PHYS 2356: Jour 8

UCL

Physique des particules élémentaires - aspects expérimentaux

Suive/complémente le PHYS 2263 (d)

La référence de base: D.H. Perkins *Introduction to High Energy Physics,* 4th edition +
PDG, *Review of Particle Physics,* les chapitres selectionnés à http://pdg.lbl.gov

+ les références supplémentaires:

Aitchison&Hey, Halzen&Martin, Ferbel(ed), Kleinknecht

Plan du cours

1.	Introduction/motivation	(3.2)
2.	Détecteurs modernes	(10.2)
3.	Collisionneurs à hautes énergies	(17.2)
4.	Systèmes des déclenchement et sélection	(24.2)
5.	Interactions e^+e^-	(3.3)
6.	Interactions *ep*	(10.3)
7.	Interactions *pp*	(17.3)
8.	Au-delà du modèle standard + physique des particules et cosmologie	(6.5)
9.	Cours d'exercices pratiques	(12.5)
10.	… et encore une fois	

Les masses des particules et le mécanisme de Higgs

$$\phi = (\phi_1 + i\phi_2)/\sqrt{2}$$

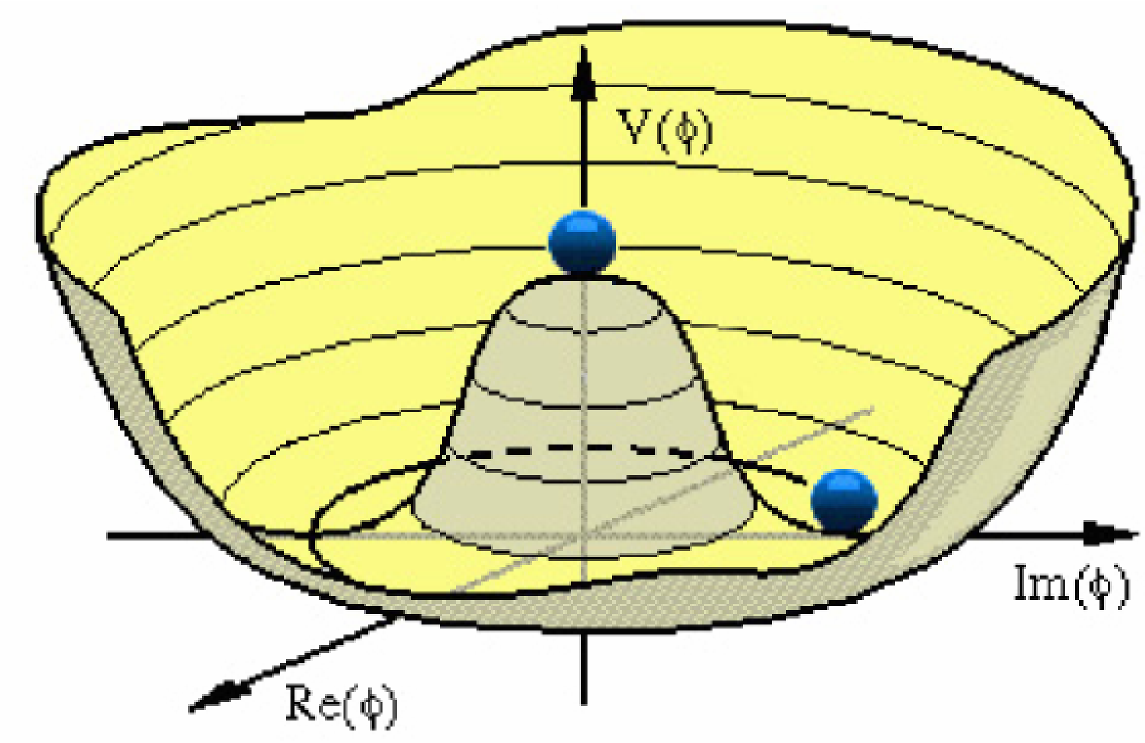
$$\mathcal{L} = (\partial_\mu \phi)^* (\partial^\mu \phi) - \underbrace{\left[\mu^2 \phi^* \phi - \lambda (\phi^* \phi)^2\right]}_{potentiel}$$

$\mu^2 > 0 \Rightarrow$

$m = \mu^2$ et l'état fondamentale est $\phi_1 = 0 = \phi_2$

$\mu^2 < 0 \Rightarrow$

l'état fondamentale est à $\phi \neq 0$; pas symétrique!



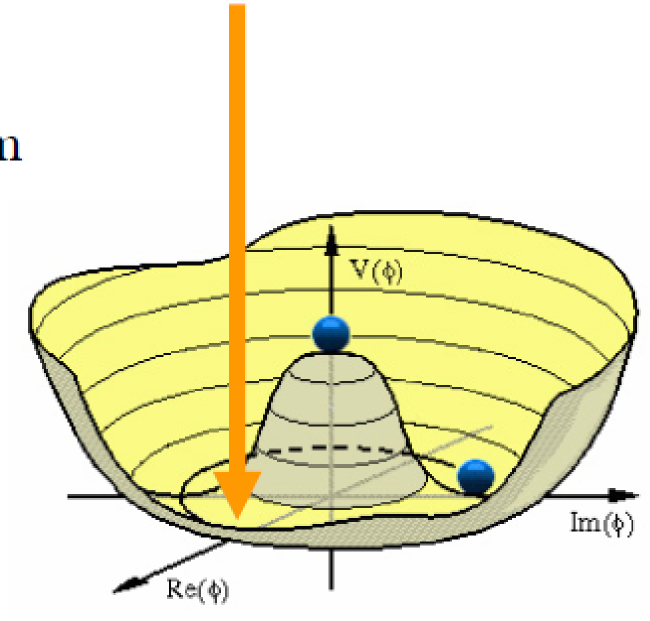
Invariance locale, le Higgs

Potentiel de Higgs :

$\mu^2 < 0; \quad \phi(x) = \eta(x) e^{-i\rho(x)}$; $\eta, \rho \in \mathbb{R}, \ \phi \in \mathbb{C}$

Invariance locale: on peut toujour choisi le minimum

$$\phi(x) = \frac{1}{\sqrt{2}}\left(v_0 + h(x)\right); \ h \text{ reel!}$$



$\Rightarrow$

$$\mathcal{L} = \tfrac{1}{2}\left(\partial_\mu h\right)\left(\partial^\mu h\right) + \underbrace{\tfrac{1}{2} g^2 v_0^{\,2}}_{\text{masse } m_A = g v_0} A_\mu A^\mu - \underbrace{\lambda v_0^{\,2}}_{m_\eta} h^2 -$$

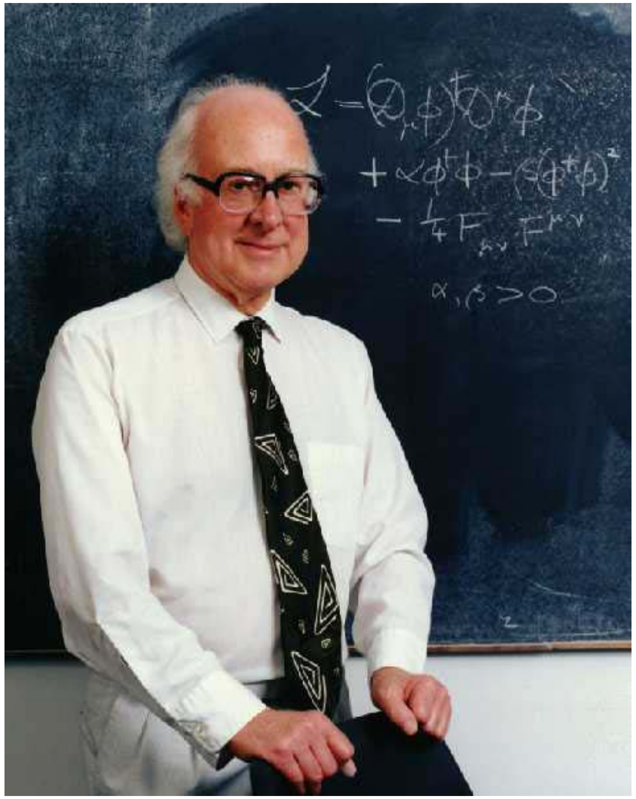
$$\underbrace{-\lambda v_0 h^3 - \lambda \frac{h^4}{4} + g^2 v_0 h A_\mu A^\mu + \tfrac{1}{2} g^2 h^2 A_\mu A^\mu - \tfrac{1}{2} F_{\mu\nu} F^{\mu\nu}}_{\text{Interactions entre les champs}}$$

A^μ ↔ est maintenant un champ avec masse! (pas le photon!)

η ↔ champ, Boson $\quad m_\eta = \sqrt{2\lambda \left| v_0^{\,2} \right|}$ masse de Higgs

Higgs search

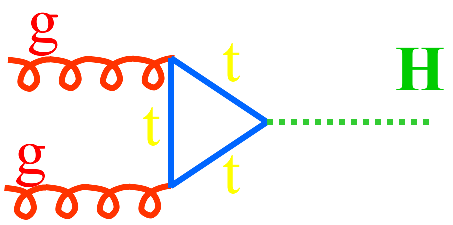
- The Higgs boson is the last SM particle still to be found
- It has a fundamental role in the SM to generate the masses of the W and Z bosons, and of the fermions
  - However one could imagine more complex mechanisms than the basic SM Higgs, pointing toward new physics



Prof. Peter Higgs

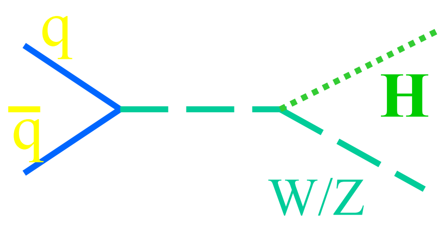
Higgs search @ Tevatron

- Light (100 – 200 GeV) Higgs production:
  - Higgs couplings prefer higher masses
  - Main production mechanisms:
    - Virtual top quark loops



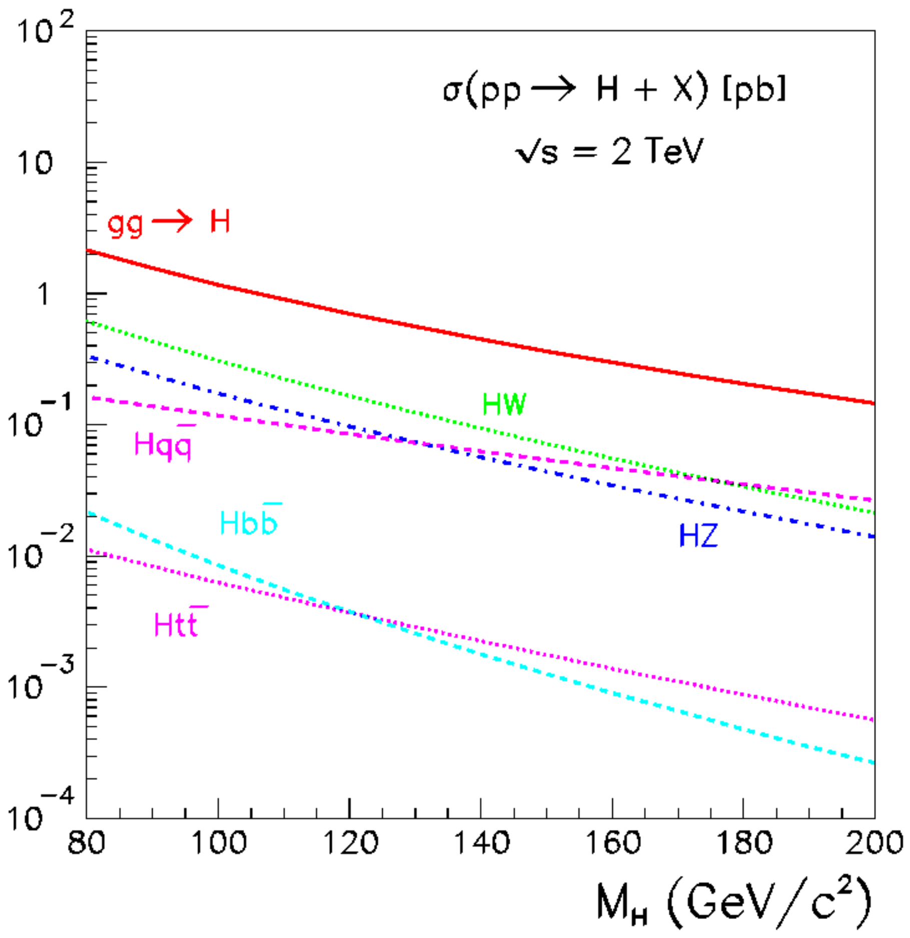
$\sigma \sim 1.0 - 0.1$ pb

    - Associated W/Z production



$\sigma \sim 0.5 - 0.02$ pb

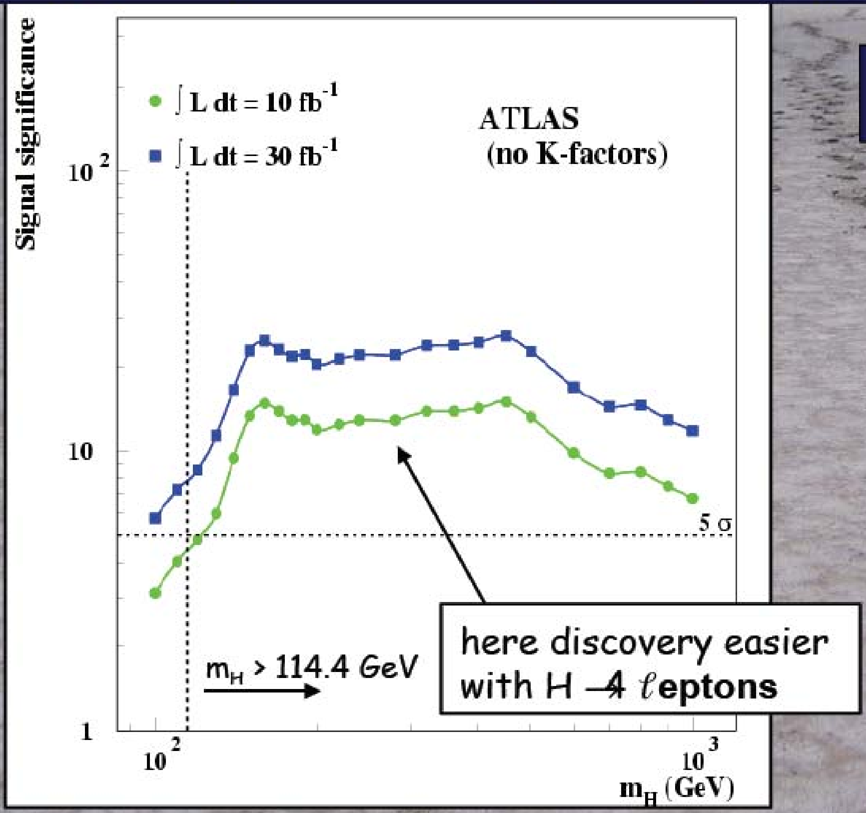
$\sigma_W \sim 2x\sigma_Z$



Cfr. Top quark $\sigma \sim 5$ pb

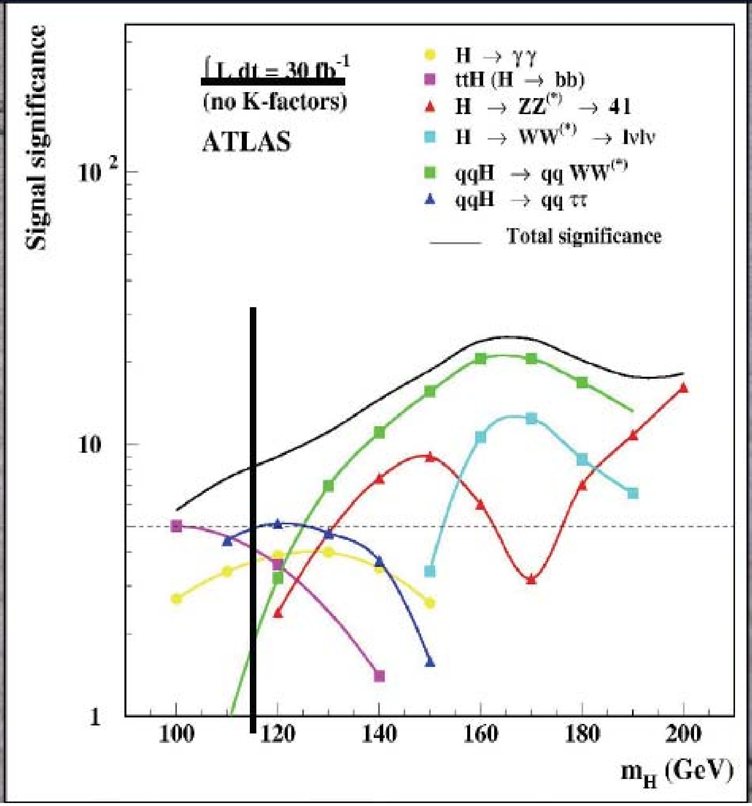
Higgs Detection at the LHC

The Higgs may be found quite quickly …

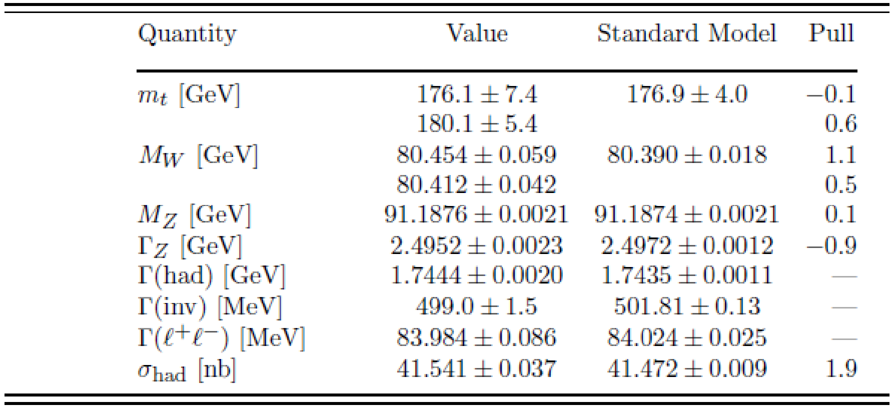


here discovery easier with H → 4 ℓeptons

… in several different channels



All data so far fits SM well…



Quantity	Value	Standard Model	Pull
m_t [GeV]	176.1 ± 7.4	176.9 ± 4.0	-0.1
	180.1 ± 5.4		0.6
M_W [GeV]	80.454 ± 0.059	80.390 ± 0.018	1.1
	80.412 ± 0.042		0.5
M_Z [GeV]	91.1876 ± 0.0021	91.1874 ± 0.0021	0.1
Γ_Z [GeV]	2.4952 ± 0.0023	2.4972 ± 0.0012	-0.9
$\Gamma(\text{had})$ [GeV]	1.7444 ± 0.0020	1.7435 ± 0.0011	—
$\Gamma(\text{inv})$ [MeV]	499.0 ± 1.5	501.81 ± 0.13	—
$\Gamma(\ell^+\ell^-)$ [MeV]	83.984 ± 0.086	84.024 ± 0.025	—
σ_{had} [nb]	41.541 ± 0.037	41.472 ± 0.009	1.9

10. Electroweak model and constraints on new physics

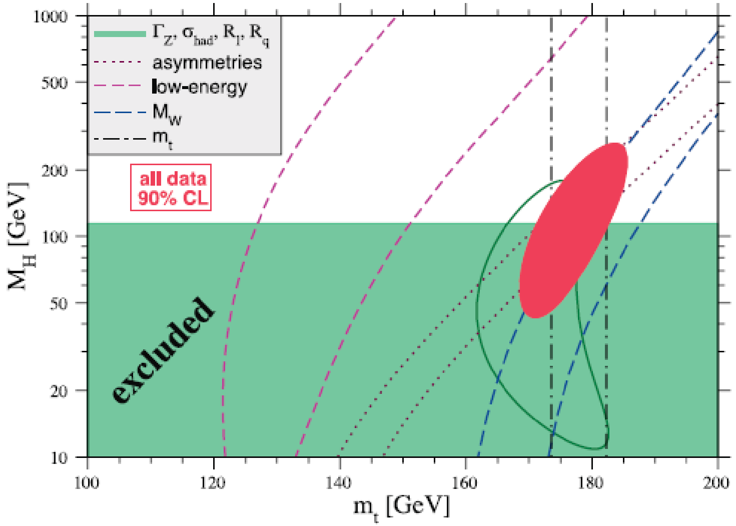
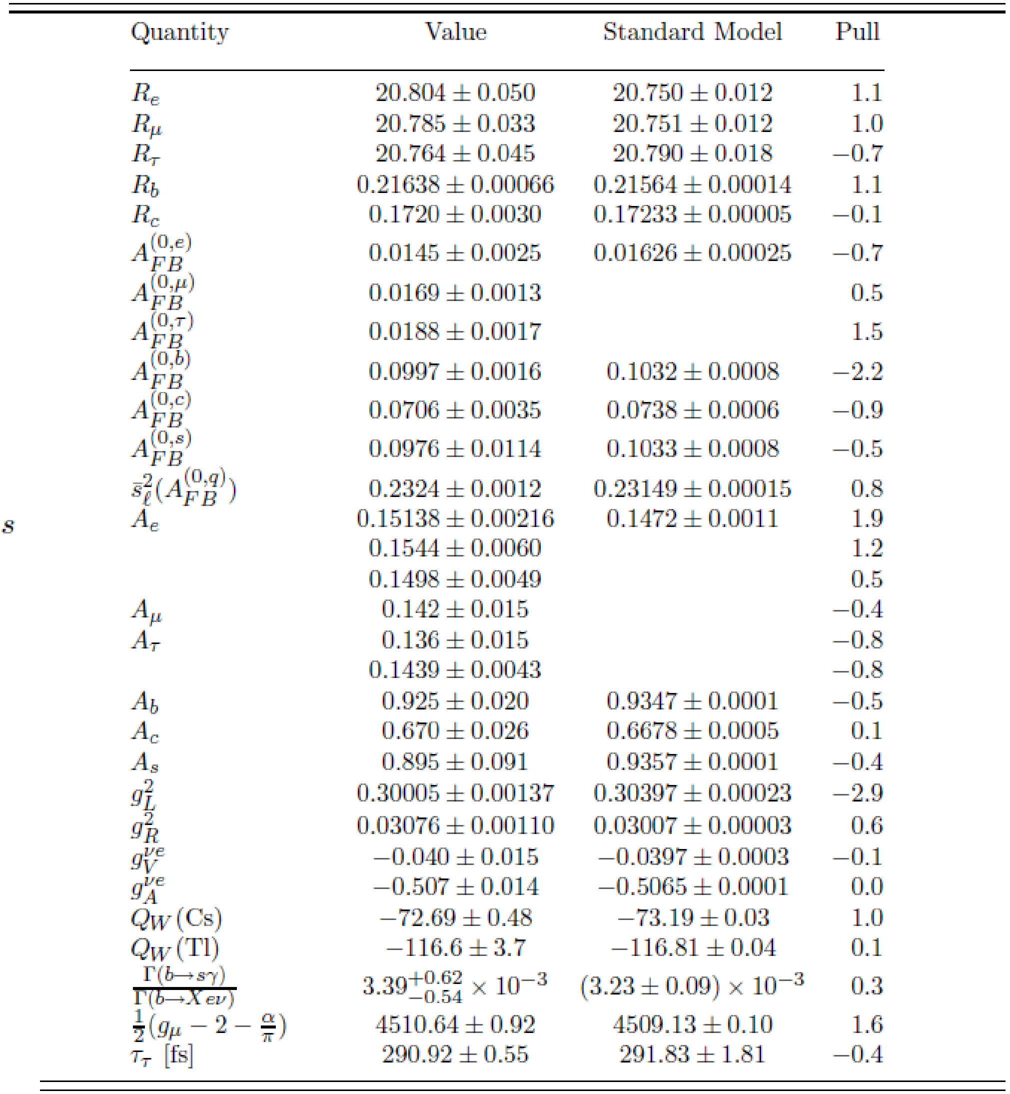


Figure 10.1: One-standard-deviation (39.35%) uncertainties in M_H as a function of m_t for various inputs, and the 90% CL region ($\Delta\chi^2 = 4.605$) allowed by all data. $\alpha_s(M_Z) = 0.120$ is assumed except for the fits including the Z-lineshape data. The 95% direct lower limit from LEP 2 is also shown See full-color version on color pages at end of book.



Quantity	Value	Standard Model	Pull
R_e	20.804 ± 0.050	20.750 ± 0.012	1.1
R_μ	20.785 ± 0.033	20.751 ± 0.012	1.0
R_τ	20.764 ± 0.045	20.790 ± 0.018	-0.7
R_b	0.21638 ± 0.00066	0.21564 ± 0.00014	1.1
R_c	0.1720 ± 0.0030	0.17233 ± 0.00005	-0.1
$A_{FB}^{(0,e)}$	0.0145 ± 0.0025	0.01626 ± 0.00025	-0.7
$A_{FB}^{(0,\mu)}$	0.0169 ± 0.0013		0.5
$A_{FB}^{(0,\tau)}$	0.0188 ± 0.0017		1.5
$A_{FB}^{(0,b)}$	0.0997 ± 0.0016	0.1032 ± 0.0008	-2.2
$A_{FB}^{(0,c)}$	0.0706 ± 0.0035	0.0738 ± 0.0006	-0.9
$A_{FB}^{(0,s)}$	0.0976 ± 0.0114	0.1033 ± 0.0008	-0.5
$\bar{s}_\ell^2(A_{FB}^{(0,q)})$	0.2324 ± 0.0012	0.23149 ± 0.00015	0.8
A_e	0.15138 ± 0.00216	0.1472 ± 0.0011	1.9
	0.1544 ± 0.0060		1.2
	0.1498 ± 0.0049		0.5
A_μ	0.142 ± 0.015		-0.4
A_τ	0.136 ± 0.015		-0.8
	0.1439 ± 0.0043		-0.8
A_b	0.925 ± 0.020	0.9347 ± 0.0001	-0.5
A_c	0.670 ± 0.026	0.6678 ± 0.0005	0.1
A_s	0.895 ± 0.091	0.9357 ± 0.0001	-0.4
g_L^2	0.30005 ± 0.00137	0.30397 ± 0.00023	-2.9
g_R^2	0.03076 ± 0.00110	0.03007 ± 0.00003	0.6
$g_V^{\nu e}$	-0.040 ± 0.015	-0.0397 ± 0.0003	-0.1
$g_A^{\nu e}$	-0.507 ± 0.014	-0.5065 ± 0.0001	0.0
$Q_W(\text{Cs})$	-72.69 ± 0.48	-73.19 ± 0.03	1.0
$Q_W(\text{Tl})$	-116.6 ± 3.7	-116.81 ± 0.04	0.1
$\frac{\Gamma(b \to s\gamma)}{\Gamma(b \to X e\nu)}$	$3.39^{+0.62}_{-0.54} \times 10^{-3}$	$(3.23 \pm 0.09) \times 10^{-3}$	0.3
$\frac{1}{2}(g_\mu - 2 - \frac{\alpha}{\pi})$	4510.64 ± 0.92	4509.13 ± 0.10	1.6
τ_τ [fs]	290.92 ± 0.55	291.83 ± 1.81	-0.4

What is wrong with SM anyway?

1. Gravity is not incorporated yet in the Standard Model

2. Many open questions in the Standard Model
   - Hierarchy problem: m_W (100 GeV) → m_{Planck} (10^{19} GeV)
   - Unification of couplings
   - Flavour / family problem
   - …..

All this calls for a ***more fundamental theory*** of which the Standard Model is a low energy approximation → **New Physics**

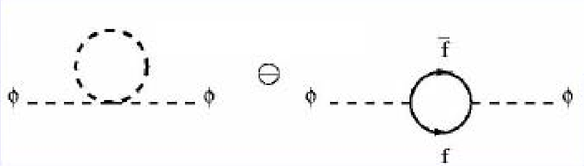
Candidate theories: Supersymmetry
Extra Dimensions
Technicolor
…….

All predict new physics at the TeV scale !!

Strong motivation for LHC mass reach ~ 3 TeV

Why Susy is so popular?

1. Quadratically divergent quantum corrections to the Higgs boson mass are avoided

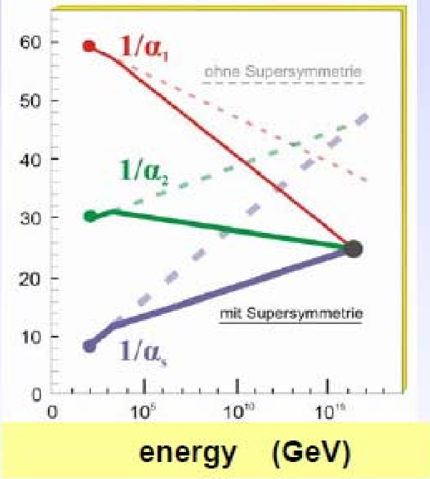


$$\Delta m_H = f(m_B^2 - m_f^2)$$

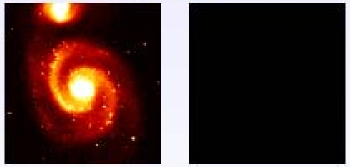
→ m_{SUSY} ~ 1 TeV

(Hierarchy or naturalness problem)

2. Unification of coupling constants of the three interactions seems possible



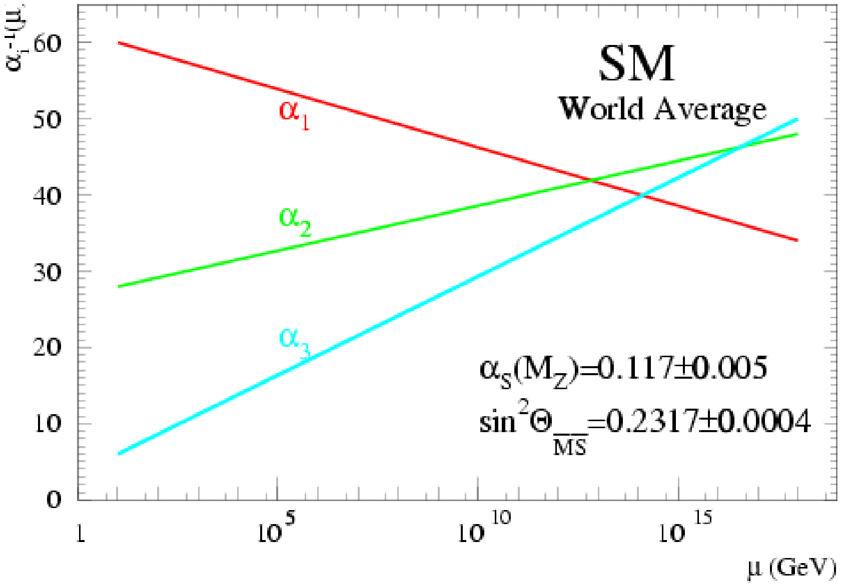
3. SUSY provides a candidate for dark matter,

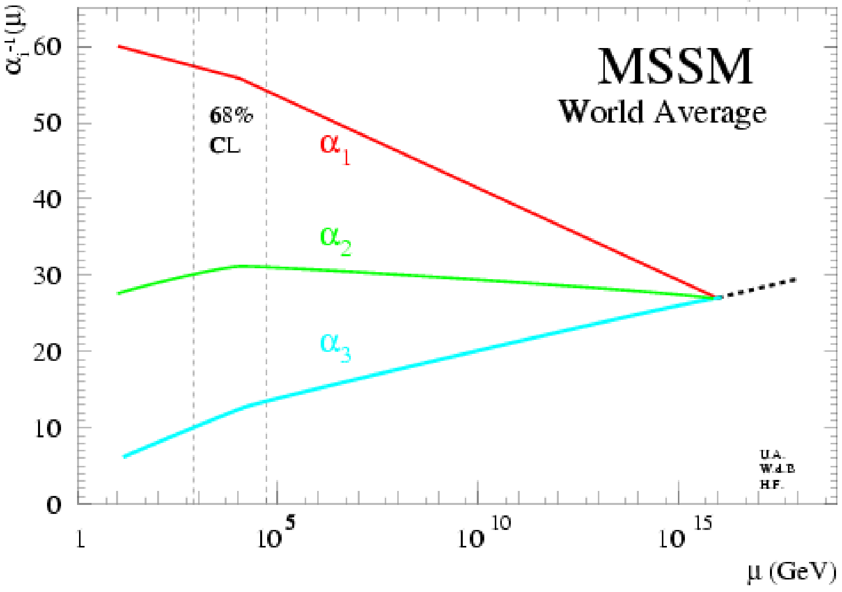


The lightest SUSY particle (LSP)

4. A SUSY extension is a small perturbation, consistent with the electroweak precision data

5. About half of the particles are already discovered !

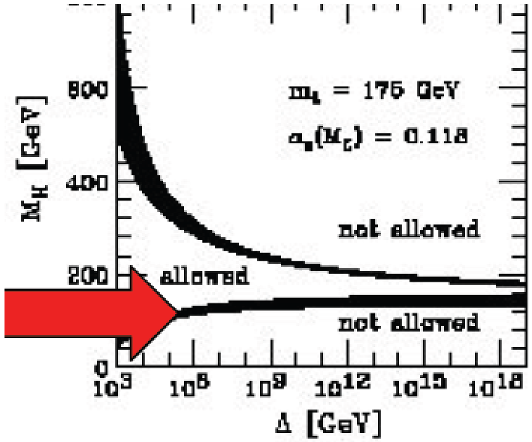




Inspiring observation:

Measured coupling constants unify at GUT scale in SUSY but not in SM,

..and stabilize Higgs potential at low masses:



…mais…

No experimental evidence for SUSY so far !

Either SUSY does not exist

OR

m_{SUSY} large (>> 100 GeV) → not accessible to present machines

LHC should say “final word” about (low energy) SUSY since theory predicts $m_{SUSY} \leq$ a few TeV

The Minimal Supersymmetric Standard Model (MSSM)

Symmetry between fermions (matter) and bosons (forces)

For each particle *p* with spin s, there exists a SUSY partner $\tilde{p}$ with spin s-1/2.

Ex. : q (s=1/2) → $\boxed{\tilde{q}}$ (s=0) squarks
g (s=1) → $\boxed{\tilde{g}}$ (s=1/2) gluino

Many new particles predicted !

Here : Minimal Supersymmetric extension of the Standard Model (MSSM)
which has minimal particle content

⬇

MSSM particle spectrum :

5 Higgs bosons : h, H, A, $H^{\pm}$

quarks → squarks $\tilde{u}, \tilde{d}$, etc.

leptons → sleptons $\tilde{e}, \tilde{\mu}, \tilde{\nu}$, etc.

$W^{\pm}$ → winos
$H^{\pm}$ → charged higgsino
} $\rightarrow \chi^{\pm}_{1}, \chi^{\pm}_{2}$
2 charginos

γ → photino
Z → zino
h, H → neutral higgsino
} $\rightarrow \chi^{0}_{1,2,3,4}$
4 neutralinos

g → gluino $\tilde{g}$

Masses not known. However charginos/neutralinos are usually lighter than squarks/sleptons/gluinos.

Present limits : m (sleptons, charginos) > 90-100 GeV LEP II
m (squarks, gluinos) > 250 GeV Tevatron Run 1
m (LSP, lightest neutralino) > ~ 45 GeV LEP II

Constraints on Supersymmetry

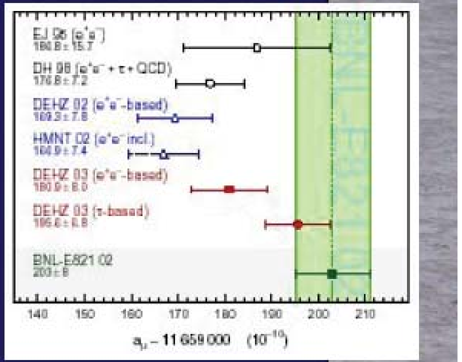
- Absence of sparticles at LEP, Tevatron

  selectron, chargino > 100 GeV

  squarks, gluino > 250 GeV

- Indirect constraints

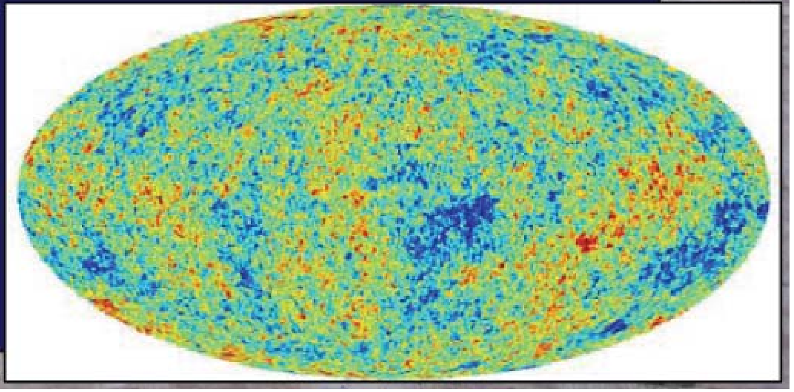
  Higgs > 114 GeV, b -> s γ $g_\mu - 2$



- Density of dark matter

  lightest sparticle χ:

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



SUSY phenomenology

There is a multiplicative quantum number:

R-parity $R_p = \begin{cases} +1 & \text{Standard Model particles} \\ -1 & \text{SUSY particles} \end{cases}$

which is conserved in most popular models (considered here).

Consequences:

- SUSY particles are produced in pairs
- Lightest Supersymmetric Particle (LSP) is stable.
  In most models LSP is also weakly interacting:

$\boxed{\text{LSP} \equiv \chi^0_1}$

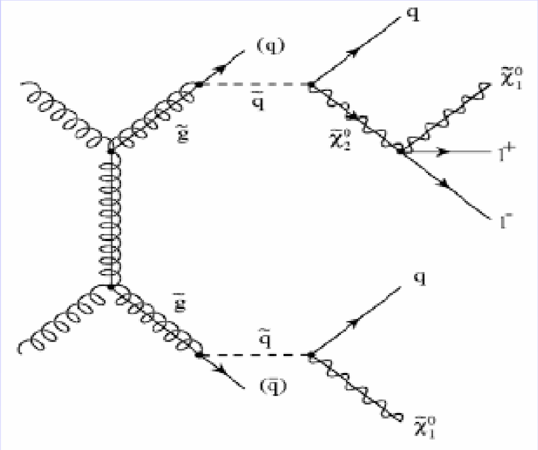
→ LSP is good candidate for cold dark matter
→ LSP behaves like a ν → escapes detection
→ E_T^{miss} (typical SUSY signature)

Search for Supersymmetry at the LHC

- If SUSY exists at the electroweak scale, a discovery at the LHC should be easy

- Squarks and Gluinos are strongly produced

  They decay through cascades to the lightest SUSY particle (LSP)



⇒ combination of Jets, Leptons, E_T^{miss}

1. Step: Look for deviations from the Standard Model
   Example: Multijet + E_T^{miss} signature

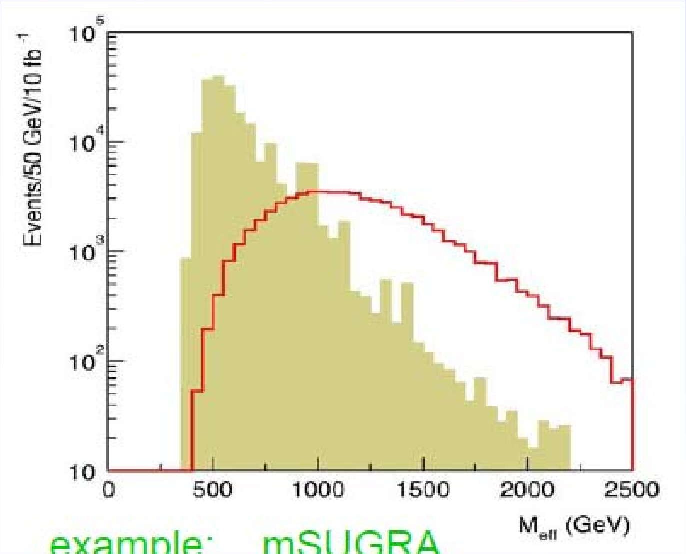
2. Step: Establish the SUSY mass scale use inclusive variables, e.g. effective mass distribution

3. Step: Determine model parameters (difficult)
   Strategy: select particular decay chains and use kinematics to determine mass combinations

K. Piotrzkowski, PHYS 2356

Squarks and Gluinos

- Strongly produced, cross sections comparable to QCD cross sections at same Q^2
- If R-parity conserved, cascade decays produce distinctive events: multiple jets, leptons, and E_T^{miss}
- Typical selection: $N_{jet} > 4$, $E_T > 100, 50, 50, 50$ GeV, $E_T^{miss} > 100$ GeV
- Define: $M_{eff} = E_T^{miss} + P_T^1 + P_T^2 + P_T^3 + P_T^4$ (effective mass)



example: mSUGRA
$m_0 = 100$ GeV, $m_{1/2} = 300$ GeV
$\tan\beta = 10$, $A_0 = 0$, $\mu > 0$

LHC reach for Squark- and Gluino masses:

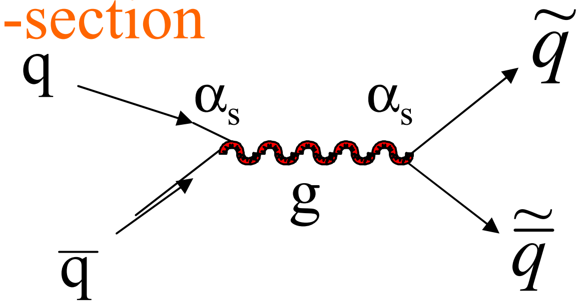
1 fb^{-1} ⇒ M ~ 1500 GeV
10 fb^{-1} ⇒ M ~ 1900 GeV
100 fb^{-1} ⇒ M ~ 2500 GeV

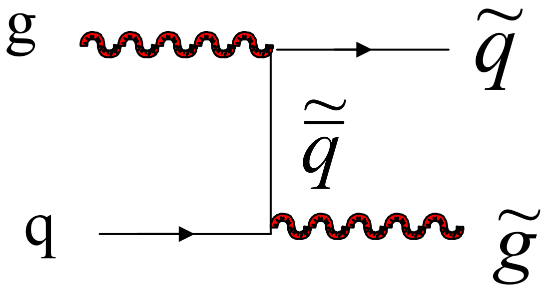
TeV-scale SUSY can be found quickly !

Production of SUSY particles at LHC

- Squarks and gluinos produced via strong processes → large cross-section

Ex.:

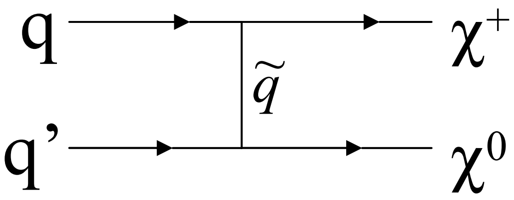




$m_{\tilde{q},\tilde{g}} \sim 1$ TeV $\sigma \sim 1$ pb → 10^4 events per year produced at low L

- Charginos, neutralinos, sleptons produced via electroweak processes → much smaller rate

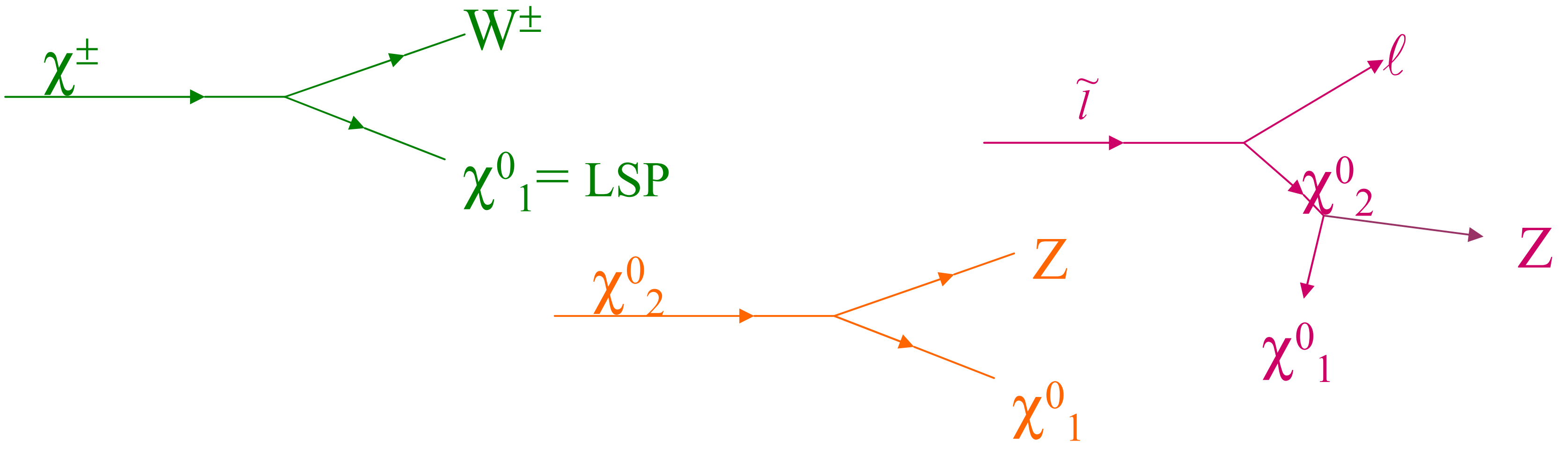
Ex.



$\sigma \approx$ pb $m_\chi \approx 150$ GeV

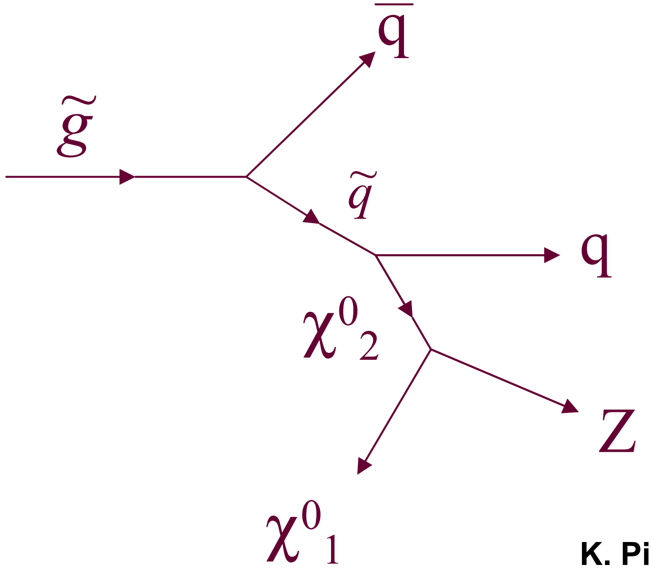
$\tilde{q}\,\tilde{q}$, $\tilde{q}\,\tilde{g}$, $\tilde{g}\,\tilde{g}$ are dominant SUSY processes at LHC
if kinematically accessible

Decays of SUSY particles : some examples



$\tilde{q}$, $\tilde{g}$ heavier → more complicated decay chains

Ex.



Cascade decays involving many leptons and /or jets + missing transverse energy (from LSP)
→ such spectacular signatures are easy to extract from the SM background

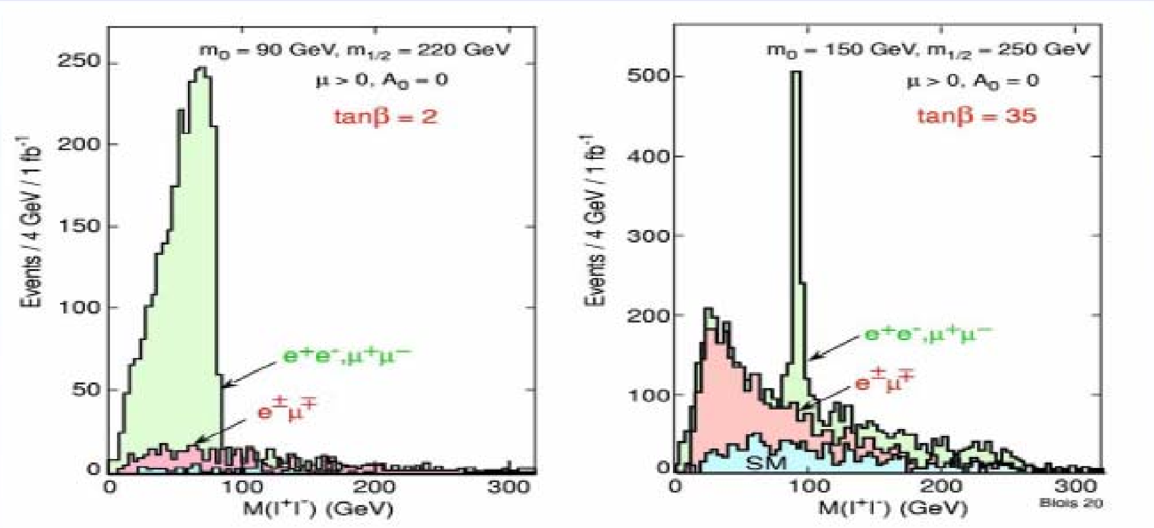
Determination of model parameters

- Invisible LSP ⇒ no mass peaks, but kinematic endpoints
  ⇒ mass combinations

- Simplest case: $\chi^0_2 \rightarrow \chi^0_1 \ell^+ \ell^-$ endpoint: $M_{\ell\ell} = M(\chi^0_2) - M(\chi^0_1)$

(significant mode if no $\chi^0_2 \rightarrow \chi^0_1 Z,\ \chi^0_1 h,\ \tilde{\ell}\ell$ decays)

- Require: 2 isolated leptons, multiple jets, and large E_T^{miss}

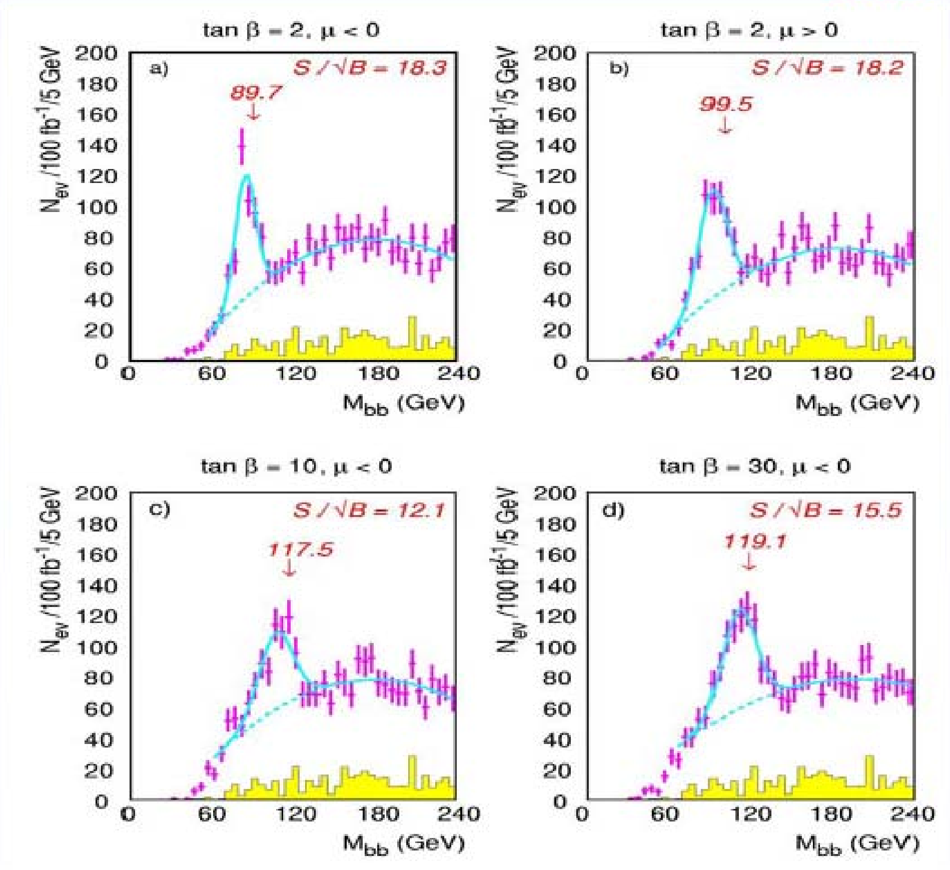


Modes can be distinguished

using shape of $\ell\ell$-spectrum

$h \rightarrow bb$:

CMS



important if $\chi^0_2 \rightarrow \chi^0_1 h$ is open;

bb peak can be reconstructed in many cases

Could be a Higgs discovery mode !

SM background can be reduced

by applying a cut on E_T^{miss}

Strategy in SUSY Searches at the LHC:

- Search for multijet + E_T^{miss} excess
- If found, select SUSY sample (simple cuts)
- Look for special features (γ's , long lived sleptons)
- Look for $\ell^\pm$, $\ell^+ \ell^-$, $\ell^\pm \ell^\pm$, b-jets, τ's
- End point analyses, global fit

Can LHC probe extra dimensions ?

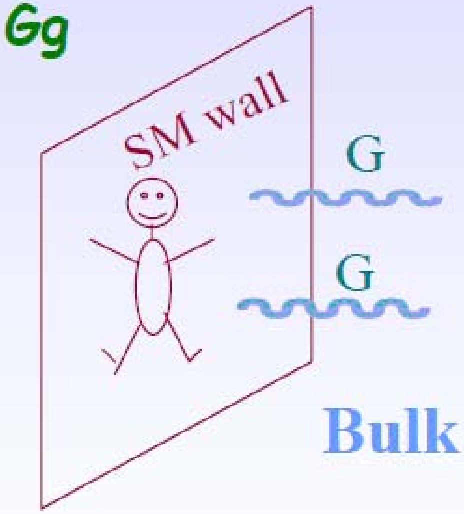
- Much recent theoretical interest in models with extra dimensions
  (Explain the weakness of gravity (or hierarchy problem) by extra dimensions)
- New physics can appear at the TeV-mass scale, i.e. accessible at the LHC
- **Gravitons** propagating in the extra dimensions will appear as massive states

Example: **Search for direct Graviton production**

$$gg \rightarrow gG \; , \; qg \rightarrow qG \; , \; q\bar{q} \rightarrow Gg$$

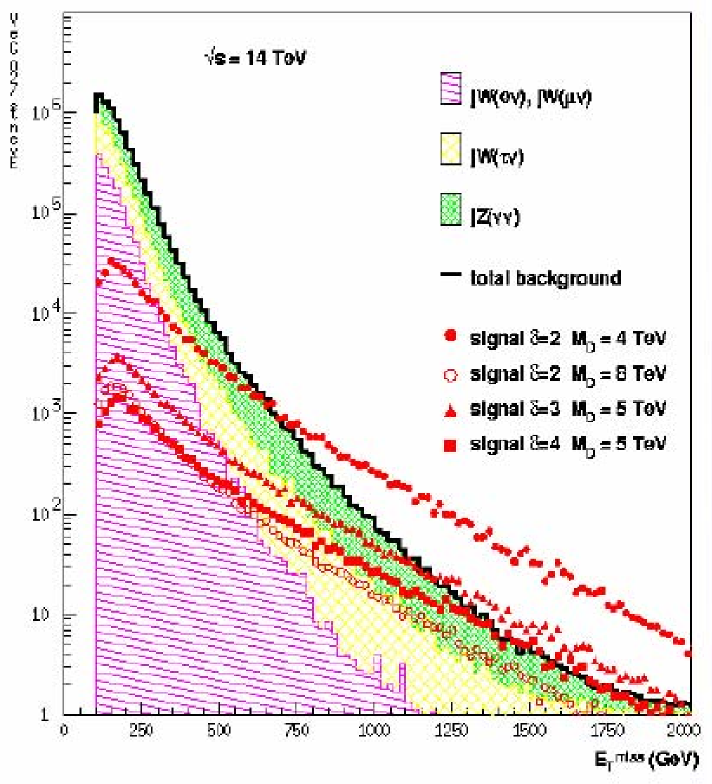
$$q\bar{q} \rightarrow G\gamma$$

$\Rightarrow$ **Jets or Photons with E_T^{miss}**



Search for escaping gravitons:

Jet + E_T^{miss} search:



Main backgrounds:
jet+Z(→νν), jet+W→jet+(e,μ,τ)ν

$$G_N^{-1} = 8\pi R^{\delta} M_D^{2+\delta}$$

δ : # extra dimensions
M_D = scale of gravitation
R = radius (extension)

M_D^{max}	**=**	**9.1,**	**7.0,**	**6.0 TeV**
	for			
δ	**=**	**2,**	**3,**	**4**
Extension:		**10^{-5},**	**10^{-10},**	**10^{-12} m**

„LHC experiments are also sensitive to this field of physics“ → robust detectors

More crazy ideas?

1. What about heavy new resonances decaying into lepton pairs

examples: W ´ and Z´

use again leptonic decay mode to search for them: $W' \rightarrow \ell \nu$
$Z' \rightarrow \ell \ell$

Increased sensitivity in the Tevatron Run II

2. What about Leptoquarks ?

Particles that decay into leptons and quarks
(violate lepton and baryon number; appear in Grand Unified theories)

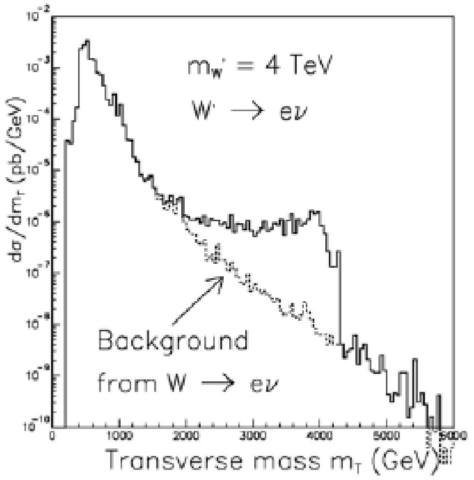
here: search for low mass Leptoquarks (TeV scale)

LHC reach for other BSM Physics

(a few examples for 30 and 100 fb^{-1})

	30 fb $^{-1}$	100 fb $^{-1}$
Excited Quarks $Q^* \rightarrow q\,\gamma$	M (q*) ~ 3.5 TeV	M (q*) ~ 6 TeV
Leptoquarks	M (LQ) ~ 1 TeV	M (LQ) ~ 1.5 TeV
$Z' \rightarrow \ell\ell$, jj $W' \rightarrow \ell\,\nu$	M (Z') ~ 3 TeV M (W') ~ 4 TeV	M (Z') ~ 5 TeV M (W') ~ 6 TeV
Compositeness (from Di-jet)	Λ ~ 25 TeV	Λ ~ 40 TeV

$\int \mathcal{L}dt = 100\ fb^{-1}$



Physics at the LHC

LHC : most difficult and ambitious high-energy physics project ever realized (human and financial resources, technical challenges, complexity, ….)

It has a crucial role in physics: can say the final word about

- -- SM Higgs mechanism
- -- low-energy SUSY and other TeV-scale predictions

↓

It will most likely modify our understanding of Nature