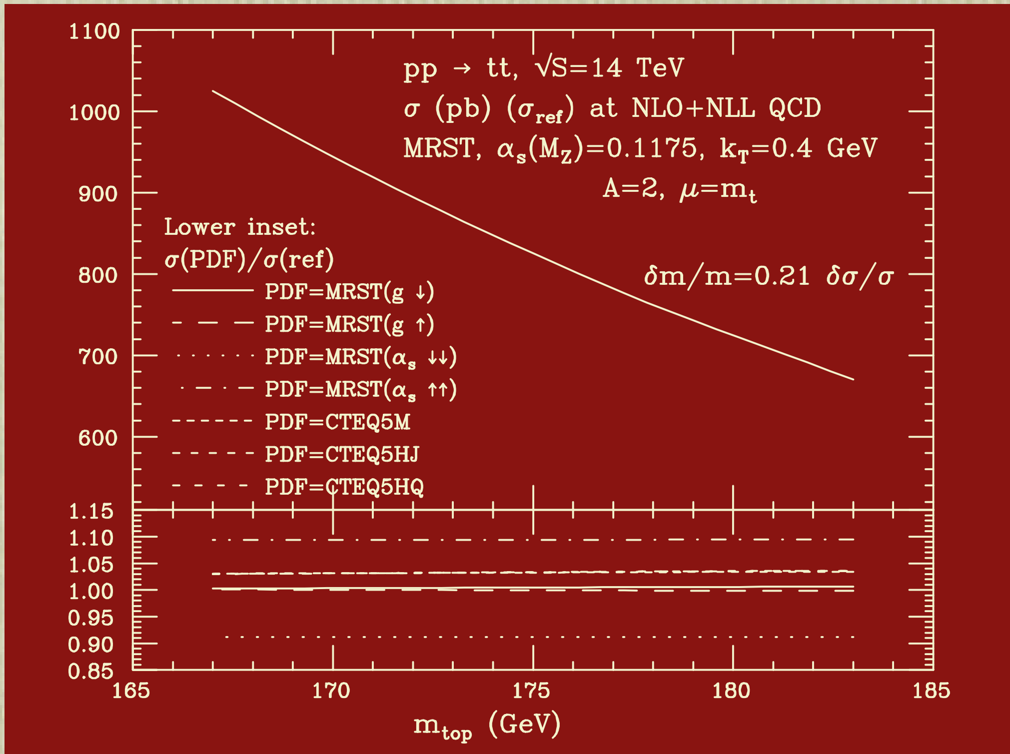
4th Workshop on Particle Physics,
National Centre for Physics,
Quaid-I-Azam University, Islamabad,
Nov 14-19, 2005

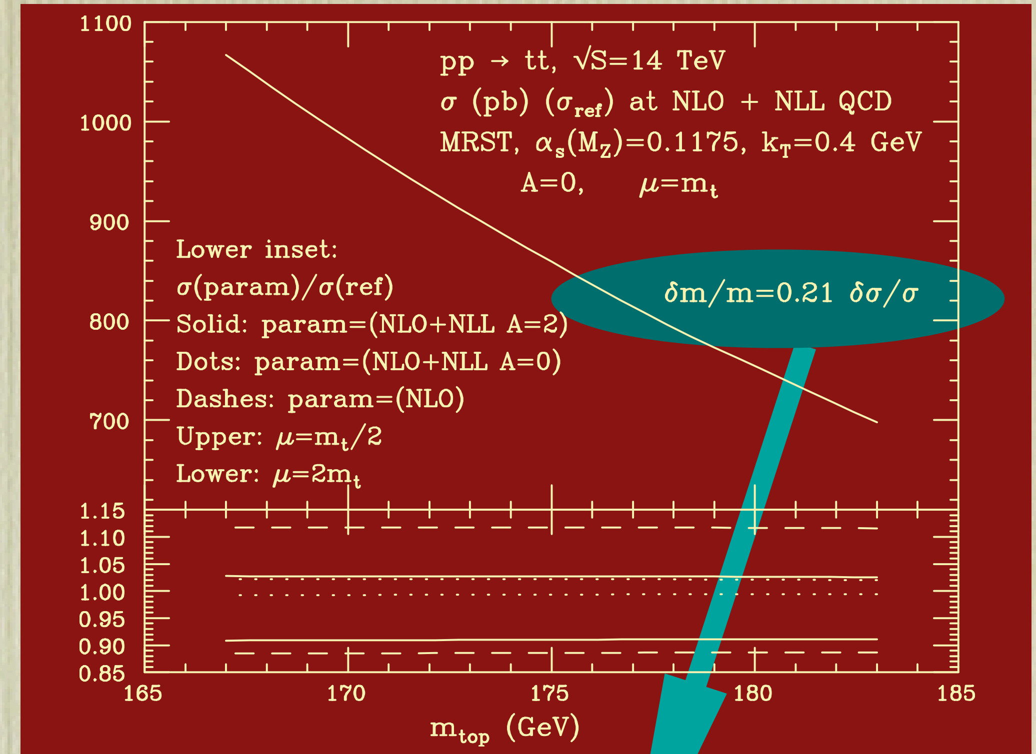
Physics at the LHC, III

Michelangelo Mangano
PH Department, Theoretical Physics,
CERN
michelangelo.mangano@cern.ch

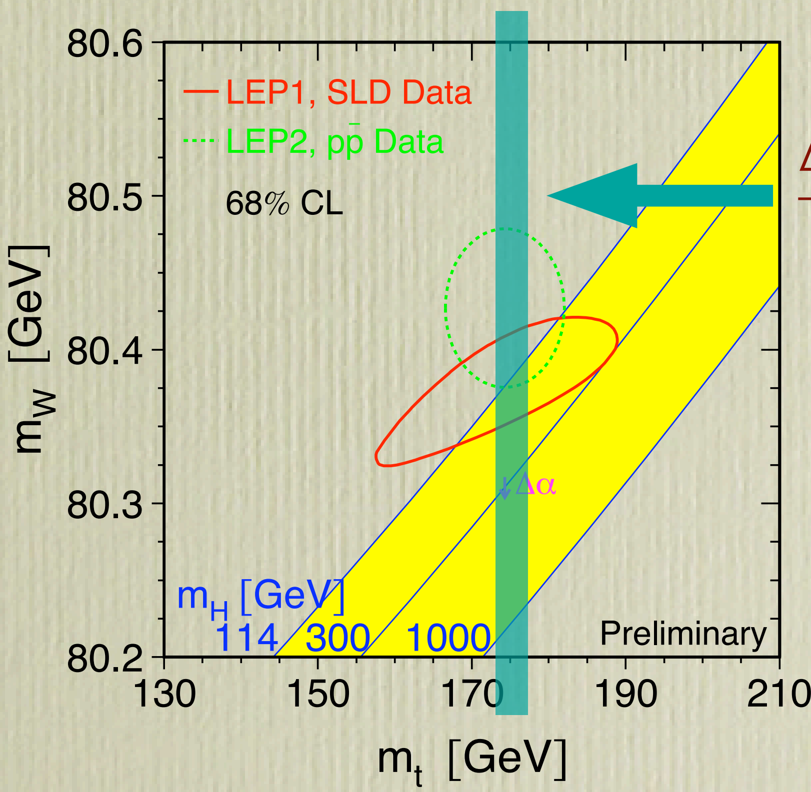
Top quark production

- Heaviest elementary particle known today
- m_{top} 175 GeV ⇒ top Yukawa coupling=1! The most natural value for a fermion mass: a special role in Nature for the top quark?
- LHC will be a "top Factory": σ~800 pb ⇒10^7 events/yr, 1Hz!
- Large statistics ⇒ statistically accurate determinations of the top properties:
  - mass (crucial to better constrain/predict Higgs mass)
  - production cross-section (accurate QCD tests)
- New physics BSM
  - rare decays (indirect searches for new physics, e.g. FCNC)
  - signal, parent, partner and background for new particle production:
    - gluino → top stop, stop → top neutralino, H^+→t bbar
    - top→H^+b



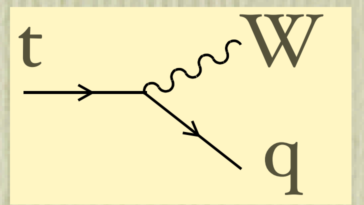


Theoretical systematics dominated today by PDF uncertainties! With the most recent analyses this is now at the level of *5%* (see luminosity plots in previous lecture)



$$\frac{\Delta\sigma}{\sigma} \sim 5\% \Leftrightarrow \Delta m \sim 2 \text{ GeV}$$

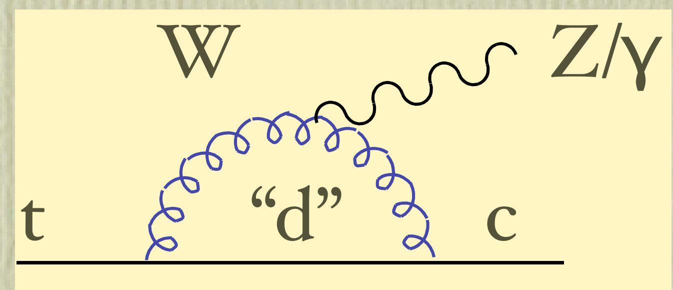
Some rare top decays

BR(


) $\propto |V_{tq}|^2 = (10^{-4},\ 1.6\,10^{-3},\ 1) \sim (1,\ \lambda^4,\ \lambda^6)$ for $q = d, s, b$

Probability of not identifying b quark large, BR(t→W+d or s) very hard to measure

GIM suppression/CKM unitarity

BR(


)

$$\propto \left[\left(\frac{m_b}{m_t} \right)^2 V_{cb}\, \alpha_W \right]^2 \sim 10^{-13}$$

Beyond any possible reach, unless new sources of FCNC. E.g., the SUSY partner of the above graph, with charginos and CKM-not-aligned down-type squarks.

t→WZb: m(b)+m(W)+m(Z)=176 GeV implies that the decay is just barely allowed by phase-space, once finite-width effects for the W and Z bosons are included. Very sensitive to m(top), could be an excellent probe of m(top). Unfortunately BR in the range of 10^{-6}, below experimental sensitivity (need to include BR(Z→ee) and BR (W→eν) as well)

Mode	SM BR	Allowed by BSM	Atlas/CMS est reach
sW	1.6 E-3	0.25 (4th family)	not been studied
dW	~1 E-4	0.01 (4th family)	not neeb studied
bWZ	2 E-6	same	1 E-4
cWW	~1 E-13	1 E-6 (FCNC)	not been studied
cg	~5 E-11	1 E-3 (MSSM)	2 E-5 (cg->t)
cγ	~5 E-13	1 E-5 (MSSM)	3 E-5
cZ	~1 E-13	1 E-4	1 E-4
cH	< E-13	1 E-4	not been studied

Higgs production at the LHC

Several production mechanisms are possible, each of them being more or less important depending on:

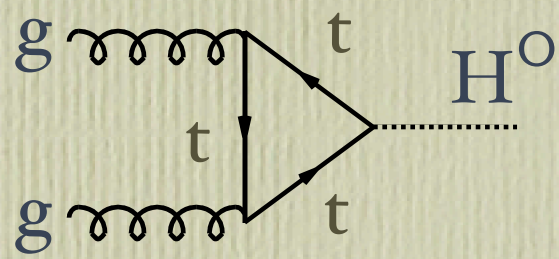
- the value of the production rate
- the value of the decay BR to usable channels
- the size of the backgrounds

The relative importance of these aspects is a function of the Higgs mass

The ability to detect more than one production and/or decay channels is crucial to fully establish the properties of the Higgs boson, and to understand whether it behaves as predicted by the Standard Model

While a complete study of the Higgs boson will require data from several accelerators (e^+e^- linear collider, photon-photon collider, muon collider), the LHC will provide the first important inputs. Depending on m_H, the value of these inputs will vary significantly.

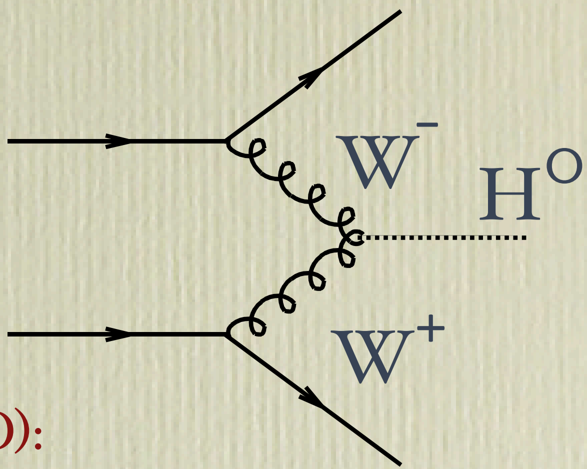
Four main production mechanisms at the LHC:

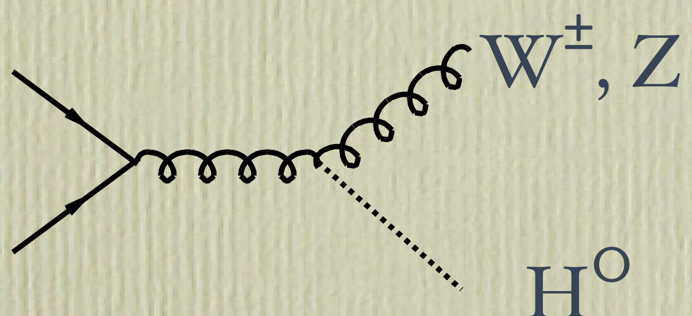


Gluon-gluon fusion (NNLO):
- Largest rate for all m(H).
- Proportional to the top Yukawa coupling, y_t

- gg initial state

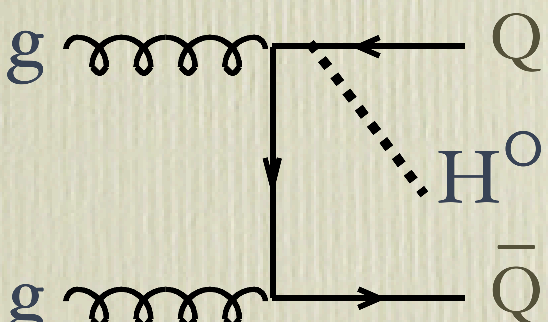
Vector-boson (W or Z) fusion (NLO):
- Second largest, and increasing rate at large m(H).
- Proportional to the Higgs EW charge
- mostly ud initial state



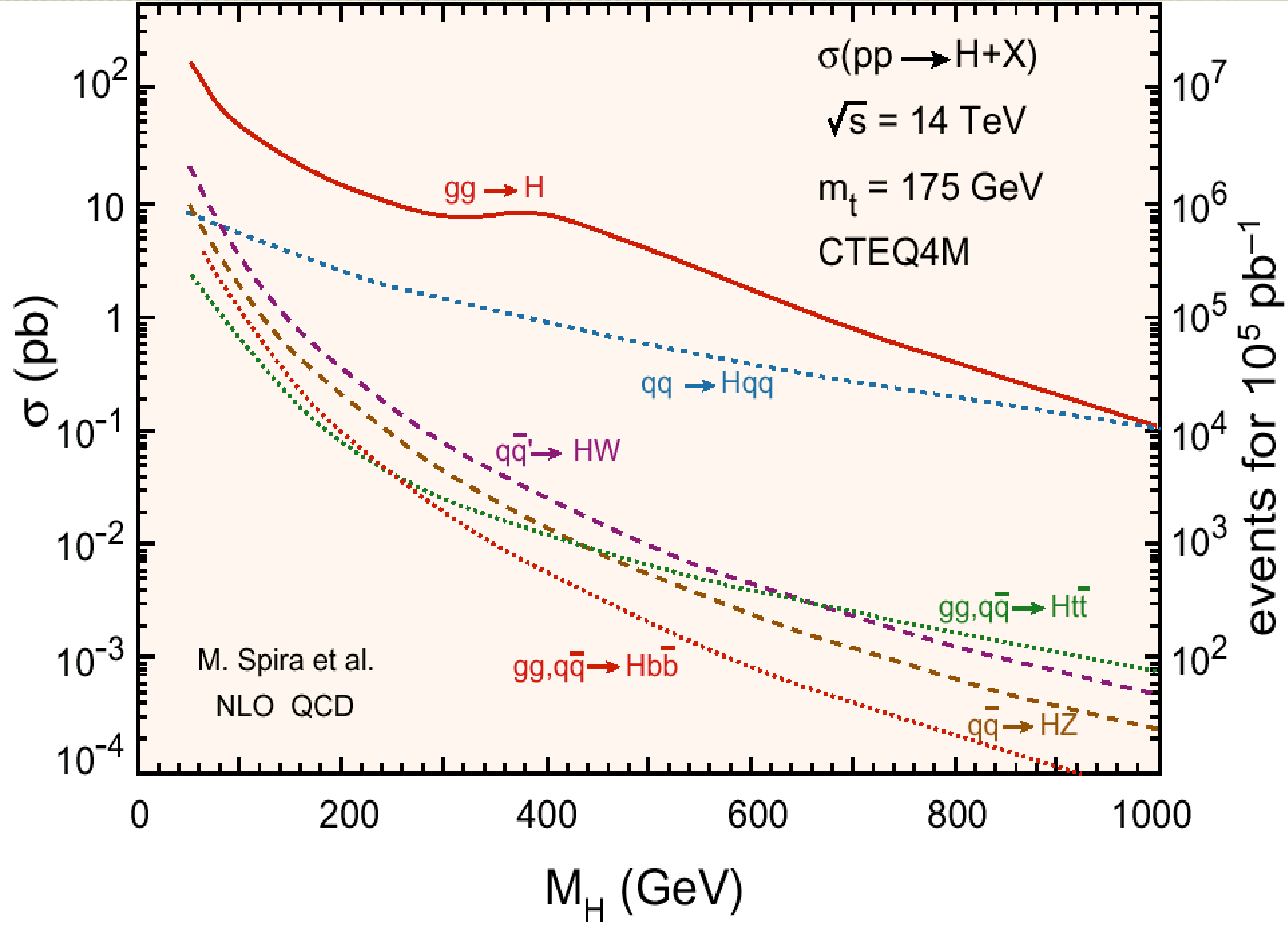


W(Z)-strahlung (NNLO):
- Same couplings as in VB fusion
- Different partonic luminosity (uniquely qqbar initial state)

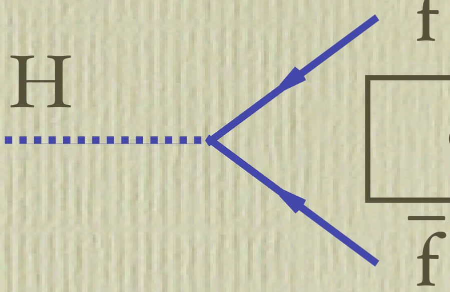
ttH/bbH associate production (NLO):
- Proportional to the heavy quark Yukawa coupling, y_Q, dominated by ttH, except in 2-Higgs models, such as SUSY, where b-coupling enhanced by the ratio of the two Higgs expectations values, $\tan\beta^2$
- Same partonic luminosity as in gg-fusion, except for different x-range



Higgs production rates at the LHC

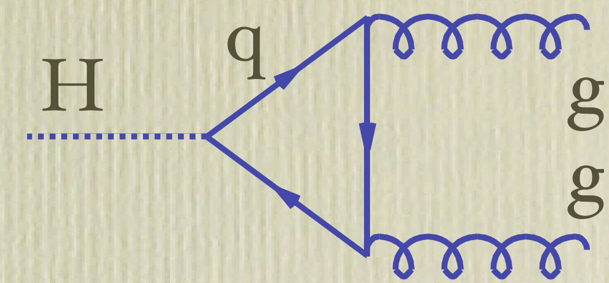


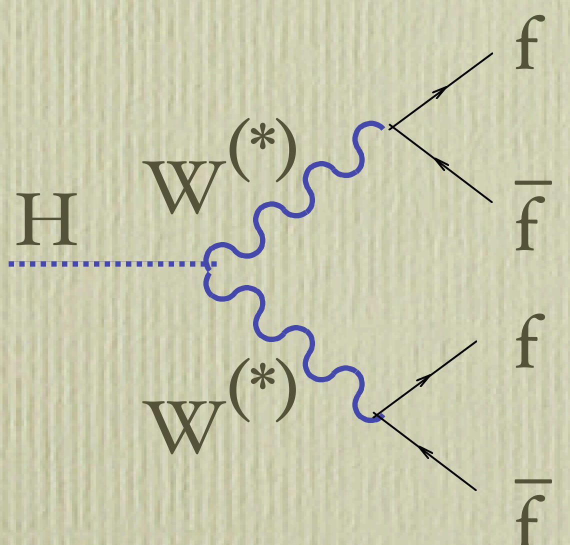
Higgs decays



$\propto m_f^2$ (evaluated at m_H, including QCD running effects)

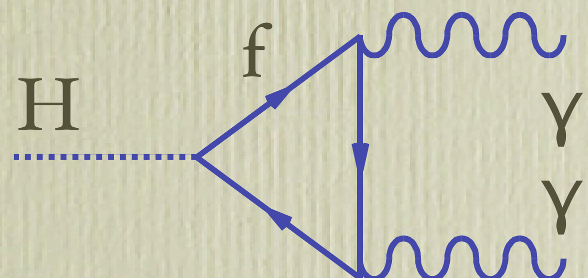
$\propto m_f^2$ (dominated by top-quark loops)



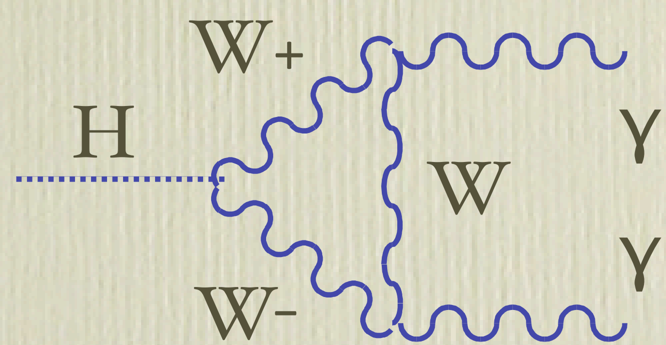


$\propto \alpha_W$ (sharp thereshold at m_H=$2m_W$, but large BR even down to 130 GeV). Similar processes with W↔Z.

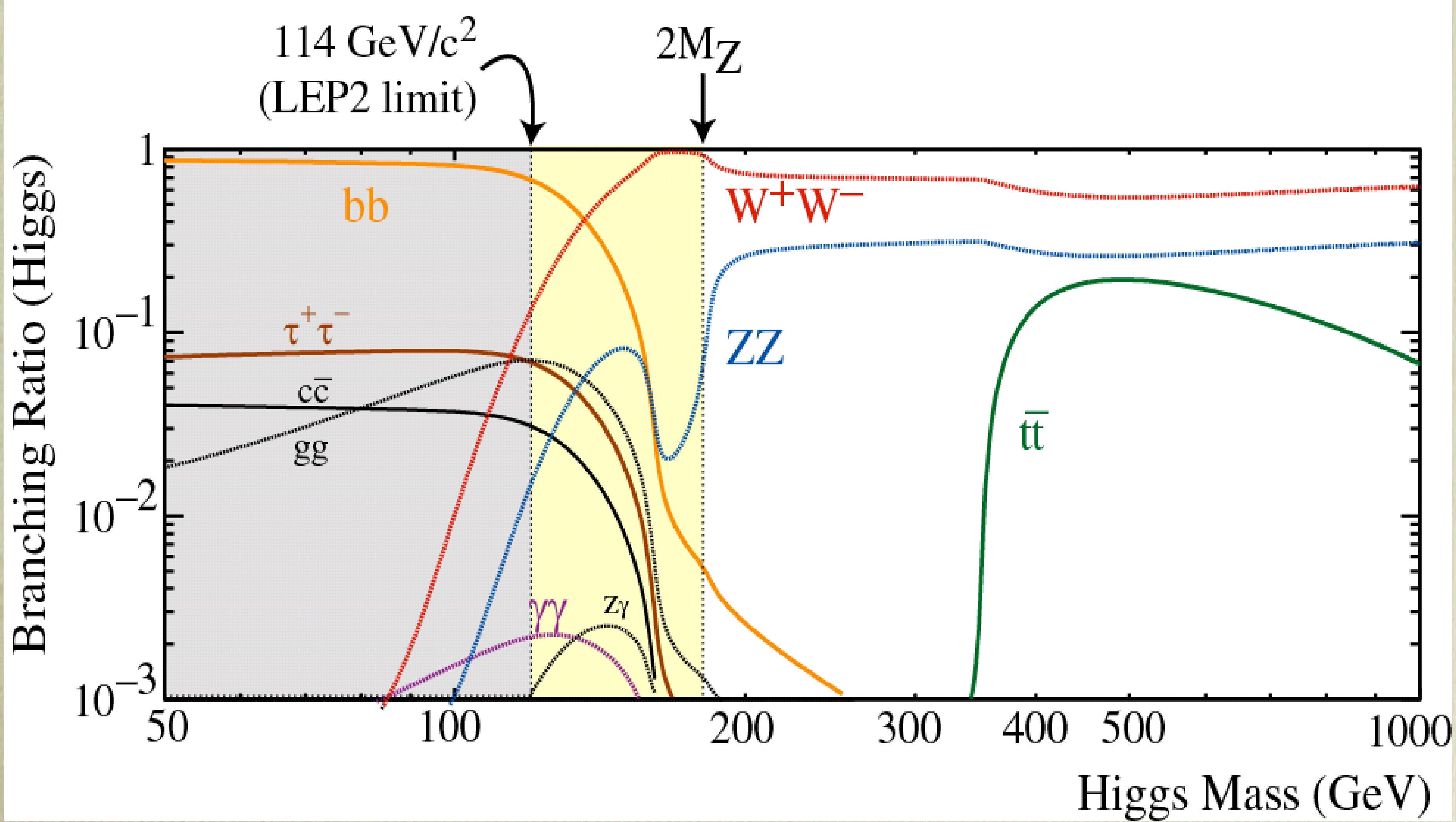
Dominated by the EW couplings, only minor contribution from top loop m ⇒ correlated to H→WW



+



Higgs decays



Not all decay modes are accessible at a given mass. Very high luminosity is required to thoroughly investigate the Higgs couplings

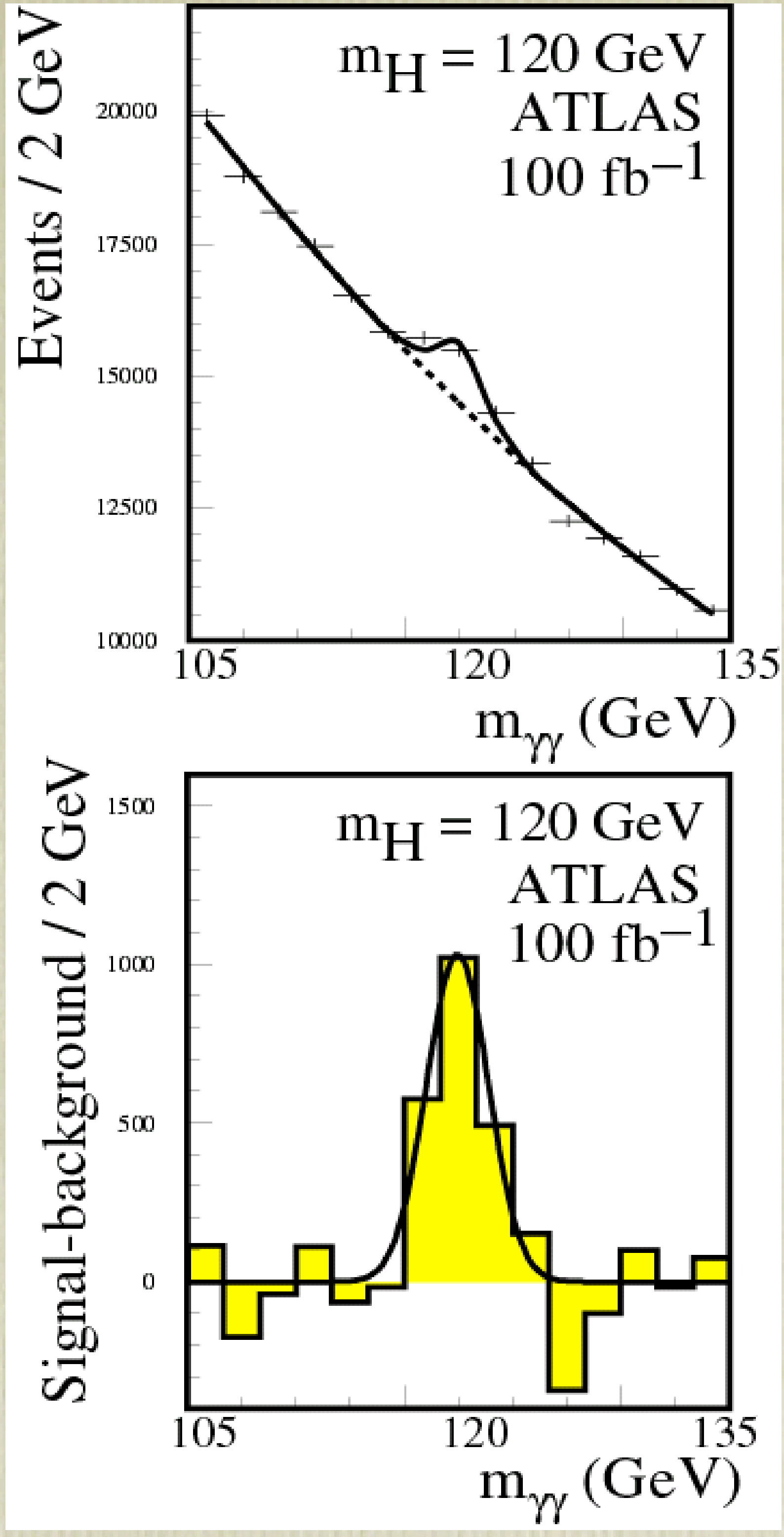
Search channels:

$$gg \to H \to \gamma\gamma$$

Acceptable BR only in the mass range m_H<140 GeV ($O(10^{-3})$).

Dominant background: QCD continuum production of γγ final states, plus tails in the QCD dijet of γ-jet production, with one or more jets fragmenting into isolated π^0, faking a γ.

Significance: 2.8 to 4.3σ for 100 fb^{-1}

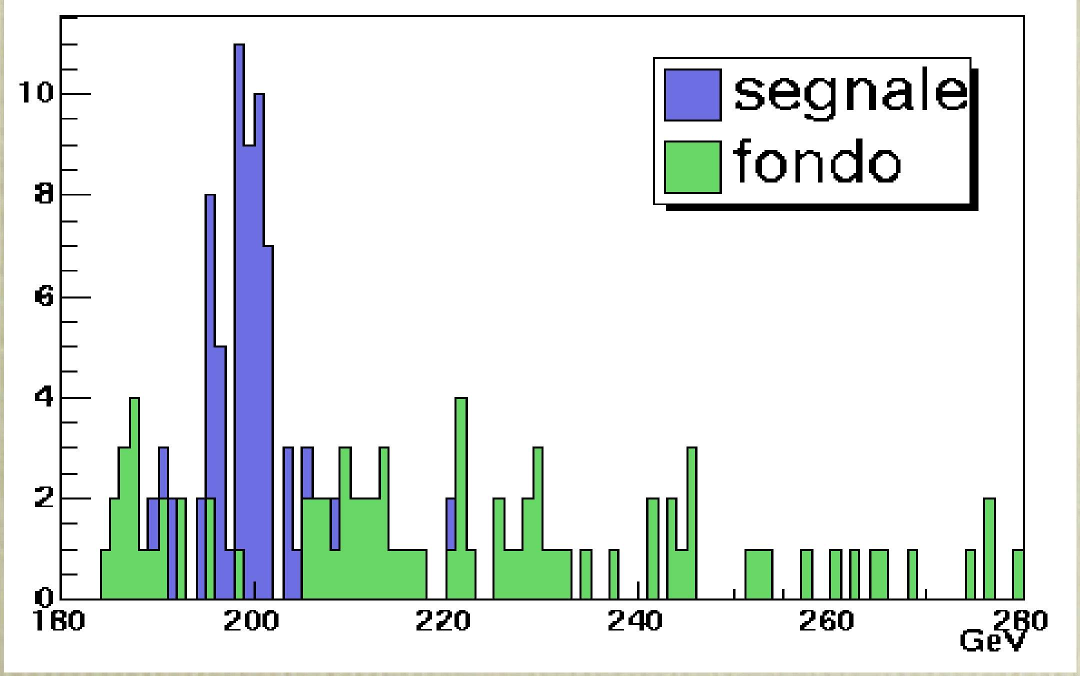


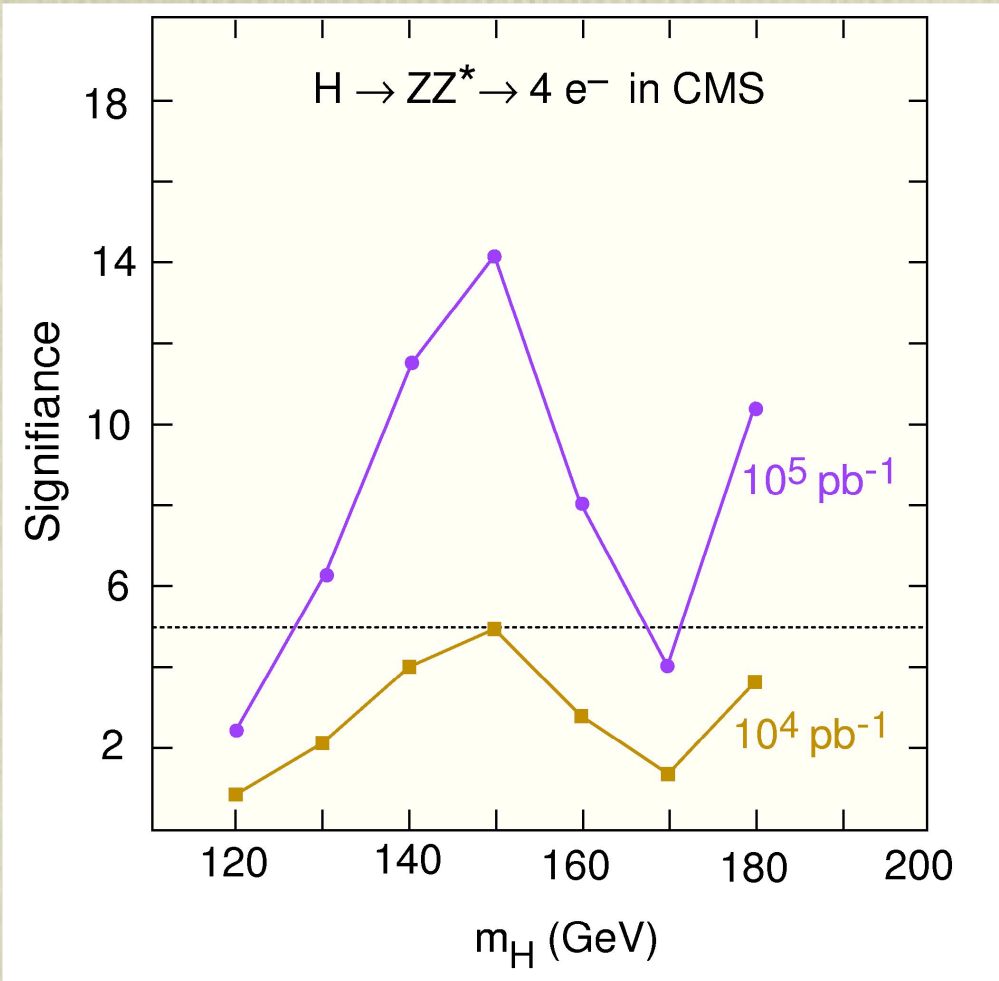
Search channels: $H \to ZZ^{(*)} \to \ell^+\ell^-\ell'^+\ell'^-$

Effective once at least one Z can be on-shell, m_H >130 GeV, both in the gluon fusion and vector boson fusion production modes

Main bg: direct QCD ZZ production

Main bg rejection criteria: low rate, sideband interpolation





Search channels: $H \to WW^{(*)} \to \ell\nu\ell'\nu'$

Effective once at least one W can be on-shell, m_H >120 GeV, both in the gluon fusion and vector boson fusion production modes

Main bg: W-pair production from tt decays, and (smaller) from direct WW production

Main bg rejection criteria:

1) absence of additional jets (as in top decays)

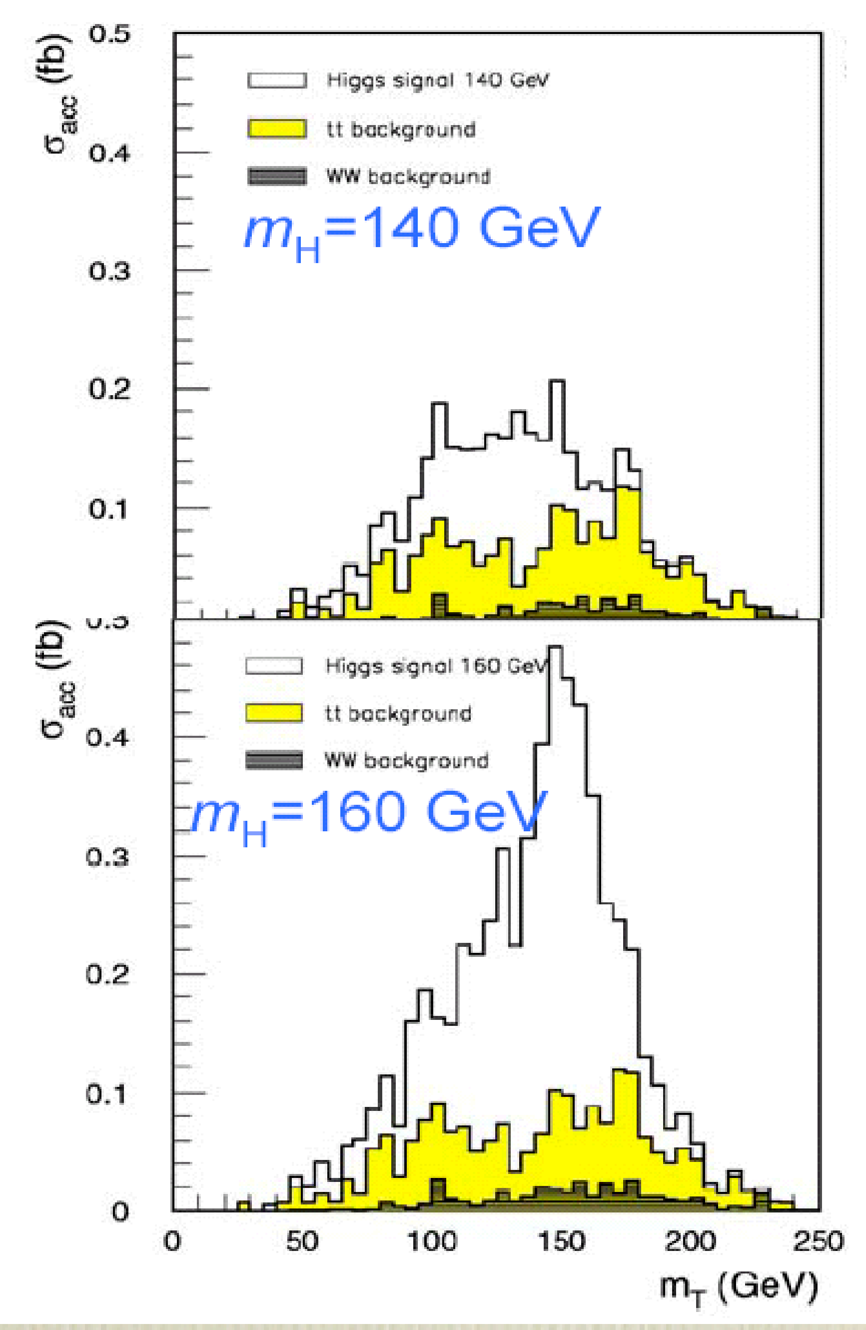
2) momentum correlation among charged leptons

3) fwd jets (for VB fusion mode)

Exercise: prove that the matrix element for the signal is maximized when the two charged leptons have small invariant mass

With 5fb^{-1}, and 5% bg systematics:

m_H(GeV)	130	150	170	190
Signal	5	13	22	14
Bg	3	4	5	7
S/√B	2.1	4.7	6.5	4.2



Search channels: $gg \to t\bar{t}H \to t\bar{t}b\bar{b}$

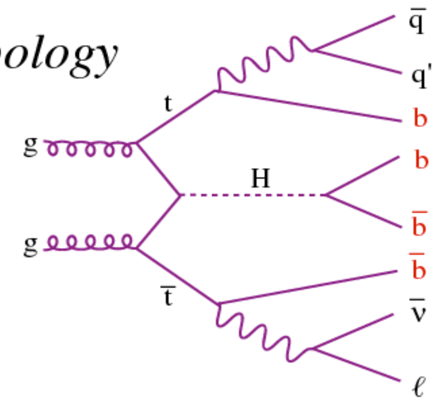
Challenging and complex topology

4 b-jets, 2 jets, 1 lepton

$H \to bb$

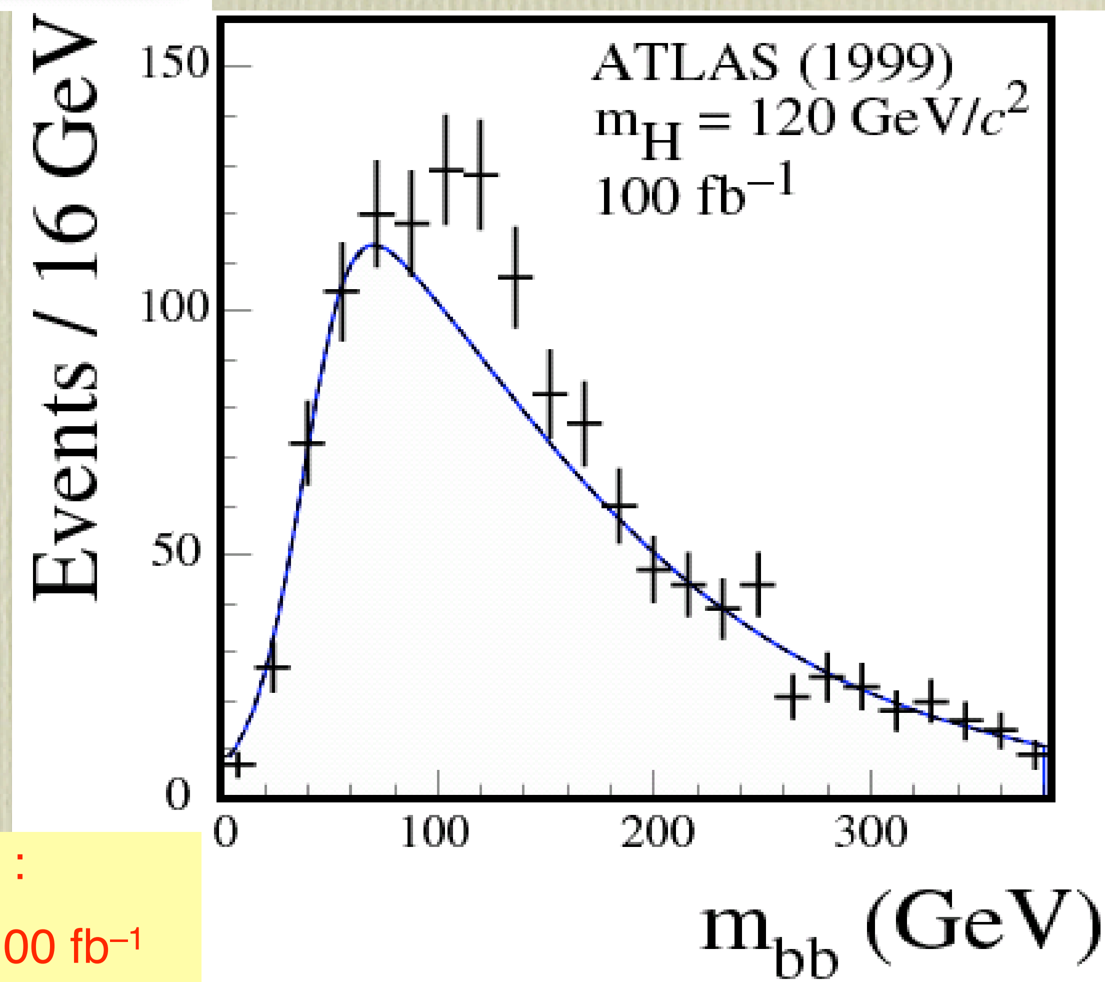
$t \to bqq'$

$t \to b\ell\nu$



Main bg: ttbar production, in association with (possibly b) jets

Main bg rejection criteria:
1) multiple b tags
2) peak in m(bb) (try to achieve as good mass resolution as possible)



Signal significance (5σ) :

mH < 120 GeV needs 100 fb^{-1}

Discovery reach for low-mass Higgs at the LEP2 limit (115 GeV), with 10 fb^{-1}

	$H \to \gamma\gamma$	$ttH \to ttbb$	$qqH \to qq\tau\tau$
S	130	15	10
B	4300	45	10
$S/\sqrt{B}$	2.0	2.2	2.7

Will require the combination of several, low-significance, channels. Combined significance:

$$4^{+2.2}_{-1.3}\ \sigma$$

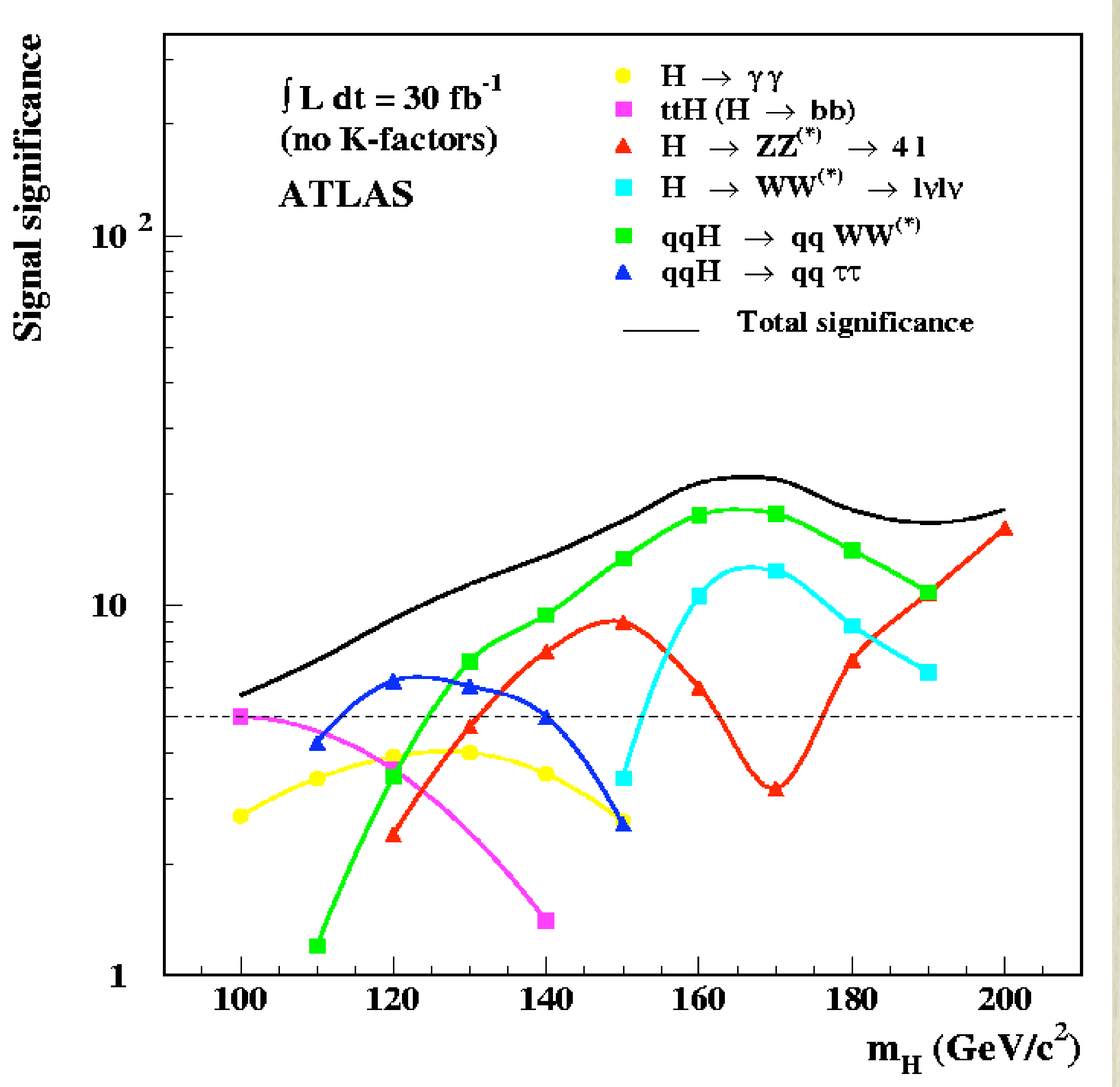
Discovery reach for low-mass Higgs just above the LEP2 limit (130 GeV), with $10 fb^{-1}$

	$H \to \gamma\gamma$	$qqH \to qqWW$	$qqH \to qq\tau\tau$	$H \to 4l$
S	120	18	8	5
B	3400	15	6	<1
$S/\sqrt{B}$	2.0	3.9	2.7	2.8

Combined significance: **6 σ**

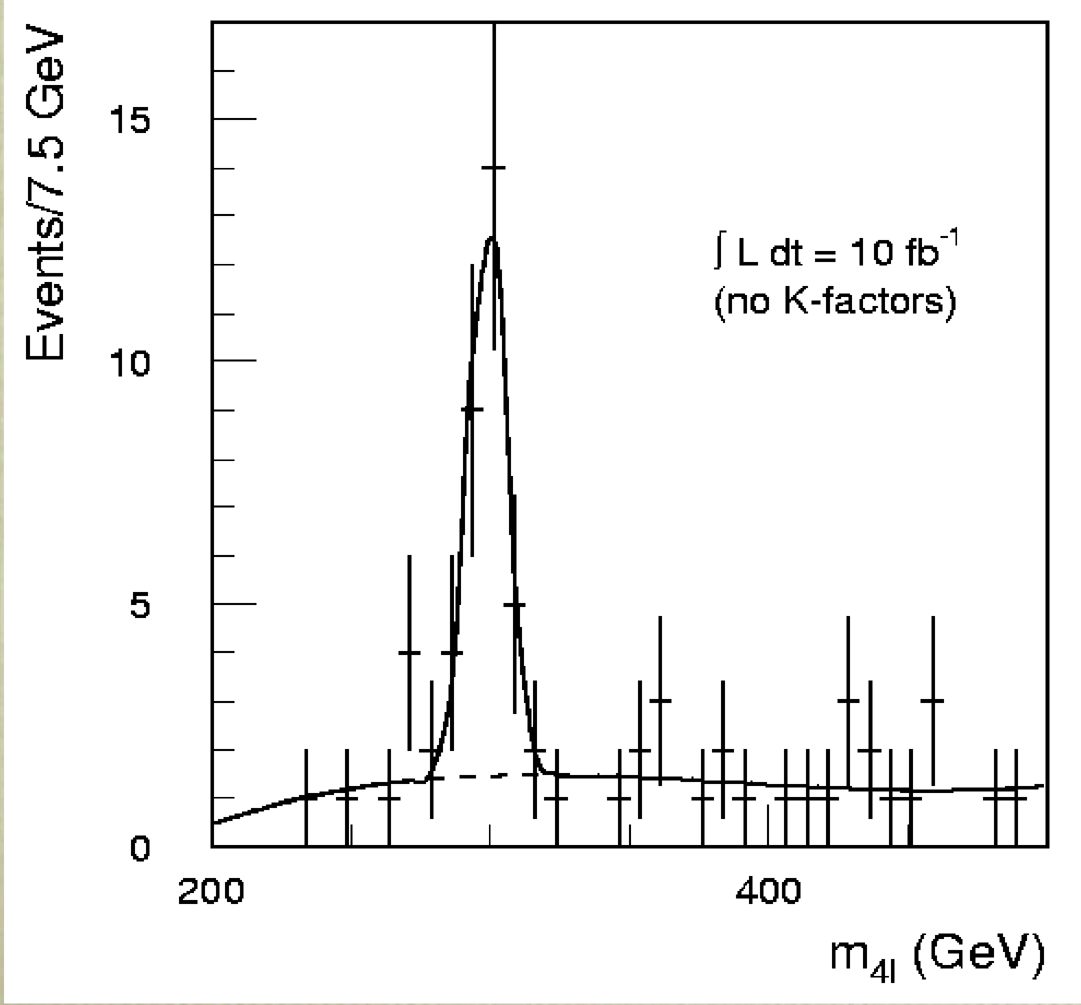
Light Higgs reach at the LHC

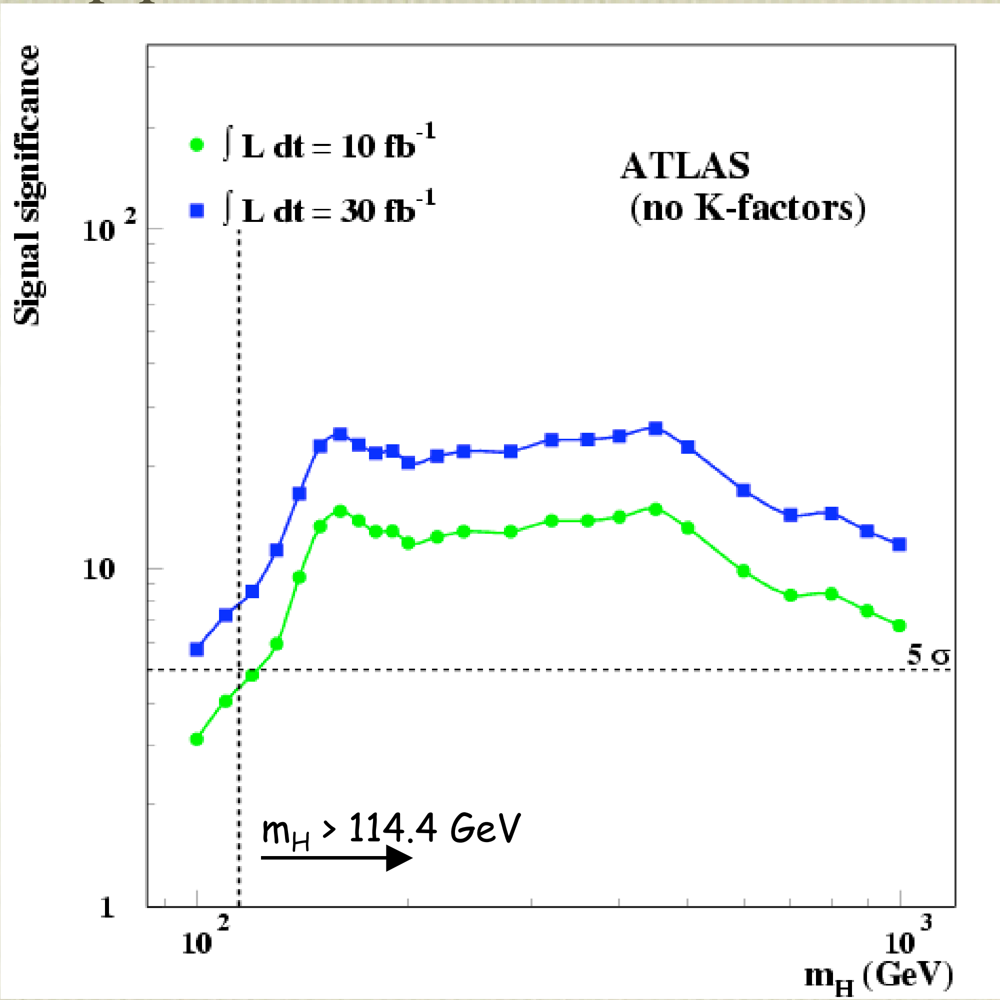
1 year of data taking at nominal luminosity should be sufficient for the two experiments to detect a Higgs through most of the expected mass range

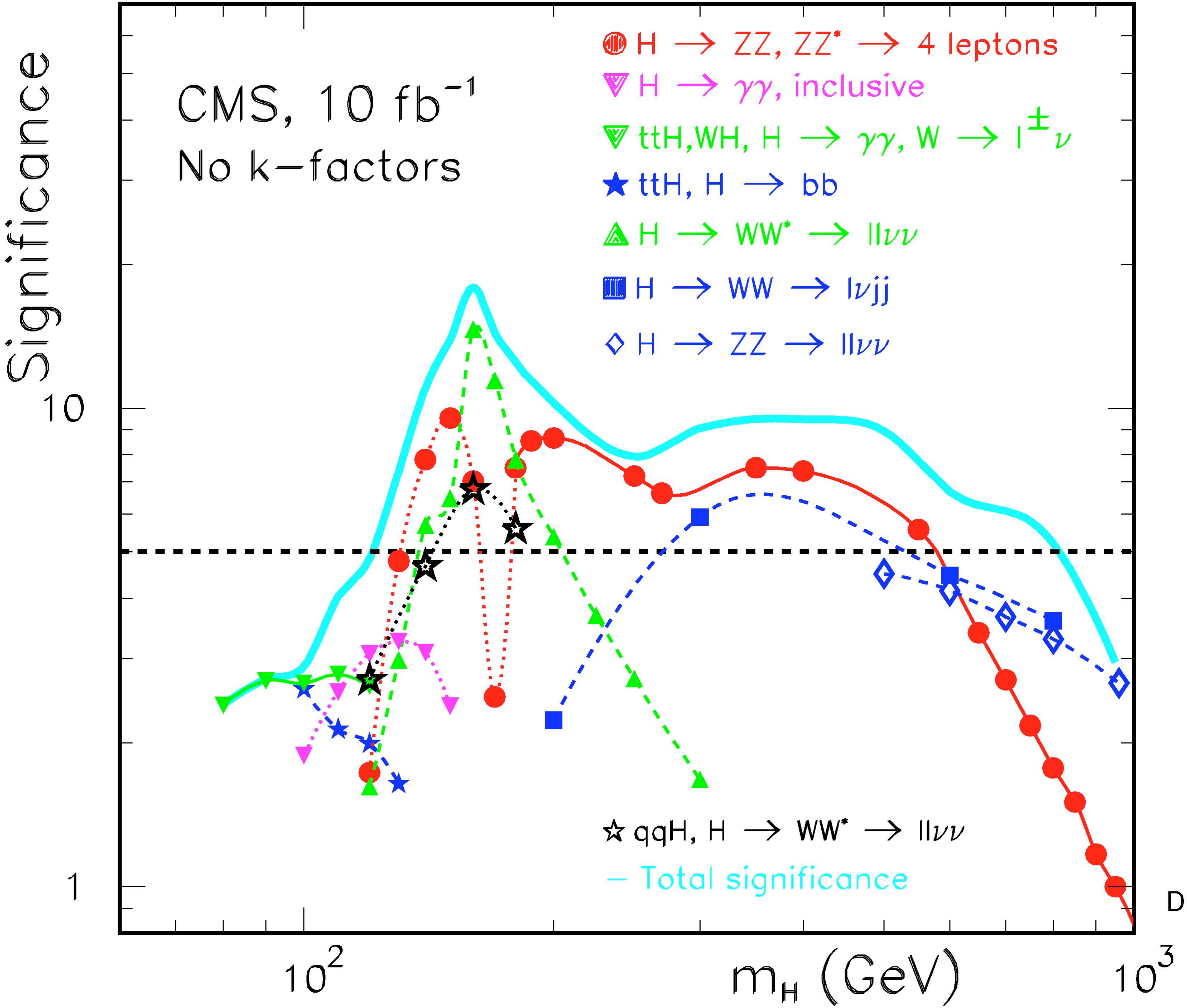


High mass region

- Easy discovery using H→ZZ→4 leptons for 200<m_H<600 GeV
- H width larger than detector resolution for m_H>300 direct measurement of total width!
- Combine several channels m_H>600 GeV:
  - H→ZZ→2lept 2 ν, 2lept q qbar
  - H→WW→lν q qbar

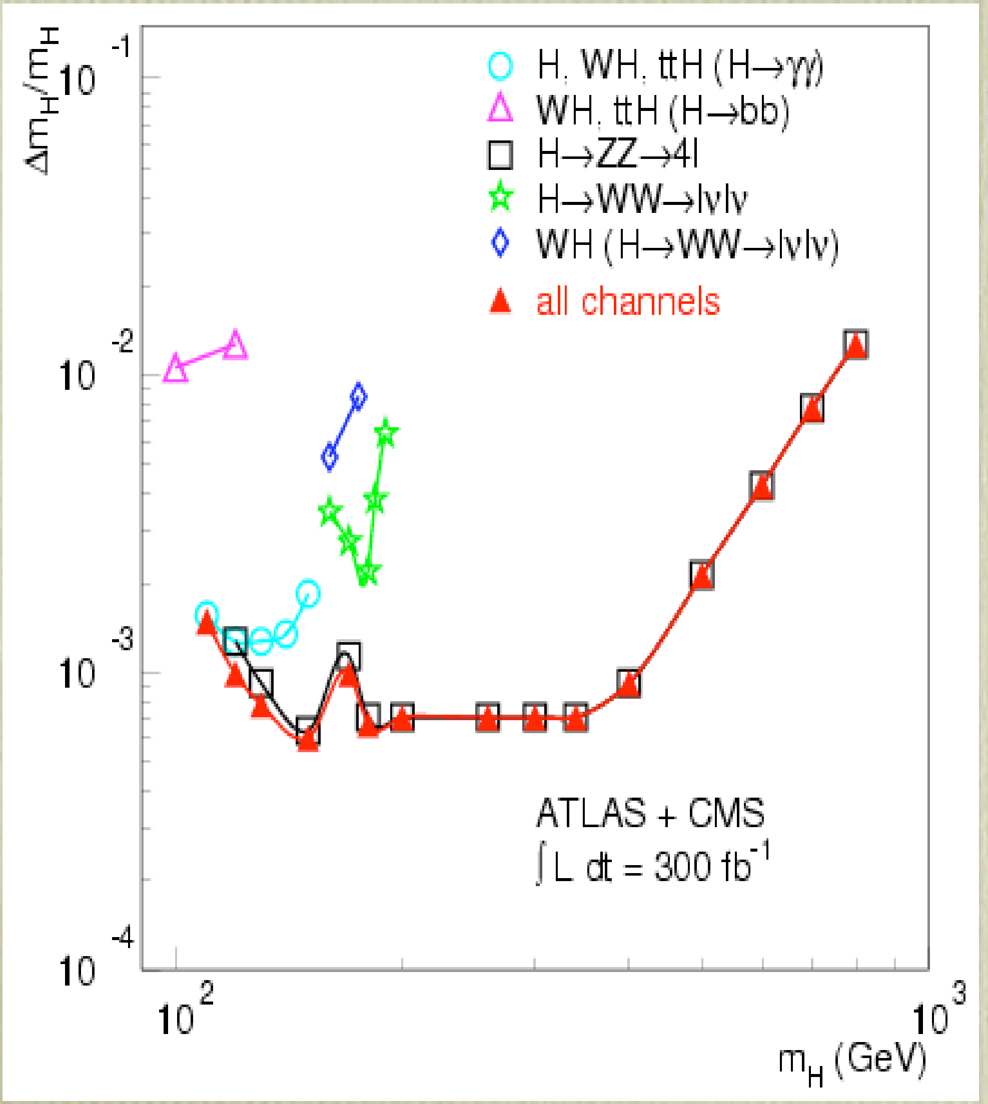


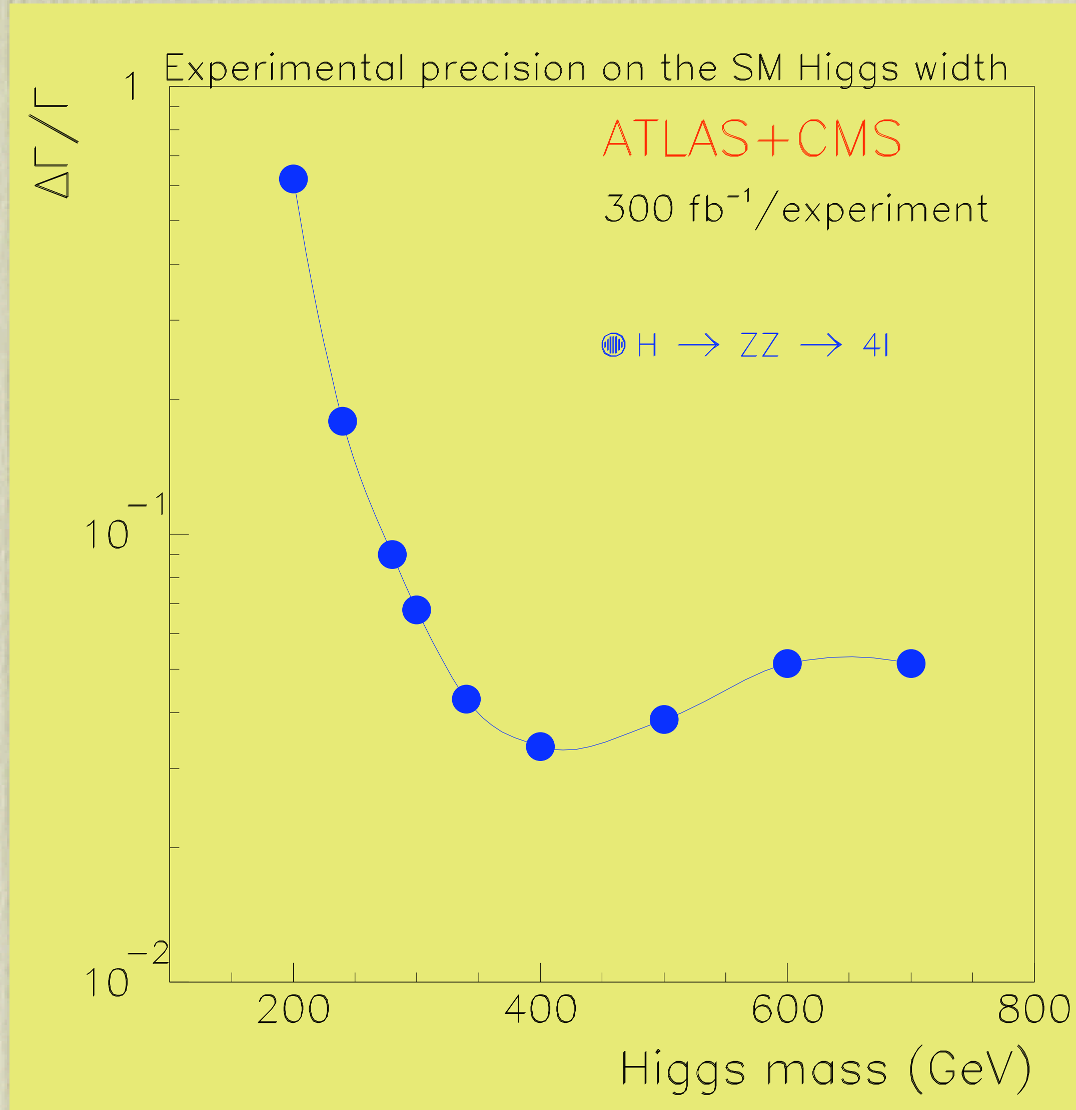




CMS, 10 fb^{-1}
No k−factors
H → ZZ, ZZ* → 4 leptons
H → γγ, inclusive
ttH,WH, H → γγ, W → l$^{\pm}$ν
ttH, H → bb
H → WW* → llνν
H → WW → lνjj
H → ZZ → llνν
qqH, H → WW* → llνν
− Total significance
Significance
10
1
10^2
10^3
m_H (GeV)

Direct measurement of Higgs mass and width





Direct measurement of Higgs couplings

Different production and decay channels provide measurements of the following combinations of partial decay widths

$$X_\gamma = \frac{\Gamma_W \Gamma_\gamma}{\Gamma} \quad from\ qq \to qqH,\ H \to \gamma\gamma\,, \qquad Y_\gamma = \frac{\Gamma_g \Gamma_\gamma}{\Gamma} \quad from\ gg \to H \to \gamma\gamma\,,$$

$$X_\tau = \frac{\Gamma_W \Gamma_\tau}{\Gamma} \quad from\ qq \to qqH,\ H \to \tau\tau\,, \qquad Y_Z = \frac{\Gamma_g \Gamma_Z}{\Gamma} \quad from\ gg \to H \to ZZ^{(*)}\,,$$

$$X_W = \frac{\Gamma_W^2}{\Gamma} \quad from\ qq \to qqH,\ H \to WW^{(*)}\,, \qquad Y_W = \frac{\Gamma_g \Gamma_W}{\Gamma} \quad from\ gg \to H \to WW^{(*)}$$

Ratios of X or Y quantities factor out not just the partial widths to either W or gluon, but also the overall initial-state parton luminosities and uncertainties on the production cross-sections.

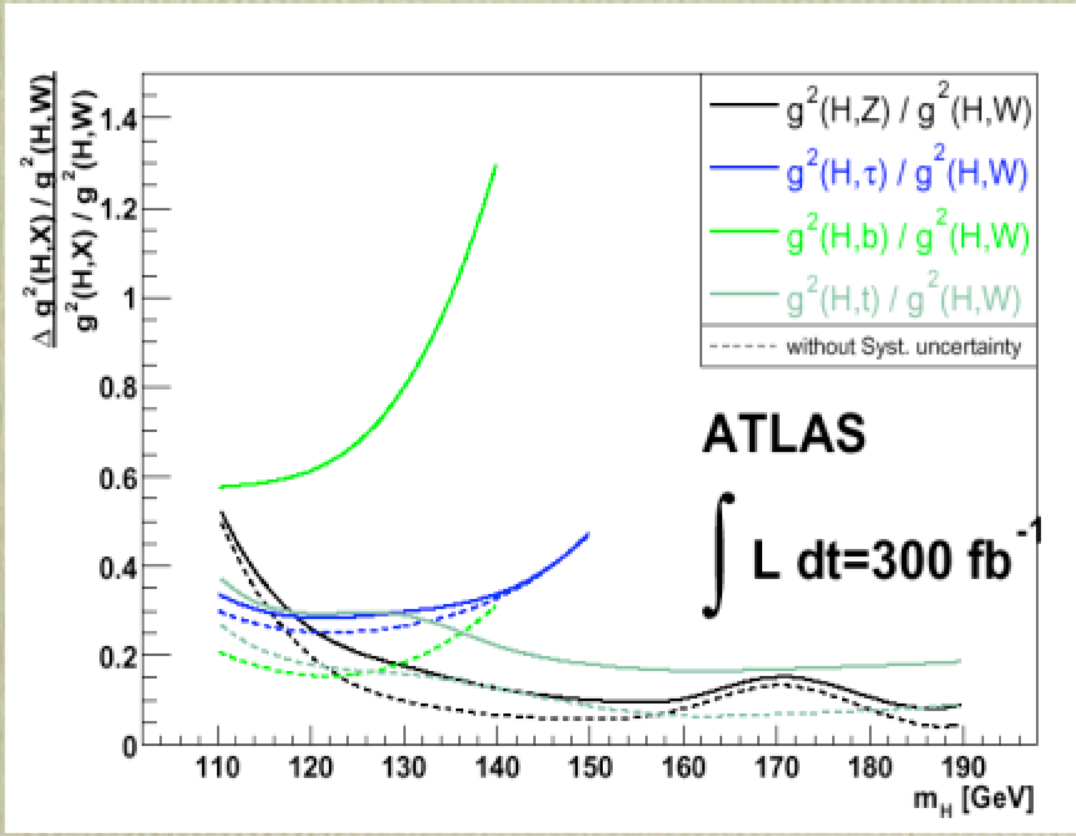
$$y = \frac{\Gamma_b}{\Gamma_\tau} = 3c_{QCD}\frac{g^2_{Hbb}}{g^2_{H\tau\tau}} = 3c_{QCD}\frac{m_b^2(m_H)}{m_\tau^2}$$

$$\varepsilon = 1 - \left(B(H \to b\bar{b}) + B(H \to \tau\tau) + B(H \to WW^{(*)}) + B(H \to ZZ^{(*)}) + B(H \to gg) + B(H \to \gamma\gamma)\right) \ll 1$$

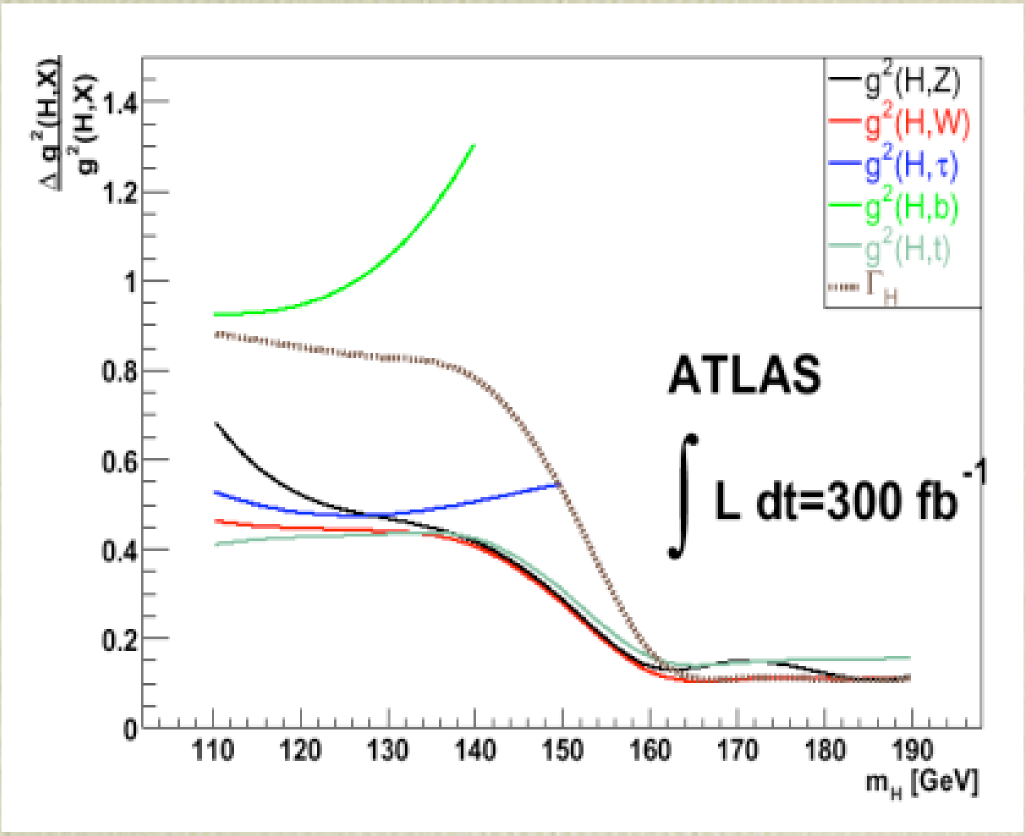
$$\tilde{\Gamma}_W = \left(\Gamma_\tau + \Gamma_b + \Gamma_W + \Gamma_Z + \Gamma_\gamma + \Gamma_g\right)\frac{\Gamma_W}{\Gamma} = (1-\varepsilon)\Gamma_W$$

Measurement of Higgs couplings

Coupling ratios



Absolute couplings



Rare Higgs decays

$H \to \mu^+\mu^-$: SM BR=10^{-4}, reach for 6000fb^{-1}

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

$H \to Z\gamma \to \mu^+\mu^-\gamma$: independent determination of HZ coupling.

Sensitivity in the range of 3.5σ with 600fb^{-1}, 11σ with 6000fb^{-1}

MSSM Higgs discovery potential

$h^0, H^0, A^0, H^{\pm}$

MSSM specific decays:

$A/H \to \mu\mu, \tau\tau, tt$

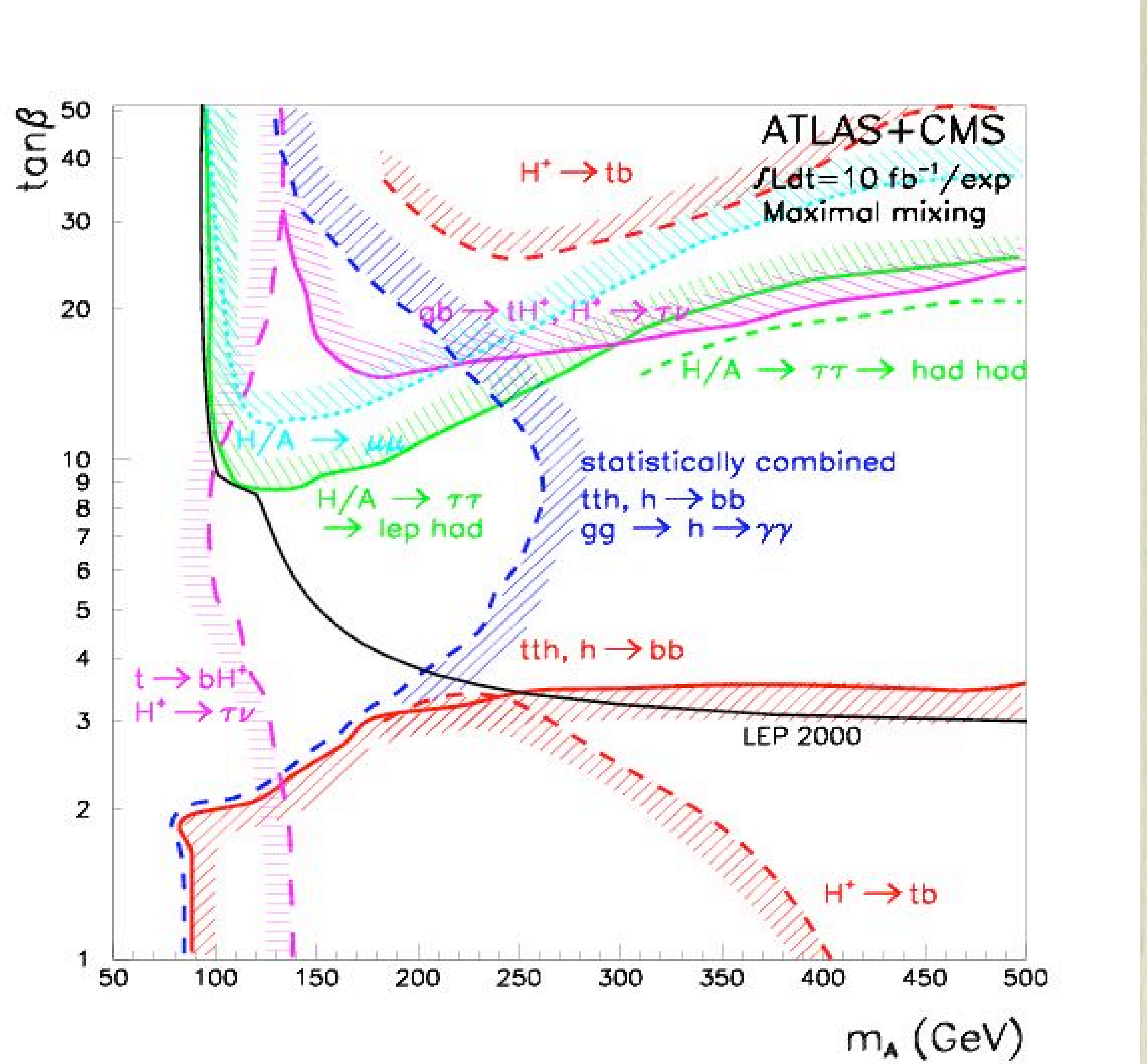
$H \to hh$

$A \to Zh$

$H^{\pm} \to \tau\nu$

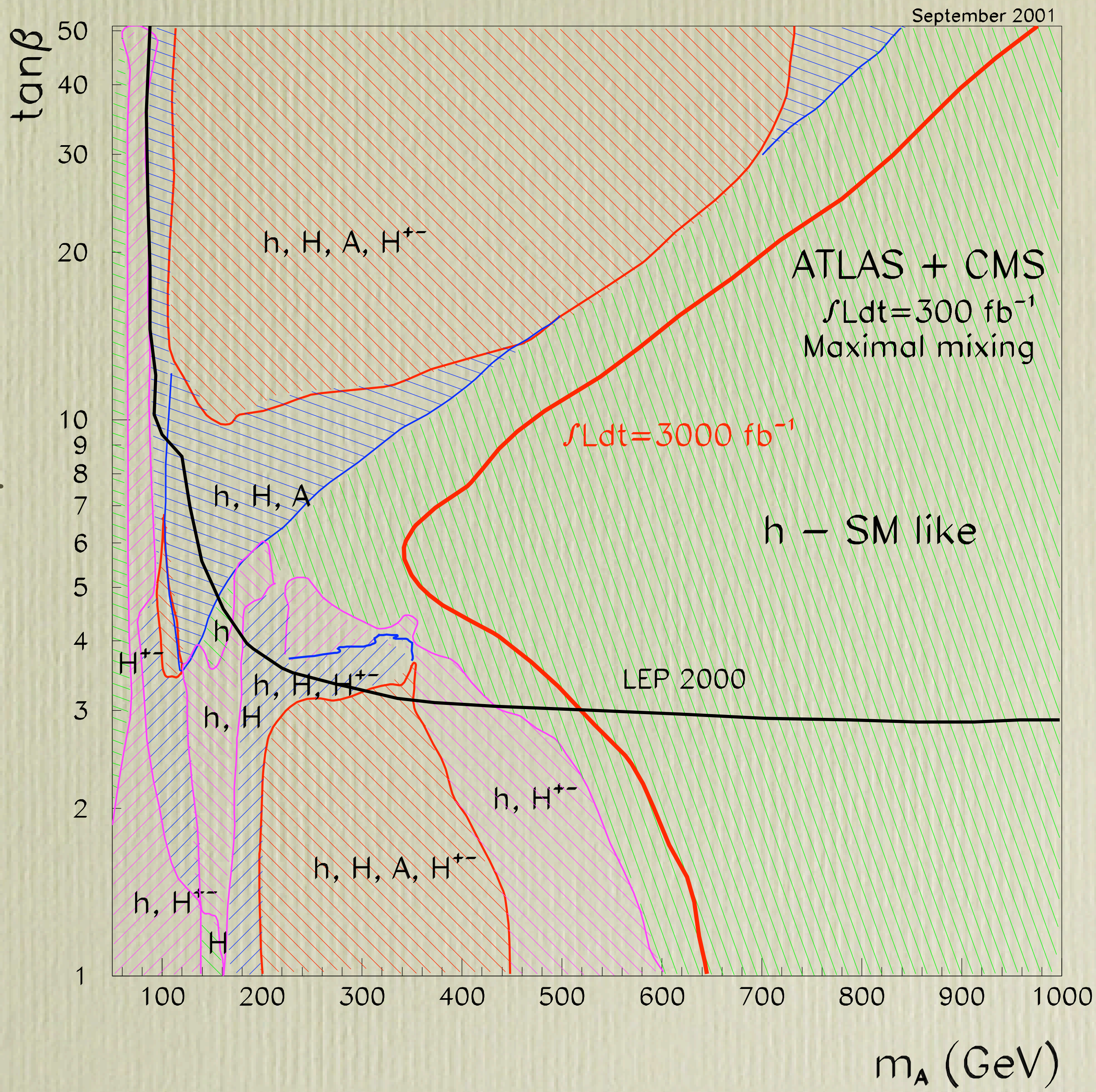
If SUSY particles light enough:

- $H/A \to \chi_2^0 \chi_2^0 \to \chi_1^0 \chi_1^0 + 4$lept's
- h produced in cascade decays

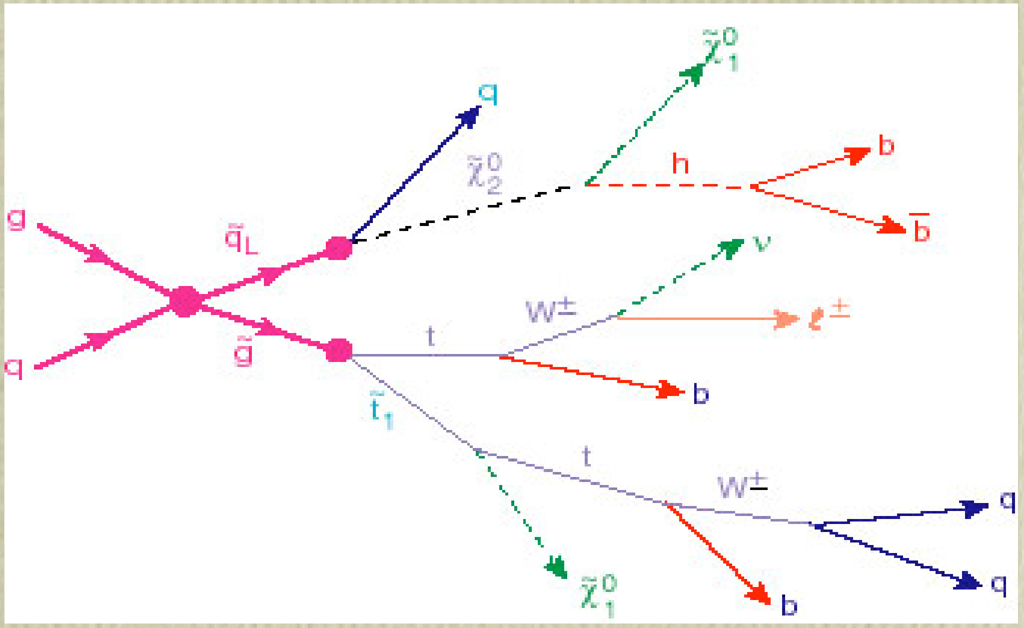


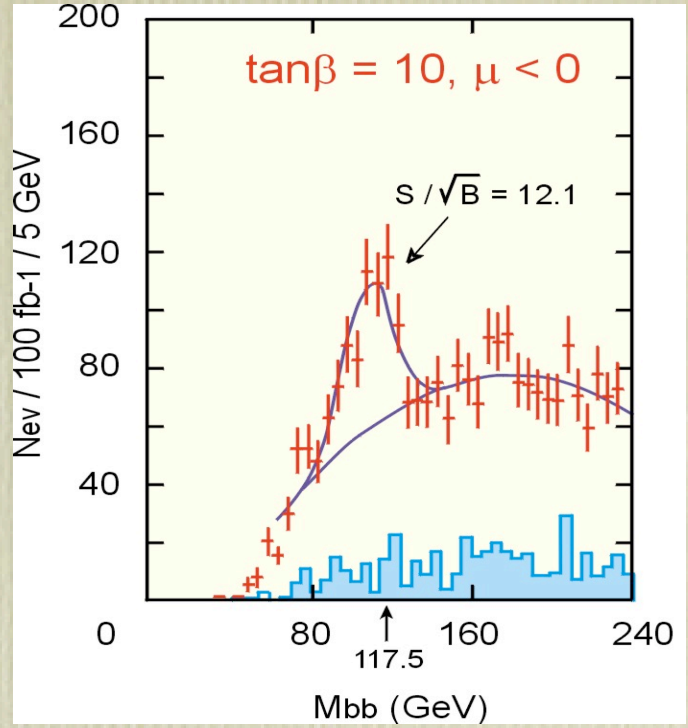
For a large fraction of the parameter space with mA<500GeV, more than one Higgs bosons will be visible with the expected luminosity

Higgs particles which can be observed with >5σ in different areas of m_A-tanβ parameter space



Example, h production in cascade decays





Supersymmetry: what, why, where

- Spectrum doubling: one bosonic degree of freedom (dof) of for each fermionic dof, and viceversa
- enhanced relations among and constraints on couplings/masses
- space-time Lorentz symmetry ⇒ particle ↔ antiparticle
- space-time Supersymmetry ⇒ particle ↔ sparticle
- SUSY has a priori fewer parameters than non-SUSY:
  - m(particle)=m(sparticle)
  - couplings(particle)=couplings(sparticle)
  - Higgs selfcoupling (λ) related to weak gauge coupling:

$$\lambda\phi^4 \sim g_W\phi^4$$

- All complexity and parameter proliferation of SUSY are just a consequence of SUSY breaking (SSB)!!

- A minimal SUSY extension of the SM, with arbitrary pattern of spontaneous SUSY breaking, has over 100 extra parameters (scalar and gauge-fermion masses, mixings among SUSY partners of quarks and leptons)
- This is not much worse than an arbitrary extension to leptons and hadrons of Fermi's theory of weak interactions, before Feynman, Gell-Mann and Cabibbo, or even before LEP/SLC firmly established the parameters of the SM. One could have needed parameters to describe:
  - non V-A couplings (S, P, T, V+A)
  - non-universal couplings to hadronic currents, and to μ or τ currents
  - more complex Higgs structures
  - different realisations of EWSB
- Therefore parameter proliferation in SUSY is most likely the consequence of our current ignorance of the specific dynamics leading to SUSY breaking.

Benchmark goal for SUSY studies at the LHC:

GET CLUES ON THE MECHANISM OF SUSY BREAKING

The accuracy of SUSY measurements at the LHC should be gauged by the above goal:

is the accuracy sufficient to discriminate among different SSB models?

Supersymmetry breaking: constraints

- No SUSY observed as yet: Susy particles must have masses typically larger than 100 GeV

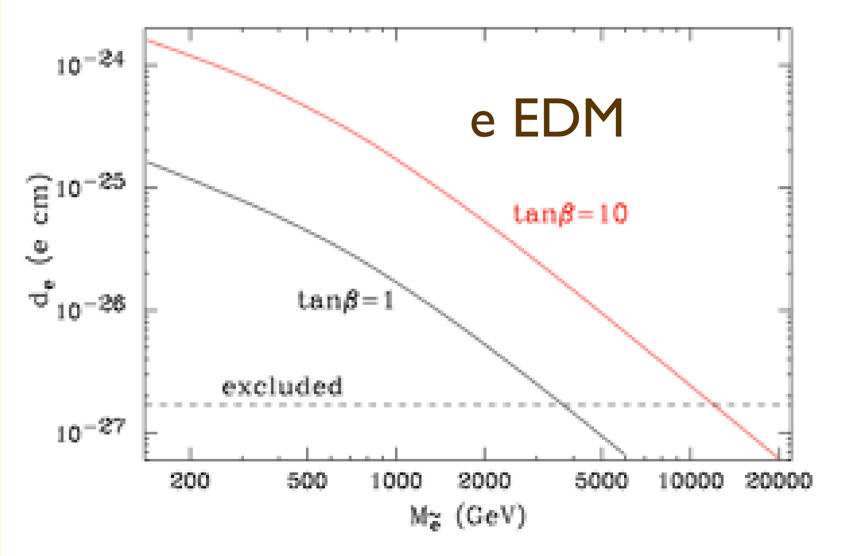
- Nevertheless they cannot be arbitrarily large, to prevent the artificial fine tuning which justified SUSY in first place:

$$m_{\tilde{p}} \not\gg 1\ \text{TeV}$$

- Generic Susy breaking (SSB) leads to unacceptable FCNC. Therefore need to require suppressed FCNC (Flavour conservation is to SUSY what GIM has been for the SM):

$$\varepsilon_K \sim \left(\frac{100\ TeV}{m_{\tilde{q}}}\right)^2 Im\left(\frac{\Delta m^2_{\tilde{d}_L\tilde{s}_L}}{m^2_{\tilde{d}}}\frac{\Delta m^2_{\tilde{d}_R\tilde{s}_R}}{m^2_{\tilde{d}}}\right) < 2\cdot 10^{-3}$$

$$\mu \not\to e\gamma \Rightarrow \sin 2\theta_{\tilde{e}\tilde{\mu}}\frac{\Delta m^2_{\tilde{e}\tilde{\mu}}}{m^2_{\tilde{e}}} < 0.01$$



Supersymmetry breaking models: minimal Supergravity

SUSY breaking at an intermediate scale:

$$M_{SSB} \sim \sqrt{m_W \, m_{Plank}} \sim 10^{11} \; GeV$$

Universal scalar and fermion SSB masses at the Planck scale:

$$m_H = m_0$$
$$m_{\tilde{V}} = m_{1/2} \quad \forall \, V = g, \gamma, W, Z$$

Implications:

- mass splitting at EW scale induced radiatively ⇒ no FCNC problems
- mass squared for H naturally driven negative by large top Yukawa coupling
- correlation between Higgs and gaugino masses
- correlations between different gaugino masses:

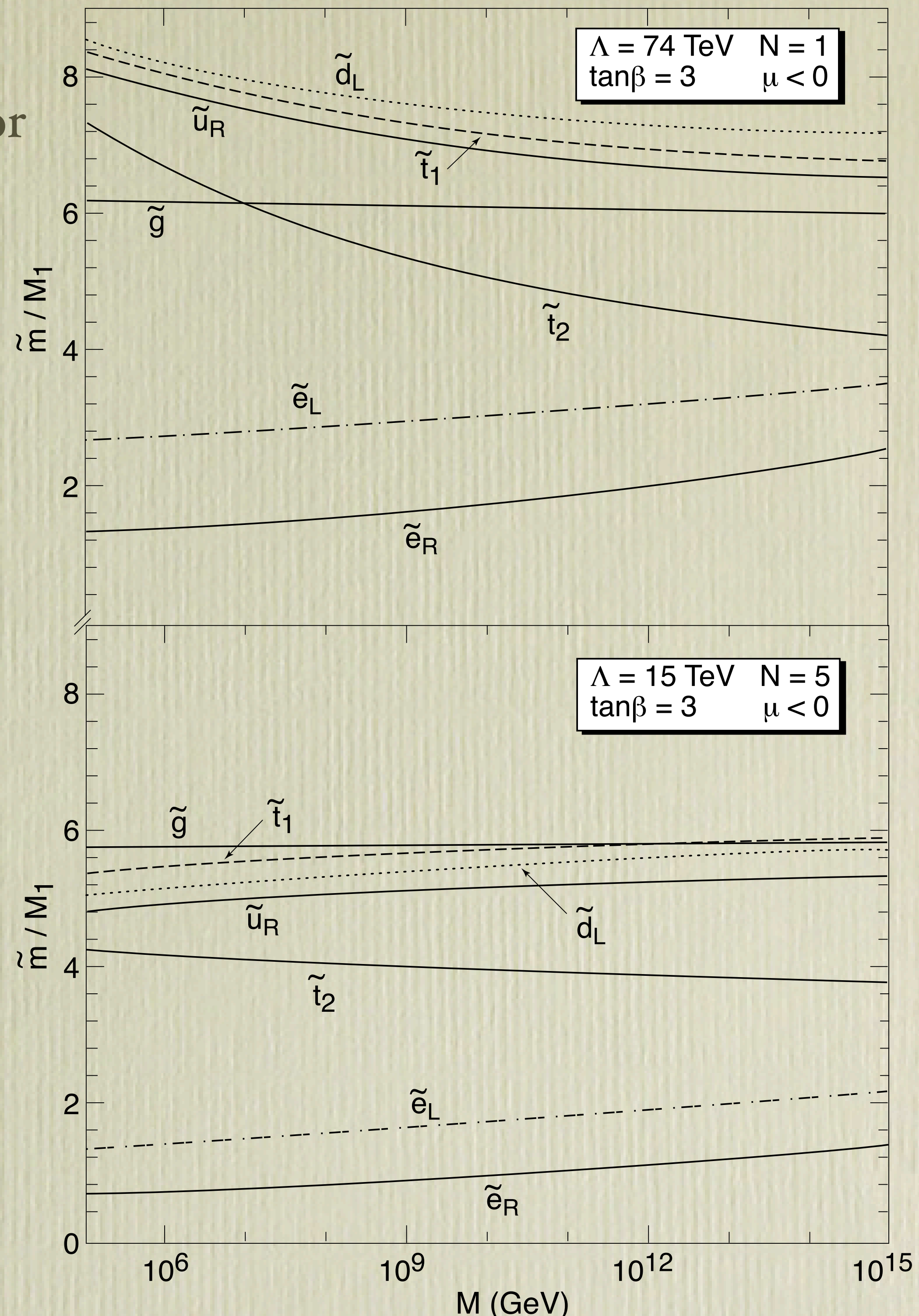
$$m(\tilde{g})/m(\tilde{\chi}) \sim \alpha_s/\alpha_W$$

$$m(\tilde{B}) = (5g'^2/3g^2)\, m(\tilde{W}) \sim 0.5 m(\tilde{W})$$

Supersymmetry breaking models: gauge-mediated SSB

SUSY breaking in a strongly coupled sector, transferred to the low energy sector only via gauge interactions at an intermediate scale:

m_{SSB} ~ 1-100 TeV



Consequences:

- SSB flavour independent ⇒ no FCNC problems
- Relations among SSB parameters determined by gauge couplings:

$$\frac{m(\tilde{q})}{m(\tilde{\ell})} \sim \frac{\alpha_s}{\alpha_w} \gg 1\,, \quad \text{unlike SUGRA}$$

$$\frac{m(\tilde{g})}{m(\tilde{\chi})} \sim \frac{\alpha_s}{\alpha_w}\,, \quad \text{like SUGRA}$$

$$m(\tilde{q}) \sim m(\tilde{g})\,, \quad m(\tilde{\ell}) \sim m(\tilde{\chi})$$

$$m(\tilde{\chi}_1^{\pm}) \sim m(\chi_2^0)$$

- gravitino as Lighest SUSY Particle:

$$\chi^0 \to \tilde{G}\gamma \quad \text{or} \quad \tilde{\ell} \to \tilde{G}\ell$$

depending on which is the NLSP

SUSY DM

Dark matter constraints on neutralinos: a CMSSM example

old:

$0.1<\Omega_\chi h^2<0.3$

new WMAP

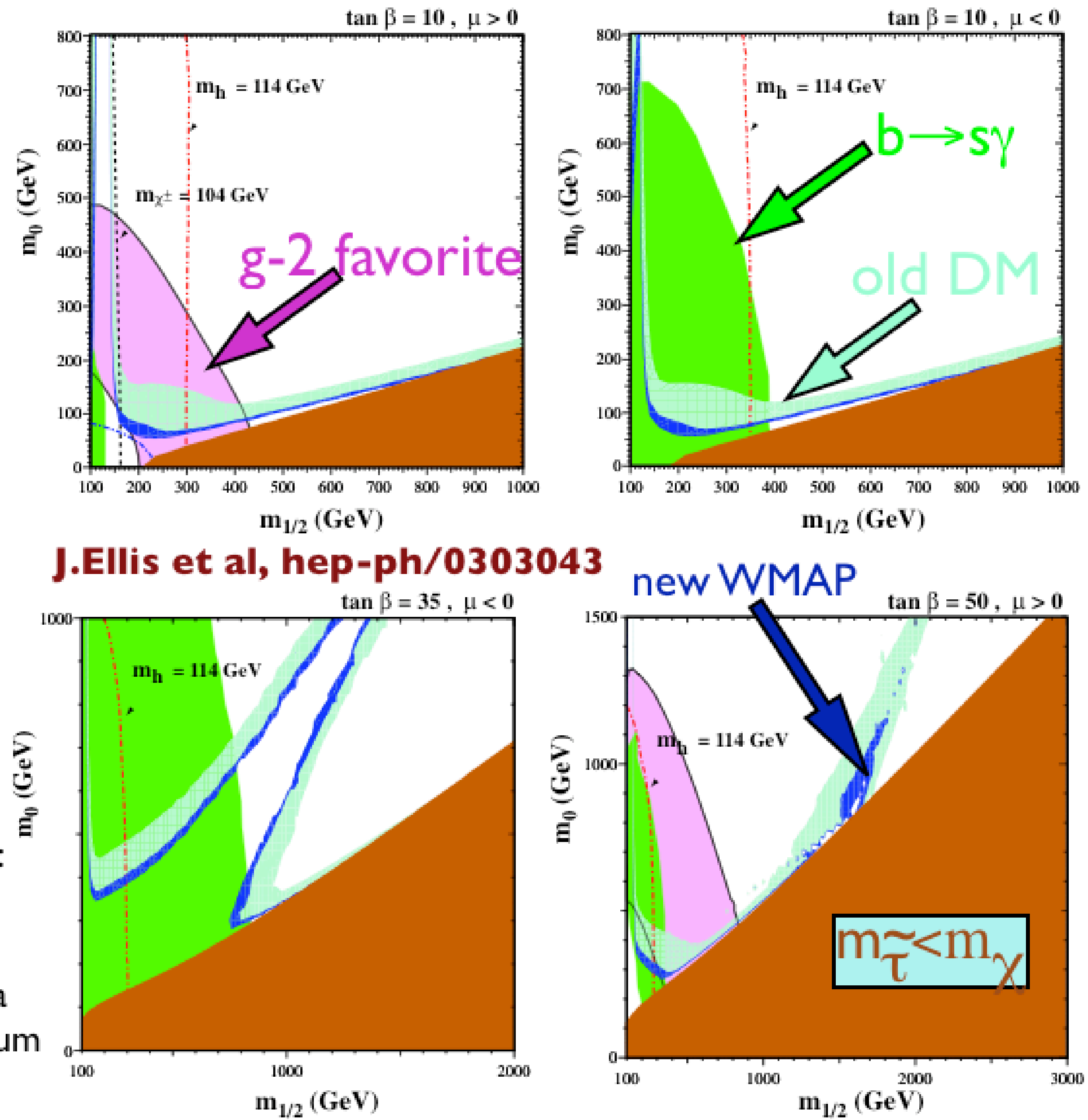
$0.094<\Omega_\chi h^2<0.129$

$\Omega_\chi h^2 \sim m_\chi\, n_\chi \Rightarrow$

upper limit on Ω_χ requires:

+ small m_χ, or

+ fast/efficient annihilation, a strong constraint on spectrum (to allow, e.g., $\chi\chi\rightarrow h$ at threshold or $\chi\tilde{\tau}\rightarrow\gamma\tau$)



J.Ellis et al, hep-ph/0303043

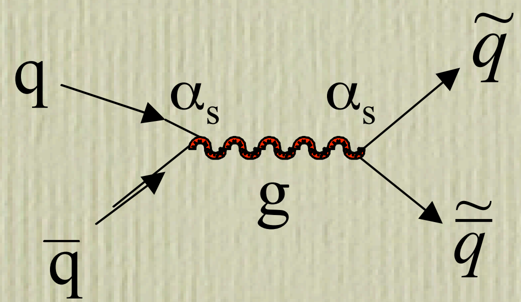
In conclusion:

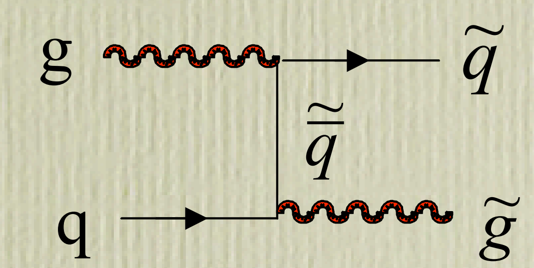
- The exploration of the SUSY spectrum provides invaluable information on the physics at scales much larger than the LHC's. For example:
    - Indications of a mSUGRA-like spectrum would set the scale of SSB at 10^{11} GeV, and would provide a probe of physics at the Grand Unification scale: connection with neutrino masses, implications for flavour changing phenomena in teh charged-lepton spectrum, etc.
    - Indications of a GMSB-like spectrum would indicate the existence of new phenomena at a scale of the order of 10-100-TeV

- The most valuable information will come from the comparison of
    - gaugino masses (gluino vs. charginos vs. neutralinos)
    - **lighest susy particle (neutralino?) properties !!**
    - scalar masses (SU(2) doublet (L-type) vs singlet (R-type) scalars, squarks vs sleptons, 1st generation vs 2nd and 3rd)
    - of particular interest is the value of the stop mass, because of its connection with the Higgs mass

Production of SUSY particles

- Discrete quantum number, R=1 for “normal” particles, R=-1 for SUSY states. If R conserved:
  - pair production.
  - lightest SUSY particle is stable (=> Dark matter candidate)
- Strongly interacting (squarks -- e.g. stops, gluinos):

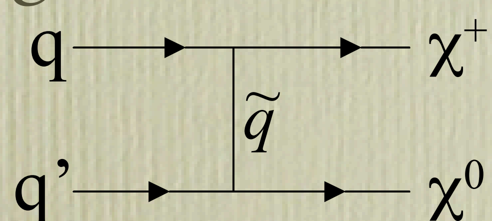




$m_{\tilde{q},\tilde{g}} \sim 1\ \text{TeV} \Rightarrow \sigma \sim 1\text{pb}^{-1}$

$\Rightarrow 10^4$ events/yr

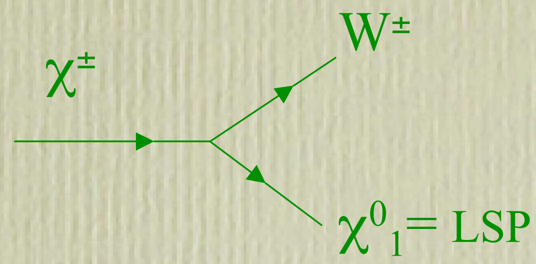
- Weakly interacting (photino, W-ino, Z-ino, higgsino => charginos/neutralinos)

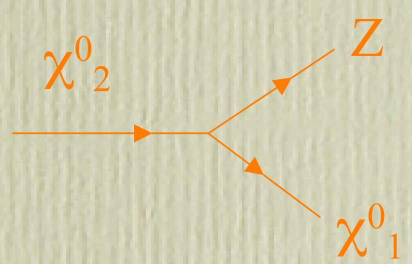


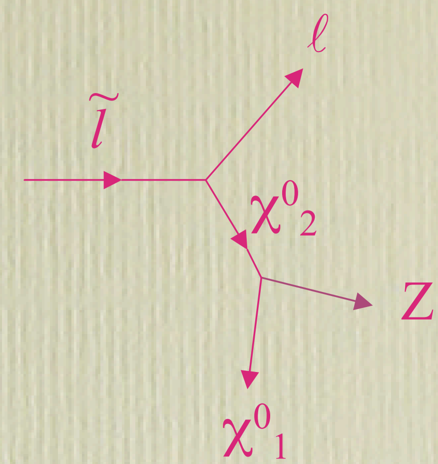
$m_{\tilde{\chi}} \sim 150\ \text{GeV} \Rightarrow \sigma \sim 1\text{pb}^{-1}$

Decays of SUSY particles

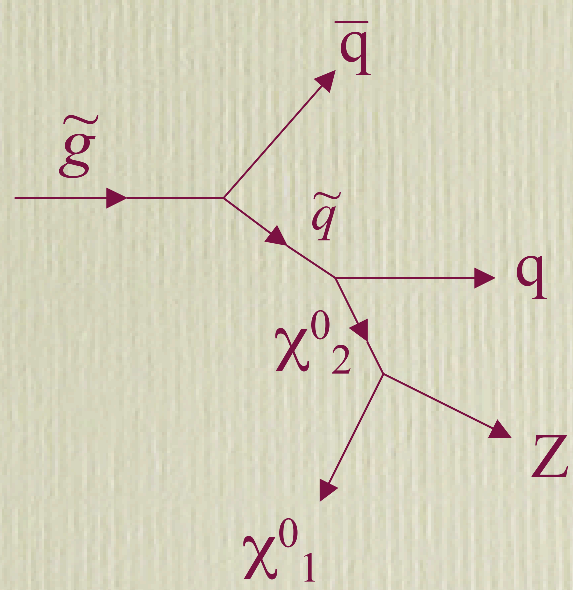
- weakly interacting:





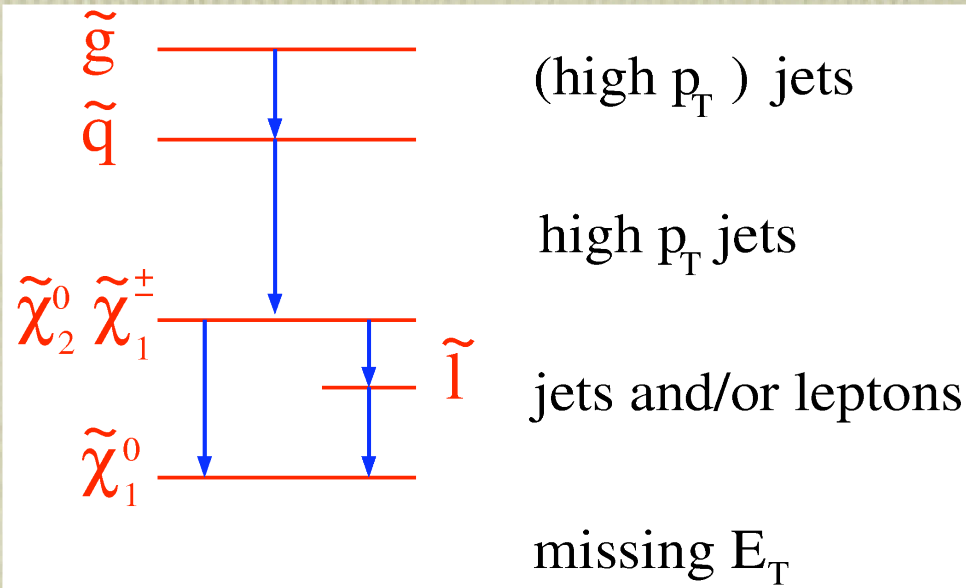


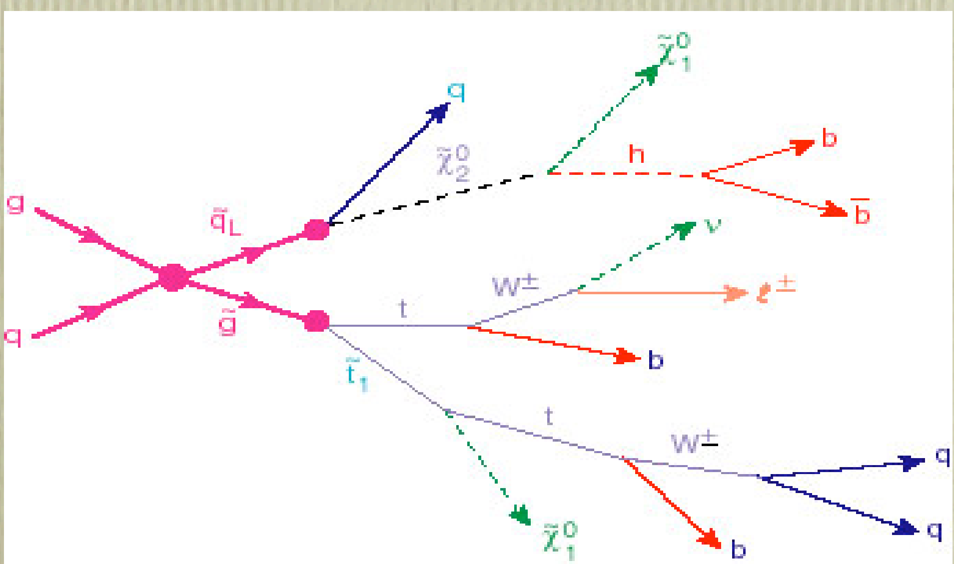
- strongly interacting: for massive states spectacular multi-body chain decays, possibly including EW sparticles, enhancing their production rate. Very difficult, but possible, to disentangle the full spectroscopy!

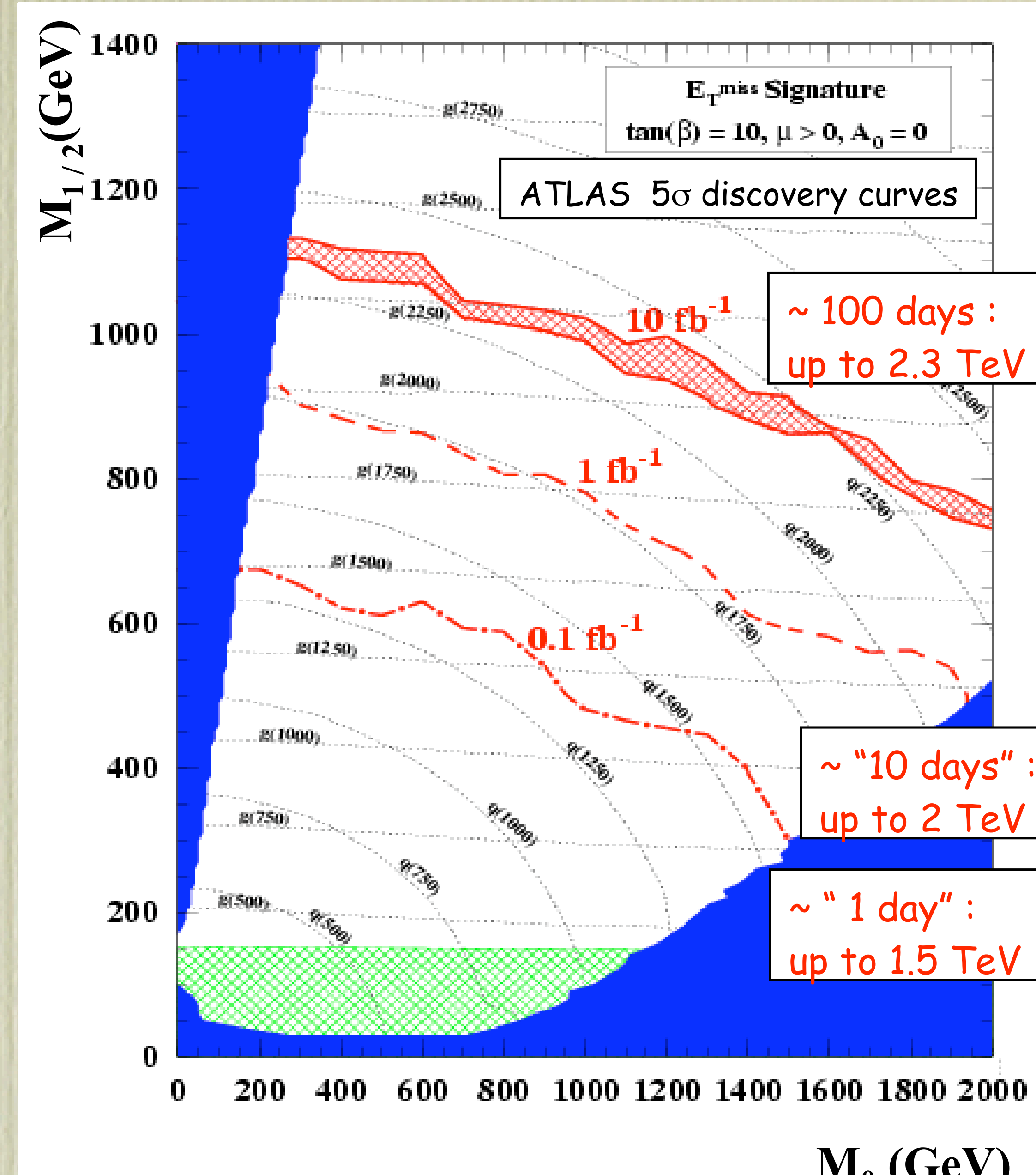


SUSY searches at the LHC

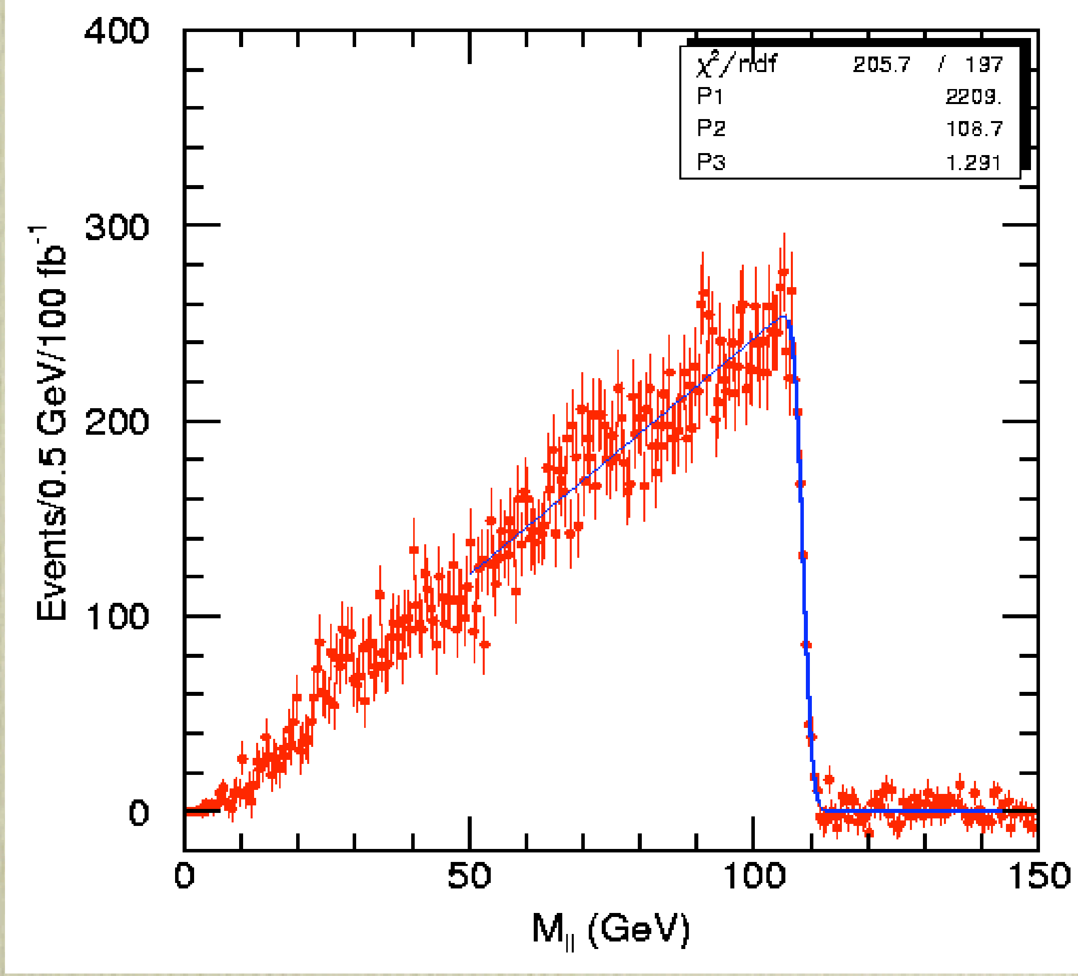
(many more details in R.Cashmore's lecture)







Example of mass reconstruction: $\chi_2^0 \to \tilde{\ell}^{\pm}\ell^{\mp} \to \chi_1^0 \ell^+ \ell^-$



$$\max\left(m(\ell^+\ell^-)\right) = m(\chi_2)\sqrt{\frac{m^2(\chi_2) - m^2(\tilde{l})}{m^2(\chi_2)}}\sqrt{\frac{m^2(\tilde{\ell}) - m^2(\chi_1)}{m^2(\ell)}}$$

Examples of measurement accuracies for a specific model, in ATLAS:

Measurement	Expected value (GeV)	Error (%) $300\ fb^{-1}$
m_0	100 GeV	± 3
$m_{1/2}$	300 GeV	± 1.3
$\tan\beta$	2.1	± 2
m_h	93	± 0.2
$m_{\ell^+\ell^-}$ end-point	109	± 0.2
$m_{\tilde{\ell}_R}$	157	± 0.3
$m_{\tilde{\ell}_L}$	240	± 1
$m_{\tilde{q}_L}$	690	± 1
$m_{\tilde{q}_R}$	660	± 1.5
$m_{\tilde{g}}$	770	± 1.5
$m_{\tilde{t}_1}$	490	± 10

Summary of LHC physics potential

- Quark substructure:
  - probed in high-transverse momentum, large-angle quark-quark scattering; measure the deviation from point-like rate. Push the "size" of the quark down by more than one order of magnitude w.r.t. today
- New gauge interactions, e.g. right-handed W bosons, extra U(1)'s (as present in string theories), etc.
  - probed in pp -> l+l- or jet-jet, searching for peaks in the invariant-mass spectrum. Can test presence of interactions with EW-like strength up to 5-6 TeV
- Discover the Higgs boson over the domain up to 1 TeV, and determine to 10-20% the value of several of its couplings
- Detect several Higgses, if SUSY, over a good fraction of parameter space

- Measure the anomalous couplings of gauge bosons, and test for possible deviations from EW dynamics at scales up to several TeV.
- Provide first key measurements of SUSY parameters:
  - m(gluino), m(chargino) -> test possible GUT relations, adding to evidence of GUT from gauge coupling unification
- **Assess whether the neutralino accounts for DM**
- Explore in unprecedented detail the physics of b-flavour: rare BR's to $1/10^9$, deviations from unitarity of the CKM mixing matrix. Potential to test the presence of virtual SUSY particles in loop-mediated decays, such as

$$B_s \to \mu^+\mu^-,\ b \to s\gamma$$

- Ready to detect the unexpected!

Conclusions

- Many independent probes of the frontier of physics exist or are being built:
  - Cosmology: WMAP, Planck, SN, Digital Sloan, Dark Matter searches ...
  - Astrophysics: Gravitational wave detectors, VHE cosmic ray arrays, ...
  - Gravity: measurements of deviations from Newton's law
  - Low-enerrgy precision tests: g-2, K physics, B-physics, Atomic Parity Violation, etc
  - and more.....
- Indirect observation of possibly revolutionary indications of new physics, however, are no substitute for the direct observation of the particles responsible for this new physics:
  - which particle is associated to DM?
  - what is the field-theory origin of the inflaton? of the quintessence?
  - what is giving g-2 different than expected?
- The next generation of accelerators will be extremely expensive (time and $$), and input from the LHC results will be crucial to define the future directions of the field.
- We unfortunately still don't know of alternatives to the quest for the most basic laws of Nature other than HEP collisions.
- LHC is a crucial step forward in this quest.