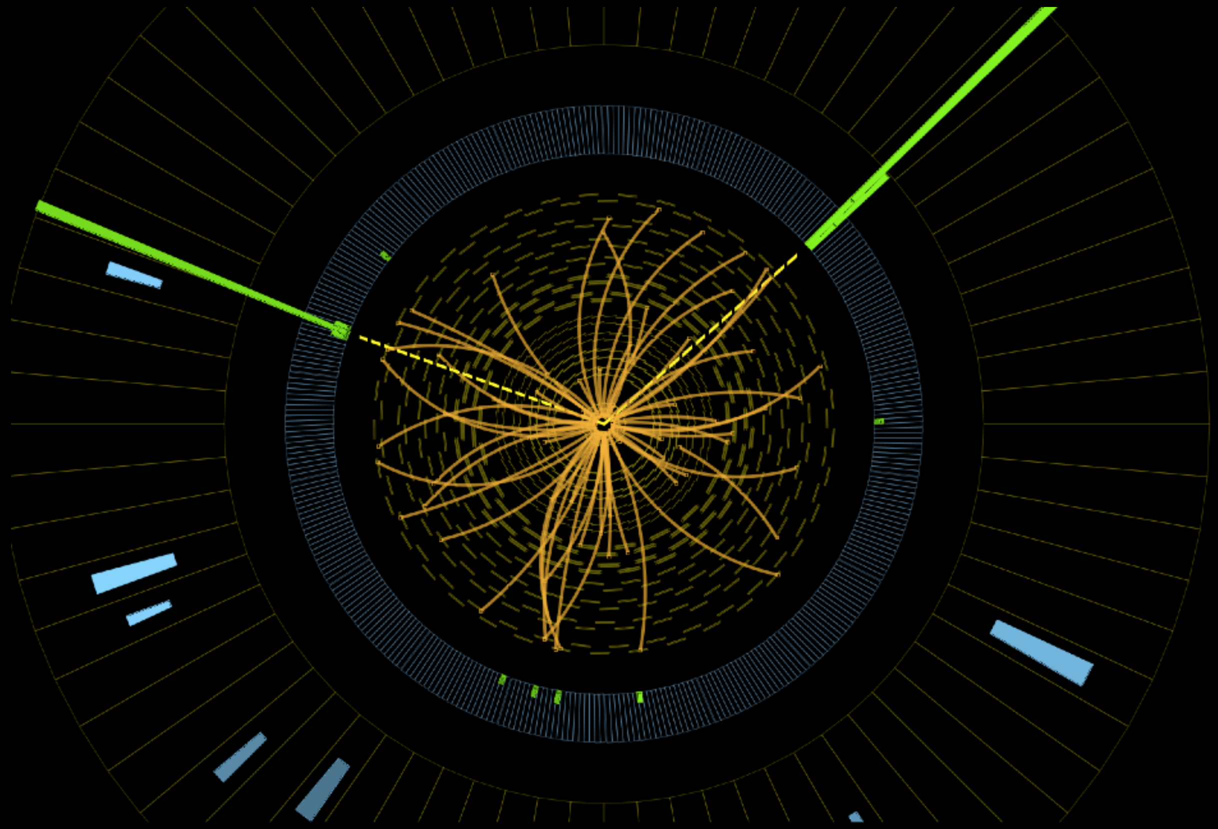
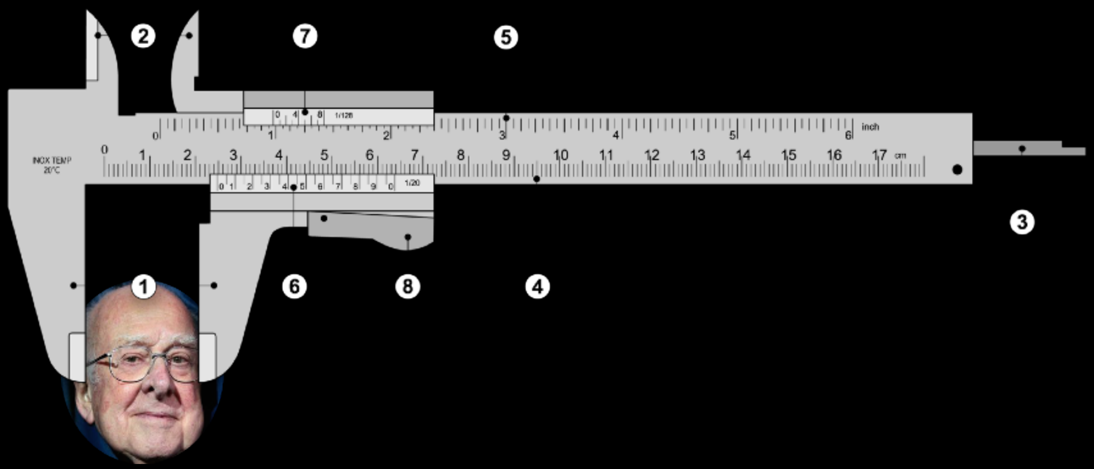
Exploring the Higgs boson with the ATLAS data

Dag Gillberg

Outline

1. What is the Higgs boson?
2. Producing and detecting Higgs boson
3. Higgs boson precision measurements



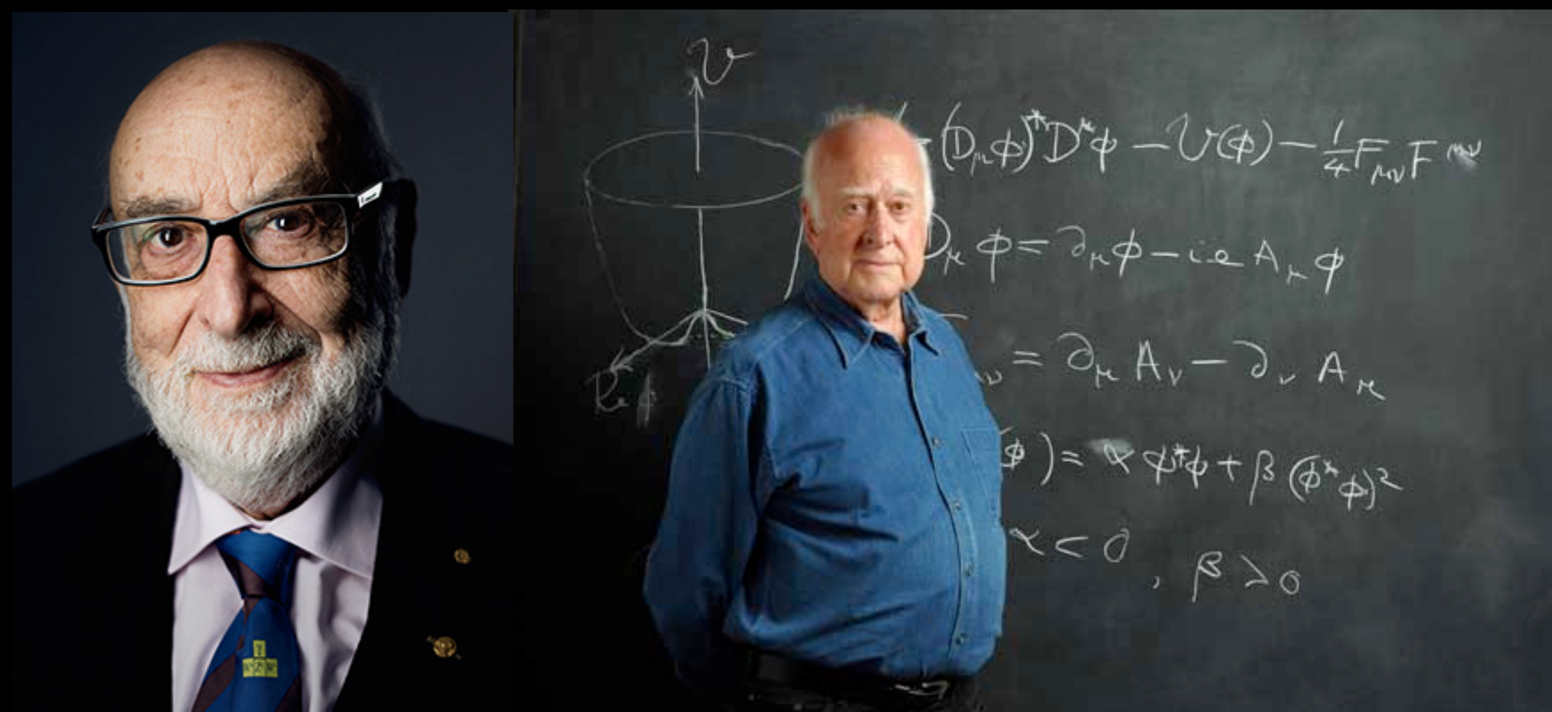


Part I

The Higgs boson in the Standard Model

THE HIGGS MECHANISM

Why do the fundamental particles have mass?



Nobel Prize in Physics 2013: François Englert and Peter W. Higgs

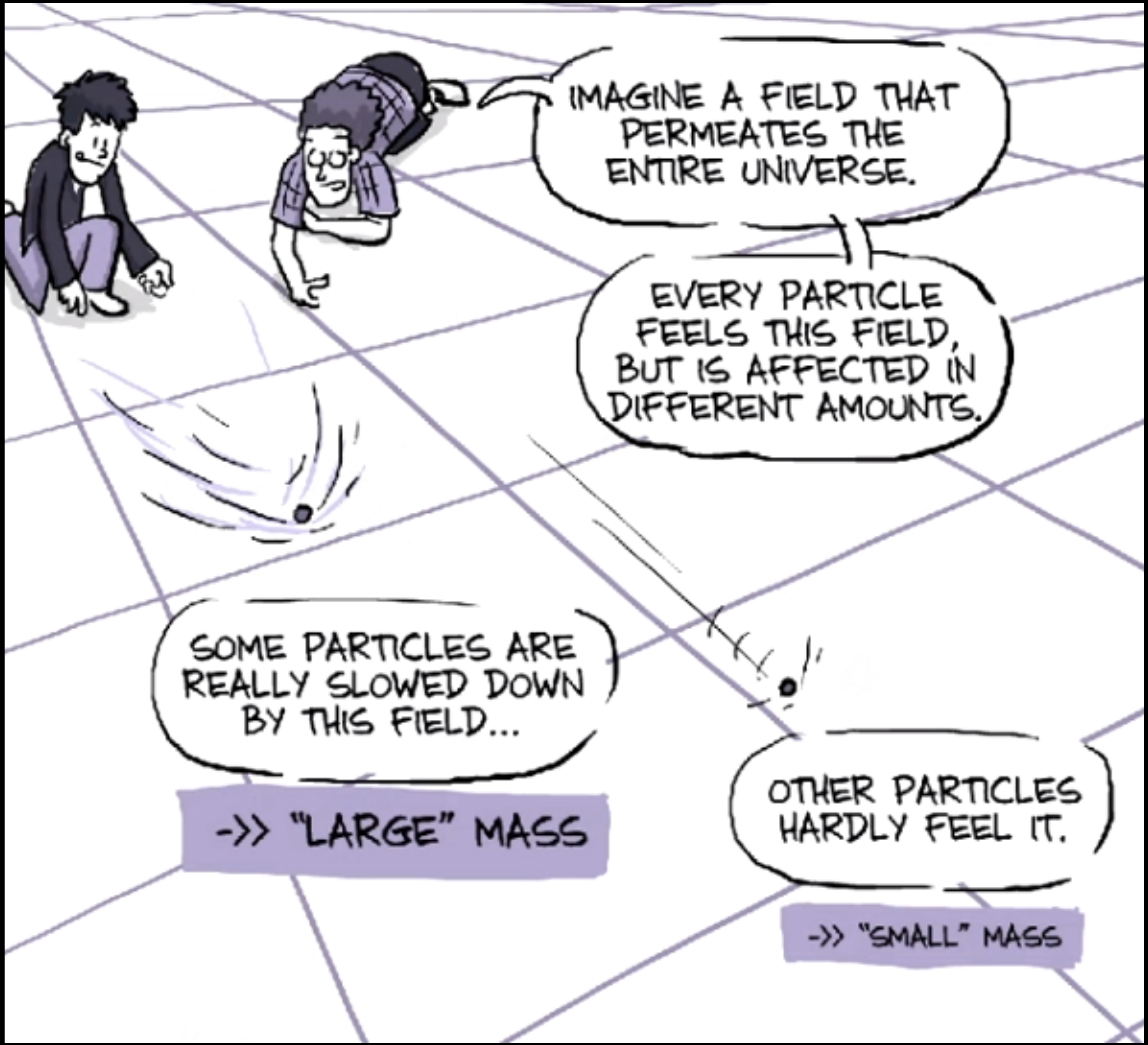
Their idea:

Imagine a field that fills all space.

Most particles ***couple*** *to this field, and feel a* ***resistance*** *as they move though space — this gives rise to their mass!*

The stronger they ***couple*** *to the field*
→ *the stronger the resistance*
→ *the larger the* ***mass*** *!*

THE HIGGS MECHANISM

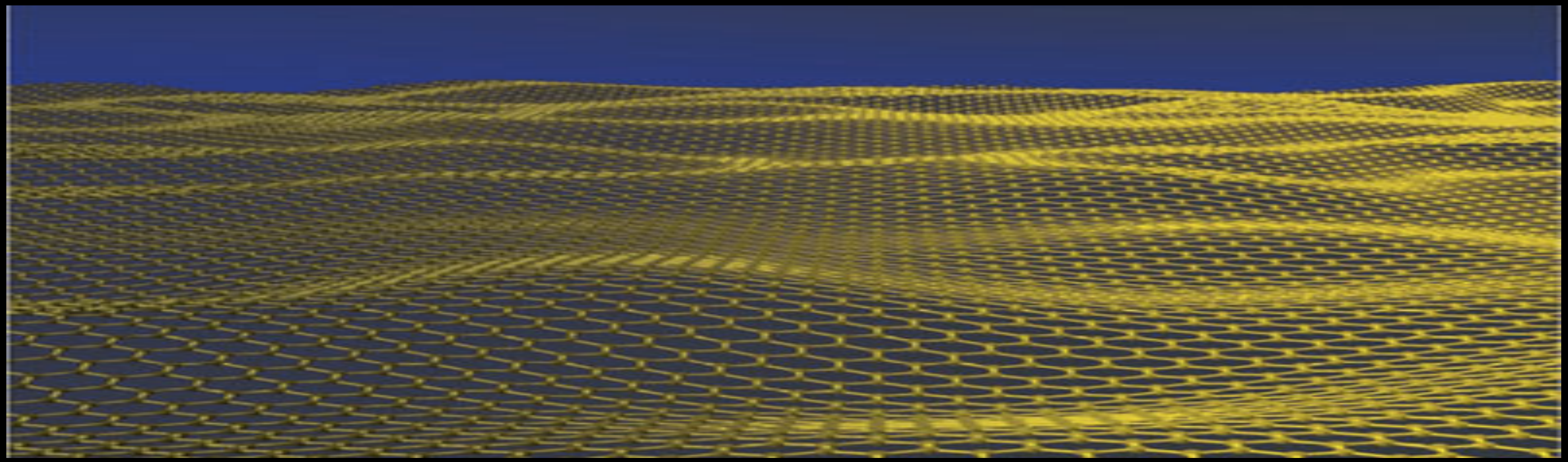


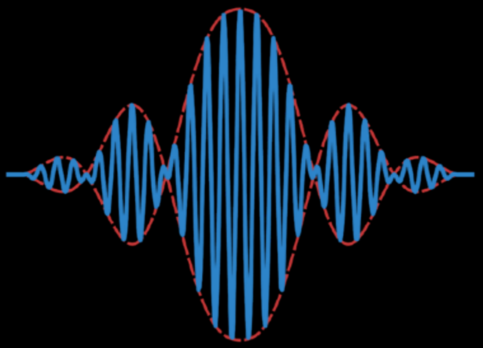
apod.nasa.gov/apod/ap120501.html

Part II: phdcomics.com/comics.php?f=1684

The Higgs boson

The Higgs mechanism makes a distinct prediction.





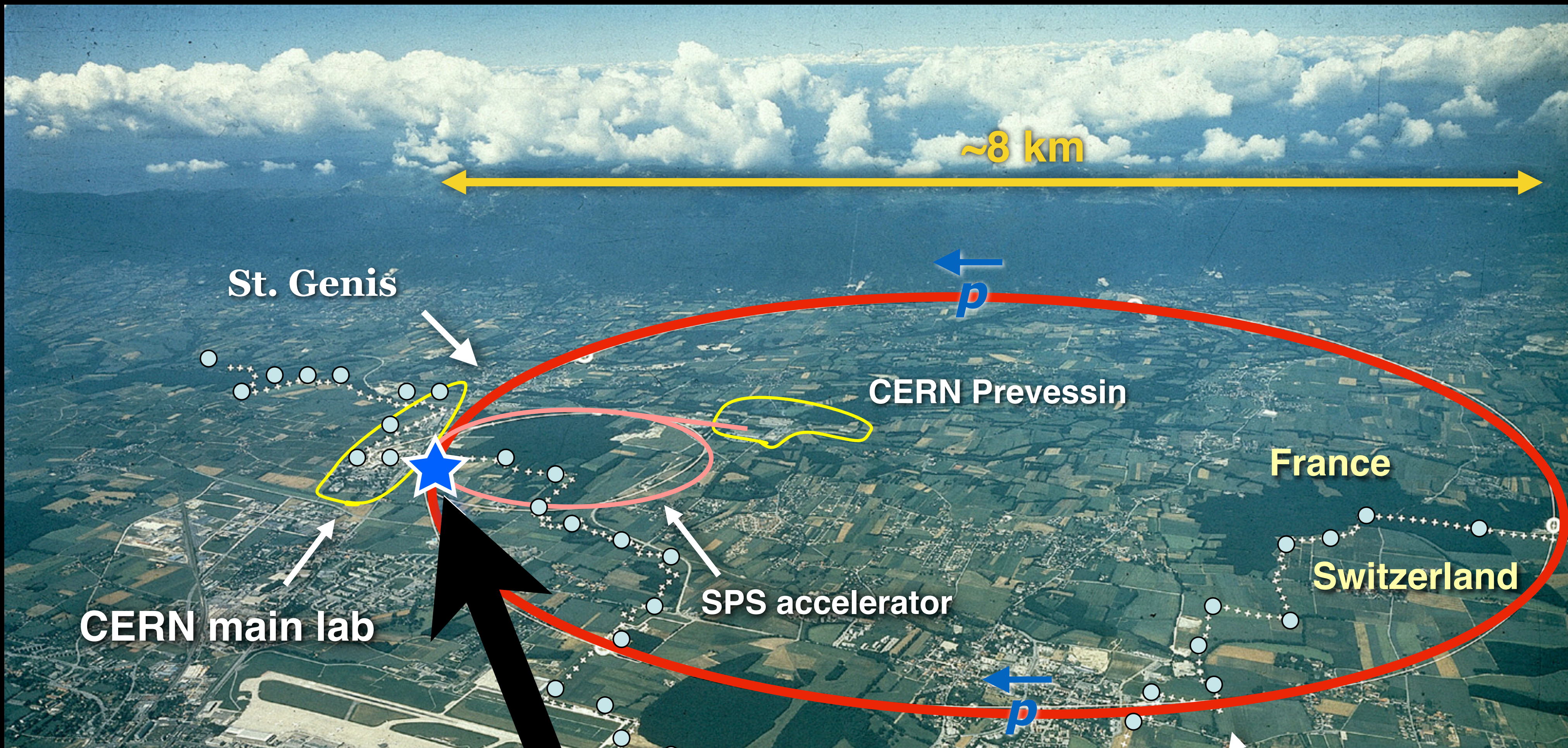
An excitation of the Higgs field will give rise to a new particle:

This particle has a mass, but we didn't know which, and hence not how much energy was needed to make it. The search for the Higgs went on for 40 years …

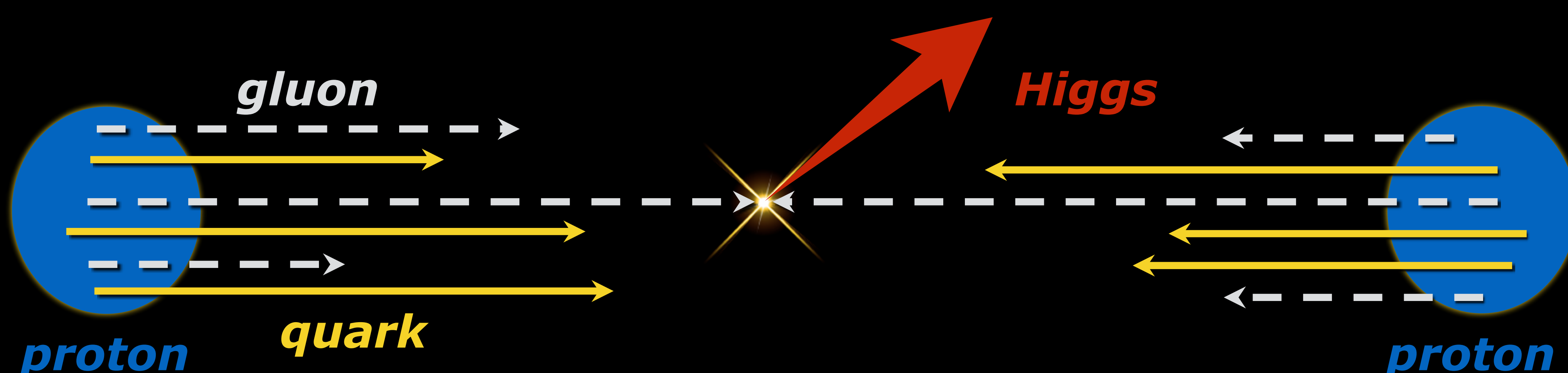
Part II

Producing and detecting Higgs bosons

LHC – the world's biggest machine

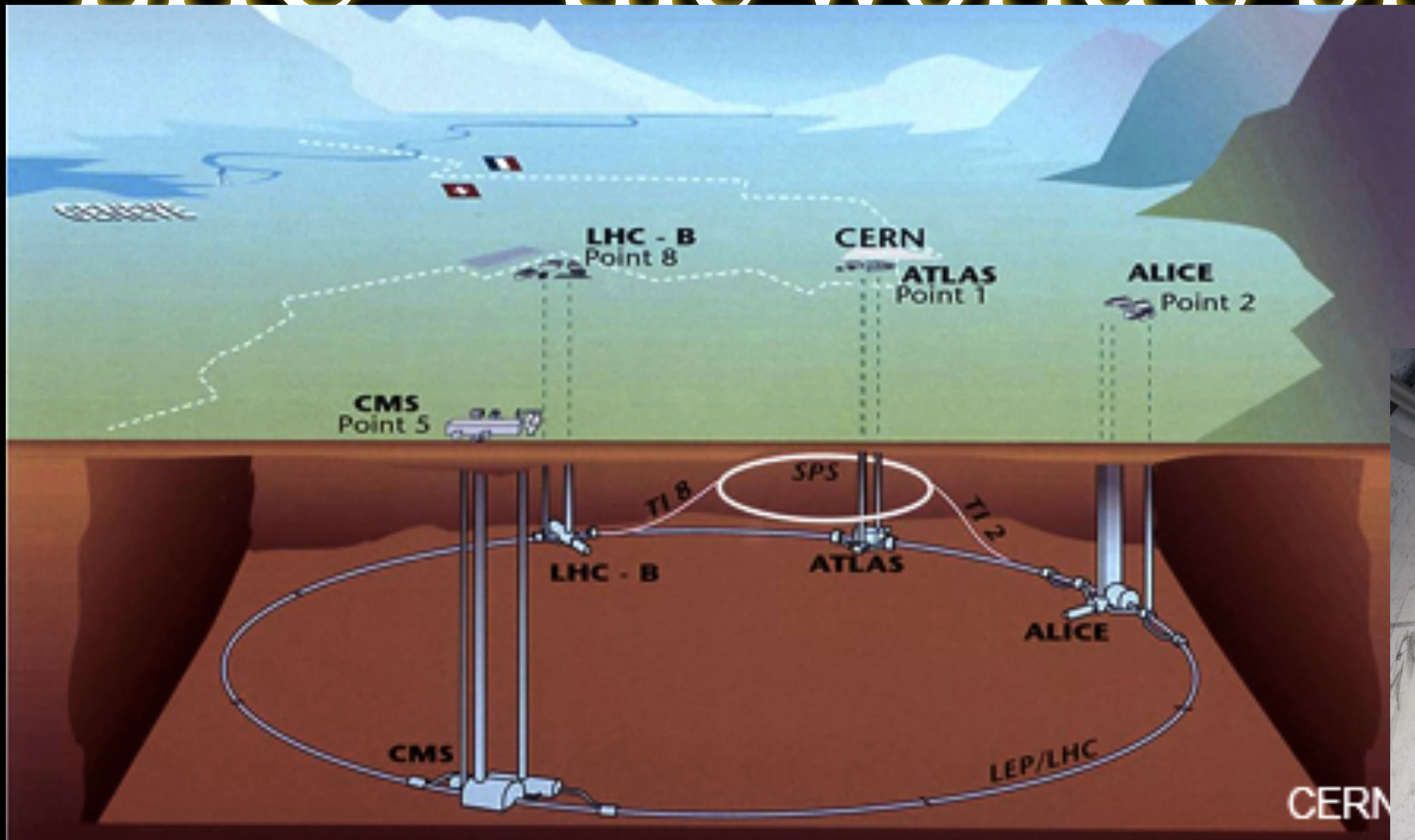


Beams of ***protons*** with lot's of energy circulated



E = 4 TeV		E = 4 TeV	2012
E = 6.5 TeV		E = 6.5 TeV	2015→

LHC — the world's biggest machine



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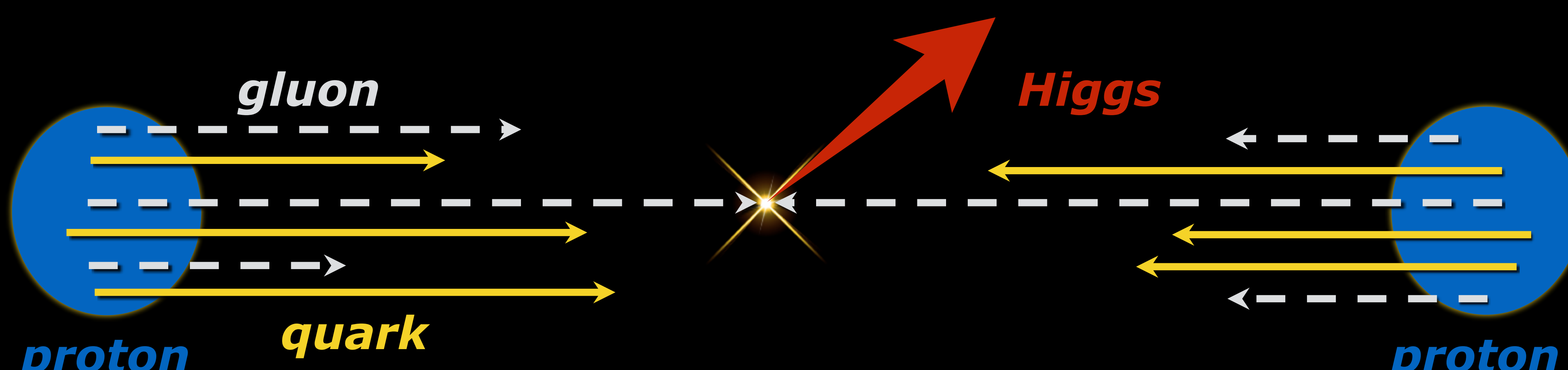

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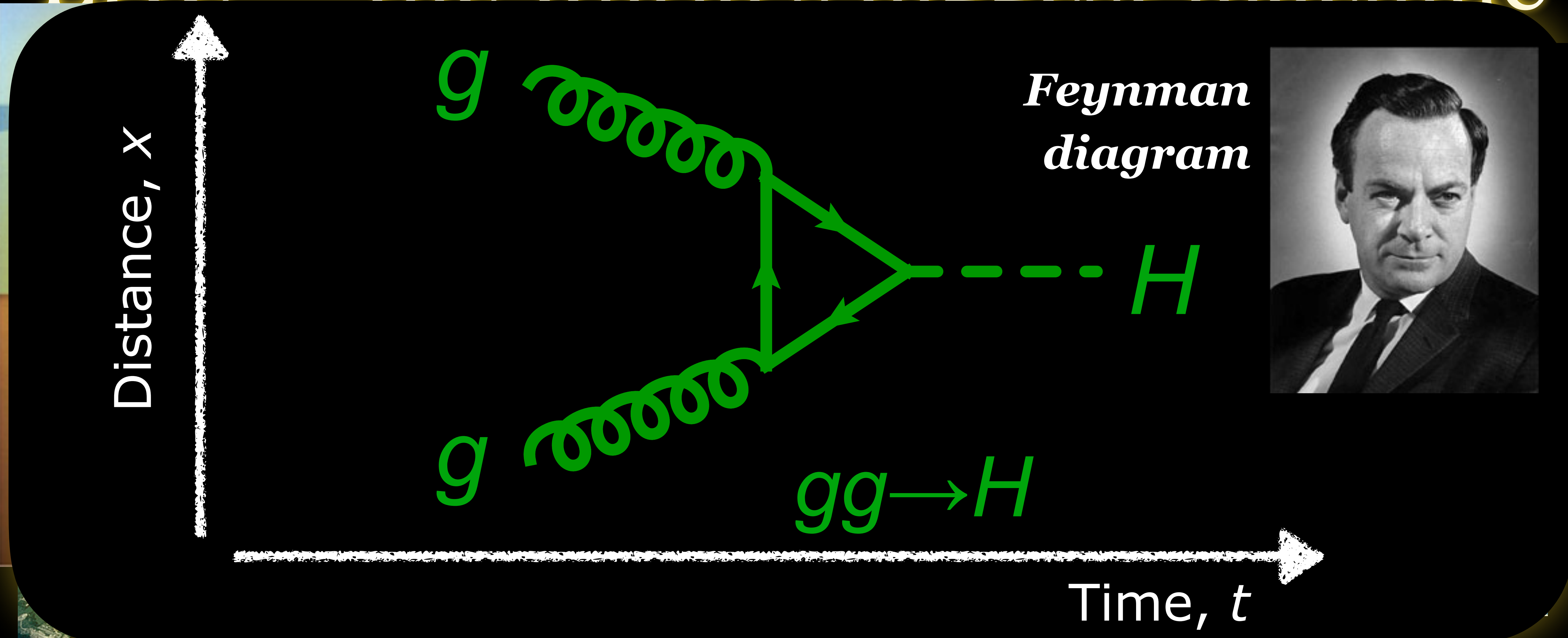

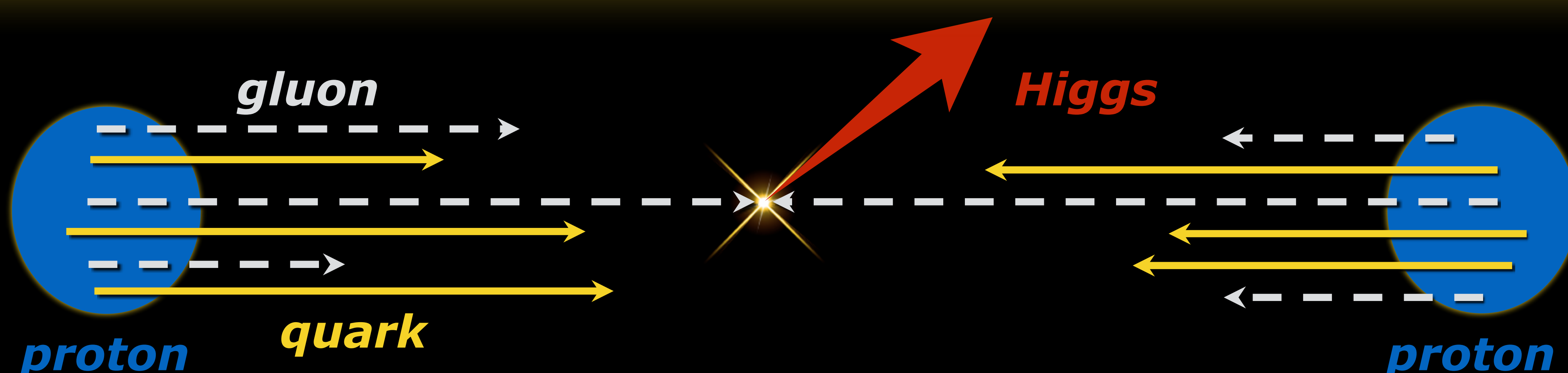

E = 4 TeV	E = 4 TeV	2012
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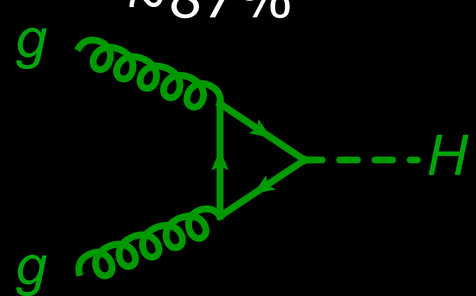
Production & decay of Higgs bosons

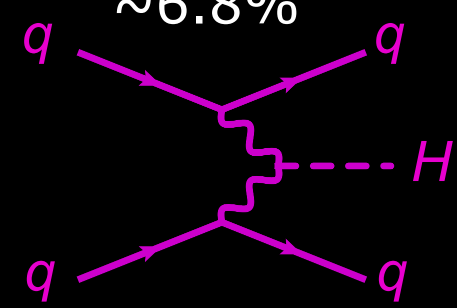
Production

~87%



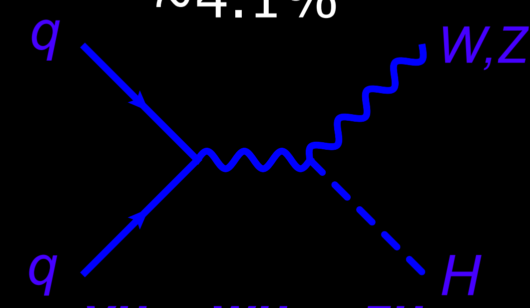
gg→H

~6.8%



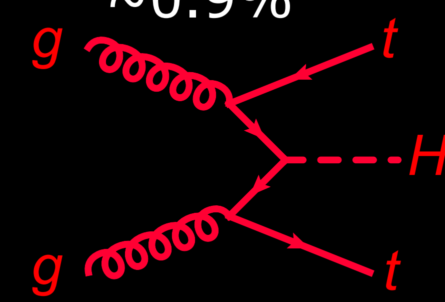
Vector Boson Fusion, VBF

~4.1%



VH ≡ WH or ZH

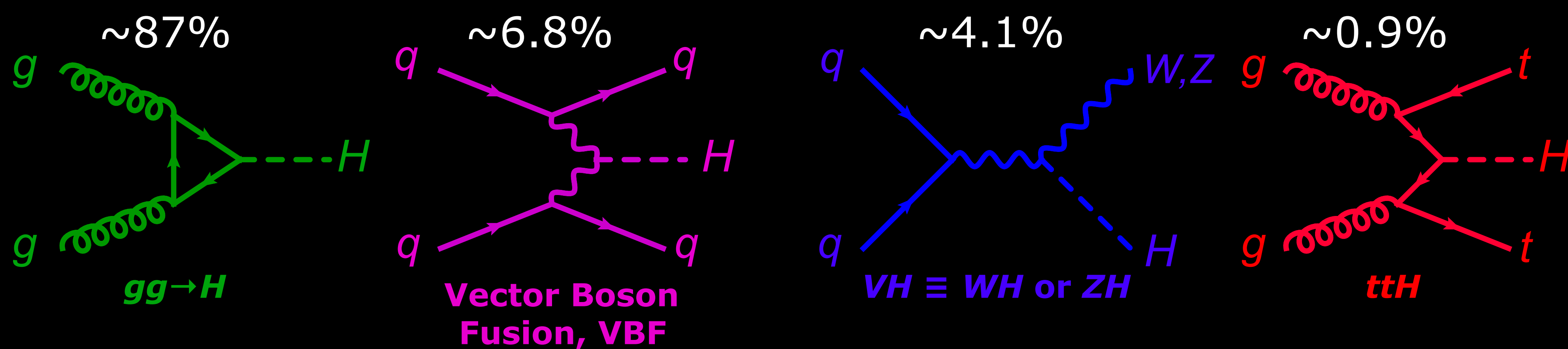
~0.9%



ttH

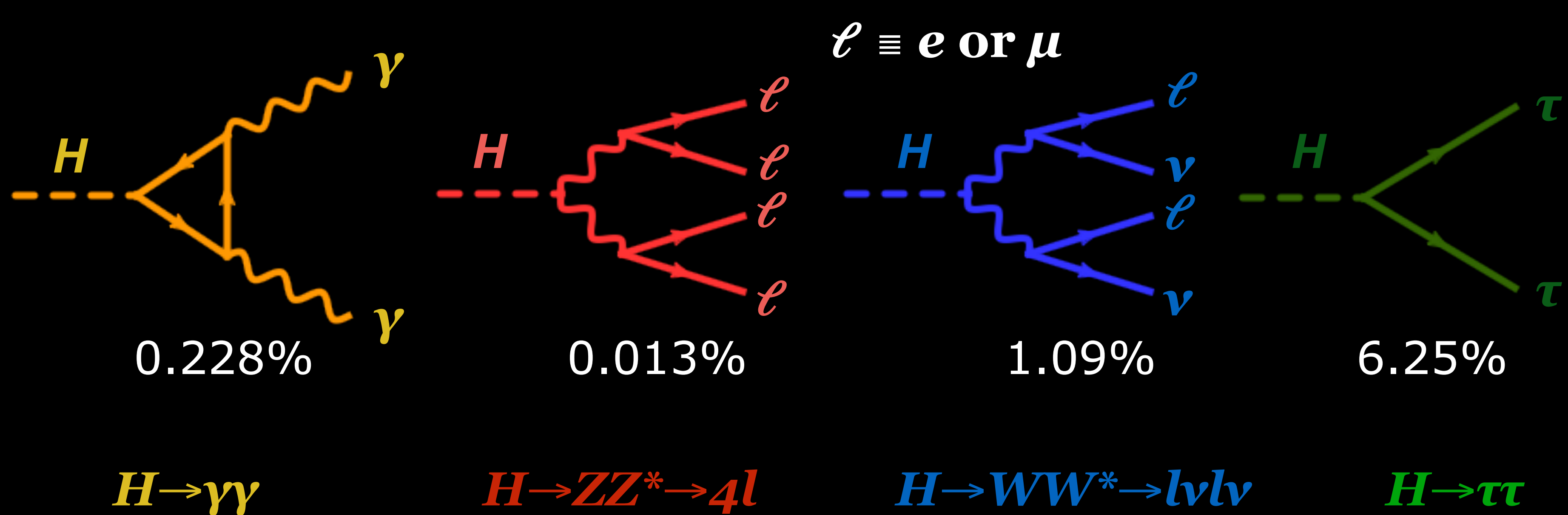
Production & decay of Higgs bosons

Production



Decay

This determines the ***signature*** *that the Higgs boson leaves.*
That is, what we look for to find the Higgs boson

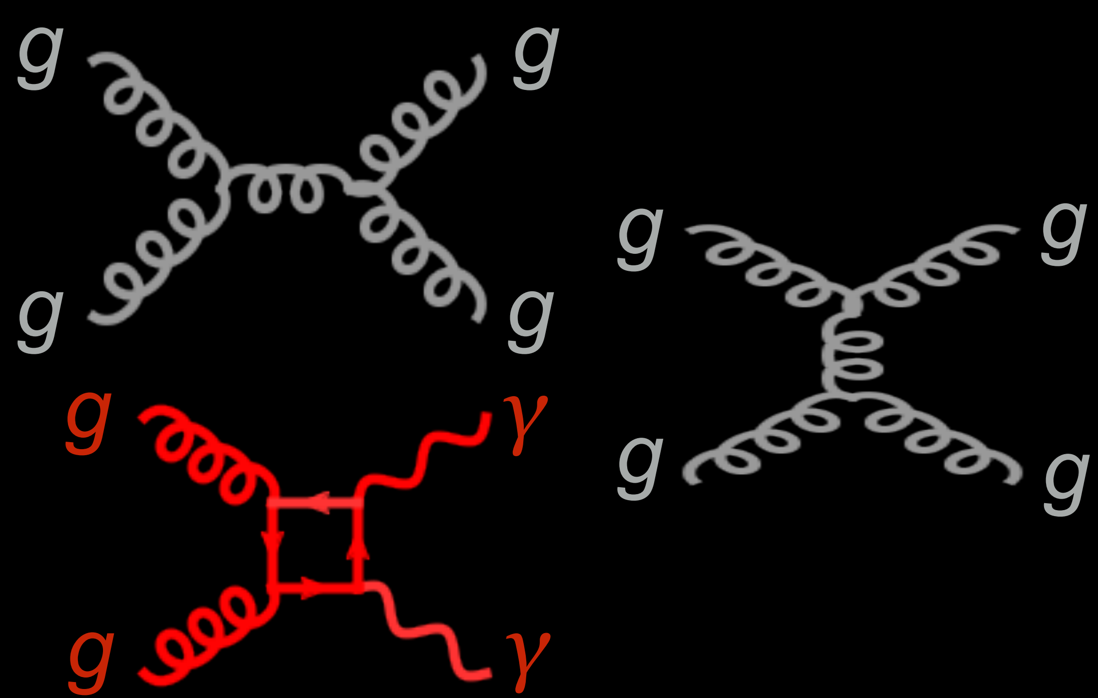


In addition:

H→bb	57.1%
H→WW*	22.1%
H→gg	8.5%
H→cc	2.9%
H→ZZ*	2.7%
. . .	

Problem: *Higgs production is rare!*

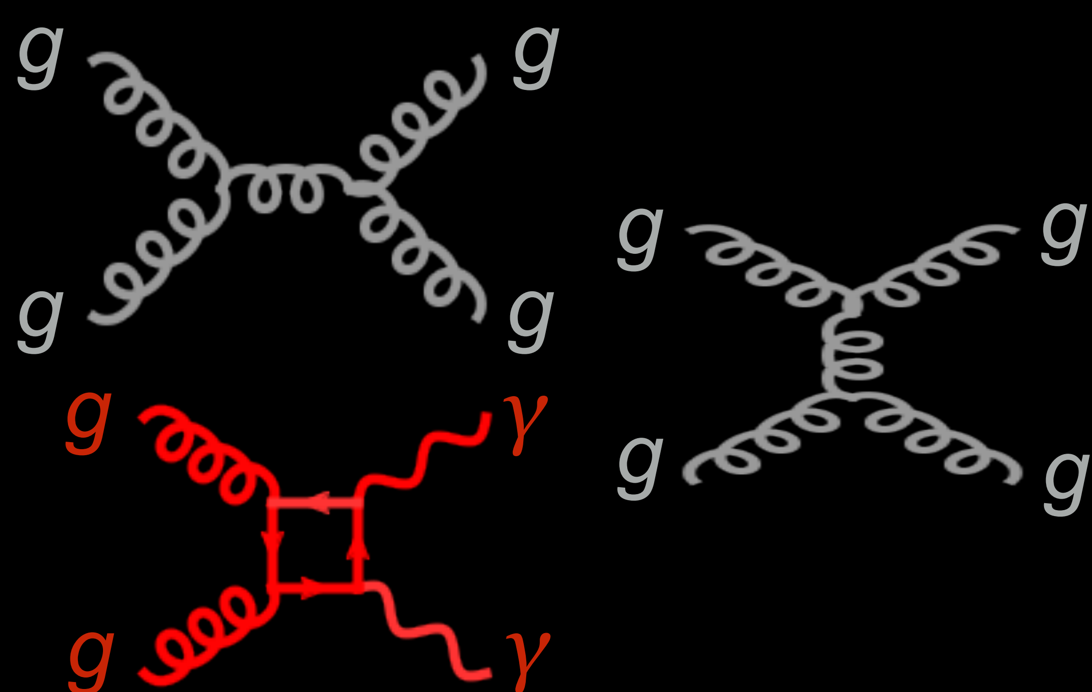
The vast majority of collision produced at the LHC do not contain any Higgs bosons



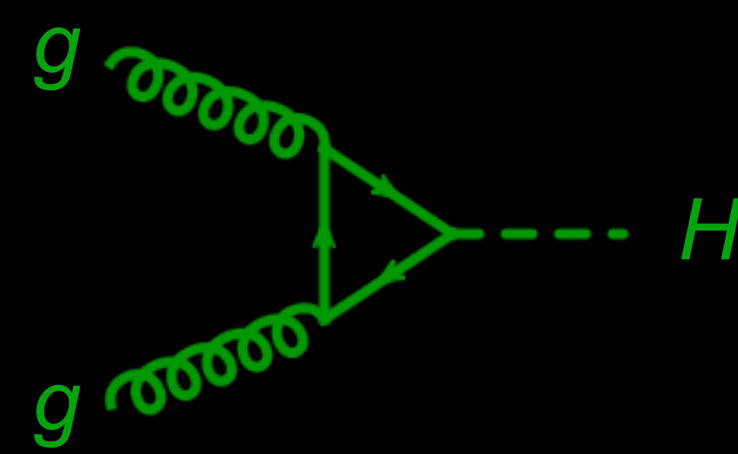
Examples of processes much, much more common than Higgs boson production

Problem: *Higgs production is rare!*

The vast majority of collision produced at the LHC do not contain any Higgs bosons



Examples of processes much, much more common than Higgs boson production

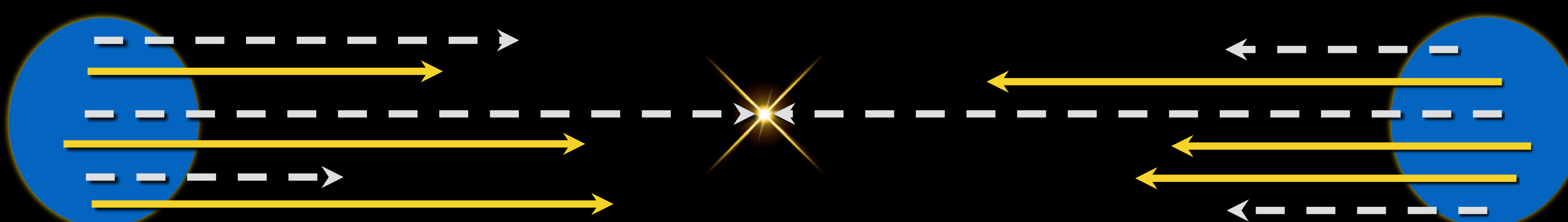


A Higgs boson is only produced in ***one collision out of 200 million***

LHC strategy

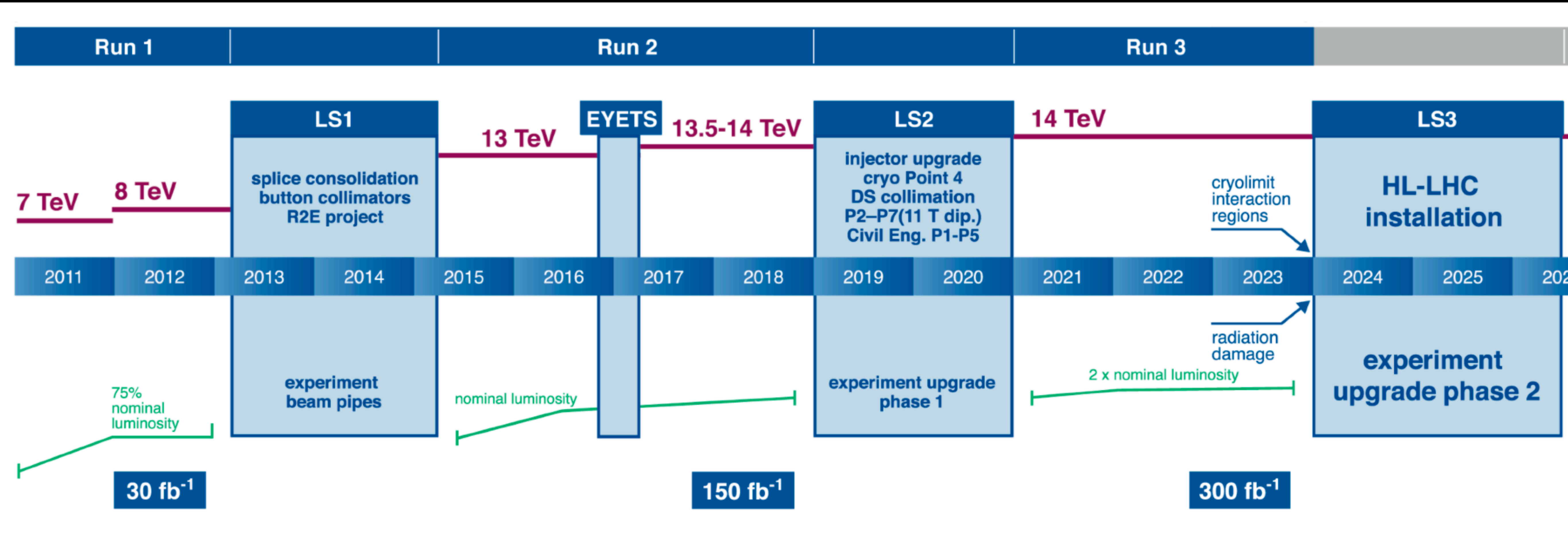
“Produce as many collisions as possible as fast as possible”

Proton-proton collision occurs **every 25 ns***; 40M per second — that’s *a lot!*

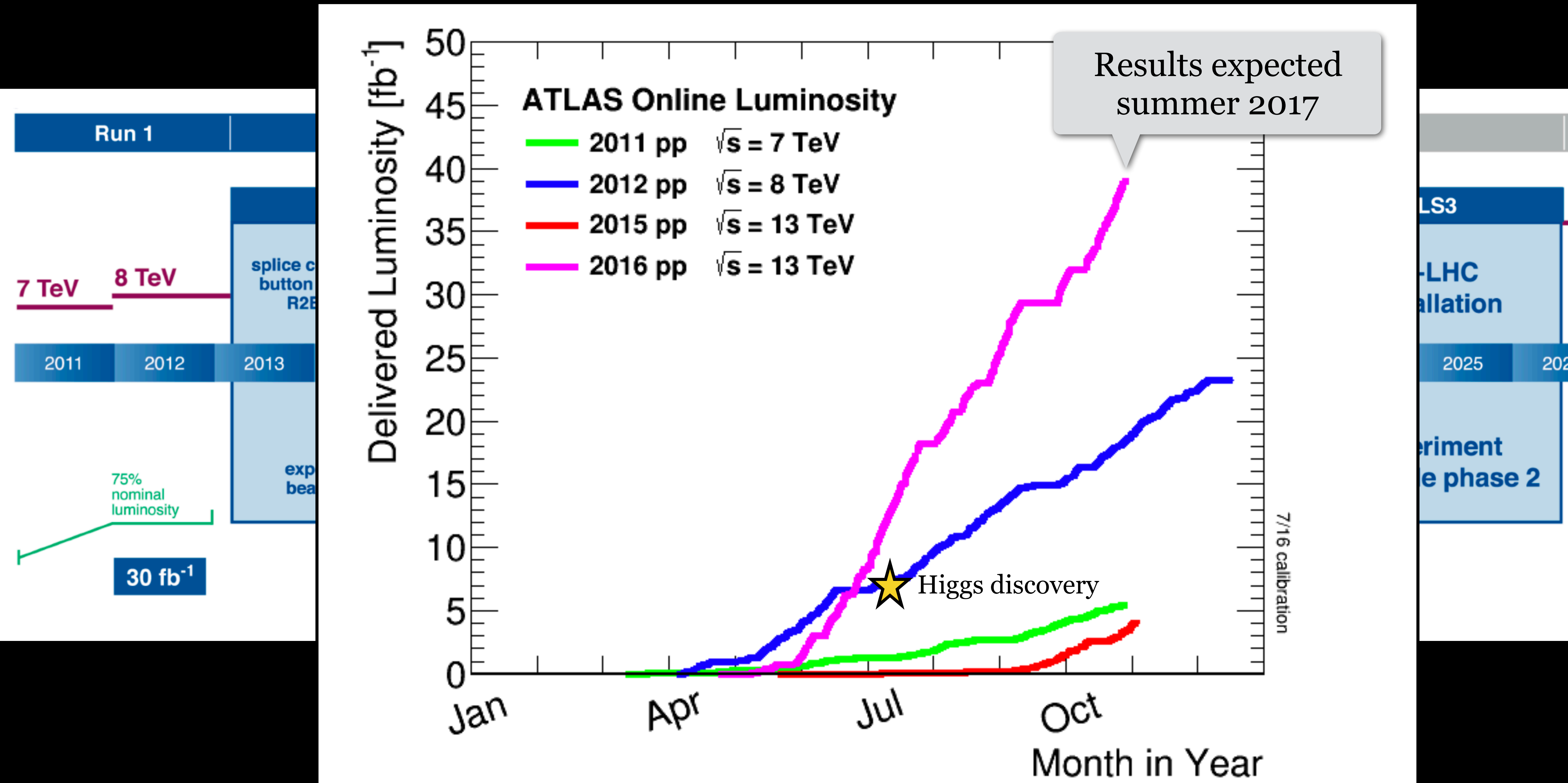


* in 2010-2012 we have had collisions every 50 ns = 20 MHz
from now on (2015) we’ll run with full speed! 40 MHz

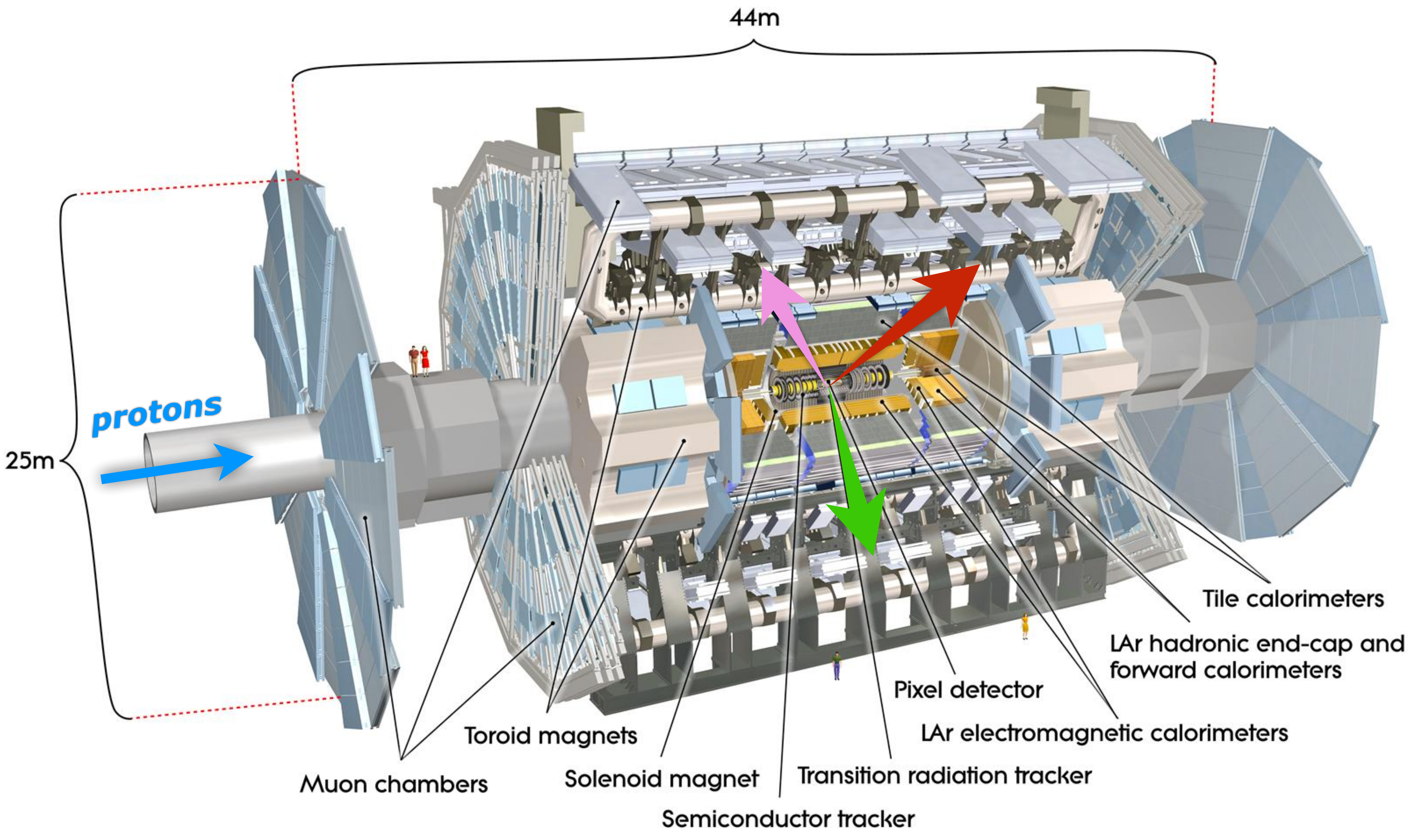
LHC schedule



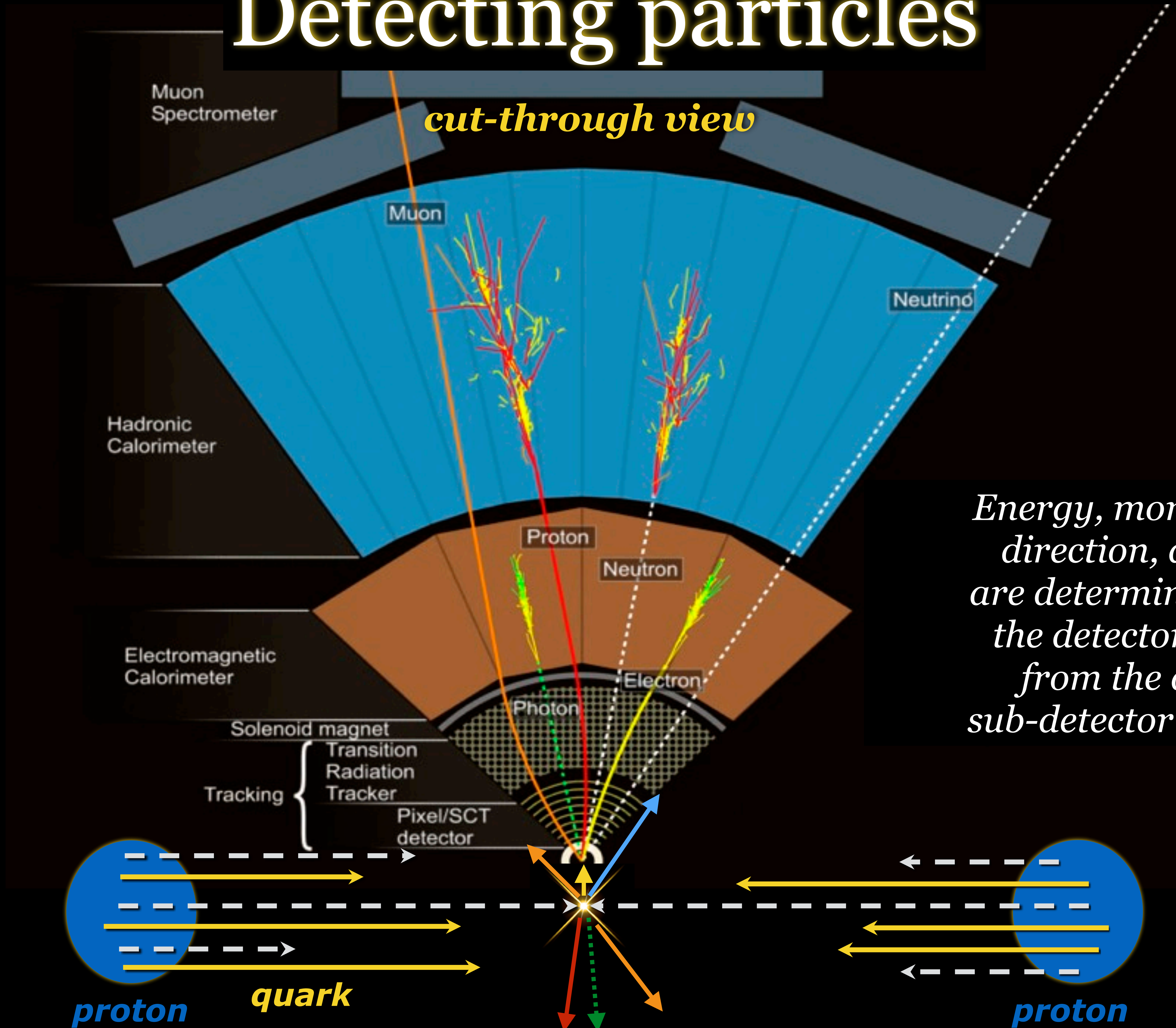
LHC schedule



The ATLAS detector

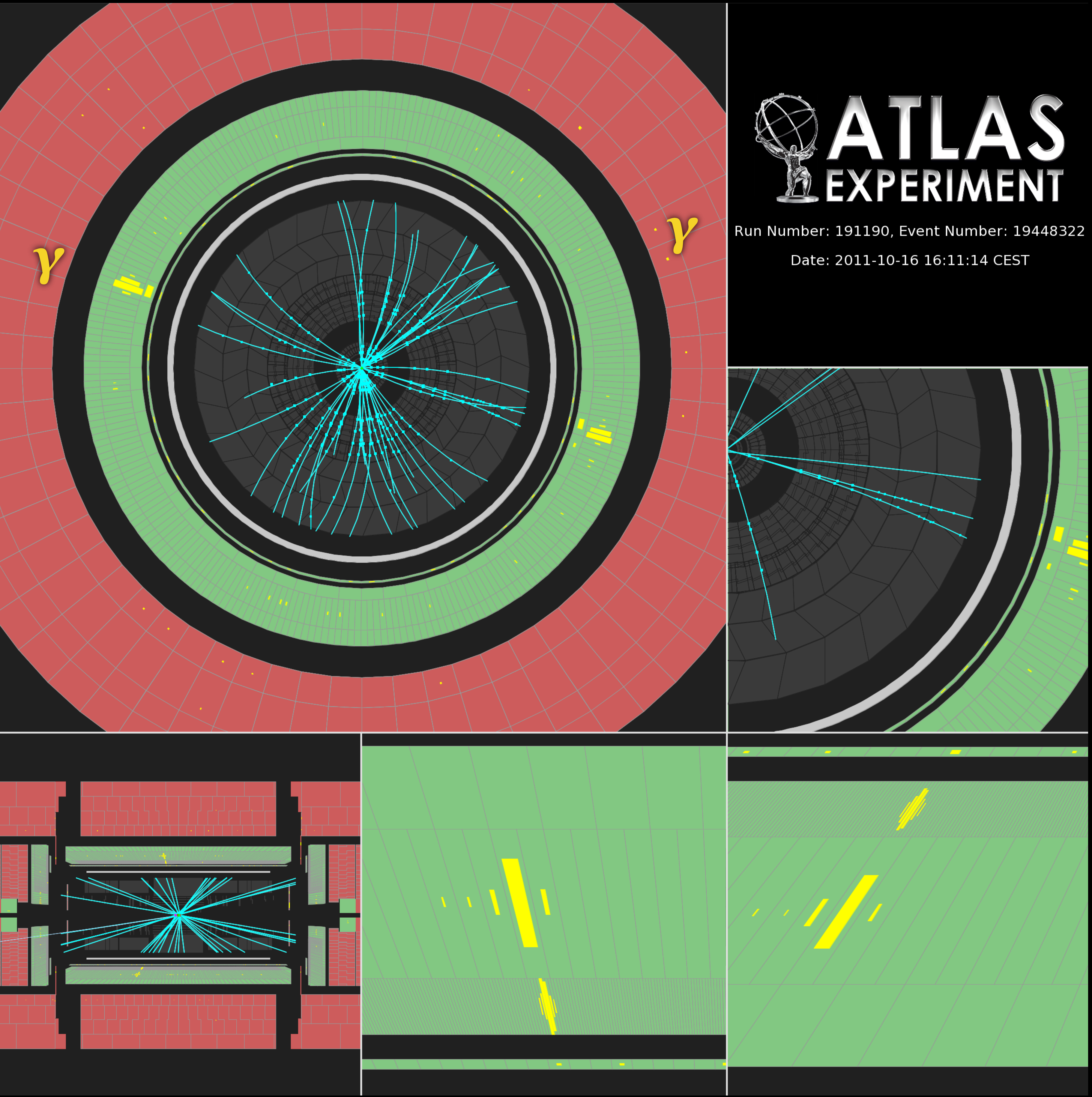


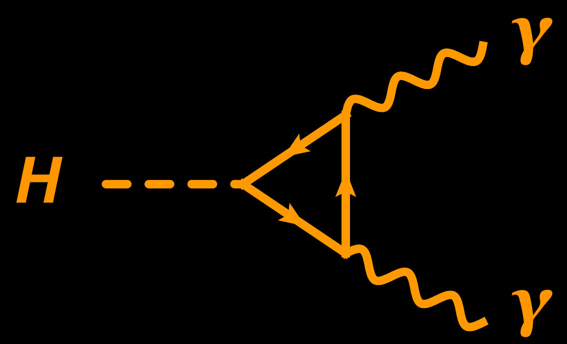
Detecting particles



Energy, momentum, direction, and type are determined from the detector signals from the different sub-detector systems

Higgs boson candidate





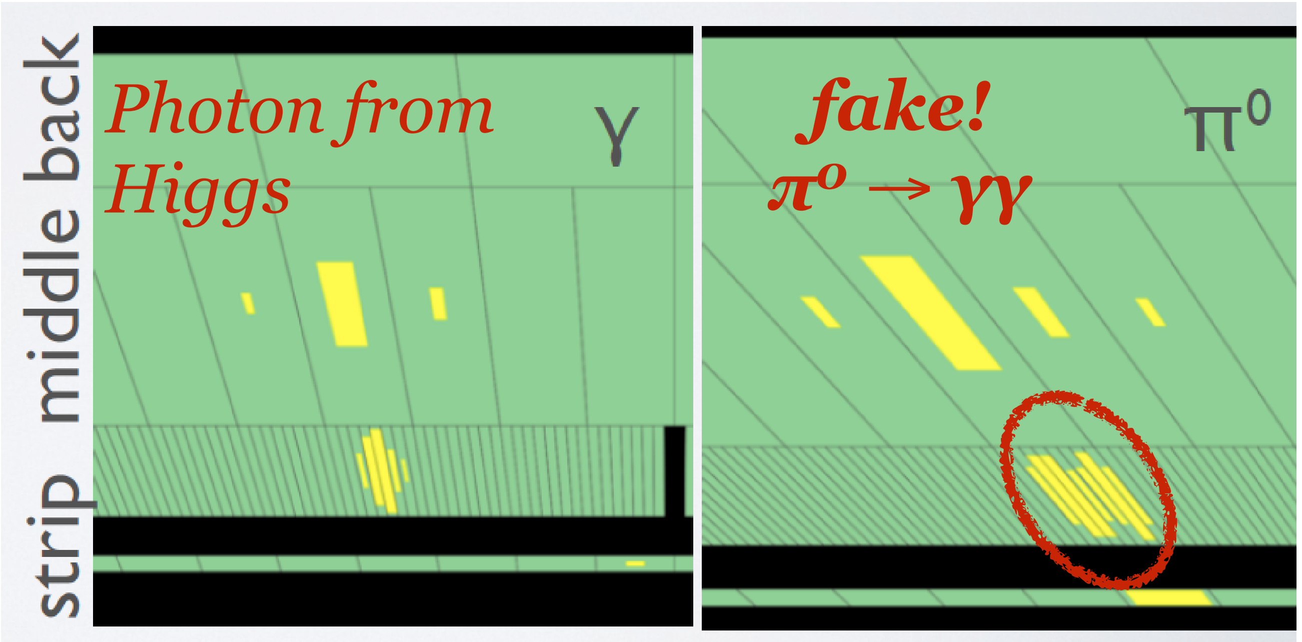
Photon energy and direction accurately measured in the EM calorimeters (green)

Most important quantity:
Diphoton invariant mass $m_{\gamma\gamma}$, *reconstructed from photon 4-momenta*

$$m_{\gamma\gamma}^2 = (p_{\gamma 1} + p_{\gamma 2})^2$$

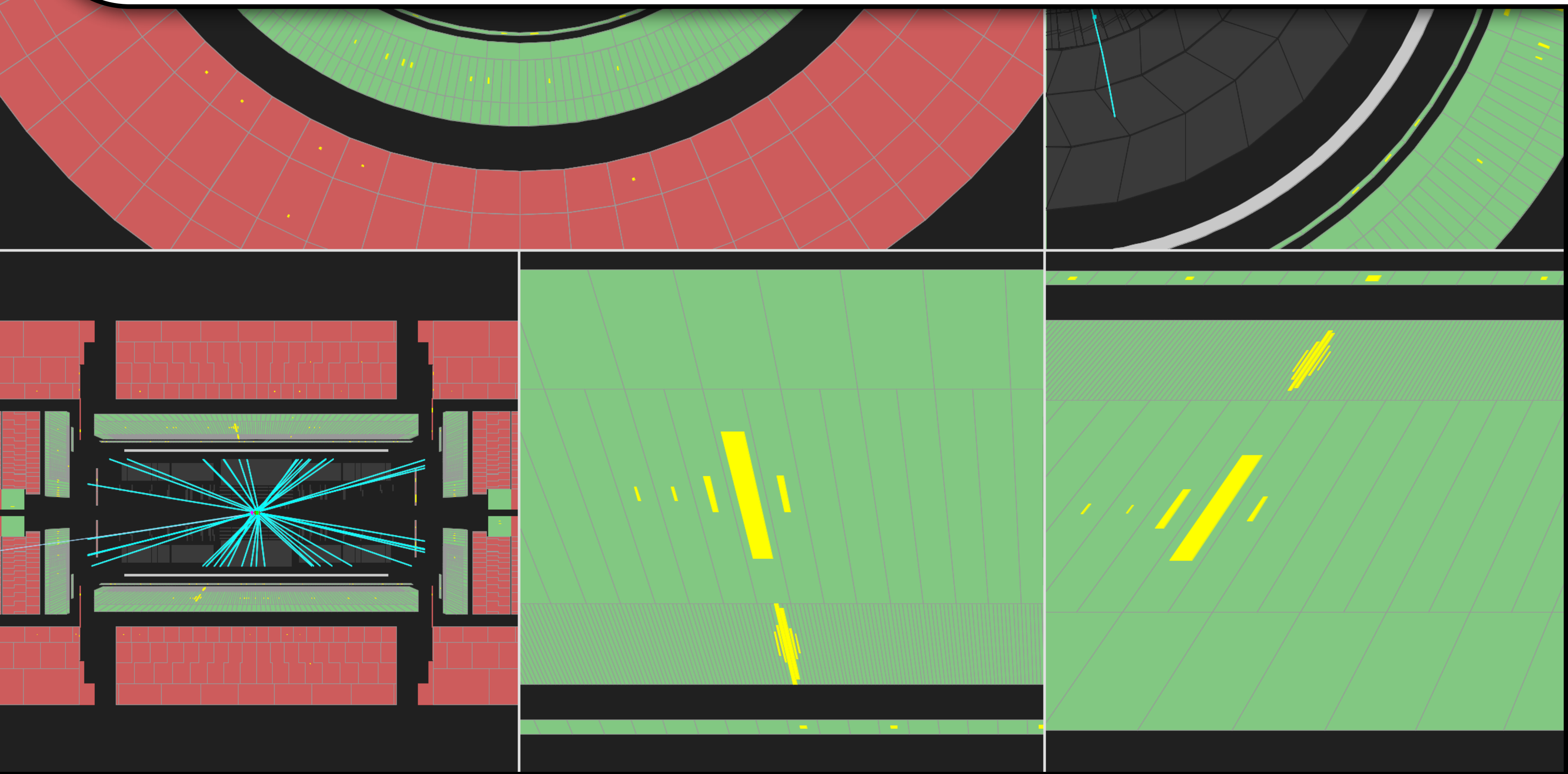
Higgs boson candidate

Fake photon suppression



Lots of ***other particles*** leave signals that look similar to photons from the Higgs boson

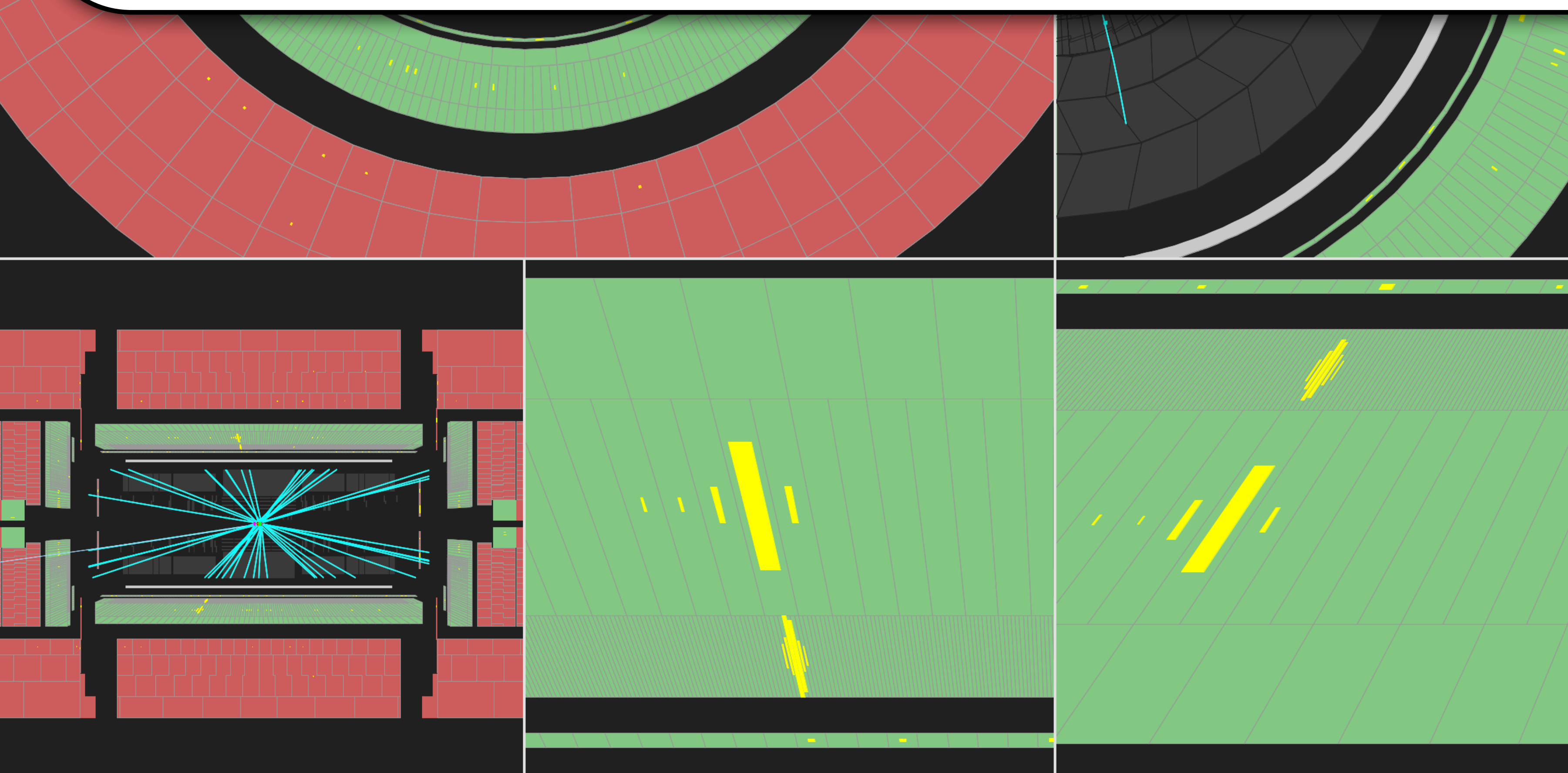
Such particles are ***suppressed*** by looking at the ***shape of energy deposits*** in the detector



Diphoton invariant mass ***$m_{\gamma\gamma}$****, reconstructed from photon 4-momenta*

$$m_{\gamma\gamma}^2 = (p_{\gamma 1} + p_{\gamma 2})^2$$

Higgs boson candidate



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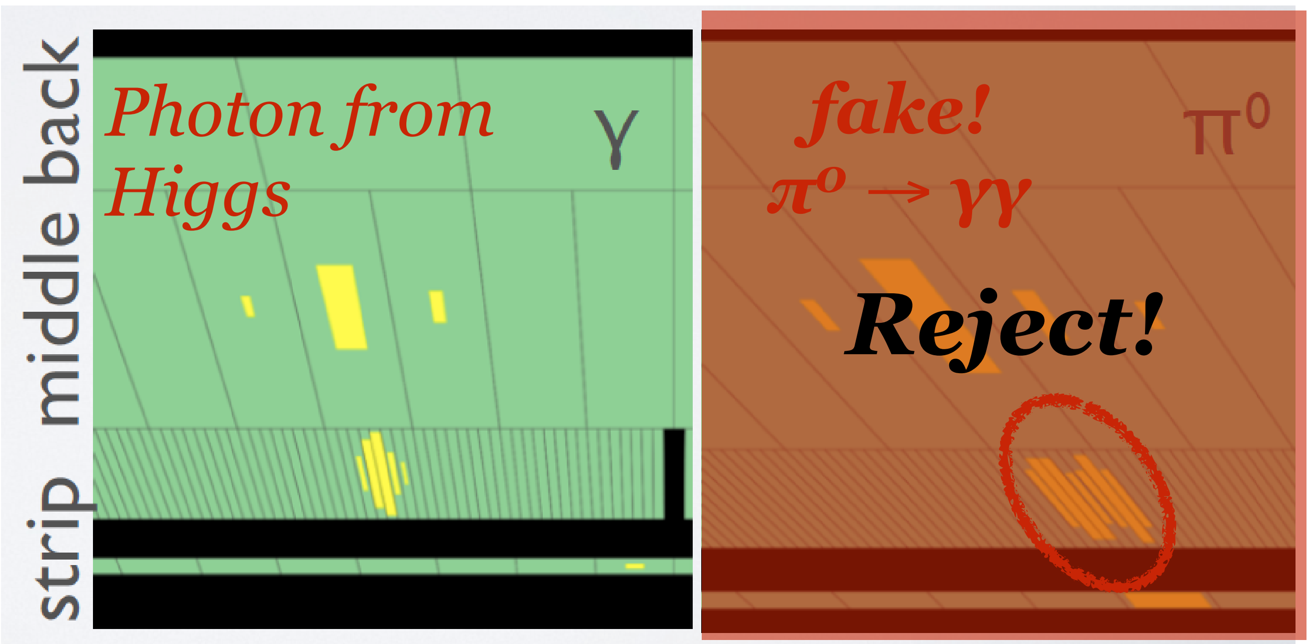


Lots of ***other particles*** leave signals that look similar to photons from the Higgs boson

Such particles are ***suppressed*** by looking at the ***shape of energy deposits*** in the detector

Diphoton invariant mass $\boldsymbol{m_{\gamma\gamma}}$*, reconstructed from photon 4-momenta*

$$m_{\gamma\gamma}^2 = (p_{\gamma 1} + p_{\gamma 2})^2$$

How many Higgs bosons do we expect?

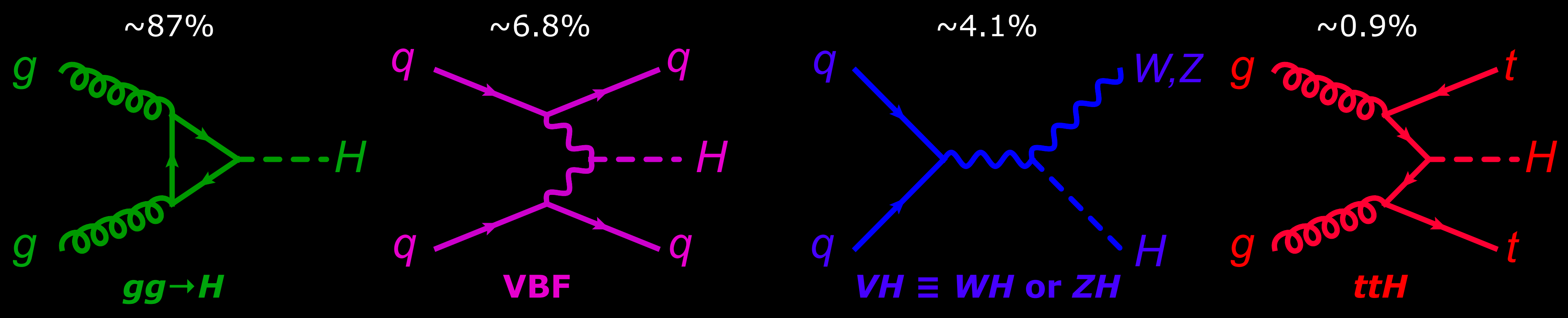
Number of expected *collisions that produce* ***Higgs bosons***
in the big 8 TeV dataset collected ***in 2012*** *(20.3 fb^{-1})*

	All Higgs events	$H \to \gamma\gamma$	Analysis selection
$gg \to H$	390k	890	350
VBF, VH, ttH, bbH	61k	140	55
total	**450k**	1030	**405**

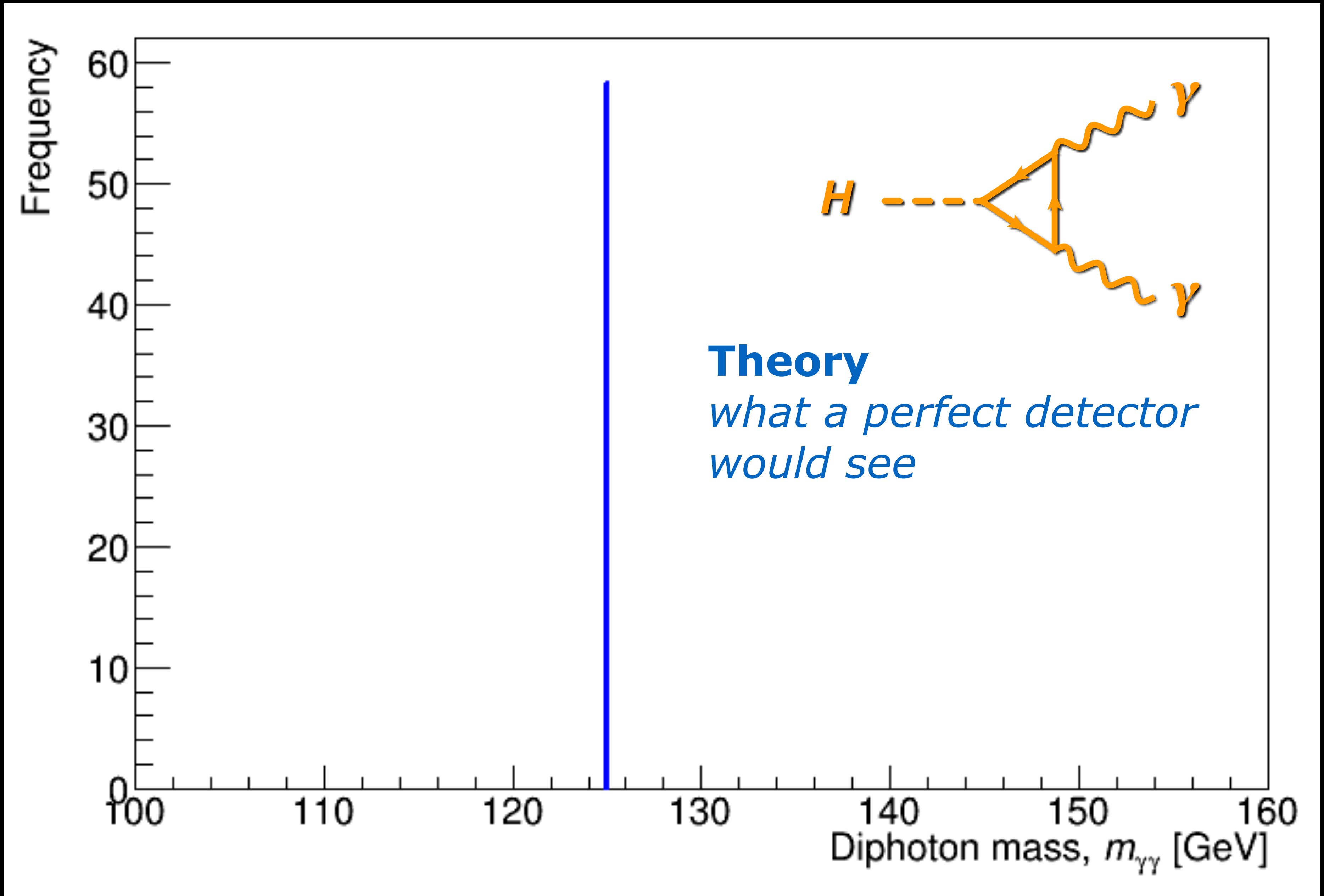
About half a million Higgs bosons in total !

Requiring photons to have sufficient energy and fulfil background rejection

1000 *decay to photons*
BR($H \to \gamma\gamma$) = 0.228%

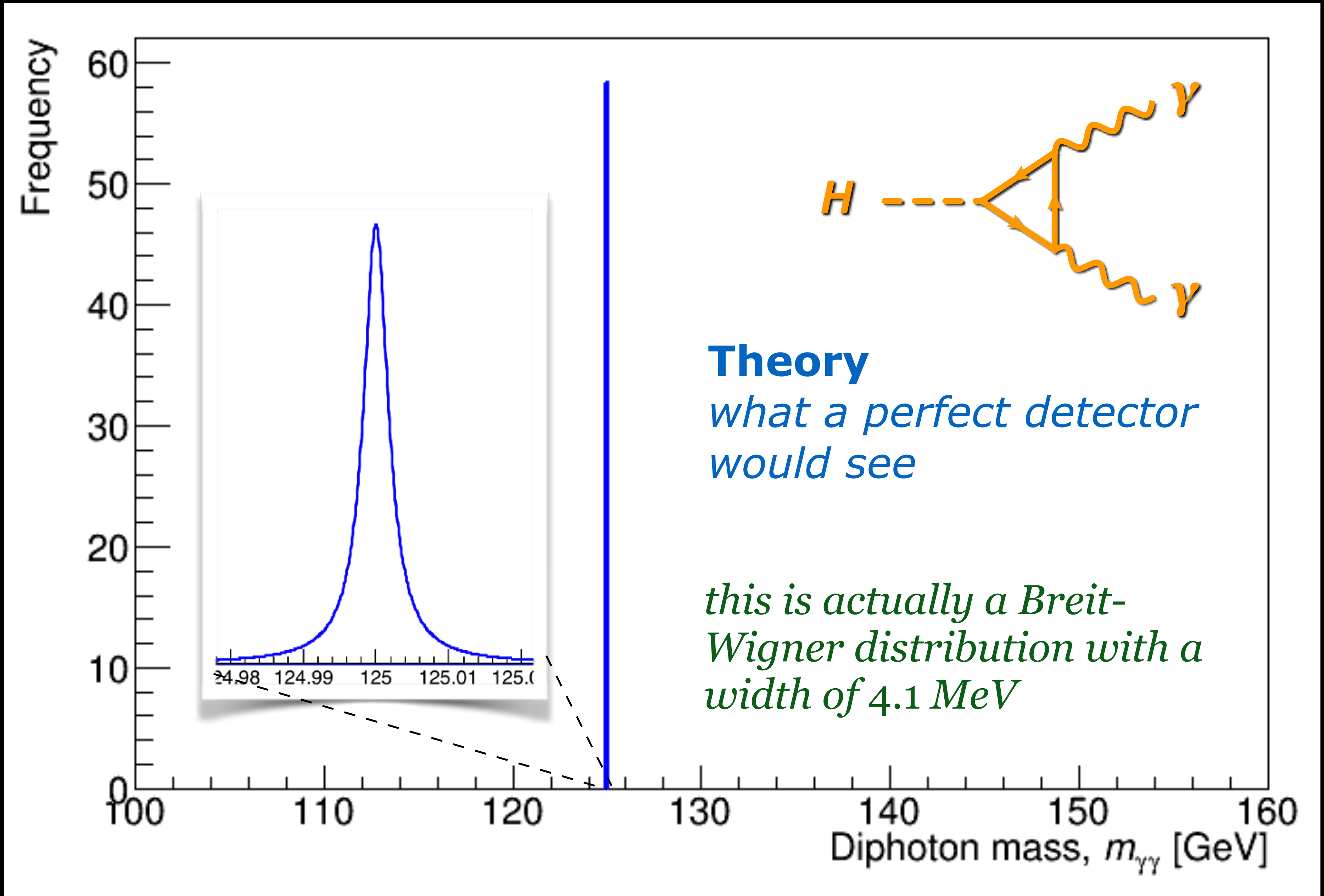


Finding the Higgs boson



*The **invariant mass** of the **diphoton** system*
→ narrow resonance around the Higgs mass, m_H = 125 GeV

Finding the Higgs boson



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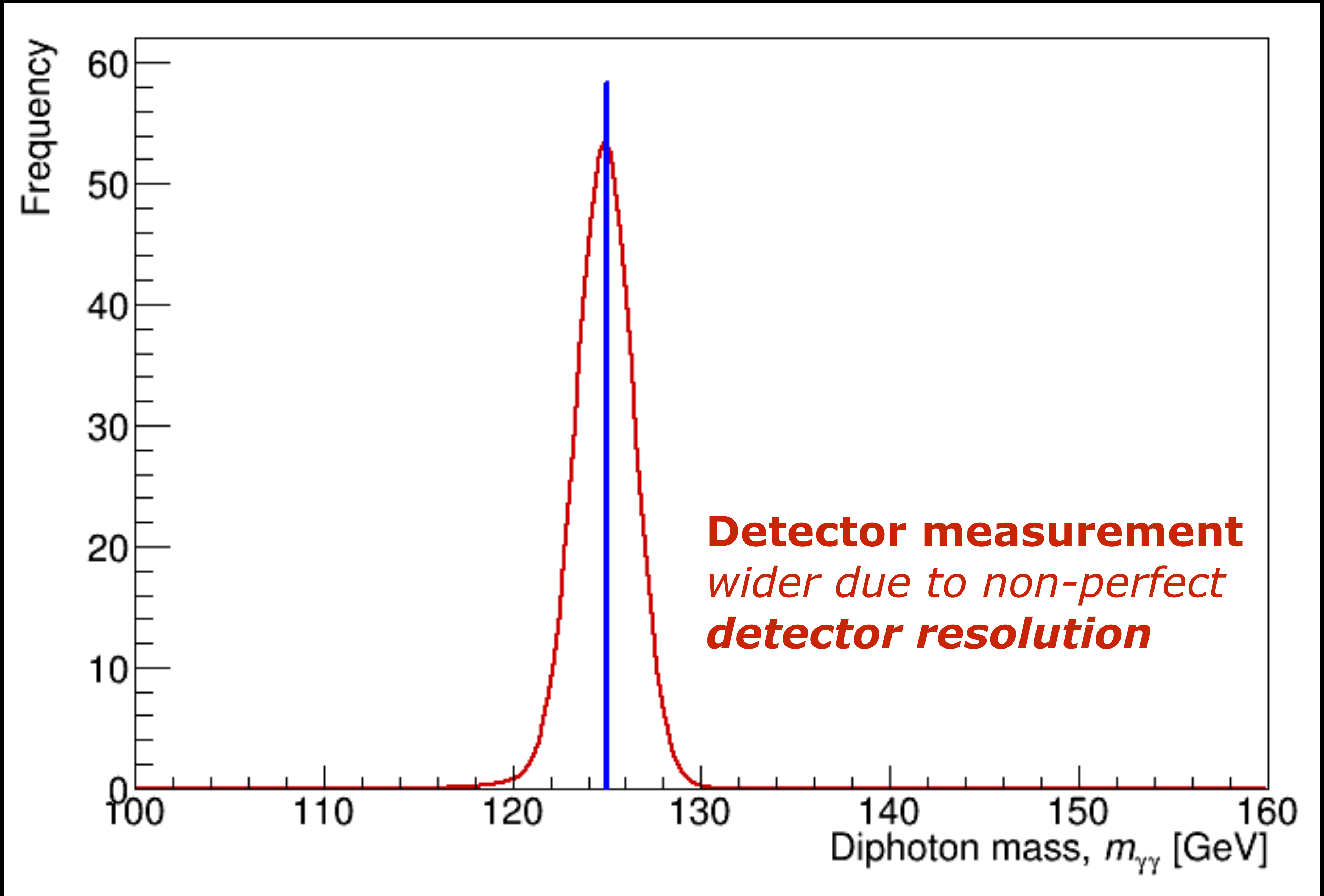
Finding the Higgs boson

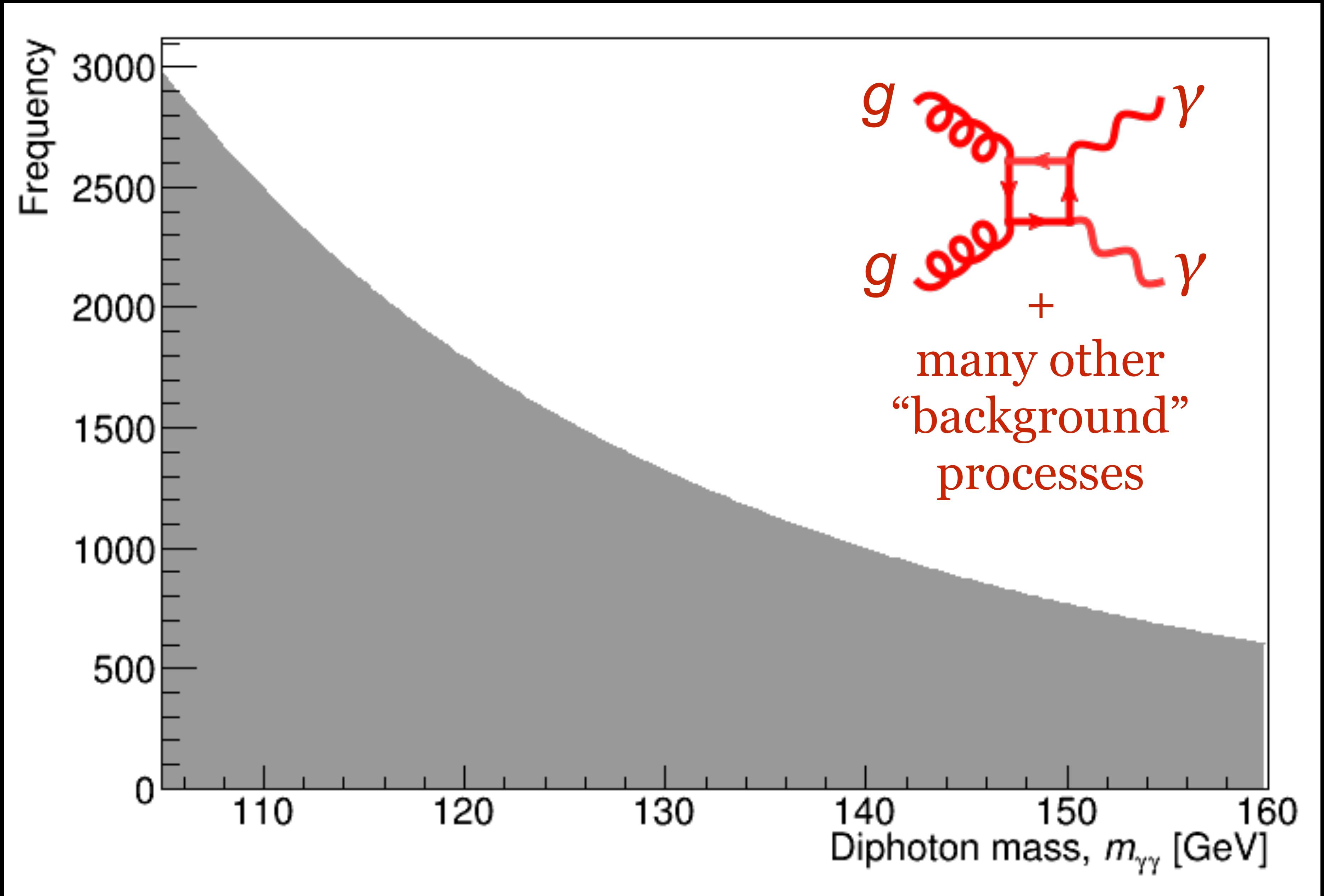


*For us experimentalists it is **extremely important** to understand the **detector performance**, for example the energy response and resolution of photons.*

The resolution of the diphoton mass (width of distribution above) is measured to be:

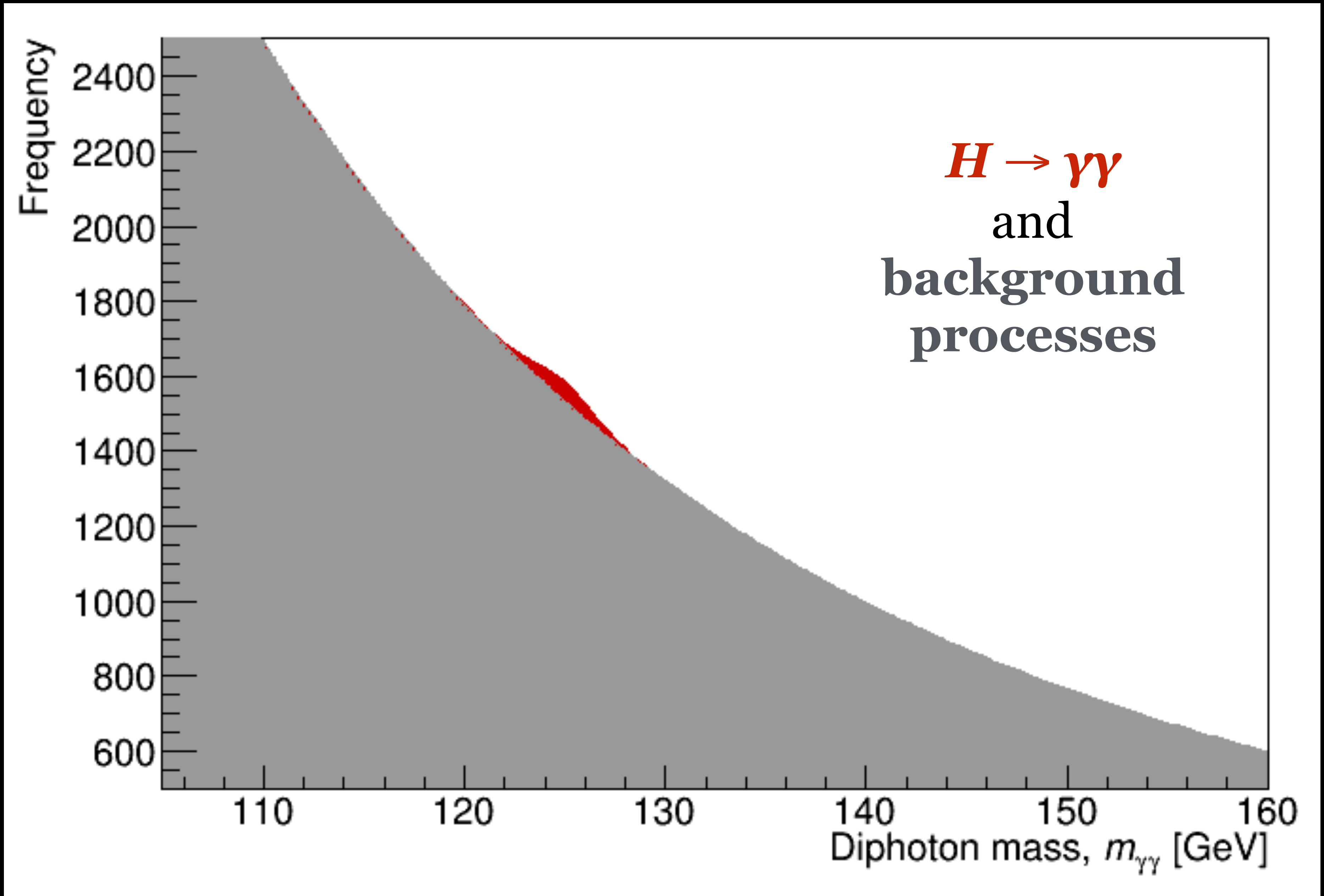
$\Delta m_{\gamma\gamma} = 1.5 \pm 0.15$ GeV

Finding the Higgs boson



*The **invariant mass** of the reconstructed **diphoton** system from non-Higgs processes that fulfil the selection*

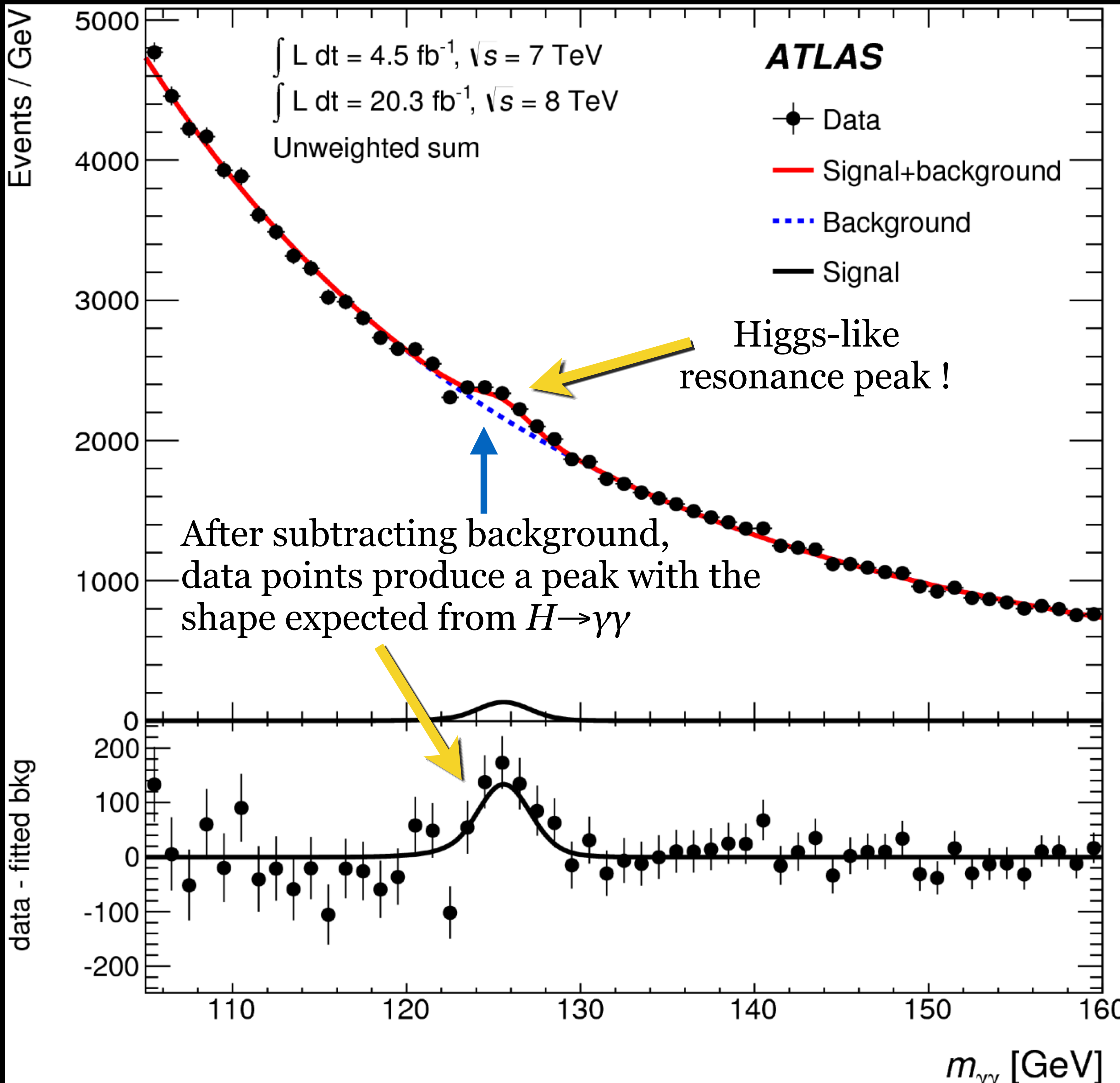
Finding the Higgs boson

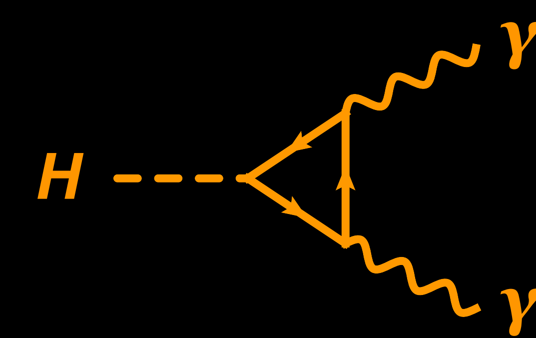


This is what we expect to see.

A small H→γγ signal on top of a smooth background distribution

What the data show





In the 2012 data (8 TeV):

Expect:
403 ± 45 Higgs events

Measure:
570 ± 130 events

... we see a bit more Higgs boson than we expect

How many Higgs bosons do we expect?

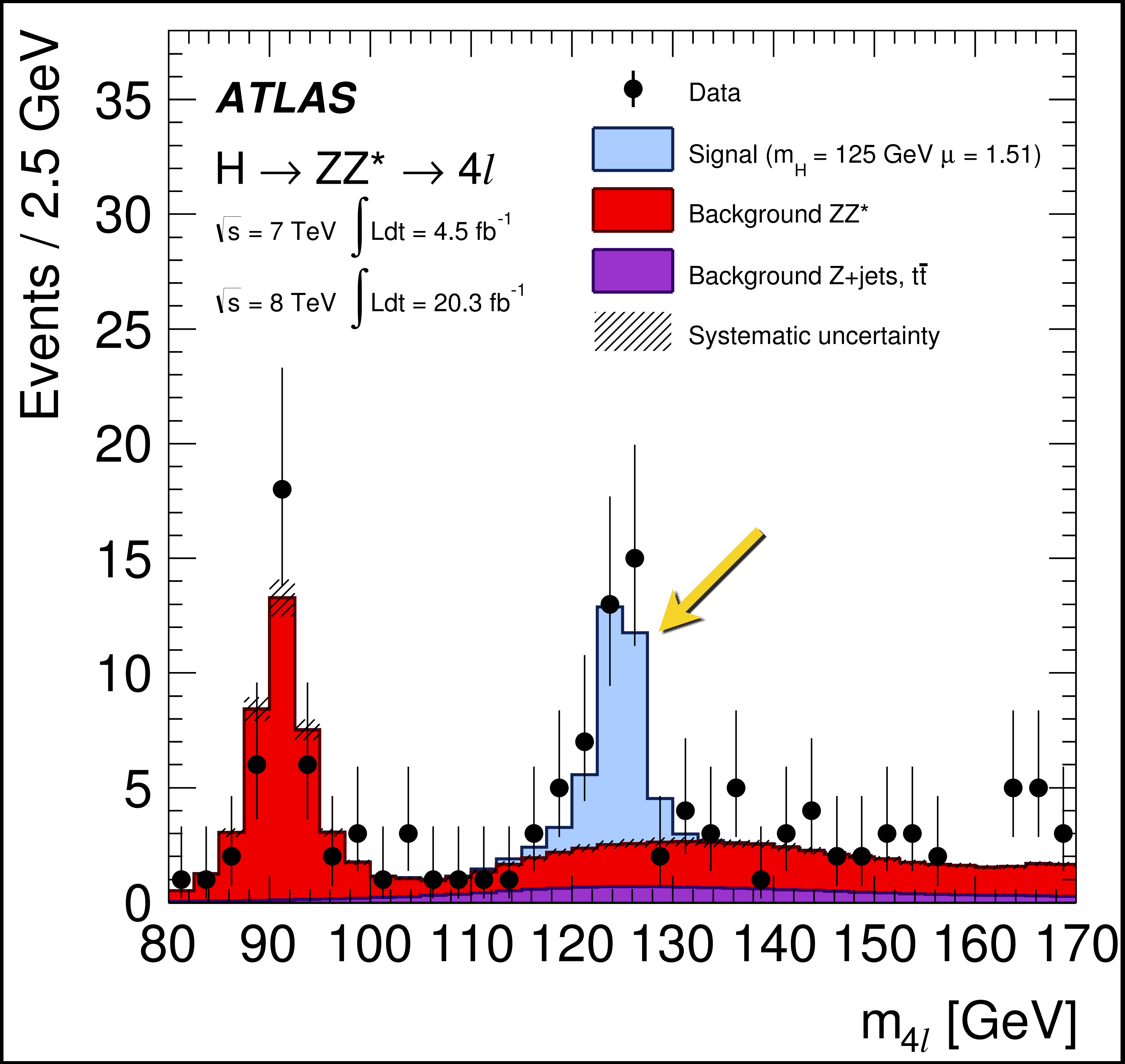
Number of expected** collisions that produce **Higgs bosons
*in the big 8 TeV dataset collected **in 2012** (20.3 fb^{-1})*

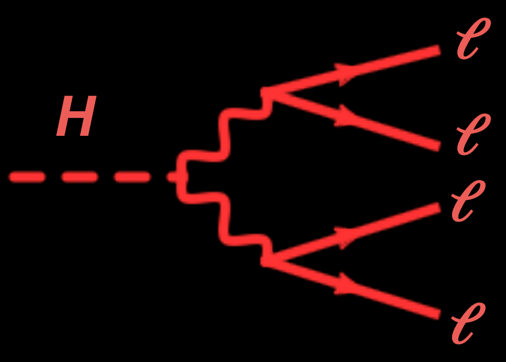
	All Higgs events	$H\rightarrow\gamma\gamma$	Analysis selection
gg→H	390k	890	349
VBF, ***VH, ttH, bbH***	61k	140	55
total	**450k**	1030	**403**

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

	All Higgs events	$H\rightarrow ZZ^*\rightarrow 4l$	Analysis selection
gg→H	390k	49	13
VBF, ***VH, ttH, bbH***	61k	8	2
total	**450k**	57	**14.6**

What the data show



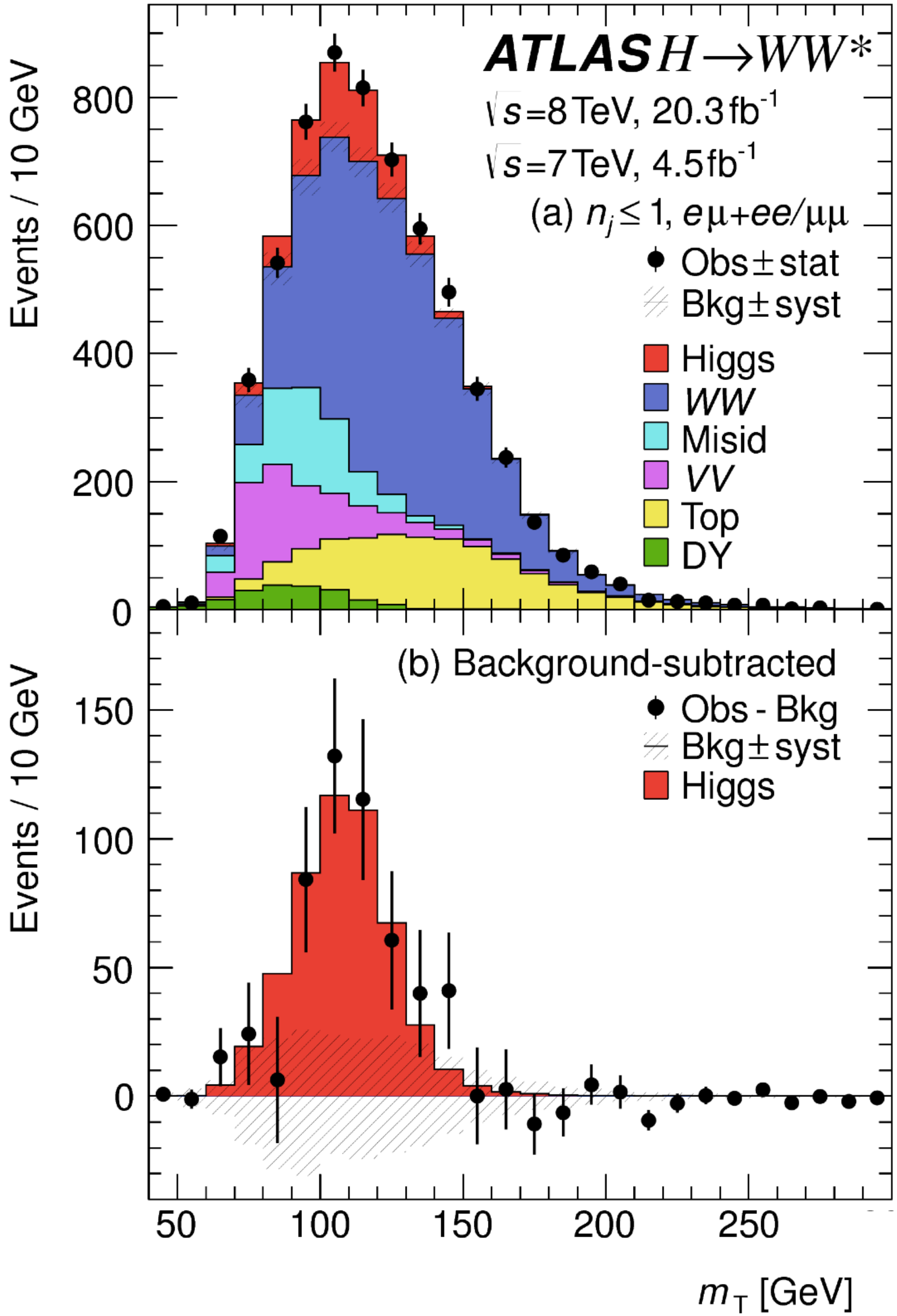


In the 2012 data (8 TeV):

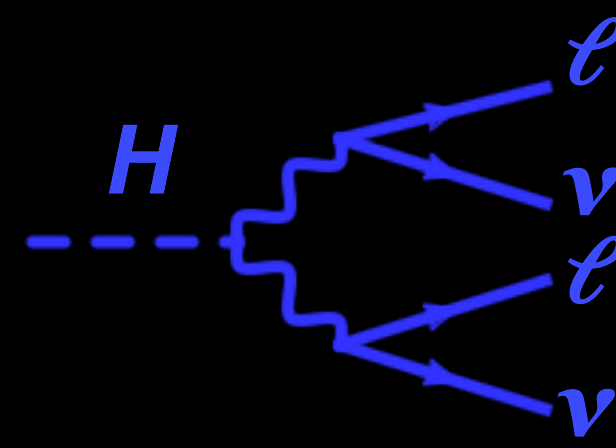
Expect:
14.6 ± 1.5 Higgs events

Measure:
24 ± 6 events

... again, we see a bit more Higgs boson than we expect



What the data show



For $H \to WW \to \ell\nu\ell\nu$,
the neutrinos ν, cannot be detected

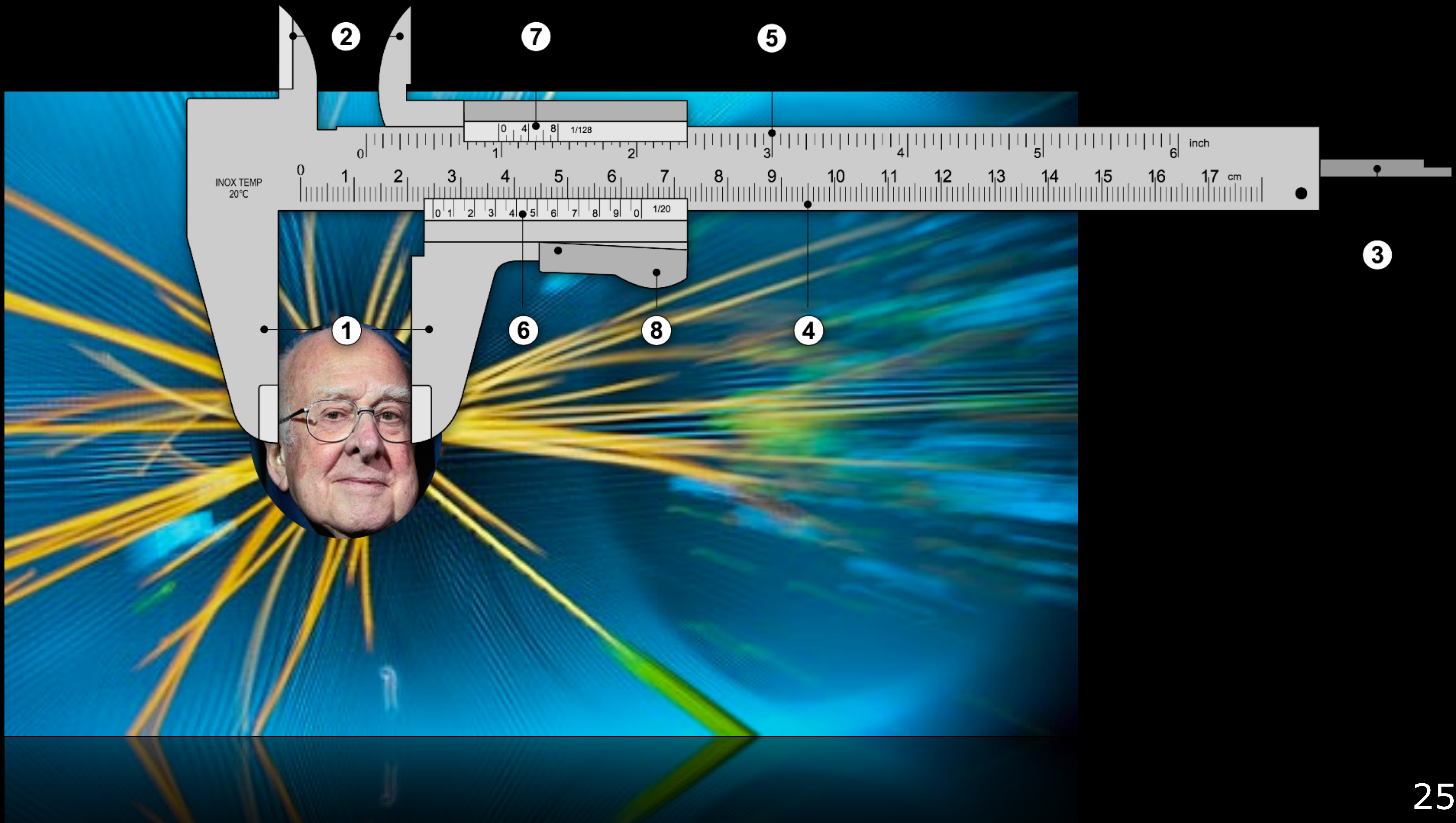
Hence, it is not possible to directly reconstruct the Higgs boson mass.

Instead, another observable, called the **transverse mass m_T** is used.

Part III

Higgs boson precision measurements

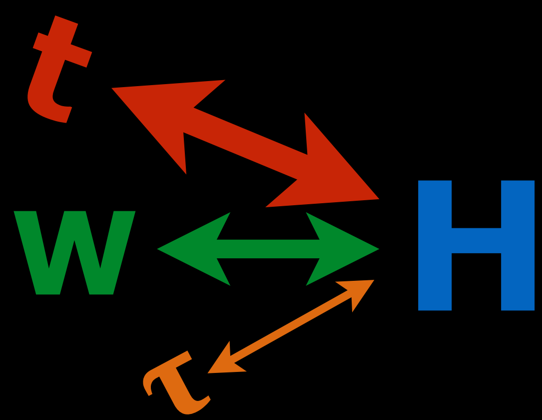
We have found a Higgs-like particle
Next challenge: measure its properties

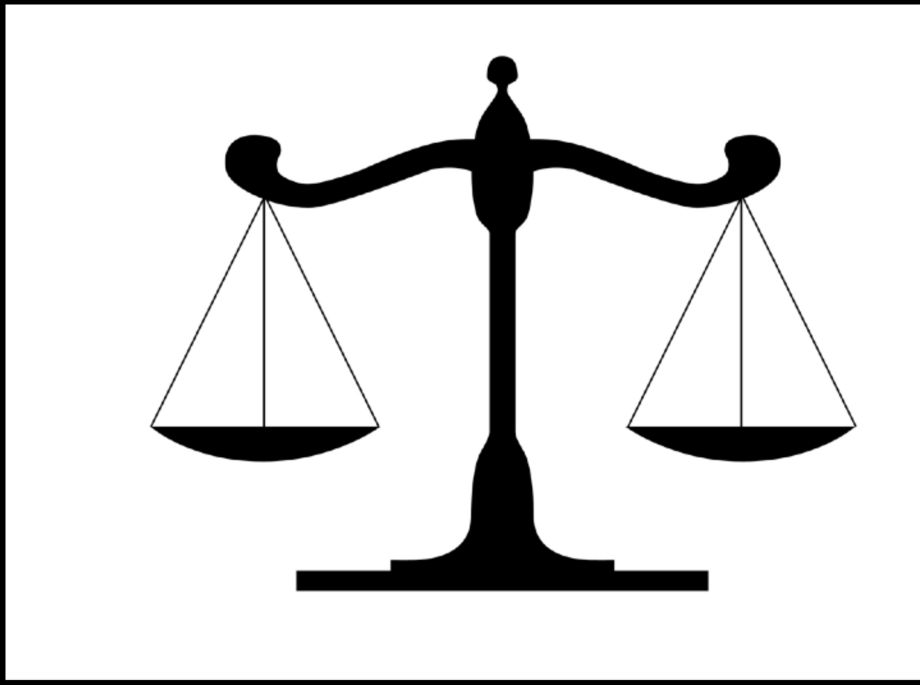


Higgs boson properties

Spin quantum number

coupling to other particles





mass

Measurements of ***cross sections*** *and differential* ***distributions***

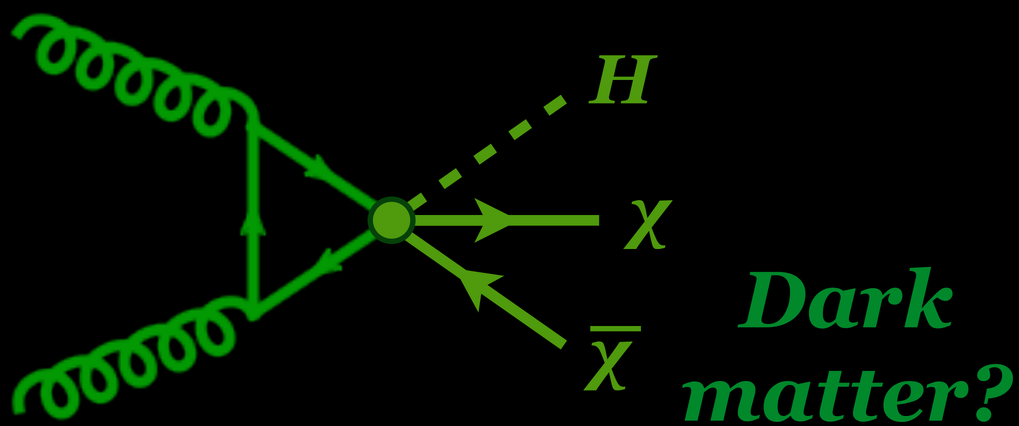
Higgs boson kinematics
  momentum, production angle …

Multiplicity and properties of of associated particles

Properties of the Higgs decay

New Higgs physics scenarios

We clearly has seen a new particle !
Does it come with some surprises ?



Perhaps it sometimes is ***produced with*** *some new,* ***exotic particles*** *?*

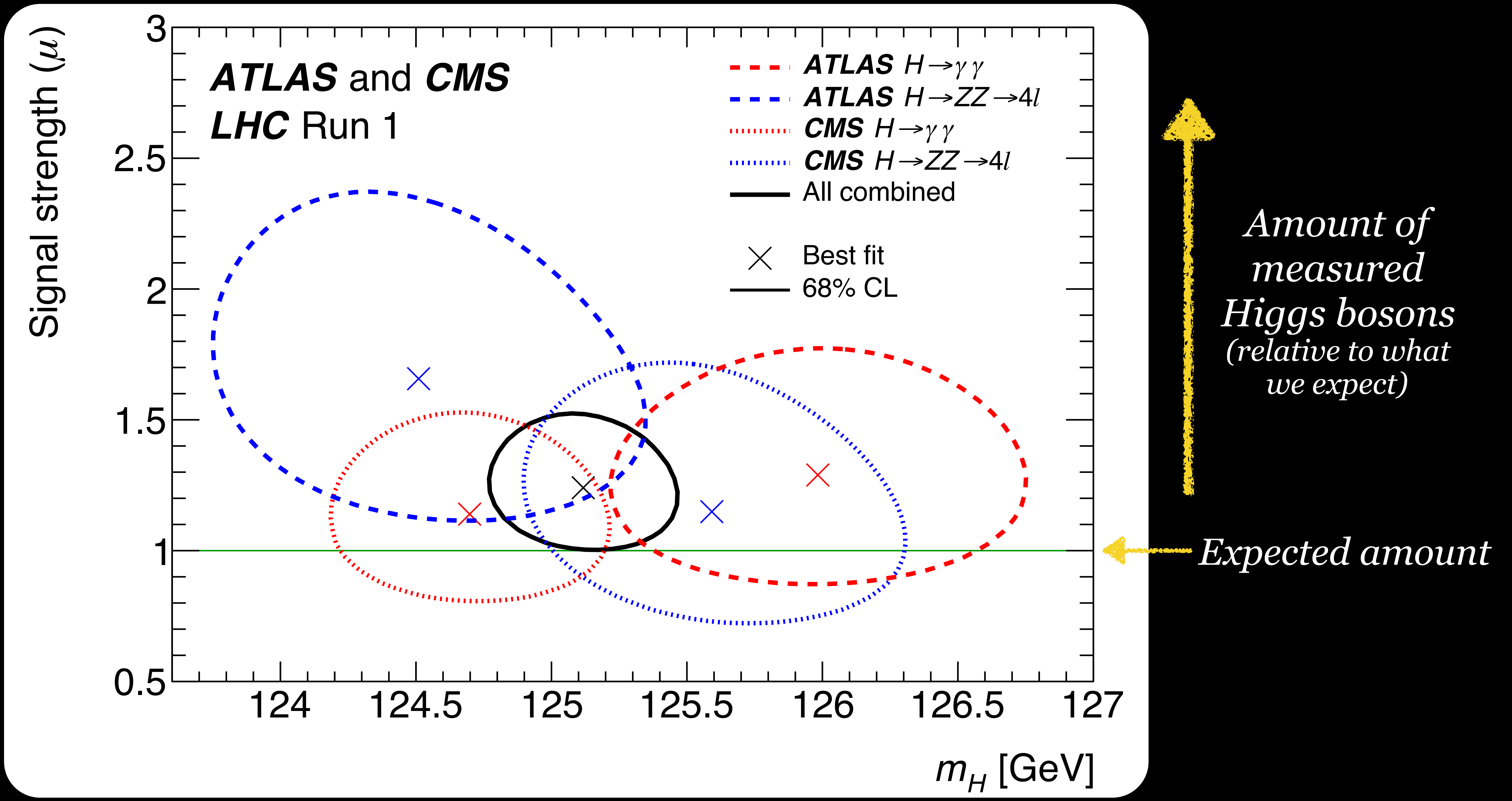
*Could it be a Higgs boson "**imposter**" that have a different spin or Charge-Parity ?*

Are there more Higgs bosons?

The MSSM SUSY model suggest there might be ***five Higgs bosons***
A, H, h, H^+ H^-

Is the Higgs truly a fundamental particle or does it have ***substructure*** *?*

Measuring the Higgs boson mass



Four measurements shown: ATLAS and CMS, $H\rightarrow\gamma\gamma$ and $H\rightarrow 4l$. They are compatible.

Combination of the measurements give: **m_H = 125.09 ± GeV**

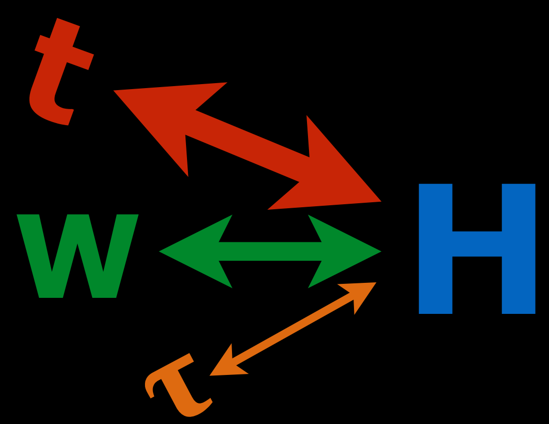
Measuring the Higgs boson couplings

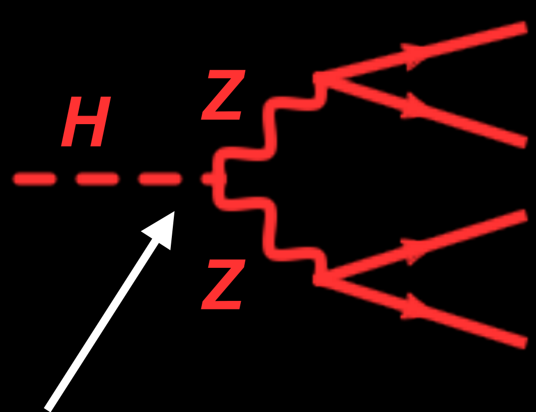
According to the Higgs mechanism, particle obtain their mass from the coupling to the Higgs field.

A ***stronger coupling***
→ more interactions
→ ***more produced Higgs bosons***

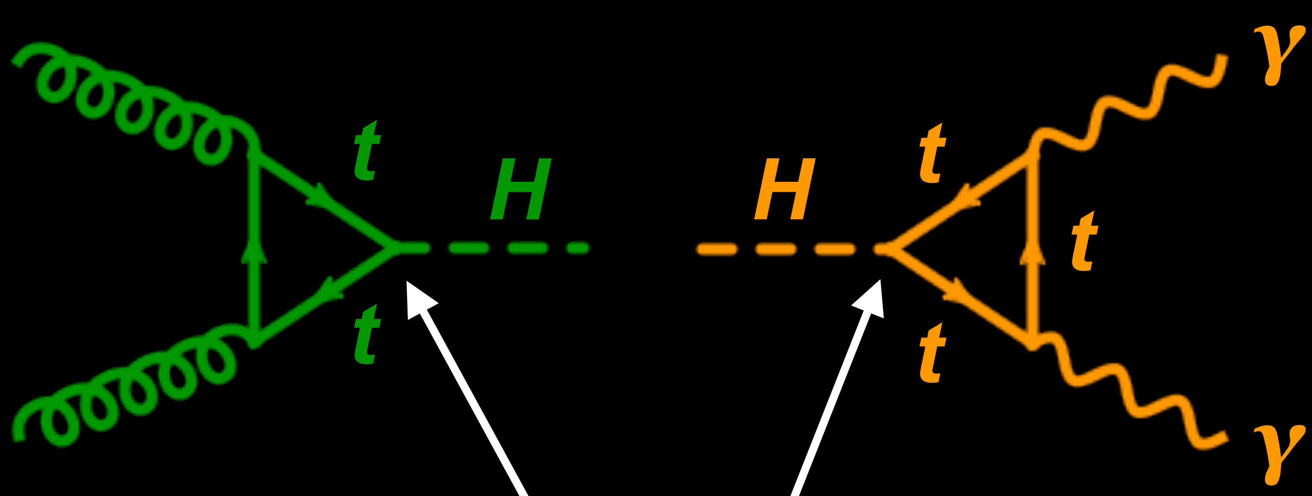
Example: coupling between Higgs and top quarks

coupling to other particles





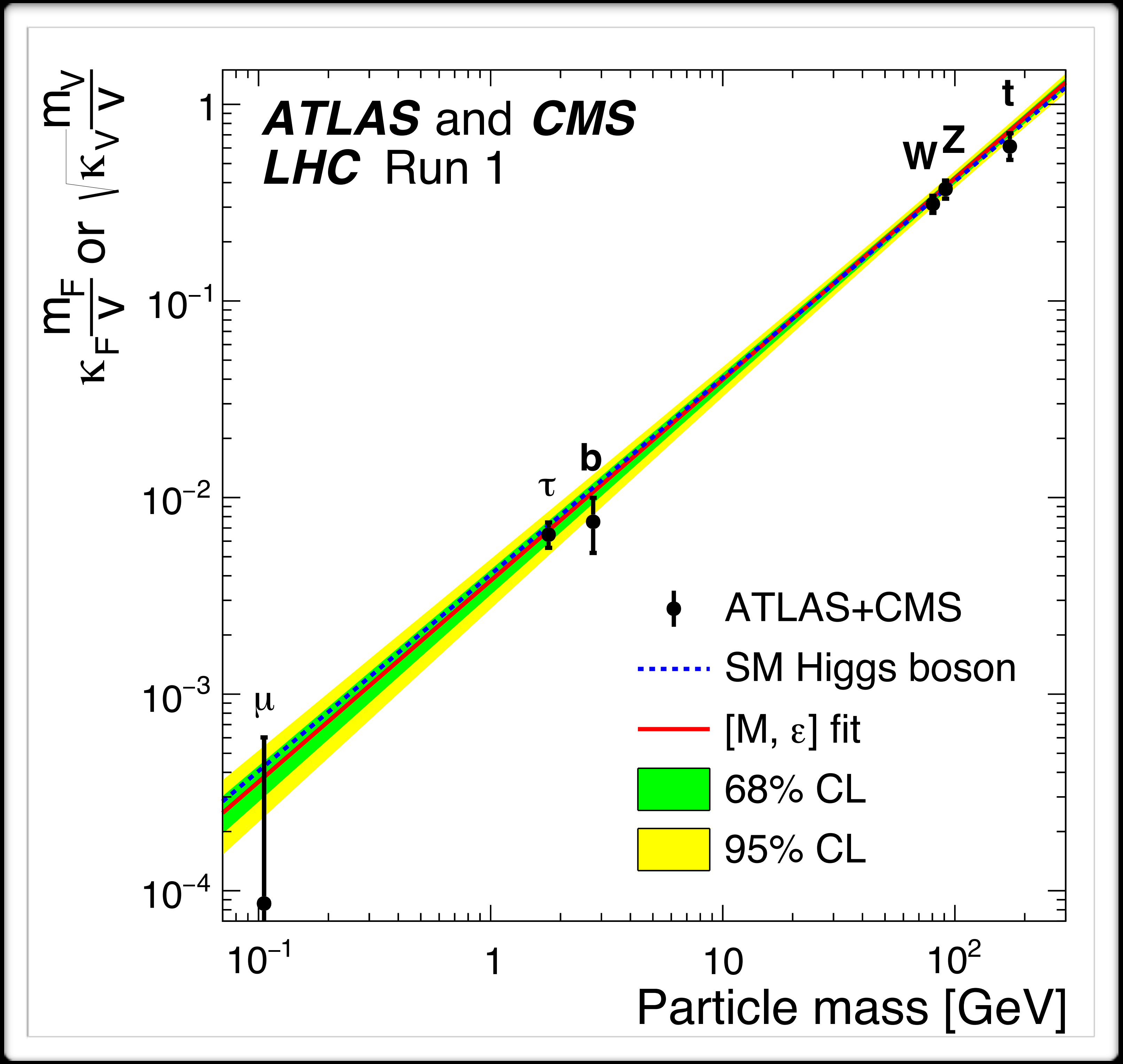
Coupling between the Higgs and the *Z* bosons



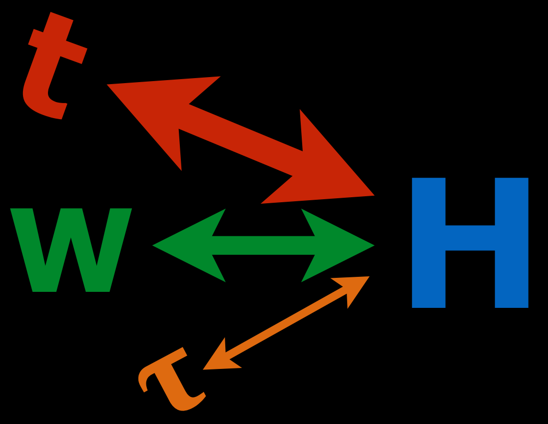
Coupling between Higgs and top

Measuring the Higgs boson couplings

Strength of coupling to the Higgs boson

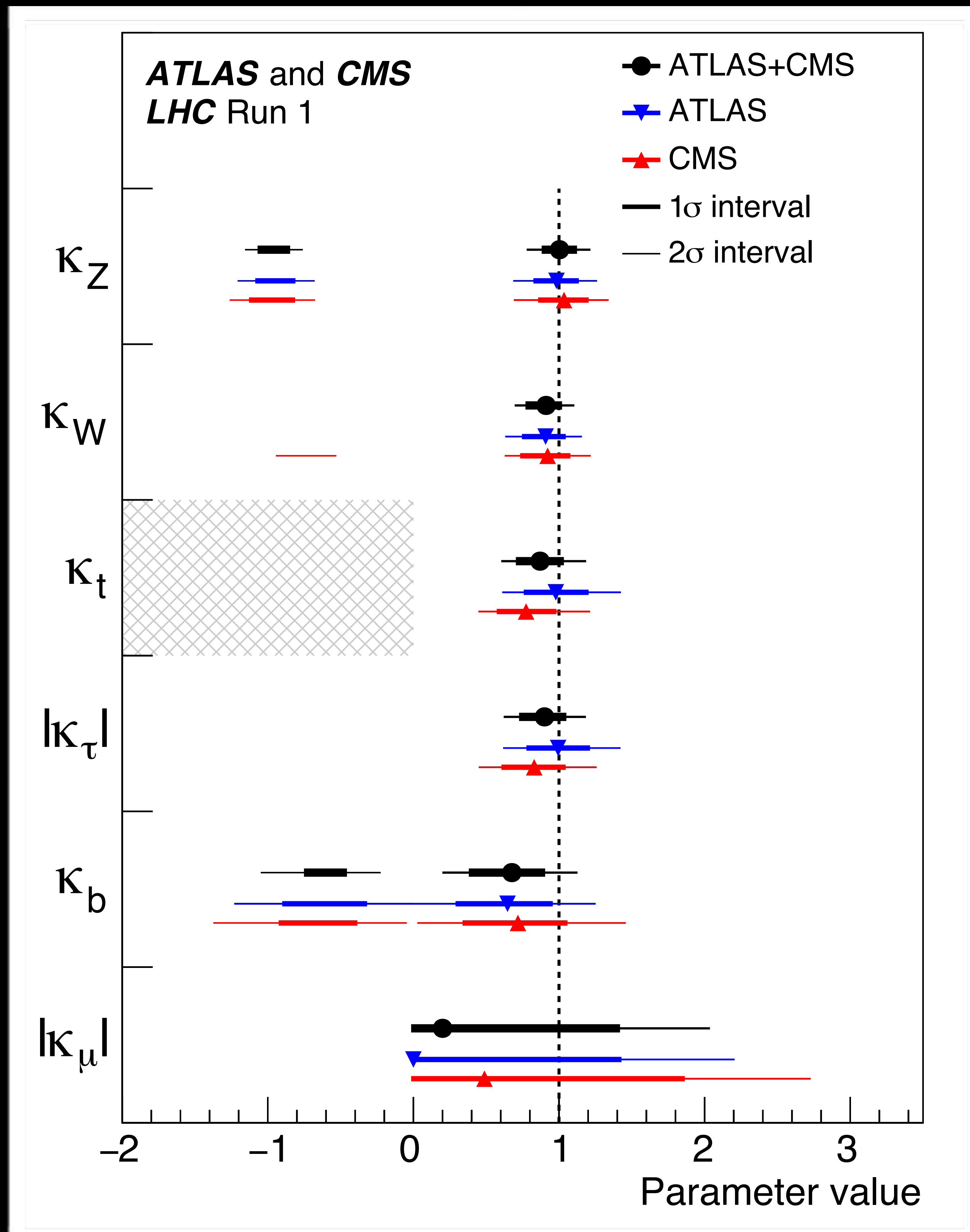


coupling to other particles

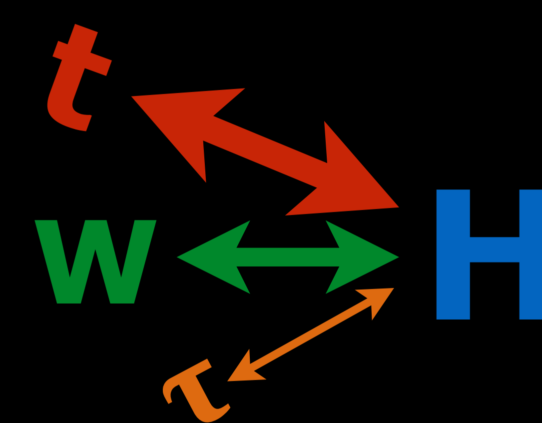


The measured strength of the coupling is proportional to the mass as expected !

Measuring the Higgs boson couplings

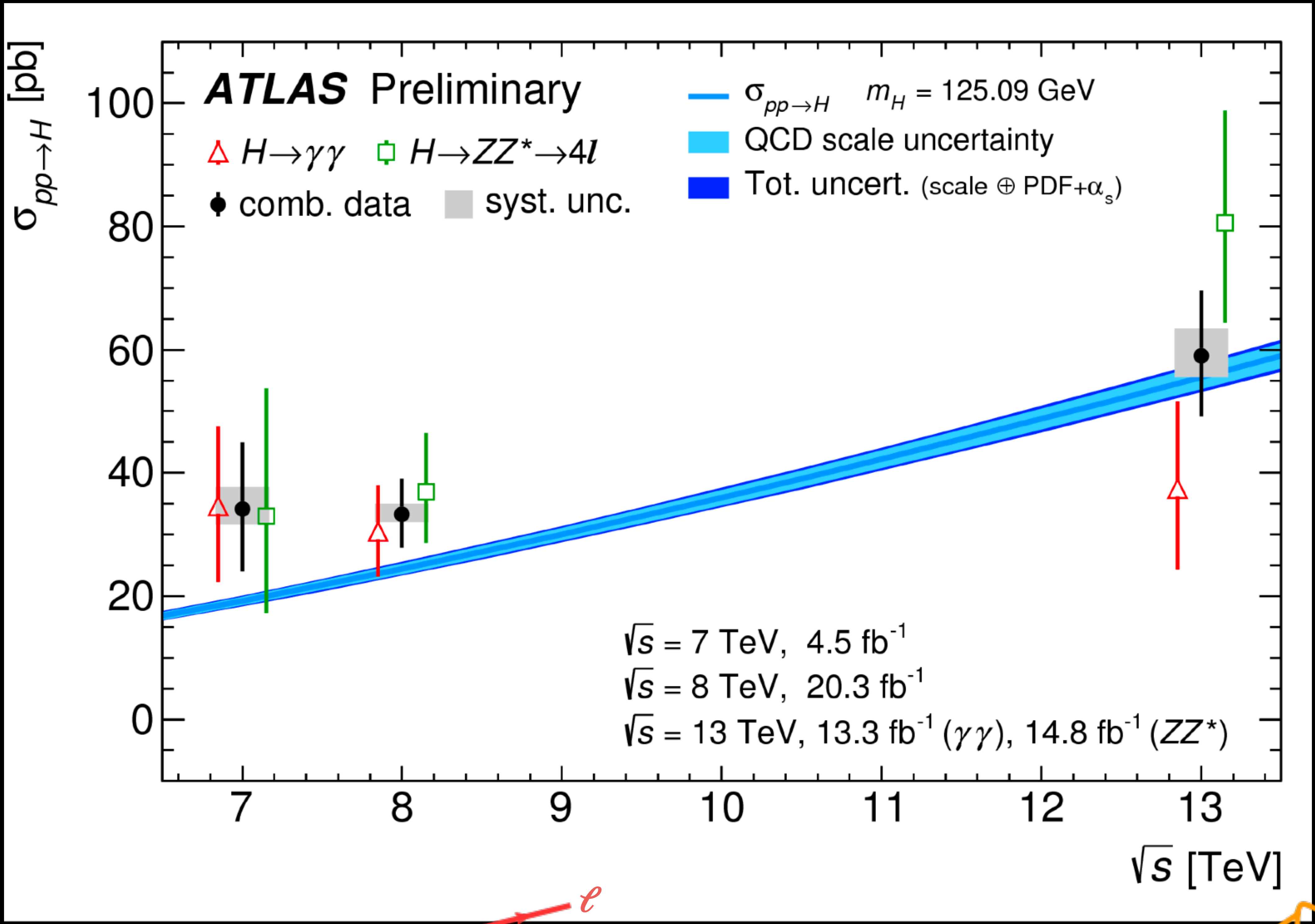


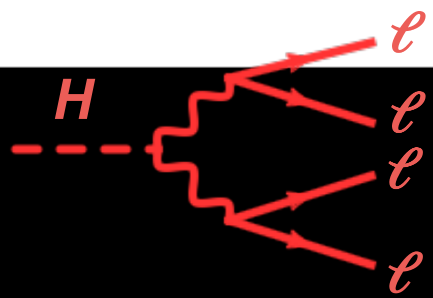
coupling to other particles

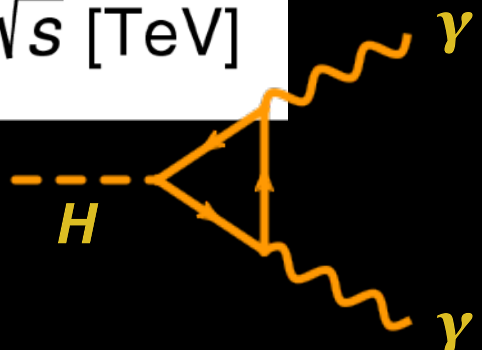


The measured strength of the coupling is proportional to the mass as expected !

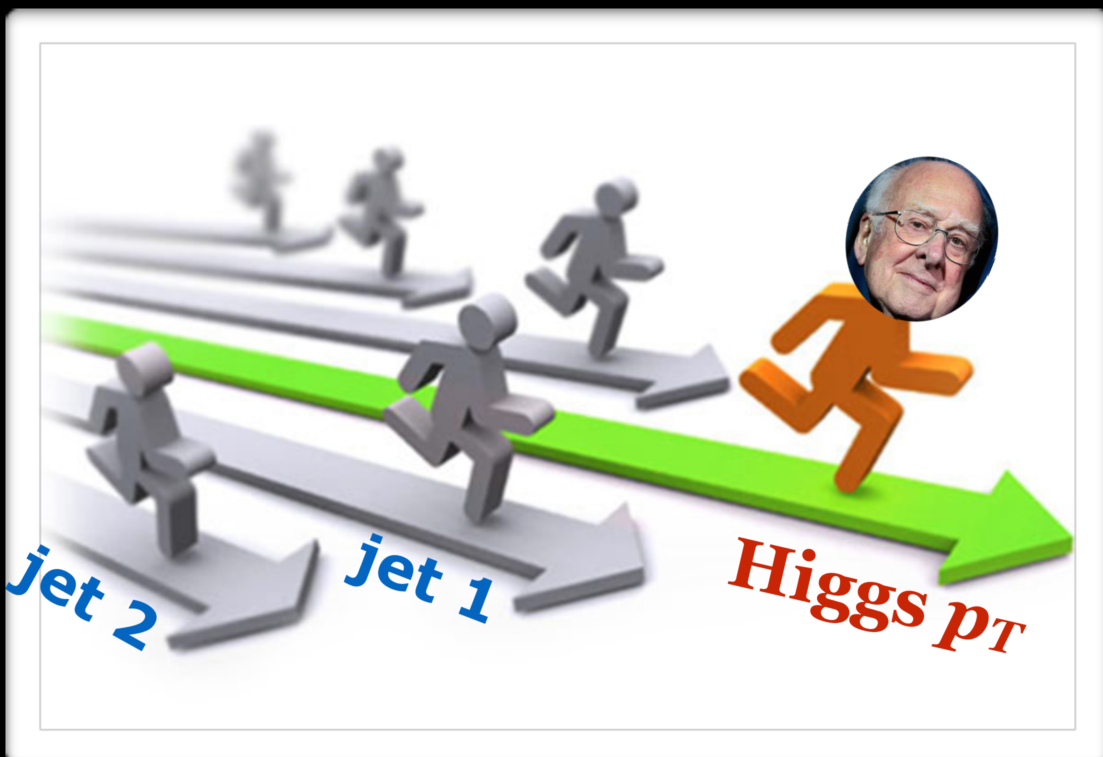
The Higgs inclusive cross section

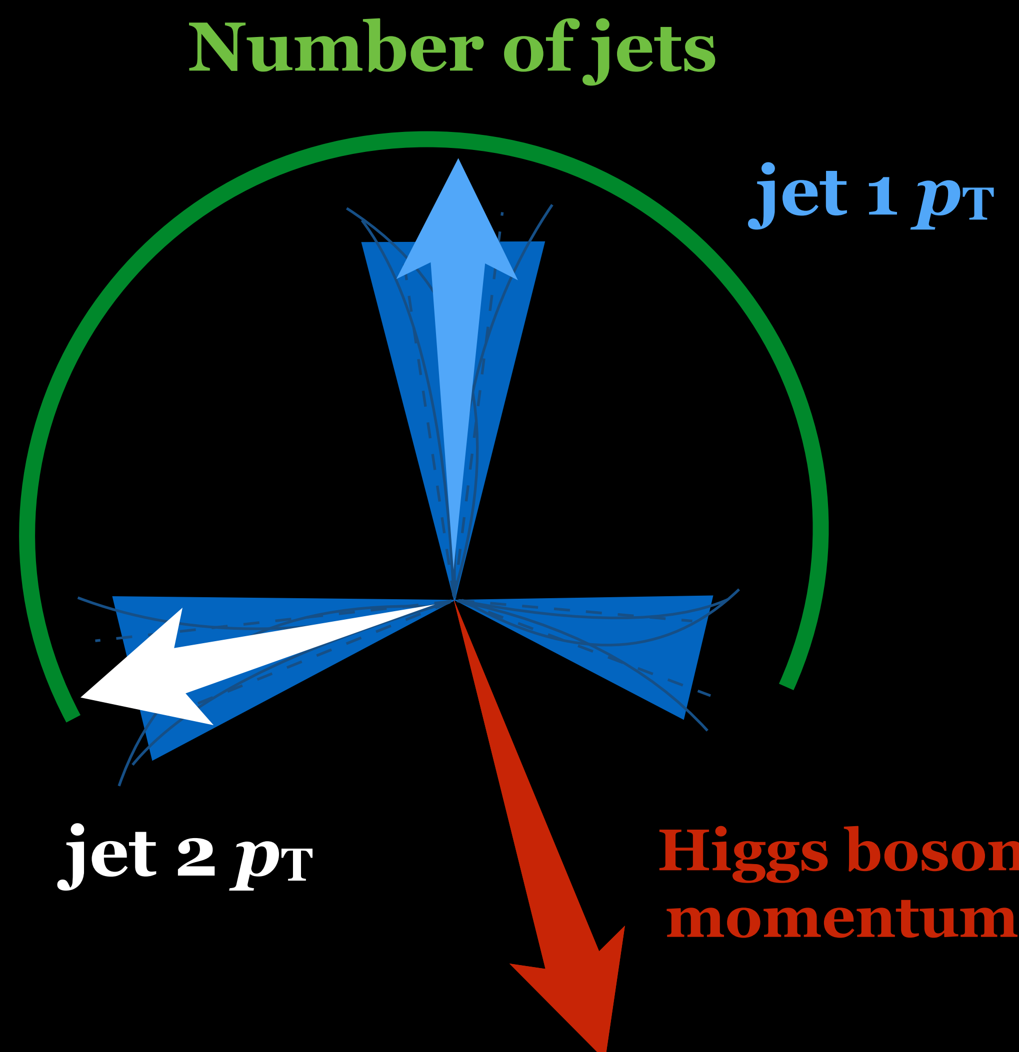






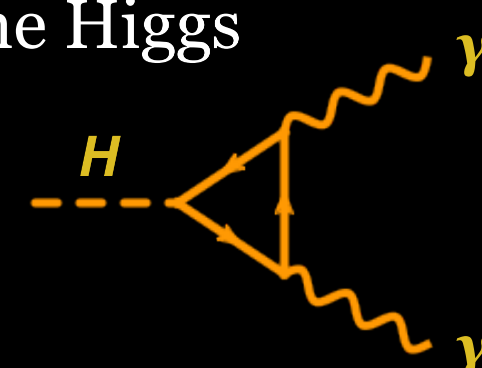
Higgs boson distributions





Example of four observables that we have measured

1. Higgs boson momentum
2. Number of jets ("quarks or gluons") produced together with the Higgs
3. The momenta of the first and second jets
4. The angle between the photons produced in the Higgs decay



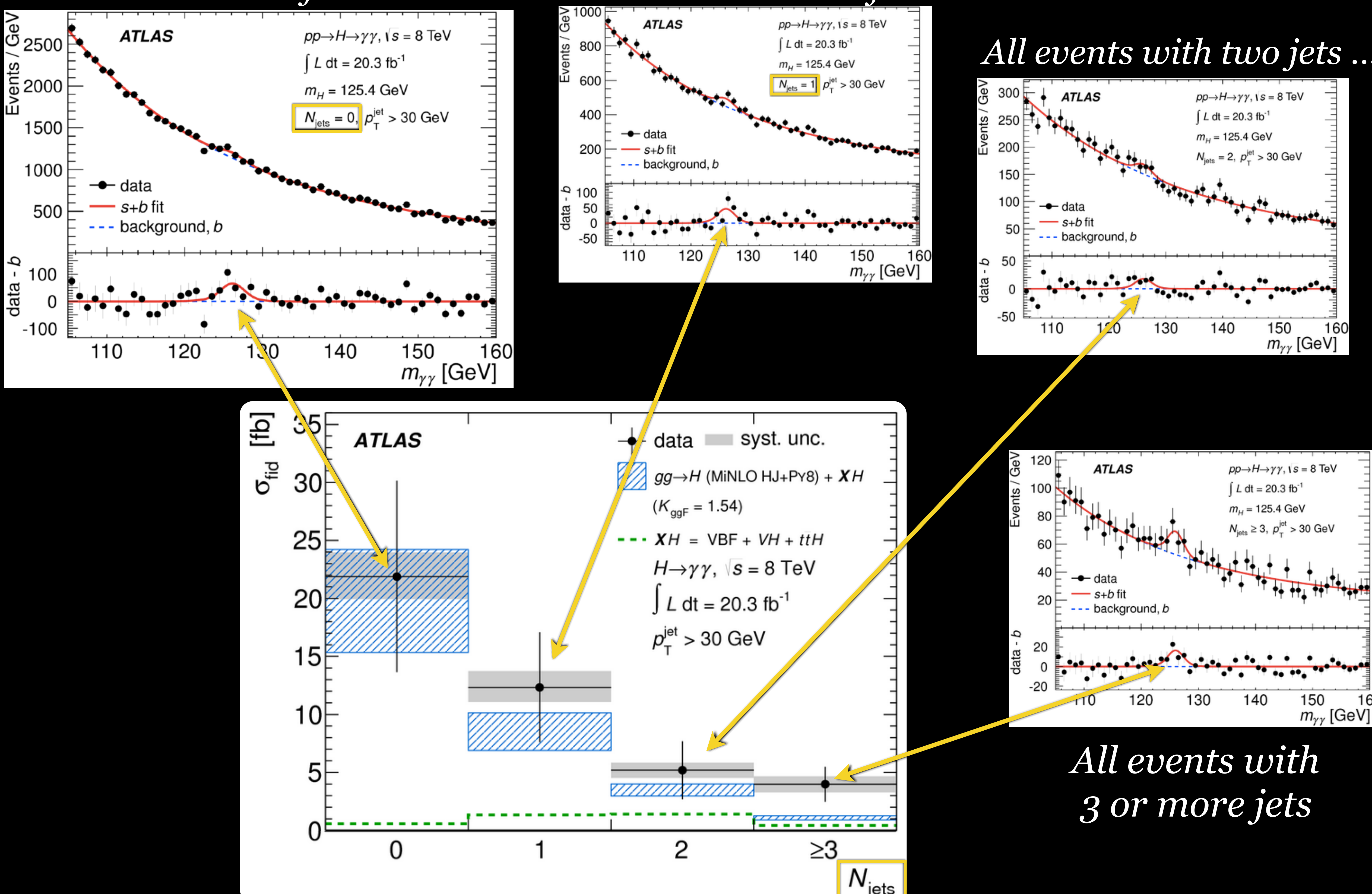
Measuring Higgs boson distributions

All events with no jets

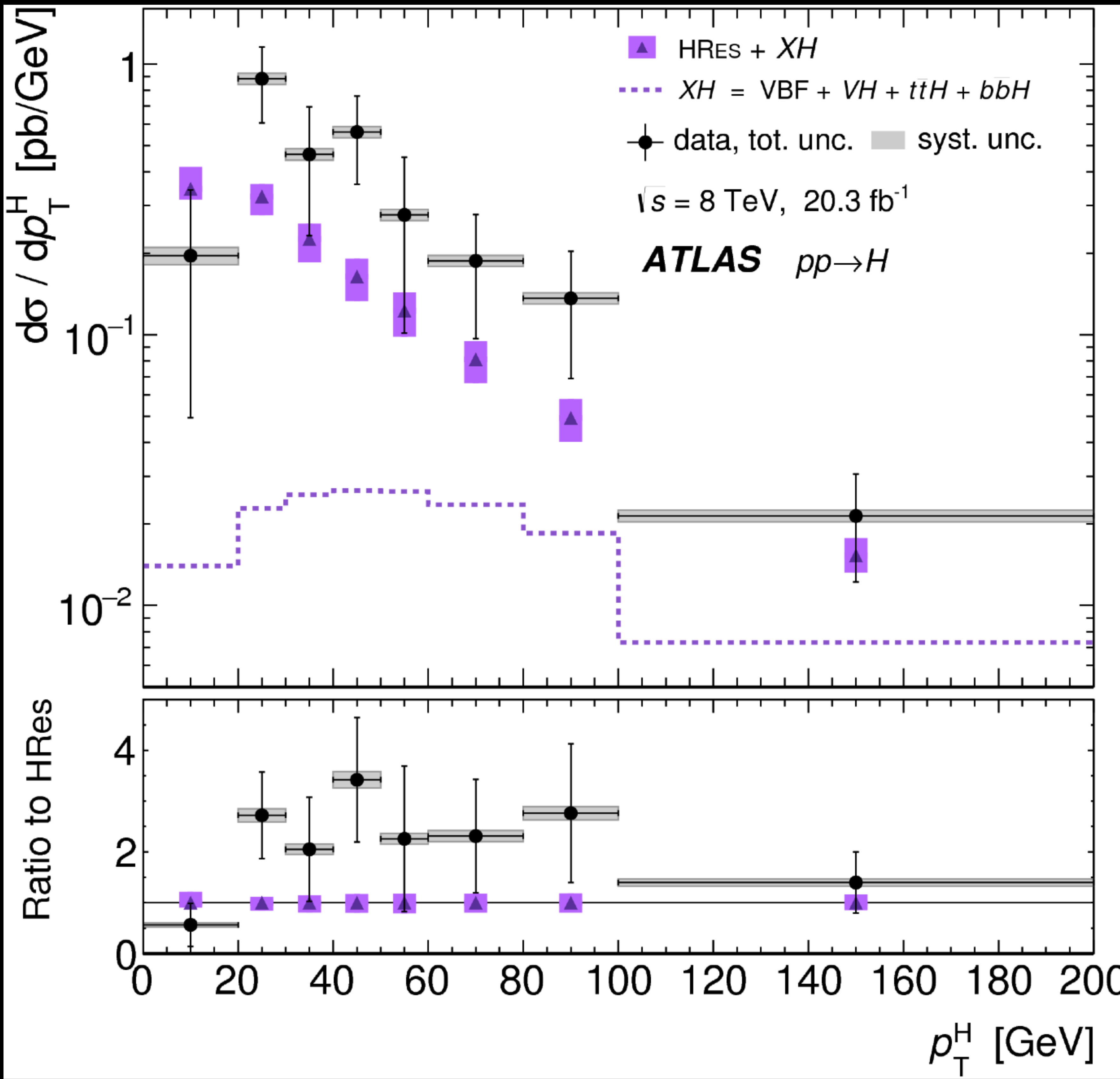
All events with one jet

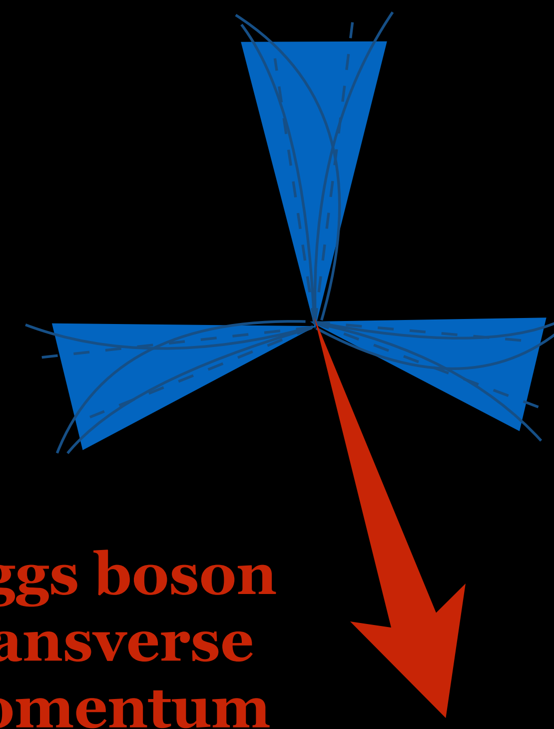
All events with two jets ...

All events with 3 or more jets



1. The Higgs boson momentum



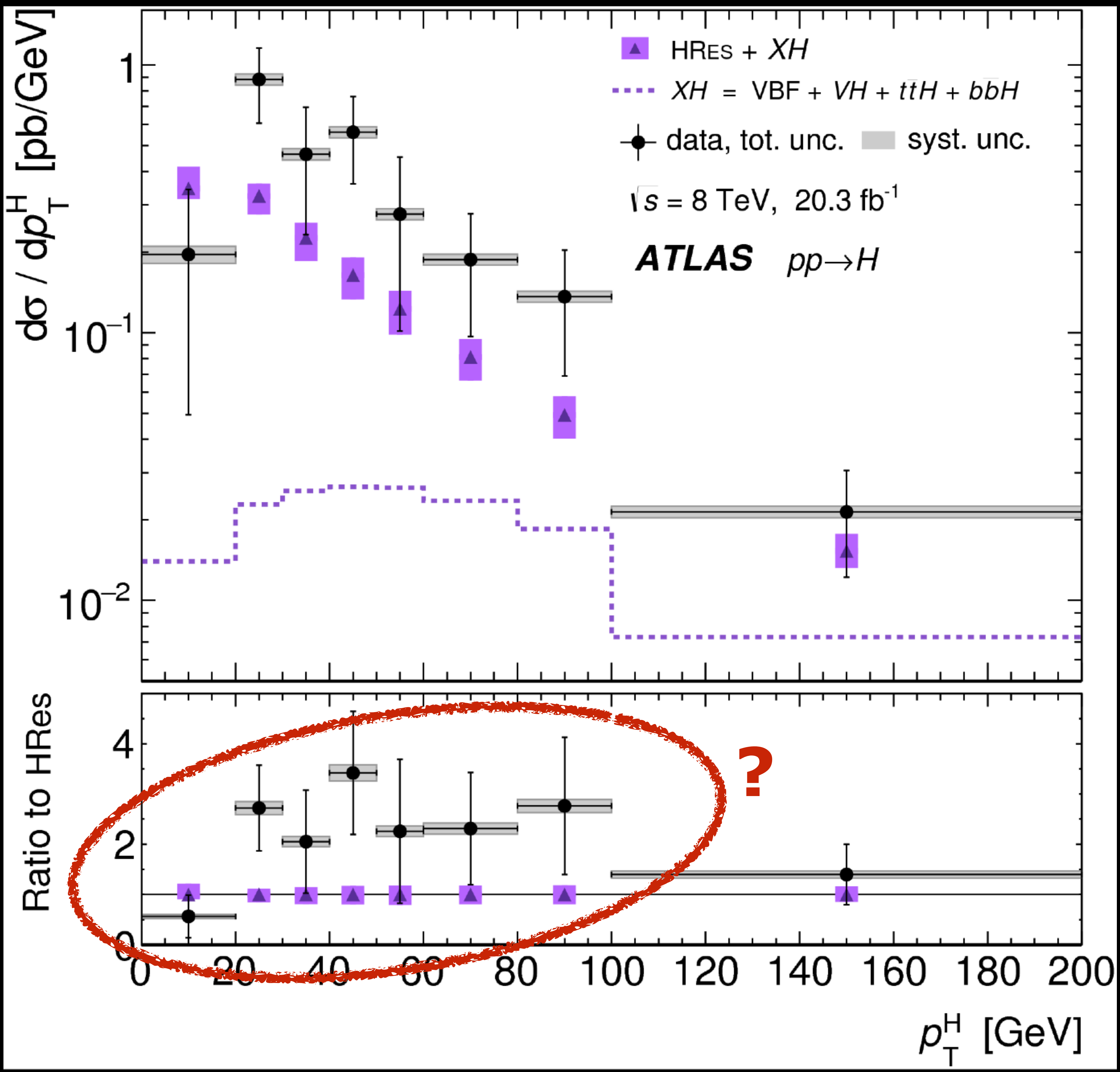


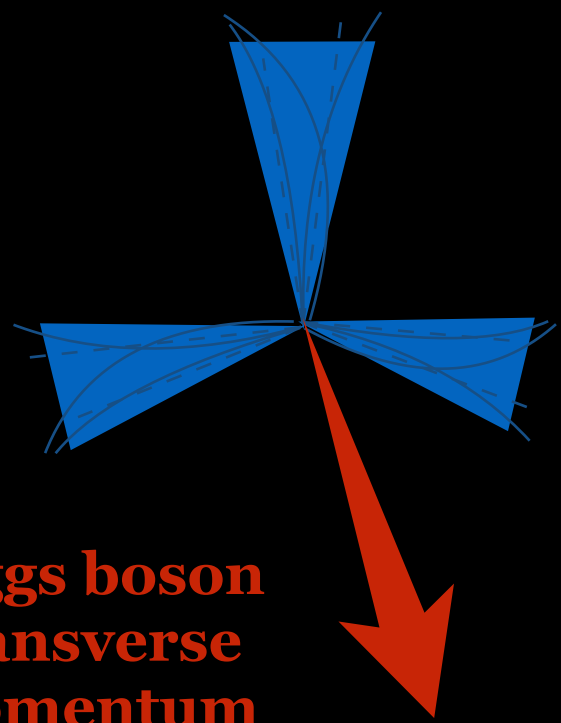
Higgs boson transverse momentum

"Micro-anomaly"
ATLAS Run-I measurement of Higgs boson transverse ***momentum*** *suggest harder spectrum than expected.*

Probability for agreement is only ~4%

1. The Higgs boson momentum





"Micro-anomaly"
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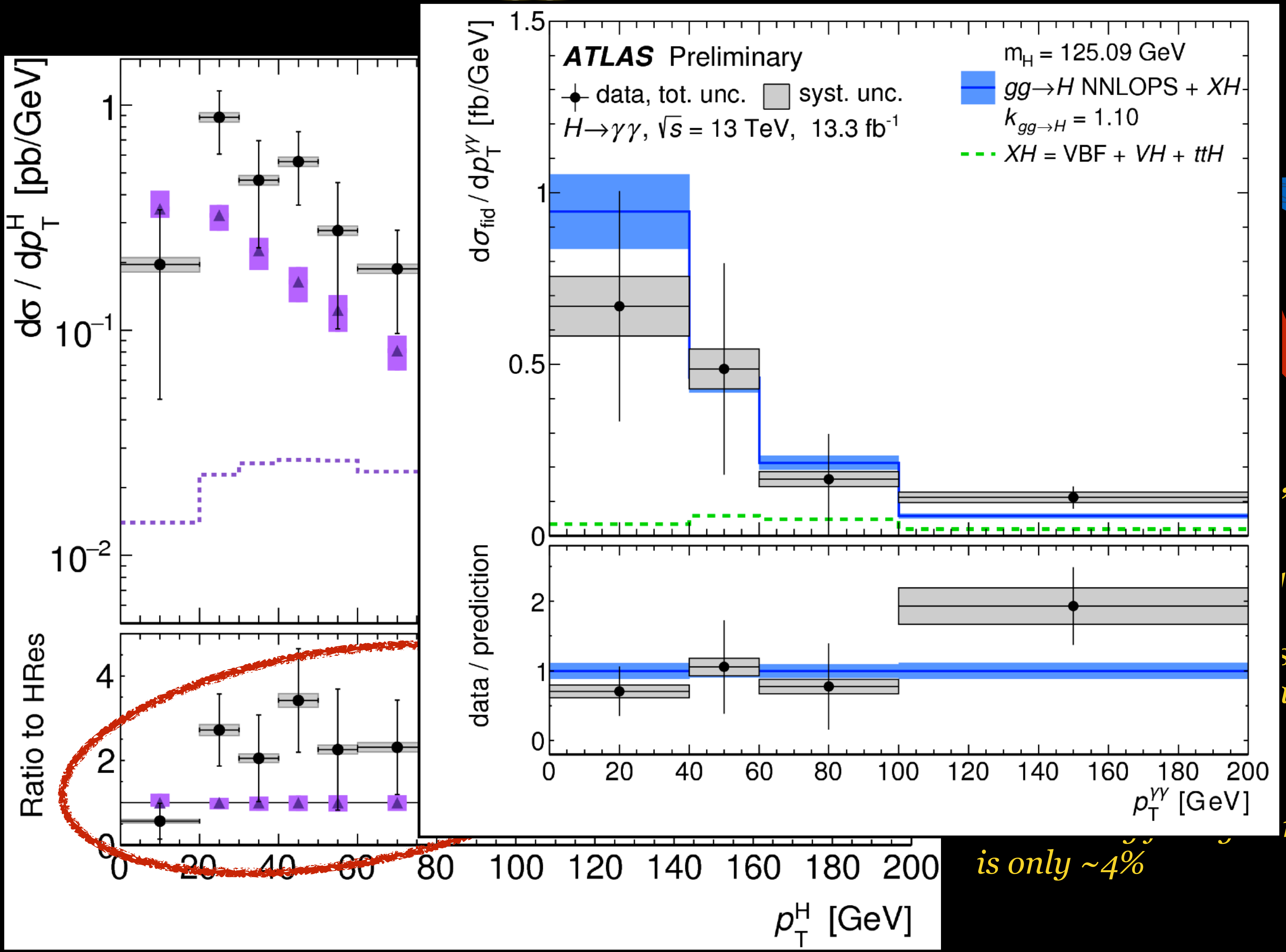
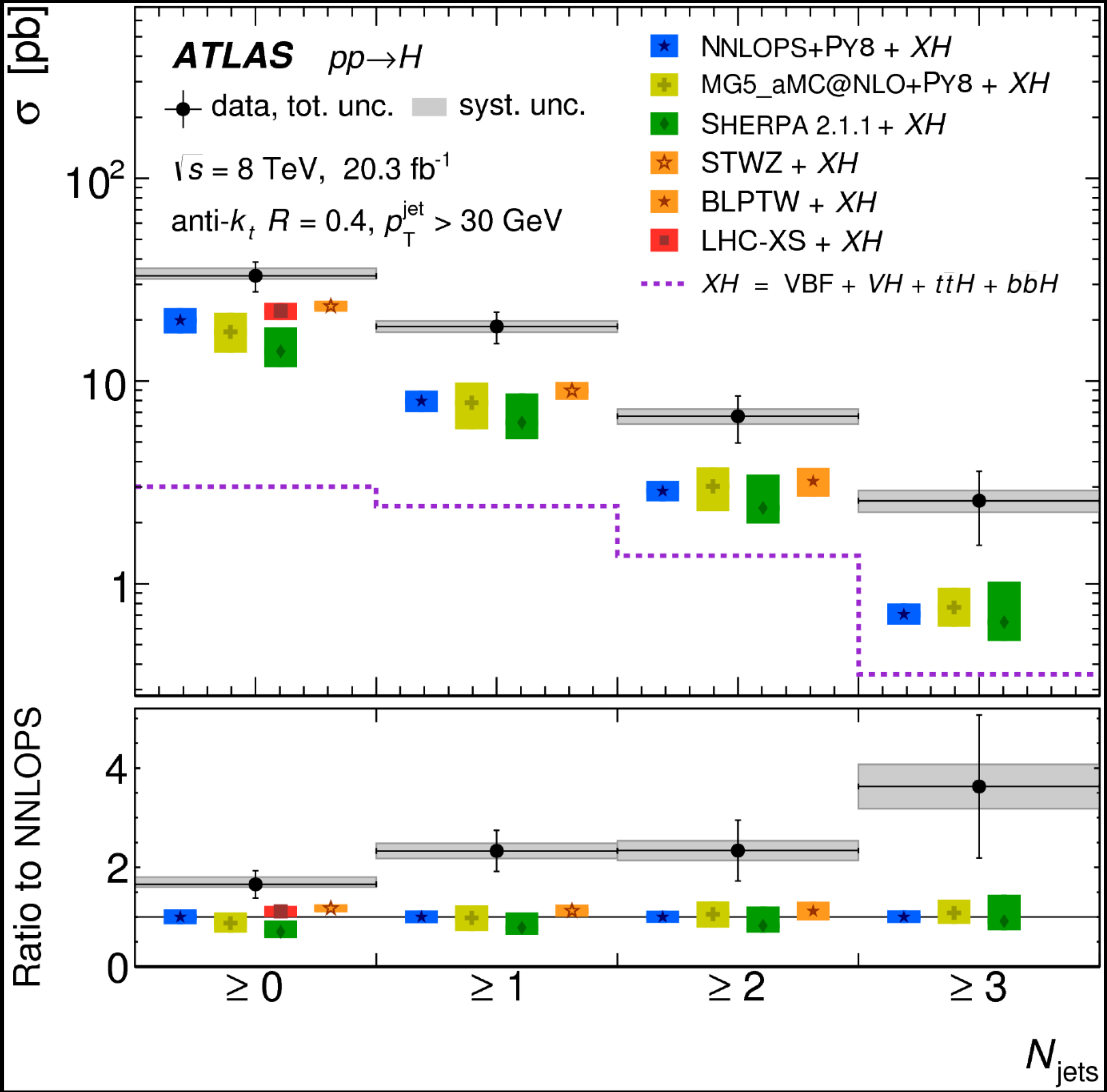


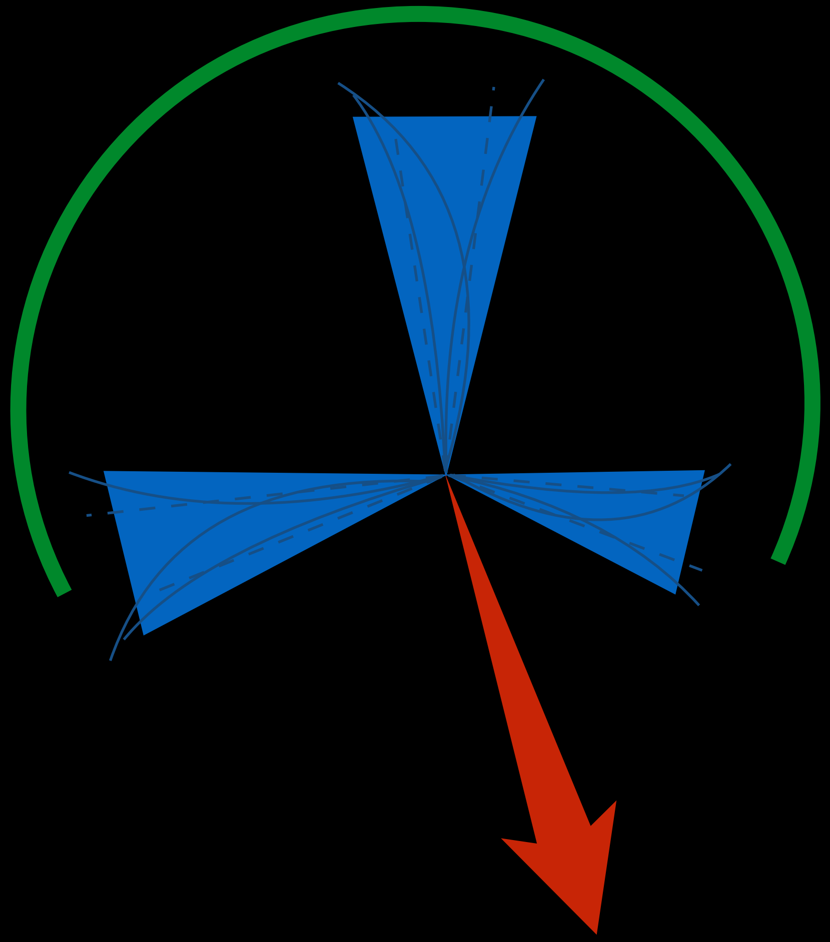
ment

is only ~4%

2. The number of jets

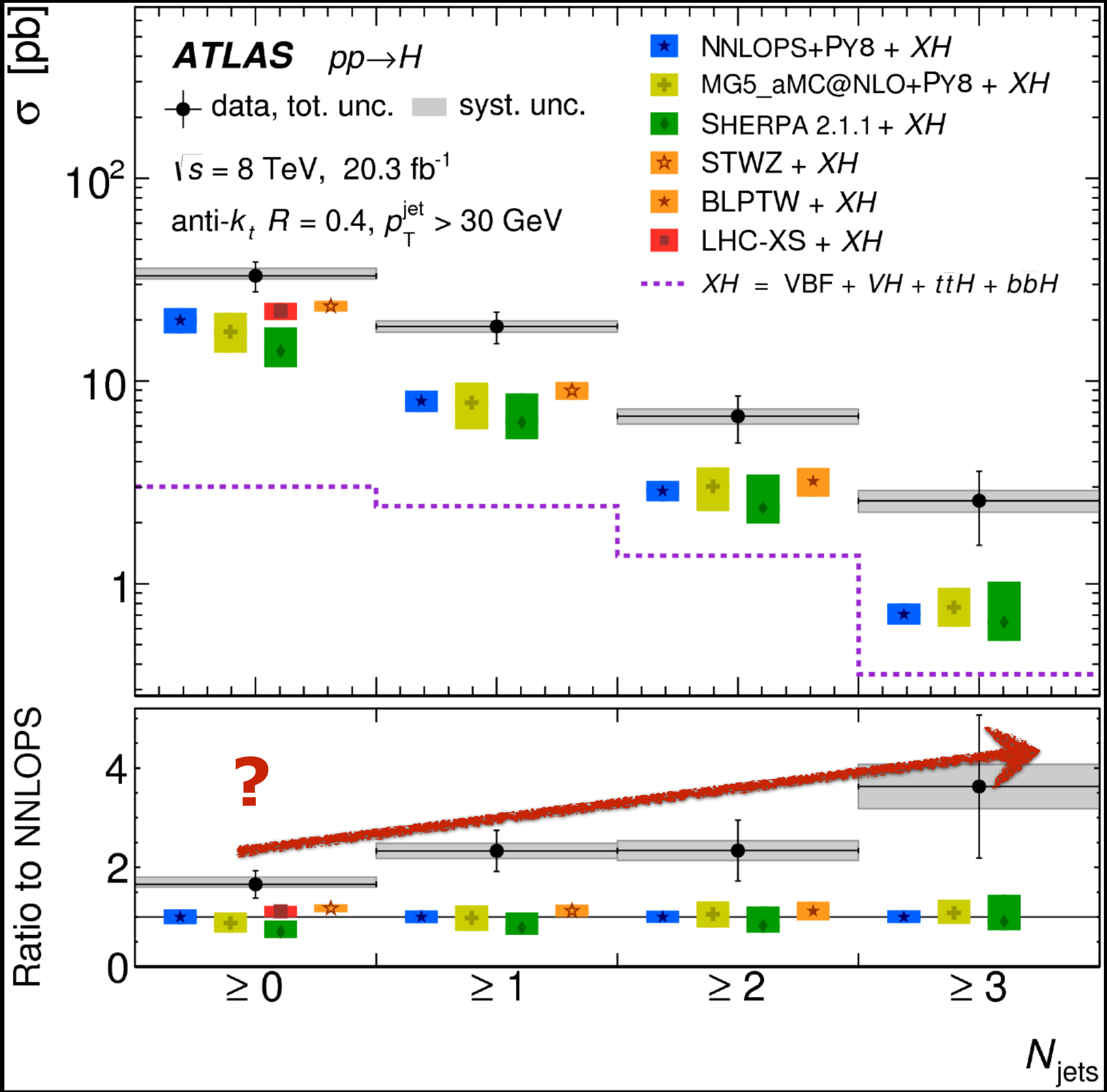


Number of jets

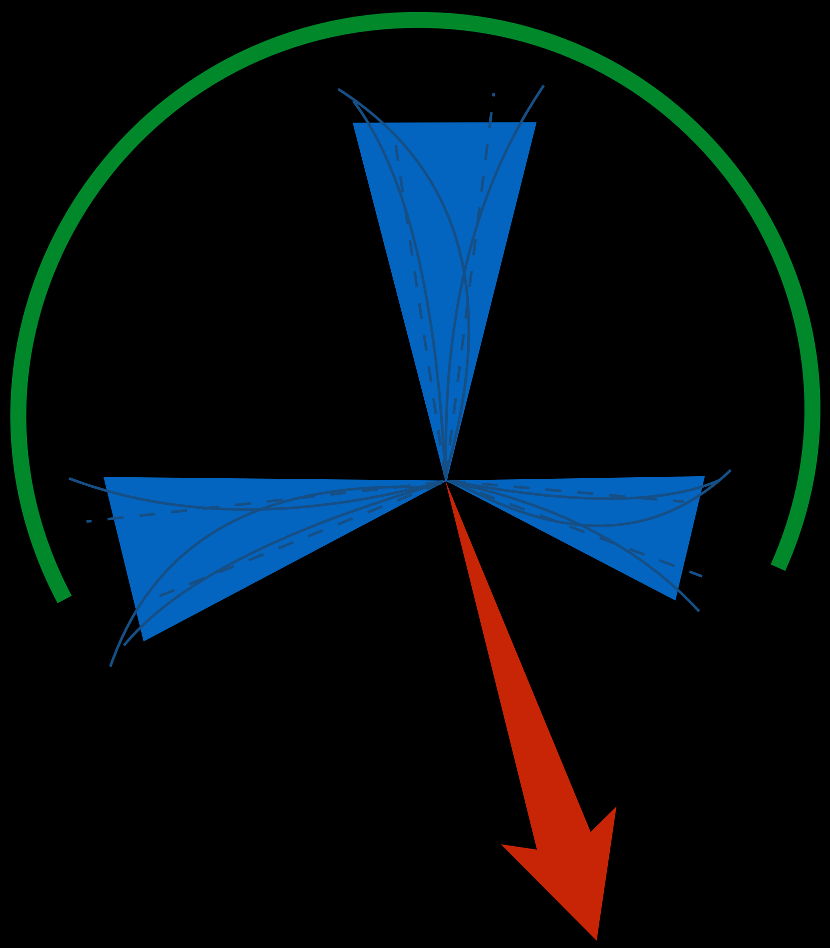


Run-I ATLAS data also indicate that ***Higgs bosons are produced with more jets … ?***

2. The number of jets



Number of jets



Run-I ATLAS data also indicate that ***Higgs bosons are produced with more jets*** *… ?*

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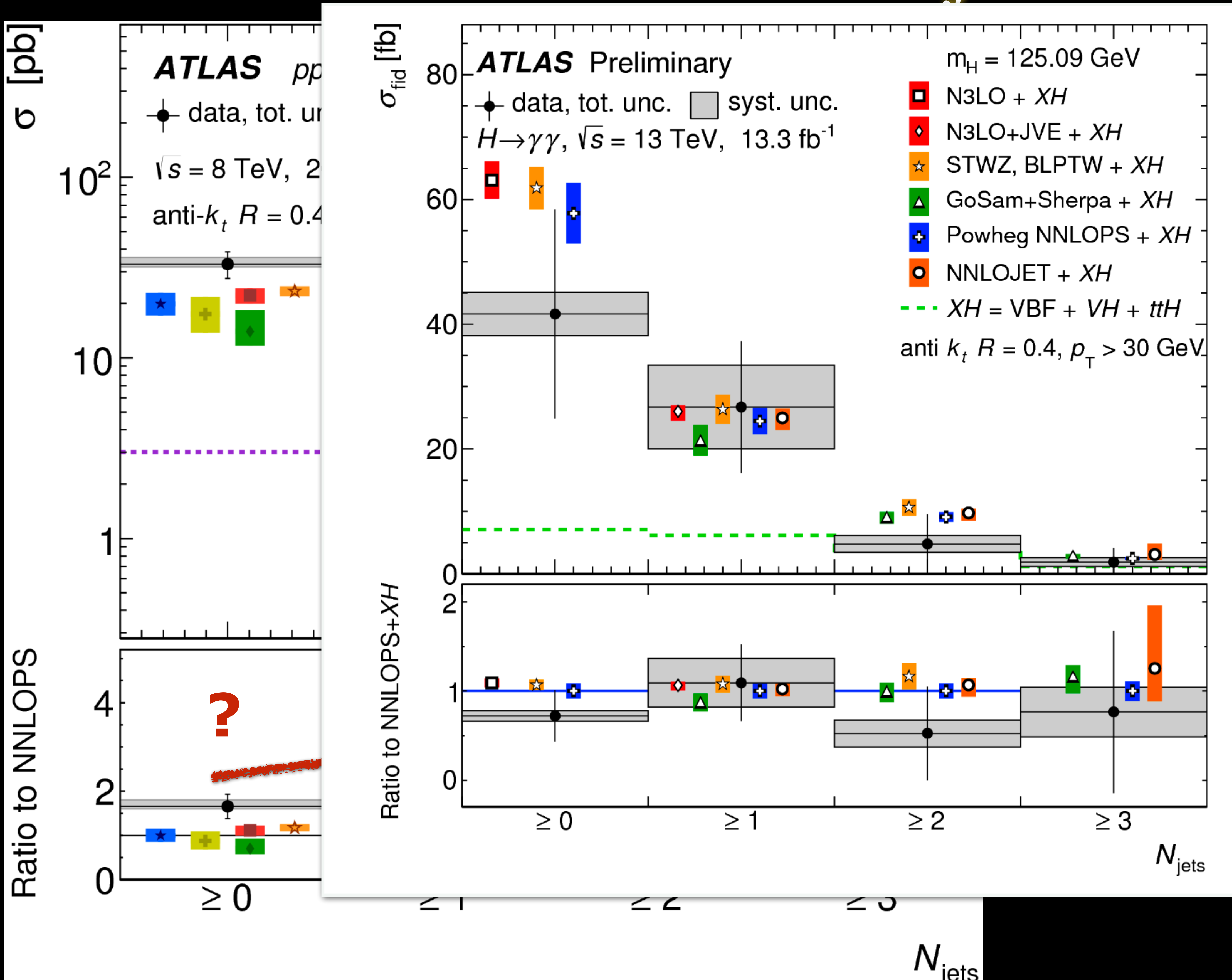
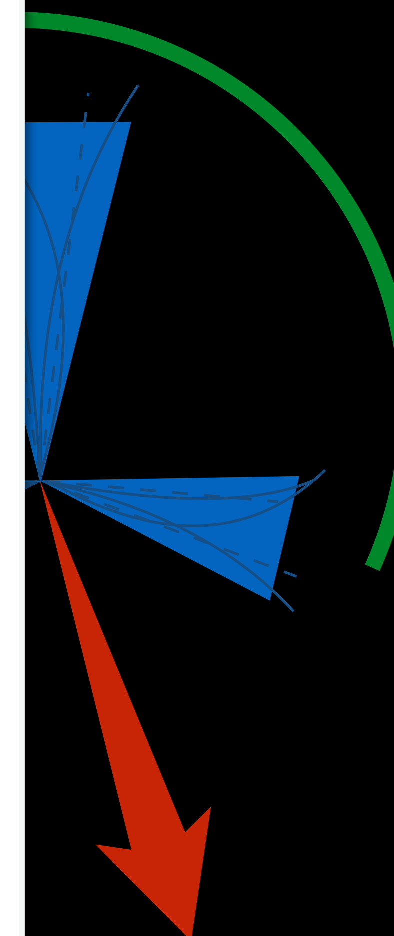


...er of jets



...data also
...iggs
...roduced
...ts … ?

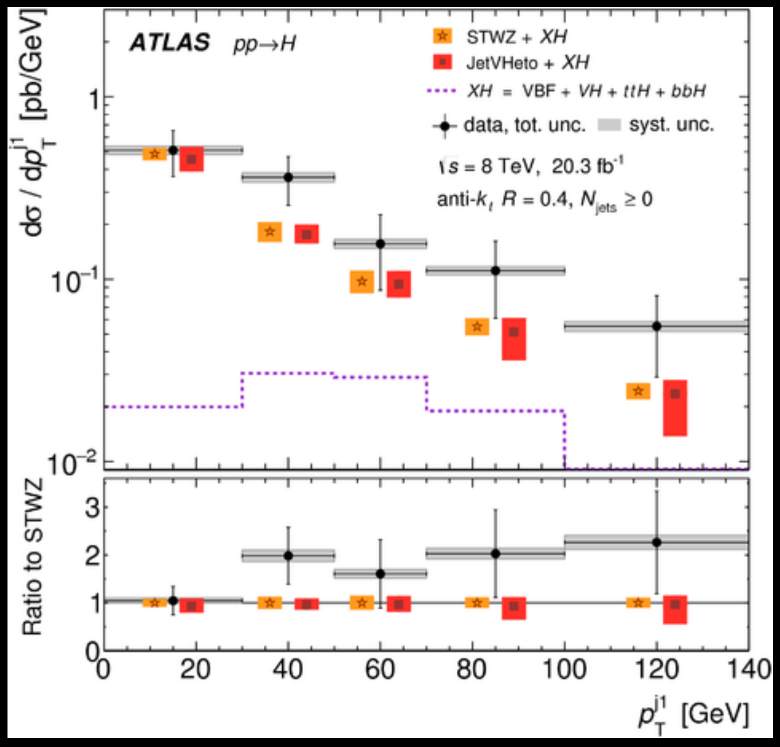
Summary

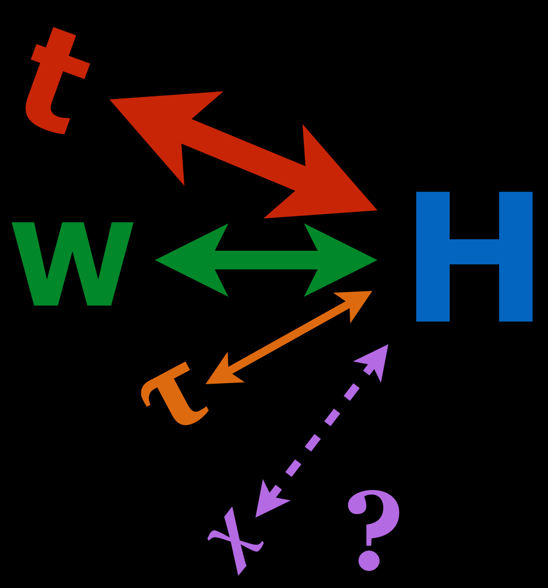
After its discovery, focus of Higgs boson analyses are shifting to precision measurements of its properties.

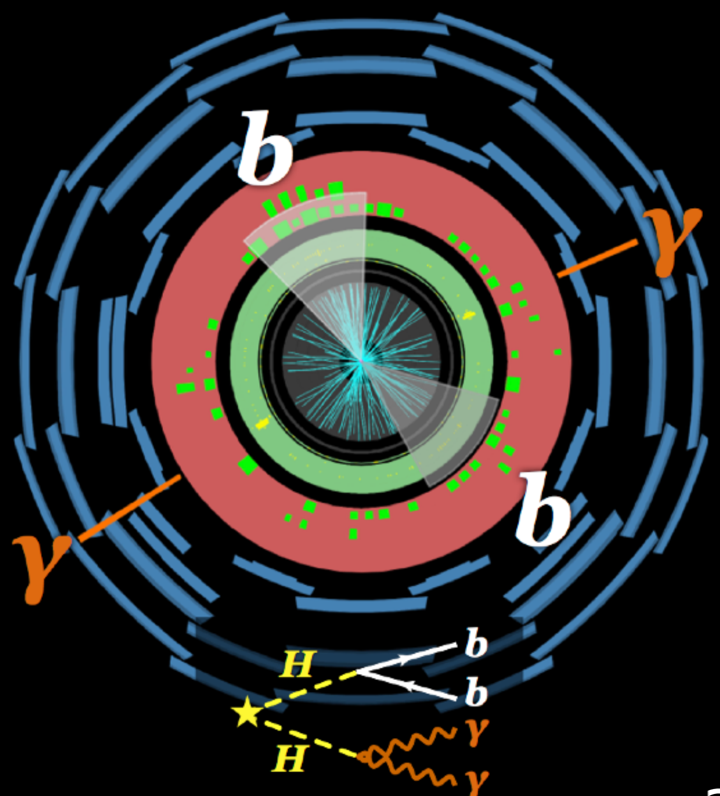
- Mass
- Spin/CP, limits on width
- Cross sections in different kinematic regions

The 2015+2016 dataset (~35 fb^{-1} @ 13 TeV) is effectively six times larger than the Run-1 dataset, results expected for summer conferences.

Exciting times ahead!

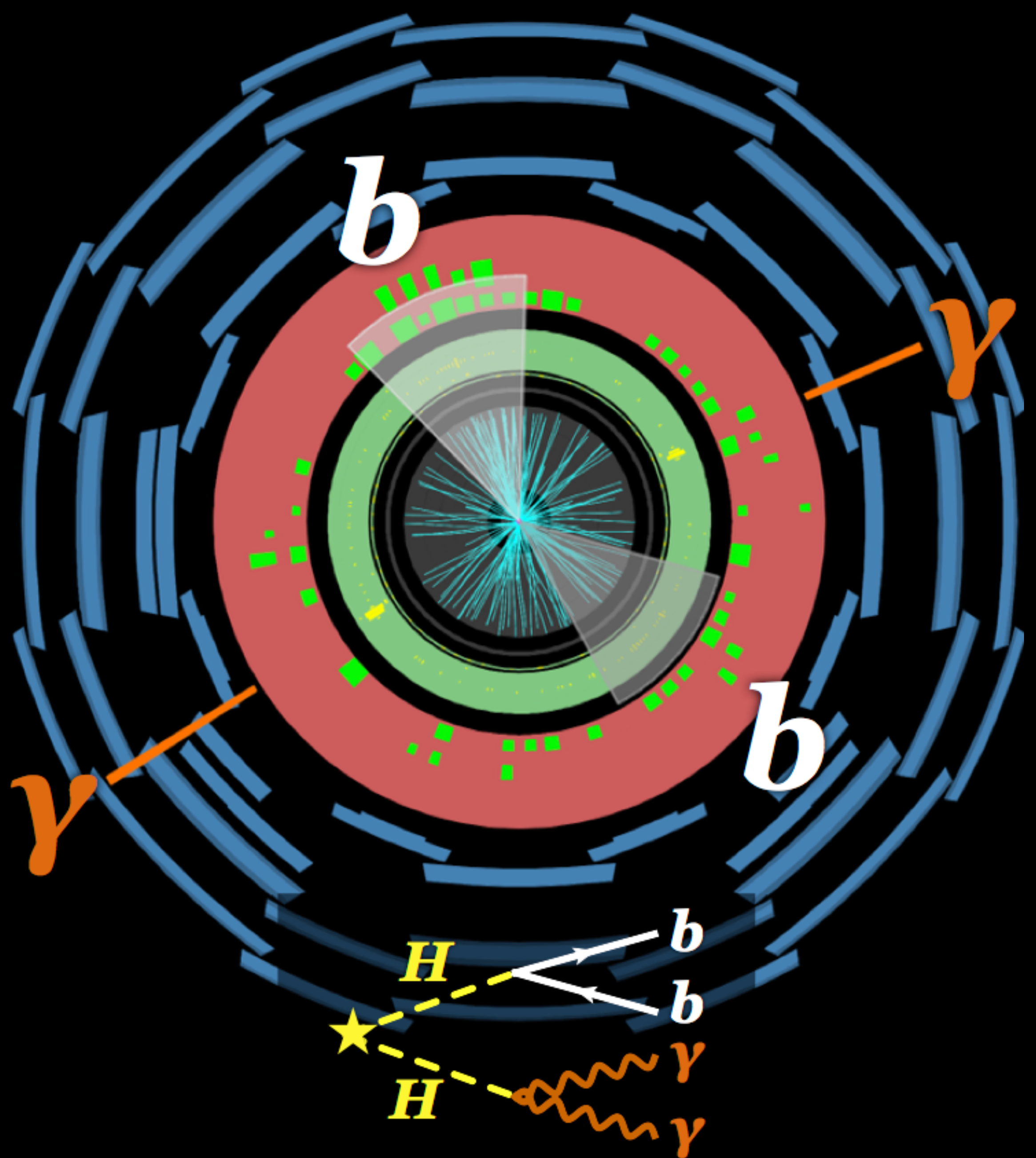


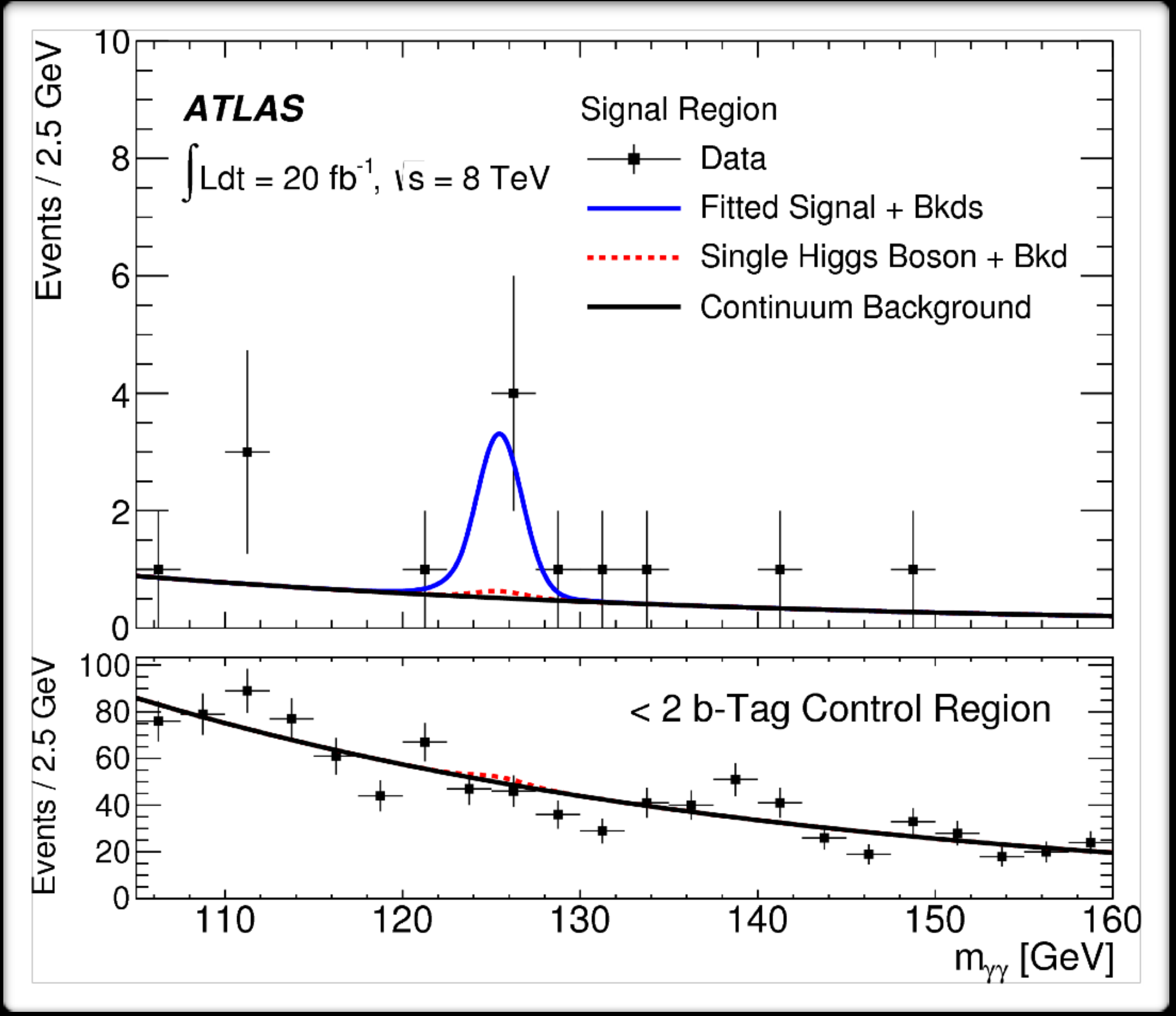





That's all Folks!
Thanks for your attention!

Search for Higgs pair production



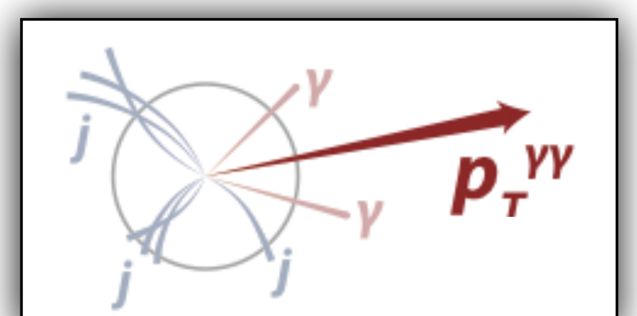


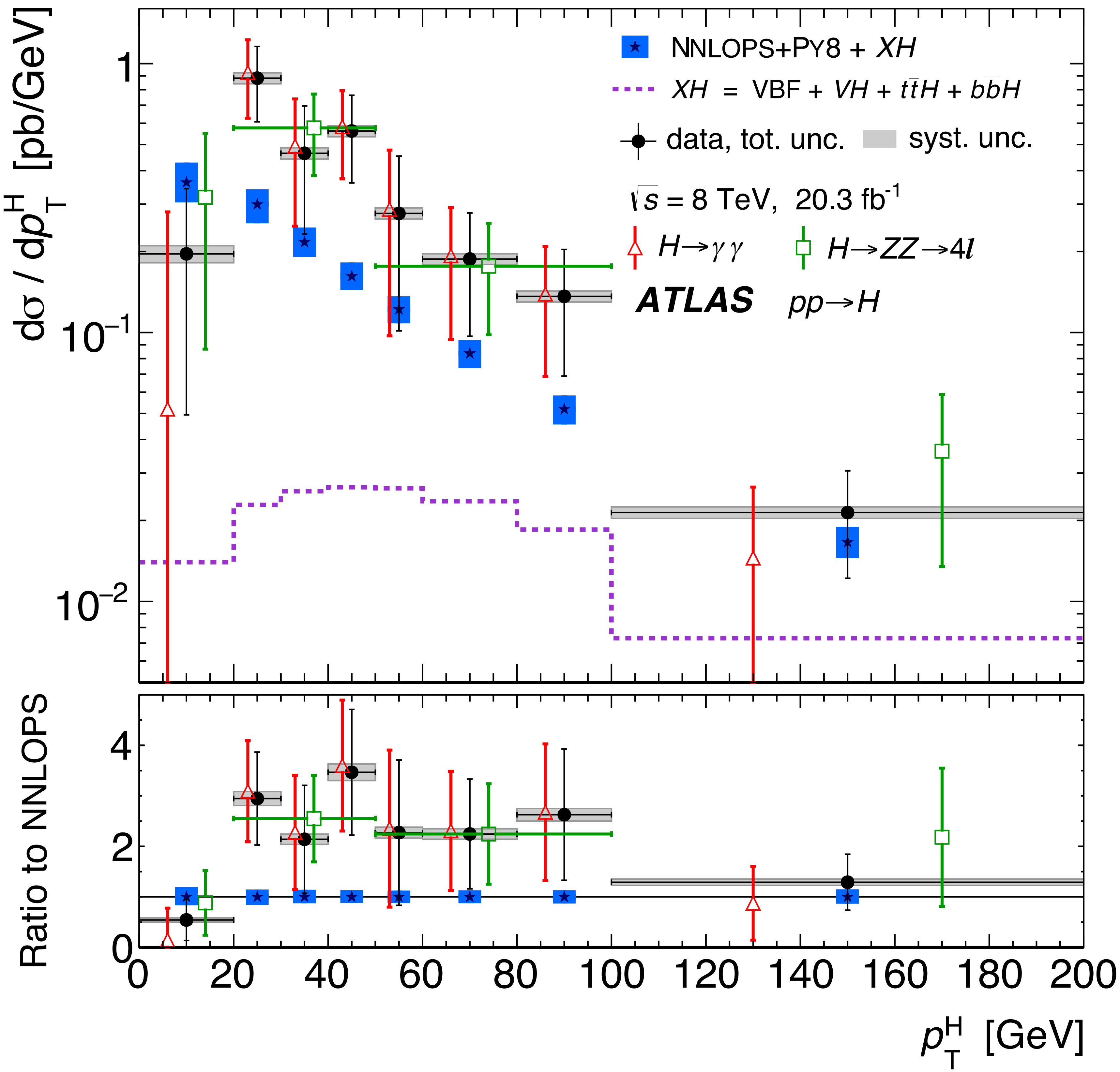
Expect one event in the signal region (a window around 125 GeV).
Observe 4 events (!)

$\gamma\gamma$ + $ZZ \to 4l$ combined

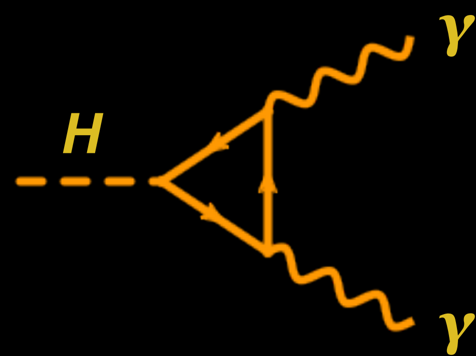
- Combination of the two spectra from the previous page
- Red = $\gamma\gamma$
  Green = $ZZ \to 4l$
  Black = combined
- γγ and ZZ are independent datasets, still very good (surprisingly good) agreement

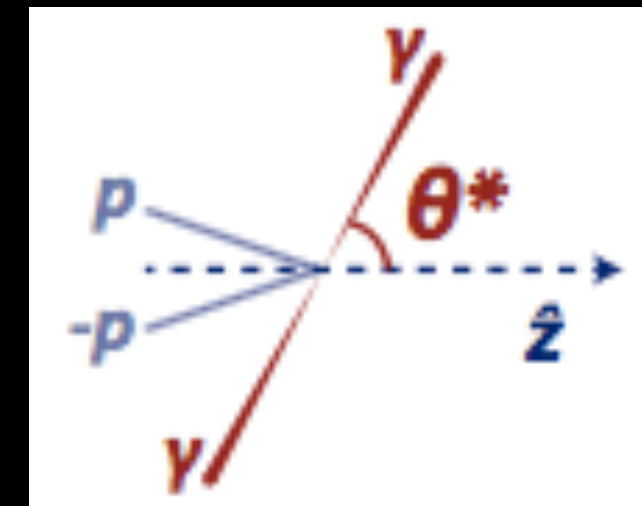
$$\sigma_i = \frac{n_i}{\mathcal{L}\, c_i\, \alpha_i\, \mathcal{B}}$$

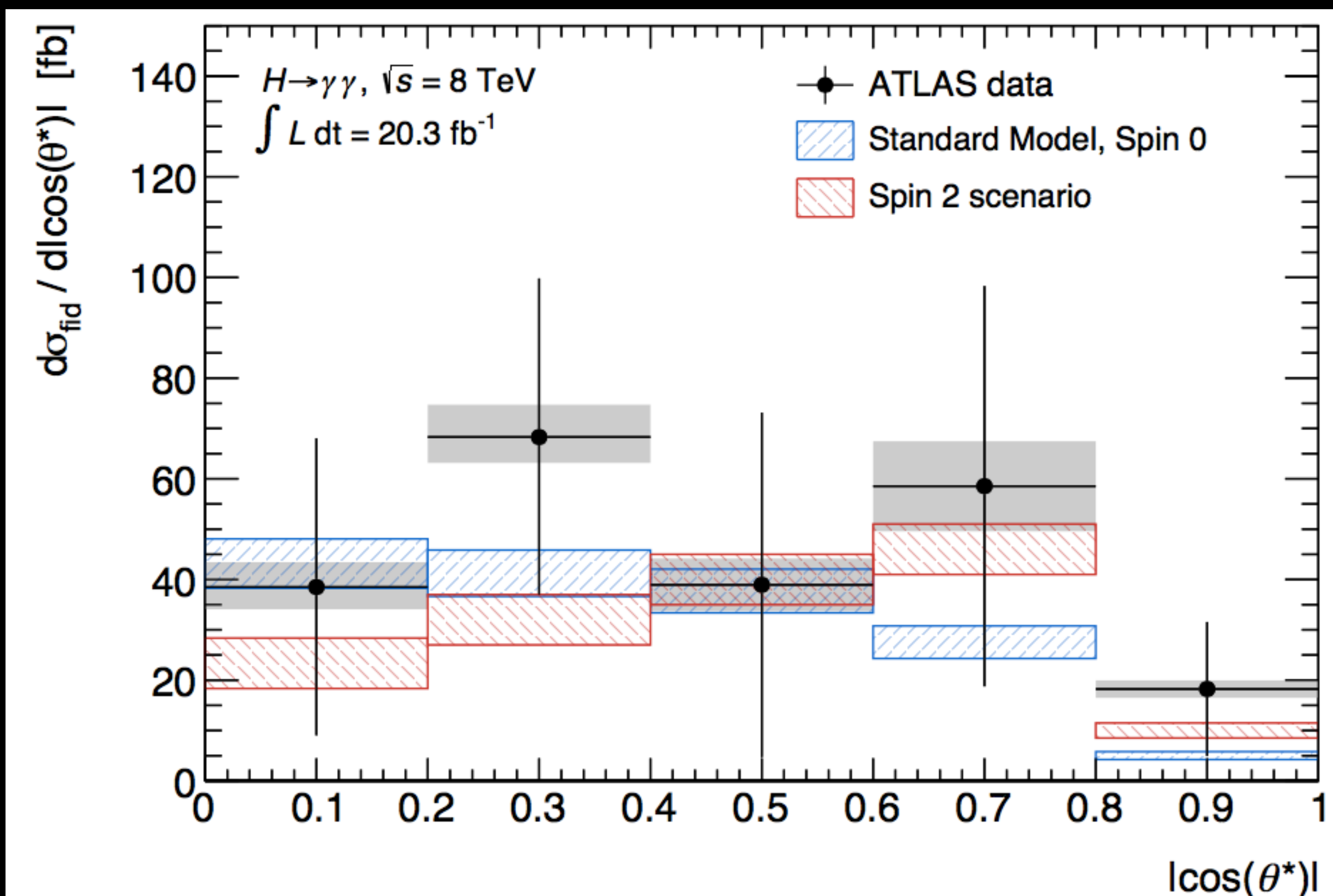




Spin of the Higgs boson







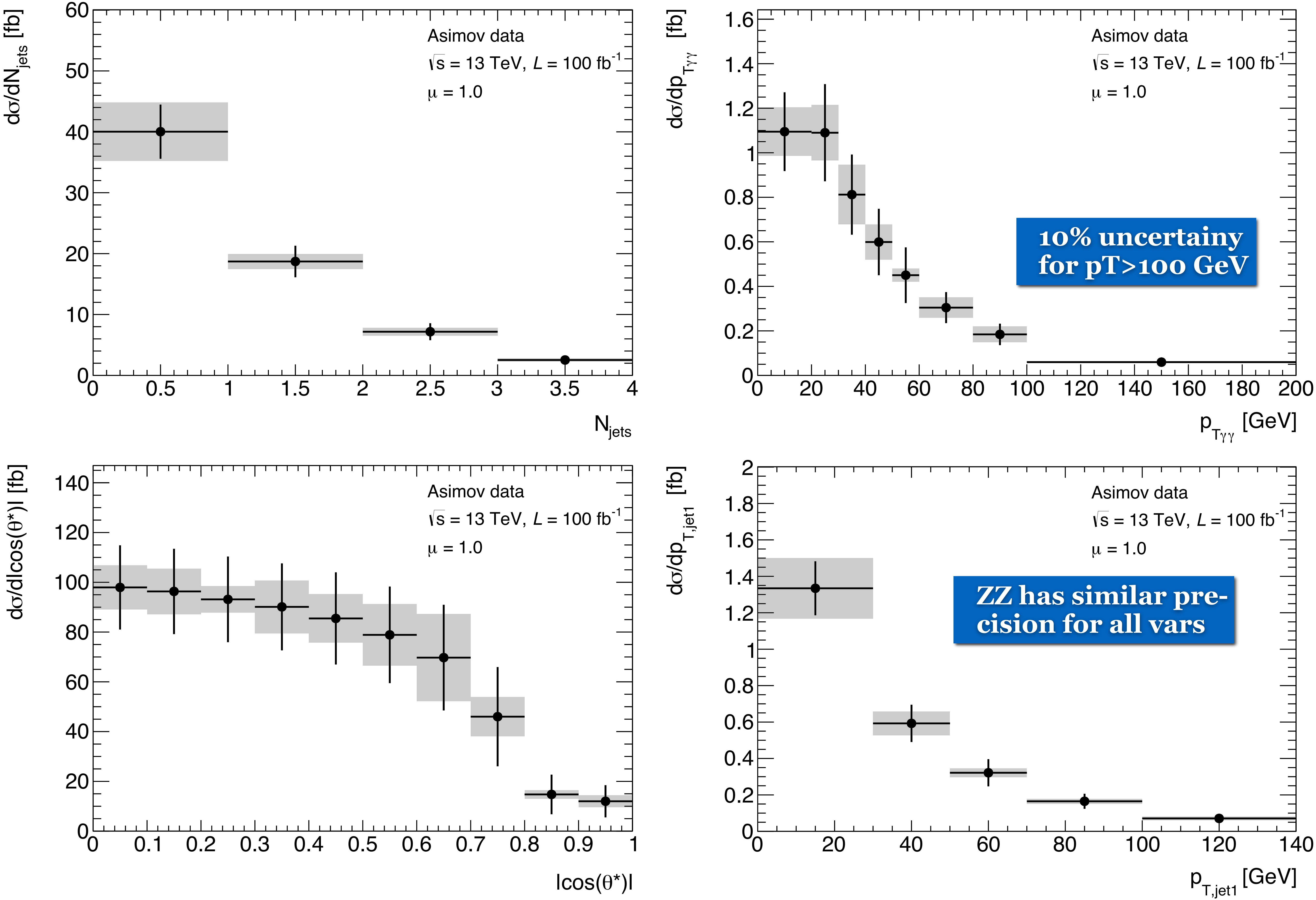
Helicity angel between of the photons in H→γγ

Is the particle we have seen an "imposter" with different spin (or parity)

That would change the helicity angle of the photons produced in the Higgs decay

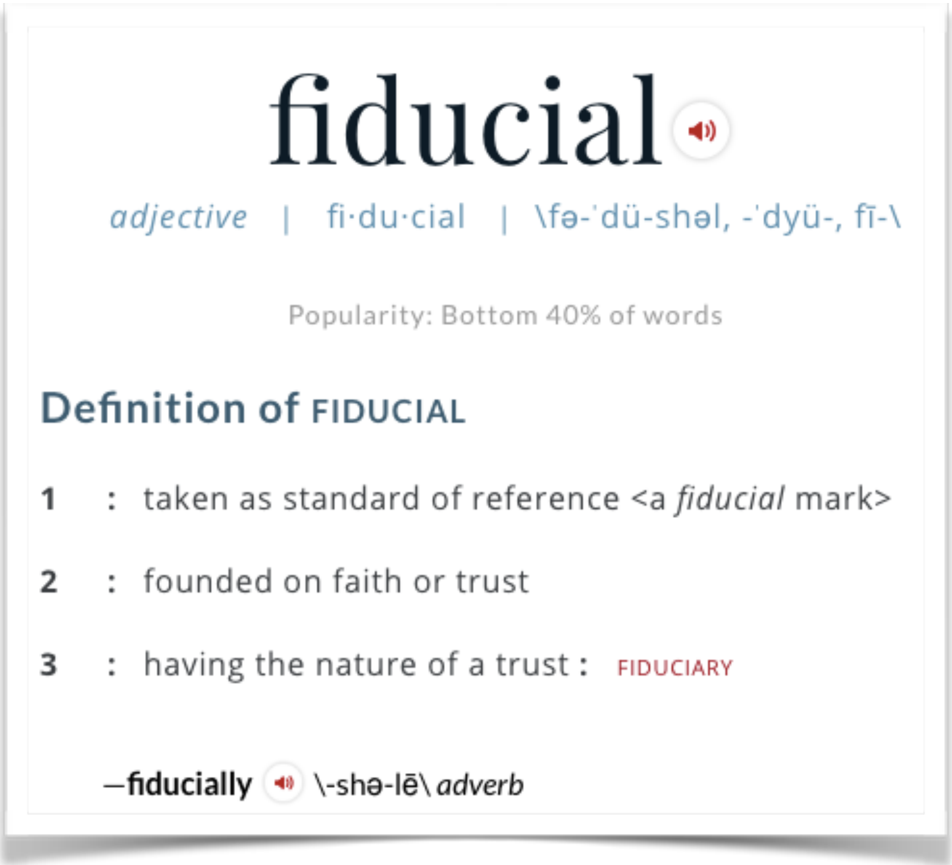
Many tests in the different Higgs decay channels suggest data agree with the Standard Model expectation

Differential cross sections with 100 fb^{-1}



Fiducial cross sections & “unfolding”

- Fiducial cross sections try to avoid extrapolations


fiducial

adjective | fi·du·cial | \fə-ˈdü-shəl, -ˈdyü-, fī-\

Popularity: Bottom 40% of words

Definition of FIDUCIAL

1 : taken as standard of reference <a *fiducial* mark>

2 : founded on faith or trust

3 : having the nature of a trust : FIDUCIARY

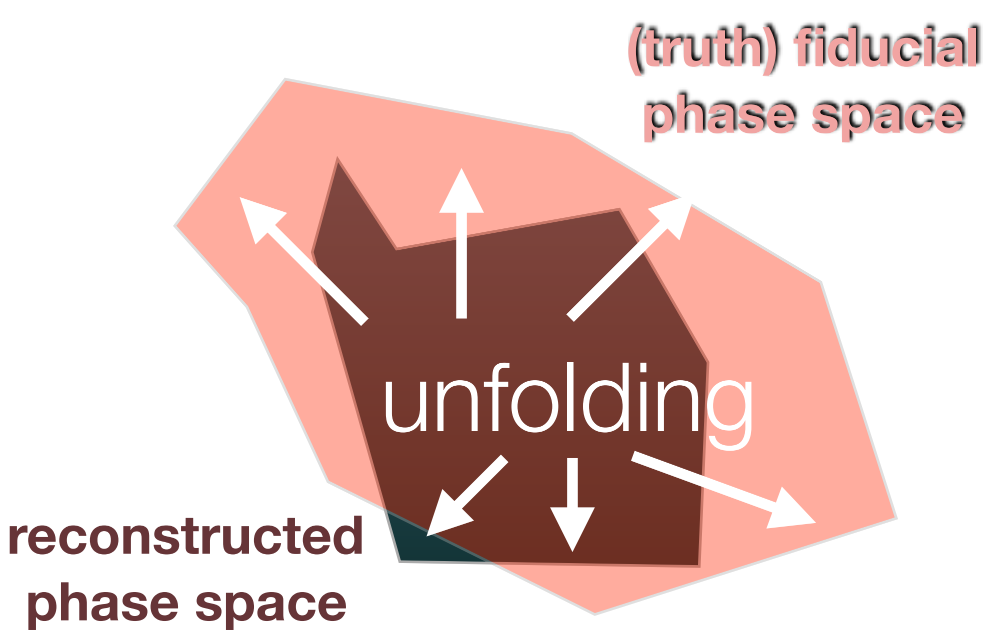
—**fiducially** \-shə-lē\ *adverb*

In particle physics

a fiducial cross-section is a cross-section measured only for the fiducial region, a clearly defined region in phase-space in which the detector operates with high efficiency, without extrapolating to regions where the experiment has no sensitivity.

The fiducial region are defined from the stable “truth” particles from the MC event record. Corresponds to what a perfect detector would see

$H \to \gamma\gamma$ fiducial definition
2 photons with $|\eta|<2.37$
$p_{T\gamma 1} / m_{\gamma\gamma} > 0.35$
$p_{T\gamma 2} / m_{\gamma\gamma} > 0.25$



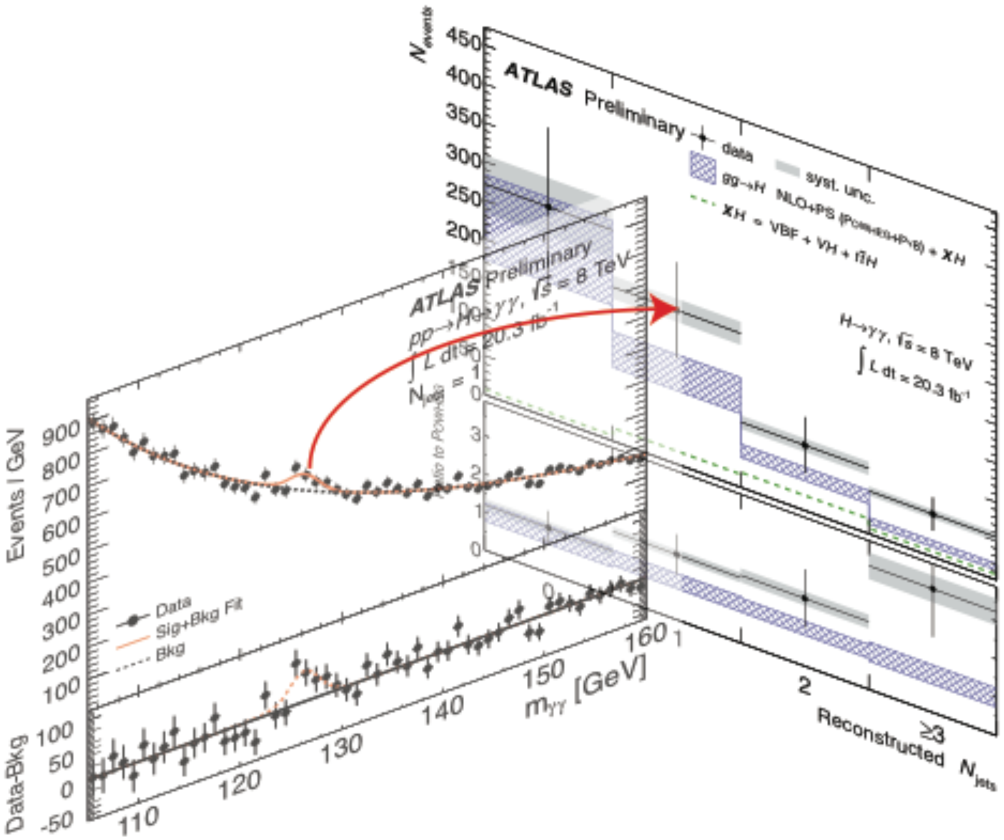
The fiducial region is selected to correspond to the analysis selection (see above). The yields measured in data need to be corrected for detector effect (inefficiencies). This is called ***unfolding***.

➡ *Some things are harder to unfold than others*

Side from Florian Bernlochner

Differential cross section measurement overview

1. Signal extraction



a) Spit dataset into bins of variable of interest (here 4 N_{jets} bins)

b) For each bin, extract s from a s+b fit to the $m_{\gamma\gamma}$ spectra

c) Large statistical uncertainty due to small s/b

2. Unfold to particle level

and divide by integrated luminosity and bin-width

$$\sigma_{\text{fid}} = \frac{n_{\text{sig},i}}{c_i \, \mathcal{L}_{\text{int}}}$$

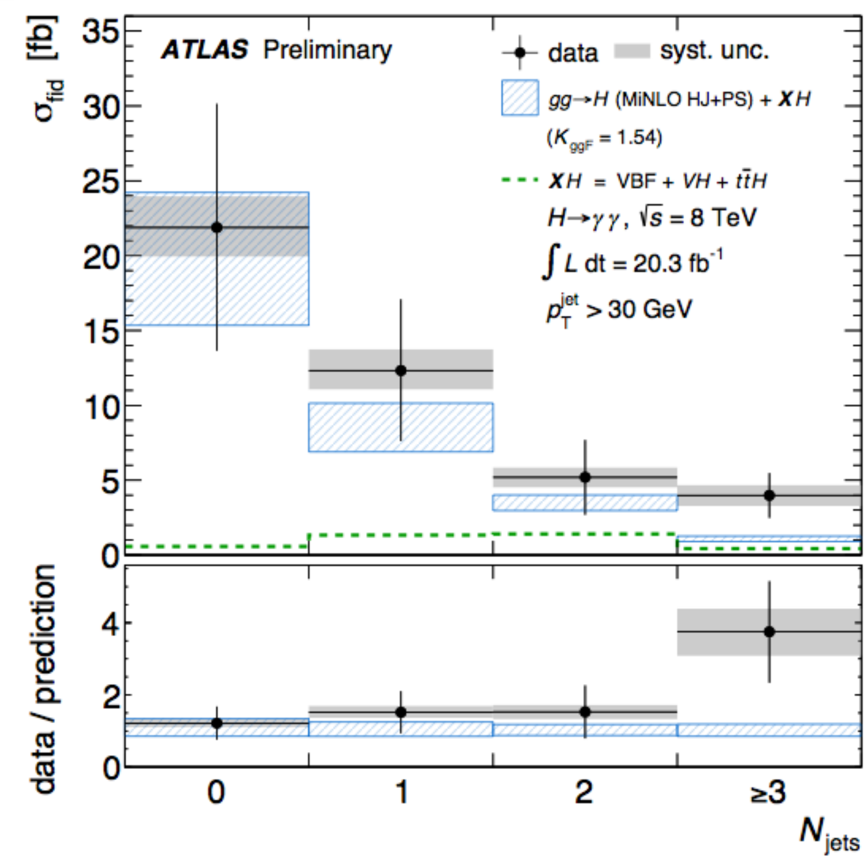
correction factor for detector effects

20.3 fb^{-1} (±2.8%)

a) correction for detector effects with bin-by-bin unfolding

b) convert to ("differential") cross section by dividing by int. lumi (and bin-width)

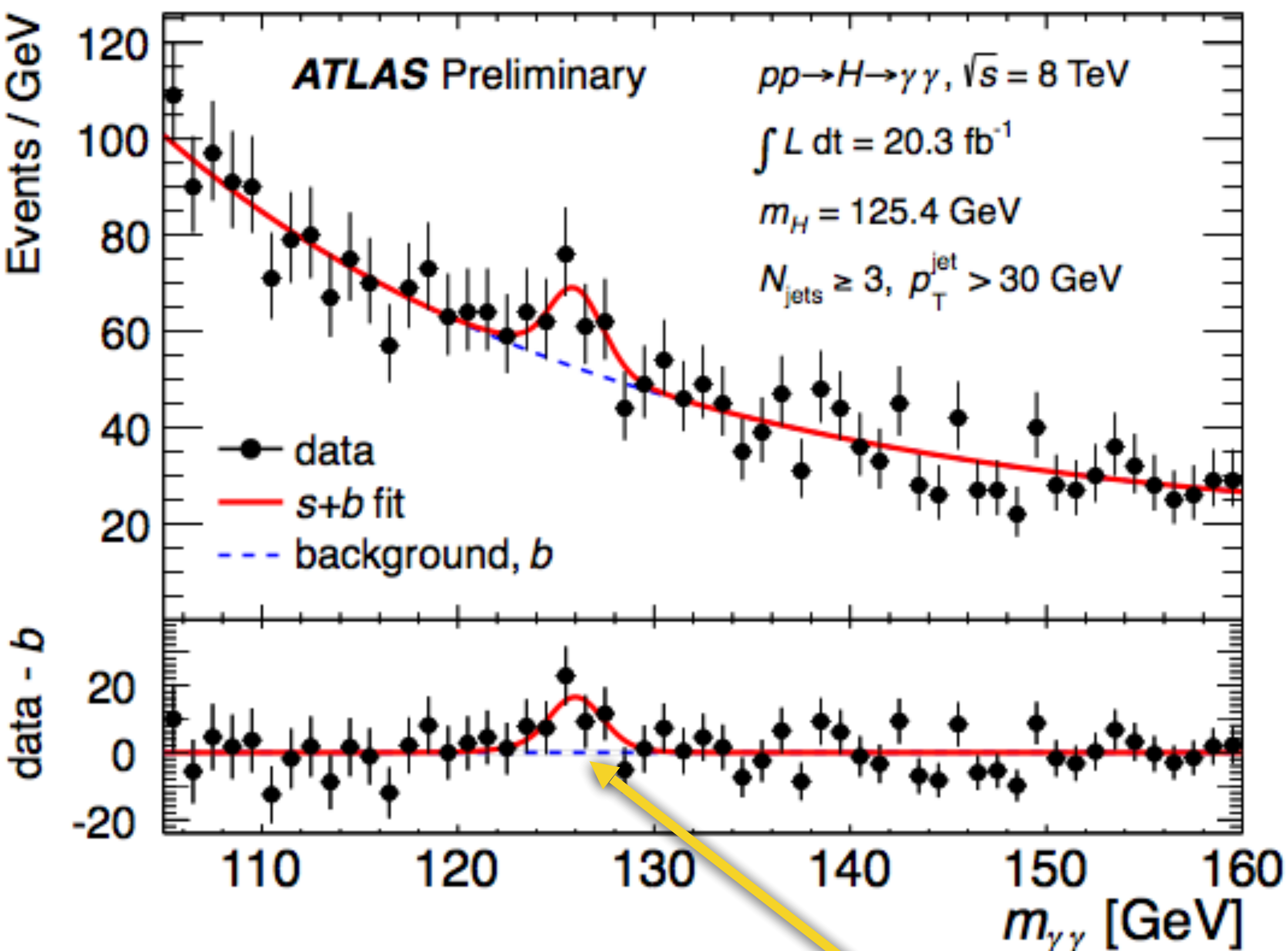
3. Plot and compare with theory

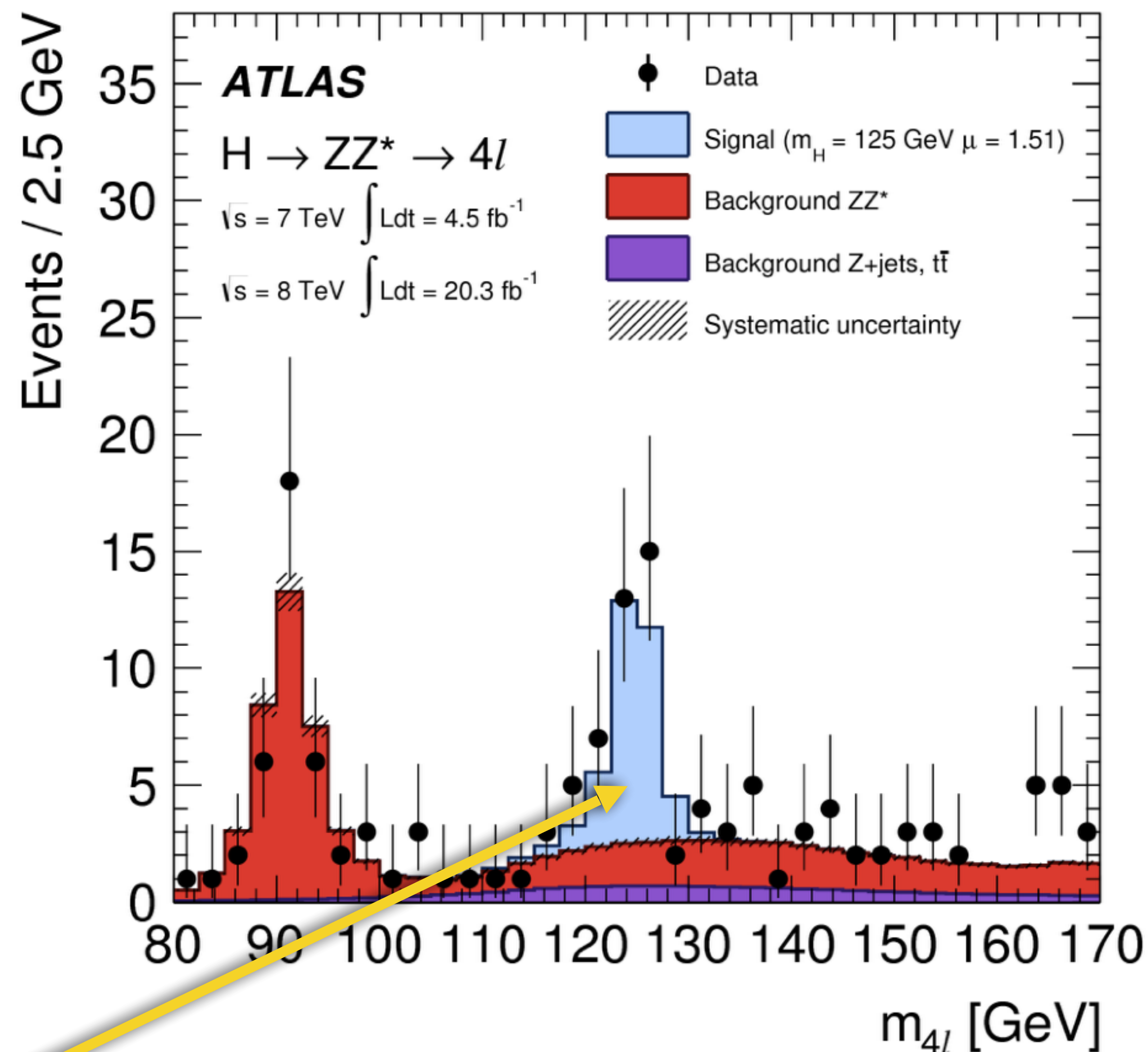


a) compare to **particle level** prediction - i.e. no need for detector simulation

b) Can also compare with analytical calculations (parton level) but then need small parton→particle level (NP) correction

Signal extraction $\gamma\gamma$





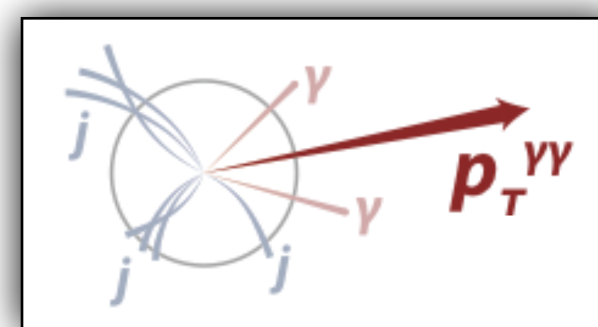
$$\sigma_{\text{fid}} = \frac{n_{\text{sig},i}}{c_i \; \mathcal{L}_{\text{int}}}$$

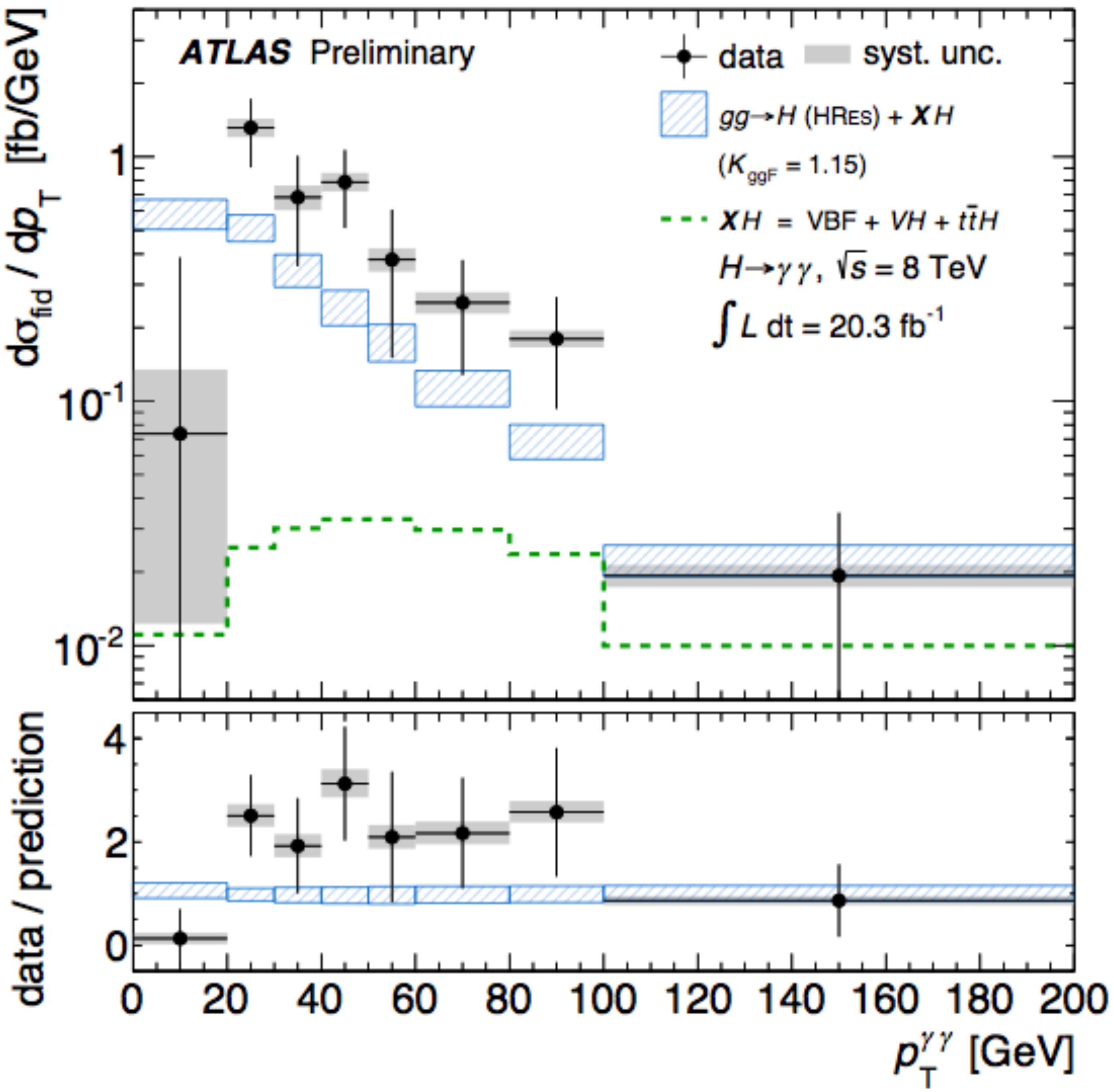
correction factor for detector effects

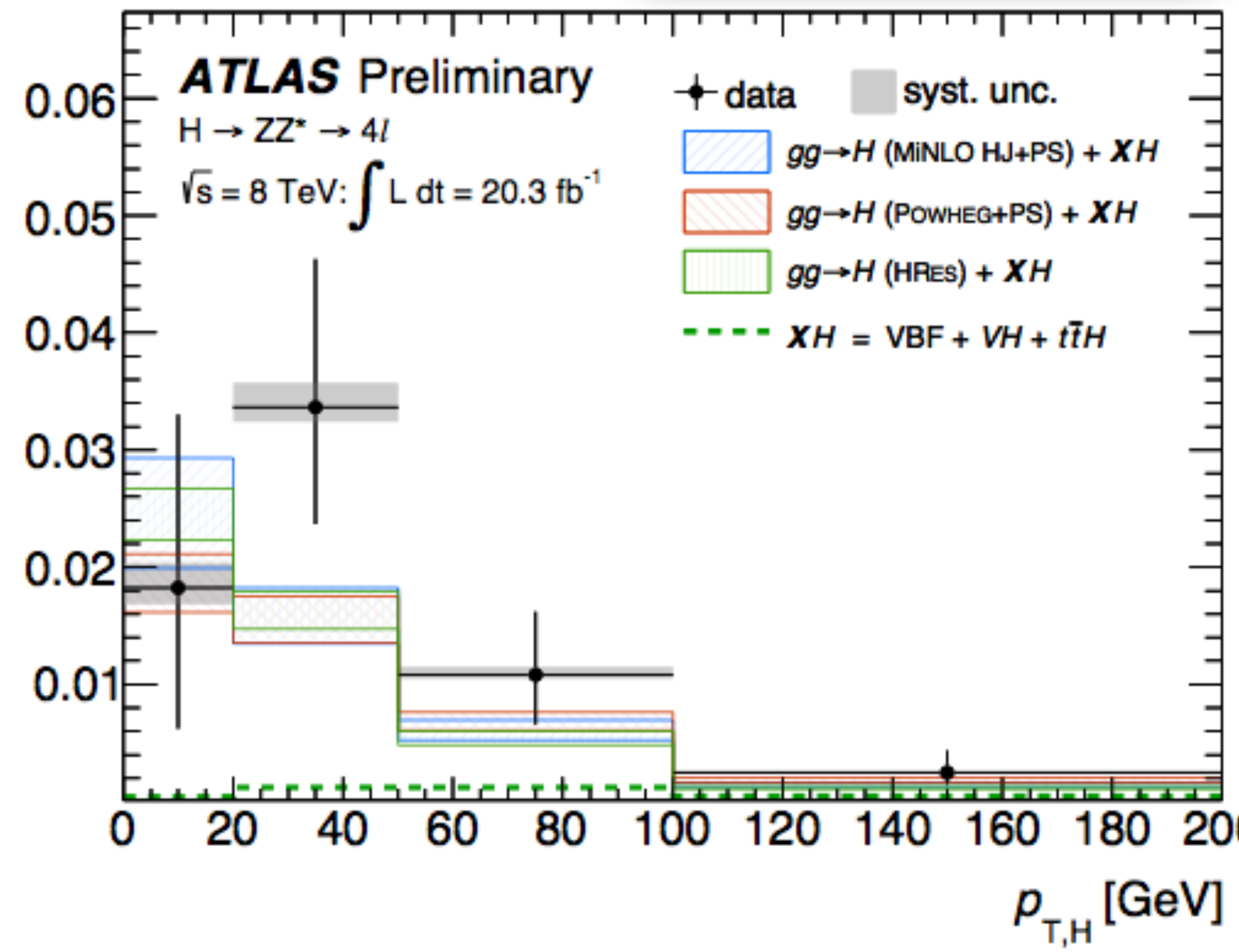
20.3 fb^{-1} (±2.8%)

Transverse momentum

- Differential cross sections as a function of transverse momentum of the Higgs-like resonance compared with theory for the γγ (left) and ZZ (right) fiducial regions







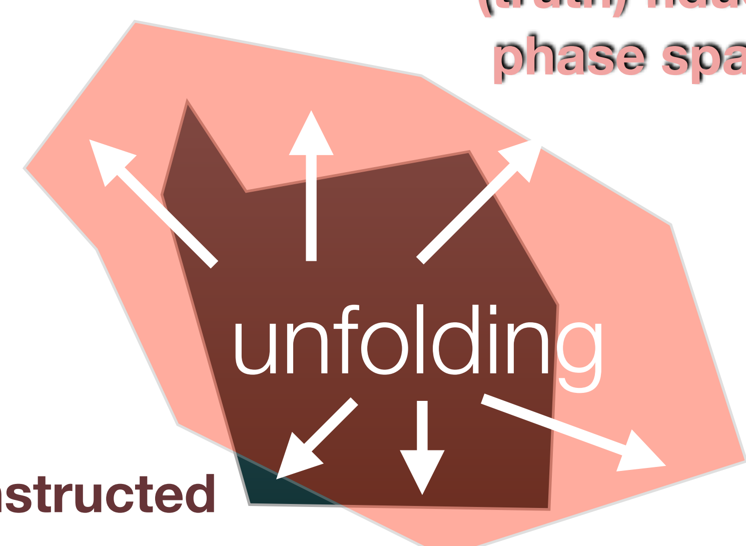
Consistent with SM theory predictions

p-values 0.09-0.12 (γγ) 0.16-0.30 (ZZ)

Extrapolation to the inclusive phase space

- In principle one can also extrapolate the fiducial cross sections to the fully inclusive region.
  - Ok, given what we just discussed — why would you want to do that?
    - Not model independent, but still less model dependent than coupling measurements.
    - Can combine differential quantities with different channels, e.g. *H to four leptons*
    - Mostly account for object (photons, leptons) acceptance, i.e. more tied to objects than production specifics.

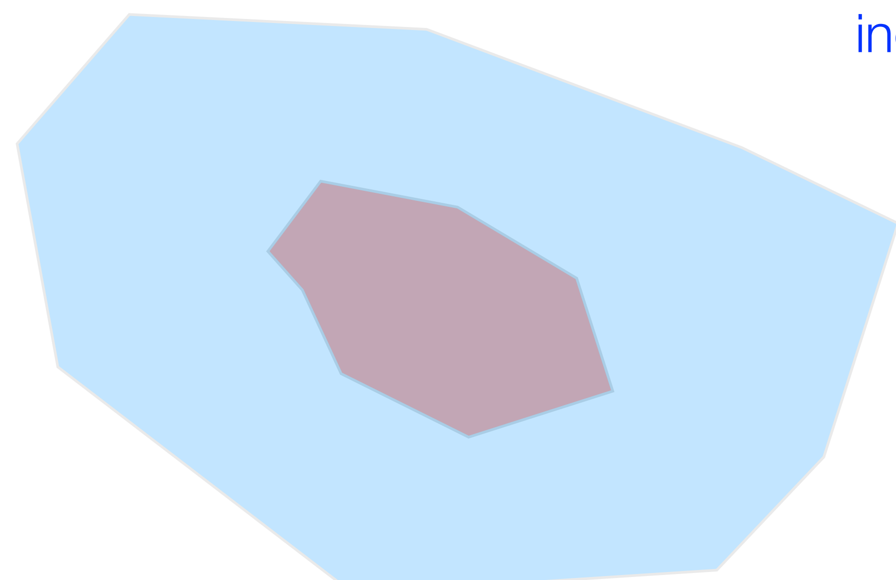
e.g. H→γγ



$$\sigma_i = \frac{n_i}{\mathcal{L}\, c_i}$$

Fiducial cross section

all of Higgs production!



Inclusive cross section

$$\sigma_i = \frac{n_i}{\mathcal{L}\, c_i \boxed{\alpha_i\, \mathcal{B}}}$$

Side from Florian Bernlochner

Extrapolation to the inclusive phase space

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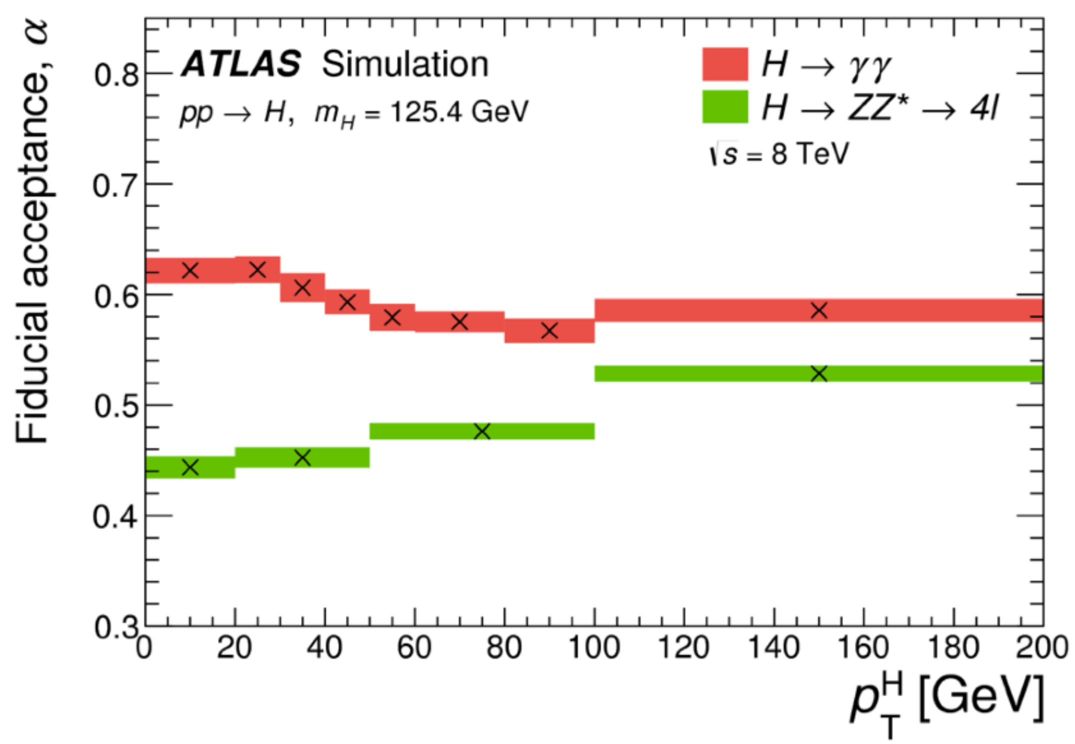
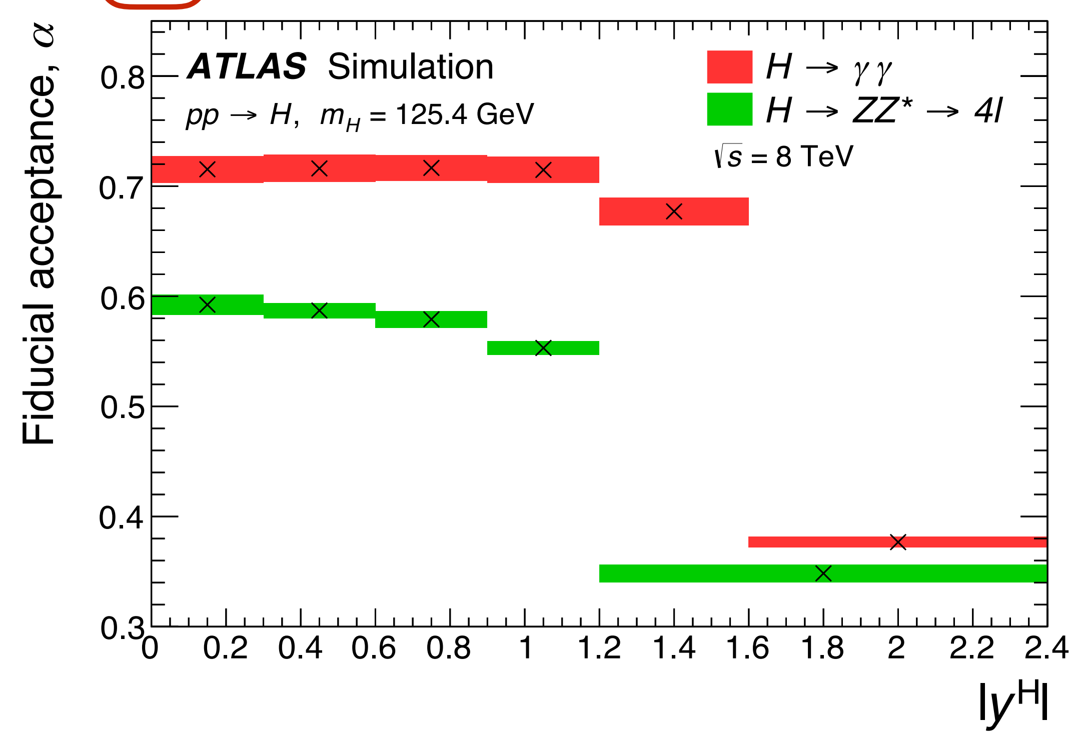
$$\sigma_i = \frac{n_i}{\mathcal{L}\, c_i\, \boxed{\alpha_i}\, \mathcal{B}}$$

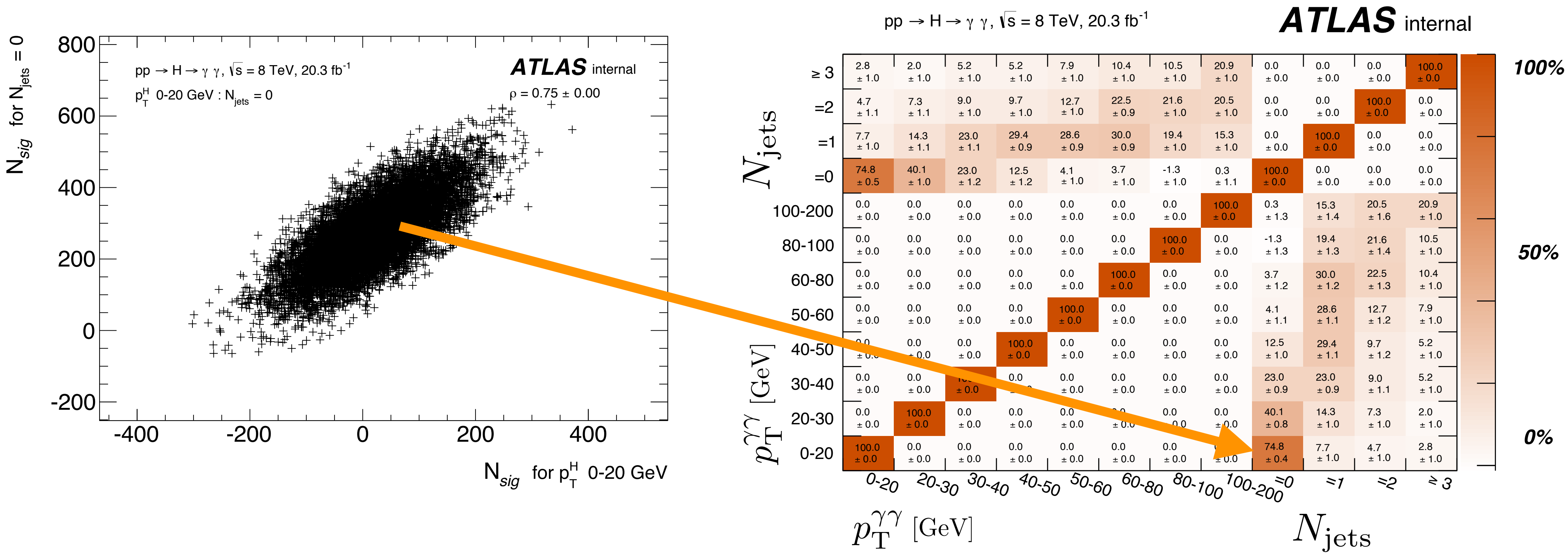




Side from Florian Bernlochner

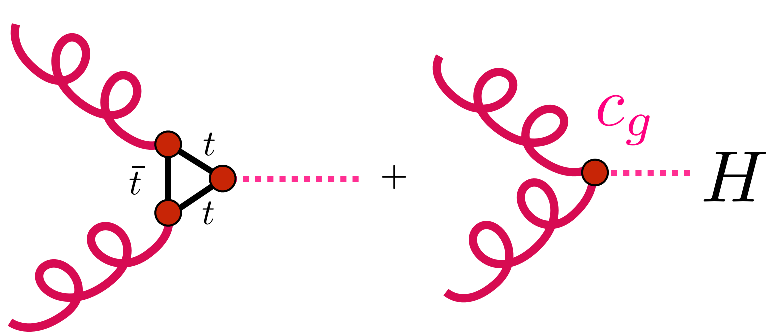
Statistical correlations between distributions

Can be estimated using a bootstrap method:



*Can use all kinematic distributions in a combined analysis and probe for **New Physics**:*

SM *NP*



$$\mathcal{L} = \bar{c}_\gamma O_\gamma + \bar{c}_g O_g + \bar{c}_{HW} O_{HW} + \bar{c}_{HB} O_{HB}$$
$$+ \tilde{c}_\gamma \tilde{O}_\gamma + \tilde{c}_g \tilde{O}_g + \tilde{c}_{HW} \tilde{O}_{HW} + \tilde{c}_{HB} \tilde{O}_{HB},$$

Effective Field Theory Analysis of differential cross sections

- Effective Field theory:

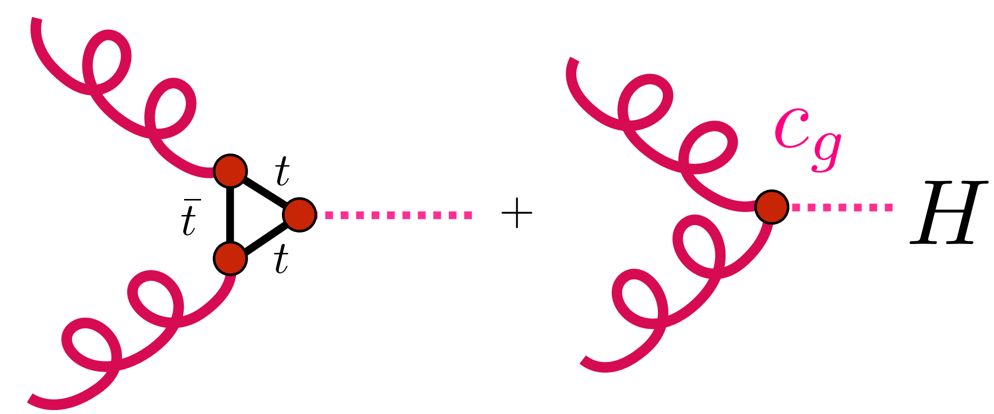
arXiv:1303.3876
arXiv:hep-ph/0703164

Strongly Interacting Light Higgs

➡ Extends SM by adding point-like interactions

$$\mathcal{L} = \bar{c}_\gamma O_\gamma + \bar{c}_g O_g + \bar{c}_{HW} O_{HW} + \bar{c}_{HB} O_{HB} + \tilde{c}_\gamma \tilde{O}_\gamma + \tilde{c}_g \tilde{O}_g + \tilde{c}_{HW} \tilde{O}_{HW} + \tilde{c}_{HB} \tilde{O}_{HB},$$

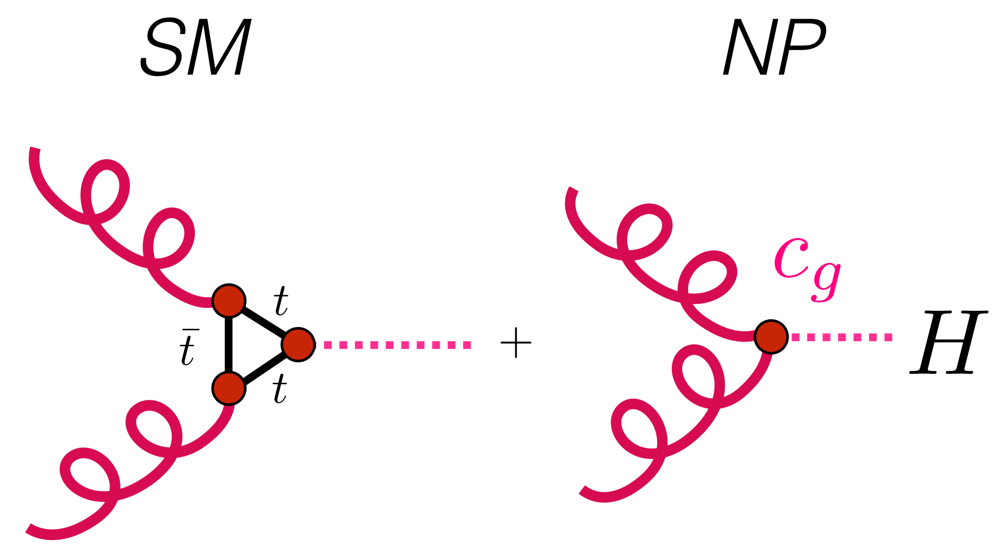
SM NP

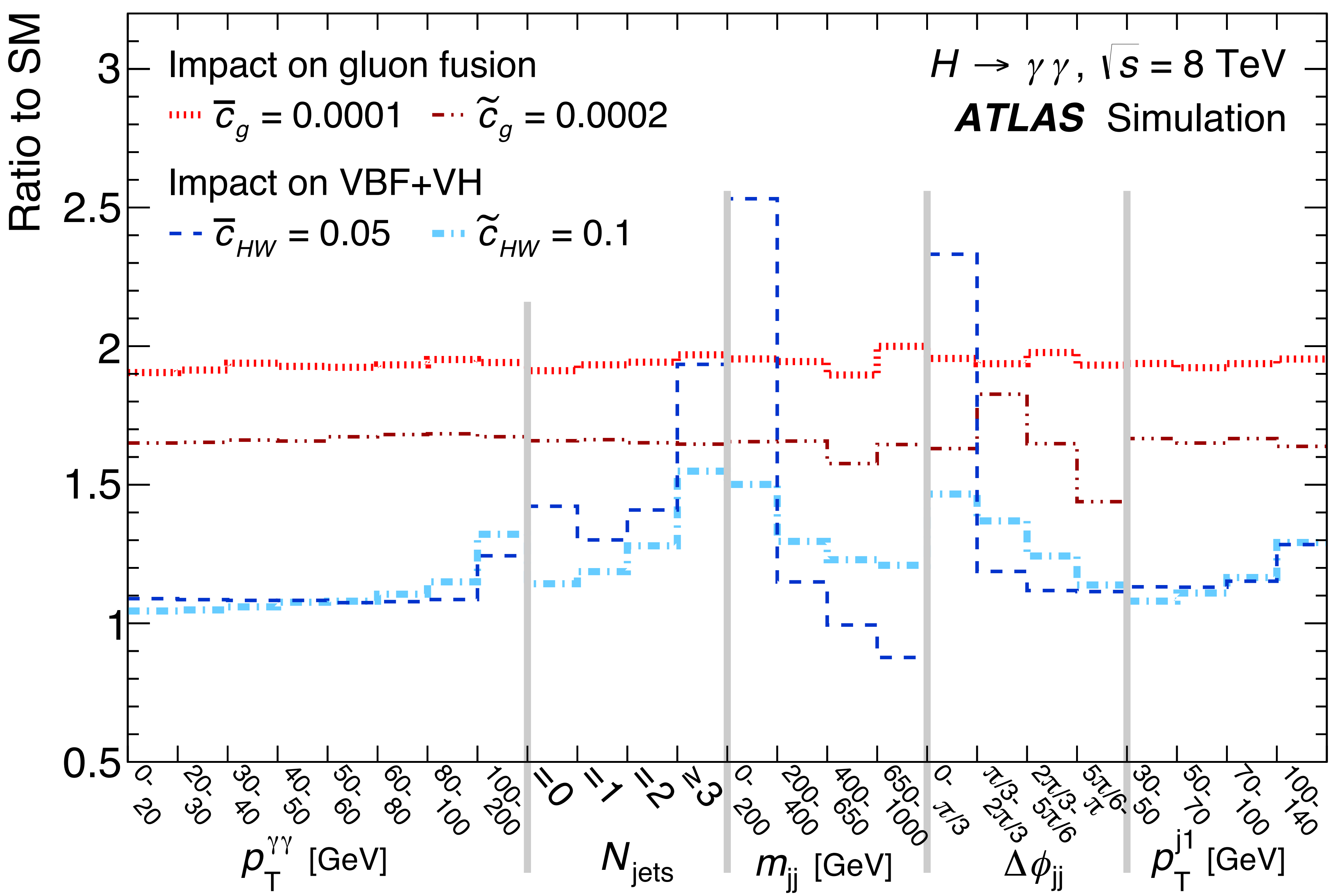


Effective Field Theory Analysis of differential cross sections

➡ Extends SM by adding point-like interactions

$$\mathcal{L} = \bar{c}_\gamma O_\gamma + \bar{c}_g O_g + \bar{c}_{HW} O_{HW} + \bar{c}_{HB} O_{HB} + \tilde{c}_\gamma \tilde{O}_\gamma + \tilde{c}_g \tilde{O}_g + \tilde{c}_{HW} \tilde{O}_{HW} + \tilde{c}_{HB} \tilde{O}_{HB},$$

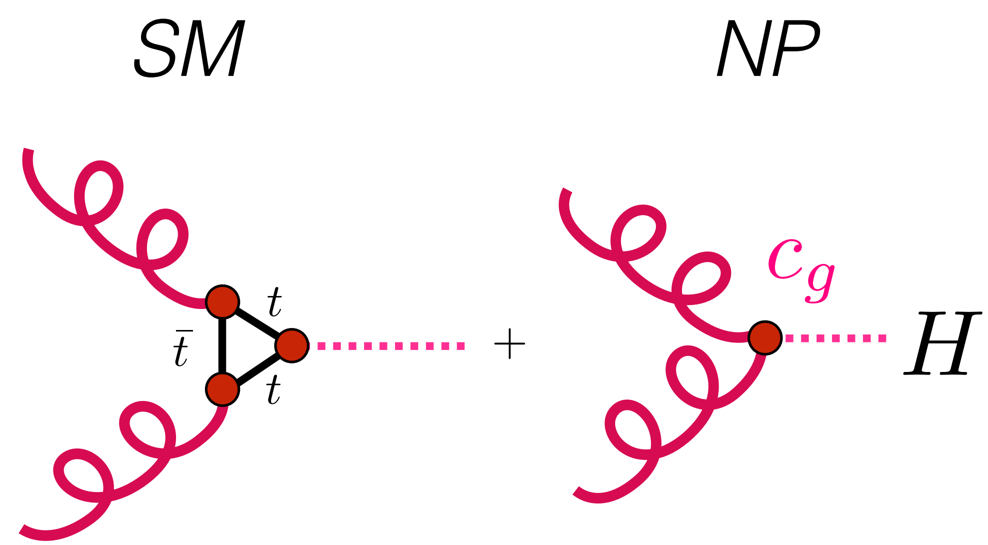


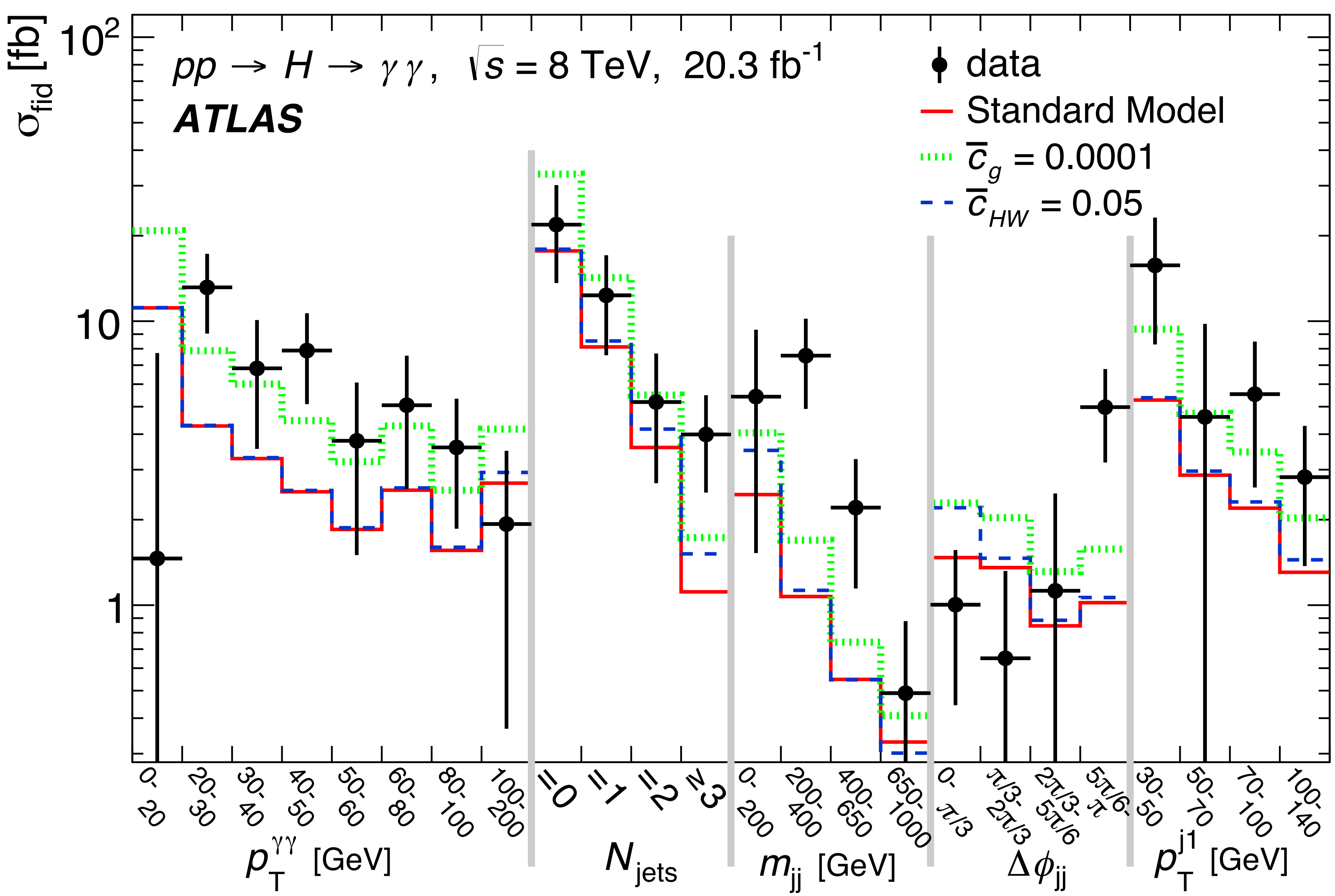


Effective Field Theory Analysis of differential cross sections

➡ Extends SM by adding point-like interactions

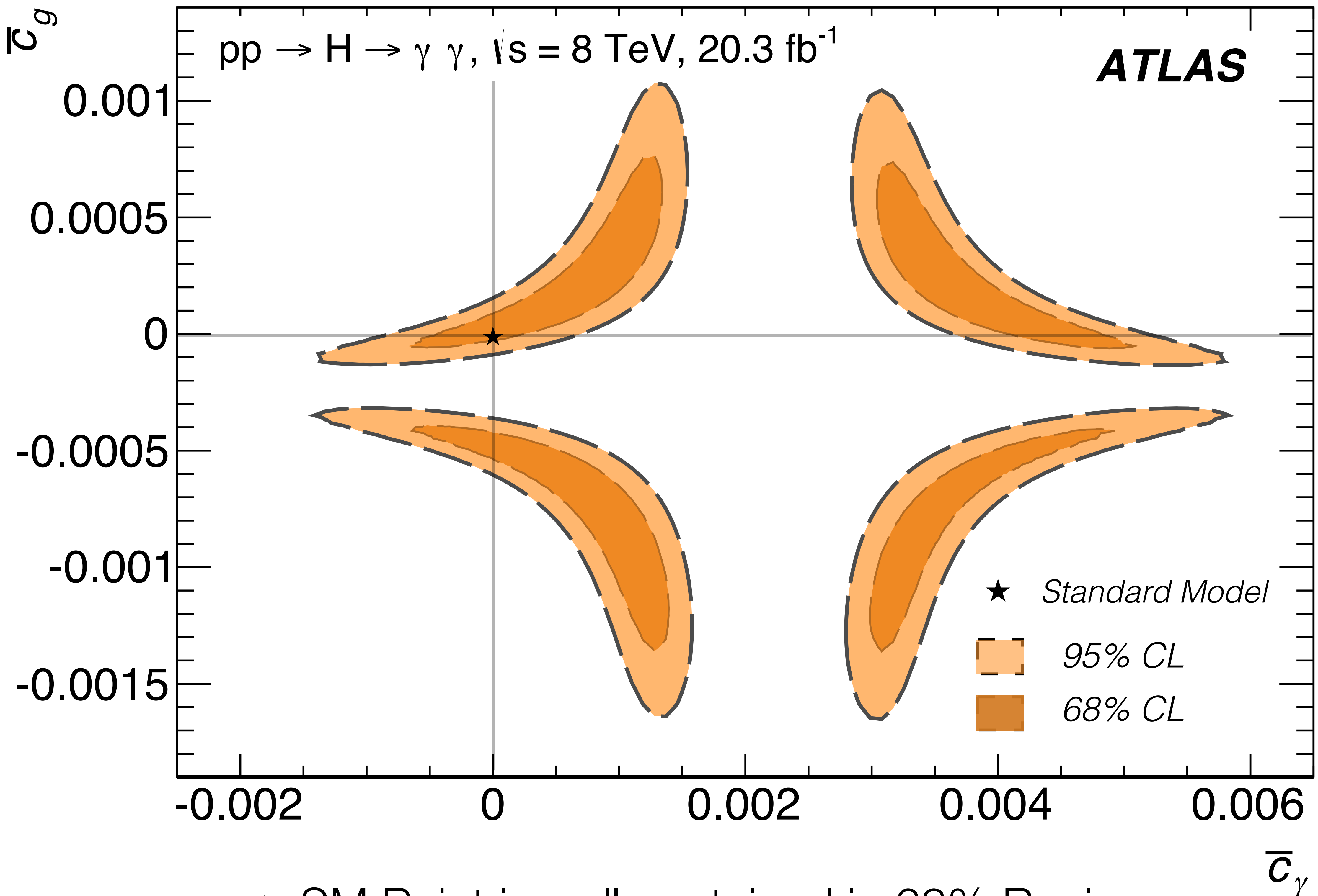
$$\mathcal{L} = \bar{c}_\gamma O_\gamma + \bar{c}_g O_g + \bar{c}_{HW} O_{HW} + \bar{c}_{HB} O_{HB} + \tilde{c}_\gamma \tilde{O}_\gamma + \tilde{c}_g \tilde{O}_g + \tilde{c}_{HW} \tilde{O}_{HW} + \tilde{c}_{HB} \tilde{O}_{HB},$$





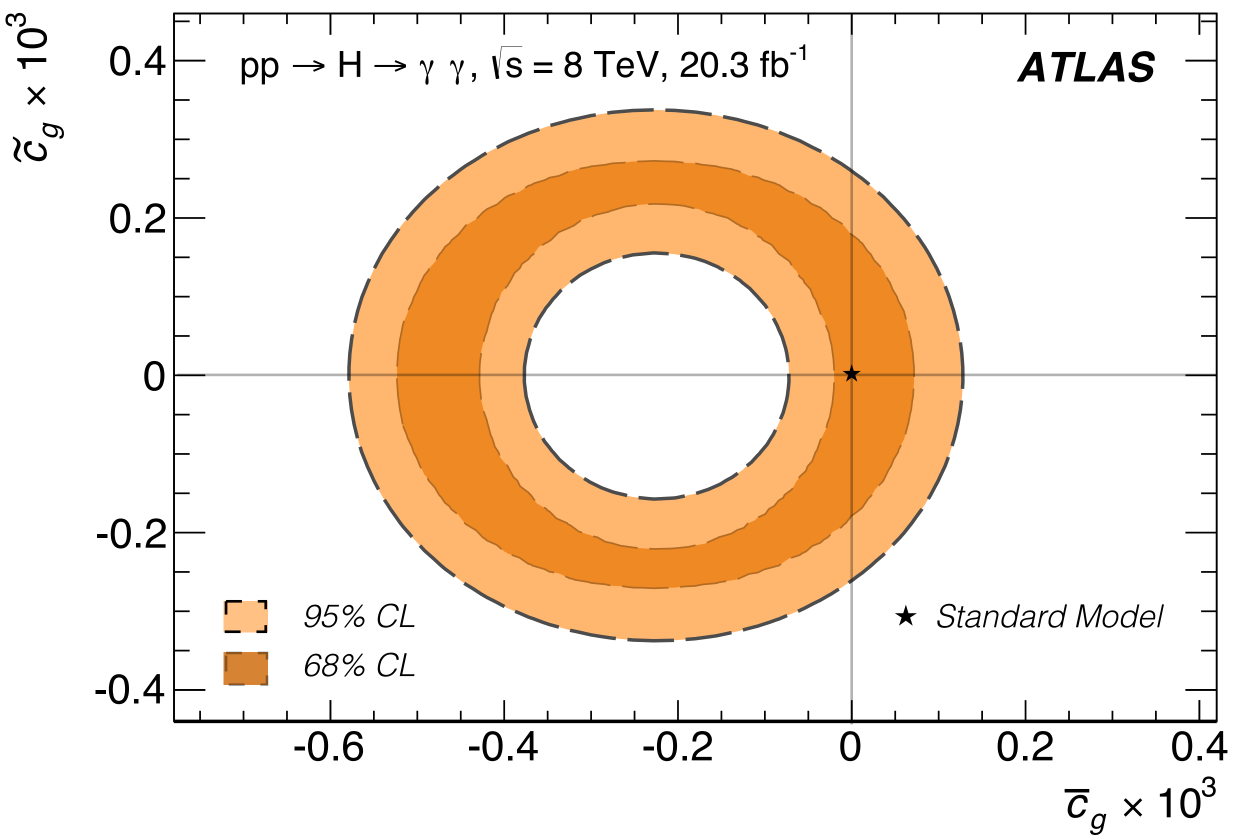
Data points published on HepData
http://arxiv.org/abs/1407.4222
JHEP09(2014)112

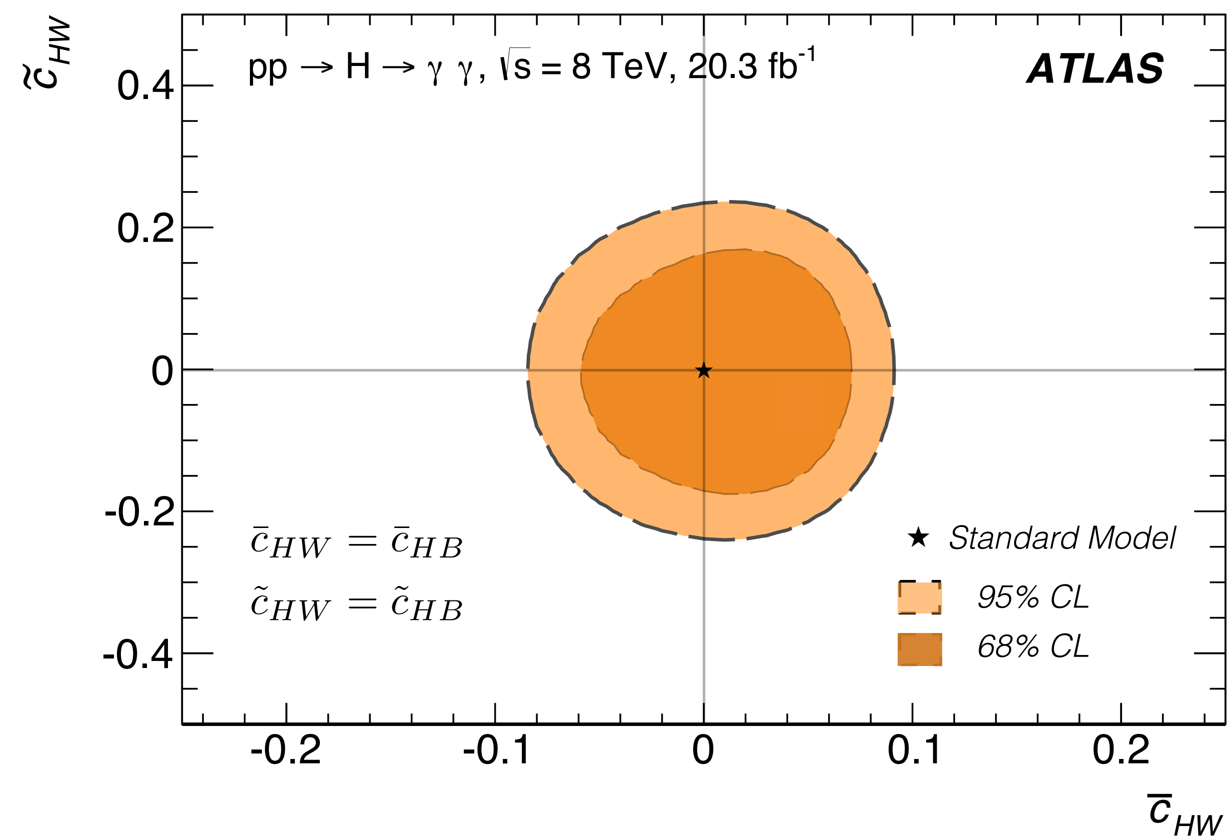
Limits on $\overline{c}_g$ and $\overline{c}_\gamma$



➡ SM Point is well contained in 68% Region

Other operators:

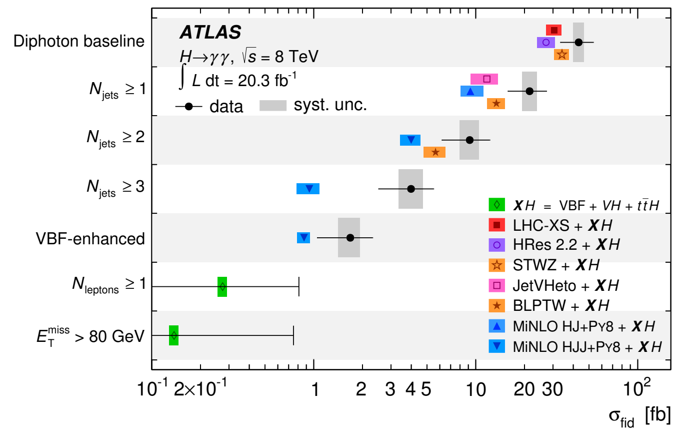


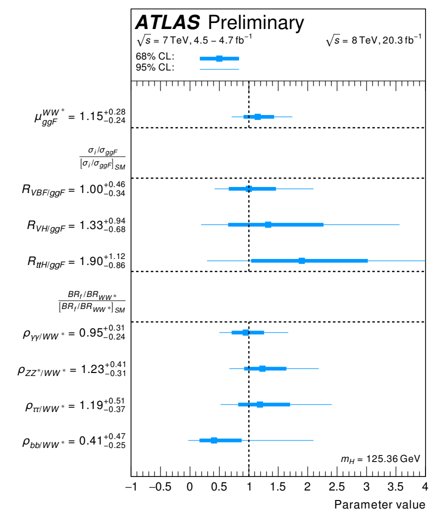


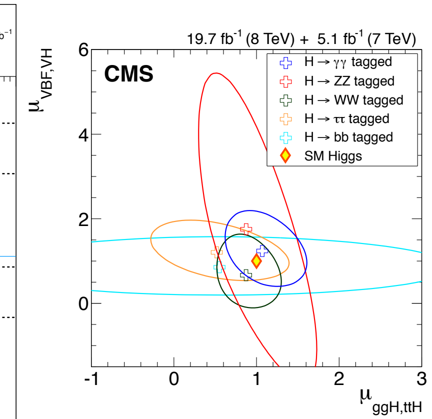
➡ No significant deviation from SM observed.

Coefficient	95% $1 - CL$ limit
$\bar{c}_\gamma$	$[-7.4, 5.7]\times10^{-4} \cup [3.8, 5.1]\times10^{-3}$
$\tilde{c}_\gamma$	$[-1.8, 1.8]\times10^{-3}$
$\bar{c}_g$	$[-0.7, 1.3]\times10^{-4} \cup [-5.8, -3.8]\times10^{-4}$
$\tilde{c}_g$	$[-2.4, 2.4]\times10^{-4}$
$\bar{c}_{HW}$	$[-8.6, 9.2]\times10^{-2}$
$\tilde{c}_{HW}$	$[-0.23, 0.23]$

Run 2: Simplified cross section framework



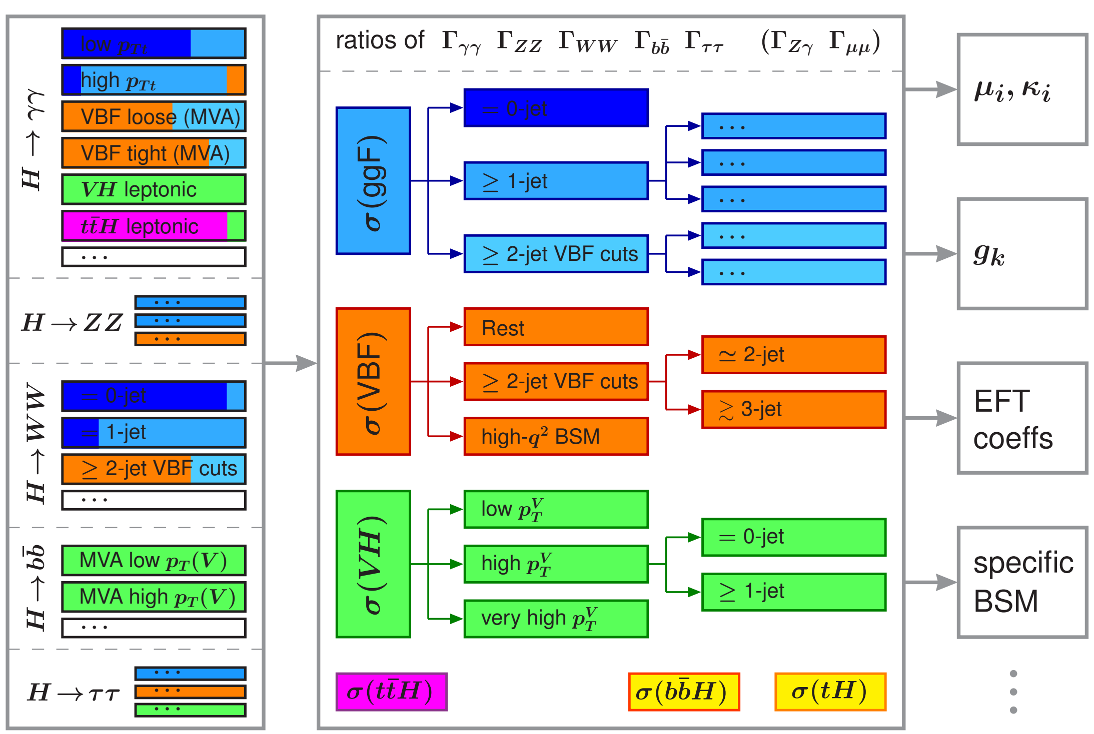


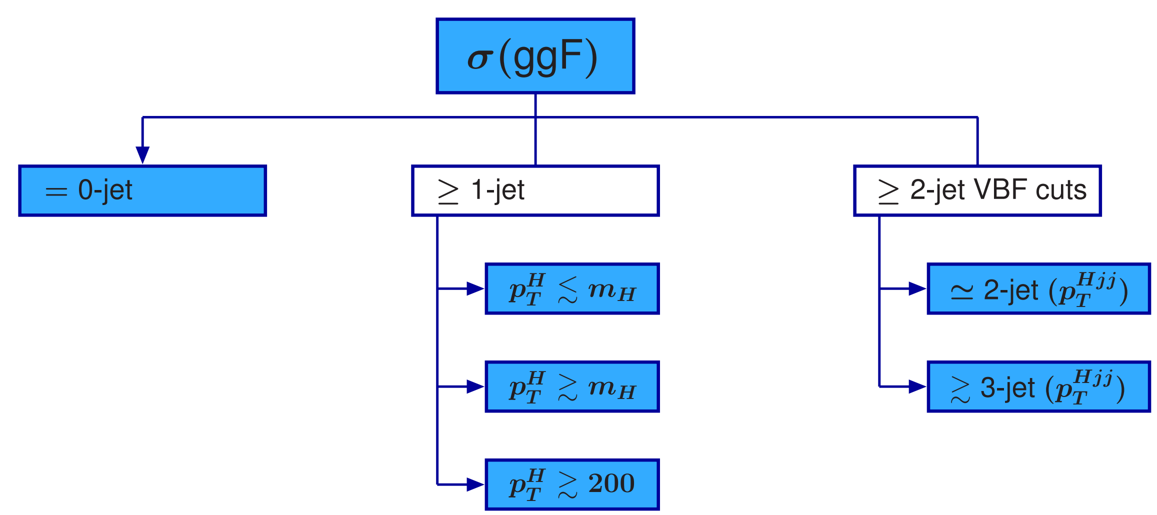


Measurement — Interpretation

theory-independent — *theory-dependent*

Meet somewhere in the middle





Jim Lacey (Carleton) has written a Rivet routine that will act as

LHC HXS WG meeting about fiducial cross sections: https://indico.cern.ch/event/399923/

https://indico.cern.ch/event/399923/session/3/contribution/20/material/slides/0.pdf

High mass "$H \rightarrow \gamma\gamma$"

PHYSICAL REVIEW LETTERS

Theorists React to the CERN 750 GeV Diphoton Data

Last December, the ATLAS and CMS Collaborations at the Large Hadron Collider reported preliminary data with a small excess of diphoton events at an invariant mass of about 750 GeV [1,2], which, if verified, would require unexpected new elementary particles. The collaborations have recently reanalyzed their data [3,4], and the signal has become slightly stronger. Though the results are extremely intriguing, more data are required to establish if the excess is real, or a statistical fluctuation.

Over 250 theory papers have appeared following the December announcement, and a number of them were submitted to us. We found it appropriate to publish a small sample of them. To maximize the coherence and fairness of our choices, we obtained informal advice from several experts.

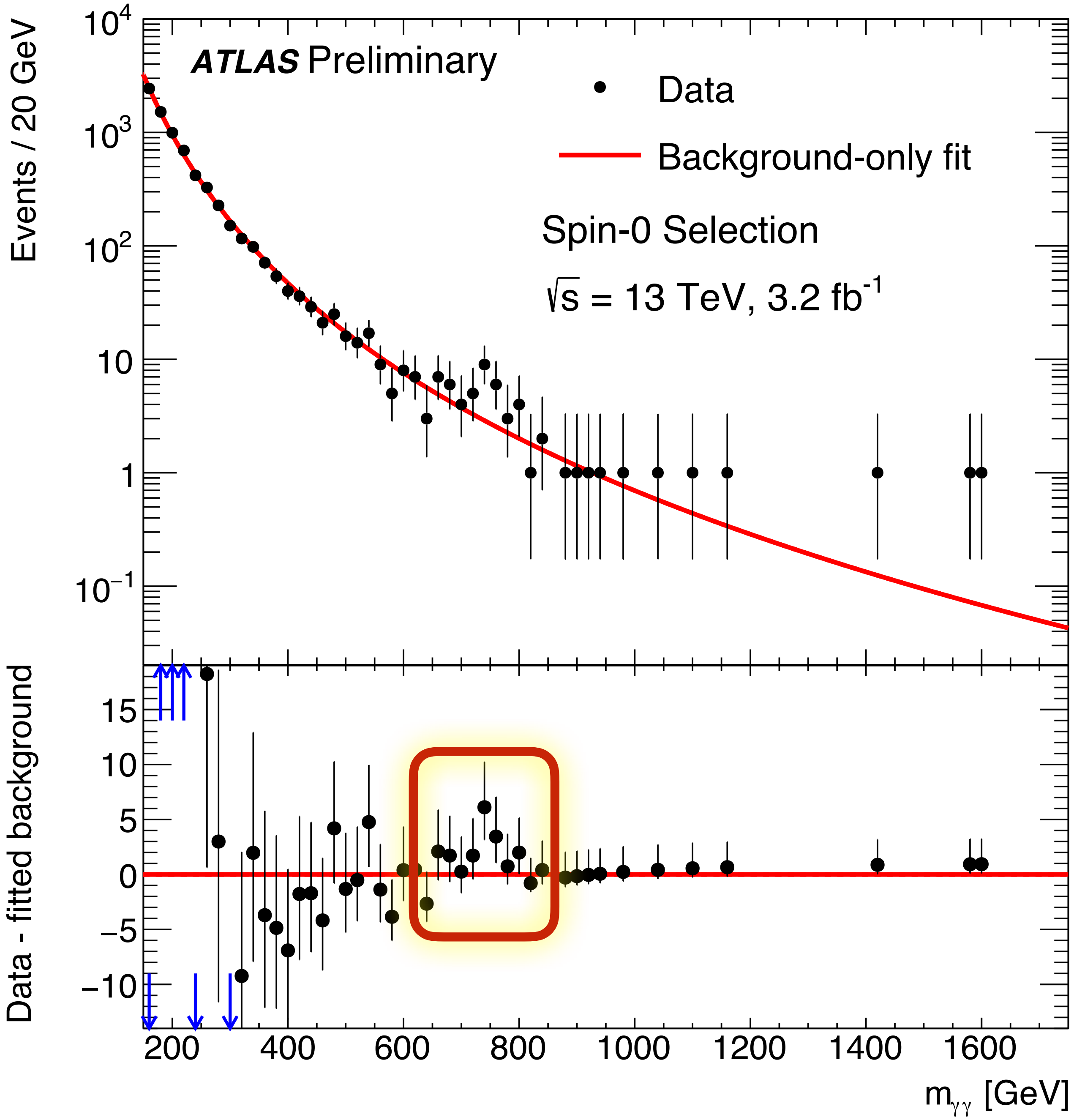
Four such Letters appear in this issue [5–8]. Others may follow, but we think that this set gives readers a sense of the kind of new physics that would be required to explain the data, if confirmed.

Robert Garisto
Editor

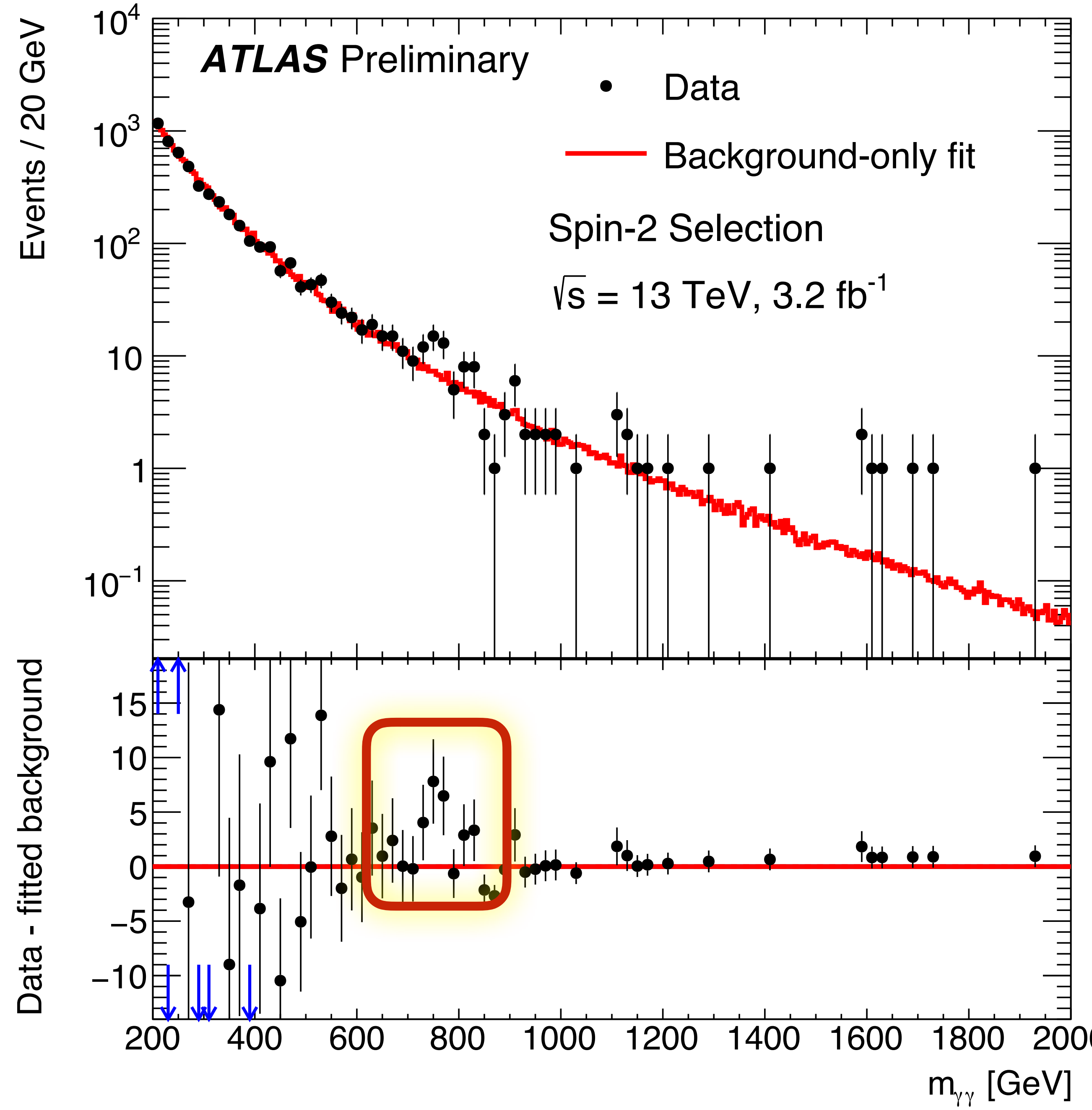
ATLAS Run II results at high $m_{\gamma\gamma}$

Slide from M. Delmastro, Moriond talk

background-only fit



background-only fit

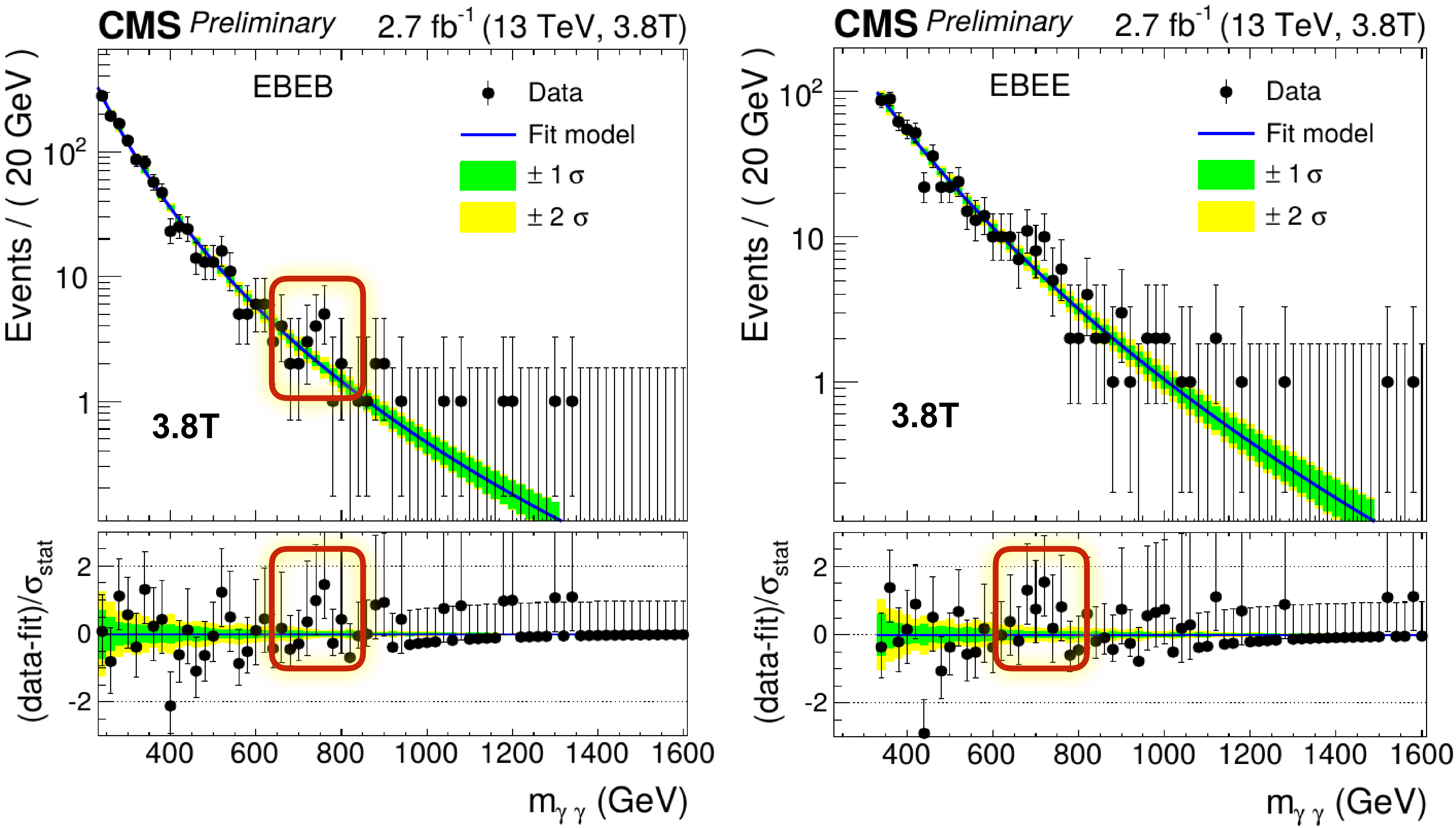


- Largest deviation from B-only hypothesis
  - ✓ m_X ~ 750 GeV, Γ_X ~ 45 GeV (6%)
  - ✓ Local Z = **3.9 σ**
  - ✓ Global Z = **2.0 σ**

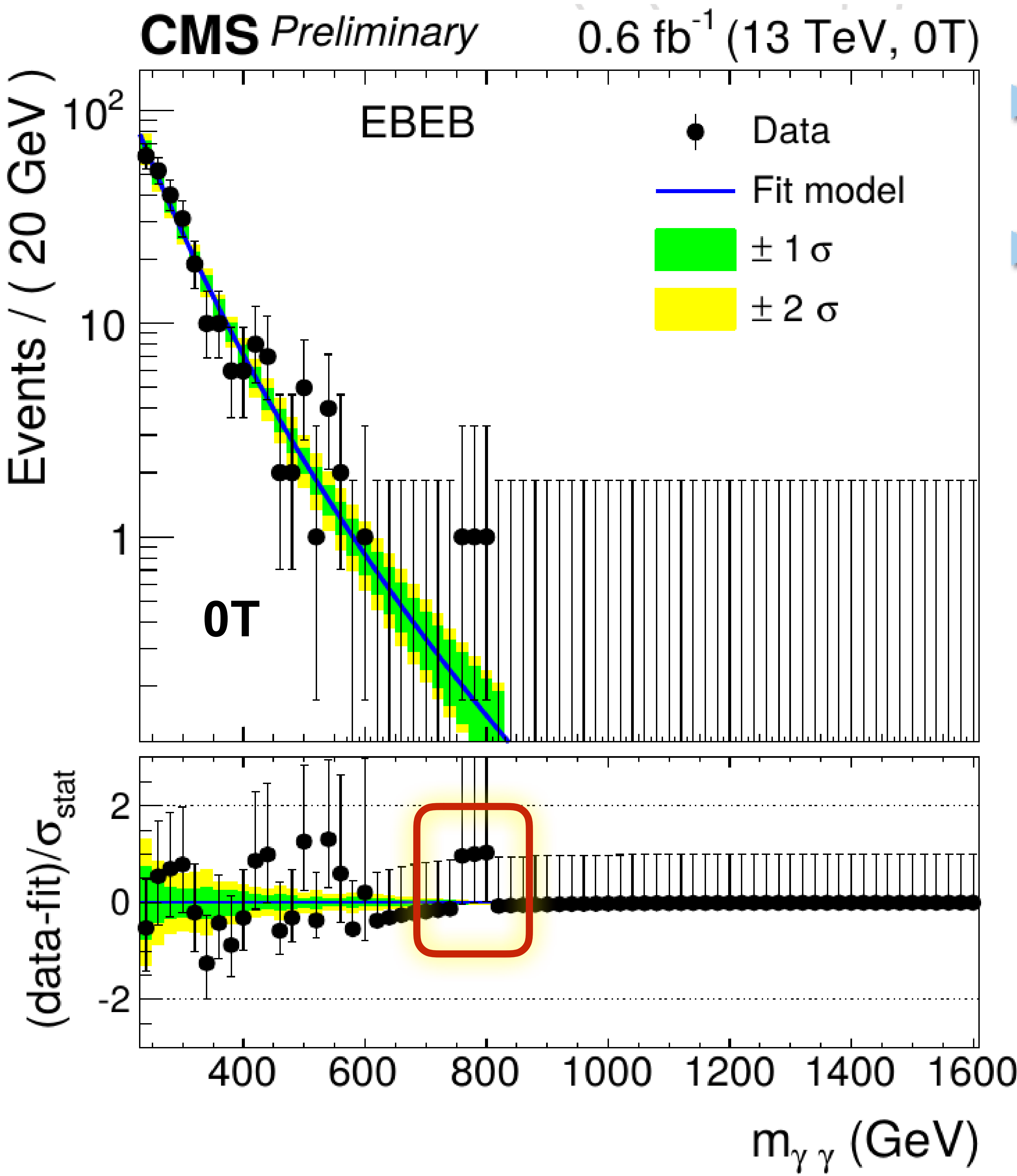
- Largest deviation from B-only hypothesis
  - ✓ m_G ~ 750 GeV, κ/M_{Pl} ~ 0.2 (Γ_G ~ 6% m_G)
  - ✓ Local Z = **3.6 σ**
  - ✓ Global Z = **1.8 σ**

CMS results - magnet on

Slide from Pascale Musella's, Moriond talk

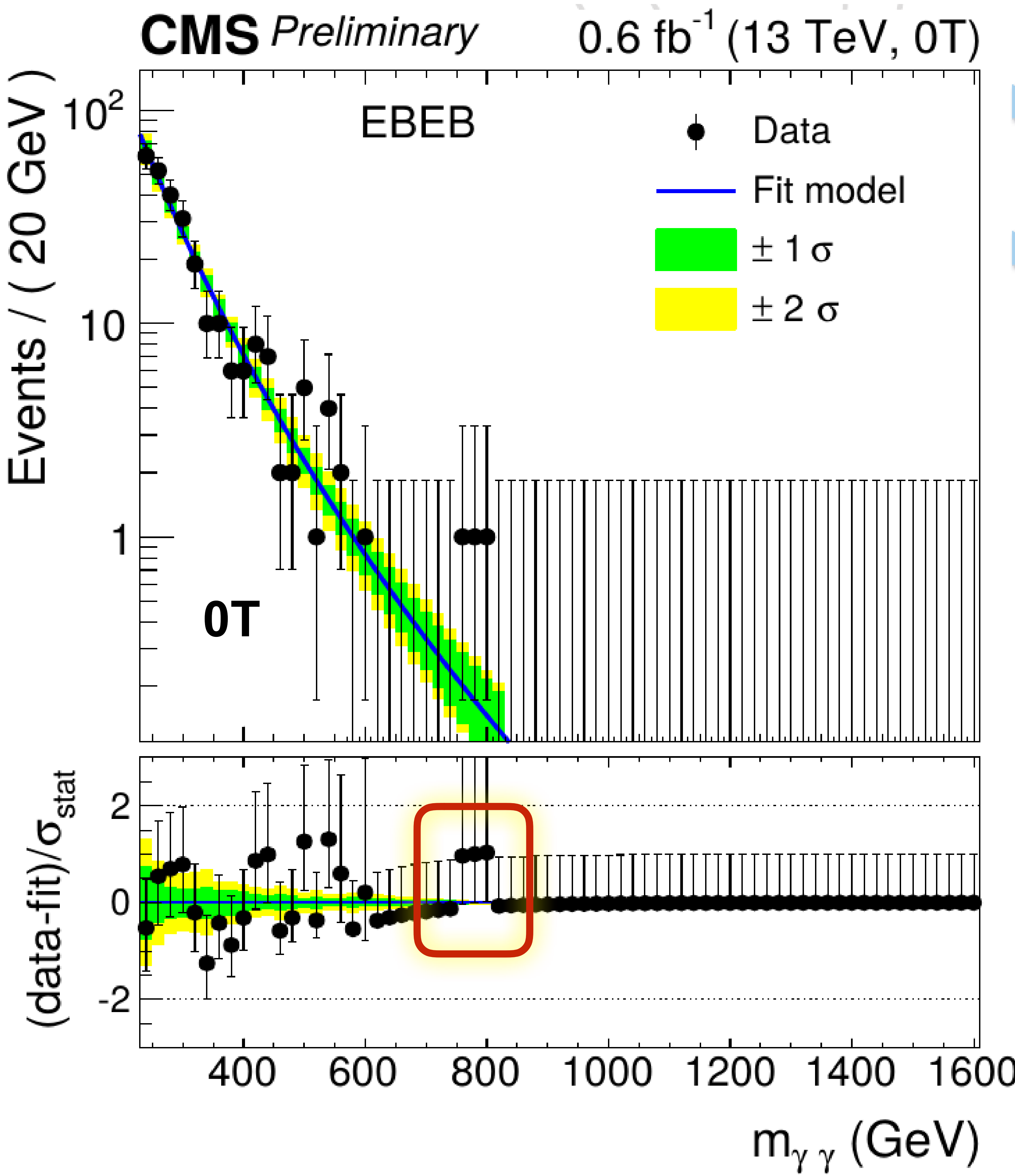


CMS result - magnet off



- **Modest excess** of events observed at **m_x = 750(760)GeV** for the 8+13TeV(13TeV) dataset.
- **Local** significance is **3.4(2.9)σ**, **reduced to 1.6(<1)σ** after accounting for look-elsewhere-effect.

CMS result - magnet off



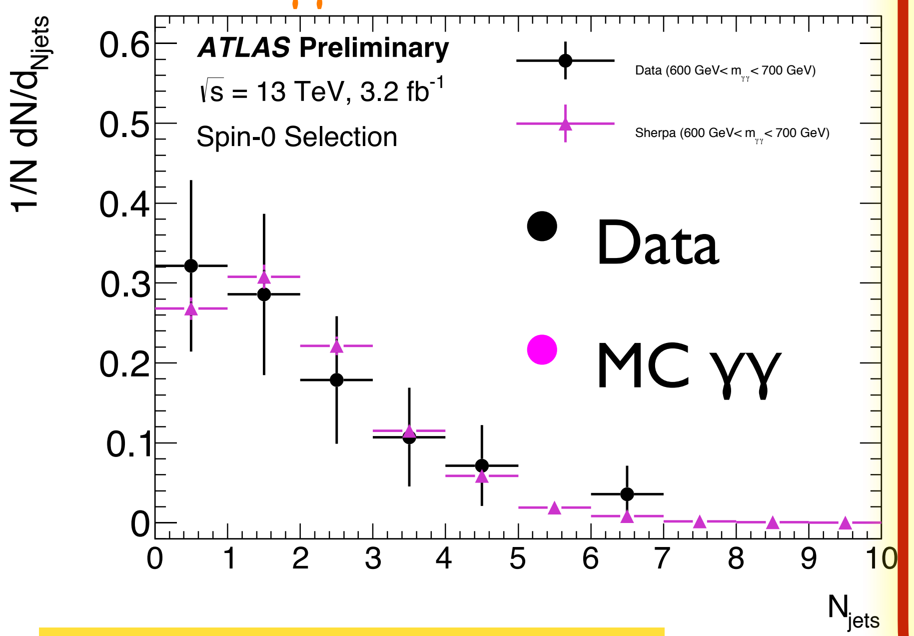
- **Modest excess** of events observed at **m_x = 750(760)GeV** for the 8+13TeV(13TeV) dataset.
- **Local** significance is **3.4(2.9)σ**, **reduced to 1.6(<1)σ** after accounting for look-elsewhere-effect.

Properties of sideband and excess regions

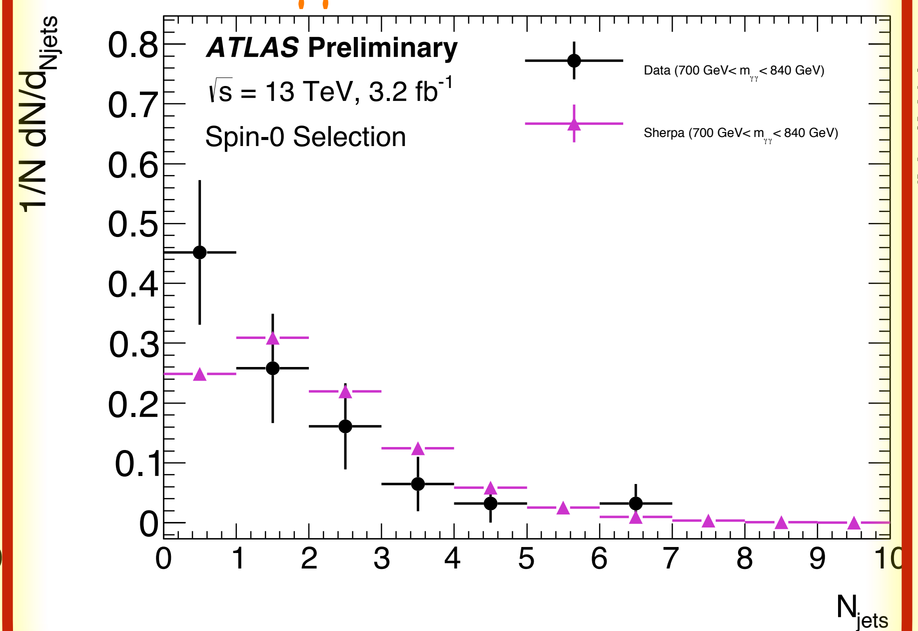
N_{jets}

SPIN-0 ANALYSIS

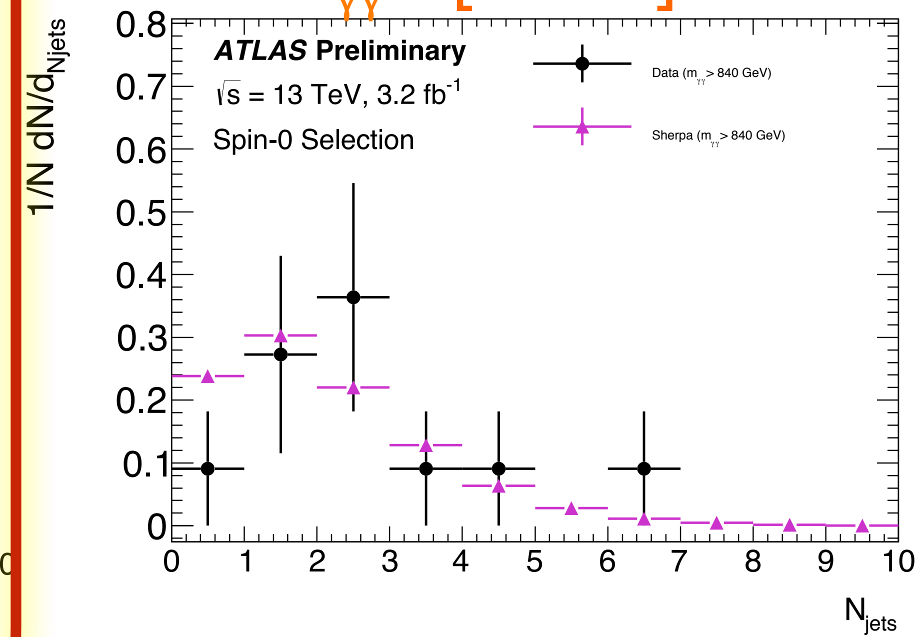
$m_{\gamma\gamma}$ = [600-700] GeV



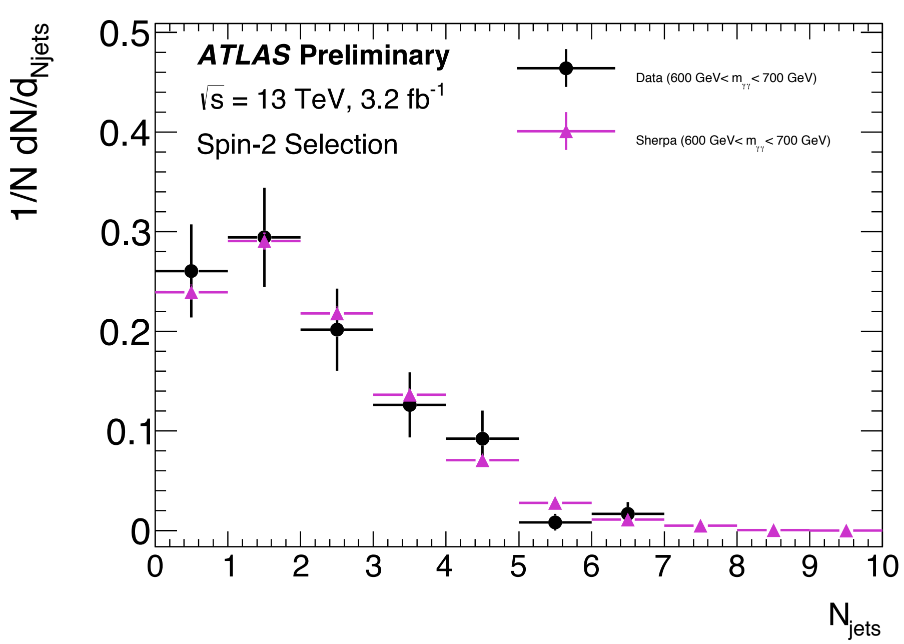
$m_{\gamma\gamma}$ = [700-840] GeV

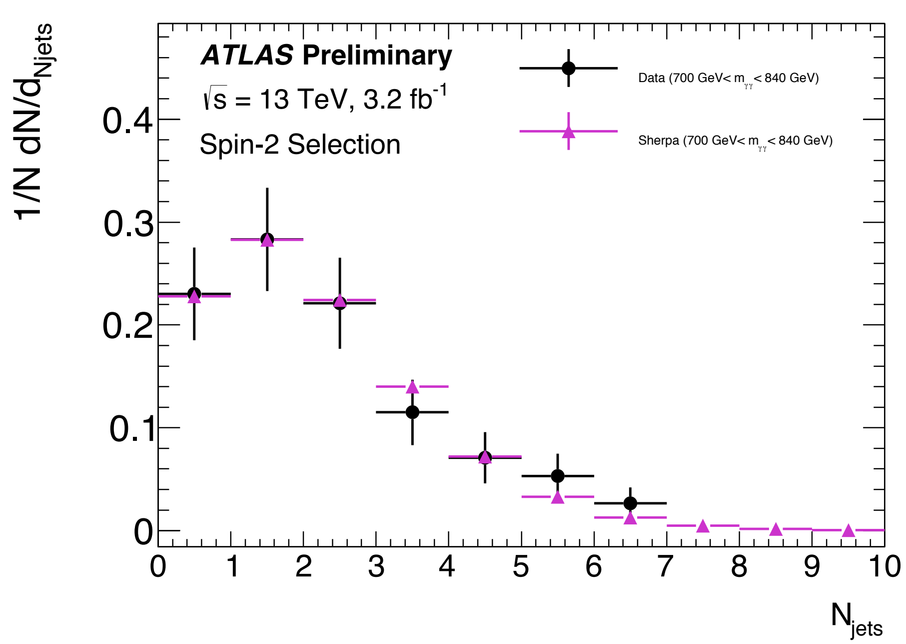


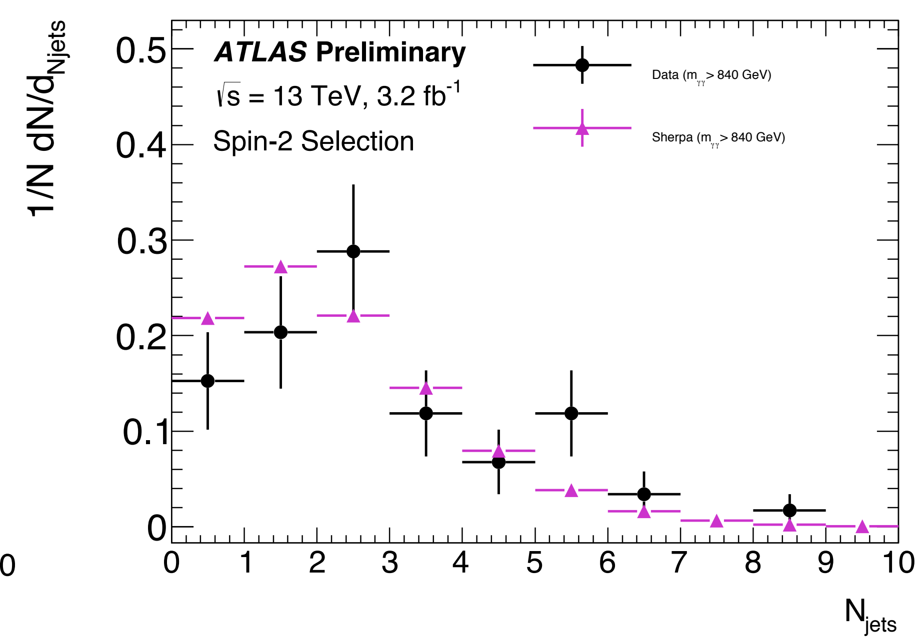
$m_{\gamma\gamma}$ =[840-∞] GeV



SPIN-2 ANALYSIS

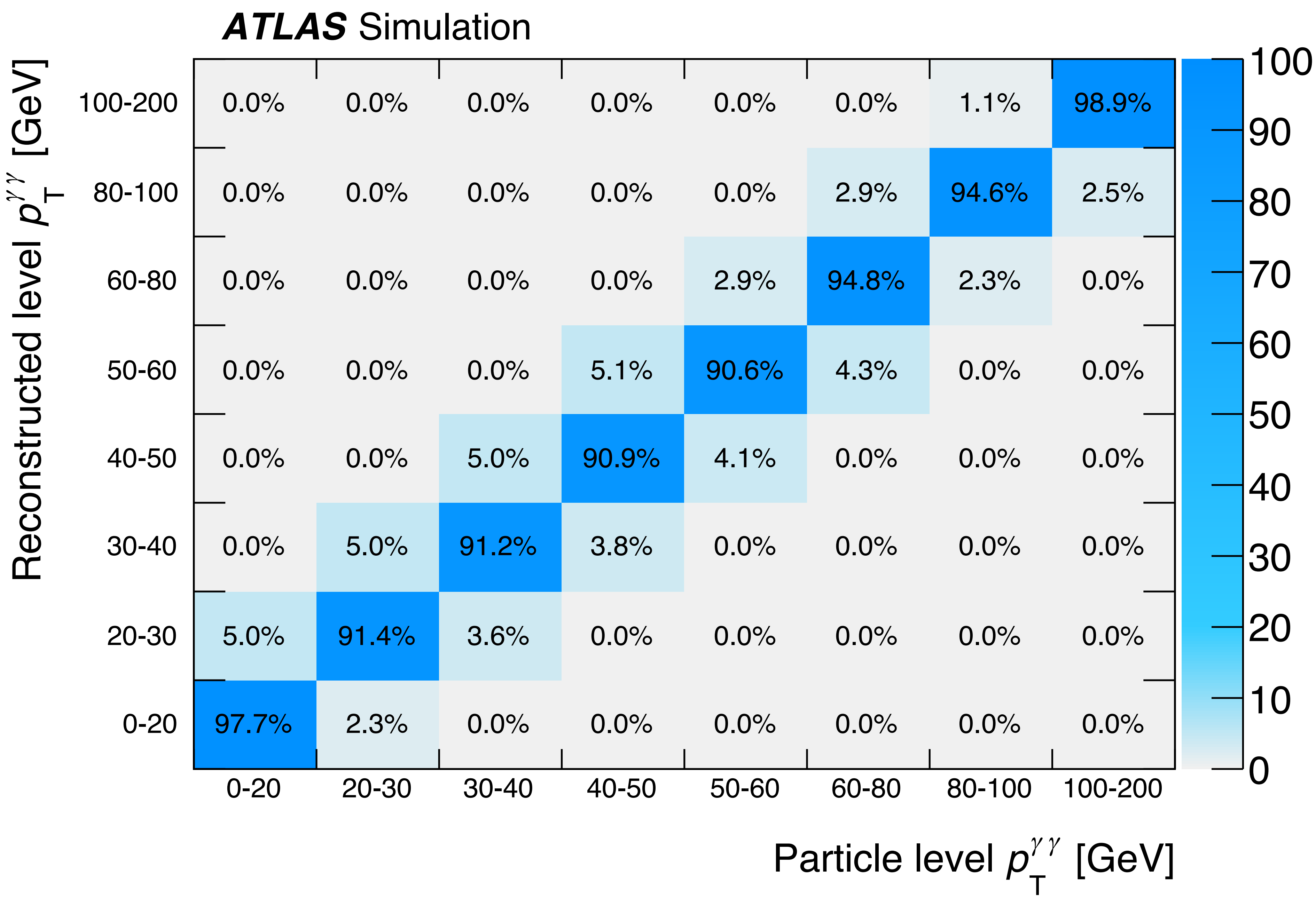




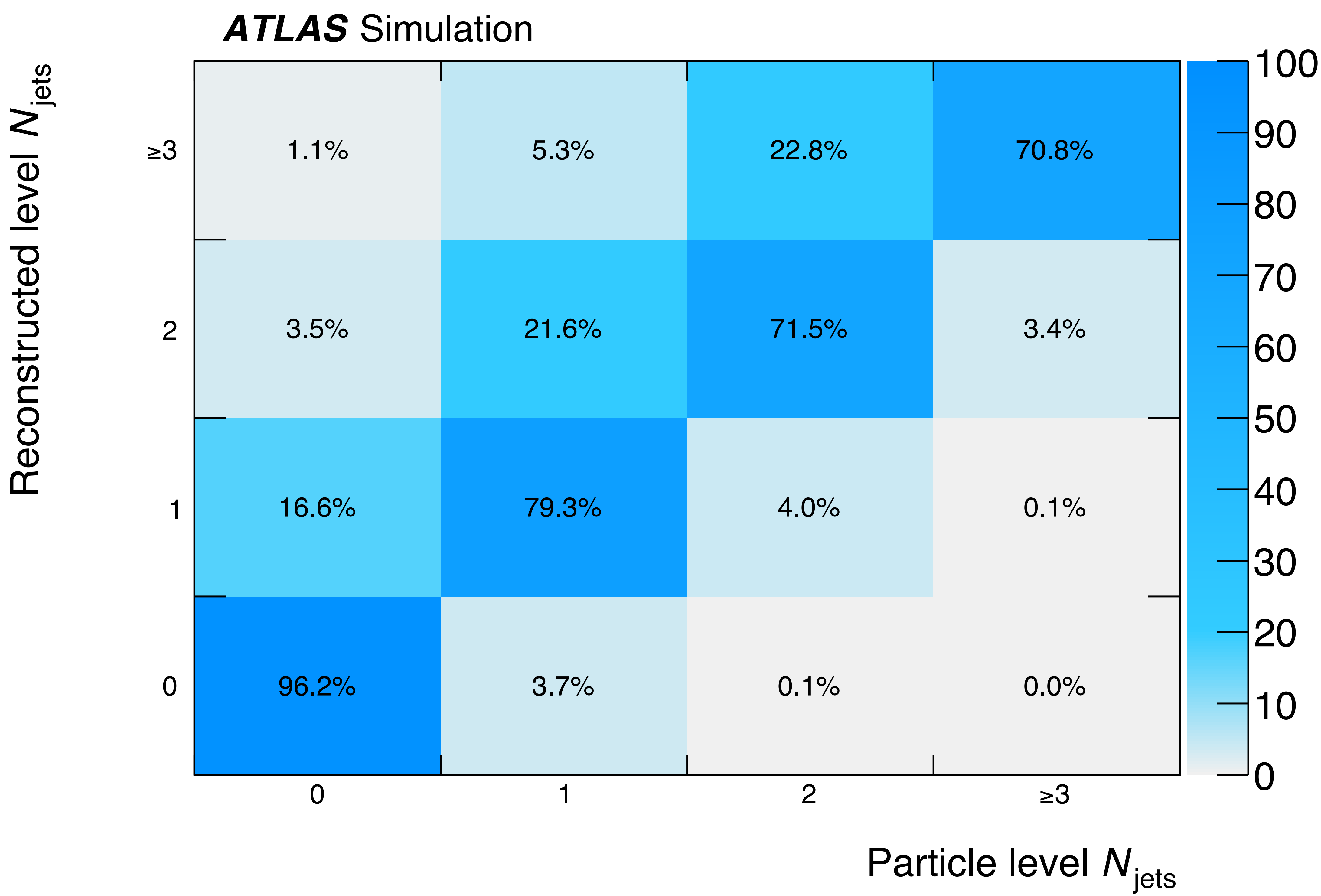


anti-k_t R-0.4 $y_j < 2.4 \rightarrow p_T^j > 25$ GeV + JVT < 0.64 $2.4 < y_j < 4.4 \rightarrow p_T^j > 50$ GeV

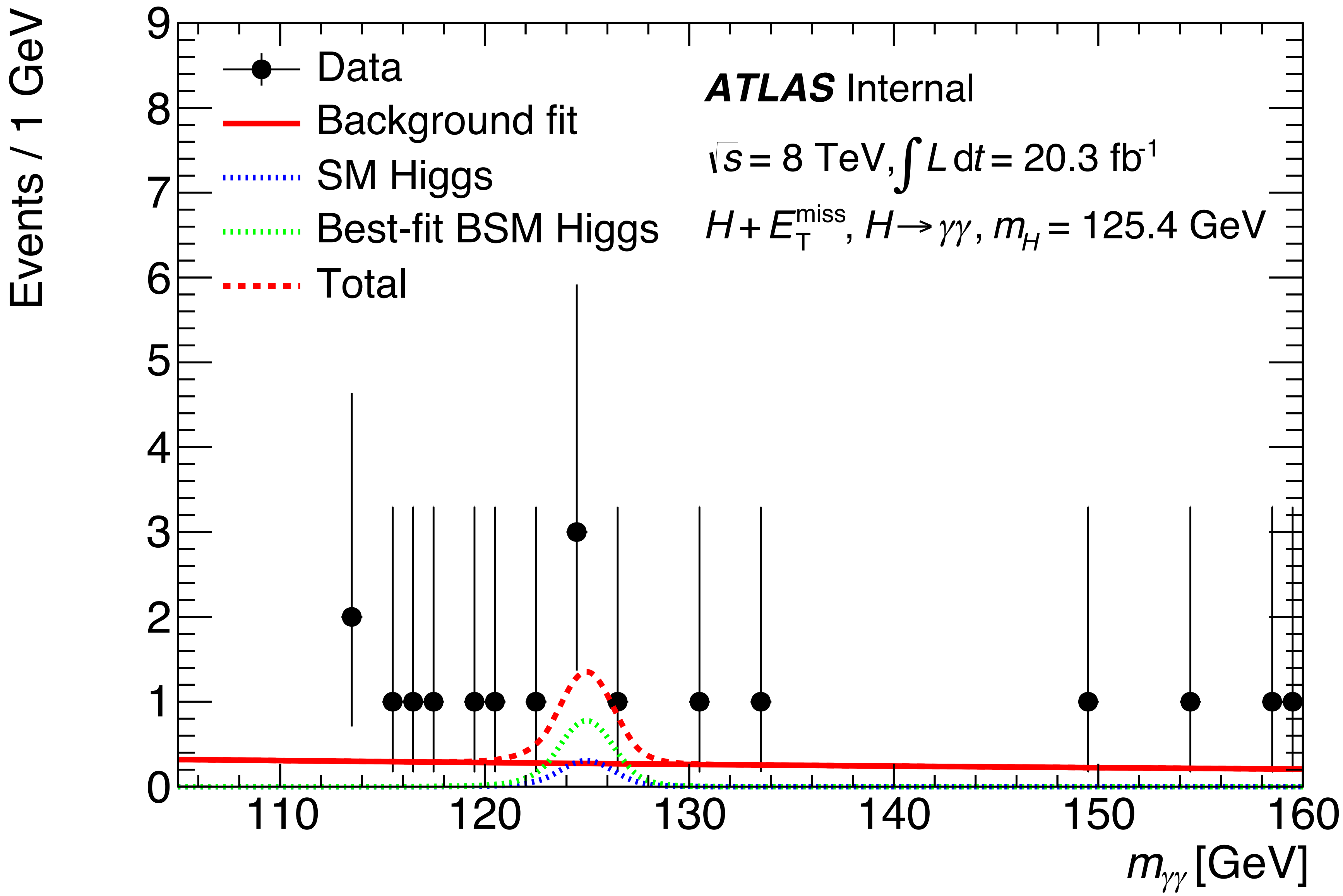
Correction for detector effects



Correction for detector effects



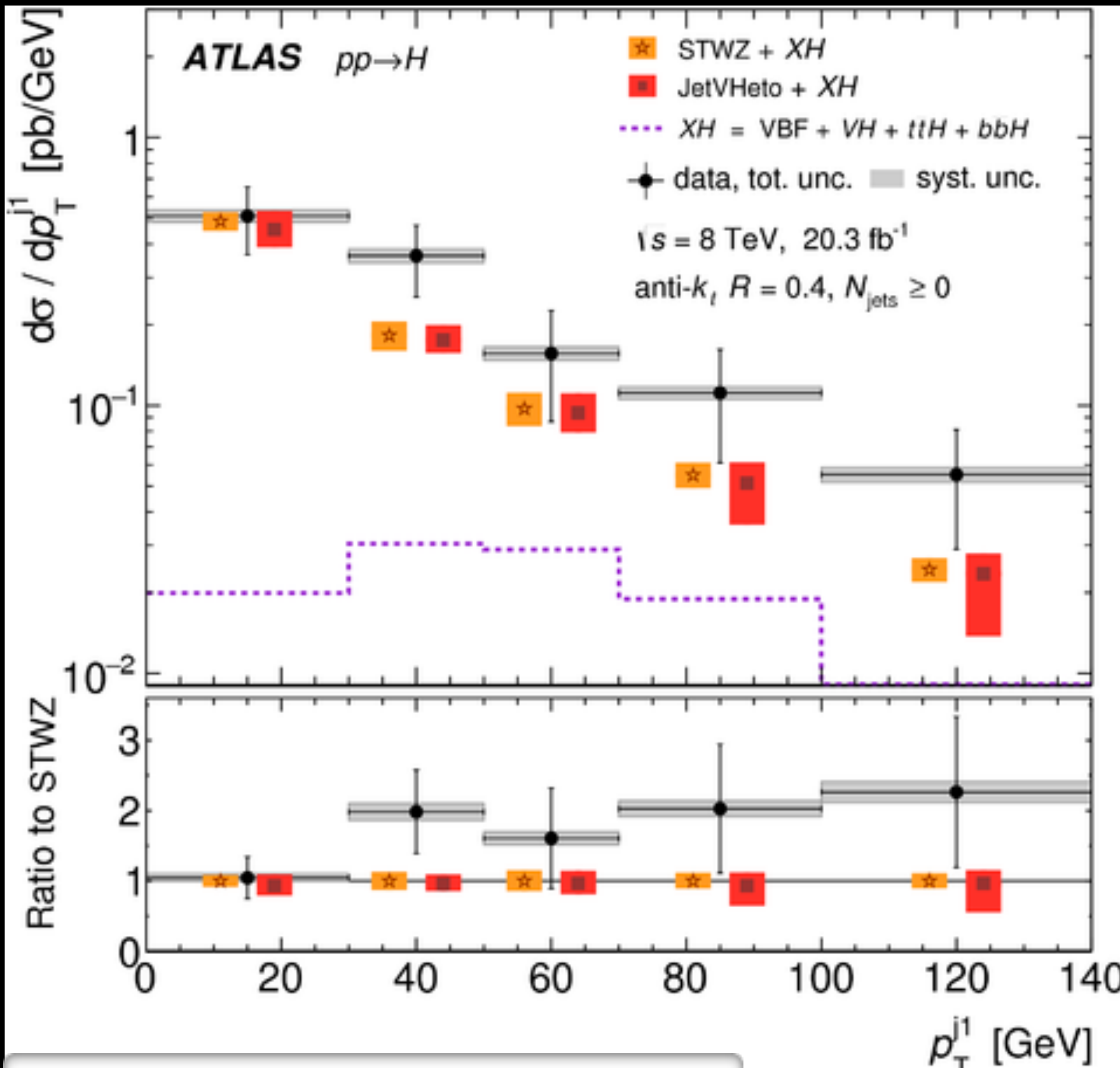
Higgs + E_T^{miss}



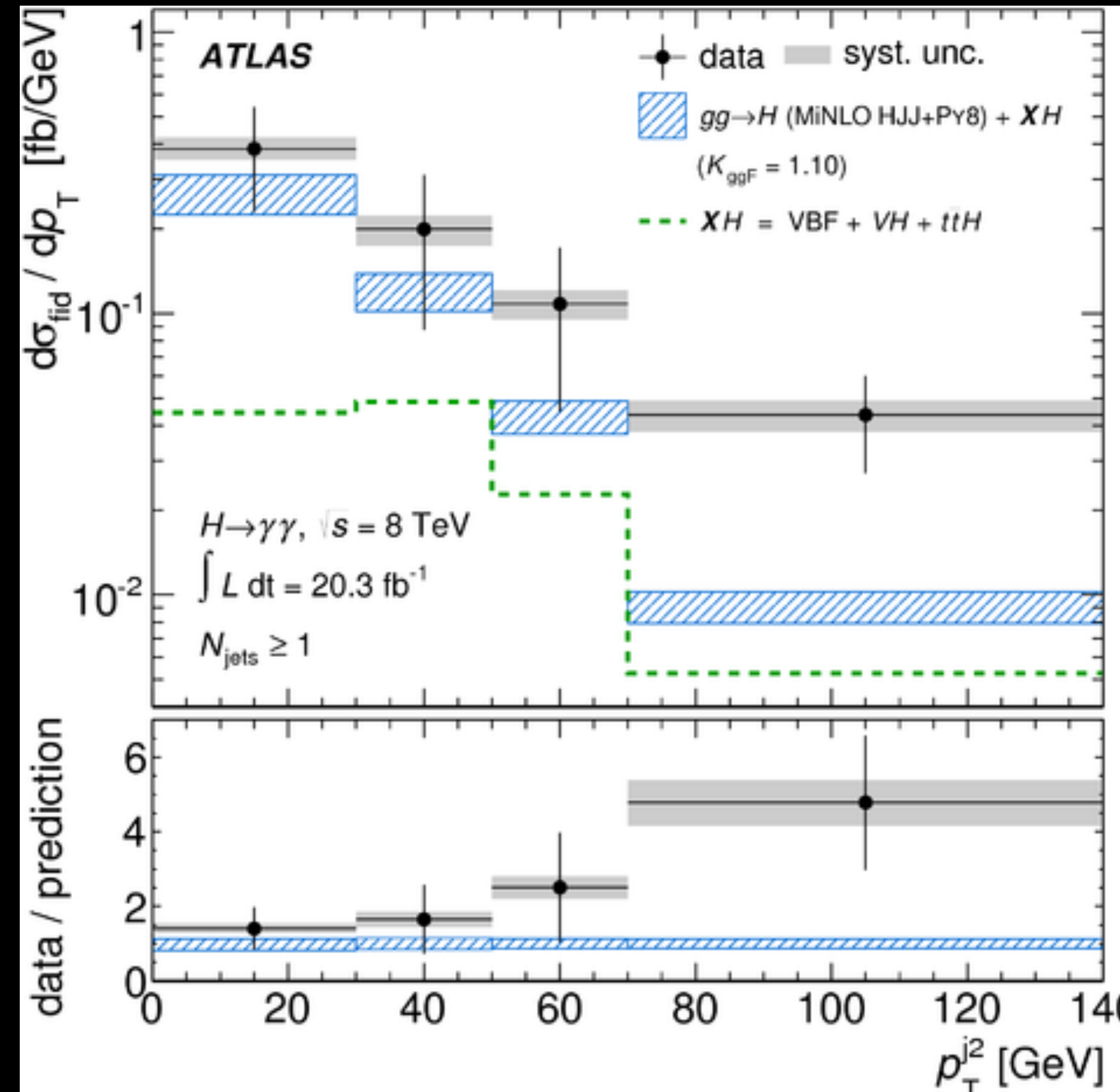
ETmiss > 90 GeV
pTγγ > 90 GeV
Target: “Mono Higgs”, Higgs + DM

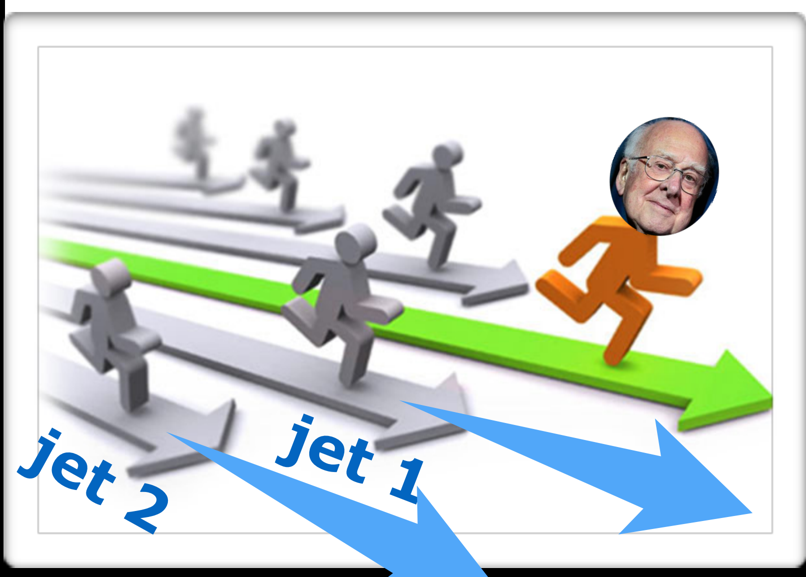
3. The momentum of the jets

Jet 1



Jet 2

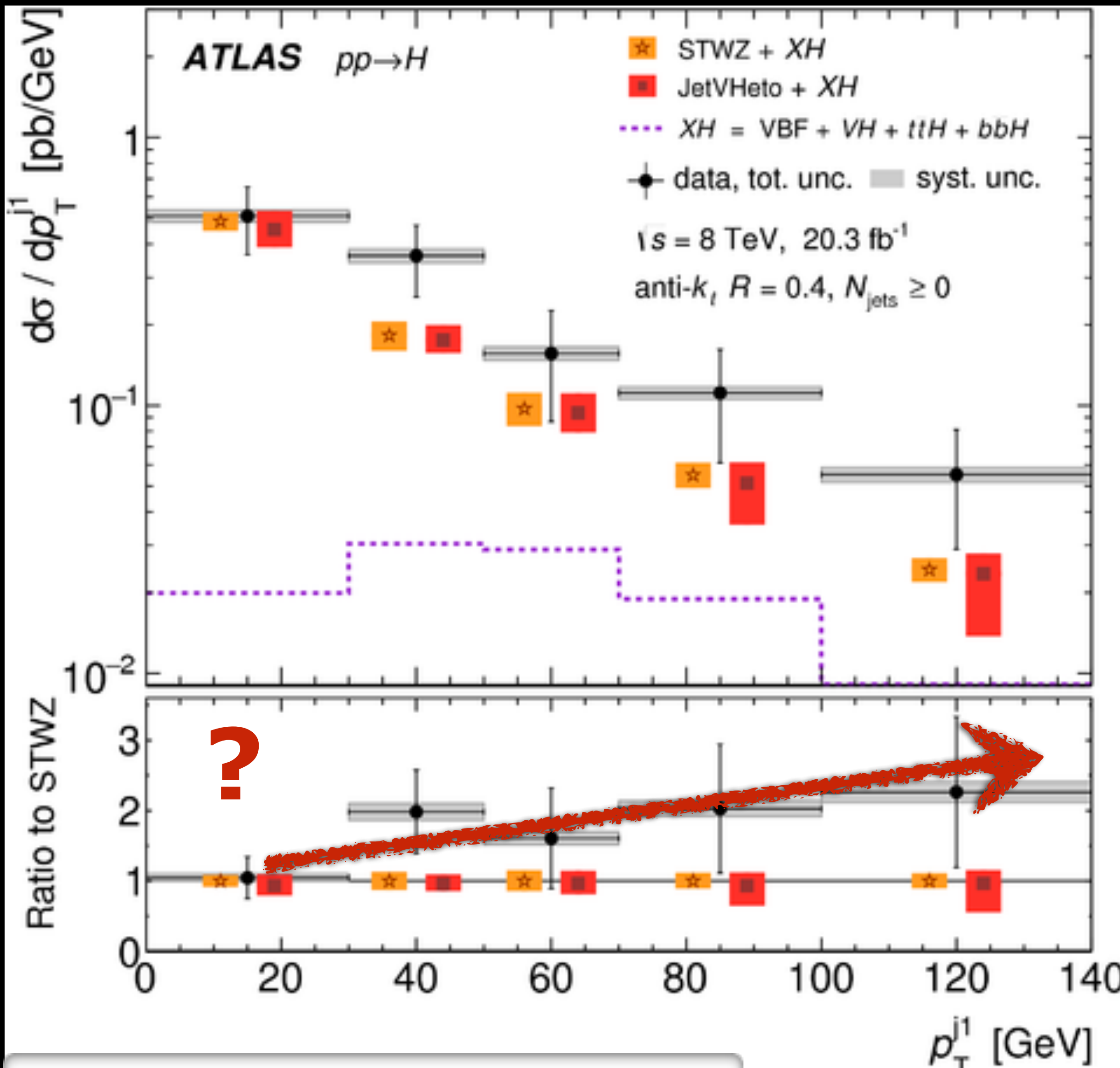




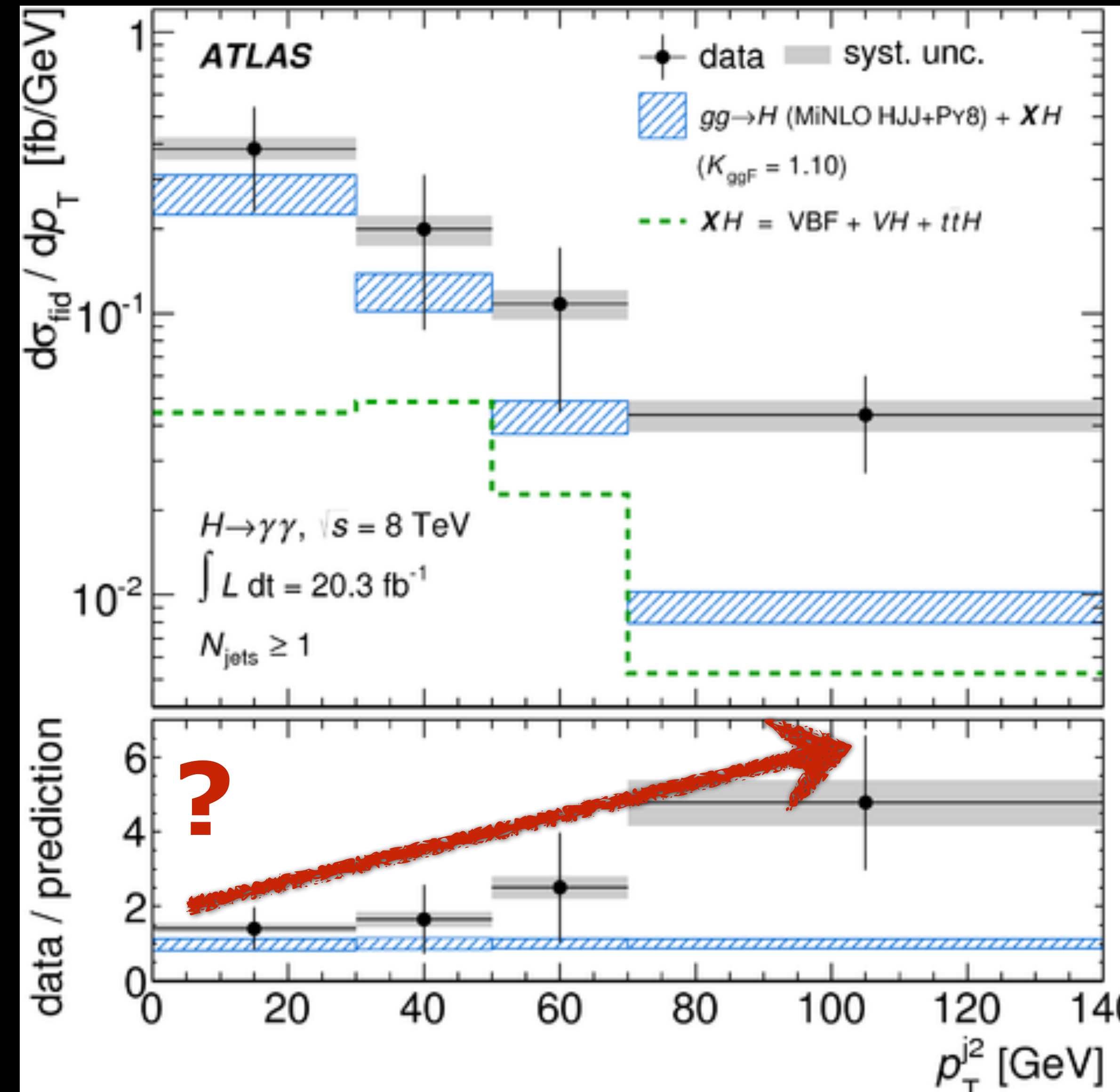
Also the highest-momentum (jet 1) and next-to-highest momentum (jet 2) jets are measured to be ***moving faster*** *(higher p_T)* ***than predicted*** *…*

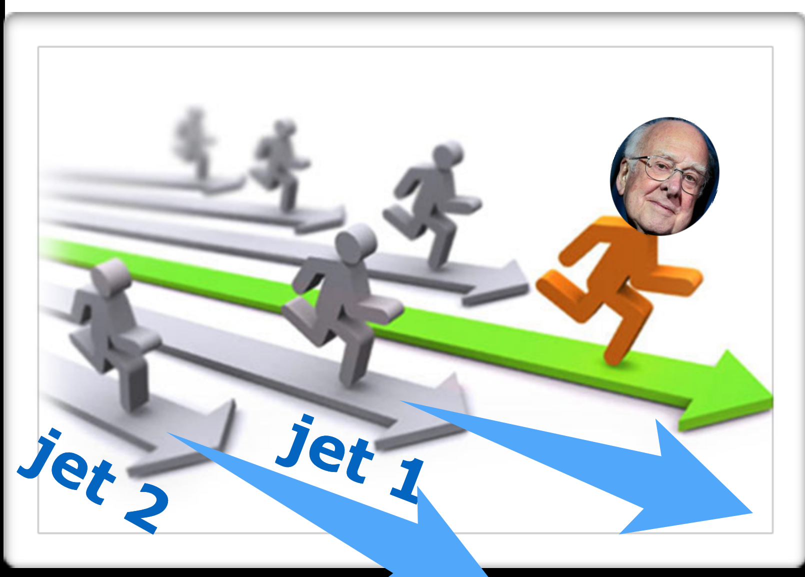
3. The momentum of the jets

Jet 1

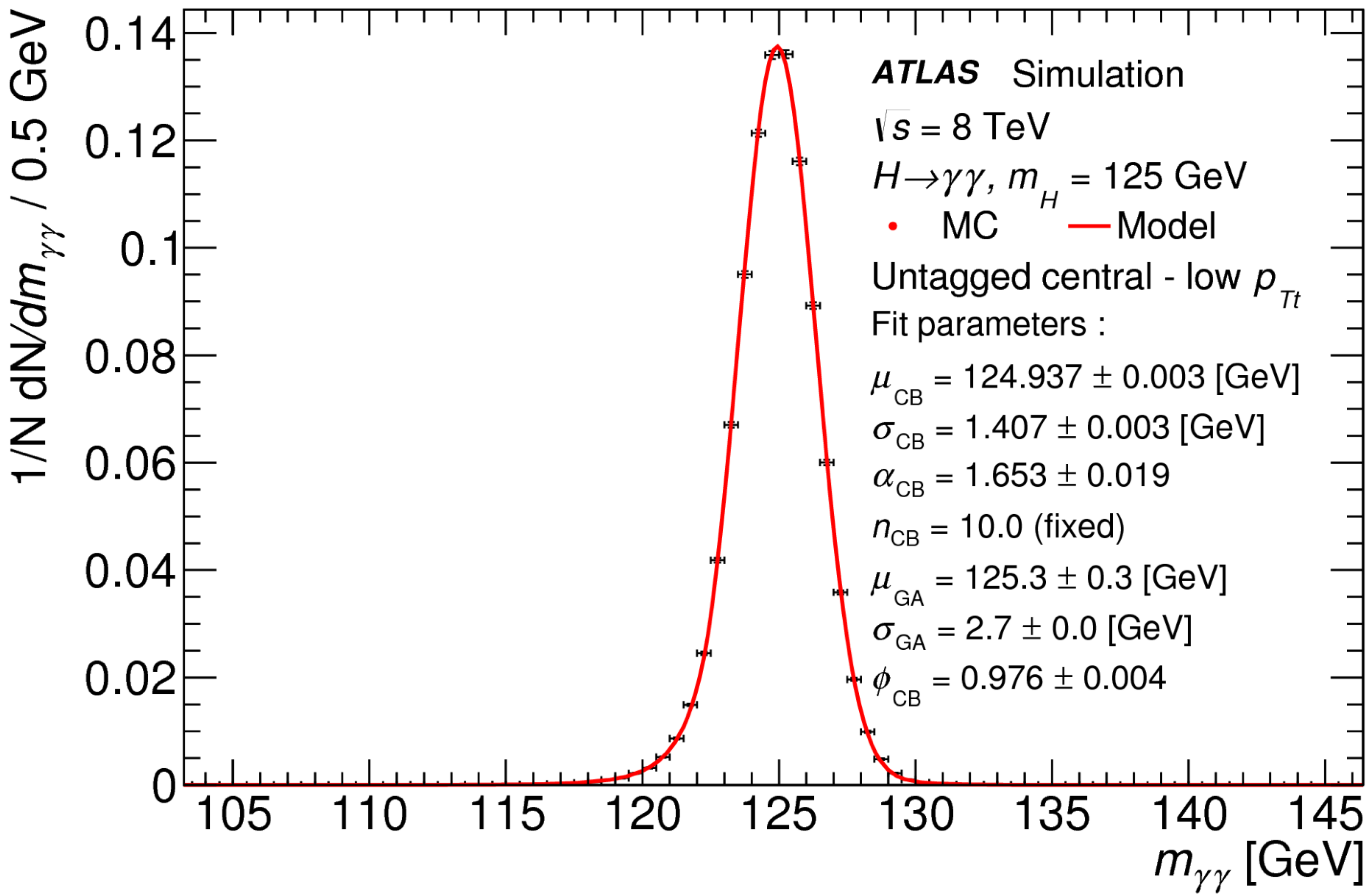


Jet 2





*Also the highest-momentum (jet 1) and next-to-highest momentum (jet 2) jets are measured to be **moving faster** (higher p_T) **than predicted** …*



ATLAS Simulation
$\sqrt{s}$ = 8 TeV
$H\rightarrow\gamma\gamma$, m_H = 125 GeV
MC
Model
Untagged central - low p_{Tt}
Fit parameters :
μ_{CB} = 124.937 ± 0.003 [GeV]
σ_{CB} = 1.407 ± 0.003 [GeV]
α_{CB} = 1.653 ± 0.019
n_{CB} = 10.0 (fixed)
μ_{GA} = 125.3 ± 0.3 [GeV]
σ_{GA} = 2.7 ± 0.0 [GeV]
ϕ_{CB} = 0.976 ± 0.004
1/N dN/$dm_{\gamma\gamma}$ / 0.5 GeV
0
0.02
0.04
0.06
0.08
0.1
0.12
0.14
105
110
115
120
125
130
135
140
145
$m_{\gamma\gamma}$ [GeV]

Comparing analytical ggF predictions with data

Analytical calculated cross sections can be corrected for acceptances and non-perturbative effects using provided correction factors for each fiducial region/bin of differential cross section SM is assumed for provided values. Uncert. from QCD-scale, PDF, MPI/fragm. tune variations

gluon fusion

other production modes
XH = VBF+VH+ttH

$$\sigma_{\rm fid} = \sigma_{\rm ggF}\ \mathcal{B}\ \alpha_{\rm kinem}\ \alpha_{\rm iso}\ f_{\rm NP} + \sigma_{{\rm fid},XH}$$

ggF cross section

Branching ratio

Kinematic acceptance for Higgs decay product to fulfil fiducial requirements

Efficiency for photons to fulfil particle level isolation
(part of γγ fiducial definition not used for ZZ)

Non-perturbative correction factor accounting for hadronization and underlying event activity

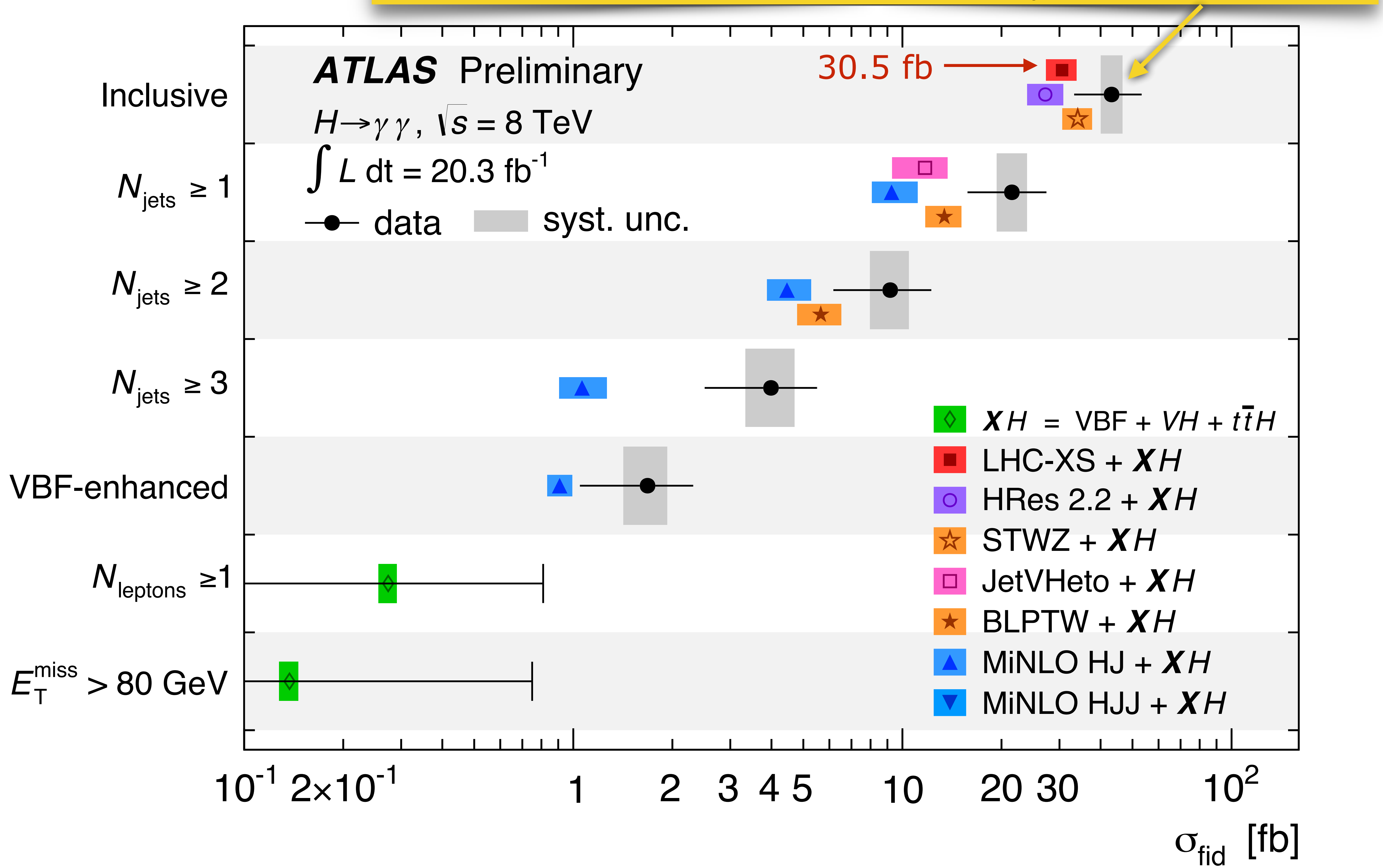
Example for H→γγ inclusive fiducial cross section, m_H = 125.4 GeV

$$\sigma_{\rm fid} = \sigma_{\rm ggF}\ \mathcal{B}\ \alpha_{\rm kinem}\ \alpha_{\rm iso}\ f_{\rm NP} + \sigma_{{\rm fid},XH} \quad = \mathbf{30.5\ fb}$$

- $\sigma_{\rm ggF}$: LHC-XS: 19.15 pb
- $\mathcal{B}$: 0.228%
- $\alpha_{\rm kinem}$: ~63%
- $\alpha_{\rm iso}$: ~98%
- $f_{\rm NP}$: 1.00
- $\sigma_{{\rm fid},XH}$: ~4 fb

$H \rightarrow \gamma\gamma$ fiducial cross sections

$$\sigma_{\rm fid}(pp \to H \to \gamma\gamma) = 43.2 \pm 9.4\,({\rm stat})\,^{+3.2}_{-2.9}\,({\rm syst}) \pm 1.2\,({\rm lumi})\ {\rm fb}$$



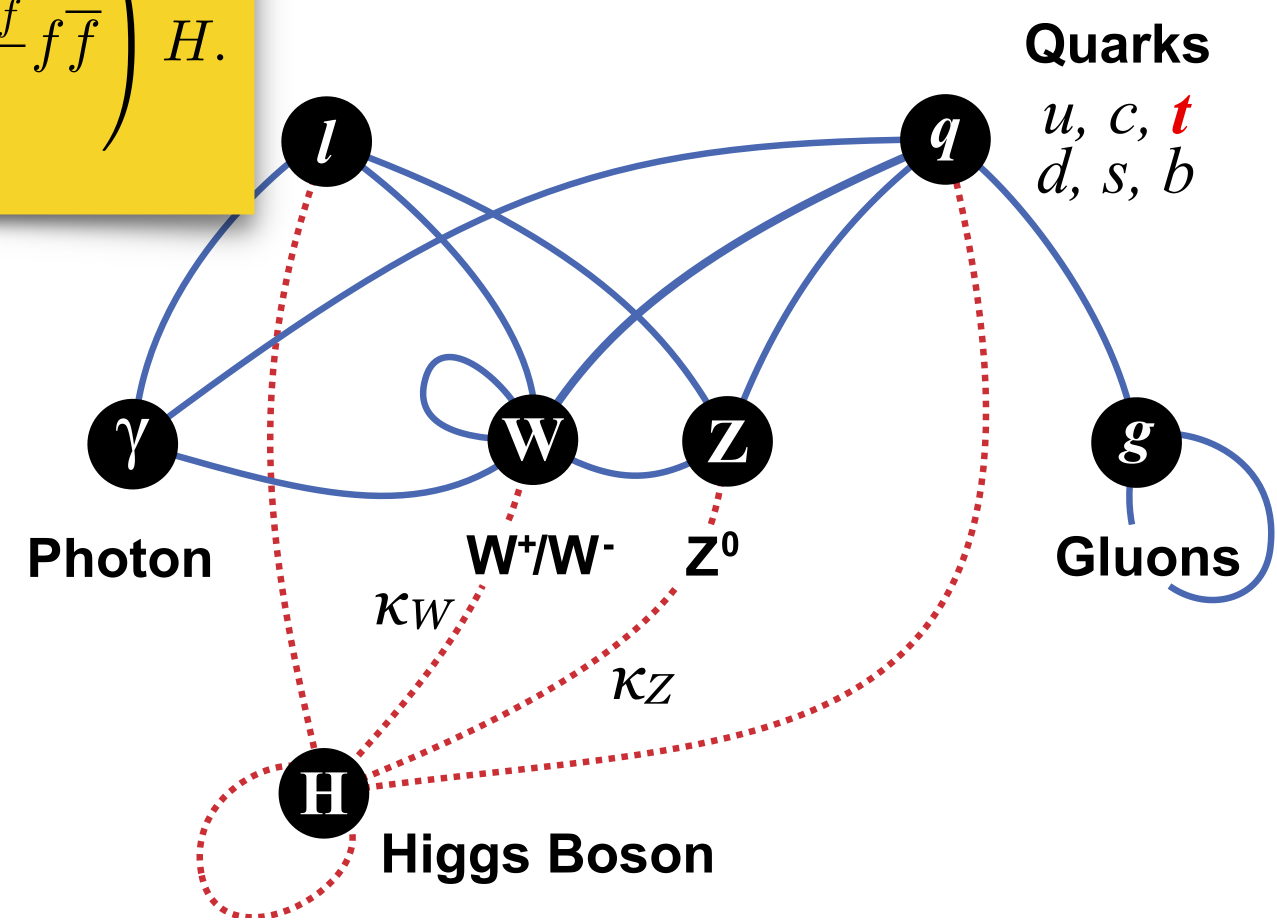
Higgs couplings

- Search for deviations from the SM Higgs coupling to other particles by introducing multipliers using a **tree-level motivated benchmark model** following the LHC Higgs XS WG recommendations: 1209.0040

$$\mathcal{L} = \kappa_3 \frac{m_H^2}{2v} H^3 + \kappa_Z \frac{m_Z^2}{v} Z_\mu Z^\mu H + \kappa_W \frac{2m_W^2}{v} W_\mu^+ W^{-\mu} H + \kappa_g \frac{\alpha_s}{12\pi v} G^a_{\mu\nu} G^{a\mu\nu} H + \kappa_\gamma \frac{\alpha}{2\pi v} A_{\mu\nu} A^{\mu\nu} H + \kappa_{Z\gamma} \frac{\alpha}{\pi v} A_{\mu\nu} Z^{\mu\nu} H + \kappa_{VV} \frac{\alpha}{2\pi v} \left(\cos^2\theta_W Z_{\mu\nu} Z^{\mu\nu} + 2\, W^+_{\mu\nu} W^{-\mu\nu}\right) H - \left(\kappa_t \sum_{f=u,c,t} \frac{m_f}{v} f\bar{f} + \kappa_b \sum_{f=d,s,b} \frac{m_f}{v} f\bar{f} + \kappa_\tau \sum_{f=e,\mu,\tau} \frac{m_f}{v} f\bar{f} \right) H.$$

Effective Lagrangian describing the Higgs couplings in unitarity gauge

Status of Higgs boson physics (PDG), page 62



Dag Gillberg