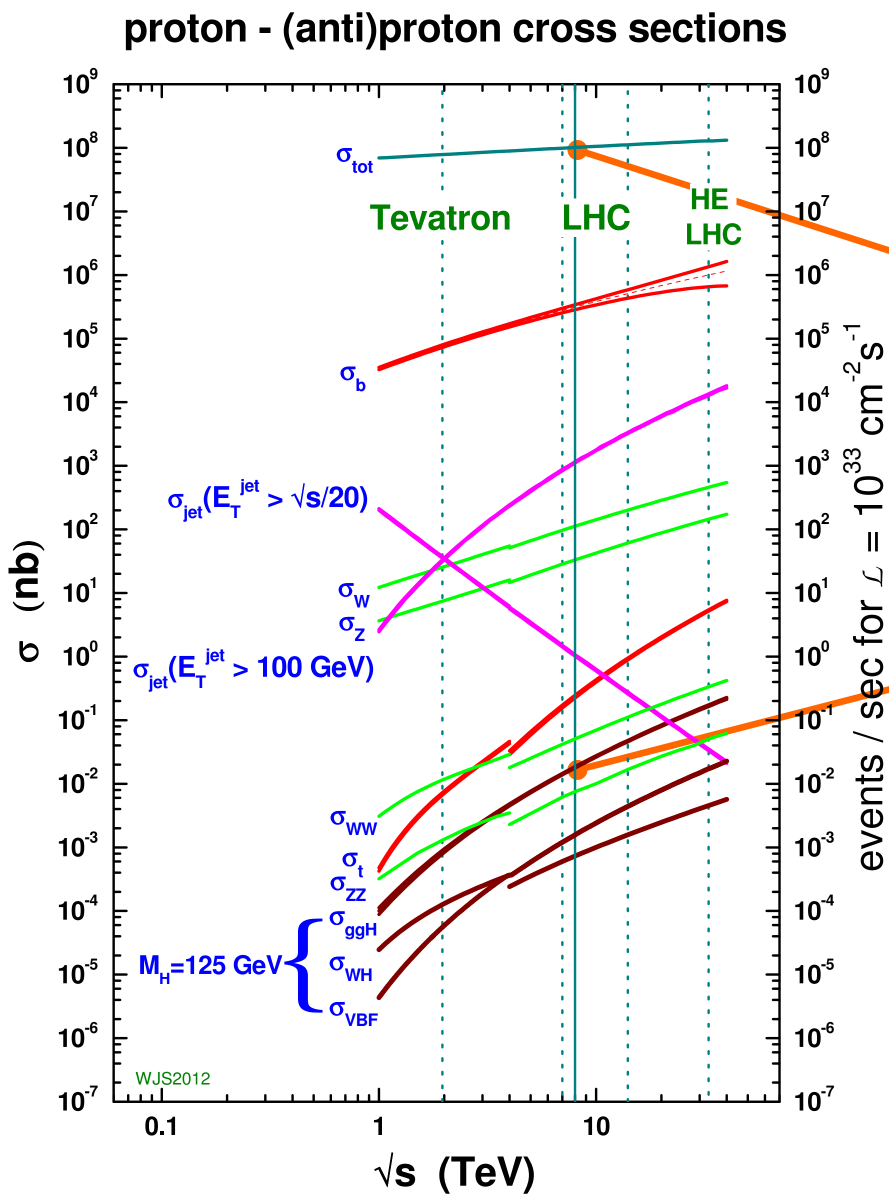
Experimental particle physics

European School of Instrumentation in Particle & Astroparticle Physics

D. a few words on S/B optimization and data analysis

Interesting processes are rare!



10^8 events/s

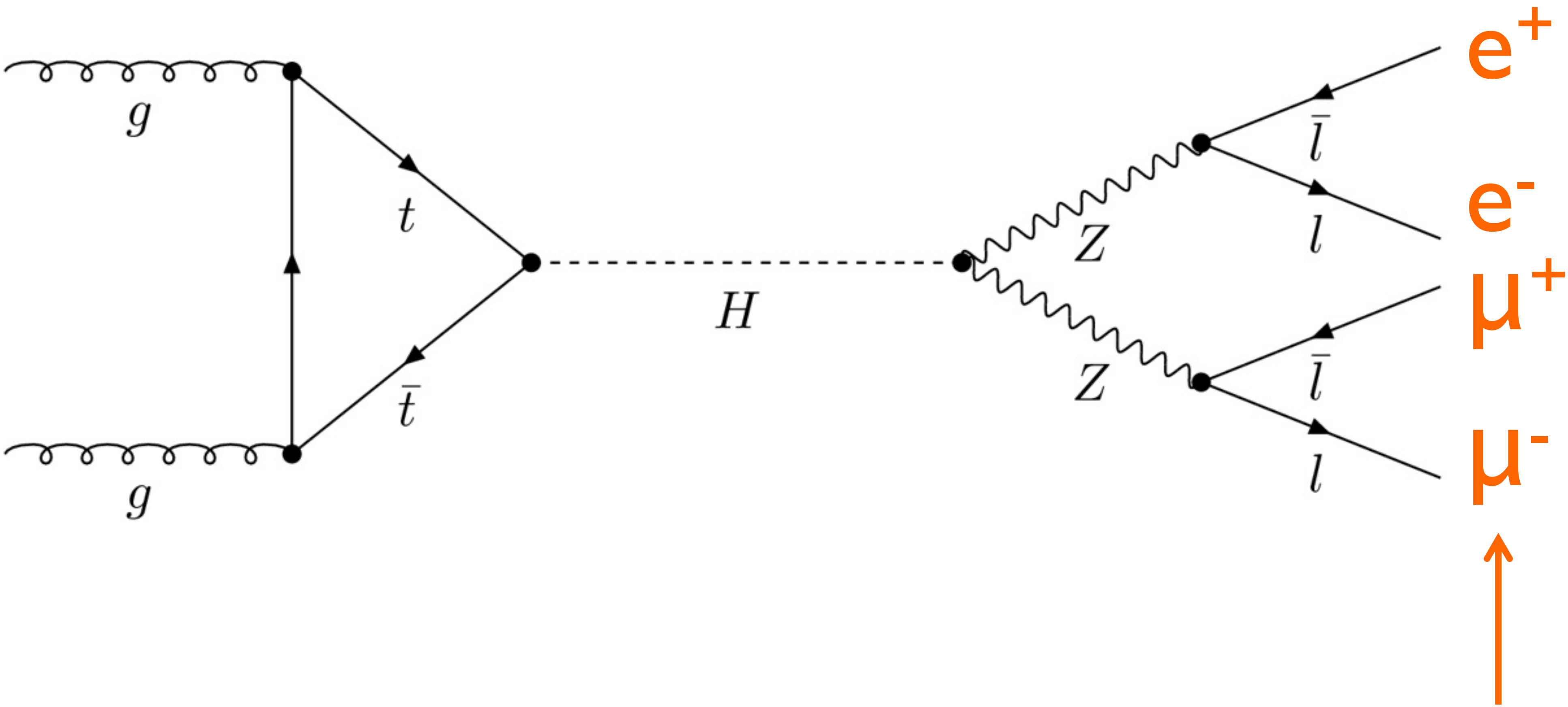
$\sim 10^{10}$

10^{-2} events/s ~ 10 events/min

[m_H ~ 125 GeV]

0.2% H → γγ
1.5% H → ZZ

There is no Higgs-boson detector!

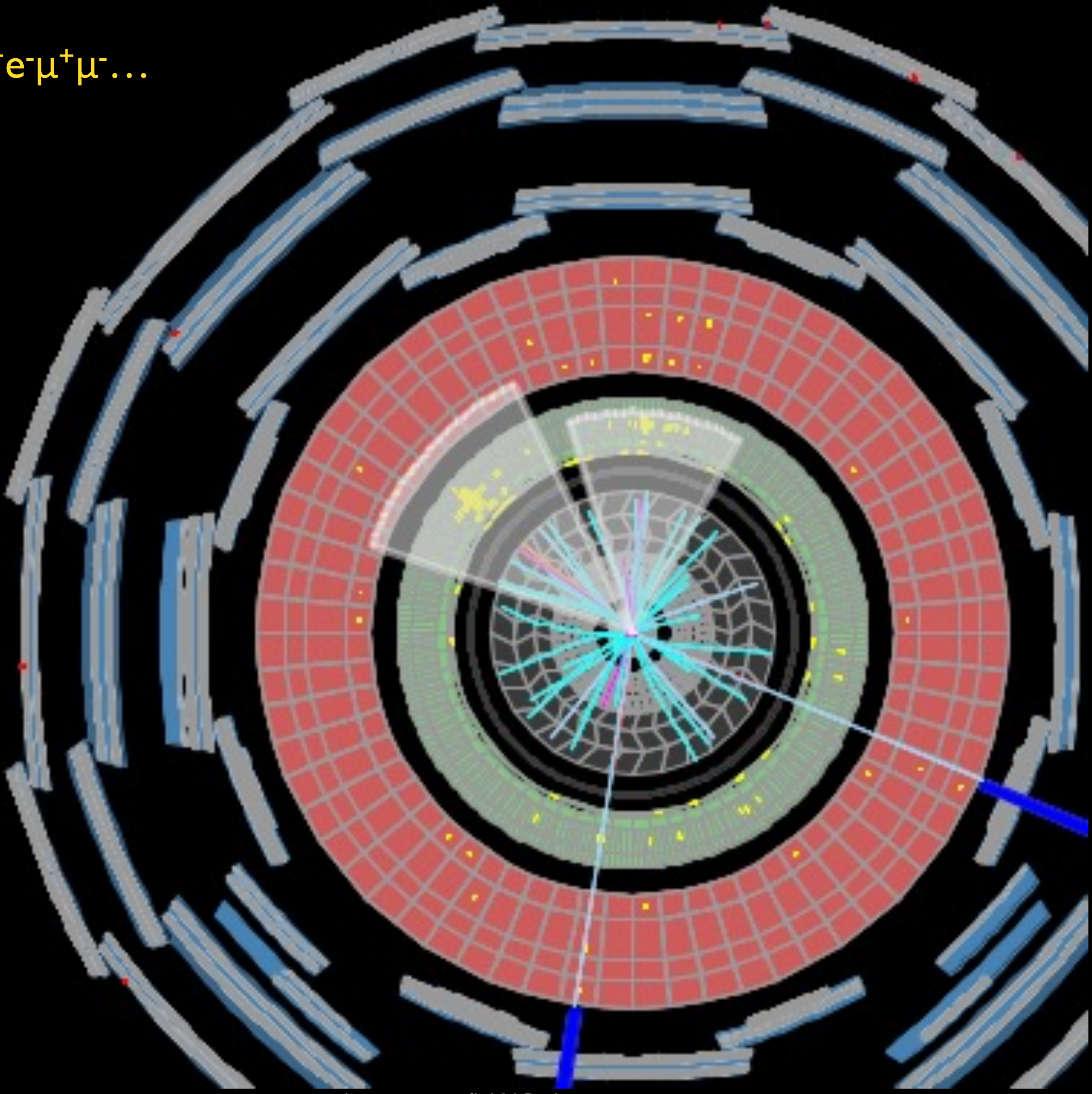


this is what we are looking for…

Step 1: find events with the right ingredients

We are looking for $e^+e^-\mu^+\mu^-$…

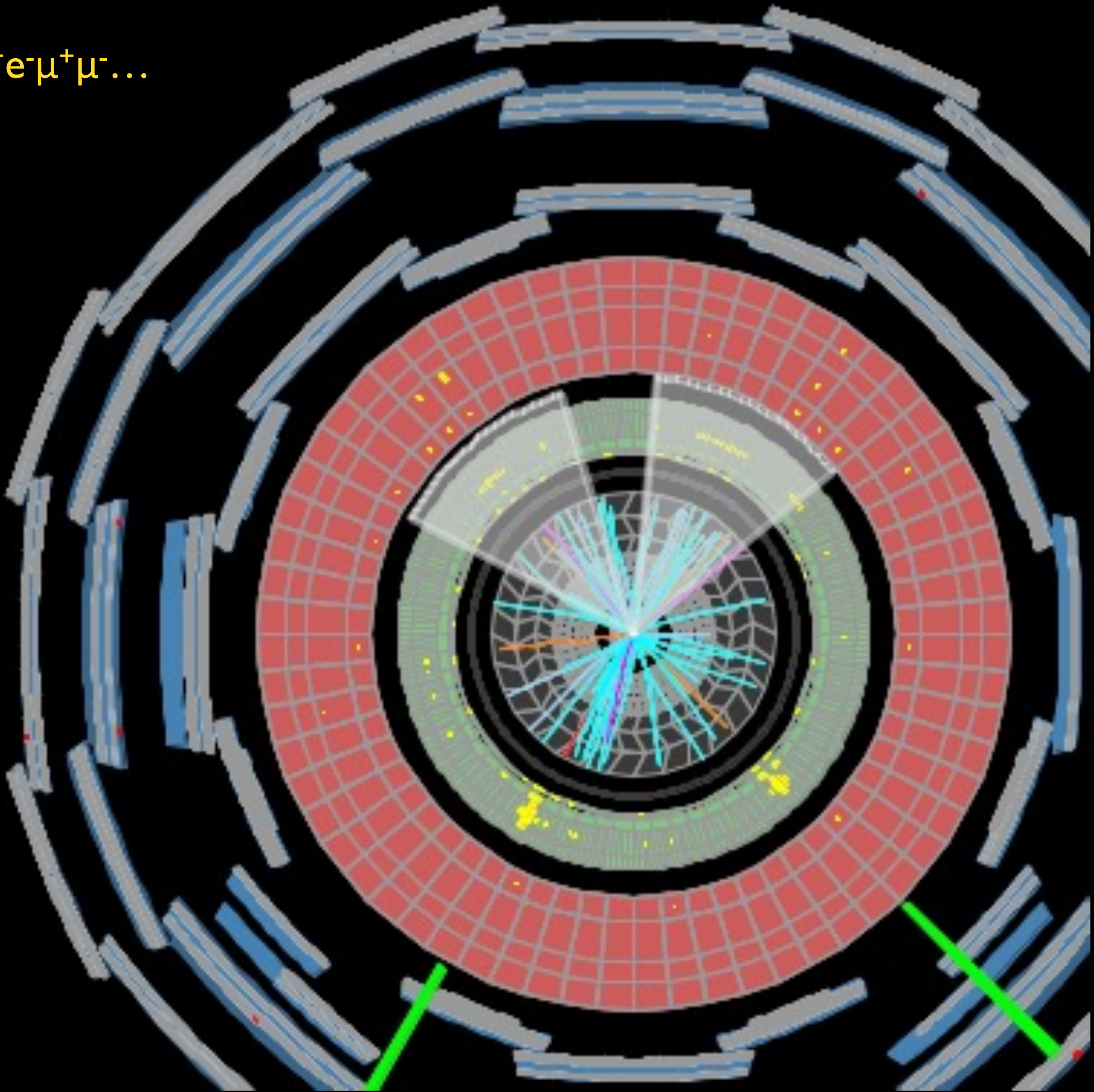
Is this event ok?



Step 1: find events with the right ingredients

We are looking for $e^+e^-\mu^+\mu^-$…

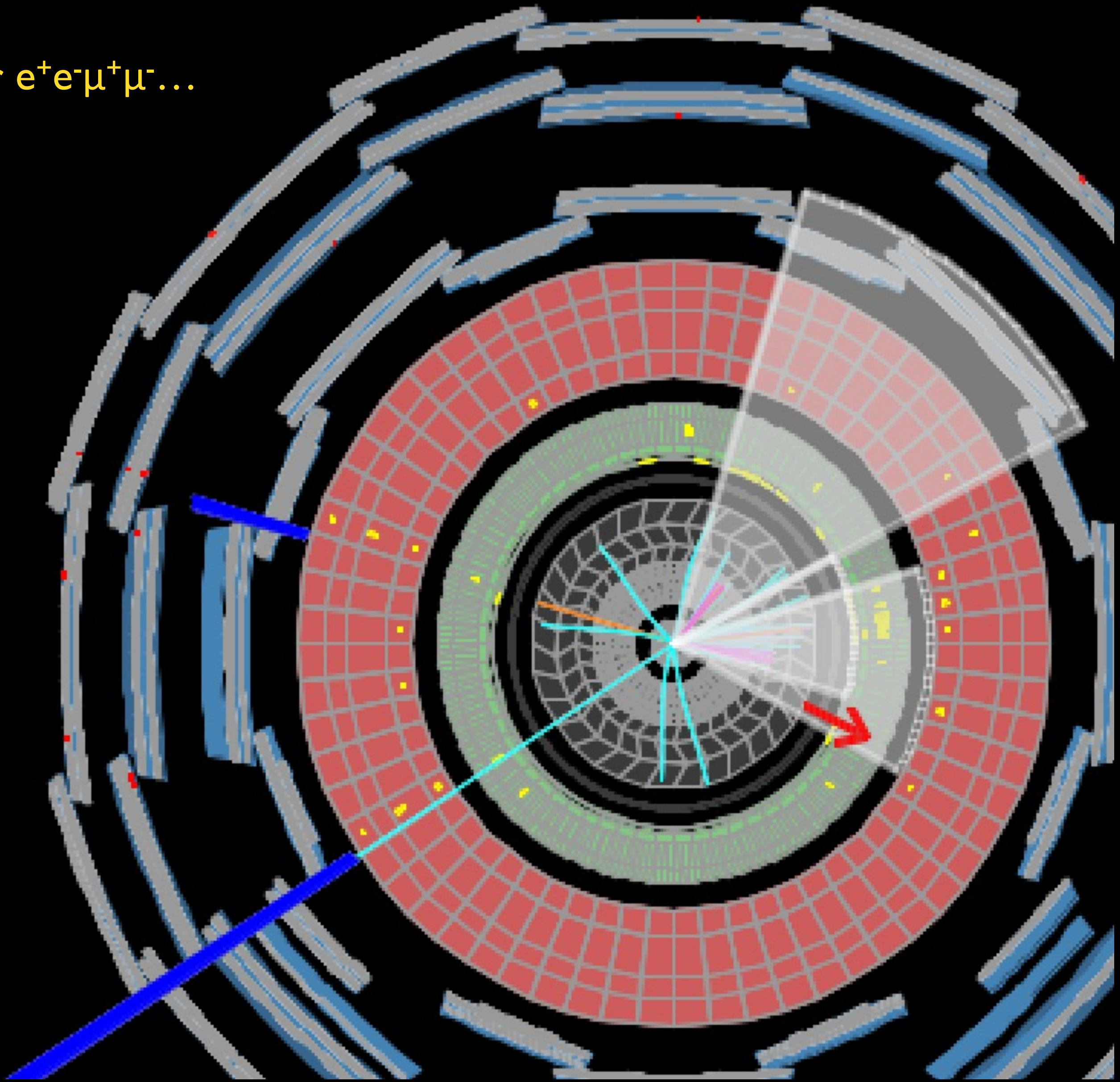
What about this one?



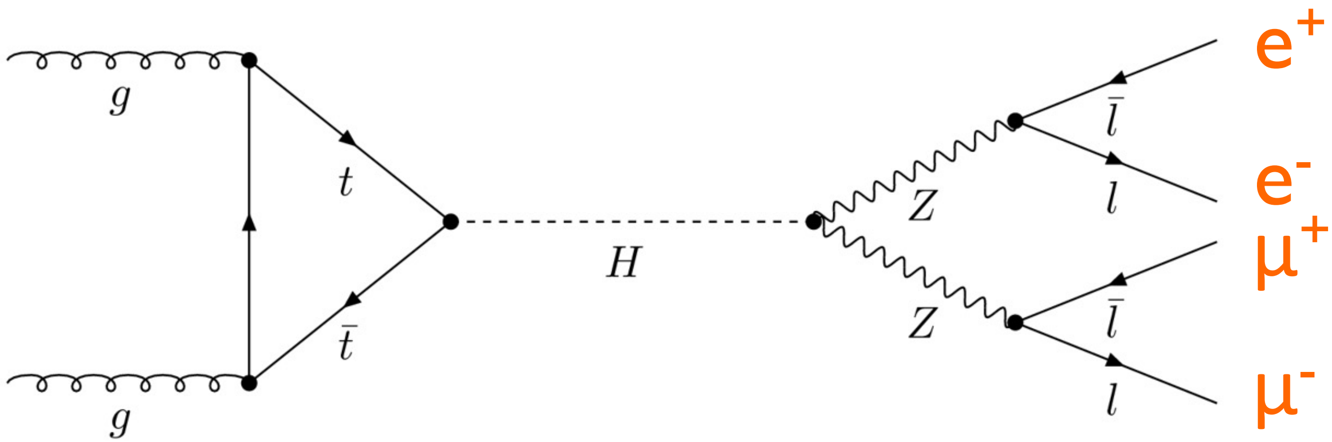
Step 1: find events with the right ingredients

We are looking for $e^+e^-\mu^+\mu^-$…

And this one?

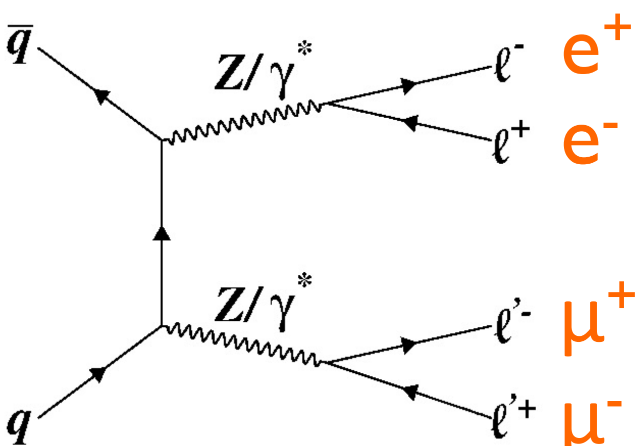


Signal and background



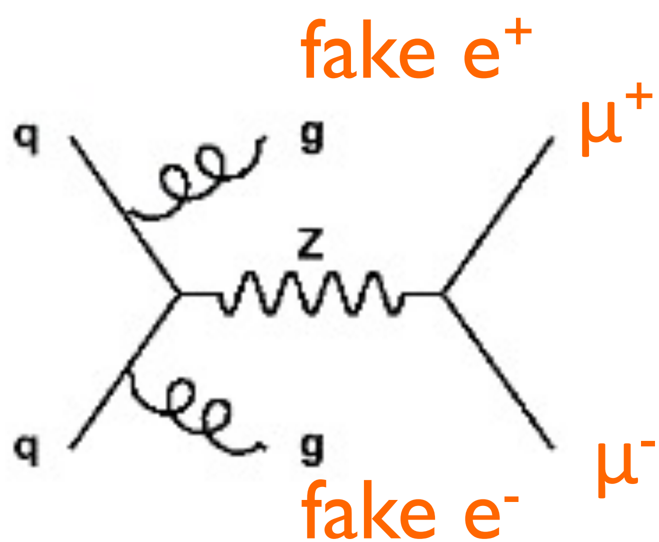
Irreducible background

The final state is exactly the same, but it does not come from the particle you are looking for



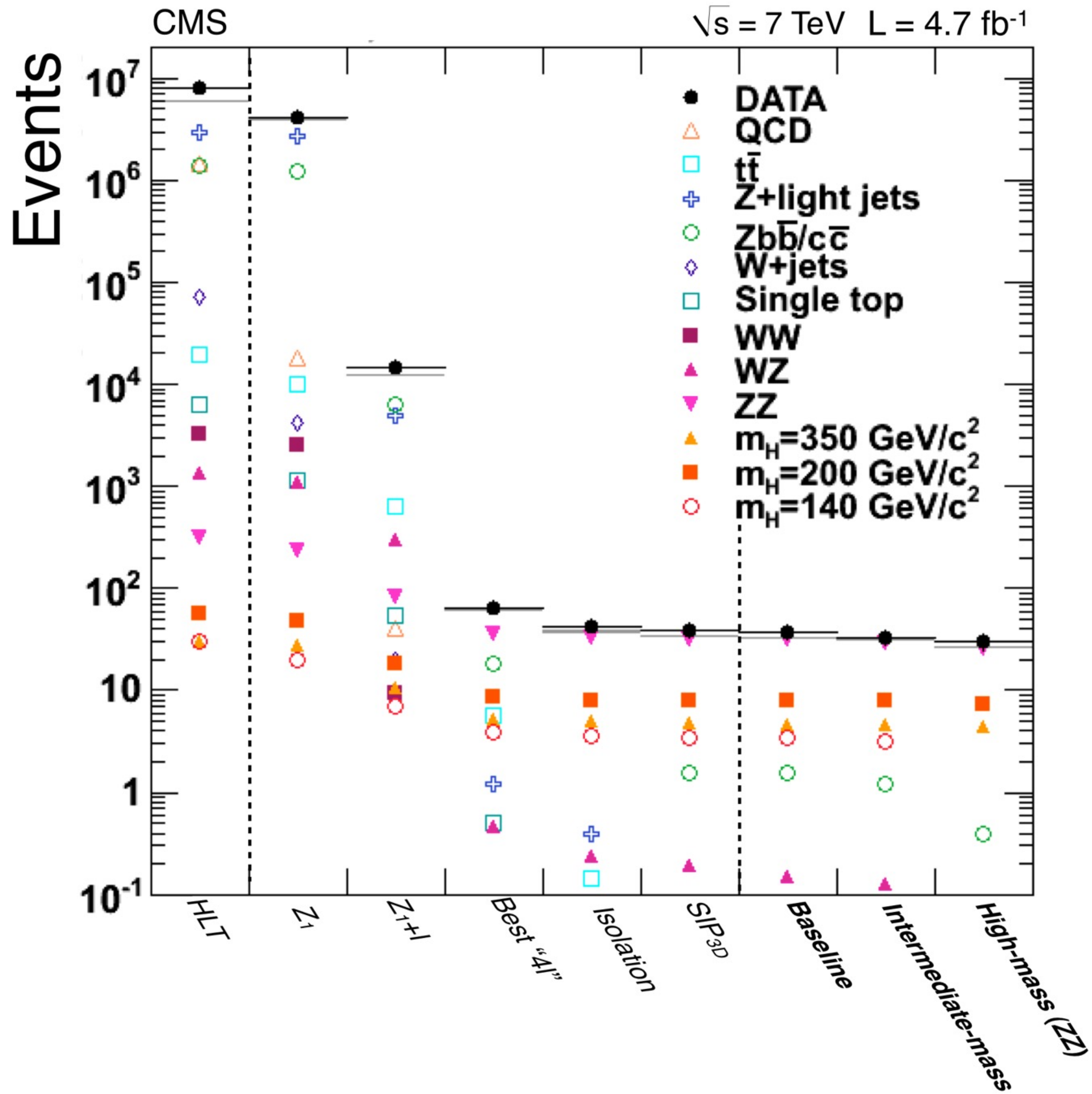
Reducible background

The final state looks like the same, but some f the particle fakes what you are looking for



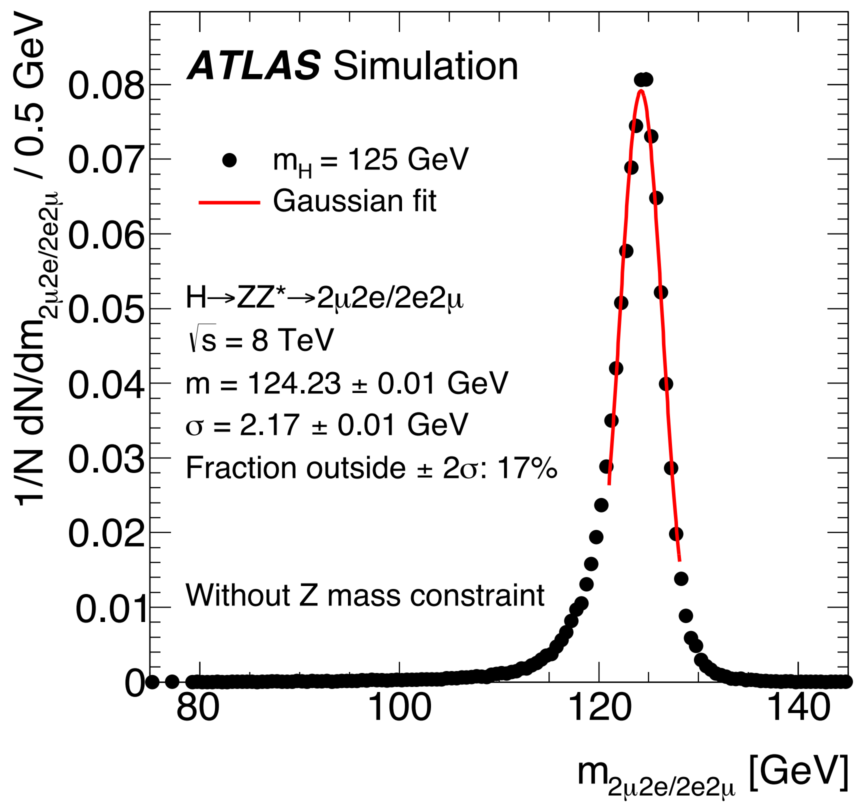
Selections

- Cut on particle properties to reduce reducible background
  - ✓ Shower shapes, track properties, …
- Cut on event properties to distinguish signal from background
  - ✓ Particle kinematics, decay kinematics event shape, …
- Try to keep signal while reducing background!
  - ✓ Increase S/B…



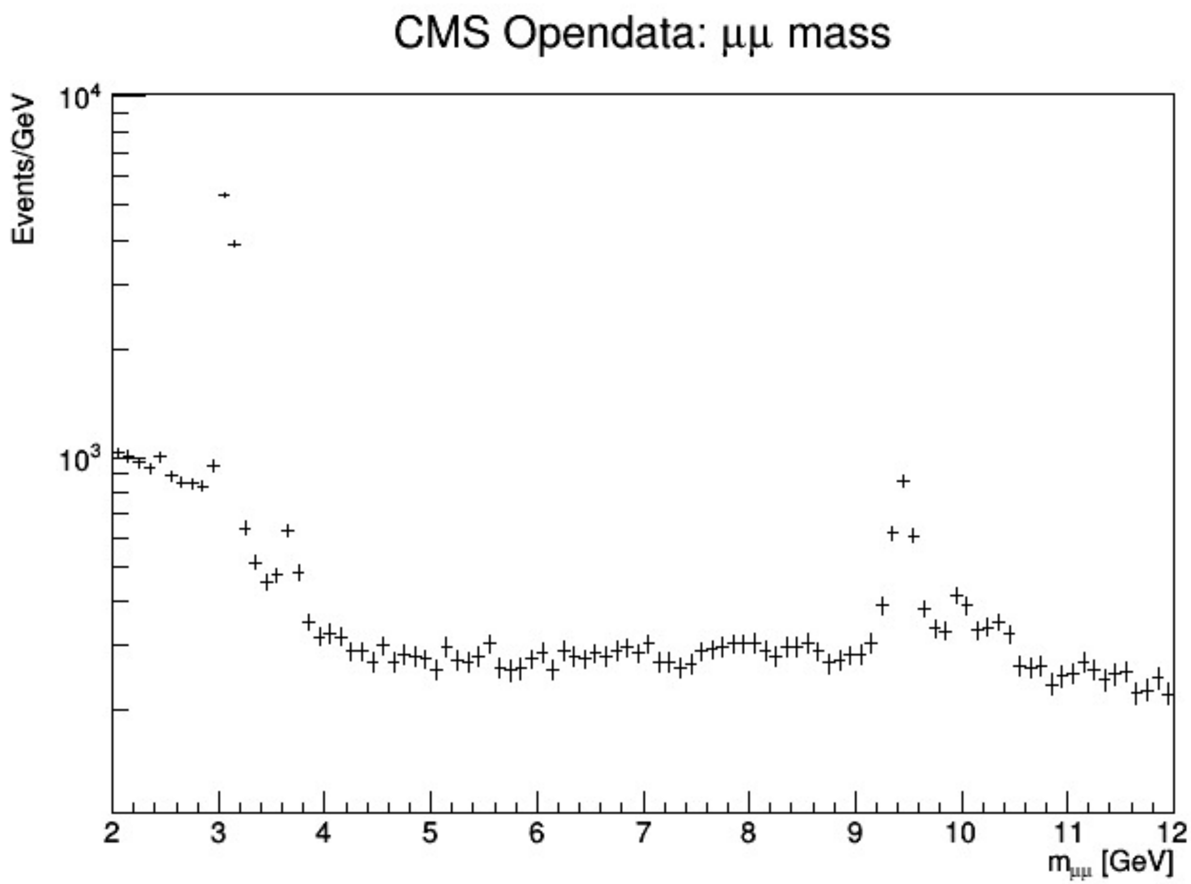
Step 2: reconstruct properties of initial particle

- We have 4 particles…
  - ✓ … with their energy (calorimeters), charge and momentum (tracker)
- Use pairs of opposite sign e^+e^- and $\mu^+\mu^-$
- Reconstruct invariant mass from the 4 particles $M = \sqrt{\left(\sum E_i\right)^2 - \left(\sum \vec{p}_i\right)^2}$

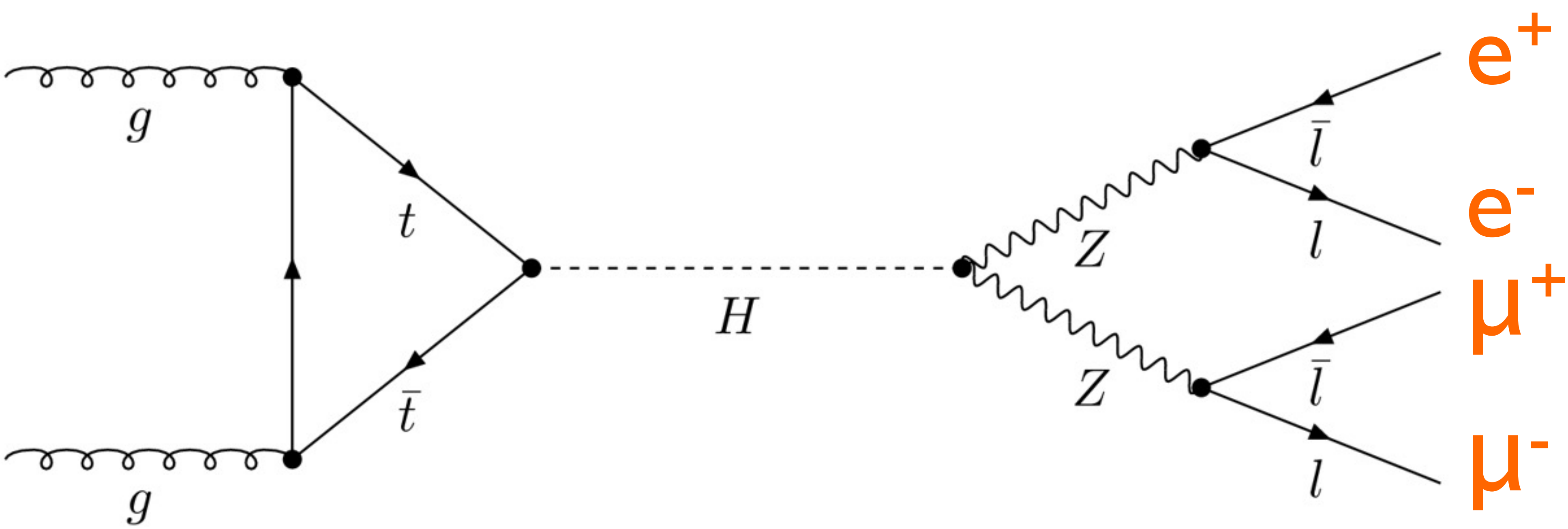


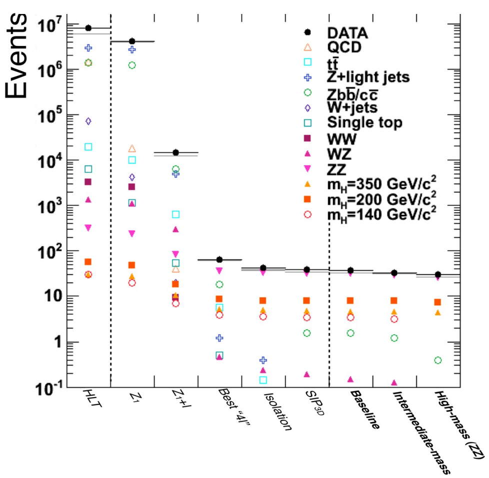
Hands-on: dimuon invariant mass

- Use real LHC data from the CMS experiment
- Select muon-antimuon pairs
- Compute and plot the di-muon invariant mass
- …

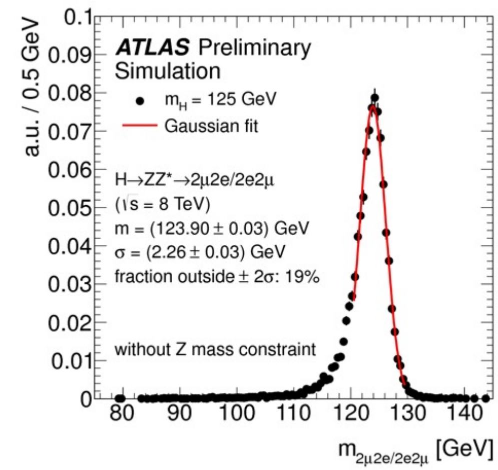


Back to the Higgs search example…



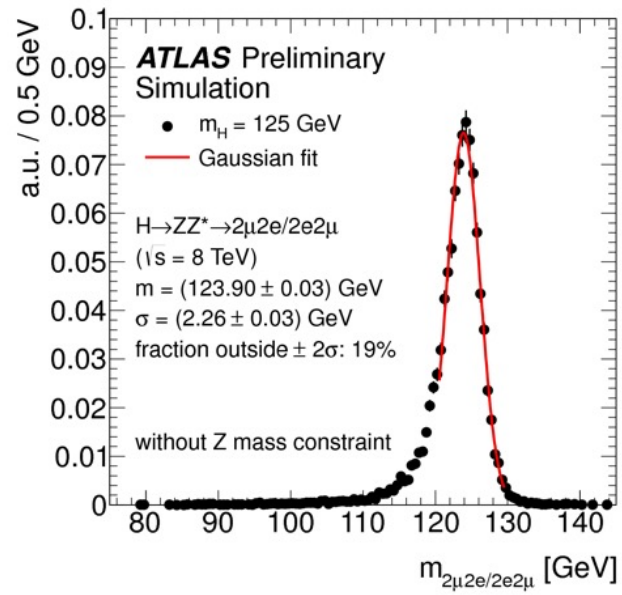


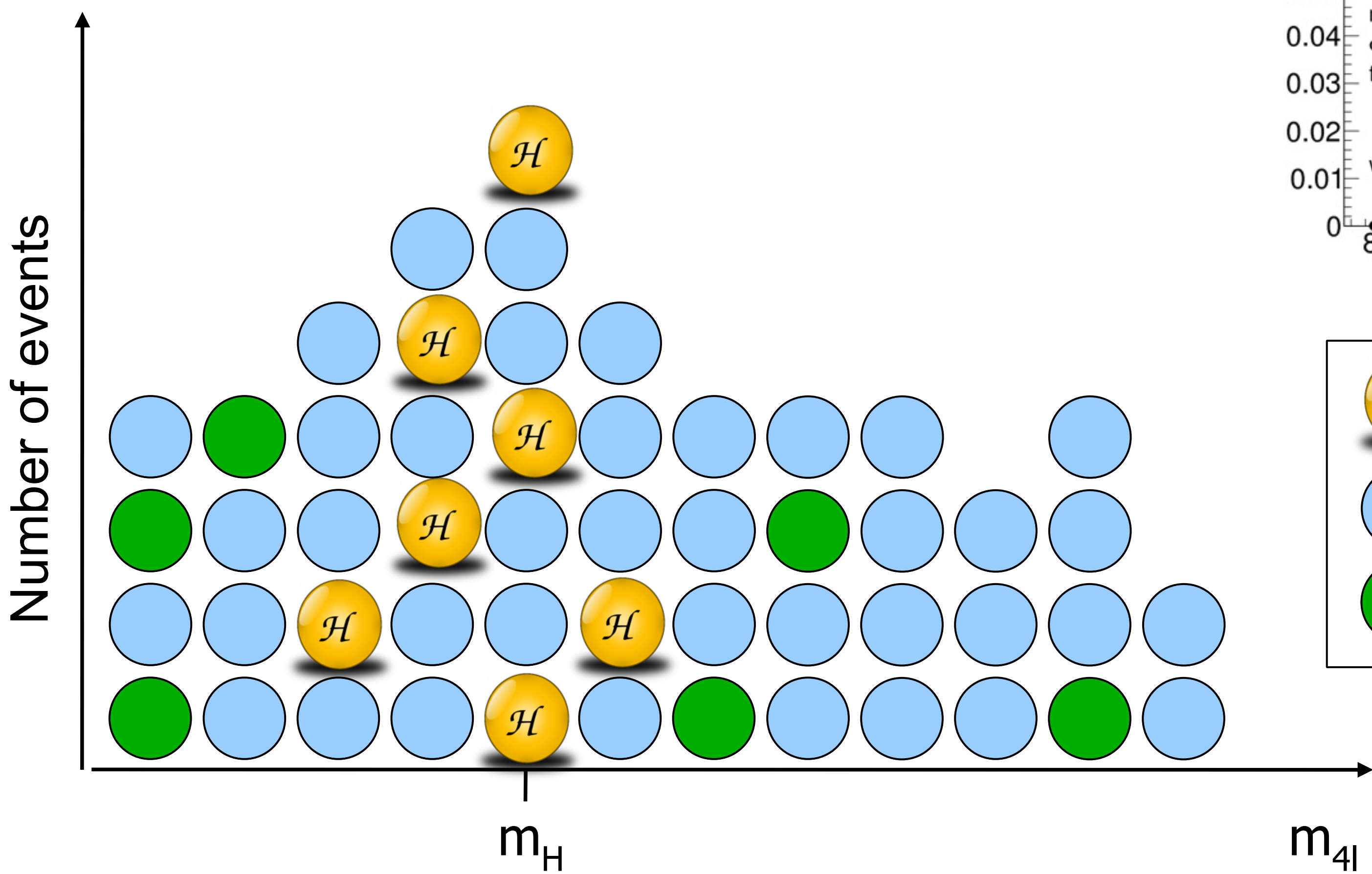
- What we (ideally) did:
  - ✓ Select all events with a di-muon and a di-electron pairs, trying to reduce the contribution from (reducible) backgrounds
  - ✓ Compute the eeμμ invariant mass and plot it…

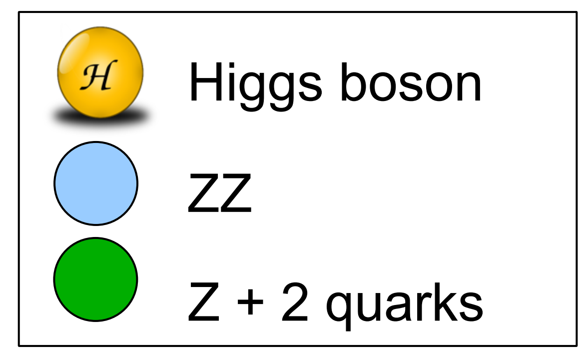


Extract signal from background

$$M = \sqrt{\left(\sum E_i\right)^2 - \left(\sum \vec{p}_i\right)^2}$$







Extract signal from background

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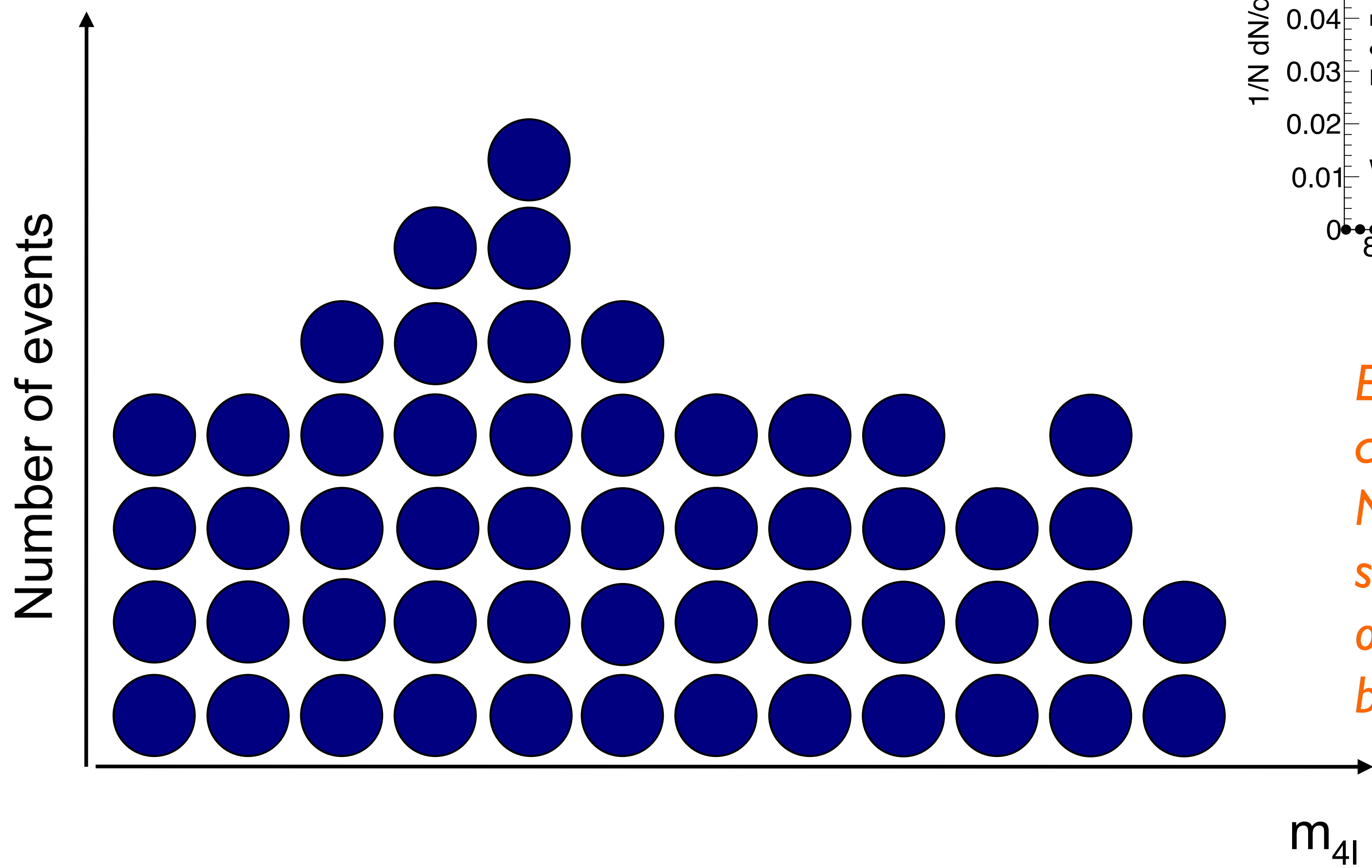
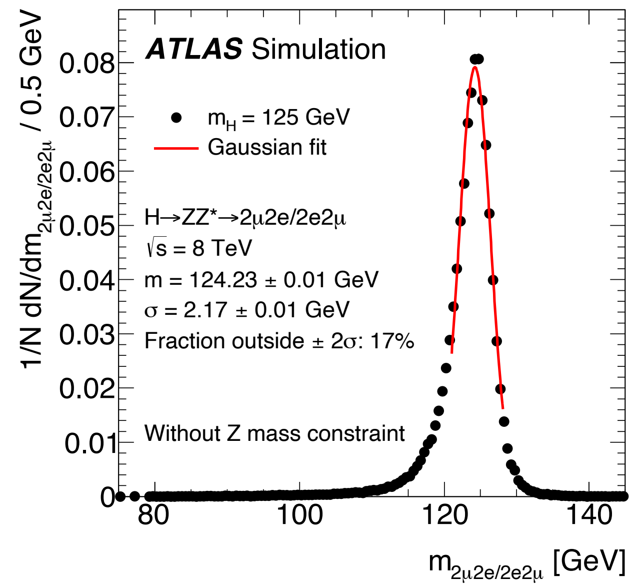
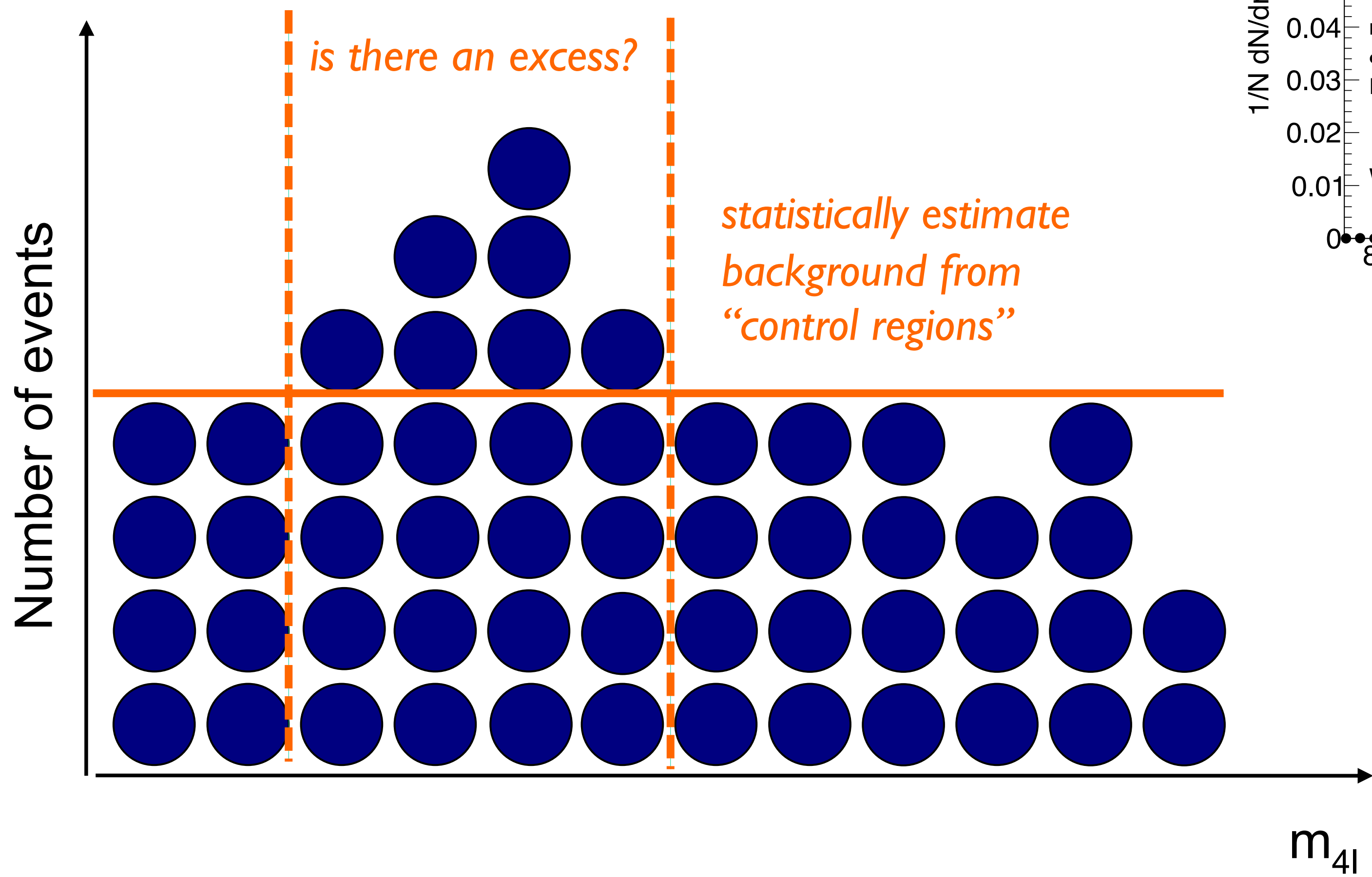


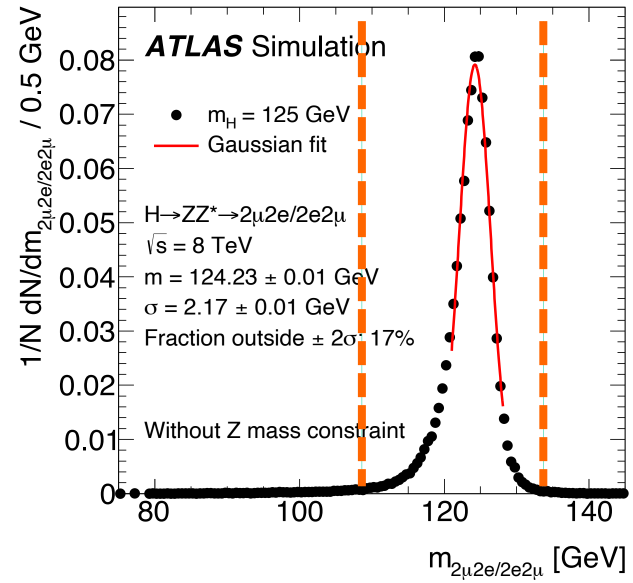


Events in real life do not come with a label!
No way to distinguish signal from background on an event-by-event base…

Extract signal from background

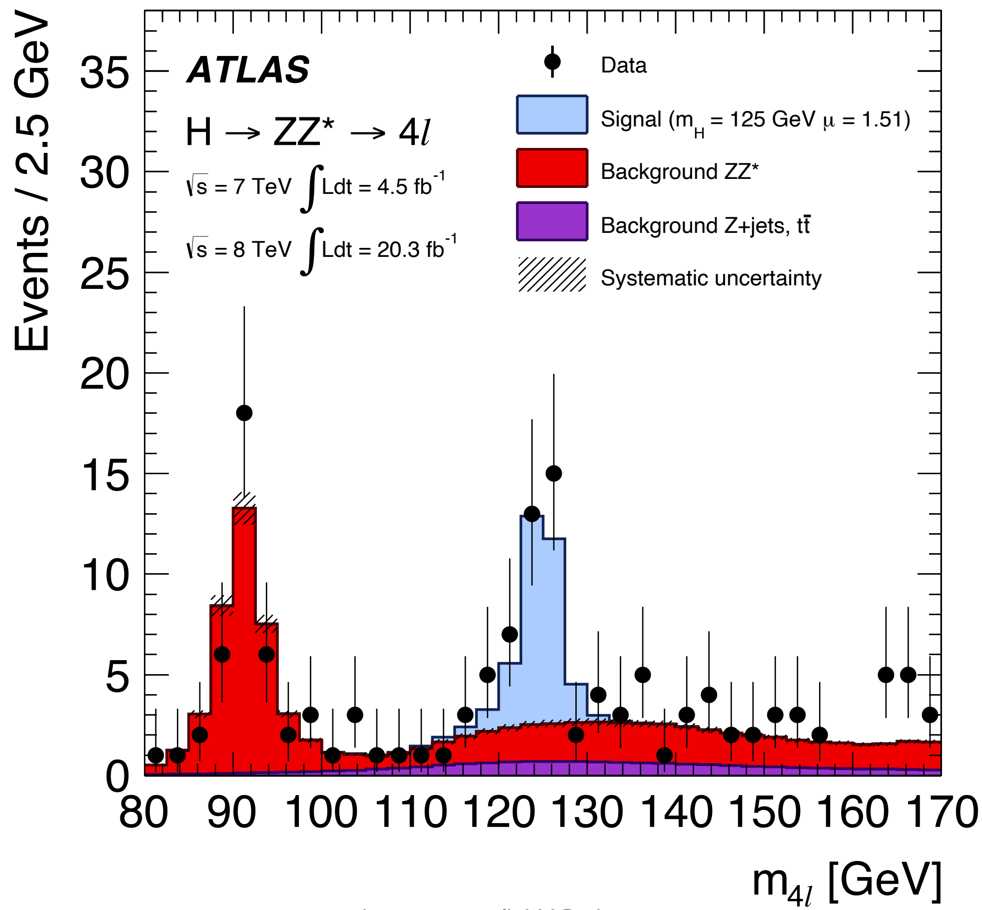
$$M = \sqrt{\left(\sum E_i\right)^2 - \left(\sum \vec{p}_i\right)^2}$$





Extract signal from background

- Background gets estimated…
  - ✓ … from simulation (normalized to data)
  - ✓ … directly from data (“control regions”, enriched in background events)



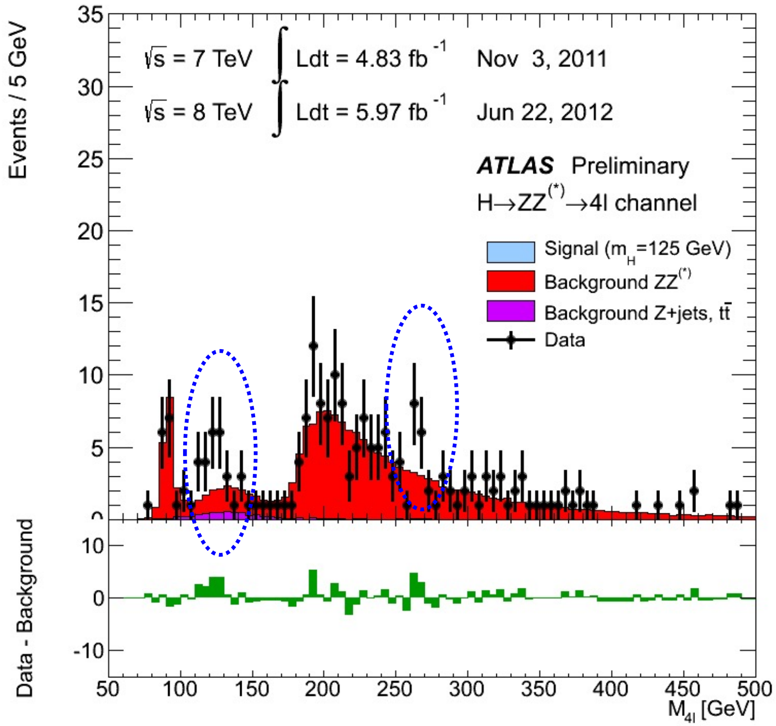
How significant is an excess?

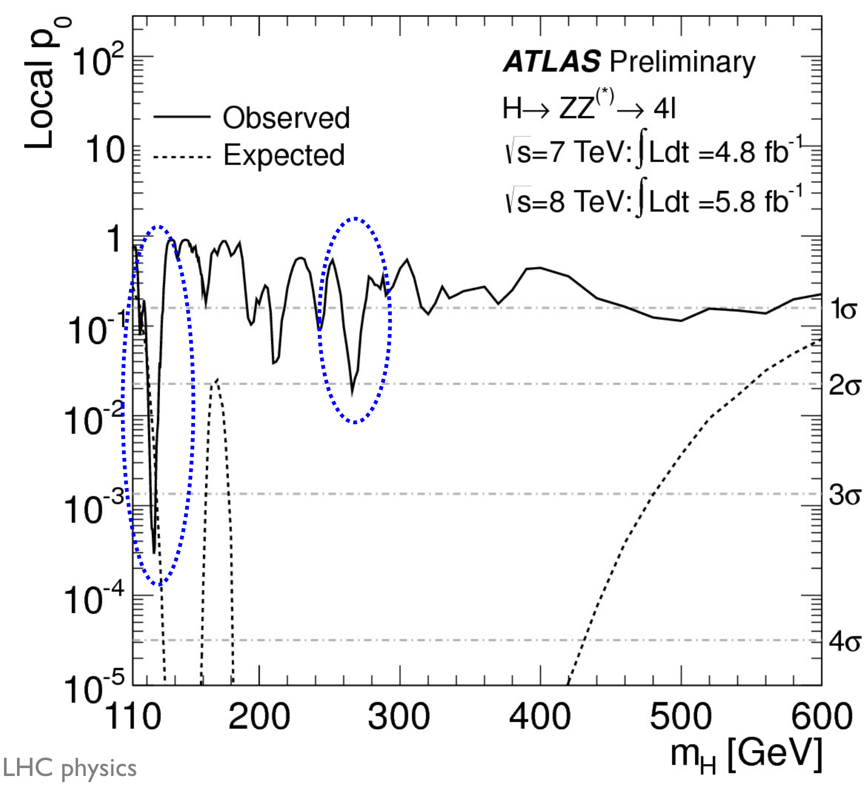
- p0: probability that the excess is due to a fluctuation of background
- Significance:

$$Z \sim \frac{S}{\sqrt{B}} \qquad p_0 = 1 - \mathrm{Erf}\left(\frac{Z}{\sqrt{2}}\right)$$

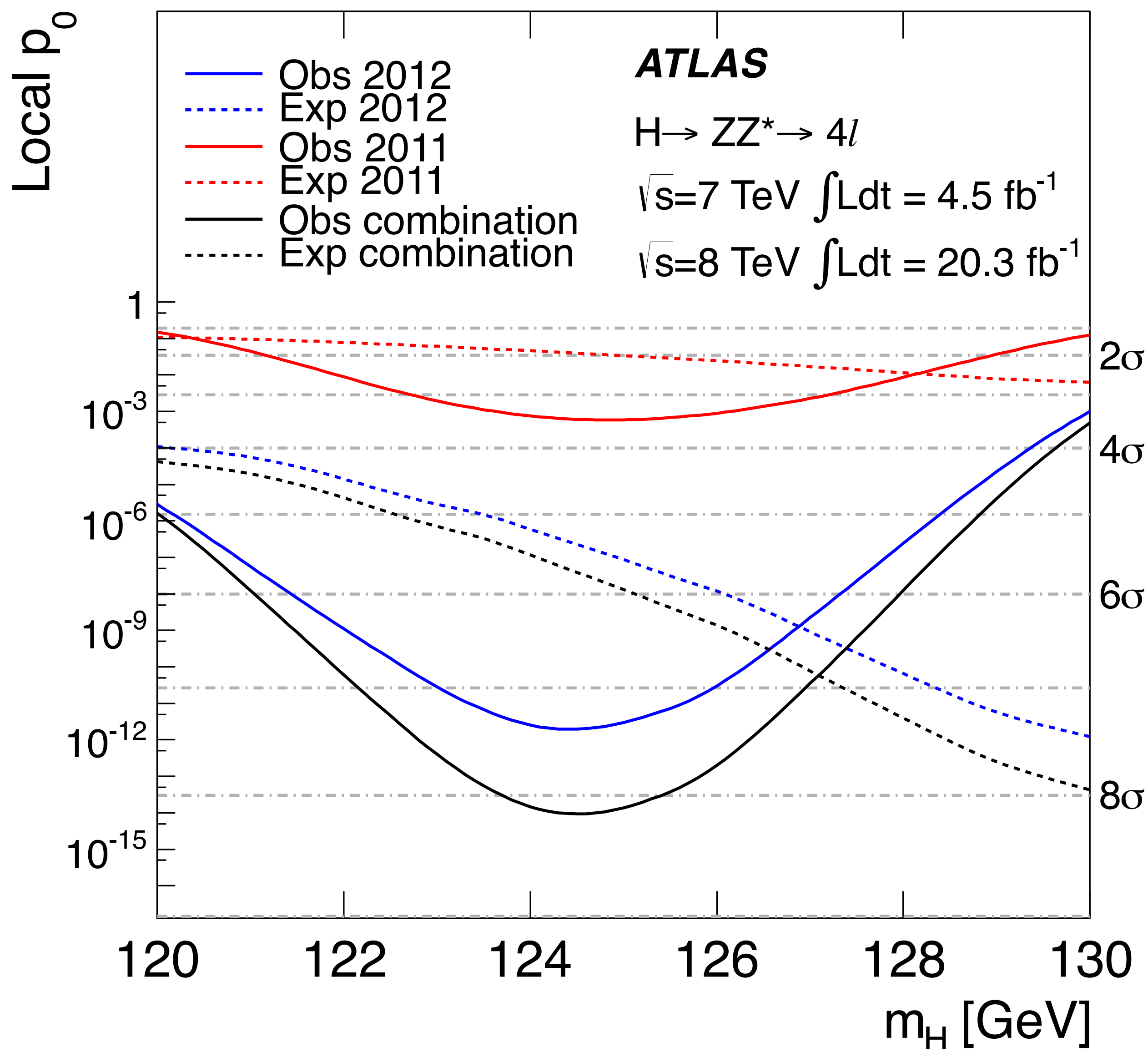
- Convention:
  - 3σ is an evidence (p_0 = 0.27%)
  - 5σ is a discovery ($p_0 = 5.7.10^{-7}$)

Erf = Error function

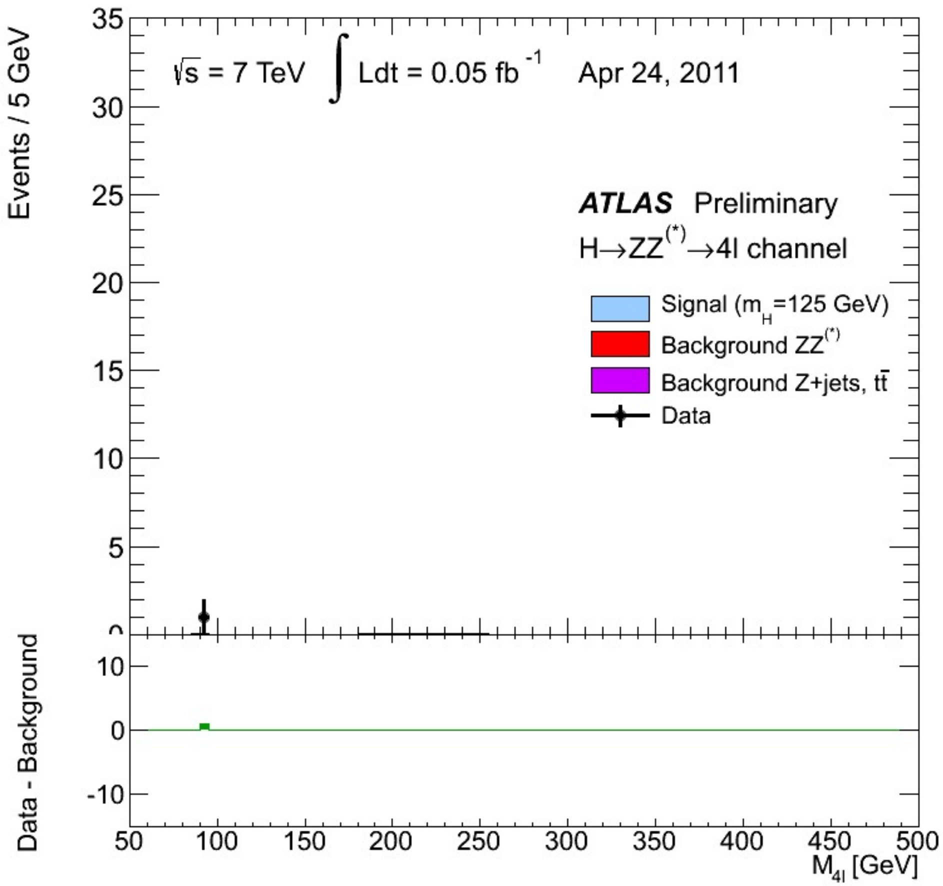


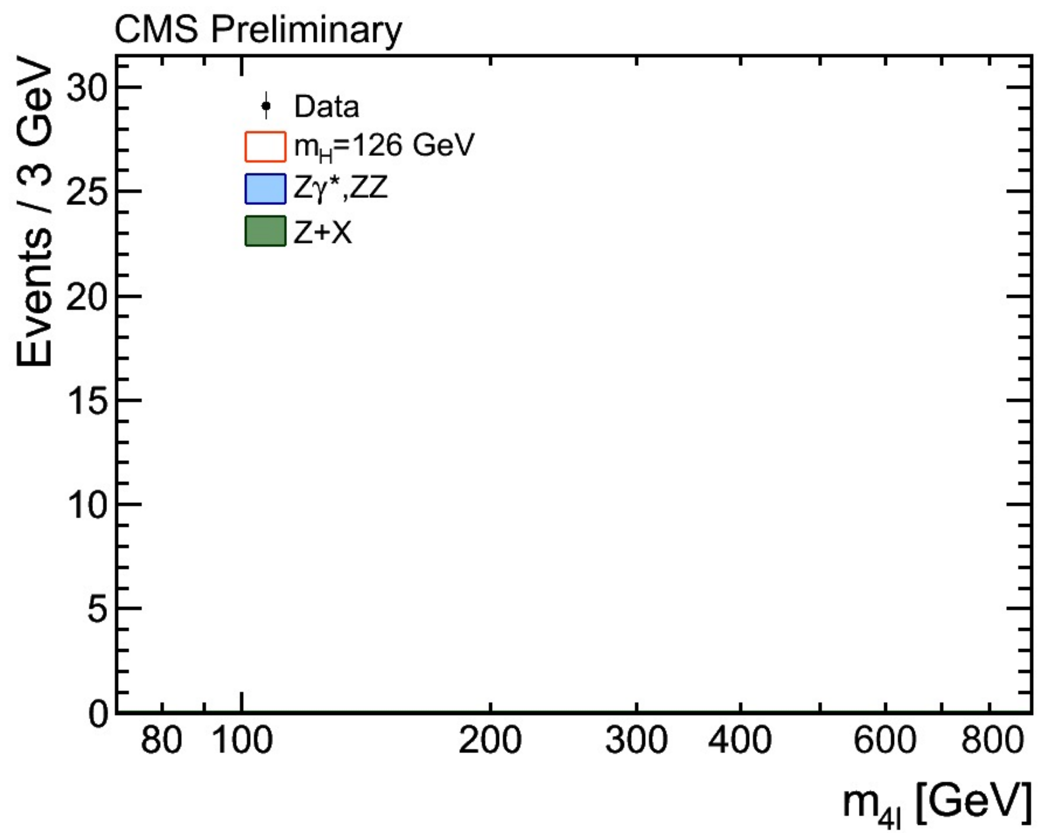


How significant is an excess?

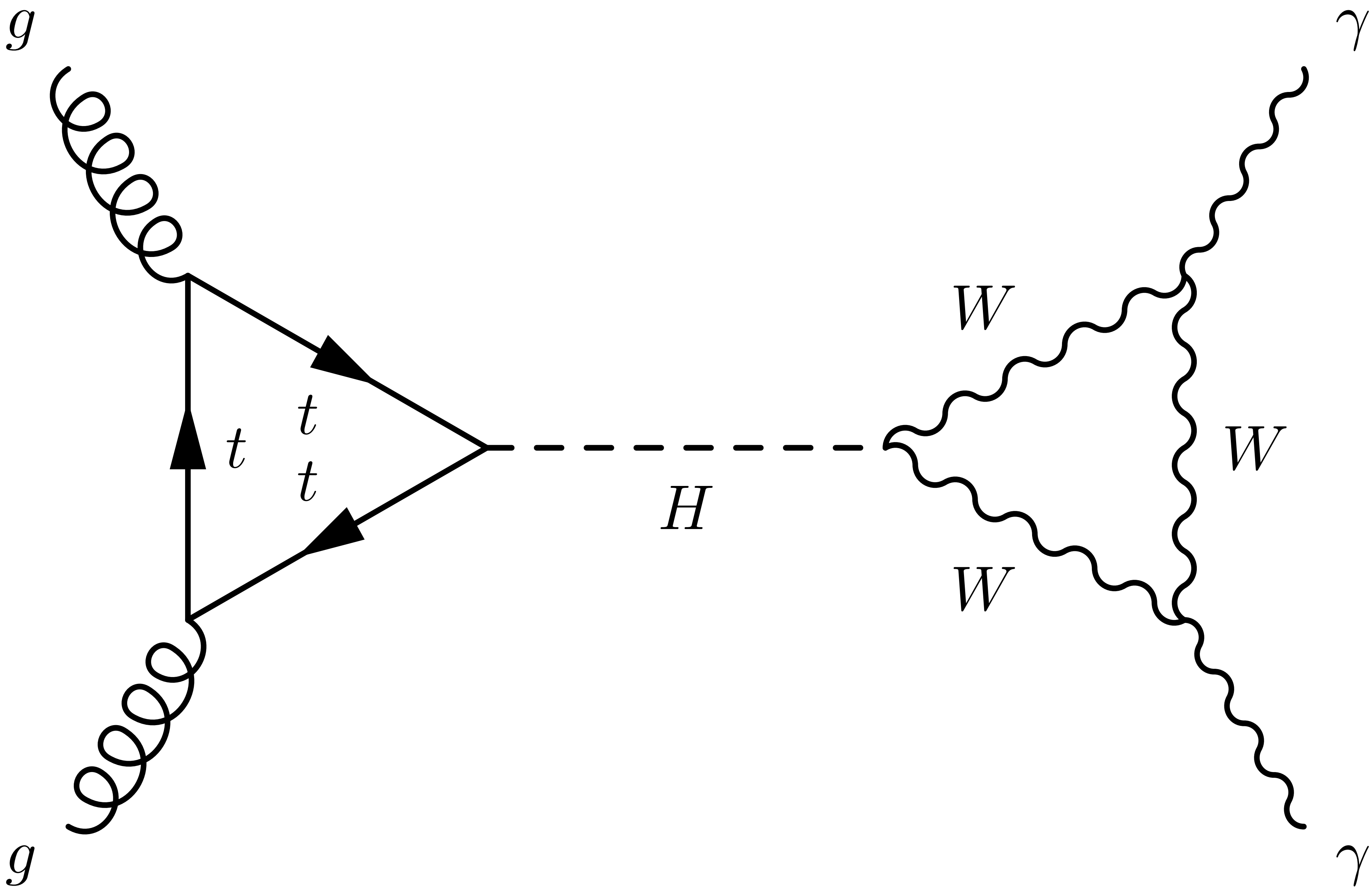


Significance increases with data (and time!)



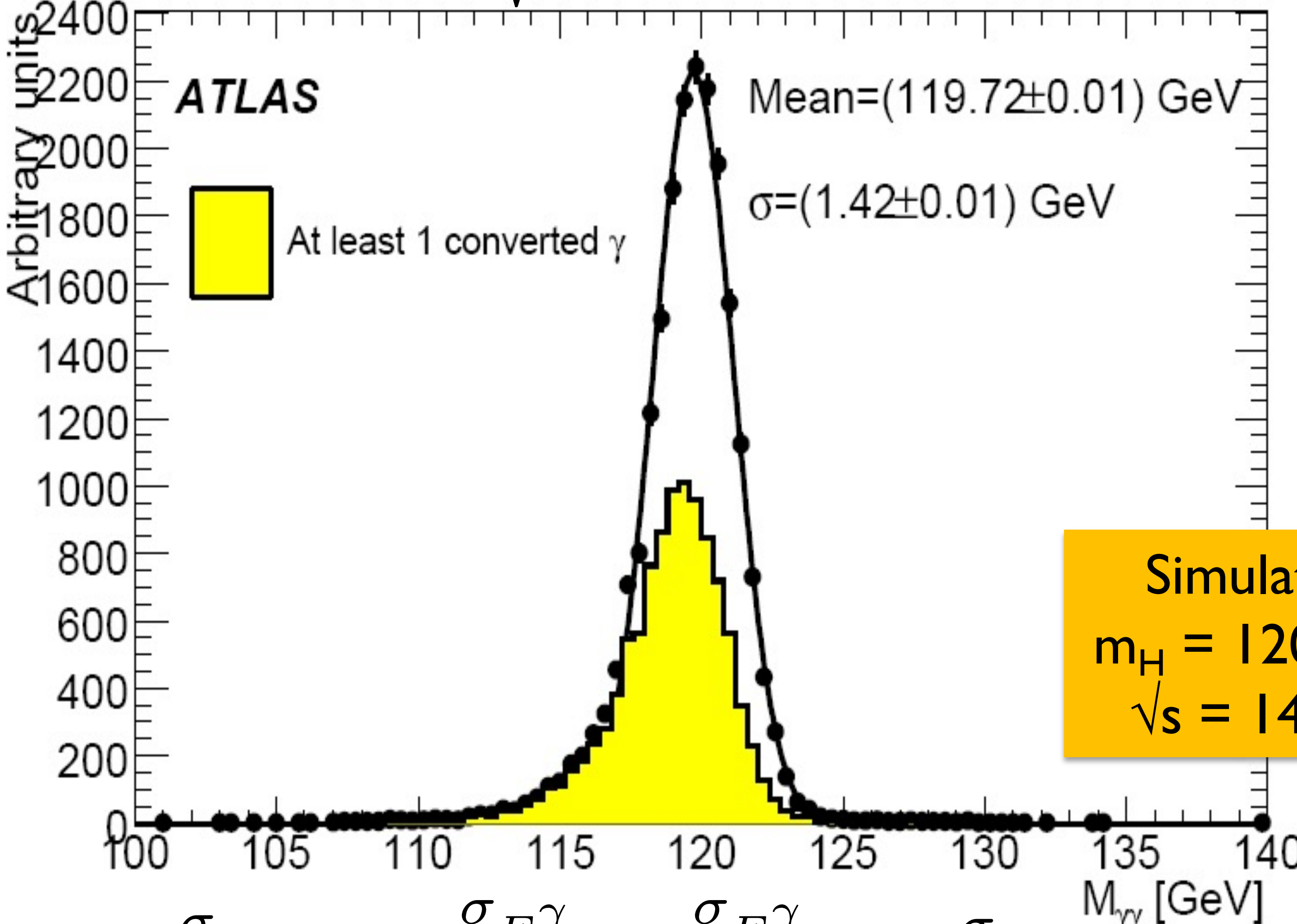


Another Higgs search example: H→γγ



A narrow mass peak…

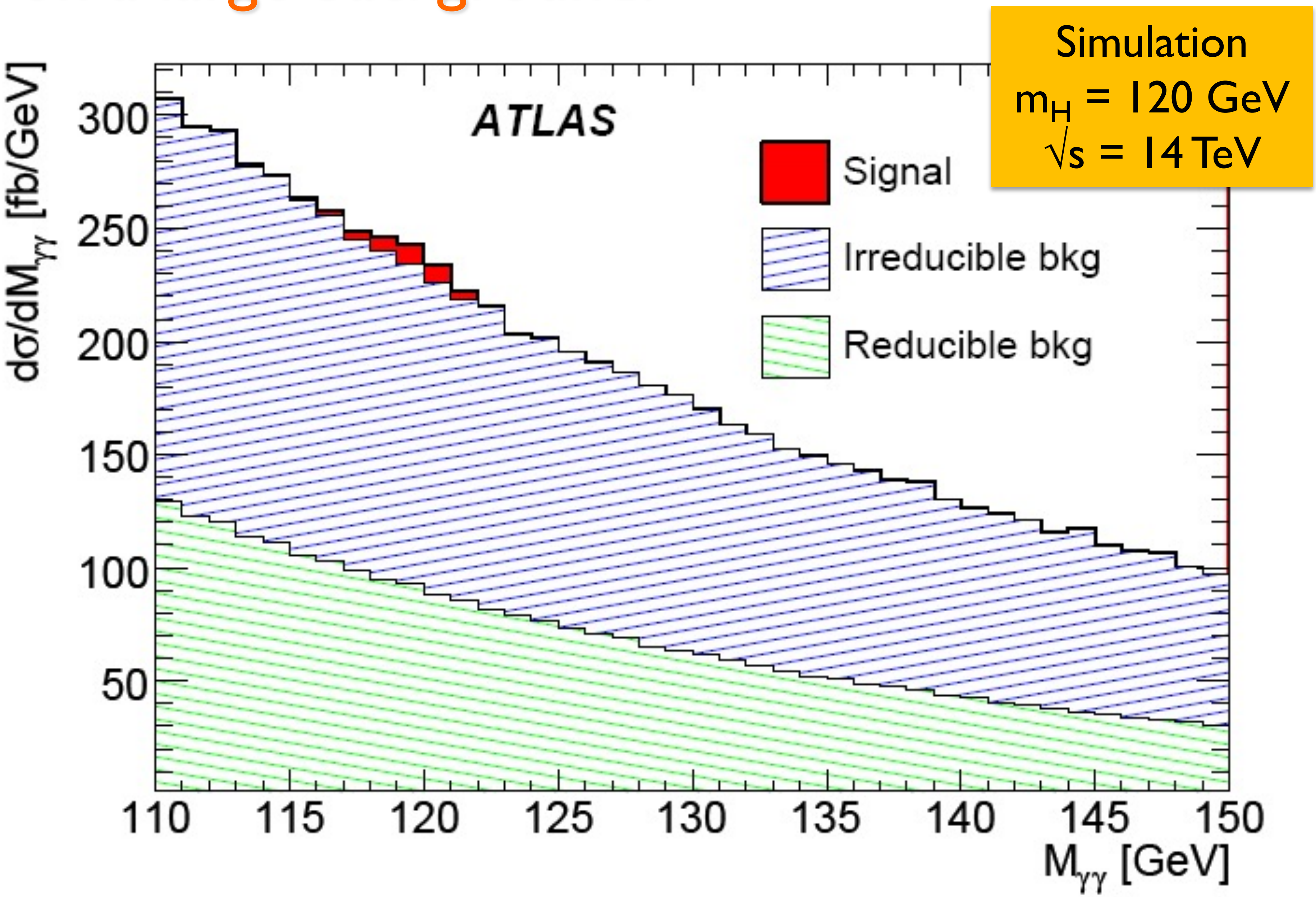
$$m_{\gamma\gamma} = \sqrt{2E_1^\gamma E_2^\gamma(1-\cos\alpha_{12})}$$



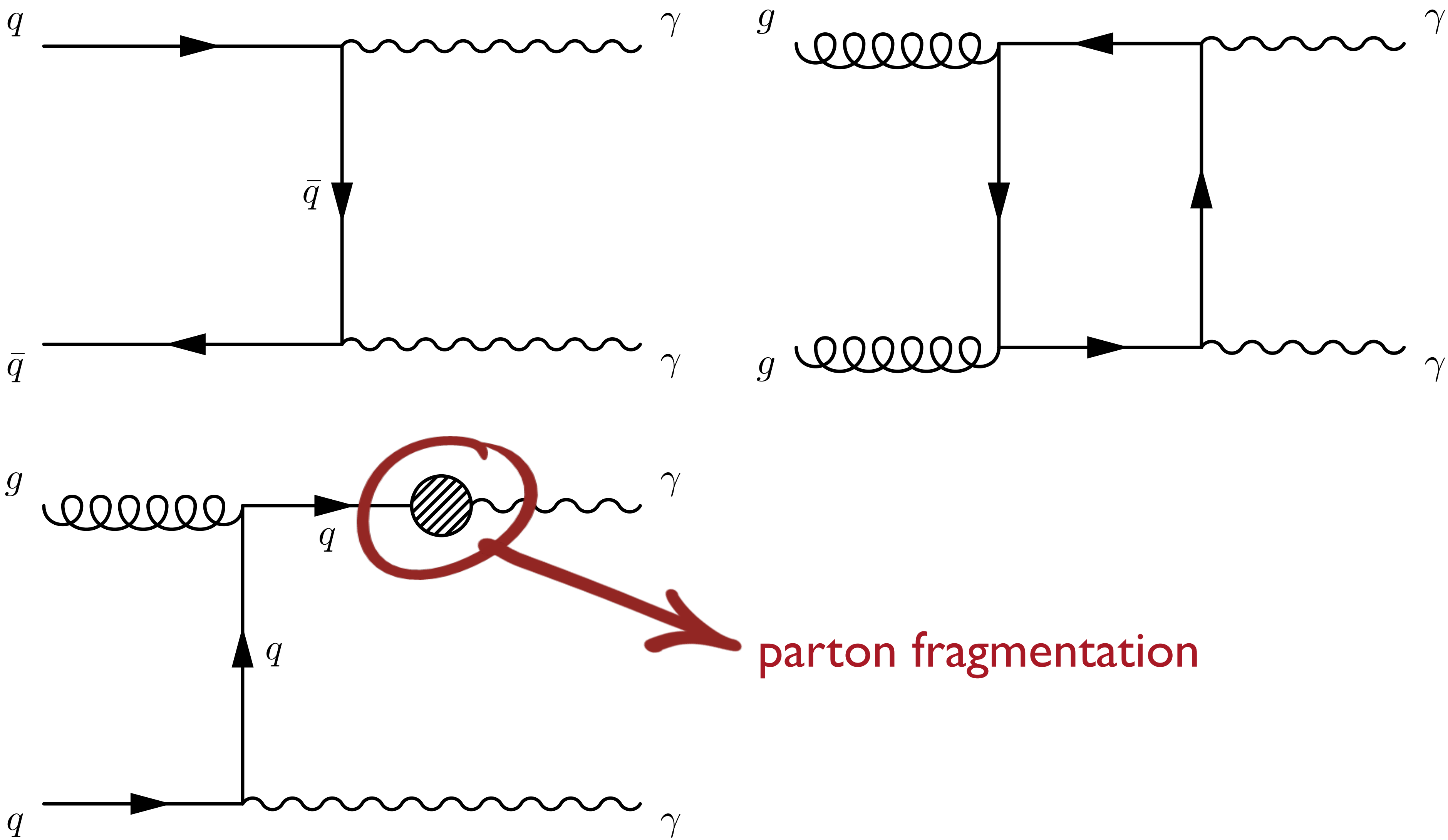
Simulation
m_H = 120 GeV
$\sqrt{s}$ = 14 TeV

$$\frac{\sigma_{m_{\gamma\gamma}}}{m_{\gamma\gamma}} = \frac{\sigma_{E_1^\gamma}}{E_1^\gamma} \oplus \frac{\sigma_{E_2^\gamma}}{E_2^\gamma} \oplus \frac{\sigma_{\alpha_{12}}}{\tan\alpha_{12}}$$

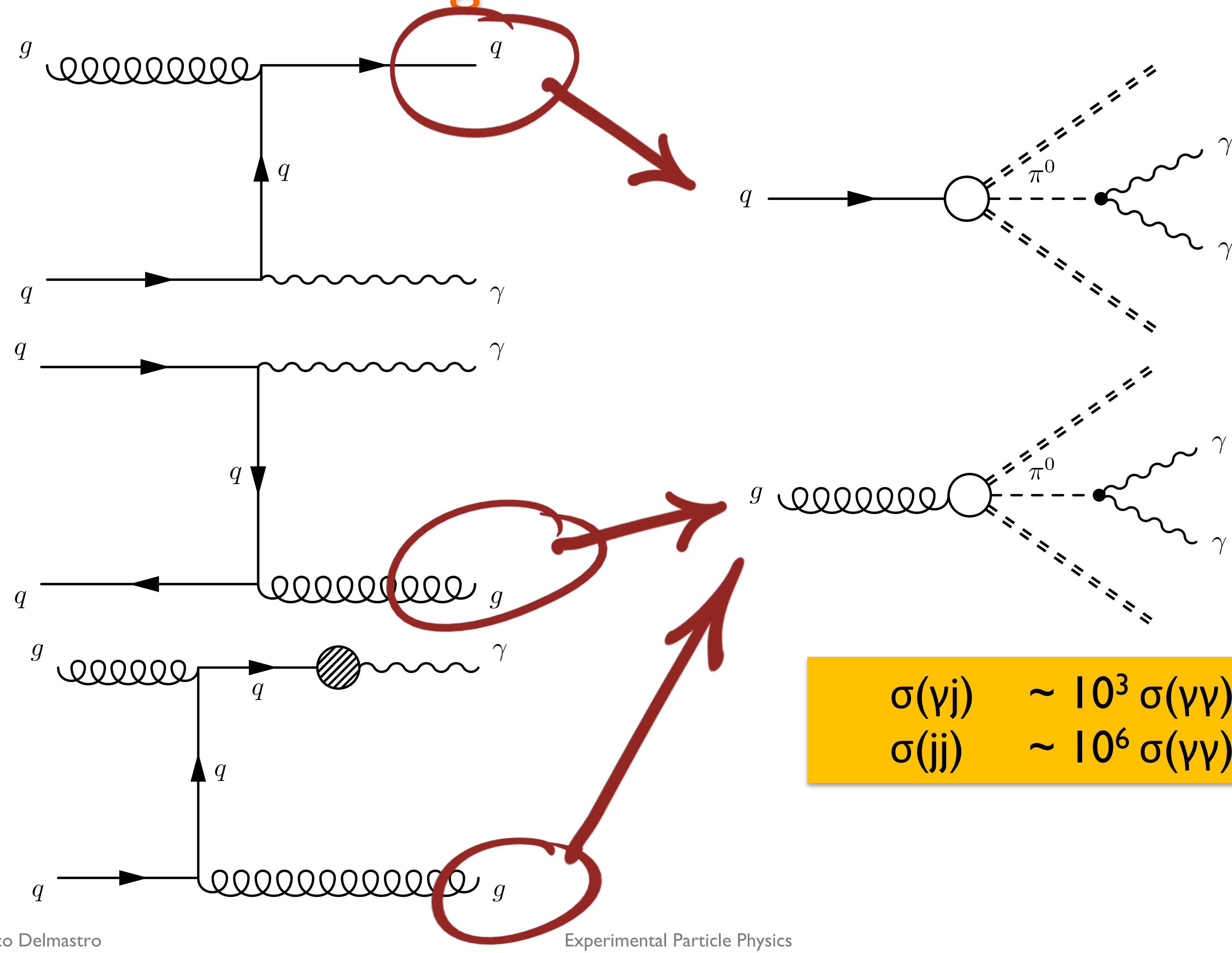
… on a large background!



“Irreducible” background



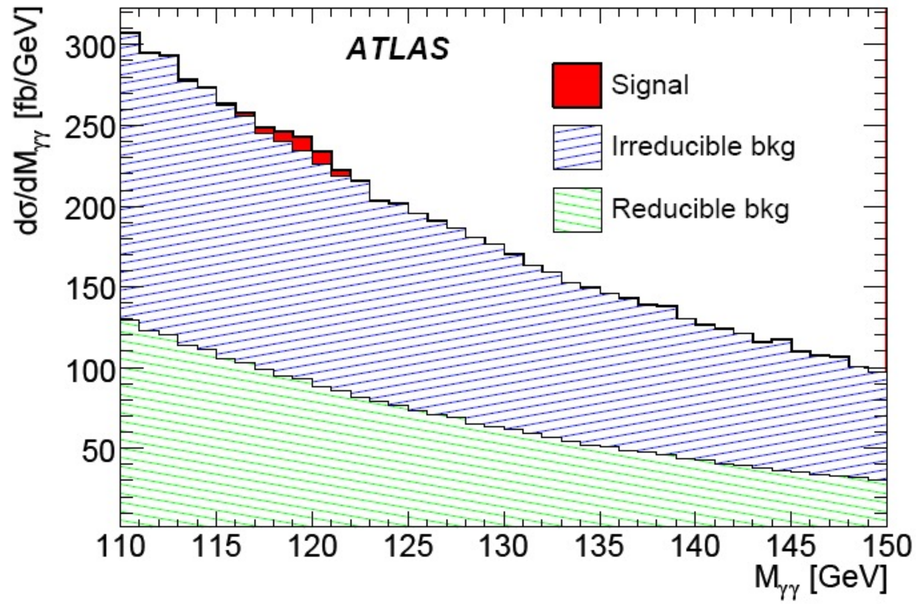
“Reducible” background

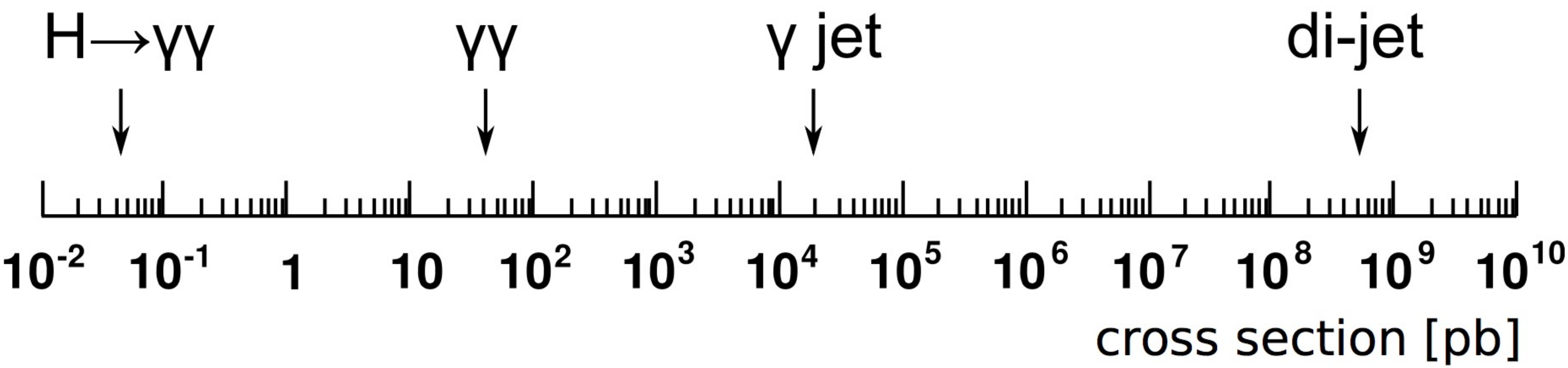


$\sigma(\gamma j) \sim 10^3\, \sigma(\gamma\gamma)$
$\sigma(jj) \sim 10^6\, \sigma(\gamma\gamma)$

Signal vs. background

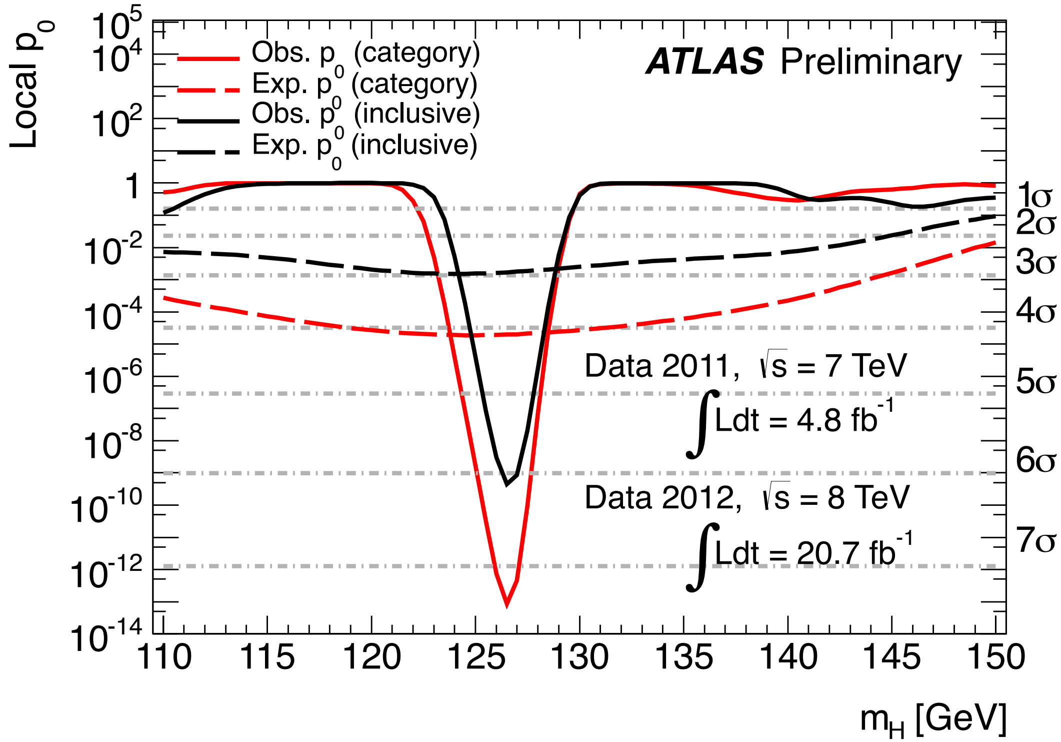
- small branching ratio (~10^{-3})
- huge background
  - ✓ γγ, γj, jj, Drell-Yan
- S/B ~ 3%





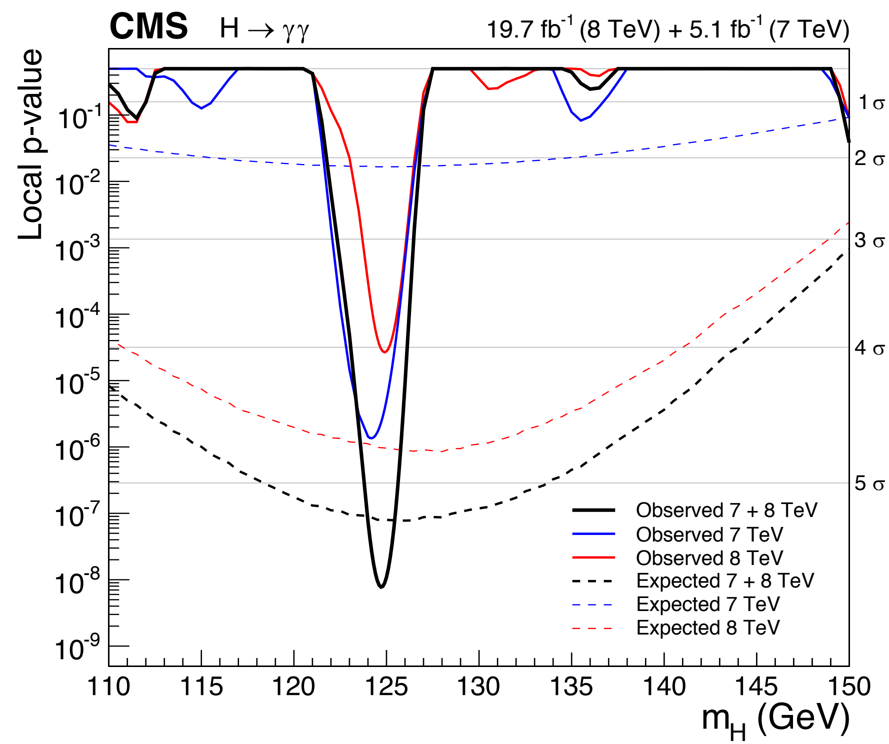
H→γγ significance

ATLAS



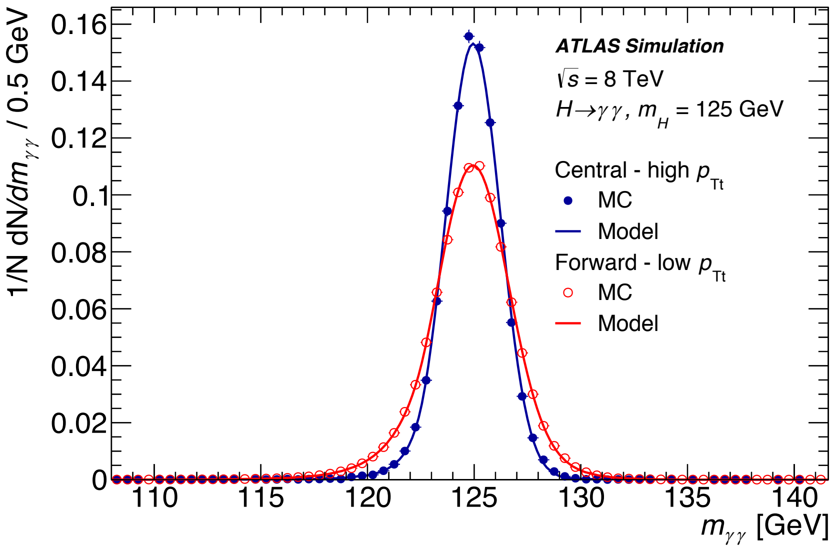
[ATLAS-CONF-2013-012]

CMS



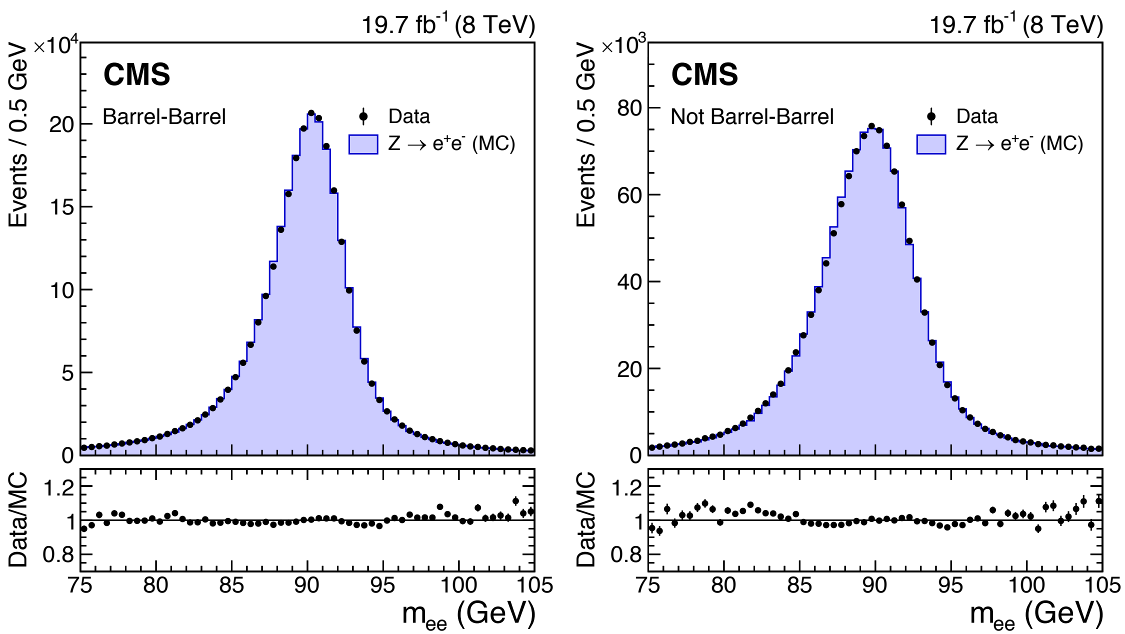
[Eur. Phys. J. C 74 (2014) 3076]

H→γγ invariant mass resolution



ATLAS

Phys. Rev. D. 90, 112015 (2014)

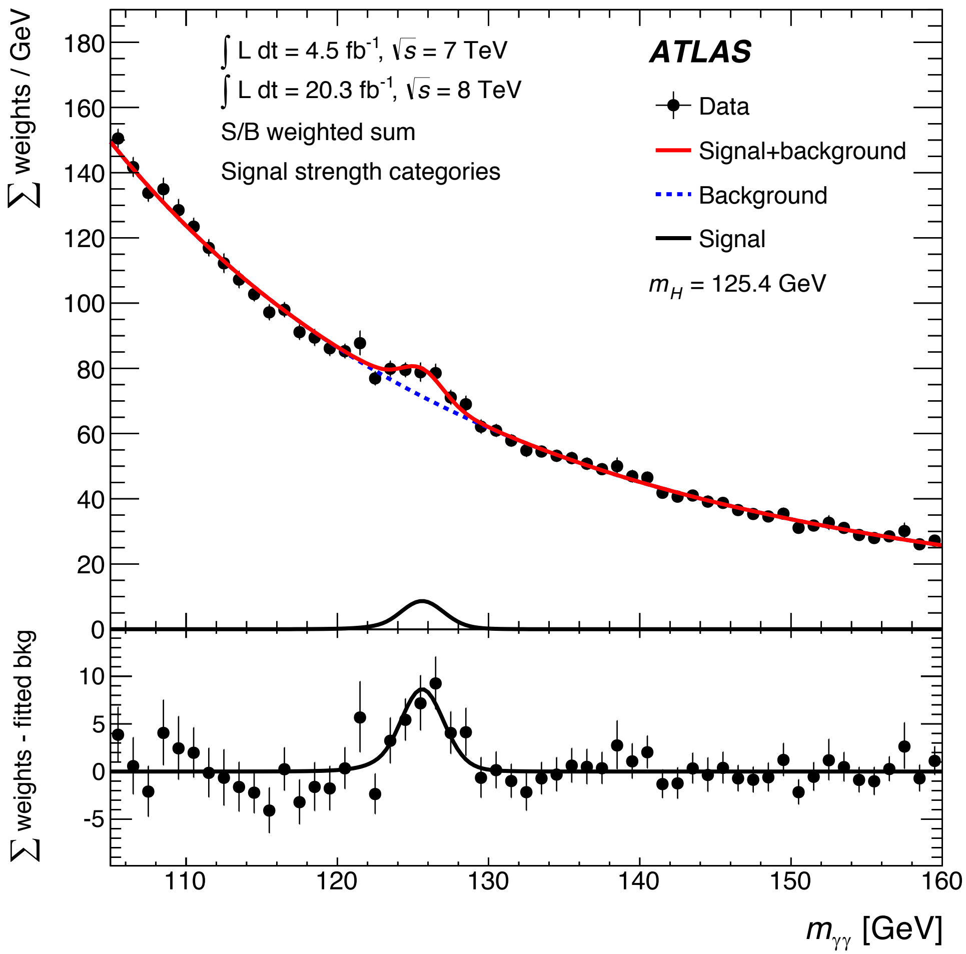


CMS

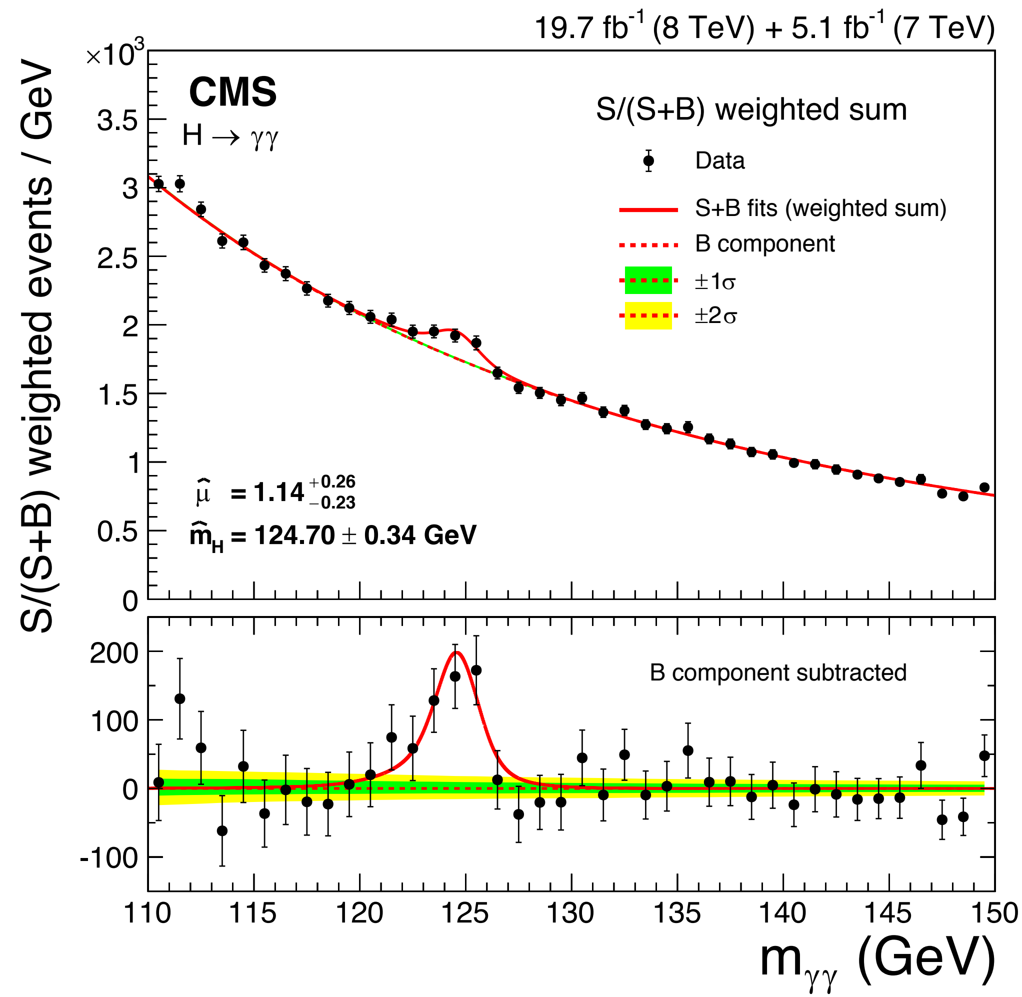
Eur. Phys. J. C 74 (2014) 3076

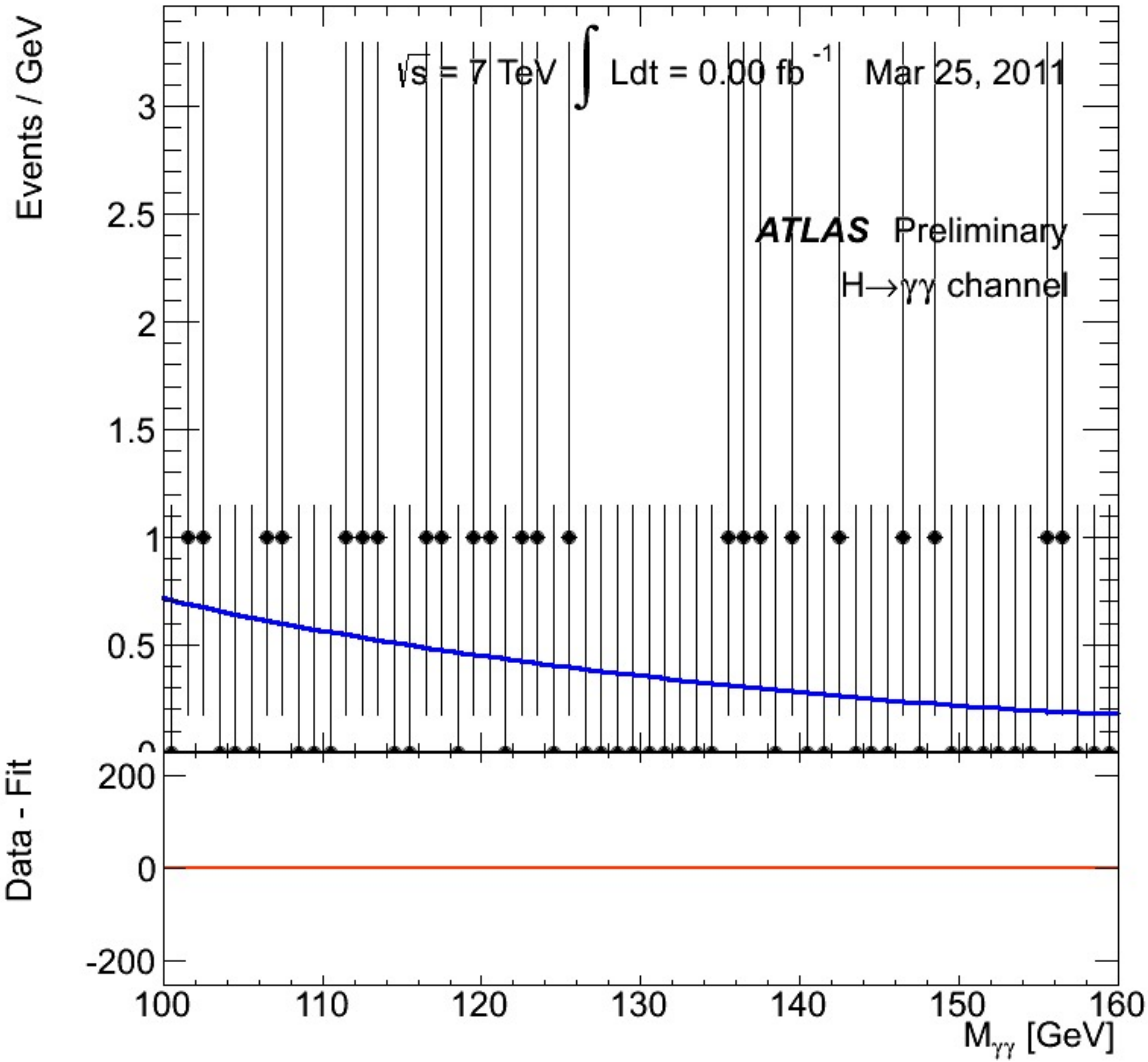
H→γγ (weighted) mass spectra

ATLAS



CMS





√s = 7 TeV ∫ Ldt = 0.00 fb⁻¹ Mar 25, 2011
ATLAS Preliminary
H→γγ channel
Events / GeV
Data - Fit
M_γγ [GeV]

Hands-on: H→γγ significance

- Use "toy" H→γγ mass spectra
- Estimate signal significance vs. luminosity (statistics) and invariant mass resolution