FIRST SCHOOL ON LHC PHYSICS

National Centre for Physics
Quaid-i-Azam University Campus
Islamabad

PHYSICS@LHC

Hafeez Hoorani

Physics@LHC

1. Searches for Higgs Boson
2. New Physics or Physics beyond the Standard Model (SM)
3. The Standard Model Physics
4. Physics of Quark-Gluon Plasma

What we want to know from LHC?

The “**Quantum Universe**” report gives nine key questions in three major areas.

I. Einstein’s dream

1. Undiscovered principles, new symmetries?
2. What is dark energy?
3. Extra space dimensions?
4. Do all forces become the same?

II. The Particle World

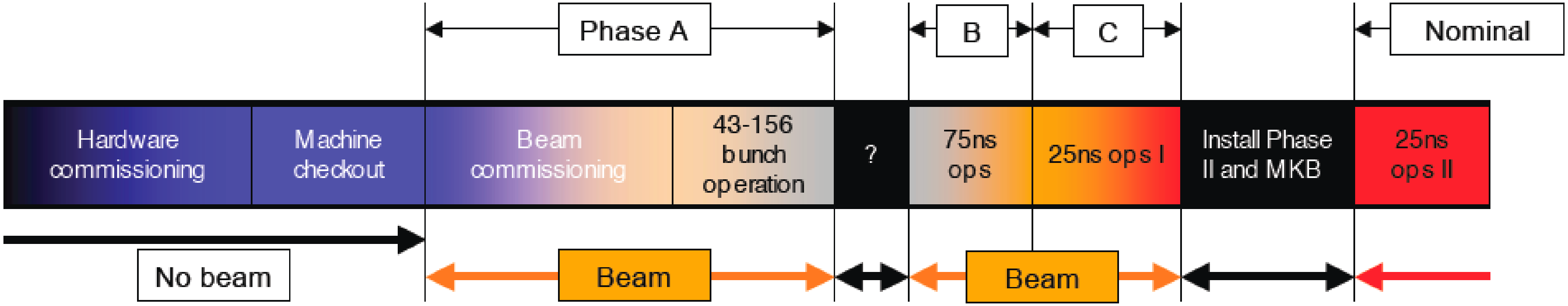
5. New particles?
6. What is dark matter?
7. What do neutrinos tell us?

III. Birth of Universe

8. How did the universe start?
9. Where is the antimatter?

The LHC will address at least eight of these.

Expectations of Luminosity Buildup



Phase A

B

C

Nominal

Hardware commissioning

Machine checkout

Beam commissioning

43-156 bunch operation

?

75ns ops

25ns ops I

Install Phase II and MKB

25ns ops II

No beam

Beam

Beam

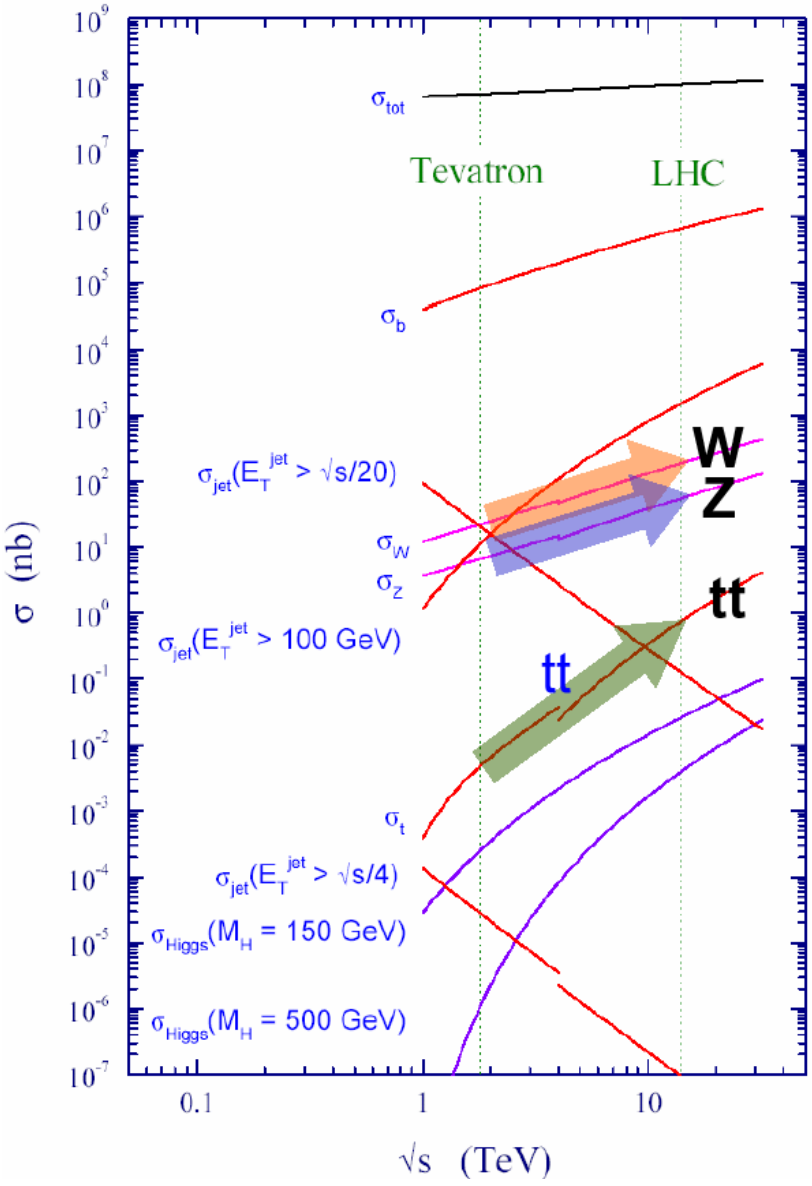
Parameter	Phase A	Phase B	Phase C	Nominal
k / no. bunches	43-156			
Bunch spacing (ns)	2021-566			
N (10^{11} protons)	0.4-0.9			
Crossing angle (μrad)	0			
$\sqrt{(\beta^*/\beta^*_{nom})}$	2			
σ^* (μm, IR1&5)	32			
L ($cm^{-2}s^{-1}$)	$6\times10^{30}-10^{32}$			
Year (?)	2008			

Bunches	β^*	I_b
1 x 1	18	10^{10}
43 x 43	18	3×10^{10}
43 x 43	4	3×10^{10}
43 x 43	2	4×10^{10}
156 x 156	4	4×10^{10}
156 x 156	4	9×10^{10}
156 x 156	2	9×10^{10}

Early Physics Programme

- Prior to beam: early detector commissioning
  - Readout & trigger tests, runs with all detectors (cosmics, test beams)
- Early beam, up to 10pb^{-1}:
  - Detector synchronization, alignment with beam-halo events, minimum-bias events. Earliest in-situ alignment and calibration
  - Commission trigger, start “physics commissioning”:
    - Physics objects; measure jet and lepton rates; observe W, Z, top
    - And, first look at possible extraordinary signatures…
- Physics collisions, 100pb^{-1}: measure Standard Model, start search
  - 10^6 W → l ν (l = e,μ); 2x10^5 Z→ll (l =e, μ); 10^4 ttbar→μ+X
    - Improved understanding of physics objects; jet energy scale from W → j j’; extensive use (and understanding) of b-tagging
    - Measure/understand backgrounds to SUSY and Higgs searches
  - Initial MSSM (and some SM) Higgs sensitivity
  - Early look for excesses from SUSY& Z′/jj resonances. SUSY hints (?)
- Physics collisions, 1000pb^{-1}: entering Higgs discovery era
  - Also: explore large part of SUSY and resonances at ~ few TeV

LHC v/s Tevatron



Huge stats for Standard Model signals. Rates@10^{33}

~10^8 events/1fb^{-1} W (200 Hz)
~10^7 events/1fb^{-1} Z (50 Hz)
~10^6 events/1fb^{-1} tt (1 Hz)

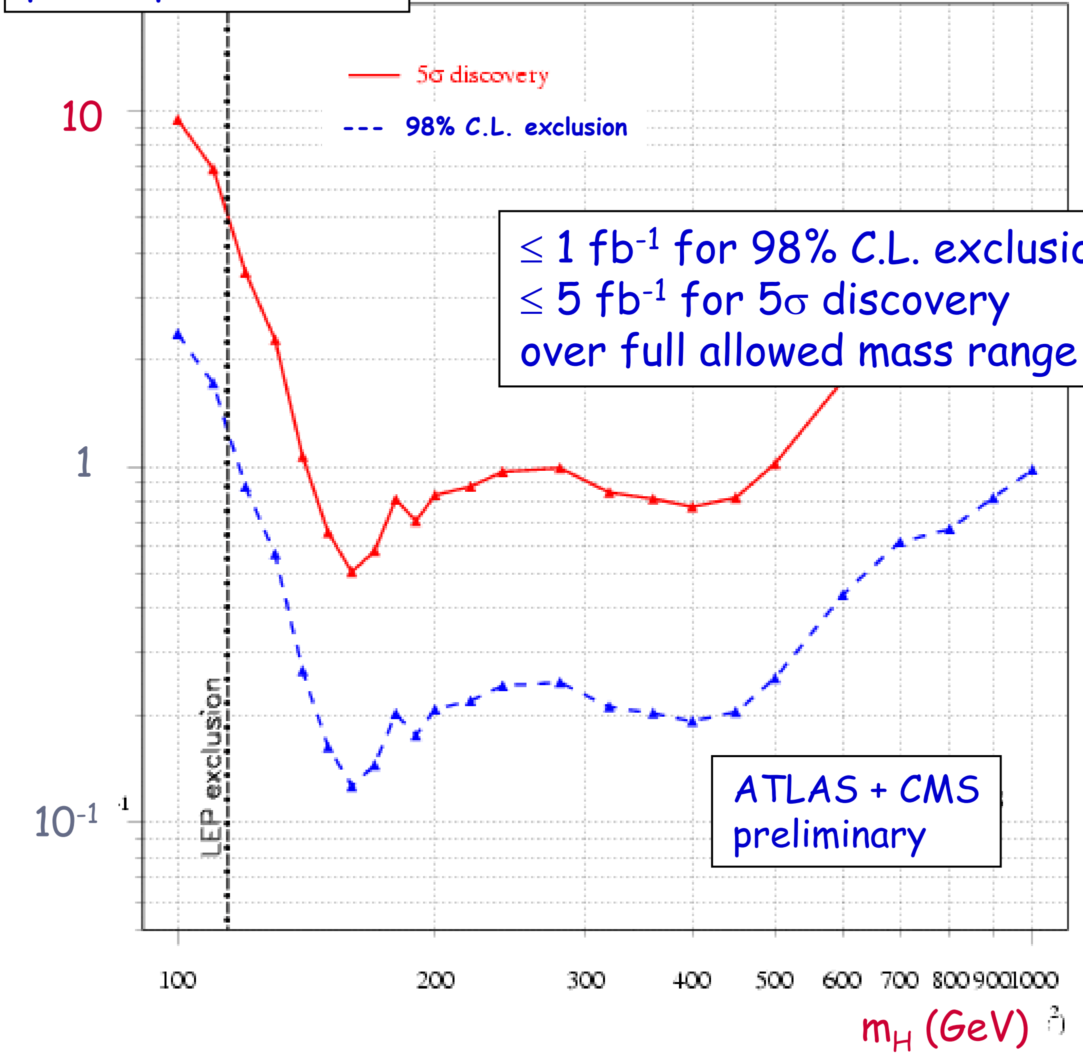
These will be used as control/ calibration samples for searches beyond the Standard Model

They can also be used to scrutinize the Standard Model further.

e.g. top sample is excellent for understanding lepton id. (incl. taus), jet corrections, jet energy scale, b tagging, ….

SM Higgs

Needed $\int L dt$ (fb^{-1})
per experiment



$\leq$ 1 fb^{-1} for 98% C.L. exclusion
$\leq$ 5 fb^{-1} for 5σ discovery
over full allowed mass range

ATLAS + CMS
preliminary

Standard Model Physics

- **QCD Studies**
  - Jet Studies
  - α_s and its running
  - Inclusive b production
- **Top Quark Physics**
  - Top pair production (σ, m_t, properties of top)
  - Single top (V_{tb},…)
- **Electroweak Physics**
  - W & Z cross-section
  - Drell-Yen
  - PDF, TGC
- **Studies of CP Violation:**
  - $B^o \rightarrow J/\psi\ K^o_s$, $B_c \rightarrow J/\psi\ \phi$
- **Calibration Channels**
  - $J/\psi \rightarrow \mu+\ \mu-$, $\psi(2s) \rightarrow \mu+\ \mu-$

Physics Studies at LHC

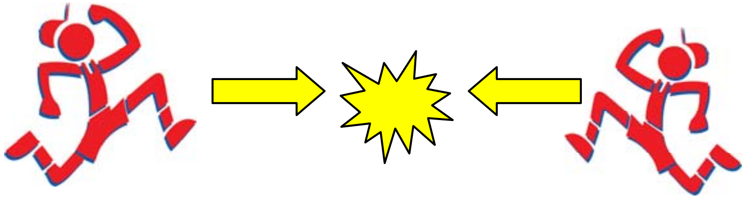
- **Higgs Searches:**
    - $M_H < 140$ GeV H → $\gamma\gamma$
    - $140 < M_H < 700$ GeV (H → llll)
    - $M_H > 500$ GeV (H → lljj)
- **Super-symmetry:**
    - SUSY Higgs Boson
    - Sparticles (sleptons, squarks, gluinos …)
- **Exited Quarks**
- **Lepoquarks**
- **Monopoles**
- **Extra-dimensions**
- **Compositeness**

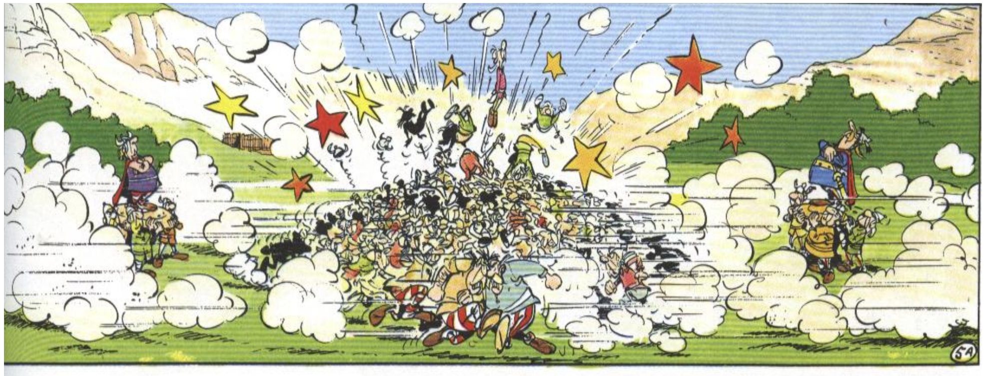
Why a Hadron Collider?

- Disadvantages:
  - Hadrons are complex objects
    - High multiplicity of other stuff
    - Energy and type of colliding parton (quark, gluon) unknown
      - Kinematics of events not fully constrained
- Advantage:
  - Can access higher energies

Lepton Collider
(collision of two point-like particles)

Hadron Collider
(collision of ~ 50 point-like particles)





The Standard Model Lagrangian

$$\begin{aligned}\mathcal{L} \;=\; & -\frac{1}{4}F^{a}_{\mu\nu}F^{a\mu\nu} \;+\; i\,\bar{\psi}\not{D}\psi \\ & +\psi_i\lambda_{ij}\psi_j h \;+\; \text{h.c.} \\ & +|D_\mu h|^2 - V(h) \\ & +\frac{1}{M}L_i\lambda^{\nu}_{ij}L_j h^2 \text{ or } L_i\lambda^{\nu}_{ij}N_j\end{aligned}$$

- gauge sector ✓
- flavour sector ✓
- EWSB sector ✓
- ν mass sector

… and beyond?

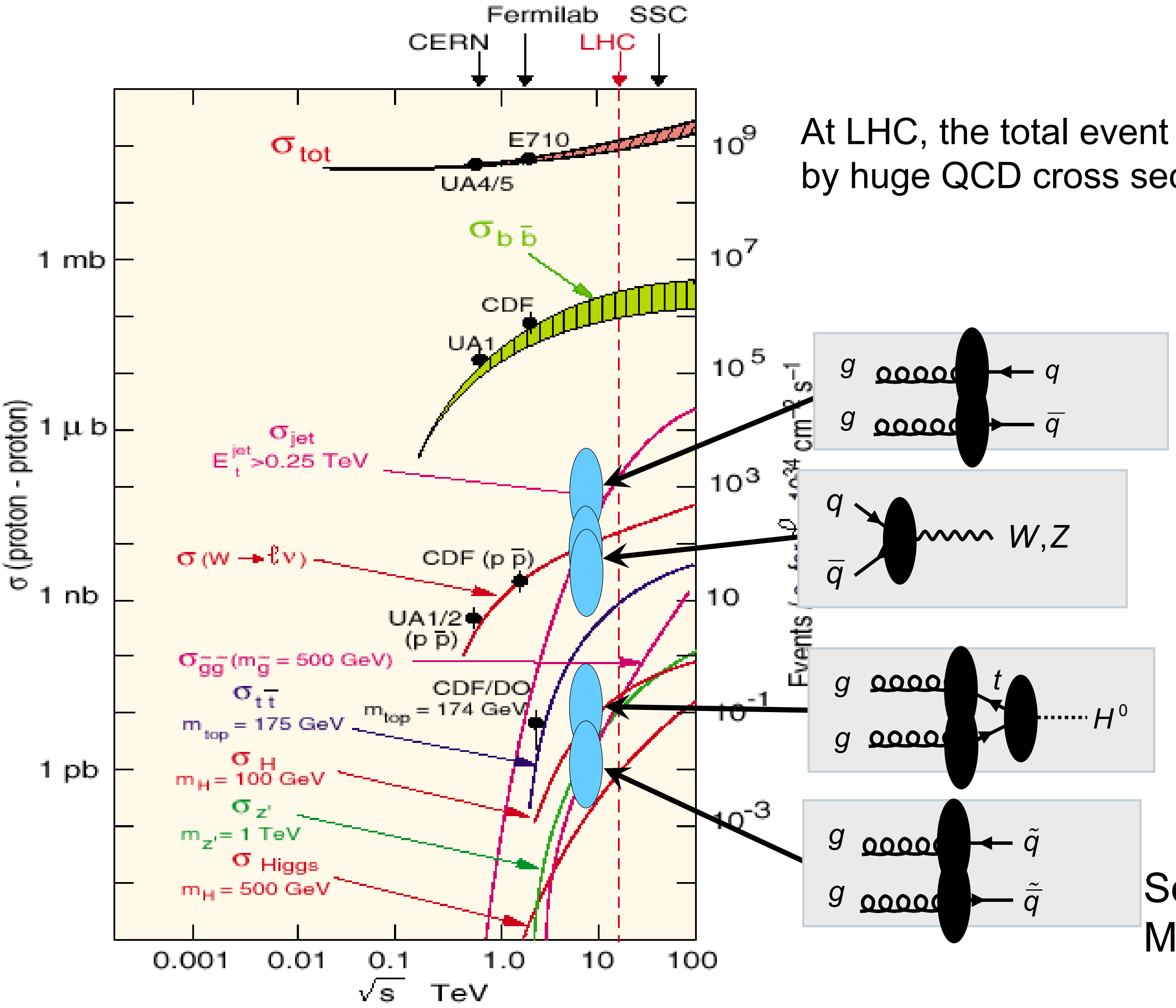
supersymmetry (many variants)
extra spacetime dimensions
compositeness
strong electroweak symmetry breaking
…
something new?! ✓

Confusion among theorist?

Need experiments to figure out which (if any) represents Nature

Cross Sections

At LHC, the total event rate is dominated by huge QCD cross section



High Pt QCD jets

W, Z production

Gluon-to-Higgs fusion

Squark, gluinos
M ~ 1 TeV

Revealing the Higgs

- The Higgs field pervades all of space, interacting with quarks, electrons W, Z etc. These interactions slow down the particles, giving them mass.
- The Higgs field causes the EM and Weak forces to differ at low energy. Three of the four Higgs fields give the longitudinal polarization states required for massive $W^{\pm}$ and Z. The fourth provides one new particle (the Higgs boson).

The Higgs boson is somewhat like the Bunraku puppeteers, dressed in black to be 'invisible', manipulating the players in the drama.

Higgs Decay Rates

Direct:

Quarks and Leptons

$$\Gamma(H \to q\bar{q}) = 3\Gamma(H \to l\bar{l}), \textit{ due to color}$$

$$\Gamma(H \to q\bar{q}) = \left[\alpha_W / 8(m_q / M_W)^2\right] M_H$$

Gauge Bosons

$$\Gamma(H \to ZZ) = \Gamma(H \to WW)/2$$

$$\Gamma(H \to WW) = \left[\alpha_W / 16(M_H / M_W)^2\right] M_H, \textit{ recall top width}$$

Loop Decays - Gauge Bosons:

$$\Gamma(H \to gg) \sim \left[\alpha_W / 9(M_H / M_W)^2\right] \quad \left[(\alpha_s / \pi)^2 \,|\, I \,|^2 / 8\right] M_H$$

$$\Gamma(H \to \gamma\gamma) \sim \left[\alpha_W / 9(M_H / M_W)^2\right] \left[(\alpha \;/ \pi)^2 \,|\, I \,|^2 / 8\right] M_H$$

Higgs couples to mass, with no direct Hγγ or Hgg coupling

Higgs - Production via gg Fusion

- The formation cross section is,

$$\boxed{d\sigma/dy \sim \pi^2\Gamma(H \rightarrow gg)/(M_H{}^3)[xg(x)]_{x1}[xg(x)]_{x2}}$$

- Using the expression for Γ(H-->gg) and normalizing the gluon distribution.

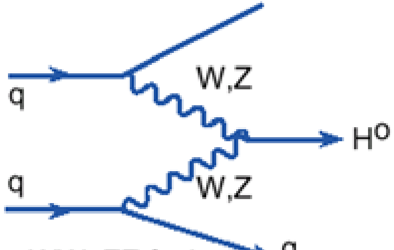
$$\boxed{d\sigma/dy \sim 49\pi^2[\Gamma(H \rightarrow gg)/(4M_H{}^3)][(1 - M_H/\sqrt{s})^{12}] \;\sim\; 49\pi^2\Gamma(H \rightarrow gg)/(4M_H{}^3)}$$

$$\boxed{d\sigma/dy \sim 49|I|^2\alpha_s{}^2\alpha_W/[288M_W{}^2].}$$

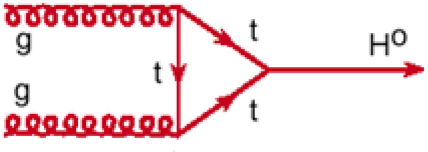
- Note that the $M_H{}^3$ behavior of Γ cancels the $1/M_H{}^3$ behavior of dσ/dy , leaving a roughly constant cross section,

Higgs Physics in one slide

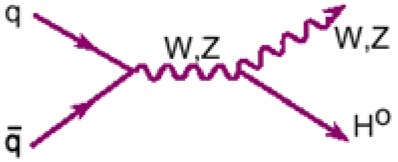
Production of Higgs:
dominant: gg→ H,
subdominant: HW, HZ, Hqq



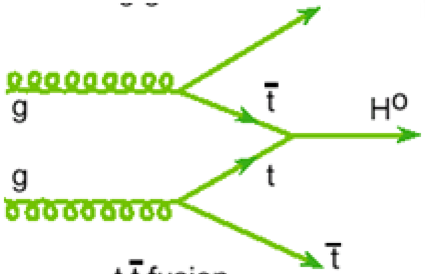
WW, ZZ fusion



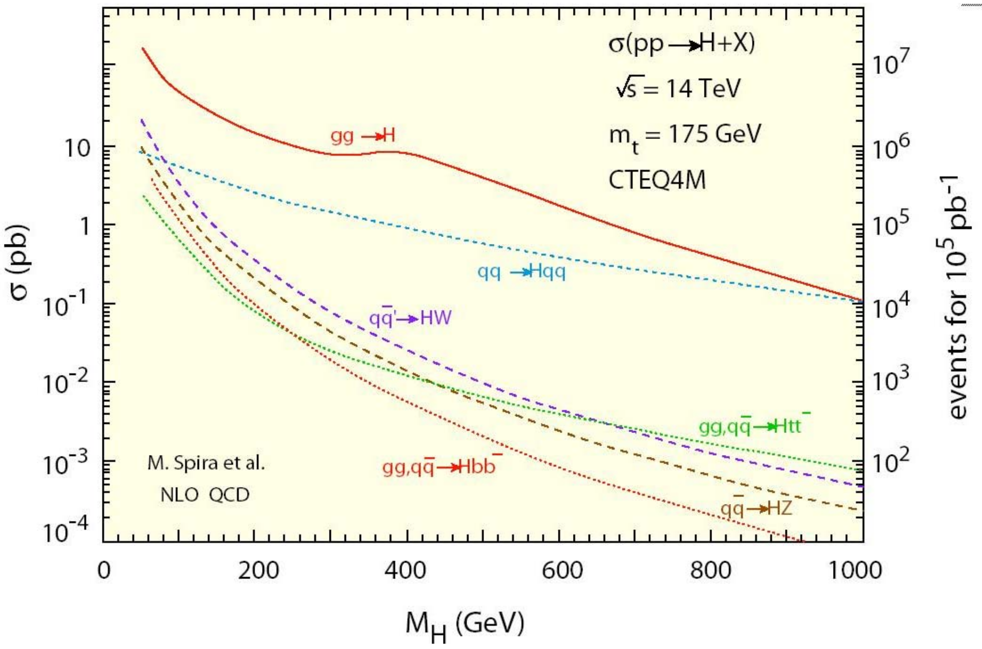
g g fusion



W, Z bremsstrahlung



t t̄ fusion



m_H < 130 GeV : H →bb, ττ dominate
Best channels at LHC: ttH → lbbX, H → γγ
m_H > 130 GeV : H → WW(*), ZZ(*) dominate
best search channels at LHC: H → ZZ(*) → 4l (gold-plated), H →WW(*) → lν lν

Higgs Decays

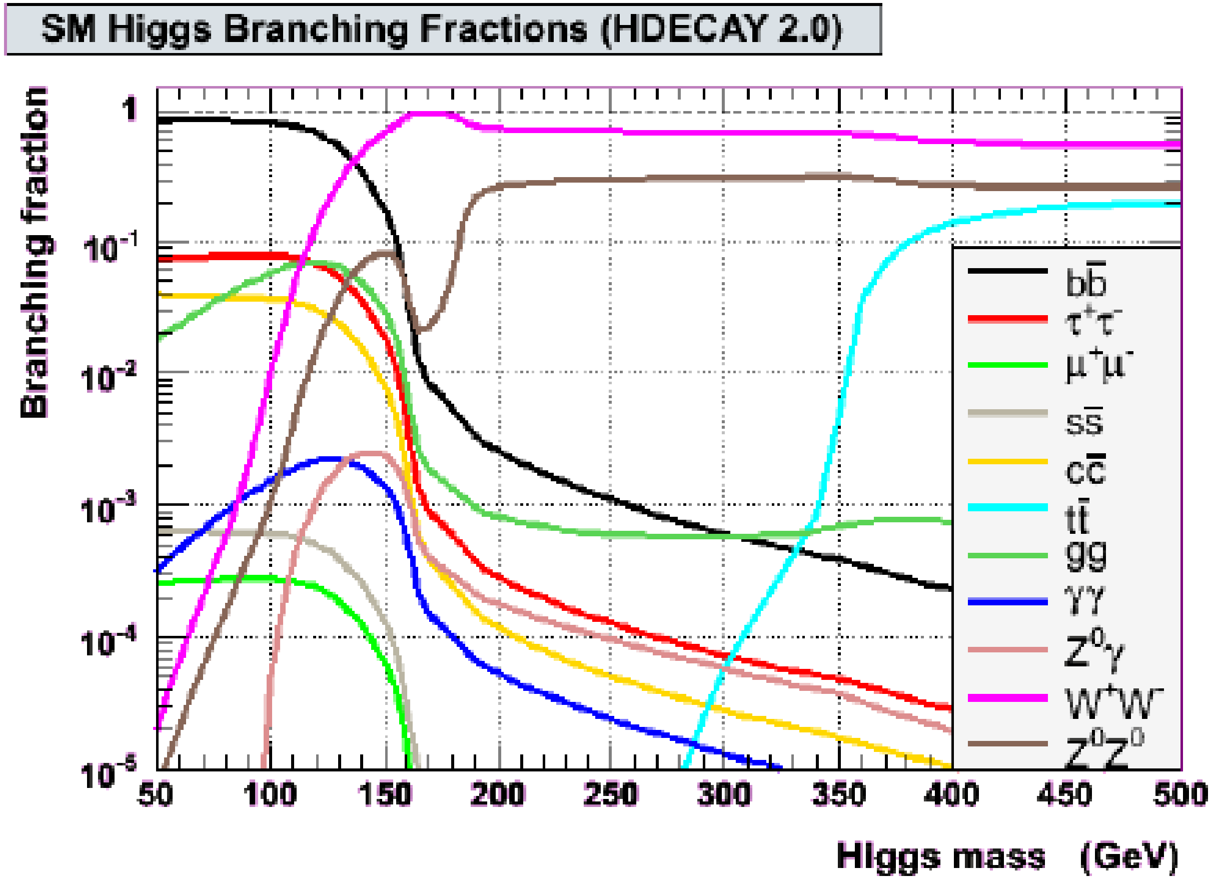
Standard Model Higgs channels considered here:

$H \rightarrow \gamma\gamma$

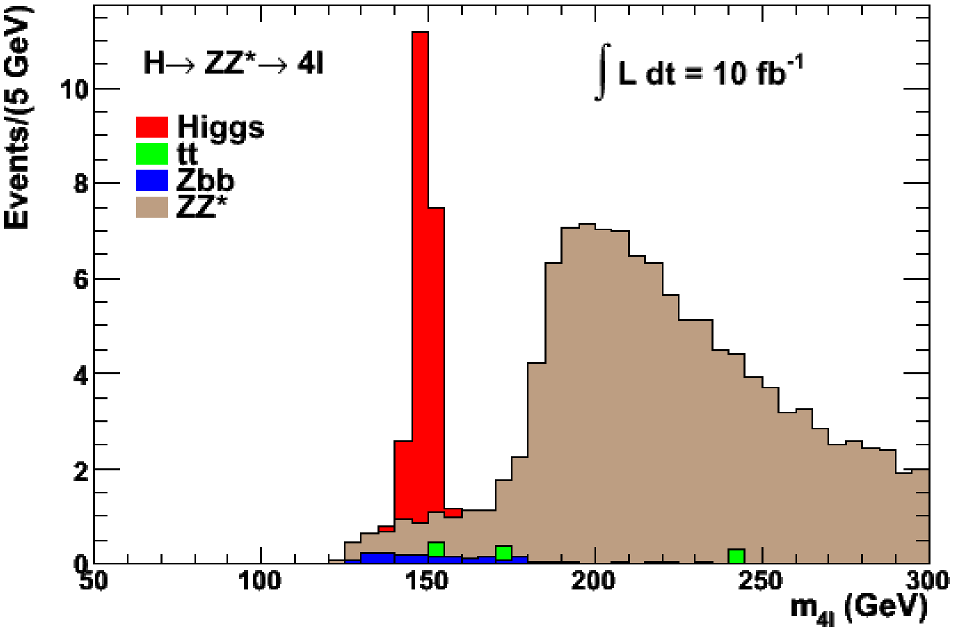
$H \rightarrow WW\,(*) \rightarrow e\nu\mu\nu$

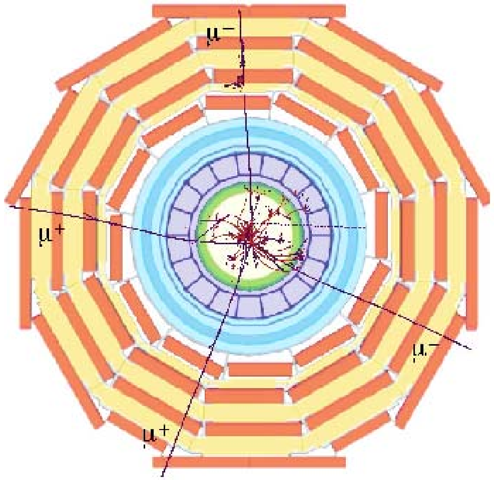
$H \rightarrow ZZ(*) \rightarrow 4l\ (l = e, \mu)$

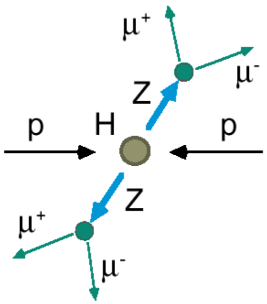
$H \rightarrow \tau^+\tau^- \rightarrow ll,\ lh$

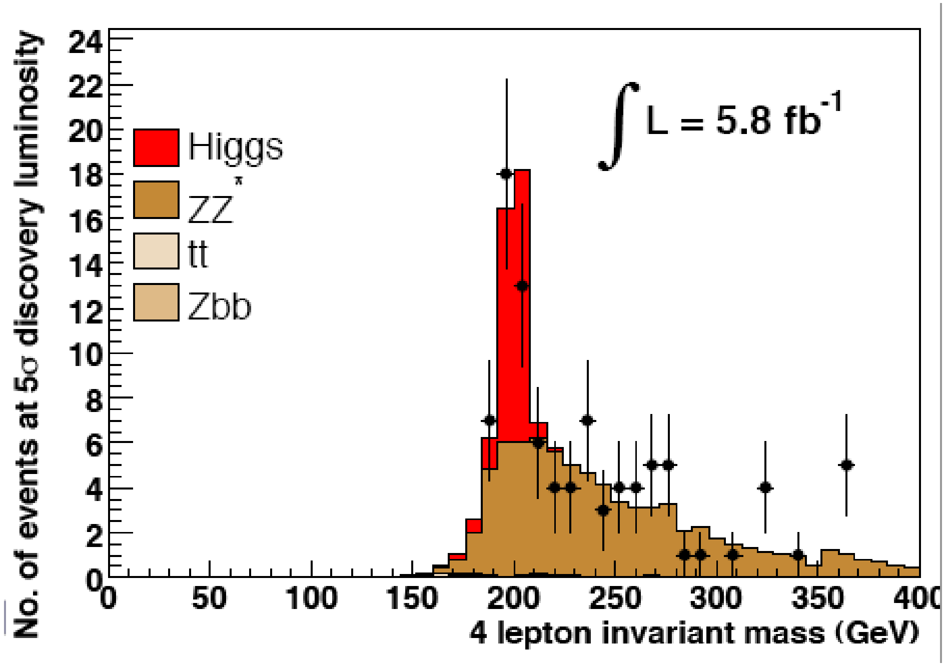


Higgs discovery?





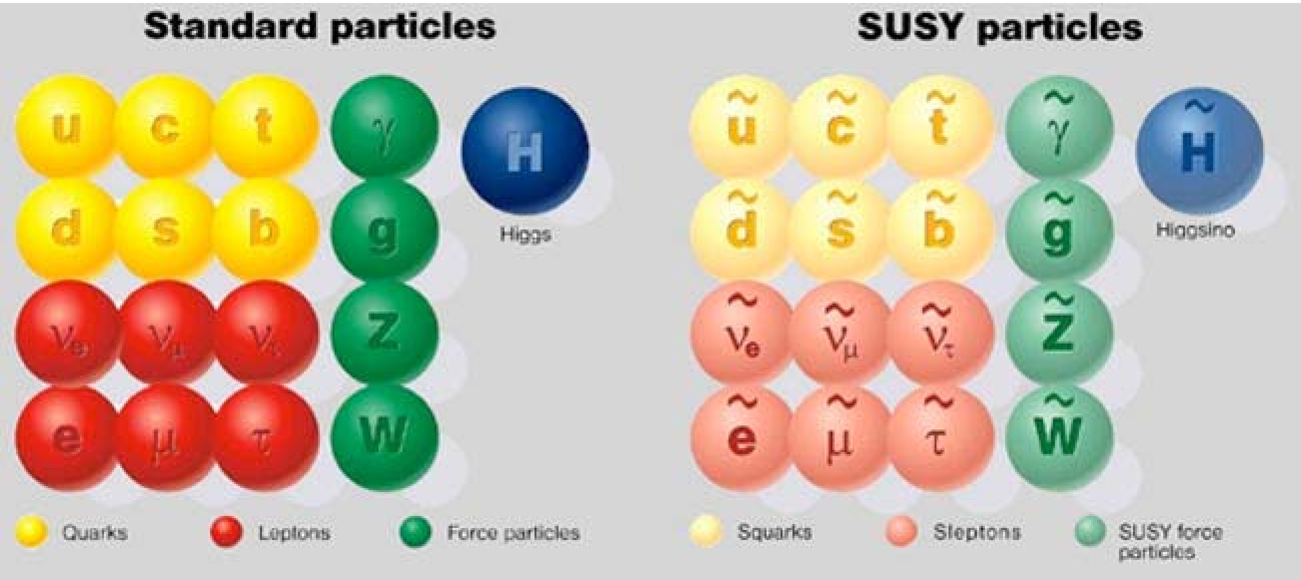




Gold-plated channel at LHC
Background Free …

Other channels are more demanding on detectors

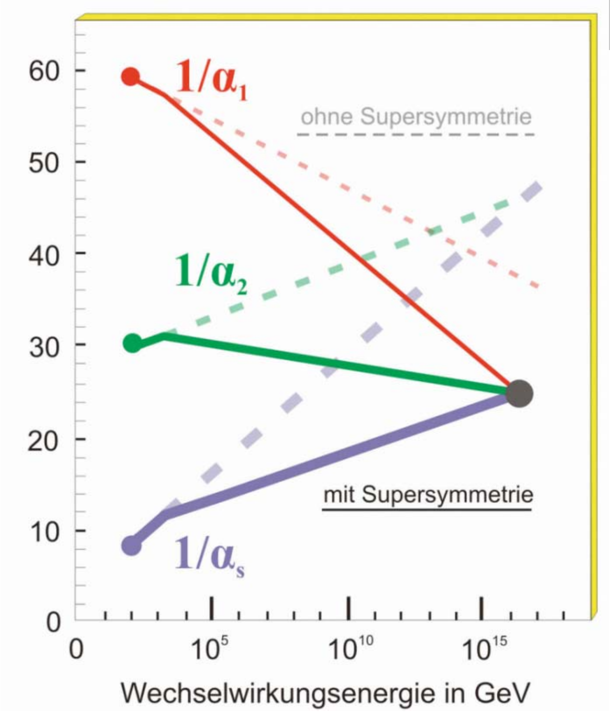
Supersymmetry (SUSY)

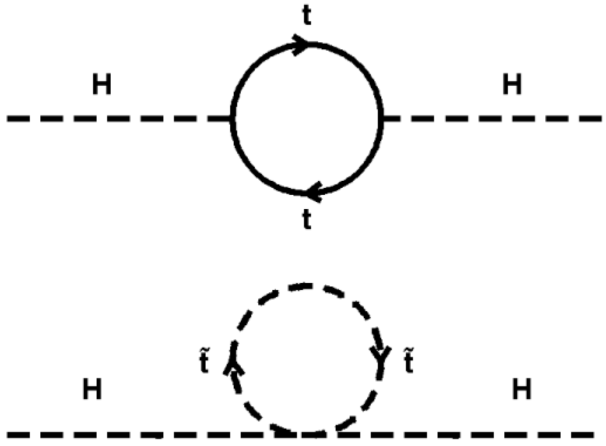


- **SM particles have supersymmetric partners:**
  - **Differ by 1/2 unit in spin**
    - **Sfermions (squark, selectron, smuon, …): spin 0**
    - **gauginos (chargino, neutralino, gluino,…): spin ½**
- **No SUSY particles found as yet:**
  - SUSY must be broken: breaking mechanism determines phenomenology
  - More than 100 parameters even in "minimal" models!

What's Nice about SUSY?

- Symmetry between bosons and fermions
- Unifications of forces possible SUSY changes running of couplings
- Dark matter candidate exists: The Lightest Supersymmetric Particle (LSP)
- No fine-tuning required: Radiative corrections to Higgs acquire SUSY corrections
- Cancellation of fermion and sfermion Loops
- Also consistent with precision measurements of M_W and M_{top}. But may change relationship between M_W, M_{top} and M_H





SUSY

SUSY has many motivations, but the most convincing one are:

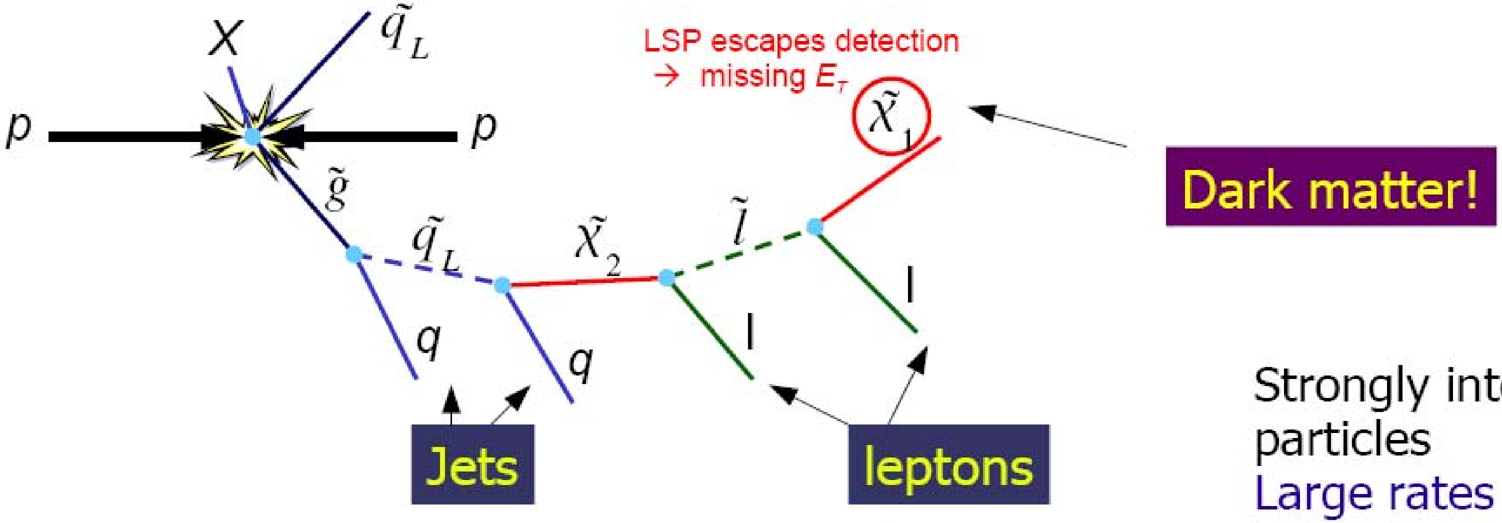
- → SUSY has the only possible extension to the Poincare symmetry of space time.
- → The Hierarchy Problem.

  If someone ever what to extend the SM by including new physics, we will need to explain why Higgs boson is so light. Super symmetry gives us the answer.
- → Note that the hierarchy problem is not really a problem if you do not include new physics at all.
- → Unification of gauge coupling at GUT scale.
- → SUSY has a good dark matter candidate the Neutralino

SUSY: phenomenology in one page

Conserved R-parity requires existence of a lightest stable SUSY particle (LSP). Since no exotic strong or EM bound states (isotopes) have been observed, the LSP should be neutral and colourless WIMP: LSP signature just as heavy neutrino

- The LSP is typically found to be a spin- neutralino, a linear combination of gauginos (in much of the SUSY parameter space the neutralino is a mixture of photino and zino)
- With R-parity: SUSY production in pairs requires energy 2 > SUSY mass !



LSP escapes detection → missing E_T

Dark matter!

Jets

leptons

Strongly interacting particles
Large rates

“Typical” SUSY decay chain at the LHC

SUSY reach

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***

$10fb^{-1}$

Experiments evaluate their SUSY discovery potential using some “standard” mSUGRA

D0 & CDF L = 0.3 fb^{-1} ~ 0.35 TeV

Ultimate (LHC):

L = 300 fb^{-1} ~2.5–3 TeV

1 year 10^{34} ~ 2.5 TeV

1 year 10^{33} ~ 1.8 TeV

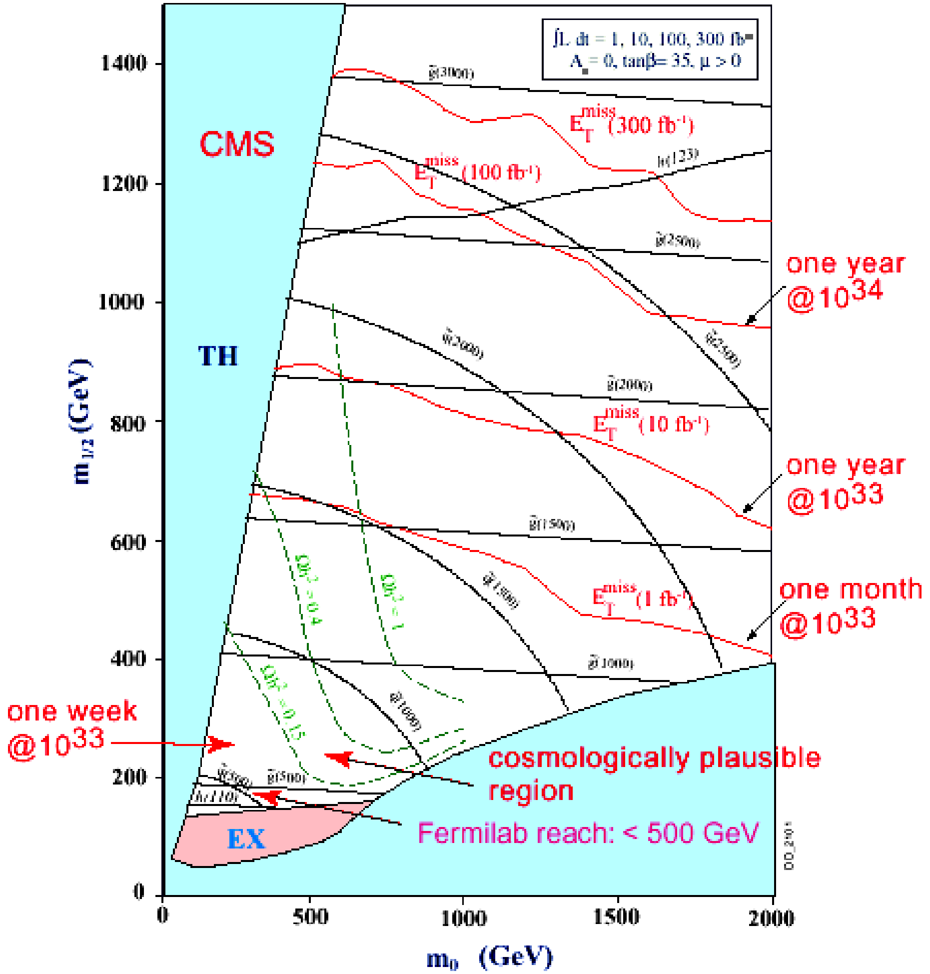
1 month 10^{33} ~ 1.3 TeV

squark/gluino masses

Luminosity

Time period [cm–2s–1]

5 standard deviations discovery contours



one year @10^{34}

one year @10^{33}

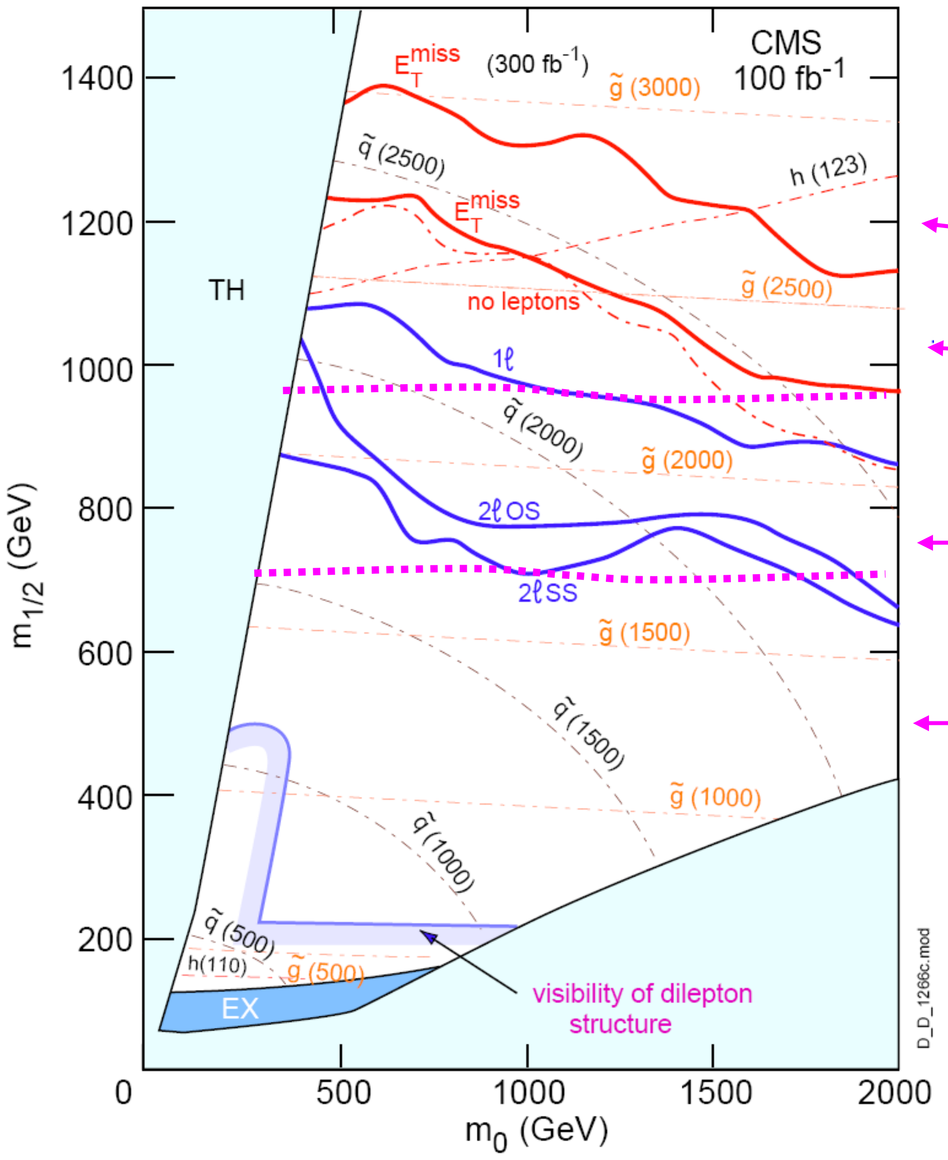
one month @10^{33}

one week @10^{33}

cosmologically plausible region

Fermilab reach: < 500 GeV

SUSY Discovery Potential



Discovery potential for squarks and gluinos in the channel

$$n\ \text{leptons} + \geq 2\ \text{jets} + \not{E}_T$$

300 fb^{-1} (three years @ high lumi)

100 fb^{-1} (one year @ high lumi)

10 fb^{-1} (one year @ low lumi)

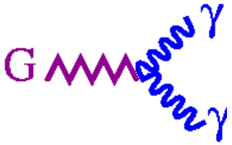
1 fb^{-1} (one month @ low lumi)

mSUGRA: $A_0 = 0$, $\tan\beta = 35$, $\mu > 0$

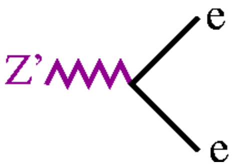
Beyond Supersymmetry

- **Strong theoretical prejudices for SUSY being true**
  - But so far there is a lack of SUSY observation….

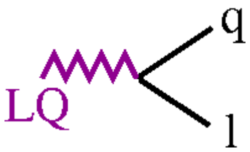
- **Need to keep an open eye for e.g.:**
  - **Extra spatial dimensions:**



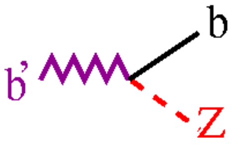
    - Addresses hierarchy problem: make gravity strong at TeV scale
  - **Extra gauge groups: Z', W'**

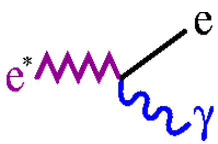


    - Occur naturally in GUT scale theories
  - **Leptoquarks:**
    - Would combine naturally the quark and lepton sector

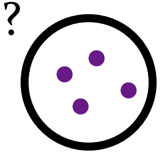


  - **New/excited fermions**
    - More generations? Compositeness?





  - **Preons:**
    - atom⇒nucleus ⇒ proton/neutron ⇒ quarks ⇒ preons?



  - **… ????:** something nobody has thought of yet

Monopole search at LHC

WHY does quantisation of the electric charge exist?

In 1931 Dirac showed that the existence of single magnetic monopole with magnetic charge g explained the quantization of electric charge e in terms of the Dirac quantization condition

$e\,g = n\,\hbar c/2$, $n=0,\pm 1,\pm 2,\ldots$ (P.A.M. Dirac, 1931)

Besides explaining the quantization of electric charge, the existence of magnetic charges restores the symmetry of the Maxwell's equations

Thus, existence of both electric and magnetic charge in the universe requires charge quantization. Since the quantization of electric charge in nature is well established but still mysterious, the discovery of just a single monopole would provide a much wanted explanation.

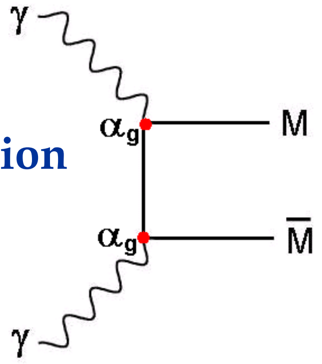
Monopole production

By a Dirac monopole we mean a particle without electric charge or hadronic interactions and with magnetic charge *g* satisfying the Dirac quantization condition.

Going from lepton to monopole production we replace

e ⟶ gβ

Two photon s=1/2

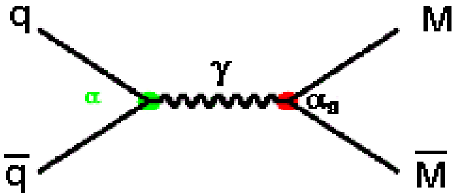


Differential cross section

$$\frac{d\sigma}{d\cos\theta} \sim A\frac{1+2\beta^2(1-\beta^2)(1-\cos^2\theta)-\beta^4\cos^4\theta}{(1-\beta^2\cos^2\theta)^2}.$$

As it follows from differential cross section we have all partial waves for two photon production. Thus, we have no any contradiction with unitarity for γγ processes.

Drell-Yan



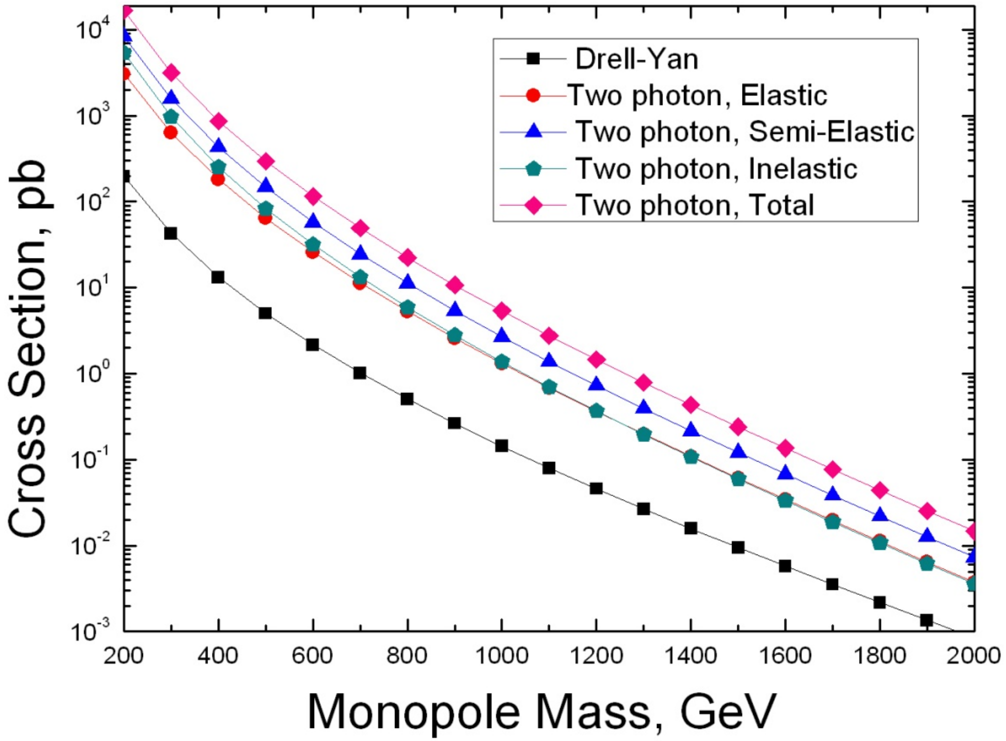
Differential cross section

$$\frac{d\sigma}{d\cos\theta} \sim B(1+b\cos\theta),\ b=-1,0,+1$$

When we make duality substitution *e* *gβ*→the Drell-Yan model satisfy the unitarity relation up to n≈3 Therefore, we need to use n=3 cross section as the unitarity limit for all n>3

Cross section

The comparison production cross-section for γγ fusion and Drell-Yan for monopole-antimonopole pair in pp-collisions at √s=14 TeV



So, γ γ production is the leading mechanism for direct monopole searches at LHC

How can we search monopole at LHC?

If magnetic monopole produced in ATLAS then monopole would be revealed by its unique characteristic.

- Transition Radiation
- The large value of a magnetic charge means that ionization energy losses will be several orders of magnitude greater for monopoles than for electrically charged particle.
- Trapped magnetic monopoles can be draft by the magnetic field and further registered.

What is Compositeness?

- Quarks may not be fundamental particles; but rather an agglomeration of smaller constituents called “preons.”
- These features are visible above a characteristic energy scale Λ below which quarks appear point like.
- Λ characterizes both strength of preon coupling and physical size of composite scale

Finding X-dimension at LHC

- The Standard Model is an effective theory. The new theory takes over at a scale Λ comparable to the Higgs boson mass, i.e. Λ ~ 1 TeV.
- Possible solution?

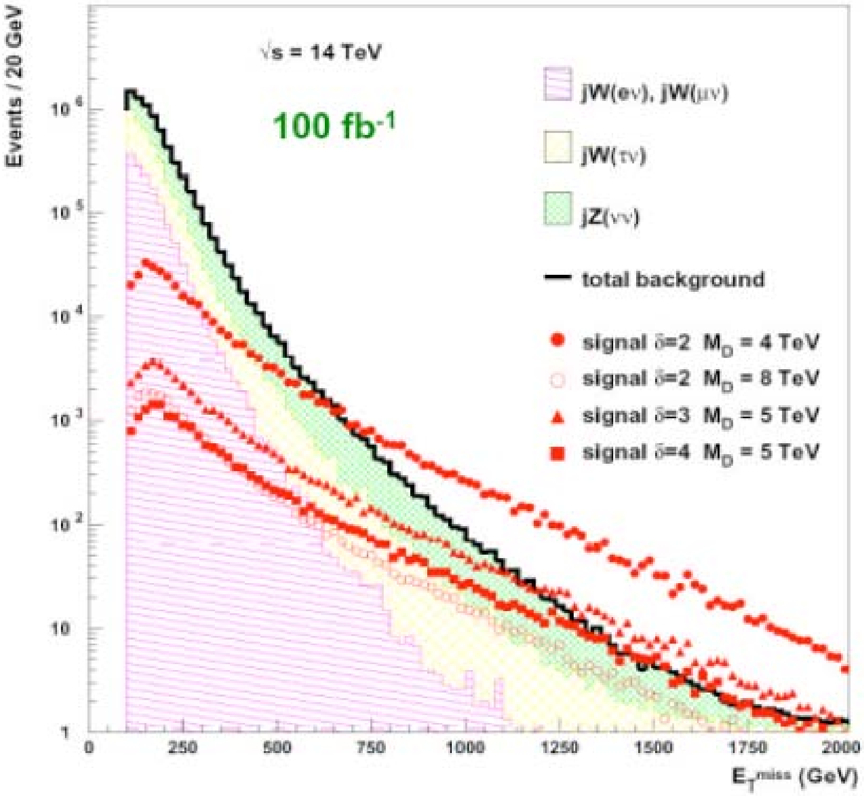
Supersymmetry : for each SM particle a SUSY partner is introduced. SM and SUSY particle contributions to Higgs mass have opposite sign.

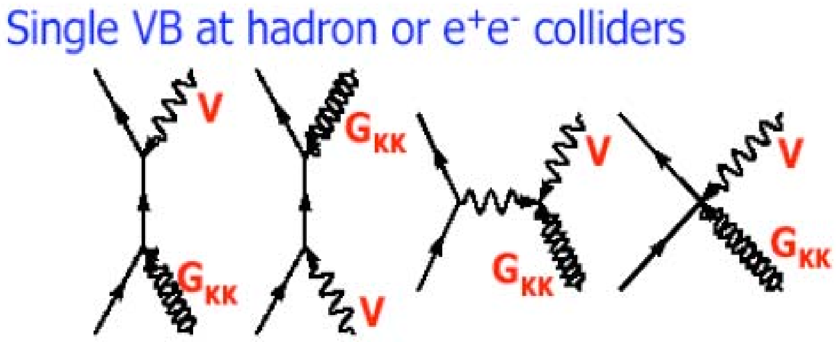
Extra Dimensions : Strong gravity at TeV scale. ED already introduced in string theory (theory for describing the gravitation using QFT with 10 or 11 dimensions, in which extra dimensions are compactified).

Large X-dimensions at LHC

Direct Searches

Isolated Photon with a large missing transverse energy (non detected G)




Single VB at hadron or e+e- colliders

Channel which will allow to confirm the discovery in the monojet channel

TeV size X-dimensions at LHC

Variation of the previous model : In addition to the large extra dim, smaller ones are introduced (of TeV-1 size) in which gauge bosons can propagate while fermions are confined on the 4dim brains.

The KK modes of the gauge bosons γ, Z, W are massive and their coupling goes like SM (* √2)

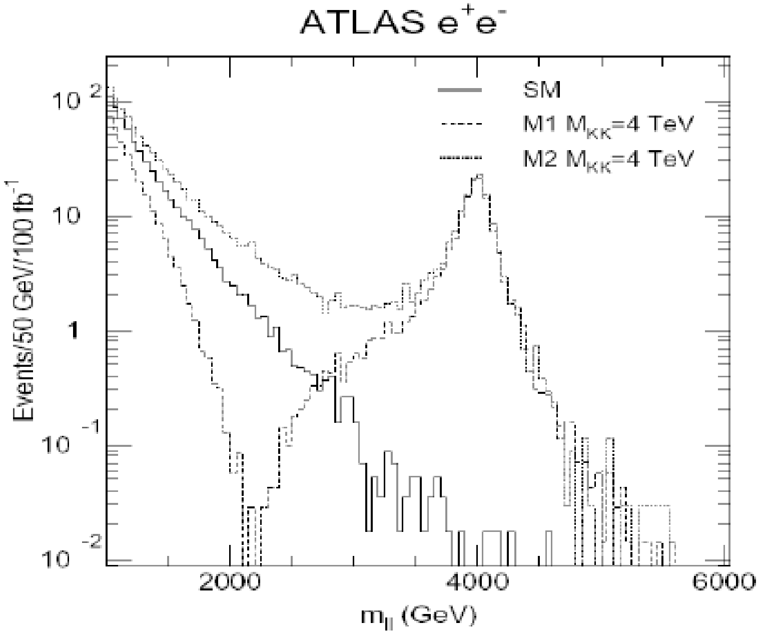
Constraints for γ and Z:

- EW Data: Mc > 4 TeV

- At LHC (mostly from ATLAS):

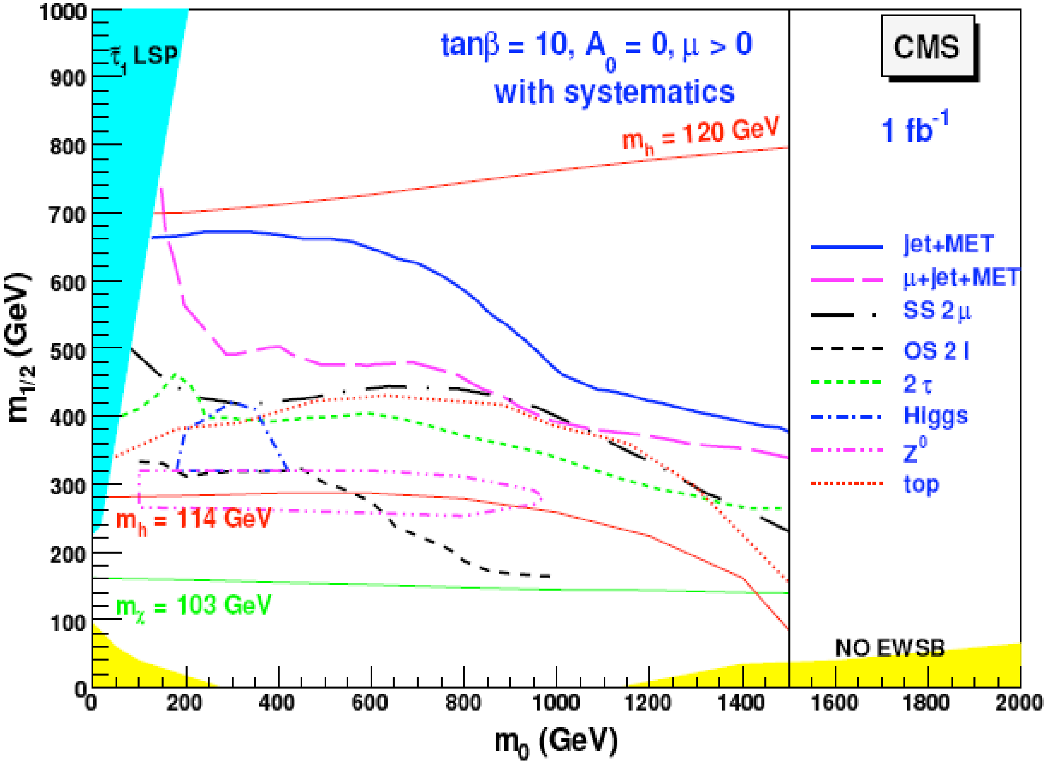
– Sensitivity in the peak: Mc max= 5.8 TeV (100 fb-1)

– From interference study: Mc max=9.5 TeV (e) for 100 fb-1 and 13.5 TeV for 300 fb-1 (e+μ)

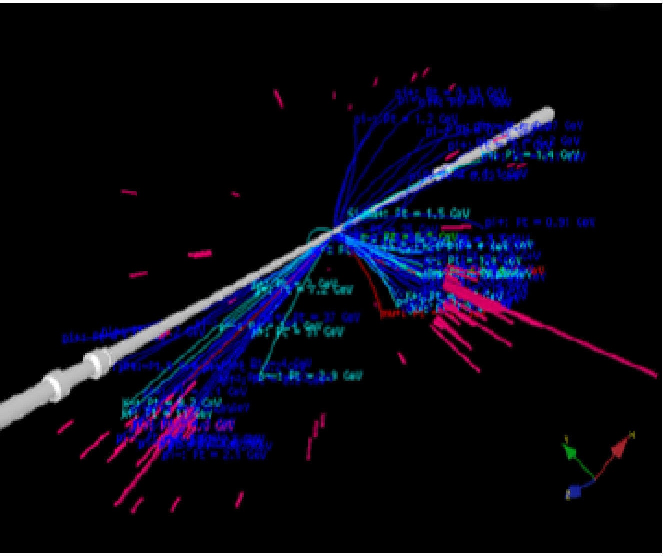


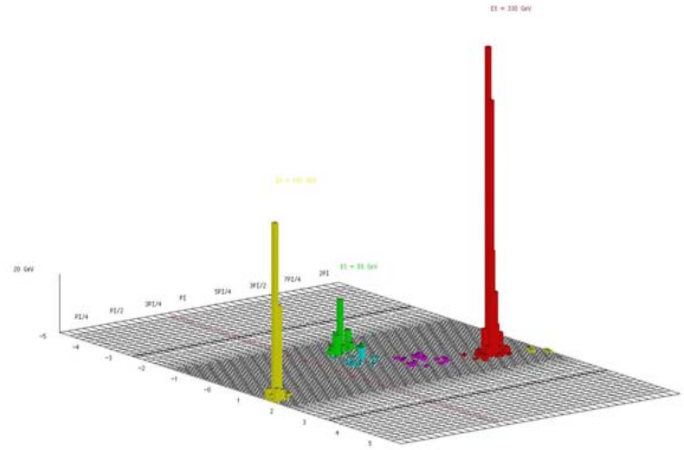
Seeking “SUSY”

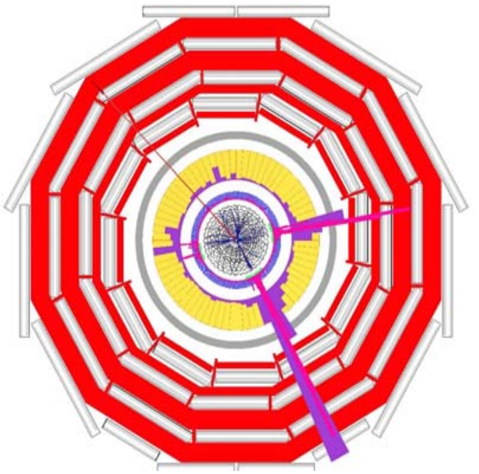
- Low-mass SUSY (M_{sp}~500GeV) accessible with O(10^{-1}) fb^{-1}. Some spectacular signatures
- Dt to discovery determined by:
  - Time to understand detector performance: E_T^{miss} tails, jet performance and energy scale, lepton id
  - Time to collect control samples -- e.g. W+jets, Z+jets, WW, top..

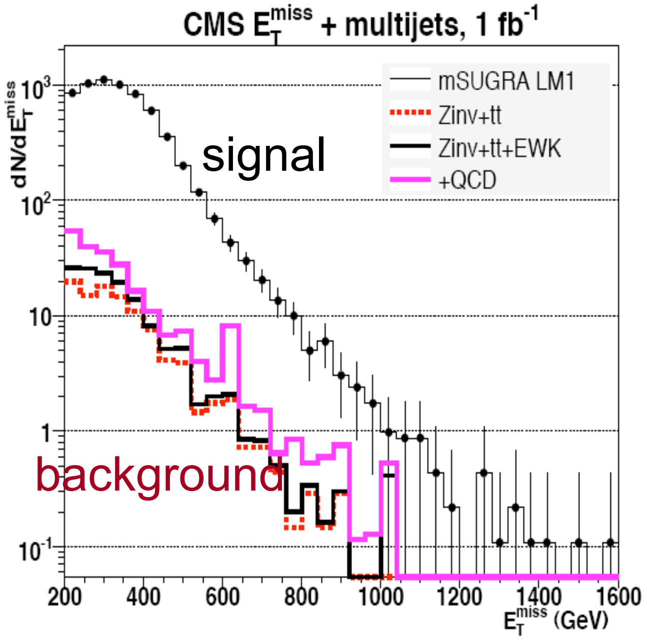


Seeking “SUSY”

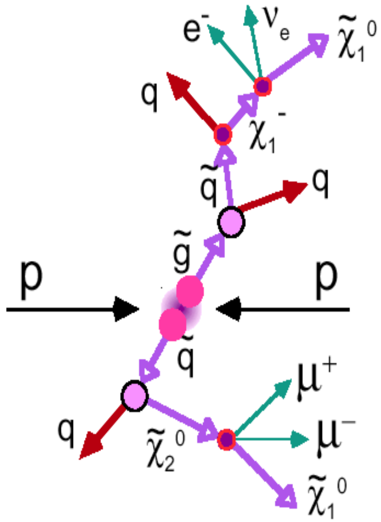


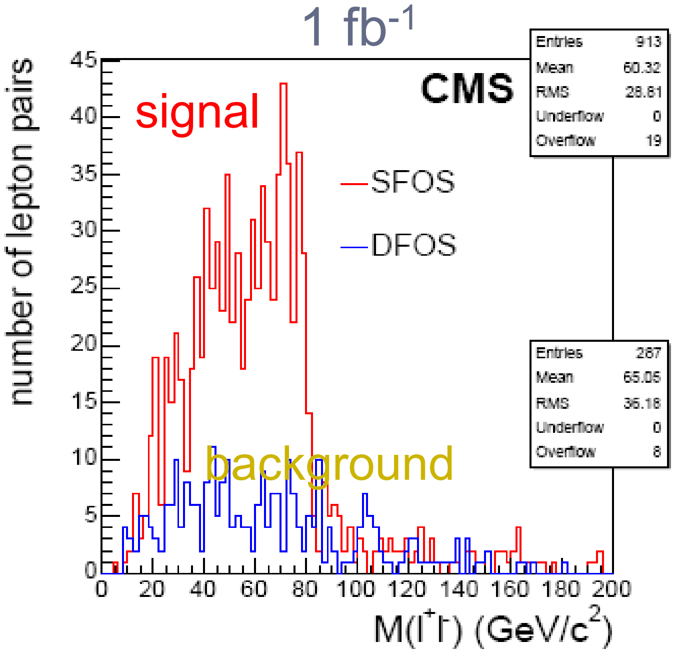






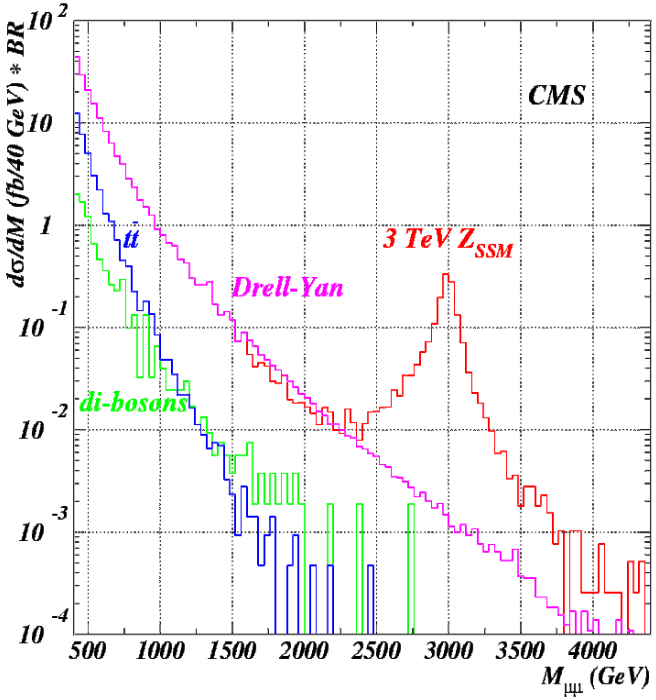
CMS E_T^{miss} + multijets, 1 fb^{-1}

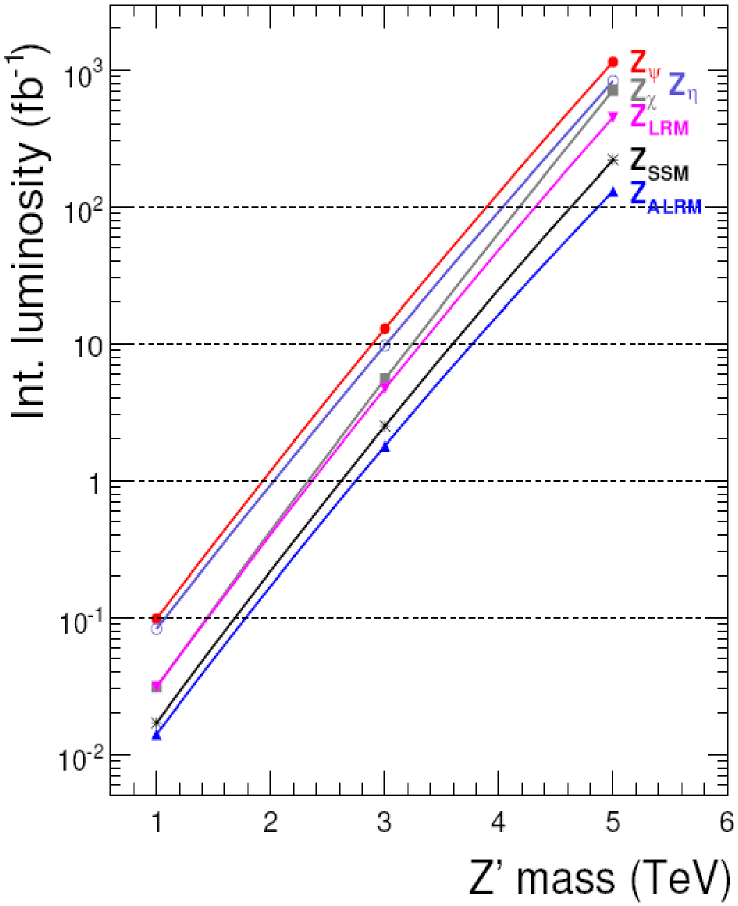




Extra Dimensions etc: Z’

$Z' \to \mu\mu$ production





Low lumi 0.1 fb^{-1} : discovery of 1-1.6 TeV possible
High lumi 100 fb^{-1}: extend range to 3.5-4.5 TeV