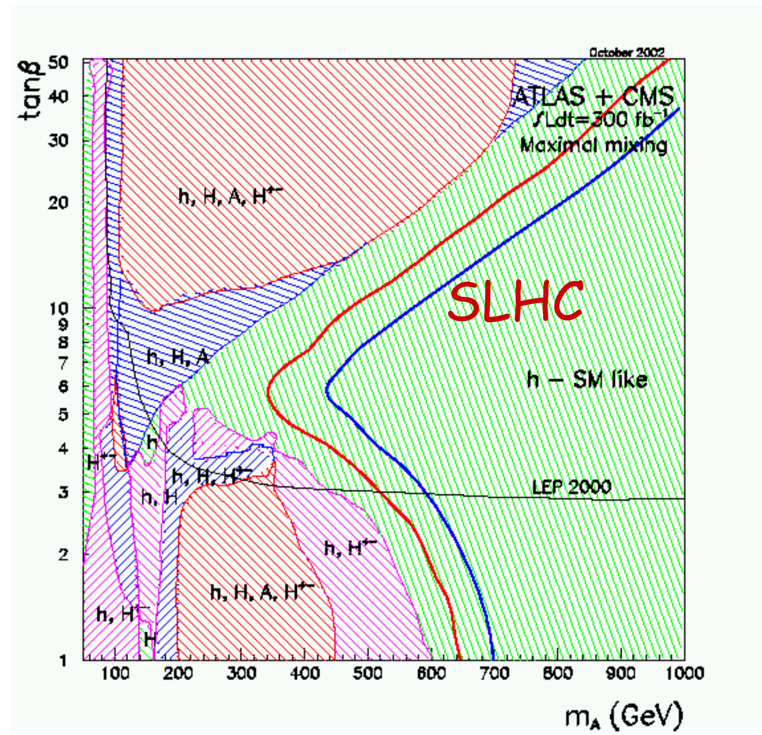
The LHC Upgrade

2007 CERN Summer Student Lectures

Albert De Roeck
CERN

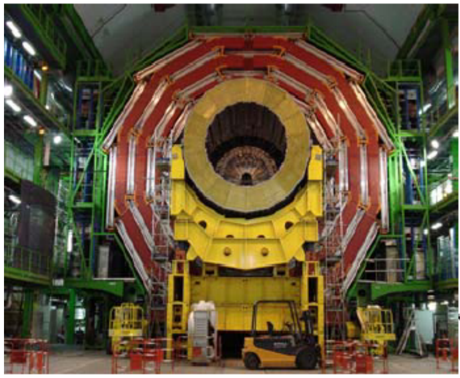


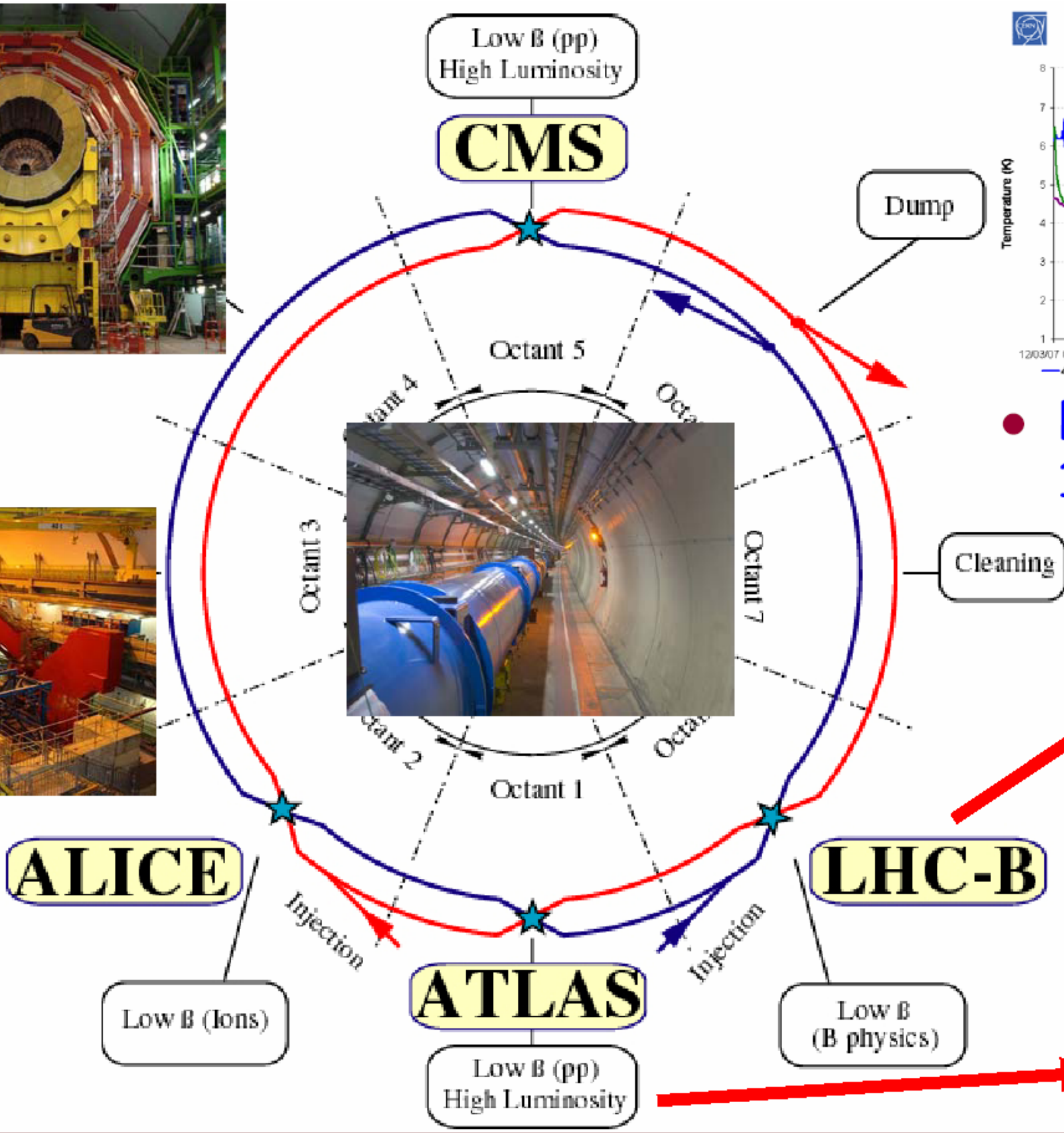
Contents of this Lecture

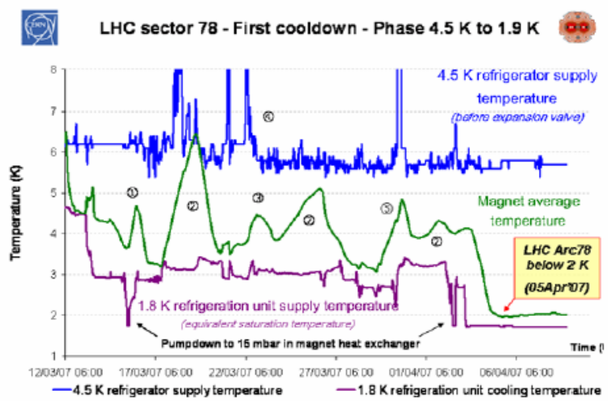
- Introduction & LHC history
- The LHC upgrade path
- Implications for the LHC detectors
- The physics case for the upgrade by examples
- Summary of this lecture

Some slides taken from S. Tapprogge/EPS-ECFA talk

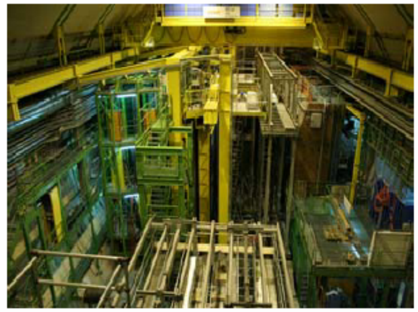
The LHC is coming

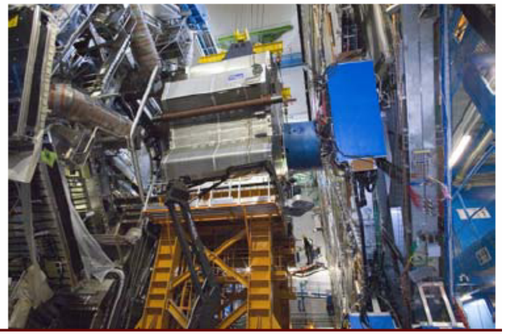






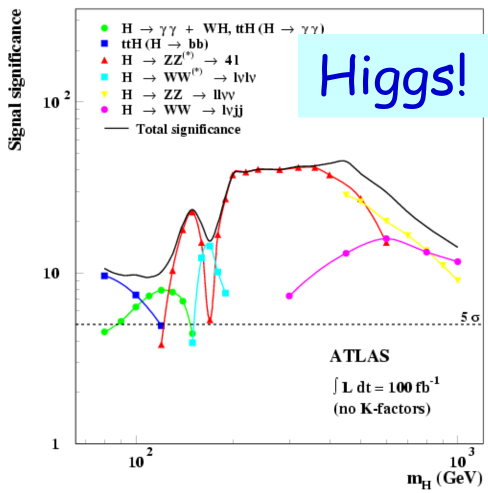
- First pp collisions at 14 TeV summer 2008

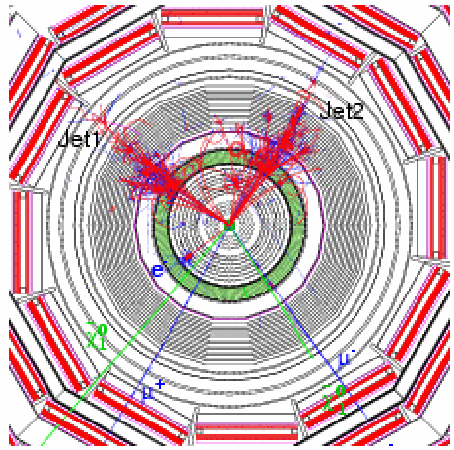




Physics at the LHC: pp @ 14 TeV

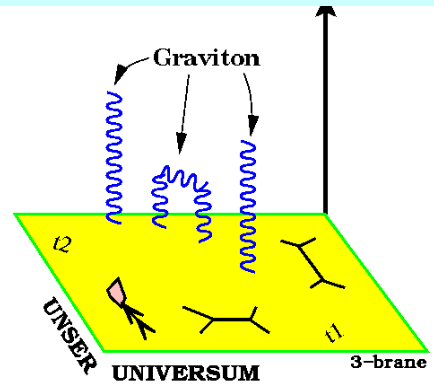
Higgs!



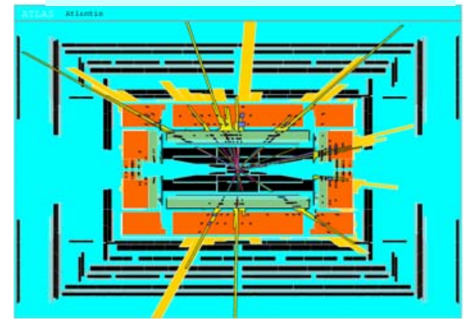


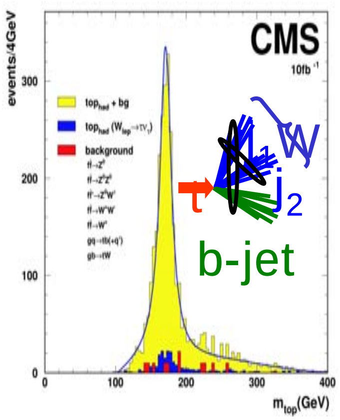
Supersymmetry?

Extra Dimensions?



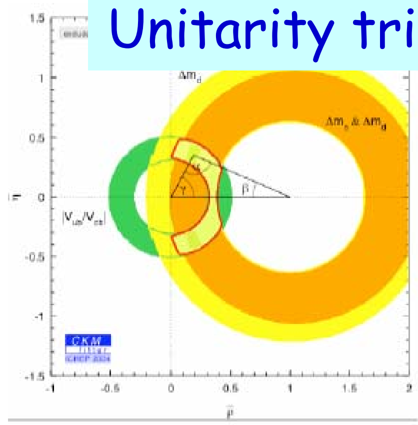
Black Holes???



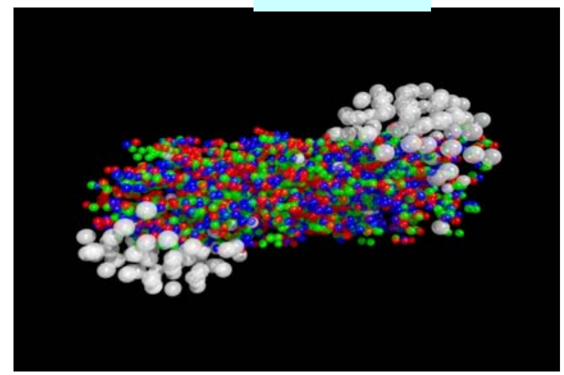


Precision measurements e.g top!

Unitarity triangle!



QGP?



The LHC will be the new collider energy frontier

The LHC: 23 Years Already!

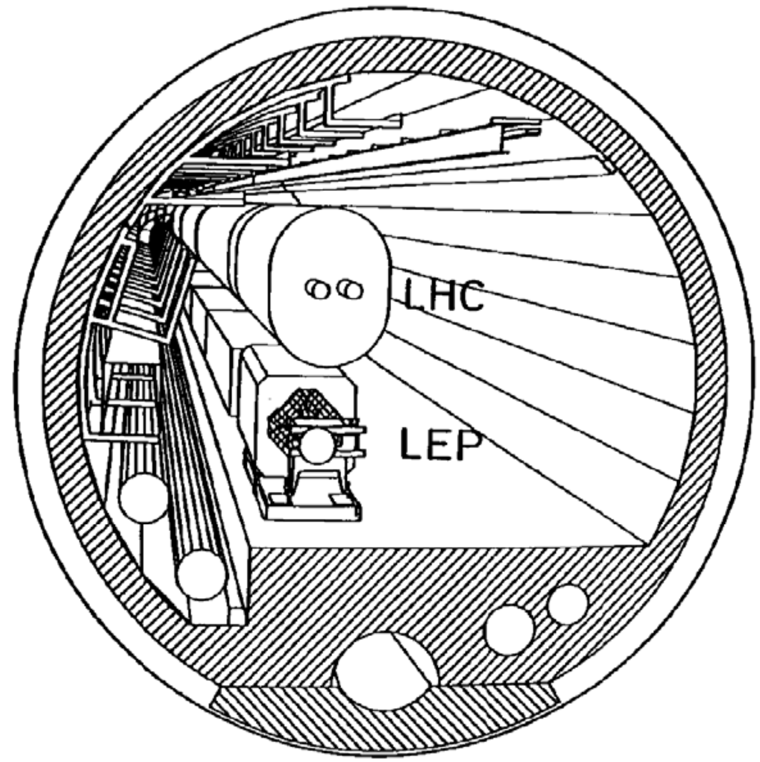
CERN: 50 YEARS AND COUNTING

The life of an experiment

1984	Workshop in Lausanne on installing a Large Hadron Collider (LHC) in the LEP tunnel
1987	CERN's long-range planning committee chaired by Carlo Rubbia recommends LHC as the right choice for lab's future
1989	ECFA Study Week on instrumentation technology for a high-luminosity hadron collider; Barcelona; LEP collider starts operation
1990	ECFA LHC workshop, Aachen
1992	General meeting on LHC physics and detectors, Evian-les-Bains
1993	Letters of intent for LHC detectors submitted
1994	Technical proposals for ATLAS and CMS approved/LHC
1998	Construction begins
2000	CMS assembly begins above ground; LEP collider closes
2003	ATLAS underground cavern completed and assembly started
2004	CMS cavern completed
2007	Experiments ready for beam
2007	First proton–proton collisions
2008	First results
2010	Reach design luminosity
>2014	Upgrade LHC luminosity by factor of 10

1984

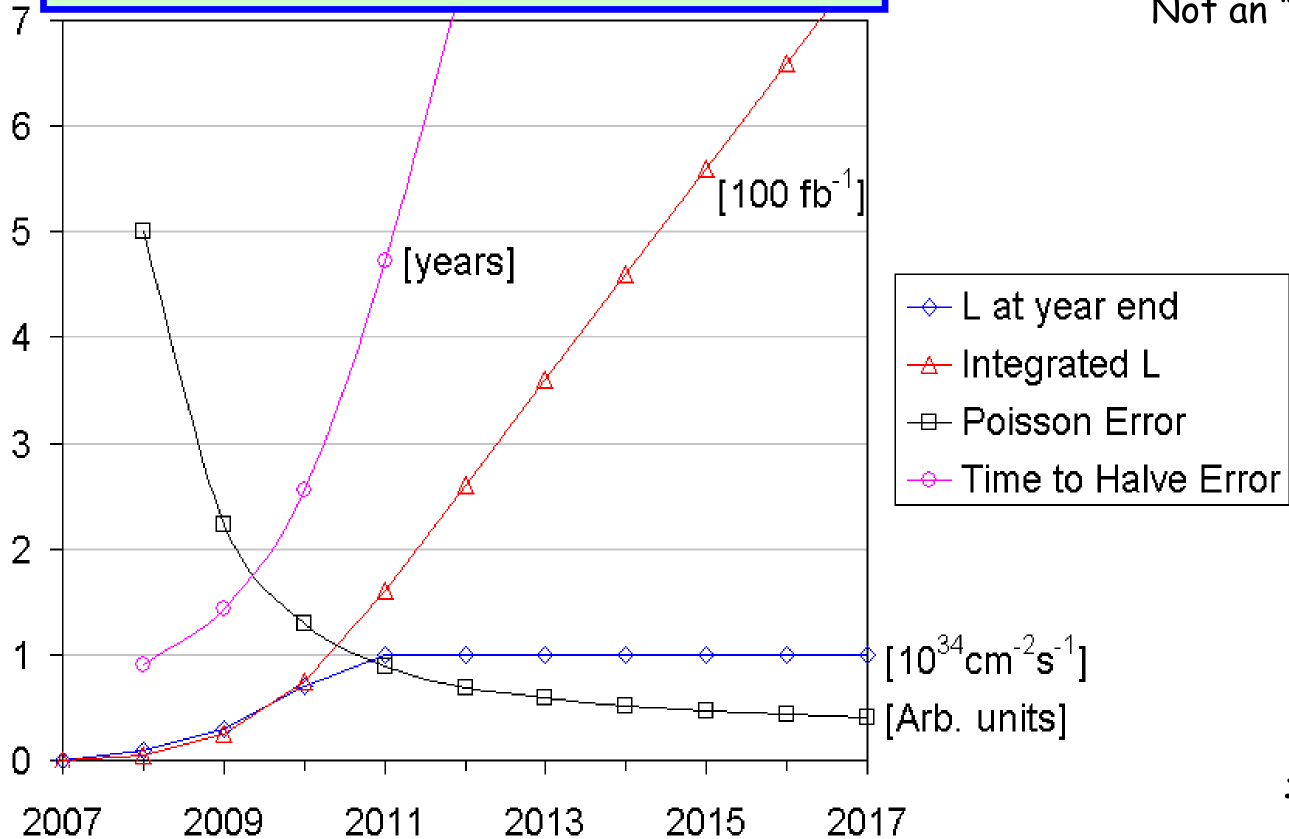
ECFA 84/85
CERN 84-10
5 September 1984



1984:	cms energy	10-18 TeV
	Luminosity	10^{31}-$10^{33}cm^{-2}s^{-1}$
1987:	cms energy	16 TeV
	Luminosity	10^{33}-$10^{34}cm^{-2}s^{-1}$
Final:	cms energy	14 TeV
	Luminosity	10^{33}-$10^{34}cm^{-2}s^{-1}$

Ramping up the LHC

hypothetical luminosity scenario



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

Statistical error→$1/\sqrt{N}$

error → error/2
⇒ N → N.•4

Constant luminosity/year
1 year→4 years→16 years

Luminosity=
#events/cross-section/time

If startup is as optimistic as assumed here (10^{34} $cm^{-2}s^{-1}$ in 2011 already)
⇒After ~3-4 years (~300 fb^{-1}) a simple continuation becomes less exciting
⇒Time for an upgrade around 2015?

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 = 10 x LHC)
  - Needs changes in machine and and particularly in the detectors
  - ⇒ Start change to SLHC mode some time 2014-2016
  - ⇒ Collect ~3000 fb^{-1}/experiment in 3-4 years data taking.

⇒Discussed in this lecture

- 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

LHC Upgrade

- three phases envisaged
  - → phase 0: stretch performance to the maximum possible ('ultimate')
    - number of protons per bunch to beam-beam limit
      - upgraded injectors
    - collisions at two IP's only
    - (dipole field to 9 T → √s = 15 TeV)
  - → phase 1: sizeable luminosity increase, keep LHC arcs unchanged
    - will concentrate on this phase here
  - → phase 2: major hardware changes
    - upgrade injectors, superconducting SPS (1 TeV)
    - new superconducting dipoles

Large Hadron Collider Project

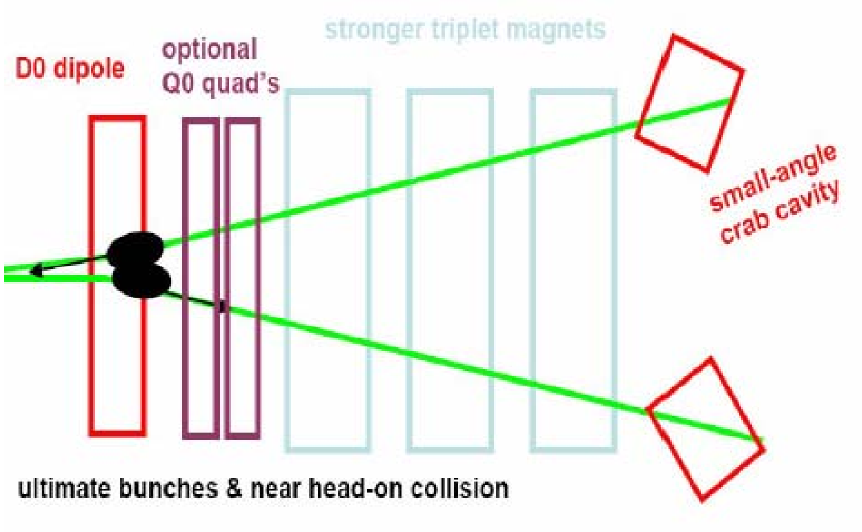
LHC Project Report 626

(2002)

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[§]

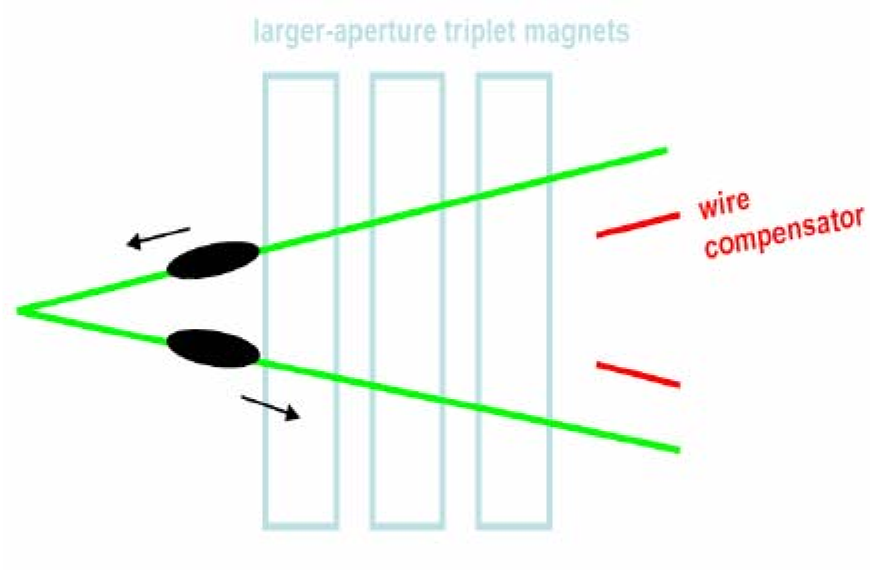
Possible Machine Scenarios



Early Separation (ES) of the beams

- Ultimate beam
- Stronger focusing
- Early separating dipoles
- Crab cavities

→ New magnets deep inside the detector
→ Crab cavities for hadron beams
→ Poor beam and luminosity lifetime



Large Piwinski Angle (LPA)

- Double bunch spacing
- More intense bunches
- Wire compensating to correct beams

→ High bunch charge/beam current
→ Operate with large Piwinski angle
→ Wire compensation (to be tested)

SLHC Machine Parameters

parameter	symbol	25 ns, small *	50 ns, long
transverse emittance	ε [μm]	3.75	3.75
protons per bunch	N_b [10^{11}]	1.7	4.9
bunch spacing	Δt [ns]	25	50
beam current	I [A]	0.86	1.22
longitudinal profile		Gauss	Flat
rms bunch length	σ_z [cm]	7.55	11.8
beta* at IP1&5	$\beta*$ [m]	0.08	0.25
full crossing angle	θ_c [μrad]	0	381
Piwinski parameter	$\phi=\theta_c\sigma_z/(2*\sigma_x*)$	0	2.0
hourglass reduction		0.86	0.99
peak luminosity	L [10^{34} cm^{-2}s^{-1}]	15.5	10.7
peak events per crossing		294	403
initial lumi lifetime	τ_L [h]	2.2	4.5
effective luminosity ($T_{turnaround}$=10 h)	L_{eff}[10^{34} cm^{-2}s^{-1}]	2.4	2.5
	$T_{run,opt}$ [h]	6.6	9.5
effective luminosity ($T_{turnaround}$=5 h)	L_{eff}[10^{34} cm^{-2}s^{-1}]	3.6	3.5
	$T_{run,opt}$ [h]	4.6	6.7
e-c heat SEY=1.4(1.3)	P [W/m]	1.04 (0.59)	0.36 (0.1)
SR heat load 4.6-20 K	P_{SR} [W/m]	0.25	0.36
image current heat	P_{IC} [W/m]	0.33	0.78
gas-s. 100 h (10 h) τ_b	P_{gas} [W/m]	0.06 (0.56)	0.09 (0.9)
extent luminous region	σ_l [cm]	3.7	5.3
comment		D0 + crab (+ Q0)	wire comp.

New upgrade scenarios

challenges

injector upgrade

Crossing with large Piwinski angle

aggressive triplet

compromises between # of pile up events and heat load

W. Scandale HCP07

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

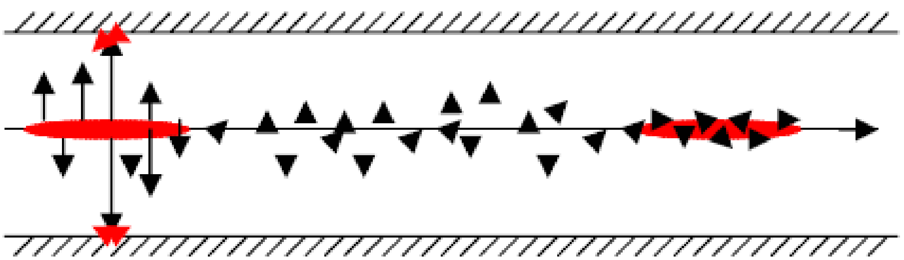
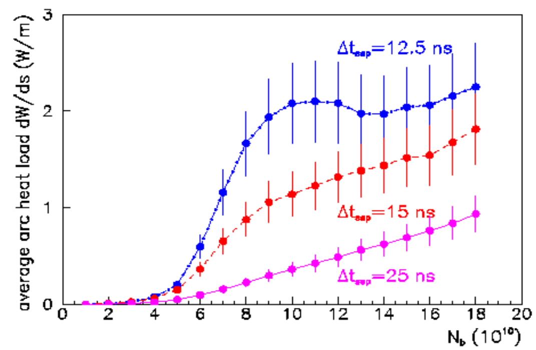


Figure 1. Schematic illustration of electron cloud effect. First bunch produces slow electrons, fields of second bunch accelerate residual electrons to produce secondary emission.

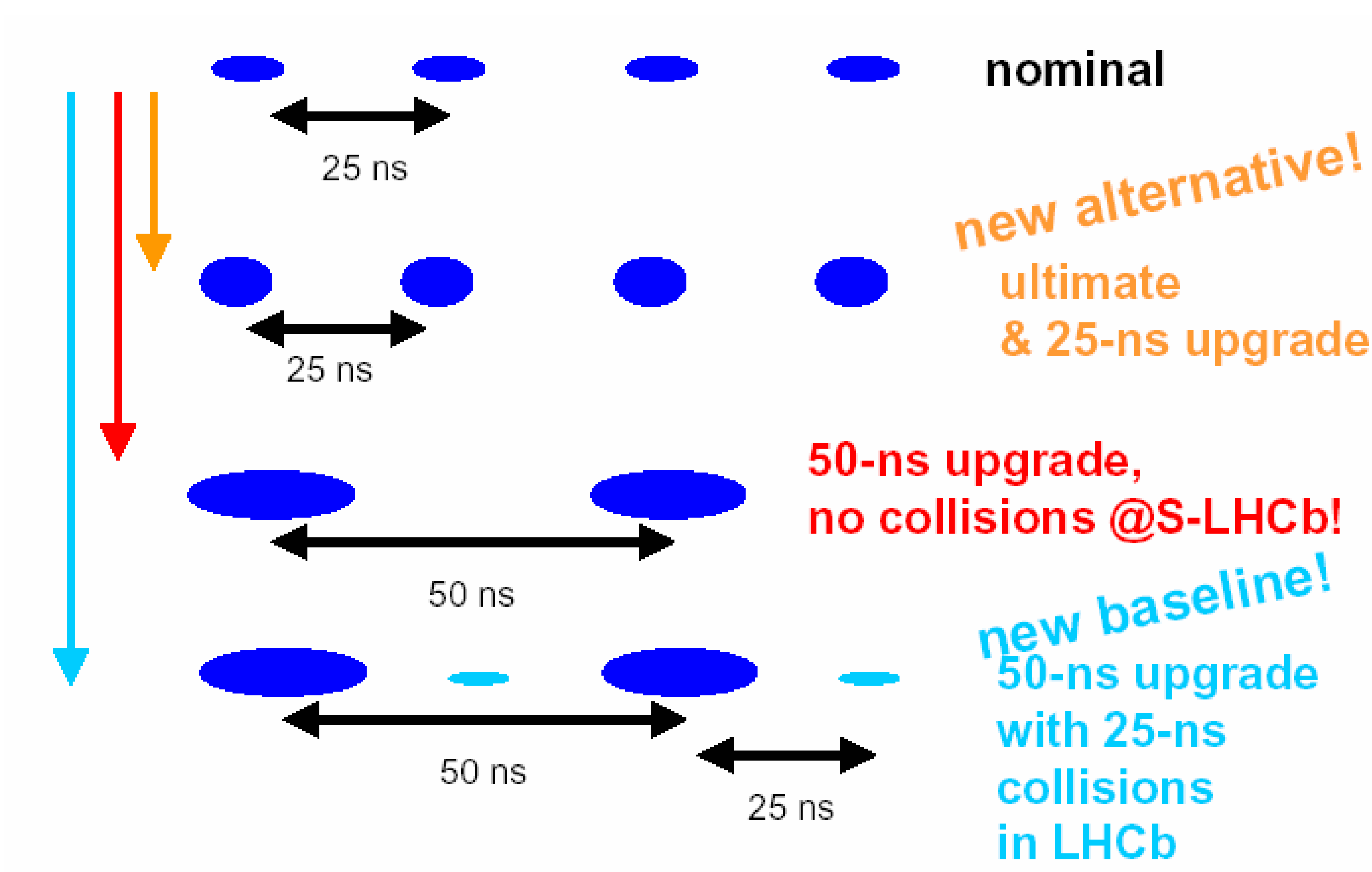


Average arc heat load as a function of bunch population for bunch spacings of 12.5 ns, 15 ns, and 25 ns, and a maximum secondary emission yield $\delta_{\max} = 1.1$. Elastically reflected electrons are included. (Courtesy F. Zimmermann)

F. Ruggiero CERN ICFA Seminar: LHC Machine Upgrade

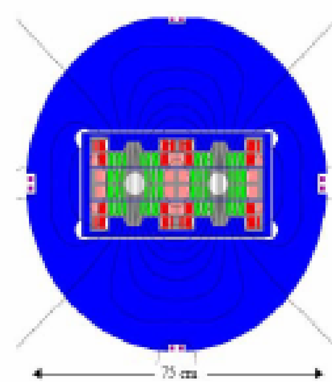
Can be preventive to run with to short bunch spacing
Will learn from LHC operation

Bunch Structure: LHC & Upgrades



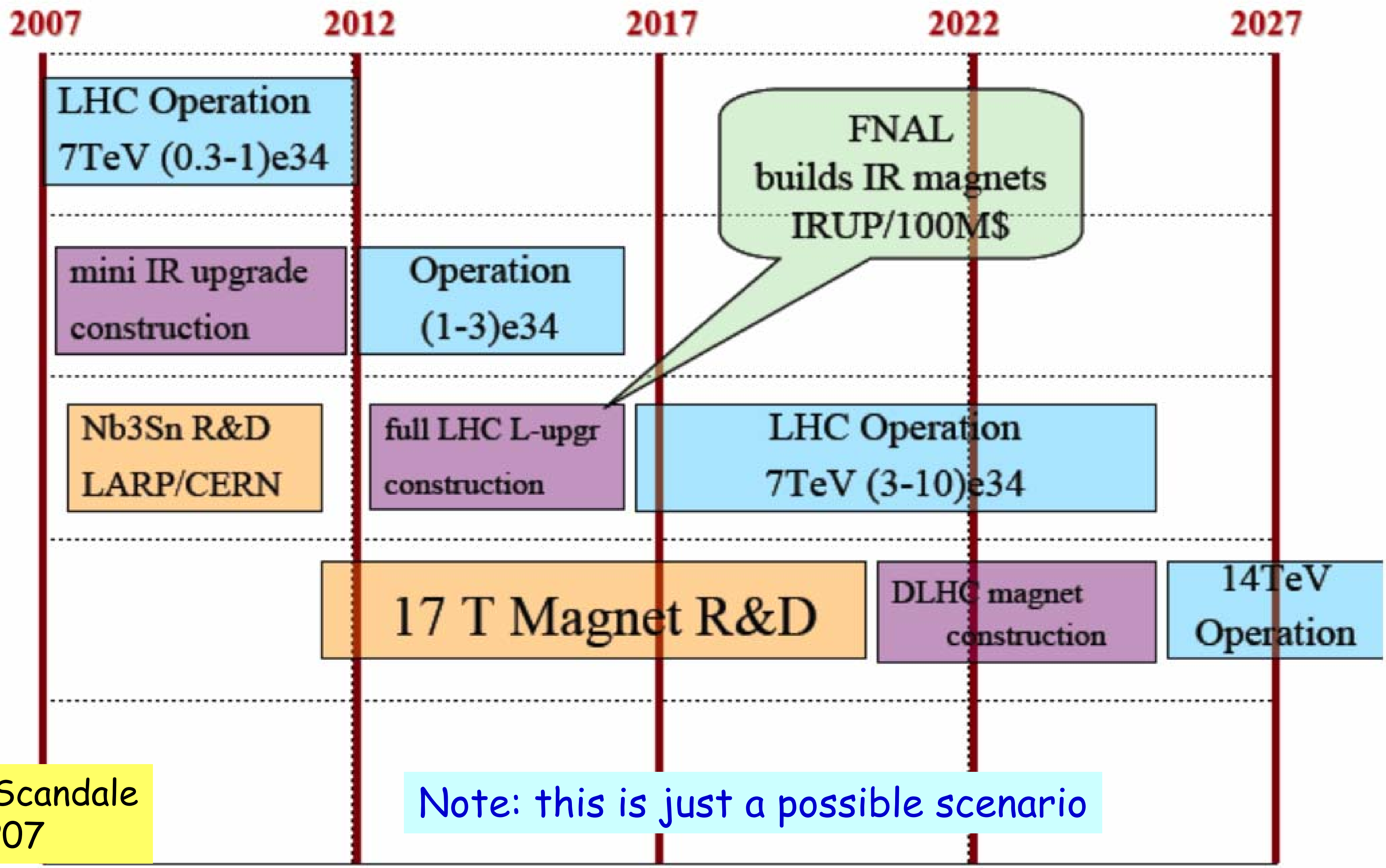
Energy Upgrade?

- doubling the energy (DLHC) $\sqrt{s}$ = 28 TeV
  - → nominal B field of 16.8 T (design for 18.5 - 19.3 T)
    - use Nb_3Sn superconductor
    - several 1m models exists (with 10 - 13 T fields)
  - → timescales
    - detailed R&D program: at least 10 years
    - production in industry: ~ 8 - 10 years
    - high cost
- tripling the energy (TLHC): $\sqrt{s}$ = 42 TeV
  - → nominal B field of 25 T (design for 28 - 29 T)
    - HTS-BSCCO supercond., to be fully demonstrated
    - large aperture needed (efficient beam screen)
  - → timescales
    - R&D program: at least 20 years
    - extremely high costs



- P. McIntyre, PAC05

LHC, sLHC, DLHC perspective



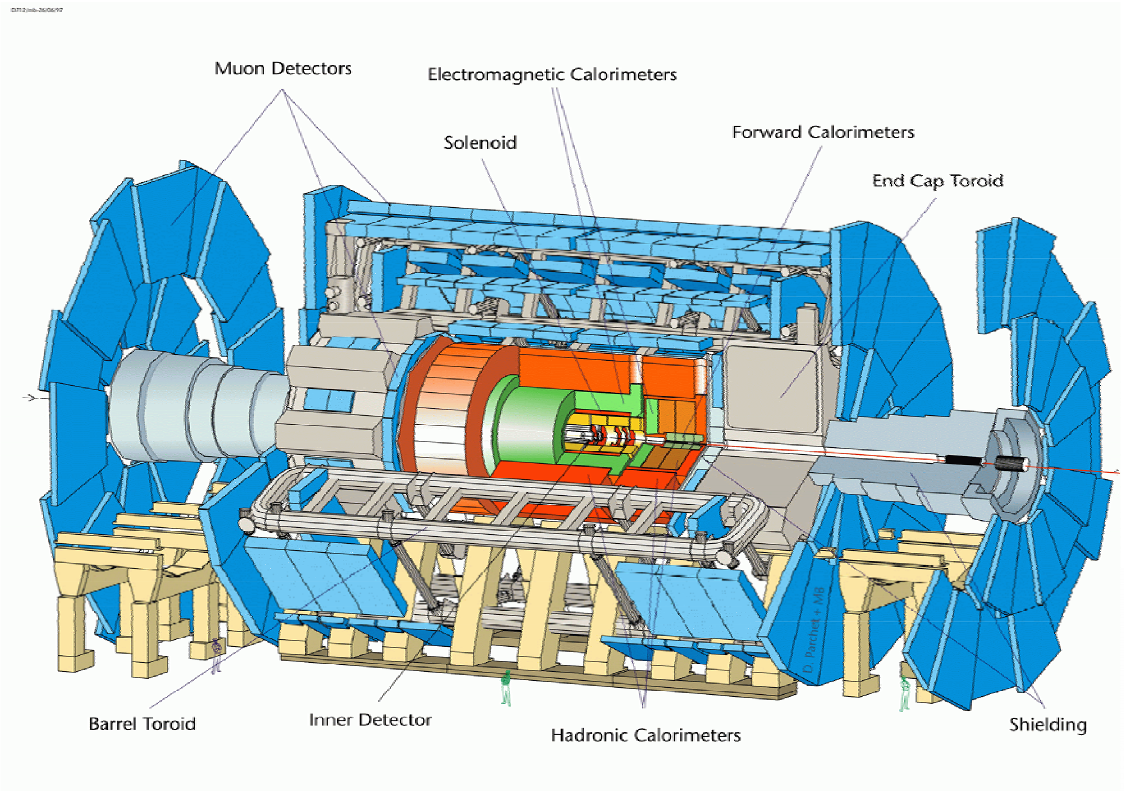
W. Scandale
HCP07

Note: this is just a possible scenario

LHC Upgrade Summary

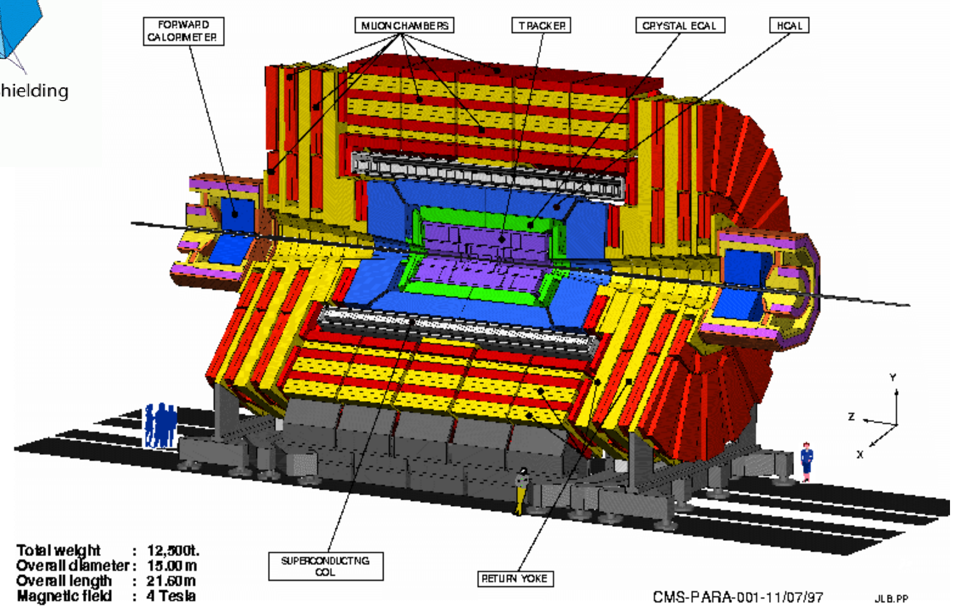
- scenarios for luminosity upgrade have evolved
  - → shorter bunch spacing (12.5 ns) now excluded
- two new scenarios developed
  - → LPA (50 ns spacing): baseline, less risks and uncertainties
  - → ES (25 ns spacing): leave as backup solution
    - both need further refinement in studies
- luminosity leveling to be seriously considered
- significant energy upgrade: much more ambitious and expensive
- keep in mind: what counts in the end is accumulated integrated luminosity!
  - → stable running at somewhat lower peak luminosity preferable to unstable running at higher peak luminosities

Detectors for SLHC



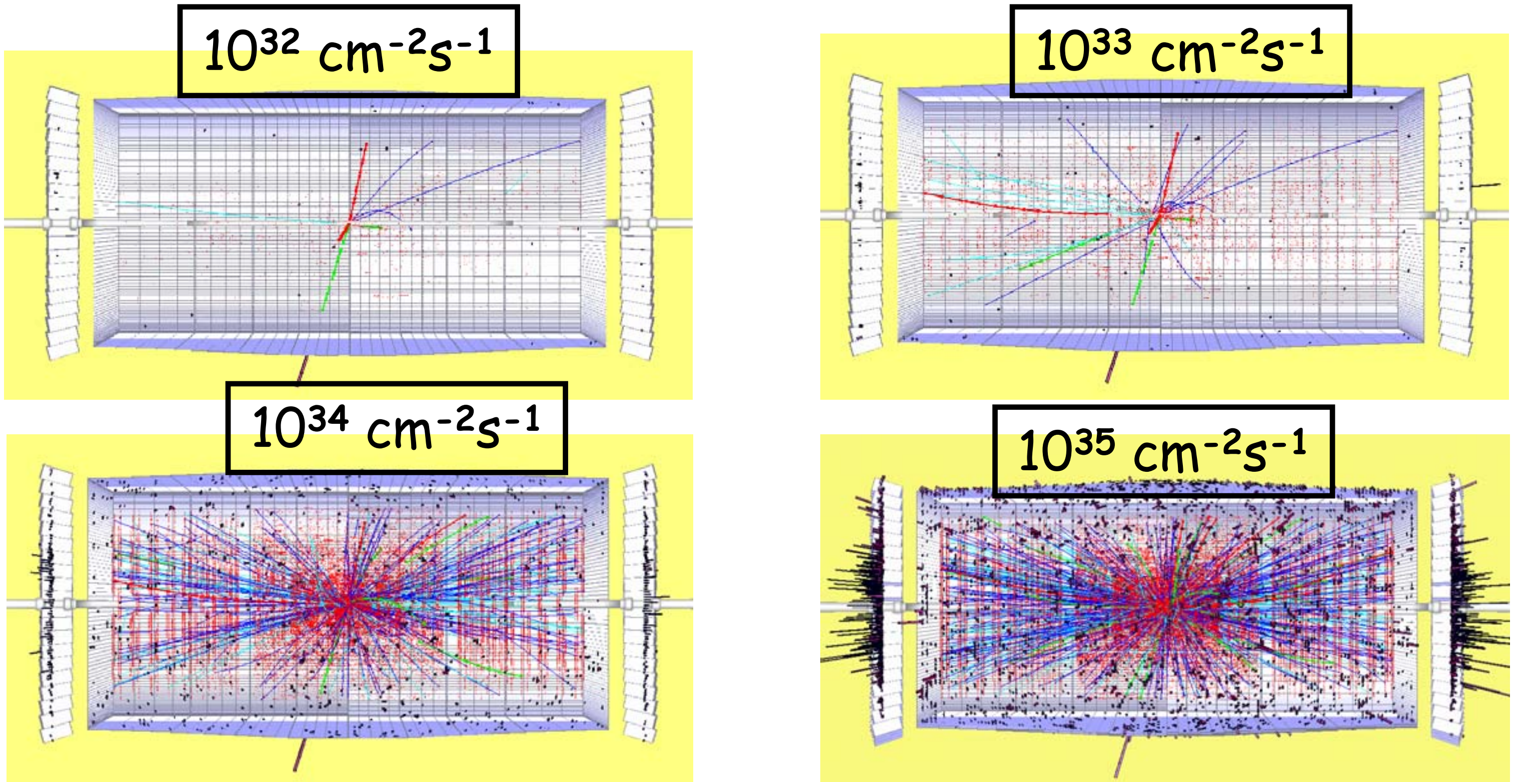
ATLAS & CMS experiments

Can these experiments be used for the LHC upgrade?



Pile-up collisions

Total pp cross section is 80 mbarns (Huge!!)
Each bunch crossing additional -mostly soft- interactions → pile up
Startup luminosity $2{\bullet}10^{33} cm^{-2}s^{-1}$ ⇒ 4 events per bunch crossing
High luminosity $10^{34} cm^{-2}s^{-1}$ ⇒ 20 events per bunch crossing
Luminosity upgrade $10^{35} cm^{-2}s^{-1}$ ⇒ 200 events per bunch crossing



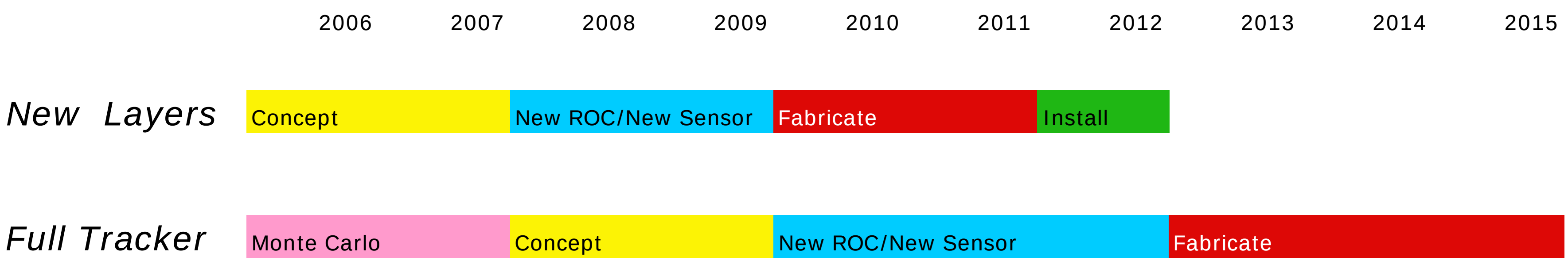
H→ZZ → μμee event + pile up events for different luminosities

Detectors for SLHC

- Requirement to fully exploit physics potential
  - → similar detector performance as 'today'
- However much more demanding environment
  - → increased backgrounds
  - → larger particle fluxes (radiation damage)
  - → higher rates
- What to upgrade/adapt?
  - → reasonable approach: can not build a new detector!
  - → replacement of tracking detectors
    - 10 y lifetime expectation @ 10^{34} – sensor/electronics damage
  - → forward region
    - new machine elements closer to interaction point?
  - → check on calorimeter and muon systems
  - → trigger and data acquisition: evolution?

Example of Detector Upgrades

Tracker detector of both CMS & ATLAS will need to be replaced
⇒ Occupancy, radiation
Include the tracker in the L1 trigger?

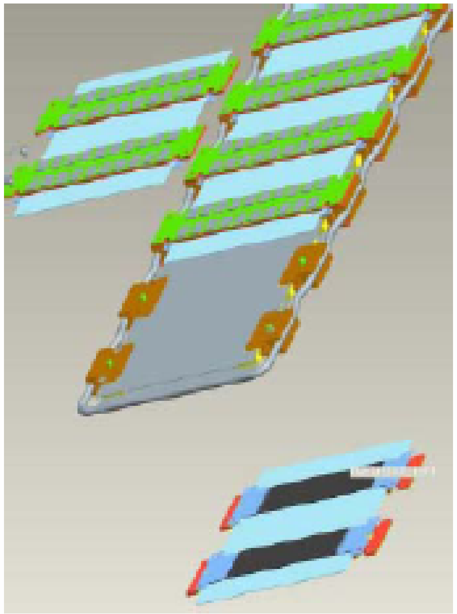


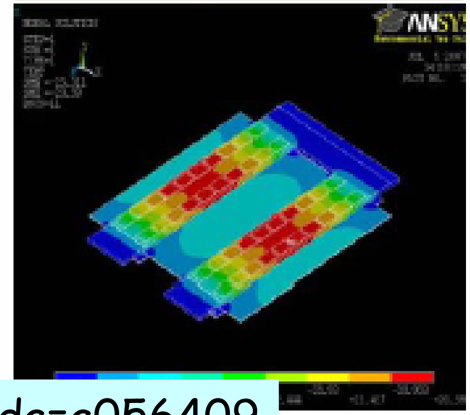
- Study, detector R&D and production takes time!
- Possible scenario: Proceed in two steps
  - Include new layers in the present tracker during the LHC running
  - Upgrade to full new tracker system by SLHC (8-10 years from LHC Startup)

⇒ ATLAS & CMS upgrade workshops since ~two years ..

Tracker Upgrade

- performance optimization
  - → occupancies, material budget, tracking performance
- radiation hard sensors
  - → use n-in-p or n-in-n sensors
    - ❍ can operate underdepleted
  - → innermost (b-)layer: new technology needed
    - ❍ 3d silicon, CVD diamond, …
- readout electronics
- optoelectronics / control links
- structures: modules, staves, …
- services
  - → cables
  - → cooling
  - → power: demands and distribution
    - ❍ serial powering, DC-DC converter, …
- activation





Academic training lectures http://agenda.cern.ch/fullAgenda.php?ida=a056409

Other Detectors

- calorimeters
  - → most parts will be kept (partially new electronics)
  - → ATLAS: forward calorimeter subject to most radiation
  - → CMS: impact of machine elements on HF, radiation damage of scintillator (HCAL) for $|\eta|>2$
- muon systems
  - → need running experience, some electronics might be replaced, background uncertainties (data needed)
  - → ATLAS: reduction of background (factor 2) by Be beampipe
- trigger and data acquisition
  - → has to cope with higher rates, occupancies, ...
  - → CMS: need for track trigger at first level

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 the SLHC will obviously depend on how EWSB and/or the new physics will manifest itself at the LHC

- 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!

See K. Jacob's Lectures

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

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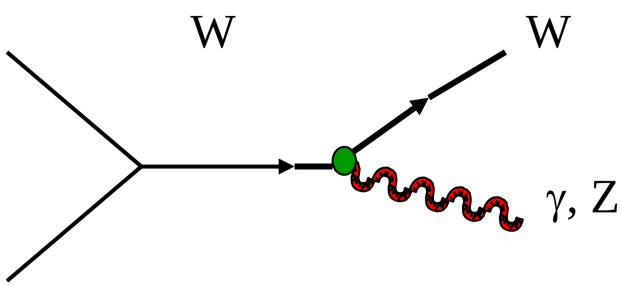
Include pile up, detector…

hep-ph/0204087

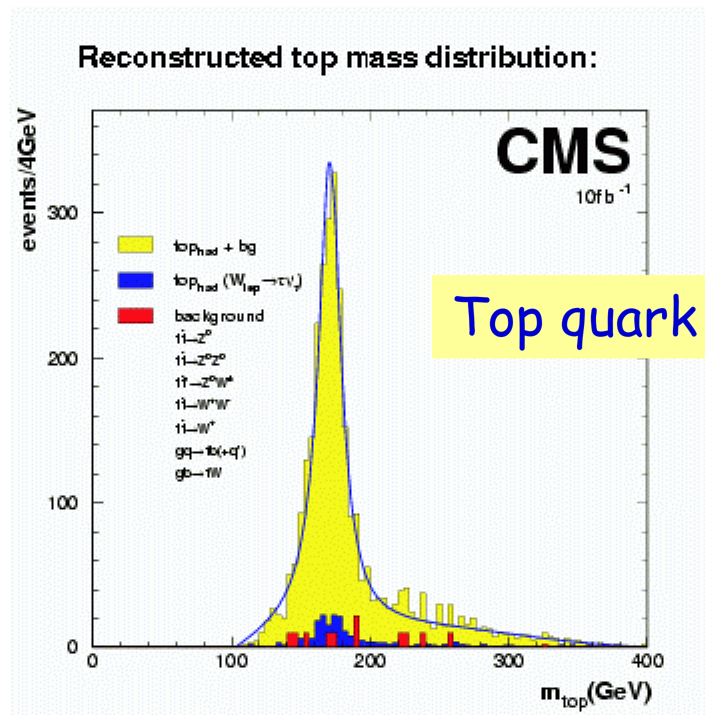
Standard Model Physics

Precision measurements of Standard Model processes and parameters
⇒Deviations of expectations can point to new physics or help to understand new observed phenomena

Triple Gauge Couplings



Lectures of A Pich



Standard Model Physics

Precision measurements of Standard Model processes and parameters
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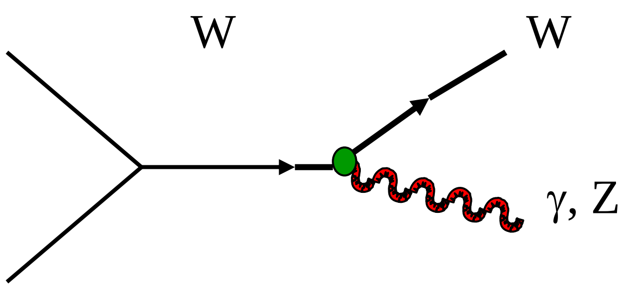
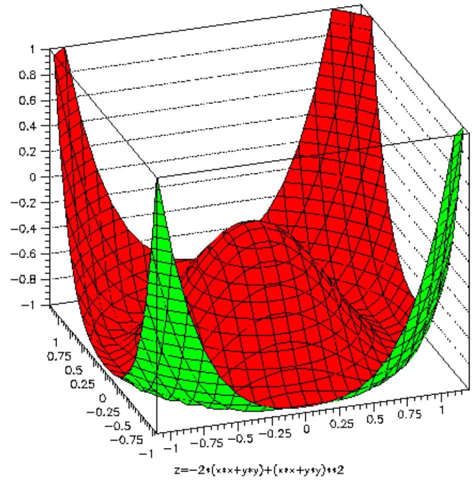
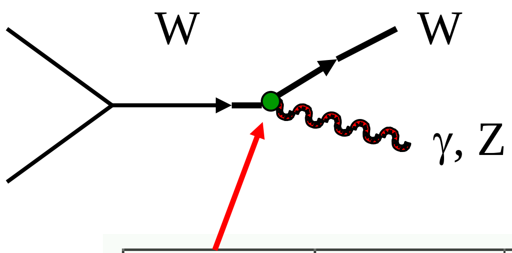


TGCs
Rare top decays
Higgs
…



Triple/Quartic Gauge Couplings



Triple gauge couplings: Wγ,WZ production

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

Production of multiple gauge bosons: statistics limited at LHC
E.g. # events with full leptonic decays, P_t>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

Typically gain of a factor of 2 in precision with SLHC

Top Quark Properties

SLHC statistics can still help for rare decays searches

$t \rightarrow q\gamma$

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

$t \rightarrow qZ$

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}

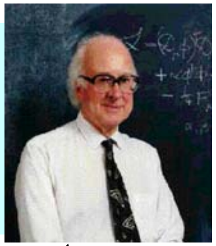
Ideal = MC 4-vector
Real = B-tagging/cuts as for $10^{34} cm^{-2}s^{-1}$
μ-tag = assume only B-tag with muons works at $10^{35} cm^{-2}s^{-1}$

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

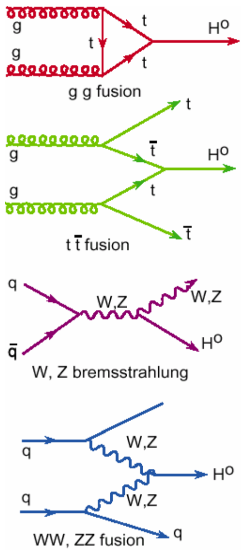
Decay	SM	two-Higgs	SUSY with $R\!\!\!/$	Exotic Quarks	Exper. Limits(95% CL)
$t \to gq$	5×10^{-11}	$\sim 10^{-5}$	$\sim 10^{-3}$	$\sim 5 \times 10^{-4}$	< 0.29 (CDF+TH)
$t \to \gamma q$	5×10^{-13}	$\sim 10^{-7}$	$\sim 10^{-5}$	$\sim 10^{-5}$	< 0.0059 (HERA)
$t \to Zq$	$\sim 10^{-13}$	$\sim 10^{-6}$	$\sim 10^{-4}$	$\sim 10^{-2}$	< 0.14 (LEP-2)

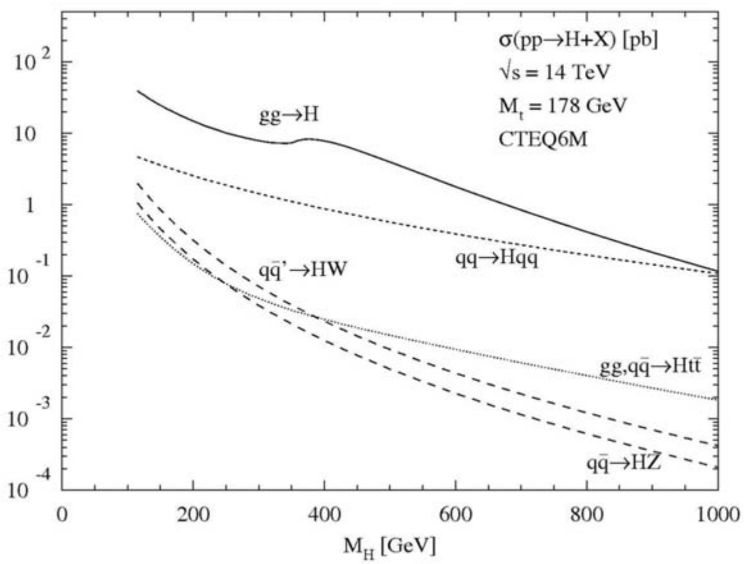
Higgs Physics

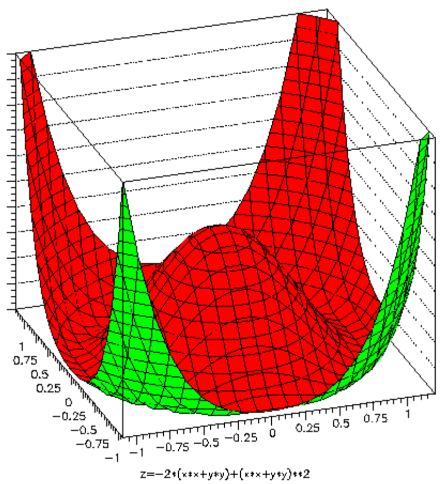
⇒ What is the origin of Electro-weak Symmetry Breaking?
⇒ If Higgs field at least one new scalar particle should exist: The Higgs
One of the main missions of LHC: discover the Higgs for m_H< 1 TeV

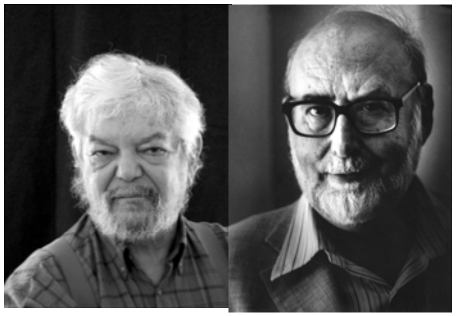


Higgs







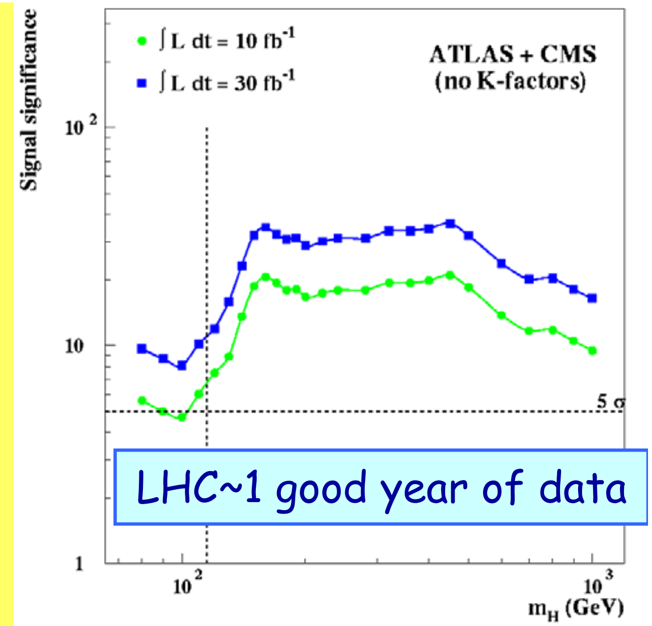


Brout, Englert

No Higgs particle seen so far: 114 GeV (LEP) <M_{Higgs}< 1 TeV (Theory)

Example: The Higgs at the LHC

- First step
  - Discover a new Higgs-like particle at the LHC, or exclude its existence
- Second step
  - Measure properties of the new particle to prove it is the Higgs
    - Measure the Higgs mass
    - Measure the Higgs width
    - Measure cross sections x branching ratios
    - Ratios of couplings to particles ($\sim m_{particle}$)
    - Measure decays with low Branching ratios (e.g $H \rightarrow \mu\mu$)
    - Measure CP and spin quantum numbers (scalar particle?)
    - Measure the Higgs self-coupling ($H \rightarrow HH$), in order to reconstruct the Higgs potential



SLHC added value

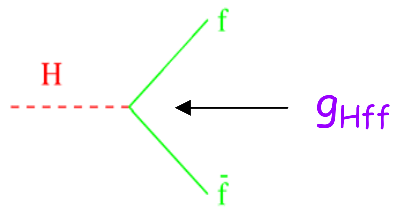
Only then we can be sure it is the Higgs particle we were looking for

Higgs Decays Modes

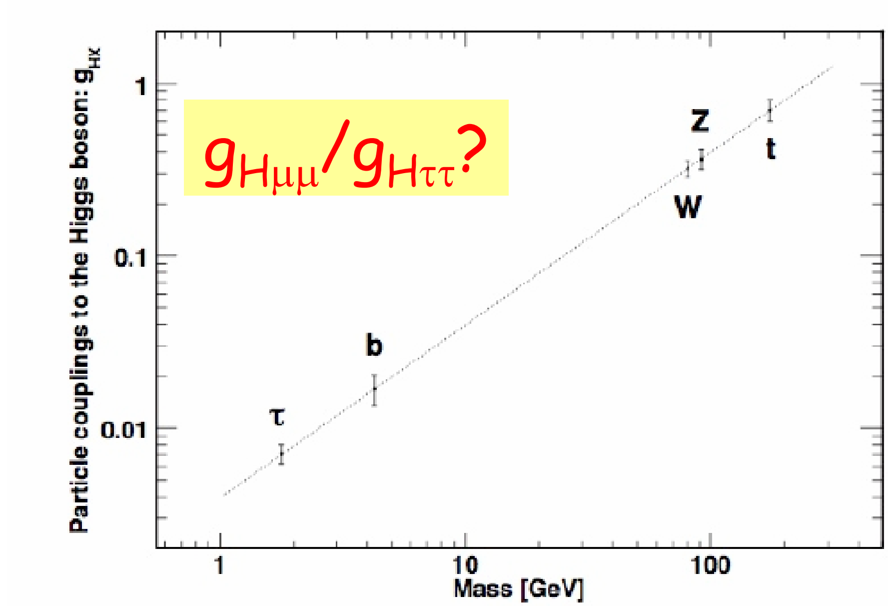
Rare Higgs Decays

Channels studied:

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



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



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)

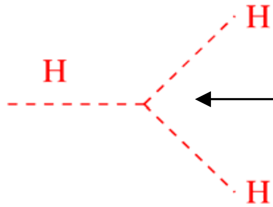
Higgs Couplings (ratios)

Can be improved with a factor of 2: 20%→10% at SLHC

Higgs Self Coupling Measurements

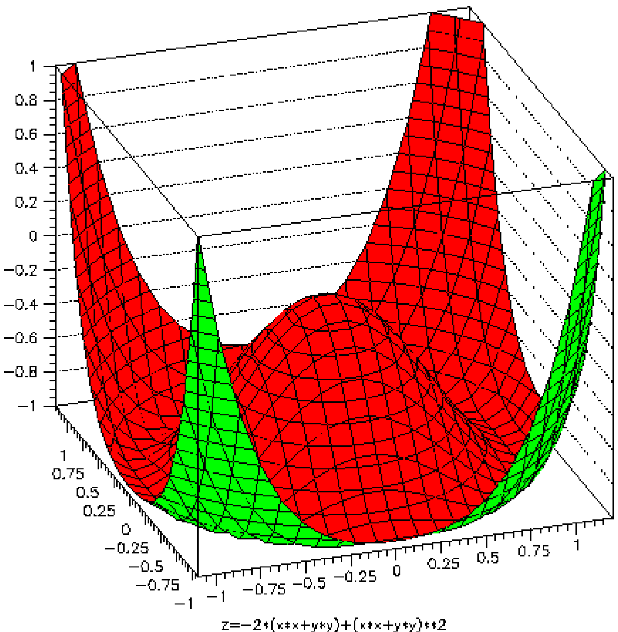
Once the Higgs particle is found, try to reconstruct the Higgs potential

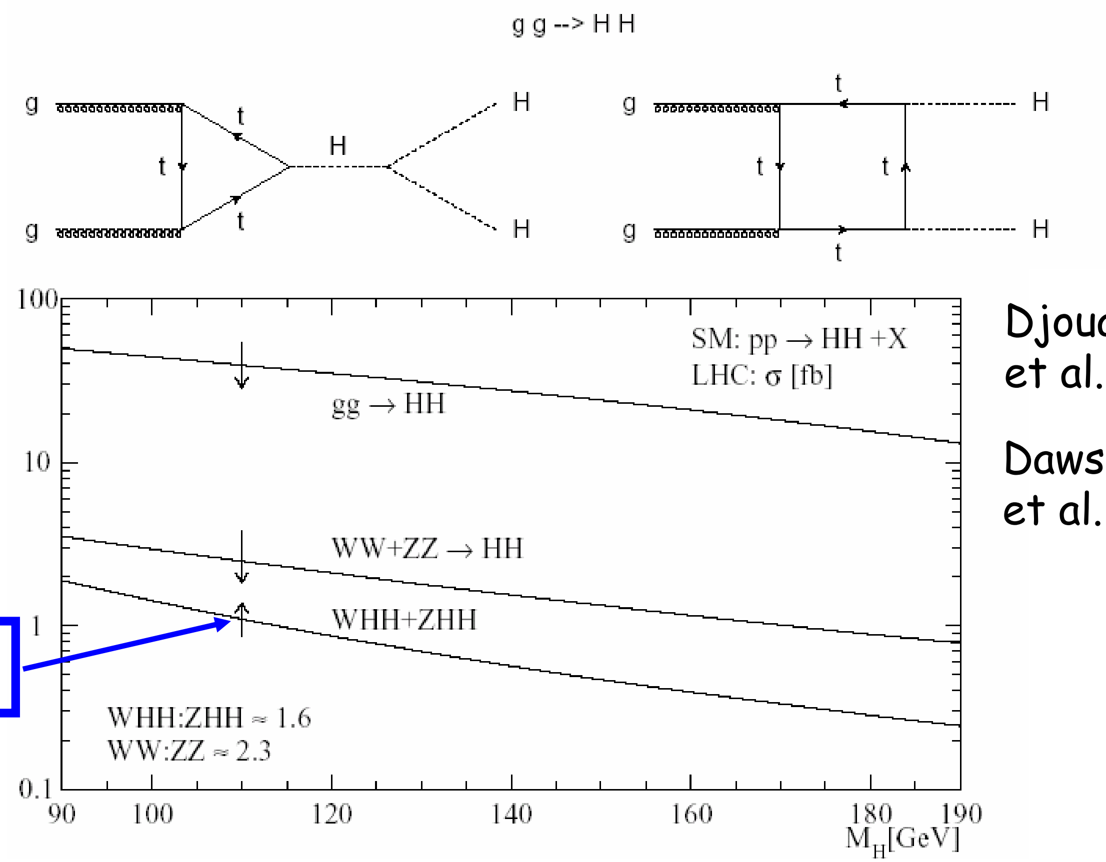
$$V(\Phi) = -\lambda v^2(\Phi^\dagger\Phi) + \lambda(\Phi^\dagger\Phi)^2$$



~ λv

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





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

Djouadi et al.

Dawson et al.

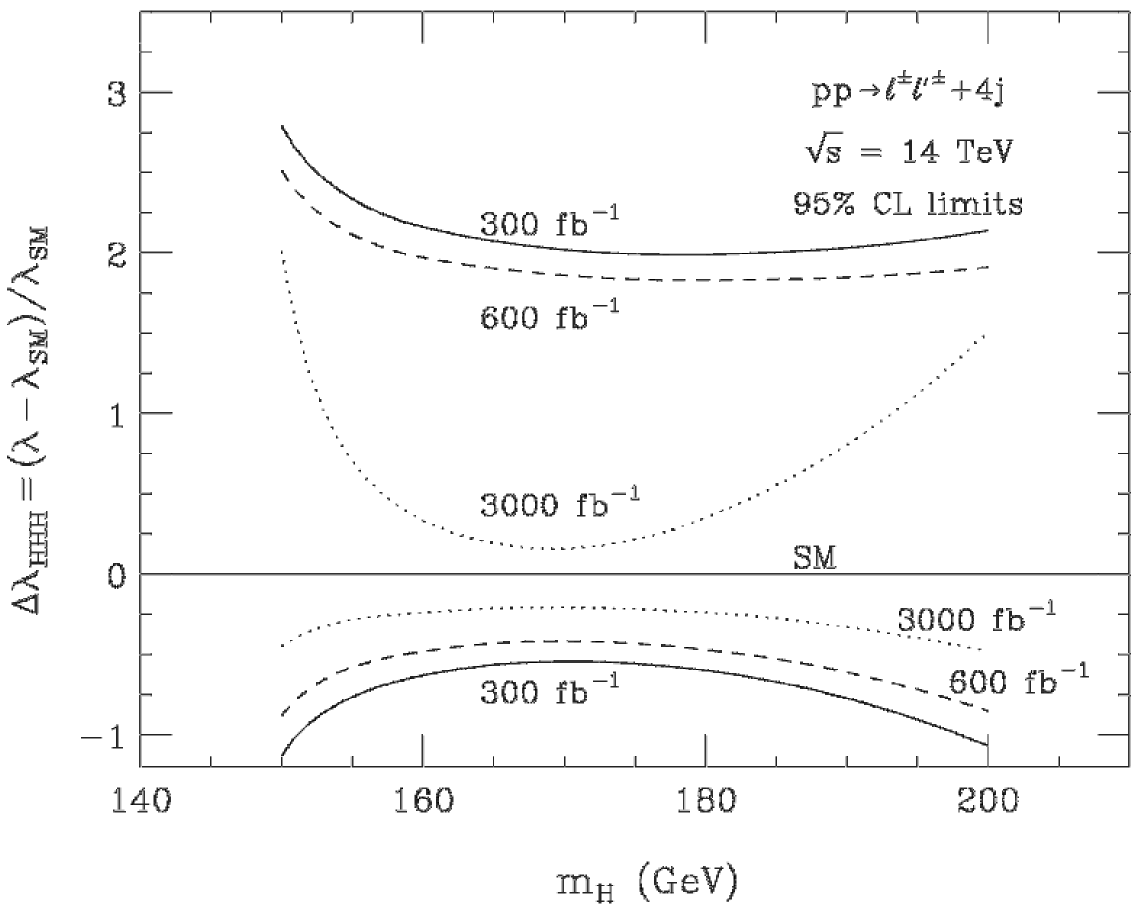
Difficult/impossible at the LHC

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 $\Delta\lambda=(\lambda-\lambda_{SM})/\lambda_{SM}$



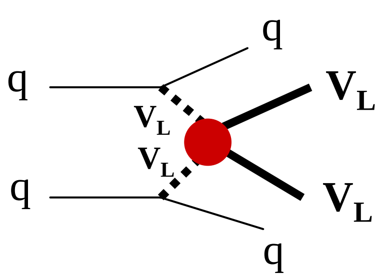
LHC: λ= 0 can be excluded at 95% CL.

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

Strongly Coupled Vector Boson System

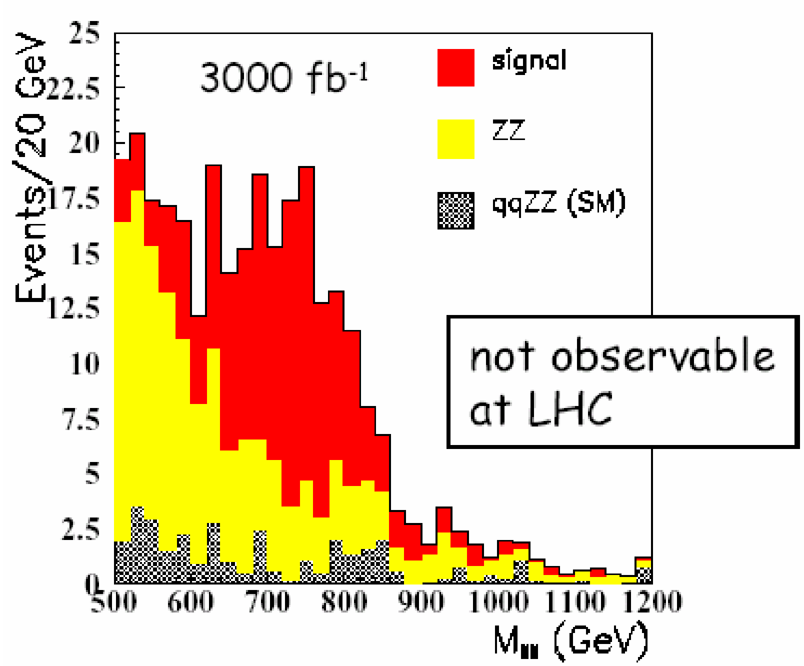
If no Higgs, expect strong $V_L V_L$ scattering (resonant or non-resonant) at $\sqrt{\hat{s}} \approx$ TeV



Could well be 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 → 5-8σ excess in $W^+_L W^+_L$ scattering
  → other low-rate channels accessible

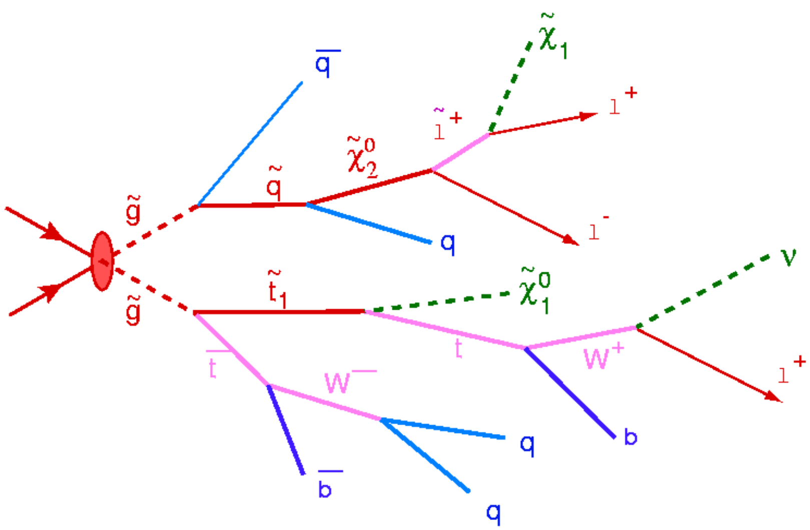
Scalar resonance $Z_L Z_L \rightarrow 4\ell$



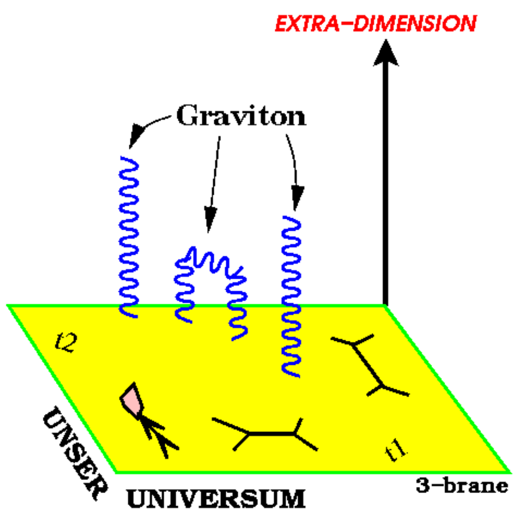
Beyond the Standard Model

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

Supersymmetry



Extra dimensions



+...

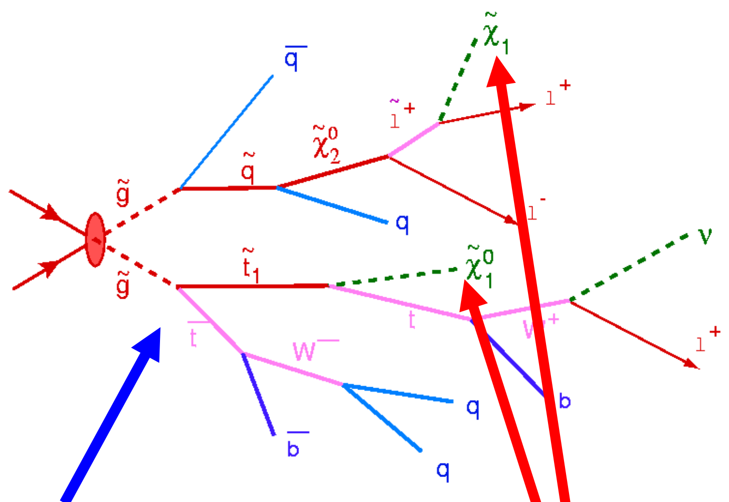
Lectures by E Kiritsis

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

Supersymmetry

Supersymmetry (SUSY) → assumes a new hidden symmetry between the bosons (particles with integer spin) and fermions (particles with half integer spin). Stabelize the Higgs mass up to the Planck scale

⇒Lots of new particles (squarks, sleptons,…) predicted with masses in the range from 10's of GeV's up to several TeV range



3 isolated leptons
+ 2 b-jets
+ 4 jets
+ E_t^{miss}

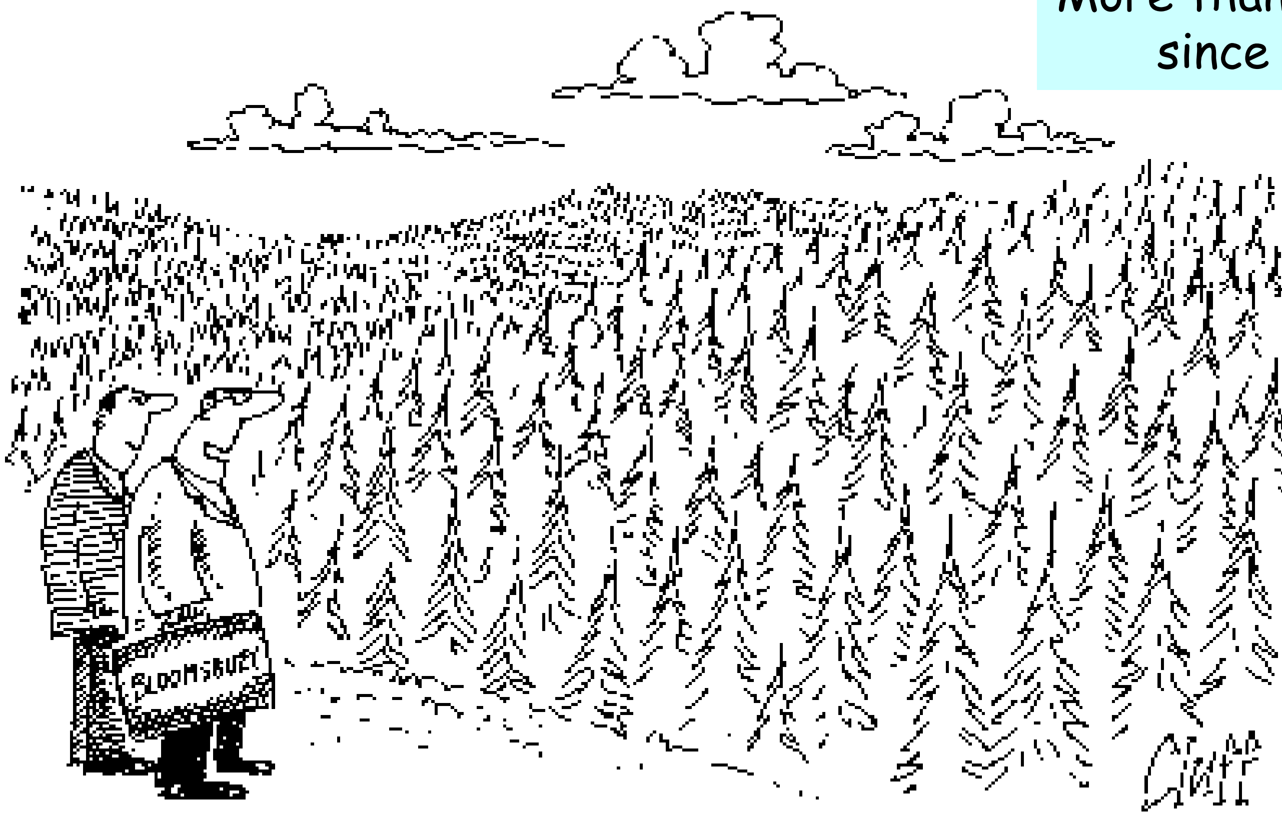
FERMIONS		SUSY PARTNER (SCALARS)	
LEPTONS			
	e	Selectron	$\tilde{e}$
	μ	Smuon	$\tilde{\mu}$
	τ	Stau	$\tilde{\tau}$
	ν_e, ν_μ, ν_τ	Sneutrinos	$\tilde{\nu}_e, \tilde{\nu}_\mu, \tilde{\nu}_\tau$
QUARKS			
	u, c, t	Squarks	$\tilde{u}, \tilde{c}, \tilde{t}$
	d, s, b		$\tilde{d}, \tilde{s}, \tilde{b}$
GAUGE 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	$\tilde{G}$

Lightest SUSY particle stable: dark matter candidate ?

Supersymmetry

A VERY popular scenario for new physics…

More than 7000 papers since 1990



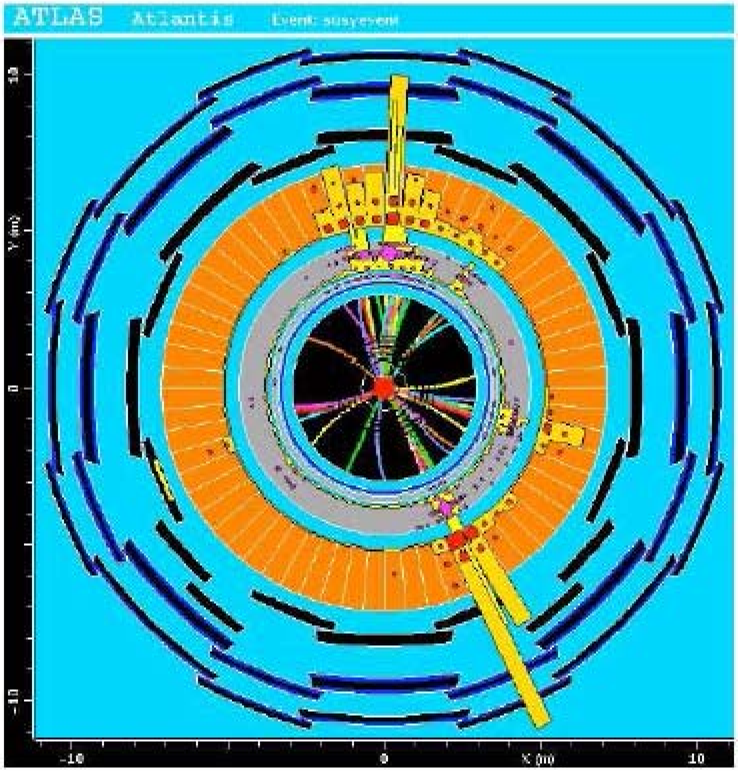
"One day, all of these will be supersymmetric phenomenology papers."

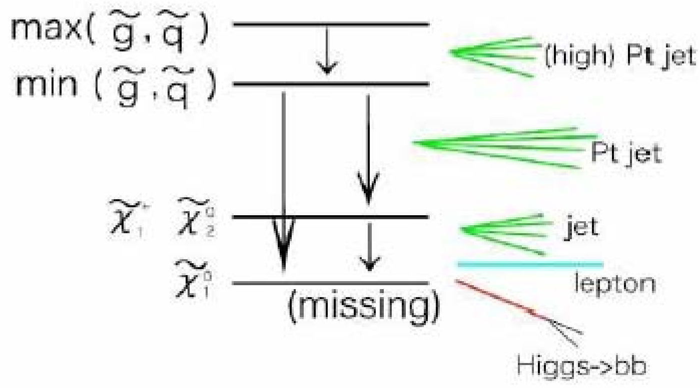
Supersymmetry

SUSY could be at the rendez-vous very early on!

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

$10 fb^{-1}$





event topologies of SUSY

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

Therefore:
SUSY one of the priorities of the "search" program

Main signal: lots of activity (jets, leptons, taus, missing E_T)
Needs however good understanding of the detector & SM processes!!

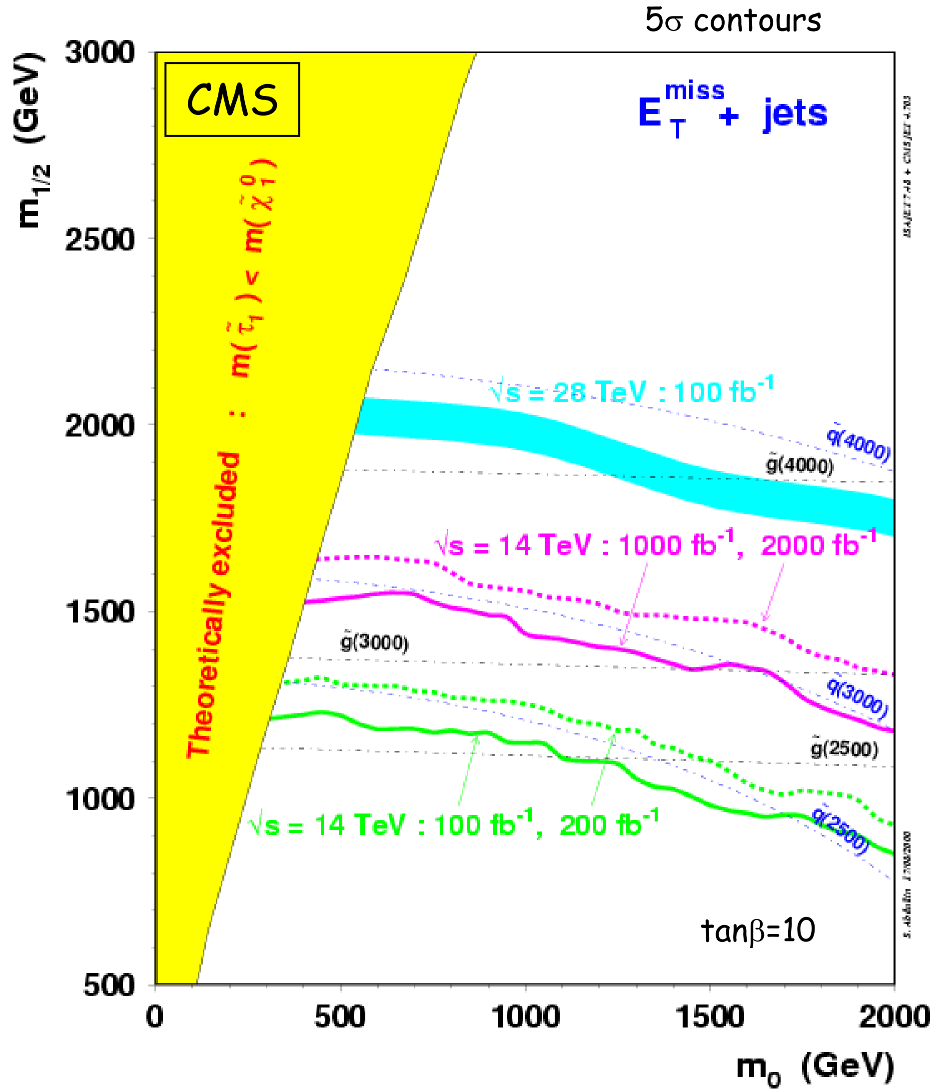
Supersymmetry

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

Usually minimal Supergravity (mSUGRA) taken for studies ⇒5 parameters

$m_{1/2}$: universal gaugino mass at GUT scale
m_0: universal scalar mass at GUT scale
$\tan\beta$: vev ratio for 2 Higgs doublets
sign(μ): sign of Higgs mixing parameter
A_0: trilinear coupling



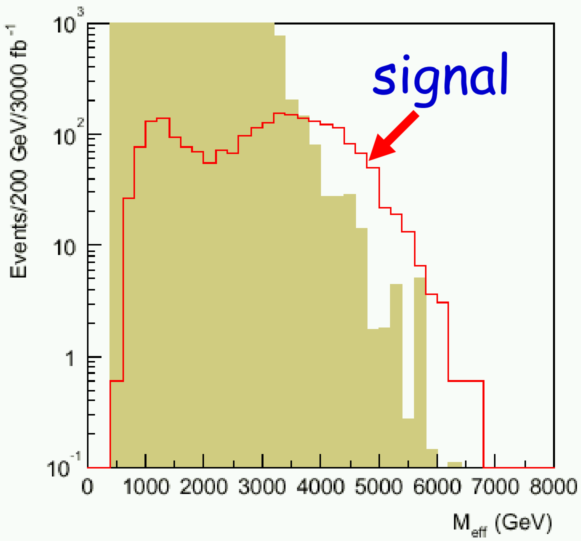
SLHC: tackle difficult SUSY scenarios

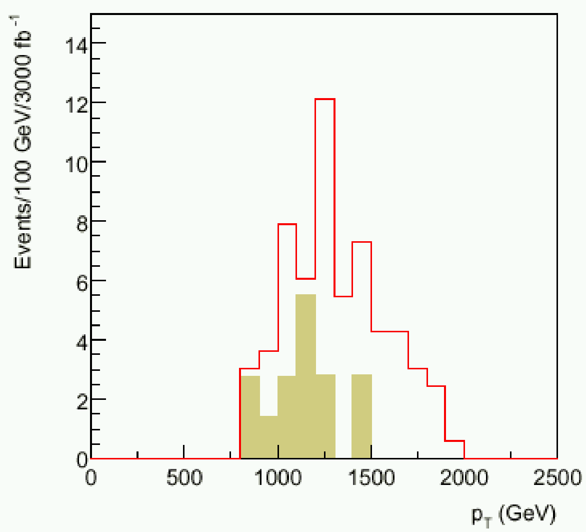
Squarks: 2.0-2.4 TeV   Gluino: 2.5 TeV
Can discover the squarks at the LHC but cannot really study them

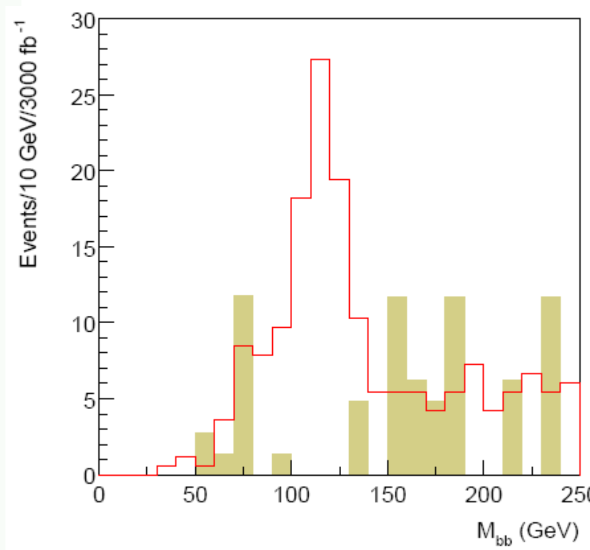
$$M_{eff} = E_T^{miss} + \sum_{jets} E_{T,jet} + \sum_{leptons} E_{T,lepton}$$

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

eg. Point K in hep-ph/0306219







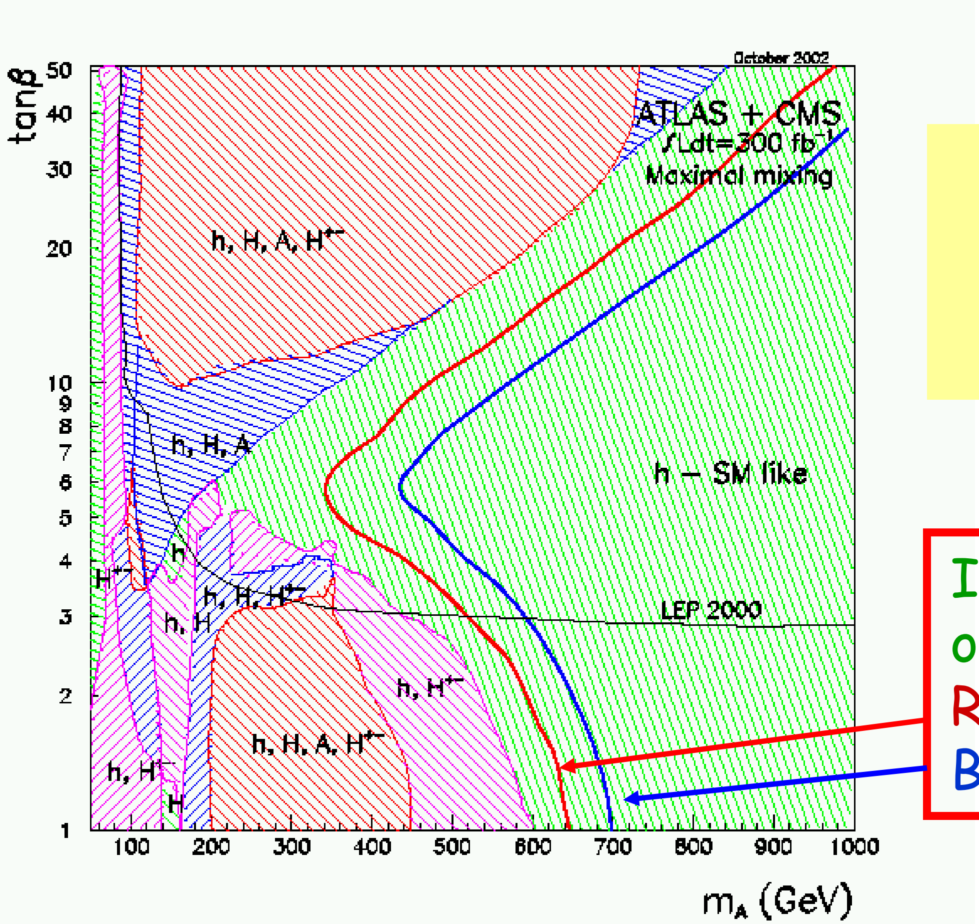
Inclusive: M_{eff} > 4000 GeV
S/B = 500/100 (3000 fb^{-1})

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 of some difficult scenarios become possible at the SLHC

SUSY Higgses h,H,A,H$^{\pm}$

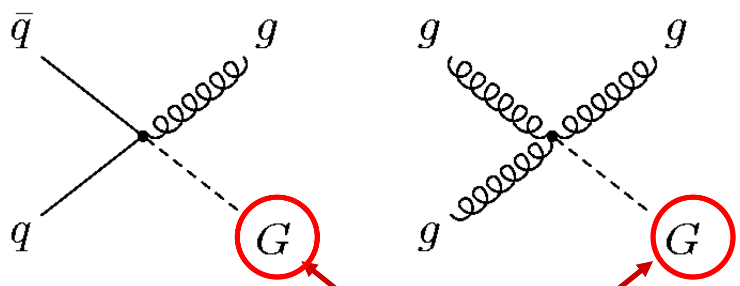


Minimal supersymmetric model
Introduces two complex higgs doublets
→ 5 Higgs particles h,H,A,H$^{\pm}$
H = CP even/ A = CP odd

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 at the SLHC.

Extra Dimension Signals at the LHC

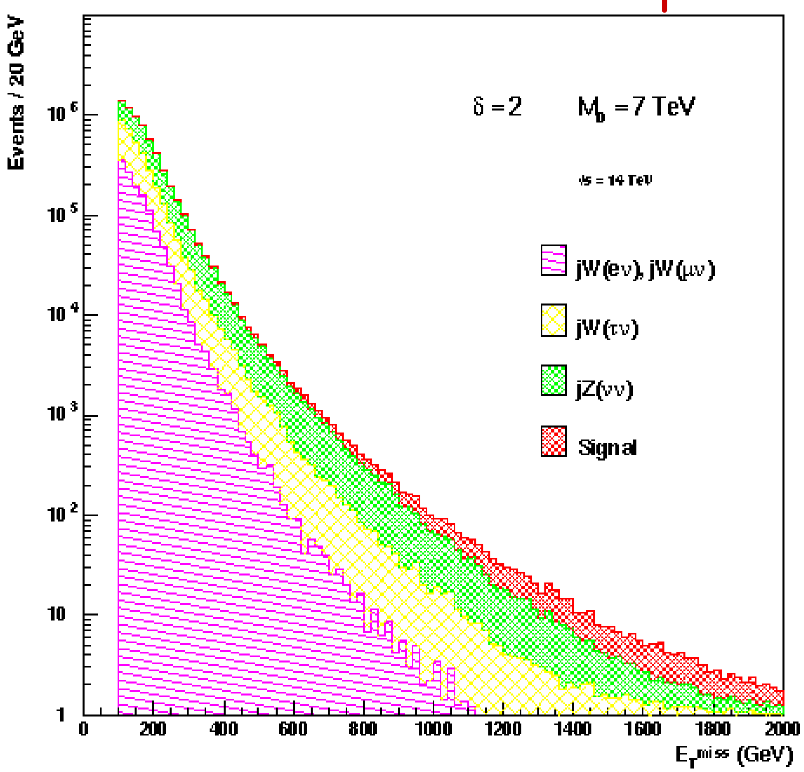


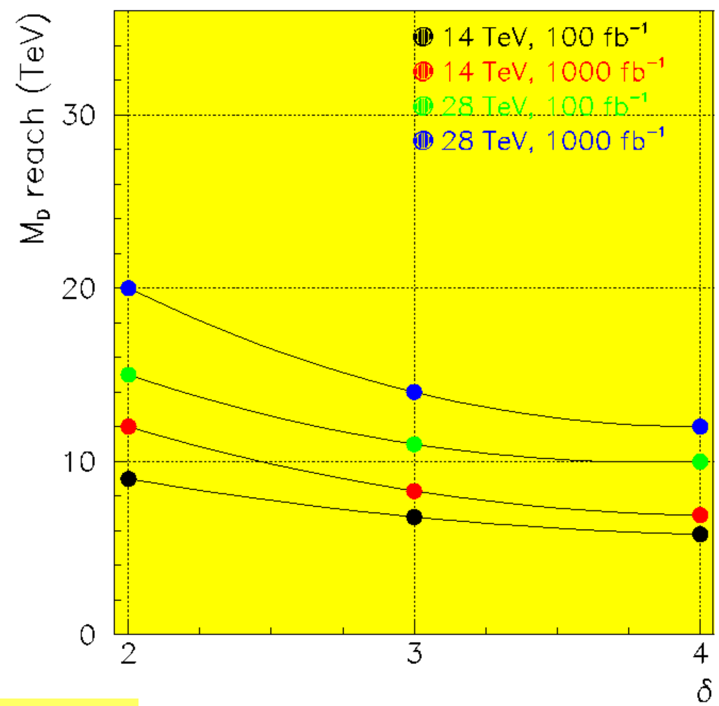
escape!

example

Graviton production!
Graviton escapes detection

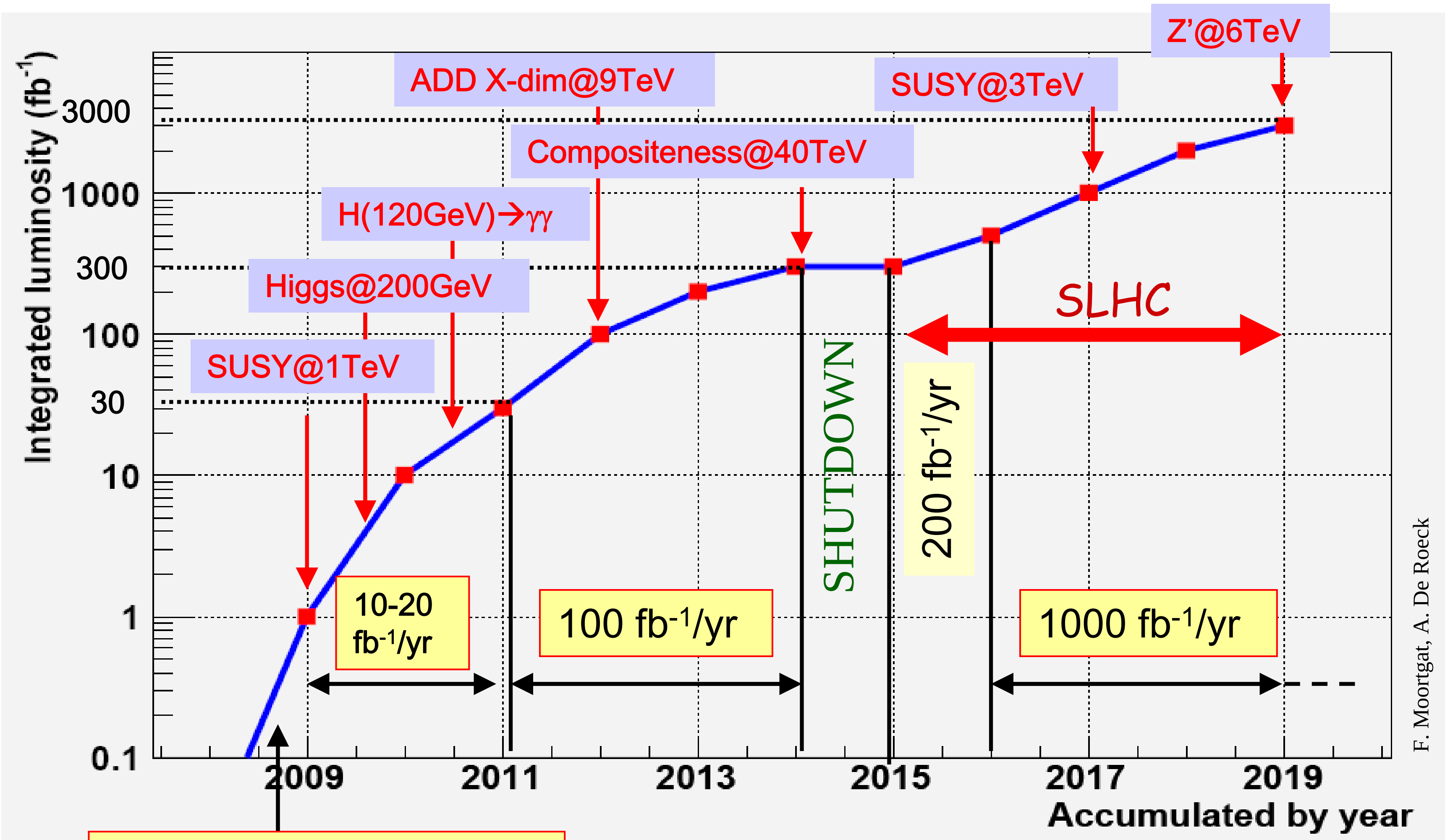
Large (ADD) type of Extra Dimensions
Signal: single jet + large missing ET





About 25% increase in reach

LHC Luminosity/Sensitivity Evolution?



First physics run: O(1fb⁻¹)

Indicative physics results

Process	LHC 14 TeV 100 fb^{-1}	SLHC 14 TeV 1000 fb^{-1}	DLHC 28 TeV 100 fb^{-1}	LC 0.8 TeV 500 fb^{-1}	CLIC 5 TeV 1000 fb^{-1}
Squarks (TeV)	2.5	3	4	0.4	2.5
$W_L W_L$ (σ)	2	4	4.5	6	90
Z′ (TeV)	5	6	8	$8^{\perp}$	$30^{\perp}$
Extra-dimens. scale (TeV)	9	12	15	$5–8.5^{\perp}$	$30–55^{\perp}$
q* (TeV)	6.5	7.5	9.5	0.8	5
Compositeness scale (TeV)	30	40	40	100	400
TGC, λ_γ (95%CL)	0.0014	0.0006	0.0008	0.0004	0.00008

$^{\perp}$*Indirect reach from precision measurements*

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

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} (DLHC) : up to ≈ 10 TeV

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 measurable with a precision of (20-30%)
- Rear decays accessible: $H \rightarrow \mu\mu$, γZ, top decays…
- Improved Higgs coupling ratios by a factor of 2,…
- TGC precision measurements…

In general: SLHC gives a good physics return for modest cost,
basically independent of the physics scenario chosen by Nature
$\Rightarrow$ It is a natural upgrade of the LHC

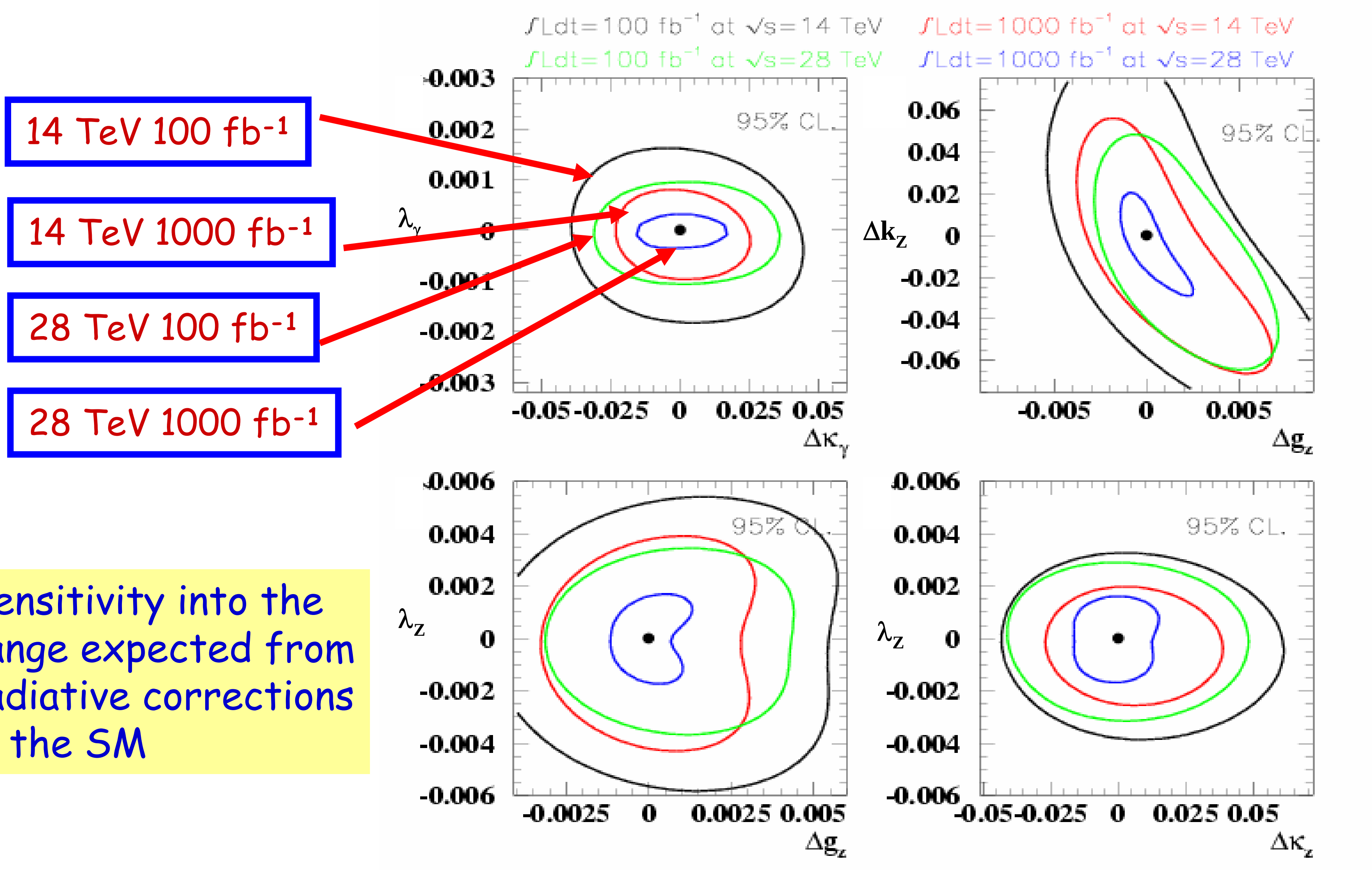
- It will be a challenge for the experiments!
- Needs detector R&D starting now: Tracking, electronics, trigger, endcaps, radiation, shielding…
- CMS and ATLAS started working groups

The energy upgrade DLHC is certainly more costly and up in the future

Backup Slides: some more physics

Electroweak Physics

Triple gauge couplings: sensitivity

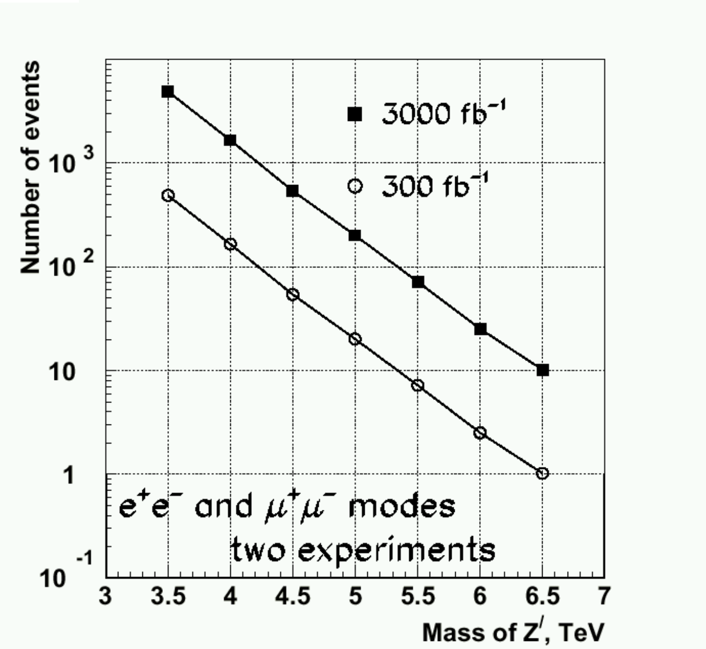


Sensitivity into the range expected from radiative corrections in the SM

SLHC: New Z' Gauge Bosons

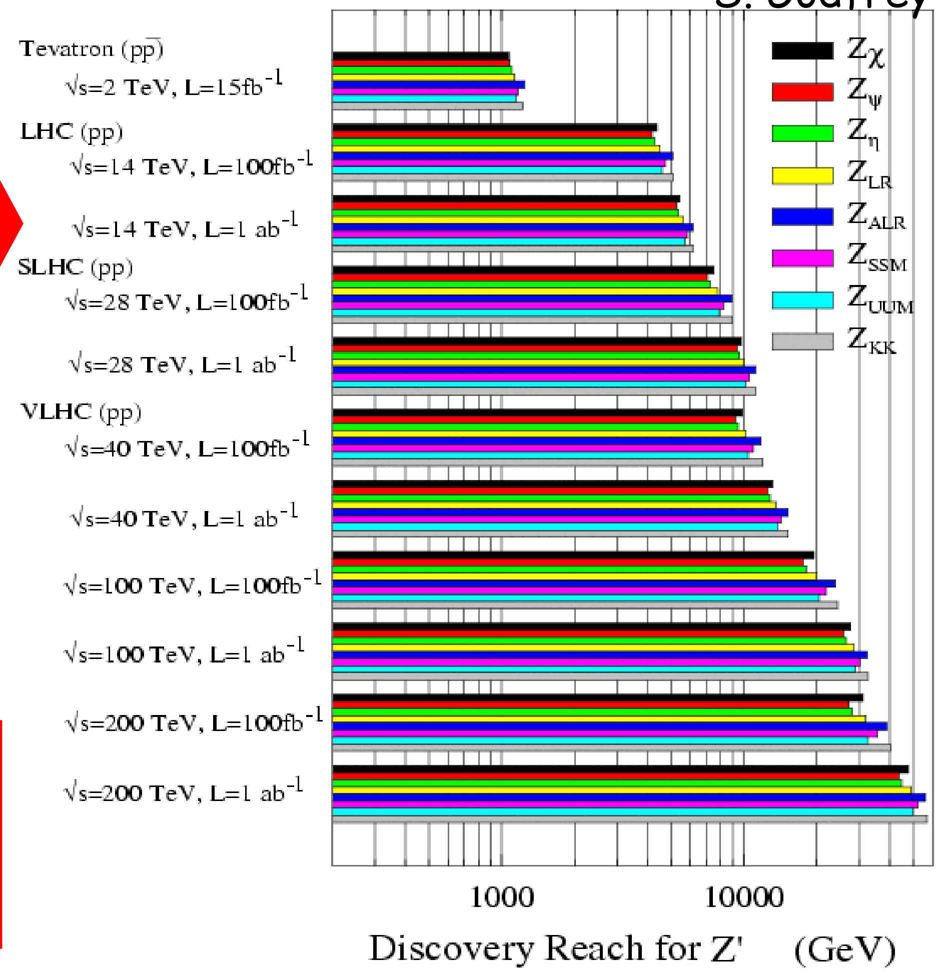
Z' mass (TeV)	1	2	3	4	5	6
$\sigma(Z' \to e^+e^-)(fb)$	512	23.9	2.5	0.38	0.08	0.026
$\Gamma_{Z'}$ (GeV)	30.6	62.4	94.2	126.1	158.0	190.0

with Z-like couplings



Includes pile-up, ECAL saturation…

S. Godfrey

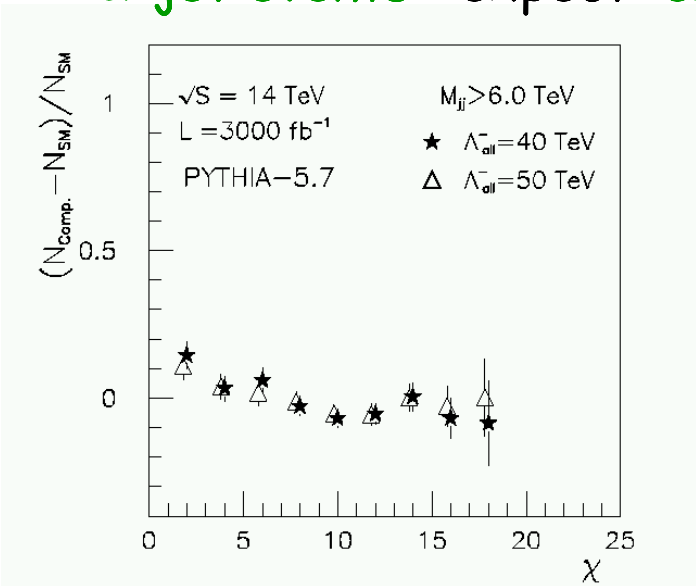


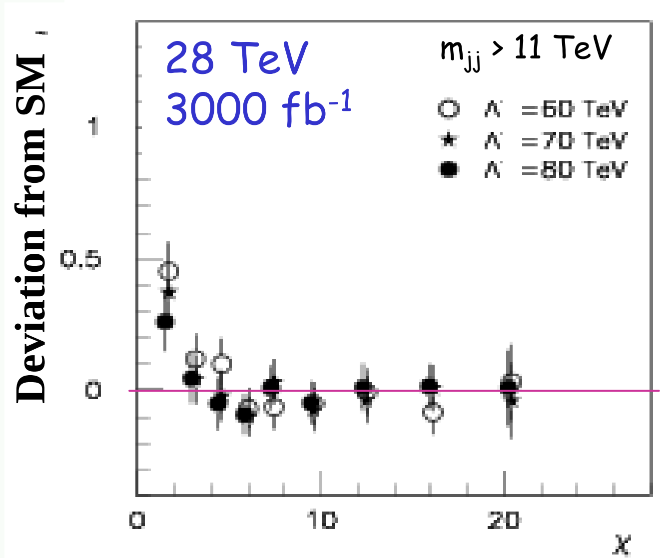
Reach:	LHC/600 fb^{-1}	5.3 TeV
	SLHC/6000 fb^{-1}	6.5 TeV
	DLHC/600 fb^{-1}	8 TeV

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)

Electroweak Physics

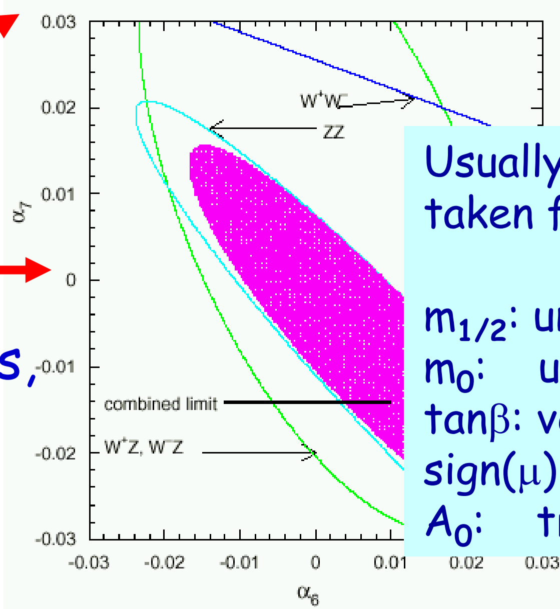
Quartic Gauge Couplings   study pp → qqVV → jjVV (V=W,Z)

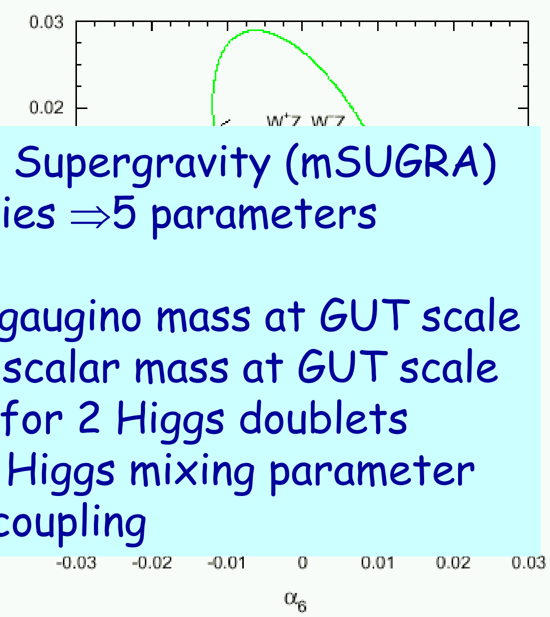
A. S. Belyaev et al:
Operators leading to genuine quartic vertices

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

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, |η|<2.5, 90% eff.
(conservative)





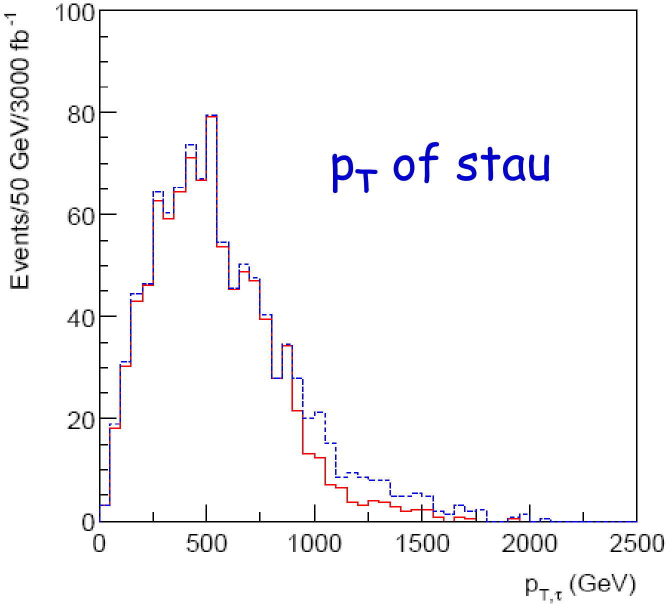
Usually minimal Supergravity (mSUGRA) taken for studies ⇒5 parameters

$m_{1/2}$: universal gaugino mass at GUT scale
m_0: universal scalar mass at GUT scale
tanβ: vev ratio for 2 Higgs doublets
sign(μ): sign of Higgs mixing parameter
A_0: trilinear coupling

SLHC: tackle difficult points

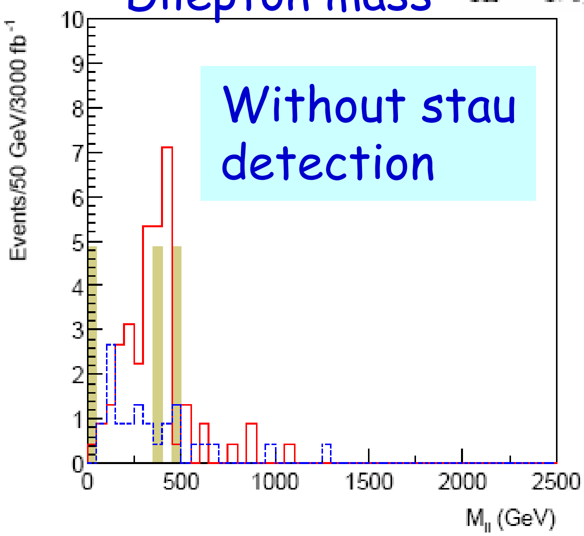
eg. Point H in hep-ph/0306219

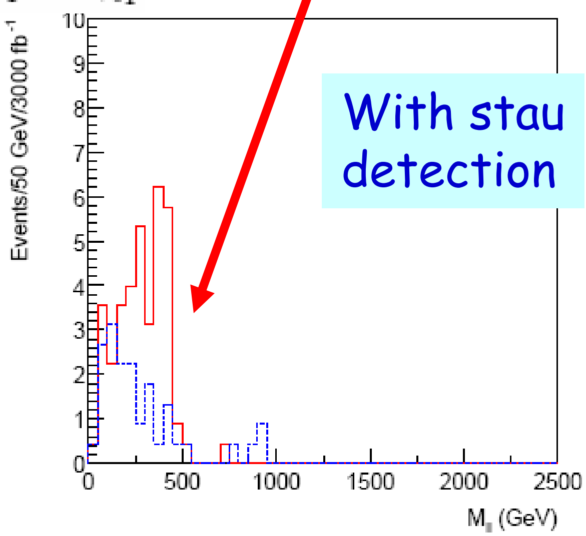
Squarks, gluino mass > 2.5 TeV
χ-stau mass difference small < 1 GeV
$\Rightarrow$ Stau lives long



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

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





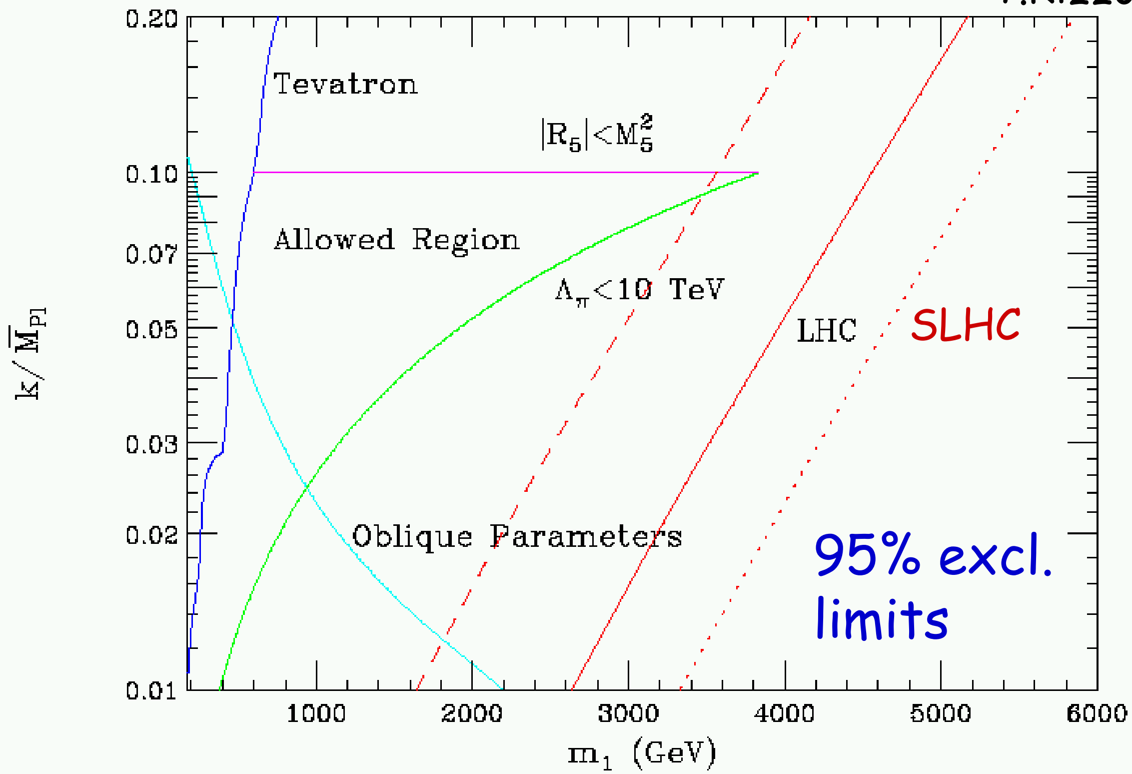
End point measurements are possible with large luminosity

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

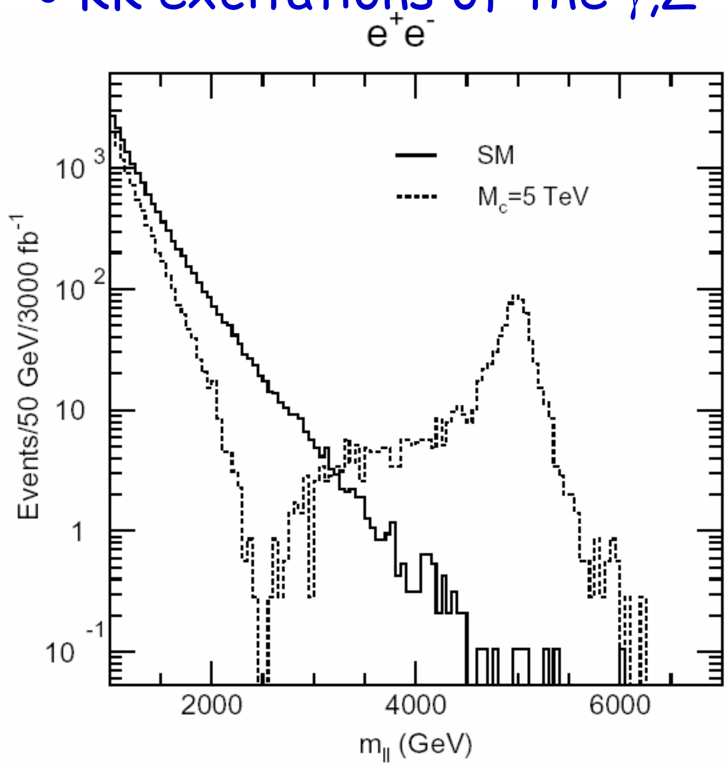
T.Rizzo



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

TeV scale ED's

- KK excitations of the γ,Z

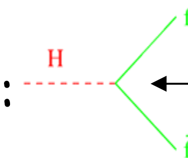


Direct: LHC/600 fb^{-1} 6 TeV
SLHC/6000 fb^{-1} 7.7 TeV
Interf:SLHC/6000 fb^{-1} 20 TeV

Higgs at SLHC

Higgs couplings!

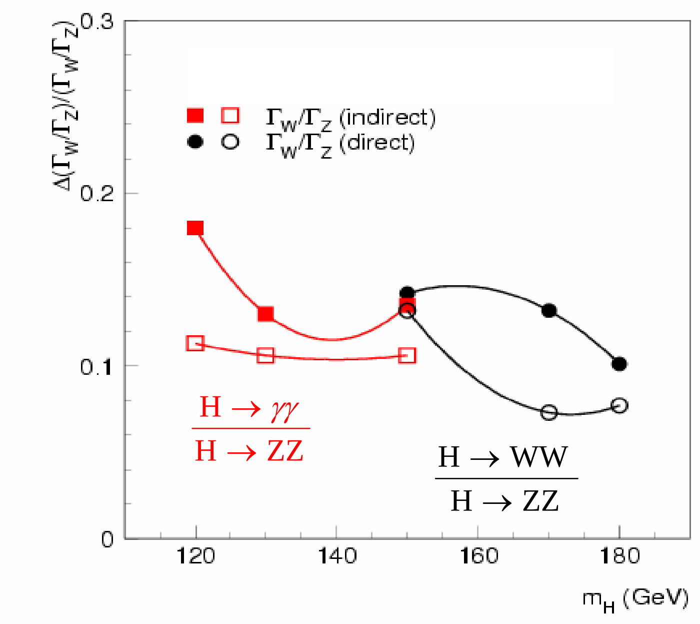
Couplings obtained from measured rate in a given production channel:



$\leftarrow g_{Hff}$

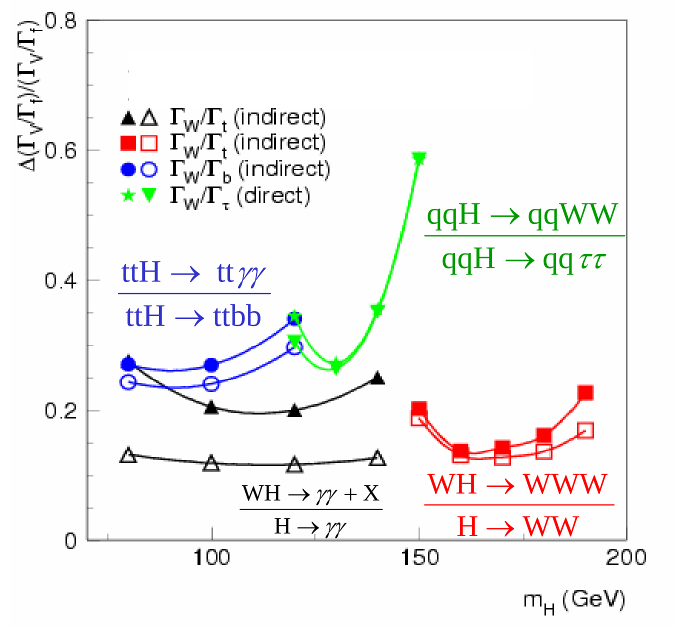
$$R_{ff} = \int L\, dt \bullet \sigma\, (e^+e^-, pp \rightarrow H + X) \bullet BR\, (H \rightarrow ff) \qquad BR\, (H \rightarrow ff) = \frac{\Gamma_f}{\Gamma_{tot}} \quad \rightarrow \text{deduce} \quad \Gamma_f \sim g^2_{Hff}$$

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



Closed symbols:
LHC 600 fb^{-1}

Open symbols:
SLHC 6000 fb^{-1}

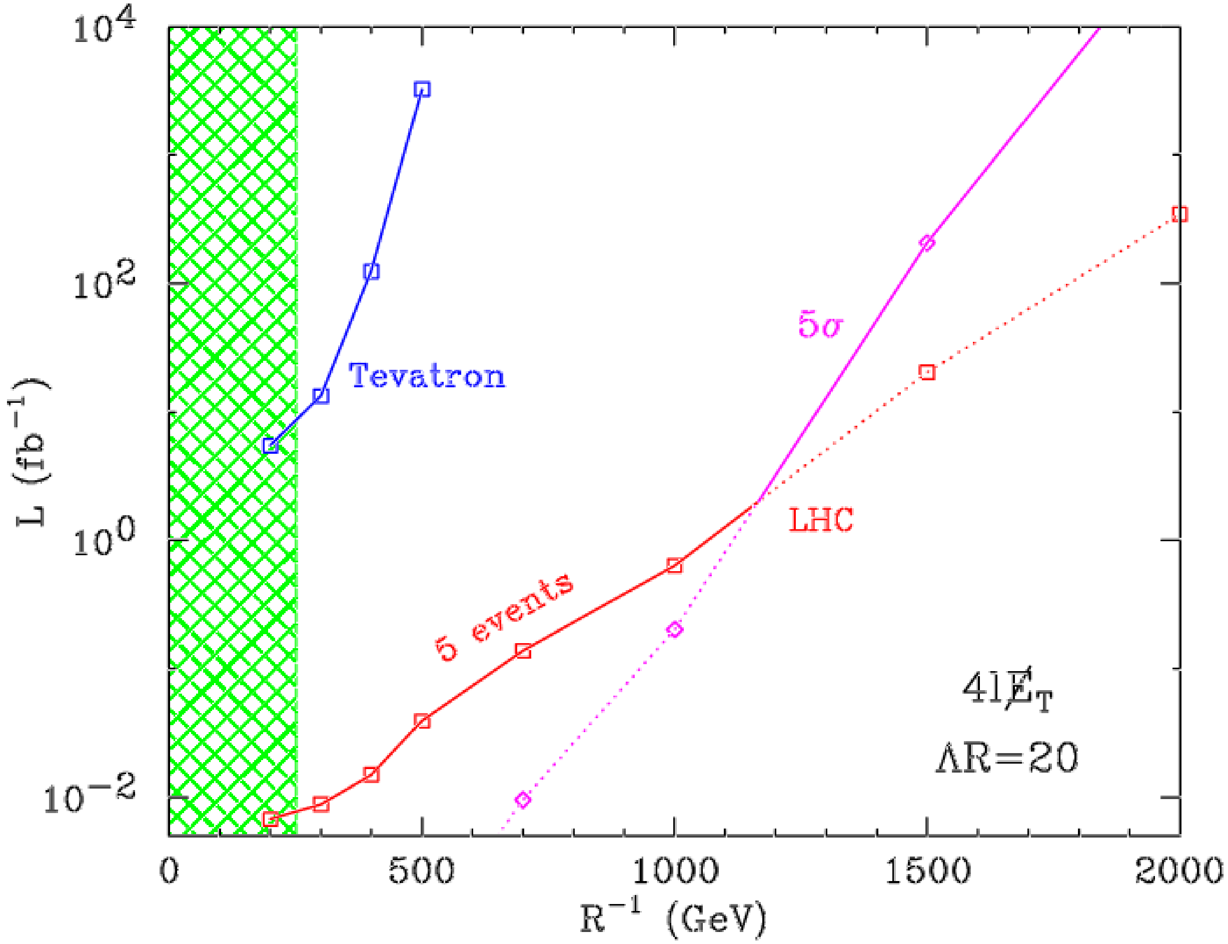


SLHC could improve LHC precision by up to ~ 2

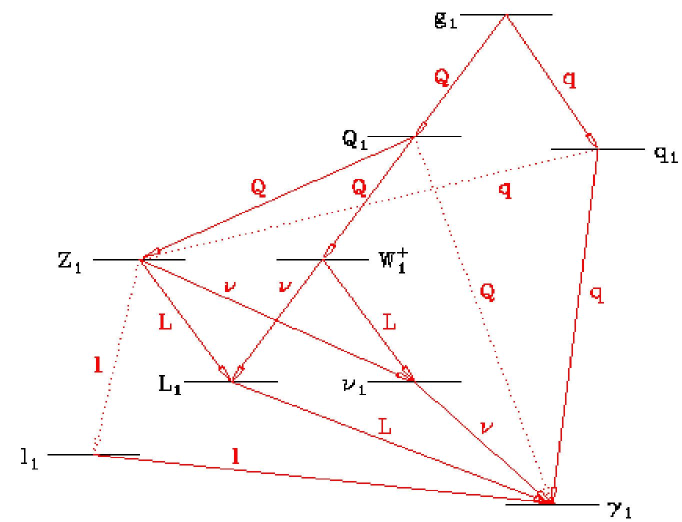
Universal Extra Dimensions

Everybody in the bulk!

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

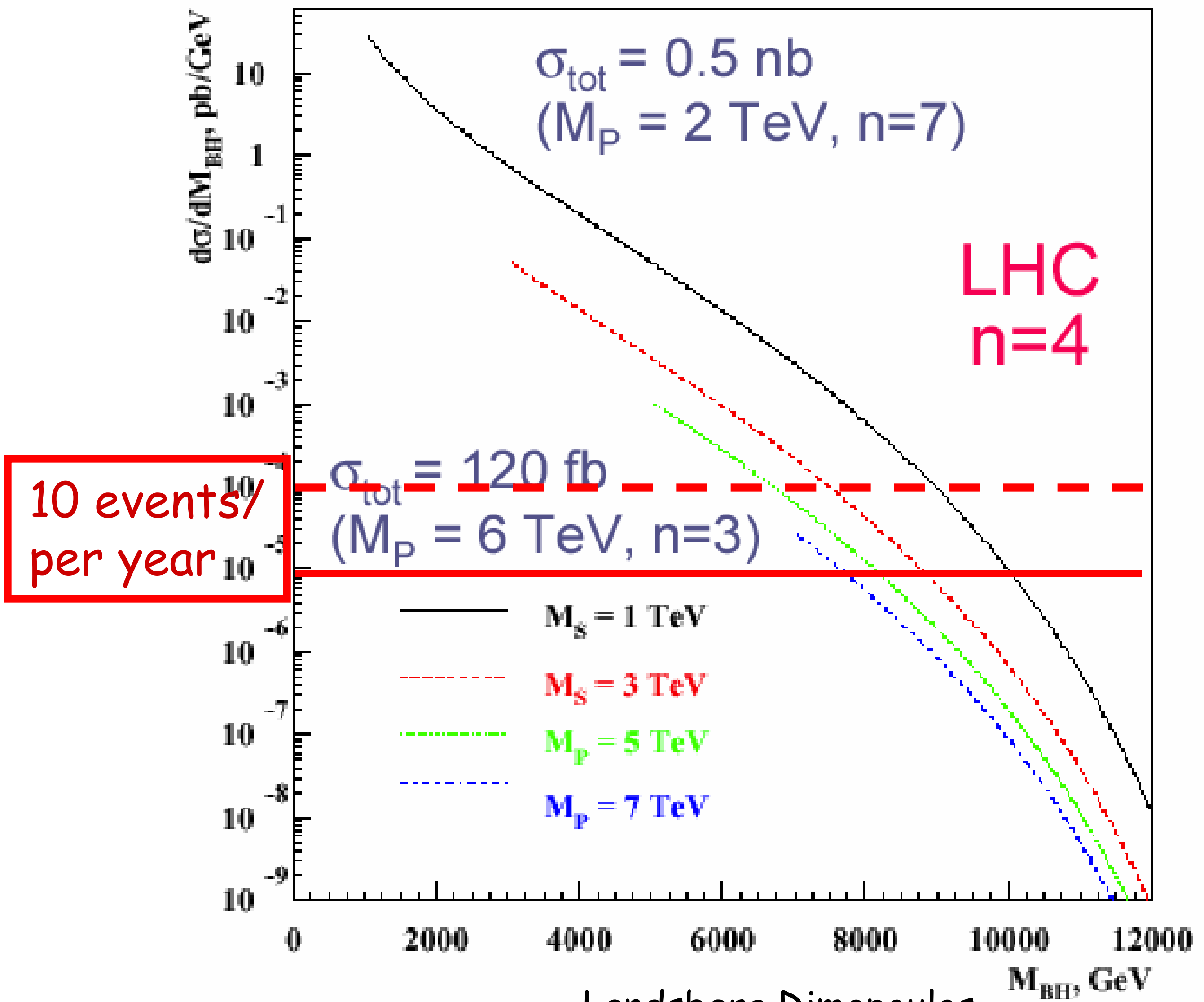


Search: e.g 4 leptons + E_T^{miss}



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

Black Holes



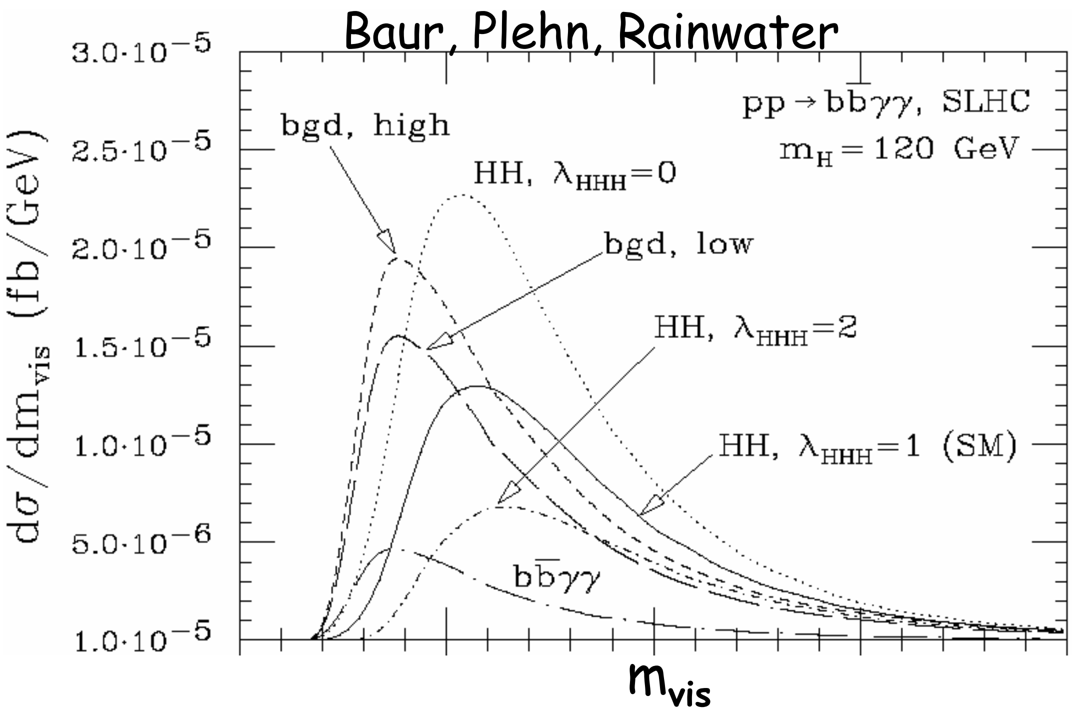
Landsberg,Dimopoulos

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

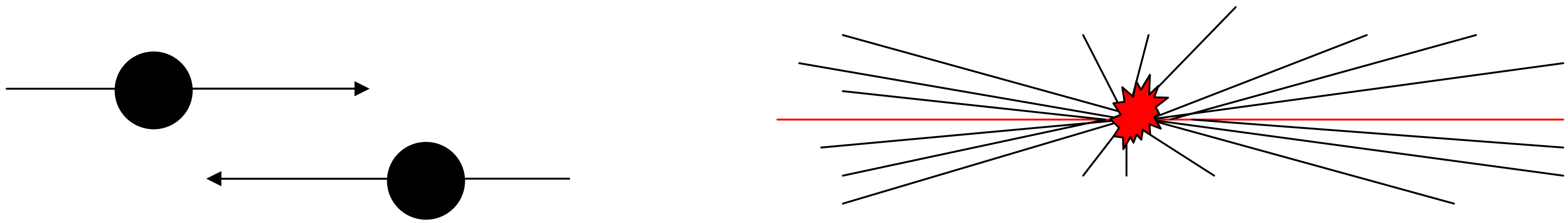
- For m_H=120 GeV and 600 fb^{-1} expect 6 events at the LHC with S/B~ 2 (single b tag)
- Interesting measurement at the SLHC (double b tag)

machine	$m_H = 120$ GeV "hi"	"lo"	bkg. sub.	$m_H = 140$ GeV "hi"	"lo"	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

Proton-proton collisions

Most interactions due to collisions at large distance between incoming protons where protons interact as " a whole "
→ small momentum transfer ($\Delta p \approx \hbar / \Delta x$)
→particles in final state have large longitudinal momentum but small
→transverse momentum (scattering at large angle is small)



$< p_T > \approx 500$ MeV of charged particles in final state

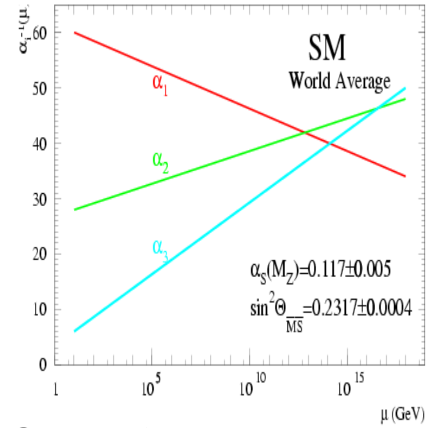
Most energy escapes down the beam pipe.

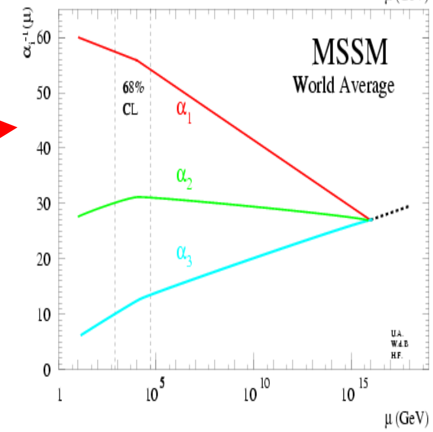
These are called minimum-bias events (" soft " events)..

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
  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 ~ 800 GeV
- Strong electroweak symmetry breaking around 1 TeV

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

LHCb Upgrade Plans

- plan to operate 5 years at $2*10^{33}$ cm^{-2} s^{-1}
  - → accumulate 100 fb^{-1}
- some of the physics goals
  - ❍ B_s physics 'unique' to LHCb
  - → weak mixing phase ϕ_s (from $B_s \rightarrow J/\psi\ \phi$)
  - → b→s transition using $B_s \rightarrow \phi\phi$
  - → CKM angle γ from $B \rightarrow DK$, $B_s \rightarrow D_s K$
- experimental upgrade independent of LHC upgrade
  - → replace VELO with more radiation hard variant
  - → add first level trigger on detached vertices
  - → further components under study

ALICE Upgrade Plans

- present physics program extends until 2017
  - → Pb Pb, p p and p ion running
  - → later low mass ions and lower energies
- present plans for further installation
  - → 2010 electromagnetic calorimeter
  - → 2012-2015 thinner beam pipe, new pixel detector, improved high p_T particle ID, improved forward instrumentation
- request for accelerator R&D to increase PbPb luminosity to $5 * 10^{27}$ cm^{-2} s^{-1}
  - → need modification to TPC, TPC electronics and DAQ

Present CERN Position on the Upgrade

CERN DG 27/6/07

Prospects for scientific activities over the period 2012-2016

Results available from LHC operation during the period 2008-2011 and from the activities proposed above should allow the CERN Council in 2010-2011 to decide on the future of CERN for more than one decade.

- If results from the LHC, as is highly likely, suggest the need for an increase in luminosity allowing a more extensive exploration of the new territory opened by the LHC, **a decision on the luminosity increase** (new RF system, new magnets for IR, increased cooling, new tracking in detectors, etc.) **will entail a simultaneous decision to build a new injector (SPL and PS) since higher LHC performance cannot be achieved reliably enough without a new injection line.**

The total cost of the investment, which is assumed to be realized in 6 years (2011-2016), is within the range 1'000-1'200 MCHF and will require a staff of 200-300 per year, thus a total budget of about 200-250 MCHF per year.