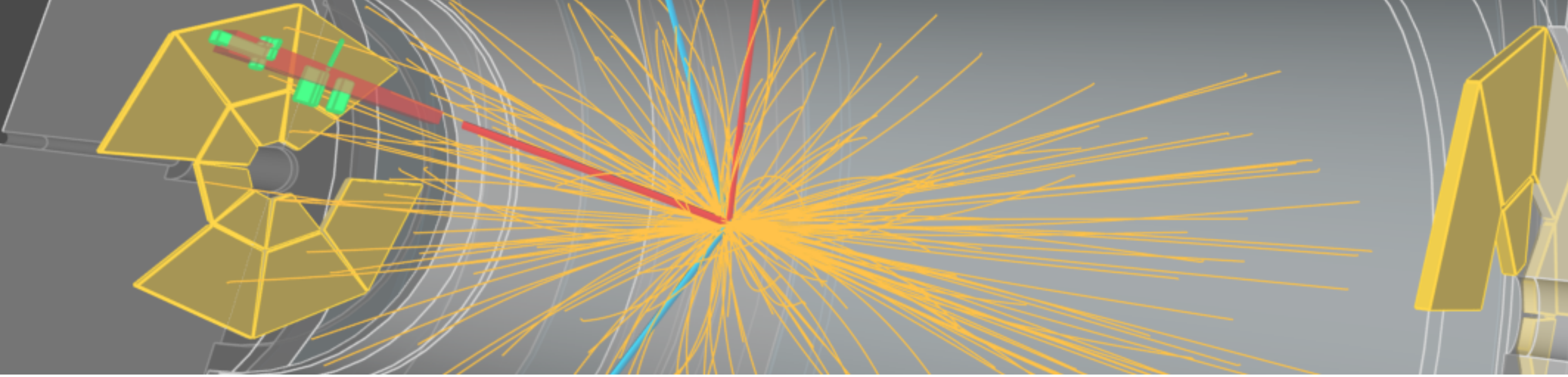


Higgs boson production at the LHC

Krisztian Peters

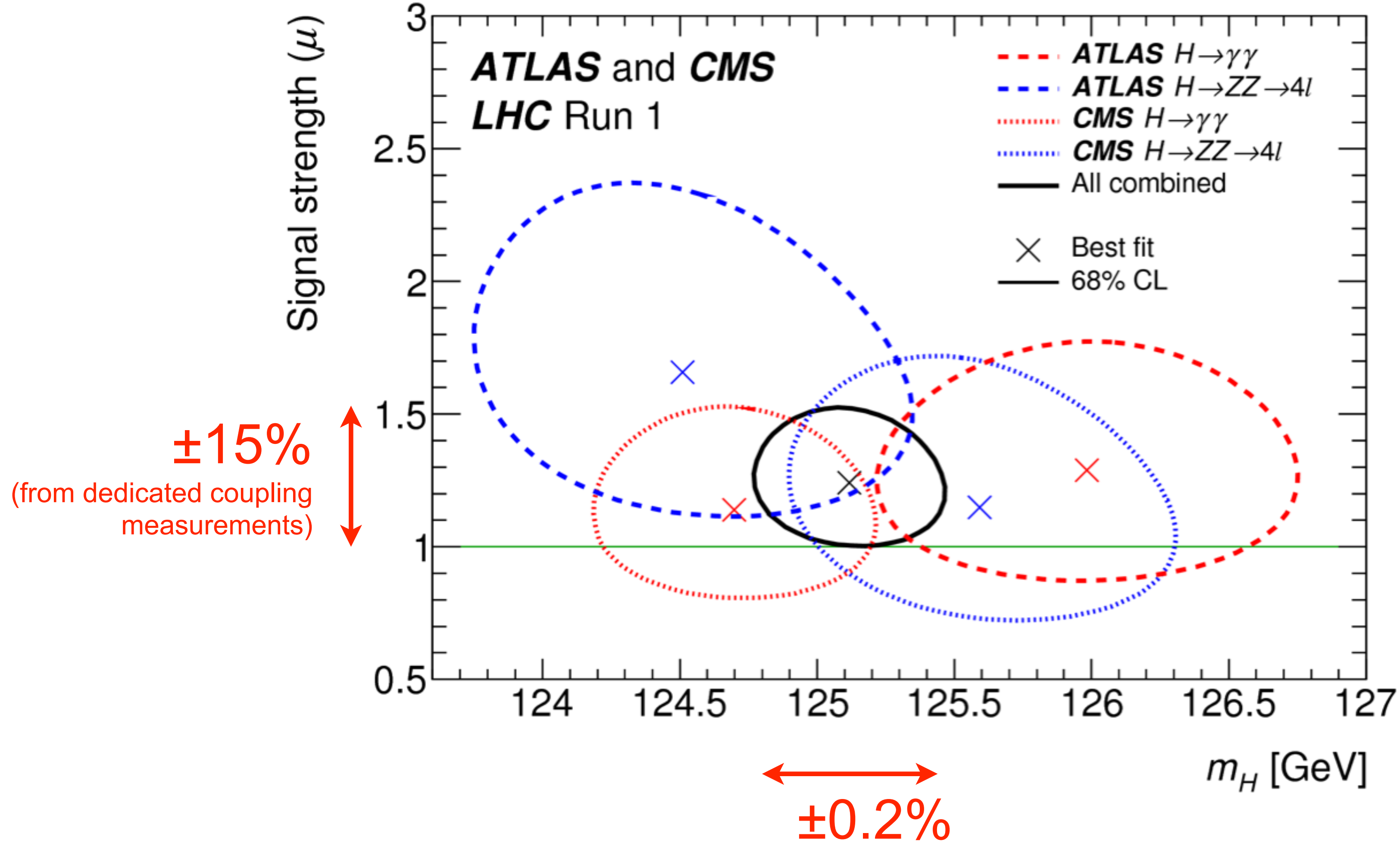
CERN

1st June 2015

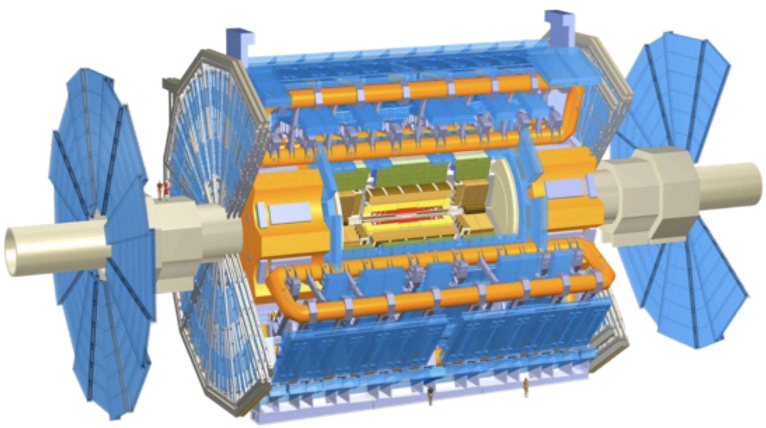
27th Rencontres de Blois

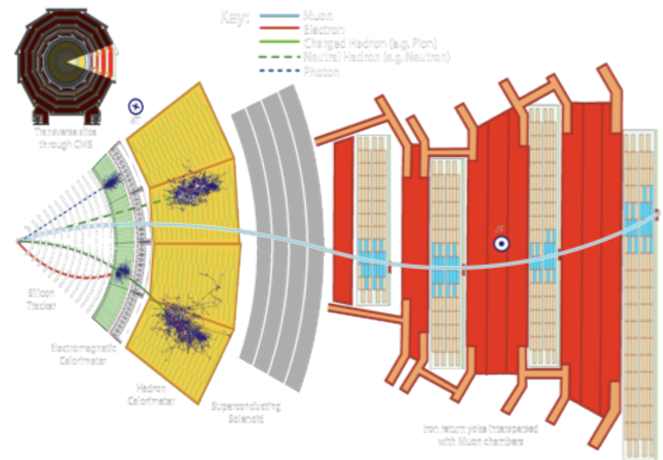
Higgs at the LHC

Breathtaking progress in $O(2)$ years



ATLAS and *CMS* experiments



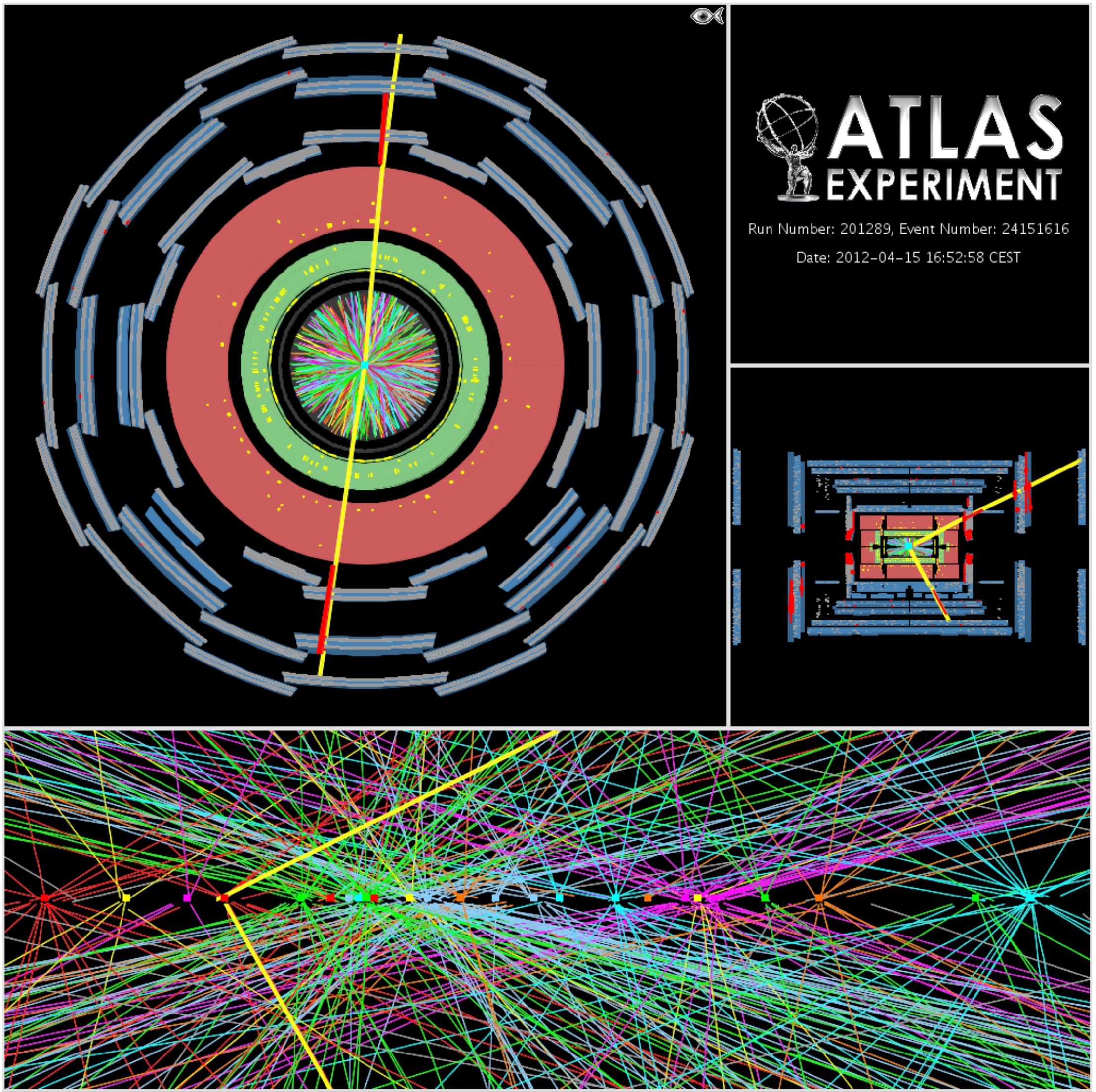


ATLAS: emphasis on excellent jet and missing E_T resolution, particle identification, and standalone muon measurement

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

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

Challenges with high luminosity



Continuously improve triggering, reconstruction and identification algorithms

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

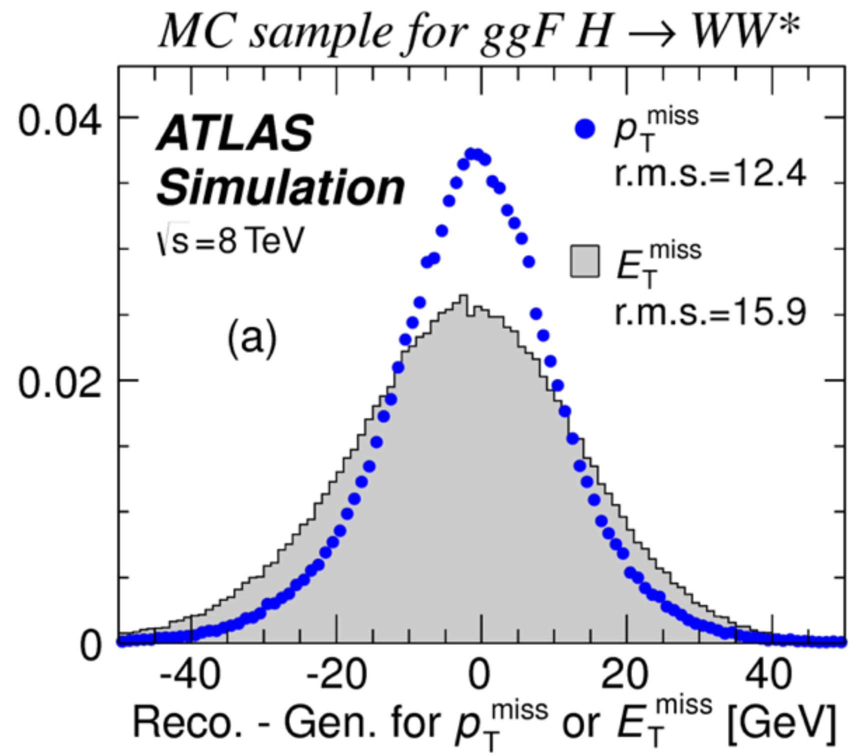
$Z \rightarrow \mu\mu$ event with 25 reconstructed vertices

Jets and missing E_T

Include tracking information to mitigate effects from pileup interactions

Several algorithms from *ATLAS* and *CMS*

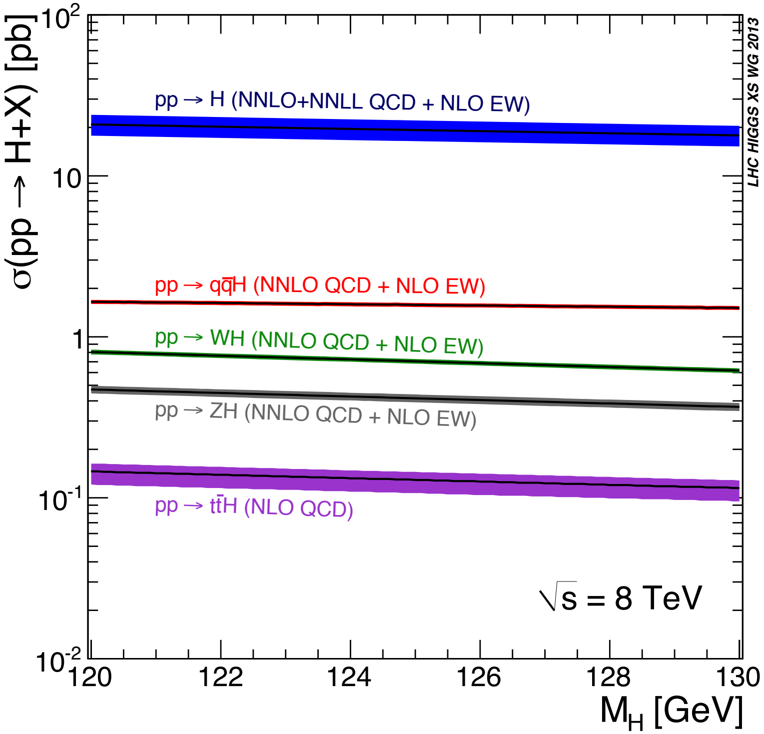
Example:
Track based measurement of soft objects, *O*(20%) resolution improvement

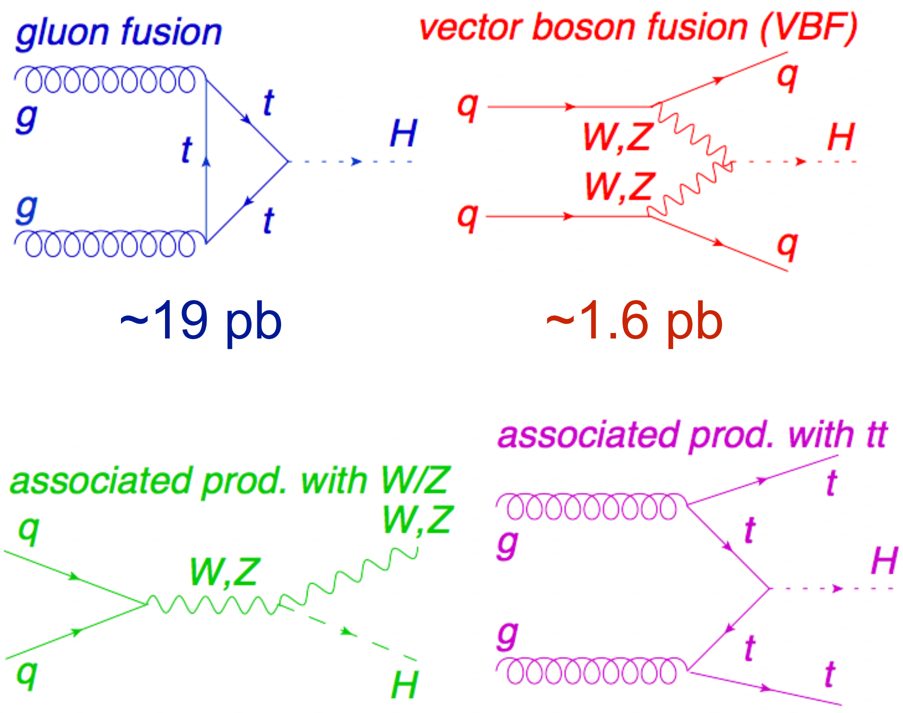


Reconstructed - True missing E_T

Higgs production at the LHC

8 TeV *pp* collisions





~19 pb

~1.6 pb

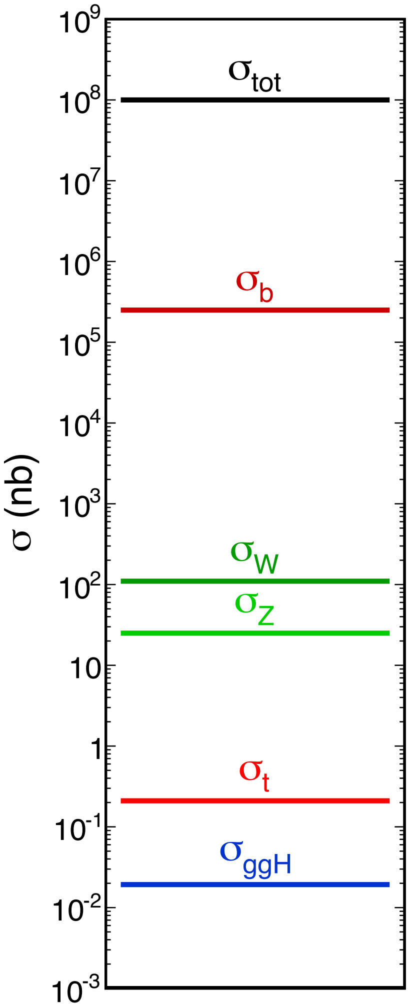
~1.1 pb

~0.13 pb

~500k Higgs bosons
produced at the LHC

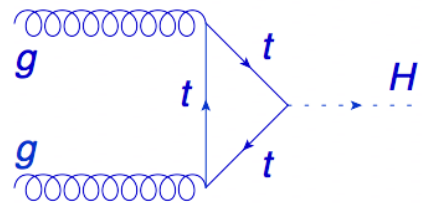
Higgs production at the LHC

pp cross sections



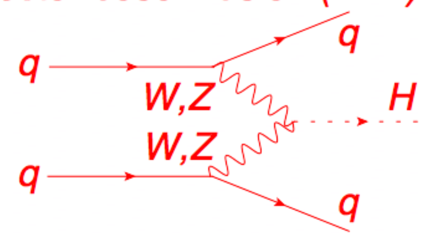
LHC at $\sqrt{s}$ = 8 TeV

gluon fusion



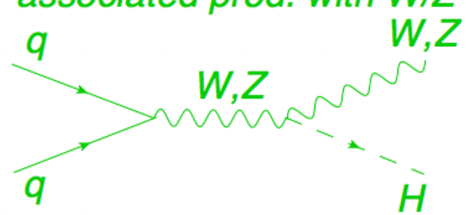
~19 pb

vector boson fusion (VBF)



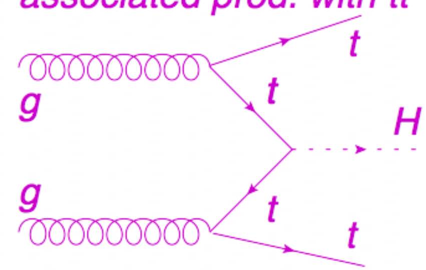
~1.6 pb

associated prod. with W/Z



~1.1 pb

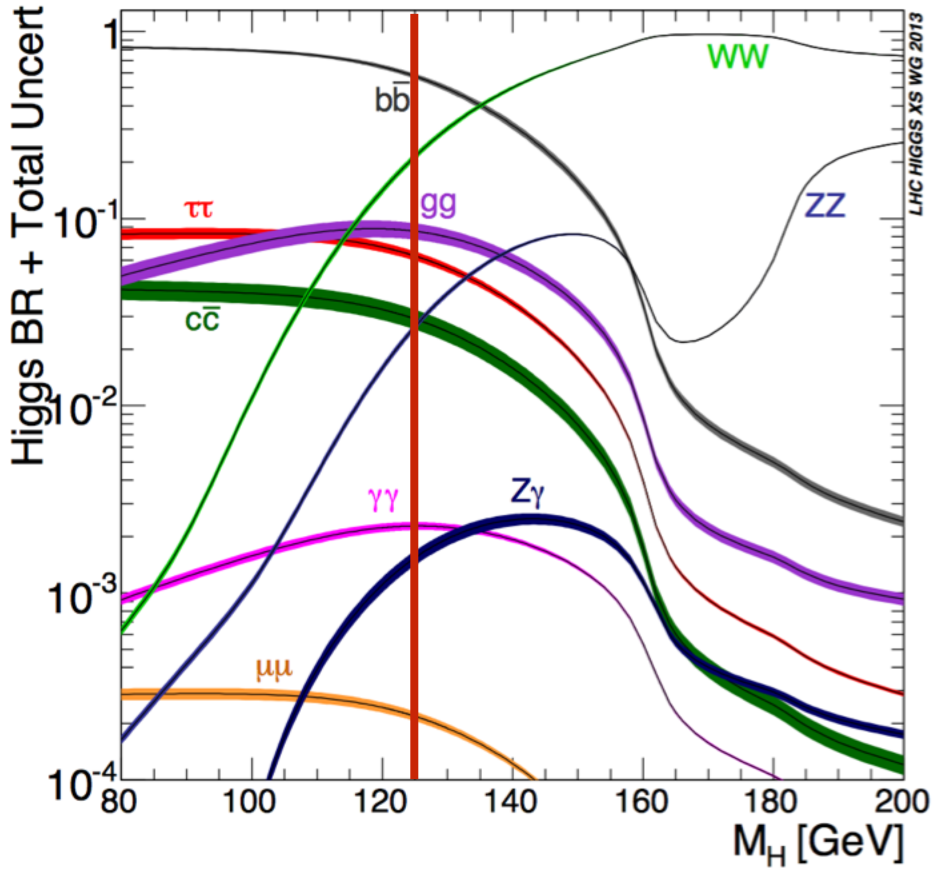
associated prod. with tt



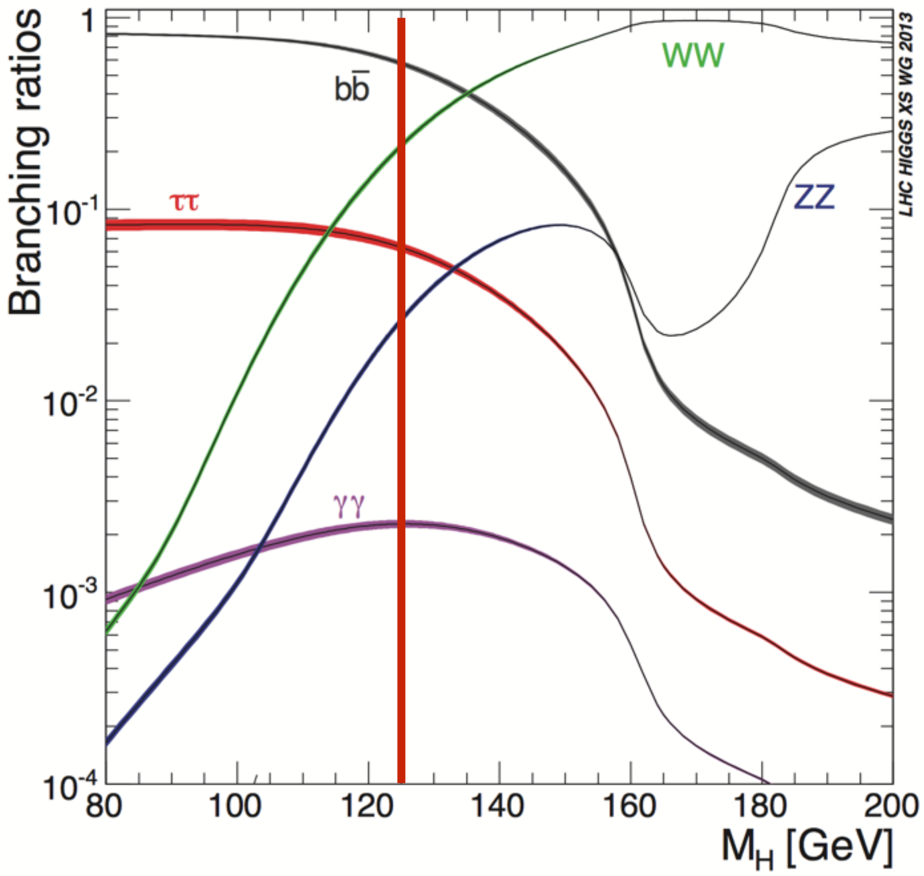
~0.13 pb

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

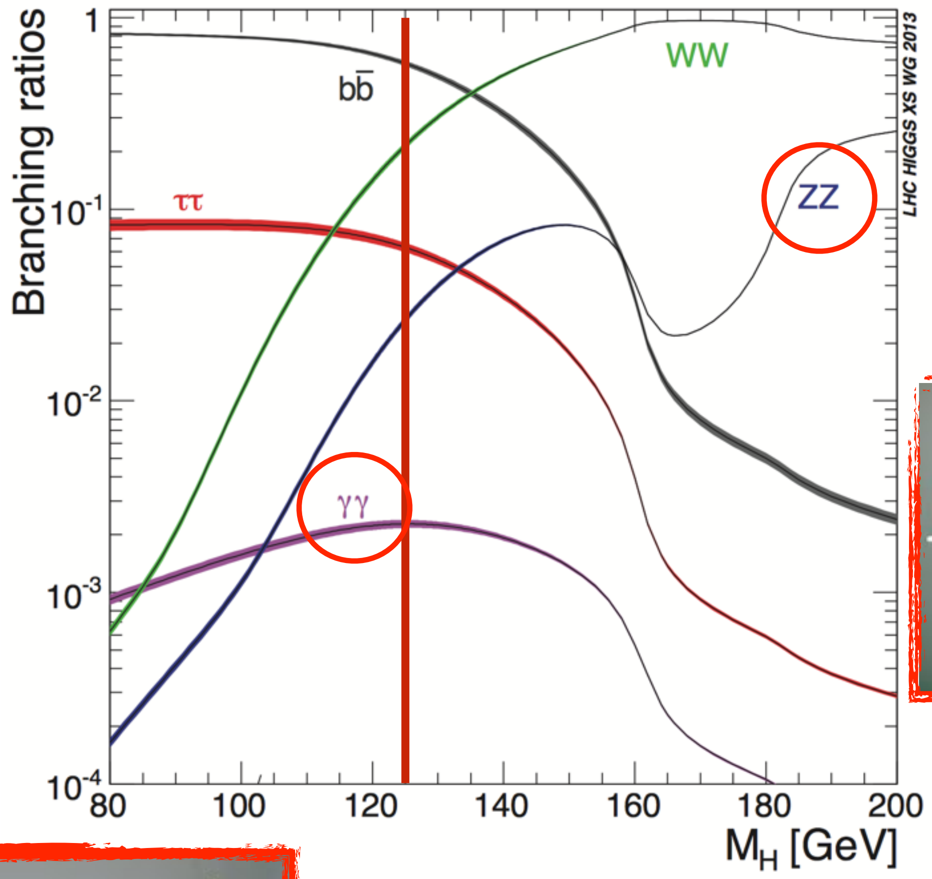
Higgs decays

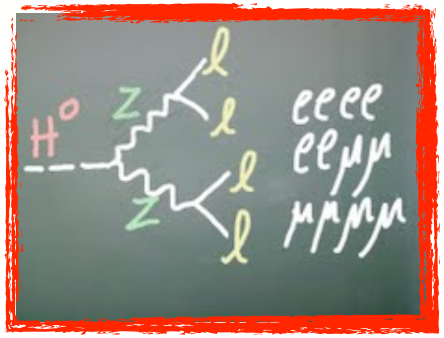


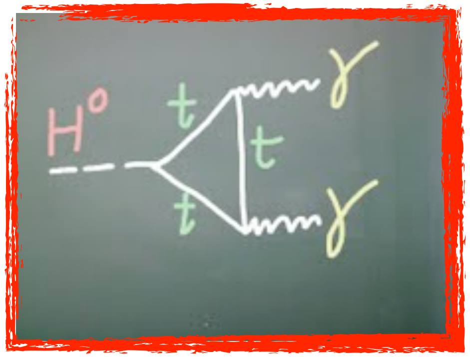
Higgs decays



Higgs decays

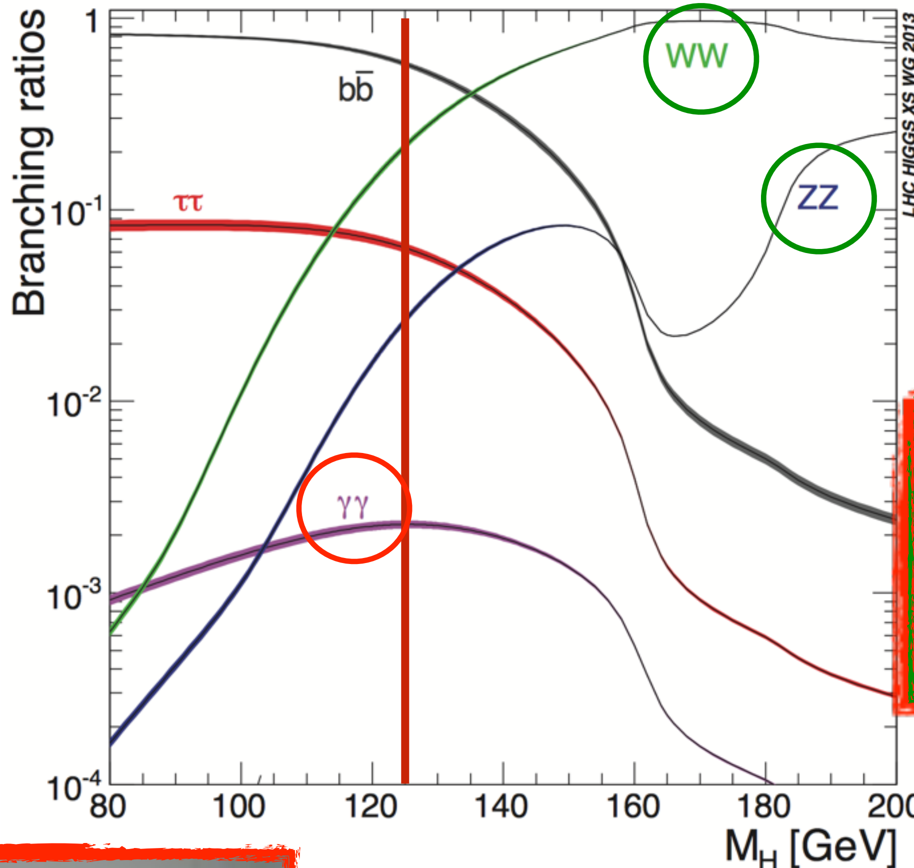


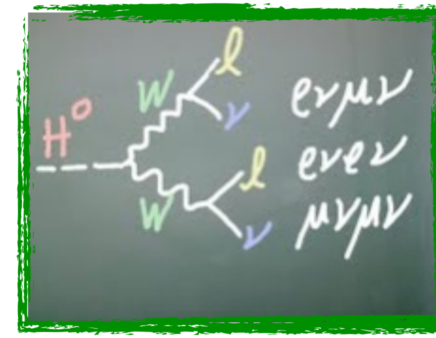




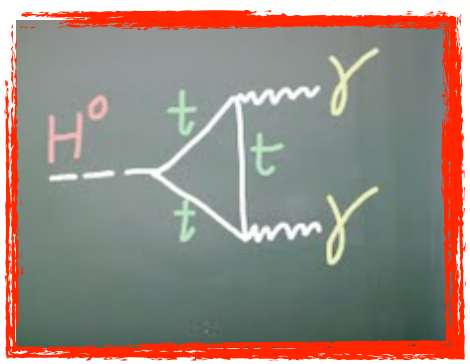
Best experimental
mass resolution

Higgs decays



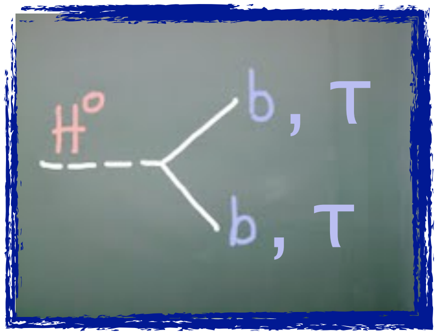


Coupling
to bosons

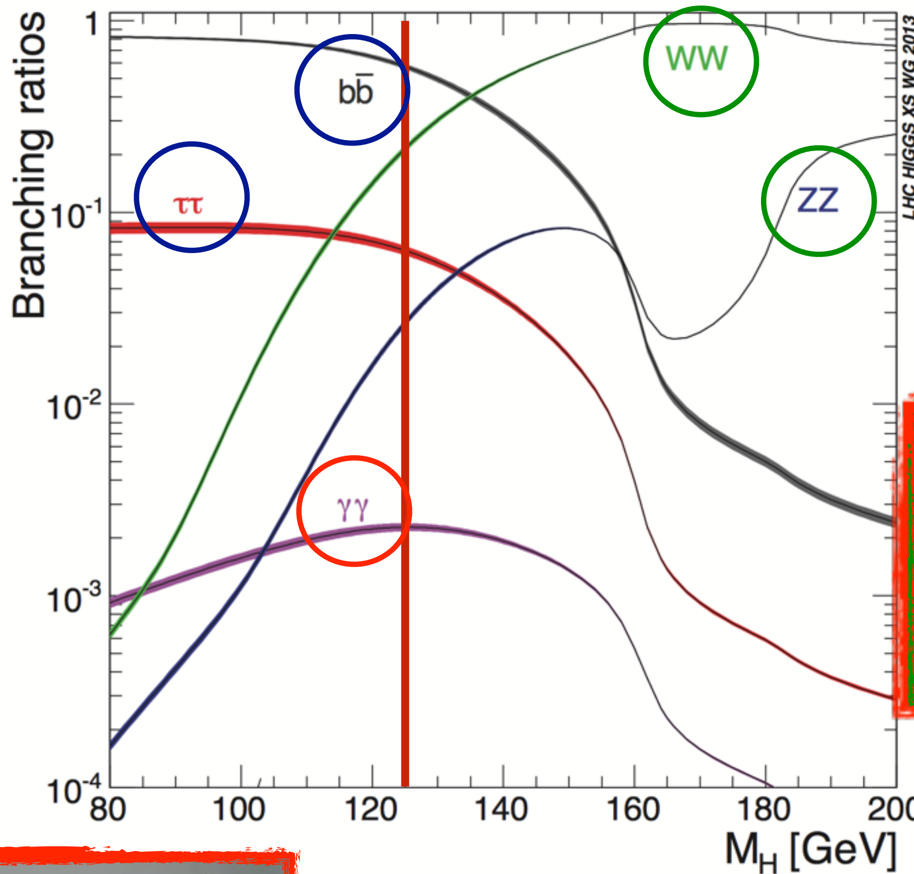


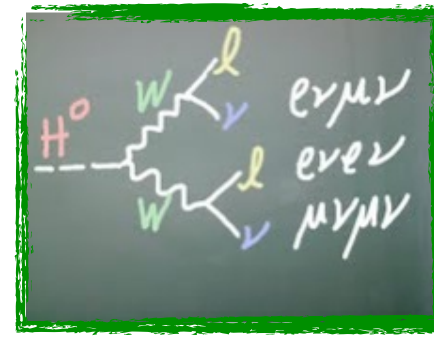
Best experimental
mass resolution

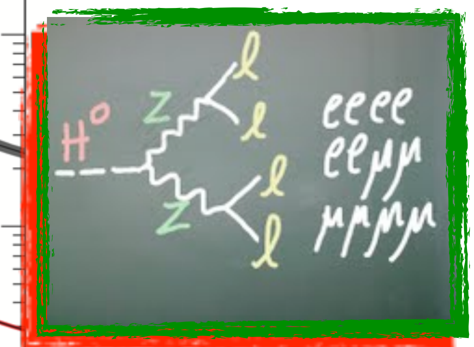
Higgs decays



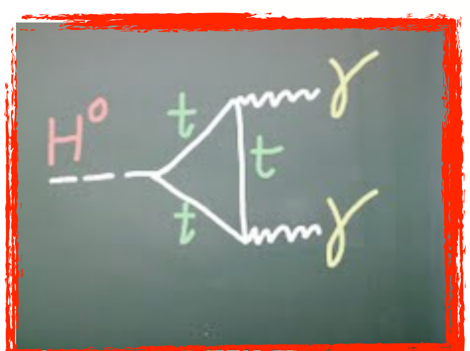
Coupling
to fermions







Coupling
to bosons



Best experimental
mass resolution

Overall experimental strategy

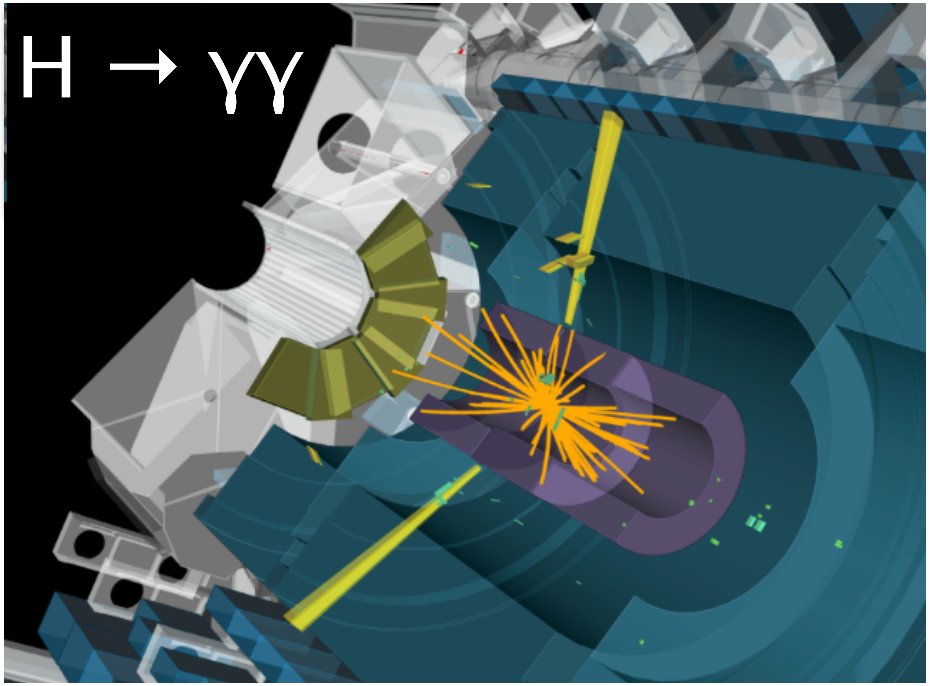
Investigate a large number of final states, with sub-channels to separate different productions (and to increase overall significance)

Probe Lagrangian structure. Measure mass, spin and CP properties → Next talk from Guillelmo

Channel	ggF	VBF	VH	ttH	Mass	Spin
$\gamma\gamma$	✓	✓	✓	✓	✓	✓
$ZZ \to 4\ell$	✓	✓	✓		✓	✓
$WW \to \ell\ell + 2\nu$	✓	✓	✓	✓		✓
$\tau\tau$	✓	✓	✓			
bb		✓	✓	✓		
$\mu\mu$	✓	✓				
$Z\gamma$	✓	✓				

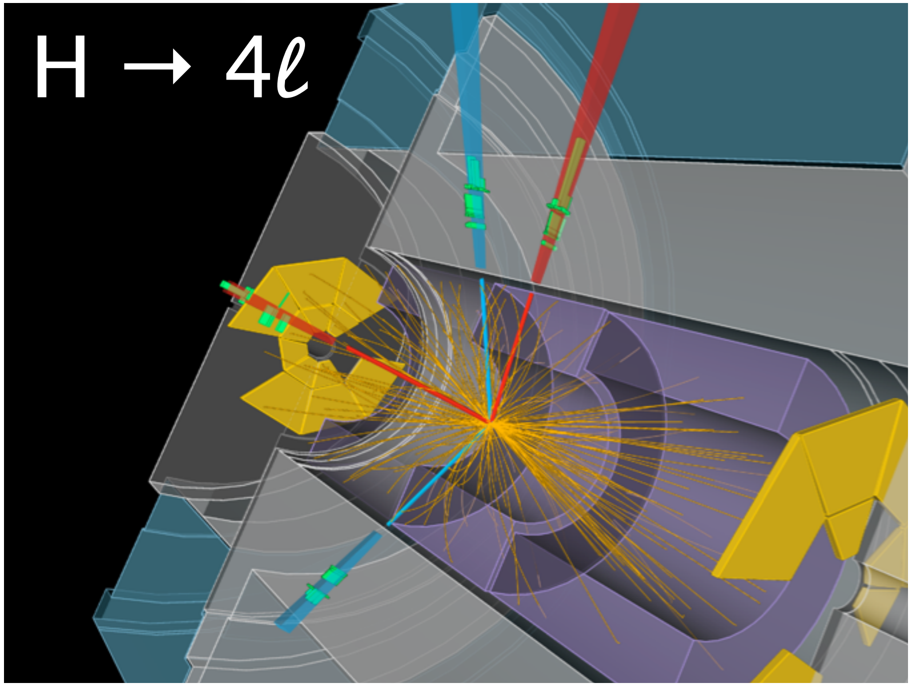
Main discovery channels

Simple signatures, with excellent mass resolution



BR ~ 0.2%

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



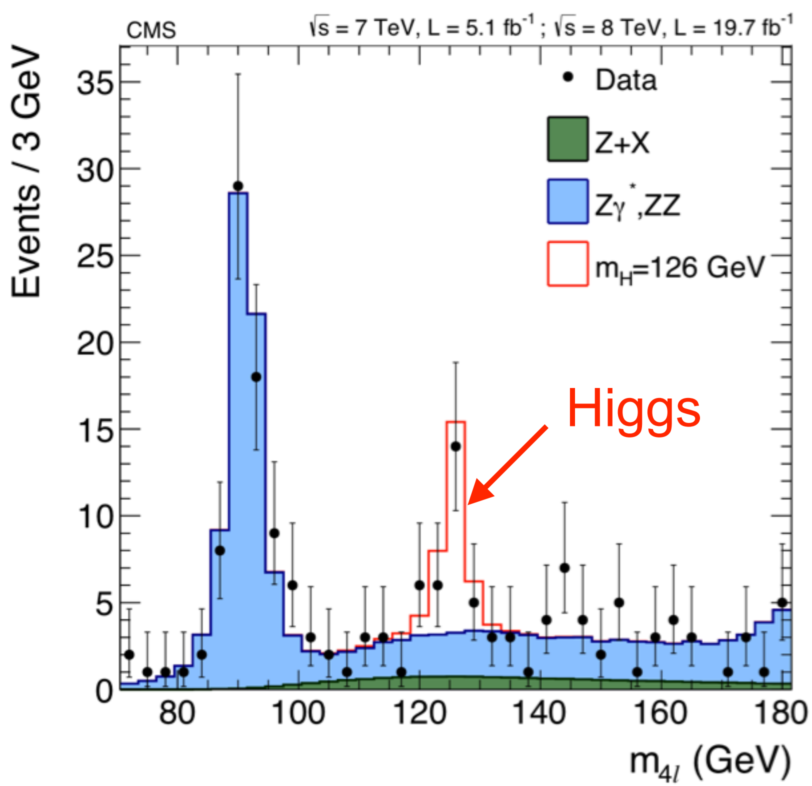
BR ~ 0.013%

Exp. signal yield	S/B
~20	~1.6

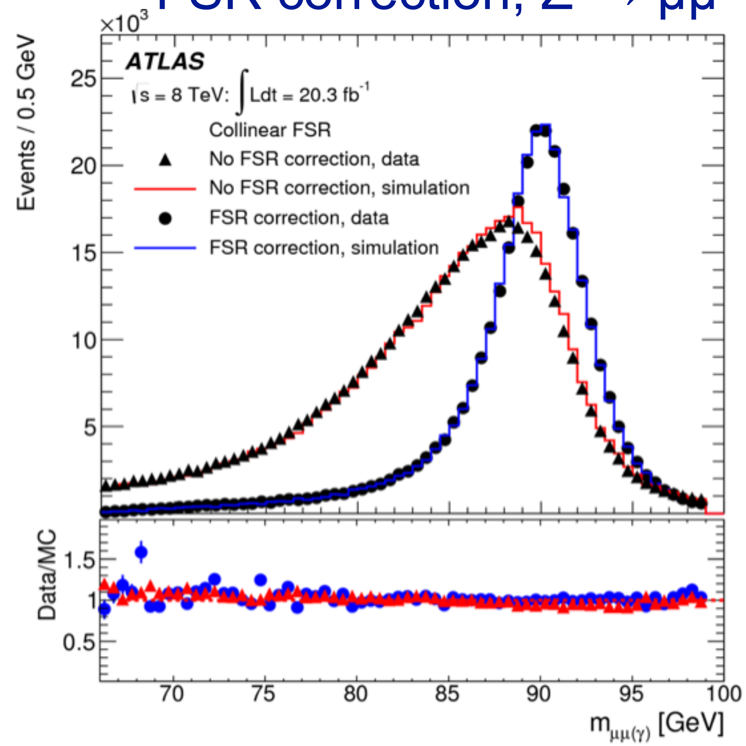
$H \rightarrow ZZ^* \rightarrow 4\ell$

Optimise for high lepton selection efficiency and good 4-lepton mass resolution

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



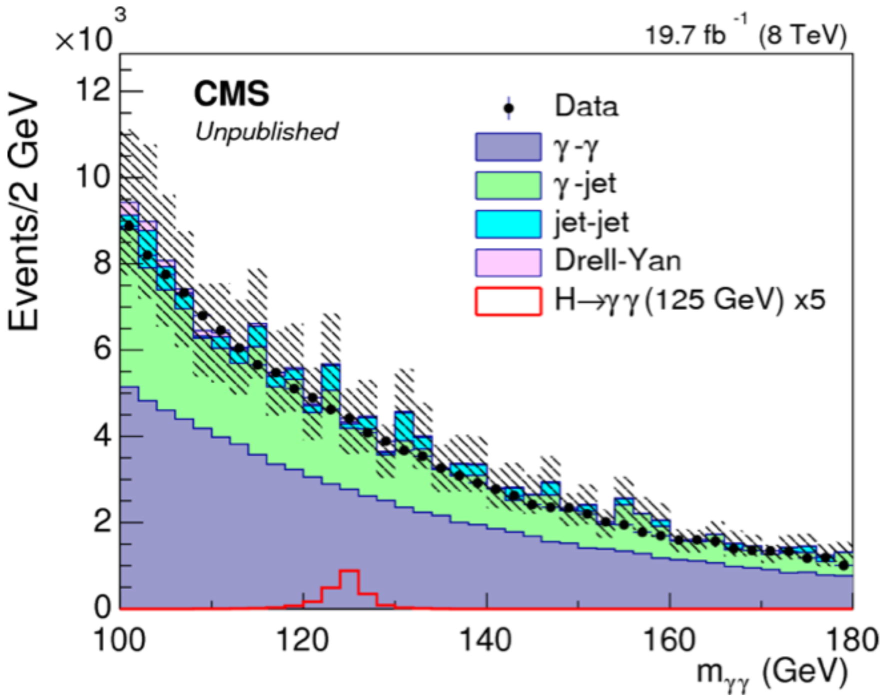
FSR correction, $Z \rightarrow \mu\mu$

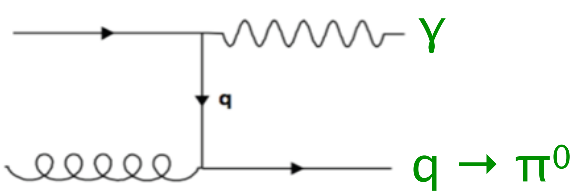


Di-photon decay mode

Select events with two isolated high pT photons

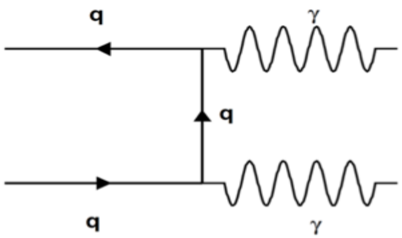
Quantify excess in steeply falling di-photon mass spectrum





Reducible

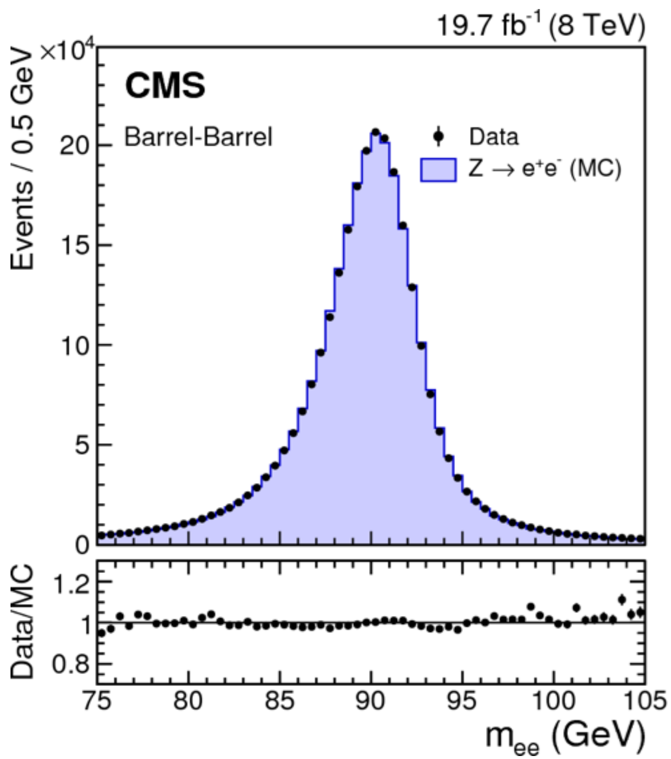
Critical to reach rejections $O(10^4)$

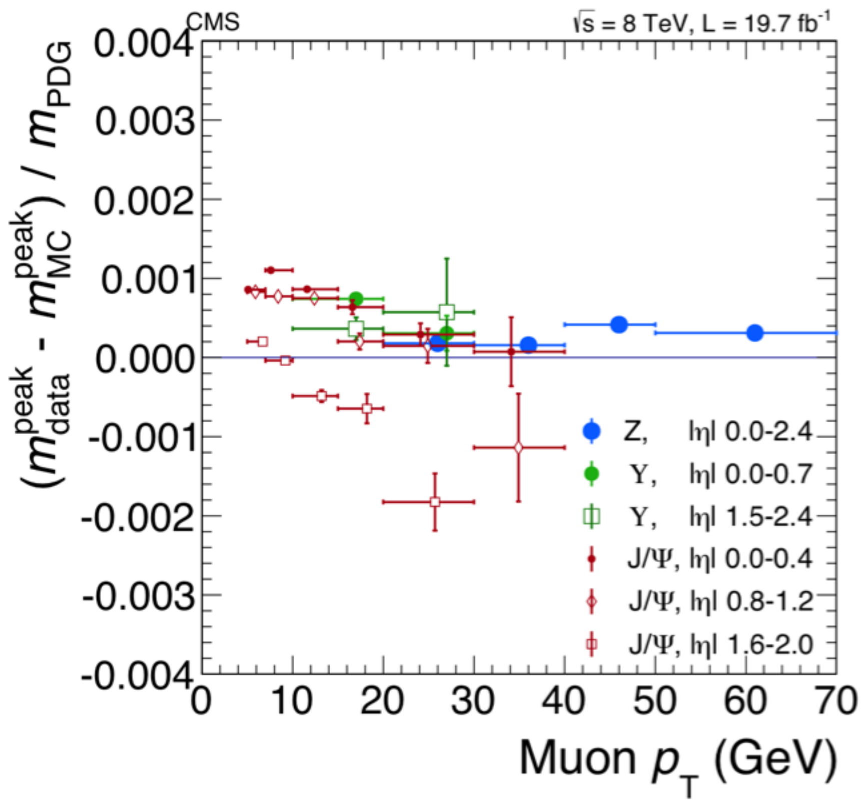


Irreducible

Energy scale and resolution

Electron and muon energy scale (and resolution) corrections determined from large Z and J/ψ samples

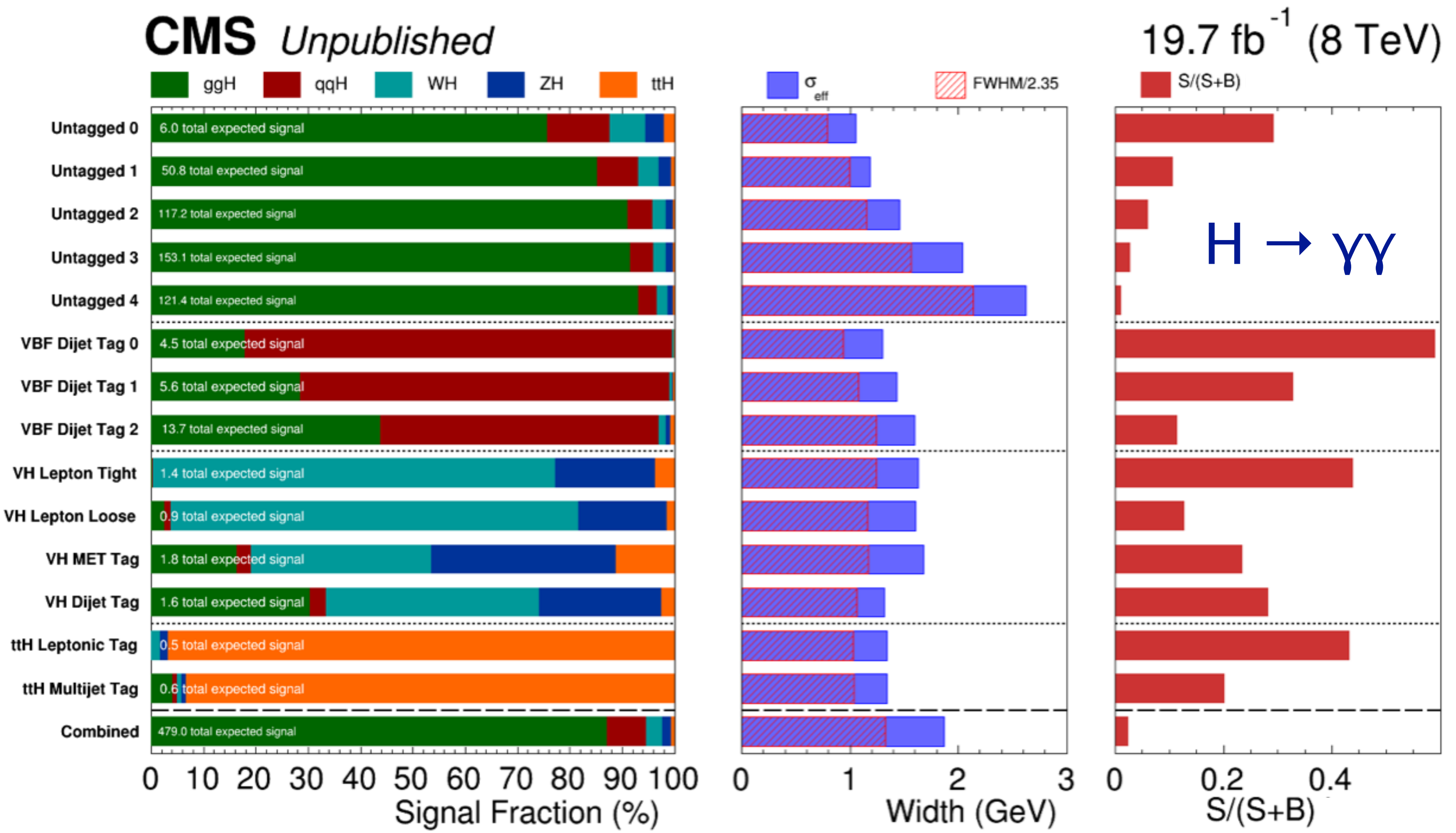


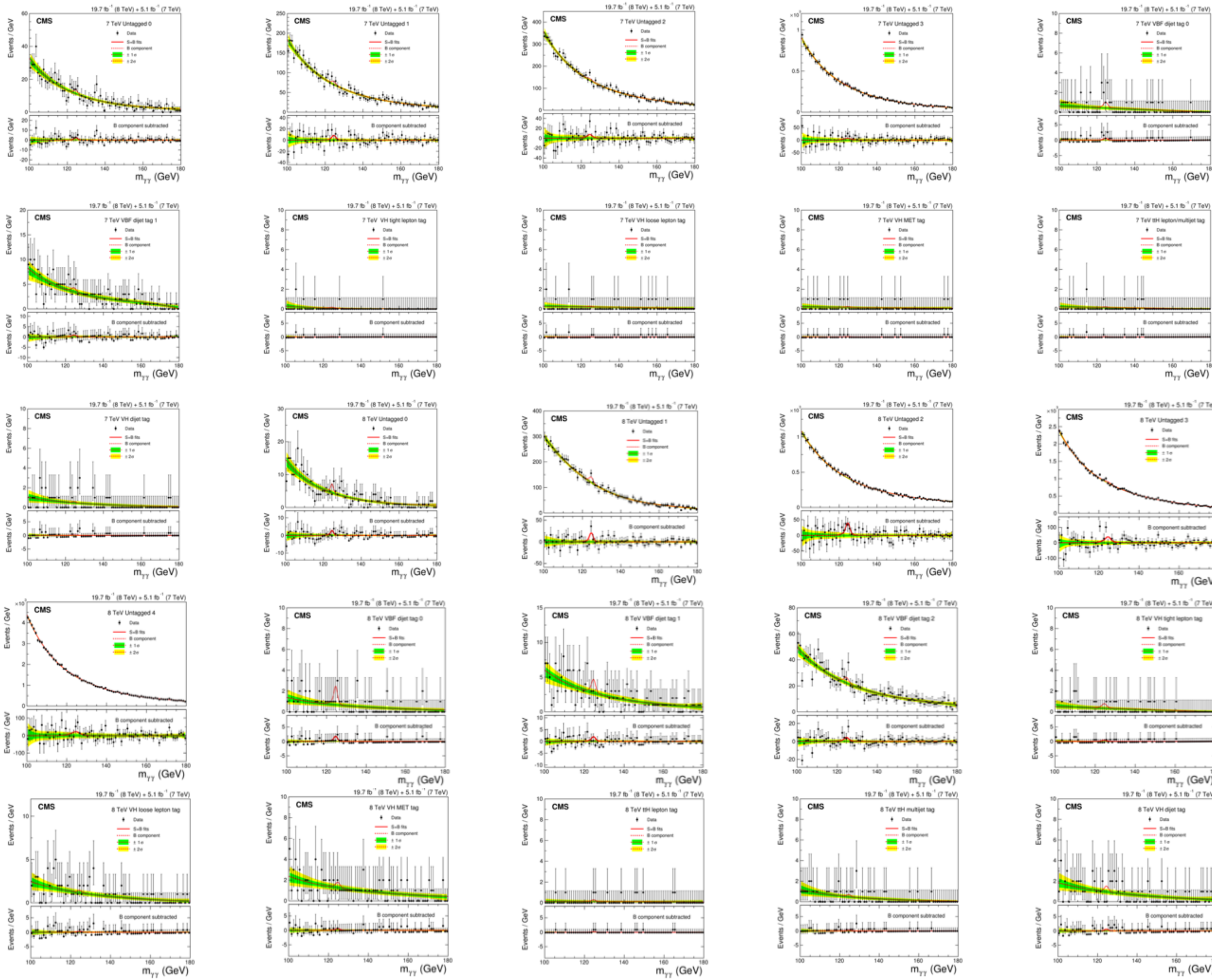


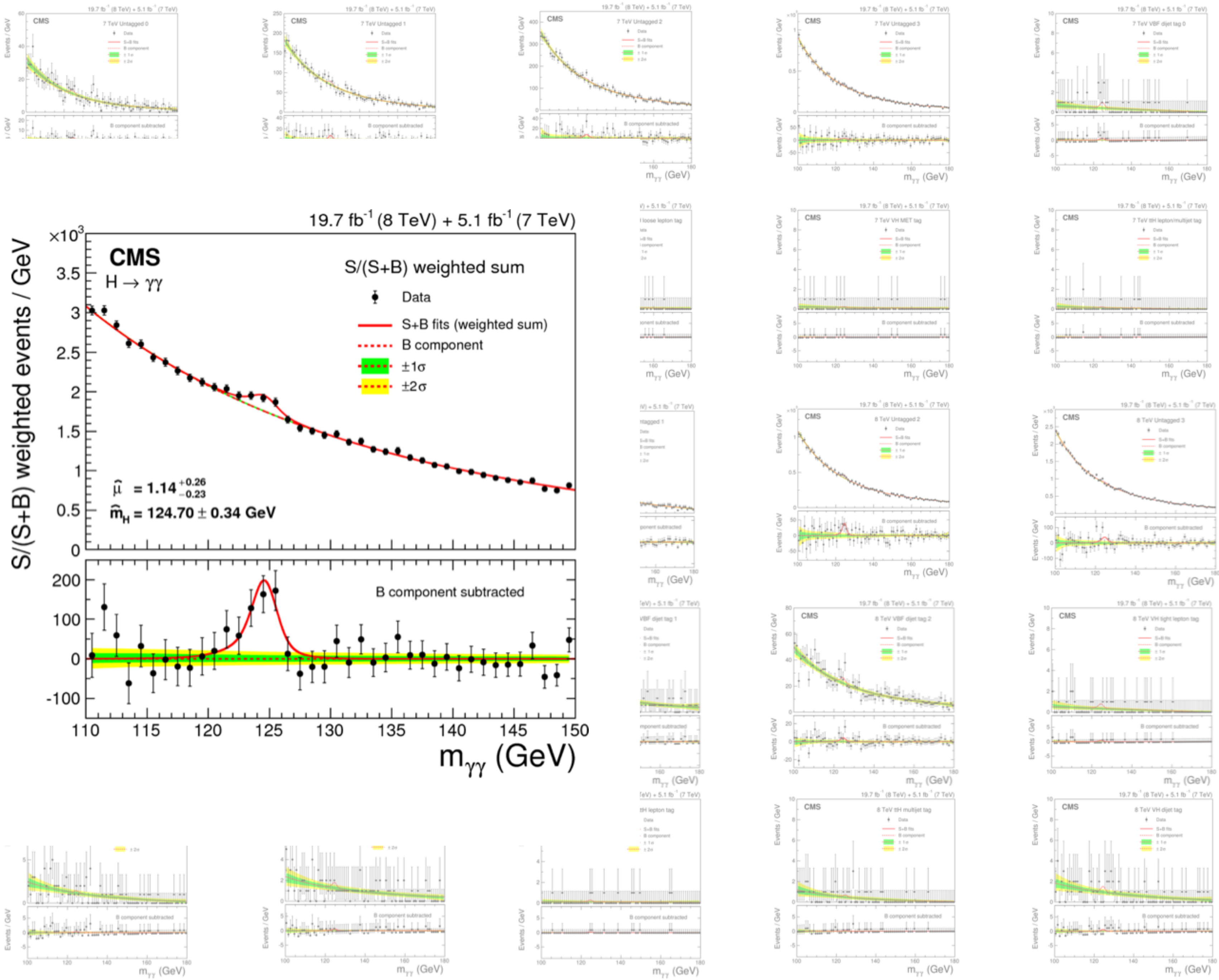
Photons need accurate material description for e → γ extrapolation, studied with several *in-situ* measurements

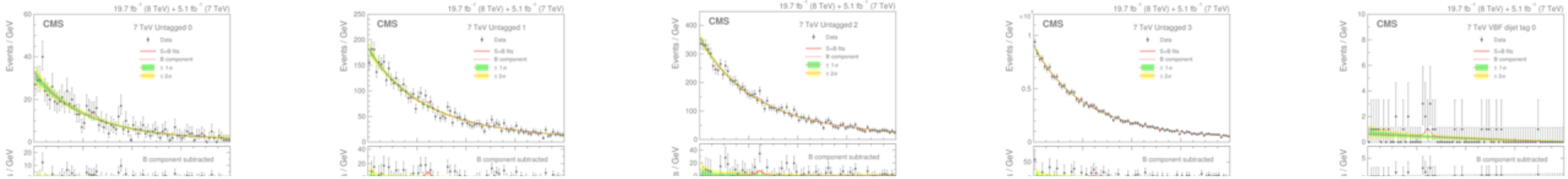
Improving the sensitivity

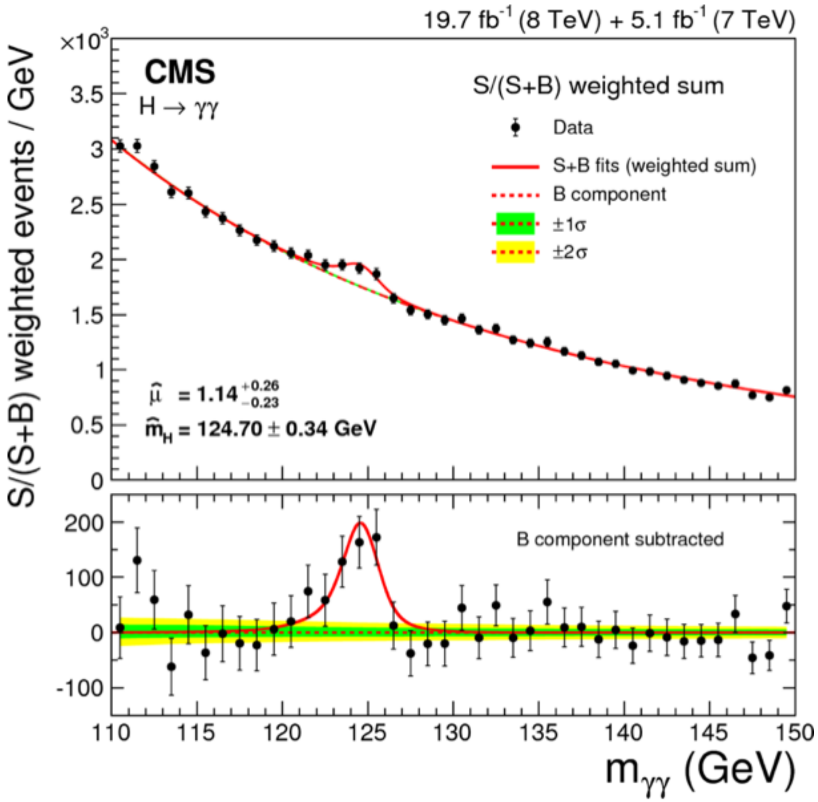
Separate events into categories with different S/B, resolutions and different relative contributions of signal production modes

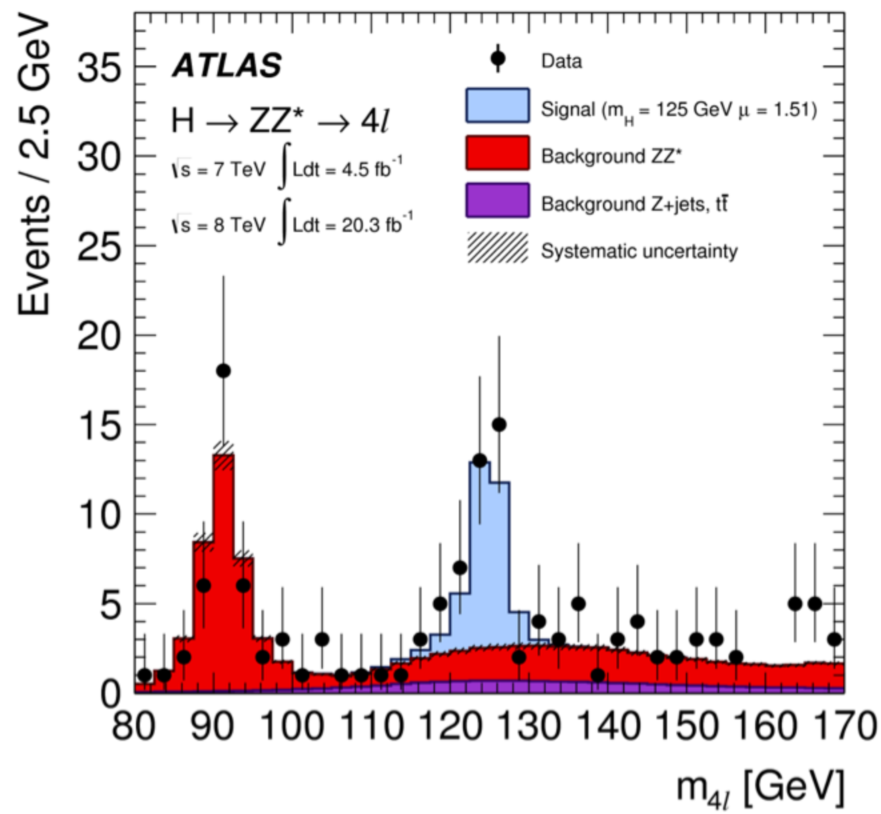


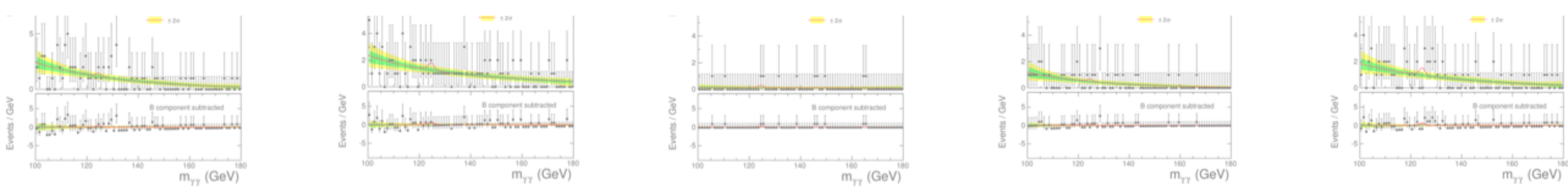

CMS
19.7 fb⁻¹ (8 TeV) + 5.1 fb⁻¹ (7 TeV)
7 TeV Untagged 0
7 TeV Untagged 1
7 TeV Untagged 2
7 TeV Untagged 3
7 TeV VBF dijet tag 0
7 TeV VBF dijet tag 1
7 TeV VH tight lepton tag
7 TeV VH loose lepton tag
7 TeV VH MET tag
7 TeV ttH lepton/multijet tag
7 TeV VH dijet tag
8 TeV Untagged 0
8 TeV Untagged 1
8 TeV Untagged 2
8 TeV Untagged 3
8 TeV Untagged 4
8 TeV VBF dijet tag 0
8 TeV VBF dijet tag 1
8 TeV VBF dijet tag 2
8 TeV VH tight lepton tag
8 TeV VH loose lepton tag
8 TeV VH MET tag
8 TeV ttH lepton tag
8 TeV ttH multijet tag
8 TeV VH dijet tag
Data
S+B fits
B component
± 1σ
± 2σ
B component subtracted
Events / GeV
m_γγ (GeV)


19.7 fb^{-1} (8 TeV) + 5.1 fb^{-1} (7 TeV)
CMS
H → γγ
S/(S+B) weighted sum
Data
S+B fits (weighted sum)
B component
±1σ
±2σ
$\hat{\mu}$ = 1.14 $^{+0.26}_{-0.23}$
$\hat{m}_H$ = 124.70 ± 0.34 GeV
S/(S+B) weighted events / GeV
×10^3
B component subtracted
$m_{\gamma\gamma}$ (GeV)
7 TeV Untagged 0
7 TeV Untagged 1
7 TeV Untagged 2
7 TeV Untagged 3
7 TeV VBF dijet tag 0
7 TeV VH MET tag
7 TeV ttH lepton/multijet tag
8 TeV Untagged 2
8 TeV Untagged 3
8 TeV VBF dijet tag 2
8 TeV VH tight lepton tag
8 TeV ttH multijet tag
8 TeV VH dijet tag



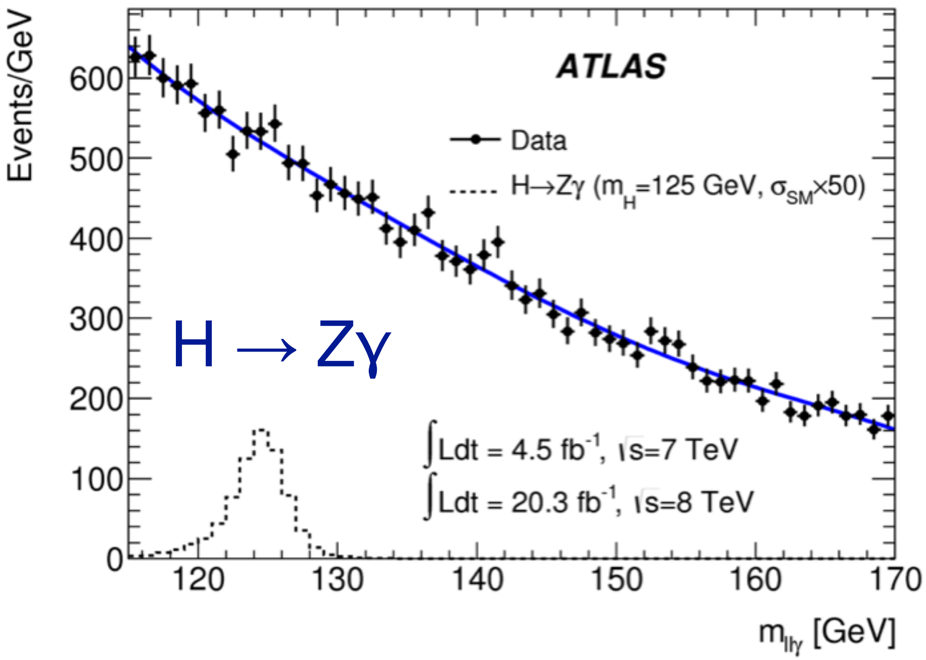

19.7 fb-1 (8 TeV) + 5.1 fb-1 (7 TeV)
CMS
H → γγ
S/(S+B) weighted sum
Data
S+B fits (weighted sum)
B component
±1σ
±2σ
μ̂ = 1.14 +0.26 −0.23
m̂H = 124.70 ± 0.34 GeV
S/(S+B) weighted events / GeV
B component subtracted
mγγ (GeV)

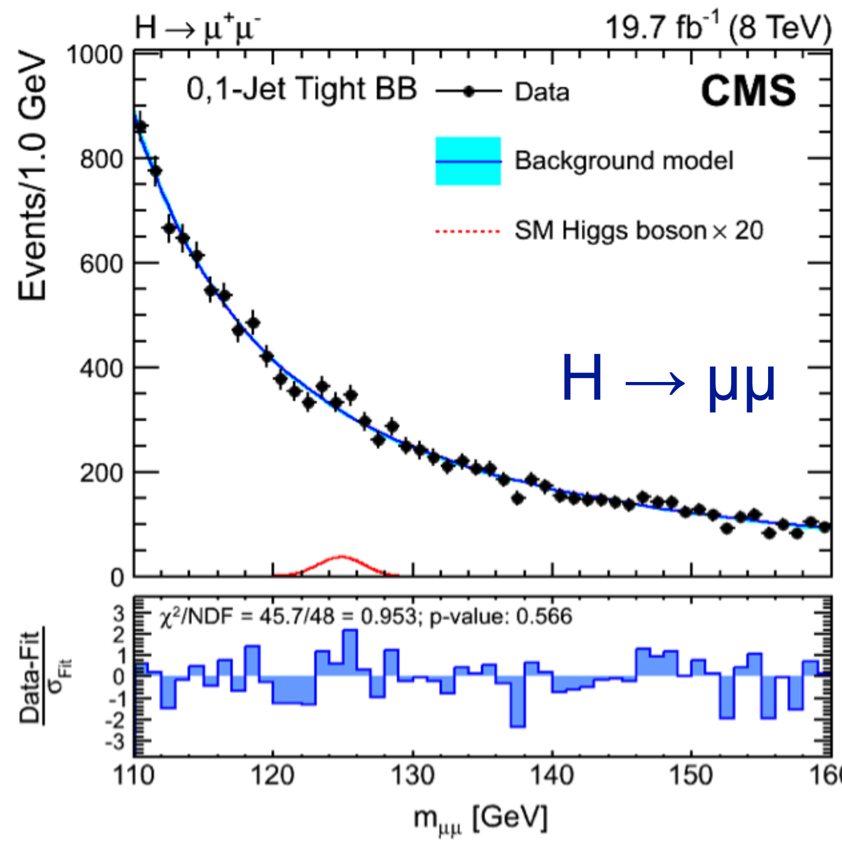

ATLAS
H → ZZ* → 4l
√s = 7 TeV ∫Ldt = 4.5 fb-1
√s = 8 TeV ∫Ldt = 20.3 fb-1
Data
Signal (mH = 125 GeV μ = 1.51)
Background ZZ*
Background Z+jets, tt̄
Systematic uncertainty
Events / 2.5 GeV
m4l [GeV]



$H \to Z\gamma$ and $H \to \mu\mu$

Both analyses exploit similar experimental techniques to $H \to \gamma\gamma$





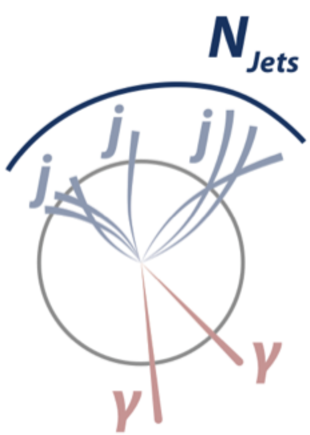
No significant excesses observed yet,
limits σ/σ_{SM} ~ 7-10 at m_H = 125 GeV

Differential cross sections

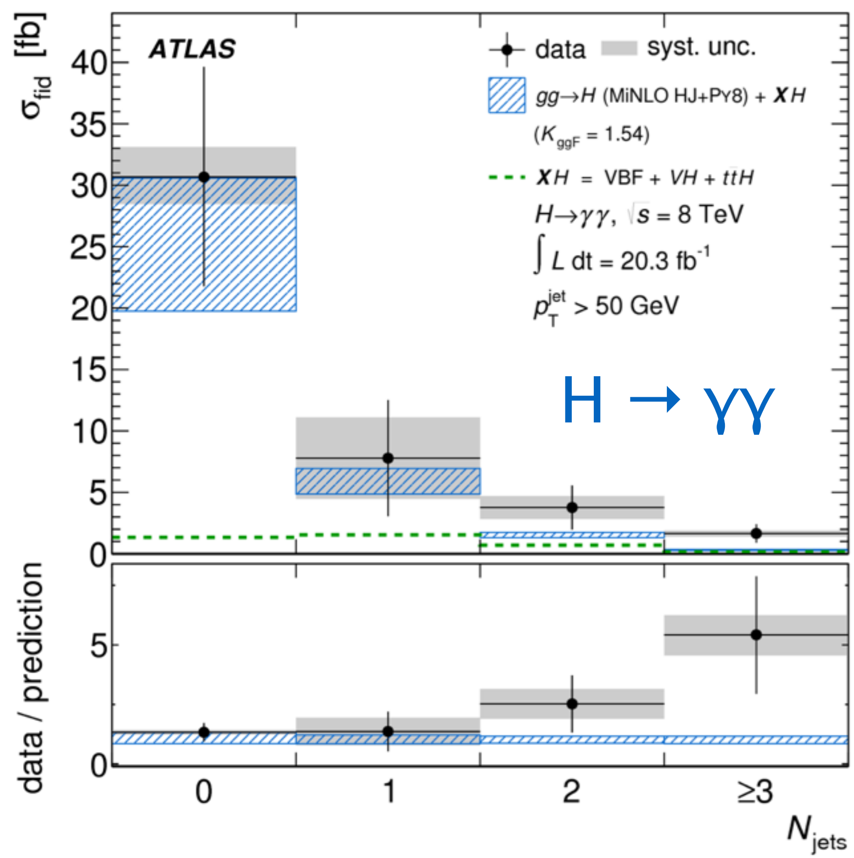
Probe underlying kinematic properties of Higgs boson production and decay

Variables specifically sensitive to:

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



Number of jets

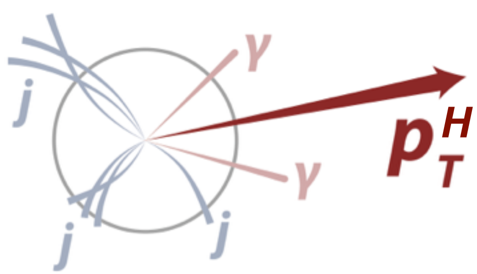


Differential cross sections

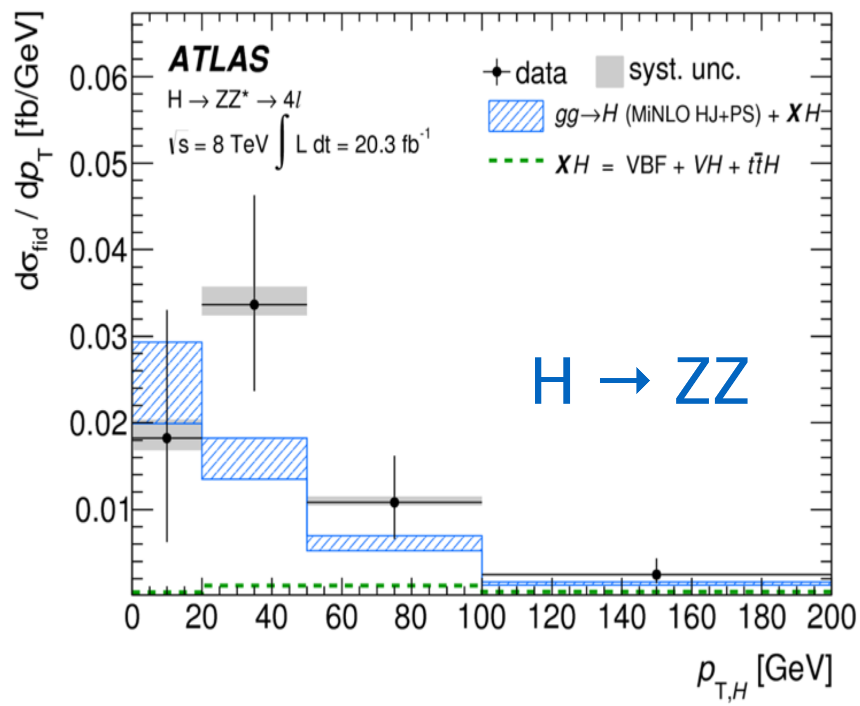
Probe underlying kinematic properties of Higgs boson production and decay

Variables specifically sensitive to:

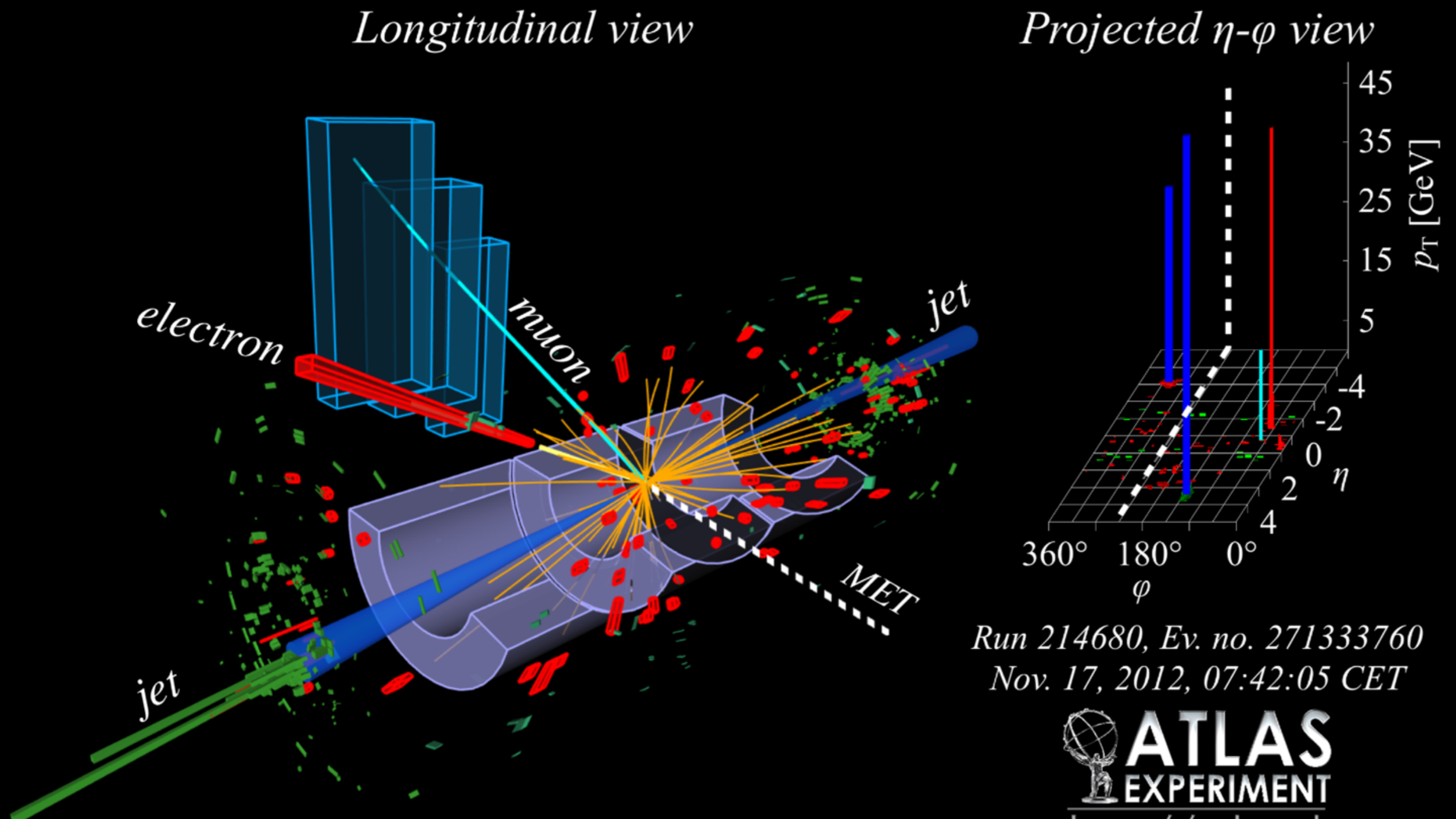
- Spin-parity
- Different production modes
- Higher-order corrections



Higgs boson transverse momenta



$H \to WW^* \to e\nu\mu\nu$ candidate and two jets with VBF topology



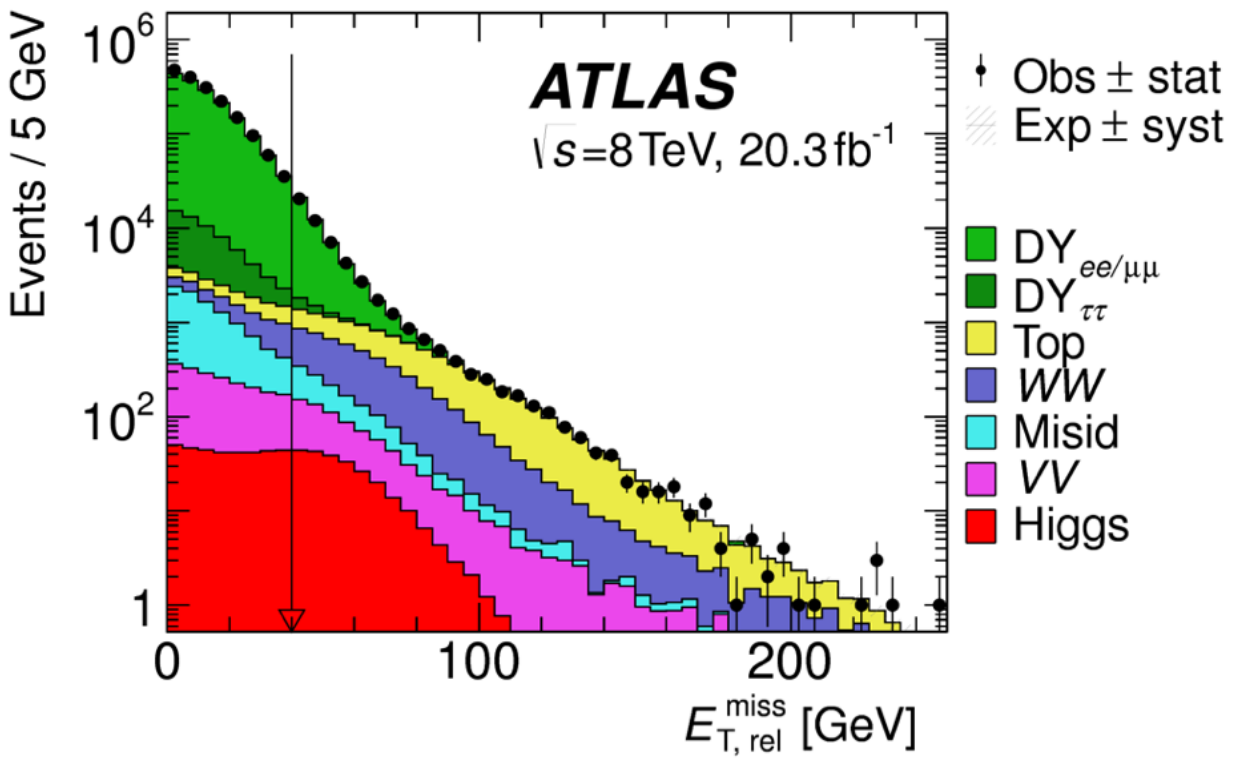
Exp. signal yield	S/B
~500	~15%

Analysis strategy

Various missing E_T related cuts to remove main DY contribution

Split by jet-multiplicity and lepton flavour

Topological cuts for further bkgr. reduction / VBF selection



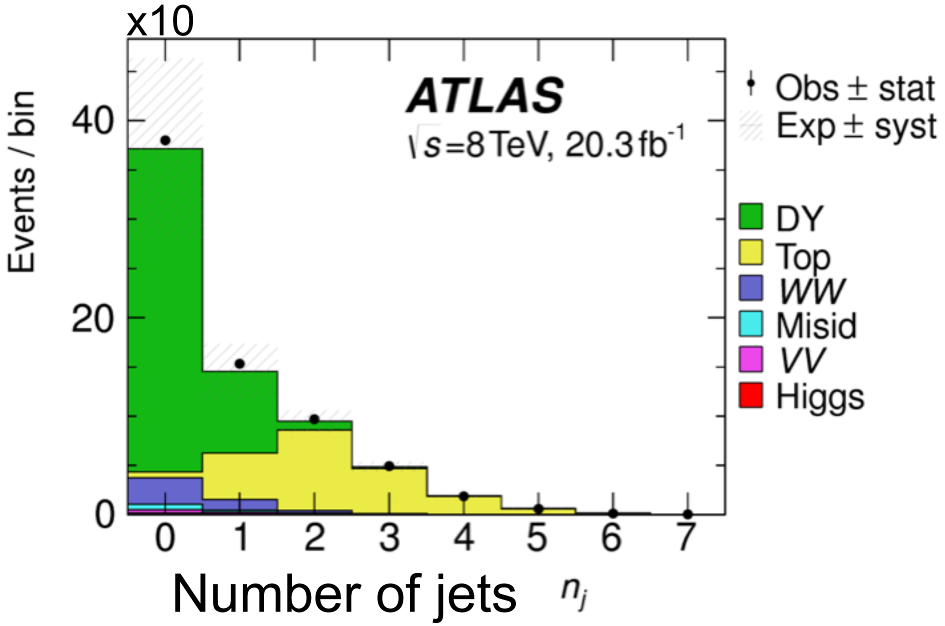
Analysis strategy

Various missing E_T related cuts to remove main DY contribution

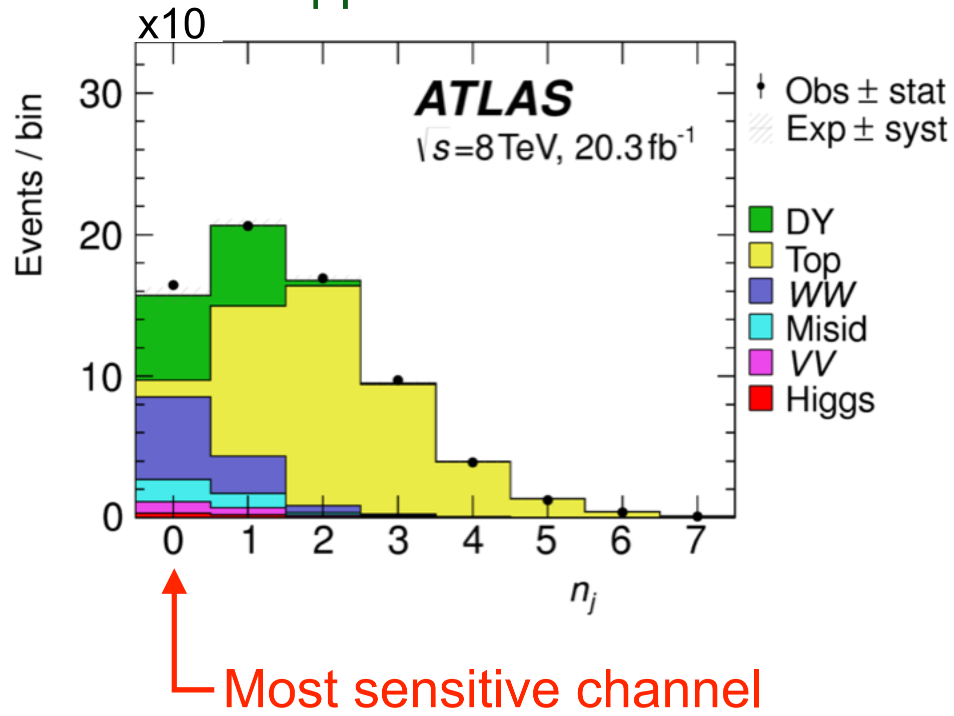
Split by jet-multiplicity and lepton flavour

Topological cuts for further bkgr. reduction / VBF selection

Same flavour

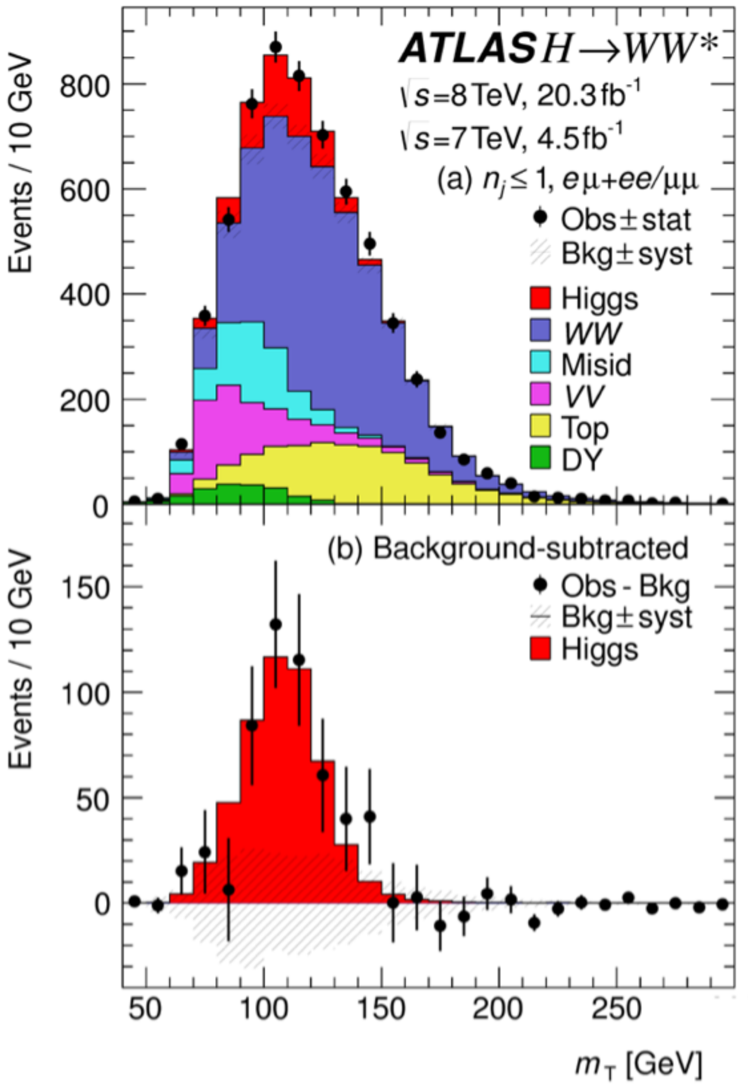


Opposite flavour

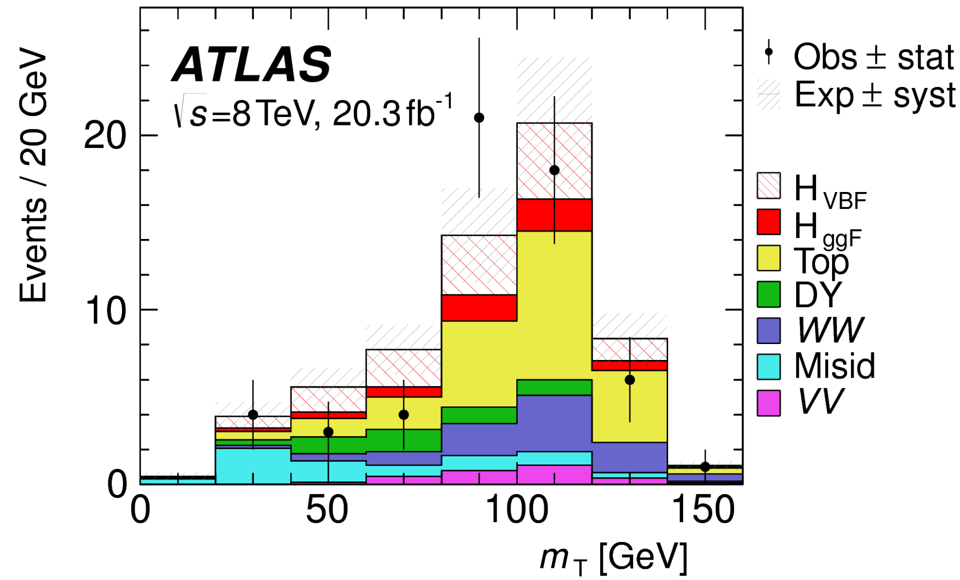


Final signal extraction

ggF enriched



VBF enriched

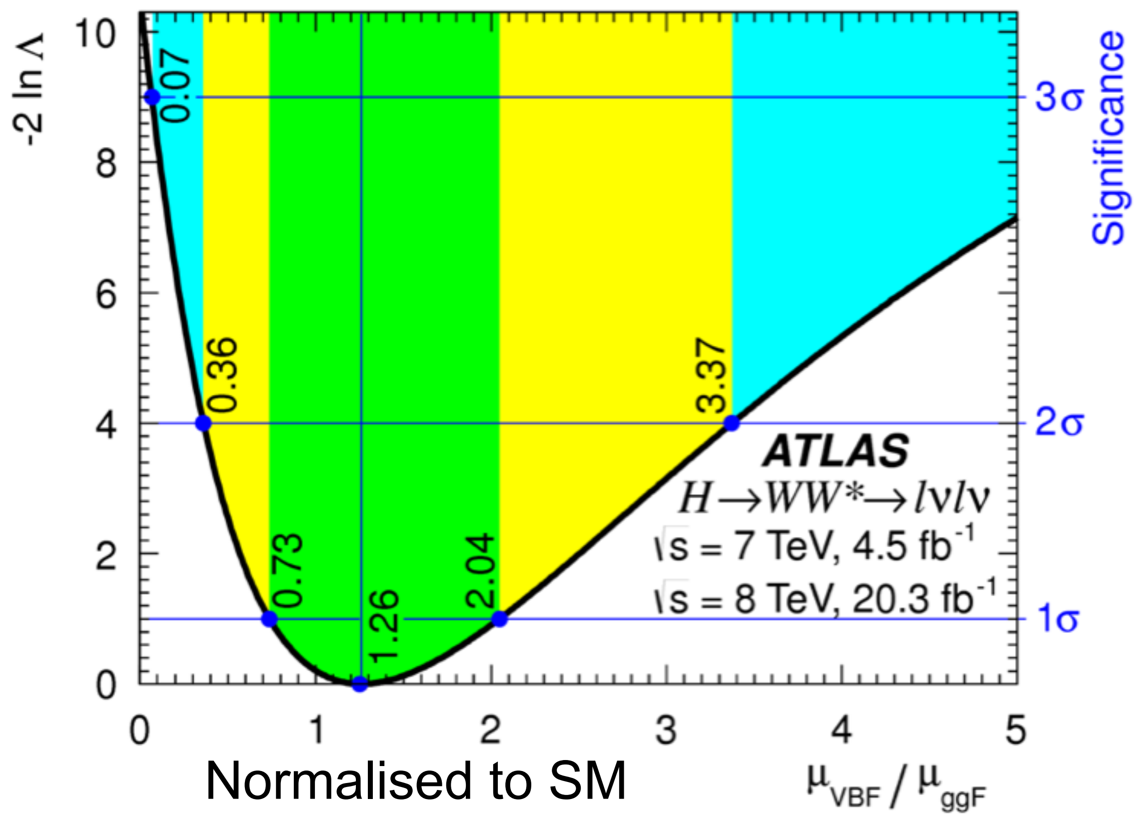


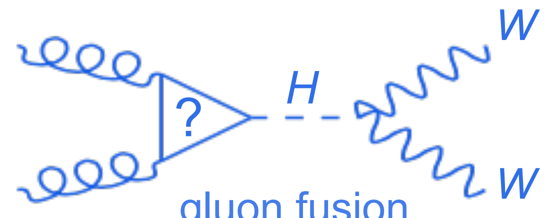
Most sensitive variable: transverse mass

Need good understanding of all high-energy SM processes

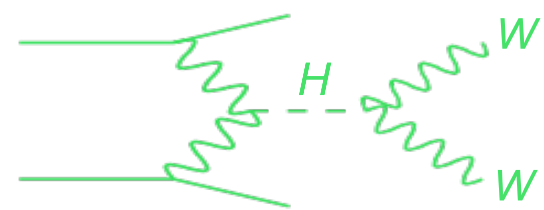
Evidence for VBF production

VBF / gluon-fusion production ratio





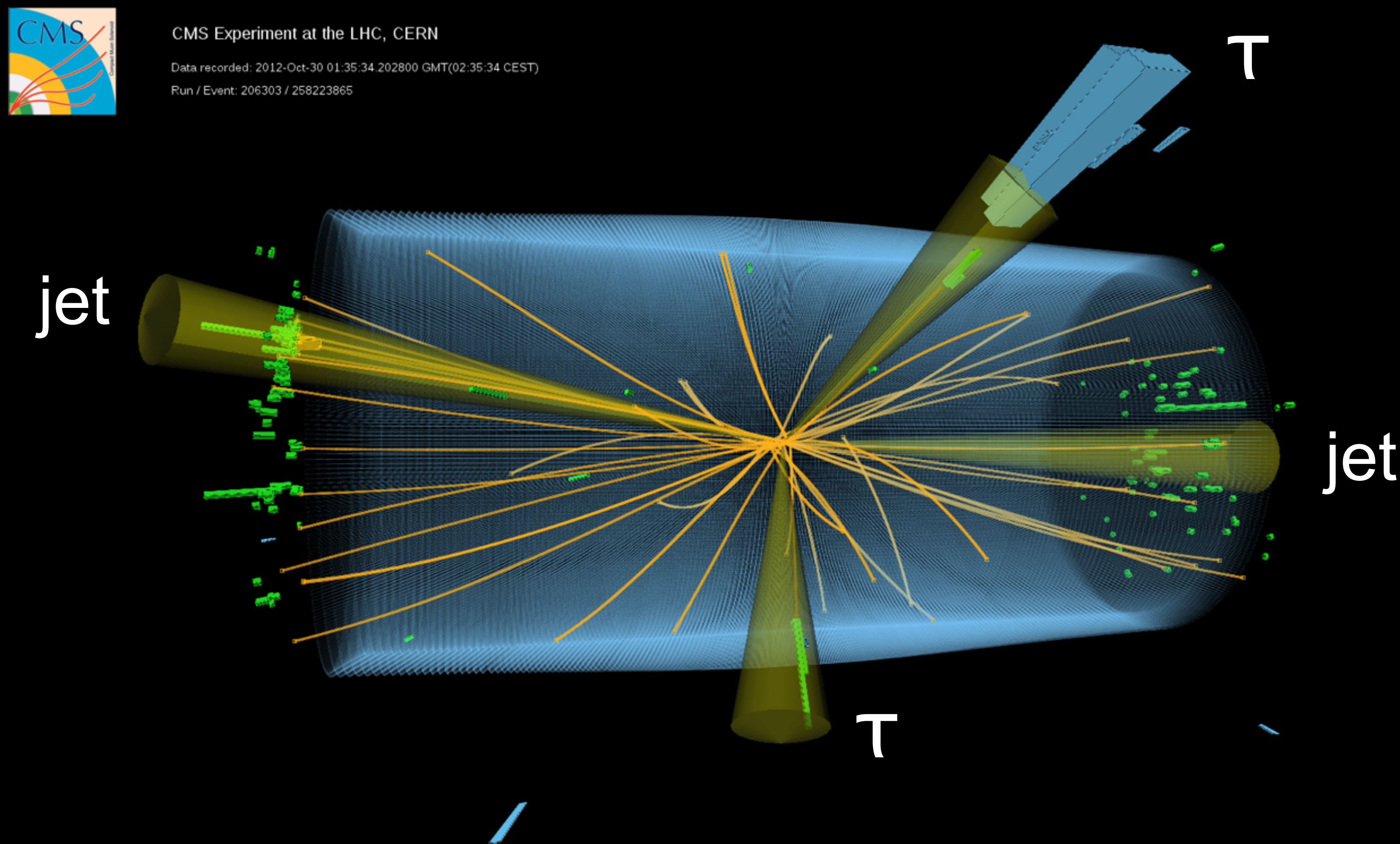
gluon fusion



vector boson fusion

Crucial for coupling measurements

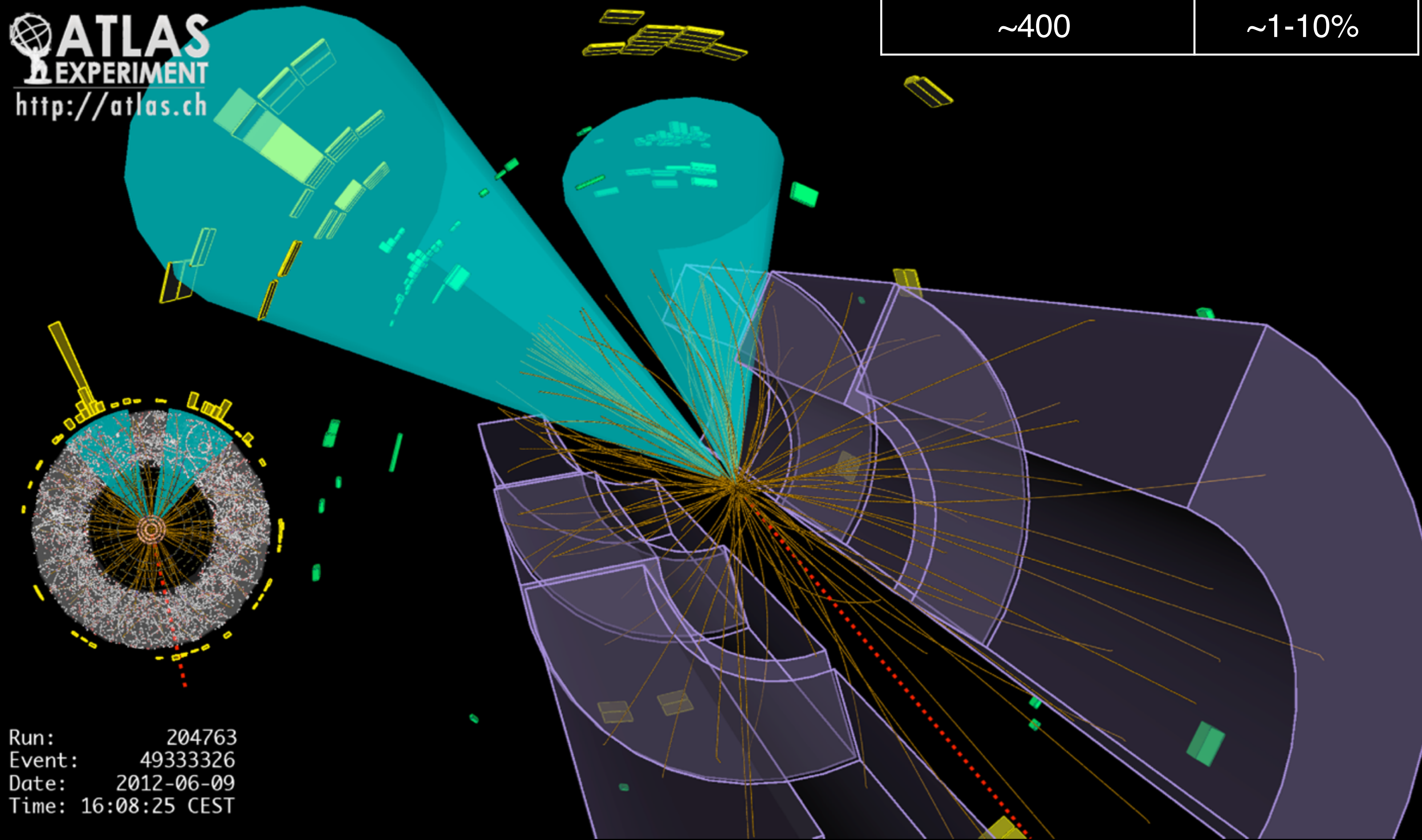
H → ττ



Exp. signal yield	S/B
~300	~1-30%

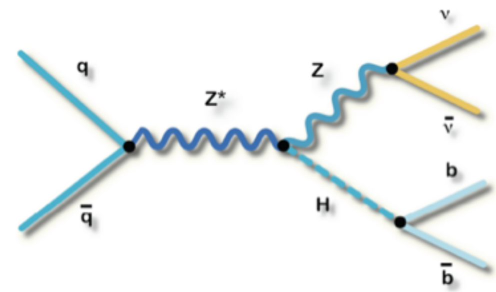
H → bb

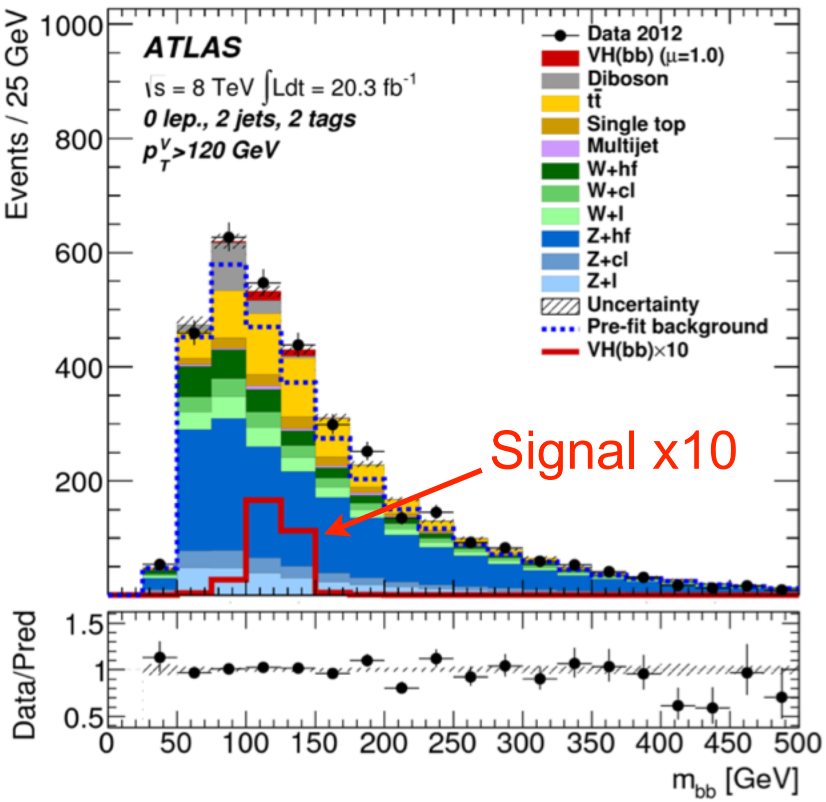
Exp. signal yield	S/B
~400	~1-10%

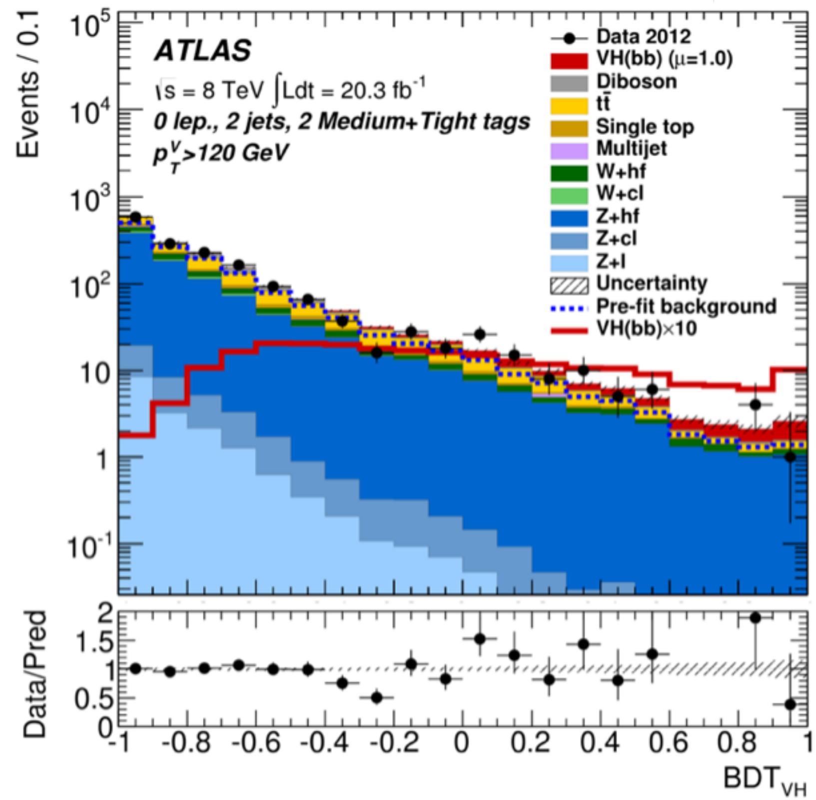


Due to overwhelming multi-jet backgrounds, need additional signature from exclusive production modes (VH, ttH, VBF)

Multivariate analysis

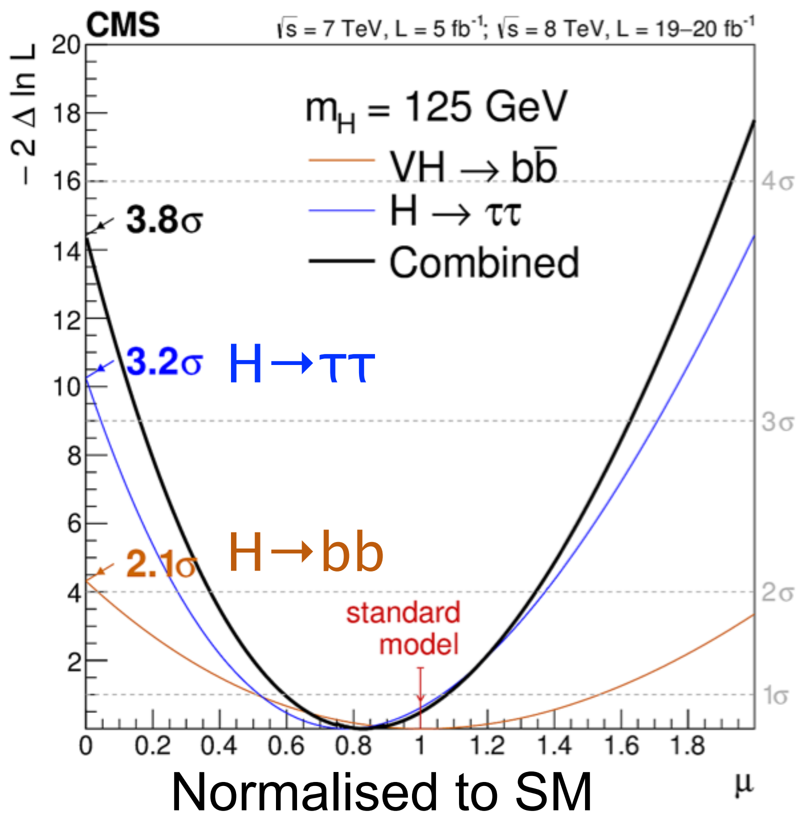


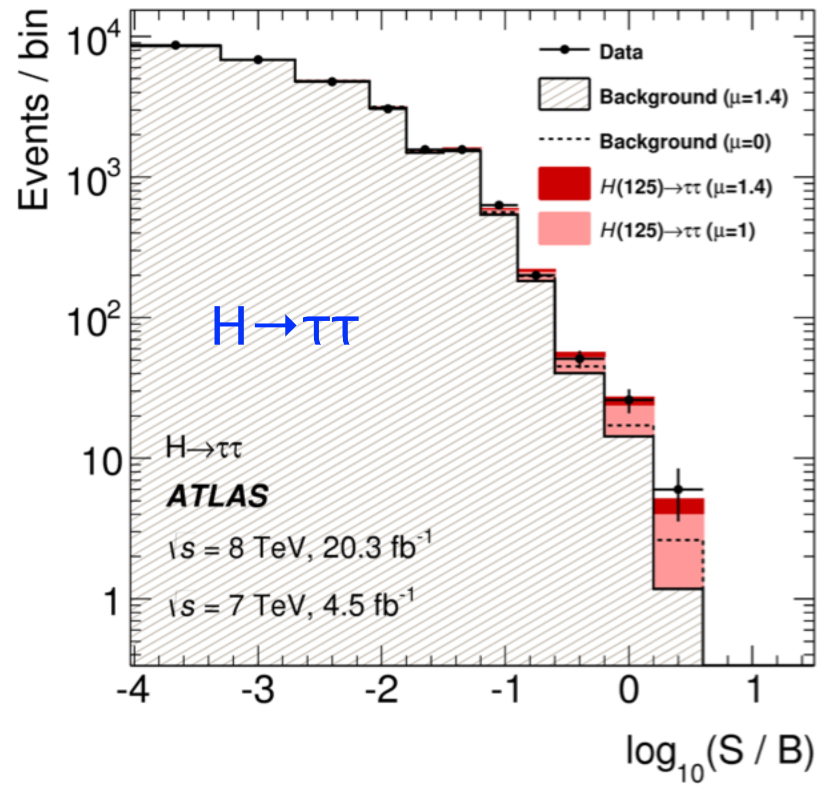




Increase signal discrimination by combining several kinematic distributions into a multivariate discriminant

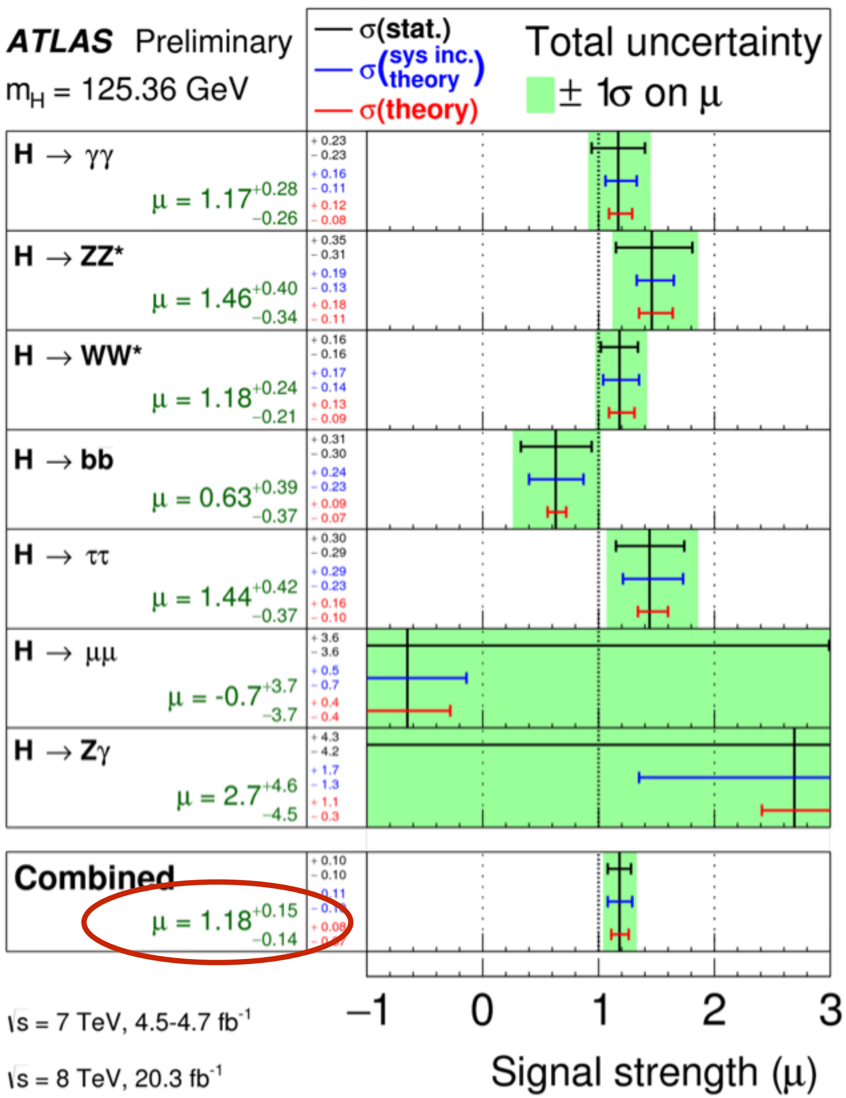
Evidence for Higgs-Yukawa coupling

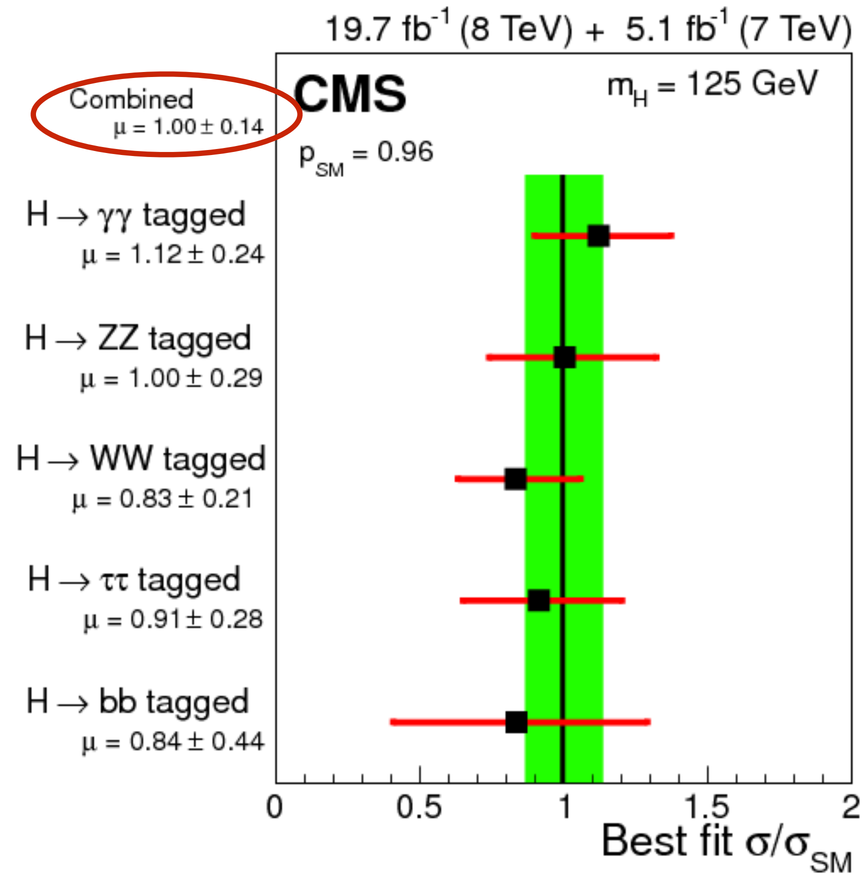




A fundamental part of the Standard Model

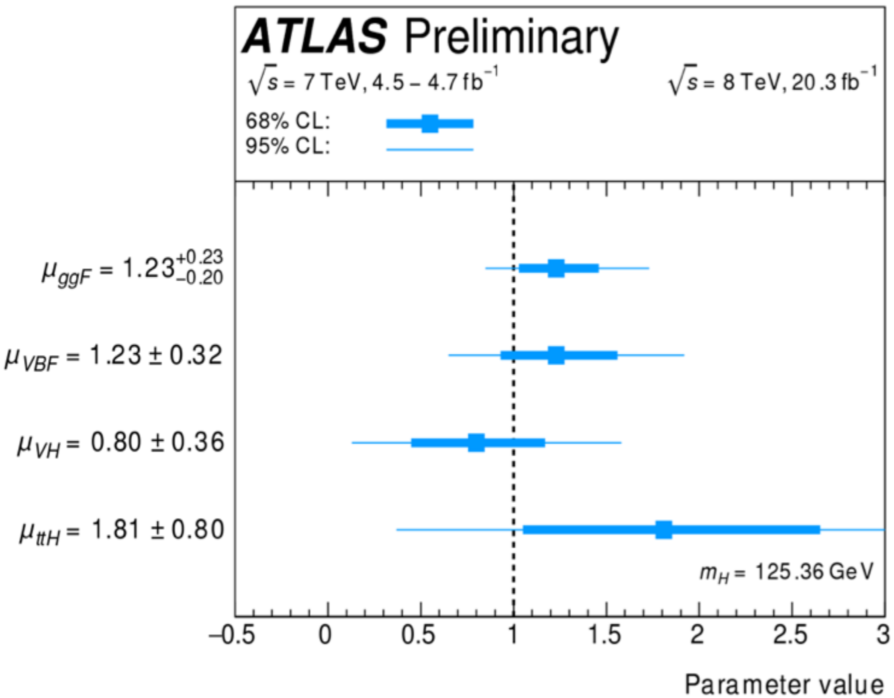
Higgs boson rates per decay channel

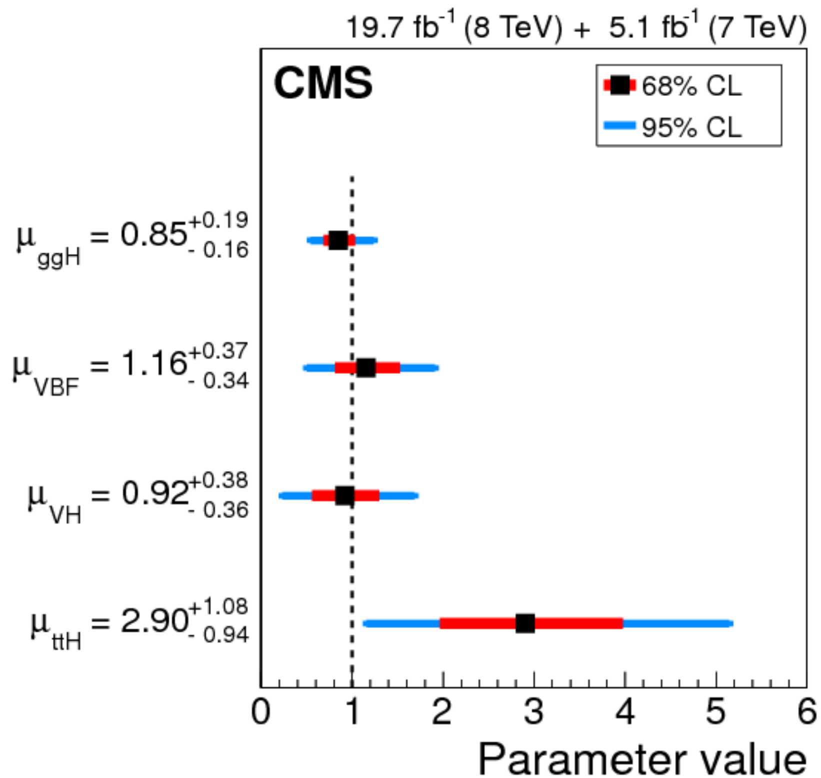




$$\mu = \frac{\sigma \cdot BR}{(\sigma \cdot BR)_{SM}}$$

Higgs boson production





Present rates in different production and decay channels in agreement with the SM expectations

The top-Yukawa coupling will be one of the most important measurements of LHC Run 2

Conclusions

The LHC Run 1 was an exciting time and a great success for particle physics

An entire new field emerged with a large number of interesting analyses

Present measurements indicate no deviations from the SM

Looking forward to LHC Run 2 for further exciting discoveries!