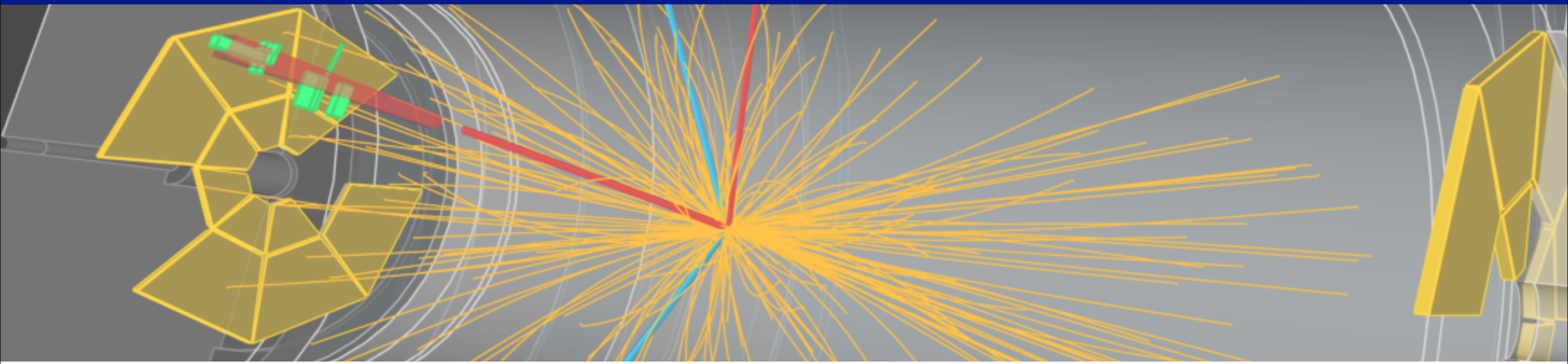


Higgs Physics at the Energy Frontier

Krisztian Peters

CERN

27th November 2013

Physics Colloquium, University of Geneva

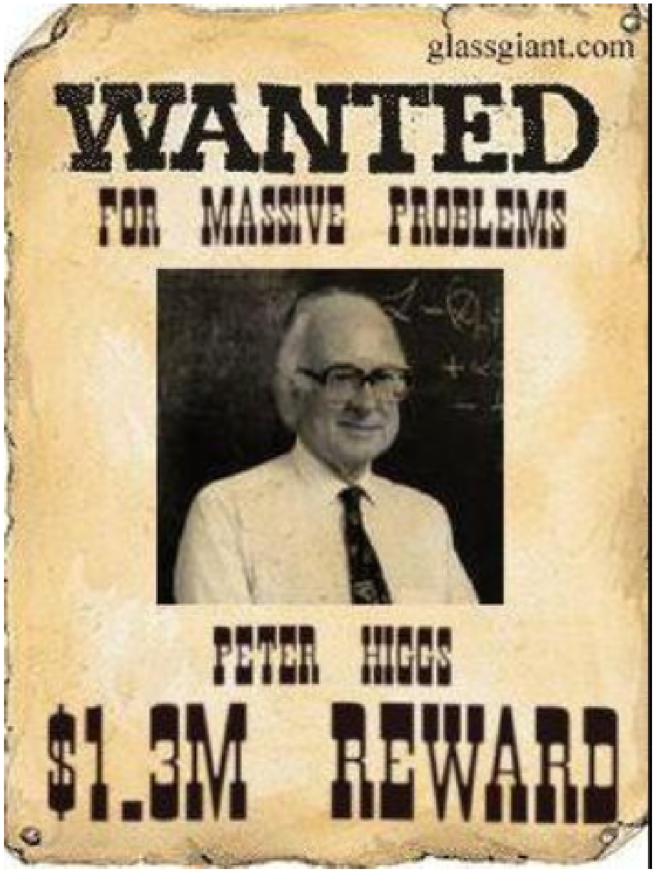
Outline

What is a Higgs boson and why do we need it?

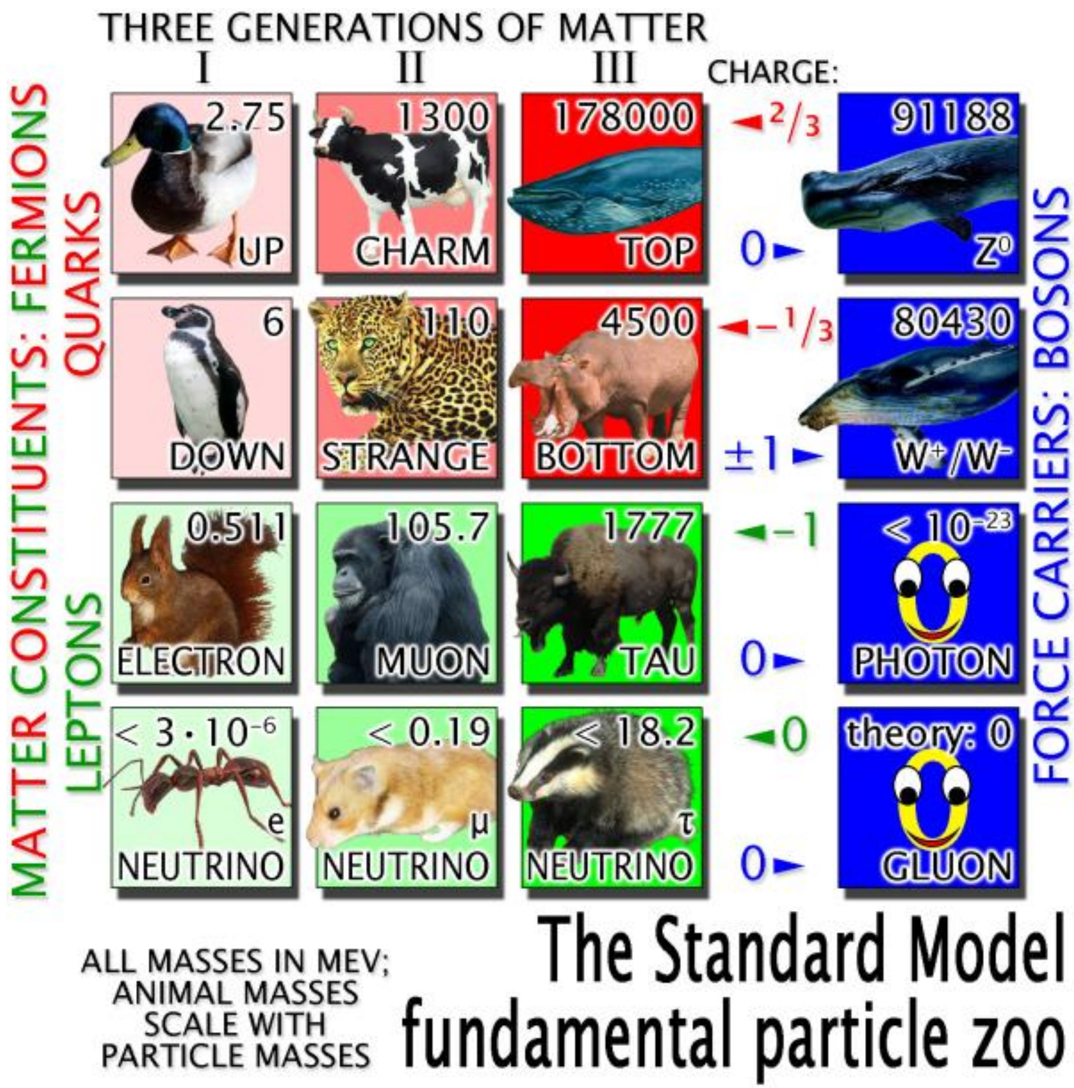
How and where did we look for it?

Year 1 after the discovery (first Higgs boson measurements)

Outlook / Conclusions



The particle zoo



Fundamental principles of the SM require massless gauge bosons

Weak interactions short range: W/Z bosons massive

Higgs mechanism at rescue of the Standard Model

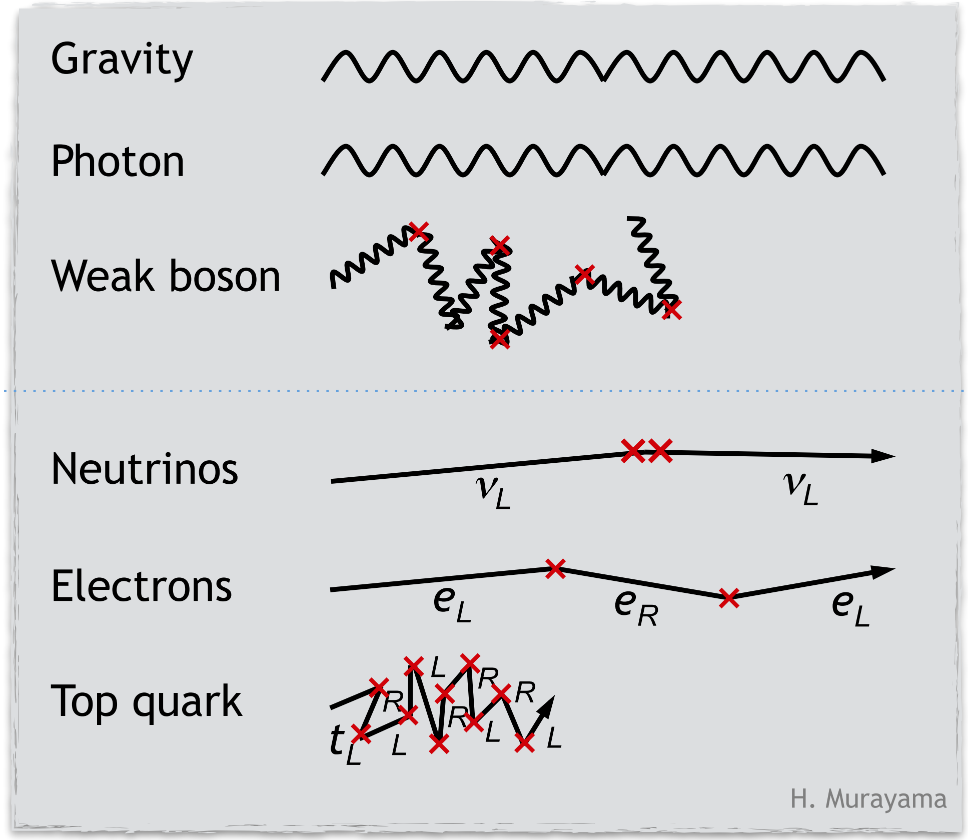
Higgs mechanism

There is a ‘quantum liquid’ filling up our entire Universe, without orientation (Higgs field, spin 0)

It does not disturb gravity or the electric force

It disturbs the weak force and makes it short ranged

It slows down all matter constituents from the speed of light. They acquire a mass proportional to the interaction strength



The superconductor analogy

Meissner effect: in a superconductor the magnetic field is expelled and has only a *finite penetration* into the superconductor

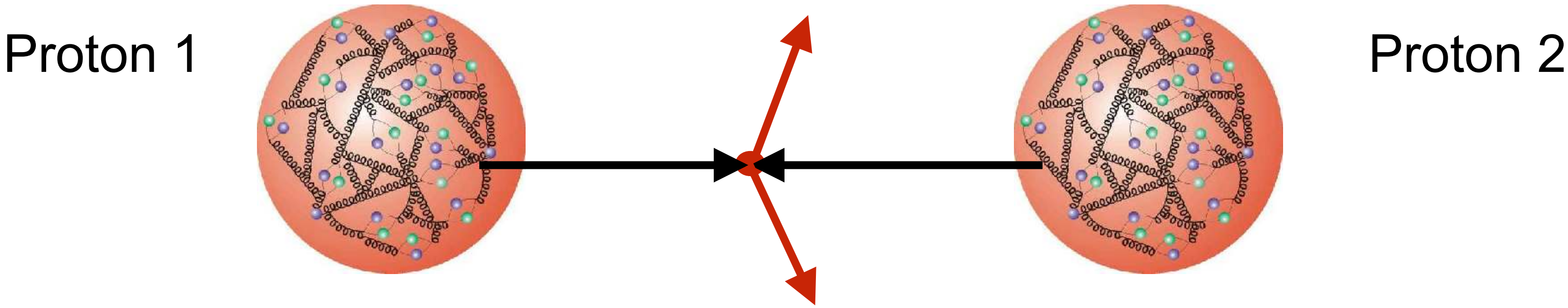
→ Photons acquire inside the superconductor an ‘effective’ mass, the magnetic field becomes short-ranged

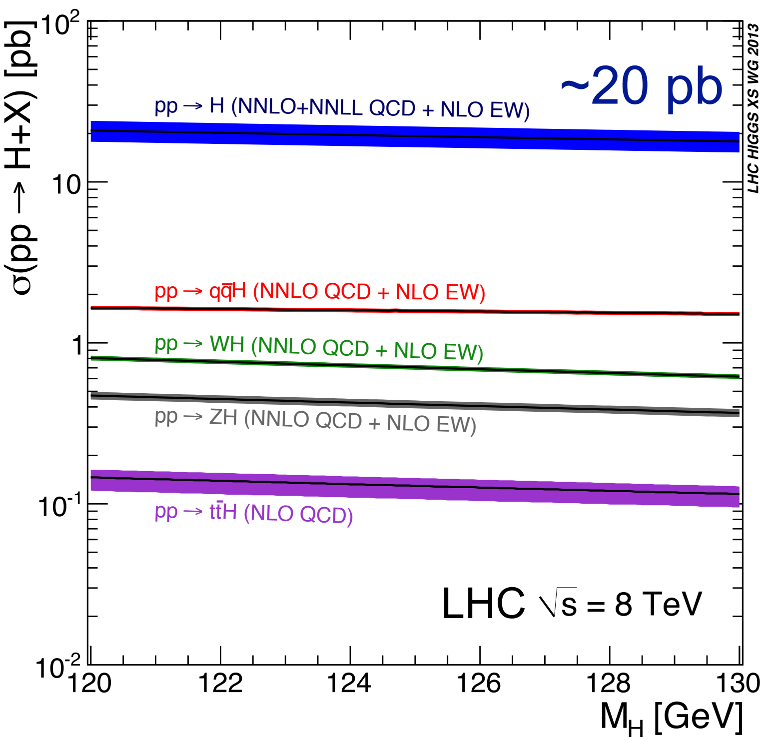
The entire Universe is a superconductor for the weak interactions

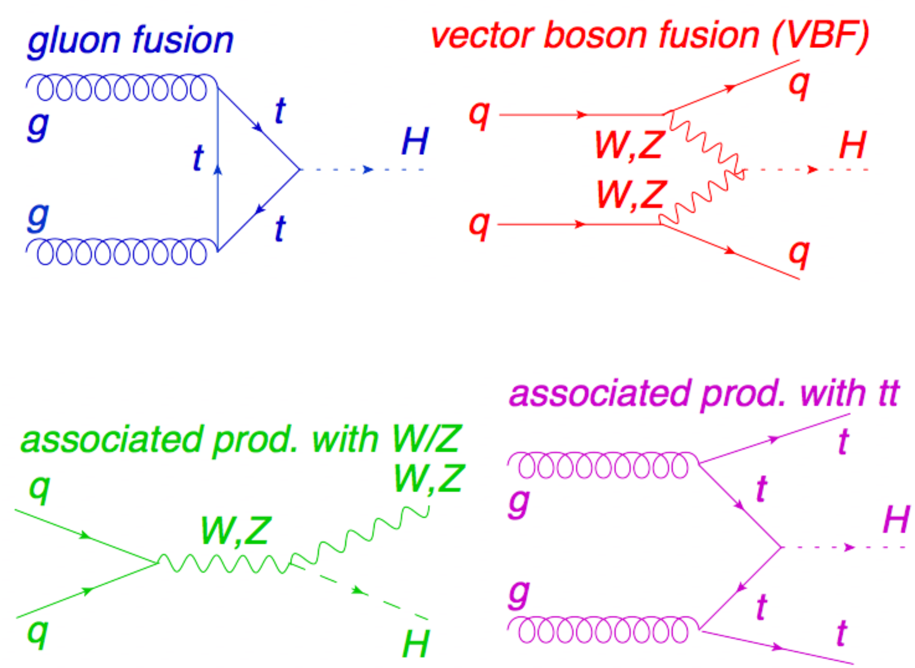
What are the Cooper-pairs (electron-pairs) of the Higgs mechanism?

The Standard Model predicts all properties of the Higgs boson. The only free parameter is its mass

Higgs production at hadron colliders

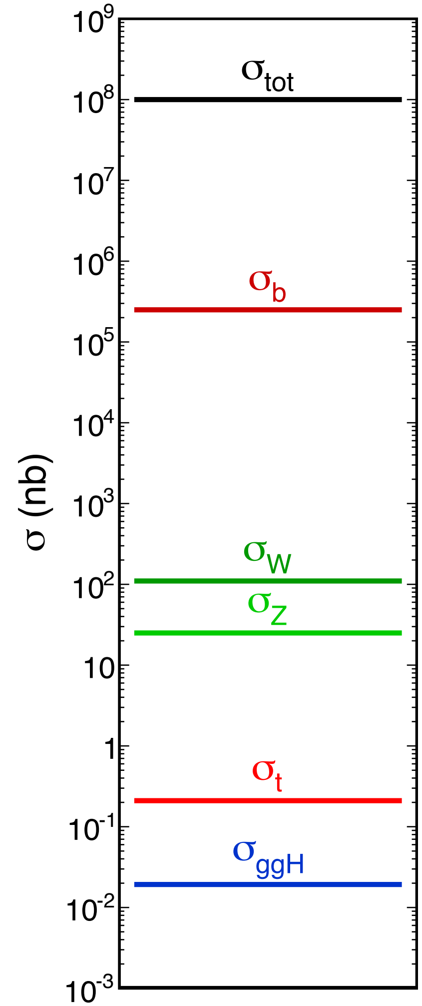






Higgs production at hadron colliders

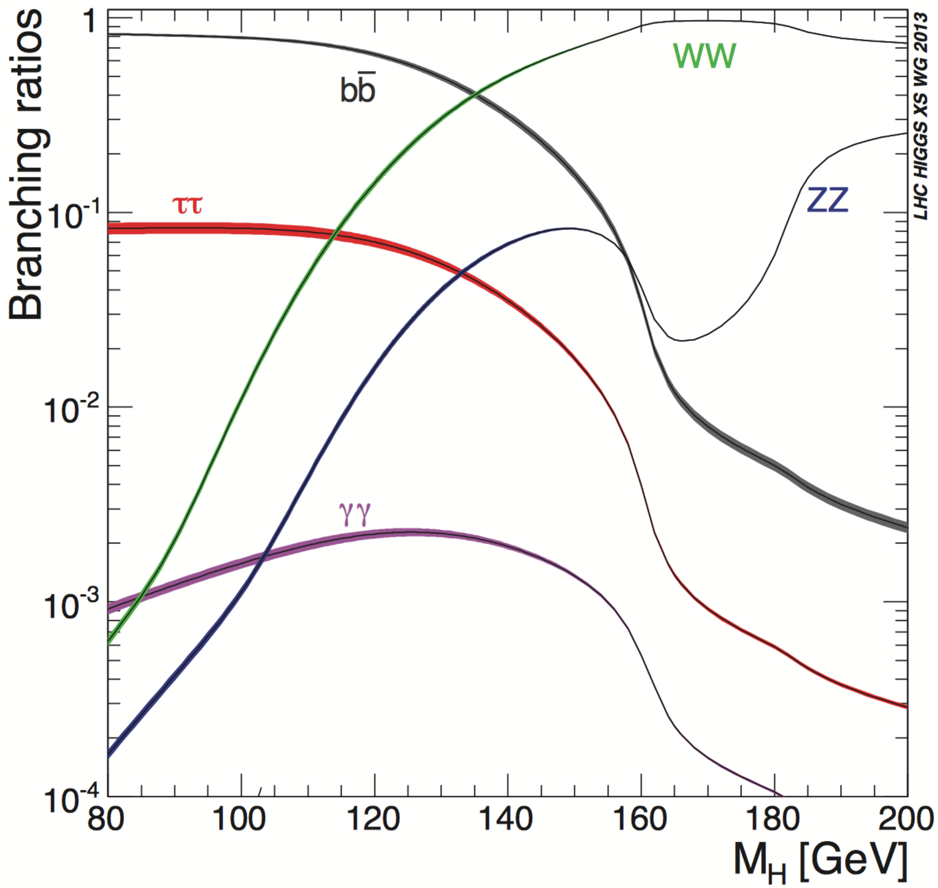
pp cross sections



LHC at $\sqrt{s}$ = 8 TeV

Only one in ~10^{10} events will be a Higgs boson at the LHC

Higgs decays

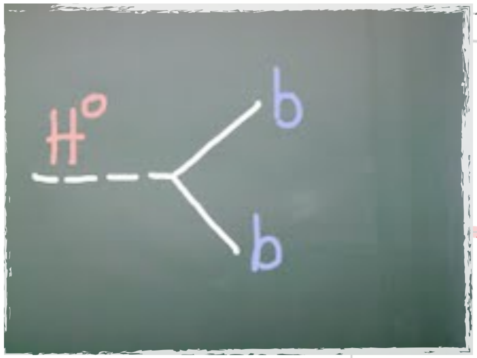


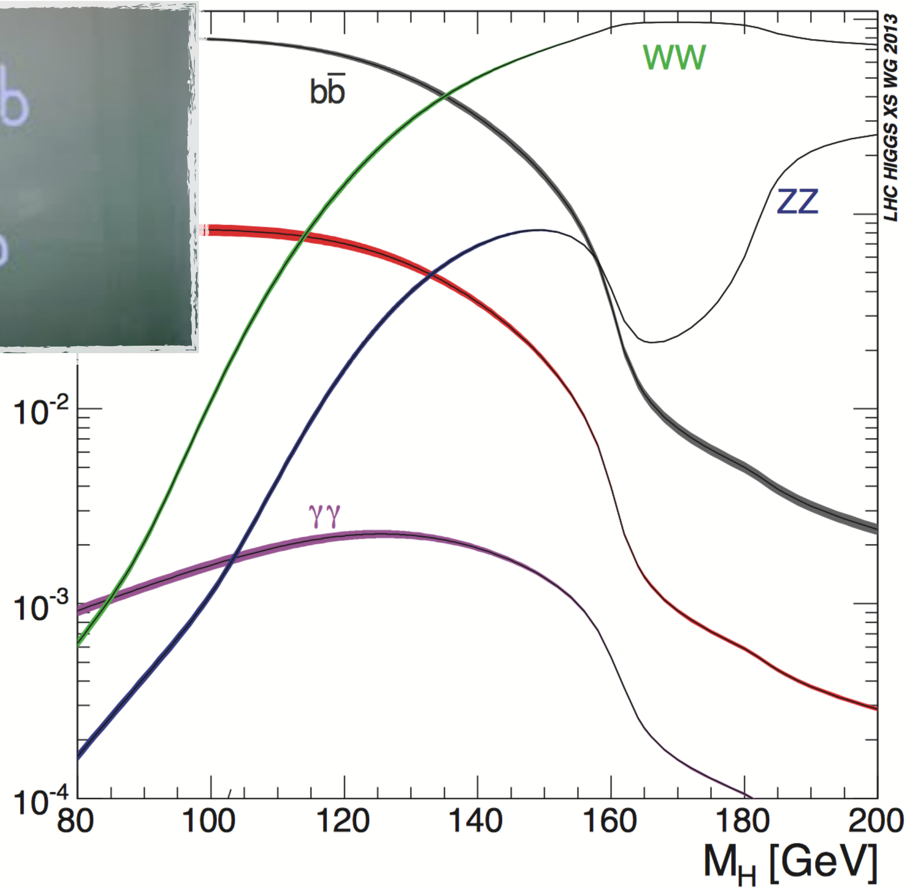
$\Gamma \sim m_f^2$ and m_V^4

Largest BRs to bb and WW

Best experimental mass resolution for γγ and ZZ(4ℓ) decays

Higgs decays





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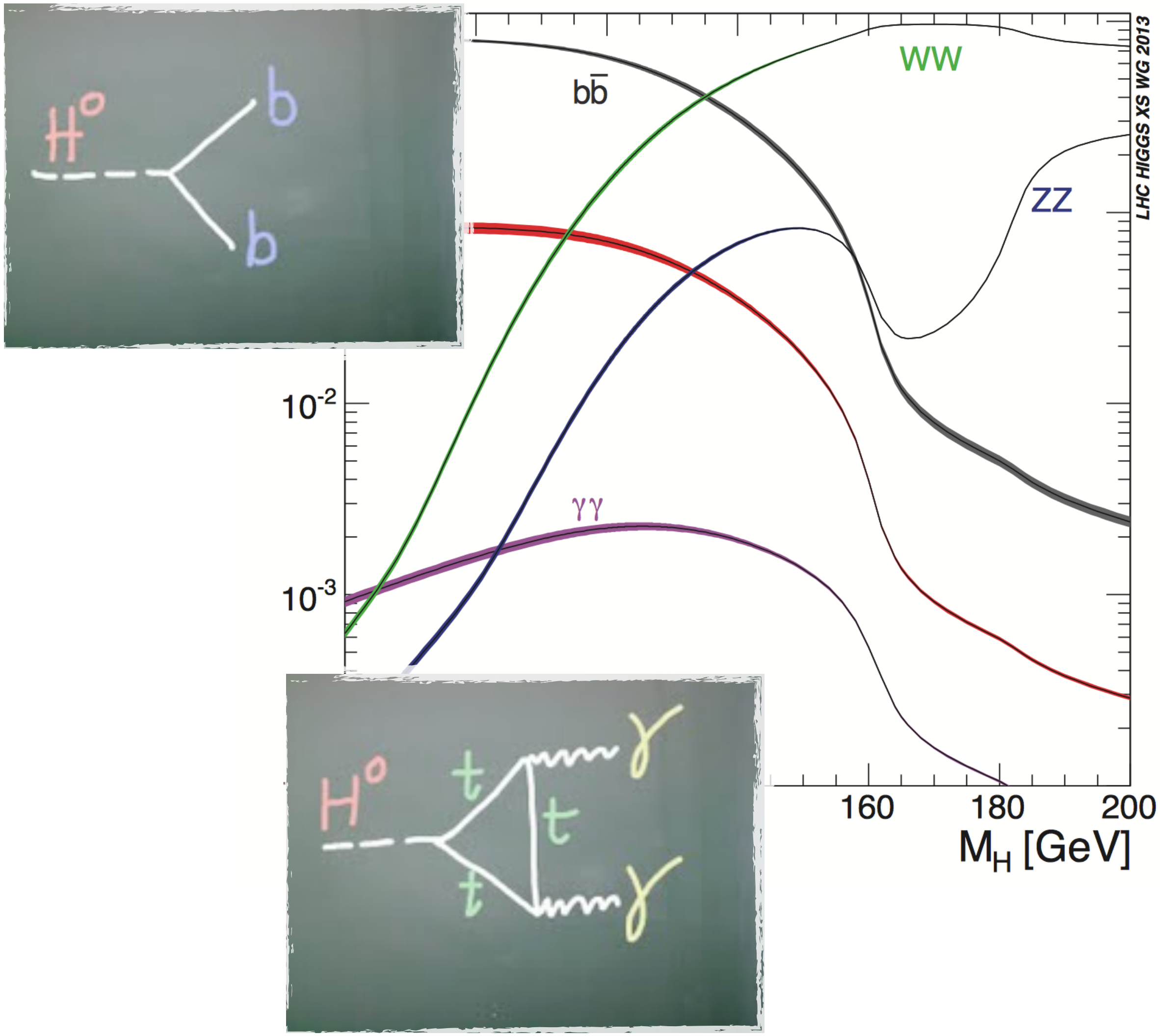

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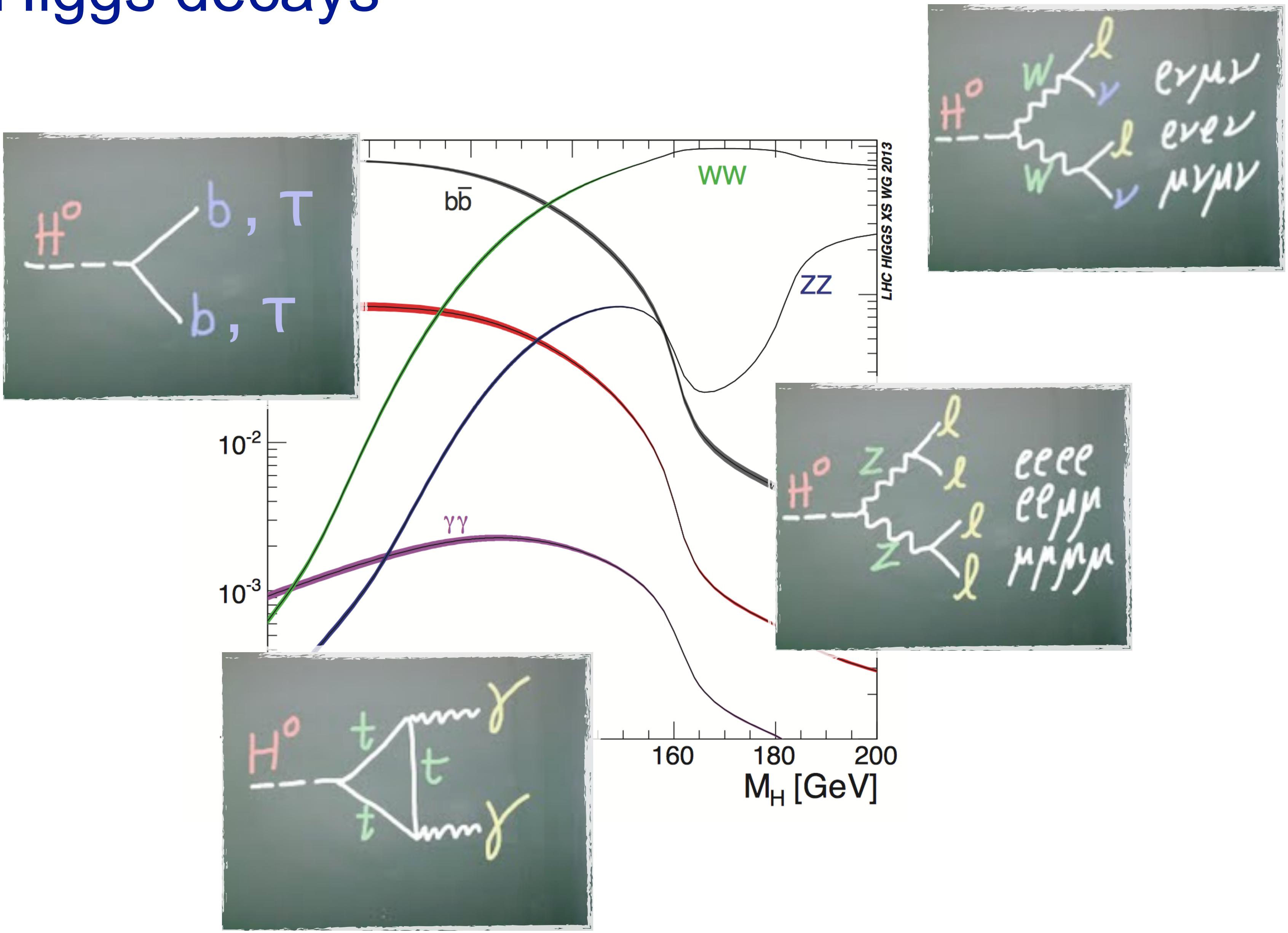
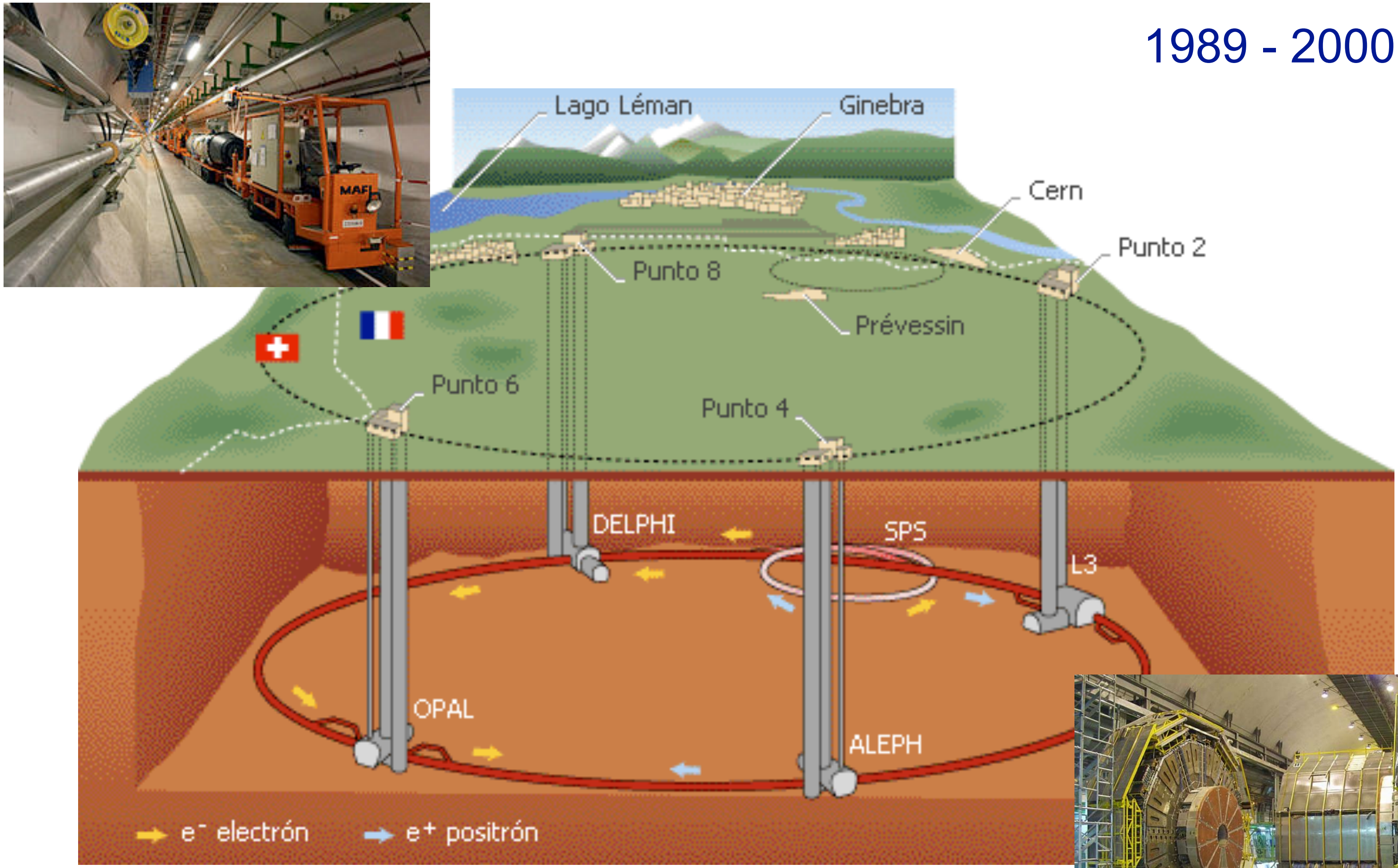
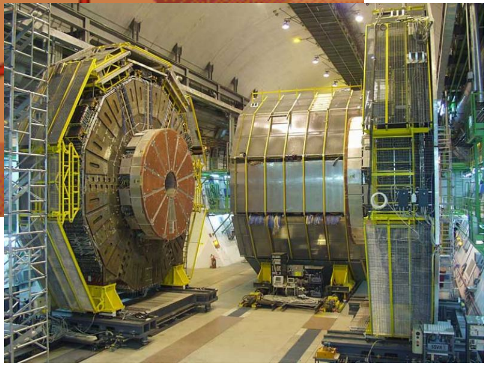
Higgs decays



The Large Electron Positron collider

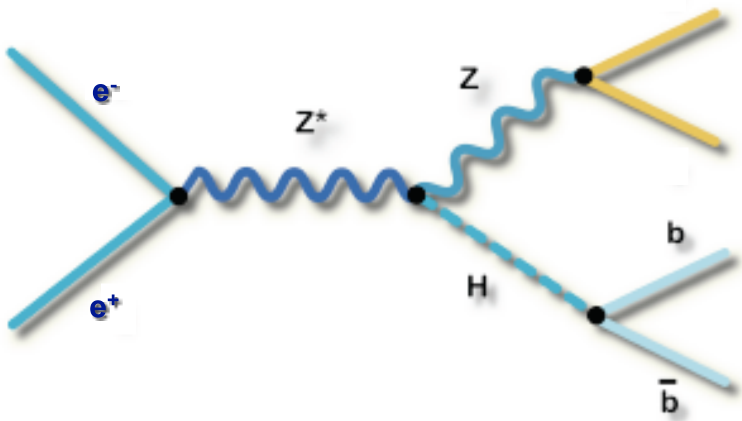
1989 - 2000





Highest centre-of-mass energy ~ 209 GeV

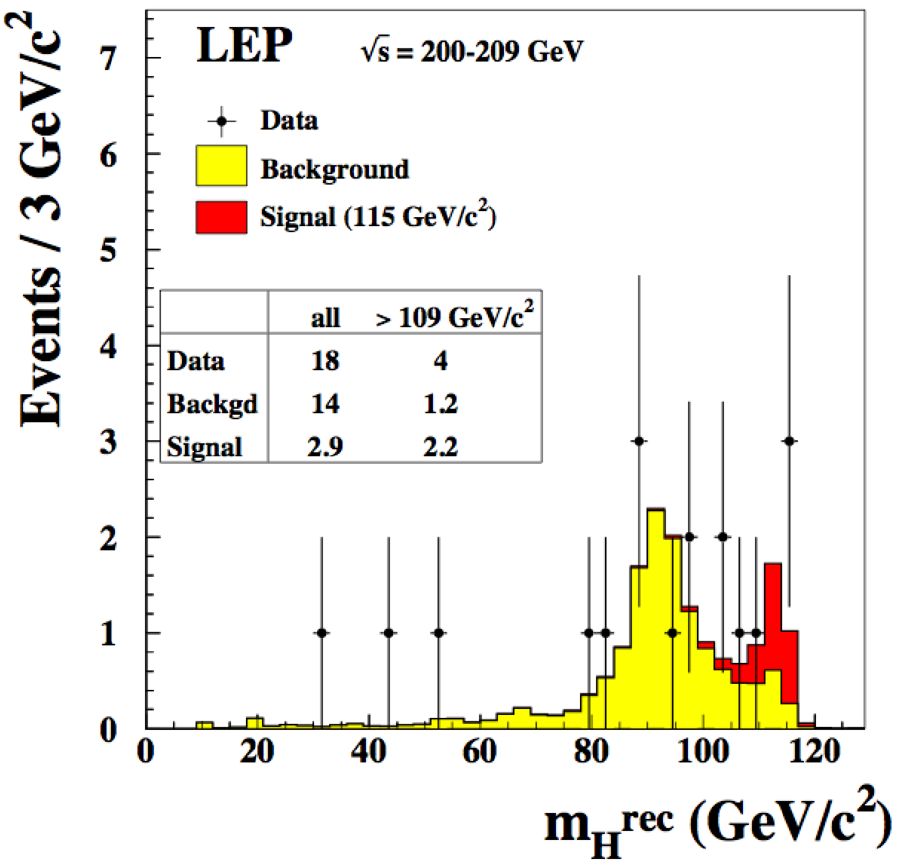
Higgs searches at LEP



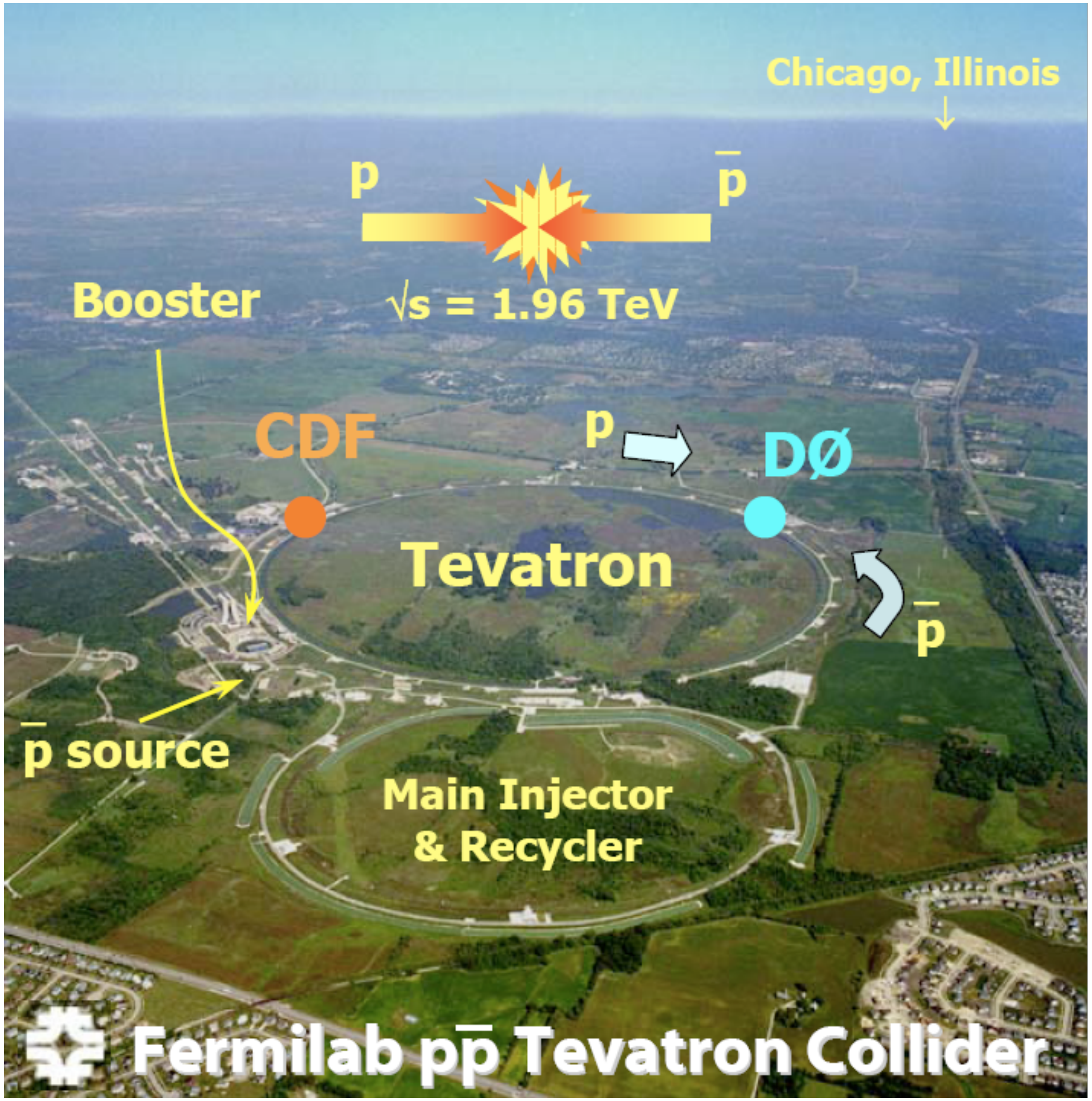
$\sqrt{s} - m_Z \approx 115$ GeV

Excess around 115 GeV
not significant

$m_H \geq 114.4$ GeV @ 95% CL



Tevatron collider in Run II

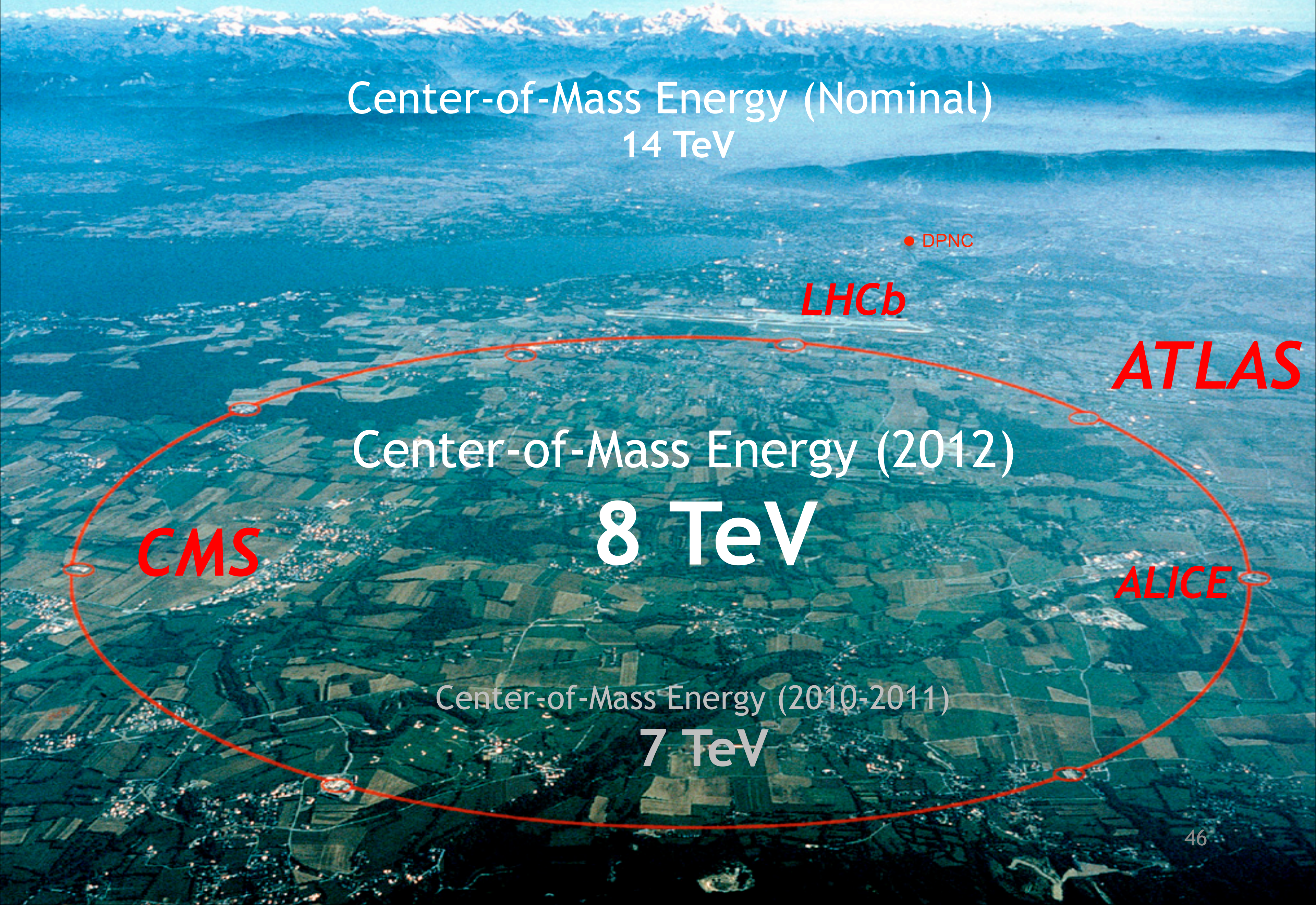


Run II 2001 - 2011

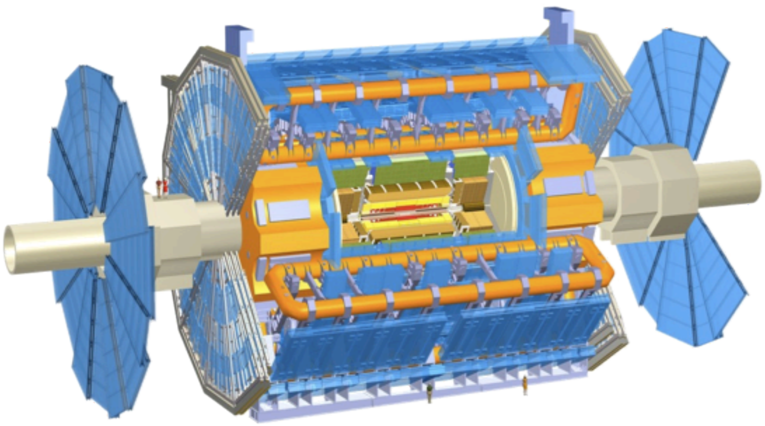
High energy frontier before the turn on of the LHC

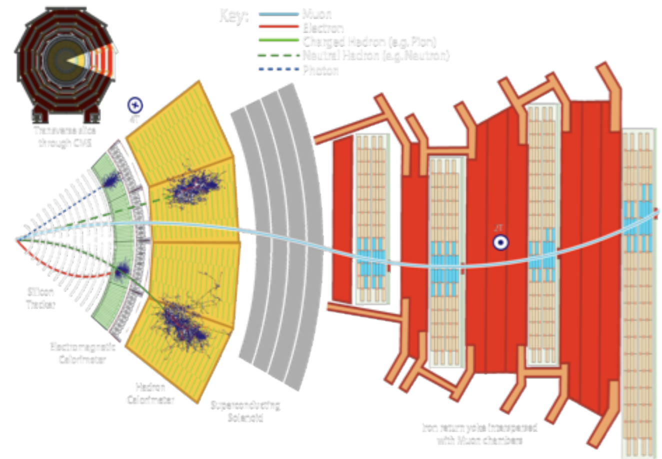
Both experiments collected a dataset of 10 fb^{-1}

LHC collider



ATLAS and *CMS* experiments





ATLAS: emphasis on excellent jet and missing E_T resolution, particle identification, and standalone muon measurement

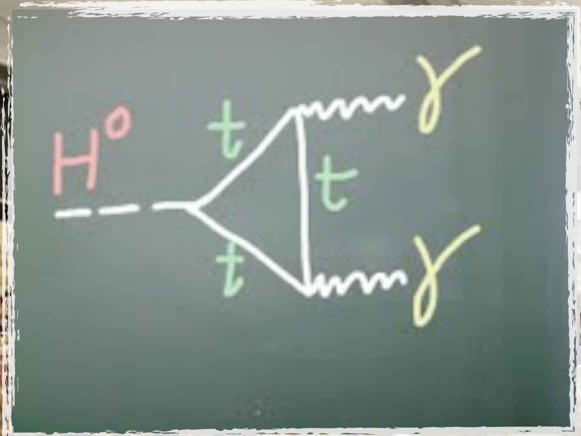
CMS: emphasis on excellent electron/photon and tracking (muon) resolution

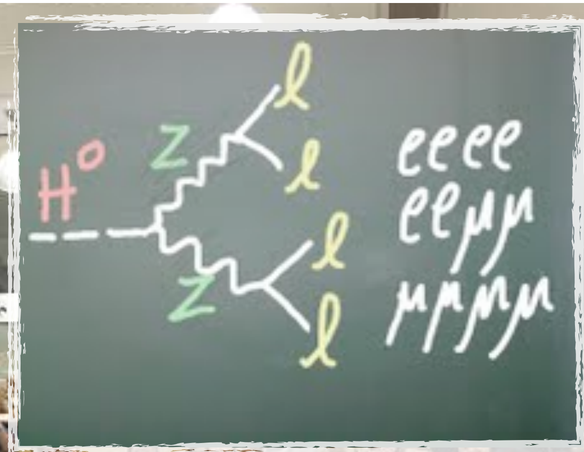
Detectors well understood, stable operation and data taking efficiencies above 90%

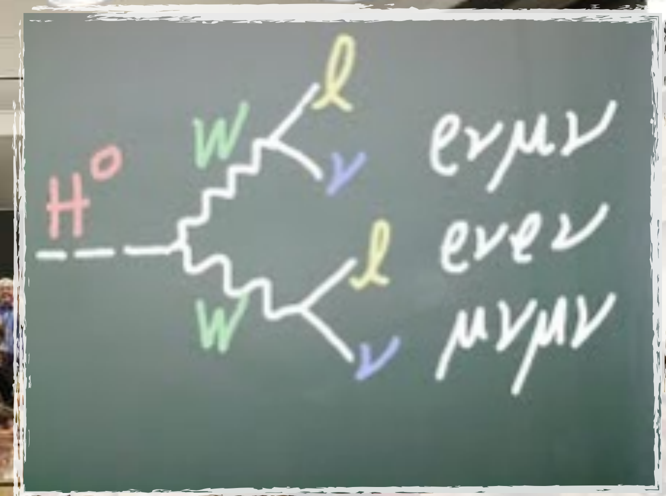
Higgs discovery at the LHC

4 July 2012

Higgs discovery at the LHC







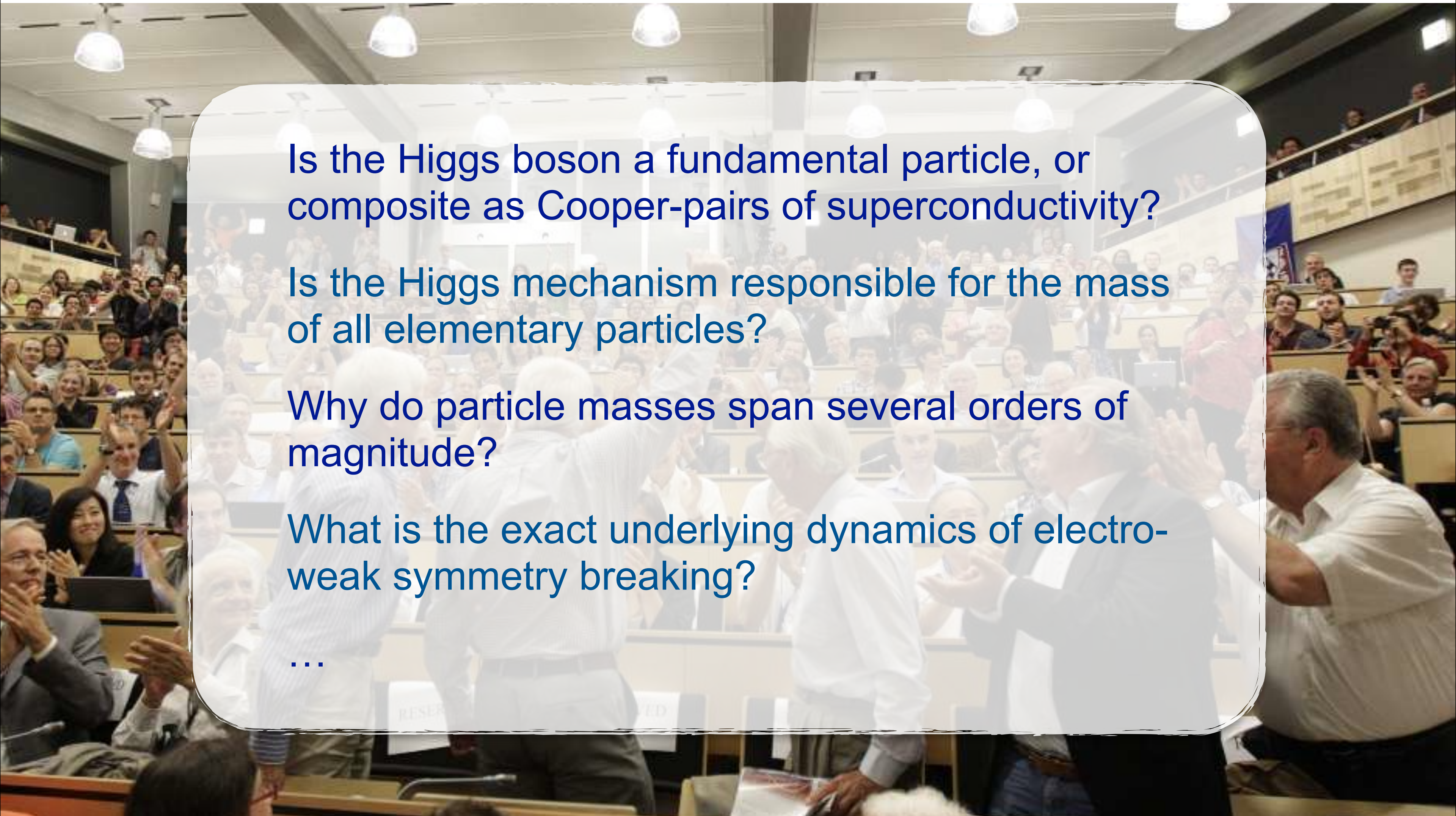
It couples to vector bosons

It is a boson (spin 0 or 2)

It has a narrow width

4 July 2012

Higgs discovery at the LHC



Is the Higgs boson a fundamental particle, or composite as Cooper-pairs of superconductivity?

Is the Higgs mechanism responsible for the mass of all elementary particles?

Why do particle masses span several orders of magnitude?

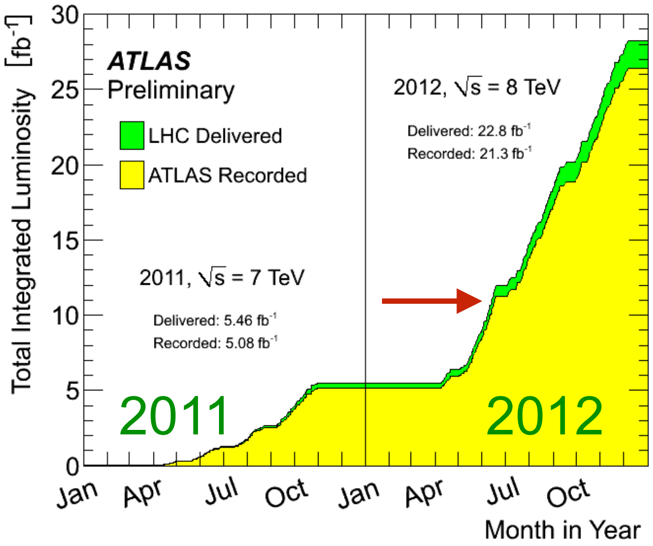
What is the exact underlying dynamics of electro-weak symmetry breaking?

…

4 July 2012

Year 1 after the discovery

Integrated luminosity



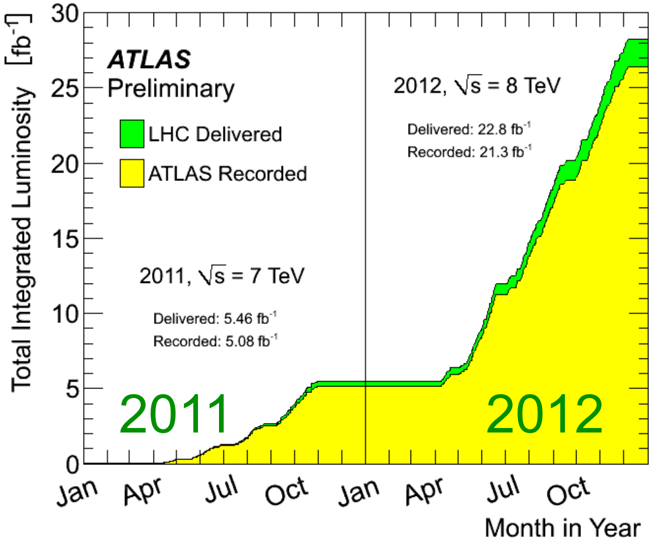
Detailed studies of the new particle

- Measurement of all decay modes
- Property measurements
  - Couplings
  - Mass
  - Spin
  - Kinematic properties of production and decay

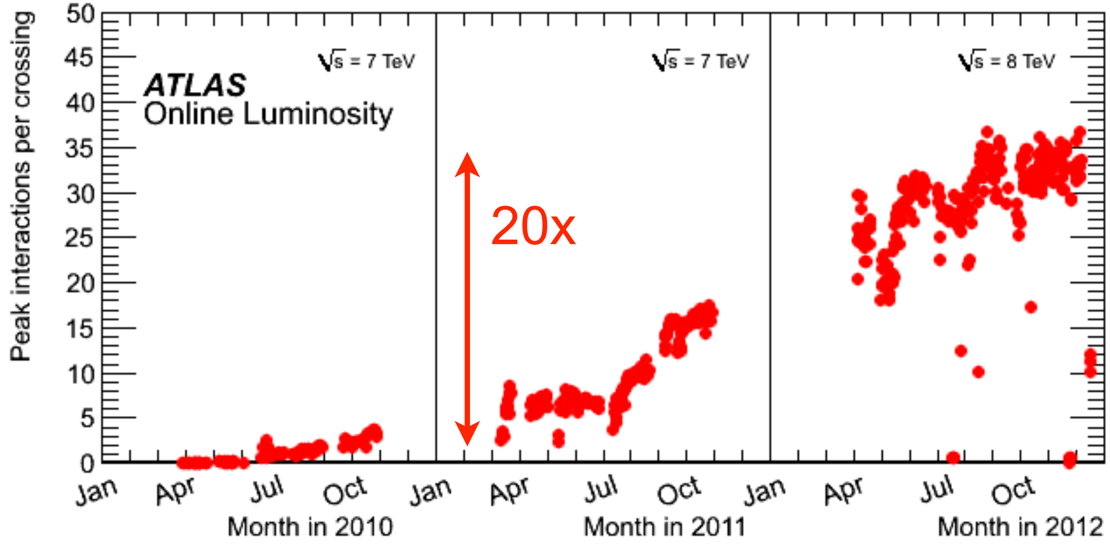
Available dataset for physics analysis 25 fb^{-1}

LHC Run I dataset

Integrated luminosity



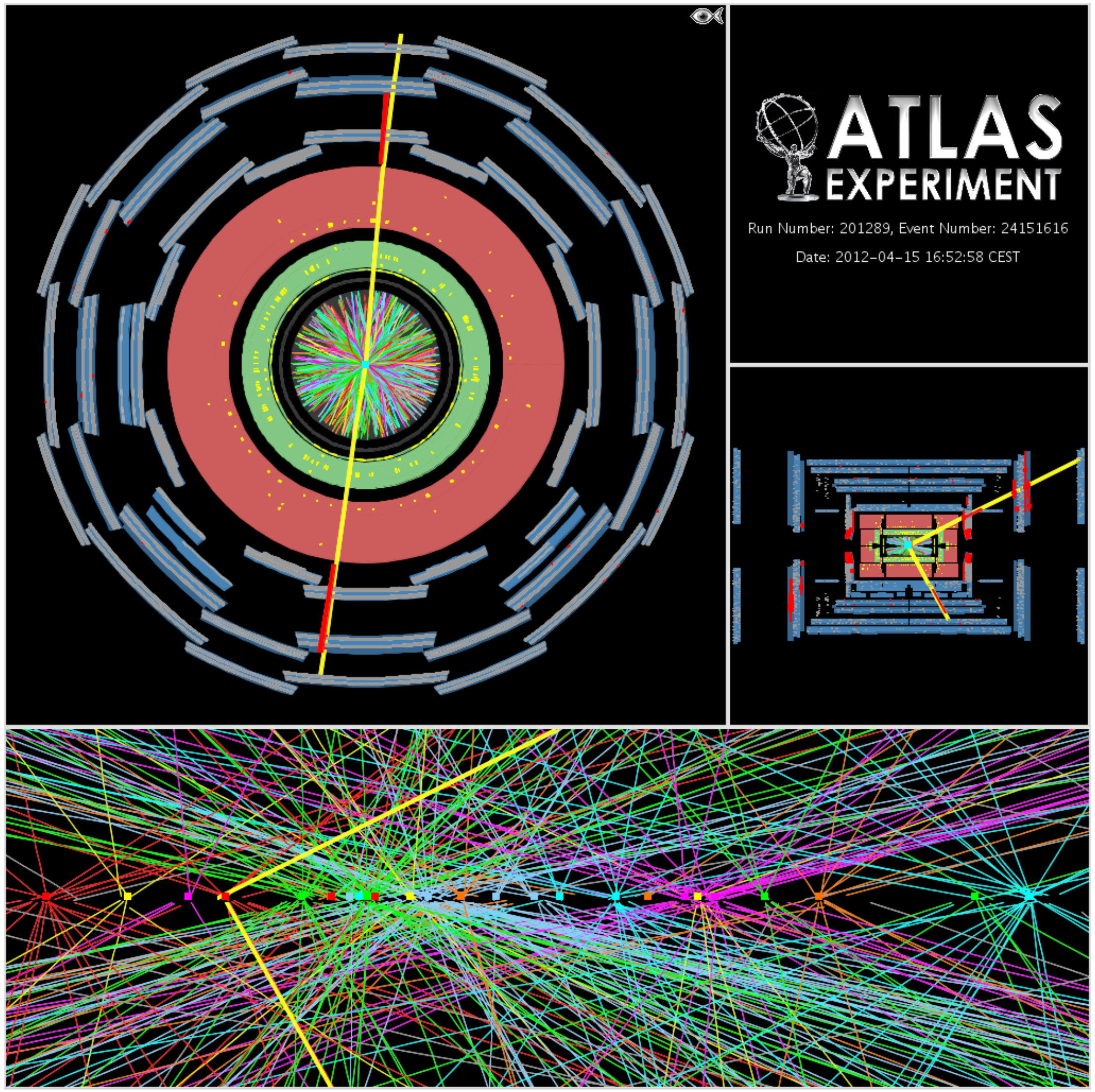
Peak interactions per beam crossing



Available dataset for physics analysis 25 fb^{-1}

More *pp* interactions per beam crossing

Challenges with high luminosity



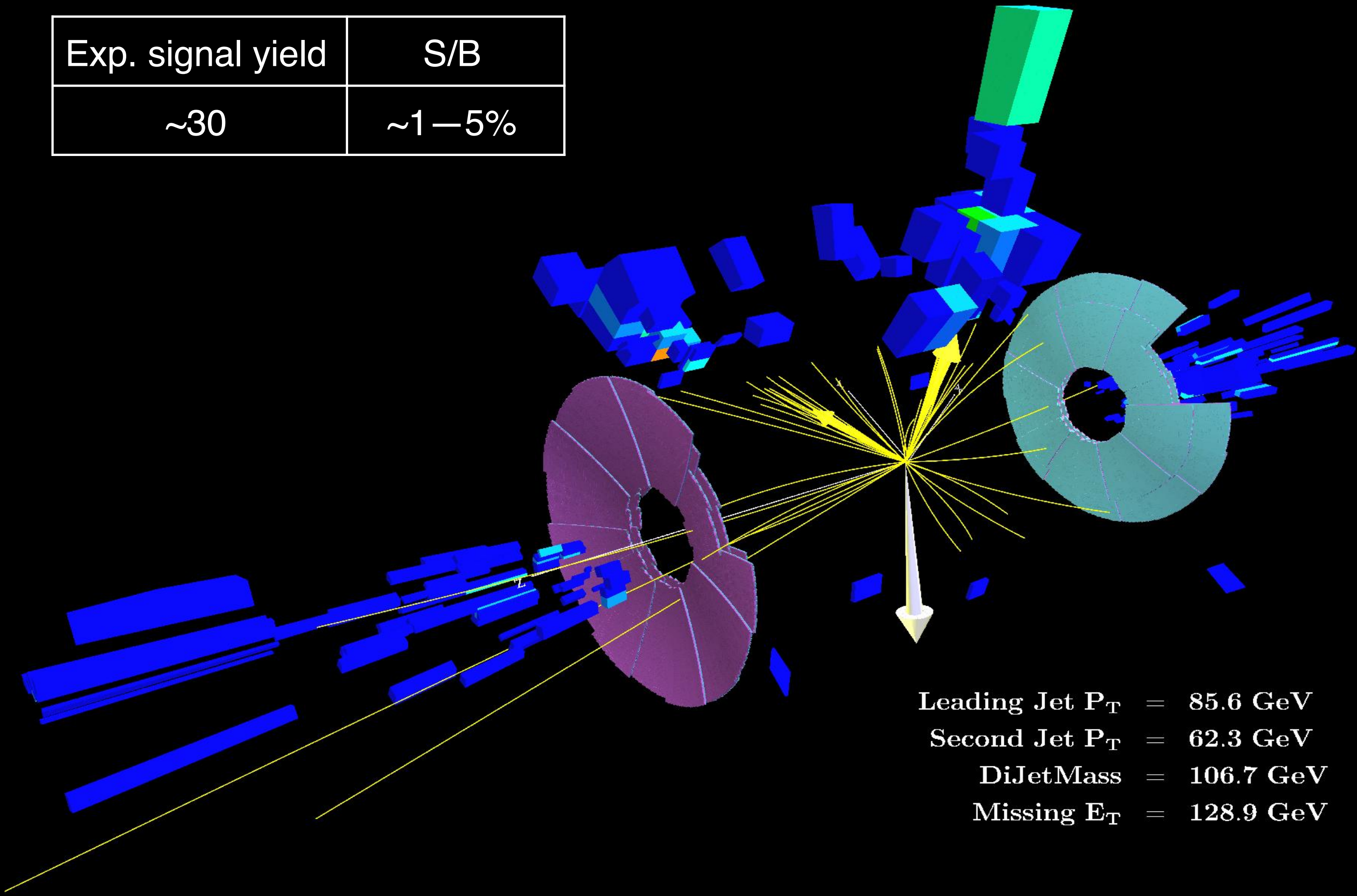
Continuously improve triggering, reconstruction and identification algorithms to cope with this challenging environment

Main impact on jets, missing E_T and tau reconstruction (as well as on trigger rates and computing)

$Z \rightarrow \mu\mu$ event with 25 reconstructed vertices

VH production with H → bb

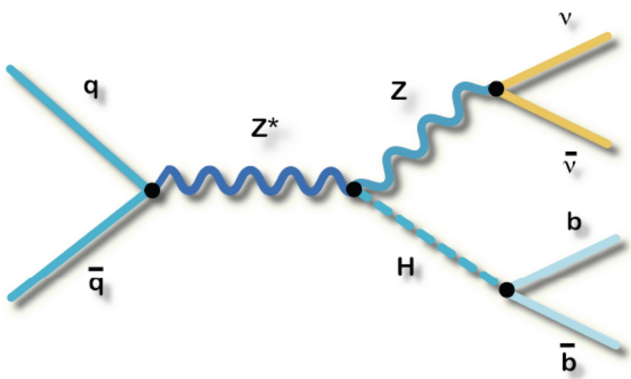
Exp. signal yield	S/B
~30	~1—5%



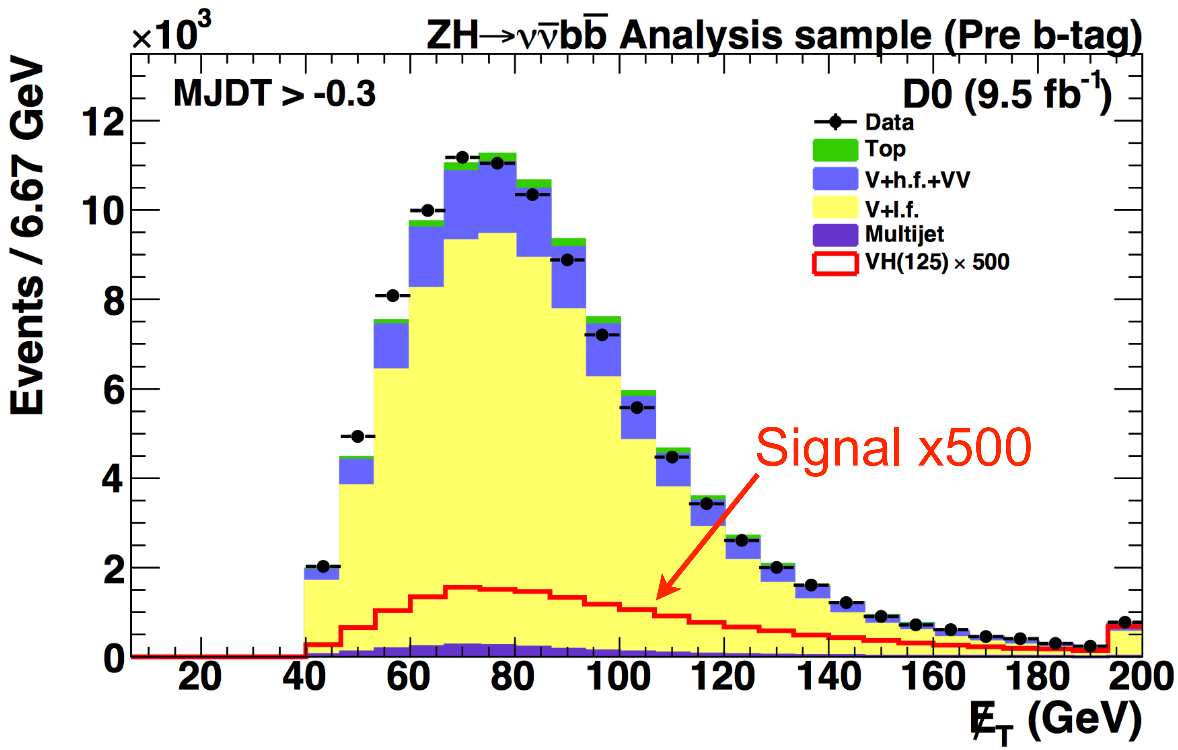
DØ Experiment

Selection

Example: $ZH \rightarrow \nu\nu bb$



First step: select events with W/Z and 2 jets

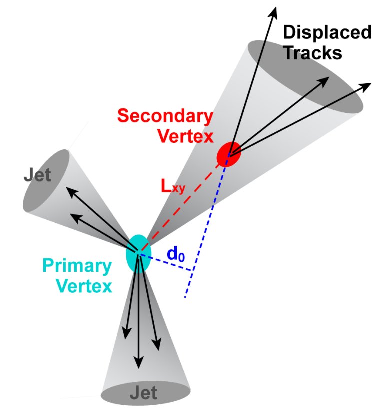


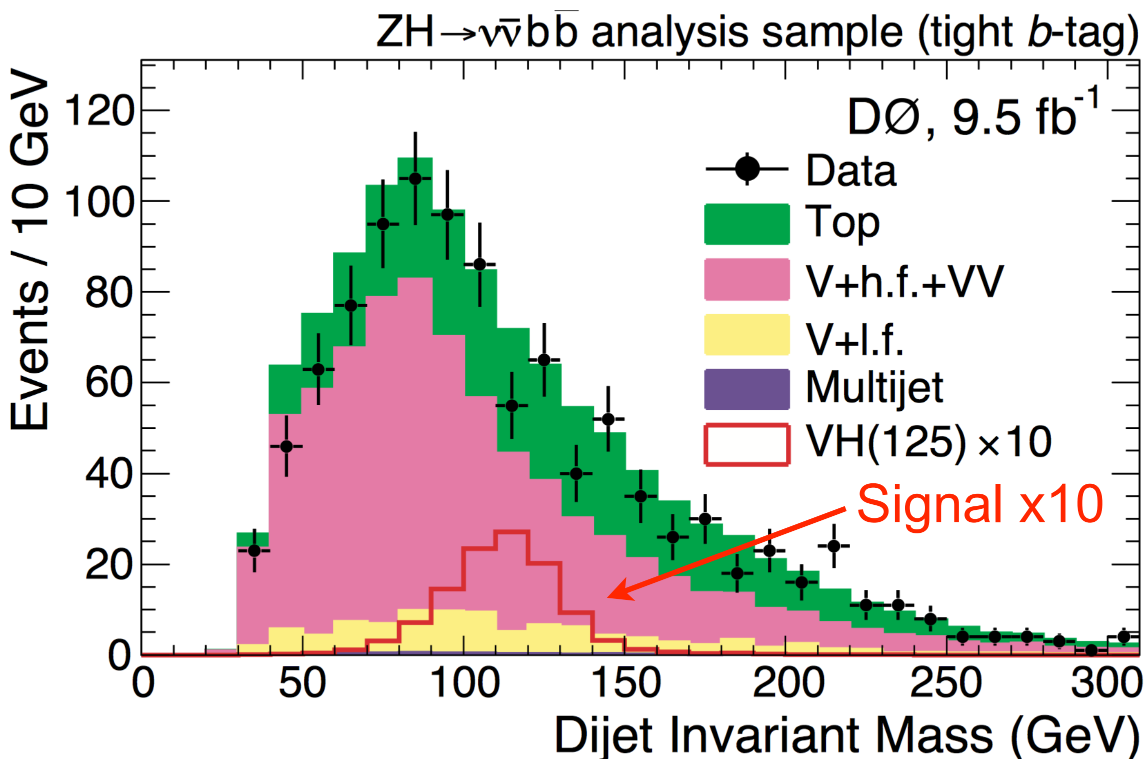
b-jet tagging

Second step: separate b from light-quark jets

Backgrounds dominated by: W/Z+bb, di-boson and top

Best discriminant: dijet invariant mass



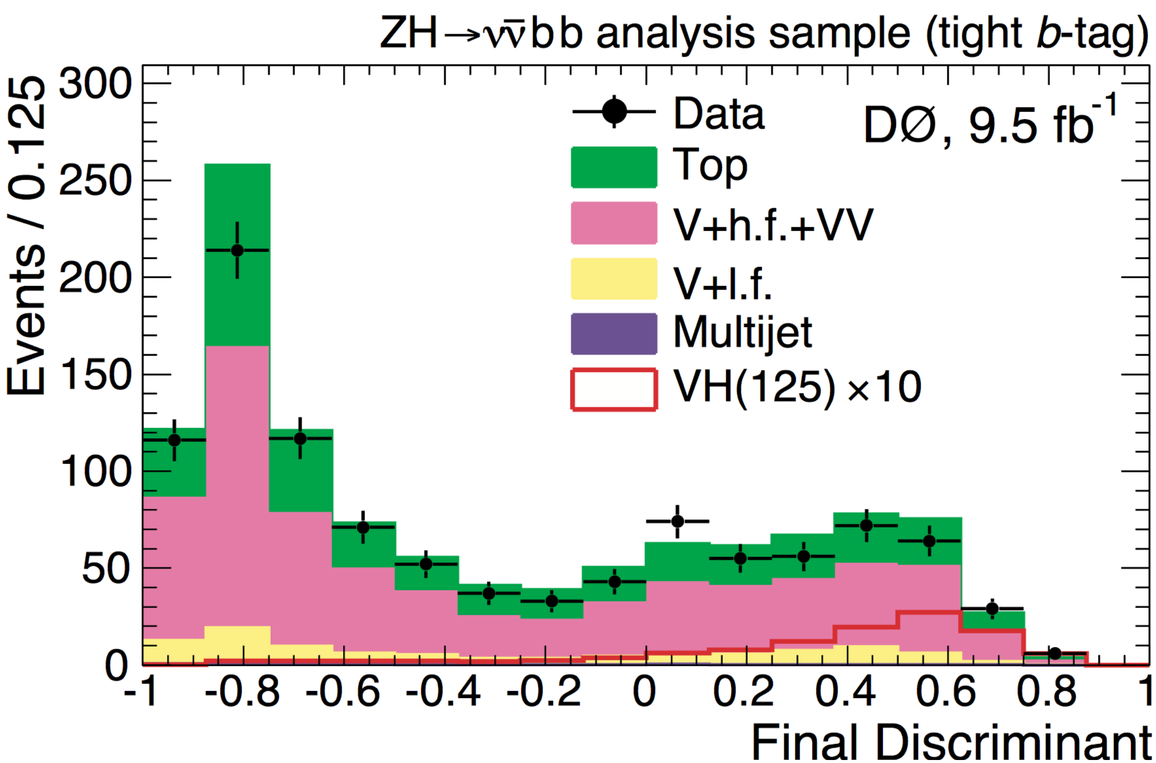


Final discrimination

Third step: Optimise separation using multivariate discriminant

Exploit information from several kinematic variables and their correlations

In combination, close to 3σ evidence for bb decays around 125 GeV

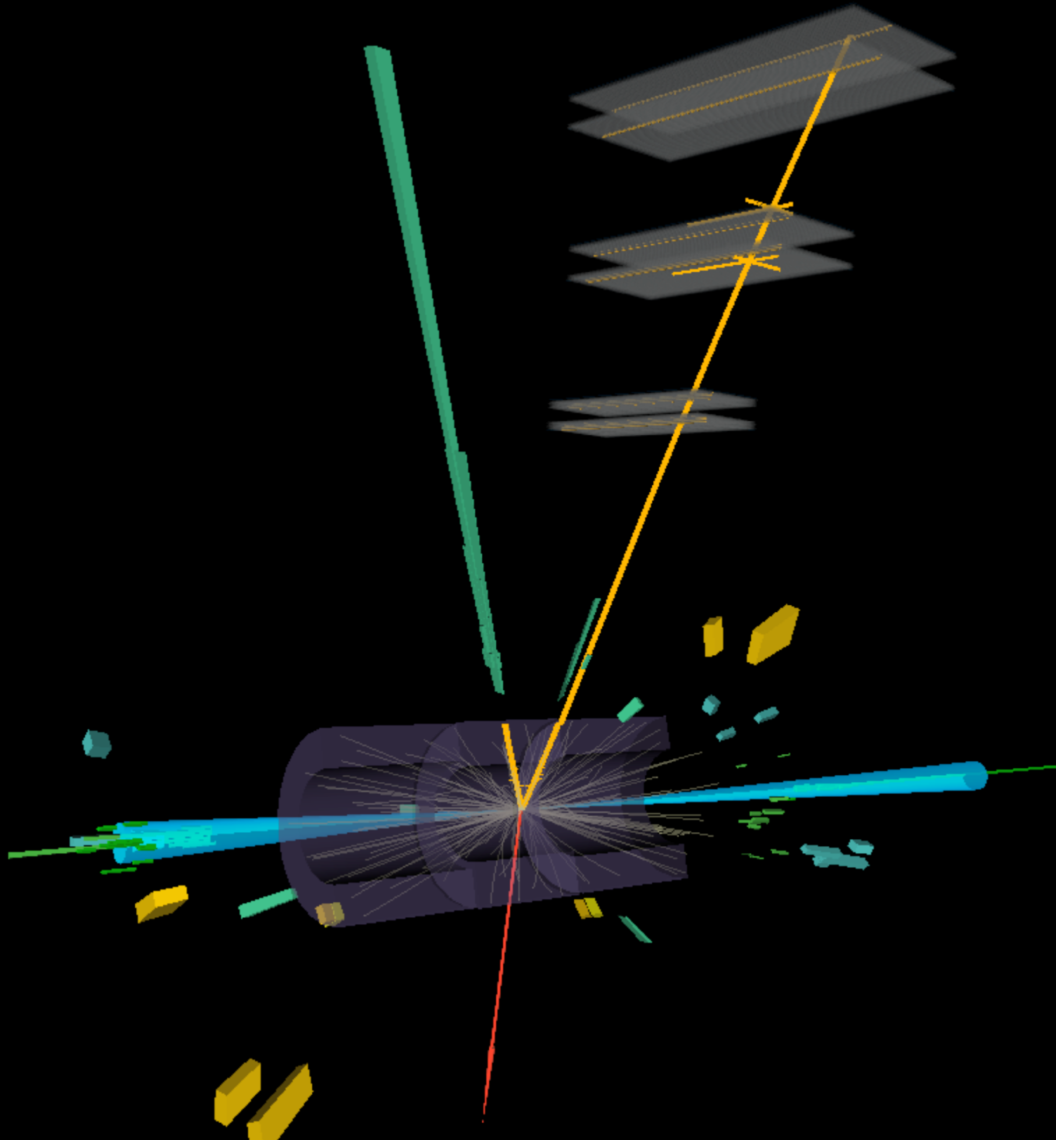


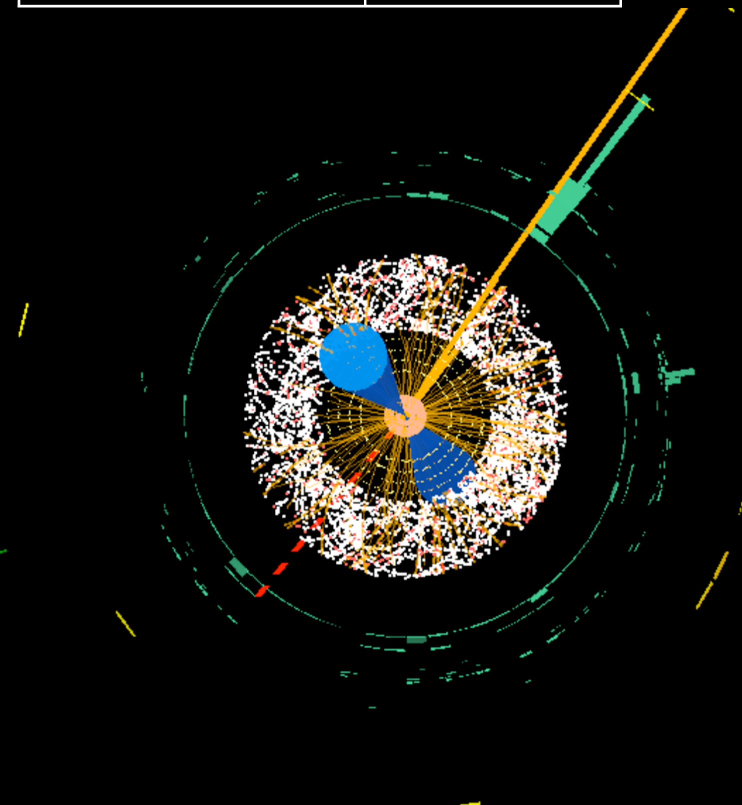
PRL **104**, 071801 (2010)
PLB **716**, 285 (2012)

$H \rightarrow WW^* \rightarrow \ell\ell + 2\nu$

ATLAS EXPERIMENT

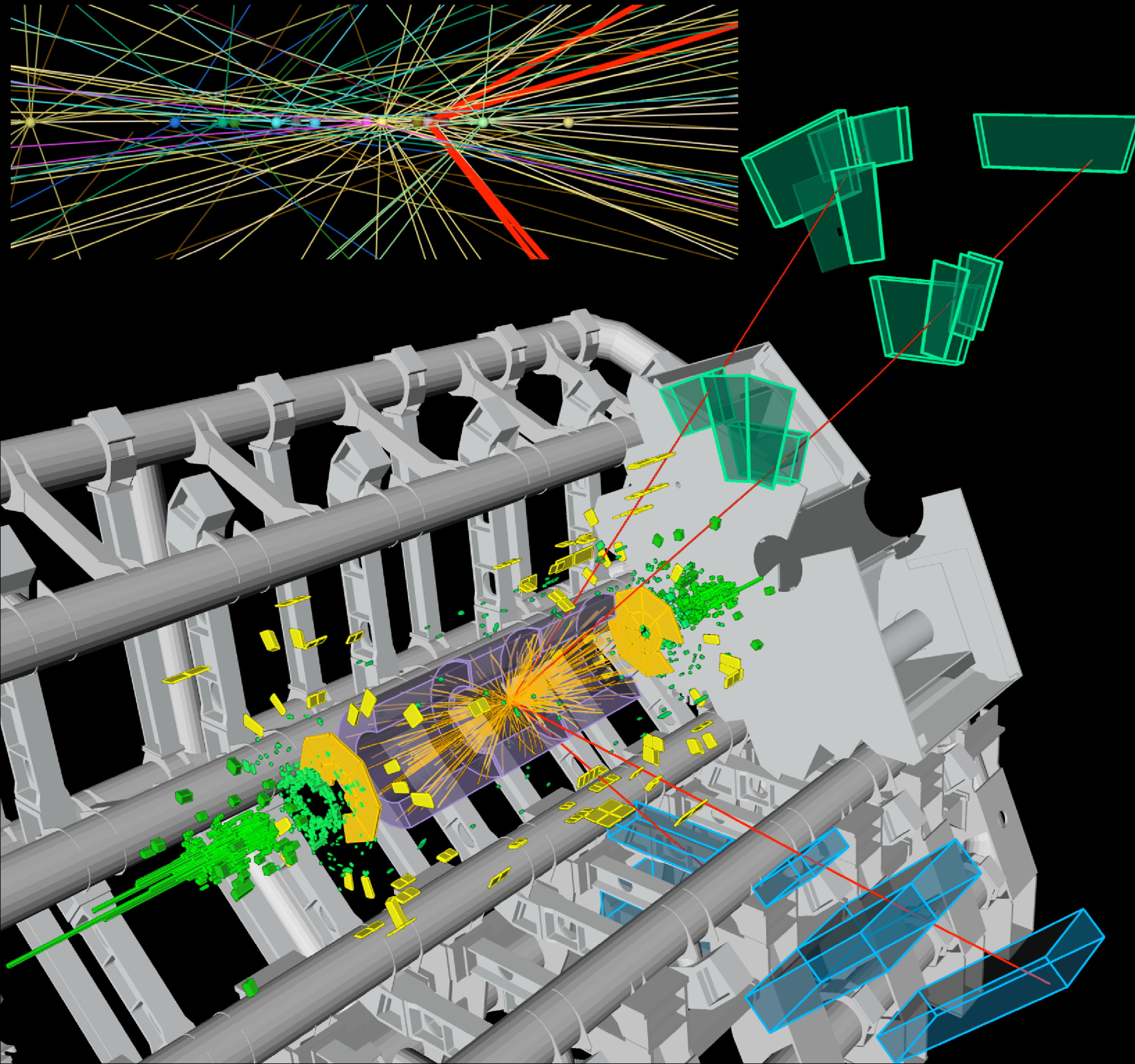
Exp. signal yield	S/B
~200	~15%

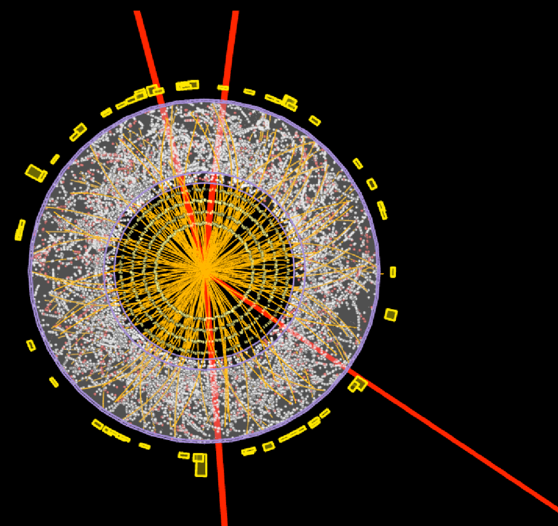




$H \to ZZ^* \to 4\ell$

2 same flavour, opposite charge lepton pairs (one) consistent with Z mass



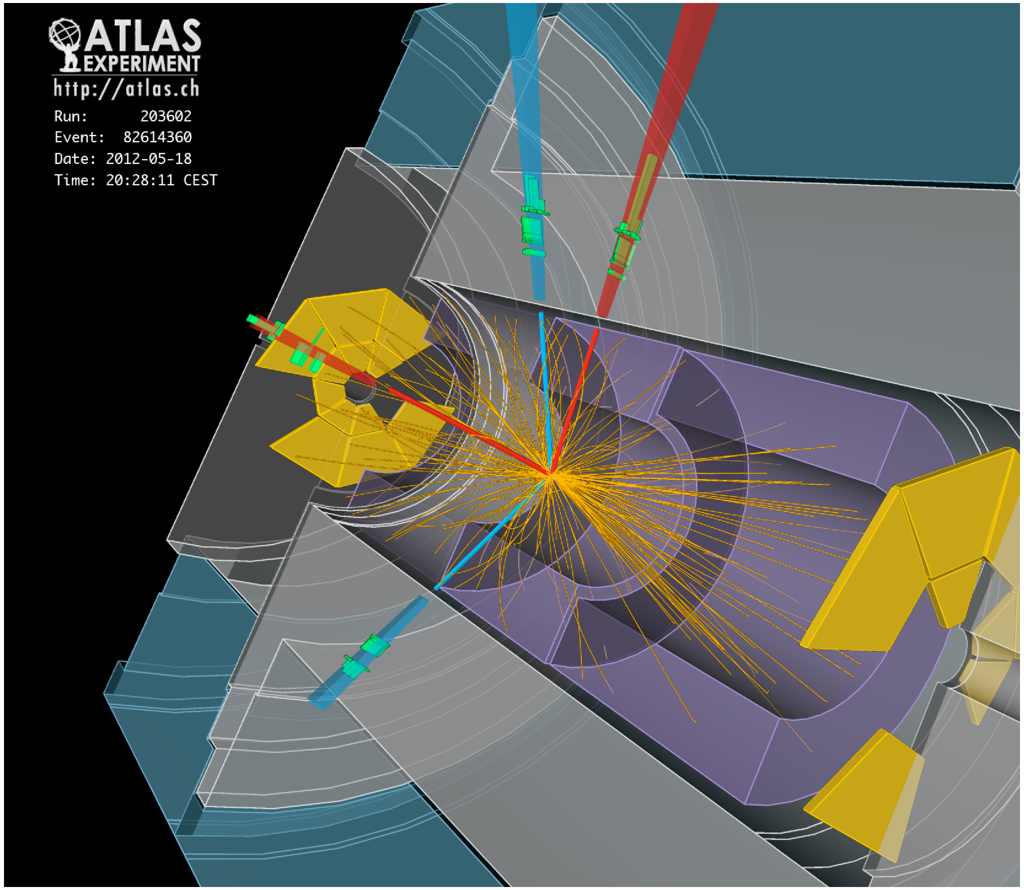


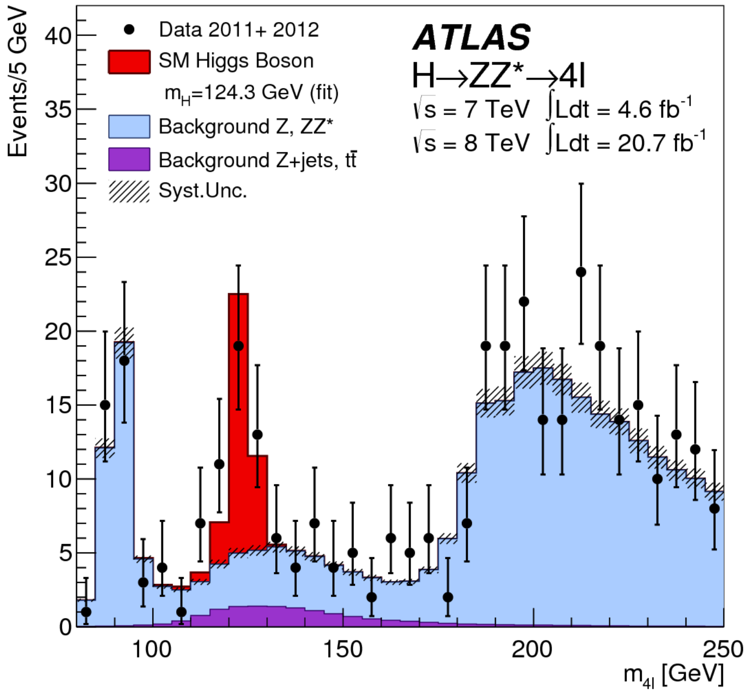
Exp. signal yield	S/B
~16	~1.4

$H \rightarrow ZZ^* \rightarrow 4\ell$

Look for a clustering of events in the 4-lepton invariant mass distribution

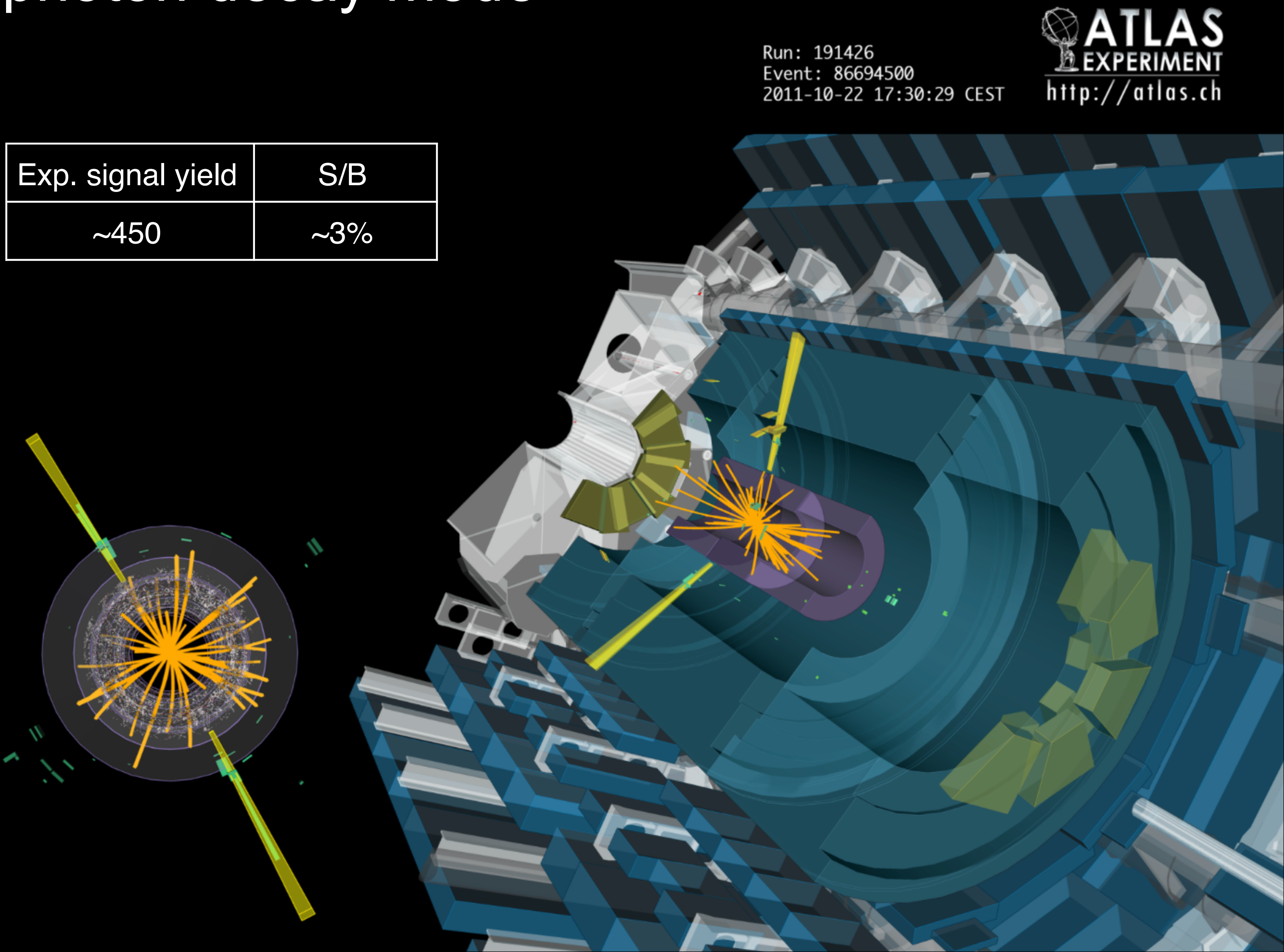
Main backgrounds: SM ZZ* production (irreducible), Top, Z+jj





Di-photon decay mode

Exp. signal yield	S/B
~450	~3%



Di-photon decay mode

Most sensitive around m_H = 125 GeV (high resolution 1-2%)

Main production and decay through loops

gluon-fusion production

decay to γγ

BR ~ 0.2%

Clean discovery channel: Select events with two isolated high pT photons. Look for bump in steeply falling di-photon mass spectrum

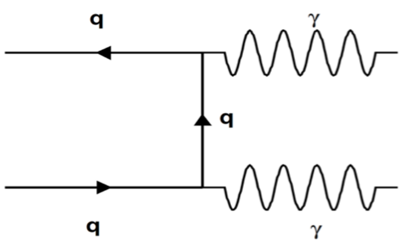
Relevant aspects:

- Photon identification / background rejection
- Good di-photon mass resolution
- Background estimation / signal extraction

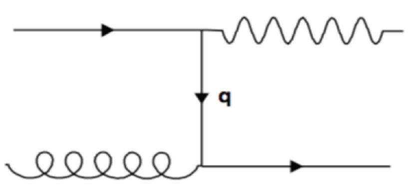
Photon purity

Main backgrounds (estimated from data)

- Irreducible: SM γγ production
- Reducible: γj production with q/g → π^0



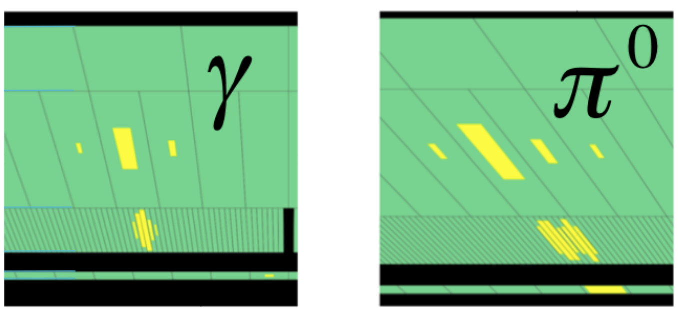
Irreducible



Reducible

Critical to reach rejections $O(10^4)$

π^0-γ Rejection



Photon purity

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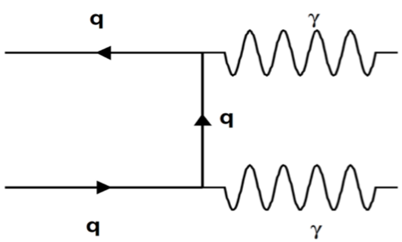
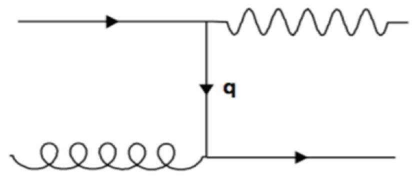
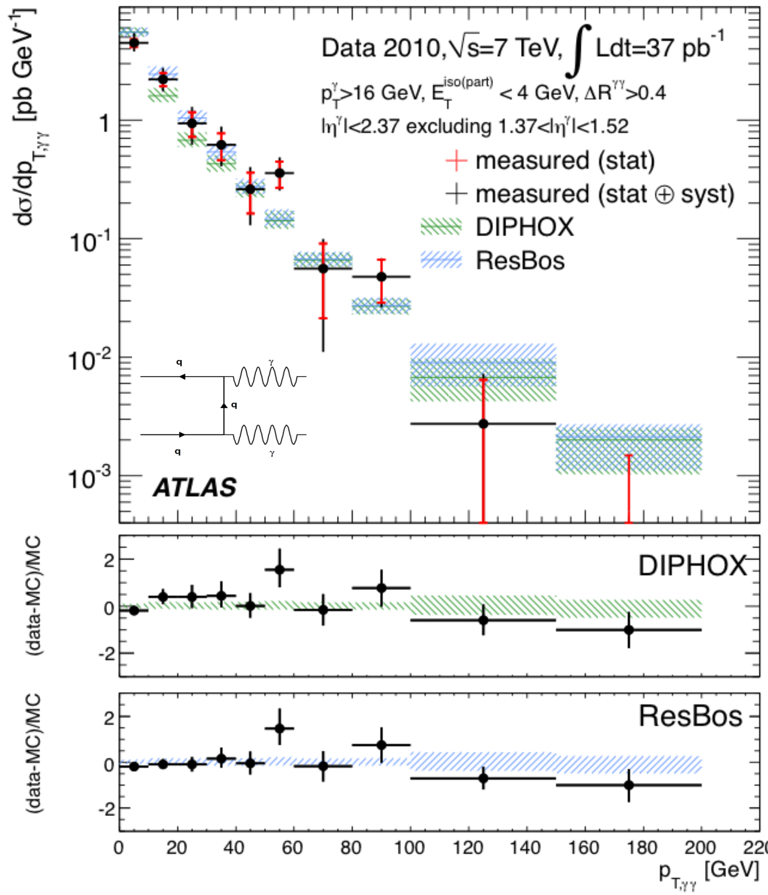


Irreducible



Reducible

SM continuum
di-photon production



PRD **85,** 012003 (2012)

Measure SM continuum di-photon production cross section

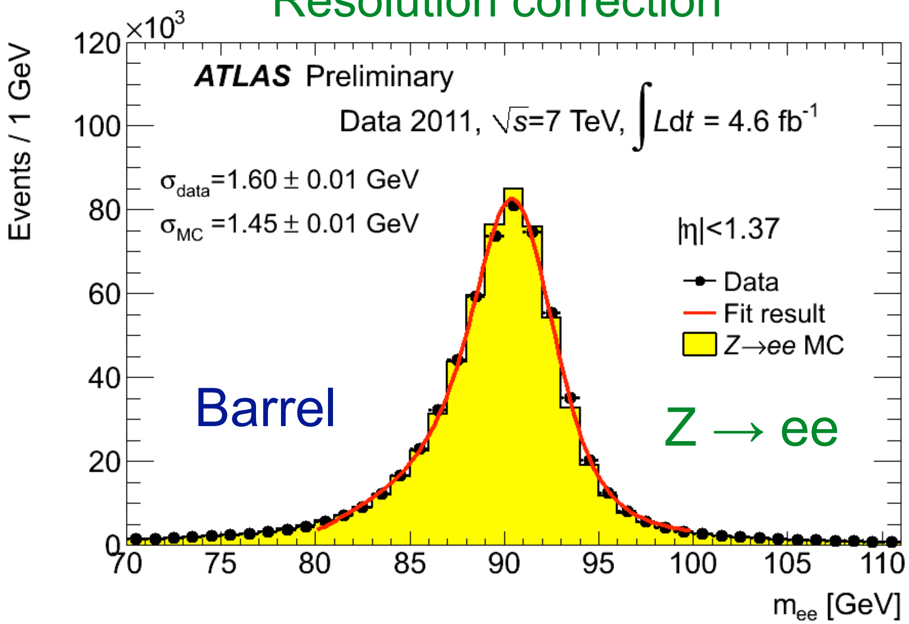
- Cross check of di-photon selection procedure
- Good understanding of dominant background

Photon energy calibration

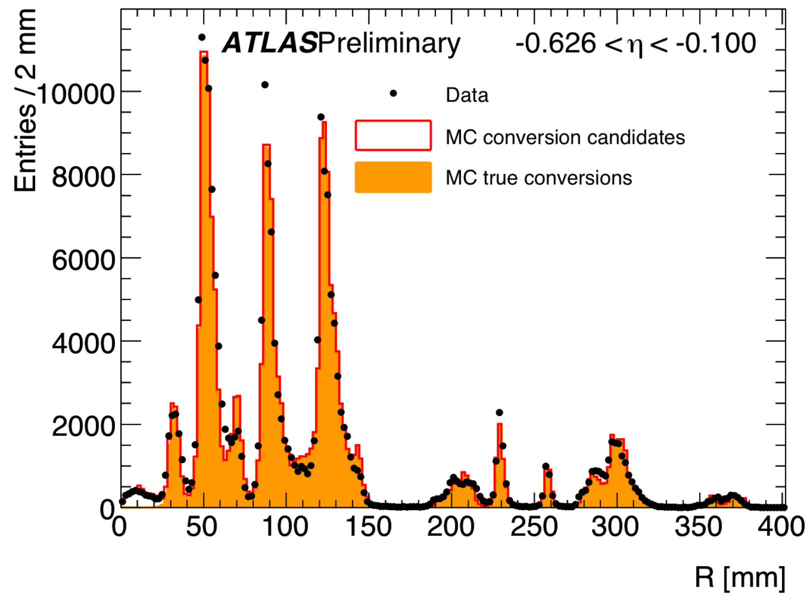
Calorimeter energy scale (and resolution) corrections from Z decay to electrons

Need accurate material description for e → γ extrapolation. Cross-checked with several *in-situ* measurements

Resolution correction



Radial distribution of photon conversions



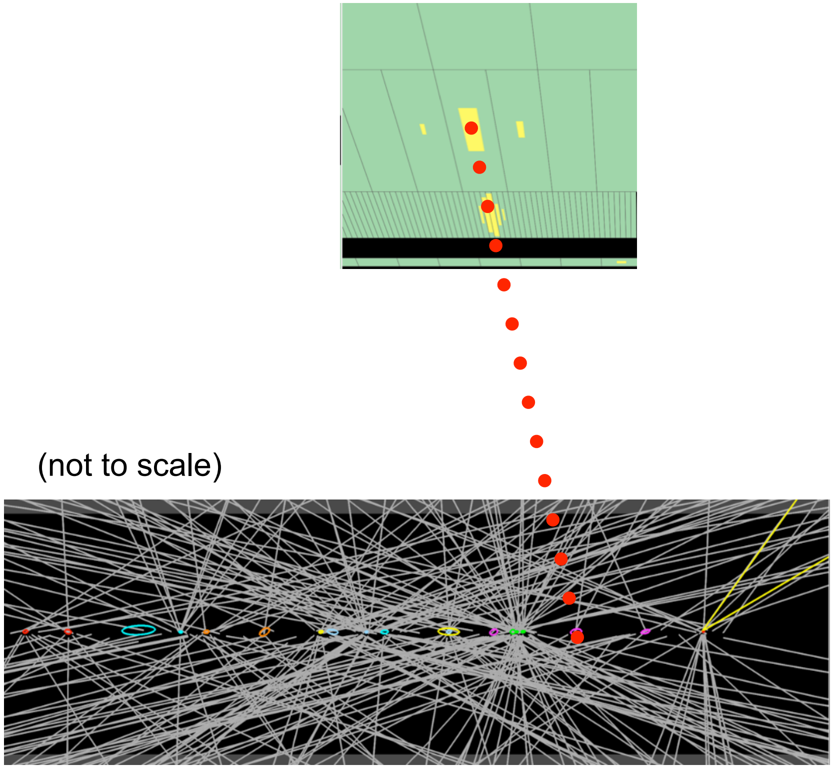
Photon direction measurement

Important ingredient for mass resolution

$$m_{\gamma\gamma}^2 = 2E_1E_2(1-\cos\theta)$$

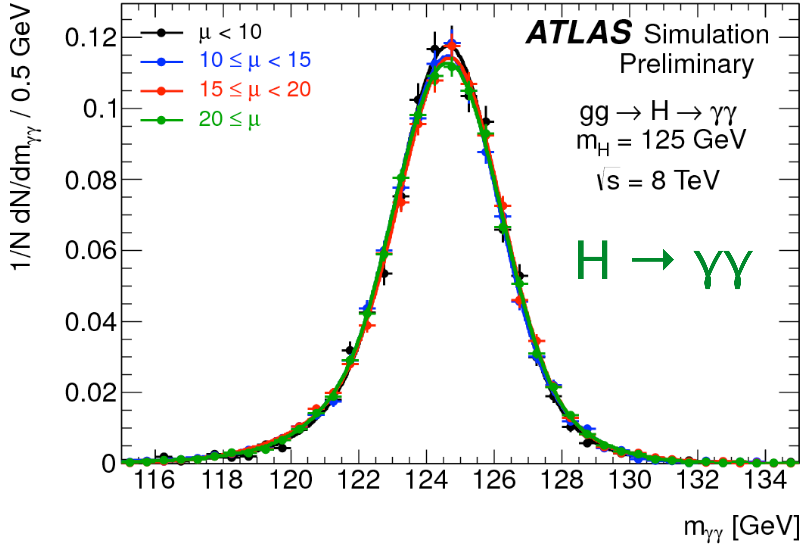
Beam spot spread ~5-6 cm, assuming detector centre origin adds 1.4 GeV in mass resolution (equivalent to intrinsic calorimeter resolution)

(not to scale)



O(20%) resolution improvement

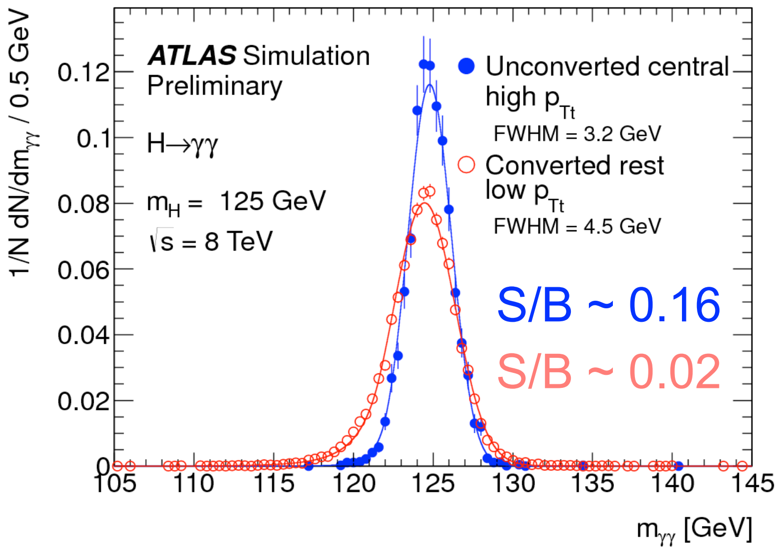
Resolution stable with number of *pp* interactions



Events categorisation

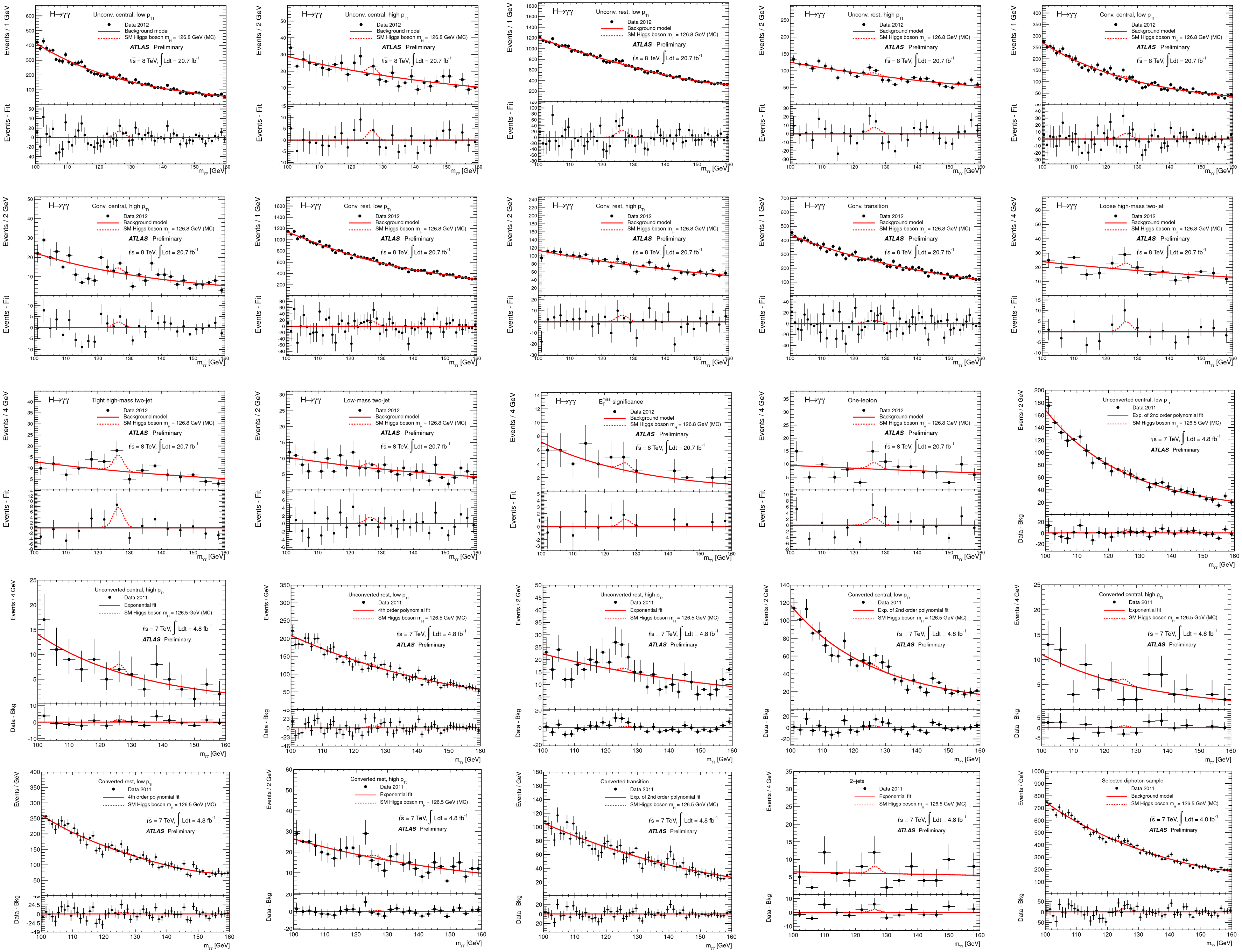
Separate events into categories with different S/B, resolutions and different relative contributions of signal production modes ("many analyses")

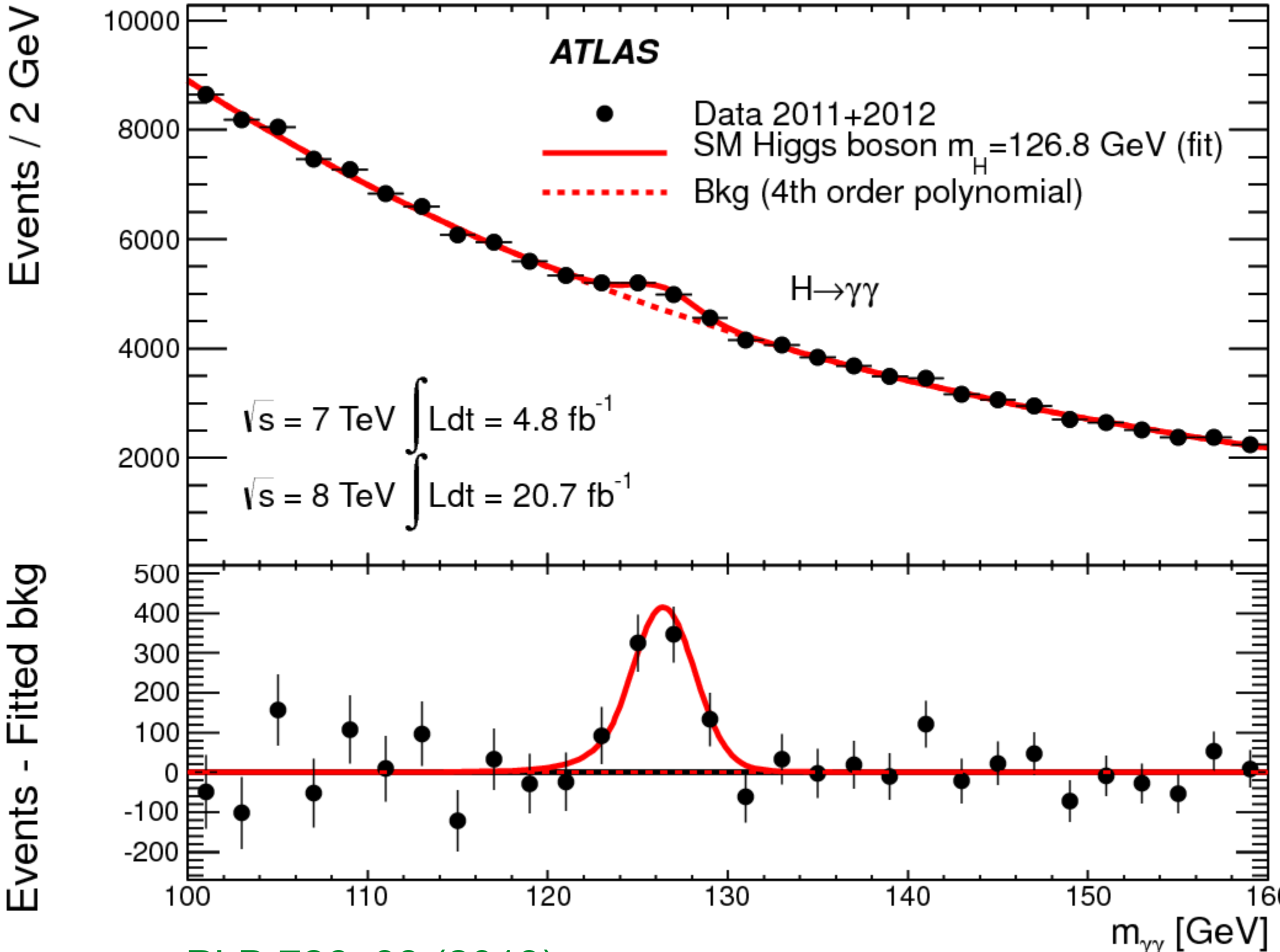
- Probe all four production modes through dedicated VBF, VH and ttH selections
- 30% increase in overall expected sensitivity
- 20% more accurate mass measurement



Examples:

- Both γ unconverted and central, high γγ p_T
- At least one γ converted and not central, low γγ p_T

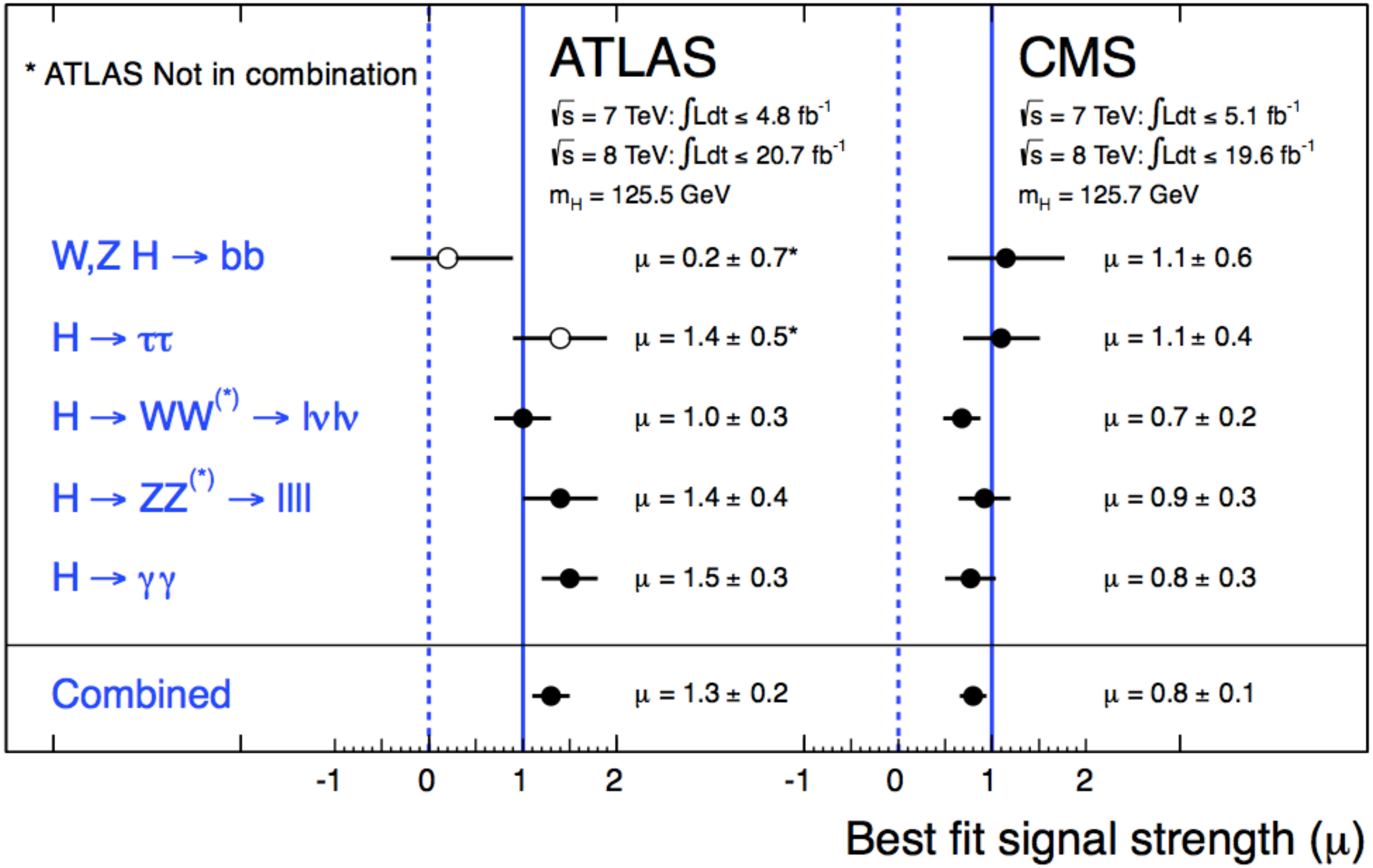

H→γγ
Unconv. central, low p_{Tt}
Unconv. central, high p_{Tt}
Unconv. rest, low p_{Tt}
Unconv. rest, high p_{Tt}
Conv. central, low p_{Tt}
Conv. central, high p_{Tt}
Conv. rest, low p_{Tt}
Conv. rest, high p_{Tt}
Conv. transition
Loose high-mass two-jet
Tight high-mass two-jet
Low-mass two-jet
E_T^{miss} significance
One-lepton
Data 2012
Background model
SM Higgs boson m_H = 126.8 GeV (MC)
ATLAS Preliminary
$\sqrt{s}$ = 8 TeV, $\int Ldt$ = 20.7 fb^{-1}
Events / 1 GeV
Events / 2 GeV
Events / 4 GeV
Events - Fit
$m_{\gamma\gamma}$ [GeV]
Unconverted central, low p_{Tt}
Unconverted central, high p_{Tt}
Unconverted rest, low p_{Tt}
Unconverted rest, high p_{Tt}
Converted central, low p_{Tt}
Converted central, high p_{Tt}
Converted rest, low p_{Tt}
Converted rest, high p_{Tt}
Converted transition
2-jets
Selected diphoton sample
Data 2011
Exp. of 2nd order polynomial fit
Exponential fit
4th order polynomial fit
Background model
SM Higgs boson m_H = 126.5 GeV (MC)
$\sqrt{s}$ = 7 TeV, $\int Ldt$ = 4.8 fb^{-1}
ATLAS Preliminary
Events / GeV
Data - Bkg



PLB **726**, 88 (2013)

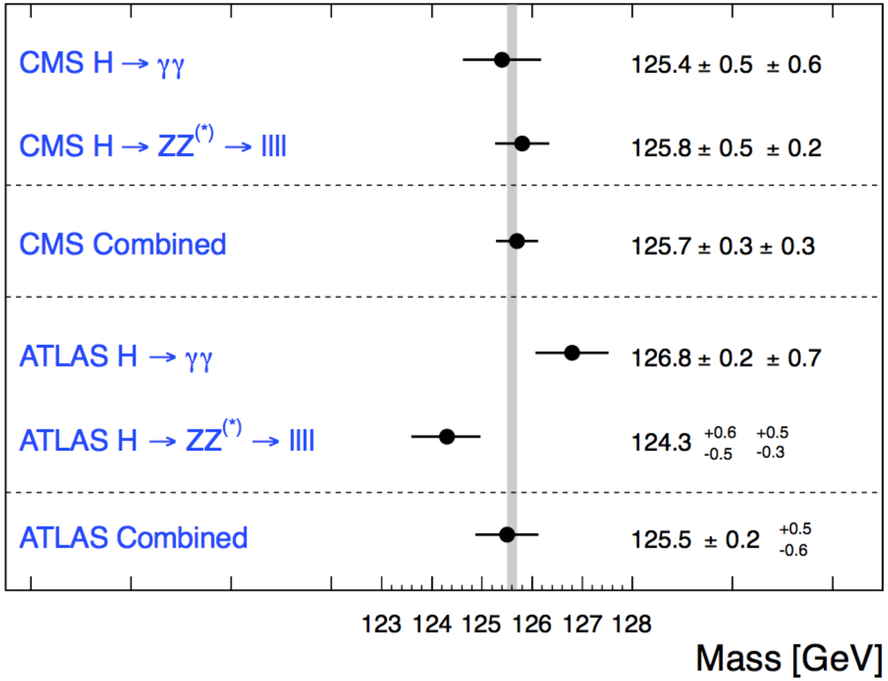
Observed significance 7.4σ (expected 4.3σ), at m_H = 126.8 GeV

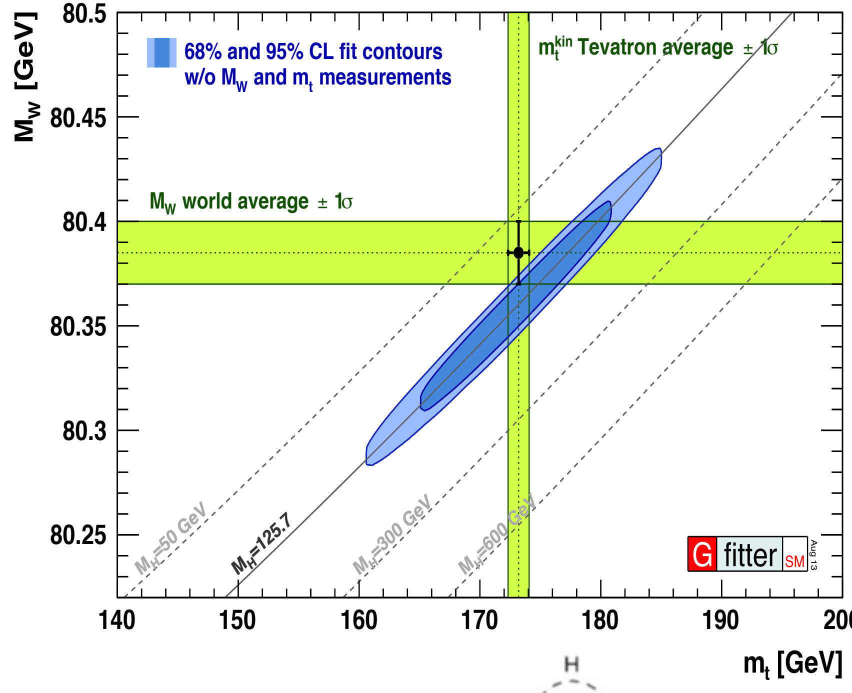
Production times decay rate

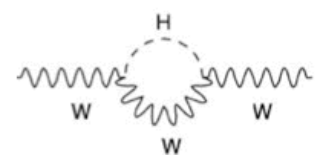


$$\mu = \frac{\sigma \cdot BR}{(\sigma \cdot BR)_{SM}}$$

Mass measurement







H → γγ and H → 4ℓ mass measurements and combinations

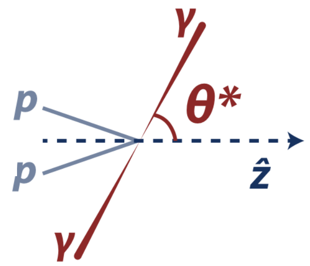
- Good agreement among the two experiments and with Standard Model fit
- *ATLAS:* compatibility of the two measurements is at the 1.5% (2.4σ level)
- Final results will require final Run 1 calibrations

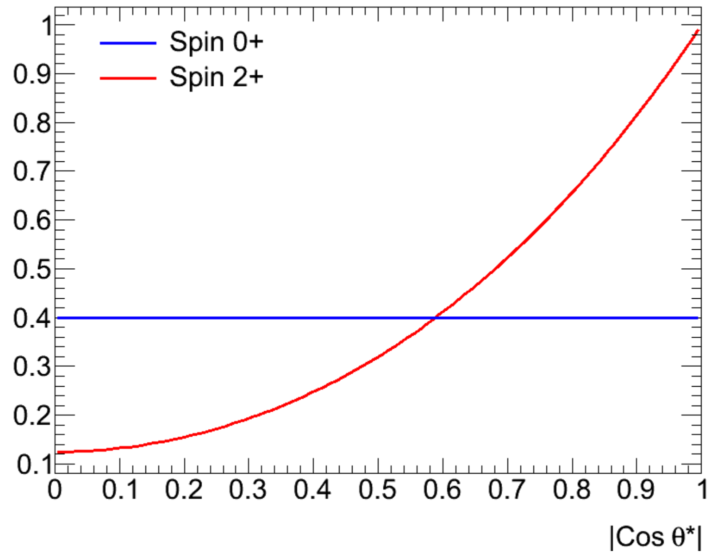
Spin

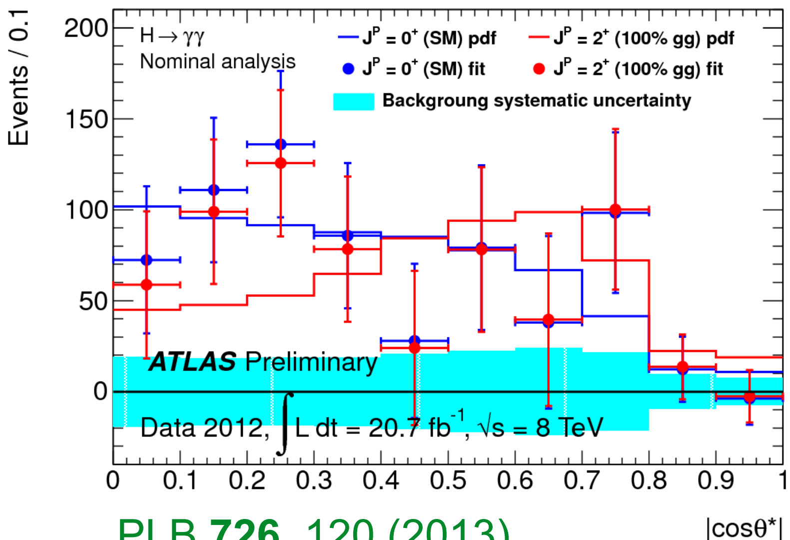
Due to angular momentum conservations spin 1 particles do not decay to two photons, main interest is to test the SM 0^+ hypothesis against spin 2^+

Main handle: production and decay angles of Higgs decay-particles

- $H \rightarrow \gamma\gamma$: photon production angle θ^* in di-photon rest frame







PLB **726**, 120 (2013)

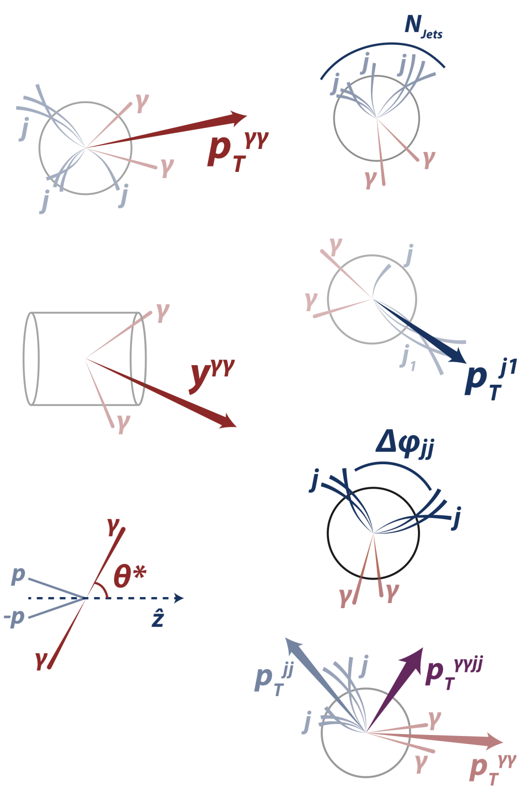
Data compatible with 0^+, exclude the 2^+ model at 95% CL

Differential cross sections

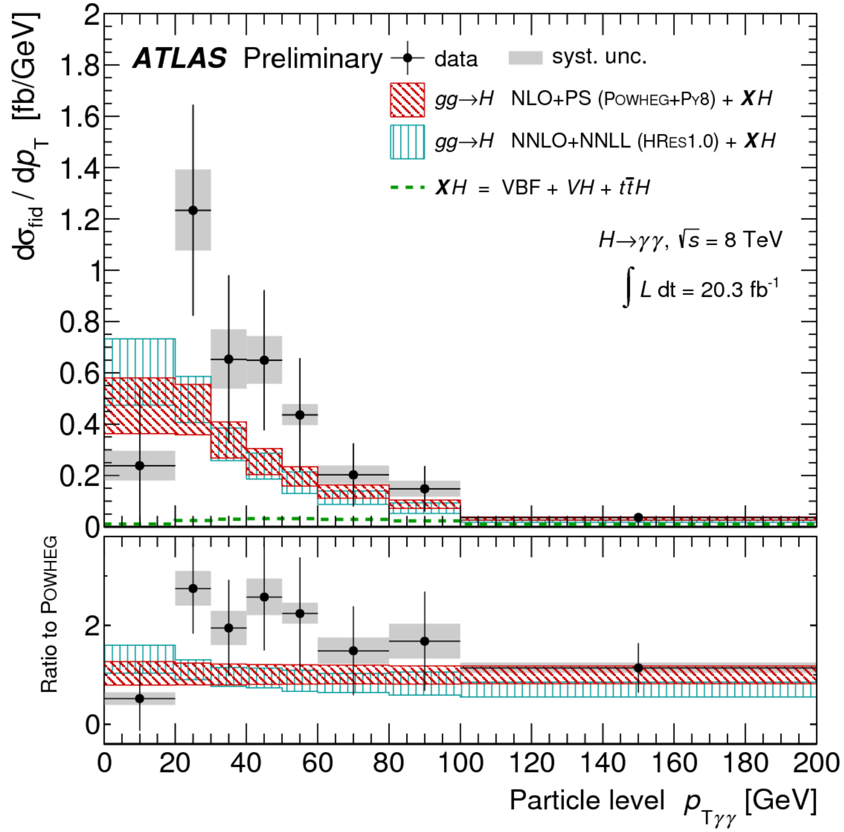
Probe underlying kinematic properties of Higgs boson production and decay

Variables specifically sensitive to:

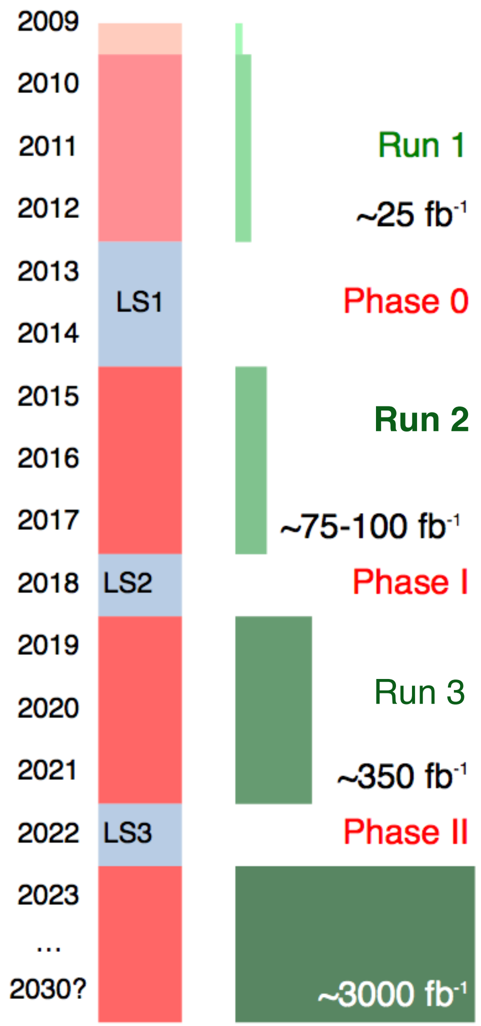
- Different production modes
- Spin-parity
- Higher-order corrections



Higgs boson p_T



What’s next?



The main pillars for a precise understanding of electroweak-symmetry breaking:

Precision measurements of the Higgs properties

Vector boson scattering at high energies

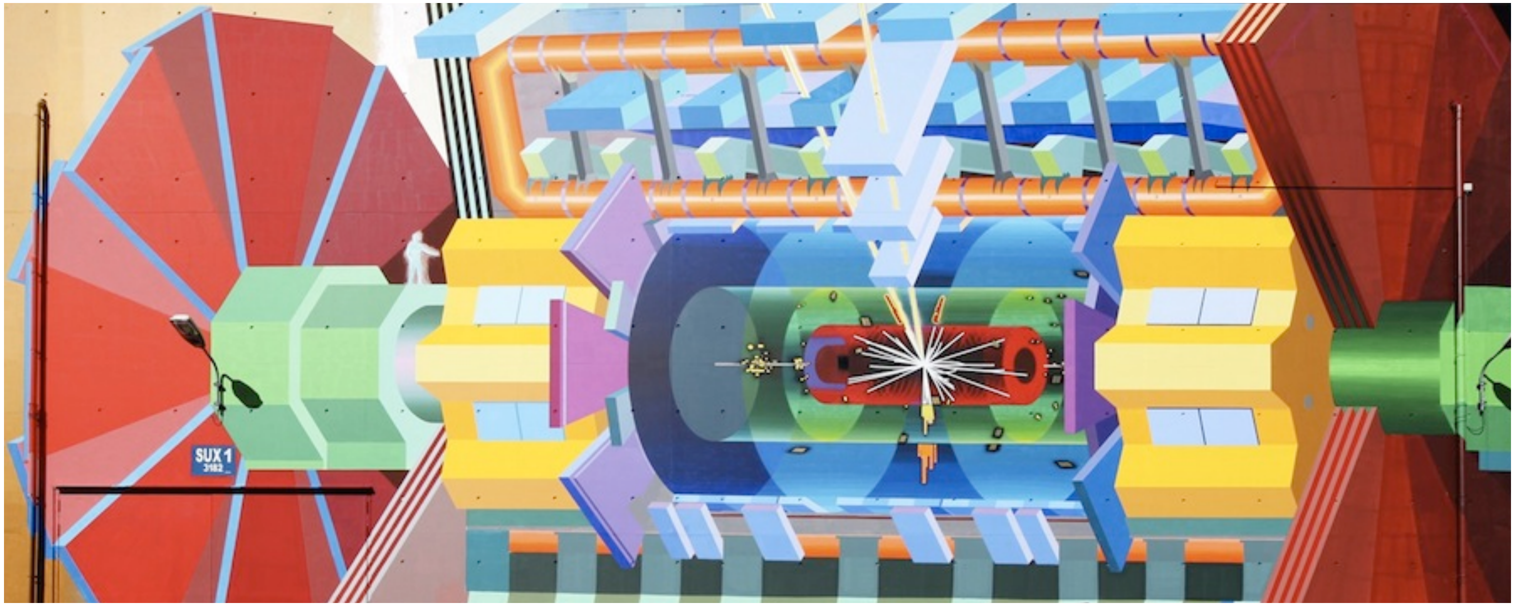
Searches for additional Higgs bosons

With $\sqrt{s}$ = 13 - 14 TeV and a dataset of around 100 fb^{-1}, LHC Run 2 offers the best opportunity to explore these complementary approaches

Conclusions

A comprehensive physics programme is well on track to obtain a precise understanding of electro-weak symmetry breaking

All current measurements in agreement with the Higgs boson as predicted by the Standard Model of particle physics

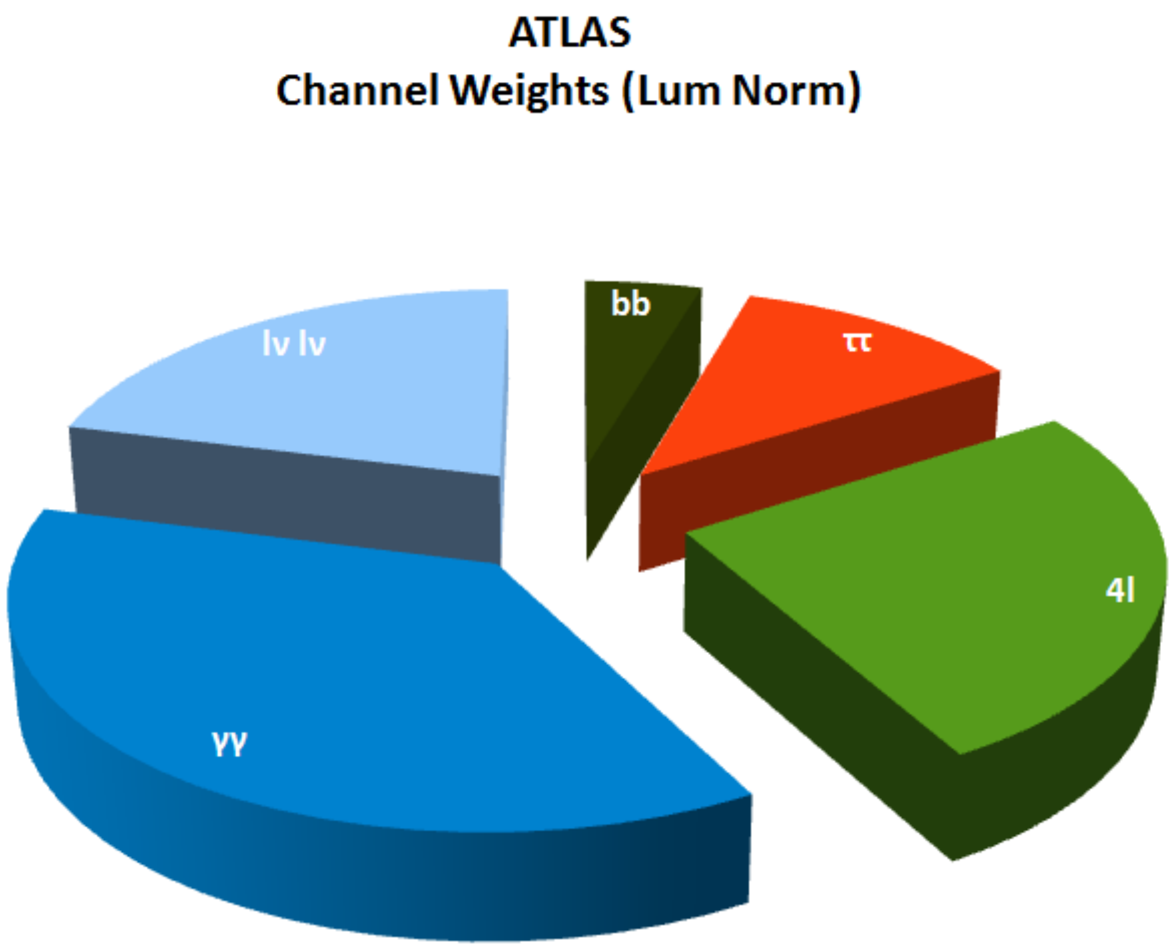


With the LHC Run 2 we are looking forward to a further exciting opportunity to understand some of the most important questions of today's particle physics

Thank you!

Backup slides

Channel weight at 125 GeV

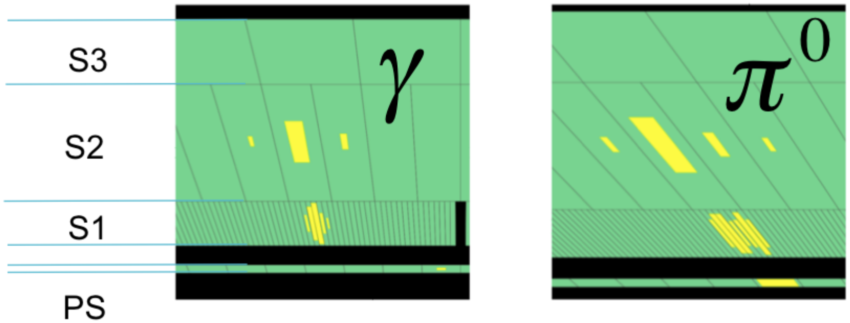


Photon selection

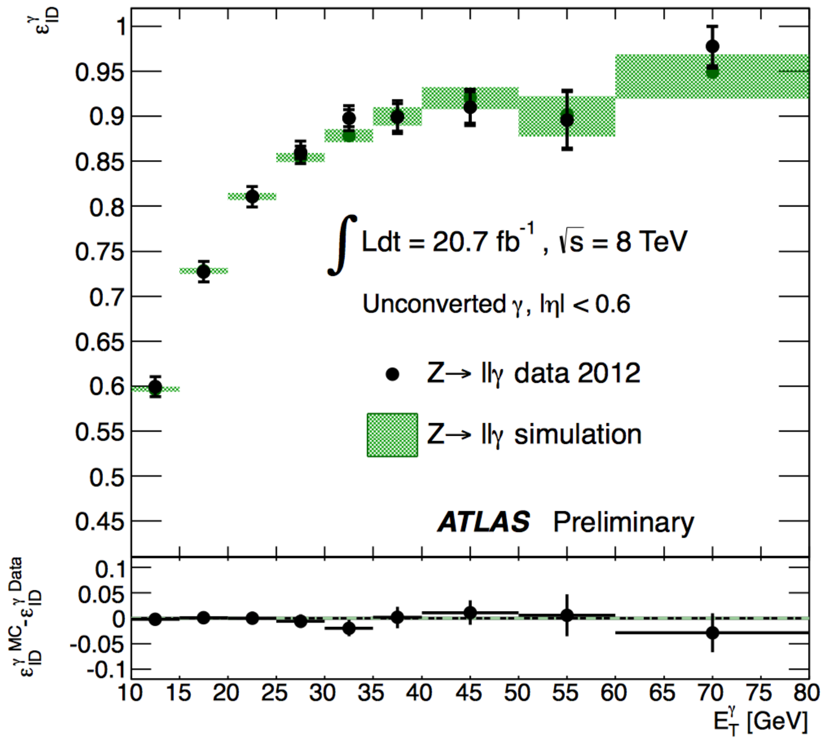
Photon reconstruction and selection based on longitudinal and lateral shower profile

- Shower shape variables
- Calorimeter based isolation
- Fine granularity of first layer

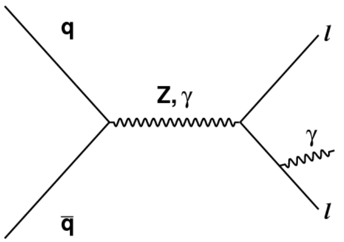
π^0-γ Rejection



Photon selection efficiency



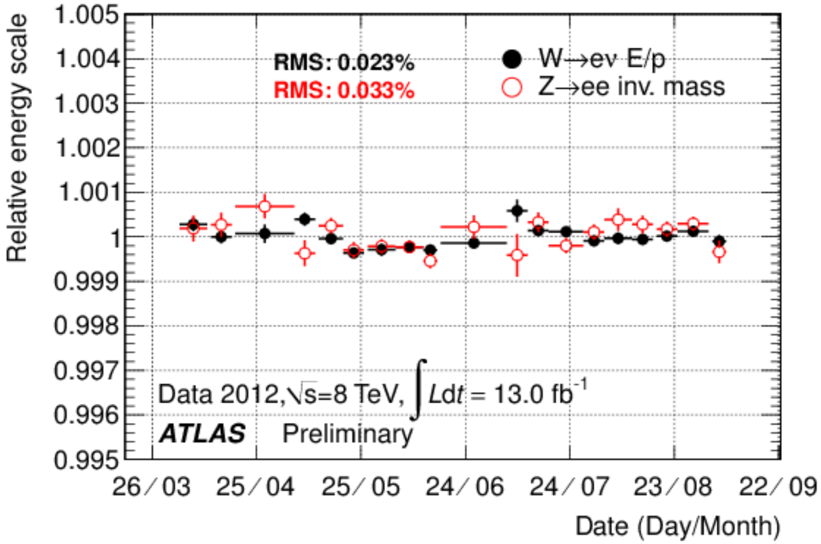
Photon selection efficiency cross-checked with several data based methods

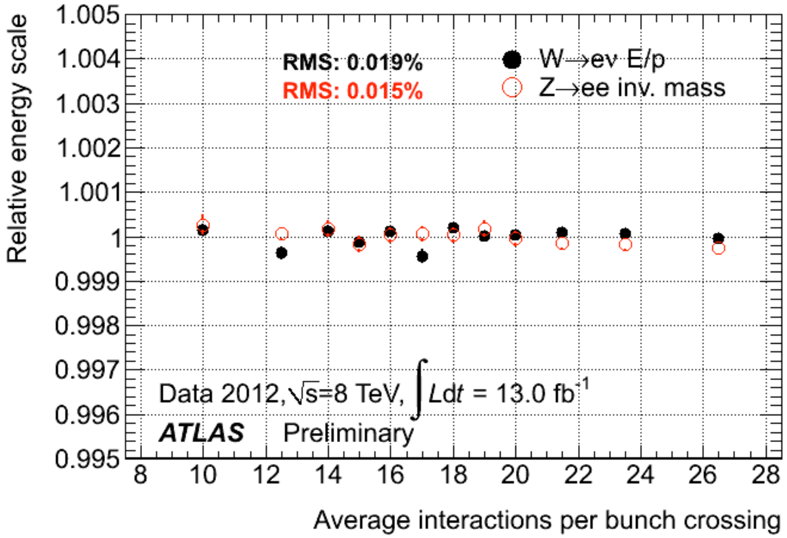


Calibration checks

In-situ energy calibration results and their stability checked with different methods (E/p with $W \to e\nu$, $J/\psi \to ee$)

Stability of EM calorimeter response vs time/pile-up better than 0.1%



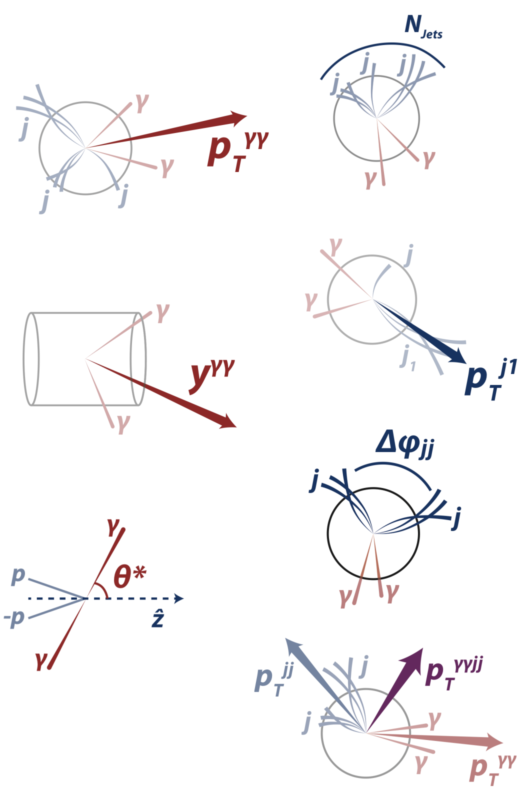


Differential cross sections

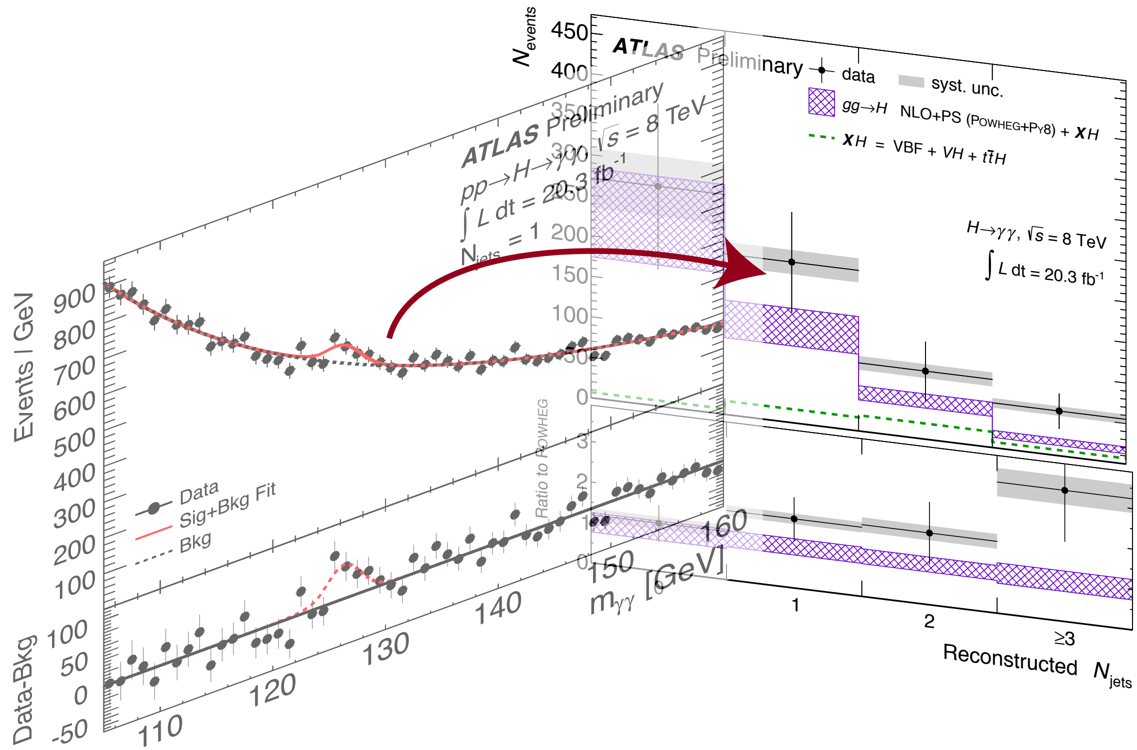
Probe underlying kinematic properties of Higgs boson production and decay

Variables specifically sensitive to:

- Different production modes
- Spin-parity
- Higher-order corrections



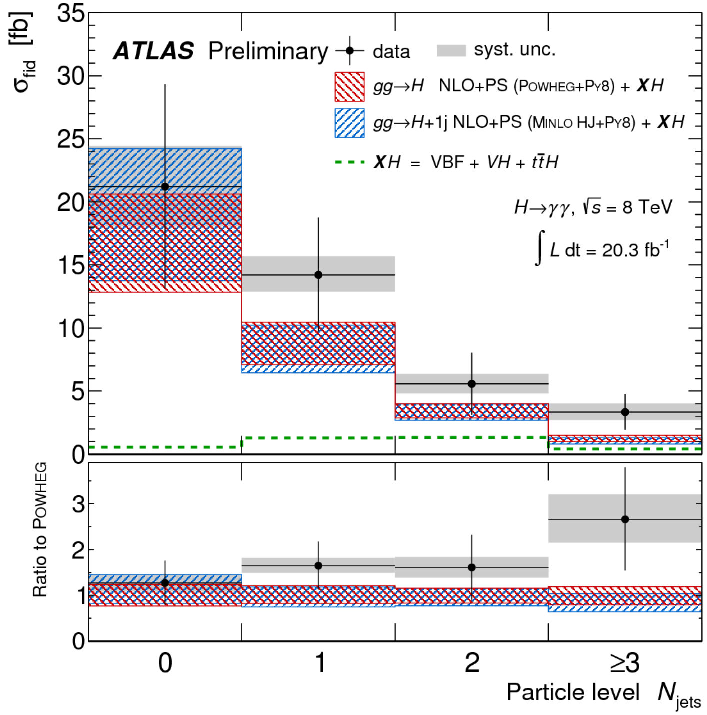
Example for number of jets



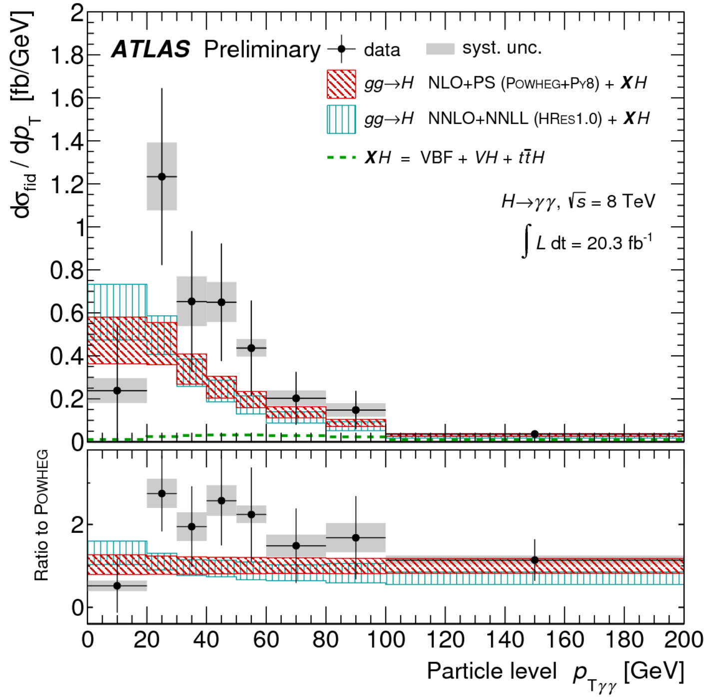
Final step: correct raw yields for detector effects

Differential cross sections

Number of jets



Higgs boson p_T



First Higgs boson differential cross section measurement

Still large uncertainties, but compatible with SM prediction

Differential measurements will highly benefit from the increased dataset expected in LHC Run 2

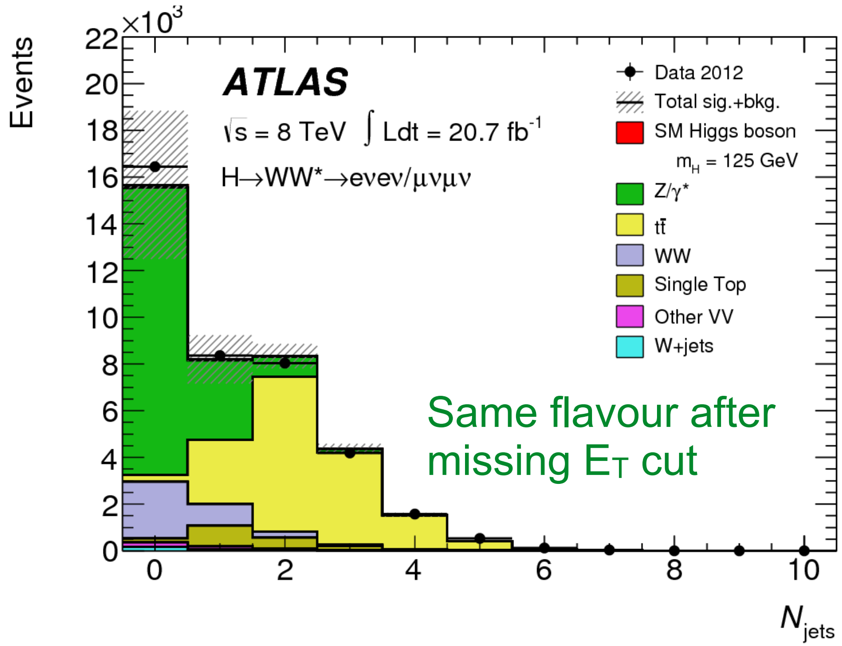
H to WW analysis strategy

Two high pT isolated leptons, split by jet-multiplicity and lepton flavour

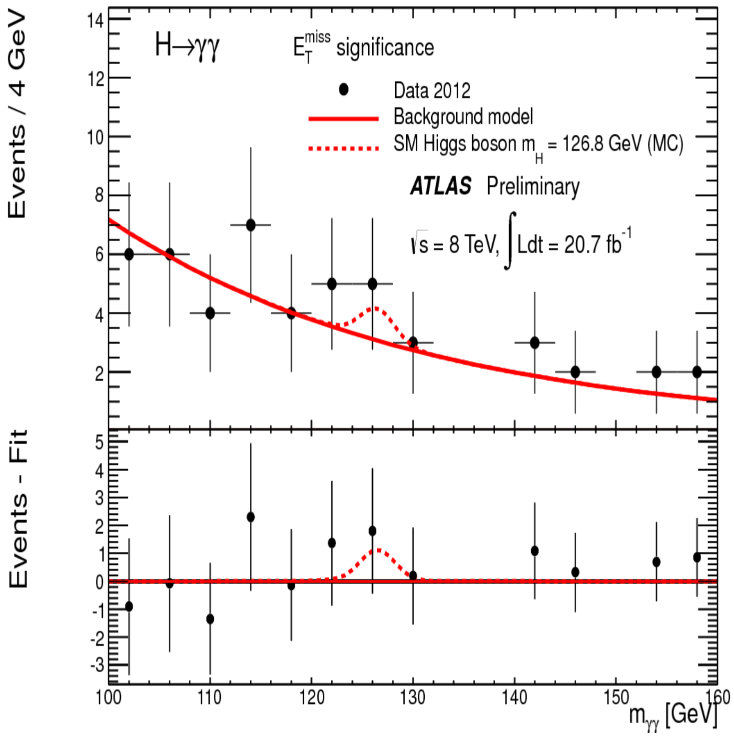
Various missing ET related cuts to remove main DY contribution

Topological cuts for further bkgr. reduction (low mll, small Δϕ) / VBF selection

Final discrimination from m_T shape

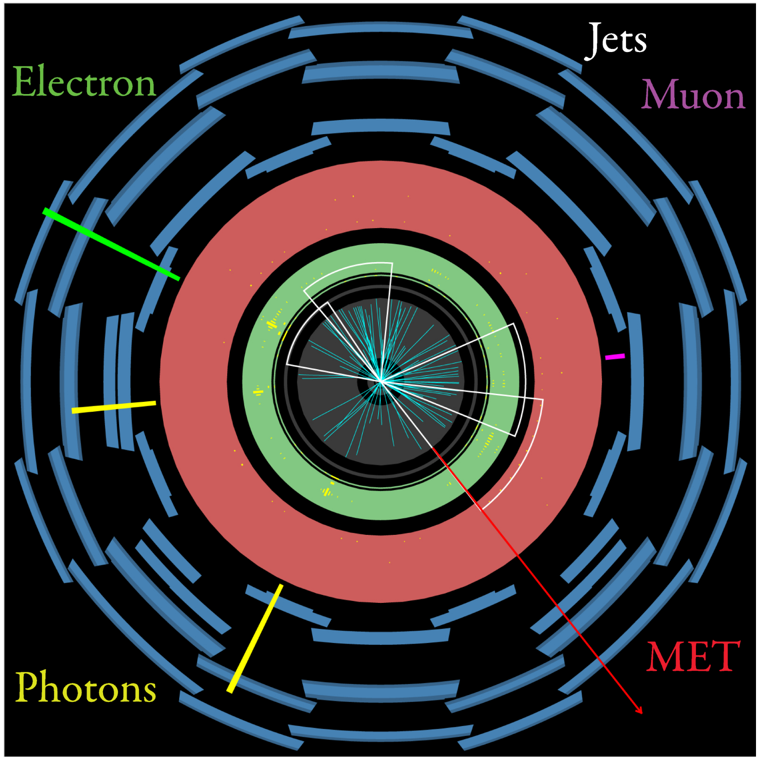


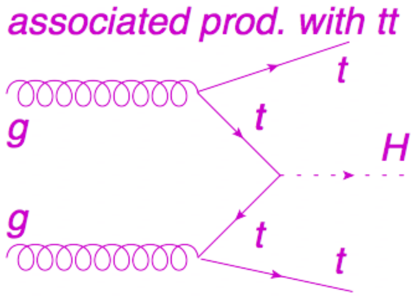
Same flavour after missing E_T cut



Test exclusive production modes

E.g. $H \rightarrow \gamma\gamma$: sensitivity to all four production modes through dedicated VBF, VH and ttH selections





Semi-leptonic tt decay:

4 jets, lepton + missing E_T

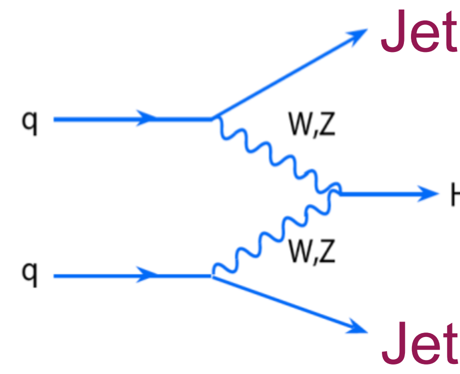
~90% ttH signal purity

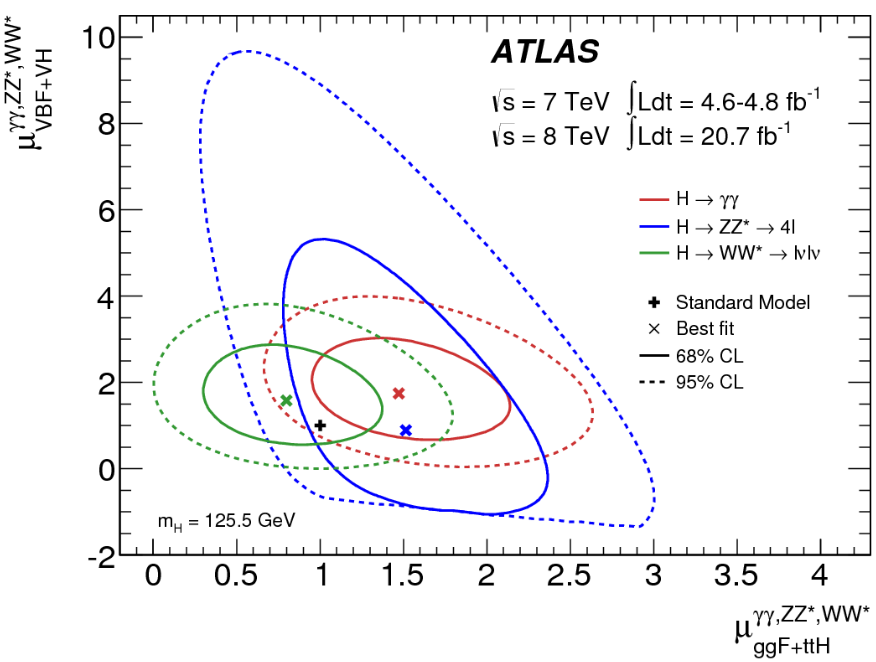
Similarly, sensitivity to WH and ZH production by tagging events with isolated leptons or large missing E_T arising from vector boson decays

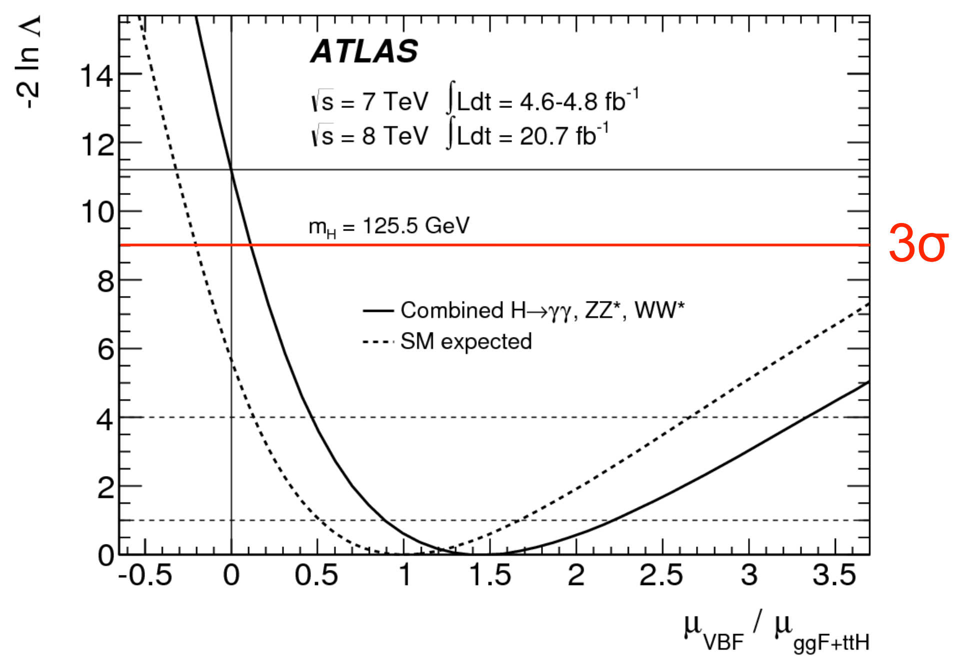
Evidence for VBF production

Separate events consistent with VBF signature

- Two high pT jets from the Higgs production vertex
- Separated in rapidity (high dijet mass)



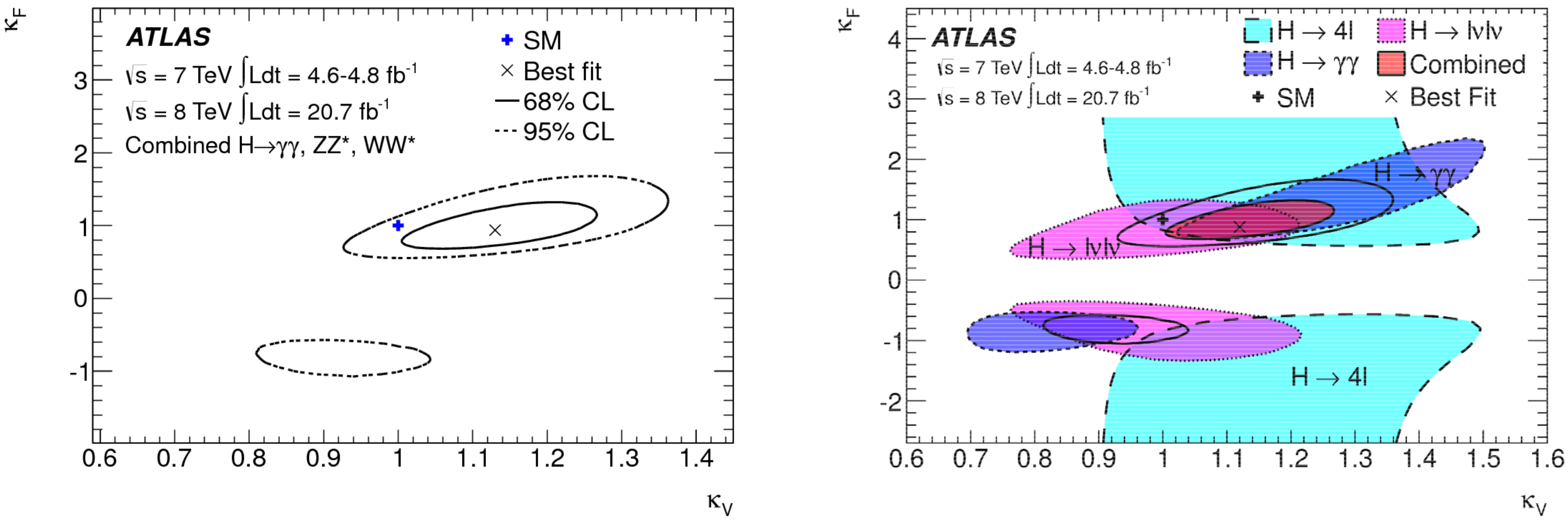




3.1σ evidence for VBF production

Higgs couplings

Characterise production cross sections and branching ratios in terms of a few common LO motivated multiplicative factors (κ^2) to the SM Higgs couplings

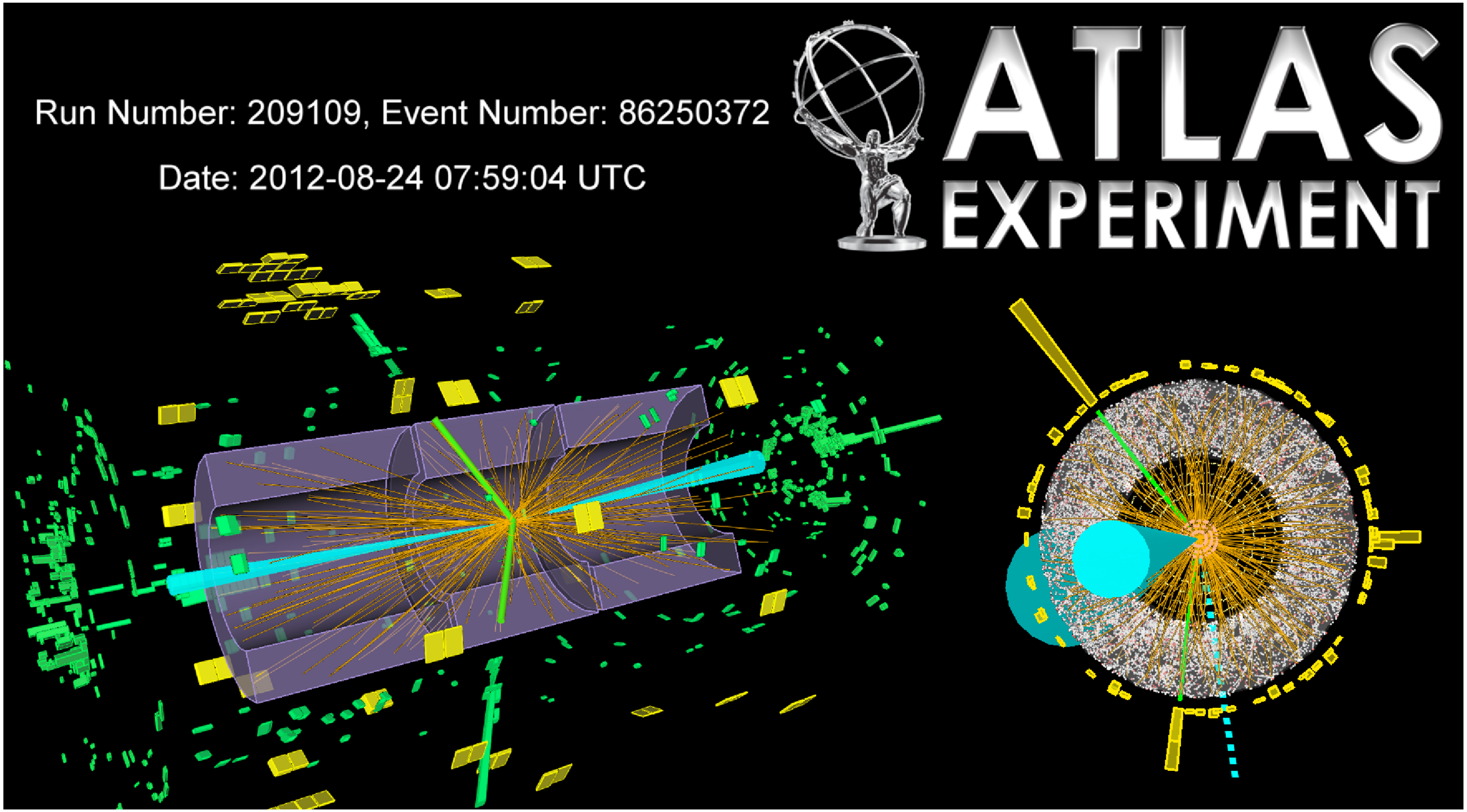


2-parameter benchmark model, group fermion (κ_F) and vector couplings (κ_V) together

- One overall not observable sign, choose $\kappa_V > 0$. Some sensitivity to κ_F sign from interference between top and W in $H \rightarrow \gamma\gamma$

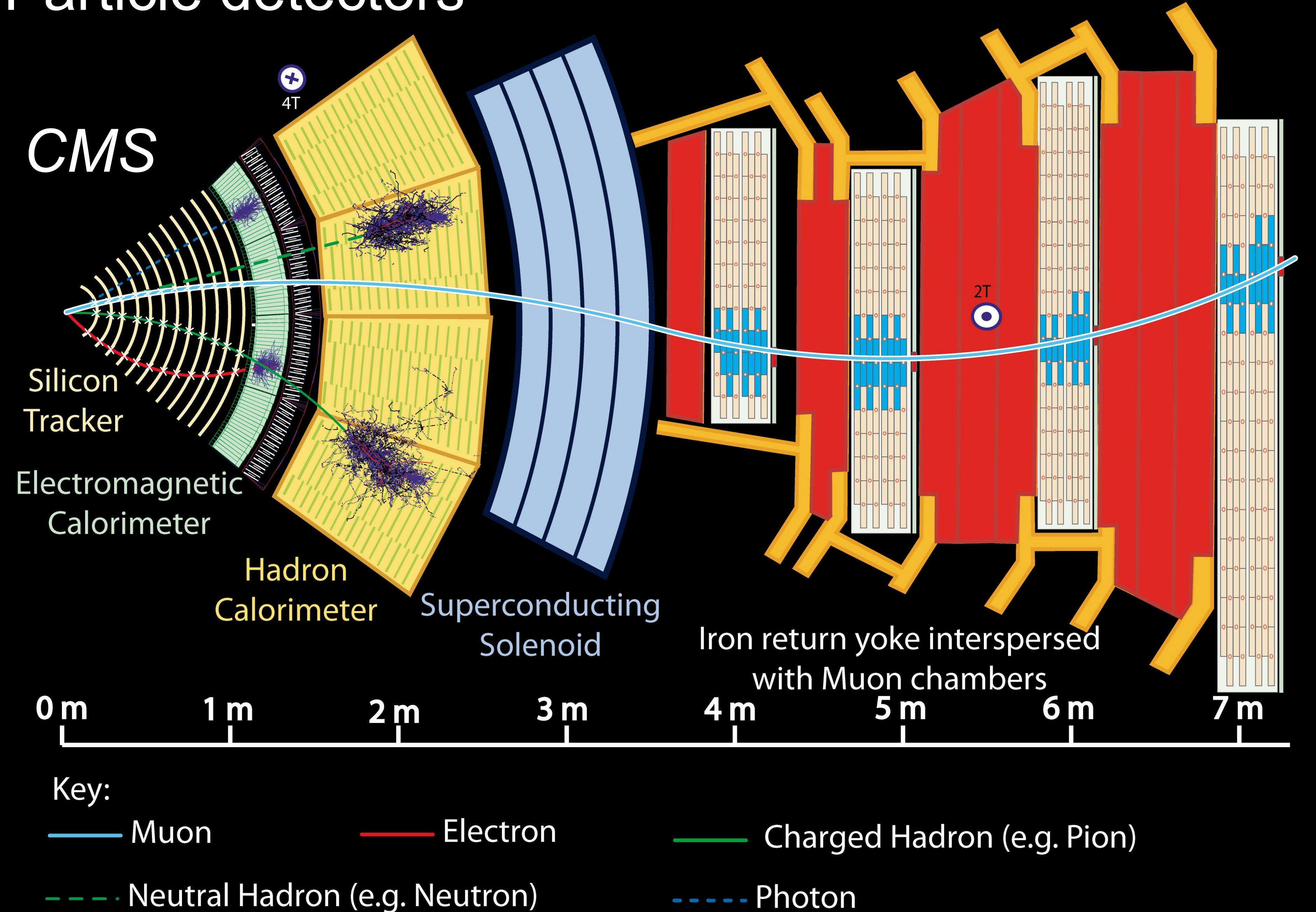
Several further benchmark tests, all without significant deviations from the SM

H → ττ



Production modes	Exp. signal yield	S/B
VBF, ggF, VH	~350	~0.3 – 30%

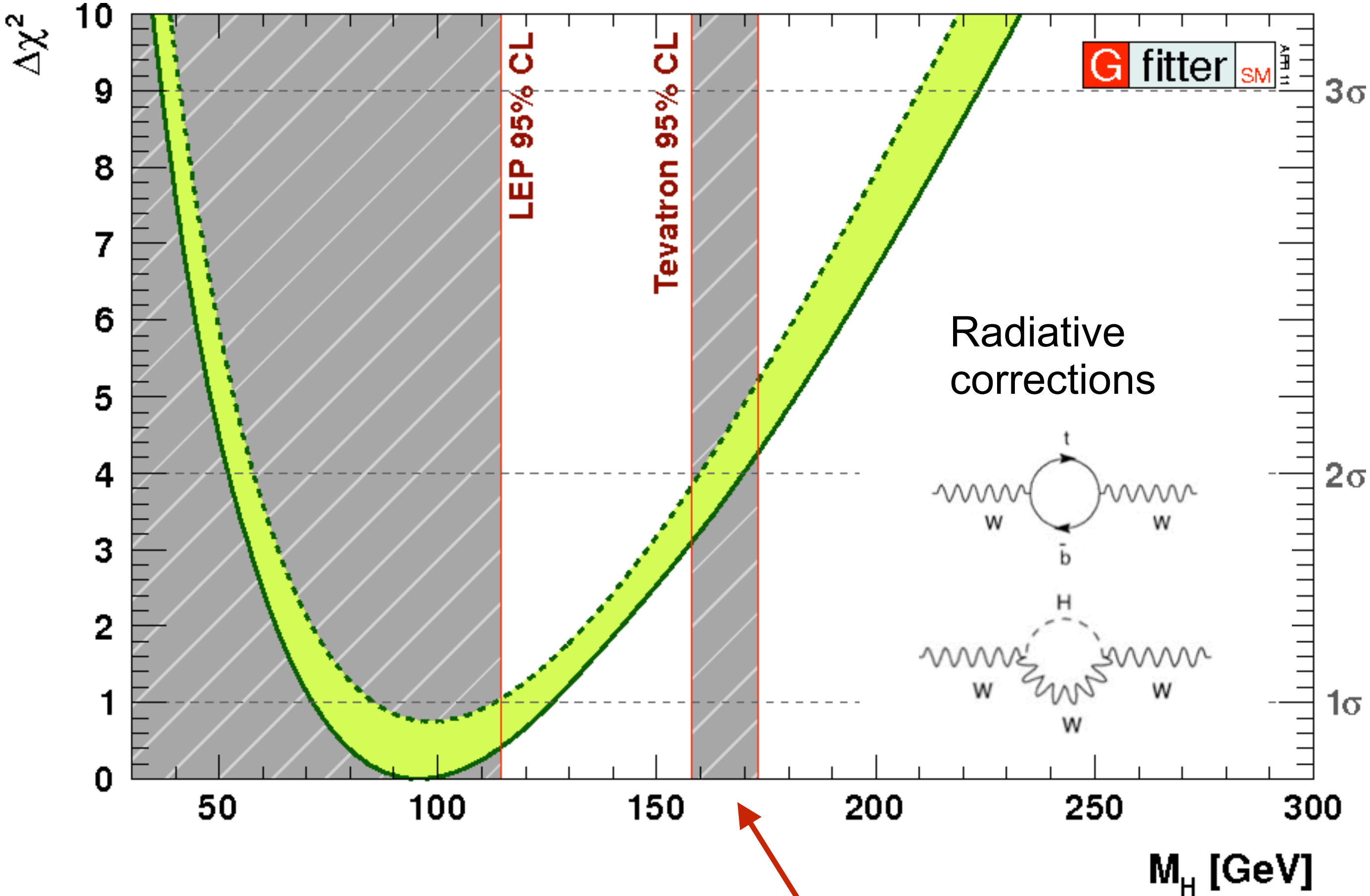
Particle detectors



BCS theory of superconductivity:	*Higgs mechanism:*
$T < T_c$	$T < T_{EW}$
Cooper pair (condensate)	Higgs boson (field)
Mass of the photon	Mass of the W/Z bosons
Electric charge (2e)	Weak charge

The entire Universe is a superconductor for the weak interactions

Stalking the Higgs

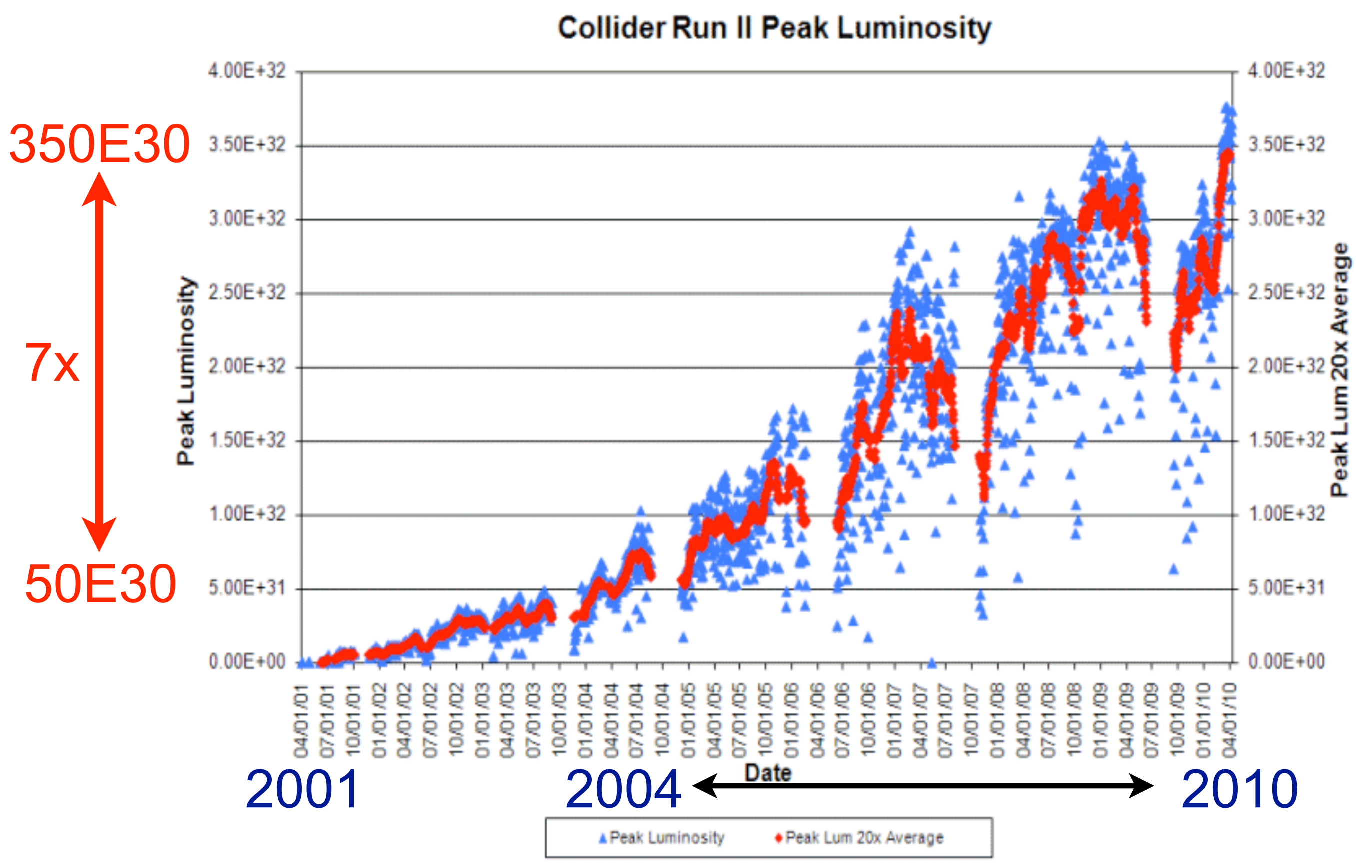


First direct exclusion since LEP!

Indirect constraints on the Higgs boson mass from global EW fits:

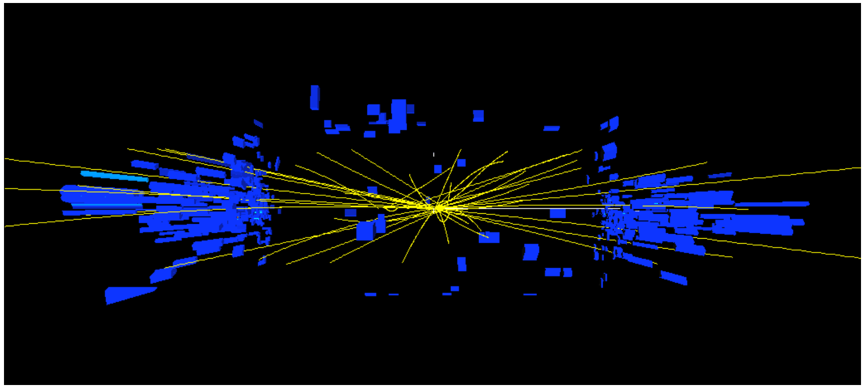
m_H < 152 GeV @95%CL

Tevatron performance

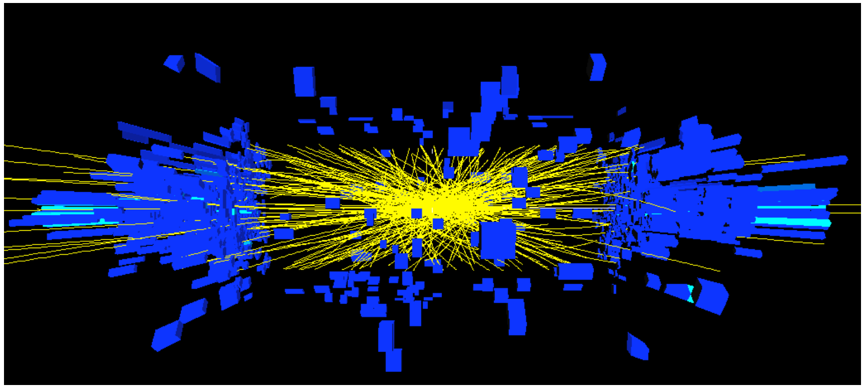


Tevatron Run II

Event @ 60E30 $cm^{-2}s^{-1}$



... and @ 240E30 $cm^{-2}s^{-1}$



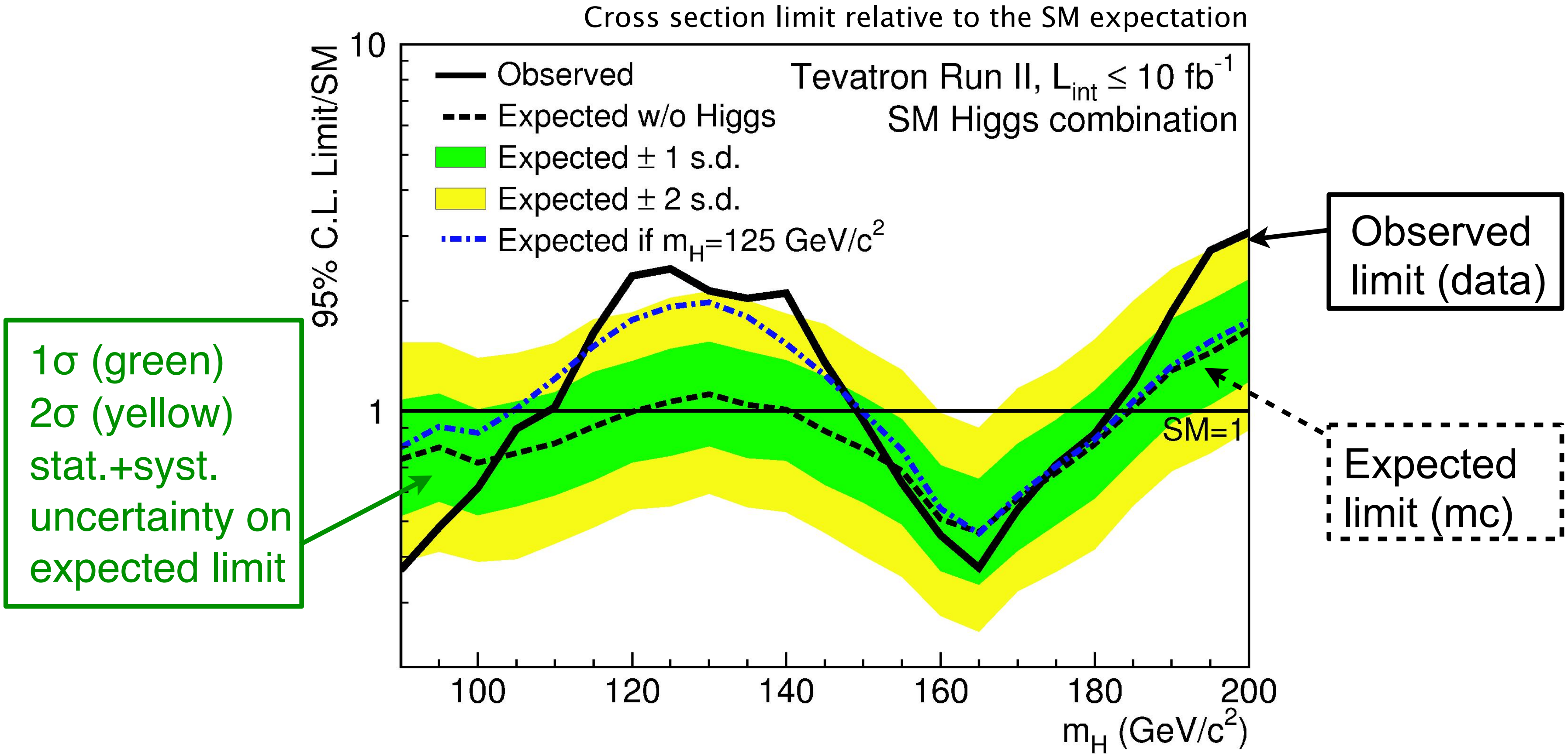
Similar situation at Tevatron Run II

To cope with challenging environment:

New techniques to improve calibration

Improve / redesign algorithms for electron, photon, jet, tau and missing transverse energy reconstruction

Combined Tevatron limits



The production of a SM Higgs boson around the mass range of 165 GeV excluded at the 95% CL. First direct exclusion since LEP in 2009!

3σ evidence for a SM Higgs boson at m_H = 125 GeV