The Higgs Boson at LHC

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1964 – Higgs mechanism (P. Higgs and others)

1967 – The Standard Model (S. Weinberg, A. Salam)

2000 – End of LEP/ Higgs boson not found

2007 – Start of LHC
- 3 years low lumi $L = 3\ 10^{4}\ pb^{-1}$
- 3 years high lumi $L = 3\ 10^{5}\ pb^{-1}$

2010 – First signal of Higgs boson at LHC

2014 – First measurements of Higgs boson propierties (mass, width, decays, couplings, etc…)

1964 - 2014 = 50 years

Why do we need a Higgs boson

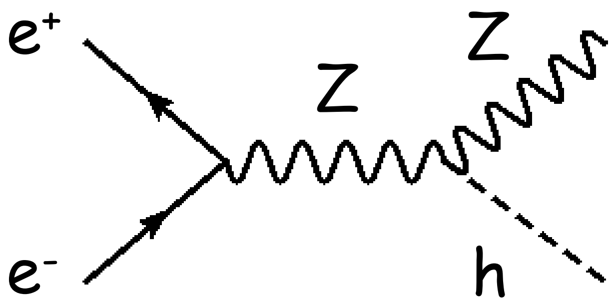
- Because we want the Standard Model to be renormalizable
- Because we don't want Goldstone bosons (spin 0 massless particles)

"From today's perspective, it may seem odd that so much attention was focused on the issue of renormalizability. Like general relativity, the old theory of weak interactions based on four fermion interactions could have been regarded as an effective quantum field theory which works perfectly well at sufficiently low energy and with the introduction of a few additional free parameters even allows the calculation of quantum corrections."

S. Weinberg, The making of Standard model
(CERN, 16 – Sept – 2003)

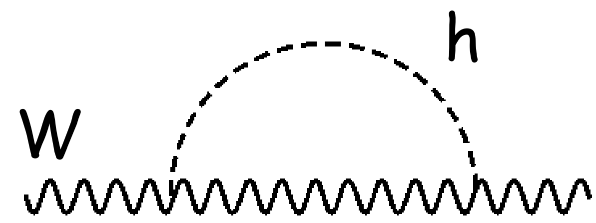
What do we know experimentally?

Direct searches at LEP

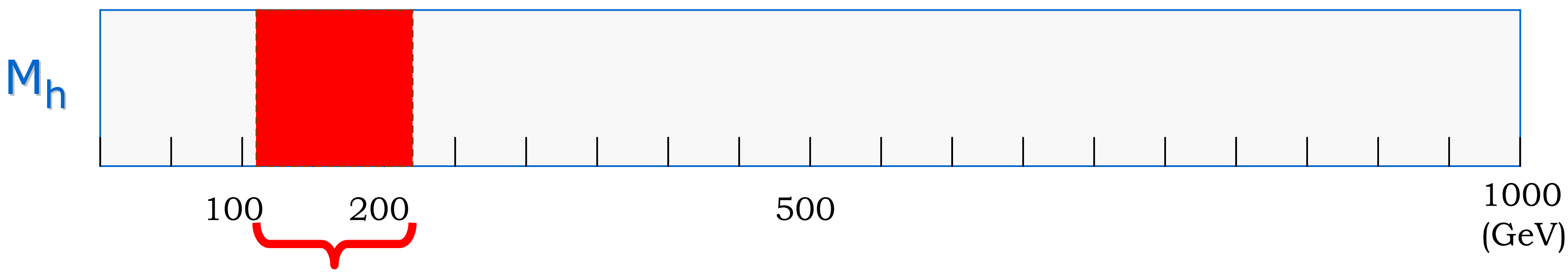


$M_h > 114$ GeV

Loop corrections → LEP observables

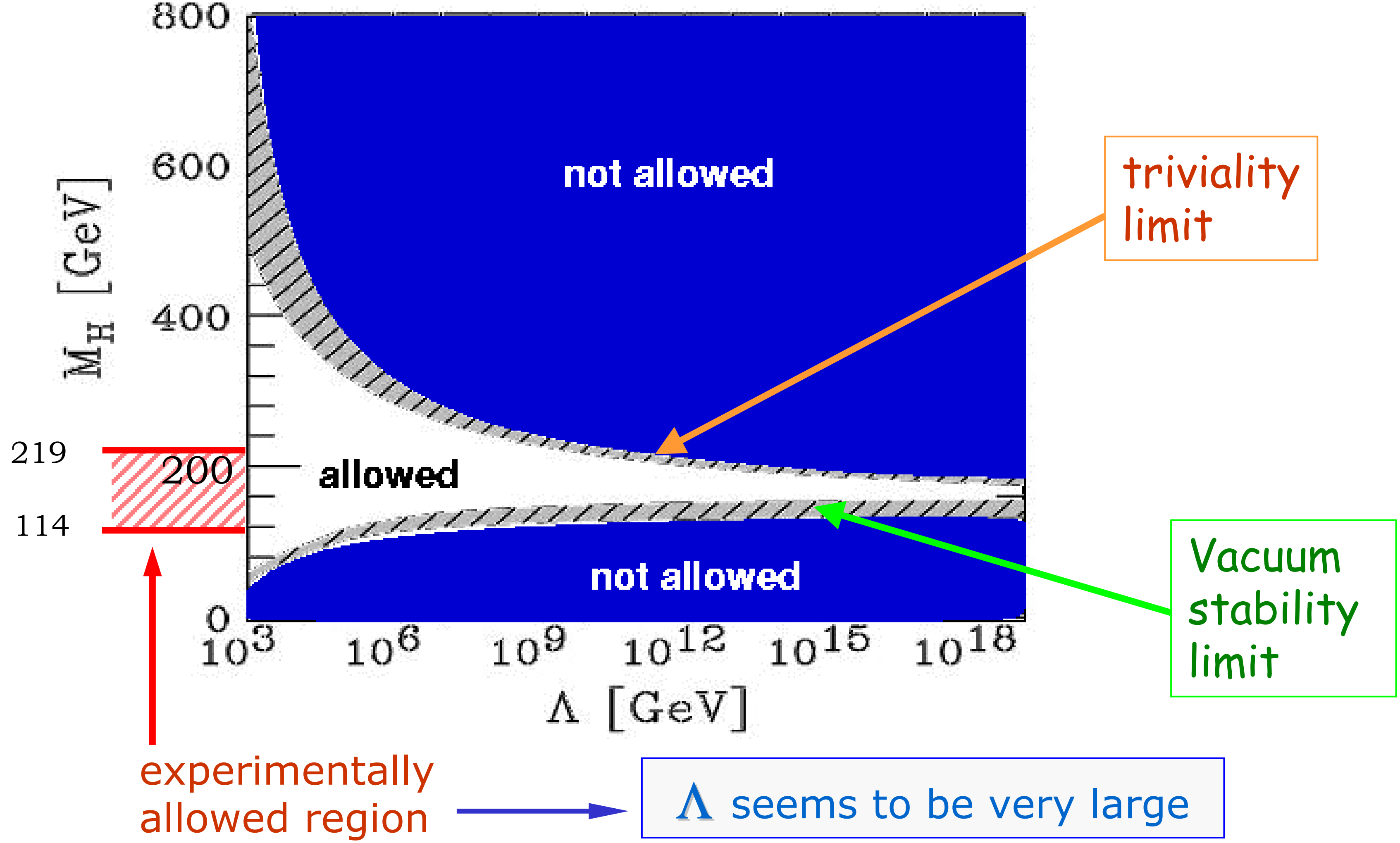


$M_h < 219$ GeV
(sensitive to $\Delta\alpha$, M_t)



Only mass window left

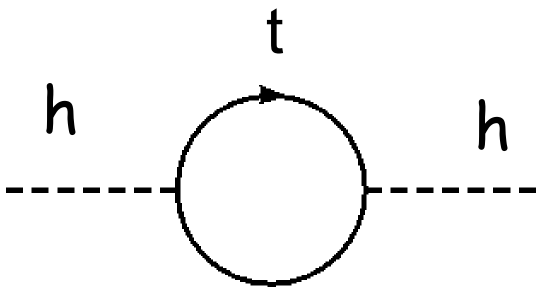
Λ = Scale for new physics beyond the Standard Model



Λ seems to be very large

Why is a light Higgs mass problematic?

Loop corrections to Higgs mass



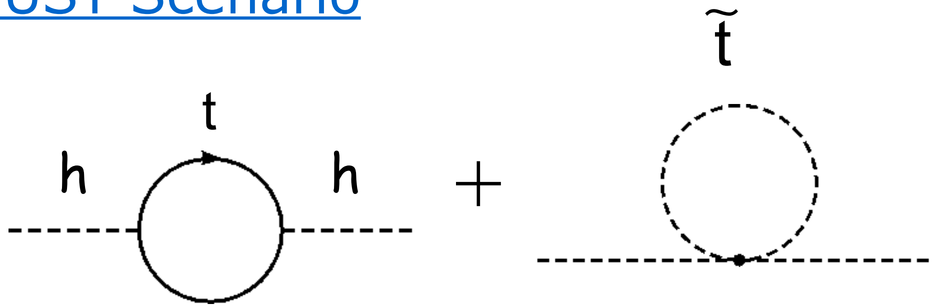
$$m_h^2 = \underbrace{m_h^2(o)}_{\text{base mass}} + \underbrace{\delta m_h^2}_{\text{loop corrections}}$$

$$\delta m_h = \sqrt{\frac{3}{2}}\,\frac{m_t}{\pi}\,\frac{\Lambda}{\Lambda_{ew}} \approx 0.3\,\Lambda$$

- Λ = scale for new physics beyond SM
- Λ_{ew} = ew scale = 244 GeV

$$\Rightarrow \quad m_h \approx \Lambda$$

The SUSY Scenario

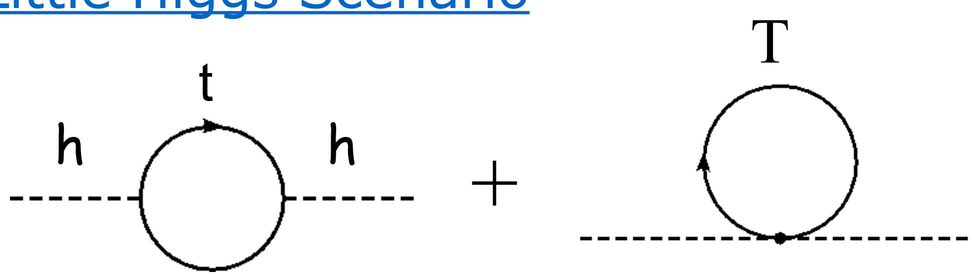


$\tilde{t}$ = spin 0 top partner

exact SUSY → $\delta m_h = 0$

broken SUSY → $\Lambda_{SUSY} \sim 1$ TeV to avoid fine tuning

The Little Higgs Scenario

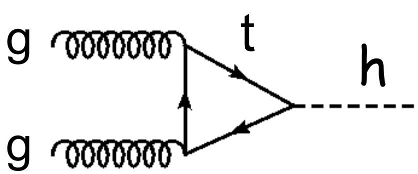


T = spin ½ heavy top

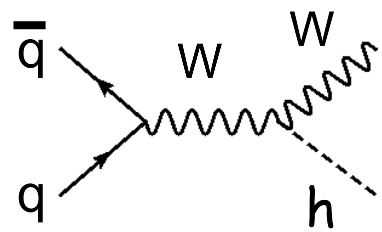
M(T) ~ 1 TeV to avoid fine tuning

Higgs production at LHC: mechanisms

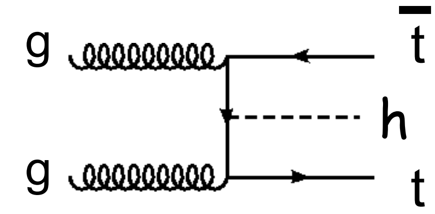
gluon-gluon fusion



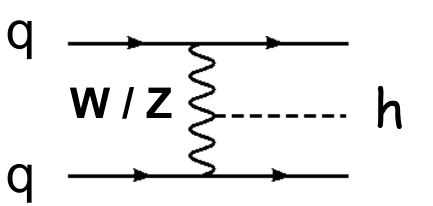
Associated prod. (W)



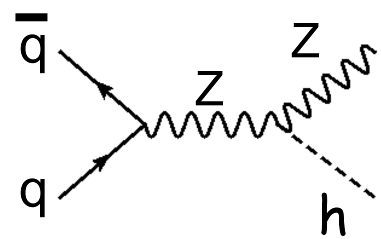
Associated prod. (t)



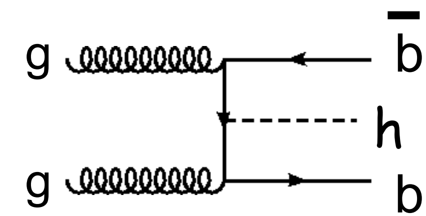
W/Z fusion (VBF)



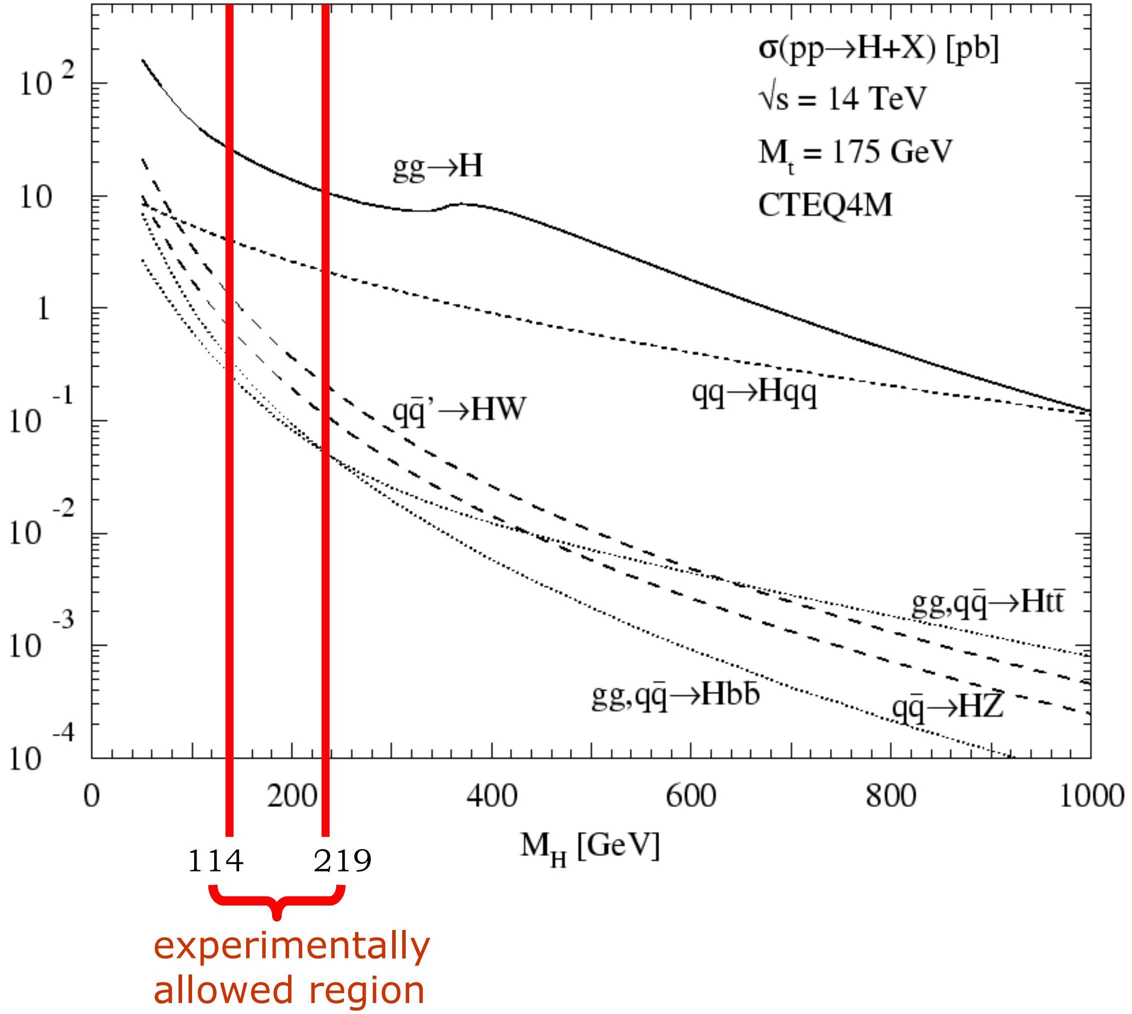
Associated prod. (Z)



Associated prod. (b)



Higgs production at LHC: Cross-sections

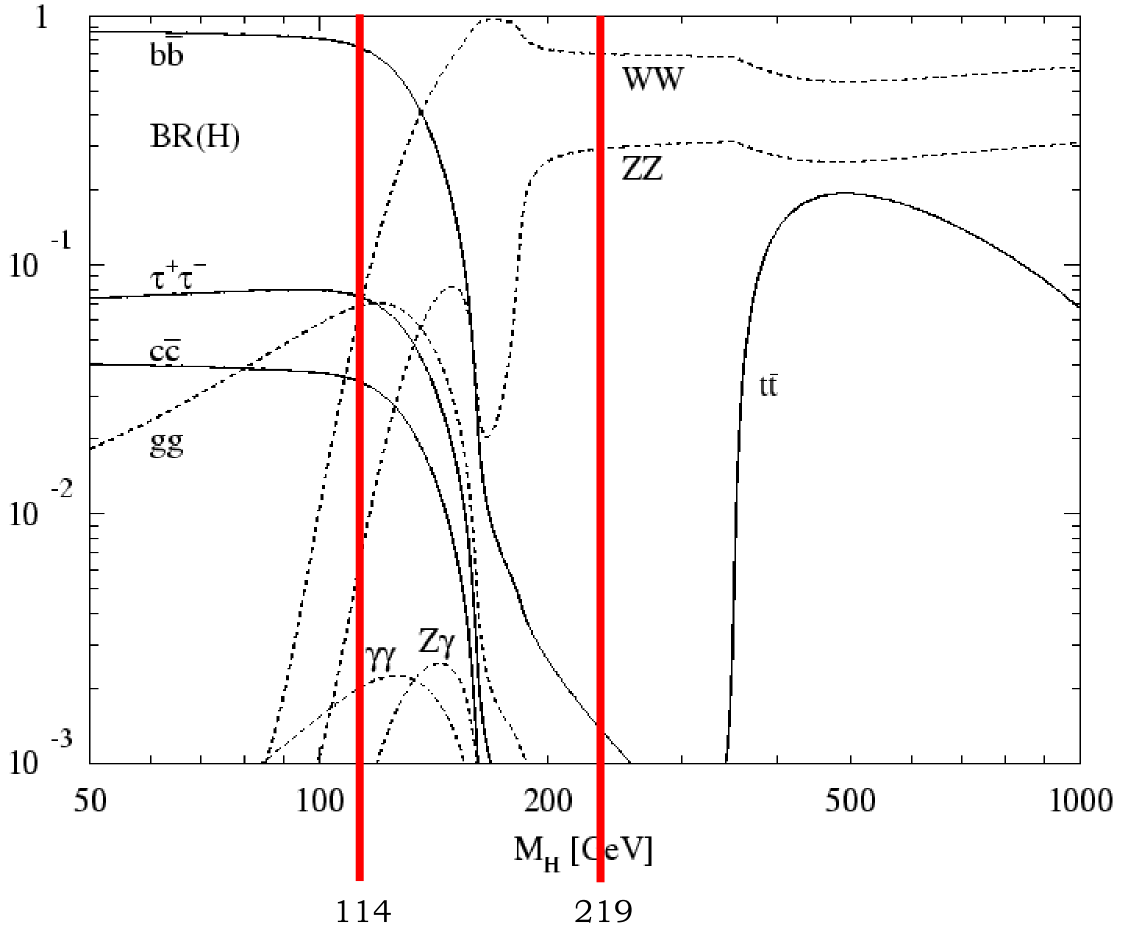


Example
m_h = 140 GeV

prod.	σ(pb)	events/year
g g → h	25	250 000
W W → h	4.0	40 000
h W	1.2	12 000
h Z	0.6	6 000
h t t	0.2	2 000
h b b	0.3	3 000

low luminosity

Branching ratios



Example
m_h = 140 GeV

decay	BR(%)
W W*	50
b b	33
Z Z*	6
g g	6
τ τ	4
c c	1
γ γ	0.2

Experimental signatures

m_h = 140 GeV

$g\,g \to h \to \gamma\gamma$

$h \to Z\,Z^* \to 4\,l$

$g\,g \to t\,\bar{t}\,h \to t\,\bar{t}\,b\,\bar{b}$

$\bar{q}\,q \to \bar{q}\,q\,h \to \bar{q}\,q\,W\,W^*$

$\to \bar{q}\,q\,\tau\,\tau$

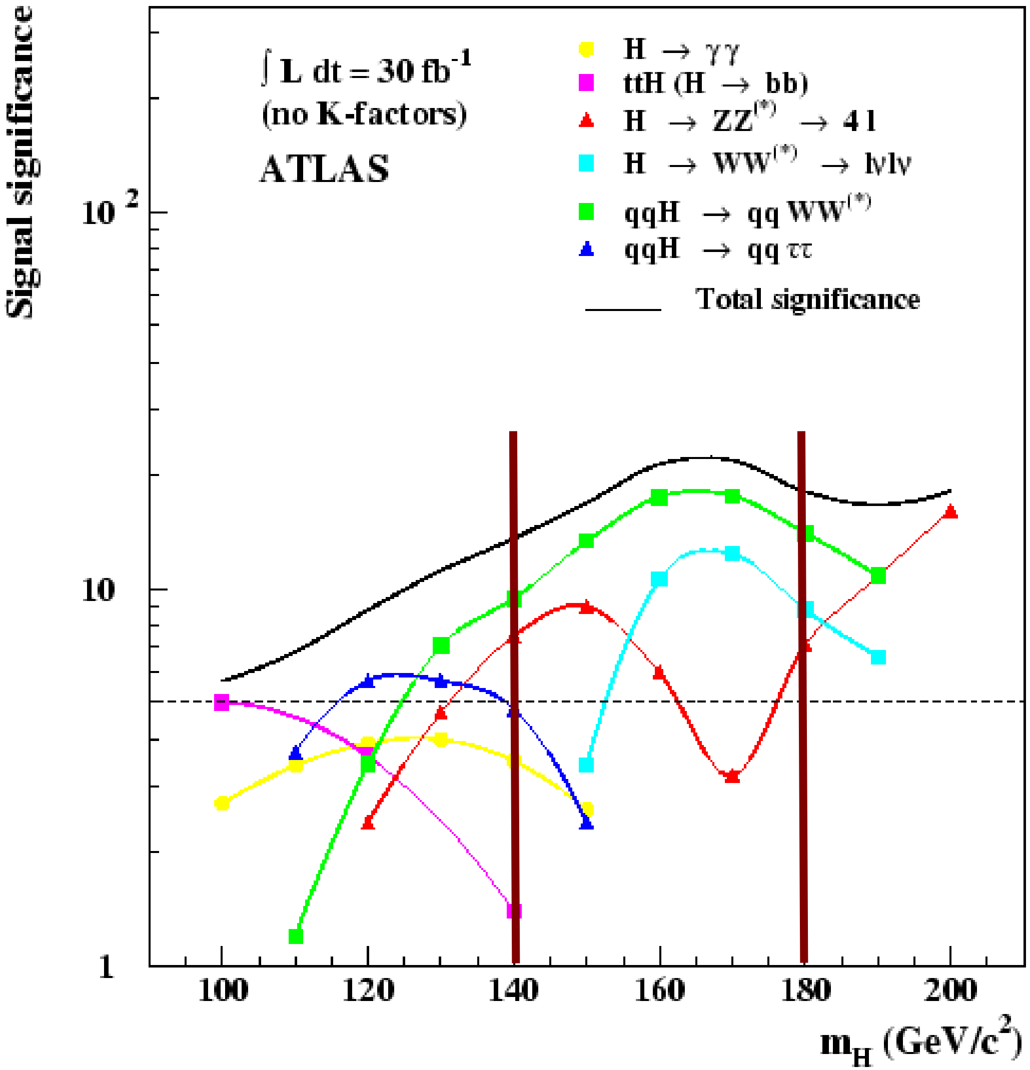
m_h = 180 GeV

$g\,g \to h \to W\,W^*$

$h \to Z\,Z^*$

$\bar{q}\,q \to \bar{q}\,q\,h \to \bar{q}\,q\,W\,W^*$

Signal significance

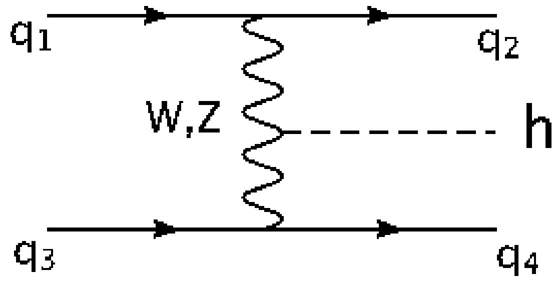


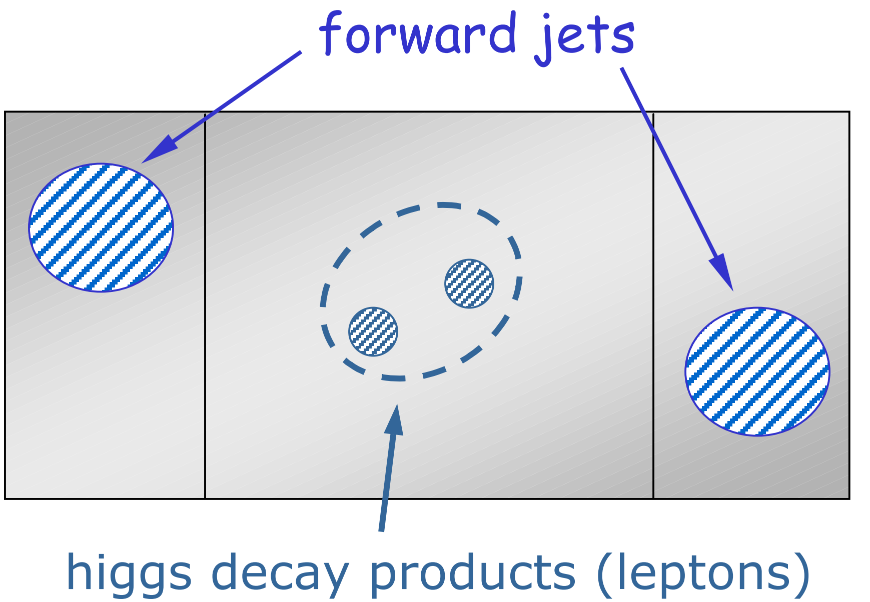
Significance $S = \frac{N(\text{signal})}{\sqrt{N(\text{bkg})}}$

$L = 30\ fb^{-1}$ = 3 years/low lumi

Discovery ⇒ S > 5

m_h=140 GeV		m_h=180 GeV	
γγ	3	WW*	9
tt bb	1	ZZ*	7
ZZ*	7		
qq WW*	9	qq WW*	13
qq ττ	5		
total S	13	total S	17





Signature:

- 2 high p_T jets with large rapidity gap
- no hadronic activity in central region

Key issues:

- trigger
- tagging of fwd/bwd jets
- central jet veto

Trigger for VBF searches

h decays: $h \to WW^* \to \ell \nu \ell \nu$

$\to \tau\tau \to \ell \nu \nu \ell \nu \nu$

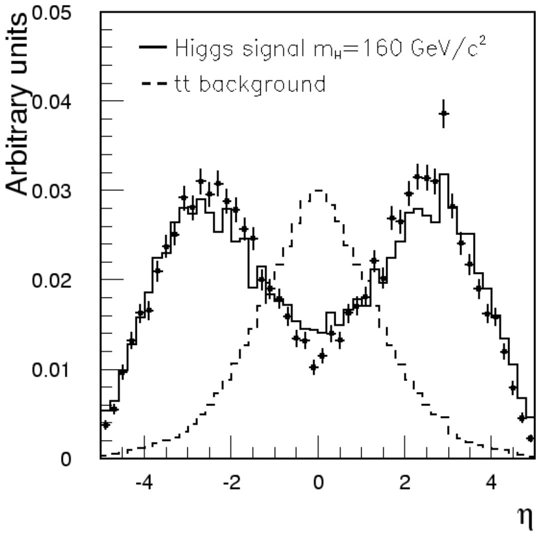
} 2 leptons

ATLAS trigger: $|\eta| < 2.5$ in all cases

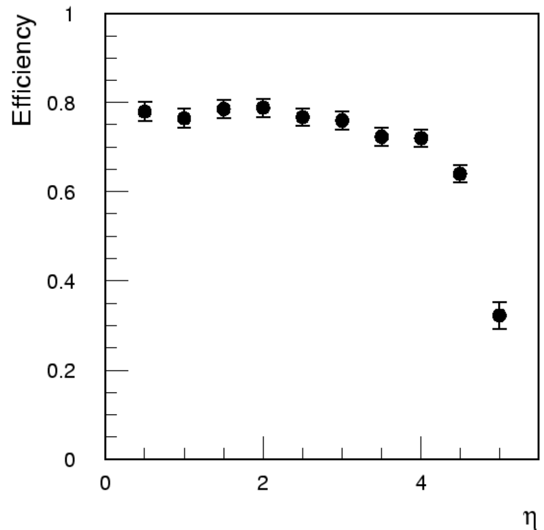
single leptons	e	$p_T > 25$ GeV
	μ	$p_T > 20$ GeV
dileptons	ee	$p_T > 15, 15$ GeV
	$\mu\mu$	$p_T > 10, 10$ GeV
	$e\mu$	$p_T > 15, 10$ GeV

Forward jets

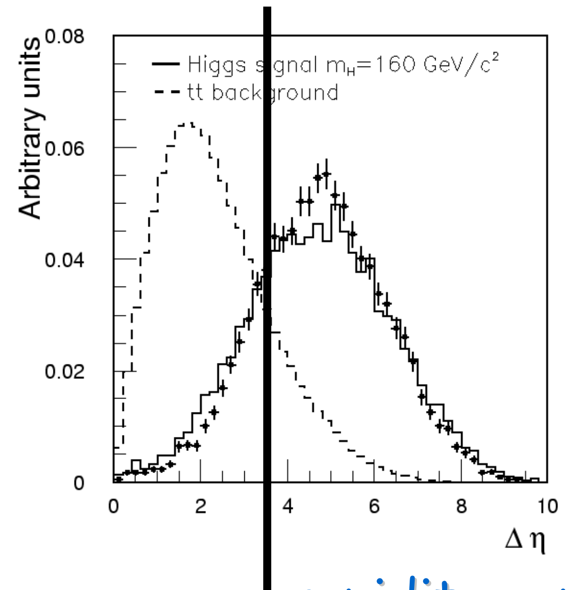
Calorimeter coverage: $|\eta| < 4.9$



Events with 2 jets with $p_T > 20$ GeV



Efficiency for reconstructing jets with $p_T > 20$ GeV



rapidity gap cut $\Delta\eta > 3.8$

jet veto

no events with a third jet with $p_T > 20$ GeV in central region ($|\eta| < 3$)

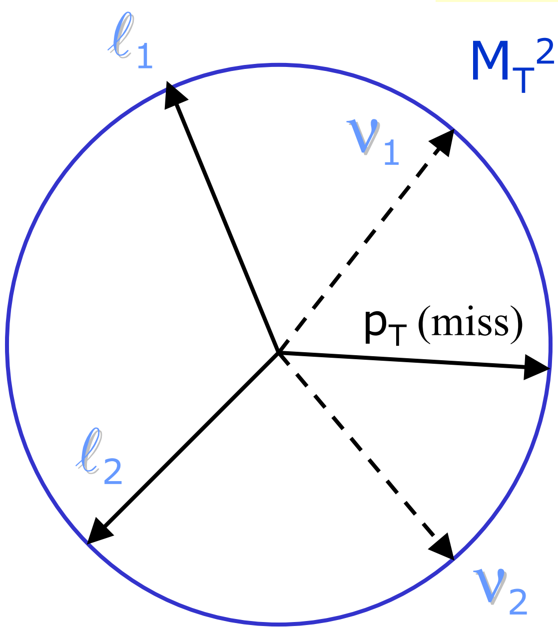
$h \to WW^*$ reconstruction

$h \to WW^* \to \ell_1 \nu_1 \ell_2 \nu_2$

Request 2 leptons + p_T (miss) > 30 GeV

only $M_T(h)$ can be reconstructed

$$M_T^2 = (E_T(\ell\ell) + E_T(\nu\nu))^2 - (\vec{p}_T(\ell\ell) + \vec{p}_T(\nu\nu))^2$$



Transverse plane

$$\begin{cases} E_T(\ell\ell)^2 = p_T(\ell\ell)^2 + m(\ell\ell)^2 \\ E_T(\nu\nu)^2 = p_T(\nu\nu)^2 + m(\nu\nu)^2 \end{cases}$$

$p_T(\nu\nu) \to p_T$(miss)

$m(\nu\nu)^2 \to \approx m(\ell\ell)^2$

$h \to WW^*$: Selection and bkg's

Example: $M_h = 160$ GeV

Selection:

jets:
- $p_T(j_1) > 40$ GeV and $p_T(j_2) > 40$ GeV
- $\Delta\eta > 3.8$ No jets with $p_T > 20$ GeV and $|\eta| < 3.2$

leptons:
- $p_T(\ell_1) > 20$ GeV and $p_T(\ell_2) > 15$ GeV and $|\eta| < 2.5$
- + angular correlations

missing energy: $|p_T(\text{miss})| > 30$ GeV

Signal vs bkg (only eμ channel)

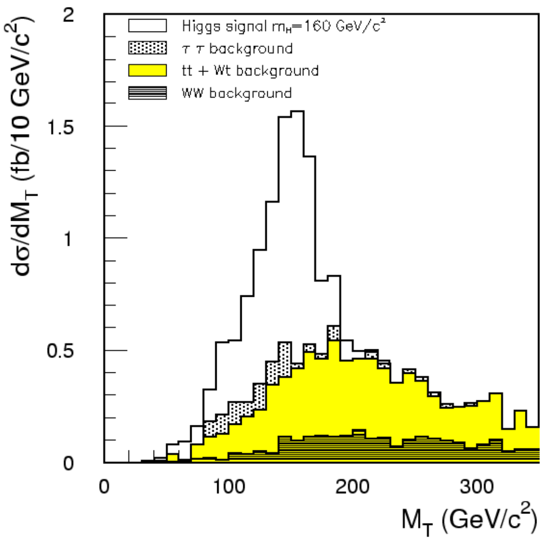
σ(fb)	Signal	tt	WW+jets	Z/γ* + jets	total bkg
before cuts	29.6	6073	14.2	6.0	-
after cuts	3.8	0.7	0.3	-	1.0

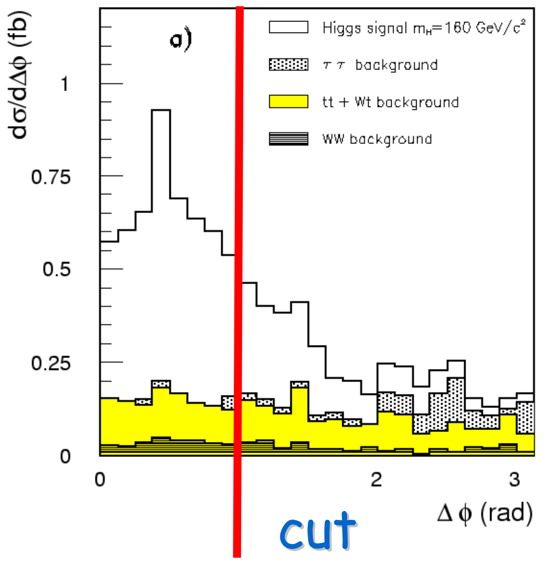
$h \to WW^*$: Signal vs bkg

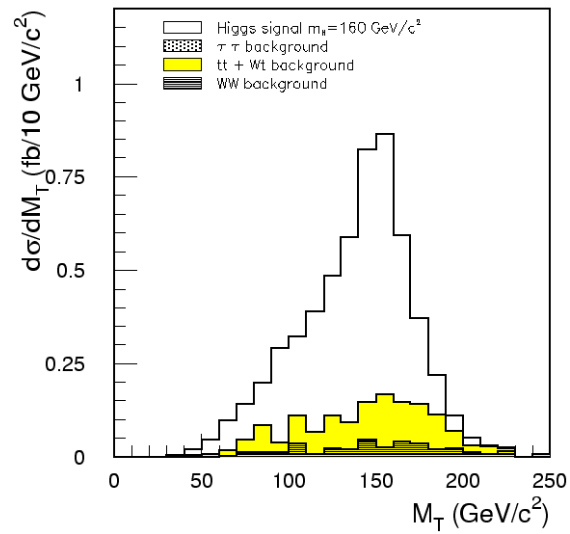
Example: M_h = 160 GeV

M_T < 175 GeV

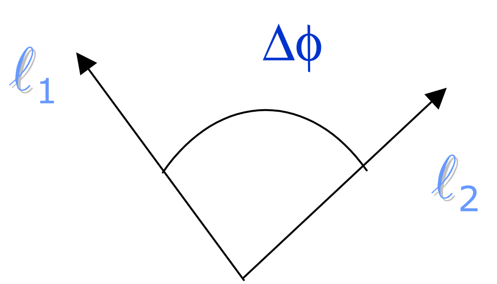
$|\Delta\phi_{\ell\ell}| < 1$







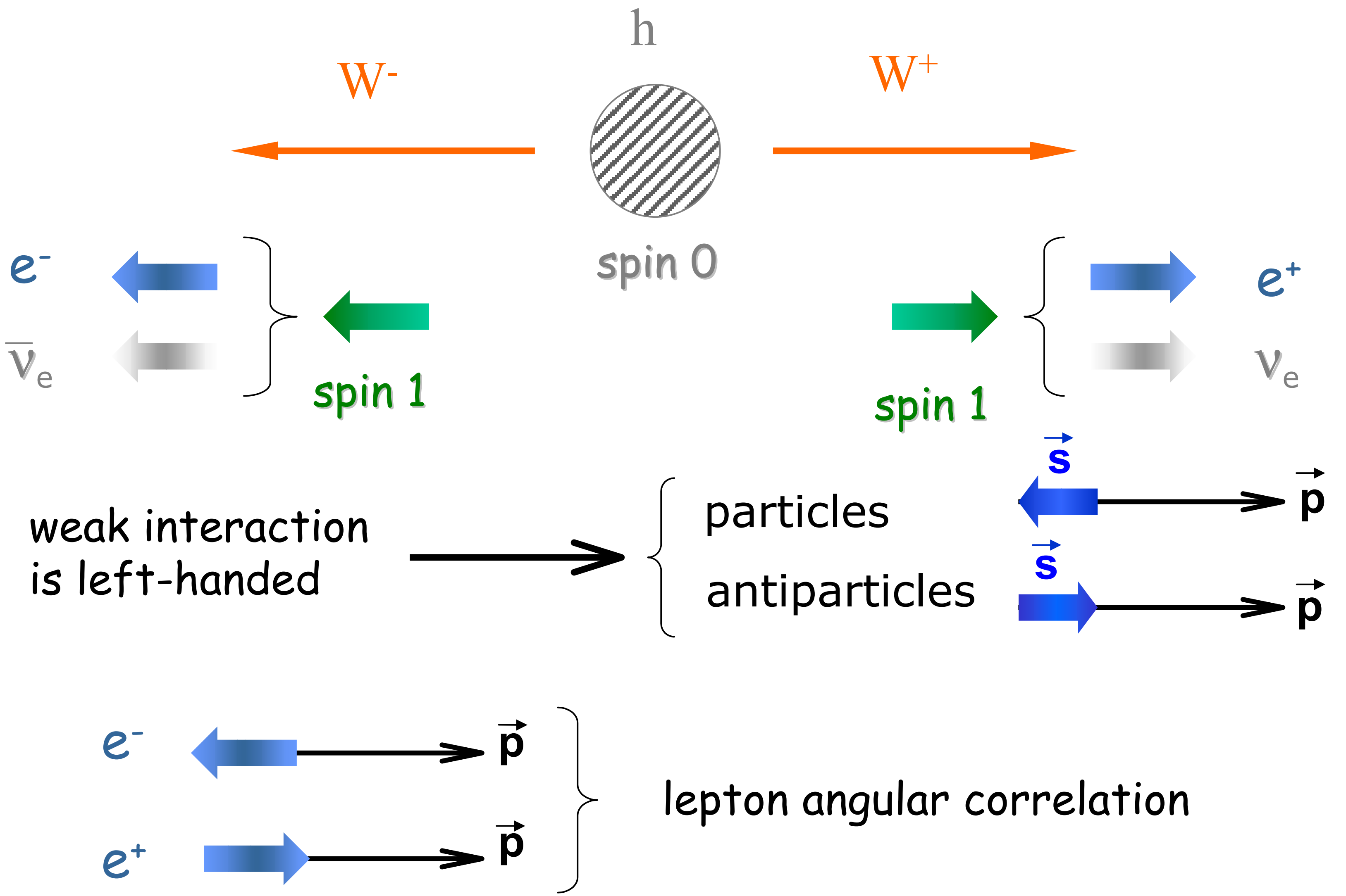
All cuts except lepton angular correlations



Transverse plane

All cuts including lepton angular correlations

$h \to WW^*$: lepton angular correlations



$h \to WW^*$: Signal significance

Example: M_h = 160 GeV
L = 10 fb^{-1}

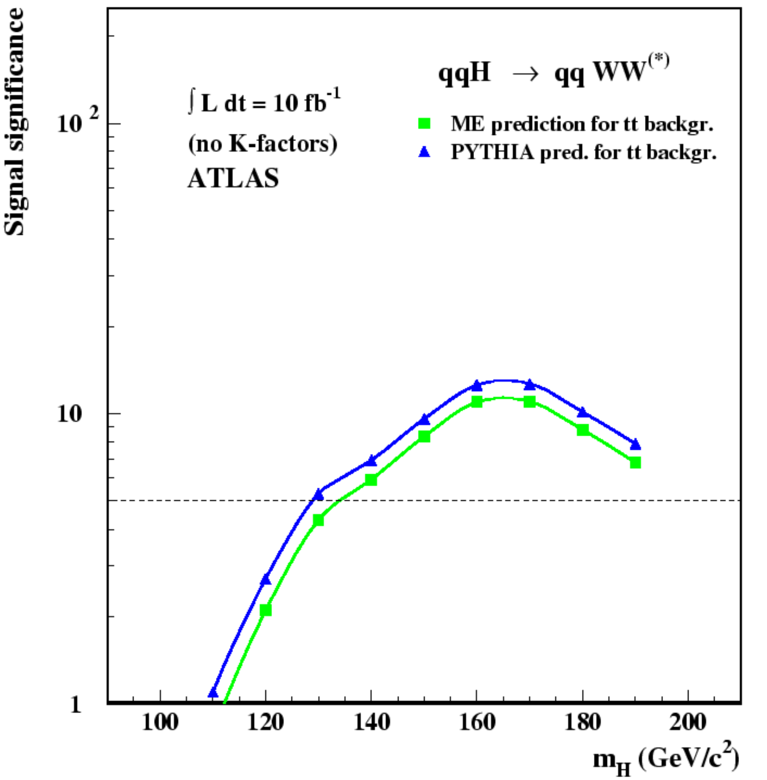
50 GeV < M_T < 175 GeV

expeted events	Signal	bkg	Signif.
$h \to WW^* \to e\mu$	42	12	8
… $\to ee + \mu\mu$	40	14	7
… $\to \ell jj$	24	18	5

- Significance calculated using Poisson statistics
- Significance includes small contribution from $gg \to h \to WW^*$

Total significance ≈ 11

$h \to WW^* \to e\mu$ / $ee + \mu\mu$ / ℓ jj

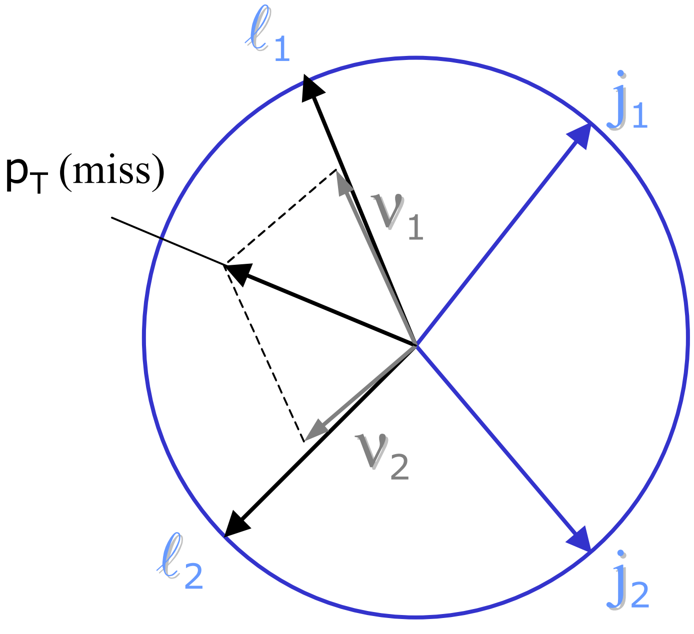


Significance > 5 for $\mathbf{M_h}$ > 130 GeV after L = 10 fb^{-1} (1 year low lumi.)

$h \rightarrow \tau\tau \rightarrow \ell_1 \nu \nu \ell_2 \nu \nu$

Request 2 leptons + p_T (miss) > 50 GeV

in this case M(h) can be reconstructed



Transverse plane

$$m_\tau = 0 \quad \begin{cases} \vec{p}_{\nu_1} = \lambda \vec{p}_{\ell_1} \\ \vec{p}_{\nu_2} = \lambda \vec{p}_{\ell_2} \end{cases}$$

$$\vec{p}_{miss} = \vec{p}_{\nu_1} + \vec{p}_{\nu_2} = \lambda_1 \vec{p}_{l_1} + \lambda_2 \vec{p}_{l_2}$$

can be solved in the transverse plane

(2 equations and 2 unknowns, λ_1 and λ_2)

$h \to \tau\tau$: Selection and bkg's

Example: M_h = 120 GeV

Selection:

jets
- $p_T(j_1) > 50$ GeV and $p_T(j_2) > 30$ GeV
- $|\Delta\eta| > 4.4$ No jets with $p_T > 20$ GeV and $|\eta| < 3.2$

leptons
- $p_T(e) > 15$ GeV $|\eta| < 2.5$
- $p_T(\mu) > 10$ GeV

2 leptons required

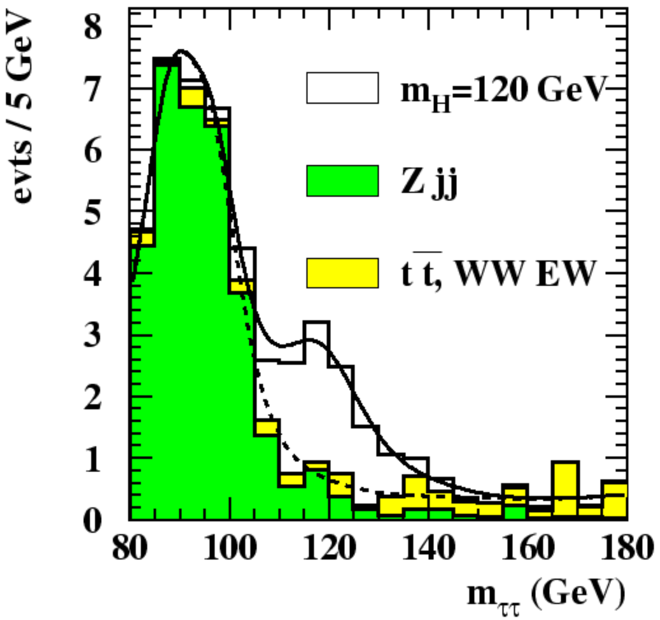
missing energy: $|p_T(\text{miss})| > 50$ GeV

Signal vs bkg (only eμ channel) 110 GeV < $M(\tau\tau)$ < 135 GeV

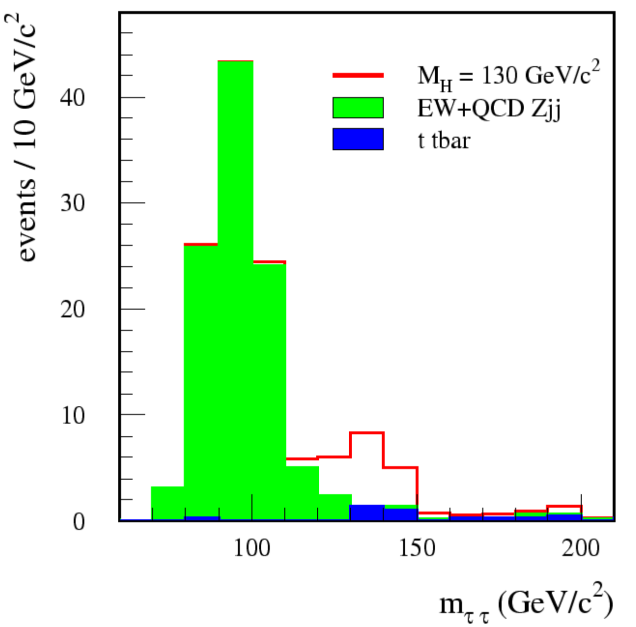
σ(fb)	Signal	tt	WW+jets	Z/γ^* + jets	total bkg
before cuts	5.6	2014	18.2	11.6	-
after cuts	0.27	0.03	0.02	0.19	0.24

$h \to \tau\tau$: signal vs bkg

eμ channel (L = 30 fb^{-1})



ℓh channel (L = 30 fb^{-1})



σ(fb)	Signal	bkg
$h \to \tau\tau \to e\mu$	0.27	0.24
… $\to ee + \mu\mu$	0.27	0.22
… $\to \ell$ h	0.52	0.27

$h \to \tau\tau$: Signal significance

Example: M_h = 120 GeV
L = 10 fb^{-1}

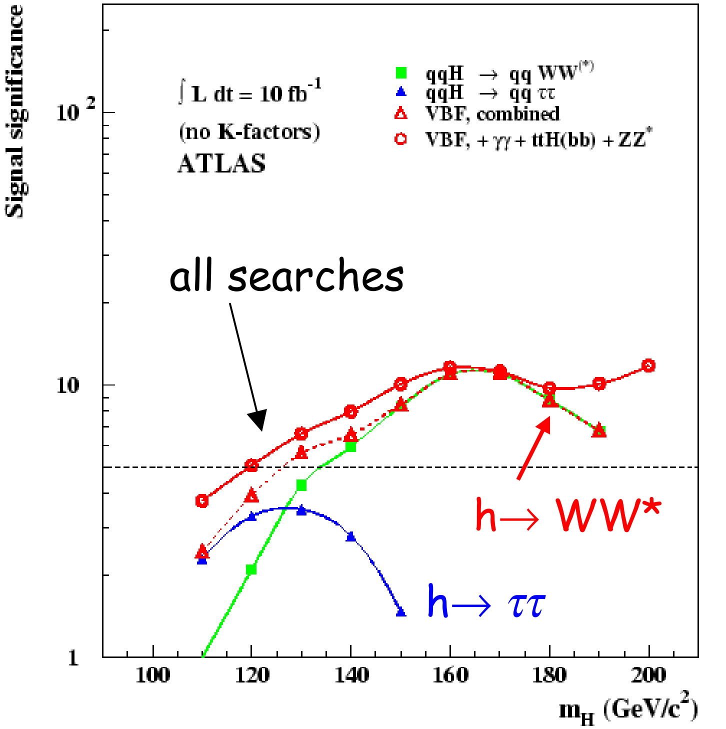
110 GeV < M($\tau\tau$) < 135 GeV

expeted events	Signal	bkg	Signif.
$h \to \tau\tau \to e\mu$	4.6	3.9	1.3
… $\to ee + \mu\mu$	4.5	3.6	1.3
… $\to \ell h$	8.5	4.2	2.3

- Significance calculated using Poisson statistics
- Significance includes small contribution from $gg \to h \to \tau\tau$

Total significance ≈ 3

$h \to \tau\tau \to e\mu$ / ee + $\mu\mu$ / ℓ h



$h \to \tau\tau$ useful if $\mathbf{M_h}$ < 130 GeV

- MSSM = Minimal Supersymmetric Standard Model
- Higgs Sector = h A H (neutral) H^+ H^- (charged)

h, H = scalars
A = pseudoscalar

mass hierarchy : $m_h < m_A < m_H$

Tree level : $m_h^2 < M_Z^2 \cos 2\beta < M_Z^2$

Only 2 free parameters = m_A, $\tan\beta$

Loop corrections: $m_h^2 < M_Z^2 \cos 2\beta + \varepsilon(M_s, M_2, \mu, X_t, m_{\tilde{g}})$

many free parameters → various scenarios

t has 2 partners ($\tilde{t}_R$, $\tilde{t}_L$) which can mix

via the mixing parameters μ, X_t

The heaviest eigenstate is called $M_{SUSY} \equiv M_S$

maximal m_h scenario: $X_t = 2\ M_S$ $\mu = -200$ GeV

No mixing scenario: $X_t = 0$ $\mu = -200$ GeV

In both cases, all other free parameters fixed:

$M_S = 1$ TeV (Stop mass)

$M_2 = 200$ GeV (Gaugino mass)

$m_{\tilde{g}} = 800$ GeV (Gluino mass)

Many other scenarios are possible

LEP Results (1)

Direct production limits

$e^+e^- \rightarrow hZ \qquad \sigma \sim \sin^2(\beta - \alpha)$

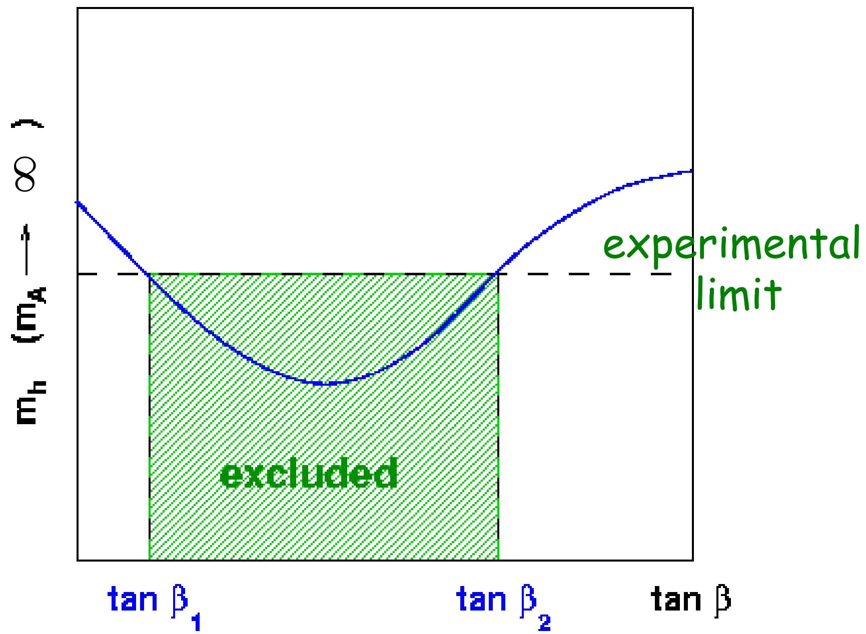
$e^+e^- \rightarrow hA \qquad \sigma \sim \cos^2(\beta - \alpha)$

$h \rightarrow b\bar{b}, \tau^+\tau^-$

$m_h > 91$ GeV

Rather scenario independent

Indirect limits



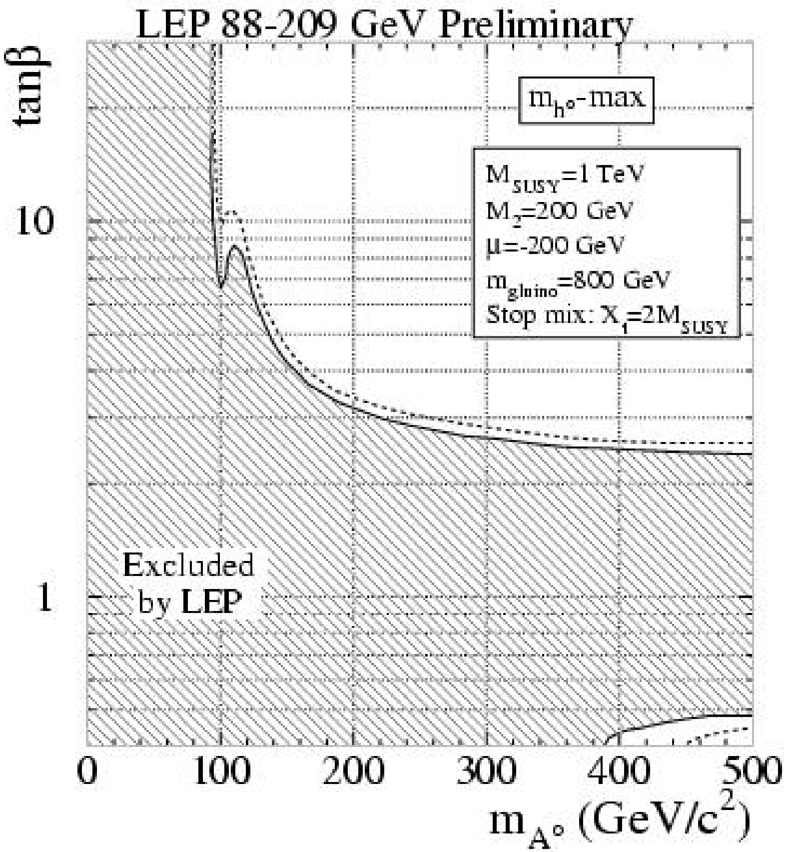
excluded regions $(m_A \rightarrow \infty)$

m_h - max scenario: $0.5 < \tan\beta < 2.4$

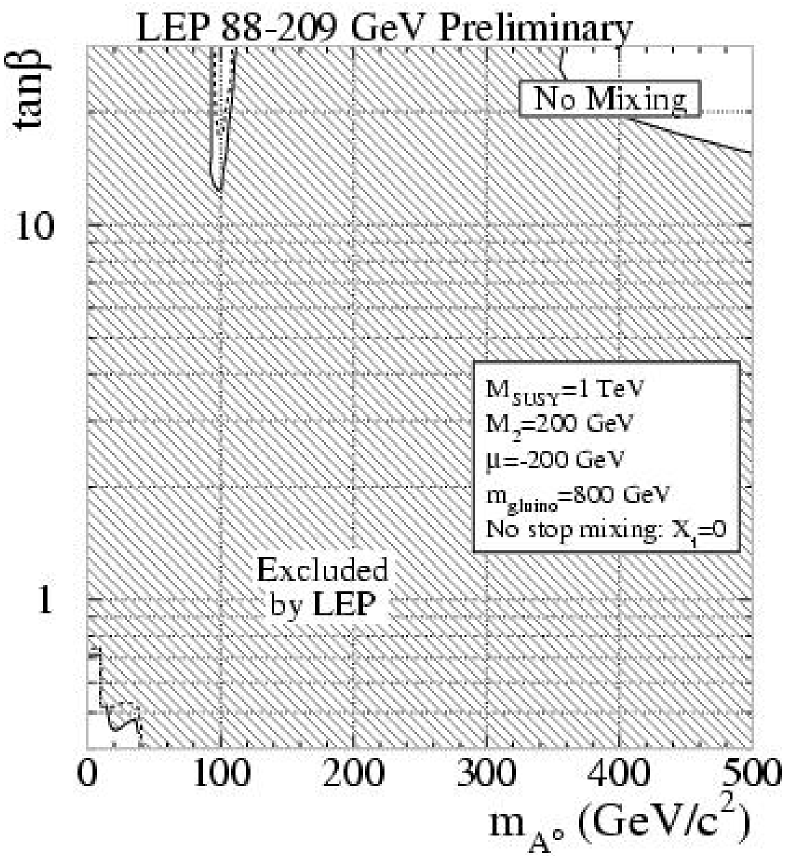
No_mix scenario: $0.7 < \tan\beta < 10.5$

LEP Results (2)

m_h - max scenario

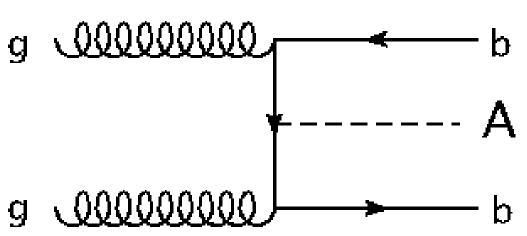


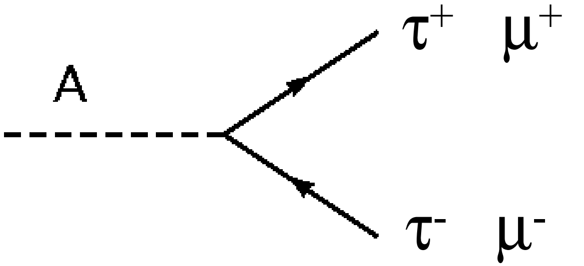
No mix scenario



- use m_h-max as benchmark scenario
  → look for large tan β values
- use SM channels to look for <u>h</u>
  → reinterpretation of results in M_A-tan β plane
- In addition to h, look for A
  (and if possible also for H^0, H^+, H^-)

$$\text{A couplings to fermions} = \left\{ \begin{array}{ll} 1/\tan\beta & (u) \\ \tan\beta & (d,l) \end{array} \right\} * \text{h (SM) couplings to fermions}$$

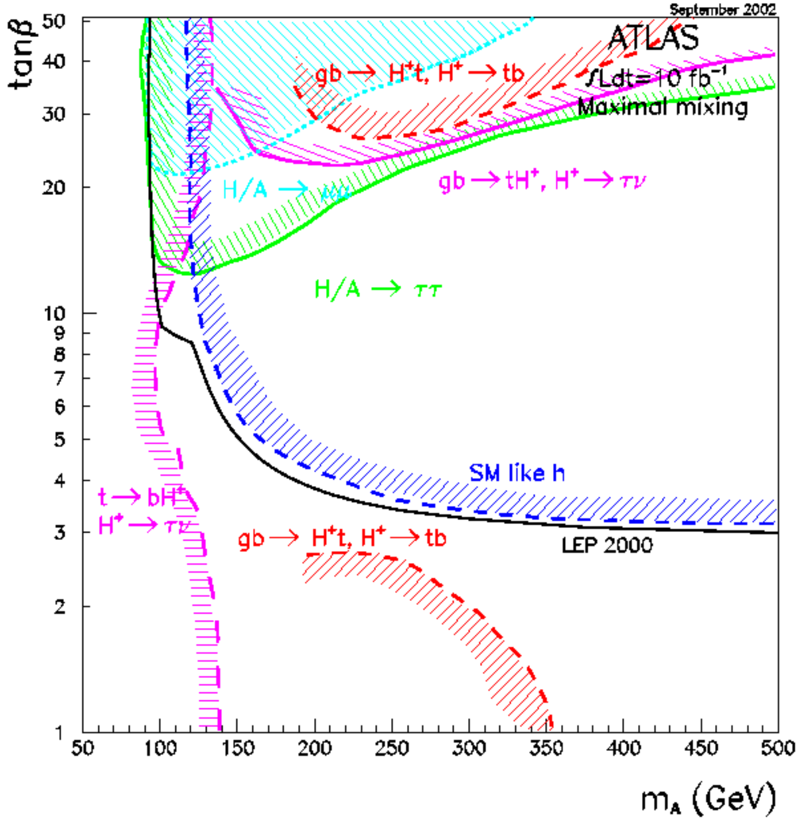




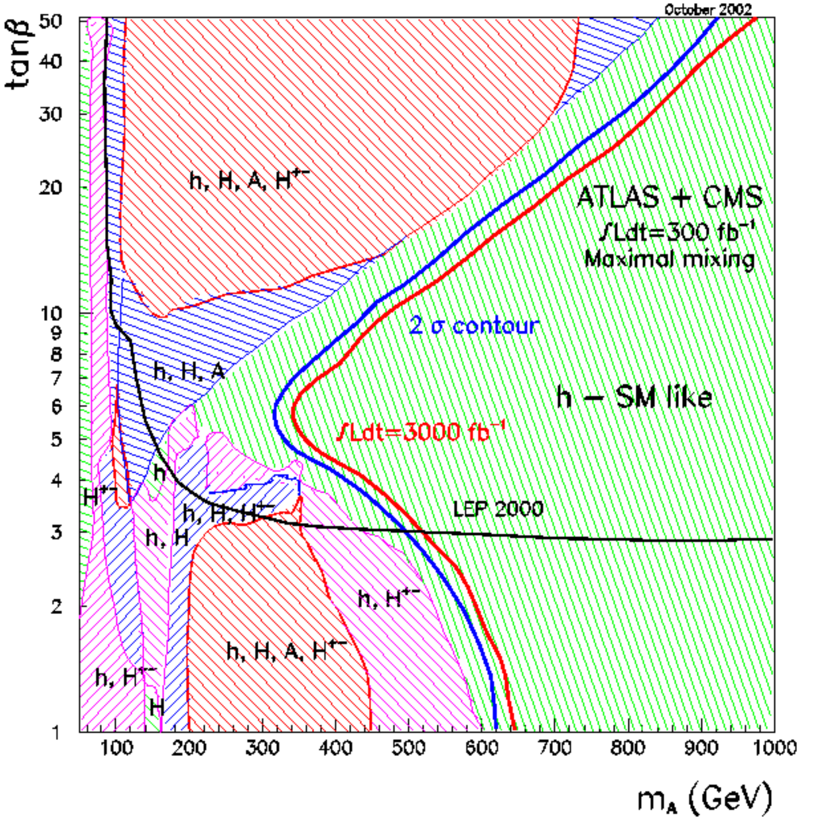
<u>production</u> <u>decay</u>

MSSM : expected performance at LHC

A exclusion plot



Search for h, A, H, H⁺, H⁻



→ max m_h scenario can be excluded at LHC
(But over large m_A – tan β region only possible to find h)

MSSM : More exotic scenarios

$gg \rightarrow h$ suppressed

$h \rightarrow b\bar{b}, \tau\tau$ suppressed

	mh - max	gluophobic	small α_{eff}
M_s	1 TeV	350 GeV	800 GeV
X_t	2 M_s	- 750 GeV	- 1.1 TeV
μ	- 200 GeV	- 200 GeV	2.5 M_s

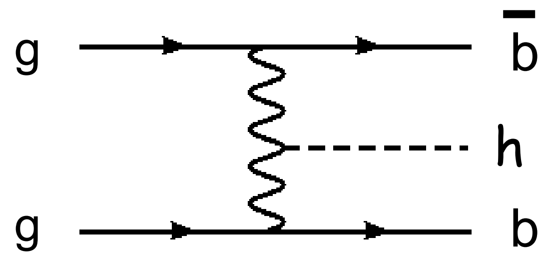
Even more exotic scenarios

$h \rightarrow \tilde{\chi}^0\,\tilde{\chi}^0$ (stable neutralinos)

$\rightarrow$ invisible Higgs

$\rightarrow$ look for channels with large $\not{E}_T$

ME approach (2 → 3)

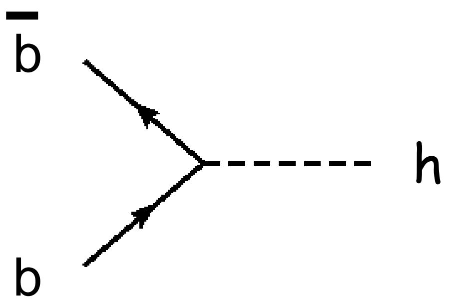


$$\sigma(s) = \int dx_1 dx_2 f_g(x_1) f_g(x_2) \sigma_{gg}(s x_1 x_2)$$

Spira, Krämer, Dittmaer

LO, NLO

Shower approach (2 → 1)



$$\sigma(s) = \int dx_1 dx_2 f_b(x_1) f_b(x_2) \sigma_{bb}(x s_1 s_2)$$

Dicus, Stelzer, Sullivan, Willenbrock

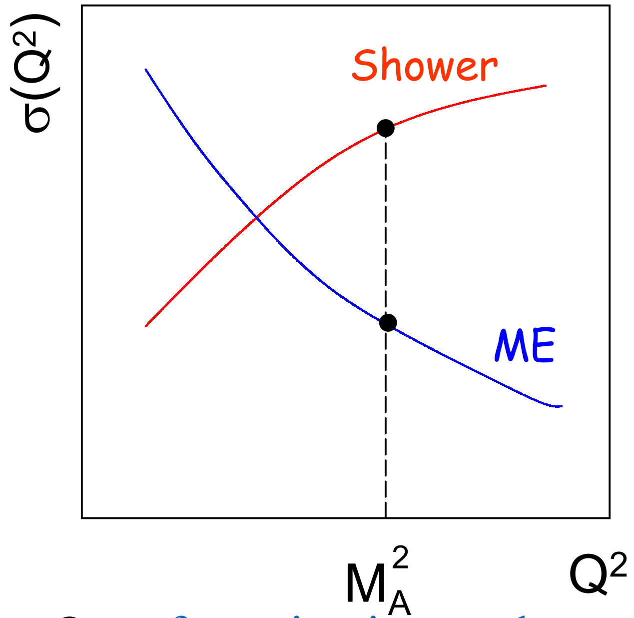
LO, NLO

The X-section for bbh production

LO

$$\sigma = \int dx_1 dx_2\, f_i(x_1) f_j(x_2)\, \sigma_{ij}(s x_1 x_2)$$

$$f \equiv f(x, Q_F^2) \qquad \sigma_{ij} \equiv \sigma_{ij}(Q_R^2)$$



Q_F = factorization scale

Q_R = Renormalization scale

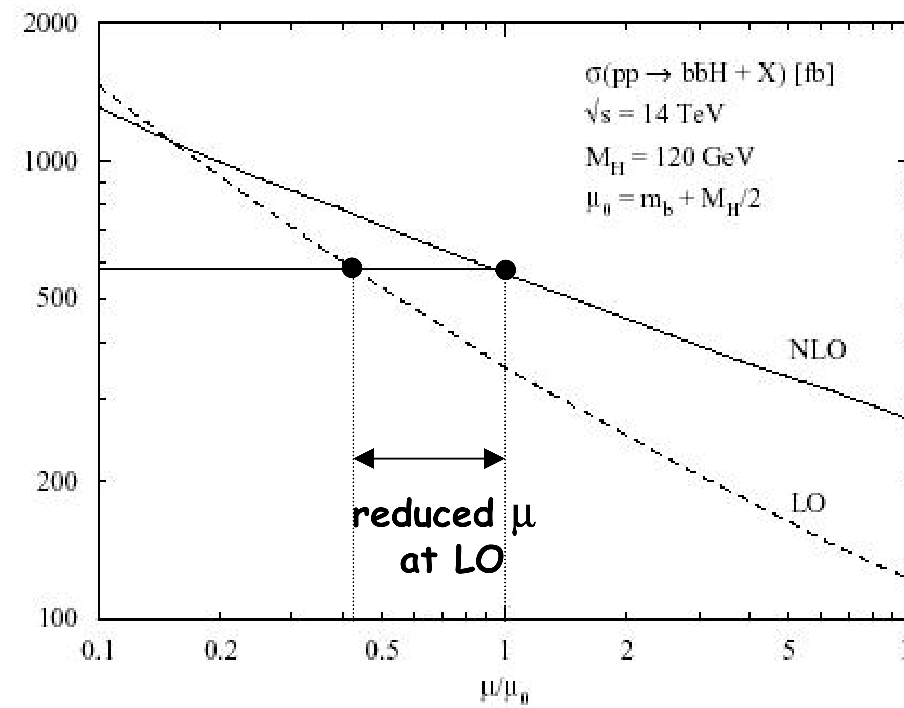
$Q_R^2 = Q_F^2 = Q^2$

NLO

hep-ph/0309204

Dittmaer, Kramer, Spira

$q\bar{q}$, gg → $b\bar{b}$h at NLO



‘ Subtle is the Lord, but not malicious ’

A. Einstein

If the Higgs boson does not exist, let us hope that there is something very similar.