Physics Beyond the Standard Model at the LHC

G G Ross, Edinburgh 7th February 2007

- The Standard Model as an Effective Field Theory
- Beyond the Standard Model
- The LHC as a probe of BSM physics

The Standard model as an effective field theory…

$SU(3)\times SU(2)\times U(1): G_\mu^{a=1..8}, W_\mu^{a=1..3}, B_\mu$ $\qquad A_\mu \to A_\mu + \partial_\mu\theta$

$\begin{pmatrix} u \\ d \end{pmatrix}_L, u_R, d_R, \quad \begin{pmatrix} \nu \\ e \end{pmatrix}_L, \quad e_R, \nu_R(?)$ $\qquad f_R \to e^{i\alpha_R} f_R$

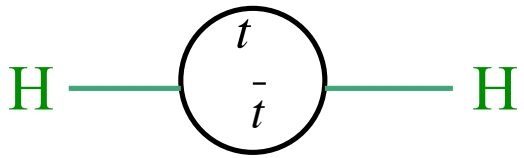
$\begin{pmatrix} H^+ \\ H^0 \end{pmatrix}$

$L^{SM}_{effective} \supset \cancel{M_A A_\mu A^\mu} + \cancel{m_f} \overline{f_L} f_R + M^2_H |H|^2$

The hierarchy problem

:

M_H not forbidden by SM symmetry:

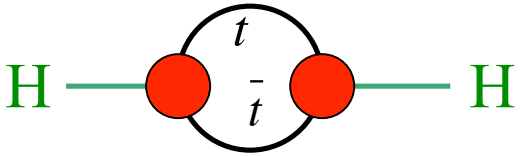


$M_H^2 \simeq \frac{h_t^2}{16\pi^2}\int_0^{\Lambda^2} dk^2 = \frac{h^2}{16\pi^2}\Lambda^2$ $\qquad \Lambda \le 1TeV$??

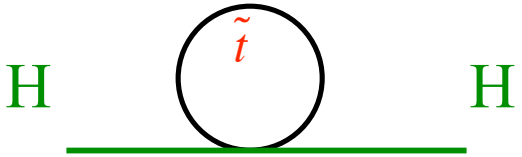
Solutions to the hierarchy problem

$\Lambda \leq 1TeV$??

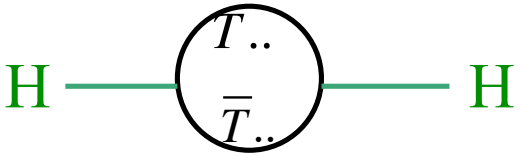
- Composite: technicolour, walking technicolor, strongly coupled Standard Model,…



- Symmetry protection — SUSY

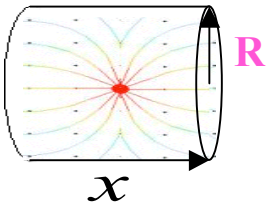


Goldstone: little Higgs



Double protection

- $\Lambda_{fundamental} \simeq 1TeV!$ — Xtra dimensions



$$V(r) = \frac{1}{M_*^{2+d} R^d} \frac{m_1 m_2}{r}, \quad D = 4 + d, \quad r \ll R$$

$$M^2_{Planck} = M_*^2 \left(M_* R \right)^d$$

(- Anthropic)

Split SUSY….

These ideas will be tested at the LHC:

$$\Lambda_{New\ physics} \leq 1TeV$$

- Composite: technicolour, walking technicolor…

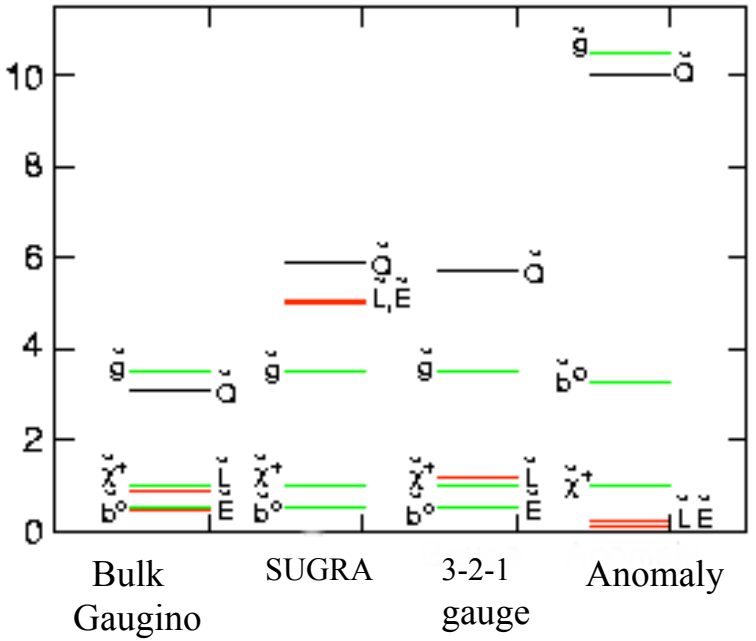
  New strong interaction, technifermions, composite structure to H, q, W…

- Symmetry protection

  SUSY SUSY states

Spectrum determined by soft SUSY breaking…many possibilities

FERMIONS	SUSY PARTNER (SCALARS)	
LEPTONS		
e	Selectron	$\tilde{e}$
μ	Smuon	$\tilde{\mu}$
τ	Stau	$\tilde{\tau}$
ν_e, ν_μ, ν_τ	Sneutrinos	$\tilde{\nu}_e, \tilde{\nu}_\mu, \tilde{\nu}_\tau$
QUARKS		
u, c, t	Squarks	$\tilde{u}, \tilde{c}, \tilde{t}$
d, s, b		$\tilde{d}, \tilde{s}, \tilde{b}$
GAUGE PARTICLES (BOSONS)	**SUSY PARTNER (FERMIONS)**	
$W^\pm, H^\pm$	Charginos	$\tilde{\chi}_1^\pm, \tilde{\chi}_2^\pm$
$\gamma, Z^0, h^0, H^0, A^0$	Neutralinos	$\tilde{\chi}_1^0, \tilde{\chi}_2^0, \tilde{\chi}_3^0, \tilde{\chi}_4^0$
g_i	Gluinos	$\tilde{g}_i$
Graviton G	Gravitino	$\tilde{G}$



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$$\Lambda_{New\ physics} \leq 1TeV$$

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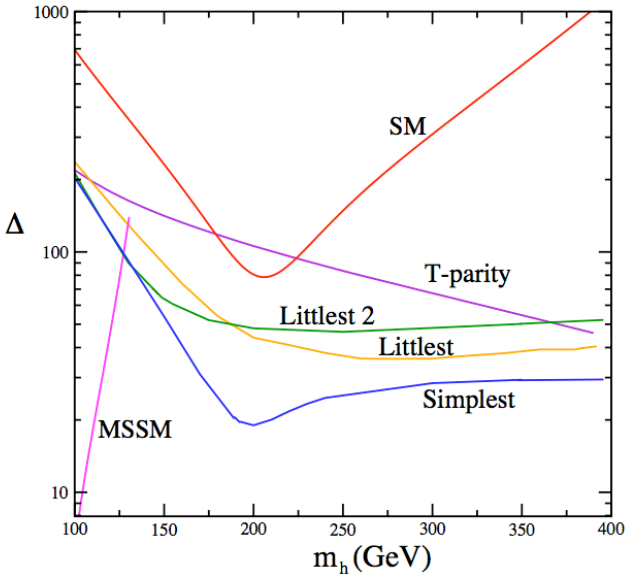
SUSY Little hierarchy problem

$$\Delta = \frac{a}{M_Z}\frac{\partial M_Z}{\partial a} \geq 20 \quad MSSM$$



Goldstone protection: little Higgs

New heavy T.. Quarks, New gauge bosons

Double protection - SUSY + Goldstone

$$SU(3)\times SU(2)_L \times SU(2)_R \times Z_2 \qquad +T,\ B,\ \tau_H,\ N \qquad \Delta = O(1)$$

$$\delta m_H^2 = -\frac{3}{8\pi^2} y_t^2 \left(m_{\tilde{t}}^2 + m_T^2\right)\ln\left(m_{\tilde{t}}^2 + m_T^2\right) - m_{\tilde{t}}^2 \ln(m_{\tilde{t}}^2) - m_T^2 \ln(m_T^2)$$

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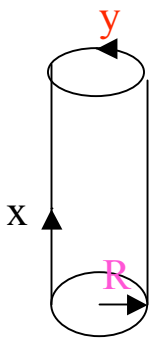
  Double protection - SUSY + Goldstone

- Xtra dimensions Kaluza Klein excitations

  String excitations

Kaluza Klein states

$0 \le y/R \le 2\pi$



e.g. 1 extra dimension compactified on a circle

$$\Phi(x,y) = \sum_{n=-\infty}^{\infty} \phi_n(x) e^{iny/R}$$

$\partial^2 \Phi = 0$ massless mode in 5D

$$(\partial_x^2 + \partial_y^2)\Phi(x,y) = \sum_{n=-\infty}^{\infty} (\partial_x^2 \phi_n(x) - \left(\frac{n}{R}\right)^2 \phi_n(x)) e^{iny/R} = 0$$

$R^4 \otimes S^1$

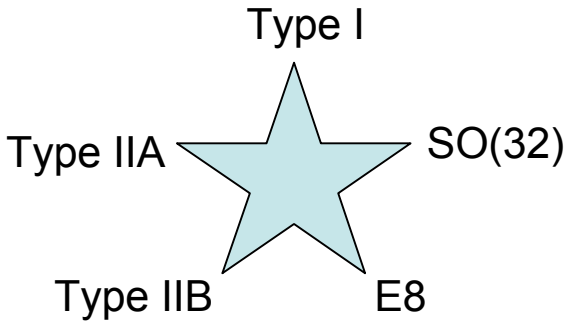
$$\partial_x^2 \phi_n(x) = m^2 \phi_n(x), \quad m^2 = \left(\frac{n}{R}\right)$$

KK tower

$$m \sim \frac{1}{R} = \left(\frac{M_*}{TeV}\right)^{\frac{n+2}{2}} 10^{\frac{12n-31}{n}} eV$$

$$= 10^{-3} eV, 20 keV, 7 MeV, 100 MeV; \quad n = 2, 4, 6, 8$$

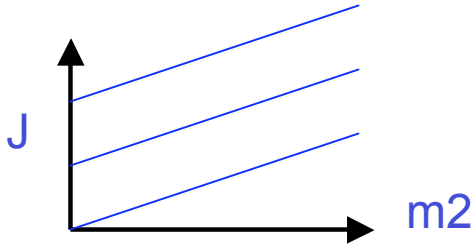
String Structure : 1st string revolution



Ghost free condition :

D=10 Fermionic (+SUSY)

String excitations : $m^2_{string} = \frac{J}{\alpha'} + C$

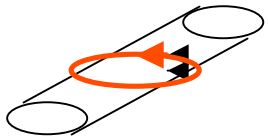


Compactification

D=10 → D=4 +(D=6)$_{\text{compactified – radius R}}$

Kaluza Klein & winding modes

$$m = \frac{n}{R} + p\frac{R}{\alpha'}$$



Green Schwarz

Gauge structure : restricted by anomaly cancellation

$$e.g.\ E_8 \otimes E_8 (D=10) \rightarrow E_8 \otimes E_6 (D=4) \otimes (N=1\ SUSY)$$

$$E_6 \subset SO(10),\ SU(5) \subset SU(3) \otimes SU(2) \otimes U(1)$$

+chiral structure for q, l ; multiplet structure determined by Calabi Yau
3 generation examples known

Supersymmetry

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  Double protection - SUSY + Goldstone

- Xtra dimensions Kaluza Klein excitations

  String excitations

(● Anthropic) Split SUSY…. Gluino stable on detector timescales

SUSY without the LHP

My preference : weak-scale SUSY

- stabilises the EW scale: $|m_F - m_B| < O(1$

- predicts a light Higgs $m_h < 130$ GeV

- accomodates heavy top quark

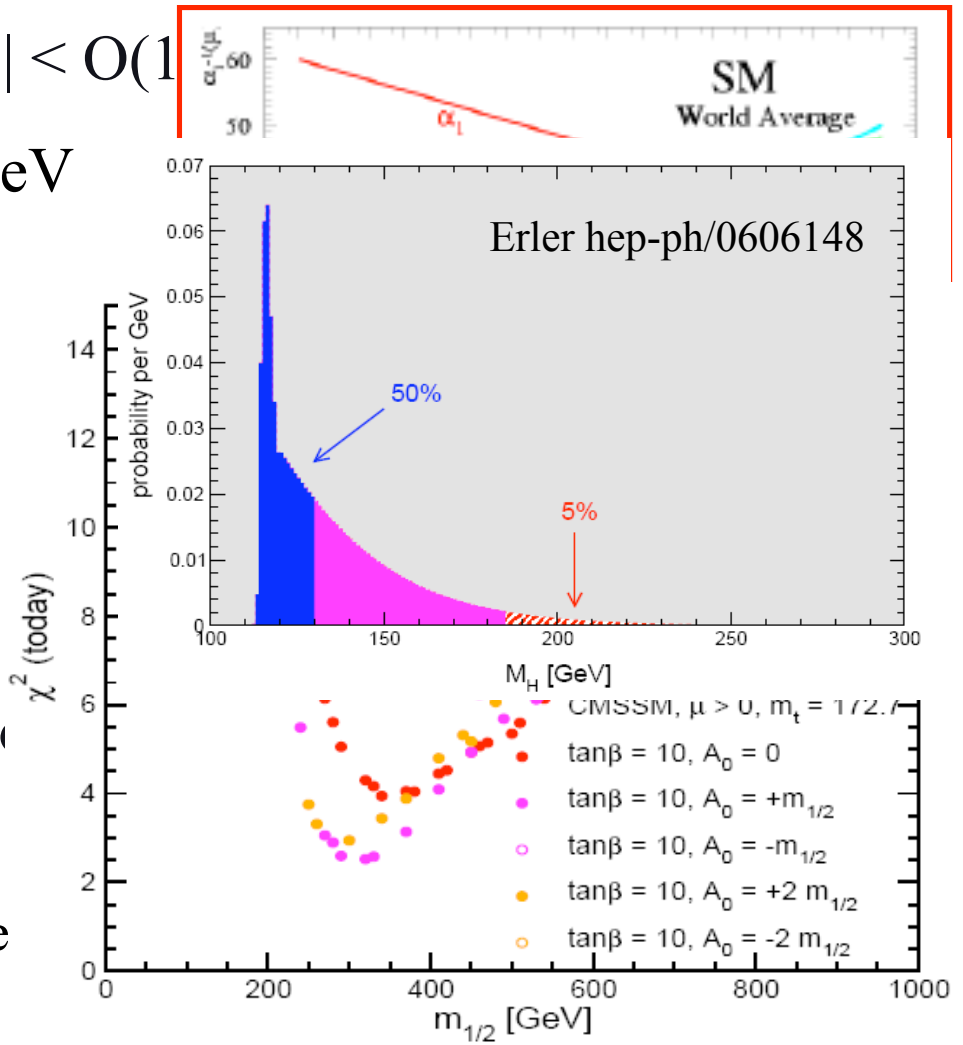
$$SU(3)\times SU(2)\times U(1) \rightarrow SU(3)\times U(1)$$

- predicts gauge unification

- dark matter candidate: neutralin

  - •WMAP constrains models, e.g.
  - • but relaxing models, opens up the parameter space

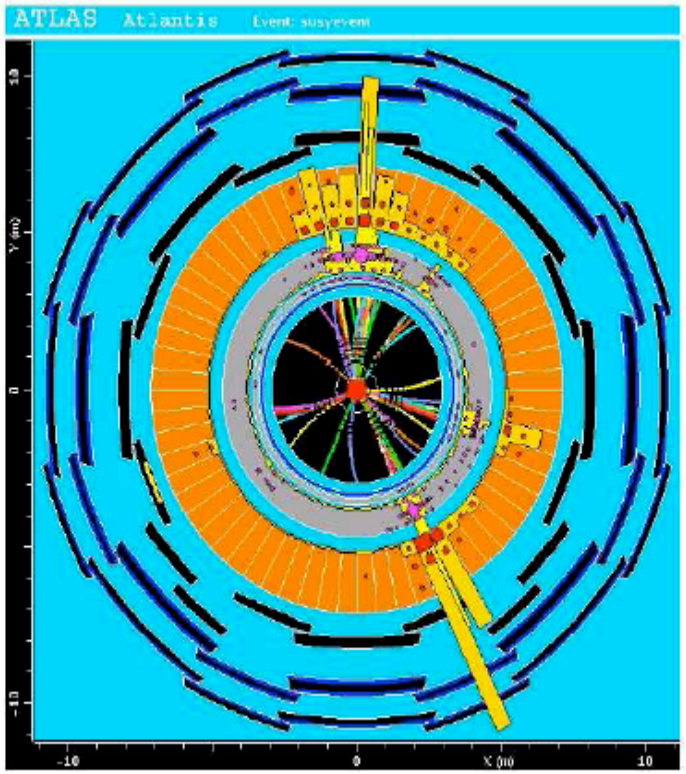
- consistent with EW data

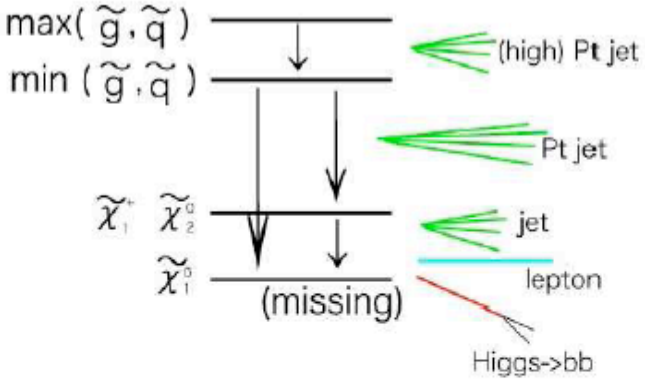


SUSY at the LHC

M_{sp}(GeV)	σ (pb)	Evts/yr
500	100	10^6-10^7
1000	1	10^4-10^5
2000	0.01	10^2-10^3

$10fb^{-1}$





Cascade decays

event topologies of SUSY

$\not{E}_T$ + High P_T jets + multi b-jets τ-jets leptons

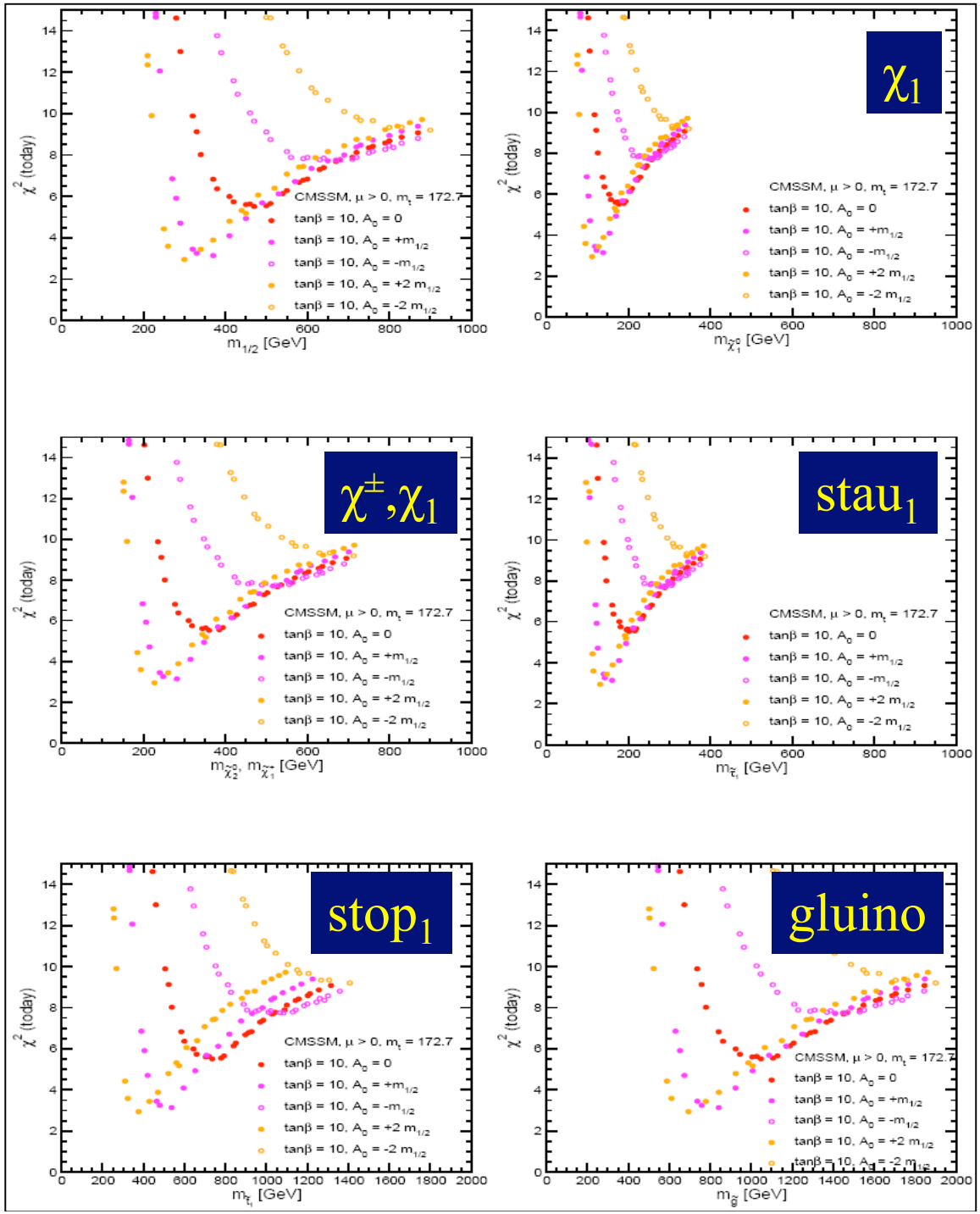
de Roeck

Main signal: lots of activity (jets, leptons, taus, missing E_T)

Needs good understanding of detector and SM processes

Global Fits to Present Data

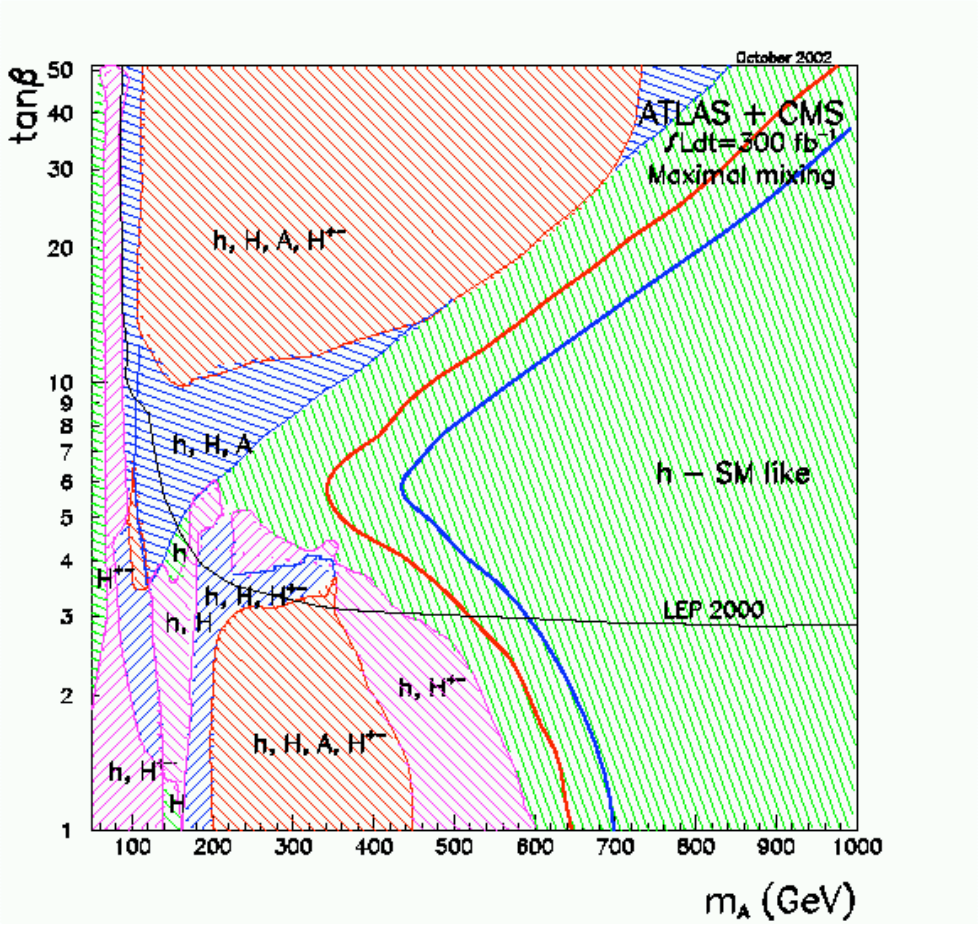
Preferred sparticle masses for tan β = 10



Ellis + Heinemeyer + Olive + Weiglein:

SUSY Higgs

5 Higgs h, H, A, $H^{\pm}$, A CP odd



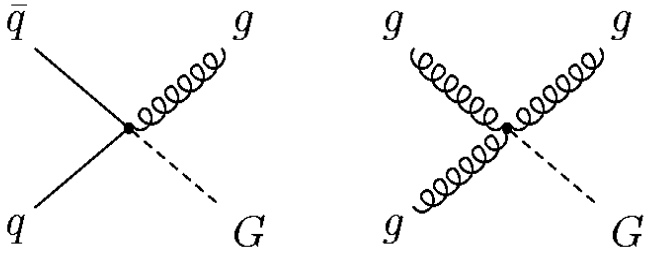
Split SUSY

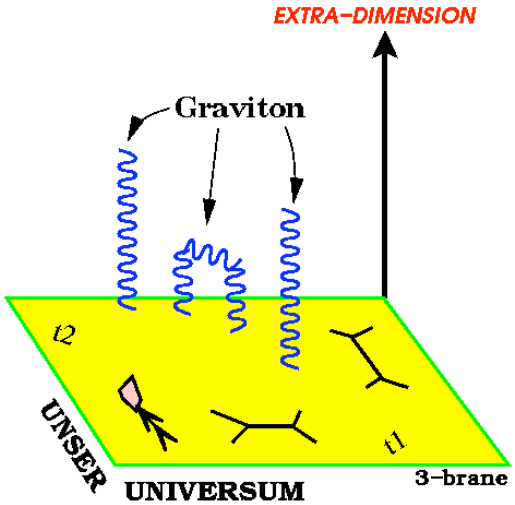
Arkani-Hamed, Dimopoulos
Romanino, Giudice

- The gluino is stable on detector time-scales
- It hadronizes in R-hadrons (-mesons, -baryons, -gluons)
- If charged: slow, highly ionizing track
- If neutral: missing energy, mild hadronic activity, triggered by single jet (gluon emission)
- Energy, charge, Baryon-number exchange
- Sensitivities:
  - Run II: ~200 GeV; LHC: 1 TeV (model independent)
  - Run II: ~400 GeV; LHC: 2.5 TeV (if charged)

  [Baer Cheung Gunion, Raby Tobe, Mafi Raby; recent studies: Kraan, Kilian Plehn Richardson Schmidt, Hewett Lillie Masip Rizzo]
- Also: gluinium [Cheung, Keung]; gluinos from cosmic rays (if seen give a lower limit on the SUSY-breaking scale) [Hewett Lillie Masip Rizzo, Anchordoqui Goldberg Nunez]

Xtra dimensions at the LHC





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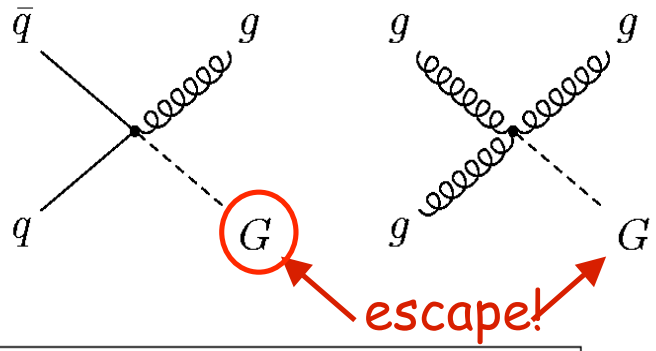
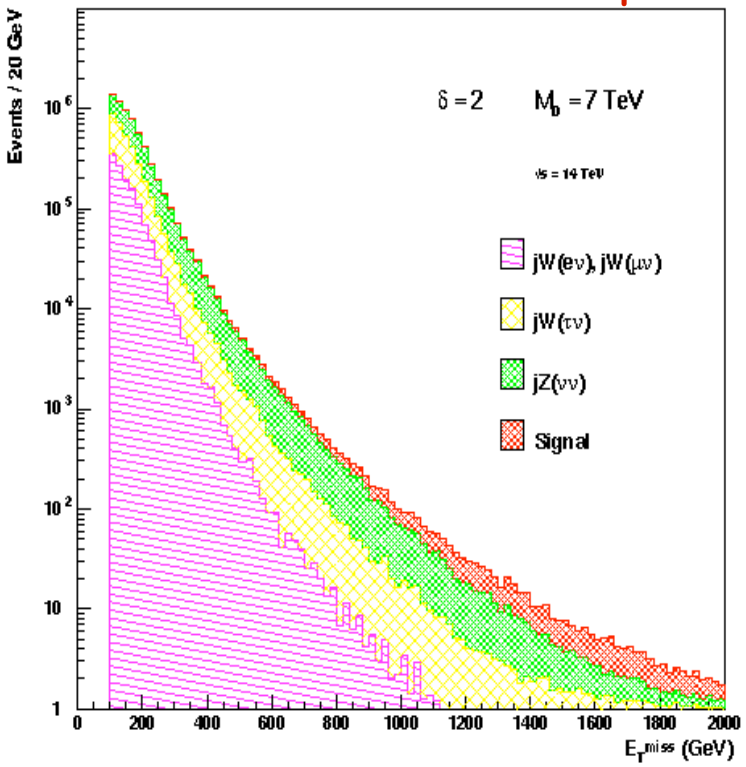


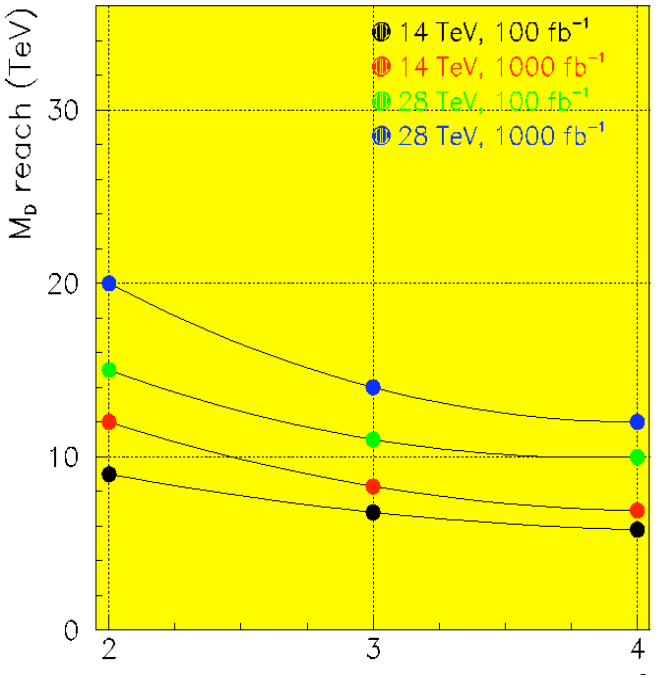
example

Graviton production…

Graviton escapes detection



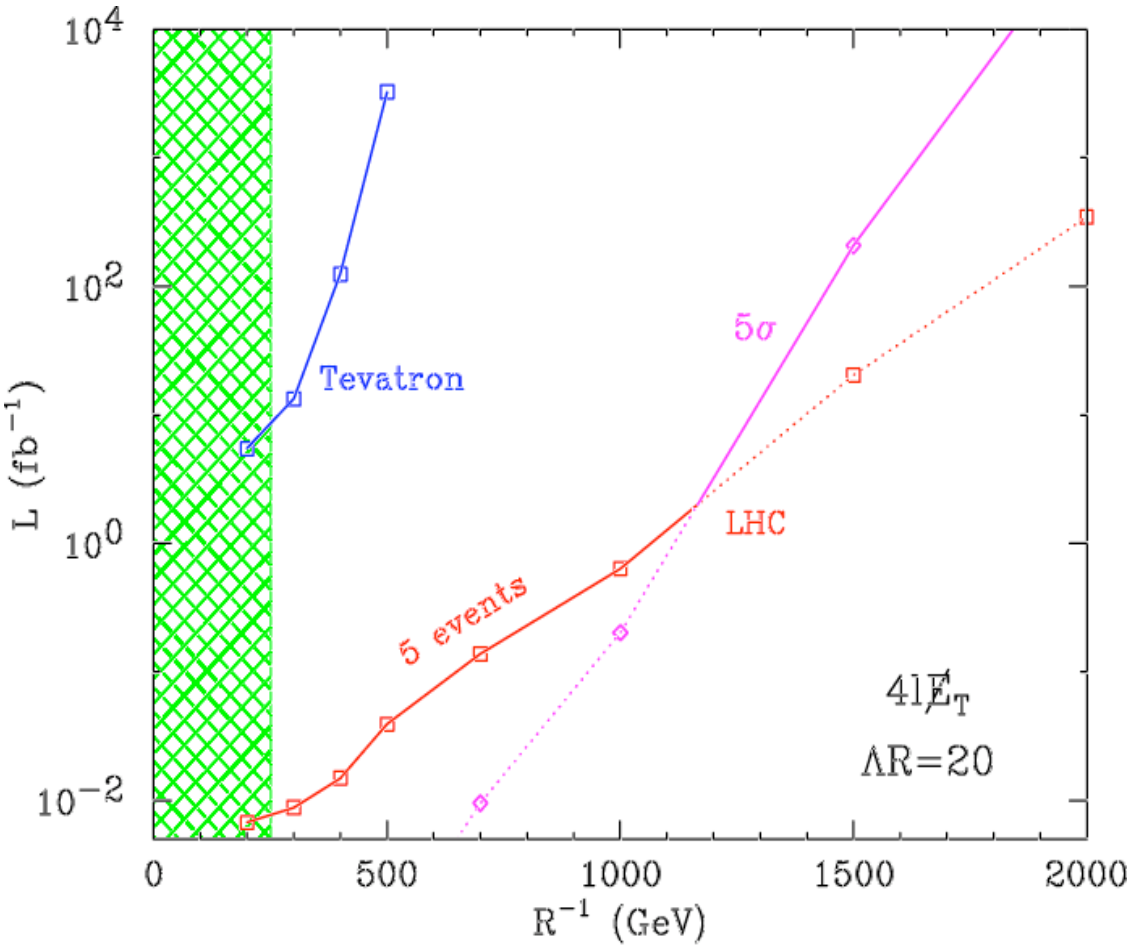
About 25% increase in reach



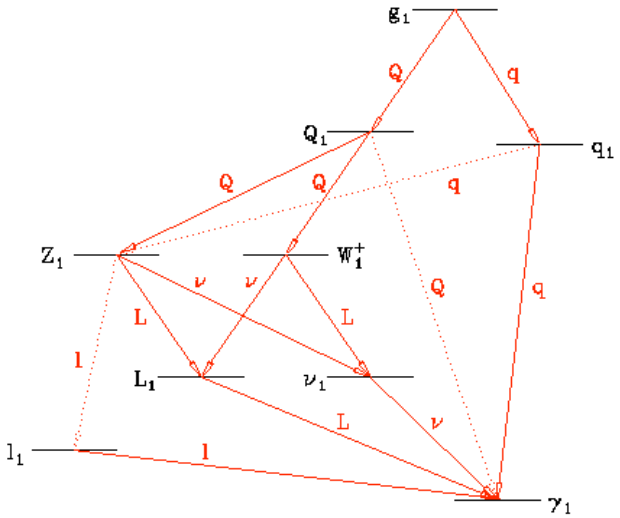
KK production - universal extra dimensions

Everybody in the bulk!

e.g. Cheng, Matchev, Schmaltz hep-ph/0205314



Search: e.g 4 leptons + E_T^{miss}



Spectrum very similar to SUSY spectrum with near degeneracy

Xtra dimensions at the LHC

Kaluza Klein production $q, l, W, ...$

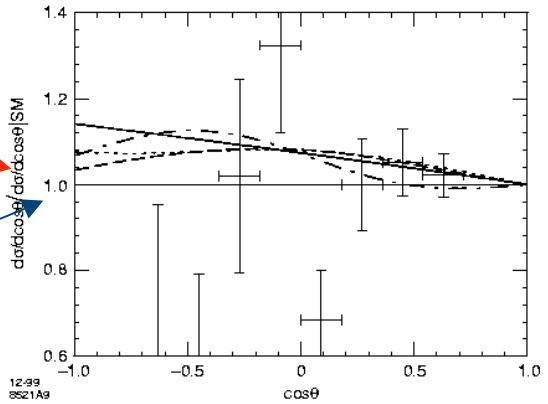
Characteristic signal …KK tc

TeV Strings

String Regge contribution may dominate over KK contribution

String model
M_S=410 GeV

KK exchange M_H=830 GEV

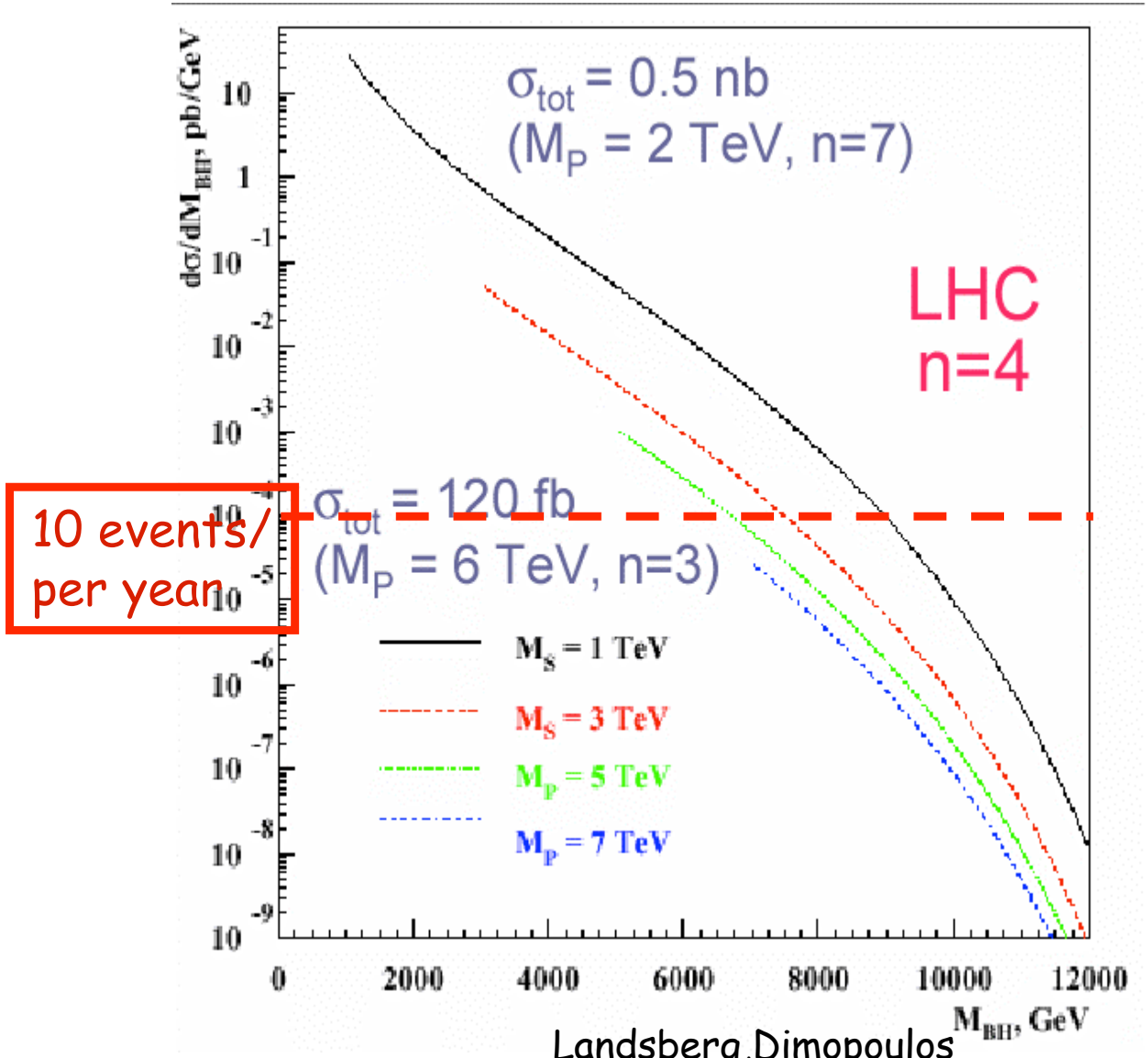


Bhabha

Cullen, Perelstein, Peskin

Cullen, Perelstein, Peskin

Black Holes



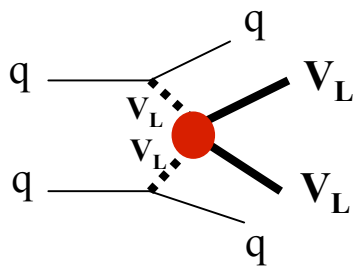
Landsberg,Dimopoulos

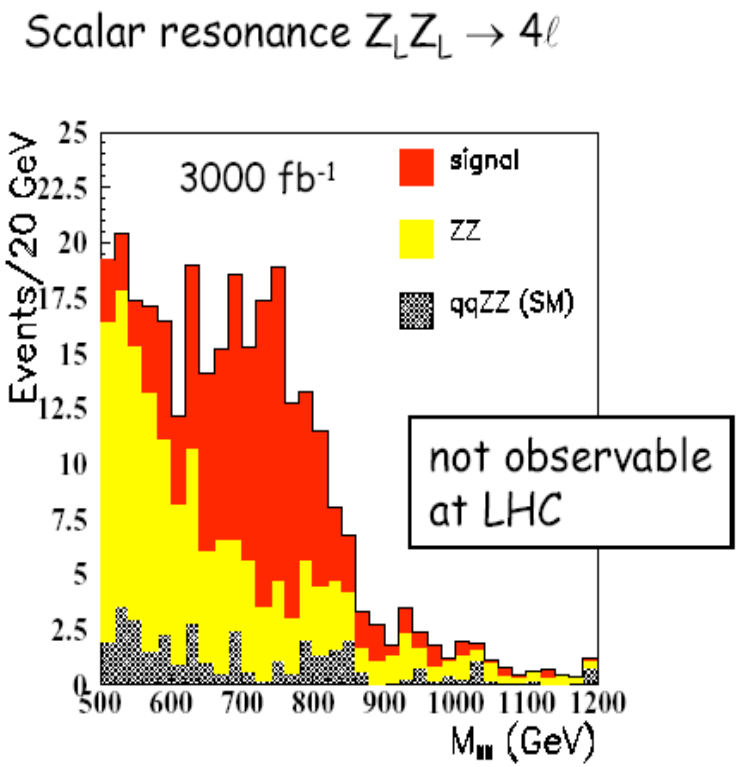
Extreme cases:

No Higgs!

Chanowitz, Gaillard

Perturbative unitarity violation:
Expect strong $V_L V_L$ scattering (resonant or non-resonant) at TeV scale





Extreme cases:

Double protection:

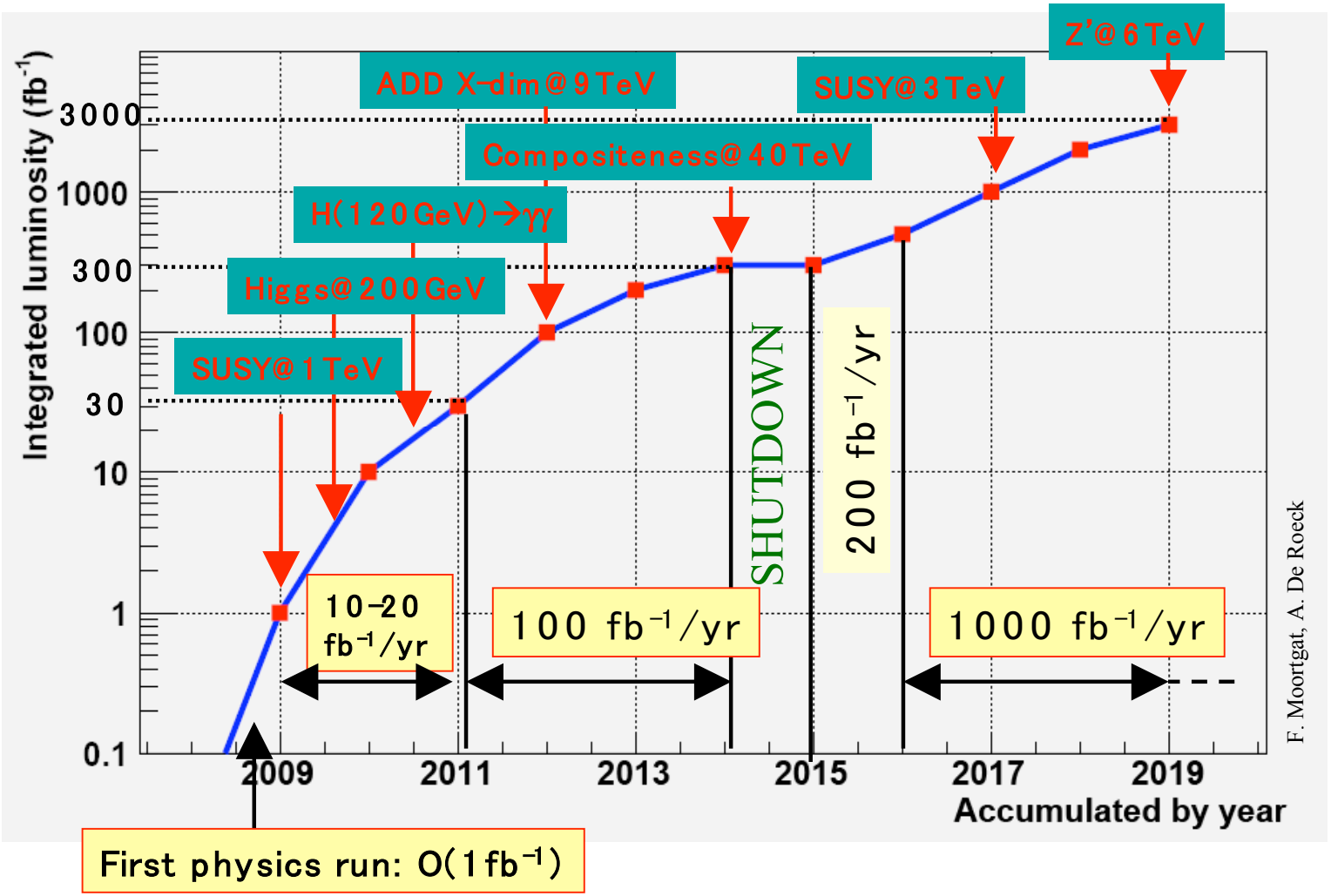
$$M_{SUSY} \to 10 TeV$$

$$M_T, M_{W_R} \leq 1 TeV$$

Berezhiani, Chanowski, Falkowsky,Pokorski, Schmaltz

Summary

LHC probes natural scale for BSM physics:



$\not{E}_T$ ... missing signals generic ....will need careful work to distinguish possibilities