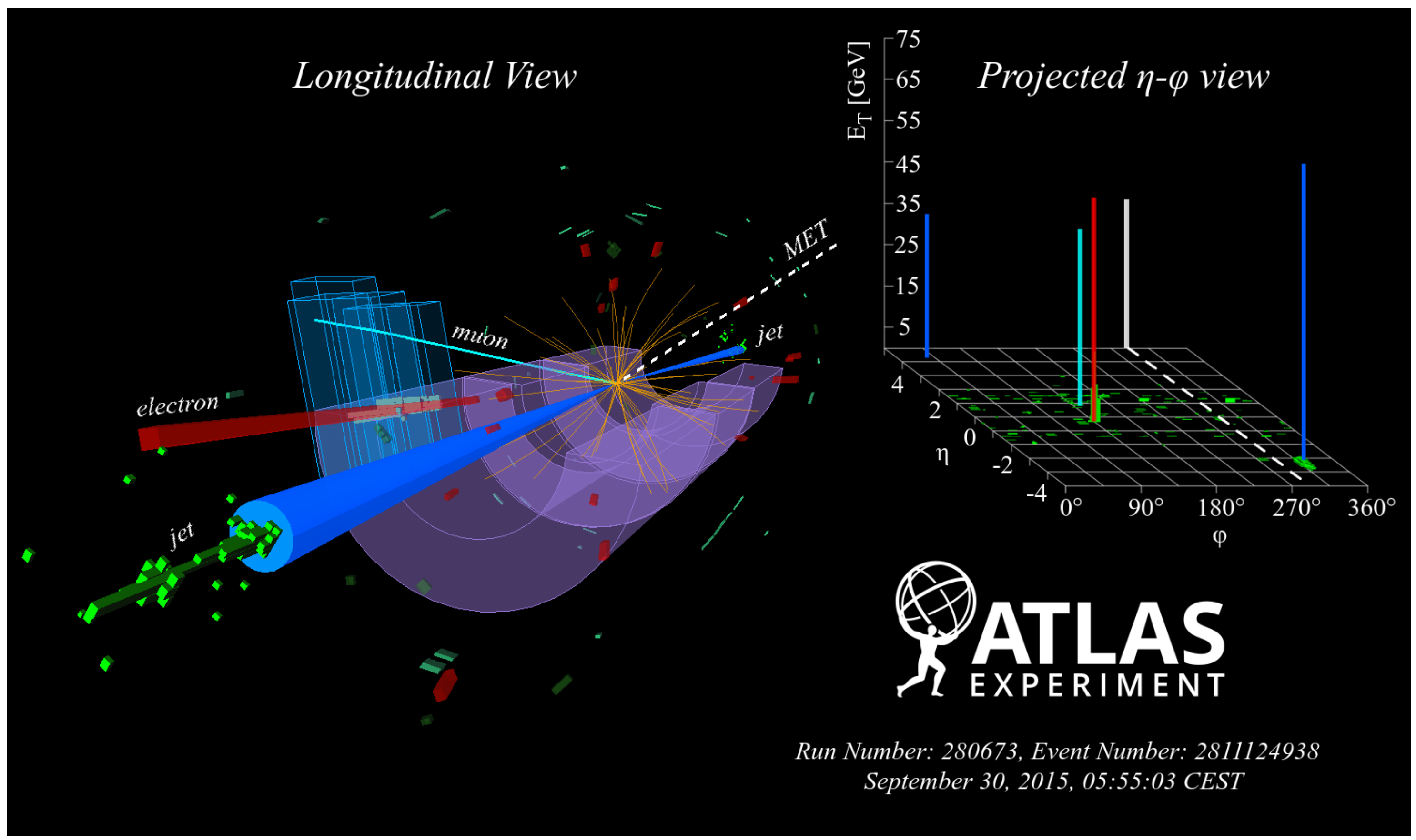
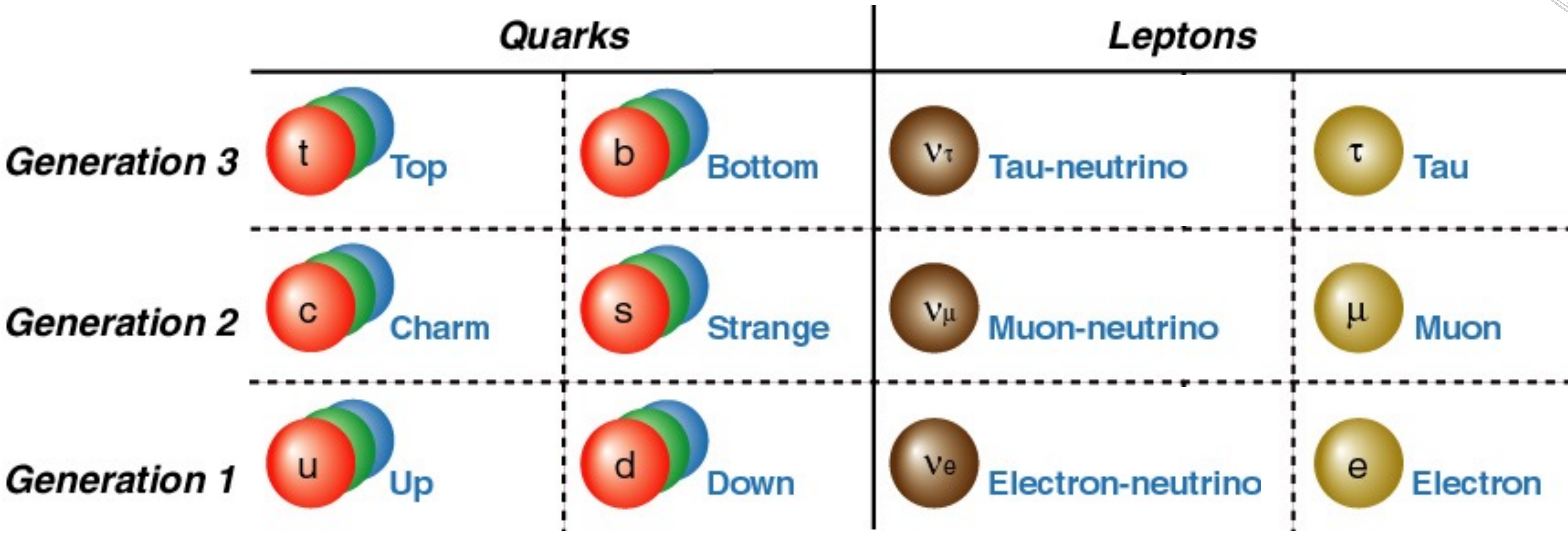
The Higgs Boson and its Properties



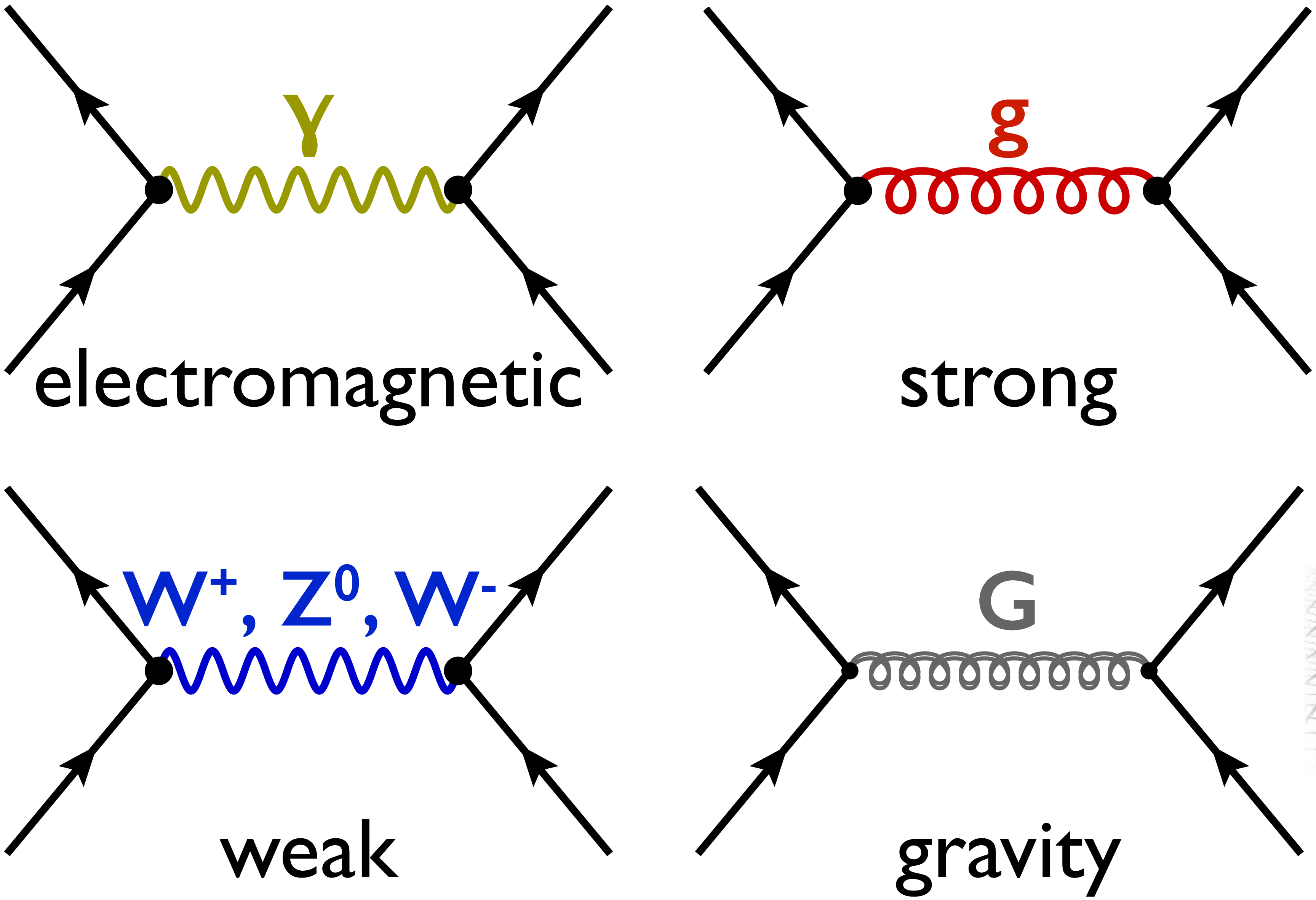
Karsten Köneke

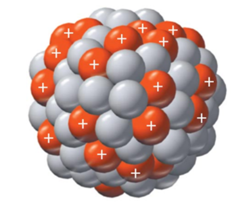
Matter

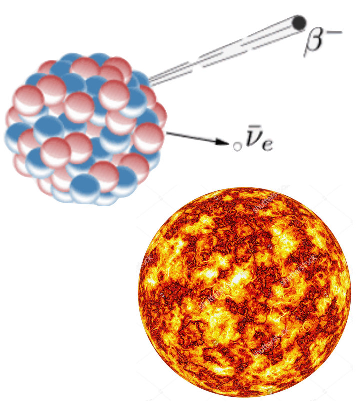


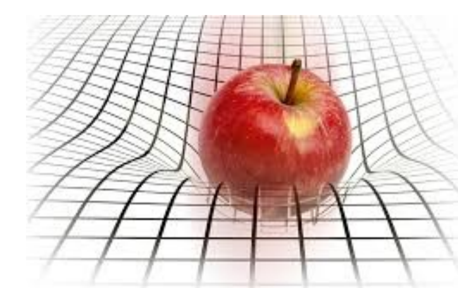
- Masses increase with each generation
  - $m_e \approx 0.5$ MeV
  - $m_\mu \approx 106$ MeV
  - $m_{top} \approx 173000$ MeV = 173 GeV ($\approx m_{Gold}$)

Forces









- Force carriers:
  - photon (γ), gluons (g), $W^{\pm}$ and Z^0 bosons
  - must be massless…

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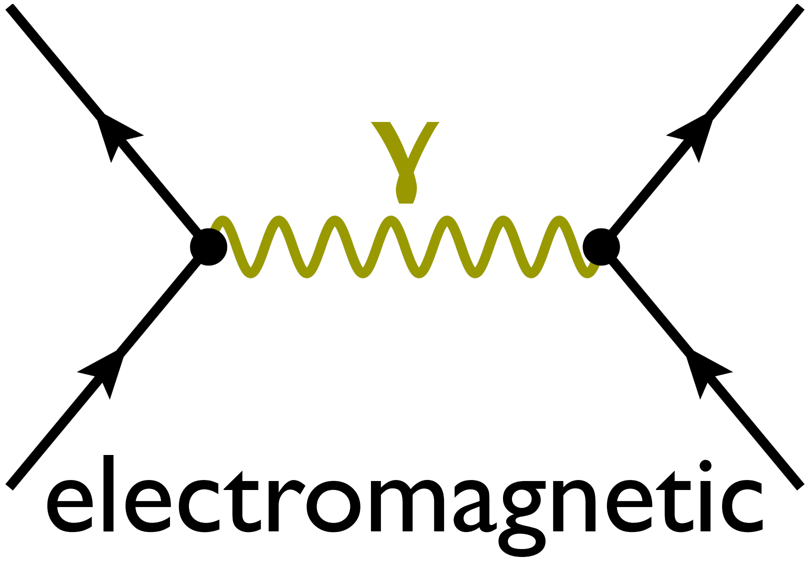

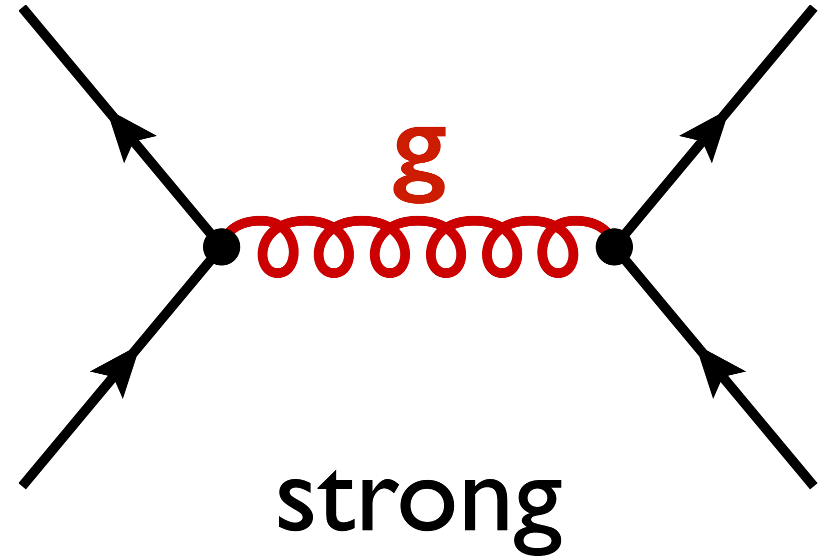

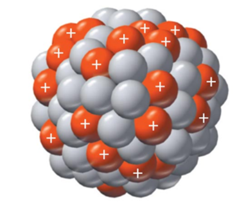

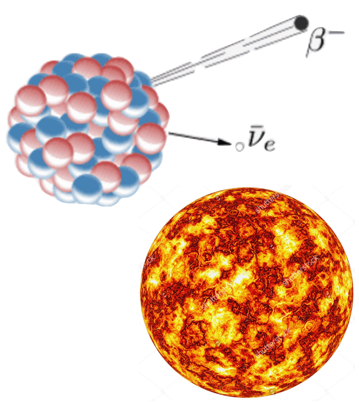

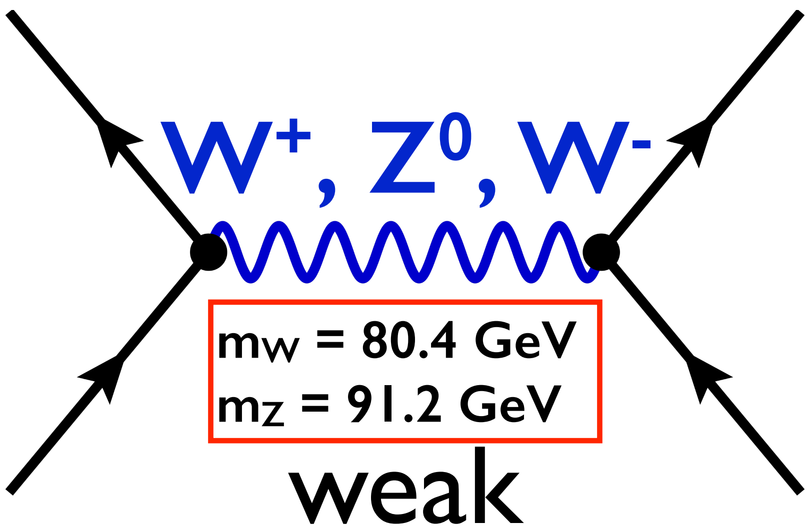

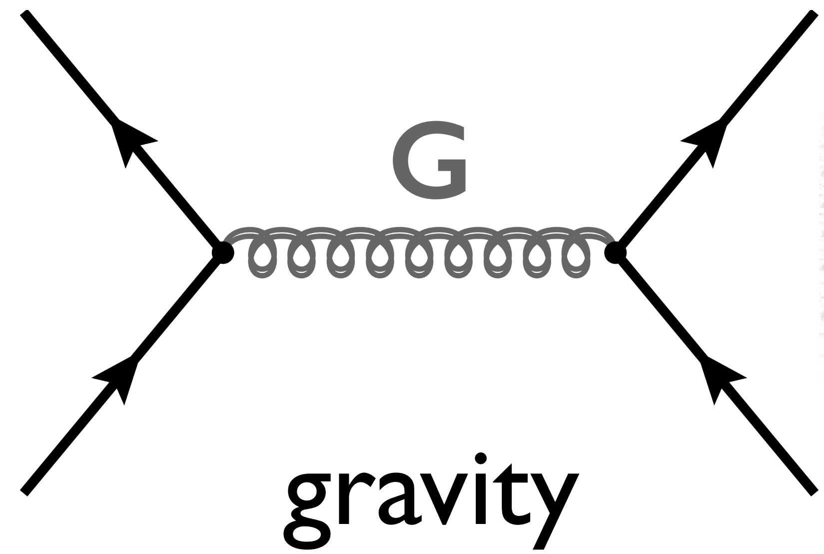

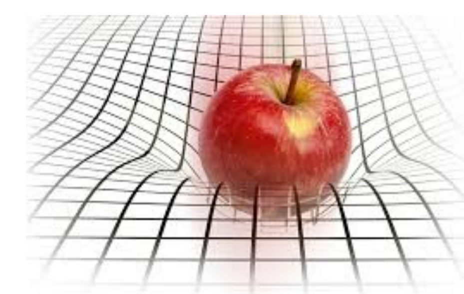

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Mass of Elementary Particles?

<u>The problem of gauge boson masses:</u>

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- Problem:

$$\frac{1}{2}m_A^2 A_\mu A^\mu = \frac{1}{2}m_A^2 \left(A_\mu + \frac{1}{e}\partial_\mu \alpha\right)\left(A^\mu + \frac{1}{e}\partial^\mu \alpha\right) \neq \frac{1}{2}m_A^2 A_\mu A^\mu$$

Brout-Englert-Higgs Mechanism

- Introduce complex scalar field:

$$\phi = \begin{pmatrix} \phi^+ \\ \phi^0 \end{pmatrix} = \frac{1}{\sqrt{2}} \begin{pmatrix} \phi_1 + i\phi_2 \\ \phi_3 + i\phi_4 \end{pmatrix}$$

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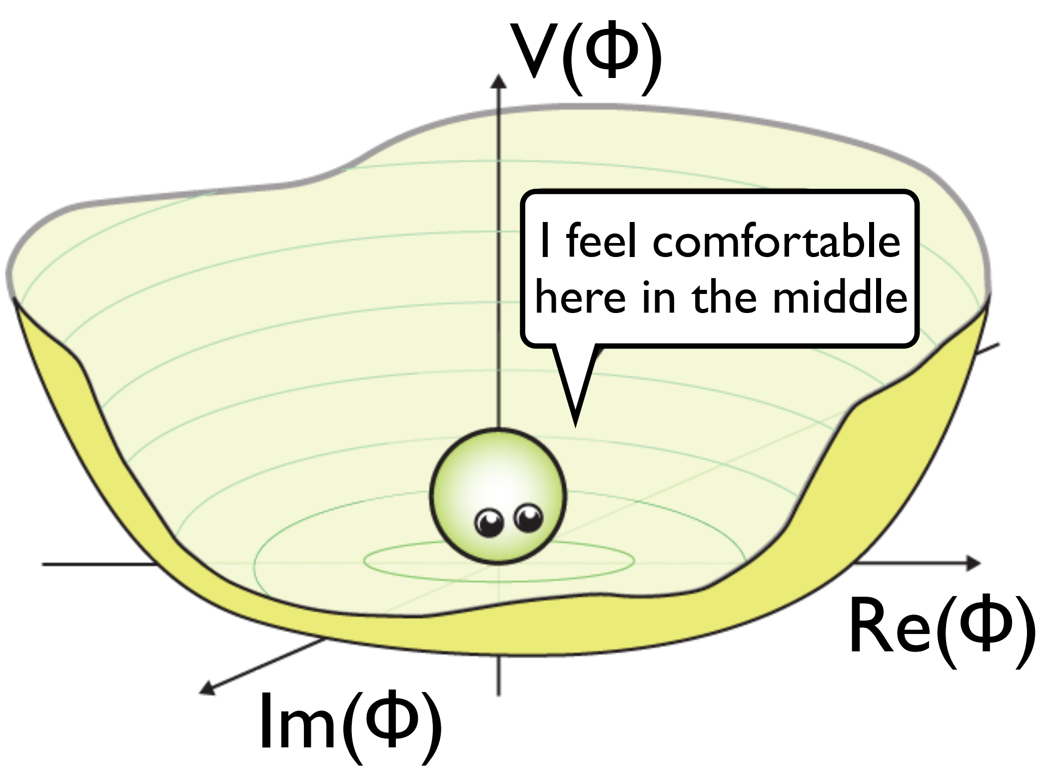
For **λ>0, μ^2>0**:



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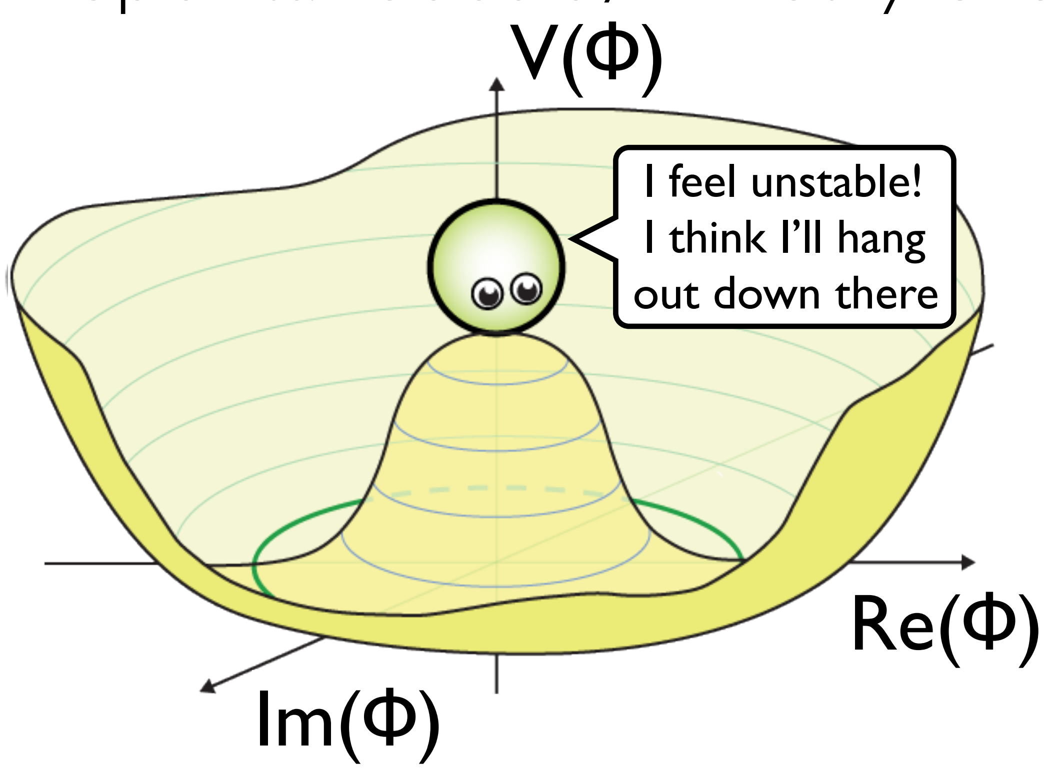

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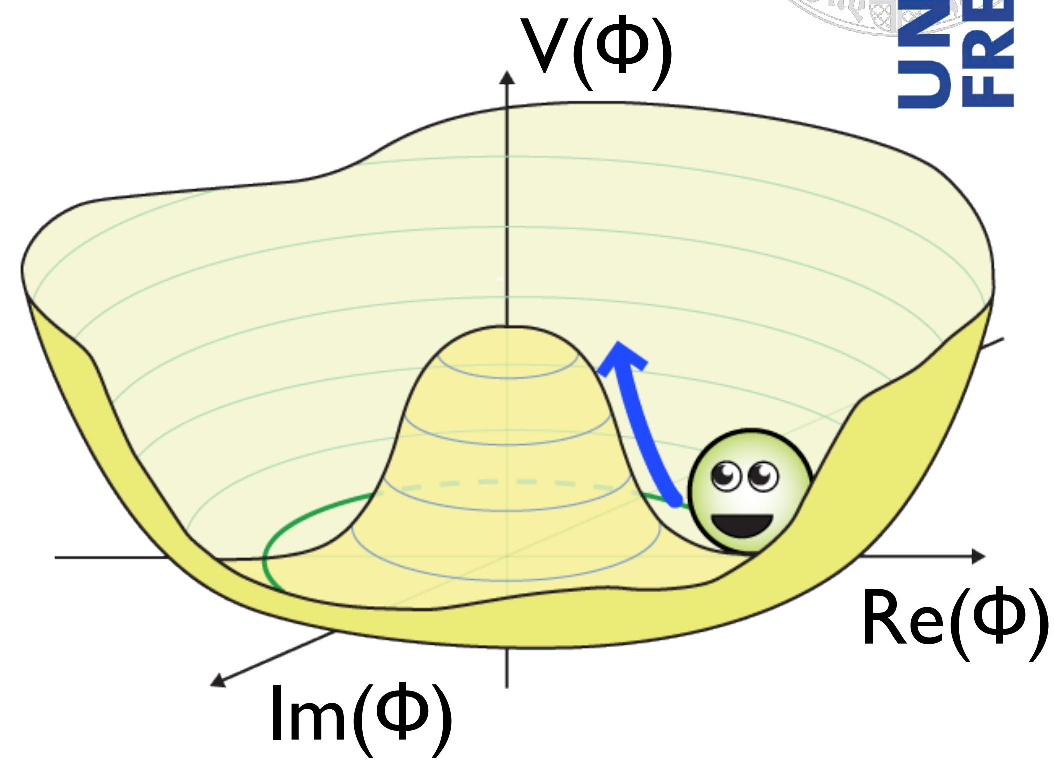

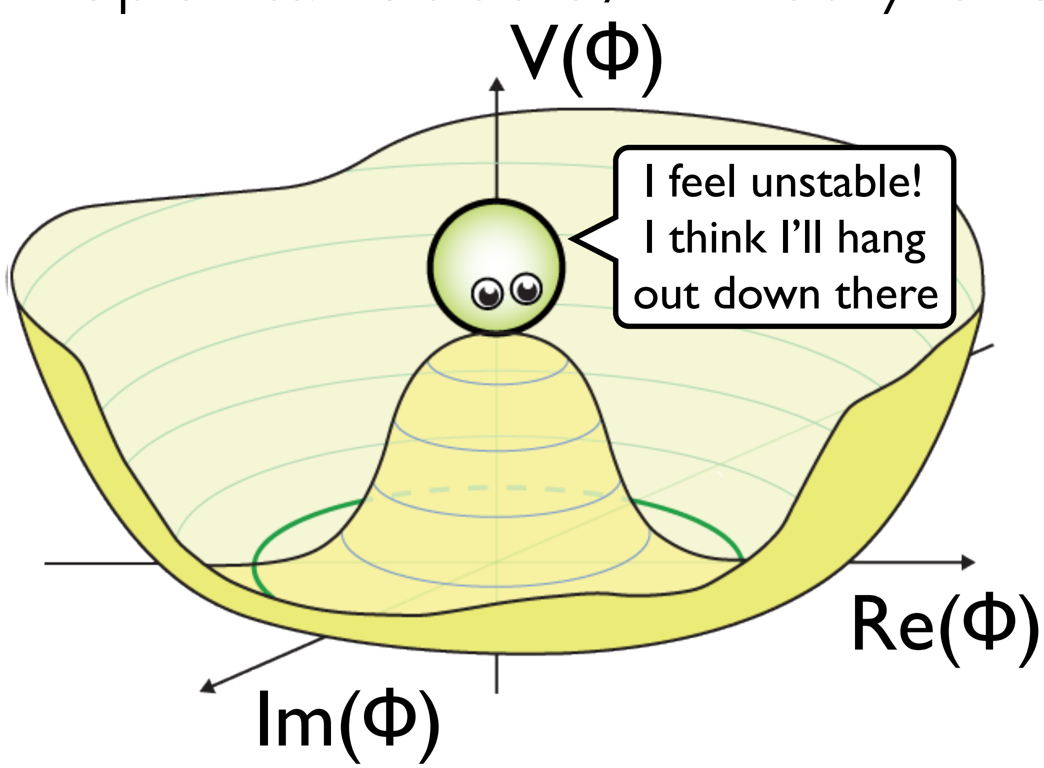

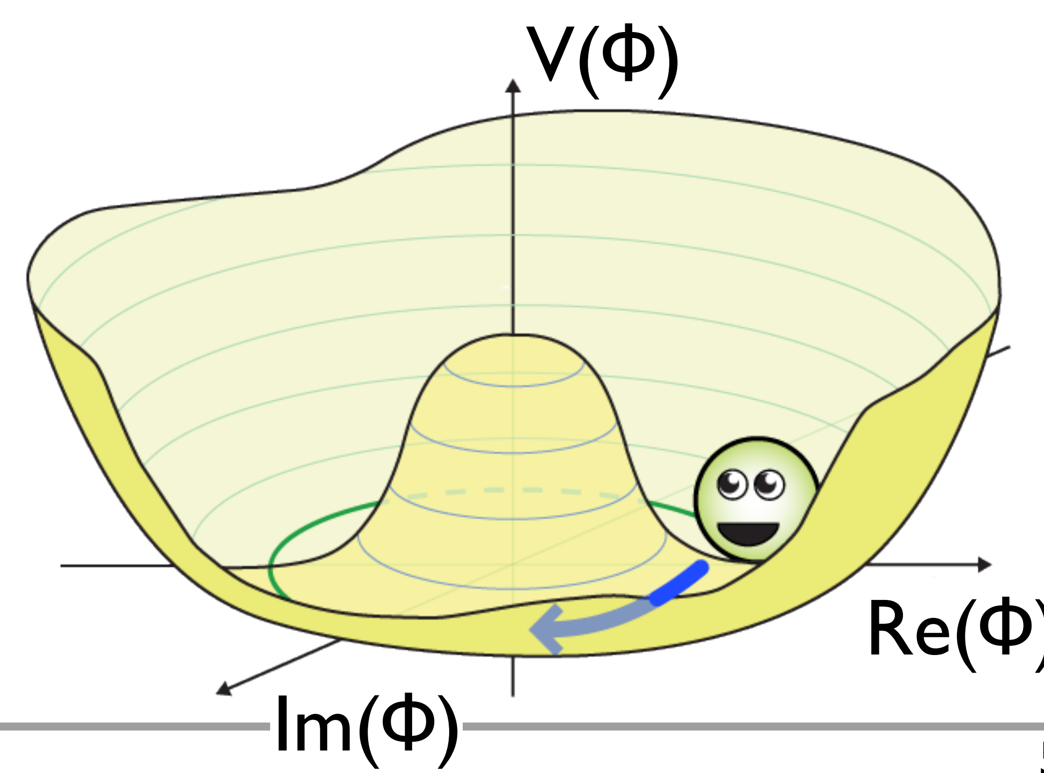

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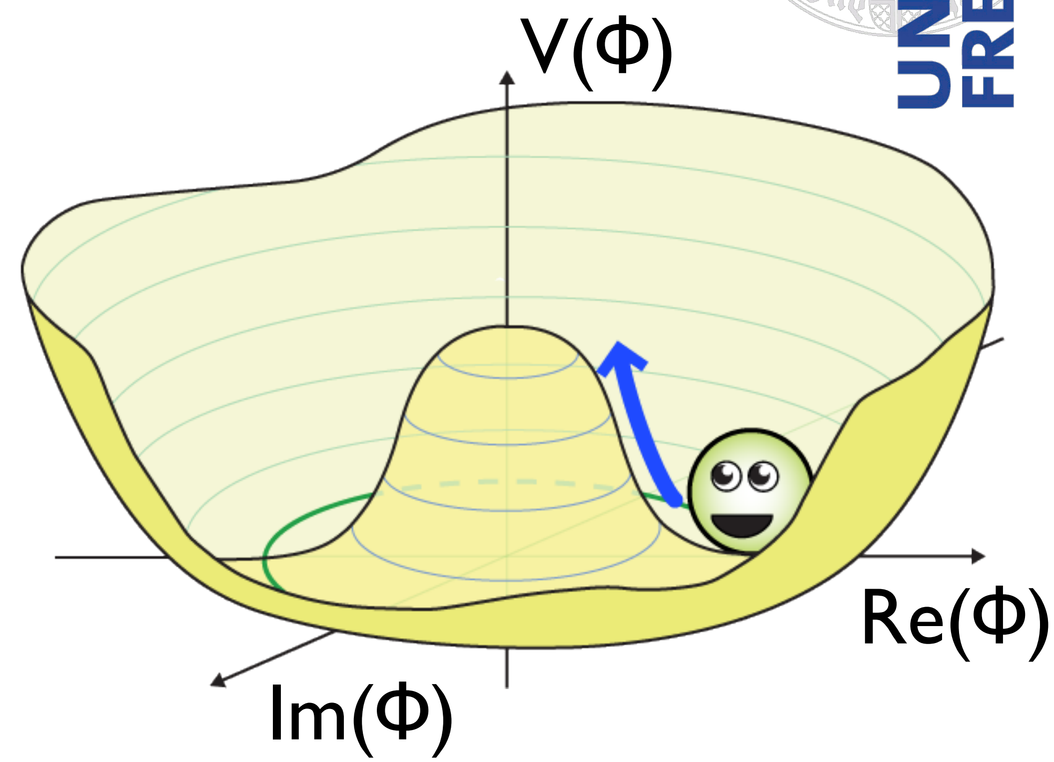

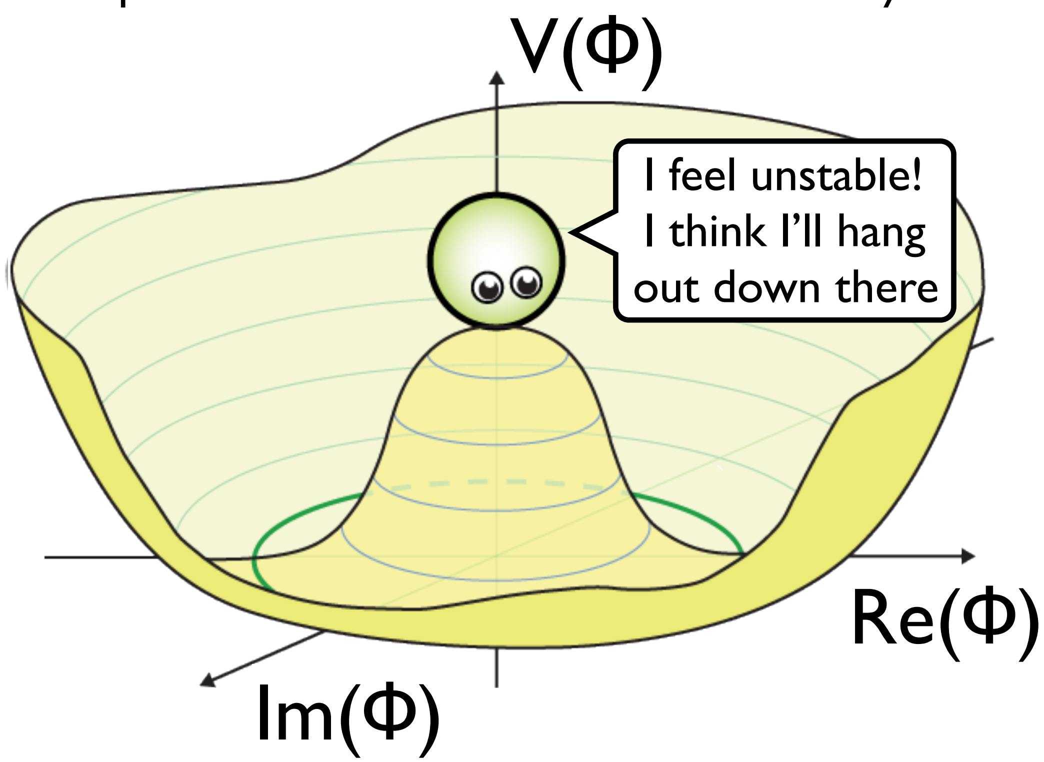

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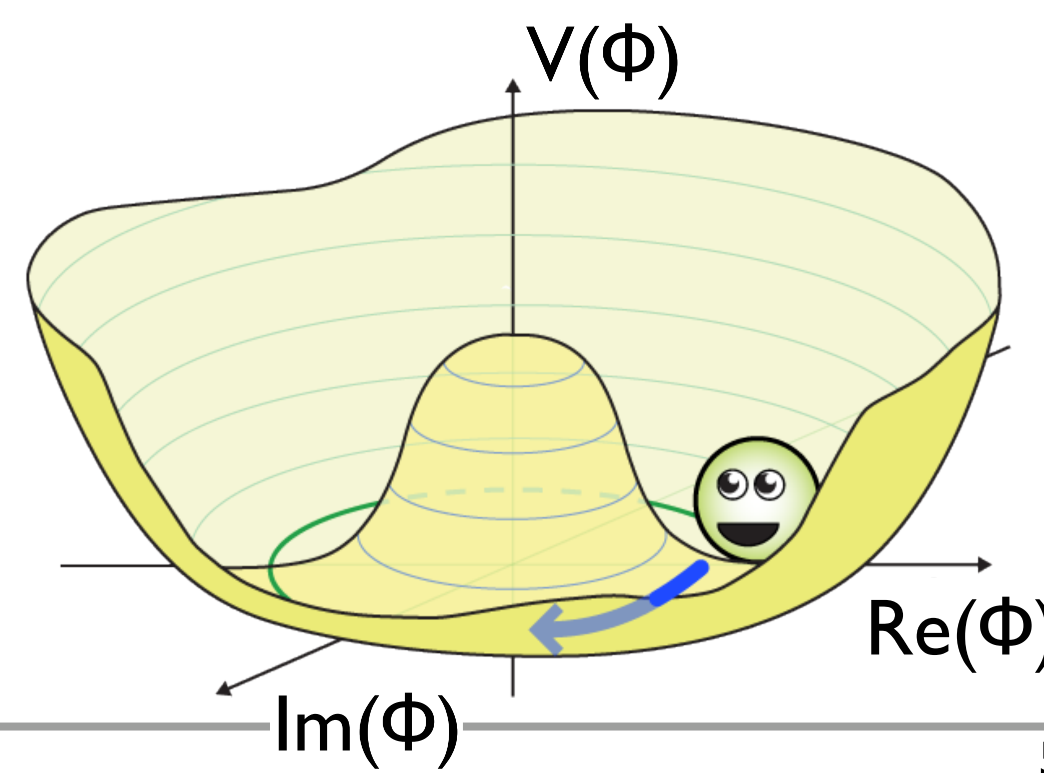

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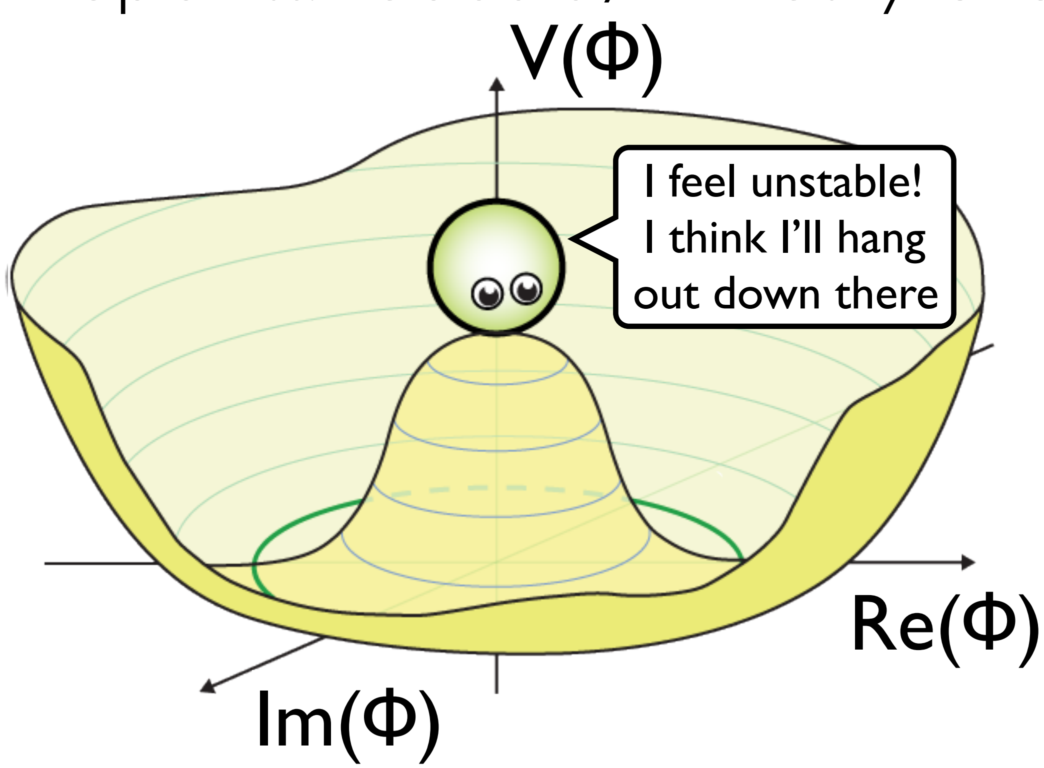
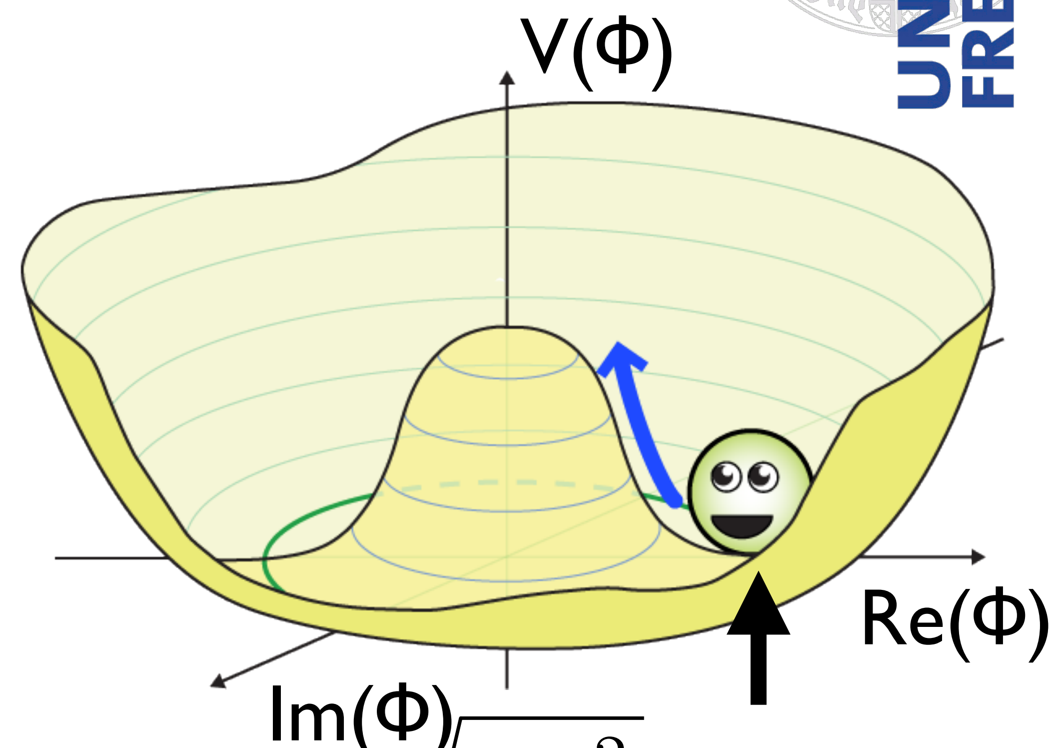
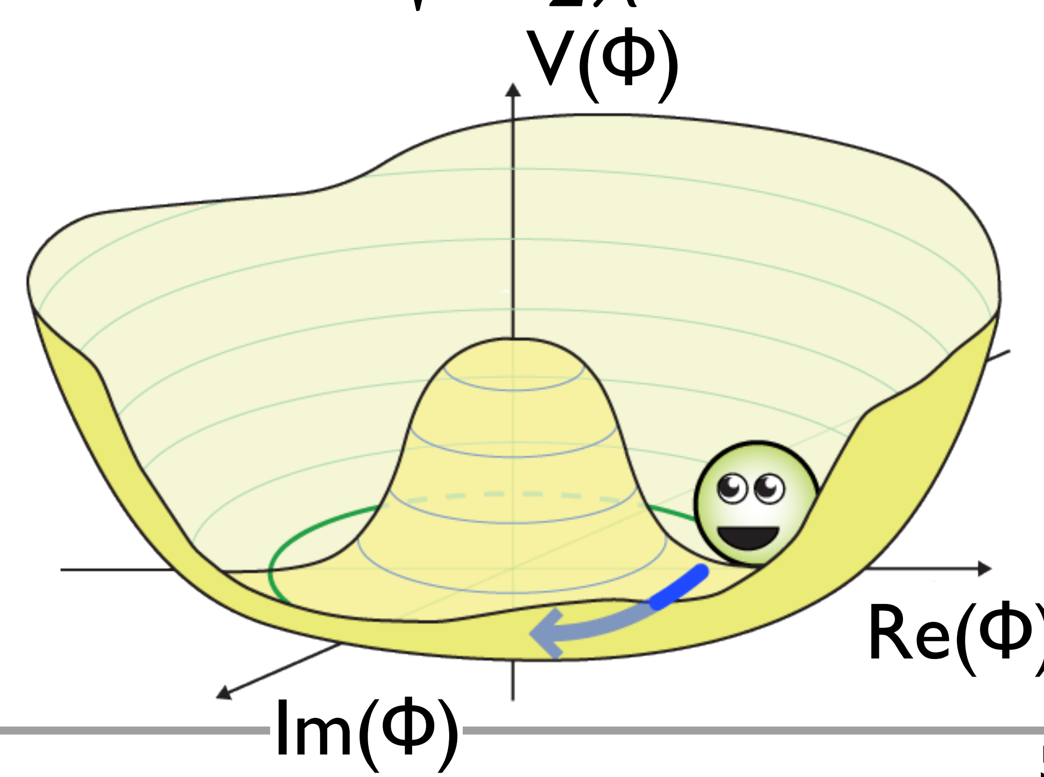




Minimum at $v = \sqrt{-\frac{\mu^2}{2\lambda}} = 246\,\mathrm{GeV}$

3×



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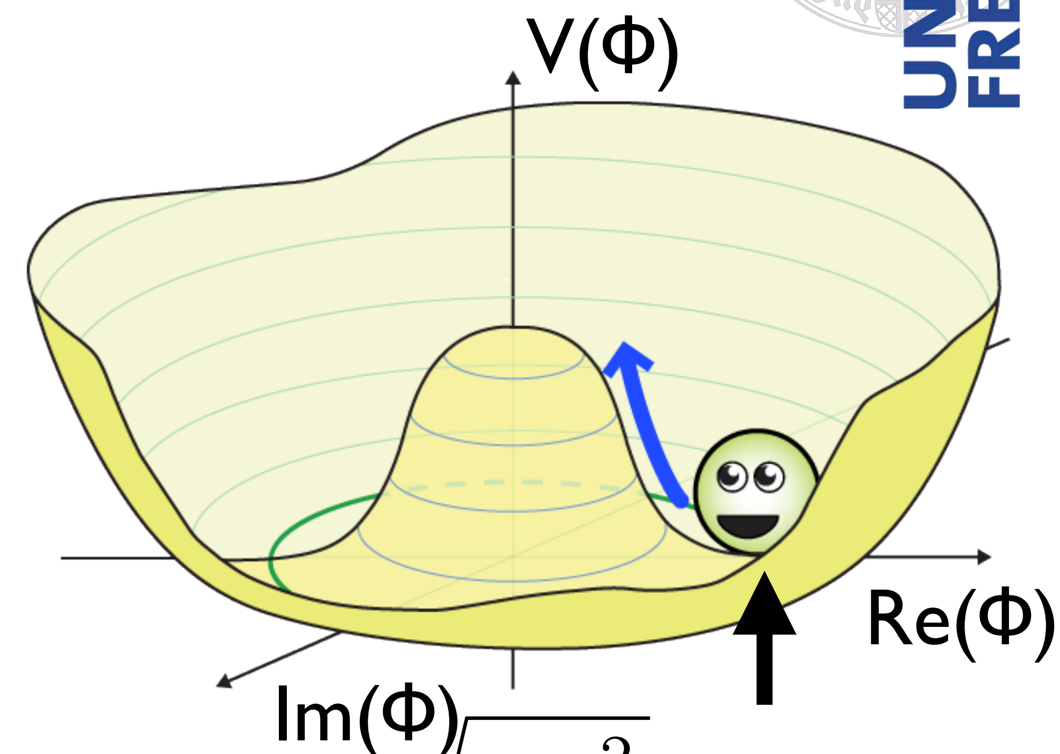

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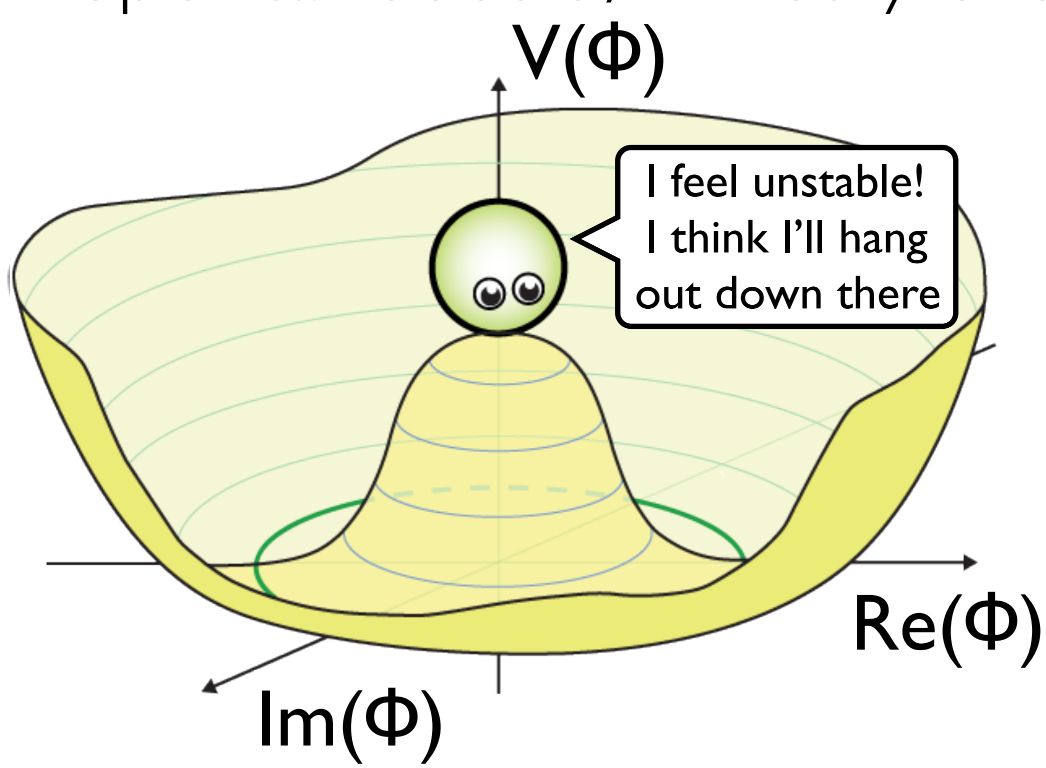

Expand **Φ**(x) around vacuum:

$$\phi(x) = \frac{1}{\sqrt{2}} \begin{pmatrix} 0 \\ v + H(x) \end{pmatrix}$$

Lagrangian after electroweak Symmetry Breaking

- Resulting Higgs-boson Lagrangian:

$$\mathcal{L}_H = \frac{1}{2}\partial_\mu H \partial^\mu H + (v+H)^2 \left(\frac{g^2}{4} W_\mu^\dagger W^\mu + \frac{g^2}{8\cos^2\theta_W} Z_\mu Z^\mu \right) - \lambda v^2 H^2 - \lambda v H^3 - \frac{\lambda}{4} H^4$$

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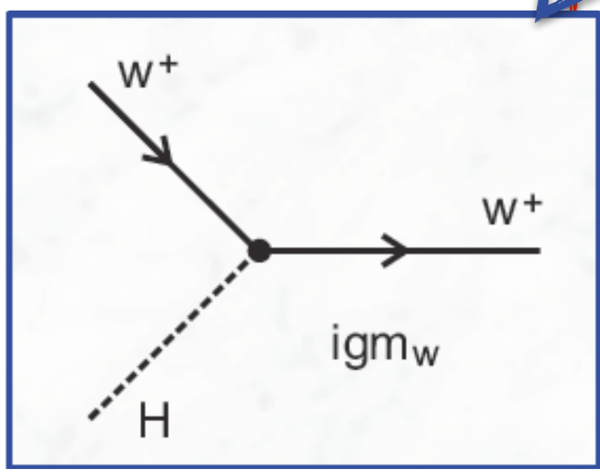

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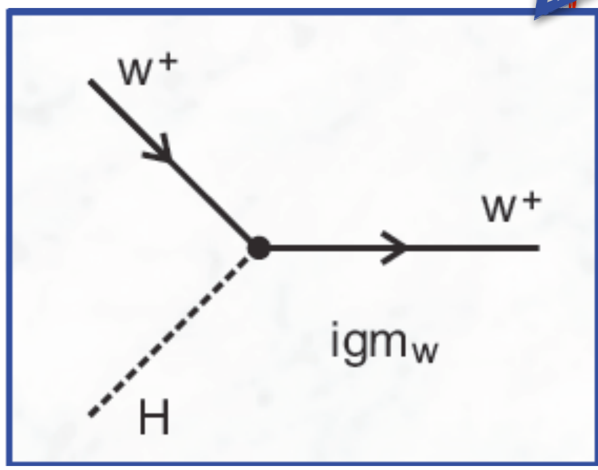

- Fermion mass terms via *Yukawa couplings* λ_f:

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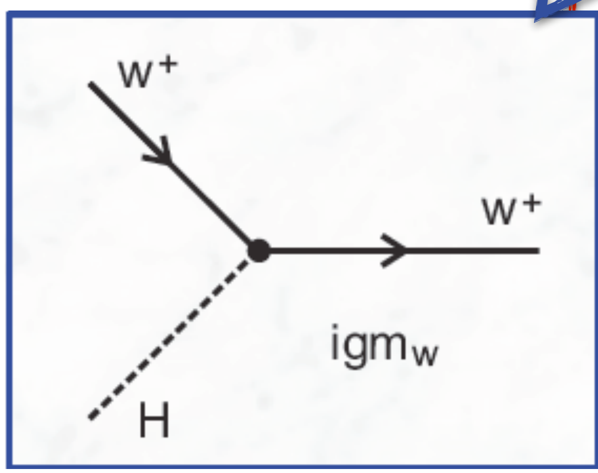

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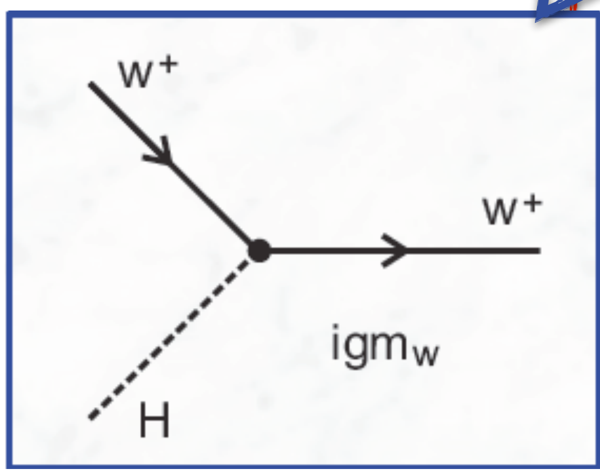

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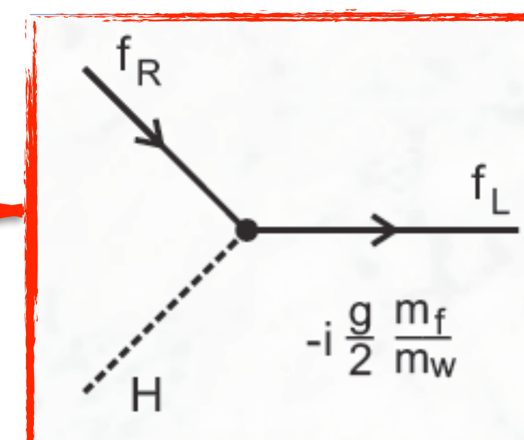

So...

One of the primary goals to build the Large Hadron Collider was to find (or exclude the presence of) the Higgs boson

The LHC

LHCb
ATLAS
CERN Meyrin
CERN Prévessin
SPS 7 km
SUISSE
FRANCE
ALICE
CMS
LHC 27 km

The LHC

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  - 7 TeV (2011), 8 TeV (2012): "Run 1"
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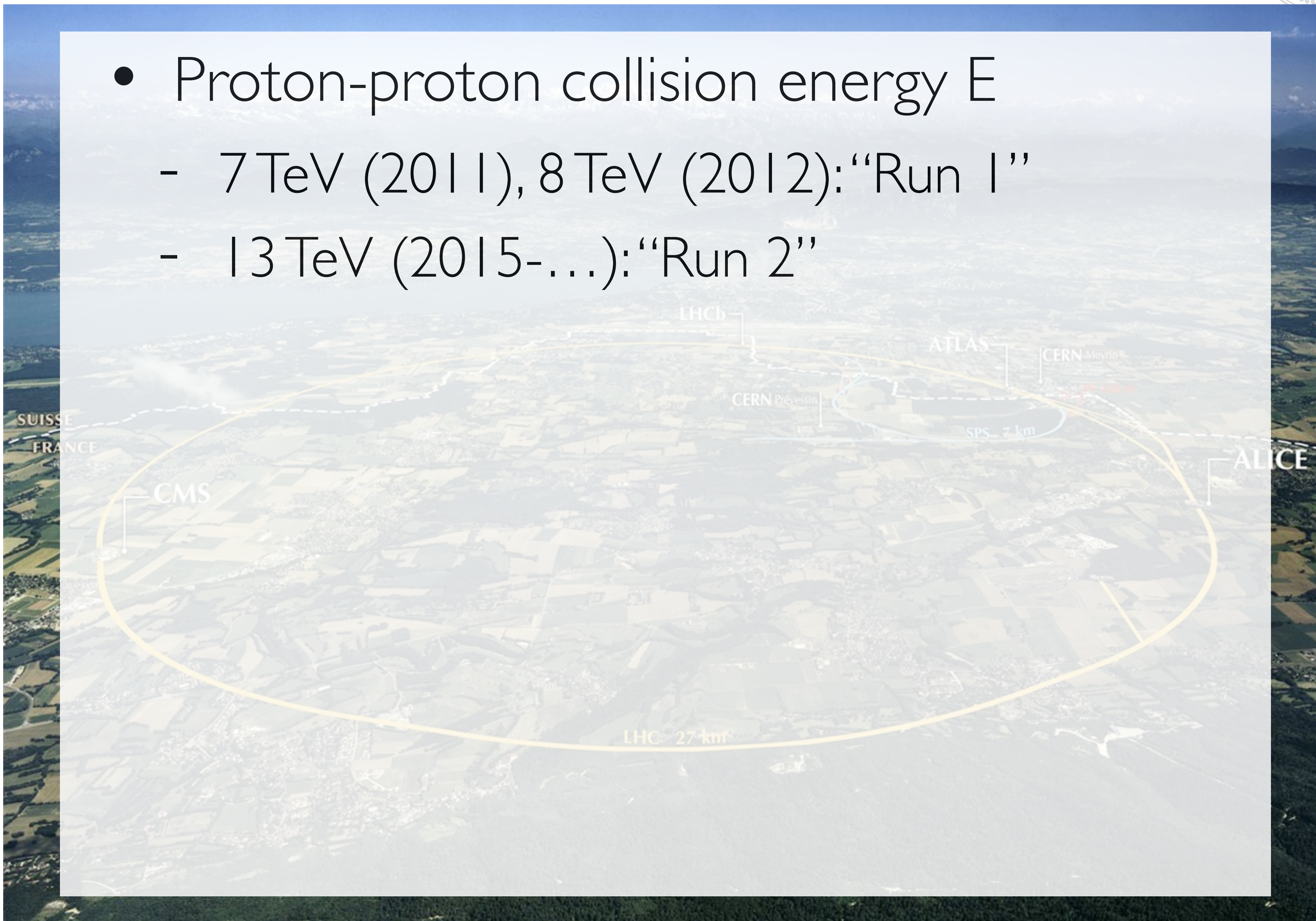

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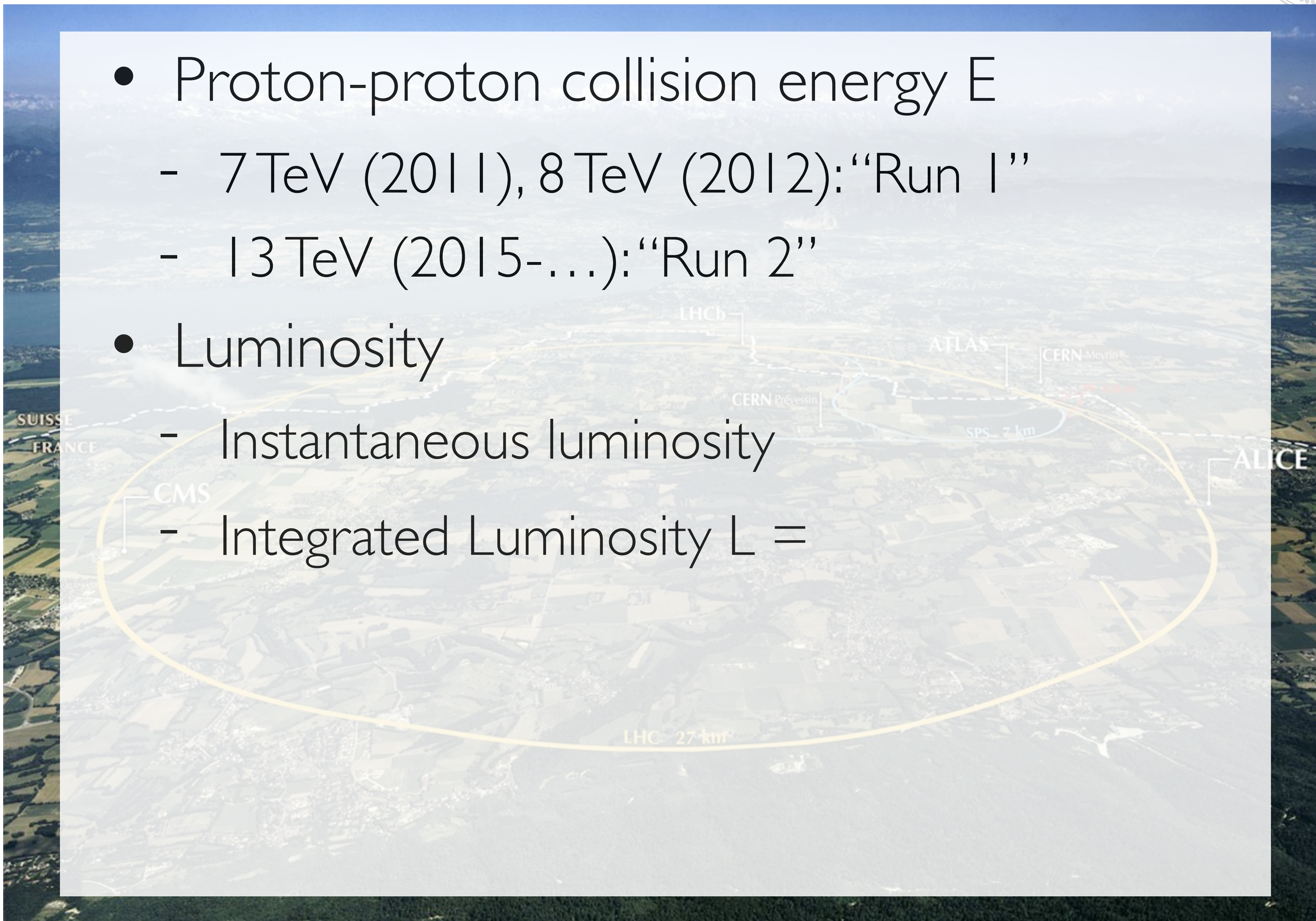

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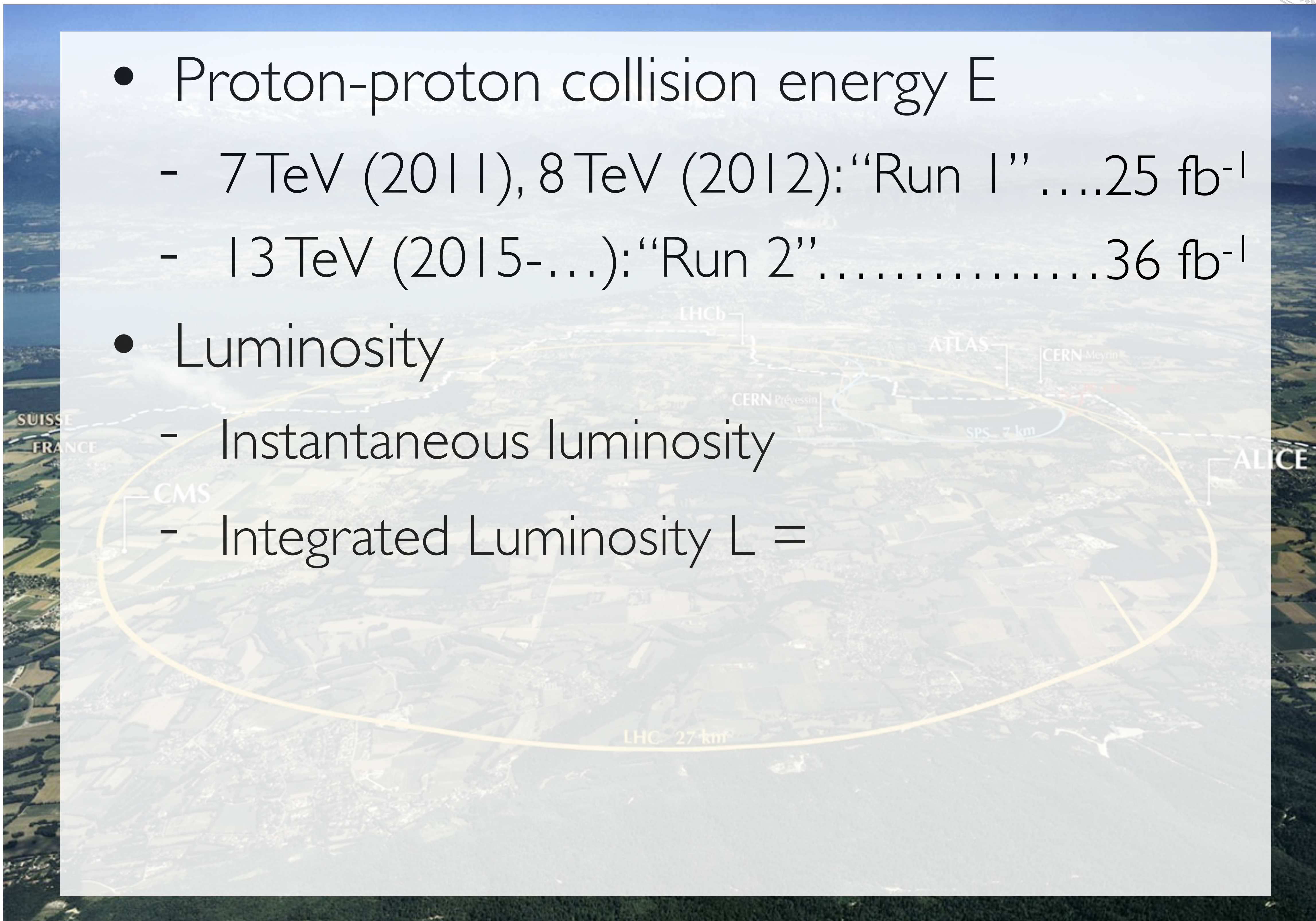

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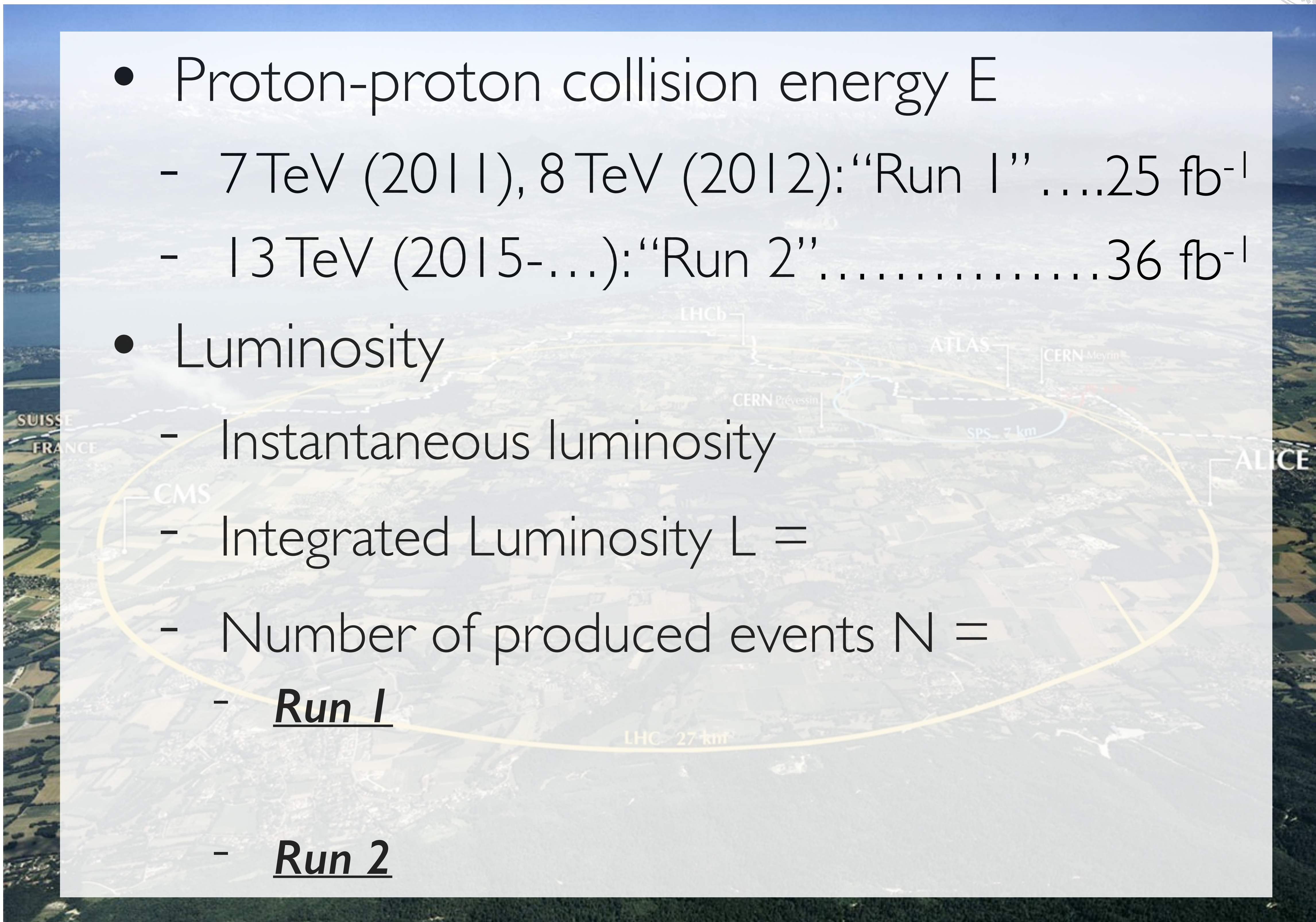

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  - Number of produced events N =
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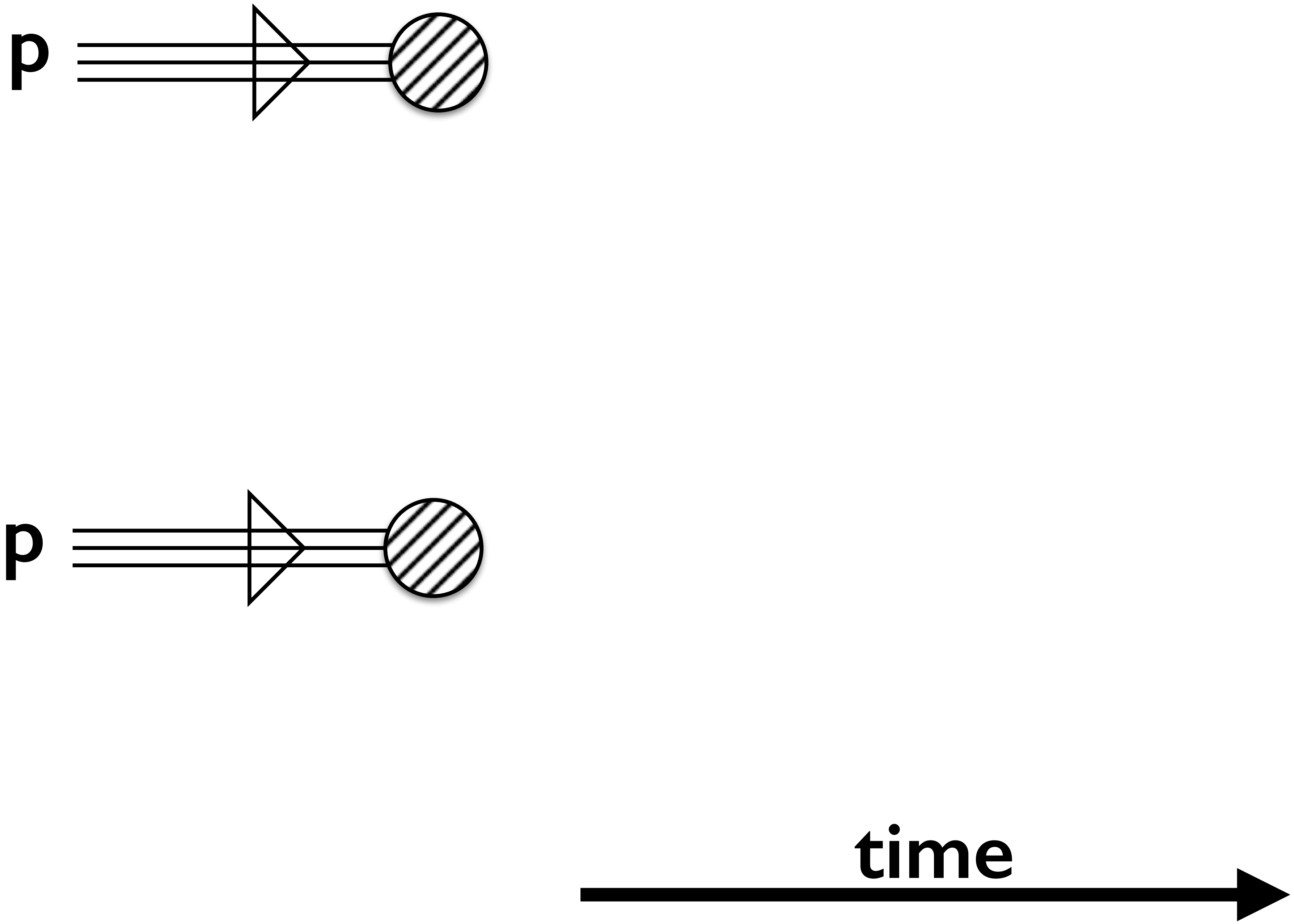
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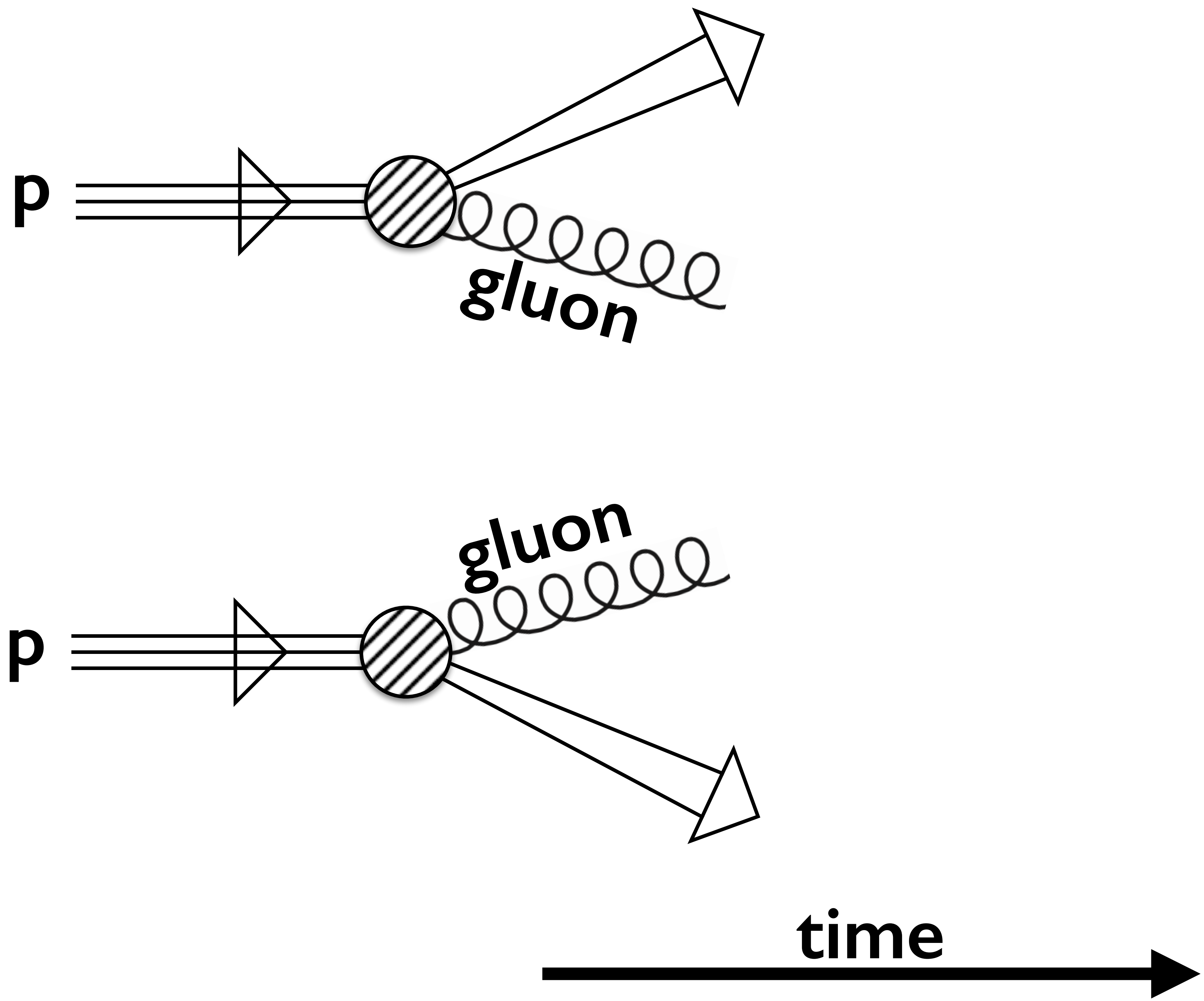
p
time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gluon
gluon
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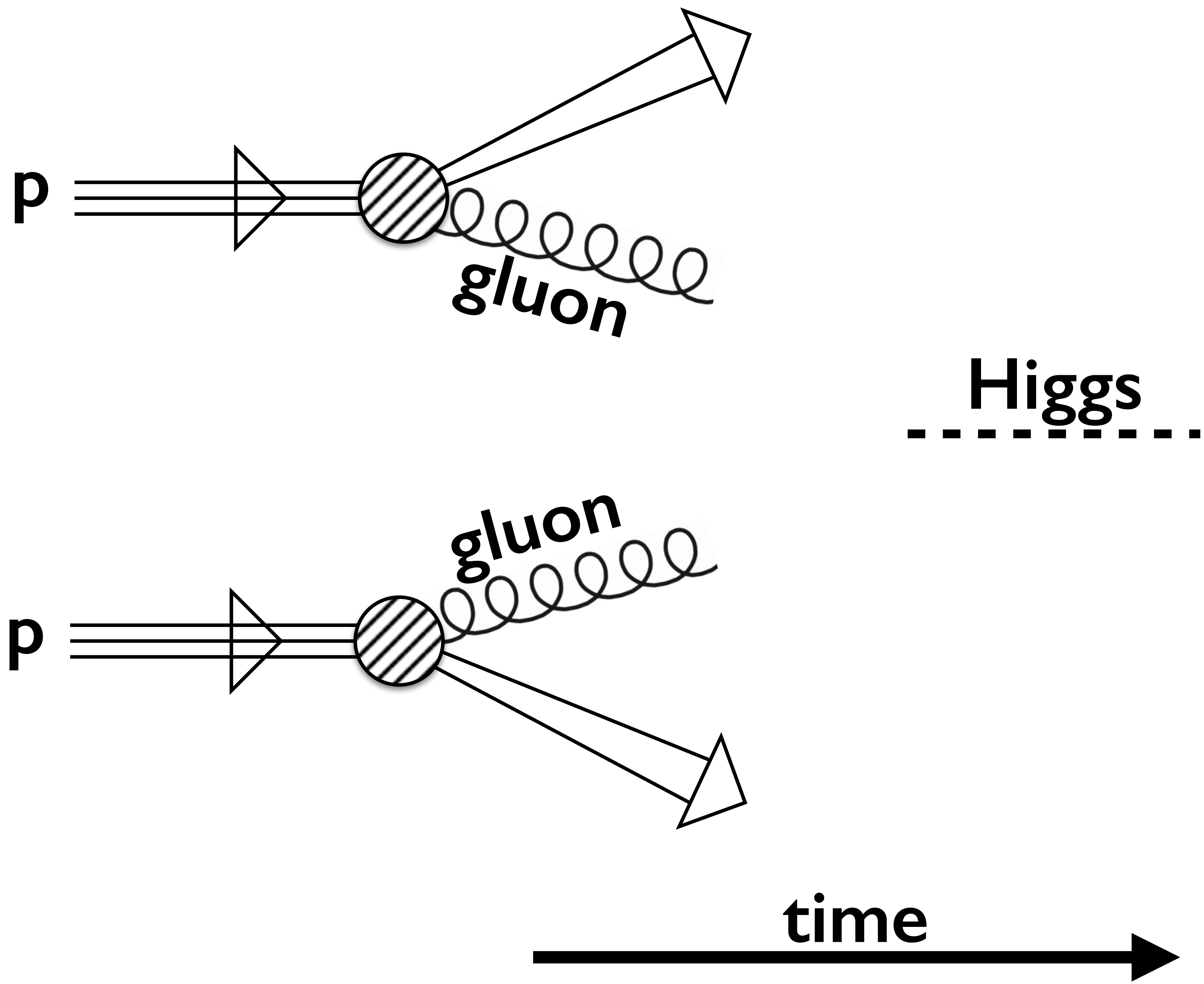
Higgs Boson Production and Decay at the LHC



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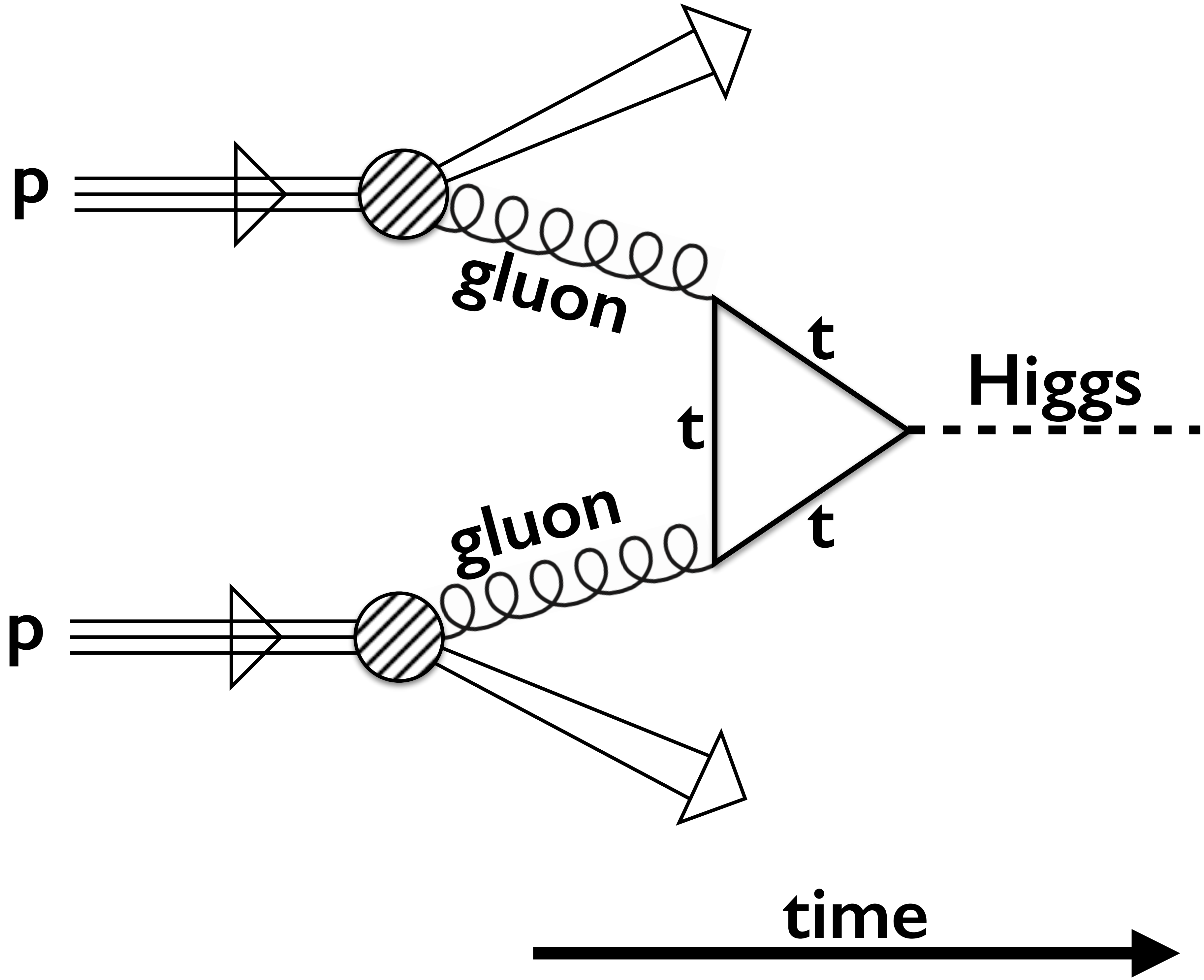

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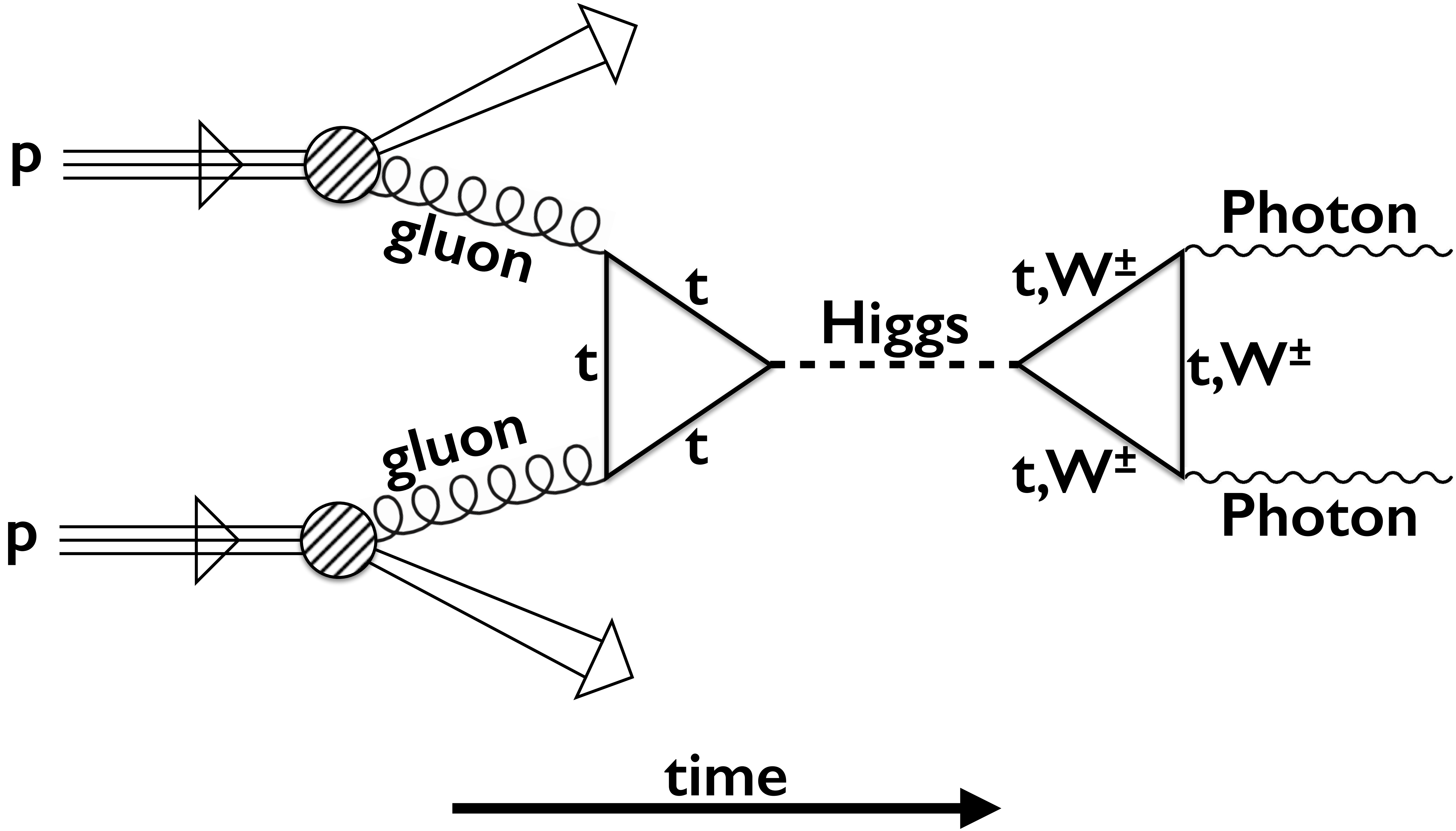

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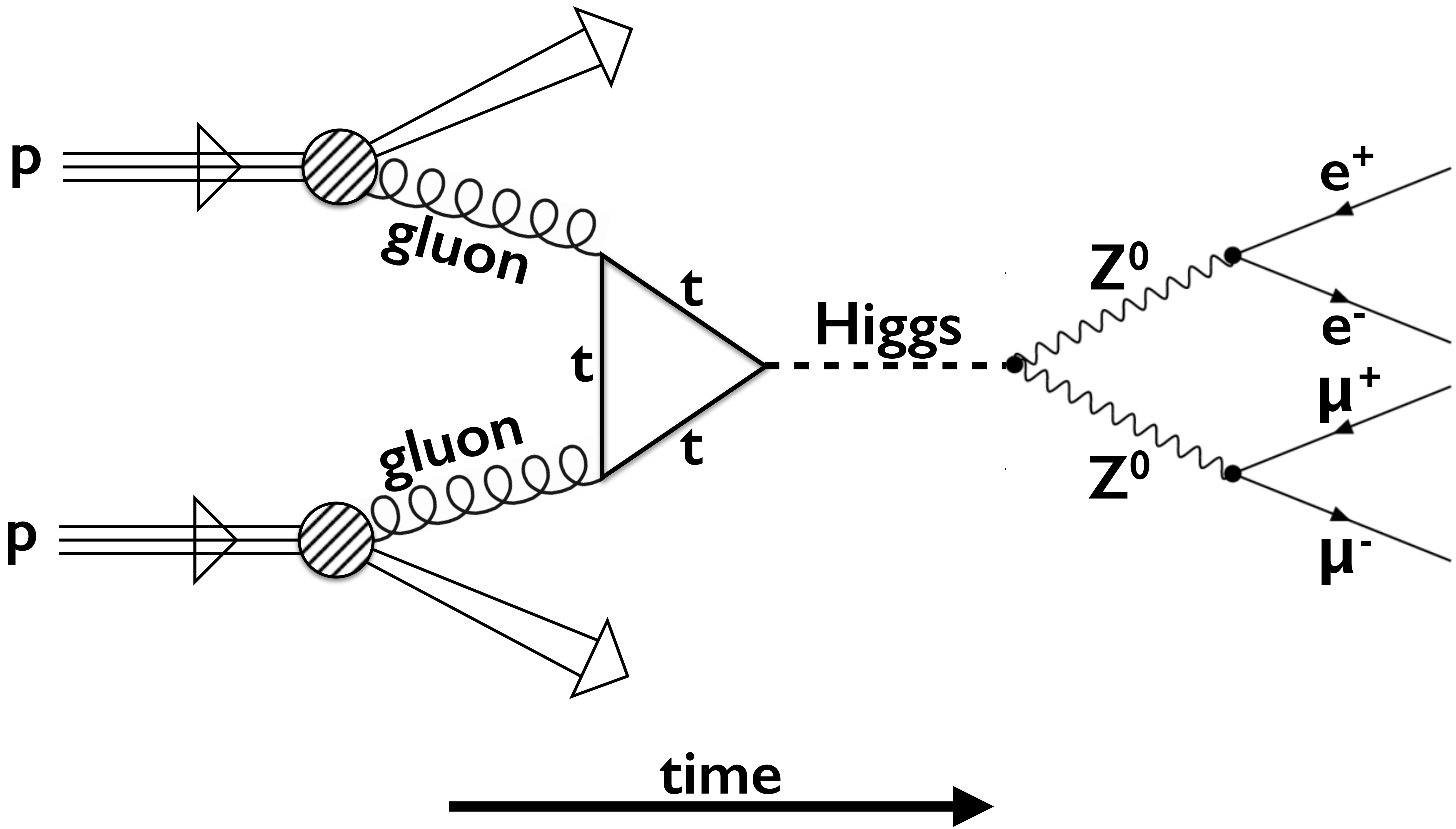

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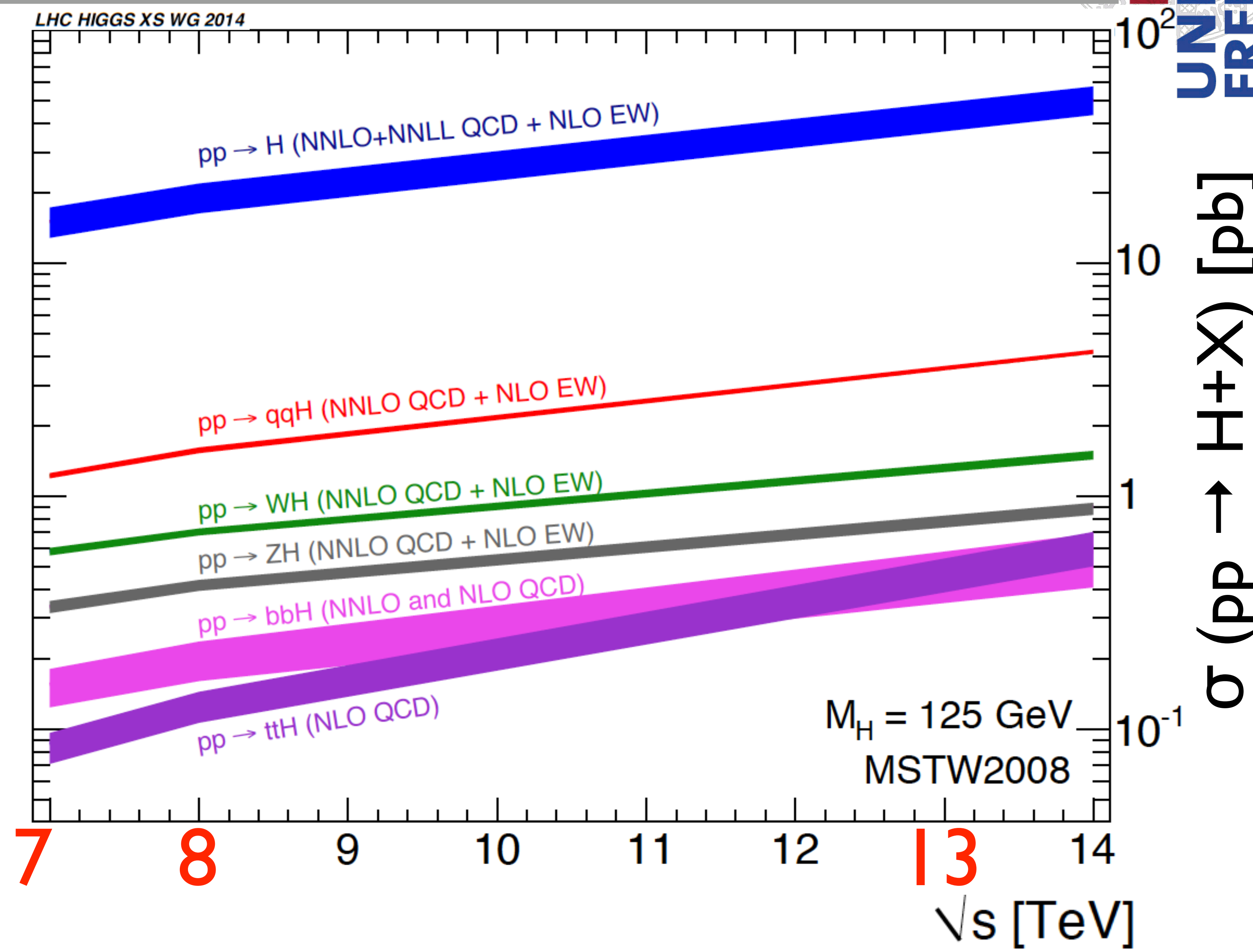
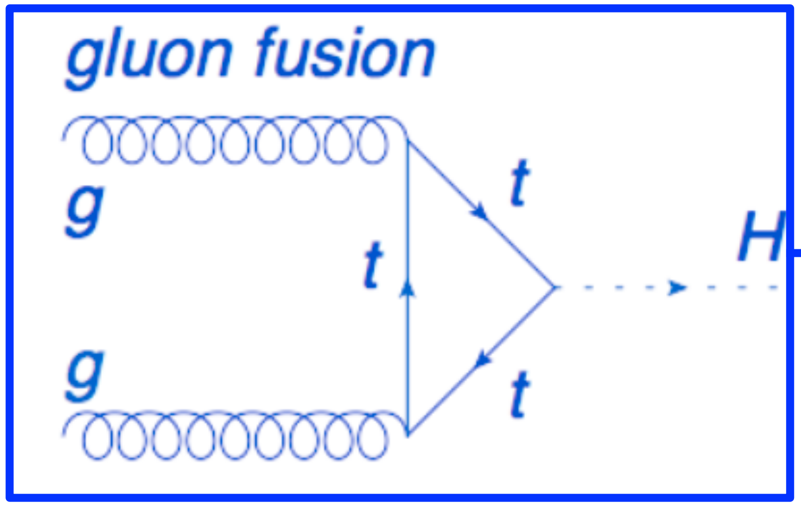
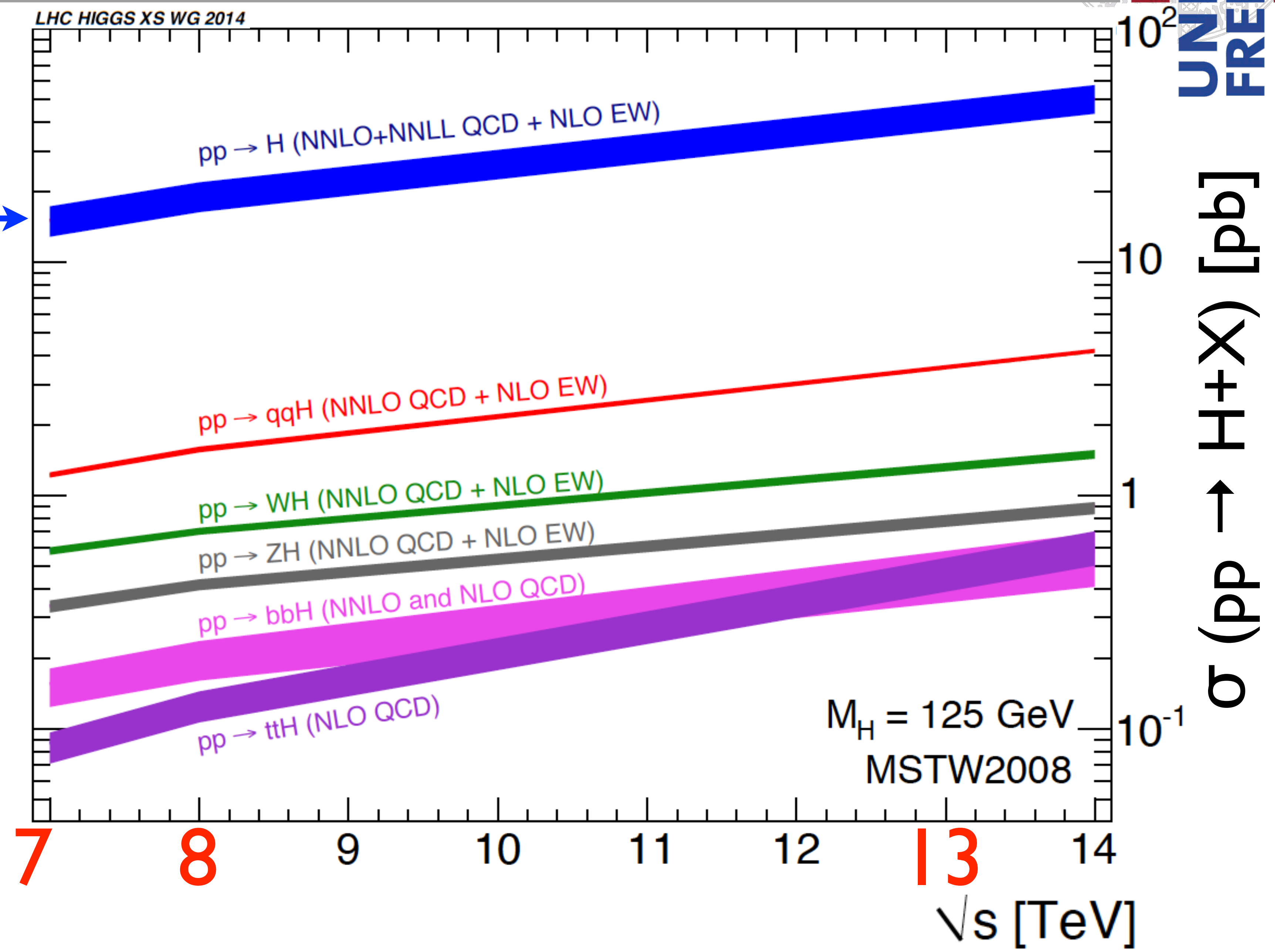
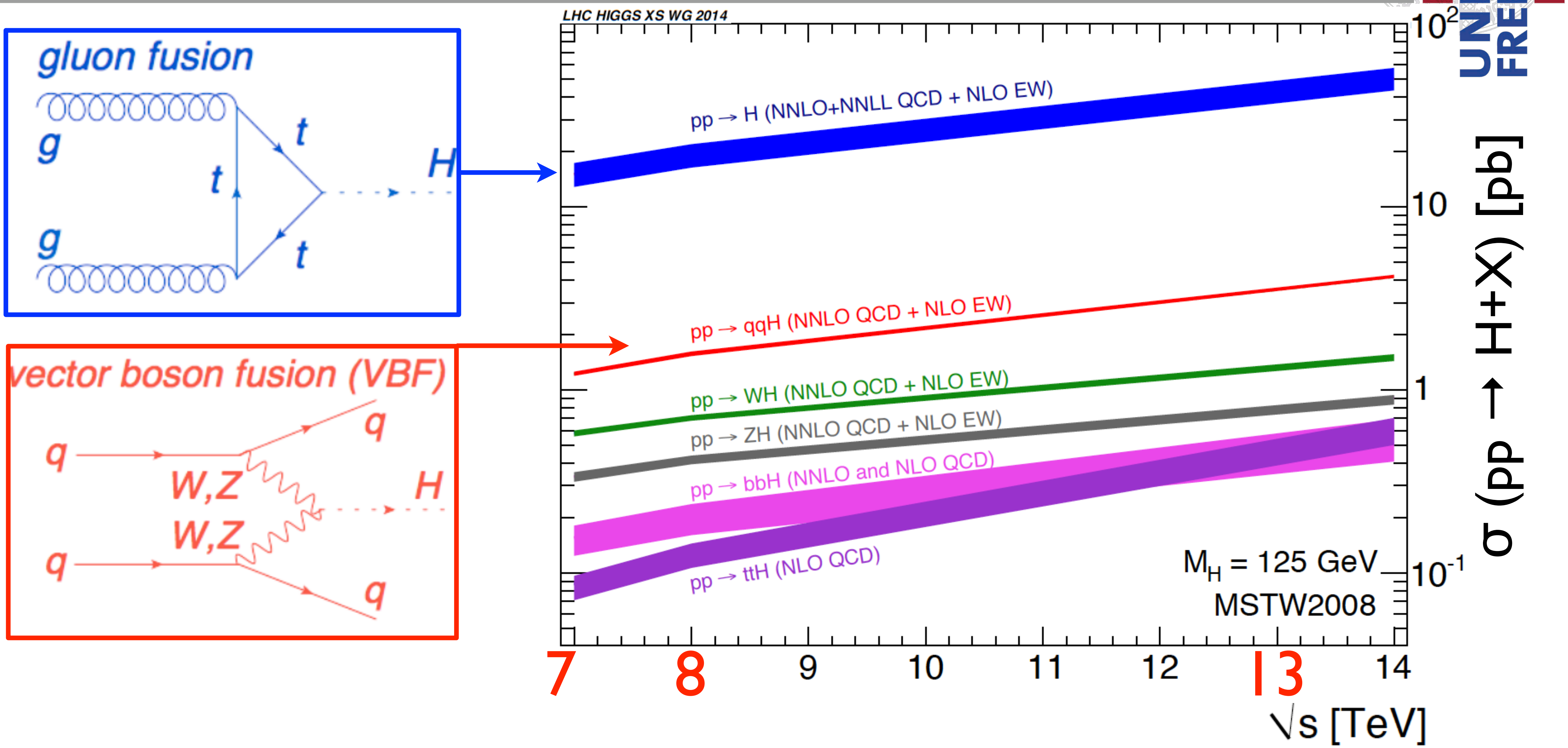


Higgs Boson Production

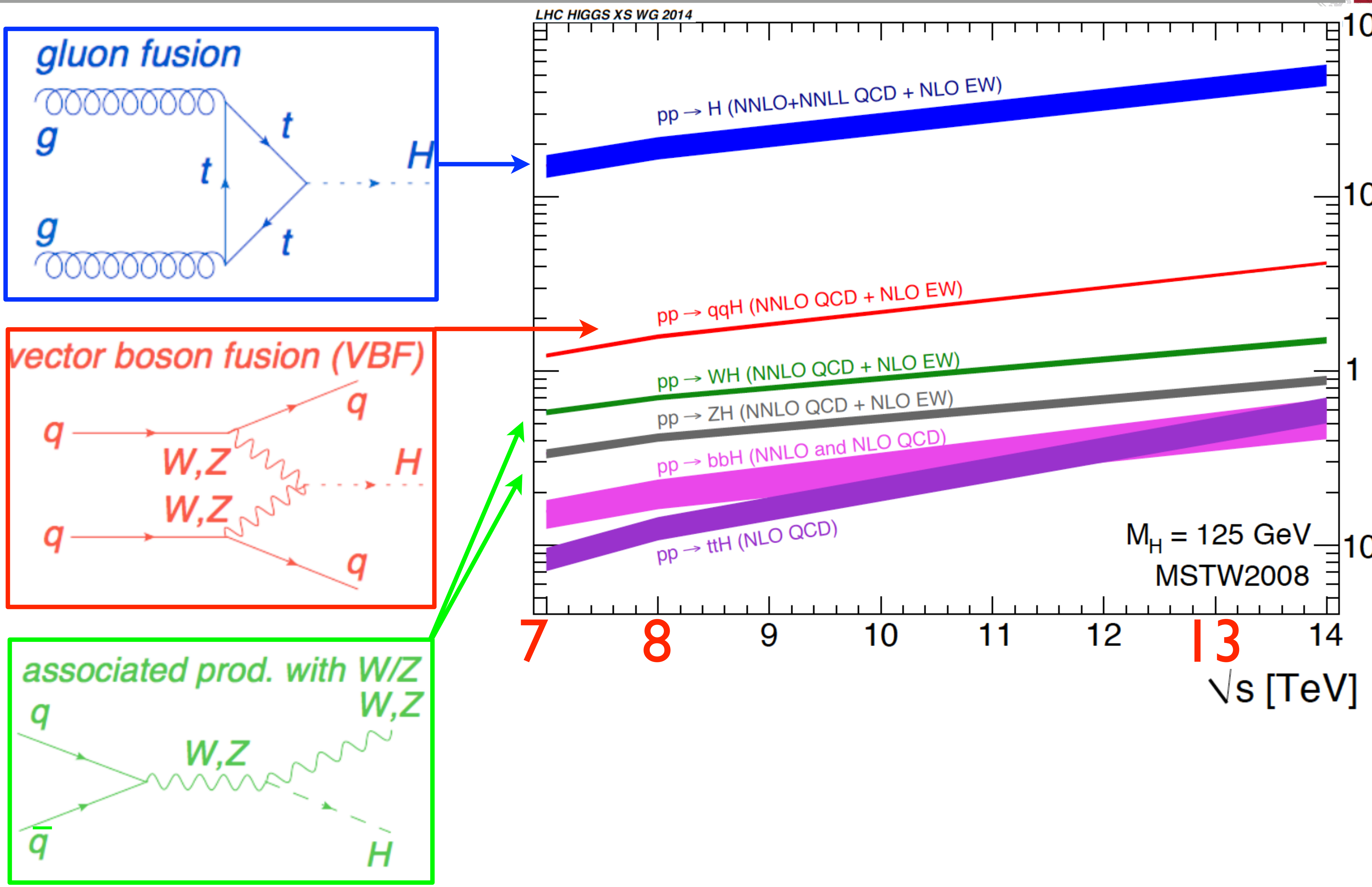




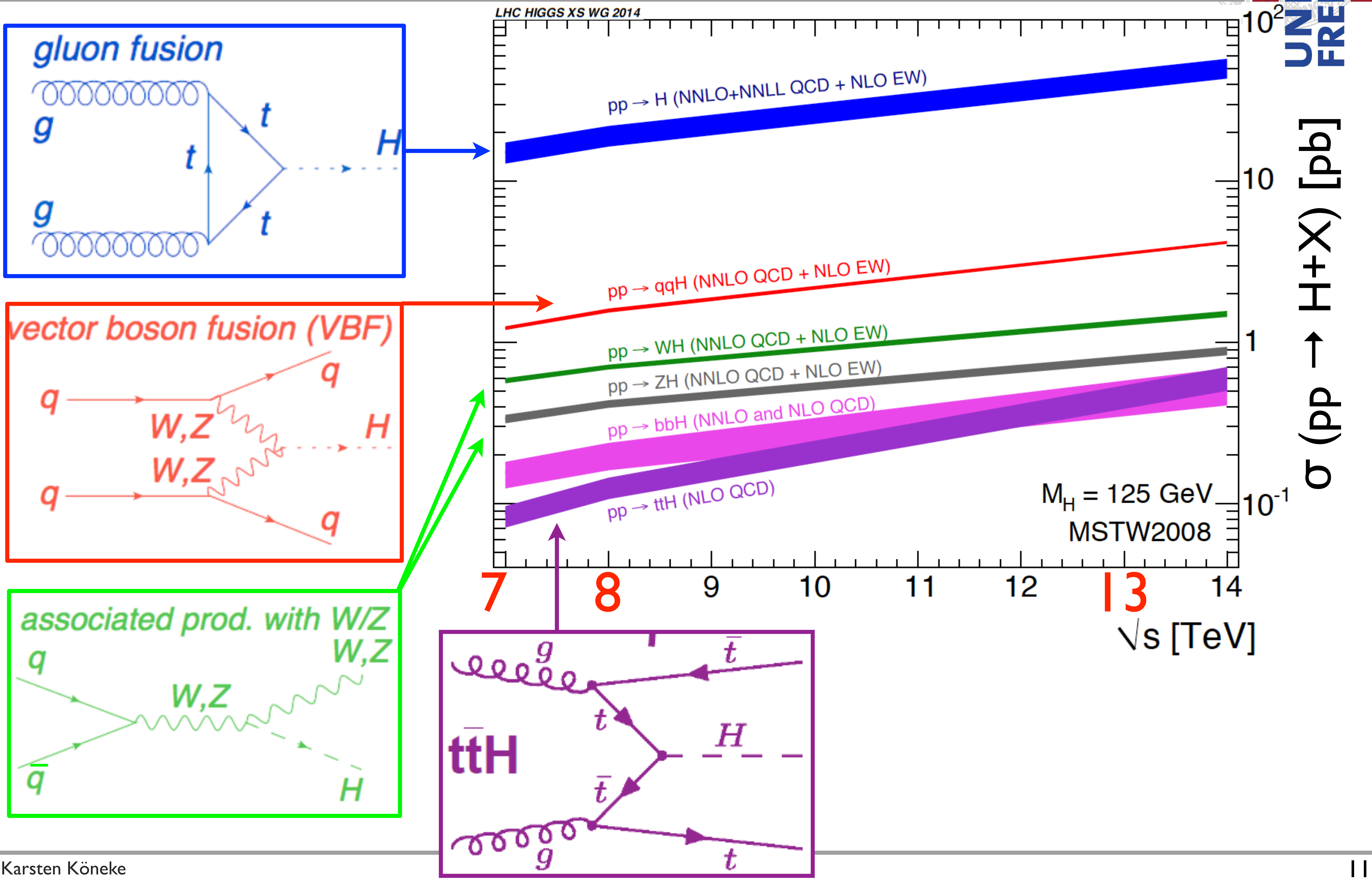
Higgs Boson Production



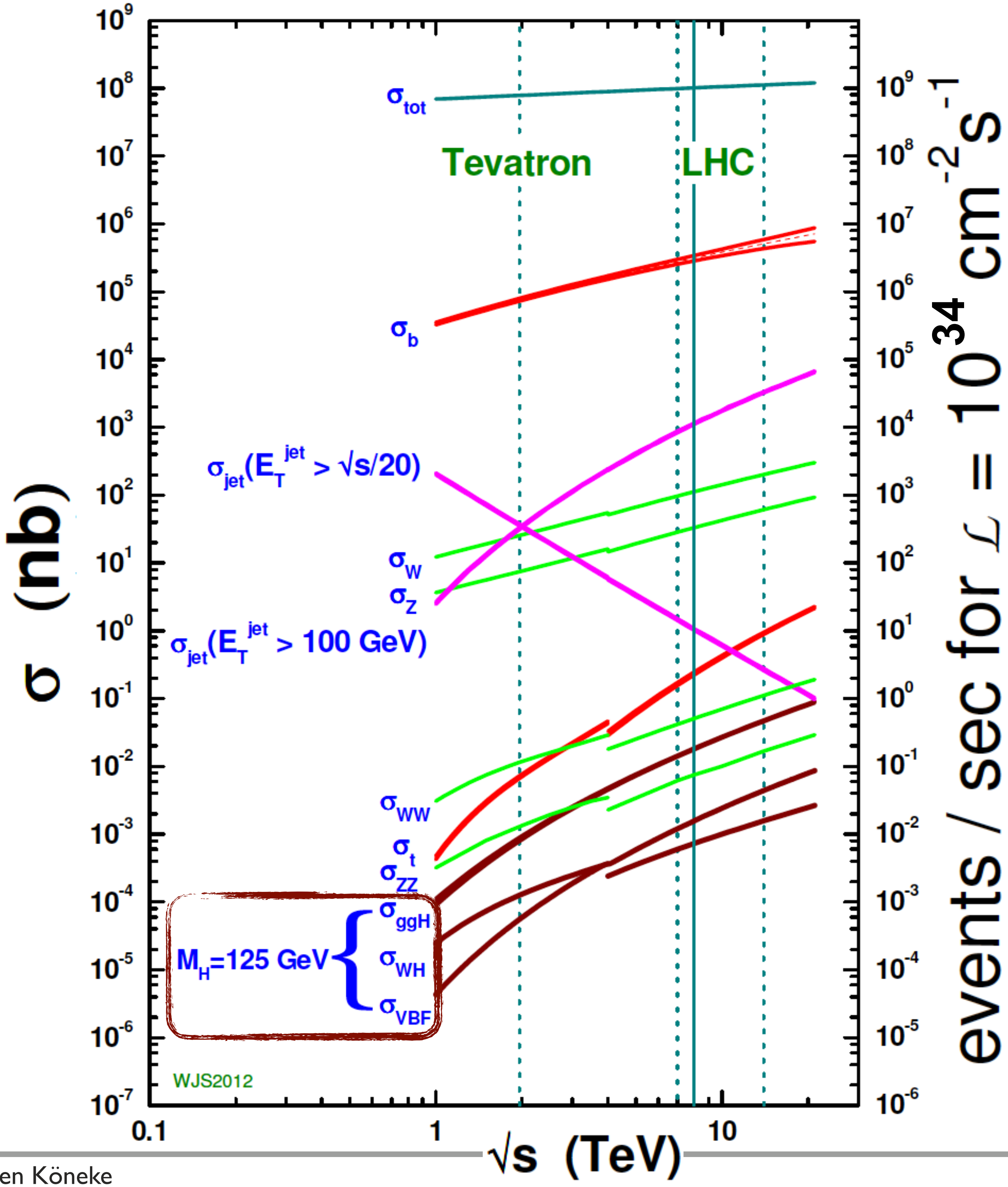
Higgs Boson Production



Higgs Boson Production



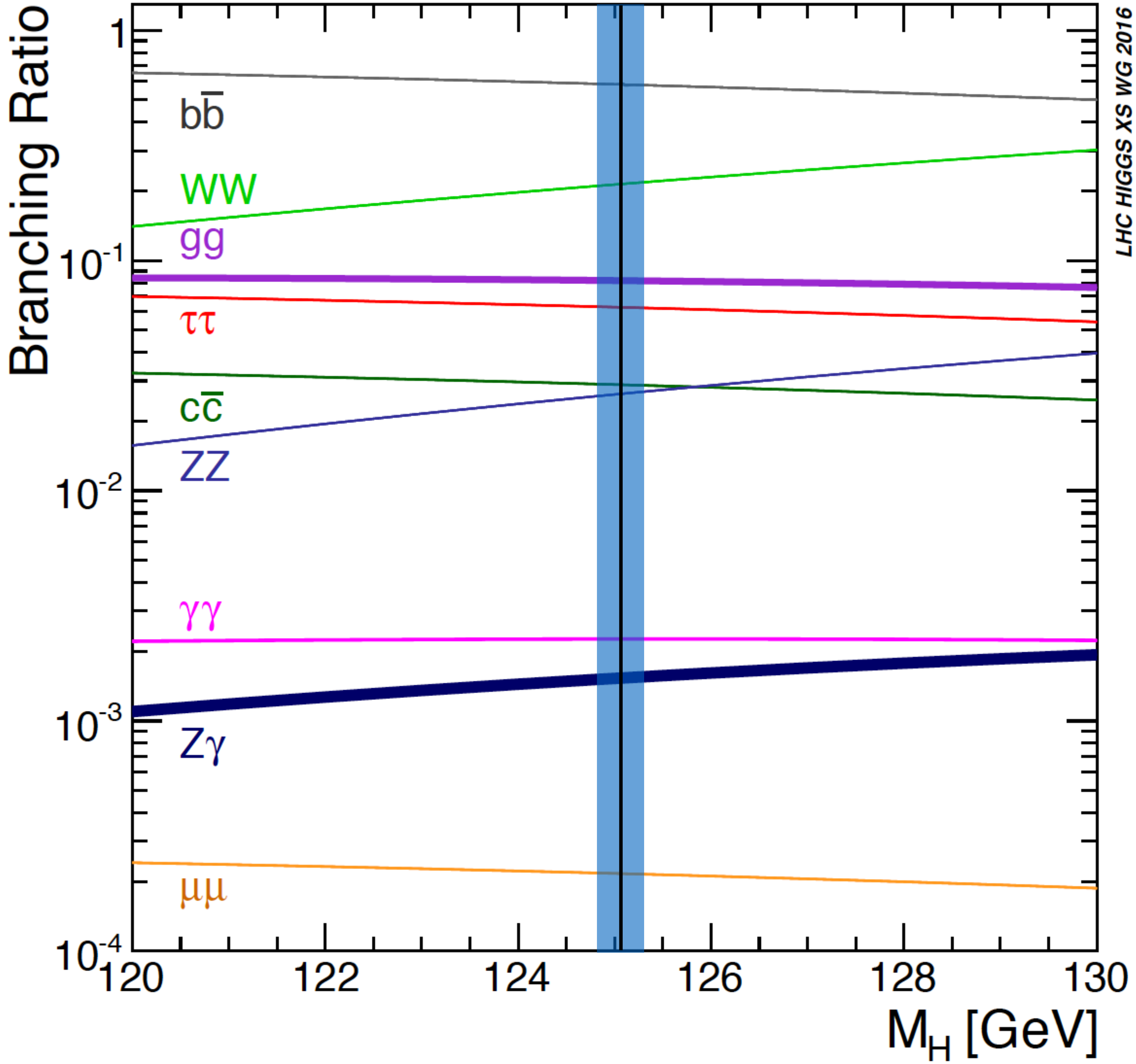
Higgs Boson Production: a rare Process



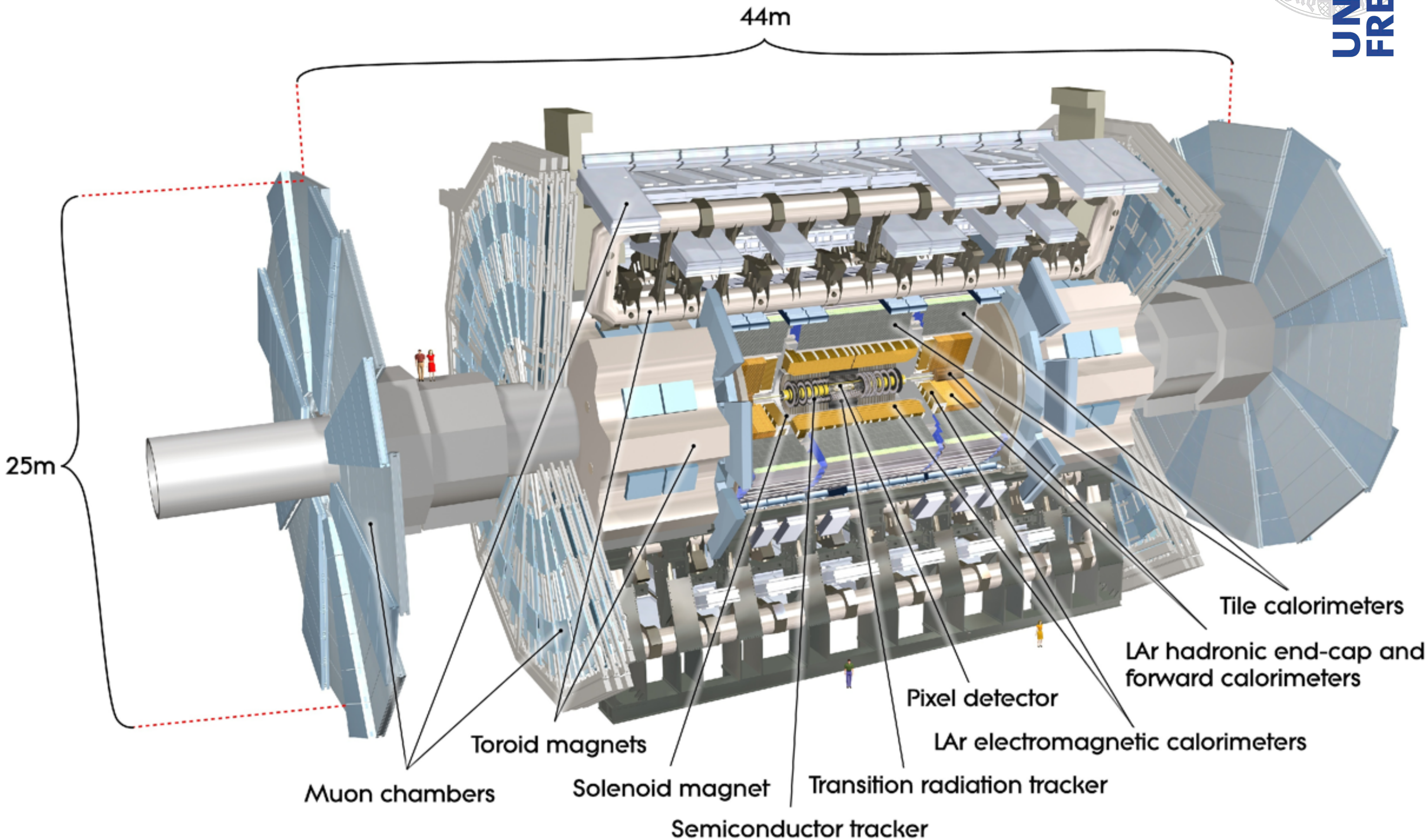
Proton-(anti)proton cross sections

A Higgs boson is produced in only 1 out of 10^9 events

Higgs Boson Decay



The ATLAS Detector

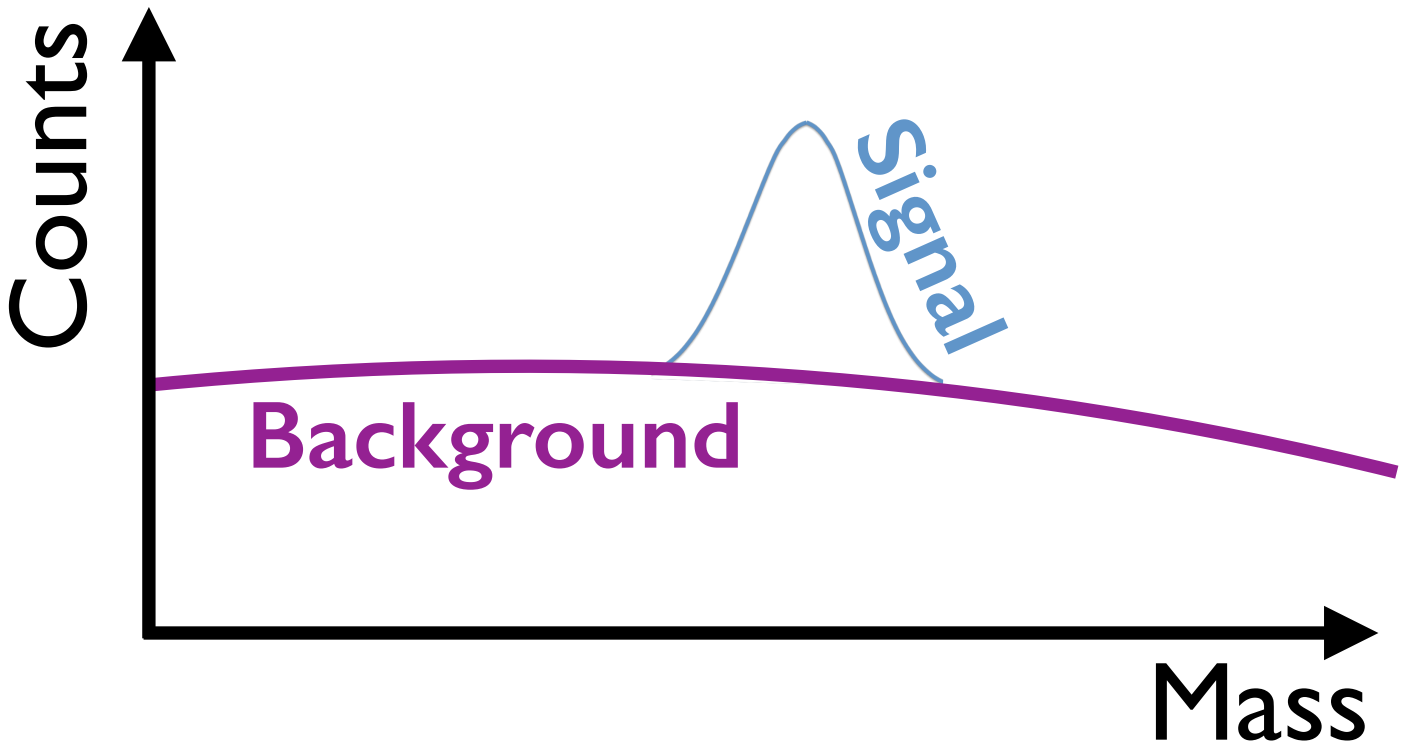


How do we find the Higgs Boson?

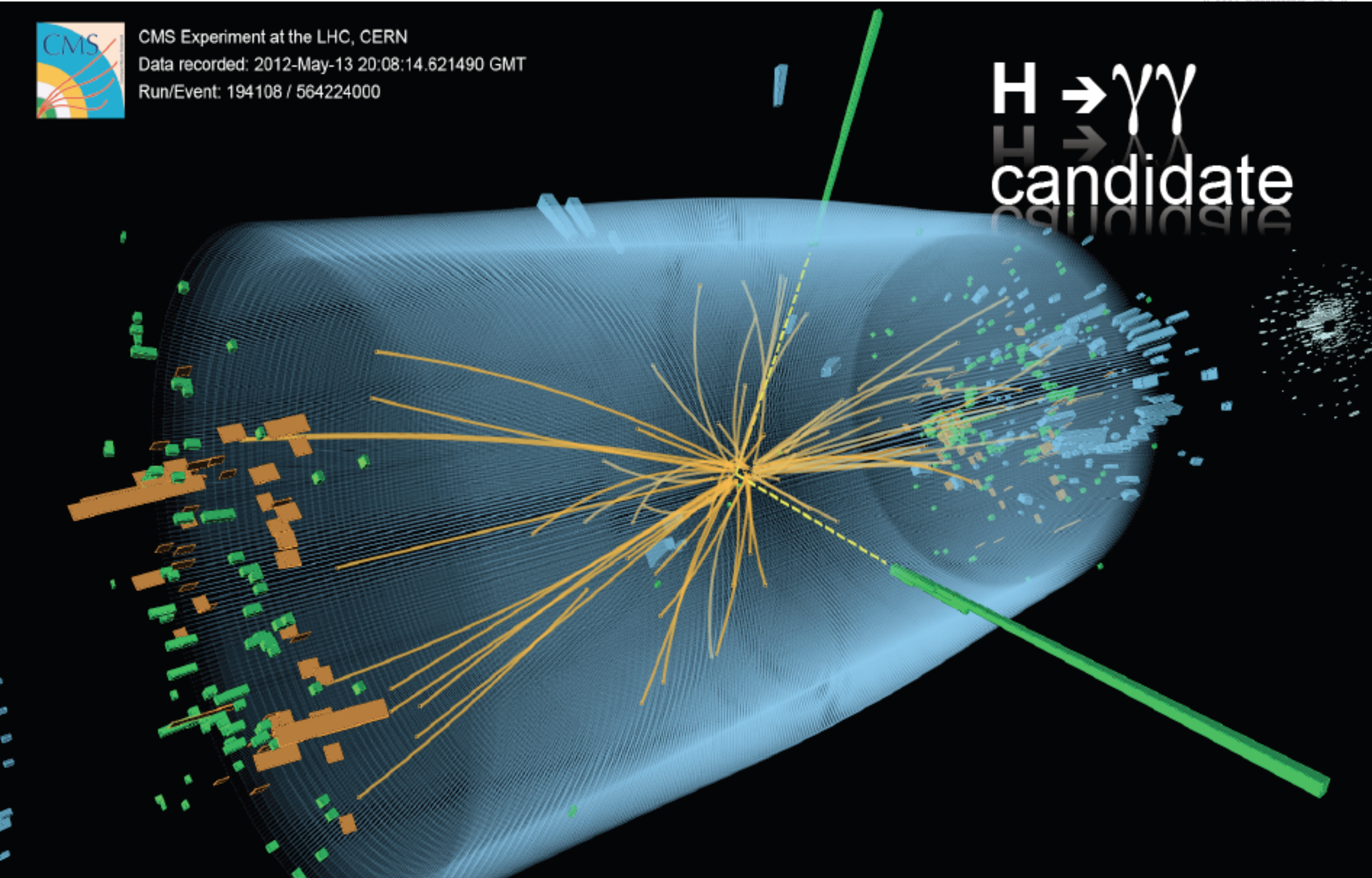
- Search in "clean" signatures: leptons or photons
- Calculate "invariant mass" of decay products

$$m^2 = |\mathbf{p}_1 + \mathbf{p}_2|^2 = (E_1 + E_2)^2 - |\vec{p}_1 + \vec{p}_2|^2$$

- Plot mass of every selected event into histogram and look for signal peak over background



$H \rightarrow \gamma\gamma$



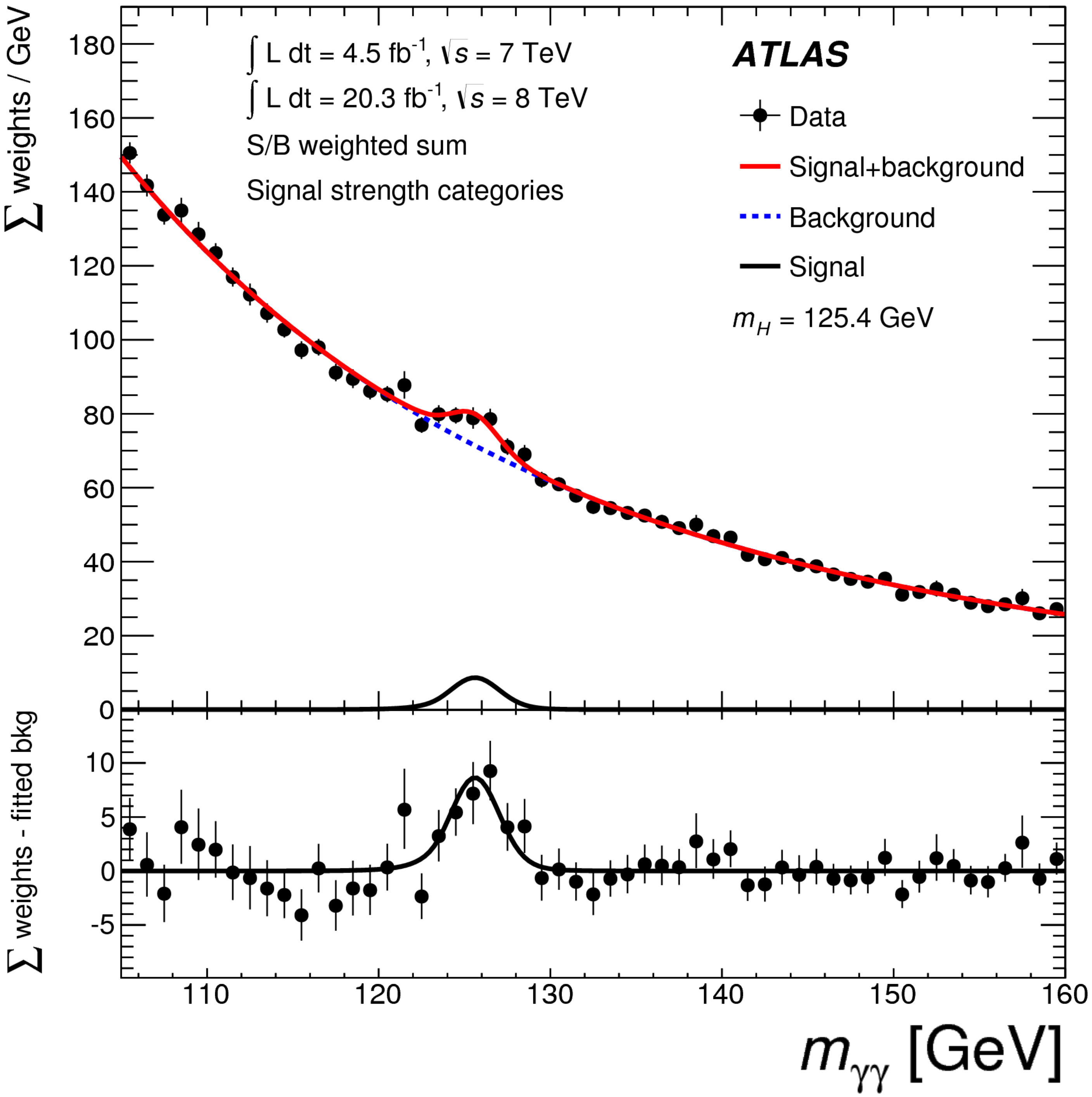
$H \rightarrow \gamma\gamma$

Strategy:

- Select two isolated photons
- Calculate di-photon invariant mass and fit distribution

Complete Run 1 data!

Expect ~1400 Higgs Bosons



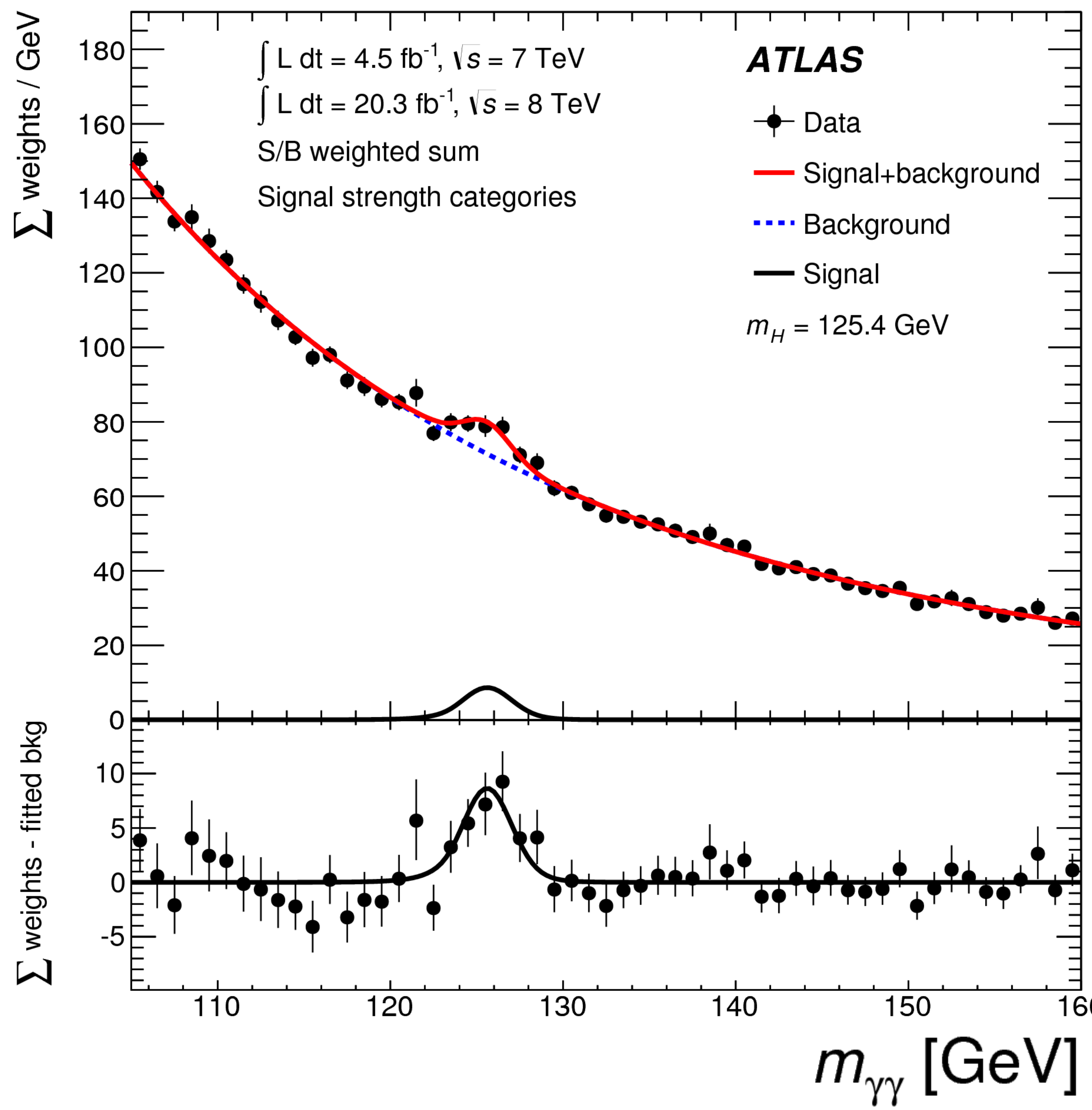
H → γγ

Strategy:

- Select two isolated photons
- Calculate di-photon invariant mass and fit distribution

Complete Run I data!

Expect ~1400 Higgs Bosons



Signal strength μ:

$$\mu := \frac{\sigma \cdot \mathcal{B}}{\sigma_{\mathrm{SM}} \cdot \mathcal{B}_{\mathrm{SM}}} = \frac{\text{observed rate}}{\text{expected rate}}$$

$$= 1.17 \pm 0.27$$

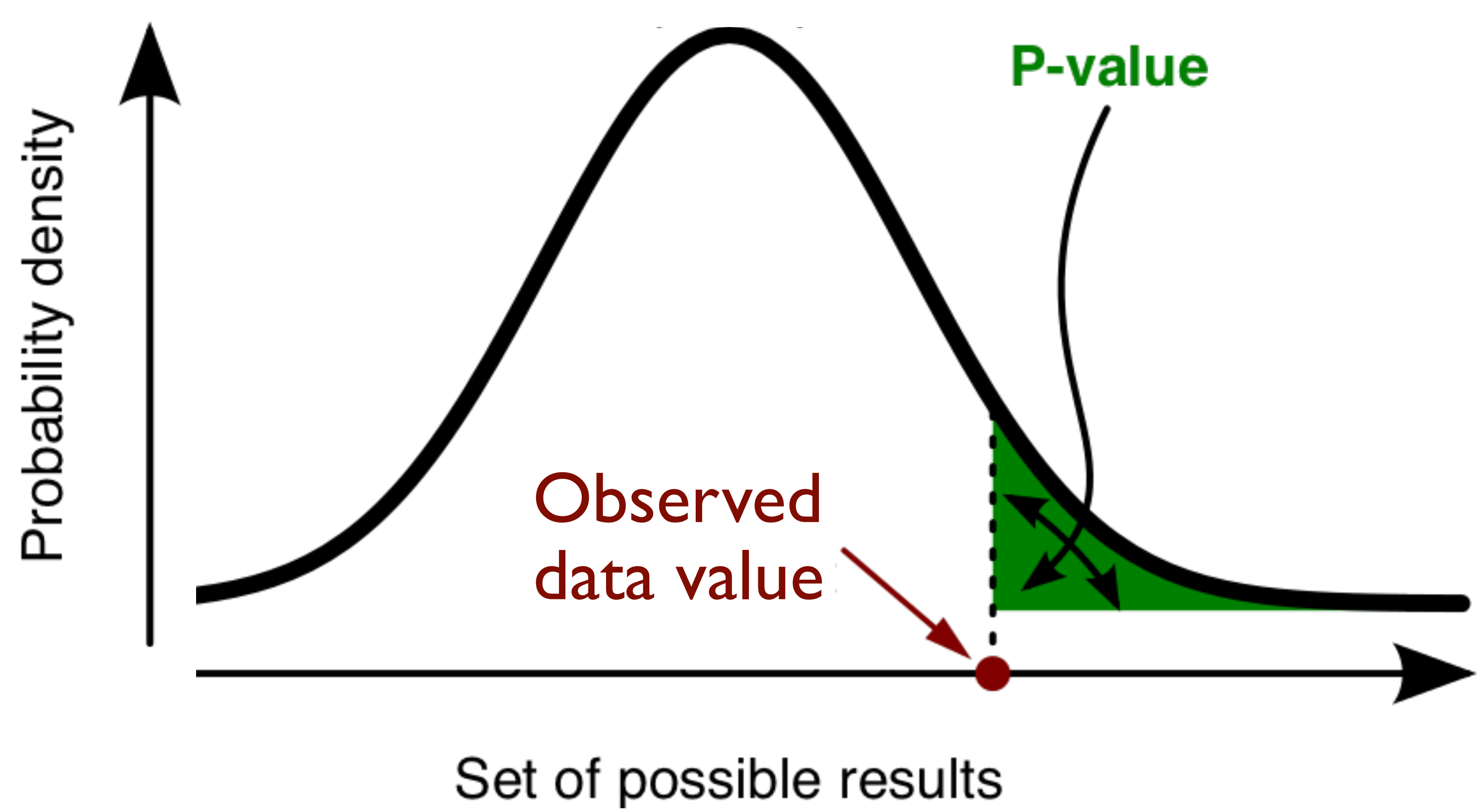
How sure are we?

- Calculate the "p-value":
  1. Build probability density distribution f for background-only hypothesis H_0: $f(x|H_0)$
  2. Probability to obtain result x_{obs} or less likely, given $f(x|H_0)$:

$$p = \int_{x_{\mathrm{obs}}}^{\infty} f\,(x|H_0)dx$$

- Map p-value to Gaussian standard deviations N_σ:

$$p = \int_{N_\sigma}^{\infty} \frac{e^{-2y^2/2}}{\sqrt{2\pi}} dy$$



How sure are we?

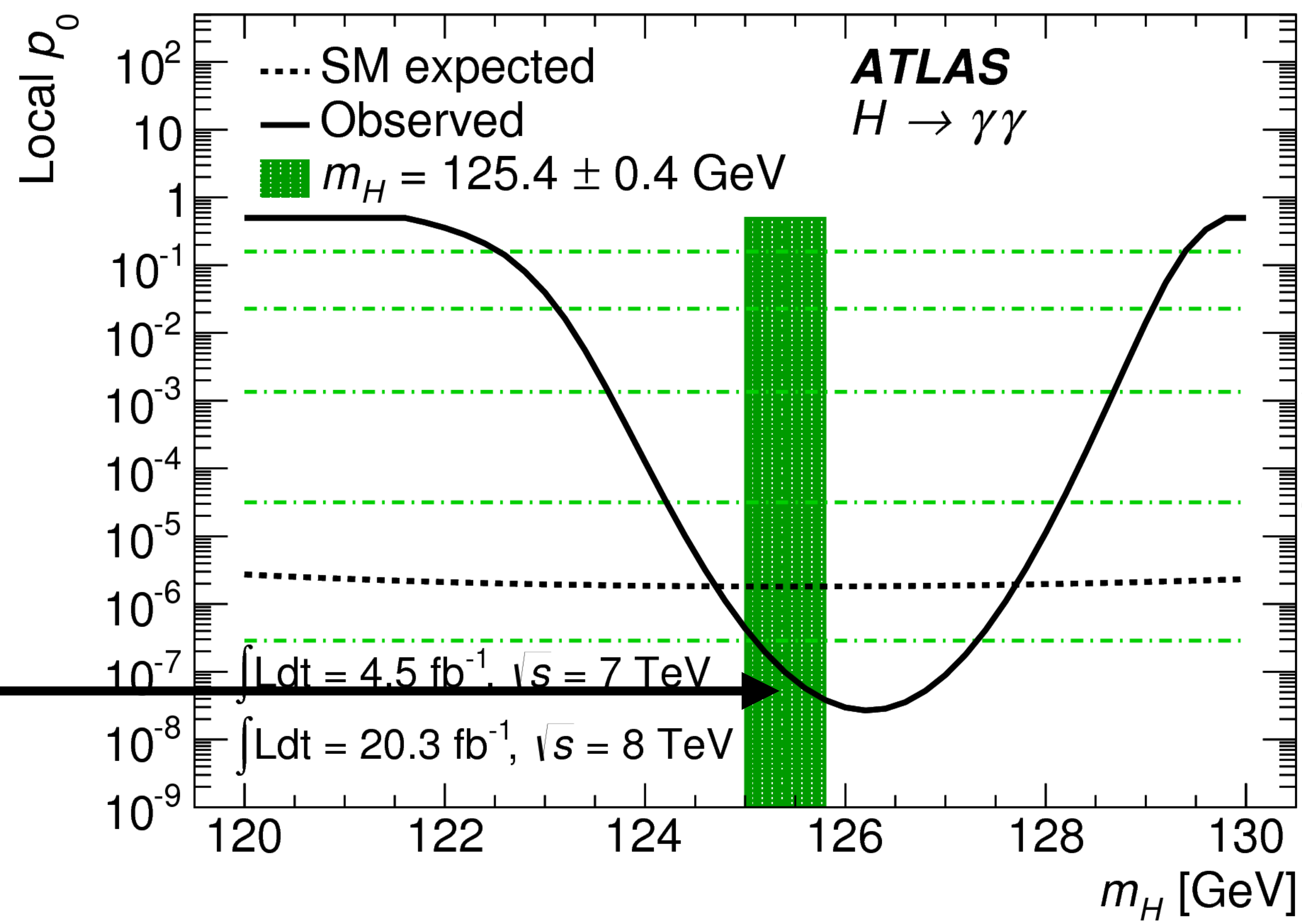
- Calculate the "p-value":
  1. Build probability density distribution *f* for background-only hypothesis H_0: $f(x|H_0)$
  2. Probability to obtain result x_{obs} or less likely, given $f(x|H_0)$:

$$p = \int_{x_{\rm obs}}^{\infty} f\,(x|H_0)dx$$

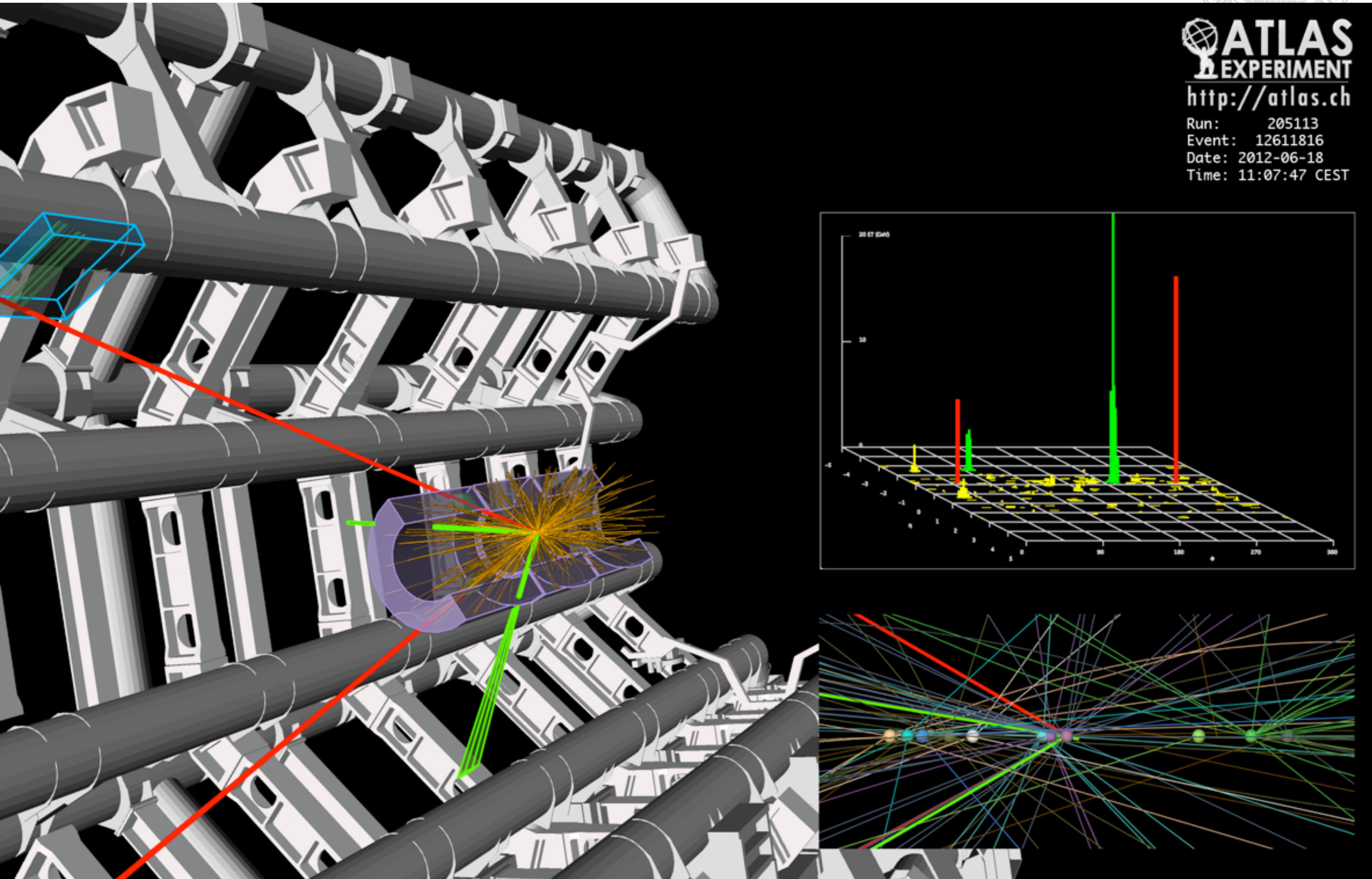
- Map p-value to Gaussian standard deviations N_σ:

$$p = \int_{N_\sigma}^{\infty} \frac{e^{-2y^2/2}}{\sqrt{2\pi}} dy$$

- Significance: **5.2σ**

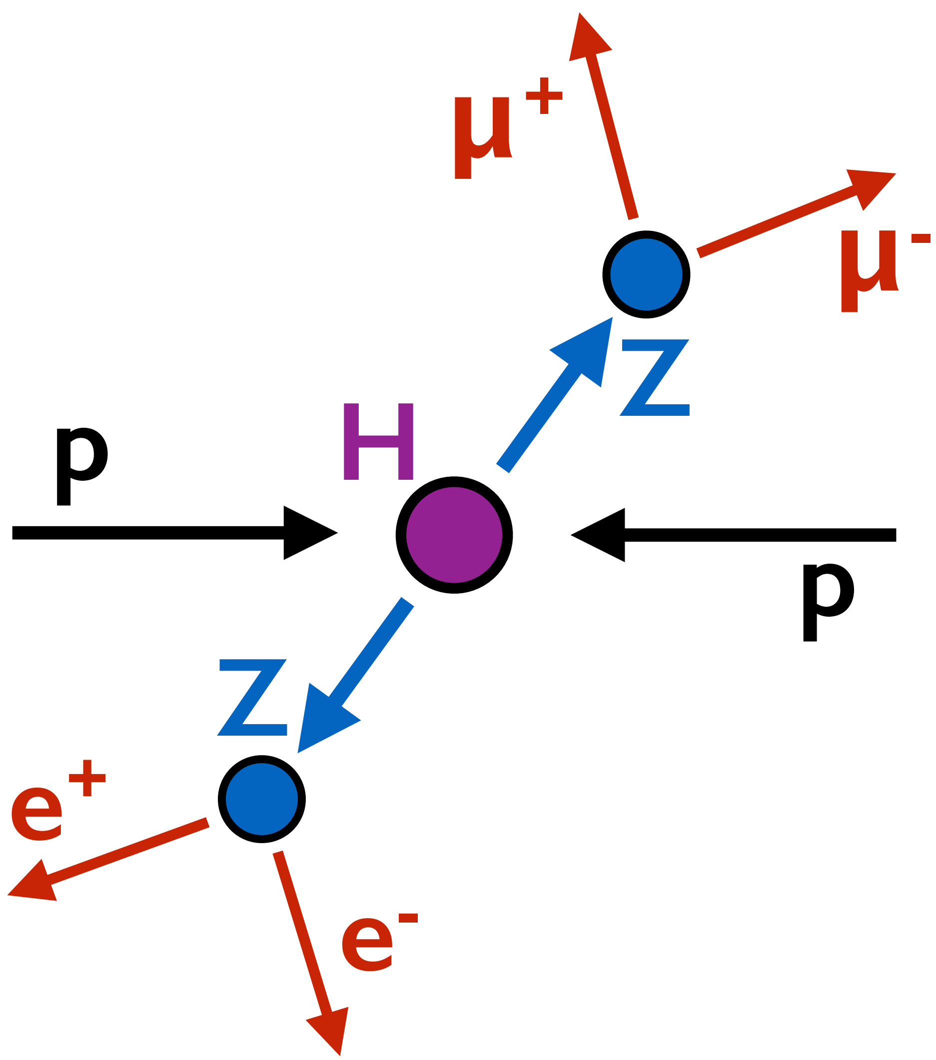


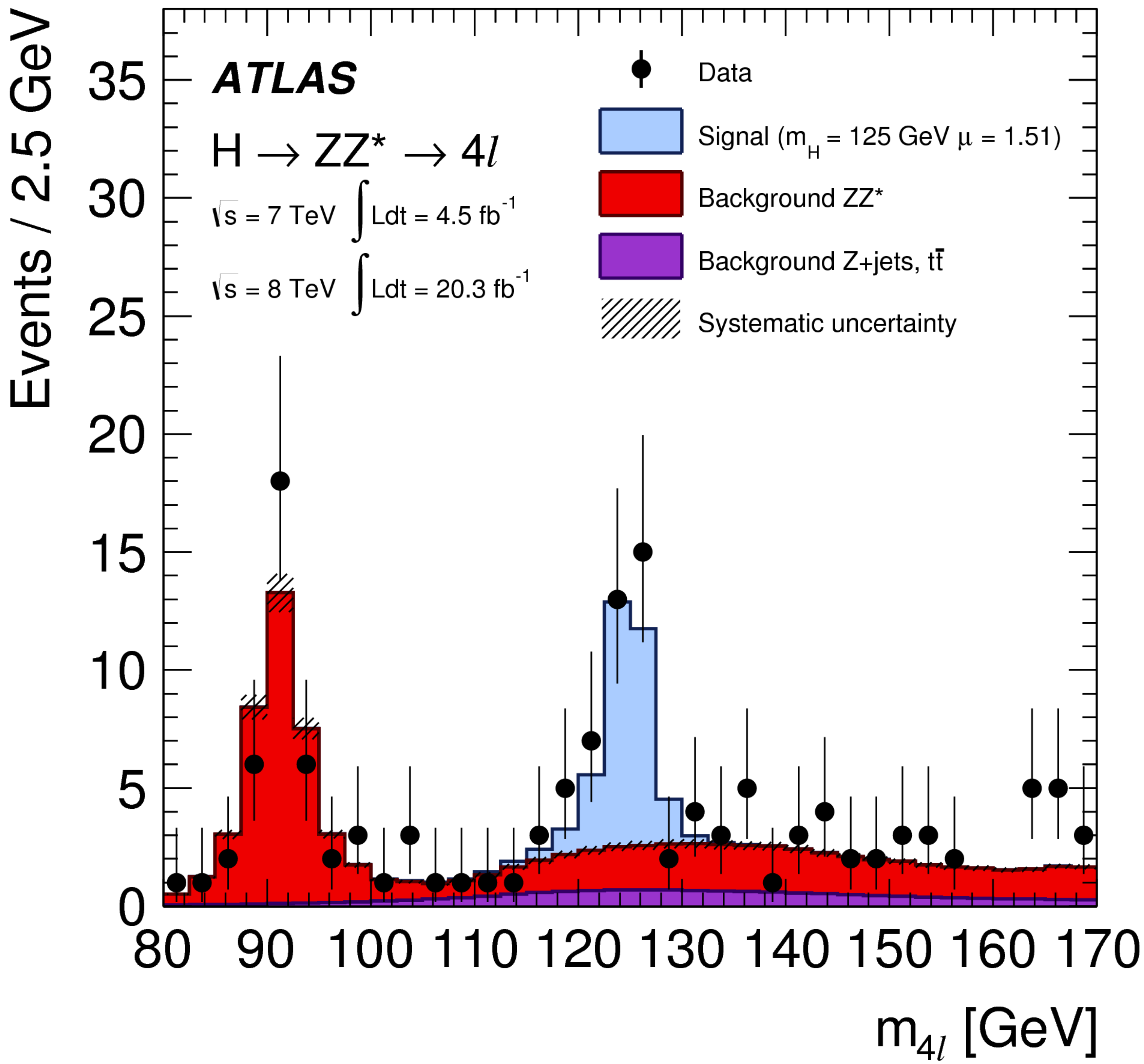
$H \rightarrow ZZ^* \rightarrow 4\ell$



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

- Strategy:
  - Identify 4 isolated leptons (electrons, muons)
  - Calculate invariant mass



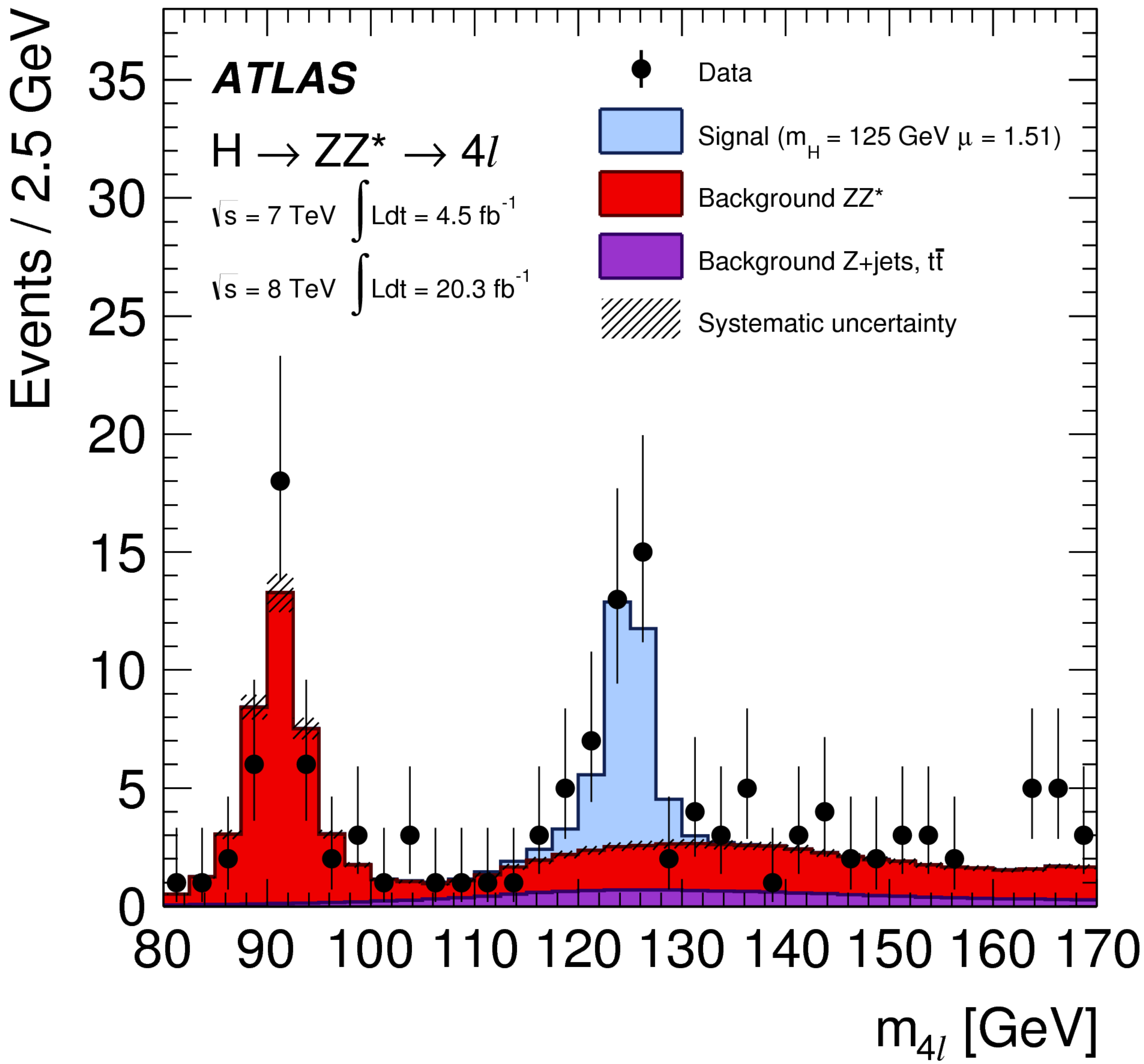


$H \to ZZ^* \to 4\ell$

- Strategy:
  - Identify 4 isolated leptons (electrons, muons)
  - Calculate invariant mass
- Conditions:
  - **Tiny overall branching ratio:**
    - $BR(H \to ZZ^*) \approx 2.6\%$
    - $BR(Z \to \ell\ell) \approx 3.4\%$

  ⇒ Expect **~75 Higgs bosons in this decay!**
- Result:
  - Significance: 8.2σ
  - Signal strength:

$$\mu = 1.50\ ^{+0.35}_{-0.31}(\mathrm{stat})\ ^{+0.19}_{-0.13}(\mathrm{sys})$$

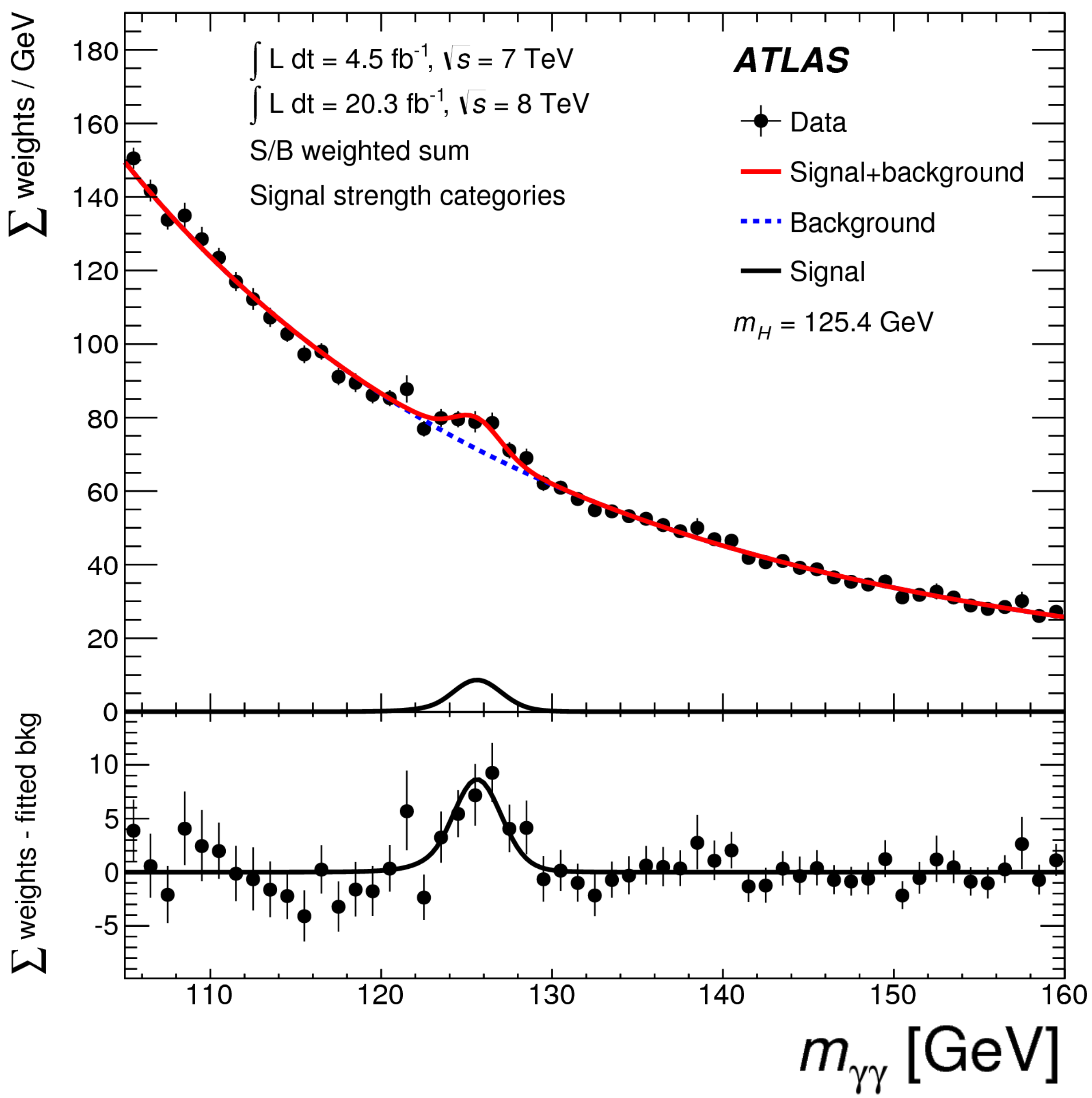


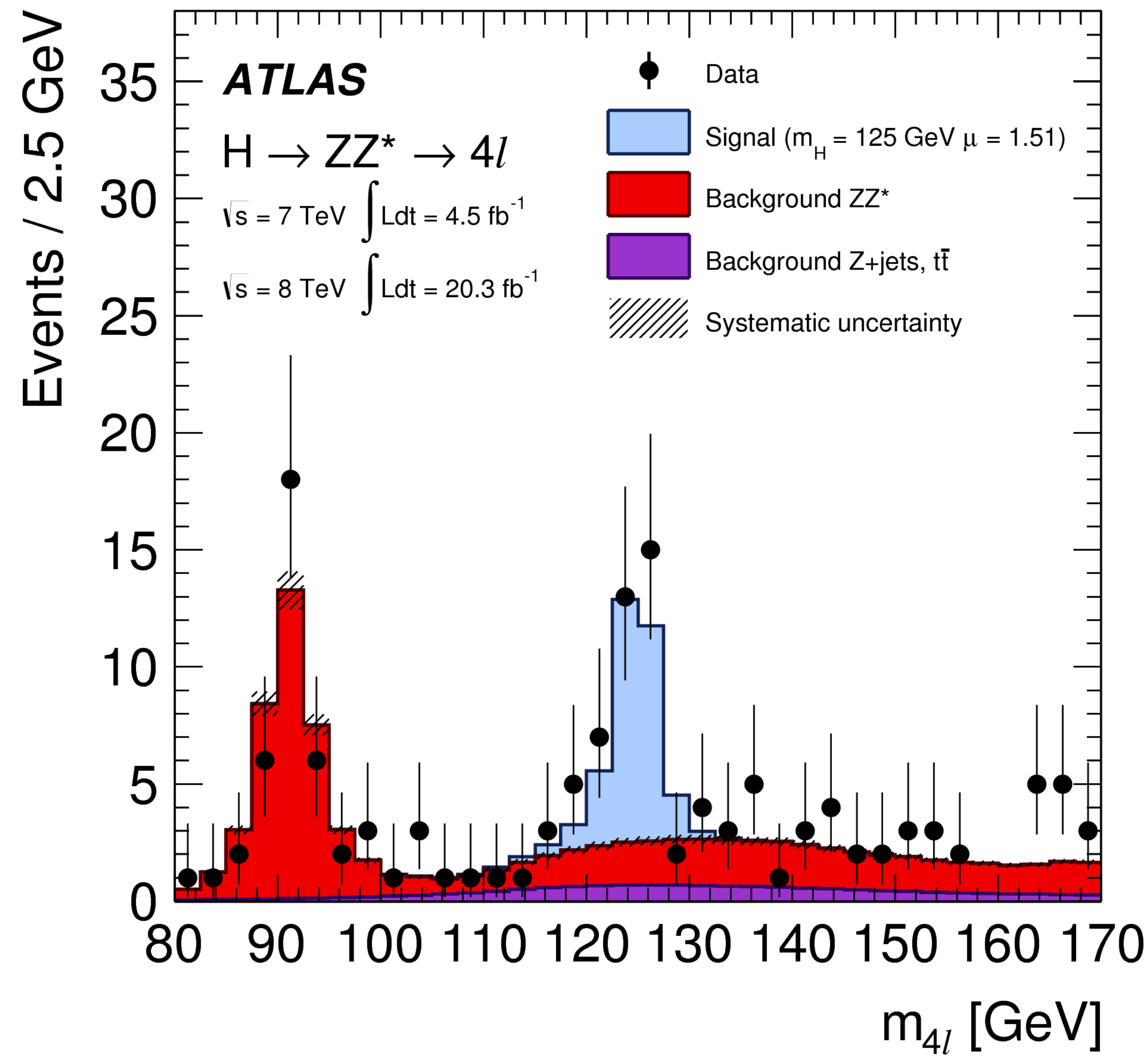
Higgs Boson Properties

- Mass m_H
- Spin and CP
- Interactions with other particles

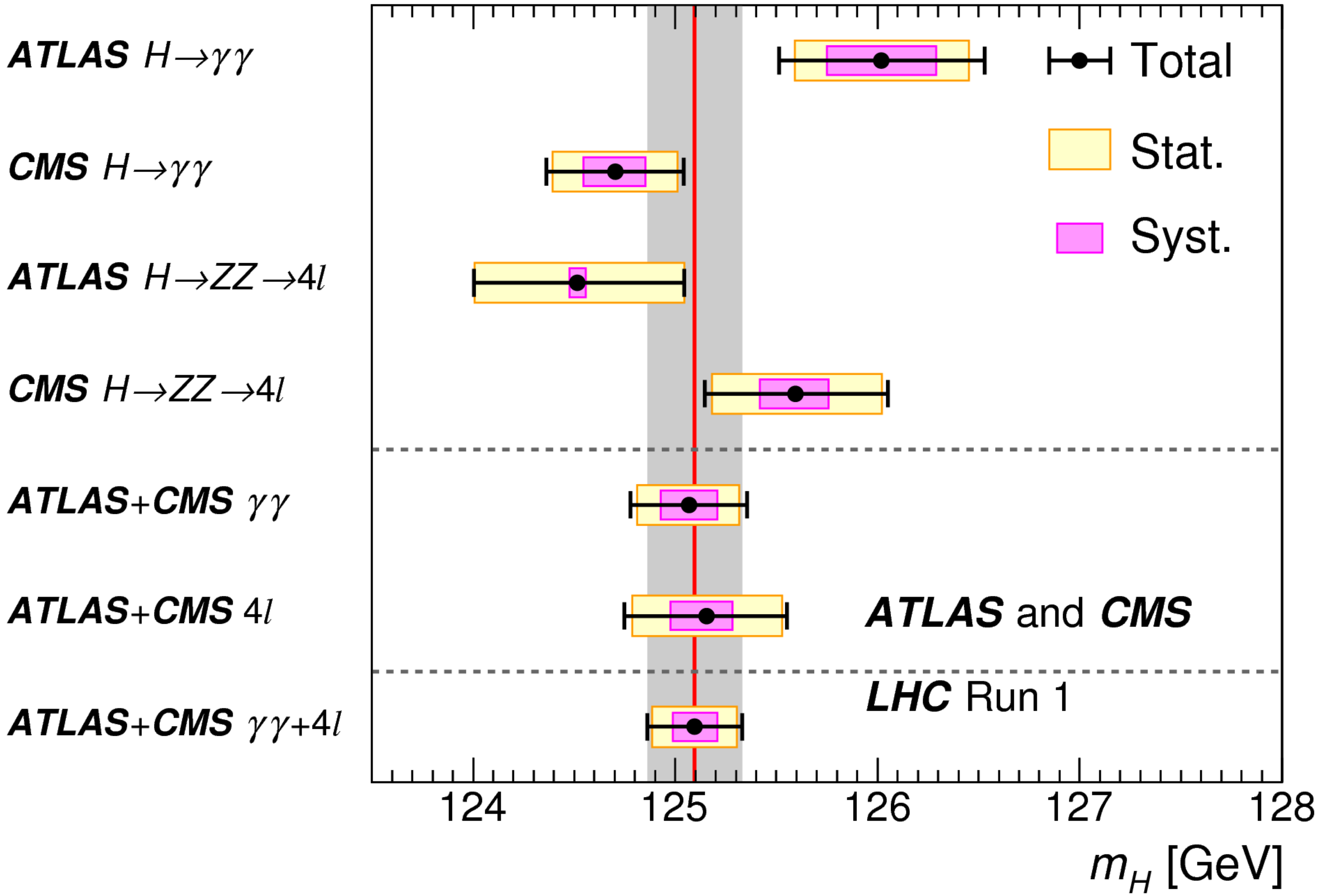
Mass Measurement

- Not predicted by theory
  - Once measured by experiment, everything else is determined
- Use high-resolution **H → γγ** and **H → ZZ* → 4ℓ** channels:





ATLAS+CMS Mass Measurement



- Result: $m_H = 125.09 \pm 0.24\ \mathrm{GeV}$

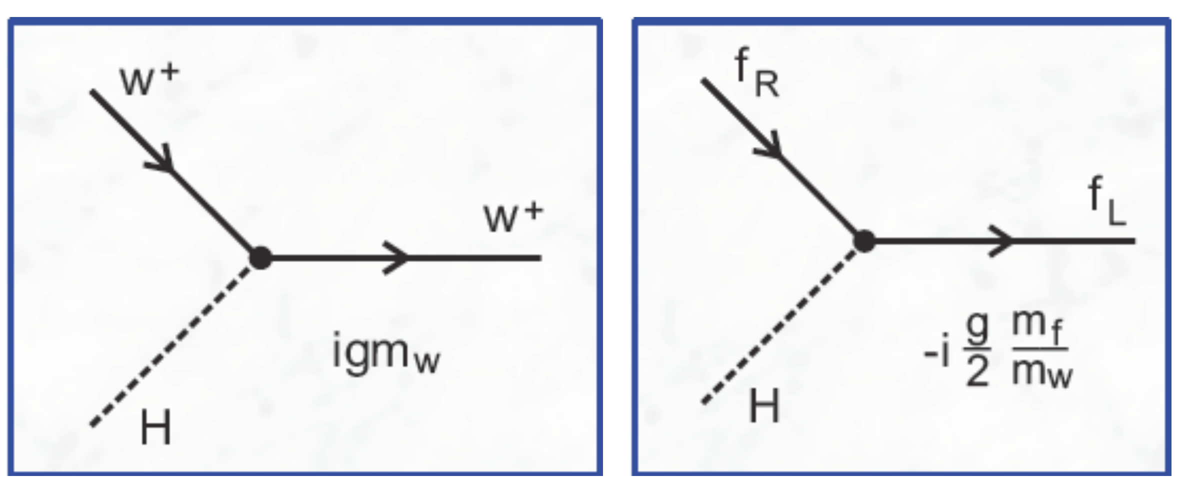
$$= 125.09 \pm 0.21\,(\mathrm{stat.}) \pm 0.11\,(\mathrm{syst.})\ \mathrm{GeV}$$

2‰ uncertainty!

But is it ***the*** Higgs Boson?

Need to determine its other properties precisely:

- Spin and CP
- Production rates
- Couplings to bosons and fermions
  - According to boson and fermion masses?



Why Spin 0?

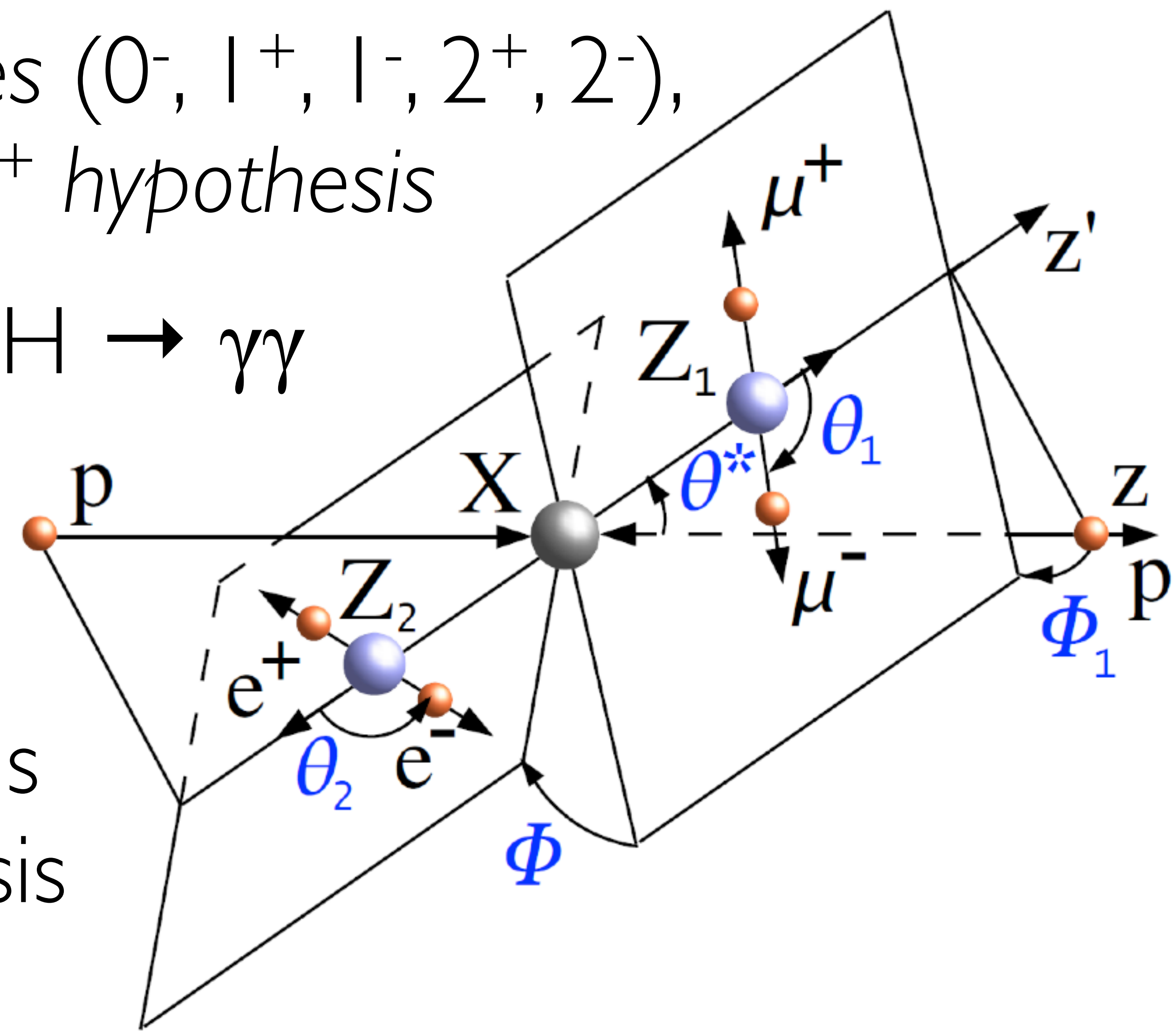
- Vacuum:
  - No charge:
  - Rotationally invariant, *i.e.*, no preferred direction
- Higgs boson should have same quantum numbers as observed vacuum:
  - No charge: 👍
  - Mass cannot depend on direction

    ⇒ **Spin 0**

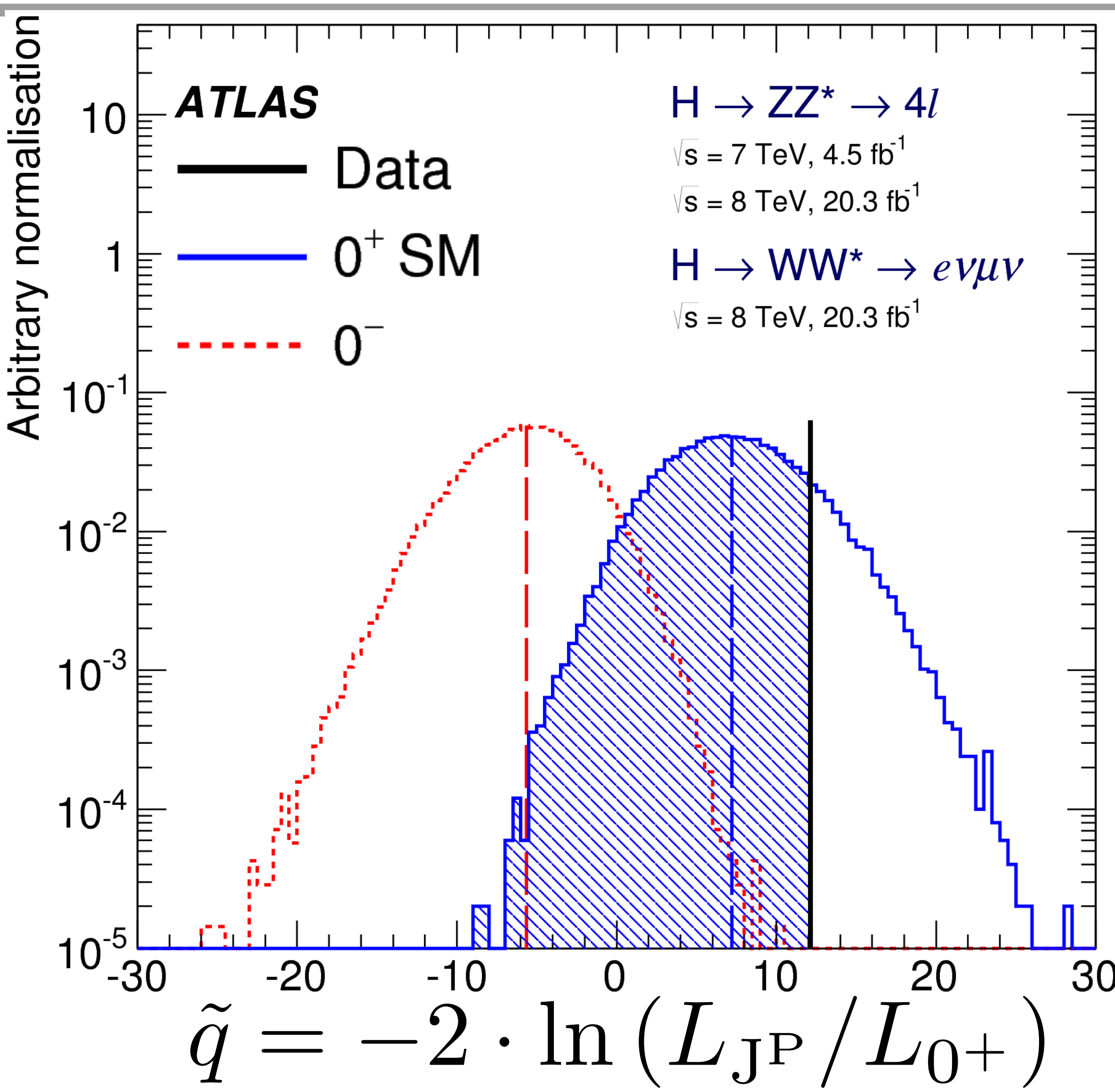
Spin and CP

Standard Model Higgs boson: $J^{PC} = 0^{++}$

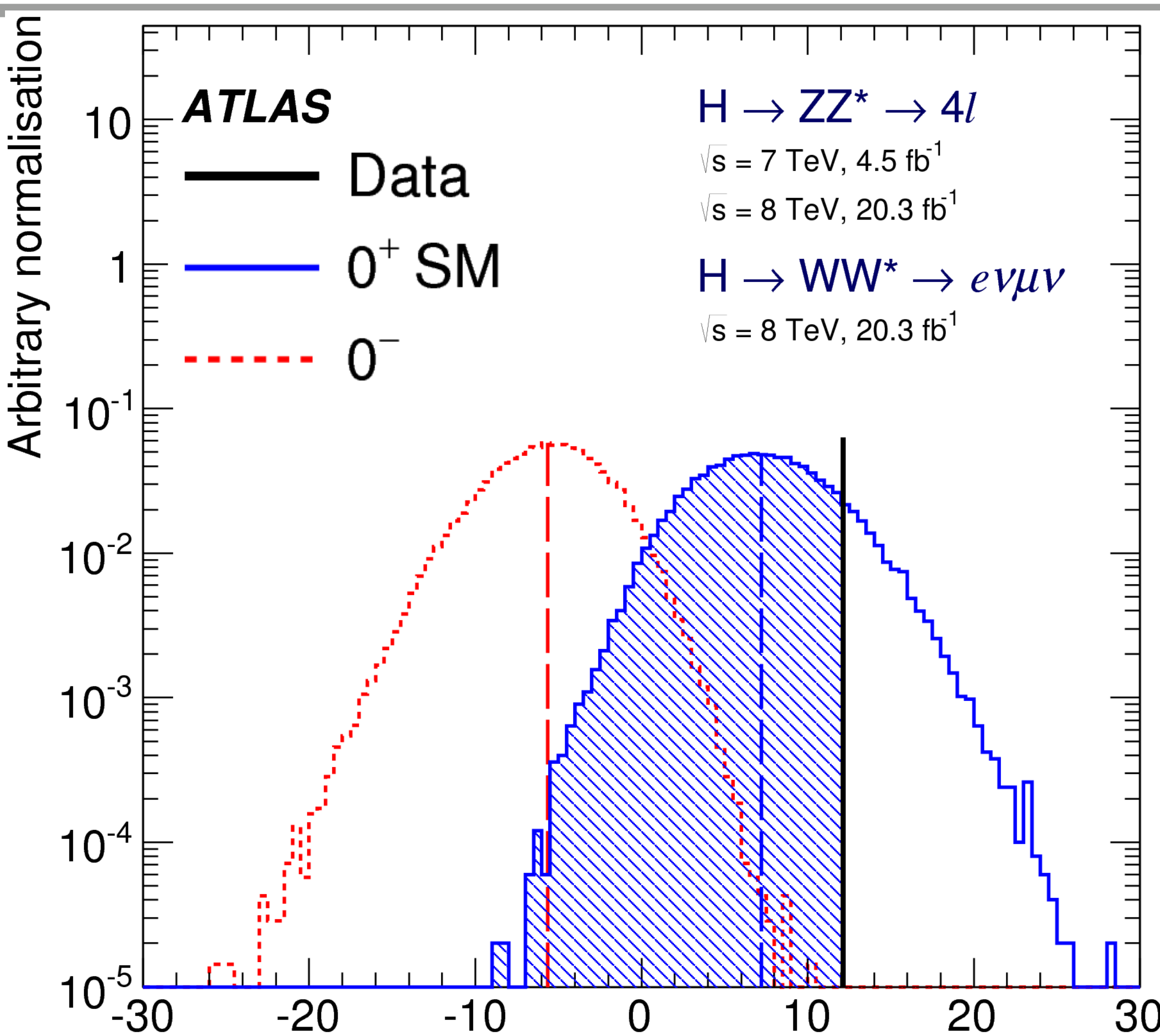
- **C**harge conjugation: change sign of all quantum numbers
- **P**arity ("mirror") transformation": $\hat{P}\,\vec{x} \longrightarrow -\vec{x}$
- Strategy: *falsify other hypotheses* (0^-, 1^+, 1^-, 2^+, 2^-), *demonstrate consistency with 0^+ hypothesis*
- Spin-1 excluded by observed $H \rightarrow \gamma\gamma$
- Use angular variables
- Calculate likelihood ratio between alternative hypothesis and standard $J^P = 0^+$ hypothesis



Spin and CP

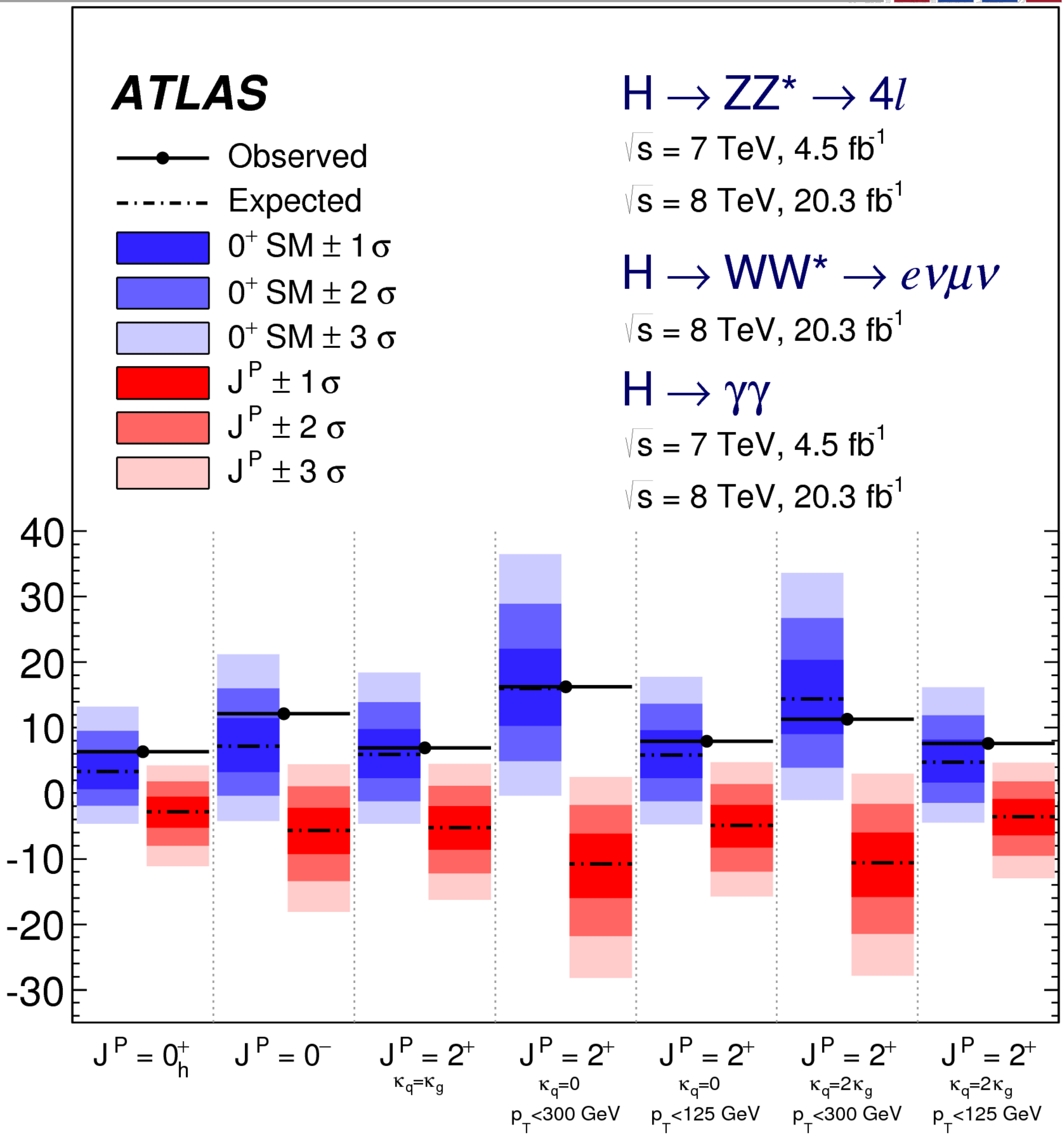

ATLAS
Data
0+ SM
0−
H → ZZ* → 4l
√s = 7 TeV, 4.5 fb-1
√s = 8 TeV, 20.3 fb-1
H → WW* → eνμν
√s = 8 TeV, 20.3 fb-1
Arbitrary normalisation
10
1
10-1
10-2
10-3
10-4
10-5
-30
-20
-10
0
10
20
30
$\tilde{q} = -2 \cdot \ln\left(L_{J^P}/L_{0^+}\right)$

Spin and CP

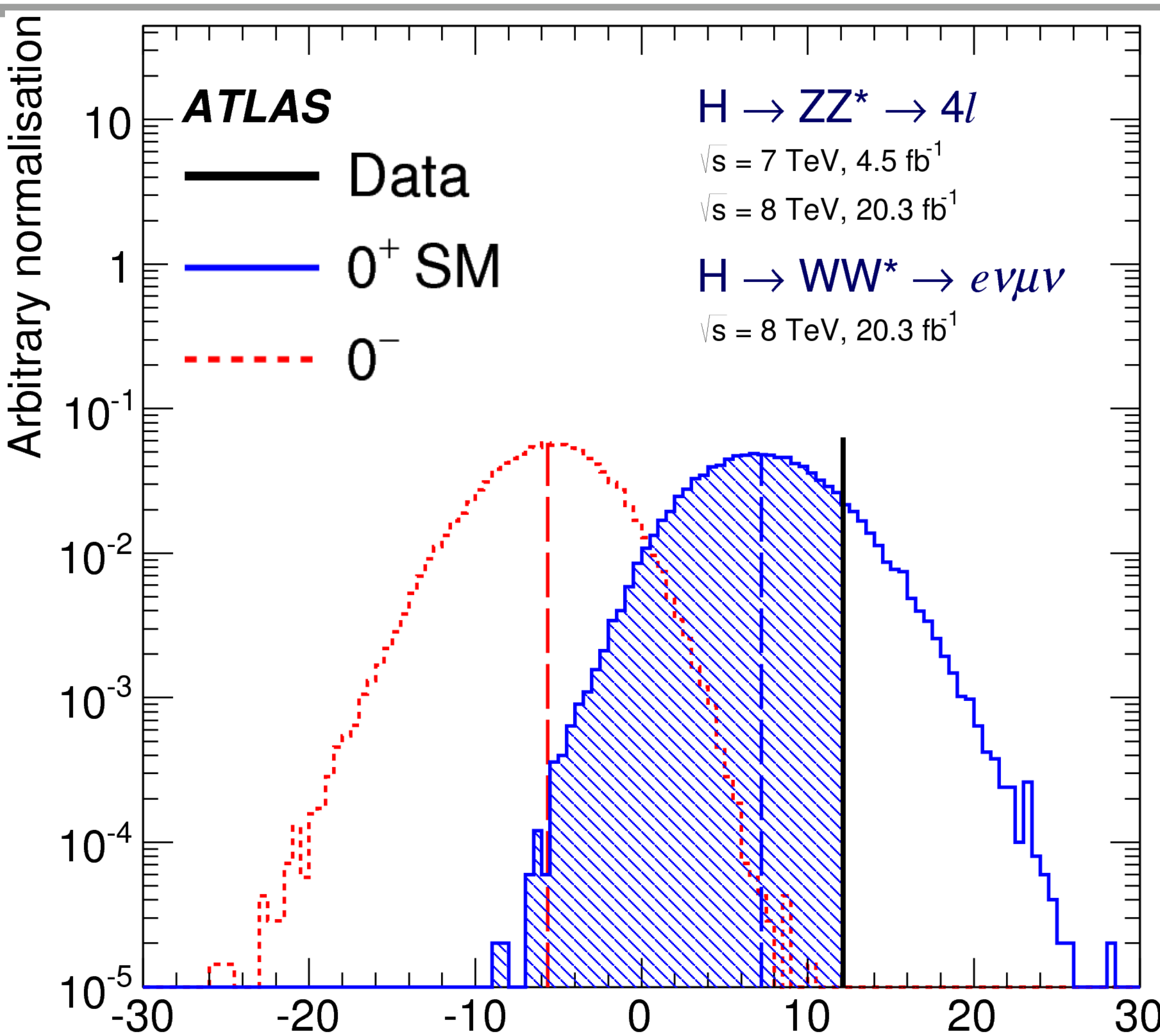


$$\tilde{q} = -2 \cdot \ln\left(L_{J^P}/L_{0^+}\right)$$

projection $\tilde{q}$

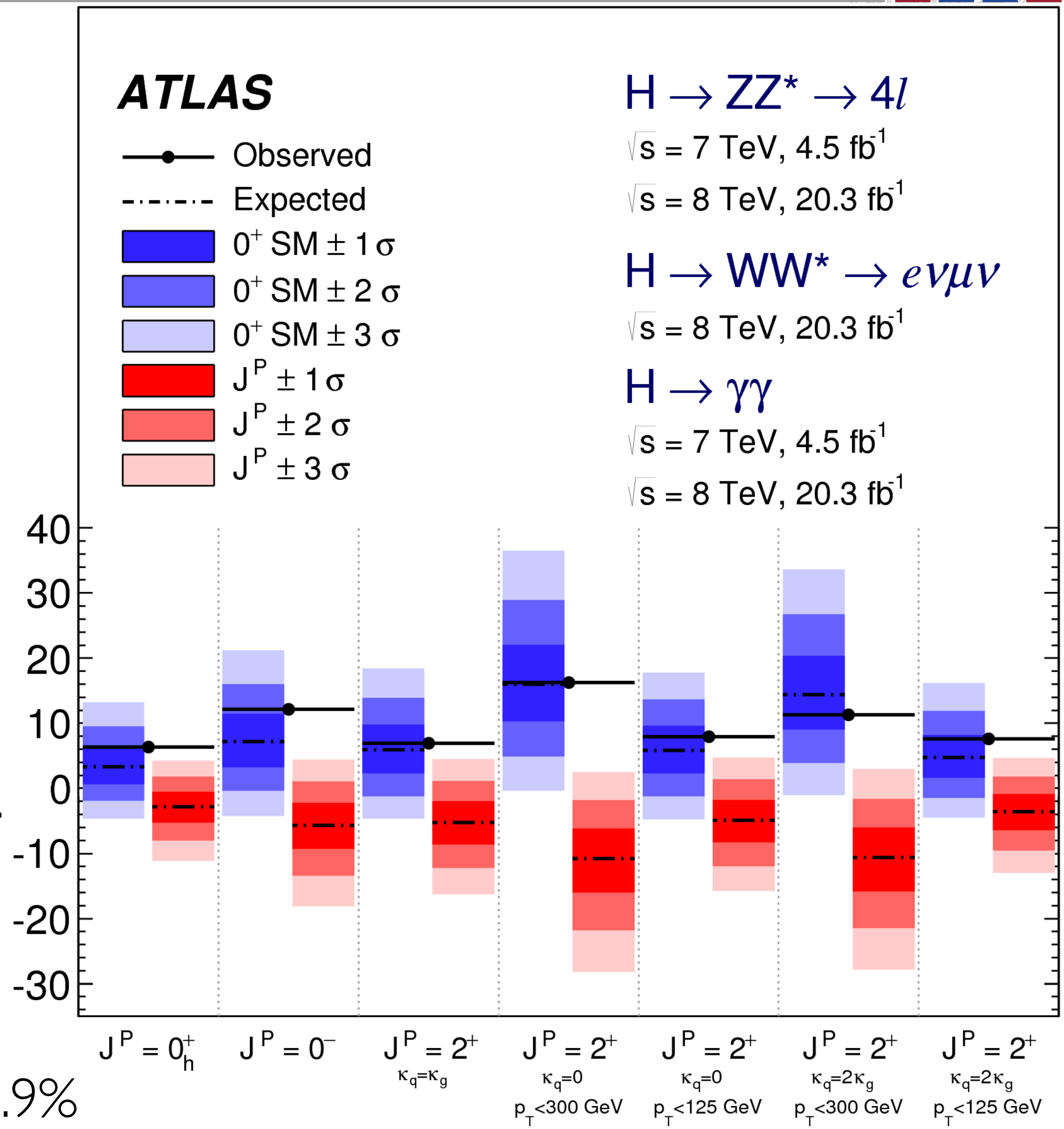


Spin and CP



$$\tilde{q} = -2 \cdot \ln\left(L_{J^P} / L_{0^+}\right)$$

projection $\tilde{q}$



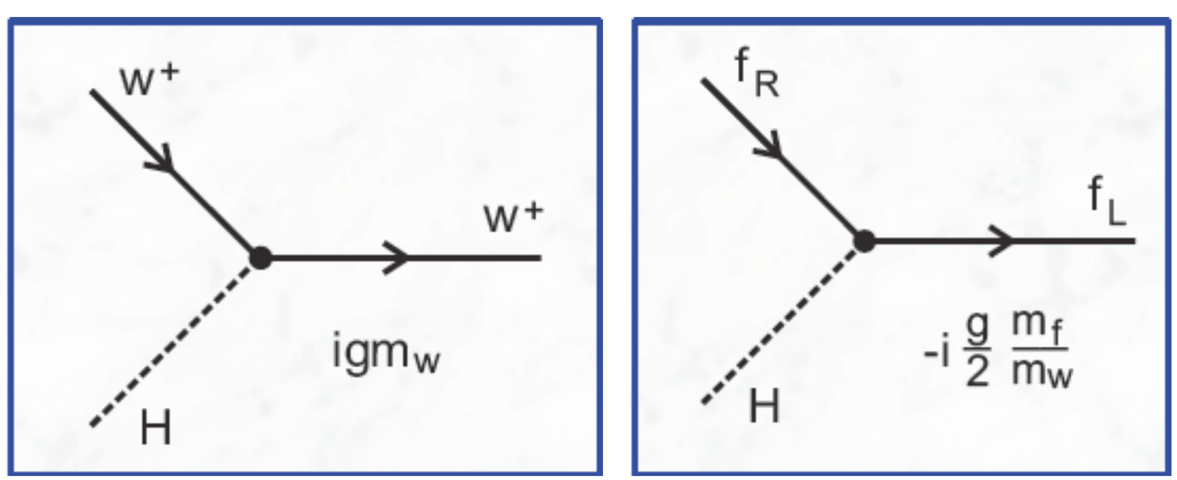
- SM $J^P = 0^+$ favored
- Other models disfavored at >99.9%

But is it ***the*** Higgs Boson?

<u>Need to determine its other properties precisely:</u>

✔ Spin and CP

- Production rates
- Couplings to bosons and fermions
  - According to boson and fermion masses?



The κ Framework

LHC Higgs XS WG (arxiv:1307.1347)

Model and fit framework:

- Once Higgs boson mass is known, all other Higgs-boson parameters are fixed in the SM
- To allow for measurement deviations from SM rates, introduce coupling scale factors: $\kappa = \dfrac{g}{g_{\mathrm{SM}}}$

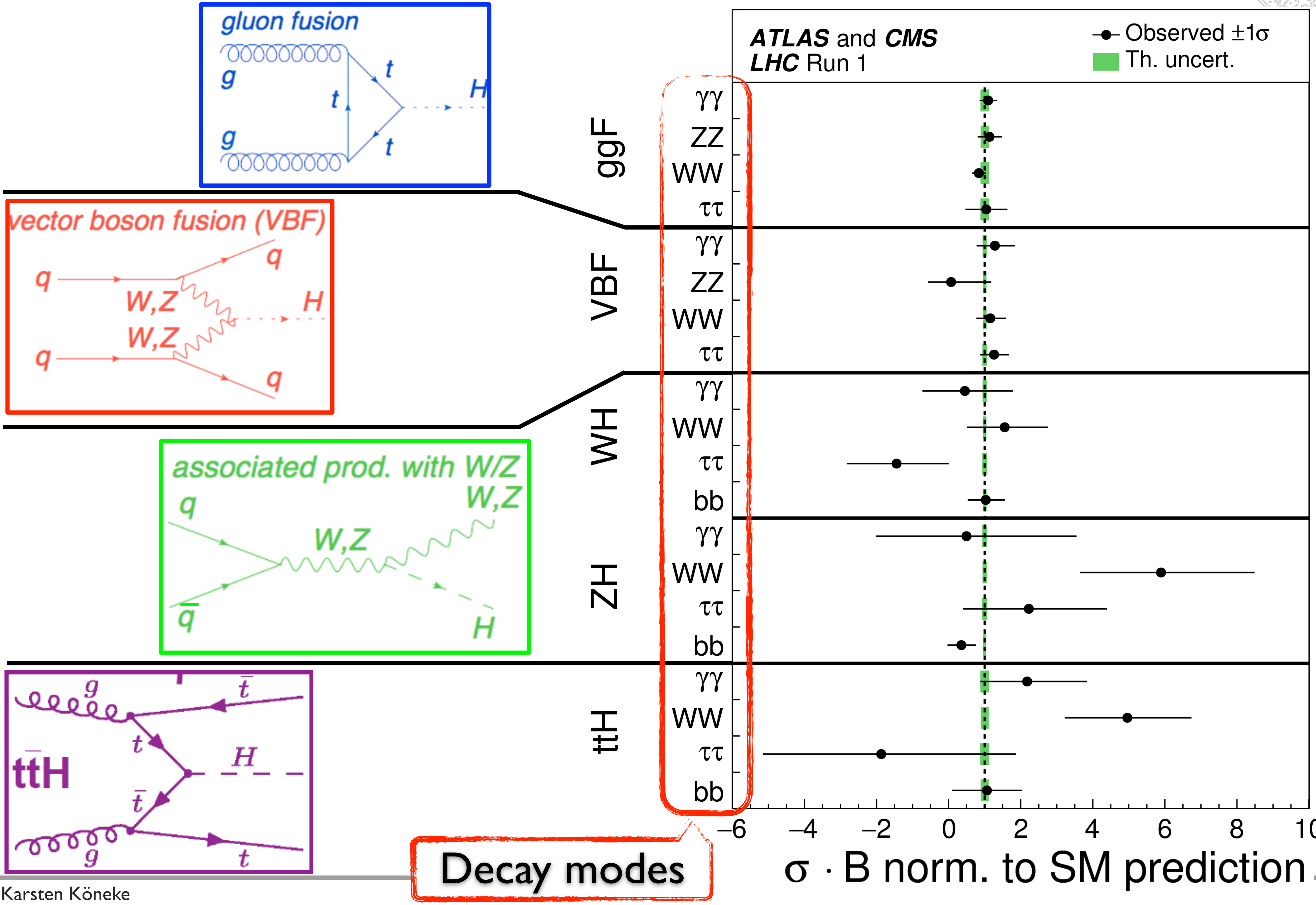
$$(\sigma \cdot \mathrm{BF})\,(i \to H \to j) = \frac{\sigma_i \cdot \Gamma_f}{\Gamma_H}$$

$$= \sigma_{\mathrm{SM}}\,(i \to H) \cdot \mathrm{BF}_{\mathrm{SM}}\,(H \to f) \cdot \frac{\kappa_i^2 \cdot \kappa_f^2}{\kappa_H^2}$$

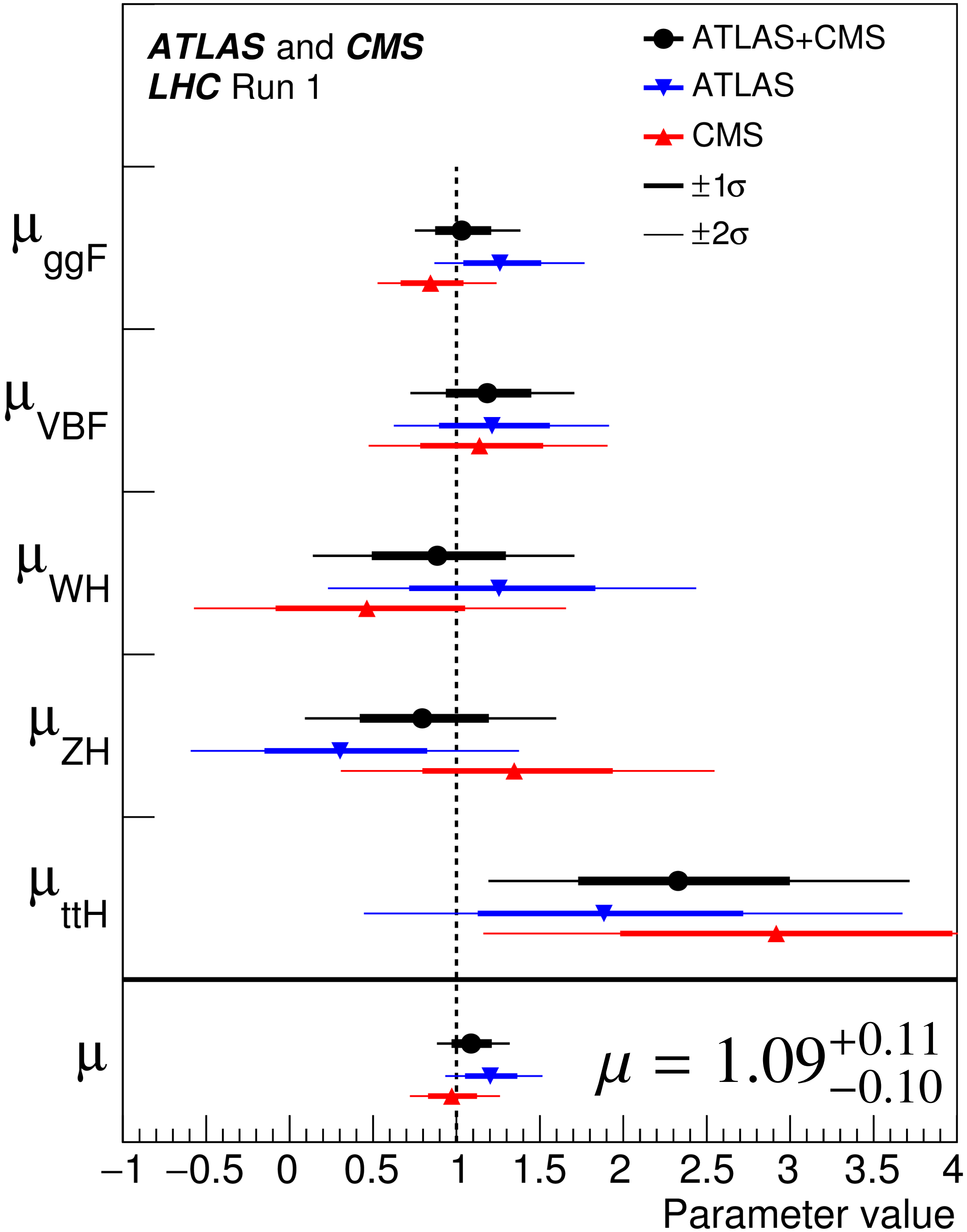
Assumption:

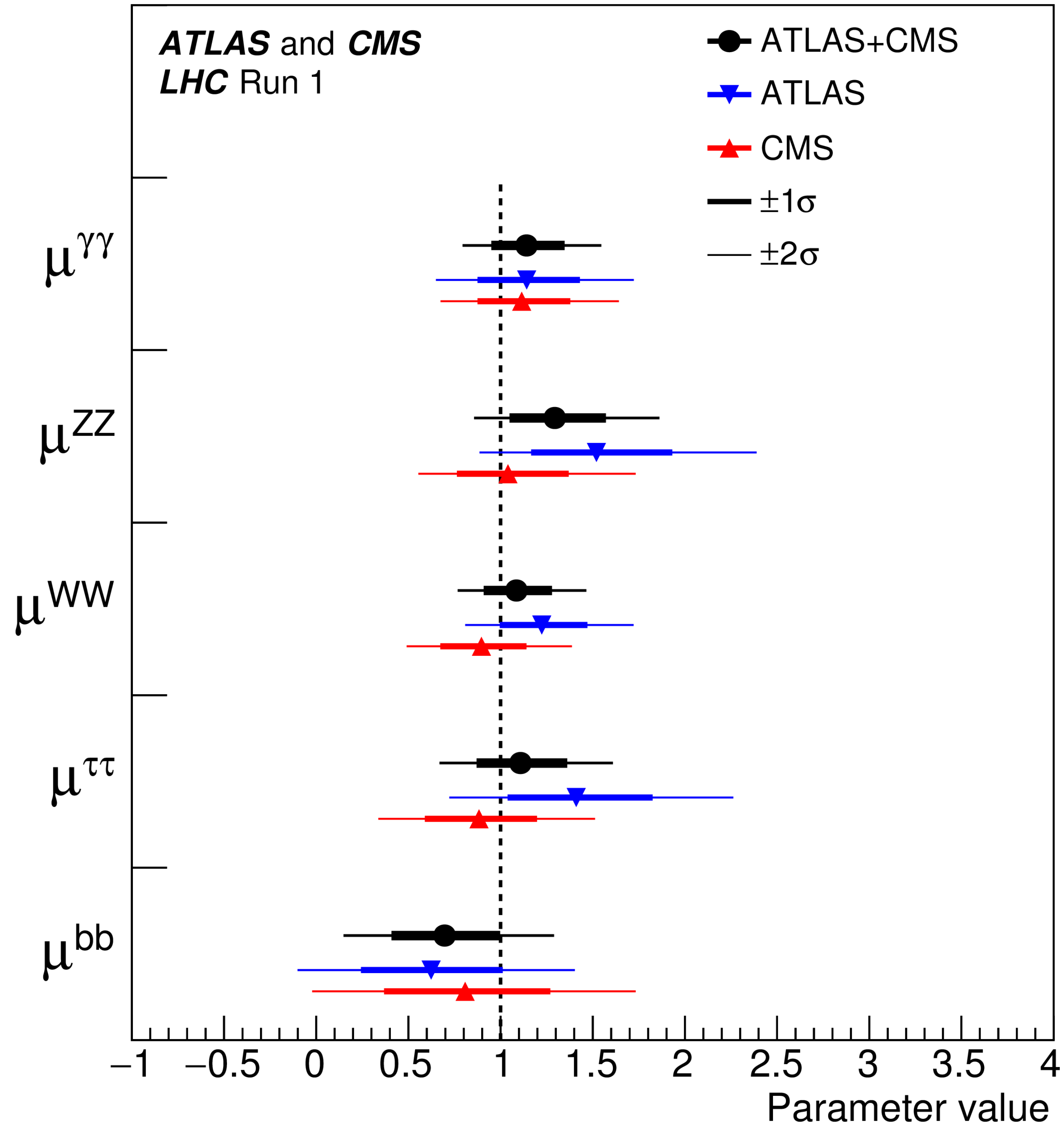
- Only one SM Higgs-like state at ~125 GeV with negligible width

Production and Decay Modes

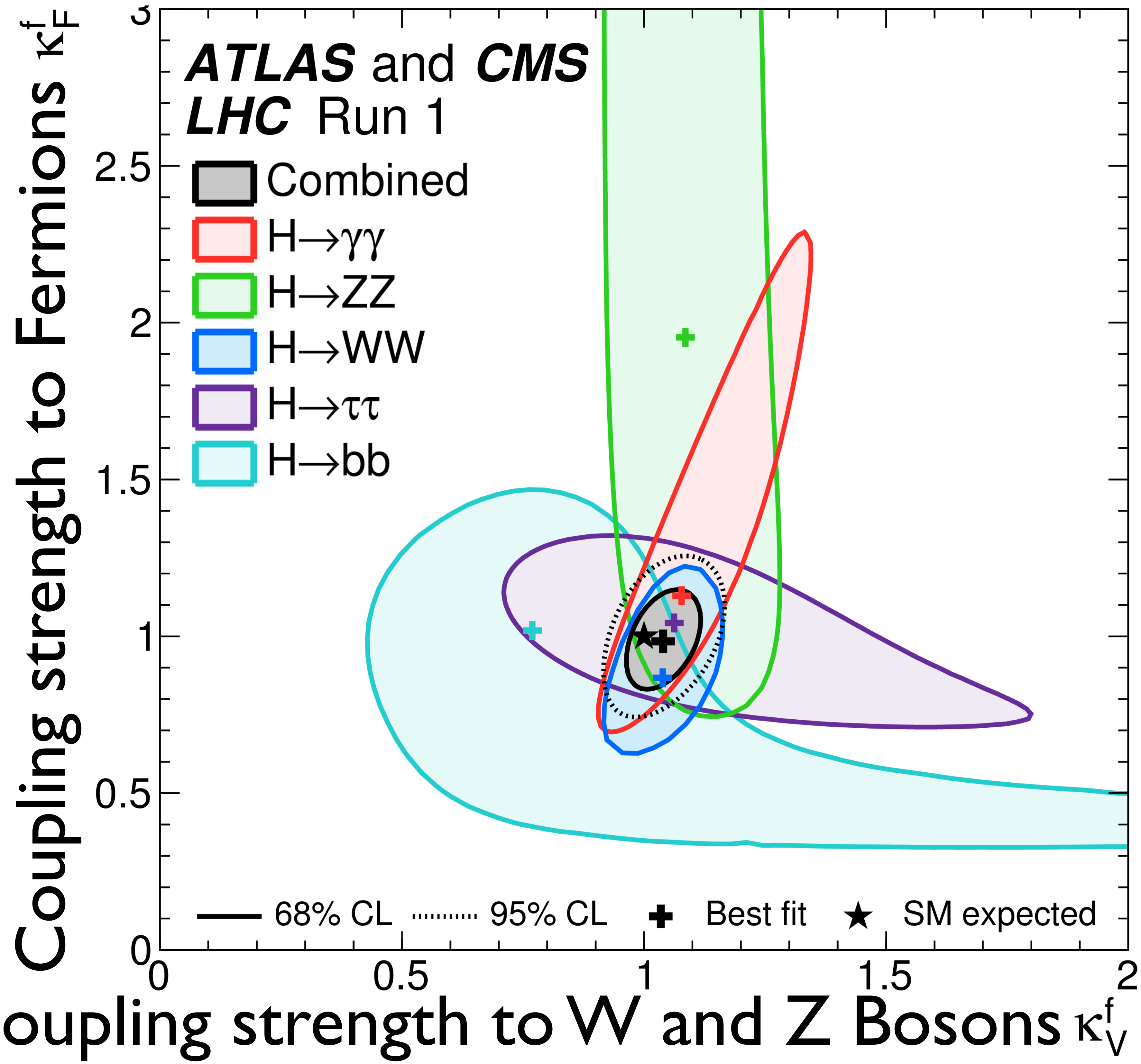


Production and Decay Modes

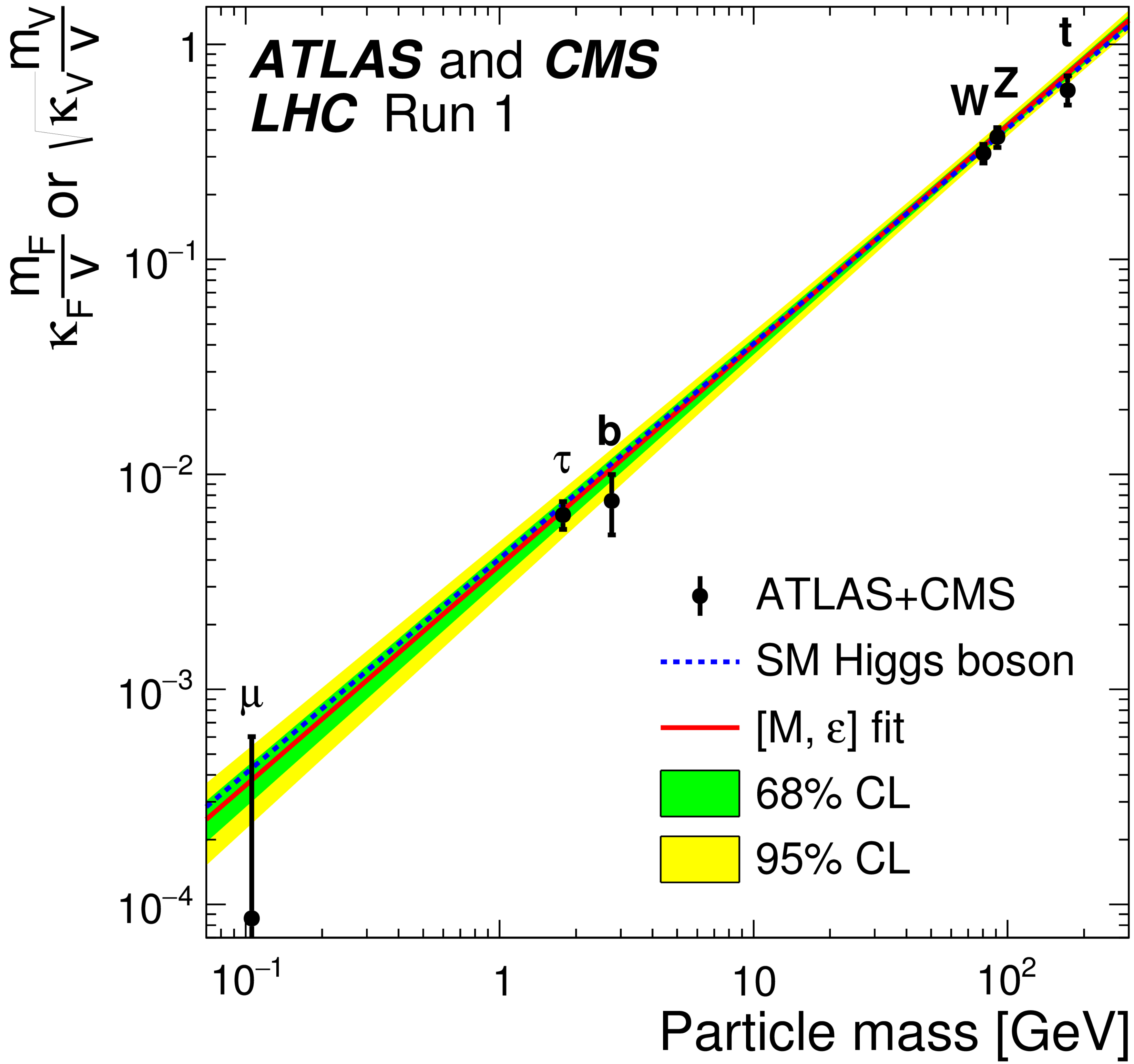




Coupling to Fermions and Bosons



Mass ~ Coupling Strength?



ATLAS and CMS see all measured couplings in agreement with SM expectations

LHC Run 2

E_{CM} = 13 TeV

$H \to \gamma\gamma$

ATL-CONF-2016-067

di-photon selection
↓
ttH - leptonic
↓
ttH - hadronic
↓
Di-lepton
$Z(\to ll)H$
↓
One-lepton
$W(\to l\nu)H$
↓
E_T^{miss} significance
$Z(\to \nu\nu)H$; $W(\to l\nu)H$
↓
Low-mass two-jets
$W(\to jj)H$, $Z(\to jj)H$ → tight / loose
↓
High-mass two-jets
VBF → tight / loose
↓
4 η-p_{Tt} rest
ggF

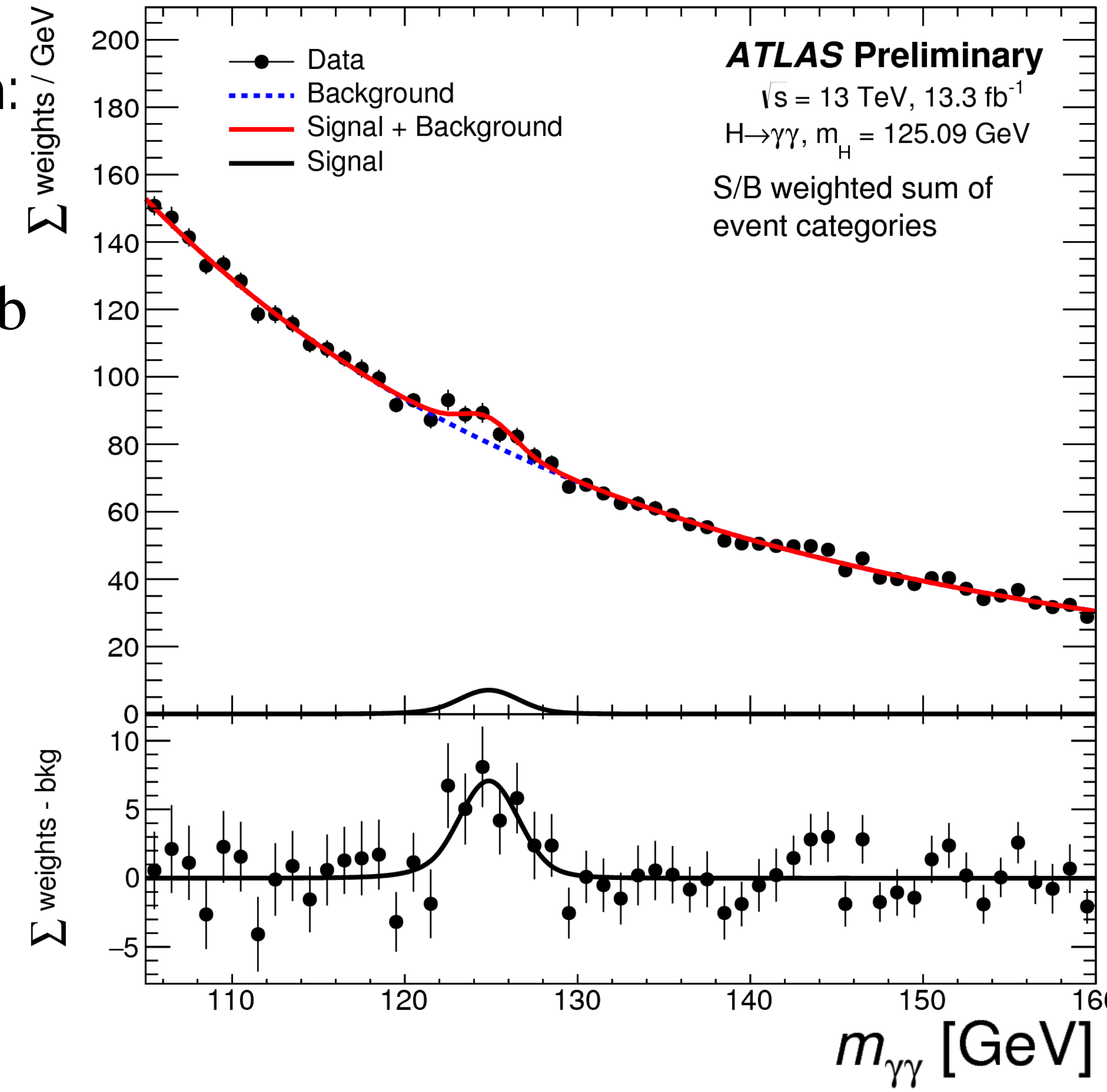
Strategy:

- Fit $m_{\gamma\gamma}$ in many production mode sensitive categories
- Measure fiducial, differential, and production cross-sections

Fiducial cross-section:

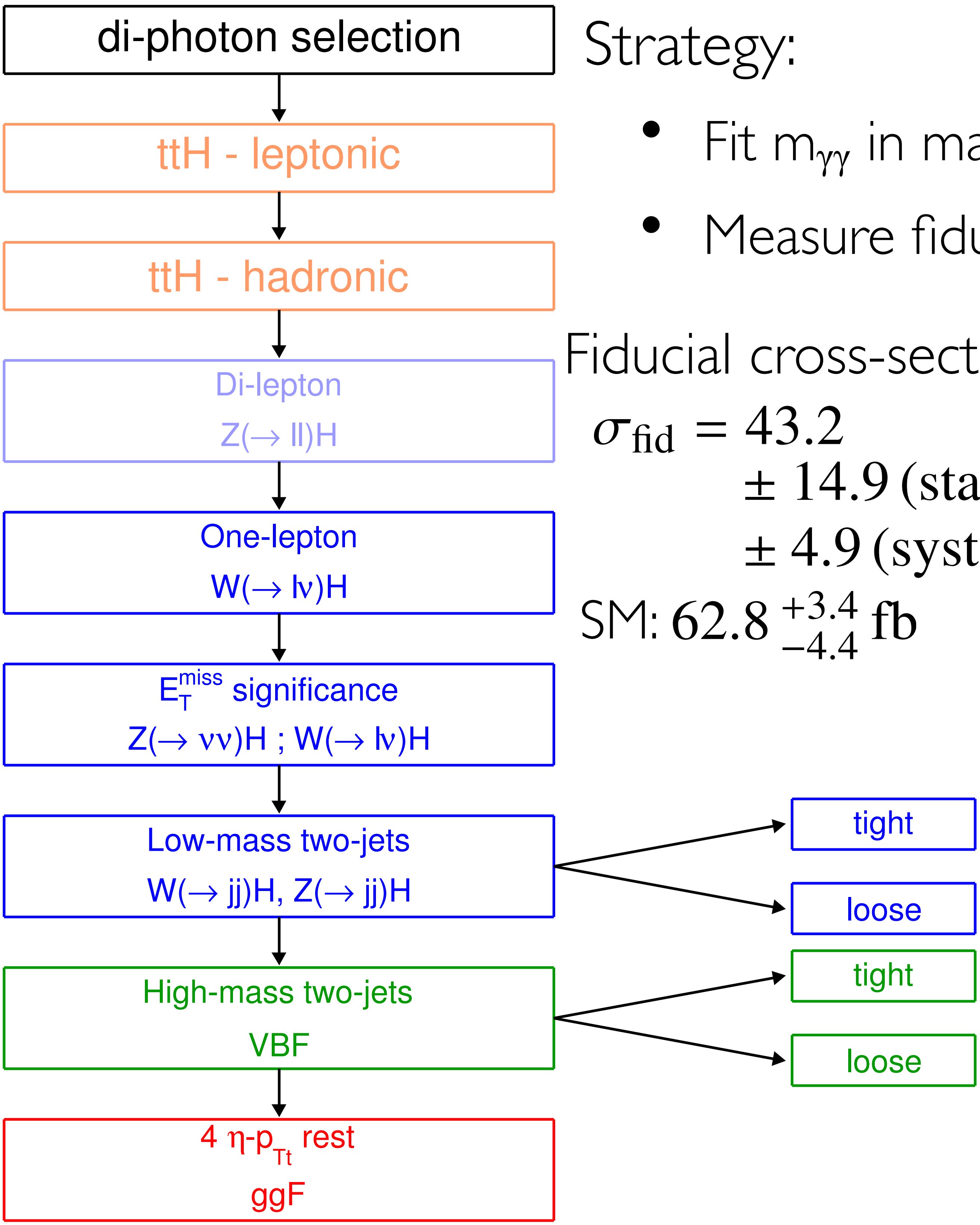
$$\sigma_{\text{fid}} = 43.2 \pm 14.9\,(\text{stat.}) \pm 4.9\,(\text{syst.})\ \text{fb}$$

SM: $62.8^{+3.4}_{-4.4}$ fb



$H \to \gamma\gamma$

ATL-CONF-2016-067



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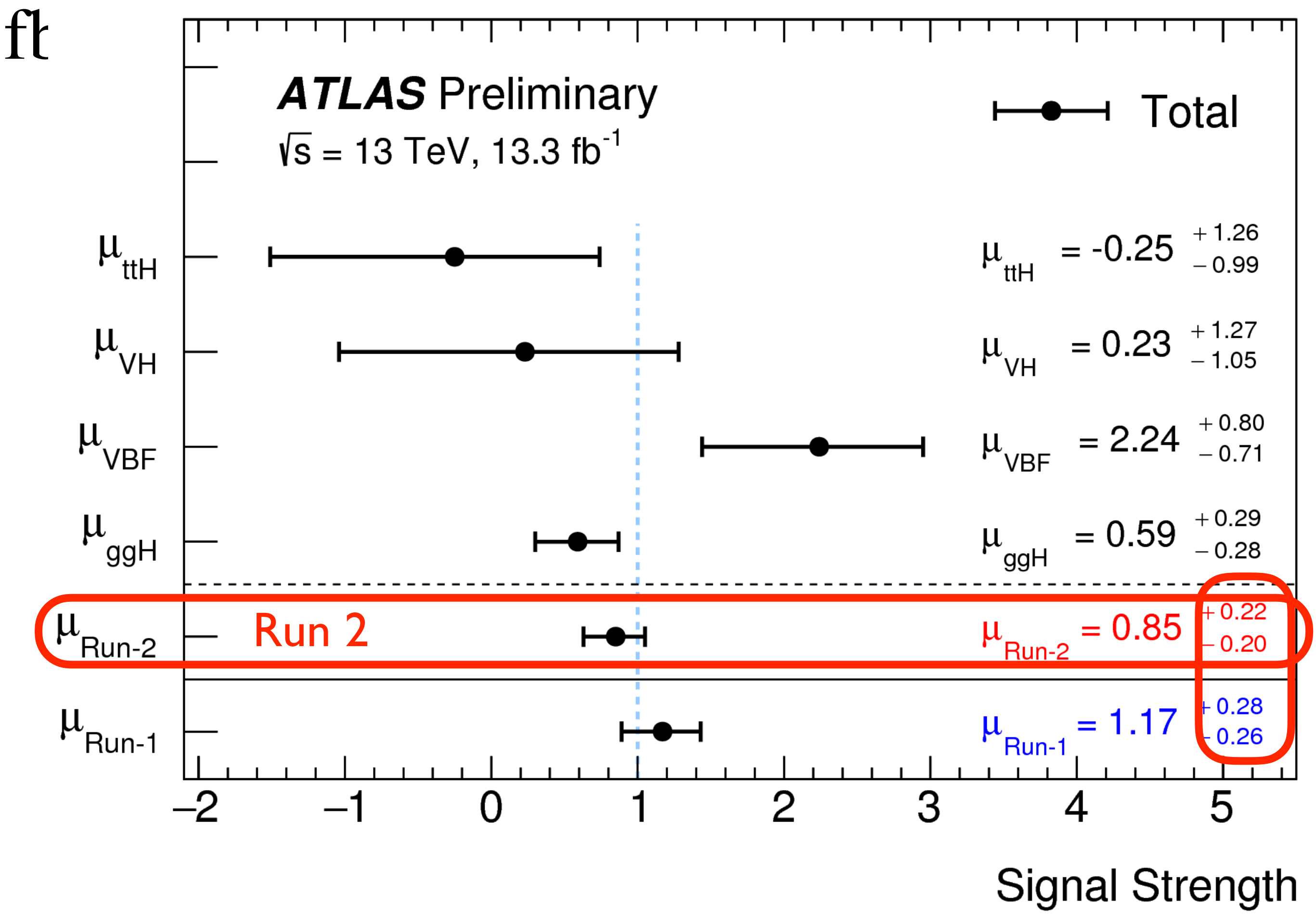


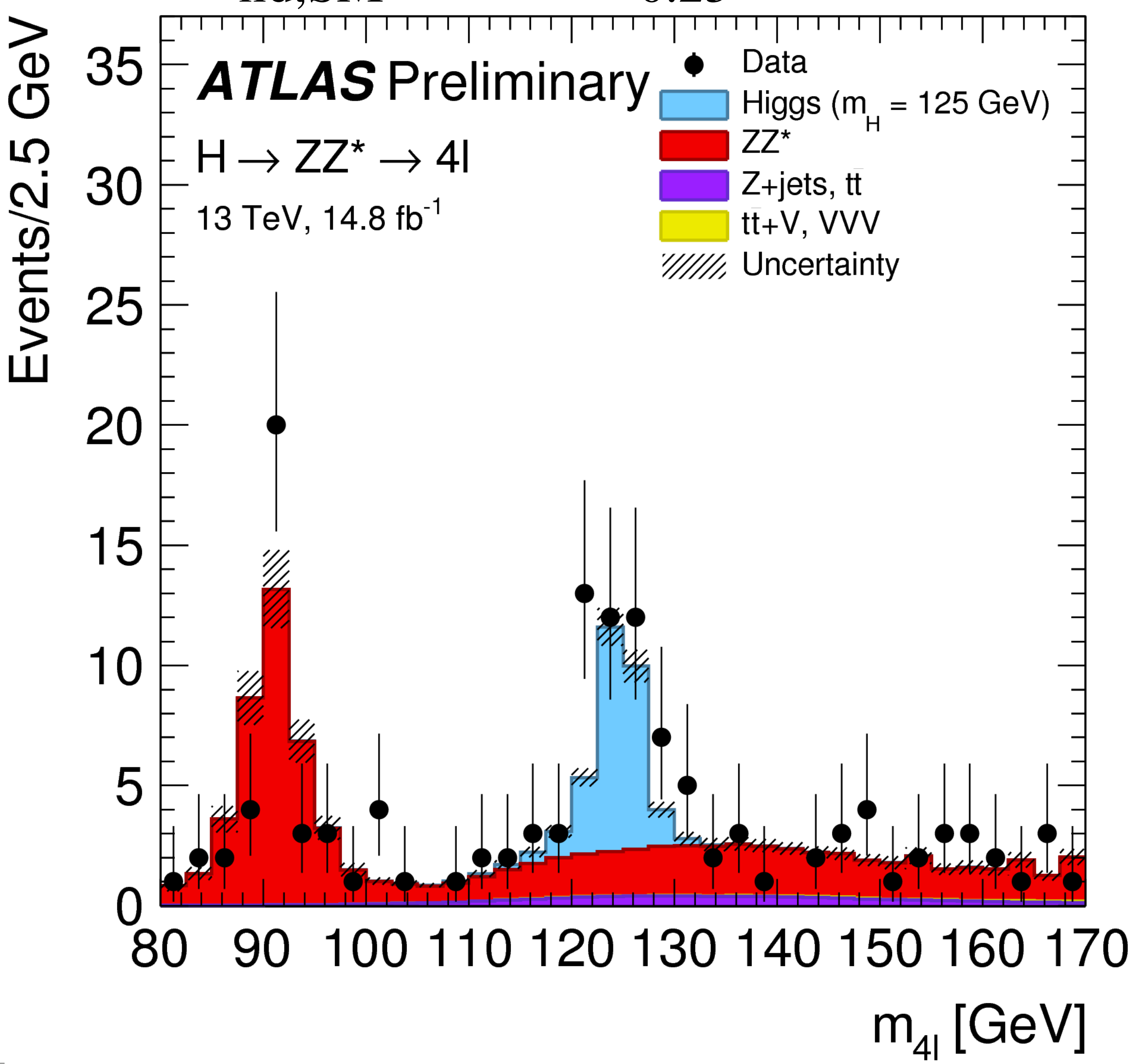
$H \rightarrow ZZ^* \rightarrow 4\ell$

ATL-CONF-2016-079

Fiducial and total x-sections:

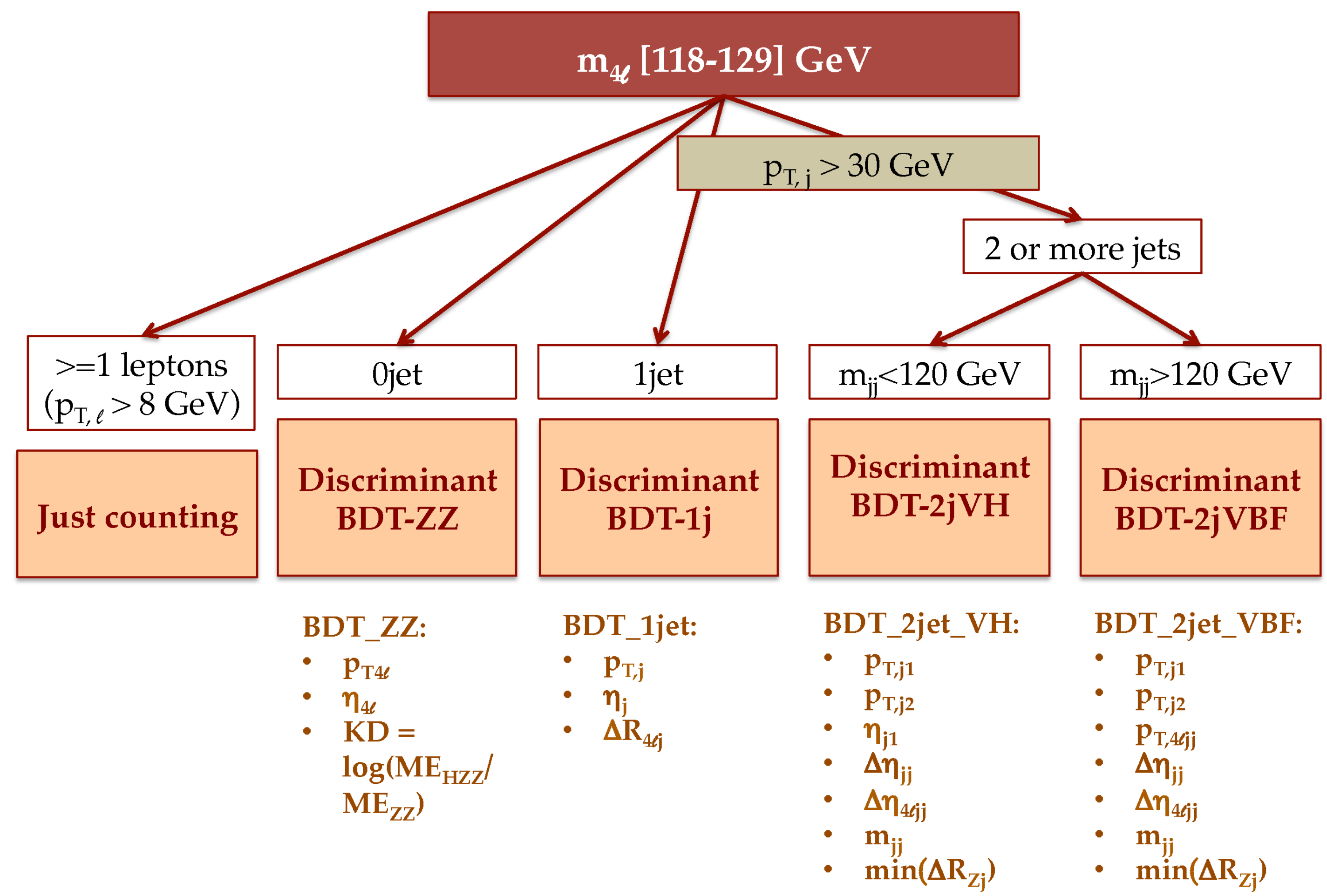
- Fit in m_{4l}
- $\sigma^{4\ell}_{\text{fid,sum}} = 4.48^{+1.01}_{-0.89}$ fb

  $\sigma^{4\ell}_{\text{fid,SM}} = 3.07^{+0.21}_{-0.25}$ fb



Production mode studies:

- Narrow m_{4l} region categorization



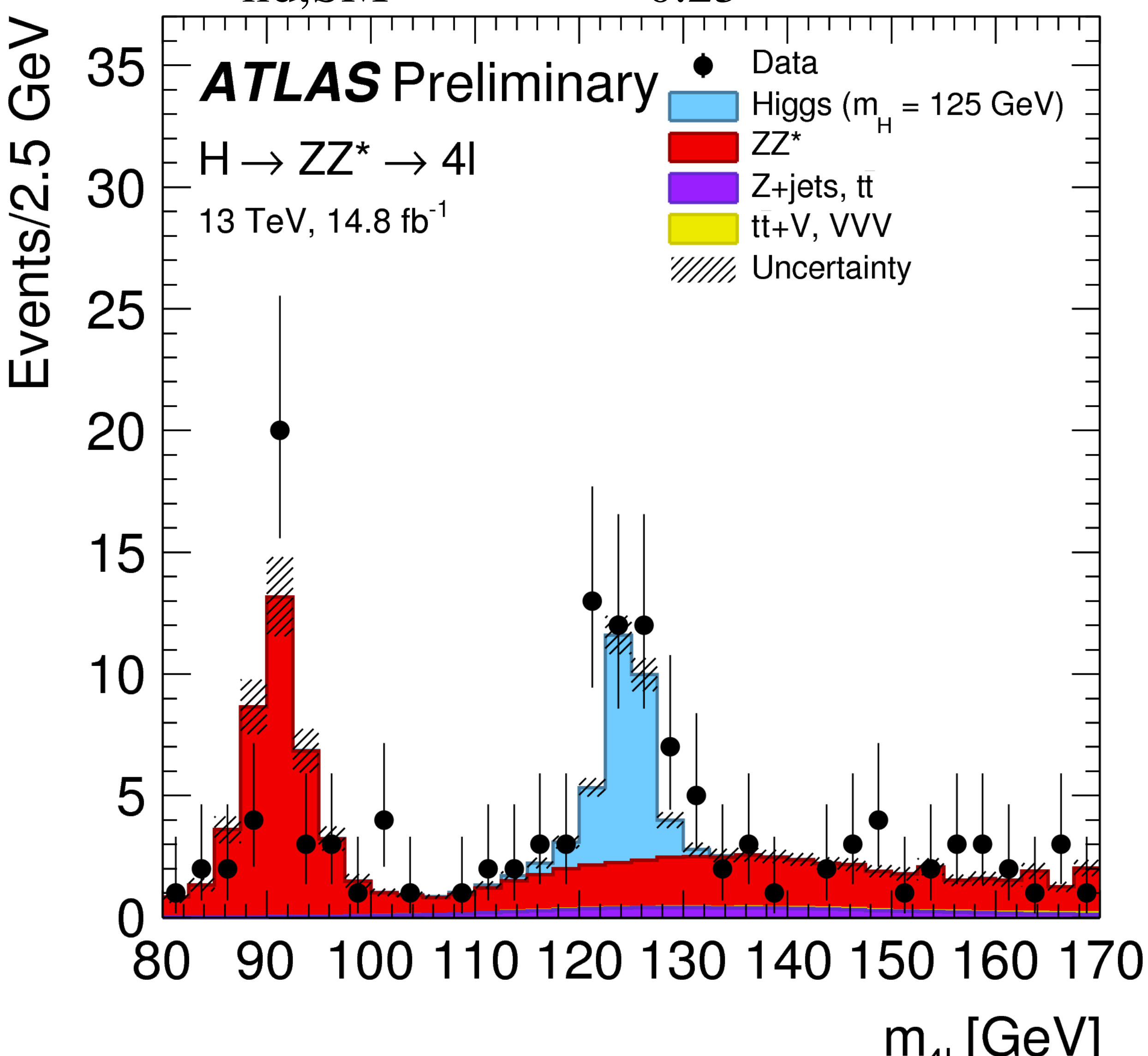
$H \rightarrow ZZ^* \rightarrow 4\ell$

ATL-CONF-2016-079

Fiducial and total x-sections:

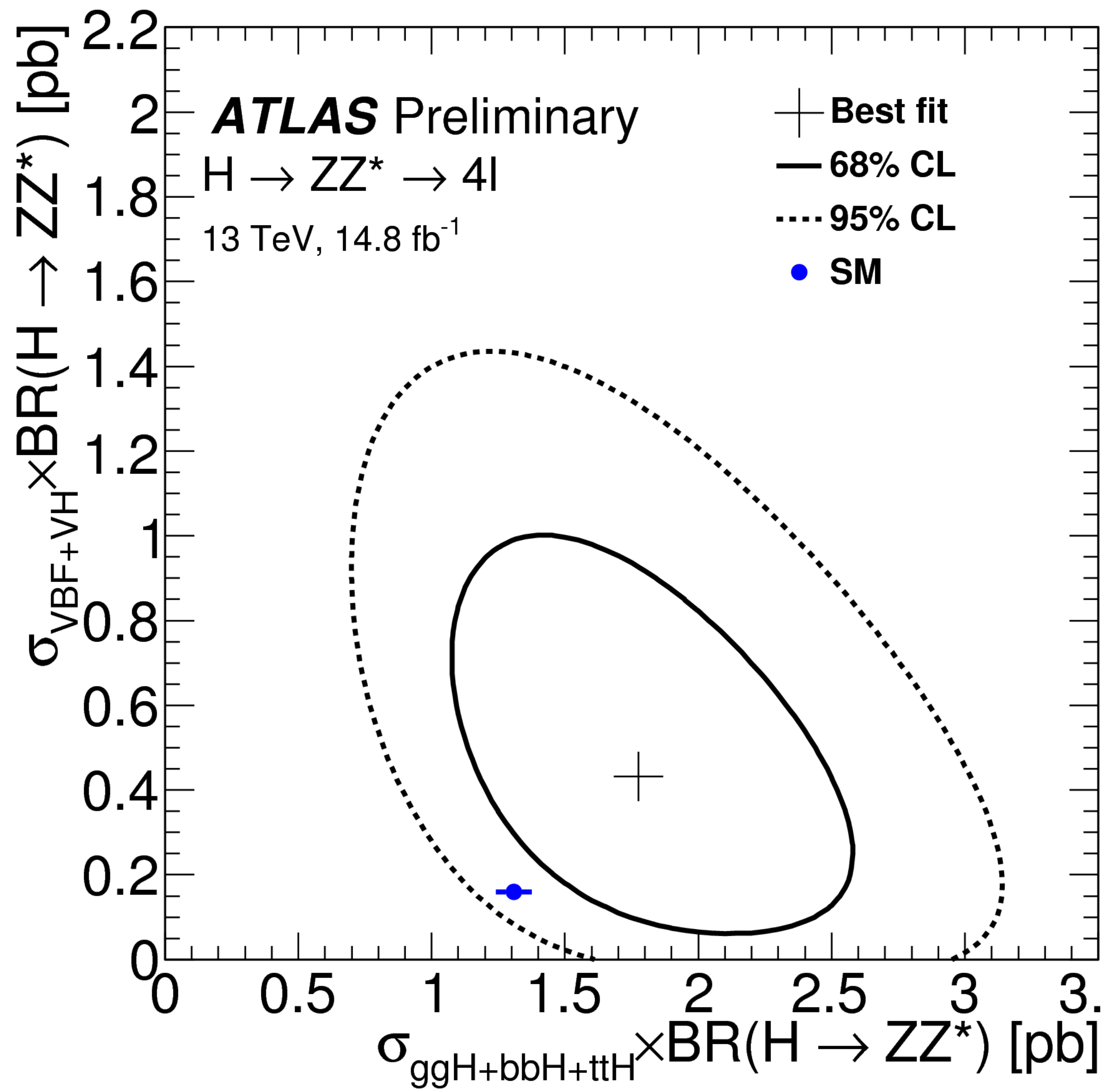
- Fit in m_{4l}
- $\sigma^{4\ell}_{\mathrm{fid,sum}} = 4.48^{+1.01}_{-0.89}$ fb

  $\sigma^{4\ell}_{\mathrm{fid,SM}} = 3.07^{+0.21}_{-0.25}$ fb



Production mode studies:

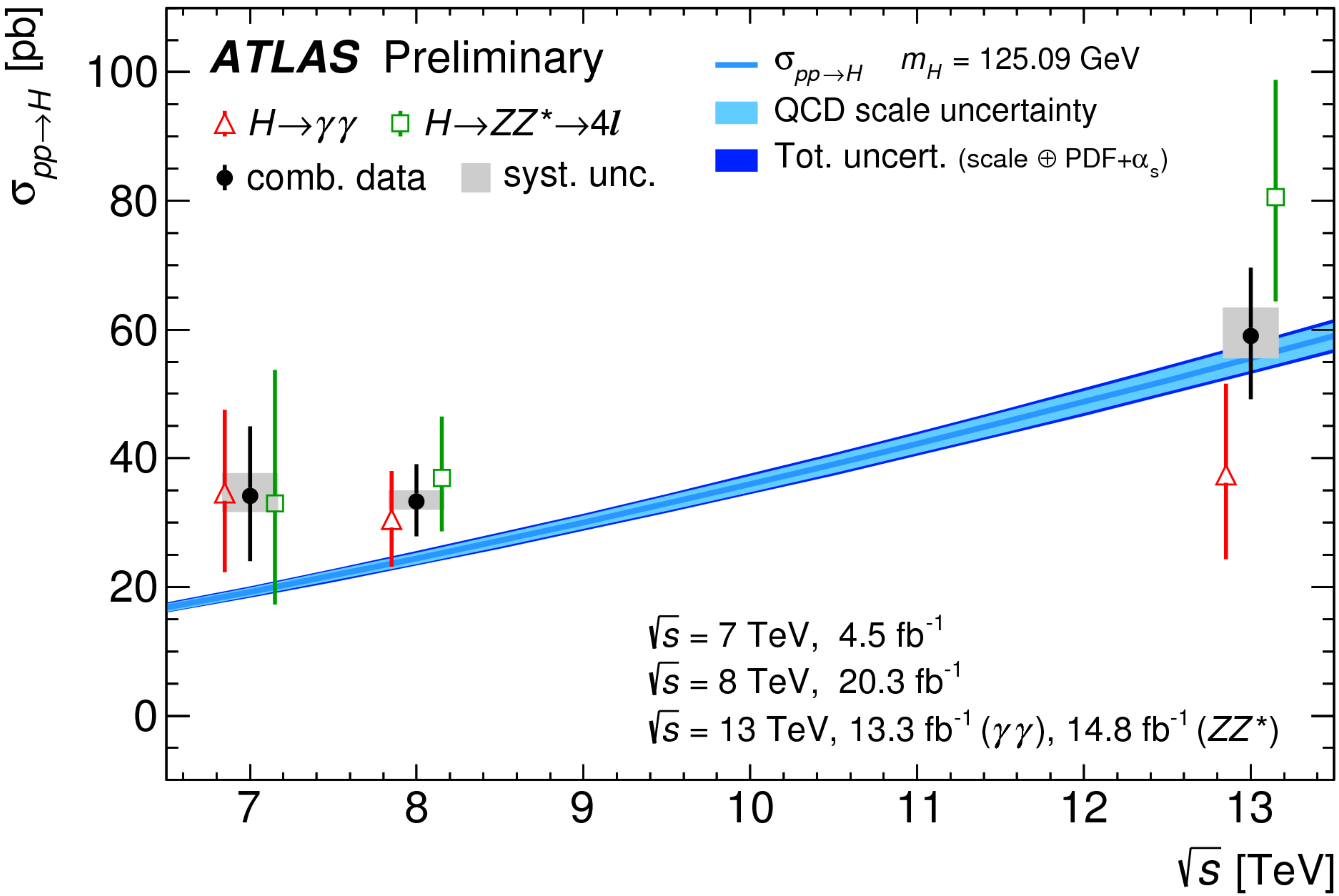
- Narrow m_{4l} region categorization



ICHEP Combination

ATL-CONF-2016-081

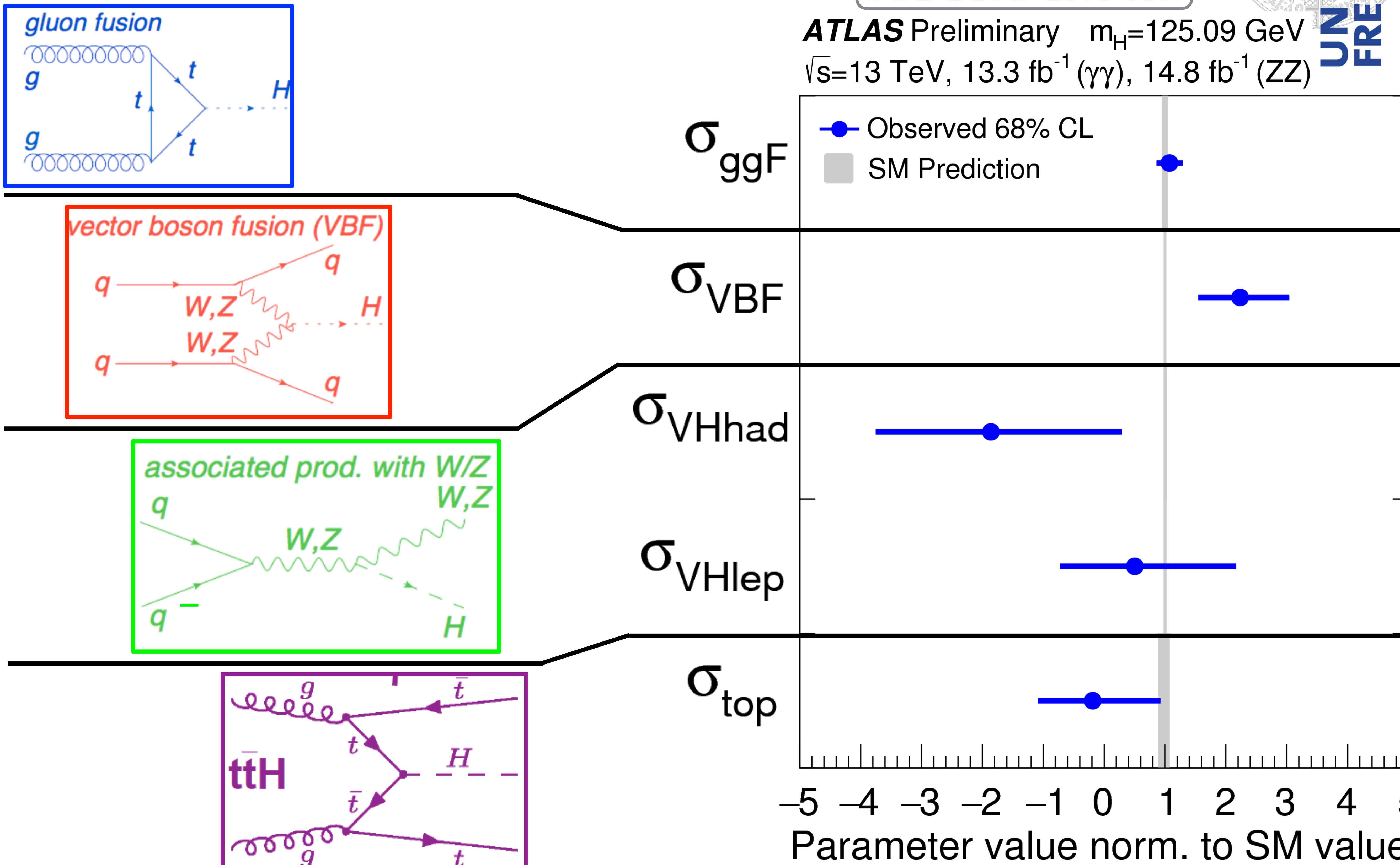
Combine $H \rightarrow \gamma\gamma$ and $H \rightarrow ZZ^* \rightarrow 4\ell$:



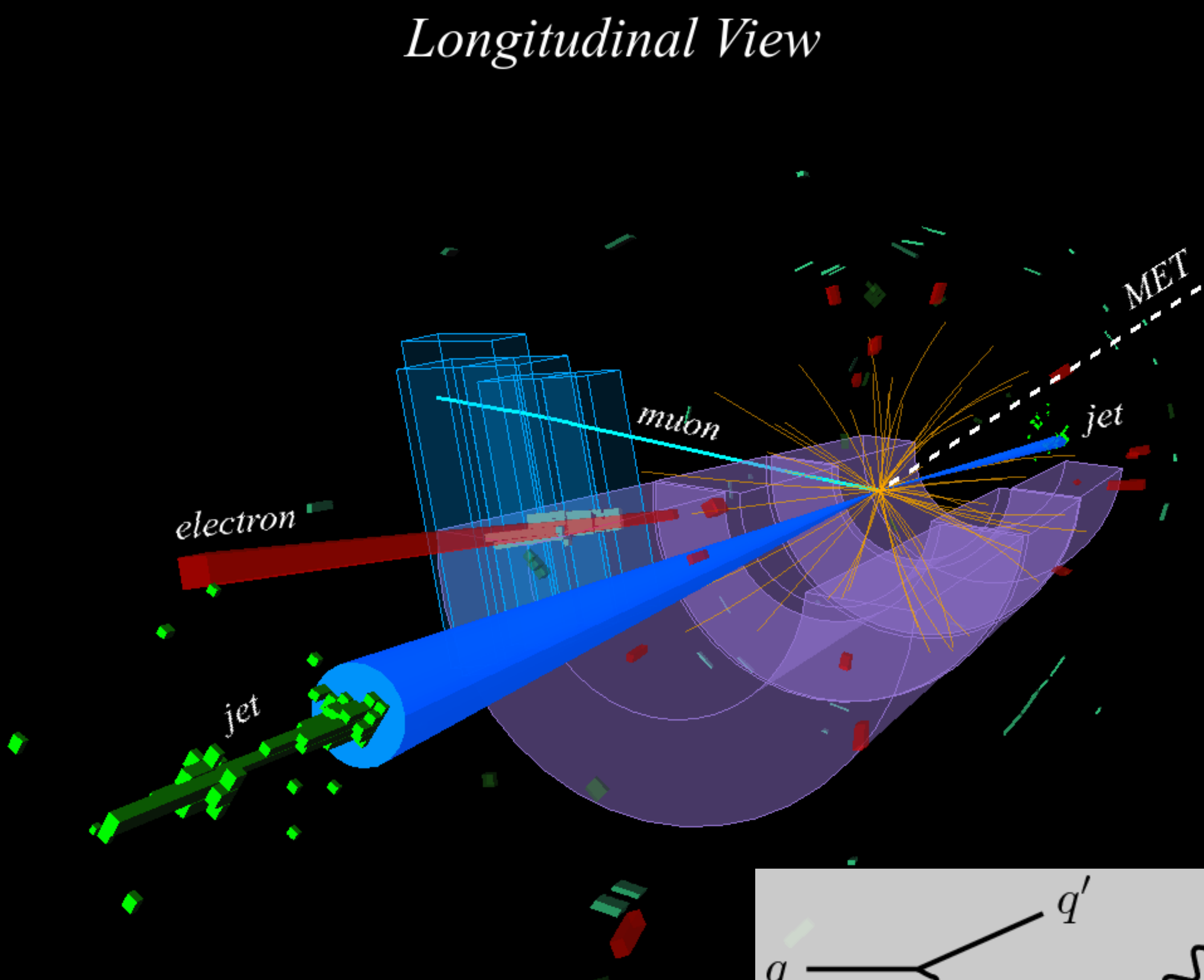
~10σ

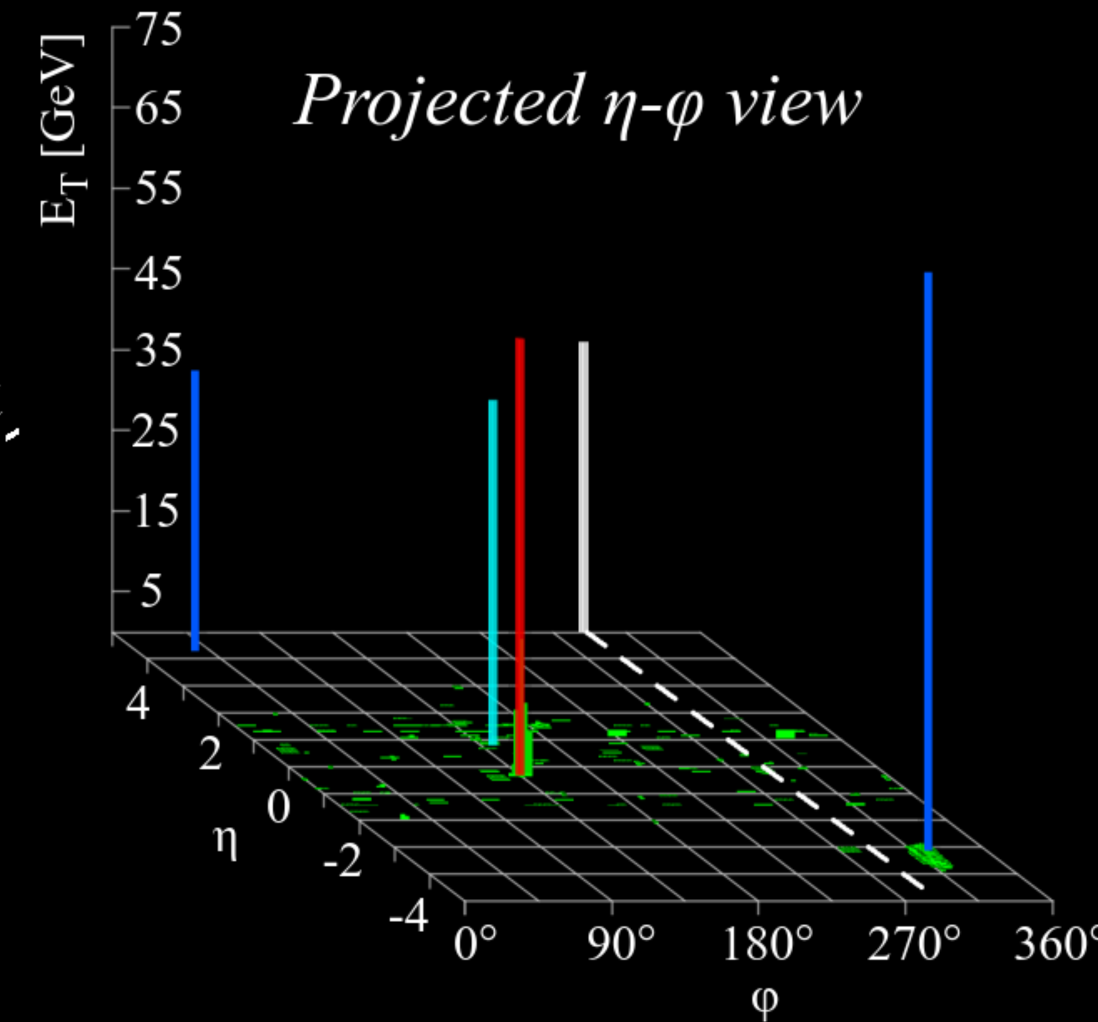
ICHEP Combination

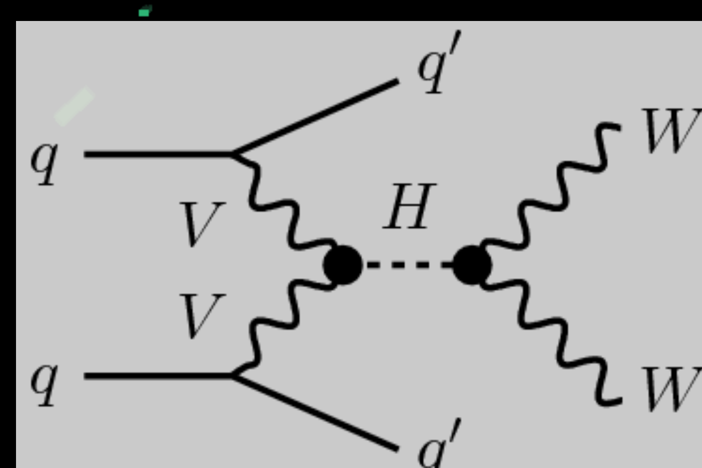
ATL-CONF-2016-081



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







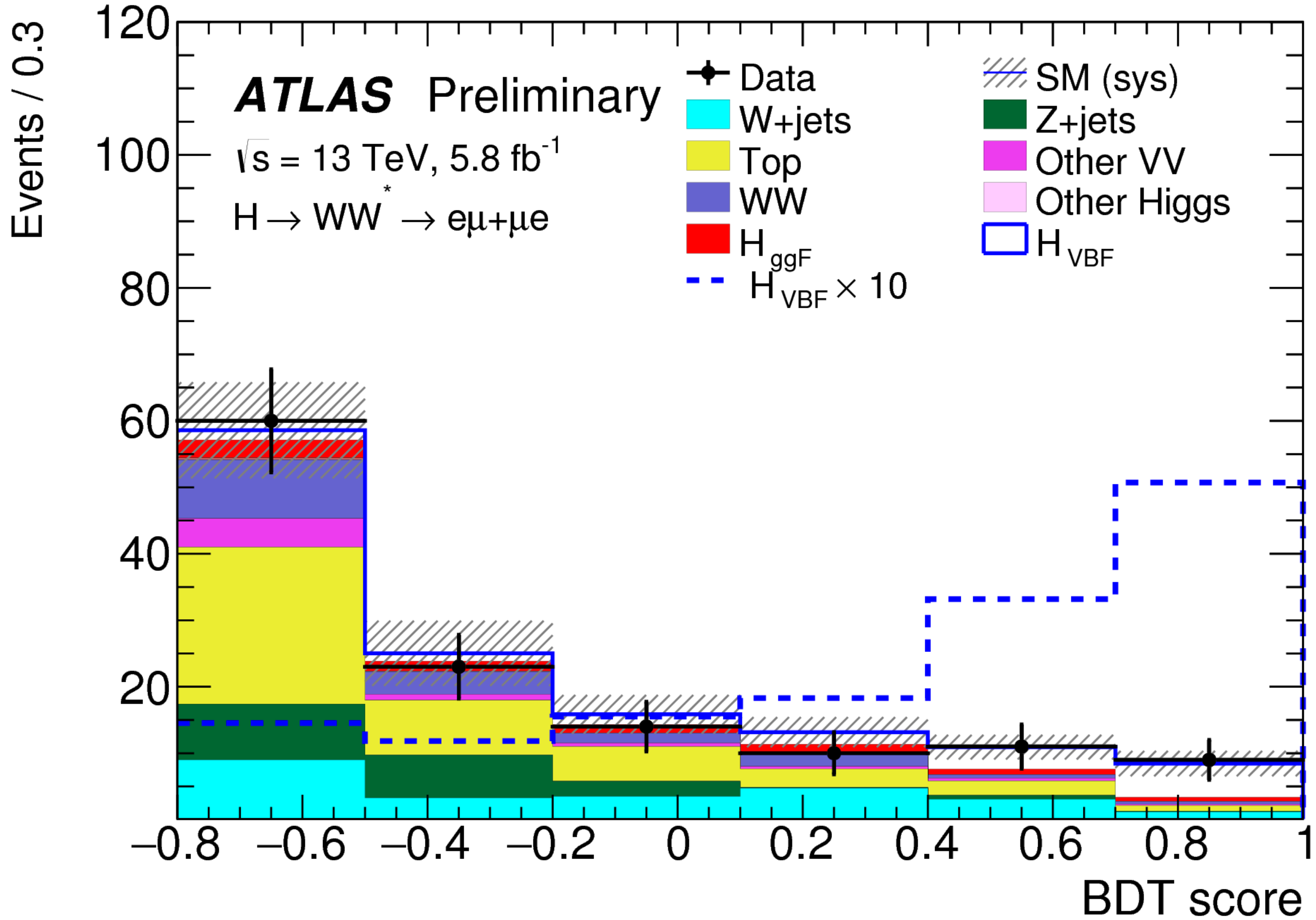
ATLAS EXPERIMENT

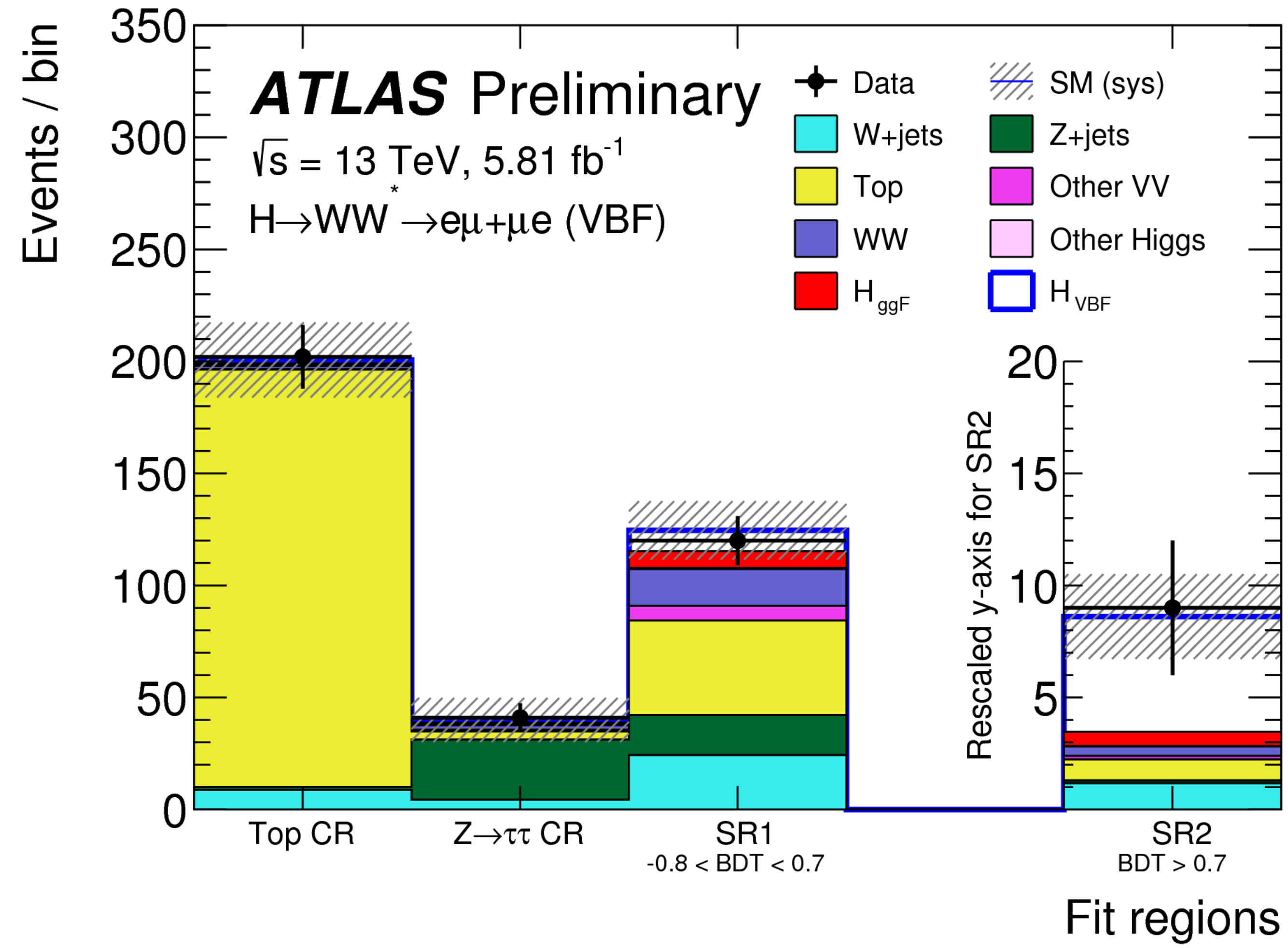
Run Number: 280673, Event Number: 2811124938
September 30, 2015, 05:55:03 CEST

VBF H → WW* → ℓνℓν

ATL-CONF-2016-112

Different-flavor BDT analysis with Top and $Z \to \tau\tau$ control regions:





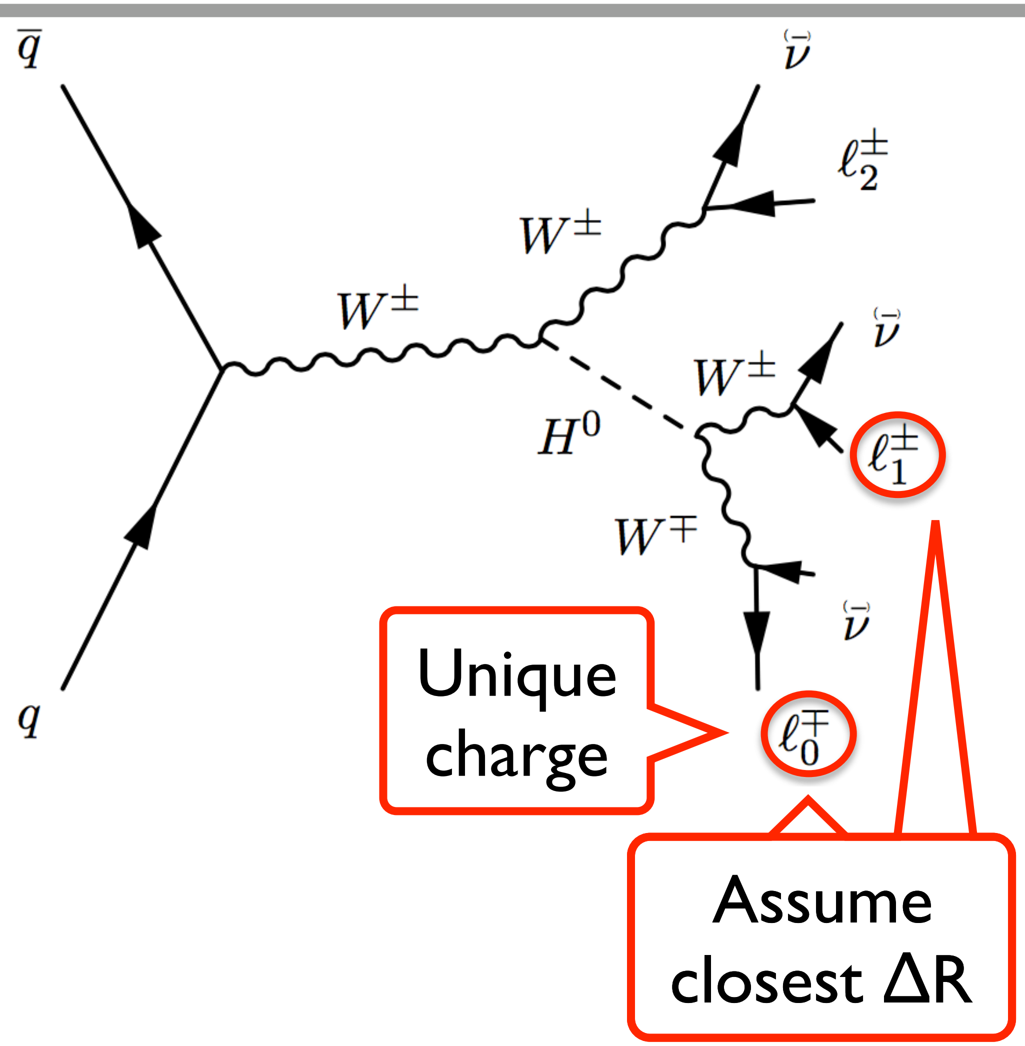
- 1.9σ (1.2σ) observed (expected)

$$\mu_{\mathrm{VBF}} = 1.7^{+1.0}_{-0.8}(\mathrm{stat})^{+0.6}_{-0.4}(\mathrm{sys})$$

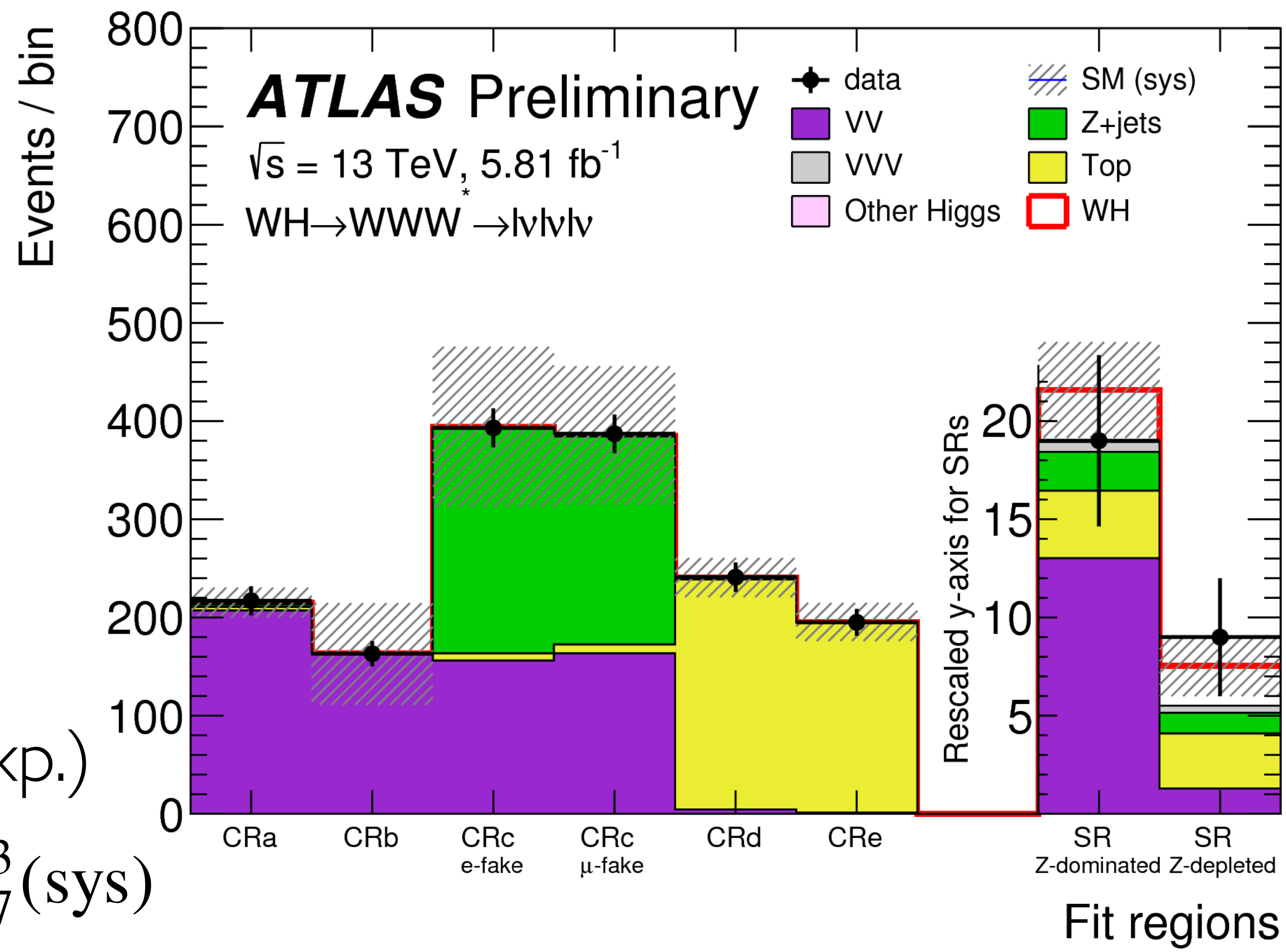
$$\sigma_{\mathrm{VBF}} \cdot \mathcal{B}_{H\to WW^*} = 1.4^{+0.8}_{-0.6}(\mathrm{stat})^{+0.5}_{-0.4}(\mathrm{sys})\ \mathrm{pb}$$

WH → WWW* → ℓνℓνℓν

ATL-CONF-2016-112



- 2 signal regions
- 6 data control regions



Results:

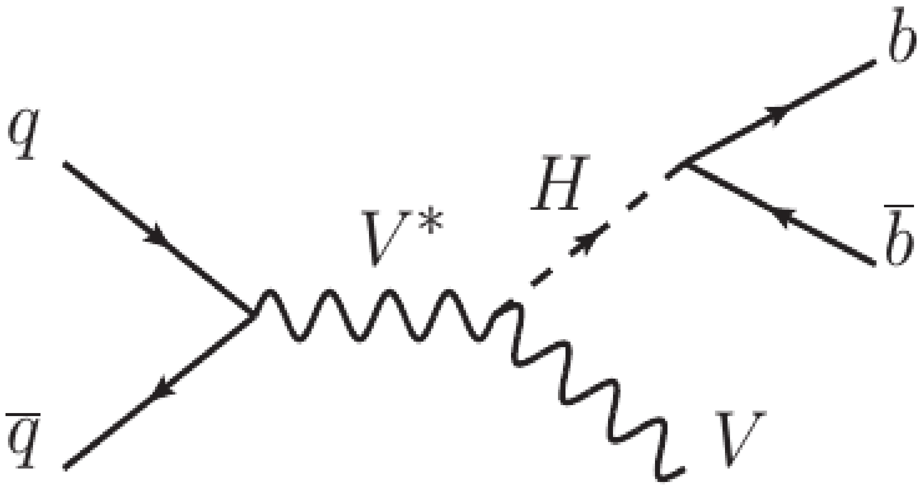
- 0.77σ (0.24σ) obs. (exp.)

$$\mu_{WH} = 3.2^{+3.7}_{-3.2}(\text{stat})^{+2.3}_{-2.7}(\text{sys})$$

$$\sigma_{WH} \cdot \mathcal{B}_{H\to WW^*} = 0.9^{+1.1}_{-0.9}(\text{stat})^{+0.7}_{-0.8}(\text{sys})\ \text{pb}$$

H → bb

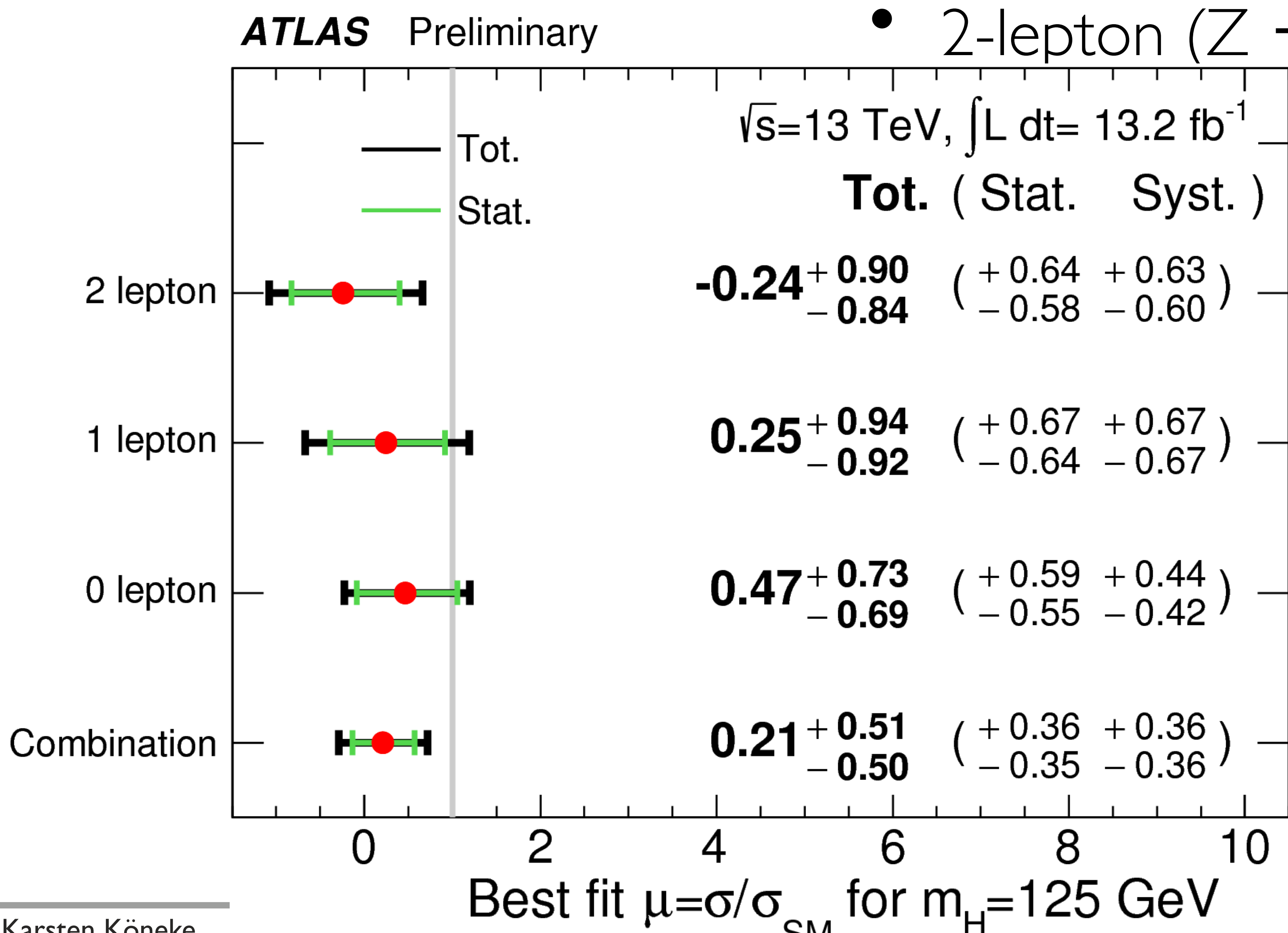
ATL-CONF-2016-091



H → bb is dominant decay (~58%)

(W/Z)H associated production:

- 0-lepton (Z → νν)
- 1-lepton (W → ℓν)
- 2-lepton (Z → ℓℓ)



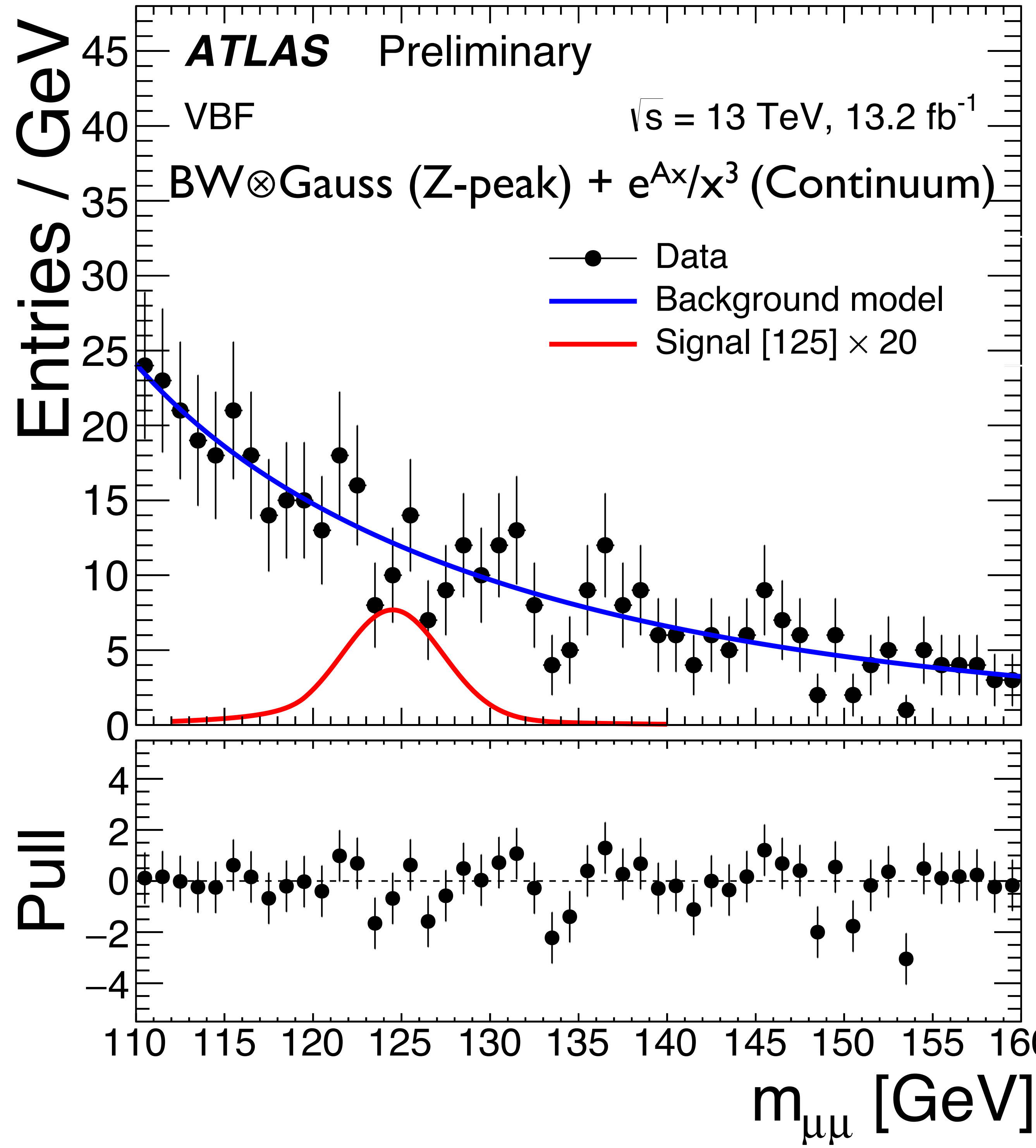
- Analysis validated with (W/Z)Z(bb): 3σ, consistent with SM
- **Results: 0.42σ (1.94σ) observed (expected)**

$H \to \mu\mu$

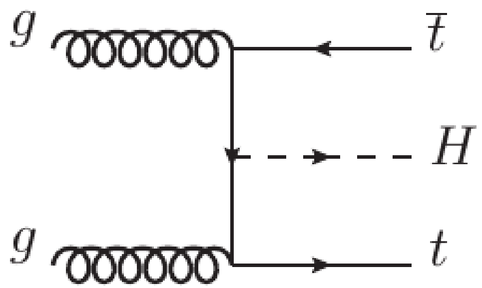
ATL-CONF-2016-041

Strategy:

- 2 opposite sign muons, MET < 80 GeV, b-veto
- VBF-enriched SR (BDT) (new in run-2)
- 6 ggF-enriched SRs:
  - 3 $p_T(\mu\mu)$ bins
  - 2 $\eta(\mu)$ bins (forward/central)



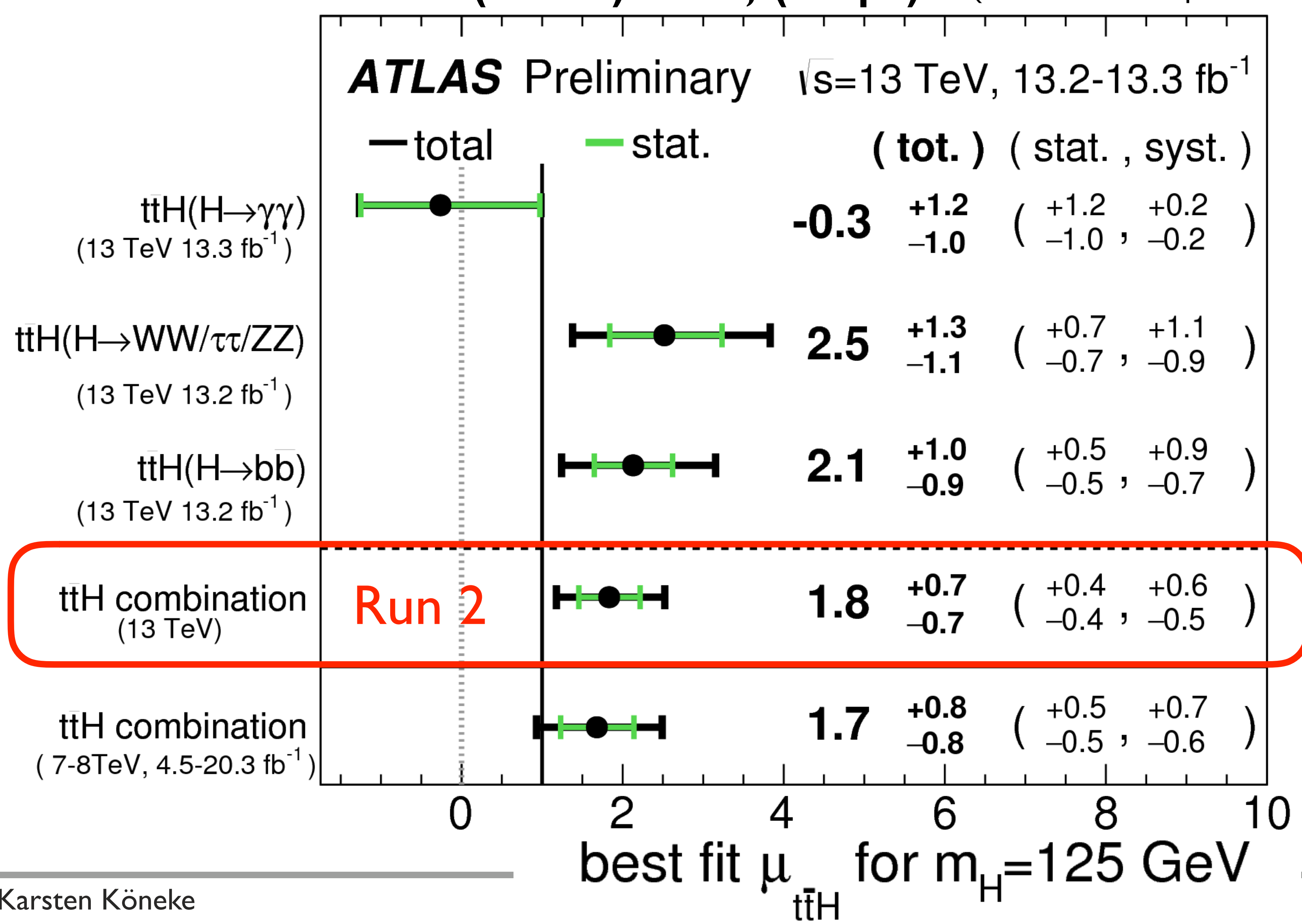
95% CL BR upper limit for m_H = 125.09 GeV
Run-1: μ < 7.1 (obs.), 7.2 (exp.)
Run-2: μ < 4.4 (obs.), 5.5 (exp.)
Combined: μ < 3.5 (obs.), 4.3 (exp.)

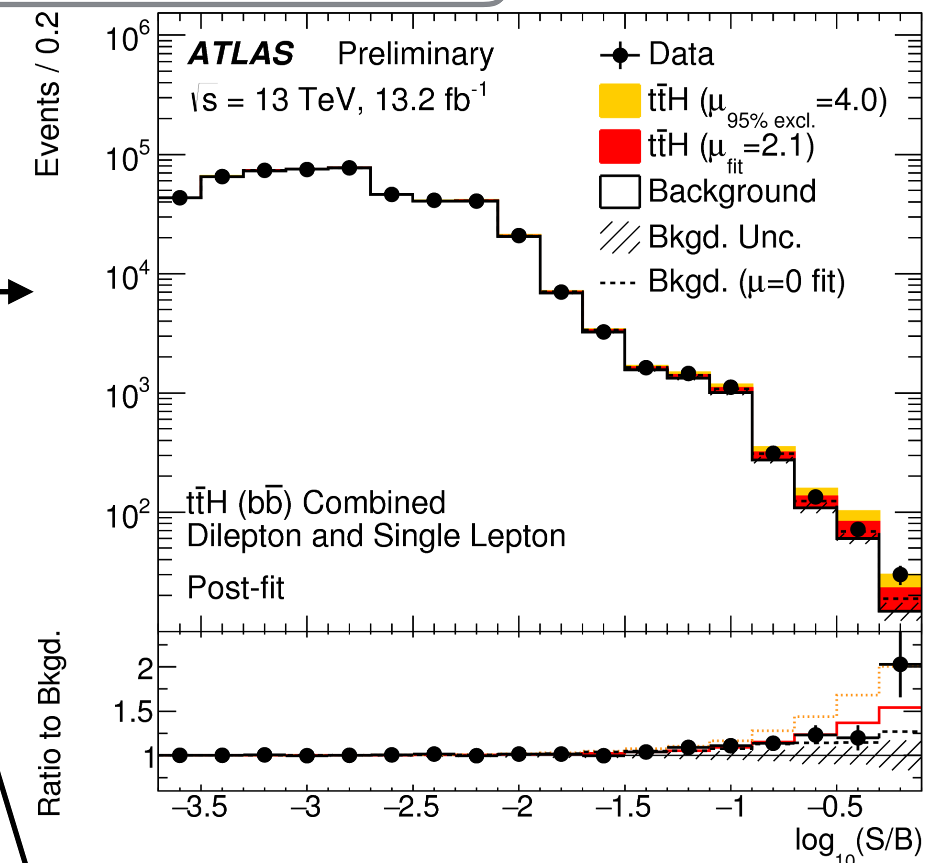


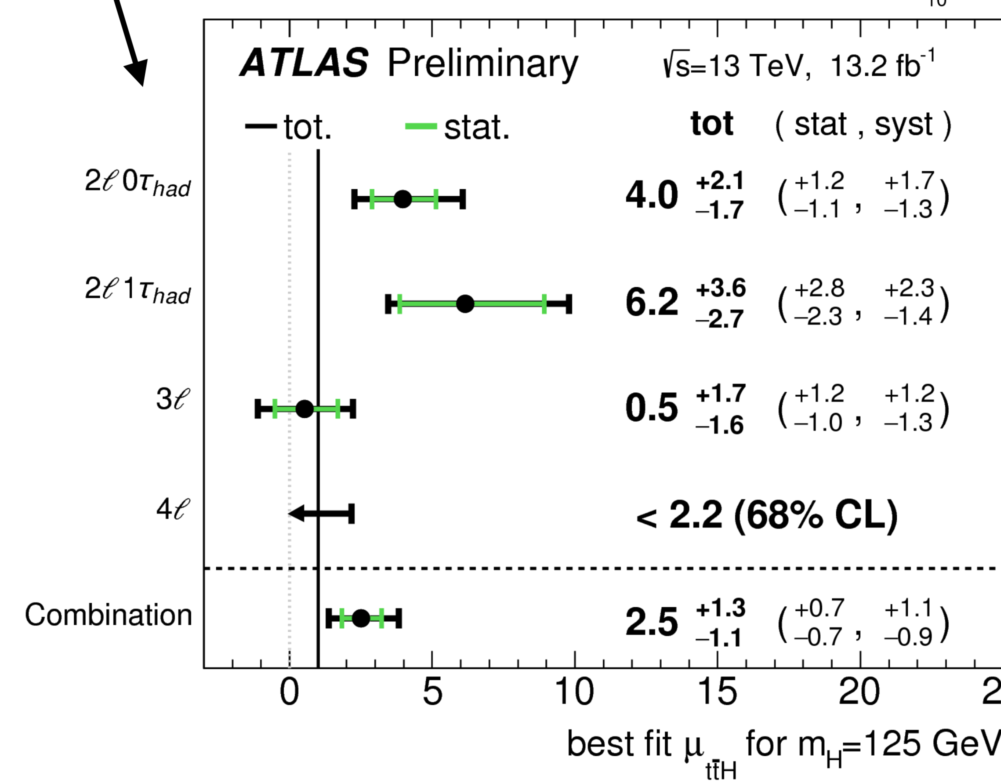
ttH

ATL-CONF-2016-068

- **Combination** of:
  - ttH(γγ): ATLAS-CONF-2016-067 (see earlier)
  - ttH(bb): ATLAS-CONF-2016-080
  - ttH multi-lepton: ATLAS-CONF-2016-058
- **Result: 2.8σ (1.8σ) obs, (exp.):** (Run 1 exp: 1.5σ)







Combination and Interpretation

So far:

- κ-framework:
  - Only considers rates
- Spin and CP measurements:
  - Only considers shapes

Want: measure full tensor structure of Higgs boson couplings

- One option: effective field theory
  - Assume no new particles below Λ < 1 TeV
  - Write down all possible interactions consistent with SM symmetries up to dimension 6

Higgs Characterization Model

arXiv:1306.6464

- Effective Lagrangian:

$$
\begin{aligned}
\mathcal{L}_0^V = \Big\{ & c_\alpha \kappa_{\rm SM}\big[\tfrac{1}{2} g_{HZZ}\, Z_\mu Z^\mu + g_{HWW}\, W_\mu^+ W^{-\mu}\big] \\
& - \frac{1}{4}\big[c_\alpha \kappa_{H\gamma\gamma} g_{H\gamma\gamma}\, A_{\mu\nu}A^{\mu\nu} + s_\alpha \kappa_{A\gamma\gamma} g_{A\gamma\gamma}\, A_{\mu\nu}\widetilde{A}^{\mu\nu}\big] \\
& - \frac{1}{2}\big[c_\alpha \kappa_{HZ\gamma} g_{HZ\gamma}\, Z_{\mu\nu}A^{\mu\nu} + s_\alpha \kappa_{AZ\gamma} g_{AZ\gamma}\, Z_{\mu\nu}\widetilde{A}^{\mu\nu}\big] \\
& - \frac{1}{4}\big[c_\alpha \kappa_{Hgg} g_{Hgg}\, G^a_{\mu\nu}G^{a,\mu\nu} + s_\alpha \kappa_{Agg} g_{Agg}\, G^a_{\mu\nu}\widetilde{G}^{a,\mu\nu}\big] \\
& - \frac{1}{4}\frac{1}{\Lambda}\big[c_\alpha \kappa_{HZZ}\, Z_{\mu\nu}Z^{\mu\nu} + s_\alpha \kappa_{AZZ}\, Z_{\mu\nu}\widetilde{Z}^{\mu\nu}\big] \\
& - \frac{1}{2}\frac{1}{\Lambda}\big[c_\alpha \kappa_{HWW}\, W^+_{\mu\nu}W^{-\mu\nu} + s_\alpha \kappa_{AWW}\, W^+_{\mu\nu}\widetilde{W}^{-\mu\nu}\big] \\
& - \frac{1}{\Lambda} c_\alpha \big[\kappa_{H\partial\gamma}\, Z_\nu \partial_\mu A^{\mu\nu} + \kappa_{H\partial Z}\, Z_\nu \partial_\mu Z^{\mu\nu} + \big(\kappa_{H\partial W}\, W_\nu^+ \partial_\mu W^{-\mu\nu} + h.c.\big)\big]\Big\} X_0
\end{aligned}
$$

SM CP-even

BSM CP-even

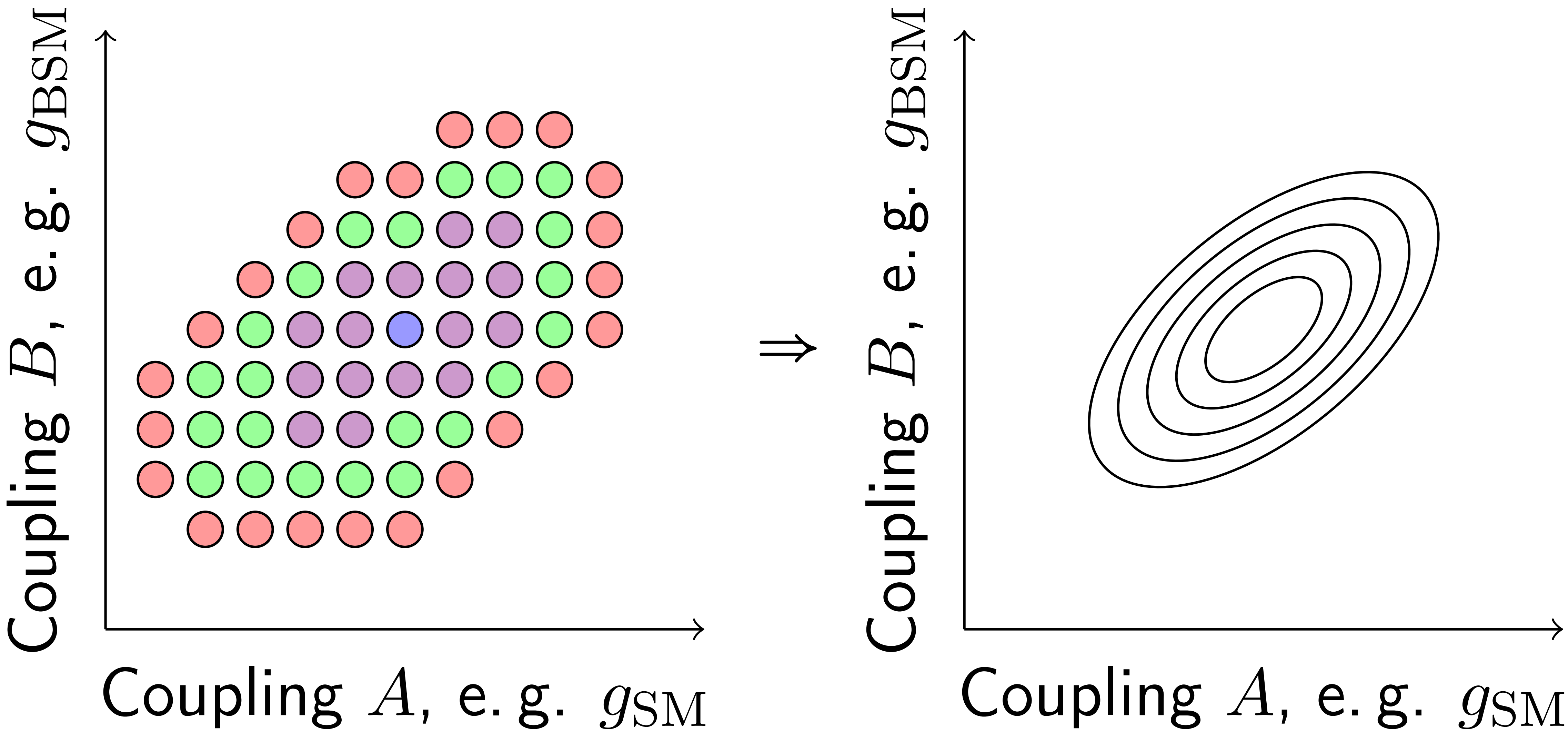
BSM CP-odd

- Fixed $\Lambda < 1$ TeV (convention), $c_\alpha = \cos(\alpha) = 1/\sqrt{2}$ (redundant)
- Implemented in MadGraph5_aMC@NLO (HC_UFO)

Morphing

ATL-PHYS-PUB-2015-047

- Measurements based on formulation of Likelihood $\mathcal{L}(x|\theta)$
- Predict observable distribution from composite model:
  - HEP model ⊗ simulation ⊗ detector response ⊗ reconstruction
- Interpolate smoothly $\mathcal{L}(x|\theta = -1, 0, 1) \longrightarrow \mathcal{L}(x|\theta)$



Template Morphing

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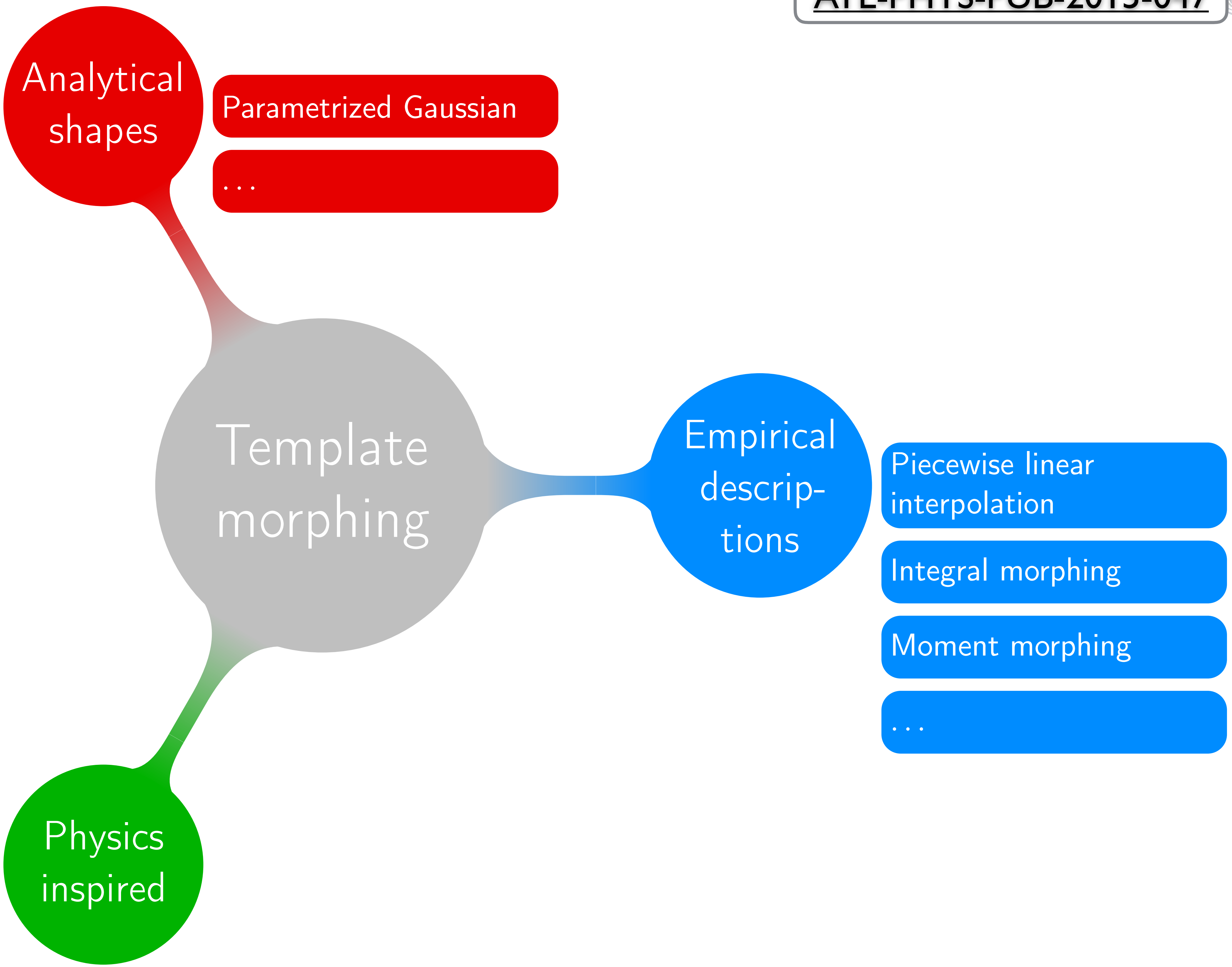


Idea of Effective Lagrangian Morphing

ATL-PHYS-PUB-2015-047

Example: g_{SM} and g_{BSM} in one vertex

- Cross section ~ |matrix element|^2:

$$\mathcal{M}(g_{\mathrm{SM}}, g_{\mathrm{BSM}}) = g_{\mathrm{SM}}\mathcal{O}_{\mathrm{SM}} + g_{\mathrm{BSM}}\mathcal{O}_{\mathrm{BSM}}$$

$$T \propto |\mathcal{M}(g_{\mathrm{SM}}, g_{\mathrm{BSM}})|^2 = g_{\mathrm{SM}}^2|\mathcal{O}_{\mathrm{SM}}|^2 + g_{\mathrm{BSM}}^2|\mathcal{O}_{\mathrm{BSM}}|^2 + 2g_{\mathrm{SM}}g_{\mathrm{BSM}}\mathcal{R}(\mathcal{O}_{\mathrm{SM}}^*\mathcal{O}_{\mathrm{BSM}})$$

Idea of Effective Lagrangian Morphing

ATL-PHYS-PUB-2015-047

Example: g_{SM} and g_{BSM} in one vertex

- Cross section ~ |matrix element|^2:

$$\mathcal{M}(g_{\mathrm{SM}}, g_{\mathrm{BSM}}) = g_{\mathrm{SM}}\mathcal{O}_{\mathrm{SM}} + g_{\mathrm{BSM}}\mathcal{O}_{\mathrm{BSM}}$$

$$T \propto |\mathcal{M}(g_{\mathrm{SM}}, g_{\mathrm{BSM}})|^2 = g_{\mathrm{SM}}^2|\mathcal{O}_{\mathrm{SM}}|^2 + g_{\mathrm{BSM}}^2|\mathcal{O}_{\mathrm{BSM}}|^2 + 2g_{\mathrm{SM}}g_{\mathrm{BSM}}\mathcal{R}(\mathcal{O}_{\mathrm{SM}}^*\mathcal{O}_{\mathrm{BSM}})$$

- With 3 unique terms, need 3 input samples $T_{i,\mathrm{in}}$:

$$T_{\mathrm{out}}(\vec{g}_{\mathrm{out}}) = \sum_{i=1}^{N_{\mathrm{in}}=3} w_i(\vec{g}_{\mathrm{out}};\vec{g}_i)\cdot T_{i,\mathrm{in}}(\vec{g}_i)$$

$\vec{g}_{\mathrm{out}}$ variable

$\vec{g}_i$ fixed

Idea of Effective Lagrangian Morphing

ATL-PHYS-PUB-2015-047

Example: g_{SM} and g_{BSM} in one vertex

- Cross section ~ |matrix element|^2:

$$\mathcal{M}(g_{\mathrm{SM}}, g_{\mathrm{BSM}}) = g_{\mathrm{SM}}\mathcal{O}_{\mathrm{SM}} + g_{\mathrm{BSM}}\mathcal{O}_{\mathrm{BSM}}$$

$$T \propto |\mathcal{M}(g_{\mathrm{SM}}, g_{\mathrm{BSM}})|^2 = g_{\mathrm{SM}}^2|\mathcal{O}_{\mathrm{SM}}|^2 + g_{\mathrm{BSM}}^2|\mathcal{O}_{\mathrm{BSM}}|^2 + 2g_{\mathrm{SM}}g_{\mathrm{BSM}}\mathcal{R}(\mathcal{O}_{\mathrm{SM}}^*\mathcal{O}_{\mathrm{BSM}})$$

- With 3 unique terms, need 3 input samples $T_{i,\mathrm{in}}$:

$$T_{\mathrm{out}}(\vec{g}_{\mathrm{out}}) = \sum_{i=1}^{N_{\mathrm{in}}=3} w_i(\vec{g}_{\mathrm{out}};\vec{g}_i)\cdot T_{i,\mathrm{in}}(\vec{g}_i)$$

$\vec{g}_{\mathrm{out}}$ variable
$\vec{g}_i$ fixed

- Ansatz: $w_i = a_{i1}\cdot g_{\mathrm{SM}}^2 + a_{i2}\cdot g_{\mathrm{SM}}g_{\mathrm{BSM}} + a_{i3}\cdot g_{\mathrm{BSM}}^2$
- Calculate a_{ij} from closure condition $w_i = \delta_{ij}$ for $\vec{g}_{\mathrm{out}} = \vec{g}_j$
- Linear system of equations, *i.e.*, matrix inversion

Example: $g_{\rm SM}$ and $g_{\rm BSM}$ in one Vertex

ATL-PHYS-PUB-2015-047

	$g_{\rm SM}$	$g_{\rm BSM}$
SM	1	0
Mix	1	1
BSM	0	1

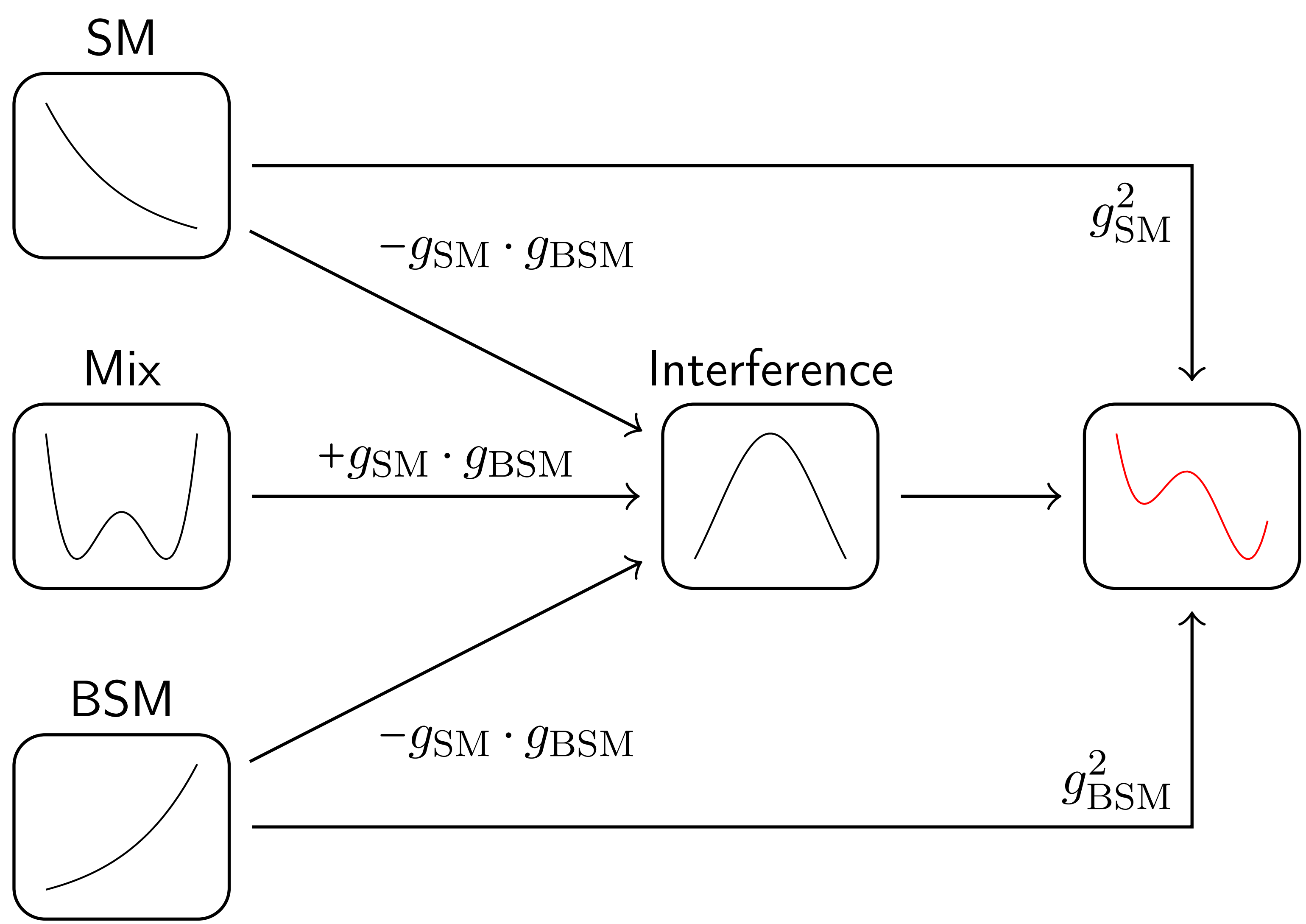
$$\xrightarrow{\text{polynomials}} \quad \begin{array}{c c} & \begin{array}{ccc} g^2_{\rm SM} & g_{\rm SM}g_{\rm BSM} & g^2_{\rm BSM} \end{array} \\ \begin{array}{c} \rm SM \\ \rm Mix \\ \rm BSM \end{array} & \begin{pmatrix} 1 & 0 & 0 \\ 1 & 1 & 1 \\ 0 & 0 & 1 \end{pmatrix} \end{array} \quad \xrightarrow{\text{inversion}} \quad \begin{array}{c c} & \begin{array}{ccc} \rm SM & \rm Mix & \rm BSM \end{array} \\ \begin{array}{c} g^2_{\rm SM} \\ g_{\rm SM}g_{\rm BSM} \\ g^2_{\rm BSM} \end{array} & \begin{pmatrix} 1 & 0 & 0 \\ -1 & 1 & -1 \\ 0 & 0 & 1 \end{pmatrix} \end{array}$$

$$T_{\rm out}(g_{\rm SM}, g_{\rm BSM}) =$$

$$+ \underbrace{(g^2_{\rm SM} - g_{\rm SM}\cdot g_{\rm BSM})}_{=w_{\rm SM}} T_{\rm SM}$$

$$+ \underbrace{g_{\rm SM}\cdot g_{\rm BSM}}_{=w_{\rm BSM}} T_{\rm Mix}$$

$$+ \underbrace{(g^2_{\rm BSM} - g_{\rm SM}\cdot g_{\rm BSM})}_{=w_{\rm BSM}} T_{\rm BSM}$$



Example: g_{SM} and g_{BSM} in one Vertex

ATL-PHYS-PUB-2015-047

	$g_{\rm SM}$	$g_{\rm BSM}$
SM	1	0
Mix	1	1
BSM	0	1

$\xRightarrow{\text{polynomials}}$

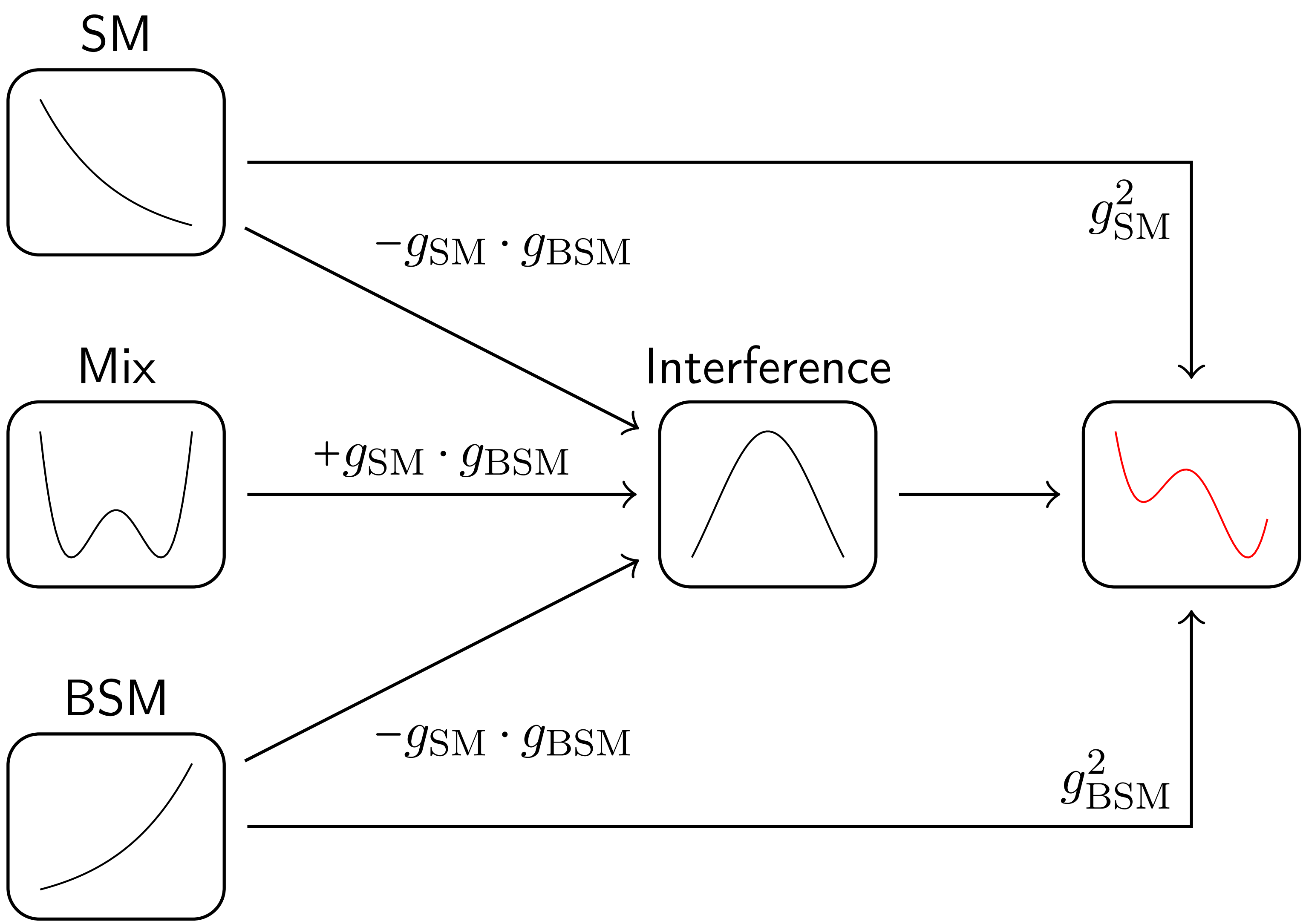
$$\begin{array}{c} \\ \mathrm{SM} \\ \mathrm{Mix} \\ \mathrm{BSM} \end{array} \begin{array}{c} \begin{array}{ccc} g_{\rm SM}^2 & g_{\rm SM}g_{\rm BSM} & g_{\rm BSM}^2 \end{array} \\ \begin{pmatrix} 1 & 0 & 0 \\ 1 & 1 & 1 \\ 0 & 0 & 1 \end{pmatrix} \end{array} \xRightarrow{\text{inversion}} \begin{array}{c} \\ g_{\rm SM}^2 \\ g_{\rm SM}g_{\rm BSM} \\ g_{\rm BSM}^2 \end{array} \begin{array}{c} \begin{array}{ccc} \mathrm{SM} & \mathrm{Mix} & \mathrm{BSM} \end{array} \\ \begin{pmatrix} {\color{red}1} & 0 & 0 \\ {\color{blue}-1} & 1 & -1 \\ 0 & 0 & 1 \end{pmatrix} \end{array}$$

$$T_{\rm out}(g_{\rm SM}, g_{\rm BSM}) =$$

$$+\underbrace{\left({\color{red}g_{\rm SM}^2} - {\color{blue}g_{\rm SM}\cdot g_{\rm BSM}}\right)}_{=w_{\rm SM}} T_{\rm SM}$$

$$+\underbrace{g_{\rm SM}\cdot g_{\rm BSM}}_{=w_{\rm BSM}} T_{\rm Mix}$$

$$+\underbrace{\left(g_{\rm BSM}^2 - g_{\rm SM}\cdot g_{\rm BSM}\right)}_{=w_{\rm BSM}} T_{\rm BSM}$$



Example: g_{SM} and g_{BSM} in one Vertex

ATL-PHYS-PUB-2015-047

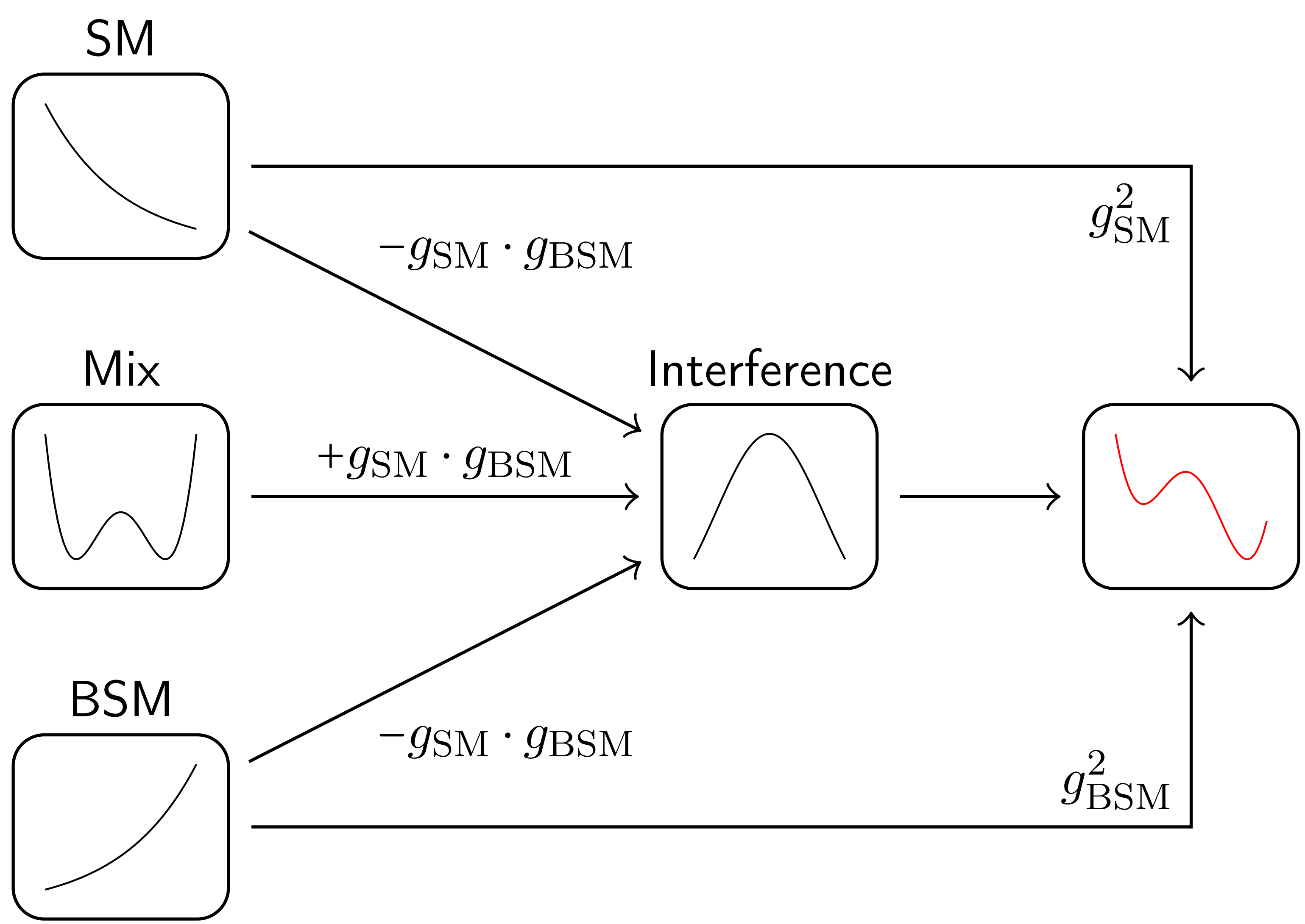
$$
\begin{array}{l|cc}
 & g_{\mathrm{SM}} & g_{\mathrm{BSM}} \\
\hline
\mathrm{SM} & 1 & 0 \\
\mathrm{Mix} & 1 & 1 \\
\mathrm{BSM} & 0 & 1
\end{array}
\xRightarrow{\text{polynomials}}
\begin{array}{c}
 \\ \mathrm{SM} \\ \mathrm{Mix} \\ \mathrm{BSM}
\end{array}
\begin{array}{c}
\begin{array}{ccc} g_{\mathrm{SM}}^2 & g_{\mathrm{SM}}g_{\mathrm{BSM}} & g_{\mathrm{BSM}}^2 \end{array} \\
\begin{pmatrix} 1 & 0 & 0 \\ 1 & 1 & 1 \\ 0 & 0 & 1 \end{pmatrix}
\end{array}
\xRightarrow{\text{inversion}}
\begin{array}{c}
 \\ g_{\mathrm{SM}}^2 \\ g_{\mathrm{SM}}g_{\mathrm{BSM}} \\ g_{\mathrm{BSM}}^2
\end{array}
\begin{array}{c}
\begin{array}{ccc} \mathrm{SM} & \mathrm{Mix} & \mathrm{BSM} \end{array} \\
\begin{pmatrix} 1 & 0 & 0 \\ -1 & 1 & -1 \\ 0 & 0 & 1 \end{pmatrix}
\end{array}
$$

$$T_{\mathrm{out}}(g_{\mathrm{SM}}, g_{\mathrm{BSM}}) =$$

$$+ \underbrace{\left(g_{\mathrm{SM}}^2 - g_{\mathrm{SM}} \cdot g_{\mathrm{BSM}}\right)}_{=w_{\mathrm{SM}}} T_{\mathrm{SM}}$$

$$+ \underbrace{g_{\mathrm{SM}} \cdot g_{\mathrm{BSM}}}_{=w_{\mathrm{BSM}}} T_{\mathrm{Mix}}$$

$$+ \underbrace{\left(g_{\mathrm{BSM}}^2 - g_{\mathrm{SM}} \cdot g_{\mathrm{BSM}}\right)}_{=w_{\mathrm{BSM}}} T_{\mathrm{BSM}}$$



Example: g_{SM} and g_{BSM} in one Vertex

ATL-PHYS-PUB-2015-047

	$g_{\rm SM}$	$g_{\rm BSM}$
SM	1	0
Mix	1	1
BSM	0	1

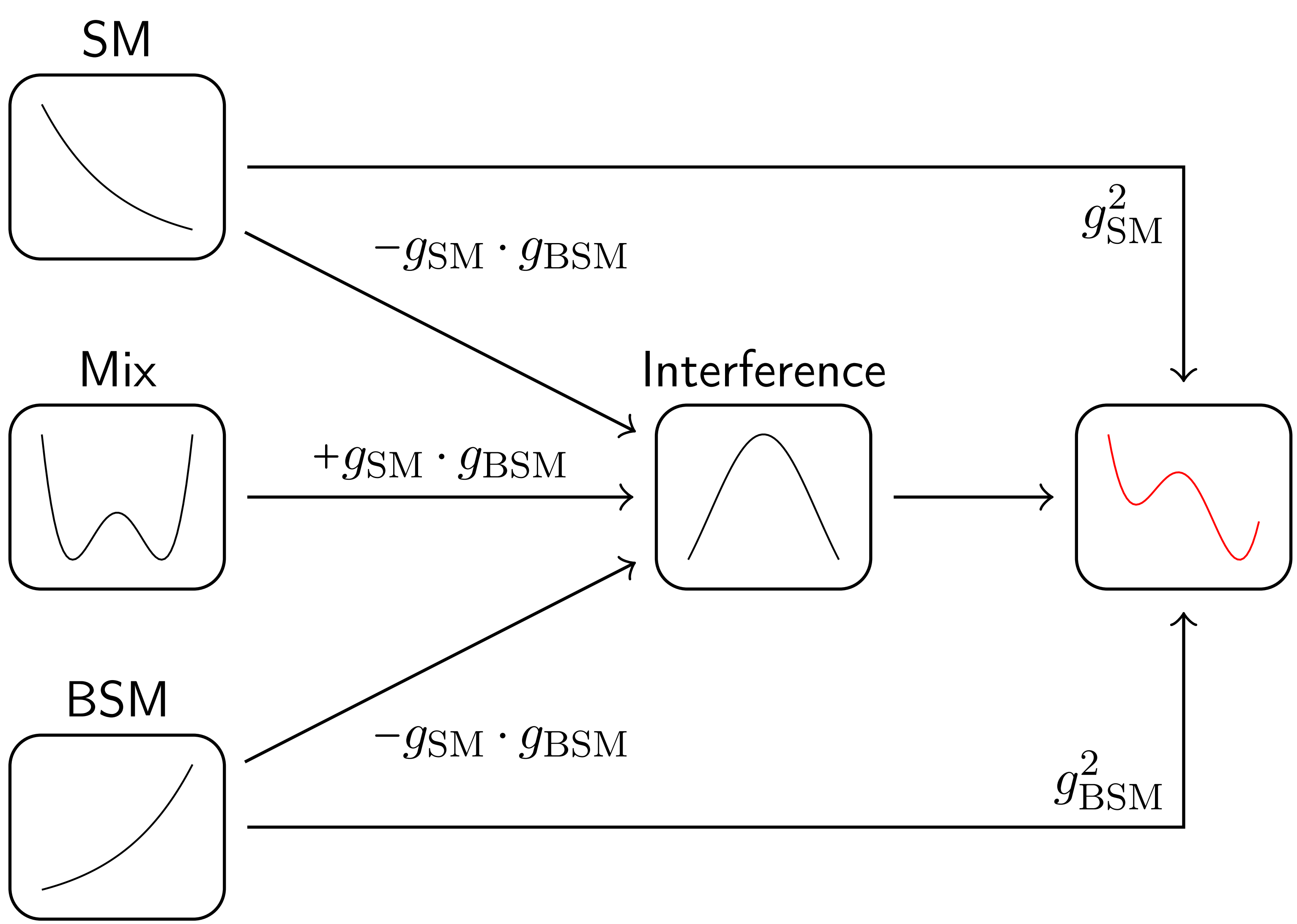
$$\xRightarrow{\text{polynomials}}\quad \begin{array}{c|ccc} & g_{\rm SM}^2 & g_{\rm SM}g_{\rm BSM} & g_{\rm BSM}^2 \\ \hline \text{SM} & & & \\ \text{Mix} & & \left(\begin{matrix} 1 & 0 & 0 \\ 1 & 1 & 1 \\ 0 & 0 & 1 \end{matrix}\right) & \\ \text{BSM} & & & \end{array} \quad \xRightarrow{\text{inversion}}\quad \begin{array}{c|ccc} & \text{SM} & \text{Mix} & \text{BSM} \\ \hline g_{\rm SM}^2 & & & \\ g_{\rm SM}g_{\rm BSM} & & \left(\begin{matrix} 1 & 0 & 0 \\ -1 & 1 & \color{blue}{-1} \\ 0 & 0 & \color{red}{1} \end{matrix}\right) & \\ g_{\rm BSM}^2 & & & \end{array}$$

$$T_{\rm out}(g_{\rm SM}, g_{\rm BSM}) =$$

$$+\underbrace{(g_{\rm SM}^2 - g_{\rm SM}\cdot g_{\rm BSM})}_{=w_{\rm SM}}\,T_{\rm SM}$$

$$+\underbrace{g_{\rm SM}\cdot g_{\rm BSM}}_{=w_{\rm BSM}}\,T_{\rm Mix}$$

$$+\underbrace{(\color{red}{g_{\rm BSM}^2} - \color{blue}{g_{\rm SM}\cdot g_{\rm BSM}})}_{=w_{\rm BSM}}\,T_{\rm BSM}$$



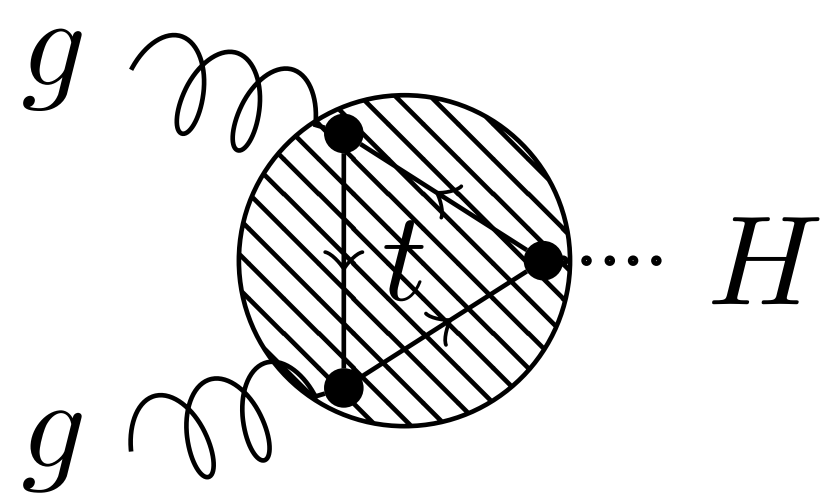
Applicability

ATL-PHYS-PUB-2015-047

- Applicable whenever matrix element factorizes:

$$|\mathcal{M}(\vec{g})|^2 = \underbrace{\left(\sum_{x\in p,s} g_\alpha \mathcal{O}(g_\alpha)\right)^2}_{\text{production}} \cdot \underbrace{\left(\sum_{x\in d,s} g_\alpha \mathcal{O}(g_\alpha)\right)^2}_{\text{decay}}$$

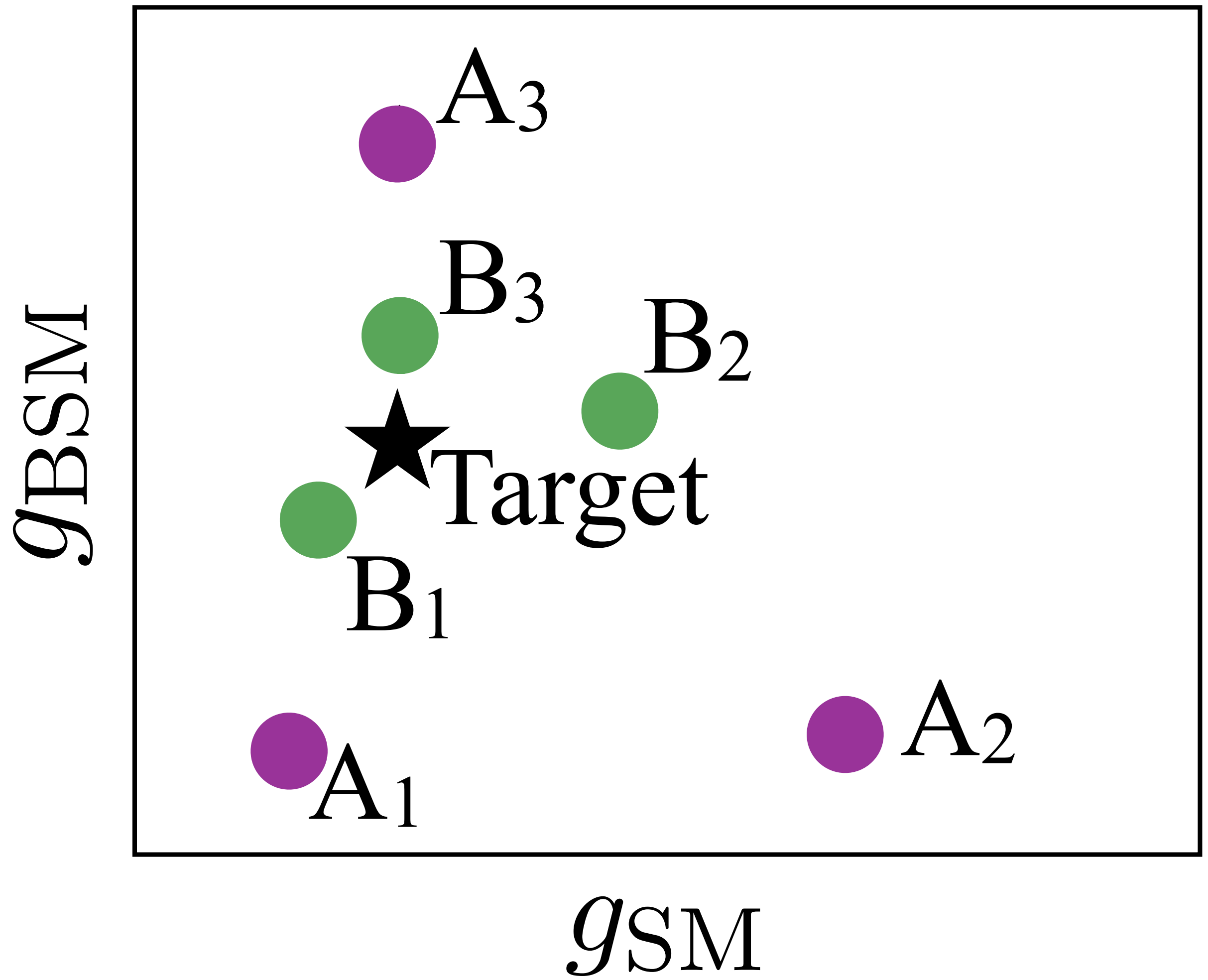
- *Example*:
  - BSM coupling parameter in interaction of Higgs boson to SM particles (EFT)

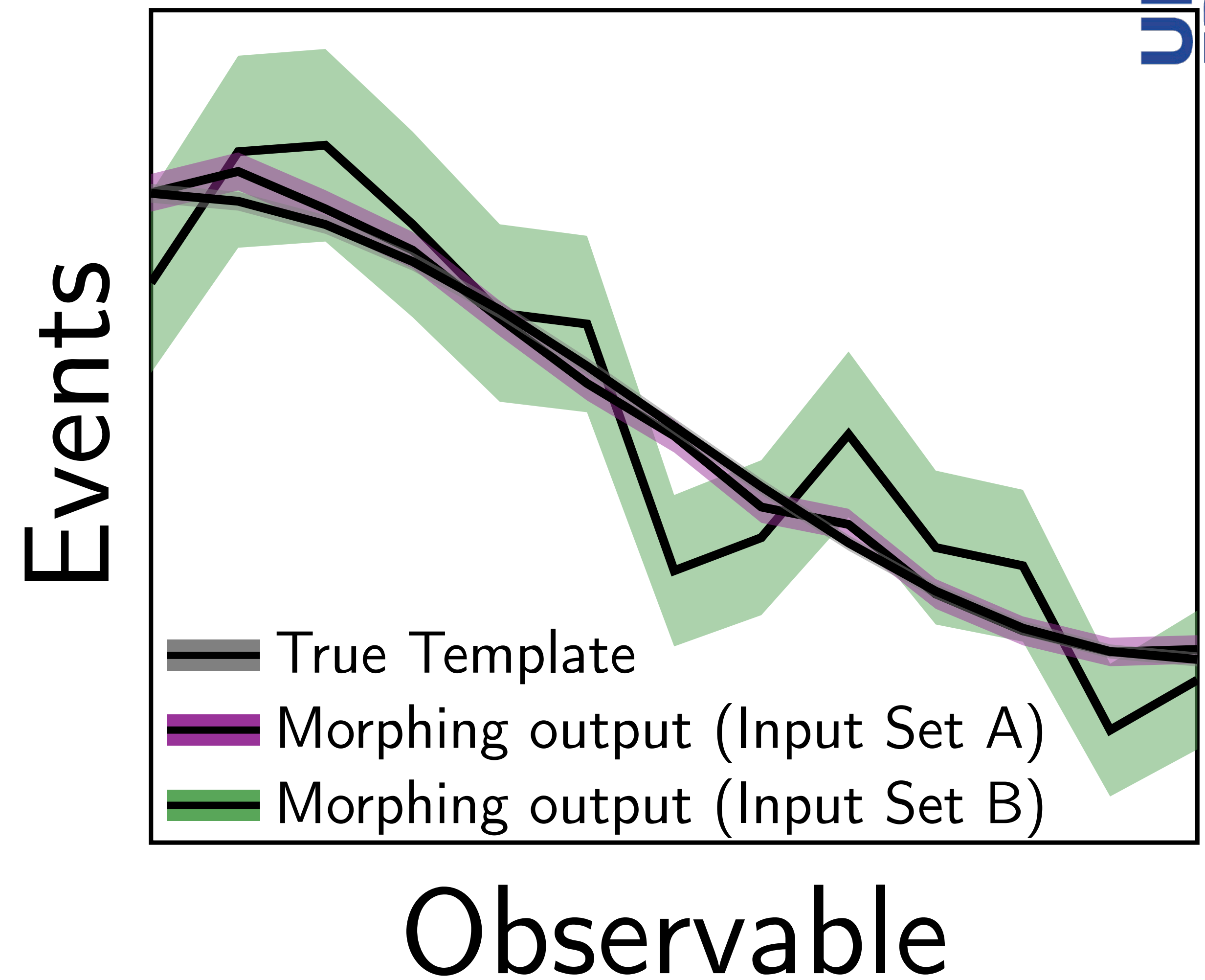


- `RooFit` implementation: `RooEFTMorphFunc`

Optimal Input Set

ATL-PHYS-PUB-2015-047





- Find set of input samples with:
  - robust morphing performance
  - minimal statistical uncertainty in target region

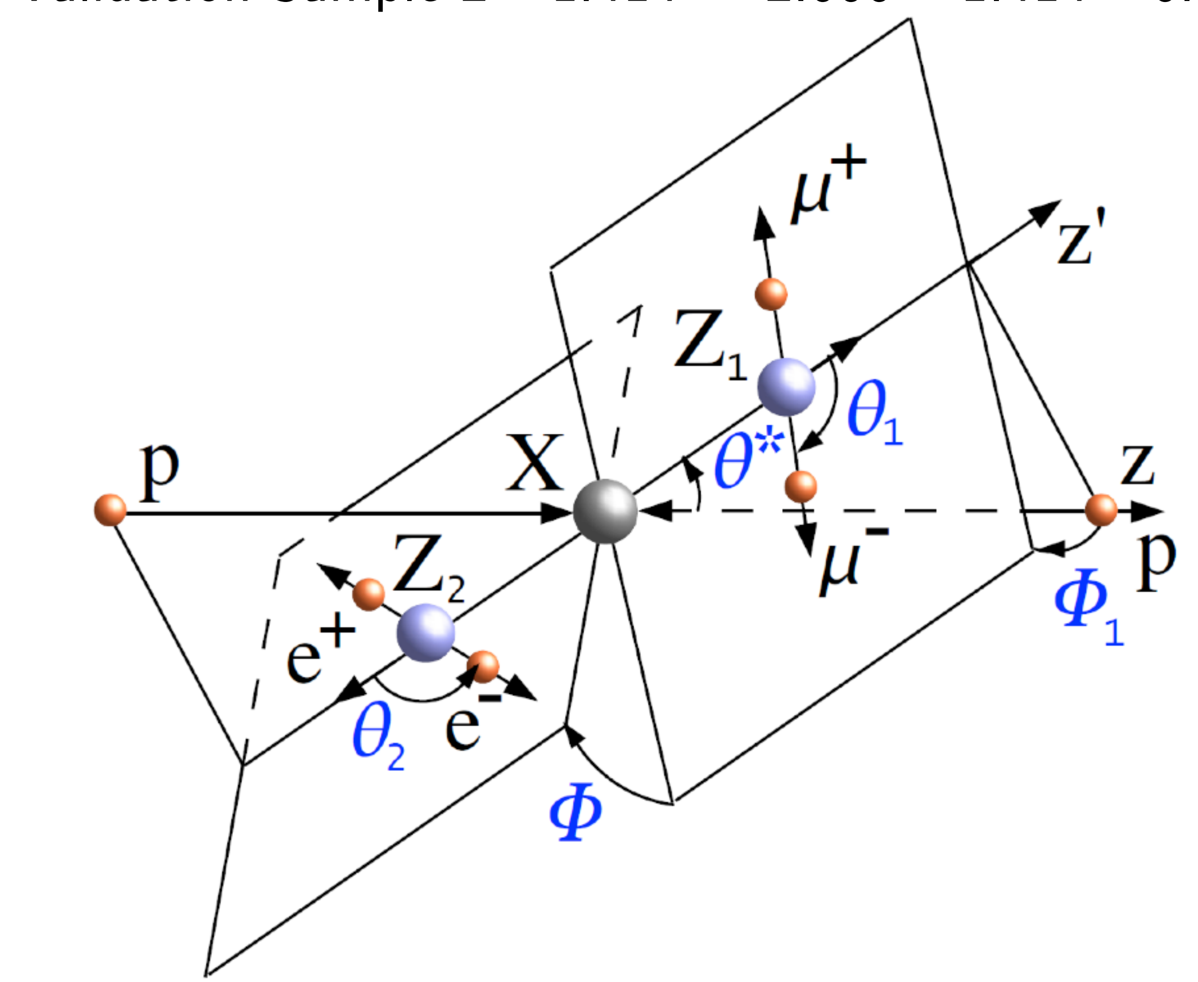
⇒ Non-trivial problem: *constrained optimization*

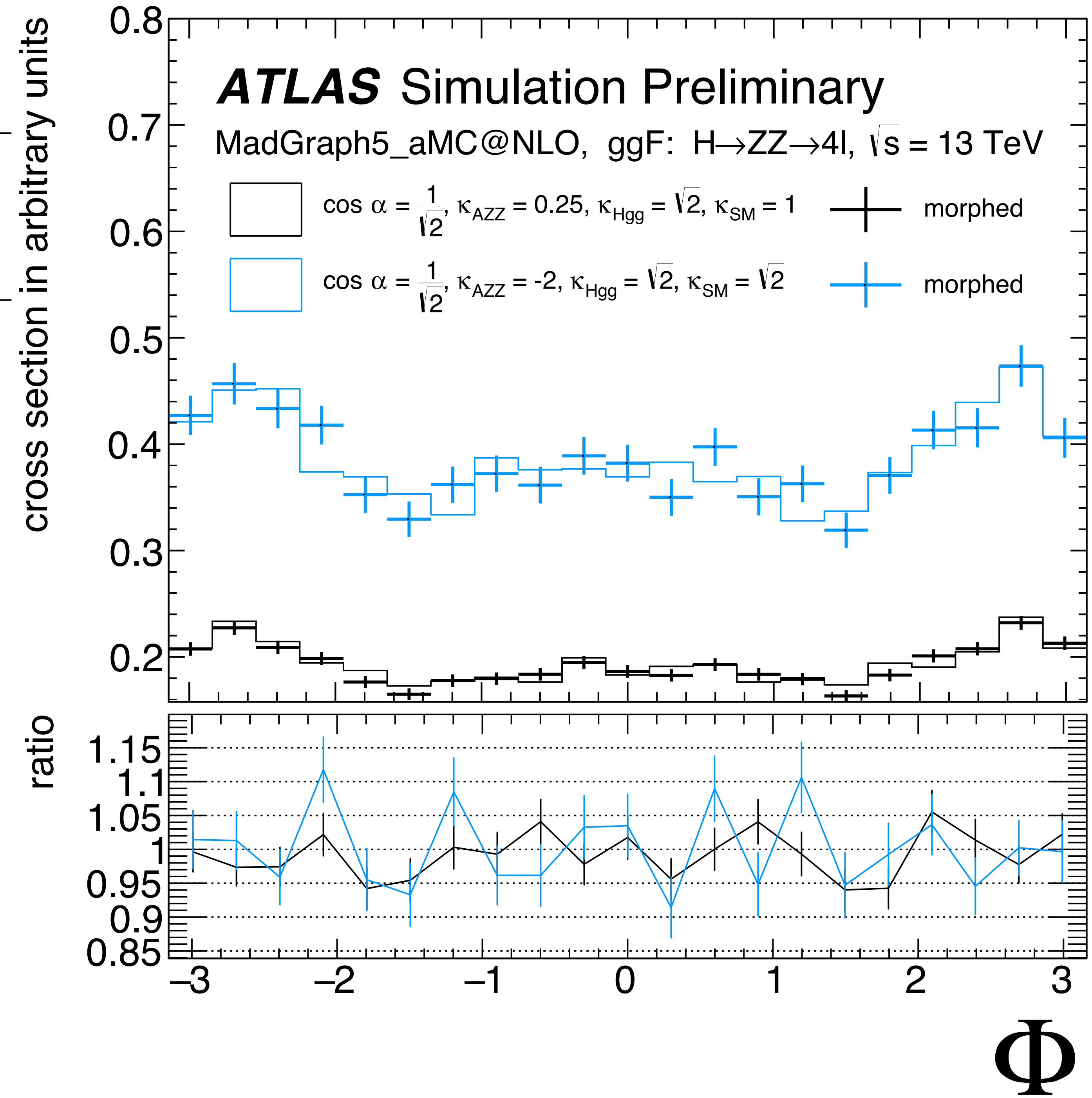
Proof-of-Concept: ggF H → ZZ* → 4ℓ

ATL-PHYS-PUB-2015-047

- Simulate 3 input samples and 2 target samples:

	κ_{SM}	κ_{Azz}	κ_{Hgg}	$\cos\alpha$
Input Sample 0	1.000	0.000	1.000	1.000
Input Sample 1	0.000	13.938	1.414	0.707
Input Sample 2	1.414	13.938	1.414	0.707
Validation Sample 1	1.000	0.250	1.414	0.707
Validation Sample 2	1.414	-2.000	1.414	0.707





Benefits of Morphing

ATL-PHYS-PUB-2015-047

- Computationally fast & convenient:

Morphing	Matrix-element reweighting
• Use final histograms • Only calculates linear sums of coefficients • All other inputs are pre-computed once	For every scenario: • write events to disk • rerun analysis • additional interpolation

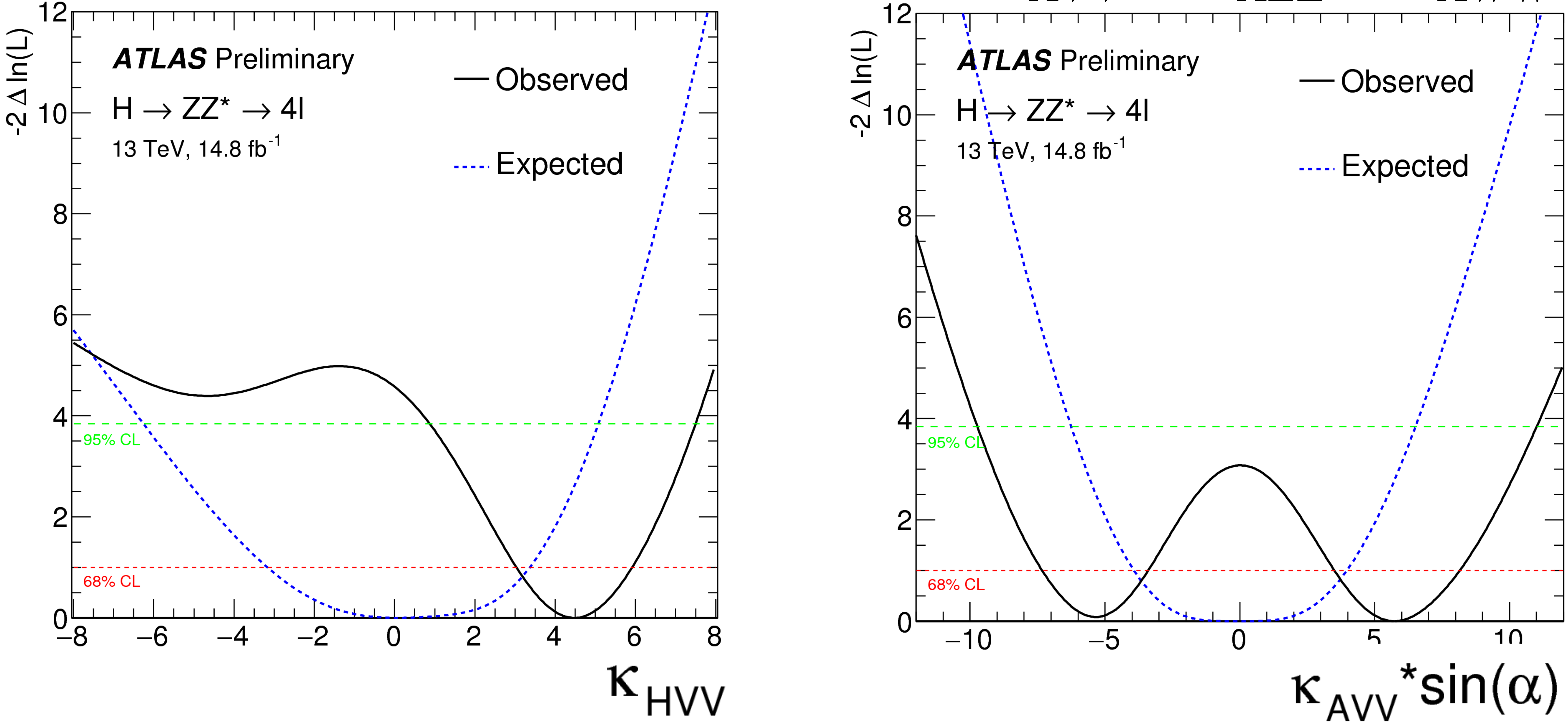
- Can be applied directly and without change to differential or total cross sections (truth or reconstructed)

- Description of **rates and shapes** is **exact**, **continuous**, and **analytical**

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

ATL-CONF-2016-079

- Assume $\kappa_{HVV} = \kappa_{HZZ} = \kappa_{HWW}$ and $\kappa_{AVV} = \kappa_{AZZ} = \kappa_{AWW}$



Not excluded range at 95% CL	κ_{HVV} expected	κ_{HVV} observed	$\kappa_{AVV} \cdot \sin\alpha$ expected	$\kappa_{AVV} \cdot \sin\alpha$ observed
	$[-6.3, 5.1]$	$[0.9, 7.5]$	$[-6.3, 6.5]$	$[-9.7, 11.0]$

- Restriction: rates morphing (no shape) with $\kappa_{SM} \equiv 1$

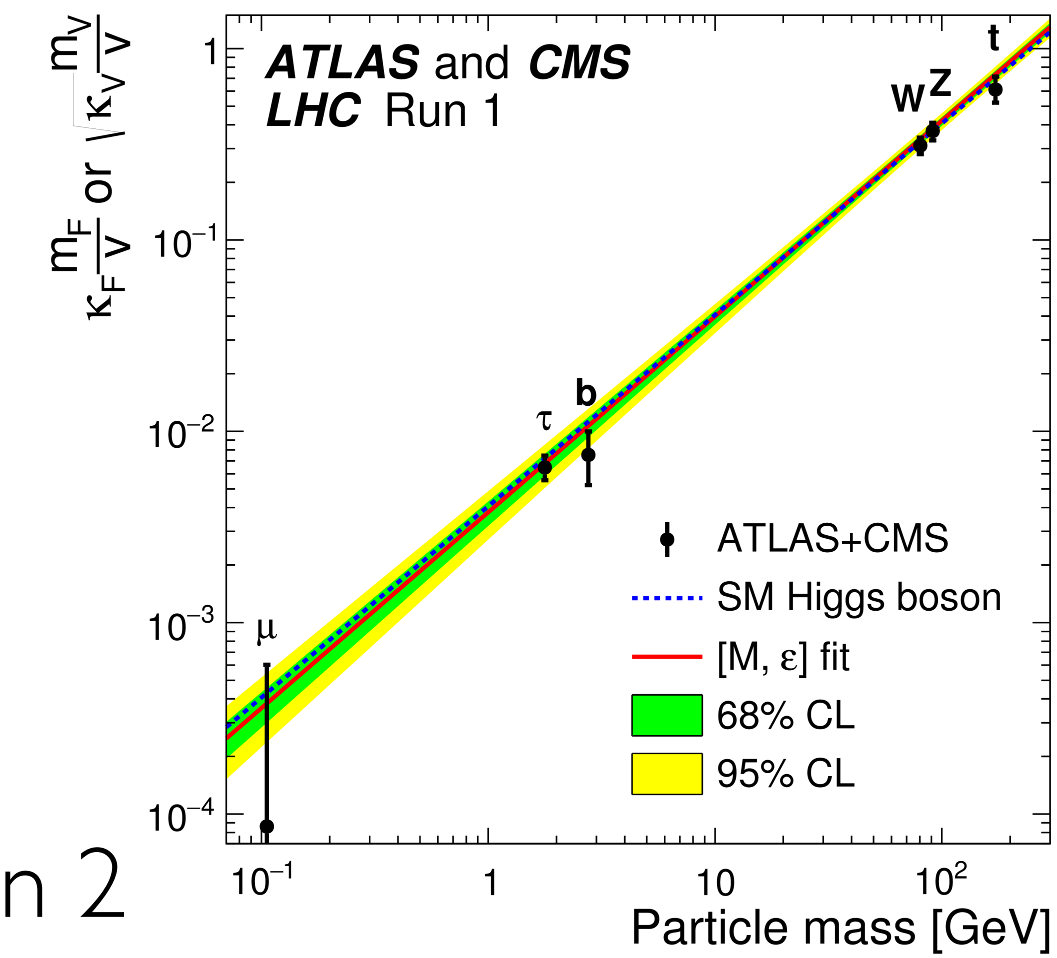
Outlook

- Many measurements are still limited by number of recorded events
- New possibilities with ***millions of produced Higgs bosons***:
  - Rare production and decay modes
  - High-precision measurements
  - Constraints on BSM parameters
- Significant advances in theory, crucial for interpretation of measurements
  - e.g., improvement in ggF cross-section calculation:
    - one more order in perturbative expansion (N^3LO QCD)
    - theory uncertainty: 8.5% $\longrightarrow$ 5.0%

Summary

Finding the Higgs boson has been a breakthrough

- One of the main reasons to build the LHC
- Higgs boson well established



What we know about the Higgs boson

- **m_H = 125.09 ± 0.24 GeV** (2‰ precision)
- Predicted **properties** ($J^P = 0^+$, couplings) **consistent with SM expectations**

Very large number of Higgs bosons in Run 2

- Transition to precision measurement phase
  - First set of $\sqrt{s}$ = 13 TeV results available
- Very active field of Higgs-boson property measurements
  - Effective Lagrangian Morphing
- Exciting possibilities to uncover new phenomena in Higgs-boson sector

References

All ATLAS references are linked from:

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

All CMS references are linked from:

https://twiki.cern.ch/twiki/bin/view/CMSPublic/PhysicsResultsHIG

But what about Mass?

What is it and

where does it come from?

Mass in “normal” Matter

Mass in Atoms:

- > 99.9% in the nucleus

Mass in "normal" Matter

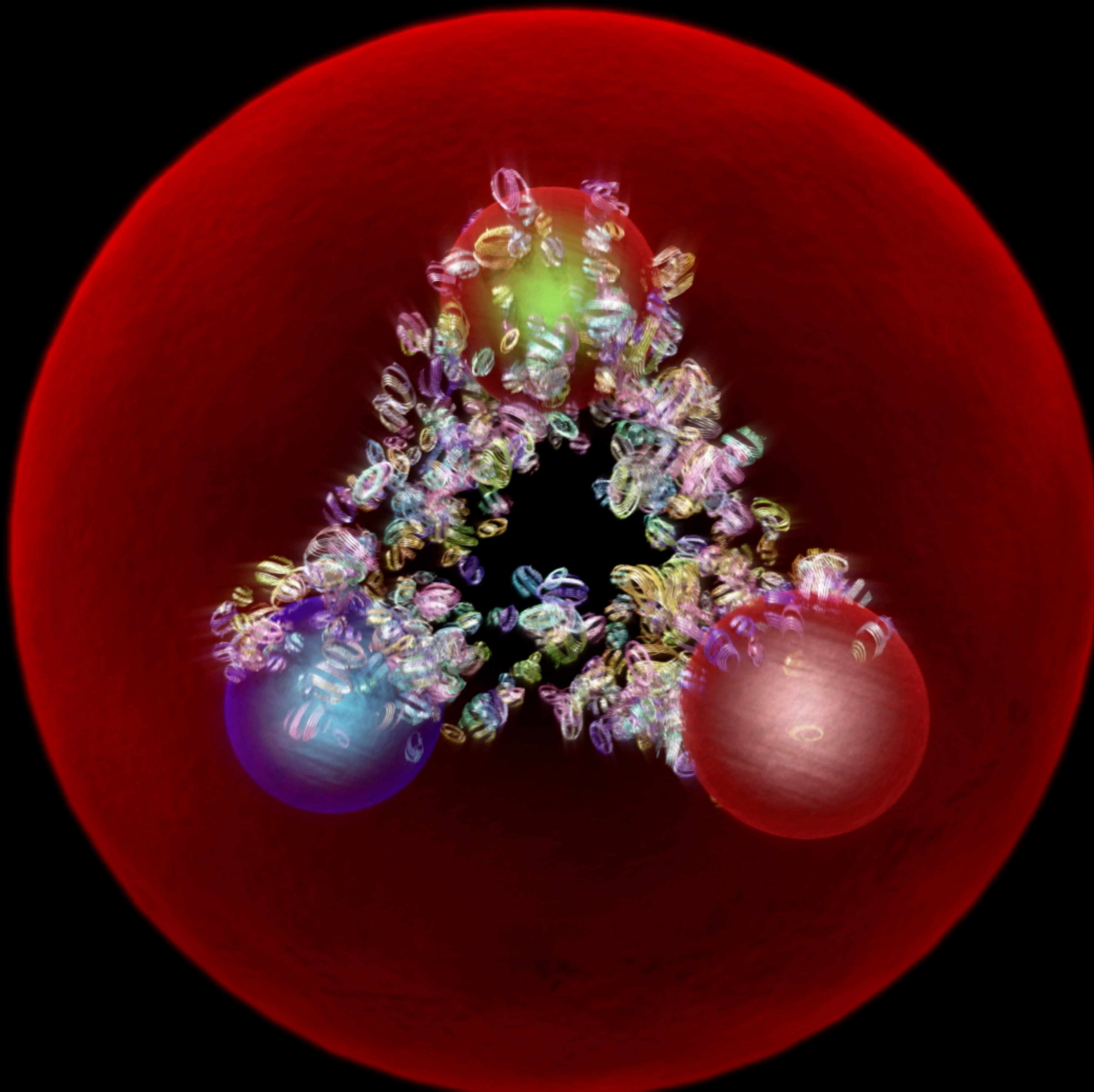
Mass in Atoms:

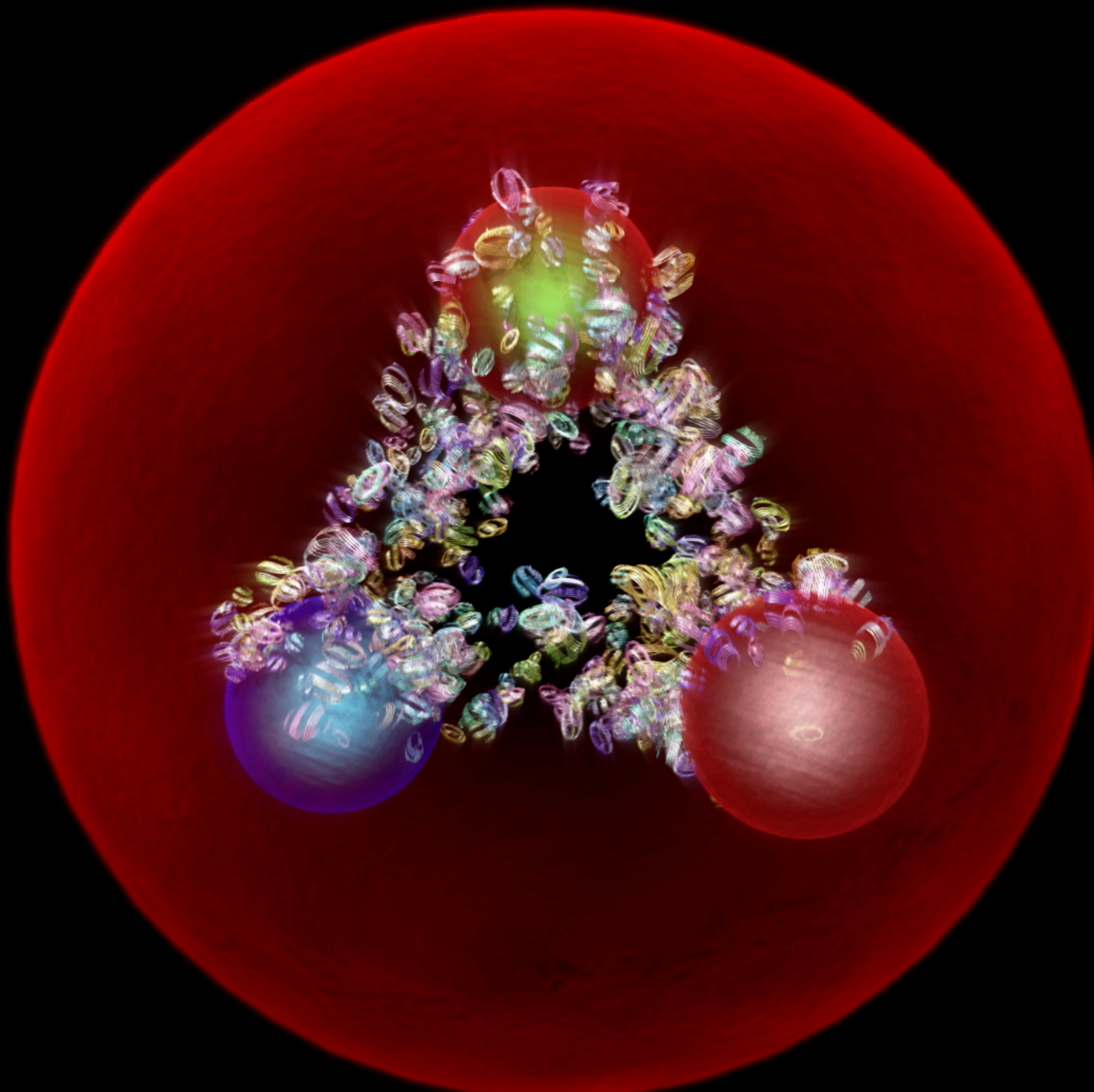
- > 99.9% in the nucleus

Mass in the nucleus:

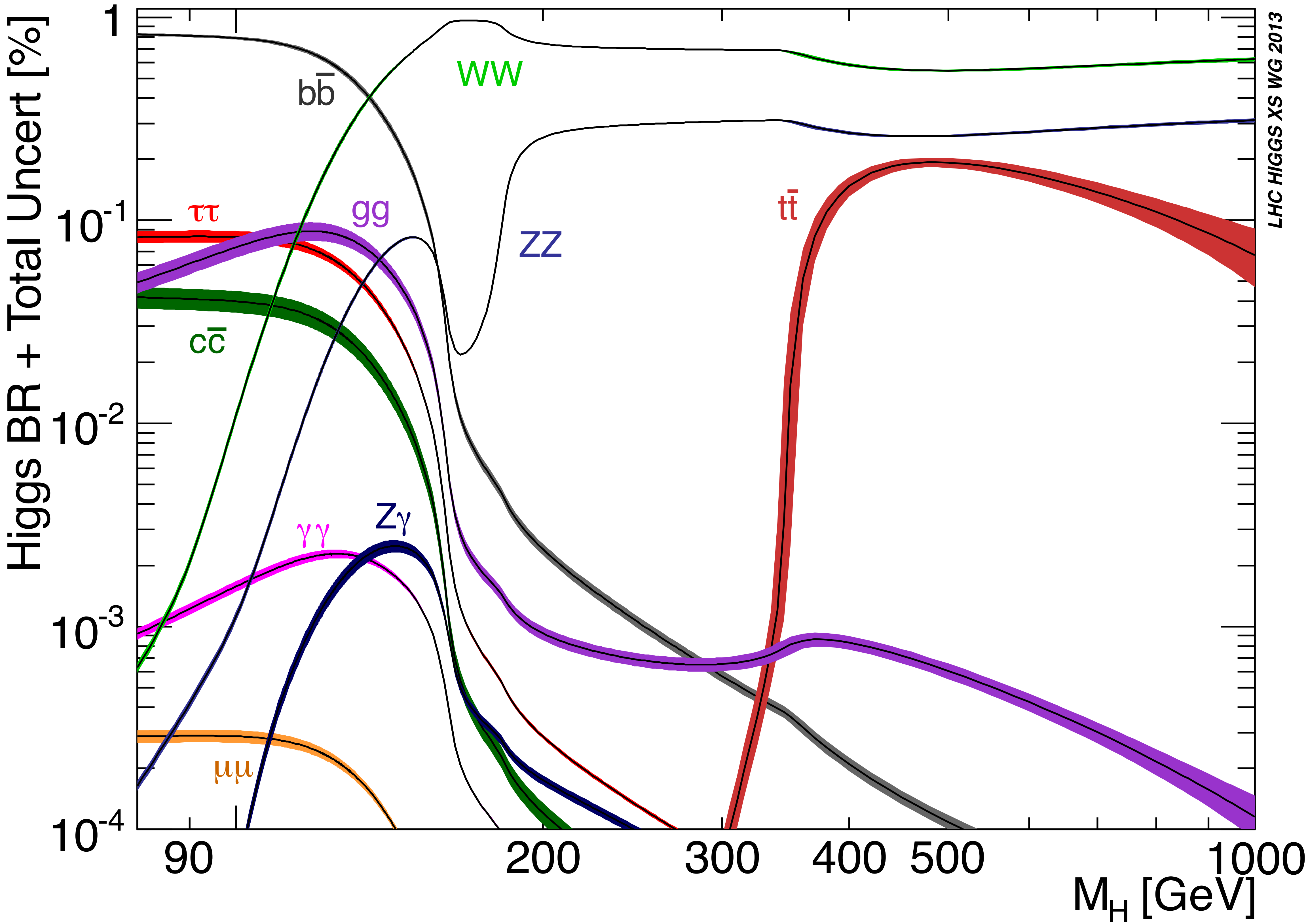
- ~95% due to **binding energy** of *strong nuclear force*

$$E = mc^2$$

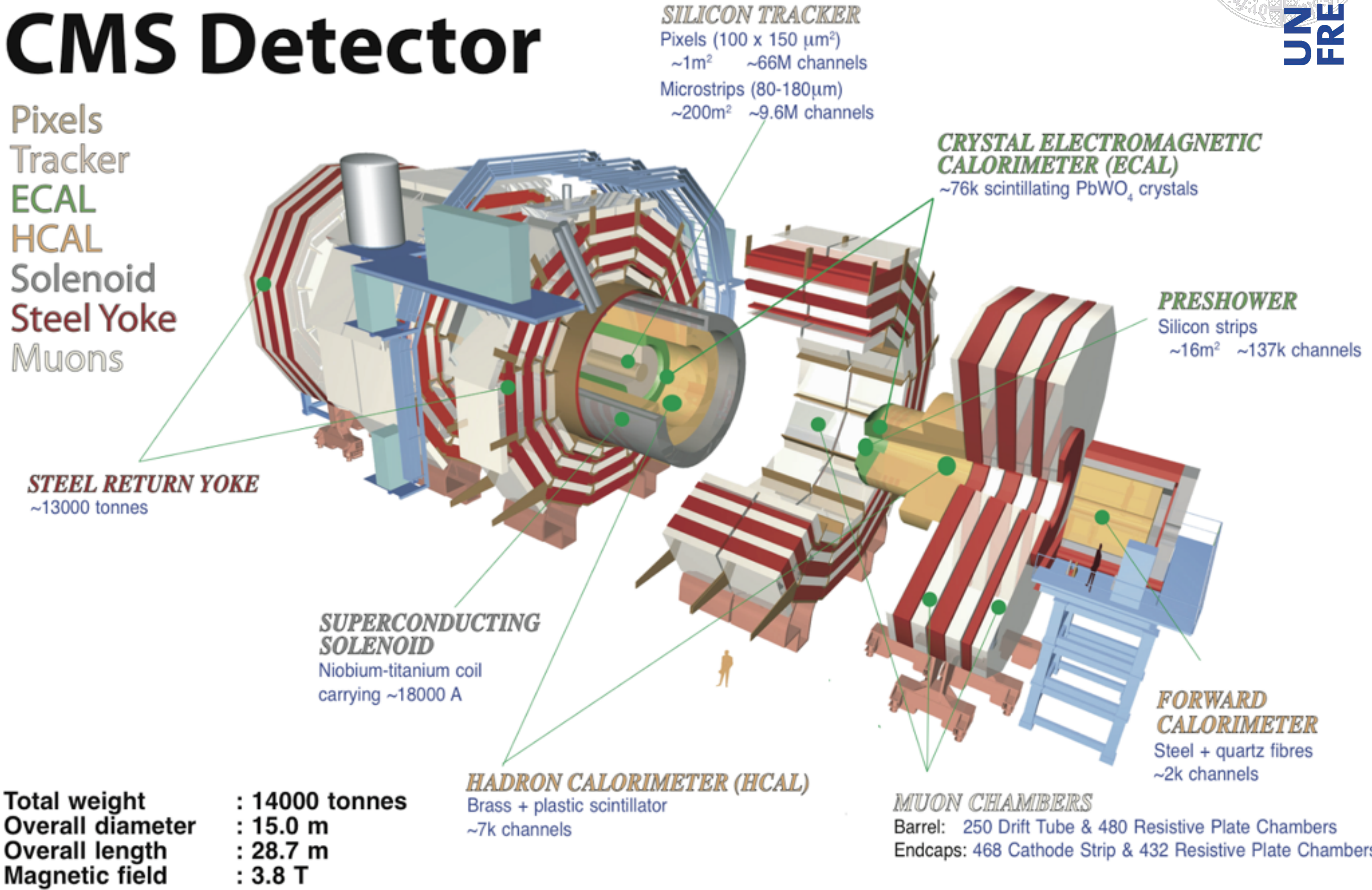




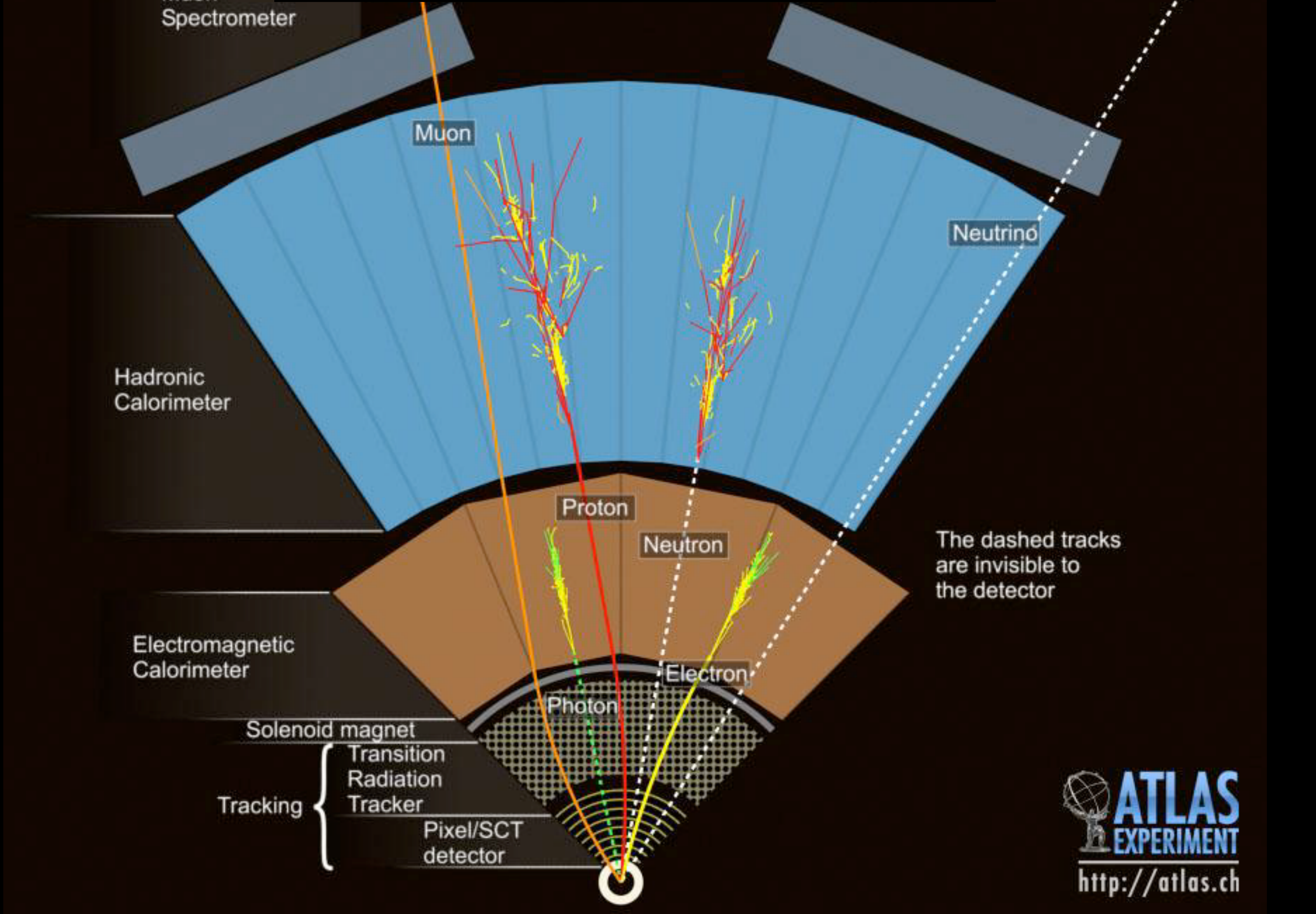
Higgs Boson Decay



The CMS Detector

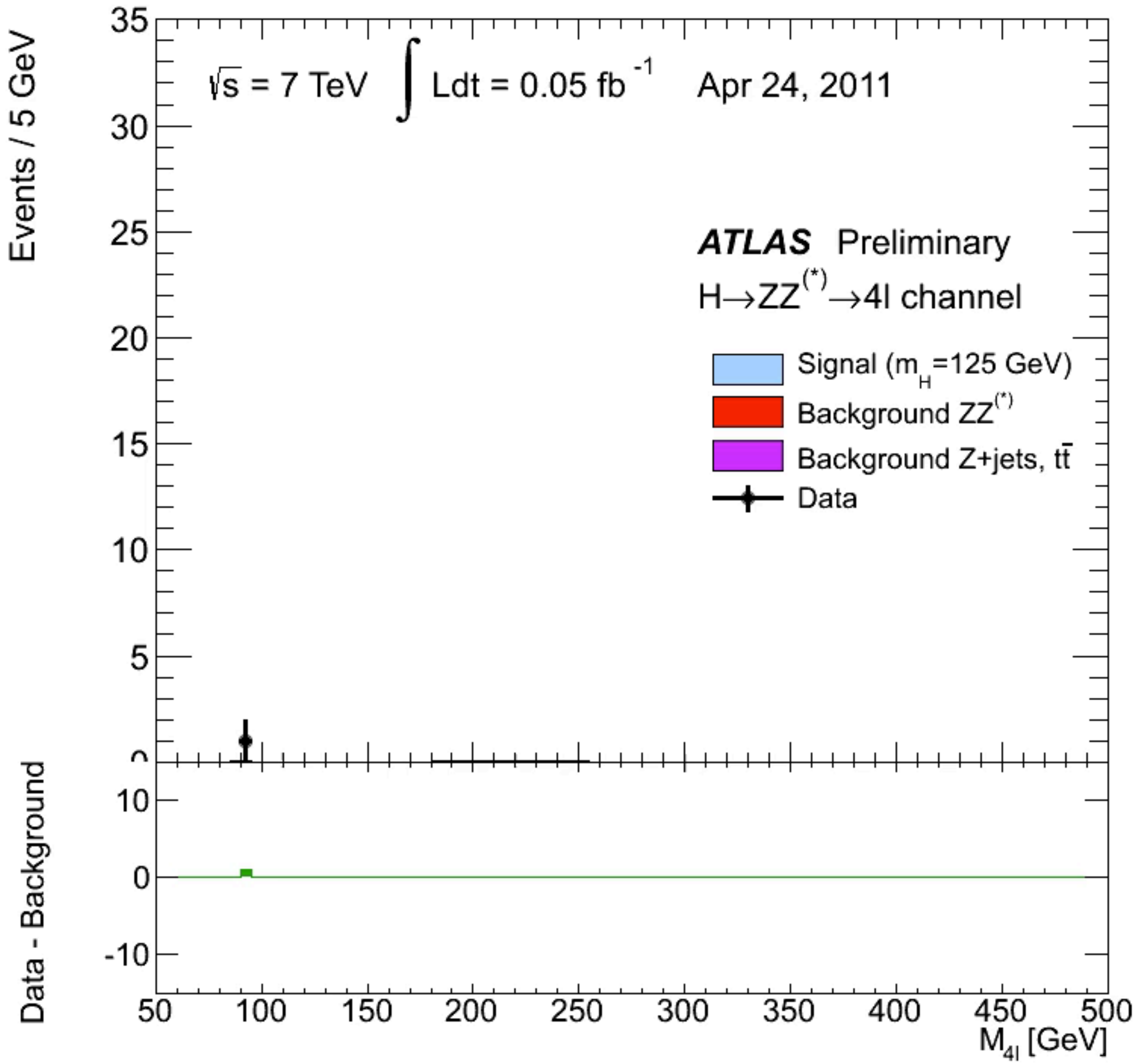


Particle detection

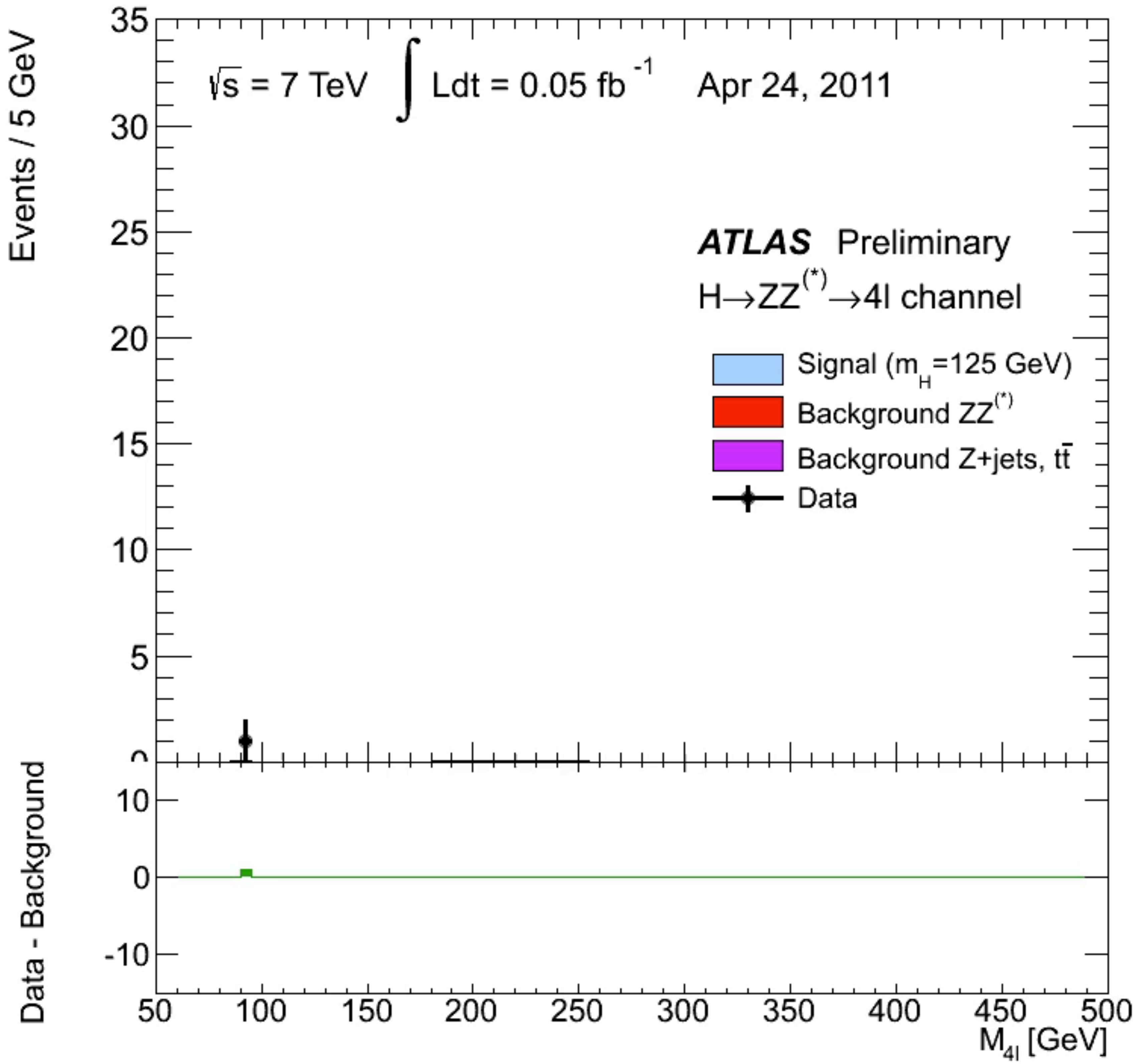


On July 4th 2012

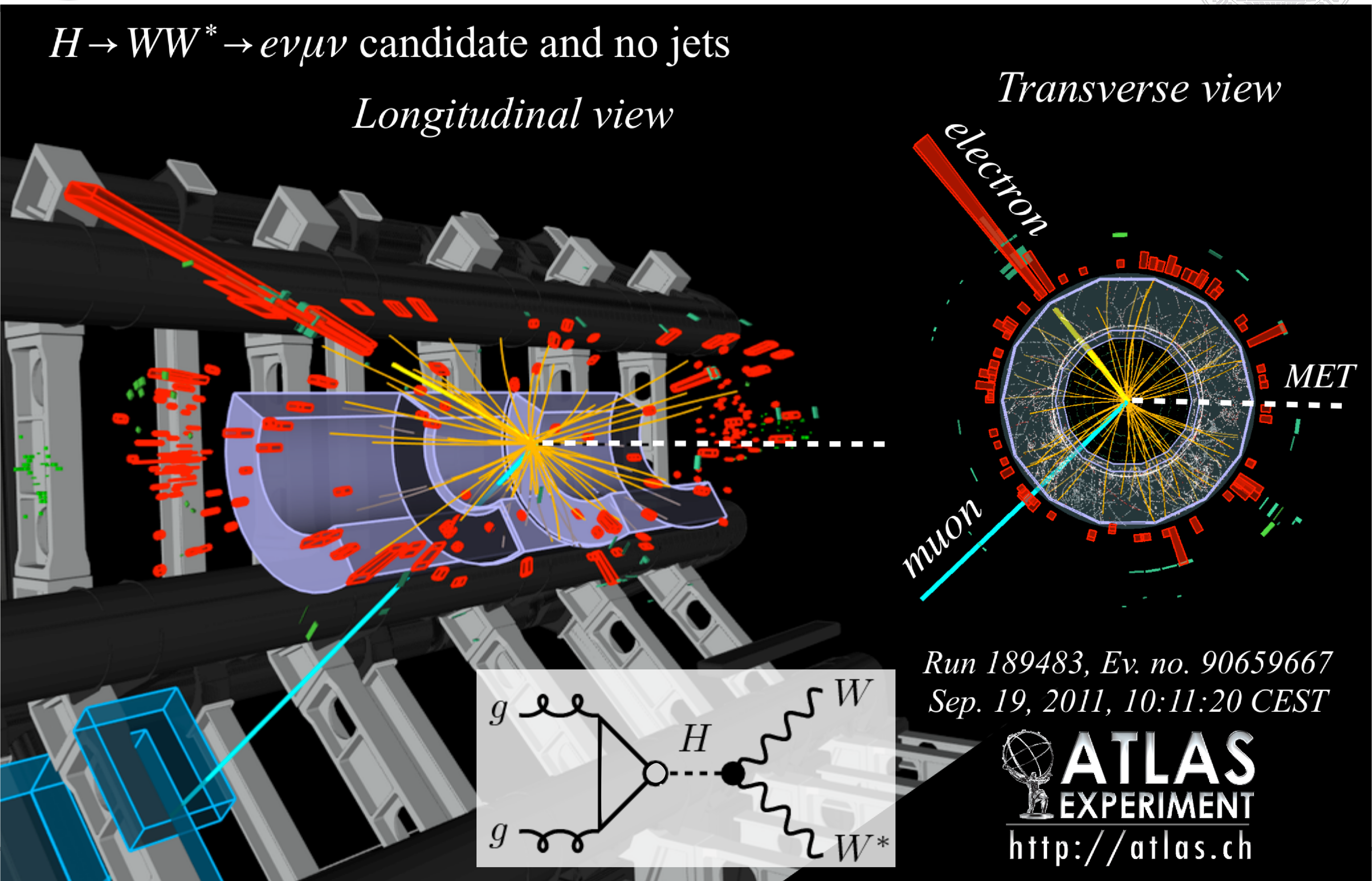
H→ZZ*→4ℓ over Time



H→ZZ*→4ℓ over Time



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

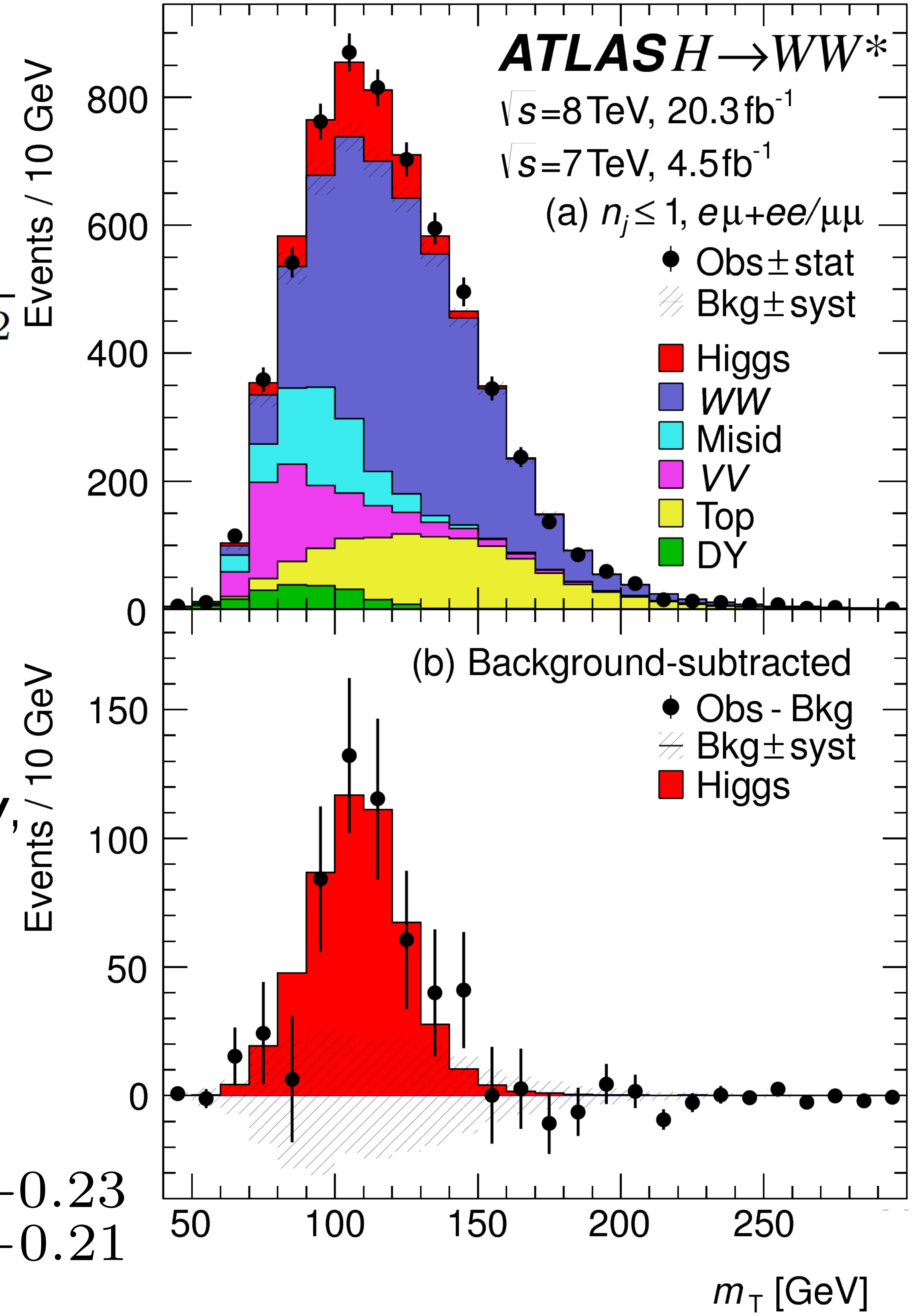


$H \to WW^* \to \ell\nu\ell\nu$

- Strategy:
  - 2 isolated leptons (electrons, muons) and missing transverse momentum (neutrinos)
  - Fit $m_{\mathrm{T}} = \sqrt{\left(E_{\mathrm{T}}^{\ell\ell} + p_{\mathrm{T}}^{\nu\nu}\right)^2 - \left|\boldsymbol{p}_{\mathrm{T}}^{\ell\ell} + \boldsymbol{p}_{\mathrm{T}}^{\nu\nu}\right|^2}$
- Conditions:
  - **Large BR(H → WW*) ≈ 22%**
    - BR(W → $\ell\nu$) ≈ 10.8%

⇒ Expect **~6500 Higgs bosons in this decay**, but also large backgrounds

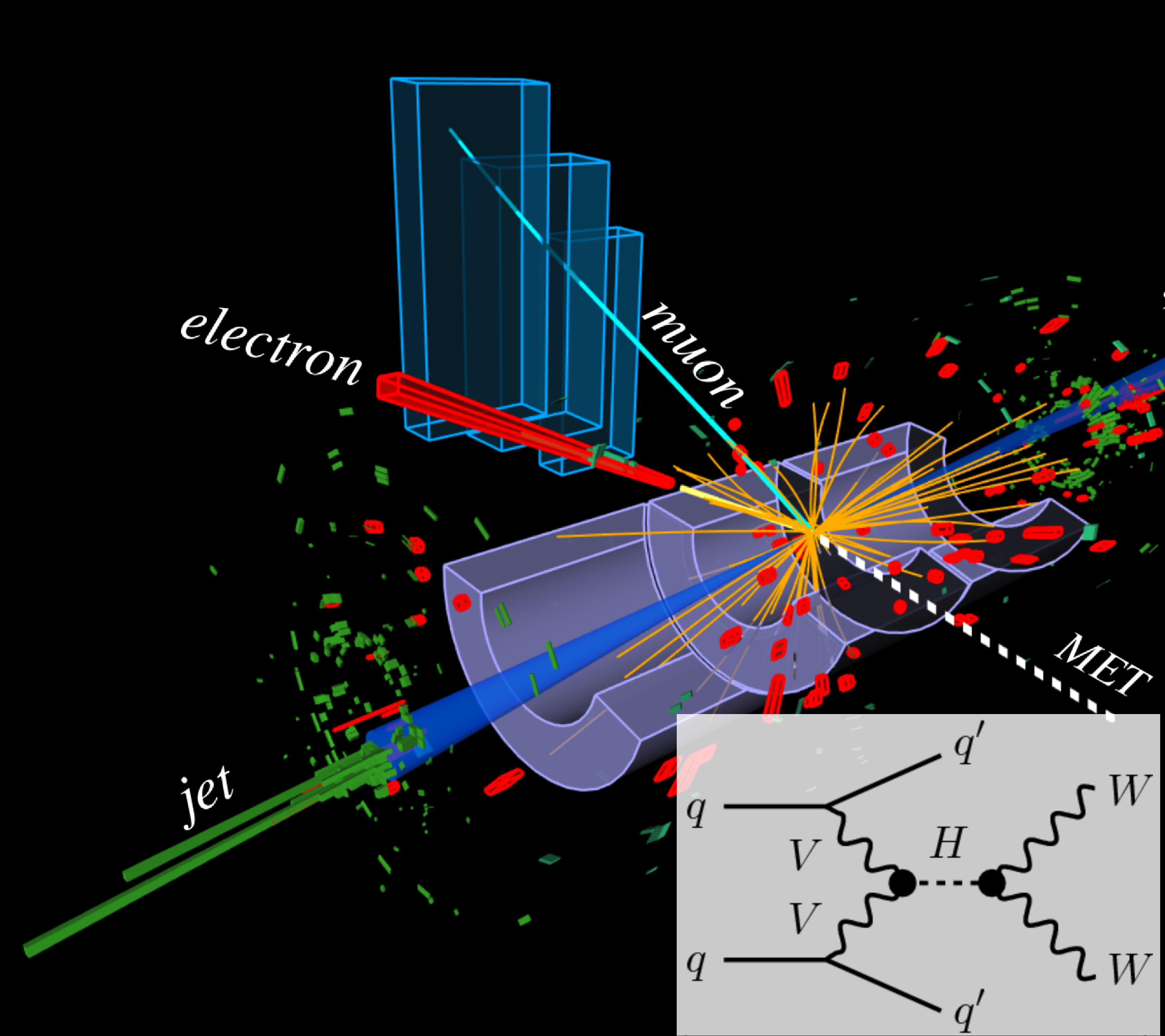
- Result:
  - Total significance (ggF+VBF): 6.1σ
  - **Combined signal strength:** $\mu = 1.09\ ^{+0.23}_{-0.21}$



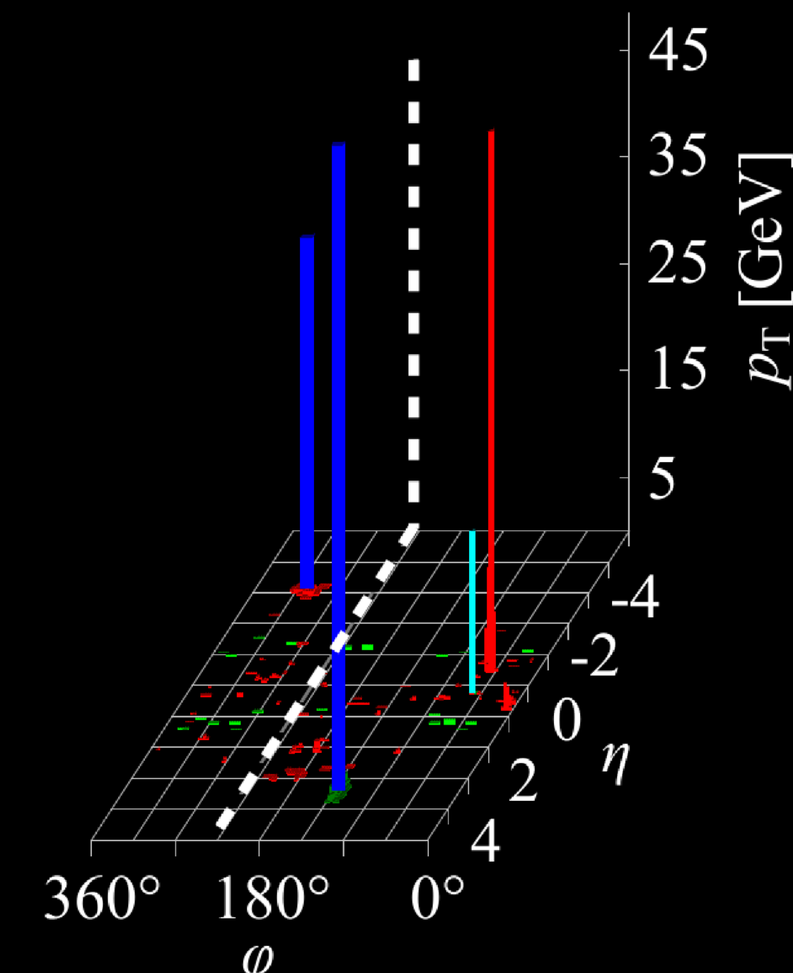
$H \to WW^* \to \ell\nu\ell\nu$

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

Longitudinal view



Projected η-φ view



Run 214680, Ev. no. 271333760
Nov. 17, 2012, 07:42:05 CET

ATLAS EXPERIMENT
http://atlas.ch

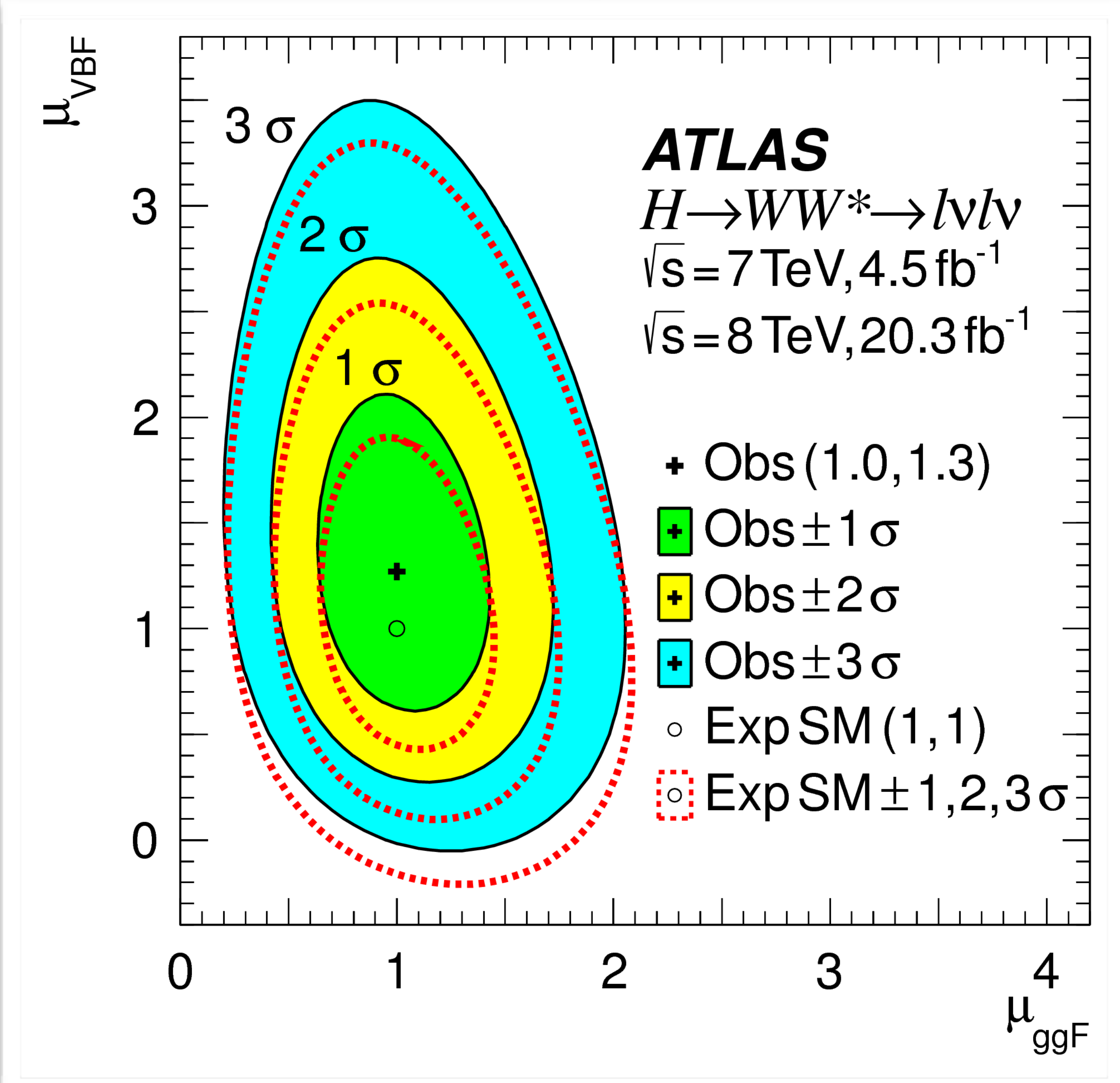
Vector-Boson Fusion vs. Gluon Fusion

Individual compatibility with SM:

- VBF significance: 3.2σ
- Fit μ_{ggF} and μ_{VBF} simultaneously
- Observed signal strengths for ggF and VBF production modes:

$$\mu_{ggF} = 1.02^{+0.29}_{-0.26}$$

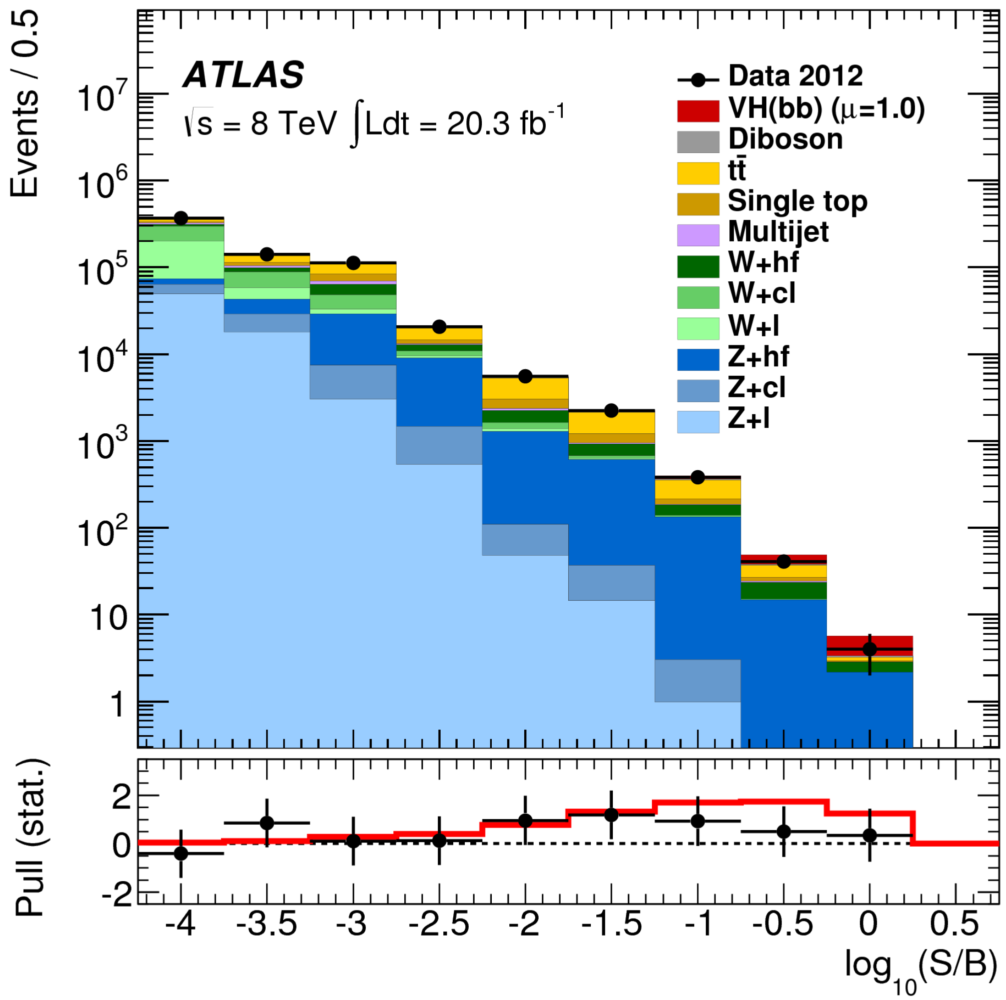
$$\mu_{VBF} = 1.27^{+0.53}_{-0.45}$$



Higgs Boson Decay into Fermions

$H \to bb$

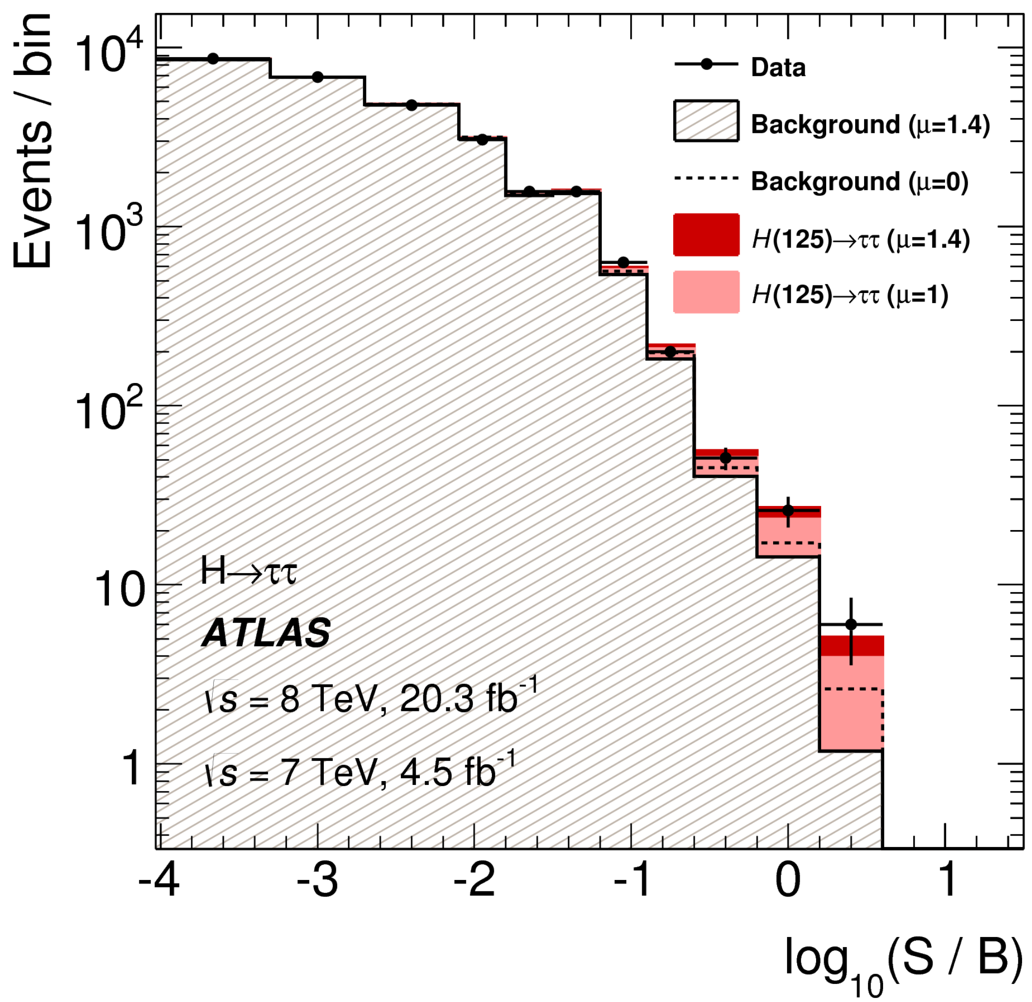
- Largest BR($\mathbf{H \to bb}$) ≈ 58%
  - but huge backgrounds
- VH associated production



$$\mu = 0.51\ ^{+0.40}_{-0.37}$$

$H \to \tau\tau$

- Moderate BR($\mathbf{H \to \tau\tau}$) ≈ 6.3%
  - all $\tau\tau$ decays analyzed
- VBF and ggF production

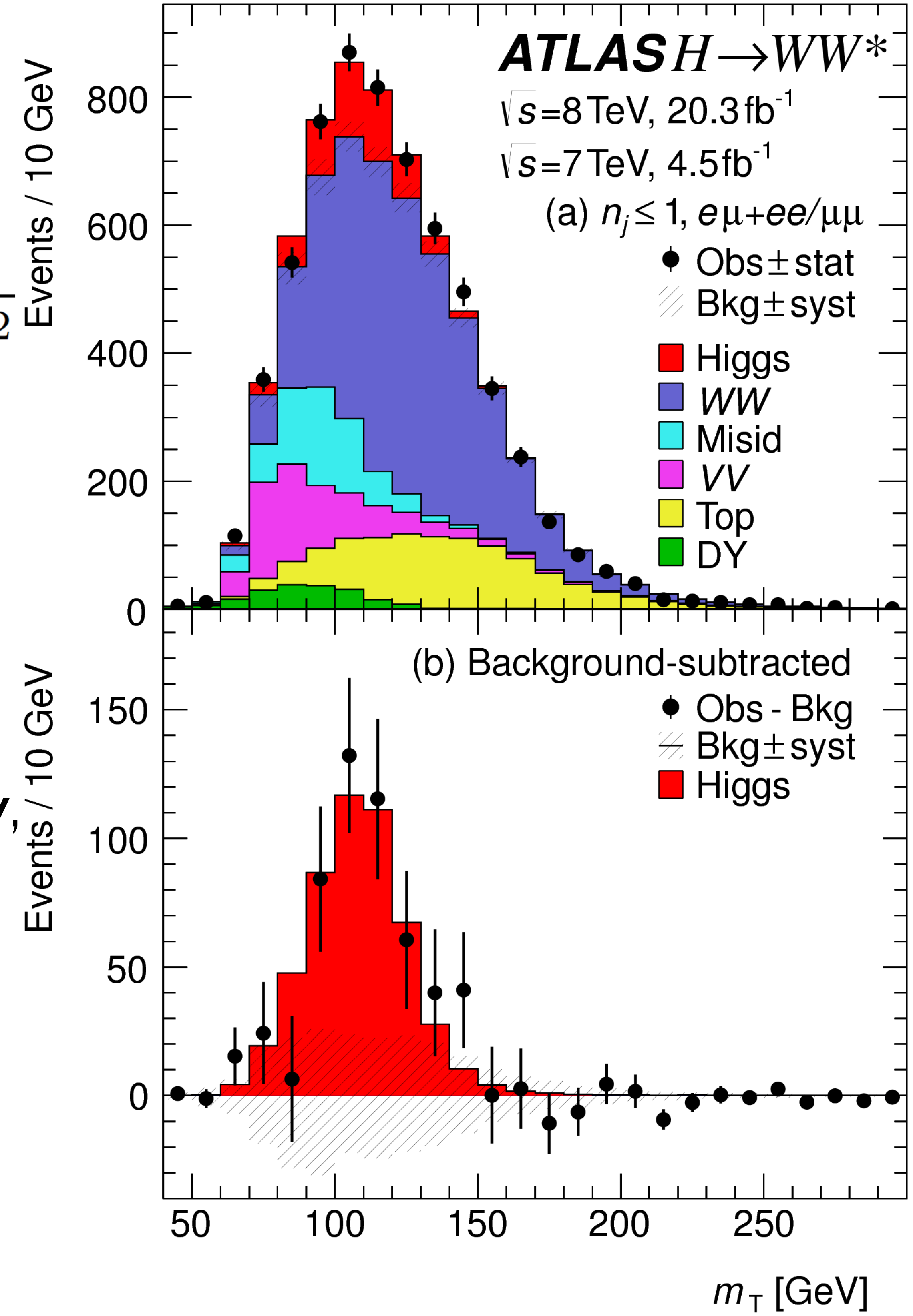


$$\mu = 1.4\ ^{+0.4}_{-0.4}$$

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

- Strategy:
  - 4 isolated leptons (electrons, muons) and missing transverse momentum (neutrinos)
  - Fit $m_T = \sqrt{\left(E_T^{\ell\ell} + p_T^{\nu\nu}\right)^2 - \left|\boldsymbol{p}_T^{\ell\ell} + \boldsymbol{p}_T^{\nu\nu}\right|^2}$
- Conditions:
  - **Large BR(H → WW*) ≈ 22%**
    - BR(W → $\ell\nu$) ≈ 10.8%

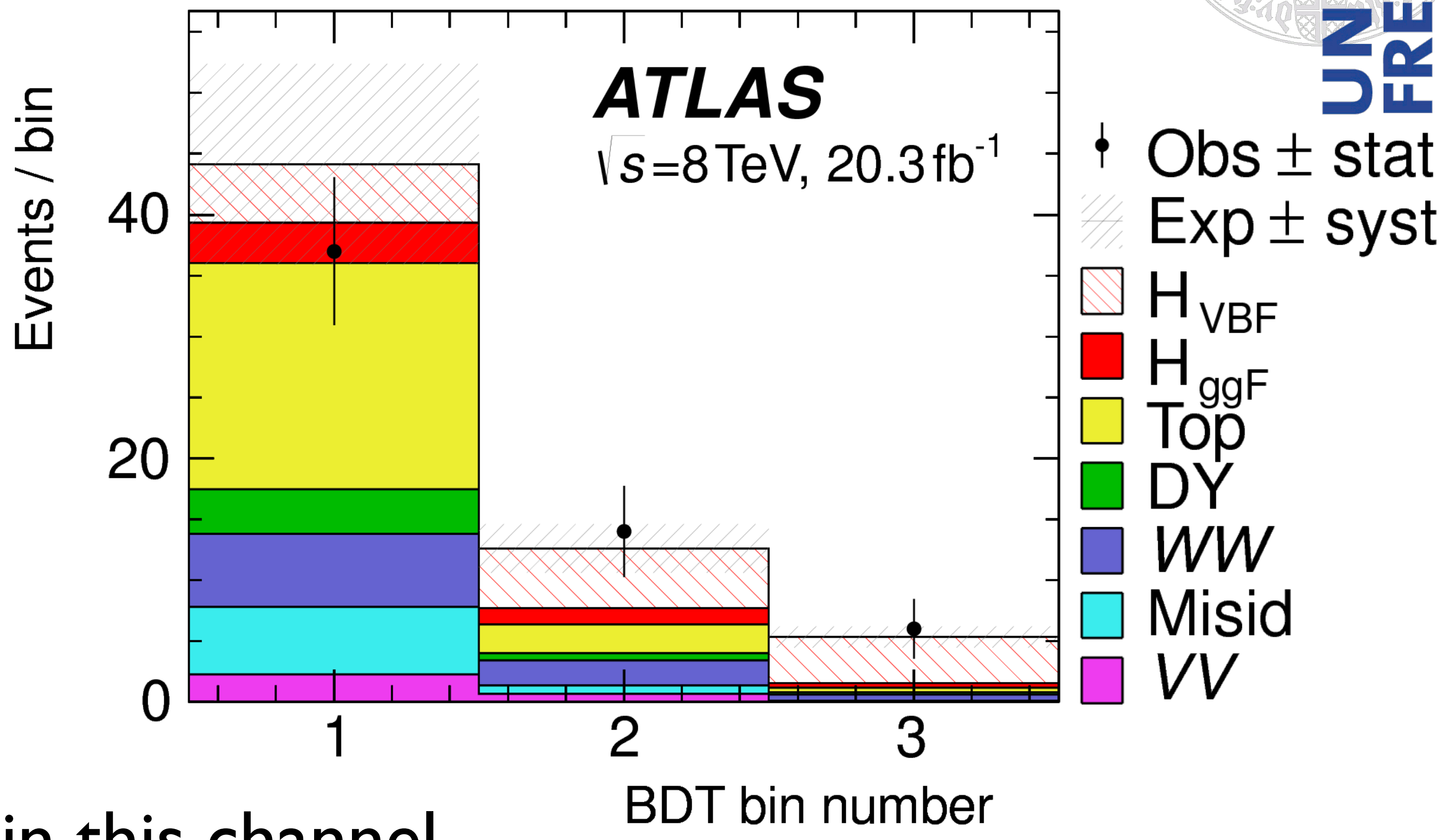
  ⇒ Expect **~6500 Higgs bosons in this decay**, but also large backgrounds
- Result:
  - Significance: 4.3σ



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

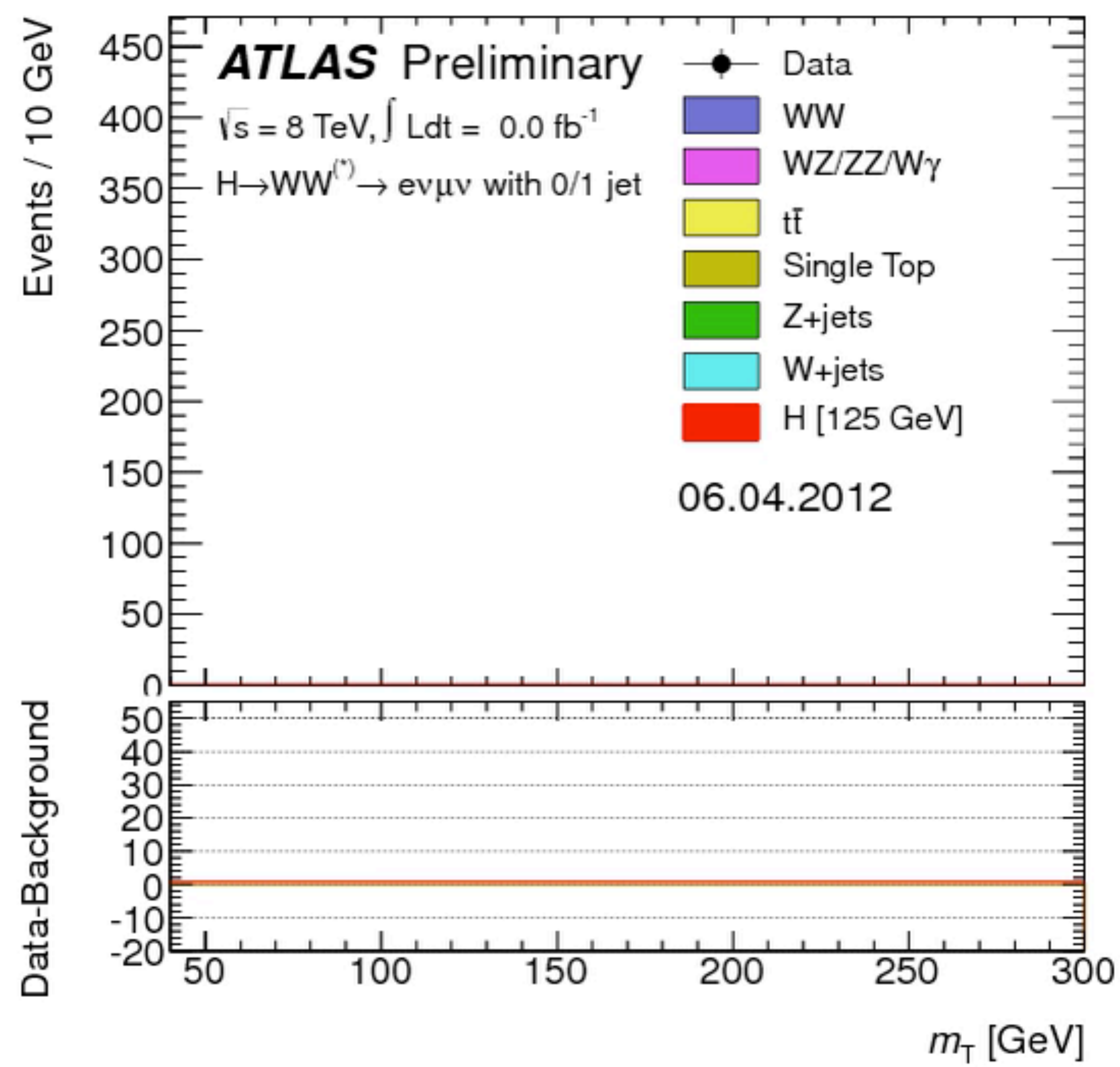
- Strategy:
  - Combine information using **machine learning**
  - Fit resulting classifier
- Conditions:
  - **Small $\sigma_{VBF} \approx 1.6$ pb**

  ⇒ Expect **~400 Higgs bosons in this channel**, and also large backgrounds

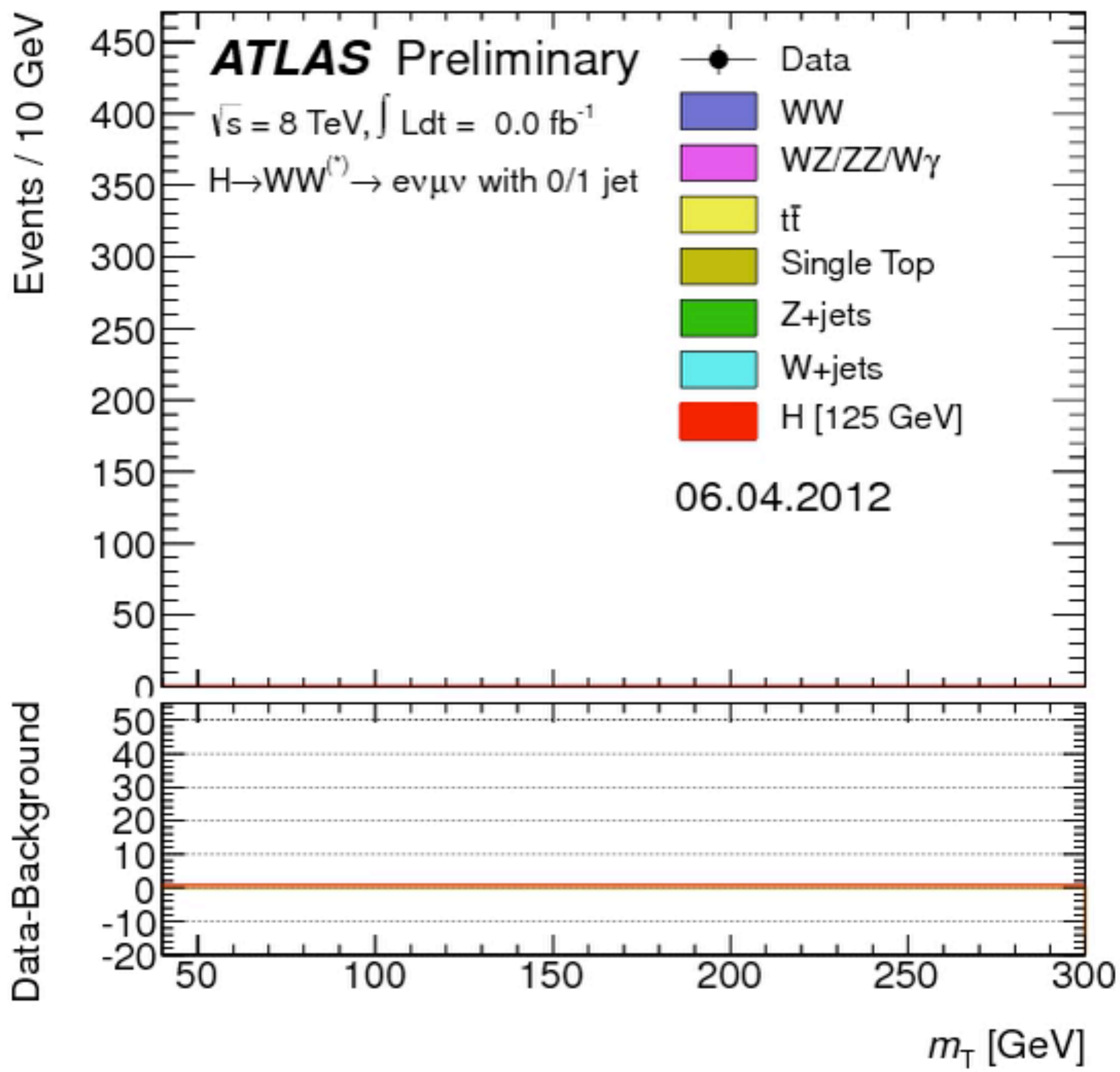


- Result:
  - Significance: 3.2σ
  - Total significance (ggF+VBF): 6.1σ
  - **Combined signal strength:** $\mu = 1.09\ ^{+0.23}_{-0.21}$

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

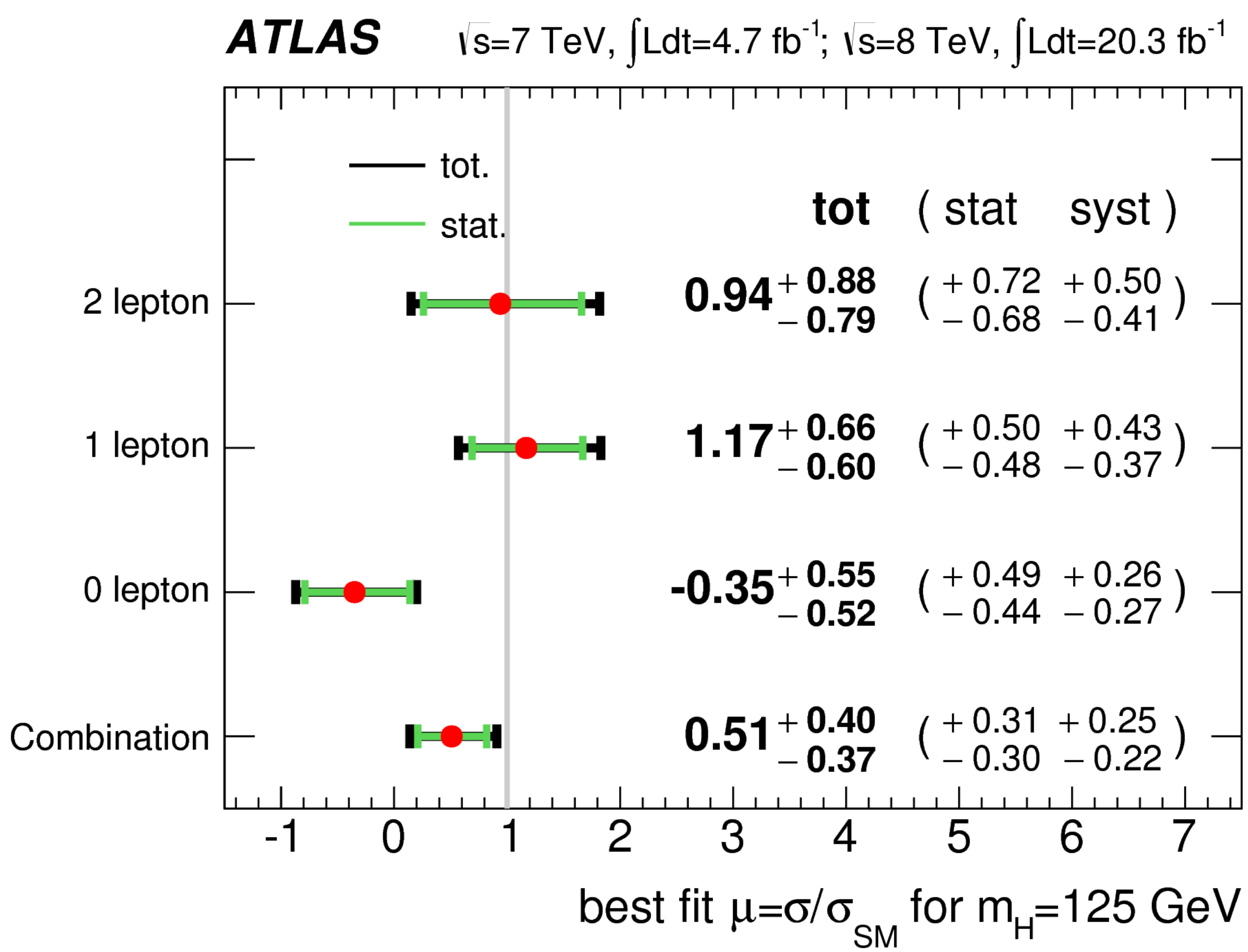


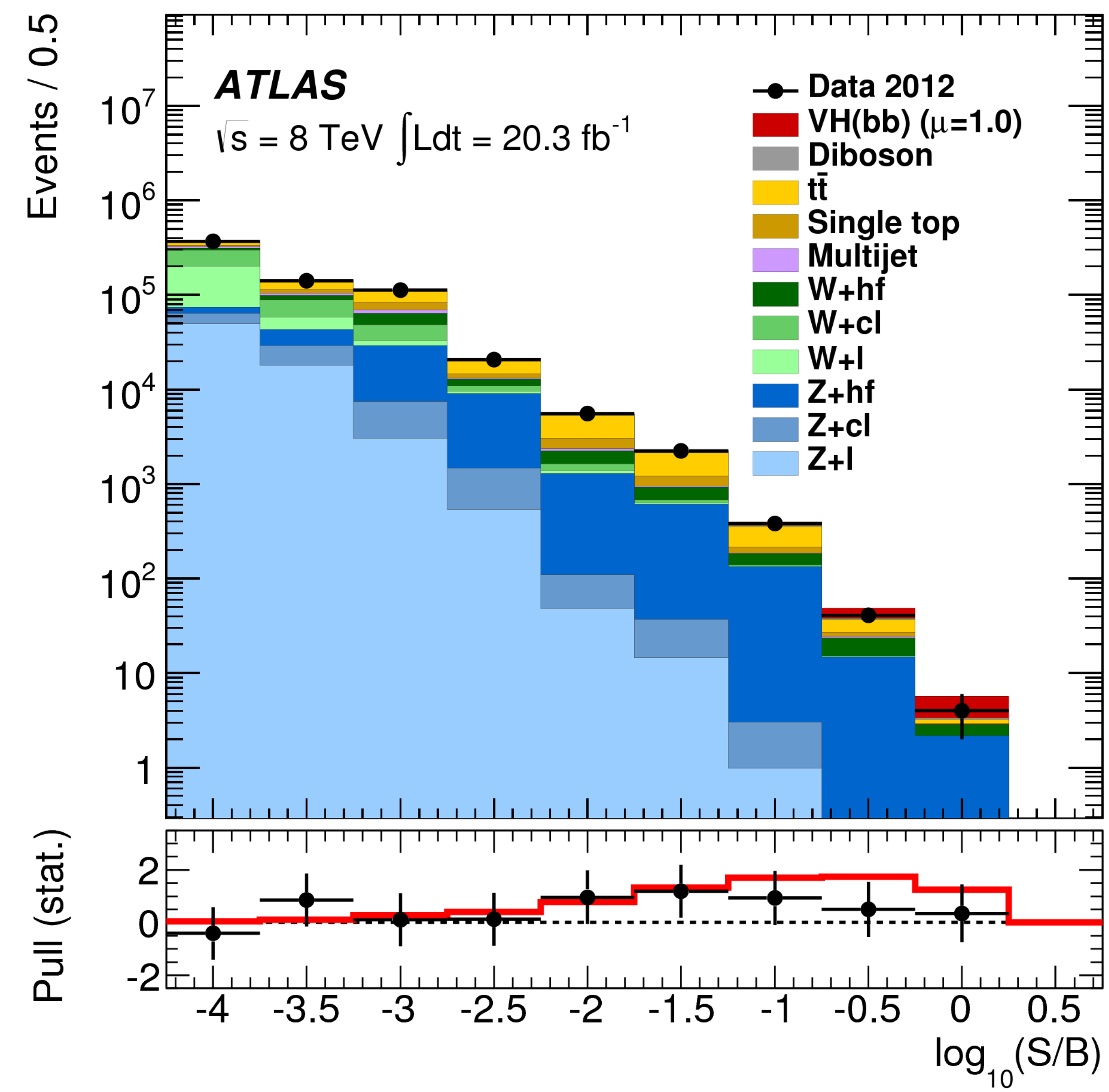
H → WW* → $\ell\nu\ell\nu$ over Time



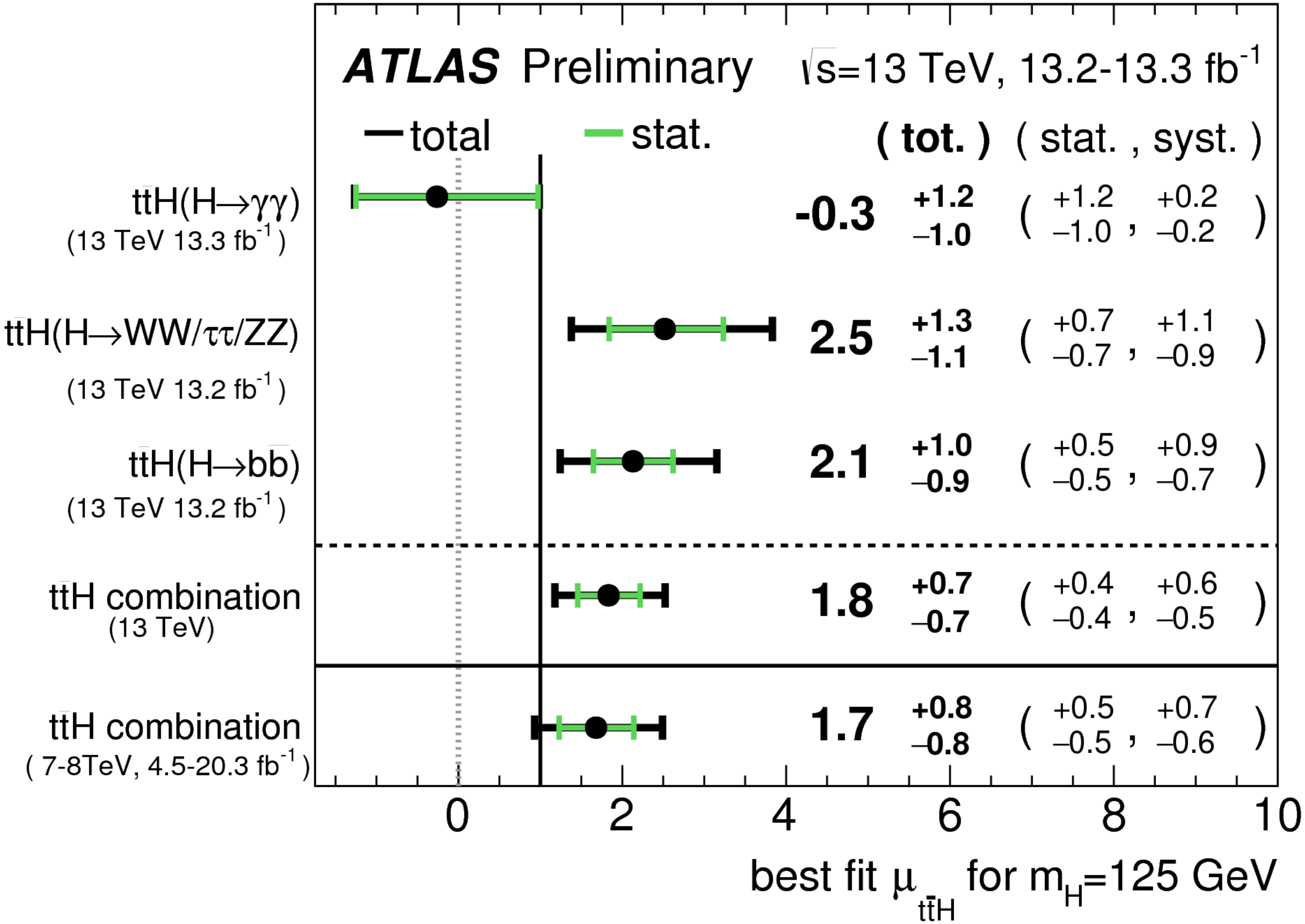
H → bb

- Largest BR(H → bb) ≈ 58%
  - but huge backgrounds
- VH associated production





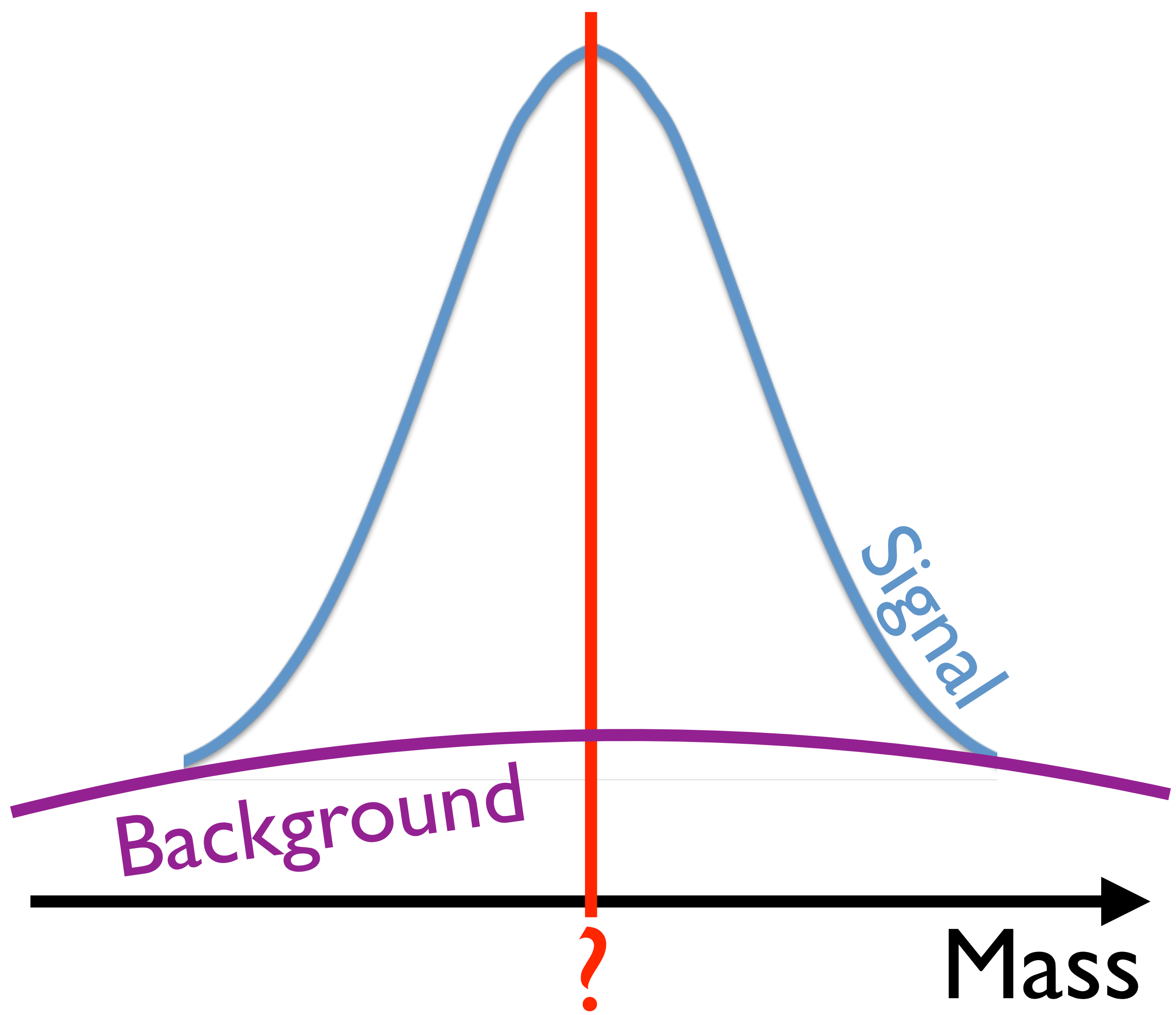
ttH



ATLAS Preliminary
√s=13 TeV, 13.2-13.3 fb^{-1}
total
stat.
(tot.) (stat. , syst.)
ttH(H→γγ) (13 TeV 13.3 fb^{-1})
-0.3 +1.2 −1.0 (+1.2 −1.0 , +0.2 −0.2)
ttH(H→WW/ττ/ZZ) (13 TeV 13.2 fb^{-1})
2.5 +1.3 −1.1 (+0.7 −0.7 , +1.1 −0.9)
ttH(H→bb) (13 TeV 13.2 fb^{-1})
2.1 +1.0 −0.9 (+0.5 −0.5 , +0.9 −0.7)
ttH combination (13 TeV)
1.8 +0.7 −0.7 (+0.4 −0.4 , +0.6 −0.5)
ttH combination (7-8TeV, 4.5-20.3 fb^{-1})
1.7 +0.8 −0.8 (+0.5 −0.5 , +0.7 −0.6)
0
2
4
6
8
10
best fit $\mu_{t\bar{t}H}$ for m_H=125 GeV

Higgs Boson Mass

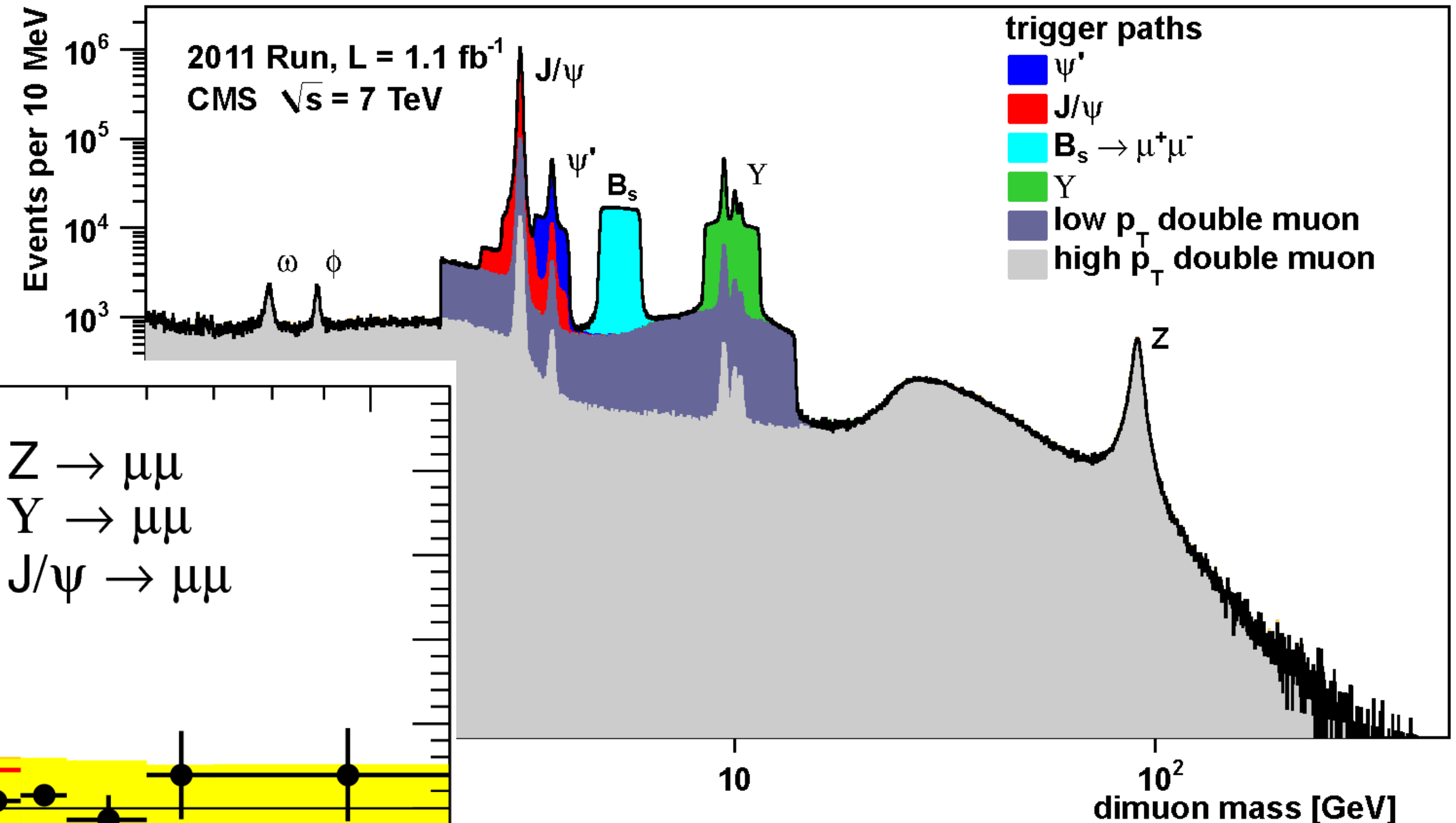
- Not predicted by theory
  - Once measured by experiment, everything else is determined

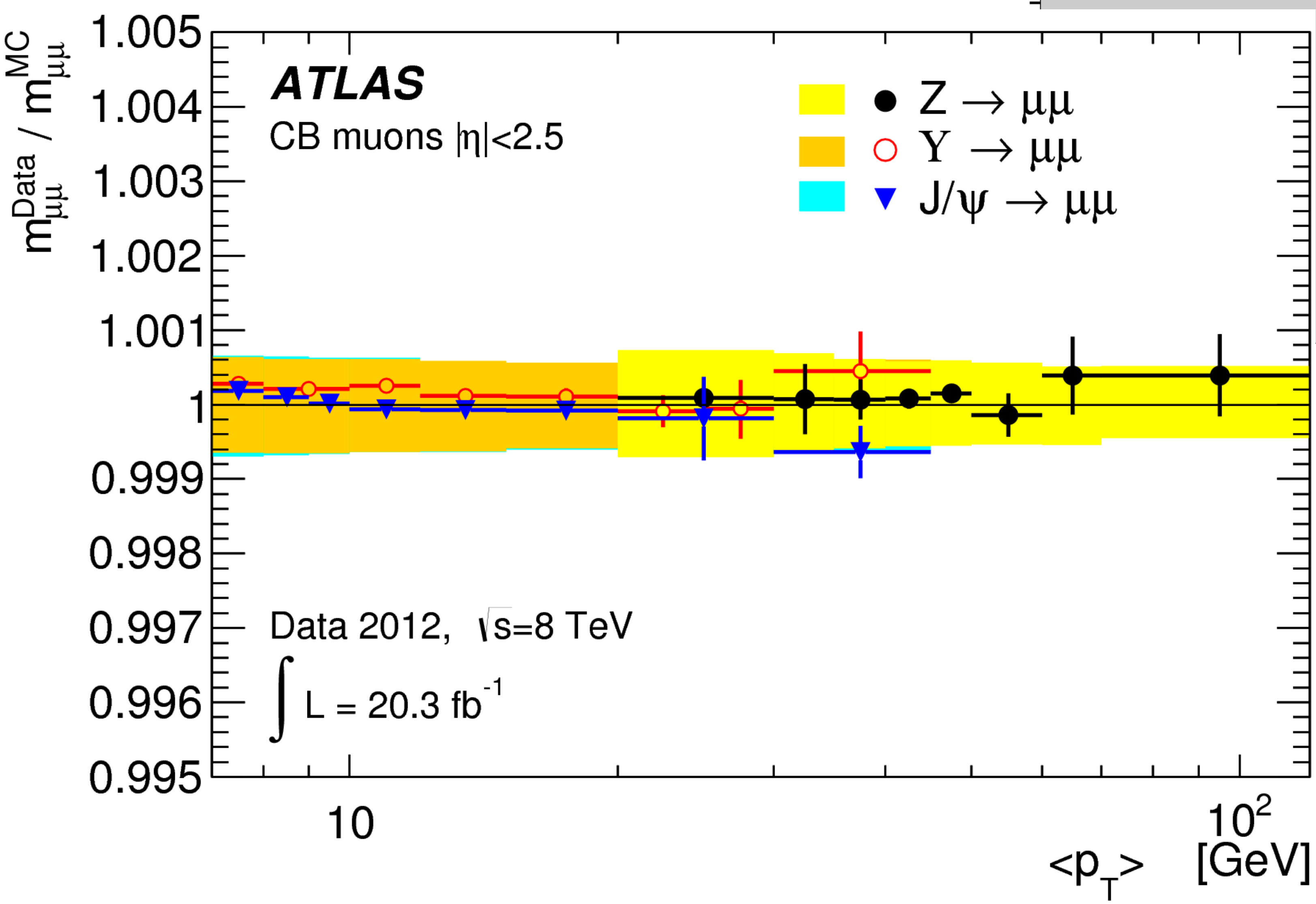


Mass Measurement

Use high-resolution **H → γγ** and **H → ZZ* → 4ℓ** channels:

- Calibrate detector as well as possible

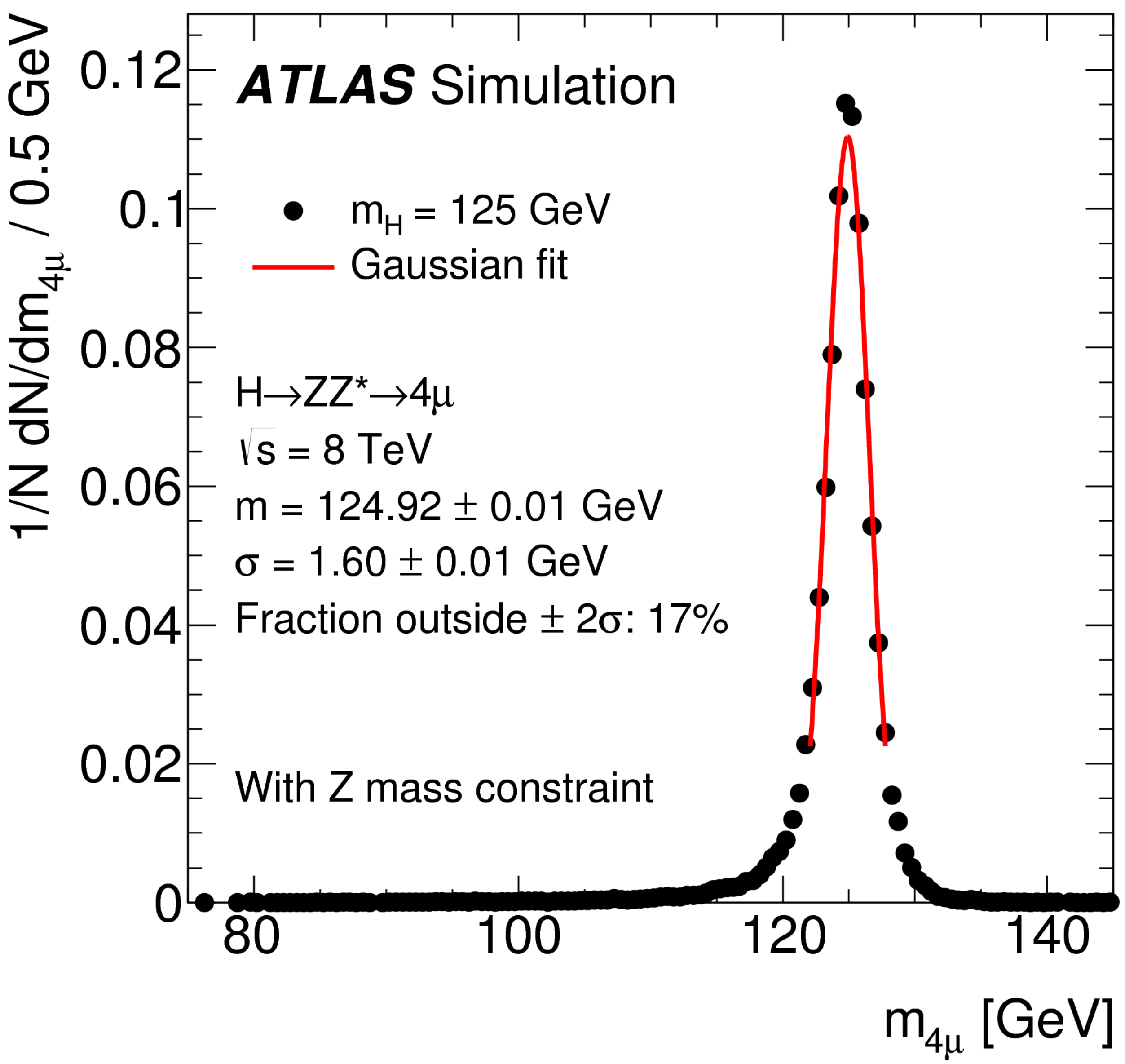


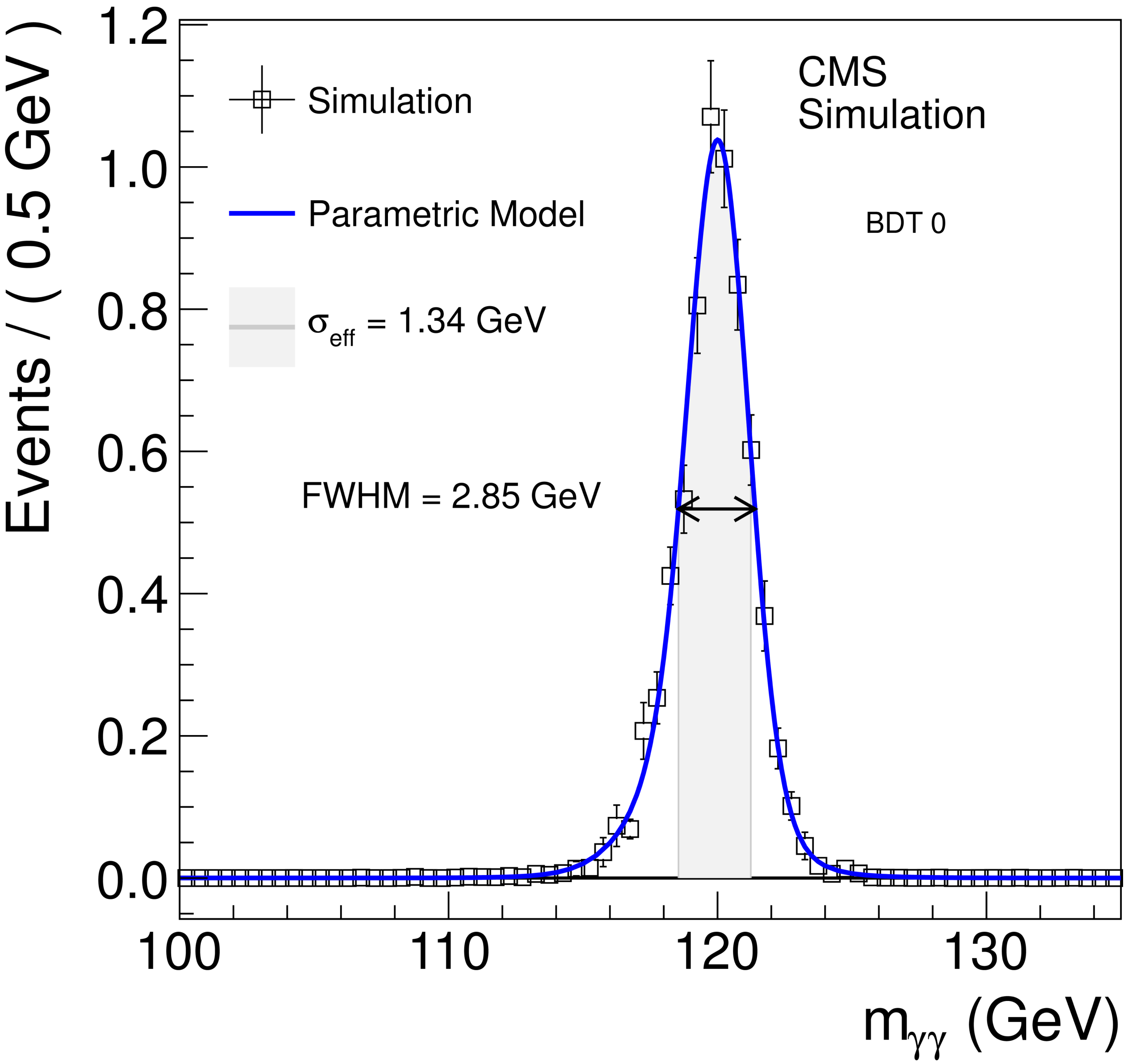


Mass Measurement

Use high-resolution $H \rightarrow \gamma\gamma$ and $H \rightarrow ZZ^* \rightarrow 4l$ channels:

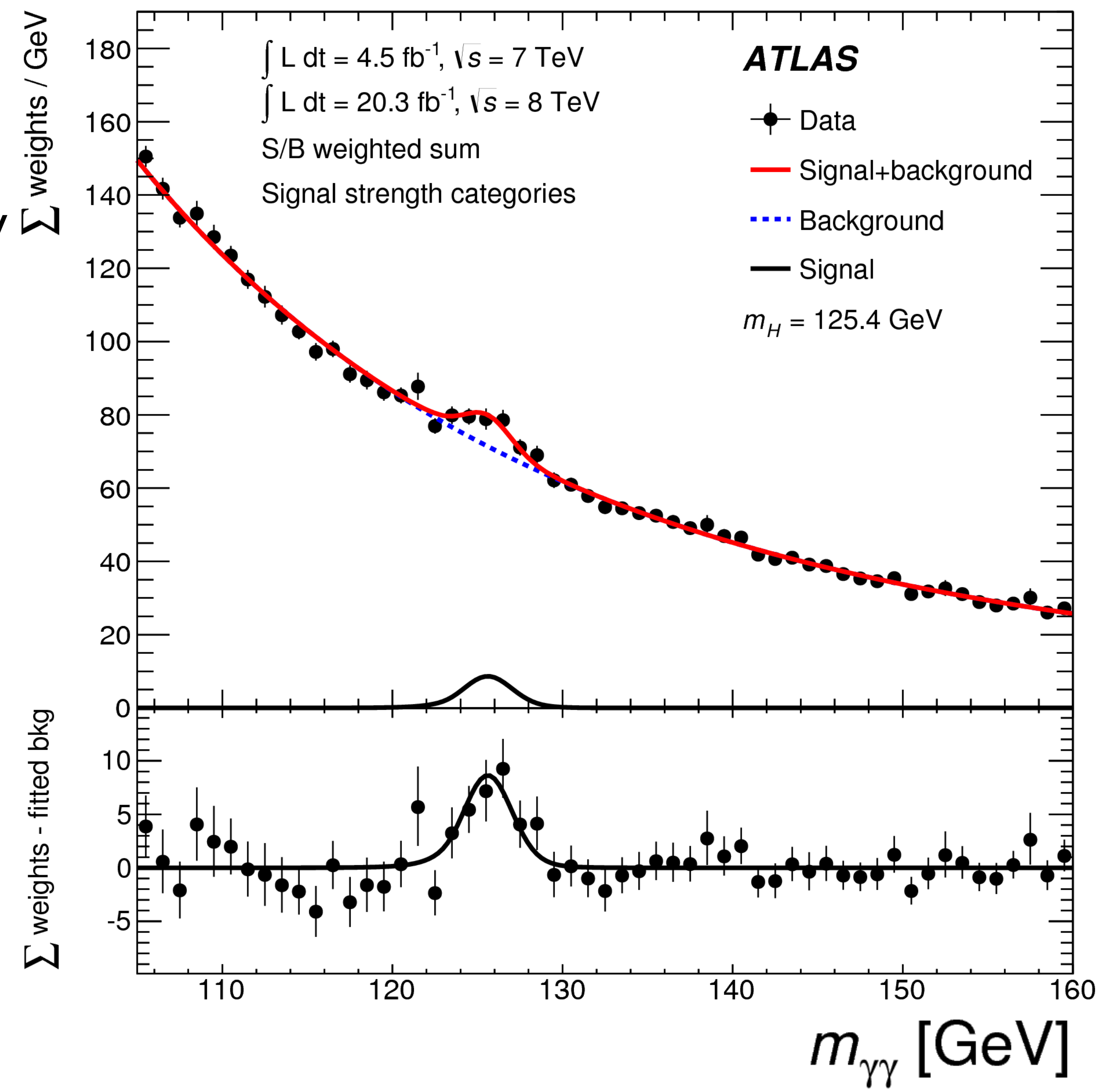
1. Calibrate your detector as good as possible
2. Determine signal line shape





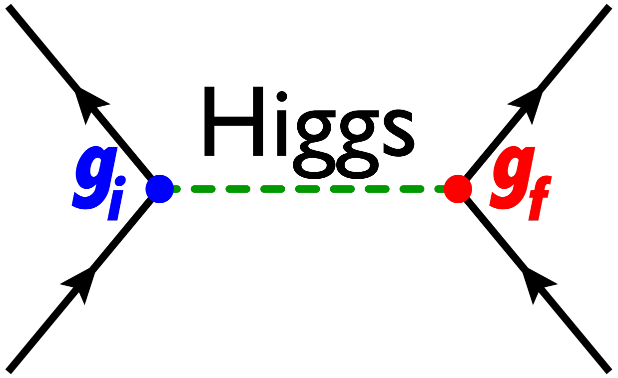
Higgs Boson Width

- Expected width: $\Gamma_{H,SM} \approx 4$ MeV
  - Too small to be measured (exp. resolution: 1-2 GeV)
  - Direct limits: $\Gamma_H < 1.7$ GeV ($\sim 400 \times \Gamma_{H,SM}$)



Indirect Contraints on Higgs Boson Width

- Idea:



  - Cross-section on-resonance:

$$\sigma^{\rm on}_{i\to H\to f} = \int \frac{g_{\rm i}^2 g_{\rm f}^2}{(s-m_{\rm H}^2)^2 + \Gamma_{\rm H}^2 m_{\rm H}^2} ds$$

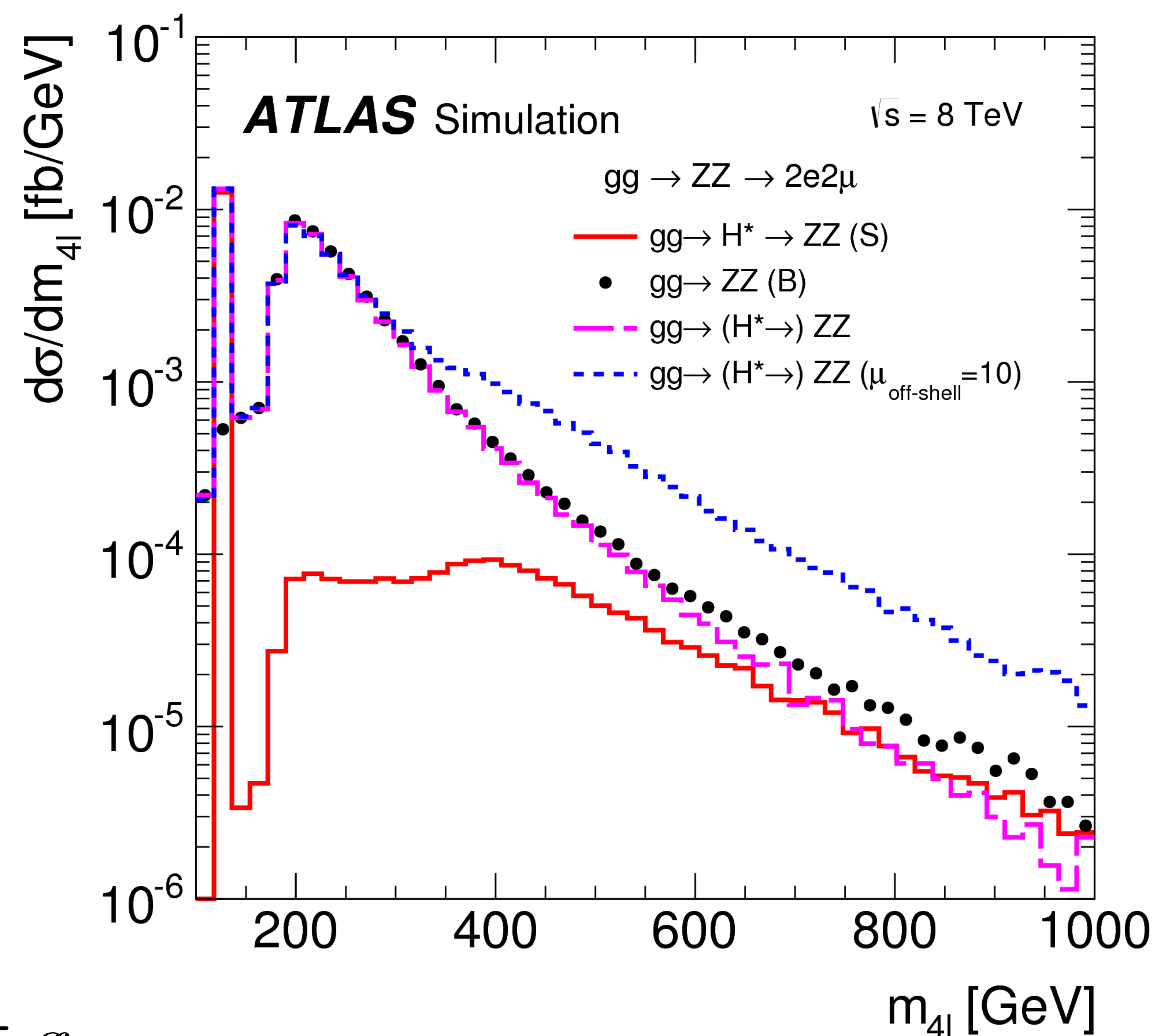
$$\propto \frac{g_{\rm i}^2 g_{\rm f}^2}{\Gamma_{\rm H}}$$

  - Cross section far above resonance ("off-shell"):

$$\sigma^{\rm off}_{i\to H\to f} = \int \frac{g_{\rm i}^2 g_{\rm f}^2}{(s-m_{\rm H}^2)^2 + \Gamma_{\rm H}^2 m_{\rm H}^2} ds$$

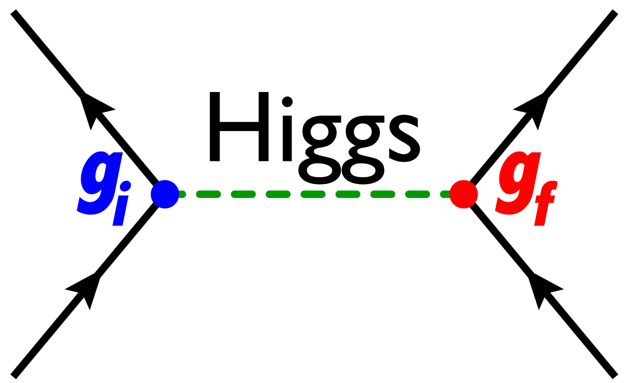
$$\propto g_{\rm i}^2 g_{\rm f}^2$$

  - Measure ratio of both: $\Gamma_{\rm H} \propto \frac{\sigma_{\rm off}}{\sigma_{\rm on}}$



Indirect Contraints on Higgs Boson Width

- Idea:



  - Cross-section on-resonance:

$$\sigma^{\text{on}}_{i\to H\to f} = \int \frac{g_{\text{i}}^2 g_{\text{f}}^2}{(s-m_{\text{H}}^2)^2 + \Gamma_{\text{H}}^2 m_{\text{H}}^2} ds$$

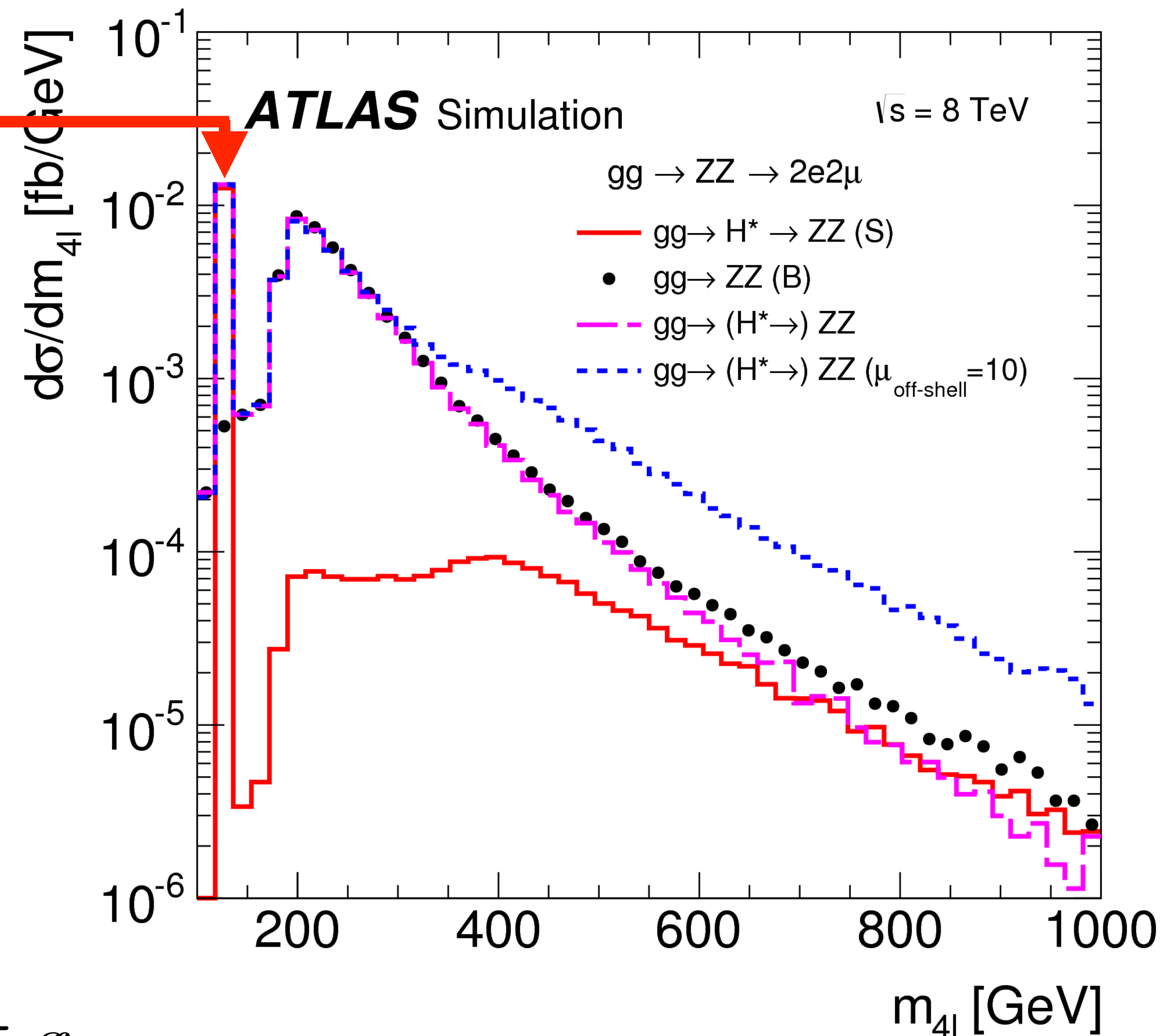
$$\propto \frac{g_{\text{i}}^2 g_{\text{f}}^2}{\Gamma_{\text{H}}}$$

  - Cross section far above resonance ("off-shell"):

$$\sigma^{\text{off}}_{i\to H\to f} = \int \frac{g_{\text{i}}^2 g_{\text{f}}^2}{(s-m_{\text{H}}^2)^2 + \Gamma_{\text{H}}^2 m_{\text{H}}^2} ds$$

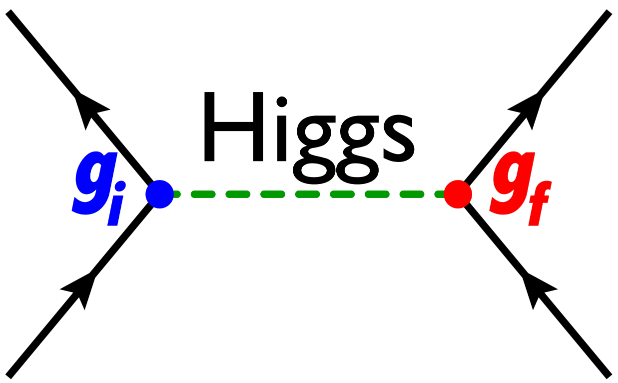
$$\propto g_{\text{i}}^2 g_{\text{f}}^2$$

  - Measure ratio of both: $\Gamma_{\text{H}} \propto \frac{\sigma_{\text{off}}}{\sigma_{\text{on}}}$



Indirect Contraints on Higgs Boson Width

- Idea:



  - Cross-section on-resonance:

$$\sigma^{\mathrm{on}}_{i\to H\to f} = \int \frac{g_{\mathrm{i}}^2 g_{\mathrm{f}}^2}{(s-m_{\mathrm{H}}^2)^2 + \Gamma_{\mathrm{H}}^2 m_{\mathrm{H}}^2} ds$$

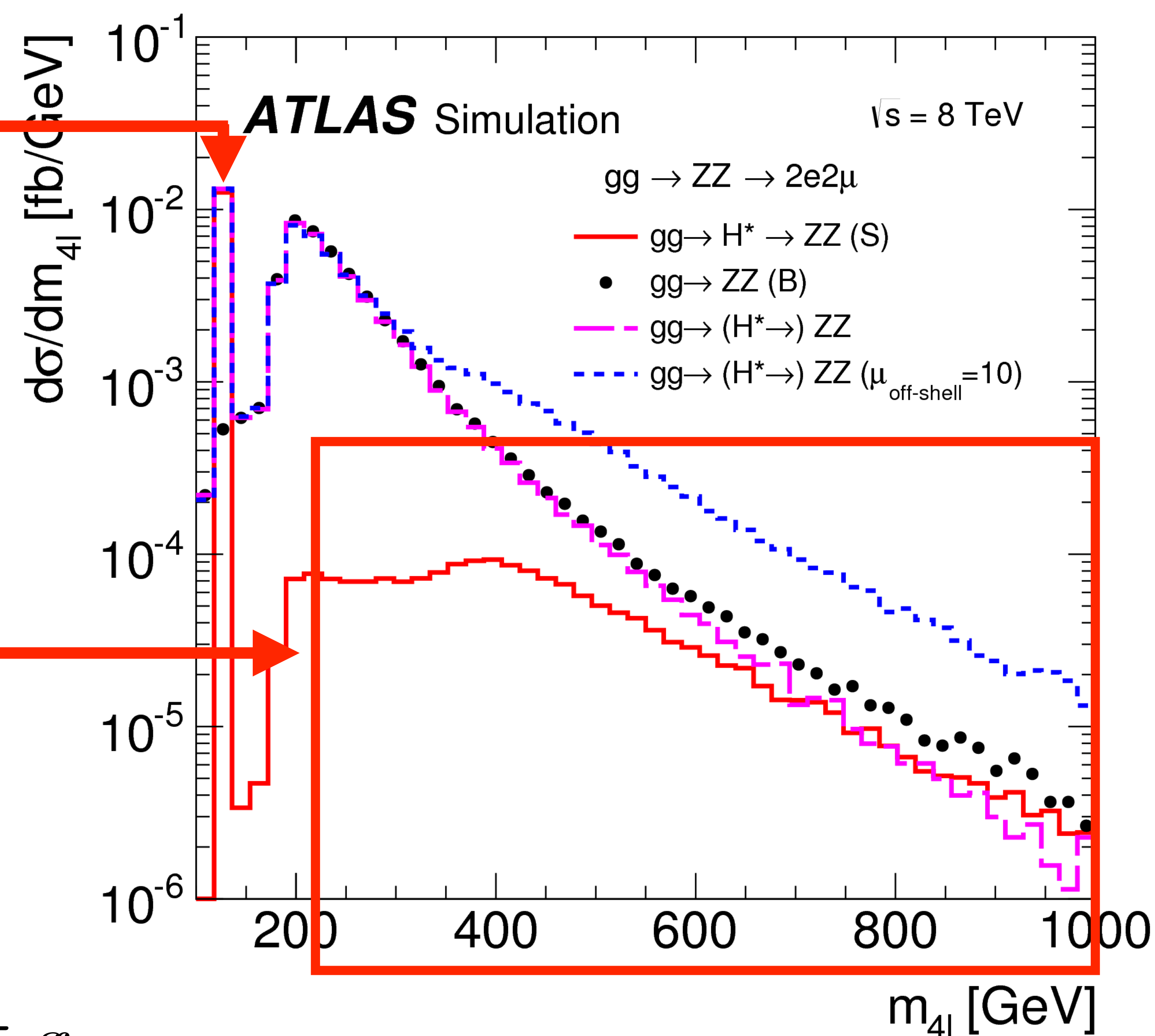
$$\propto \frac{g_{\mathrm{i}}^2 g_{\mathrm{f}}^2}{\Gamma_{\mathrm{H}}}$$

  - Cross section far above resonance ("off-shell"):

$$\sigma^{\mathrm{off}}_{i\to H\to f} = \int \frac{g_{\mathrm{i}}^2 g_{\mathrm{f}}^2}{(s-m_{\mathrm{H}}^2)^2 + \Gamma_{\mathrm{H}}^2 m_{\mathrm{H}}^2} ds$$

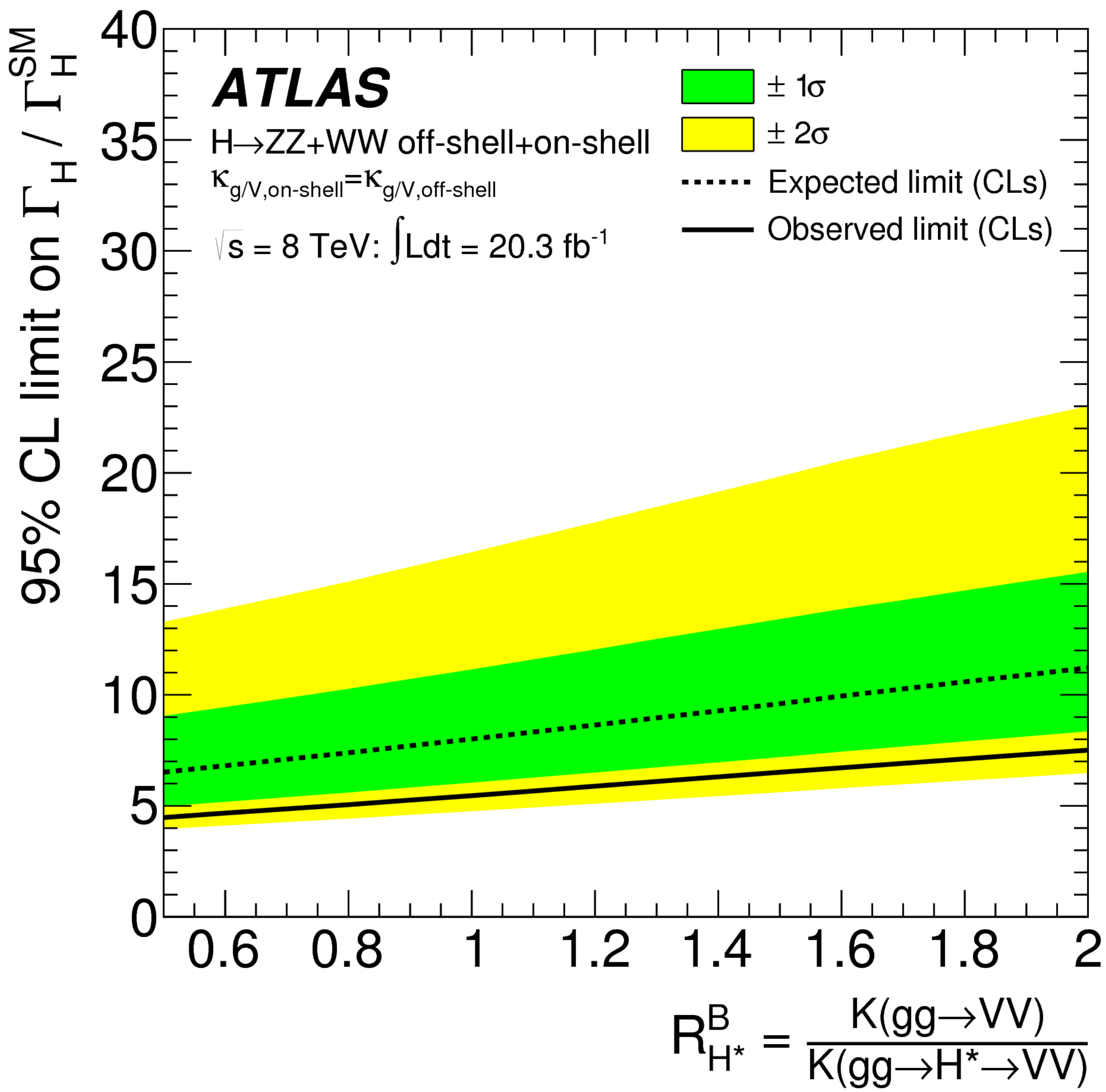
$$\propto g_{\mathrm{i}}^2 g_{\mathrm{f}}^2$$

  - Measure ratio of both: $\Gamma_{\mathrm{H}} \propto \frac{\sigma_{\mathrm{off}}}{\sigma_{\mathrm{on}}}$



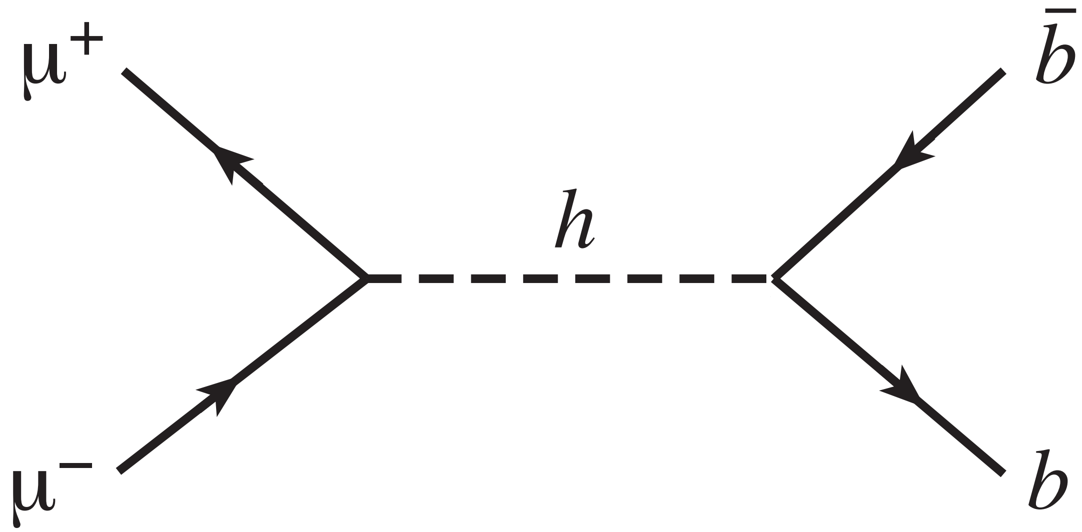
Indirect Contraints on Higgs Boson Width

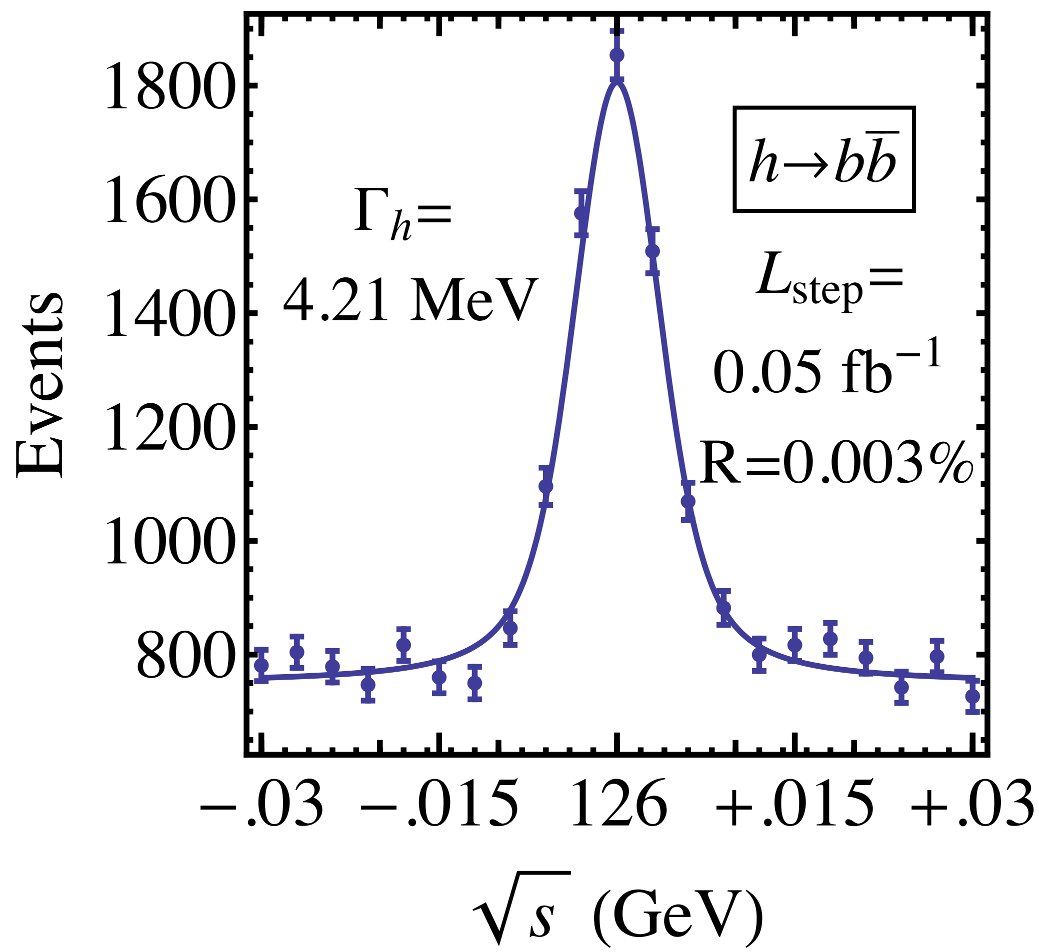
- Use H → WW$^{(*)}$ and H → ZZ$^{(*)}$
- ATLAS result: **Γ_H < 22.7 MeV** @ 95% CL (5.5 × $\Gamma_{H,SM}$)
- Caveats:
  - gg → WW and gg → ZZ cross sections not well known
    - Vary by factor 2
  - New physics effects could change high-mass behavior
  - Assuming on-shell coupling is same as off-shell coupling
    - Disputed assumption



Only direct Width Measurement

- s-channel production at future muon collider:



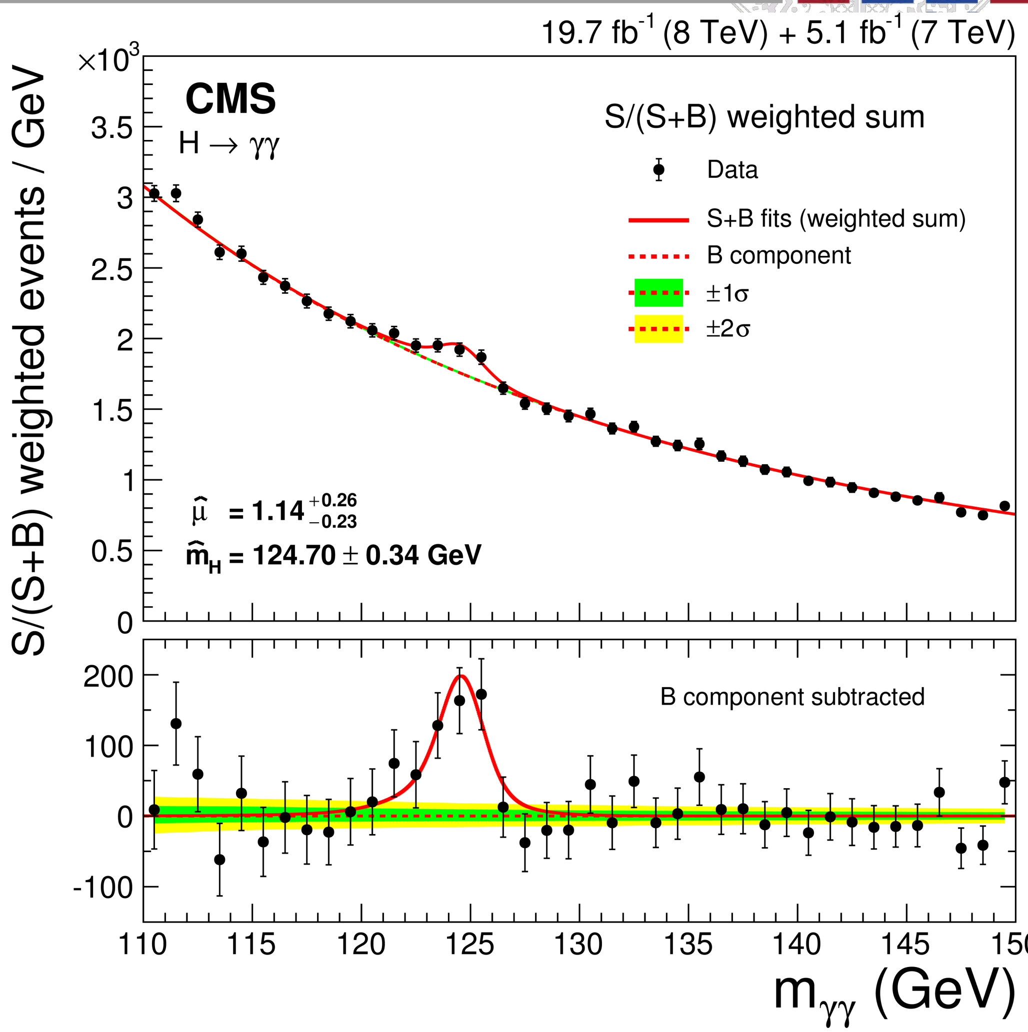


- Precision ~5%

(arxiv:1308.2143)

Higgs Boson Width

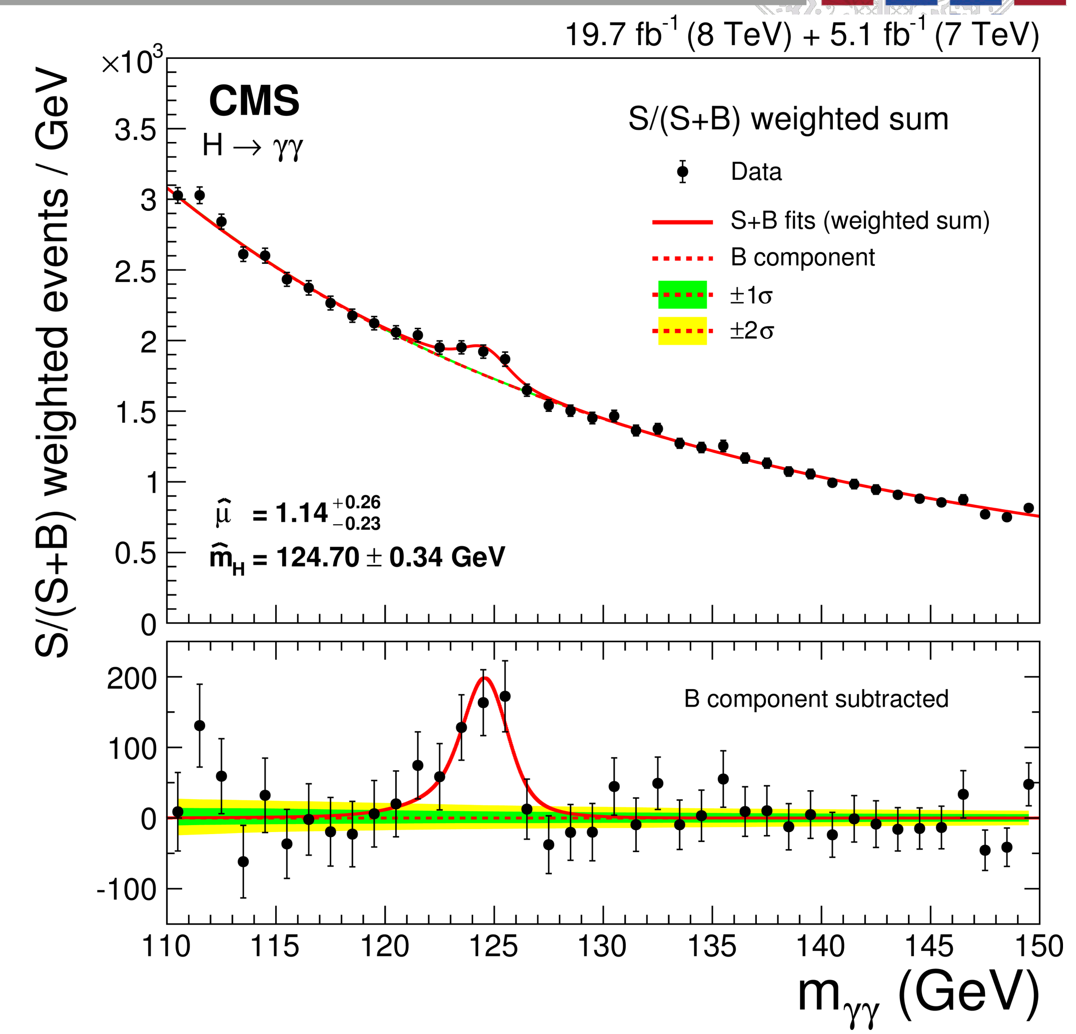
- Expected width: $\Gamma_{H,SM} \approx 4$ MeV
  - Too small to measure (exp. resolution: 1-2 GeV)
  - Direct limits: $\Gamma_H < 1.7$ GeV ($\sim 400 \times \Gamma_{H,SM}$)

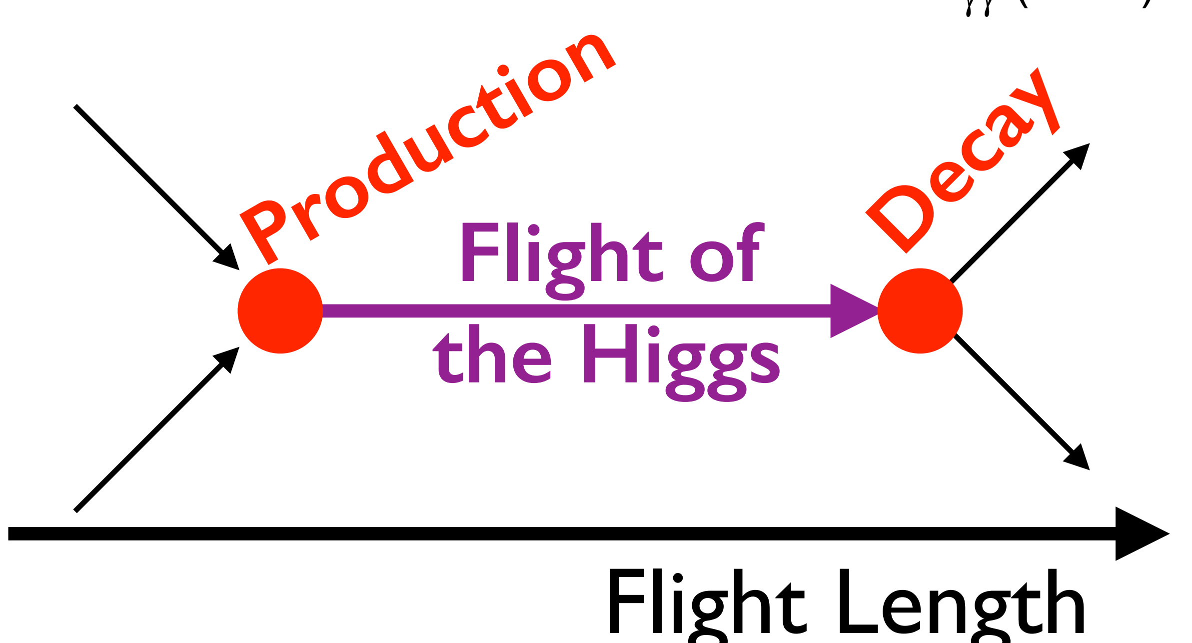


Higgs Boson Width

- Expected width: $\Gamma_{H,SM} \approx 4$ MeV
  - Too small to measure (exp. resolution: 1-2 GeV)
  - Direct limits: $\Gamma_H < 1.7$ GeV ($\sim 400 \times \Gamma_{H,SM}$)
- Maybe via lifetime, i.e., if it flies far enough?
  - $\tau = \hbar/\Gamma \approx 1.6 \times 10^{-22}$ s $\Rightarrow c\tau \approx 5 \times 10^{-14}$ m

    $\Rightarrow$ too short to measure



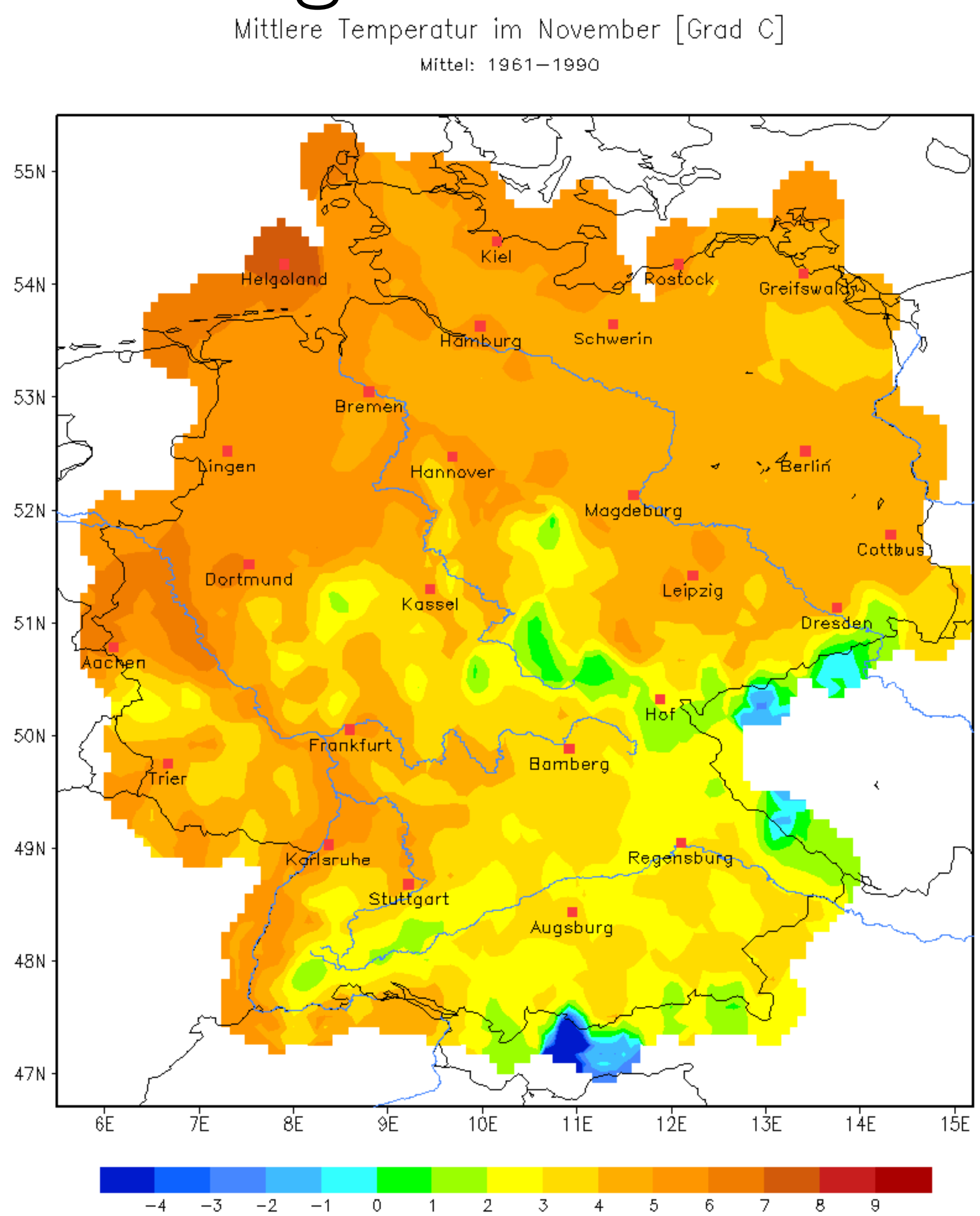


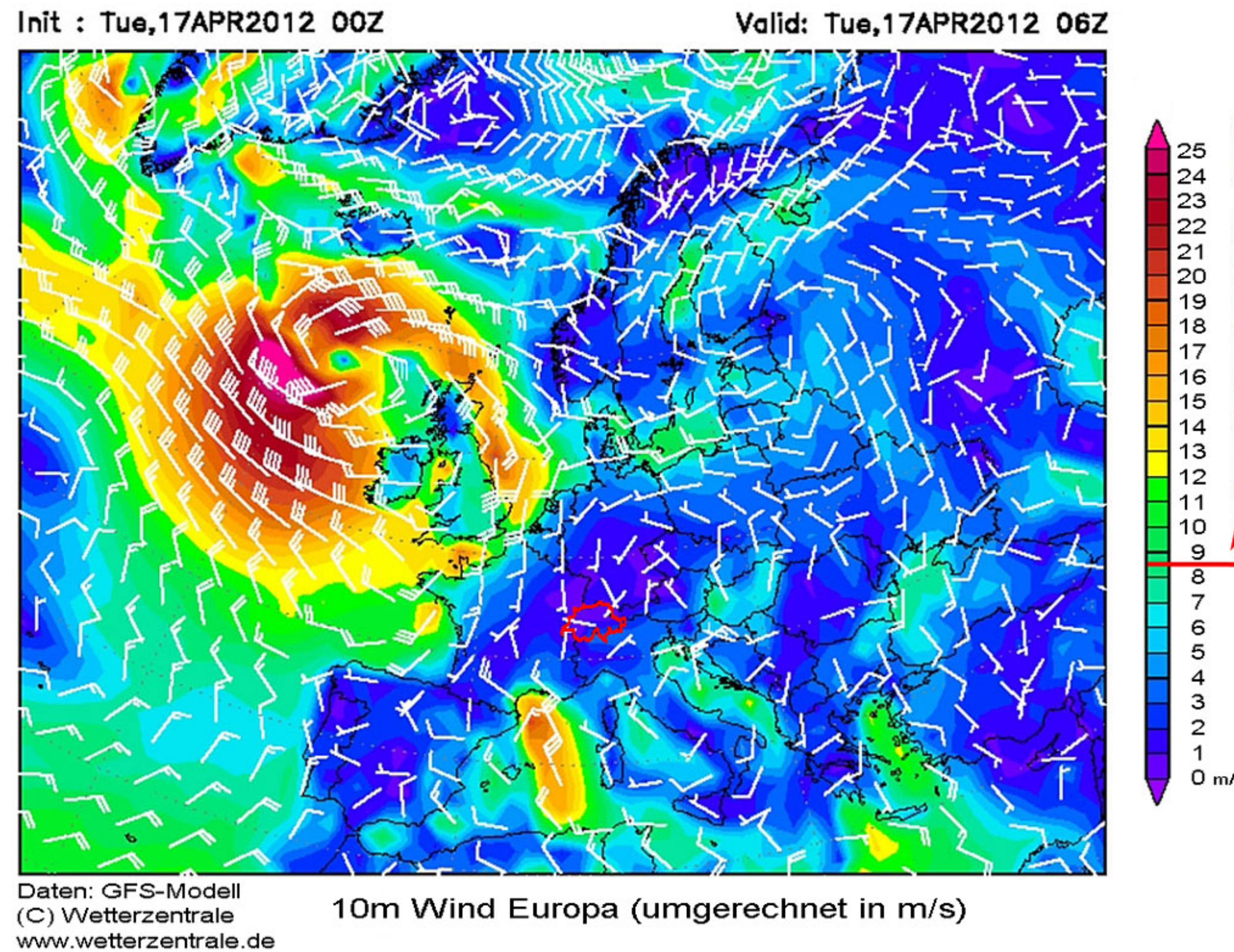
Why Spin 0 and even Parity?

- Should have same quantum numbers as observed vacuum:
  - No charge: 👍
  - Rotationally invariant, *i.e.*, no preferred direction
  - Invariant under ***Parity*** (“mirror”) transformation: $\hat{P}\ \vec{x} \longrightarrow -\vec{x}$

Why Spin 0 and even Parity?

Analogon:





Temperature: T(x,y,z,t)

Each point has magnitude ⇒ **Spin 0**

Windspeed: $\vec{W}$(x,y,z,t)

Each point has also direction ⇒ **Spin 1**

Why Spin 0 and even Parity?

- Should have same quantum numbers as observed vacuum:
  - No charge: 👍
  - Rotationally invariant, *i.e.*, no preferred direction
  - Invariant under ***Parity*** ("mirror") transformation: $\hat{P}\,\vec{x} \longrightarrow -\vec{x}$
- Mass cannot depend on direction
  ⇒ Higgs-field must be **Spin 0**
- Vacuum invariant unter mirror transformation:
  $\hat{P}\,\Psi(\vec{x},t) = \Psi(-\vec{x},t) = +\Psi(\vec{x},t)$
  ⇒ **even parity:** $\mathbf{P \overset{!}{=}}$ **"+"**

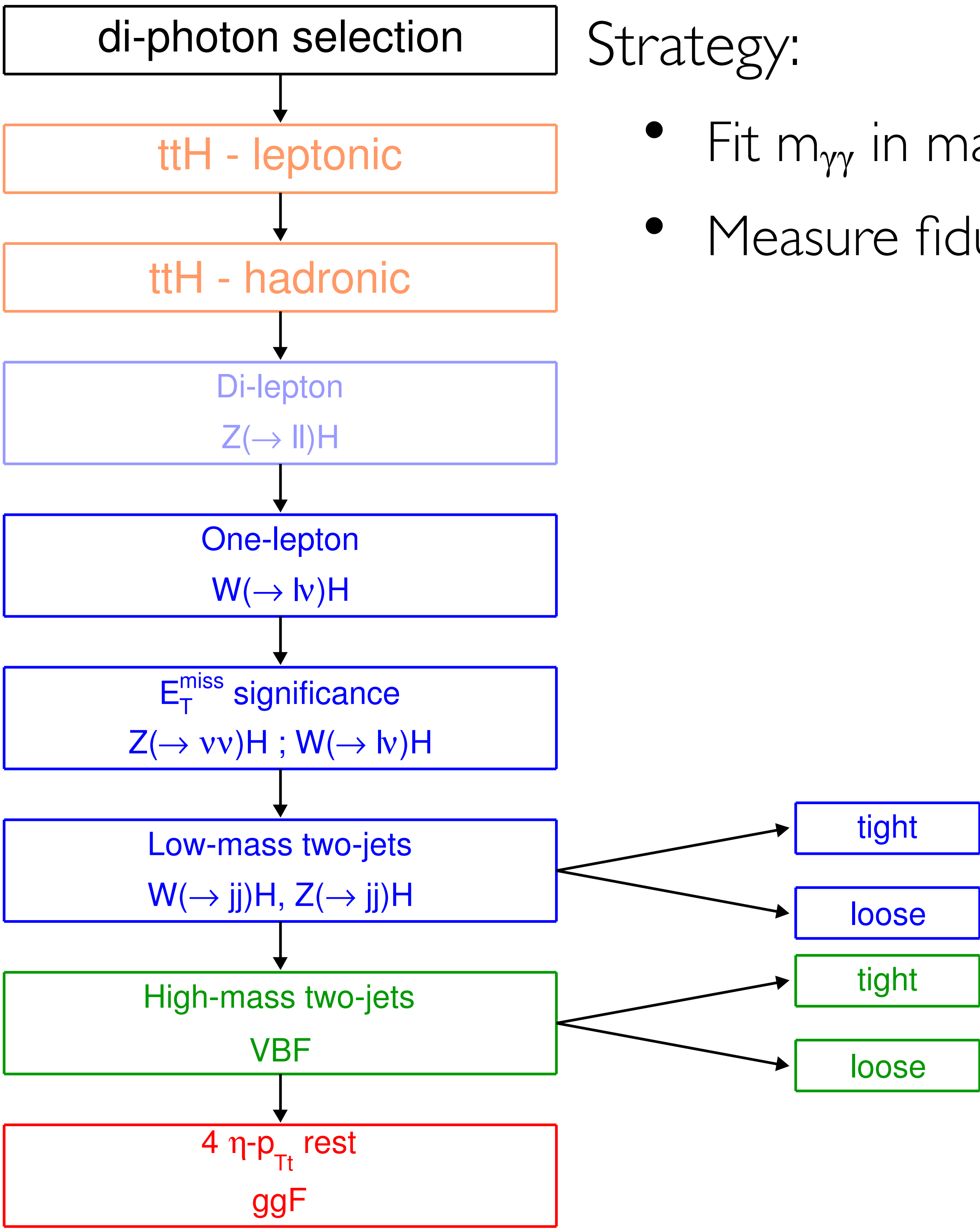
μ-dependence on κ for WW and ZZ

$$\mu_{\mathrm{ggF}} \propto \frac{\kappa_F^2 \cdot \kappa_V^2}{\left(\mathcal{B}_{H \to f\bar{f}} + \mathcal{B}_{H \to gg}\right)\kappa_F^2 + \left(\mathcal{B}_{H \to VV}\right)\kappa_V^2}$$

$$\mu_{\mathrm{VBF}} \propto \frac{\kappa_V^4}{\left(\mathcal{B}_{H \to f\bar{f}} + \mathcal{B}_{H \to gg}\right)\kappa_F^2 + \left(\mathcal{B}_{H \to VV}\right)\kappa_V^2}$$

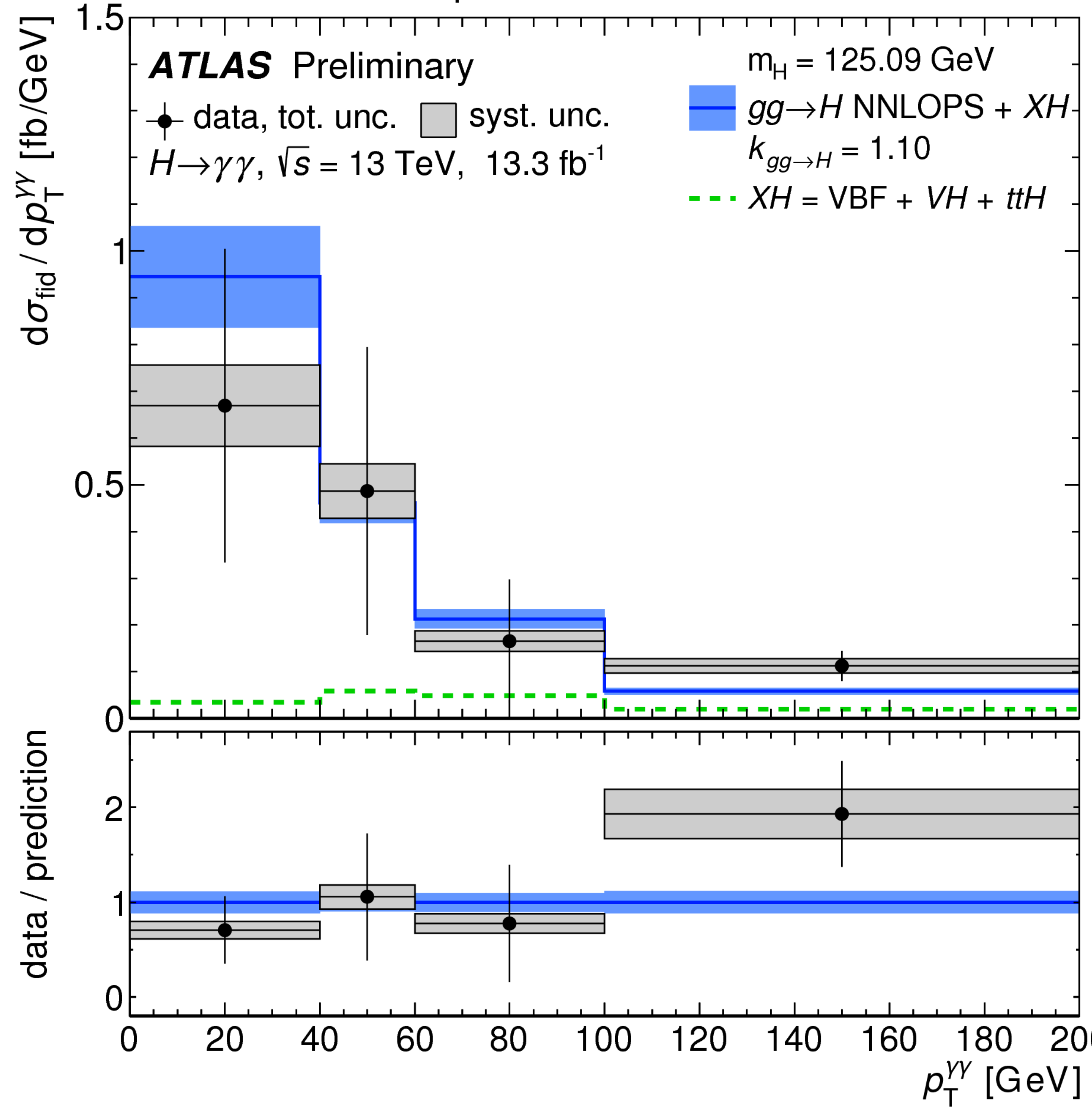
$H \rightarrow \gamma\gamma$

ATL-CONF-2016-067



Strategy:

- Fit $m_{\gamma\gamma}$ in many production mode sensitive categories
- Measure fiducial, differential, and production cross-sections

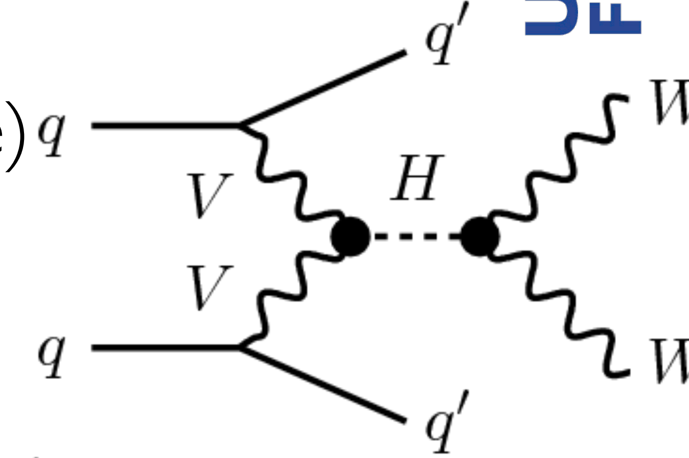


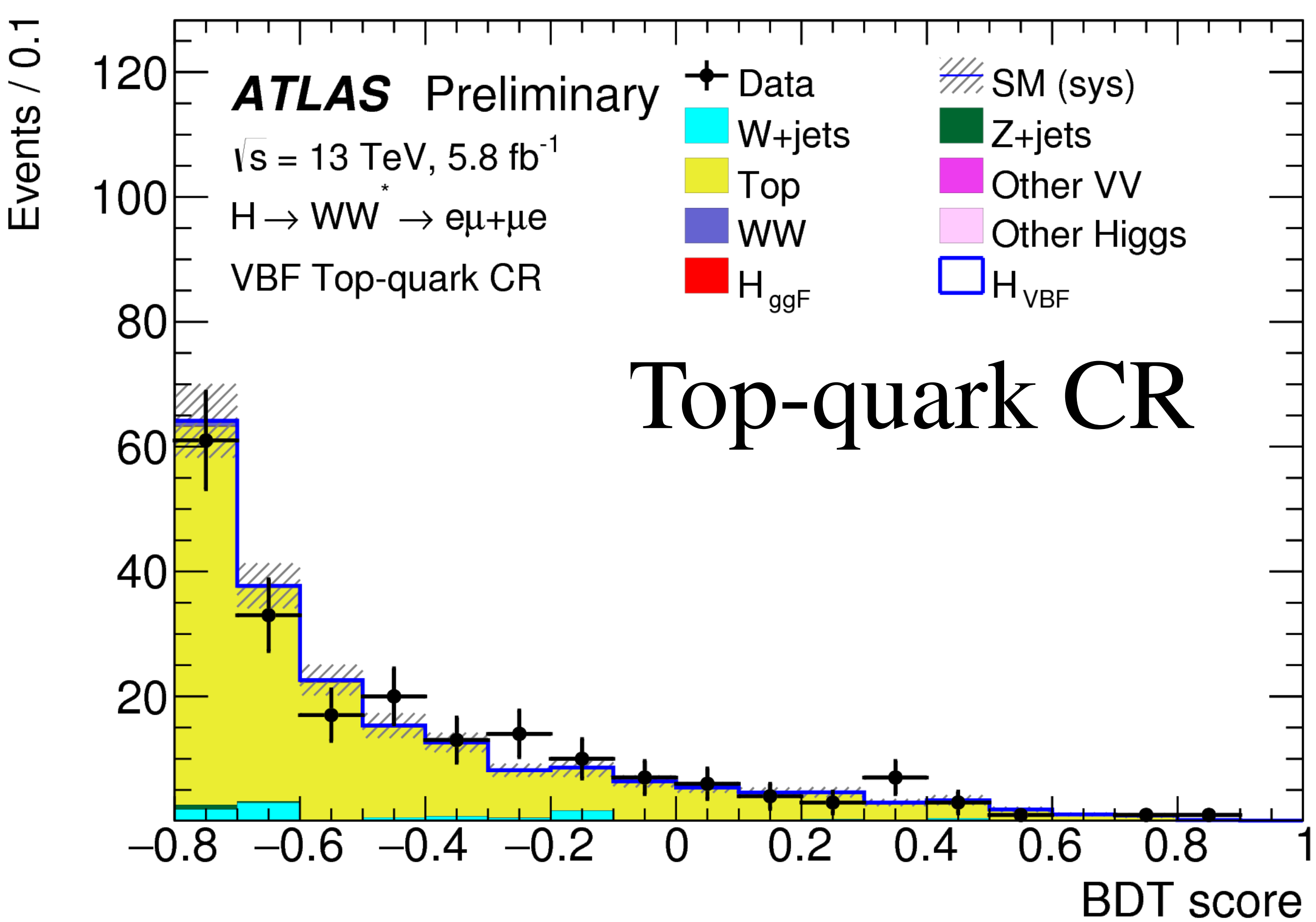
VBF $H \to WW^* \to \ell\nu\ell\nu$

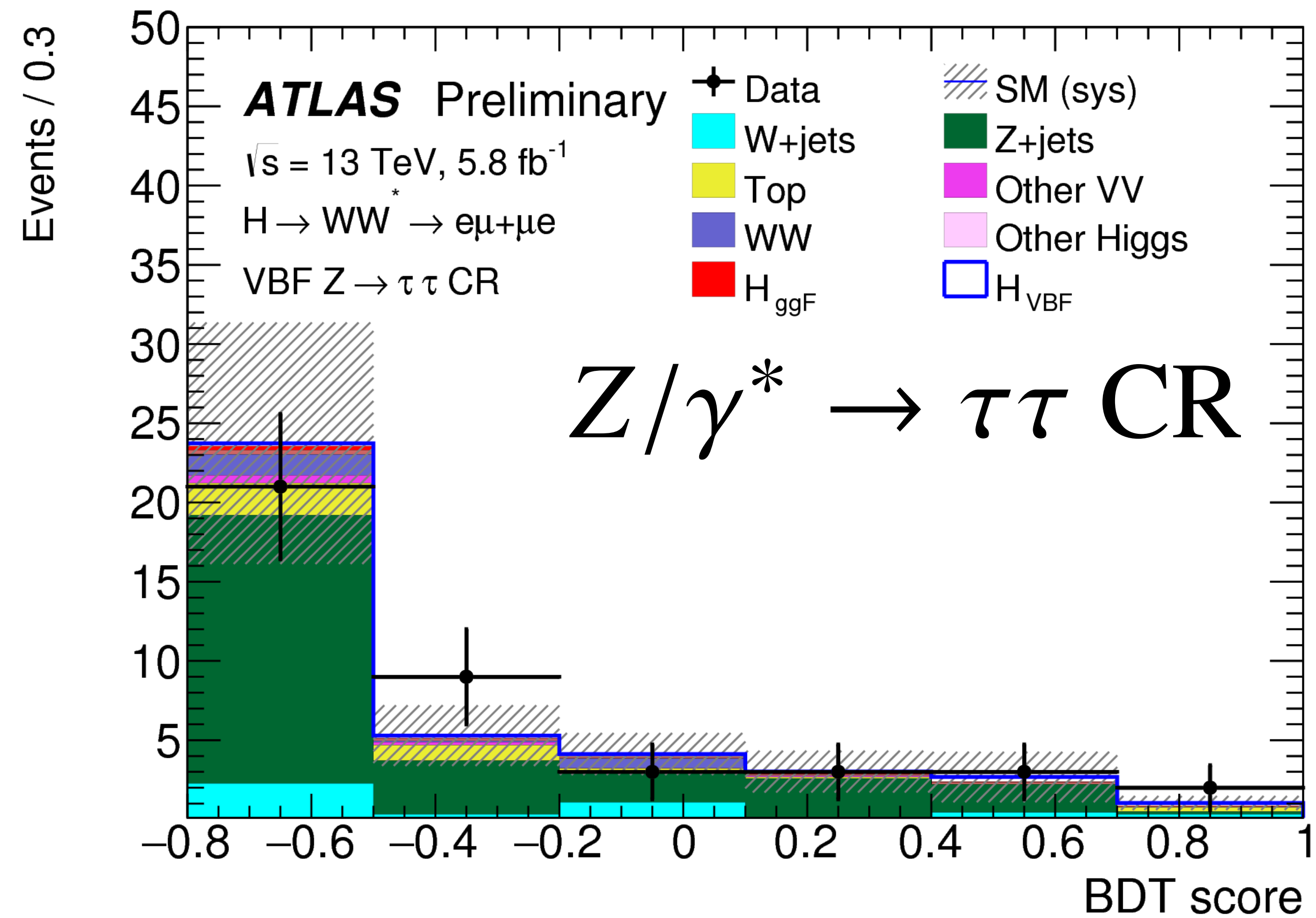
ATL-CONF-2016-112

Strategy:

- Isolated electron and muon (different flavor, opposite charge)
- Combine sensitive variables in BDT
- Data-driven fake-lepton estimate from di-jet data
- Fit BDT output with Top and Z+jets normalization from dedicated control regions







Number of Input Samples

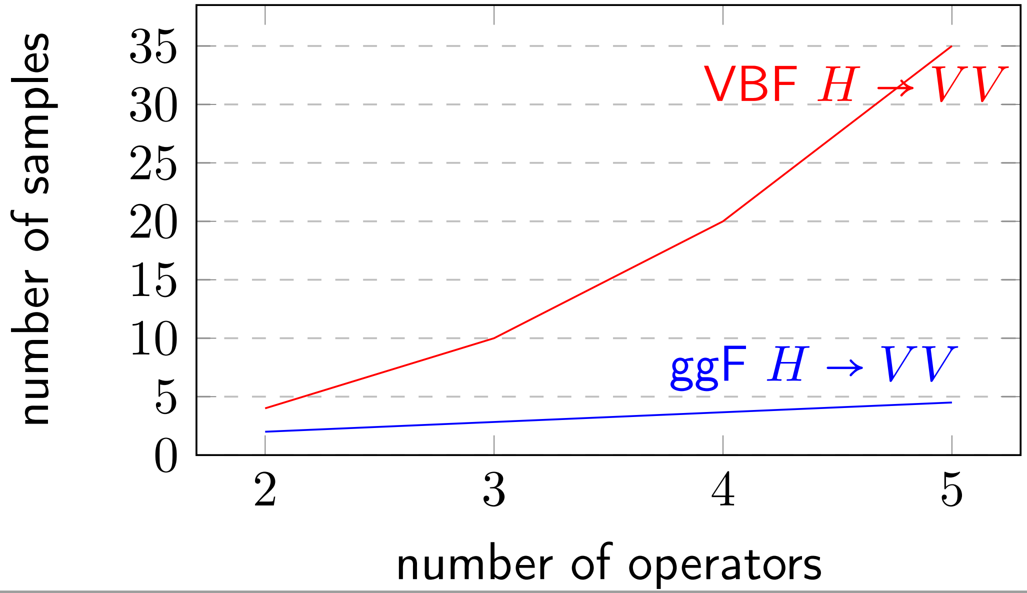
ATL-PHYS-PUB-2015-047

- As many input templates N as unique terms in $|\mathcal{M}(\vec{g})|^2$

$$T(\vec{g}) \propto |\mathcal{M}(\vec{g})|^2 = \underbrace{\left(\sum_{i=1}^{n_p+n_s} g_i \mathcal{O}_i\right)^2}_{\text{production vertex}} \cdot \underbrace{\left(\sum_{j=1}^{n_d+n_s} g_j \mathcal{O}_j\right)^2}_{\text{decay vertex}}$$

- n_s: Number of shared couplings in production and decay vertex.
- n_p: Number of couplings only in production.
- n_d: Number of couplings only in decay.

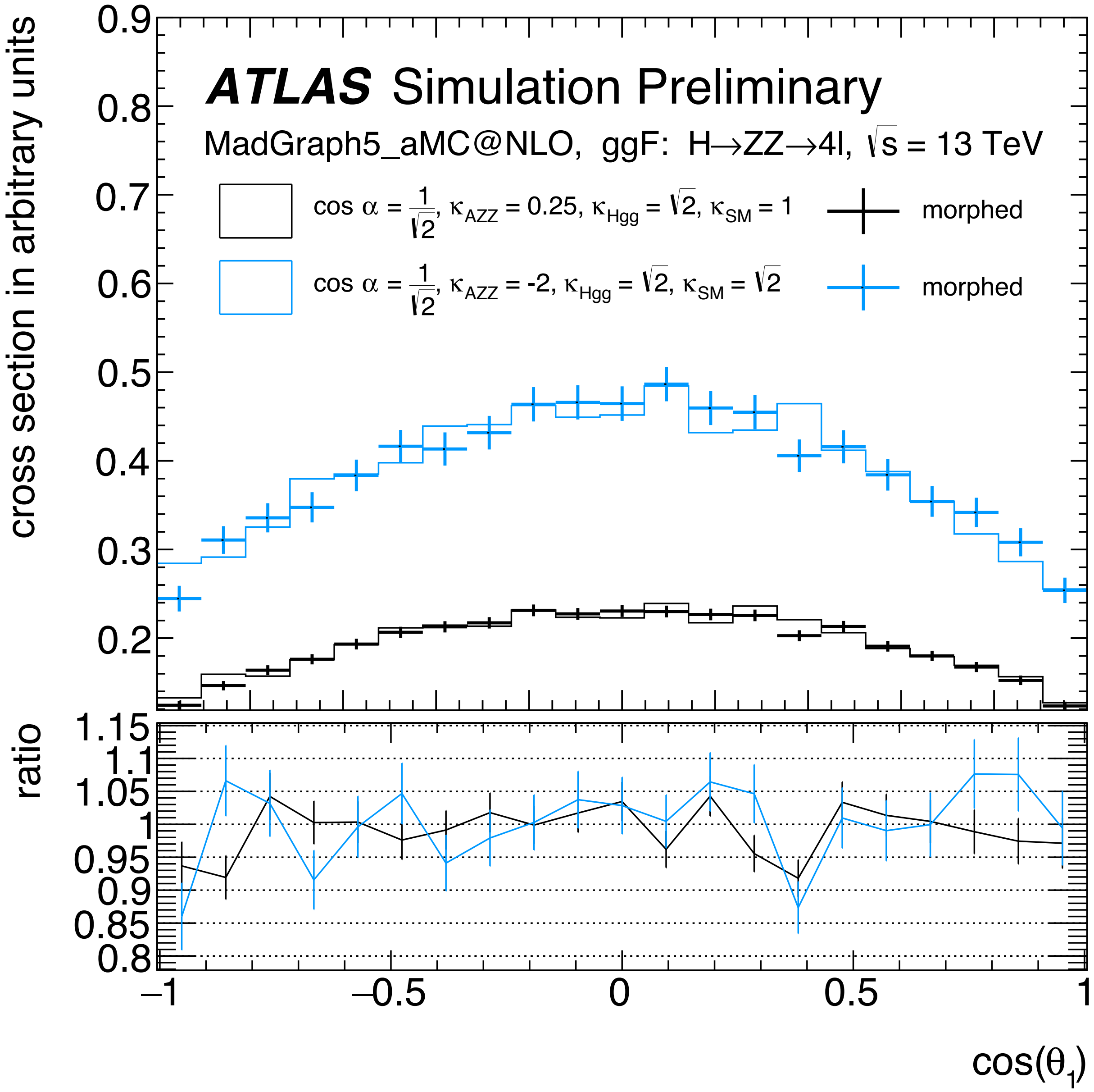
$$\begin{aligned} N = \ & \frac{n_p(n_p+1)}{2} \cdot \frac{n_d(n_d+1)}{2} + \binom{4+n_s-1}{4} \\ & + \left(n_p \cdot n_s + \frac{n_s(n_s+1)}{2}\right) \cdot \frac{n_d(n_d+1)}{2} \\ & + \left(n_d \cdot n_s + \frac{n_s(n_s+1)}{2}\right) \cdot \frac{n_p(n_p+1)}{2} \\ & + \frac{n_s(n_s+1)}{2} \cdot n_p \cdot n_d + (n_p + n_d)\binom{3+n_s-1}{3}. \end{aligned}$$

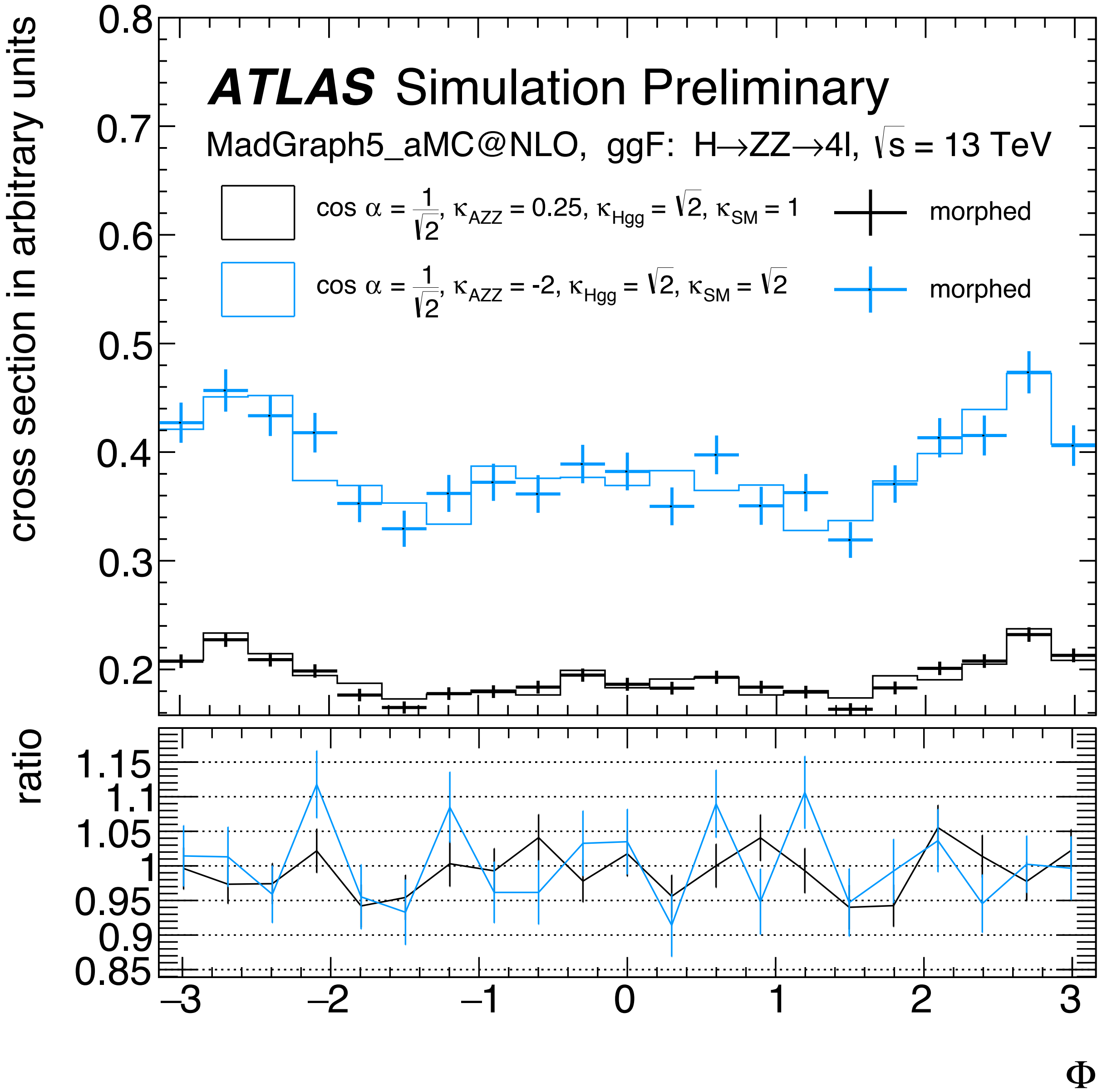


Proof-of-Concept: ggF $H \to ZZ^* \to 4\ell$

ATL-PHYS-PUB-2015-047

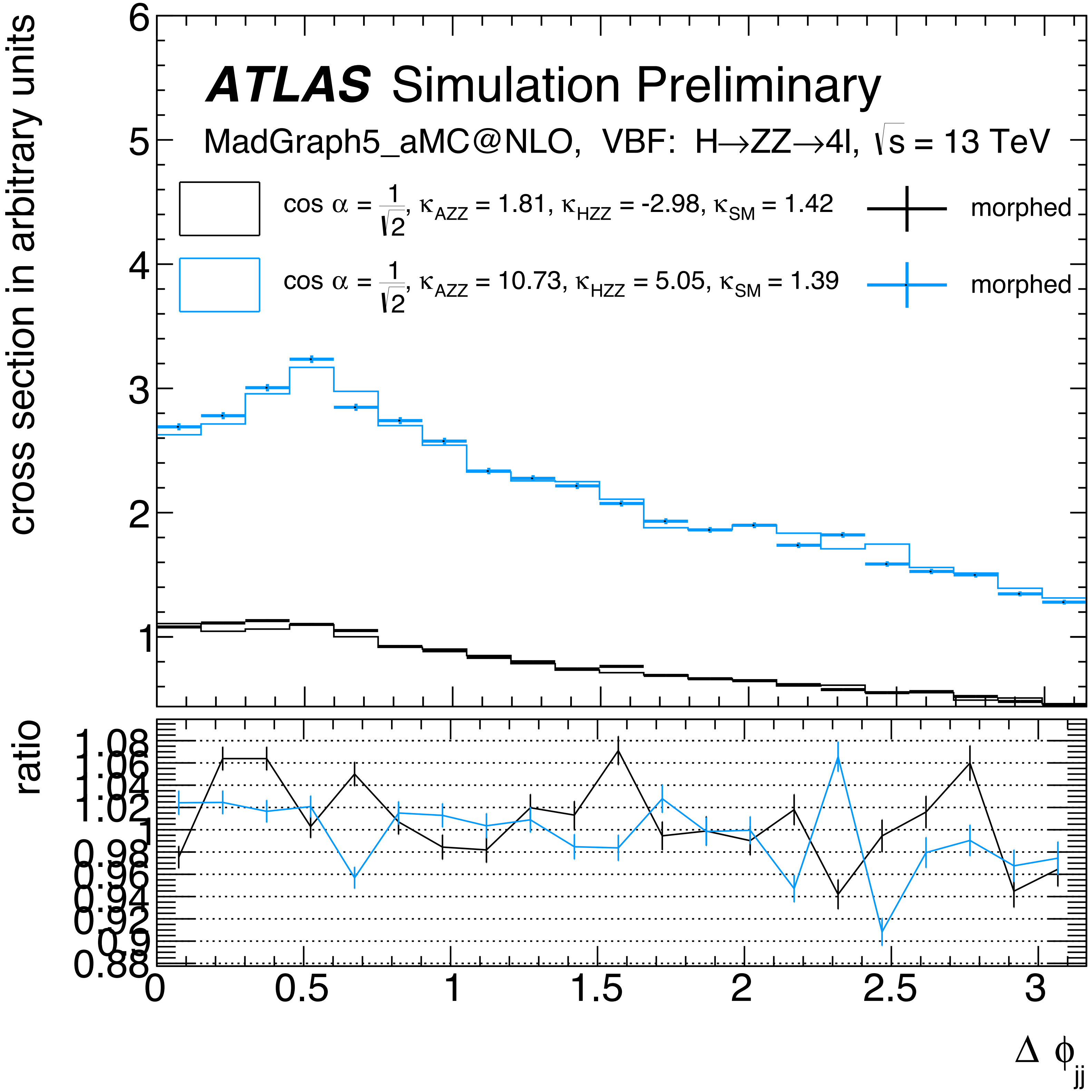
	κ_{SM}	κ_{Azz}	κ_{Hgg}	$\cos\alpha$
Input Sample 0	1.000	0.000	1.000	1.000
Input Sample 1	0.000	13.938	1.414	0.707
Input Sample 2	1.414	13.938	1.414	0.707
Validation Sample 1	1.000	0.250	1.414	0.707
Validation Sample 2	1.414	-2.000	1.414	0.707



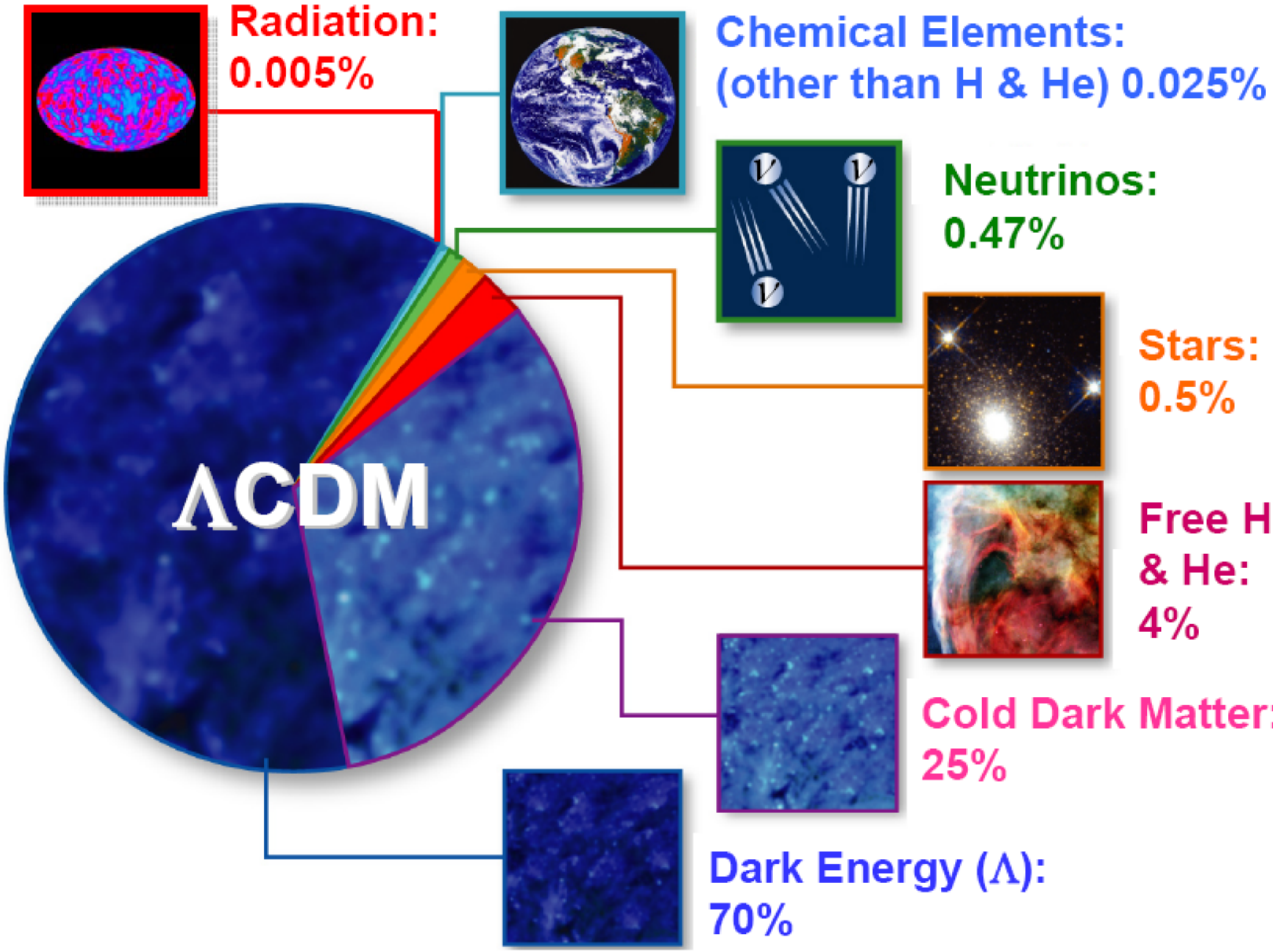


Proof-of-Concept: VBF $H \to ZZ^* \to 4\ell$

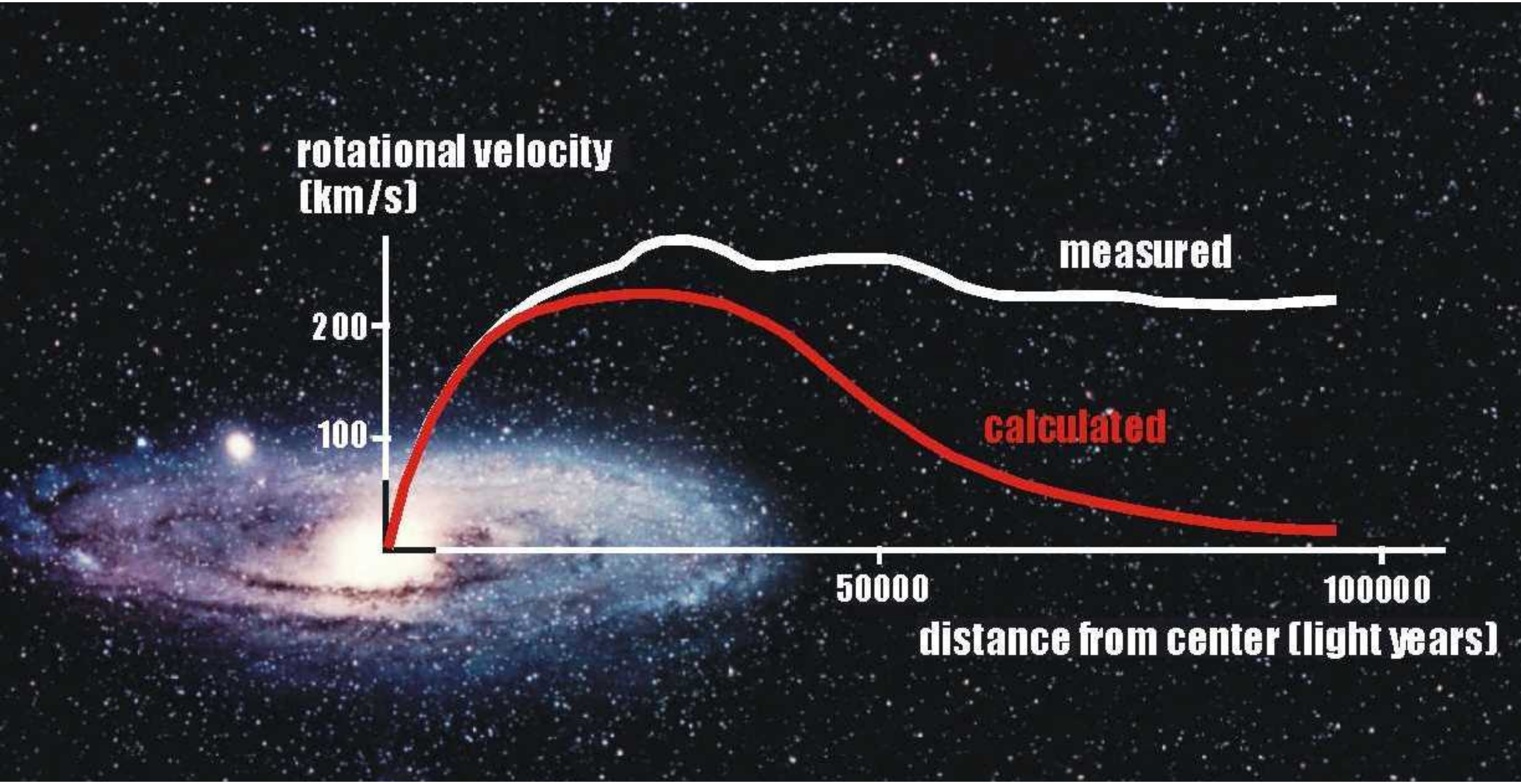
ATL-PHYS-PUB-2015-047



Mass in our Universe

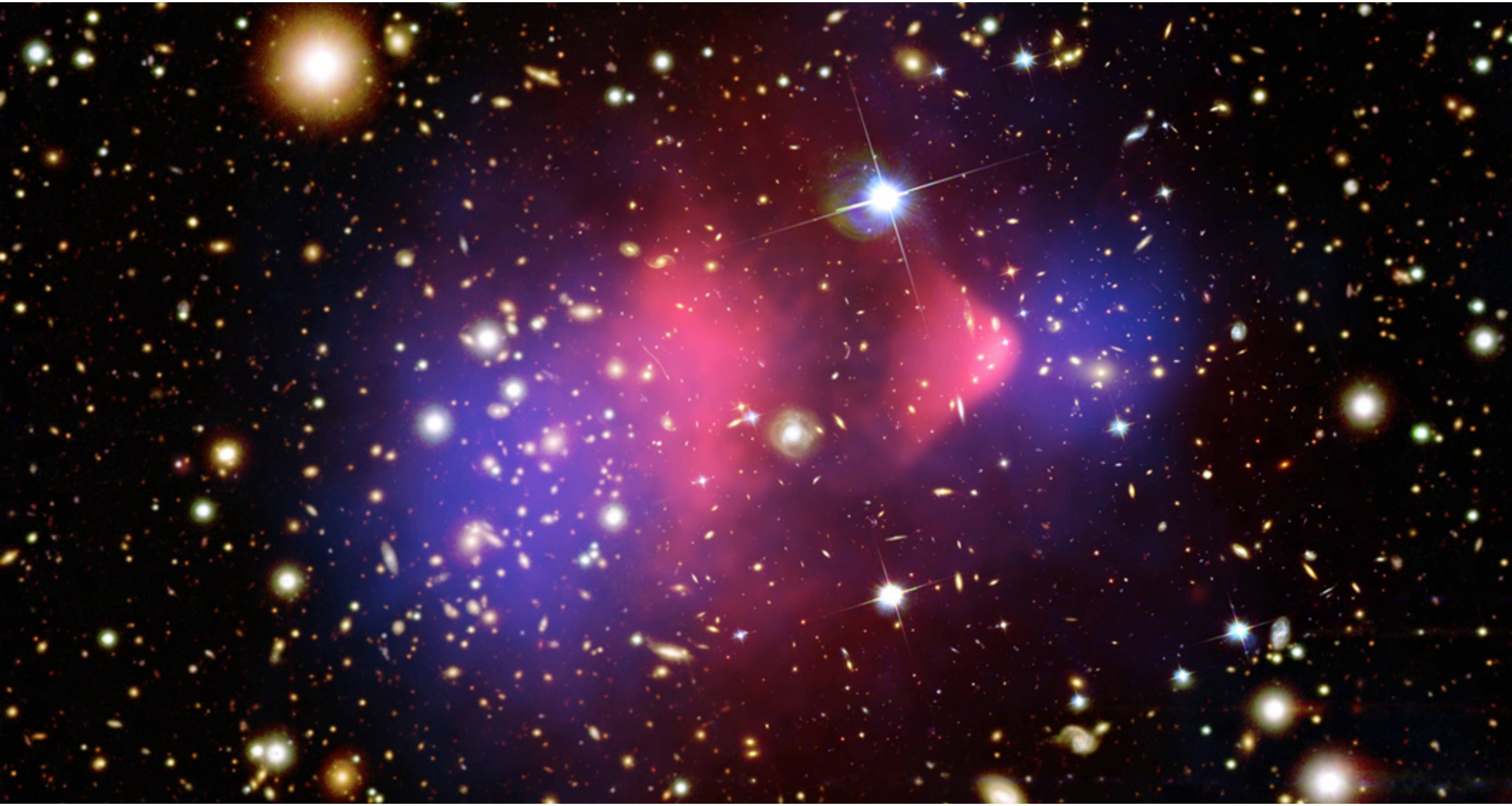


Dark matter



rotational velocity
(km/s)
200
100
measured
calculated
50000
100000
distance from center (light years)

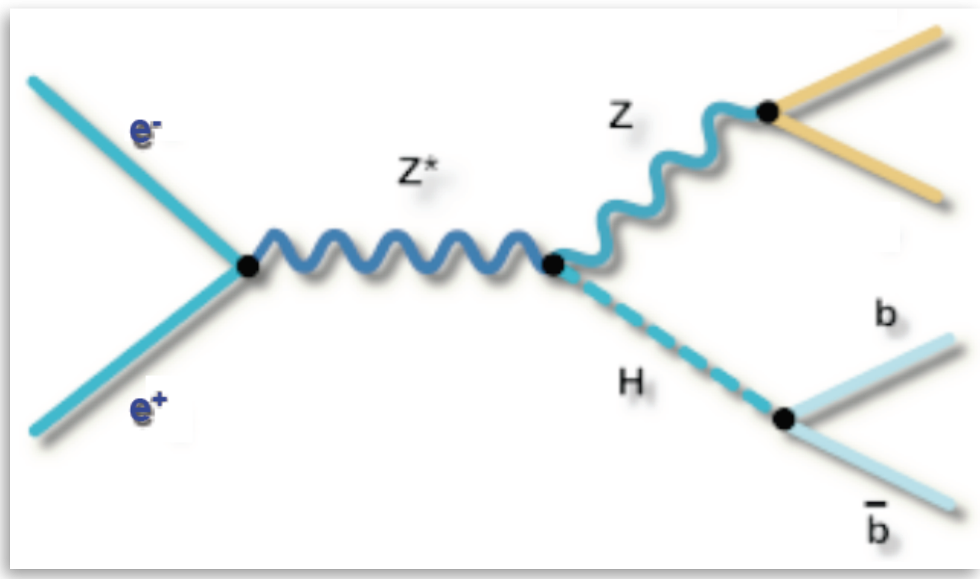
Dark matter



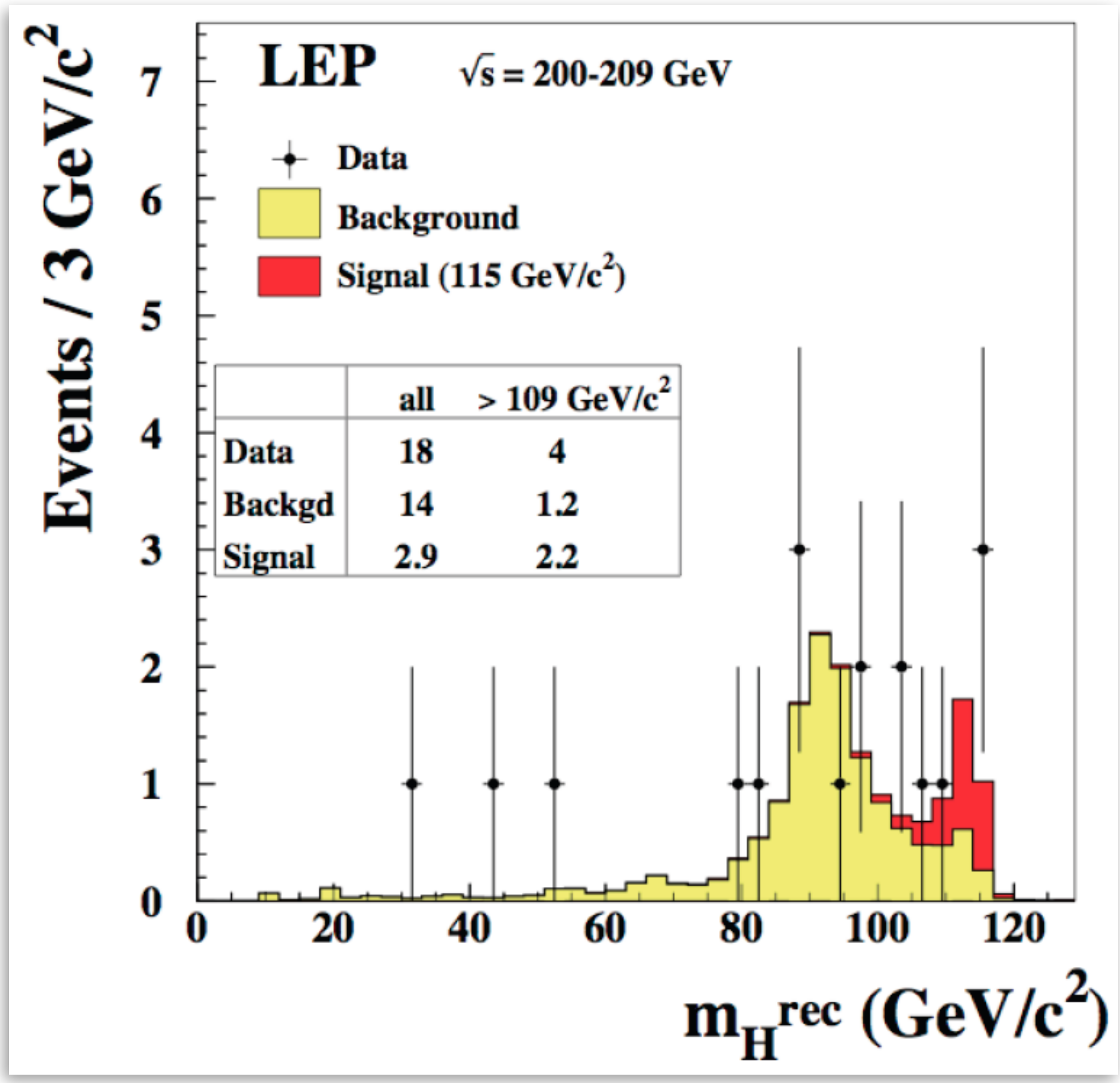
What did we know before the LHC?

At LEP:

- Large Electron-Positron Collider



$\sqrt{s} - m_Z = 206 - 91$ GeV = 115 GeV

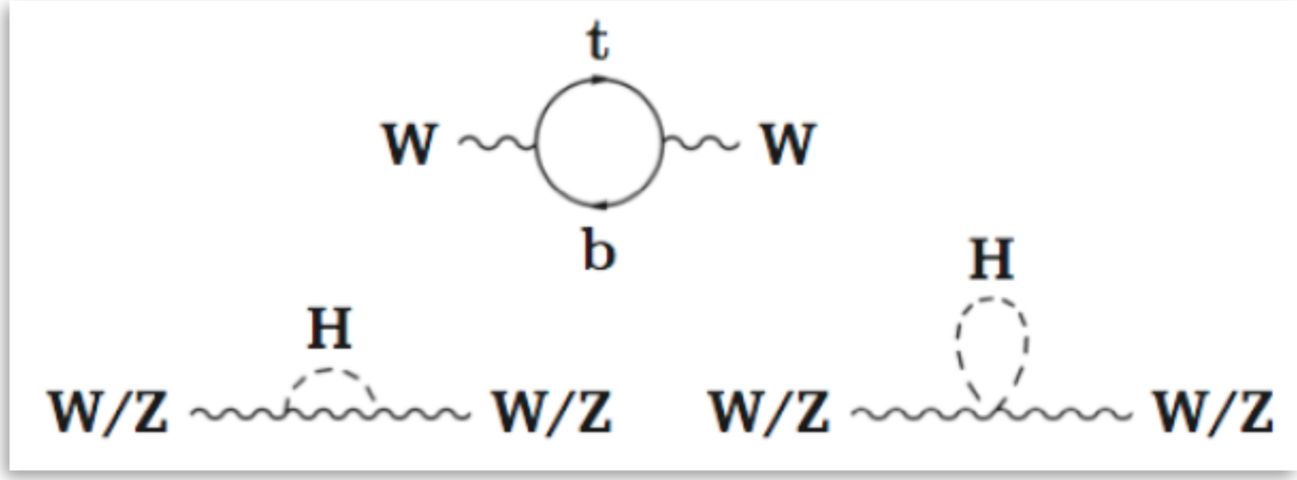


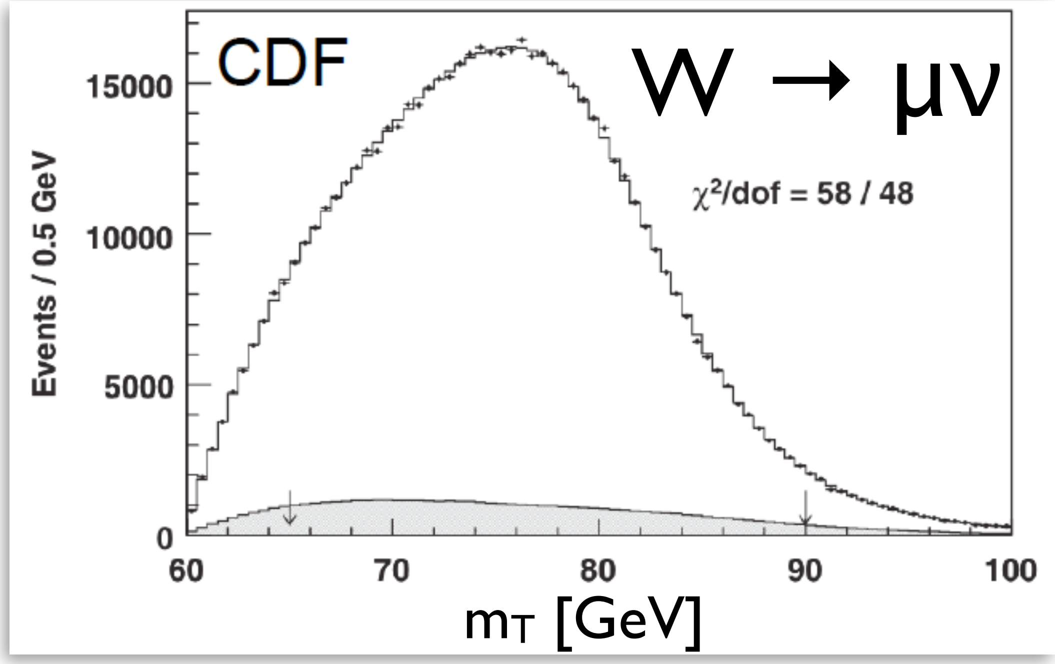
No significant Higgs signal

$m_H > 114.4$ GeV @ 95% CL

Indirect Higgs-mass determination

m_H, m_t and m_W are connected through radiative corrections in the Standard Model:



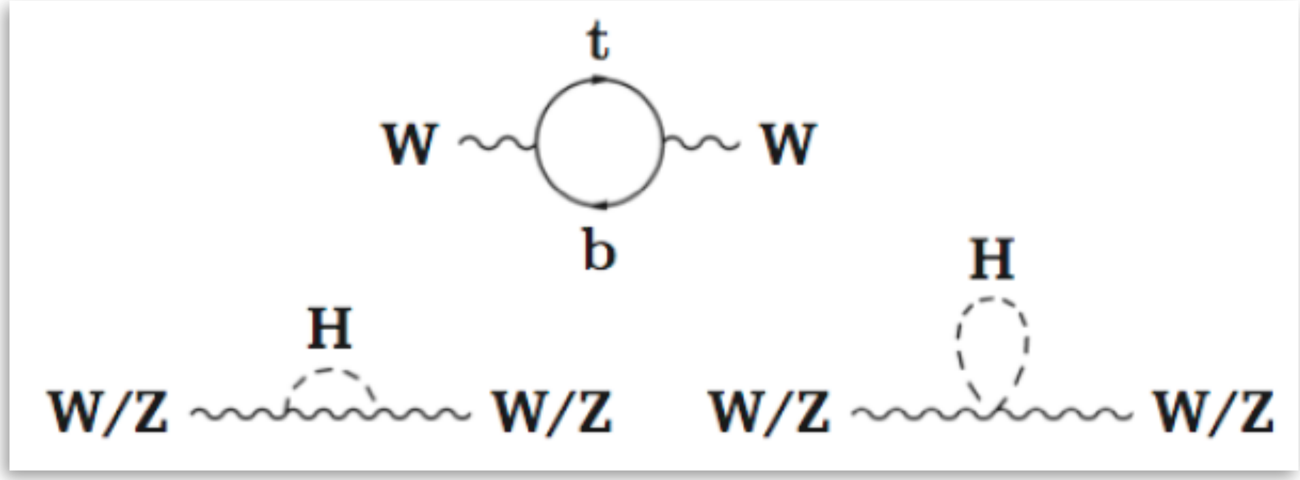


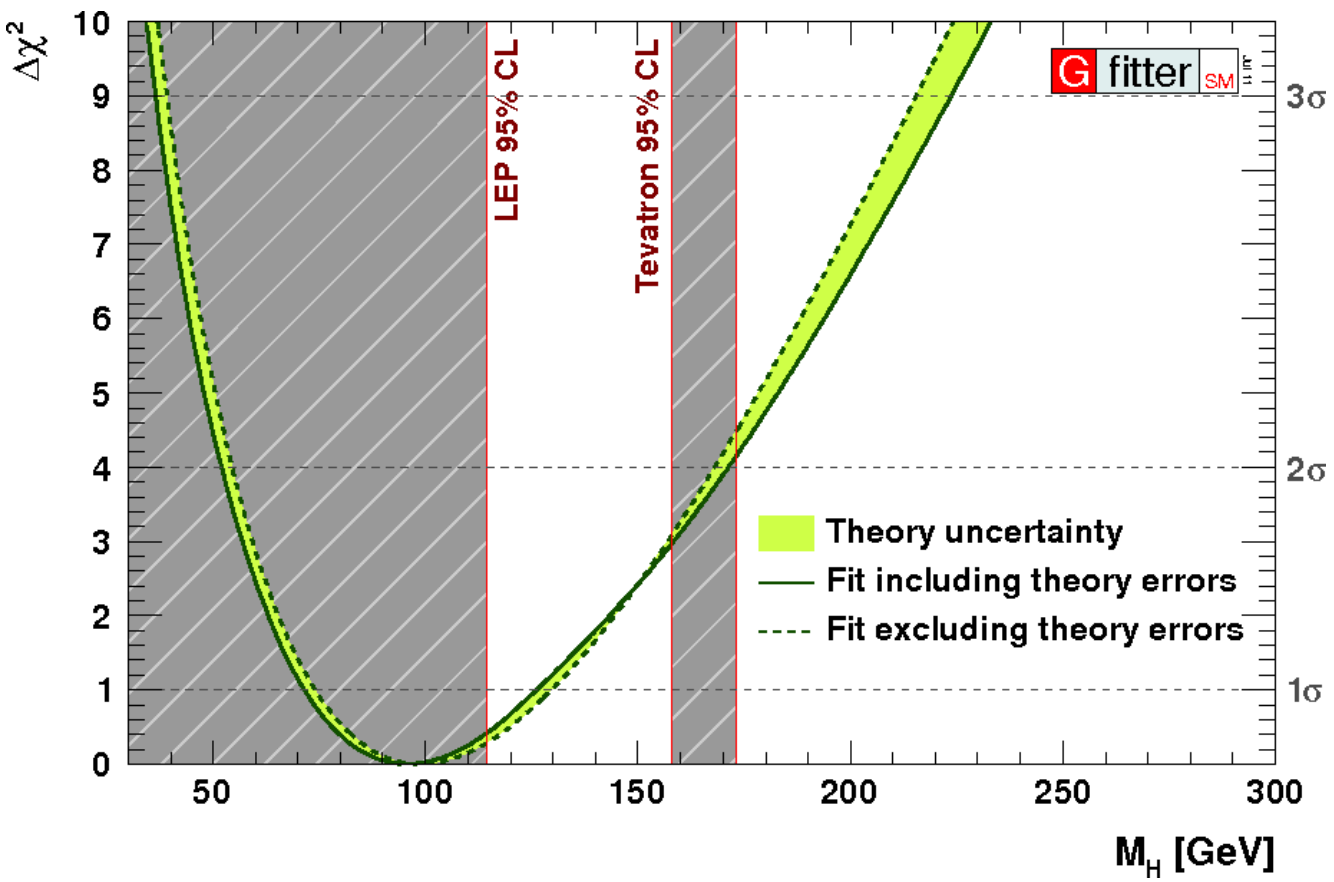
W mass (CDF+DØ): 80385 ± 15 MeV

Top mass (CDF+DØ): 173.2 ± 0.9 GeV

Indirect Higgs-mass determination

m_H, m_t and m_W are connected through radiative corrections in the Standard Model:





Data-taking conditions

<u>*LHC delivered excellent data!*</u>

- ATLAS recorded it with very high efficiency!
- $\delta\mathscr{L}/\mathscr{L}$ = 1.8% for 2011 data!

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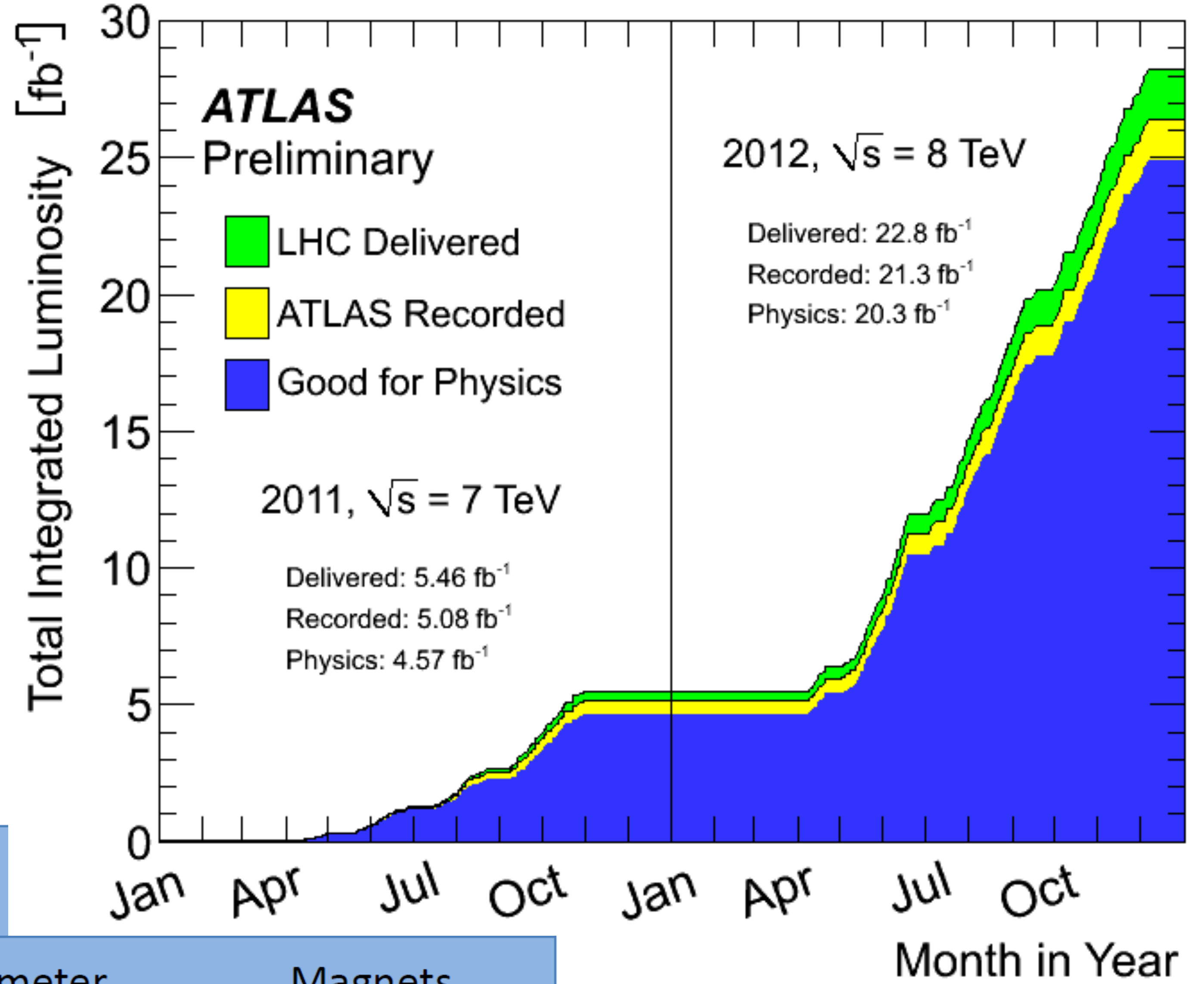


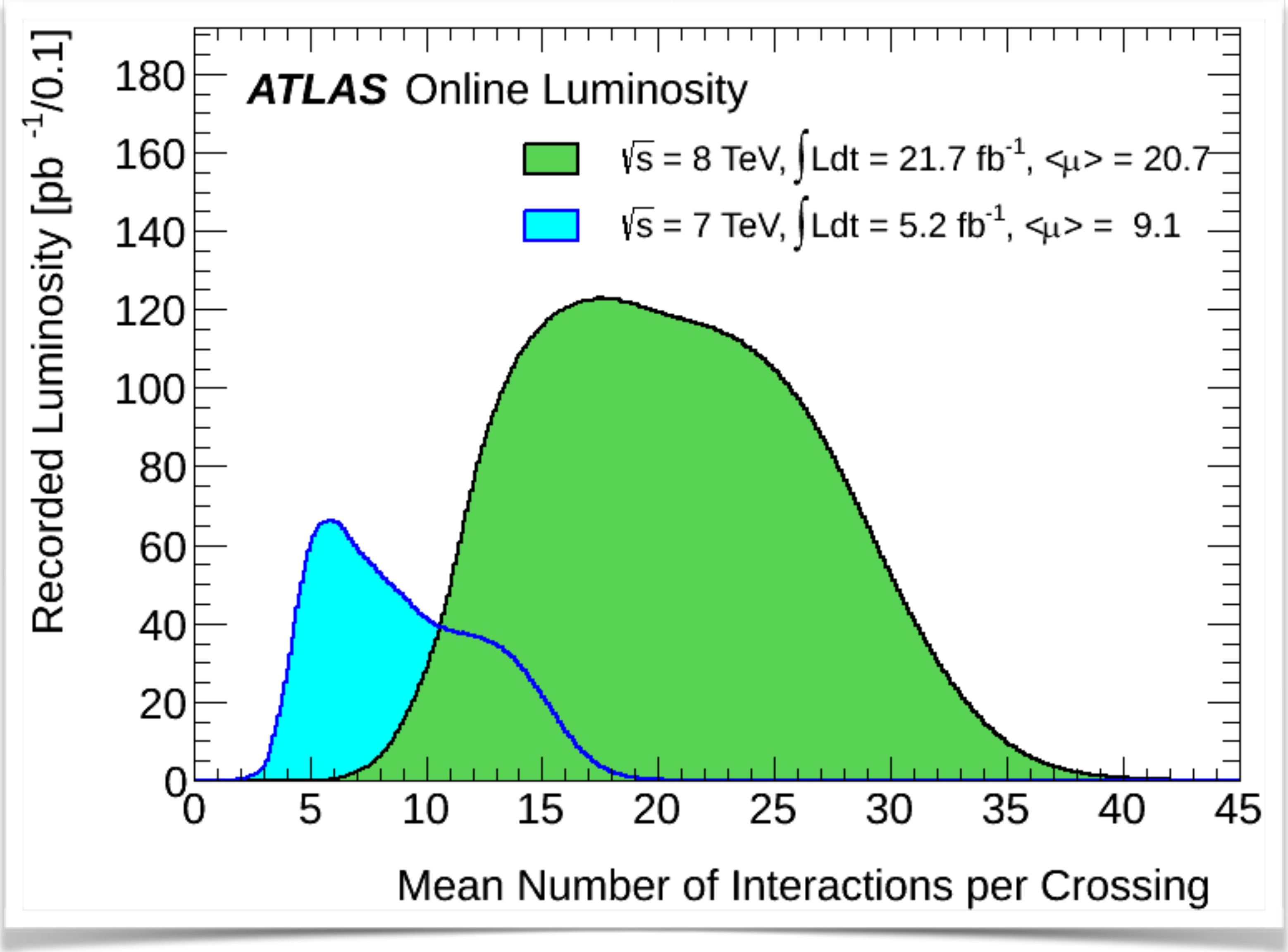
ATLAS p-p run: April-December 2012

Inner Tracker			Calorimeters		Muon Spectrometer				Magnets	
Pixel	SCT	TRT	LAr	Tile	MDT	RPC	CSC	TGC	Solenoid	Toroid
99.9	99.1	99.8	99.1	99.6	99.6	99.8	100.	99.6	99.8	99.5

All good for physics: 95.5%

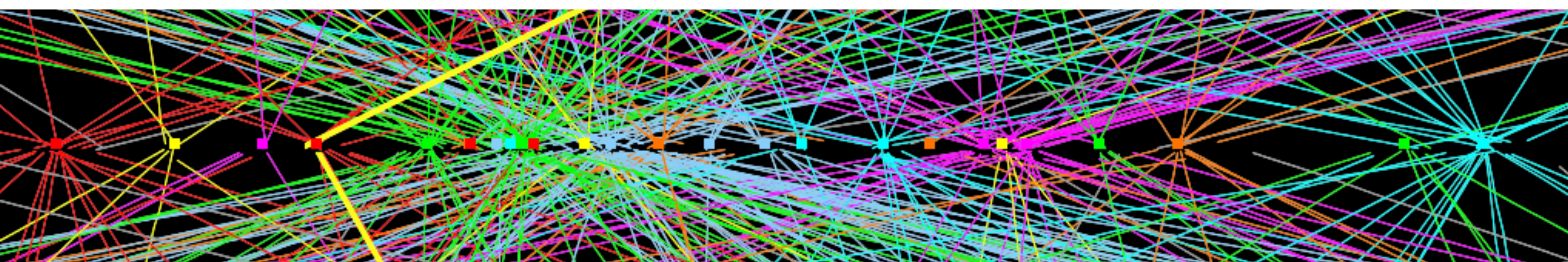
Luminosity weighted relative detector uptime and good quality data delivery during 2012 stable beams in pp collisions at √s=8 TeV between April 4th and December 6th (in %) – corresponding to 21.3 fb^{-1} of recorded data.

Data-taking conditions

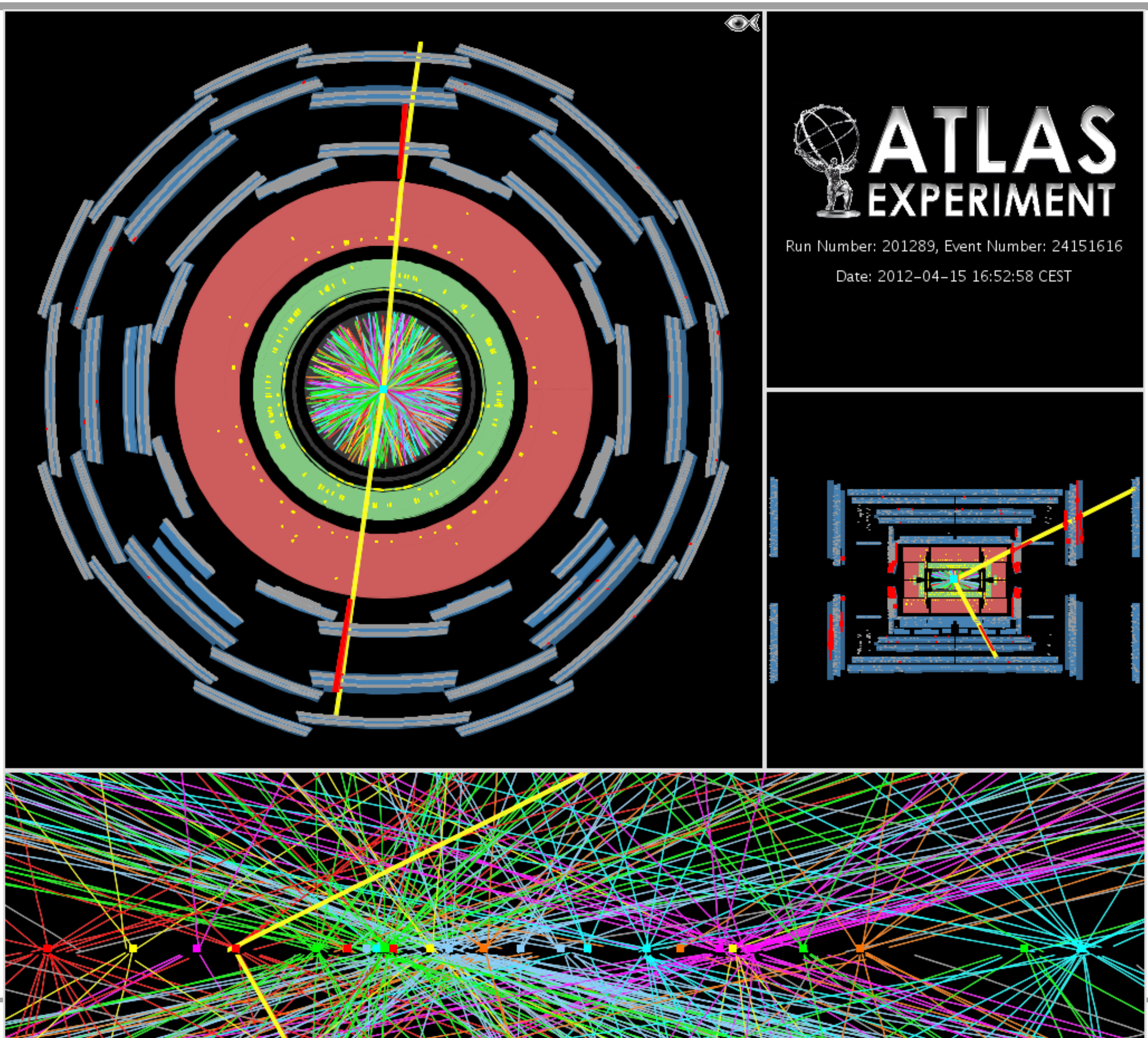


LHC conditions:

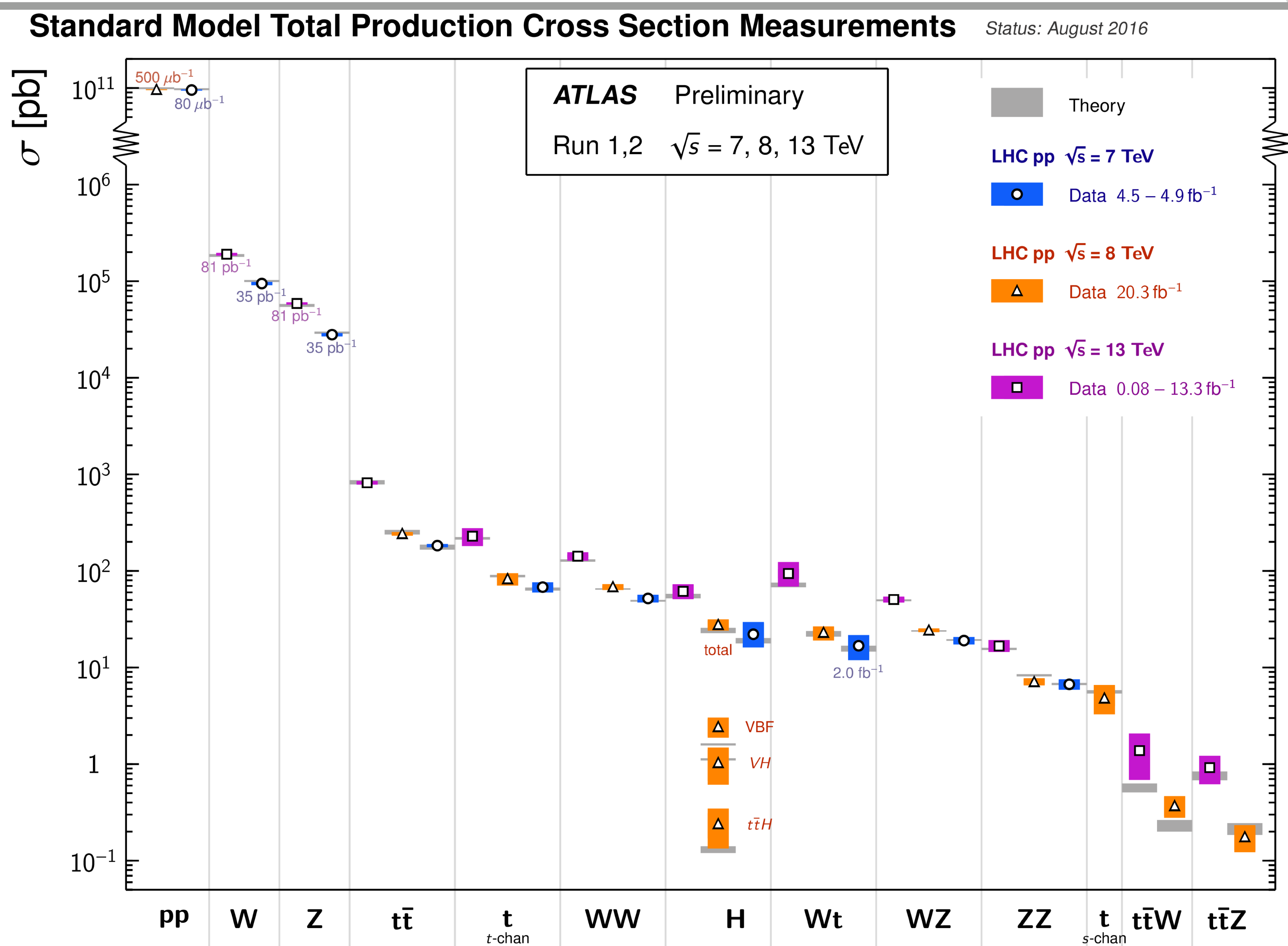
- High Luminosity comes with a price: PILEUP



$Z \rightarrow \mu^+\mu^-$ with 25 pp interactions

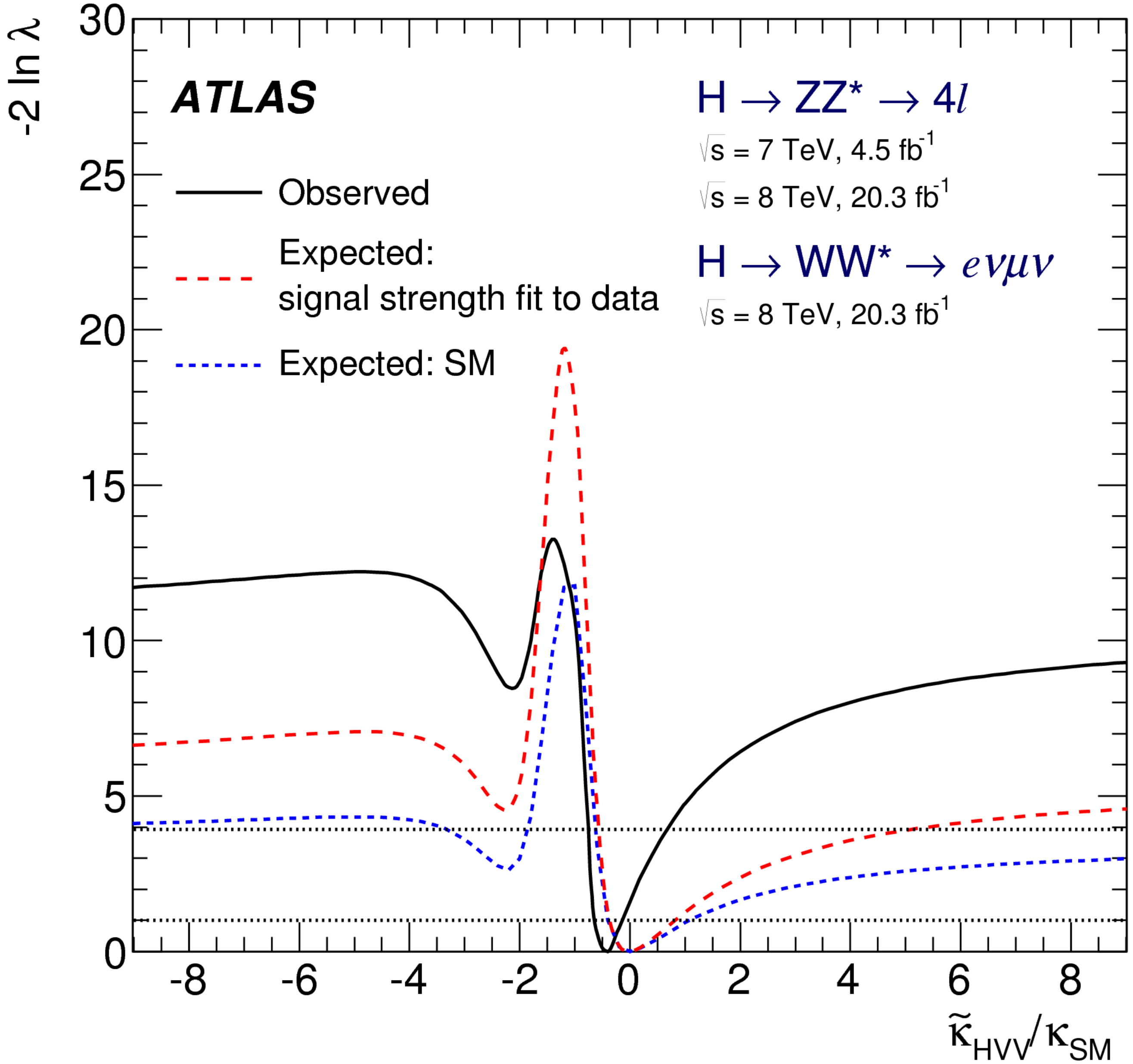


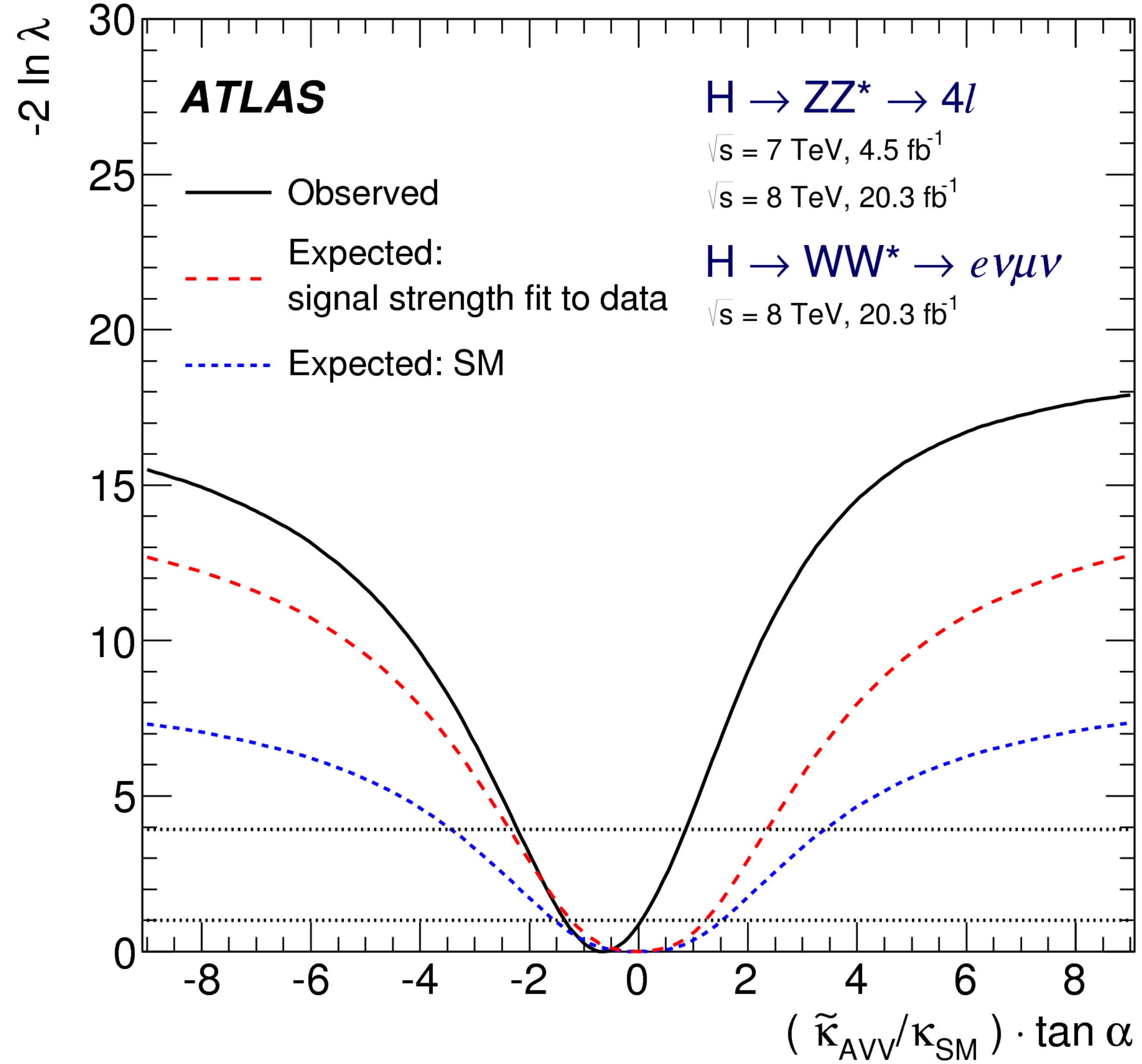
Rediscovery of the Standard Model



CP Admixture

- Higgs boson could be mixed state of CP-even and CP-odd
  - Mixing described by cosα
  - Beyond-SM coupling to vector bosons described by κ_{HVV} (CP-even) and κ_{AVV} (CP-odd)

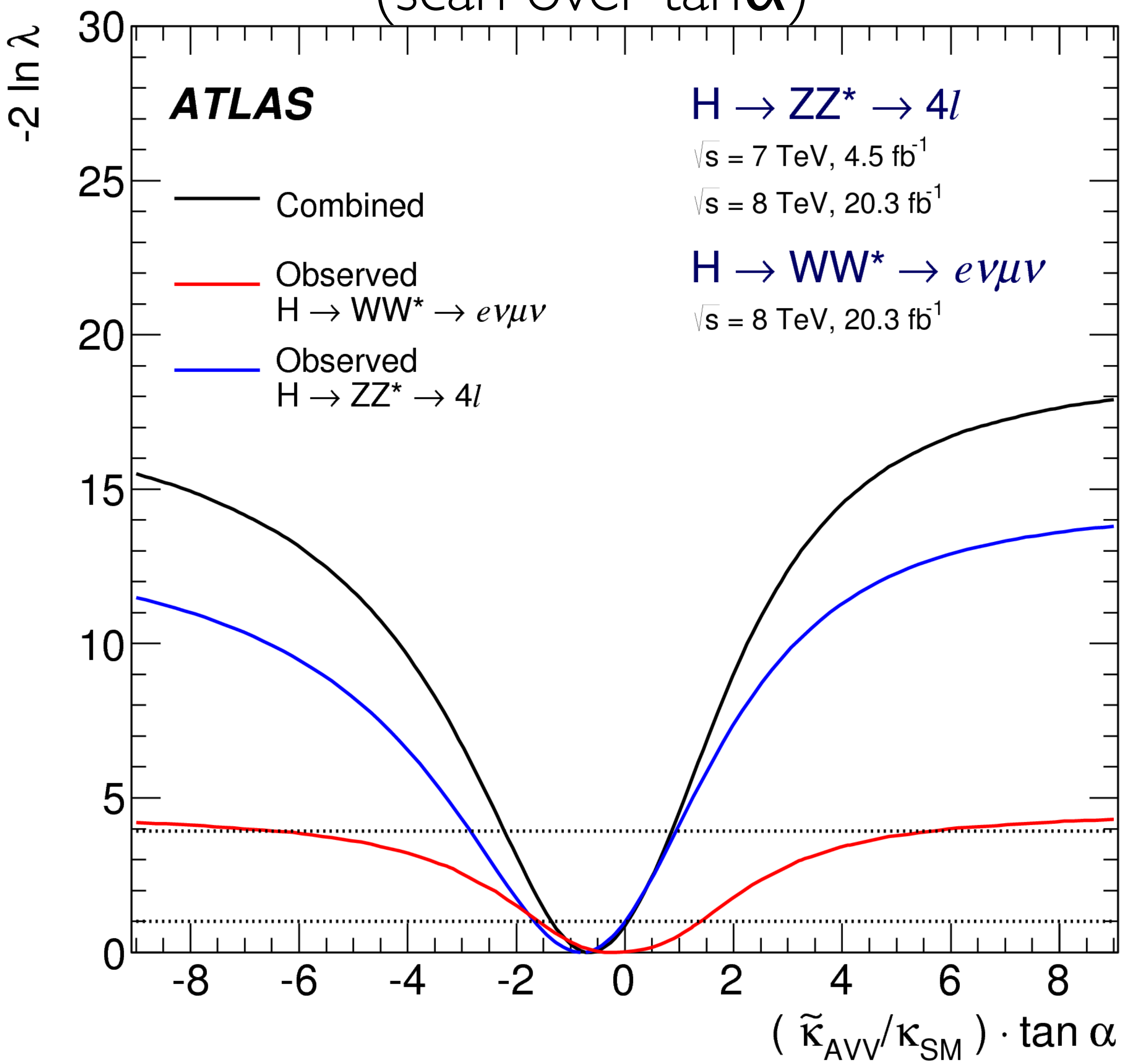




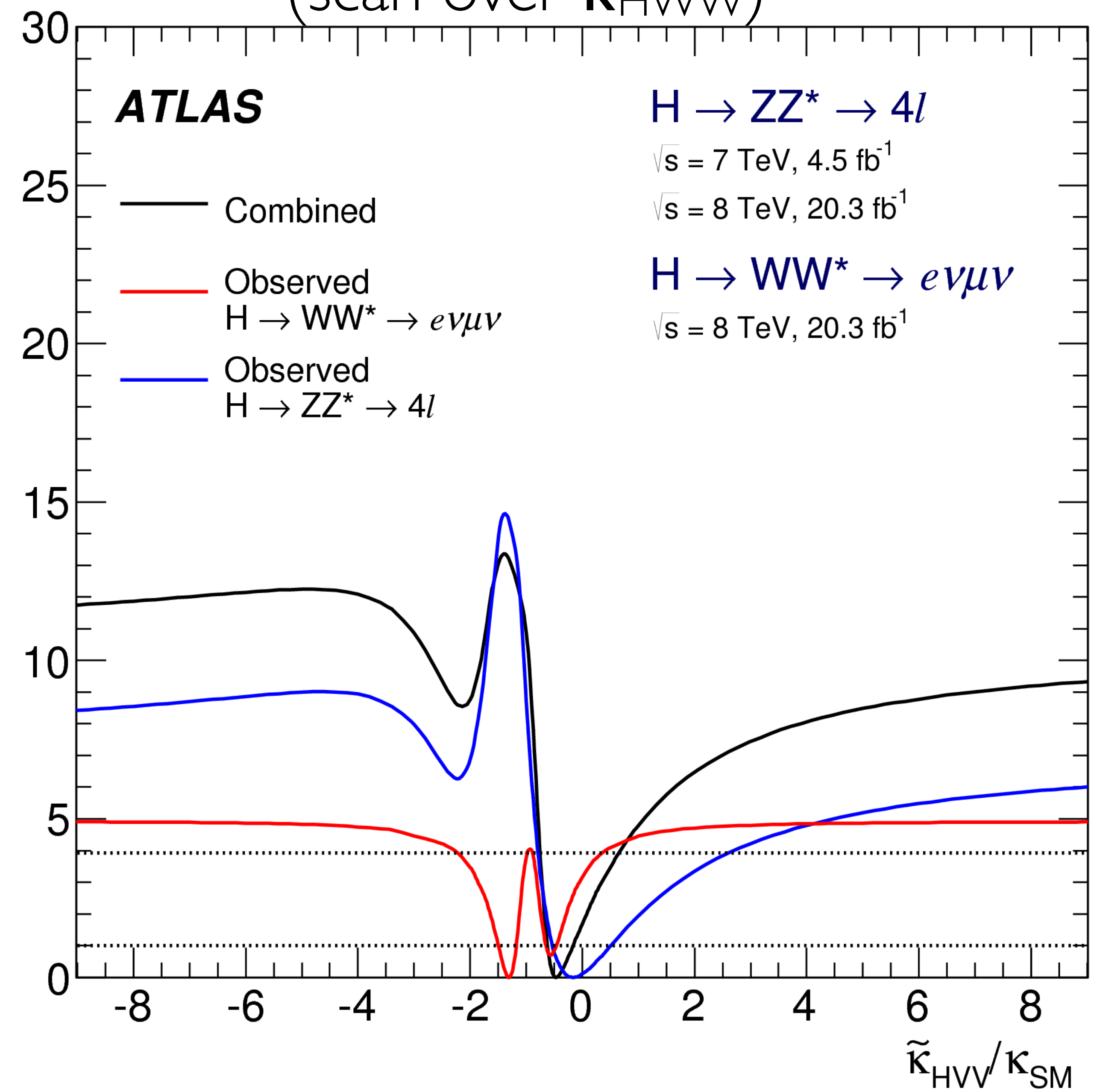
ATLAS Combined Spin and CP Results

Spin 0 mixing between:

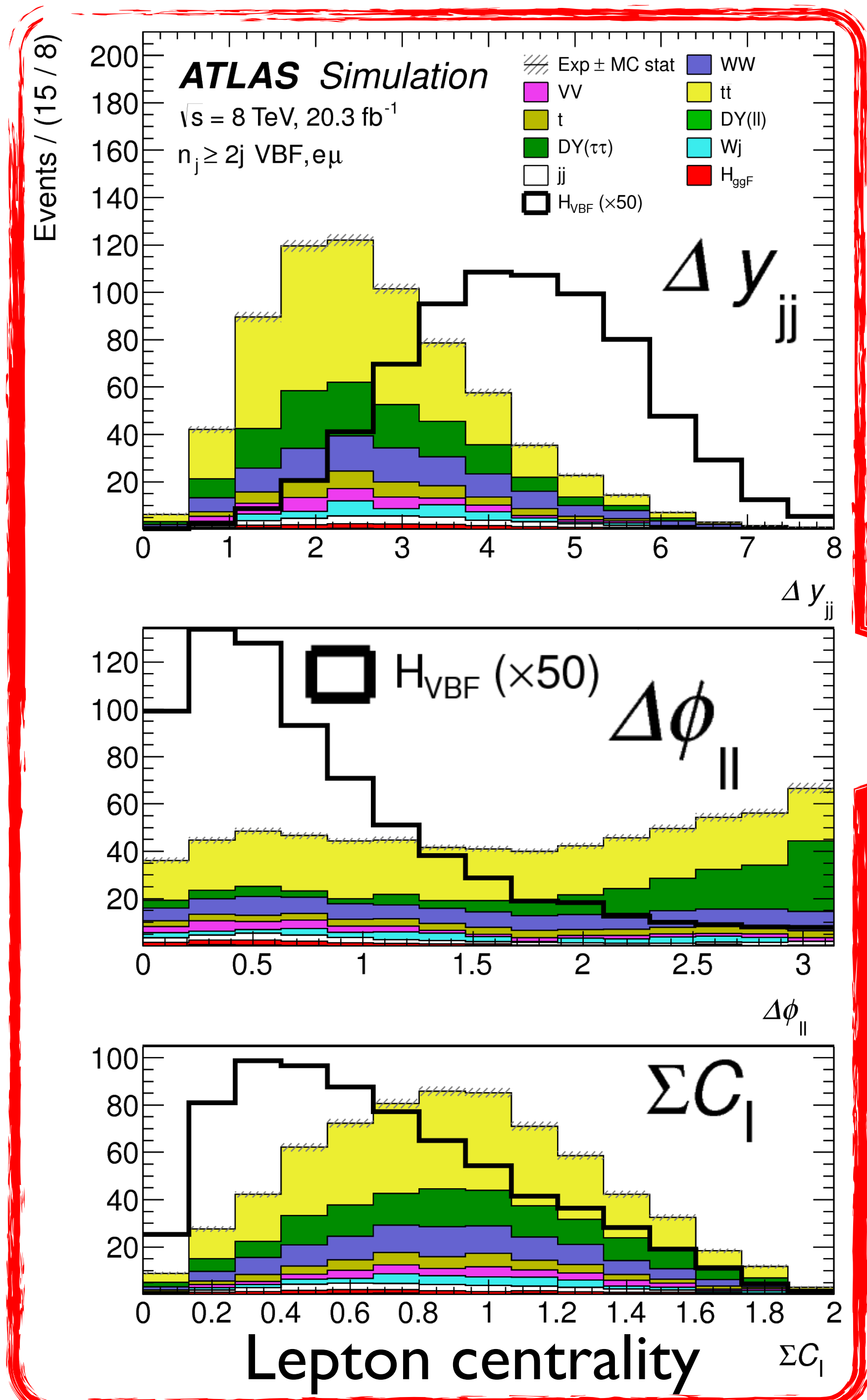
CP-even SM Higgs and
CP-odd BSM Higgs
(scan over tan**α**)



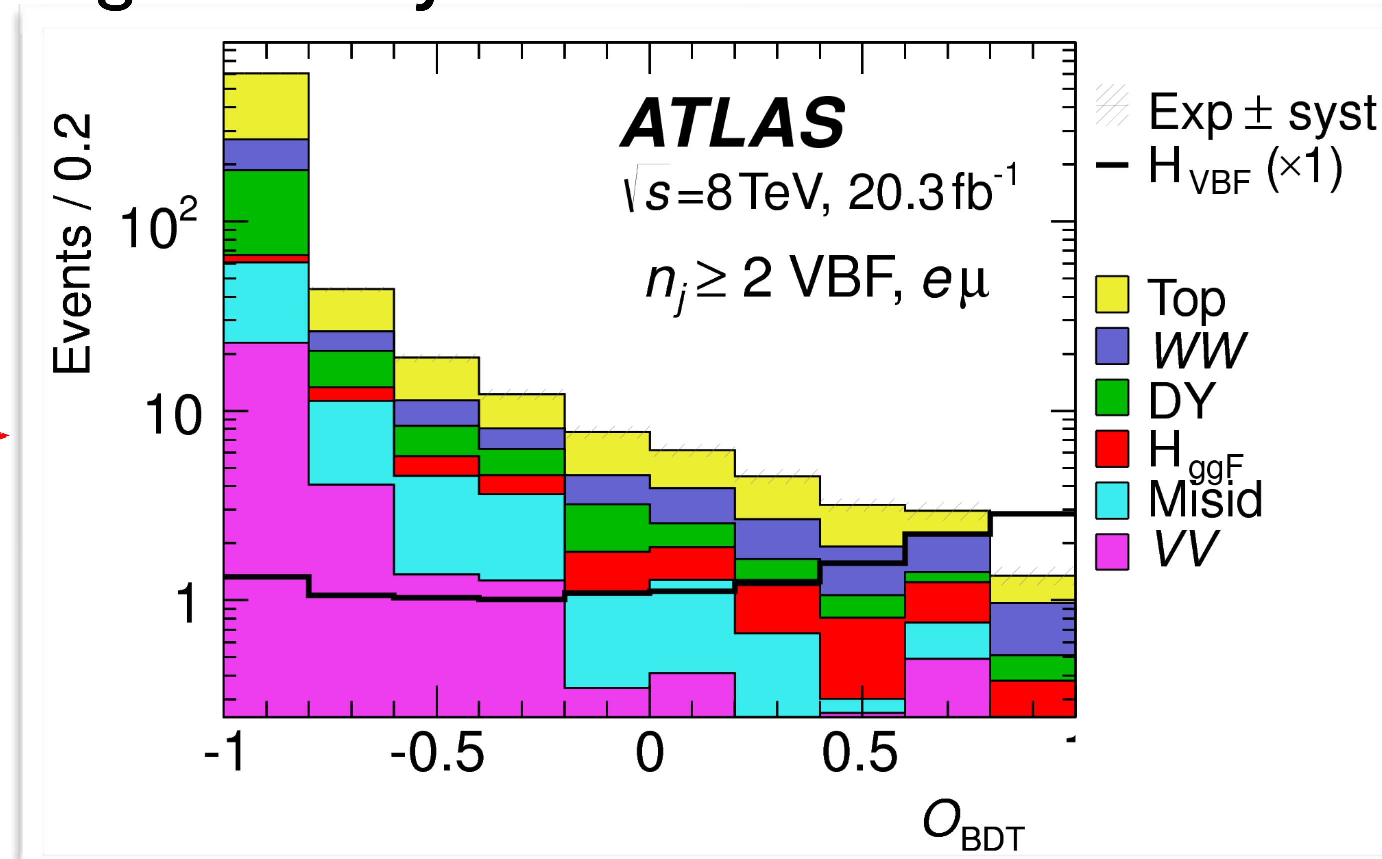
CP-even SM Higgs and
CP-even BSM Higgs
(scan over κ_{HWW})



Combine background-discriminating variables into BDT



- Input variables for *VBF production topology*, *Higgs boson decay topology*, as well as *background rejection*



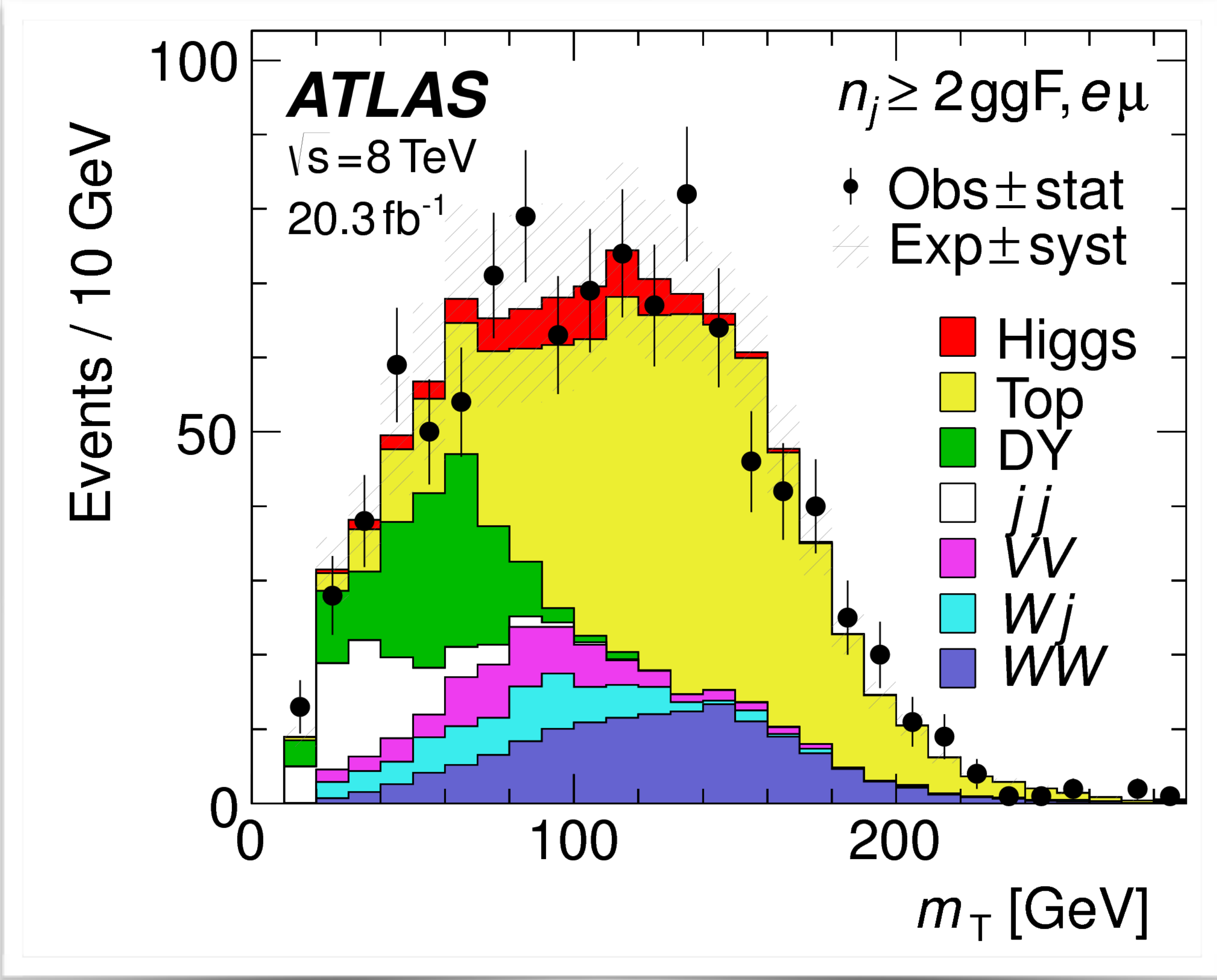
Fit re-binned BDT distribution

- BDT modelling validated in background regions

Results: Gluon Fusion

Also look at ≥2 jet ggF region:

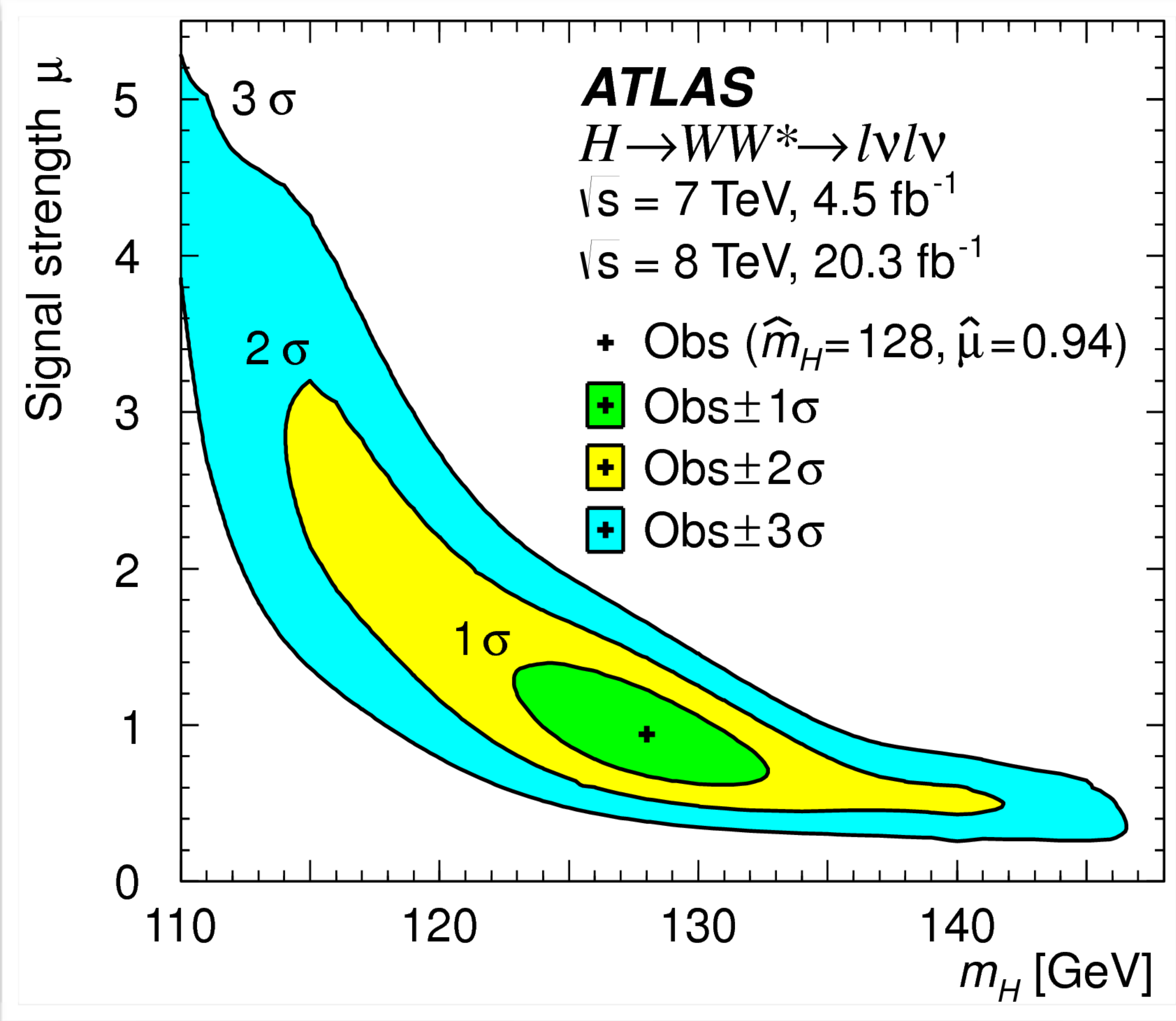
- Result is part of combined ggF significance shown on previous page
- *ggF signal significance in ≥2 jet region alone:* **1.4 σ** (1.2 σ)
  observed (expected) @m_H = 125.36 GeV



Signal Strength vs. m_H

Assess compatibility with SM:

- Observed best-fit value μ vs. m_H
- Let total yield and m_H unconstrained

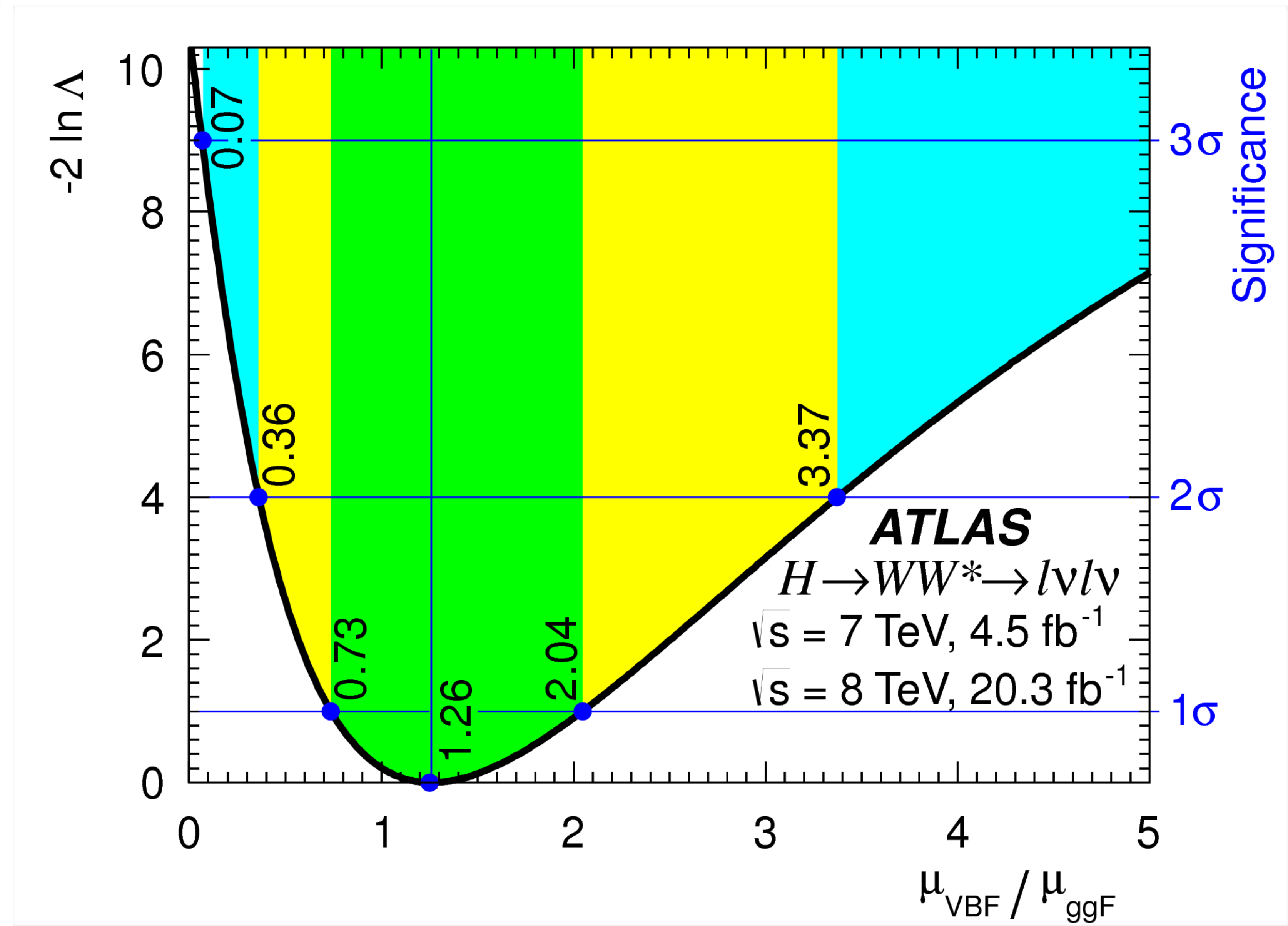


Vector-Boson Fusion

Evidence for VBF production:

- ggF contribution in ≥2-jet region is ~30%
- Run global fit to determine μ_{VBF}/μ_{ggF}
- Branching fraction cancels in ratio

$$\frac{\mu_{\rm VBF}}{\mu_{\rm ggF}} = 1.26\,^{+0.79}_{-0.53}$$



Fermion vs. Boson Couplings

Fit simultaneously for coupling scale factor to fermions and vector bosons:

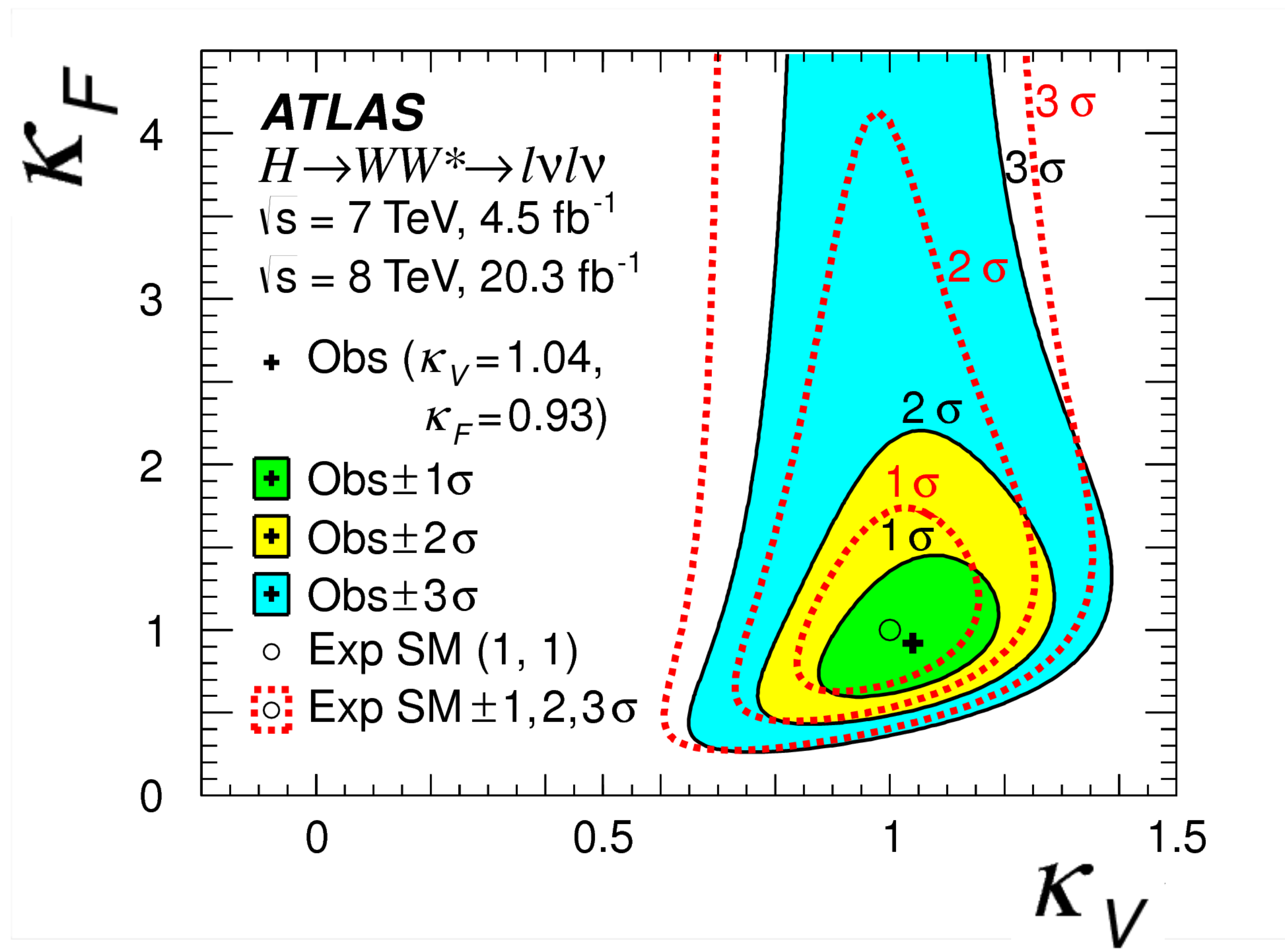
- Fermion coupling from top-loop in gluon-fusion production
- Vector-boson coupling from decay and VBF production

Observations:

$\kappa_V = 1.04 \pm 0.11$

$\kappa_F = 0.93^{+0.32}_{-0.23}$

- Excellent agreement with SM expectation
- Good precision for κ_V

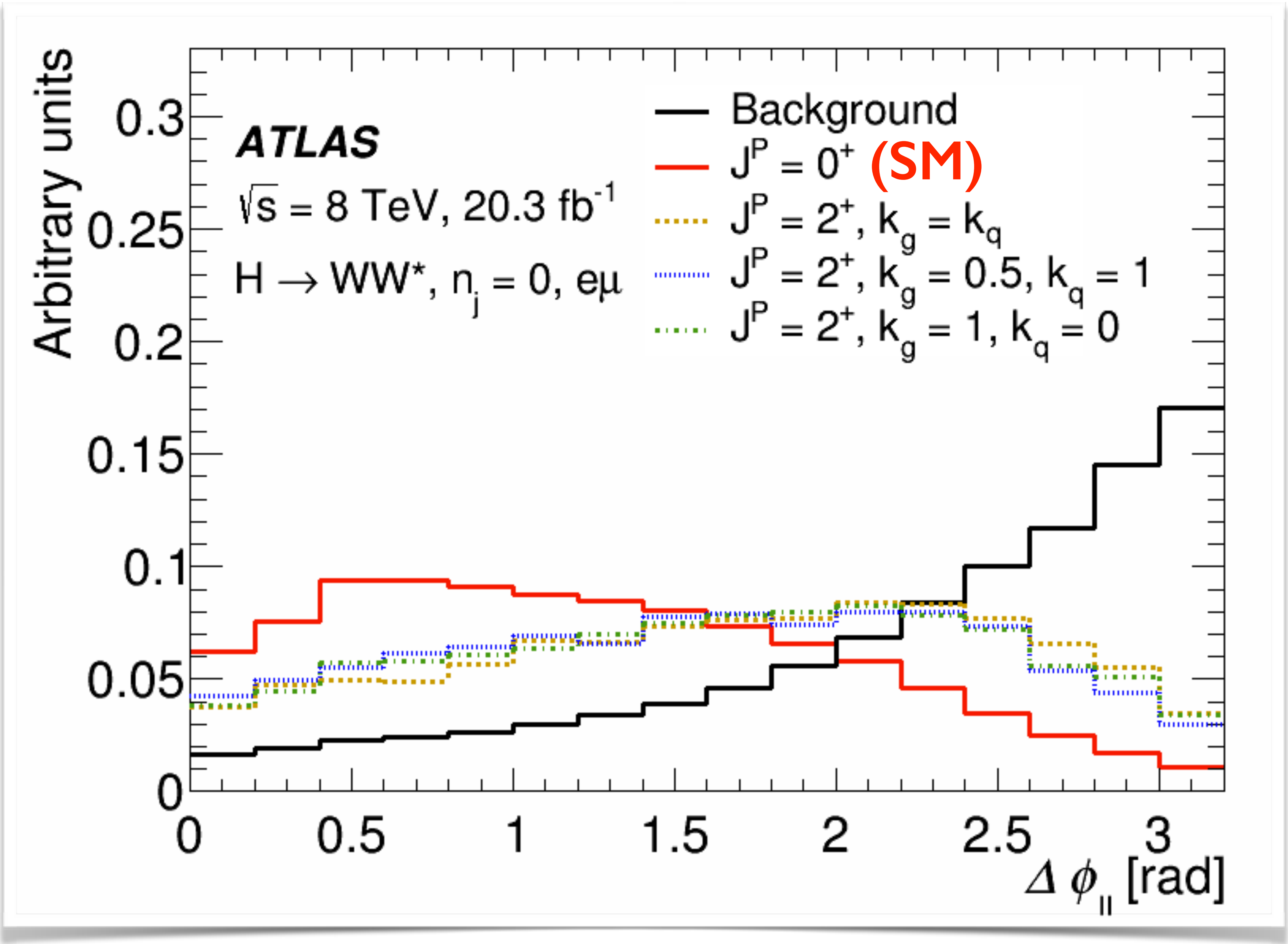


Determining the Spin and CP Structure

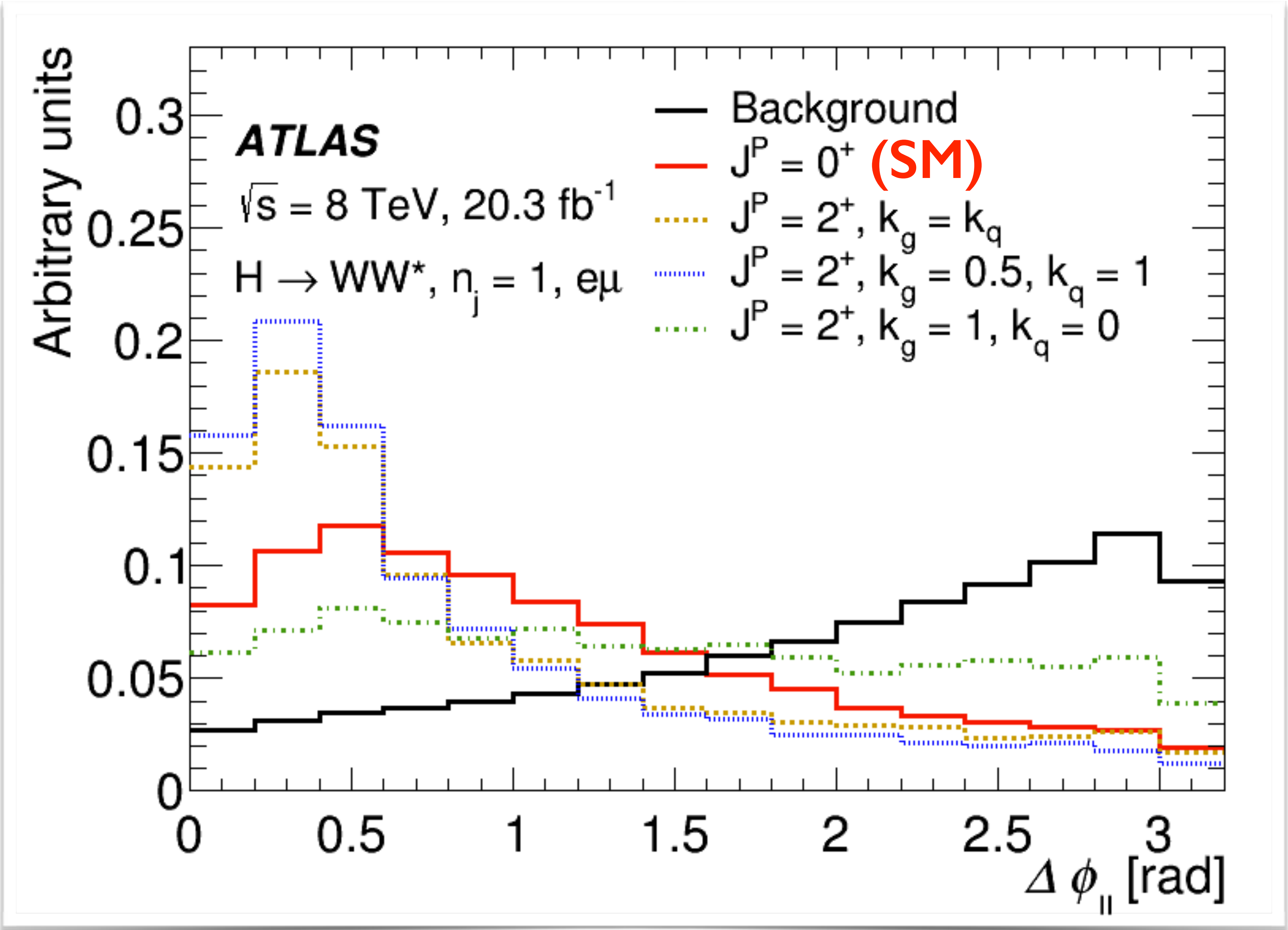
- Standard Model Higgs boson: $J^{CP} = 0^{++}$
- Test against alternative hypothesis:
  - Spin 2 minimal coupling models (graviton-like):

$$\mathcal{L}_2^p = \sum_{p=V,f} -\frac{1}{\Lambda}\kappa_p T^p_{\mu\nu} X_2^{\mu\nu}$$

Determining the Spin and CP Structure



Determining the Spin and CP Structure



Determining the Spin and CP Structure

- Standard Model Higgs boson: $J^{CP} = 0^{++}$
- Test against alternative hypothesis:
  - Spin 2 minimal coupling models (graviton-like):

$$\mathcal{L}_2^p = \sum_{p=V,f} -\frac{1}{\Lambda}\kappa_p T^p_{\mu\nu} X_2^{\mu\nu}$$

  - Spin 0, including mixing between SM and BSM states:

$$\mathcal{L}_0^W = \Big\{ c_\alpha \kappa_{\mathrm{SM}} [g_{\mathrm{HWW}} W_\mu^+ W^{-\mu}] - \frac{1}{2}\frac{1}{\Lambda}[c_\alpha \kappa_{\mathrm{HWW}} W^+_{\mu\nu} W^{-\mu\nu} + s_\alpha \kappa_{\mathrm{AWW}} W^+_{\mu\nu} \widetilde{W}^{-\mu\nu}] - \frac{1}{\Lambda} c_\alpha [(\kappa_{\mathrm{H}\partial\mathrm{W}} W_\nu^+ \partial_\mu W^{-\mu\nu} + h.c.)] \Big\} X_0 \,,$$

Determining the Spin and CP Structure