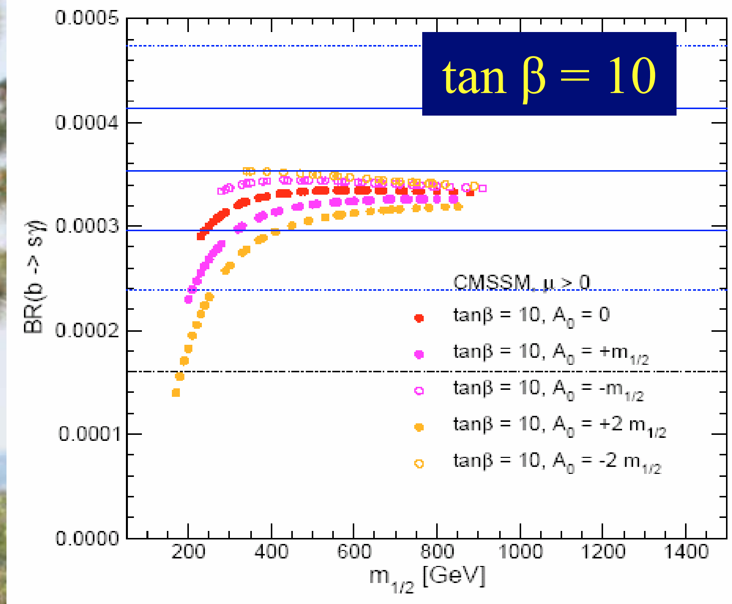


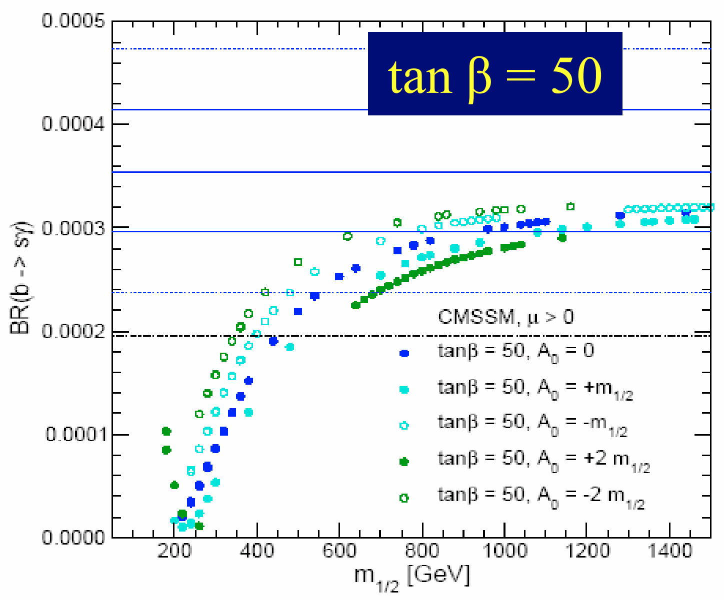
Present & possible
future errors

JE + Heinemeyer + Olive + Weiglein

More Observables

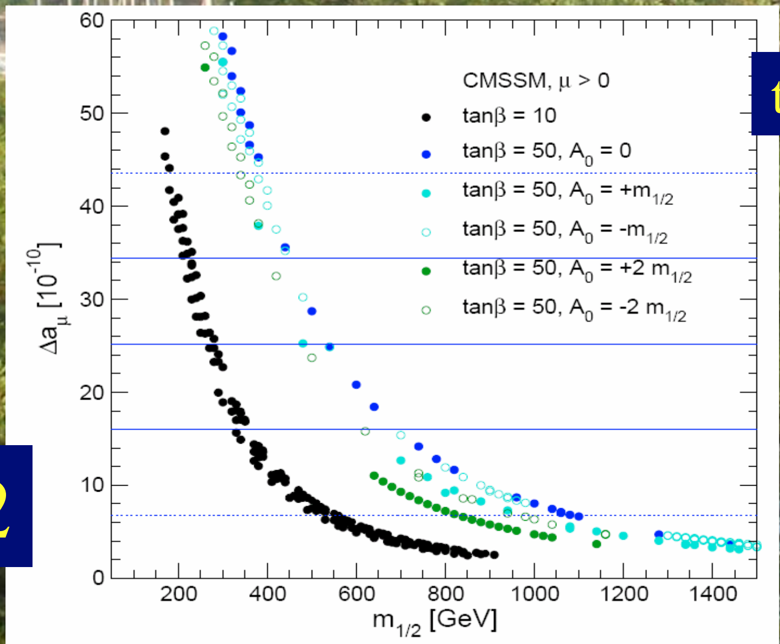
$b \to s\gamma$



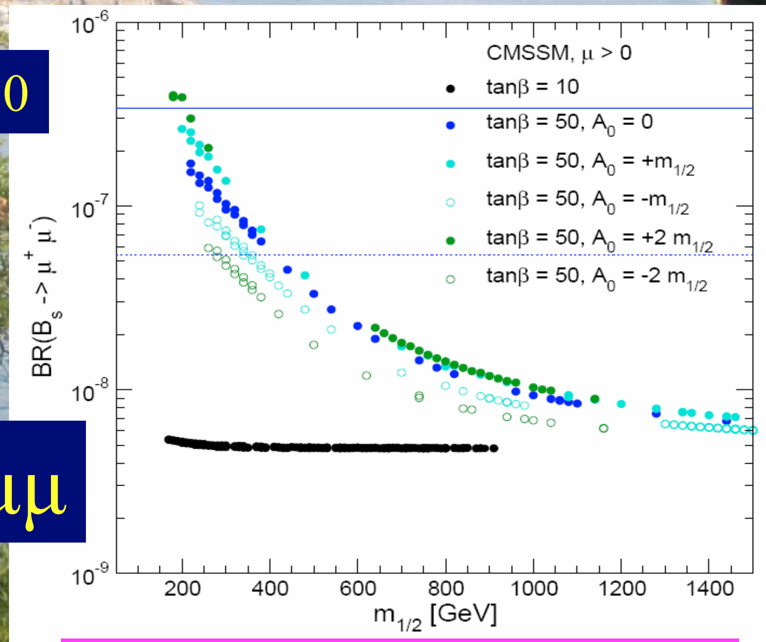


$\tan\beta = 10, 50$

$g_\mu - 2$



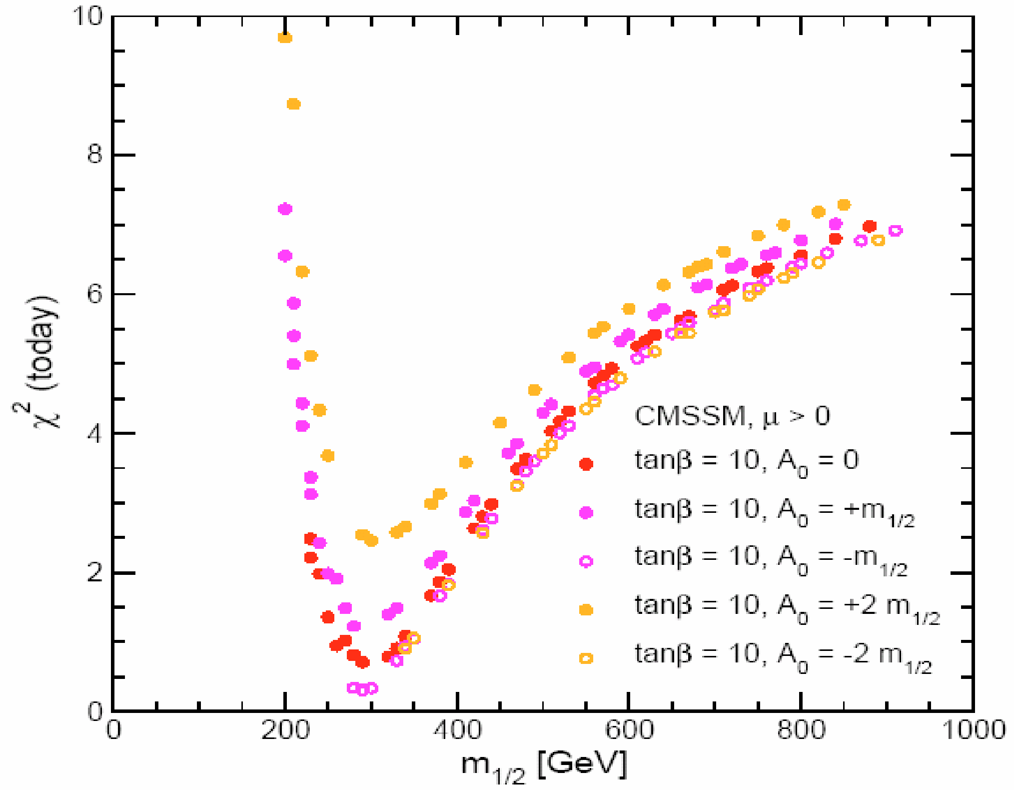
$B_s \to \mu\mu$

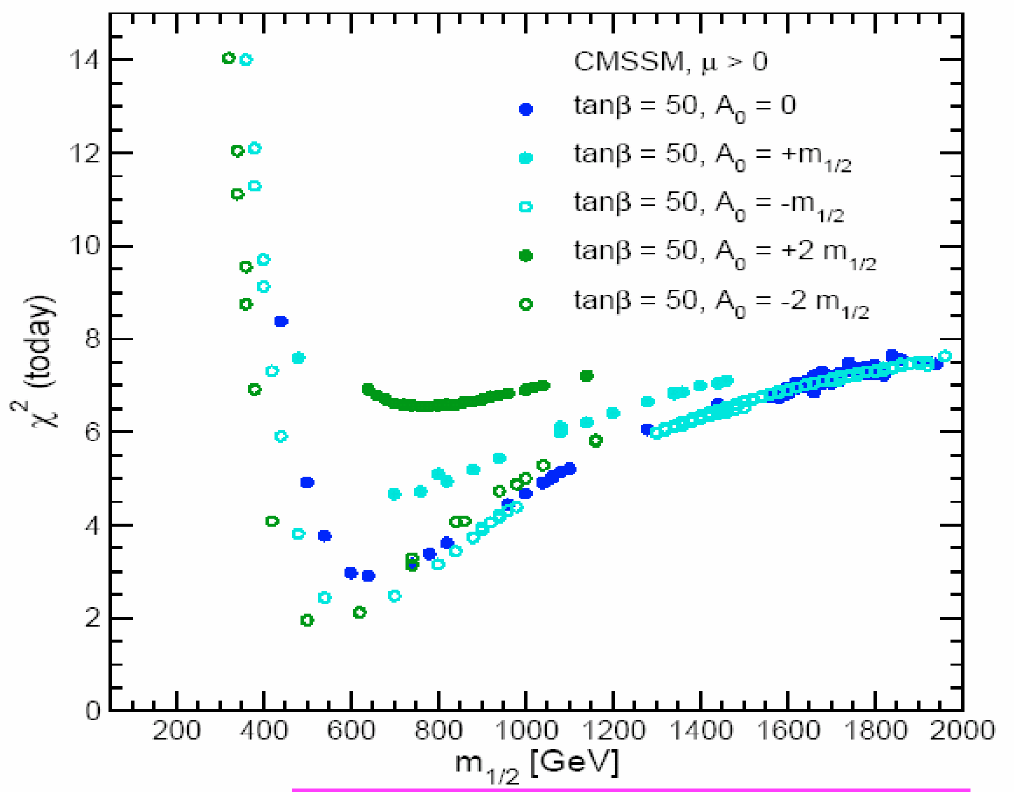


JE + Heinemeyer + Olive + Weiglein

Global Fits to Present Data

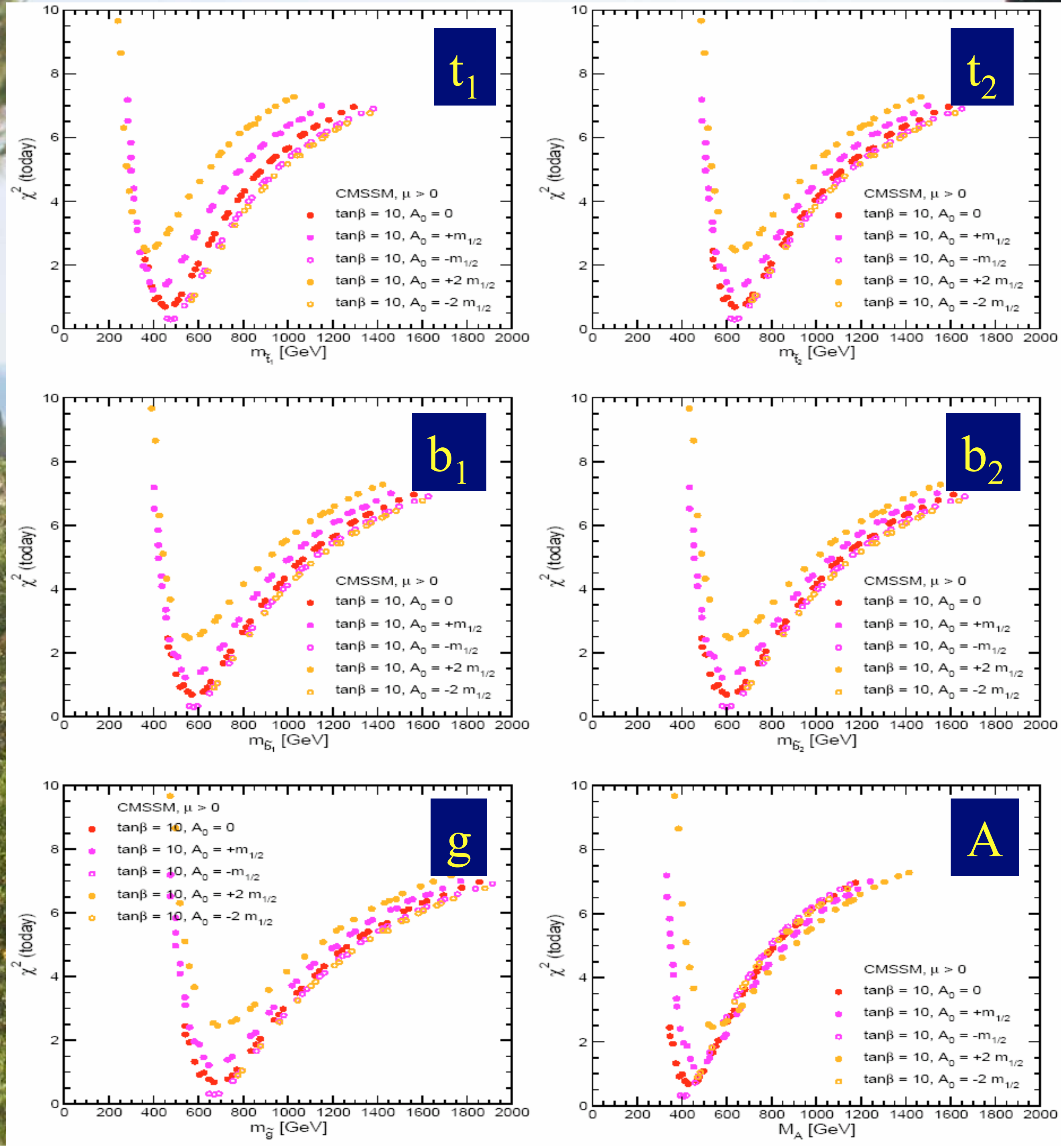
As functions of $m_{1/2}$ in CMSSM for tan β = 10, 50





JE + Heinemeyer + Olive + Weiglein

Global Fits to Present Data

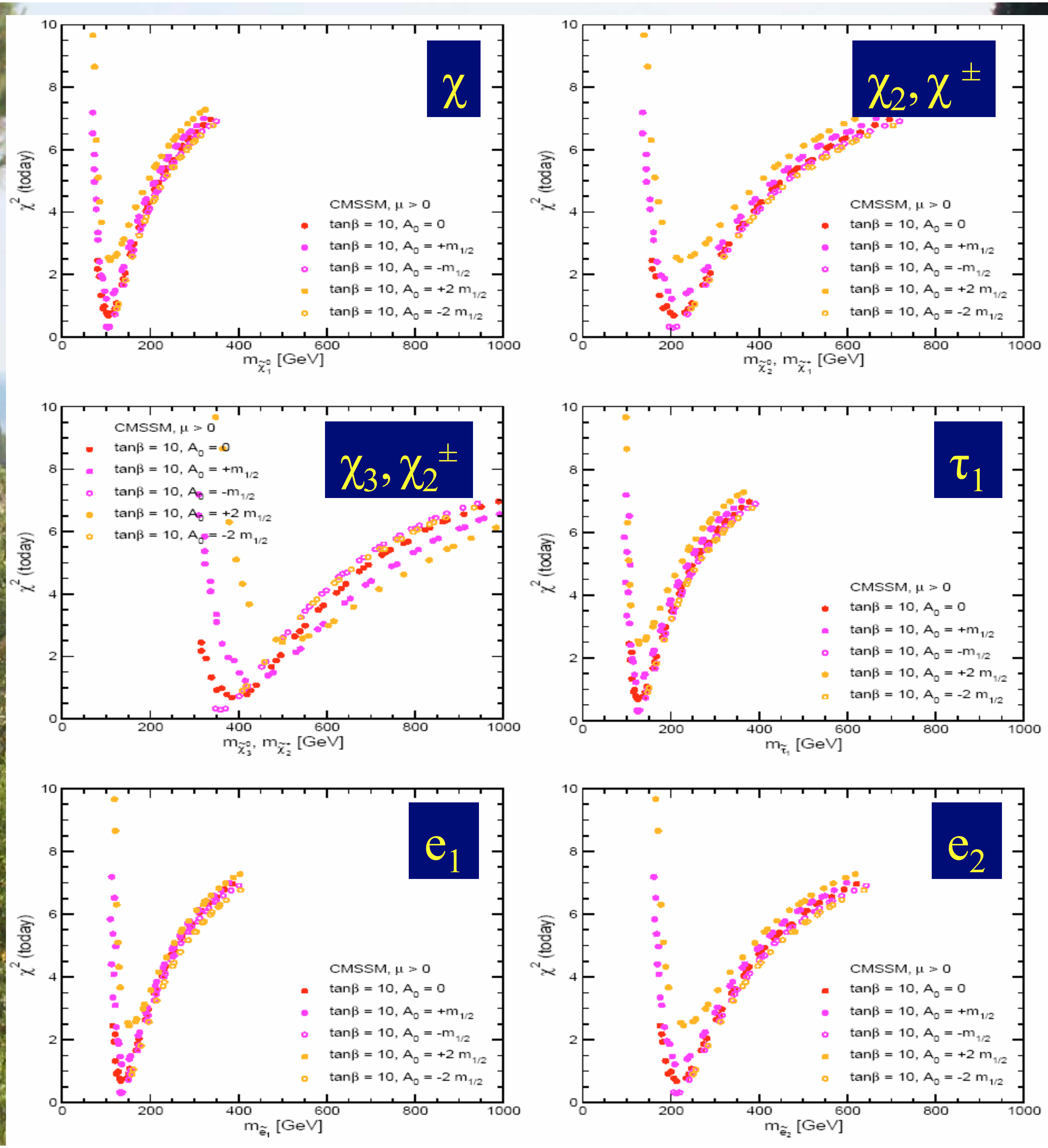


Preferred sparticle masses for $\tan\beta = 10$

JE + Heinemeyer + Olive + Weiglein

Global Fits to Present Data

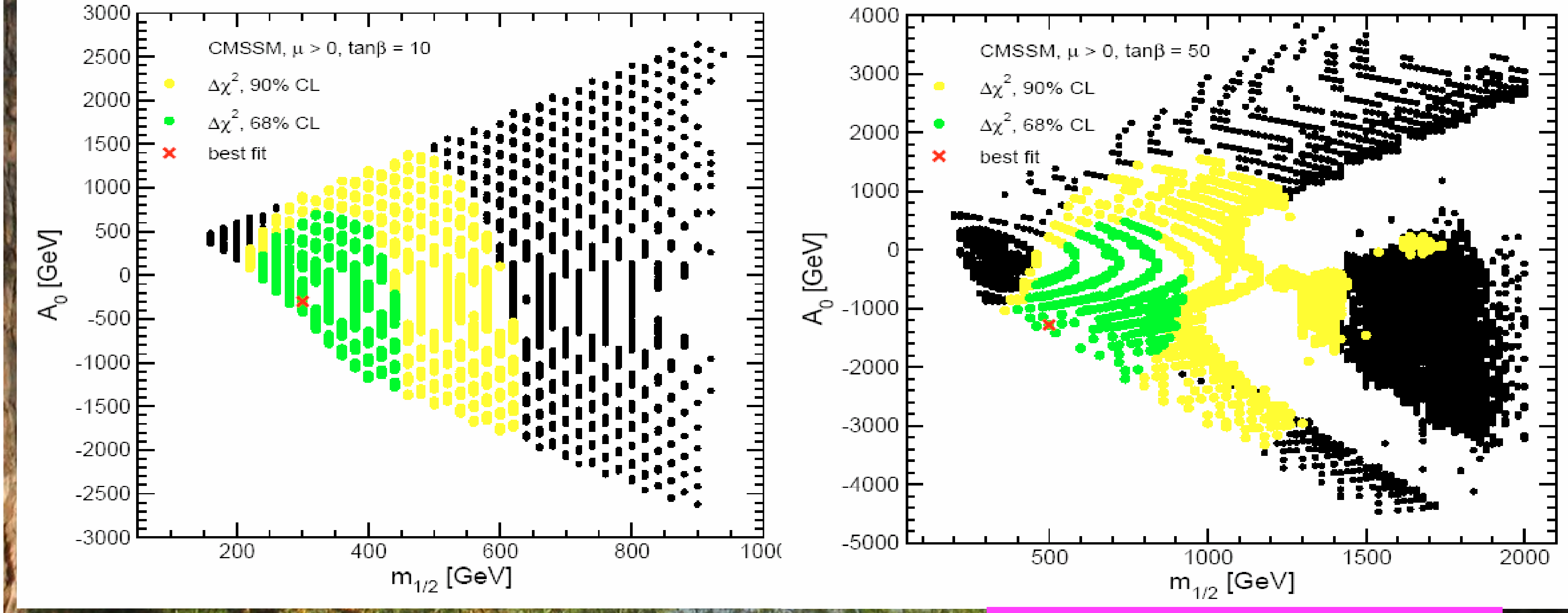
Preferred sparticle masses for tan β = 10



JE + Heinemeyer + Olive + Weiglein

Global Fits to Present Data

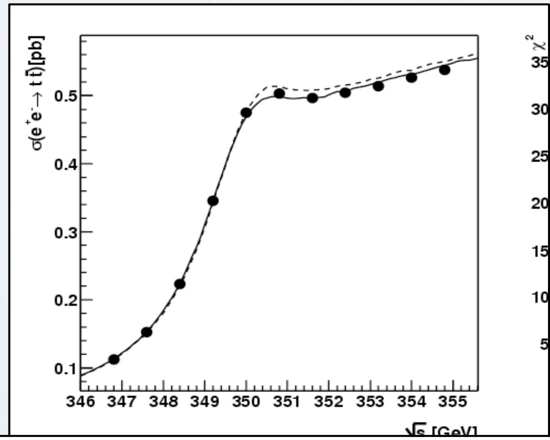
($m_{1/2}$, A_0) planes in CMSSM for tan β = 10, 50

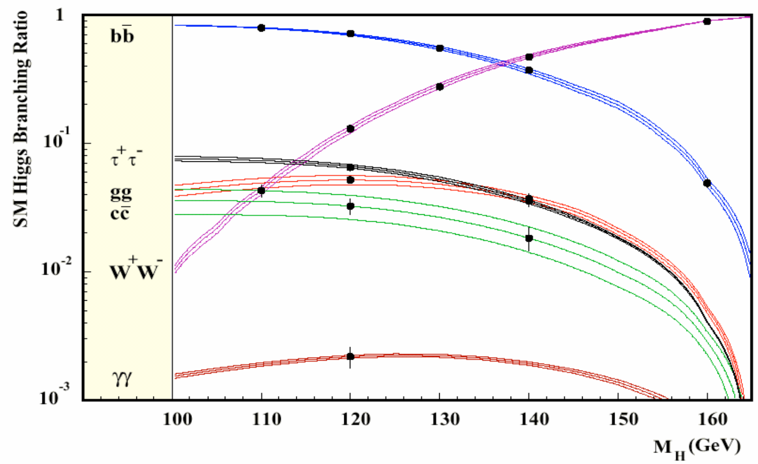


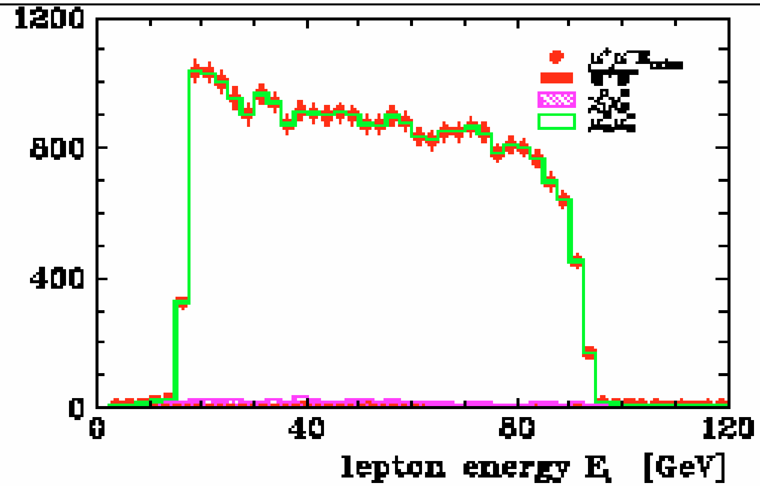
JE + Heinemeyer + Olive + Weiglein

Tasks for the TeV ILC

- Measure m_t to < ± 100 MeV
- If there is a light Higgs of any kind, pin it down:
  - Does it have standard model couplings?
  - What is its precise mass?
- If there are extra light particles:
  - Measure mass and properties
- If LHC sees nothing new below ~ 500 GeV:
  - Look for indirect signatures

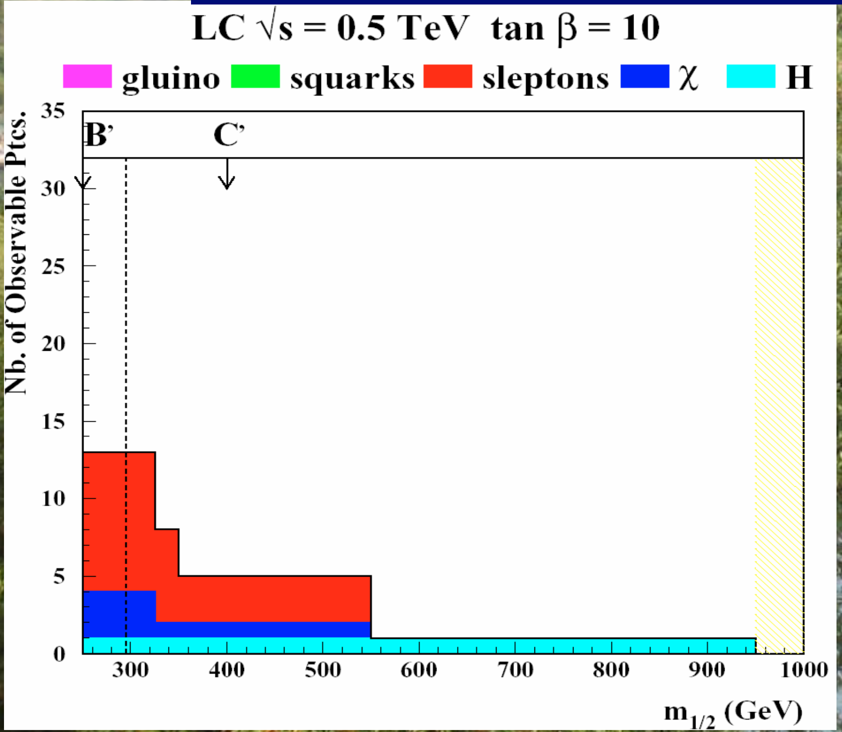


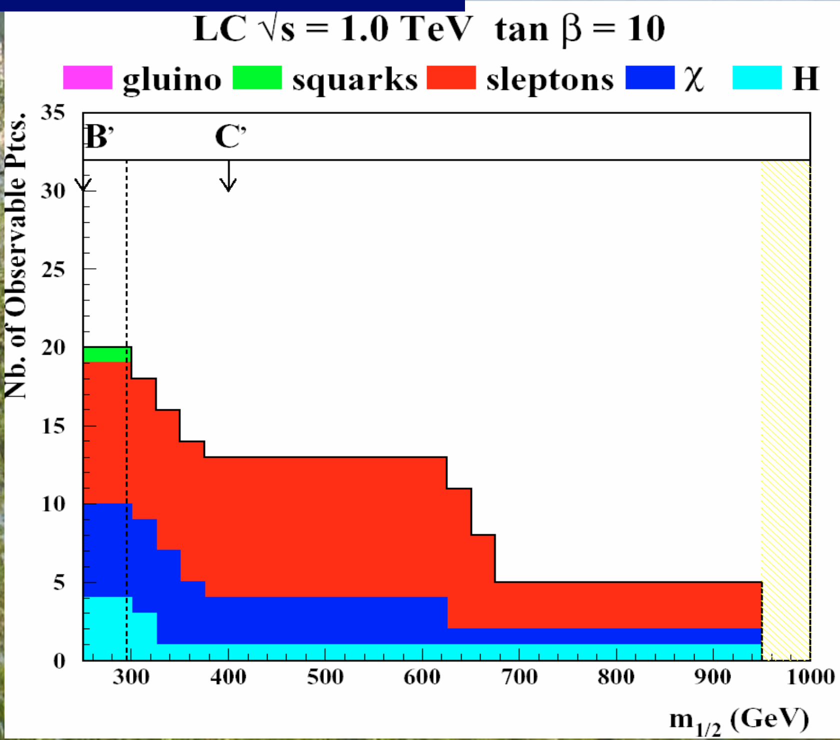




Sparticles at LC along WMAP Line

Complementary to LHC: weakly-interacting sparticles





Battaglia, De Roeck, Gianotti, JE, Olive, Pape

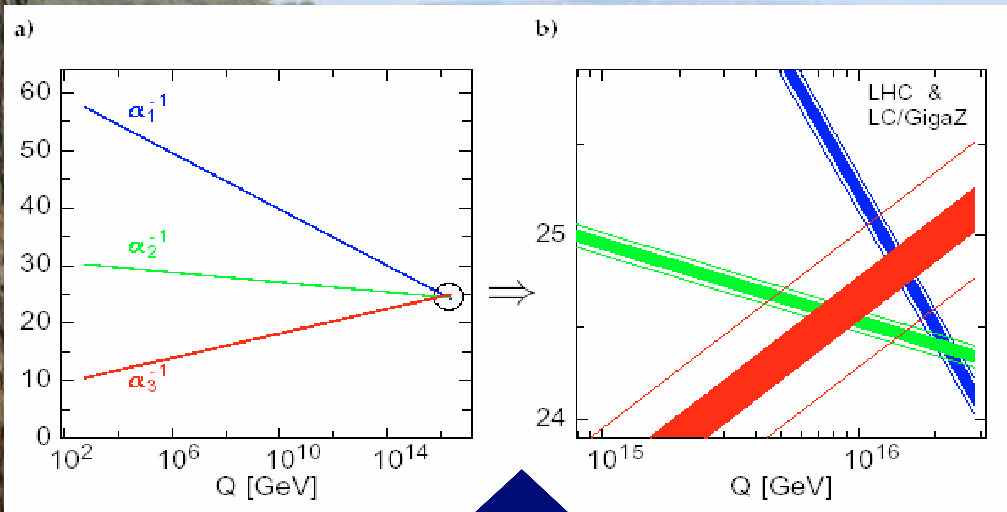
Added Value of LC Measurements

	m_{SPS1a}	LHC	LC	LHC+LC		m_{SPS1a}	LHC	LC	LHC+LC
h	111.6	0.25	0.05	0.05	H	399.6		1.5	1.5
A	399.1		1.5	1.5	$H+$	407.1		1.5	1.5
χ_1^0	97.03	4.8	0.05	0.05	χ_2^0	182.9	4.7	1.2	0.08
χ_3^0	349.2		4.0	4.0	χ_4^0	370.3	5.1	4.0	2.3
$\chi_1^\pm$	182.3		0.55	0.55	$\chi_2^\pm$	370.6		3.0	3.0
$\tilde{g}$	615.7	8.0		6.5					
$\tilde{t}_1$	411.8		2.0	2.0					
$\tilde{b}_1$	520.8	7.5		5.7	$\tilde{b}_2$	550.4	7.9		6.2
$\tilde{u}_1$	551.0	19.0		16.0	$\tilde{u}_2$	570.8	17.4		9.8
$\tilde{d}_1$	549.9	19.0		16.0	$\tilde{d}_2$	576.4	17.4		9.8
$\tilde{s}_1$	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	17.4		9.8
$\tilde{c}_1$	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]		[illegible]
$\tilde{e}_1$	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]
$\tilde{\mu}_1$	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]
$\tilde{\tau}_1$	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]
$\tilde{\nu}_e$	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]

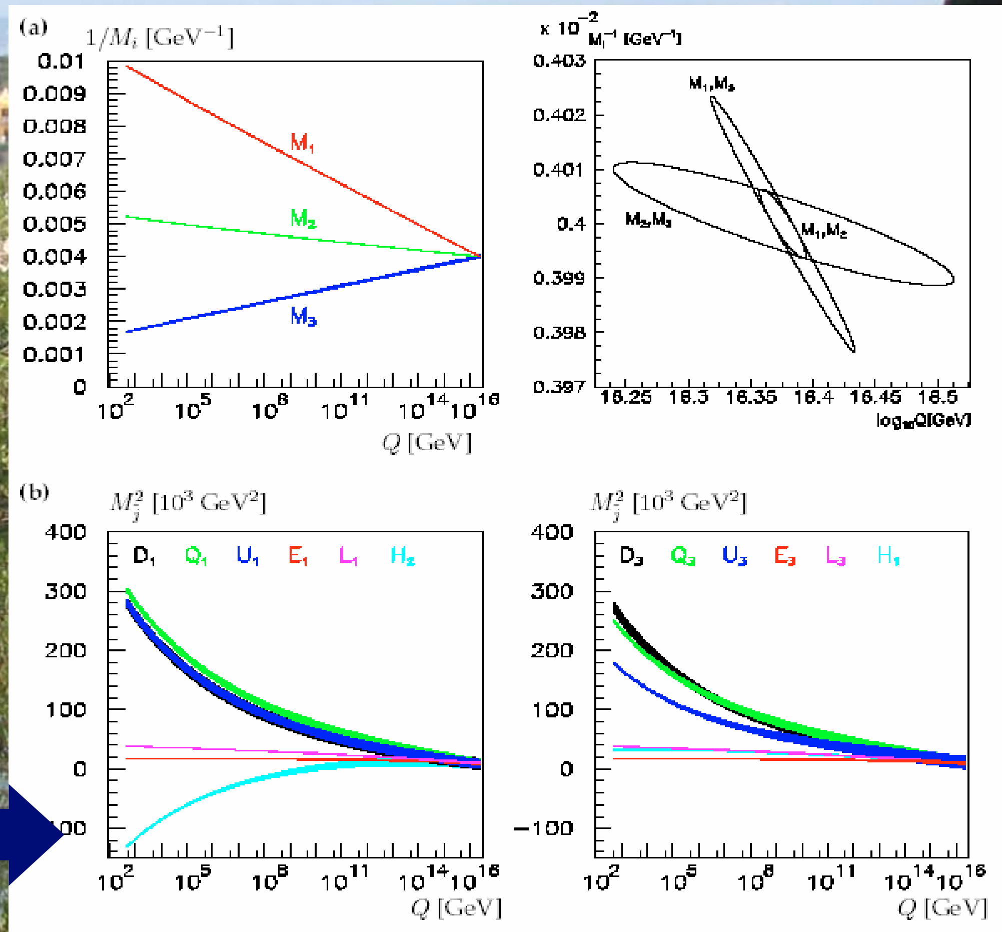
Determination of CMSSM parameters

	SPS1a	StartFit	LHC	Δ_{LHC}	LC	Δ_{LC}	LHC+LC	Δ_{LHC+LC}
M_0	100	500	100.03	4.0	100.03	0.09	100.04	0.08
$M_{1/2}$	250	500	249.95	1.8	250.02	0.13	250.01	0.11
$\tan\beta$	10	50	9.87	1.3	9.98	0.14	9.98	0.14
A_0	-100	0	-99.29	31.8	-98.26	4.43	-98.25	4.13

Tests of Unification Ideas



For gauge couplings



For sparticle masses

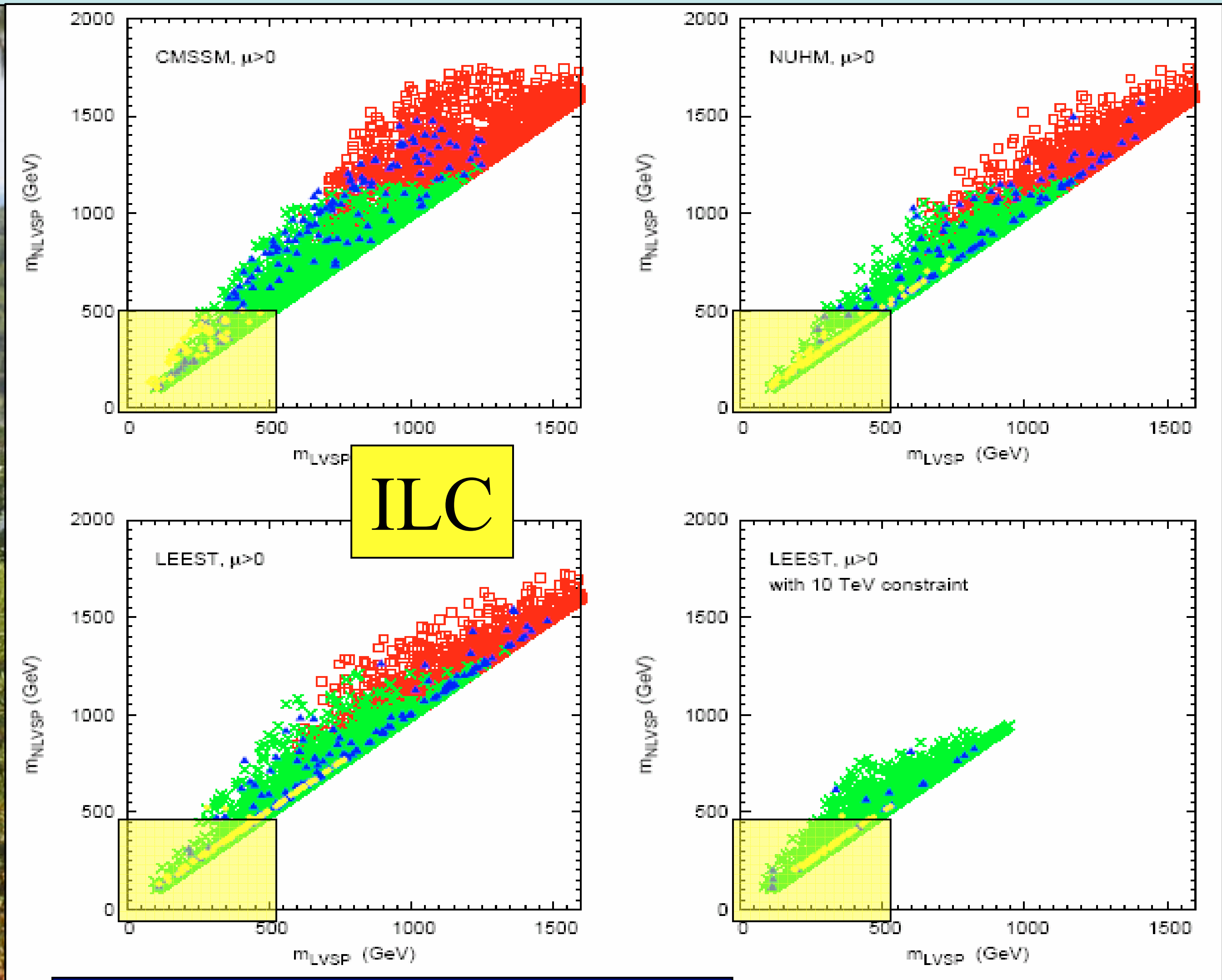
Sparticles may not be very light

Full Model samples

Detectable @ LHC

Provide Dark Matter

Dark Matter Detectable Directly

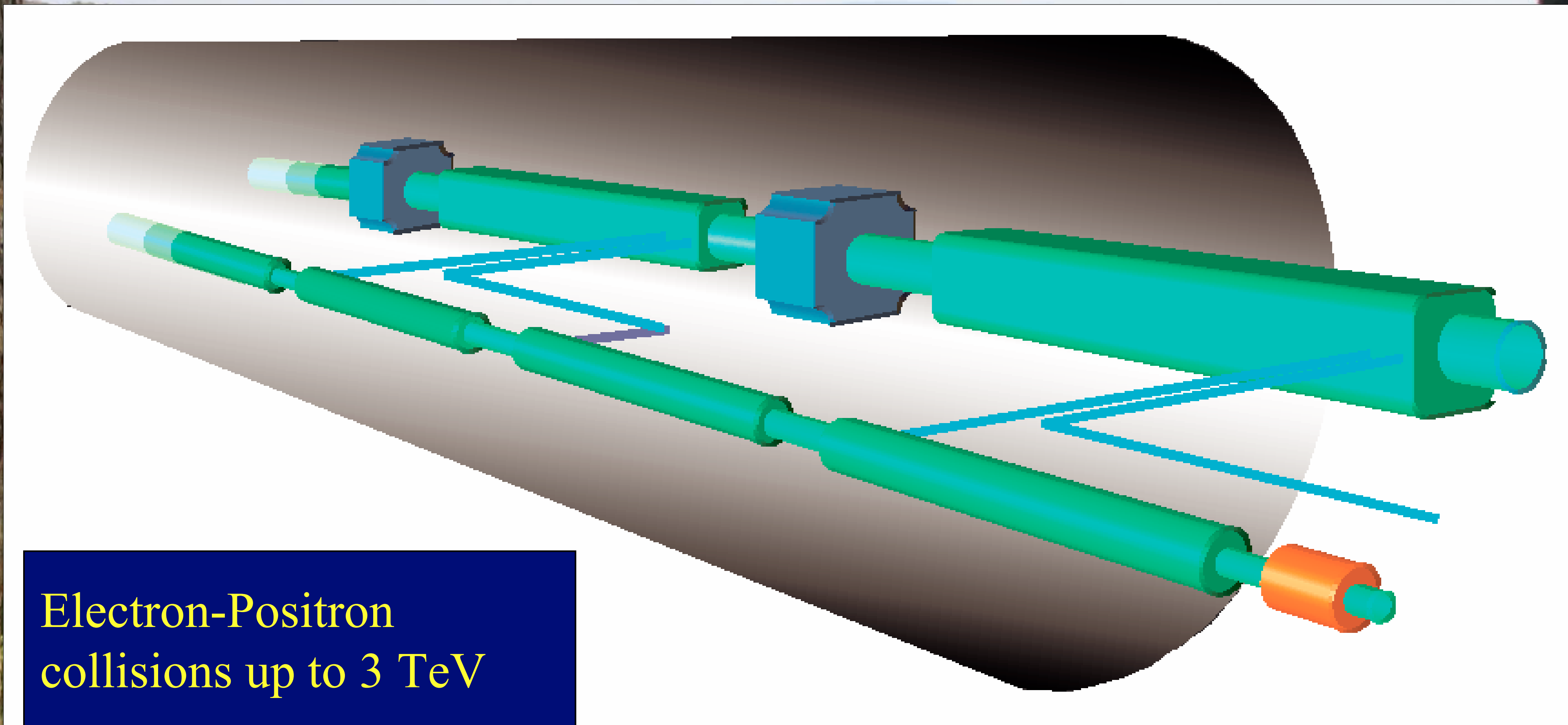


← Second lightest visible sparticle

Lightest visible sparticle →

JE + Olive + Santoso + Spanos

After LHC @ CERN - CLIC?



Electron-Positron collisions up to 3 TeV

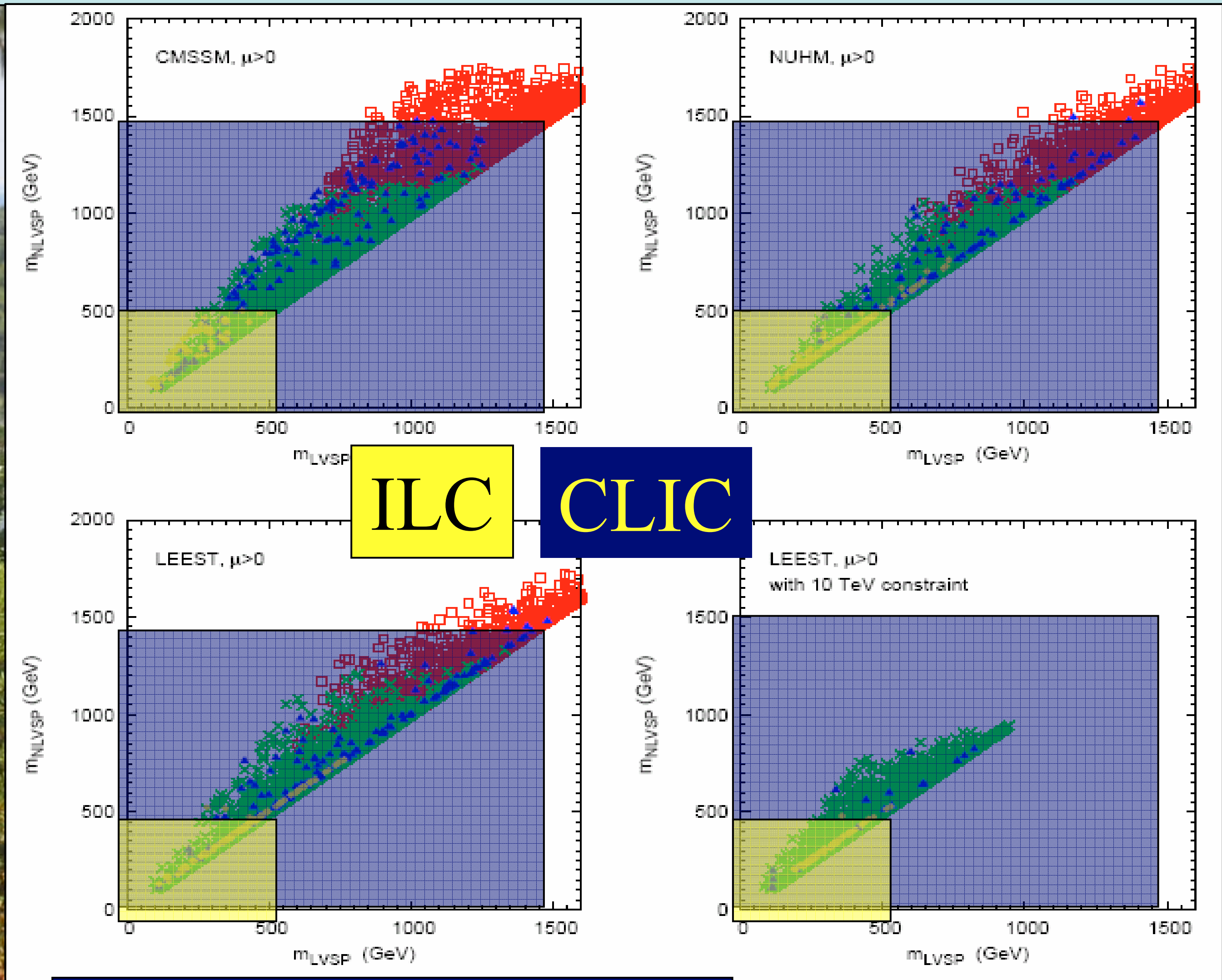
Sparticles may not be very light

Full Model samples

Detectable @ LHC

Provide Dark Matter

Dark Matter Detectable Directly



← Second lightest visible sparticle

Lightest visible sparticle →

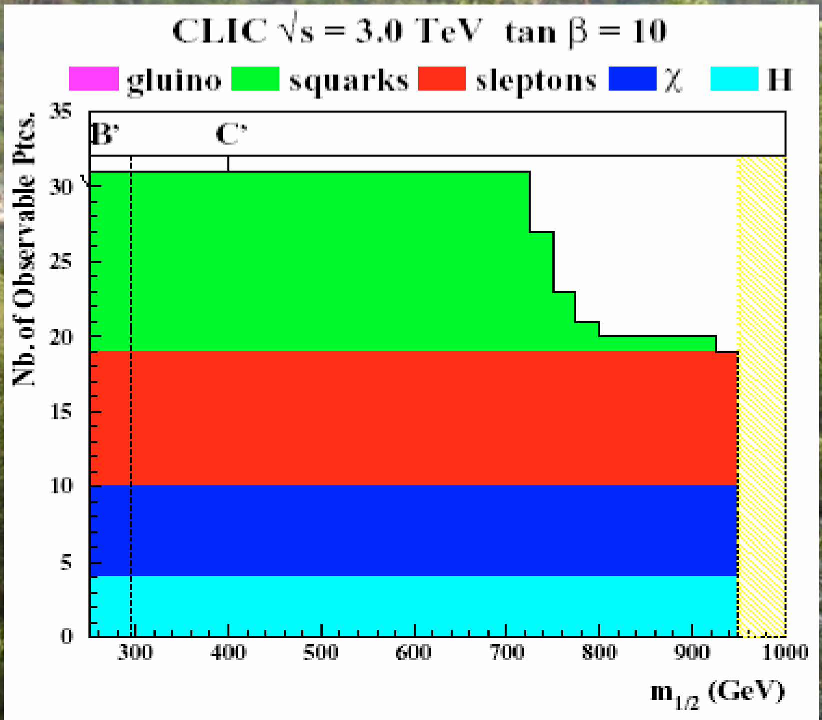
JE + Olive + Santoso + Spanos

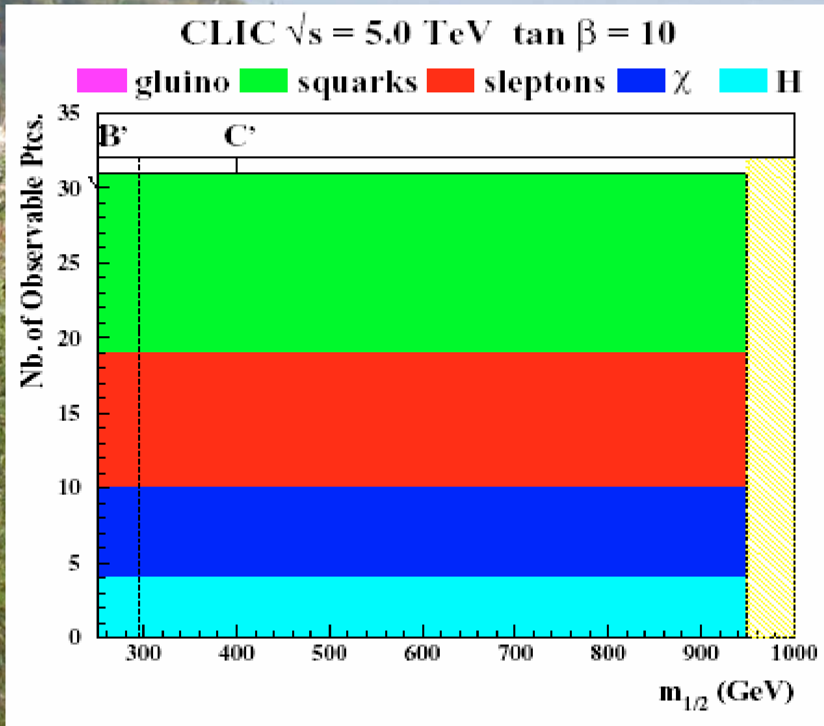
Sparticle Visibility at Higher E

CMSSM

3 TeV

5 TeV



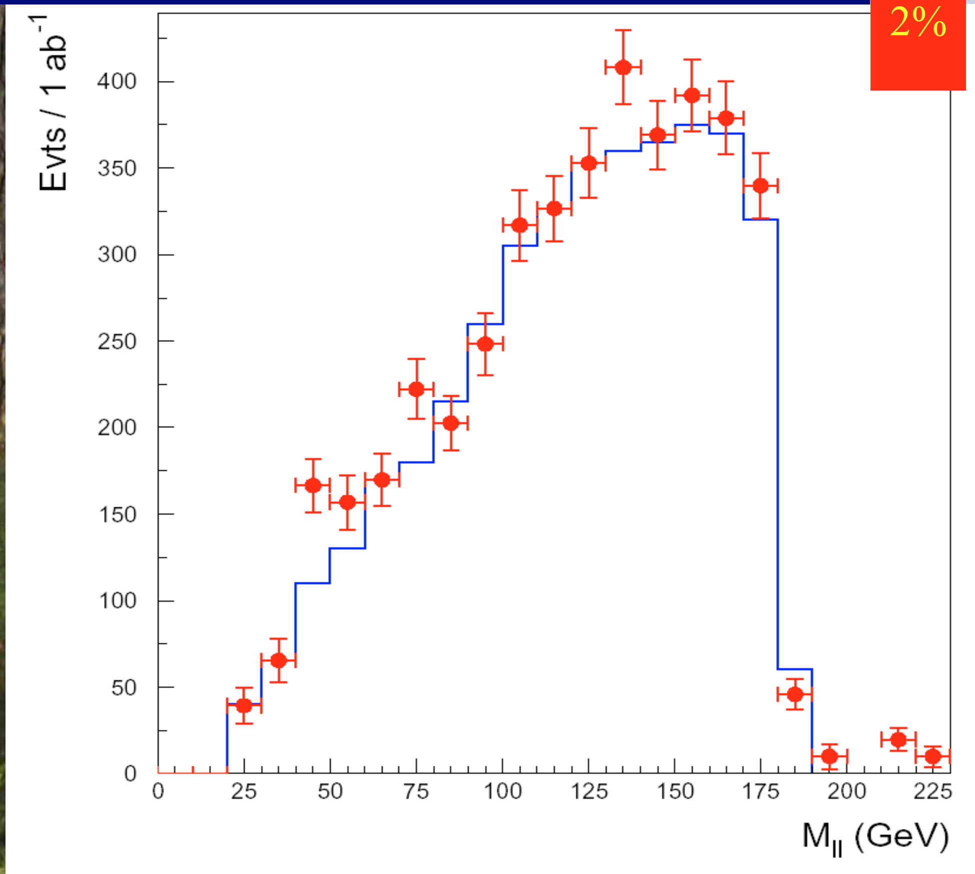


See `all' sparticles: measure heavier ones better than LHC

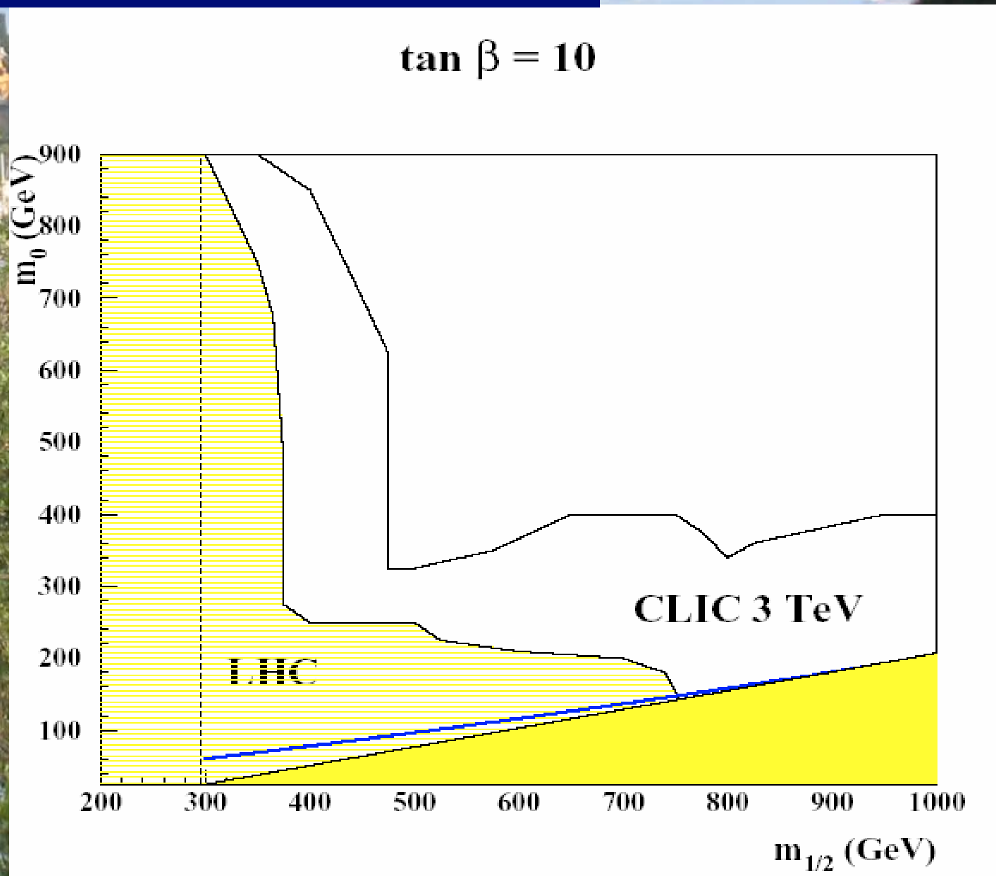
Example of CLIC Sparticle Search

Dilepton spectrum in neutralino decay

2%

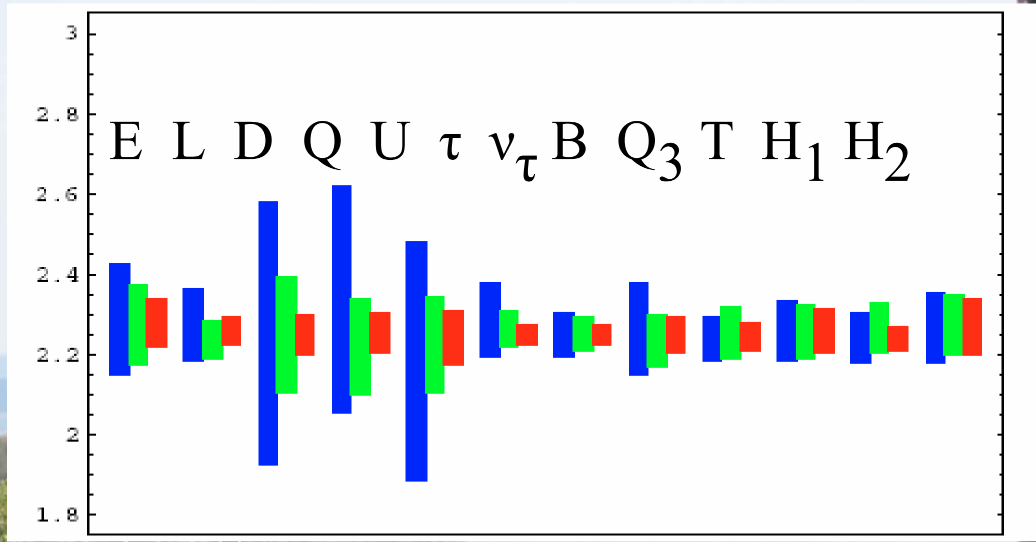


Reach in parameter space

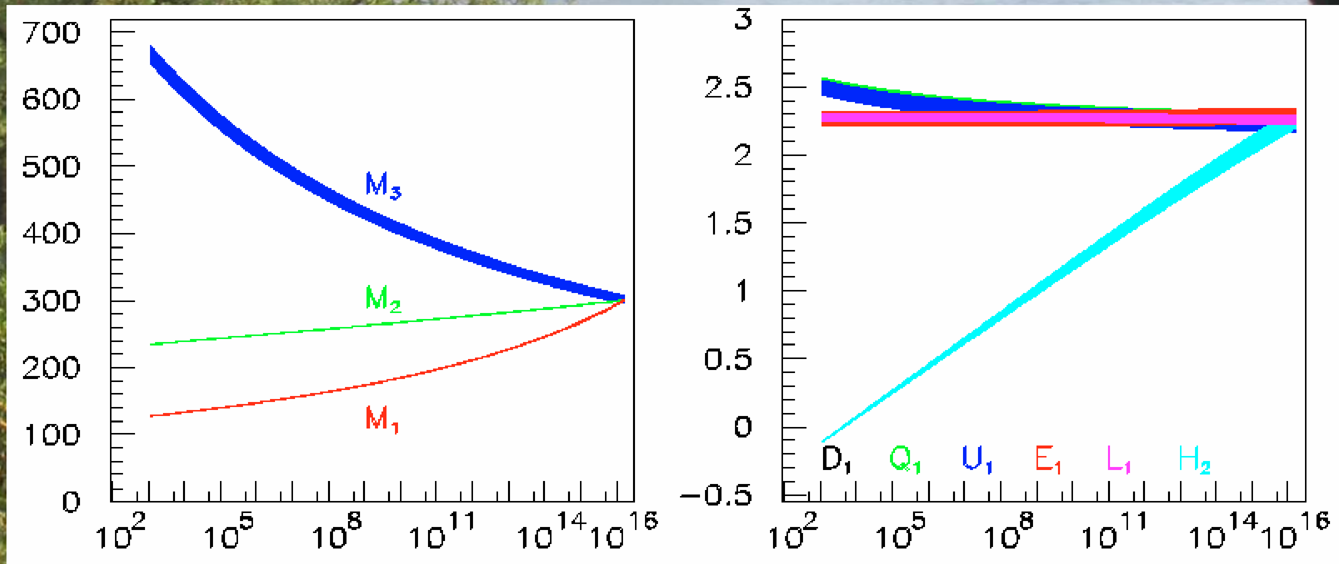


Sparticle Mass Unification ?

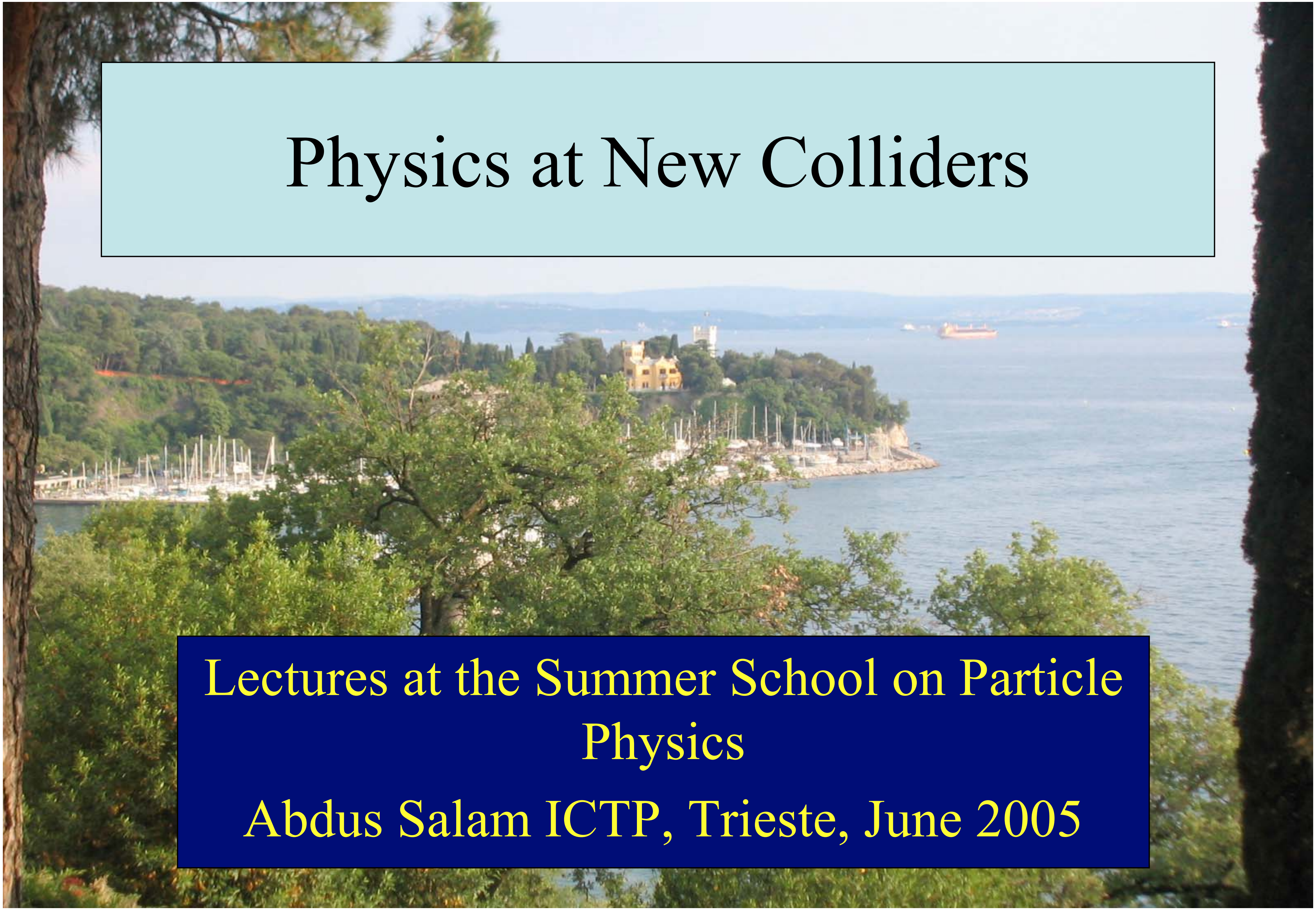
Accuracy in measuring sparticle masses squared



Can test unification of sparticle masses – probe of string models?



Physics at New Colliders



Lectures at the Summer School on Particle Physics

Abdus Salam ICTP, Trieste, June 2005

Plan of the Lectures

- Status of the Standard Model
- Open issues beyond the Standard Model
- Origin of particle masses
- Search for the Higgs boson
- Supersymmetry
- Searches for supersymmetry
- Possible other new physics at colliders

The Big Collider in the Sky

Strategies for Detecting Supersymmetric Dark Matter

- Annihilation in galactic halo

  $\chi - \chi \rightarrow$ antiprotons, positrons, …?

- Annihilation in galactic centre

  $\chi - \chi \rightarrow \gamma + \ldots?$

- Annihilation in core of Sun or Earth

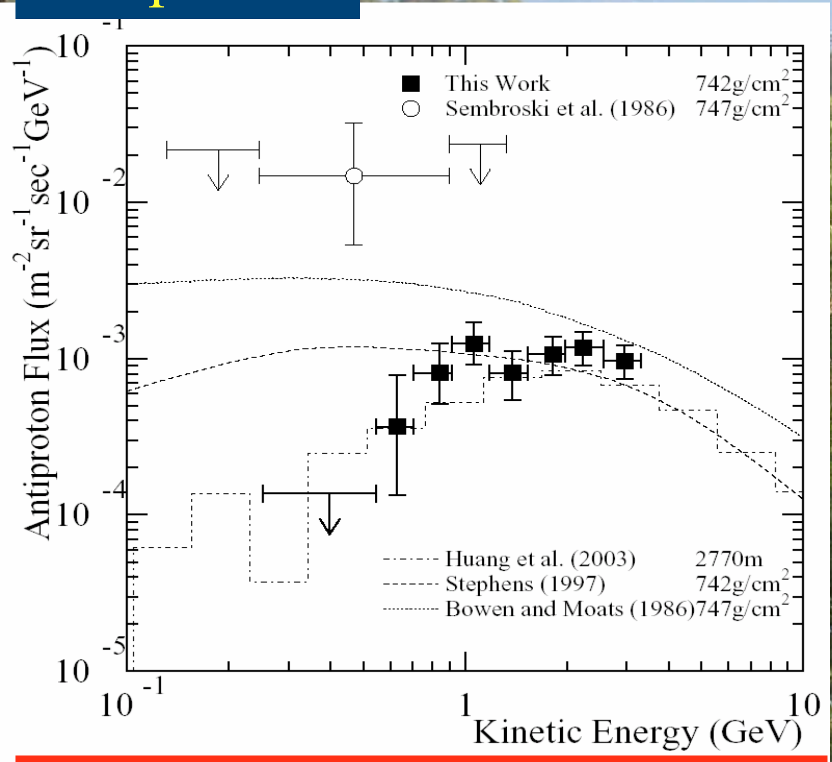
  $\chi - \chi \rightarrow \nu + \ldots \rightarrow \mu + \ldots$

- Scattering on nucleus in laboratory

  $\chi + A \rightarrow \chi + A$

Annihilation in Galactic Halo

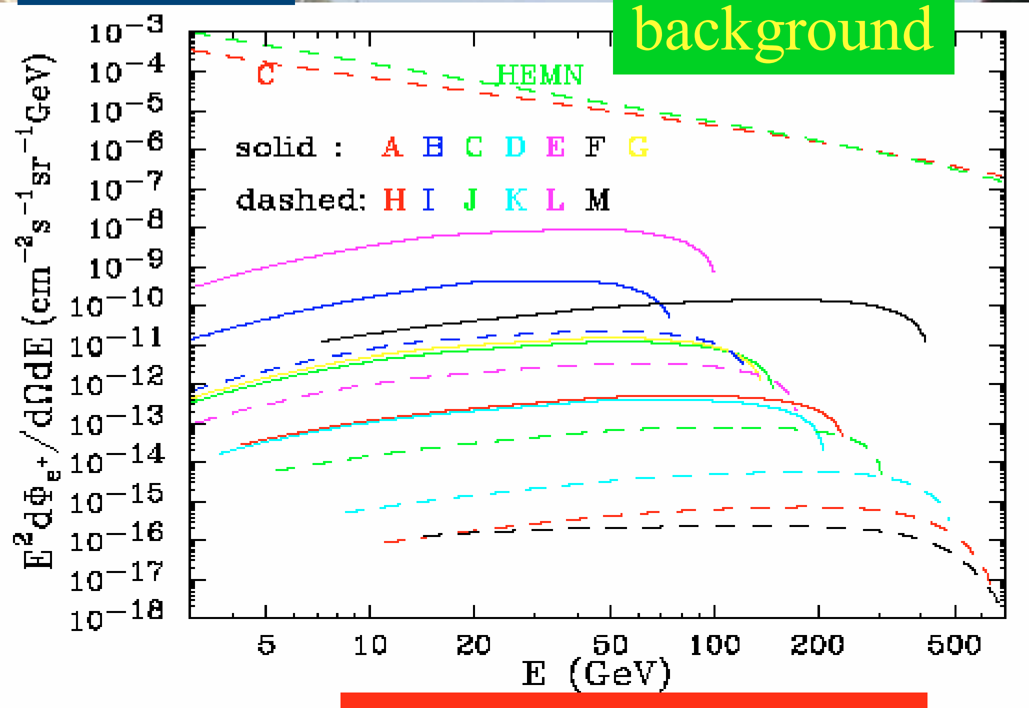
Antiprotons



Consistent with production by primary matter cosmic rays

Positrons

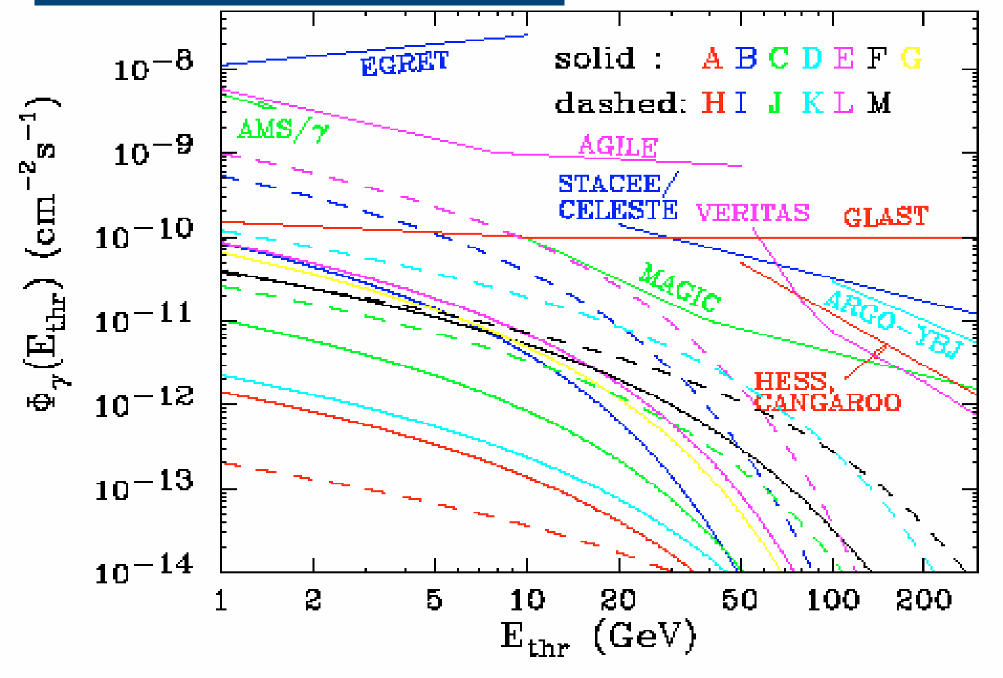
Cosmic-ray background



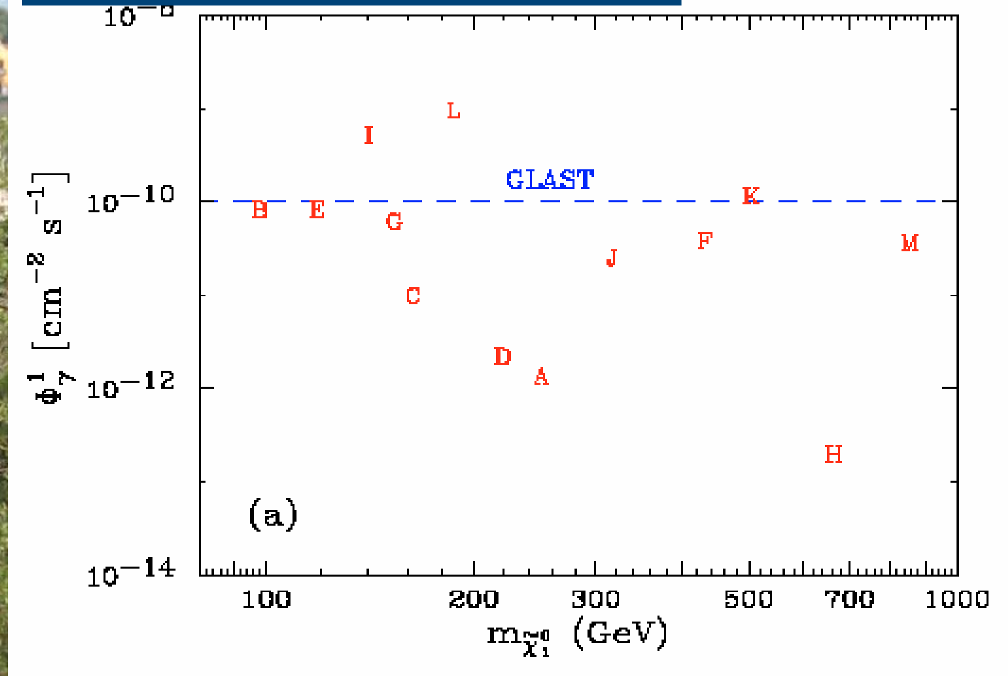
Benchmark scenarios

Annihilations in Galactic Centre

Benchmark spectra



Benchmarks → GLAST

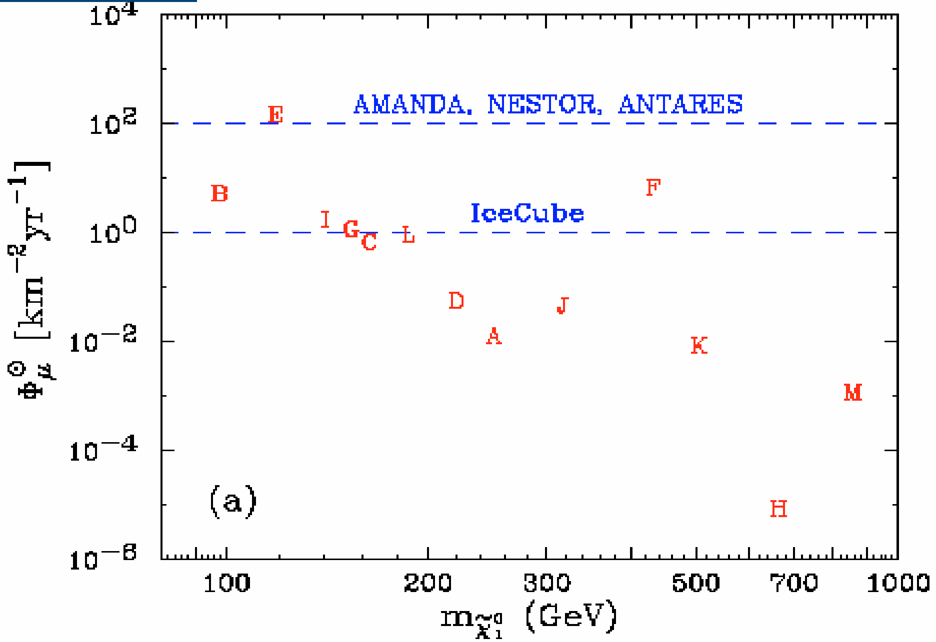


Enhancement of rate uncertain by factor > 100!

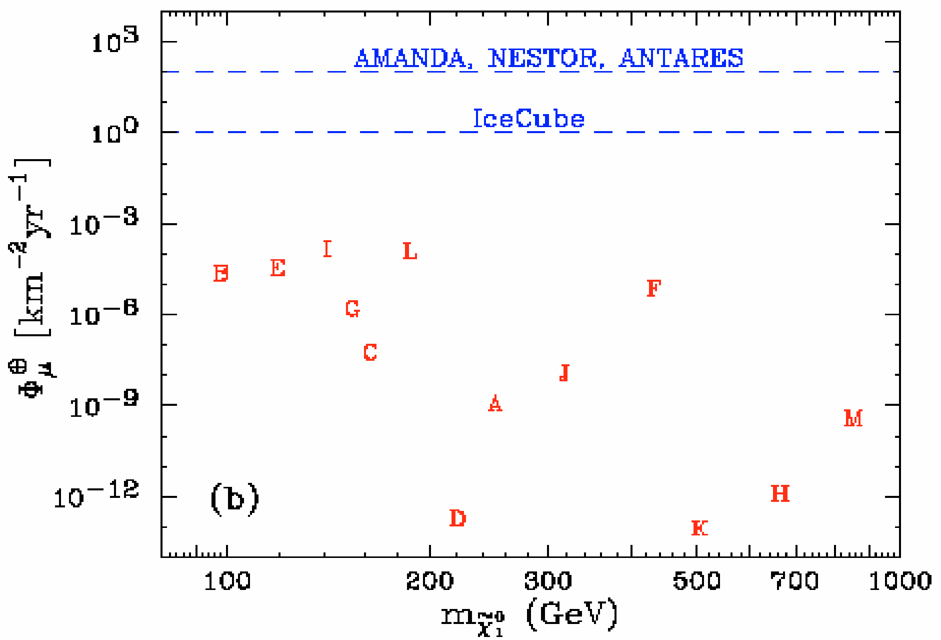
JE + Feng + Matchev + Olive

Annihilations in Solar System …

… Sun



… Earth



Prospective experimental sensitivities

Benchmark scenarios

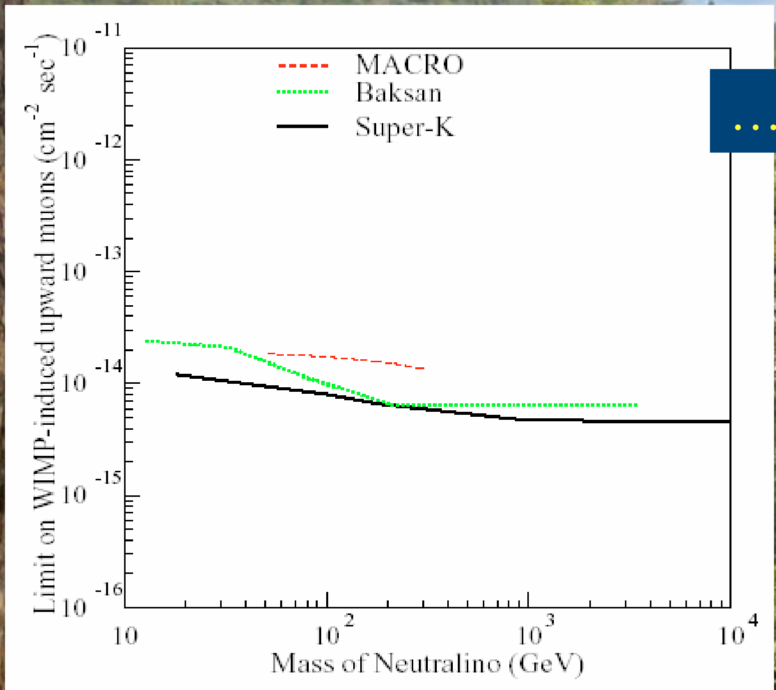
JE + Feng + Matchev + Olive

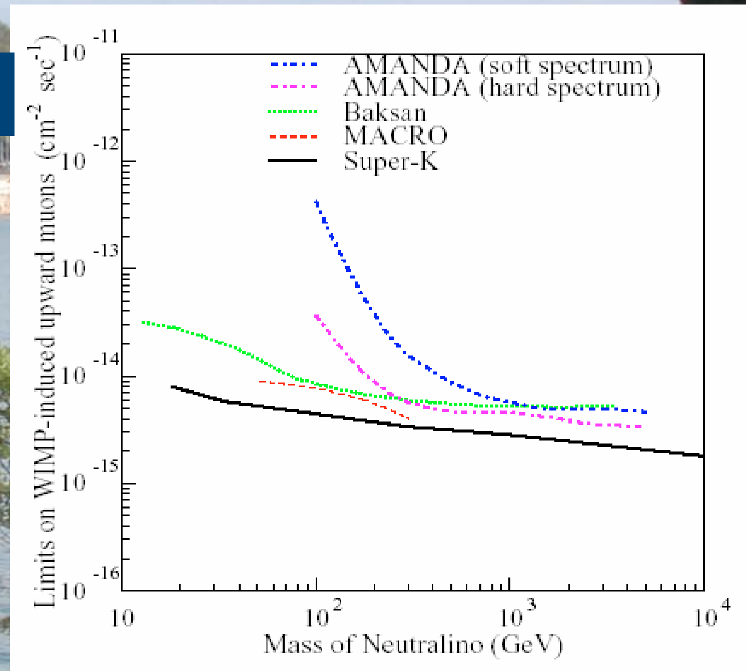
Annihilations in Solar System …

Present upper limits > 100/km^2/year

… after capture inside …

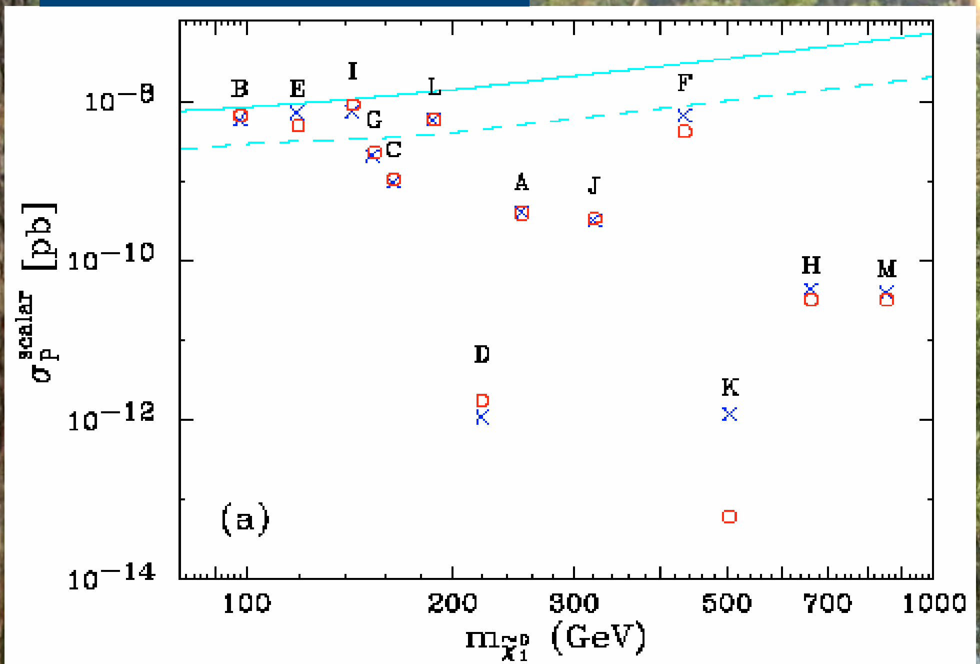
… Earth



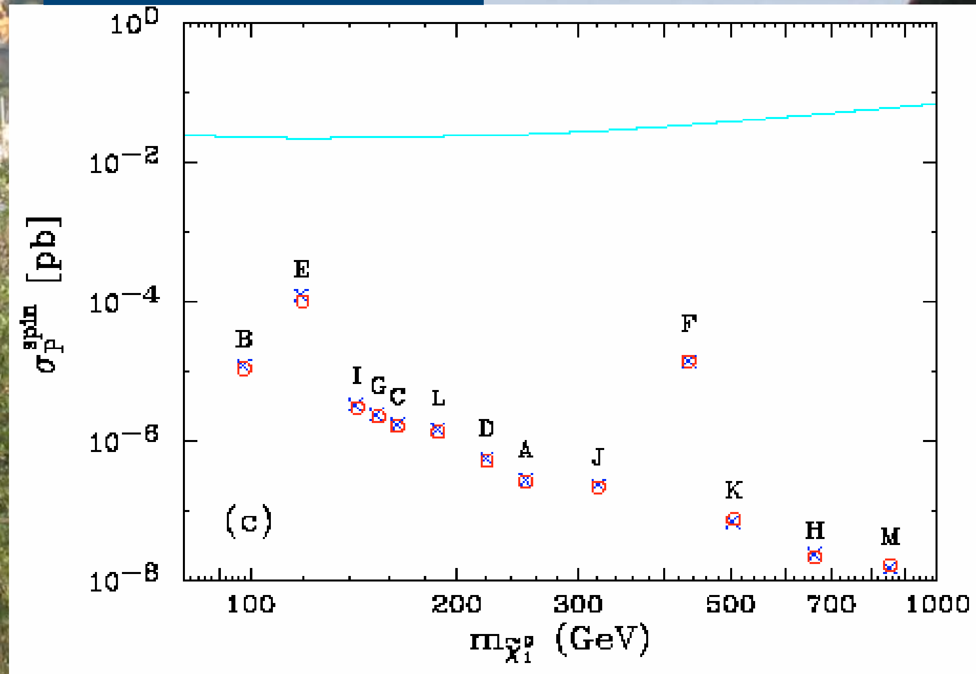


Scattering Cross Sections in Benchmark Scenarios

Spin-independent



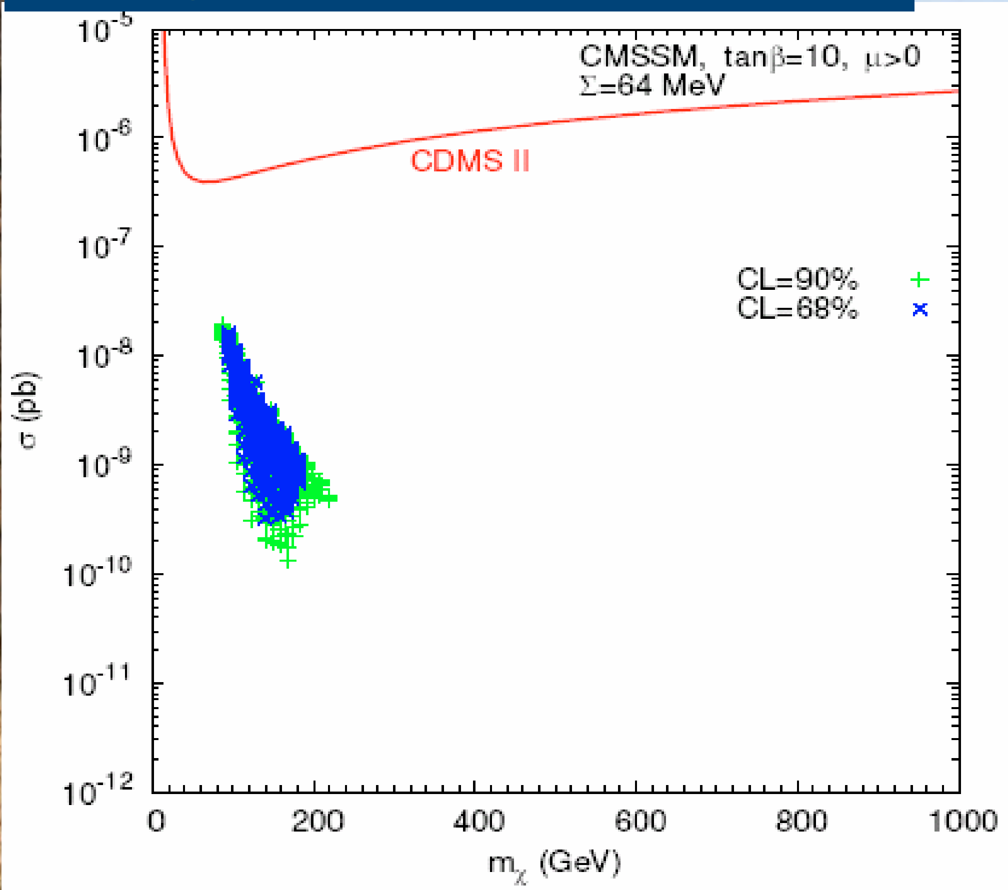
Spin-dependent



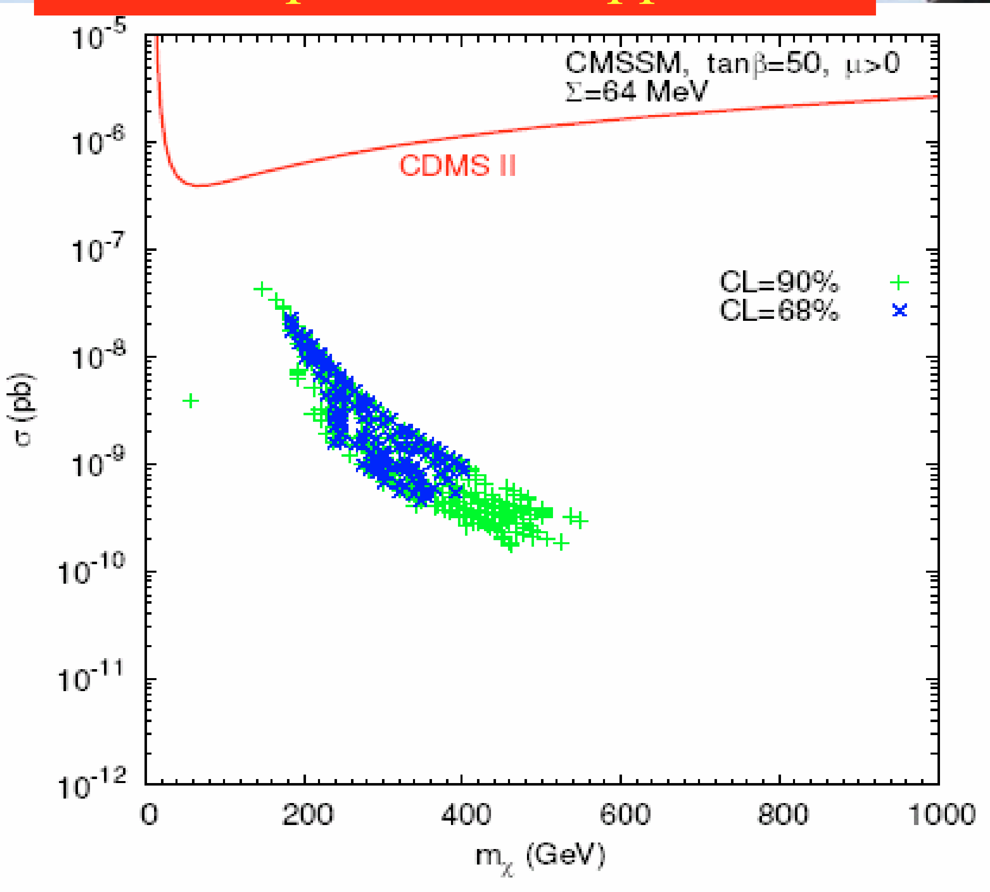
Compared with possible future experimental sensitivities

Elastic Scattering Cross Sections

From global fit to accelerator data



Latest experimental upper limit



JE + Olive + Santoso + Spanos: hep-ph/0502001

Beyond the CMSSM

More General Supersymmetric Models

- MSSM with more general pattern of supersymmetry breaking:

  non-universal scalar masses m_0

  and/or gaugino masses $m_{1/2}$

  and/or trilinear couplings A_0

- Nature of the lightest supersymmetric particle (LSP)
- Extended particle content:

  non-minimal supersymmetric model (NMSSM)

Non-Universal Scalar Masses

- Different sfermions with same quantum #s?

  e.g., d, s squarks?

  disfavoured by upper limits on flavour-changing neutral interactions

- Squarks with different #s, squarks and sleptons?

  disfavoured in various GUT models

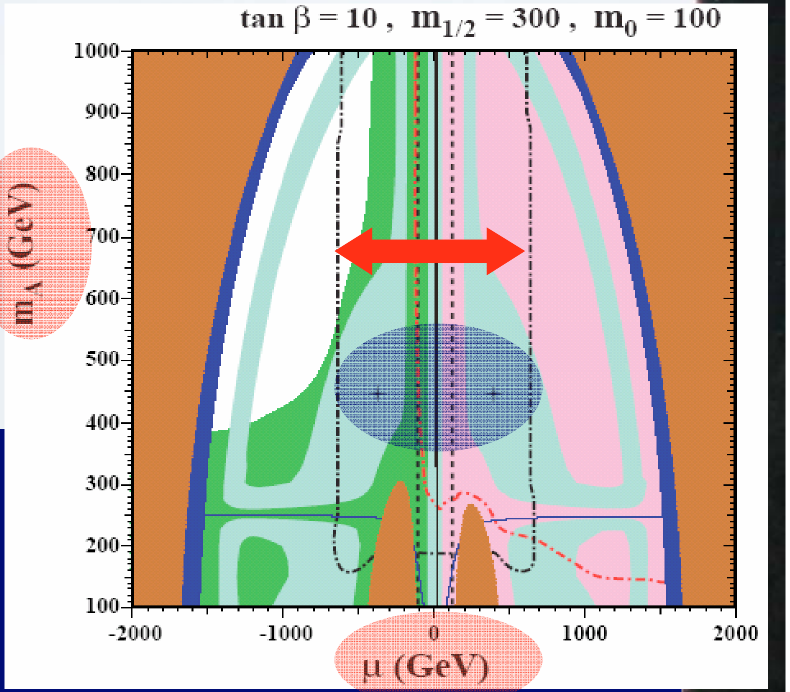
  e.g., $d_R = e_L$, $d_L = u_L = u_R = e_R$ in SU(5), all in SO(10)

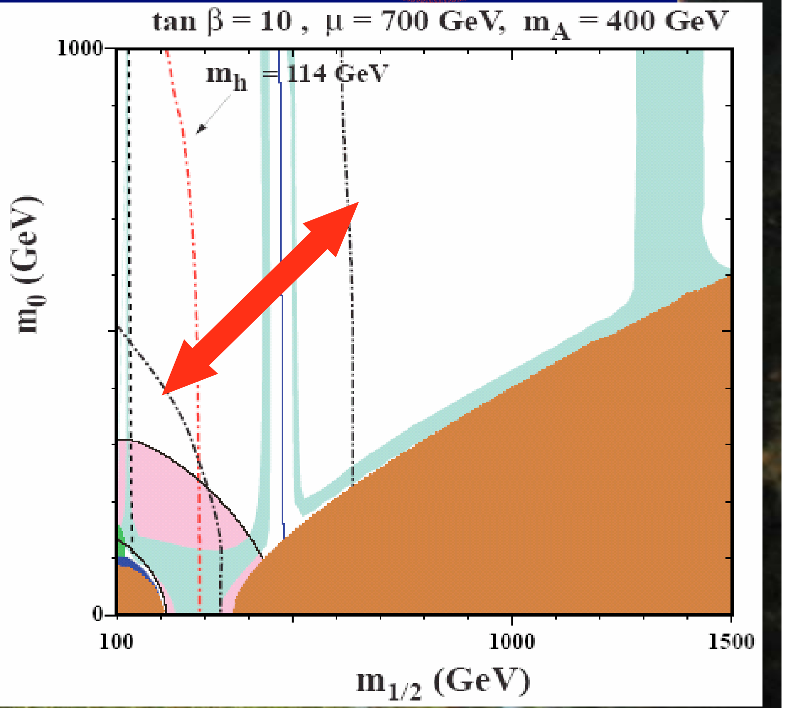
- Non-universal susy-breaking masses for Higgses?

  No reason why not!

Non-Universal Higgs Masses

- Generalize CMSSM (+)
  $$m_{Hi}^2 = m_0^2(1 + \delta_i)$$
- Free Higgs mixing μ, pseudoscalar mass m_A
- Larger parameter space
- Constrained by vacuum stability





Possible Nature of LSP

- No strong or electromagnetic interactions
  - Otherwise would bind to matter
  - Detectable as anomalous heavy nucleus
- Possible weakly-interacting scandidates
  - Sneutrino
    - (Excluded by LEP, direct searches)
  - Lightest neutralino χ
  - Gravitino
    - (nightmare for detection)

Possible Nature of NLSP

- NLSP = next-to-lightest sparticle
- Very long lifetime due to gravitational decay, e.g.:

$$\Gamma_{\tilde{\tau}\to\tilde{G}\tau} = \frac{1}{48\pi}\frac{1}{M_P^2}\frac{m_{\tilde{\tau}}^5}{m_{3/2}^2}\left(1-\frac{m_{3/2}^2}{m_{\tilde{\tau}}^2}\right)^4$$

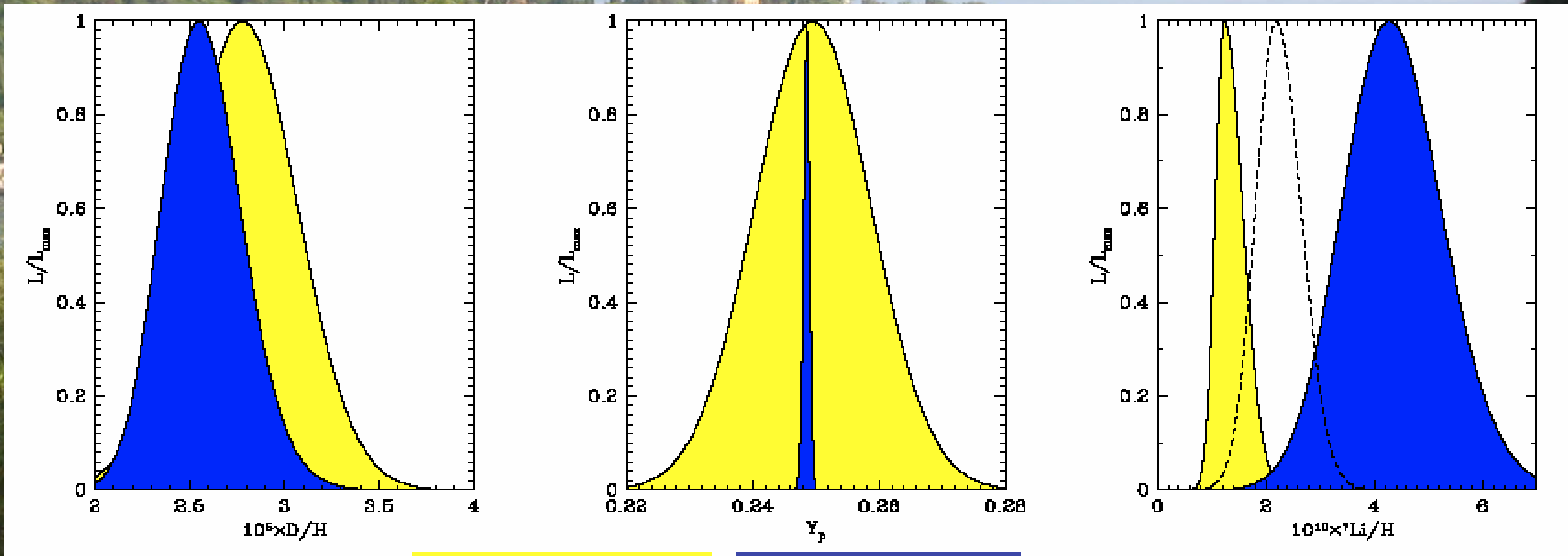
- **Could be hours, days, weeks, months or years!**
- Generic possibilities:

  lightest neutralino χ

  lightest slepton, probably lighter stau
- Constrained by astrophysics/cosmology

Light Nuclei: BBN vs CMB

Good agreement for D/H, 4He: discrepancy for 7Li?



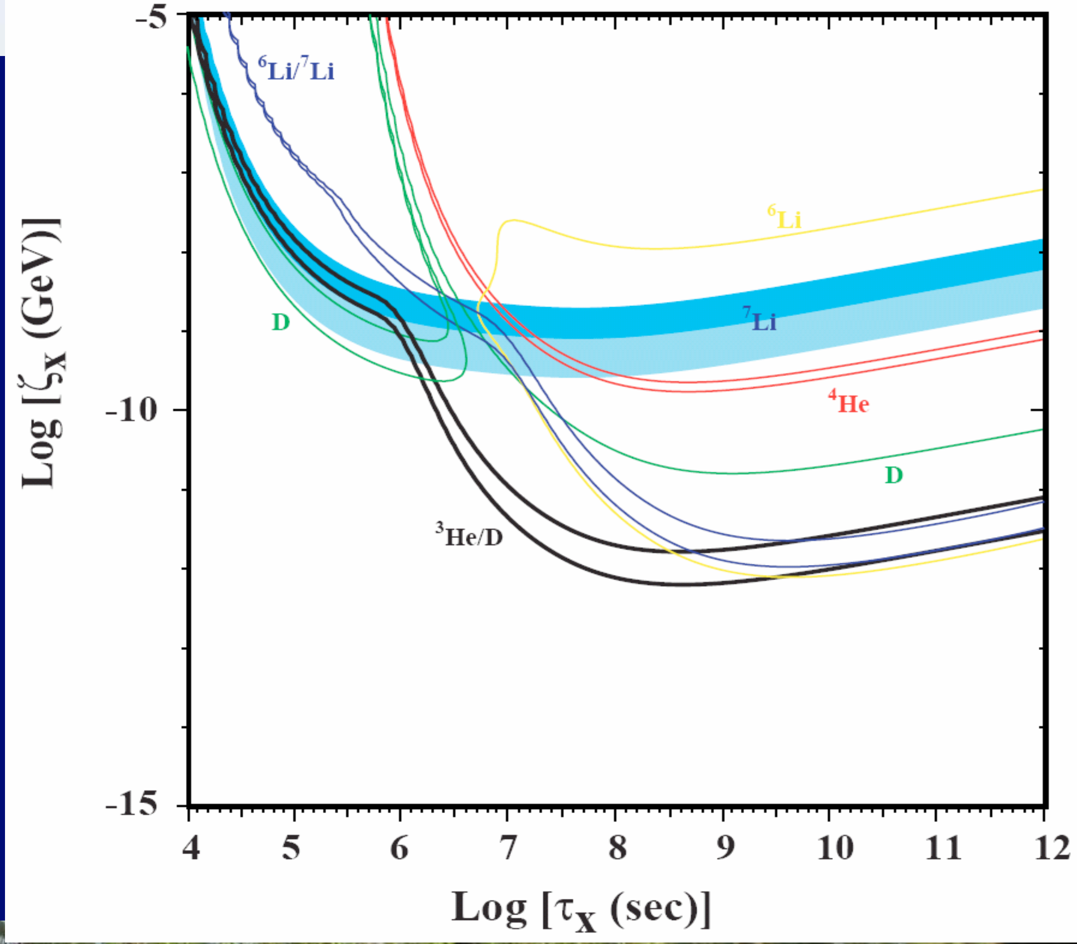
Observations

Calculations

Cyburt + Fields + Olive + Skillman

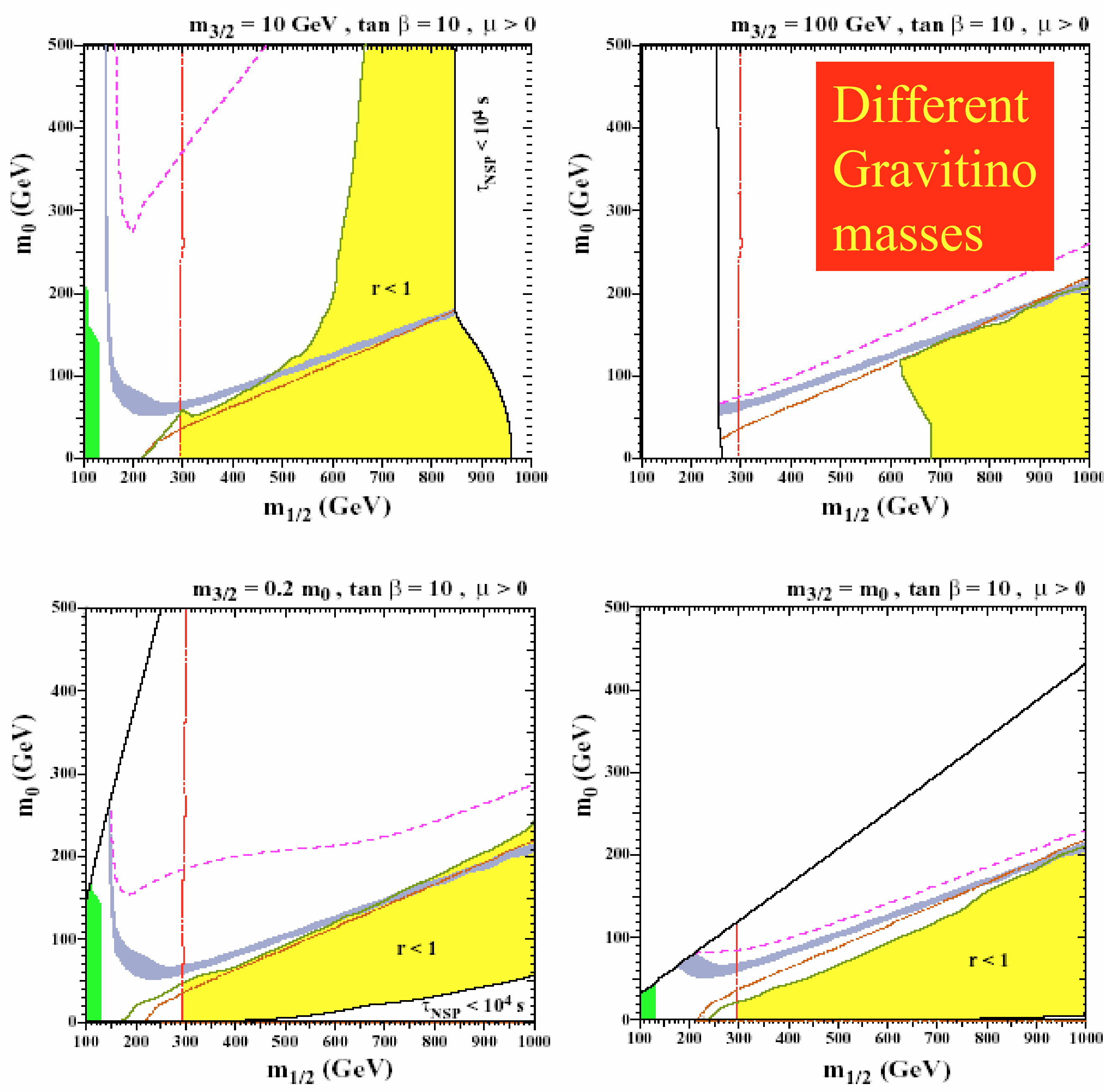
Constraints on Unstable Relics

- ^7Li < BBN?
- Effect of relic decays?
- Problems with D/H
- ^3He/D too high!
- Interpret as upper limits on abundance of metastable heavy relics



JE + Olive + Vangioni

Different Regions of Sparticle Parameter Space if Gravitino LSP



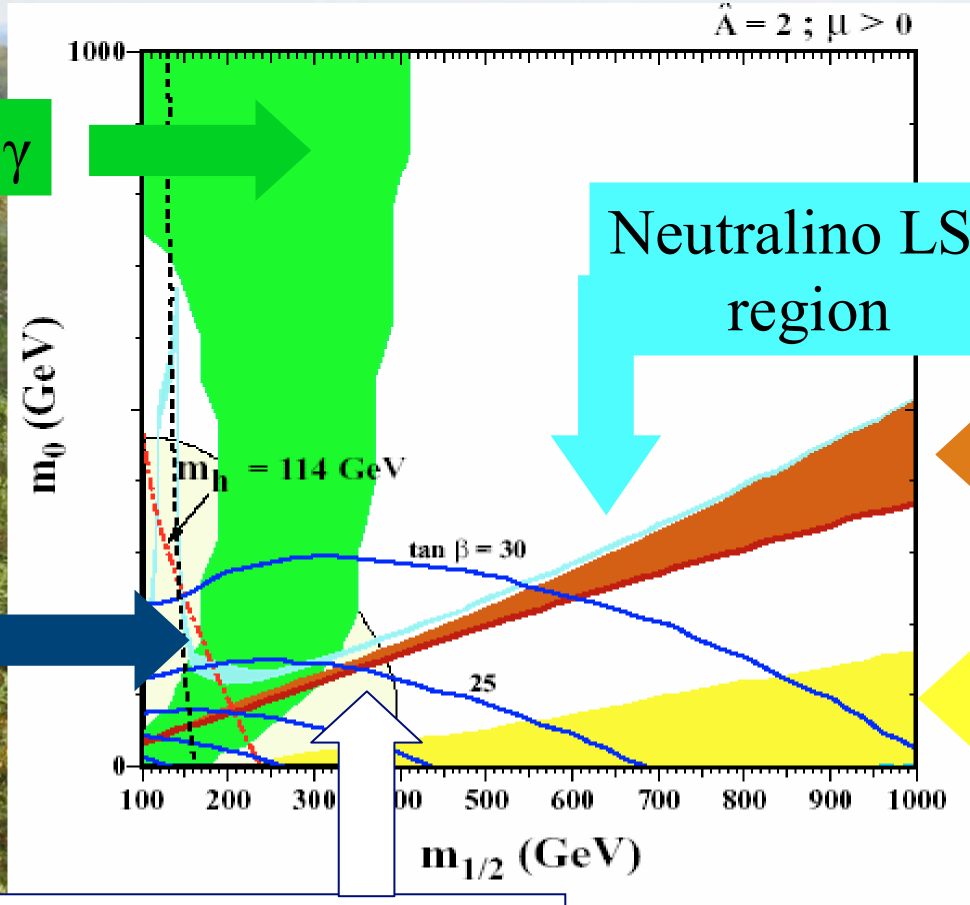
Different Gravitino masses

Density below WMAP limit

Decays do not affect BBN/CMB agreement

Minimal Supergravity Model

More constrained than CMSSM: $m_{3/2} = m_0$, $B_\lambda = A_\lambda - 1$



Excluded by b → s γ

Neutralino LSP region

stau LSP (excluded)

LEP constraints On m_h, chargino

Gravitino LSP region

tan β fixed by vacuum conditions

JE + Olive + Santoso + Spanos

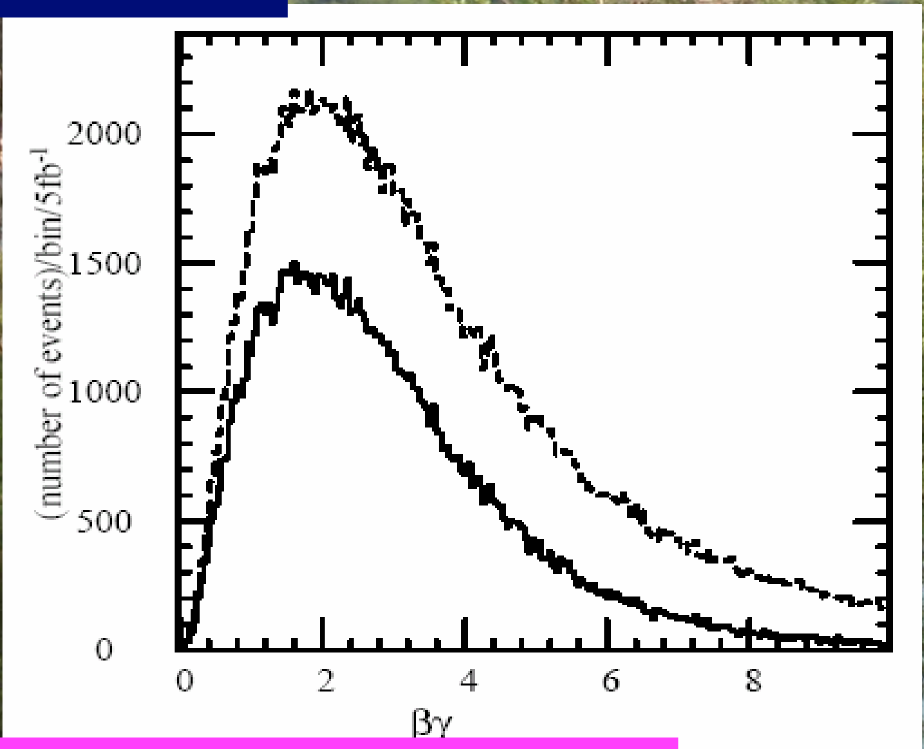
Slepton Trapping at the LHC?

If stau next-to-lightest sparticle (NLSP)

may be metastable

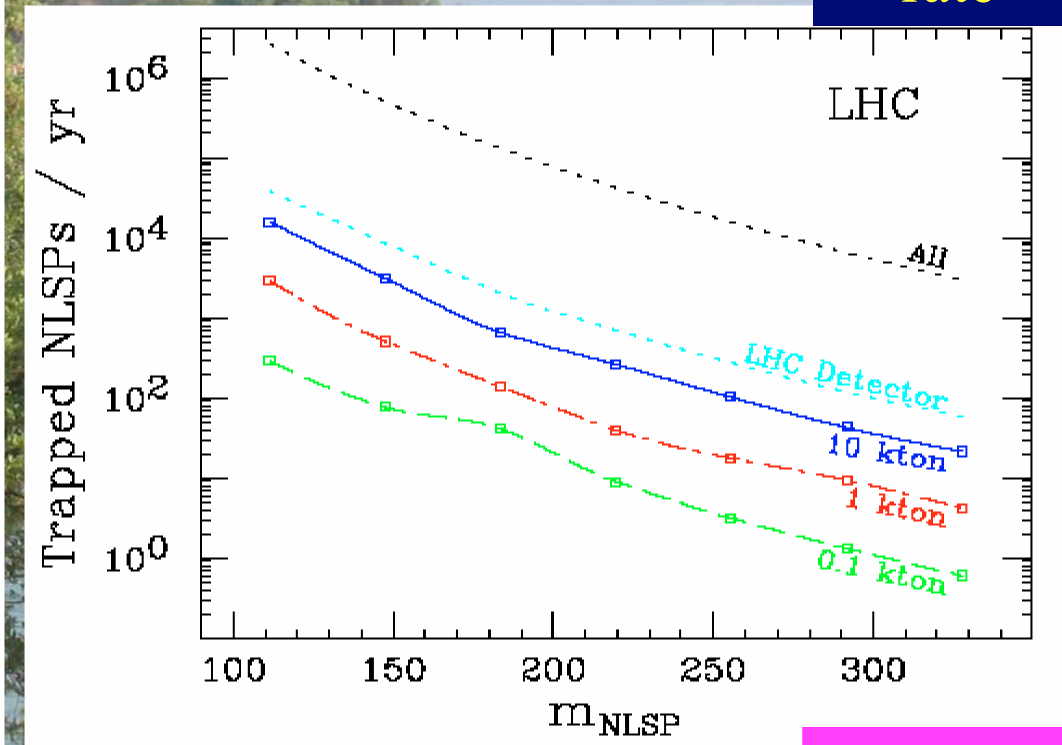
may be stopped in detector/water tank

Kinematics



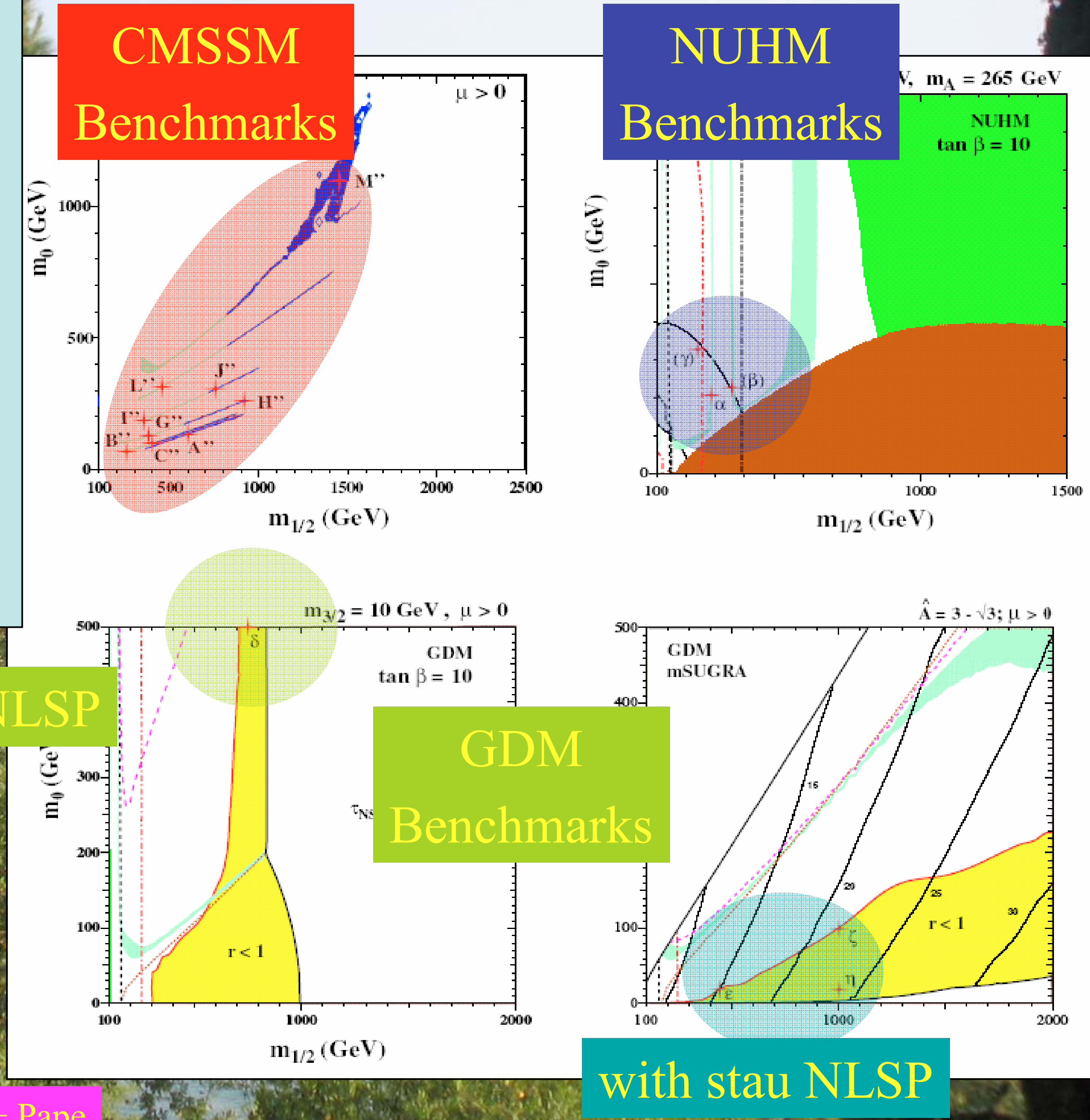
Hamaguchi + Kuno + Nakaya + Nojiri

Trapping rate



Feng + Smith

Regions Allowed in Different Scenarios for Supersymmetry Breaking



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Spectra in NUHM and GDM Benchmark Scenarios

Typical example of non-universal Higgs masses:

$$m^2_{H_1} = -(333\text{GeV})^2,\ m^2_{H_2} = +(294\text{GeV})^2$$

Models with gravitino LSP

Models with stau NLSP

Supersymmetric spectra in NUHM and GDM benchmark scenarios

Model	α	β	γ	δ	ϵ	ζ	η
$m_{1/2}$	285	360	240	750	440	1000	1000
m_0	210	230	330	500	20	100	20
$\tan\beta$	10	10	20	10	15	21.5	23.7
sign(μ)	+	+	+	+	+	+	+
A_0	0	0	0	0	25	127	25
m_t	178	178	178	178	178	178	178
Masses							
$\|\mu\|$	375	500	325	978	610	1176	1161
h^0	115	117	114	122	119	124	124
H^0	266	325	240	1177	641	1307	1277
A^0	265	325	240	1177	641	1307	1277
$H^\pm$	277	335	253	1179	646	1310	1279
χ_1^0	113	146	95	323	183	436	436
χ_2^0	212	279	178	625	349	840	840
χ_3^0	388	515	341	954	578	1176	1165
χ_4^0	406	528	358	964	593	1186	1175
$\chi_1^\pm$	212	279	177	625	349	840	840
$\chi_2^\pm$	408	529	360	965	594	1186	1176
$\tilde{g}$	674	835	575	1610	986	2097	2097
e_L, μ_L	296	346	376	702	298	664	657
e_R, μ_R	216	241	328	571	169	383	370
ν_e, ν_μ	285	337	367	697	287	660	652
τ_1	212	239	315	564	150	340	322
τ_2	298	348	377	700	302	661	655
ν_τ	285	337	364	695	285	651	644
u_L, c_L	648	793	612	1532	897	1892	1889
u_R, c_R	637	778	607	1480	867	1817	1814
d_L, s_L	653	797	617	1534	901	1893	1891
d_R, s_R	630	768	599	1474	864	1807	1805
t_1	471	596	433	1159	682	1465	1472
t_2	652	784	600	1429	879	1758	1756
b_1	590	727	540	1395	824	1726	1723
b_2	629	767	594	1468	862	1781	1775

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Properties of NUHM and GDM Models

Relic density $\Omega_\chi h^2, b \to s\gamma$ and $g_\mu - 2$ in post-WMAP benchmark scenarios, also τ_{NLSP} in the GDM models

	α	β	γ	δ	ϵ	ζ	η
$\Omega_{LSP}h^2$	0.12	0.10	0.09	0.07	1.0×10^{-3}	0.9×10^{-2}	1.6×10^{-3}
$\delta a_\mu(10^{-9})$	1.5	1.0	2.6	0.2	1.8	0.5	0.5
$B_{s\gamma}(10^{-4})$	4.1	4.4	2.8	3.7	3.6	3.6	3.6
$\tau_{NLSP}(\mathrm{s})$	∞	∞	∞	1.8×10^4	3.3×10^6	2.0×10^6	6.8×10^4

- Relic density ~ WMAP in NUHM models
- Generally < WMAP in GDM models

  Need extra source of gravitinos at high temperatures, after inflation?

- NLSP lifetime: 10^4s < τ < few X 10^6s

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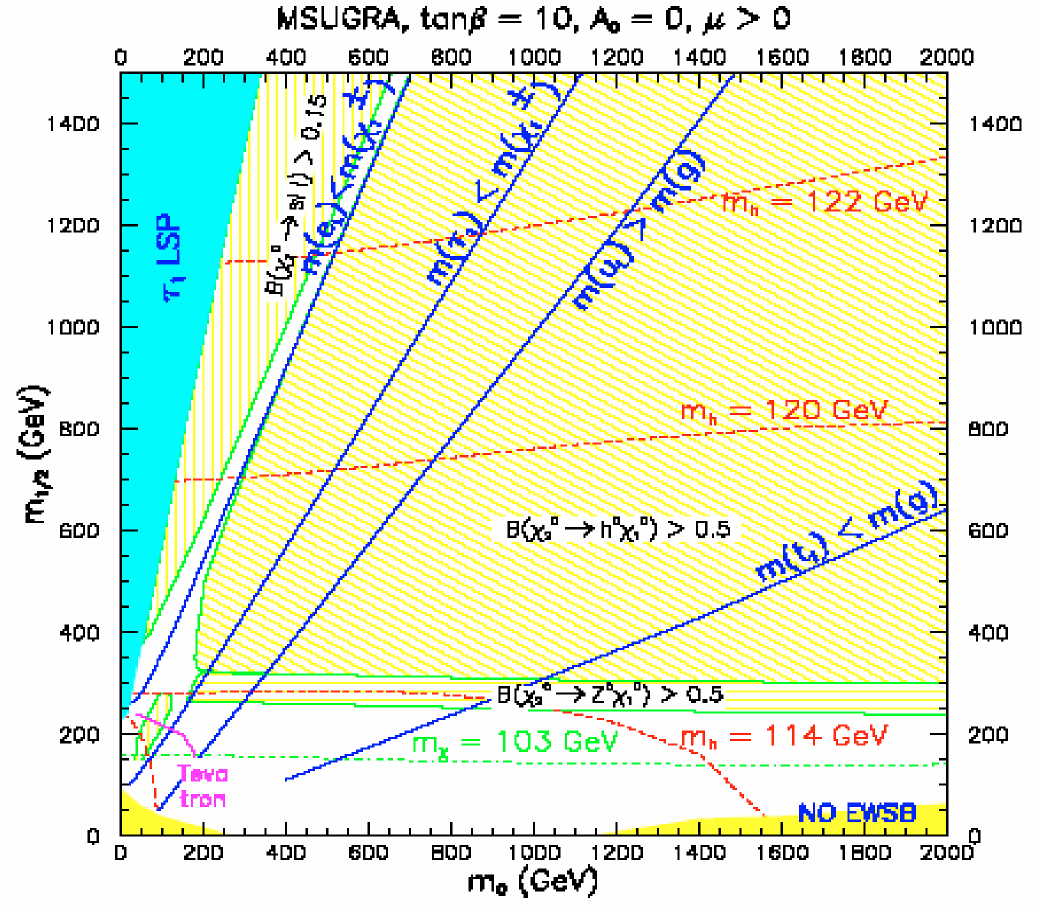
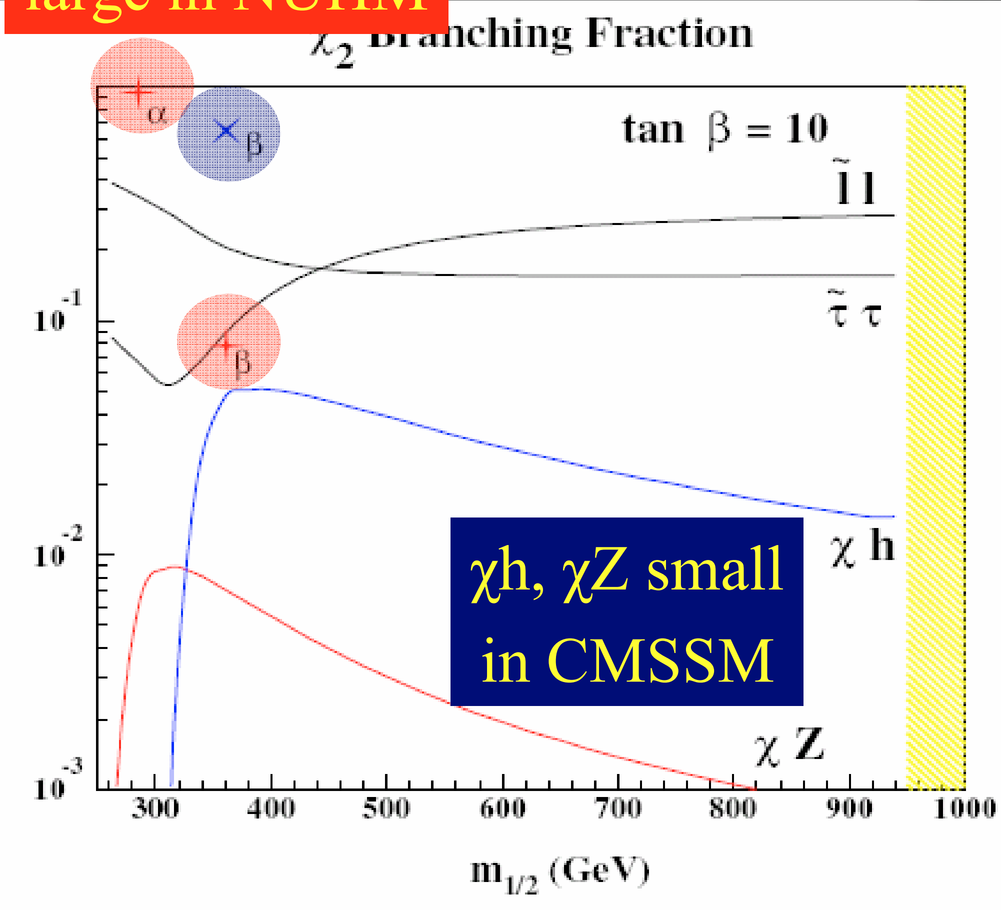
Neutralino Masses and Decay Modes



χh, χZ may be large in NUHM



χh, χZ small in CMSSM

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Final States in GDM Models with Stau NLSP

- All decay chains
  end with lighter stau
- Generally via χ
- Often via heavier
  sleptons
- Final states contain
  2 staus, 2 τ,
  often other leptons

Final state	ϵ	ζ	η
via χ_2^0			
$\tilde{q}_L \longrightarrow q l l \tilde{\tau}_1 \tau$	6%	7%	6%
$\tilde{q}_L \longrightarrow q l l' l' \tilde{\tau}_1 \tau$	0.5%	2.3%	2.9%
$\tilde{q}_L \longrightarrow q(Z^0, h^0) \tilde{\tau}_1 \tau$	1.3%	4%	4%
$\tilde{q}_L \longrightarrow q \tau \tau \tilde{\tau}_1 \tau$	1.2%	0.8%	0.6%
$\tilde{q}_L \longrightarrow q \tau \tau l l \tilde{\tau}_1 \tau$	0.1%	0.3%	0.3%
$\tilde{q}_L \longrightarrow q \tilde{\tau}_1 \tau$	4%	1.3%	1.5%
decays with νs	18%	17%	17%
via $\chi_1^\pm$			
$\tilde{q}_L \longrightarrow q' W \tilde{\tau}_1 \tau$	6%	10%	10%
decays with νs	57%	56%	54%
via χ_1^0			
$\tilde{q}_R \longrightarrow q \tilde{\tau}_1 \tau$	92%	75%	69%
$\tilde{q}_R \longrightarrow q l l \tilde{\tau}_1 \tau$	8%	25%	31%

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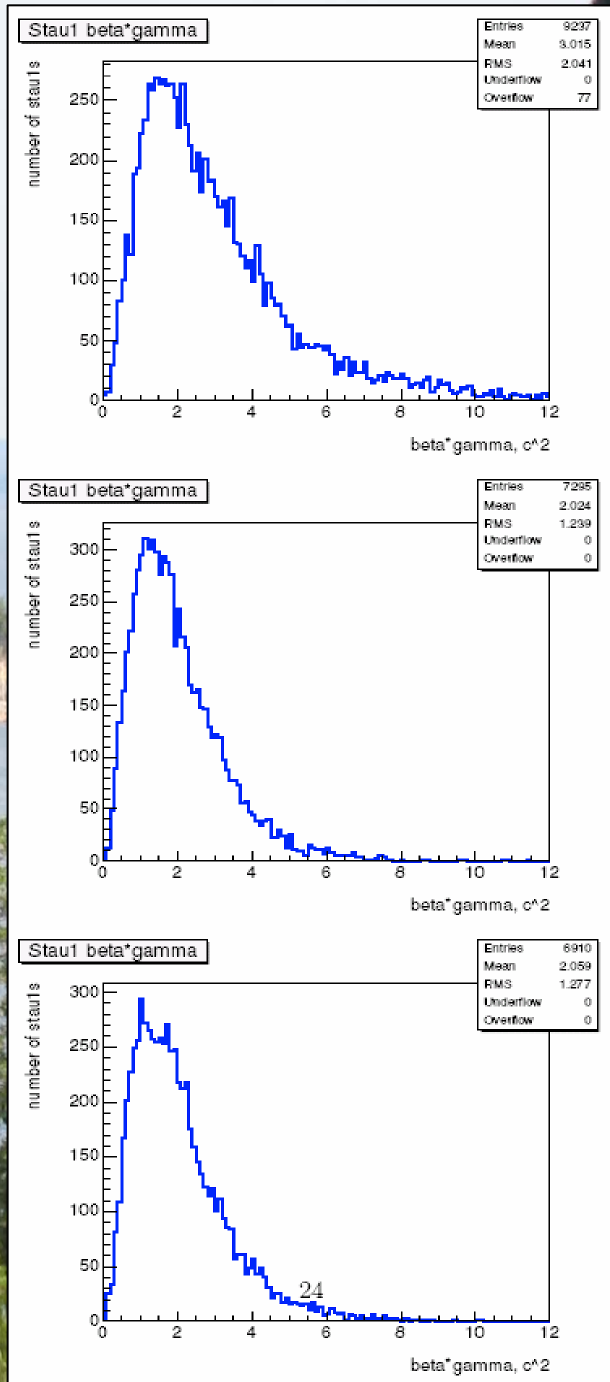
Stau Momentum Spectra

- βγ typically peaked ~ 2
- Staus with βγ < 1 leave central tracker after next beam crossing
- Staus with βγ < ¼ trapped inside calorimeter
- Staus with βγ < ½ stopped within 10m
- Can they be dug out?

Model	ϵ	ζ	η
Number of particles with $\beta\gamma < 0.25$	850	7	7
Range in C (cm)	60	136	129
Range in Fe (cm)	29	65	61
Number of particles with $\beta\gamma < 0.5$	7700	100	90
Range in C (cm)	600	1360	1290
Range in Fe (cm)	290	650	610



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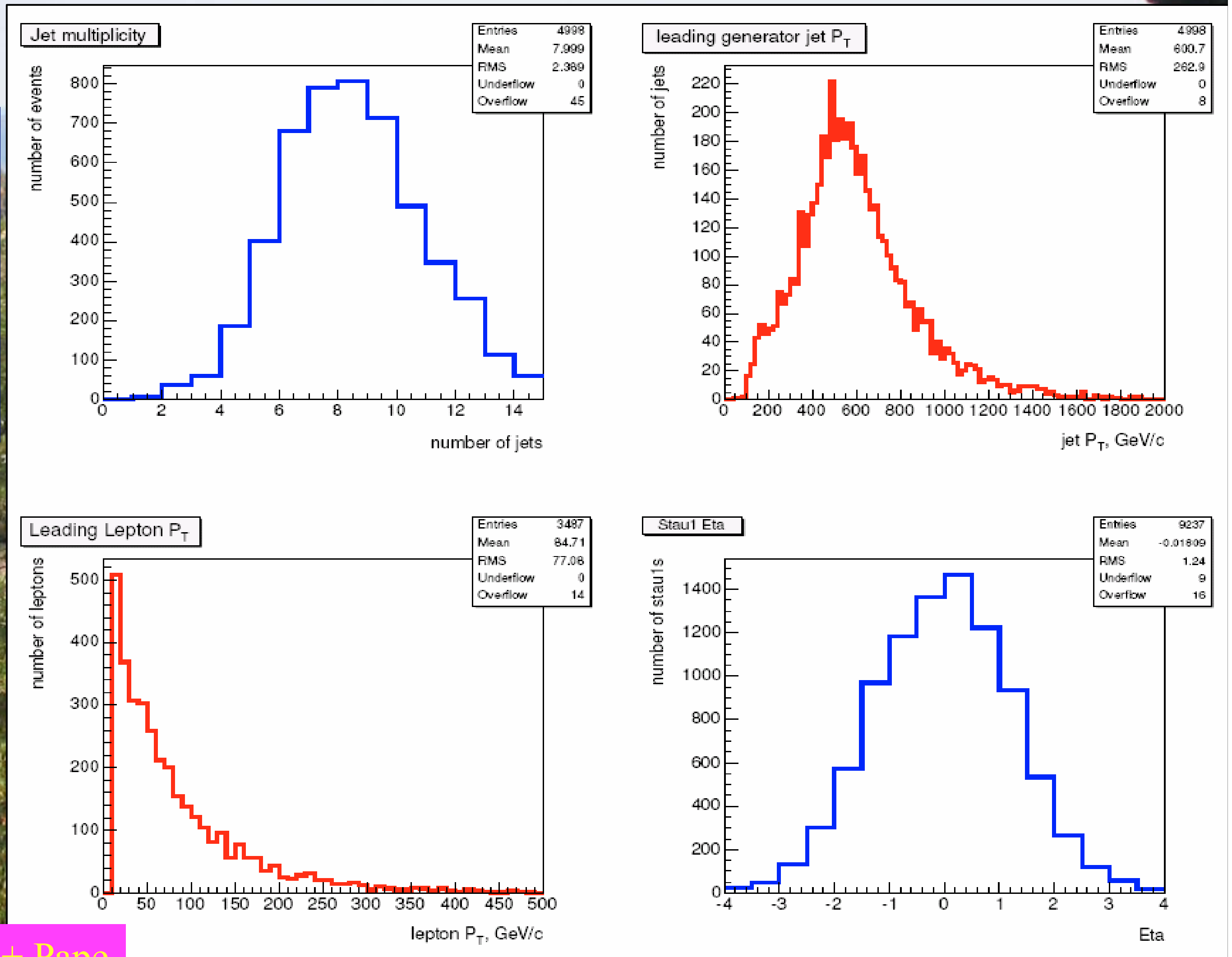
Kinematic Distributions: Point ε

- Staus come with many jets & leptons with p_T hundreds of GeV, produced centrally



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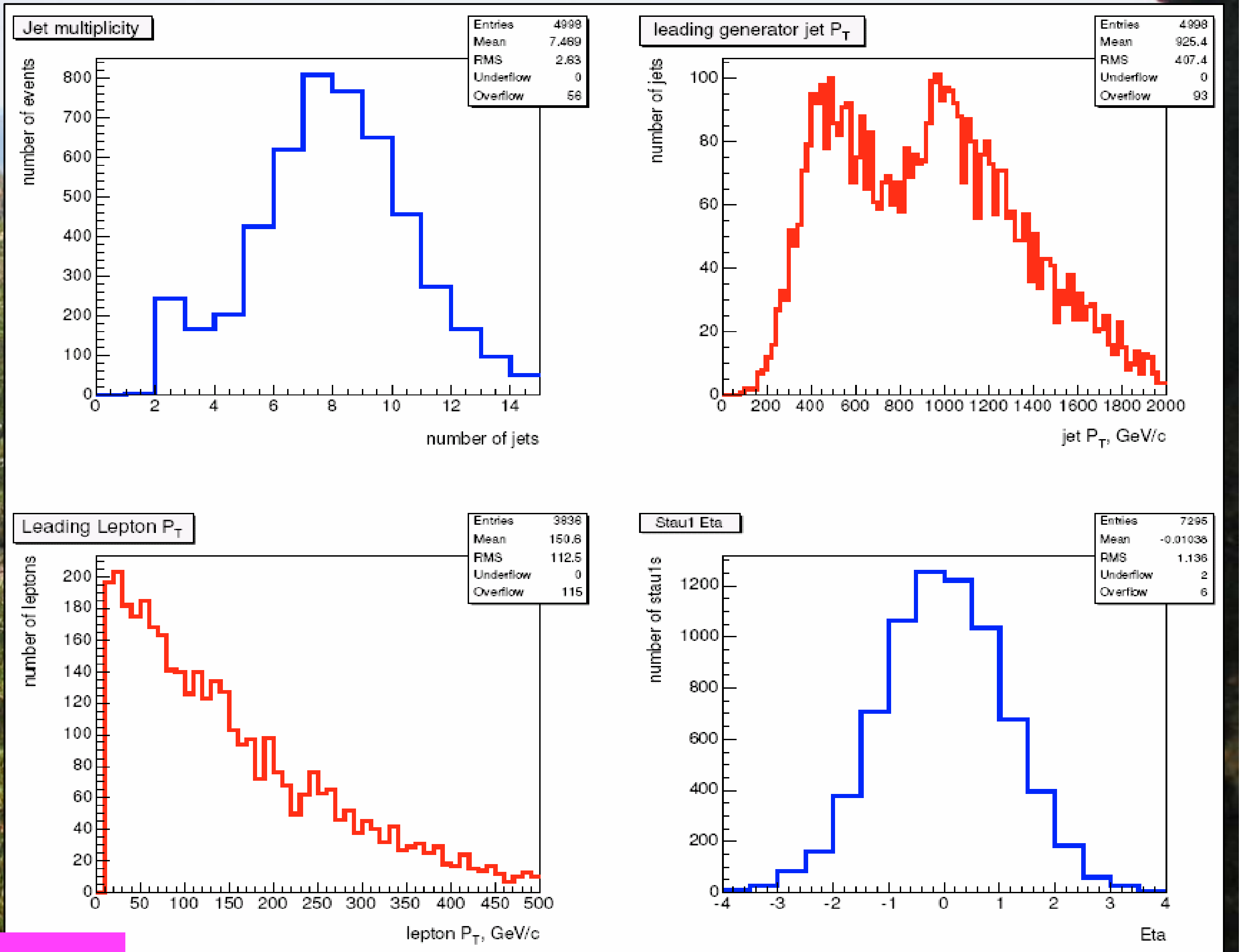
Kinematic Distributions: Point ζ

- Staus come with many jets & leptons with p_T hundreds of GeV, produced centrally



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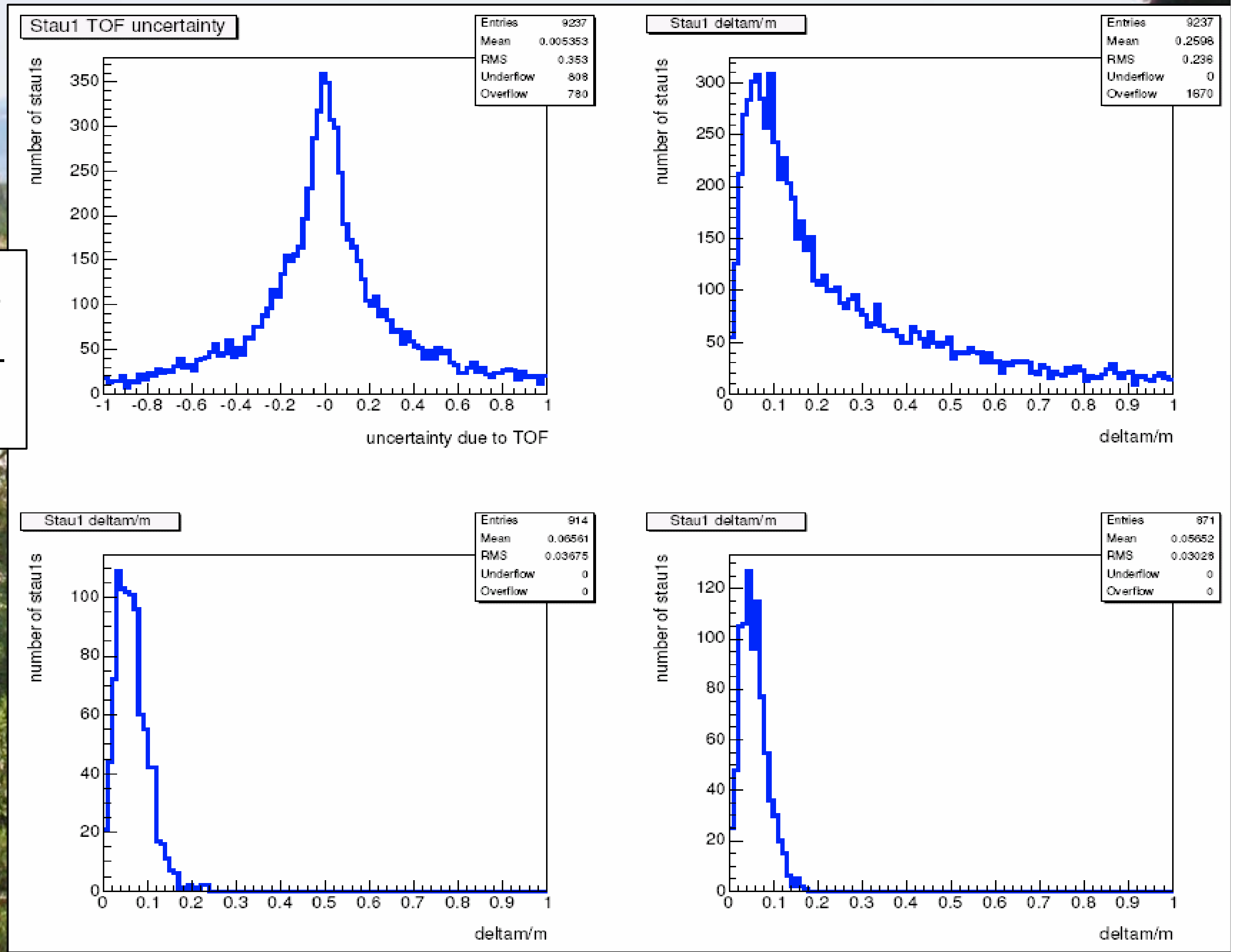
Stau Mass Measurements by Time-of-Flight

$$\frac{\Delta M}{M} = \frac{\Delta p}{p} \oplus \beta\gamma^2 \frac{c\Delta t}{L}$$

- Event-by-event accuracy < 10%
- < 1% with full sample



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Potential Measurement Accuracies

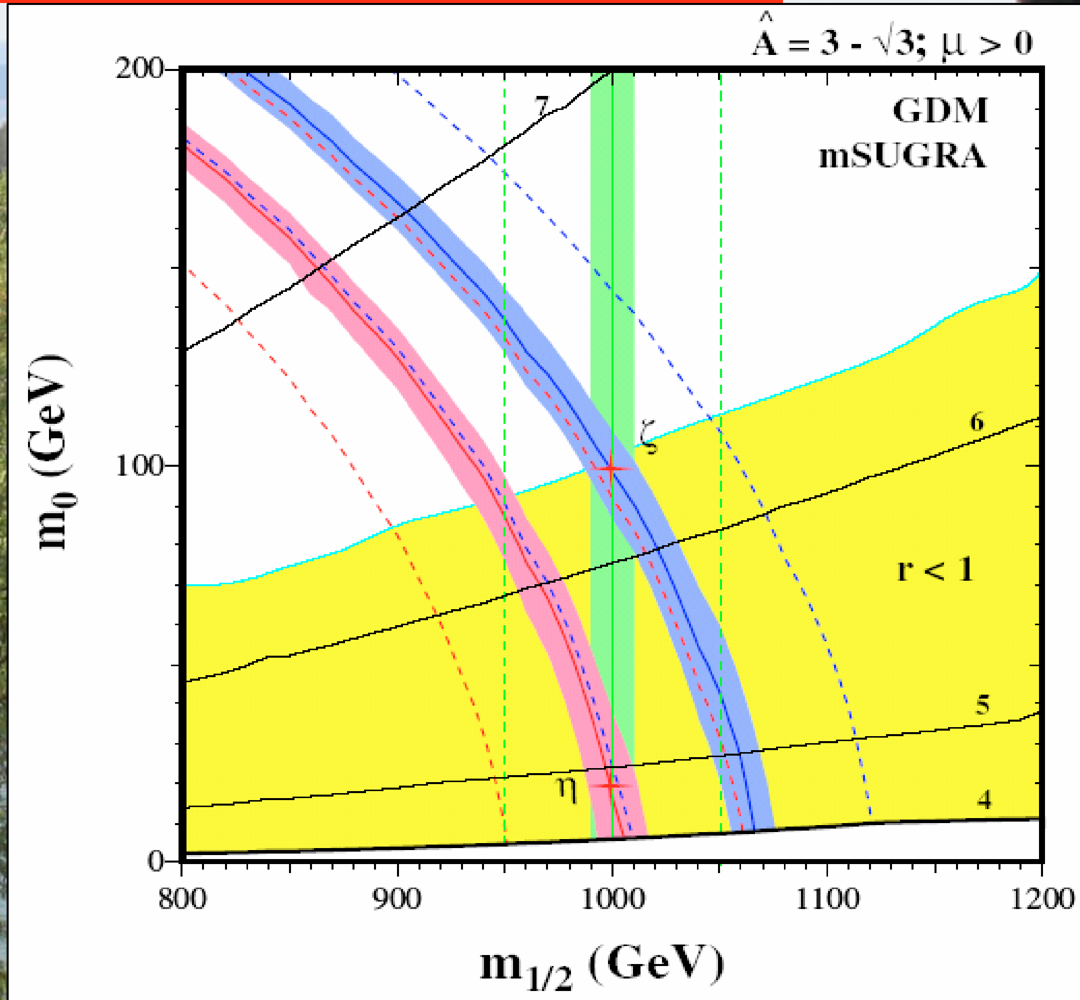
Gravitino Dark Matter even more interesting than Neutralino Dark Matter!

Measure stau mass to 1%

Measure $m_{1/2}$ to 1%

via cross section, other masses?

Distinguish points ζ, η



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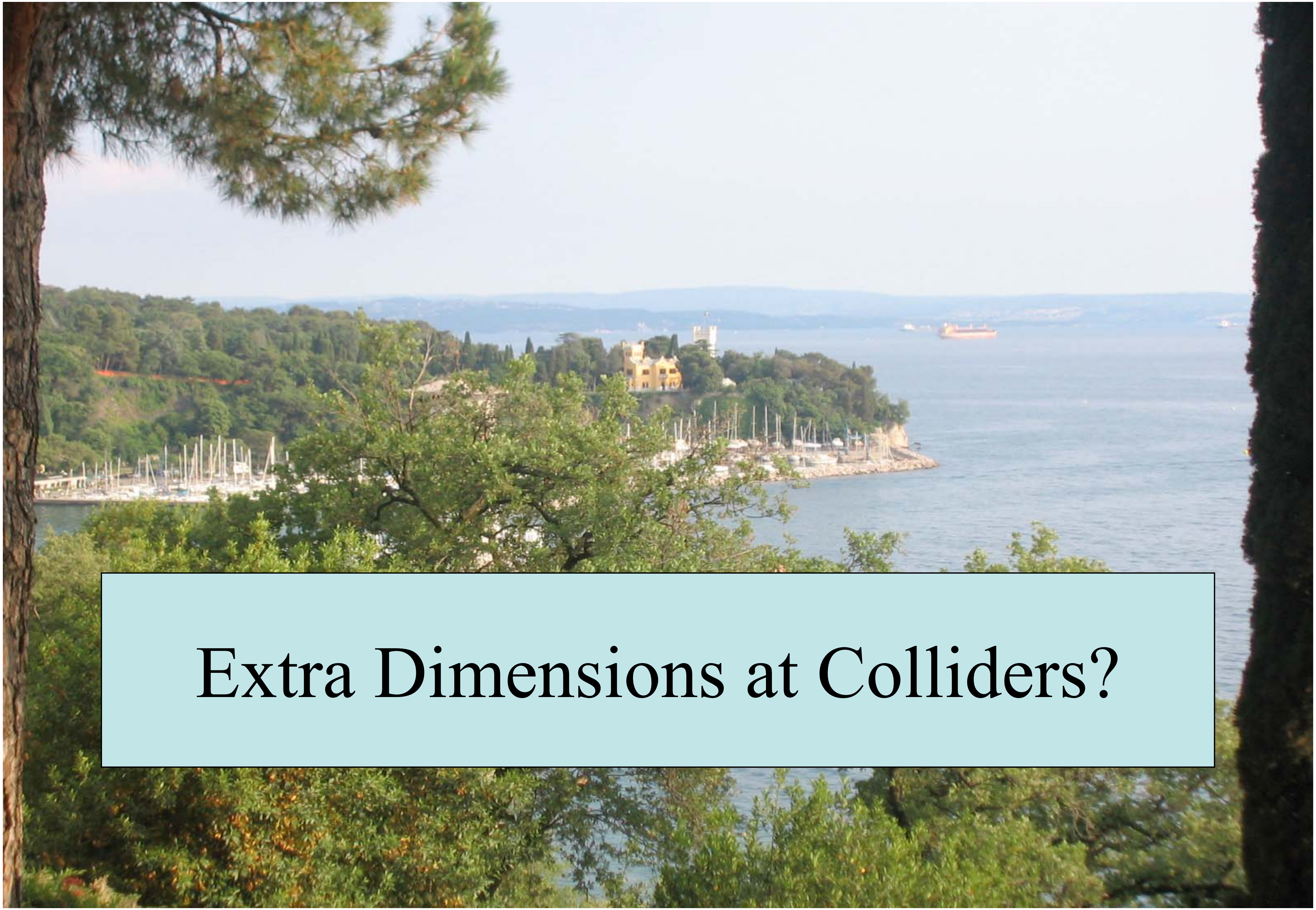


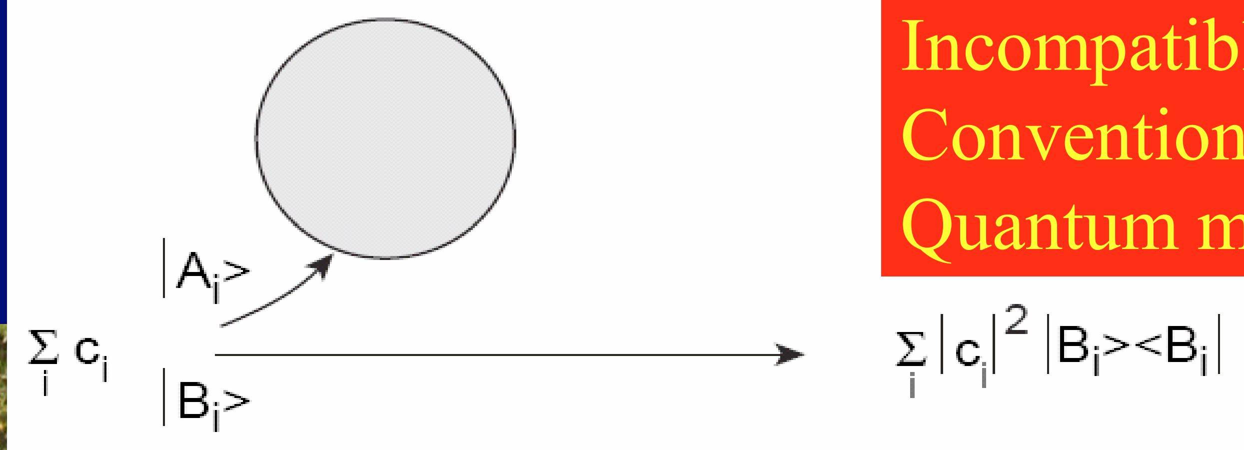
Extra Dimensions at Colliders?

Problems of Quantum Gravity

- Gravity grows with energy: $\sigma_G \sim E^2 / m_P^4$
- Two-graviton exchange is infinite:

$$\int^{\Lambda \to \infty} d^4k \left(\frac{1}{k^2}\right) \leftrightarrow \int_{1/\Lambda \to 0} d^4x \left(\frac{1}{x^6}\right) \sim \Lambda^2 \to \infty$$

- **Gravity is a non-renormalizable theory**
- Pure states evolve to mixed states?



Incompatible with Conventional Quantum mechanics

String Theory

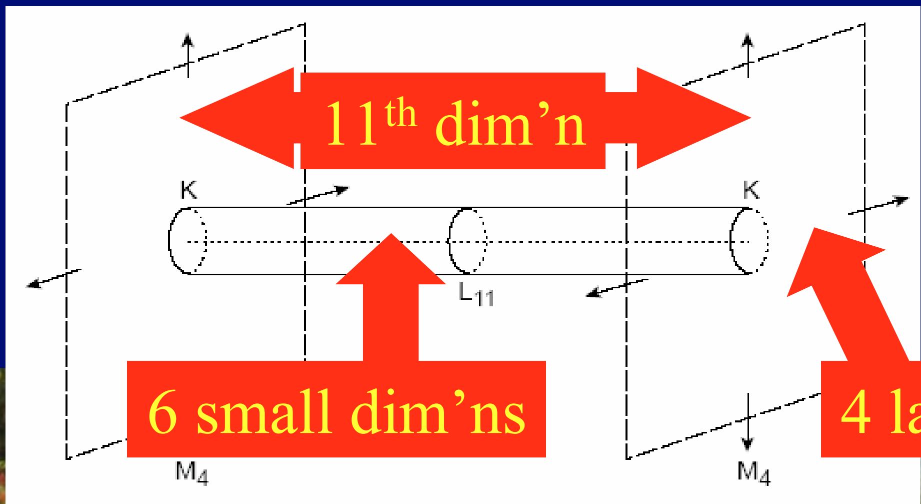
- Point-like particles → extended objects
- Simplest possibility: lengths of string
- Open and/or closed
- Quantum consistency fixes # dimensions:
- Bosonic string: 26, superstring: 10
- Must compactify extra dimensions, scale ~ $1/m_P$?
- Perturbative string unification scale:

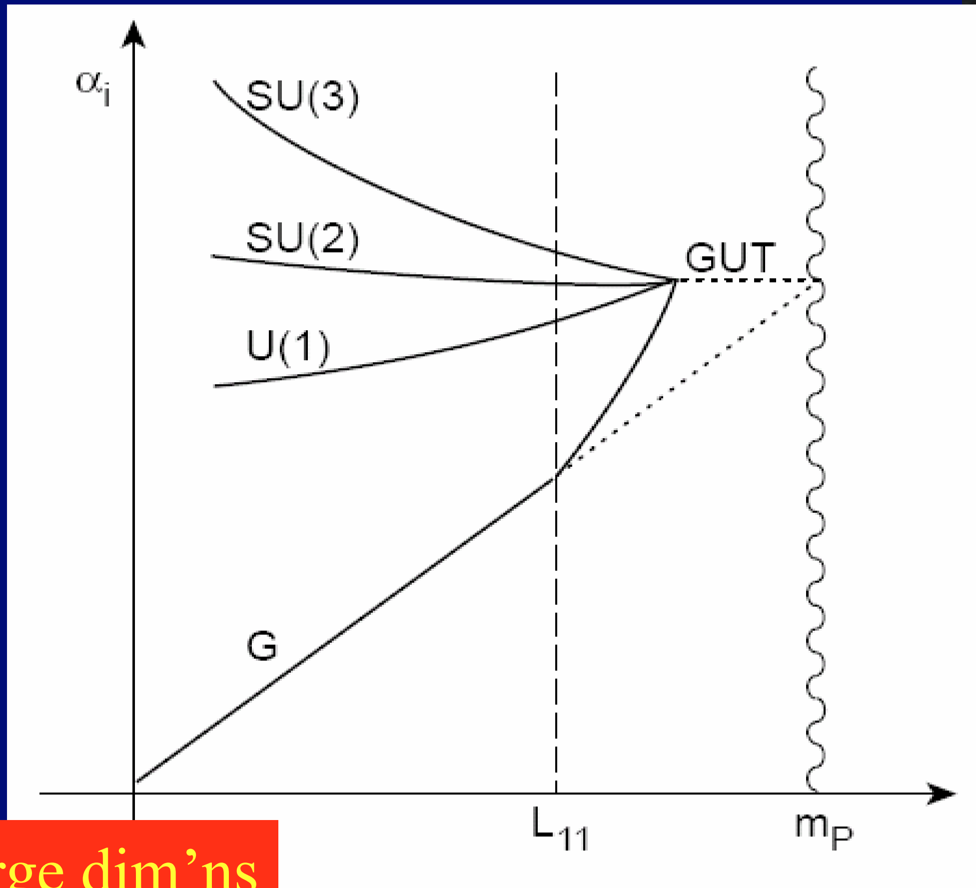
$$M_{GUT} = O(g) \times \frac{m_P}{\sqrt{8\pi}} \simeq \text{few} \times 10^{17}\text{GeV}$$

Close to GUT scale, but larger?

Scenario for String Unification

- Extra dimension below GUT scale: gravity grows faster with energy, unify
  at 10^{16} GeV?
- E.g., in M theory with large 11^{th} dimension



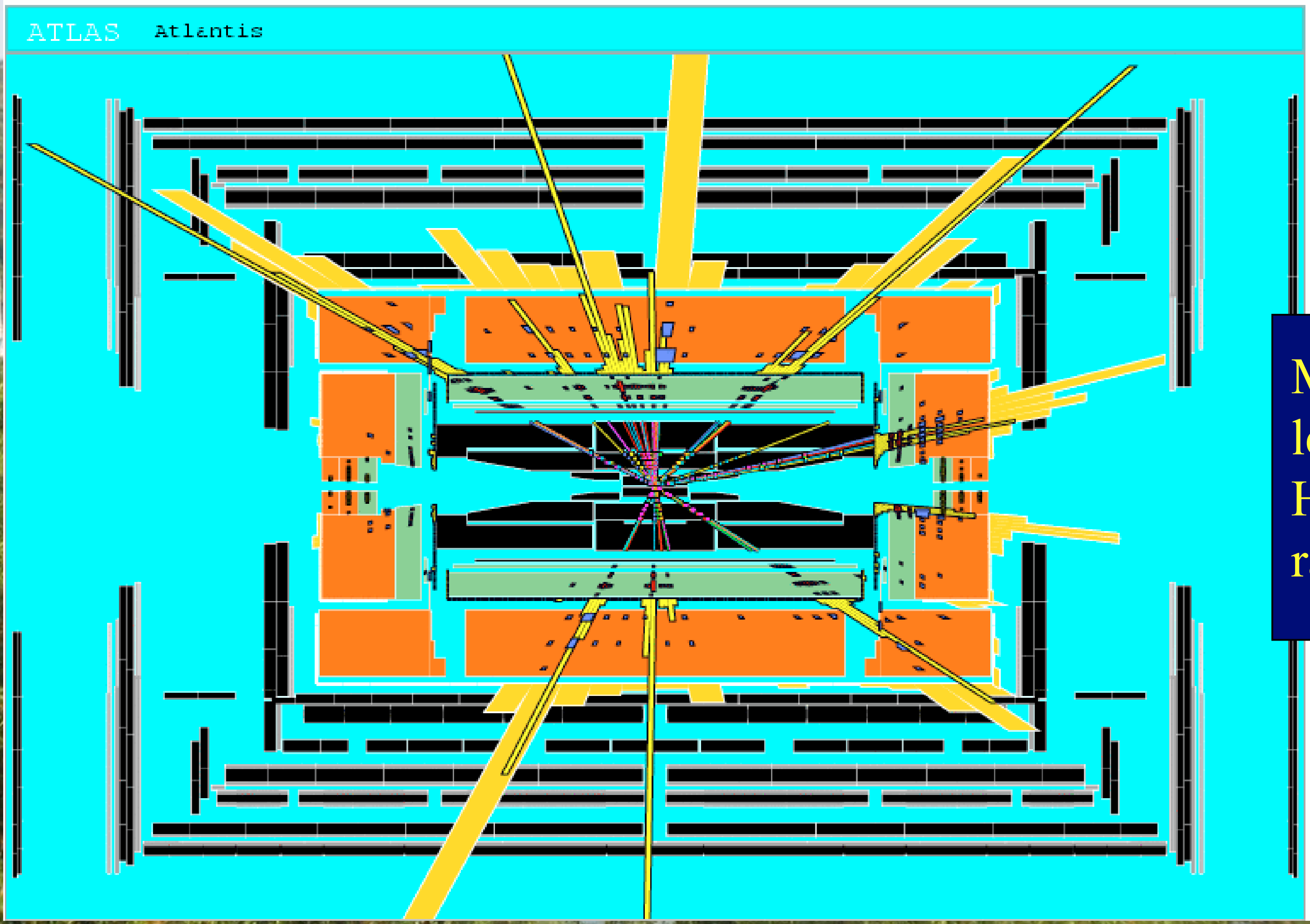


How large could extra Dimensions be?

- 1/TeV?
  - could break supersymmetry, electroweak
- micron?
  - can rewrite hierarchy problem
- Infinite?
  - warped compactifications
- **Look for black holes, Kaluza-Klein excitations @ colliders?**

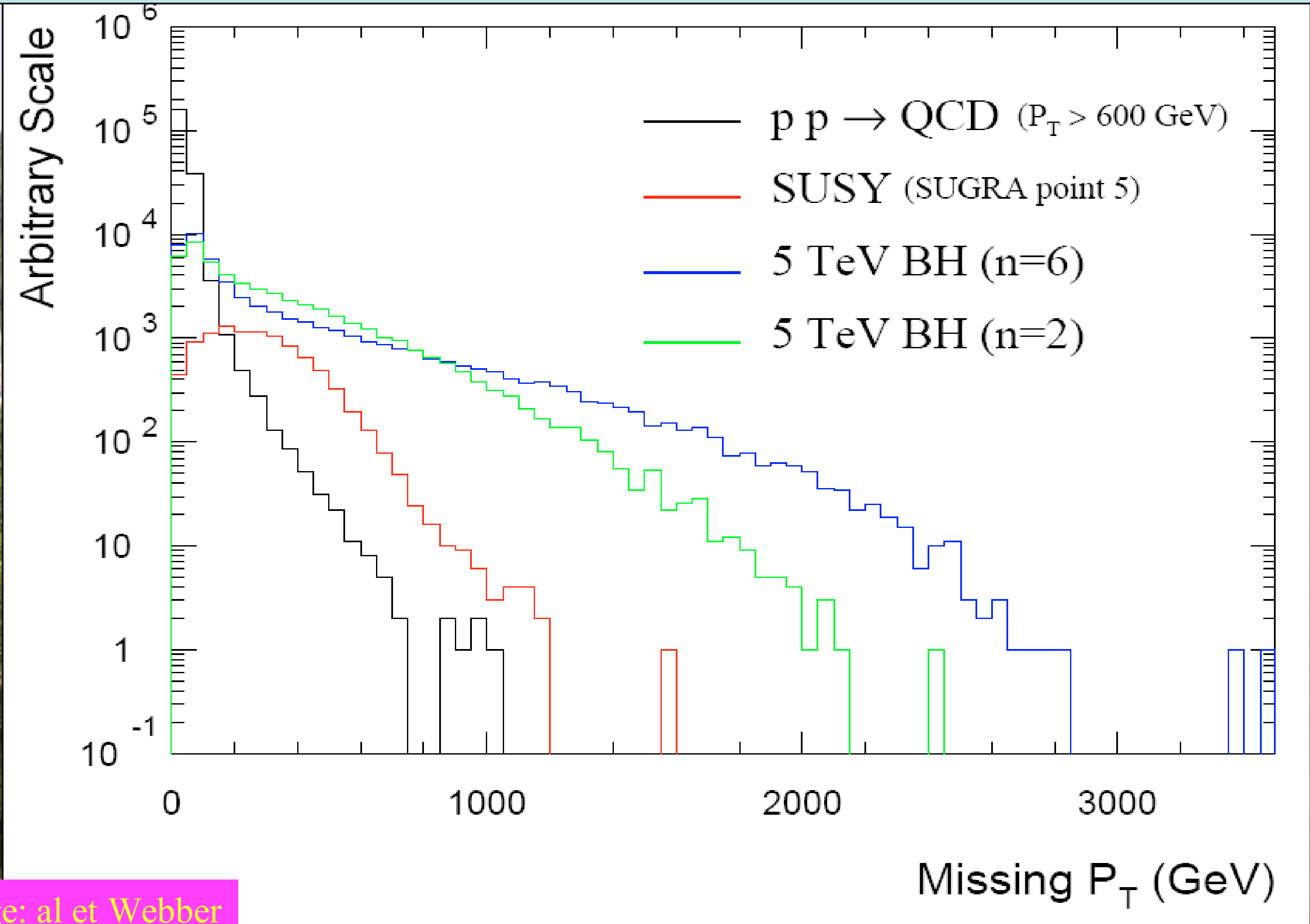
And if gravity becomes strong at the TeV scale …

Black Hole Production at LHC?



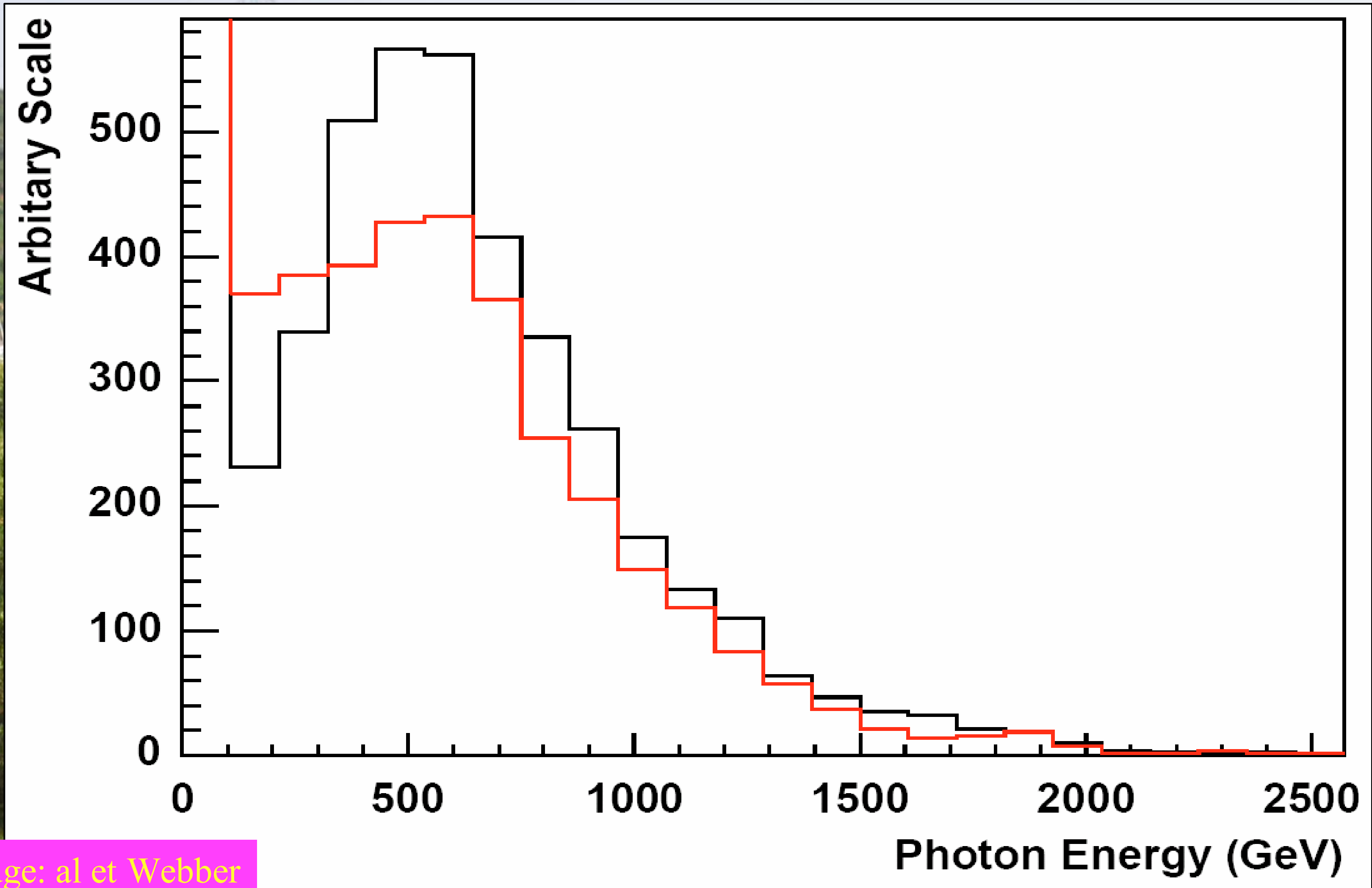
Multiple jets, leptons from Hawking radiation

Black Hole Production



Cambridge: al et Webber

Black Hole Decay Spectrum



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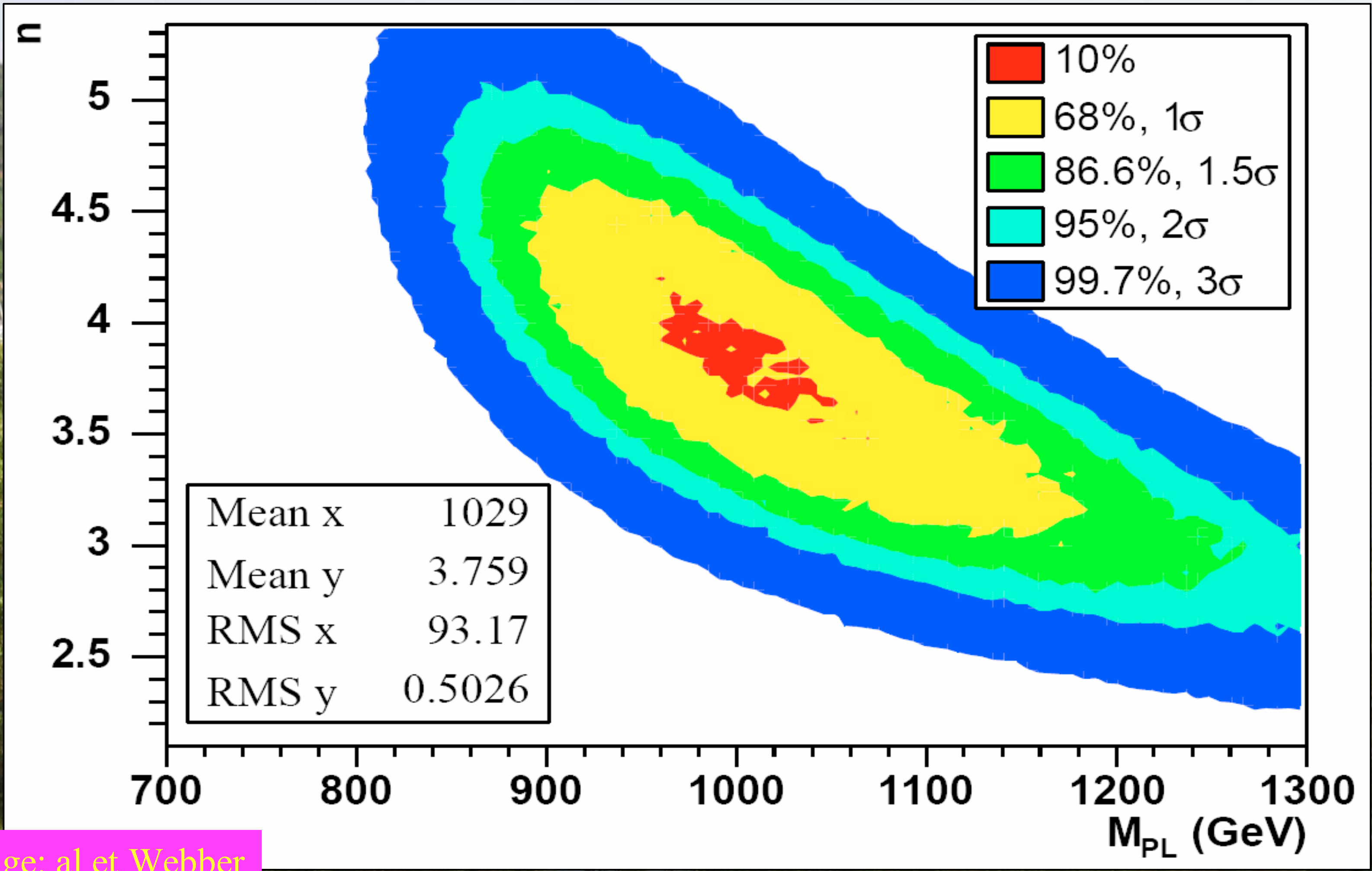
Measuring Extra Dimensions



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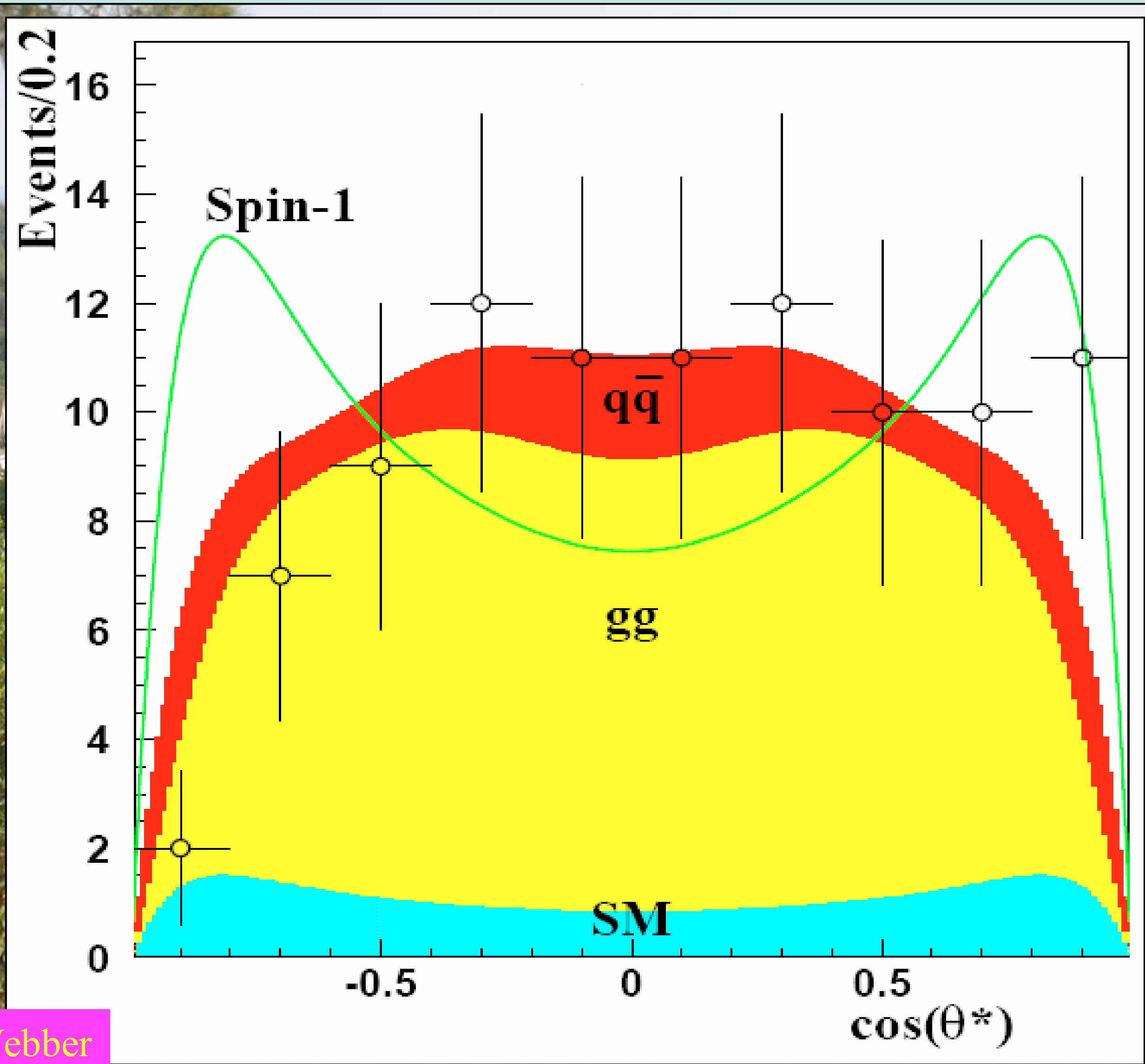
Identifying a Graviton Resonance



Cambridge: al et Webber

Summary

- There are good prospects for new physics discoveries with upcoming colliders
- Reasons to expect new physics @ TeV
  - Higgs, supersymmetry, extra dimensions (?)
- Distinctive experimental signatures
- The LHC @ CERN will open new energy range
- Linear e+e- colliders could explore in more detail
  - LHC will tell us the optimal energy