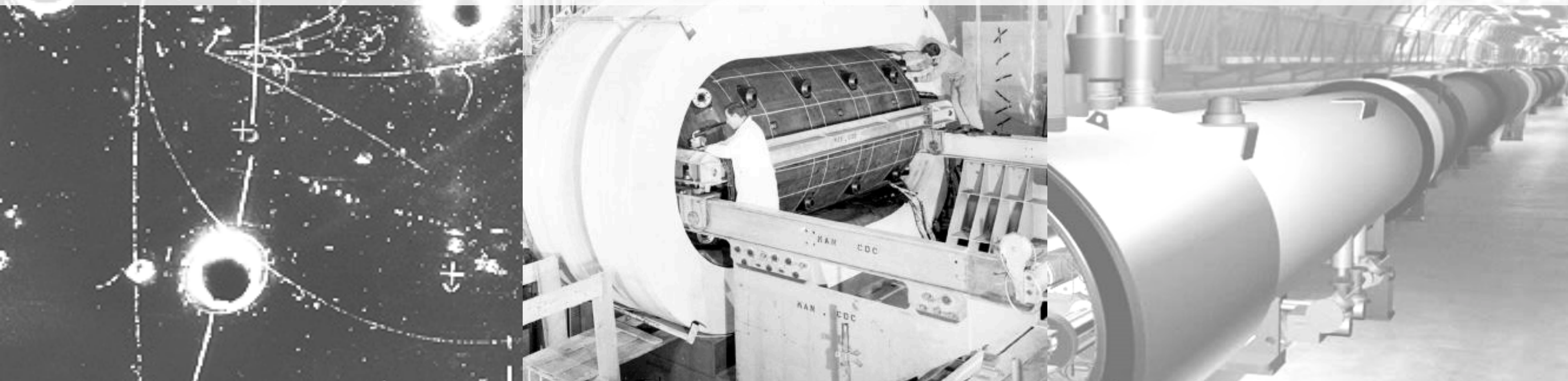
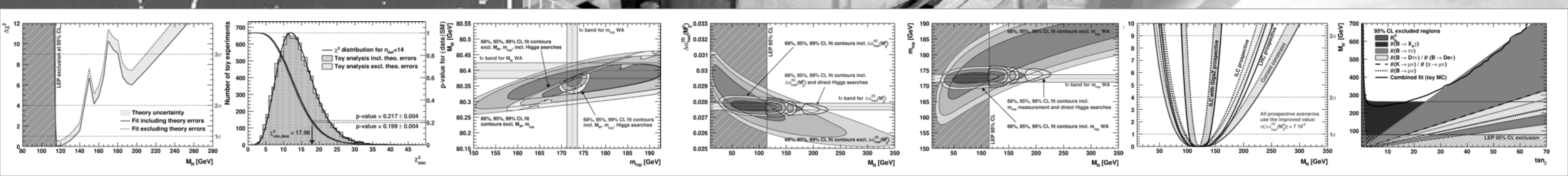
Introduction to Higgs and Electroweak Precision Physics (II)

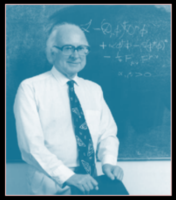
Andreas Hoecker (CERN)

Cargèse 2010: Physics at TeV Colliders – From Tevatron to LHC





Higgs Boson Properties



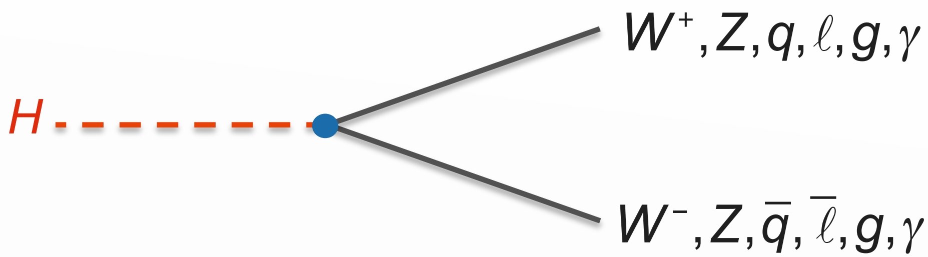
Higgs coupling to fermions and gauge bosons proportional to mass:

$$g_{Hff} = -ig \frac{m_f}{2M_W}$$

$$g_{HVV} = \begin{cases} igM_W & \text{for } V = W \\ ig \dfrac{M_Z}{\cos\theta_W} & \text{for } V = Z \end{cases}$$

Higgs Boson Decays

The Higgs decay branching fractions are predicted by the SM …



…as a function of the Higgs mass

Because of the coupling to the mass of the decay particles:

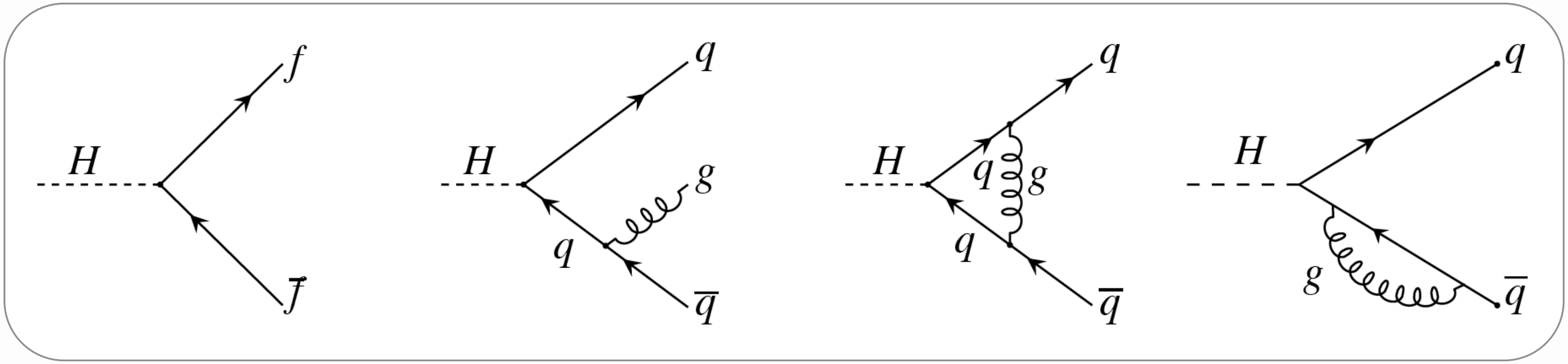
- … the Higgs will decay with preference to the heaviest particles allowed by phase space.
- … the Higgs does not couple directly to photons and gluons, but only via triangular loops involving heavy intermediate states (*e.g.*, top, *W*)

Higgs Boson Decay into Fermion Pair

Decay width of Higgs to two fermions:

$$\Gamma_{LO}(H \to f\bar{f}) = \frac{G_F N_C}{4\sqrt{2}\pi} M_H m_f^2 \beta_f^3$$

where $N_C = 3(1)$ for quarks (leptons), $\beta^2 = 1 - 4m_f^2/M_H^2$ is the fermion velocity in the Higgs rest system, suppressing this decay at threshold.



Leading and next-to-leading order $H \to f\bar{f}$ diagrams

Hadronic decays require NLO calculation: parts of the large higher order logarithms can be absorbed by using a running quark mass instead of the pole mass, reducing Γ_{LO} by factor of 4 (not for top quark). NLO corrections increase Γ_{LO} by 20%.

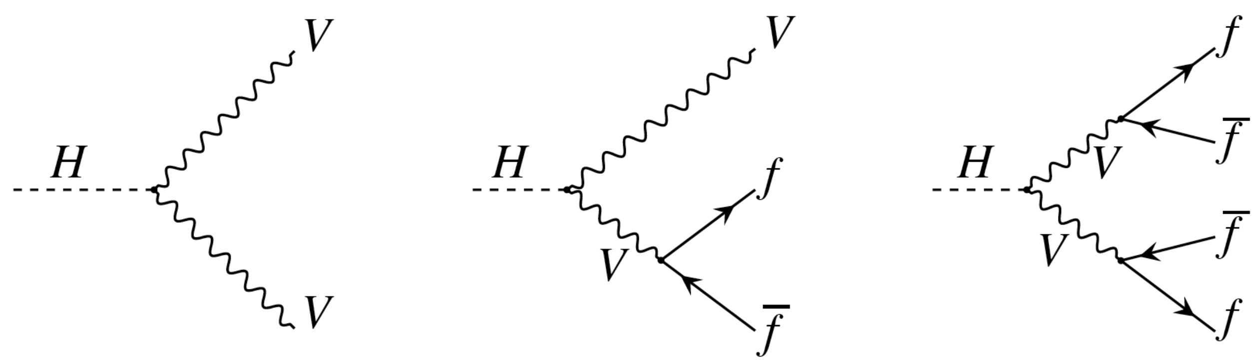
Higgs Boson Decay into Weak Bosons

For M_H > 160 GeV, the Higgs decays dominantly to W or Z pairs

$$\Gamma(H \to VV) = \frac{G_F}{16\sqrt{2}\pi} M_H^3 \cdot \delta_V \cdot \beta_V \cdot \left(1 - 4x^2 + 12x^4\right)$$

where $\delta_W = 2$, $\delta_Z = 1$, and $x = M_V / M_H$. For heavy Higgs: $\Gamma(H \to WW) \approx 2\Gamma(H \to ZZ)$.

A heavy Higgs is also very broad: $\Gamma(H \to WW + ZZ) \approx 0.5$ TeV $(M_H / 1\ \text{TeV})^3$, with $\Gamma \approx \Gamma_L$



Higgs decaying into 2 real and/or virtual weak bosons

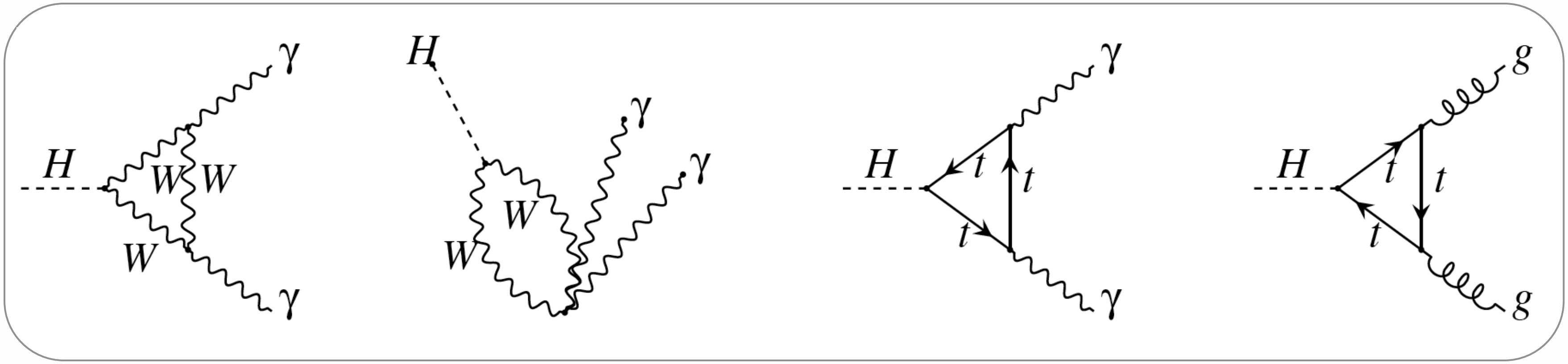
Below threshold, the Higgs decays as $H \to VV^* \to Vff$, ie, as a 3-body decay

Higgs Boson Decay into Photon Pair

Indirect coupling to photons (and gluons) through heavy charged loop

$$\Gamma(H \to \gamma\gamma) = \frac{G_F \alpha^2}{128\sqrt{2}\pi^3} M_H^3 \cdot \left| \sum_f N_C Q_f^2 A_{1/2}^H(\tau_f) + A_1^H(\tau_W) \right|^2$$

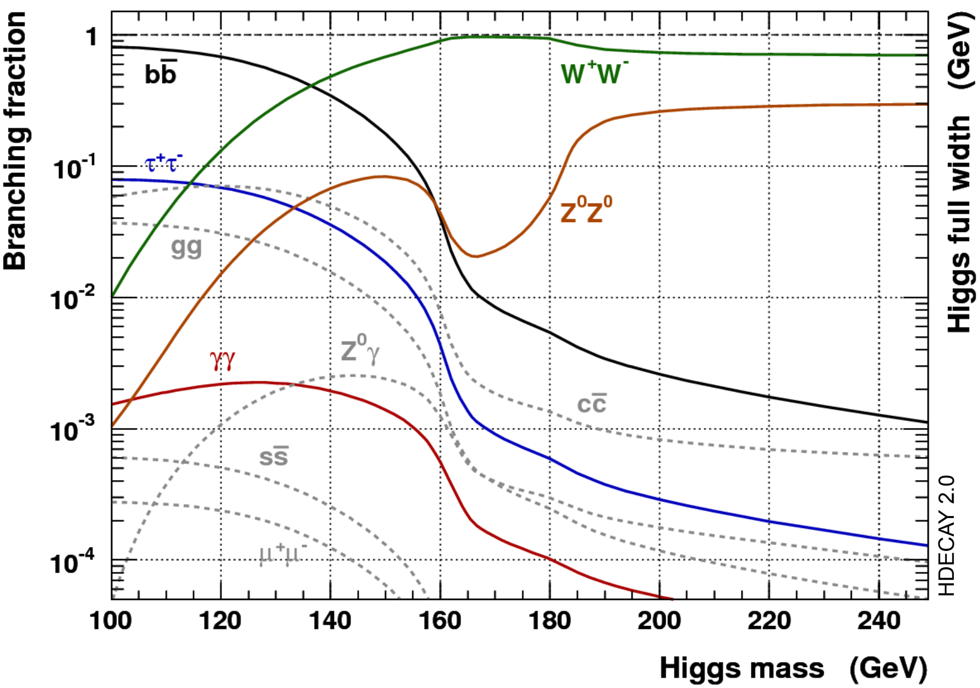
where the $A_{1/2(1)}$ are form factors for spin ½ (1) particles. The W loop dominates Γ.

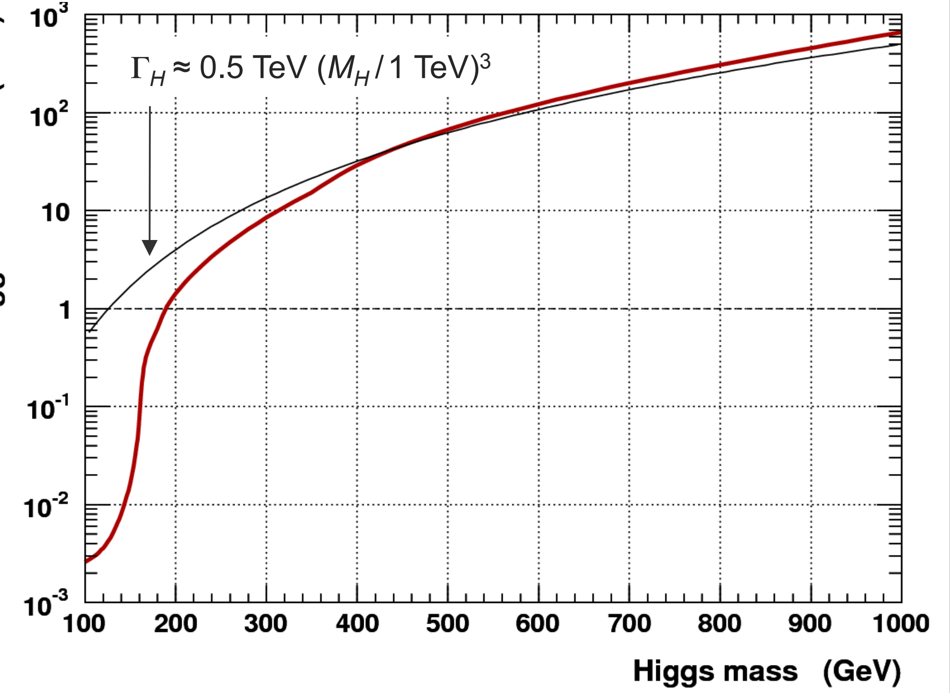


Higgs decaying into 2 photons or gluons

Summary of Higgs Boson Decays

Higgs branching fractions and full width as function of Higgs boson mass





Golden search modes:

- $H \to \gamma\gamma$: rare, but clean (low mass only)
- $H \to WW^{(*)}$: abundant, but not clean
- $H \to ZZ^{(*)}$: sizable branching fraction, and clean

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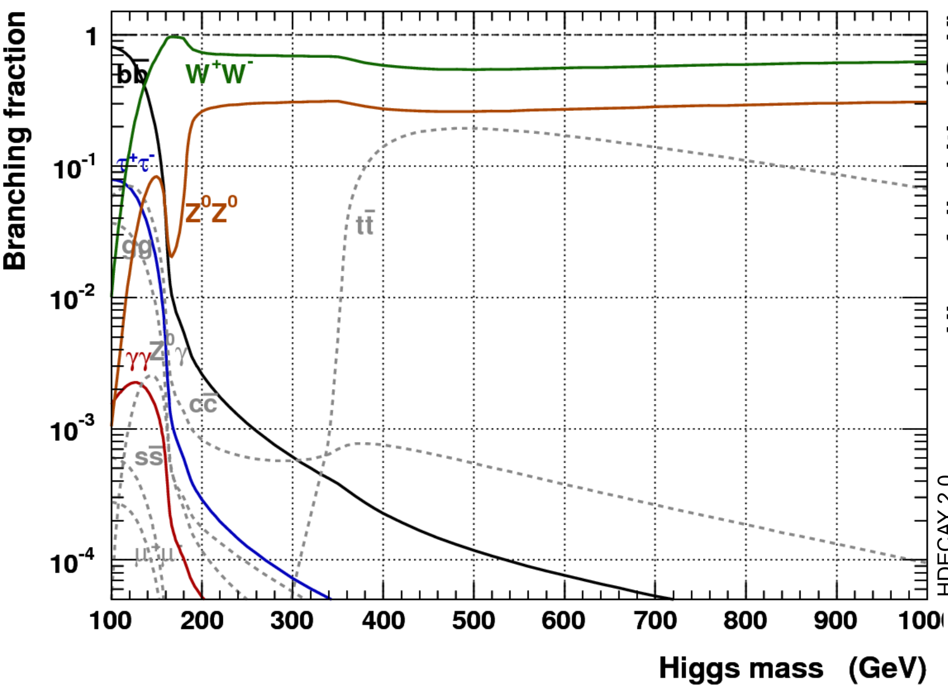

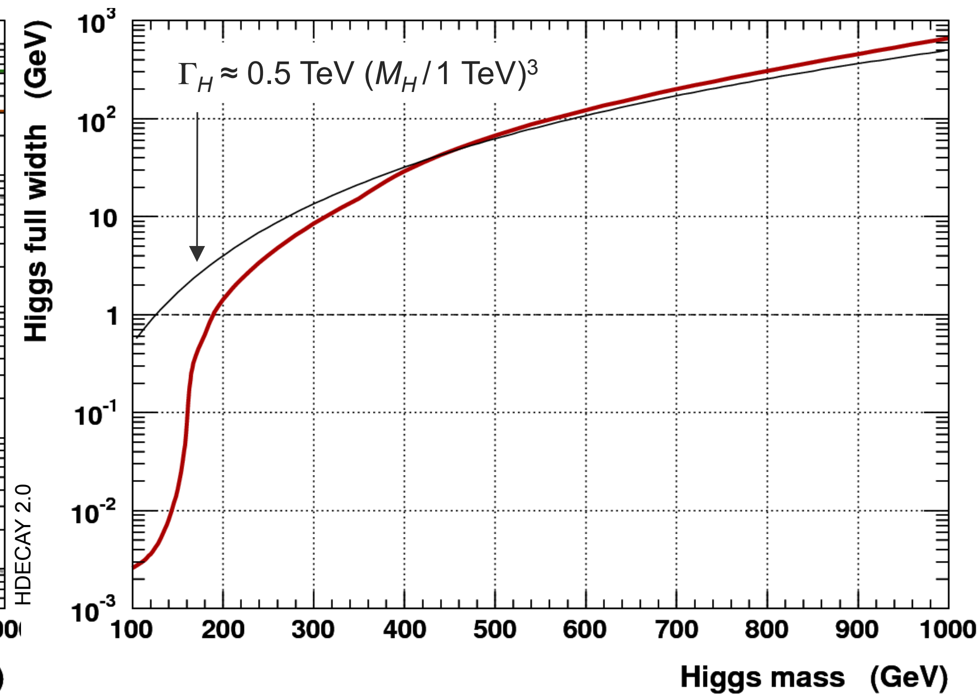

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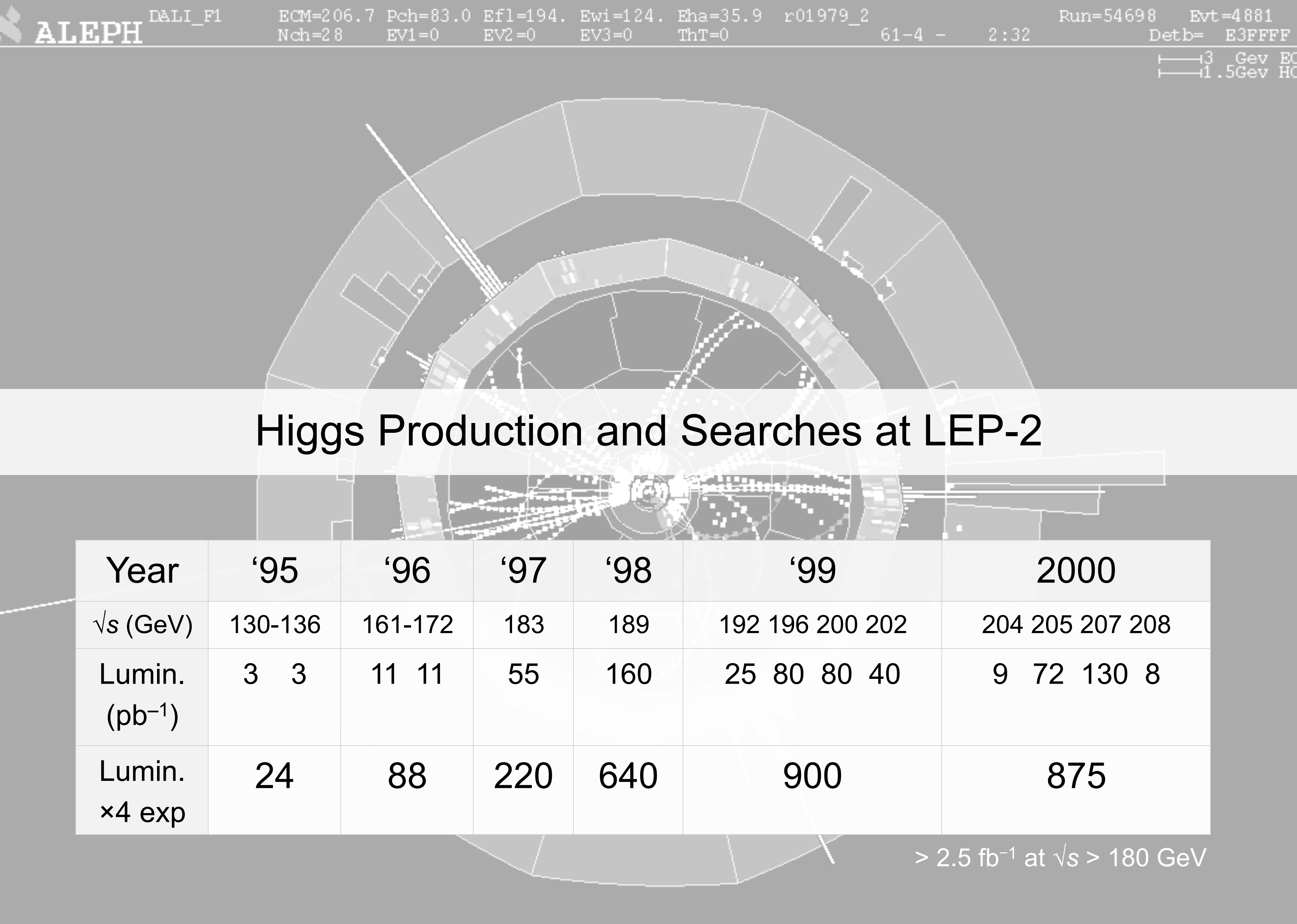


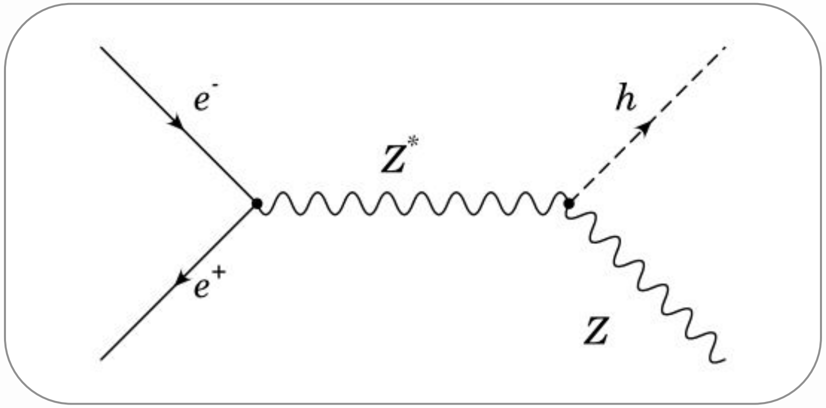
Higgs Production and Searches at LEP-2

Year	‘95	‘96	‘97	‘98	‘99	2000
$\sqrt{s}$ (GeV)	130-136	161-172	183	189	192 196 200 202	204 205 207 208
Lumin. (pb^{-1})	3 3	11 11	55	160	25 80 80 40	9 72 130 8
Lumin. ×4 exp	24	88	220	640	900	875

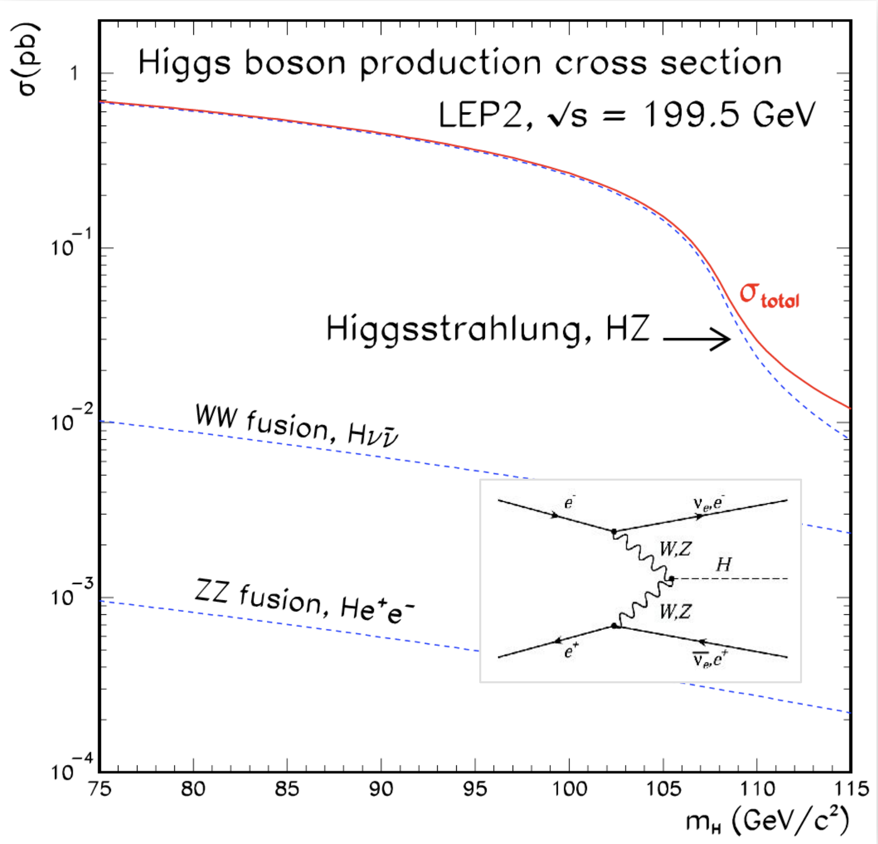
> 2.5 fb^{-1} at $\sqrt{s}$ > 180 GeV

Higgs Production in e^+e^- Annihilation

At the LEP e^+e^- collider Higgs bosons are dominantly produced via $H + Z$ Higgs-strahlung (dominant, but requires $M_H < \sqrt{s} - M_Z$), and W/Z fusion



Higgs production at LEP. Higgs-strahlung diagram



Explored energy range: $\sqrt{s}$ = 60 – 115 GeV

Higgs branching fractions for M_H = 115 GeV:

- BR ($H \to bb$) = 74%
- BR ($H \to \tau\tau$, WW, gg) = 7% each
- BR ($H \to cc$) = 4%

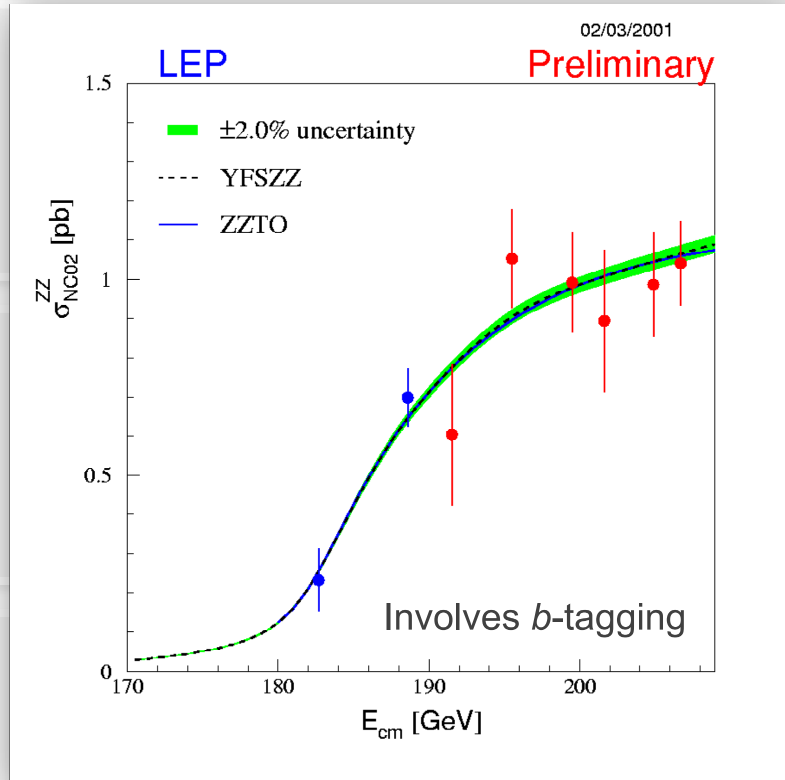
Higgs Searches at LEP

Signal topologies … and Background:

Signal topologies	Background
Four-jet channel: $Z \to qq \;\; H \to bb$ 70% × 80% > 50% Kinematics & *b*-tag	***ZZ* "irreducible background"** $Z \to qq \,/\, \nu\nu \,/\, ll \;\; Z \to bb$ σ ~1 pb (× 30% if *bb*) "The Reference"
Missing energy channel: $Z \to \nu\nu \;\; H \to bb$ 20% × 80% > 15% Energy flow & *b*-tag	***WW* background** $WW \to qqqq \quad WW \to qq\tau\nu$ σ ~18 pb "No *b*-tag (except Vcb)"
Leptonic channels: $Z \to ll\,(e/\mu/\tau) \;\; H \to bb$ $Z \to qq \;\; H \to \tau\tau$ (70% × 7% ~5%) Lepton id (& *b*-tag)	**Two fermion (Z/γ) background** ISR (single/double) QCD: *qq* (*g*)(*g*)

Higgs Searches at LEP

Signal topologies … and Background:



Lepton id (& *b*-tag)

ZZ "irreducible background"

$Z \to qq\ /\ \nu\nu\ /\ ll\ \ Z \to bb$

σ ~1 pb (× 30% if *bb*)

"The Reference"

WW background

$WW \to qqqq \quad WW \to qq\tau\nu$

σ ~18 pb

"No *b*-tag (except Vcb)"

Two fermion (Z/γ) background

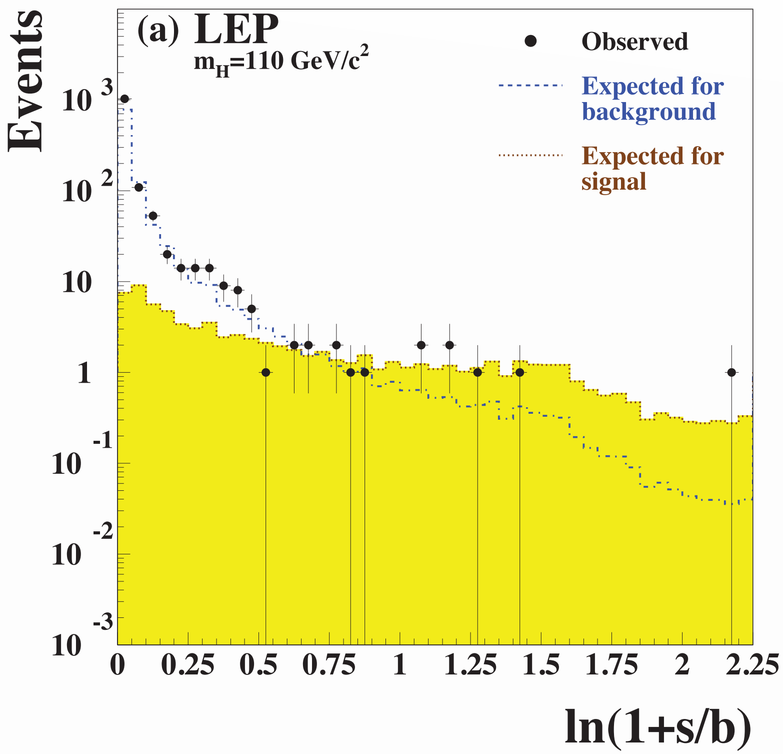
ISR (single/double)

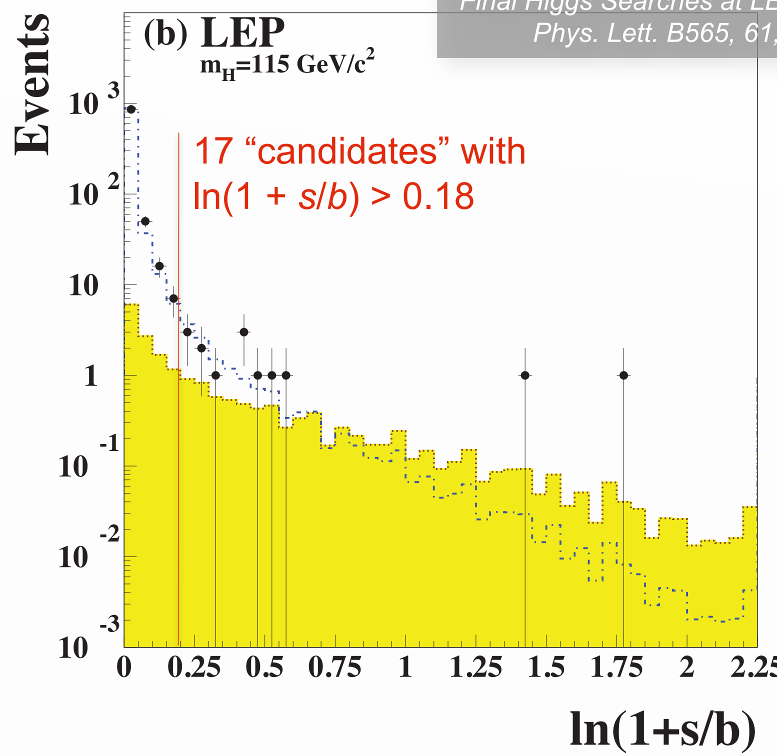
QCD: $qq\,(g)(g)$

Higgs Searches at LEP

Background fighting with cuts and multivariate analyses (likelihood, NN)

Final Higgs Searches at LEP published
Phys. Lett. B565, 61, 2003





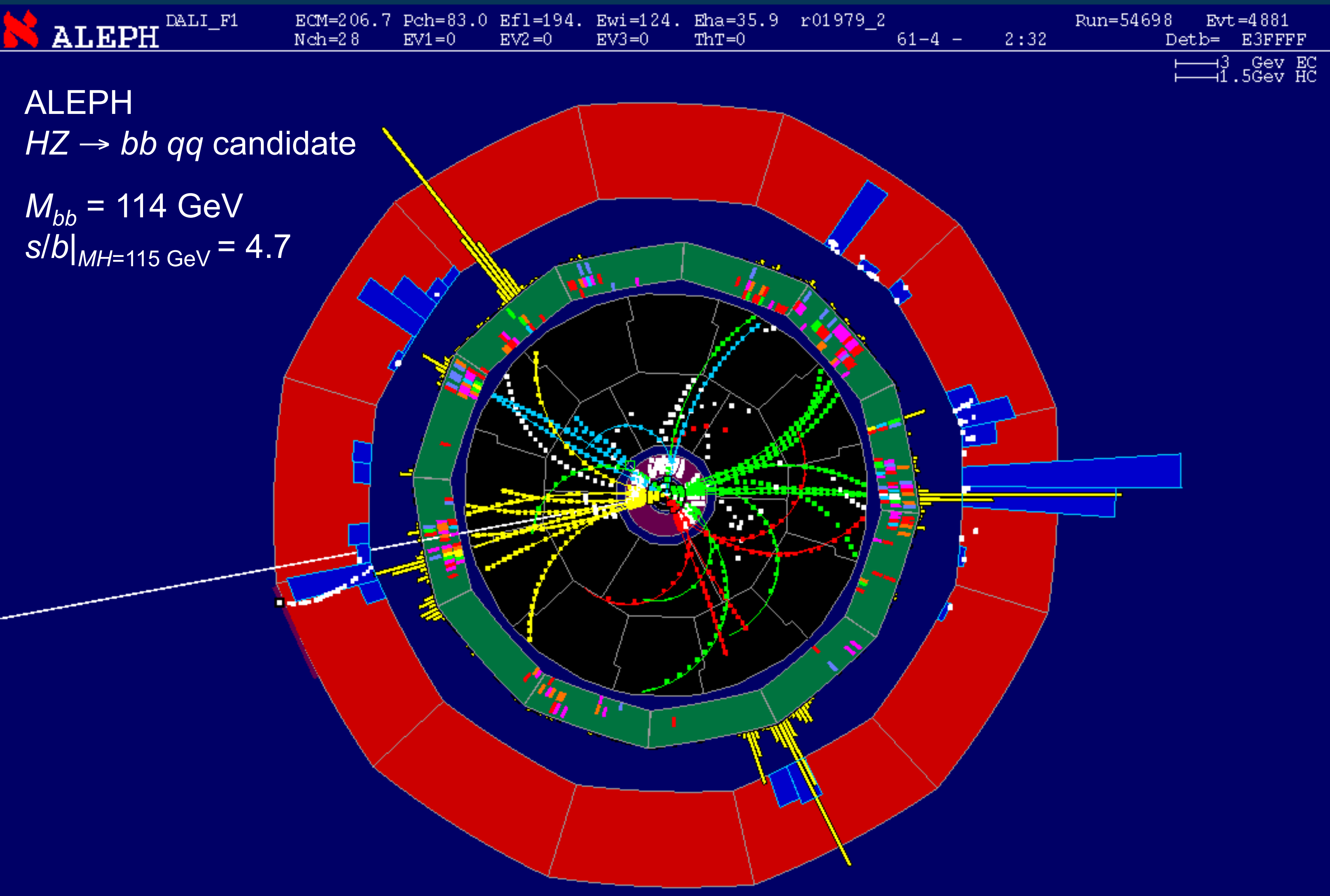
Distributions of “event weights” $\ln(1 + s/b)$ for different M_H hypotheses

ALEPH

HZ → *bb qq* candidate

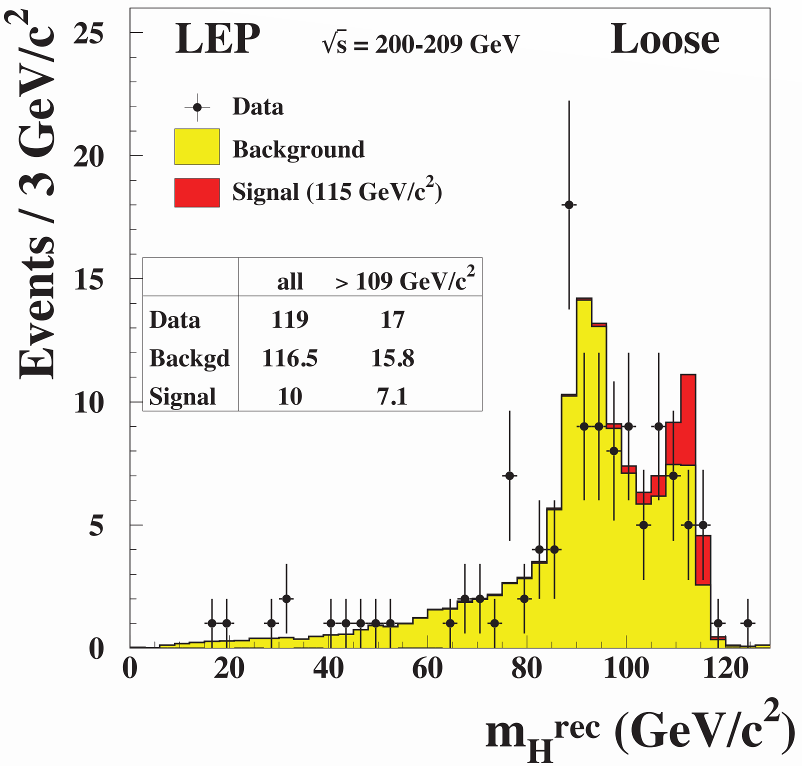
M_{bb} = 114 GeV

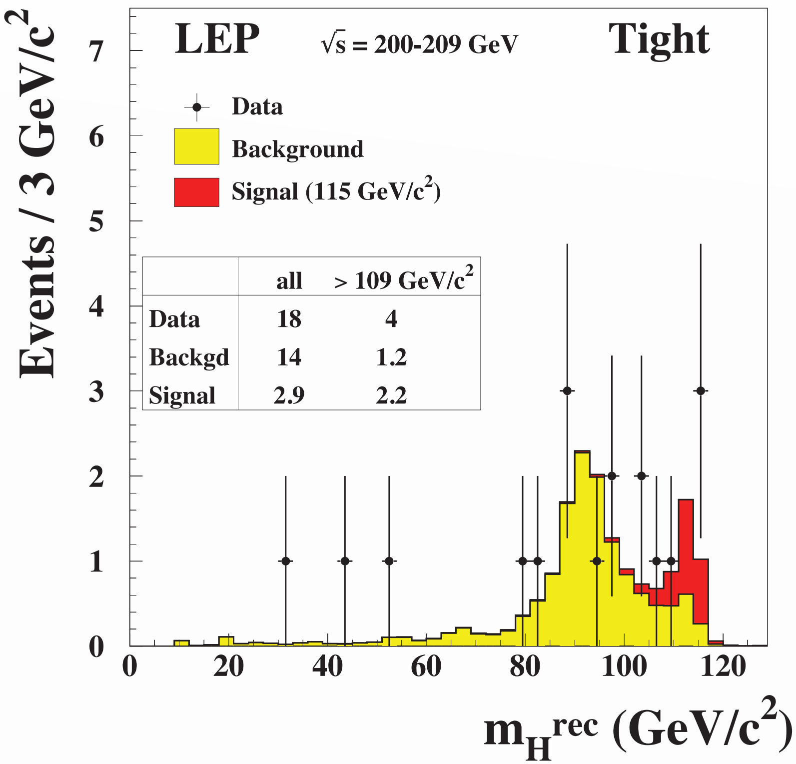
$s/b|_{MH=115\ \text{GeV}}$ = 4.7



Higgs Searches at LEP

M_H distributions for samples with different s/b purity requirements

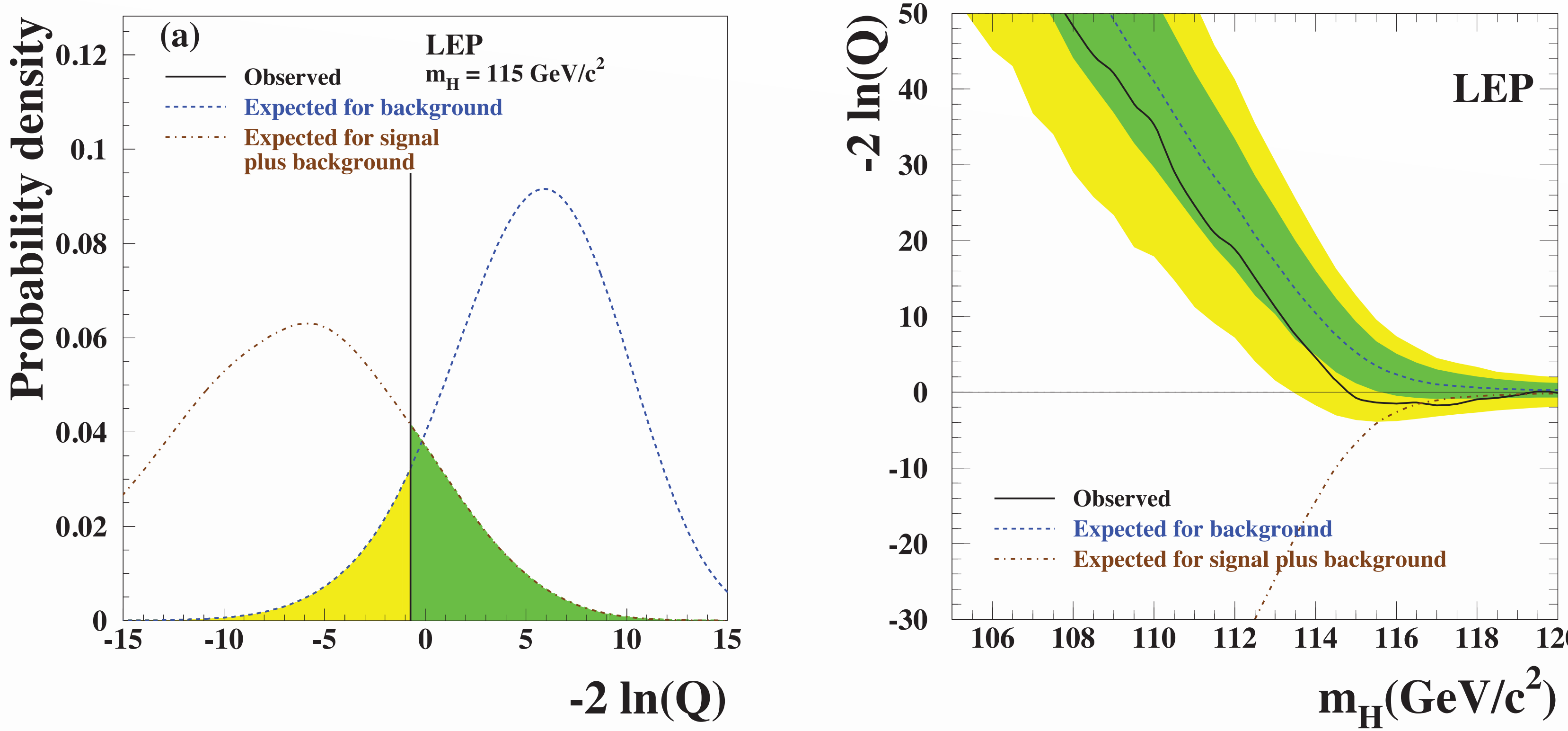




Peak around Z mass from $e^+e^- \rightarrow ZZ$ background

Higgs Searches at LEP

No significant excess at $M_H = 115$ GeV: $1–CL_b = 0.09$ (1.7σ), but $CL_{s+b} = 0.15$



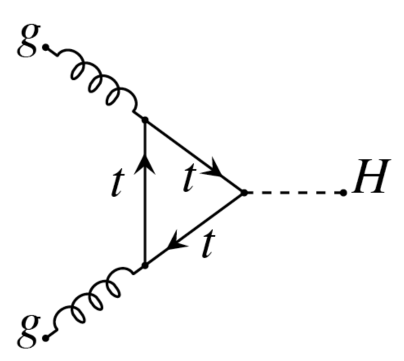
Stringent **lower limit of 114.4 GeV at 95% CL** on Higgs mass obtained by LEP experiments

Expected limit (sensitivity): 115.3 GeV

Higgs Boson Production at Hadron Colliders

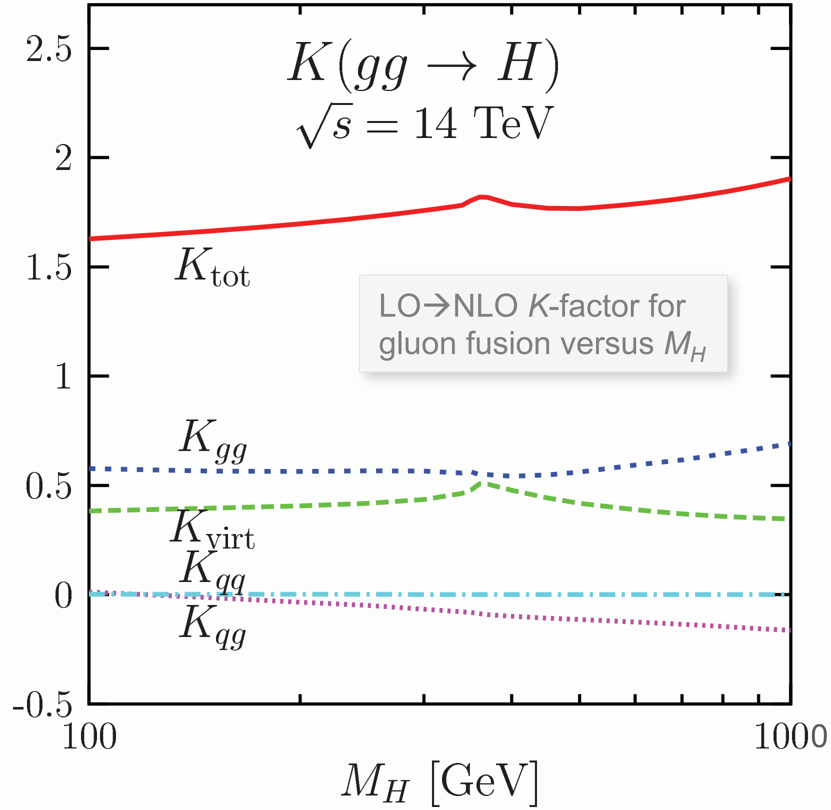
Higgs Production via Gluon Fusion

As for decays, Higgs production goes primarily via couplings to heavy fields



Feynman graph for Higgs production via **gluon–gluon fusion** through top triangle.

At LO, the Higgs is produced with $p_T = 0$! Only NLO corrections permit boosted Higgs.



LO→NLO *K*-factor for gluon fusion versus M_H

The cross section calculation involves the form factor $A_{1/2}(\tau_Q) \sim 4/3$ (if $m_t \to \infty$)

NLO corrections include virtual gluon corrections in LO diagram, gluon radiation in final state, and guon–quark and quark–antiquark collisions.

NLO corrections increase LO cross section by 60–90% ("*K-factor*"). NNLO corrections add another ~30%.

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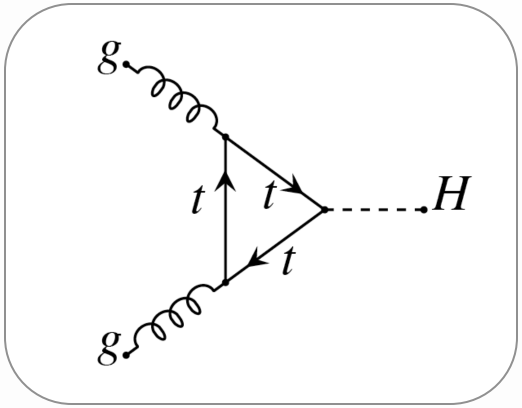

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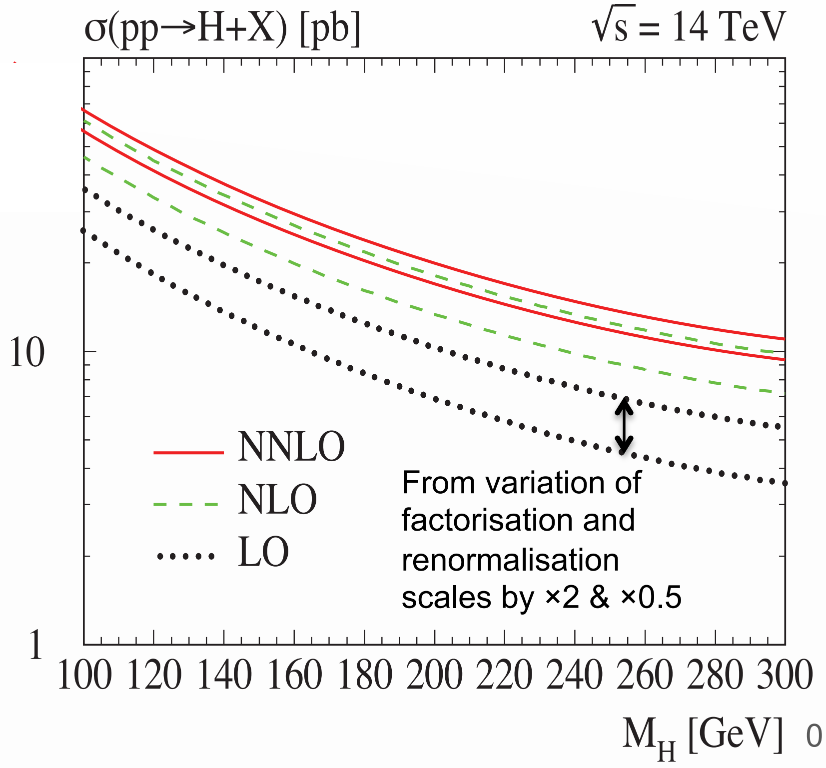

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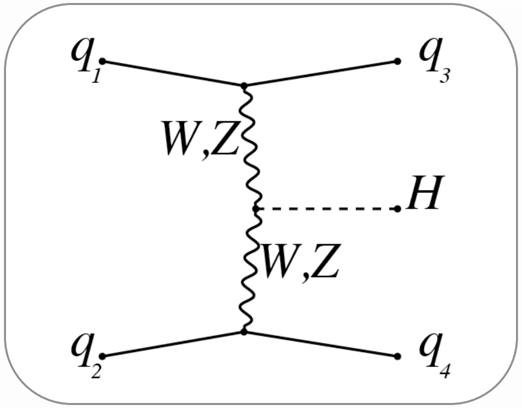
NLO corrections include virtual gluon corrections in LO diagram, gluon radiation in final state, and guon–quark and quark–antiquark collisions.

NLO corrections increase LO cross section by 60–90% ("*K-factor*"). NNLO corrections add another ~30%. Soft gluon resummation add 11%, and EW corrections +6%

Higgs Production via Weak Boson Fusion

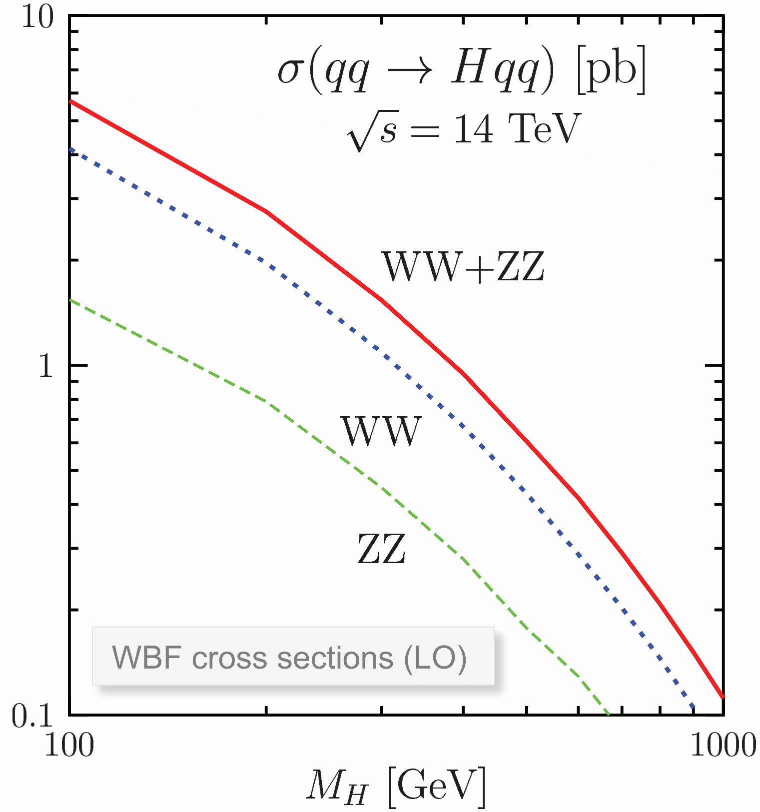
WBF is more important at LHC than at Tevatron as it involves dominantly longitudinally polarised bosons, whose interactions increase with energy



Feynman graph for Higgs production via **weak boson fusion.**

WW mode dominant. Negligible interference between *Z*/*W* amplitudes.

$gq \to Hqq + q$ included in NLO corrections.



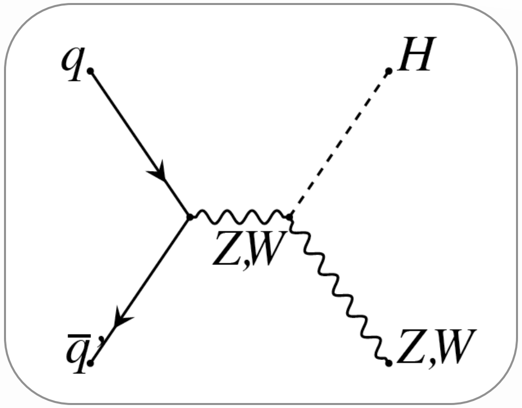
Striking event signature: small q^2 between quarks and W/Z's ($M_H/2$ each q) → large $\Delta\eta$ between jets!

NLO corrections include quark self energies and gluon ISR and FSR. No gluon exchange between initial (final) colour-singlet quarks at NLO level.

NLO corrections small and constant vs. M_H. K-factor of 1.05–1.1.

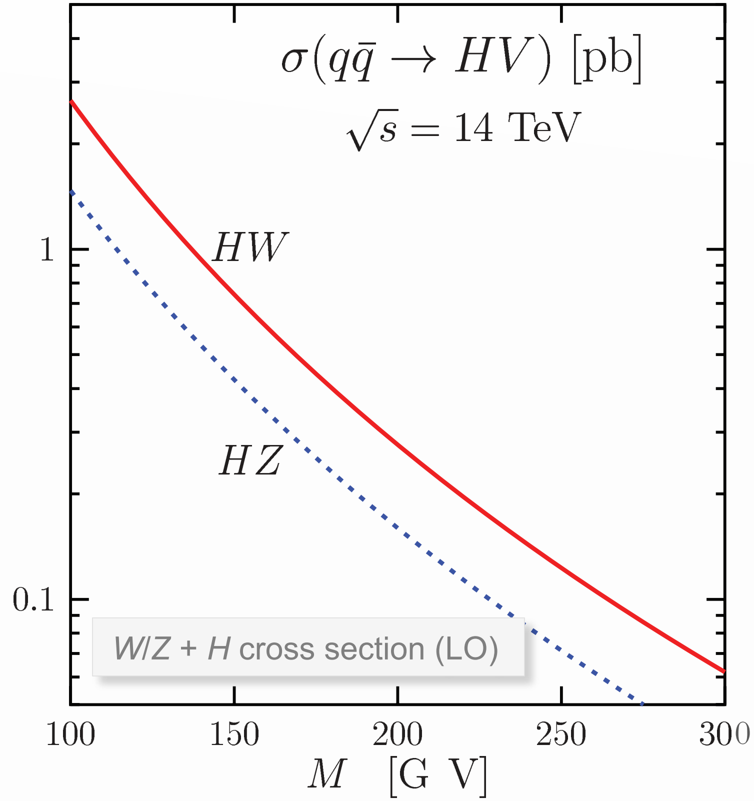
Higgs Production with *W/Z Association*

Higgs production in association with a weak boson resembles Drell-Yan production of a virtual boson, which decays into *H* + *Z*/*W* with opposite p_T



Feynman graph for associated *W*/*Z* + Higgs production.

At NNLO level also the production *gg* → *HZ* via quark boxes or triangles contributes.



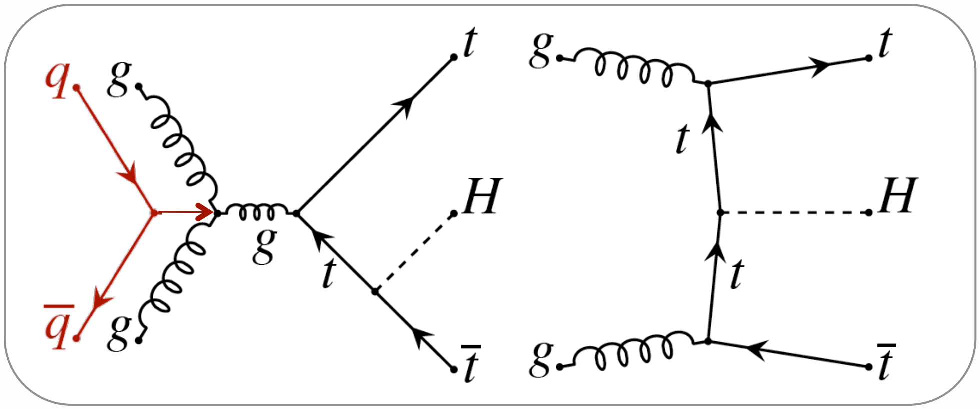
W/*Z* + *H* cross section (LO)

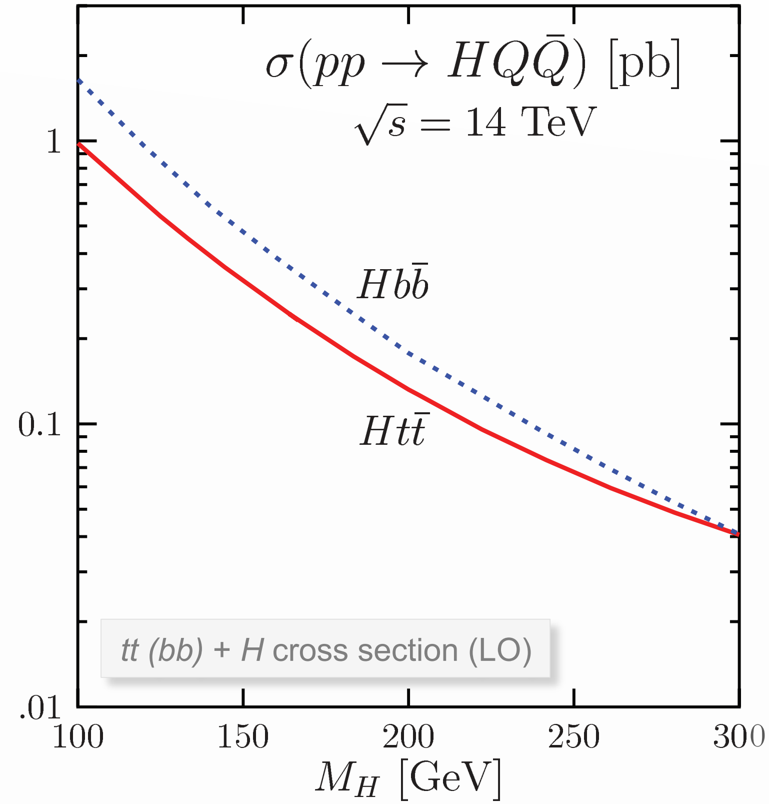
The Drell-Yan picture can be used to decompose cross section computation at all orders in PT.

NLO corrections are ~ constant vs. M_H. *K*-factor of 1.25–1.3. Electroweak corrections reduce the cross section by 5–10%.

Higgs Production with *tt* Association

Higgs production in association with a top–antitop pair is the most complex production mode both in terms of Feynman graphs and the heavy final states





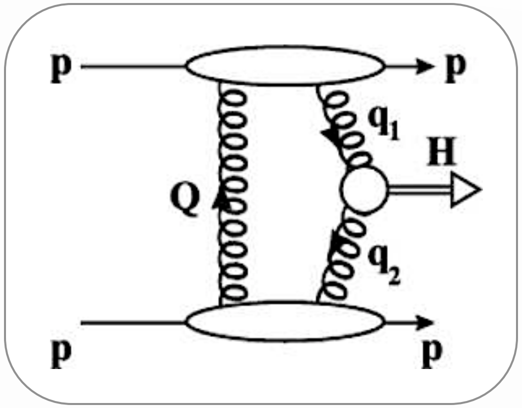
Strong cross section dependence on M_H through rapid phase space reduction for heavy Higgs.

Clean experimental signature for *tt* + *H* mode in semileptonic *tt* decays. However, *bb* + *H* mode undetectable in Standard Model.

NLO corrections difficult to compute. *K*-factor of 1.2–1.4.

Diffractive Higgs Production

Possibly interesting production mode for small M_H where 2 colour-singlet fields (*eg*, gluons) are exchanged, and one emits Higgs through *ggH* vertex



Very distinctive signature: central Higgs boson production and two protons at large rapidity

$$pp \to p + H(\to b\bar{b}) + p, \quad \text{with } \Delta\eta_{pp} \gg 1$$

Cross section of ~3 fb for M_H = 120 GeV at LHC

Clean signal if the two protons are tagged with Roman Pots. Compute Higgs mass via:

- measurement of missing mass of the diffractive protons in Roman Pots (σ ~ 1–2 GeV)
- via reconstruction of Higgs decay products (*e.g.* σ ~ 10 GeV on M_{bb} for $H \to bb$)

Measuring both masses and comparing them provides background suppression handle

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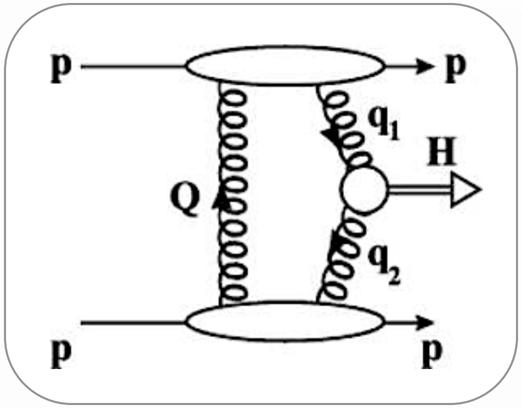

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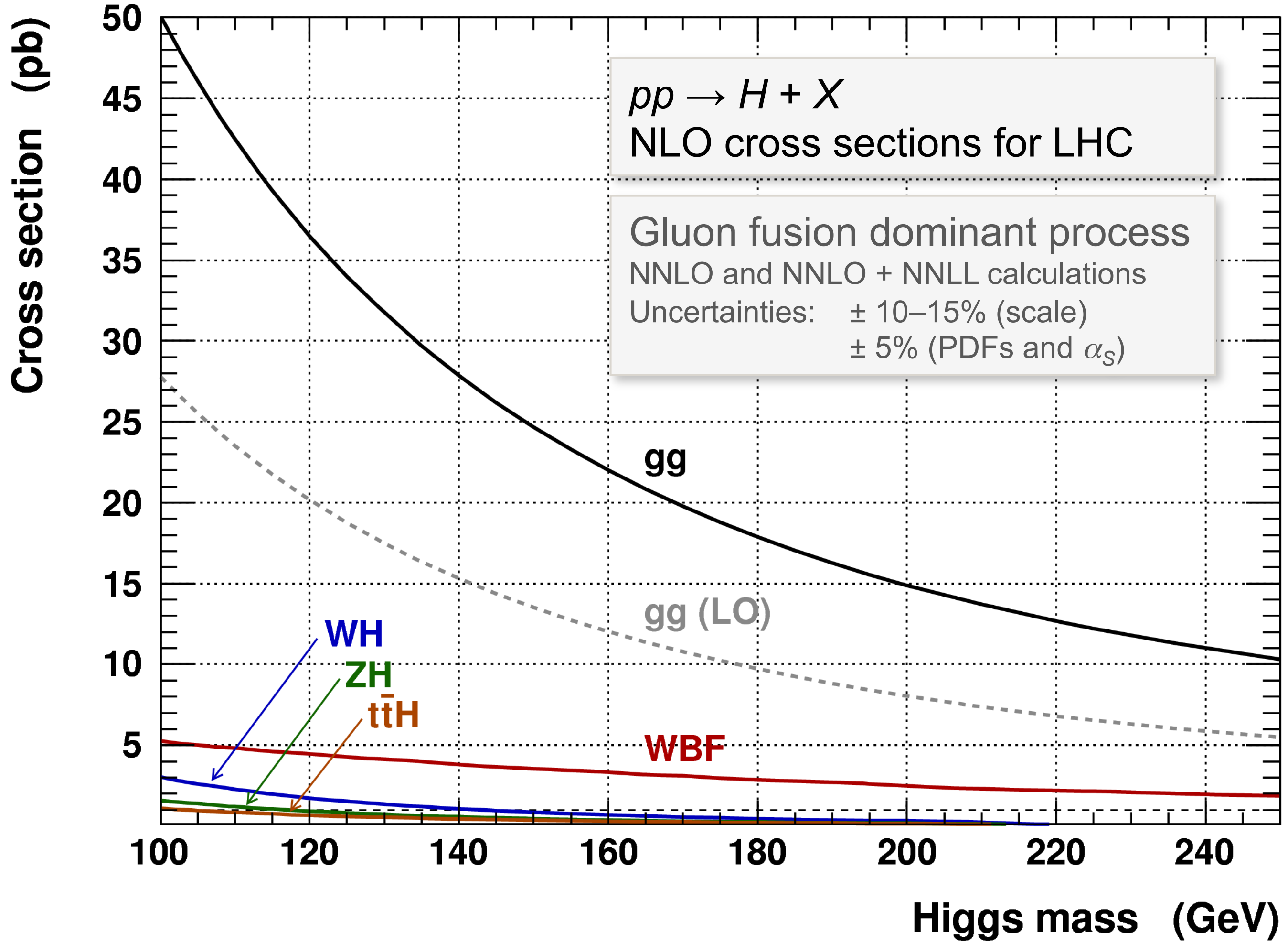
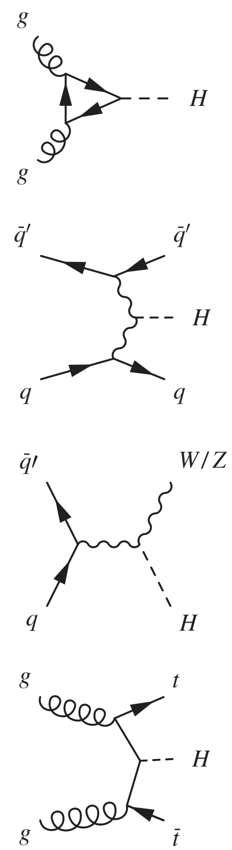
Higgs Production at the LHC – Summary





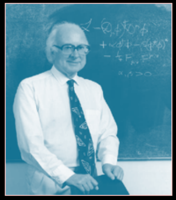
Higgs Production at the LHC – Summary

Huge theoretical effort to compute the signal processes, but also the background, at (N)NLO level

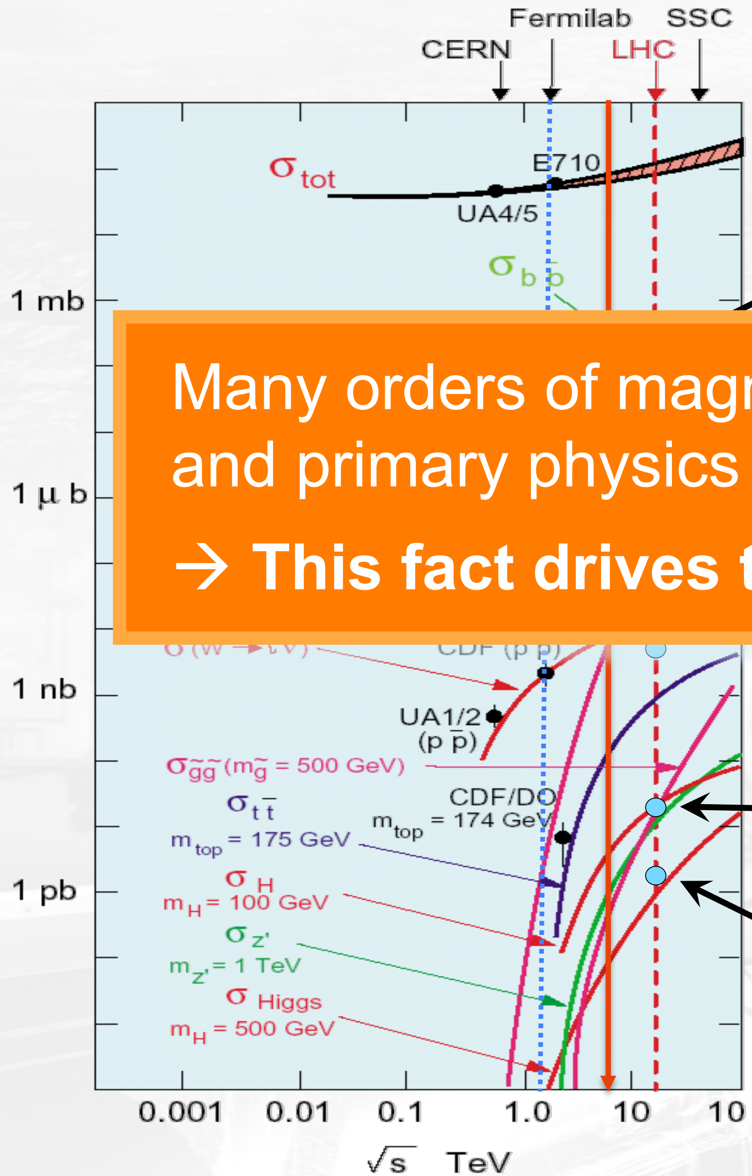
New generators and tools used and *validated* (with data) by experimentalists

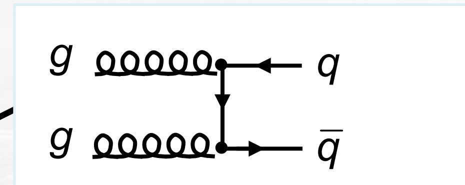
1. New (N)NLO Monte Carlos (also for backgrounds):
   - MCFM Monte Carlo, J. Campbell and K. Ellis, Web
   - MC@NLO Monte Carlo, S.Frixione and B. Webber, Web
   - T. Figy, C. Oleari and D. Zeppenfeld, Phys. Rev. D68, 073005 (2003)
   - E.L.Berger and J. Campbell, Phys. Rev. D70, 073011 (2004)
   - FEHIP, C. Anastasiou, K. Melnikov and F. Petriello, hep-ph/0409088 and hep-ph/0501130 (differential cross sections through NNLO)
   - HNNLO, S. Catani and M. Grazzini (2007, 2008)
2. New approaches to match parton showers and matrix elements
   (based on algorithm developed by Catani, Krauss, Kuhn and Webber (CKKW)*)
   - ALPGEN Monte Carlo + MLM matching, M. Mangano et al.
   - PYTHIA, adapted by S. Mrenna
   - SHERPA Monte Carlo, F. Krauss et al., Web

Higgs Searches at Hadron Colliders



Cross Sections at Hadron Colliders

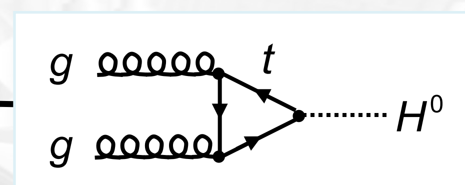




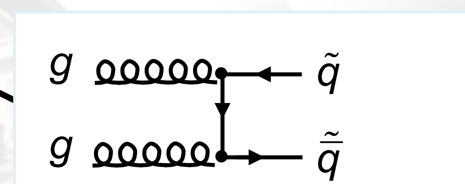
Quark-flavour production

Many orders of magnitude between QCD background and primary physics channels

→ **This fact drives the detector design**



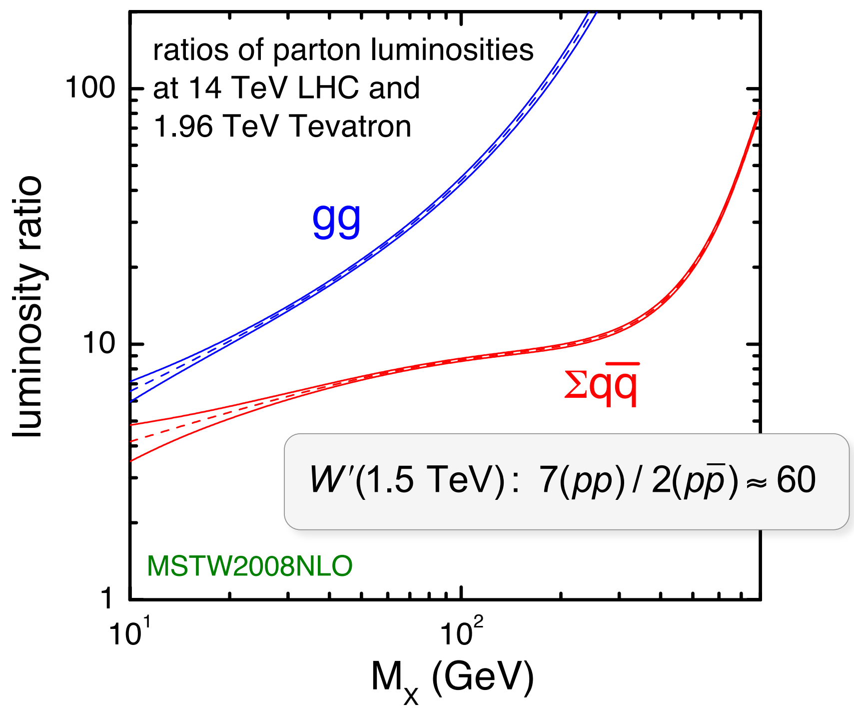
gluon-to-Higgs fusion

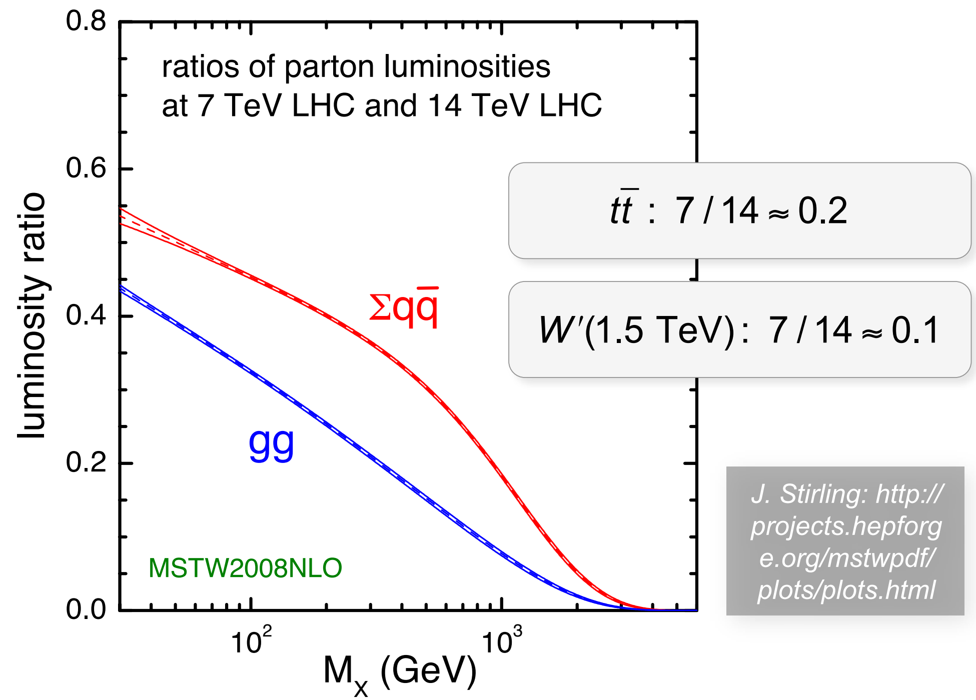


squarks, gluinos
(m ~ 1 TeV)

Higgs Cross Sections at Hadron Colliders

Ratio of parton luminosities of LHC-to-Tevatron and LHC 7 TeV-to-14 TeV





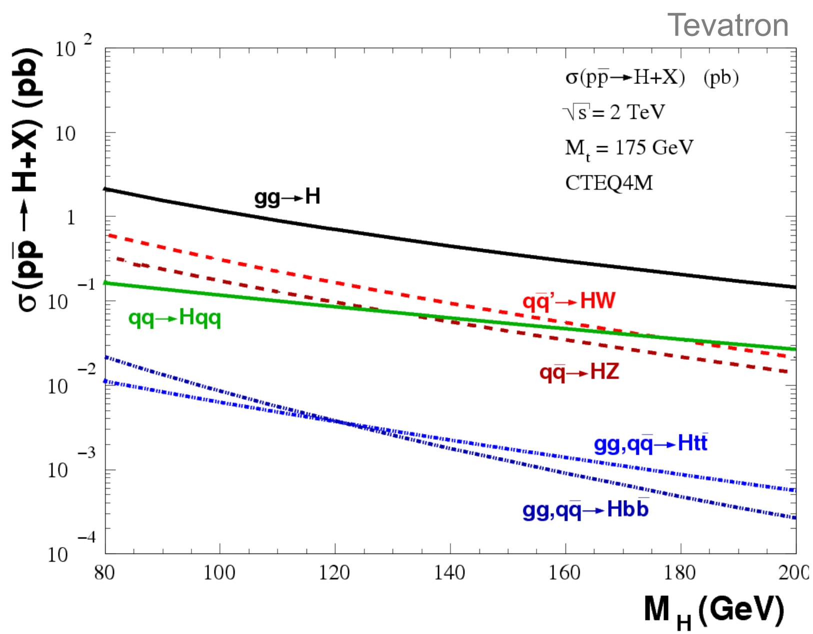
J. Stirling: http://projects.hepforge.org/mstwpdf/plots/plots.html

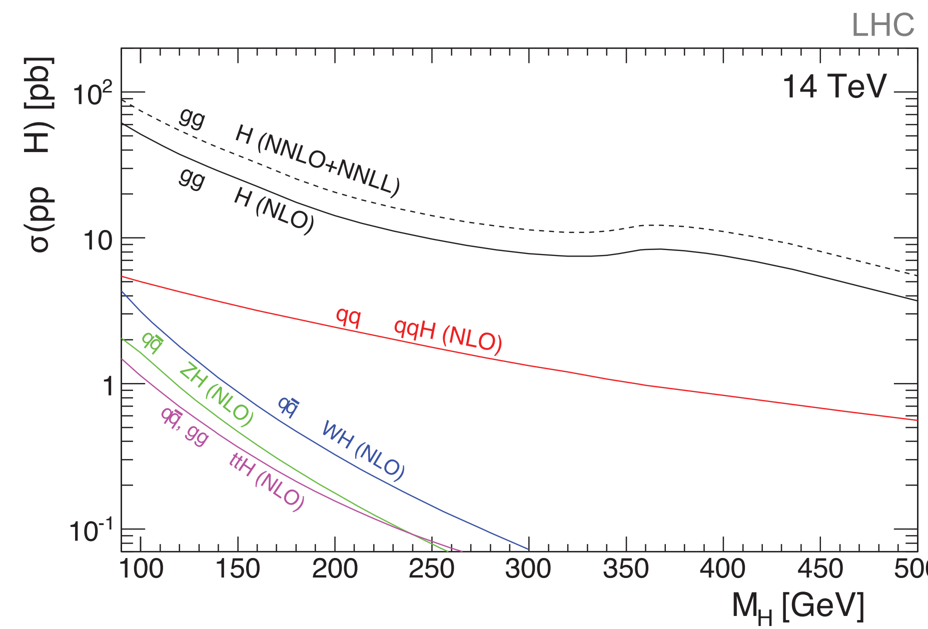
High M_X production through gluon fusion requires large CM energy

Less so for quark-antiquark scattering which has slow rise for M_X < 300 GeV

Higgs Cross Sections at Hadron Colliders

Higgs production cross sections versus M_H at the Tevatron and the LHC

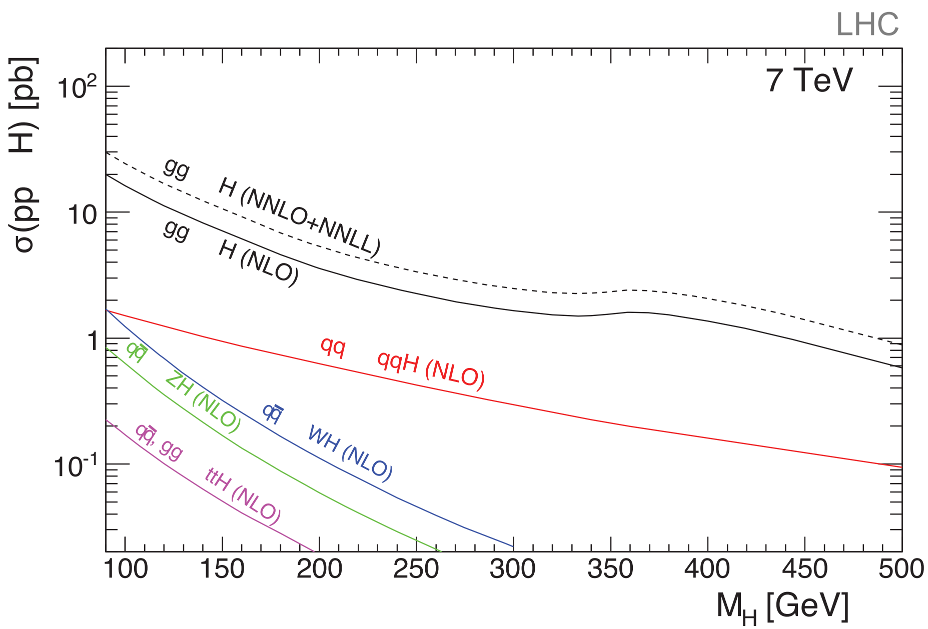


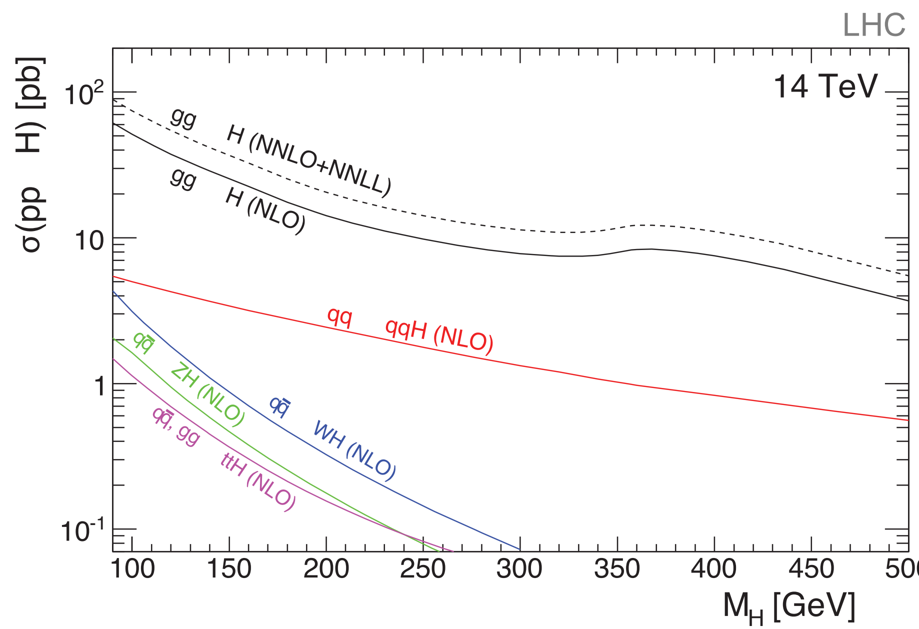


$qq \to W/Z + H$ cross sections	~10 ×	larger at the LHC
$gg \to H$	~70–80 ×	larger at the LHC

Higgs Cross Sections at Hadron Colliders

Unfortunately, the LHC runs only at 7 TeV CM energy in 2010 and 2011

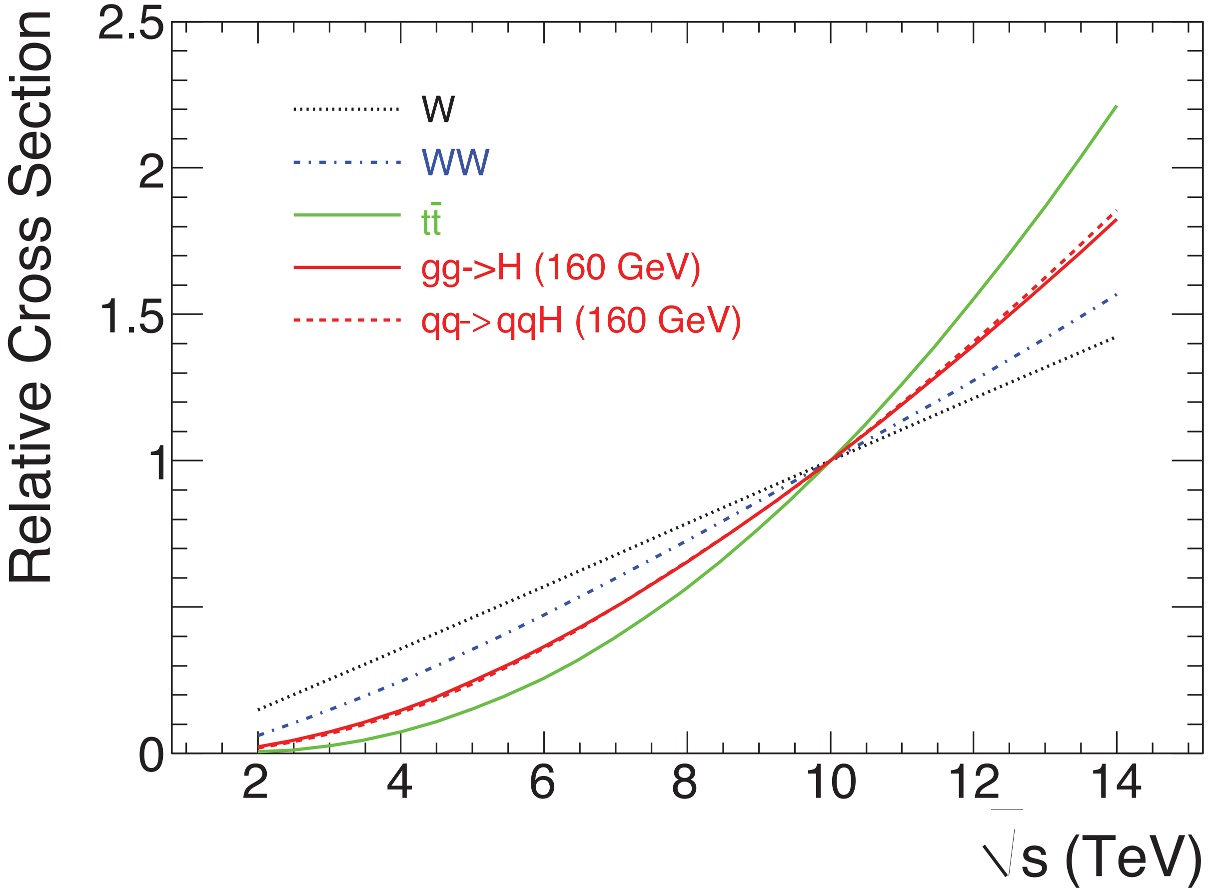




For M_H = 160 GeV, reduction by factor of ~3.6 for $gg \rightarrow H$
~2.8 for $qq \rightarrow W/Z + H$
~3.7 for $qq \rightarrow qqH$

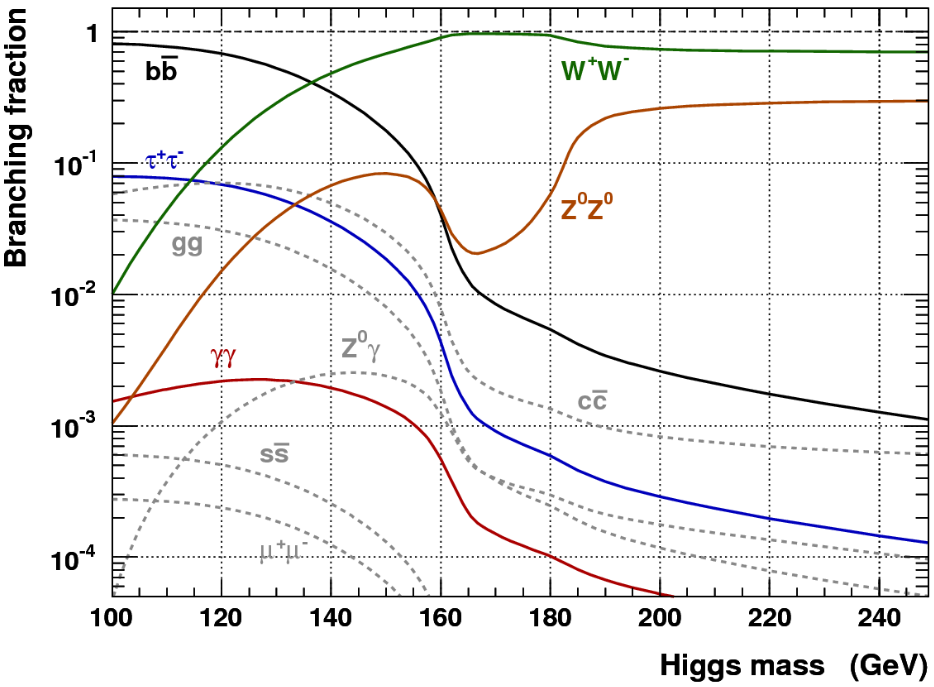
Higgs Cross Sections at Hadron Colliders

Relative NLO cross section as a function of $\sqrt{s}$ and for M_H = 160 GeV



Searching for the Higgs at Hadron Collliders

The dependence of the branching fractions on M_H drive search strategy



For heavy Higgs:

- Lepton final states via *WW*, *ZZ*

For light Higgs:

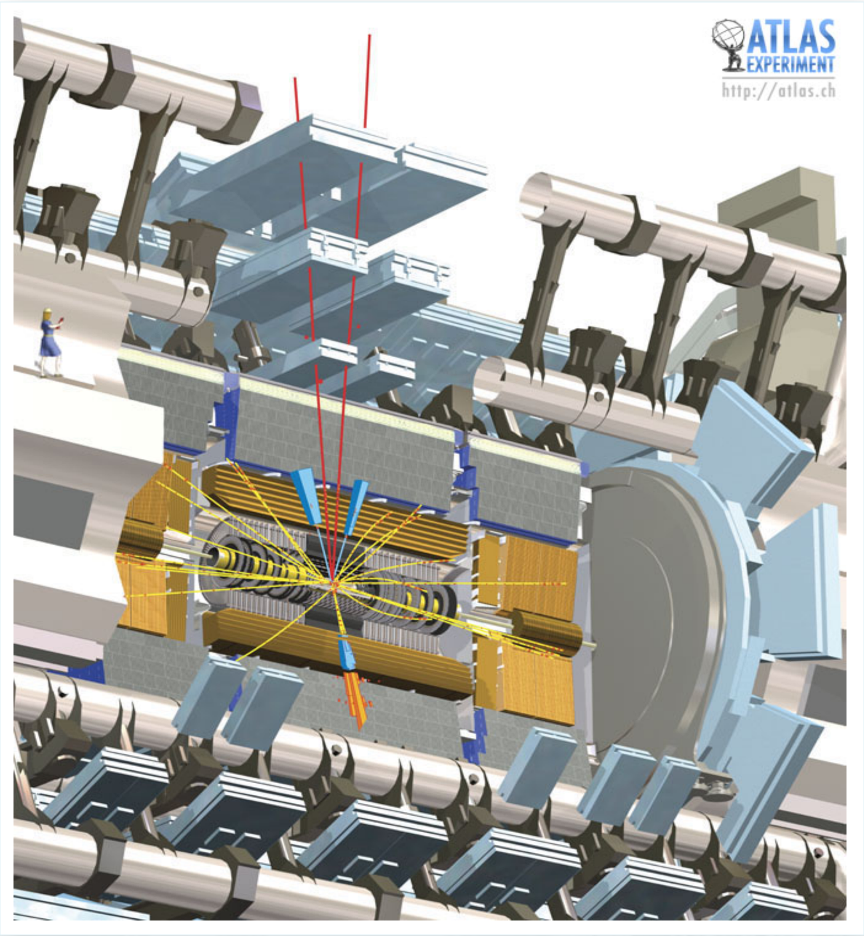
- Lepton final states via *WW**, *ZZ**
- Di-photon final state
- Di-tau final state

The dominant $H \rightarrow bb$ mode is only exploitable in association with *W*/*Z* or *tt*

(associated leptons help to reduce overwhelming QCD background)

Searching for the Higgs at Hadron Collliders

Detector requirements for Higgs searches and measurements



Excellent identification and measurement of high-p_T muons, electrons and photons

Excellent measurement of missing transverse energy (for W and τ final states) requiring energy measurement up to very forward region ($|\eta| \sim 5$)

Jet tagging in forward direction (for weak-boson-fusion process)

Efficient and pure *b*-tagging* and τ identification

*requiring silicon pixel detectors close to beam pipe

The Tevatron Collider at Fermilab

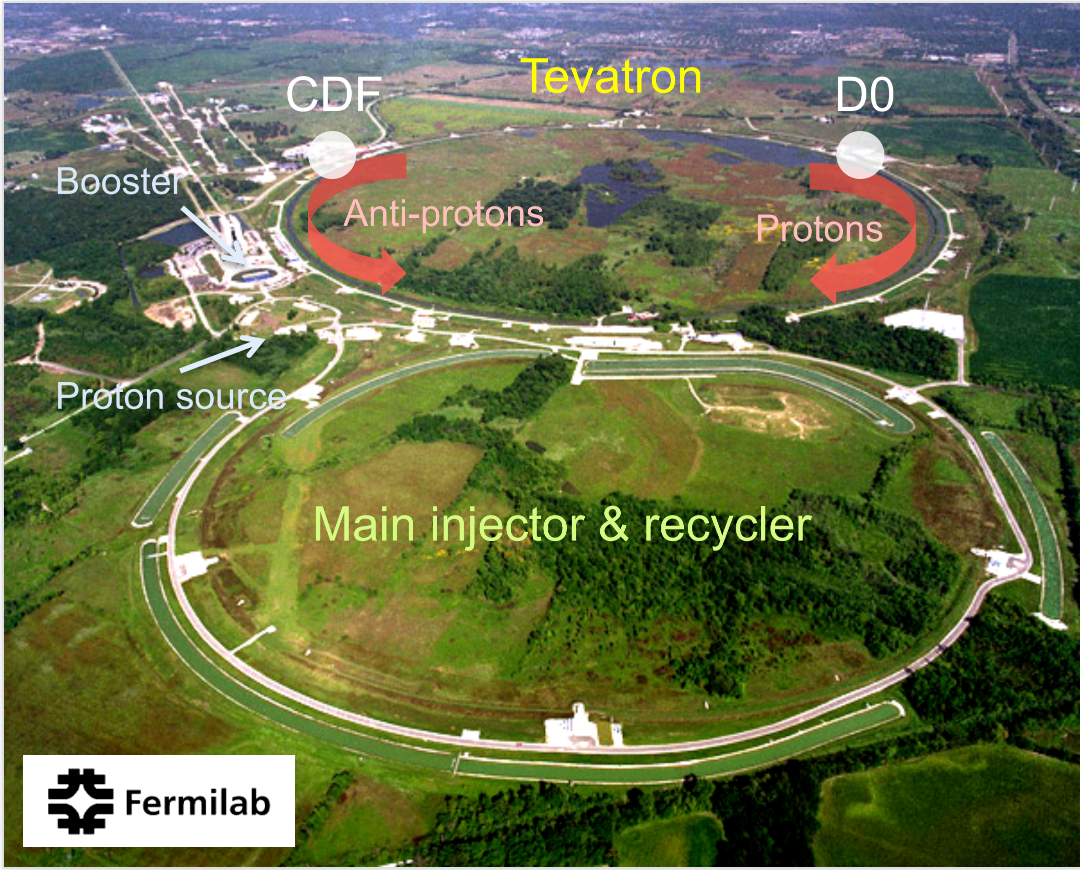
Proton–antiproton collider:

- 6.5 km circumference
- 0.98 TeV beam E (E_{CM} = 1.96 TeV)
- 36 bunches at 396 ns separation
- main challenge: antiproton production and storage
  → luminosity & operational stability

Two general purpose experiments:
CDF and D0

Tevatron is running in Run II:

- Run I (1990–1996, 0.13 fb^{-1} lumin.): top discovery
- Run IIa (2001–2006, 1.2 fb^{-1}): B_s oscillation discovery
- Run IIb (2006–2012 ?, 10–12 fb^{-1}) : Higgs exclusion at ~ 160 GeV



Tevatron Luminosity

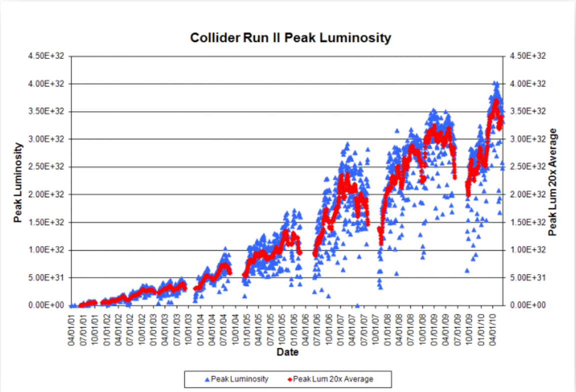
Peak luminosity:

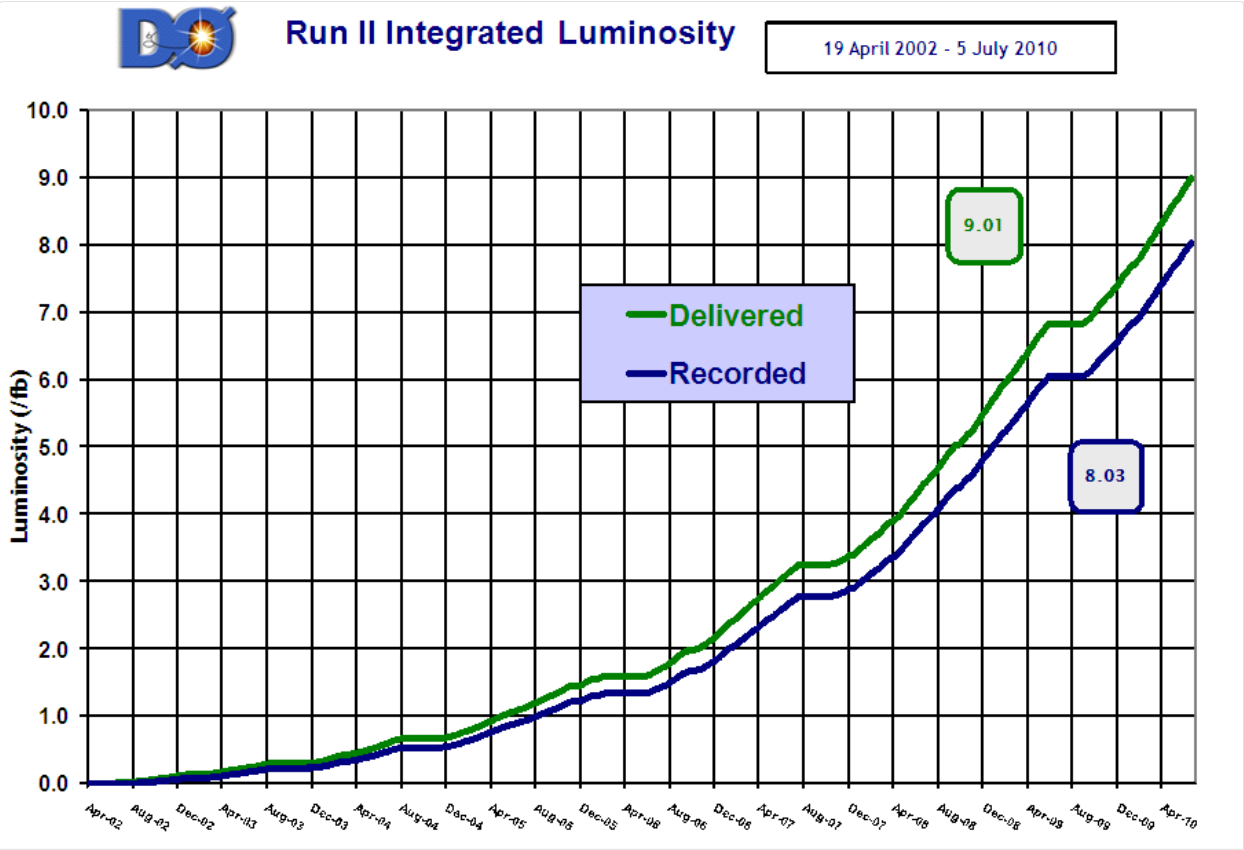
$4.0 \times 10^{32}\ \text{cm}^{-2}\text{s}^{-1}$

Integrated luminosity:

$9.0 \times 10^{32}\ \text{fb}^{-1}$

Anticipate 10 fb^{-1} end of 2010, and 12–13 fb^{-1} end of 2011



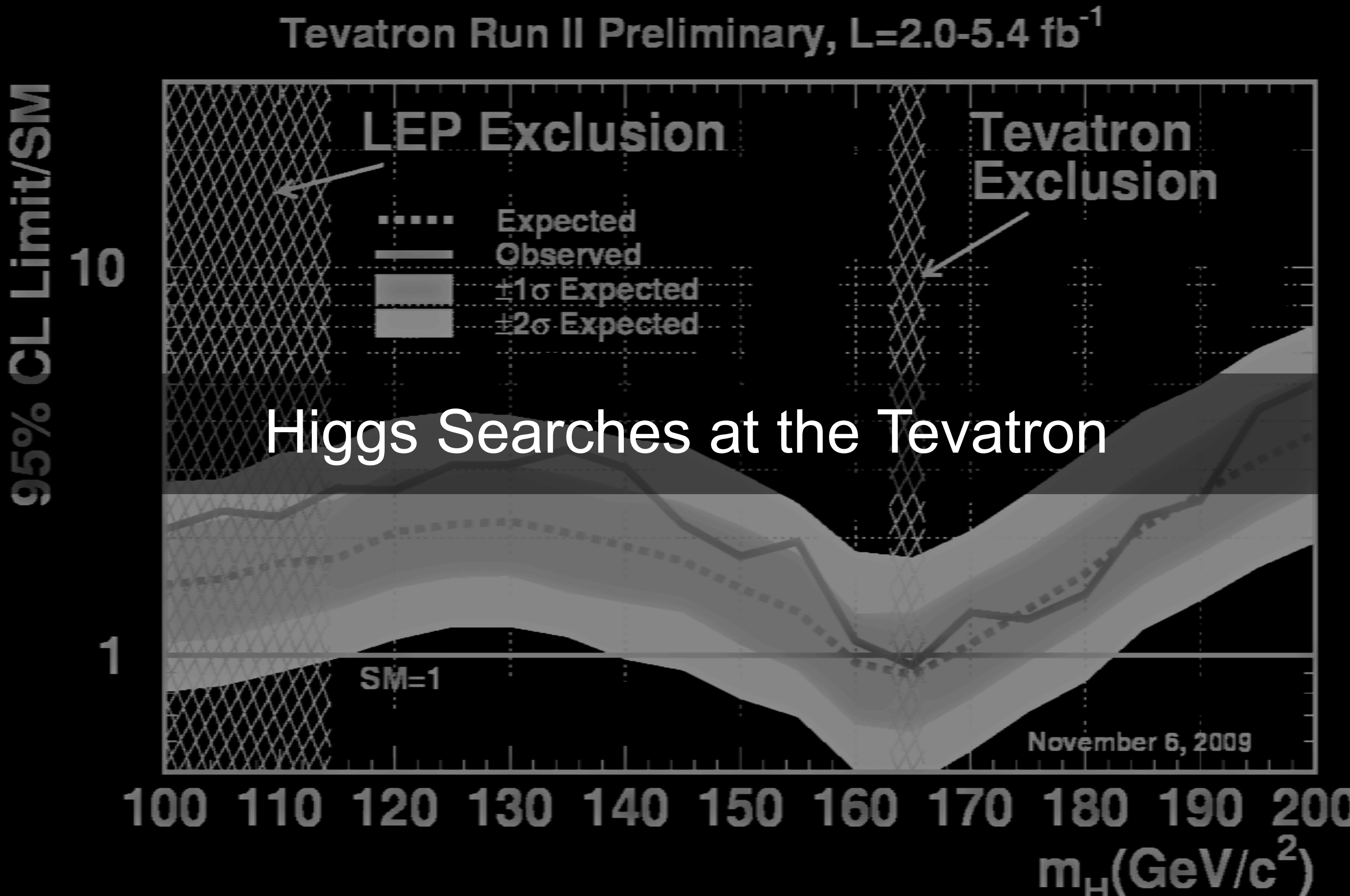


Tevatron versus LHC

	Tevatron (achieved)	**LHC** (design)
Centre-of-mass energy	1.96 TeV	14 TeV
Number of bunches	36	2808
Bunch spacing	396 ns	25 ns
Protons / bunch [$\times 10^{11}$]	0.9(anti-*p*) / 2.8(*p*)	1.2
Energy stored / beam	1 MJ	360 MJ
Peak luminosity	4×10^{32} cm^{-2}s^{-1}	10^{33}–10^{34} cm^{-2}s^{-1}
Integrated luminosity / year	~3 fb^{-1}	10–100 fb^{-1}
Inelastic interactions / crossing	10	~24

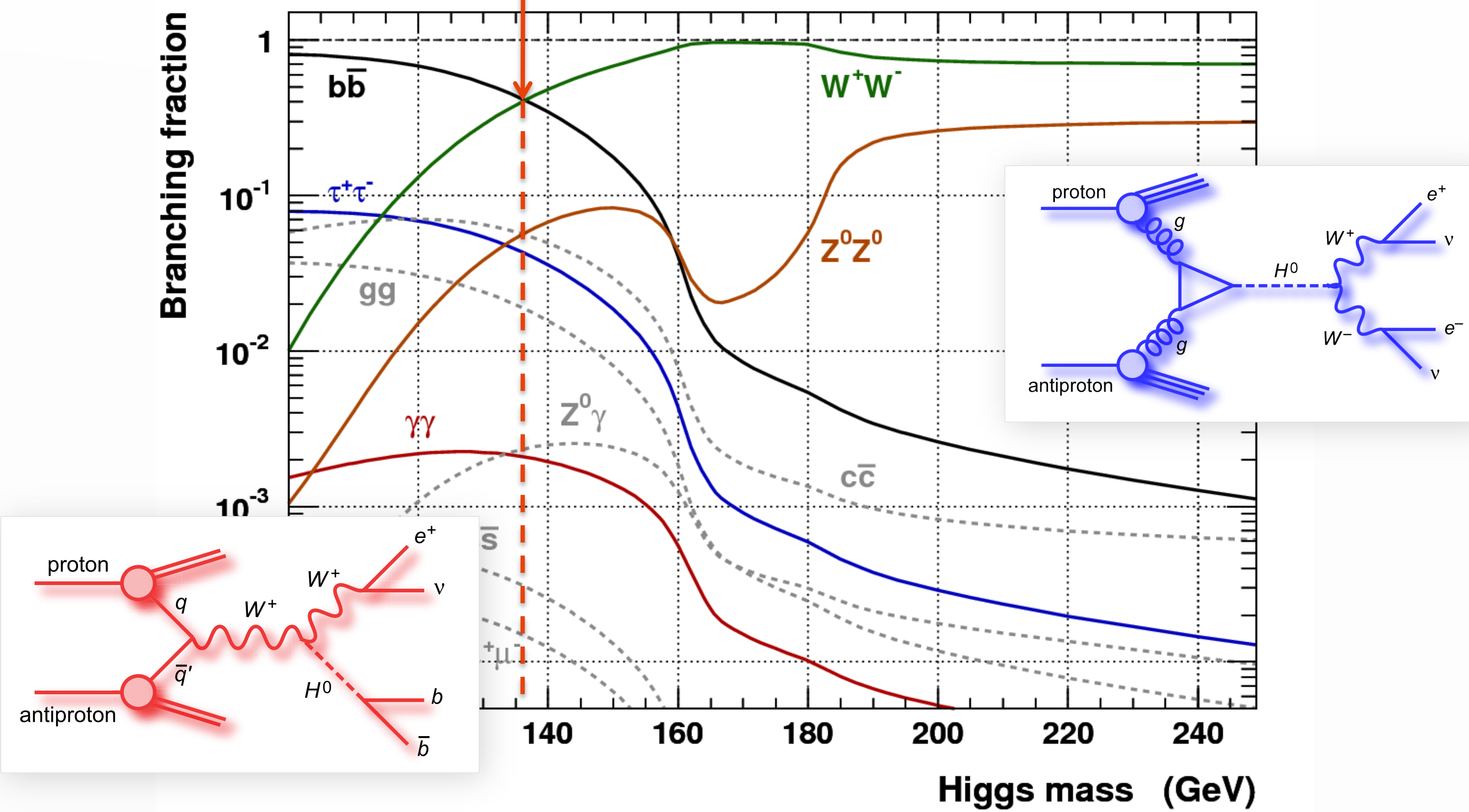
- 7 times more centre-of-mass energy at LHC
- 3–30 times higher peak luminosity
- 10–100 times larger physics cross sections for hard scattering reactions

Higgs Searches at the Tevatron

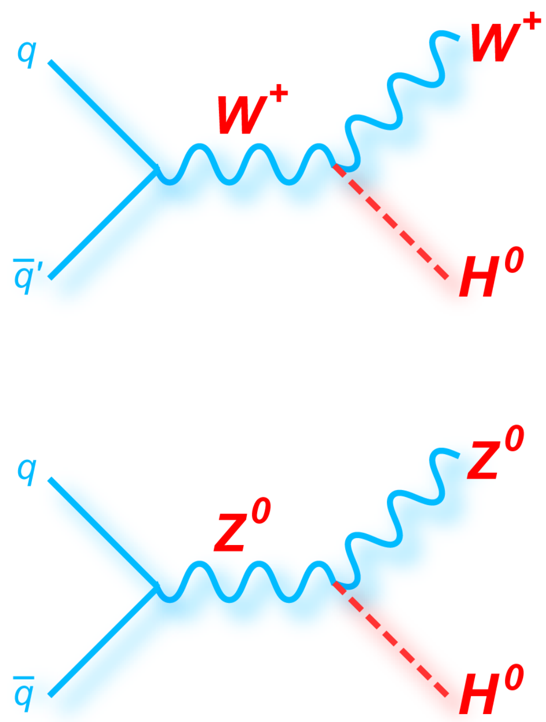


Higgs Search Strategy

135 GeV • Separate analyses into low-mass and high-mass searches



Low Mass Search: $M_H < 135$ GeV



$WH \rightarrow \ell\nu b\bar{b}$: lepton + E_T^{miss} + bb

Largest *VH* cross section –
however strongly background contaminated

$ZH \rightarrow \ell^+\ell^- b\bar{b}$: 2 leptons + bb

Smaller cross section than *WH* –
but less background

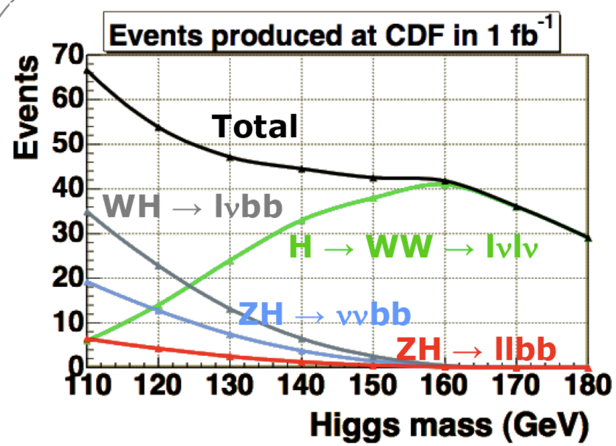
$ZH \rightarrow \nu\nu b\bar{b}$: E_T^{miss} + bb

3 × more signal than charged-lepton mode –
however large and difficult backgrounds

(includes events from *WH* mode when lepton missed)

Low Mass Search

Number of events produced per Tevatron experiment in 1 fb^{-1} versus the Higgs mass

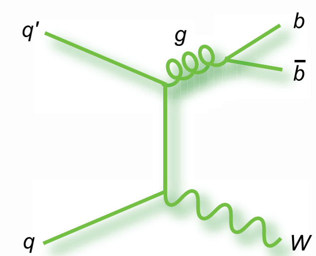


Channel	Events/fb M_H = 115 GeV
$WH \to l\nu bb$	28
$ZH \to \nu\nu bb$	16
$ZH \to llbb$	5
$H \to WW \to lnln$	9
Total	58

$WH \to \ell\nu b\bar{b}$: lepton + E_T^{miss} + bb

Signal: $\sigma(M_H$=115 GeV) × BR ~ 14 fb / lepton

Large backgrounds from W + jet production:



$W + bb$: $\sigma \times$ BR = 4×10^4 fb
$W + cc$: $\sigma \times$ BR = 1×10^5 fb
$W + qq$: $\sigma \times$ BR = 2×10^6 fb

Additional backgrounds:

WW:	$\sigma \times$ BR = 13 pb
top-antitop:	$\sigma \times$ BR = 7 pb
single-top:	$\sigma \times$ BR = 3 pb

+ multi-jet QCD backgrounds

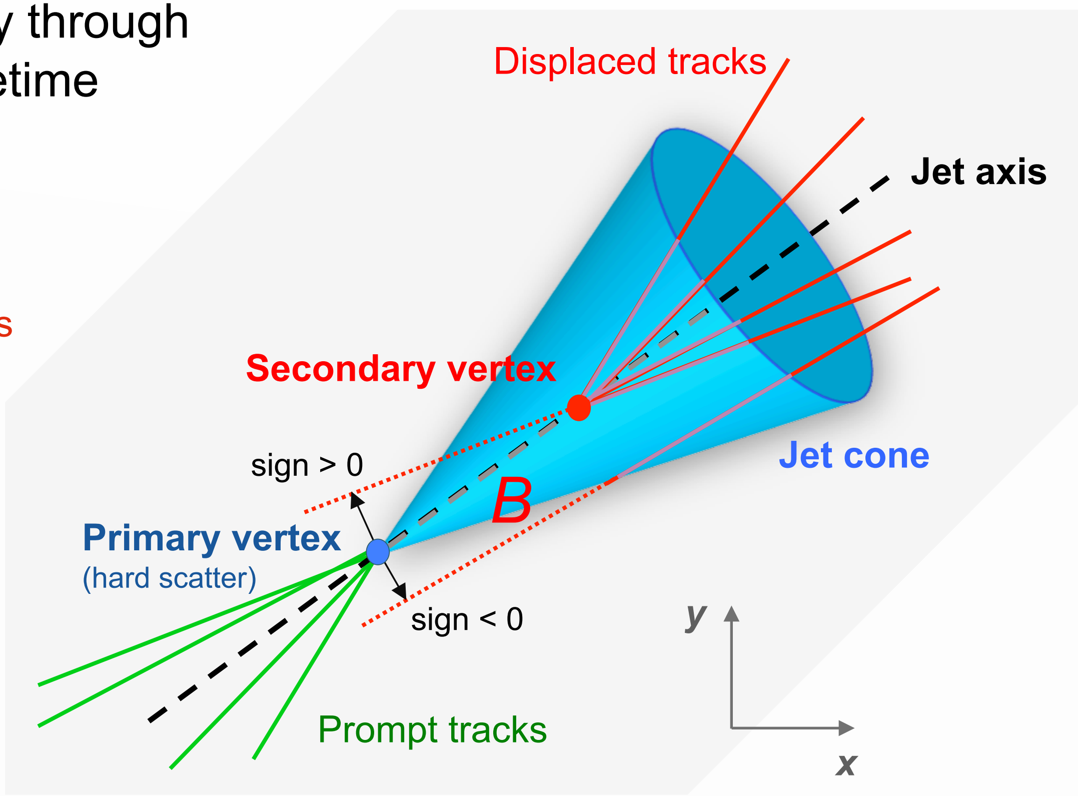
b-Tagging

Hadrons with open *b* flavour decay through weak interactions with picosec. lifetime

This is exploited to “tag” *b*-jets

Several methods developed:

- Lifetime tags, signed impact parameters
- Reconstructed secondary vertices
- *B*-jet properties, soft leptons in jet



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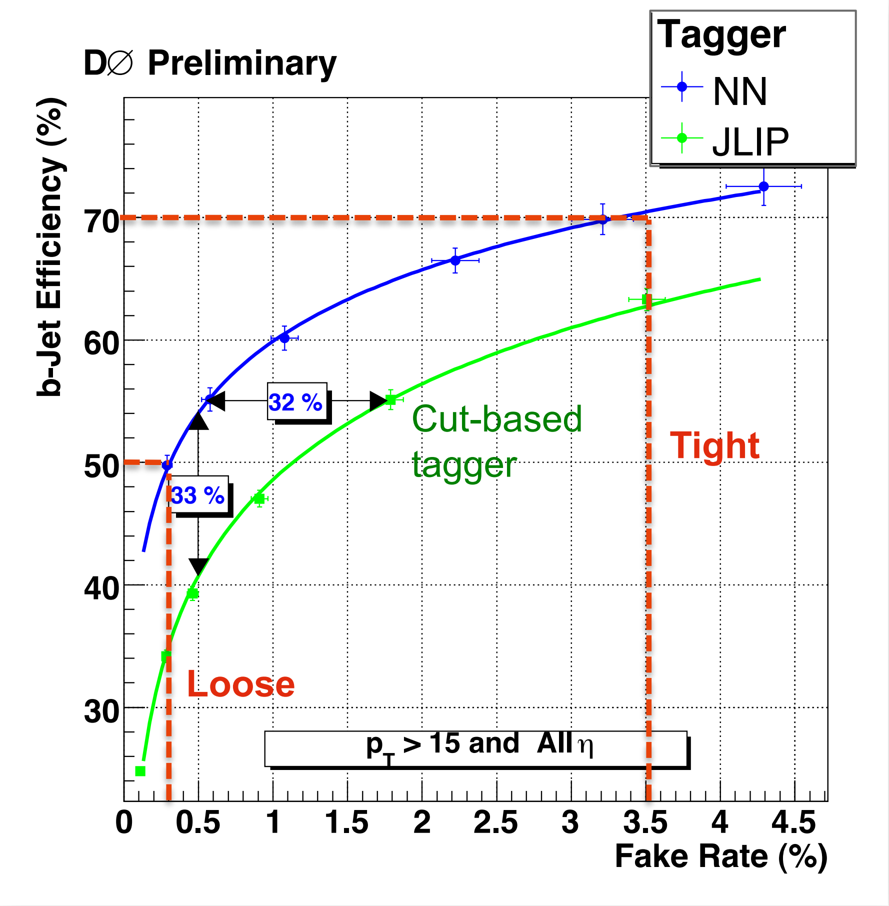
- Reconstructed secondary vertices
- *B*-jet properties, soft leptons in jet

Optimal approach combines all methods in multivariate variable (neural network – NN)

D0 achieves with NN
(impact parameter, sec. vertex)

- "**Loose**" 70% b-tag efficiency, 3.5% mistag
- "**Tight**": 50% b-tag efficiency, 0.3% mistag

Similar results for CDF



General Search Strategy

Example: $WH \rightarrow \ell\nu b\bar{b}$: lepton + E_T^{miss} + bb

1) Select ***Z*/*W* + 2 jets** candidate events

Large *W*+jet and *Z*+jet backgrounds

2) Apply ***b*-tagging**

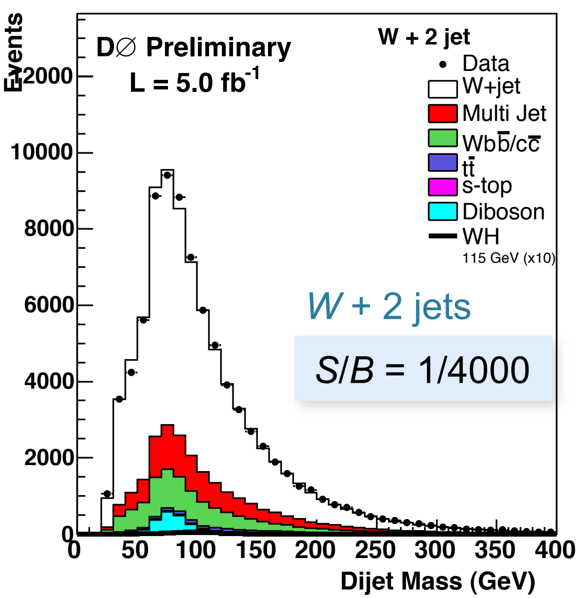
Even after *b*-tagging S-to-B ratio remains small, requires multivariate analysis tools

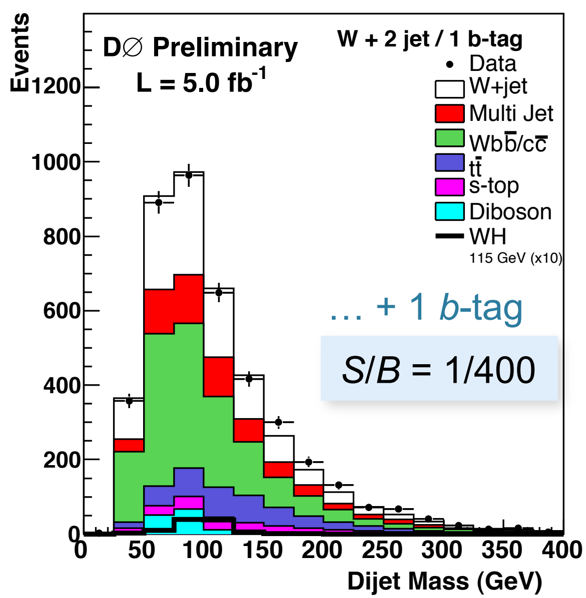
3) Optimise separation with **multivariate** tools

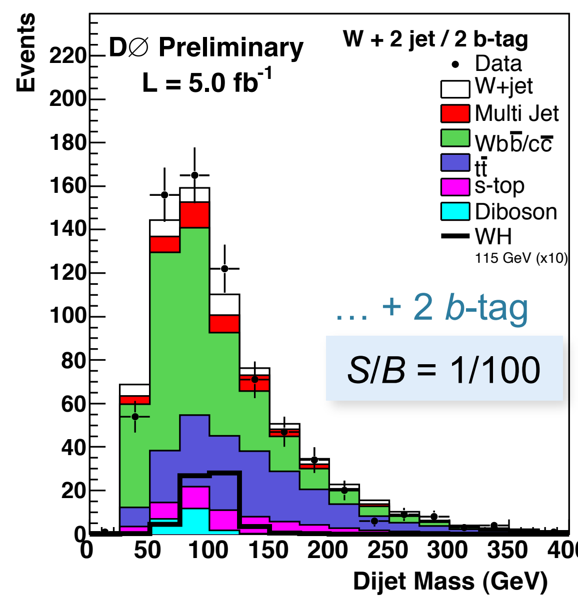
Good input variables:

- Di-jet mass
- p_T of the di-jet system
- p_T of *W*/*Z*
- Sphericity
- ΔR_{jj}, $\Delta\eta_{jj}$, $\Delta\phi_{jj}$

D0 plots of di-jet invariant mass after each analysis step:







General Search Strategy

Example: $WH \to \ell\nu b\bar{b}$: lepton + E_T^{miss} + bb

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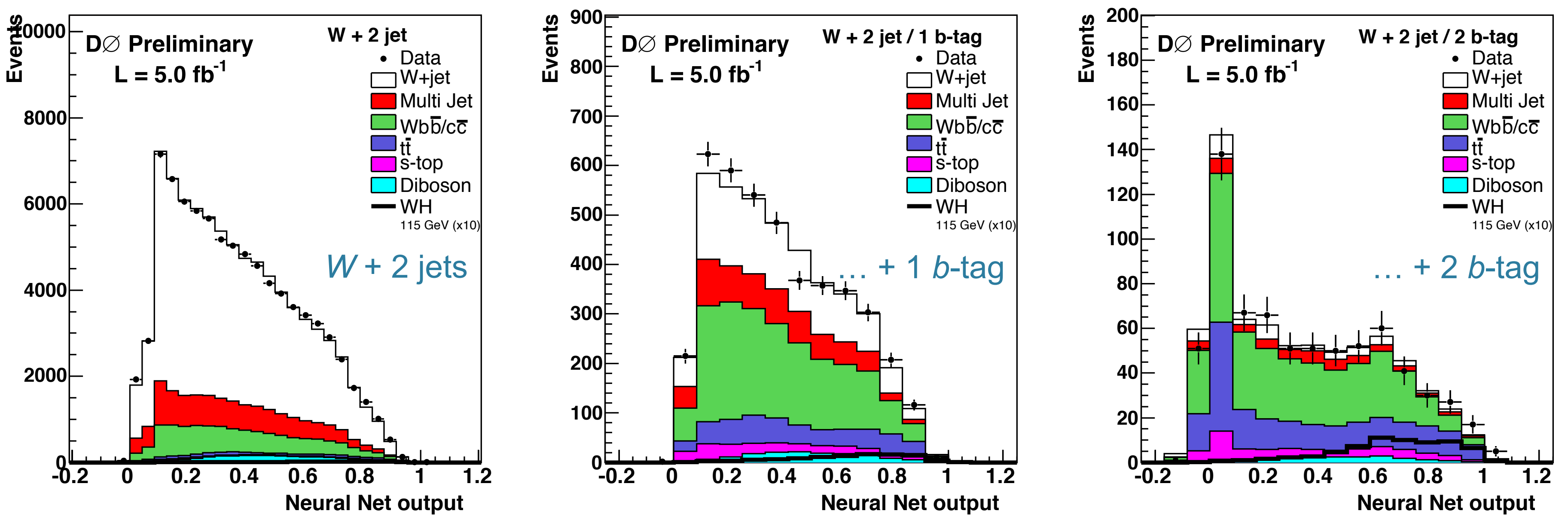
3) Optimise separation with **multivariate** tools

Good input variables:

- Di-jet mass
- p_T of the di-jet system
- p_T of W/Z
- Sphericity
- ΔR_{jj}, $\Delta\eta_{jj}$, $\Delta\phi_{jj}$

D0 plots of neural network output after each analysis step:



Low Mass Search

Example: $WH \to \ell\nu b\bar{b}$: lepton + E_T^{miss} + bb

Background Estimation: 4.8 fb^{-1}, 2 jets

Process	SVSV	SVJP	SVnoJP
All Pretag. Cands.	103564	103564	91545
WW	0.76 ± 0.17	2.8 ± 1.1	90.5 ± 11.3
WZ	7.1 ± 1.0	5.3 ± 0.9	30.0 ± 3.3
ZZ	0.26 ± 0.04	0.22 ± 0.04	1.18 ± 0.18
$t\bar{t}$ (lepton+jets)	40.2 ± 6.6	32.2 ± 5.9	176 ± 24
$t\bar{t}$ (dilepton)	24.1 ± 4.0	17.1 ± 2.9	68.0 ± 9.4
Single top (t-channel)	5.4 ± 0.9	5.4 ± 1.1	99.0 ± 14.3
Single top (s-channel)	22.5 ± 3.7	15.7 ± 2.6	56.5 ± 7.8
Z+jets	3.6 ± 0.6	4.40 ± 1.12	68.3 ± 10.4
Total MC	**104 ± 13**	**83.0 ± 12.7**	**589 ± 51**
Wbb	122 ± 39	103 ± 34	835 ± 252
Wcc/Wc	11.9 ± 4.1	39.1 ± 14.5	818 ± 252
Total HF	**134 ± 43**	**142 ± 47**	**1653 ± 502**
Wjj	4.1 ± 1.3	16.1 ± 9.2	819 ± 119
Non$-W$	14.8 ± 5.9	25.9 ± 10.4	250 ± 100
Total Prediction	**257 ± 45**	**268 ± 51**	**3311 ± 528**
WH115	**3.5 ± 0.4**	**2.4 ± 0.3**	**8.8 ± 0.7**
Observed	**245**	**263**	**3313**

CDF Background estimates

SVSV: events where two or more jets are tagged by the SecVtx algorithm.

SVJP: events with only one jet tagged by SecVtx and the other by the JetProbability algorithm.

SVnoJP: events with only one jet tagged by SecVtx

Sensitivity of Low-Mass Search

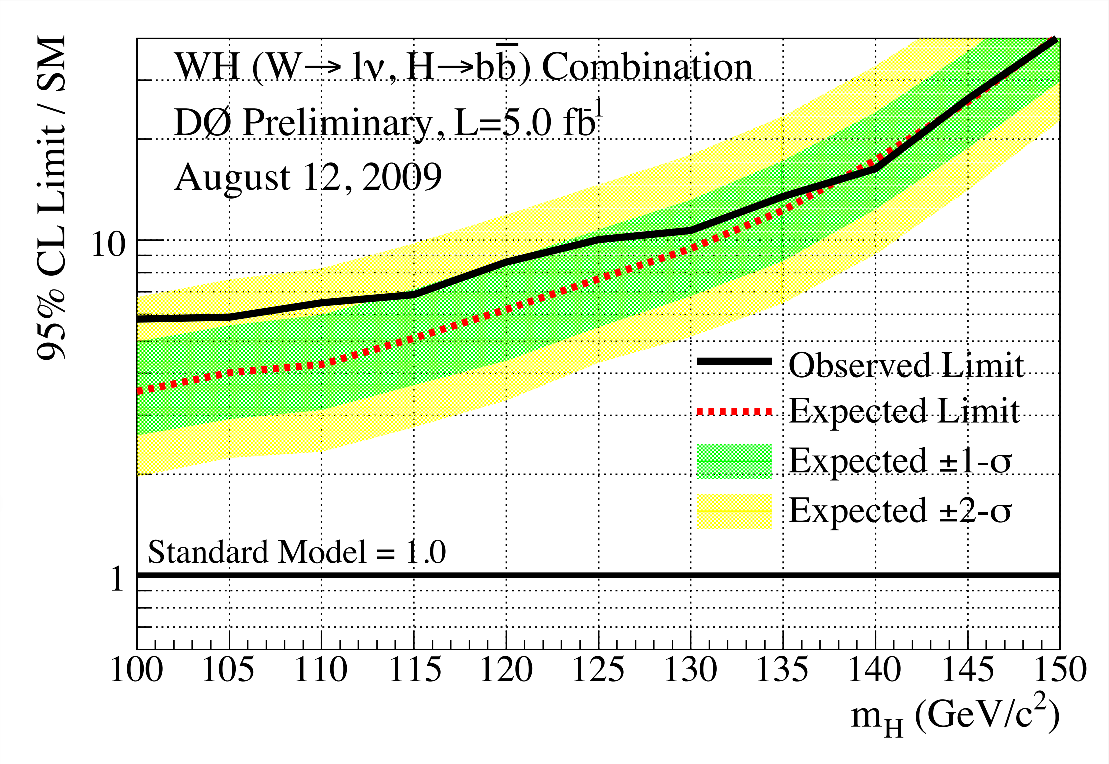
Example: $WH \to \ell\nu b\bar{b}$: lepton + E_T^{miss} + bb

Limits for individual channels a factor of 5–10 away from SM cross section at M_H = 115 GeV

→ **Combination** of all contributing channels **is crucial**

Excluded cross section:
(95% CL, M_H = 115 GeV)

D0: $\sigma(95) = 6.9 \times \sigma(SM)$
CDF: $\sigma(95) = 4.3 \times \sigma(SM)$



Main systematic uncertainties for low mass channels:

- Signal (total 15%): cross section, *b*-tagging, PID efficiencies
- Background (total 25–30%): normalisation of *W*/*Z* + jets heavy flavour samples, modelling of the multi-jet and *W*/*Z* + jet backgrounds, *b*-tagging

Example: $ZH \to \nu\nu b\bar{b}$: E_T^{miss} + bb

Includes also *WH* and missed lepton

ZH excluded cross section:

(95% CL, M_H = 115 GeV)

For missing-E_T ($\nu\nu$) mode:

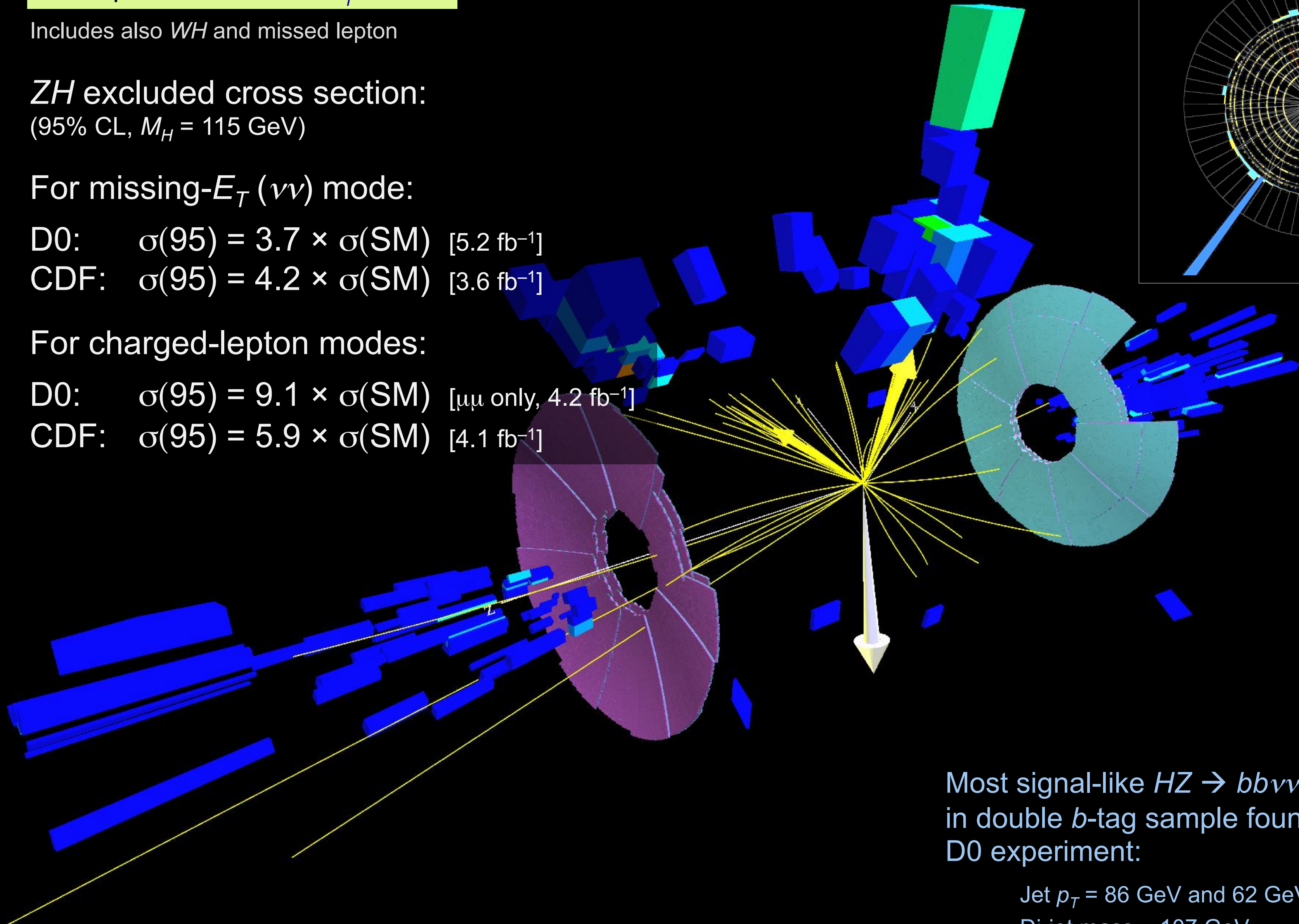
D0: $\sigma(95) = 3.7 \times \sigma(SM)$ [5.2 fb^{-1}]

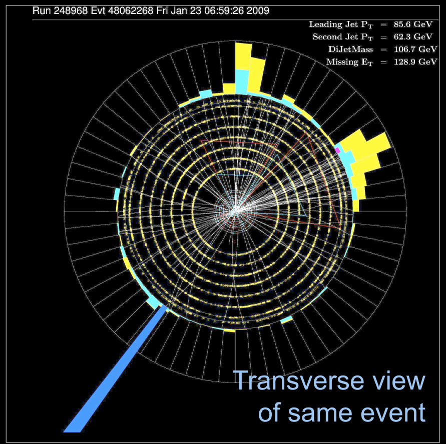
CDF: $\sigma(95) = 4.2 \times \sigma(SM)$ [3.6 fb^{-1}]

For charged-lepton modes:

D0: $\sigma(95) = 9.1 \times \sigma(SM)$ [$\mu\mu$ only, 4.2 fb^{-1}]

CDF: $\sigma(95) = 5.9 \times \sigma(SM)$ [4.1 fb^{-1}]





Most signal-like $HZ \to bb\nu\nu$ candidate in double *b*-tag sample found by the D0 experiment:

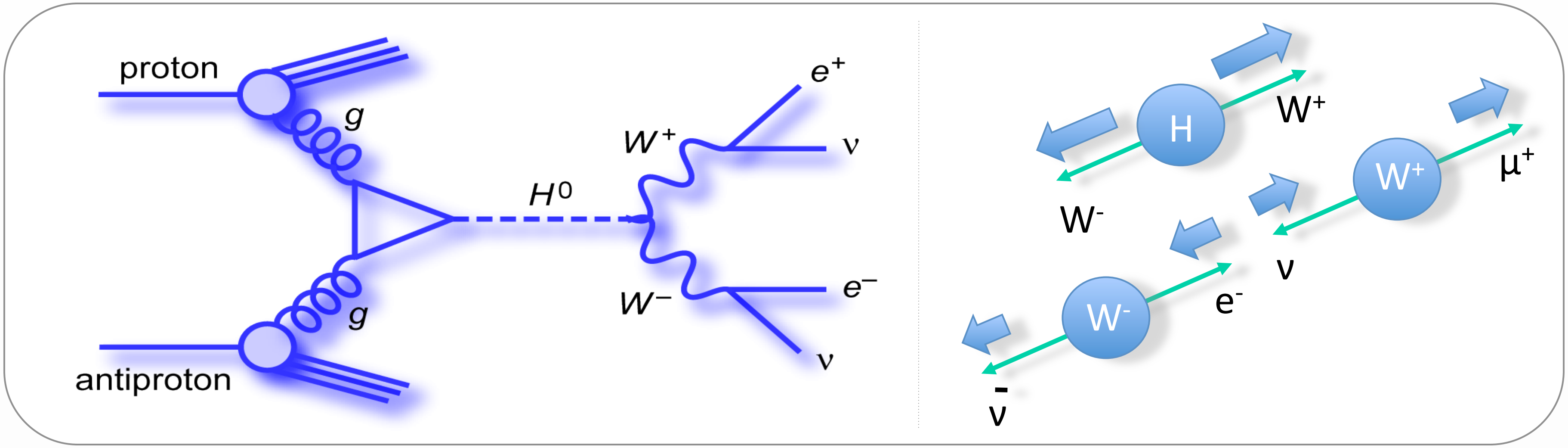
Jet p_T = 86 GeV and 62 GeV

Di-jet mass = 107 GeV

Missing E_T = 129 GeV

[Phys. Rev. Lett. 104, 071801 (2010)]

High Mass Search: $M_H > 135$ GeV



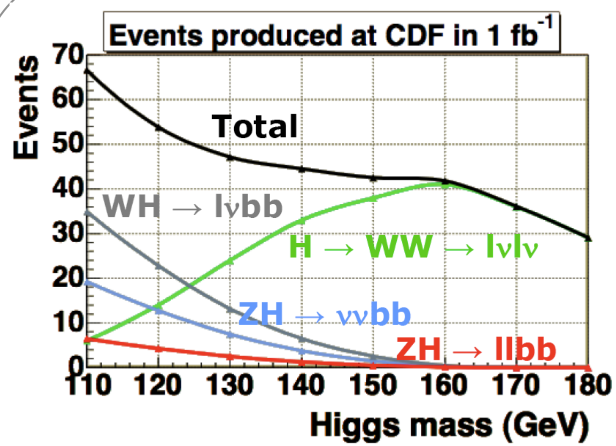
W polarisation: correlated lepton emission.
Di-lepton opening angle is strongest discriminant

$p\bar{p} \to H + X \to W^+W^- + X \to \ell^+\nu\ell^-\bar{\nu} + X$: leptons + E_T^{miss} + $W_{polarised}$

Dominant cross section > 135 GeV, most sensitive channel – signal contributions also from *W/Z* + *H* and *qqH* production

High-Mass Search

Number of events produced per Tevatron experiment in 1 fb^{-1} versus the Higgs mass



Channel	Events/fb
$WH \to l\nu bb$	0.1
$ZH \to \nu\nu bb$	0.07
$ZH \to llbb$	0.02
$H \to WW \to lnln$	38
Total	38

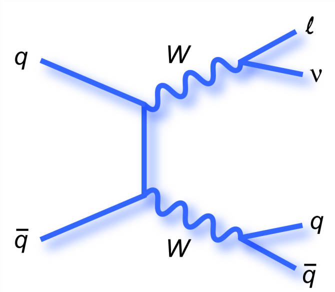
M_H = 165 GeV

$H \to W^+W^- \to \ell^+\nu\ell^-\bar{\nu}$: leptons + E_T^{miss} + $W_{polarised}$

Signal: $\sigma(M_H$=160 GeV) × BR ~ 40 fb

Associated *WH* and *qqH* modes increase signal by ~30%

Significant di-boson backgrounds:



WW: σ × BR = 13 pb
WZ: σ × BR = 4.0 pb
ZZ: σ × BR = 1.5 pb

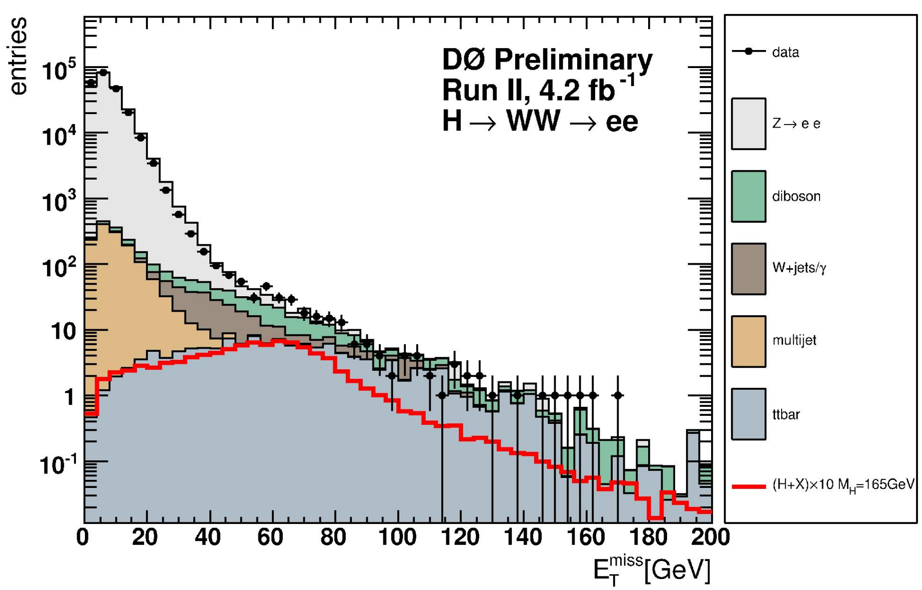
Additional backgrounds:

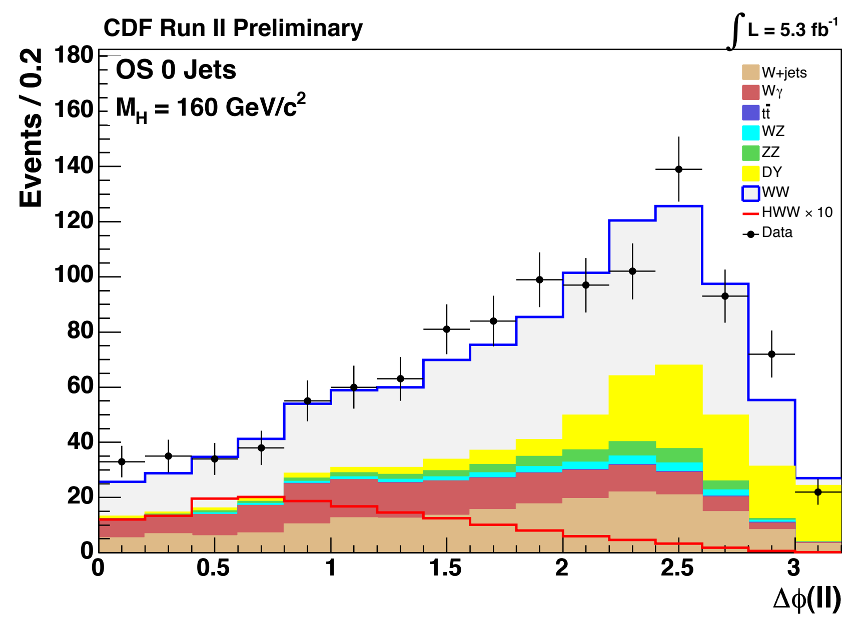
top-antitop: σ × BR = 7 pb
single-top: σ × BR = 3 pb
+ multi-jet QCD backgrounds

High-Mass Search

Dominant Drell-Yan background can be reduced with cuts on $E_{T,\text{miss}}$ and its isolation (distance to nearest object)

Spin correlation provides discriminant against irreducible background from nonresonant *WW* production

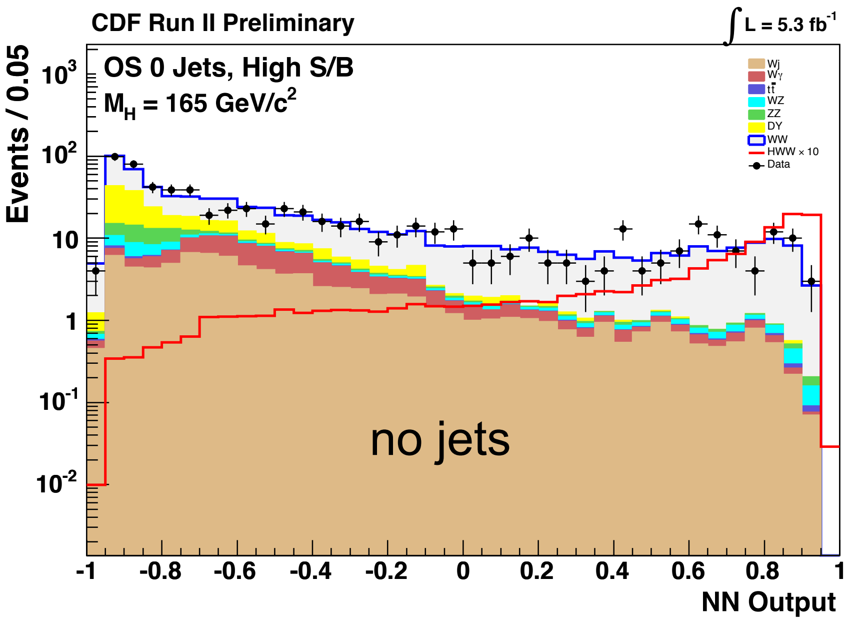


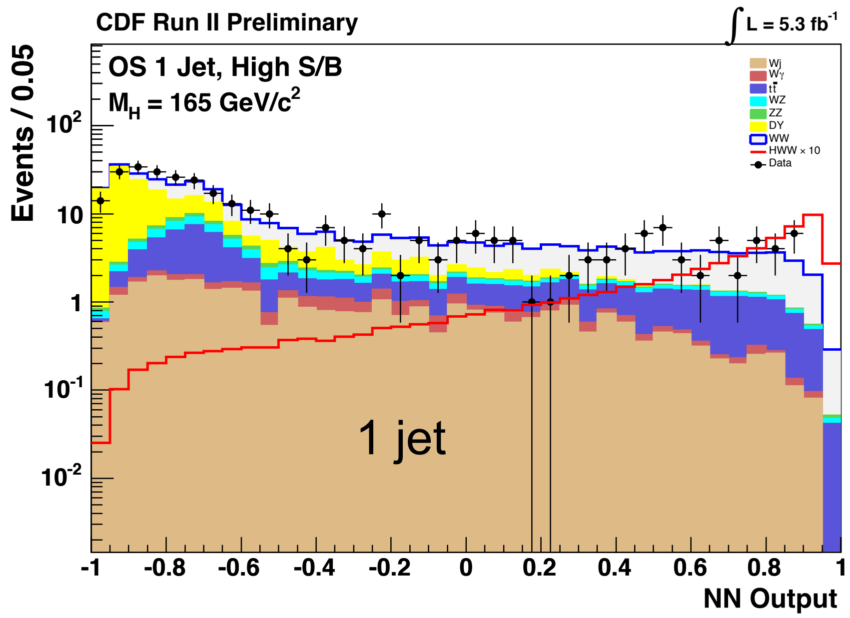


Increase sensitivity by splitting data sample into *ee*, $e\mu$, $\mu\mu$, and into 0-jet, 1-jet, ≥2-jets subsets → benefit from different S/B. Apply tight *b*-tag veto.

High-Mass Search

Combined kinematic and topological information (lepton transverse momenta, event properties ex. H_T, angular distributions, number of jets) from the event into neural network.





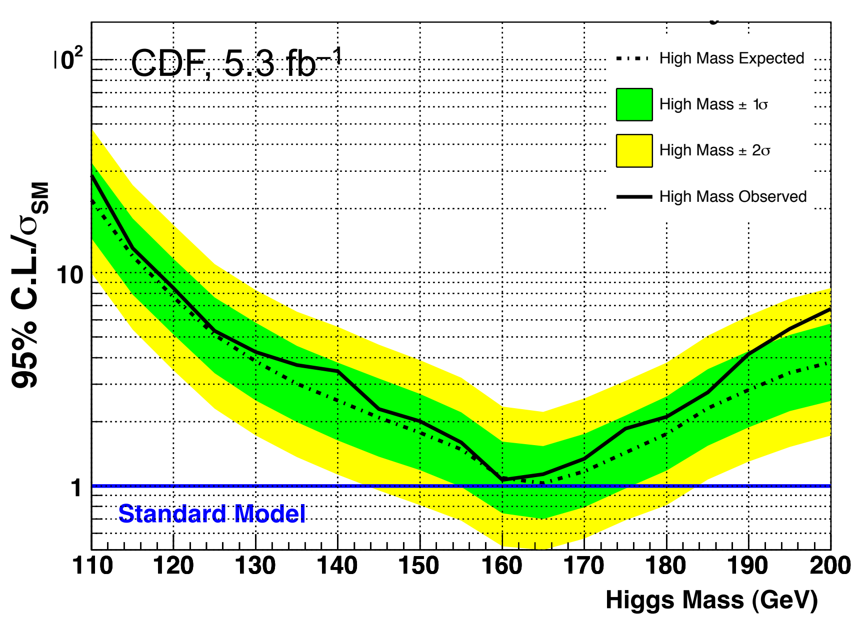
Background contributions changes radically between 0/1/2 jets.

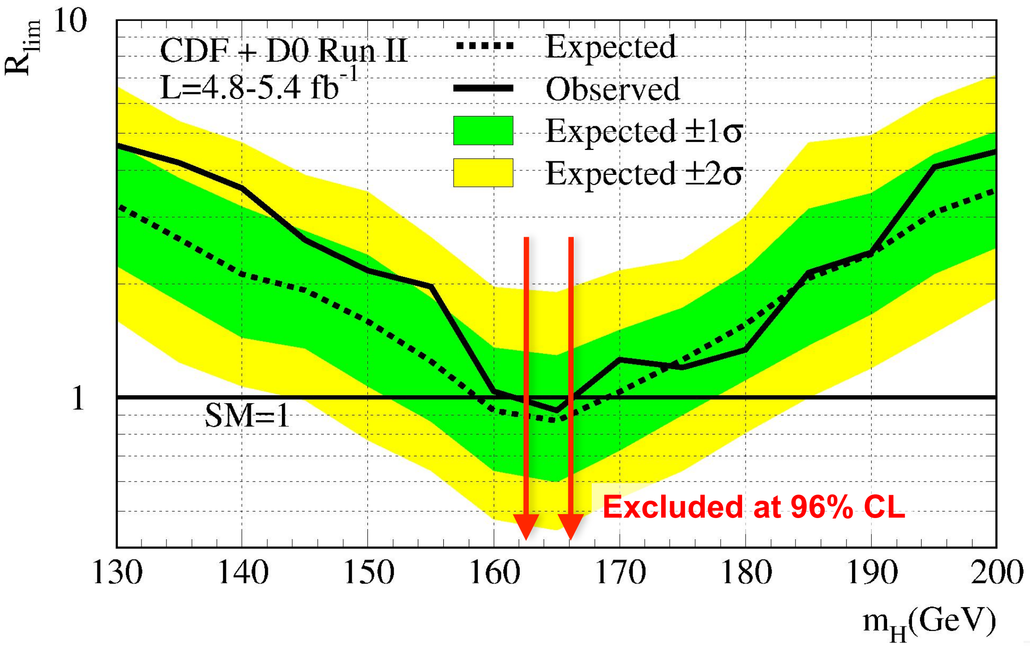
Also: extra signal from *VH*, *WBF*: ~20% in 1-jet, and ~60% in 2-jet

Sensitivity of High-Mass Search

Excluded cross section for CDF (left) and after combination with D0 (right)

Combination between experiments is not just a √2 factor: many correlated systematic errors!

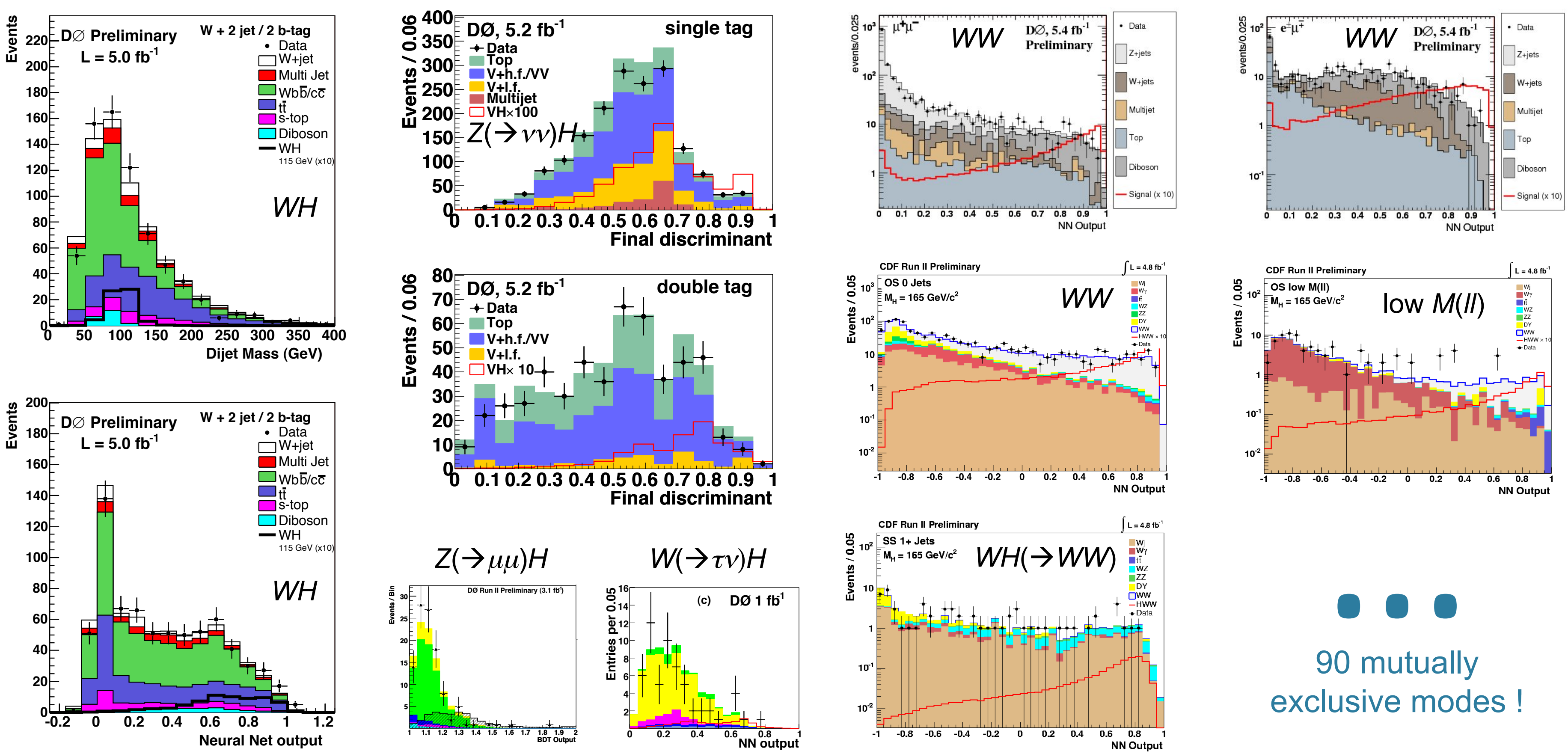




Combination and Limit Setting

Exclusion of any M_H is not possible by a single Tevatron channel / experiment

Need statistical combination of all the direct searches



90 mutually exclusive modes !

Systematic Uncertainties

The analysis are affected by significant systematic uncertainties, such as:

- Background normalisation (7 ~ 20%) and shape modelling (2 ~ 20%)
- Jet modelling (up to 20%) and Jet energy scale (~3%)
- *b*-tagging (0 ~ 9%)
- Luminosity (4 ~ 6%) and signal cross section (up to 11%), many more effects …

Systematic uncertainties for background rates are generally several times larger than the signal expectation itself

To minimize the degrading effect of systematic uncertainties on the search sensitivity, the individual background contributions are fitted to the data observation by maximising a likelihood function

Nuisance parameters allow for variations within errors

Each systematic error (incl. the error on the signal cross section) is folded into the signal and background expectation via Gaussian distributions

Correlations between nuisance parameters (due to common origin) are identified and preserved

Combination and Limit Setting

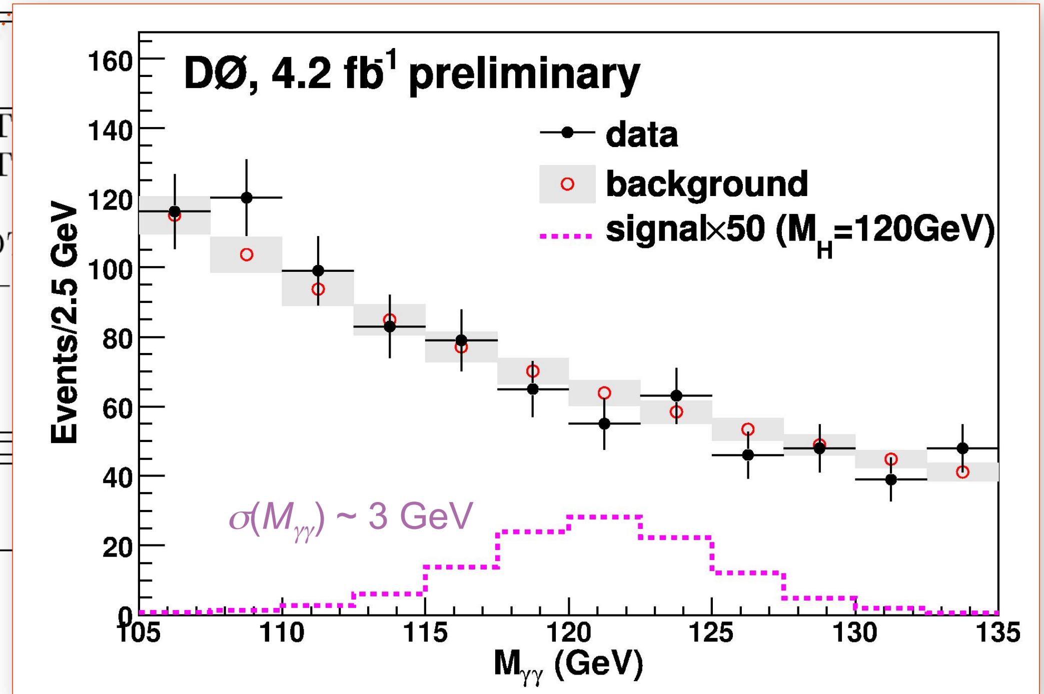
Exclusion of any M_H is not possible by a single Tevatron channel / experiment

Need statistical combination of all the direct searches

Lists of final states considered

CDF

Channel
$WH \to \ell\nu bb$ 2-jet channels 3×(TDT,LDT
$WH \to \ell\nu b\bar{b}$ 3-jet channels 2×(TDT,LDT
$ZH \to \nu\bar{\nu}b\bar{b}$ (TDT,LDT,ST)
$ZH \to \ell^+\ell^- b\bar{b}$ (low,high s/b)×(TDT,LD
$H \to W^+W^-$ (low,high s/b)×(0,1 jets)+
$WH \to WW^+W^- \to \ell^\pm\nu\ell^\pm\nu$
$H + X \to \tau^+\tau^- + 2$ jets
$WH + ZH \to jjb\bar{b}$



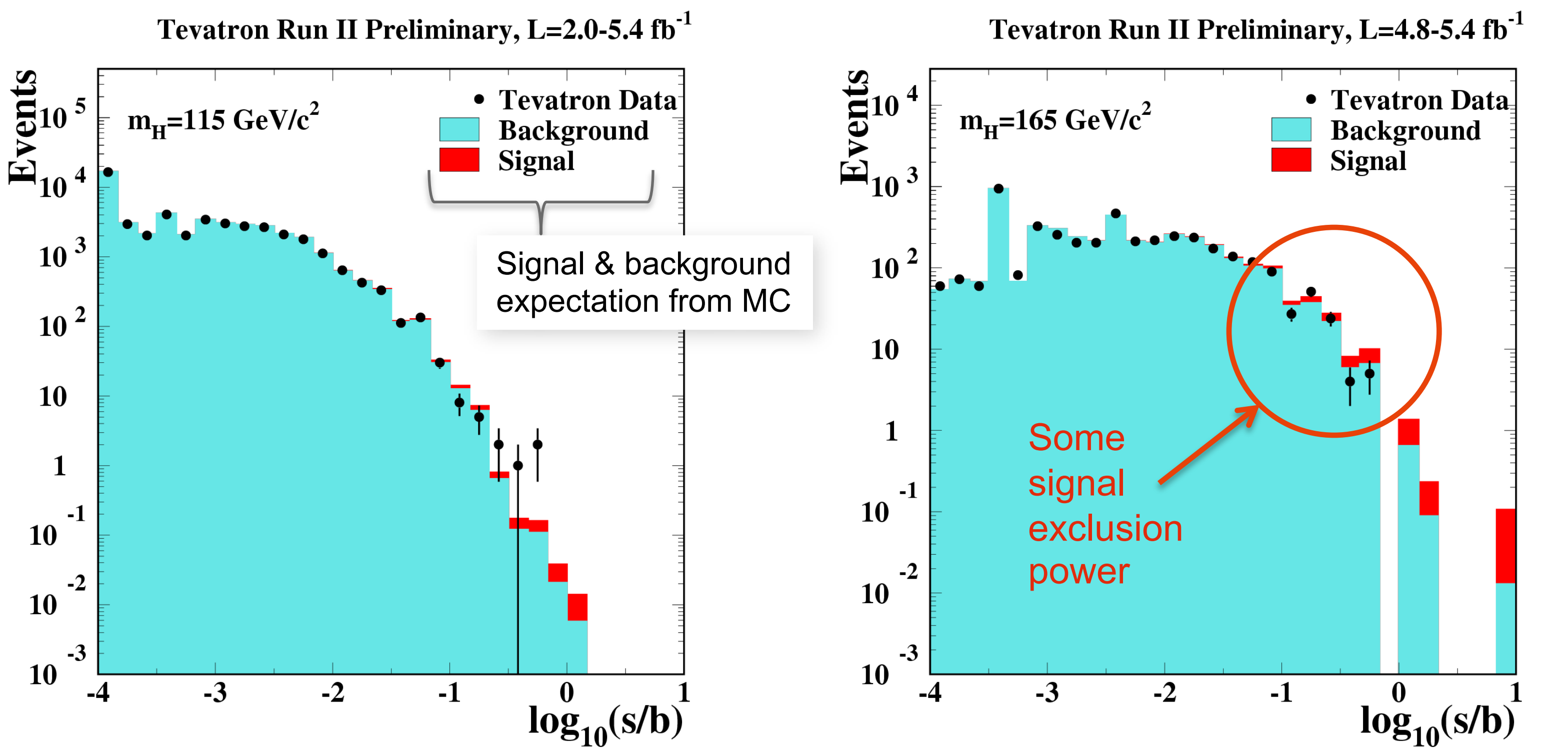
DØ

Channel		
$WH \to \ell\nu bb$ 2×(ST,DT)		
$VH \to \tau\tau b\bar{b}/q\bar{q}\tau\tau$		
$ZH \to \nu\bar{\nu}b\bar{b}$ (ST,TLDT)		
$ZH \to \ell^+\ell^- b\bar{b}$ 2×(ST,DT)		
$WH \to WW^+W^- \to \ell^\pm\nu\ell^\pm\nu$	3.6	120-200
$H \to W^+W^- \to \ell^\pm\nu\ell^\mp\nu$	5.4	115-200
$H \to \gamma\gamma$	4.2	100-150
$t\bar{t}H \to t\bar{t}b\bar{b}$ 2×(ST,DT,TT)	2.1	105-155

Combination and Limit Setting

Aggregate data bins according to their *S*/*B* ratio (for given M_H hypothesis) and plot

Including all data from CDF and D0



Hypothesis Testing

The observed data are subjected to a likelihood-ratio test of 2 hypotheses:

- Background scenario (no Higgs signal assumed)
- Signal + Background scenario (Higgs signal with assumed mass added)

Statistical analysis of *hypothesis* M_H is based on likelihood ratio:

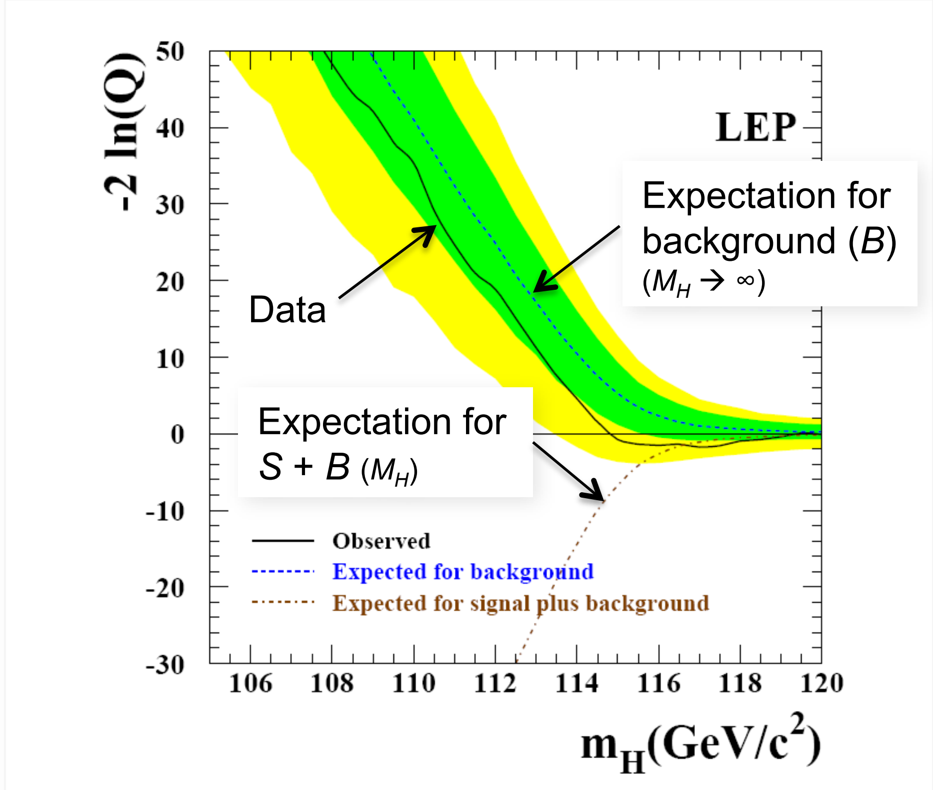
$$Q(M_H) \equiv \frac{L_{s+b}(M_H)}{L_b(M_H)}$$

Use the log-likelihood ratio

$$\mathrm{LLR}(M_H) \equiv -\ln Q(M_H)$$

as *test statistics*

The expected distribution (PDF) of $\mathrm{LLR}(M_H)$ is obtained from MC and compared to data



Hypothesis Testing

Quantify the level of agreement of the data

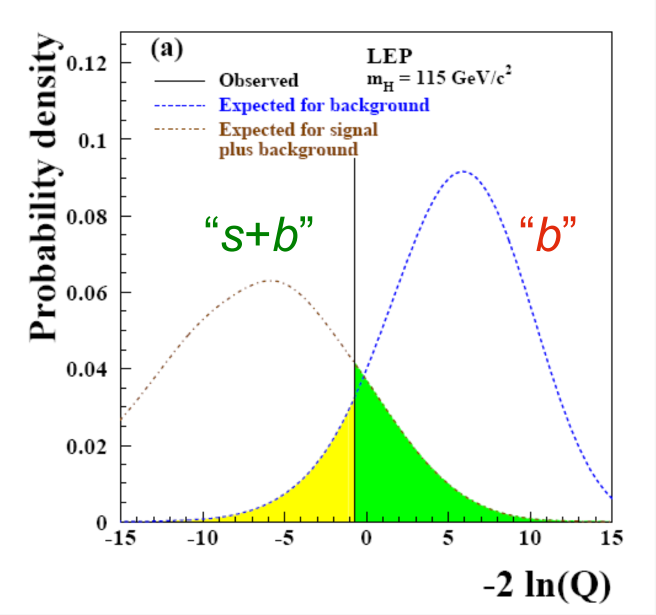
- with the "*b* only" hypothesis by estimating

  $CL_b = 1 - P(LLR < LLR_{Data} \mid B)$

  using pseudo ("toy") MC experiments
- with the "*s*+*b*" hypothesis by estimating

  $CL_{s+b} = P(LLR > LLR_{Data} \mid S+B)$

  using pseudo MC experiments



A frequentist exclusion limit is usually computed using CL_{s+b}

The "*s*+*b*" hypothesis is excluded at 95% CL if $CL_{s+b} < 0.05$

However, if the data undershoot the background, then CL_{s+b} small even if no sensitivity to signal !

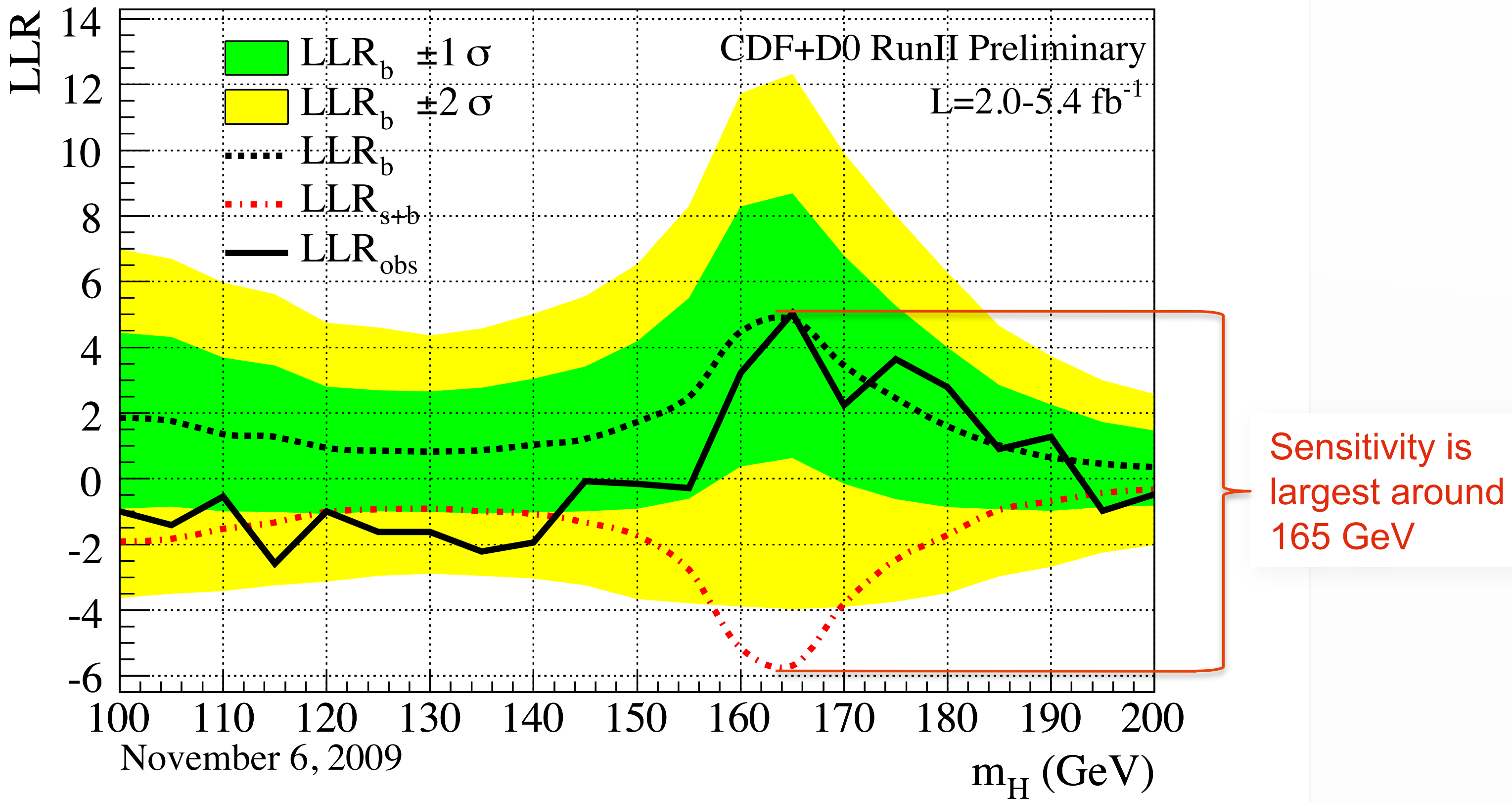
As a protection, collaborations use

$CL_s = CL_{s+b} / CL_b$

for exclusion limits

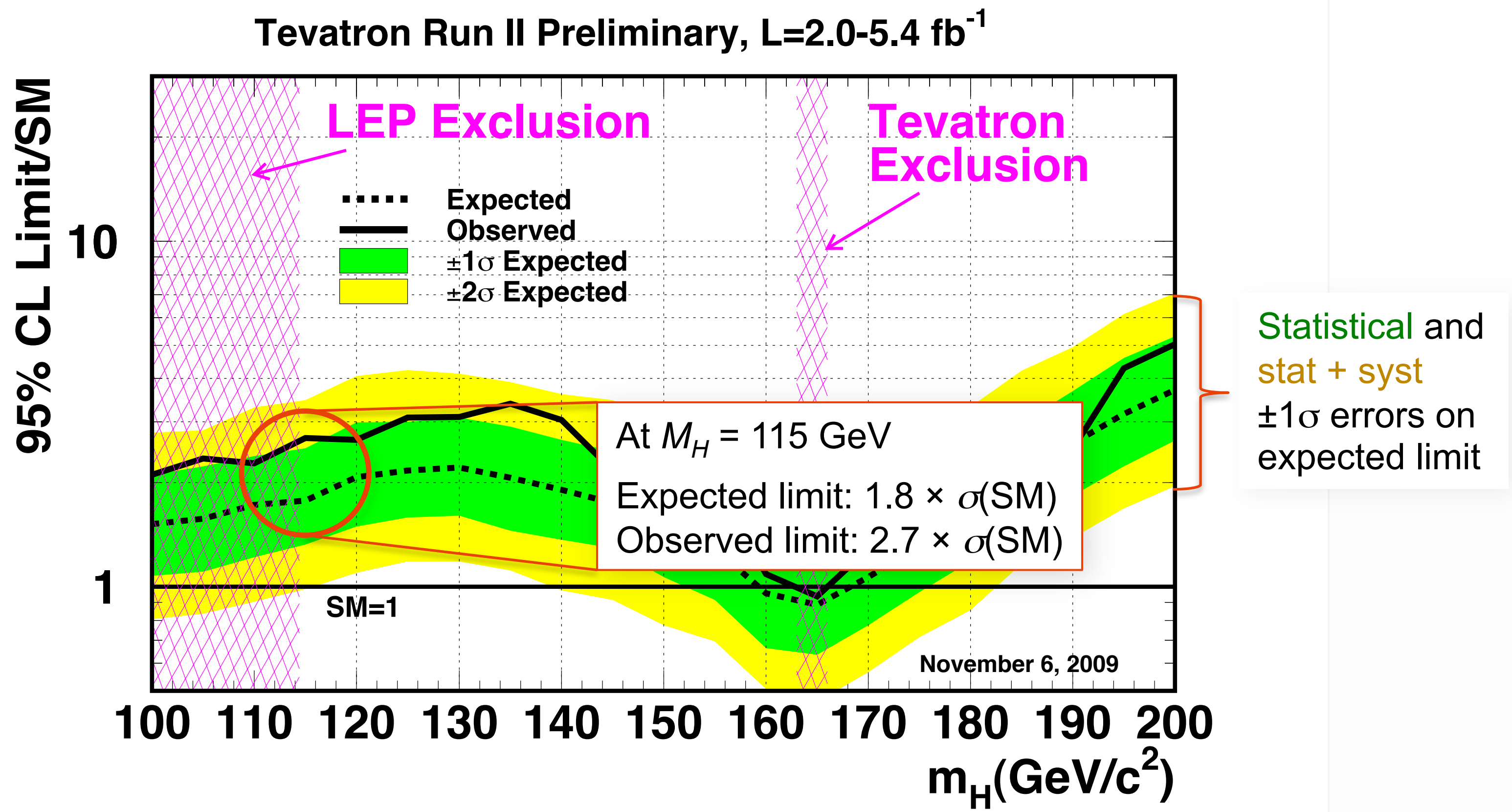
- *Modified frequentist approach* (conservative, as: $CL_s > CL_{s+b}$)
- If $CL_s < 0.05$: "hypothesis excluded at 95% CL"

Results of Tevatron Combination



Observed LLR is consistent with background hypothesis, although at low mass, *S*+*B* is slightly favoured

Results of Tevatron Combination



Tevatron experiments set a 95% CL exclusion of a SM Higgs boson in the mass region 162 – 166 GeV (first direct exclusion since LEP)

Comments on Tevatron Higgs Search

Karl Jakobs, Freiburg

The expected signal and background contributions were estimated with NLO MC or better, or were obtained from data via fits of nuisance parameters

With this, the Tevatron experiments have reached sensitivity (expected limit) for the SM Higgs boson in the mass range around 160 GeV

With increased luminosity, the sensitivity in this region could reach 3σ level:

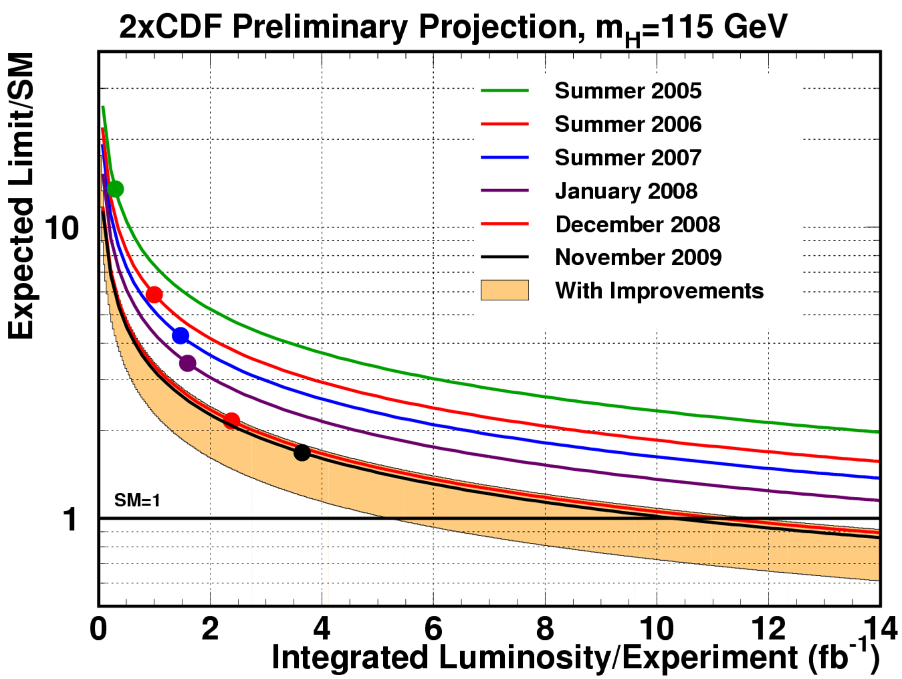
> *Either a large mass region can be excluded with 95% CL, or first evidence (3σ) for a SM Higgs boson can be found.*
>
> *However: not a single "evidence channel" available. Need the combination of many channels and of the two experiments !*

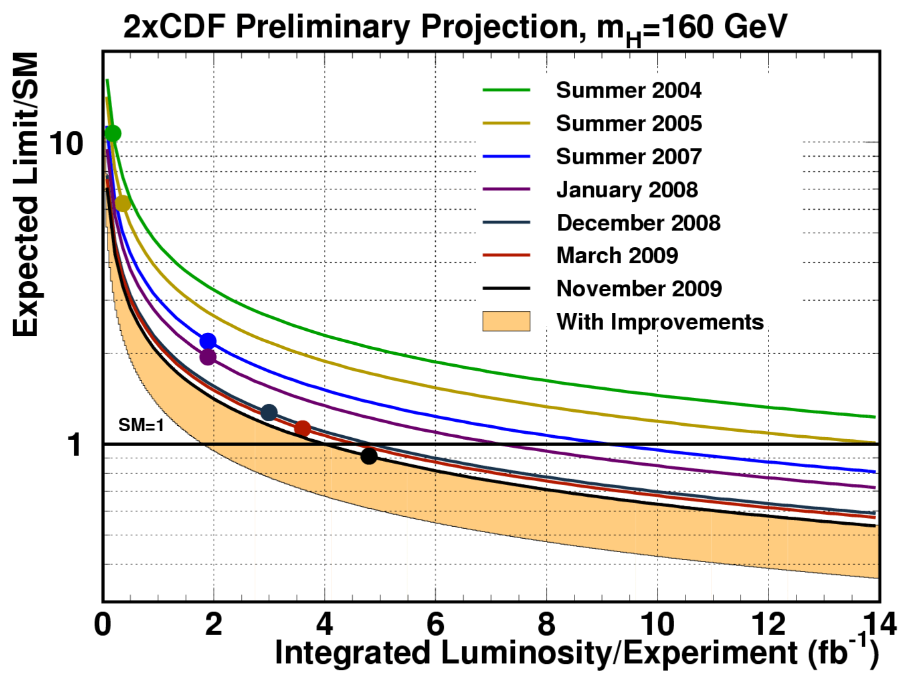
The Higgs search in the mass range below ~130 GeV is challenging (also at the LHC!)

Search for the *bb* final state at the Tevatron will provide complementary information to the LHC searches in the $H \rightarrow \gamma\gamma$ and $qqH \rightarrow qq\tau\tau$ channels

Expected Future Tevatron Sensitivity

Limit projections by CDF Collaboration:





For 10 fb^{-1}, expect 95% CL exclusion for a Higgs boson mass of 115 GeV

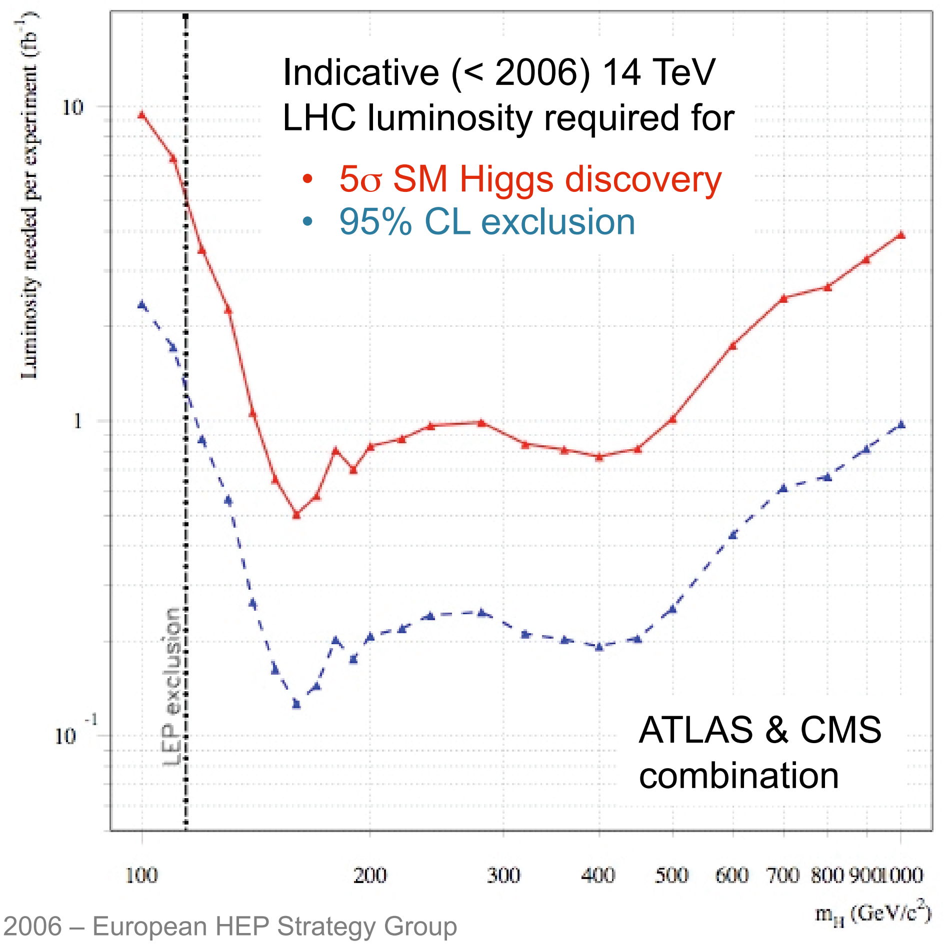
May be reached faster, if analysis (e.g., improved *bb* mass resolution, *b*-tagging, PID) improvements can be achieved → may be able to exclude M_H for 115 – 200 GeV

Higgs Searches at the LHC

Many LHC prospective studies shown here based on $\sqrt{s}$ = 14 TeV.
Use preliminary results for $\sqrt{s}$ = 7 TeV, where available.

CMS: CERN / LHCC 2006-021
ATLAS: CERN-OPEN 2008-020

If the Standard Model Higgs exist, it should be discovered at the LHC



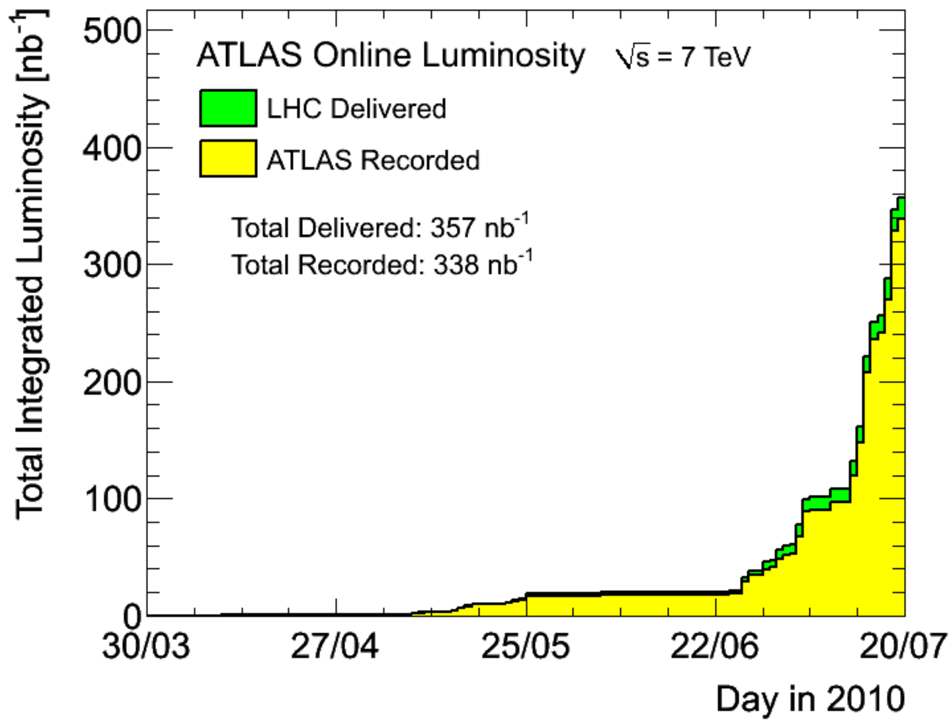
2006 – European HEP Strategy Group

$< 1\ fb^{-1}$ needed to set a 95% CL limit in most of the mass range

Low mass ~115 GeV most difficult

Curved may be optimistic

LHC has started at 7 TeV on March 30, 2010, safely rising inst. luminosity



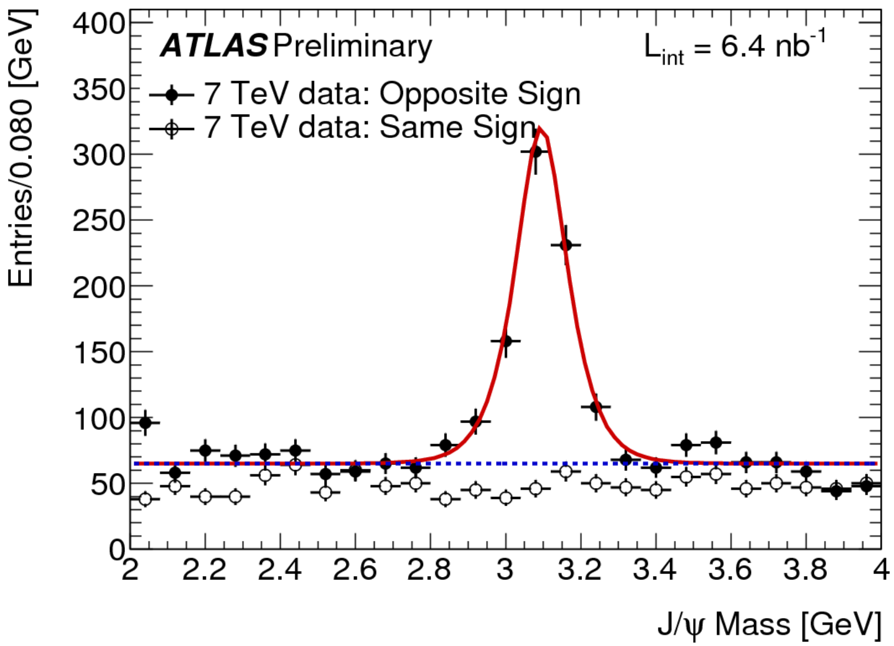
~90% data taking efficiency for ATLAS.
Similar numbers for CMS, and comparable to CDF after many years of Run II operation !

LHC commissioning projections expect instantaneous luminosity of 10^{32} cm^{-2}s^{-1} end of 2010, and 1 fb^{-1} at planned shutdown end of 2011

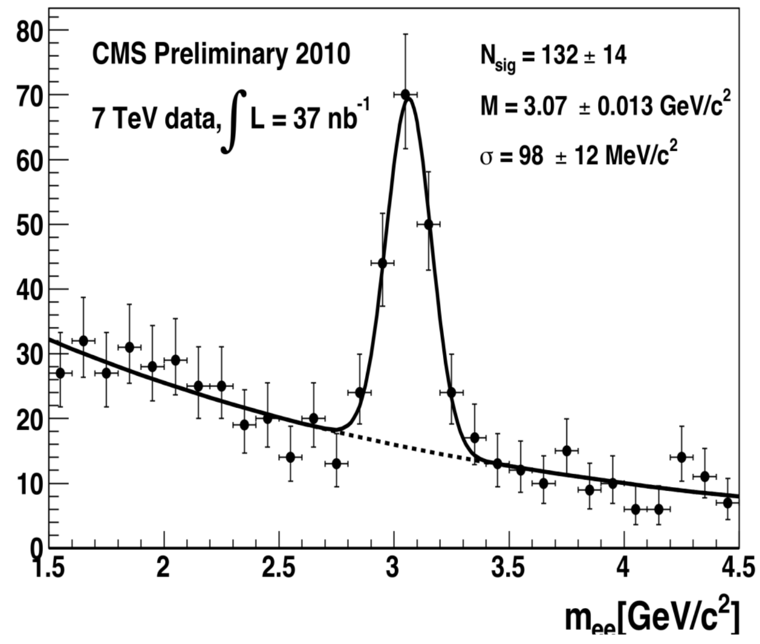
10^{32} cm^{-2}s^{-1} *instantaneous* luminosity corresponds to an *integrated* luminosity of 0.1 nb^{-1} per second

→ 180 pb^{-1} per month (assuming 70% LHC efficiency for physics)

Available data sample useful for performance studies … (e/μ ID)

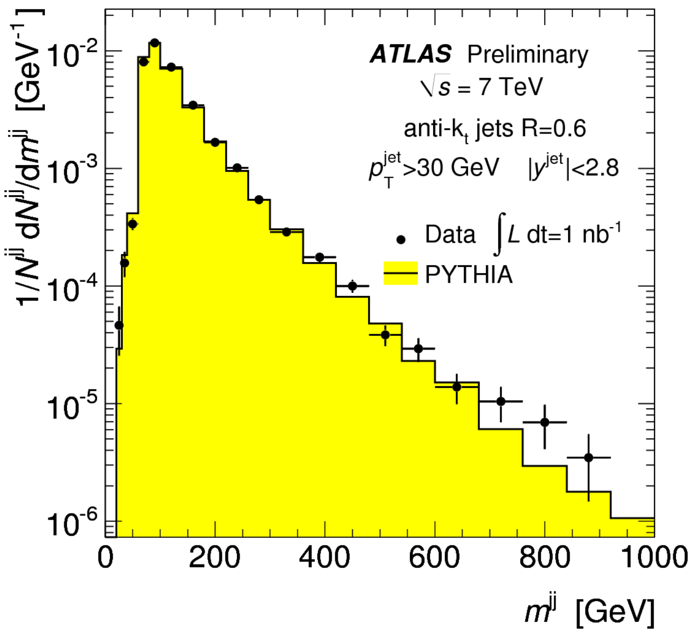


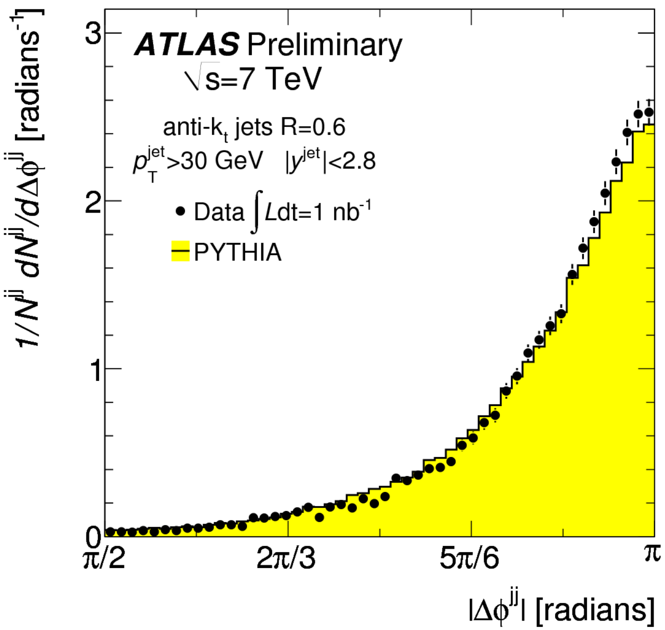
$J/\psi \rightarrow \mu\mu$ invariant mass reconstructed from identified muons and momenta measured in the inner tracking detectors and muon spectrometer



Challenging reconstruction of $J/\psi \rightarrow ee$ requiring bremsstrahlung recovery (particle flow)

… of many features required for Higgs searches … (jets)

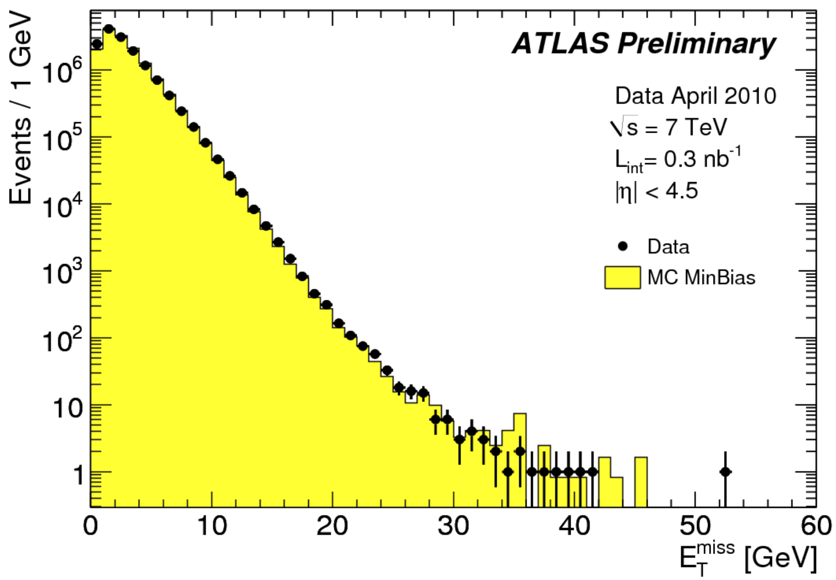




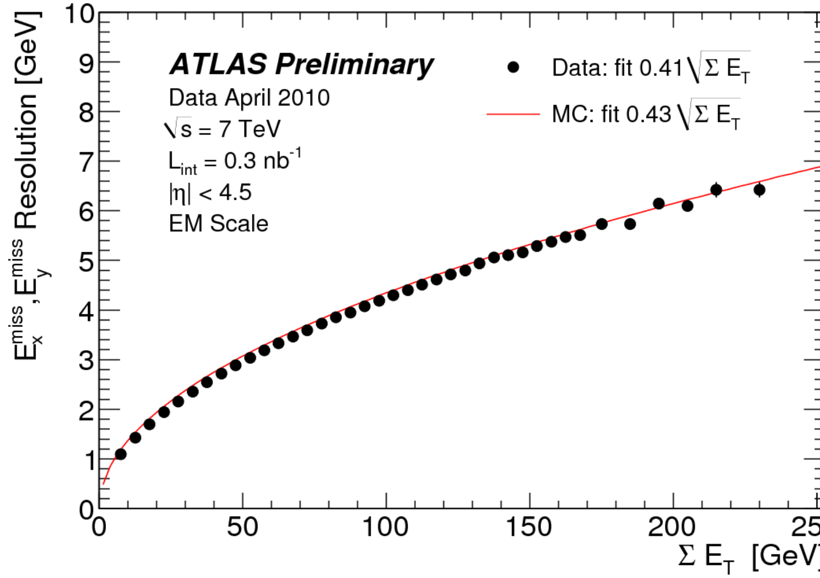
Invariant mass and azimuthal balance (right) of di-jet events with p_T > 30 GeV, $|\eta|$ < 2.8, for data and MC simulation

CMS applies **particle flow algorithm**, based on ID of particles in jets / contributing to $E_{T,\text{miss}}$. Obtain best energy estimate for each particle type: γ in ECAL, charged hadrons in tracker, e in ECAL + tracker, neutral hadrons in CALO, μ in tracker and muon system → build composites (τ, π_0, …).

… of many features required for Higgs searches … ($E_{T,miss}$)

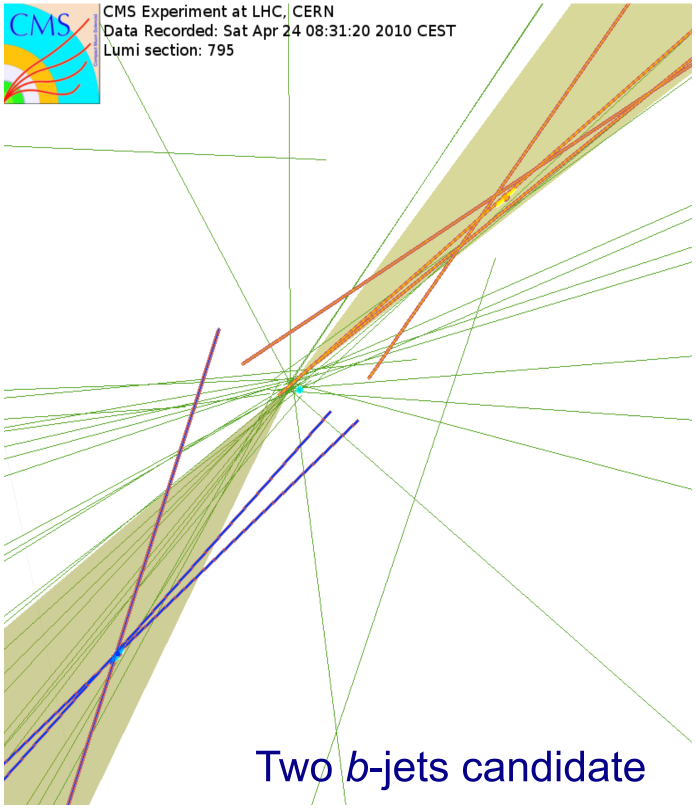


Inclusive missing transverse energy (EM scale) distribution in ATLAS, reproduced in shape by MC simulation over 6 orders of magnitude

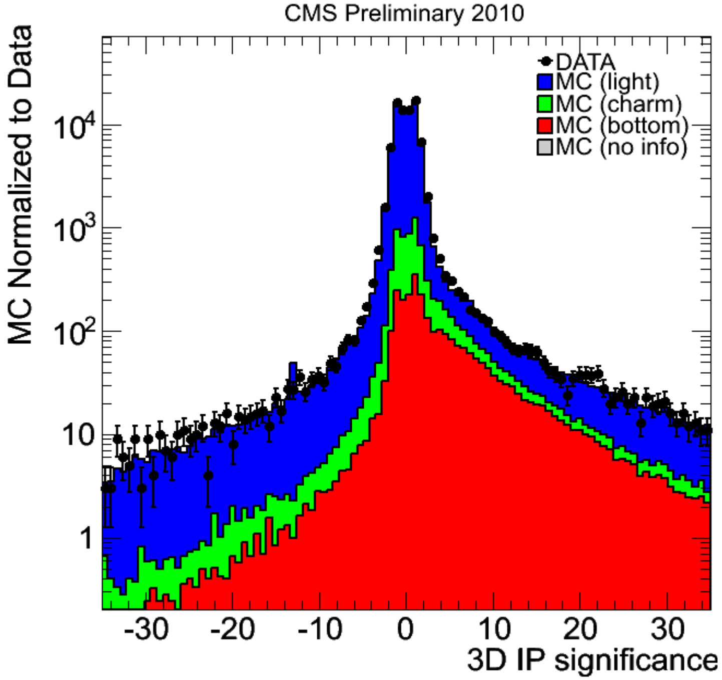


Missing transverse energy resolution behaves as as expected as a function of the measured total transverse energy

… of many features required for Higgs searches … (*b*-tagging)

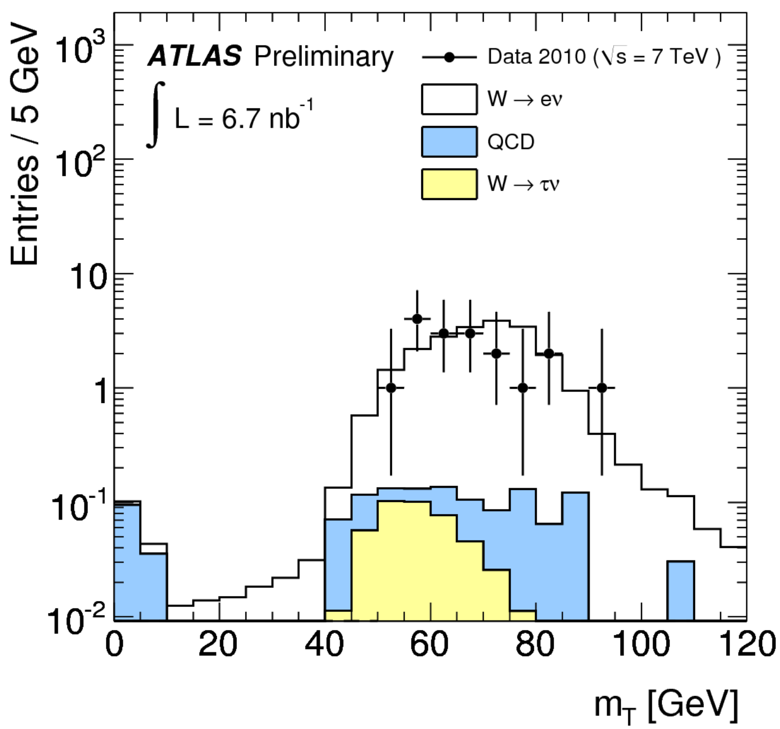


Two *b*-jets candidate

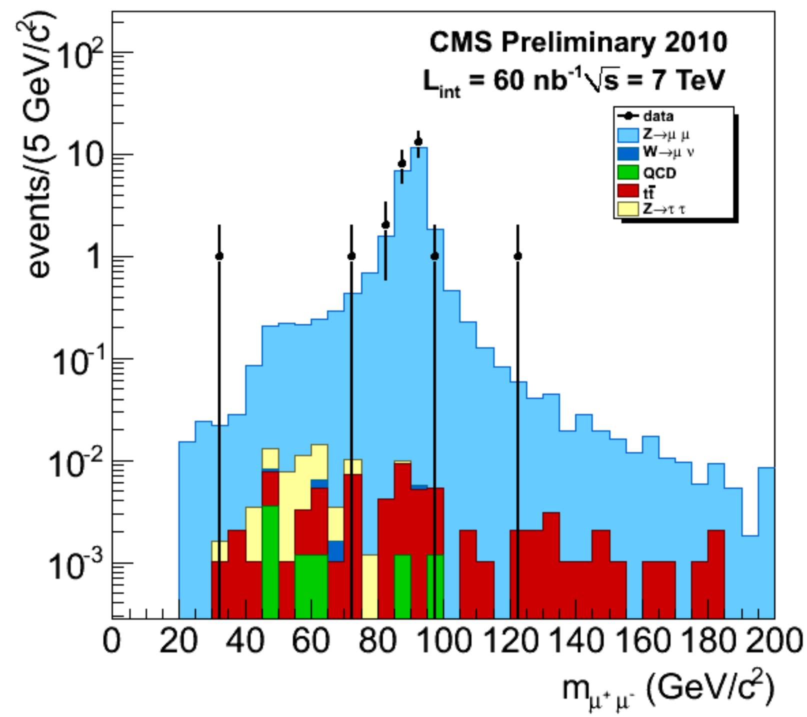


b-tagging significance in 7 TeV data and expected contributions from MC simulation.

… it allows to perform QCD measurements, and first *W* and *Z* studies

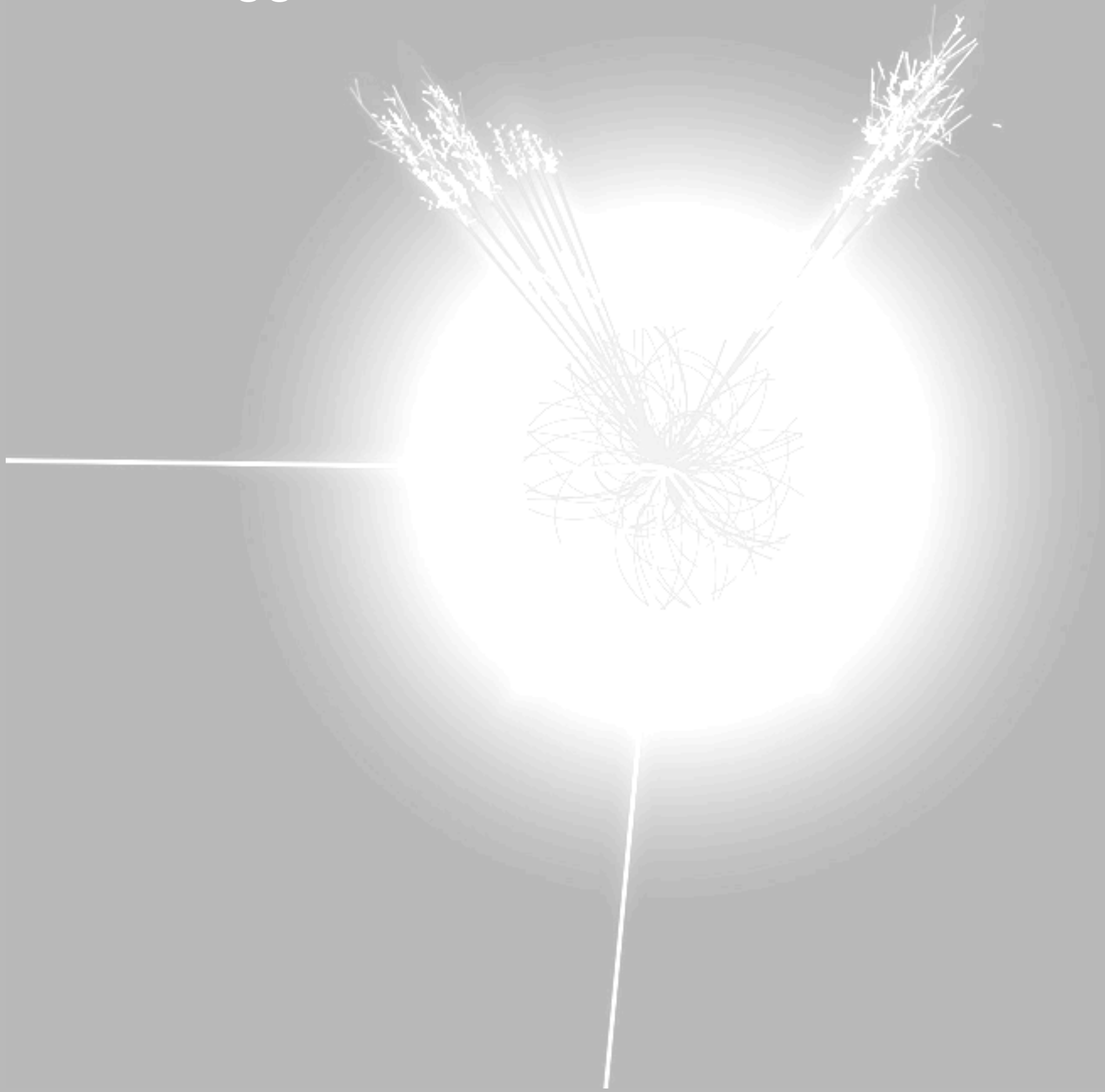


Transverse mass distribution and
$W \rightarrow e\nu$ candidates from ATLAS

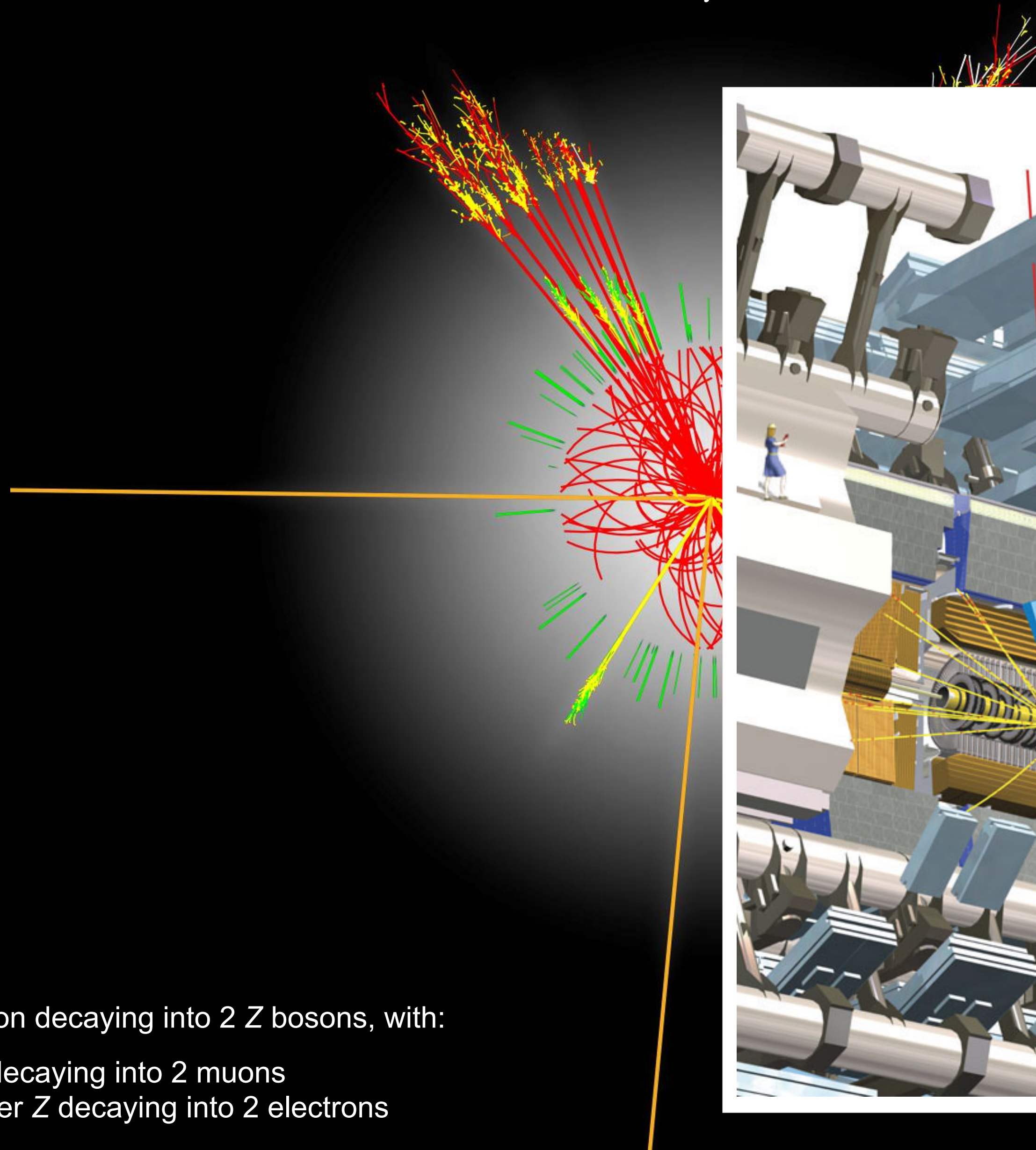


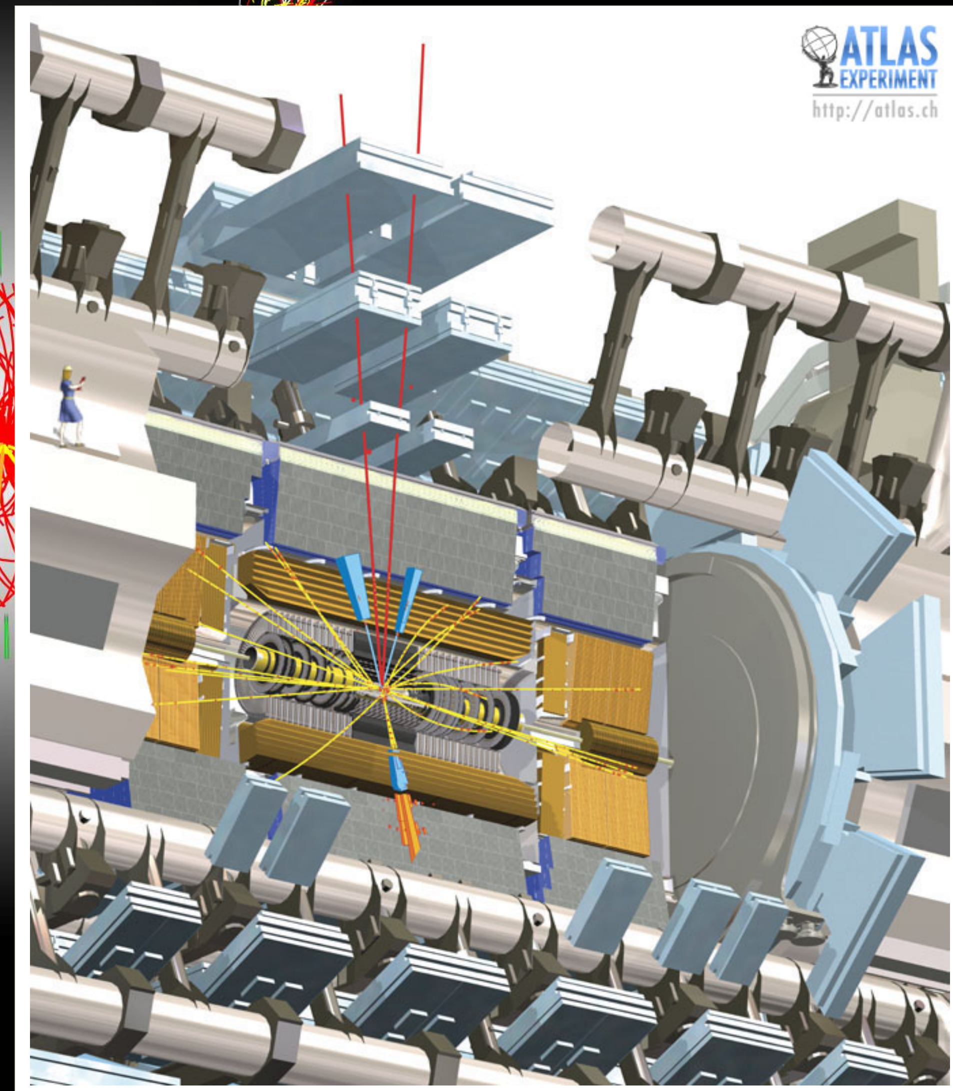
Di-muon invariant mass and
$Z \rightarrow \mu\mu$ candidates from CMS

How would a Higgs event look like in ATLAS ?



Simulation of a $H \rightarrow ZZ^{(*)} \rightarrow 2e2\mu$ event in ATLAS





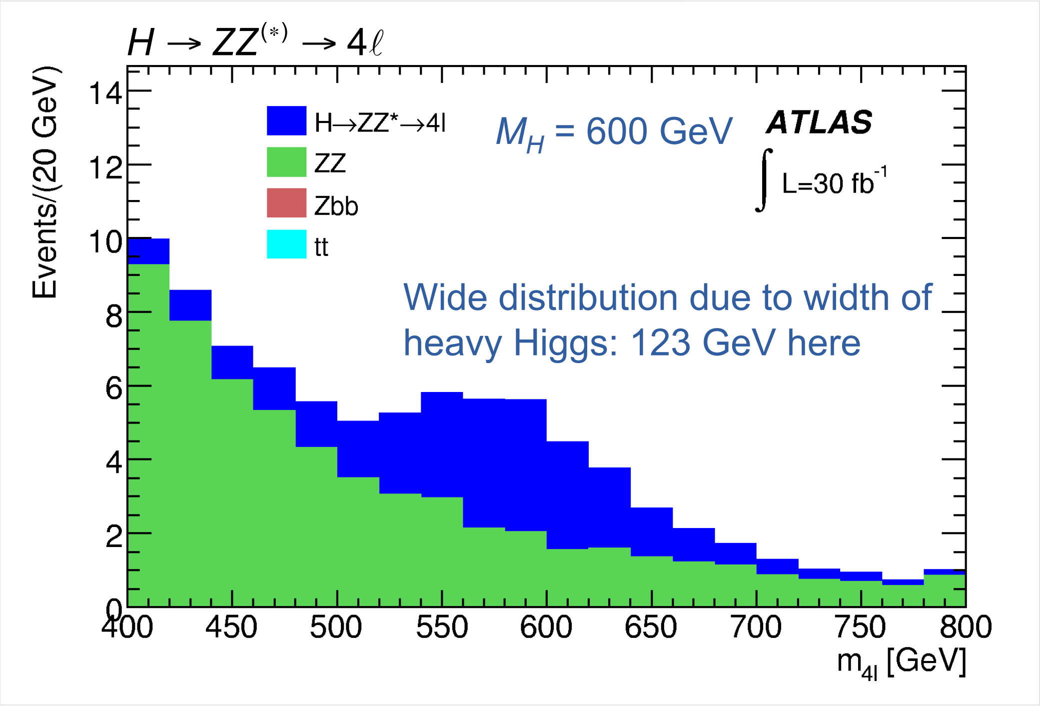
Higgs boson decaying into 2 *Z* bosons, with:

- One *Z* decaying into 2 muons
- The other *Z* decaying into 2 electrons

$H \rightarrow ZZ^{(*)} \rightarrow$ 4 leptons

Golden discovery channel for intermediate Higgs mass: $\sigma \times$ BR (115 GeV) ≈ 50 fb

Signal selection: p_T(1,2/3,4) > 20/7 GeV, $|\eta|$<2.5, isolated leptons, $M(i,j) \sim M_Z$, $M(n,m) \sim < M_Z$



Backgrounds:

Top production

$t\bar{t} \rightarrow WbWb \rightarrow \ell\nu\ c\ell\nu\ \ell\nu\ c\ell\nu$

$\sigma \times$ BR ≈ 1.3 pb

Also: associated *Zbb* production

$Zbb \rightarrow \ell\ell\ c\ell\nu\ c\ell\nu$

Reject these backgrounds:

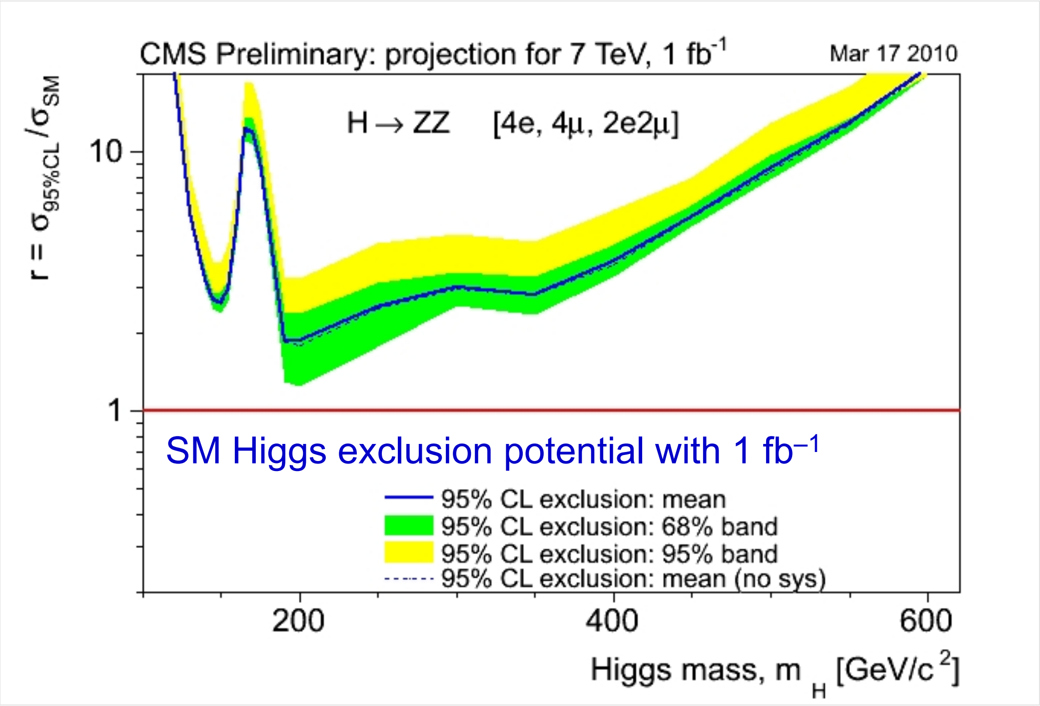
Leptons from *b*-quark decays are not isolated and stem from secondary vertex (τ_B = 1.5 ps)

Dominant background after isolation cuts: *ZZ* continuum

$H \rightarrow ZZ^{(*)} \rightarrow$ 4 leptons

Golden discovery channel for intermediate Higgs mass: $\sigma \times$ BR (115 GeV) ≈ 50 fb

Signal selection: p_T(1,2/3,4) > 20/7 GeV, $|\eta|$<2.5, isolated leptons, $M(i,j) \sim M_Z$, $M(n,m) \sim < M_Z$



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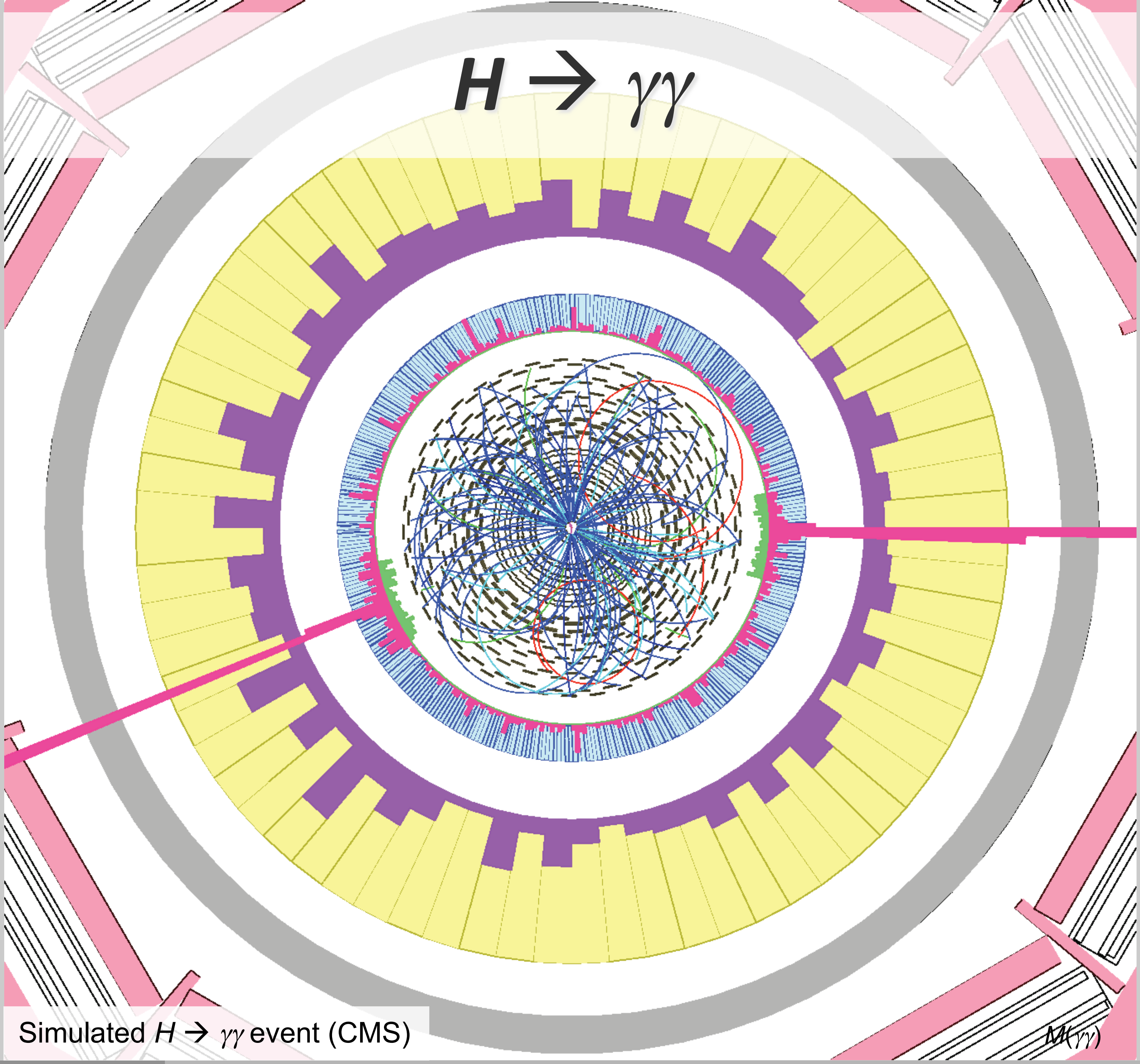
H → γγ



Simulated $H \rightarrow \gamma\gamma$ event (CMS)

$H \rightarrow \gamma\gamma$

Clean discovery channel for light Higgs: σ × BR (115 GeV) ≈ 10 fb

Signal selection: need excellent E_γ resolution, and efficient & pure photon ID; use MVA: $M_{\gamma\gamma}$, $\cos\theta^*$, $p_{T,\gamma\gamma}$

$$\frac{\sigma(E)}{E} = \frac{S}{\sqrt{E\ (\text{GeV})}} \oplus C \oplus \frac{N}{E\ (\text{GeV})}$$

"Noise term"

Electronics noise (pile-up also contributes)

"Constant term"

Non-uniformities in calorimeter response due to inhomogeneities, non-linearities

Constant	ATLAS	CMS
S	10–12 %	3–5.5 %
C	0.2–0.35 %	0.5 %
N	250 MeV	200–600 MeV

Back-on-the-envelope for $H \rightarrow \gamma\gamma$: $\sigma_{M_{\gamma\gamma}}(E_\gamma)\Big|_{p_H=0} \propto \frac{M_H}{\sqrt{2}} \frac{\sigma_{E_\gamma}}{E_\gamma} \underset{M_H=120\text{ GeV}}{\approx} \begin{cases} 1.2\text{ GeV} & \text{(ATLAS)} \\ 0.7\text{ GeV} & \text{(CMS)} \end{cases}$

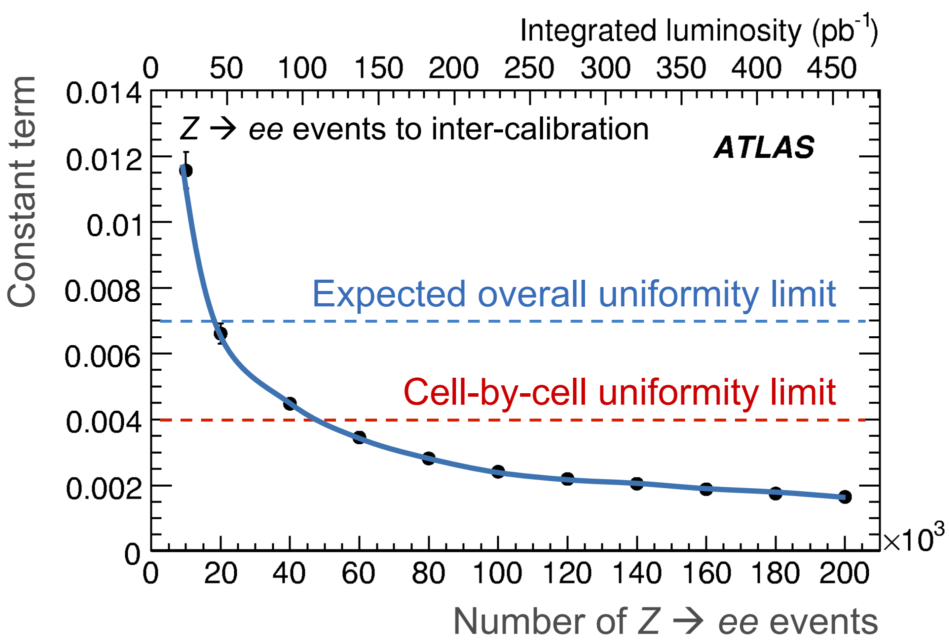
But: full picture must include error on opening angle ($\theta_{\gamma\gamma}$), and $\gamma \rightarrow ee$ conversions !

$H \rightarrow \gamma\gamma$

Require also good calorimeter uniformity = small constant term

Use $Z \rightarrow ee$ events to inter-calibration eletromagnetic calorimeter

- Back-on-the-envelope test for effect of constant term on Higgs discovery(*)



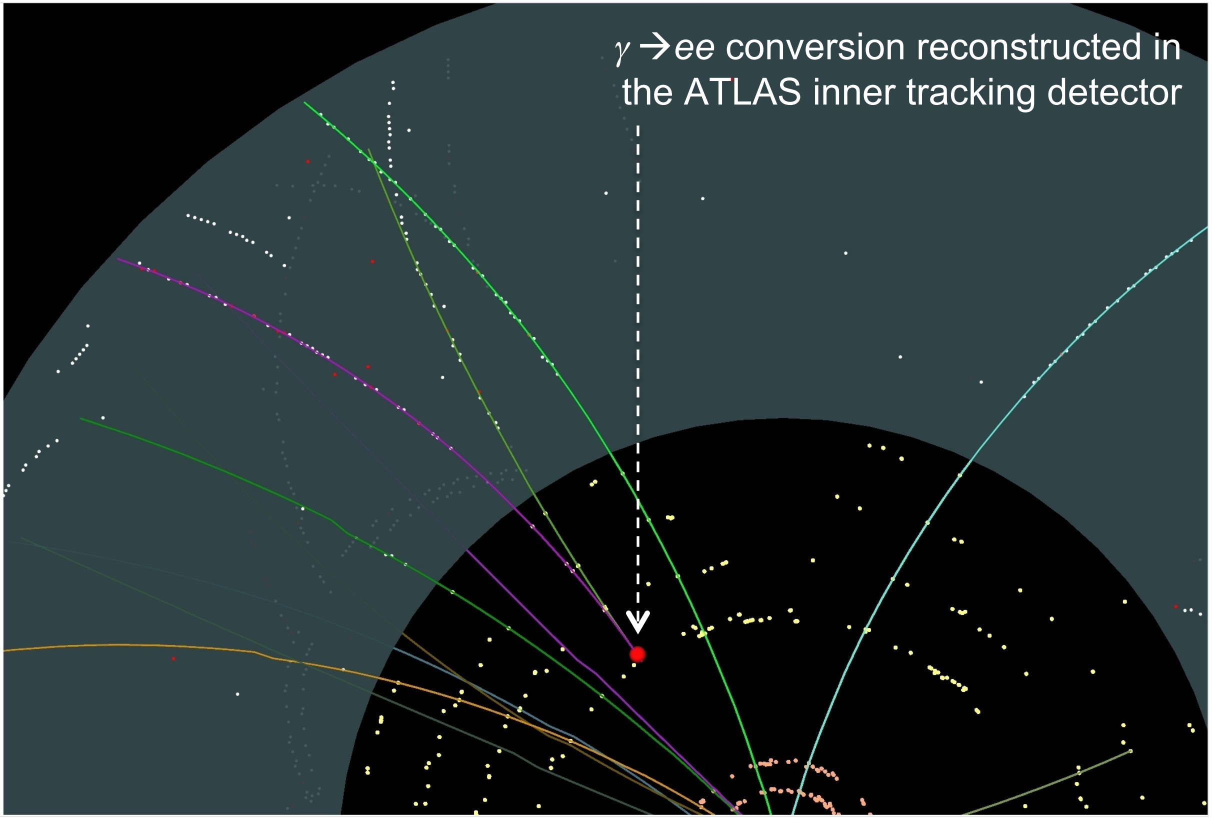
Example for 20 fb^{-1} : 690 $H \rightarrow \gamma\gamma$ and ~170,000 background in [110, 150] mass window

Constant term	Signal significance
0.7%	2.9 σ
1.0 %	2.4 σ
2.0 %	1.8 σ

(*) Note that this test uses the simplest possible $H \rightarrow \gamma\gamma$ analysis approach: a more sophisticated fit using more discriminating variables and detector-specific "categories" boosts the fit performance significantly.

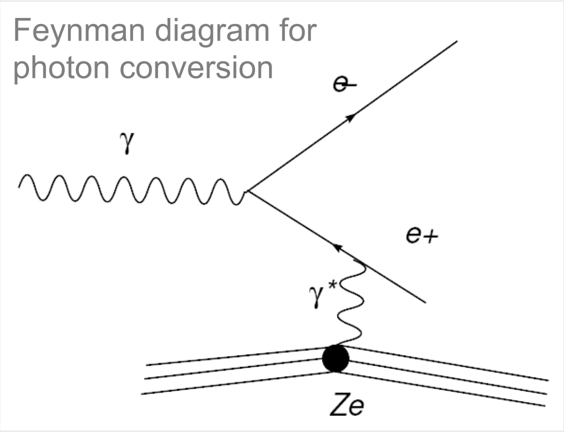
$H \to \gamma\gamma$

Significant amount of material in the ATLAS and CMS inner tracking systems (X/X_0 ~ 0.4 – 1.4) requires to include and efficiently reconstruct $\gamma \to ee$ conversions



Fractions of converted photons (CMS):

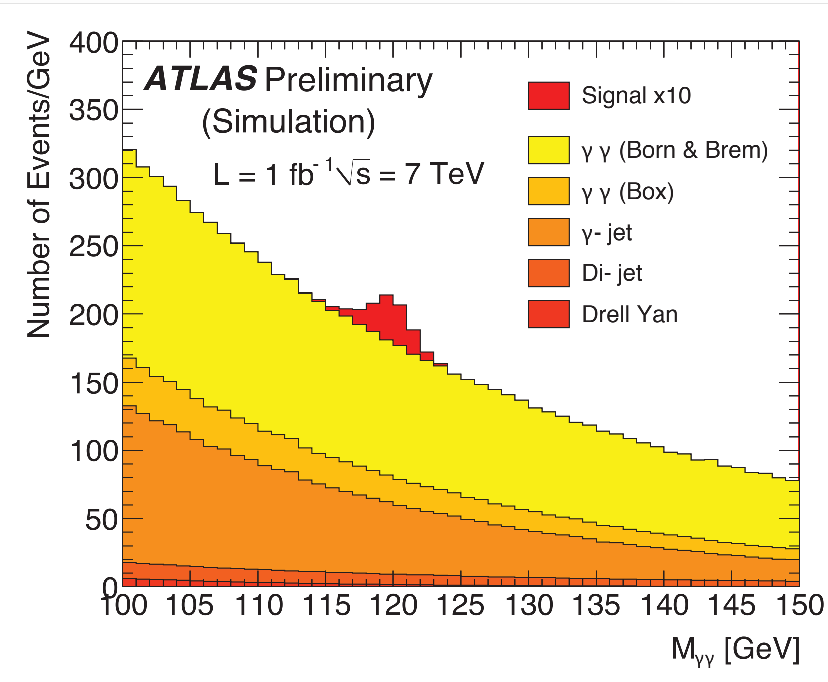
Barrel region: 42.0 %
Endcap region: 59.5 %



$H \rightarrow \gamma\gamma$

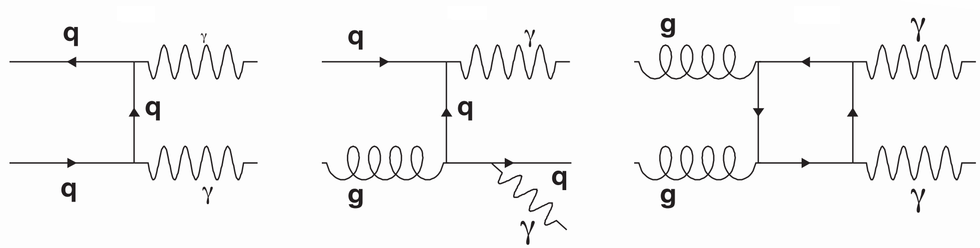
Clean discovery channel for light Higgs: $\sigma \times$ BR (115 GeV) ≈ 10 fb

Signal selection: need excellent E_γ resolution, and efficient & pure photon ID; use MVA: $M_{\gamma\gamma}$, $\cos\theta^*$, $p_{T,\gamma\gamma}$



Backgrounds:

$\gamma + \gamma$ ("irreducible" – not quite)

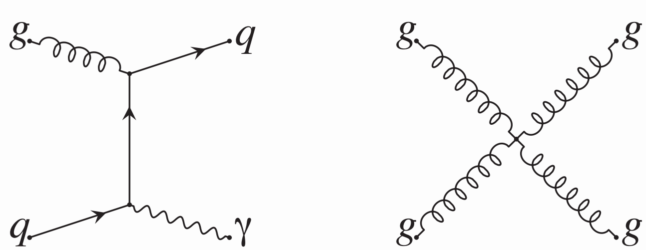


Quark annihilation (dominant: $O(\alpha^2)$)

Brensstrahlung, $O(\alpha^2\alpha_S)$ (1 non-isolated photon)

Box diagram $O(\alpha^2\alpha_S{}^2)$, ≈ q-ann.

γ + jet and jet + jet (reducible, but ~10^6 × larger than $\gamma\gamma$)



Requires excellent calorimeter based γ–jet separation

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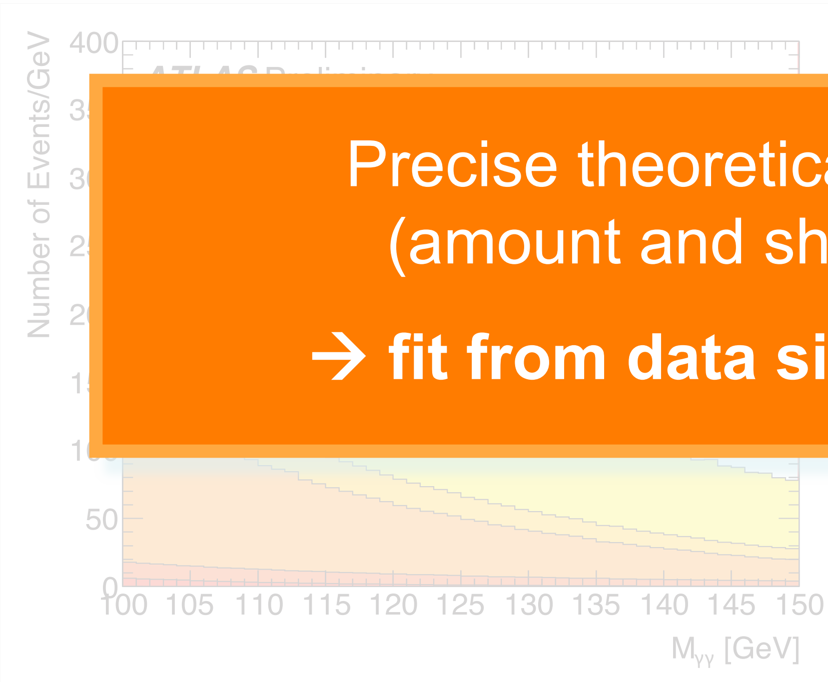


Backgrounds:

Precise theoretical prediction of background (amount and shape) not actually needed:

→ **fit from data simultaneously with signal !**

γ + jet and jet + jet (reducible, but ~10^6 × larger than $\gamma\gamma$)

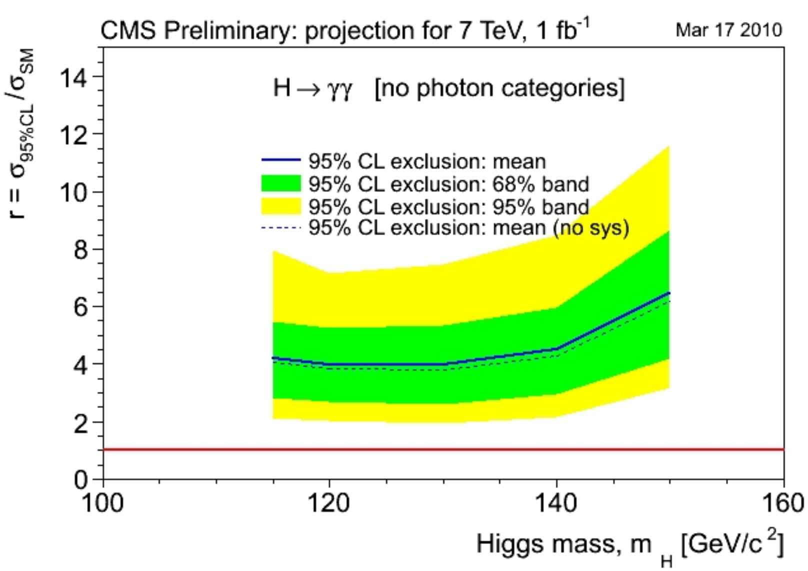
Requires excellent calorimeter based γ–jet separation

$H \rightarrow \gamma\gamma$

Clean discovery channel for light Higgs: $\sigma \times$ BR (115 GeV) ≈ 10 fb

Signal selection: need excellent E_γ resolution, and efficient & pure photon ID; use MVA: $M_{\gamma\gamma}$, $\cos\theta^*$, $p_{T,\gamma\gamma}$

SM Higgs Exclusion potential with 1 fb^{-1}



Backgrounds:

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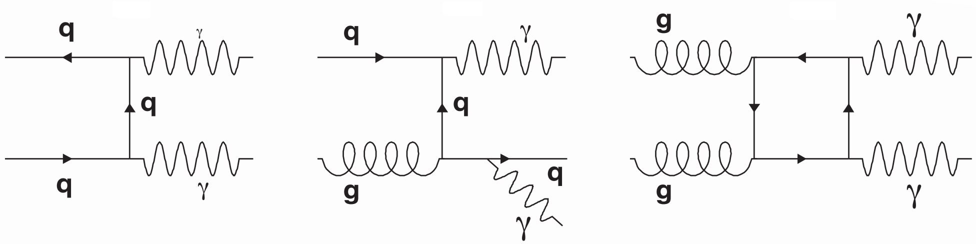

Quark annihilation (dominant: O(α^2))

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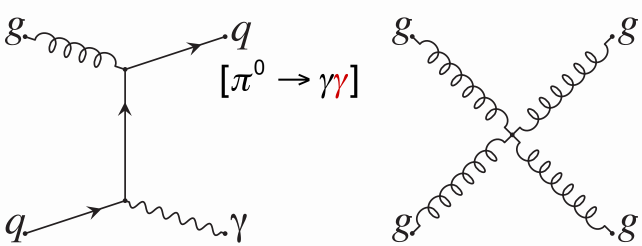
Box diagram $O(\alpha^2\alpha_S{}^2)$, ≈ q-ann.

γ + jet and jet + jet (reducible, but ~10^6 × larger than $\gamma\gamma$)



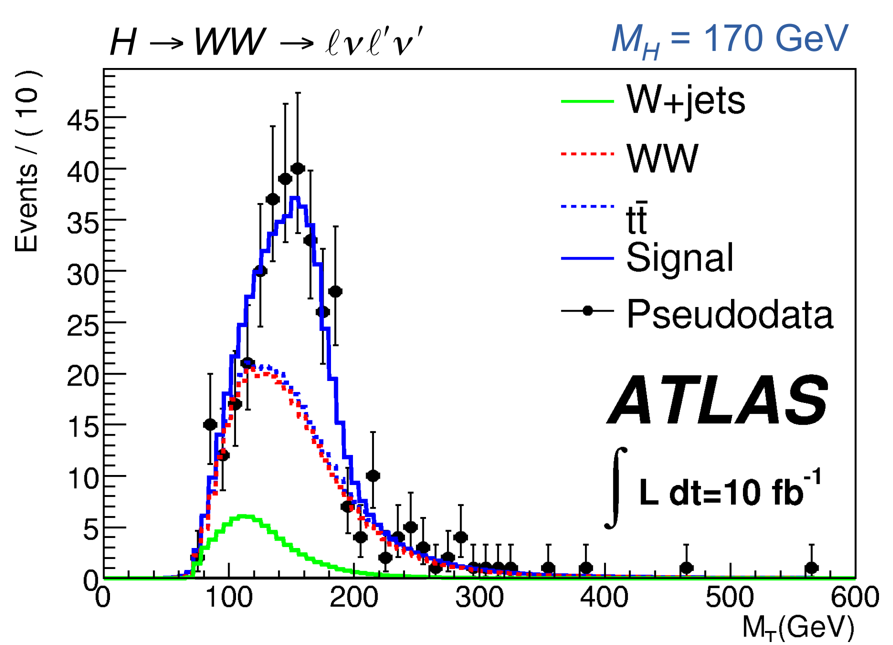
Requires $R = 10^3$–10^4 calorimeter based γ–jet separation

$H \to WW \to$ 2 leptons + 2ν

Not a clean channel (undetected neutrinos → no mass peak) but large cross section

Signal selection: large transverse mass ($M_T^2 = 2p_{T,ll}E_T(1-\cos(\Delta\phi))$, exploit *W* polarisation, central jet veto

Separate analysis in *H* + 0/1 jet (gluon fusion), and *H* + 2 jets (weak boson fusion)



Backgrounds:

Large backgrounds: *WW*, *W*+jets (*t*), *t*

Need precise knowledge of background normalisation:

Use control regions in data and extrapolate to signal region

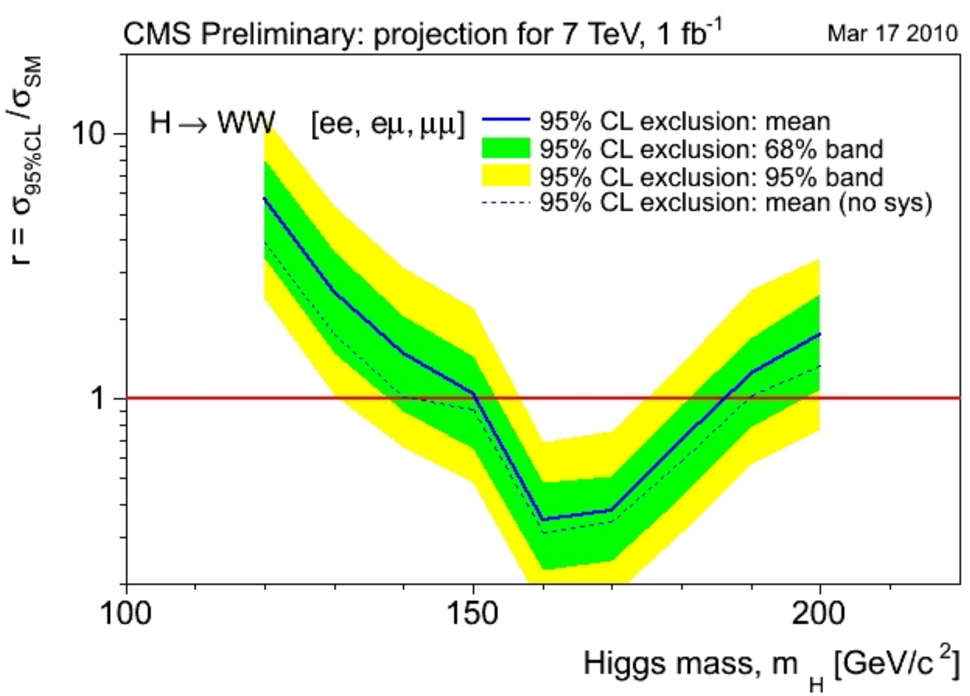
Jet veto efficiencies need to be understood for signal and background

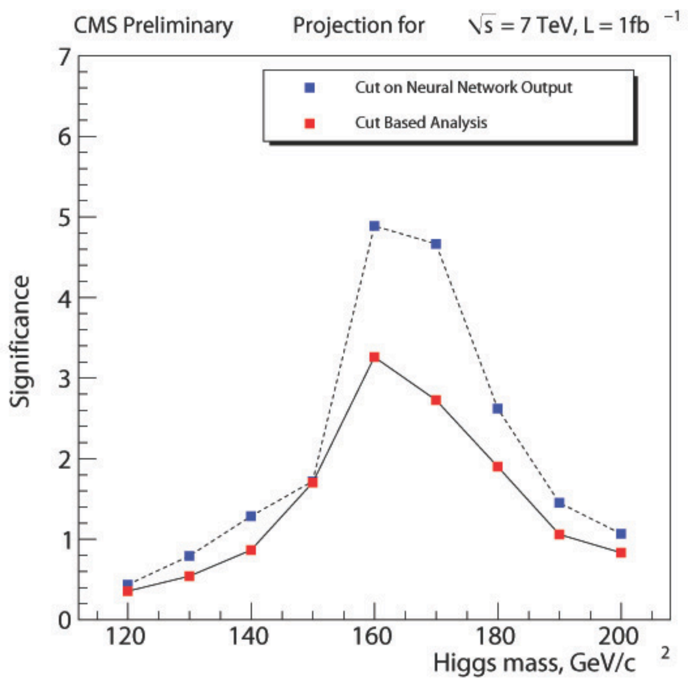
Use multivariate approach to increase background rejections

$H \to WW \to$ 2 leptons + 2ν

Promising search for heavy Higgs, provided that backgrounds can be controlled

Exclusion reach with 1 fb^{-1} comparable to that of the Tevatron

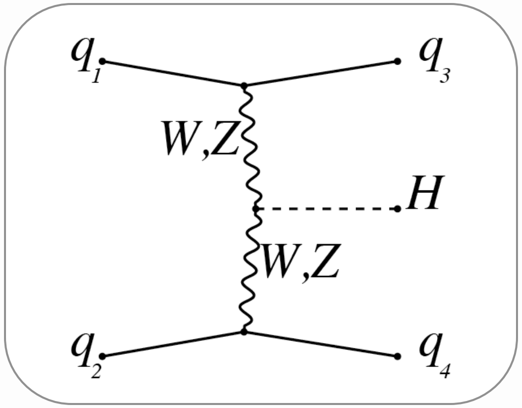




Weak Boson Fusion

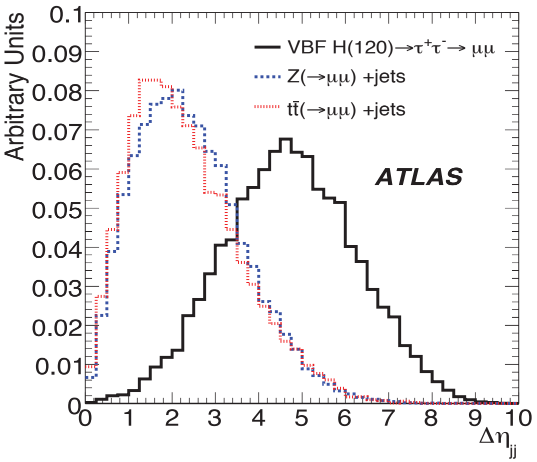
Weak boson fusion – motivation for a search of $qq \rightarrow Hqq$

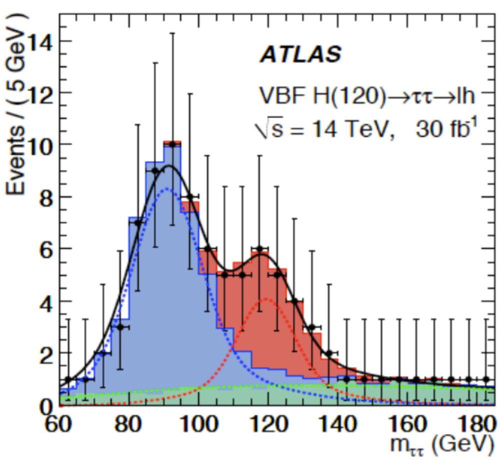
- Increase discovery potential at low mass
- Extend measurement of Higgs boson parameters (couplings to bosons, fermions)
- Gives reach to difficult modes, such as $H \rightarrow \tau\tau$, with sensitivity to new physics



Distinctive signature:

- 2 forward ("**tag**") jets (large pseudorapidity difference)
- little jet activity in central region (no colour flow) "**veto**"

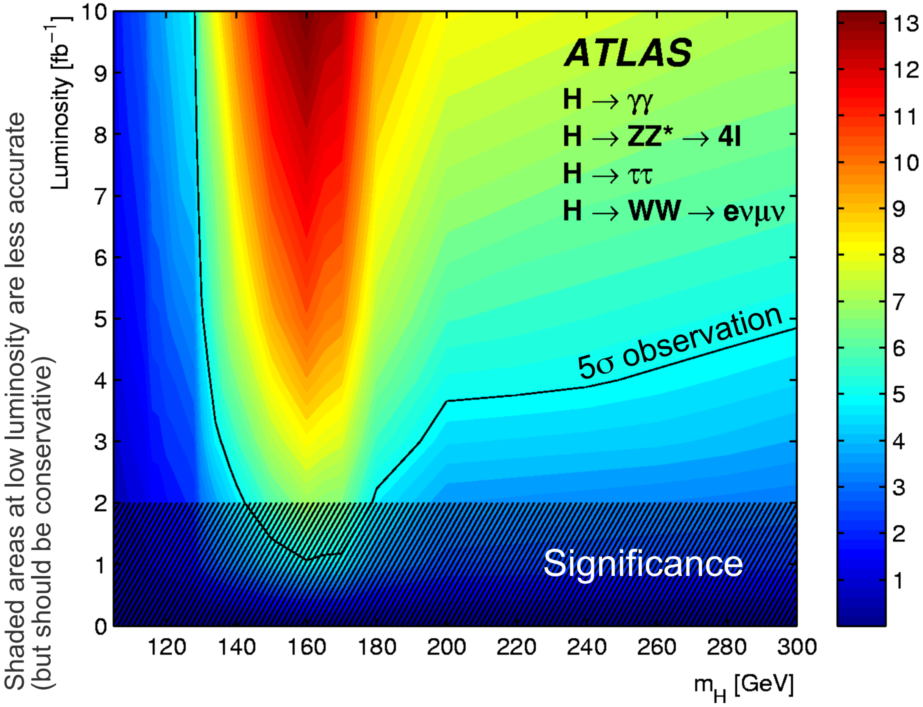




Discovery Potential – Summary

Expected discovery (left) and exclusion reach (right)

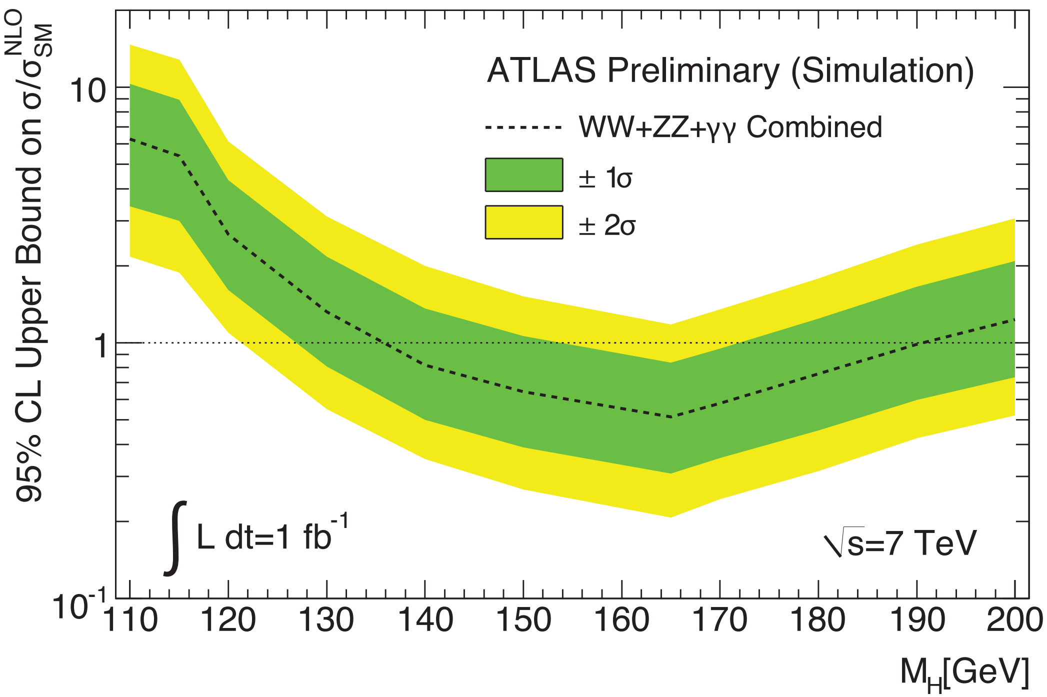
ATLAS 14 TeV study – indicative only; comparable discovery potential for ATLAS and CMS



With 1 fb^{-1} could barely discover Higgs with 150 ~ 170 GeV, end exclude Higgs > ~127 GeV

1 fb^{-1} Exclusion Potential – Summary

Combination of the $\gamma\gamma$, *ZZ*, *WW* decay channels at 7 TeV with 1 fb^{-1} luminosity



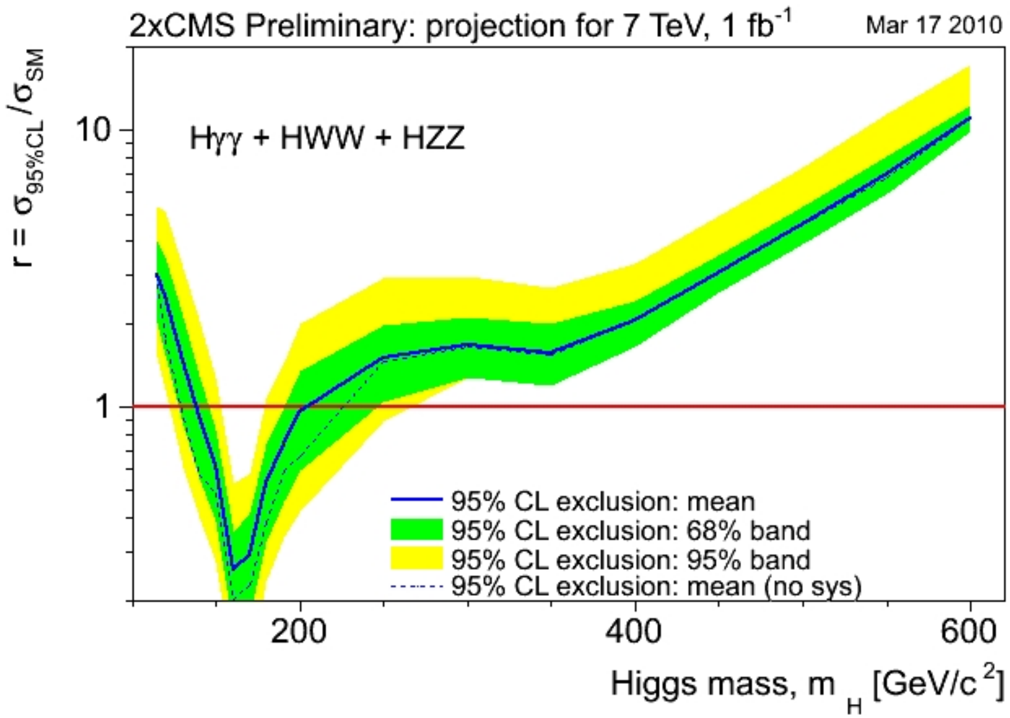
Mass range in the region between 145 and 190 GeV can be excluded within one experiment

1 fb^{-1} Exclusion Potential – Summary

Combination of the $\gamma\gamma$, *ZZ*, *WW* decay channels at 7 TeV with 1 fb^{-1} luminosity

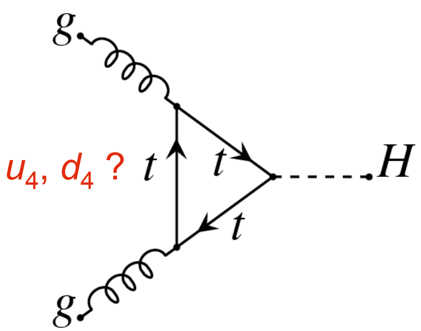
CMS study, preliminary, numbers from 14 TeV scaled down

Combine two experiments



A 4th Generation?

Gluon fusion is very sensitive to additional heavy quarks, which do not decouple in the high-mass limit, and thus contribute ~ as the top quark to the triangular anomaly



$$\Gamma_{H\to gg} = \frac{G_F \alpha_S^2 M_H^3}{36\sqrt{2}\pi^3} \left| \frac{3}{4} \sum_f A_f(\tau_f) \right|^2, \quad \text{where: } \tau_f = \frac{M_H^2}{4m_f^2}$$

$$\text{for } m_f \gg M_H: \ A(\tau_f) = \frac{4}{3} + \frac{14}{45}\tau_f + O(\tau_f^2)$$

Hence, the two additional heavy quarks from a 4th generation, if the Higgs is light, give a *K*-factor of ~3^2 = 9

If a Higgs has been found, the measurement of its cross section provides thus stringent information on the existence of a 4th generation.

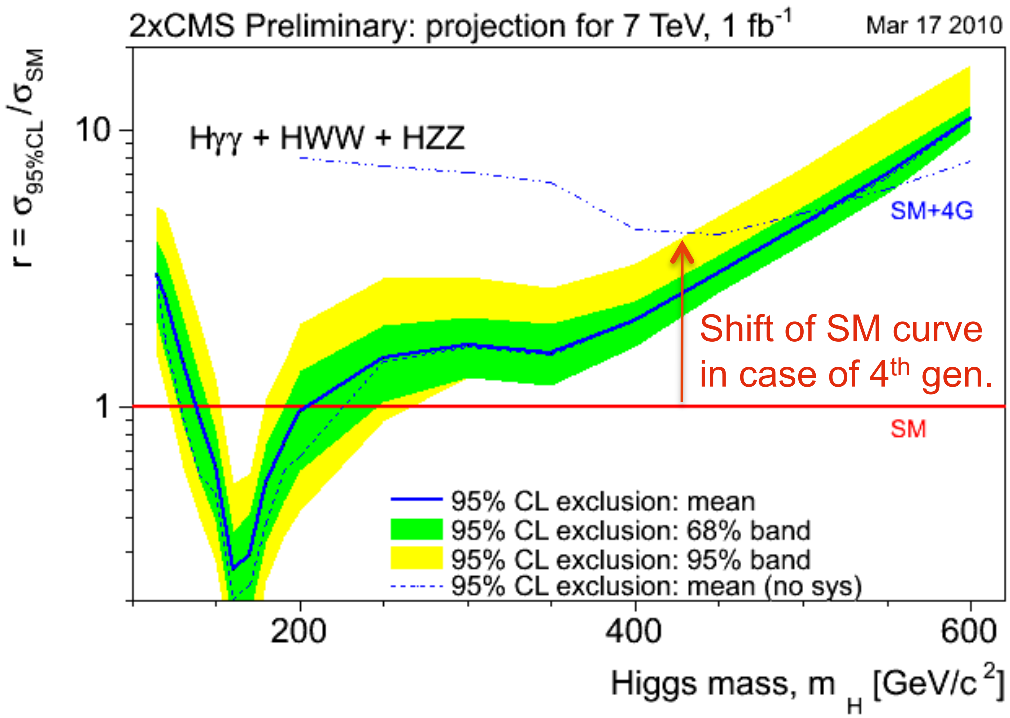
A 4th Generation?

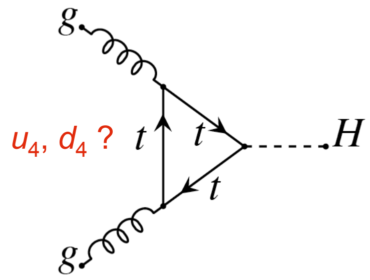
Gluon fusion is very sensitive to additional heavy quarks, which do not decouple in the high-mass limit, and thus contribute ~ as the top quark to the triangular anomaly

Exclusion found for a particular 4th generation model.

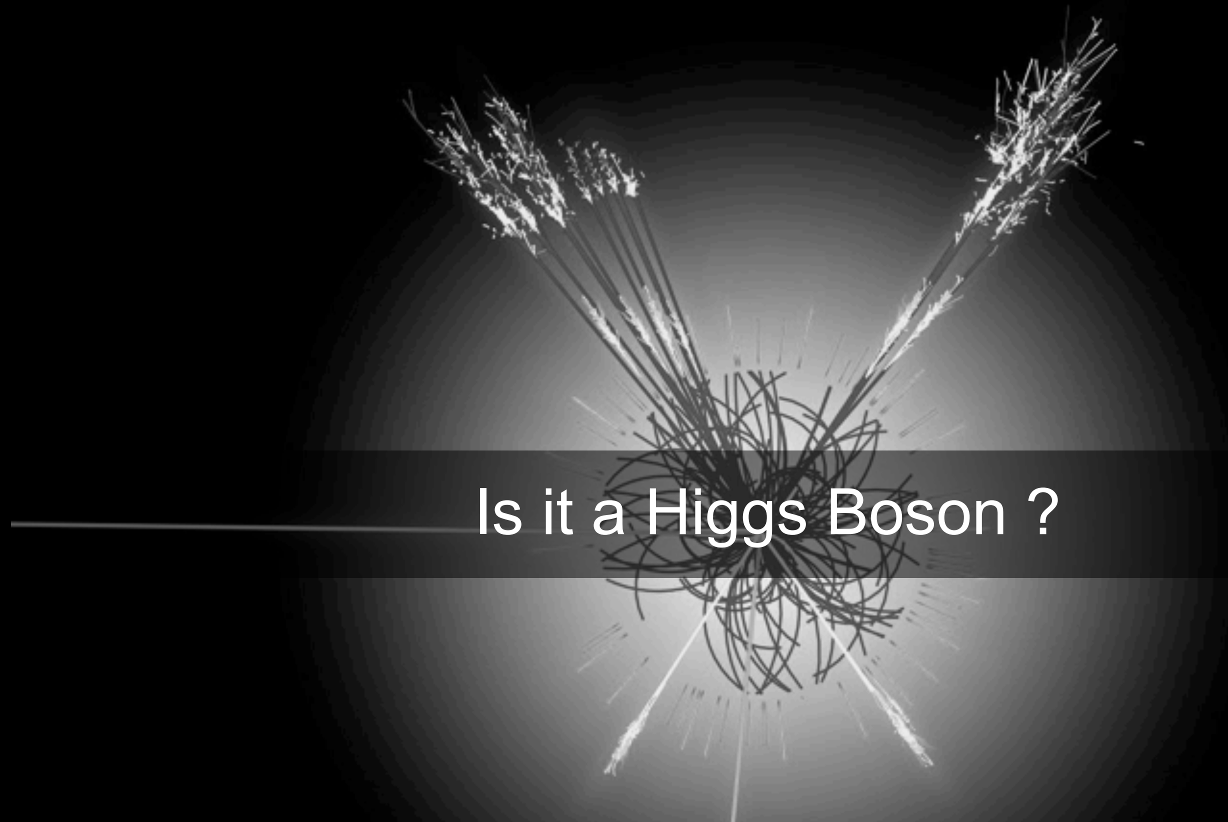
With 1 fb^{-1}: Higgs masses smaller than 500 GeV can be excluded.

Tevatron data already exclude M_H between 130 and 210 GeV for 4th generation.





Now ask that question !



Is it a Higgs Boson ?

After a Higgs-like discovery, one needs to measure the properties of the new particle to consolidate whether it is indeed the wanted SM Higgs. For this, one needs to measure its

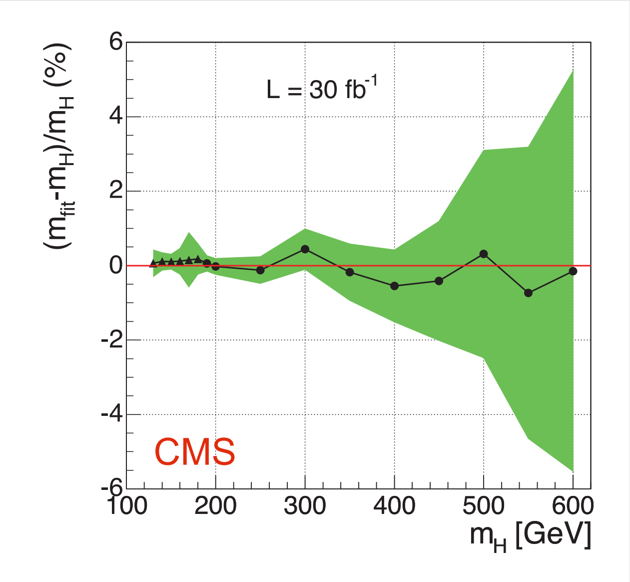
- *Mass*
- *Couplings to fermions and bosons (and to itself)*
- *Spin and CP*

The Higgs Boson Mass and Couplings

Mass

- The Higgs mass is a parameter of SM precision tests (see tomorrow's lecture). Logarithmic dependence, so moderate precision required only
- The Higgs mass goes strongly into the prediction of the Higgs couplings

➠ $H \rightarrow \gamma\gamma$ and $H \rightarrow ZZ^{(*)}$ allow to measure M_H to better than 1% with 30 fb^{-1}

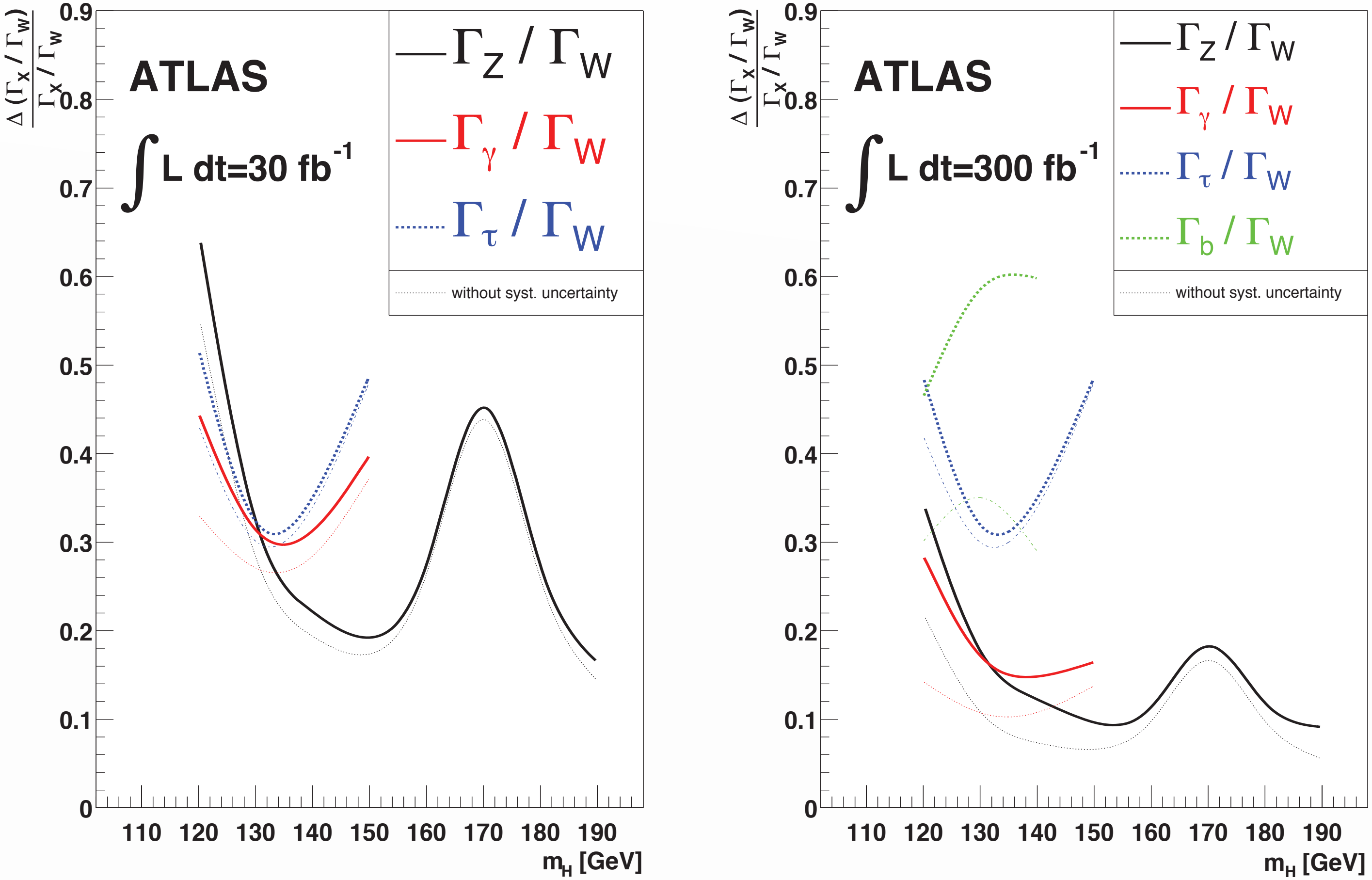


Expected error in M_H from $H \rightarrow ZZ^{(*)} \rightarrow 4\mu$

Couplings (SM-like ?)

- The Higgs couplings can be obtained from ratios of measured rates, $\sigma_{yy\rightarrow H} \times BR_{H\rightarrow xx} = \Gamma_x\Gamma_y / \Gamma_H$, where the unmeasured Γ_H cancels
- Use all measurable production and decay channels and perform global fit
- Additional theoretical assumptions can be inserted to achieve measurement of absolute couplings

The Higgs Boson Mass and Couplings



Duehrssen et al., hep-ph/0407190

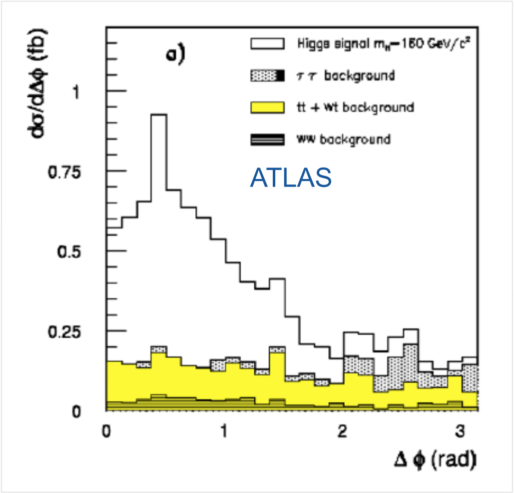
Relative uncertainty obtained on the measurement of ratios of branching fractions (or, equivalently, ratios of decay widths) for integrated luminosities of 30 fb^{-1} and 300 fb^{-1}. The dotted lines exclude systematic errors

The Higgs Boson Spin and *CP*

Spin (0 ?)

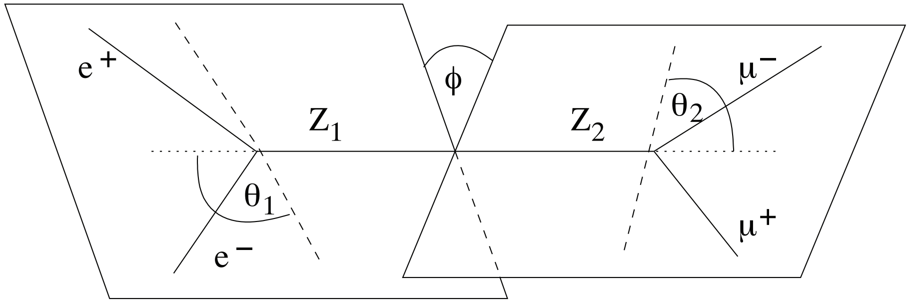
- If the decay $H \to \gamma\gamma$ is seen, Higgs spin must be *even*
  Coupling *Hvv* forbidden if *H* has spin 1 and *v* is massless vector particle (e.g. *g* or γ) due to angular momentum conservation and Pauli principle. Spin-1 Higgs would have no *gg* fusion production process.
- Angular correlations ($\Delta\phi \approx 0$) in $H \to WW^{(*)} \to l\nu l\nu$
- Angular correlations in $H \to ZZ^{(*)} \to$ 4 leptons

$|\Delta\phi|$ in $H \to WW \to l\nu\, l\nu$



CP (even ?)

- Angular correlations in $ZZ^{(*)} \to$ 4 leptons
- Angular correlation of tagging jets in vector boson fusion production
- Angular correlations in associated *ttH* decays



Definition of helicity and decay-plane angles

Extending the Higgs Sector

Although a mechanism for the breaking of electroweak symmetry is needed, there is no reason for it to be necessarily minimal. Also, we have seen already that the scalar sector in the SM is unprotected against radiative corrections.

Many new physics scenarios come with an extended Higgs sector.

Example: there could be 2 Higgs doublets ("2HDM" – *next-to-minimal extension*)

- It is motivated by the strong mass hierarchy of up-quark to down-quark sector: up and down quarks would receive their masses from different Higgs doublets
- A total of 8 degrees of freedom give rise to 5 physical Higgs states:

$$h,\ H_{CP=+1},\ A_{CP=-1},\ H^{+},\ H^{-}$$

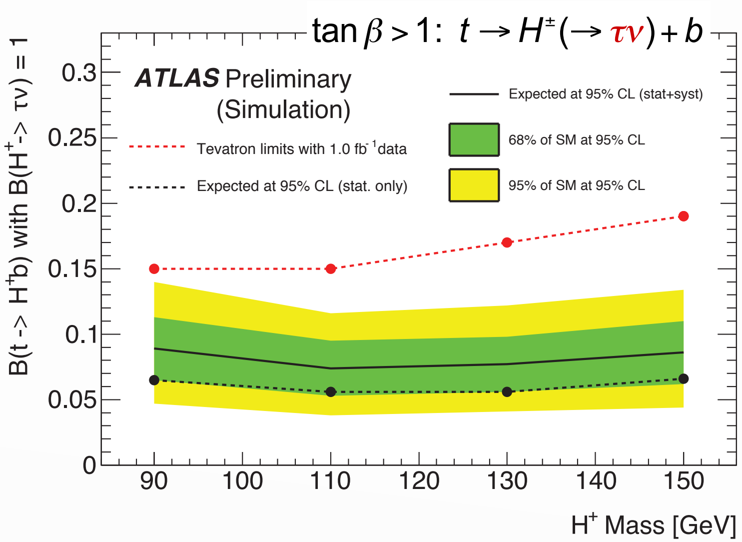
- **Minimal Supersymmetry** features 2 Higgs doublets. Tight upper limit on M_h
- Hard to detect charged Higgs experimentally due to absence of $H^{+}W^{-}Z$ and $H^{+}W^{-}\gamma$ vertices at tree level
- Indirect constraints from the EW precision and flavour sectors exist (→ see tomorrow's lecture)

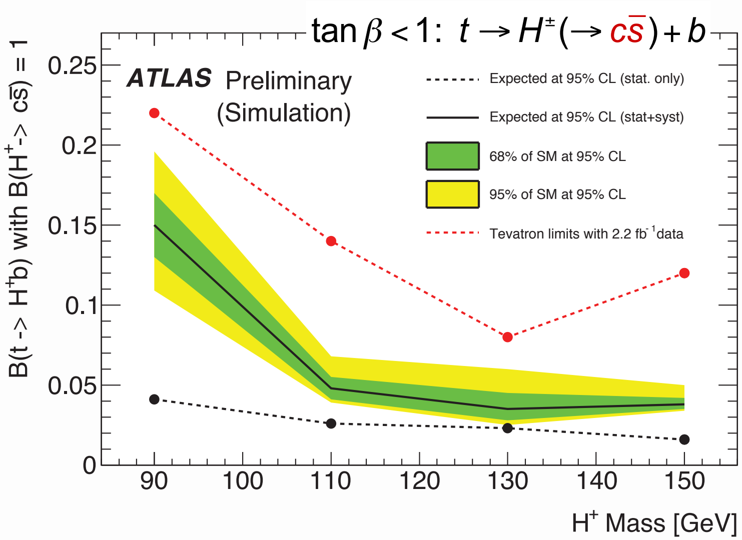
A Charged Higgs ?

Production of a charged Higgs depends strongly on its mass (LEP: $M_{H\pm}$ > 78.6 GeV)

1. via top decays: $t \rightarrow H^{\pm} b$
2. via $gg \rightarrow H^{\pm} tb$, or $gb \rightarrow H^{\pm} t$
3. via gg, $qq \rightarrow H^{\pm} W$
4. via $qq \rightarrow H^{+}H^{-}$

Decay also strongly mass dependent. In a large fraction of the 2HDM parameter space the decay $H^{\pm} \rightarrow \tau^{\pm}\nu$ (or, if allowed, $\rightarrow tb$) dominates (BR > 90% for $\tan\beta > 3$)

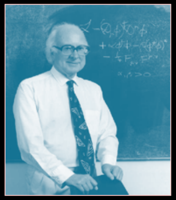




Exclusion potential for light $H^{\pm}$ in di-lepton (left) and semi-leptonic (right) tt events, and for 1 fb^{-1} (at $\sqrt{s}$ = 7 TeV)

And tomorrow …

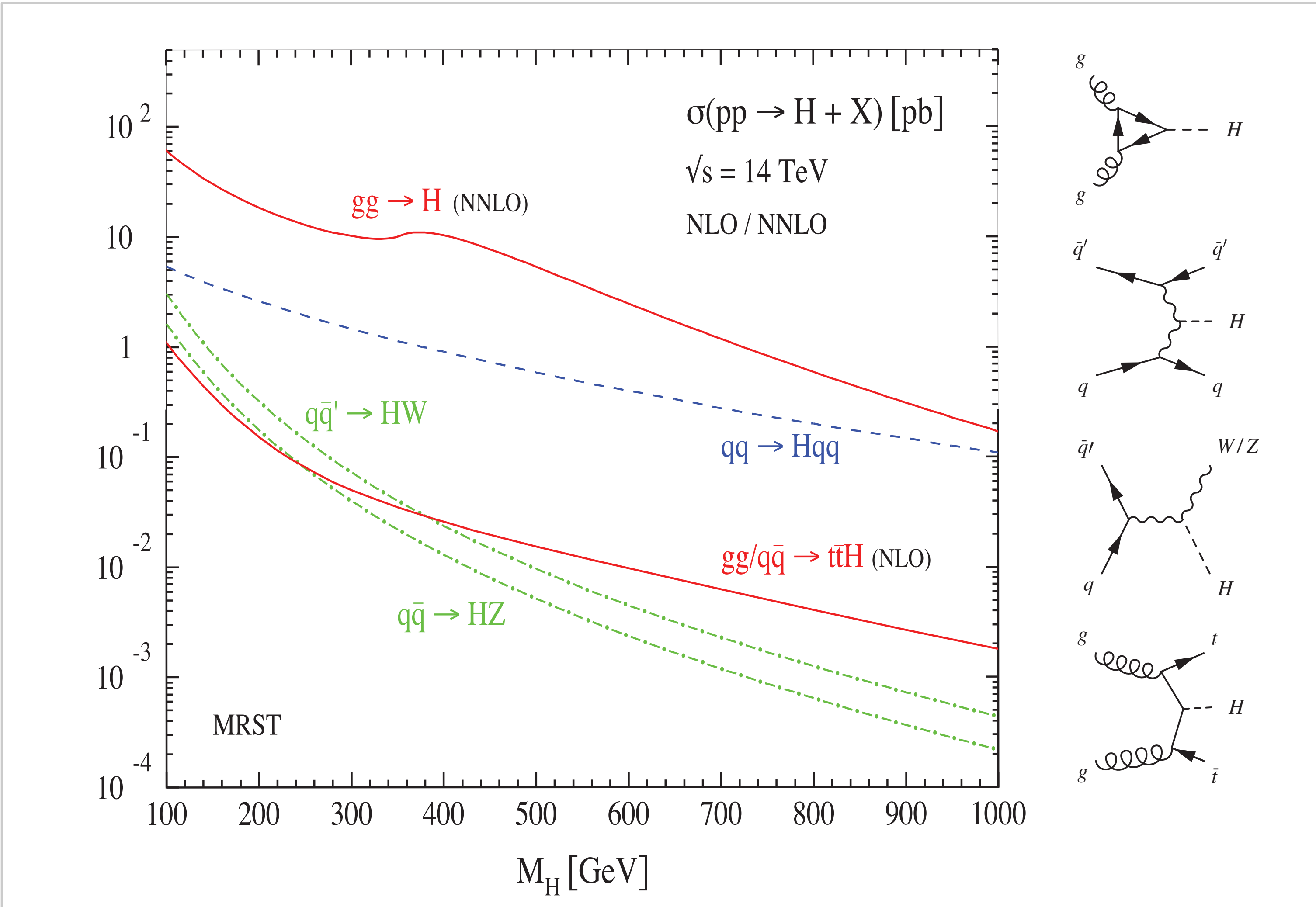
Indirect Constraints on the Higgs



from Electroweak Precision Data

Remember the question ?

b a c k u p

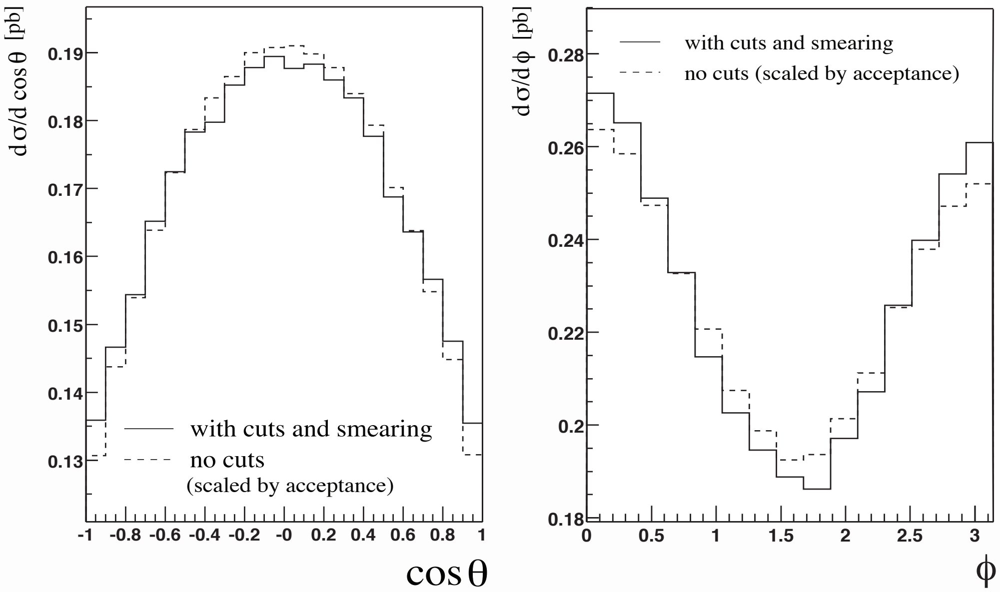


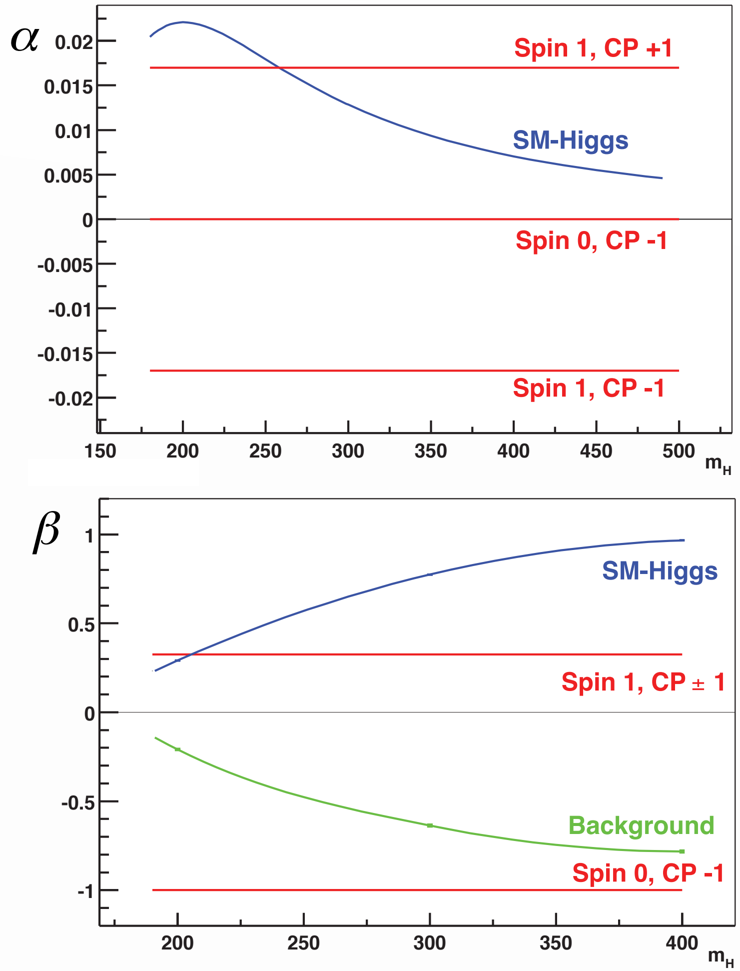
σ(pp → H + X) [pb]
√s = 14 TeV
NLO / NNLO
gg → H (NNLO)
qq̄' → HW
qq → Hqq
gg/qq̄ → tt̄H (NLO)
qq̄ → HZ
MRST
10^2
10
1
10^-1
10^-2
10^-3
10^-4
100
200
300
400
500
600
700
800
900
1000
M_H [GeV]
g
H
q̄′
q
W/Z
t
t̄

Spin & *CP* in H → ZZ$^{(*)}$ →4 leptons

Buszello et al,
Eur. Phys. J. C32, 209 (2004)

Fit angular distributions to determine spin and *CP* properties of Higgs-like resonance decaying into 4 leptons



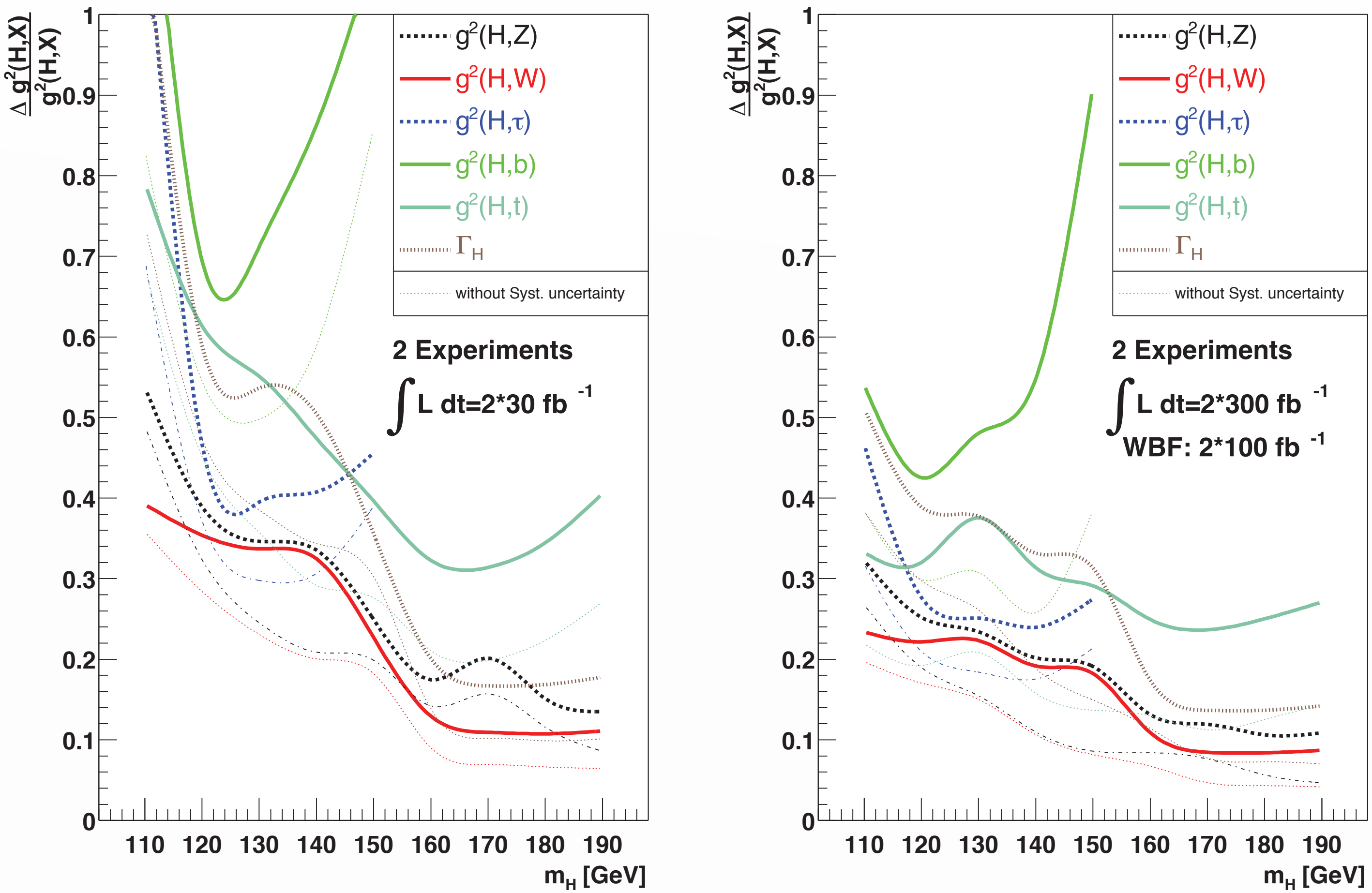


Fit to distributions:

$$F(\phi) = \alpha \cdot \cos\phi + \beta \cdot \cos 2\phi$$

$$F(\theta) = T \cdot (1+\cos^2\theta) + L\sin^2\theta \,, \quad R = (L-T)/(L+T)$$

The Higgs Boson Mass and Couplings



Duehrssen et al., hep-ph/0407190

Relative precision of fitted Higgs couplings-squared as a function of the Higgs mass for two luminosity scenarios. Weak assumption that $g^2(H, V) < 1.05 \cdot g^2(H,V,SM)$ ($V = W,Z$) are made, but new particles in the $H \to \gamma\gamma$ and $gg \to H$ loops, and for unobservable decay modes are allowed.