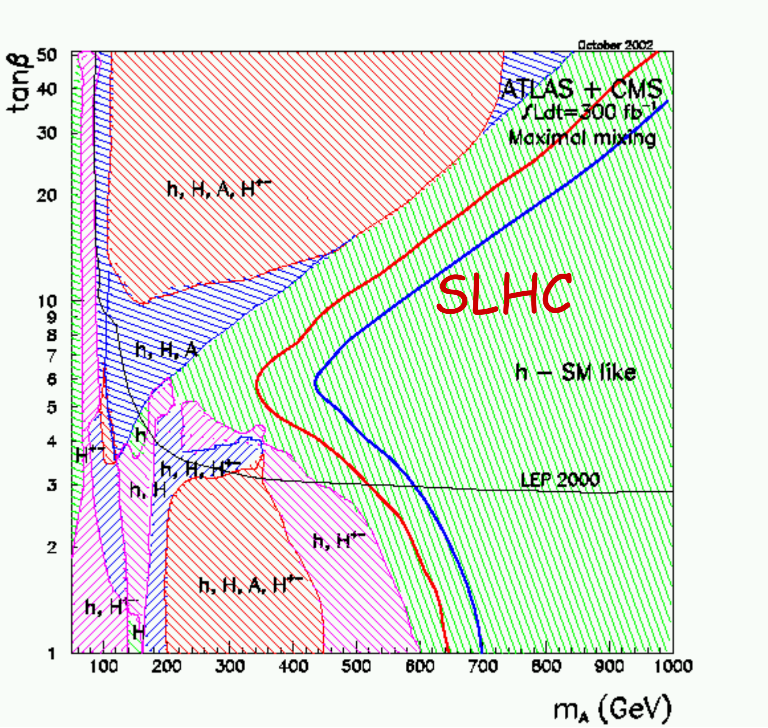
LHC Luminosity Upgrade: Detector Challenges

CERN Academic Training

Lecture 1: Machine and Physics

Albert De Roeck
CERN



Contents of this Lecture

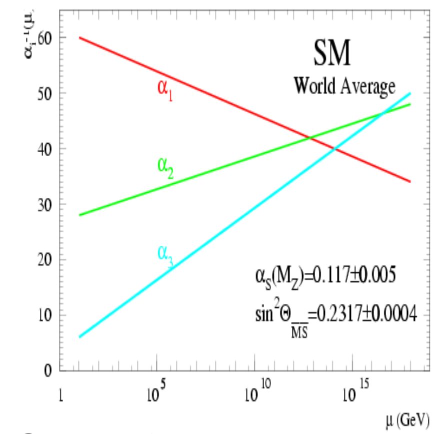
- Introduction: The Physics Landscape
- The LHC upgrade path
- The physics case by examples
- Summary of this lecture

Physics case for new High Energy Machines

Understand the mechanism Electroweak Symmetry Breaking

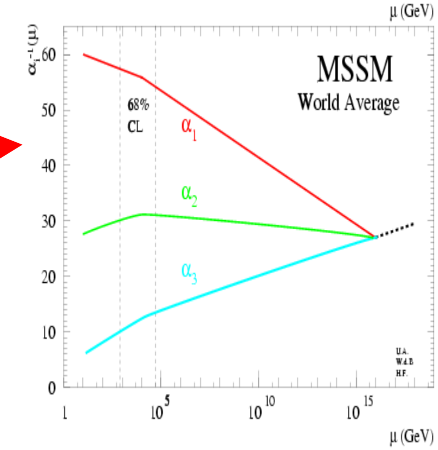
Discover physics beyond the Standard Model

Reminder: The Standard Model
- tells us how but not why (contains 19 parameters!)
  3 flavour families? Mass spectra? Hierarchy?
- needs fine tuning of parameters to level of 10^{-30} !
- has no connection with gravity
- no unification of the forces at high energy



Most popular extensions these days

If a Higgs field exists:
- Supersymmetry
- Extra space dimensions



If there is no Higgs below ~ 700 GeV
- Strong electroweak symmetry breaking around 1 TeV

Other ideas: more gauge bosons/quark & lepton substructure, Little Higgs models…

What can we expect?
Ask an (un)baised theorist:

Murayama LP03

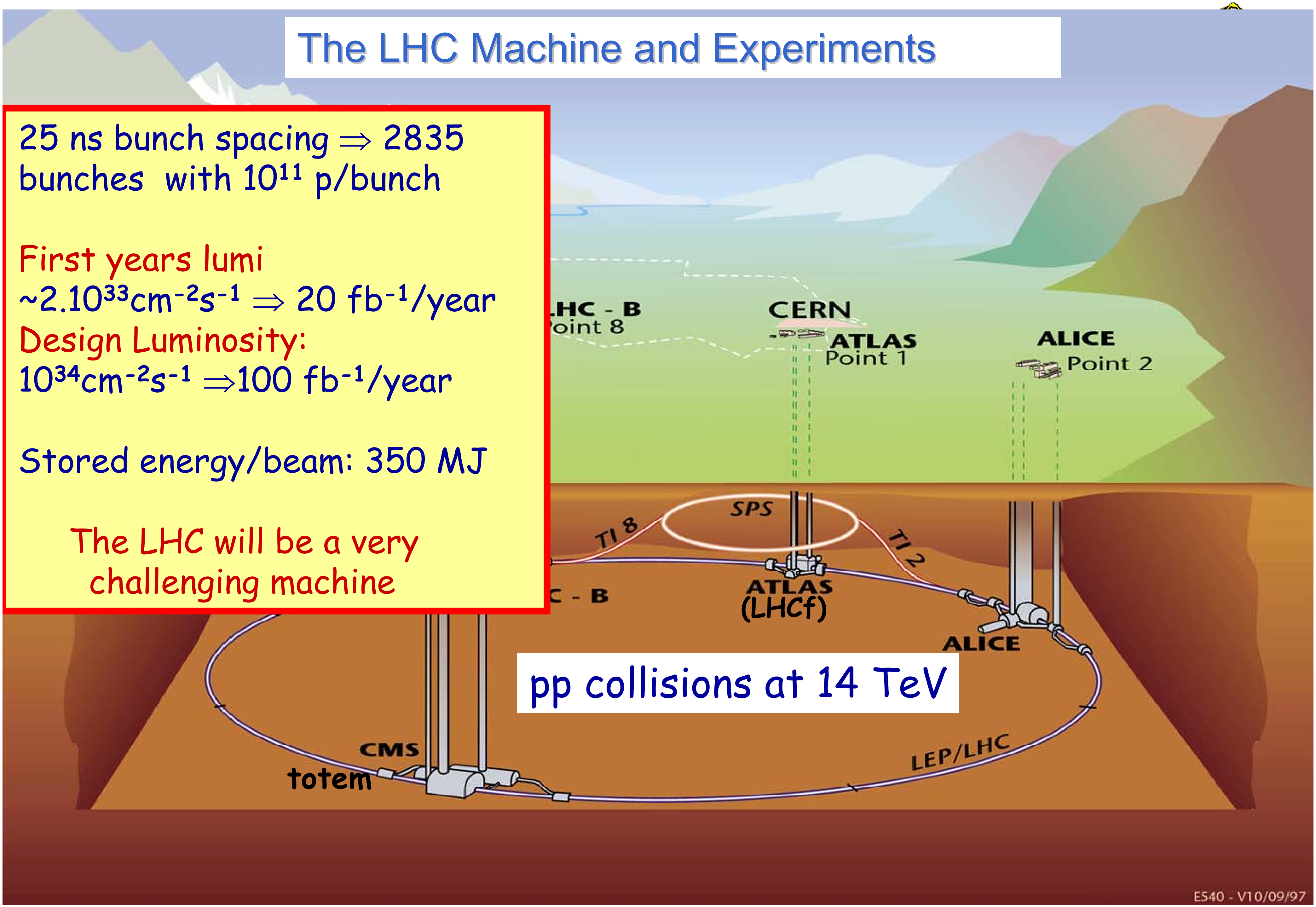
The LHC Machine and Experiments

25 ns bunch spacing ⇒ 2835 bunches with 10^{11} p/bunch

First years lumi
$\sim 2.10^{33} cm^{-2}s^{-1}$ ⇒ 20 fb^{-1}/year
Design Luminosity:
$10^{34} cm^{-2}s^{-1}$ ⇒100 fb^{-1}/year

Stored energy/beam: 350 MJ

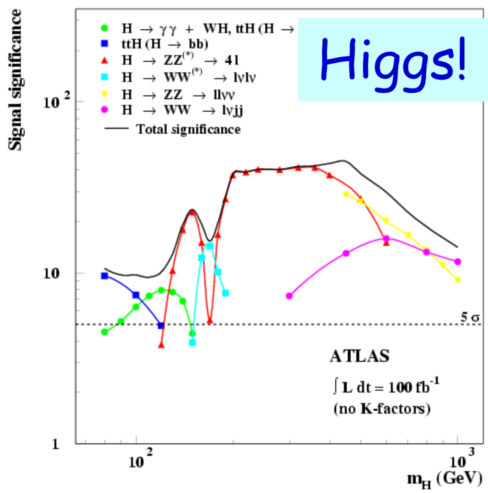
The LHC will be a very challenging machine

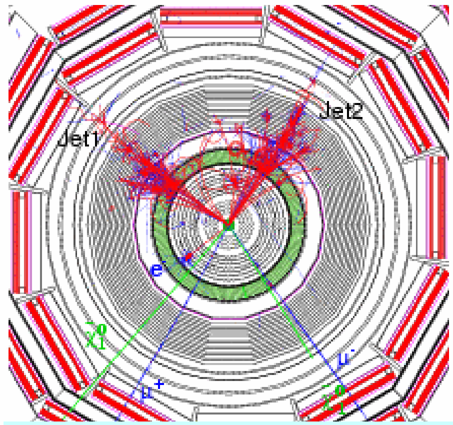


pp collisions at 14 TeV

New Particles/Physics at the LHC

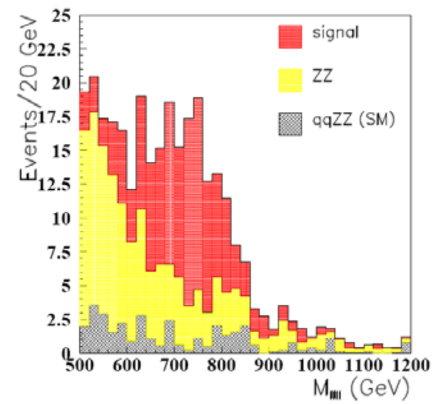
Higgs!



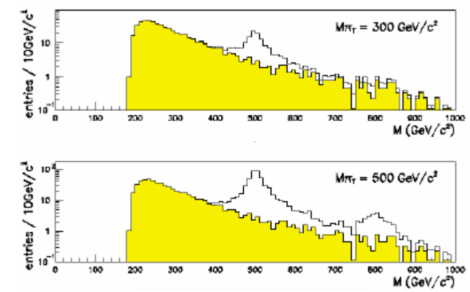


Supersymmetry?

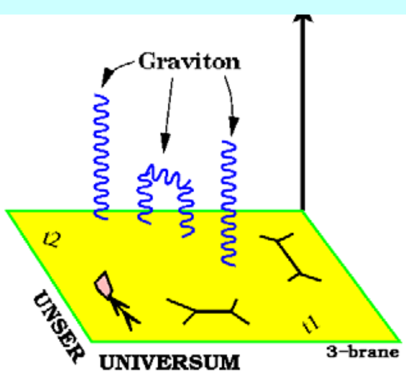
ZZ/WW resonances?



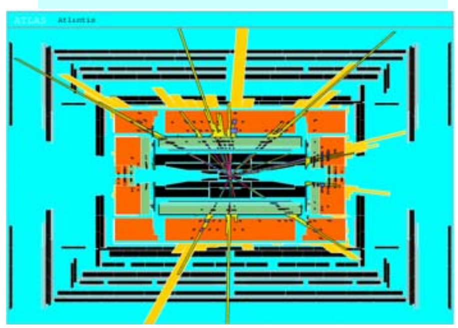
Technicolor?



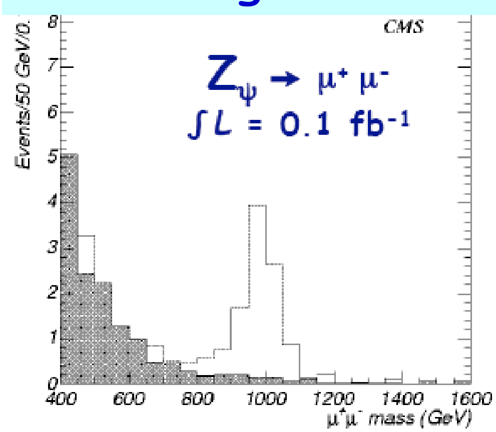
Extra Dimensions?



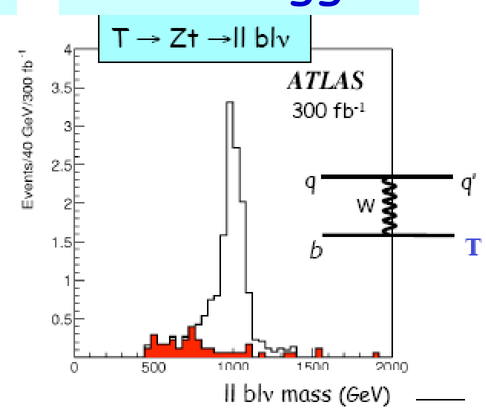
Black Holes???



New Gauge Bosons?



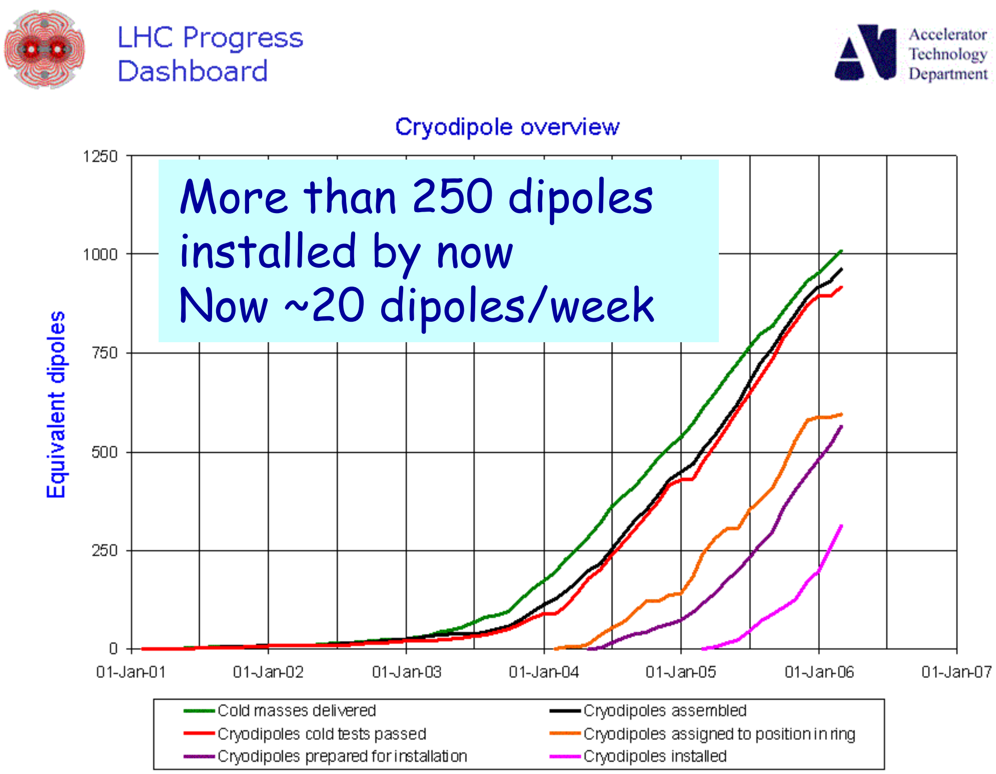
Little Higgs?



- LHC will explore directly the highly-motivated TeV-scale and say the final word about the SM Higgs mechanism and many TeV-scale New Physics predictions
- Also LHC will be a great machine for: QCD, B-physics, Heavy Ions, EW precision..

The LHC Progress & Schedule

Crucial part: 1232 superconducting dipoles
Can follow progress on the LHC dashboard
http://lhc-new-homepage.web.cern.ch/lhc-new-homepage/



More than 250 dipoles installed by now
Now ~20 dipoles/week

The LHC Schedule(*)

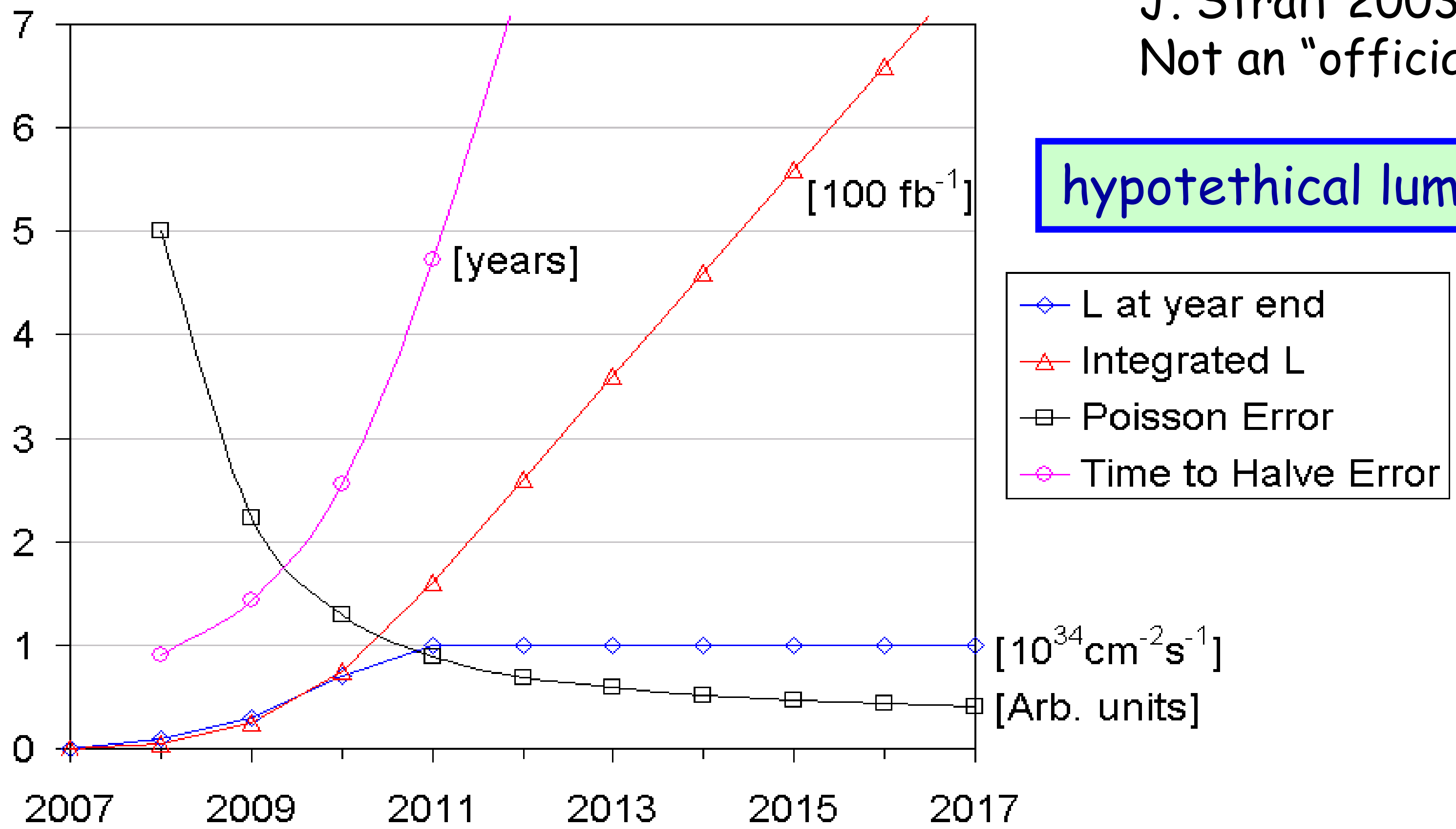
- LHC will be closed and set up for beam on 1 July 2007
- First beam in machine: August 2007
  LHC commissioning will take time!
- First collisions expected in October/November 2007
  Followed by a short pilot run
  O(10) pb^{-1} ?
- First physics run in 2008
  one to a few fb^{-1}?
- Physics run in 2009 +…
  10-20 fb^{-1}/year $\Rightarrow$100 fb^{-1}/year

(*) eg. M. Lamont et al, April 2005.
Achtung! Lumi estimates are mine, not from the machine
Update in June-July 2006

Upgrades of the LHC

J. Strait 2003:
Not an "official" LHC plot

hypotethical lumi scenario



If startup is as optimisitc as assumed here (10^{34} $cm^{-2}s^{-1}$ in 2011 already)
⇒After ~3 years the simple continuation becomes less exciting
⇒Time for an upgrade?

The LHC upgrade: SLHC

Already time to think of upgrading the machine if wanted in ~10 years

Two options presently discussed/studied

- Higher luminosity ~10^{35}cm^{-2} s^{-1} (SLHC)
  - Needs changes in machine and and particularly in the detectors
  - ⇒ Start change to SLHC mode some time 2013-2016
  - ⇒ Collect ~3000 fb^{-1}/experiment in 3-4 years data taking.

⇒Discussed in these lectures

- Higher energy? (DLHC)
  - LHC can reach $\sqrt{s}$ = 15 TeV with present magnets (9T field)
  - $\sqrt{s}$ of 28 (25) TeV needs ~17 (15) T magnets ⇒ R&D needed!
  - Even some ideas on increasing the energy by factor 3 (P. McIntyre)

	Run I $\sqrt{s}$	Run I $\sqrt{s}$	Int Lumi	Int. Lumi (expected)
Tevatron	1.8 TeV	1.96 TeV	100 pb	~5fb
HERA	300 GeV	320 GeV	100 pb	~500 pb

Physics Case for the SLHC

→ Either at least one Higgs exisits with mass below 1 TeV, or new phenomena (strong EWSB?) set on in the TeV region
→ New physics prefers the TeV scale (Hierarchy problem, fine tunning) but not fully guaranteed

The use/need for for the SLHC will obviously depend on how EWSB and/or the new physics will manifest itself

- LHC should have told us, say, by 2010 (with ~10-30 fb^{-1})
  - Whether a light (or heavy) Higgs exist ..unveil the EWSB mechanism
  - Whether the world is or could be (low energy) supersymmetric
  - Whether we can produce dark matter in the lab
  - Whether there are more space time dimensions, micro-black holes…
  - Whether it is all different than what we thought
  - Whether there is nothing strikingly new found in its reach…unlikely!

Machine Upgrade Studies

Large Hadron Collider Project

LHC Project Report 626

2002 Report on study

LHC Luminosity and Energy Upgrade: A Feasibility Study

O. Brüning[§], R. Cappi[‡], R. Garoby[‡], O. Gröbner[†], W. Herr[§], T. Linnecar[§], R. Ostojic[†], K. Potter[*], L. Rossi[†], F. Ruggiero[§] (editor), K. Schindl[‡], G. Stevenson[¶], L. Tavian[†], T. Taylor[†], E. Tsesmelis[*], E. Weisse[§], and F. Zimmermann[§]

Upgrade in 3 main Phases:

- Phase 0 – maximum performance without hardware changes
  Only IP1/IP5, N_b to beam beam limit→ $\mathcal{L}$ = 2.3•10^{34} cm^{-2} s^{-1}
- Phase 1 – maximum performance while keeping LHC arcs unchanged
  Luminosity upgrade (β^*=0.25m,#bunches,...)→ $\mathcal{L}$ = 5-10•10^{34} cm^{-2} s^{-1}
- Phase 2 – maximum performance with major hardware changes to the LHC
  Energy (luminosity) upgrade → E_{beam} = 12.5 TeV

Possible Machine Parameters

parameter	nom.	ult.	upgrades	
no. of bunches n_b	2808	2808	2808	1
rms bunch length σ_z [cm]	7.6	7.6	7.6, 4.2	7500
rms energy spread σ_δ [10^{-4}]	1.1	1.1	1.1, 3.7	5.8
beta at IP [m] β^*	0.5	0.5	0.25	0.25
crossing angle θ [μrad]	300	315	485	1000
beam current I_b [A]	0.56	0.86	1.3, 1.3	1.0
luminosity L [10^{34} $cm^{-2}s^{-1}$]	1	2.3	7.3, 9.7	9.0
σ_δ IBS growth time τ_{IBS} [h]	134	86	56, 674	1712

Latest parameter set:
F. Ruggiero et al.
PAC2003 report
May 2003

A luminosity of $10^{35}cm^{-2}\ s^{-1}$ seems possible

(*) Superbunch: 1 bunch of 75 m (rms) in each ring
Good for electron cloud effects/bad for experiments: 50000 events/25 ns slice

Recent Machine Parameters

Effective luminosity for various upgrade options

parameter	symbol	nominal	ultimate	shorter bunch	longer bunch
protons per bunch	N_b [10^{11}]	1.15	1.7	1.7	6.0
bunch spacing	Δt_{sep}[ns]	25	25	12.5	75
average current	I [A]	0.58	0.86	1.72	1.0
longitudinal profile		Gaussian	Gaussian	Gaussian	flat
rms bunch length	σ_z [cm]	7.55	7.55	3.78	14.4
ß* at IP1&IP5	ß* [m]	0.55	0.50	0.25	0.25
full crossing angle	θ_c [µrad]	285	315	445	430
Piwinski parameter	$\theta_c \sigma_z/(2\sigma^*)$	0.64	0.75	0.75	2.8
peak luminosity	L [10^{34} cm^{-2} s^{-1}]	1.0	2.3	9.2	8.9
events per crossing		19	44	88	510
IBS growth time	$\tau_{x,IBS}$ [h]	106	72	42	75
nuclear scatt. lumi lifetime	τ_N/1.54 [h]	26.5	17	8.5	5.2
			1.2	6.5	4.5
			.8	2.4	1.9
			2.3	8.9	7.0
effective luminosity	L_{eff} [10^{34} cm^{-2} s^{-1}]	0.5	1.0	3.3	2.7
(T_{turn}=5 h)	T_{run} [h] optimum	10.8	9.1	6.7	5.4

LHC upgrade scenarios | CERN | F. Ruggiero and F. Zimmermann

10^{35}cm^{-2}s^{-1} peak luminosity still on the map
Bunch crossing somewhere between 12.5→ 75 ns

Electron Cloud Effect

- Electrons from gas molecules, ionized by the proton bunch & synchrotron radiation.
- Once released, electrons get accelerated to 100-1000 eV and hit the wall
  $\Rightarrow$ surface heating

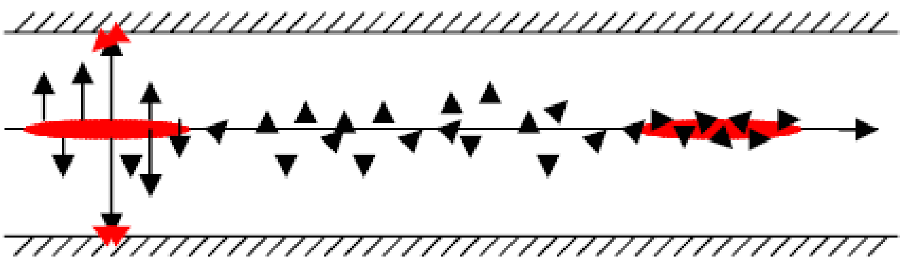
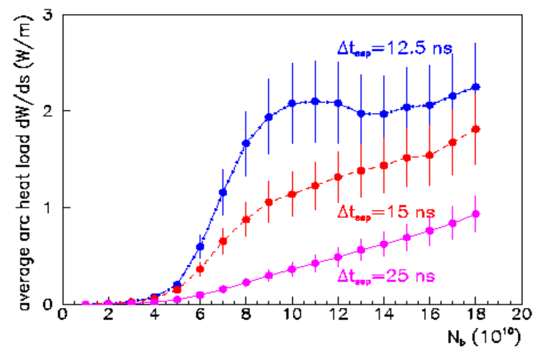


Figure 1. Schematic illustration of electron cloud effect. First bunch produces slow electrons, fields of second bunch accelerate residual electrons to produce secondary emission.

Can be preventive to run with to short bunch spacing
Will learn from LHC operation



Average arc heat load as a function of bunch population for bunch spacings of 12.5 ns, 15 ns, and 25 ns, and a maximum secondary emission yield $\delta_{max} = 1.1$. Elastically reflected electrons are included. (Courtesy F. Zimmermann)

F. Ruggiero CERN ICFA Seminar: LHC Machine Upgrade

Machine Upgrade Studies

Studies in the context of the CARE HHH Network
HHH = High Energy High Intensity Hadron-Beam facilities in Europe
http://care-hh.web.cern.ch/CARE-HHH/

Phase 1: steps to reach maximum performance with only IR changes

1) Modify the insertion quadrupoles and/or layout ⇒ $\beta^* = 0.25$ m
2) Increase crossing angle θ_c by $\sqrt{2}$ ⇒ $\theta_c = 445$ μrad
3) Increase N_b up to ultimate intensity ⇒ $L = 3.3 \times 10^{34}$ cm^{-2}s^{-1}
4) Halve σ_z with high harmonic RF system ⇒ $L = 4.6 \times 10^{34}$ cm^{-2}s^{-1}
5) Double the no. of bunches n_b (and increase θ_c) ⇒ $L = 9.2 \times 10^{34}$ cm^{-2}s^{-1}
excluded by electron cloud? **Step 5 belongs to Phase 2**

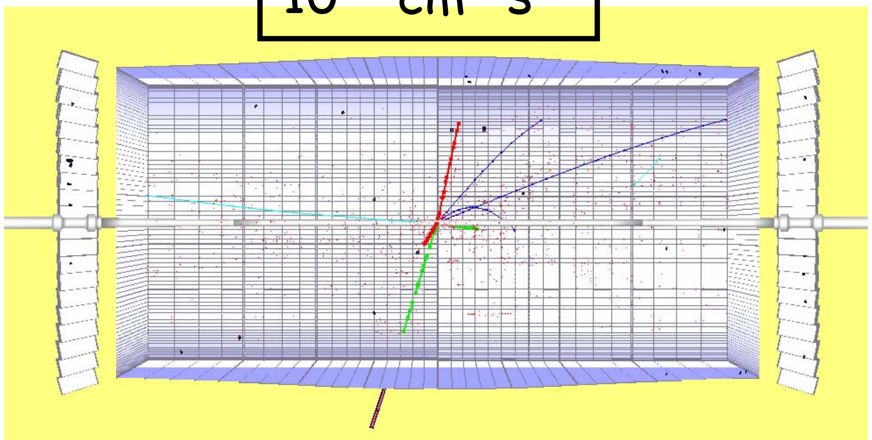
Step 4 requires a new RF system
Step 5: upgrade LHC cryogenics, collimation, beam dump systems…

Further possible paths: flat beams, dipoles close to IP, crab cavities…
Challenging but bigger challenges on the detector side

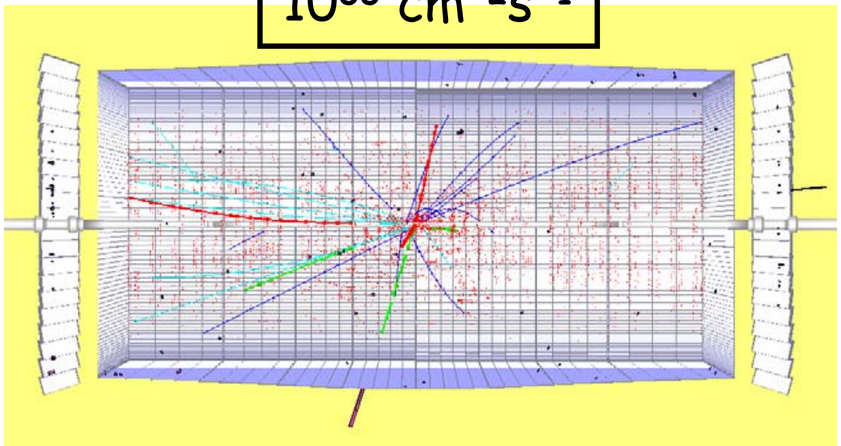
Pile-up

$H \to ZZ \to \mu\mu ee$ event with M_H= 300 GeV for different luminosities

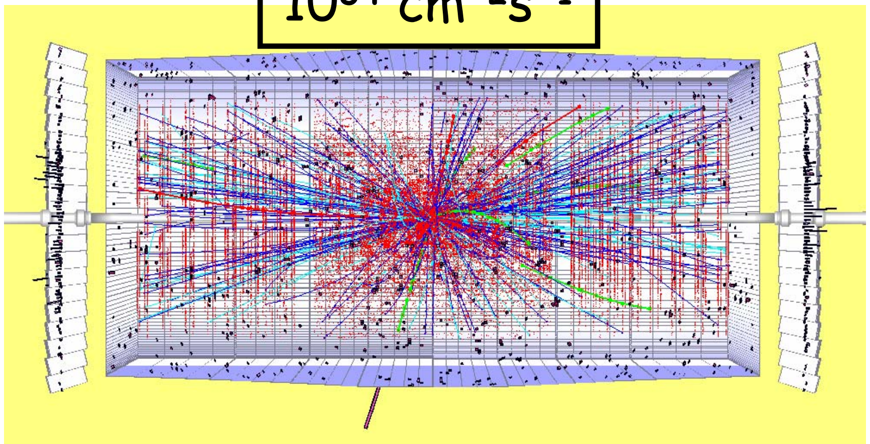
$10^{32}\ cm^{-2}s^{-1}$



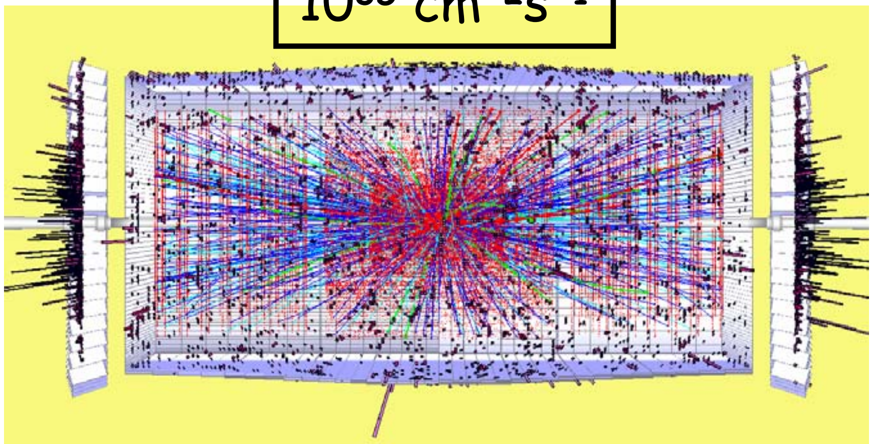
$10^{33}\ cm^{-2}s^{-1}$



$10^{34}\ cm^{-2}s^{-1}$



$10^{35}\ cm^{-2}s^{-1}$



Detectors: General Considerations

	LHC	SLHC
$\sqrt{s}$	14 TeV	14 TeV
Luminosity	10^{34}	10^{35}
Bunch spacing Δt	25 ns	12.5/25 ns
σ_{pp} (inelastic)	~ 80 mb	~ 80 mb
N. interactions/x-ing ($N = L\,\sigma_{pp}\,\Delta t$)	~ 20	~ 100/200
$dN_{ch}/d\eta$ per x-ing	~ 150	~ 750/1500
$\langle E_T \rangle$ charg. particles	~ 450 MeV	~ 450 MeV
Tracker occupancy	1	5/10
Pile-up noise in calo	1	~3
Dose central region	1	10

The other Lectures this week will deal with these challenges

Normalised to LHC values.

10^4 Gy/year R=25 cm

In a cone of radius = 0.5 there is $E_T \sim$ 80GeV.
This will make low E_t jet triggering and reconstruction difficult.

Detectors Upgrades for SLHC

- Modest upgrade of ATLAS, CMS needed for channels with hard jets, μ, large E_T^{miss}
- Major upgrades (new trackers ..) for full benefit of higher L: $e^{\pm}$ ID, b-tag, τ-tag, forward jet tagging (?) , trigger…

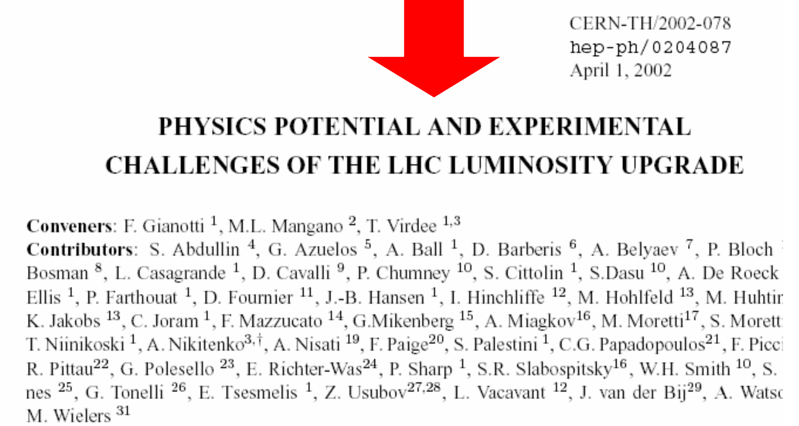
Assumptions for the study

- Detector Performance
  - Performance at $\mathcal{L} = 10^{35}$ $cm^{-2}s^{-1}$ is comparable to that at 10^{34} $cm^{-2}s^{-1}$!!
  - Some know degradations taken into account in individual analyses
- Integrated Luminosity per Experiment
  - 1000 (3000) fb^{-1} per experiment for 1 (3) year(s) of at $\mathcal{L} = 10^{35}$ cm^{-2} s^{-1}.
- Pile up
  - Corresponding to 12.5 bunch crossing distance scenario

Extending the Physics Potential of LHC

- Electroweak Physics
  - Production of multiple gauge bosons ($n_V \geq 3$)
    - triple and quartic gauge boson couplings
  - Top quarks/rare decays
- Higgs physics
  - Rare decay modes
  - Higgs couplings to fermions and bosons
  - Higgs self-couplings
  - Heavy Higgs bosons of the MSSM
- Supersymmetry
- Extra Dimensions
  - Direct graviton production in ADD models
  - Resonance production in Randall-Sundrum models TeV^{-1} scale models
  - Black Hole production
- Quark substructure
- Strongly-coupled vector boson system
  - $W_L Z_L$ g $W_L Z_L$, $Z_L Z_L$ scalar resonance, $W^+_L W^+_L$
- New Gauge Bosons

Examples studied in some detail



CERN-TH/2002-078
hep-ph/0204087
April 1, 2002

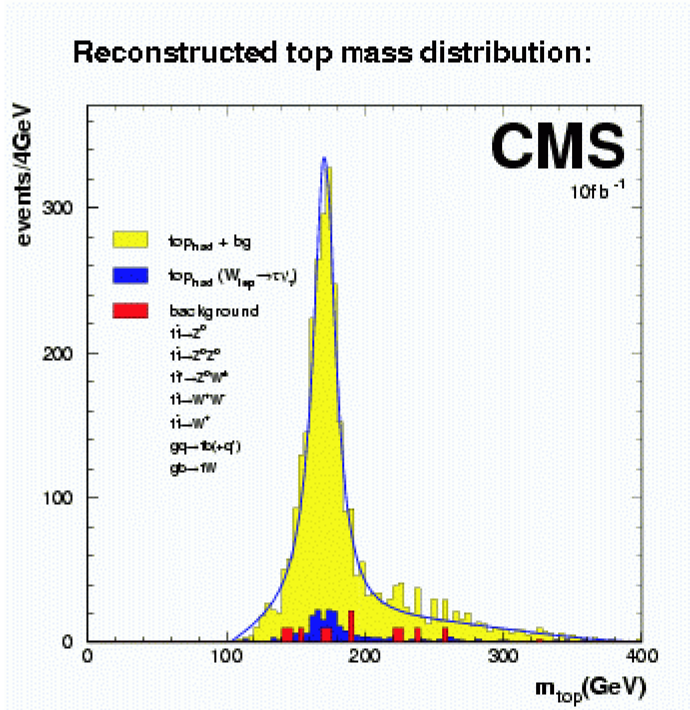
PHYSICS POTENTIAL AND EXPERIMENTAL CHALLENGES OF THE LHC LUMINOSITY UPGRADE

Conveners: F. Gianotti [1], M.L. Mangano [2], T. Virdee [1,3]
Contributors: S. Abdullin [4], G. Azuelos [5], A. Ball [1], D. Barberis [6], A. Belyaev [7], P. Bloch
Bosman [8], L. Casagrande [1], D. Cavalli [9], P. Chumney [10], S. Cittolin [1], S.Dasu [10], A. De Roeck
Ellis [1], P. Farthouat [1], D. Fournier [11], J.-B. Hansen [1], I. Hinchliffe [12], M. Hohlfeld [13], M. Huhtir
K. Jakobs [13], C. Joram [1], F. Mazzucato [14], G.Mikenberg [15], A. Miagkov[16], M. Moretti[17], S. Morett
T. Niinikoski [1], A. Nikitenko[3,†], A. Nisati [19], F. Paige[20], S. Palestini [1], C.G. Papadopoulos[21], F. Picc
R. Pittau[22], G. Polesello [23], E. Richter-Was[24], P. Sharp [1], S.R. Slabospitsky[16], W.H. Smith [10], S.
nes [25], G. Tonelli [26], E. Tsesmelis [1], Z. Usubov[27,28], L. Vacavant [12], J. van der Bij[29], A. Watso
M. Wielers [31]

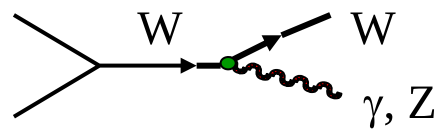
Include pile up, detector…

Standard Model Physics

Precision measurements of Standard Model processes and parameters



Triple/Quartic Gauge Couplings



Production of multiple gauge bosons: statistics limited at LHC
E.g. # events with full leptonic decays, Pt>20 GeV/c, |η|<2.5, 90% eff for 6000 fb^{-1}

Process	WWW	WWZ	ZZW	ZZZ	$WWWW$	$WWWZ$
N(m_H=120 GeV)	2600	1100	36	7	5	0.8
N(m_H=200 GeV)	7100	2000	130	33	20	1.6

quintuple couplings?

Coupling	14 TeV 100 fb^{-1}	14 TeV 1000 fb^{-1}	28 TeV 100 fb^{-1}	28 TeV 1000 fb^{-1}	LC 500 fb^{-1}, 500 GeV
λ_γ	0.0014	0.0006	0.0008	0.0002	0.0014
λ_Z	0.0028	0.0018	0.0023	0.009	0.0013
$\Delta\kappa_\gamma$	0.034	0.020	0.027	0.013	0.0010
$\Delta\kappa_Z$	0.040	0.034	0.036	0.013	0.0016
g_1^Z	0.0038	0.0024	0.0023	0.0007	0.0050

Triple gauge couplings: Wγ,WZ production

Use only muon and photon final state channels, statistical errors only
⇒ Equal or better than LC for λ type of couplings, worse for κ

Electroweak Physics

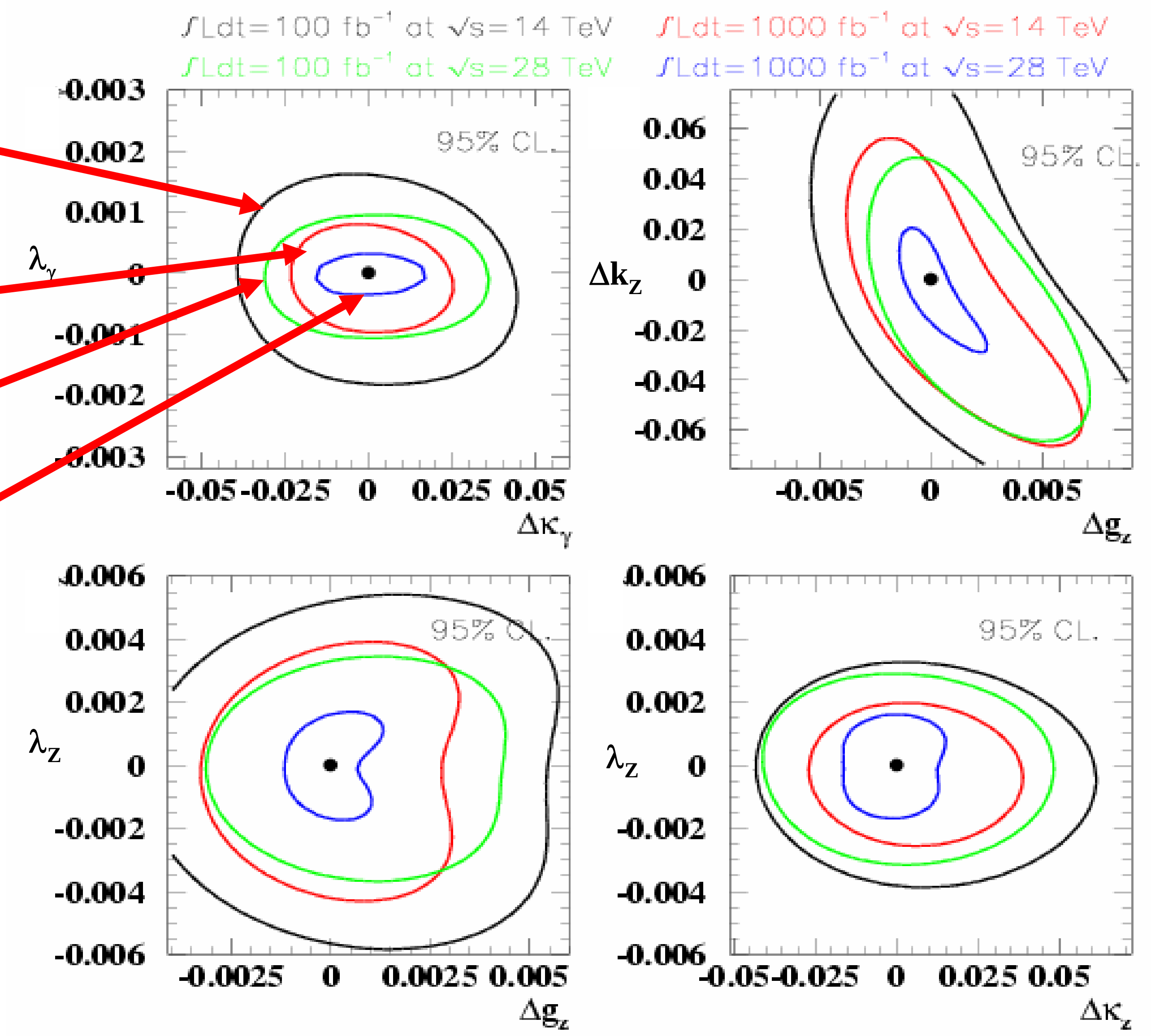
Triple gauge couplings: sensitivity

14 TeV 100 fb^{-1}

14 TeV 1000 fb^{-1}

28 TeV 100 fb^{-1}

28 TeV 1000 fb^{-1}



Sensitivity into the range expected from radiative corrections in the SM

Top Quark

LHC: $\Delta M(top)$ down to 1.0 GeV (and ΔM_W down to 15 MeV)

⇒Limited by systematics/no significant improvement expected

Statistics can still help for rare decays

$t \to q\gamma$

b-tagging	ideal	real.	μ-tag
600 fb^{-1}	0.48	0.88	3.76
6000 fb^{-1}	0.14	0.26	0.97

$t \to qg$

b-tagging	ideal	real.	μ-tag
600 fb^{-1}	22.3	60.8	210.
6000 fb^{-1}	7.04	19.2	66.2

$t \to qZ$

b-tagging	ideal	real.	μ-tag
600 fb^{-1}	0.46	1.1	83.3
6000 fb^{-1}	0.05	0.11	8.3

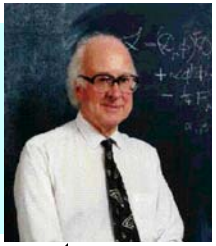
Results in units of 10^{-5}

Ideal = MC 4-vector
Real = B-tagging/cuts as for $10^{34} cm^{-2}s^{-1}$
μ-tag = assume only B-tag with muons works at $10^{35} cm^{-2}s^{-1}$

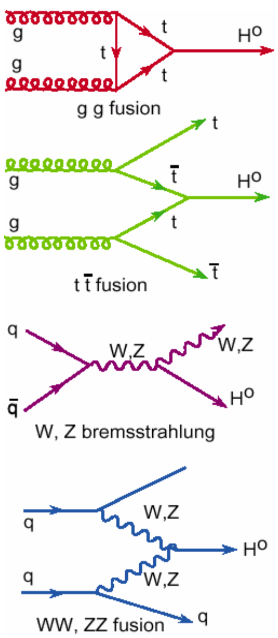
Can reach sensitivity down to ~10^{-6} BUT vertex b-tag a must at $10^{35} cm^{-2}s^{-1}$

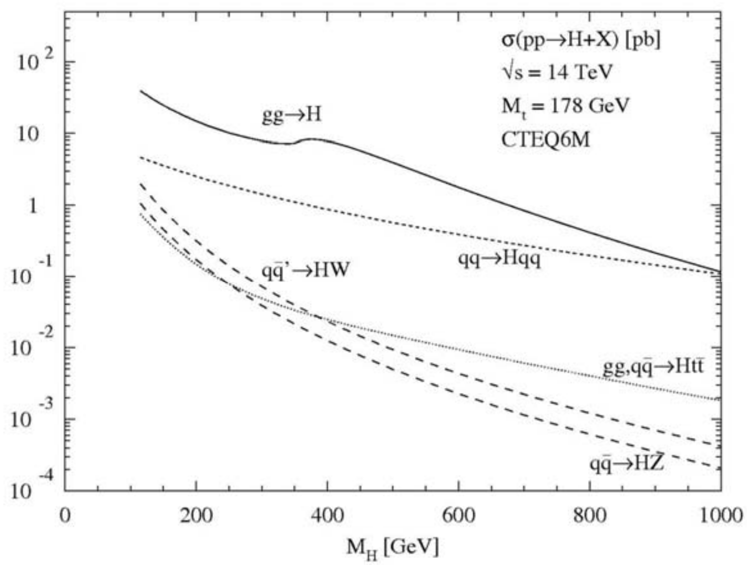
Higgs Physics

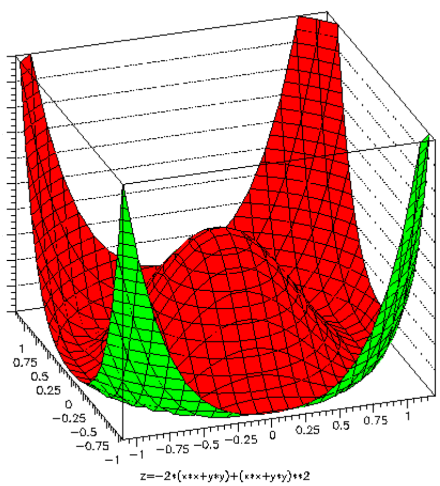
⇒ What is the origin of Electro-weak Symmetry Breaking?
⇒ If Higgs field at least one new scalar particle should exist: The Higgs
One of the main missions of LHC: discover the Higgs for $m_H < 1$ TeV

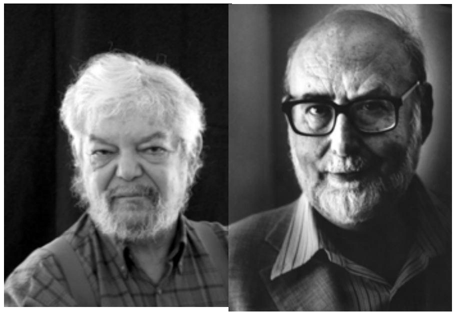


The only Higgs sighted so far



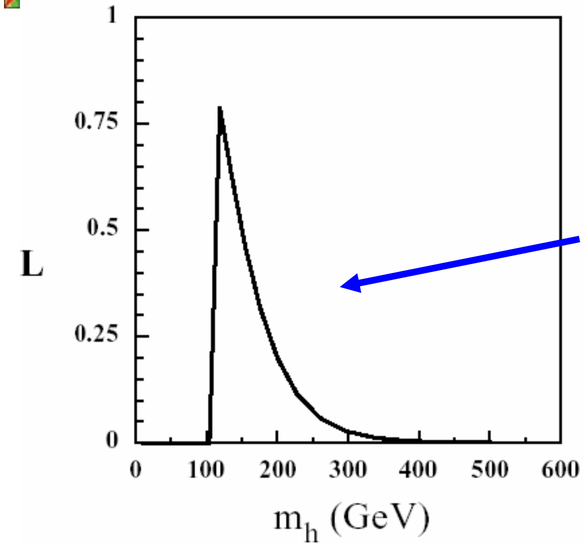




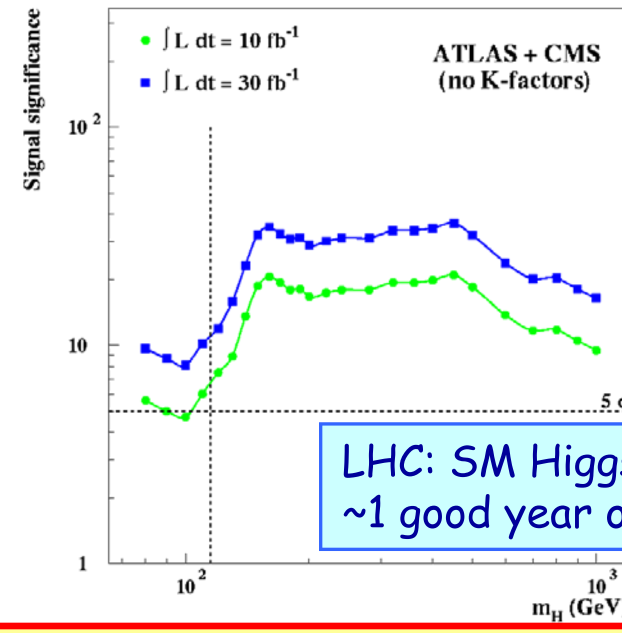


Brout, Englert

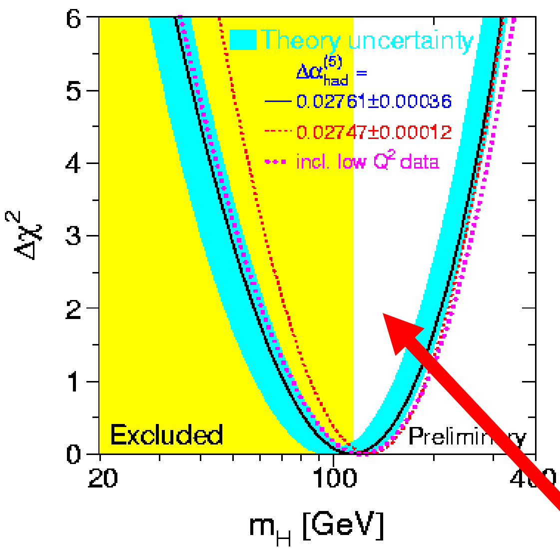
What do we know about the Higgs?



Probability for m_H combining direct and indirect information



LHC: SM Higgs with 10 fb^{-1}
~1 good year of data taking



114.4 < M_{higgs} < 186 GeV

⇒ Light Higgs preferred by EW data
⇒ Light Higgs needed for SUSY (<135 GeV)

Caution … some recent developments

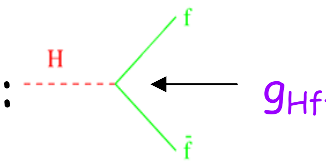
- Higgs + higher dimensional operators
  (→ Higgs could be heavy)
- Higgsless models in Extra Dimensions scenarios
- EW fit criticism…

⇒ A light Higgs is not guaranteed

Higgs at SLHC

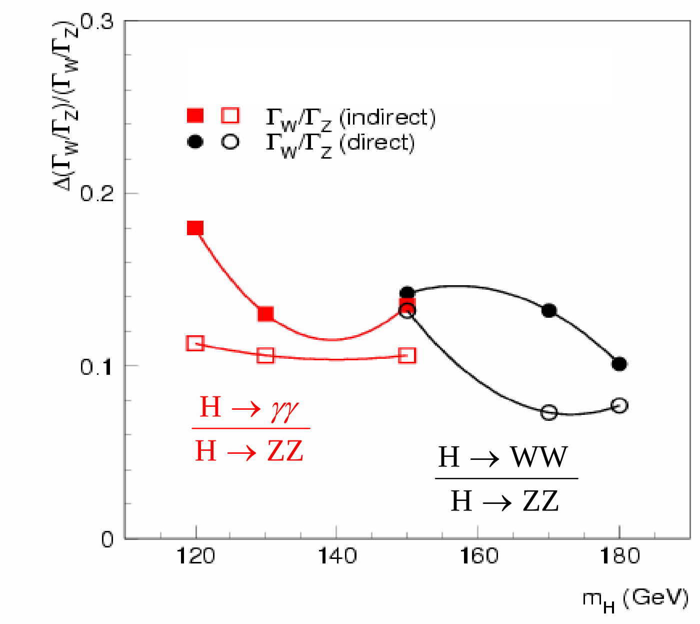
Higgs couplings!

Couplings obtained from measured rate in a given production channel:



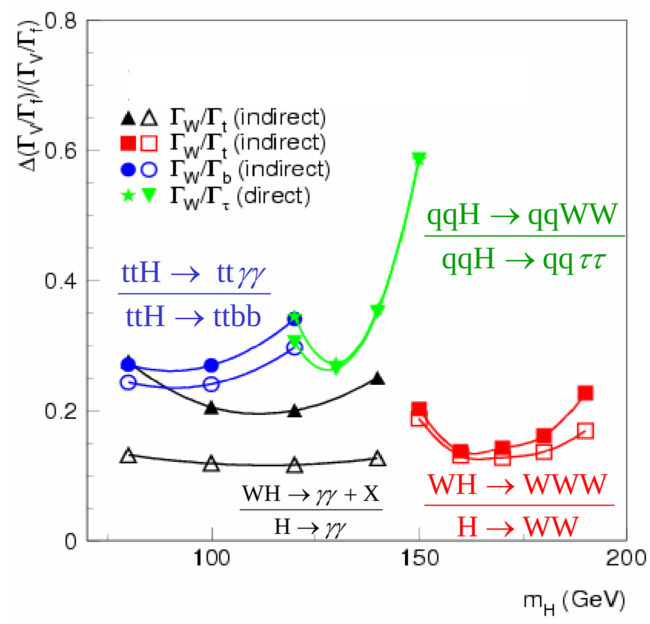
$R_{ff} = \int L\,dt \bullet \sigma\,(e^+e^-, pp \to H + X) \bullet BR\,(H \to ff)$ $\quad BR\,(H \to ff) = \frac{\Gamma_f}{\Gamma_{tot}}$ $\quad \to$ deduce $\Gamma_f \sim g^2_{Hff}$

- Hadron Colliders: Γ_{tot} and σ (pp → H+X) from theory → without theory inputs measure ratios of rates in various channels (Γ_{tot} and σ cancel) → $\Gamma_f/\Gamma_{f'}$



Closed symbols: LHC 600 fb^{-1}

Open symbols: SLHC 6000 fb^{-1}



SLHC could improve LHC precision by up to ~ 2

Rare Higgs Decays Modes

BR ~ 10^{-4} for these channels!
Cross section ~ few fb

Channels studied:

- $H \to Z\gamma \to \ell\ell\gamma$
- $H \to \mu\mu$

m_H (GeV)	$S/\sqrt{B}$	$\frac{\delta\sigma\times BR(H\to\mu\mu)}{\sigma\times BR}$
120 GeV	7.9	0.13
130 GeV	7.1	0.14
140 GeV	5.1	0.20
150 GeV	2.8	0.36

3000 fb^{-1}

Channel	m_H	$S/\sqrt{B}$ LHC ($600\ fb^{-1}$)	$S/\sqrt{B}$ SLHC ($6000\ fb^{-1}$)
$H \to Z\gamma \to \ell\ell\gamma$	~ 140 GeV	~ 3.5	~ 11
$H \to \mu\mu$	130 GeV	~ 3.5 (gg+VBF)	~ 9.5 (gg)

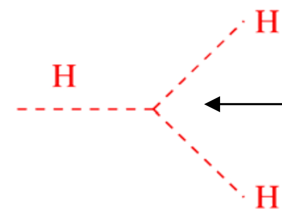
Additional coupling measurements :
e.g. Γ_μ/Γ_W to ~ 20%

Note: also a challenge at a ILC: e.g. $\Delta g_{H\mu\mu}$ ~ 16 % for 1 ab^{-1} at 800 GeV

Higgs Self Coupling Measurements

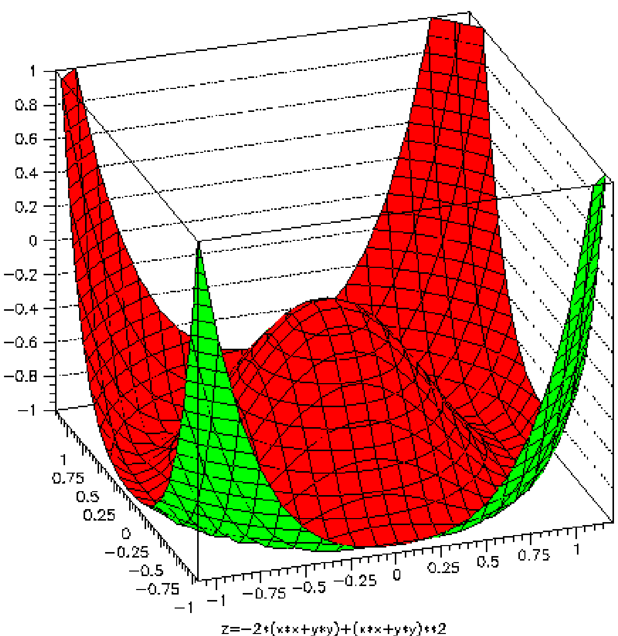
Once the Higgs particle is found, try to reconstruct the Higgs potential

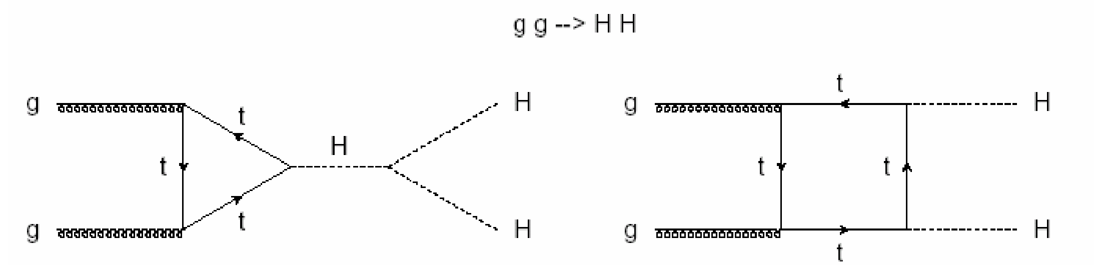
$$V(\Phi) = -\lambda v^2(\Phi^\dagger\Phi) + \lambda(\Phi^\dagger\Phi)^2$$

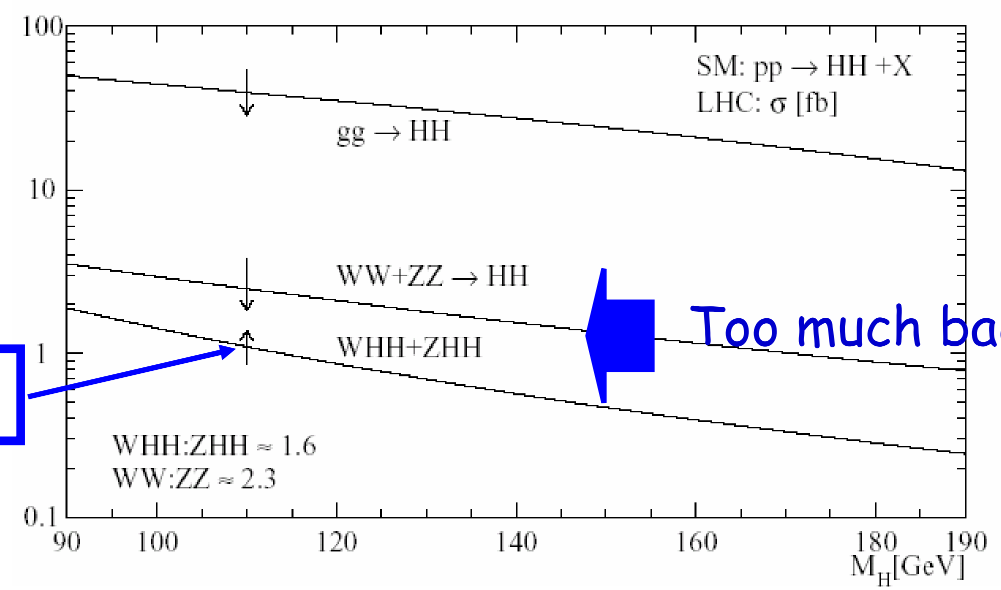


~ λv

$m_H^2 = 2\,\lambda\, v^2$







Djouadi et al.

Dawson et al.

Too much backgr.

$\lambda/2 < \lambda < 3\lambda/2$

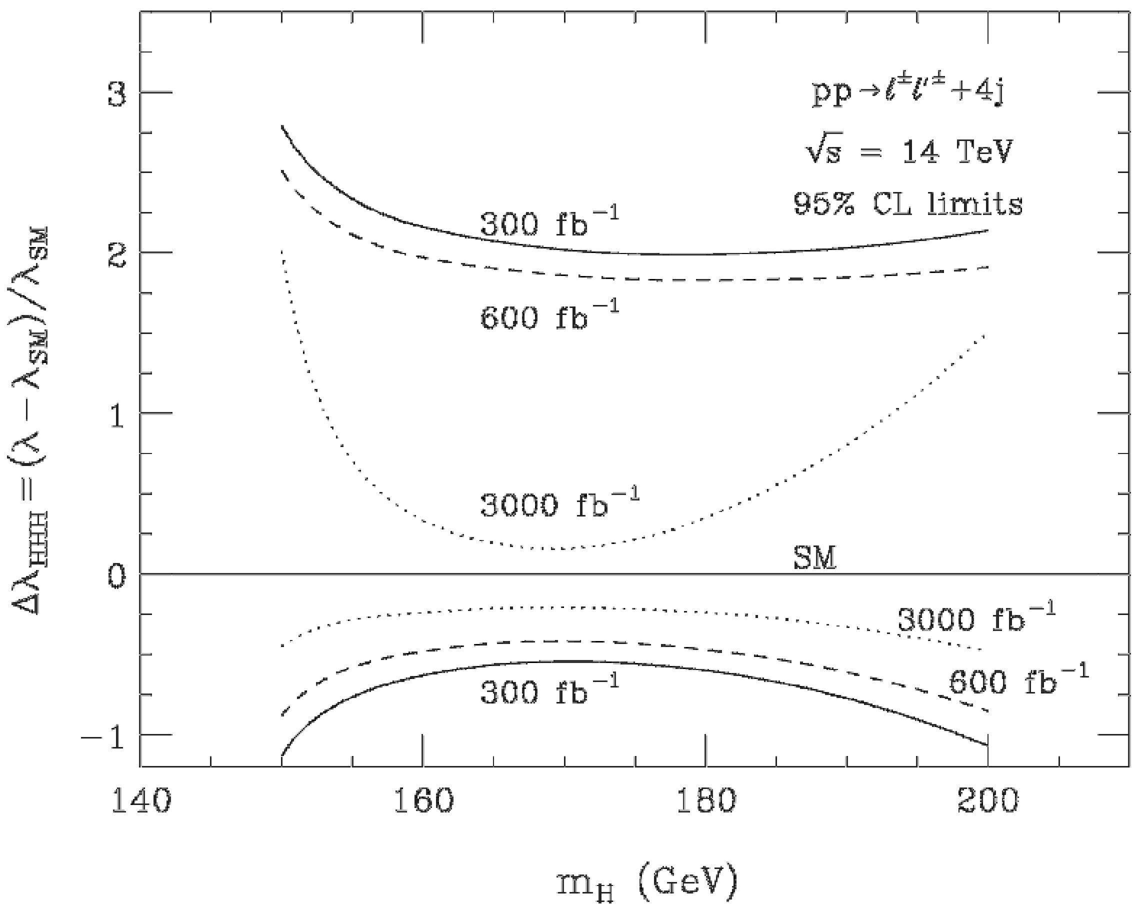
Difficult/impossible at the LHC

Higgs Self Coupling

Baur, Plehn, Rainwater

$HH \to W^+ W^- W^+ W^- \to \ell^\pm \nu jj \ \ \ell^\pm \nu jj$

Limits achievable at the 95% CL. for $\Delta\lambda=(\lambda-\lambda_{SM})/\lambda_{SM}$



LHC: λ= 0 can be excluded at 95% CL.

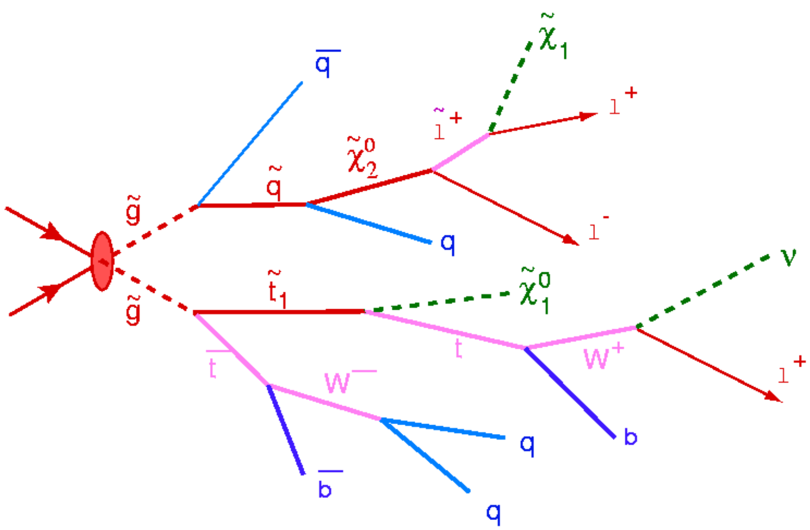
SLHC: λ can be determined to 20-30% (95% CL)

Note: Different conclusion from ATLAS study →no sensitivity at LHC and smaller sensitivity at SLHC. Jury is still out

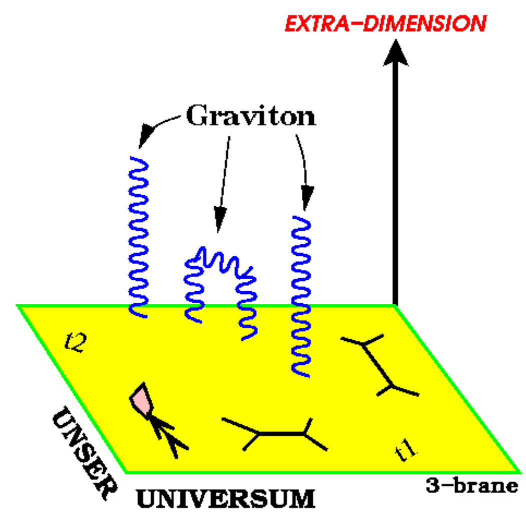
Beyond the Standard Model

New physics expected around the TeV scale ⇒
Stabelize Higgs mass, Hierarchy problem, Unification of gauge couplings, CDM,...

Supersymmetry



Extra dimensions

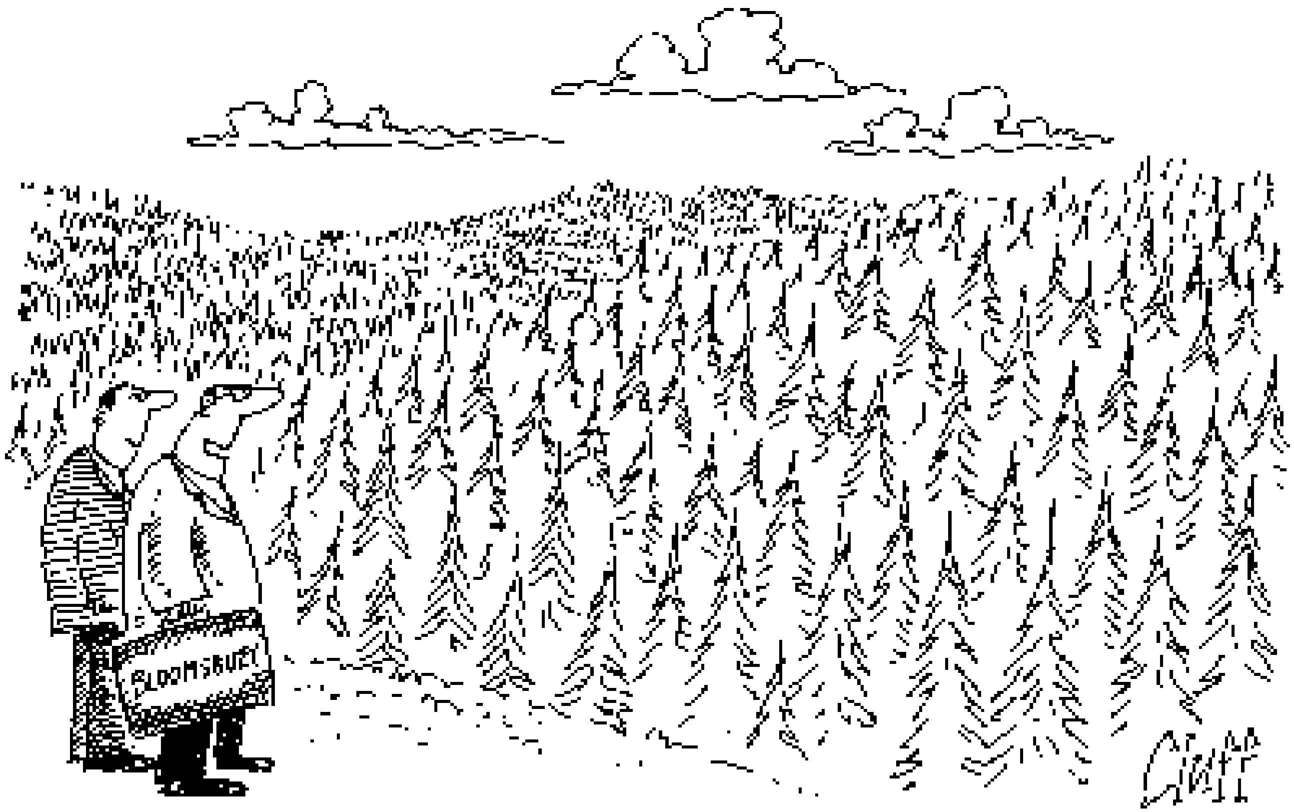


+...

+ a lot of other ideas...
Split SUSY, Little Higgs models, new gauge bosons, technicolor, compositness,..

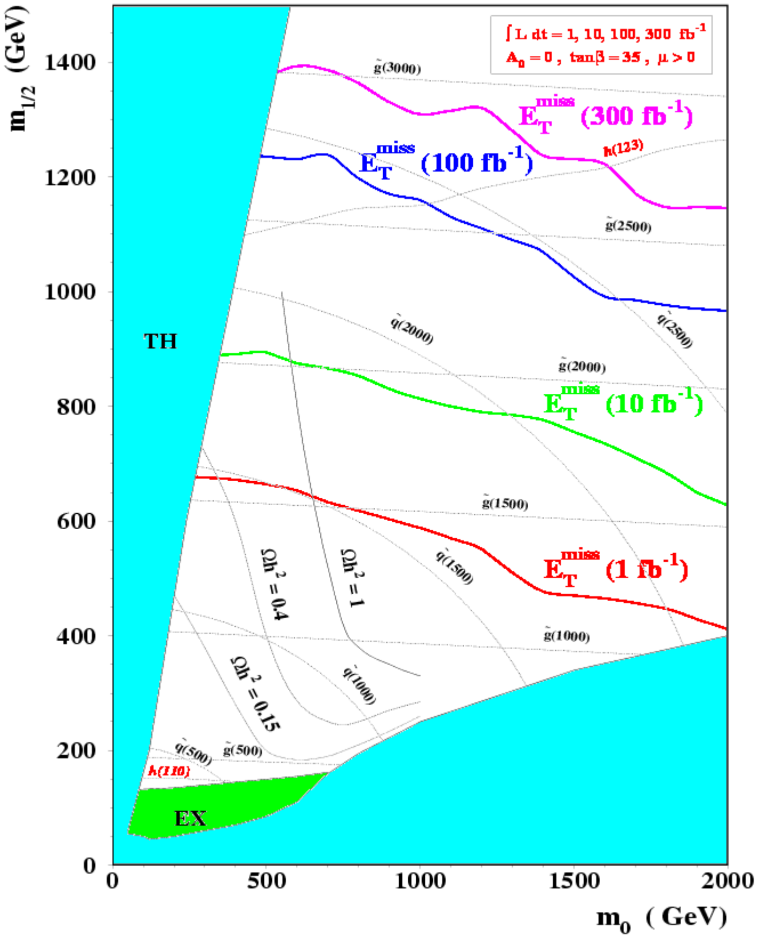
Supersymmetry

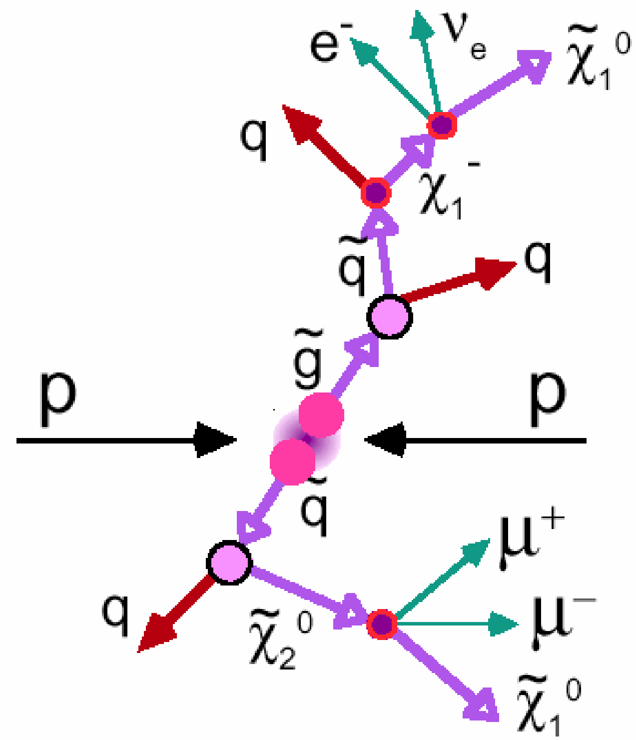
A popular benchmark…



"One day, all of these will be supersymmetric phenomenology papers."

LHC: low scale SUSY discovery





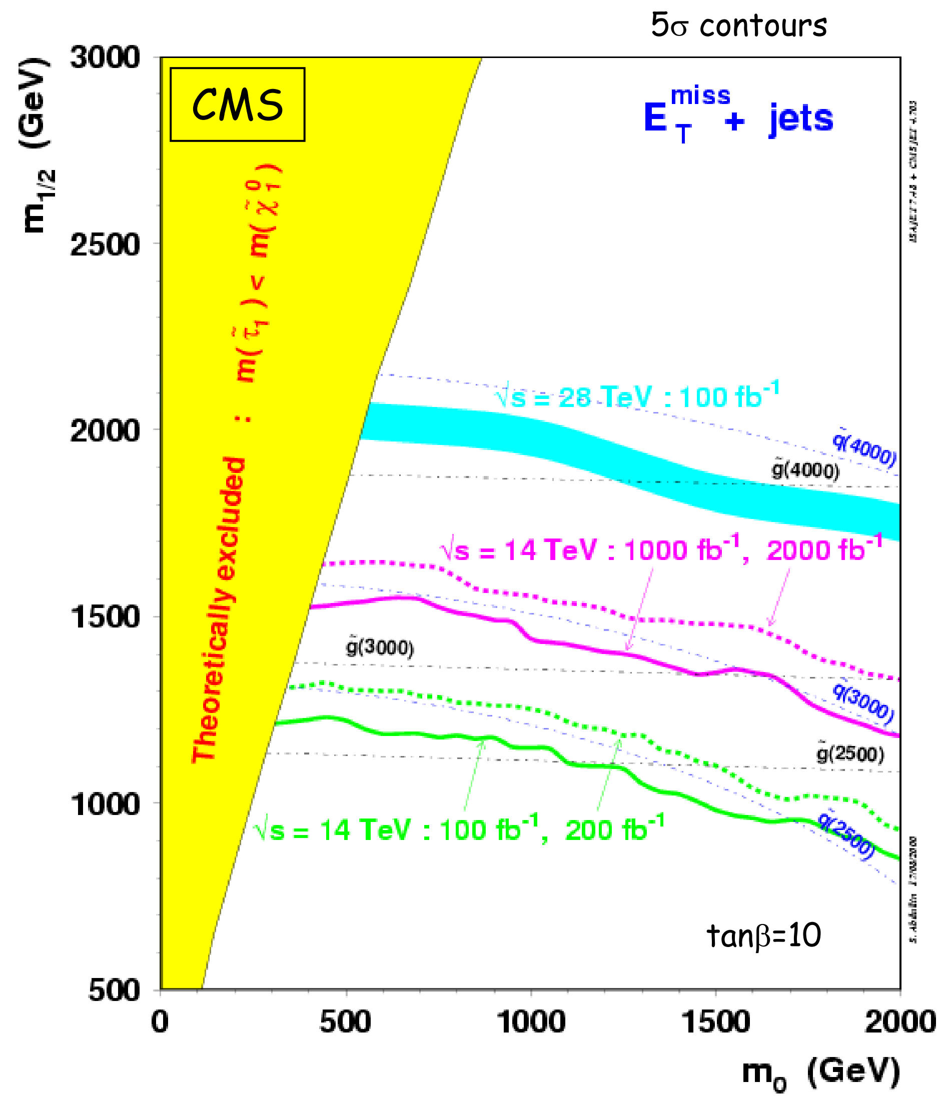
⇒ If low scale SUSY: then large production of squarks/gluinos at the LHC
⇒ LSP responsible for dark matter? Comparison with WMAP to within 15%

Discovery reach
300 fb^{-1}: 2.5-3 TeV
1 fb^{-1}: 1-1.5 TeV already

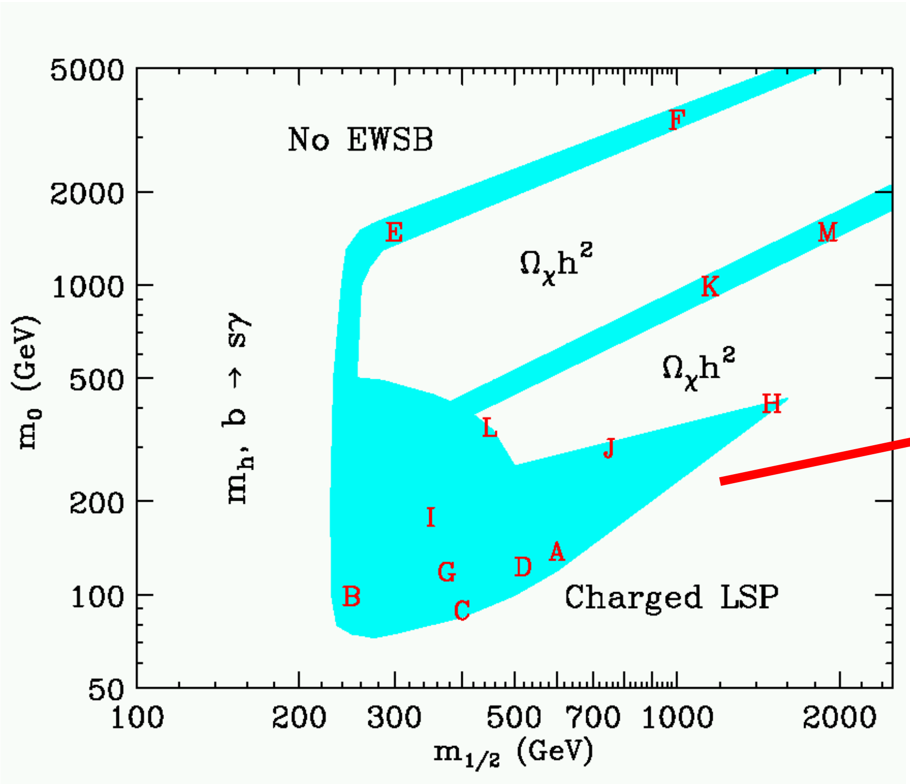
Supersymmetry

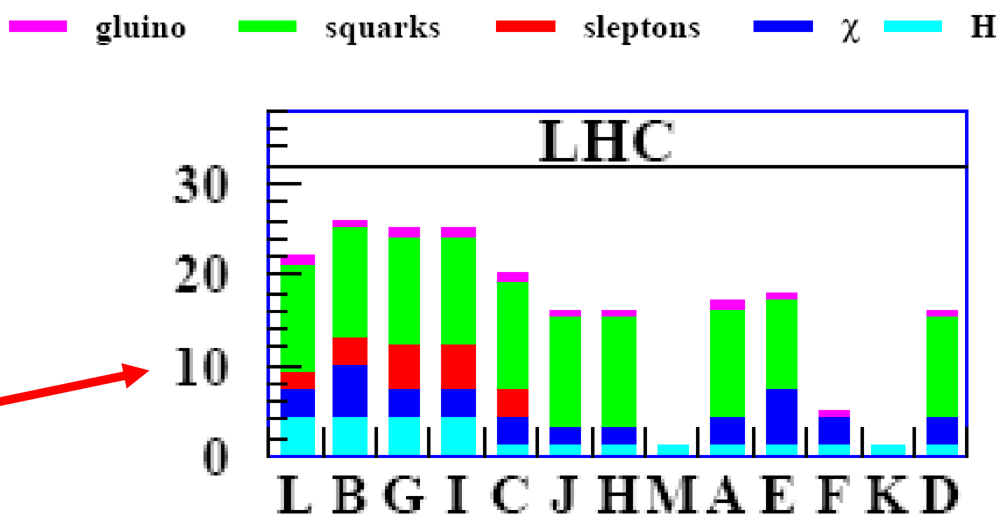
Impact of the SLHC
Extending the discovery region by roughly 0.5 TeV i.e. from
~2.5 TeV → 3 TeV

This extension involved high E_T jets/leptons and missing E_T
⇒ Not compromised by increased pile-up at SLHC



SUSY Measurements





# of particles/species detectable

Benchmark points (Battaglia et al./hep-ph/0306219)
Difficult points F,H,K, (M) …high masses/low event rate
High Luminosity beneficial to complete further the spectra

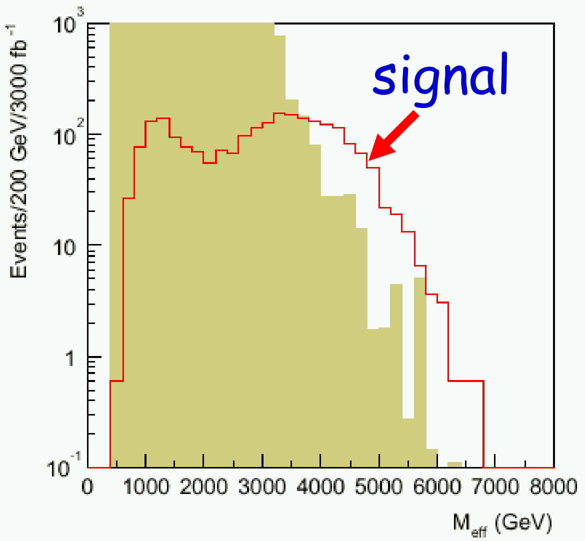
SLHC: tackle difficult points

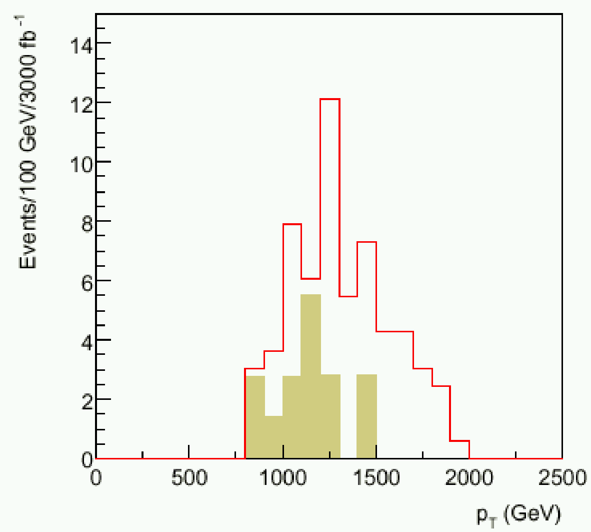
Squarks: 2.0-2.4 TeV   Gluino: 2.5 TeV
Can discover the squarks at the LHC but cannot really study them

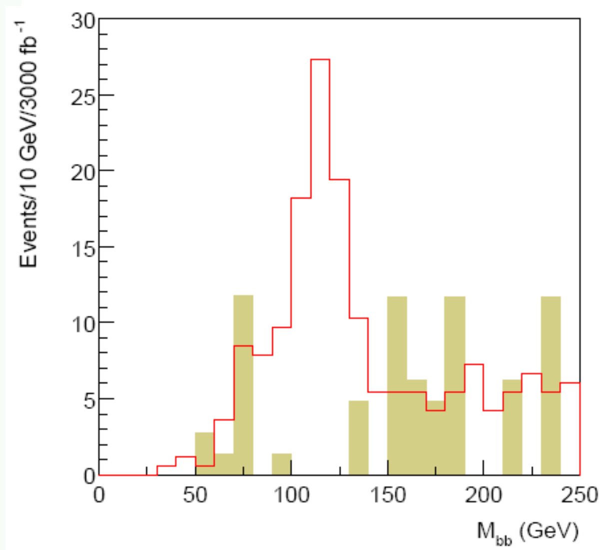
$$M_{eff} = E_T^{miss} + \sum_{jets} E_{T,jet} + \sum_{leptons} E_{T,lepton}$$

P_t >700 GeV & E_t^{miss}>600 GeV
P_t of the hardest jet

eg. Point K in hep-ph/0306219







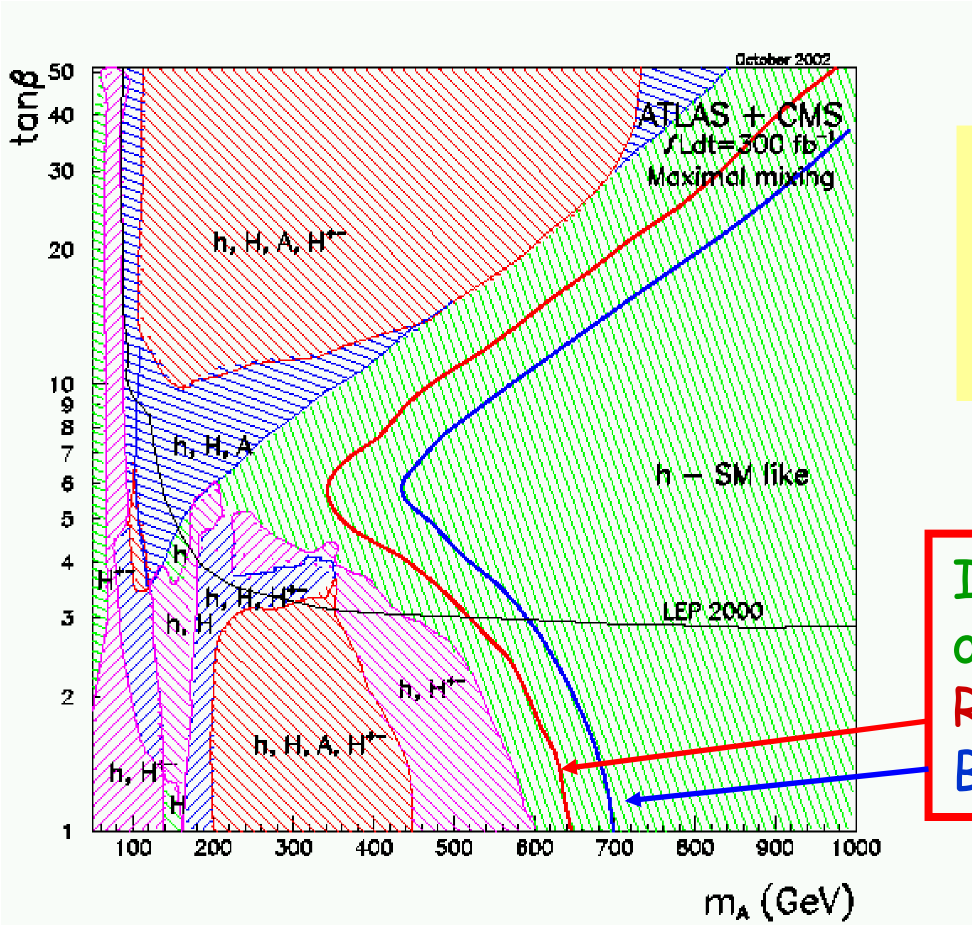
Inclusive: M_{eff} > 4000 GeV
S/B = 500/100 (3000 fb^{-1})

Exclusive channel
$\tilde{q}\tilde{q} \rightarrow \chi_1^0 \chi_1^0 qq$
S/B =120/30 (3000fb^{-1})

Higgs in χ_2 decay
$\chi_2 \rightarrow \chi_1 h$ becomes
Visible at 3000 fb^{-1}

Measurements become possible

MSSM Higgs h,H,A,H$^{\pm}$

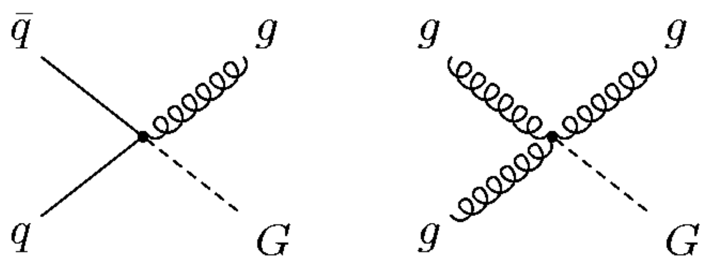


Minimal supersymmetric model
Introduces two complex higgs doublets
→ 5 Higgs particles h,H,A,H$^{\pm}$
H = CP even/ A = CP odd

In the green region only SM-like h observable with 300 fb^{-1}/exp
Red line: extension with 3000 fb^{-1}/exp
Blue line: 95% excl. with 3000 fb^{-1}/exp

Heavy Higgs observable region increased by ~100 GeV.

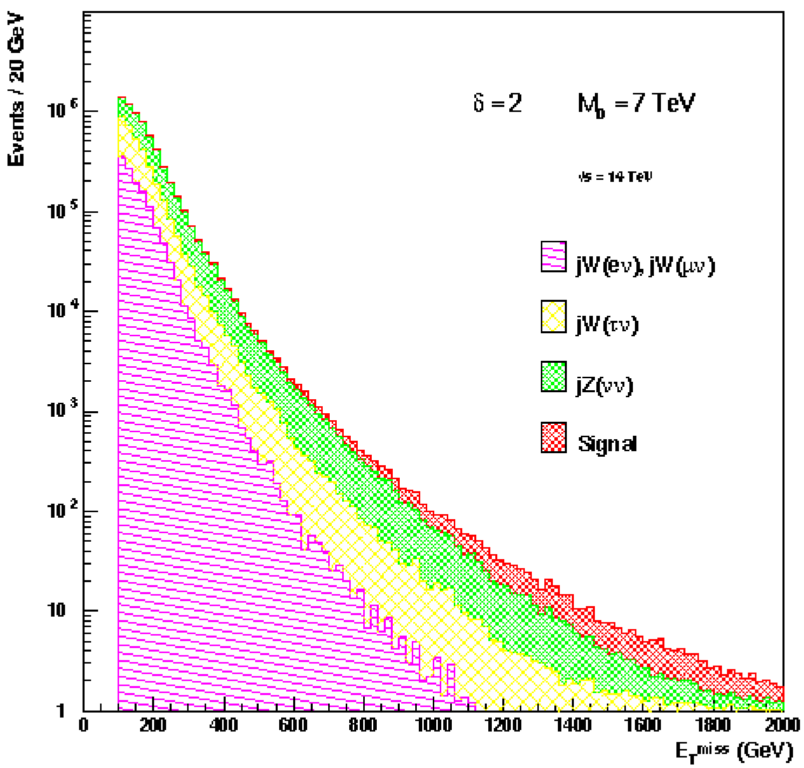
Extra Dimension Signals at the LHC

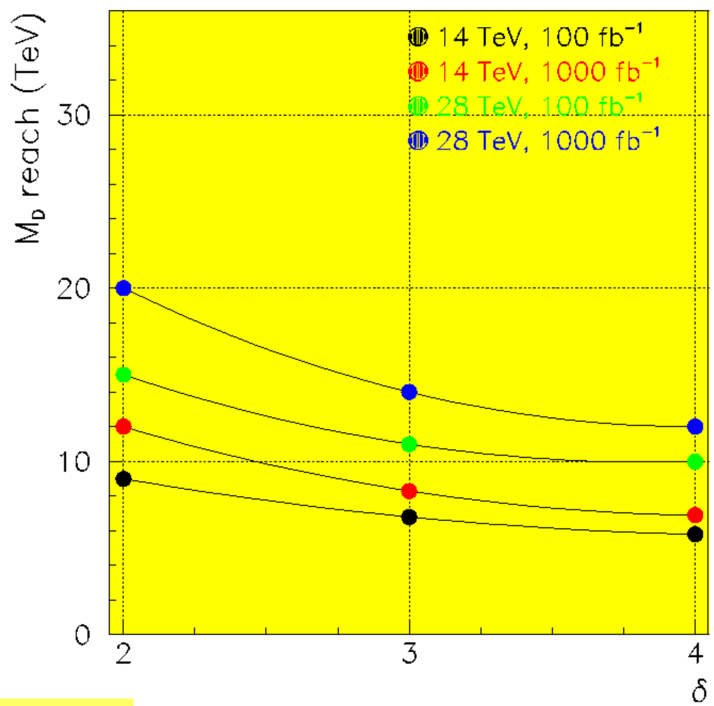


Graviton production!
Graviton escapes detection

ADD type of Extra Dimensions

Signal: single jet + large missing ET

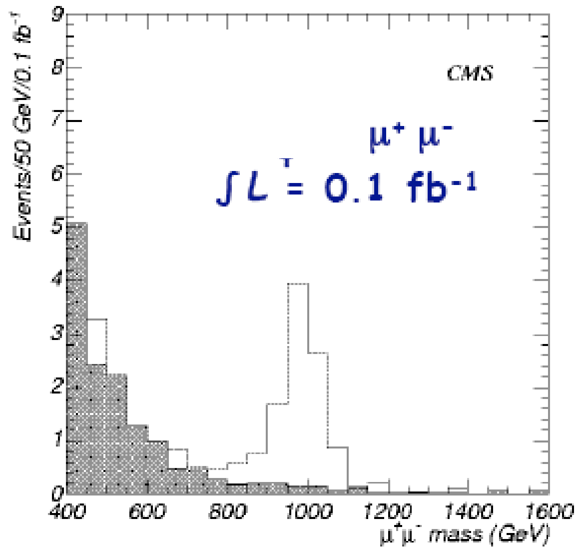




About 25% increase in reach

Di-lepton Resonance Production

May be seen very early: first weeks of the LHC



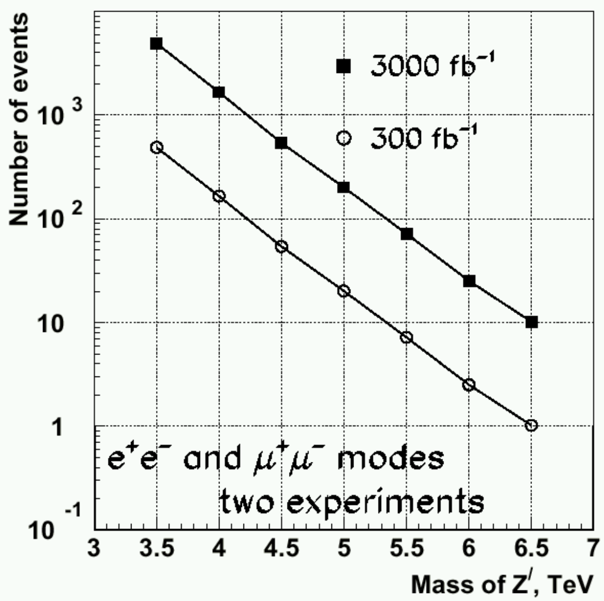
Example : The Di-lepton channel

- Z′ (New gauge bosons)
- A_H, Z_H (Little Higgs)
- $G^{(1)}$ (Randall-Sundrum)
- $\gamma^{(1)}/Z^{(1)}$ (TeV^{-1} Extra Dimensions)
- $G^{(KK)}$ (ADD)
- ...

SLHC: New Z' Gauge Bosons

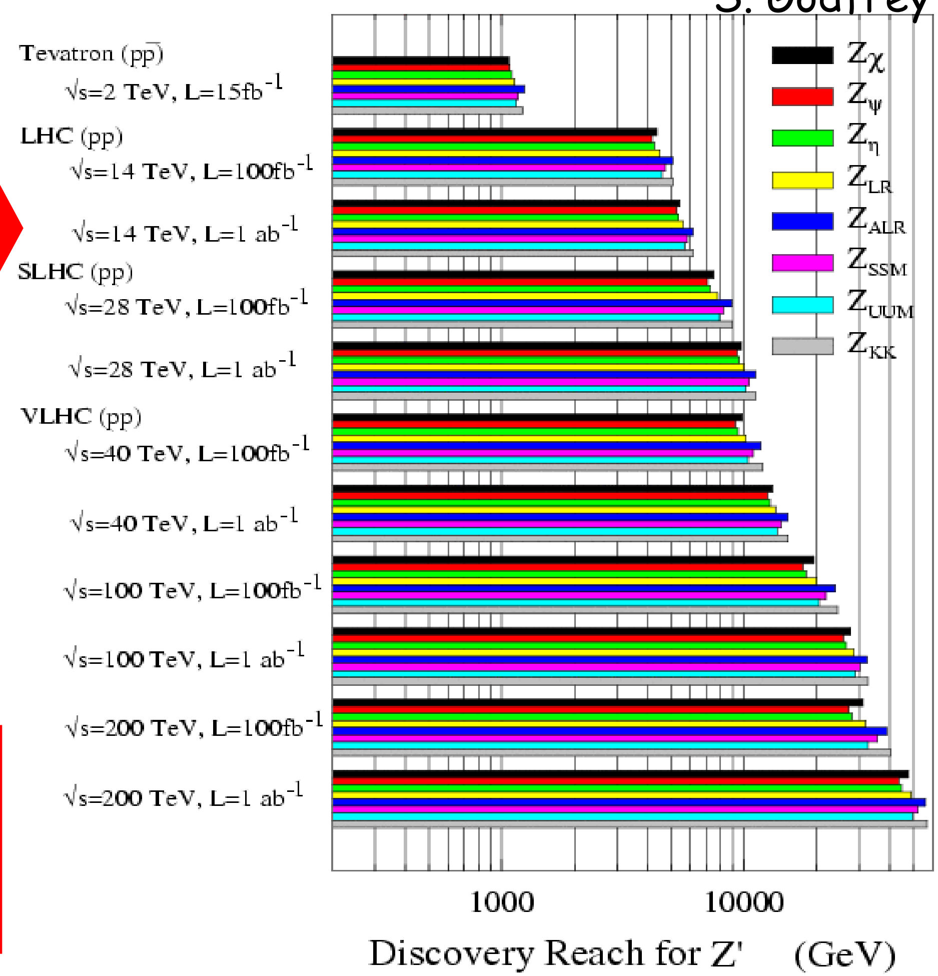
Z' mass (TeV)	1	2	3	4	5	6
$\sigma(Z' \to e^+e^-)(fb)$	512	23.9	2.5	0.38	0.08	0.026
$\Gamma_{Z'}$ (GeV)	30.6	62.4	94.2	126.1	158.0	190.0

with Z-like couplings



Includes pile-up, ECAL saturation...

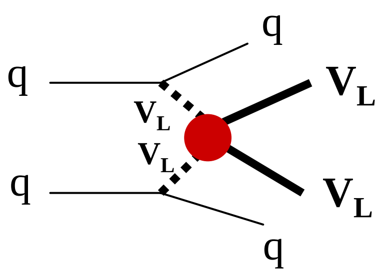
S. Godfrey



Reach:	LHC/600 fb^{-1}	5.3 TeV
	SLHC/6000 fb^{-1}	6.5 TeV
	DLHC/600 fb^{-1}	8 TeV

Strongly Coupled Vector Boson System

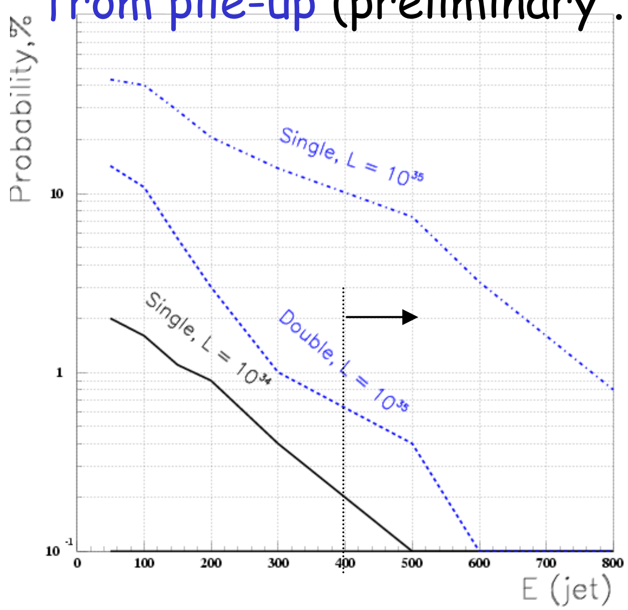
If no Higgs, expect strong $V_L V_L$ scattering (resonant or non-resonant) at $\sqrt{\hat{s}} \approx$ TeV

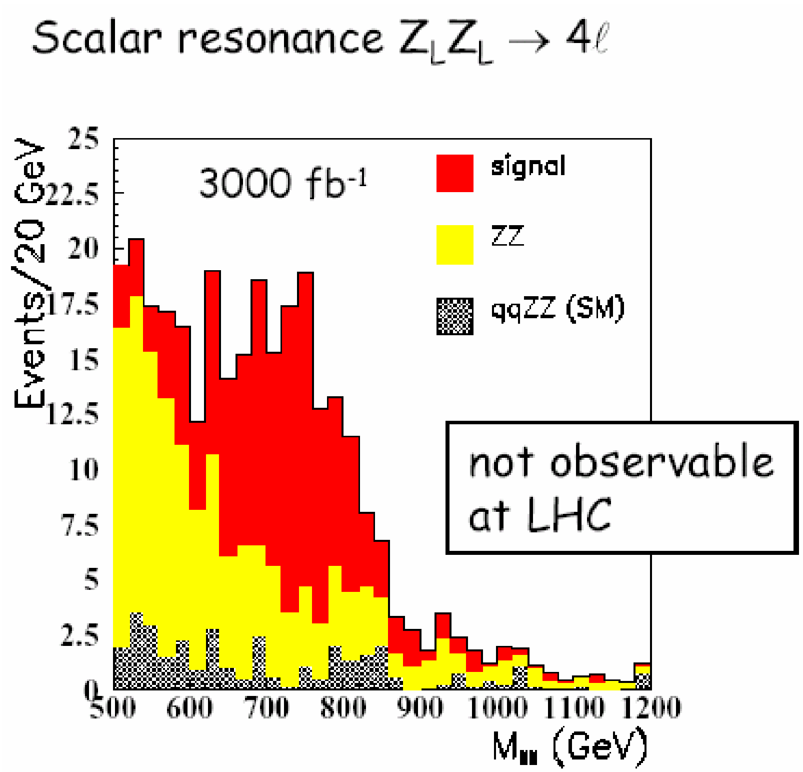


Difficult at LHC. What about SLHC?

- degradation of fwd jet tag and central jet veto due to huge pile-up
- BUT : factor ~ 10 in statistics $\rightarrow$ 5-8σ excess in $W^+_L\ W^+_L$ scattering
  $\rightarrow$ other low-rate channels accessible

Fake fwd jet tag ($|\eta|$ > 2) probability from pile-up (preliminary ...)

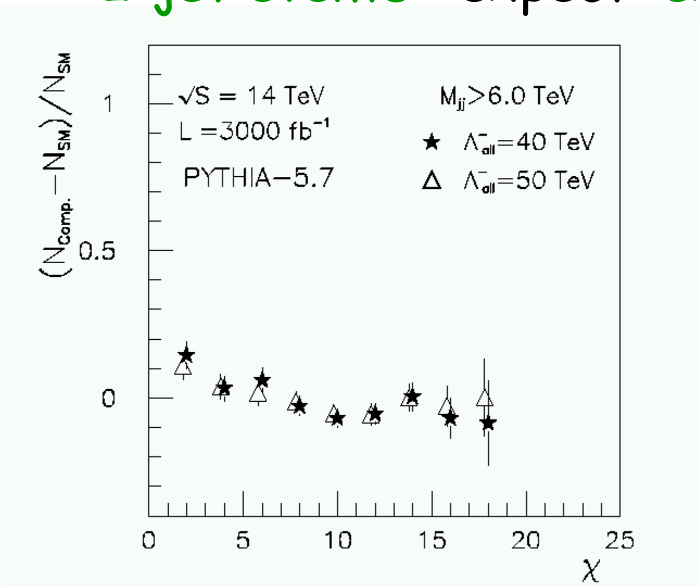


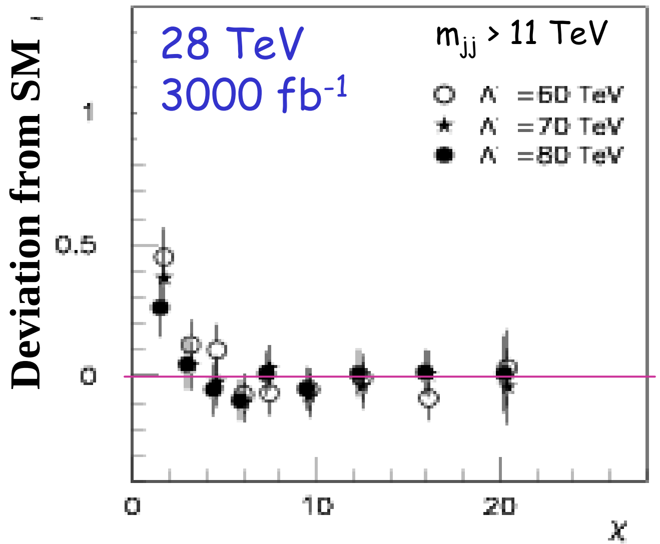


Compositeness

$\sqrt{\hat{s}} << \Lambda$: contact interactions $qq \to qq$

2-jet events: expect excess of high-E_T centrally produced jets.





$$\chi = \frac{1+|\cos\theta^*|}{1-|\cos\theta^*|}$$

θ^* angle btw jet & beam
If contact interactions
→ excess at low χ

95% CL	14 TeV 300 fb^{-1}	14 TeV 3000 fb^{-1}	28 TeV 300 fb^{-1}	28 TeV 3000 fb^{-1}
Λ (TeV)	40	60	60	≈ 85

- For this study, no major detector upgrade needed at SLHC (but b-jet tag may be important)

Indicative Physics Reach

Ellis, Gianotti, ADR
hep-ex/0112004+ few updates

Units are TeV (except $W_L W_L$ reach)

☞ $\int Ldt$ correspond to 1 year of running at nominal luminosity for 1 experiment

PROCESS	LHC 14 TeV 100 fb^{-1}	SLHC 14 TeV 1000 fb^{-1}	28 TeV 100 fb^{-1}	VLHC 40 TeV 100 fb^{-1}	VLHC 200 TeV 100 fb^{-1}	LC 0.8 TeV 500 fb^{-1}	LC 5 TeV 1000 fb^{-1}
Squarks	2.5	3	4	5	20	0.4	2.5
$W_L W_L$	2σ	4σ	4.5σ	7σ	18σ	6σ	90σ
Z'	5	6	8	11	35	8†	30†
Extra-dim (δ=2)	9	12	15	25	65	5-8.5†	30-55†
q*	6.5	7.5	9.5	13	75	0.8	5
Λcompositeness	30	40	40	50	100	100	400
TGC (λ_γ)	0.0014	0.0006	0.0008		0.0003	0.0004	0.00008

† indirect reach
(from precision measurements)

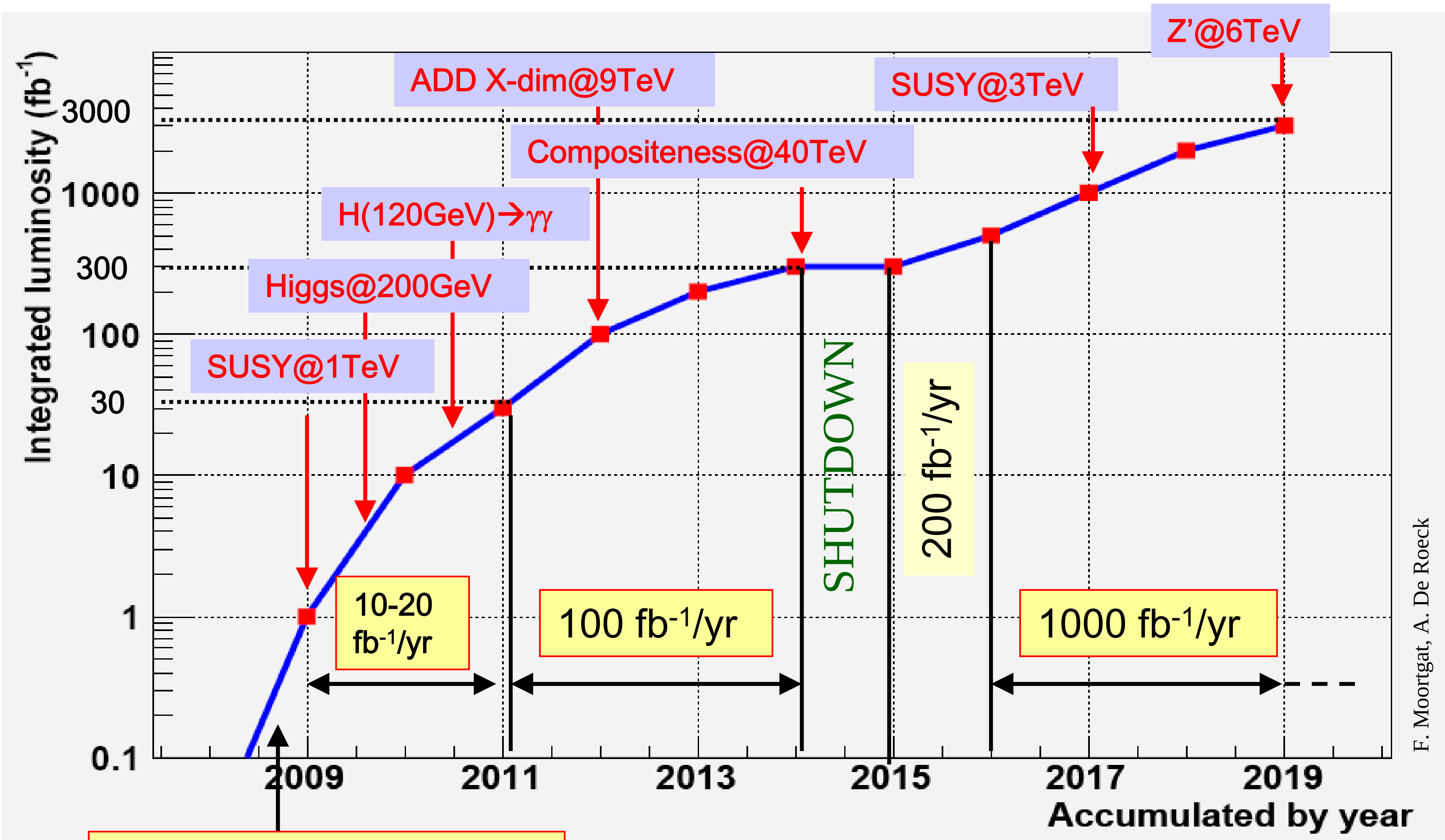
Approximate mass reach machines:

$\sqrt{s}$ = 14 TeV, $L=10^{34}$ (LHC) : up to ≈ 6.5 TeV

$\sqrt{s}$ = 14 TeV, $L=10^{35}$ (SLHC) : up to ≈ 8 TeV

$\sqrt{s}$ = 28 TeV, $L=10^{34}$: up to ≈ 10 TeV

LHC Luminosity/Sensitivity Evolution?



First physics run: O(1fb^{-1})

Summary: LHC Upgrade

The LHC luminosity upgrade to 10^{35} $cm^{-2}s^{-1}$

- Extend the LHC discovery mass range by 25-30% (SUSY,Z',,EDs)
- Higgs self-coupling (20-30%)
- Rear decays: $H\rightarrow\mu\mu$, γZ, top decays…
- Improved Higgs coupling ratios,…
- TGC precision measurements…

In general: SLHC looks like giving a good physics return for modest cost, basically independent of the physics scenario chosen by Nature

$\Rightarrow$ Looks like a natural upgrade of the machine

- It will be a challenge for the experiments!
- Needs detector R&D starting now: Tracking, electronics, trigger, endcaps, radiation, shielding…
- CMS and ATLAS started working groups

$\Rightarrow$This will be the subject of the next lectures

Backup Slides: some more physics

Electroweak Physics

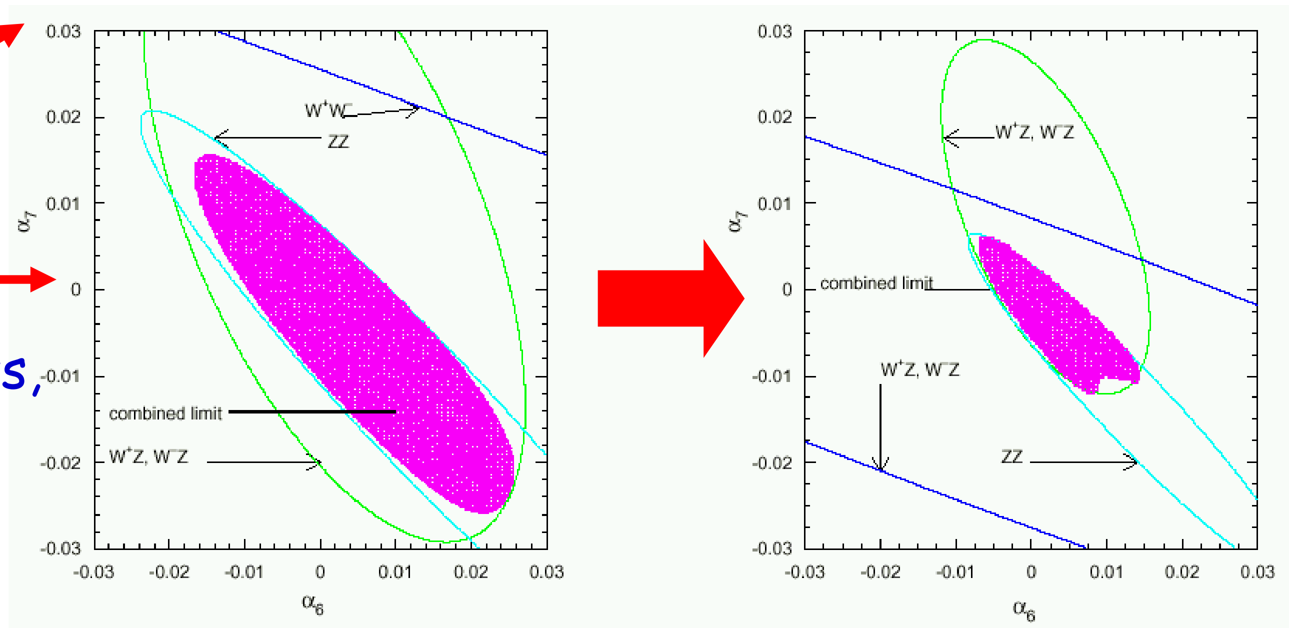
Quartic Gauge Couplings   study pp $\rightarrow$ qqVV $\rightarrow$jjVV   (V=W,Z)

A. S. Belyaev et al:
Operators leading to genuine quartic vertices

$$\mathcal{L}_4 = \alpha_4 \left[\mathrm{Tr}\left(V_\mu V_\nu\right)\right]^2 ,$$
$$\mathcal{L}_5 = \alpha_5 \left[\mathrm{Tr}\left(V_\mu V^\mu\right)\right]^2 ,$$
$$\mathcal{L}_6 = \alpha_6 \,\mathrm{Tr}\left(V_\mu V_\nu\right) \mathrm{Tr}\left(TV^\mu\right) \mathrm{Tr}\left(TV^\nu\right) ,$$
$$\mathcal{L}_7 = \alpha_7 \,\mathrm{Tr}\left(V_\mu V^\mu\right) \left[\mathrm{Tr}\left(TV^\nu\right)\right]^2 ,$$
$$\mathcal{L}_{10} = \frac{\alpha_{10}}{2} \left[\mathrm{Tr}\left(TV_\mu\right)\ \mathrm{Tr}\left(TV_\nu\right)\right]^2 .$$

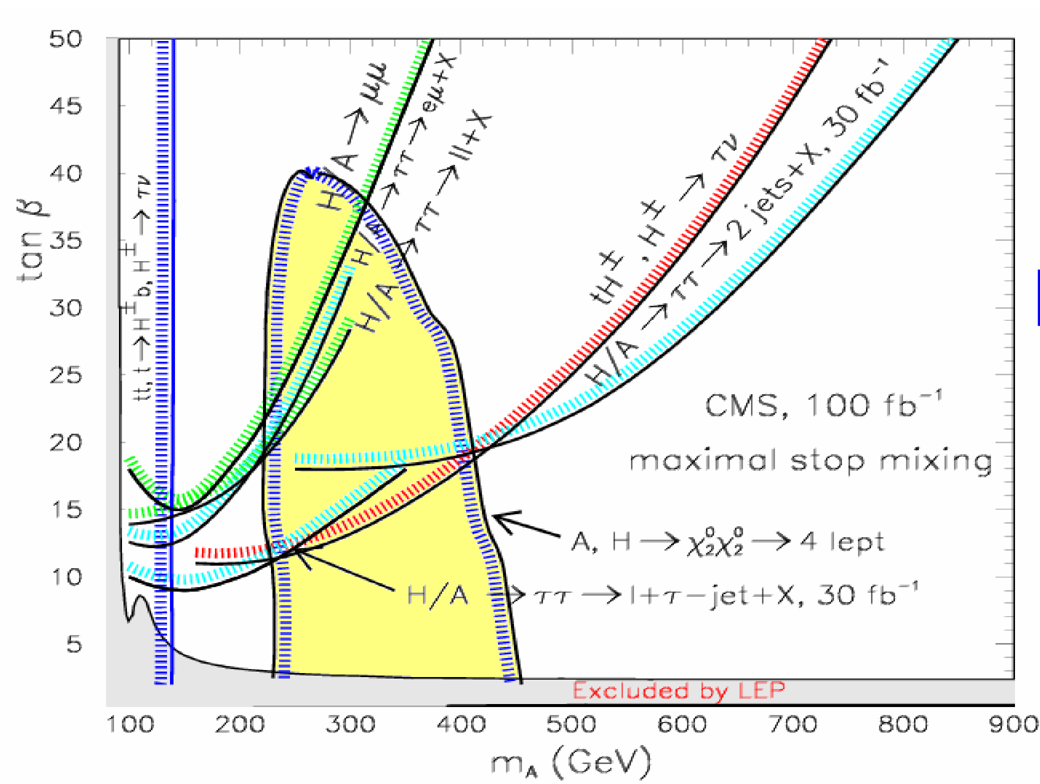
Coupling	Indirect Limits (1σ) ($\times 10^{-3}$)	LHC, 100 fb^{-1} (1σ) ($\times 10^{-3}$)	LHC, 6000 fb^{-1} (1σ) ($\times 10^{-3}$)	LHC, 6000 fb^{-1} 95% C.L. ($\times 10^{-3}$)
α_4	$-120. \le \alpha_4 \le 11.$	$-1.1 \le \alpha_4 \le 11.$	$-0.67 \le \alpha_4 \le 0.74$	$-0.92 \le \alpha_4 \le 1.1$
α_5	$-300. \le \alpha_5 \le 28.$	$-2.2 \le \alpha_5 \le 7.7$	$-1.2 \le \alpha_5 \le 1.2$	$-1.7 \le \alpha_5 \le 1.7$
α_6	$-20. \le \alpha_6 \le 1.8$	$-9.6 \le \alpha_6 \le 9.1$	$-3.5 \le \alpha_6 \le 3.2$	$-4.3 \le \alpha_6 \le 3.9$
α_7	$-19. \le \alpha_7 \le 1.8$	$-10. \le \alpha_7 \le 7.4$	$-4.4 \le \alpha_7 \le 2.2$	$-5.4 \le \alpha_7 \le 2.8$
α_{10}	$-21. \le \alpha_{10} \le 1.9$	$-24. \le \alpha_{10} \le 24.$	$-4.1 \le \alpha_{10} \le 4.1$	$-4.8 \le \alpha_{10} \le 4.8$

Results for events with full leptonic decays, P_t>20 GeV/c, $|\eta|$<2.5, 90% eff. (conservative)

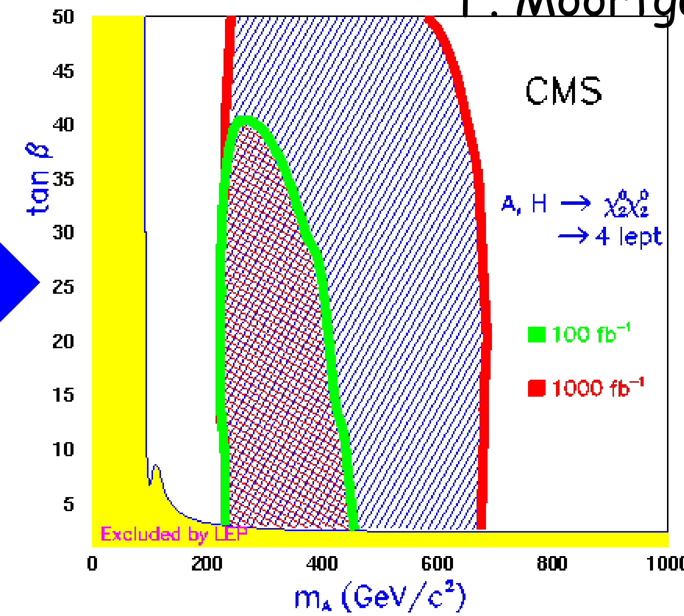


Other ways to 'cover the wedge'

Use decays of H,A into SUSY particles, where kin. allowed



F. Moortgat



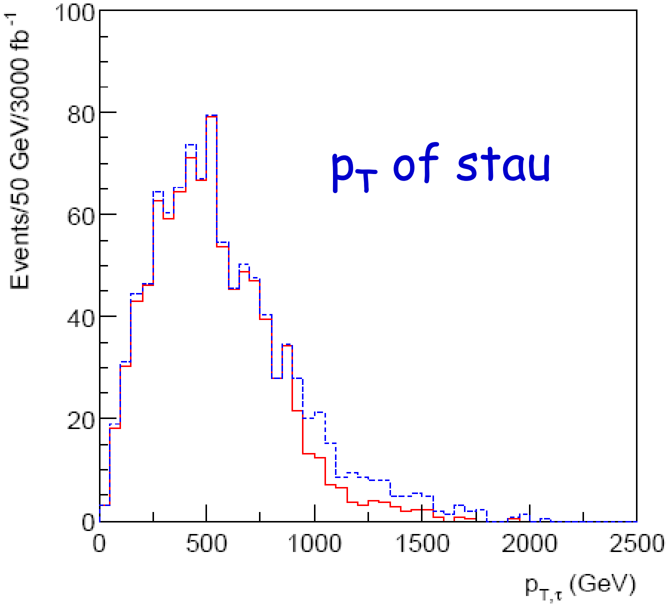
$A/H \rightarrow \chi\chi \rightarrow 4$ leptons

Strongly model/MSSM parameter dependent

$M_2 = 120$ GeV,
$\mu = -500$ GeV,
$M_{sleptons} = 2500$ GeV,
$M_{squark,\ gluino} = 1$TeV

SLHC: tackle difficult points

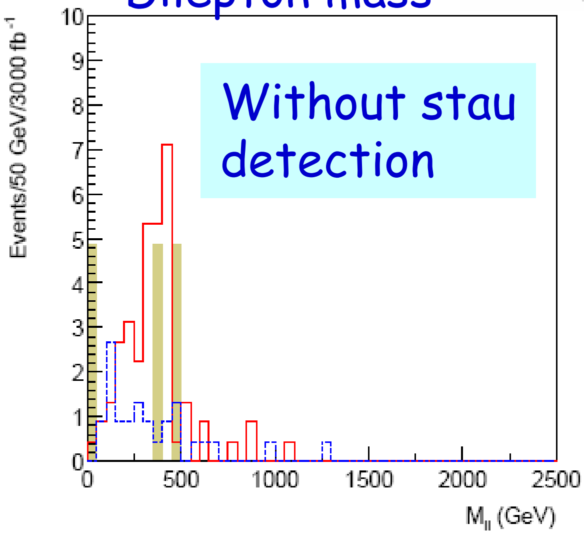
eg. Point H in hep-ph/0306219

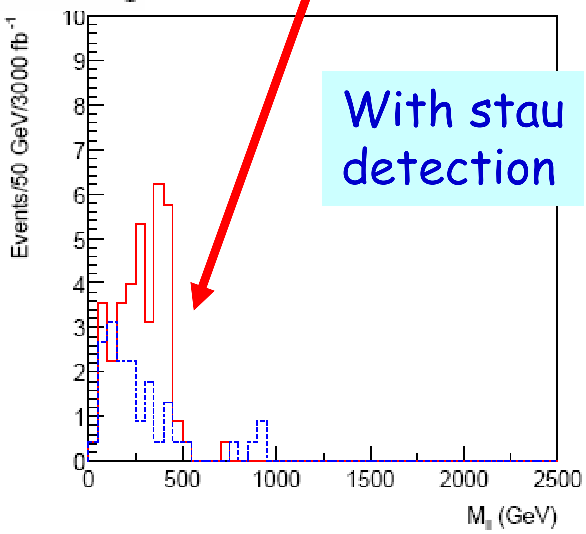


Squarks, gluino mass > 2.5 TeV
χ-stau mass difference small < 1 GeV
$\Rightarrow$ Stau lives long

$$\sqrt{\frac{(M^2_{\tilde{\chi}^0_2} - M^2_{\tilde{\ell}_L})(M^2_{\tilde{\ell}_L} - M^2_{\tilde{\chi}^0_1})}{M^2_{\tilde{\ell}_L}}} = 447.3\,\mathrm{GeV}$$

Dilepton mass $\tilde{q}_L \to q\tilde{\chi}^0_2 \to q\ell^+\ell^-\tilde{\chi}^0_1$.





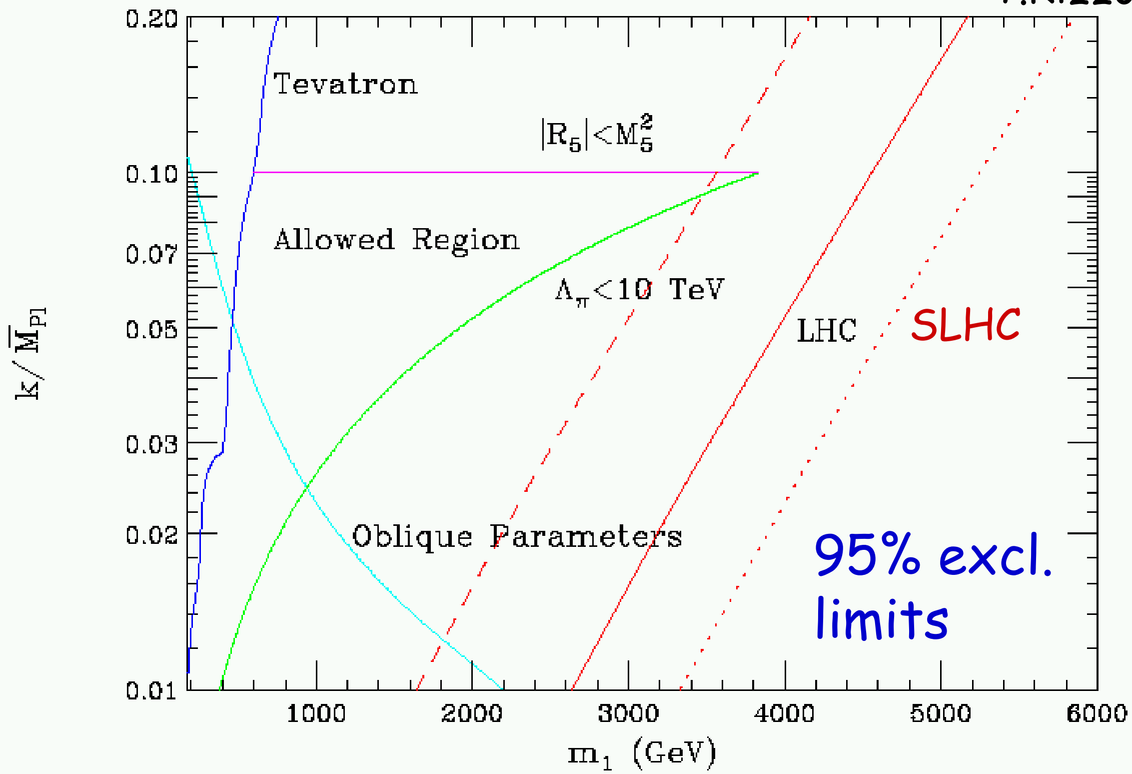
End point measurements are possible with large luminosity

SLHC: KK gravitons

Randall Sundrum model

- Predicts KK graviton resonances
- k= curvature of the 5-dim. Space
- m_1 = mass of the first KK state

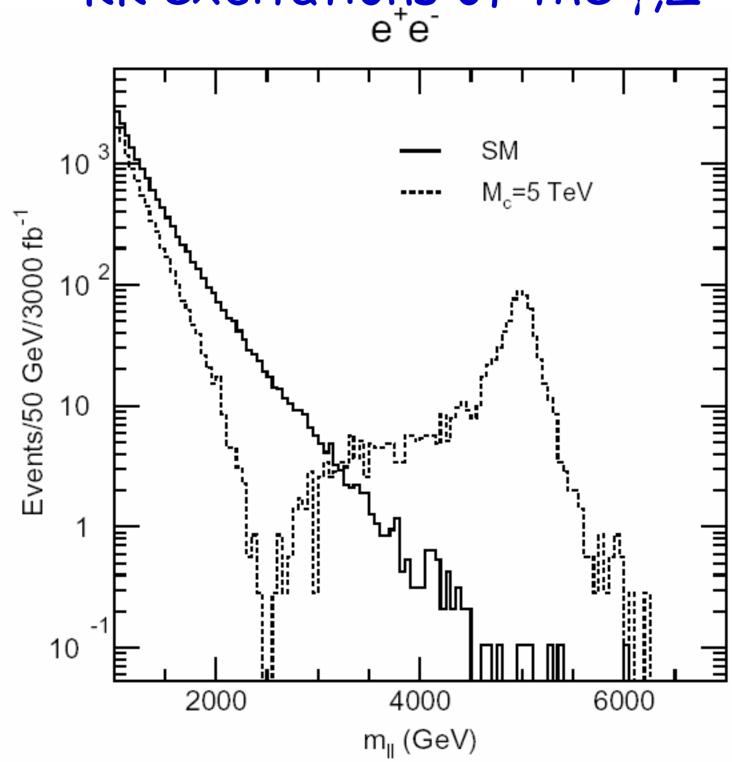
T.Rizzo



100→1000 fb^{-1}: Increase in reach by 25%

TeV scale ED's

- KK excitations of the γ,Z

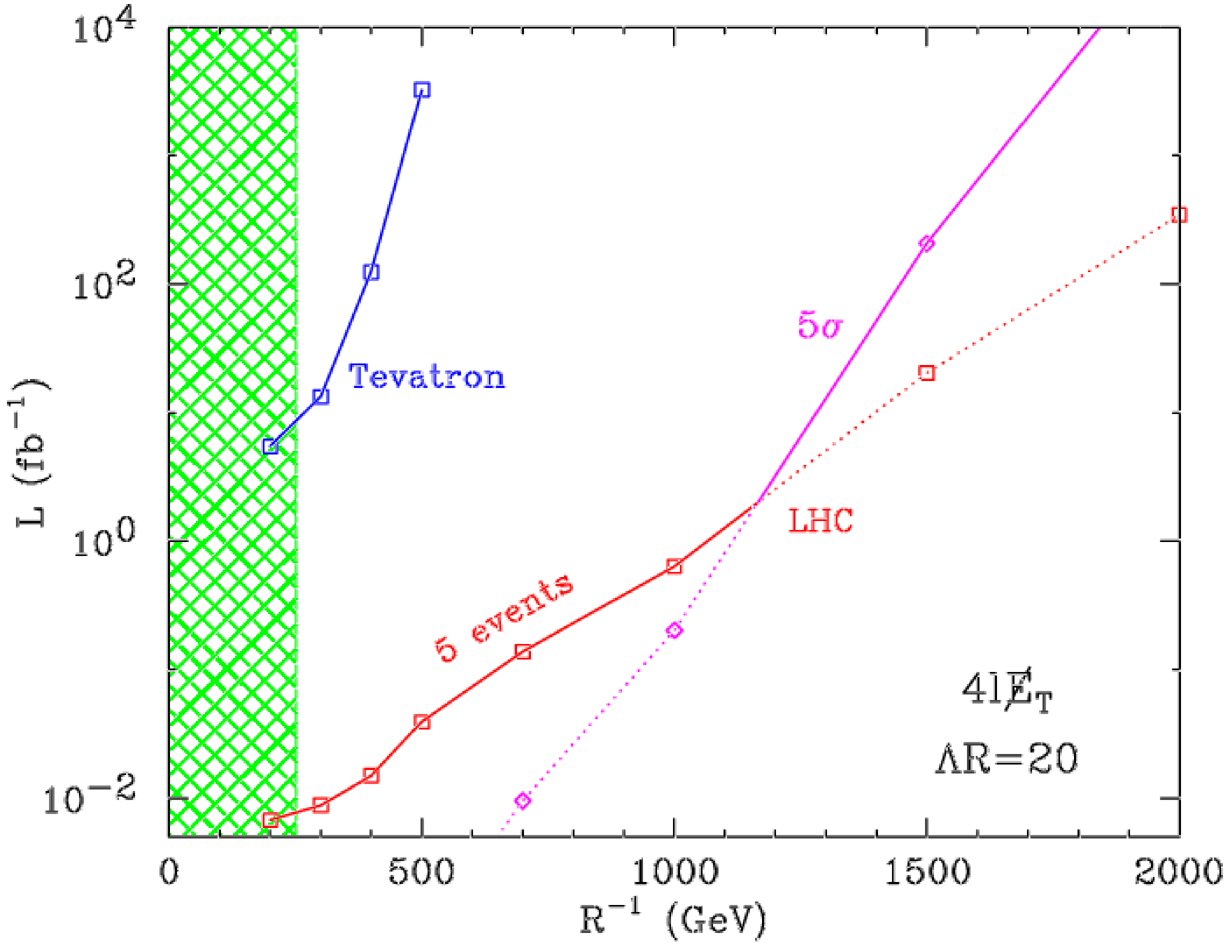


Direct: LHC/600 fb^{-1} 6 TeV
SLHC/6000 fb^{-1} 7.7 TeV
Interf:SLHC/6000 fb^{-1} 20 TeV

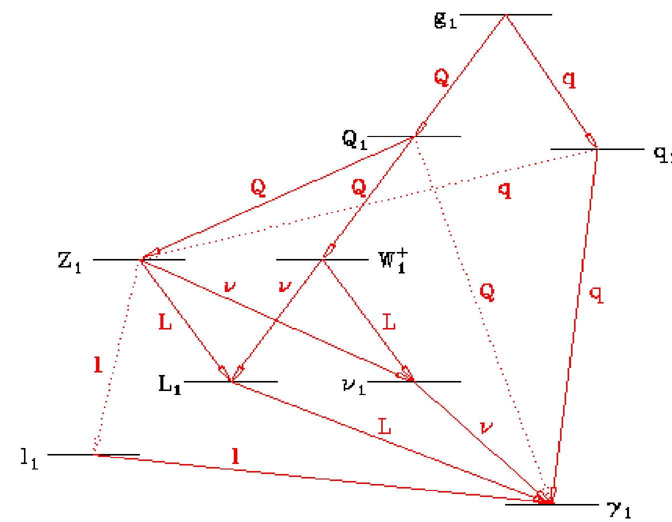
Universal Extra Dimensions

Everybody in the bulk!

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

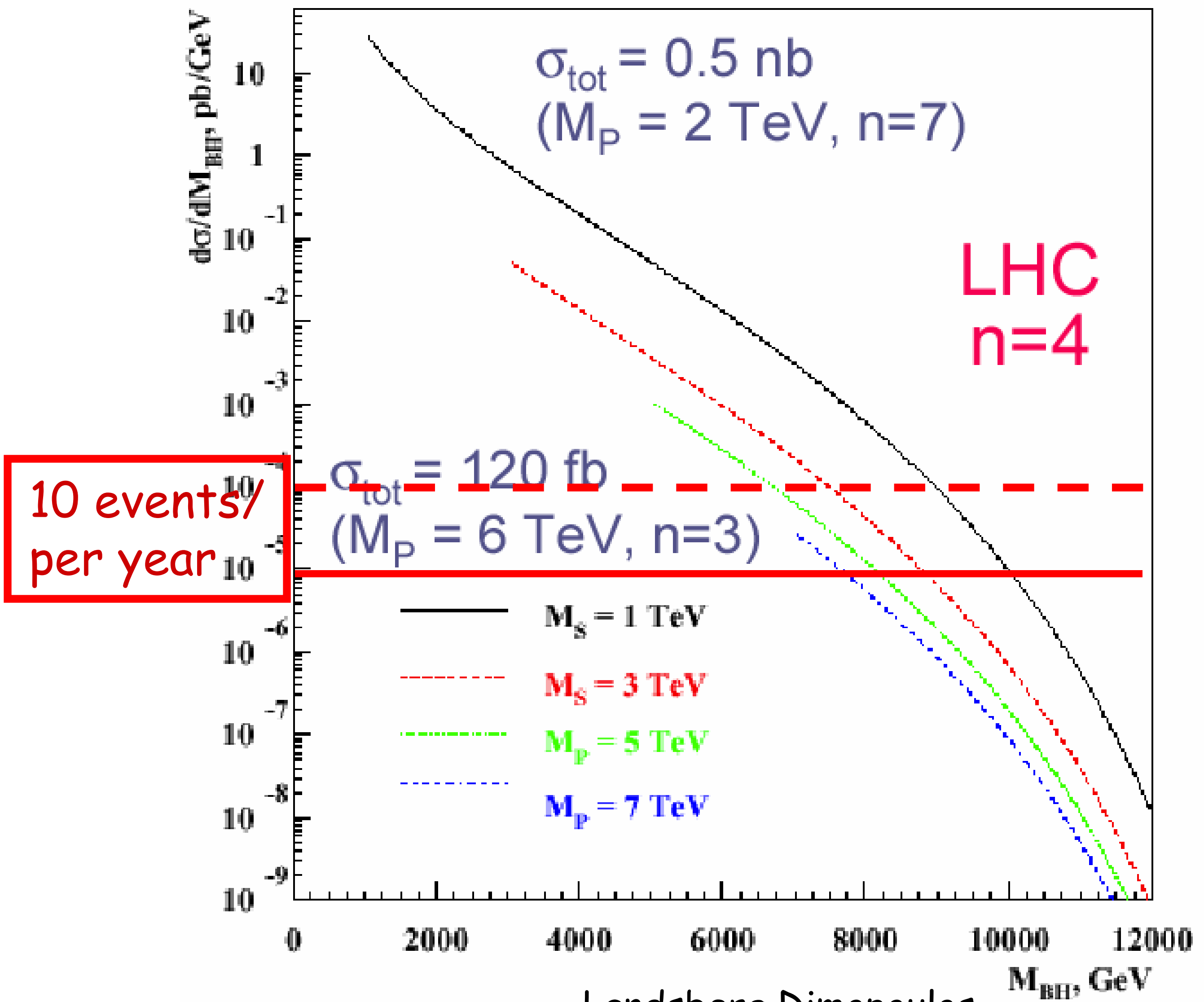


Search: e.g 4 leptons + E_T^{miss}



Increase of the sensitivity to R^{-1} from 1.5 TeV to 2 TeV

Black Holes



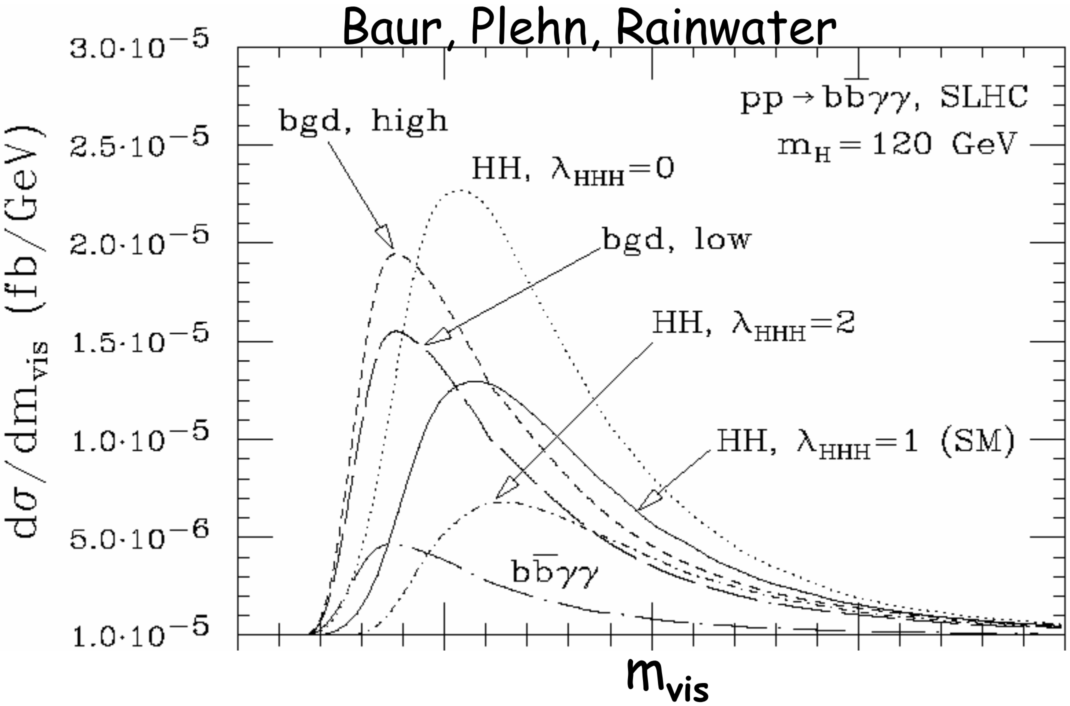
Landsberg,Dimopoulos

Example:
Cross sections for black holes can be very large

May dominate the particle production at the LHC

But can also be statistics limited for large M_S and M_{BH} (add ~ 1 TeV)

Higgs Self Coupling for low M_H



pp→bbbb not useable
pp→bbττ difficult
pp→bbμμ not useable

New

pp→bbγγ promising

- For m_H=120 GeV and 600 fb^{-1} expect 6 events at the LHC with S/B~ 2 (single b tag)
- Interesting measurement at the SLHC (double b tag)

machine	$m_H = 120$ GeV "hi"	$m_H = 120$ GeV "lo"	$m_H = 120$ GeV bkg. sub.	$m_H = 140$ GeV "hi"	$m_H = 140$ GeV "lo"	$m_H = 140$ GeV bkg. sub.
LHC, 600 fb^{-1}	$^{+1.9}_{-1.1}$	$^{+1.6}_{-1.1}$	$^{+0.94}_{-0.74}$	–	–	–
SLHC, 6000 fb^{-1}	$^{+0.82}_{-0.66}$	$^{+0.74}_{-0.62}$	$^{+0.52}_{-0.46}$	$^{+1.7}_{-0.9}$	$^{+1.4}_{-0.8}$	$^{+0.76}_{-0.58}$
VLHC, 600 fb^{-1}	$^{+0.44}_{-0.42}$	$^{+0.42}_{-0.40}$	$^{+0.32}_{-0.30}$	$^{+0.82}_{-0.62}$	$^{+0.66}_{-0.54}$	$^{+0.38}_{-0.34}$
VLHC, 1200 fb^{-1}	$^{+0.32}_{-0.30}$	$^{+0.30}_{-0.28}$	$^{+0.26}_{-0.22}$	$^{+0.76}_{-0.58}$	$^{+0.62}_{-0.50}$	$^{+0.36}_{-0.32}$

Needs accurate prediction of the bbγγ background rate
Needs detector simulation