Theoretical physics for the LHC, Lecture IV

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Higgs production at the LHC

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

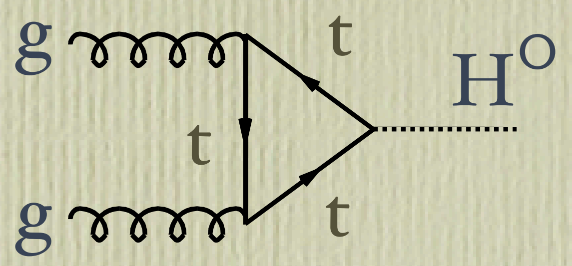
- the value of the production rate
- the value of the decay BR to usable channels
- the size of the backgrounds

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:



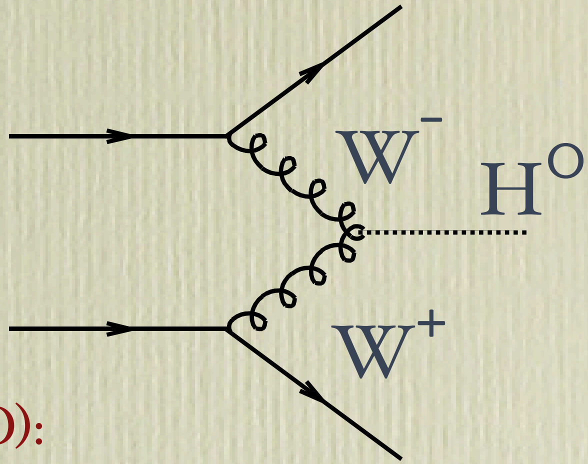
Gluon-gluon fusion (NNLO):

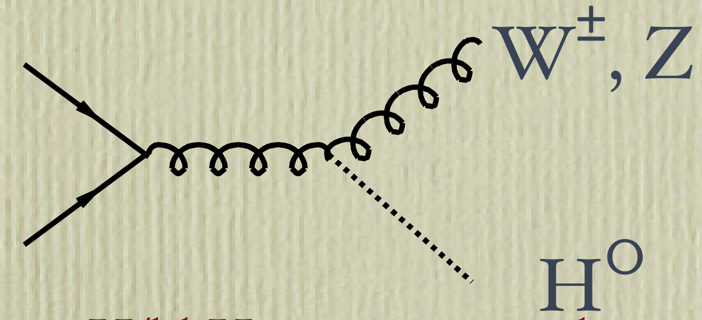
- Largest rate for all m(H).
- Proportional to the top Yukawa coupling, y_t

- 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





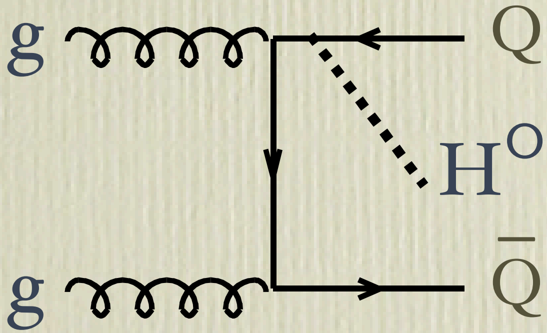
W(Z)-strahlung (NNLO):

- Same couplings as in VB fusion
- Different partonic luminosity (uniquely qqbar initial state)

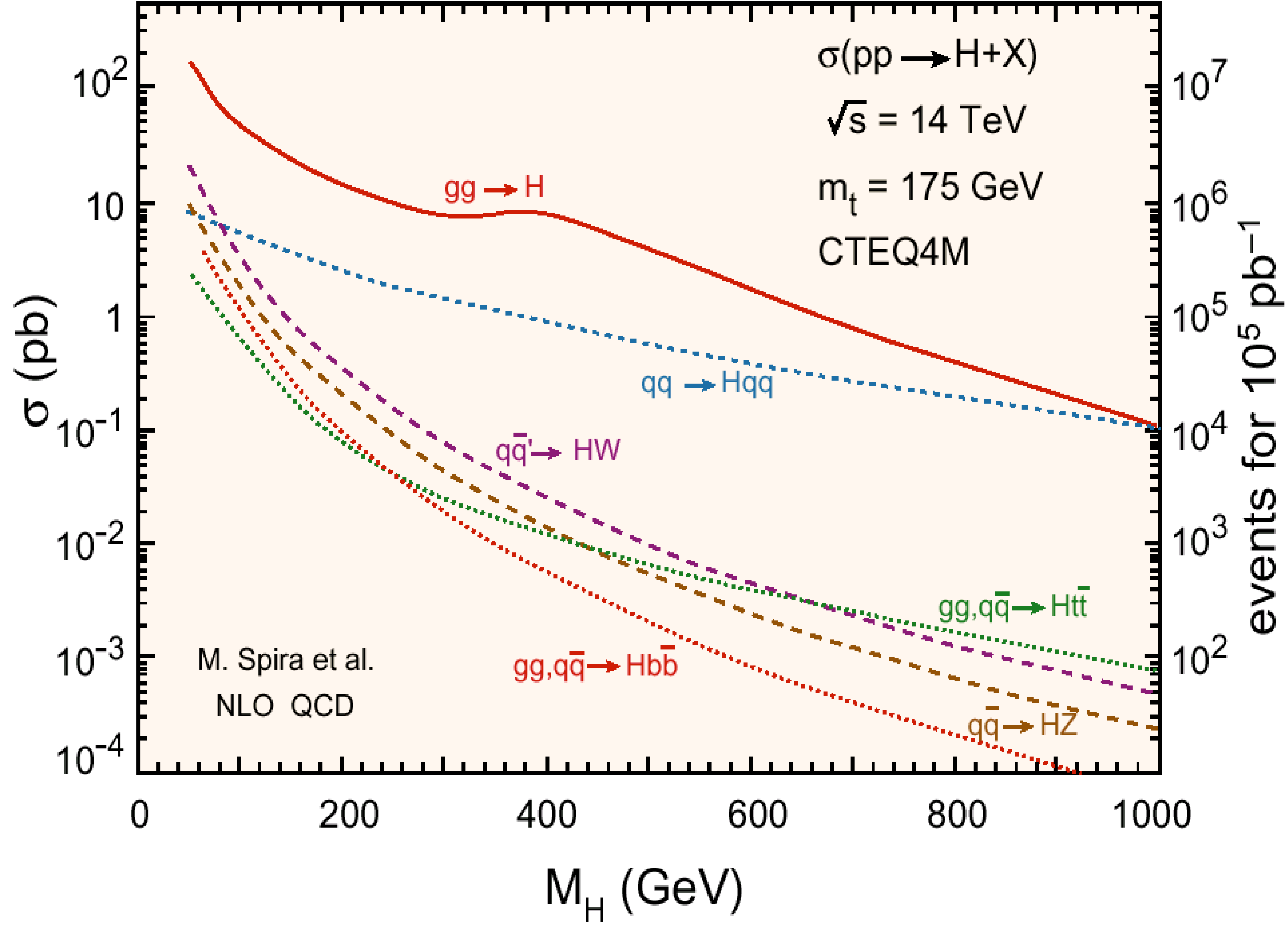
ttH/bbH associate production (NLO):

- 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, $\tan\beta^2$

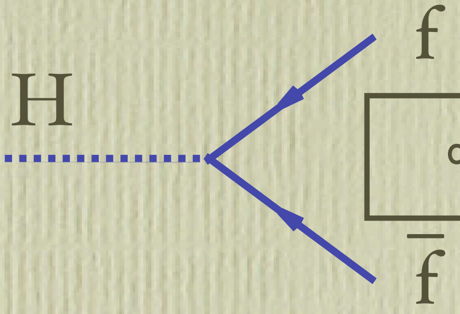
- Same partonic luminosity as in gg-fusion, except for different x-range



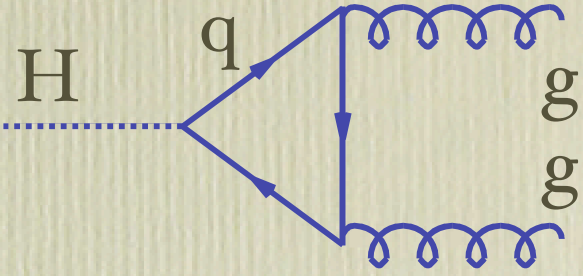
Higgs production rates at the LHC



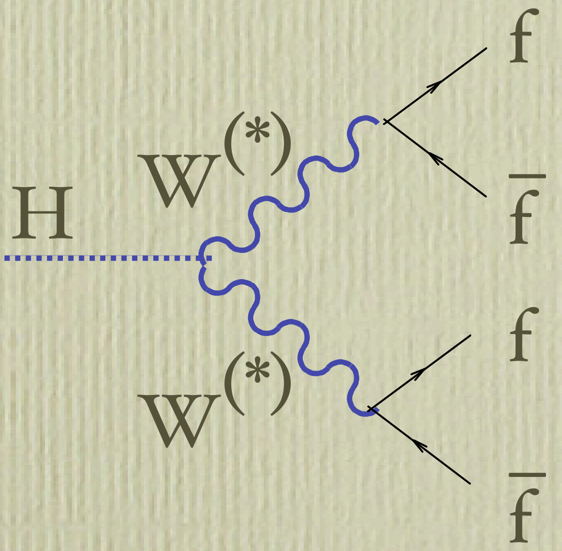
Higgs decays



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

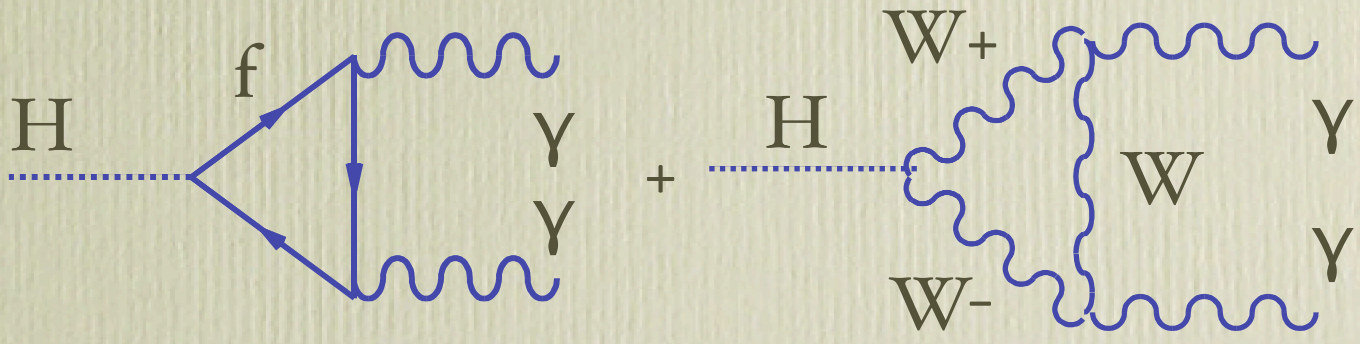


$\propto m_f^2$ (dominated by top-quark loops)

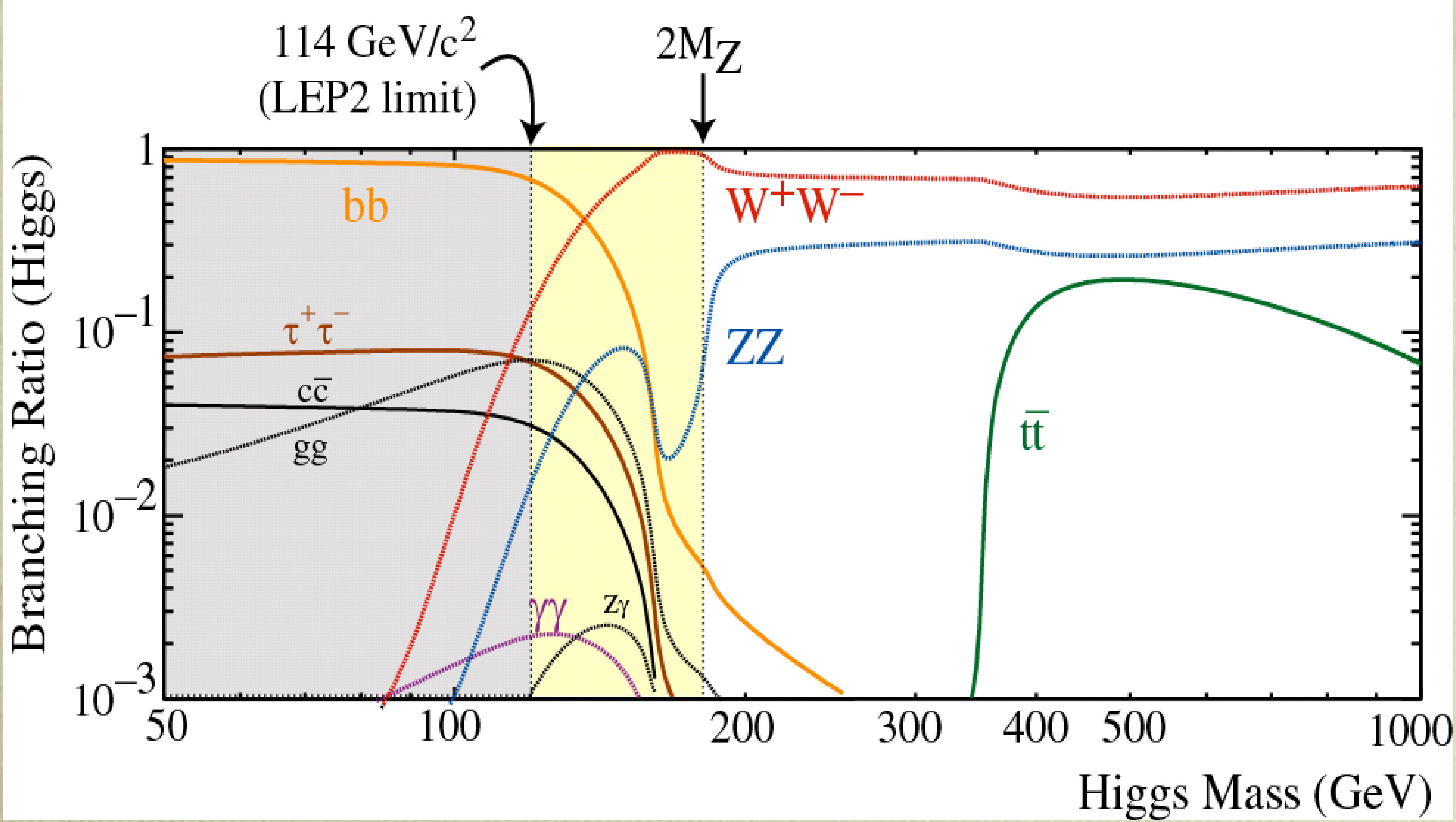


$\propto \alpha_W$ (sharp thereshold at $m_H=2m_W$, but large BR even down to 130 GeV). Similar processes with W↔Z.

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

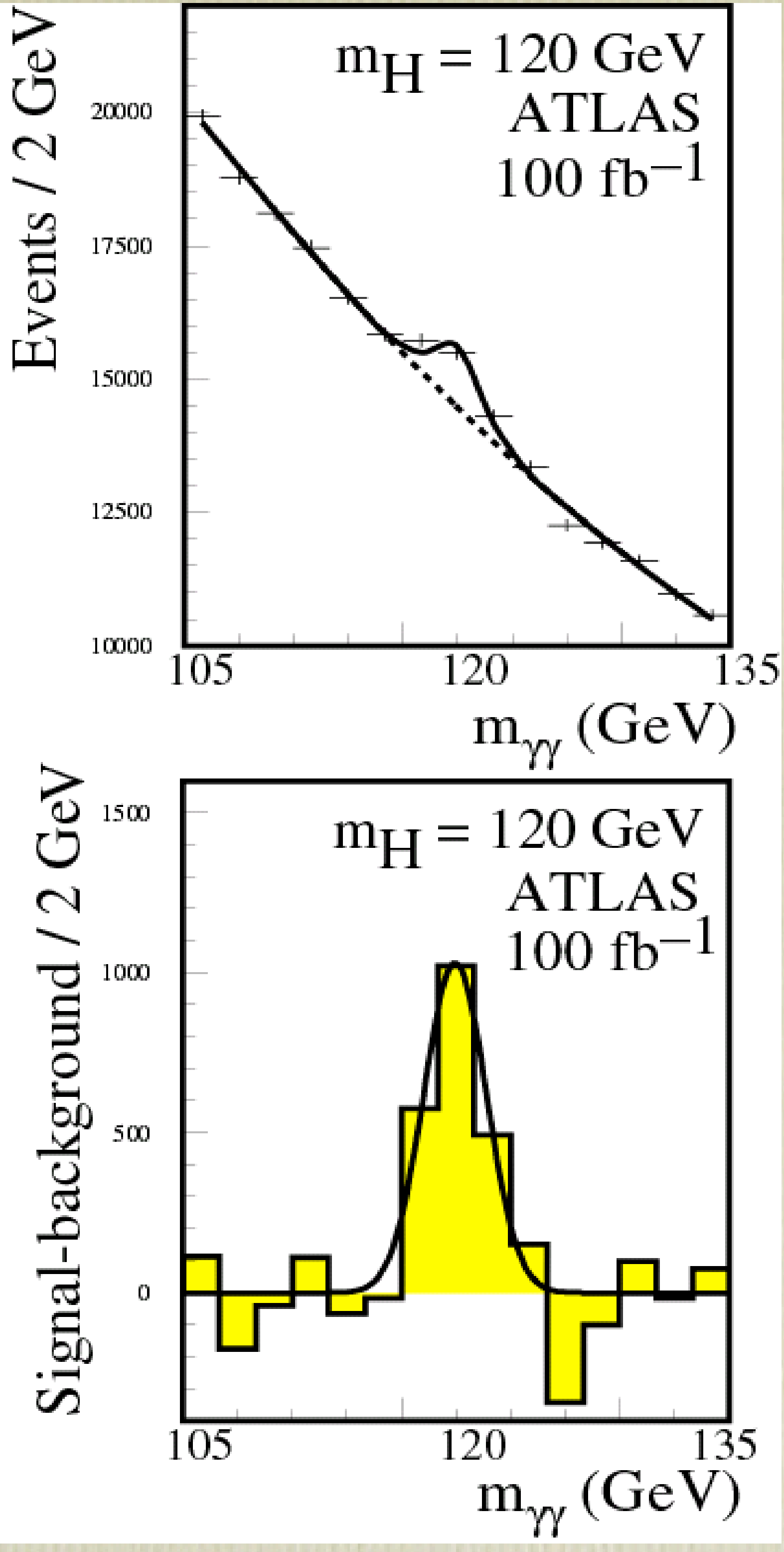
Search channels:

$$gg \rightarrow H \rightarrow \square$$

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 4.3□
for 100 fb^{-1}

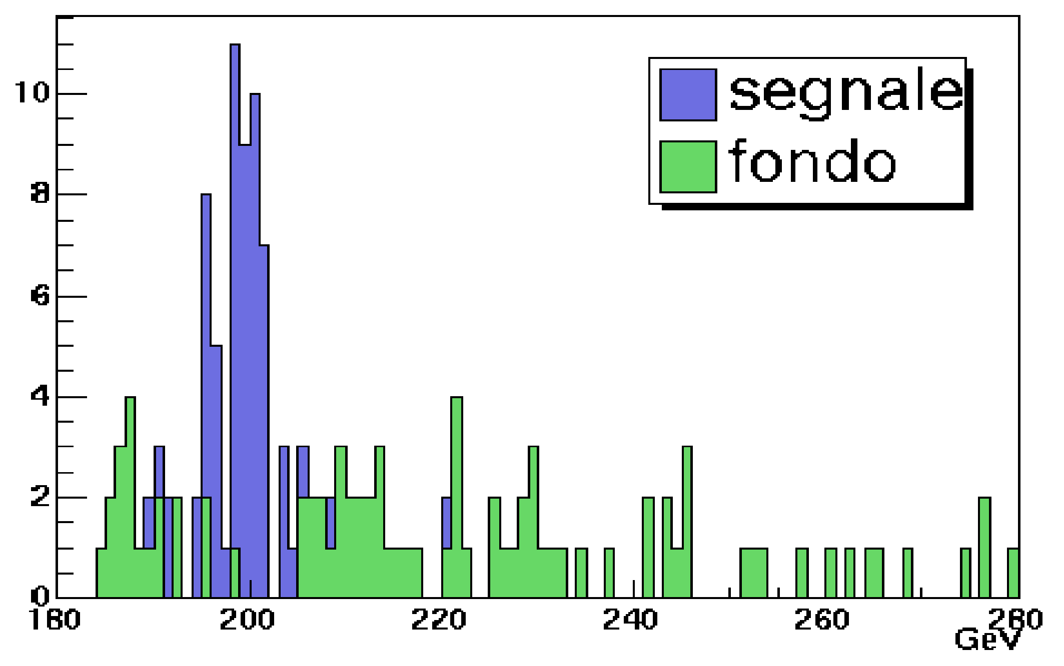


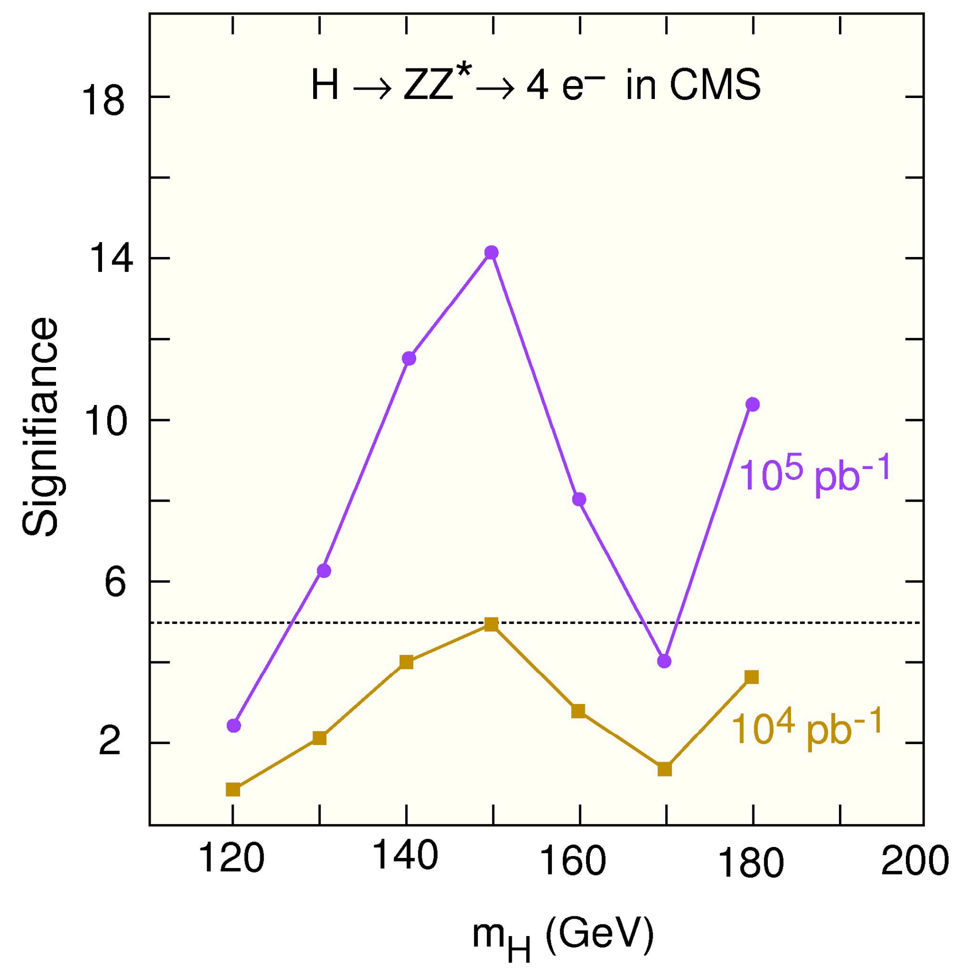
Search channels: $H \rightarrow ZZ^{(*)} \rightarrow \ell^+\ell^-\ell'^+\ell'^-$

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: $H \to WW^{(*)} \to \ell\Pi\ell'\Pi'$

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)

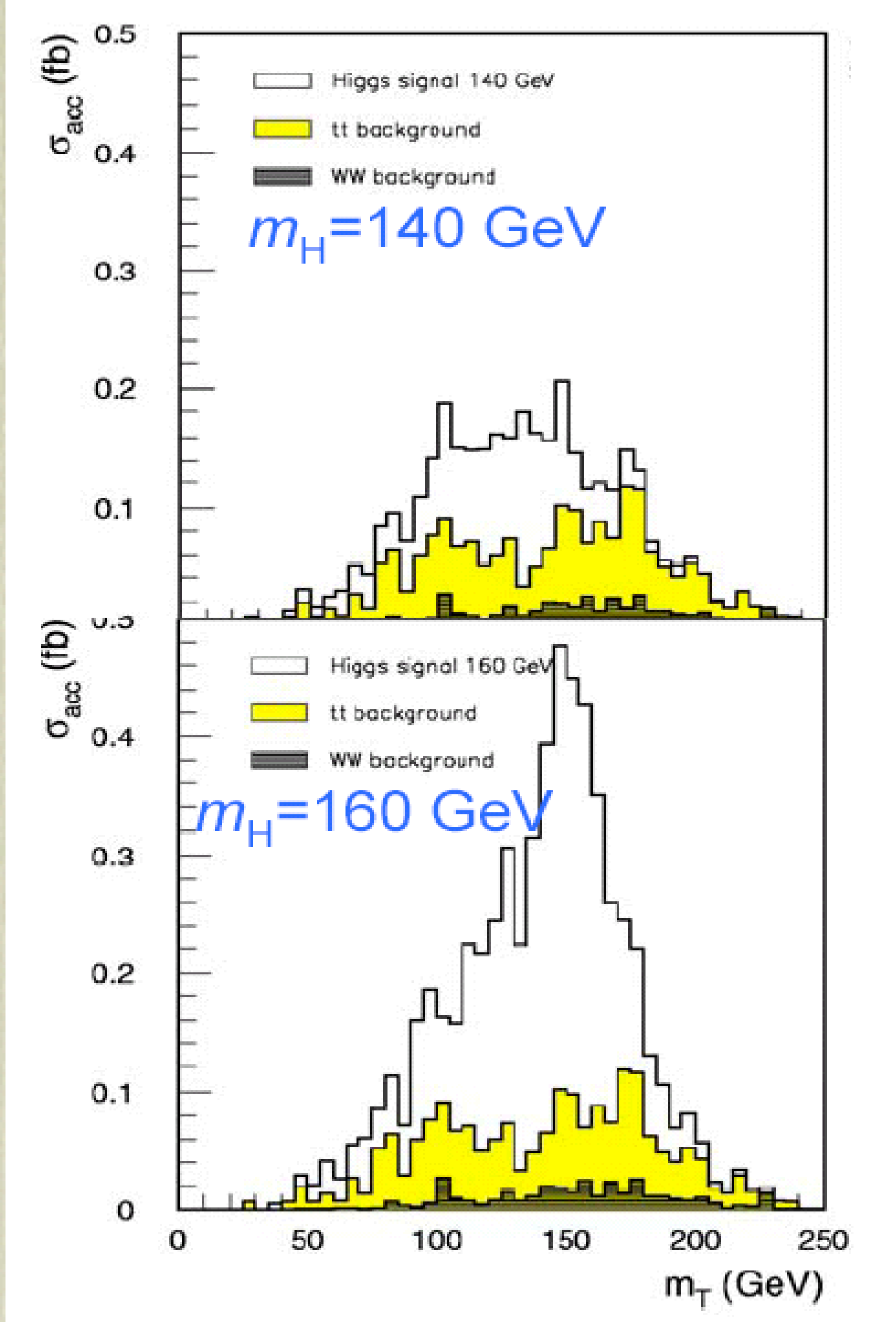
2) momentum correlation among charged leptons

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: $gg \longrightarrow t\bar{t}H \longrightarrow t\bar{t}b\bar{b}$

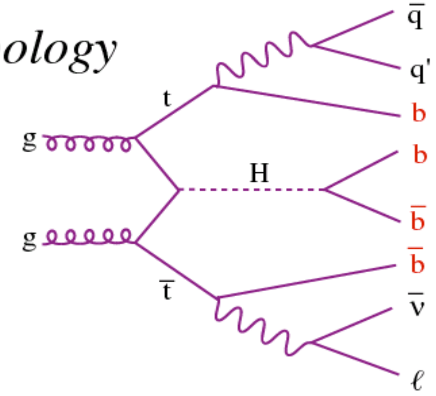
Challenging and complex topology

4 b-jets, 2 jets, 1 lepton

$H \to bb$

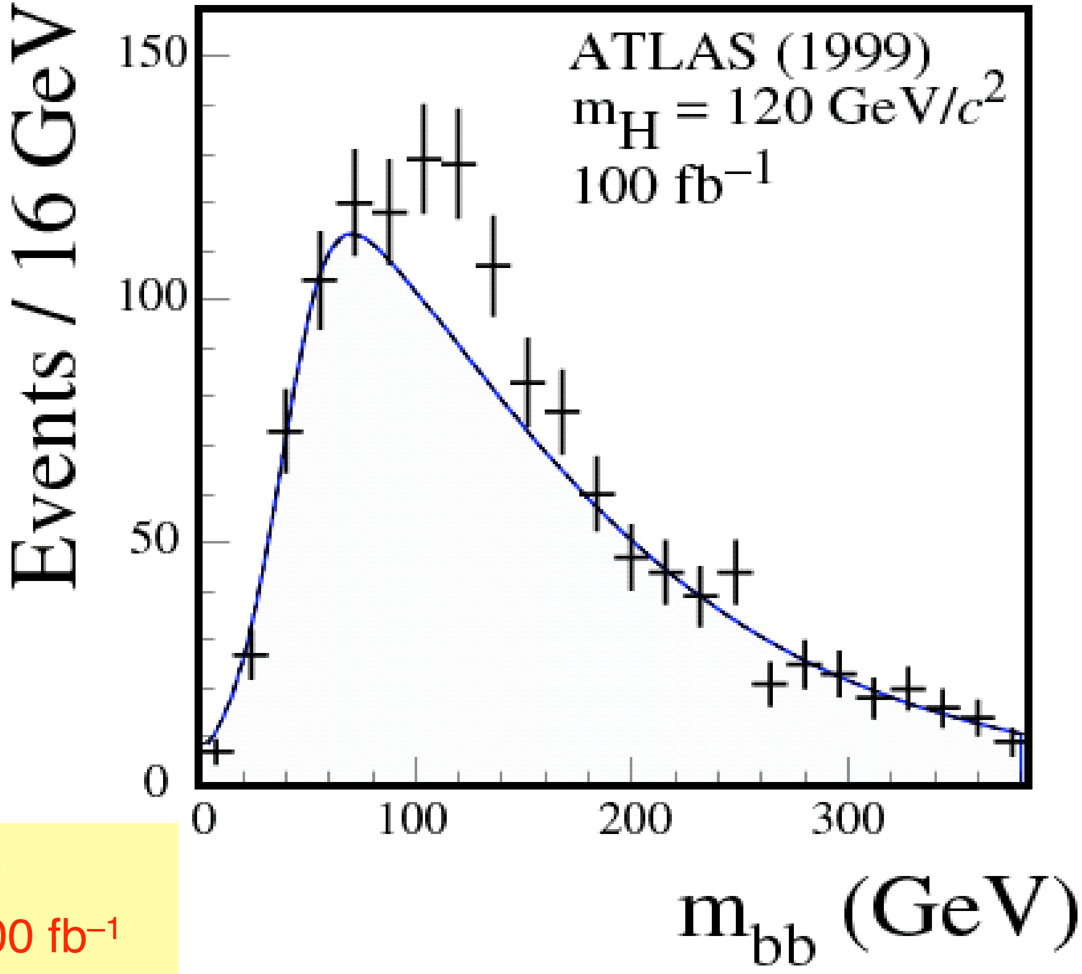
$t \to bqq'$

$t \to b\ell\nu$



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 (5□) :

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

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

	H→γγ	ttH→ttbb	qqH→qqττ
S	130	15	10
B	4300	45	10
S/√B	2.0	2.2	2.7

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

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

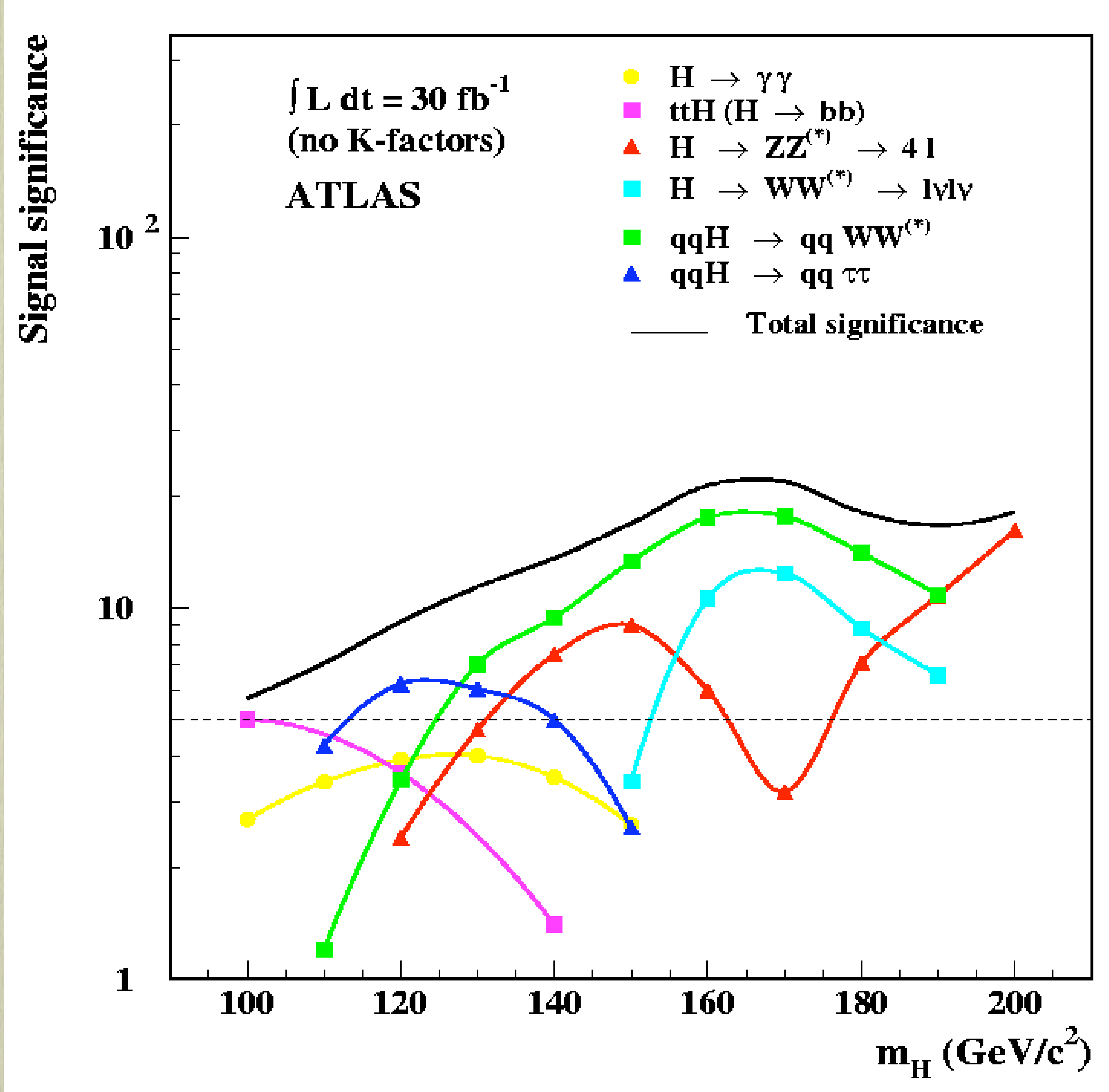
Discovery reach for low-mass Higgs just above the LEP2 limit (130 GeV, 10fb-1)

	H→γγ	qqH→qqWW	qqH→qqττ	H→4l
S	120	18	8	5
B	3400	15	6	<1
S/√B	2.0	3.9	2.7	2.8

Combined significance: **6 σ**

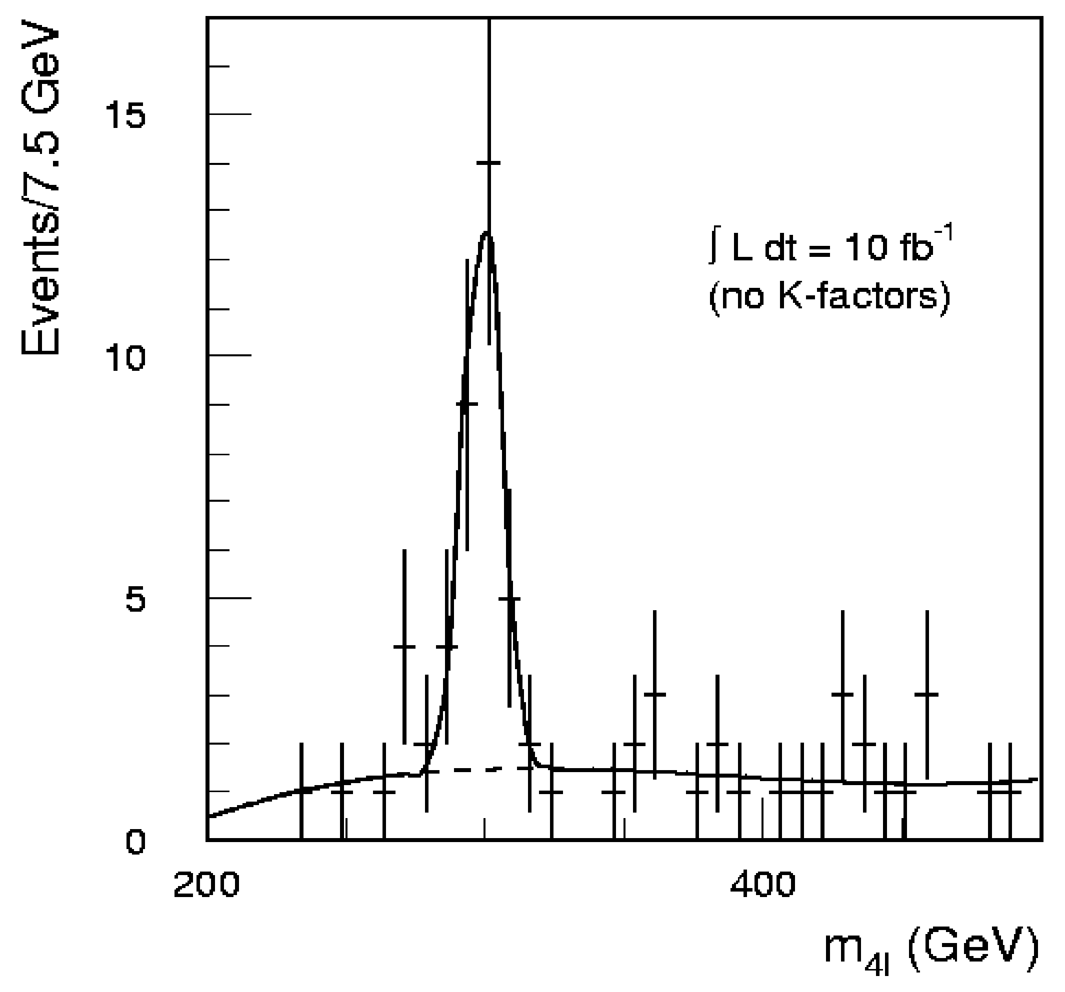
Light Higgs reach at the LHC

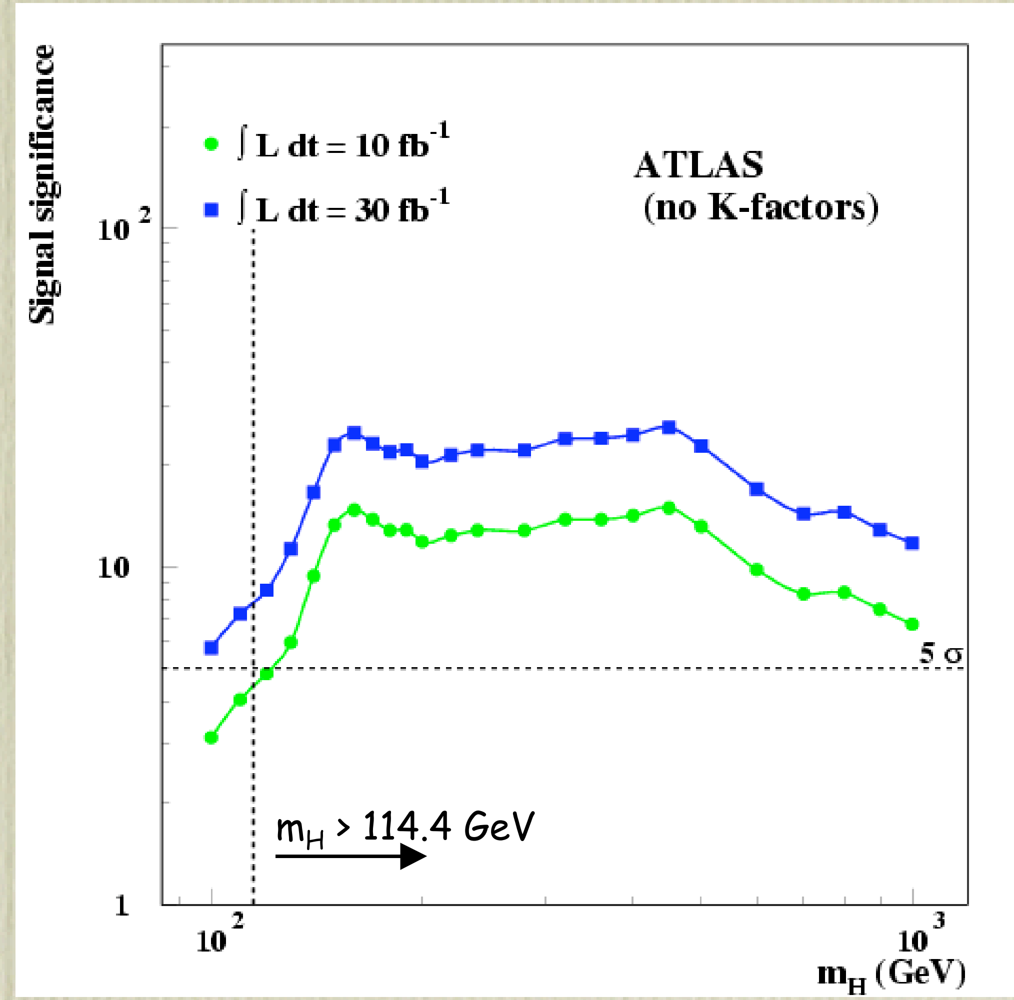
1 year of data taking at nominal luminosity should be sufficient for the two experiments to detect a Higgs through most of the expected mass range

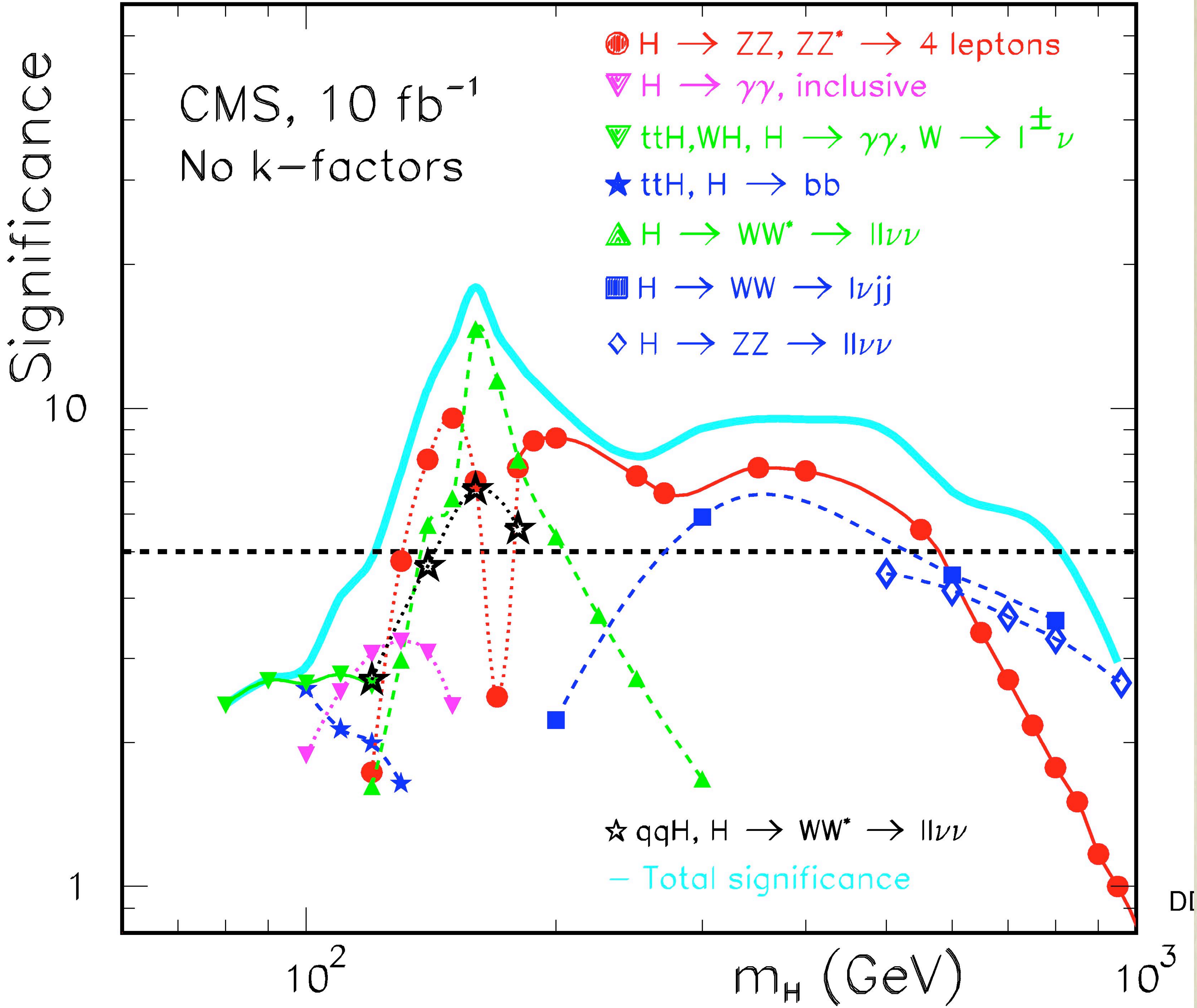


High mass region

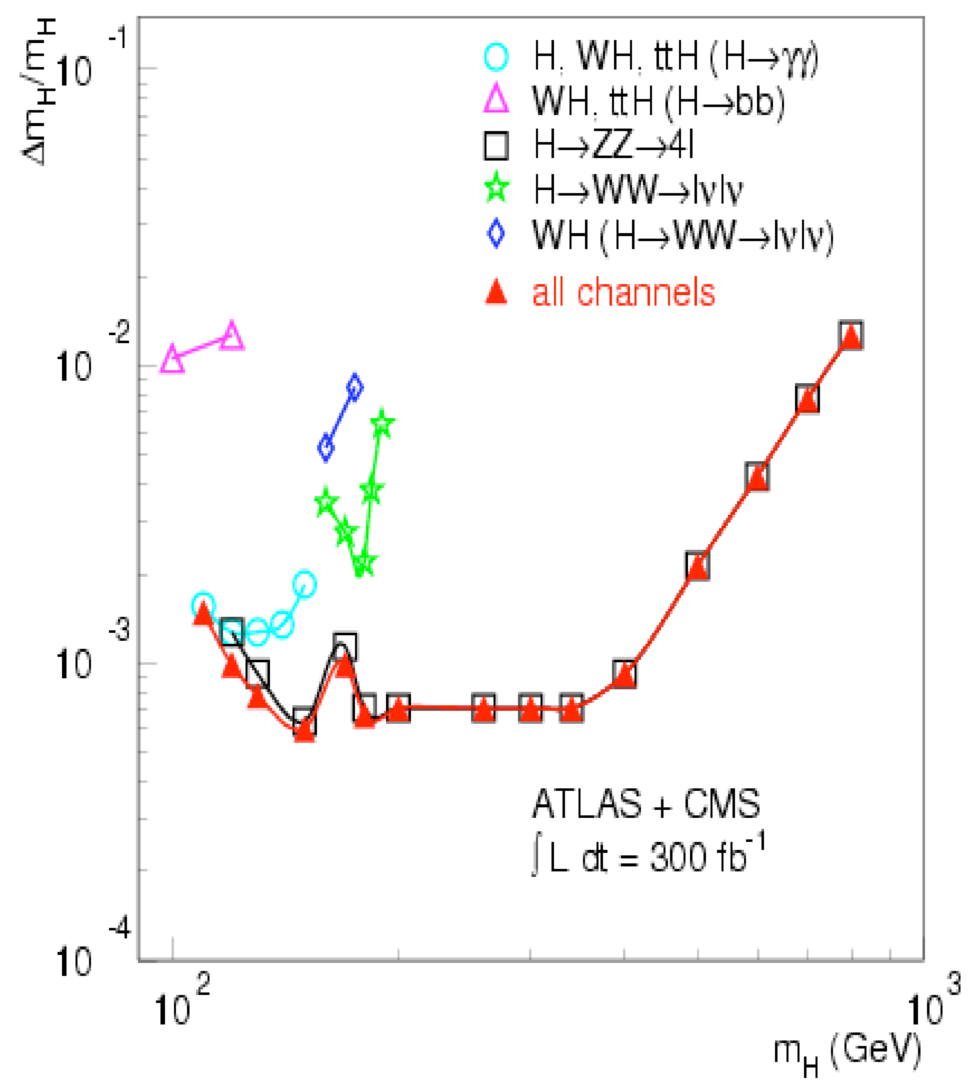
- Easy discovery using H→ZZ→4 leptons for $200<m_H<600$ GeV
- H width larger than detector resolution for $m_H>300$ direct measurement of total width!
- Combine several channels $m_H>600$ GeV:
  - H→ZZ→2lept 2 ν, 2lept q qbar
  - H→WW→lν q qbar

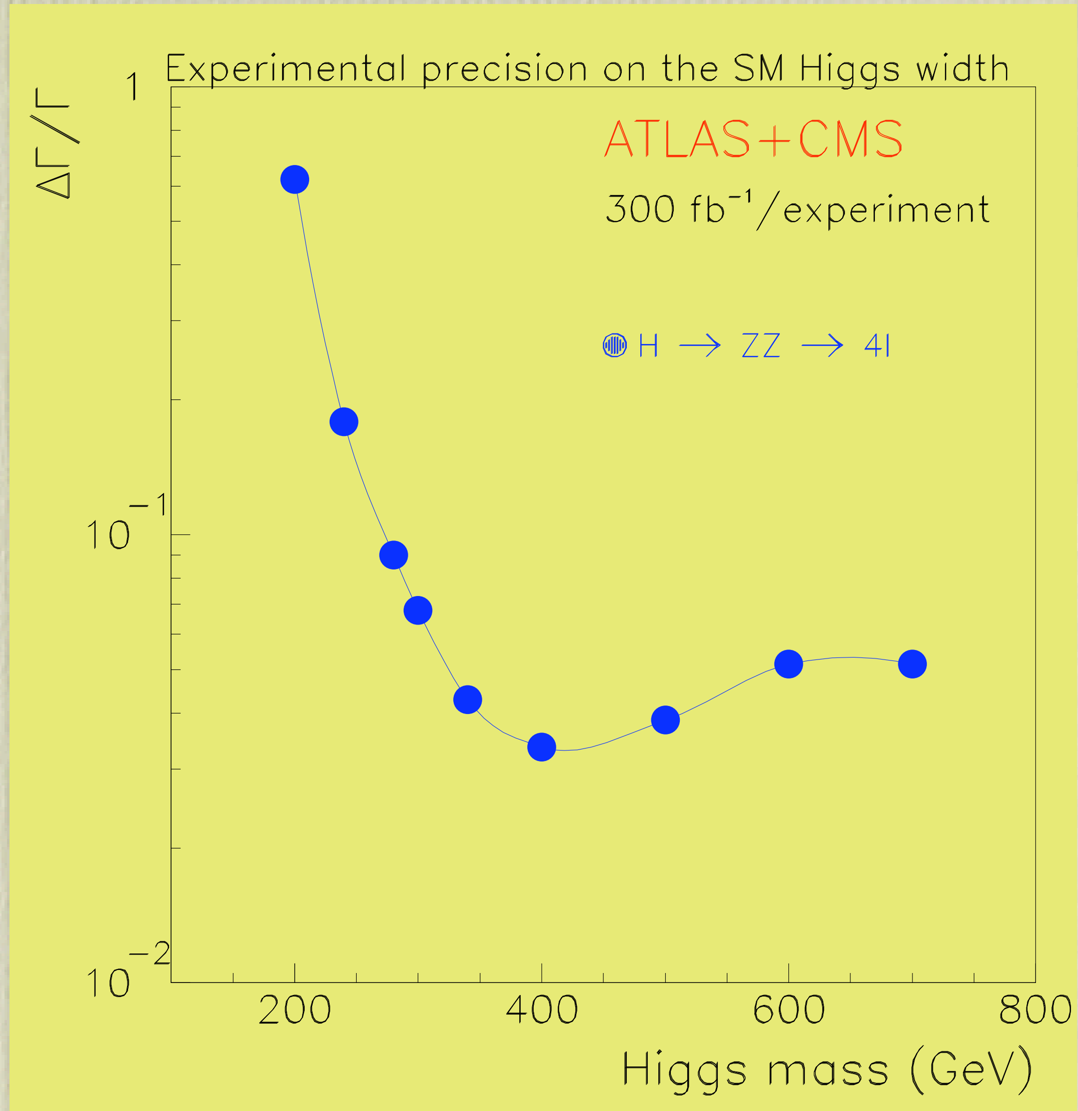





CMS, 10 fb^{-1}
No k−factors
H → ZZ, ZZ* → 4 leptons
H → γγ, inclusive
ttH,WH, H → γγ, W → l$^{\pm}$ν
ttH, H → bb
H → WW* → llνν
H → WW → lνjj
H → ZZ → llνν
qqH, H → WW* → llνν
− Total significance
Significance
10
1
10^2
10^3
m$_H$ (GeV)
DD

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.

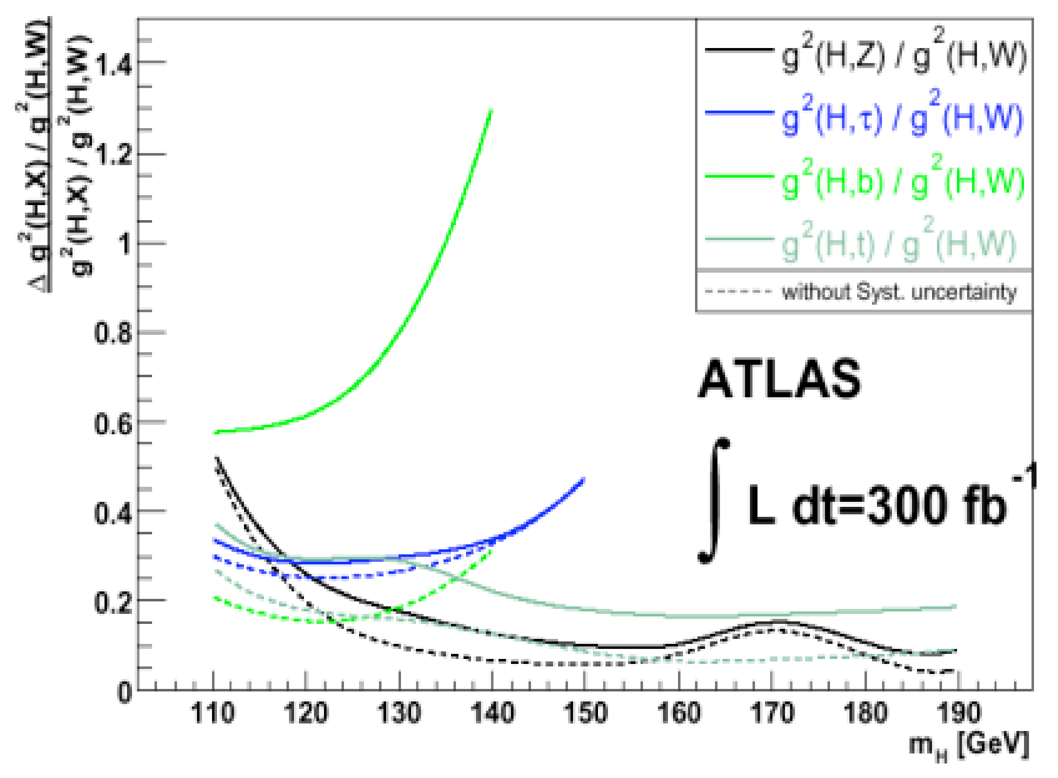
$$y = \frac{\Gamma_b}{\Gamma_\tau} = 3c_{QCD}\frac{g_{Hbb}^2}{g_{H\tau\tau}^2} = 3c_{QCD}\frac{m_b^2(m_H)}{m_\tau^2}$$

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

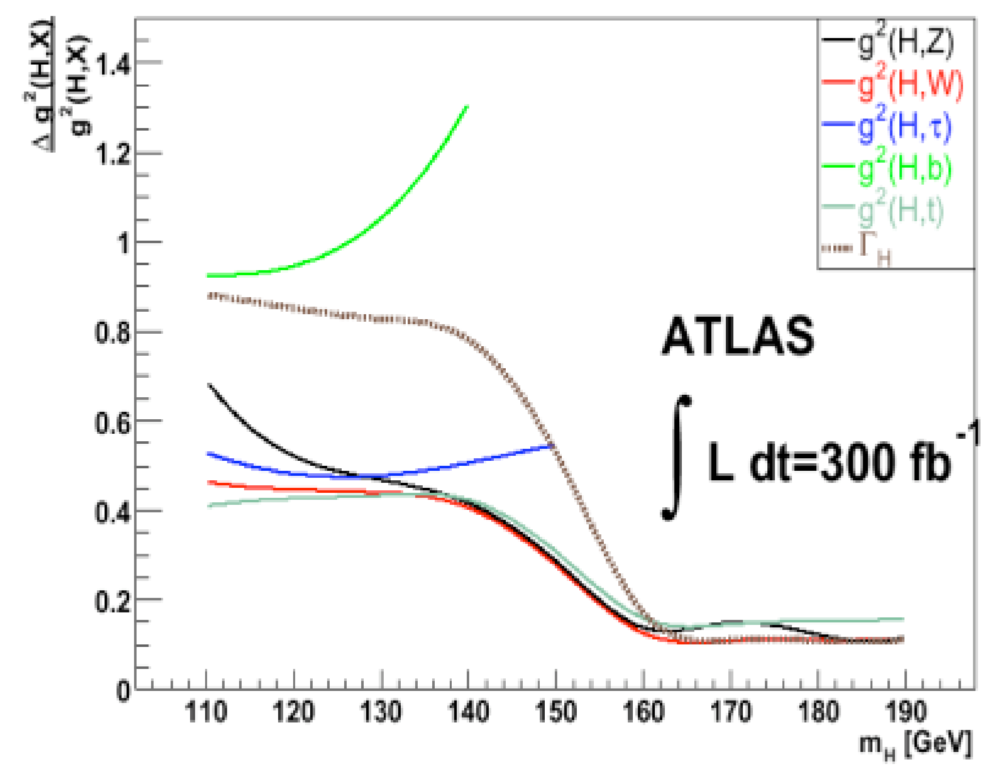
$$\tilde{\Gamma}_W = \left(\Gamma_\tau + \Gamma_b + \Gamma_W + \Gamma_Z + \Gamma_\gamma + \Gamma_g\right)\frac{\Gamma_W}{\Gamma} = (1-\epsilon)\Gamma_W$$

Measurement of Higgs couplings

Coupling ratios



Absolute couplings



Rare Higgs decays

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

m_H(GeV)	S/√B	δσ×BR/σ×BR
120	7.9	0.13
130	7.1	0.14
140	5.1	0.20
150	2.8	0.36

$H\to Z\gamma\to\ {}^{+}\ {}^{-}\gamma$: 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→ , ττ, tt

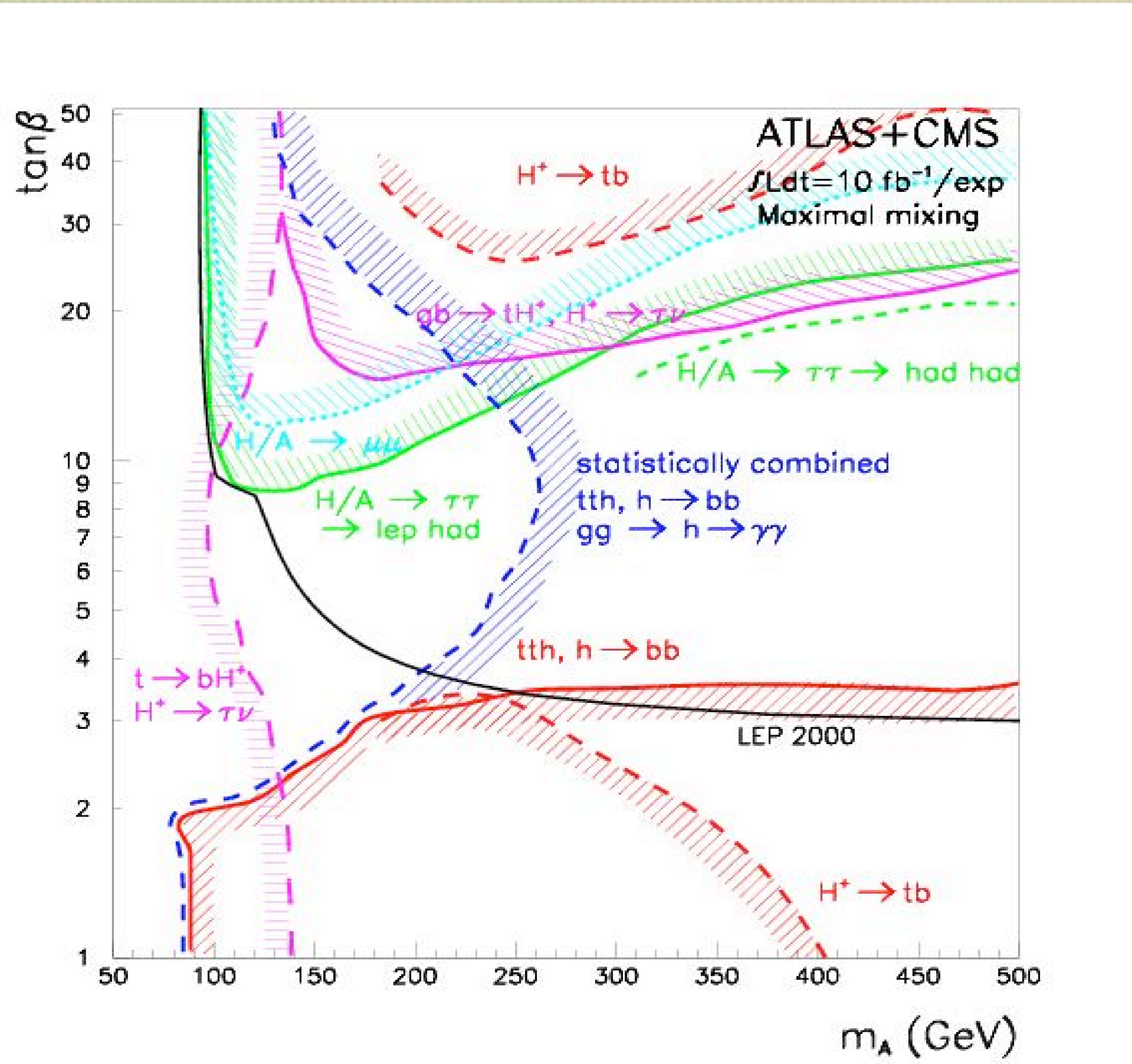
H → hh

A → Zh

$H^\pm$ → τν

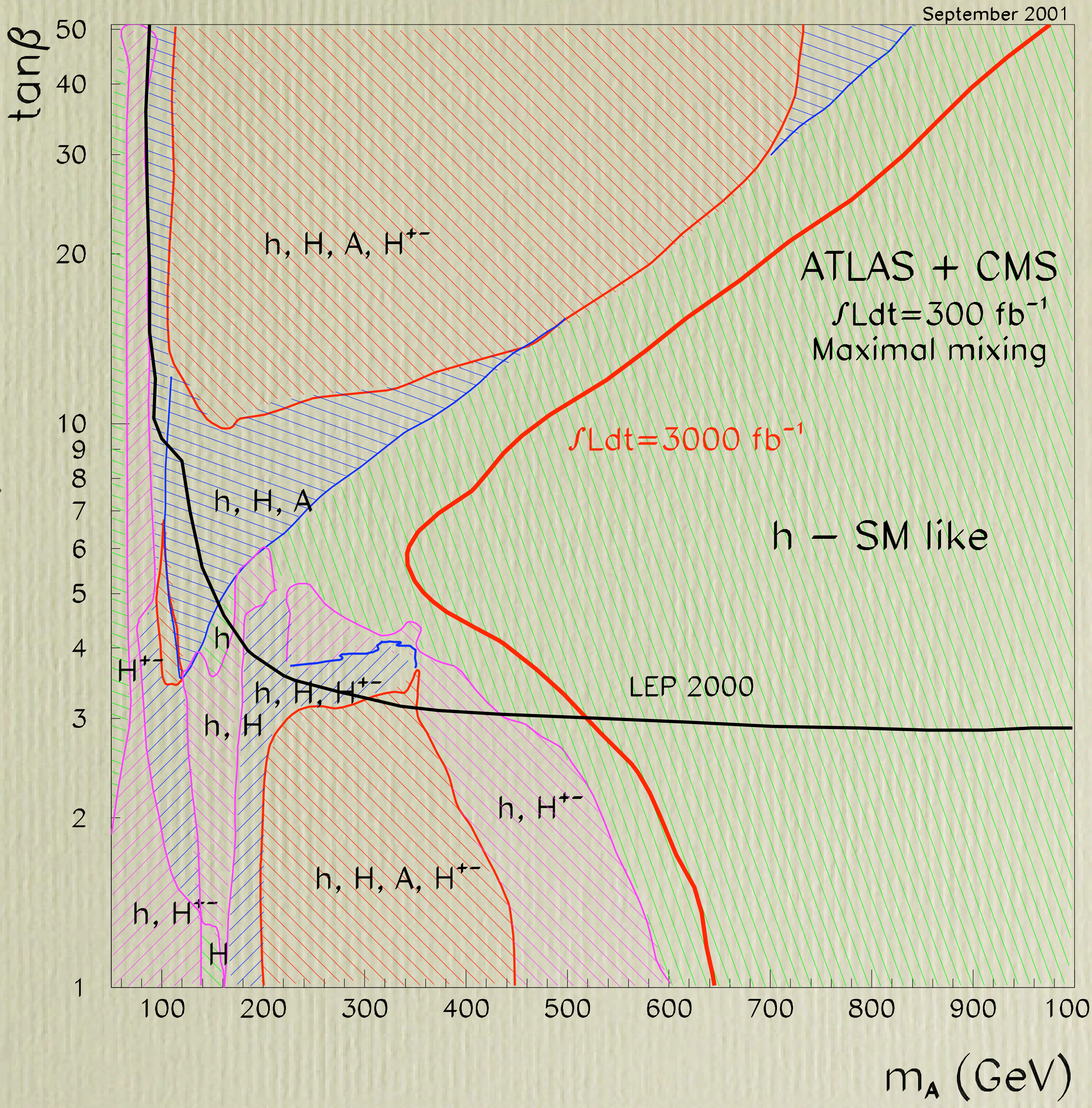
If SUSY particles light enough:

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

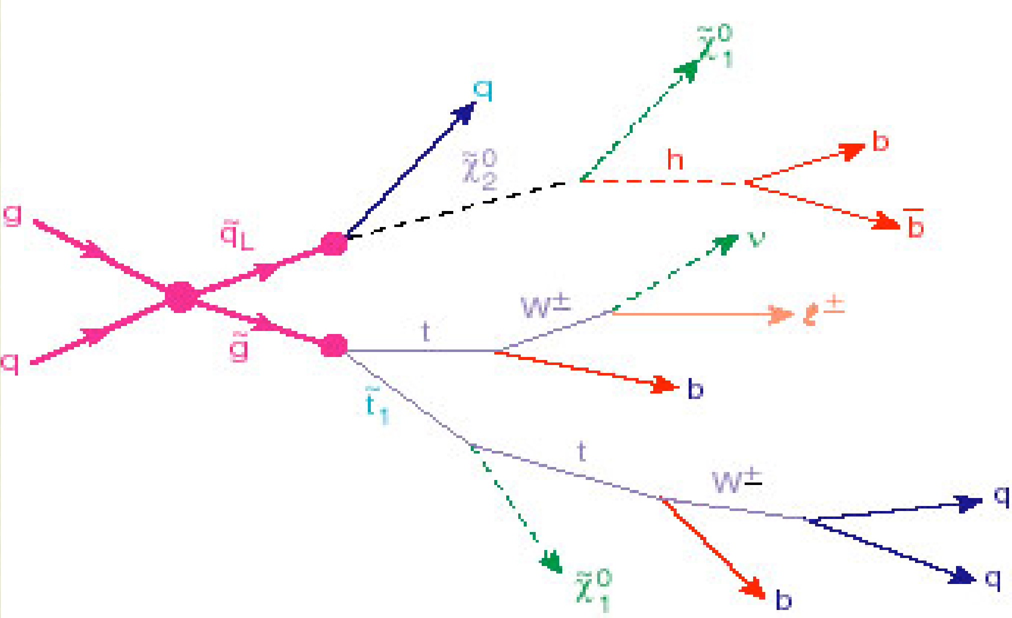


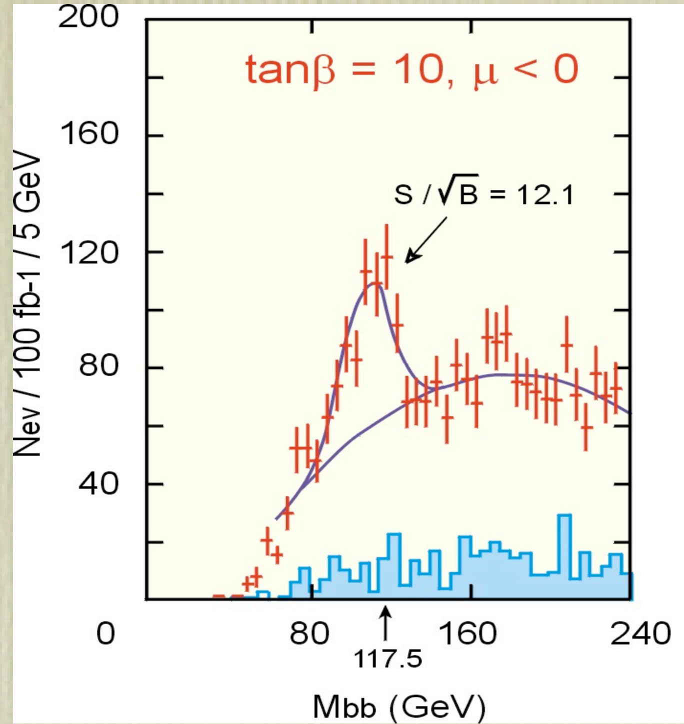
For a large fraction of the parameter space with mA<500GeV, more than one Higgs bosons will be visible with the expected luminosity

Higgs particles which can be observed with $>5\sigma$ 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:

$$\square\square^4 \sim g_W\square^4$$

- 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 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:

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

- 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):

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

$$\mu \not\to e\square \Rightarrow \sin 2\square_{\tilde{e}\tilde{\mu}}\frac{\square m^2_{\tilde{e}\tilde{\mu}}}{m^2_{\tilde{e}}} < 0.01$$

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:

$$m_H = m_0$$

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

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:

$$m(\tilde{g})/m(\tilde{\square}) \sim \square_s/\square_W$$

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

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:

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

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

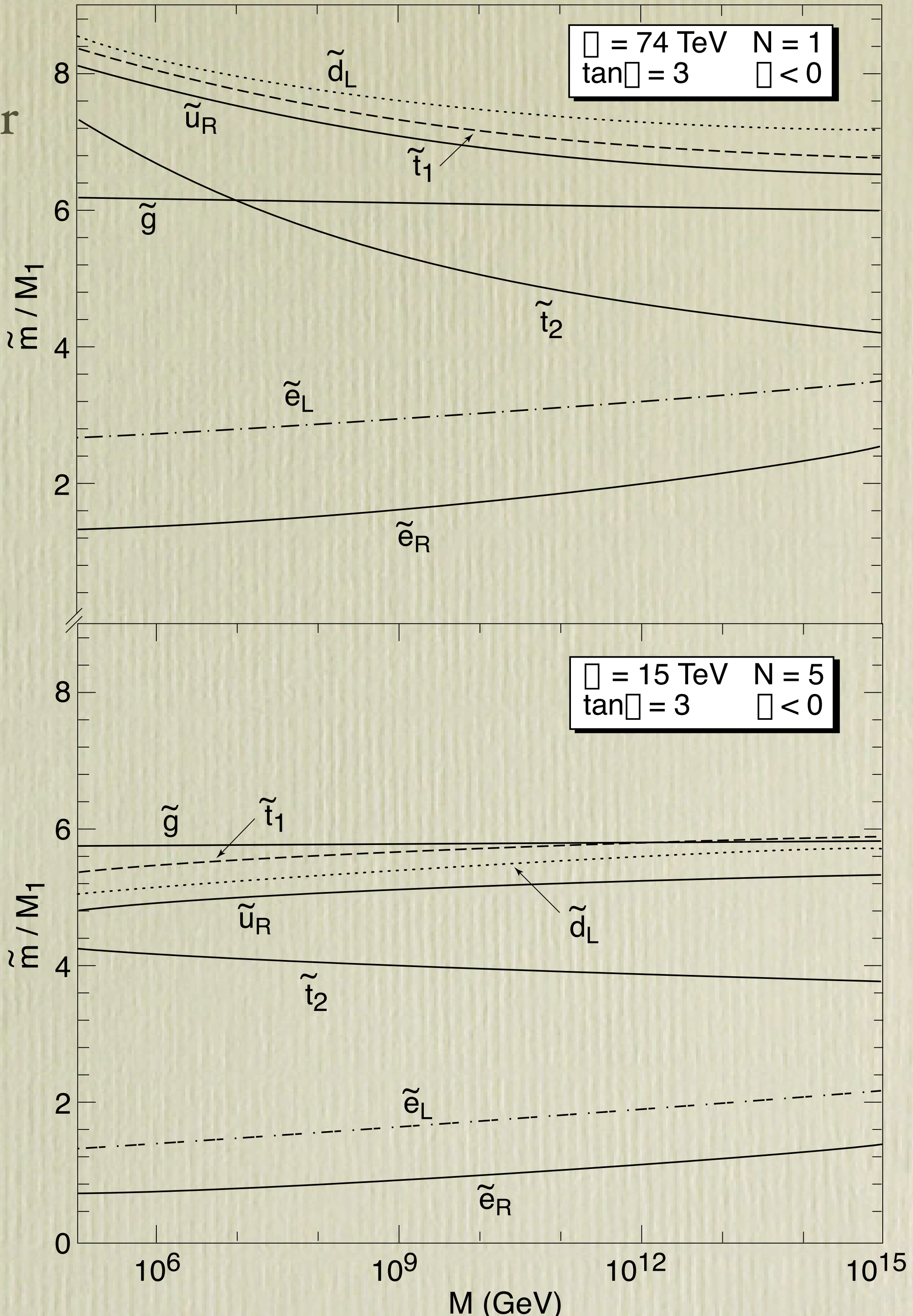
$$m(\tilde{q}) \sim m(\tilde{g})\,, \quad m(\tilde{\ell}) \sim m(\tilde{\chi})$$

$$m(\tilde{\chi}_1^{\pm}) \sim m(\tilde{\chi}_2^{0})$$

- 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

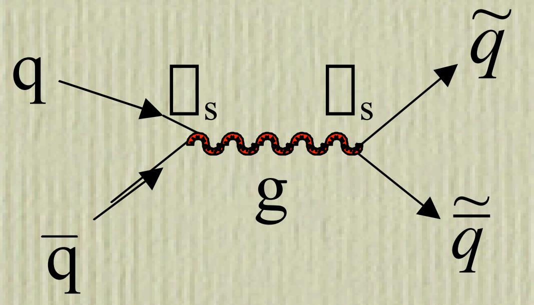


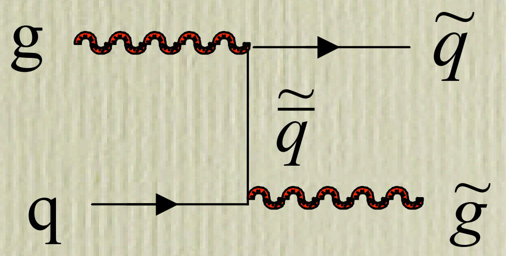
In conclusion:

- The exploration of the SUSY spectrum provides invaluable information on the physics at scales much larger than the LHC's.
- Indications of a mSUGRA-like spectrum would set the scale of SSB at 10^{11} GeV, and would provide indication of no interesting phenomena up to that scale
- 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)
  - 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):

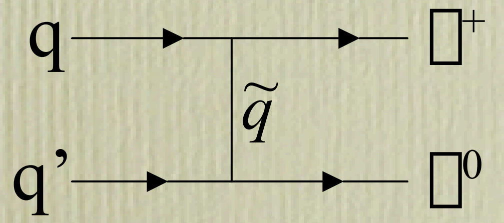




$$m_{\tilde{q},\tilde{g}} \sim 1\ \text{TeV} \Rightarrow \square \sim 1\text{pb}^{-1}$$

$$\Rightarrow 10^4\ \text{events/yr}$$

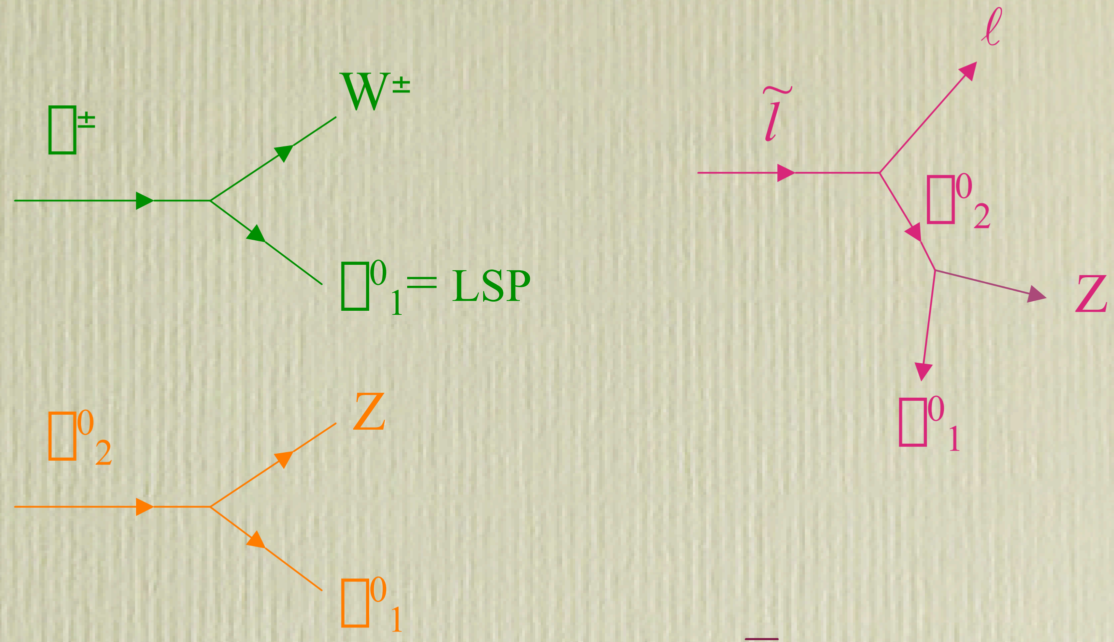
- Weakly interacting (photino, W-ino, Z-ino, higgsino => charginos/neutralinos)



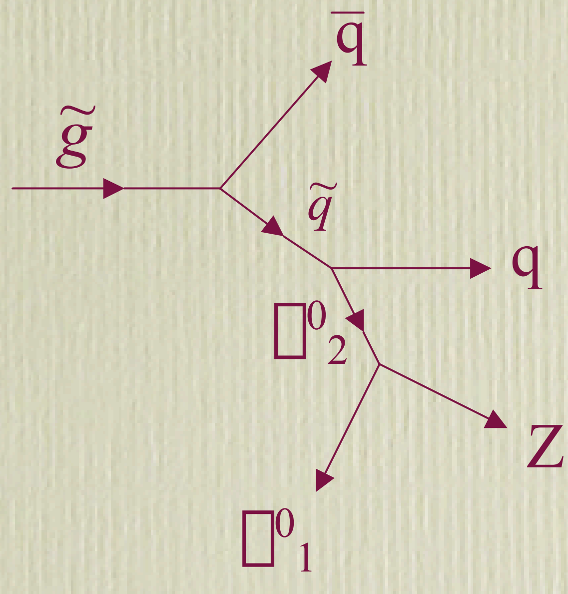
$$m_{\square} \sim 150\ \text{GeV} \Rightarrow \square \sim 1\text{pb}^{-1}$$

Decays of SUSY particles

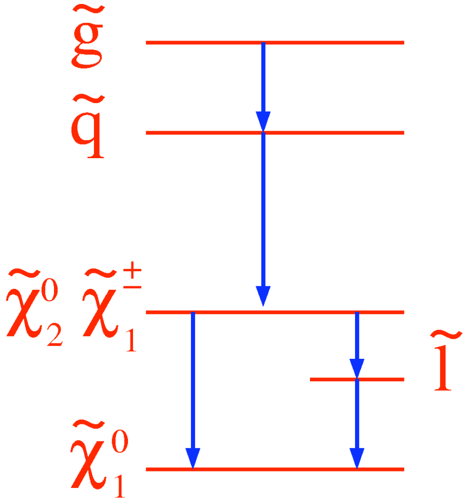
- weakly interacting:



- 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

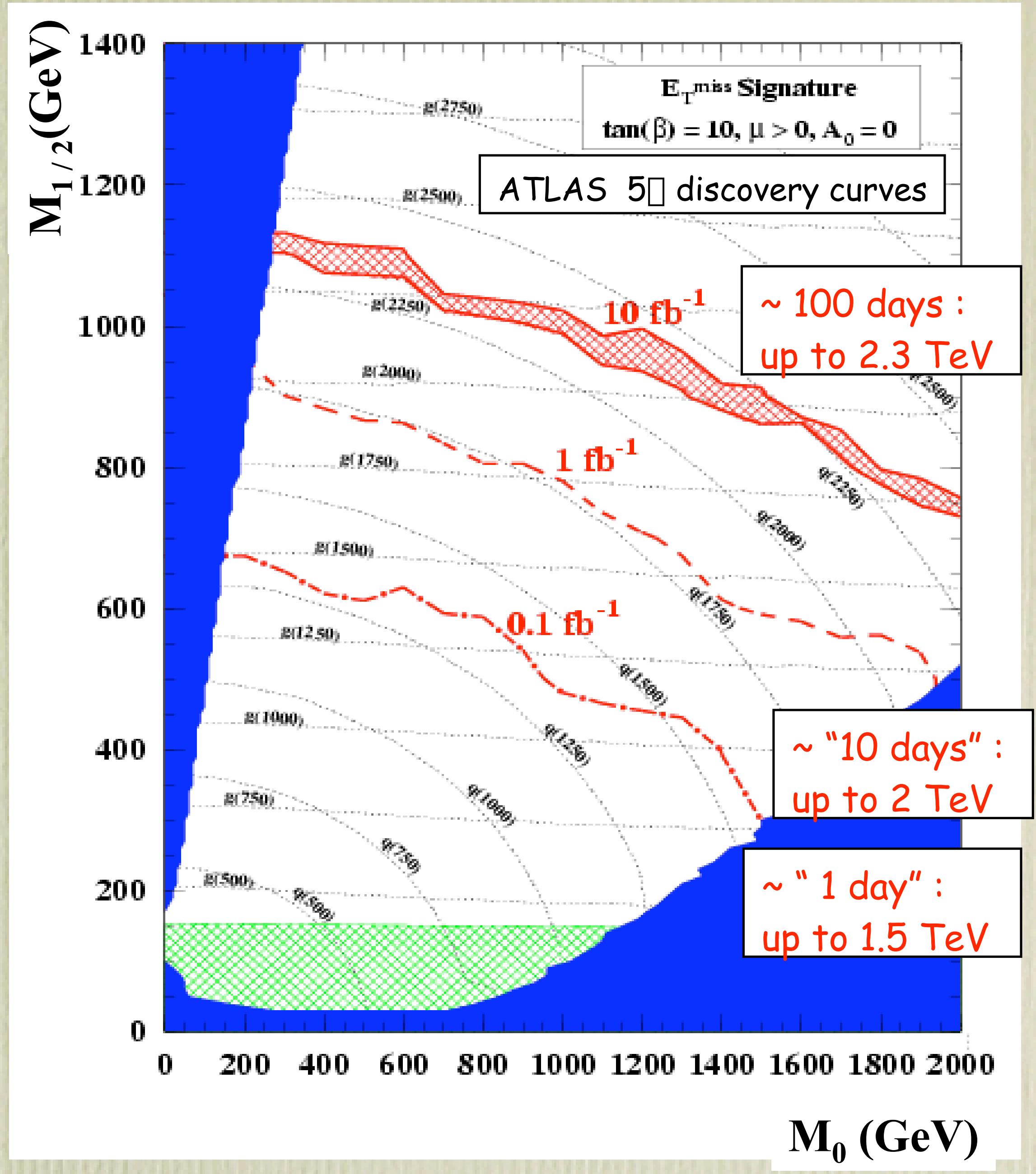


(high p_T) jets

high p_T jets

jets and/or leptons

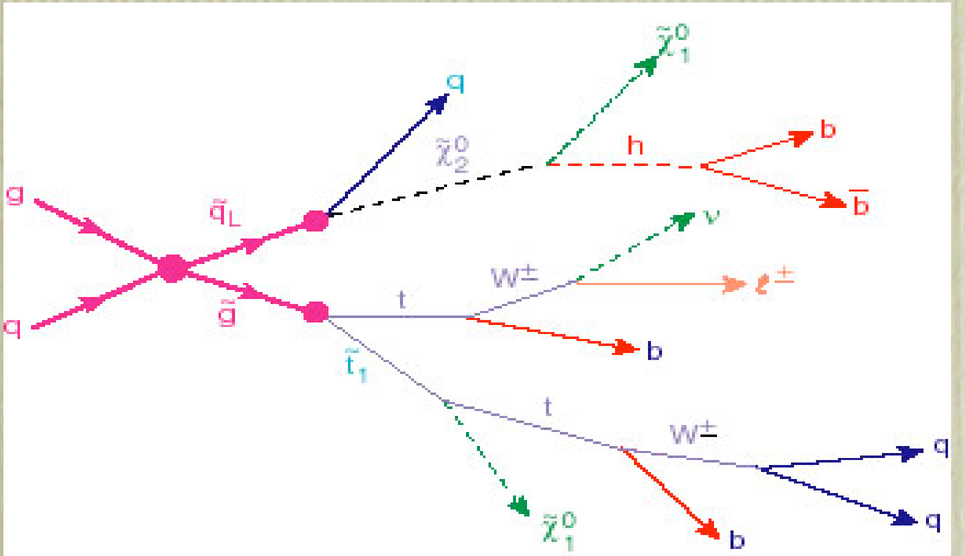
missing E_T



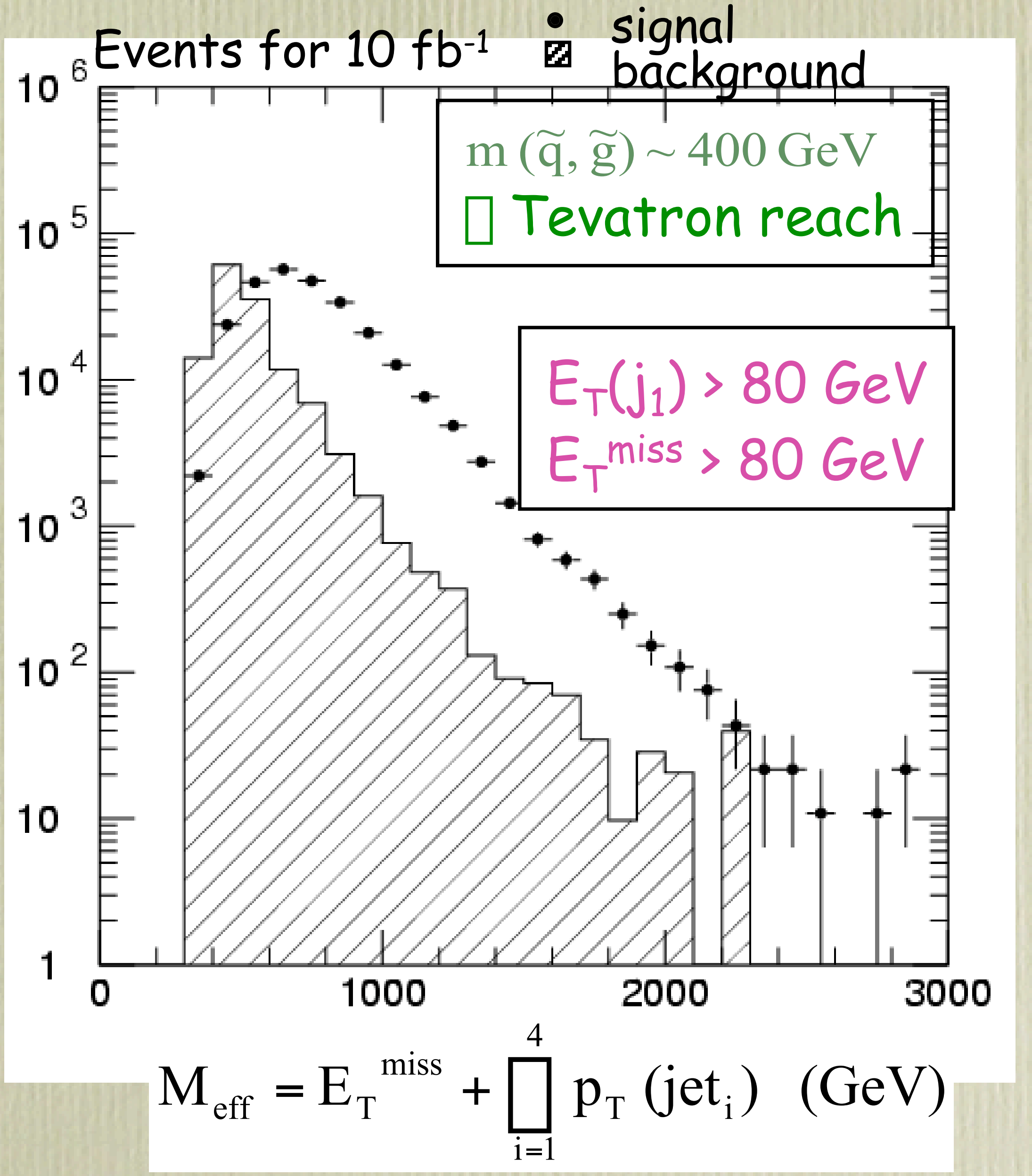
~ 100 days :
up to 2.3 TeV

~ “10 days” :
up to 2 TeV

~ “ 1 day” :
up to 1.5 TeV

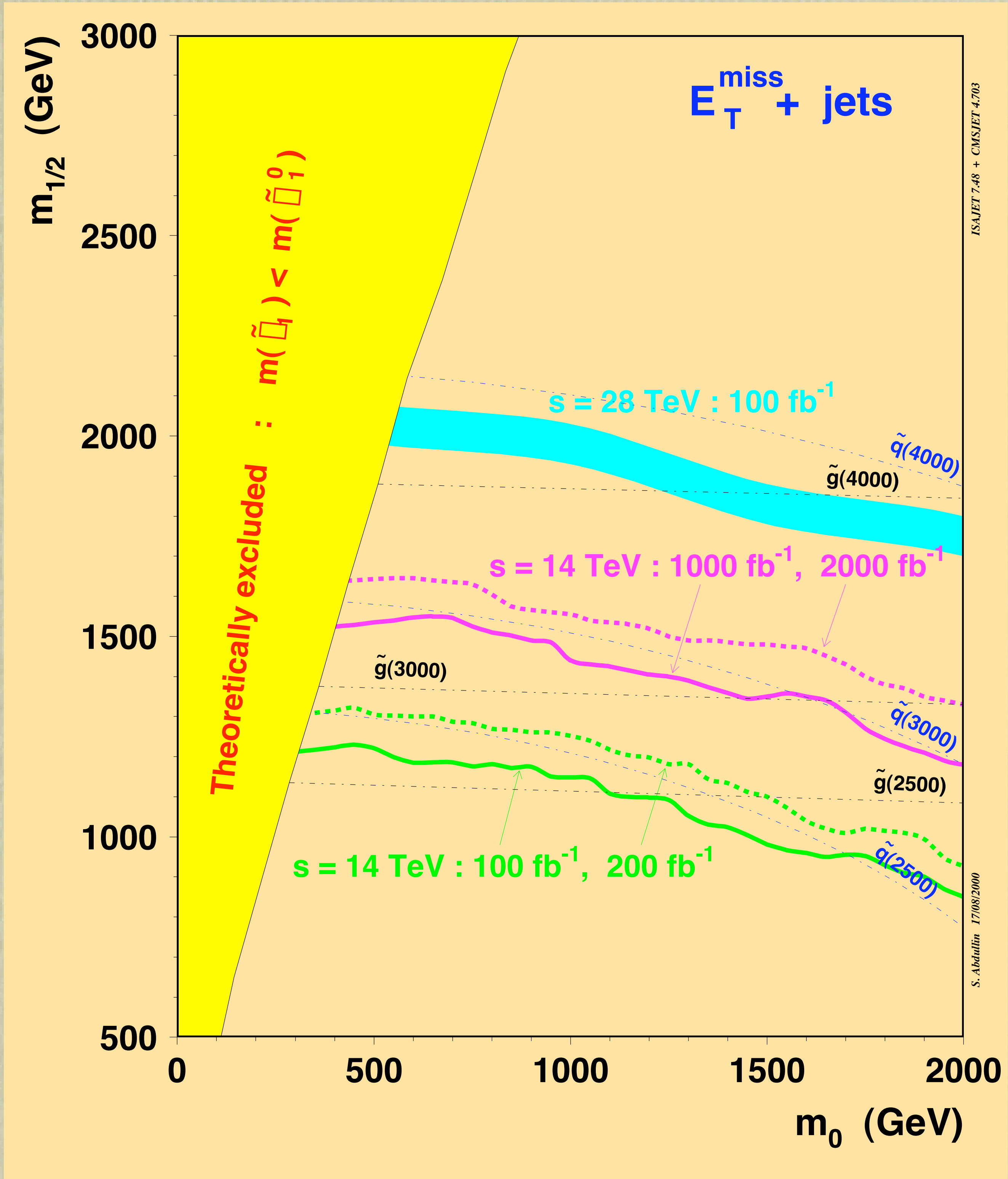


Low-mass matching with Tevatron's discovery reach: trigger thresholds!

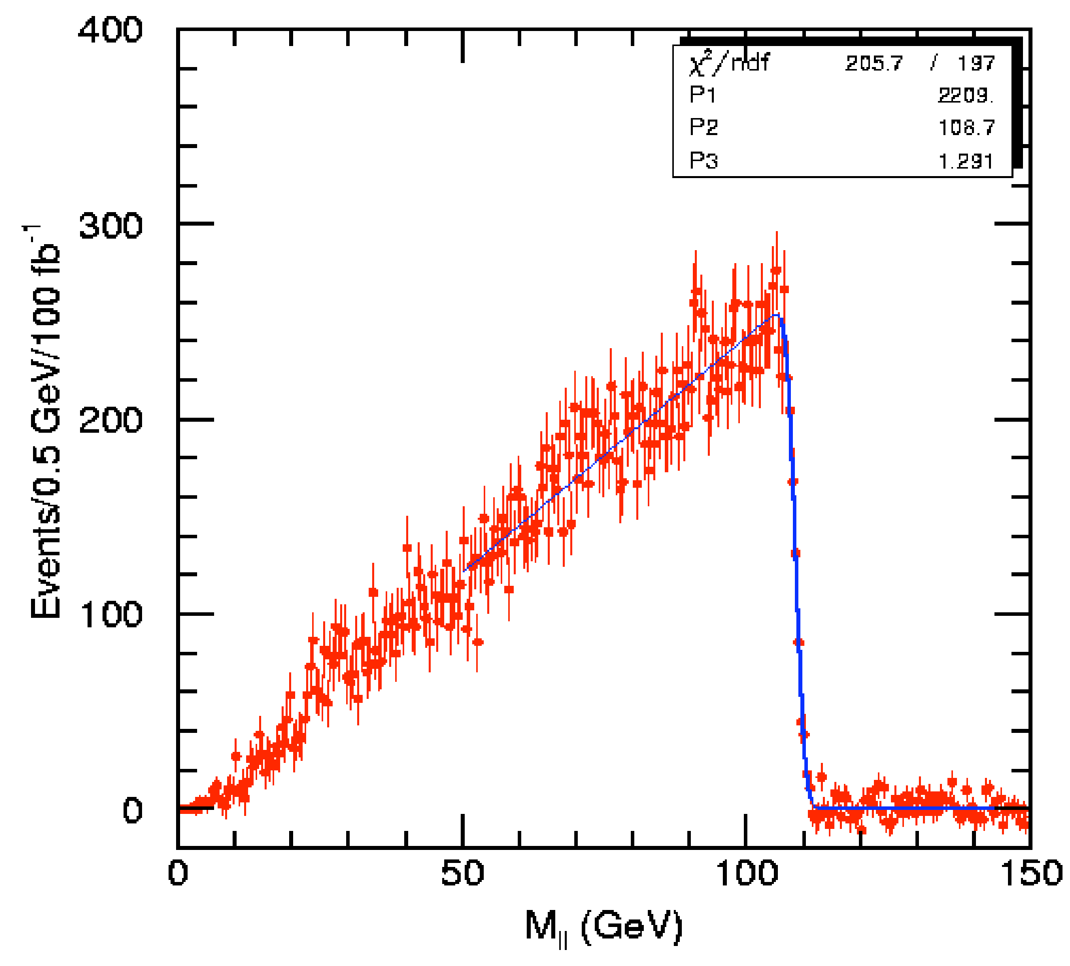


$$M_{eff} = E_T^{miss} + \sum_{i=1}^{4} p_T\,(jet_i) \quad (\mathrm{GeV})$$

Discovery reach for mSUGRA models, with various luminosity and CM energy options



$$\square_2^0 \rightarrow \tilde{\ell}^{\pm}\ell^{\mp} \rightarrow \square_1^0 \ell^+\ell^-$$



$$\max\left(m(\ell^+\ell^-)\right) = m(\square_2)\sqrt{\frac{m^2(\square_2) - m^2(\tilde{l})}{m^2(\square_2)}}\sqrt{\frac{m^2(\tilde{\ell}) - m^2(\square_1)}{m^2(\ell)}}$$

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

Measurement	Expected value	Error (%)
	(GeV)	$300\ \text{fb}^{-1}$
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 tet the presence of virtual SUSY particles in loop-mediated decays, such as $B_s \to \mu^+\mu^-$, $b \to s[$
- 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.