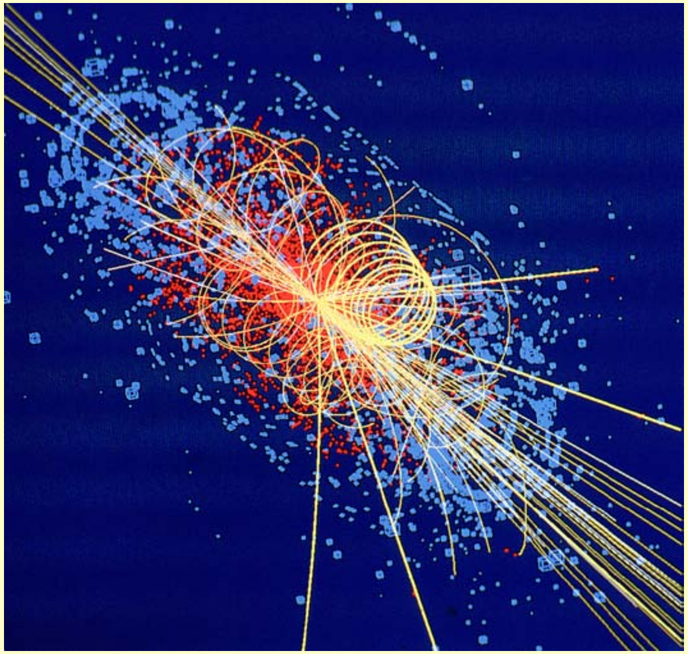
Physics at the LHC and sLHC



- Introduction
- Early measurements at the LHC
- The physics reach of the (s)LHC
  - Searches for Physics Beyond the SM
  - Higgs bosons
  - Precision physics

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Key Questions of Particle Physics

1. Mass: What is the origin of mass?

- How is the electroweak symmetry broken ?
- Does the Higgs boson exist ?

2. Unification: What is the underlying fundamental theory ?

- Can the interactions be unified at larger energy?
- How can gravity be incorporated ?
- What is the nature of the Dark Matter in the Universe ?
- Is our world supersymmetric ?
- …..

3. Flavour: or the generation problem

- Why are there three families of matter?
- Neutrino masses and mixing?
- What is the origin of CP violation?

- Supersymmetry
- Extra dimensions
- ….
- Little Higgs models
- Invisibly decaying Higgs bosons
- Leptoquarks
- New gauge bosons
- ….
- Composite squarks and leptons
- …

The role of the LHC

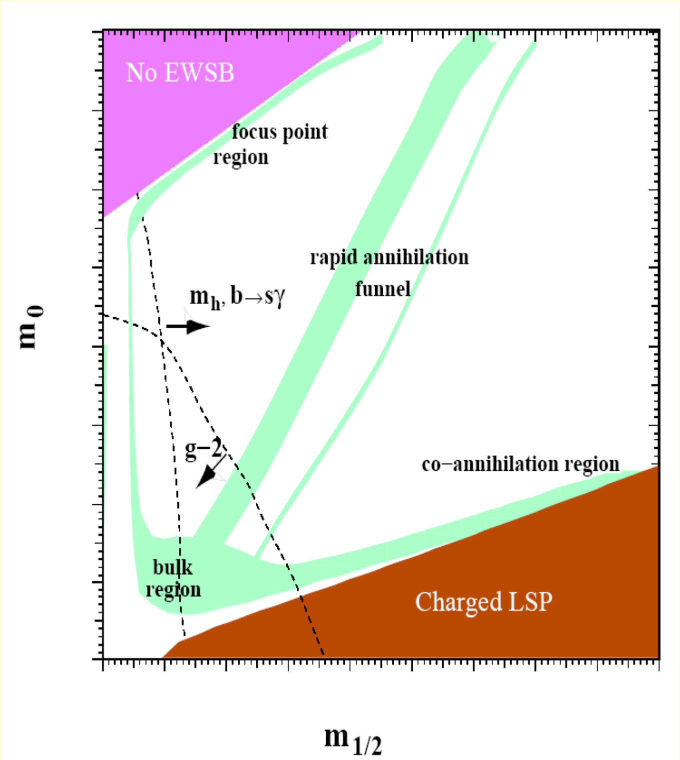
1. Explore the TeV mass scale

- What is the origin of the electroweak symmetry breaking ?
- The search for “low energy” supersymmetry
- Other scenarios beyond the Standard Model
- …….

sLHC can extend the mass reach !

Look for the “expected”, but we need to be open for surprises

The link between SUSY and Dark Matter ?

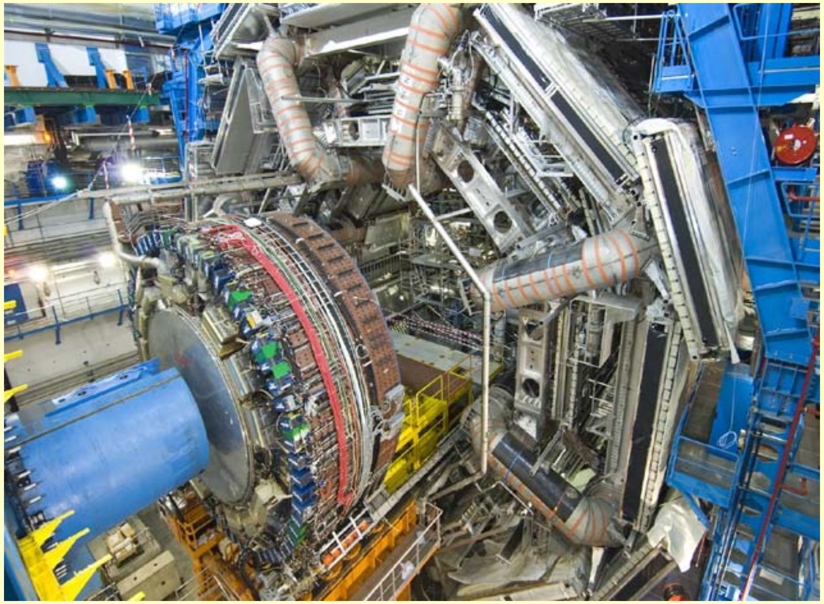


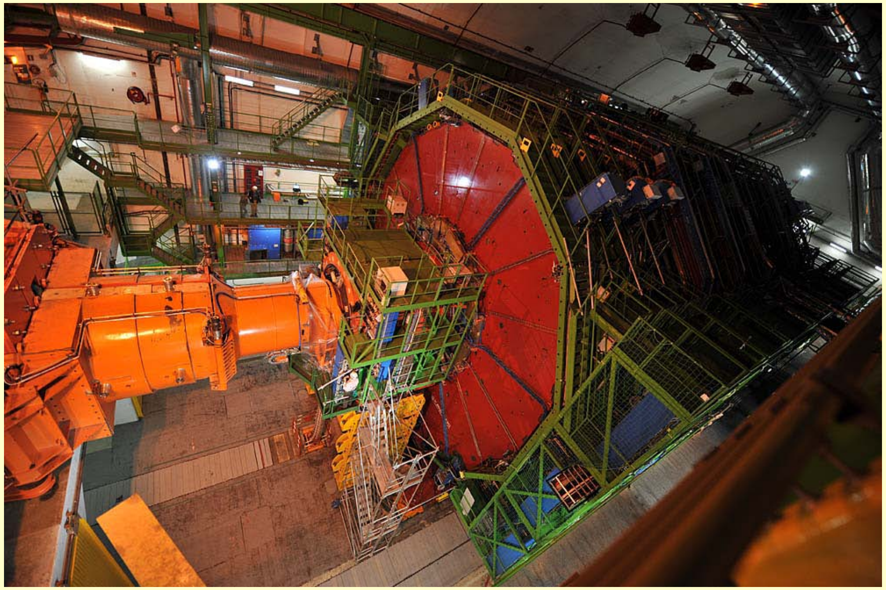
M. Battaglia, I. Hinchliffe, D.Tovey, hep-ph/0406147

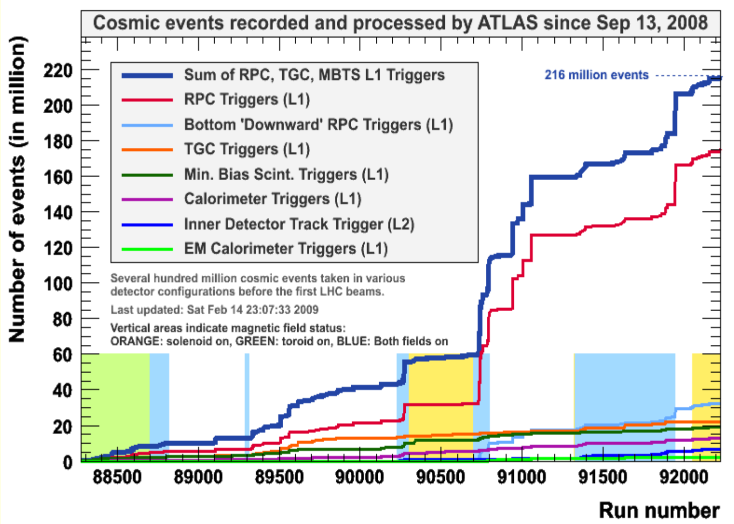
2. Precise tests of the Standard Model

- There is much sensitivity to Physics Beyond the Standard Model in the precision area
  * Standard measurements (m_W, m_t) at the LHC
  * Rare Decays at the sLHC

The ATLAS and CMS experiments

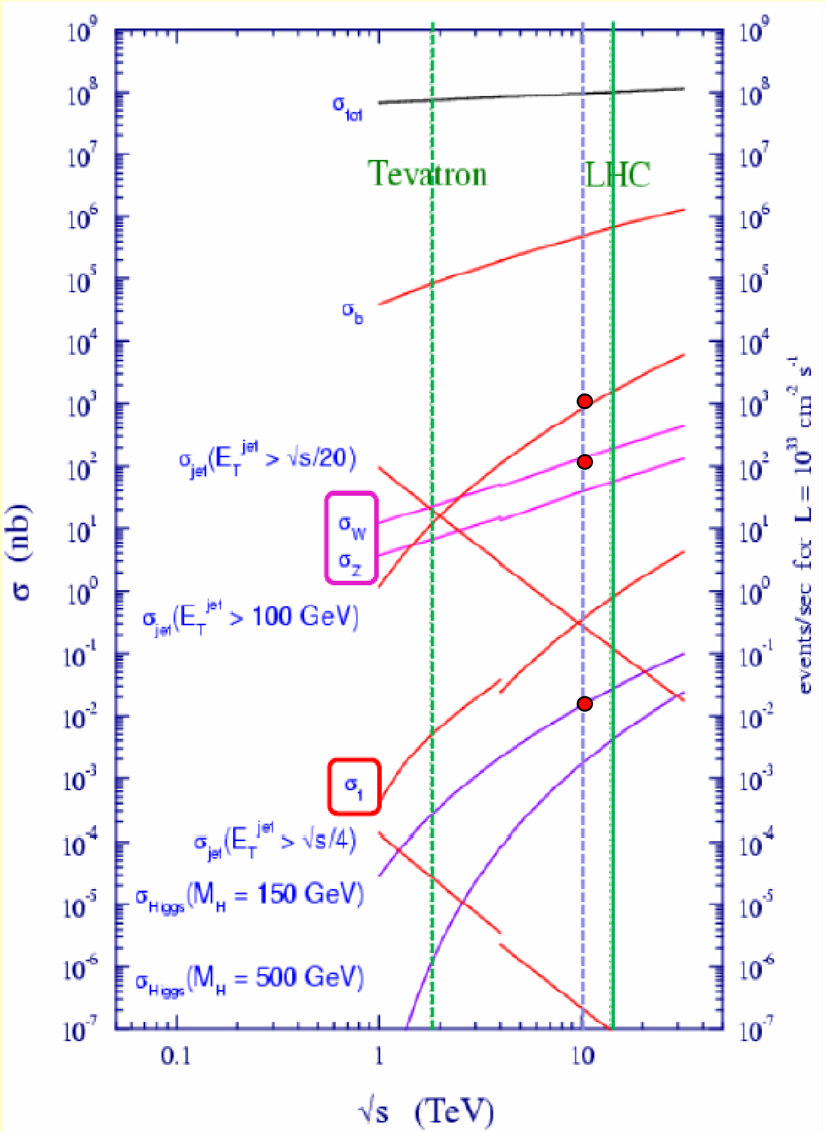


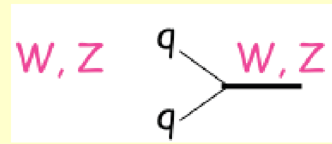


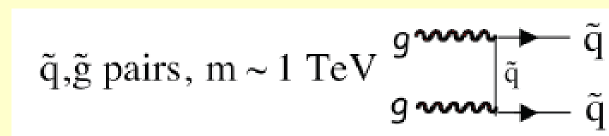


The experiments were ready for collisions in 2008,
….they will be in better shape in 2009.

Cross Sections and Production Rates



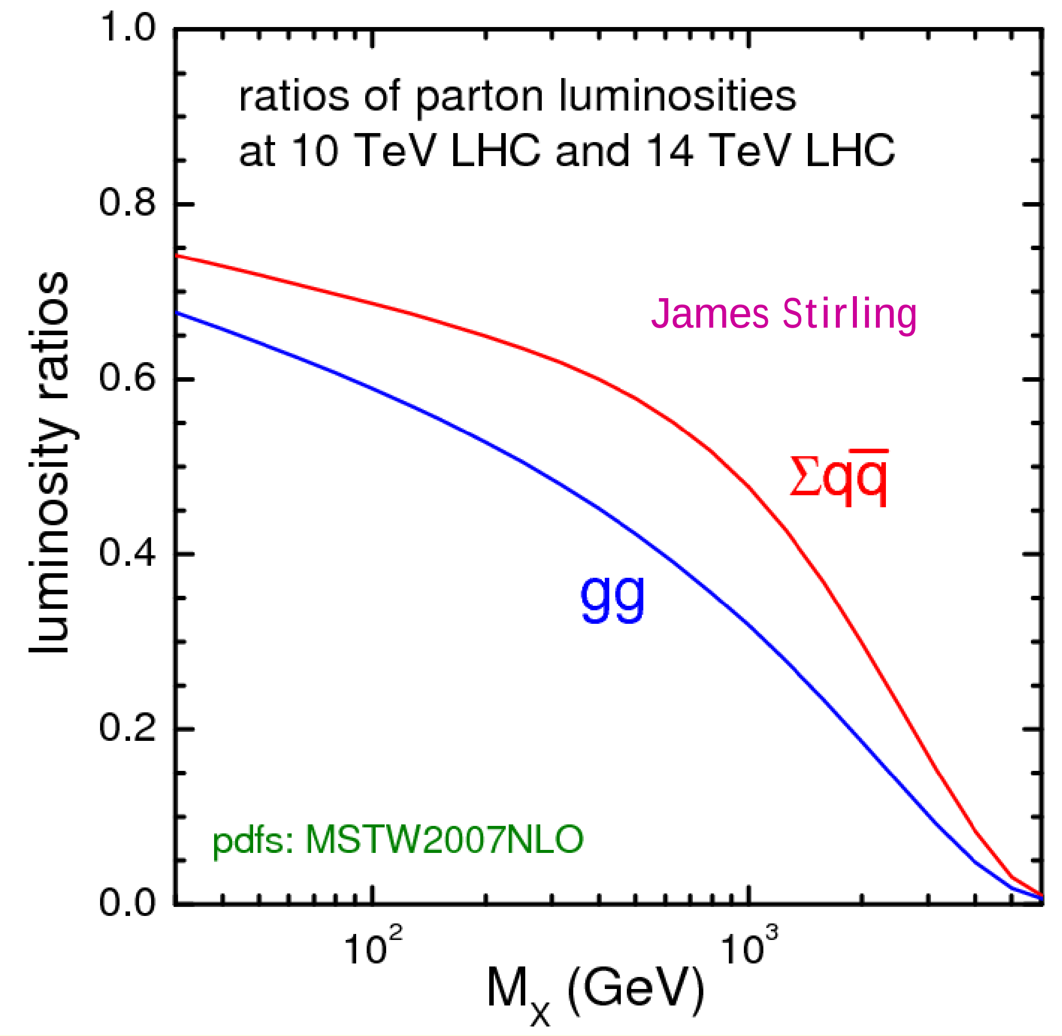




- Large cross sections for QCD jet, W/Z and tt production

- First physics results expected in these areas however: already sensitivity to new physics with early data; reach depends strongly on energy and integrated luminosity

Energy dependence: 10 vs 14 TeV ?



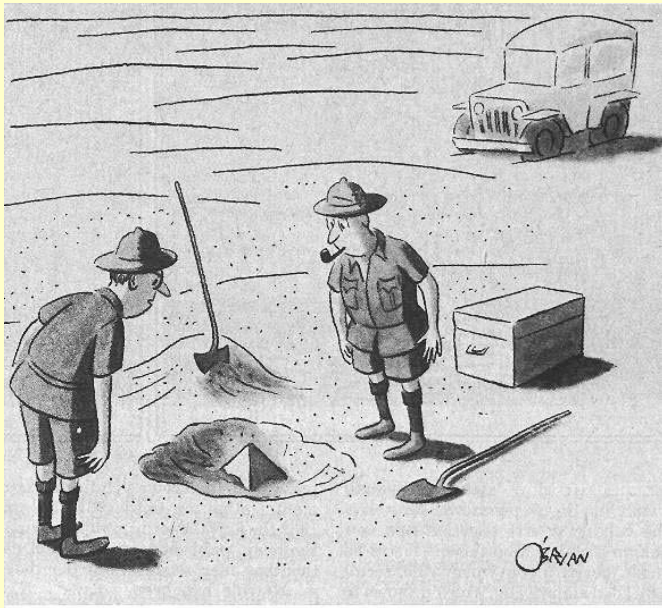
- At 10 TeV, more difficult to create high mass objects...
- Below about 200 GeV, this suppression is <50% (process dependent)

	√s [TeV]	Cross section
W-> lν	14	20.5 nb
	10	14.3 nb
Z-> ll	14	2.02 nb
	10	1.35 nb
ttbar	14	833 pb
	10	396 pb

- Above ~2-3 TeV the effect is more marked

14 TeV simulation results will be shown throughout the talk, unless stated otherwise

Towards First Physics Results in 2010



"This could be the discovery of the century. Depending, of course, on how far down it goes."

Physics with 20 – 200 pb^{-1}:

- Establish Standard Model signals
- Use them to understand the detector performance
- Look for first, striking deviations from the Standard Model (however: $\sqrt{s}$ = 7 TeV)

First goals …. (2010) (?)

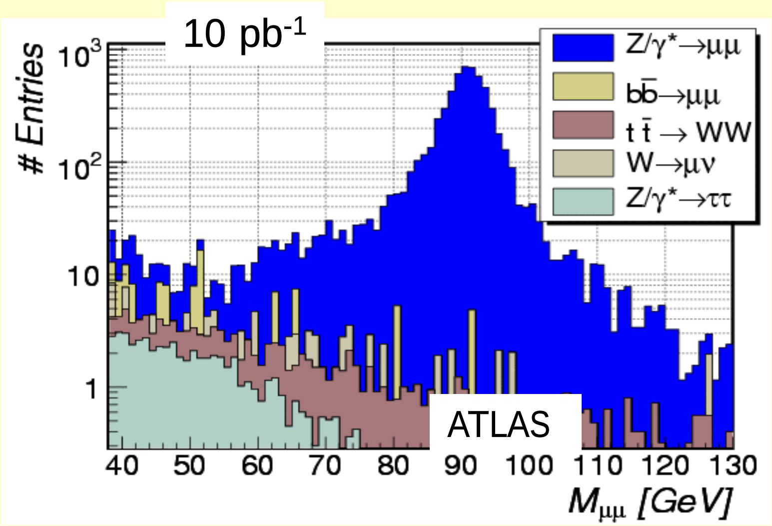
- Understand and calibrate detector and trigger

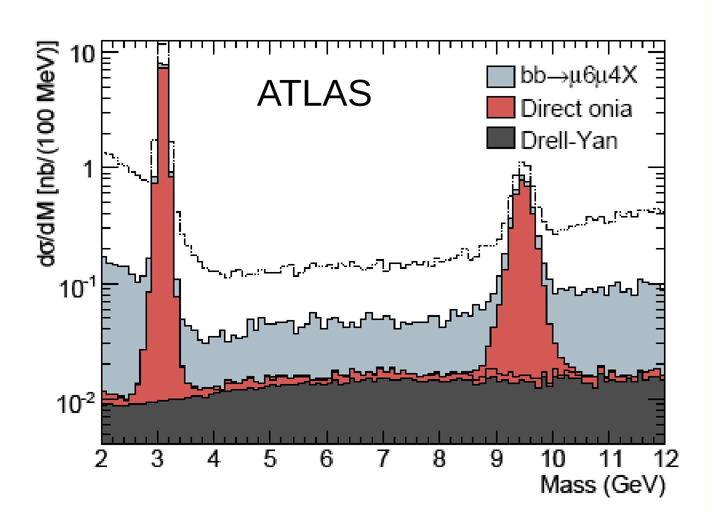
  in situ using well-known physics samples

e.g. - $Z \to ee, \mu\mu$ tracker, calorimeter, muon chambers calibration and alignment

- $tt \to b\ell\nu\ bjj$ 10^2 events / day after cuts at 10^{32} cm^{-2} s^{-1}

  $\to$ b-tag performance

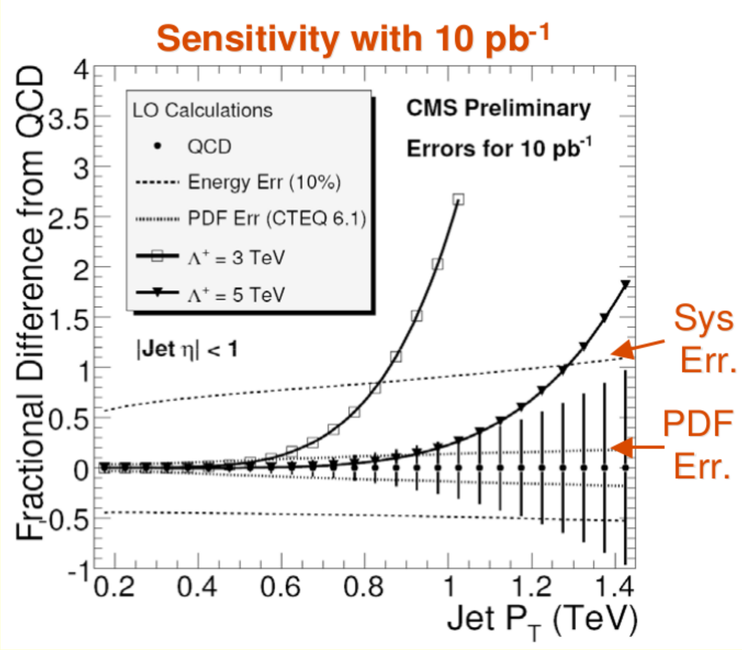




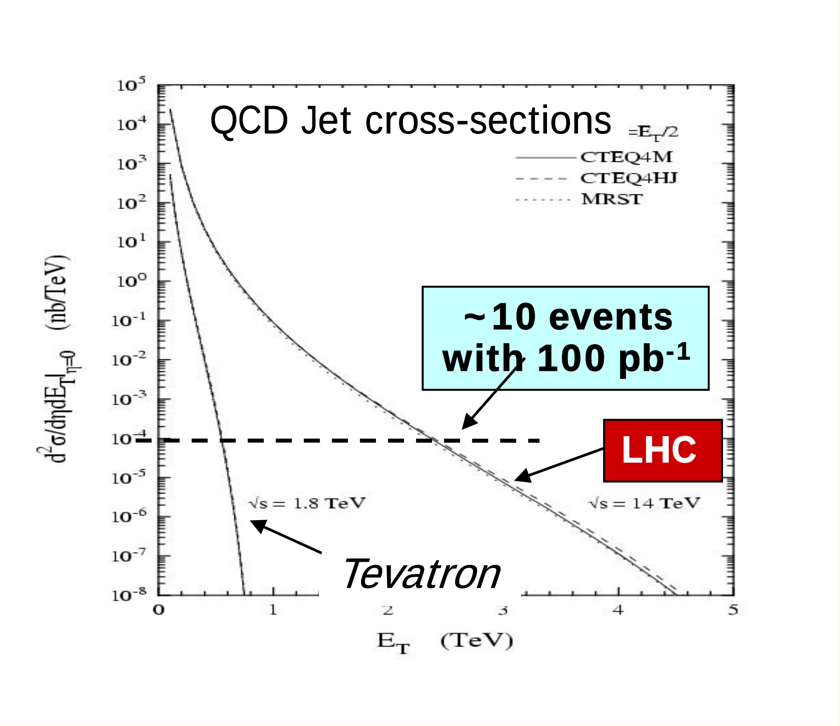
1 pb^{-1}, low p_T muon triggers

Jets from QCD production

- Rapidly probe perturbative QCD in at a new energy (above Tevatron)
- New physics sensitivity at high E_T
  - compositeness
  - new resonances at high mass



- Even with JES uncertainties expected with early data, compositeness scales of 3 TeV can be reached with 50 pb^{-1} at $\sqrt{s}$ = 10 TeV (close to present Tevatron reach of Λ = 2.7 TeV)



95% C.L. limits on compositeness scale Λ

		95% CL limits
14 TeV	300 fb^{-1} 3000 fb^{-1}	40 TeV 60 TeV
28 TeV	300 fb^{-1} 3000 fb^{-1}	60 TeV 85 TeV

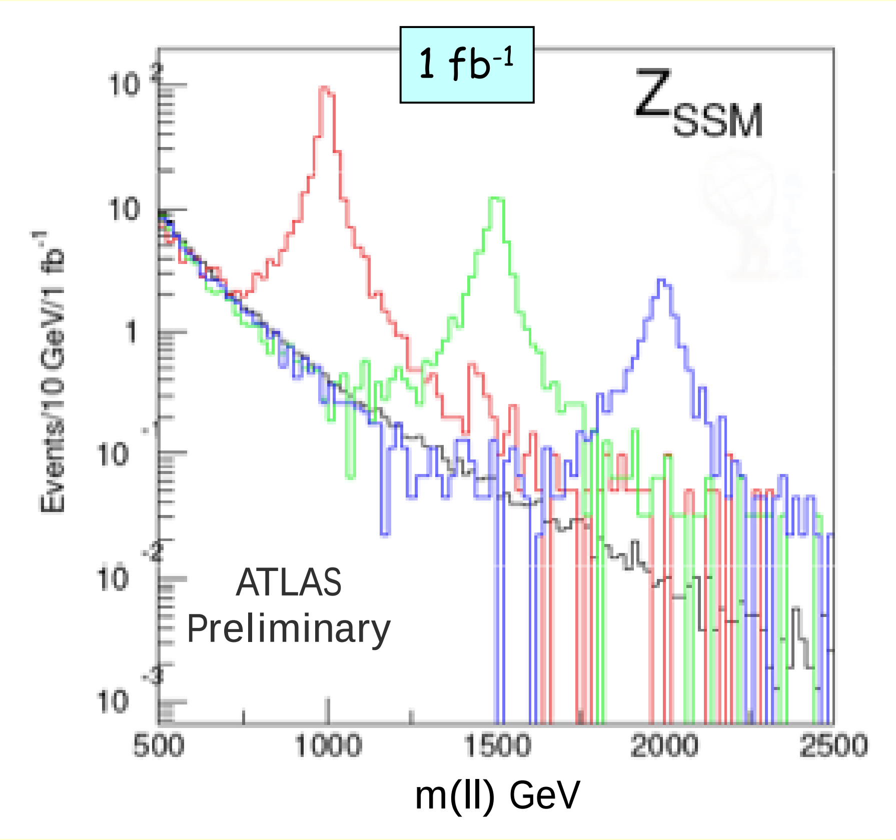
Early Surprises ??

- as already mentioned, the experiments must be open for surprises / unknowns / unexpected discoveries

- requires unbiased measurements of
  - inclusive lepton spectra
  - dileptons spectra……
  - ETmiss spectrum…….
  - ……

One example of many….

$Z' \rightarrow e^+e^-$ with SM-like couplings (Z_{SSM})

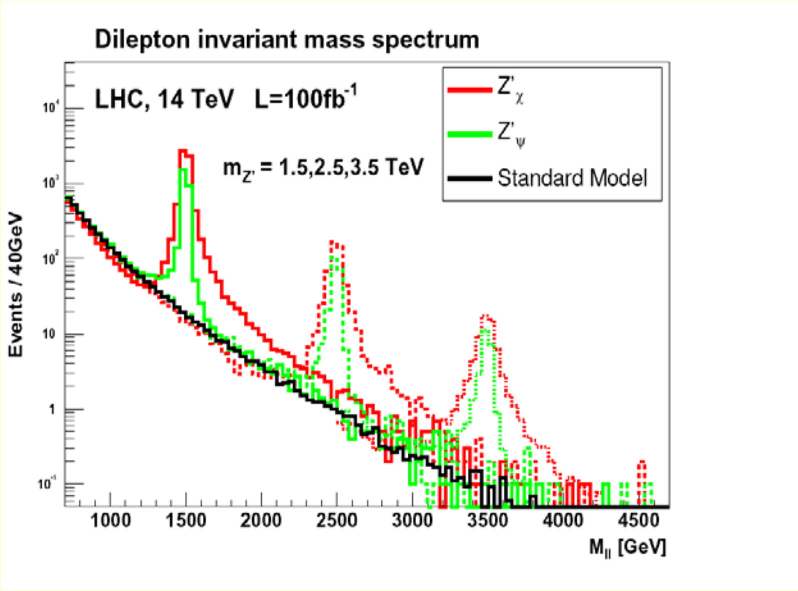


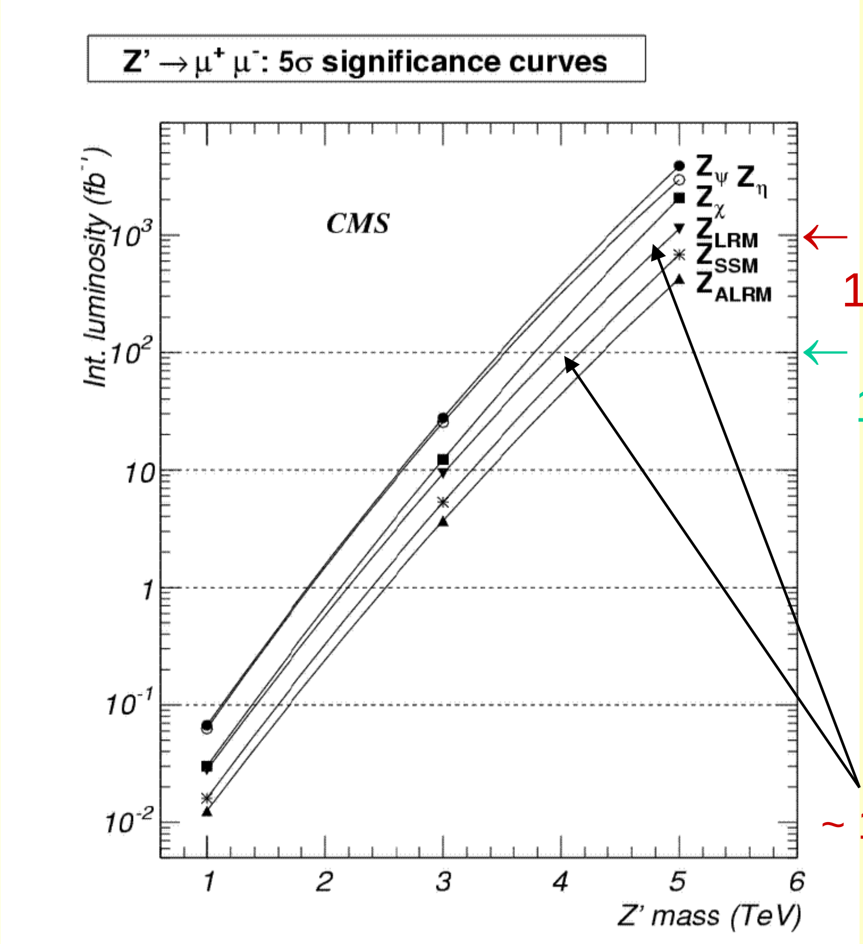
$\sqrt{s}$ = 14 TeV

Mass (TeV)	Events / fb^{-1} (after cuts)	Luminosity needed for a 5σ discovery + (10 obs. events)
1	~160	~70 pb^{-1}
1.5	~30	~300 pb^{-1}
2	~7	~1.5 fb^{-1}

Discovery window above Tevatron limits
m ~ 1 TeV, perhaps even in 2010/11 (?)

Z' mass reach as function of the luminosity





← SLHC 1000 fb^{-1}

← LHC 100 fb^{-1}

~ 1.0 TeV

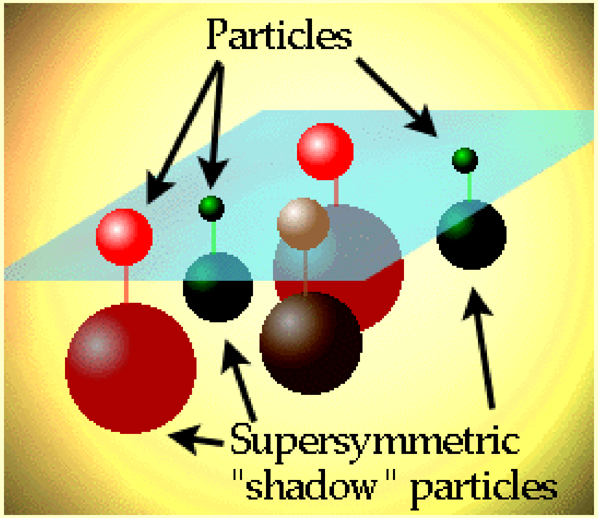
- LHC reach: ~ 4 TeV with 100 fb-1 (somewhat model dependent)
- Gain in reach: ~ 1 TeV i.e. 25-30% in going from LHC to sLHC

Search for

Supersymmetry

- First hints of supersymmetry might show up as well already in early data……
- Ultimate mass reach needs the sLHC

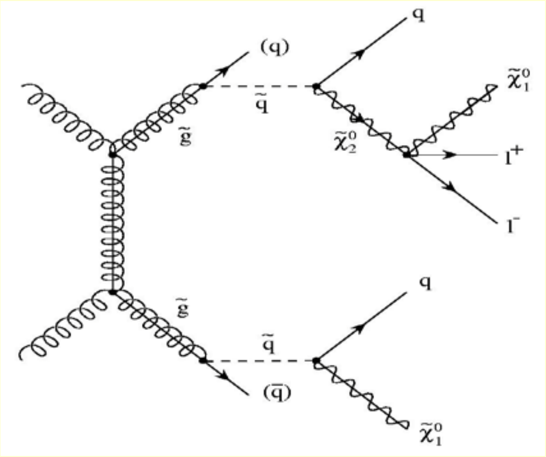
  (theorists don't tell us the mass scale)



Search for Supersymmetry

- Squarks and Gluinos are strongly produced

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



$\Rightarrow$ combination of Jets, Leptons, E_T^{miss}

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

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

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

Supersymmetry Reach: LHC and SLHC

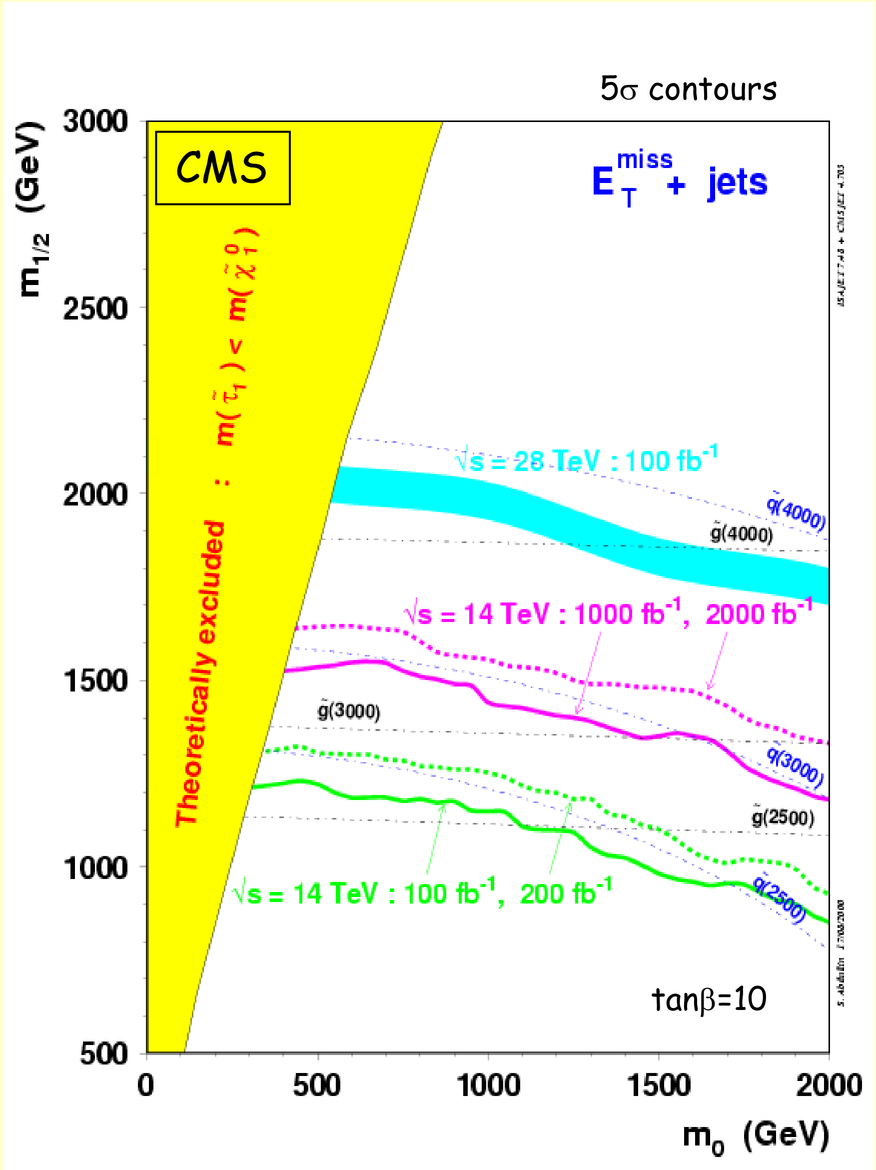
Impact of the SLHC

Extend the discovery region for squarks and gluinos by roughly 0.5 TeV, i.e. from

~2.5 TeV → 3 TeV

This extension involved high E_T jets/leptons and large missing E_T

⇒ Not much compromised by increased pile-up at SLHC



$m_{1/2}$: universal gaugino mass at GUT scale

m_0: universal scalar mass at GUT scale

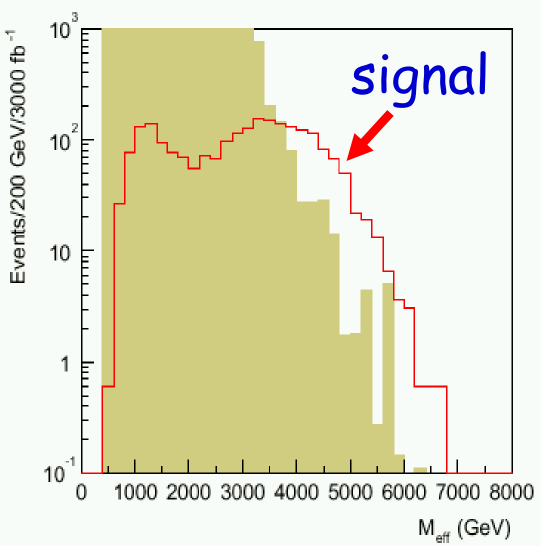
SLHC: tackle difficult SUSY scenarios

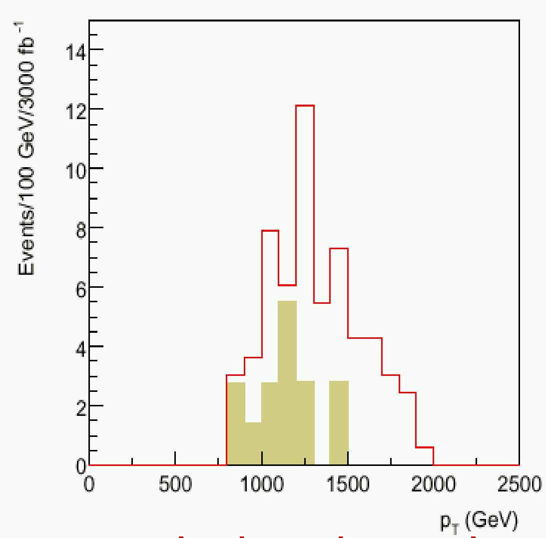
Squarks: 2.0-2.4 TeV Gluino: 2.5 TeV
Can discover the squarks at the LHC but cannot really study them

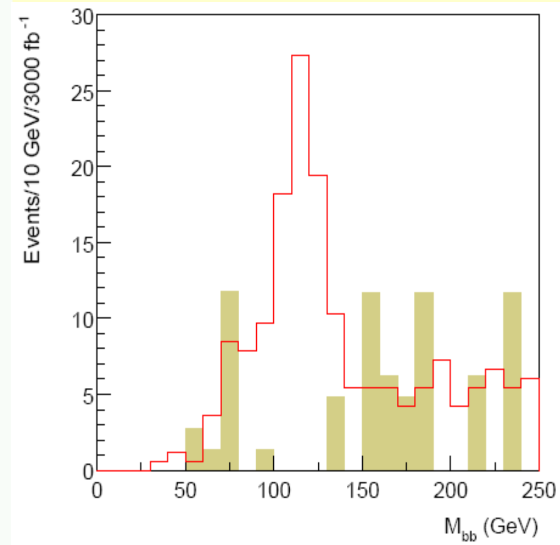
$$M_{eff} = E_T^{miss} + \sum_{jets} E_{T,jet} + \sum_{leptons} E_{T,lepton}$$

$P_T^1 > 700$ GeV & $E_T^{miss} > 600$ GeV

eg. Benchmark Point K in hep-ph/0306219







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

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

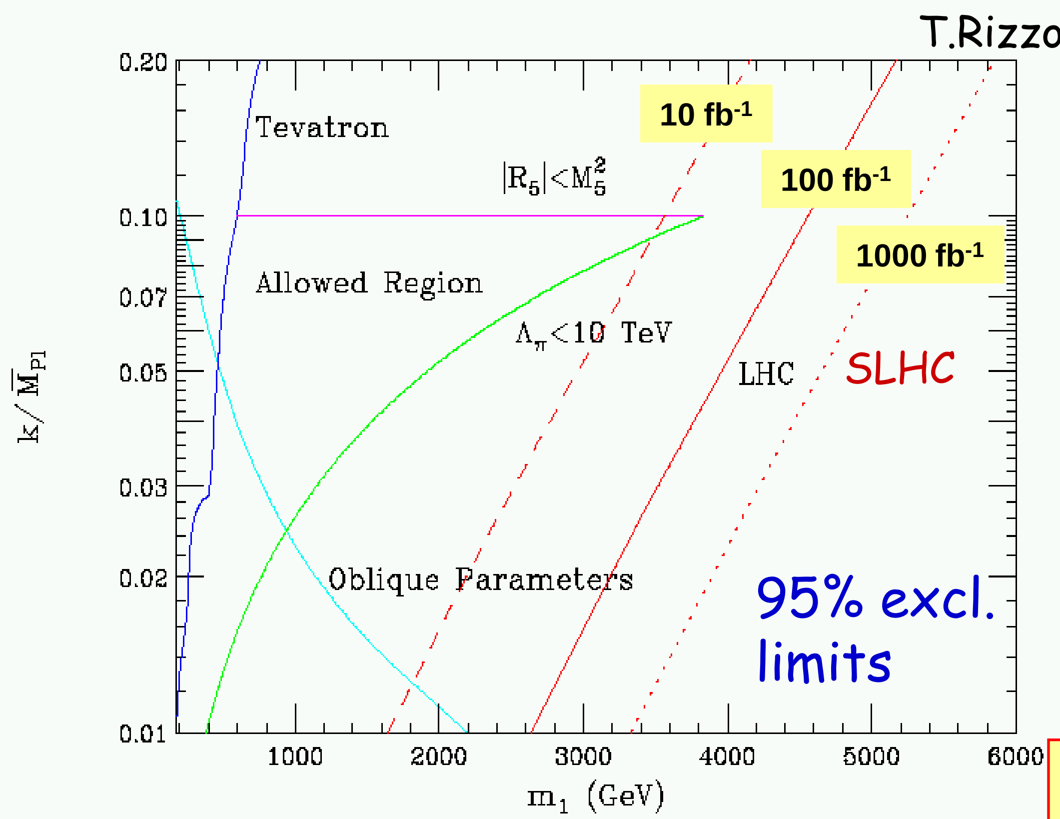
Higgs in χ_2 decay
$\chi_2 \to \chi_1 h$ becomes visible at 3000 fb^{-1}

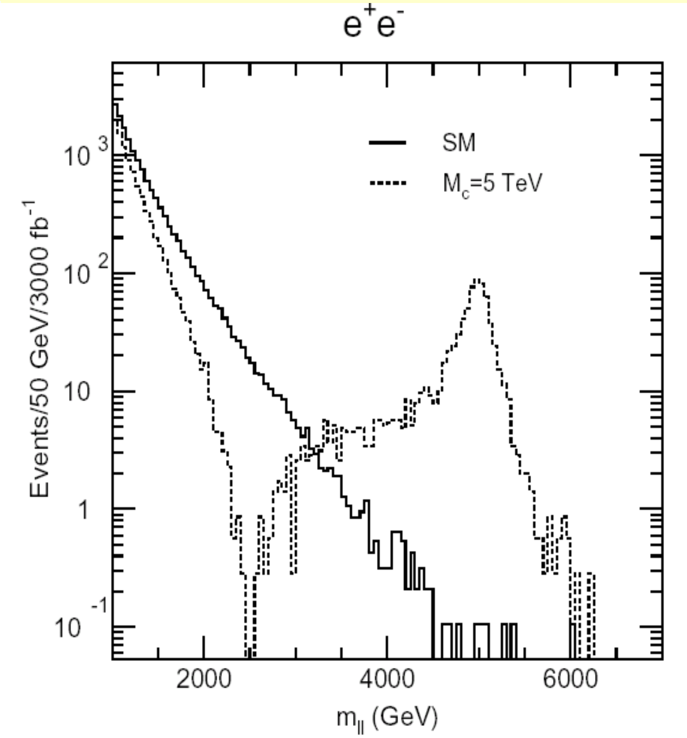
Measurements of some difficult scenarios become possible at the sLHC

Extra Dimensions: KK Gravitons at the sLHC

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

TeV scale extra dimensions
- KK excitations of the γ,Z



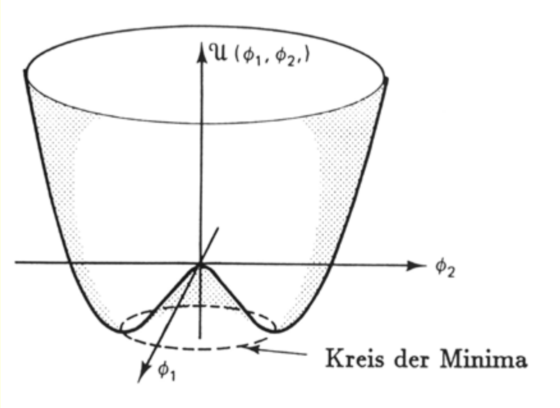


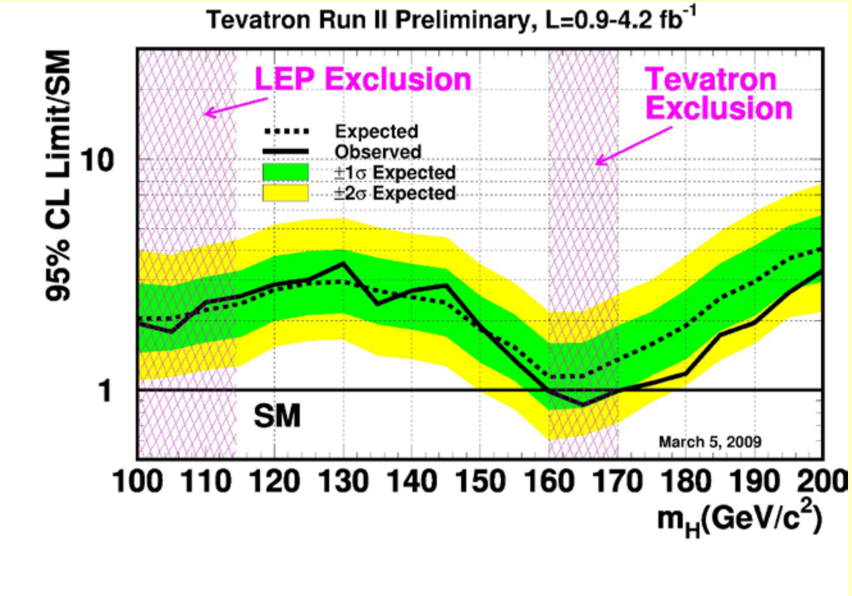
100 $\rightarrow$ 1000 fb^{-1}: Increase in reach by ~25%

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

Where is the

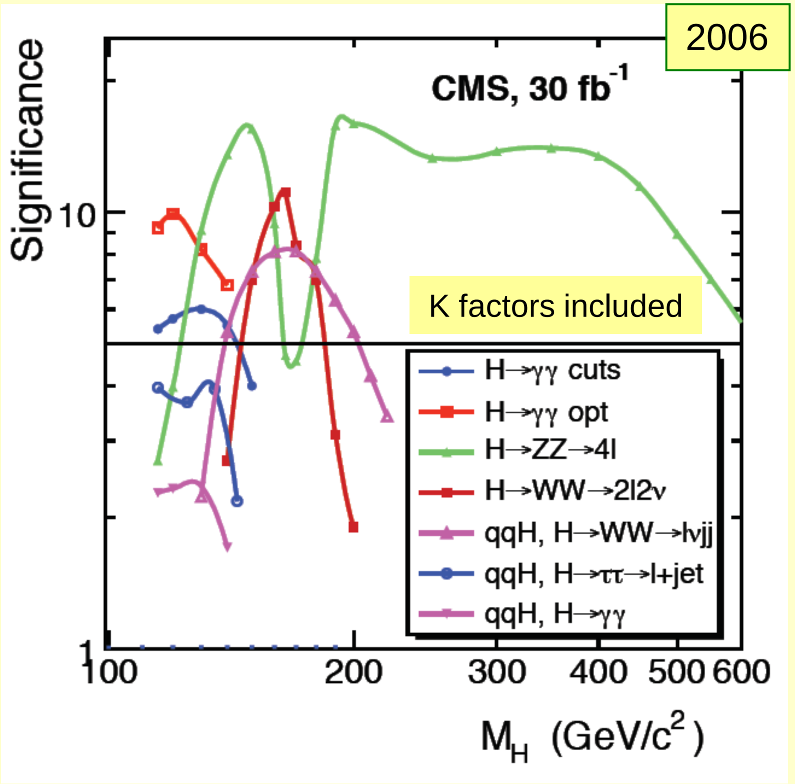
Higgs Boson ?

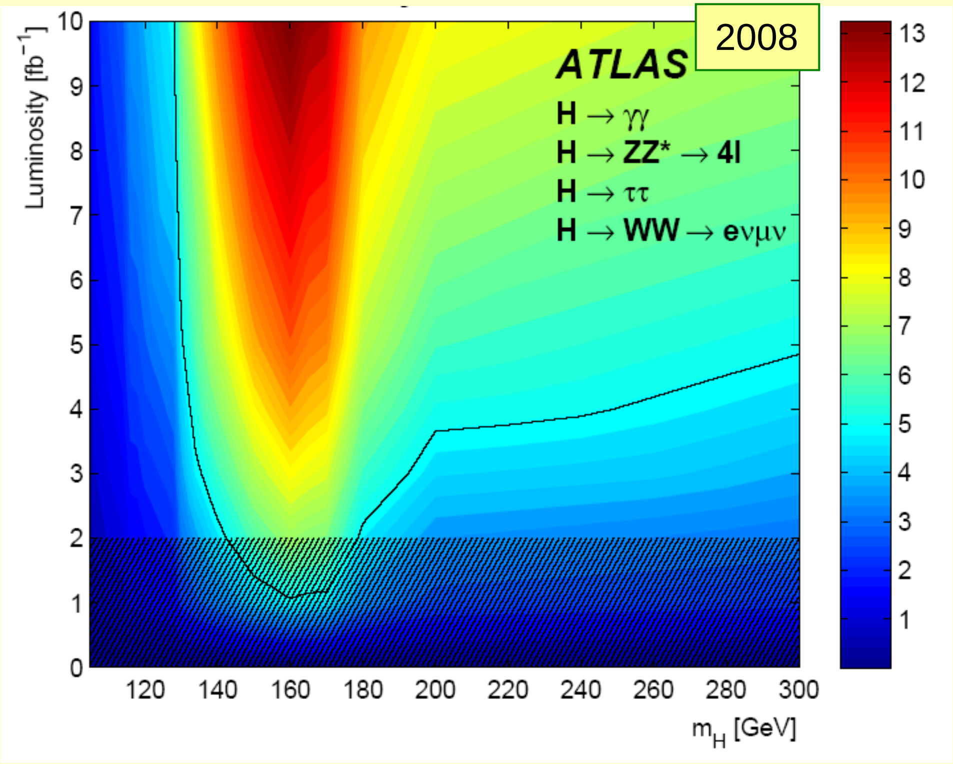




1. **Discovery of a Higgs-like resonance**
2. Determination of its parameters
3. Higgs self coupling / potential (?)

LHC Higgs boson discovery potential





- Comparable performance in the two experiments
  [at high mass: more channels (in WW and ZZ decay modes) available than shown here]
- Several channels and production processes available over most of the mass range
  → calls for a separation of the information + global fit (see below)
- Detection of a Standard Model Higgs boson does not require the sLHC

Important changes w.r.t. previous studies:

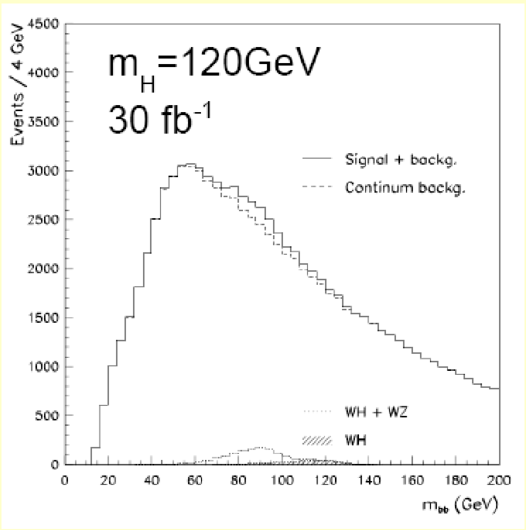
- **ttH → tt bb** disappeared in both ATLAS and CMS studies from the discovery plot

New hope for H→ bb decays at the LHC: W/Z H, H → bb

NEW!

The most important channels at the TEVATRON at low mass!

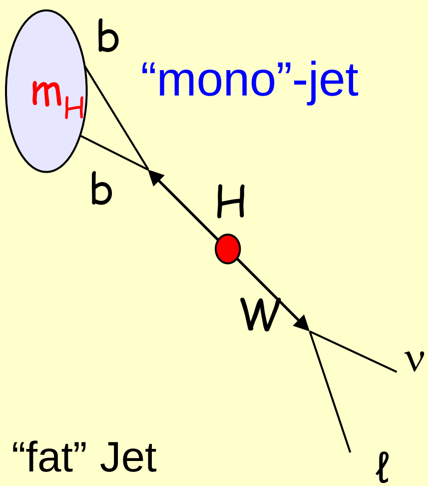
But: signal to background ratio less favourable at the LHC



$S/\sqrt{B}$	2.1
S/B	1.3%

Follow idea of J. Butterworth, et al. [PRL 100 (2008) 242001]

Select events (≈5% of cross section), in which H und W bosons have large transverse momenta: p_T > 200 GeV



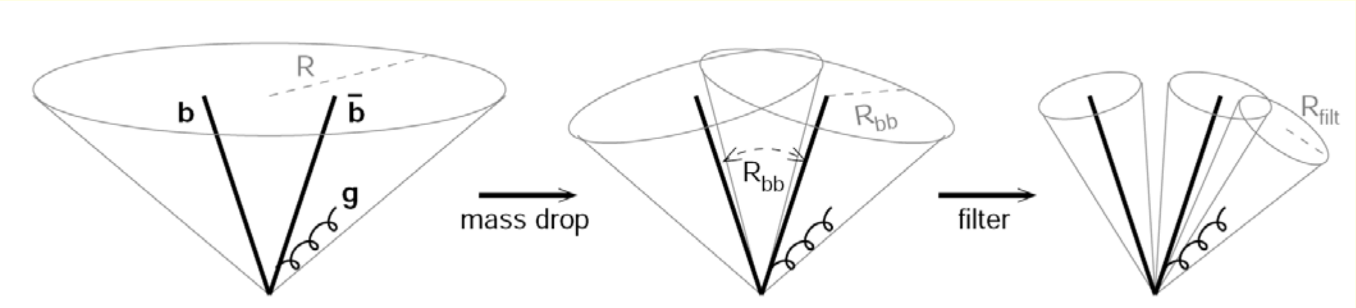
→ b-Quarks in one "fat" Jet

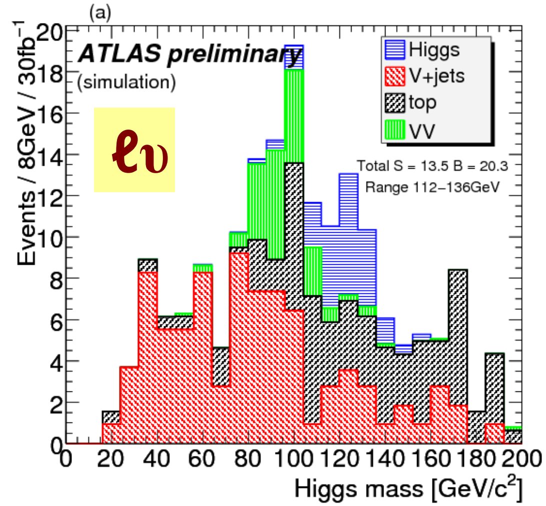
+ Acceptance (more central in detector)
+ Lepton-Identification, b-Tagging

High p_T W/Z H, H → bb

ATL-PHYS-PUB-2009-088

Analyze jet structure:





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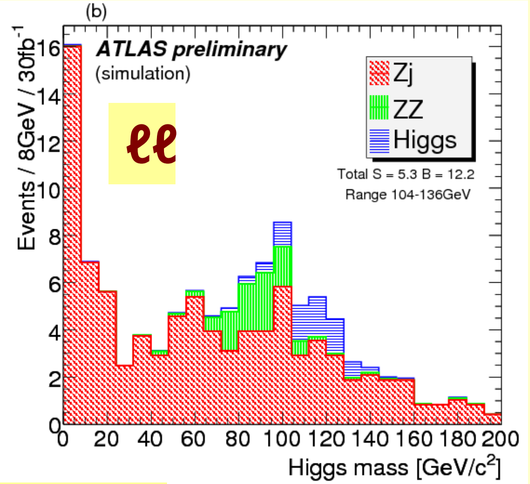
$$L^{int.} = 30\ fb^{-1} : \frac{S}{\sqrt{B}} = 3.0$$



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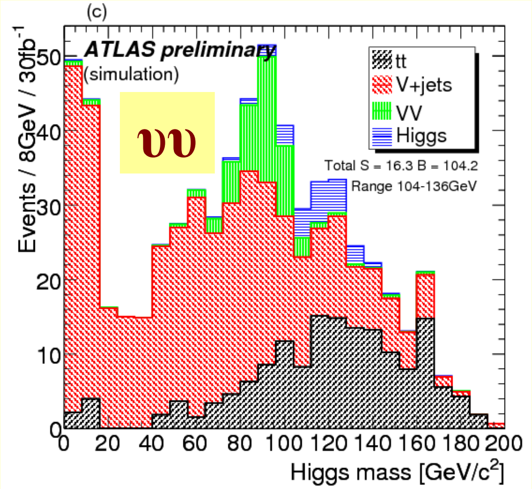
M_H = 120 GeV

$$\frac{S}{\sqrt{B}} = 1.5$$



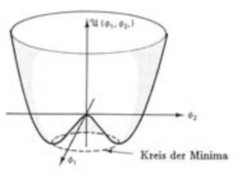
νν

$$\frac{S}{\sqrt{B}} = 1.6$$

Combined: $$\frac{S}{\sqrt{B}} = 3.7$$

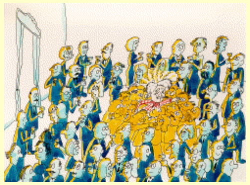
(Pile-Up not yet included)

- S/B much better than for ttH
- Different backgrounds for different channels
- Still good sensitivity including systematics
  (e.g. S/√B = 3.0 for 15% uncertainty on all backgrounds)



Is it a Higgs Boson ?

-can the LHC measure its parameters ?-



1. Mass

- Higgs boson mass can be measured with a precision of 0.1% over a large mass range (130 - ~450 GeV/c^2)

($\gamma\gamma$ and ZZ→ 4ℓ resonances, el.magn. calo. scale uncertainty assumed to be ± 0.1%)

2. Couplings to bosons and fermions

- Relative couplings (Z/W, t/W, t/W) can be measured with a precision of ~20% (for 300 fb^{-1})
- Improvements at the sLHC possible, but not impressive, systematics limited
- Additional information from rare decay modes (not accessible at the LHC), e.g. H → $\mu\mu$, H → Zγ, ttH, H→ $\gamma\gamma$

3. Spin and CP

Angular correlations in H → ZZ(*) → 4 ℓ and $\Delta\phi_{jj}$ in vector boson fusion are sensitive to spin and CP (achievable precision is statistics limited, requires high luminosity → sLHC might contribute, details depend on how well vector boson fusion can be measured)

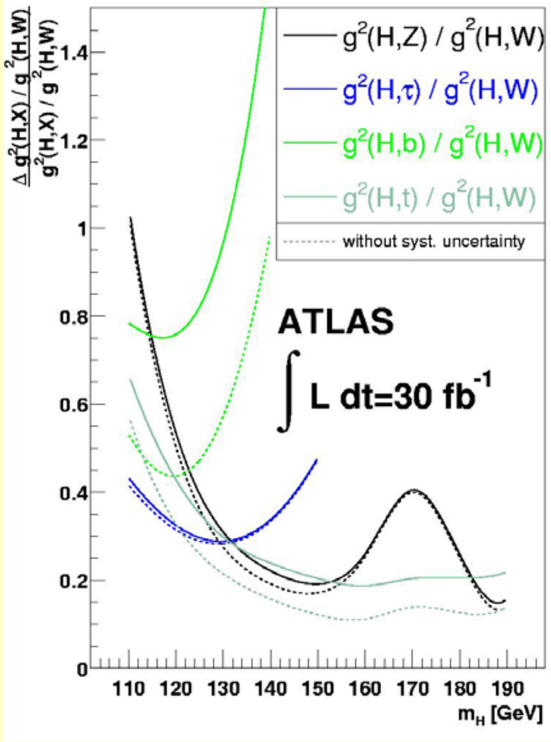
4. Higgs boson self coupling

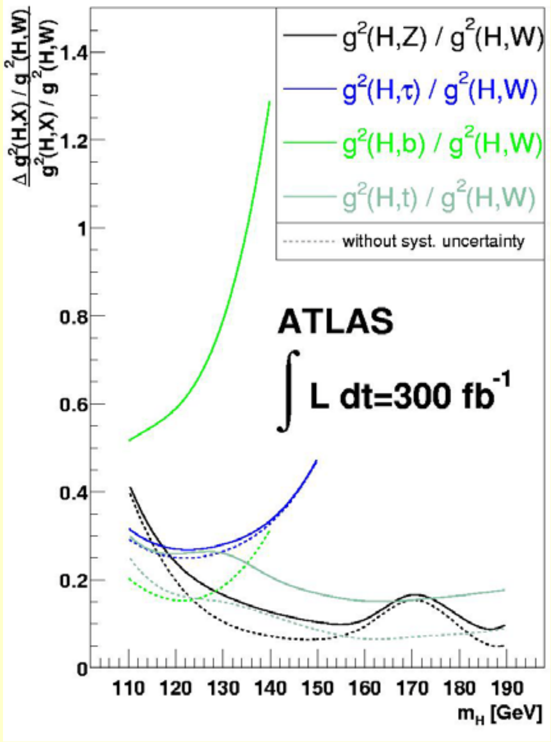
No measurement possible at the LHC;
Very difficult at the sLHC, there might be sensitivity in HH → WW WW for m_H ~ 160 GeV
Situation needs to be re-assessed with more realistic simulations

(ii) Measurement of Higgs Boson Couplings

Global likelihood-fit (at each possible Higgs boson mass)
Input: measured rates, separated for the various production modes

Output: Higgs boson couplings, normalized to the WW-coupling



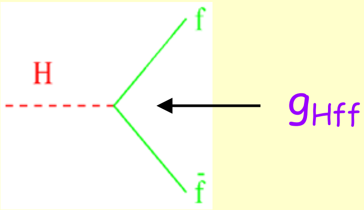


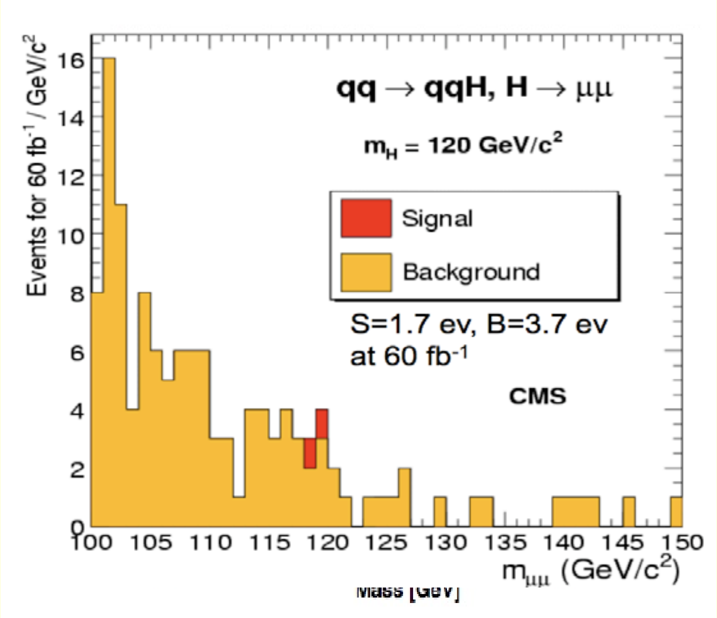
Relative couplings (Z/W, τ/W, t/W) can be measured with a precision of ~20% (for 300 fb^{-1})

Rare Higgs Decays Modes accessible at the sLHC

Channels studied:

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



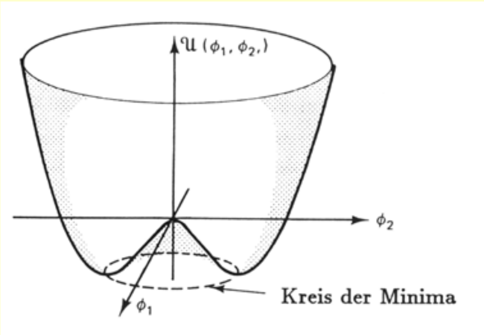


Branching ratio ~ 10^{-4} for these channels!
Cross section ~ few fb

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

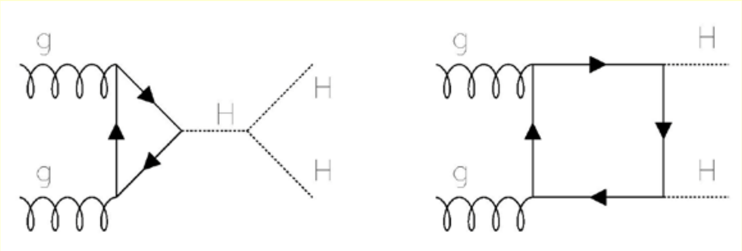
(iv) Higgs boson self-coupling ?

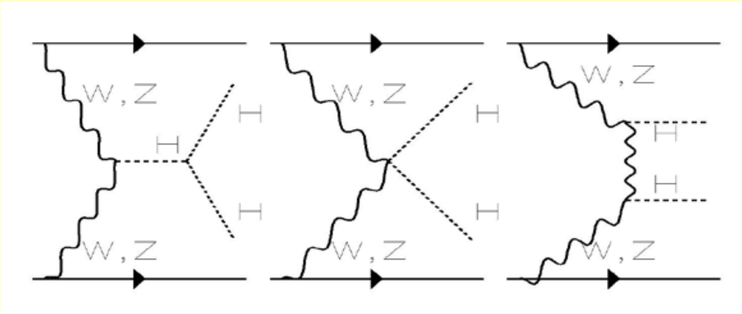
To finally establish the Higgs mechanism the Higgs boson self-coupling has to be measured:

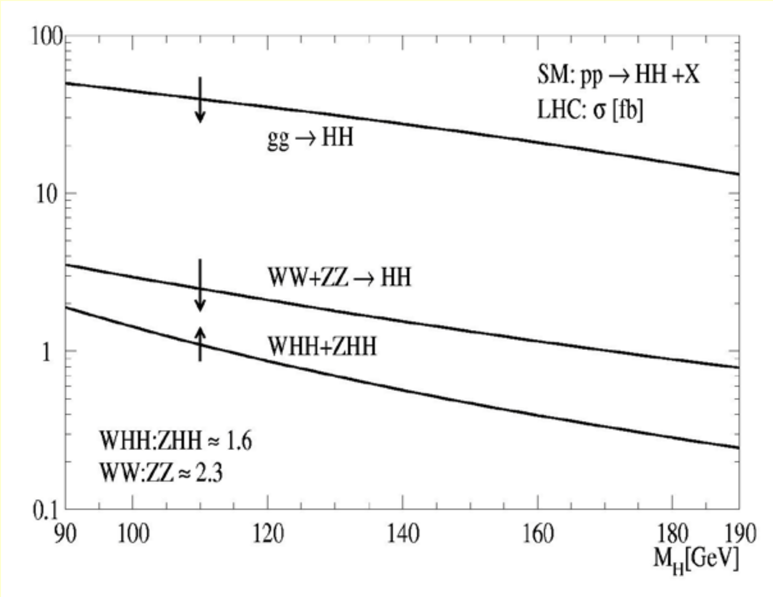


$$\lambda^{SM}_{HHH} = 3\,\frac{m_H^2}{v}\,, \qquad \lambda^{SM}_{HHHH} = 3\,\frac{m_H^2}{v^2}$$

Cross sections for HH production:







small signal cross-sections, large backgrounds from tt, WW, WZ, WWW, tttt, Wtt,...

⇒ no significant measurement possible at the LHC

need Super LHC $L = 10^{35}$ cm^{-2} sec^{-1}, 6000 fb^{-1}

Most sensitive channel: $gg \rightarrow HH \rightarrow WW\,WW \rightarrow \ell\nu\, jj\;\; \ell\nu\, jj$

- accessible in mass range around 160 GeV
- bb- or $\gamma\gamma$ decay modes at lower masses are hopeless

Selection (old analysis):

- 2 isolated, high P_T, like sign leptons (from different Higgs bosons)
- 4 high P_T jets, compatible with W-mass

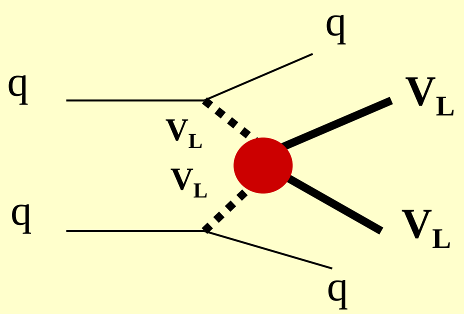
m_H	Signal	$t\bar{t}$	$W^{\pm}Z$	$W^{\pm}W^{+}W^{-}$	$t\bar{t}W^{\pm}$	$t\bar{t}t\bar{t}$	$S/\sqrt{B}$
170 GeV	350	90	60	2400	1600	30	5.4
200 GeV	220	90	60	1500	1600	30	3.8

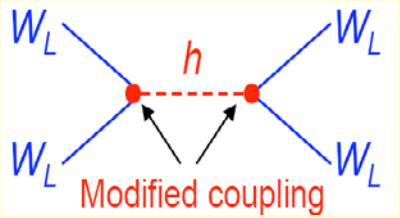
6000 fb $^{-1}$ $\Rightarrow$ $\Delta\lambda_{HHH} / \lambda_{HHH}$ = 19 % (stat.) (for m_H = 170 GeV)
$\Delta\lambda_{HHH} / \lambda_{HHH}$ = 25 % (stat.) (for m_H = 200 GeV)

Note: - background contributions (tt and WWW) underestimated
- Estimates are based on fast detector simulation
- No pile-up effects and no realistic sLHC performance assumed

$\Rightarrow$ Study needs to be updated with more realistic simulations, before more reliable estimates can be given

What if the LHC does not find the Higgs Boson ?





- Study of longitudinal gauge boson scattering is the key
  High luminosities, i.e. sLHC, required to make quantitative measurements (strong physics case)

- If no Higgs, expect strong V_LV_L scattering (resonant or non-resonant) at ~ 1TeV

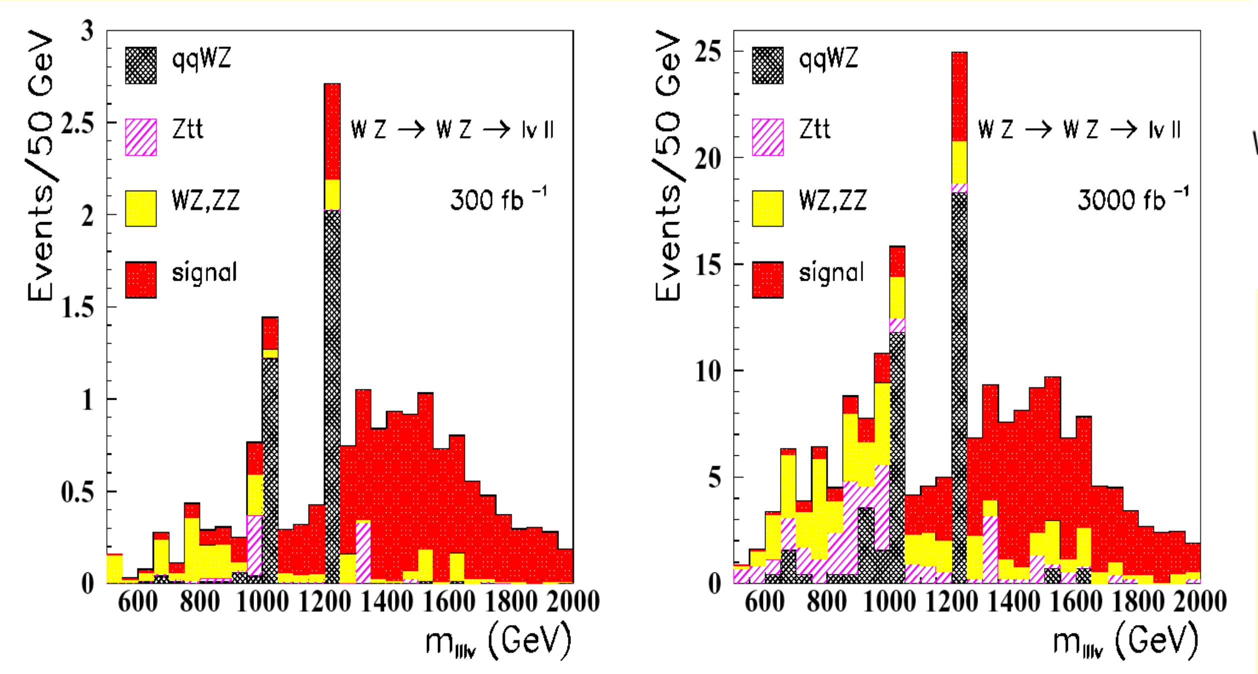
- Also the question of a composite Higgs boson must be addressed at high energy
  (in spite of a light Higgs boson, the longitudinal gauge boson scattering amplitude might violate unitarity)

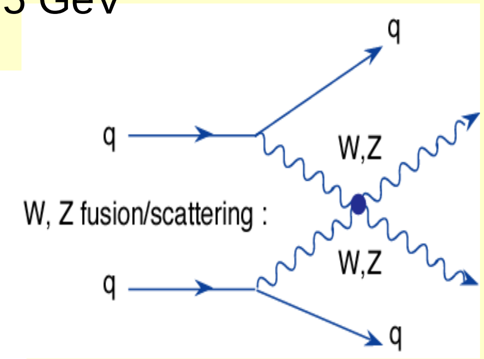
WZ resonances in Vector Boson Scattering

Example: Vector resonance (ρ-like) in $W_L Z_L$ scattering
from Chiral Lagrangian model

m = 1.5 TeV $\Rightarrow$ 300 fb^{-1} (LHC) vs. 3000 fb^{-1} (sLHC)

Lepton cuts: $p_T^1 > 150$ GeV, $p_T^2 > 100$ GeV, $p_T^3 > 50$ GeV; $E_T^{miss} > 75$ GeV



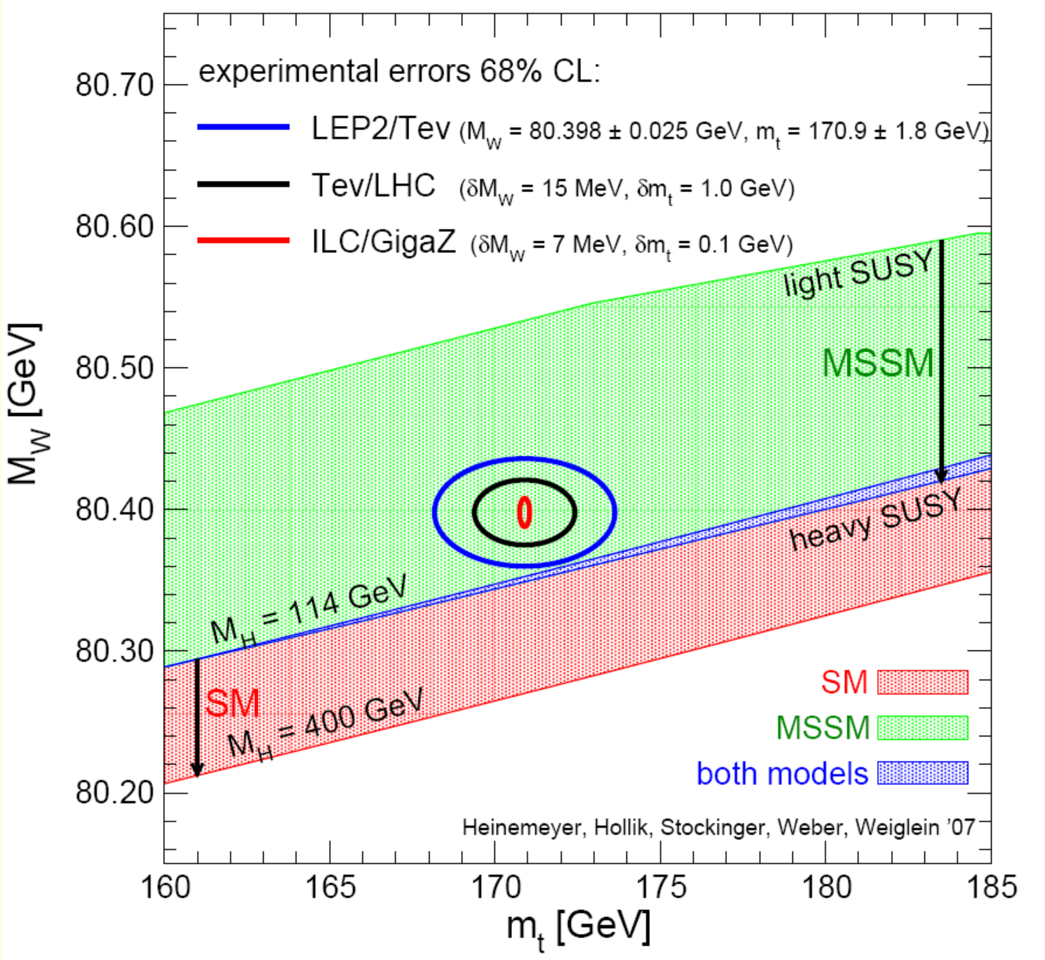


These studies require both forward jet tagging and central jet vetoing!
Expected (degraded) sLHC performance is included

At LHC: S = 6.6 events,
B = 2.2 events

At sLHC: $S/\sqrt{B} \sim 10$

Expectation for precision measurements at the LHC



<u>Expected precision</u>:

Tevatron (2 fb^{-1}):
$\delta\, m_W$ = ± 25 MeV/c^2
$\delta\, m_t$ = ±1.5 GeV/c^2

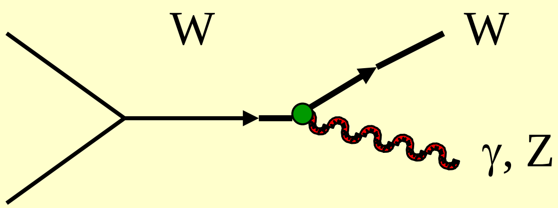
LHC (10 fb^{-1}):
$\delta\, m_W$ ~ ±15 MeV/c^2
$\delta\, m_t$ ~ ±1.0 GeV/c^2

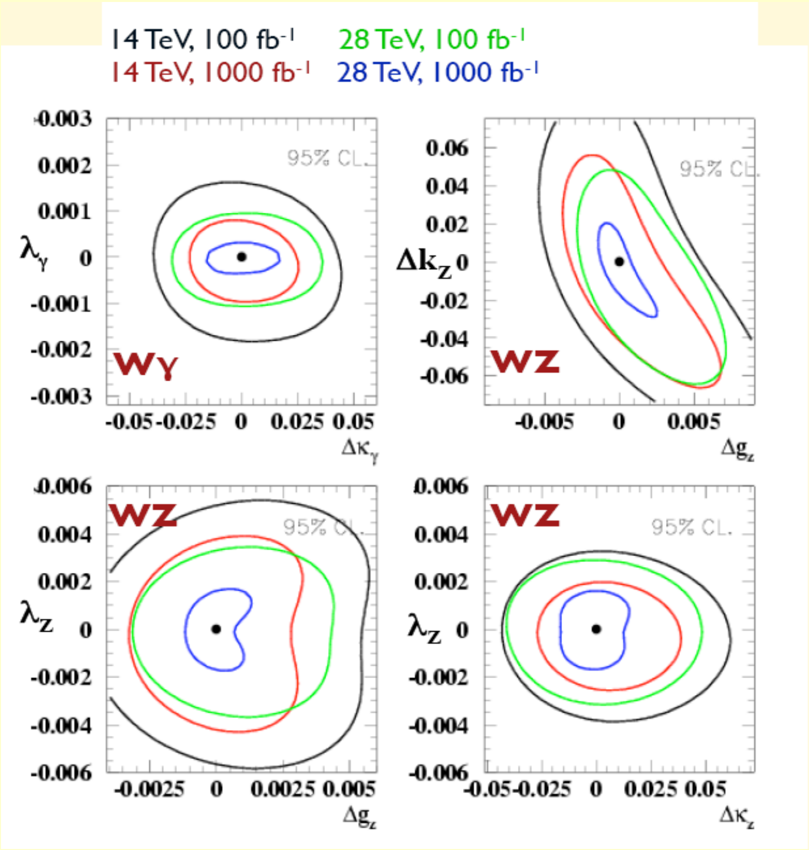
The experimental precision is limited experimentally by the precise knowledge of the lepton energy scale

sLHC will not help !

sLHC Precision physics

- Precision Measurement of triple and quartic **gauge boson couplings**





- **Rare top quark decays**

(search for / limits on FCNC)

$t \rightarrow q\, g$ (q = u,c)
$t \rightarrow q\, Z$ (q = u,c)
$t \rightarrow q\, g$ (q = u,c)

Sensitivities for branching ratios down to 10^{-6} can be reached, however, b-tagging is assumed to work at 10^{35} cm^{-2} s^{-1} (similar performance as at 10^{34} cm^{-2} s^{-1})

Summary / Conclusions

sLHC:

- Appears as a natural extension to fully exploit the physics potential of the LHC facility
- Gives access to higher masses (SUSY, or other BSM scenarios,….)
- Might have a vital role to play in the investigation of the nature of electroweak symmetry breaking;
  (regardless whether there is a Higgs-like resonance or not, the scattering of longitudinal gauge bosons at high energy must be studied)
- For many key physics studies at the sLHC the basic signatures including b-tagging, forward jet tagging,….. have to be present

→ **The new / upgraded tracking detectors have to work !**

<u>More details / references</u>:

- **F. Gianotti et al., Eur. Phys. J. C39 (2005) 293; hep-ph/0204087.**

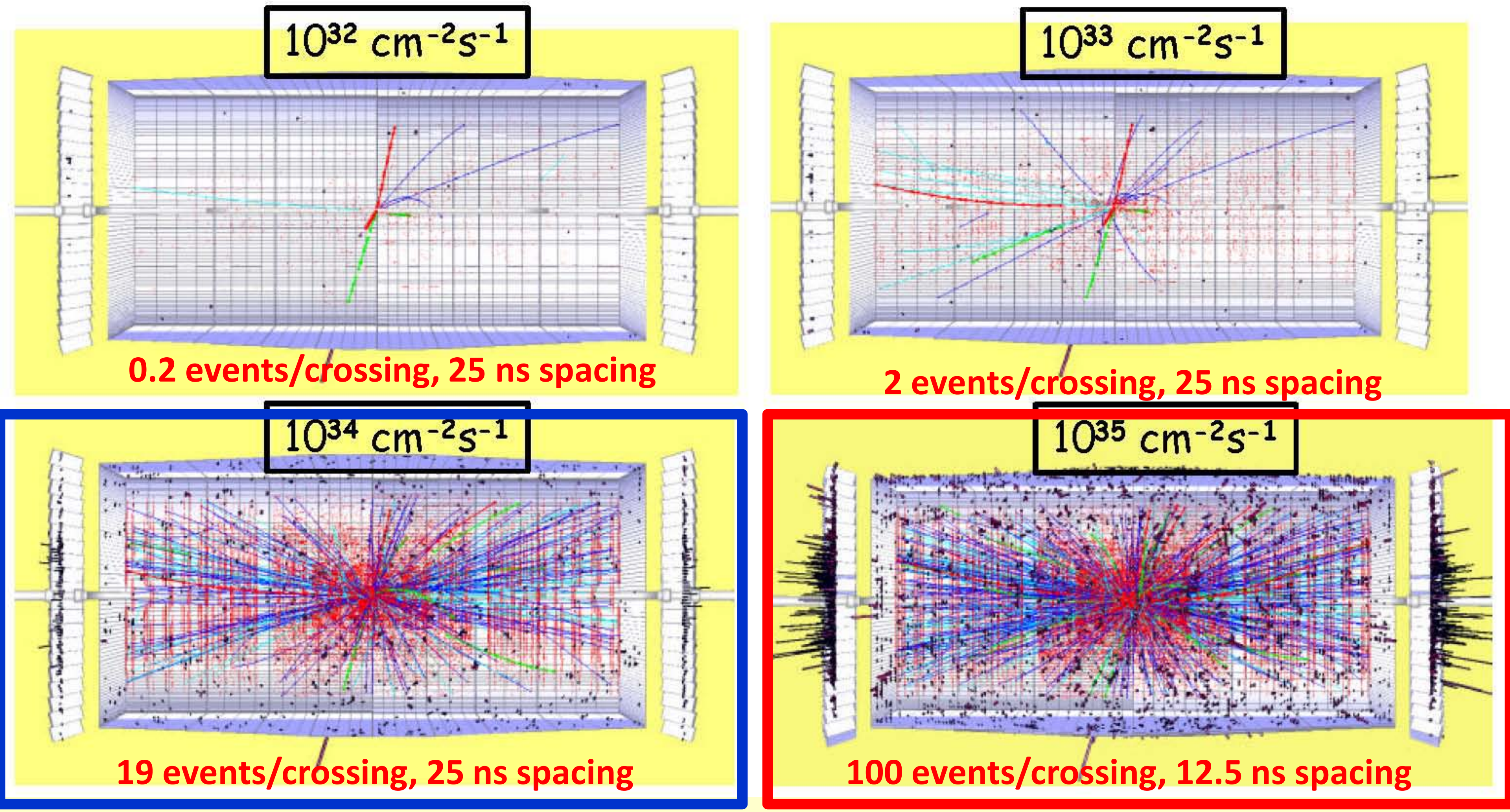
- M. Mangano, *Physics opportunities for the sLHC*, SLHC kickoff meeting, CERN, April 2008.

- G. Giudice, *Physics Motivations for sLHC*, Physics at LHC conference, Split 2008.

- A. De Roeck, *SLHC Physics Impact*, XXXVII SLAC Summer Institute, 2009.

Backup slides

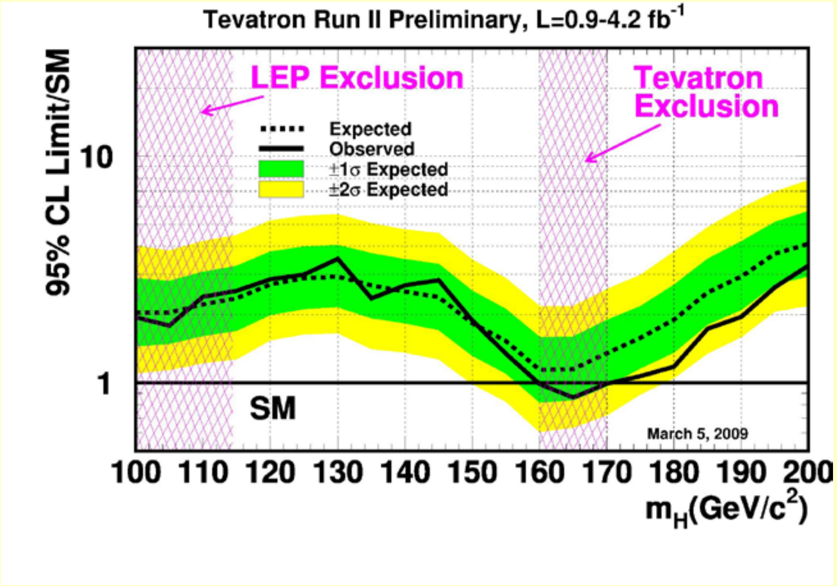
Event Pile-up at various luminosities (CMS simulation)



$H \rightarrow ZZ \rightarrow \mu\mu ee$ event with m_H= 300 GeV embedded

p_T > 1 GeV cut, i.e. all soft tracks removed

What do we already know?

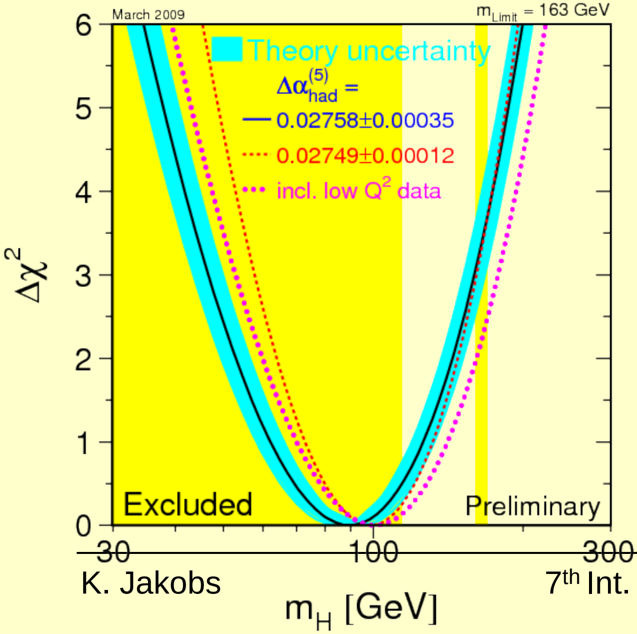


- Direct searches at LEP

m_H > 114.4 GeV/c^2 (95% CL)

- Direct searches at the TEVATRON

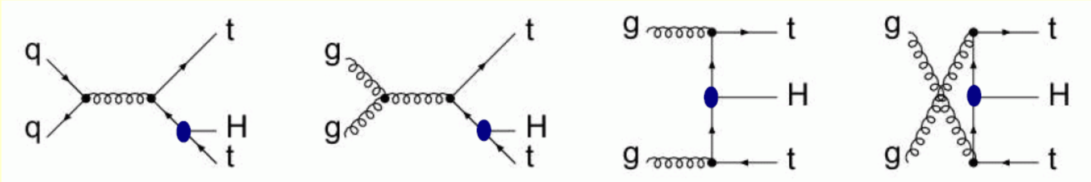
Exclude 160 GeV < m_H < 170 GeV (95% CL)



- Electroweak precision measurements

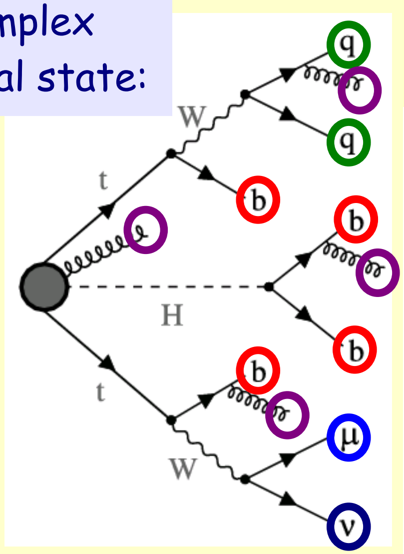
m_H < 163 GeV (95% CL)
(191 GeV incl. LEP Limit)

ttH, H → bb



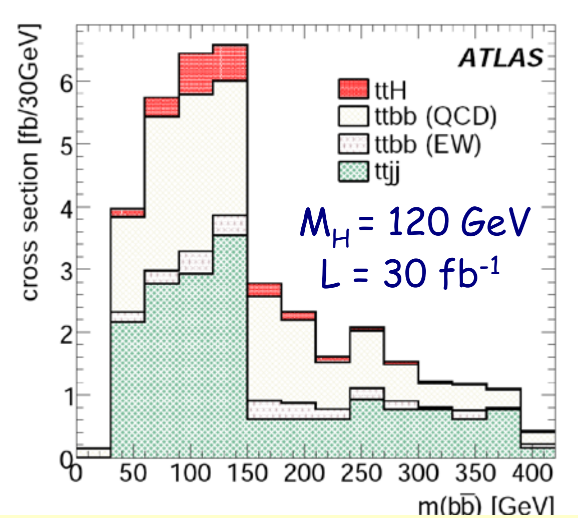
- Appeared to be a promising search channel at low mass some years ago
- Access to t and b Yukawa couplings

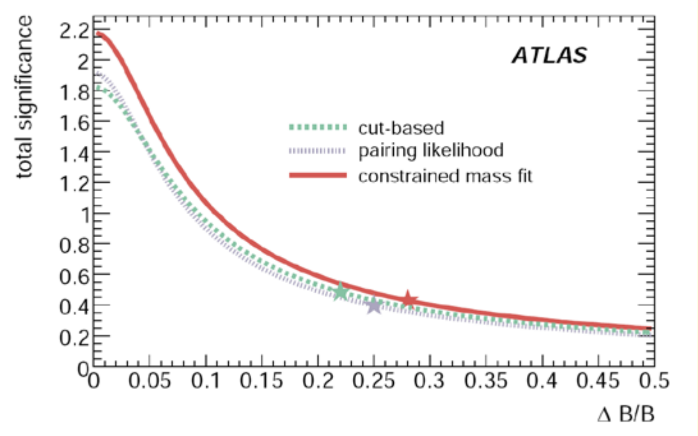
Complex final state:



Main Backgrounds:
ttbb, ttjj

Now:

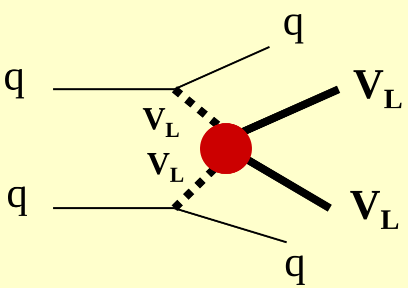




- Need precise background normalization
- Has to come from data!
- Pile-Up: impact on selection efficiency and mass resolution

Strongly Coupled Vector Boson System

If no Higgs, expect strong $V_L V_L$ scattering (resonant or non-resonant) at ~ 1TeV

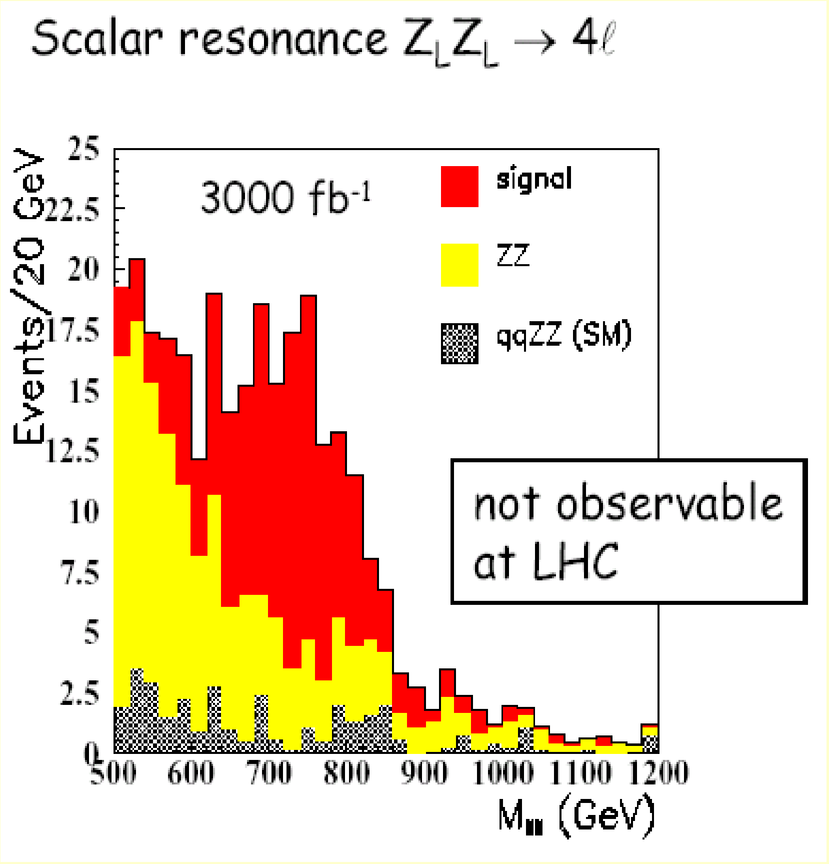


- **In general rate limited at the LHC**

sLHC:

- Degradation of forward jet tagging and central jet veto due to huge pile-up

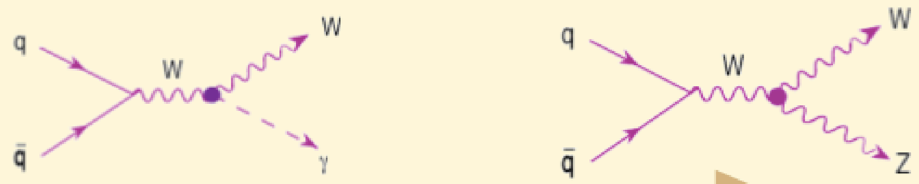
- However: factor ~ 10 in statistics
  $\rightarrow$ 5-8σ excess in $W^+_L W^+_L$ scattering
  $\rightarrow$ other low-rate channels accessible



sLHC reach on gauge boson couplings

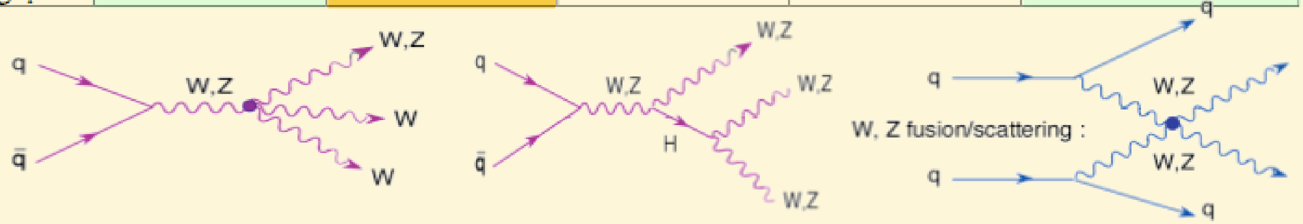
Precise determinations of the self-couplings of EW gauge bosons

5 parameters describing weak and EM dipole and quadrupole moments of gauge bosons. The SM predicts their value with accuracies at the level of 10^{-3}, which is therefore the goal of the required experimental precision



LHC options

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^Z_1	0.0038	0.0024	0.0023	0.0007	0.0050



(LO rates, CTEQ5M, k ~ 1.5 expected for these final states)						
Process	*WWW*	*WWZ*	*ZZW*	*ZZZ*	*WWWW*	*WWWZ*
N(m_H = 120 GeV)	2600	1100	36	7	5	0.8
N(m_H = 200GeV)	7100	2000	130	33	20	1.6