Physics Expectations at the LHC

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III

April 11,2008

IPM String School 2008, Isfahan, Iran

Plan of the Lectures

1. **About the LHC**

   (the six-billion dollar experiment…)

2. **Standard Model of Particle Physics**

   (what we already know…)

3. **Physics beyond the Standard Model**

   (what we would like to know…)

4. **Physics Prospects at the LHC**

   (what we could find in the next few years…)

Part 4

Physics Prospects at the LHC

(what we could find in the next two years…)

Collider Parameters

Scattering experiments:

- fixed target 
- collider 

Colliding beam design maximises available energy for new particle creation

$$s = \left(p_1 + p_2\right)^2 = \left(E_1 + E_2\right)^2 = 4E_b^2$$

LHC has $E_b = 7.0 \ \ \mathrm{TeV} \Rightarrow \sqrt{s} = 14.0 \ \ \mathrm{TeV}$

Luminosity:

$$\mathcal{L} = \frac{n_1 n_2 \nu}{4\pi A}$$

$$\mathcal{R} = \mathcal{L} \times \sigma$$

Luminosity $cm^{-2}\ s^{-1}$

Event rate s^{-1}

$n_{1,2}$ = number density of bunches

ν = number of crossings per second

A = cross-sectional area of bunches

σ = reaction cross section

Integrated Luminosity:

End of collider run

$$L = \int_0^T dt \ \mathcal{L}$$

Start of collider run

Number of events (for a particular process A)

$$N = \int dt \ \mathcal{R} = \int dt \ \mathcal{L} \times \sigma_A = L \times \sigma_A$$

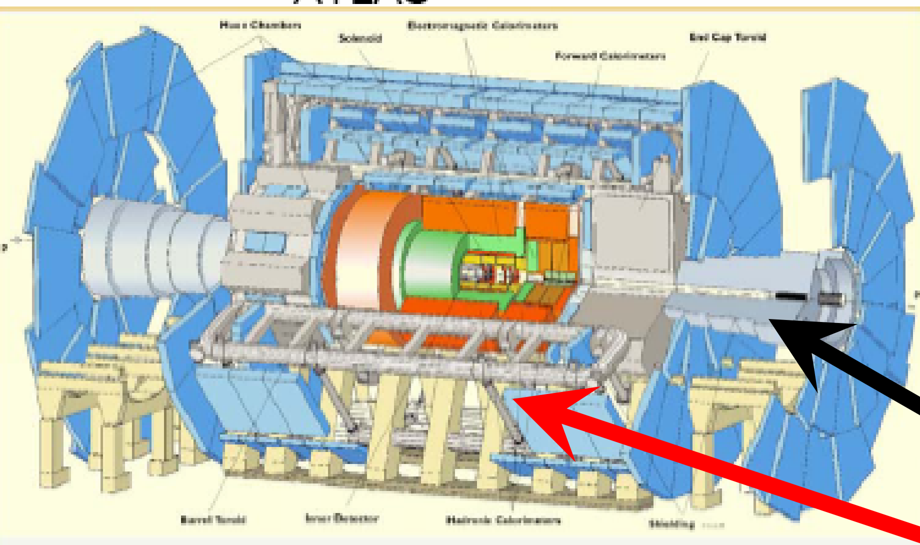
$$[\mathcal{L}] = \mathrm{cm}^{-2}\mathrm{s}^{-1} \Rightarrow [L] = \mathrm{cm}^{-2} = \mathrm{fb}^{-1}$$

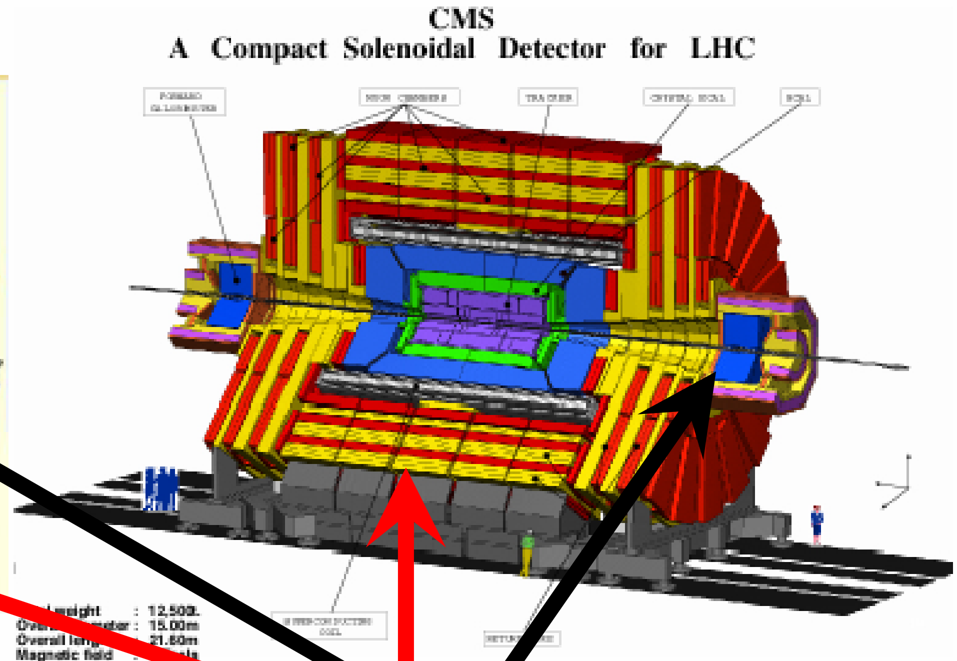
$$\mathcal{L} = 1 \ \mathrm{cm}^{-2}\mathrm{s}^{-1} \approx 3.16 \times 10^{-32} \ \mathrm{fb}^{-1} / \mathrm{yr}$$

LHC parameters

pp collider, $\sqrt{s} = 14$ TeV   starting: 2007, 2 detectors

ATLAS





First year proton parameters:

- luminosity: 1.2×10^{33} cm^{-2}s^{-1}
- bunch crossing: 25 ns

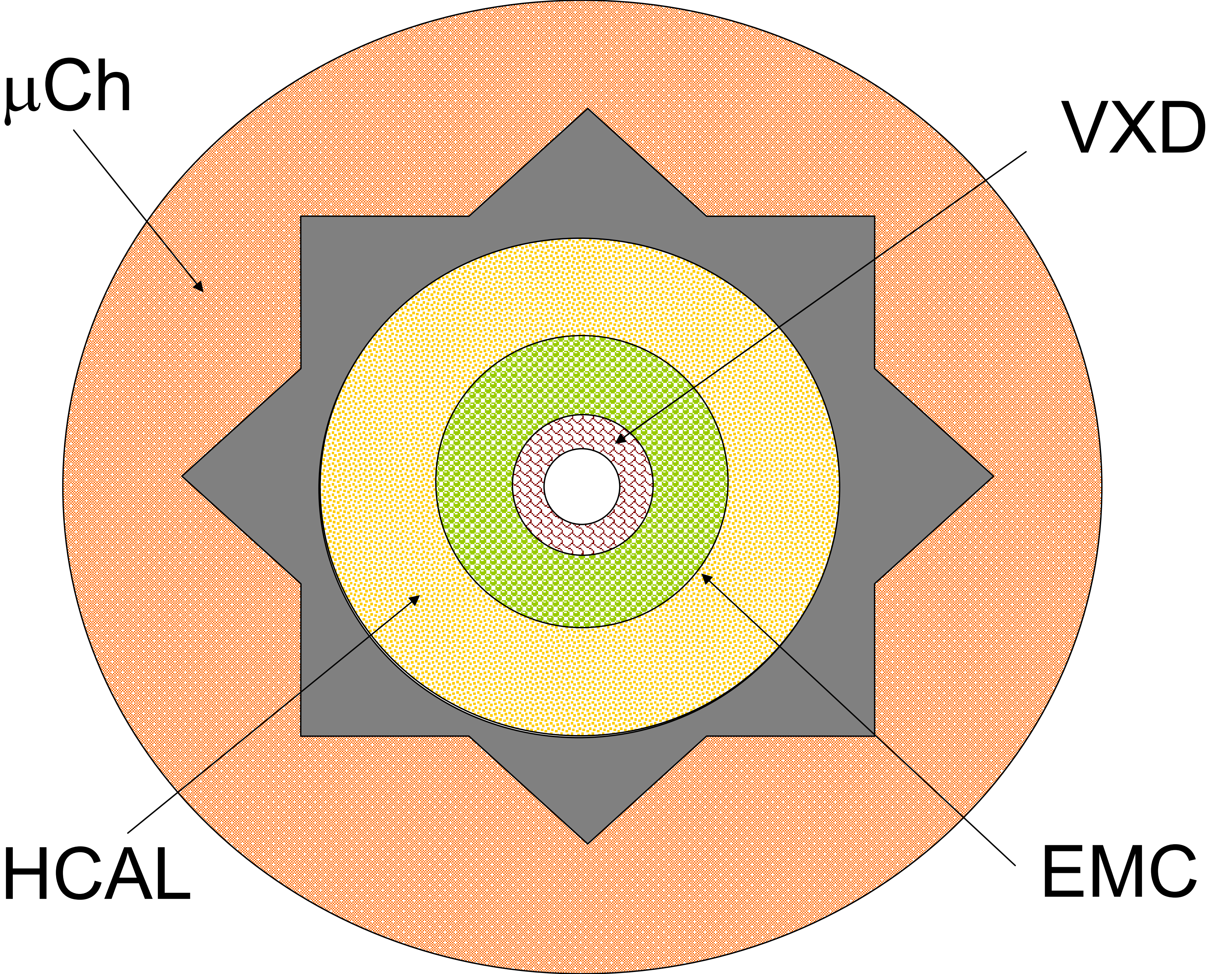
Nominal parameters:

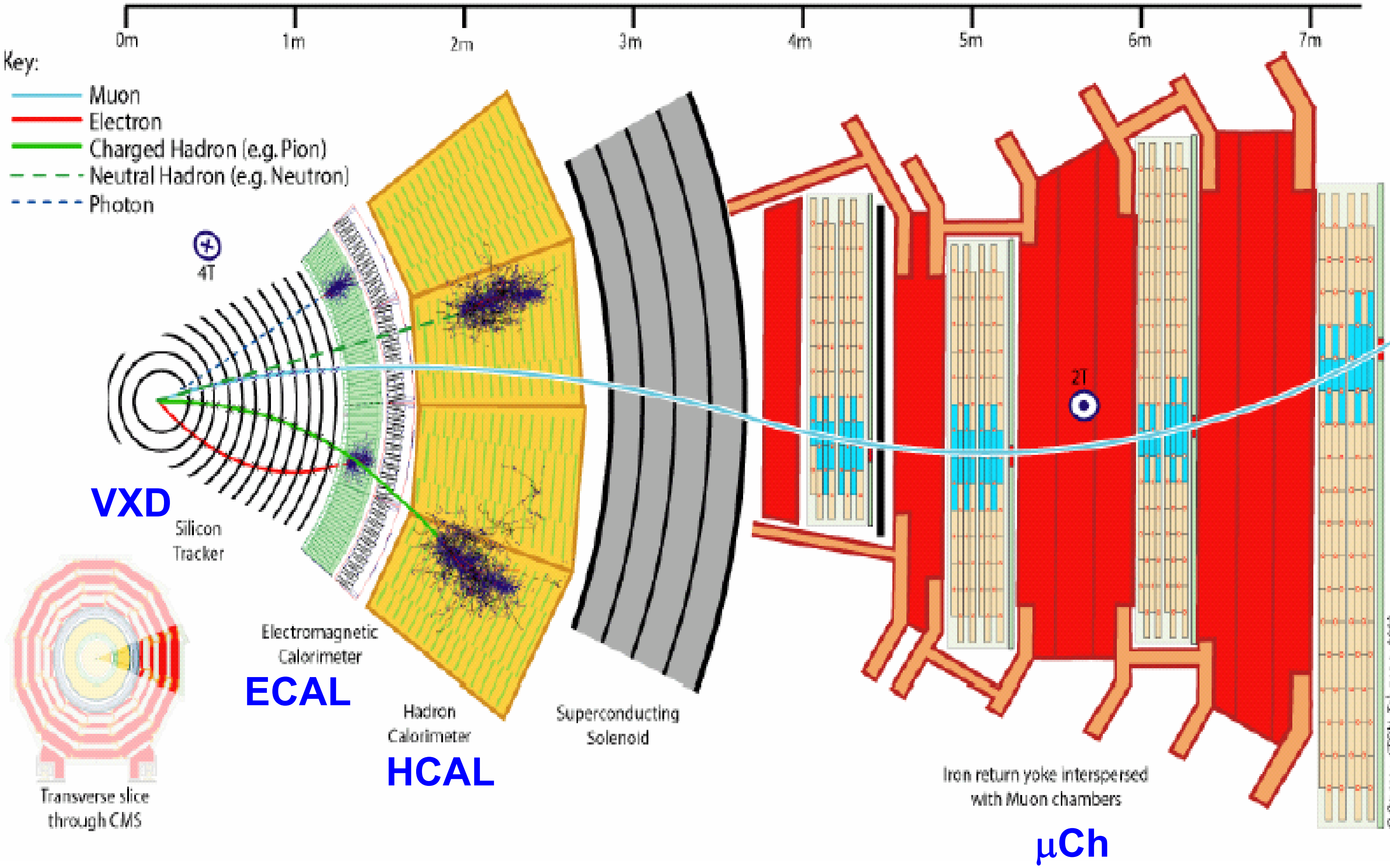
- luminosity: 1.0×10^{34} cm^{-2}s^{-1}
- bunch crossing: 25 ns

End-cap / **barrel**

radiation hardened; / radiation sensitive;

low efficiency / high efficiency


μCh
VXD
HCAL
EMC



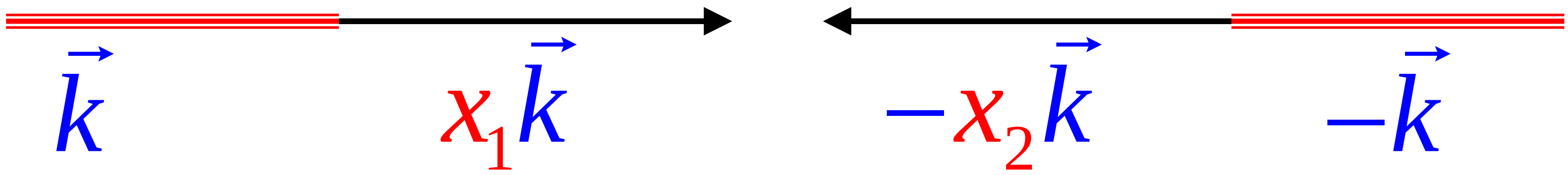
CMS Detector

Particle detection at the LHC

ν	No signals at all ; only missing energy
e	Track in VXD ; energy deposit in ECAL
μ	Track in VXD ; tracks/deposits in μCH
γ	No track in VXD; only deposit in ECAL
$q\,/\,g\,/\,\tau$	Hadronic jets ; signals in all devices
$W\,/\,Z$	Decay at the interaction vertex itself
b	Displaced vertices in VXD; deposit in HCAL
$t\,/\,H$	Decay at the interaction vertex itself

Everything must be reconstructed only from these effects

Choice of Variables



Partonic system has an (unknown) longitudinal boost

$$\beta \approx \frac{x_1 - x_2}{x_1 + x_2}$$

Each collision event will have a different β

$\Rightarrow$ we must choose variables which are independent of longitudinal boosts

Commonest Variables

1. Transverse momentum : $p_T = \sqrt{p_x^2 + p_y^2}$ $E_T = \sqrt{p_T^2 + m^2}$

2. Rapidity : $y = \frac{1}{2}\log\frac{E + p_z}{E - p_z}$ $\rightarrow y + \frac{1}{2}\log\frac{x_2}{x_1}$ Δy

3. Pseudo rapidity : $\eta = -\log\tan\frac{\theta}{2}$ $\approx y \quad \text{if} \quad m \rightarrow 0$

$\theta =$	0	5°	10°	30°	90°
$\eta =$	∞	3.13	2.44	1.32	0

4. Angular separation : $\Delta R = \sqrt{\Delta\eta^2 + \Delta\varphi^2}$

5. Invariant mass : $M_{12}^2 = (p_1 + p_2)^2$

Signal and Background

If a certain final state (including phase space characteristics) is predicted by a theory, the cross-section for producing that final state is called the **signal**

$$N_S = \mathcal{L} . \sigma_S$$

If it is possible to produce the same final state (including phase space characteristics) in an older, well-established theory (e.g. Standard Model), that cross-section is called a **background**

$$N_B = \mathcal{L} . \sigma_B$$

Experimental results will have errors: $N_{\exp} \pm \delta N_{\exp}$

$\delta N_{\exp} \Rightarrow$ standard deviation σ

What constitutes a discovery?

Excess/depletion over background : $\left| N_{\exp} - N_B \right|$

Assuming random (Gaussian) fluctuations, the probability that this deviation is just a statistical effect is about :

$$33\% \quad \text{if} \quad \left| N_{\exp} - N_B \right| \approx \delta N_{\exp} \quad \Rightarrow \quad \text{deviation at 67\% C.L.}$$

$$5\% \quad \text{if} \quad \left| N_{\exp} - N_B \right| \approx 2\delta N_{\exp} \quad \Rightarrow \quad \text{deviation at 95\% C.L.}$$

$$1\% \quad \text{if} \quad \left| N_{\exp} - N_B \right| \approx 3\delta N_{\exp} \quad \Rightarrow \quad \text{deviation at 99\% C.L.}$$

$$0.01\% \quad \text{if} \quad \left| N_{\exp} - N_B \right| \approx 5\delta N_{\exp} \quad \Rightarrow \quad \text{deviation at 99.99\% C.L.}$$

Consensus: **3σ deviation is exciting;**
5σ deviation constitutes a discovery;
8σ deviation leaves no room for doubt

Limiting the parameter space

Once there is a well-established deviation from the background, we compare it with the signal:

$$N_S \approx \left| N_B - \left(N_{\exp} \pm \delta N_{\exp} \right) \right|$$

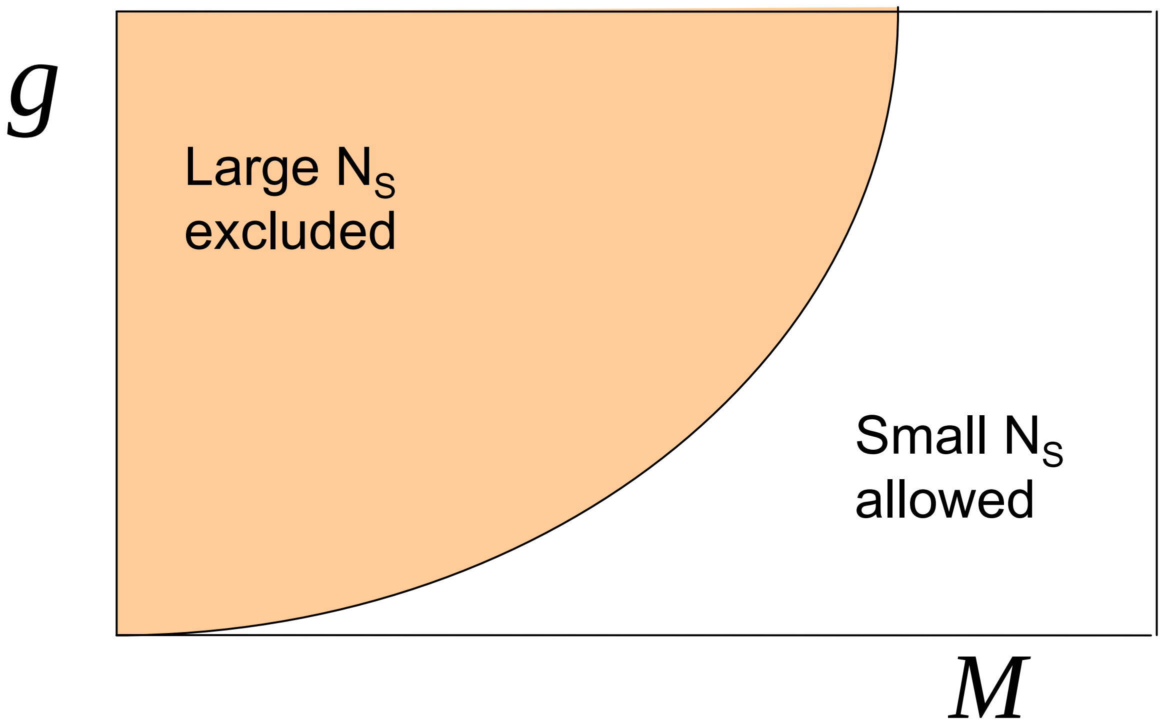
If the numbers match, we can start claiming a discovery…

Usually this matching can always be achieved by tuning the free parameters in the (new) theory…

Comparison essentially serves to constrain the parameter space of the (new) theory

If $N_{\exp} \approx N_B$ we must have very small $N_S \ll \delta N_{\exp}$

Typical new physics bounds arising when experimental cross-sections match with backgrounds :



If experimental data are there, this is called an **exclusion plot**

If the data are projected, this is called a **search limit**

LHC

If both signal and background are present, the prediction is that experiment will see the sum of both predictions.

<u>Typical case:</u> background is large; signal is small

$$N_S \ll N_B$$

In this case $N_{\exp} \approx N_B$ and $\delta N_{\exp} \gg N_S$

Will be very difficult to observe any signal over the experimental error…

Require to reduce the background (without reducing the signal)

Kinematic Cuts

Fermi's Golden Rule : $\sigma = \frac{1}{F}\int |M|^2 \, d\Phi$

Phase space integral has to be over all <u>accessible</u> final states

$$d\Phi = \prod_i \frac{d^3\vec{p}_i}{(2\pi)^3 2E_i}$$

Experimental cross-section may not be able to (wish to) access all the possible momentum final states

$\Rightarrow$ phase space integral must be done with appropriate kinematic cuts

- **acceptance cuts** : forced on us by the detector properties.
- **selection cuts** : chosen to prefer one process over another.

Examples of acceptance cuts:

- minimum p_T for the final states :
  - very soft particles will not cause showering in the ECAL/HCAL
  - different cuts for barrel and endcap
- maximum η for the final states :
  - no detector coverage in/near beam pipe
- isolation cut on ΔR for leptonic final states :
  - no hadronic deposit within a cone of $\Delta R = 0.4$
  - to be sure that the lepton is coming from the interaction point and not from a hadron semileptonic decay inside a jet

Will be somewhat different for ATLAS and CMS

Selection cuts can be of different kinds depending on the process and the purpose for which it is made…

Example of a selection cut:

Suppose we want to select more electrons from the process

$$pp \to e^+ e^- \qquad (1)$$

instead of electrons from the process

$$pp \to e^+ e^- \gamma \qquad (2)$$

From simple energy-sharing arguments, the electron in (1) will have more p_T than the electron in (2)

Impose the selection cut : $p_T^e > p_T^{\min}$

Ensures that the accessible phase space for (2) shrinks without seriously affecting that of (1) → reflected in the cross-section

A variety of selection cuts can be used to reduce the background without affecting the signal (much).

Much of the collider physicist's ingenuity lies in devising a suitable set of selection cuts to get rid of the background(s).

Often the background can be reduced really dramatically – to maybe 1 in 10000…

Nevertheless, often this reduction of backgrounds to negligible values may also reduce the already weak signal to less than one event in the whole running life of LHC!

High luminosity is essential !!

What are signals which the LHC is planning to look for ?

Two paradigms:

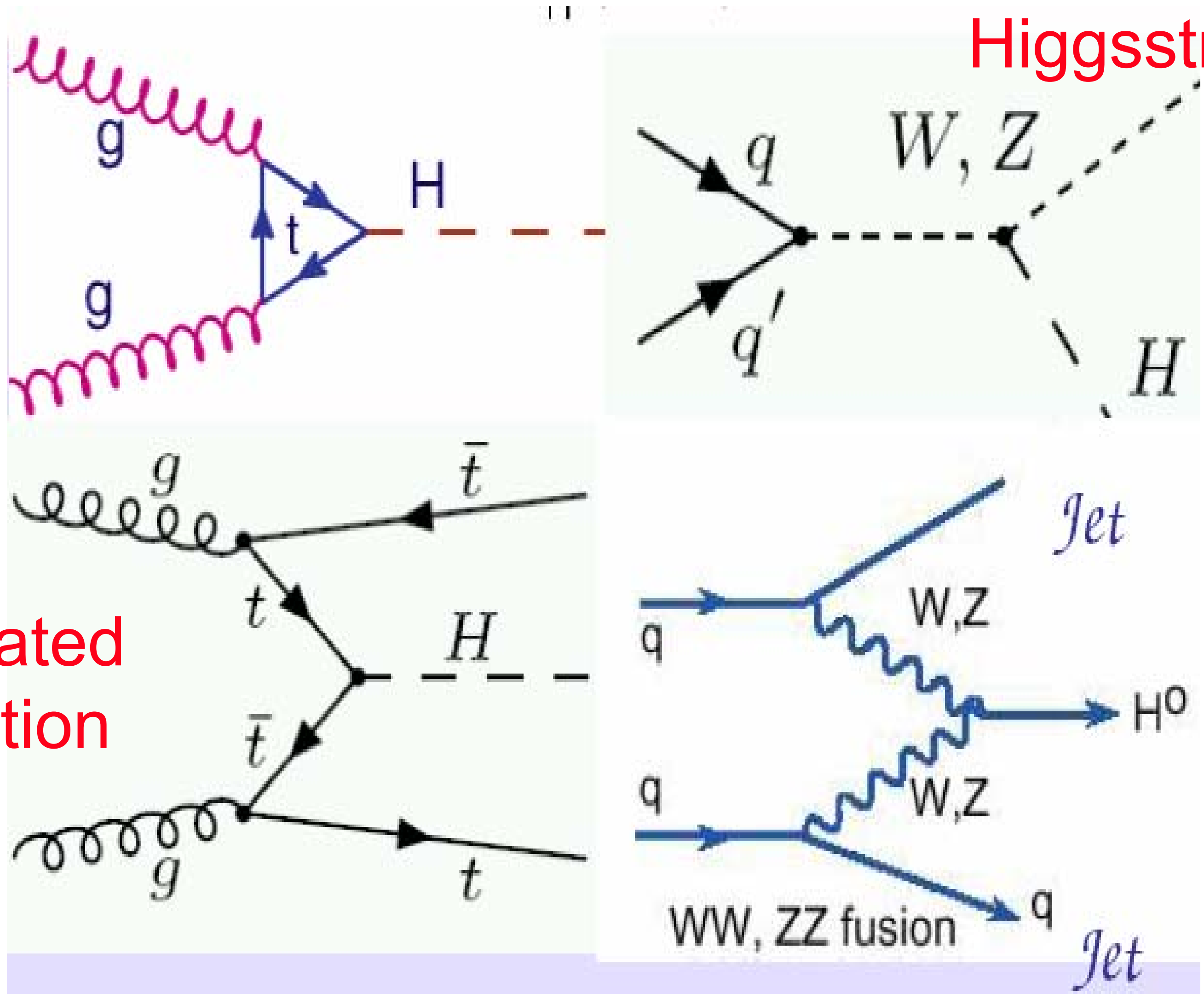
- Study predictions of a existing models :
SM, GUTs, Technicolour, MSSM, little-H, ADD/RS,…
- Model-independent studies : inverse problem…

Standard Model Higgs Boson

Higgs boson production channels at LHC

Gluon fusion

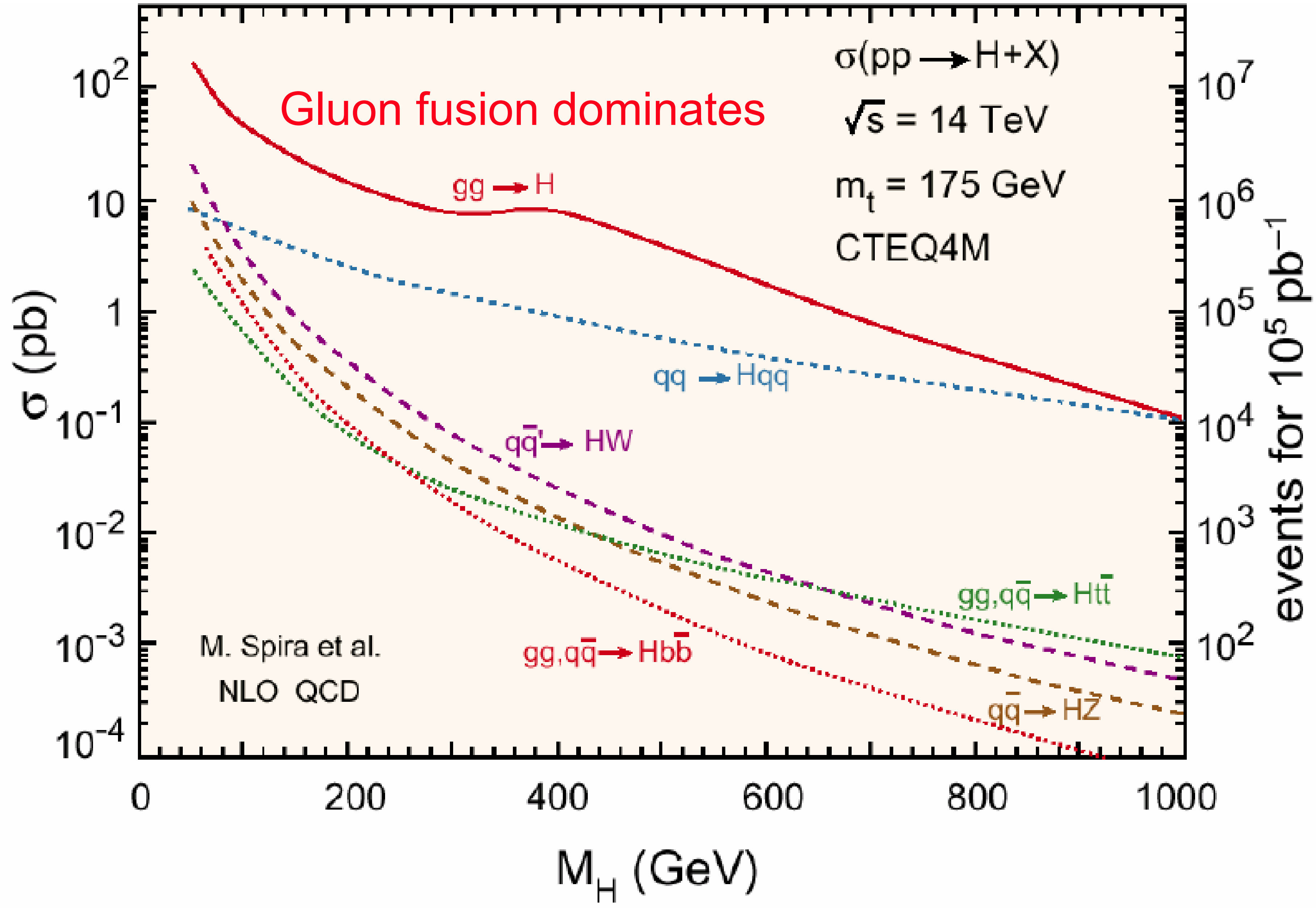
Higgsstrahlung



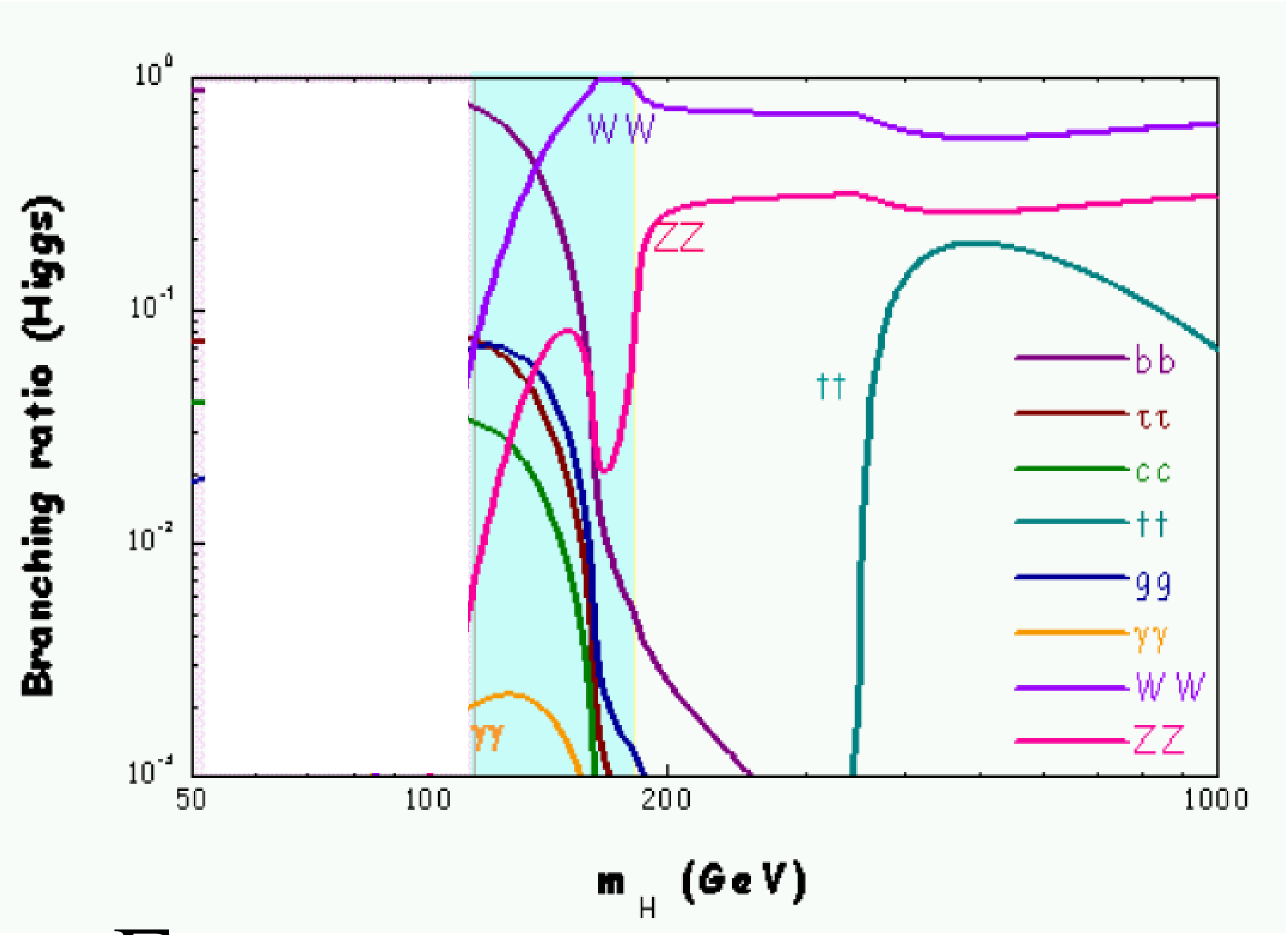
Associated production

Vector boson fusion

Higgs boson production channels at LHC



Higgs boson branching ratios



$$BR = \frac{\Gamma_{partial}}{\Gamma_{total}}$$

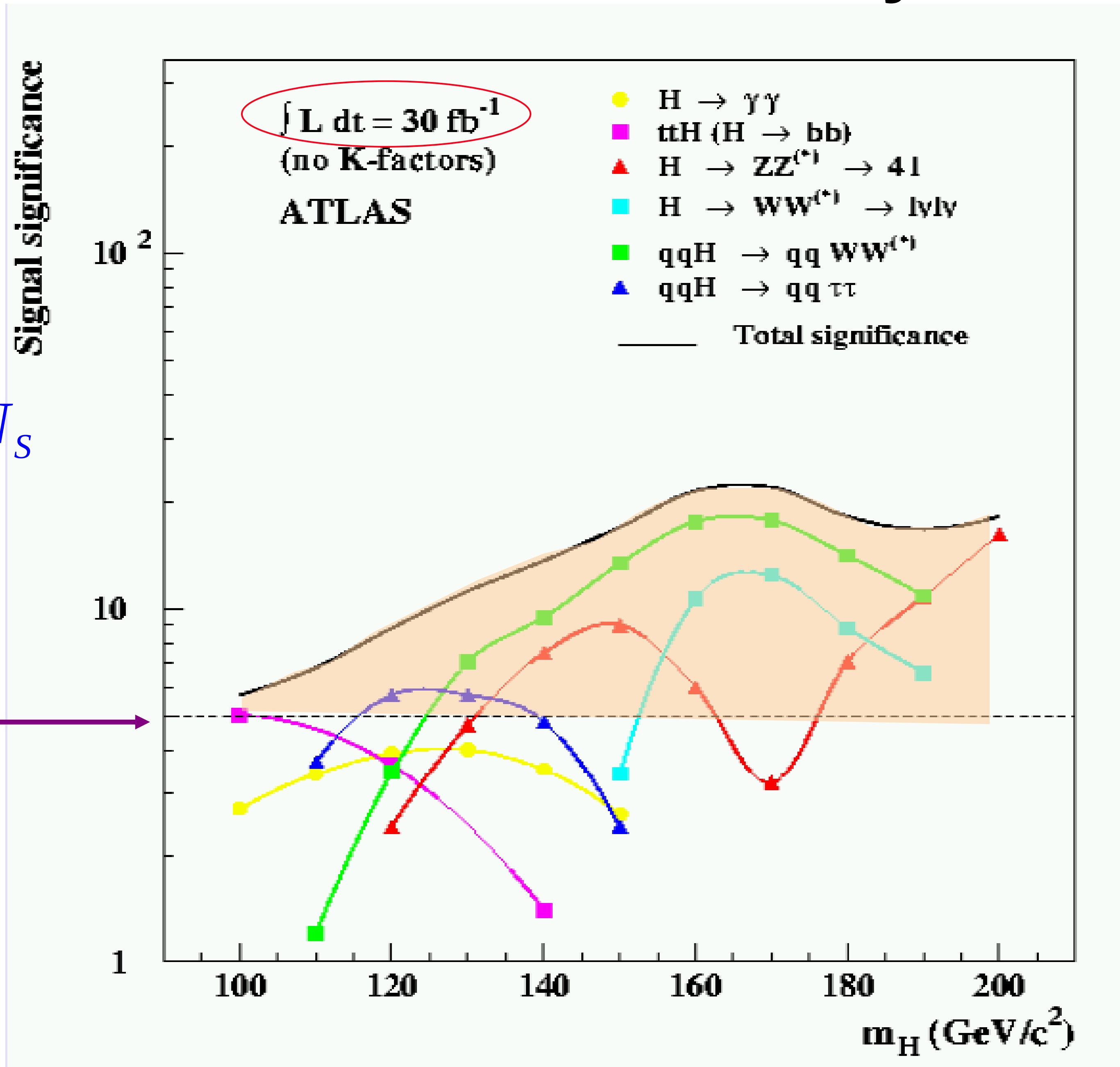
- H $\rightarrow$ bb feasible in associated production (ttH).
- H $\rightarrow \gamma\gamma$ suppressed but provides clear signature.
- H $\rightarrow \tau\tau$ important for VBF at masses above LEP limit.
- At large mass, vector boson decays dominate.

Higgs boson should be found in 3 years!

$$\sigma \approx \frac{N_S}{\delta N_{\exp}}$$

$$N_{\exp} \approx N_B + N_S$$

5σ



Is it a Higgs?

- How do we know what we've found?
- Measure couplings to fermions & gauge bosons

$$\frac{\Gamma(h \to b\bar{b})}{\Gamma(h \to \tau^+\tau^-)} \approx 3\frac{m_b^2}{m_\tau^2}$$

- Measure spin/parity

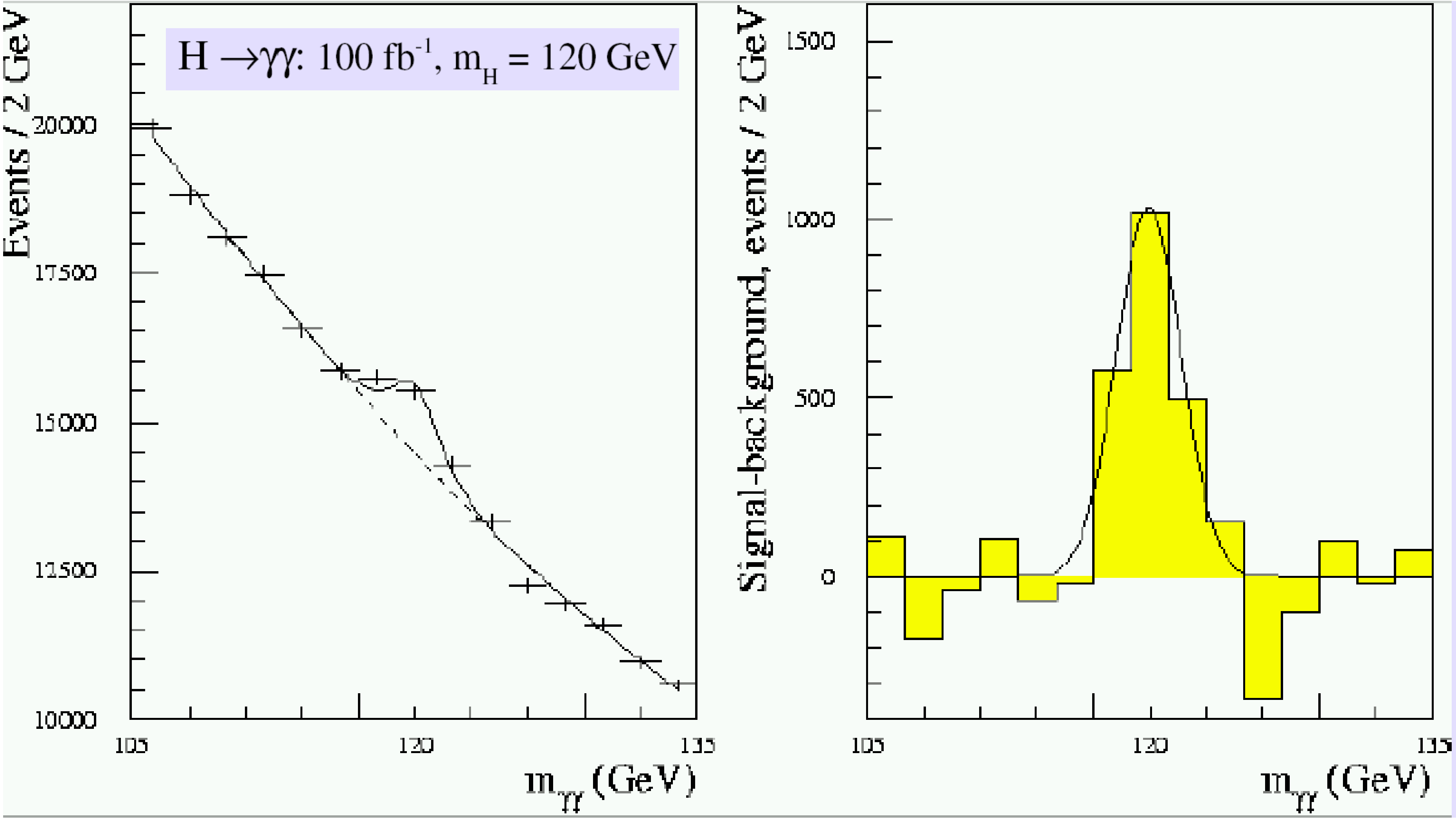
$$J^{PC} = 0^{++}$$

- Measure self interactions

$$V = \frac{M_h^2}{2}h + \frac{M_h^2}{2v}h^3 + \frac{M_h^2}{8v^2}h^4$$

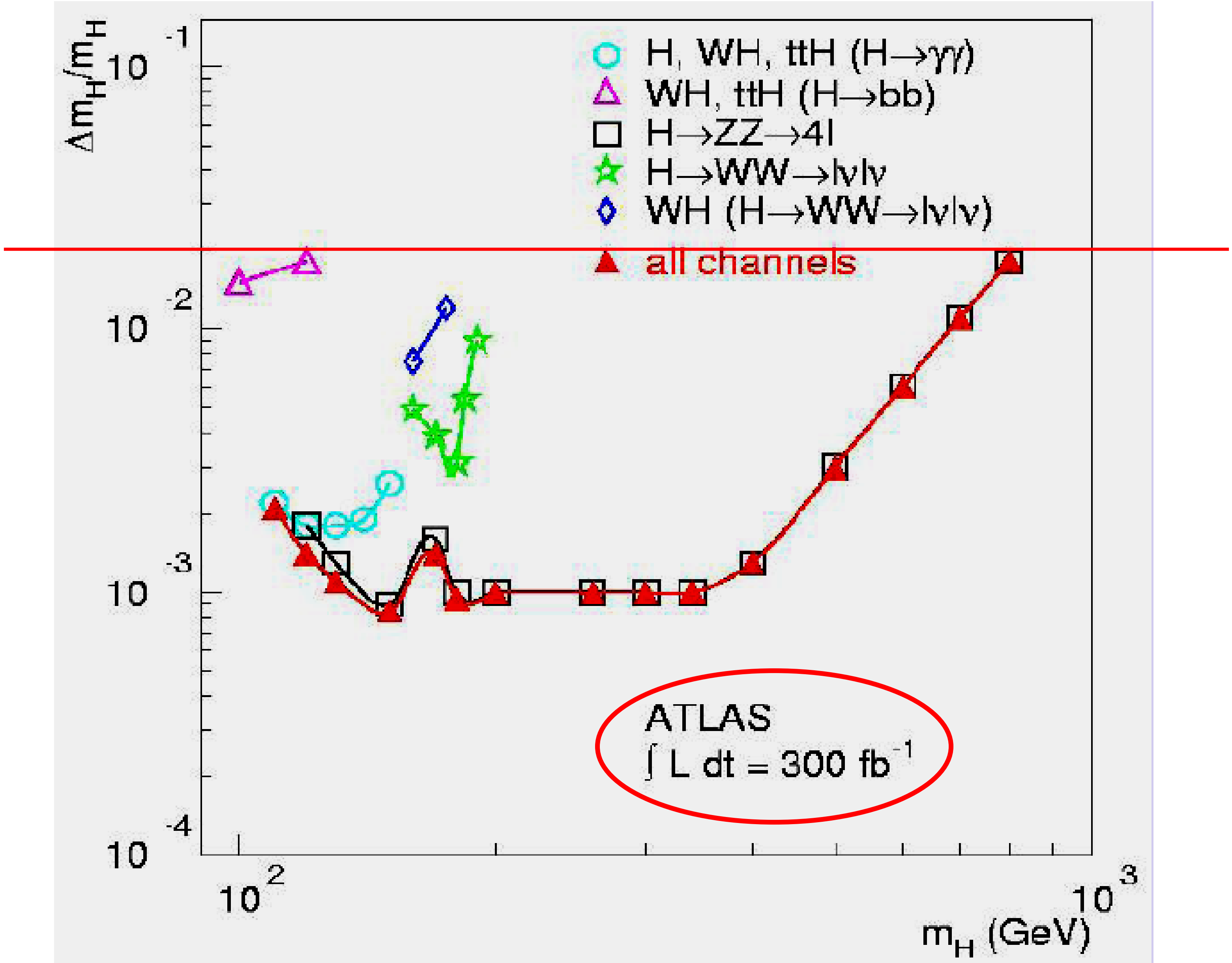
S.Dawson 2004

Light Higgs boson mass



Diphoton invariant mass $m_{\gamma\gamma} = \left(p_\gamma + p_{\gamma'}\right)^2 = p_H^2 \approx M_H^2$

Higgs boson mass (comprehensive study)



Other properties:

Spin: consider $H \rightarrow ZZ \rightarrow$ 4 charged leptons

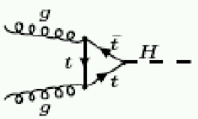
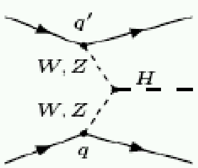
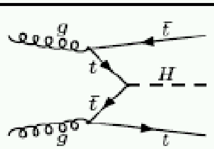
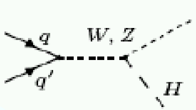
Event kinematics can be completely re-constructed from the final states

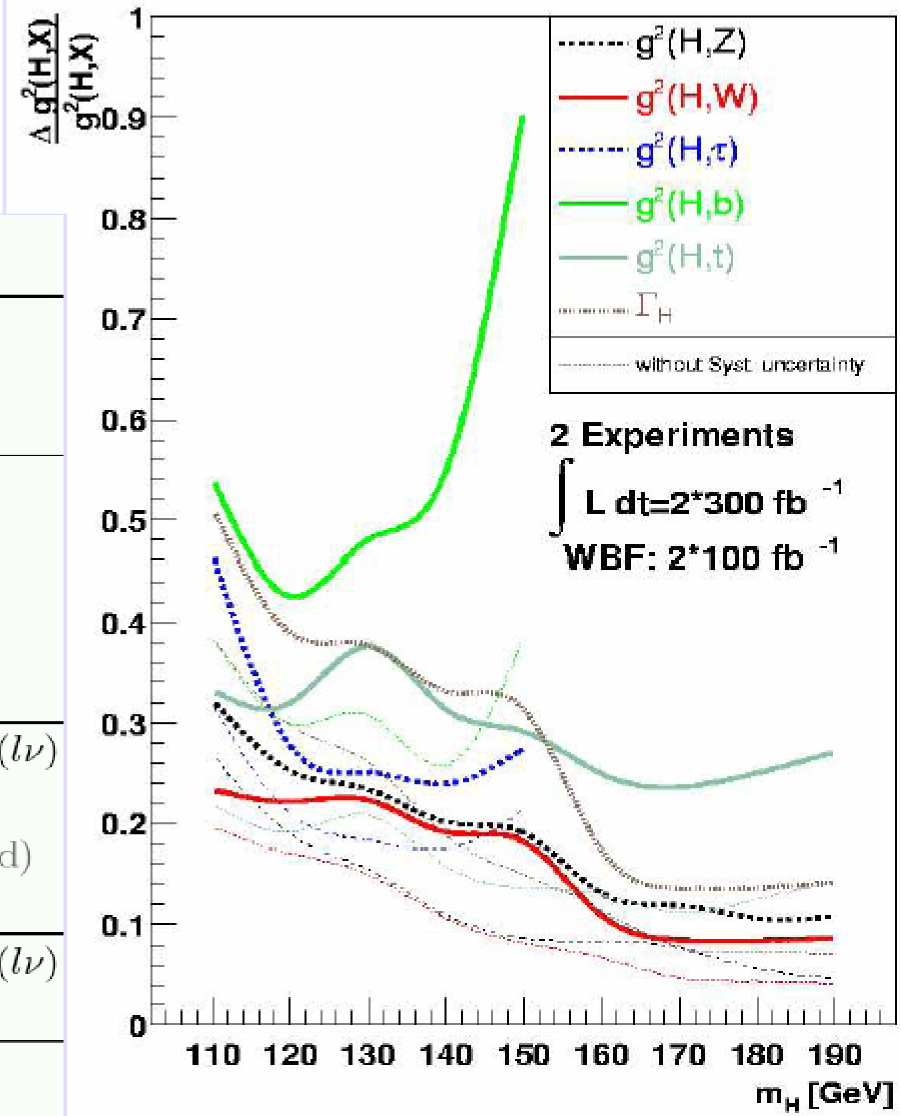
Angular distribution of final states will distinguish between spin 0, spin 1, etc…

CP: construct CP sensitive observables from dot and cross-products of lepton momenta

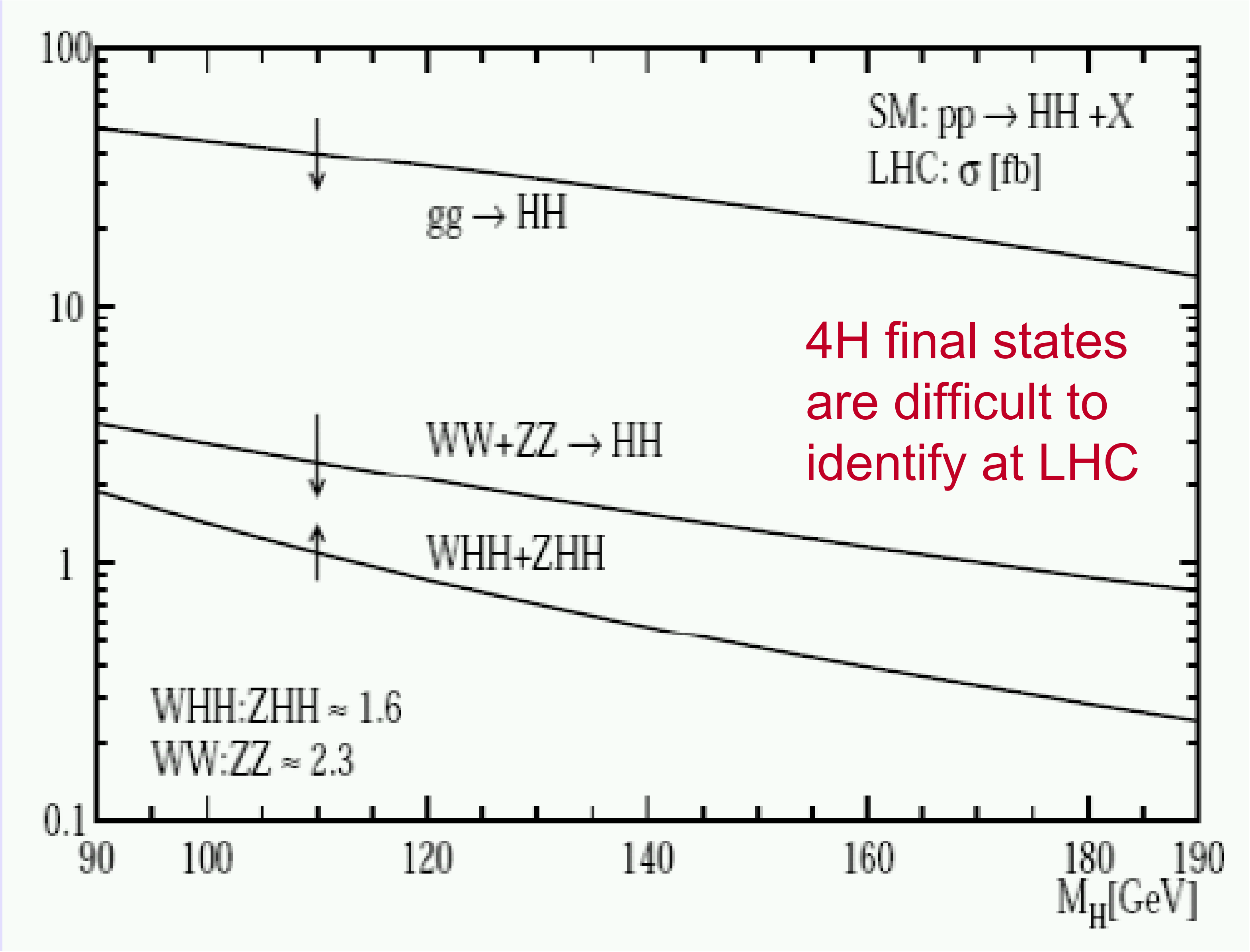
Works rather well for heavier Higgs bosons, but not so well for light ones. Diphoton decay would tell us it's not a vector….

Reconstructing the non-gauge interactions

Production		Decay
	GF: Gluon Fusion ($gg \to H$)	$H \to ZZ^{(*)} \to 4l$ $H \to WW^{(*)} \to l\nu\, l\nu$ $H \to \gamma\gamma$
	WBF: Weak Boson Fusion ($qq\,H$)	$H \to ZZ^{(*)} \to 4l$ $H \to WW^{(*)} \to l\nu\, l\nu$ $H \to \tau\tau \to l\nu\nu\, l\nu\nu$ $H \to \tau\tau \to l\nu\nu$ hadν $H \to \gamma\gamma$
	$t\bar{t}H$	$H \to WW^{(*)} \to l\nu\, l\nu\,(l\nu)$ $H \to b\bar{b}$ $H \to \tau\tau$ (not included) $H \to \gamma\gamma$
	WH	$H \to WW^{(*)} \to l\nu\, l\nu\,(l\nu)$ $H \to \gamma\gamma$
	ZH	$H \to \gamma\gamma$



Reconstructing the self-coupling



4H final states are difficult to identify at LHC

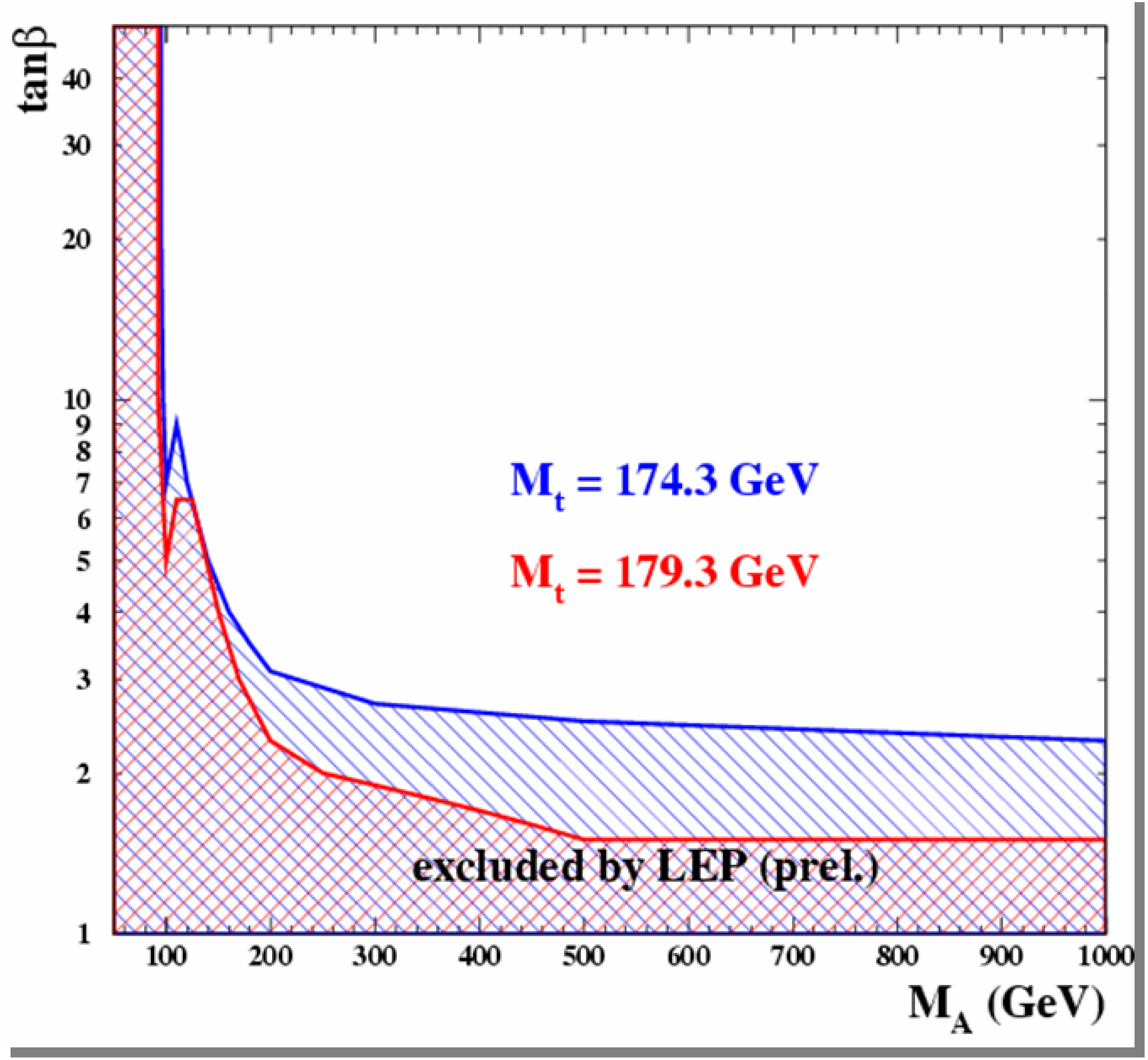
- If the Standard Model Higgs boson exists and is in the relatively low mass region hinted by electroweak precision measurements, LHC will certainly find it by about 2010
- In 10 years of running, LHC should be able to clearly identify the found particle as a Higgs boson of the SM and measure its J^{PC} to high accuracy.
- Reconstruction of the SM Yukawa sector will also progress well – for the heavier fermions
- Reconstruction of the Higgs potential will require a high energy (linear) e^+e^- collider

MSSM Higgs Bosons

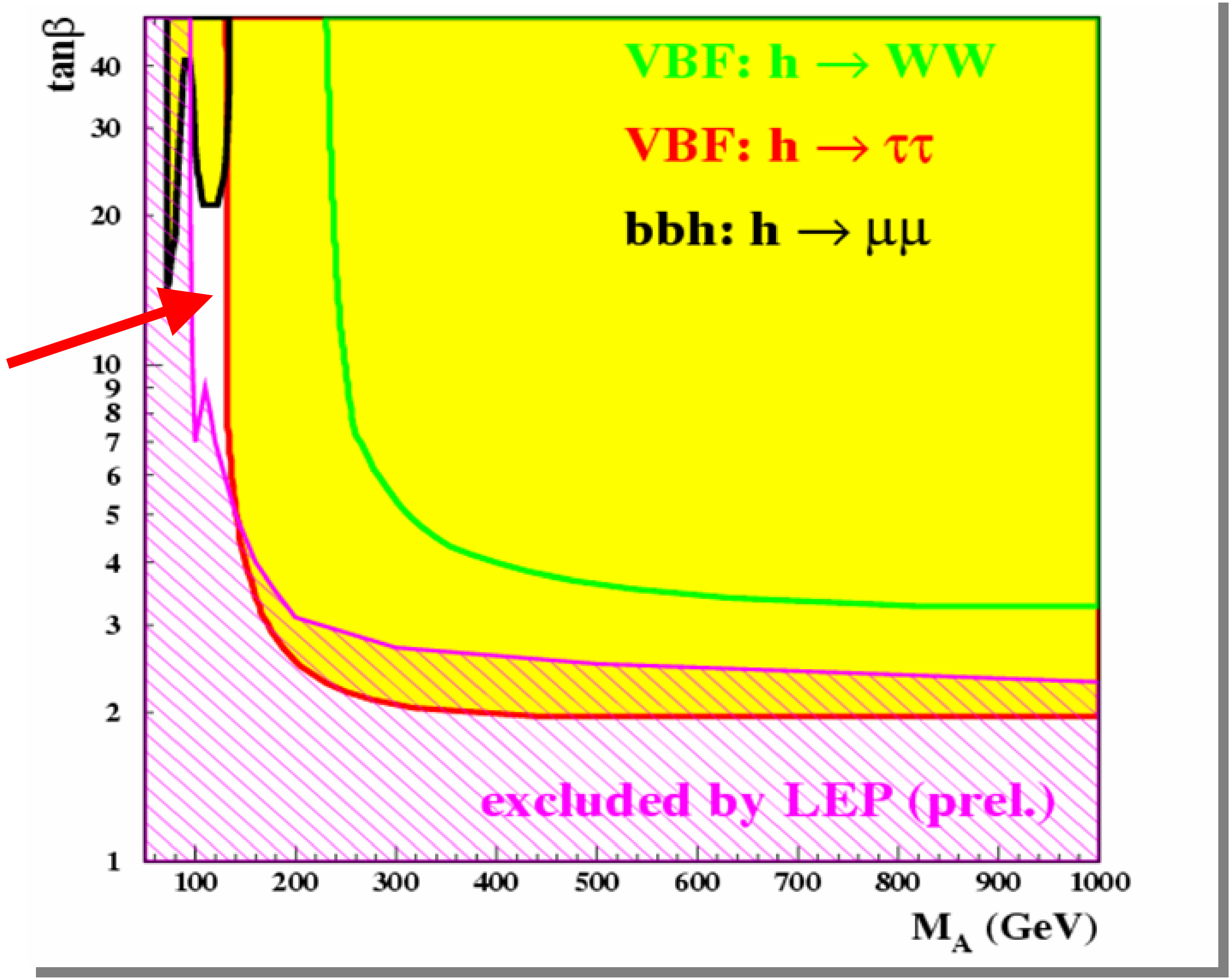
- Processes are very similar
- Techniques of study are also very similar
- Only parameter space is extended

$$M_H \rightarrow M_A, \tan\beta$$

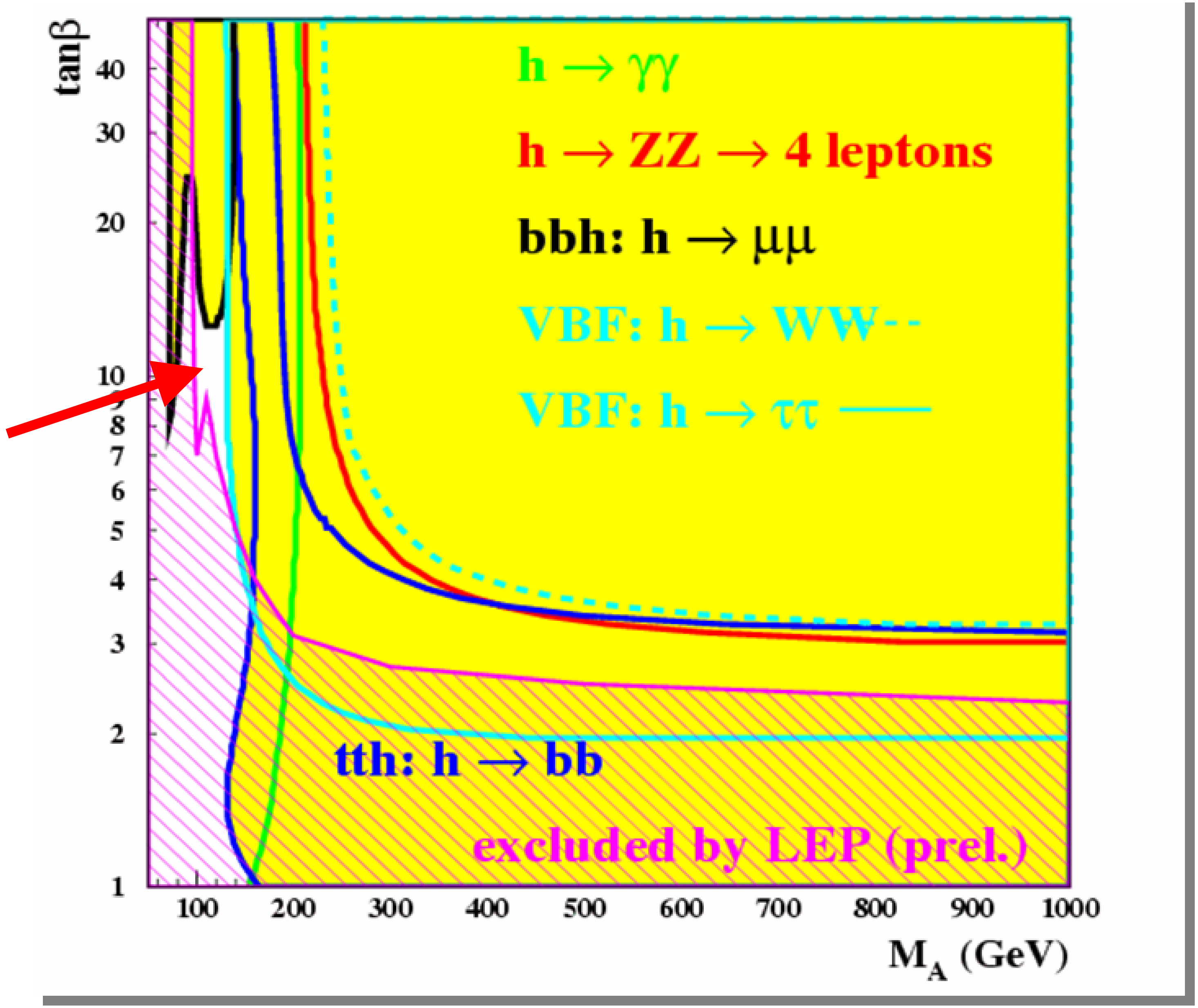
MSSM Higgs parameter space – now



MSSM Higgs parameter space – 3 yr LHC



MSSM Higgs parameter space – high lumi

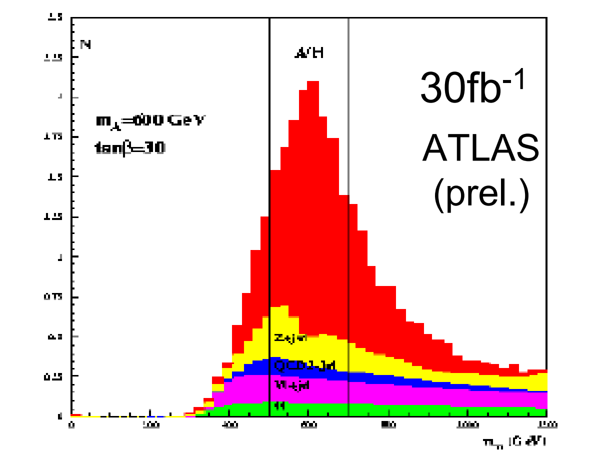


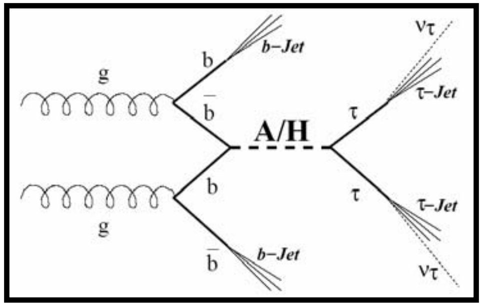
Neutral Heavy Higgs Bosons (H/A)

➢ example: bbH/A, H/A → ττ

- σ_{prod} ~ $(\tan\beta)^2$; important at large tanβ
- new analysis: ττ→ had. had.
- BR(H/A → ττ) ~ 10 % , rest is bb

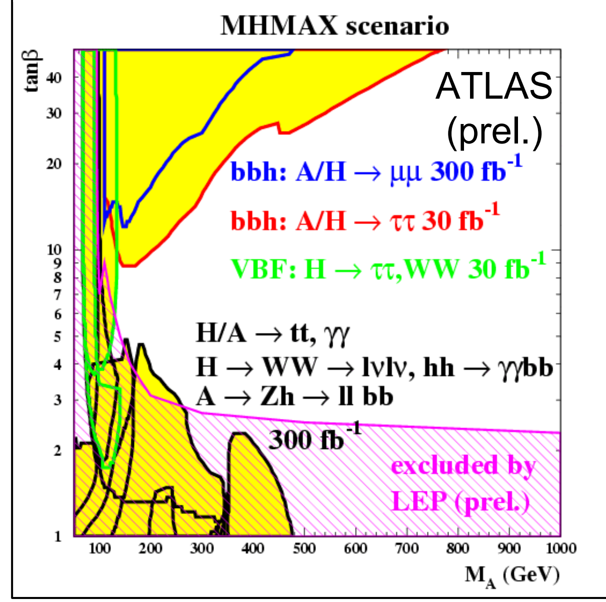
rec. mass for ττ→had.had.





New: take running b-quark mass for σ_{prod}

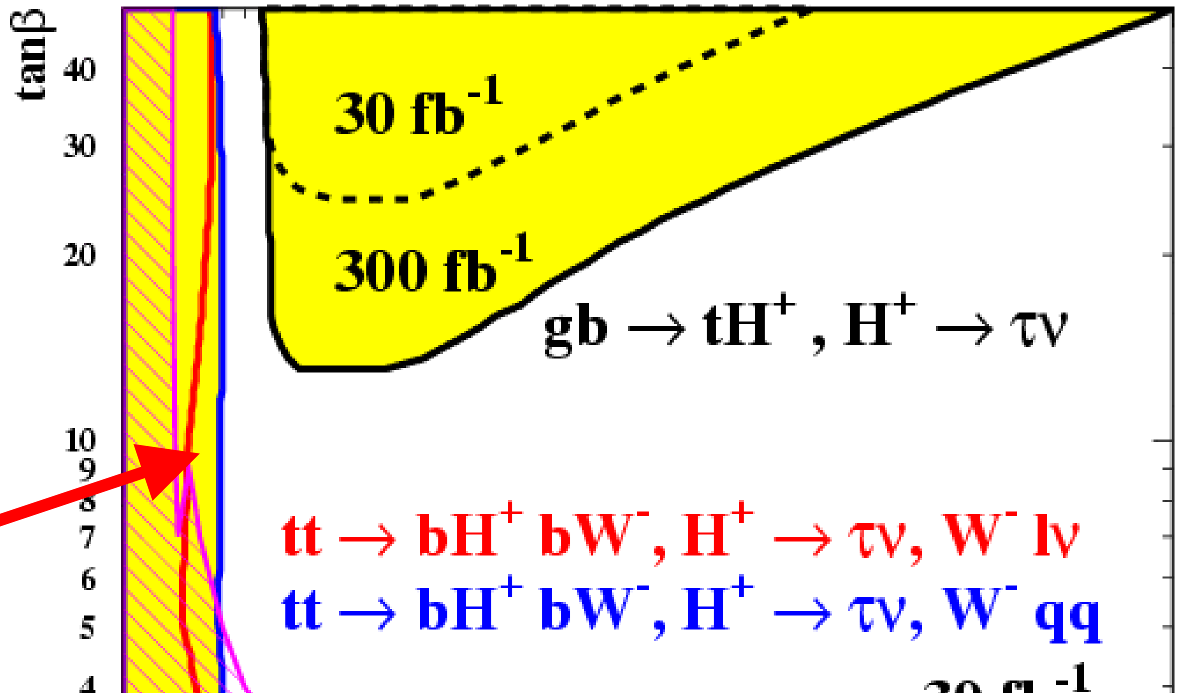
discovery reach for H/A:



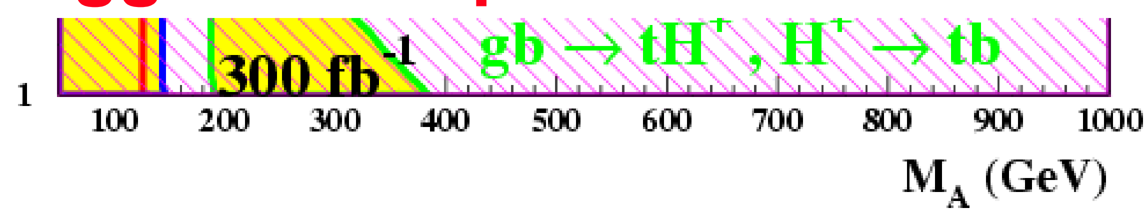
- ➢ only very few events remain after cuts (acceptance ~10^{-3})
- ➢ LVL1 trigger performance crucial
- ➢ detailed study: >90% LVL1 efficiency for M_A>450GeV via "jet+$E_{T,miss}$" and "τ+ $E_{T,miss}$" triggers with a rate of ~1.4 kHz (within rate limit)

- ➢ bb H/A → bb ττ covers large tanβ region
- ➢ other scenarios similar
- ➢ intermediate tanβ region not covered

Charged Higgs boson can fill up the hole



The LHC should be able to scan the entire MSSM Higgs parameter space and find the light Higgs boson predicted in the MSSM



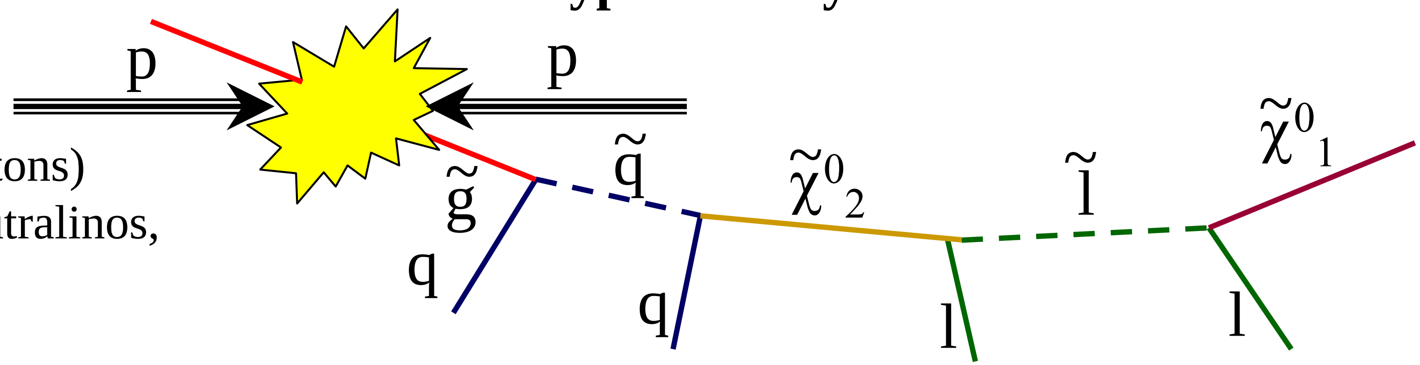
Sparticle Searches

- In the usual construction of the MSSM, sparticles always appear in pairs
- Conservation of R-parity
- Lightest SUSY particle (LSP) must be stable
- LSP will escape detection at LHC (like a neutrino)
- Missing energy and momentum
- In mSUGRA models the lightest neutralino is always the LSP

How SUSY looks like (to an experimental physicist)

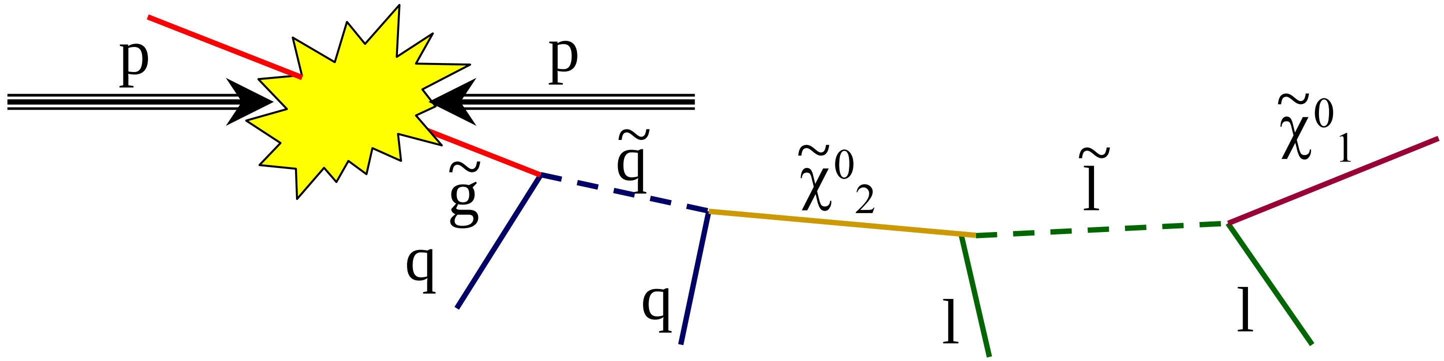
A typical decay chain:

SUSY particles:
Scalars (s-quarks, sleptons)
Gaugino (gluino, 4 neutralinos, 2 charginos)
5 Higgs bosons



- **Strongly interacting sparticles (squarks, gluinos) dominate production.**
- **Heavier than sleptons, gauginos etc. : cascade decays to LSP.**
- **Long decay chains and large mass differences between SUSY states**
  - **Many high p_T objects observed (leptons, jets, b-jets).**
- **If R-Parity conserved LSP (lightest neutralino in mSUGRA) stable and sparticles pair produced.**
  - **Large E_T^{miss} signature**
- **Closest equivalent SM signature top pair production**
  - **Top physics important for commissioning (and important background)**

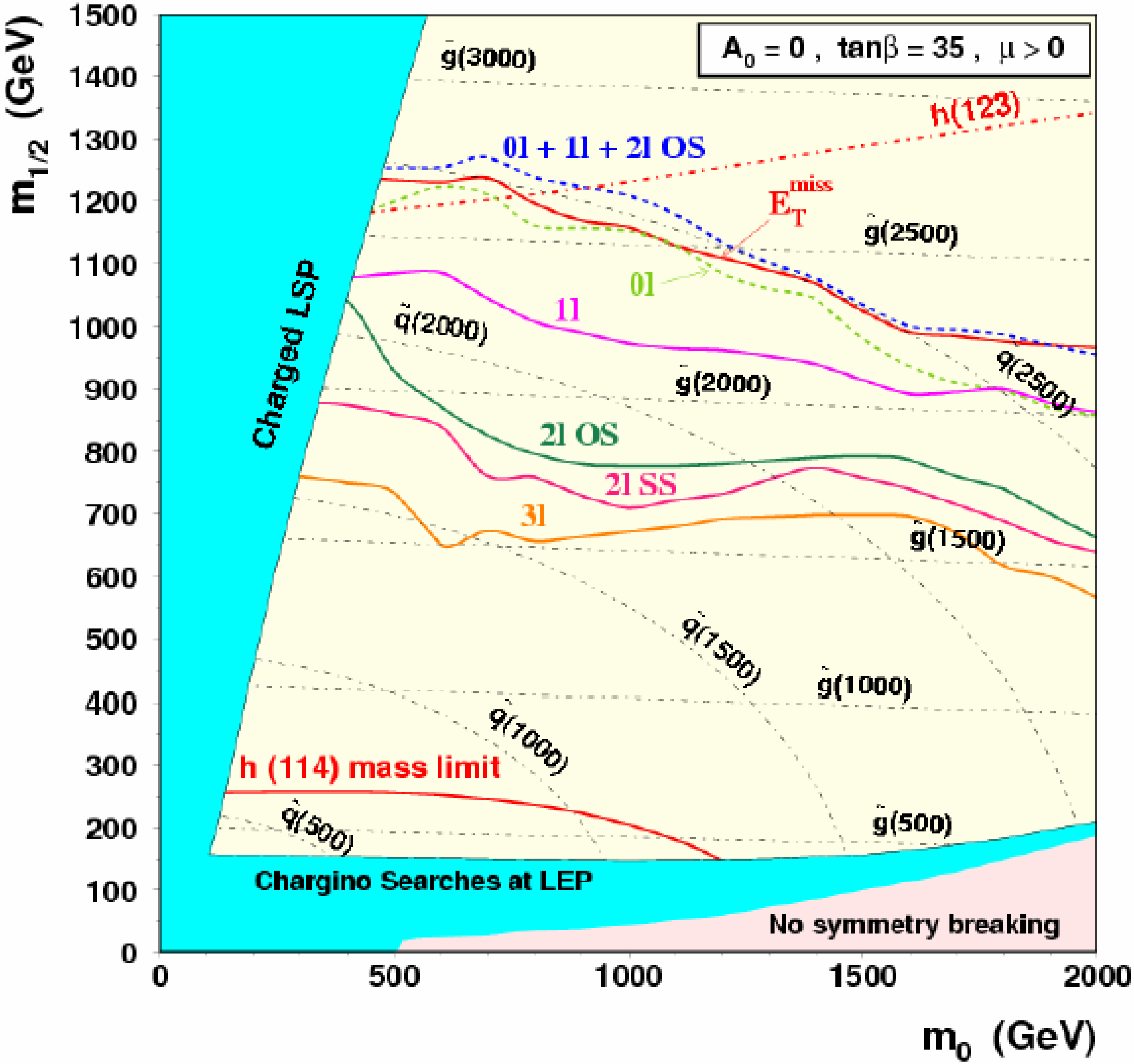
Sparticle Search strategies



Final states: jets + leptons + missing p_T

For concrete predictions go to a specific SUSY-breaking model, e.g. mSUGRA

Try to constrain the parameter space: usually $m_0 - m_{1/2}$ plane

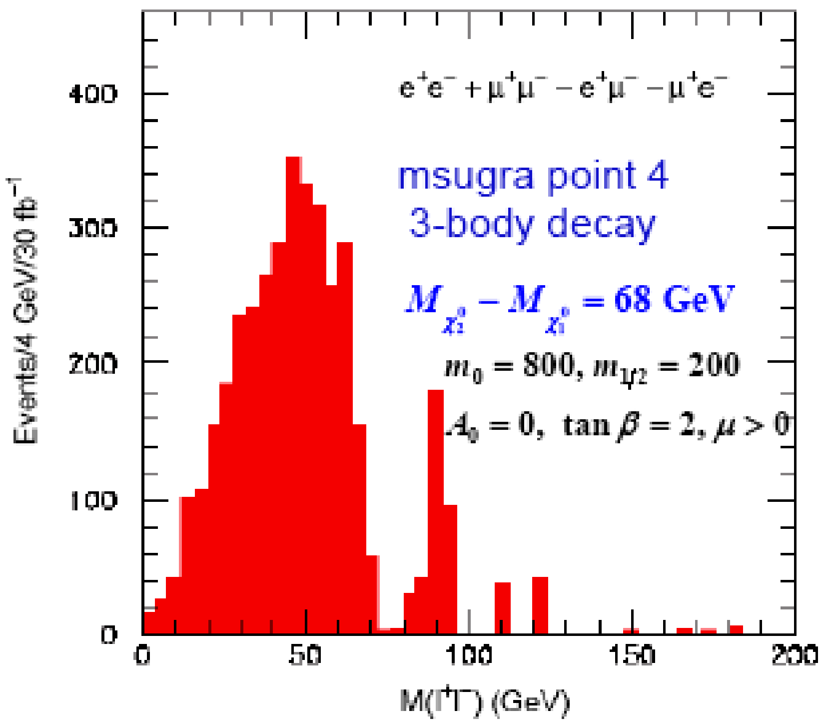


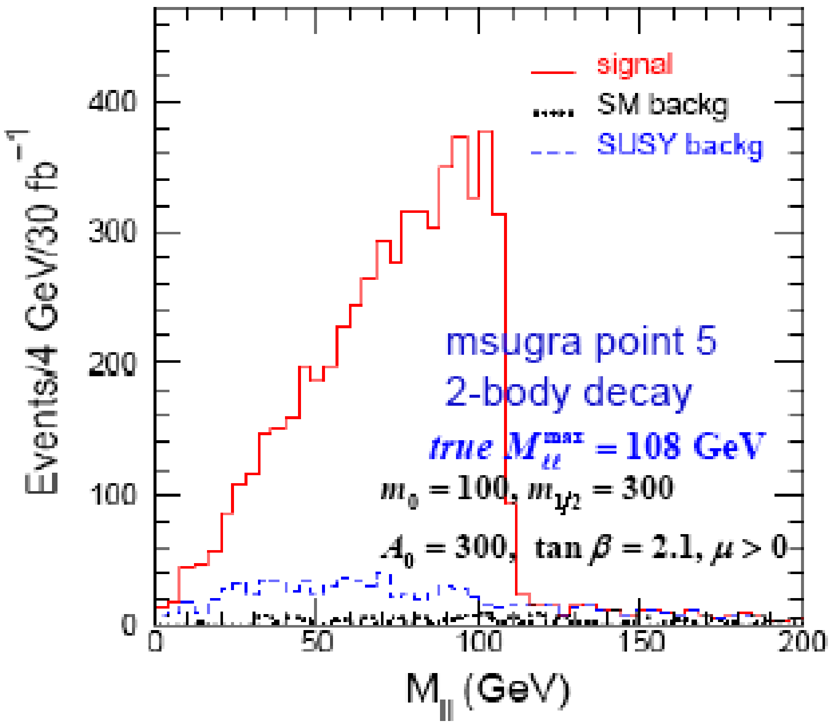
$A_0 = 0$, $\tan\beta = 35$, $\mu > 0$
Charged LSP
$\tilde{g}(3000)$
h(123)
0l + 1l + 2l OS
E_T^{miss}
$\tilde{g}(2500)$
0l
1l
$\tilde{q}(2000)$
$\tilde{g}(2000)$
$\tilde{q}(2500)$
2l OS
2l SS
3l
$\tilde{g}(1500)$
$\tilde{q}(1500)$
$\tilde{g}(1000)$
$\tilde{q}(1000)$
h (114) mass limit
$\tilde{q}(500)$
$\tilde{g}(500)$
Chargino Searches at LEP
No symmetry breaking
$m_{1/2}$ (GeV)
m_0 (GeV)

- **Mass reconstruction from di-lepton endpoints**

3-body decay: $\tilde{\chi}_2^0 \rightarrow \tilde{\chi}_1^0 \ell^+ \ell^- \Rightarrow M_{\ell\ell} < M_{\tilde{\chi}_2^0} - M_{\tilde{\chi}_1^0}$

2-body decay: $\tilde{\chi}_2^0 \rightarrow \tilde{\ell}^\pm \ell^\mp \rightarrow \tilde{\chi}_1^0 \ell^+ \ell^- \Rightarrow M_{\ell\ell} < \frac{\sqrt{(M^2_{\chi_2^0} - M^2_{\tilde{\ell}})(M^2_{\tilde{\ell}} - M^2_{\chi_1^0})}}{M_{\tilde{\ell}}}$





SM background removed by subtracting distributions with opposite flavor leptons
precision in end-point measurement: ~ 1-2 %

- **GMSB**
  - $LSP : \tilde{G}, \quad NLSP : \tilde{\chi}_1^0$ or $\tilde{\ell}\ (\tilde{\tau}_R)$
  - jets + E_t^{miss}: ~ similar reach as MSugra
  - signatures: Kawagoe, Vienna 2004
    - $\tilde{\chi}_1^0 \to \tilde{G}\ell^+\ell^-$ for short lifetimes, or
    - $\tilde{\chi}_1^0 \to \tilde{G}\gamma$: non-pointing photons for long lifetimes
    - $\tilde{\ell} \approx$ slow "muon" $\Rightarrow$ TOF measurements
    - $\tilde{\ell} \to \ell\chi_1^0 \to \ell\ \gamma\tilde{G}$: non-pointing photons
- **AMSB**
  - light $\tilde{W}$ or $\tilde{\nu}$
  - $\tilde{\ell}$ pairs: $p\overline{p} \to \tilde{\nu}_L\tilde{\ell}_L^{\pm} \to \ell^{\mp}\tilde{W}^{\pm}\ \ell^{\pm}\tilde{W}^0$; displaced vtx from $\tilde{W}^{\pm} \to \tilde{W}^0\pi^{\pm}$
- **Generic SUSY search by statistical method**

  Duchovni, SN-ATLAS-2004-043
- **R-parity violating processes**
- **Split Supersymmetry**
  - heavy, stable gluino → R-hadron

If there are low-lying sparticle states, the LHC will certainly find them

However, the sparticles could lie beyond the kinematic reach of the LHC (little hierarchy)

The phenomenology is greatly model-dependent – except for a light Higgs within 115-200 GeV

Can be cross-checked with other constraints, e.g. cold dark matter…

Many detailed studies have been done, but one needs to do many more…

LHC has a busy Physics program…

Technicolor: technipion resonances

Little Higgs: heavy T quark, heavy W’ and Z’

Braneworlds: missing energy, black holes (ADD)

graviton resonances, radion (RS)

KK resonances (UED)

Extra Z’ bosons, excited leptons, excited quarks, strongly-coupled W sector, contact interactions, doubly-charged Higgs bosons, leptoquarks, dileptons and diquarks, higgsless models, monopoles, unparticles, …

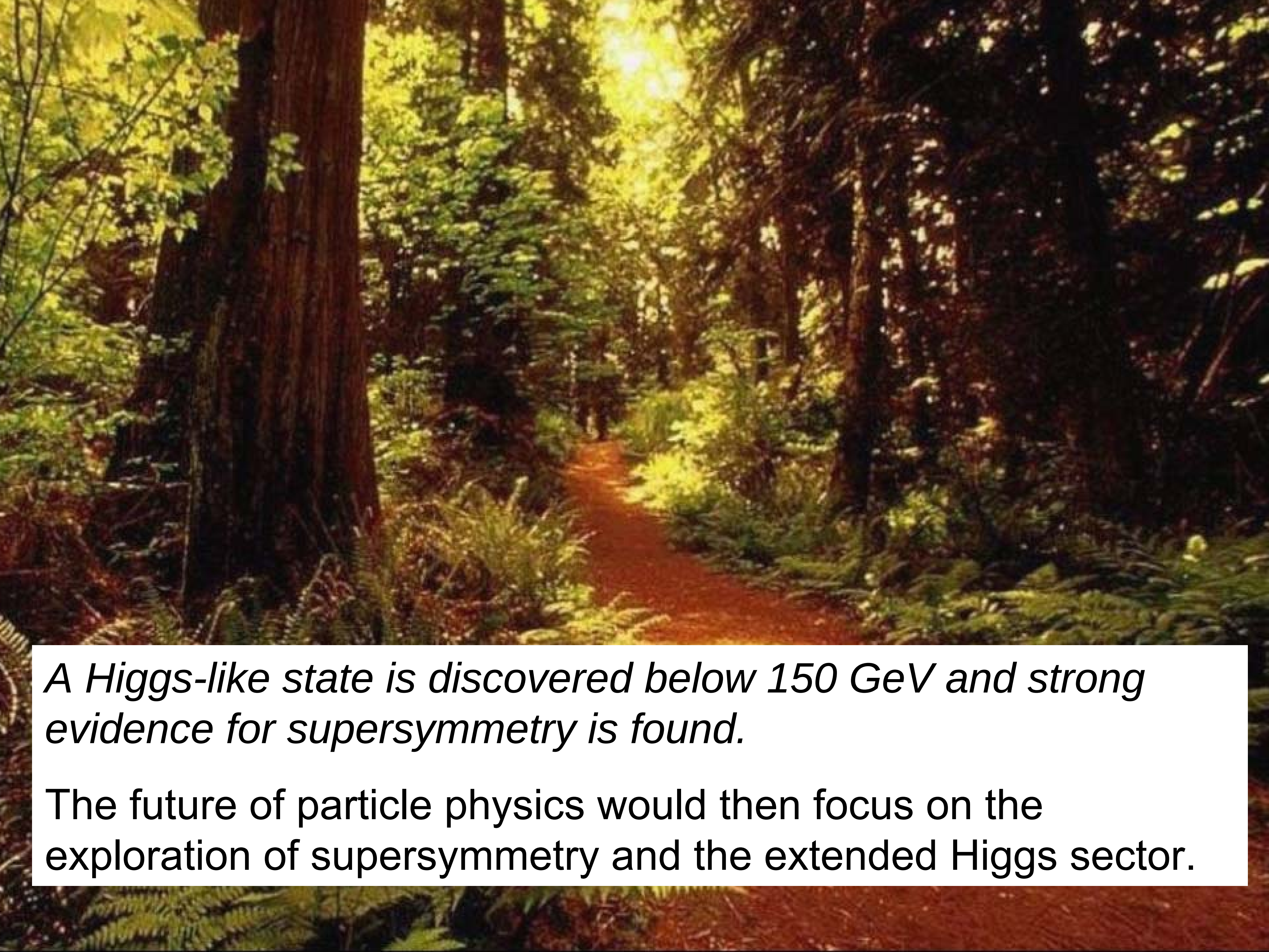
more precision tests of SM itself…

What do we expect the LHC to find?

Many good reasons to expect a light scalar Higgs boson

For the rest…

Like asking what a new continent is going to be like when we can just glimpse the shore….



A Higgs-like state is discovered below 150 GeV and strong evidence for supersymmetry is found.

The future of particle physics would then focus on the exploration of supersymmetry and the extended Higgs sector.

A Higgs particle is seen and no evidence for supersymmetry is found.

The future of particle physics would then focus on the Higgs boson properties, including all details of the non-gauge sector of the Standard Model.

No new particles are found.

The future of particle physics would then focus on the gaps in our understanding of the electroweak sector, such as WW scattering

A wealth of new phenomena is sighted.

The future of particle physics would then follow a long and rich program, studying and mapping out all these sources of new physics.

There is always the possibility that one may find something really exotic….

THANK YOU