The Higgs Boson Discovery

Michel Lefebvre
University of Victoria
Alan Astbury Memorial Symposium
27-28 April 2015

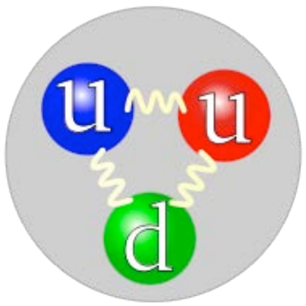
The Higgs boson discovery

- The Brout-Englert-Higgs mechanism
- The search for the Higgs boson
  - LEP, Tevatron, early LHC
- Discovery at the LHC
  - LHC performance
  - ATLAS
- Individual channels
- Combinations
  - properties
- Future Prospects

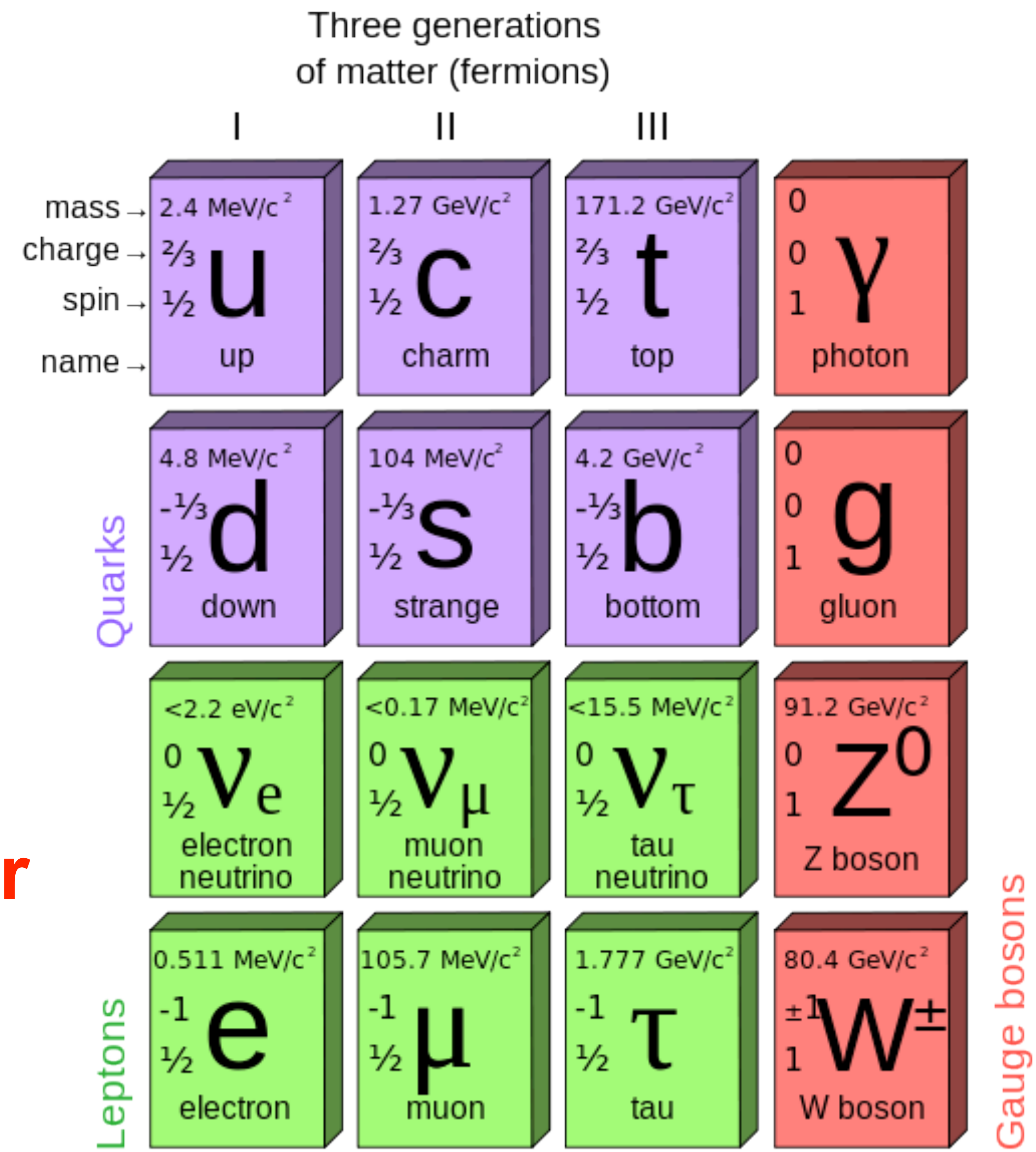
I will focus on ATLAS results, and will include some CMS results

One discovery leads to another...!

Matter and forces



the **proton**: three bound quarks



Matter: spin 1/2 fermions

and Antimatter

Forces: mediated by spin 1 bosons

Gauge invariance

- We wish to generate the EM, weak, and strong forces from a gauge invariance of the type

$$U(1)_Y \times SU(2)_L \times SU(3)_C$$

Standard Model gauge

$$\begin{pmatrix} \nu_e \\ e^- \end{pmatrix} \qquad \begin{pmatrix} \mathbf{u} \\ \mathbf{u} \\ \mathbf{u} \end{pmatrix}$$

- But **ALL masses** violate this assumption!

gauge boson mass terms

$$M Z^\mu Z_\mu$$

fermion mass terms because of $SU(2)_L$

$$m\bar{\psi}\psi = m\left(\bar{\psi}_L\psi_R + \bar{\psi}_R\psi_L\right)$$

We need a gauge invariant mechanism to generate mass

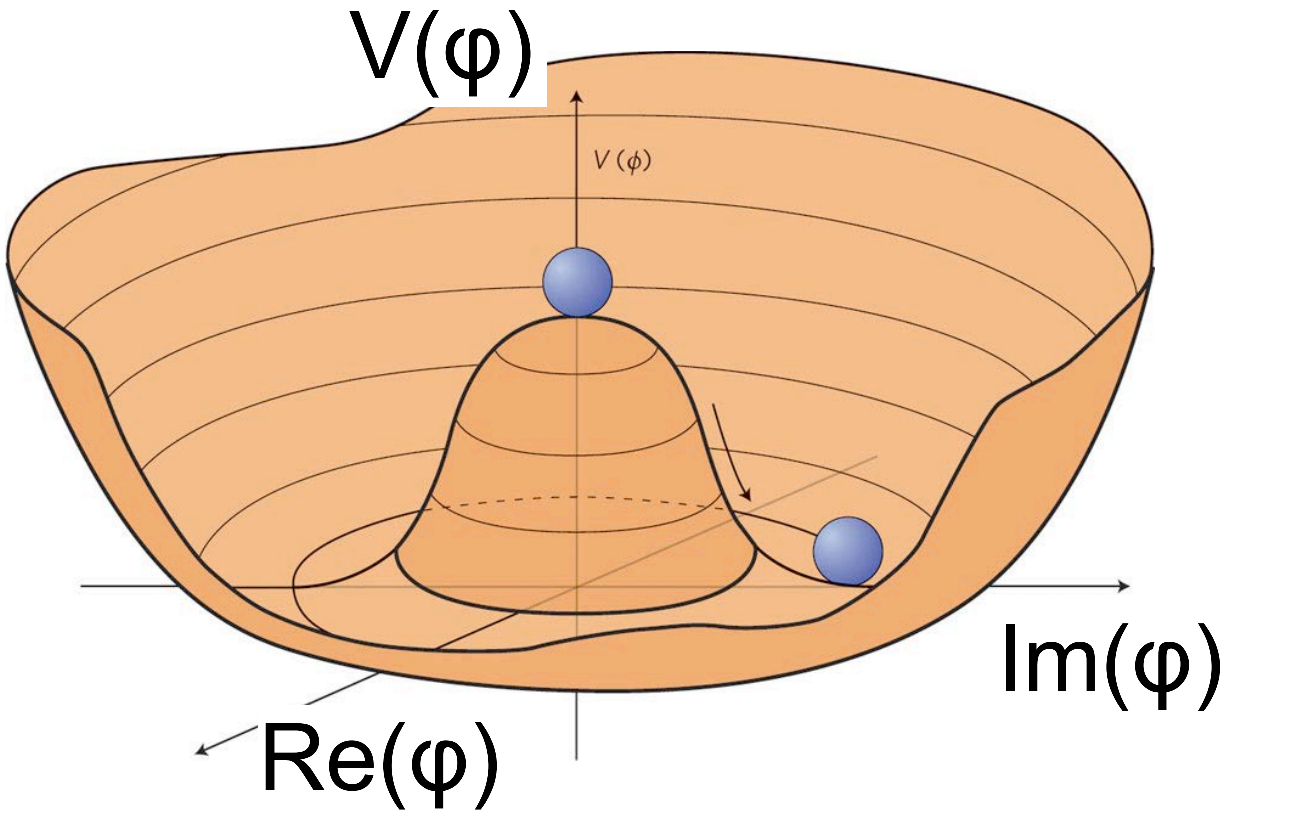
Higgs mechanism!

R. Brout, F. Englert, P. Higgs, G.S. Guralnik, C.R. Hagen, and T.W.B. Kibble

Brout-Englert-Higgs mechanism

- The Higgs mechanism postulates the existence of a Higgs field φ
  - with its potential, and couplings to fermions

$$V(\phi) = -\mu^2 \phi^\dagger \phi + \lambda \left(\phi^\dagger \phi\right)^2 \quad \lambda > 0$$



- The equilibrium state is φ ≠ 0 and not unique!
  - nature makes a choice, partially **hiding the gauge invariance**
  - gauge bosons W^+,W^-, Z **acquire mass**
  - all fermions **acquire mass**
  - **prediction of one neutral scalar Higgs boson particle:** H^0

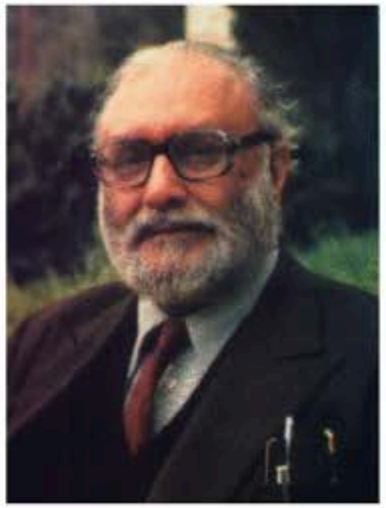
F. Englert and P. Higgs at CERN July 4th 2012

The Standard Model

Gauge invariance
$U(1)_Y \times SU(2)_L \times SU(3)_C$

complex doublet scalar Higgs field

Glashow
1932-



Salam
1926-1996

Weinberg
1933-

Spontaneous symmetry hiding in the electroweak sector

Higgs mechanism: $U(1)_Y \times SU(2)_L \rightarrow U(1)_Q$

Residual (non-hidden) symmetry: $U(1)_Q \times SU(3)_C$

massless photons ($U(1)_Q$)

massless gluons ($SU(3)_C$)

Higgs interactions

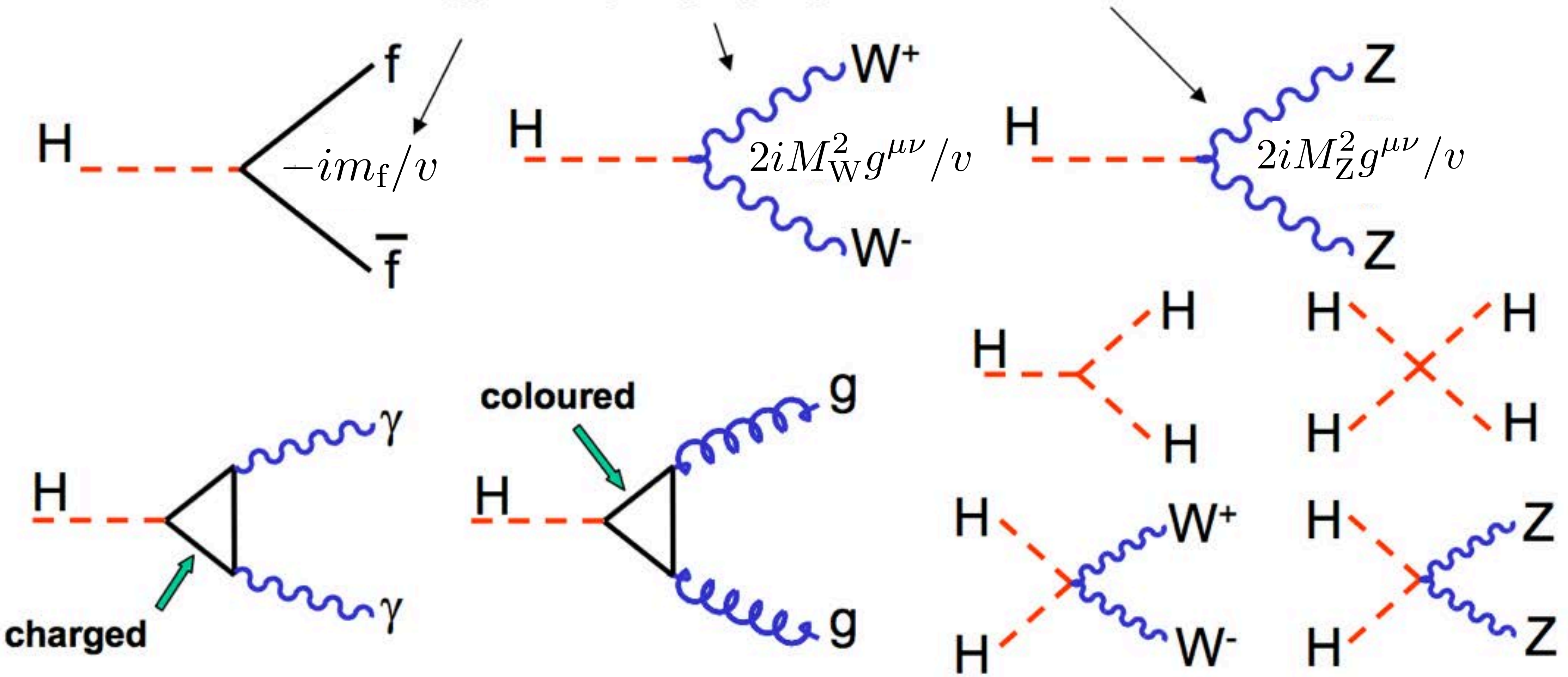
SM → Higgs mechanism with $U(1)_Y \times SU(2)_L$ gauge

φ(*x*) is a complex doublet → W^+, W^-, Z acquire mass
left with one massive Higgs boson

$v = \left(\sqrt{2}G_F\right)^{-1/2} = 246\,\text{GeV}$

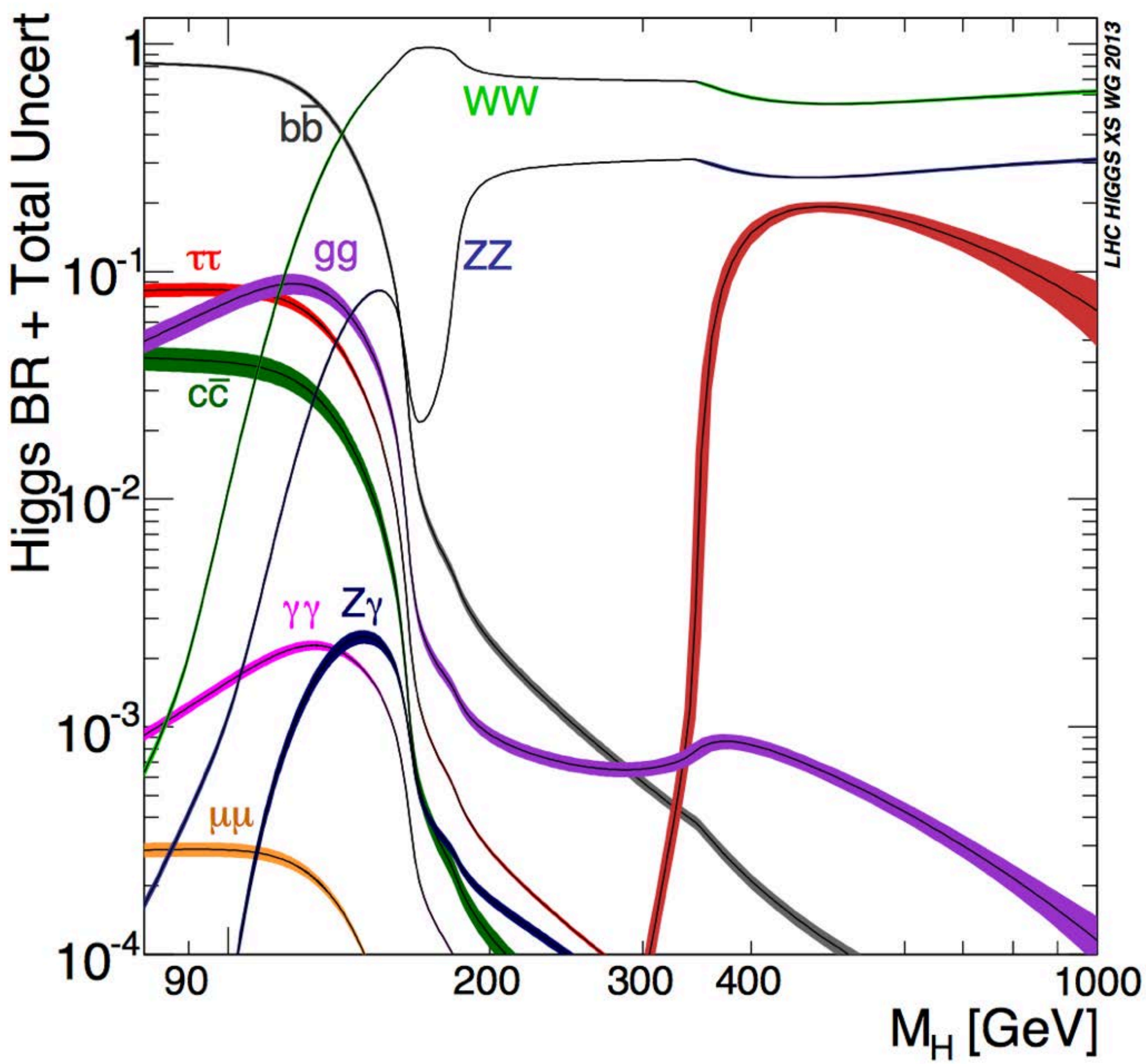
φ(*x*) coupling with massless fermion fields → fermion masses

Higgs couplings proportional to mass $^{(2)}$

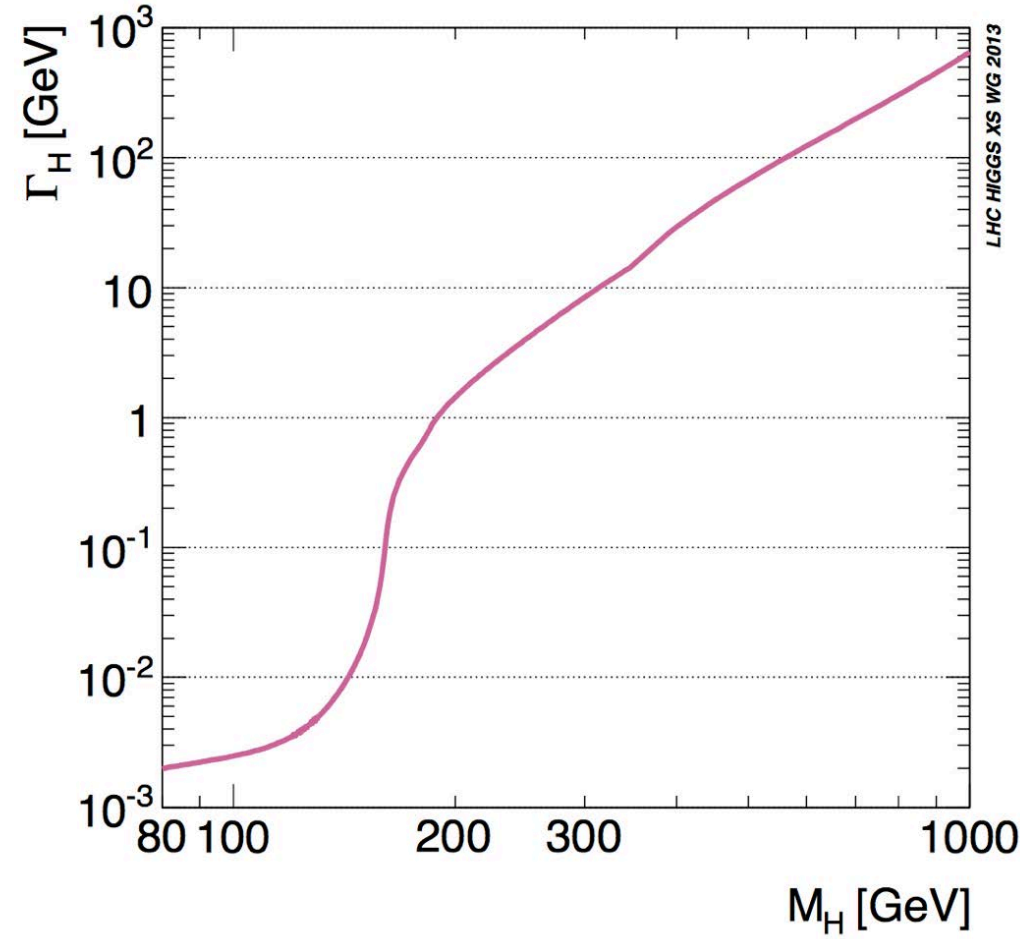


Higgs decays

- Higgs branching ratios prediction



- Higgs width



- 4.1 MeV @ 125 GeV

Higgs boson mass?

A PHENOMENOLOGICAL PROFILE OF THE HIGGS BOSON

John ELLIS, Mary K. GAILLARD * and D.V. NANOPOULOS **
CERN, Geneva

Nucl. Phys. B 106, 292 (1976).

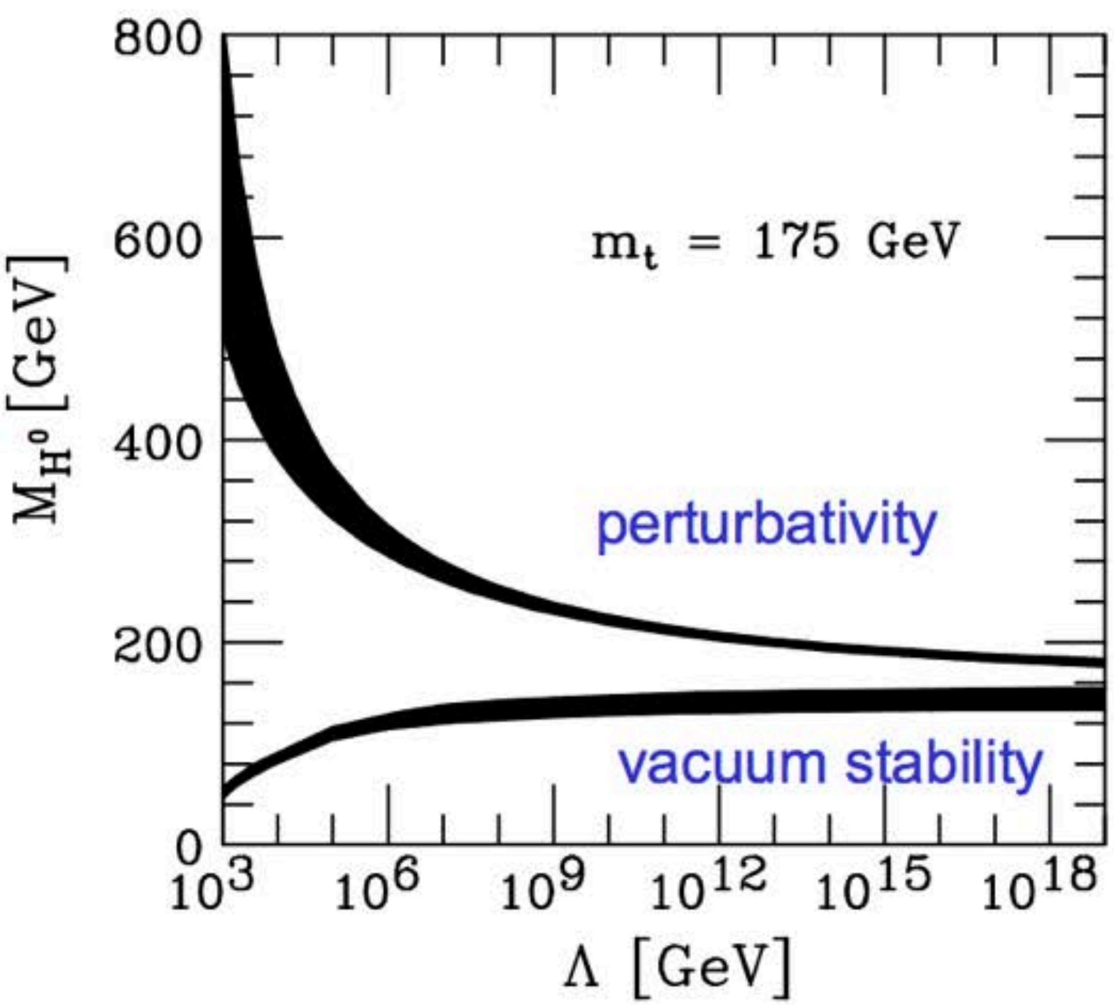
Received 7 November 1975

We should perhaps finish with an apology and a caution. We apologize to experimentalists for having no idea what is the mass of the Higgs boson, unlike the case with charm [3,4] and for not being sure of its couplings to other particles, except that they are probably all very small. For these reasons we do not want to encourage big experimental searches for the Higgs boson, but we do feel that people performing experiments vulnerable to the Higgs boson should know how it may turn up.

Higgs boson mass: input from theory

M_H is a free parameter of SM

but it must lie in a limited region for electroweak symmetry hiding to work

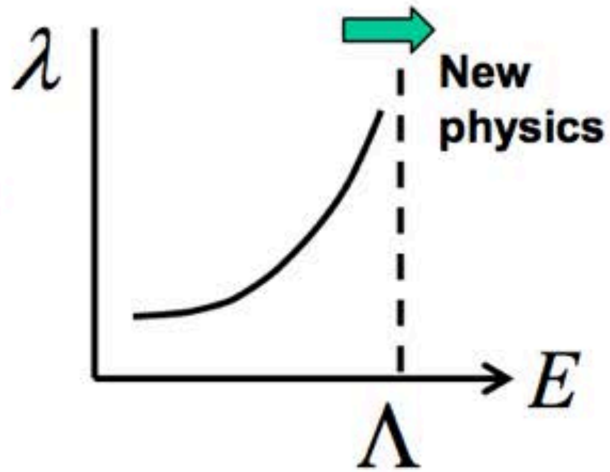


$130\,\text{GeV} \approx< M_H \approx< 180\,\text{GeV}$

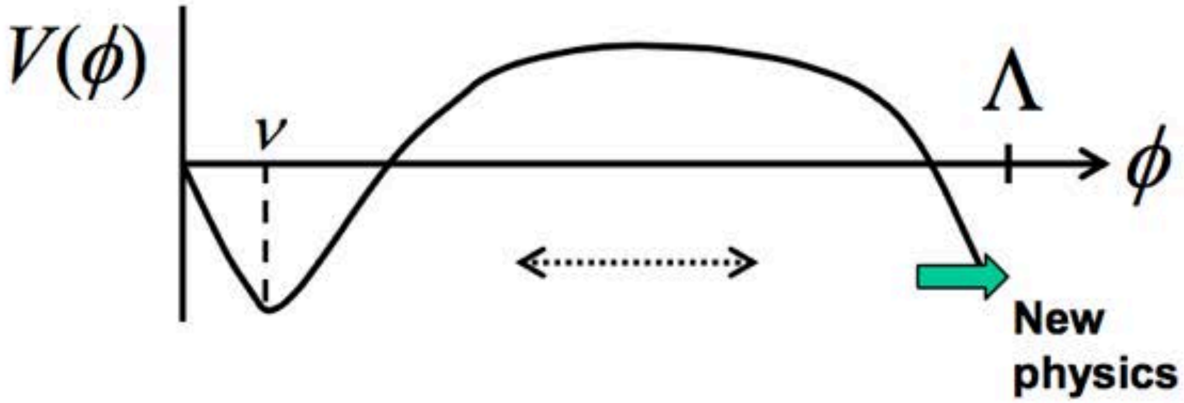
then, in principle consistent with $\Lambda = M_{PL}$

M_H is too large: the higgs self-coupling blows up at some scale Λ

$$m_H^2 = 2\lambda(m_H)v^2$$

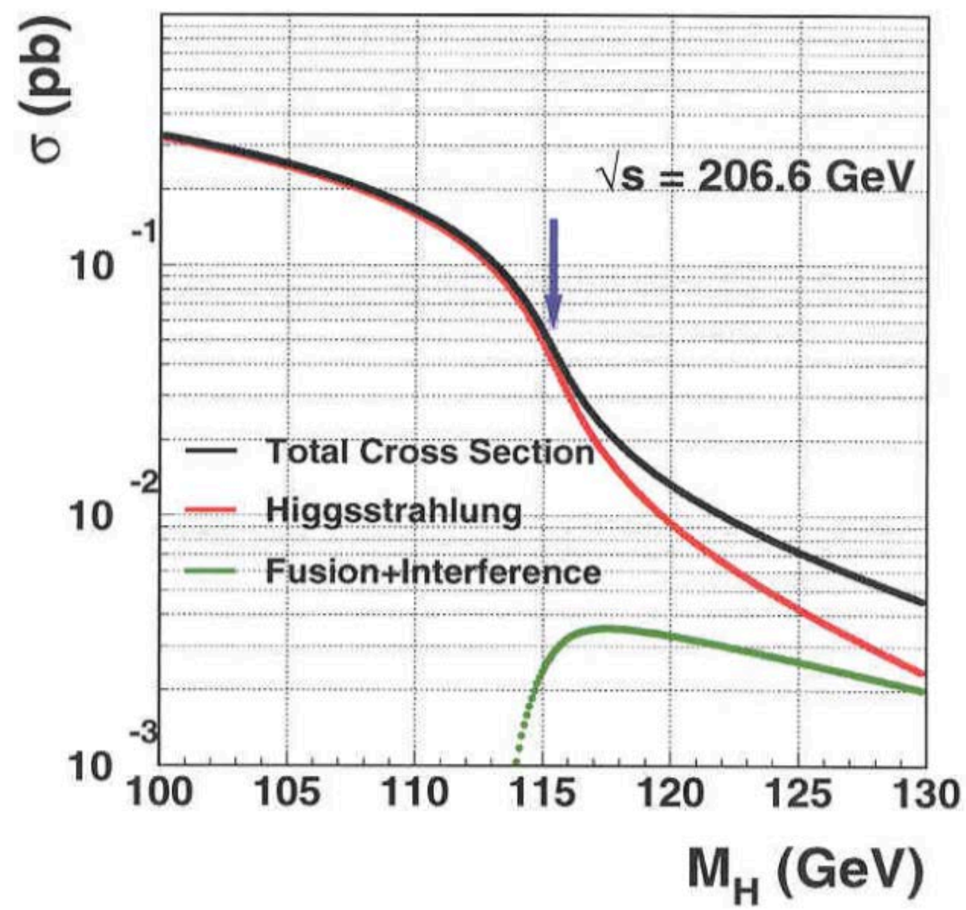


M_H is too small: the higgs potential develops a second (global!) minimum values of the scalar field of the order of Λ

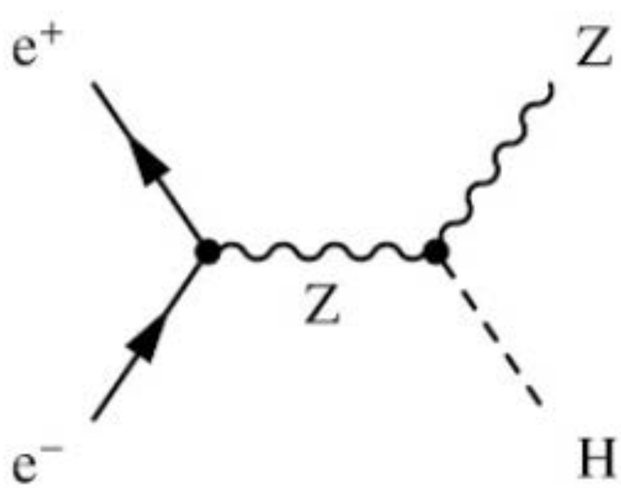


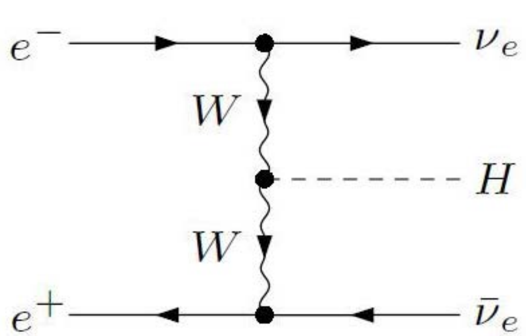
Higgs search at LEP

- The Large Electron-Positron collided electrons-positrons
  - $\sqrt{s}$ ~ 206 GeV in 2000
- Higgs coupling to electron too weak
  - dominant production through Z and Higgsstrahlung
  - search sensitivity up to $\sqrt{s}$ - M_Z ~ 115 GeV

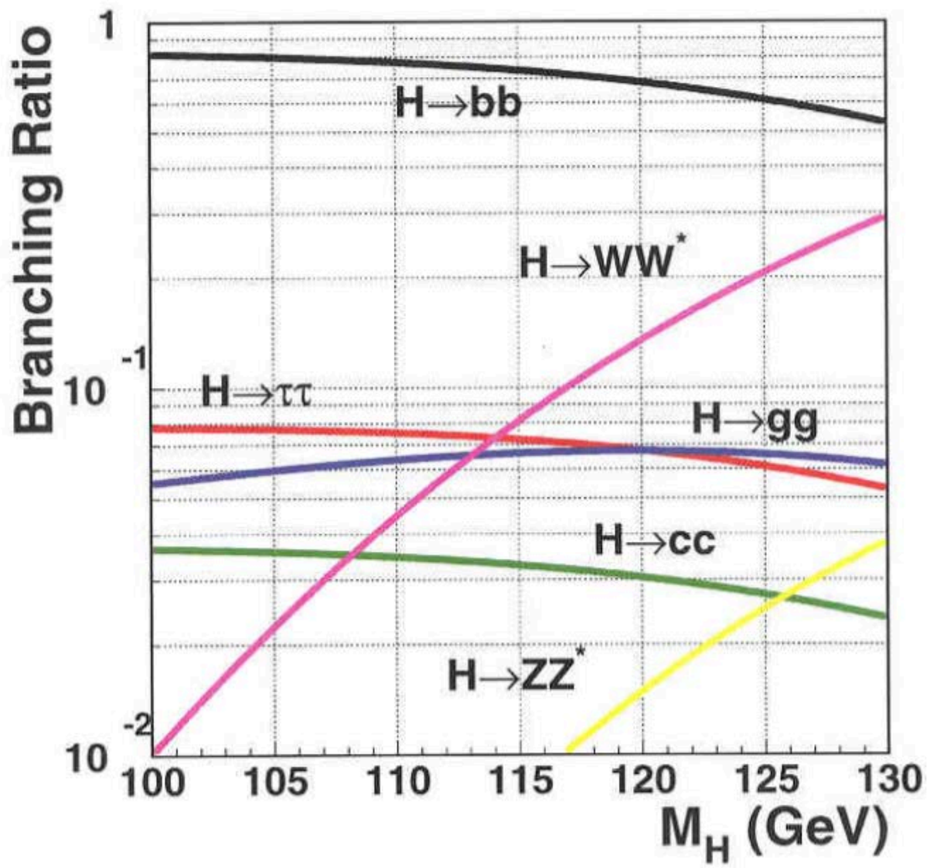


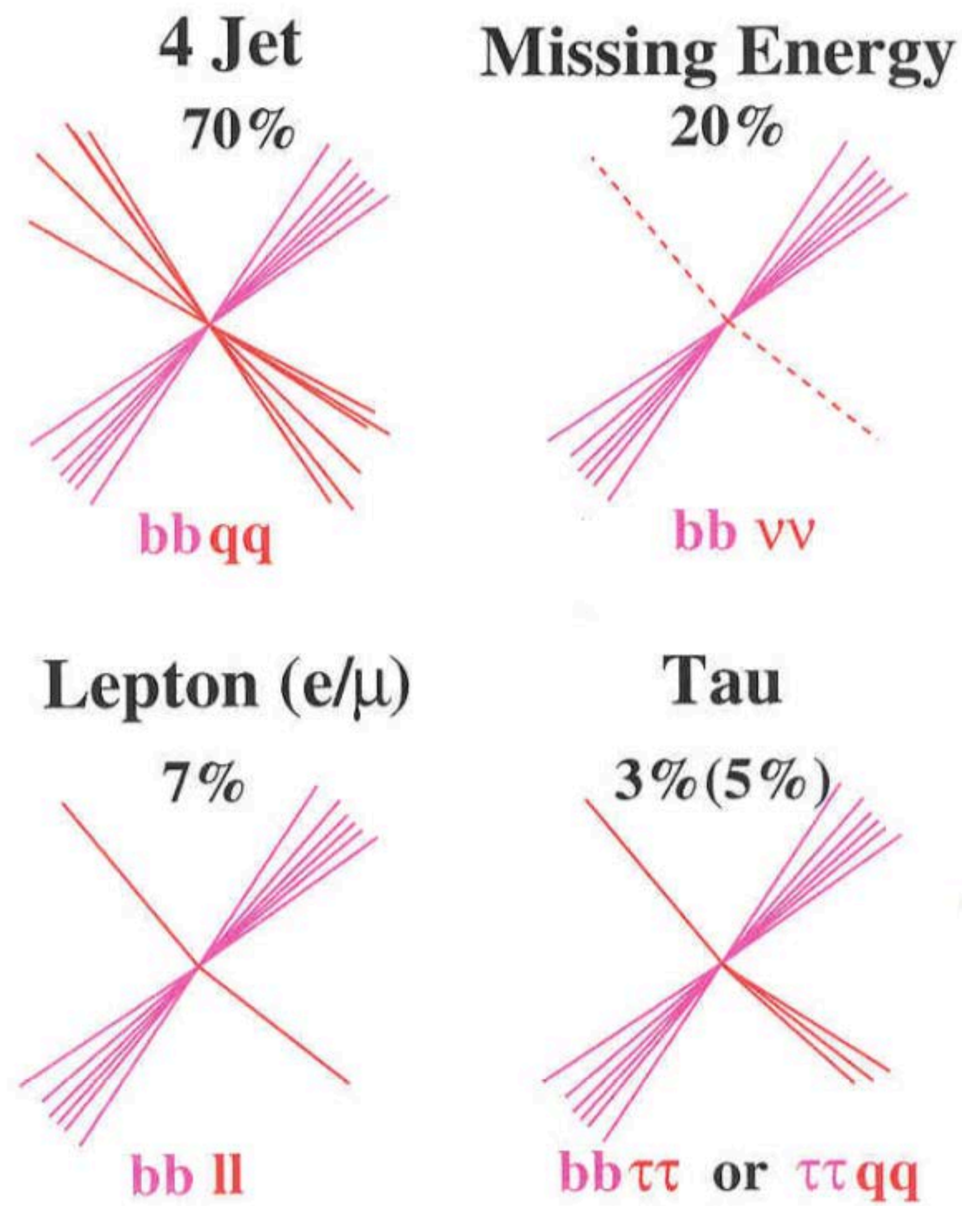
Stage	$\sqrt{s}$	Year	Luminosity
LEP 1	$\approx M_{Z^0}$	1989-1995	175 pb^{-1}
LEP 1.5	130-140 GeV	1995	5 pb^{-1}
LEP 2	161 GeV	1996	10 pb^{-1}
	172 GeV	1996	10 pb^{-1}
	183 GeV	1997	55 pb^{-1}
	189 GeV	1998	180 pb^{-1}
	192–202 GeV	1999	230 pb^{-1}
	200–209! GeV	2000	220 pb^{-1}





Higgs search at LEP

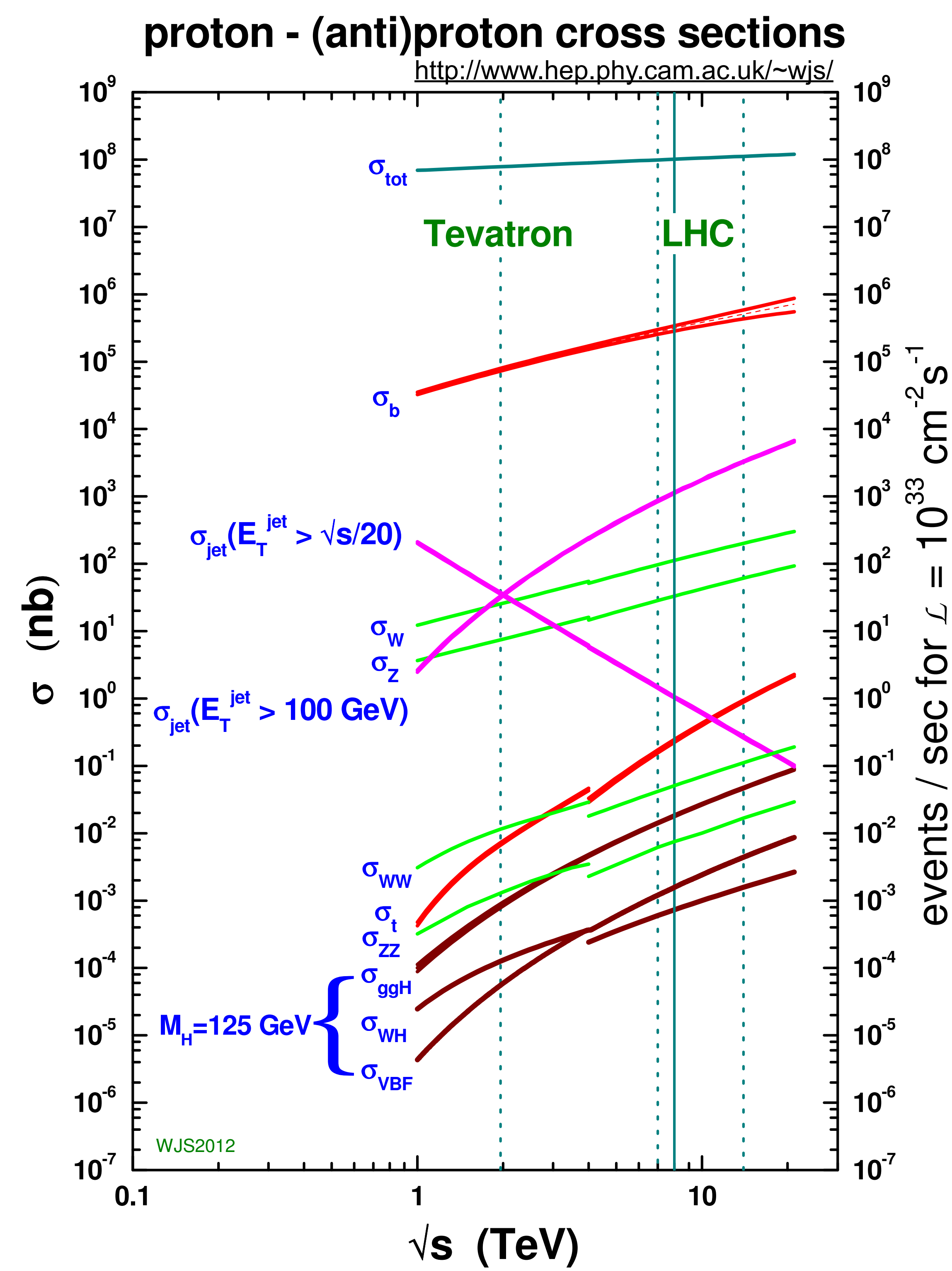




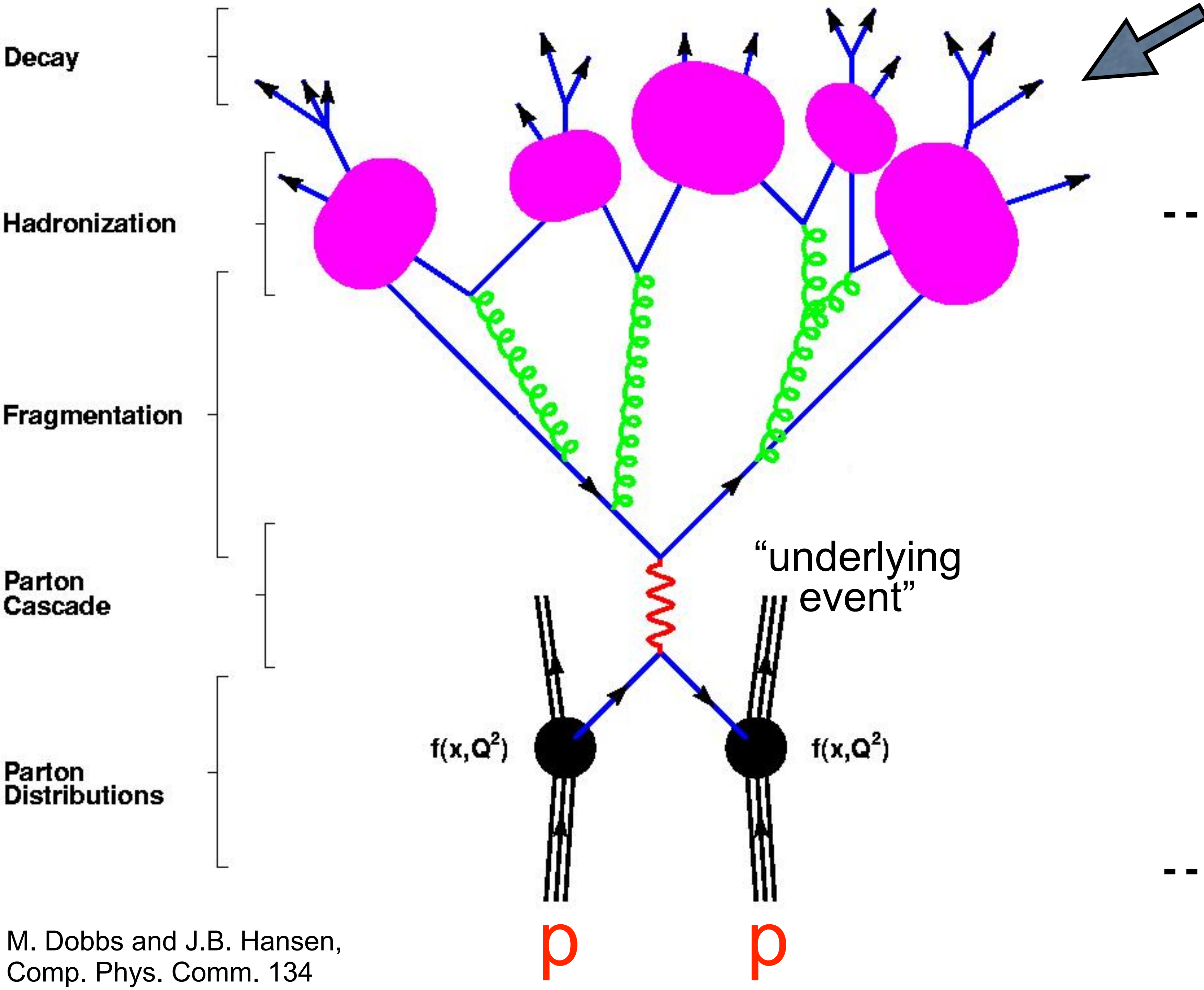
- ALEPH reported a small excess at ~115 GeV
  - not confirmed by DELPHI, L3, OPAL
- M_H > 114.4 GeV at 95% CL

Higgs production at hadron colliders

- Partons carrying only part of the energy
  - CM energy of hard scatter not known a priori event-by-event
  - requires good detector coverage and missing transverse momentum capability
- Hadronic environment
  - far less clean than at LEP
- Higgs production cross section is small!
  - improves with energy
  - but beware of pileup of inelastic events

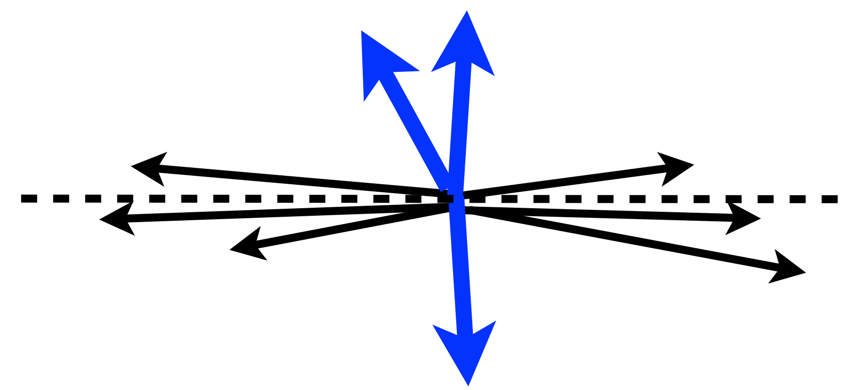


Proton-(anti)proton collisions

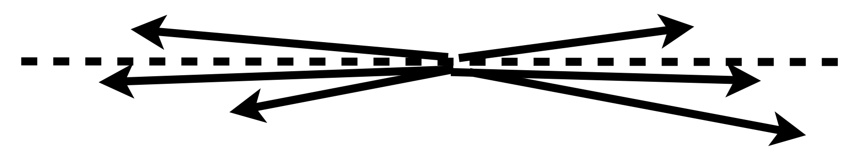


M. Dobbs and J.B. Hansen, Comp. Phys. Comm. 134 (2001) 41-46.

Hard scatter

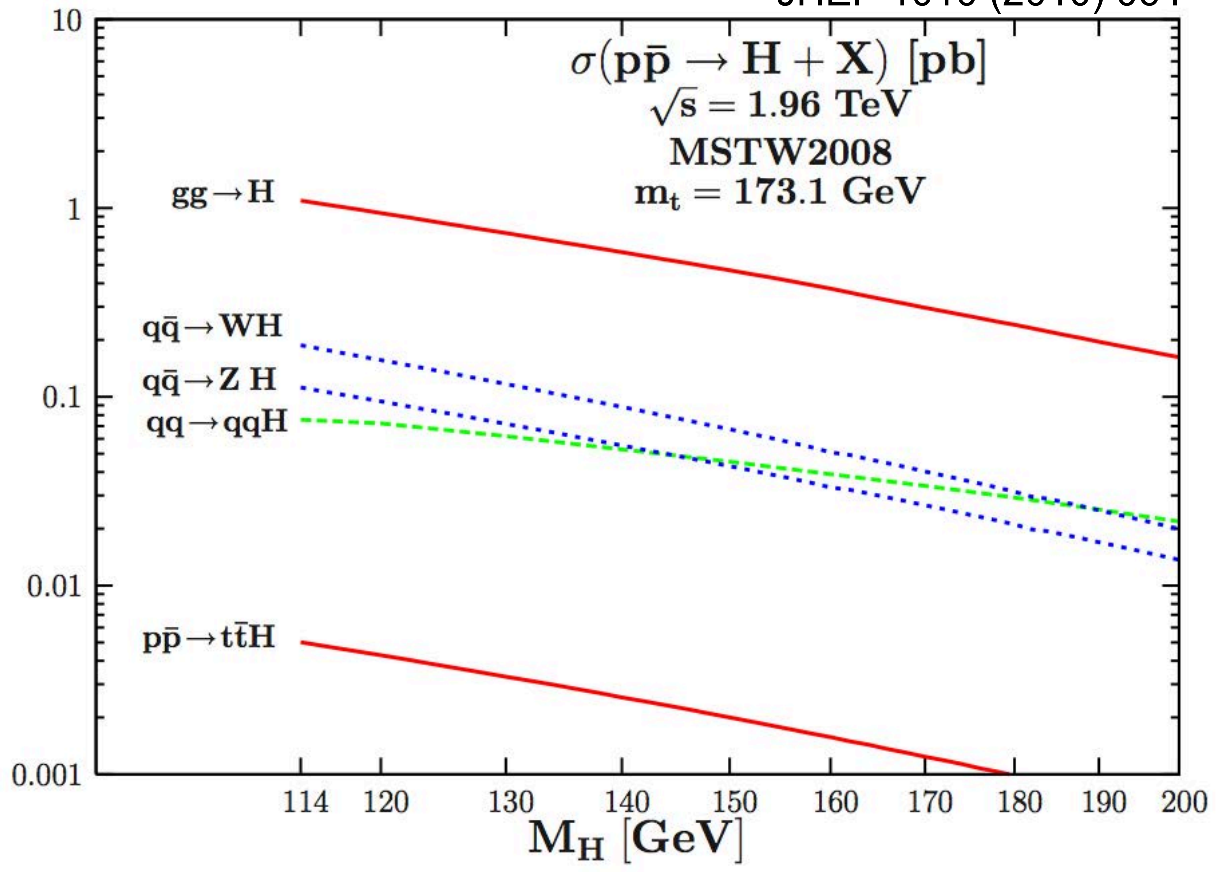


soft scatter

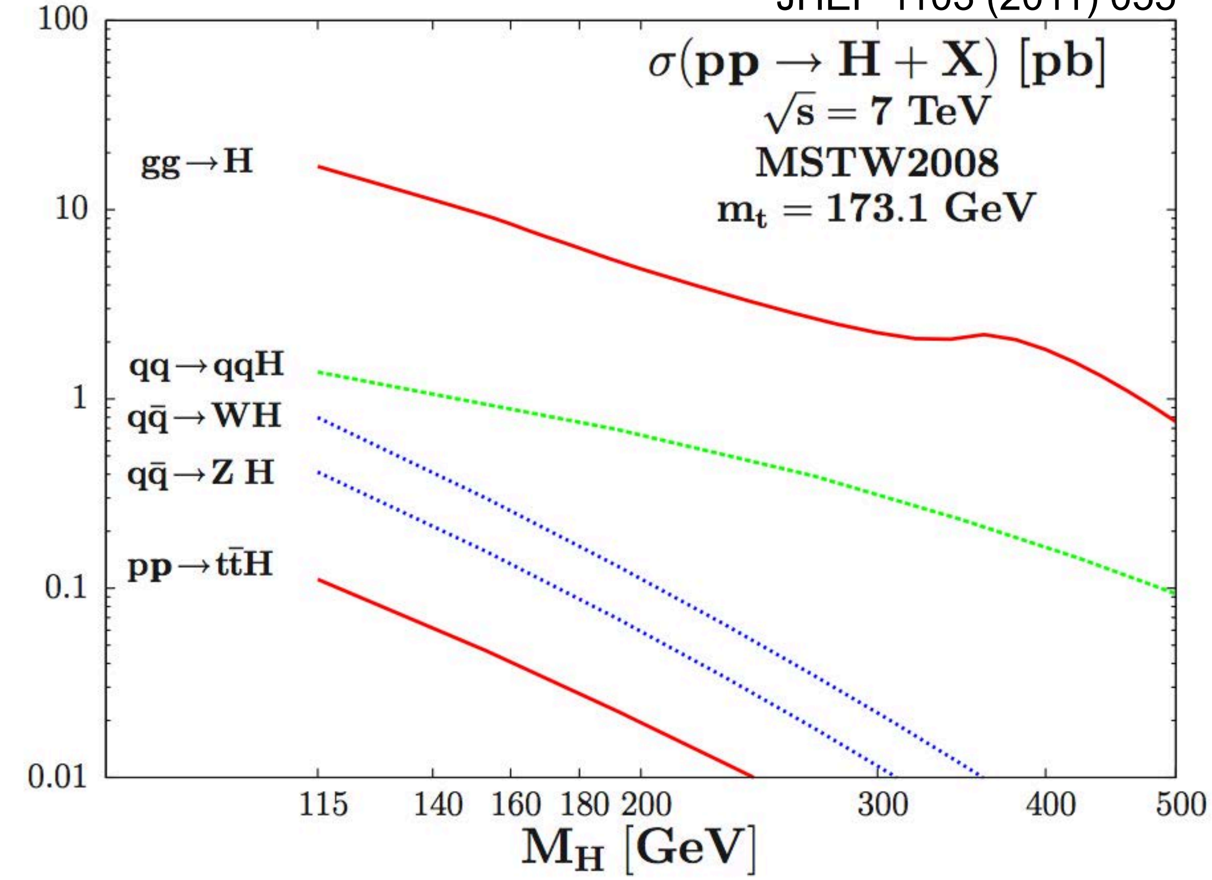


Higgs production at hadron colliders

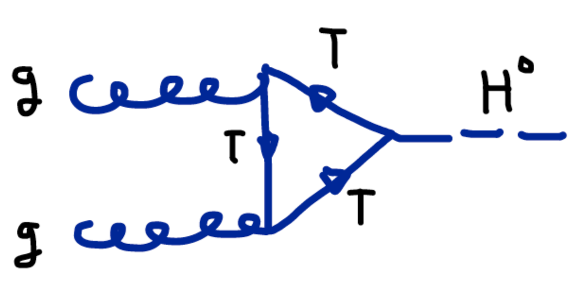
JHEP 1010 (2010) 064



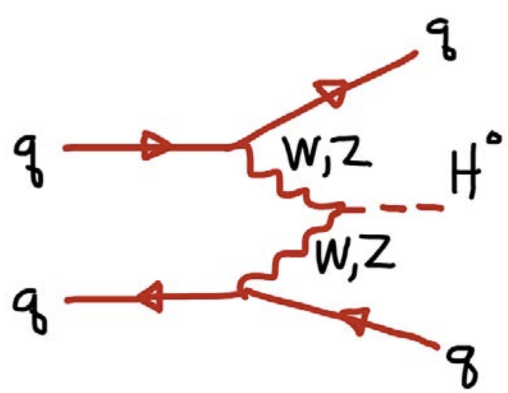
JHEP 1103 (2011) 055



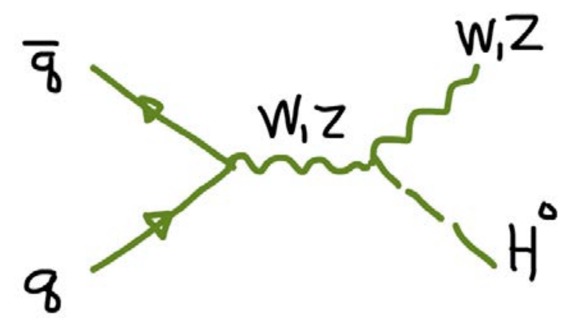
- Different production channels



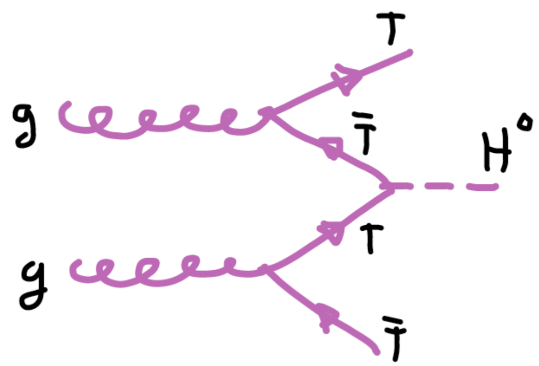
gluon-gluon fusion
ggF



vector boson fusion
VBF



Higgsstrahlung
VH

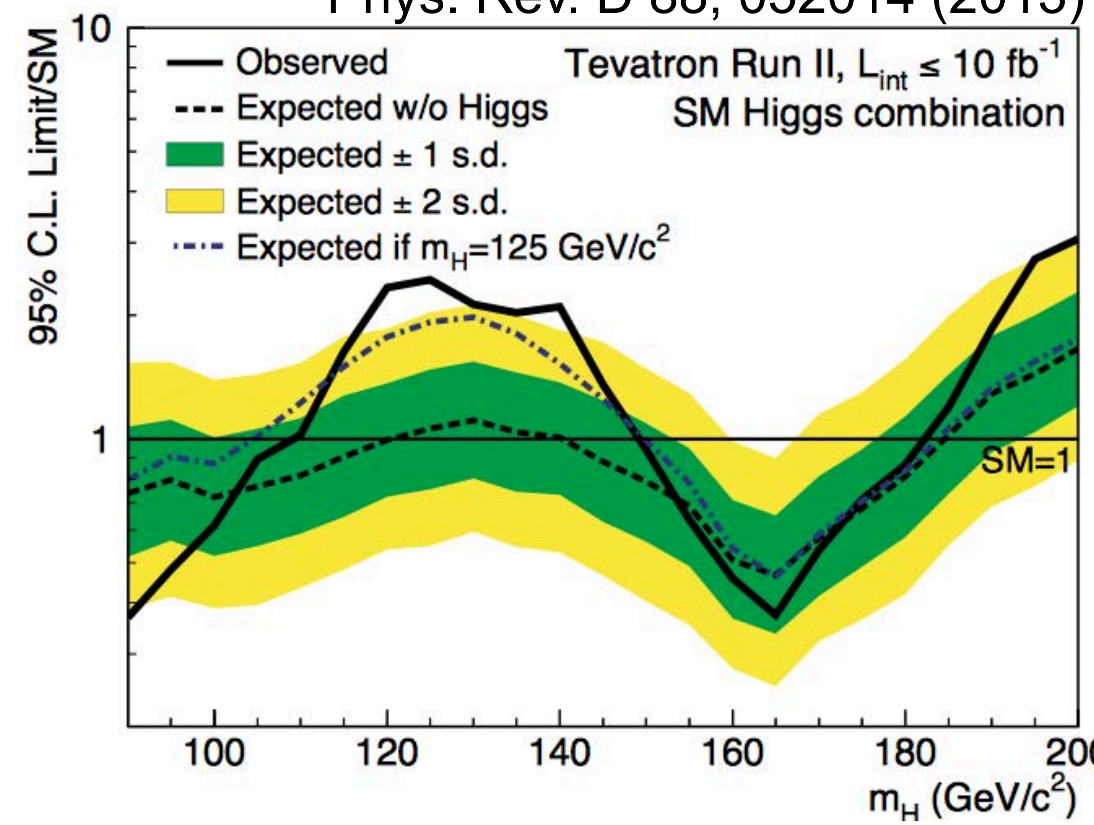


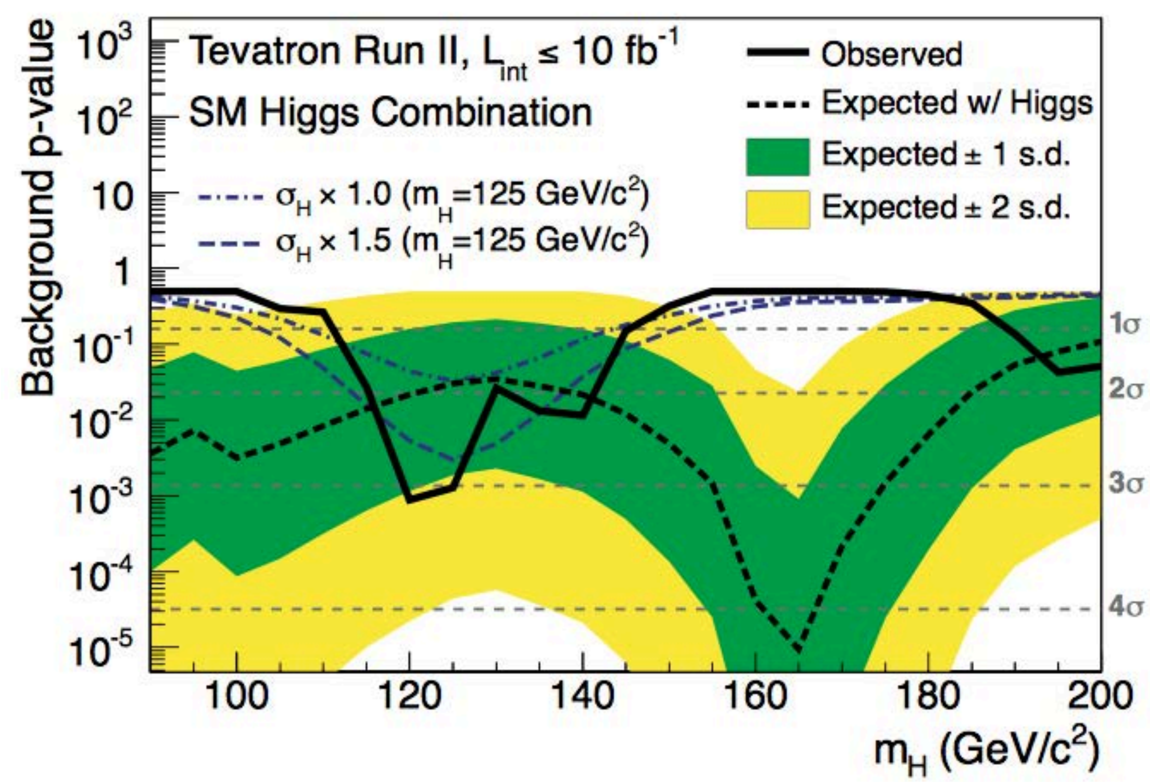
in association
with q-qbar
ttH

Higgs search at the Tevatron

- Collided proton-antiproton at $\sqrt{s}$ = 1.96 TeV
  - stopped on 30 Sep 2011
- For M_H > 130 GeV, $H \to W^+ W^-$ dominates
- For lower M_H, best option was HW and HZ final states
  - with leptonic decay of W/Z and $H \to b\, bbar$
- Huge effort
  - deployment of MVA techniques
- Excluded **149 < M_H < 182 GeV** at 95% CL
- ~3σ excess in 115 < M_H < 140 GeV

Phys. Rev. D 88, 052014 (2013)





Higgs search at the Tevatron

Phys. Rev. D 88, 052014 (2013)

- CDF

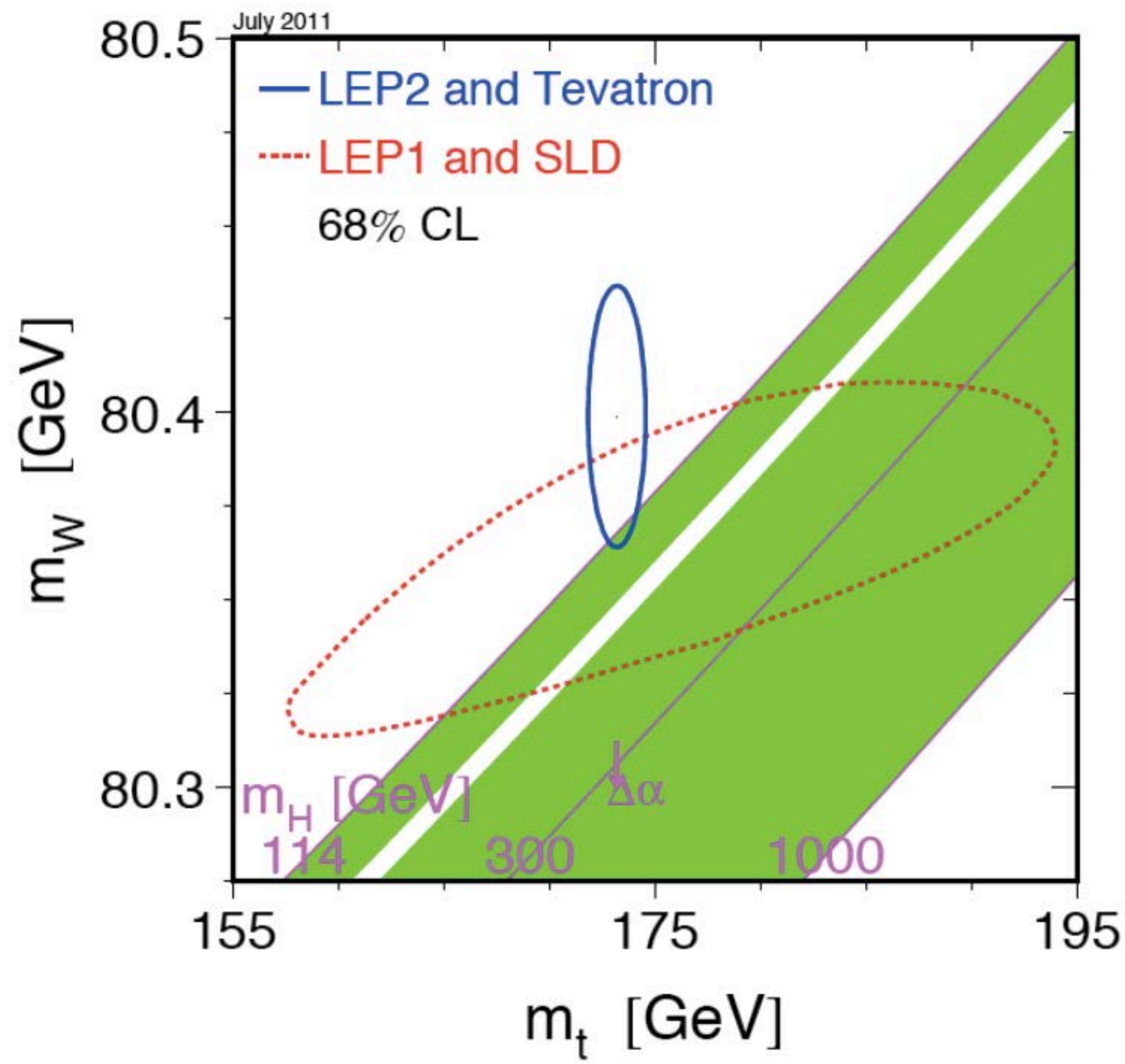
Channel		Luminosity (fb^{-1})	m_H range (GeV/c^2)
$WH \to \ell\nu b\bar{b}$ 2-jet channels $4\times$(5 b-tag categories)		9.45	90–150
$WH \to \ell\nu b\bar{b}$ 3-jet channels $3\times$(2 b-tag categories)		9.45	90–150
$ZH \to \nu\bar{\nu}b\bar{b}$ (3 b-tag categories)		9.45	90–150
$ZH \to \ell^+\ell^- b\bar{b}$ 2-jet channels $2\times$(4 b-tag categories)	$H \to b\bar{b}$	9.45	90–150
$ZH \to \ell^+\ell^- b\bar{b}$ 3-jet channels $2\times$(4 b-tag categories)		9.45	90–150
$WH + ZH \to jjb\bar{b}$ (2 b-tag categories)		9.45	100–150
$t\bar{t}H \to W^+bW^-\bar{b}b\bar{b}$ (4 jets,5 jets,$\geq$6 jets)$\times$(5 b-tag categories)		9.45	100-150
$H \to W^+W^-$ $2\times$(0 jets)+$2\times$(1 jet)+$1\times$($\geq$2 jets)+$1\times$(low-$m_{\ell\ell}$)		9.7	110–200
$H \to W^+W^-$ (e-τ_{had})+(μ-τ_{had})		9.7	130–200
$WH \to WW^+W^-$ (same-sign leptons)+(tri-leptons)	$H \to W^+W^-$	9.7	110–200
$WH \to WW^+W^-$ (tri-leptons with 1 τ_{had})		9.7	130–200
$ZH \to ZW^+W^-$ (tri-leptons with 1 jet,$\geq$2 jets)		9.7	110–200
$H \to \tau^+\tau^-$ (1 jet)+($\geq$2 jets)	$H \to \tau^+\tau^-$	6.0	100–150
$H \to \gamma\gamma$ $1\times$(0 jet)+$1\times$($\geq$1 jet)+$3\times$(all jets)	$H \to \gamma\gamma$	10.0	100–150
$H \to ZZ$ (four leptons)	$H \to ZZ$	9.7	120–200

- D0

Channel		Luminosity (fb^{-1})	m_H range (GeV/c^2)
$WH \to \ell\nu b\bar{b}$ 2-jet channels $2\times$(4 b-tag categories)		9.7	90–150
$WH \to \ell\nu b\bar{b}$ 3-jet channels $2\times$(4 b-tag categories)		9.7	90–150
$ZH \to \nu\bar{\nu}b\bar{b}$ (2 b-tag categories)	$H \to b\bar{b}$	9.5	100–150
$ZH \to \ell^+\ell^- b\bar{b}$ $2\times$(2 b-tag)$\times$(4 lepton categories)		9.7	90–150
$H \to W^+W^- \to \ell^\pm\nu\ell^\mp\nu$ $2\times$(0 jets,1 jet,$\geq$2 jets)		9.7	115–200
$H + X \to W^+W^- \to \mu^\mp\nu\tau^\pm_{had}\nu$ (3 τ categories)		7.3	115–200
$H \to W^+W^- \to \ell\bar{\nu}jj$ $2\times$(2 b-tag categories)$\times$(2 jets, 3 jets)		9.7	100–200
$VH \to e^\pm\mu^\pm + X$	$H \to W^+W^-$	9.7	100–200
$VH \to \ell\ell\ell + X$ ($\mu\mu e$, $3\times e\mu\mu$)		9.7	100–200
$VH \to \ell\bar{\nu}jjjj$ $2\times$($\geq$4 jets)		9.7	100-200
$VH \to \tau_{had}\tau_{had}\mu + X$ (3 τ categories)	$H \to \tau^+\tau^-$	8.6	100-150
$H+X \to \ell^\pm\tau^\mp_{had}jj$ $2\times$(3 τ categories)		9.7	105–150
$H \to \gamma\gamma$ (4 categories)	$H \to \gamma\gamma$	9.6	100-150

Precision measurements

- Precise Standard Model measurements put constraints on the Higgs mass
  - Higgs couples to mass... look at heavy particles!



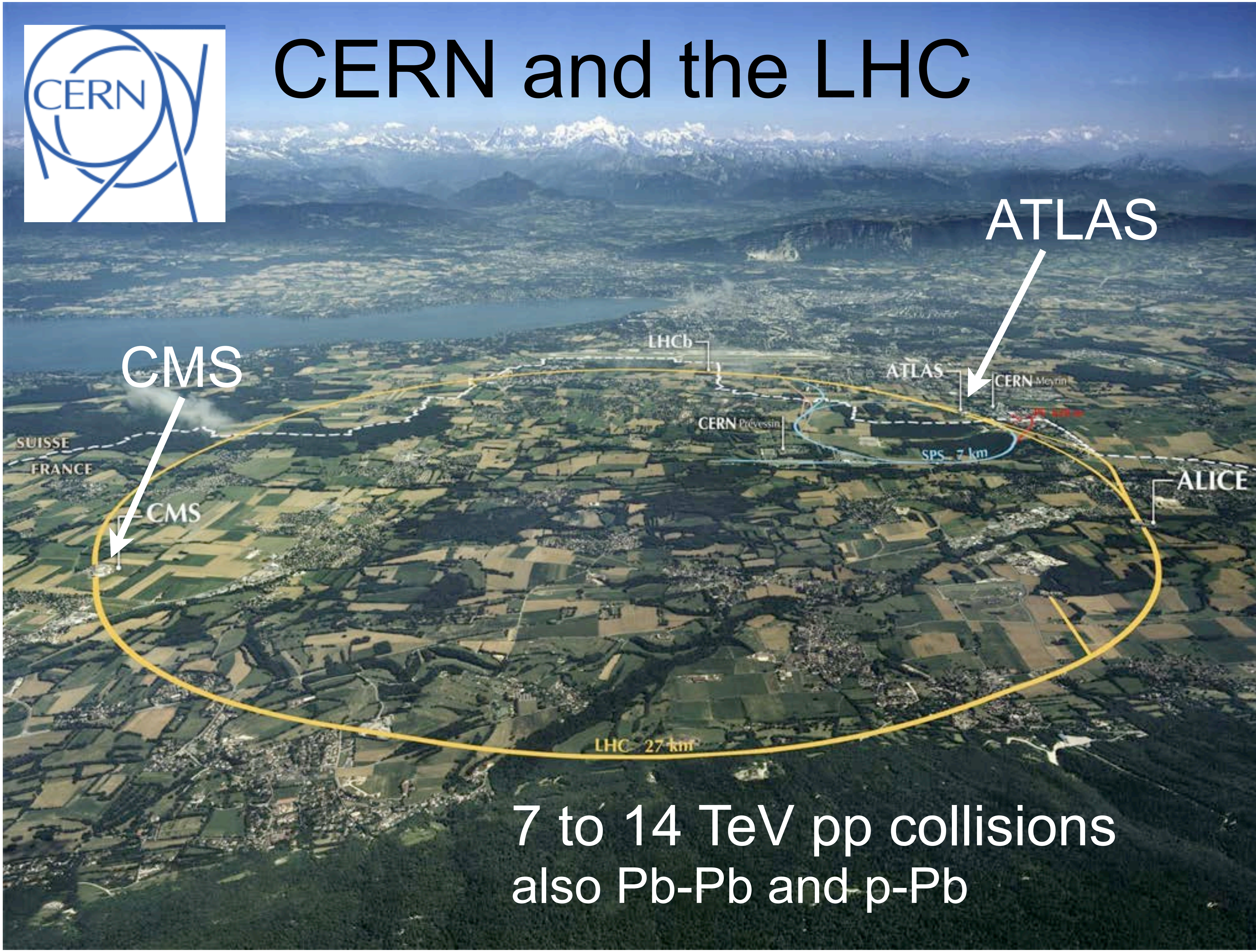
Higgs mass constraints

$114 < M_H < 161$ GeV 95%CL

Direct searches

Indirect: precision measurements. Assumes SM

CERN and the LHC



7 to 14 TeV pp collisions
also Pb-Pb and p-Pb

CERN PhotoLab CERN-MI-0807031

ATLAS and Canada

Alberta
Carleton
McGill
Montréal
SFU
Toronto
TRIUMF
UBC
Victoria
York

- ATLAS celebrated its 22th anniversary on 1 Oct 2014
- Over 150 Canadian scientists
- ATLAS Canada Collaboration
  - Founded in 1992 — ML Spokesperson, UVic
  - Spokesperson (07-) — Rob McPherson, UVic/IPP
  - Deputy — Manuella Vincter, Carleton
  - Physics Coordination — Andreas Warburton, McGill
  - Computing Coordination — Reda Tafirout, TRIUMF
- Contributions to the ATLAS detector construction
  - Calorimetry, cryogenics, electronics, trigger, radiation
  - Now much more: trigger, tracking, muon, beam monitor
- Contributions to the LHC construction (TRIUMF)
- Many ATLAS roles including now
  - ATLAS Deputy Spokesperson — Rob McPherson
  - Higgs working group co-convener — Pierre Savard
  - Top working group co-convener — Alison Lister

Evian March 1992 with Alan!

Canada and the LHC

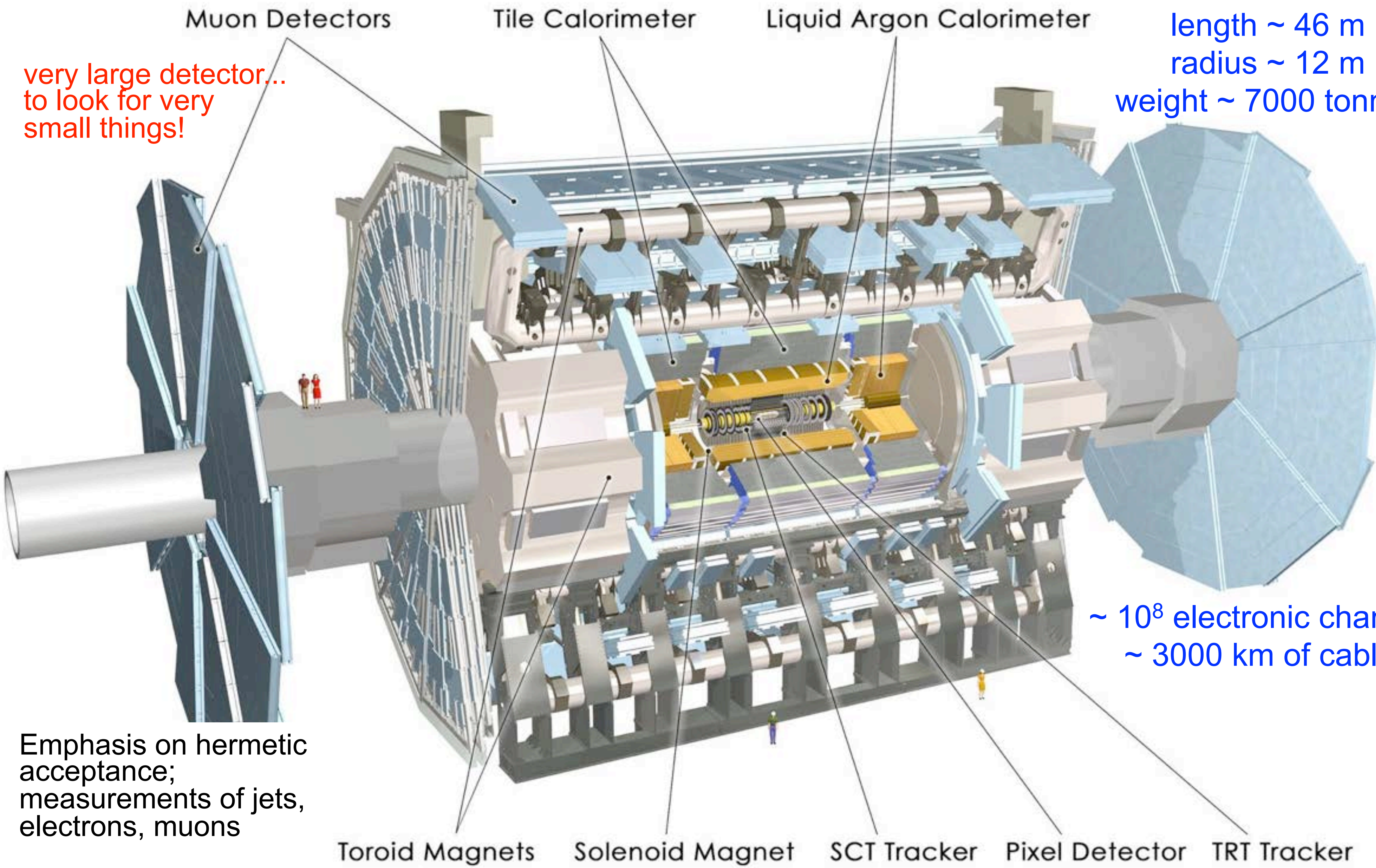
Canada made important contributions to the LHC machine: warm insertions and injector upgrades, with TRIUMF engineering

48 + 4 warm twin-aperture quadrupoles for cleaning insertions

The ATLAS detector

very large detector... to look for very small things!

length ~ 46 m
radius ~ 12 m
weight ~ 7000 tonnes



~ 10^8 electronic channels
~ 3000 km of cables

Emphasis on hermetic acceptance; measurements of jets, electrons, muons

ATLAS calorimetry

- **LAr system: 182,468 cells**
- **Tile system: 10,364 cells**

Fe-Scintillator
|η| < 1.7

Tile barrel

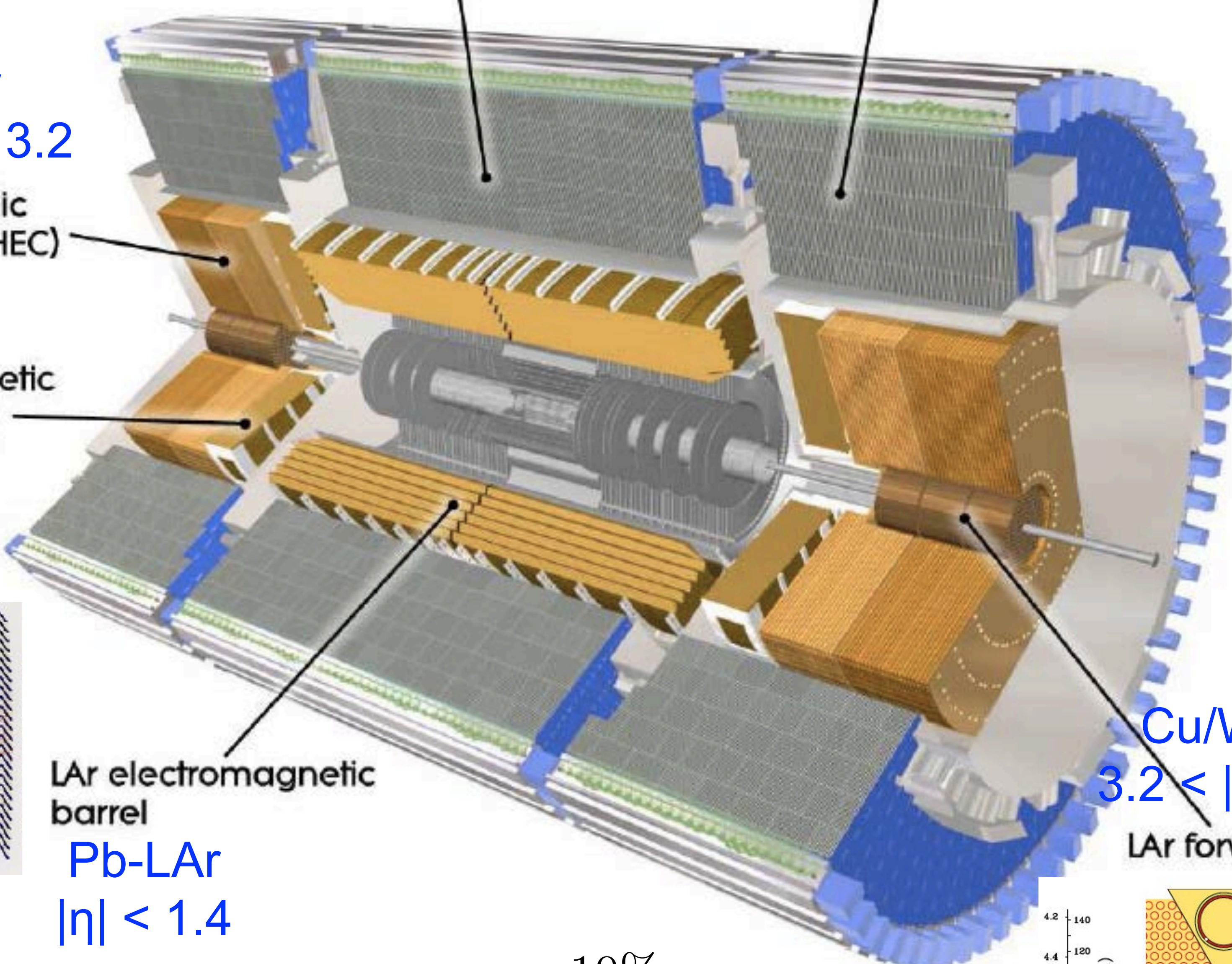
Tile extended barrel

Cu-LAr
1.5 < |η| < 3.2

LAr hadronic end-cap (HEC)

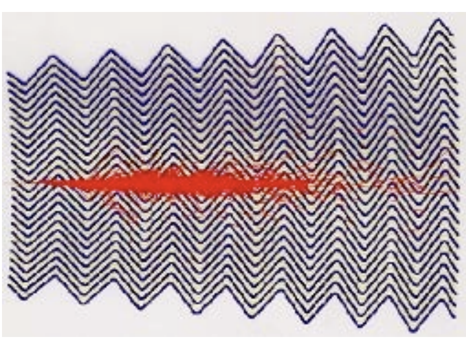
LAr electromagnetic end-cap (EMEC)

Pb-LAr
1.375 < |η| < 3.2



Segmented in depth and in pseudorapidity η and azimuthal angle ϕ

$$\eta = -\ln\left[\tan\left(\frac{\theta}{2}\right)\right]$$



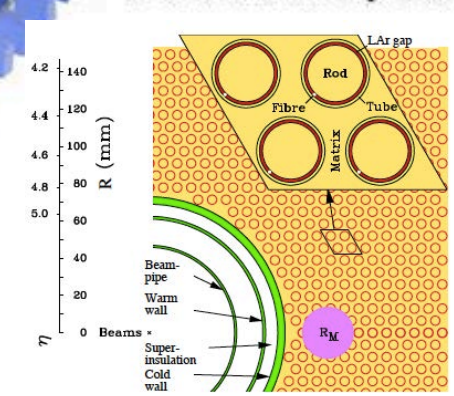
photon pointing!

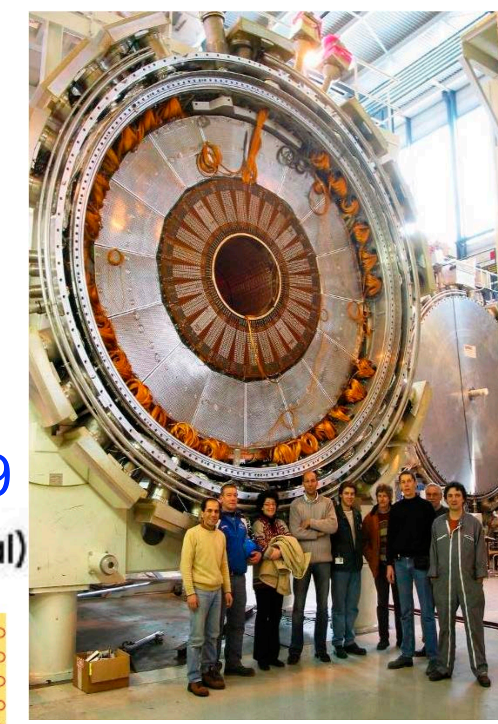
LAr electromagnetic barrel

Pb-LAr
|η| < 1.4

Cu/W-LAr
3.2 < |η| < 4.9

LAr forward (FCal)





ATLAS Experiment © 2012 CERN

e/γ/jet trigger, identification, *E* measurement

EM: $$\frac{\sigma}{E} = \frac{10\%}{\sqrt{E[\mathrm{GeV}]}} \oplus 0.7\%$$

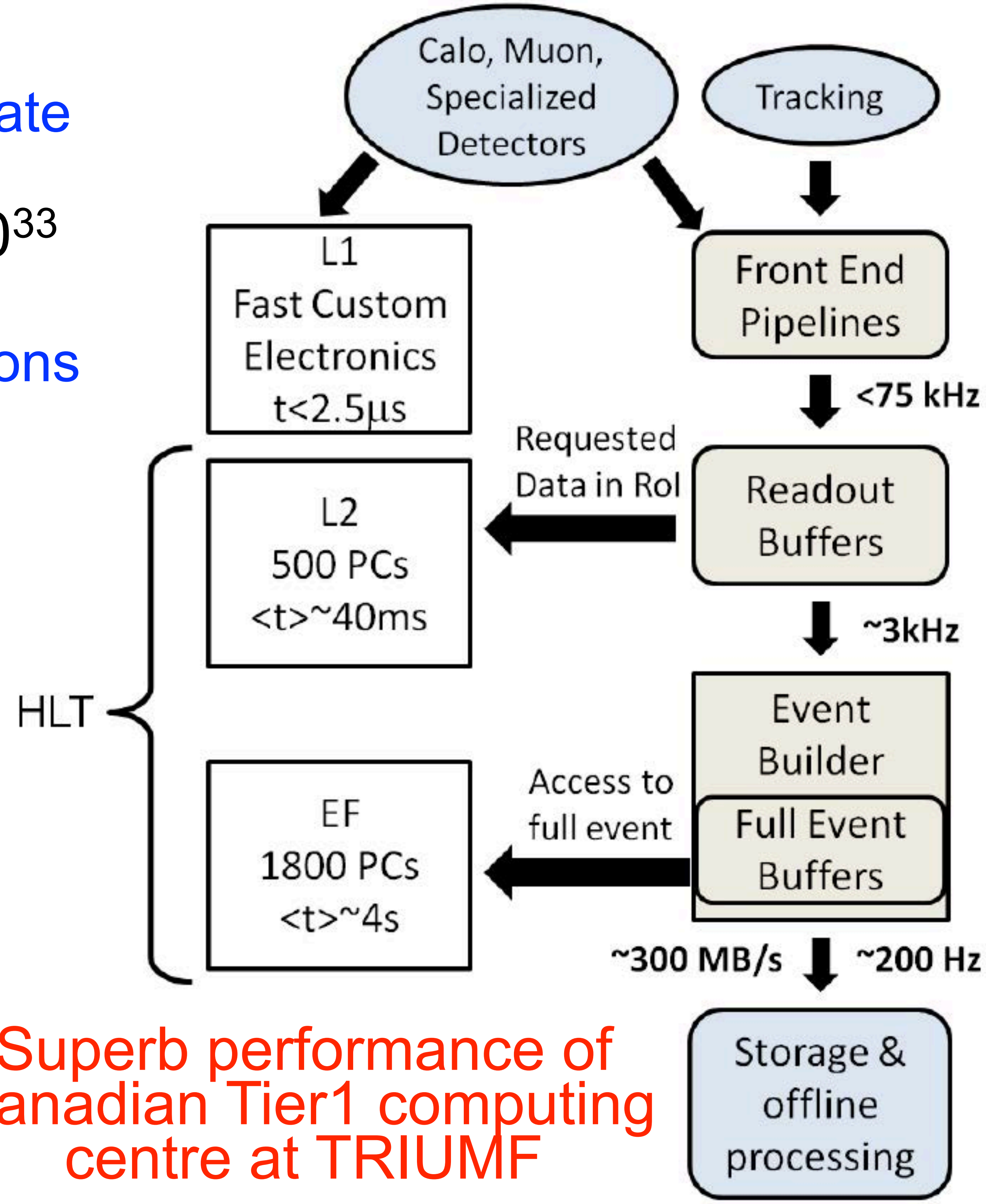
Had: $$\frac{\sigma}{E} = \frac{50\%}{\sqrt{E[\mathrm{GeV}]}} \oplus 3\%$$

LAr cryogenics feedthrough production at UVic, 2002

Trigger system

- Three-level trigger system
  - designed to reduce the data rate from 40 MHz to ~200 Hz
- Menu now optimized for 7×10^{33} cm^{-2} s^{-1}
  - improvement of object selections and trigger algorithms
- Good performance in 2012!

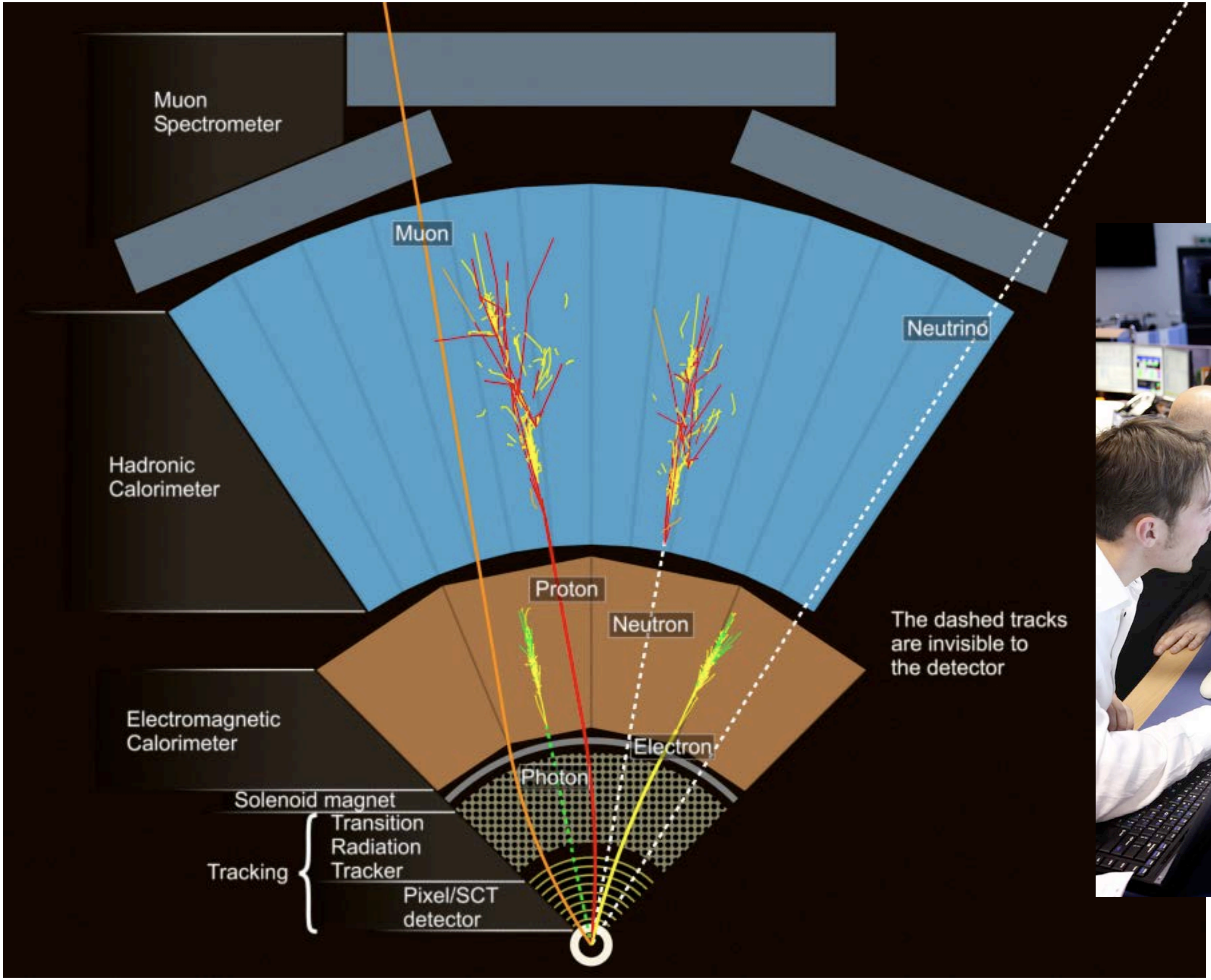
Main triggers at 7×10^{33} $cm^{-2}s^{-1}$				
Offline (GeV)	L1 thr (GeV)	L1 rate (kHz)	EF thr (GeV)	EF rate (Hz) @5 10^{33}
e > 25	18	17	24	70
μ > 25	15	8	24	45
dilepton	10-15	15	8-18	21
2γ 25-40	10-16	12	20-35	17
2τ 30-45	11-15	12	20-29	12
Jet > 360	75	2	2	5
MET 120	40	2	80	17

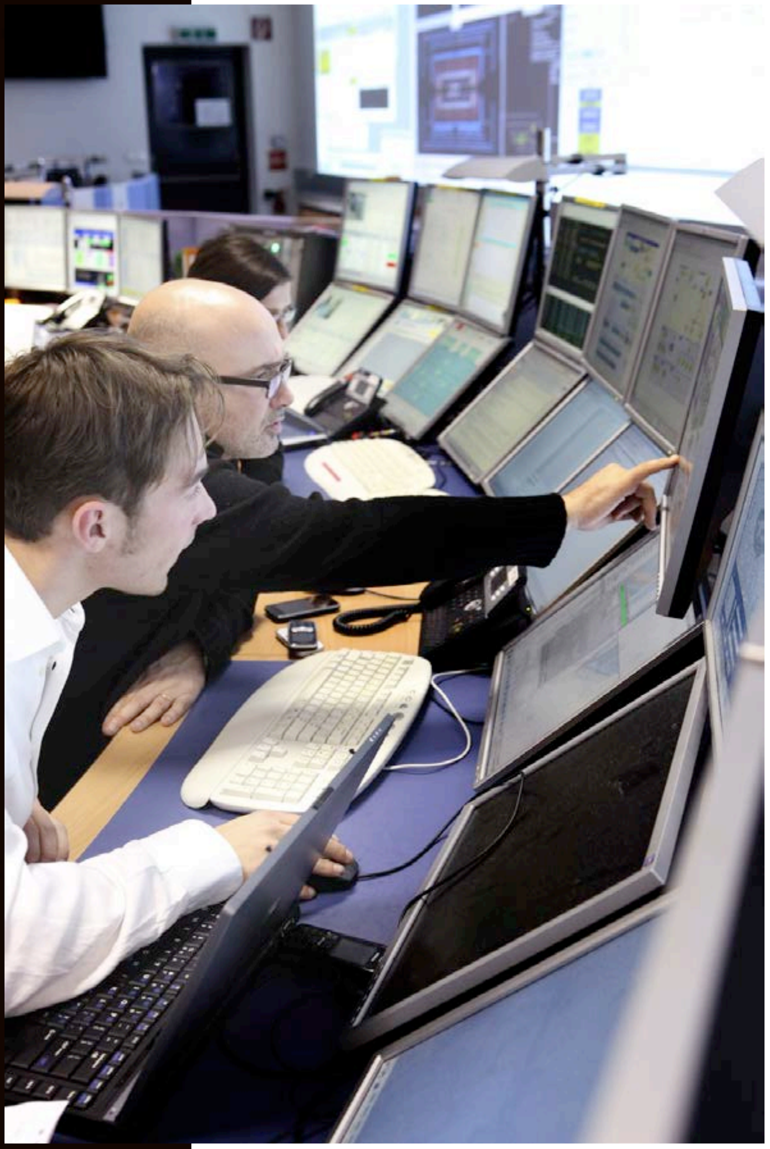


Superb performance of Canadian Tier1 computing centre at TRIUMF

Eur.Phys.J. C72 (2012) 1849

Particle identification in ATLAS



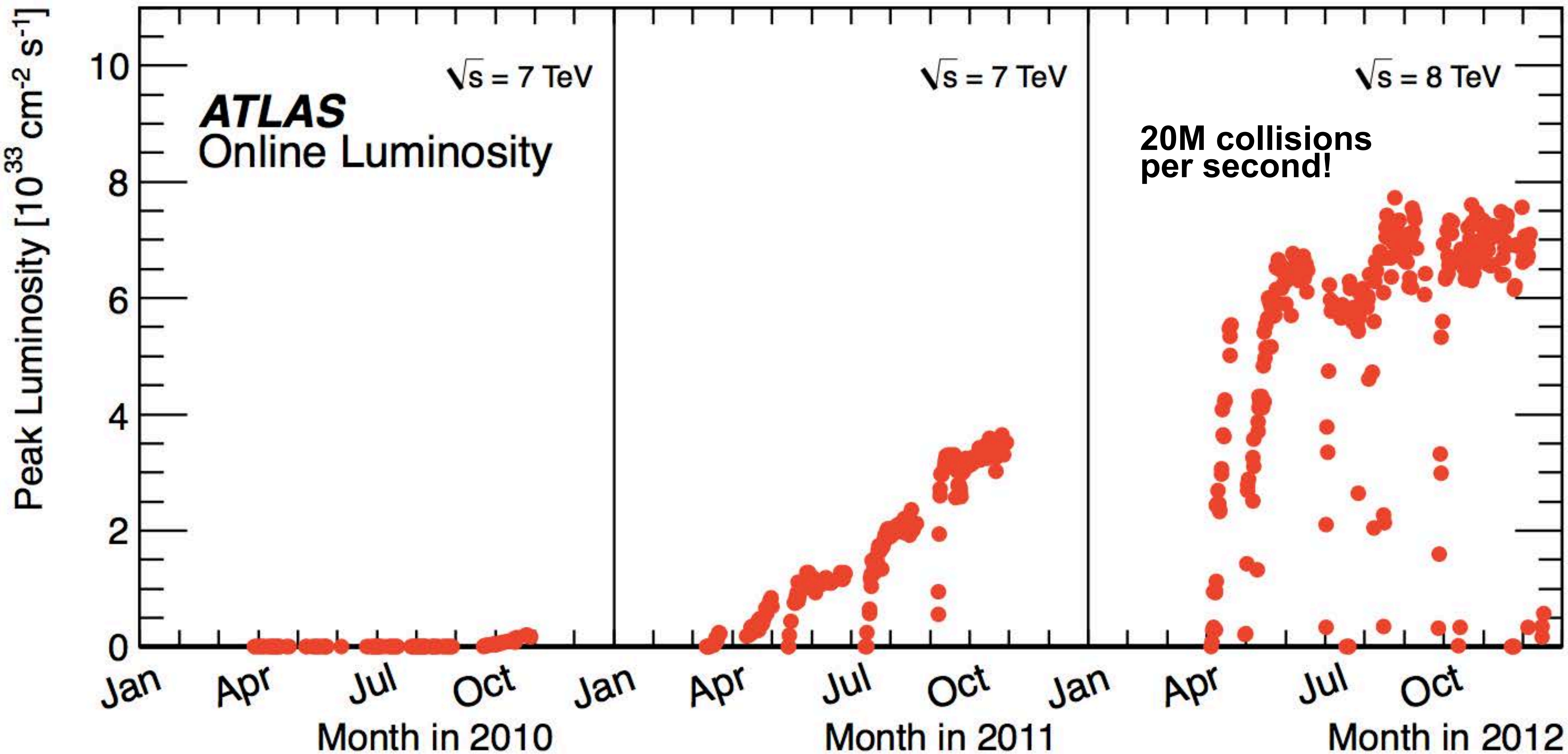


LHC luminosity, pp collisions

Superb LHC performance!!

Peak luminosity: 7.73×10^{33} cm^{-2} s^{-1}

https://twiki.cern.ch/twiki/bin/view/AtlasPublic/LuminosityPublicResults

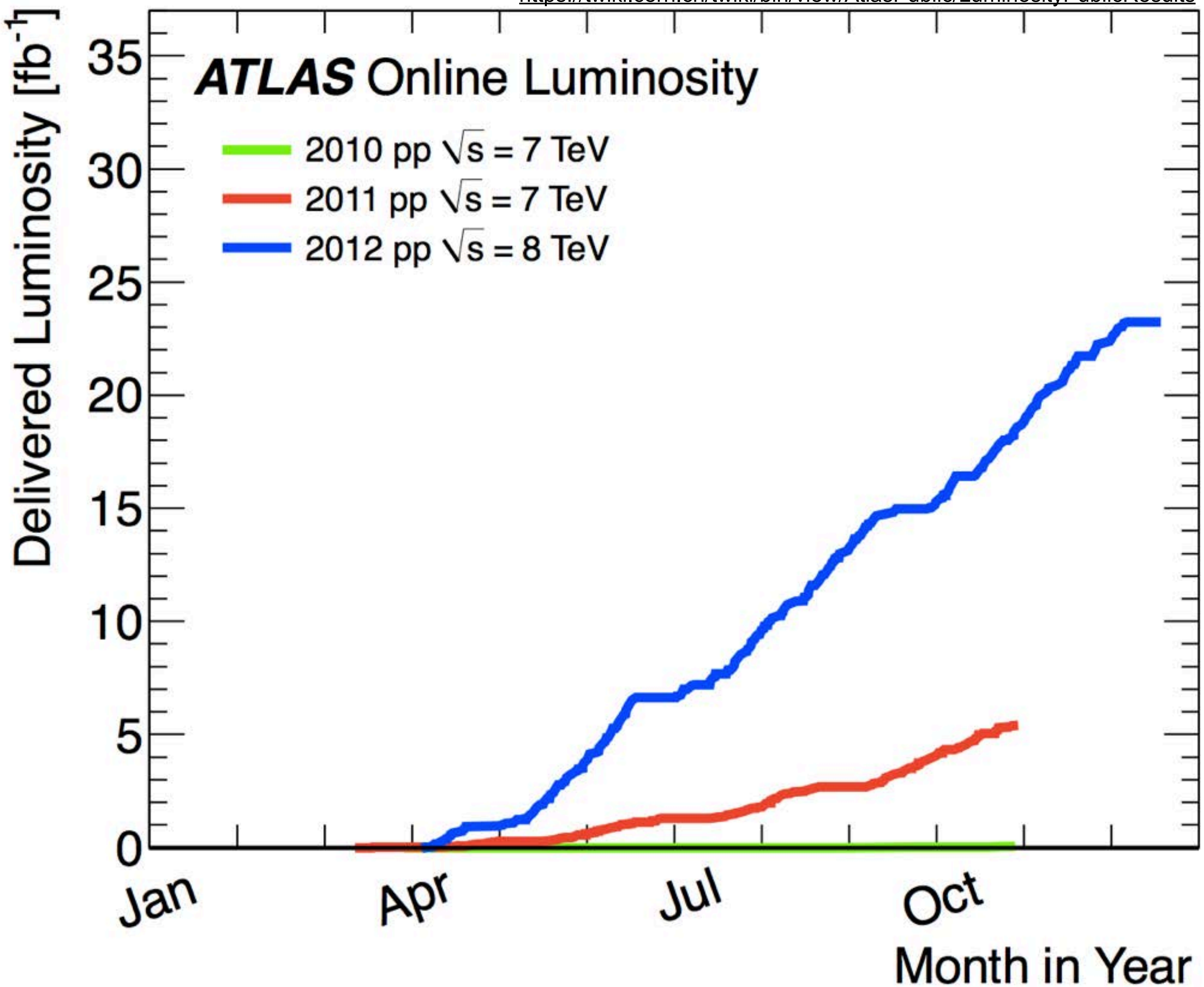


A challenge for the experiments to keep up!

LHC integrated luminosity, pp

Superb LHC performance!!

https://twiki.cern.ch/twiki/bin/view/AtlasPublic/LuminosityPublicResults



$$\int L\,dt$$

23.3 fb^{-1} **8 TeV**

5.6 fb^{-1} **7 TeV**

48.9 pb^{-1} **7 TeV**

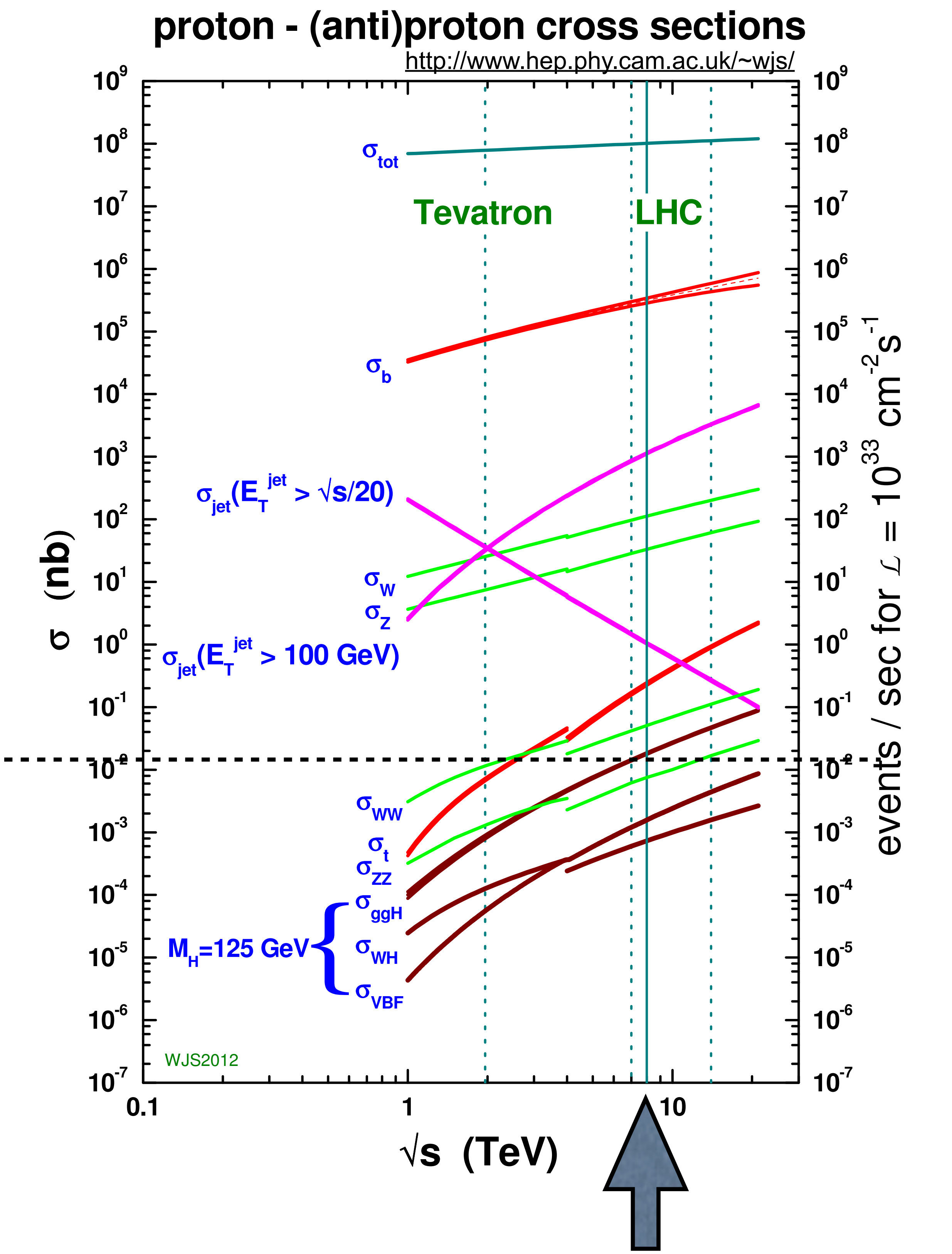
Cross sections and event rates

$$\sigma_{\rm tot} \sim 115 \text{ mb} \sim \left(3.4 \times 10^{-15} \text{ m}\right)^2$$

@ 7×10^{33} cm^{-2} s^{-1}

process	σ(nb)	R(Hz)
inelastic	$\sim 7.5 \times 10^7$	0.53×10^9
Z	~35	250
ttbar	~0.24	1.7
$H_{(125GeV)}$	~0.022	0.15

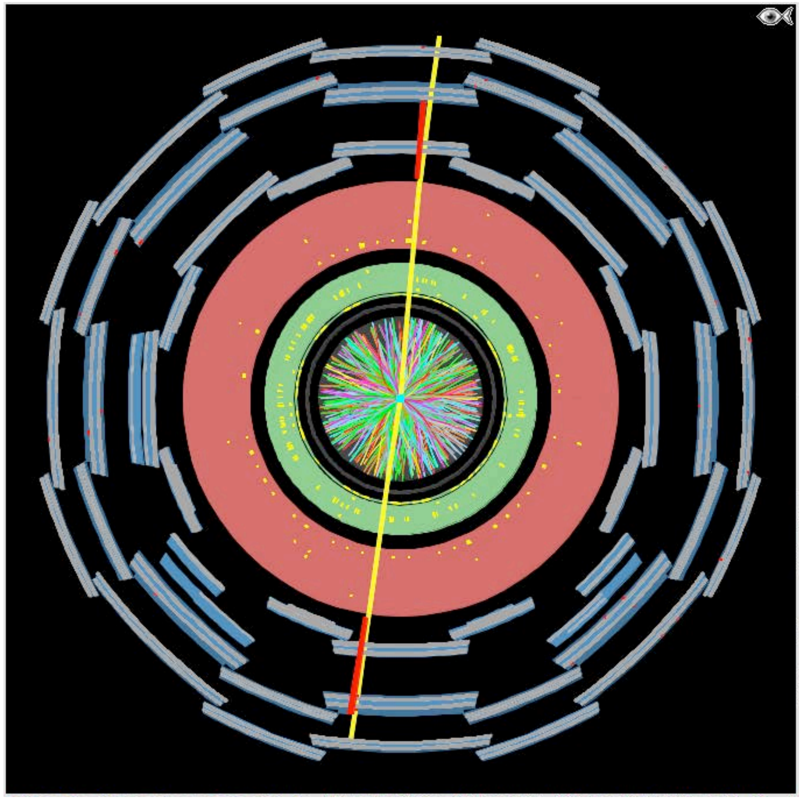
~0.5 M in 2012!



Higgs production is nearly **10 orders of magnitude** less than the total cross section!

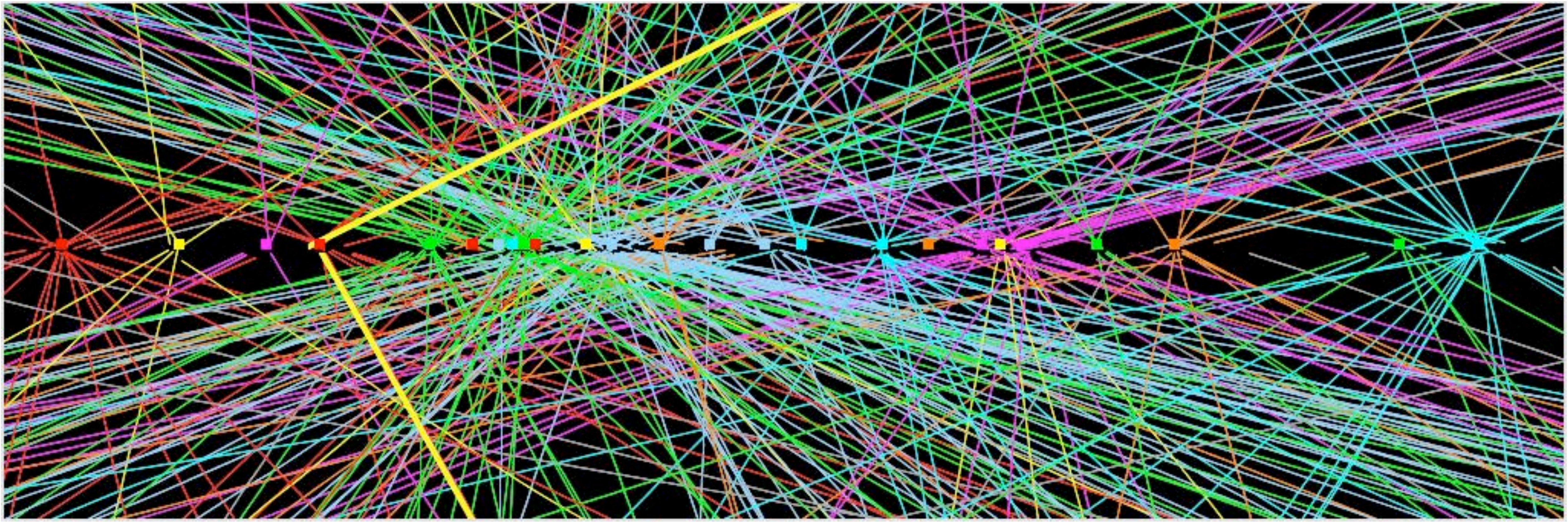
Experimental challenge: Pile-up

- In-time pile-up
  - due to multiple collisions per bunch crossing
  - in 2012, up to 40 events per bunch crossing!!
- Out-of-time pile-up
  - superposition of signal from preceding (and following) bunch crossing

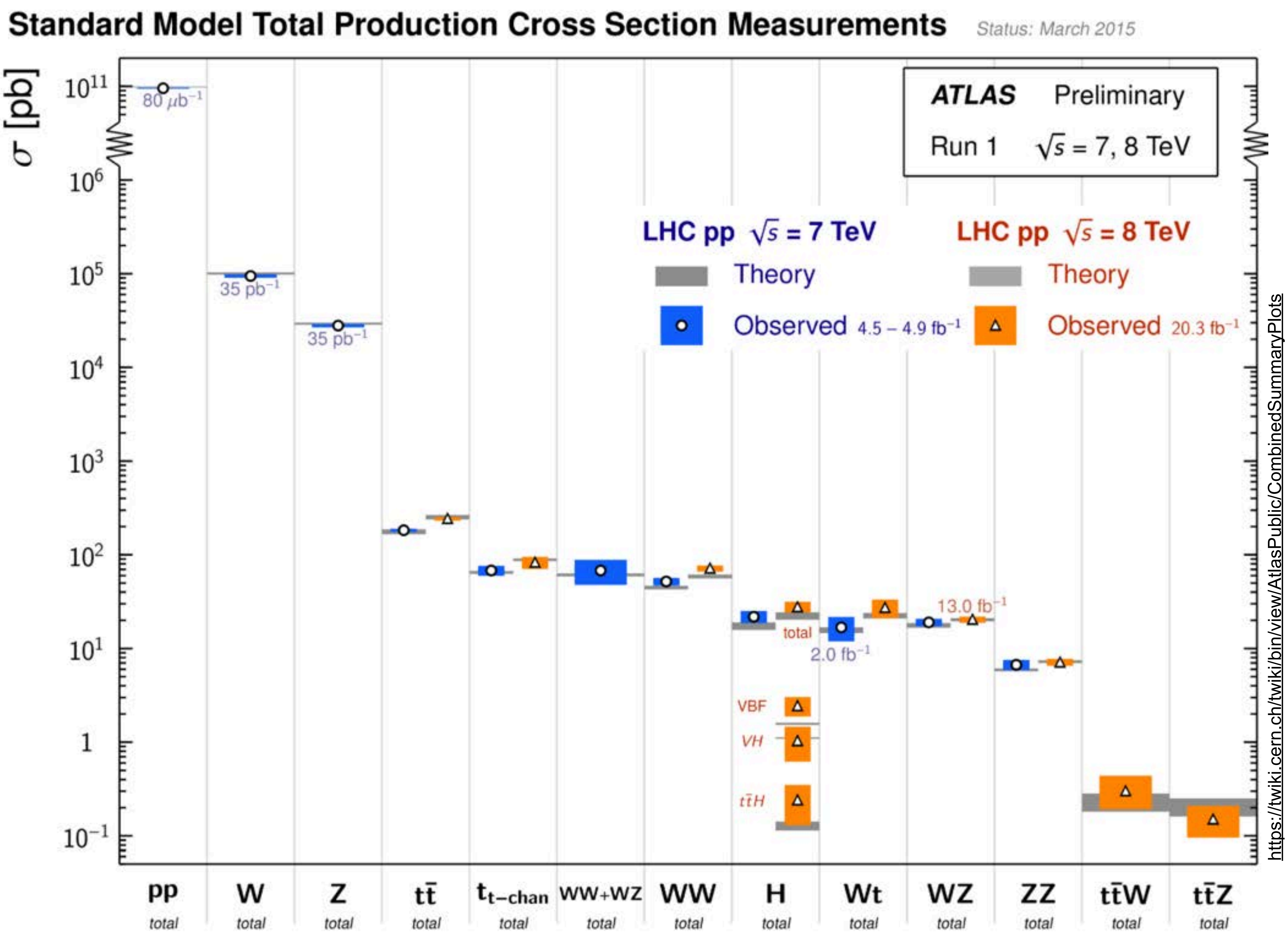


$Z \rightarrow \mu^+\mu^-$ event with 25 vertices

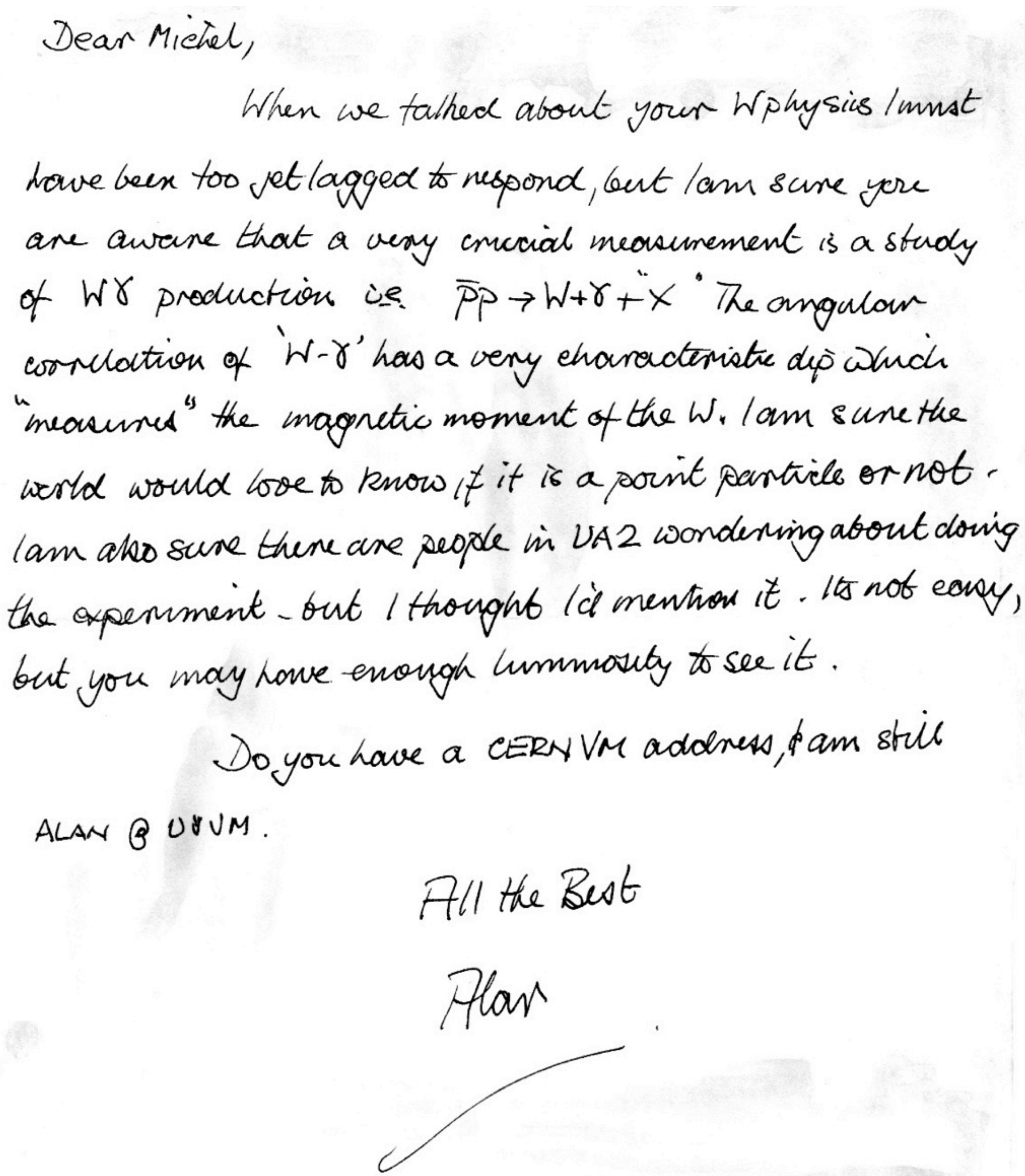
~1cm



SM production cross sections



SM challenges... 1987/07/21



Dear Michel,

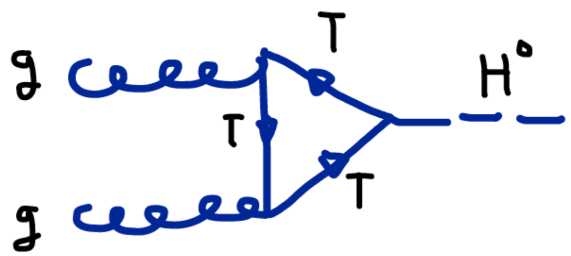
When we talked about your W physics I must have been too jet lagged to respond, but I am sure you are aware that a very crucial measurement is a study of $W\gamma$ production i.e. $\bar{p}p \to W + \gamma + X$. The angular correlation of 'W-γ' has a very characteristic dip which "measures" the magnetic moment of the W. I am sure the world would love to know if it is a point particle or not. I am also sure there are people in UA2 wondering about doing the experiment – but I thought I'd mention it. Its not easy, but you may have enough luminosity to see it.

Do you have a CERN VM address, I am still ALAN @ UVVM.

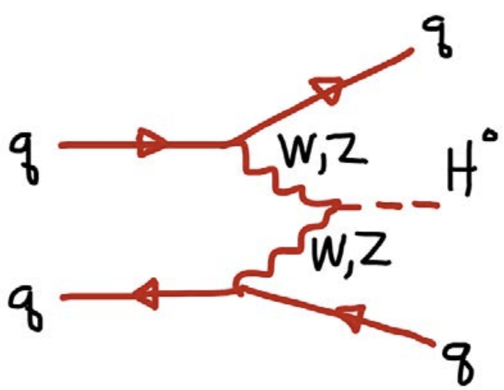
All the Best

Alan

SM Higgs production

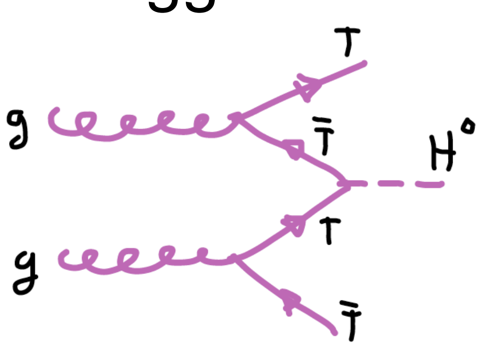


gluon-gluon fusion: ggF



vector boson fusion: VBF

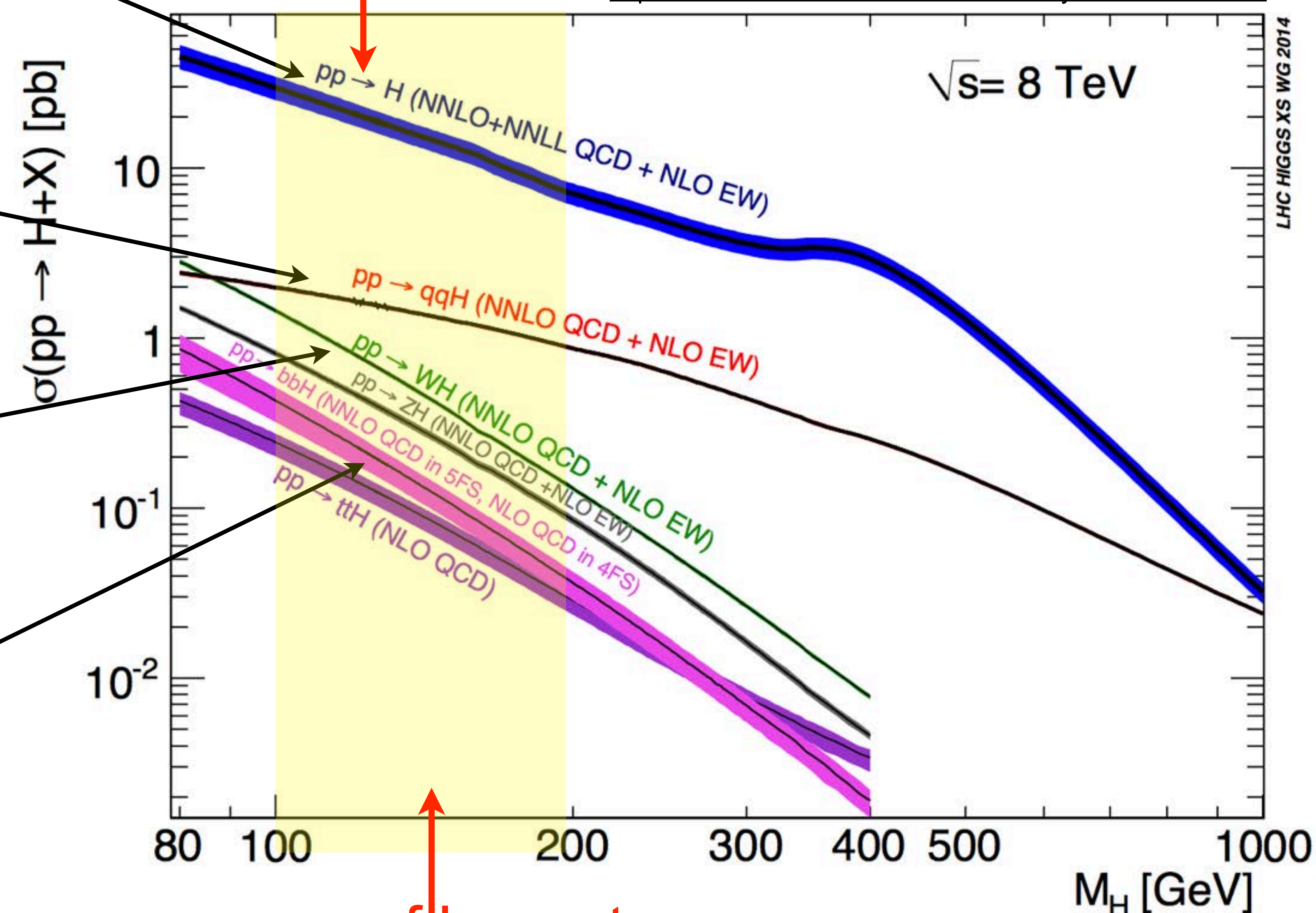
Higgsstrahlung: VH



in association
with q-qbar : ttH

Predicted cross sections for
M_H = 125 GeV @ 8 TeV : **22.3 pb**

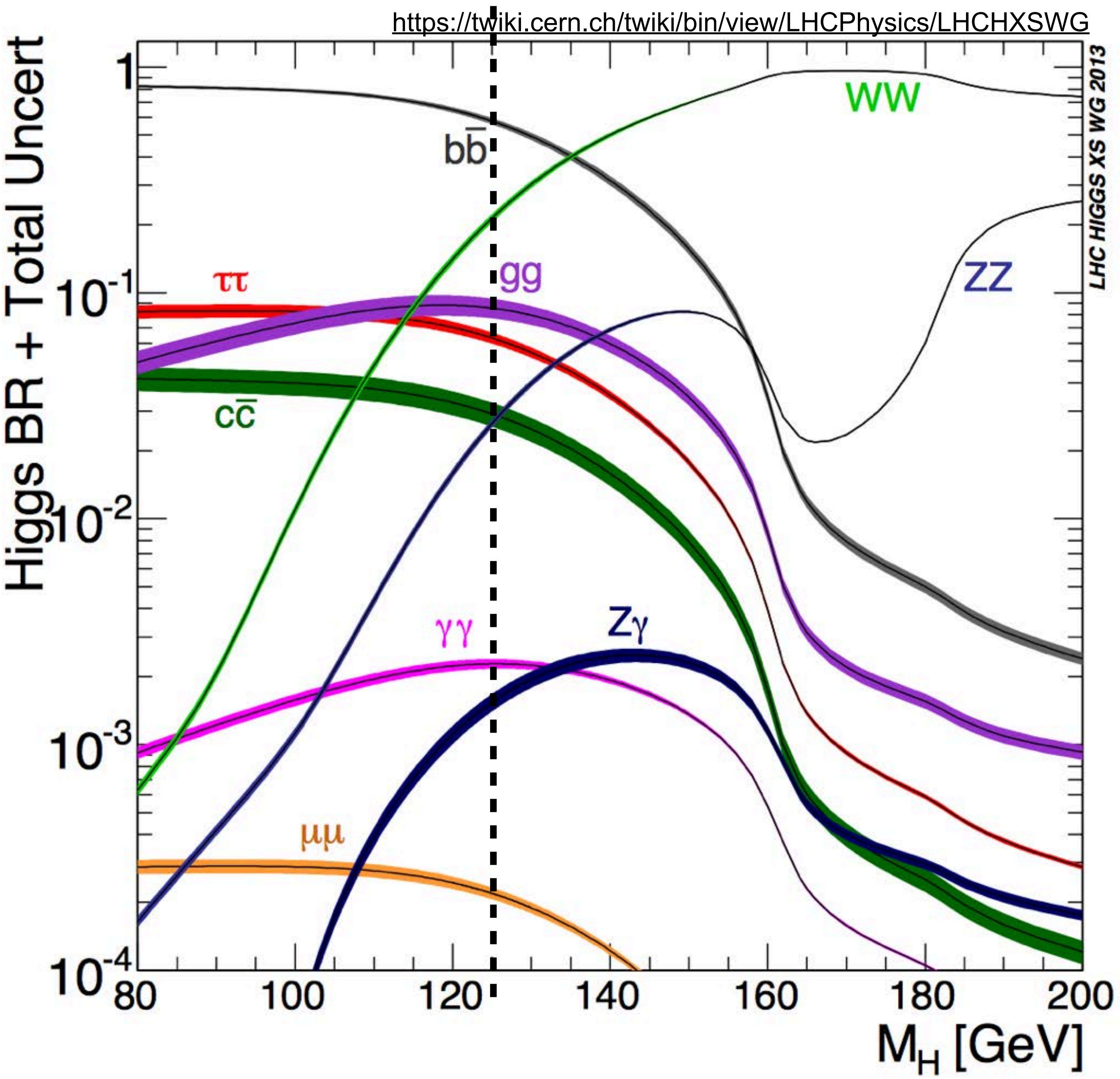
https://twiki.cern.ch/twiki/bin/view/LHCPhysics/LHCHXSWG



area of largest
interest

Standard Model Higgs decays

Many possible decay channels of the Higgs
the cleanest are also the rarest...



The most important decays for searches, with fractions for M_H = 125 GeV

58% $H \to b\bar{b}$

6.3% $H \to \tau\,\tau$

0.51% $H \to W\,W^{(*)} \to e\,\nu\,\mu\,\nu$

0.23% $H \to \gamma\,\gamma$

0.014% $H \to Z\,Z^{(*)} \to 4\ell$ e or μ pairs

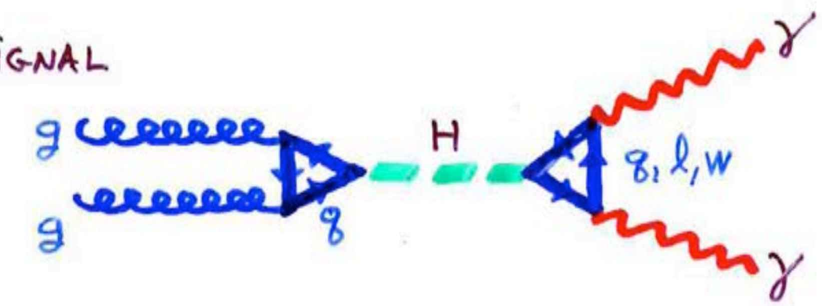
Memorabilia: CAP Congress June 1996

$H \to \gamma\gamma$

- BEST CHANNEL FOR 80 GeV < M_H < 120 GeV

  PRESENT DIRECT LIMIT FOR SM H : $M_H > 65.2$
  EXPECT LEP (192 GeV) : $M_H > 95$ GeV 95%

- SIGNAL

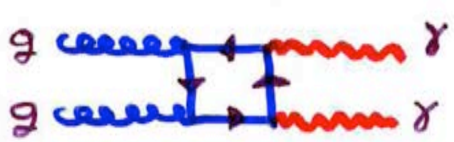


g FUSION

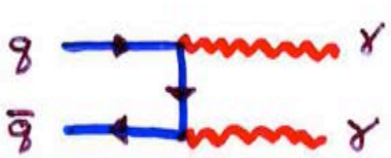
- BACKGROUND

  IRREDUCIBLE : QCD PRODUCTION

q BREM



$gg \to \gamma\gamma$ (BOX)



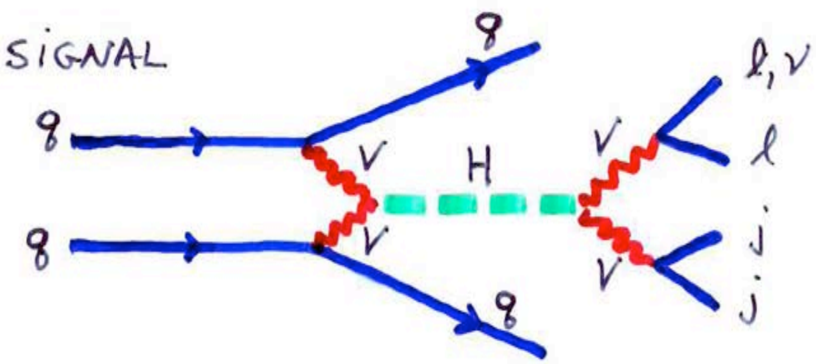
$q\bar{q} \to \gamma\gamma$ (BORN)

  REDUCIBLE : QCD JETS / $Z \to ee$ } WITH FAKE γ

- CHALLENGING CHANNEL

$H \to WW \to l\nu jj$ / $ZZ \to lljj$

- INTERESTING BECAUSE 150× BRANCHING RATIO OF $\ell\ell$ CHANNEL
- SIGNAL



V FUSION

- BACKGROUND

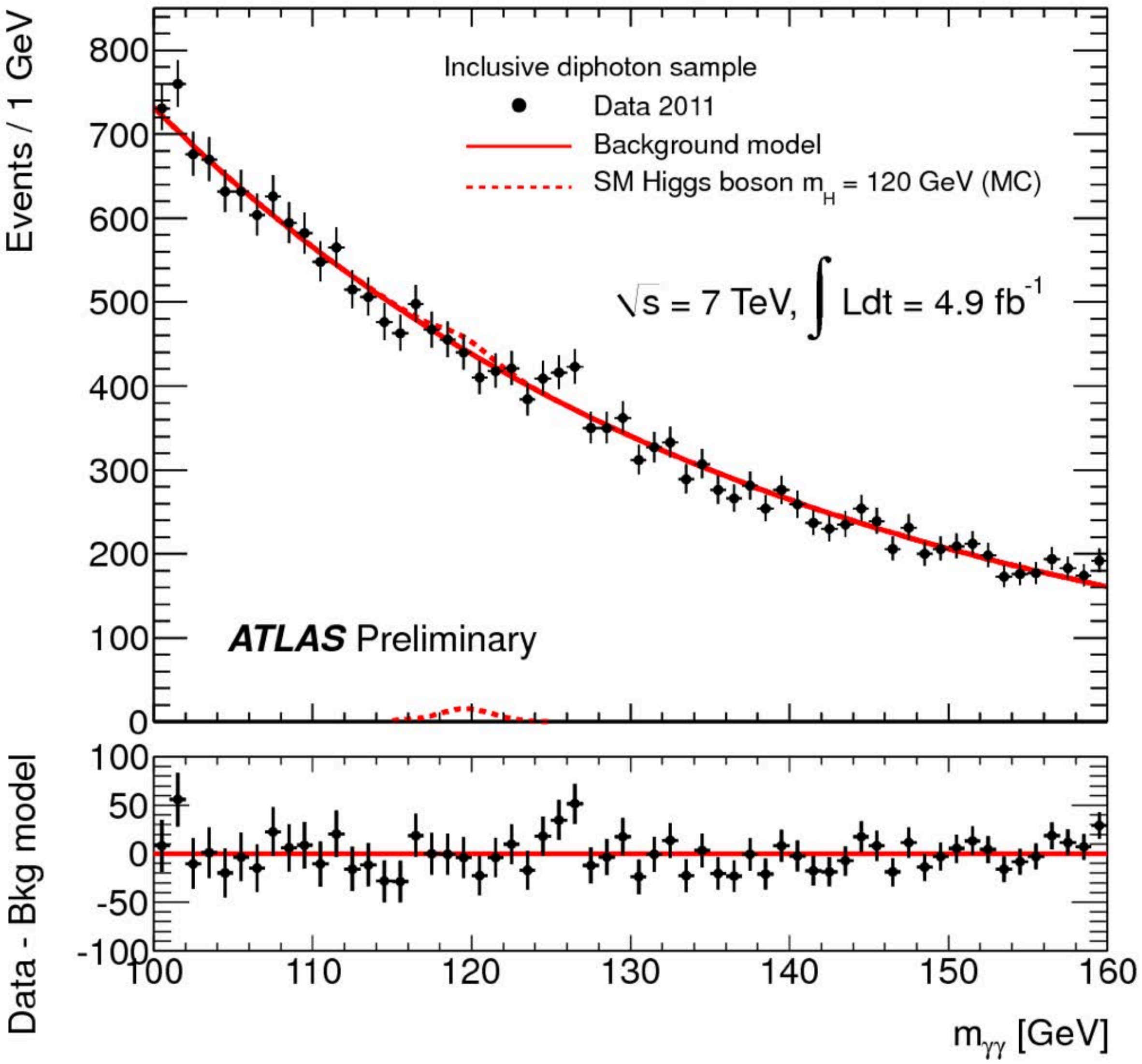
  $t\bar{t}$, W + JETS

- TO CONTROL BACKGROUND
  - NEED A GOOD $\sigma_{M_{jj}}$ FOR M_W, M_Z RECONSTRUCTION
    - → CALORIMETER GRANULARITY
    - → PILEUP CONTROL
  - FORWARD JET TAGGING $2 < |\eta| < 5$
  - CENTRAL JET VETO

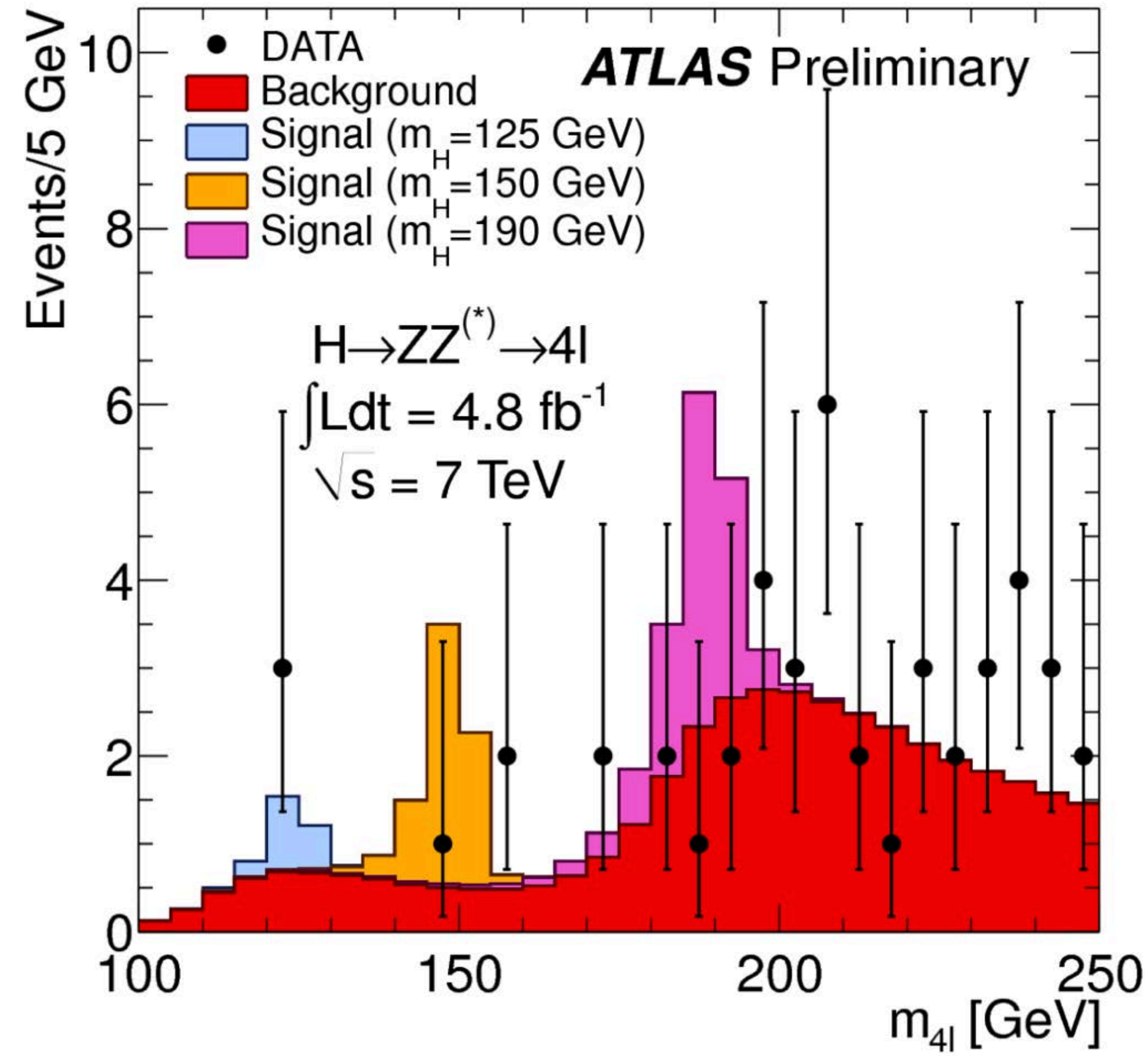
ATLAS and CMS were optimized to find the Higgs!

Higgs searches at 7 TeV

ATLAS-CONF-2011-161



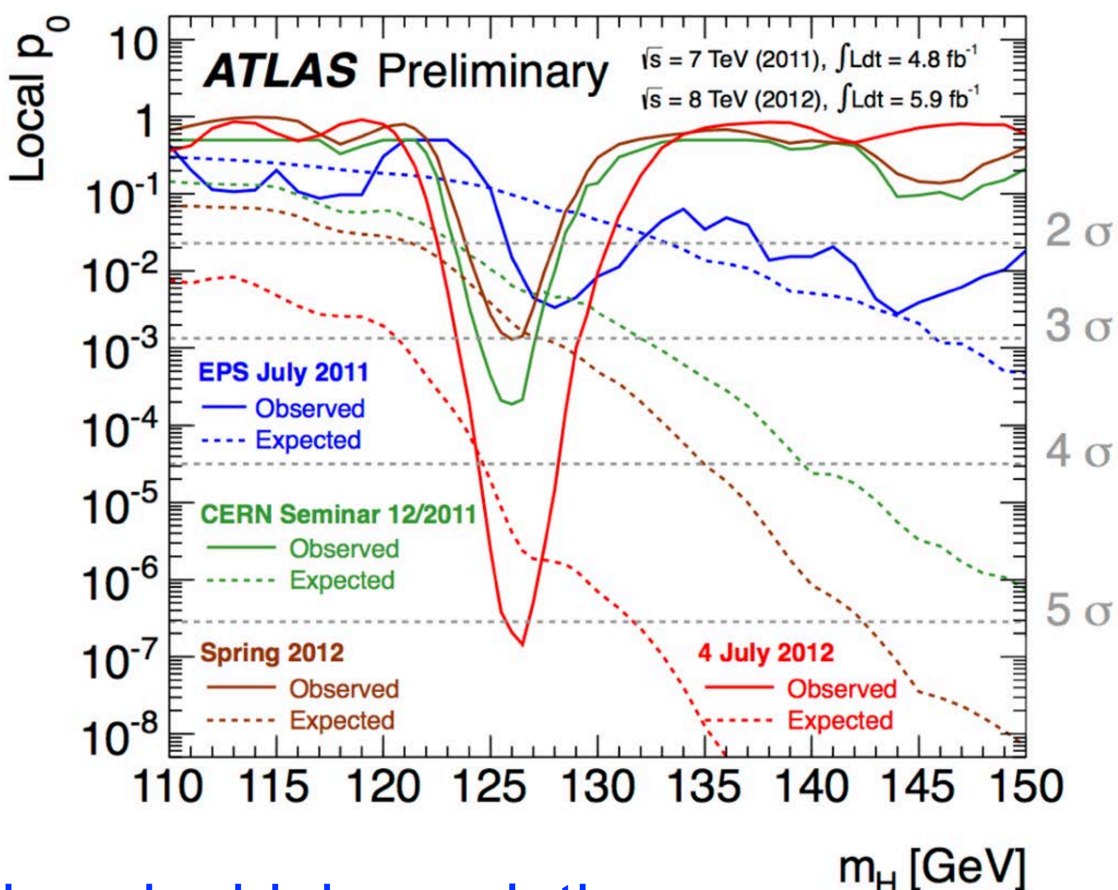
ATLAS-CONF-2011-162

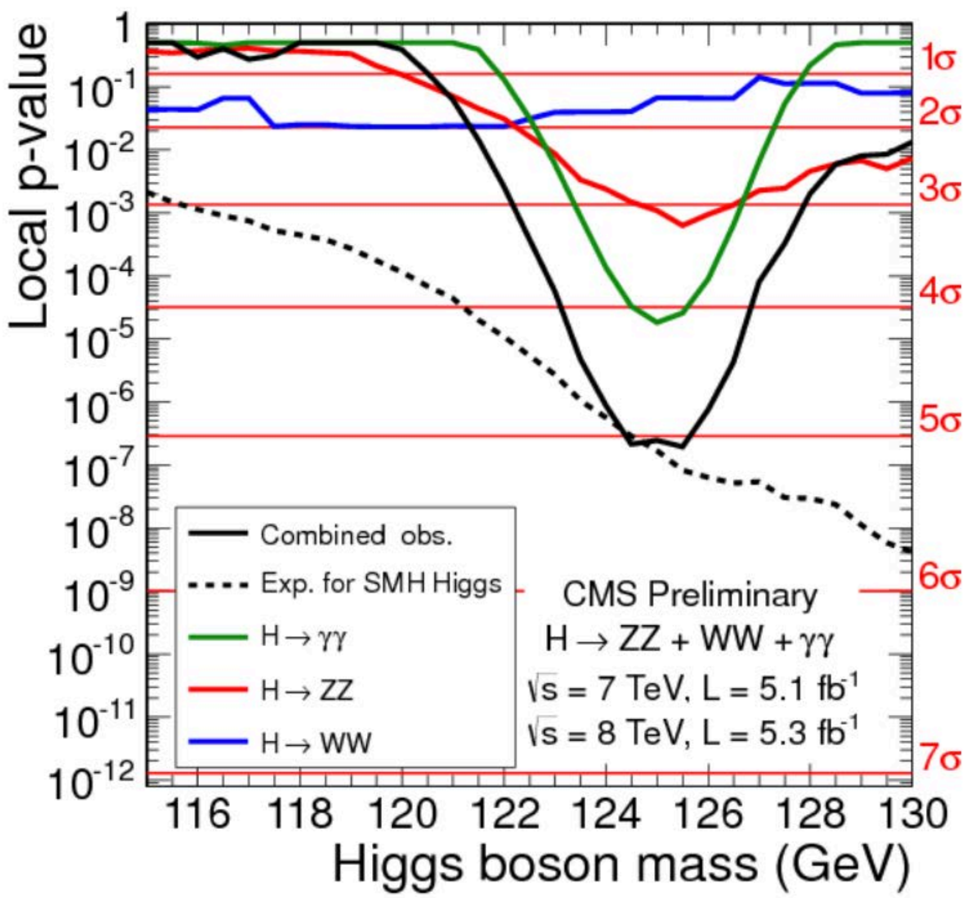


- Exclusion for M_H > 131 GeV at 95% CL
  - Higgs cornered!!
- No convincing excess so far, but a few “fluctuations”...

Discovery 4 July 2012

https://indico.cern.ch/event/197461/

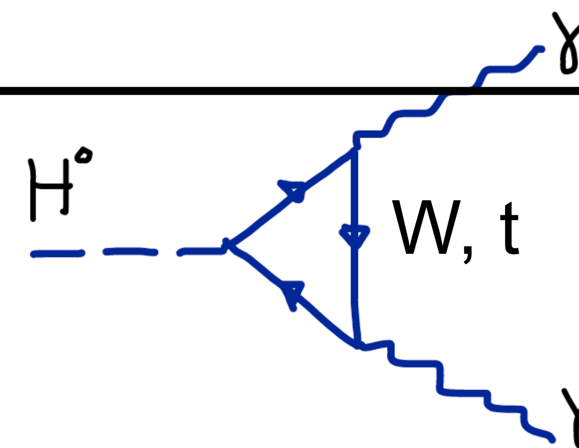




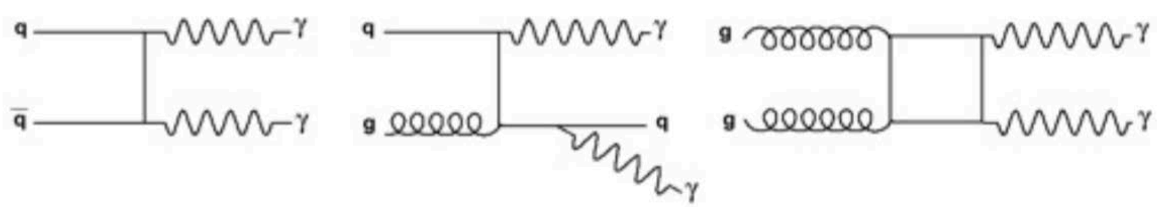
Driven by high resolution channels: γγ and ZZ

p-values: probability that the background fluctuates to give an excess as large as the average signal size measured or expected for a SM Higgs boson

$H \rightarrow \gamma\ \gamma$

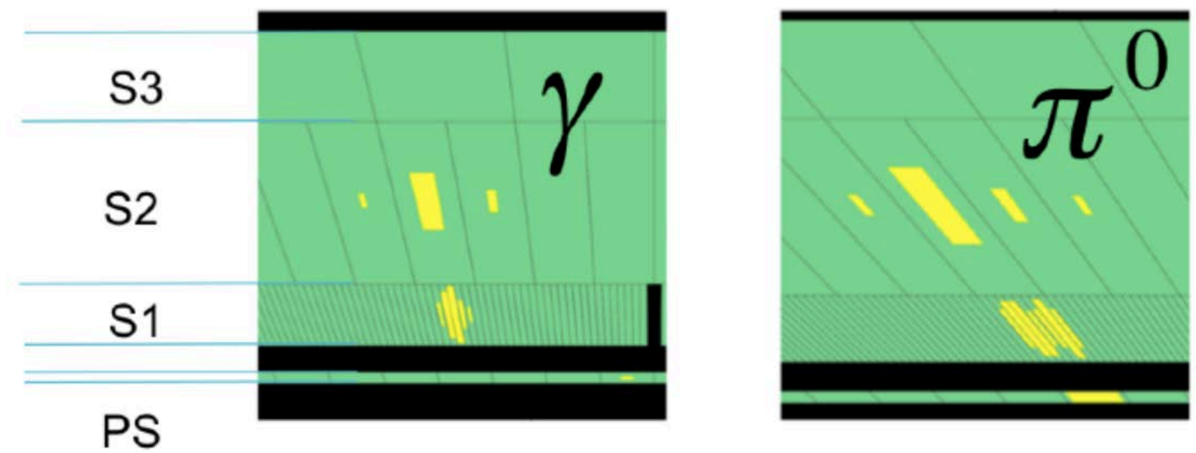


- Look for two isolated high energy photons
  - need good photon identification
- Large background
  - irreducible SM 2-photon production

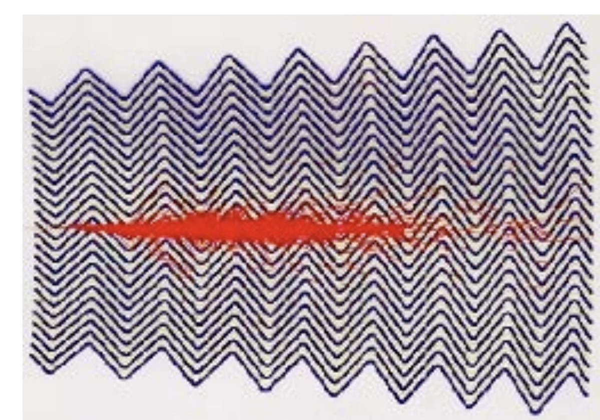


  - fake photons (neutral pions)
    - use shower shape in LAr calorimeter segmented readout

π^0-γ Rejection



- Reconstruct the 2-photon invariant mass
  - look for a signal mass bump over a large background



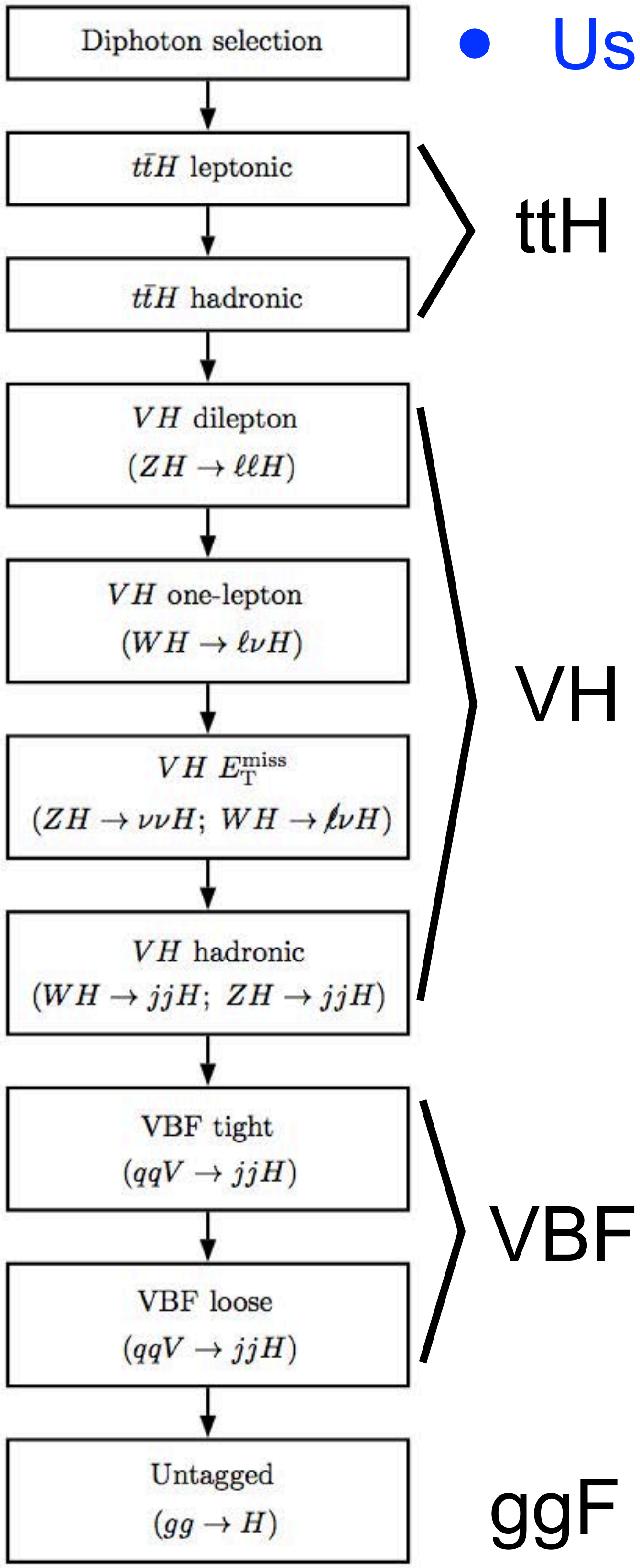
$$M_{\gamma\gamma}^2 = 2E_1E_2(1-\cos\alpha)$$

need good photon energy calibration
use $Z \rightarrow$ ee and MC extrapolation

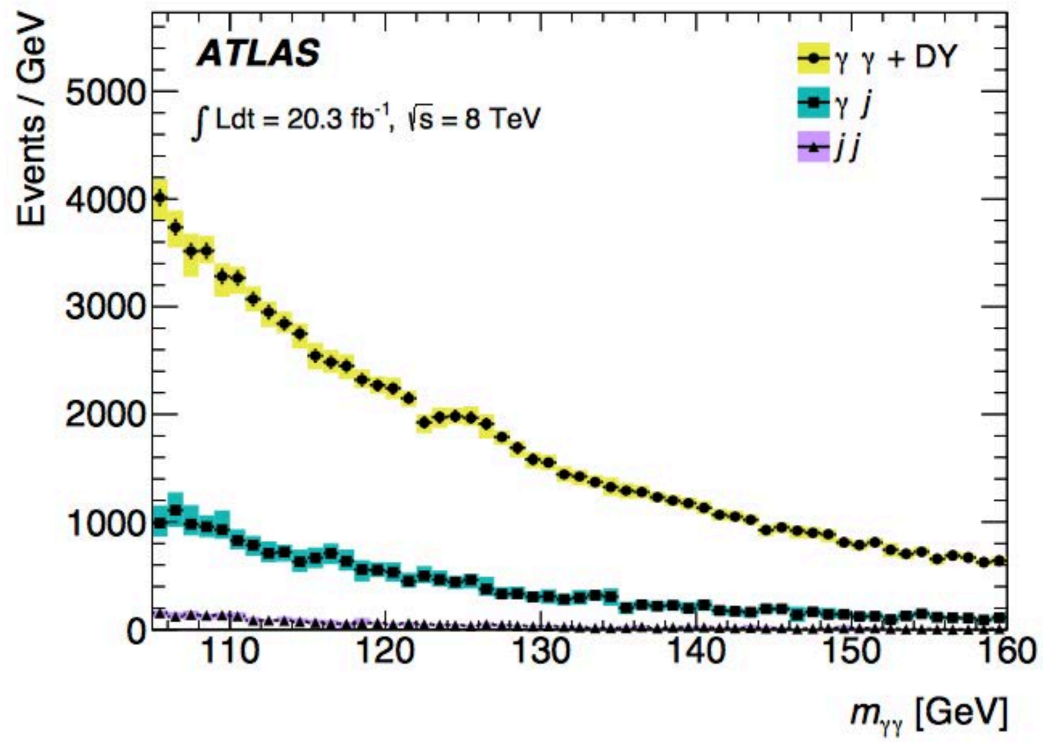
opening angle between the two photons: need good photon direction

H → γ γ

Phys Rev D 90, 112015 (2014)



- Use 12 categories targeting different production modes



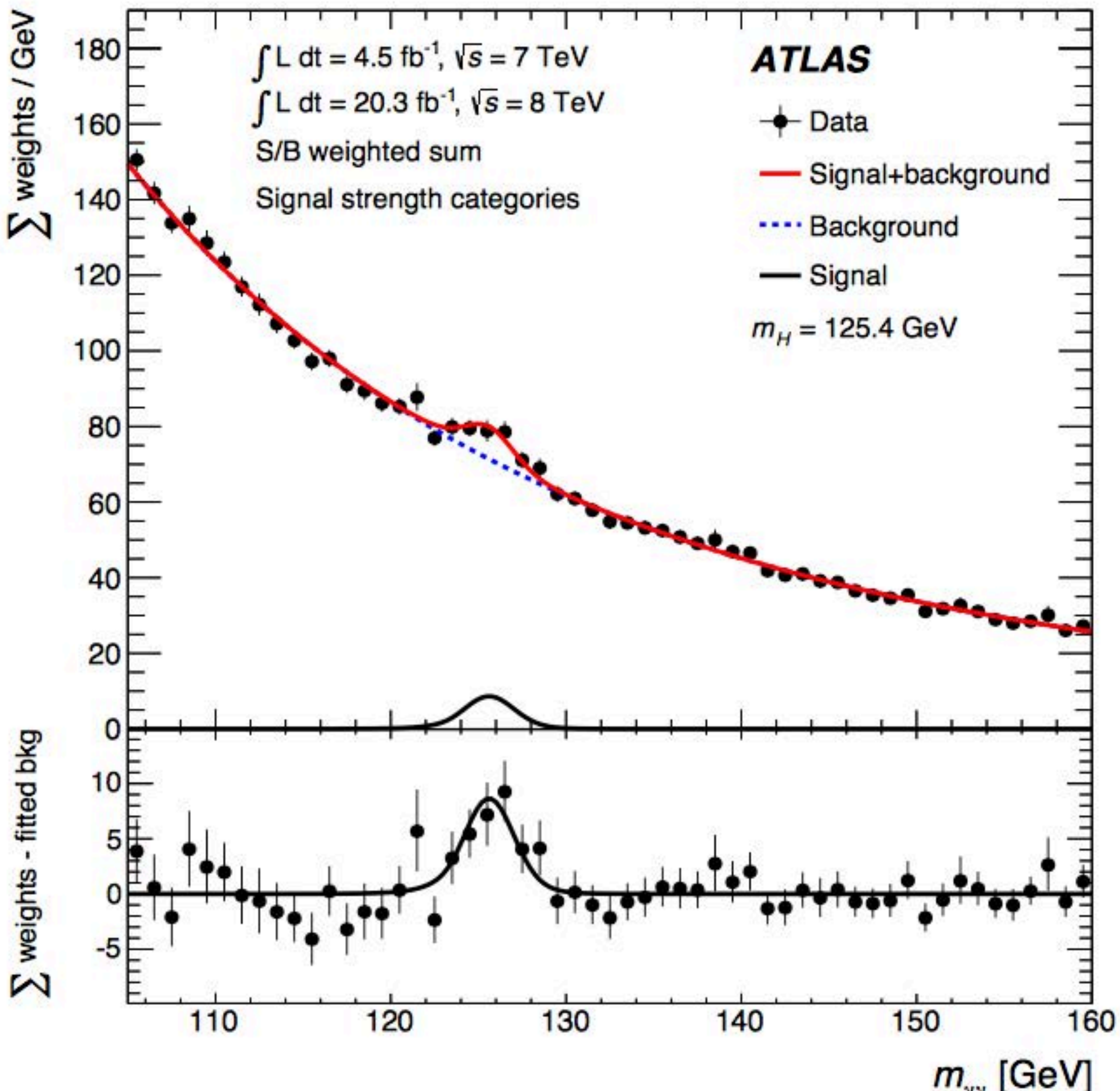
- Extract background from control regions

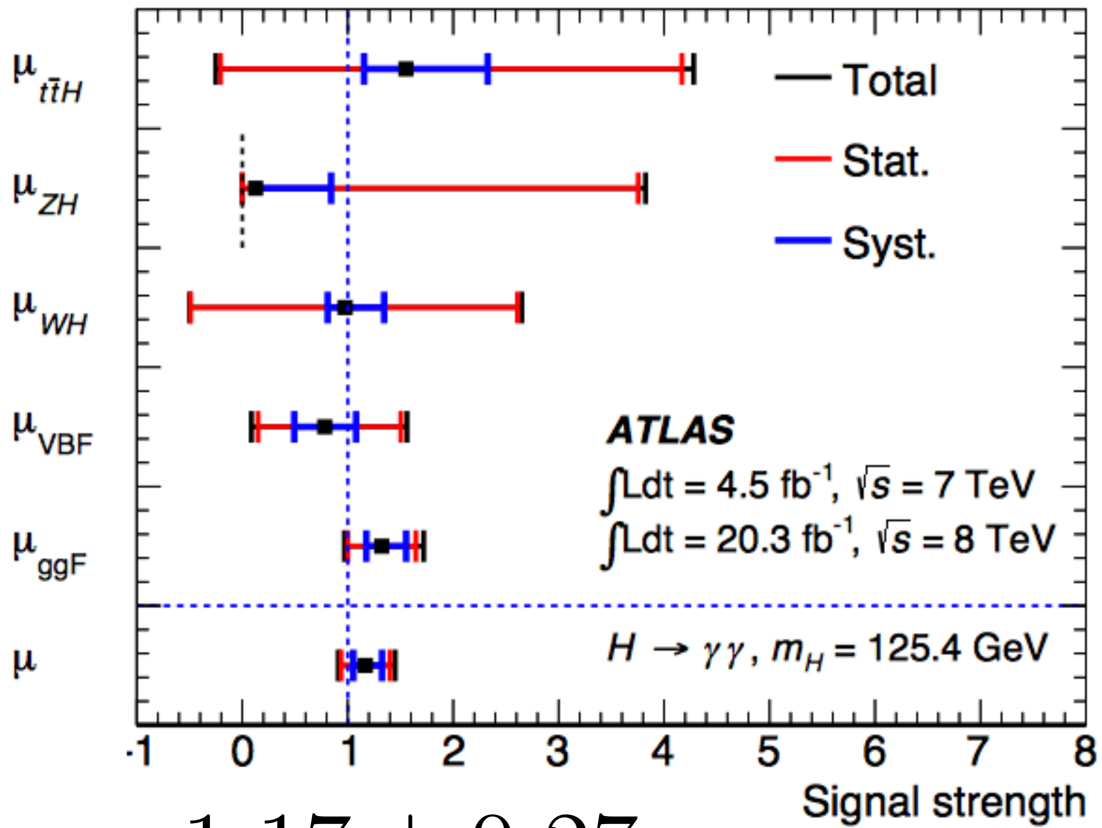
Uncertainty group	$\sigma_\mu^{syst.}$
Theory (yield)	0.09
Experimental (yield)	0.02
Luminosity	0.03
MC statistics	< 0.01
Theory (migrations)	0.03
Experimental (migrations)	0.02
Resolution	0.07
Mass scale	0.02
Background shape	0.02

- Theory uncertainty
  - QCD scale (ggF: ±7%)
  - PDF (ggF: ±7%)
  - BR: ±5%
  - leading uncertainty despite NNLO+NNL QCD calculations

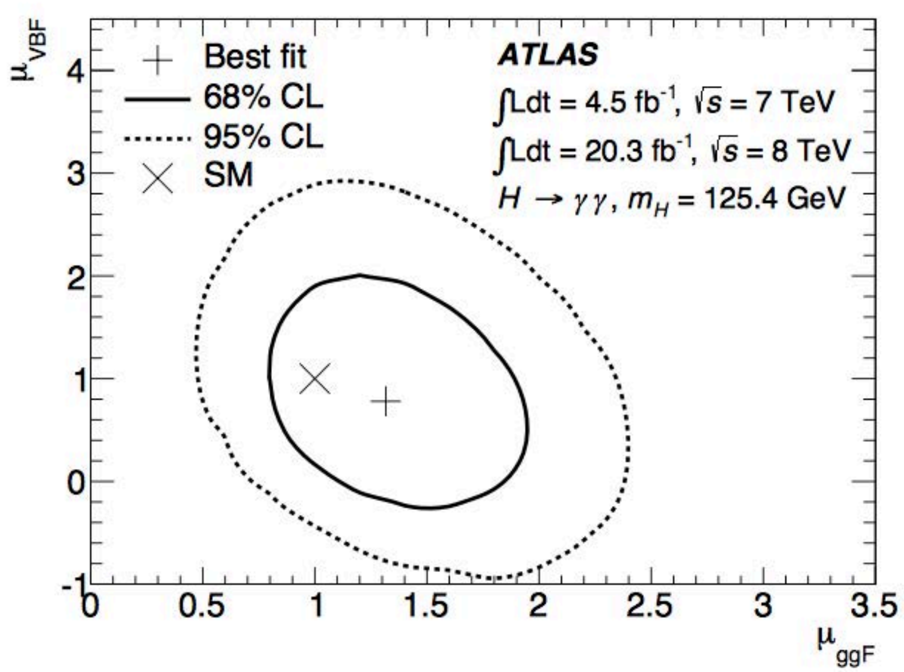
$H \to \gamma\ \gamma$

Phys Rev D 90, 112015 (2014)





$$\mu = 1.17 \pm 0.27$$

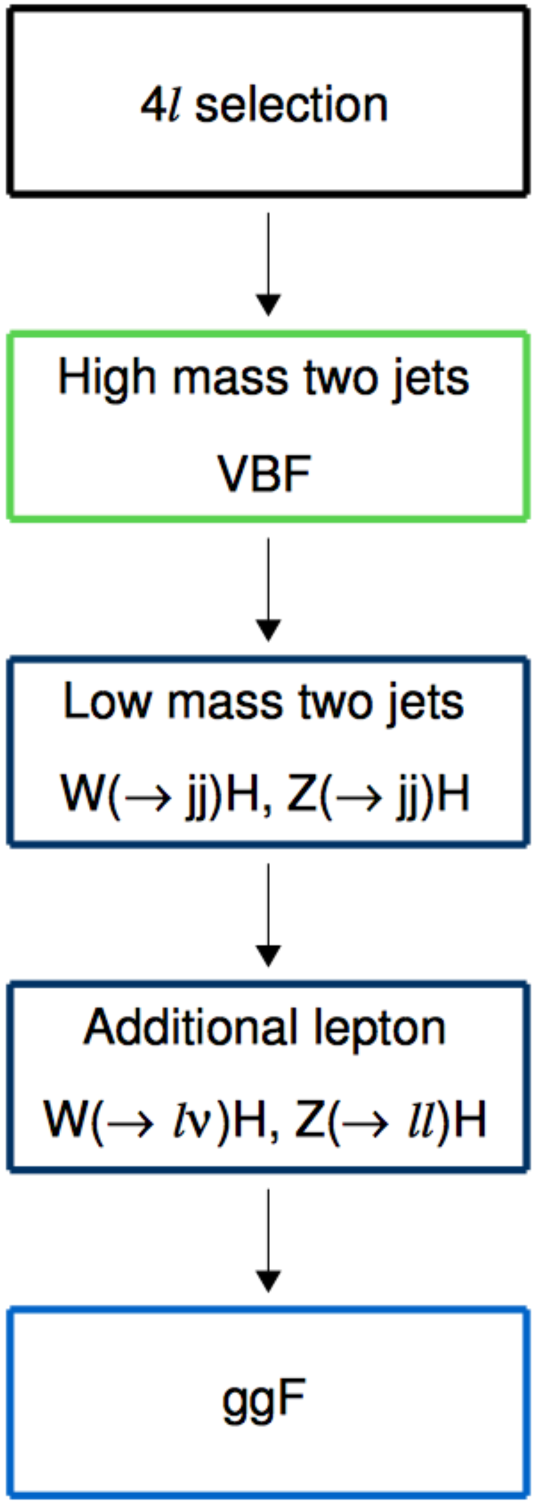


local p-value of 5.2σ

expected 4.6σ

H → Z Z* → 4 leptons (e or μ)

Phys Rev D 91, 012006 (2015)



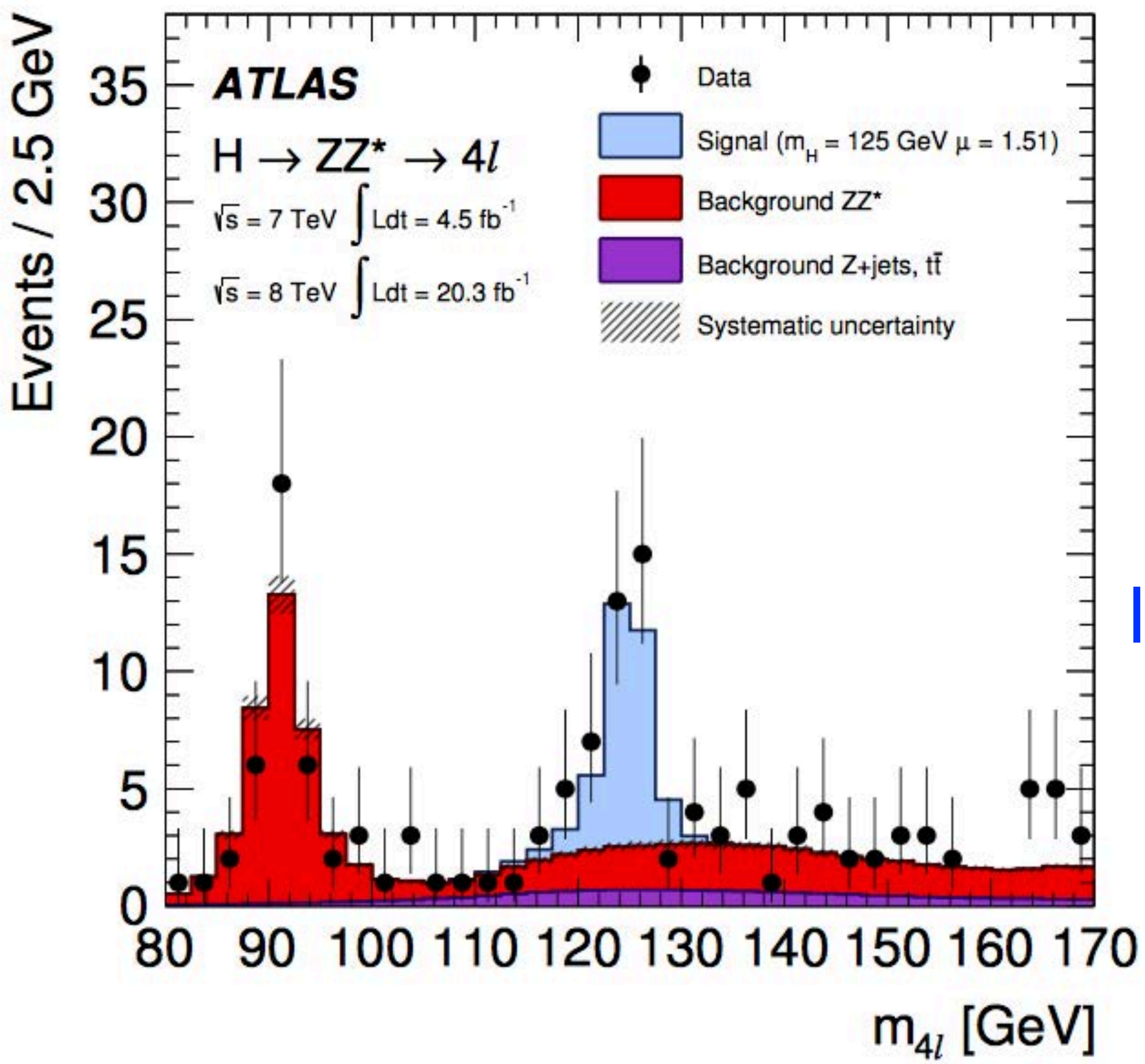
- Small signal rate
  - clean 4 lepton signature, lepton selection efficiency crucial
- Small background rate
  - irreducible: $ZZ^{(*)}$ continuum (interference negligible)
  - reducible: Z+bb, Z+jets, ttbar
- Use 4 categories: VBF, VH, ggF production modes
- Theory uncertainty dominates
  - but jet energy scale systematics important for the VBF and VH categories

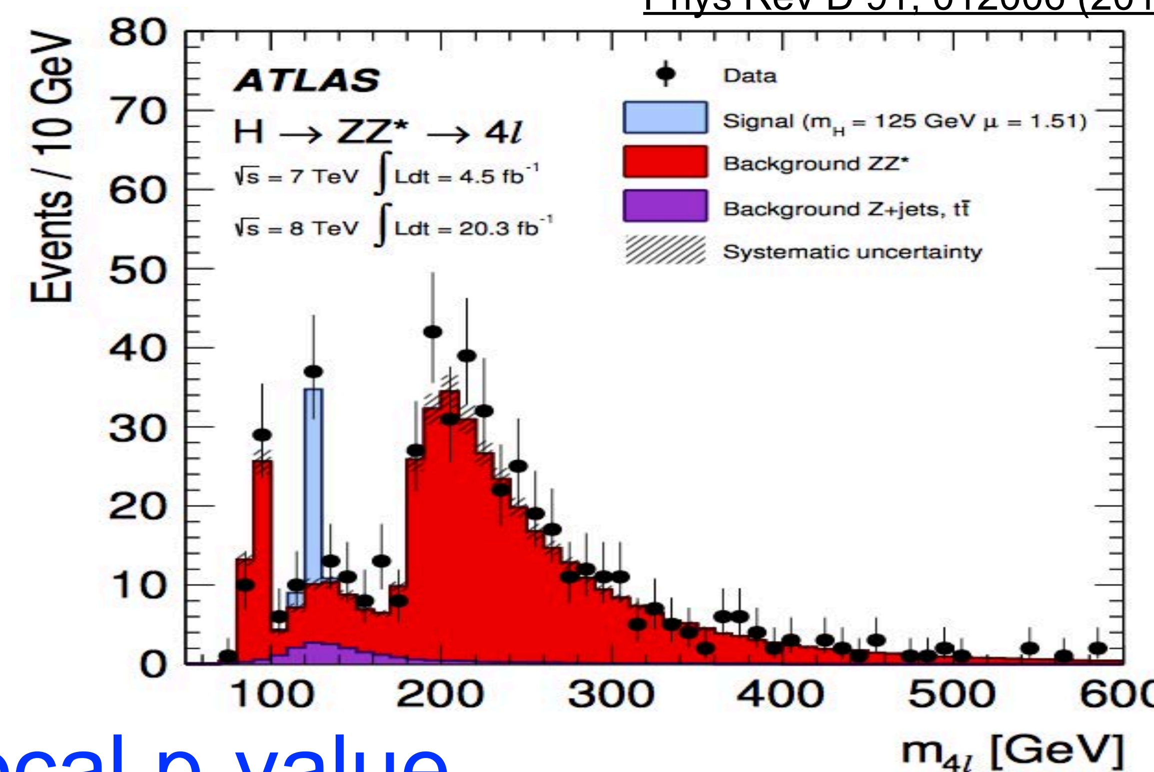
Phys Rev D 91, 012006 (2015)

Source of uncertainty	4μ	$2e2\mu$	$2\mu 2e$	$4e$	combined
Electron reconstruction and identification efficiencies	–	1.7%	3.3%	4.4%	1.6%
Electron isolation and impact parameter selection	–	0.07%	1.1%	1.2%	0.5%
Electron trigger efficiency	–	0.21%	0.05%	0.21%	<0.2%
$\ell\ell + ee$ backgrounds	–	–	3.4%	3.4%	1.3%
Muon reconstruction and identification efficiencies	1.9%	1.1%	0.8%	–	1.5%
Muon trigger efficiency	0.6%	0.03%	0.6%	–	0.2%
$\ell\ell + \mu\mu$ backgrounds	1.6%	1.6%	–	–	1.2%
QCD scale uncertainty					6.5%
PDF, α_s uncertainty					6.0%
$H \to ZZ^*$ branching ratio uncertainty					4.0%

H → Z Z* → 4 leptons (e or μ)

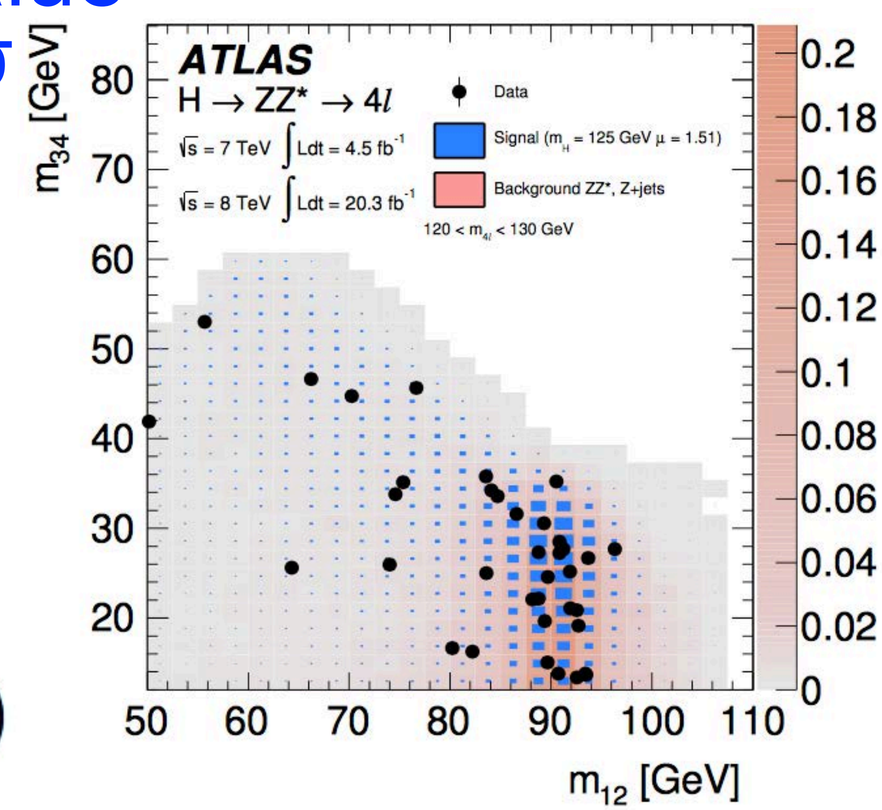
Phys Rev D 91, 012006 (2015)





local p-value of 8.1σ

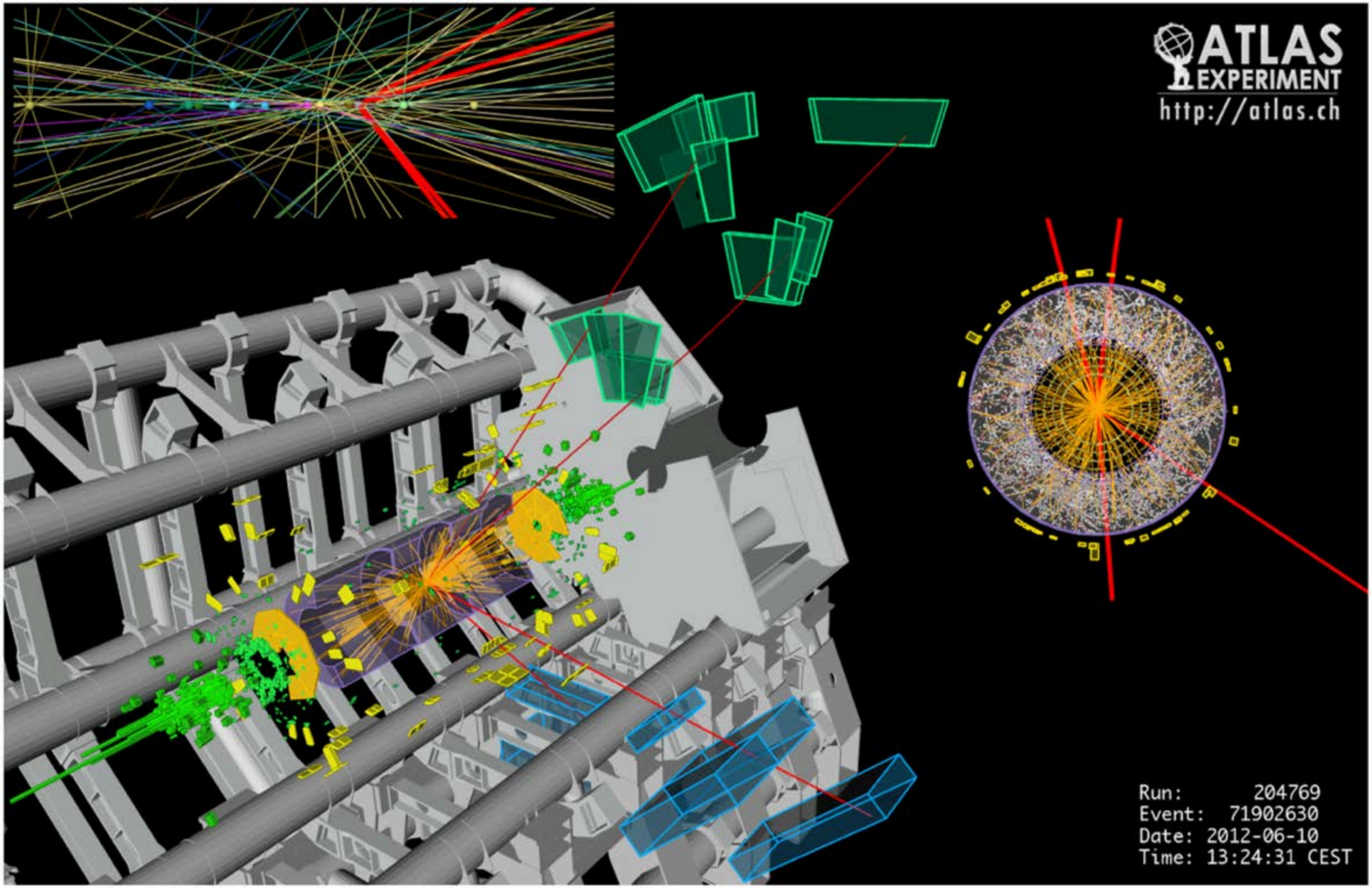
expected 6.2σ



- Combined signal strength

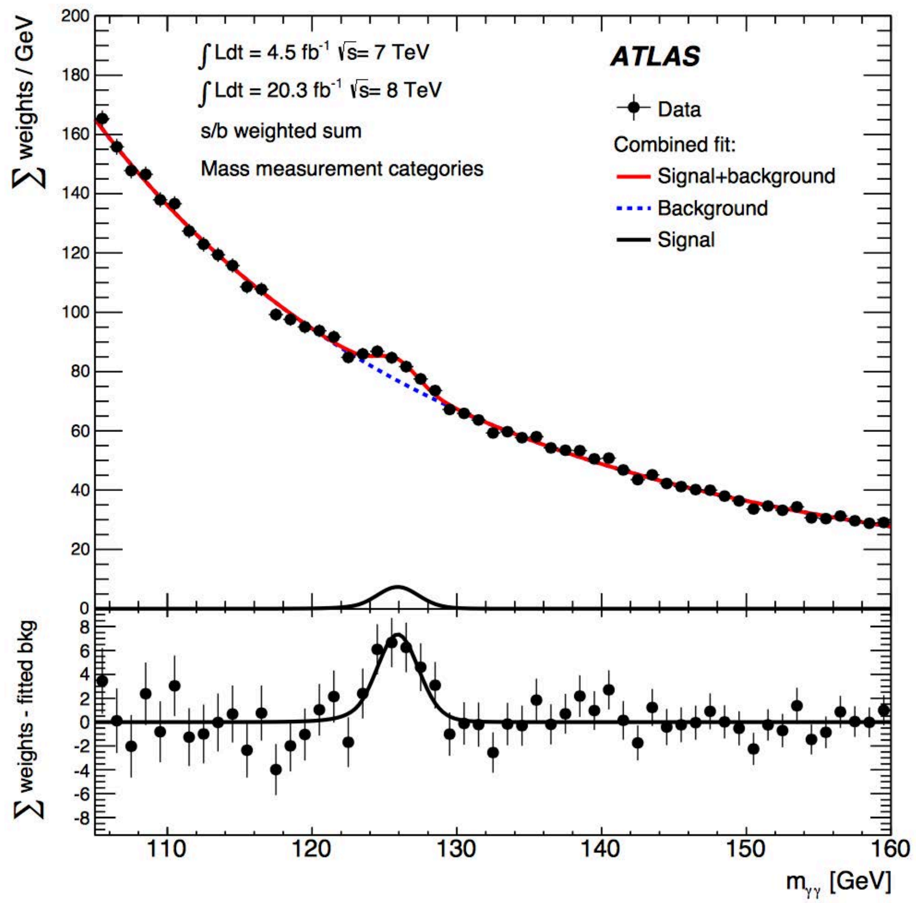
$$\mu \times B/B_{\mathrm{SM}} \text{ is } 1.44\ ^{+0.34}_{-0.31}\ (\mathrm{stat})\ ^{+0.21}_{-0.11}\ (\mathrm{syst})$$

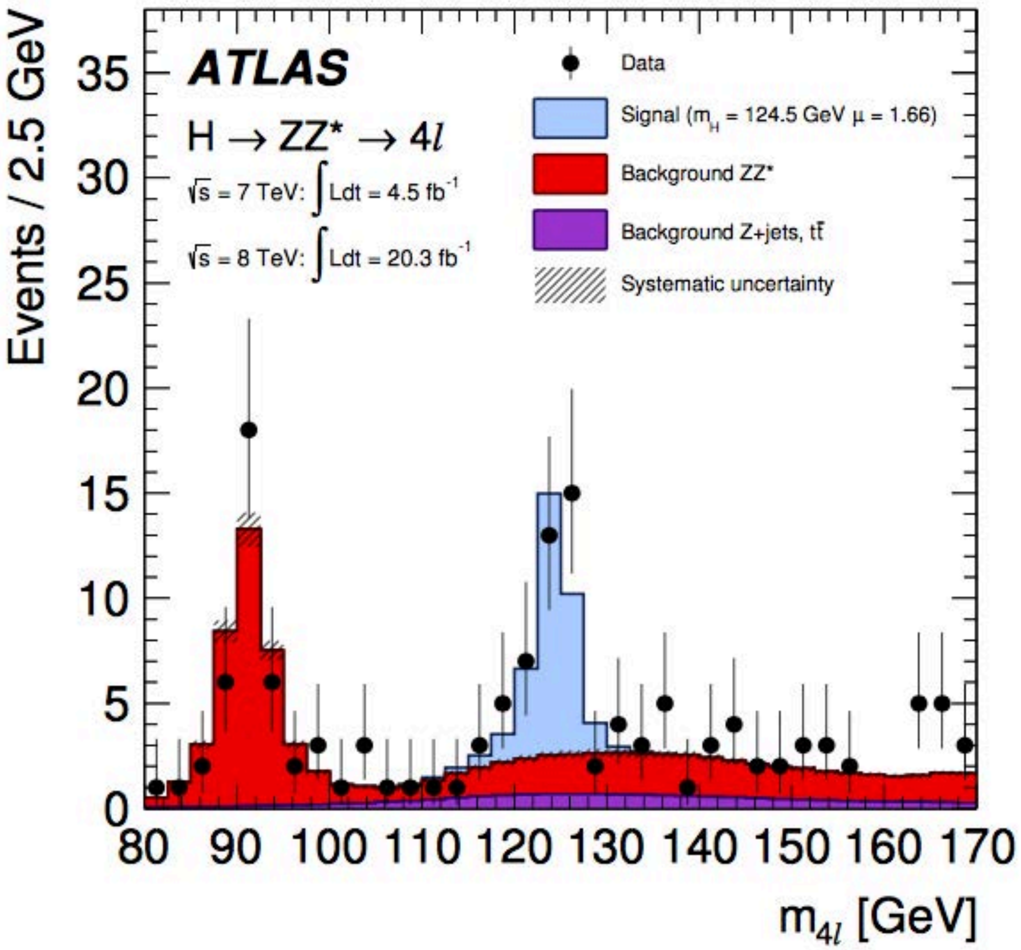
$H \rightarrow Z Z^* \rightarrow 4\mu$ candidate ($m_{4\mu}$ = 125.1 GeV)



ATLAS Higgs mass combination

Phys Rev D 90, 052004 (2014)





- Optimize event categories
  - converted vs unconverted
  - η-regions, p_T

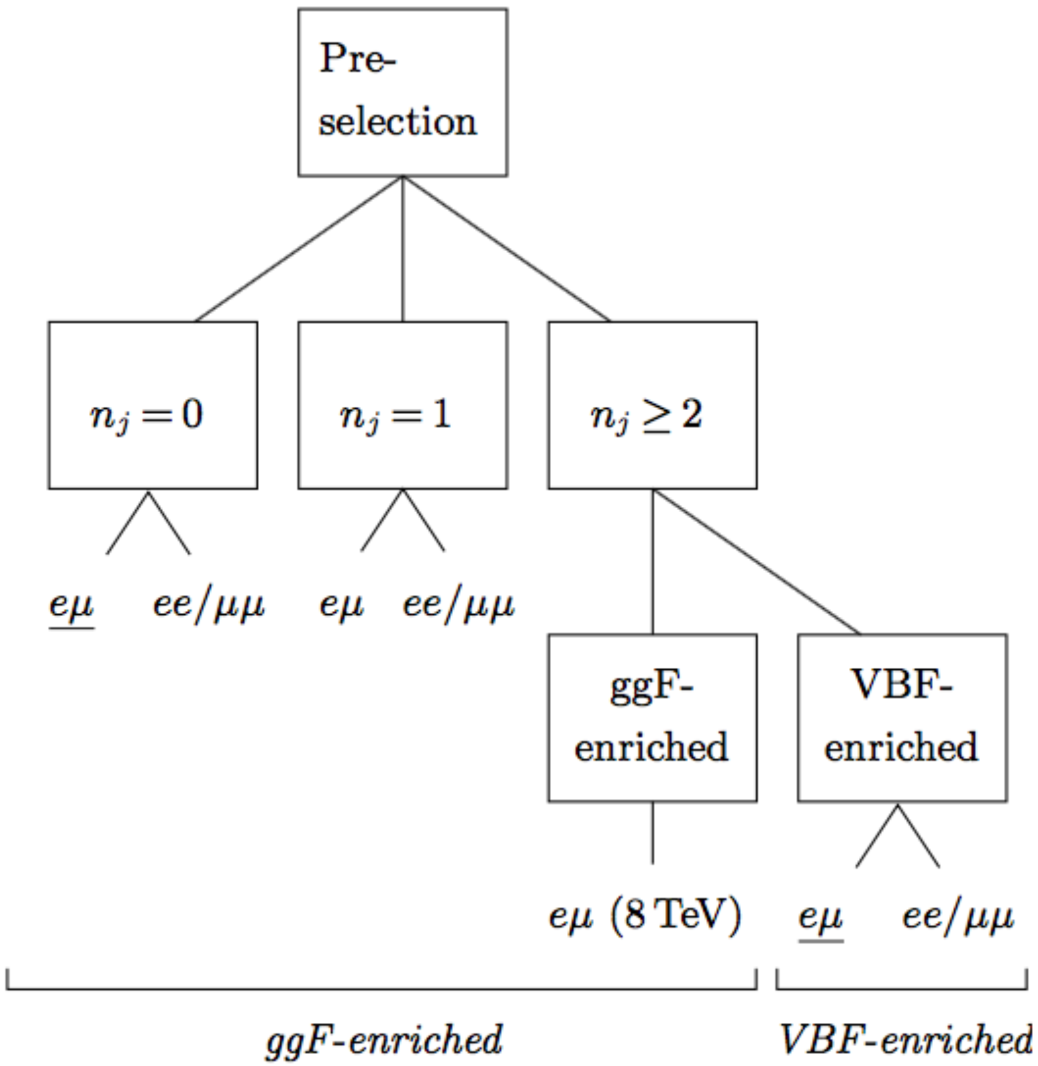
- 2-D background PDF: m4l, BDT
- Z mass constraint

Channel	Mass measurement [GeV]
$H \to \gamma\gamma$	$125.98 \pm 0.42\,(\text{stat}) \pm 0.28\,(\text{syst}) = 125.98 \pm 0.50$
$H \to ZZ^* \to 4\ell$	$124.51 \pm 0.52\,(\text{stat}) \pm 0.06\,(\text{syst}) = 124.51 \pm 0.52$
Combined	$125.36 \pm 0.37\,(\text{stat}) \pm 0.18\,(\text{syst}) = 125.36 \pm 0.41$

2σ compatibility

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

arXiv:1412:2641, accepted in PRD



$$m_T = \sqrt{\left(E_T^{\ell\ell} + p_T^{\nu\nu}\right)^2 - \left|\boldsymbol{p}_T^{\ell\ell} + \boldsymbol{p}_T^{\nu\nu}\right|^2}$$

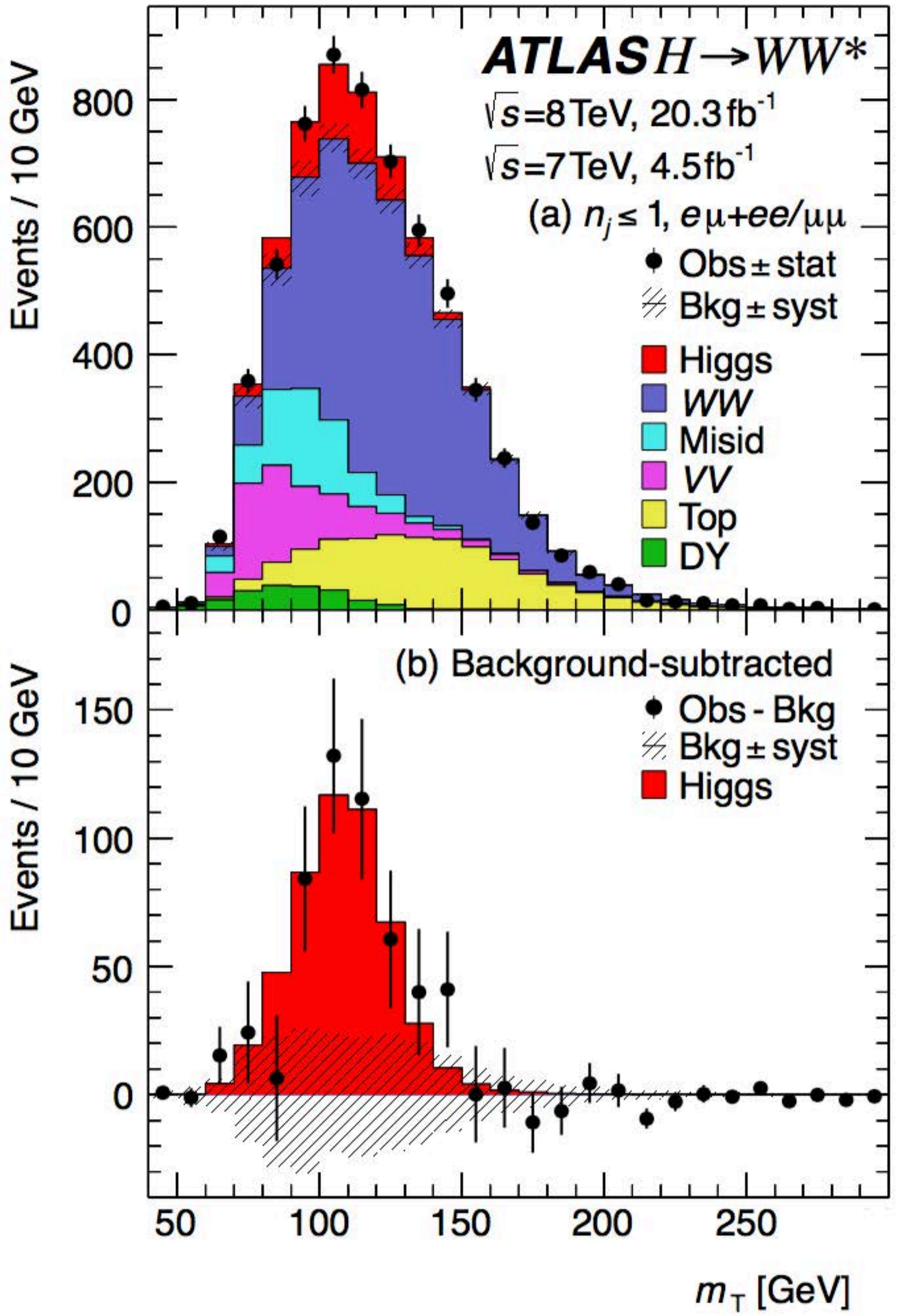
$$E_T^{\ell\ell} = \sqrt{(p_T^{\ell\ell})^2 + (m_{\ell\ell})^2}$$

$$\vec{p}_T^{\,\nu\nu} = \vec{p}_T^{\,\rm miss} \qquad p_T^{\nu\nu} = E_T^{\rm miss}$$

- Complicated signature: leptons, jets, missing transverse momentum
  - escaping neutrinos: no mass peak
- Large background rate, complicated processes
  - WW continuum, top, W+jets, multijets (fake leptons)
- Large signal rate
  - scalar Higgs transmit some spin correlation to W pair leptonic decay: discriminant against WW continuum
  - enough to separate the VBF and ggF production modes
- Event categories
  - N_{jets}, same/different flavour leptons
    - ggF or VBF enriched: p_T of subleading lepton, m_{ll}
- Fit to
  - m_T for ggF mode
  - BDT discriminant for VBF mode

$H \to WW^* \to \ell\nu\ell\nu$

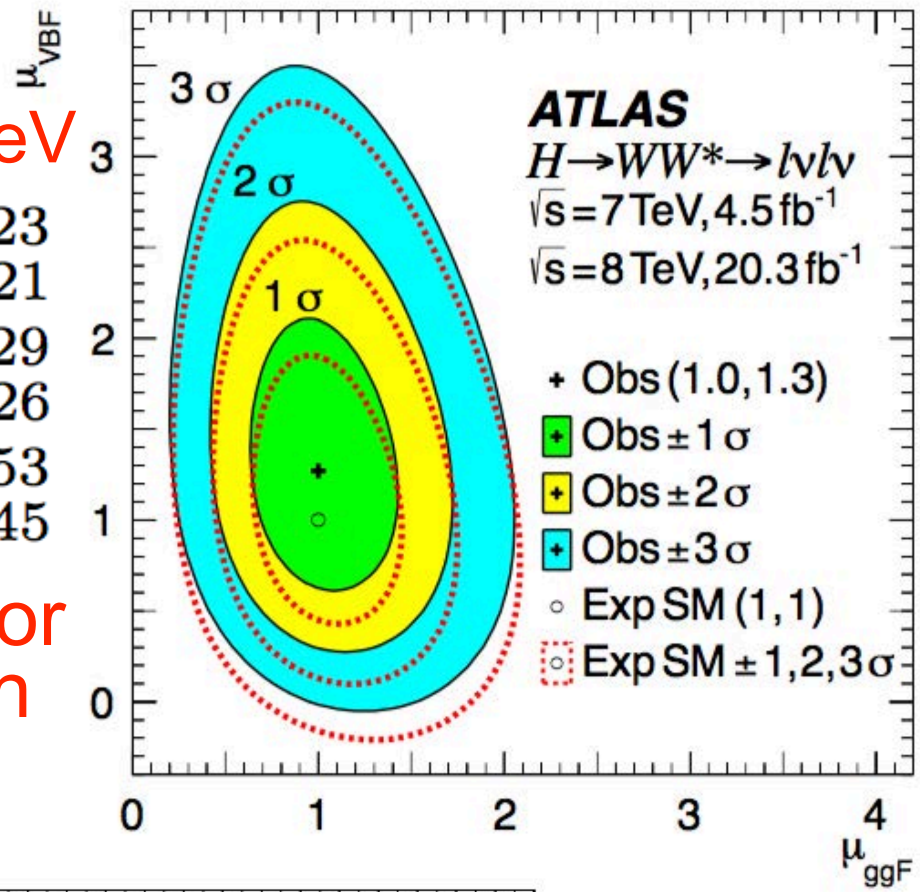
arXiv:1412:2641, accepted in PRD

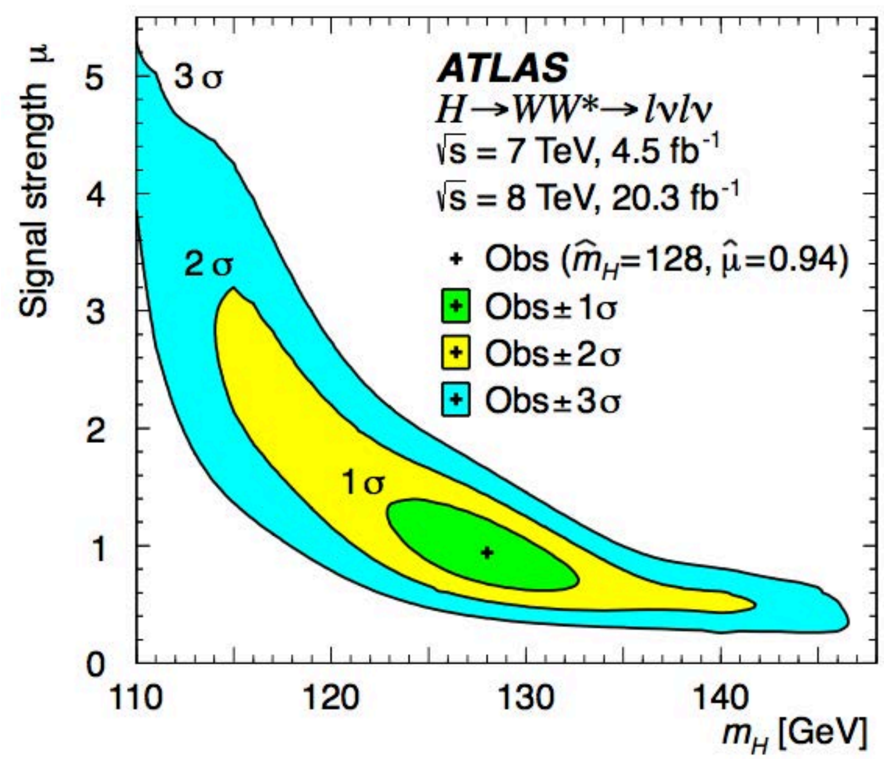


at M_H = 125.36 GeV

$$\mu = 1.09\,^{+0.23}_{-0.21}$$
$$\mu_{ggF} = 1.02\,^{+0.29}_{-0.26}$$
$$\mu_{VBF} = 1.27\,^{+0.53}_{-0.45}$$

3.2σ evidence for VBF production





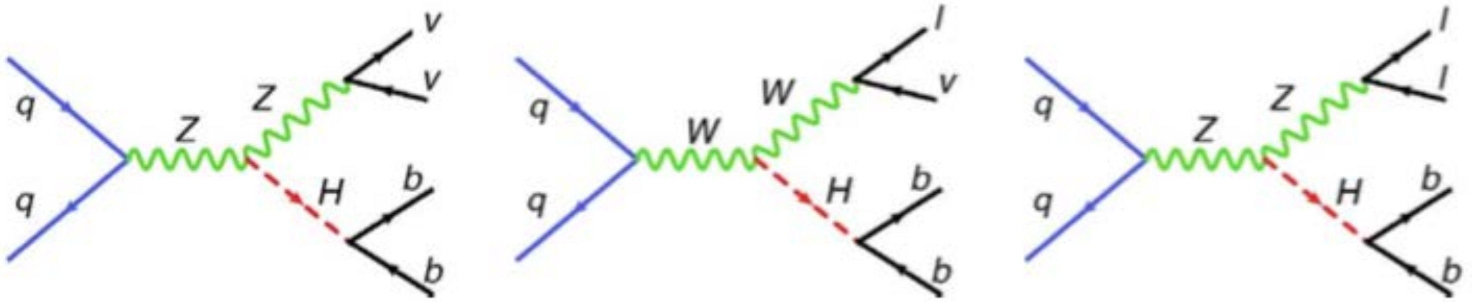
local p-value of 6.1σ

expected 5.8σ

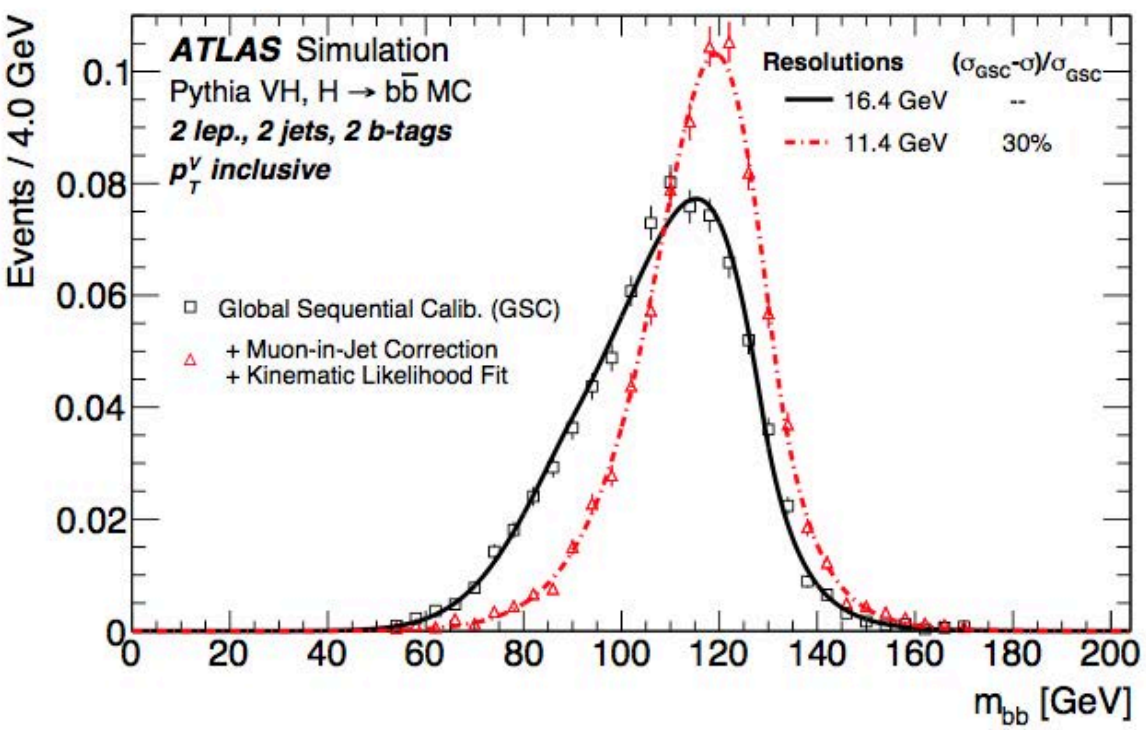
$VH \to Vb\bar{b}$ V = W,Z

JHEP 01(2015) 069

- Large branching fraction, dominating the H width
- Three channels: 0, 1, 2 leptons
- Categories
  - 2 $p_T(V)$ regions
  - 4 b-tag regions
  - 2 jet bins (2 and 3 jets)



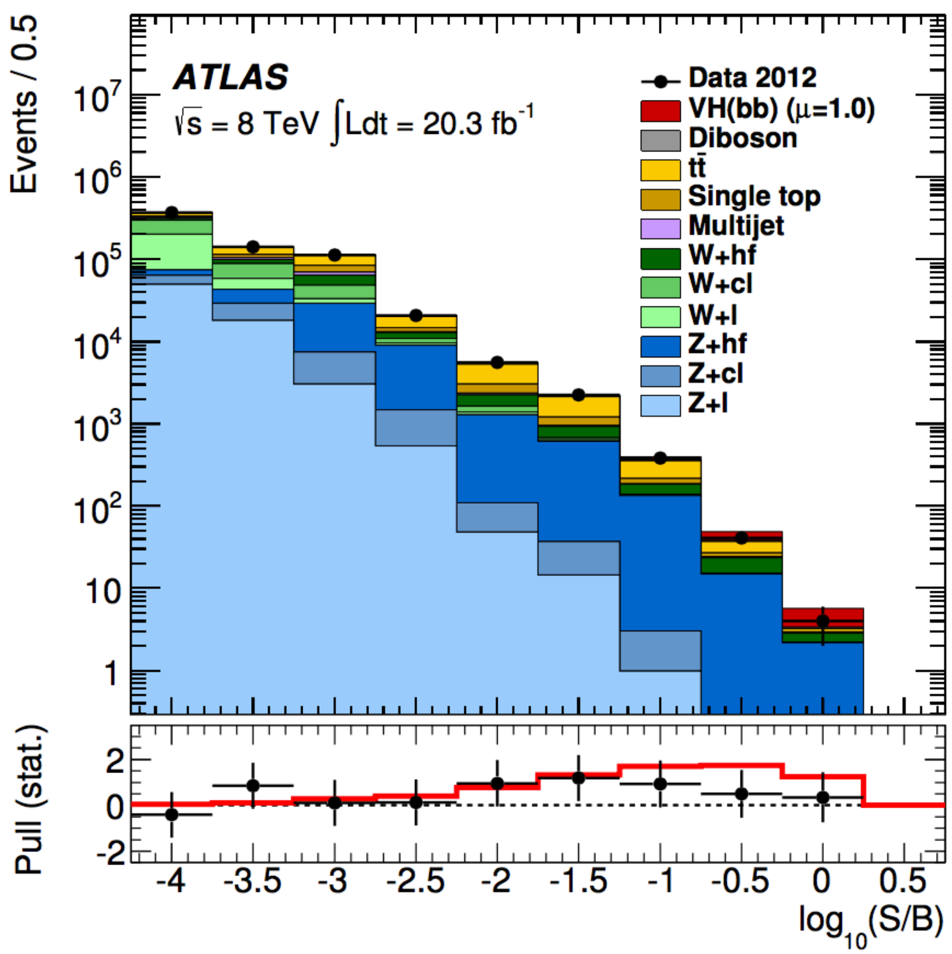
- Large top and Z+heavy flavour background
- For 2 b-tag, use BDT (m_{bb}, $p_T(V)$, b-tab discriminant)
- Statistically limited
- Main experimental uncertainties
  - jet energy scale
  - b-tagging
  - background modeling (W+bb, +bl)



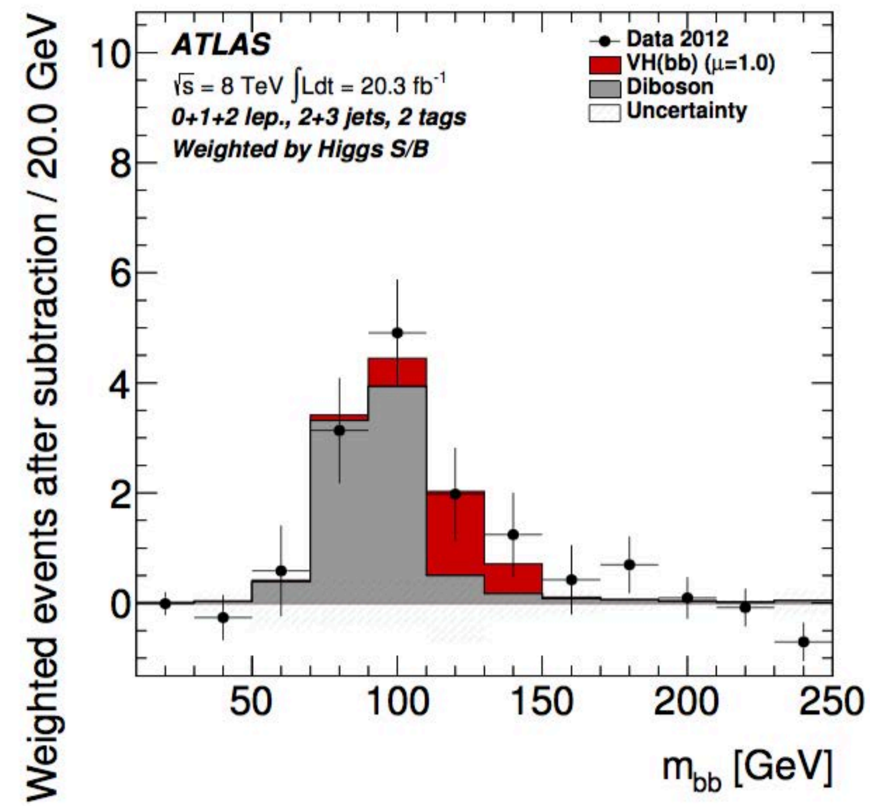
$VH \rightarrow Vb\bar{b}$ $V = W,Z$

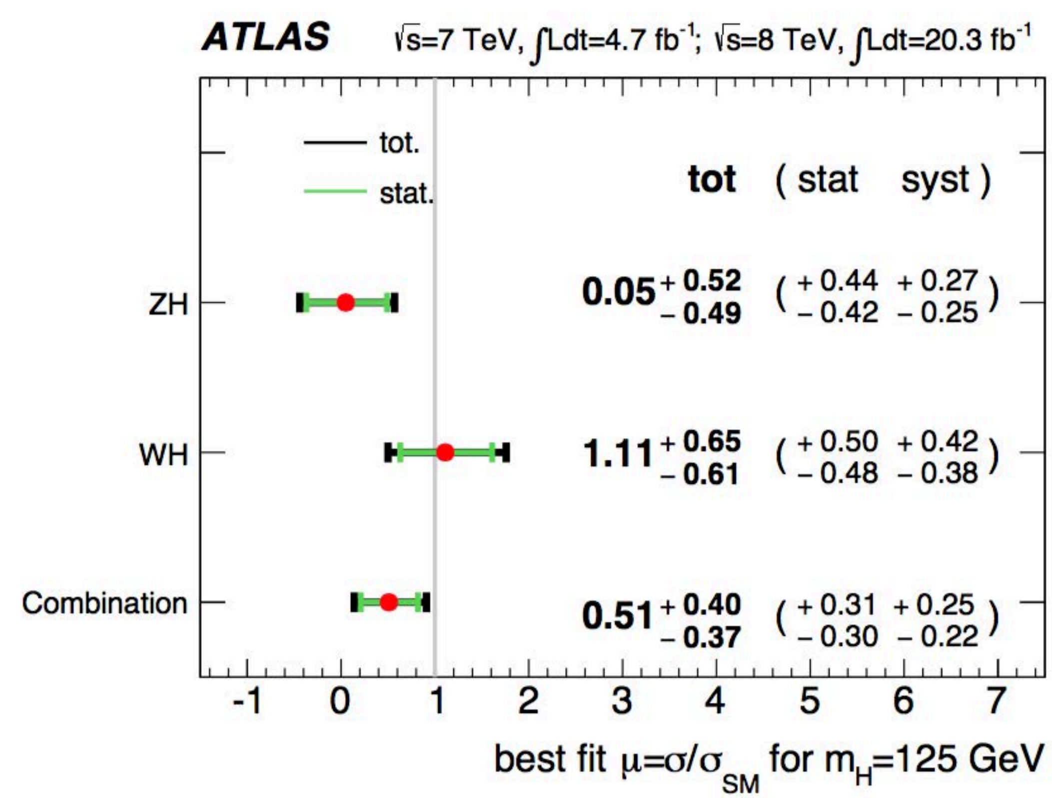
JHEP 01(2015) 069

- Not yet seen any significant signal
  - local p-value of 1.4σ expected 2.6σ



S and B taken from BDT output bin of each event. B from global fit.



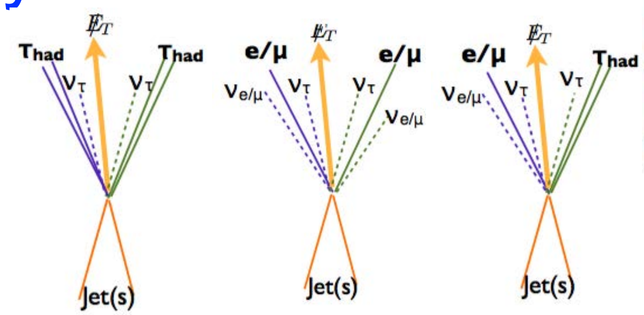


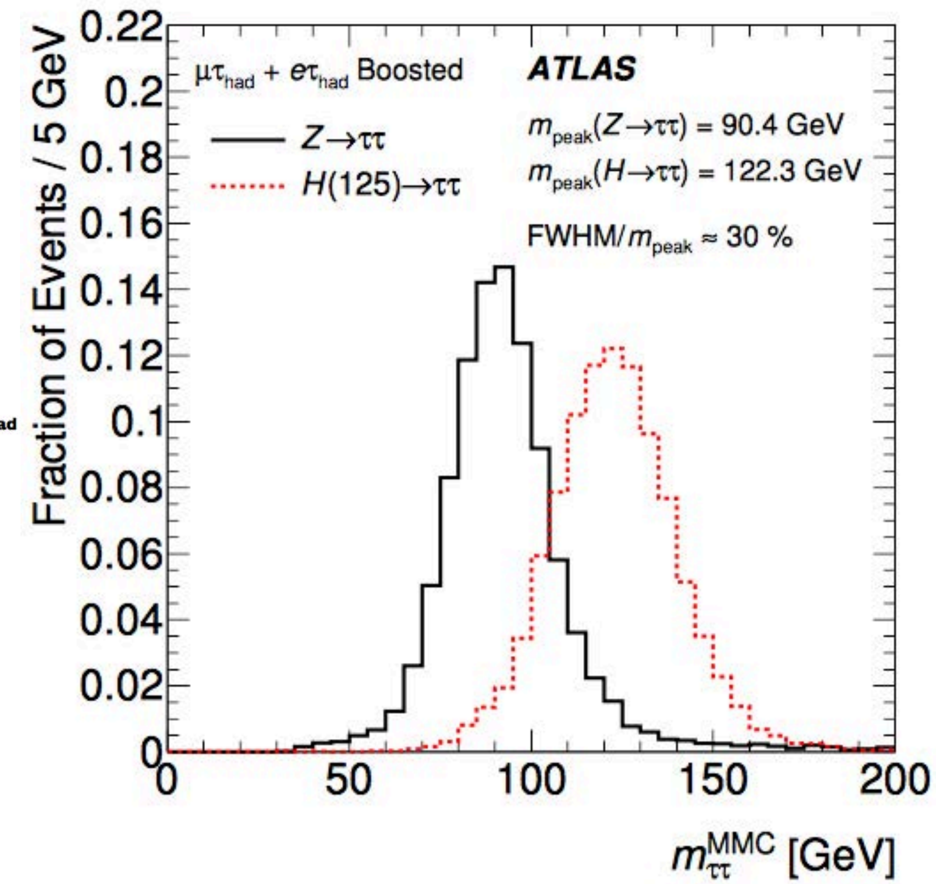
$H \to \tau\tau$

arXiv:1501.04943, accepted in JHEP

- Direct probe of fermionic coupling
  - large branching ratio
  - complex analysis
- Three channels: taus decay mode
  - had-had, lep-lep, had-lep
- Two main categories
  - VBF
  - Boosted (~ggH with $p_T(H)$ > 100 GeV)
    - signal discrimination, mass determination
- BDT with main discriminant the di-tau invariant mass (MMC missing mass calculator, key to the analysis)
  - solving an underconstrained system of 6 to 8 unknowns related to the neutrinos
  - use the measured (p_x^{miss} , p_y^{miss}) and visible tau-tau mass as constraints
  - takes into account the E_T^{miss} resolution and tau decay topology

H: simulation
Z: embeddings



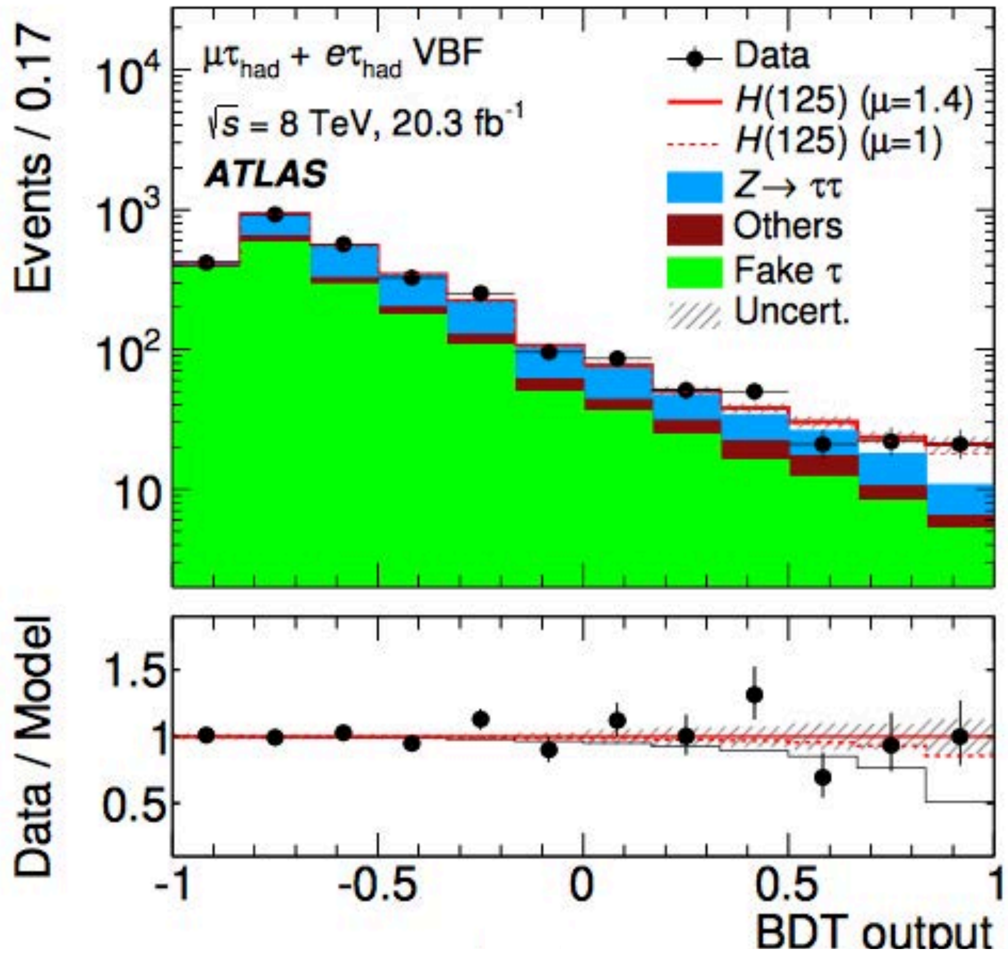


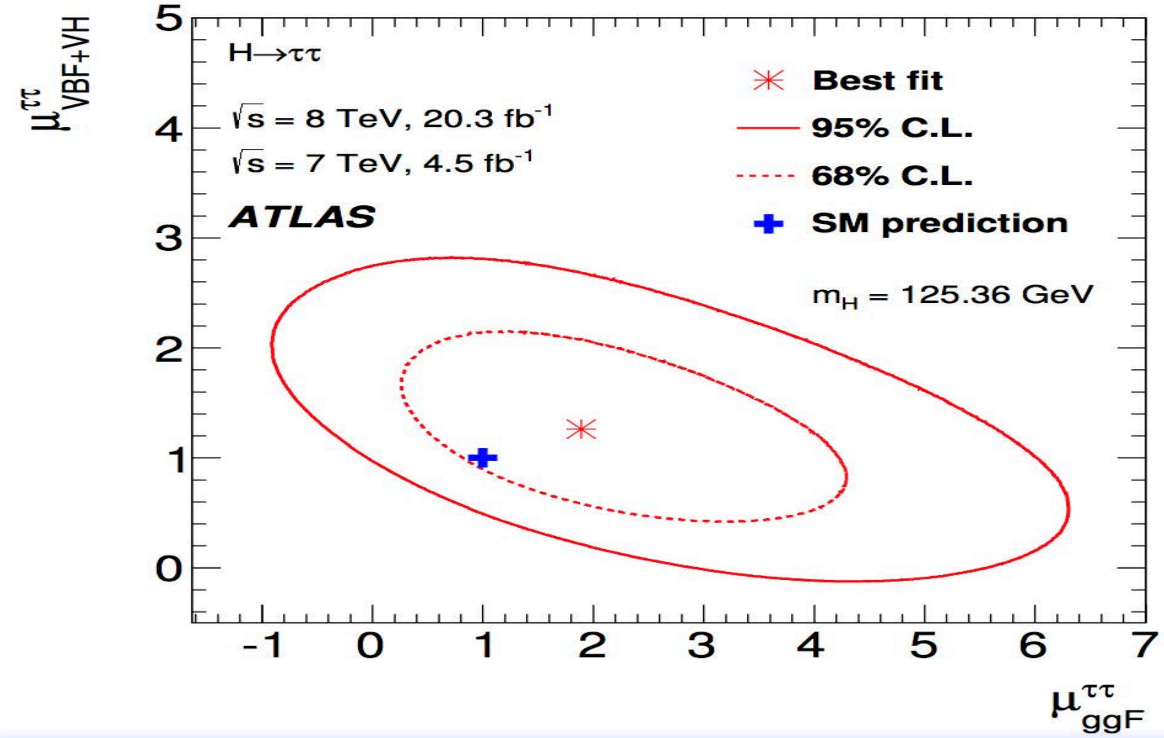
Source of Uncertainty	Uncertainty on μ
Signal region statistics (data)	$^{+0.27}_{-0.26}$
Jet energy scale	$\pm$ 0.13
Tau energy scale	$\pm$ 0.07
Tau identification	$\pm$ 0.06
Background normalisation	$\pm$ 0.12
Background estimate stat.	$\pm$ 0.10
BR ($H \to \tau\tau$)	$\pm$ 0.08
Parton shower/Underlying event	$\pm$ 0.04
PDF	$\pm$ 0.03
Total sys.	$^{+0.33}_{-0.26}$
Total	$^{+0.43}_{-0.37}$

forward/central intercalibration
Ztautau and top

H → ττ

arXiv:1501.04943, accepted in JHEP





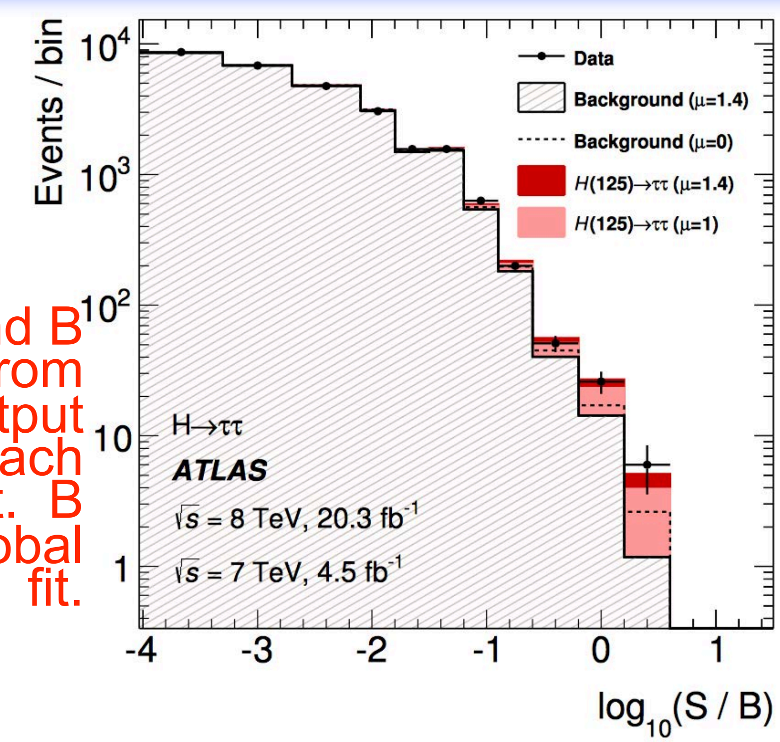
$$\mu = 1.43\ ^{+0.27}_{-0.26}(\text{stat.})\ ^{+0.32}_{-0.25}(\text{syst.})\ \pm 0.09(\text{theory syst.})$$

4.5σ evidence for the tau Yukawa coupling

expected 3.4σ

Channel and Category	Expected Significance (σ)	Observed Significance (σ)
$\tau_{lep}\tau_{lep}$ VBF	1.15	1.88
$\tau_{lep}\tau_{lep}$ Boosted	0.57	1.72
$\tau_{lep}\tau_{lep}$ Total	1.25	2.40
$\tau_{lep}\tau_{had}$ VBF	2.11	2.23
$\tau_{lep}\tau_{had}$ Boosted	1.11	1.01
$\tau_{lep}\tau_{had}$ Total	2.33	2.33
$\tau_{had}\tau_{had}$ VBF	1.70	2.23
$\tau_{had}\tau_{had}$ Boosted	0.82	2.56
$\tau_{had}\tau_{had}$ Total	1.99	3.25
Combined	3.43	4.54

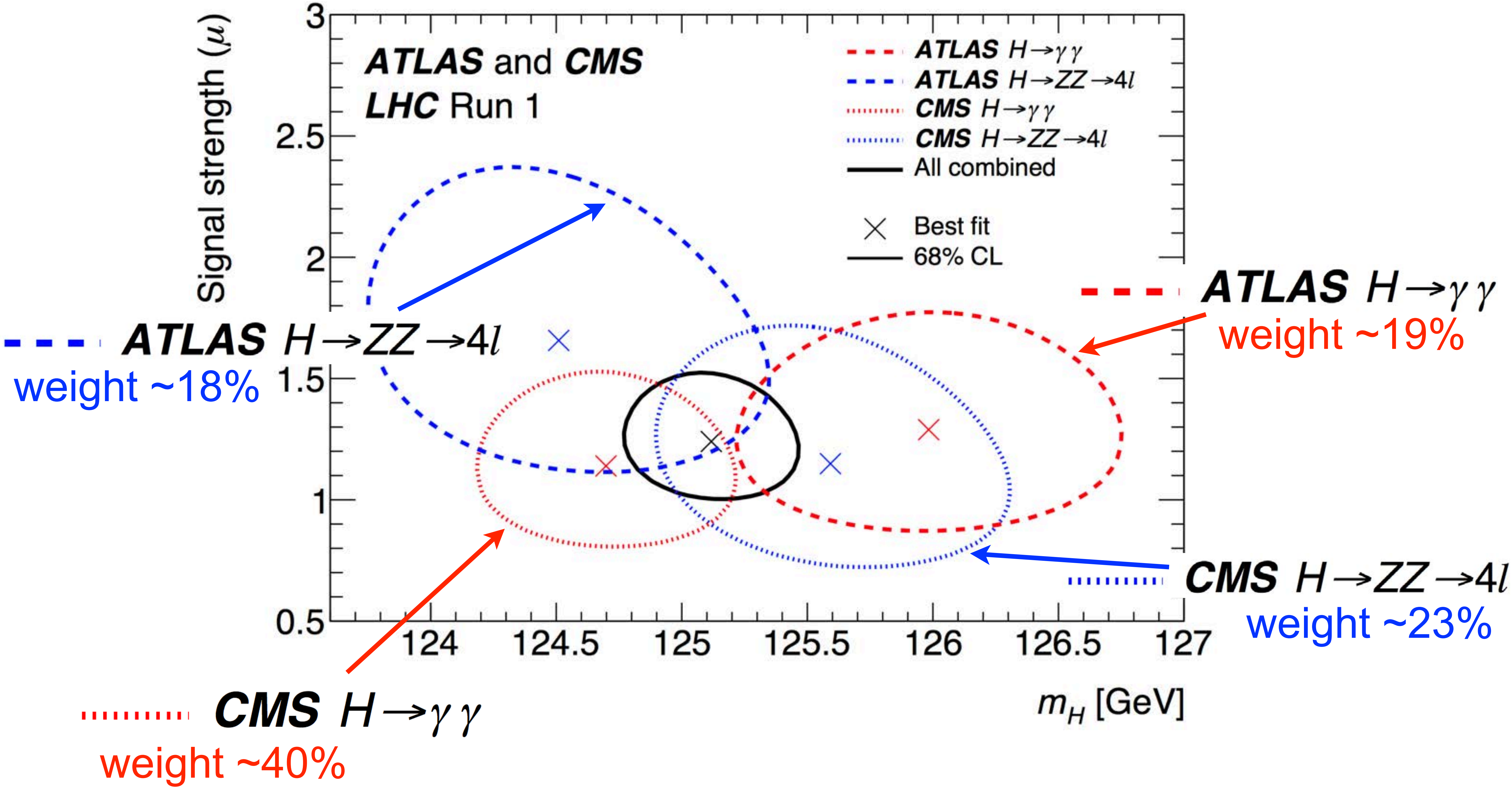
S and B taken from BDT output bin of each event. B from global fit.



ATLAS+CMS Higgs mass combination

arXiv:1503:07589, accepted in PRL

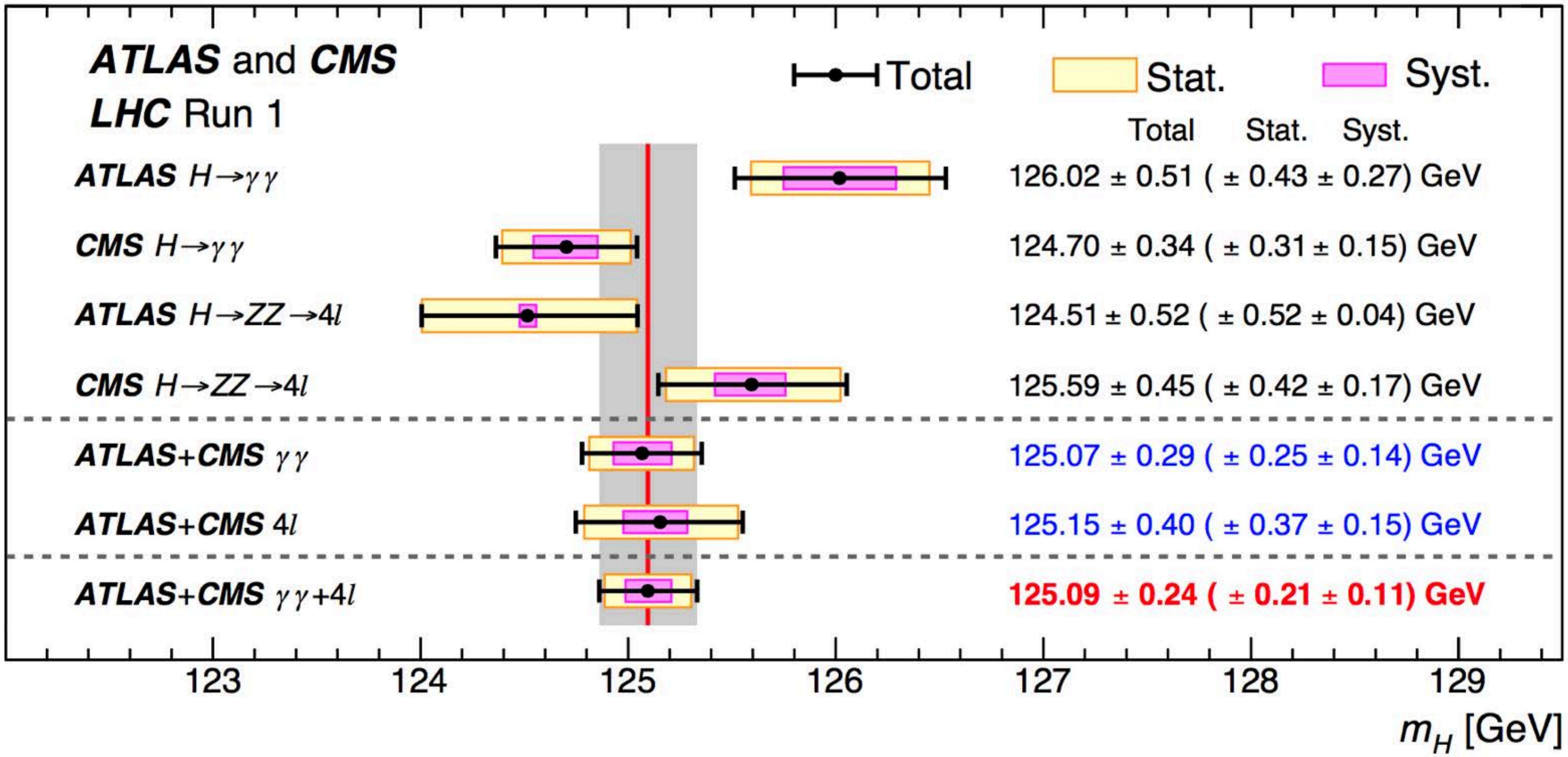
- Combination of ATLAS+CMS mass measurements: H→γγ, 4l
  - 3 signal strengths “profiles” in the fit: gg→H→γγ, VBF H→γγ, H→4l



ATLAS+CMS Higgs mass combination

arXiv:1503:07589, accepted in PRL

- Combining mass measurements very compatible with each other
  - tension only within each experiments

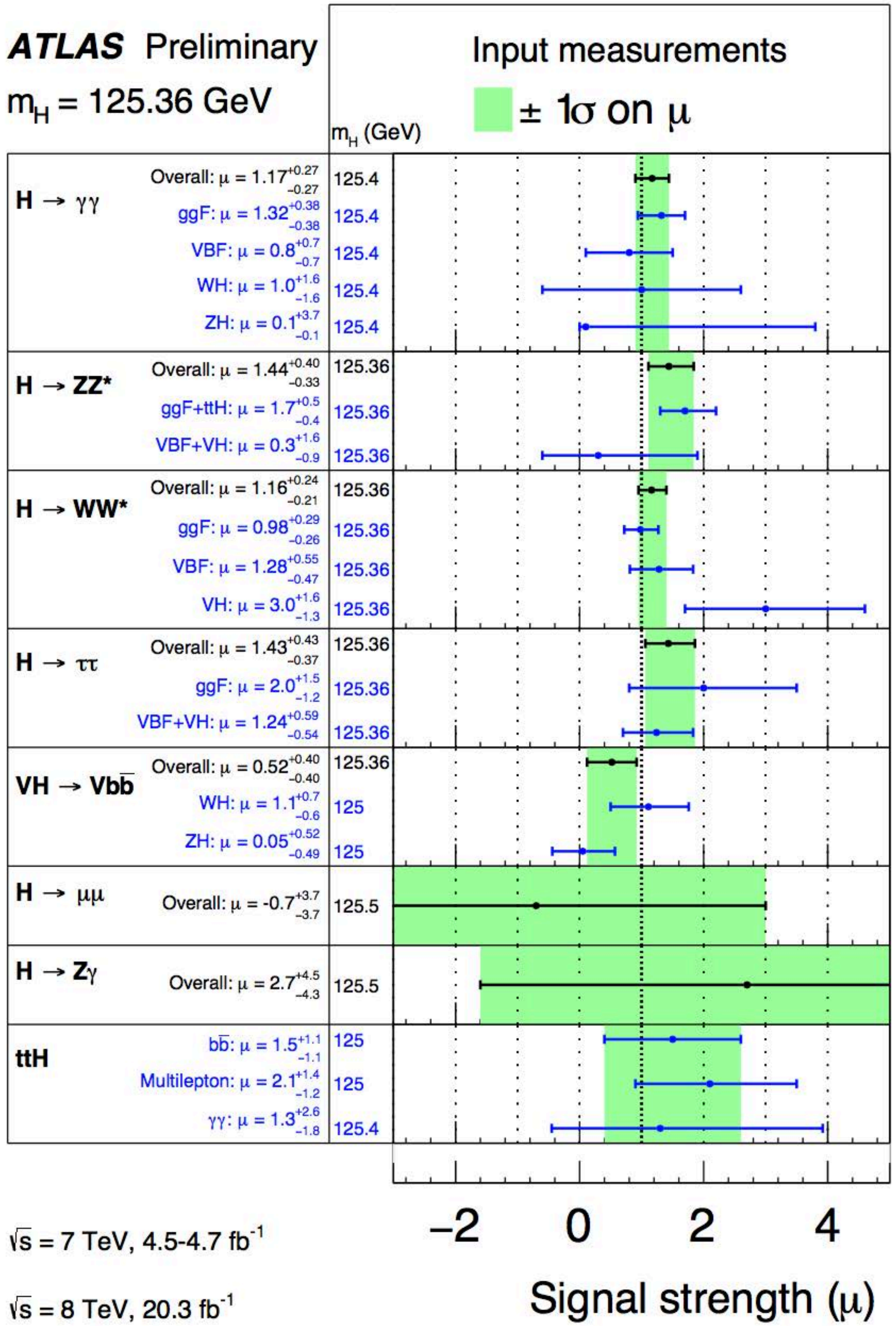


$$m_H = 125.09 \pm 0.24 \text{ GeV}$$ **(0.19% precision!)**

$$= 125.09 \pm 0.21(\text{stat.}) \pm 0.11(\text{syst.}) \text{ GeV}$$

Combo: Signal strength

ATLAS-CONF-2015-007

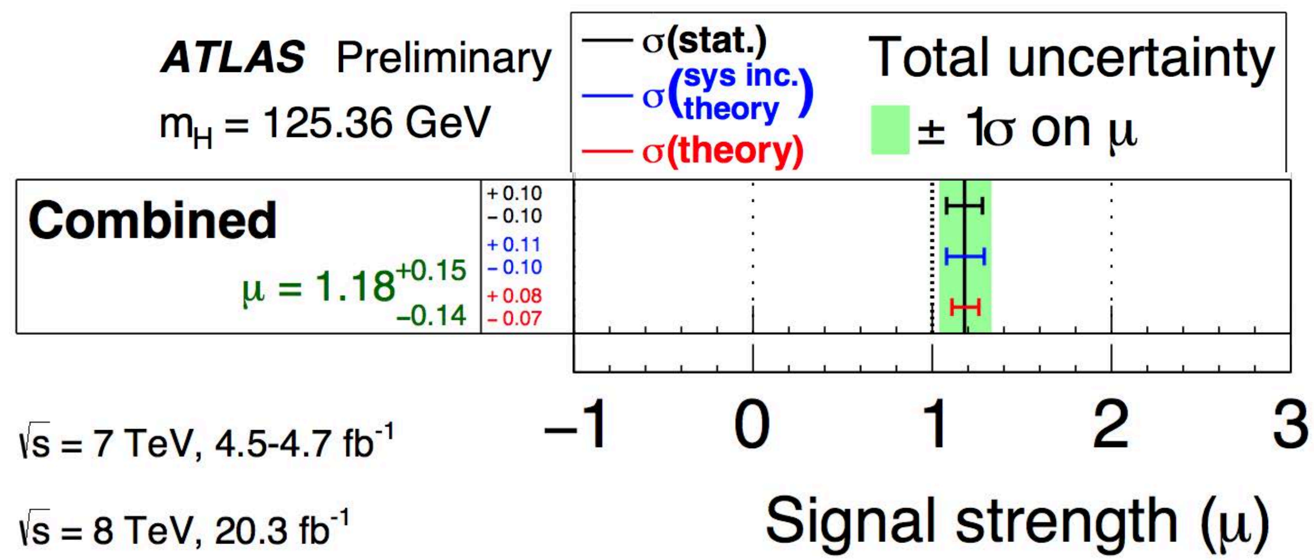


SM predictions for M_H = 125.36 GeV

Production process	Cross section (pb) $\sqrt{s}$ = 7 TeV	Cross section (pb) $\sqrt{s}$ = 8 TeV
ggF	15.0 ± 1.6	19.2 ± 2.0
VBF	1.22 ± 0.03	1.57 ± 0.04
WH	0.573 ± 0.016	0.698 ± 0.018
ZH	0.332 ± 0.013	0.412 ± 0.013
bbH	0.155 ± 0.021	0.202 ± 0.028
ttH	0.086 ± 0.009	0.128 ± 0.014
tH	0.012 ± 0.001	0.018 ± 0.001
Total	17.4 ± 1.6	22.3 ± 2.0

Decay channel	Branching ratio (%)
$H \to b\bar{b}$	57.1 ± 1.9
$H \to WW^*$	22.0 ± 0.9
$H \to gg$	8.53 ± 0.85
$H \to \tau\tau$	6.26 ± 0.35
$H \to c\bar{c}$	2.88 ± 0.35
$H \to ZZ^*$	2.73 ± 0.11
$H \to \gamma\gamma$	0.228 ± 0.011
$H \to Z\gamma$	0.157 ± 0.014
$H \to \mu\mu$	0.022 ± 0.001

These 5 channels account for ~88% of all SM decays



$$\mu = 1.18^{+0.15}_{-0.14}$$

CMS: 1.00 ± 0.14

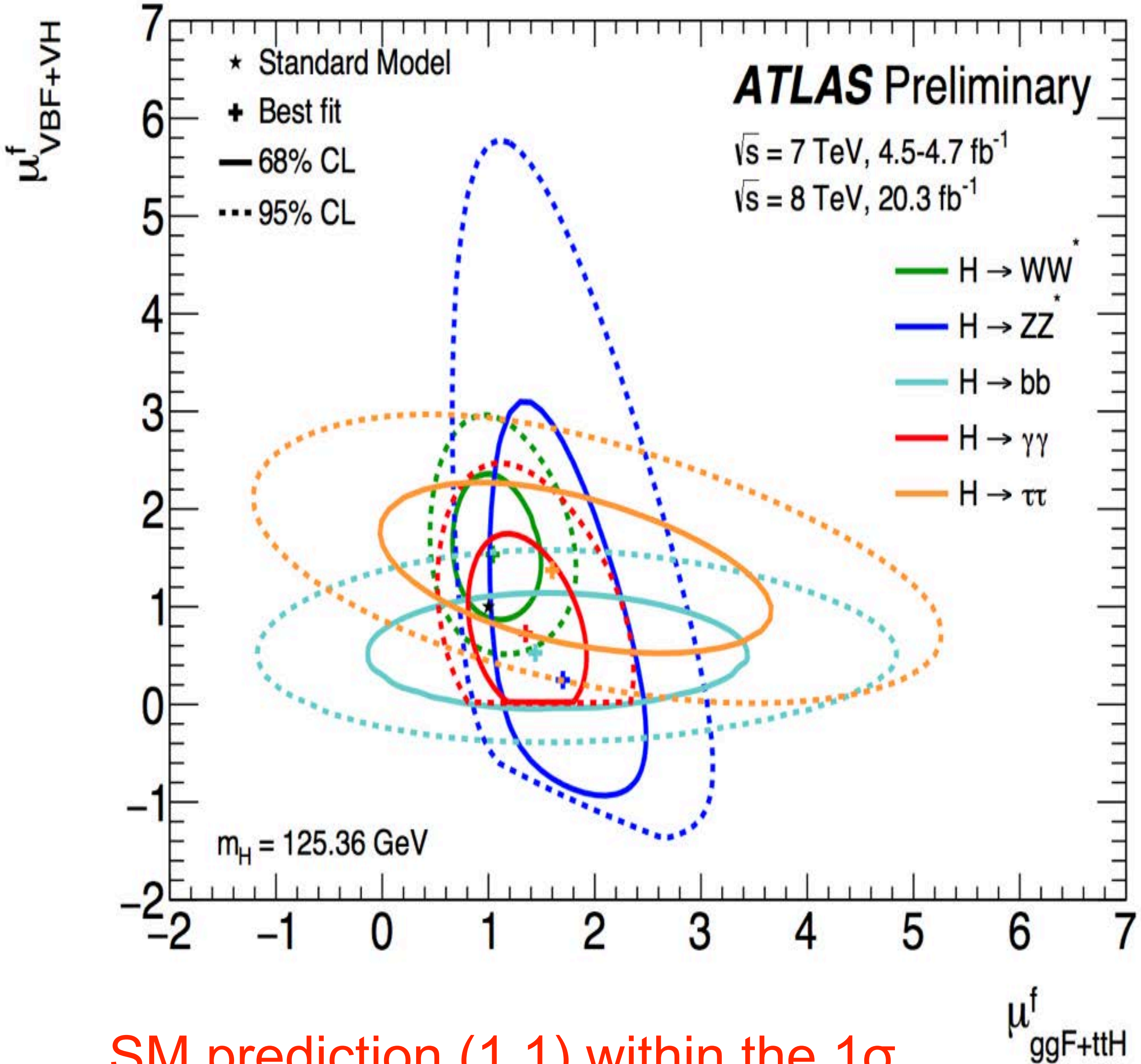
$$\mu = 1.18\,^{+0.15}_{-0.14} = 1.18 \pm 0.10\,(\text{stat.}) \pm 0.07\,(\text{expt.})\,^{+0.08}_{-0.07}\,(\text{theo.})$$

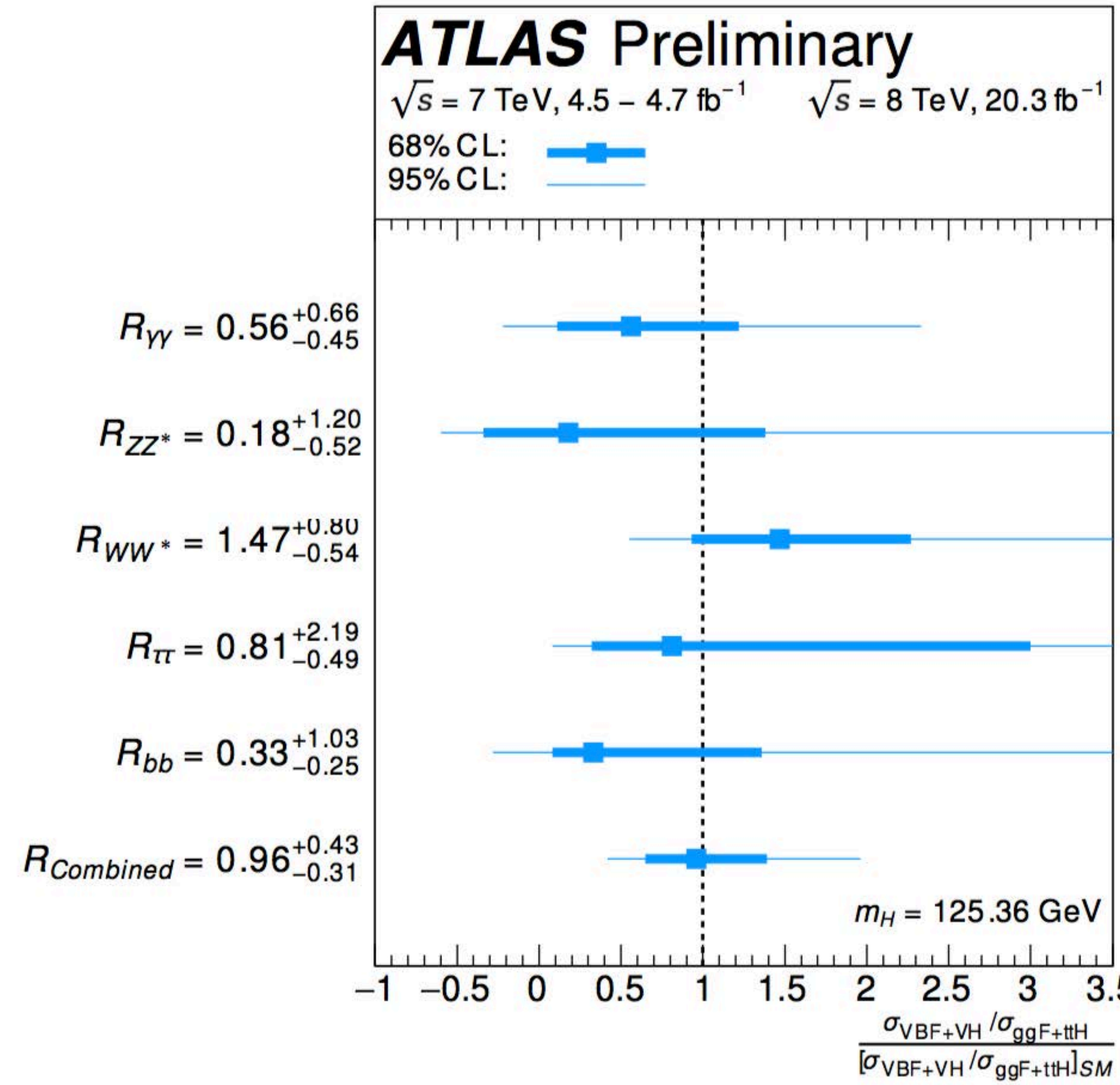
Combo: Boson vs fermion mediated

ATLAS-CONF-2015-007

$$\mu^f_{\mathrm{VBF}+VH}/\mu^f_{\mathrm{ggF}+ttH} = \frac{\sigma_{\mathrm{VBF}+VH}/\sigma_{\mathrm{ggF}+ttH}}{\left[\sigma_{\mathrm{VBF}+VH}/\sigma_{\mathrm{ggF}+ttH}\right]_{\mathrm{SM}}} \equiv R_{ff}$$

boson-mediated vs fermion-mediated





SM prediction (1,1) within the 1σ contours of most channels

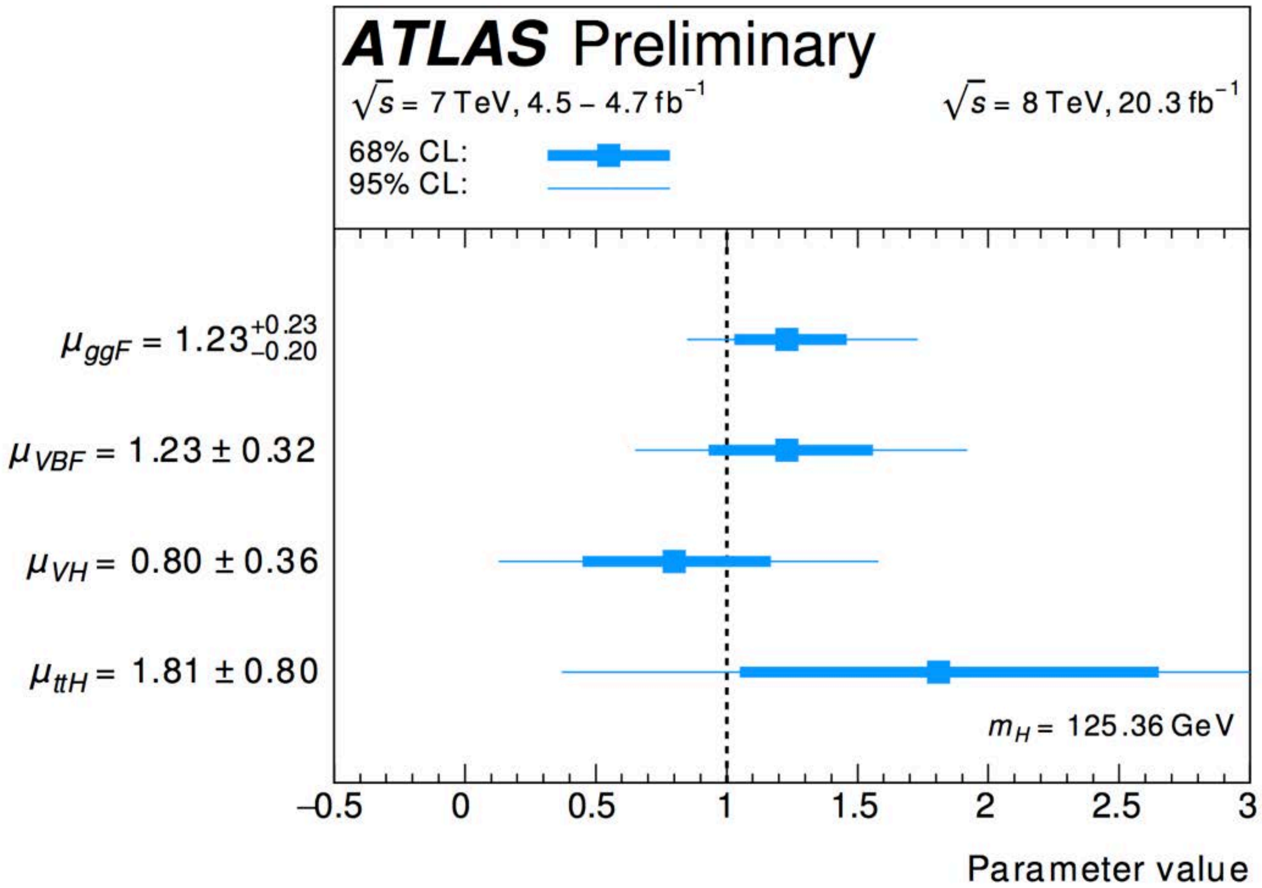
$$R_{\mathrm{Combined}} = 0.96^{+0.43}_{-0.31} = 0.96^{+0.34}_{-0.26}\,(\mathrm{stat.})\,^{+0.19}_{-0.13}\,(\mathrm{expt.})\,^{+0.18}_{-0.10}\,(\mathrm{theo.})$$

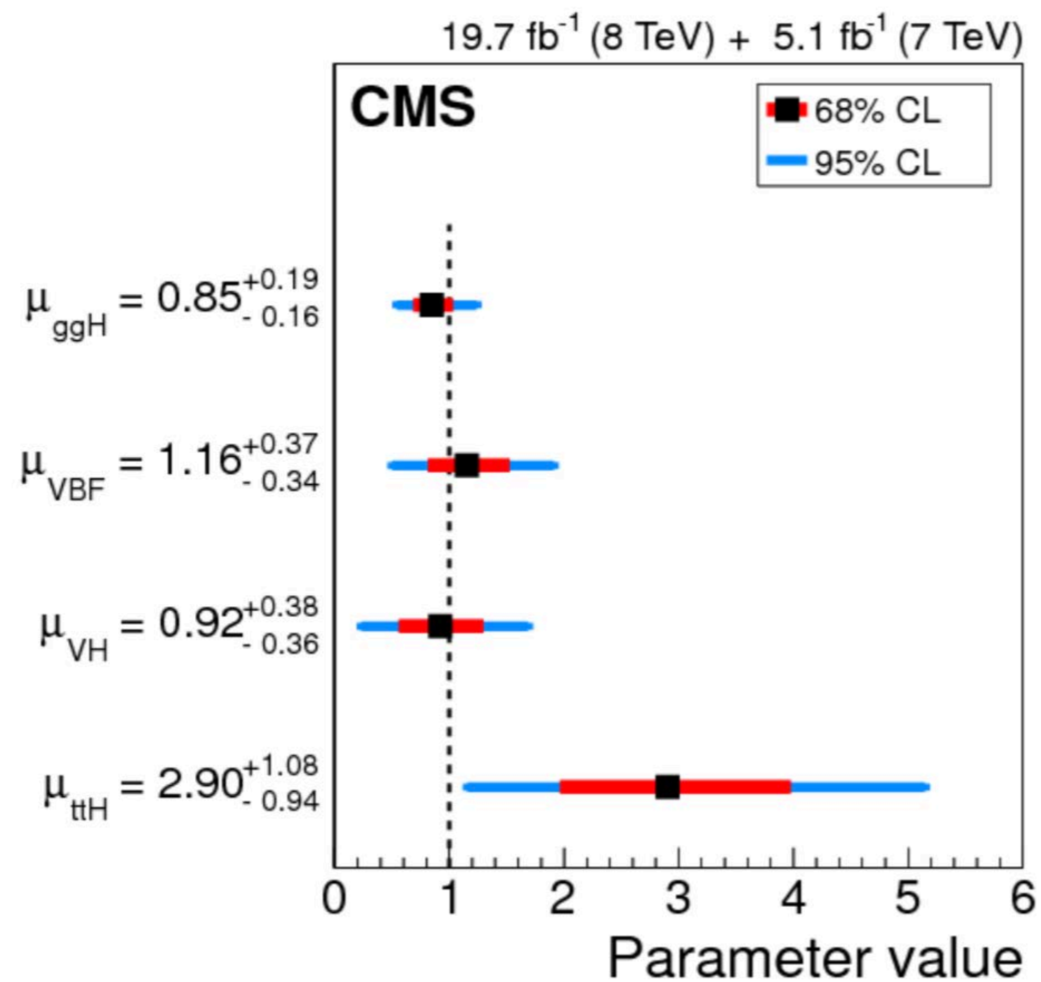
Branching ratios cancel!

Combo: individual signal strength

ATLAS-CONF-2015-007

- assuming SM values for the branching ratios
  - consistent with the SM... may hope for a ttH excess!



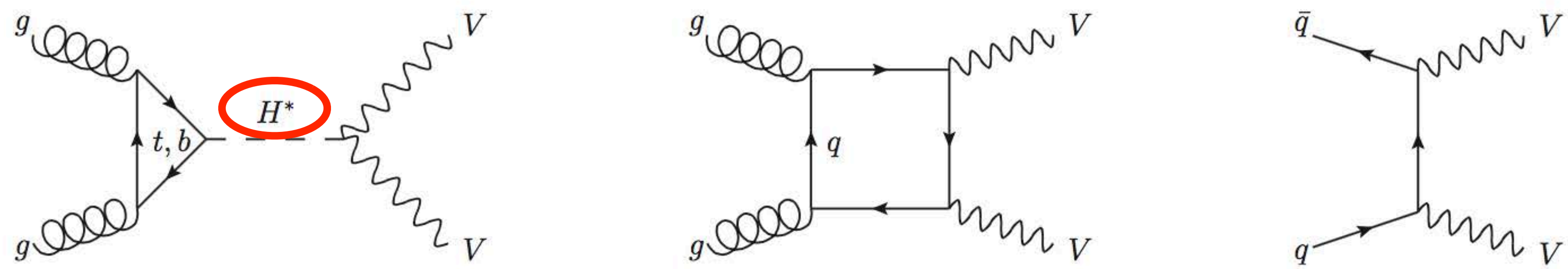


Moriond QCD 2015

H* → Z Z, WW

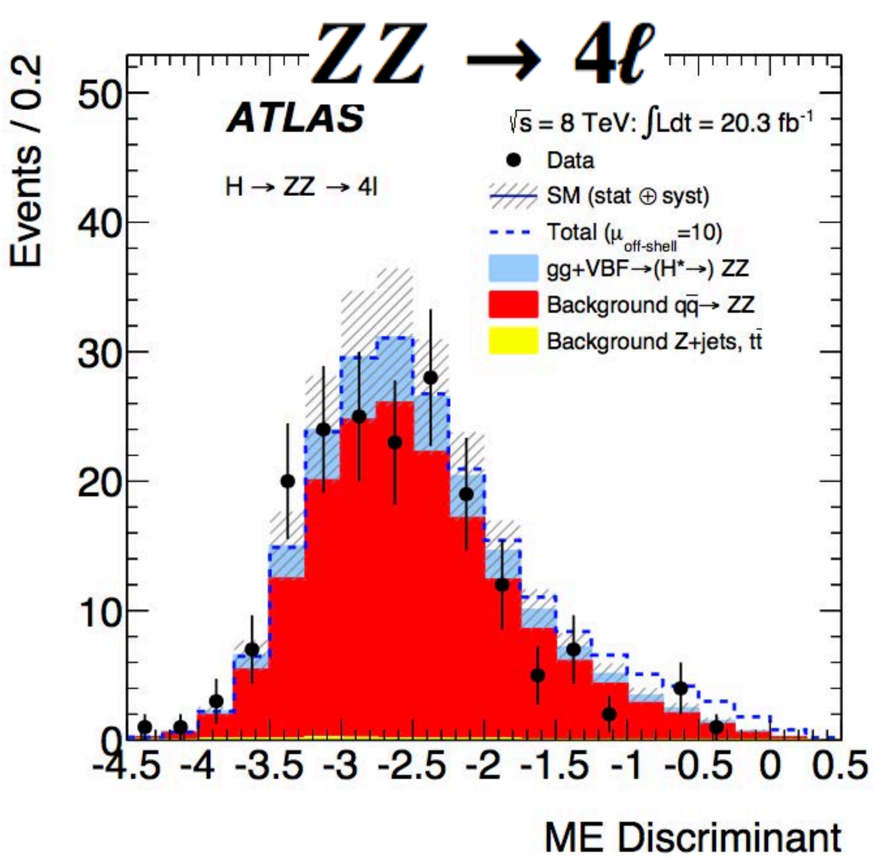
arXiv:1503.01060, submitted to EPJC

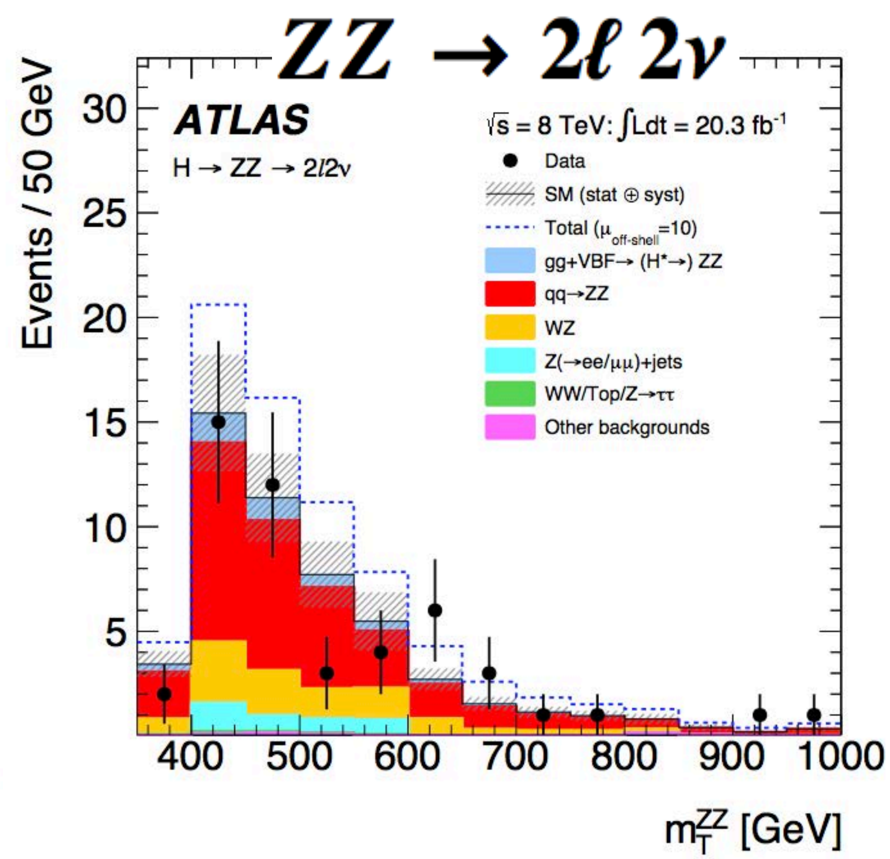
- Off-shell Higgs boson coupling
  - measure the Higgs boson signal strength for $M_{VV} \gg 2M_V$

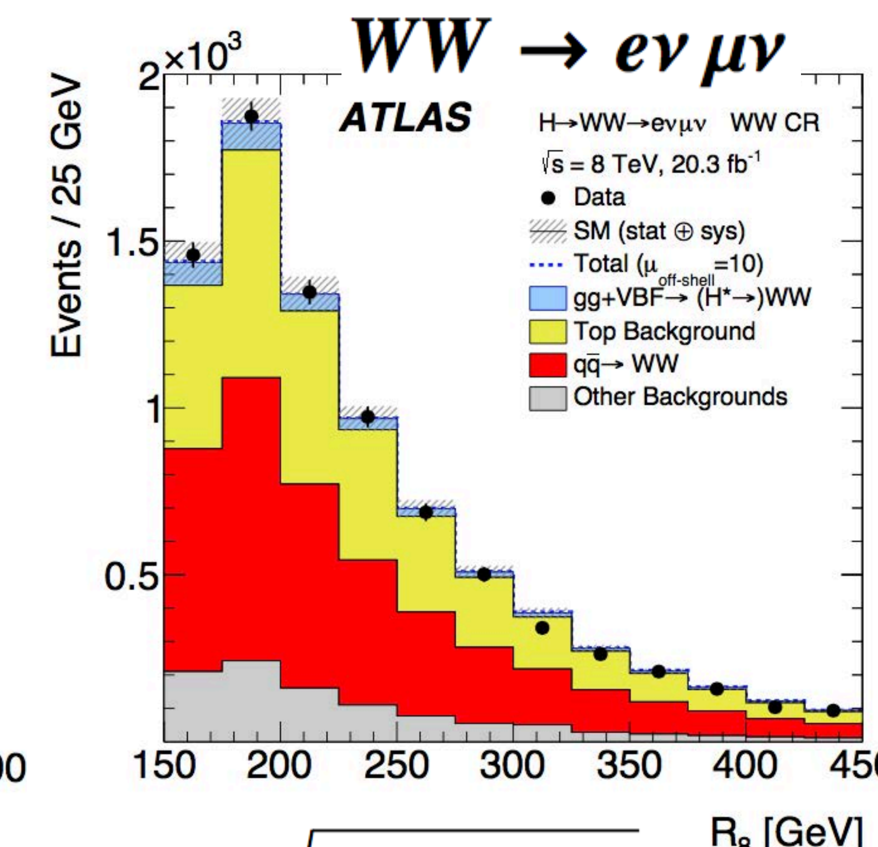


gg → VV only known to LO and QCD correction for signal known inclusively in jet multiplicity:
→ include all jets
→ try to reduce p_T^{VV} dependence

  - three channels considered







$$ME = \log_{10}\left(\frac{P_H}{P_{gg} + c \cdot P_{q\bar{q}}}\right)$$

$$m_T^{ZZ} \equiv \sqrt{\left(\sqrt{m_Z^2 + |\boldsymbol{p}_T^{\ell\ell}|^2} + \sqrt{m_Z^2 + |\boldsymbol{E}_T^{miss}|^2}\right)^2 - |\boldsymbol{p}_T^{\ell\ell} + \boldsymbol{E}_T^{miss}|^2}$$

$$R_8 = \sqrt{m_{\ell\ell}^2 + \left(0.8\, m_T^{WW}\right)^2}.$$

$$m_T^{WW} = \sqrt{\left(E_T^{\ell\ell} + p_T^{\nu\nu}\right)^2 - |\boldsymbol{p}_T^{\ell\ell} + \boldsymbol{p}_T^{\nu\nu}|^2} \qquad E_T^{\ell\ell} = \sqrt{(p_T^{\ell\ell})^2 + (m_{\ell\ell})^2}$$

$H^* \to ZZ, WW$

arXiv:1503.01060, submitted to EPJC

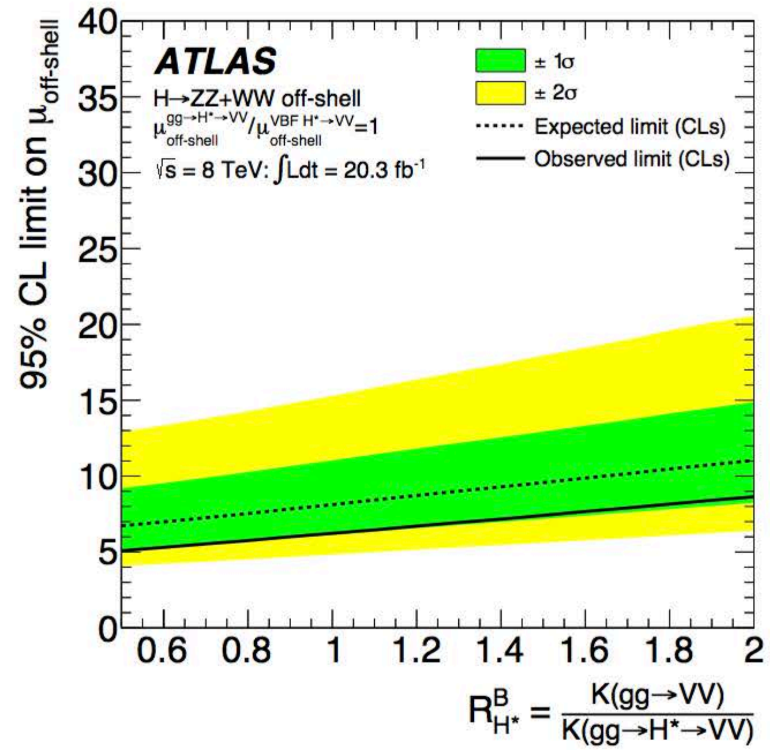
- Measurement of an upper limit on the off-shell signal strength

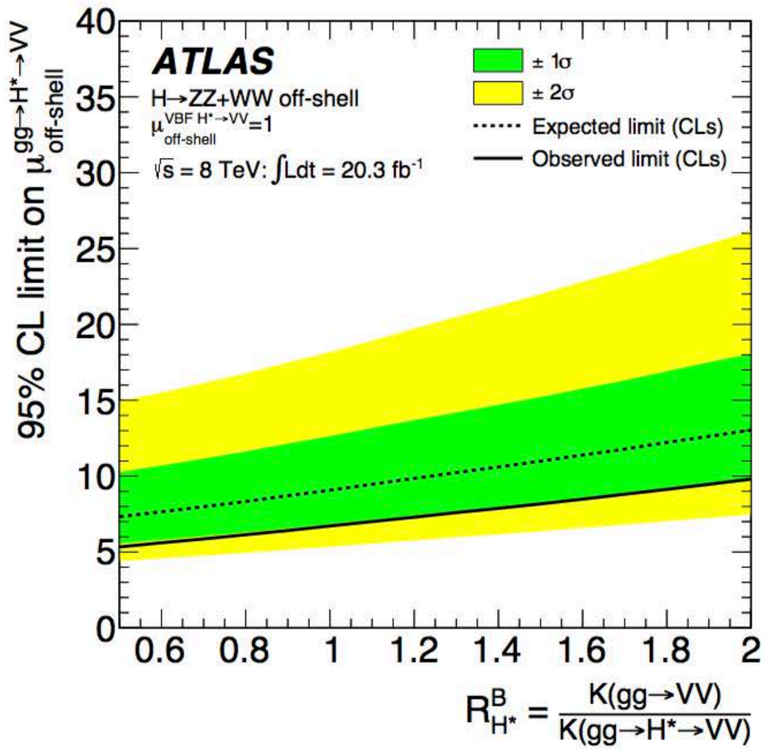
$$\mu_{\text{off-shell}}(\hat{s}) \equiv \frac{\sigma^{gg\to H^*\to VV}_{\text{off-shell}}(\hat{s})}{\sigma^{gg\to H^*\to VV}_{\text{off-shell, SM}}(\hat{s})}$$

limited statistics:
neglect s dependence
for range considered

$R^B_{H^*}$	Observed 0.5	Observed **1.0**	Observed 2.0	Median expected 0.5	Median expected **1.0**	Median expected 2.0	Assumption
$\mu_{\text{off-shell}}$	5.1	**6.2**	8.6	6.7	**8.1**	11.0	$\mu^{gg\to H^*}_{\text{off-shell}}/\mu^{VBF}_{\text{off-shell}}=1$
$\mu^{gg\to H^*\to VV}_{\text{off-shell}}$	5.3	**6.7**	9.8	7.3	**9.1**	13.0	$\mu^{\text{VBF } H^*\to VV}_{\text{off-shell}}=1$

- as a function of the unknown K-factor ratio $R^B_{H^*} = \frac{K(gg\to VV)}{K(gg\to H^*\to VV)} = \frac{K^B(m_{VV})}{K^{H^*}_{gg}(m_{VV})}$





$H^* \to ZZ, WW$

arXiv:1503.01060, submitted to EPJC

- Combine with on-shell analysis: sensitivity to the Higgs width

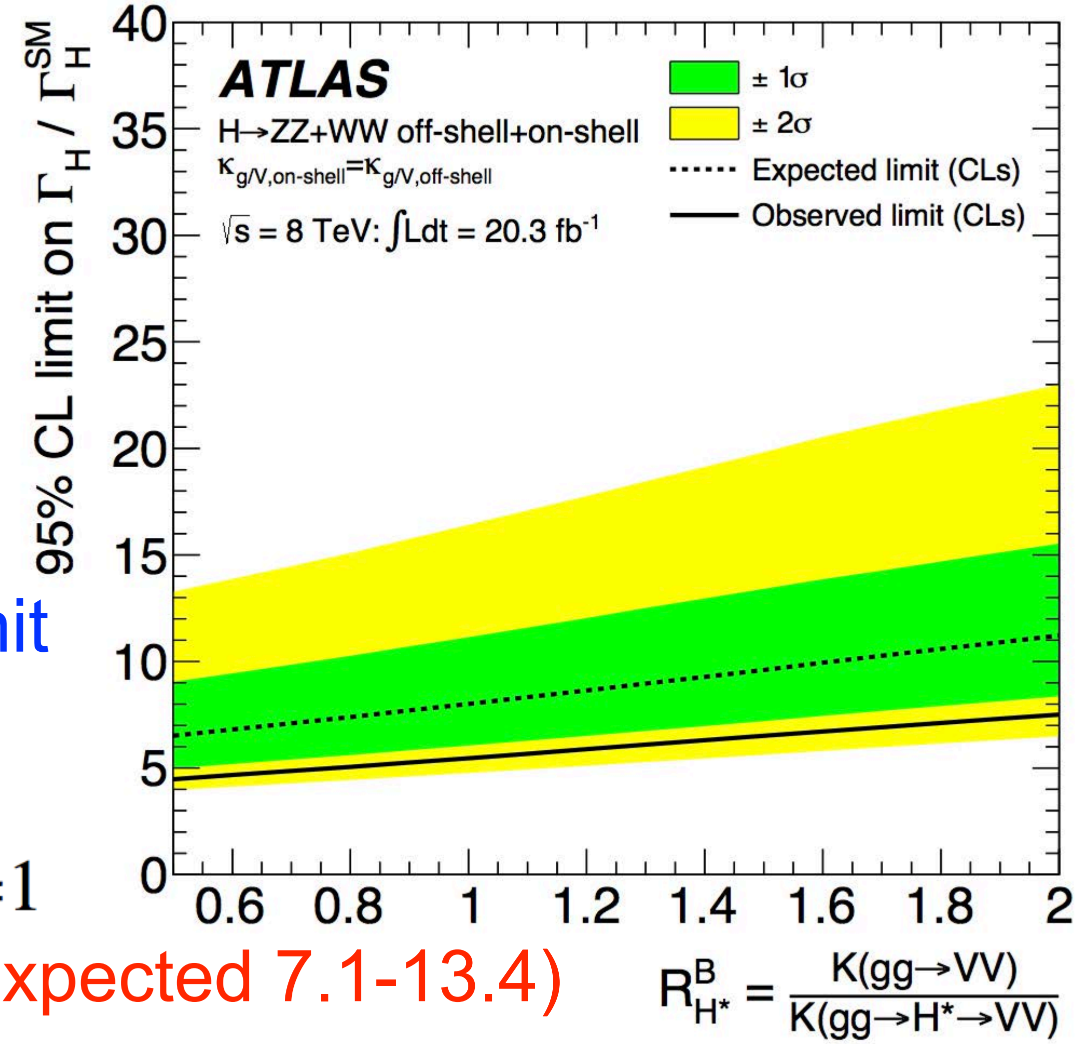
$$\mu_{\text{off-shell}}(\hat{s}) \equiv \frac{\sigma^{gg\to H^*\to VV}_{\text{off-shell}}(\hat{s})}{\sigma^{gg\to H^*\to VV}_{\text{off-shell, SM}}(\hat{s})} = \kappa^2_{g,\text{off-shell}}(\hat{s}) \cdot \kappa^2_{V,\text{off-shell}}(\hat{s})$$

Independent of Higgs width

$$\mu_{\text{on-shell}} \equiv \frac{\sigma^{gg\to H\to VV}_{\text{on-shell}}}{\sigma^{gg\to H\to VV}_{\text{on-shell, SM}}} = \frac{\kappa^2_{g,\text{on-shell}} \cdot \kappa^2_{V,\text{on-shell}}}{\Gamma_H/\Gamma_H^{SM}}$$

Dependent on Higgs width

- with current sensitivity, can only get an upper limit on the higgs width
  - sufficient assumption $\kappa^2_{g,\text{on-shell}} \cdot \kappa^2_{V,\text{on-shell}} \leq \kappa^2_{g,\text{off-shell}} \cdot \kappa^2_{V,\text{off-shell}}$
- 95% CL upper limit on Γ_H/Γ_H^{SM} is
  - 4.5-7.5 (expected 7.1-13.4)
- Assuming $R^B_{H^*} = 1$ obtain an upper limit on the Higgs boson total width
  - 22.7 MeV (expected 33.0 MeV)
- Assuming $\kappa_{V,\text{on-shell}} = \kappa_{V,\text{off-shell}}$, $\Gamma_H/\Gamma_H^{SM}=1$
  - find $R_{gg} = \kappa^2_{g,\text{off-shell}}/\kappa^2_{g,\text{on-shell}}$ in 4.7-8.6 (expected 7.1-13.4)



Combo: Higgs spin

ATLAS-CONF-2015-008

- The SM Higgs boson is predicted to be $J^{CP} = 0^+$
- Half integer spin excluded: the Higgs is observed to decay to boson pairs
- Spin 1 excluded: observation of $H \to \gamma\gamma$ and the Landau-Yang theorem
  - also experimentally excluded at more than 99% CL in $H \to VV$ decays
    - Phys. Lett. B726 (2013) 120–144
- Scenarios considered (Λ = 1 TeV)
  - spin 2
    - inspired by gravitation
  - 0^+ (BSM) or 0^- (fixed CP)
  - mixture of 0^+ and 0^- states

$$\mathcal{L}_2 = \frac{1}{\Lambda}\left[\sum_V \kappa_V X^{\mu\nu}\mathcal{T}^V_{\mu\nu} + \sum_f \kappa_f X^{\mu\nu}\mathcal{T}^f_{\mu\nu}\right]$$

	Choice of QCD couplings	p_T^X cut-off (GeV)	
$\kappa_q = \kappa_g$	Universal couplings	–	–
$\kappa_q = 0$	Low light-quark fraction	300	125
$\kappa_q = 2\kappa_g$	Low gluon fraction	300	125

WW, ZZ and γγ modes

$$\mathcal{L}_0^V = \Big\{c_\alpha\kappa_{SM}\left[\tfrac{1}{2}g_{HZZ}Z_\mu Z^\mu + g_{HWW}W^+_\mu W^{-\mu}\right] - \tfrac{1}{4}\tfrac{1}{\Lambda}\left[c_\alpha\kappa_{HZZ}Z_{\mu\nu}Z^{\mu\nu} + s_\alpha\kappa_{AZZ}Z_{\mu\nu}\tilde{Z}^{\mu\nu}\right] - \tfrac{1}{2}\tfrac{1}{\Lambda}\left[c_\alpha\kappa_{HWW}W^+_{\mu\nu}W^{-\mu\nu} + s_\alpha\kappa_{AWW}W^+_{\mu\nu}\tilde{W}^{-\mu\nu}\right]\Big\} X_0$$

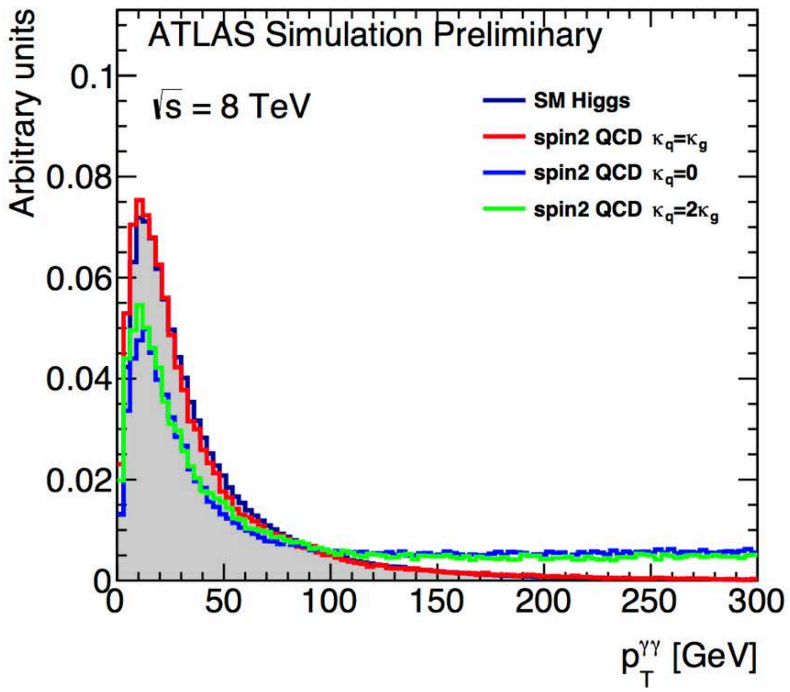
J^P	Model	Choice of tensor couplings			
		κ_{SM}	κ_{HVV}	κ_{AVV}	α
0^+	Standard Model Higgs boson	1	0	0	0
0^+_h	BSM spin-0 CP-even	0	1	0	0
0^-	BSM spin-0 CP-odd	0	0	1	$\pi/2$

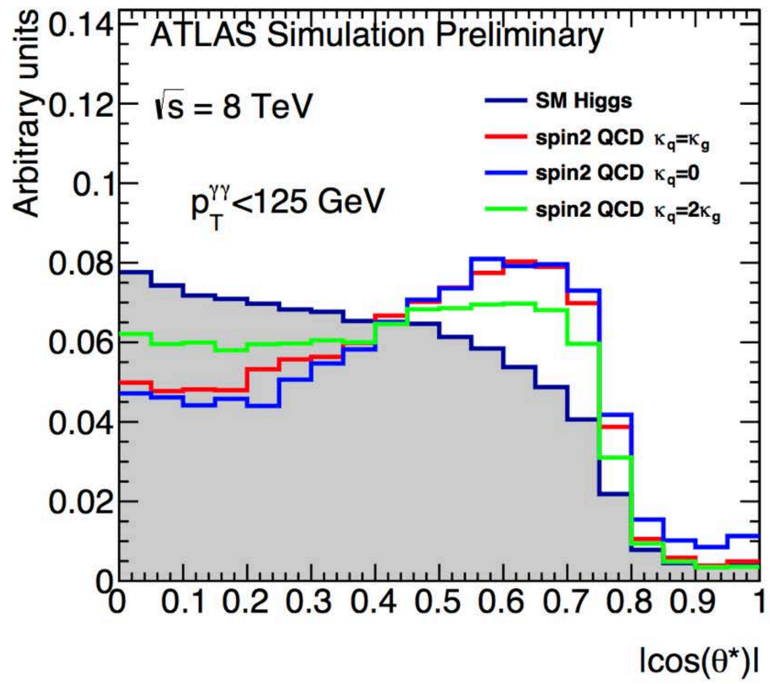
CP violation if mixing angle $\alpha \neq 0$ and π

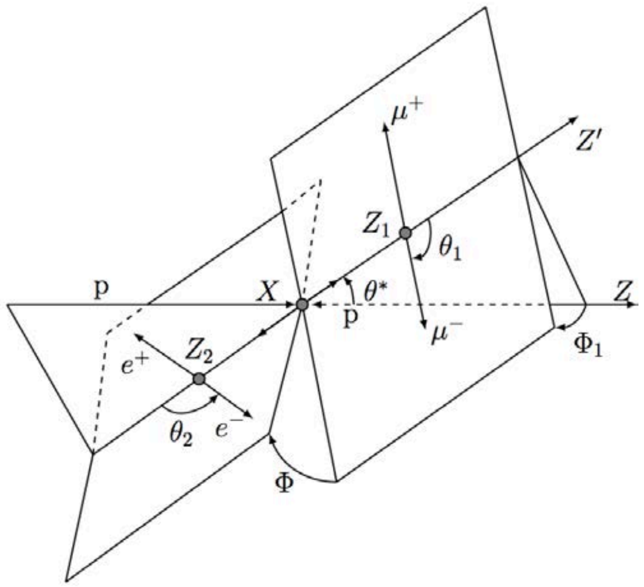
Combo: Higgs spin

ATLAS-CONF-2015-008

- Study of event kinematics
  - eg: expected distribution for $p_T^{\gamma\gamma}$
  - eg: kinematics handle for H→4l







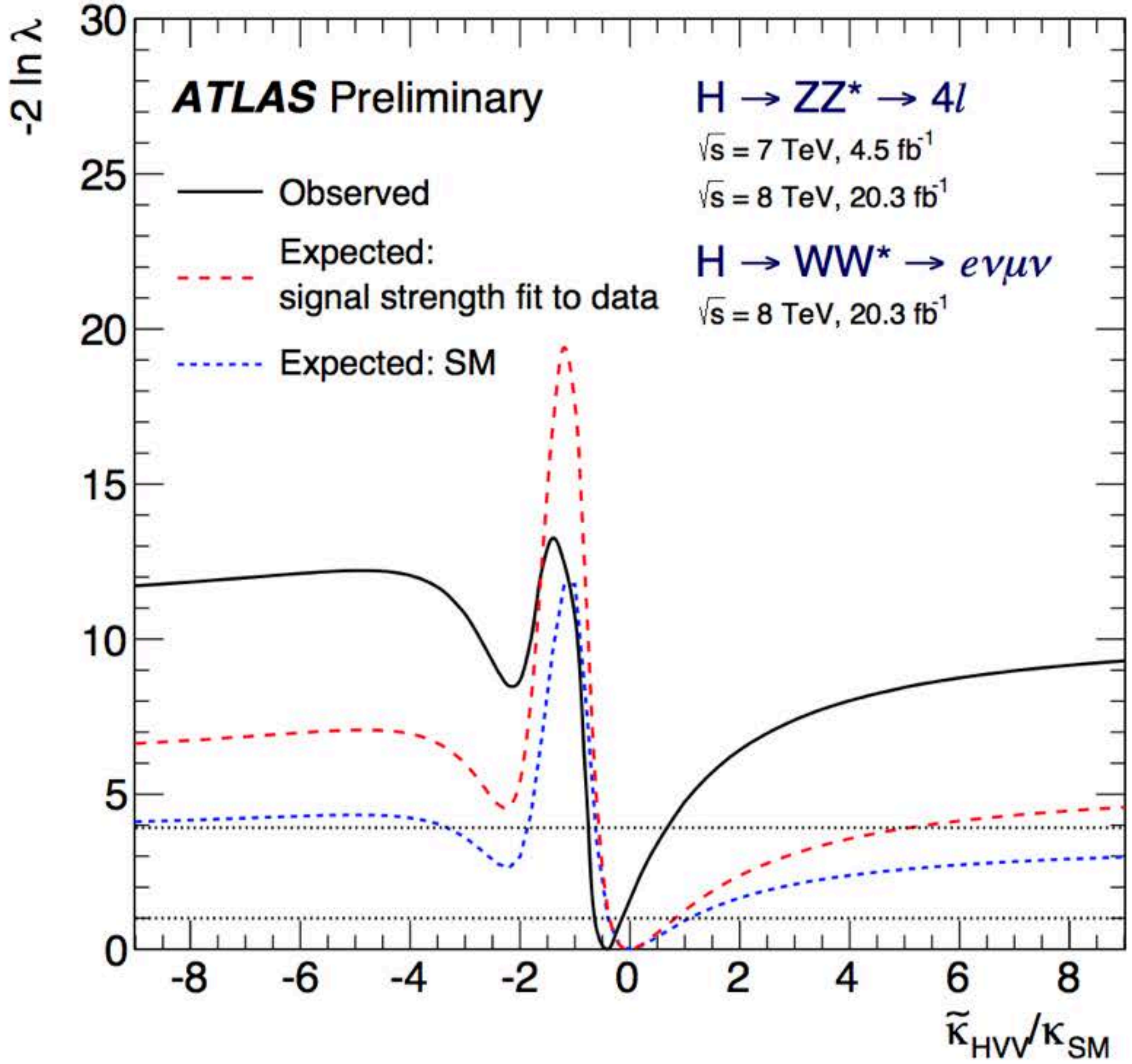
Tested Hypothesis	$p^{ALT}_{exp,\mu=1}$	$p^{ALT}_{exp,\mu=\hat{\mu}}$	p^{SM}_{obs}	p^{ALT}_{obs}	Obs. CL_S (%)
0^+_h	$2.5 \cdot 10^{-2}$	$4.7 \cdot 10^{-3}$	0.85	$7.1 \cdot 10^{-5}$	$4.7 \cdot 10^{-2}$
0^-	$1.8 \cdot 10^{-3}$	$1.3 \cdot 10^{-4}$	0.88	$< 3.1 \cdot 10^{-5}$	$< 2.6 \cdot 10^{-2}$
2^+	$4.3 \cdot 10^{-3}$	$2.9 \cdot 10^{-4}$	0.61	$4.3 \cdot 10^{-5}$	$1.1 \cdot 10^{-2}$
$2^+(\kappa_q = 0;\ p_T < 300)$	$< 3.1 \cdot 10^{-5}$	$< 3.1 \cdot 10^{-5}$	0.52	$< 3.1 \cdot 10^{-5}$	$< 6.5 \cdot 10^{-3}$
$2^+(\kappa_q = 0;\ p_T < 125)$	$3.4 \cdot 10^{-3}$	$3.9 \cdot 10^{-4}$	0.71	$4.3 \cdot 10^{-5}$	$1.5 \cdot 10^{-2}$
$2^+(\kappa_q = 2\kappa_g;\ p_T < 300)$	$< 3.1 \cdot 10^{-5}$	$< 3.1 \cdot 10^{-5}$	0.28	$< 3.1 \cdot 10^{-5}$	$< 4.3 \cdot 10^{-3}$
$2^+(\kappa_q = 2\kappa_g;\ p_T < 125)$	$7.8 \cdot 10^{-3}$	$1.2 \cdot 10^{-3}$	0.80	$7.3 \cdot 10^{-5}$	$3.7 \cdot 10^{-2}$

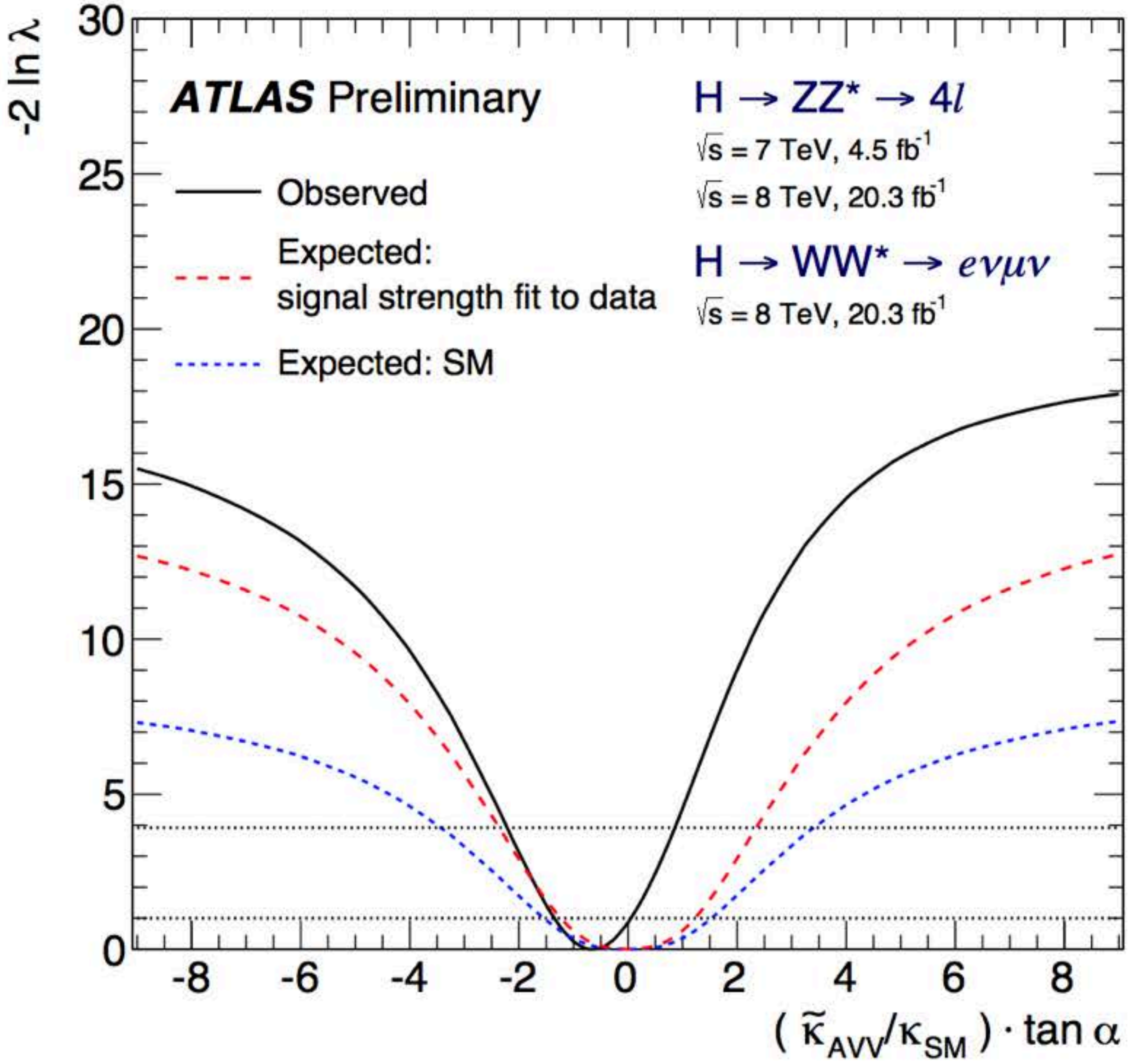
All considered non-SM spin models excluded at more than 99% CL

Combo: Higgs spin

ATLAS-CONF-2015-008

- Tensor structure of the HVV interaction in the spin-0 hypothesis
  - one BSM tensor coupling investigated at a time (others set to 0)
  - observed distributions of $\tilde{\kappa}_{HVV}/\kappa_{SM}$ and $(\tilde{\kappa}_{AVV}/\kappa_{SM}) \cdot \tan\alpha$ are compatible with SM values



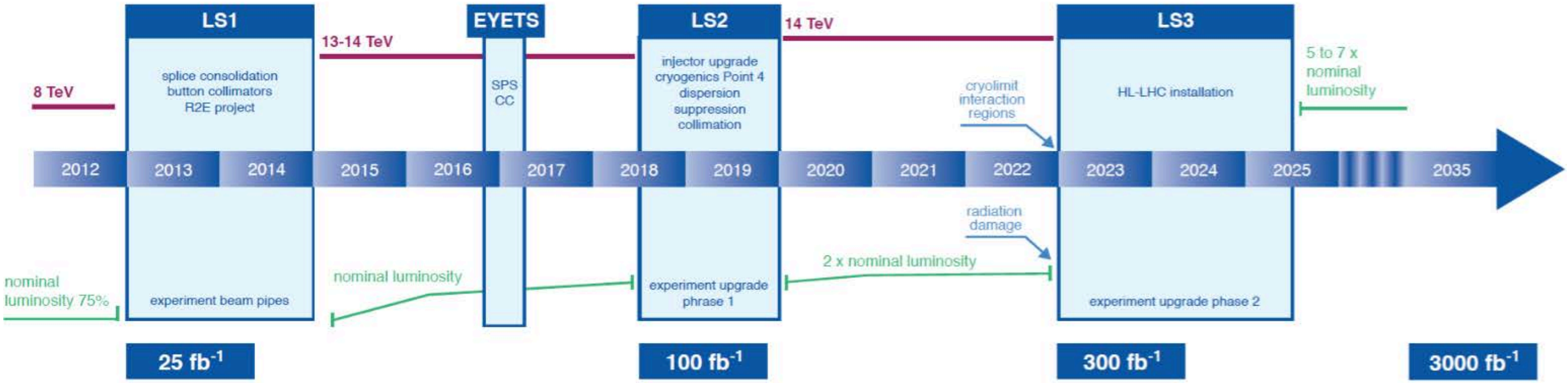


And more!

- I have not shown (nor read) everything!
  - search for rare decays
  - Higgs and associated jets (Higgs production kinematics)
  - Higgs p_T distribution
  - κ-framework coupling measurements
- ...all compatible with THE SM Higgs
  - but... ttH production?
  - but... CMS excess in H→tau+μ?

Future prospects

- Great opportunity to study the new particle



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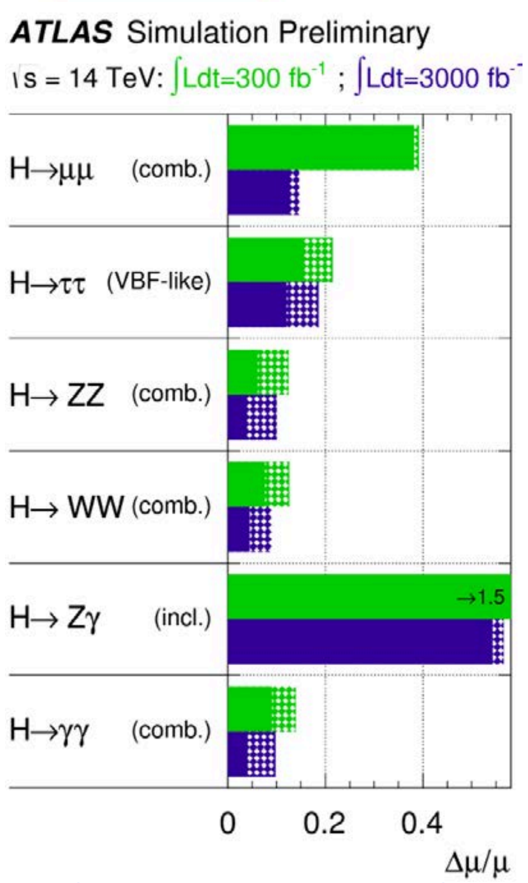

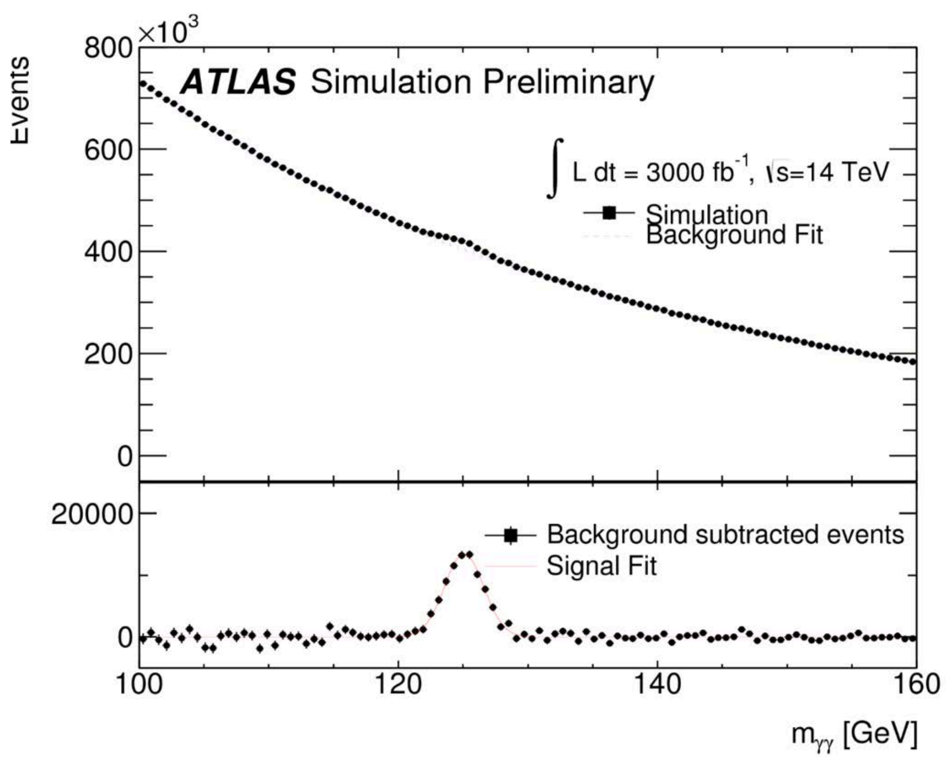

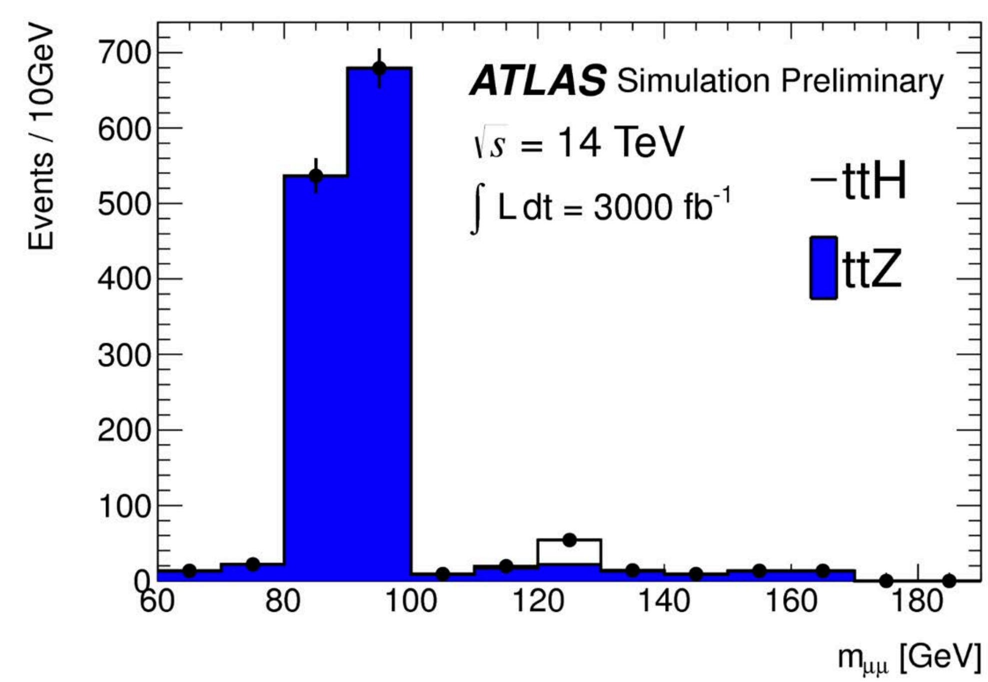

... and Higgs self couplings!

A few concluding words

- The study of the mechanism of electroweak symmetry breaking is one of the principal goals of the CERN LHC program
  - SM: complex doublet scalar field, yielding one Higgs boson
- The discovered resonance is consistent with THE SM Higgs boson
  - yields, couplings, spin, CP
  - Run 1 channel combination measurements have been made
  - extensive search for deviations from the SM prediction
    - production and $H \rightarrow VV$ decay kinematics
    - signal strength
      - all categories of all observable final states
    - couplings
  - a fundamental scalar! But is it?
  - many lessons learned from Run 1 analyses... on to Run 2 and beyond!
    - many measurement still limited by systematics (theory, background)
- Soldiering on to Run 2 and beyond
  - first need to “rediscover the Higgs” at 13-14 TeV
  - the Higgs may well be the “portal” to new physics!

Thank you Alan
for your wit,
strength, energy,
guidance,
your friendship