# Higgs discovery and measurements of its properties at LHC

## CERN Academic Training


Marumi Kado
Sapienza (Roma), CERN  and LAL (Orsay)

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Contact: marumi.kado@cern.ch

# Outline



**This lecture follow's John's theoretical and historical review of Higgs physics**


**Disclaimers**

- It will not cover the 20 years of immense preparatory work of design, development, construction, and commissioning of the LHC machine and the experiments
- It will not give a complete review of all results achieved so far

Higgs 10 symposium at CERN

CERN 10 years HIGGS boson discovery

Review see latest PDG review

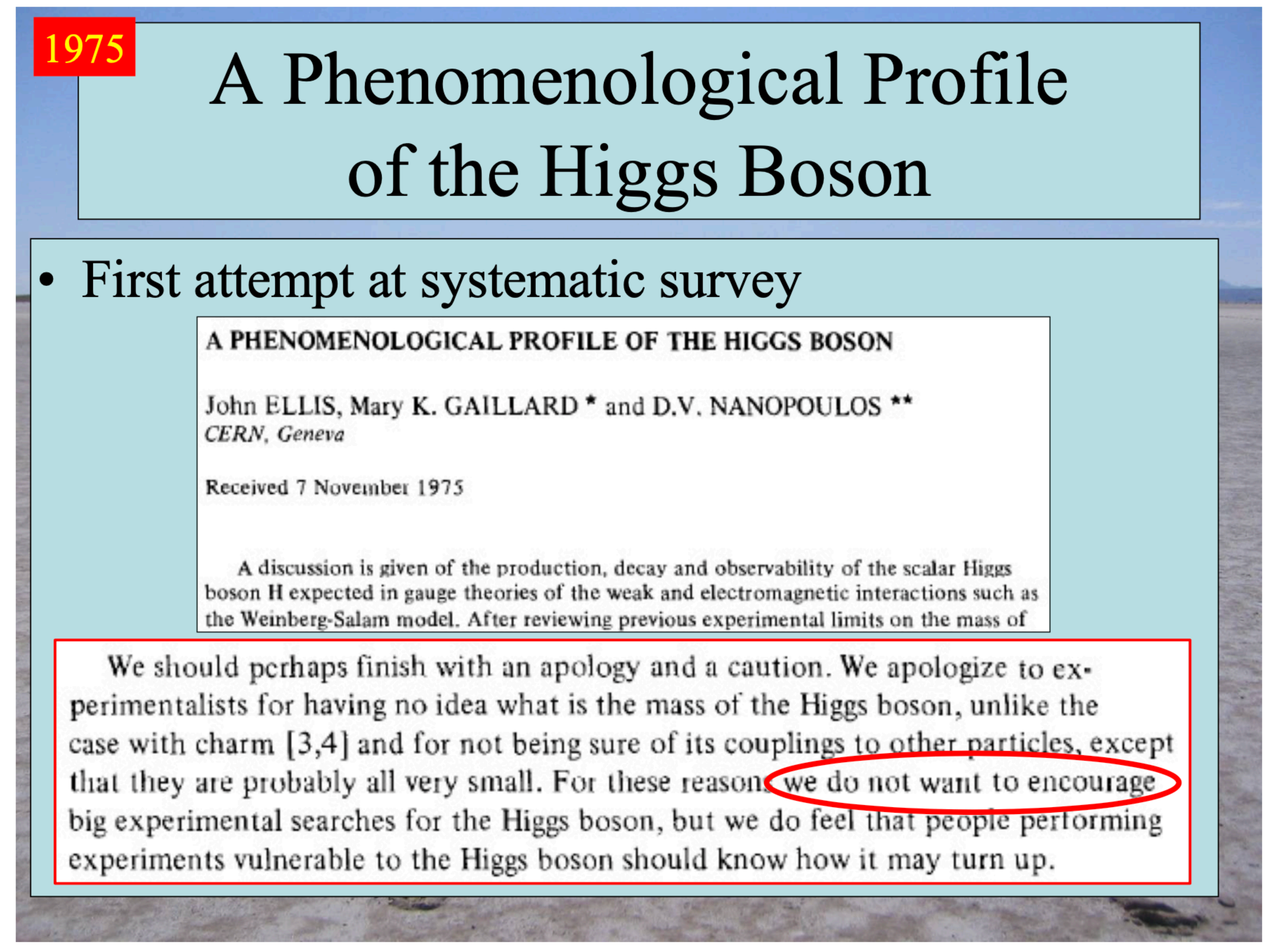
PDG particle data group

1. Reminder of the Higgs discovery at LHC **Run 1** and how it established of the Higgs boson to all gauge bosons (W and Z, g, $\gamma$)
2. The **Run 2**, landmark result and the observation of the coupling of the Higgs boson to fermions (t, b, $\tau$)
3. The **Run 2** evidences for new Higgs decay channels $H \to \mu\mu$, $H \to \gamma\gamma^*$ and $H \to Z\gamma$
4. Constraints on widths (invisible and total), rare and the very precious HH production modes at **Run 2**

# The LHC a « Marvel of Technology »



**First mention of the LHC in 1977 by sir John Adams (former CERN director) as an option of a superconducting hadron collider to be hosted in the LEP tunnel** (requesting that the LEP be made large enough to host a proton collider of at least 3 TeV beam energy). That was a period very busy with extremely important physics results.




- 1984: CERN and ECFA workshop in Lausanne.
- 1988: LEP tunnel completed (Europe's largest civil engineering project prior to the channel tunnel).
- 1992: ATLAS and CMS letters of intent.
- 1994: Approval of the LHC (1993 cancellation of 40 TeV SSC).
- 1995: LHC CDR published.
- 1997-98: ATLAS, CMS, LHCb and ALICE experiments approved.
- 2003-2005: Caverns completed installation started.
- 2007: LHC dipoles installed in LHC (after having been all individually checked at SM18).
- 2008: Experiments installed.
- 2008 September 10: Start of the LHC.
- 2008 September 19: Incident occurs between dipole and quadrupole.
- **2009** November: Beams are back in the LHC!

**Since 2009: 12 years of successful operations and landmark results!**

# The Large Hadron Collider (LHC) - the Energy Frontier



**Unrivalled at the Energy Frontier**

**13 TeV (centre-of-mass energy)**

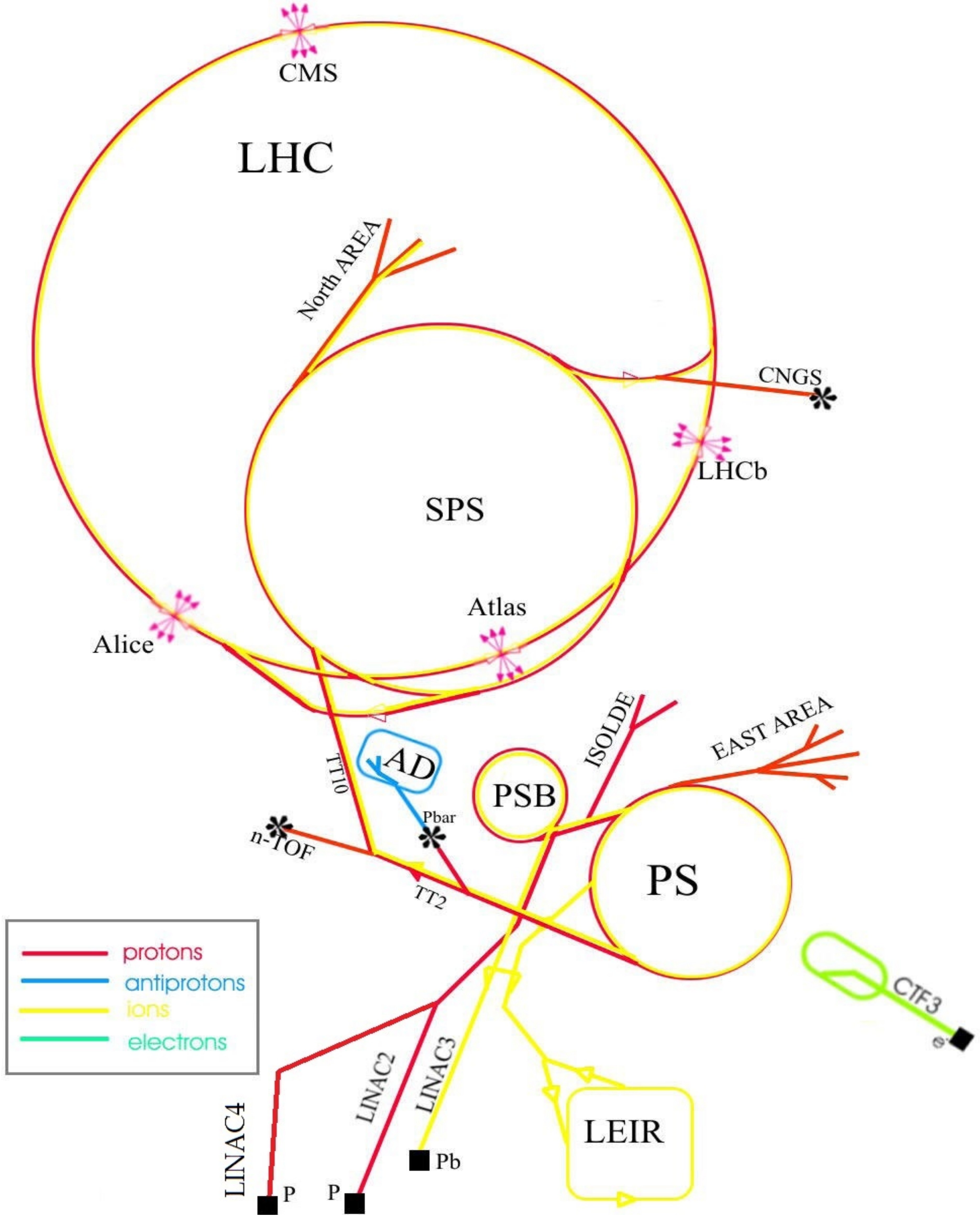
**Outstanding at Intensity Frontier**

**Record Luminosity* of** $2.14 \times 10^{34}\ cm^2 s^{-1}$

## The LHC is « the most ambitious scientific experiment in history »

An Zeptospace Odyssey   G. Giudice

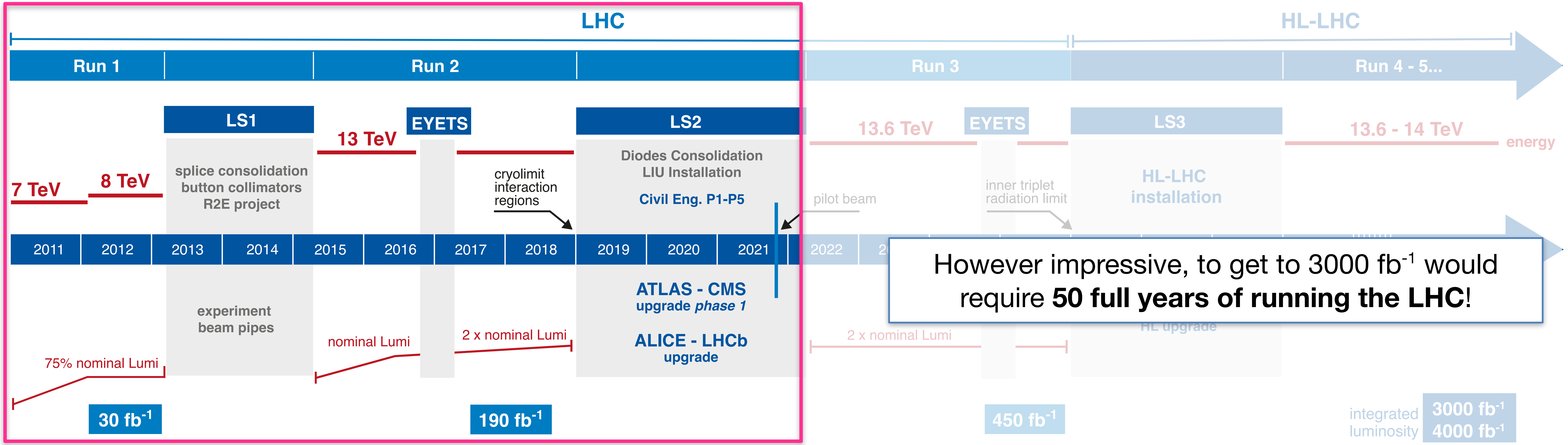
*« The LHC is a gigantic microscope peering distances of ~100 zeptometers ~ 100 x $10^{-21}$ m) »*



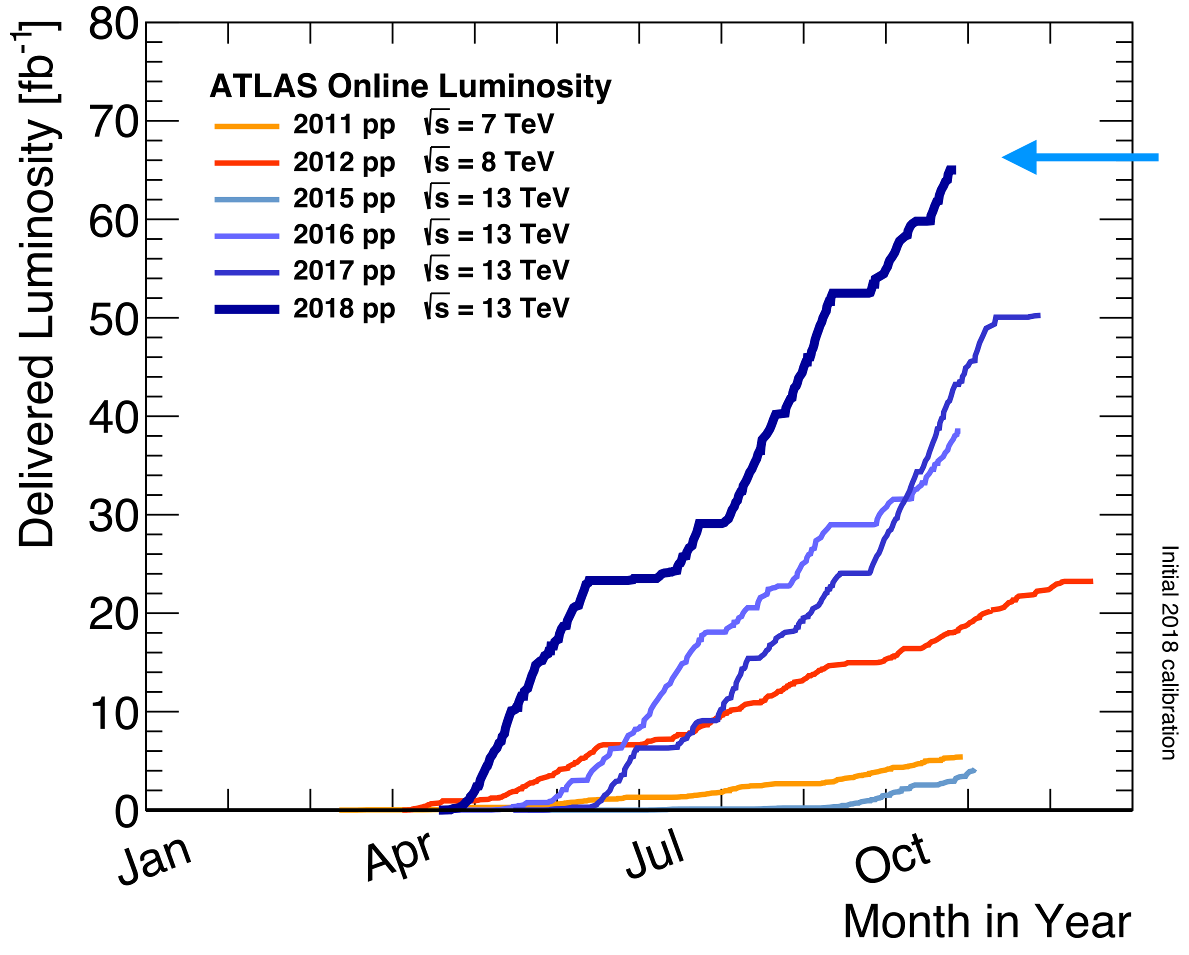

*Surpassed in June 2020 by SuperKEKB at $2.2 \times 10^{34}\ cm^2 s^{-1}$

# 10 Years of LHC

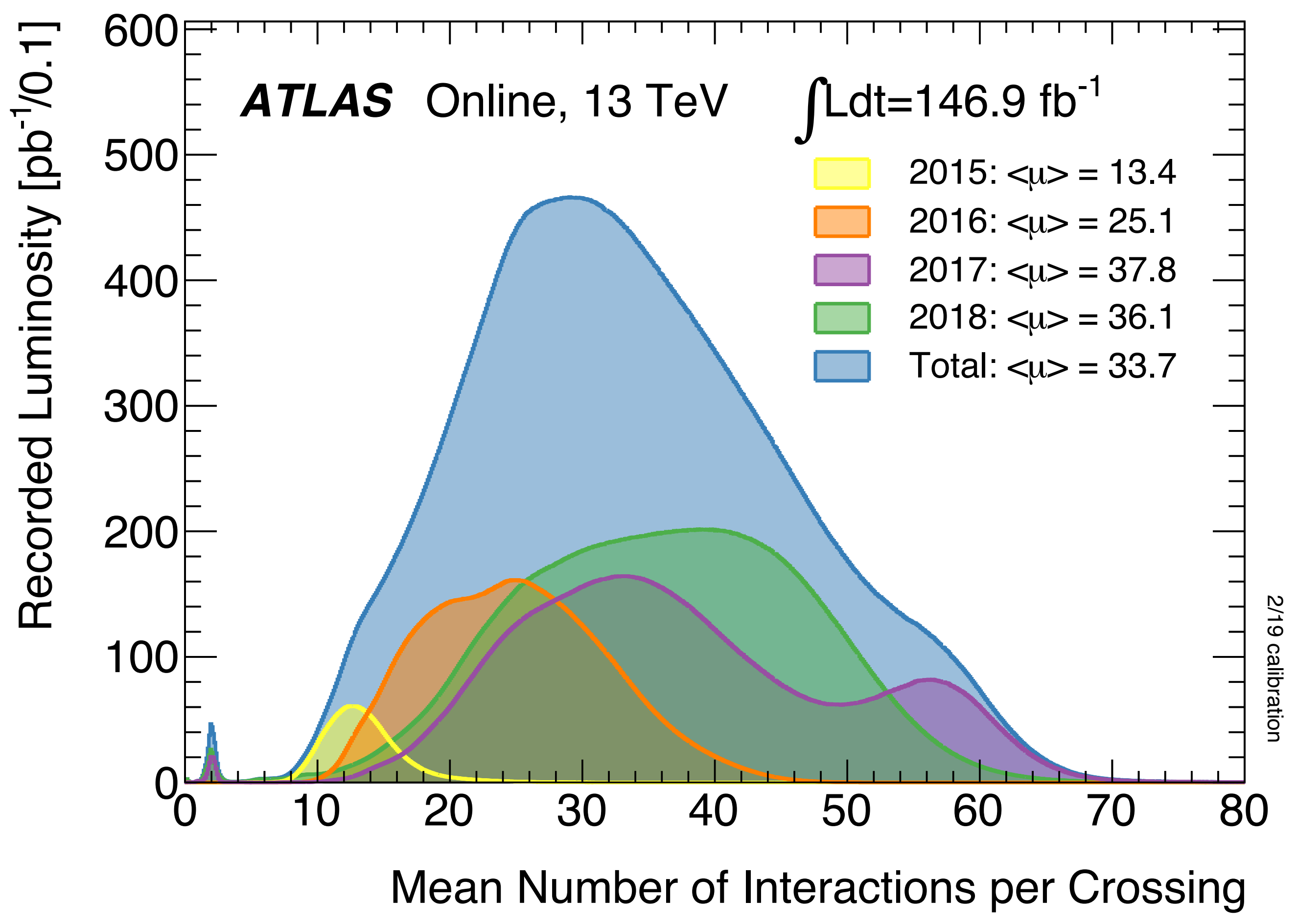





However impressive, to get to 3000 $fb^{-1}$ would require **50 full years of running the LHC**!




**Record 2018**
More than 60 $fb^{-1}$ collected by experiments



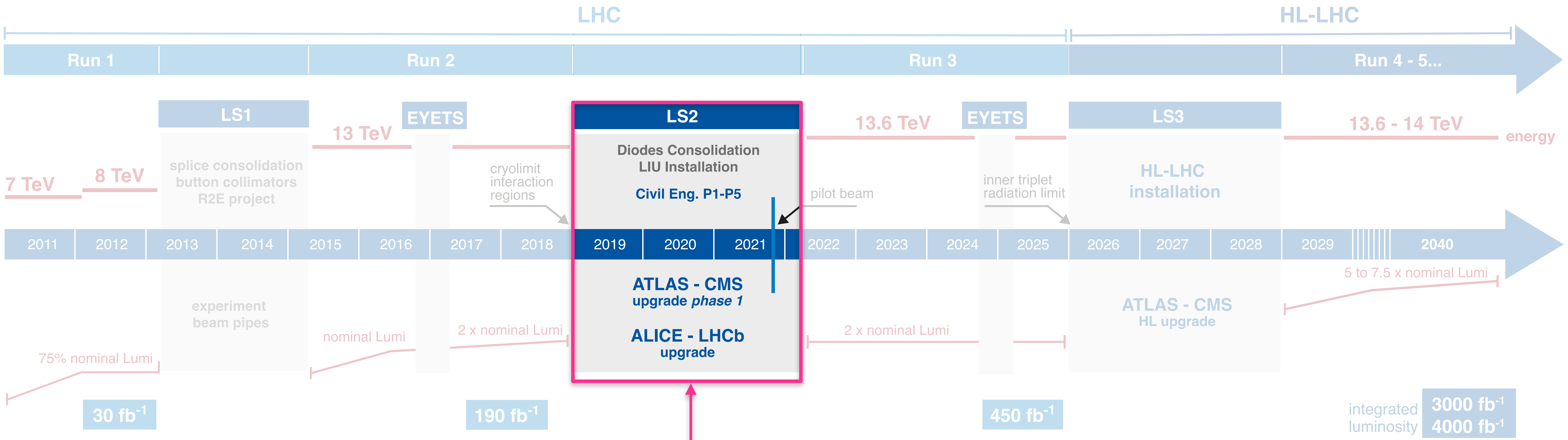

- **Run 1 :** COM Energies of 7 and 8 TeV and luminosities of ~20 fb-1 for ATLAS and CMS and Pile-Up of ~30-40.

- **Run 2 :** COM Energy of 13 TeV and luminosities (for ATLAS and CMS) of ~**140** $\mathbf{fb^{-1}}$ with Pile Up of ~30-40 (at 25ns - makes quite a difference out-of-time PU!)

**Huge number of lessons learned on how to mitigate PU.**

# The Long Shutdown 2 towards HL-LHC






**Phase 1** (Deployment now during LS2)

**ATLAS**

- New Small Wheel (Forward muons) for L1 muon trigger
- Topological L1 trigger processors
- High granularity L1 Calorimeter trigger.

**CMS**

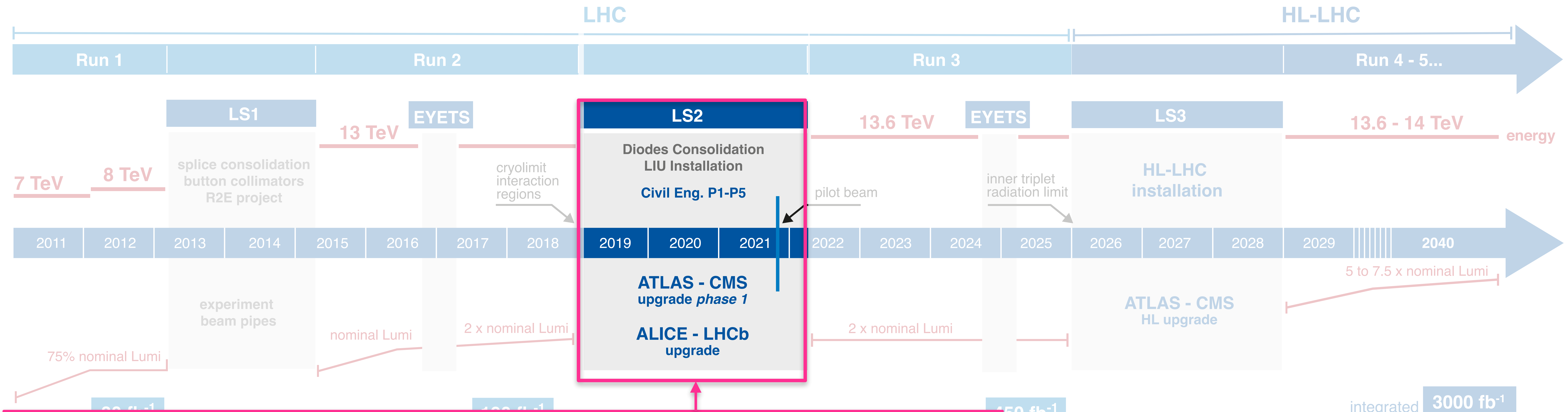
- L1 trigger upgrade
- HCAL electronics

Outcome of the 2013 European Strategy: HL-LHC!

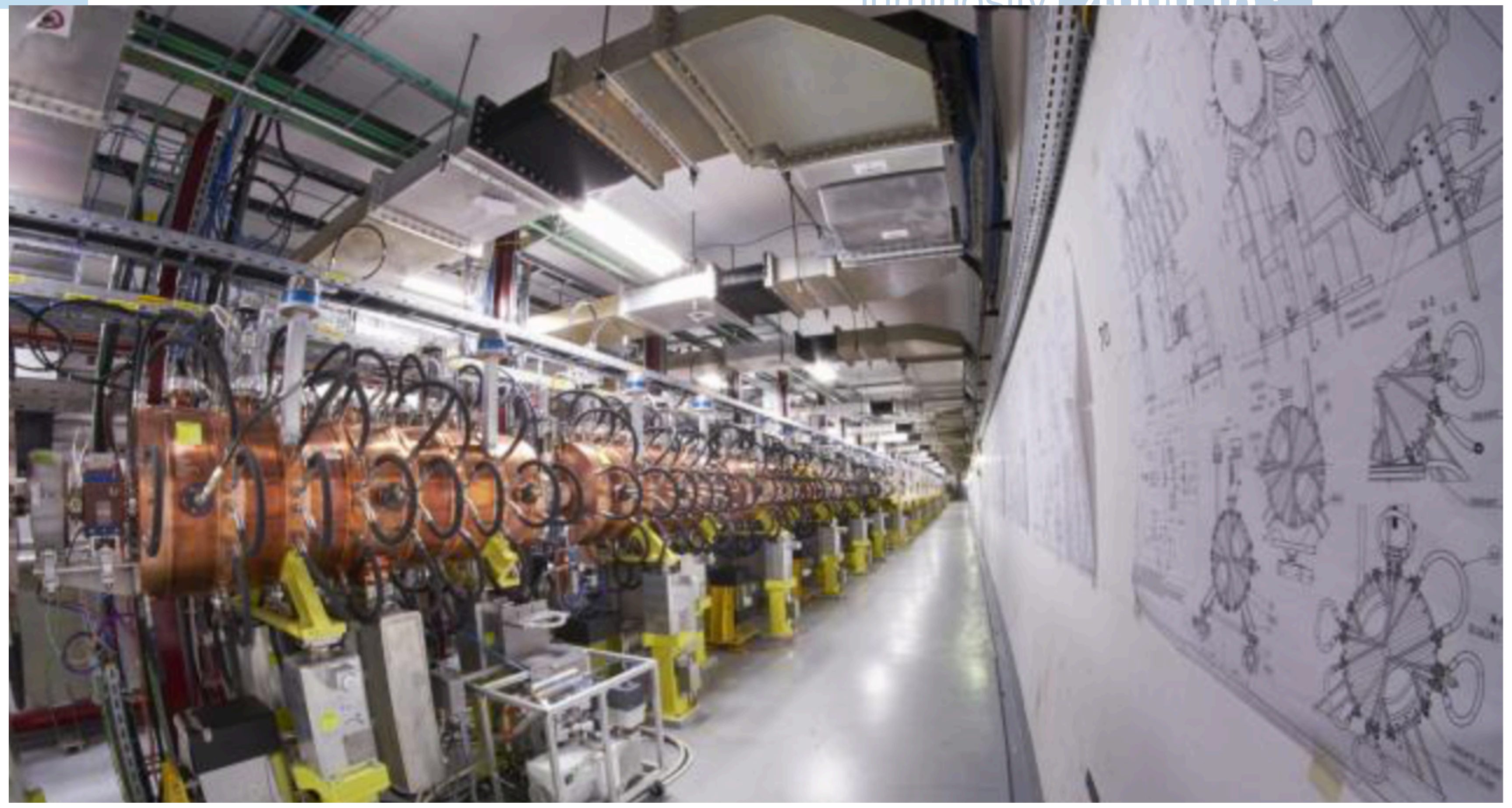
European Strategy 2012-2013 Recommendations

# The Long Shutdown 2 towards HL-LHC





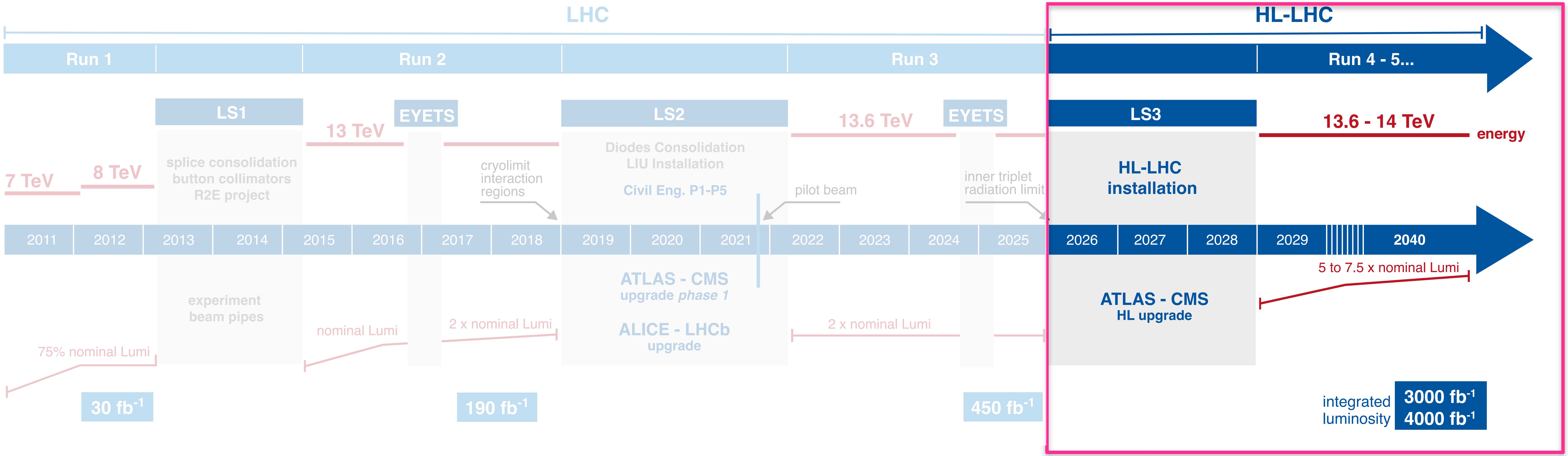

- LINAC 4: Extremely important milestone on the road towards higher luminosities (90 meters machine).
- « Crabbing protons » also one additional major step towards the High Luminosity, successfully tested at SPS.
- Ni3Sn ~100 magnet elements (dipoles and quadrupoles) with fields above 10T.
- TDIS (dump/absorber to protect downstream equipment)
- Collimation upgrades.
- Civil engineering at P1 - P5.

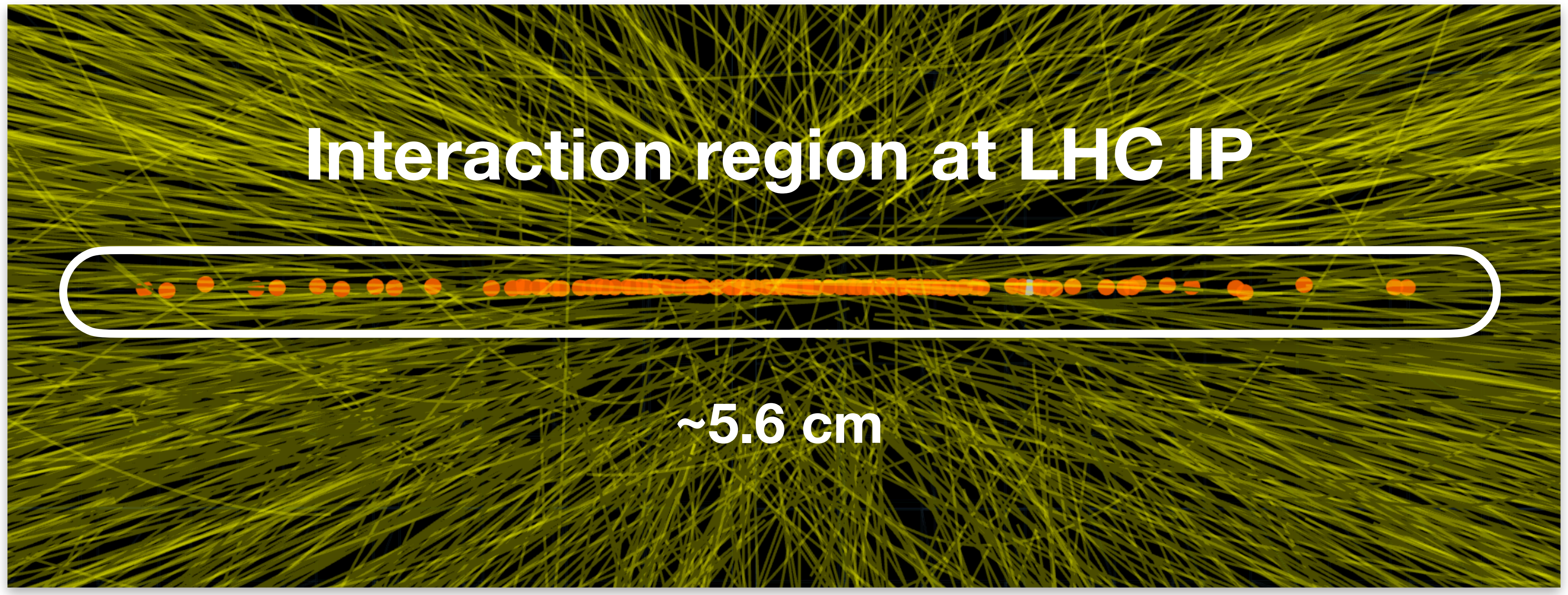


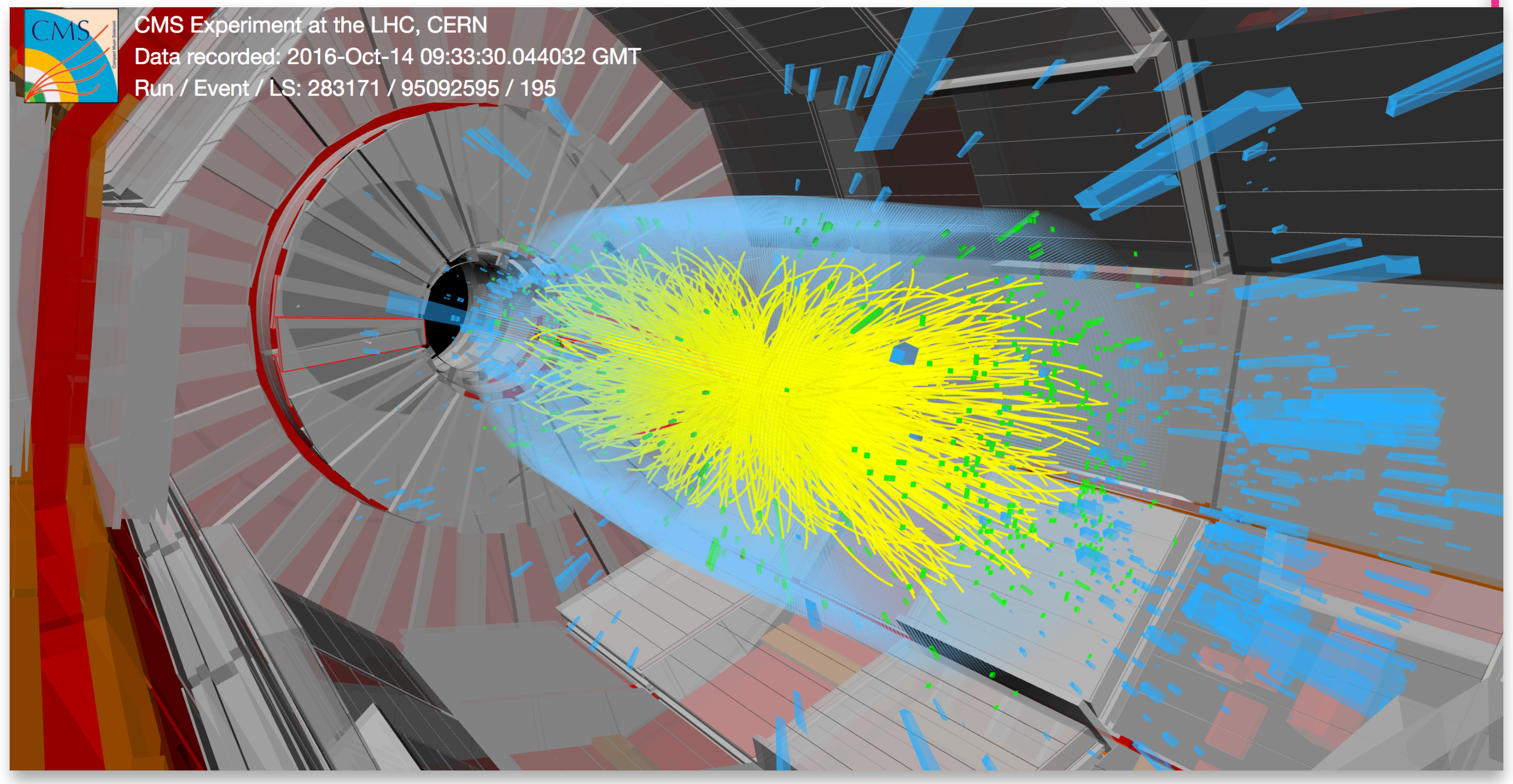
Will be accelerating negative Hydrogen ions. The electrons are stripped from the proton from the LINAC to the PS Booster (improves efficiency, intensity and quality).

# The next 20 Years of LHC: Towards HL-LHC





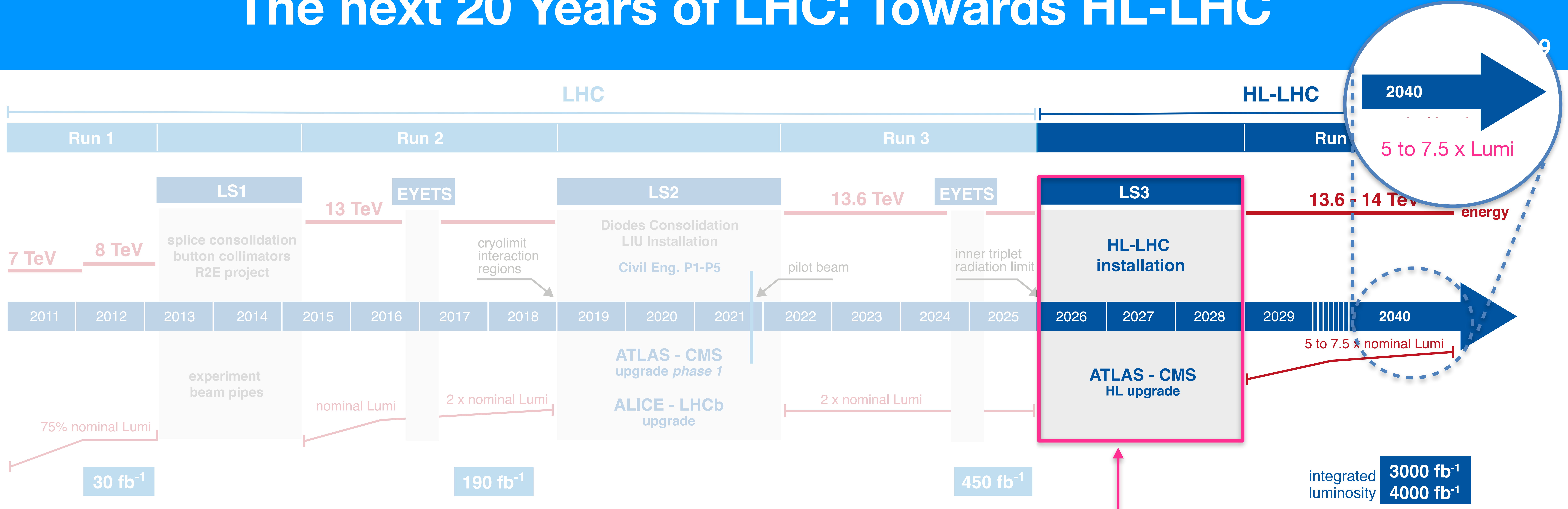




**5-7 times the nominal luminosity!**

At Run 2 average PU per event was approximately 40.

Expected PU at HL-LHC **140-200**

# The next 20 Years of LHC: Towards HL-LHC




**Phase 2** (Major **ATLAS** and **CMS** upgrades with deployment during LS3) **2024-2026**

**ATLAS**

- **Full Si tracker up to 4 (**with HW track trigger).
- Calorimeter electronics upgrade
- **Timing detector** with partial eta coverage (2.4 - 4) LGAD silicon: 30 ps resolution.
- Muon coverage (also possibly at LS4)

**CMS**

- **Strips and pixels replaced with higher granularity up to 3.8** (and HW trigger).
- New EndCap calorimeters HGCAL (High granularity) Silicon Pb/Steel 26 X0 and Scintillator/Steel 9 Int. Lengths.
- ECAL Barrel: New shaping with faster time rise to reach 30 ps timing resolution!
- **Full coverage timing** detector (up to eta 3) LGAD silicon: 30-40 ps resolution.

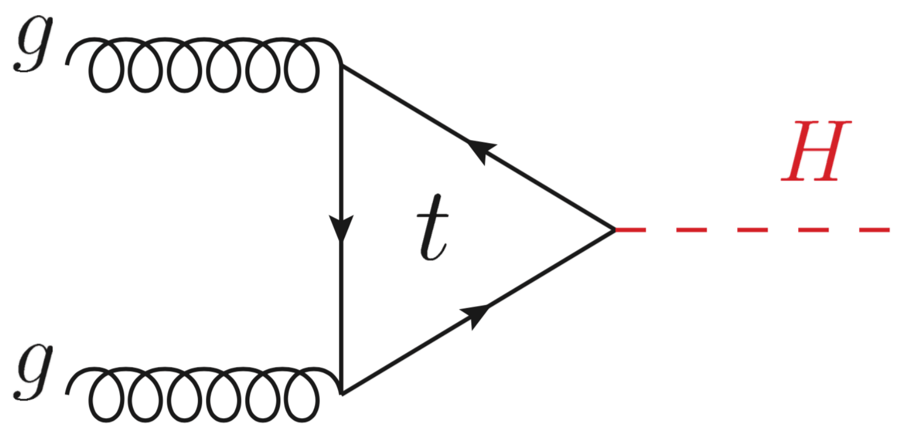
**Longer term** LS4 **2030**

Upgrades planned and under discussion

# Higgs boson (main) Production Modes

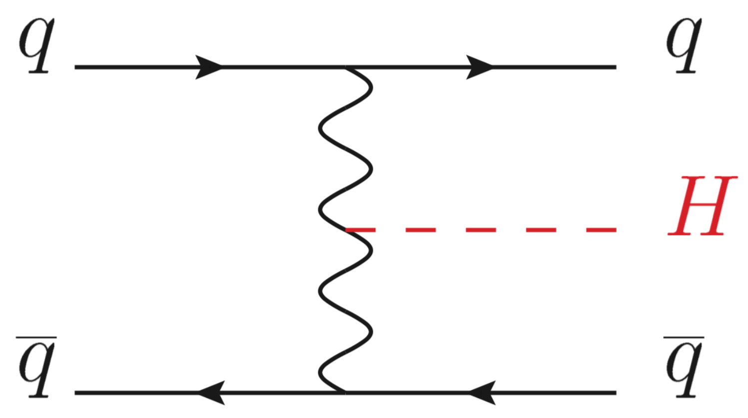


## Production rates at Run 2 (13 TeV) for ~150 fb$^{-1}$




**Gluon fusion process**

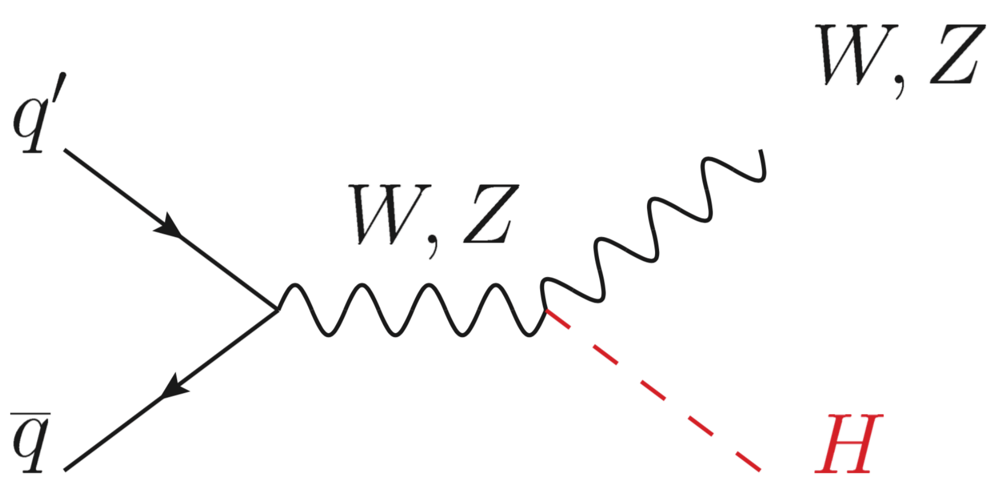
~8 M events produced




**Vector Boson Fusion**

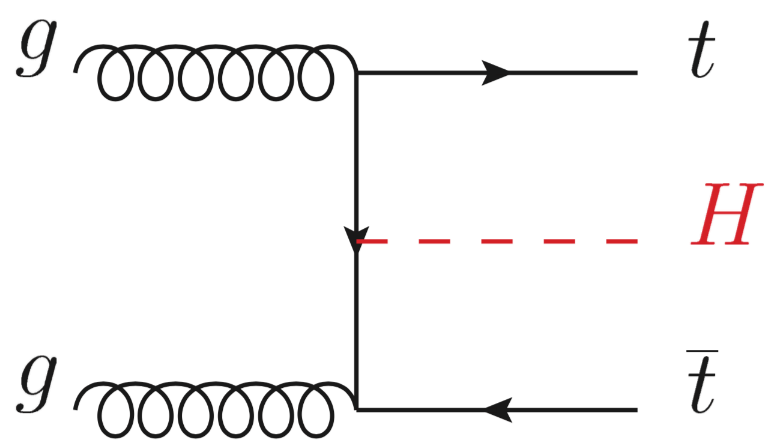
Two forward jets and a large rapidity gap

~600 k events produced




**W and Z Associated Production**

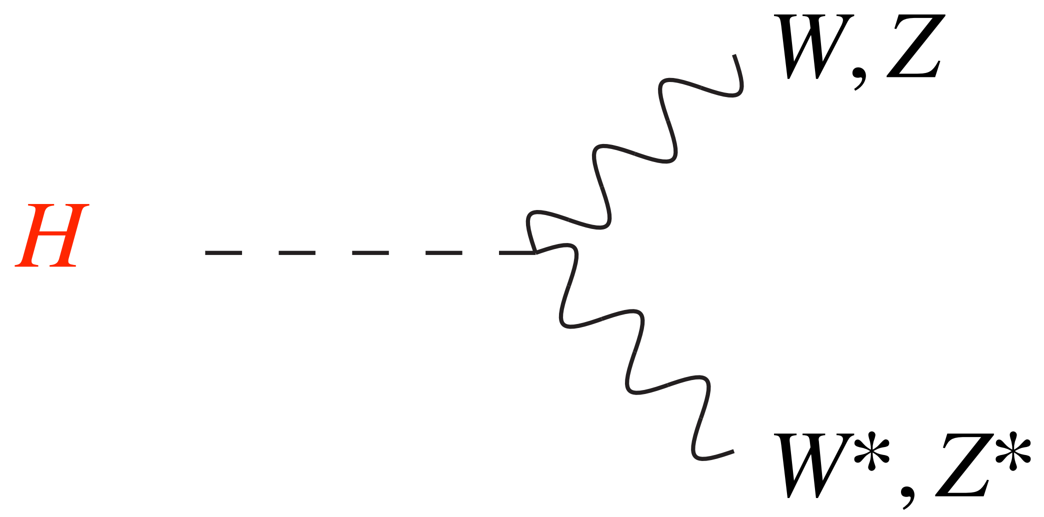
~400 k events produced




**Top Assoc. Prod.**

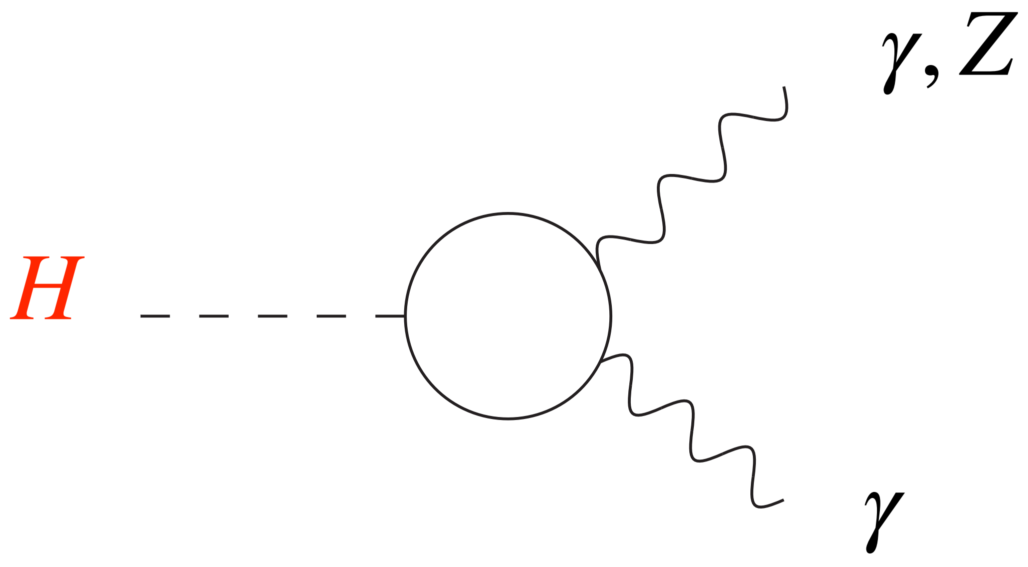
~80 k evts produced

## Decay branching fractions



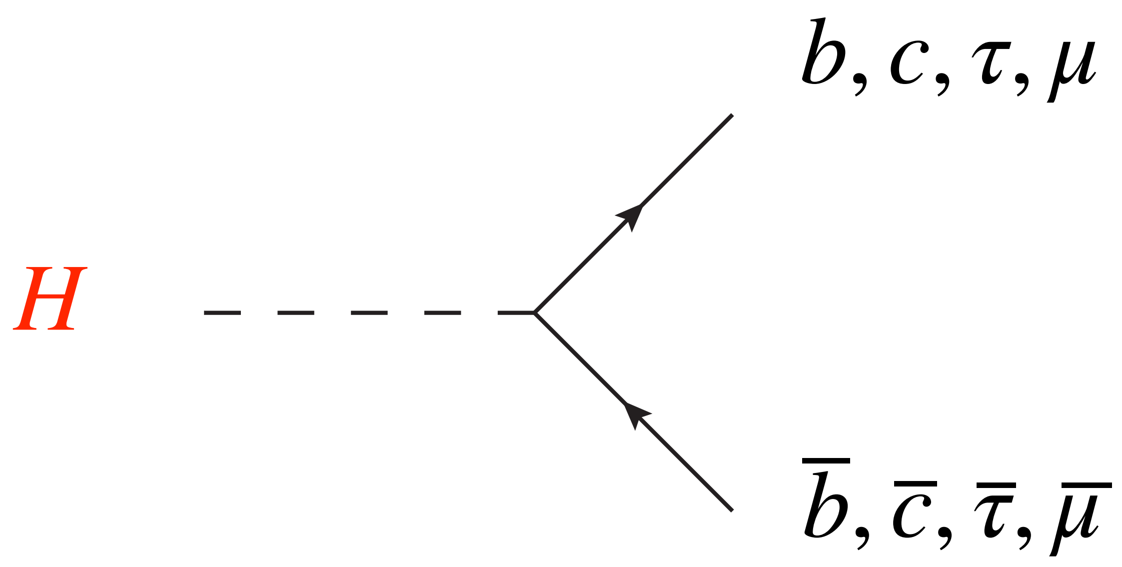

$\mathrm{Br}(H \to WW^*) = 22\,\%$

$\mathrm{Br}(H \to ZZ^*) = 3\,\%$




$\mathrm{Br}(H \to \gamma\gamma) = 0.2\,\%$

$\mathrm{Br}(H \to Z\gamma) = 0.2\,\%$




$\mathrm{Br}(H \to b\bar{b}) = 57\,\%$

$\mathrm{Br}(H \to \tau^+\tau^-) = 6.3\,\%$

$\mathrm{Br}(H \to c\bar{c}) = 3\,\%$

$\mathrm{Br}(H \to \mu^+\mu^-) = 0.02\,\%$

# Higgs Physics at the LHC



Outcome of the 2013 European Strategy: HL-LHC!

European Strategy 2012-2013 Recommendations

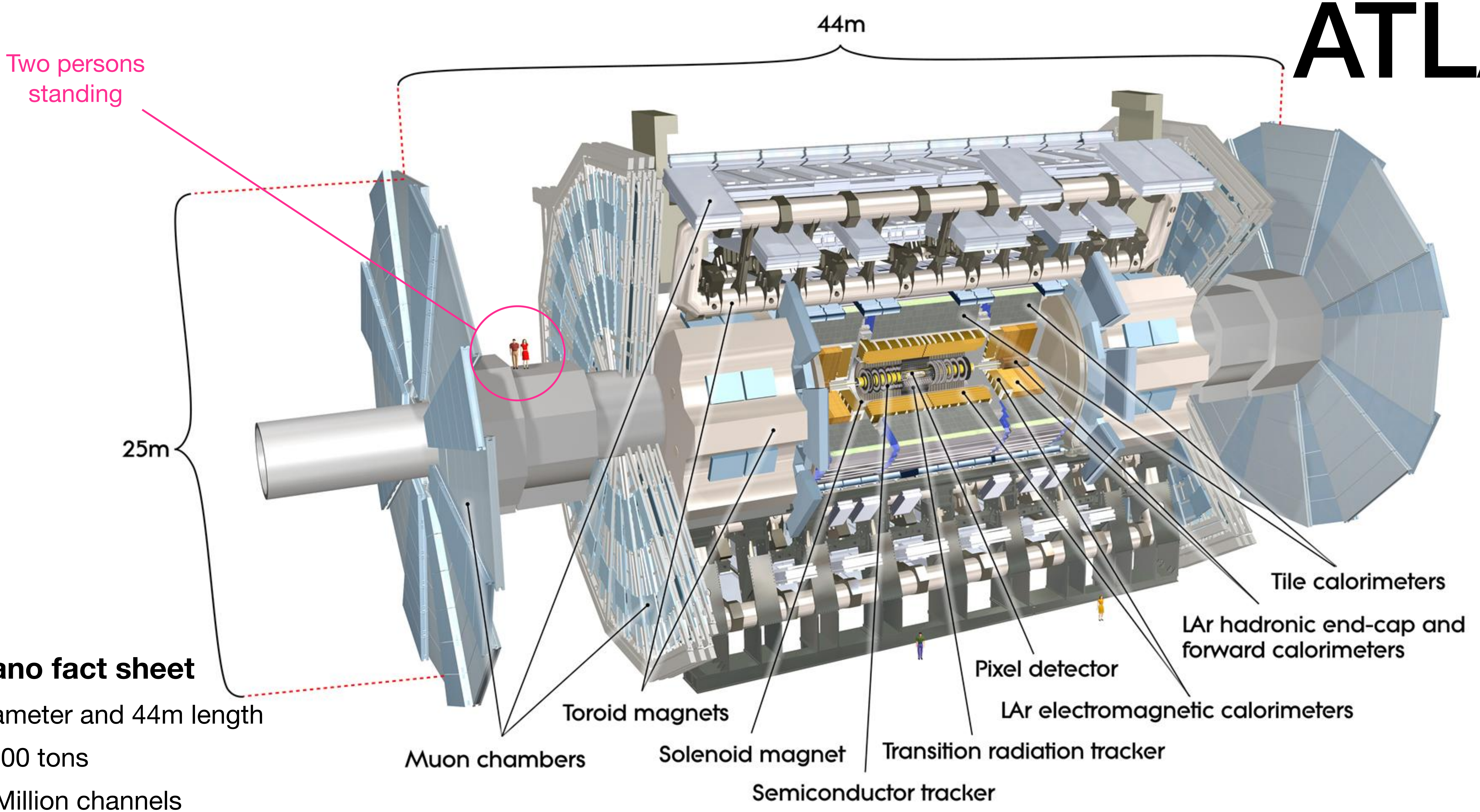
**HL-LHC** is a **Higgs factory** ~160 M Higgs events

In comparison Future ee up to ~1.3 M Higgs Events, but much cleaner and « usable » events

| Process | ggF | HH | ttH |
|---|---|---|---|
| **13 TeV / 8 TeV** | **2.3** | **2.4** | **3.9** |
| **13.6 TeV / 13 TeV** | **7%** | **11%** | **13%** |
| 14 TeV / 13.6 TeV | 6% | 7% | 7% |

# Detectors to search for the Higgs Boson

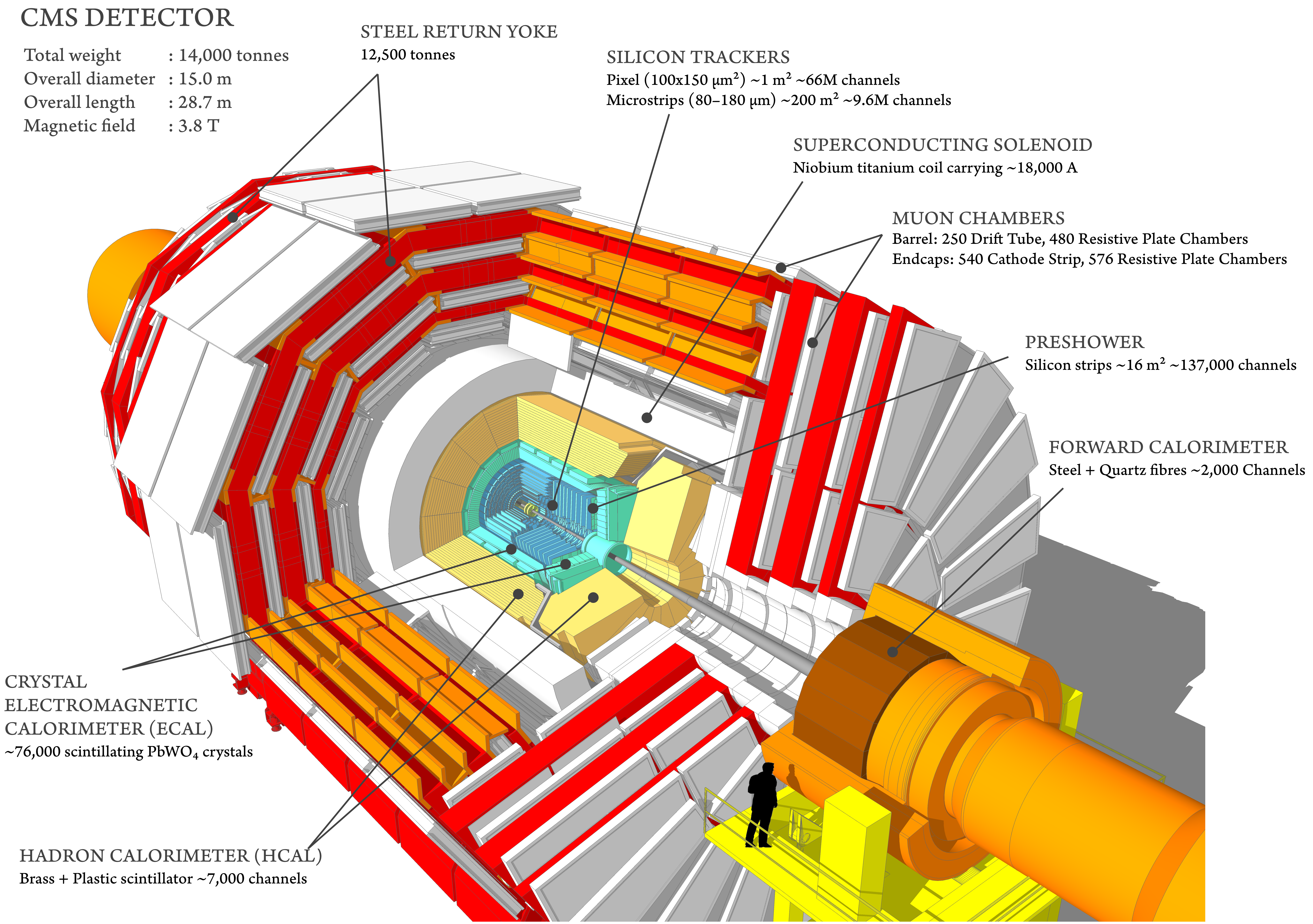
# ATLAS




**ATLAS nano fact sheet**

- 25m Diameter and 44m length
- Over 7000 tons
- O(100) Million channels

# Detectors to search for the Higgs Boson



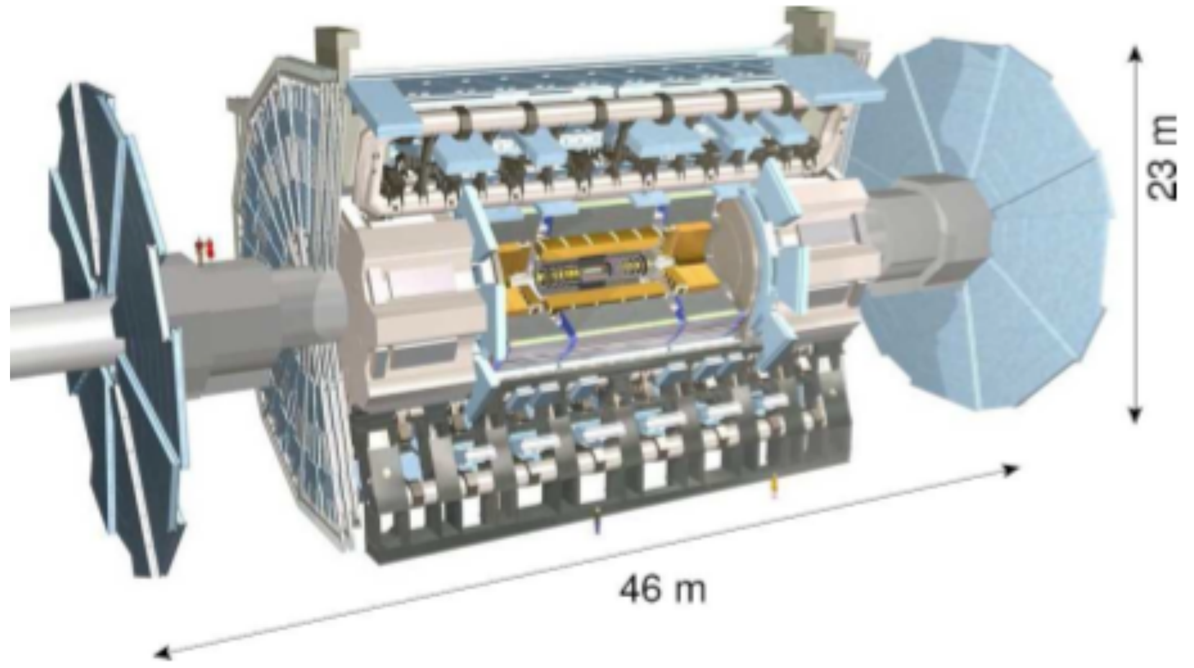
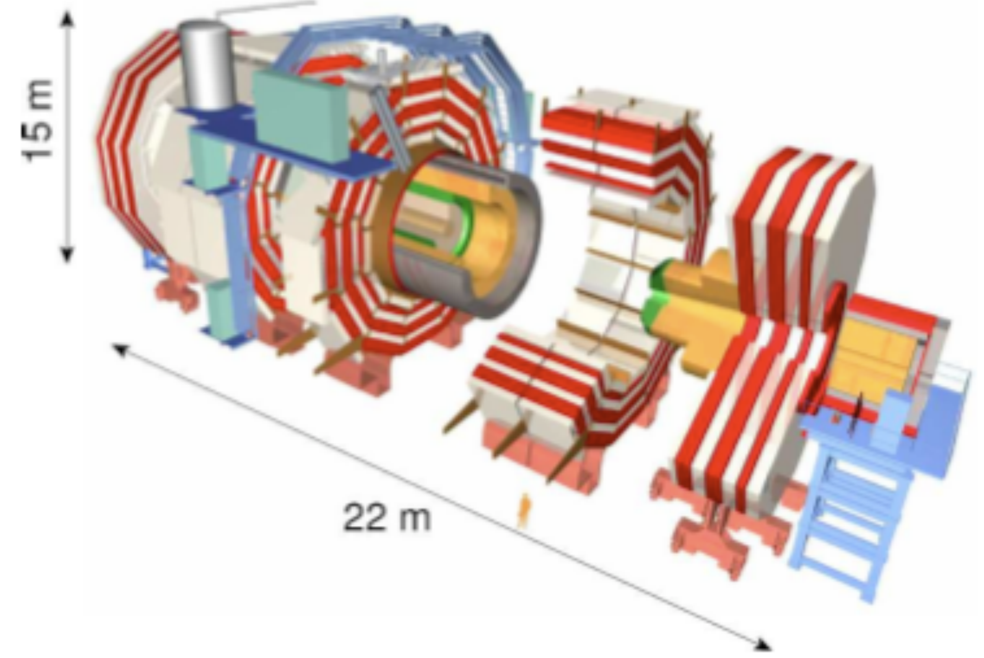

# CMS

Each experiments needs to read out and reconstruct approximately O(100M) electronics channels with crossings at ~30 MHz to take a decision whether to keep or to remove the event **(Trigger)**

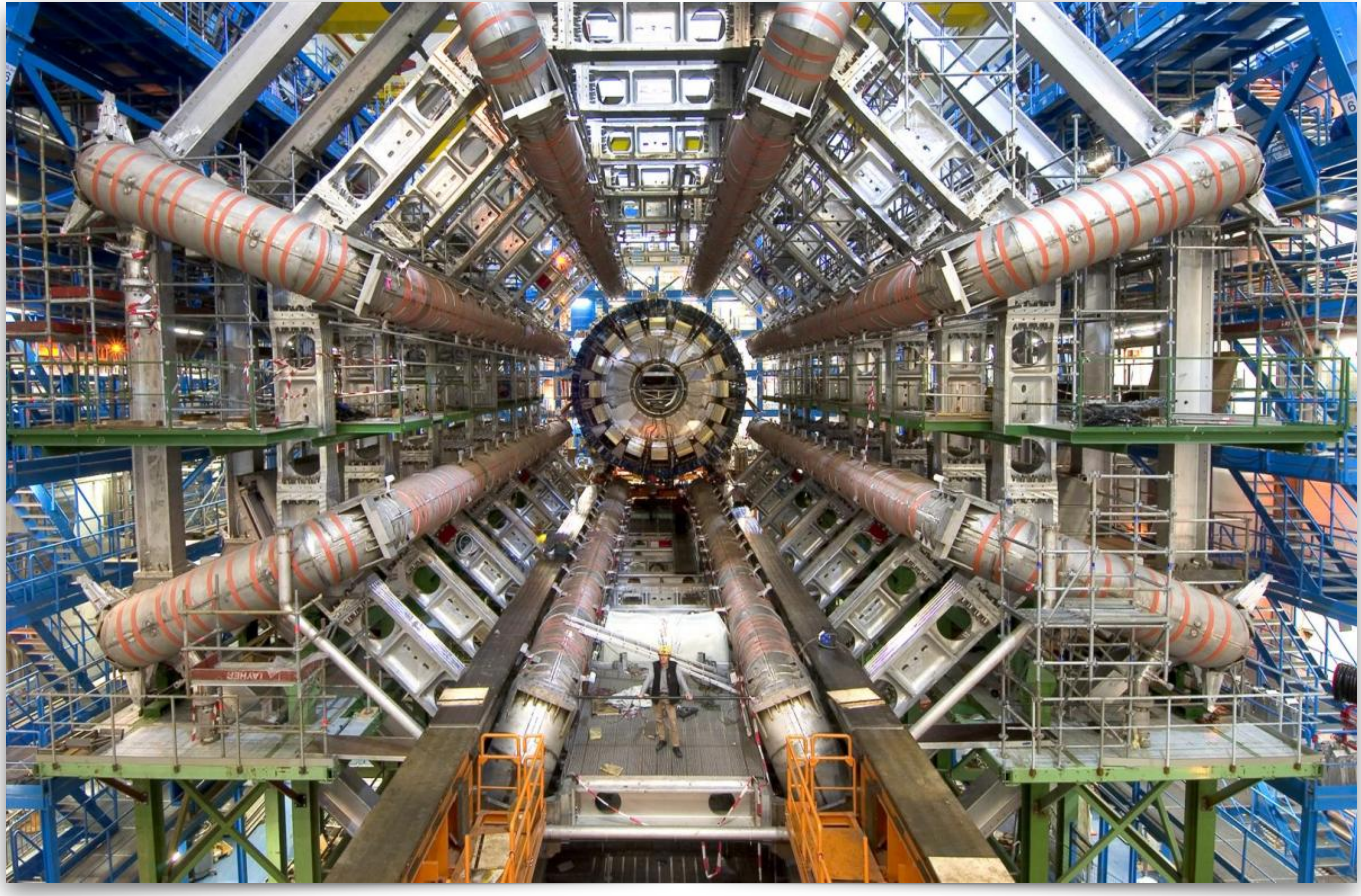
Keep approximately 1kHz and reconstruct more finely the event

Fast and efficient decision as crucial !

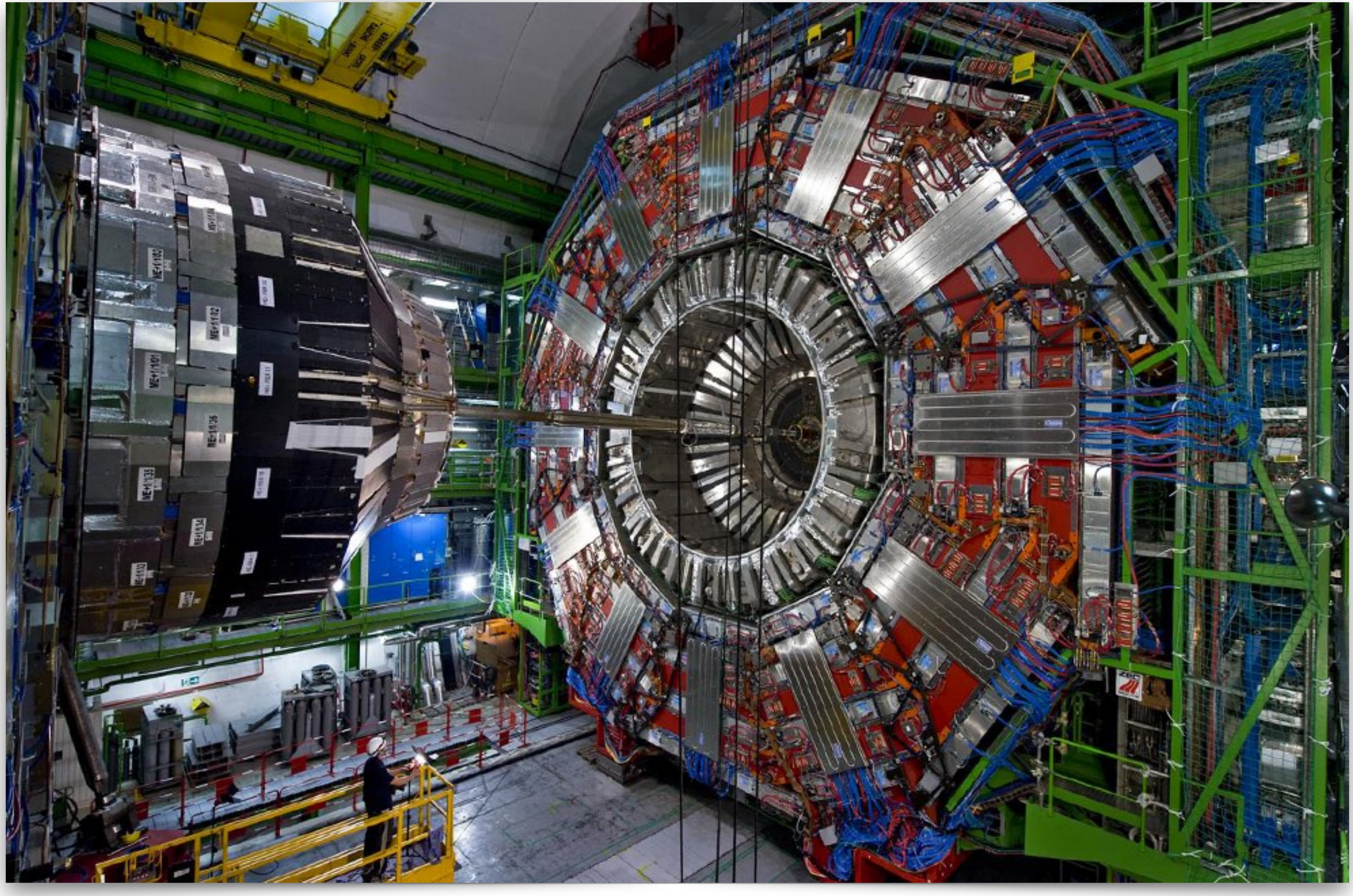
# ATLAS and CMS in a Nutshell

| Sub System | ATLAS | CMS |
|---|---|---|
| Design |  |  |
| Magnet(s) | Solenoid (within EM Calo) 2T<br>3 Air-core Toroids | Solenoid 3.8T<br>Calorimeters Inside |
| Inner Tracking | Pixels, Si-strips, TRT<br>PID w/ TRT and dE/dx<br>$\sigma_{p_T}/p_T \sim 5 \times 10^{-4} p_T \oplus 0.01$ | Pixels and Si-strips<br>PID w/ dE/dx<br>$\sigma_{p_T}/p_T \sim 1.5 \times 10^{-4} p_T \oplus 0.005$ |
| EM Calorimeter | Lead-Larg Sampling<br>w/ longitudinal segmentation<br>$\sigma_E/E \sim 10\%/\sqrt{E} \oplus 0.007$ | Lead-Tungstate Crys. Homogeneous<br>w/o longitudinal segmentation<br>$\sigma_E/E \sim 3\%/\sqrt{E} \oplus 0.5\%$ |
| Hadronic Calorimeter | Fe-Scint. & Cu-Larg (fwd) $\gtrsim 11\lambda_0$<br>$\sigma_E/E \sim 50\%/\sqrt{E} \oplus 0.03$ | Brass-scint. $\gtrsim 7\lambda_0$ & Tail Catcher<br>$\sigma_E/E \sim 100\%/\sqrt{E} \oplus 0.05$ |
| Muon Spectrometer System<br>Acc. ATLAS 2.7 & CMS 2.4 | Instrumented Air Core (std. alone)<br>$\sigma_{p_T}/p_T \sim 4\,\%$ (at 50 GeV)<br>$\sim 11\,\%$ (at 1 TeV) | Instrumented Iron return yoke<br>$\sigma_{p_T}/p_T \sim 1\%$ (at 50 GeV)<br>$\sim 10\%$ (at 1 TeV) |

# The Ultimate Microscopes : ATLAS



# The Ultimate Microscopes : CMS



# Trigger, DAQ and Software Challenges



- **Read out and reconstruct** approximately **O(100M)** electronics channels at ~1 kHz. *Raw event size 1.5 MB*

- **Trigger Challenge** : select ~400-1000 out of 20M events per second while keeping the interesting (including unknown) physics

- **Computing Challenge** : reconstruct, store and distribute 1000 complex events per second and the very large amount of simulation (over 150 PB per experiment - Several farms of up to 400k Cores).

- **Analysis Challenge** : Maintain high (and as much as possible stable) reconstruction and identification efficiency.

- **Deep Learning** : Ideal environment to develop Machine Learning techniques: in particular in areas such as trigger, reconstruction, object identification, calibration and Pile up Mitigation.

CERN Computing Center

# Performance Achievements: Trigger



- Run 1 and Run 2: So far excellent trigger and object reconstruction performance in **increasing levels of PU**. Trigger Thresholds kept relatively stable throughout.

- The gain in acceptance and in performance with new detectors (to improve PU mitigation), new algorithms and new computing capabilities is expected to at least match current experimental performance.
    - Keeping Trigger thresholds at similar levels
    - Object reconstruction performance (efficiency vs rejection and energy scale and resolution) at stable levels.
    - Challenge to come: improve calibrations not only with more data to come but also improved strategies.

**Menus at LHC and for HL-LHC**

| Signature | Run 1 | Run 2 | HL-LHC |
|---|---|---|---|
| Single e (isolated) | 25 | 27 | 22 / 27 |
| Single photon | 120 | 140 | 120* |
| HT | 700 | 700 | 375 / 350 |
| MET | 150 | 200 | 200 |

From A. Sfyrla LHCP 2018

- Increase readout rate 750-1000 kHz (currently 100 kHz).
- Increased latency and higher granularity.
- Enhanced data processing capabilities, storage rate up to 10 kHz (currently 1-2 kHz).

# Performance Achievements: Object Reconstruction



**Electrons, photons and muons**

- Multivariate methods used for identification (at many levels) and calibration
- In-situ calibration using Z, W, J/Psi and Upsilons

**Jets/MET**

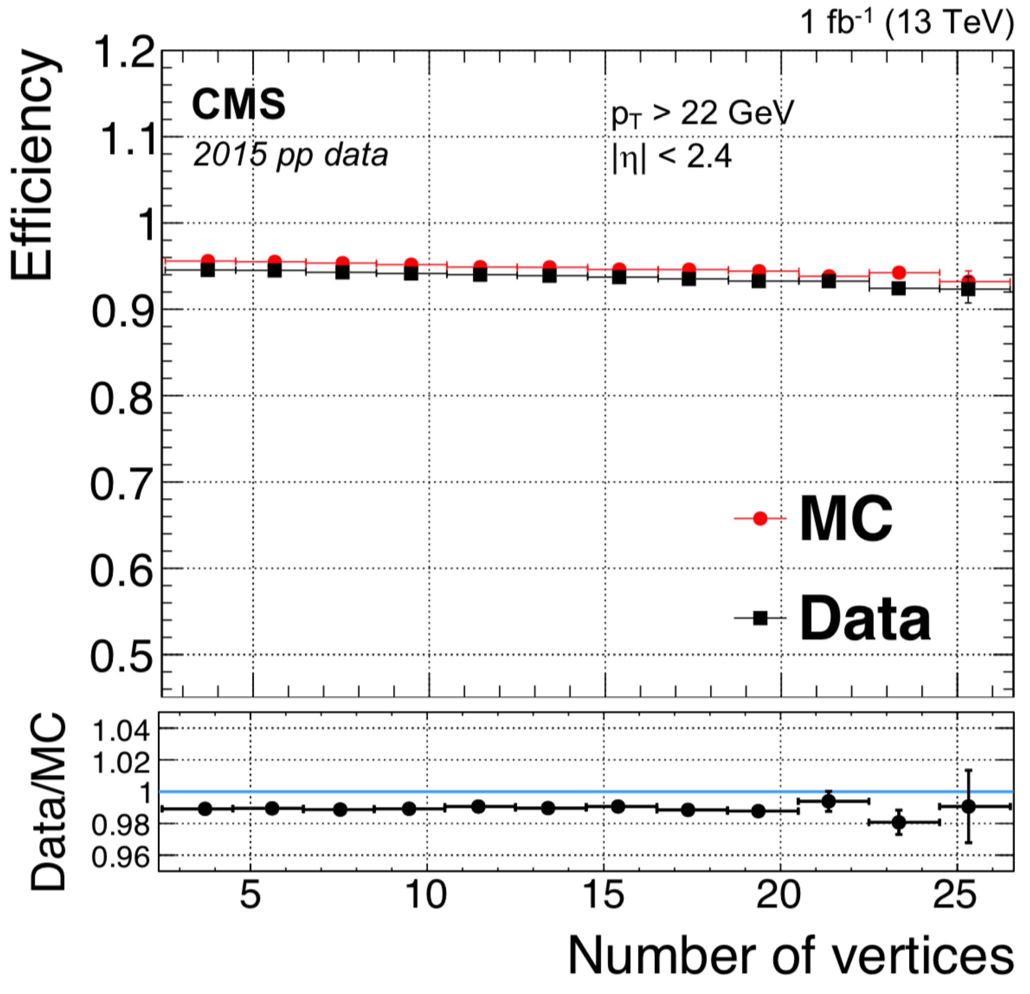
- JES *in situ* uncertainty reach ~1% level already (central and intermediate pT range) – using Z, γ and multi-jets.
- PU mitigation using associated tracks (jets and soft term in MET)

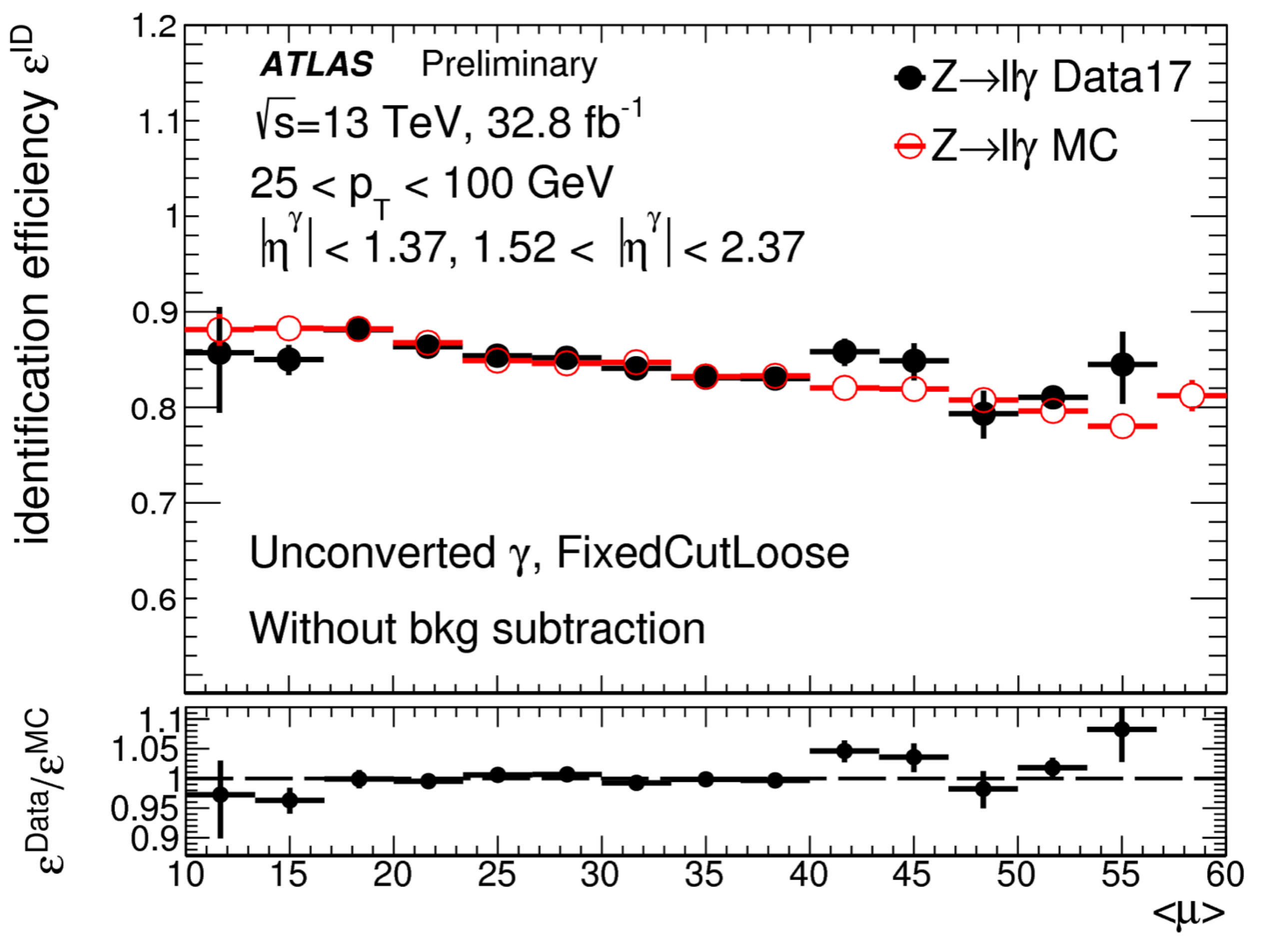
**Taus**

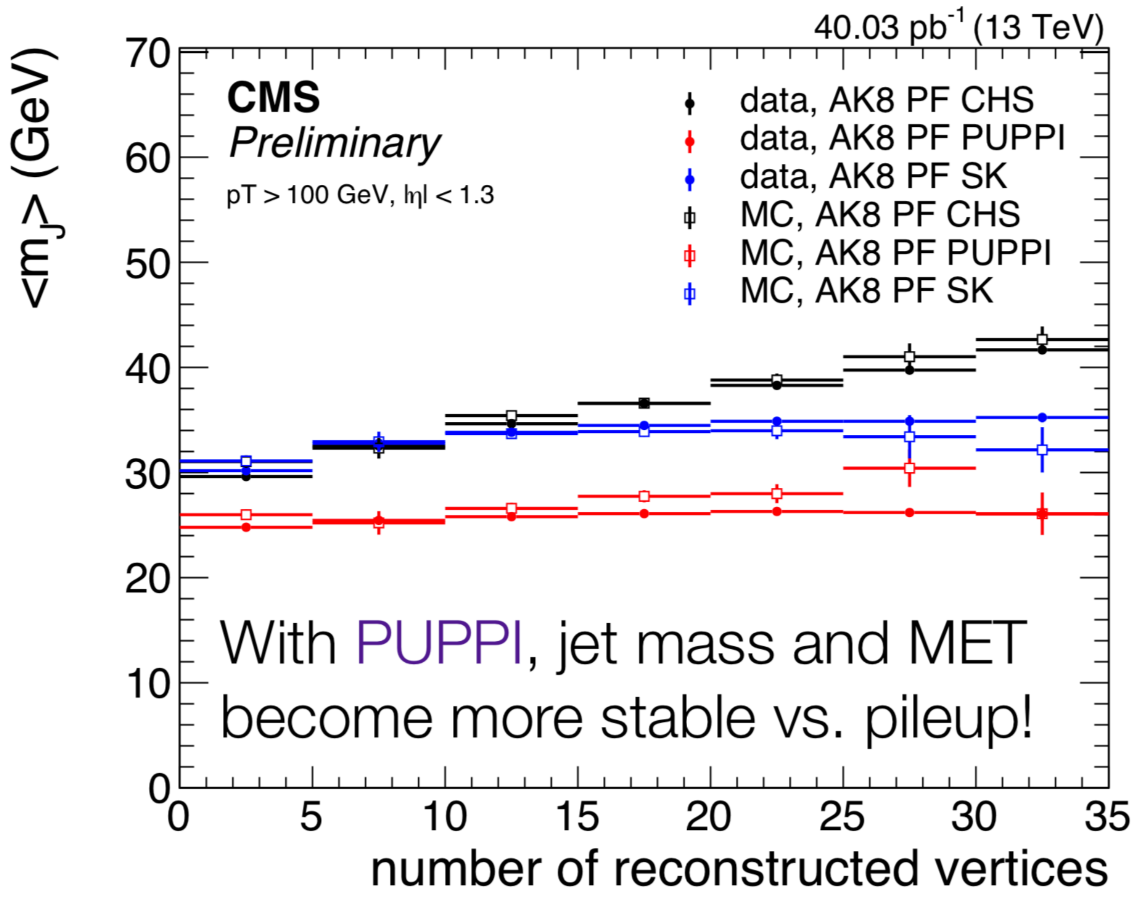
- BDT and RNN based identification (70% eff. and ~50 rej.)
- In-situ calibration based on Z events

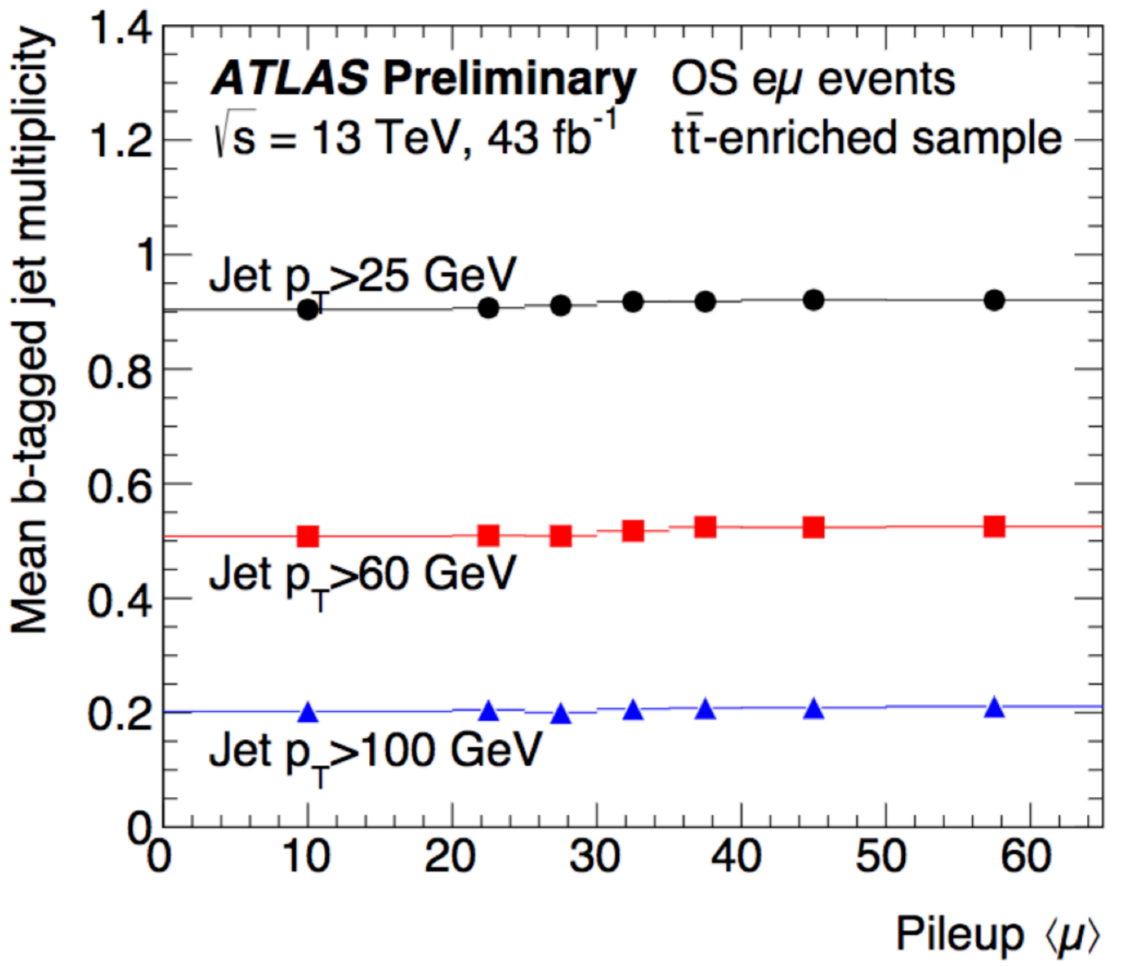
**B- and C-jets**

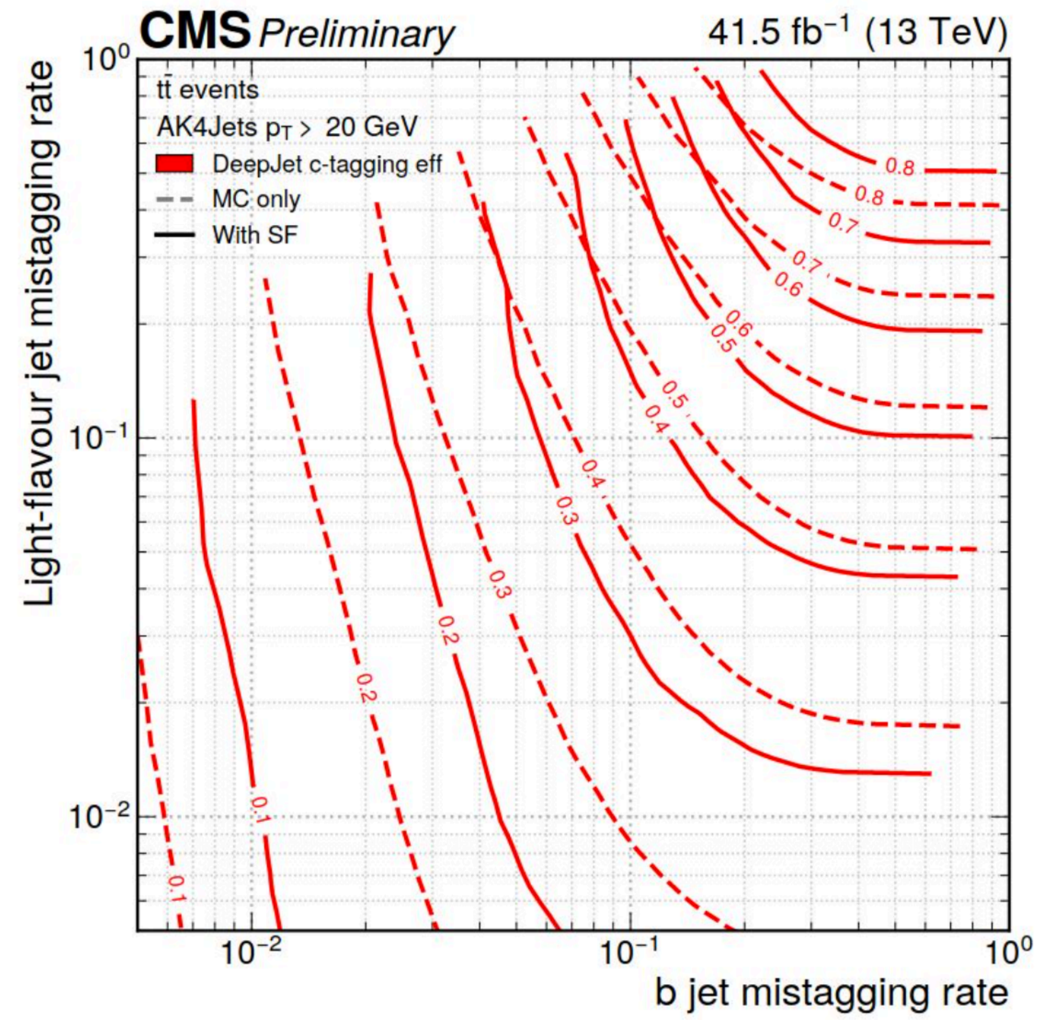
- In-situ calibration of b-tag efficiency (using top events and/or diet events)
- DL techniques from low level variables bring significant improvements

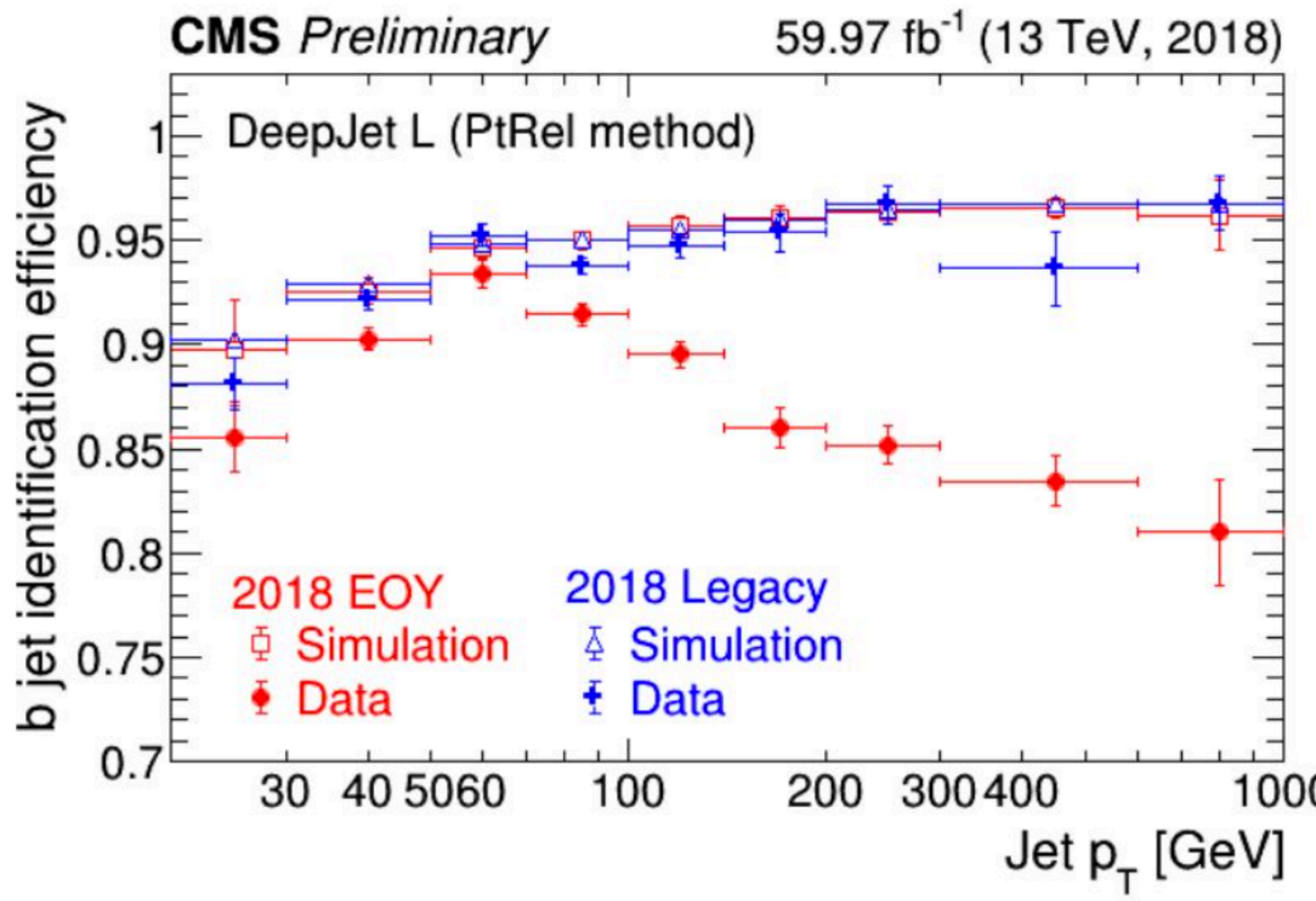


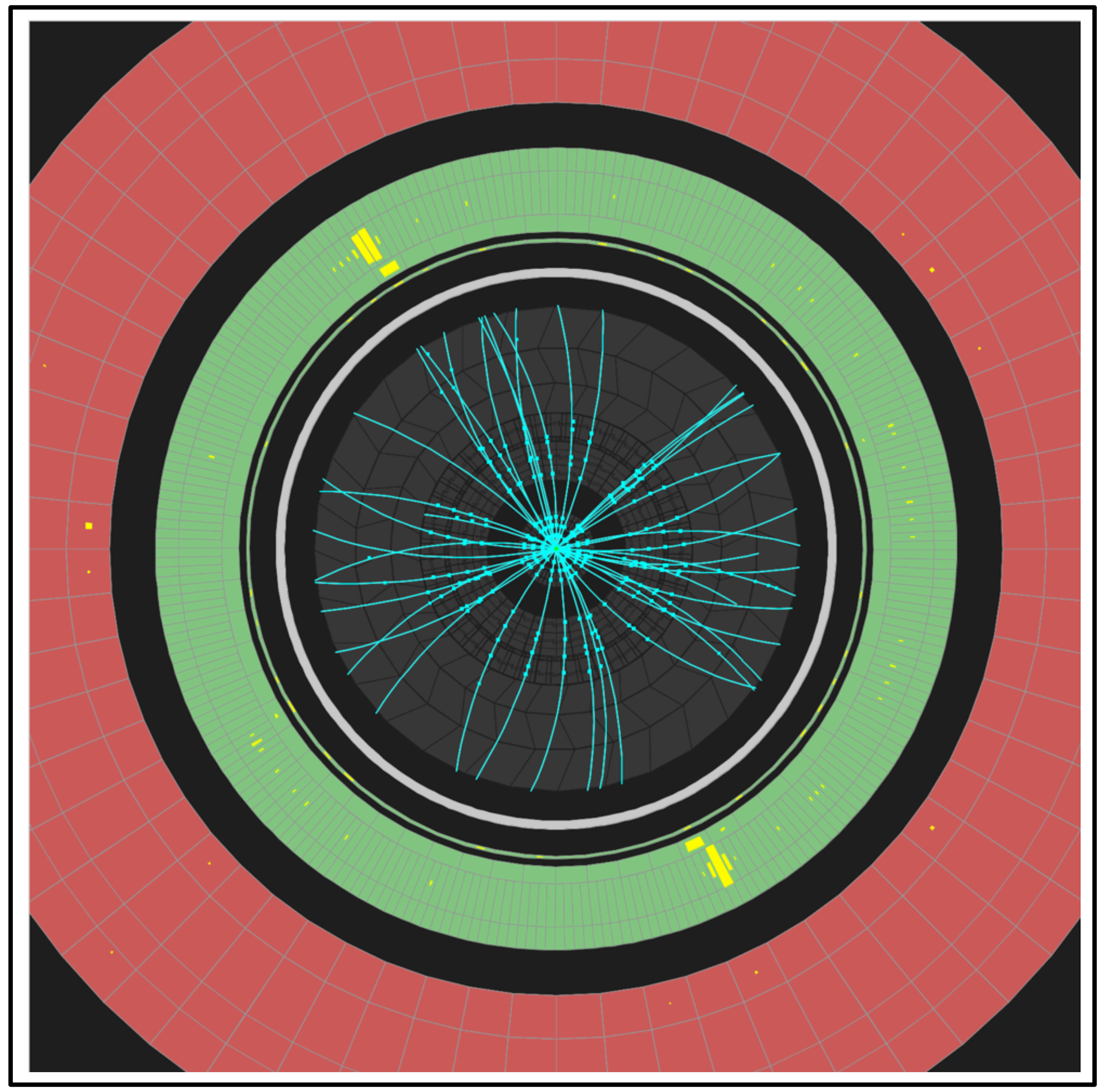




**Reconstruction performance so far well calibrated and robust to PU!!**

# 1.- The Higgs discovery

# The Discovery Channels

## « Bread and Butter » Mass peak signals: the diphoton channel

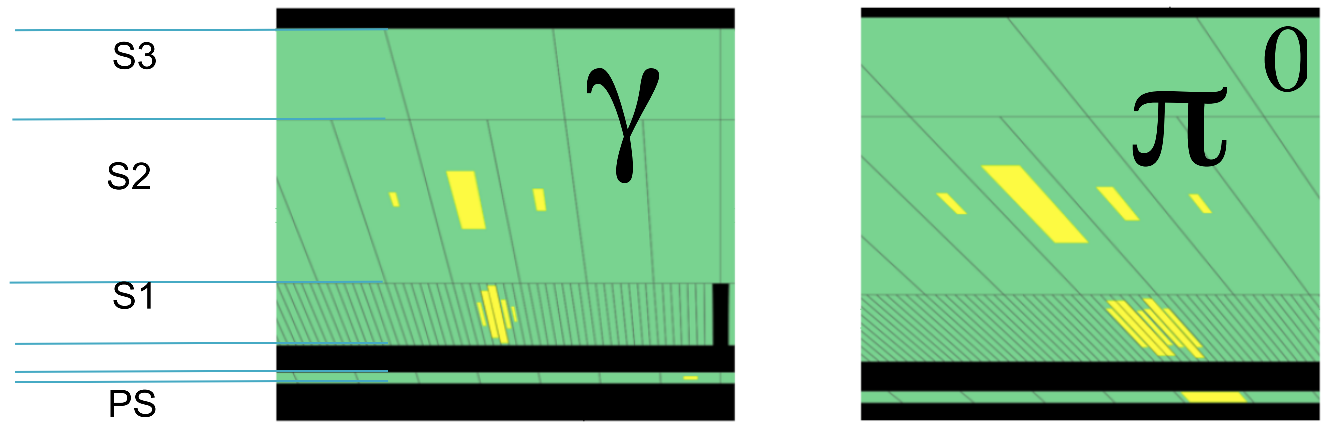


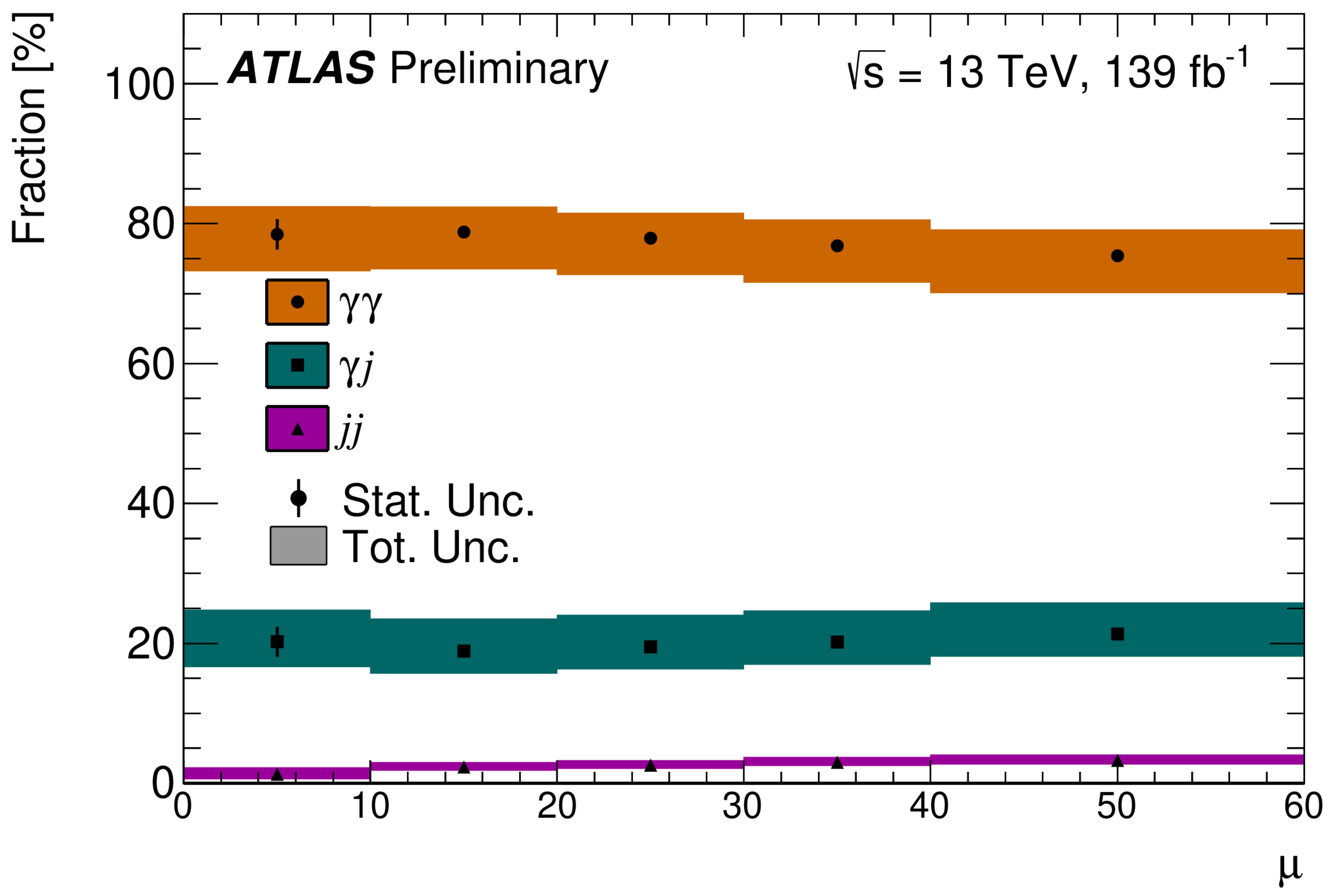
**Large (reducible) background from jets!**

**Granularity is key!**

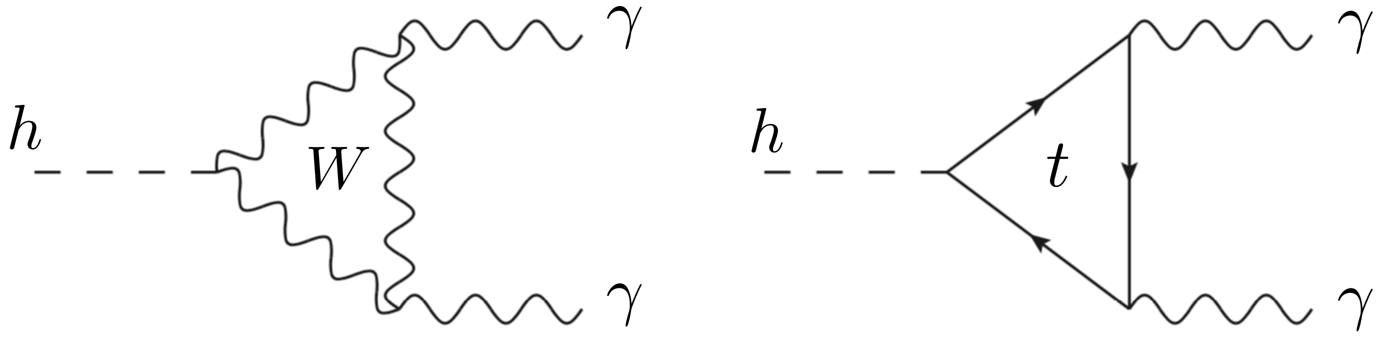
Requires a rejection of jets of ~10,000
- Photon – Pion discrimination
- Pointing direction reconstruction (helps in mass resolution!)

$\pi^0$-$\gamma$ Rejection



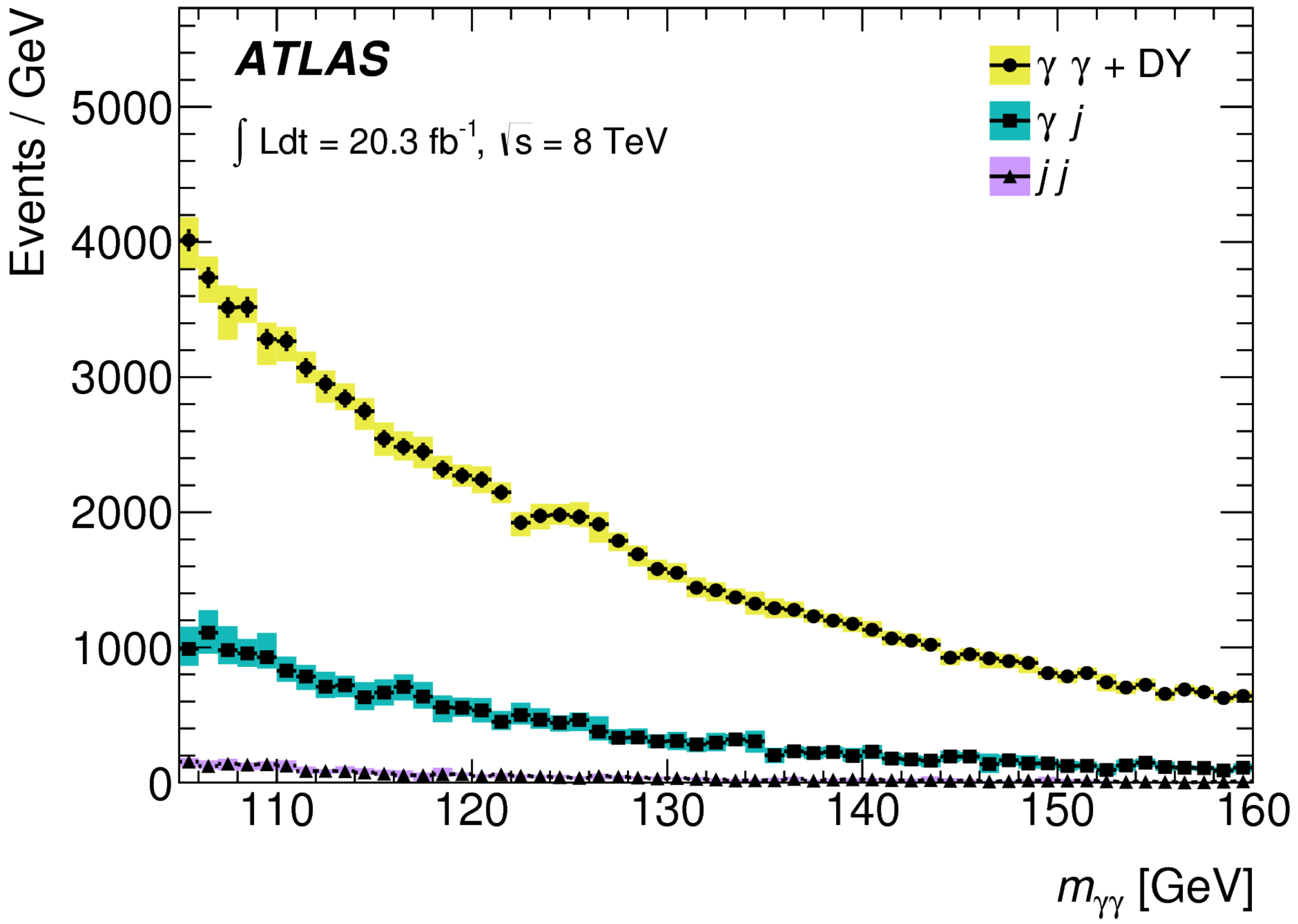




Main production and decay processes occur through loops :




Excellent probe for new physics !

Latest ATLAS results from our full Run 2 LHC Dataset (see CONF note)



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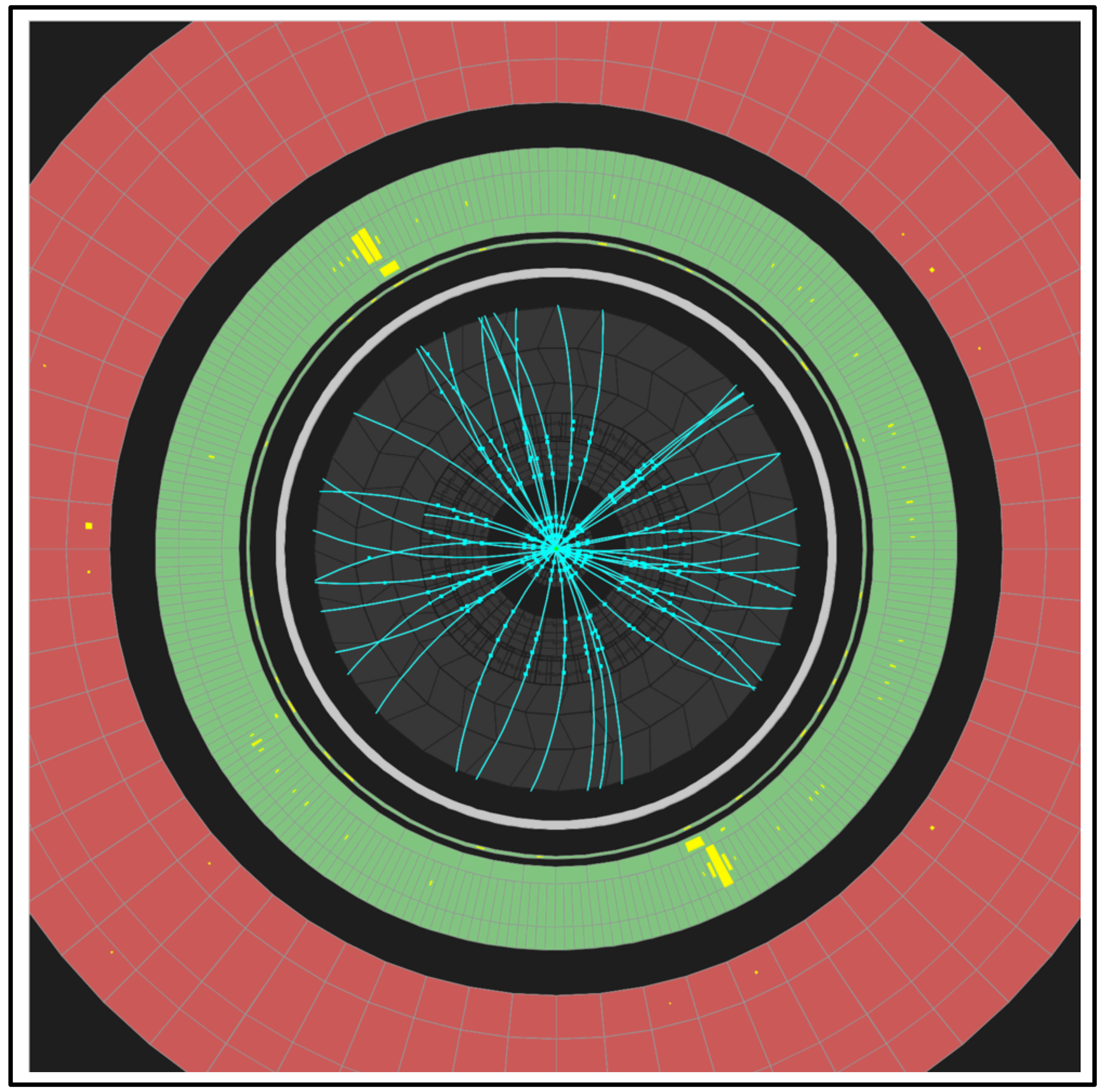

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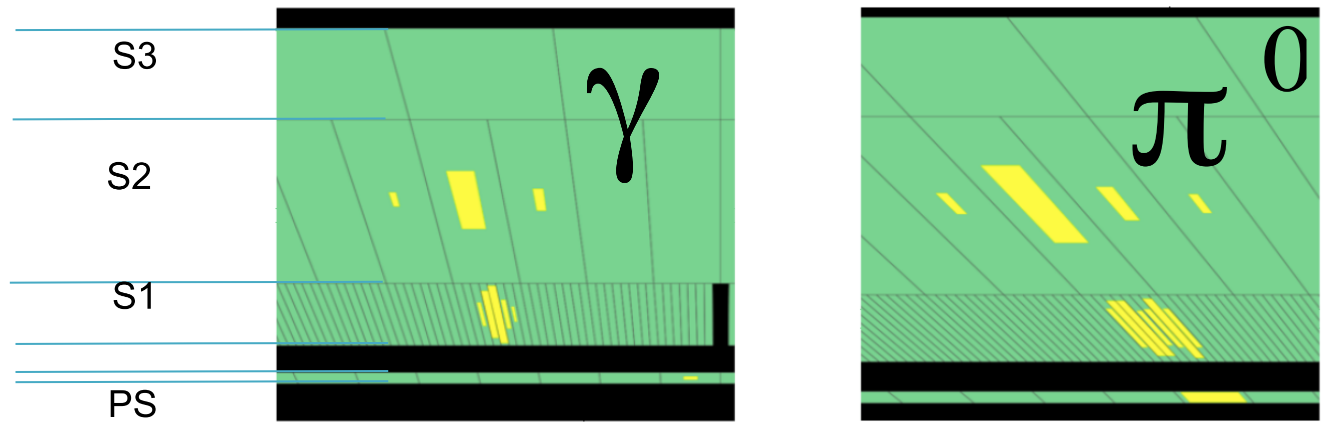
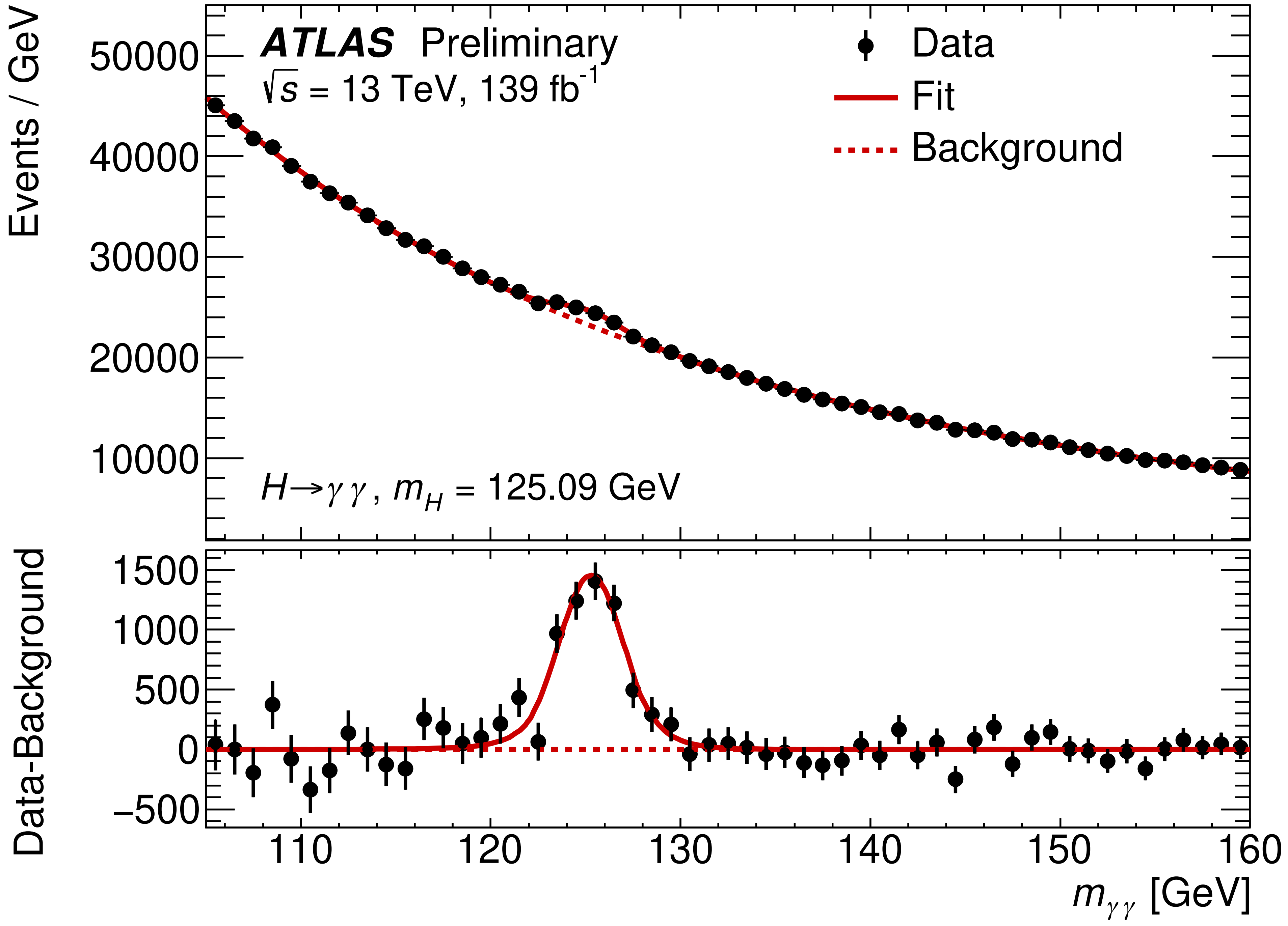



**Energy resolution is key!**

- High mass resolution channel O(1%) allowing data driven estimates of background in the sidebands.

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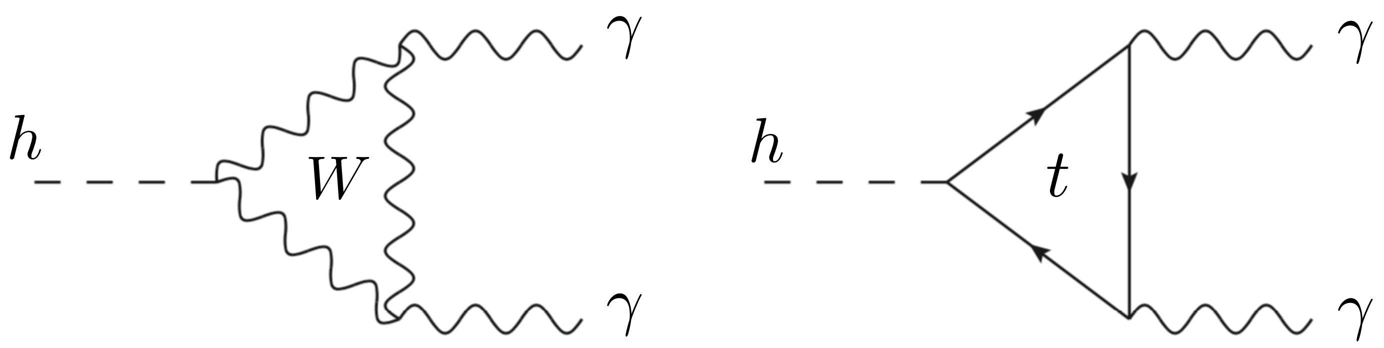


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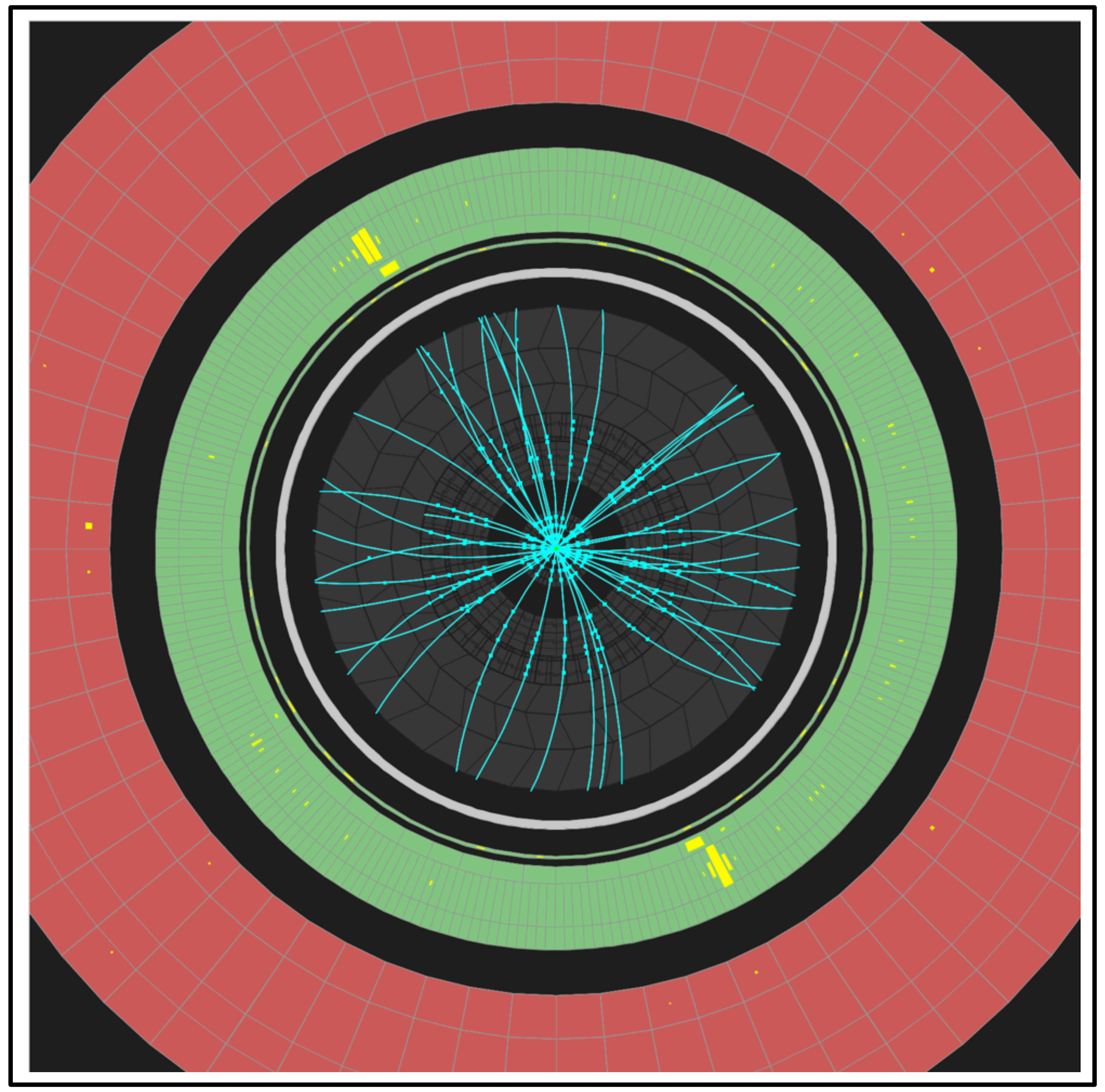

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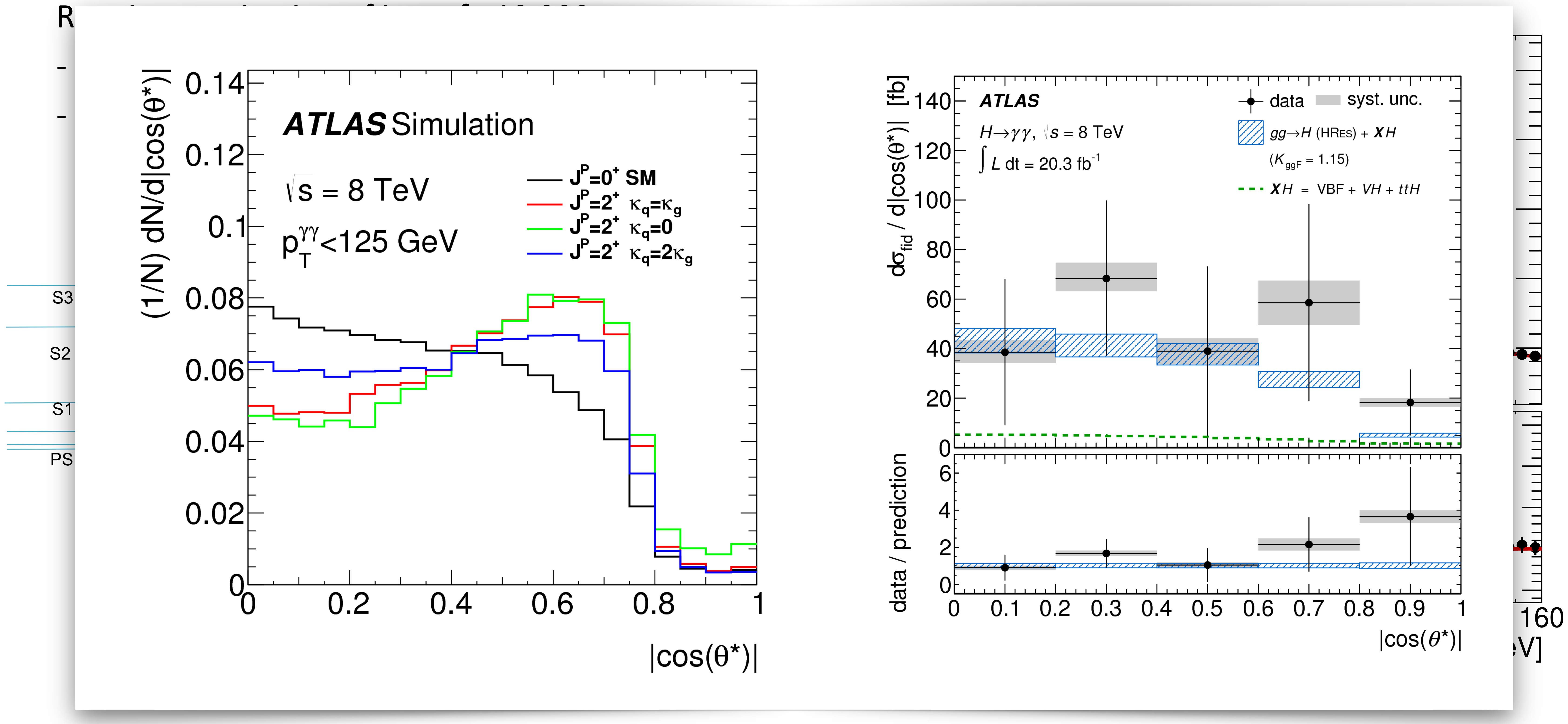
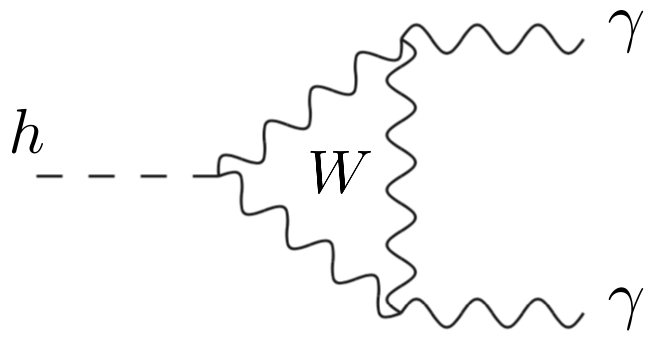
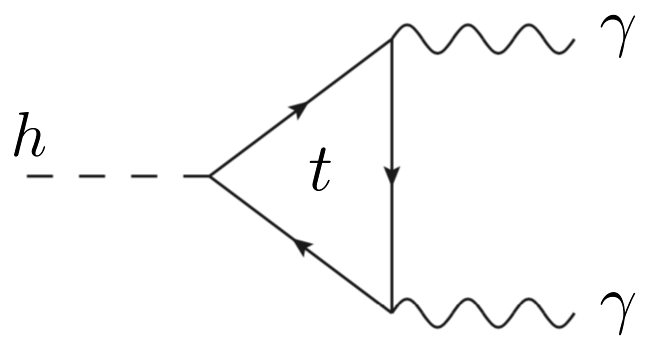



Main production and decay processes occur through loops :



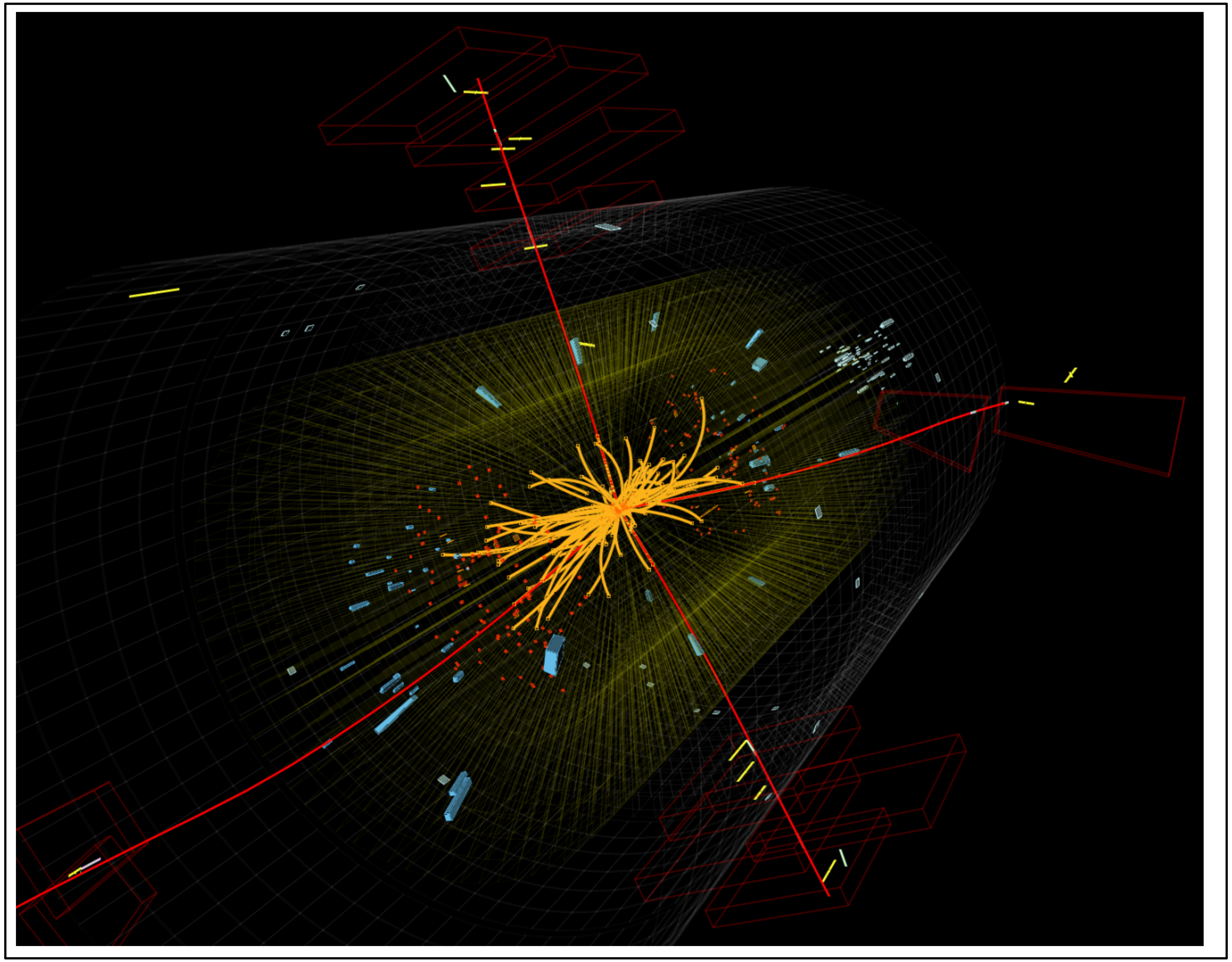

Excellent probe for new physics !

ATLAS results from our full Run 2 LHC Dataset (see CONF note)

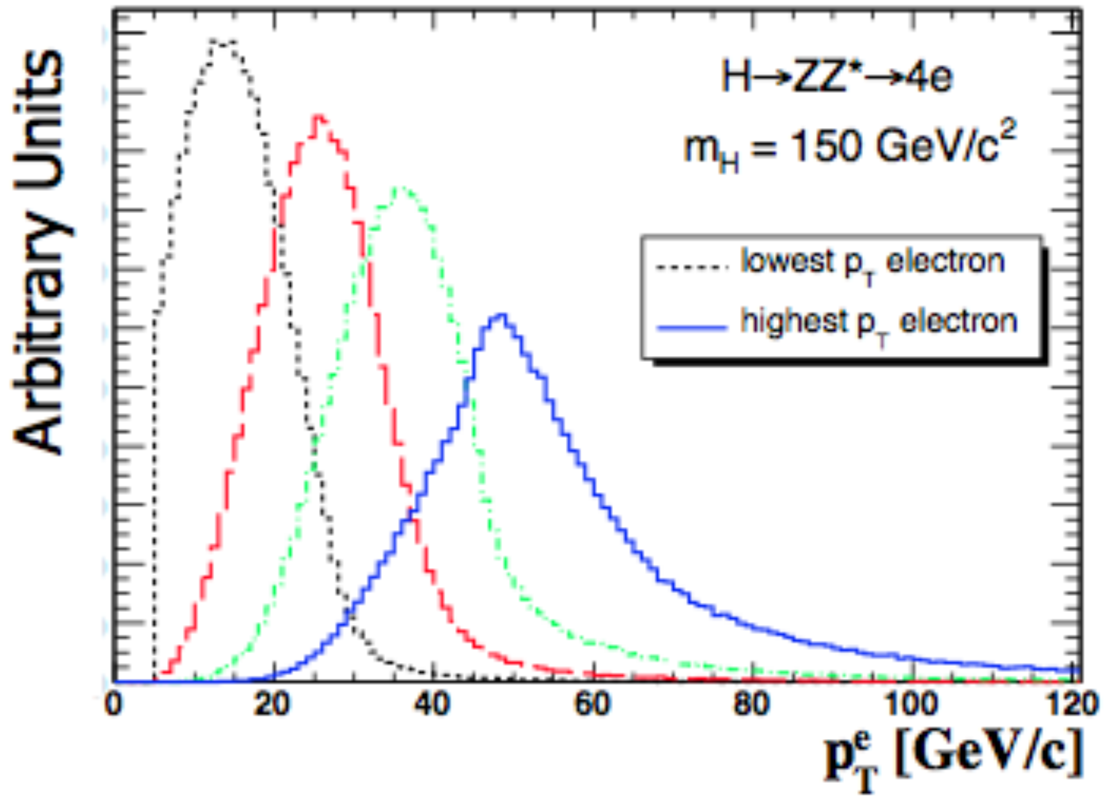
# The Discovery Channels

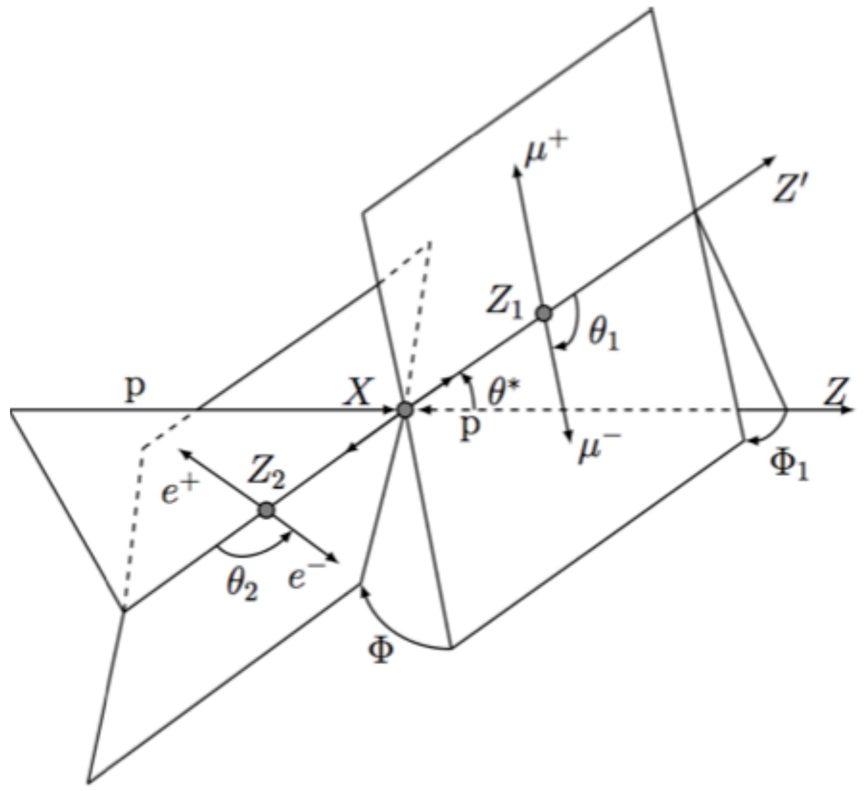
## « Bread and Butter » Mass peak signals: the four leptons channel

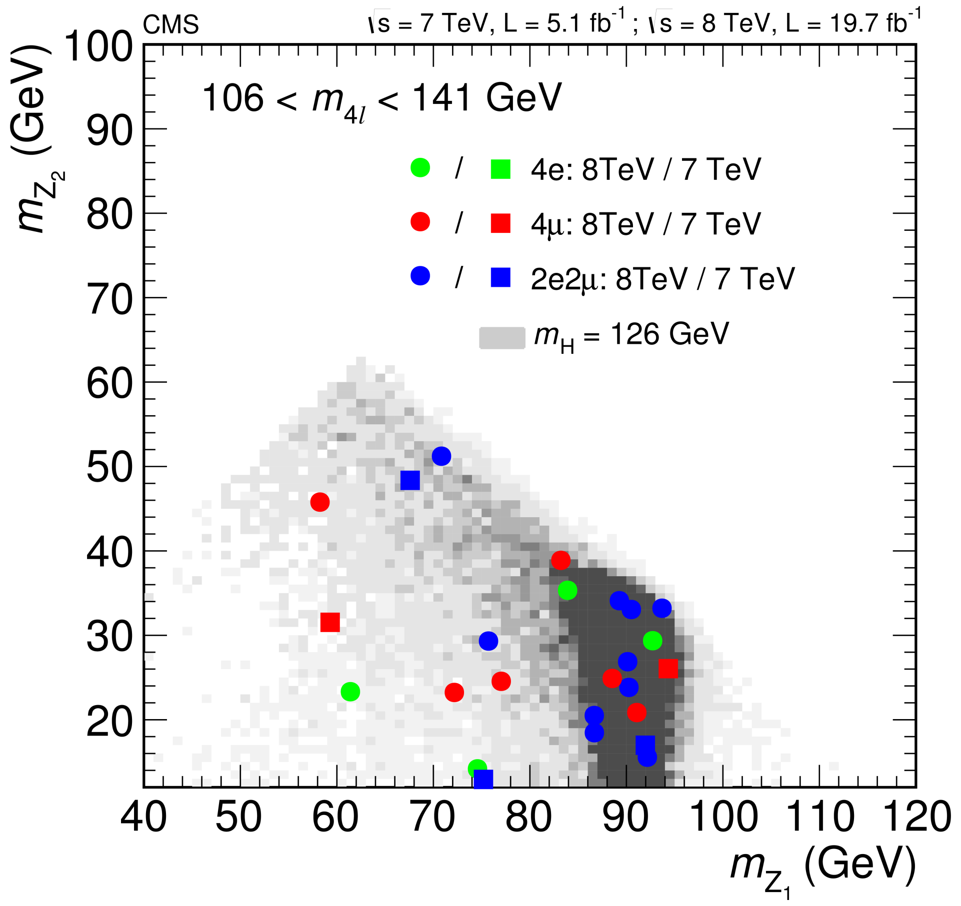




- Important features:
    - Very low rate! Efficiency is key!
    - The trailing lepton is at low pT.
    - The polarisation of the two Z can be reconstructed.
    - Typically one Z is on-mass shell



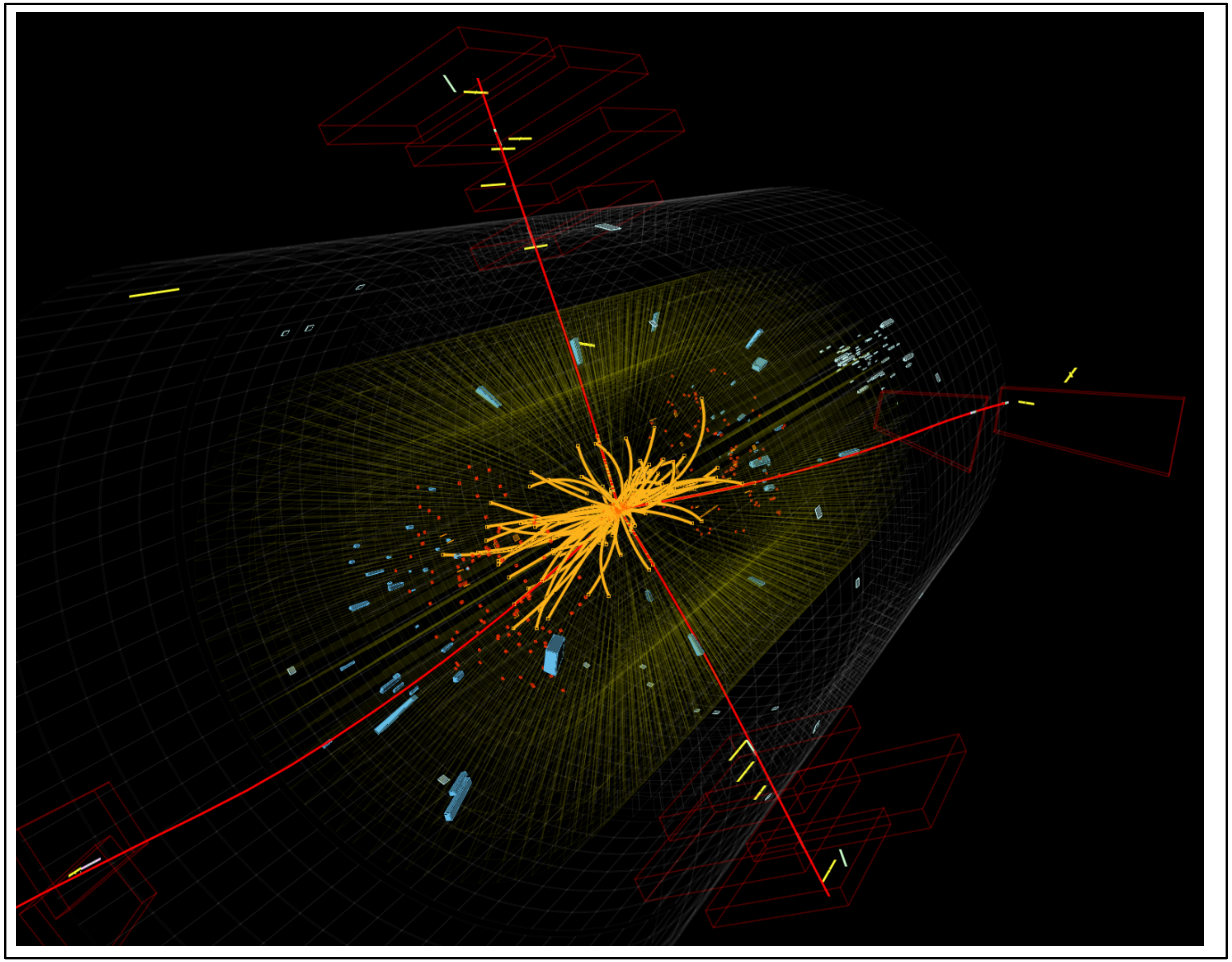



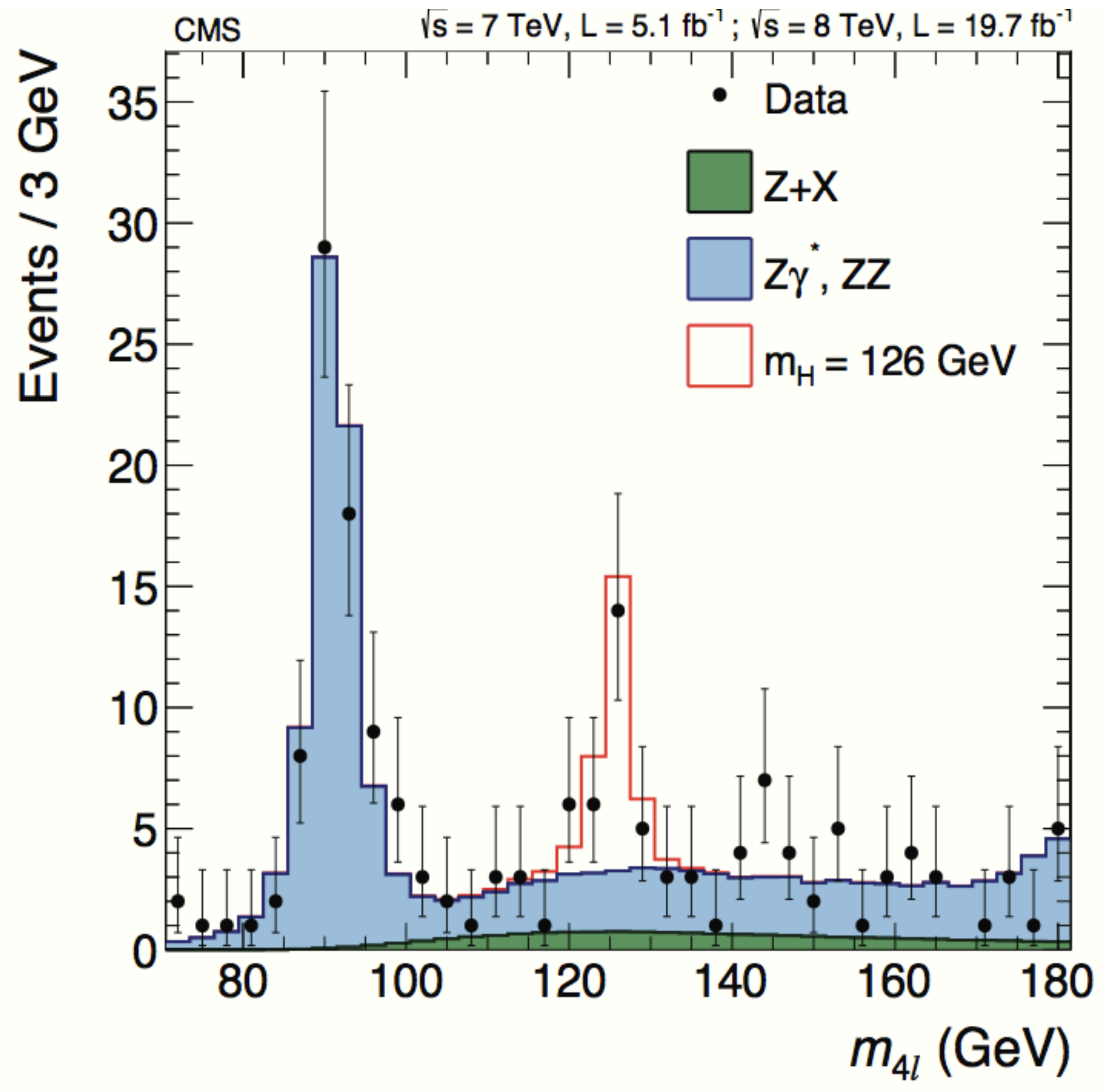
# The Discovery Channels

## « Bread and Butter » Mass peak signals: the four leptons channel





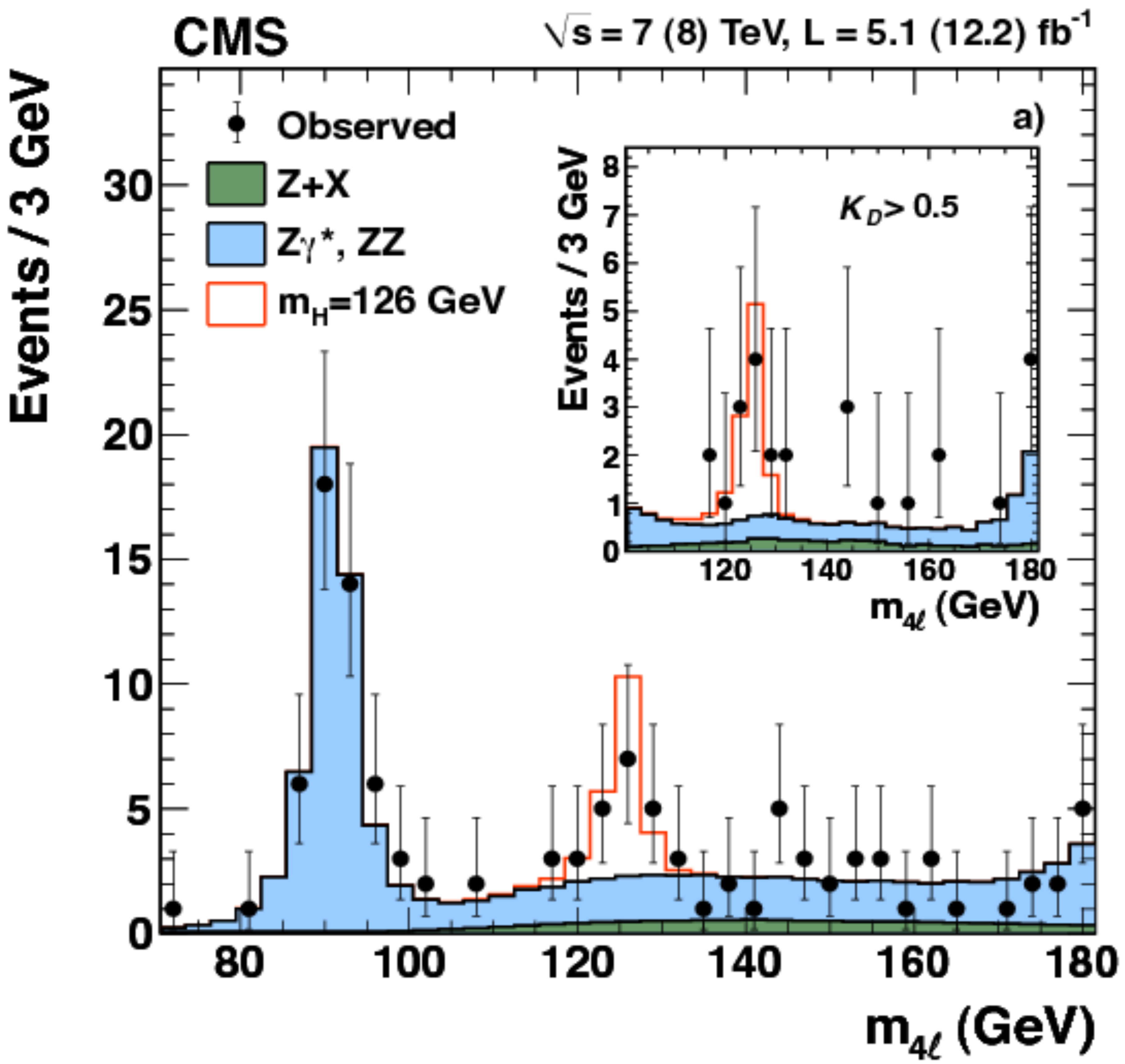
- Important features:
  - Very low rate! Efficiency is key!
  - The trailing lepton is at low pT.
  - The polarisation of the two Z can be reconstructed.
  - Typically one Z is on-mass shell
- Channel with High s/b ratio from approximately 2 up to more than 10!
- Backgrounds can be estimated from MC.



# The ZZ Channel Historical Prospective



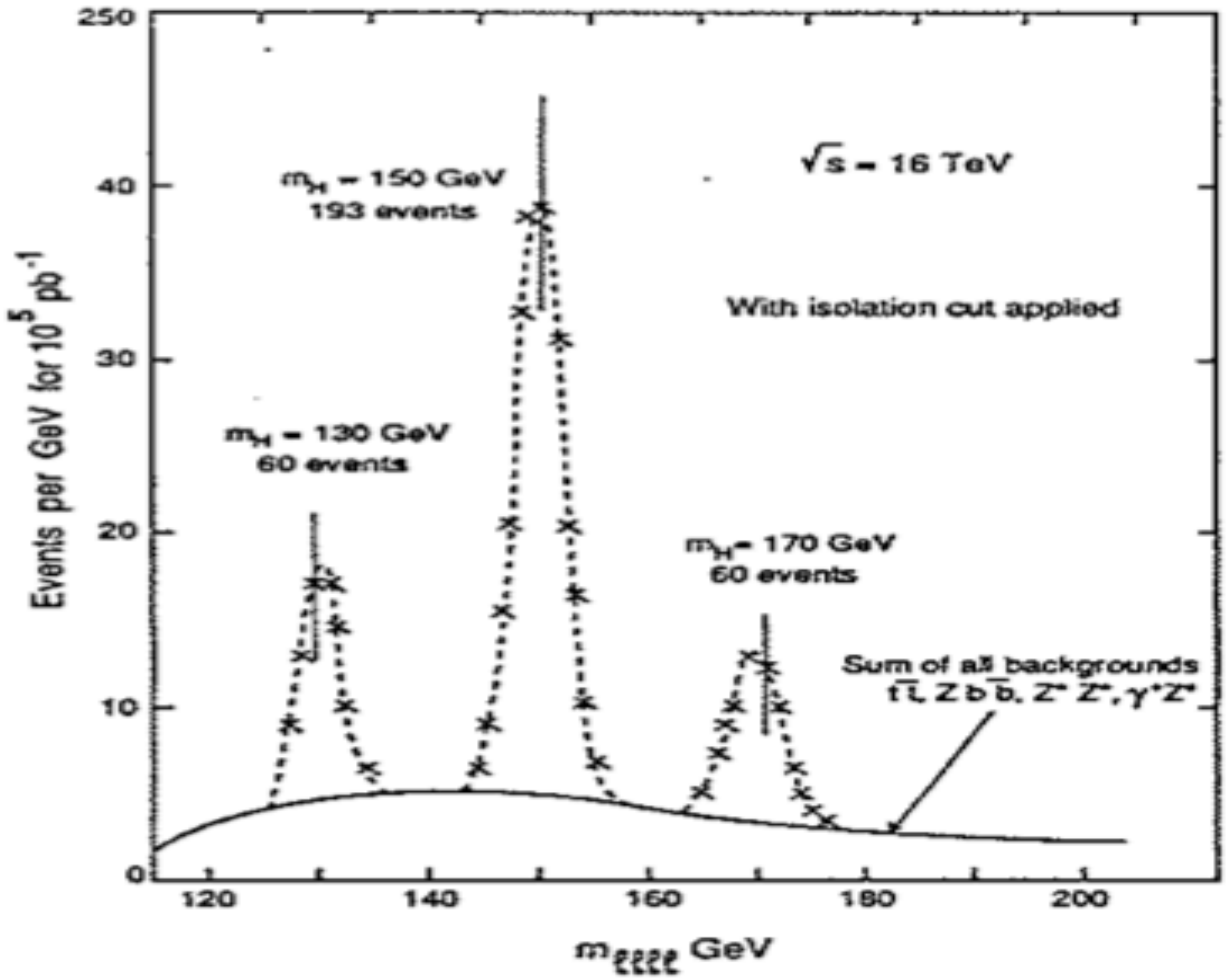
**2012**




7 - 8 TeV, ~25 fb$^{-1}$

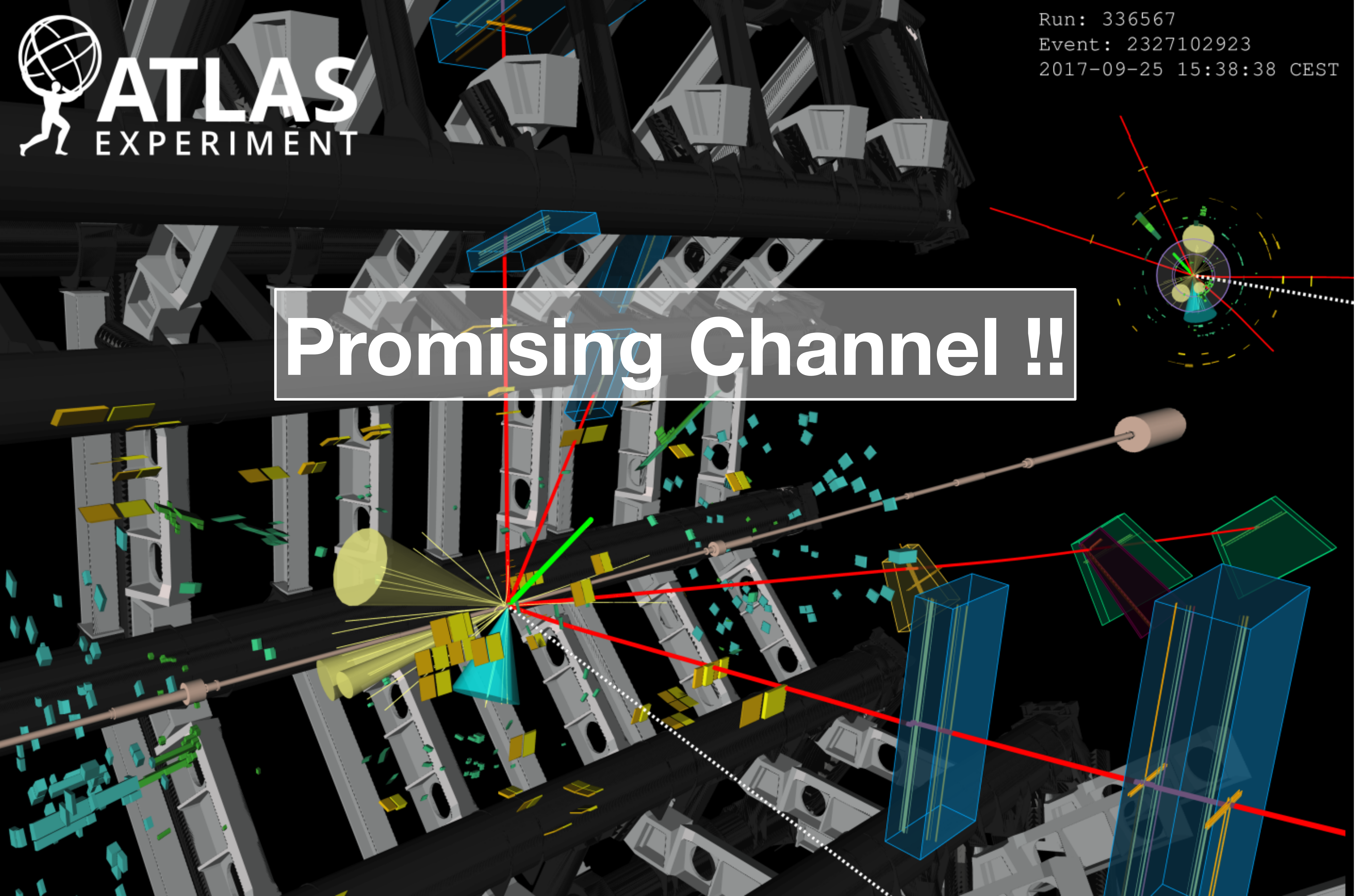
Significance ~7 σ

**1992**




16 TeV, 100 fb$^{-1}$

Significance ~6 σ

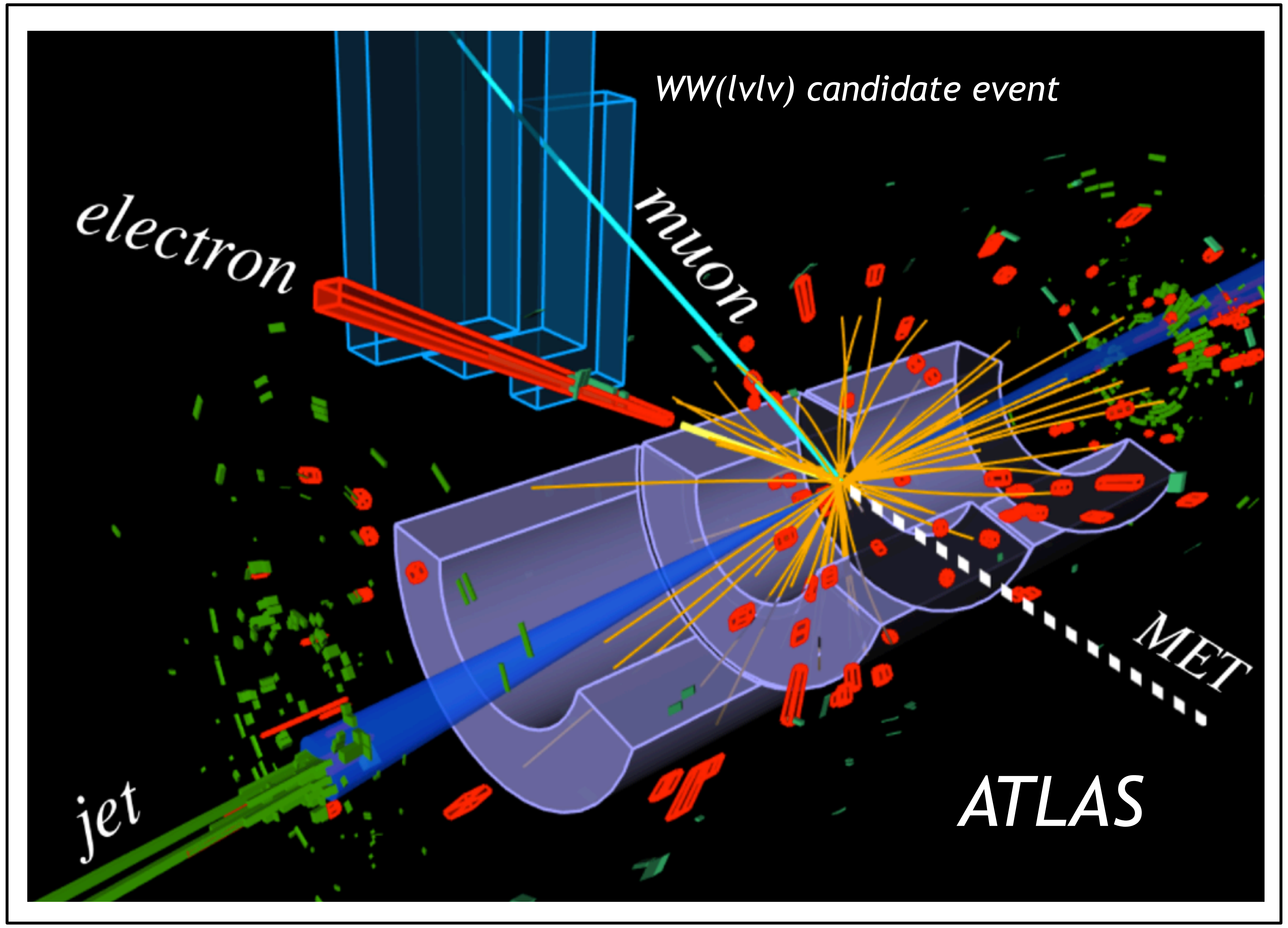



4 muon event with mass 124.4 GeV, one Z mass of 89,3 GeV and the lower mass of 33 GeV, one electron, four jets, lowest pT has tight b-tagging.

$$s/b \sim 30$$

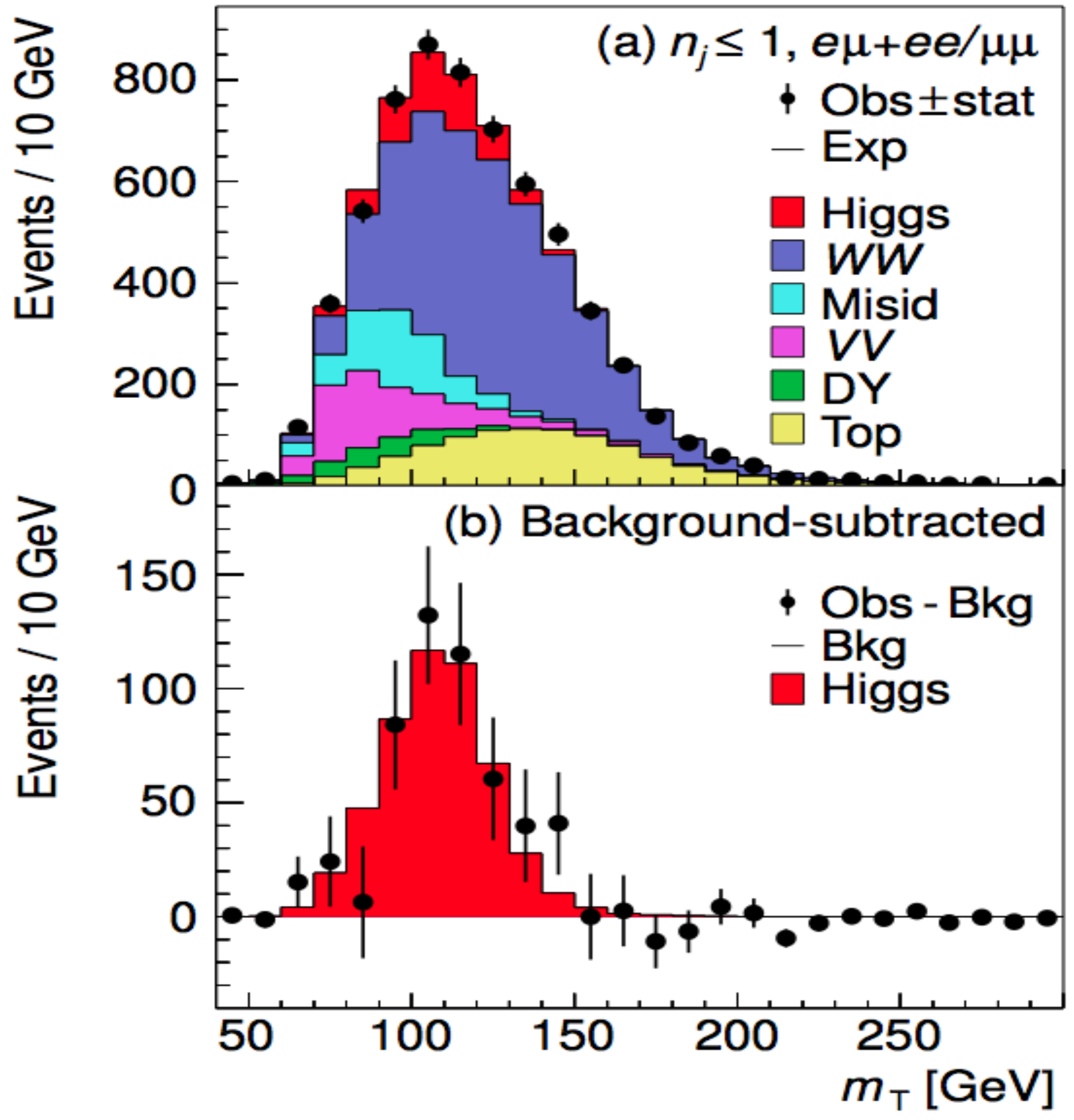
# The Discovery Channels

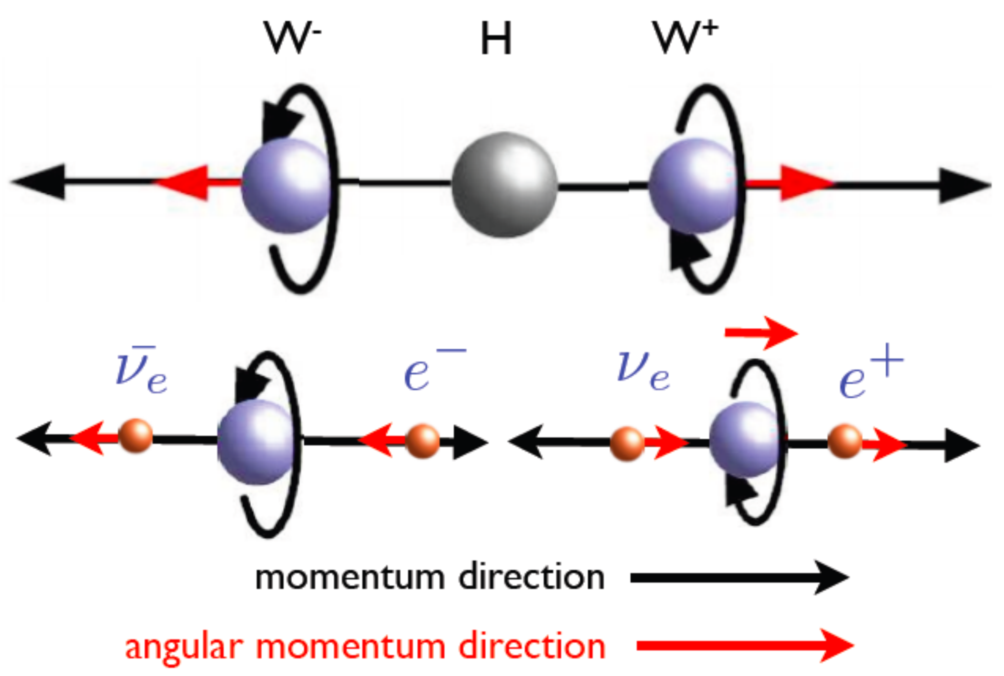
## A discovery channel of a different kind: the WW




Requires good simulation of backgrounds and control regions in the data.

Uses the V-A nature of the W coupling that transfers the W spin correlation to the electrons.



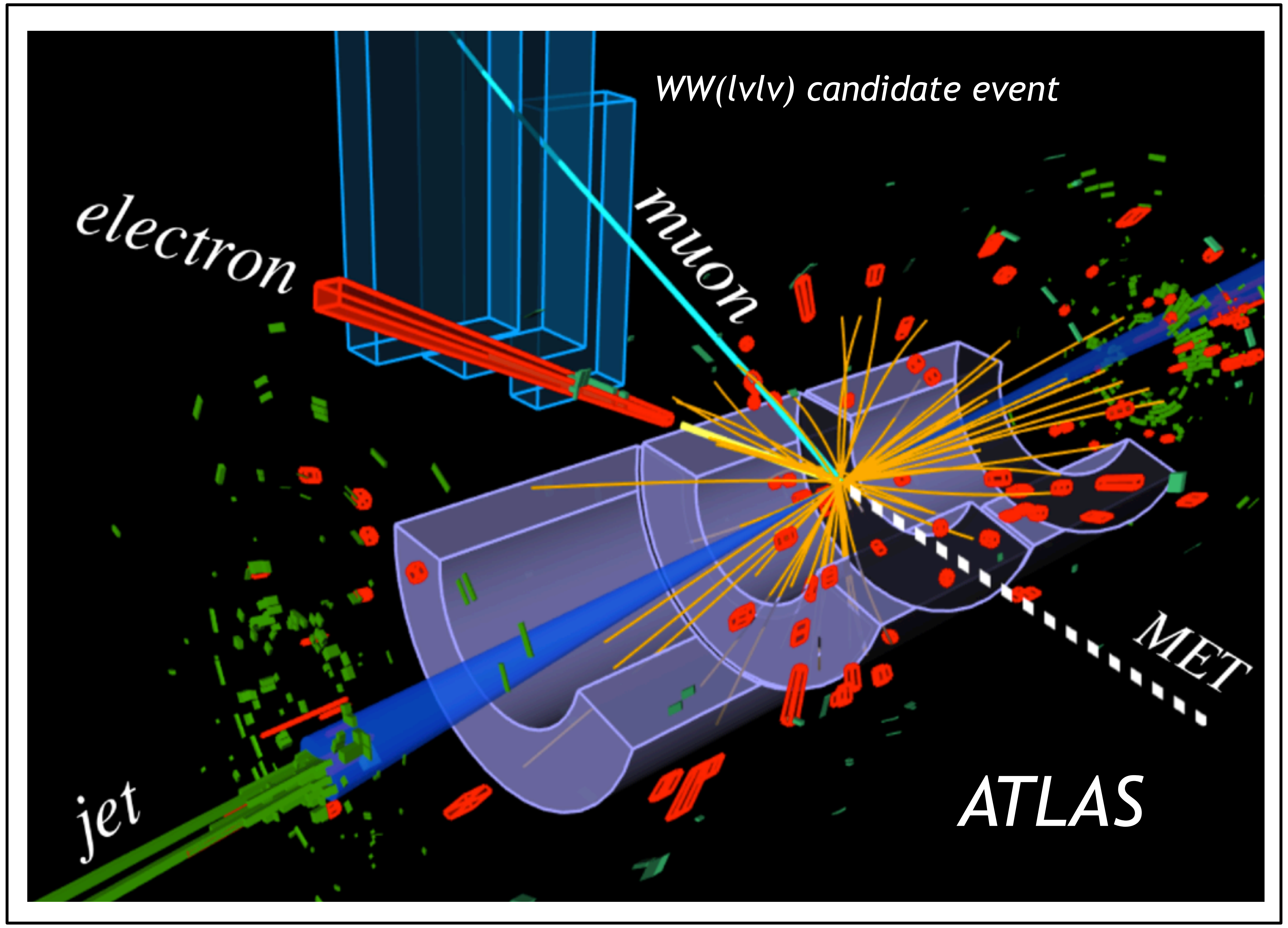




Channel where each W decay to leptons, the mass resolution is spoiled by the neutrinos!

Large event rate, but also large backgrounds from the WW and top production.

# The Discovery Channels

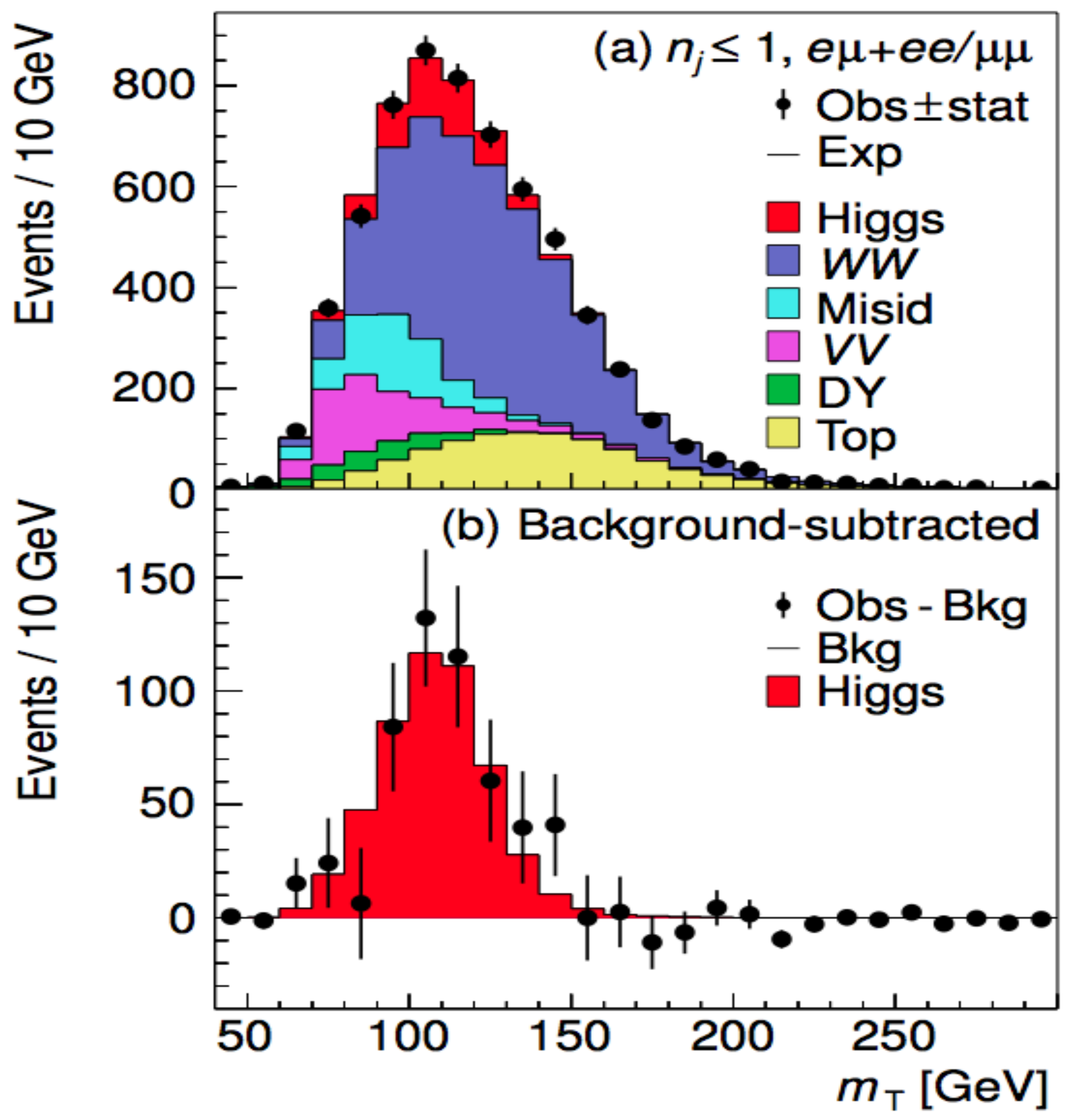
## A discovery channel of a different kind: the WW



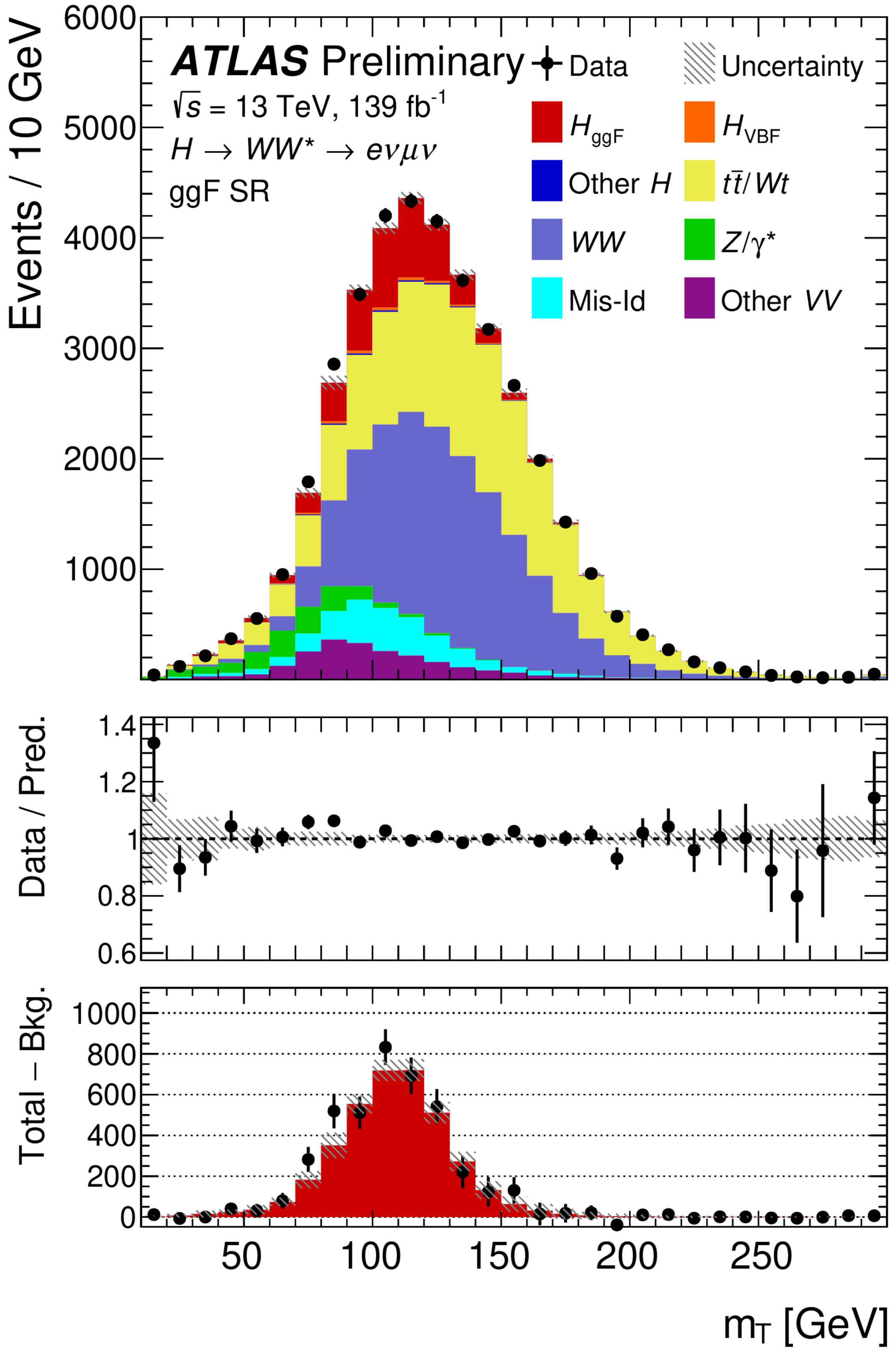

Requires good simulation of backgrounds and control regions in the data.

Uses the V-A nature of the W coupling that transfers the W spin correlation to the electrons.

Run 1




Run 2



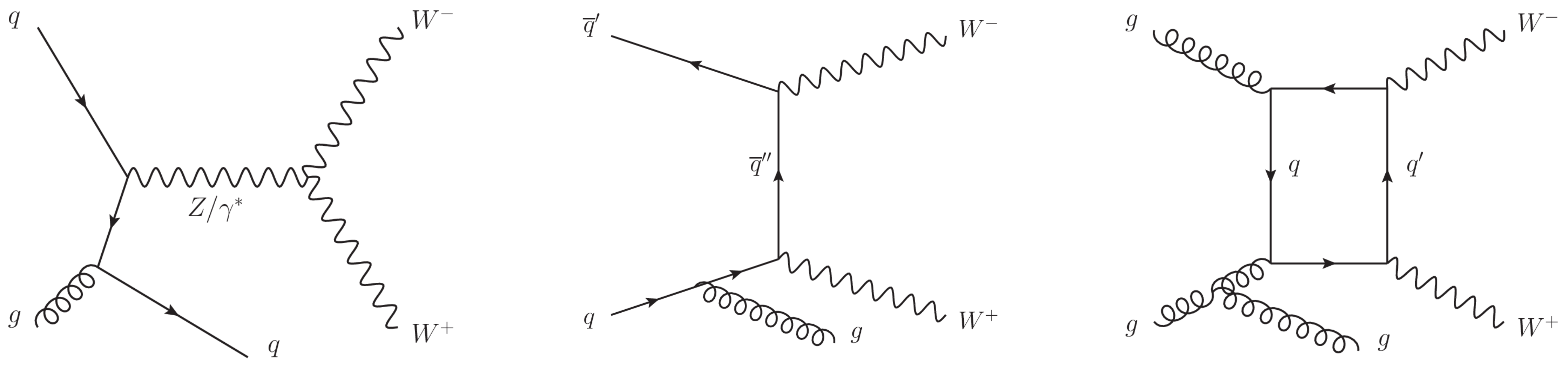

Channel where each of the W decays to leptons, the mass resolution is spoiled by the neutrinos!

Large event rate, but also large backgrounds from the WW and top production.

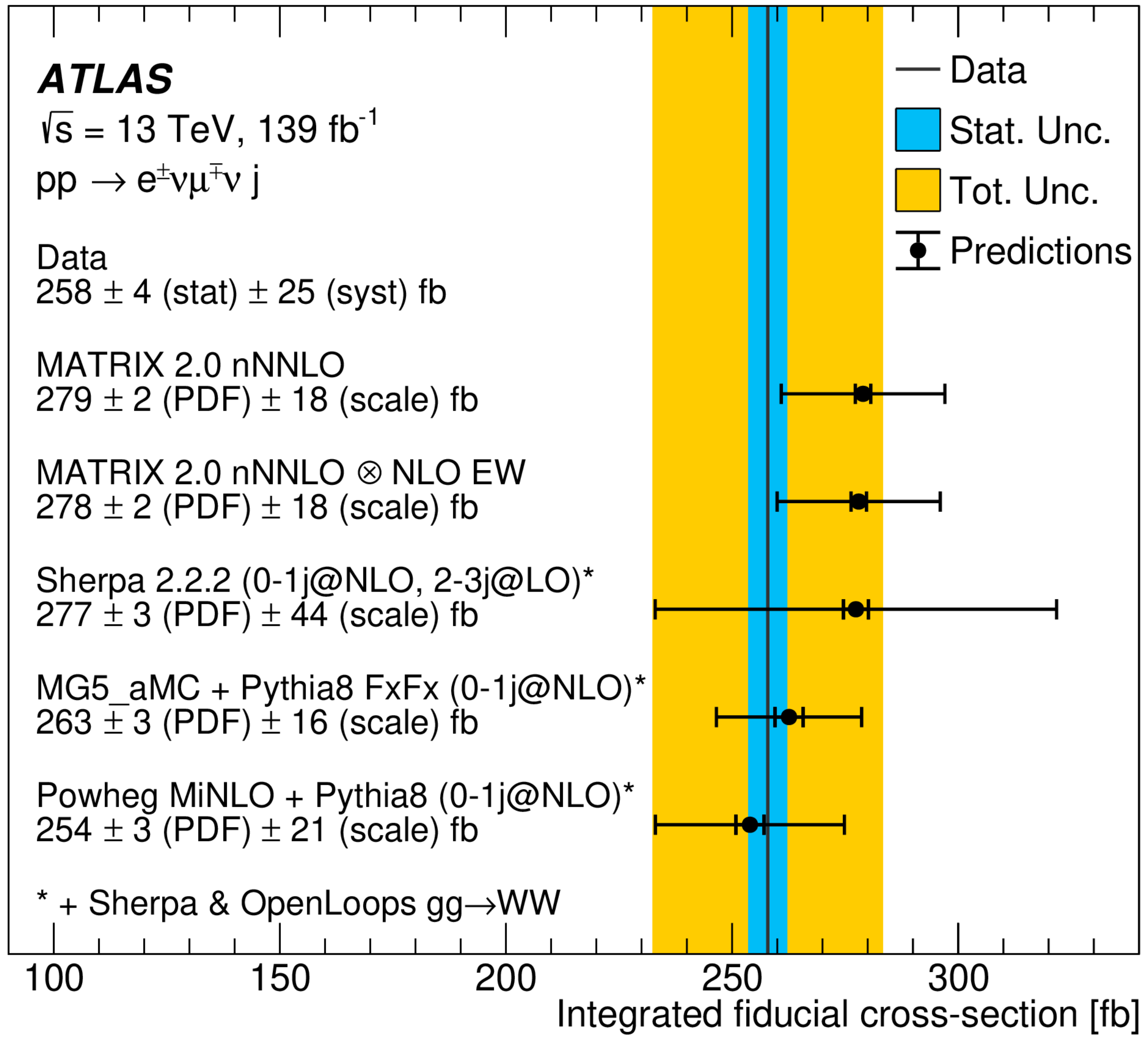
# Importance of Ancillary Measurements

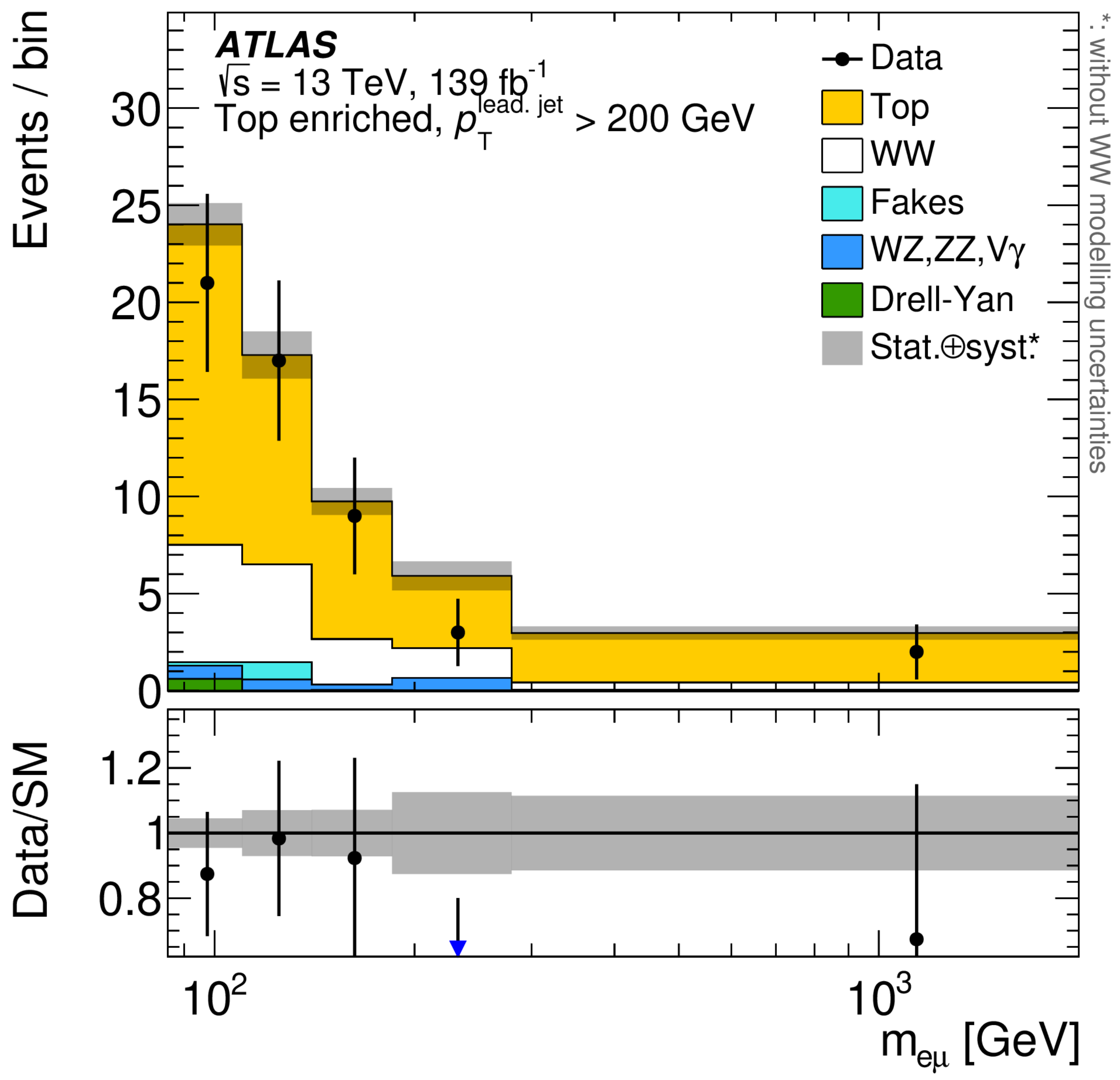
## Diboson WW associated 1-jet production





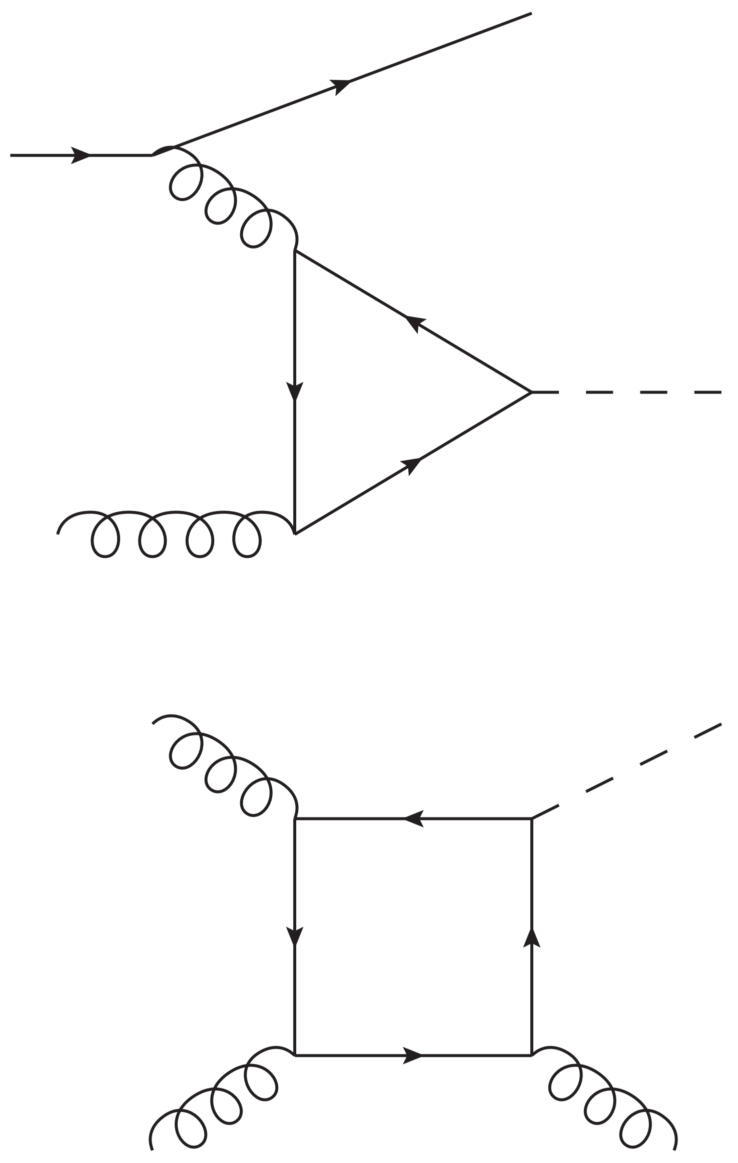

Measurements of inclusive and differential $pp \rightarrow WW \rightarrow e\nu\mu\nu$ + 1 jet cross sections

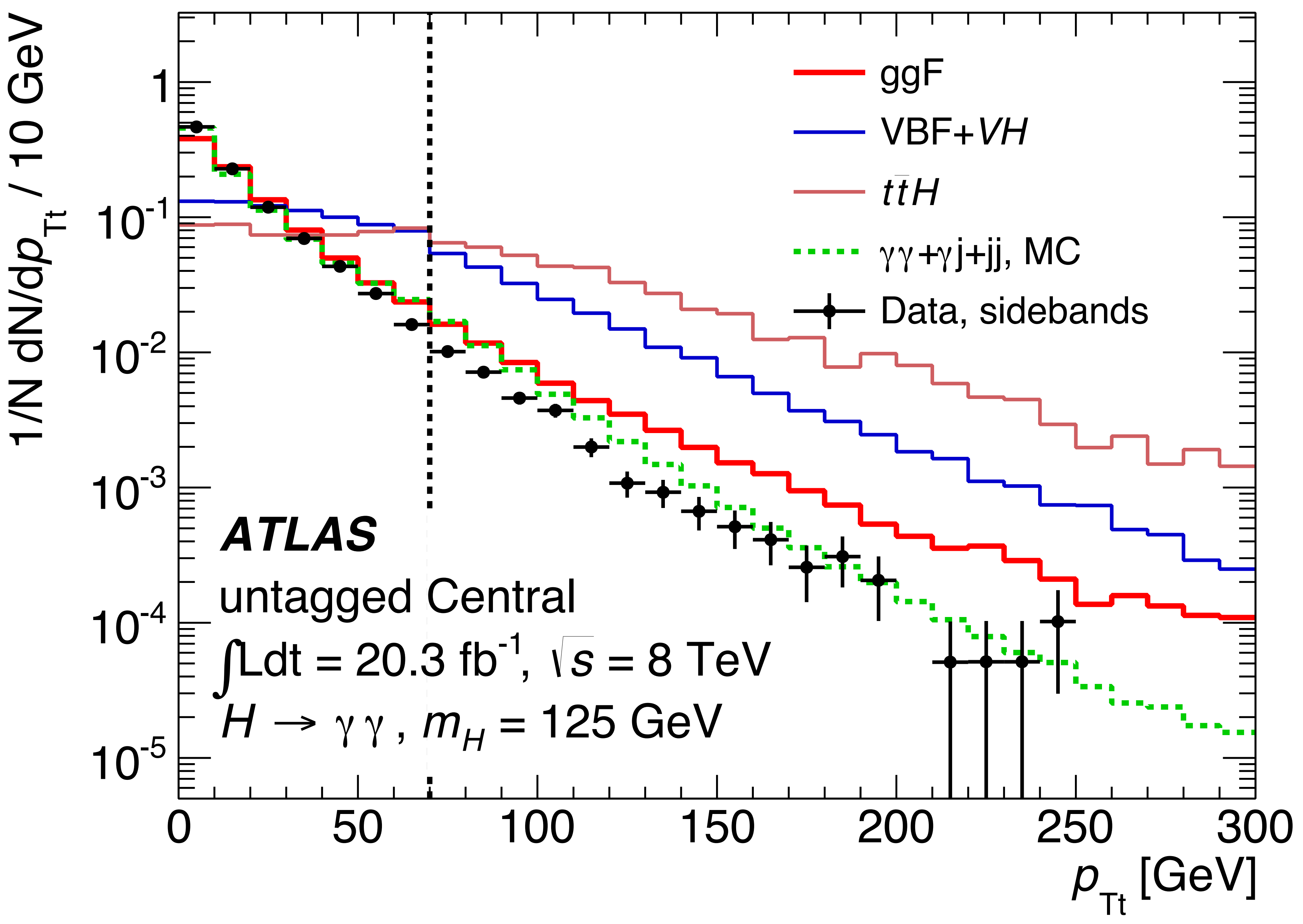



Provide excellent ancillary measurements for other channels such as HWW, but also excellent probe of anomalous **Triple gauge couplings aTGCs** (in particular at higher energies using the jet in the initial state).

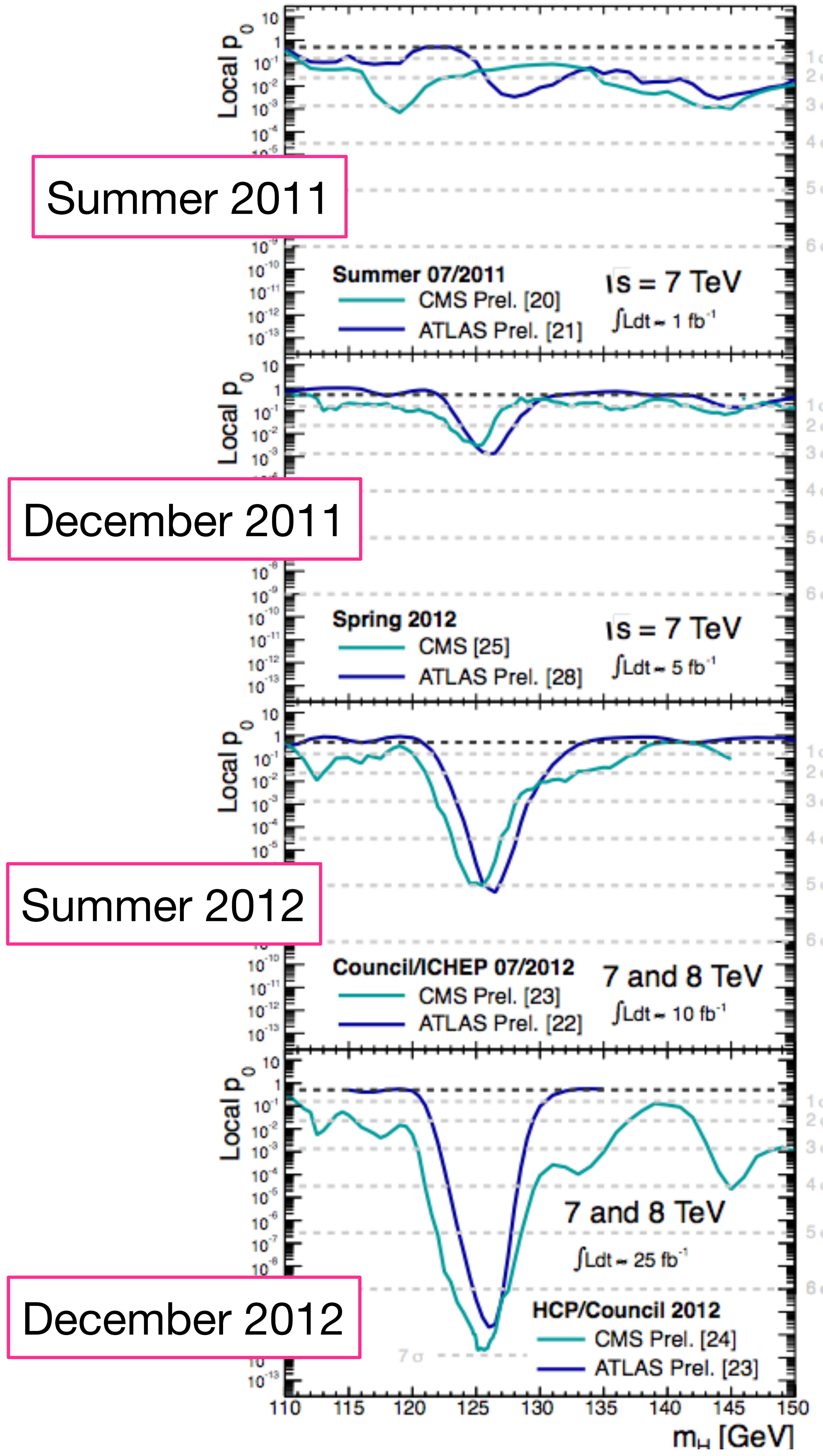
# The Importance of the Higgs Boson HO corrections






- Inclusive Higgs production has large higher order corrections
- Transverse momentum and/or additional jets bring invaluable additional signal-background discrimination (played an important role in the discovery)

# A Textbook and Timely Discovery




- Summer 2011: EPS and Lepton-Photon

  First (and last) focus on limits (scrutiny of the $p_0$)

- December 2011: CERN Council

  First hints

- Summer 2012: CERN Council and ICHEP

  Discovery!

- December 2012: CERN Council

  Beginning of a new era

✓ Strongly Motivated

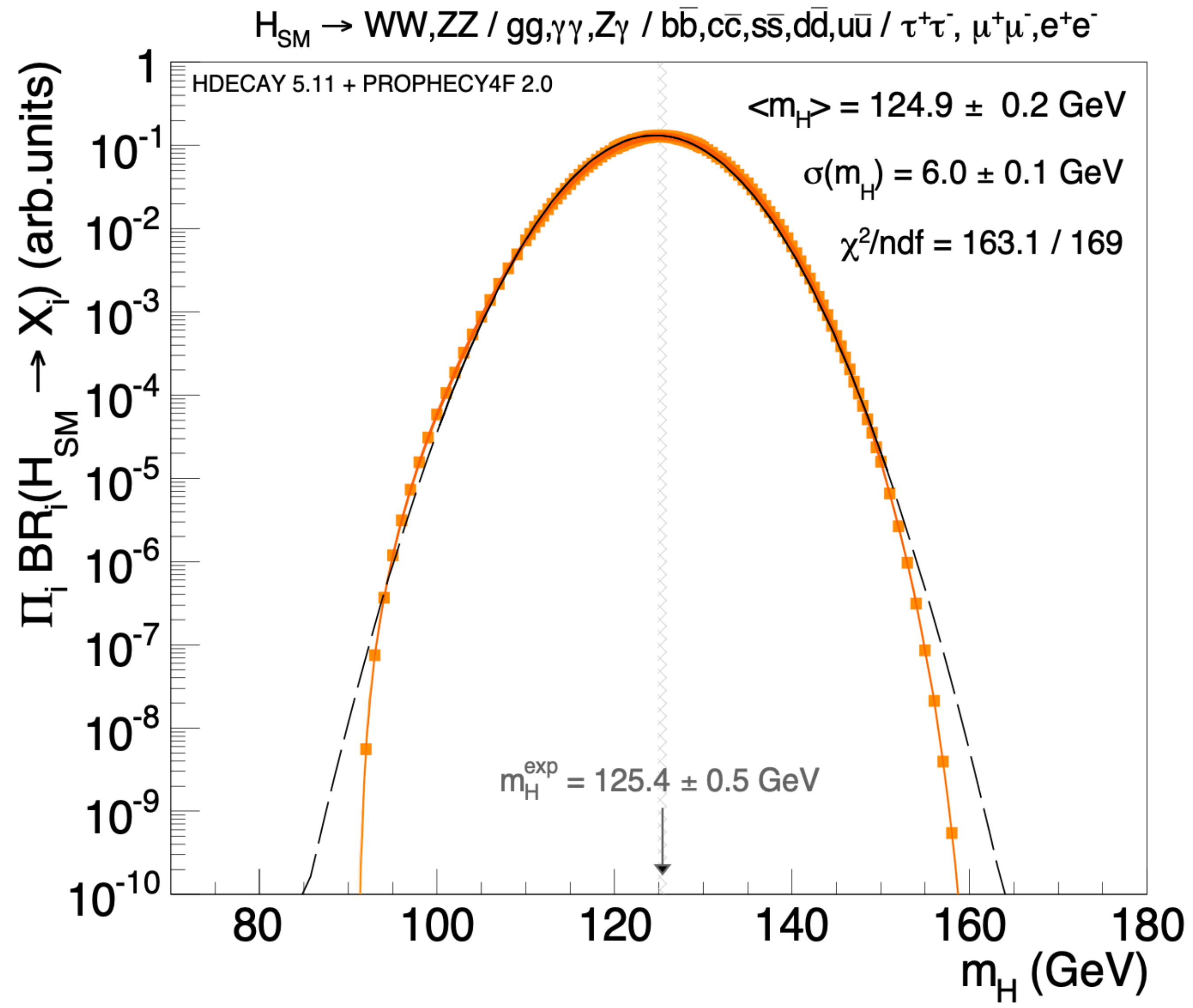
✓ Significance increased with luminosity to reach unambiguous levels

✓ Two experiments

✓ Several channels

“A Gift of Nature”

Fabiola Gianotti (July 4, 2012 CERN)




D. d’Enterria

# Higgs Discovery Announcement

CERN Main auditorium      July 4th 2012

# Landmark Results

**The discovery of the Higgs boson** through diboson channels has corroborated the electroweak symmetry breaking model and thus how the electroweak interaction is short ranged.

THE BEH-MECHANISM,
INTERACTIONS WITH SHORT RANGE FORCES
AND
SCALAR PARTICLES

KUNGL. VETENSKAPS-AKADEMIEN
THE ROYAL SWEDISH ACADEMY OF SCIENCES

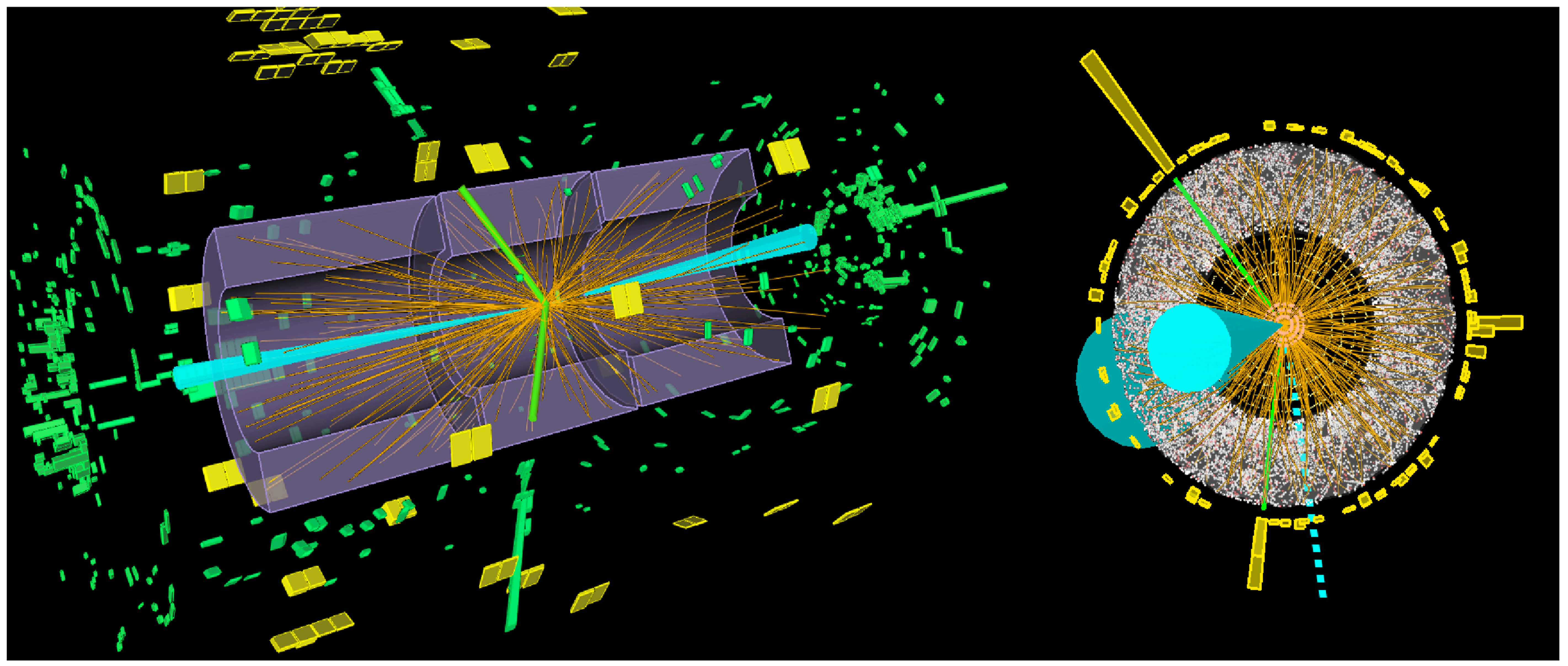
It is the first example we've seen of the simplest possible type of elementary particle. It has no spin, no charge, only mass, and this extreme simplicity makes it theoretically perplexing.

*Nima Arkani Hamed*

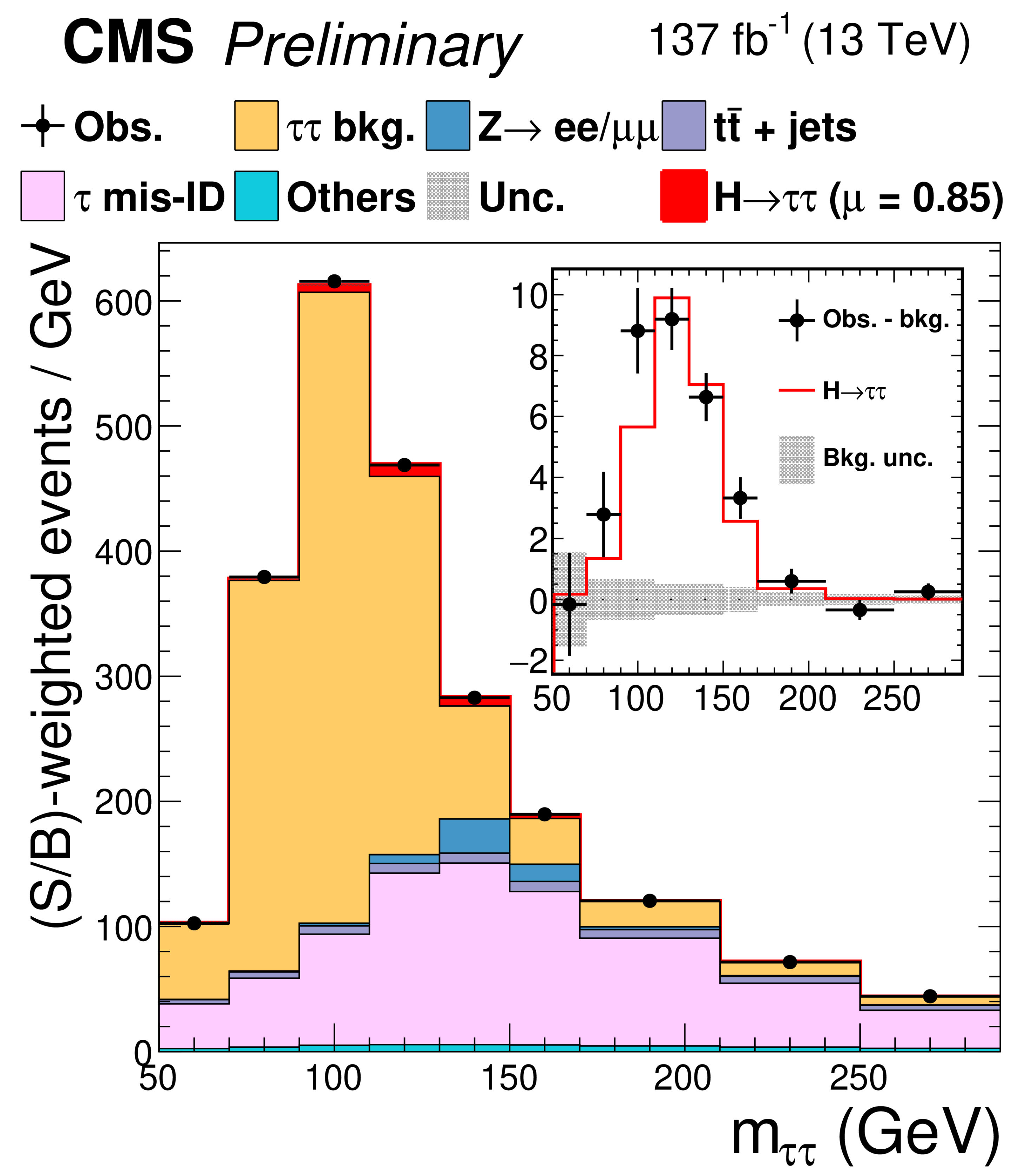
# 2.- The Yukawa couplings at Run 2

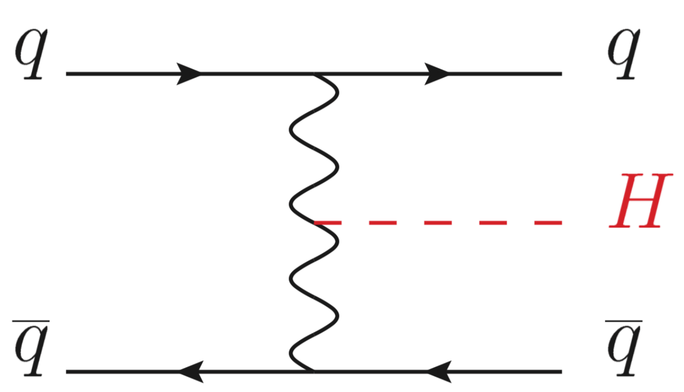
# Higgs boson decays to Taus





[CMS-PAS-HIG-19-010]

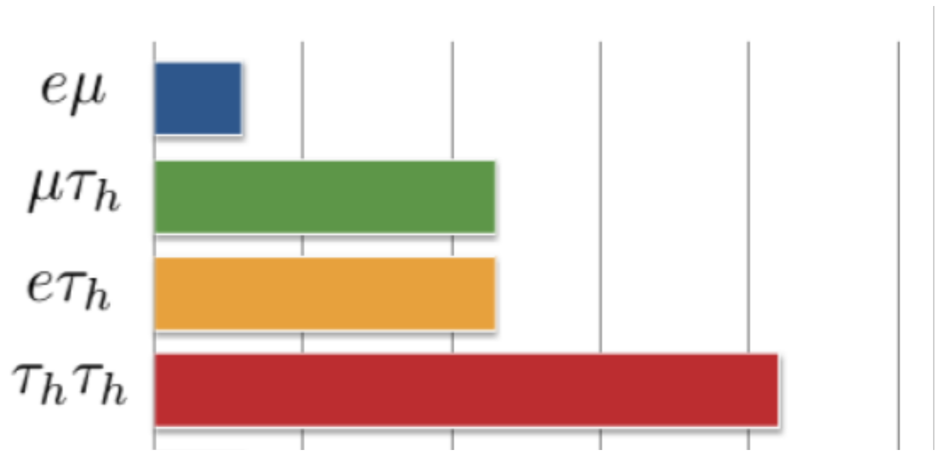



## VBF process

With two forward jets and a large rapidity gap between the jets (due to the color singlet exchange in the t-channel

Tau to leptons ~18% (rest is hadrons)




Background is Z production with two jets, in this region of phase space it is difficult to predict!

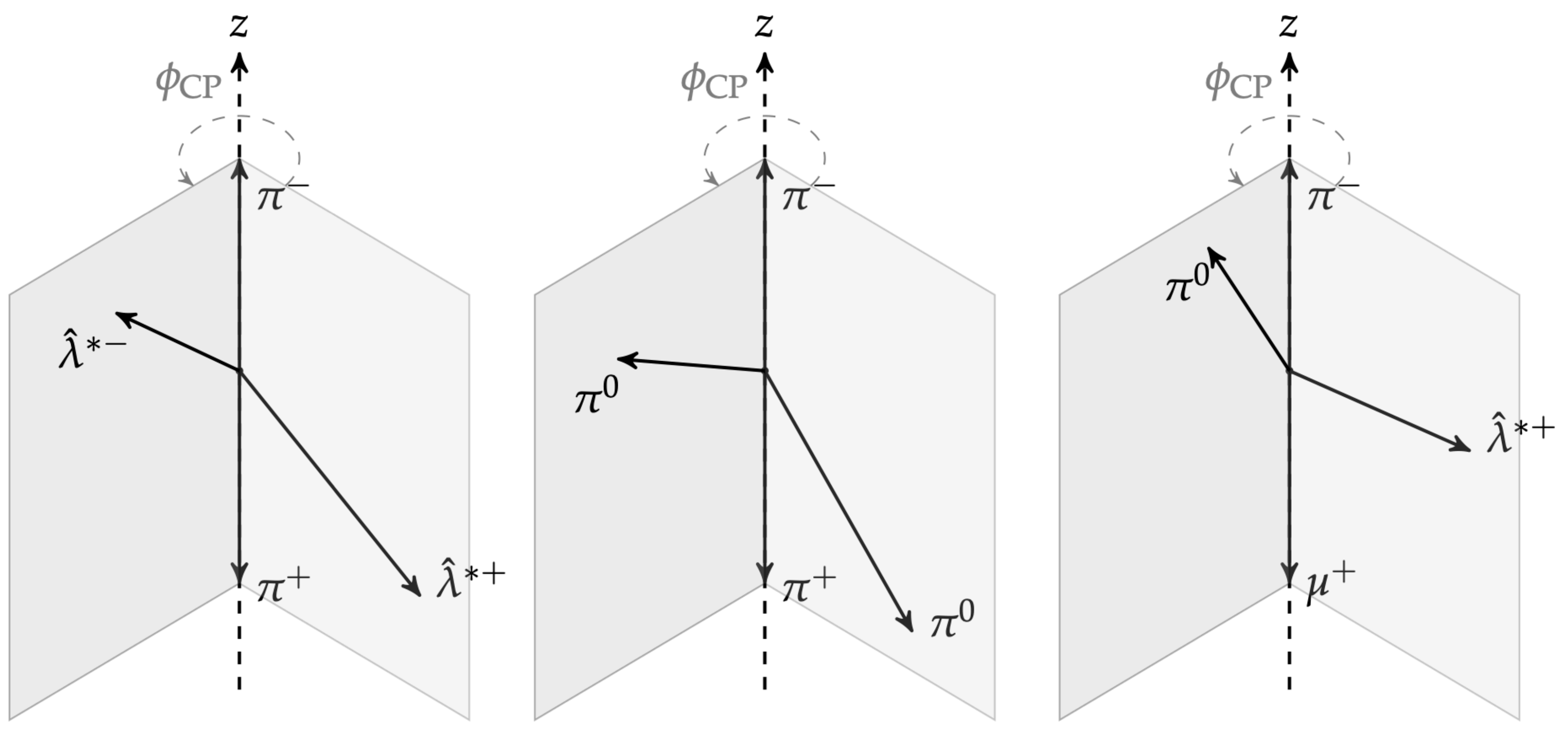
Analysis based on several channels depending on the decay mode of the tau.

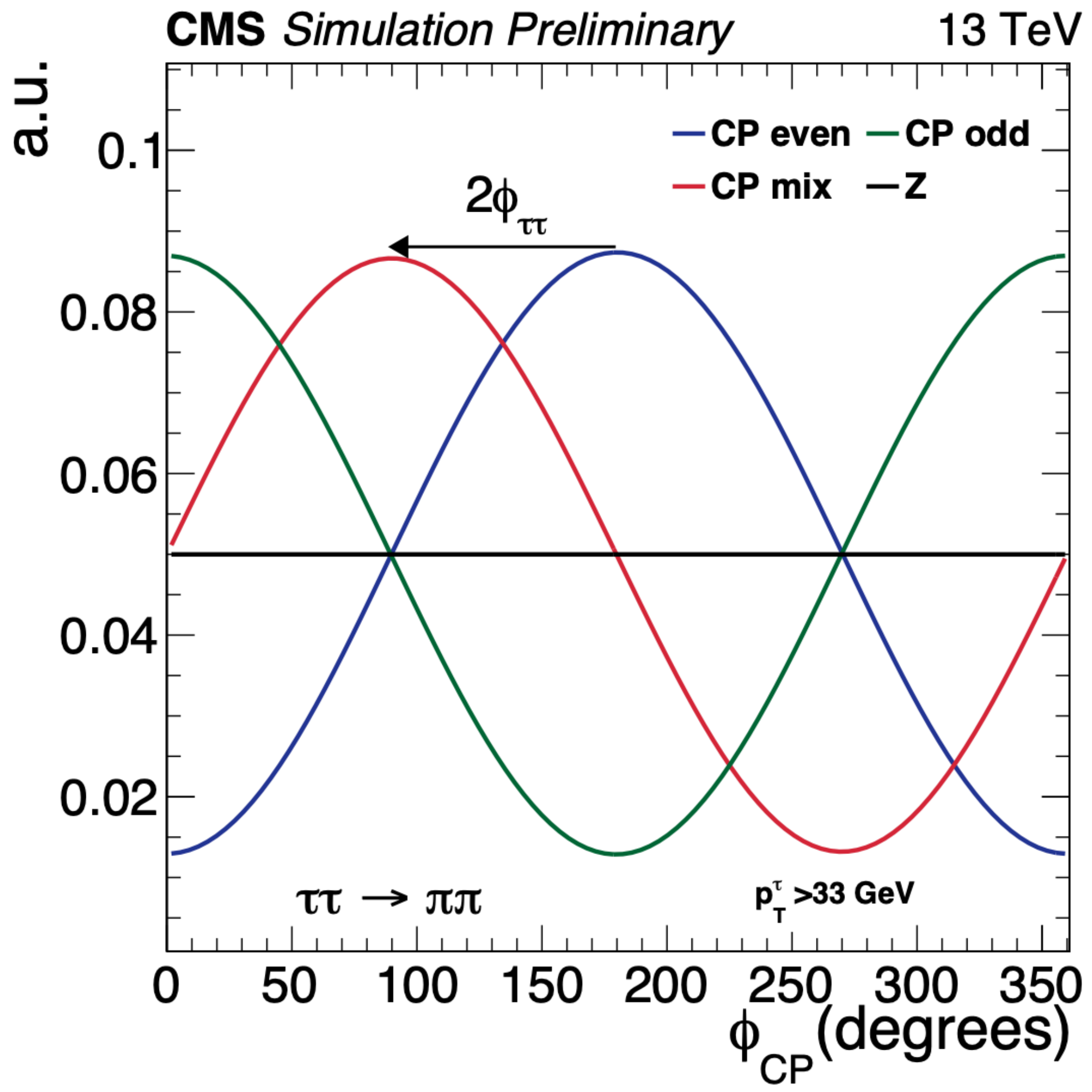
Analysis requires data driven methods to do so: e.g. the embedding of taus in Z to di-muon events.

# CP properties of the Tau Yukawa

## Through polarisation sensitive variable

CMS PAS HIG-20-006



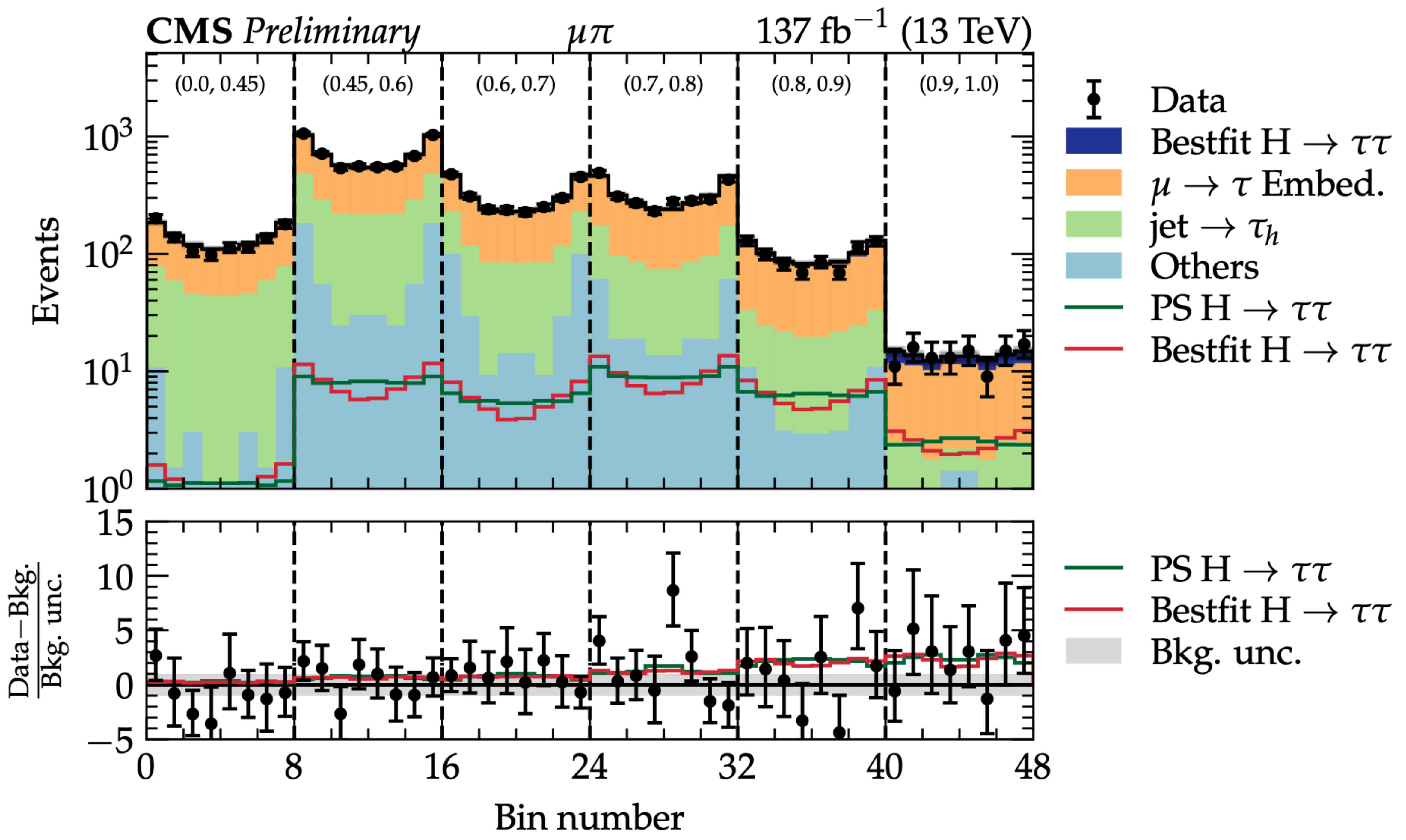




Uses either the impact parameter direction for single-prong taus ($\pi^{\pm}$) only or using the $\pi^0$ momentum for the

$$\tau \to \pi^{\pm}\pi^0 \ [\rho(770 \text{ MeV})] \ \nu_\tau$$

This method works also for the three prong tau decays with a $\rho^0 \to \pi^+\pi^-$

Tau decays are selected with a BDT and the $\phi_{CP}$ distribution is considered in different bins of this BDT score

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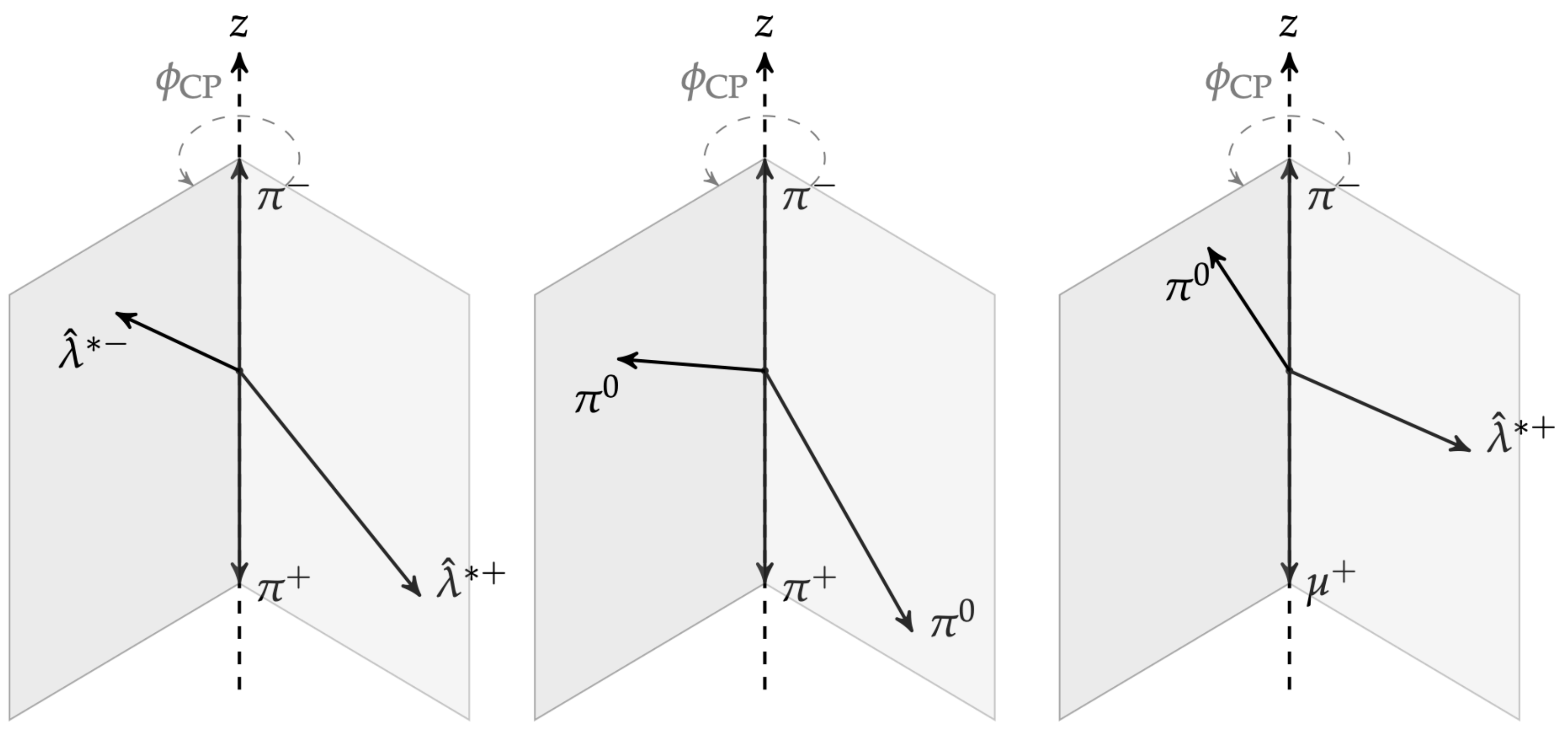
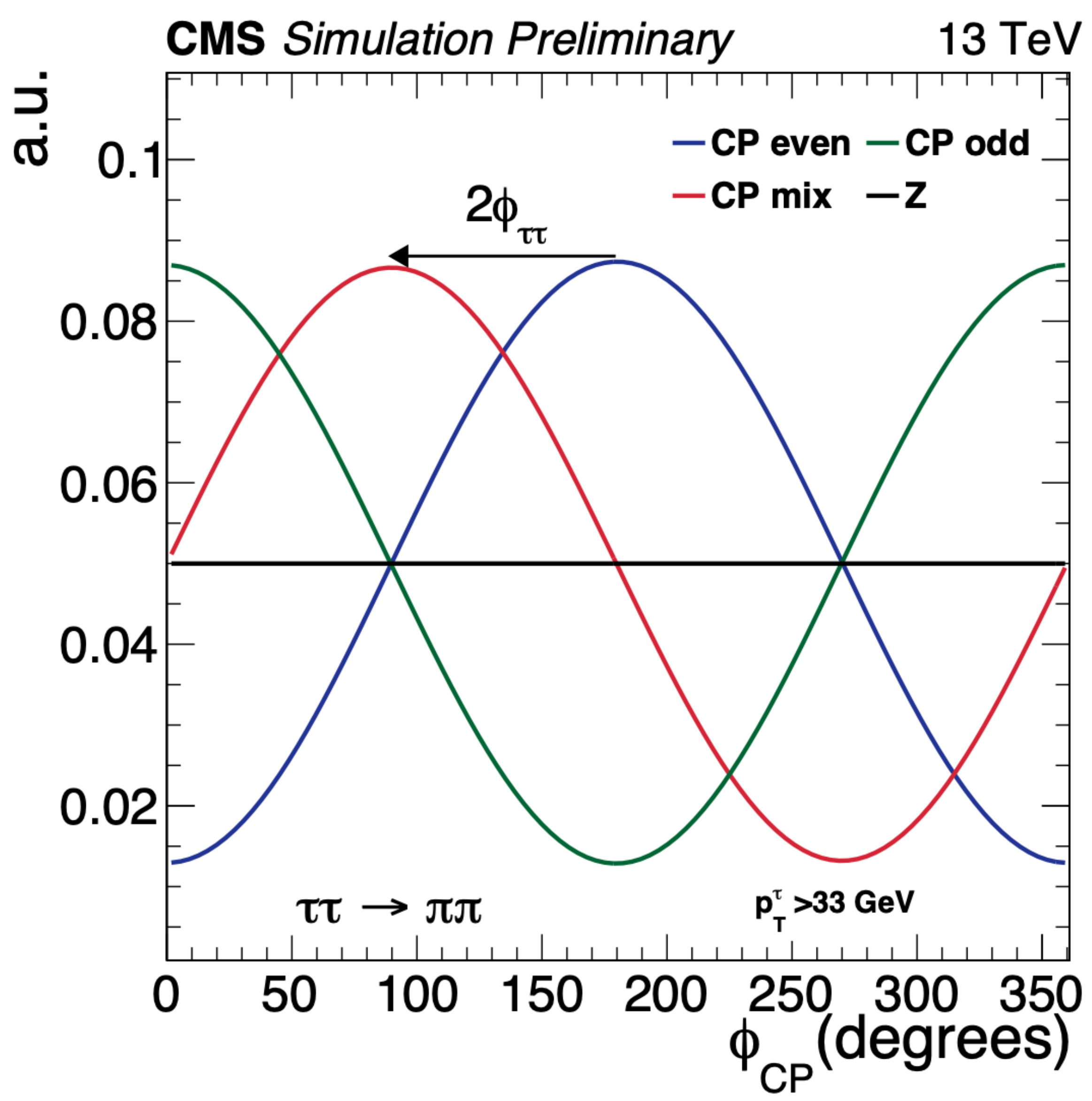
# CP properties of the Tau Yukawa

## Through polarisation sensitive variable

CMS PAS HIG-20-006



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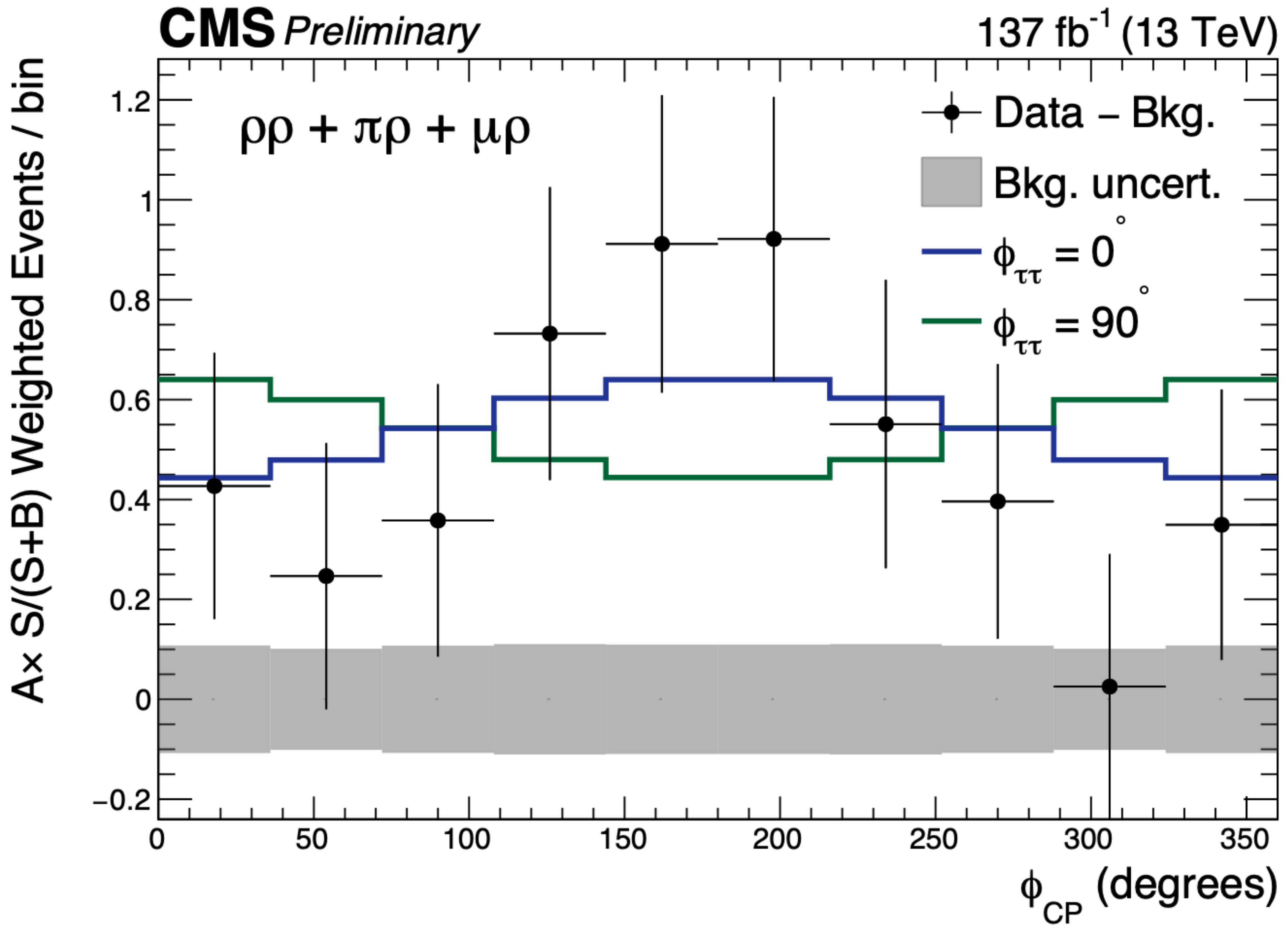
This method works also for the three prong tau decays with a $\rho^0 \rightarrow \pi^+\pi^-$

Tau decays are selected with a BDT and the $\phi_{CP}$ distribution is considered in different bins of this BDT score

Overall weighted distribution for all channels:

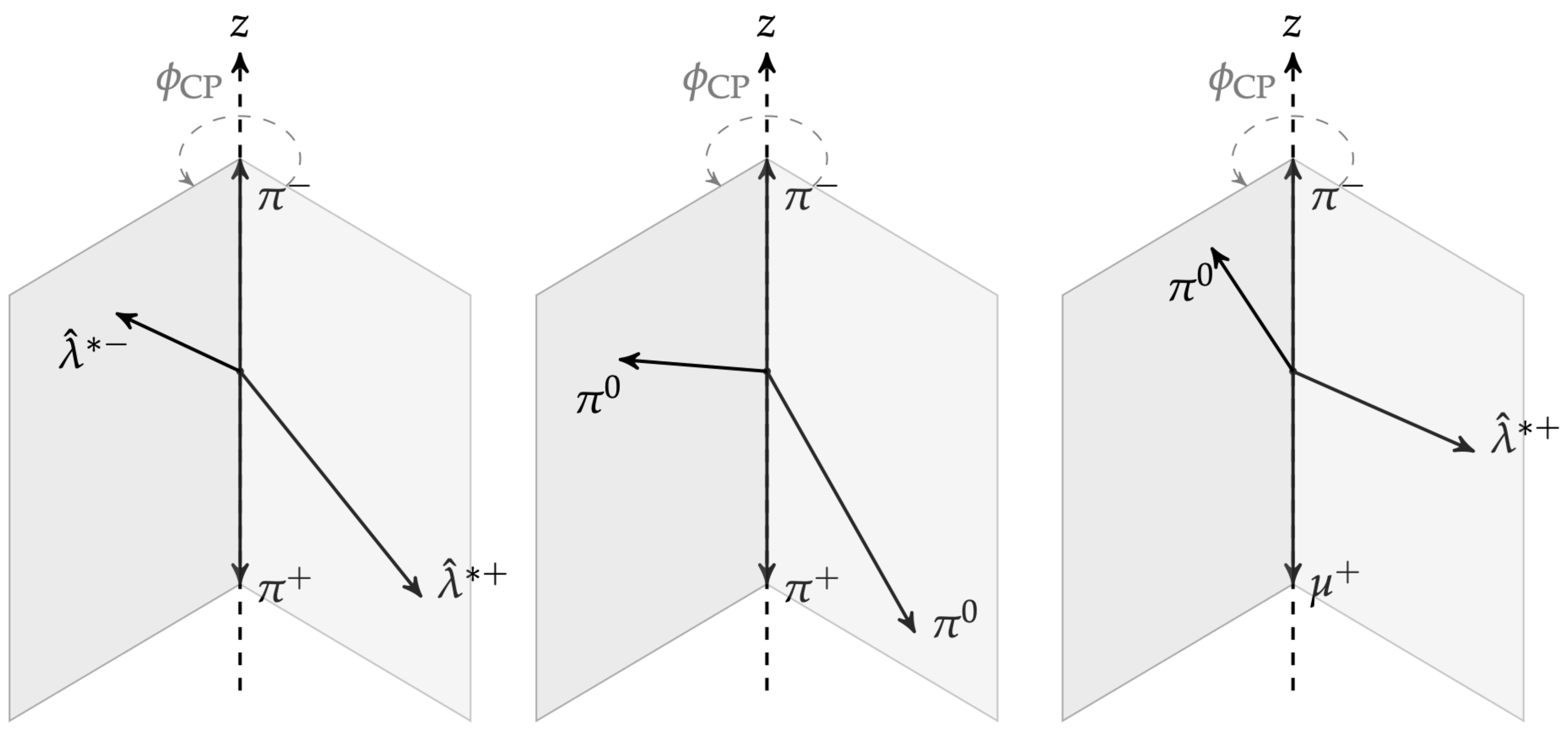


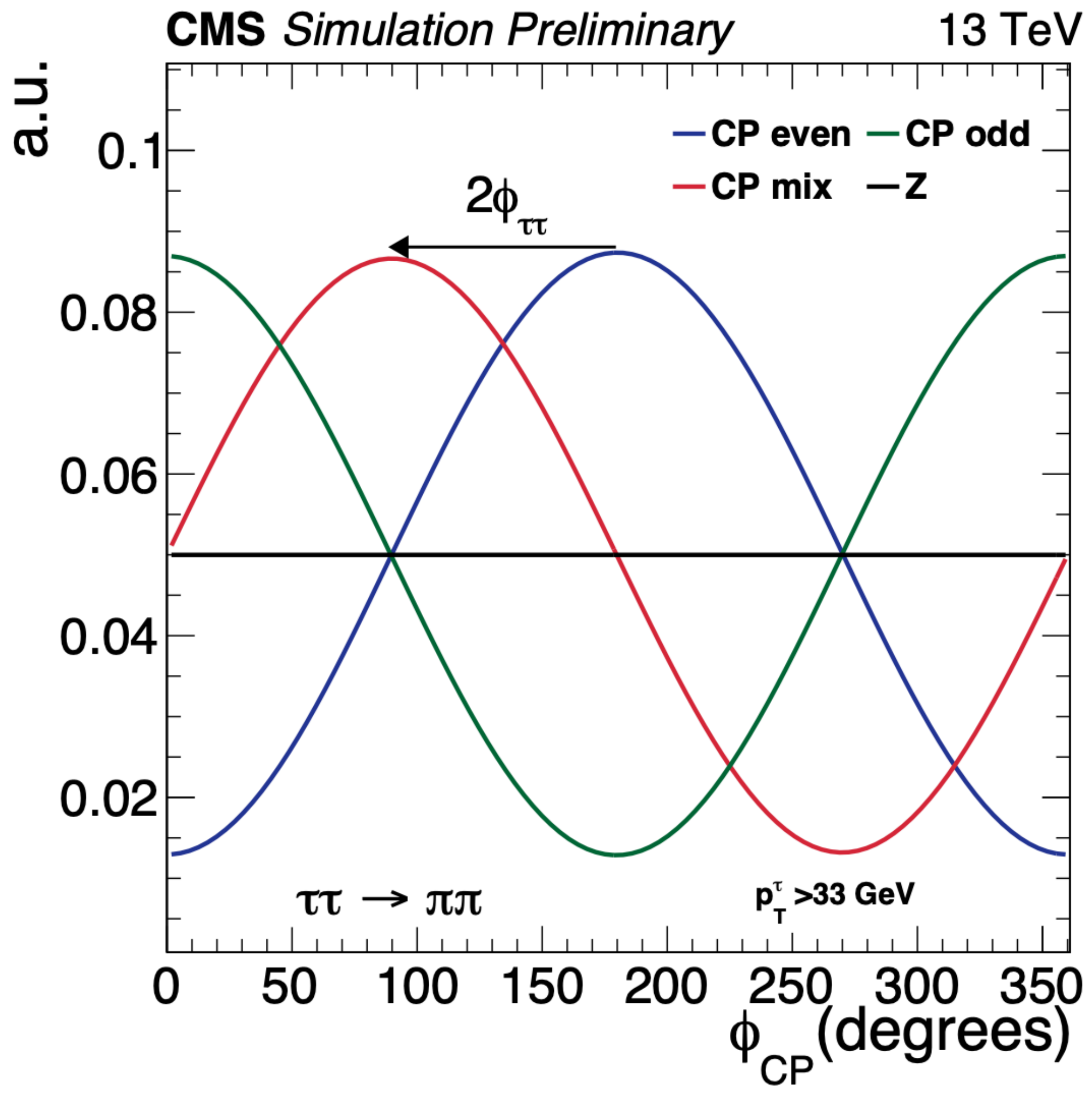
# CP properties of the Tau Yukawa

## Through polarisation sensitive variable



[CMS PAS HIG-20-006](CMS PAS HIG-20-006)




Uses either the impact parameter direction for single-prong taus ($\pi^{\pm}$) only or using the $\pi^0$ momentum for the

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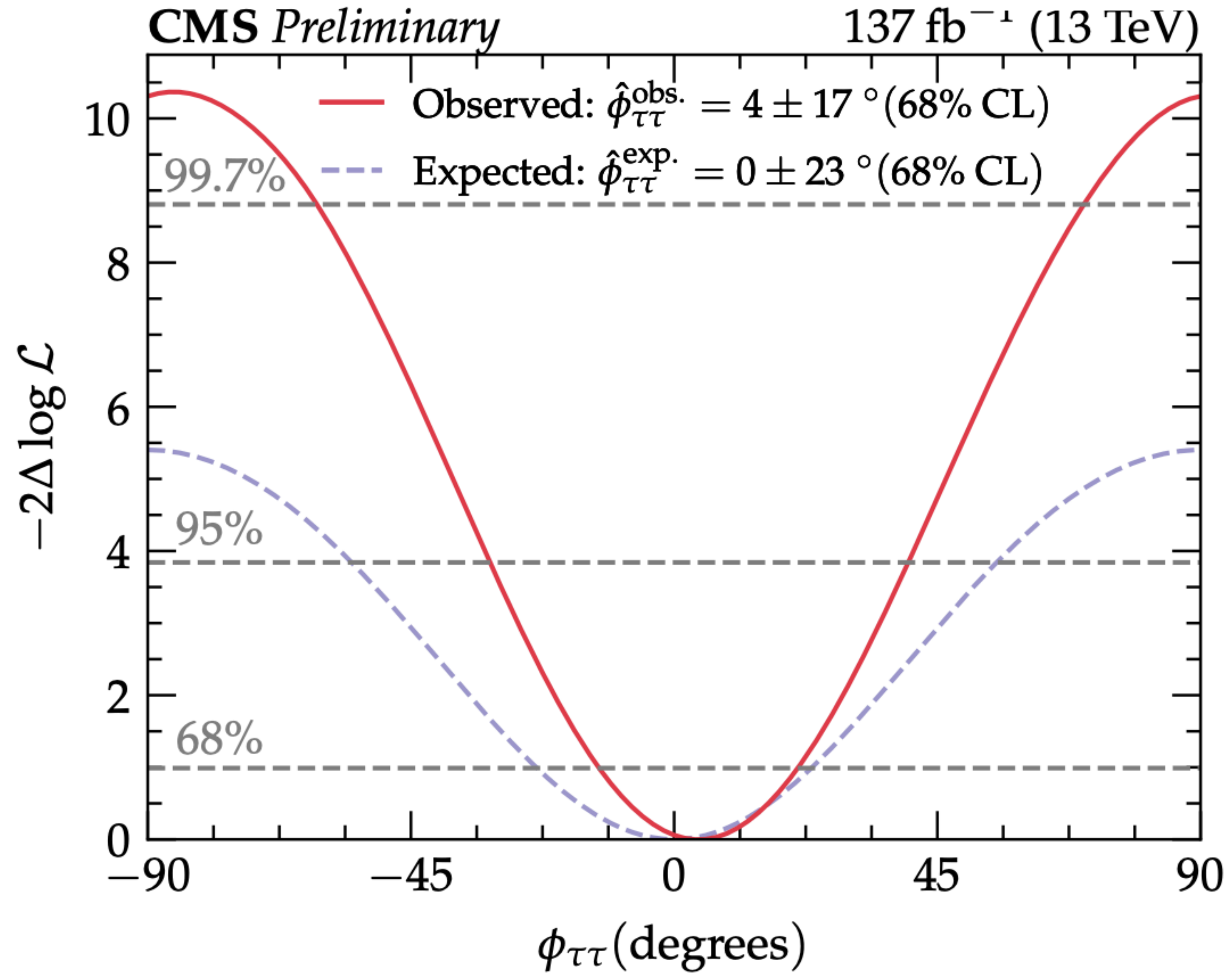
This method works also for the three prong tau decays with a $\rho^0 \rightarrow \pi^+\pi^-$

Tau decays are selected with a BDT and the $\phi_{CP}$ distribution is considered in different bins of this BDT score

Fit is performed in order to estimated the ratio of the CP-odd to CP-even couplings - CP mixing angle:

$$\mathcal{L}_Y = -\frac{m_\tau \mathrm{H}}{\mathrm{v}}(\kappa_\tau \bar{\tau}\tau + \tilde{\kappa}_\tau \bar{\tau} i \gamma_5 \tau) \qquad \tan(\phi_{\tau\tau}) = \frac{\tilde{\kappa}_\tau}{\kappa_\tau}$$



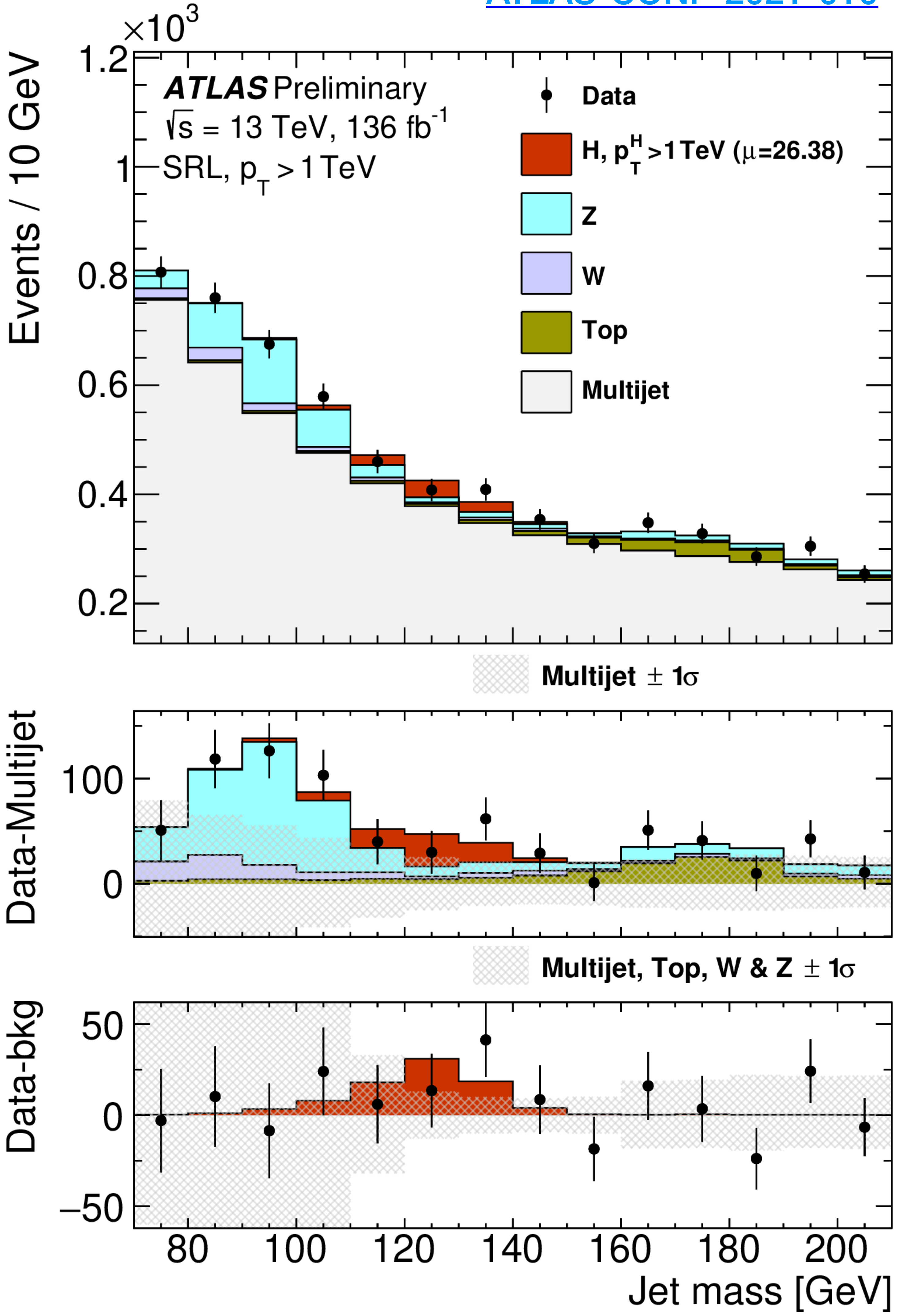

$$\phi_{\tau\tau} = 4 \pm 17^o\ (23^o\ \mathrm{exp.})$$

CP-even preferred vs CP-Odd at ~3$\sigma$ level

# Higgs boson decays to b-quarks



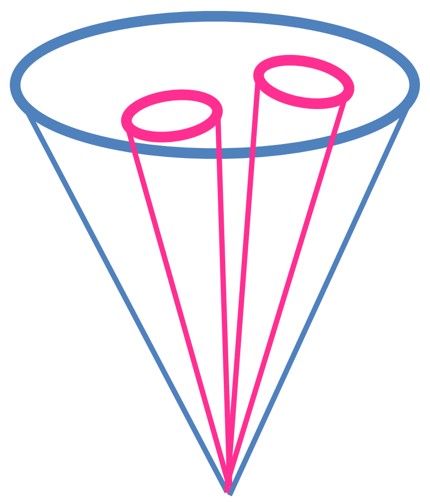
ATLAS-CONF-2021-010




## Inclusive boosted analysis in bb

at highest pT (using jet substructure)

Illustration of the importance of jet substructure reconstruction techniques

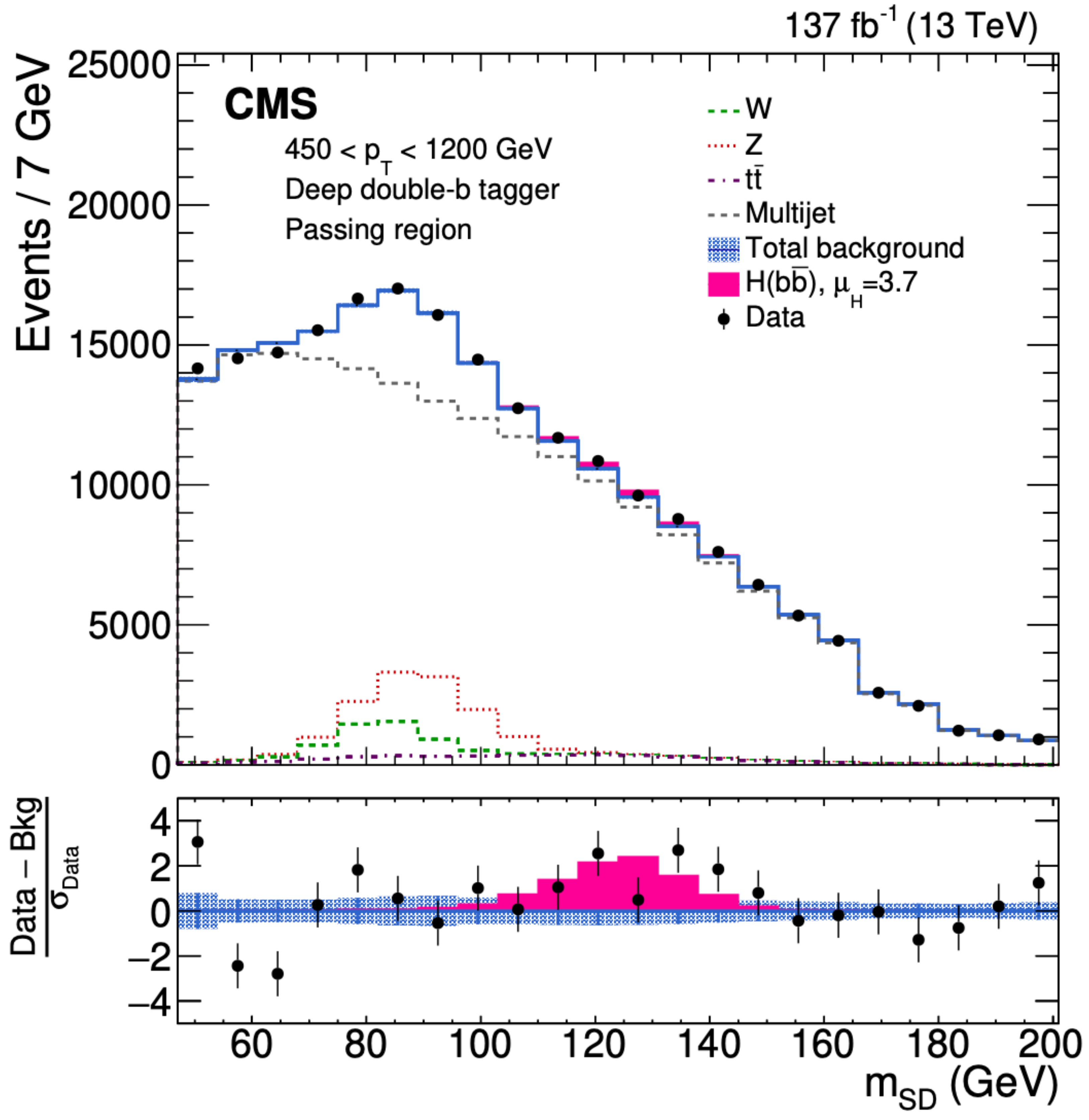


## ATLAS

| Result | $\mu_H$ | $\mu_Z$ | $\mu_{t\bar{t}}$ |
|---|---|---|---|
| Expected | $1.0 \pm 3.0$ | $1.00 \pm 0.17$ | $1.00 \pm 0.07$ |
| Observed | $1.1 \pm 3.6$ | $1.25 \pm 0.22$ | $0.81 \pm 0.06$ |

## CMS

| | |
|---|---|
| Expected $\mu_{\mathrm{H}}$ | $1.0 \pm 1.4$ |
| Observed $\mu_{\mathrm{H}}$ | $3.7^{+1.6}_{-1.5}$ |
| Expected H significance ($\mu_{\mathrm{H}} = 1$) | $0.7\,\sigma$ |
| Observed H significance | $2.5\,\sigma$ |



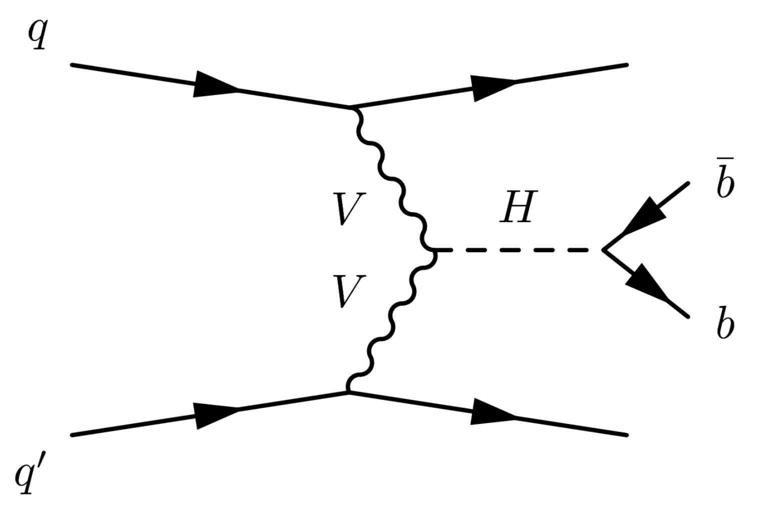

Estimate of sensitivity tricky as it requires the precise estimate of the acceptance for the signal!

Overall excess observed w.r.t. expectation

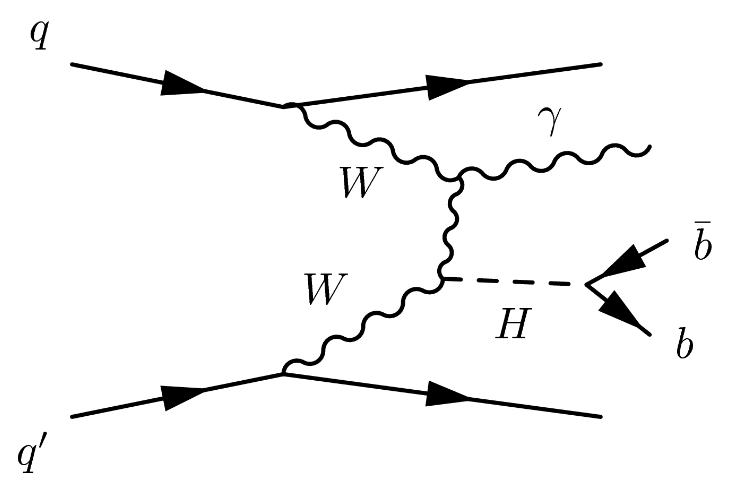
# Higgs boson decays to b-quarks

EPJC 81 (2021)

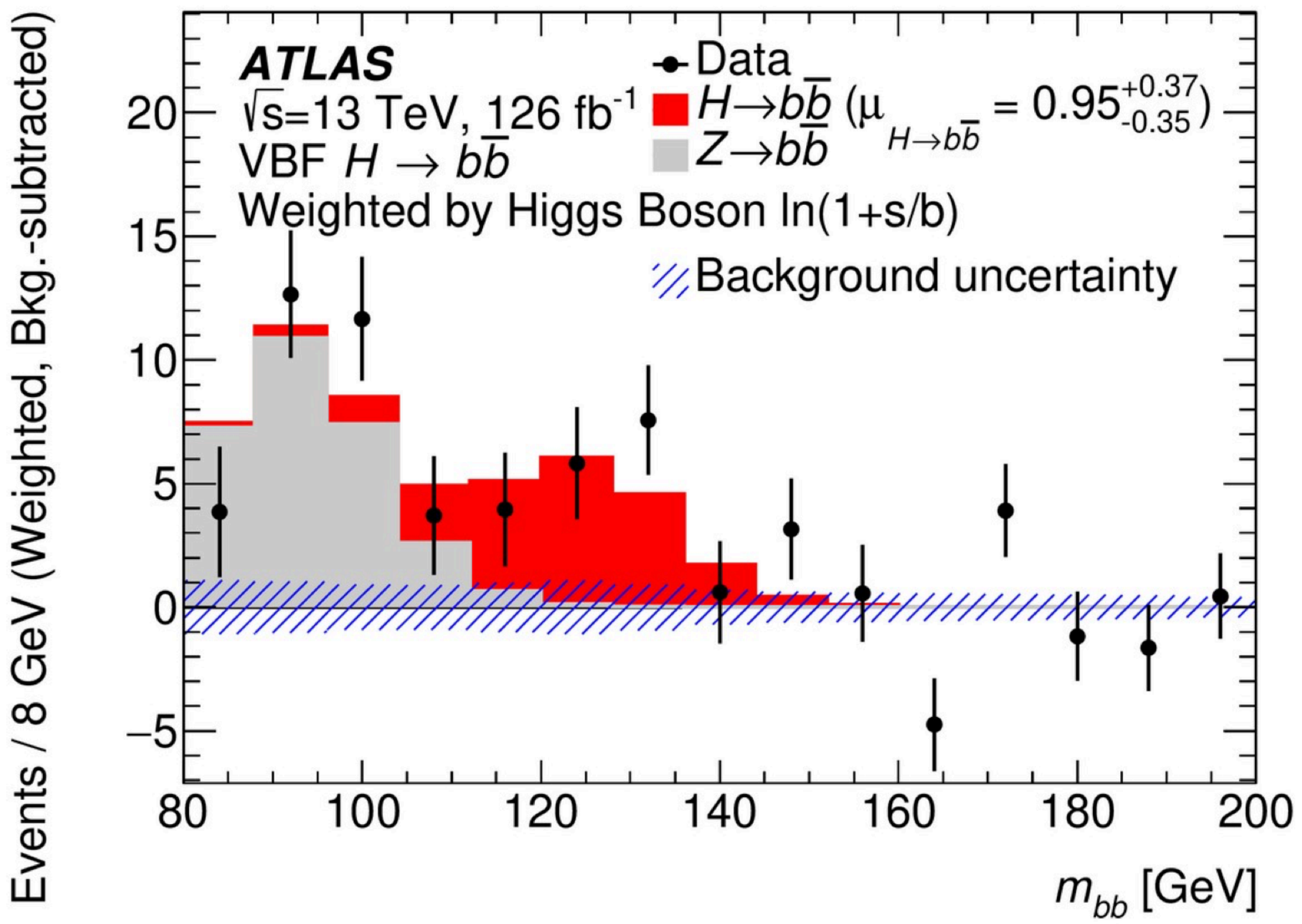
VBF analysis with Higgs in bb including channel with photon

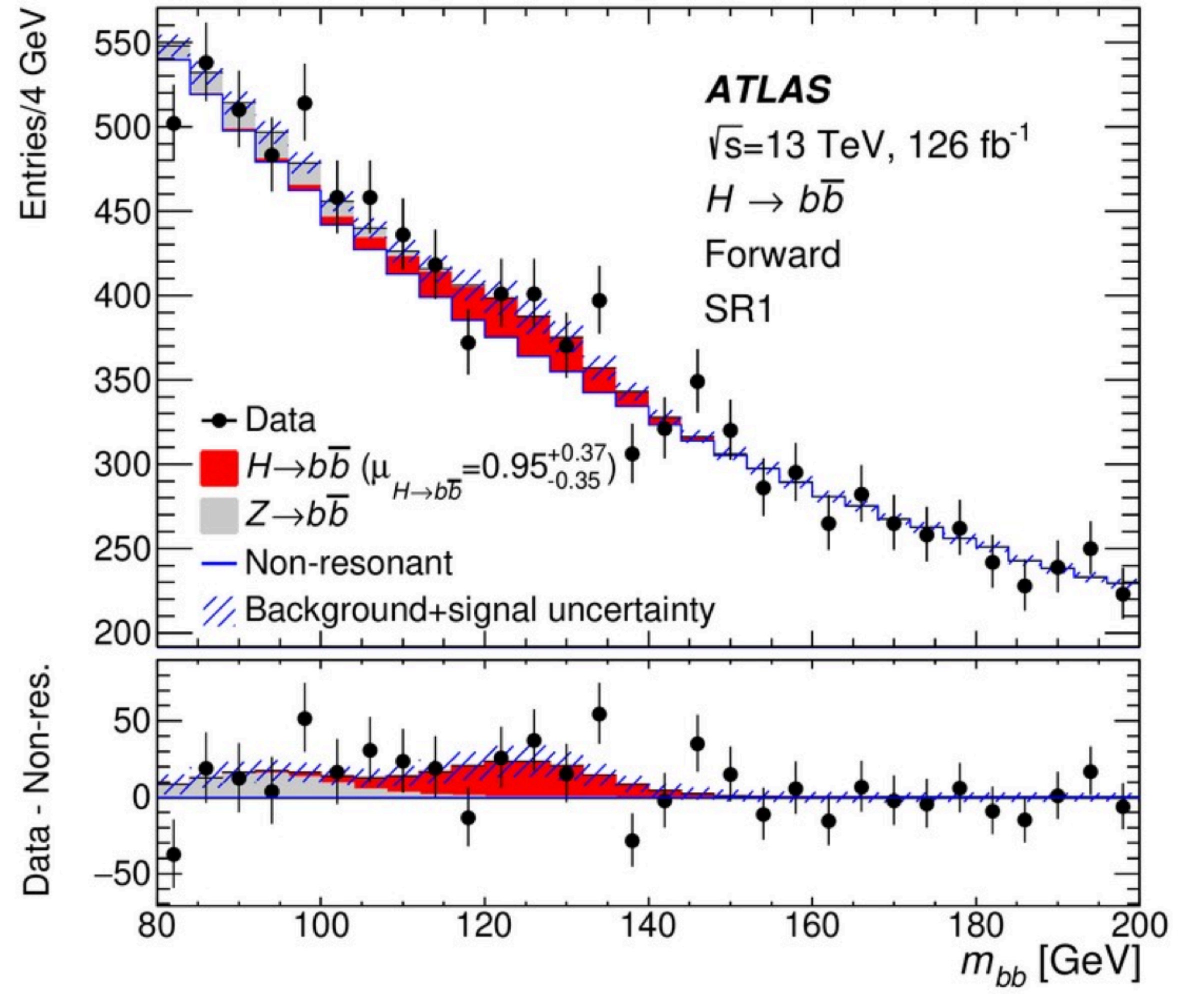


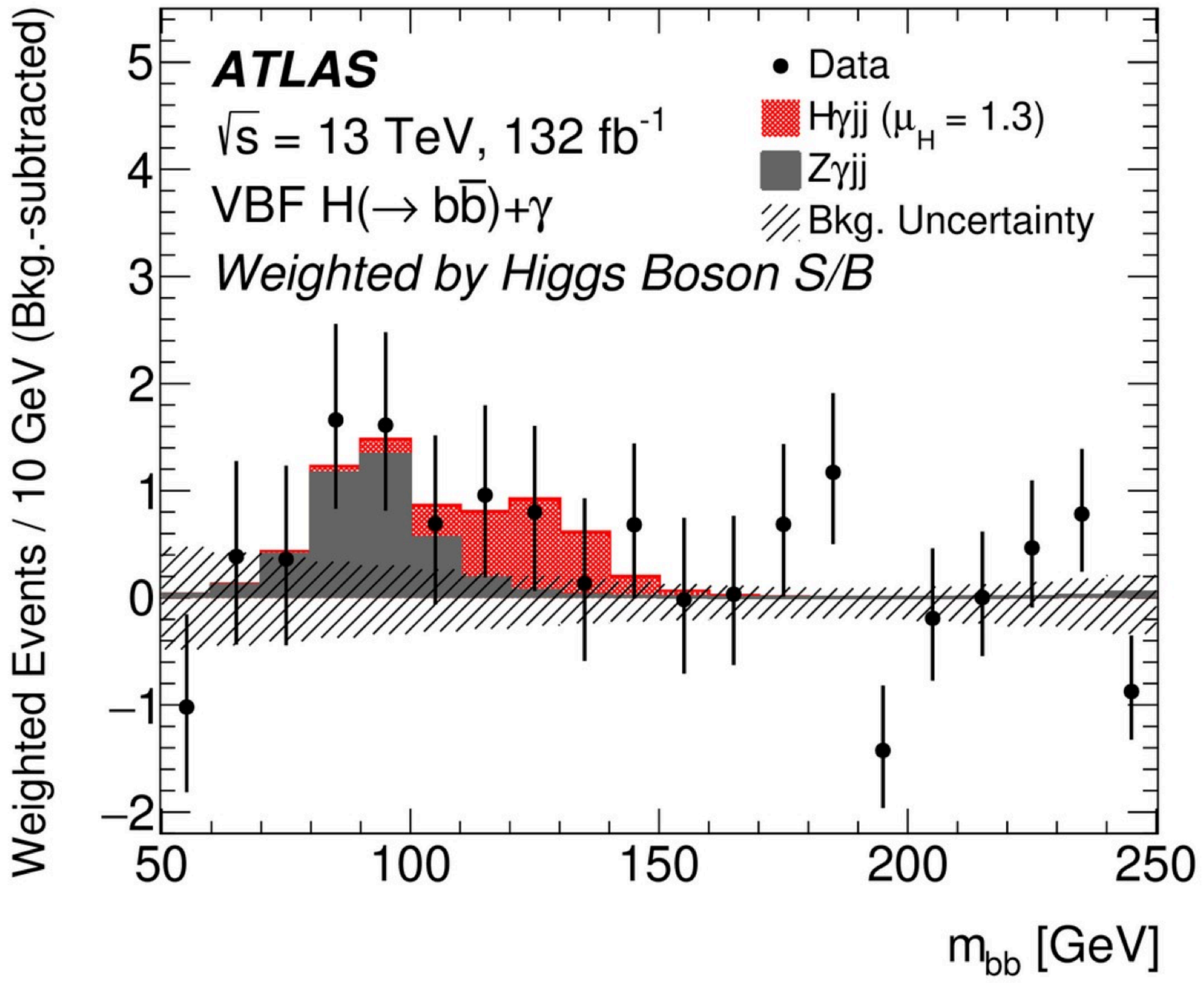

Non trivial trigger requirements!




Taking advantage of the VBF with a photon topology which reduces significantly QCD background which has a destructive interference! It is also very useful to trigger on.




**VBF-inclusive** Continuous background from low selection NN - Z background from embedding!

$$0.95^{+0.31}_{-0.31}(\text{stat.})^{+0.20}_{-0.17}(\text{syst.})$$

2.6σ (3.0σ expected)

**VBF-photon** Fit of signal (and peaking background) on smoothly fallen background

$$1.3 \pm 1.0(stat.) \pm 0.3(syst.)$$

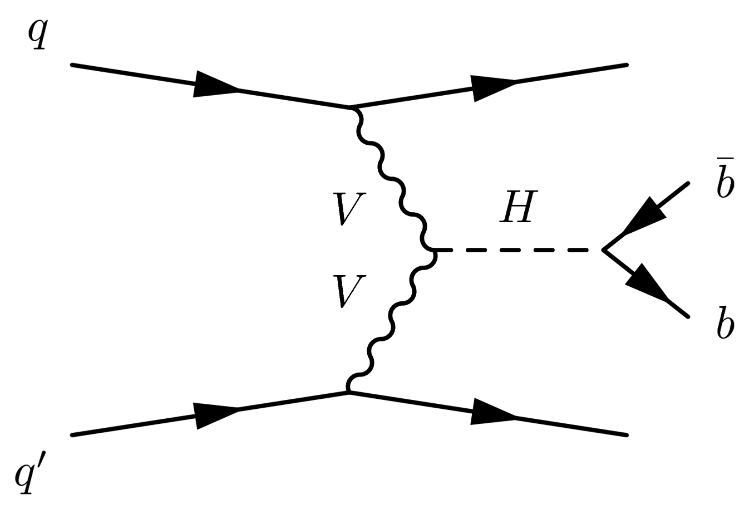
1.3σ (1.0σ expected)

# Higgs boson decays to b-quarks

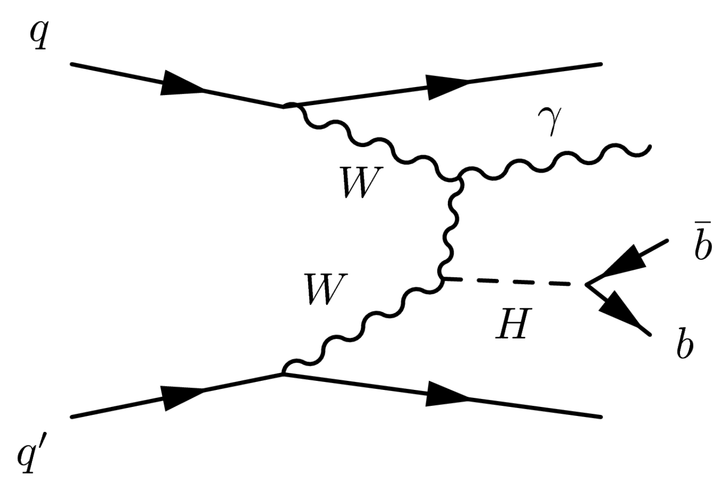


EPJC 81 (2021)

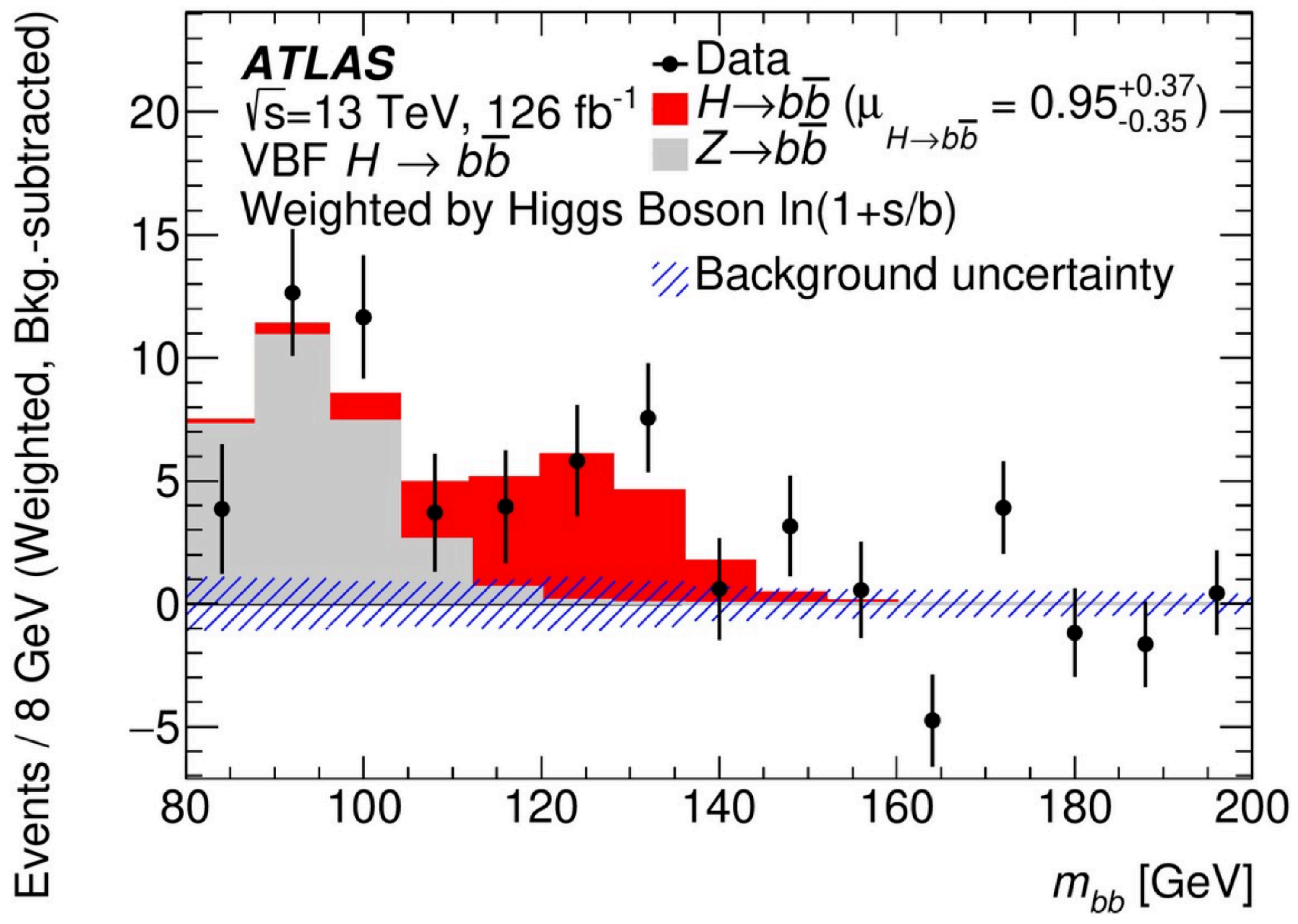
VBF analysis with Higgs in bb including channel with photon

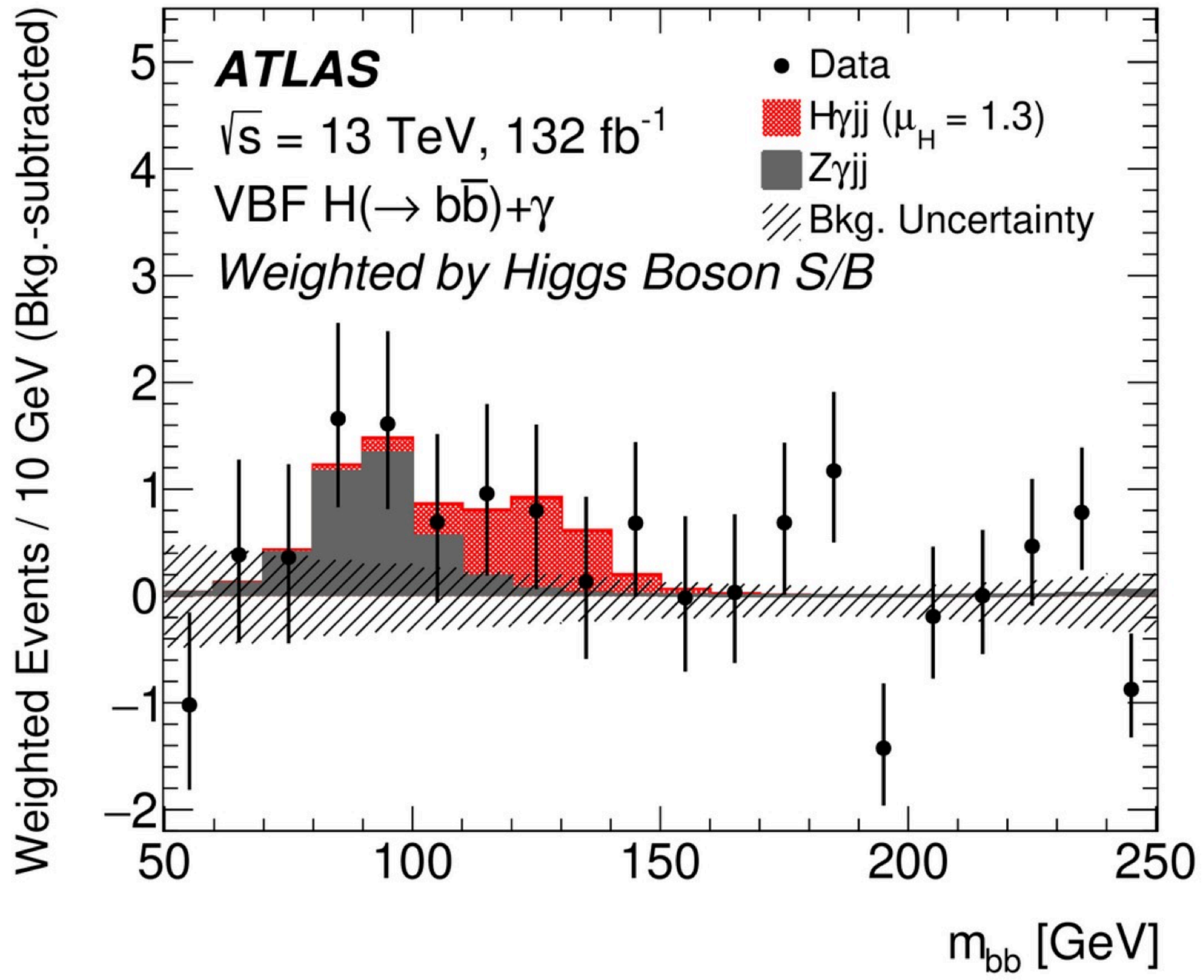


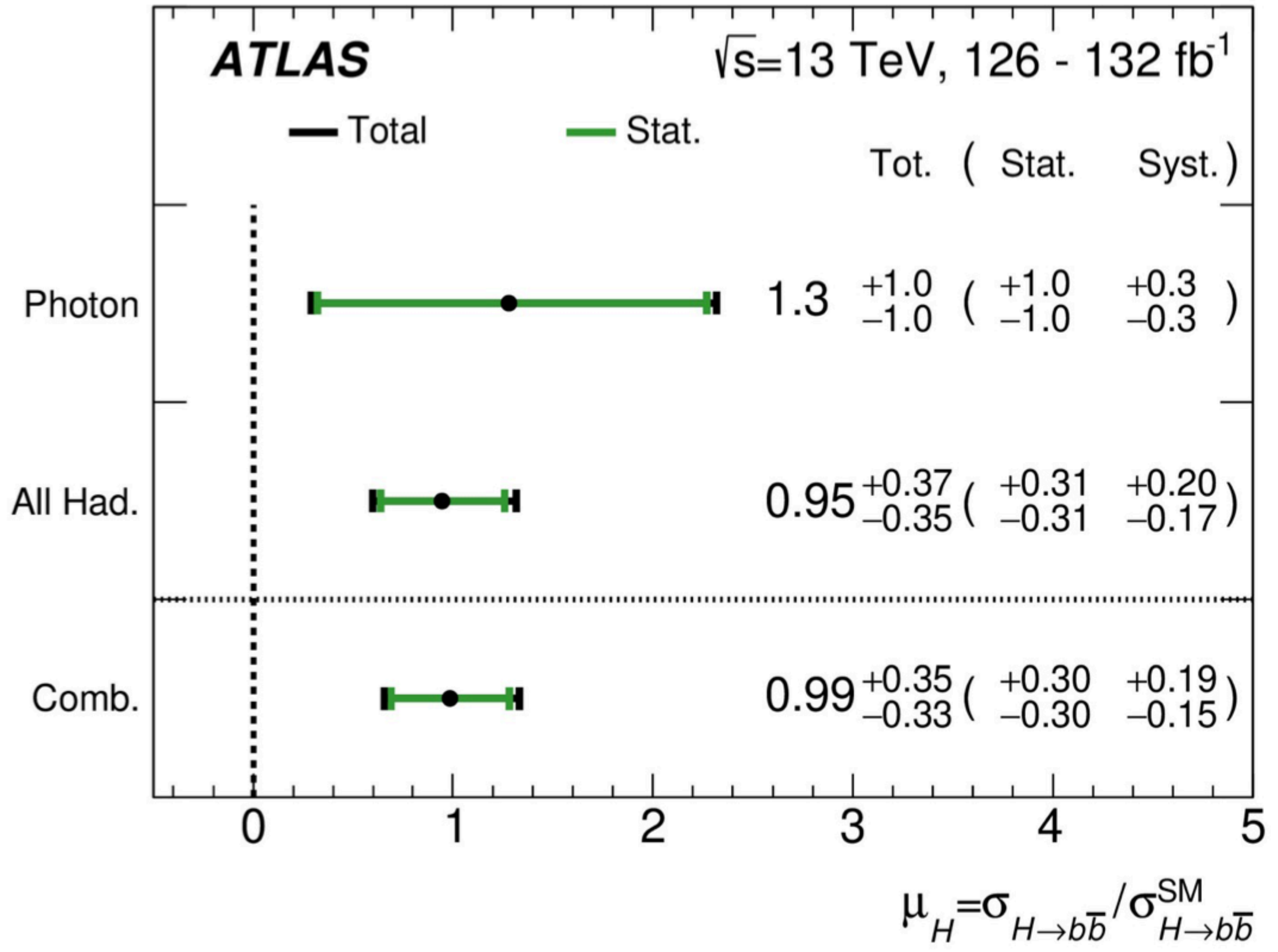

Non trivial trigger requirements!




Taking advantage of the VBF with a photon topology which reduces significantly QCD background which has a destructive interference! It is also very useful to trigger on.



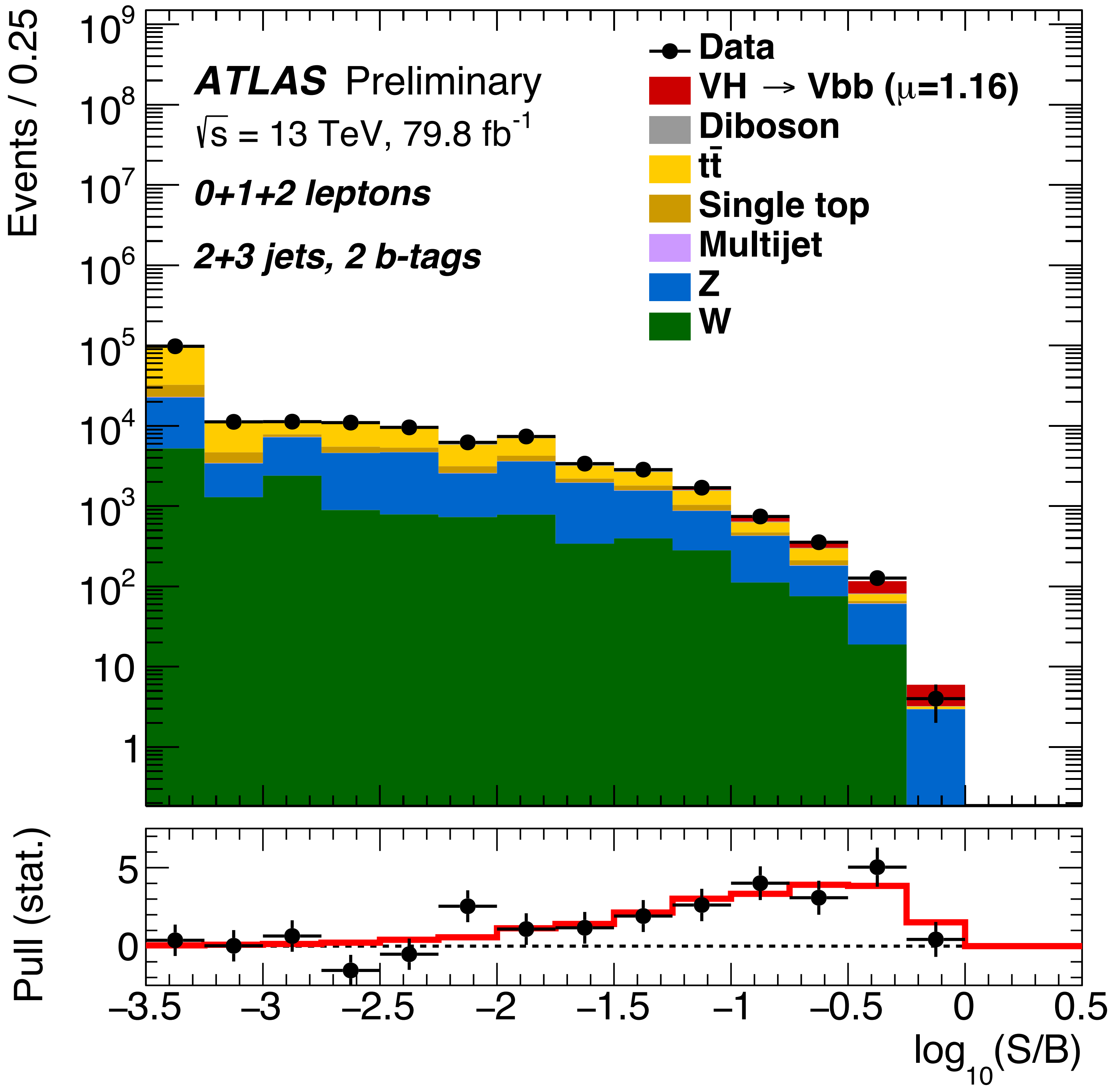



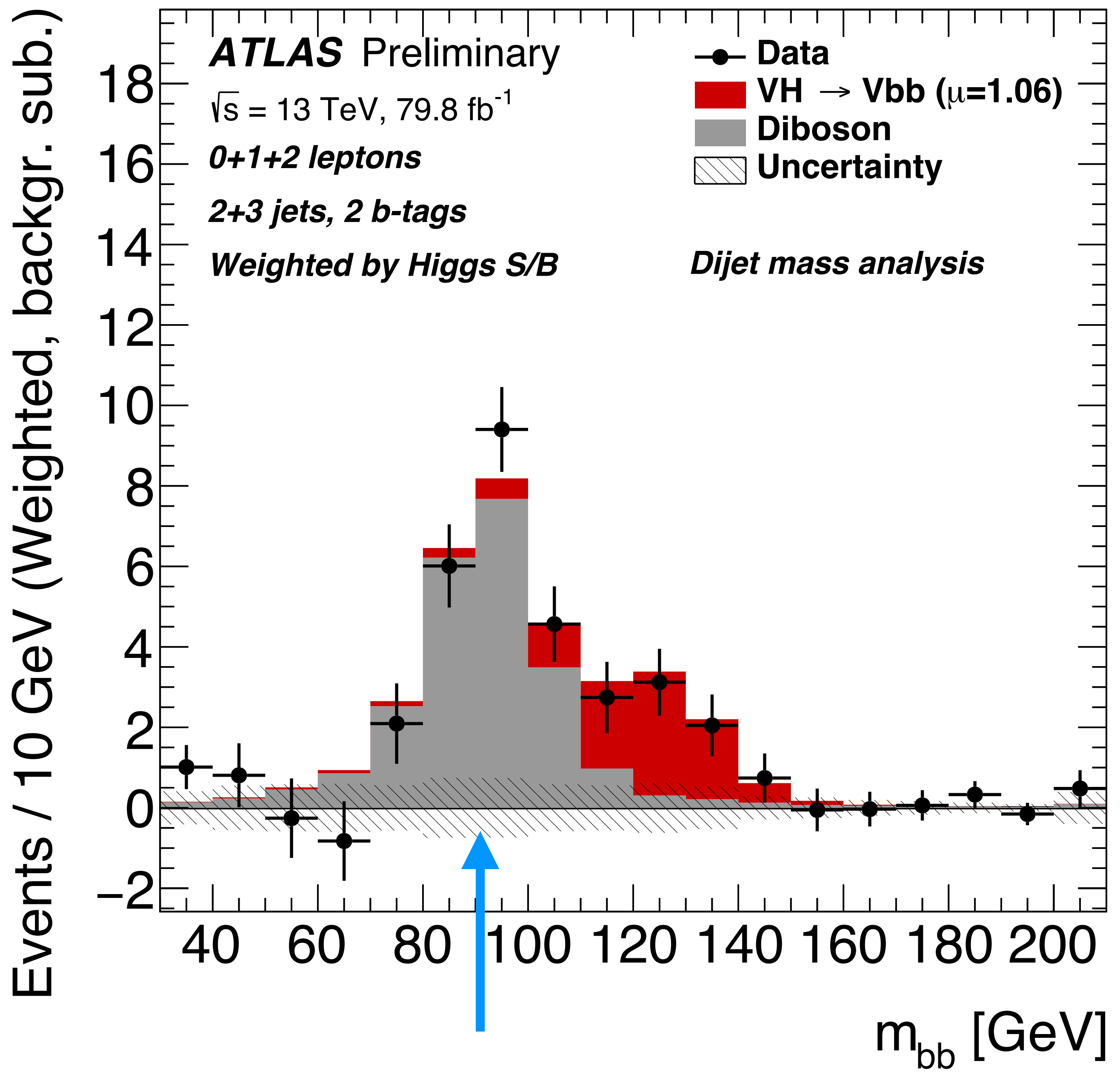

3.0σ (3.0σ expected)

**Evidence!**

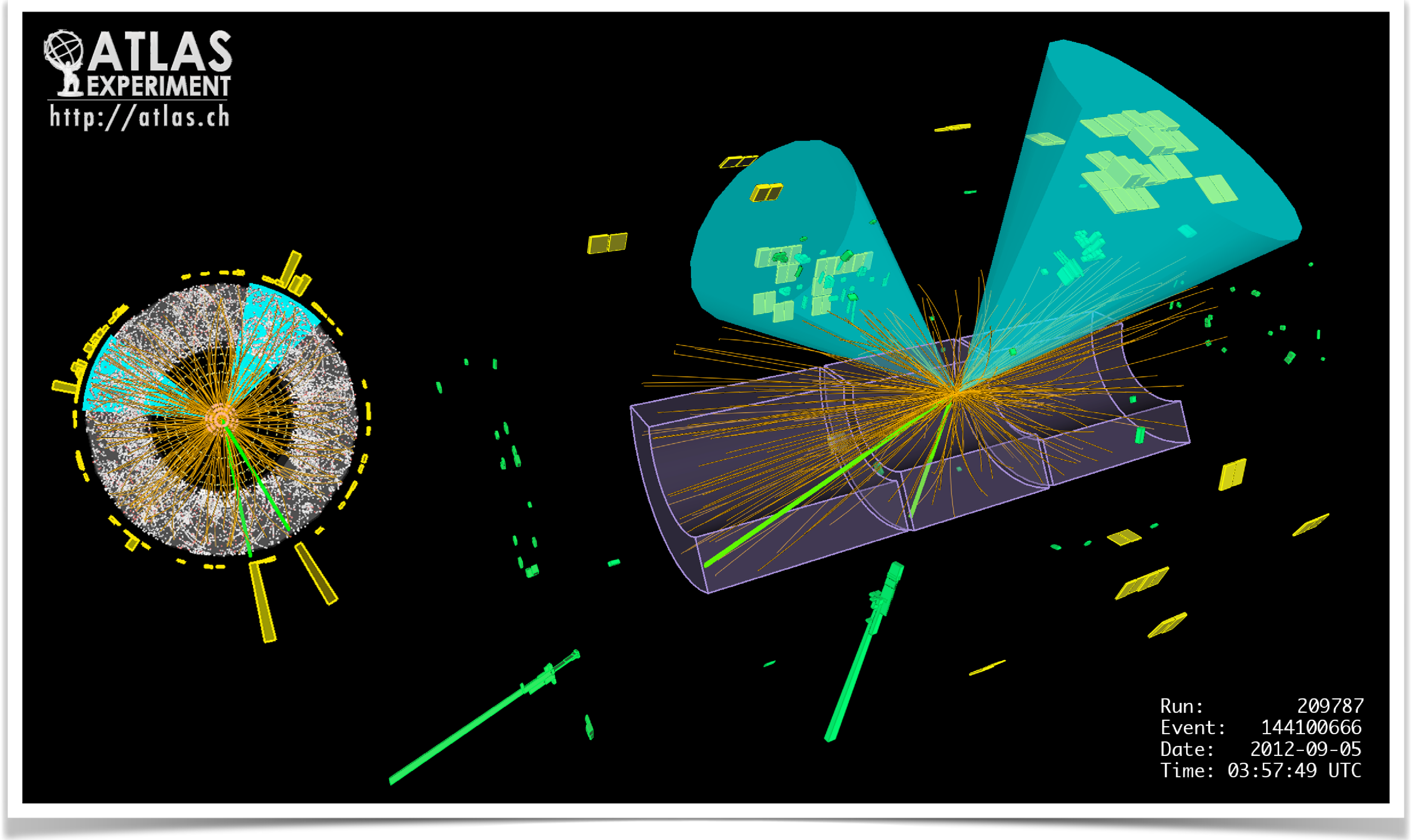
# Higgs boson decays to b-quarks






Analysis is sensitive to Z decays to b-quarks, provide an important check.




Main background is V+jets (in particular b-jets), relies on a good simulation, but is controlled in the mass side-bands!

Very important measurement of VZ process with Z to b quarks as a check.

Analysis based on three main channels targeting WH and ZH production, based on the W or Z decays:

- 0 « leptons » (for neutrino decays of the Z)
- 1-lepton (W decaying to an electron or a muon)
- 2-leptons (Z decaying to electrons or muons)

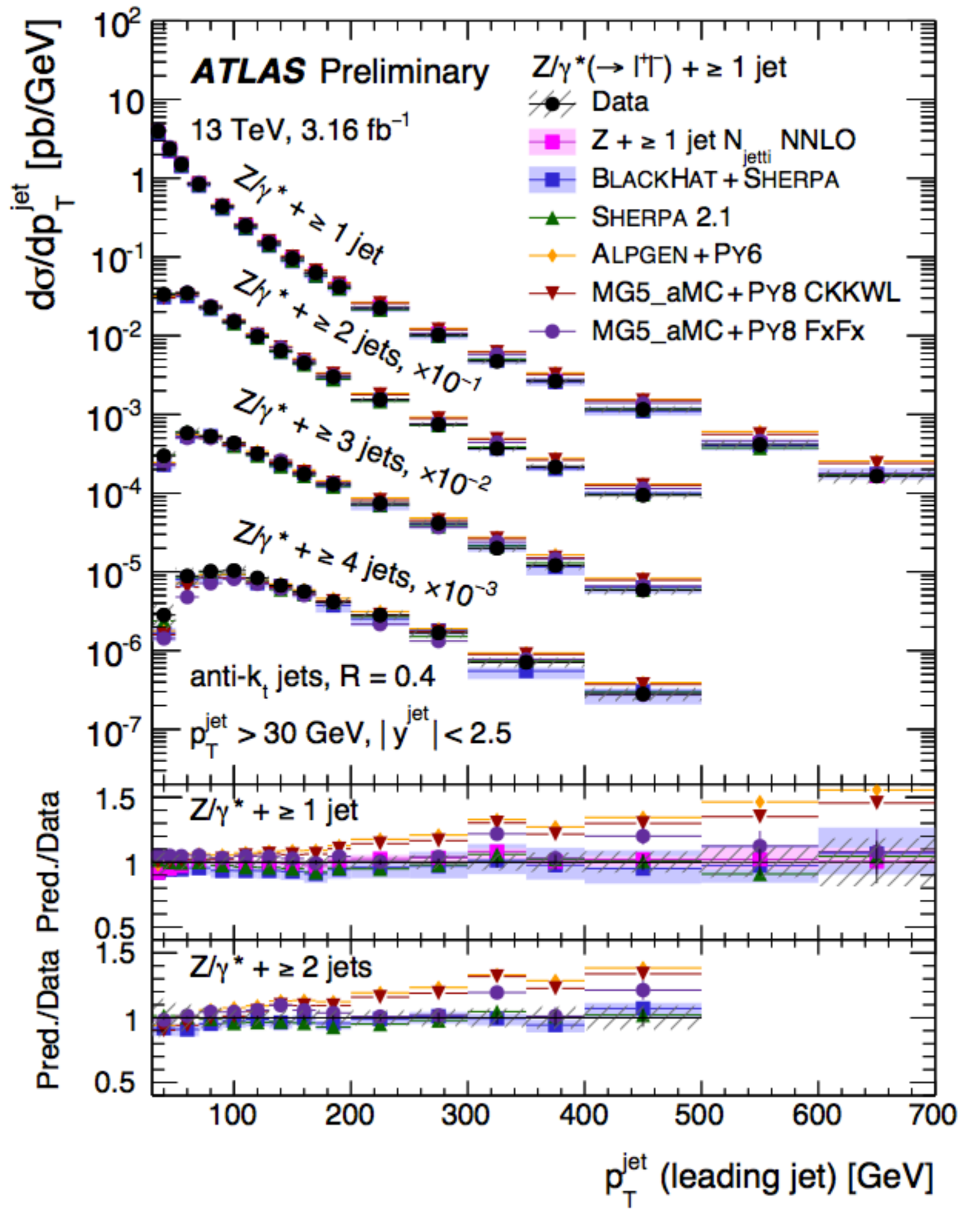
| | | | | |
|---|---|---|---|---|
| **ATLAS** | Observed | $5.4\sigma$ | Expected | $5.5\sigma$ |
| **CMS** | Observed | $5.5\sigma$ | Expected | $5.6\sigma$ |

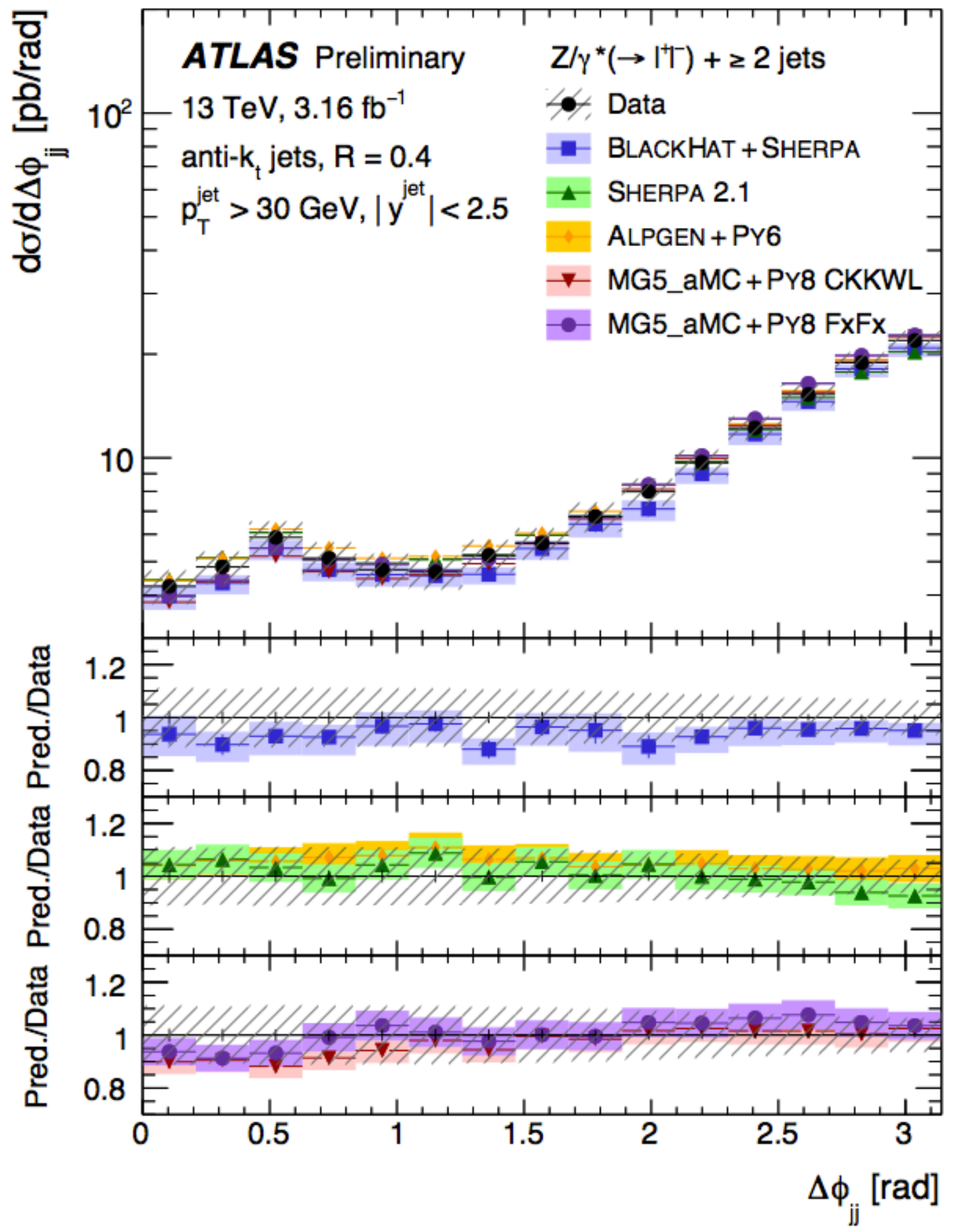
**Observation!!**

# Modeling, Ancillary Measurements and HEP Data

Huge effort to move to State-of-the-Art MC and Importance of differential fiducial results

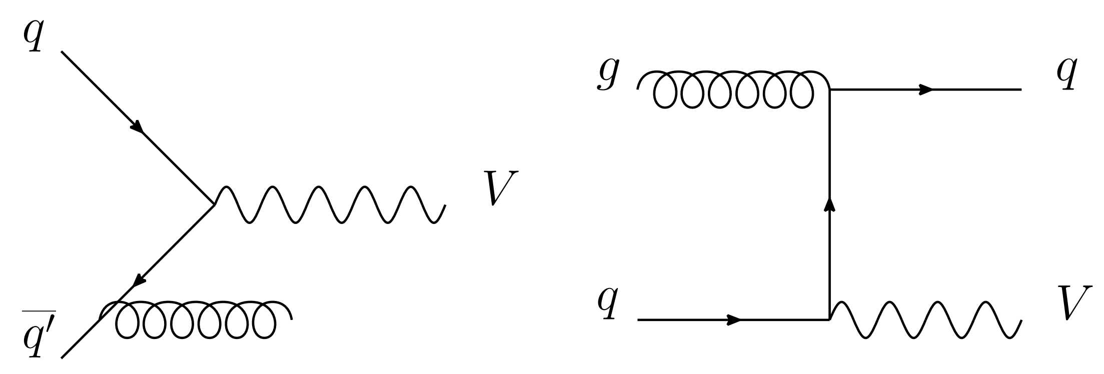




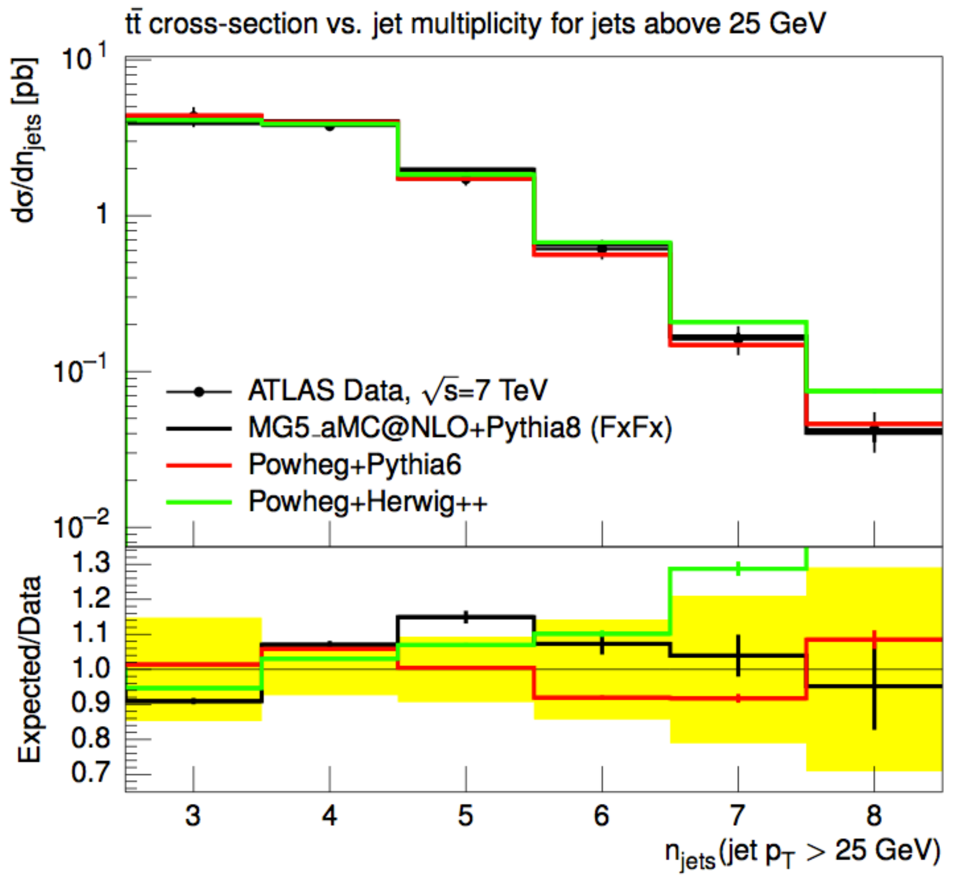

## V+jets production

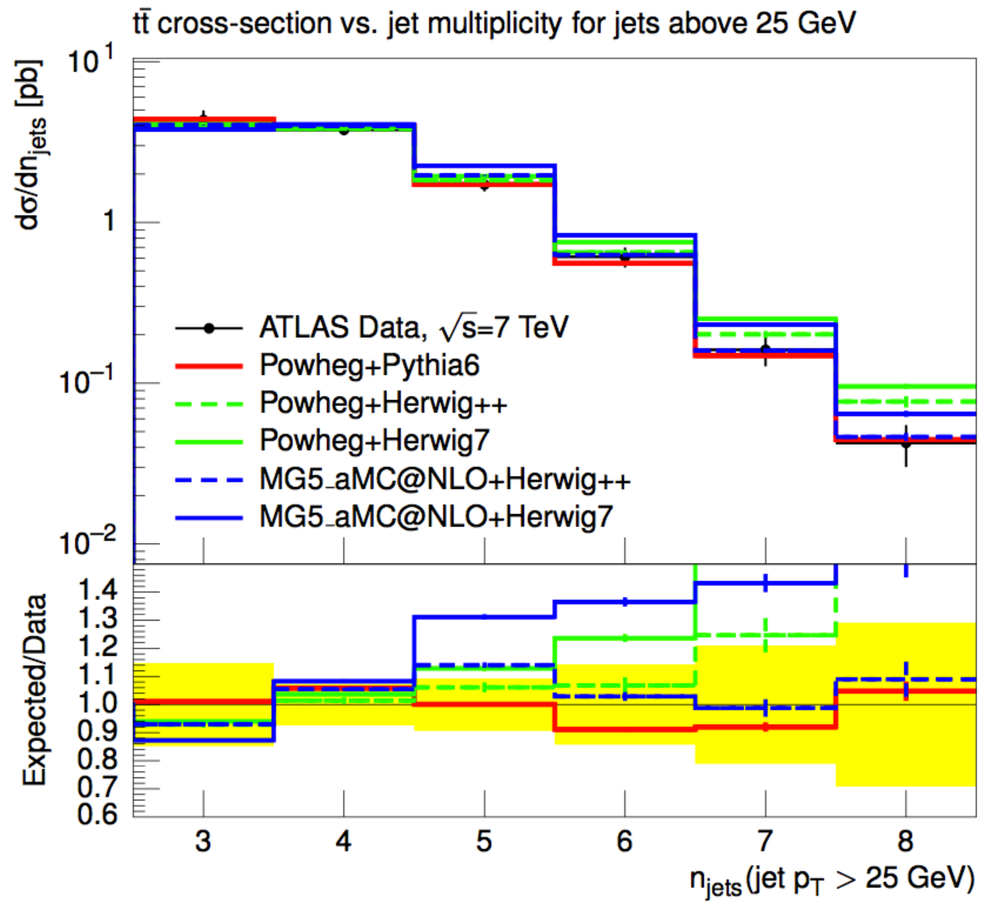
Crucial in the VH(bb) analysis and many more



Already improvements w.r.t. to Run 1 and for the full dataset considering Sherpa 2.2.

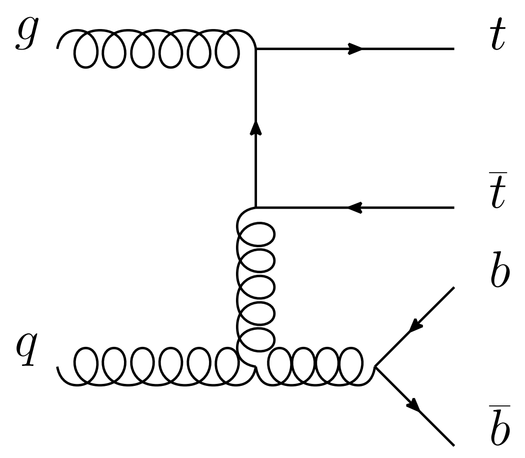
This illustrates the very fast turn around to include latest MC developments.




## Top(+jets) production

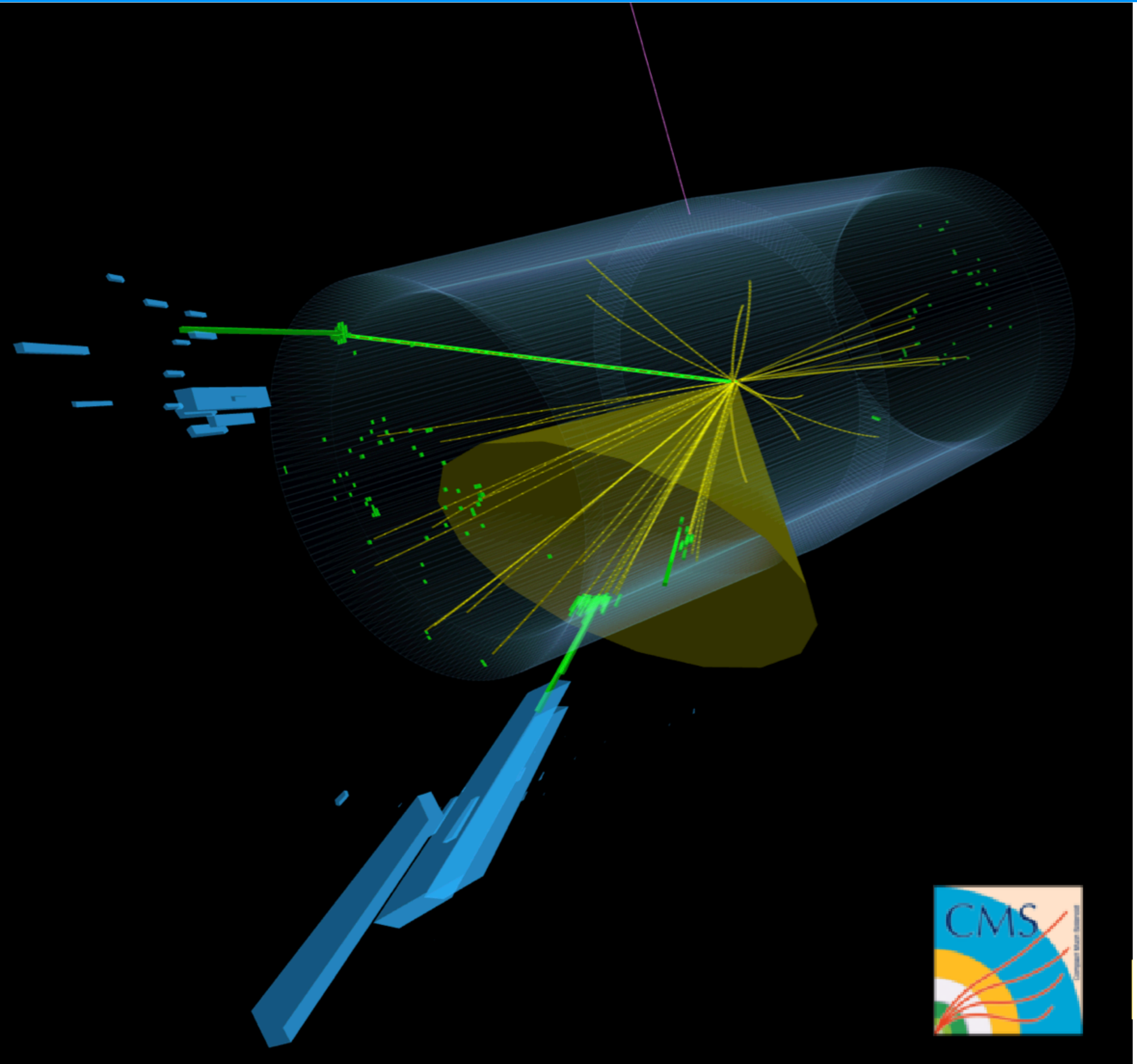
Crucial in the ttH(bb) analysis and many more



**Crucial role played by HEPData and Rivet !**

# The challenging Yukawa coupling to charm





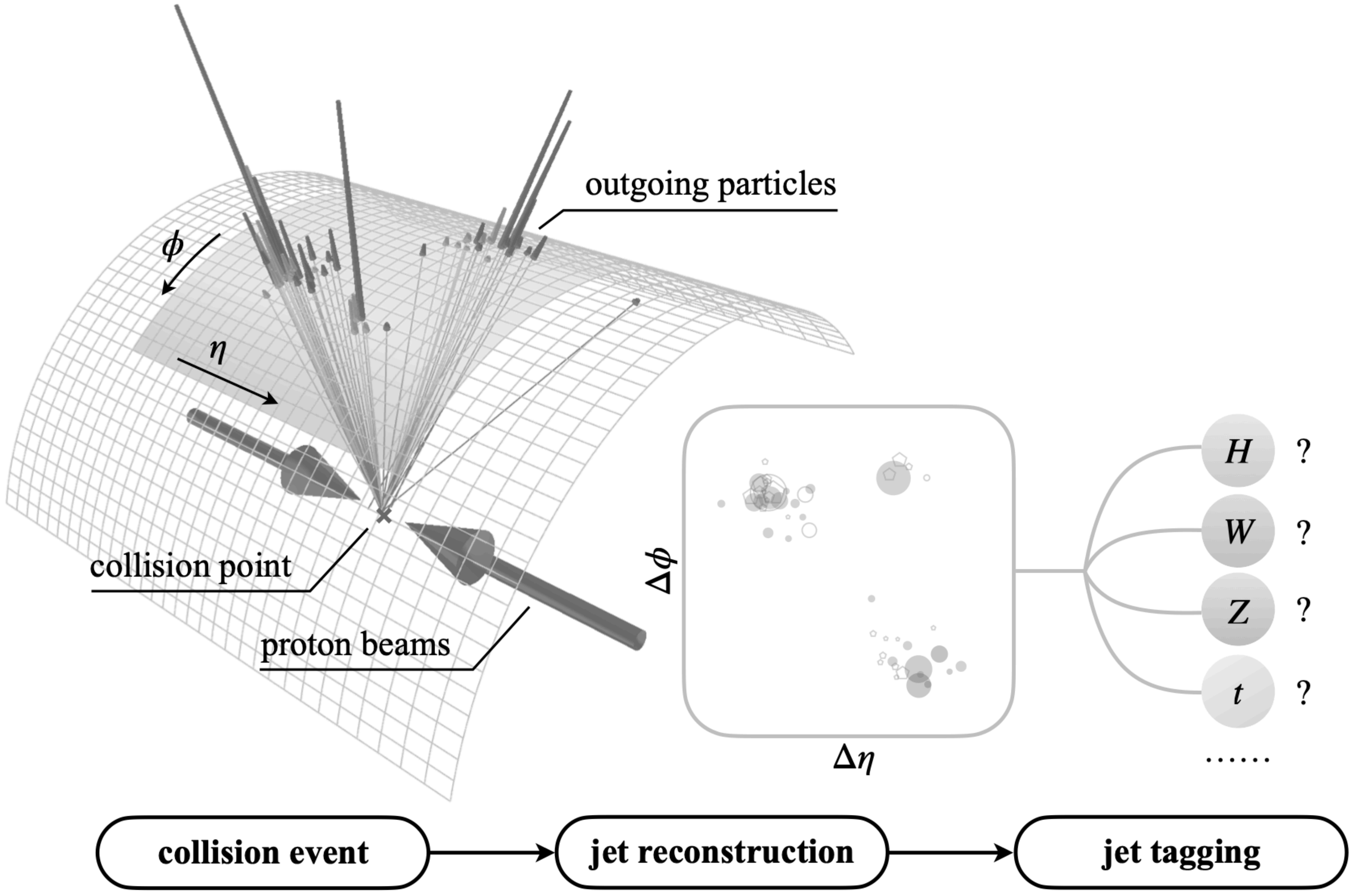




**Illustration from Particle Transformer**

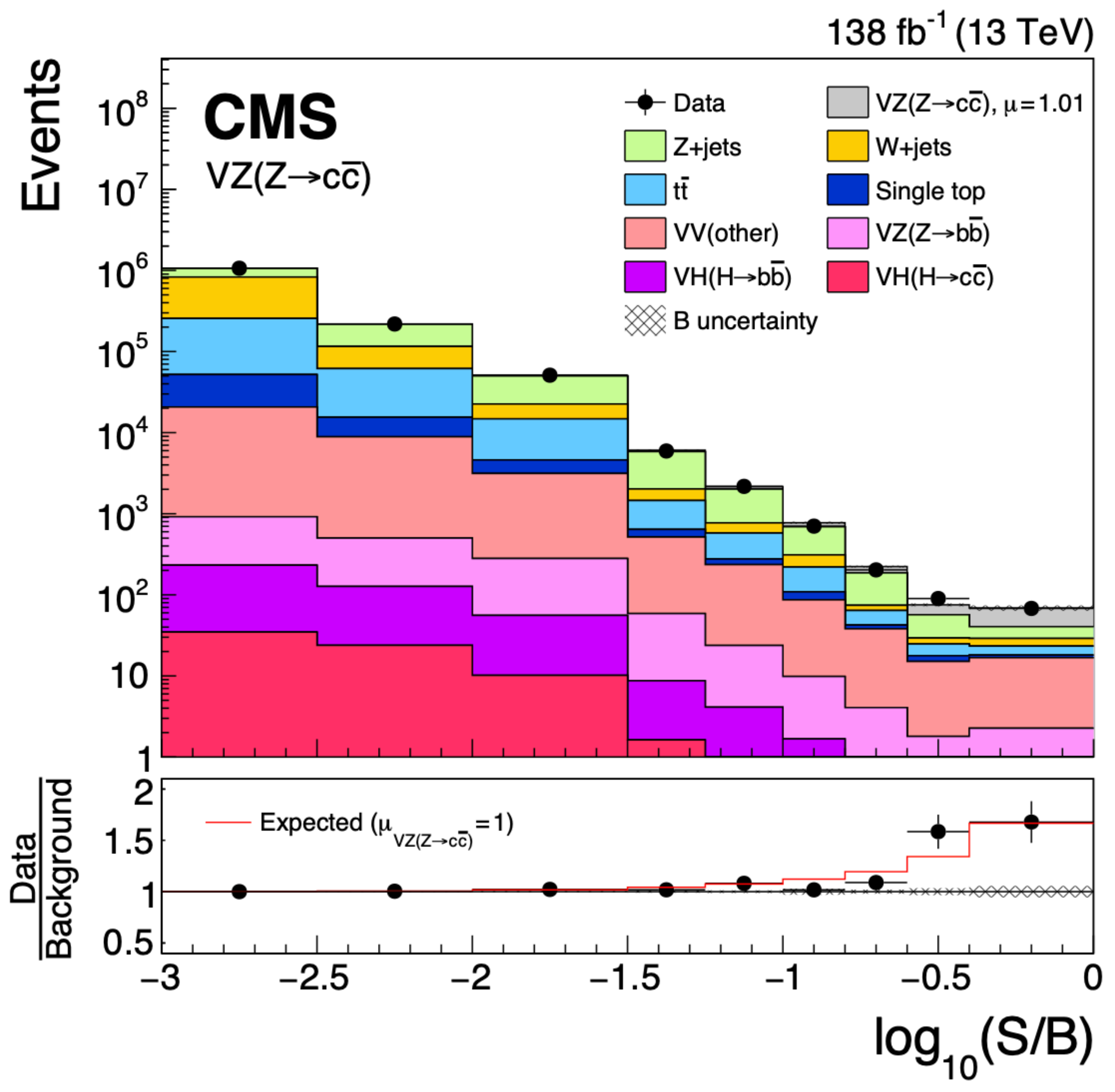
Use of state-of-the-art ML techniques

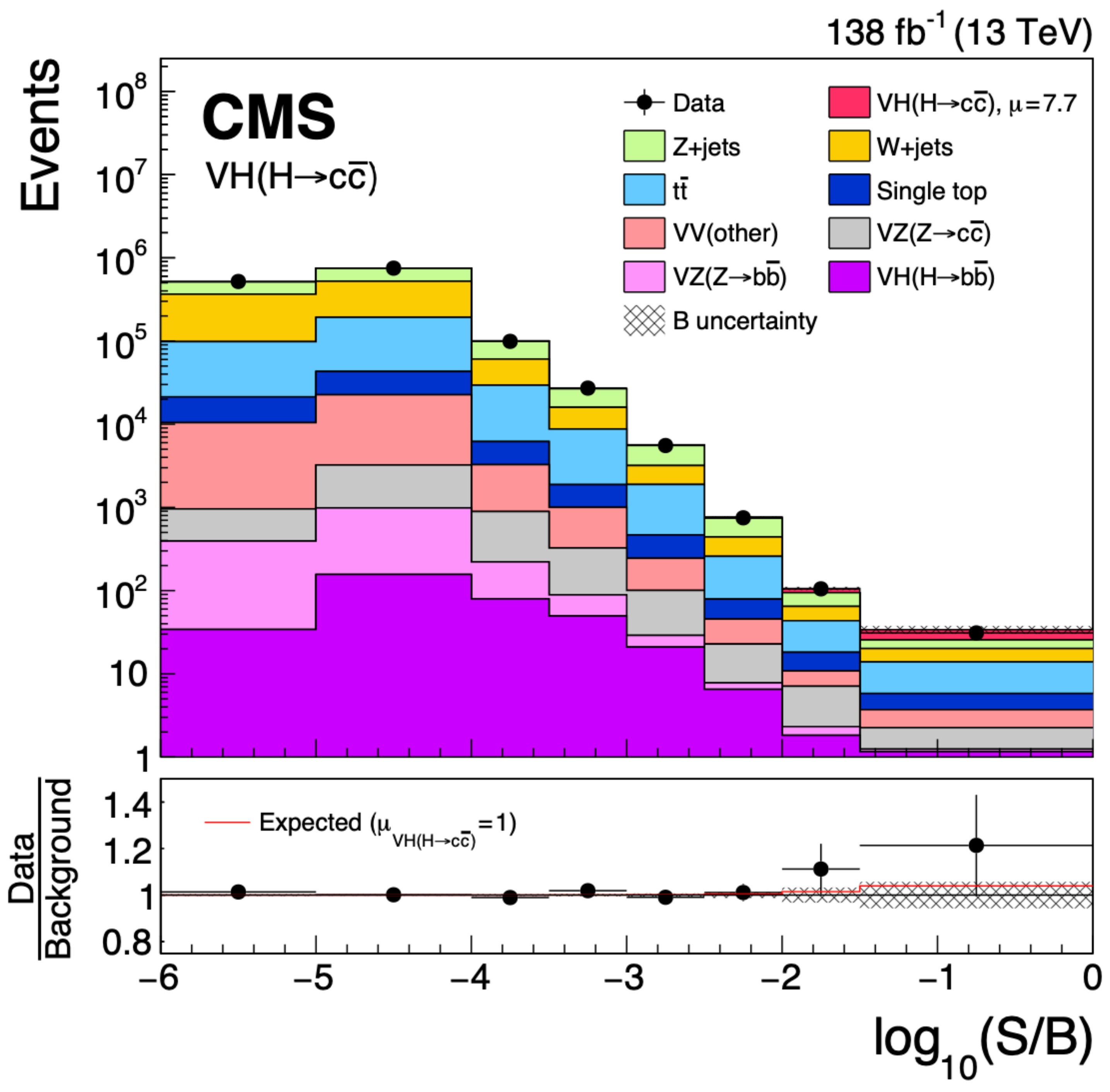
Use "particle clouds" (with more info than only 3D coordinates - 2D eta-phi, pT, charge, particle

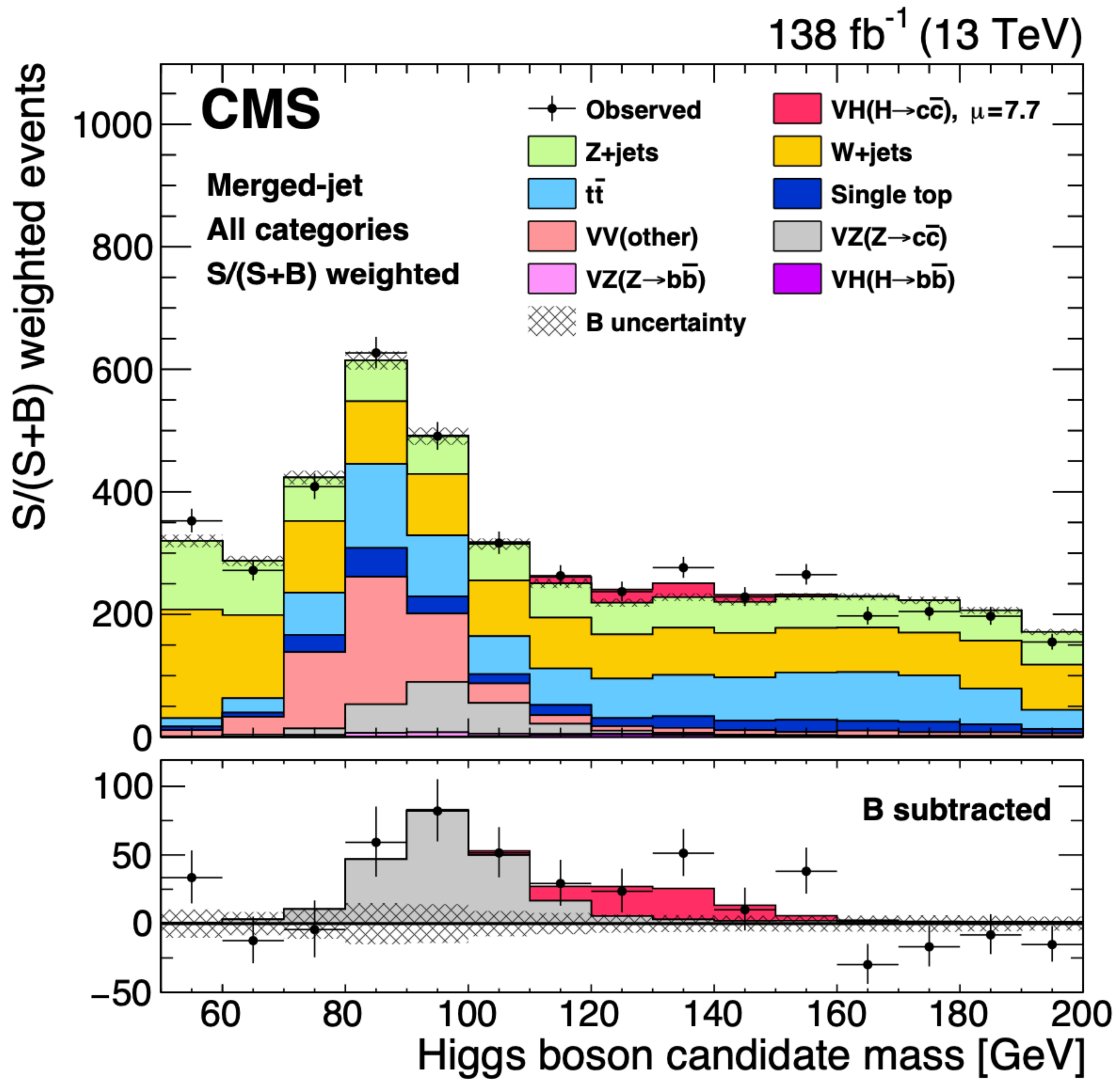
Particle Net uses Dynamic Graph CNN

# The challenging Yukawa coupling to charm






**Limit on signal strength**:
Exclude μ > 14.4 @ 95% CL

**Impressive impact of boosted**
analysis:Resolved alone: 19.0 (exp)
Boosted alone: 8.8 (exp)
Combined: 7.6 (exp)

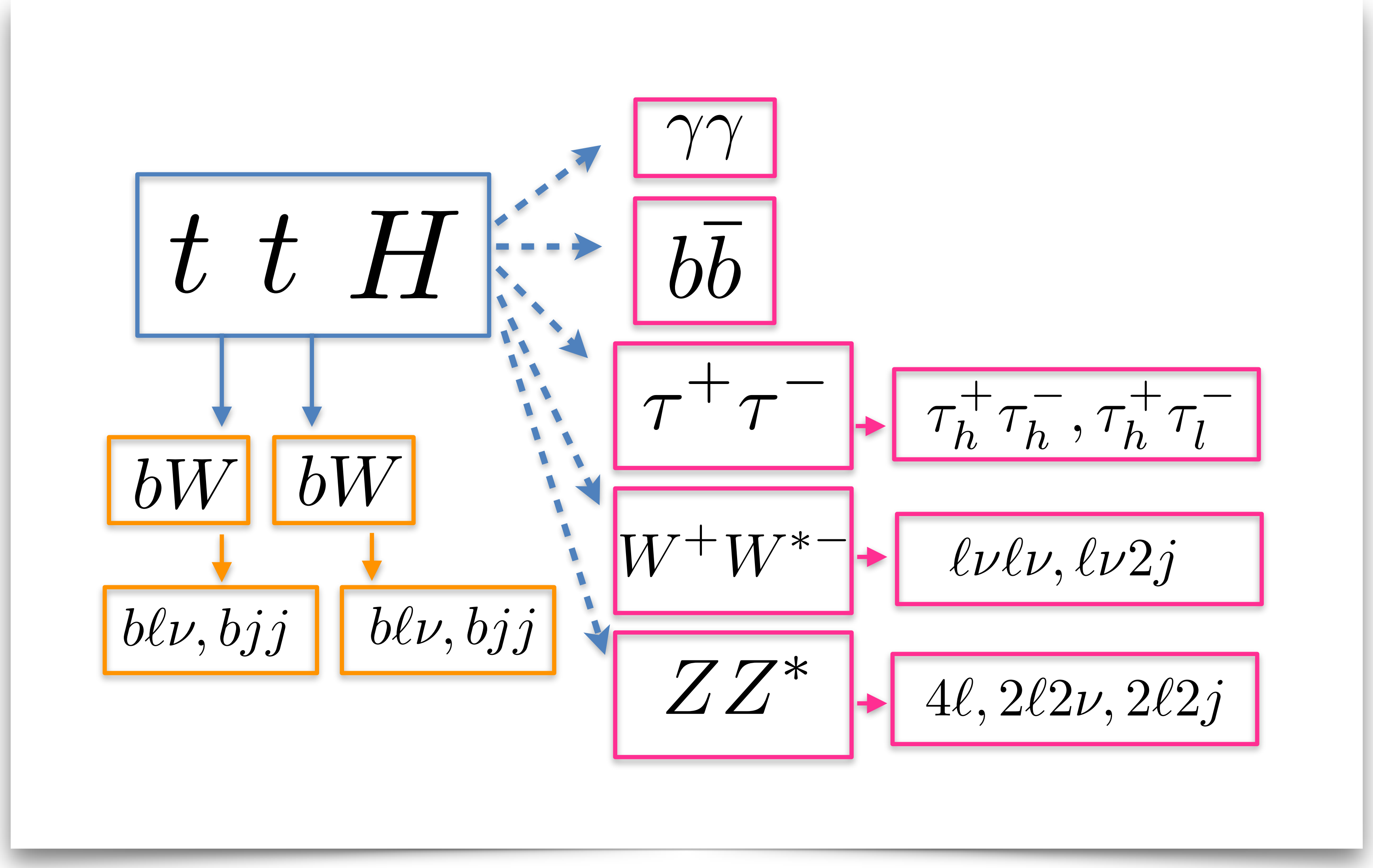
**Impressive constraints on charm Yukawa**
$$1.1 < \kappa_c < 5.5$$

**This result is very encouraging on the possibility of being sensitivity to this process at the LHC**

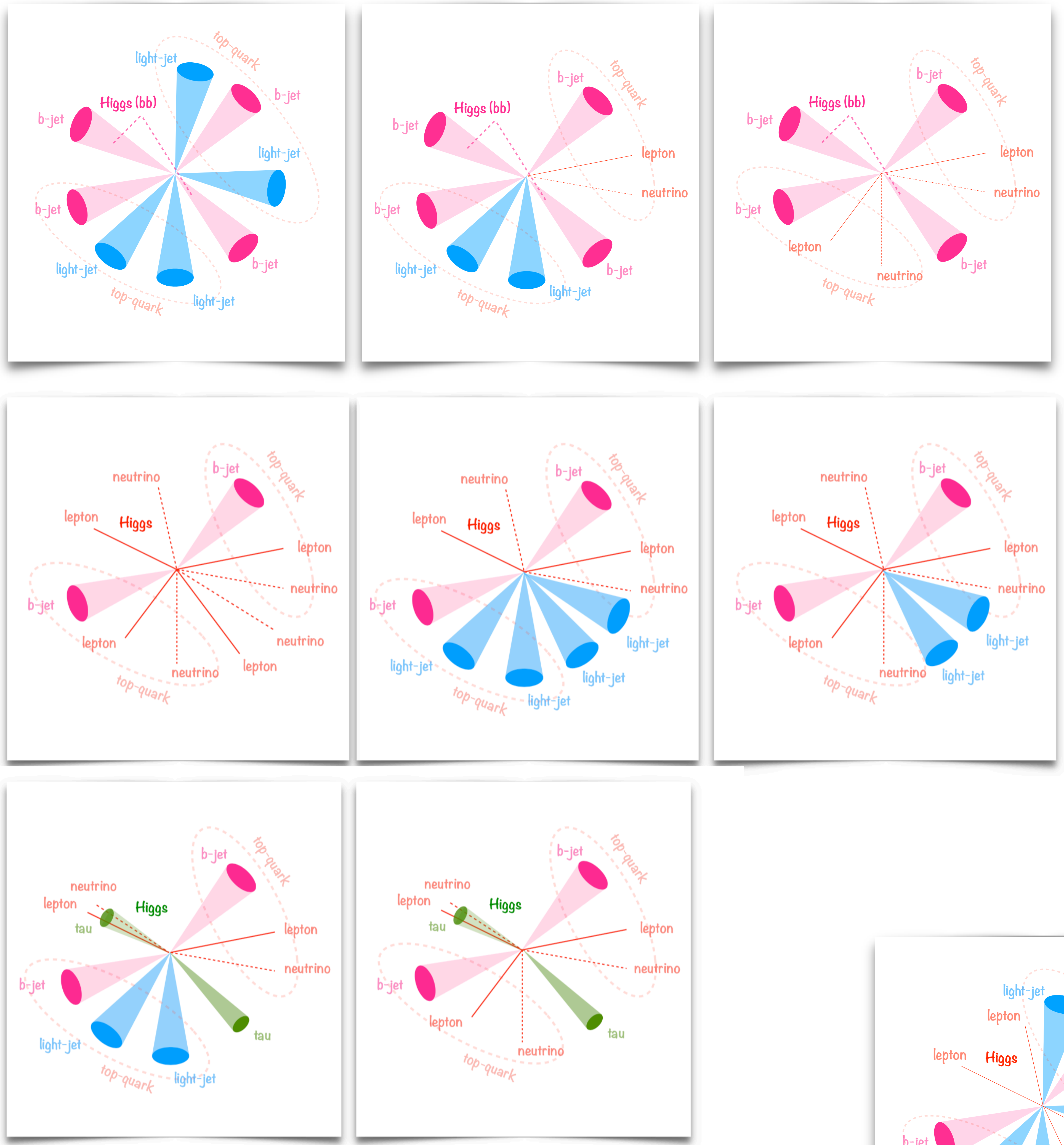
# Direct probe of the top Yukawa coupling



**ttH Analyses at LHC: Massively Complex!**




- Large number of final states which are typically very complex (mixture of b-jets, leptons, taus and photons)
- But, many different channels, also means different backgrounds and different systematic uncertainties and therefore also a strength!
- With the new Run at close to double centre-of-mass energy and increased statistics, changes in leading channels.



ttH(bb)

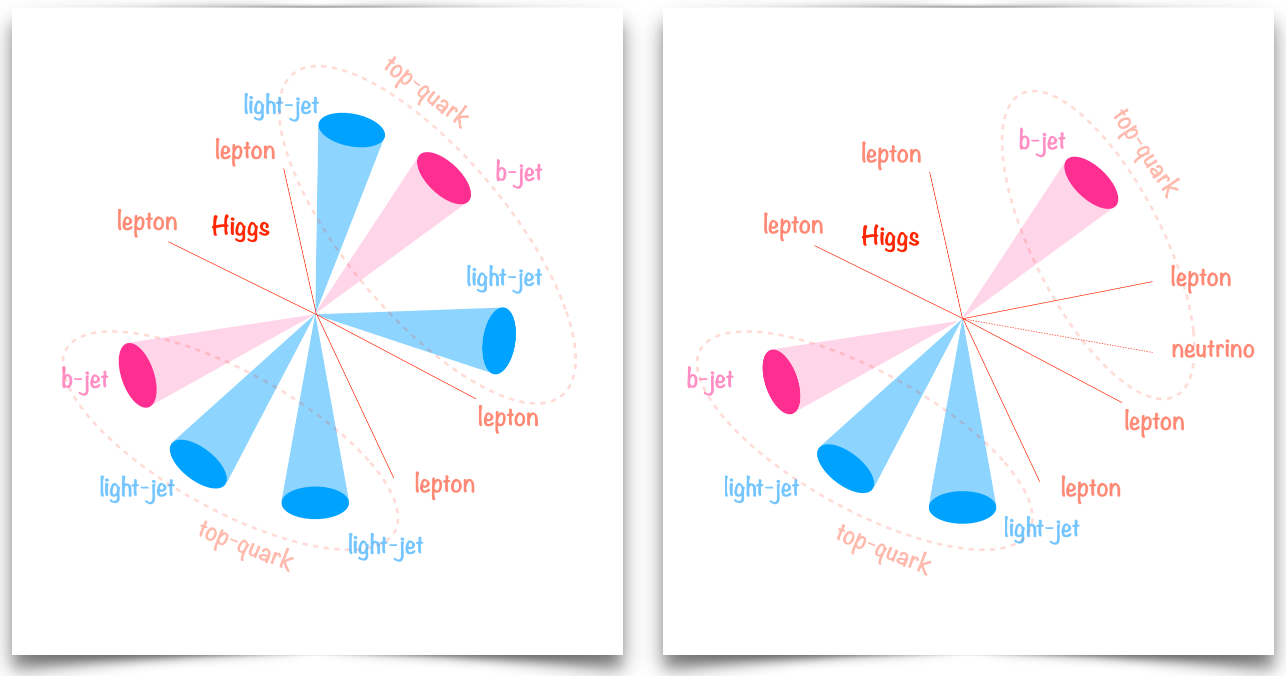
Very large backgrounds of top pair production associated with b jets

Dominated by background modelling uncertainties

ttH(WW, ZZ and tau tau)

So-called multi-lepton channel

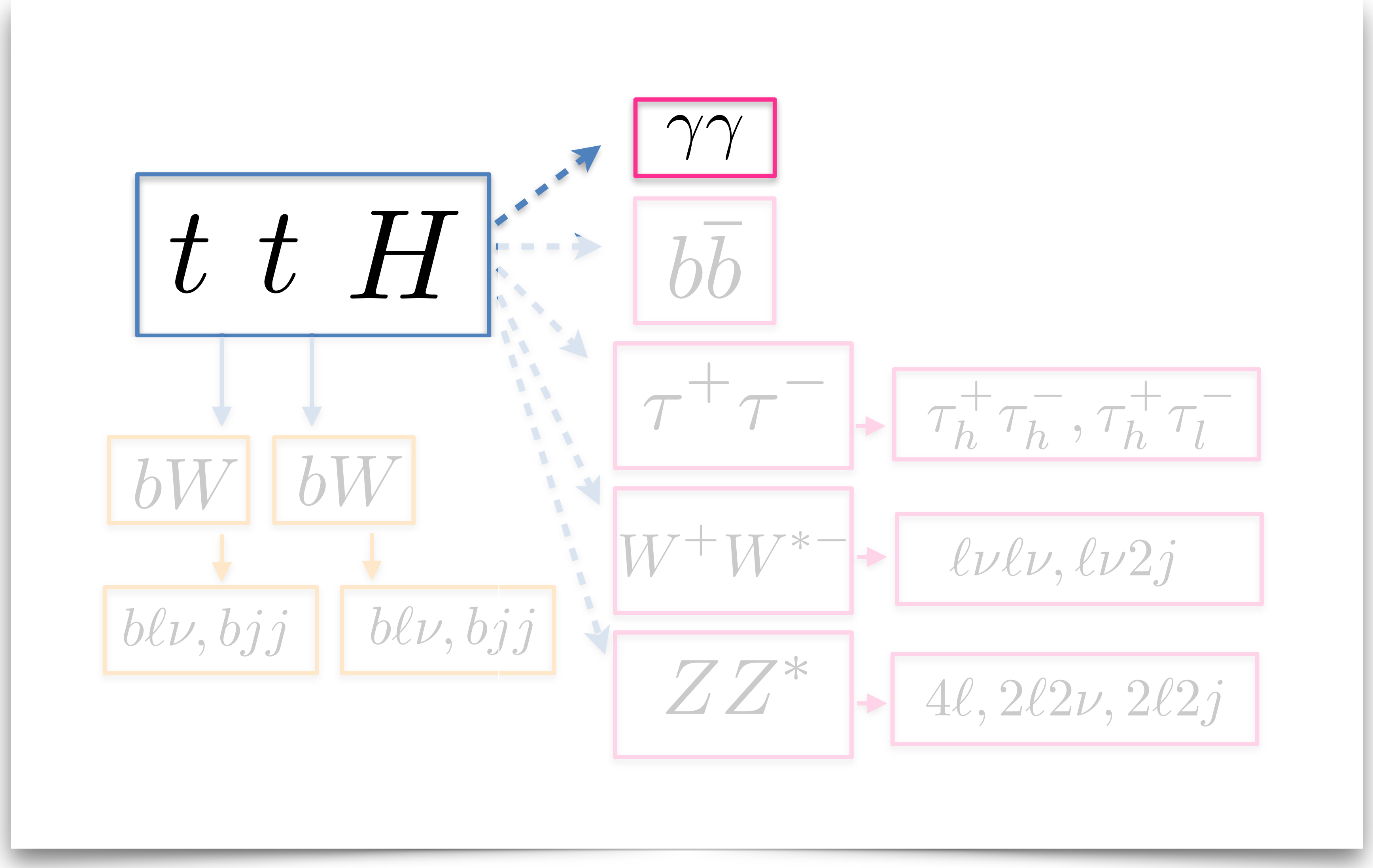
Large number of topologies intricate reducible backgrounds of jets faking leptons.



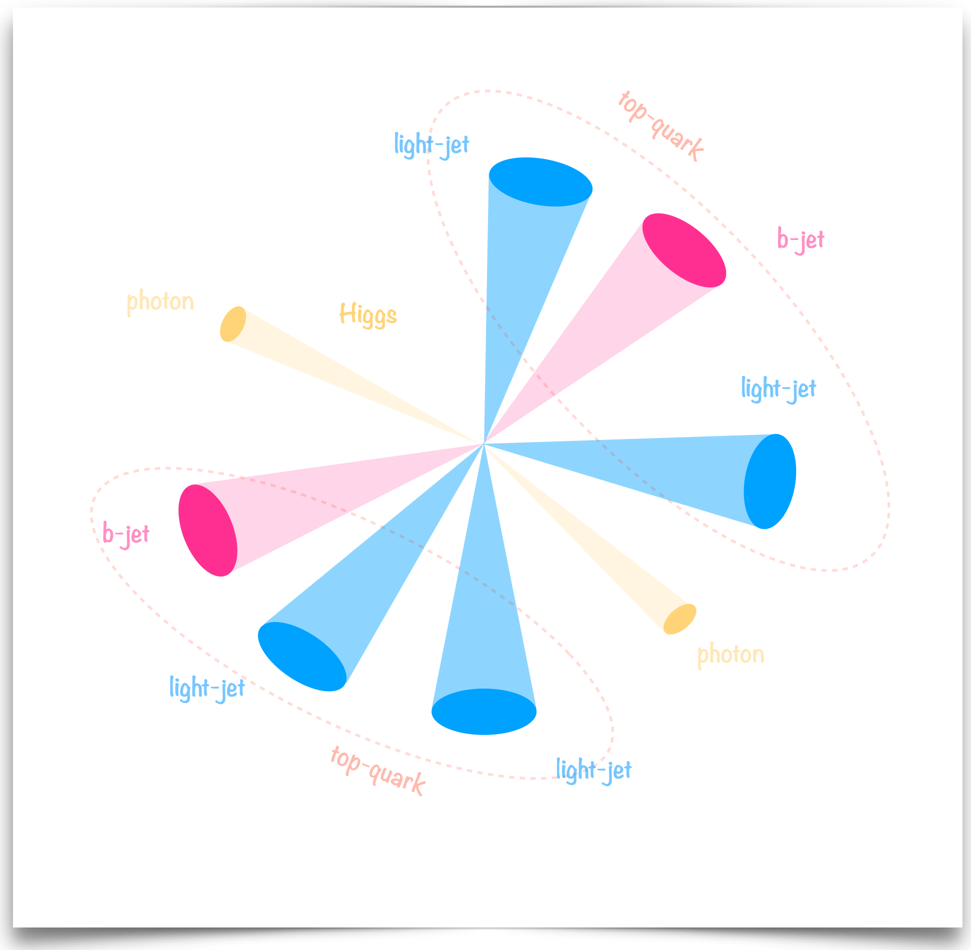
# Direct probe of the top Yukawa coupling

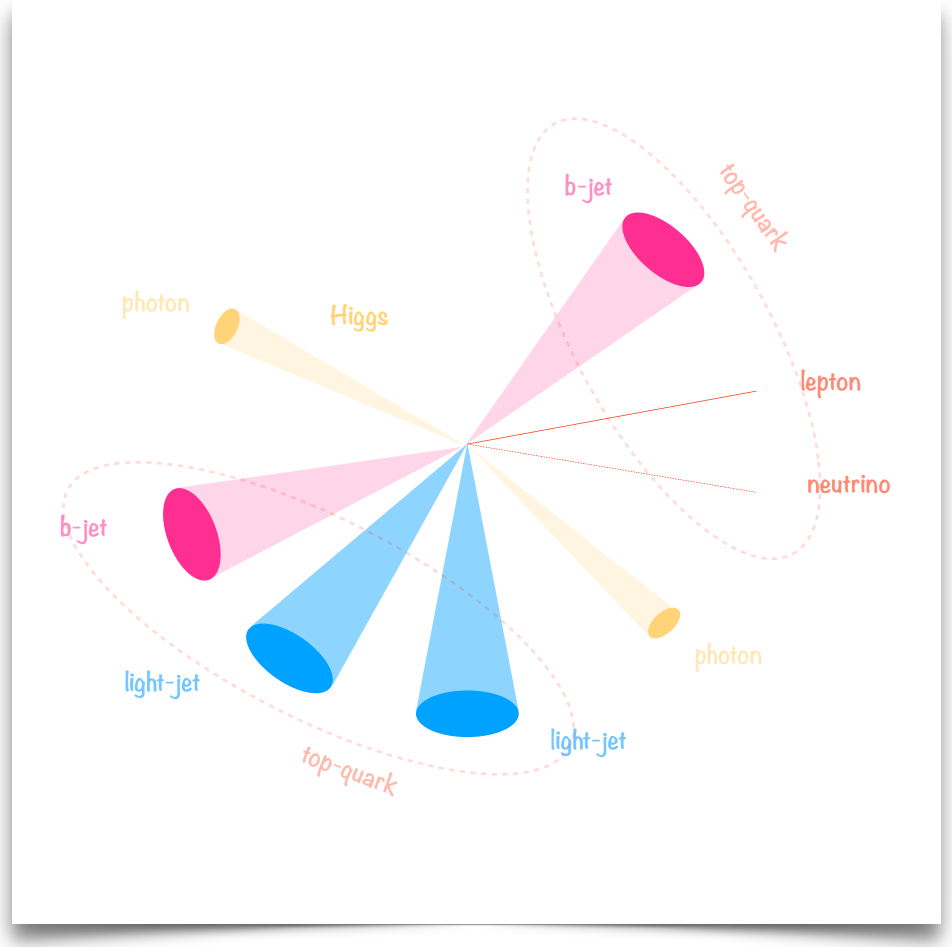


s

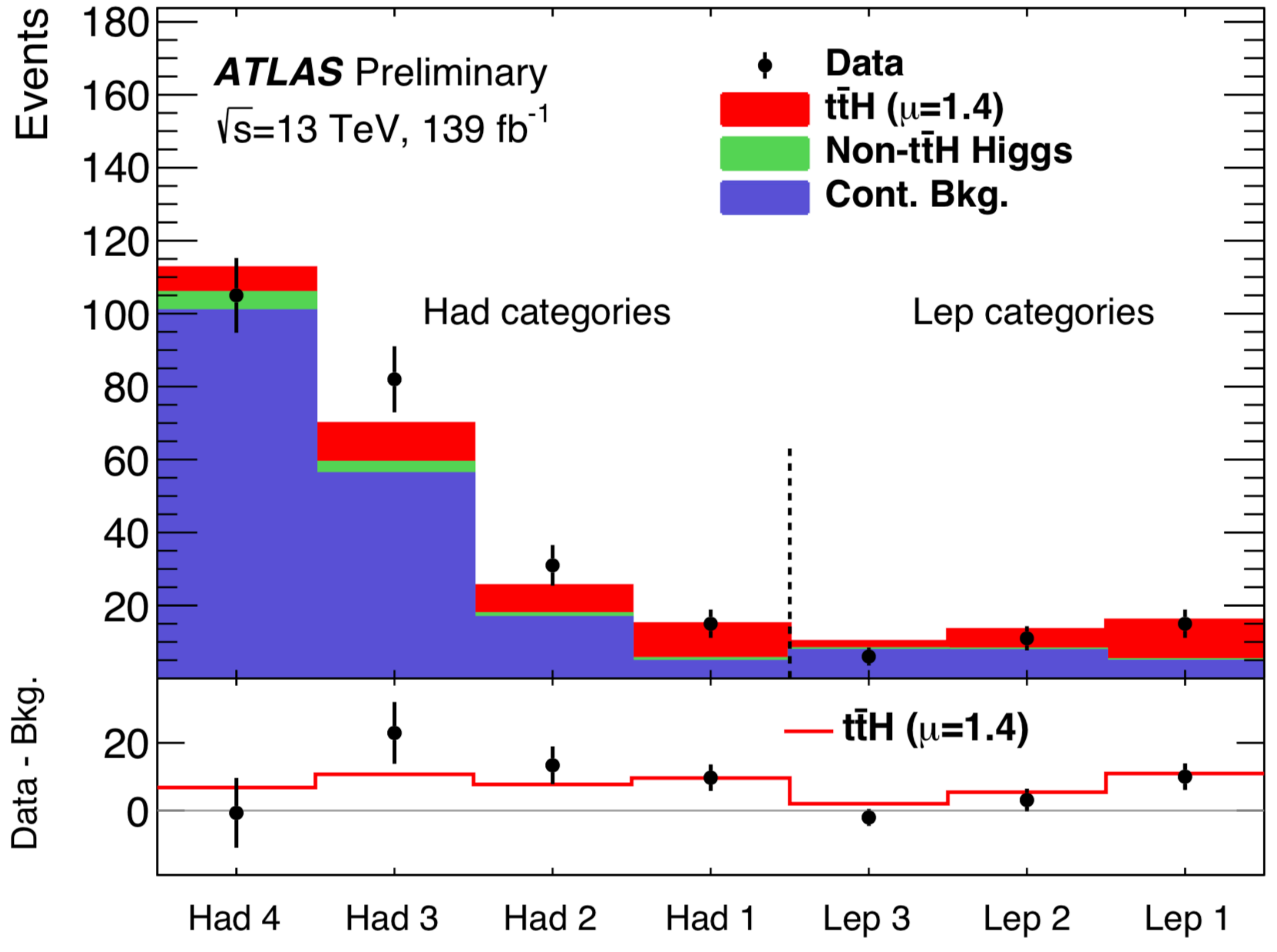


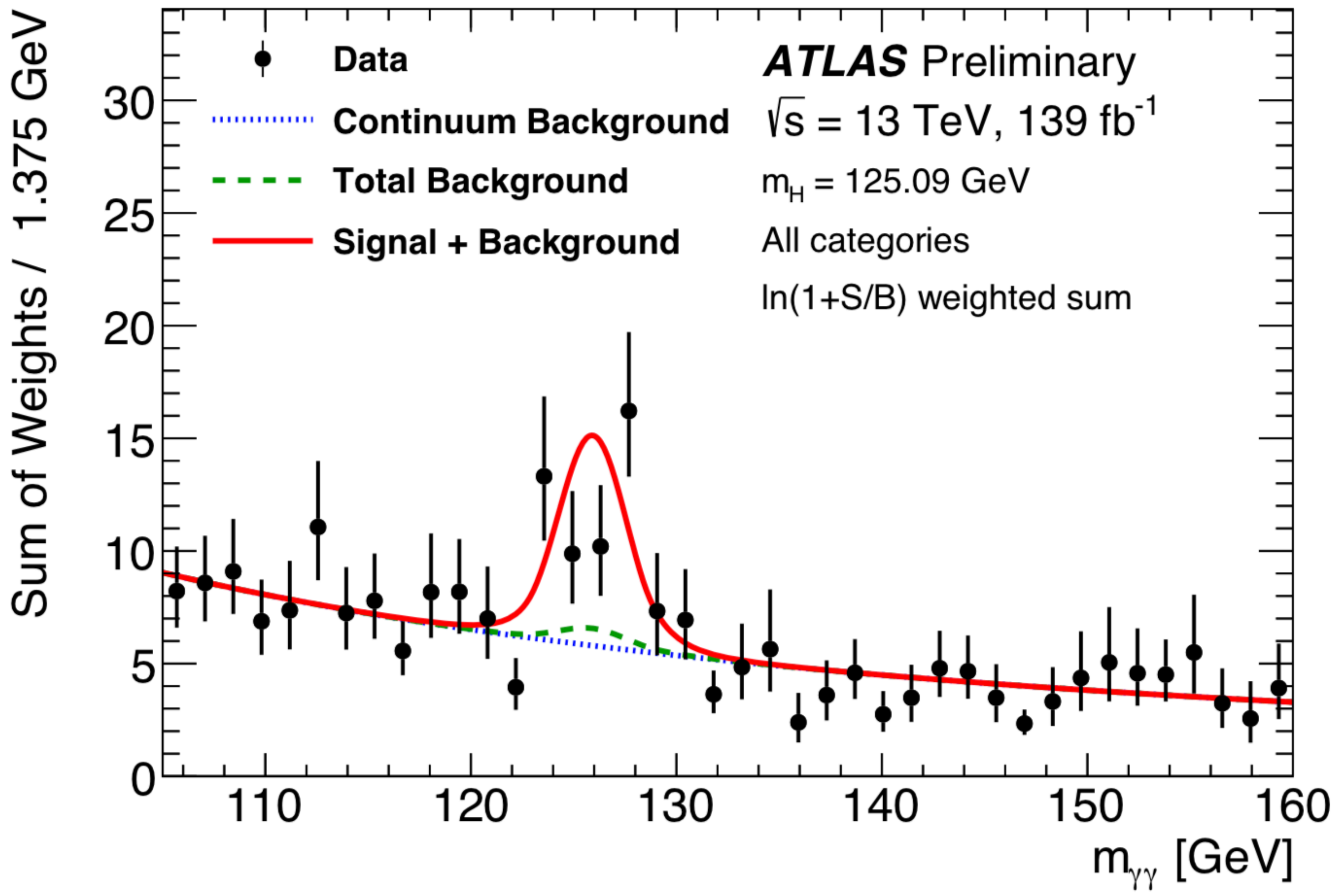

Currently most sensitive channel



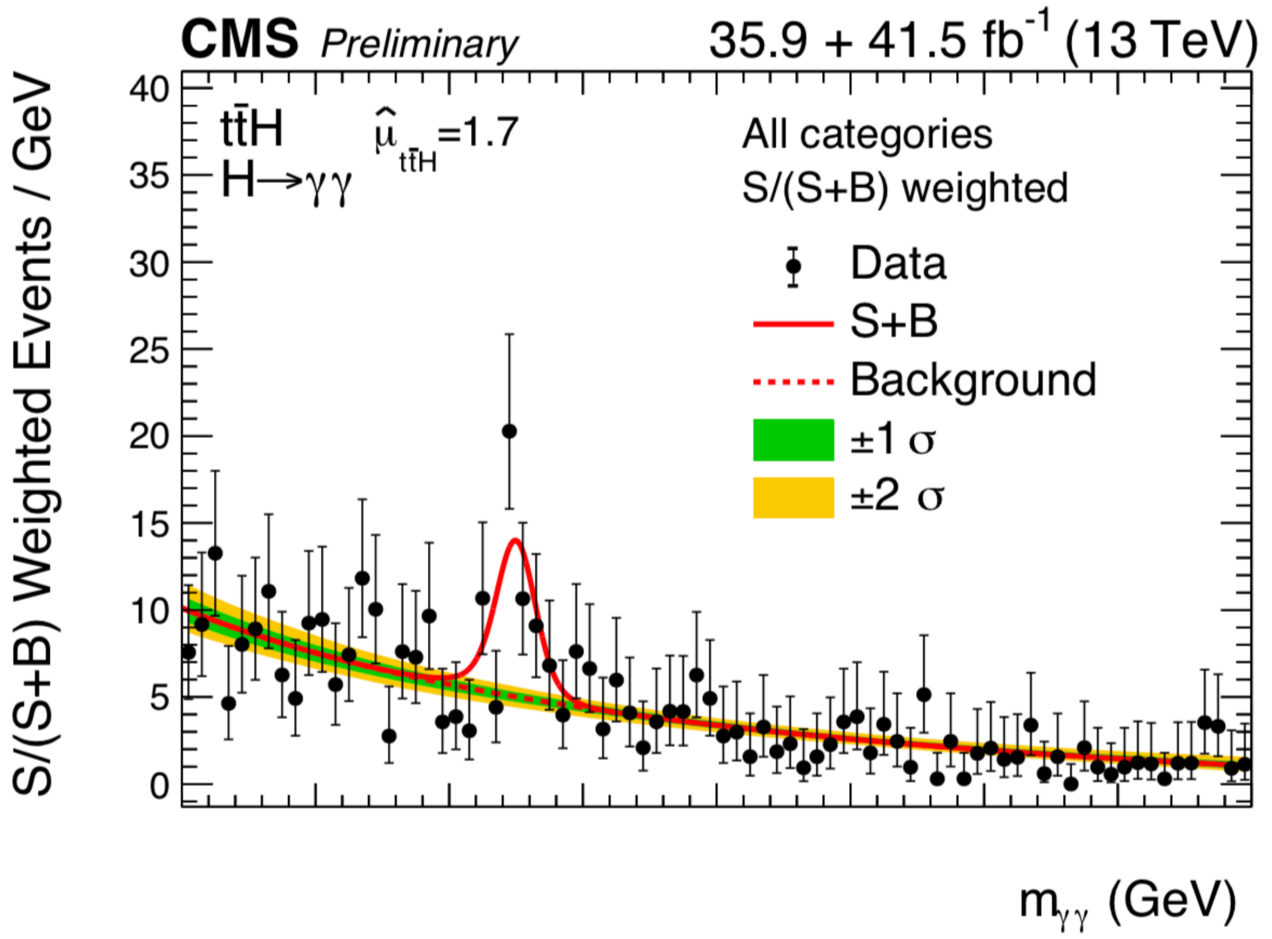

Background and signal modelled using analytic functions.




Cross section dominated by statistical uncertainties:

$$1.59^{+0.38}_{-0.36}\ (\text{stat.})\ ^{+0.15}_{-0.12}\ (\text{exp.})\ ^{+0.15}_{-0.11}\ (\text{theo.})\ \text{fb}$$




| | | |
|---|---|---|
| **ATLAS** | Expected | $5.1\sigma$ |
| | Observed | $6.3\sigma$ |
| **CMS** | Expected | $(2.7\sigma)$ |
| | Observed | $4.1\sigma$ |

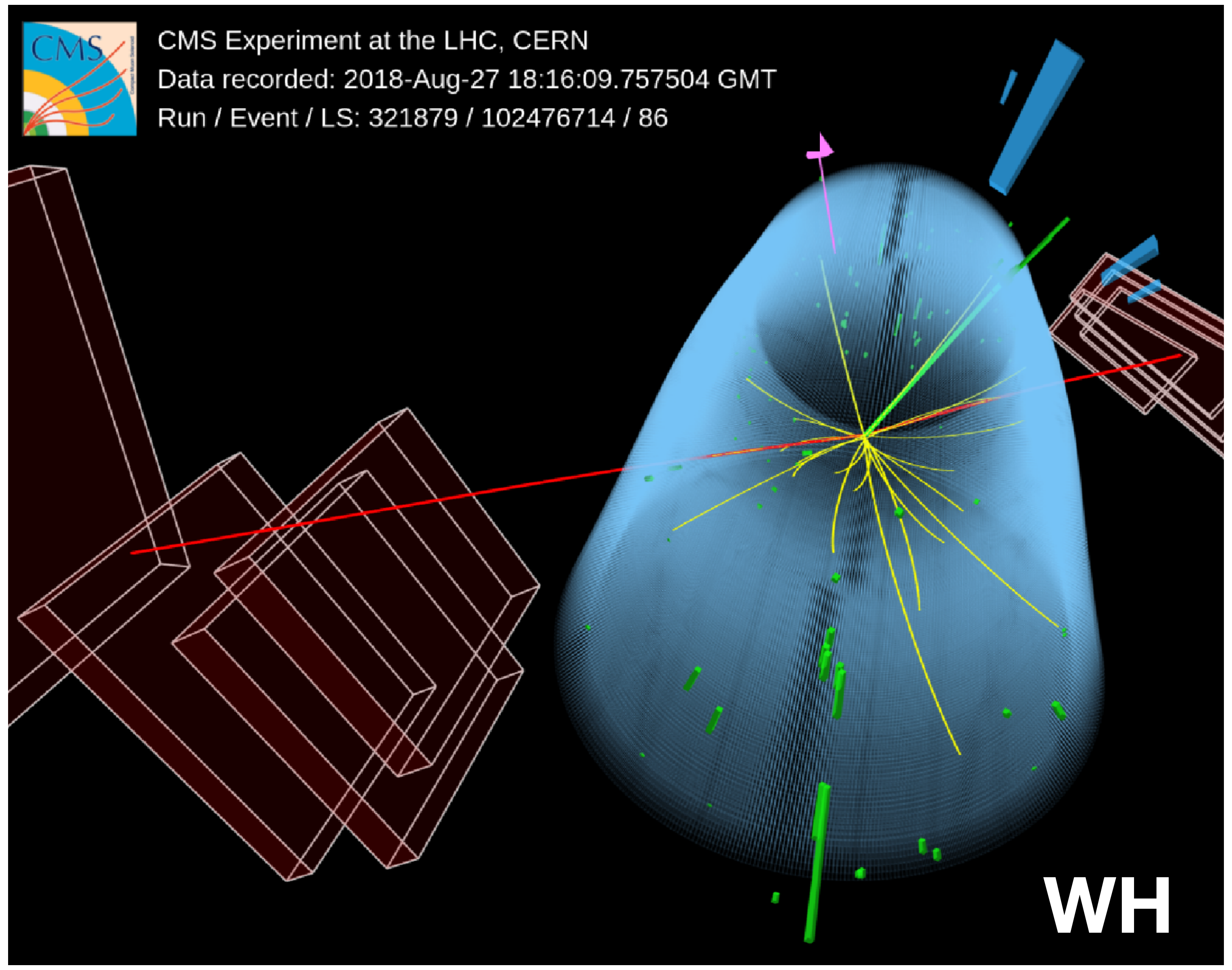
Ratio to SM expectation:

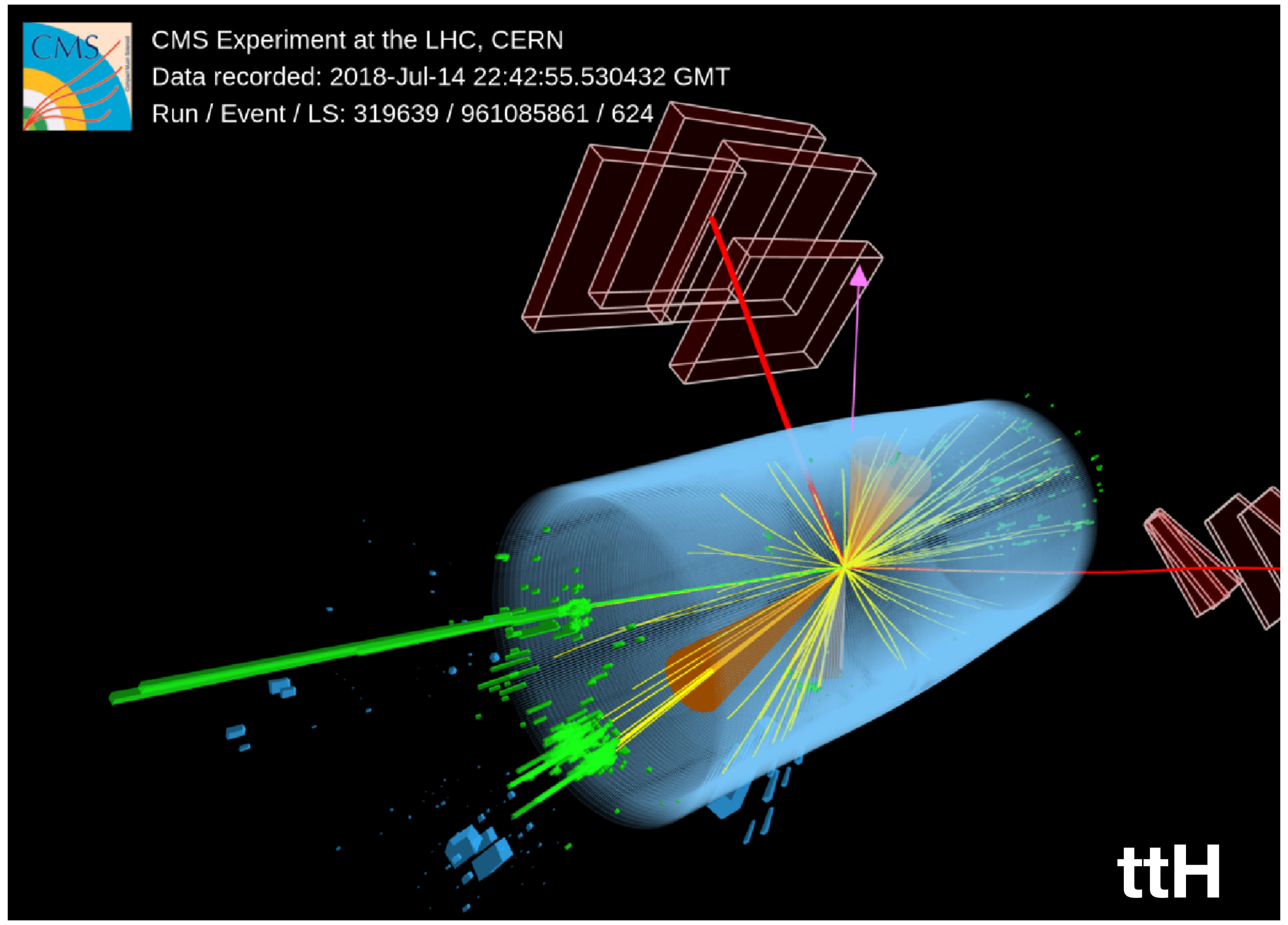
$$\mu_{ttH} = 1.7^{+0.6}_{-0.5}$$

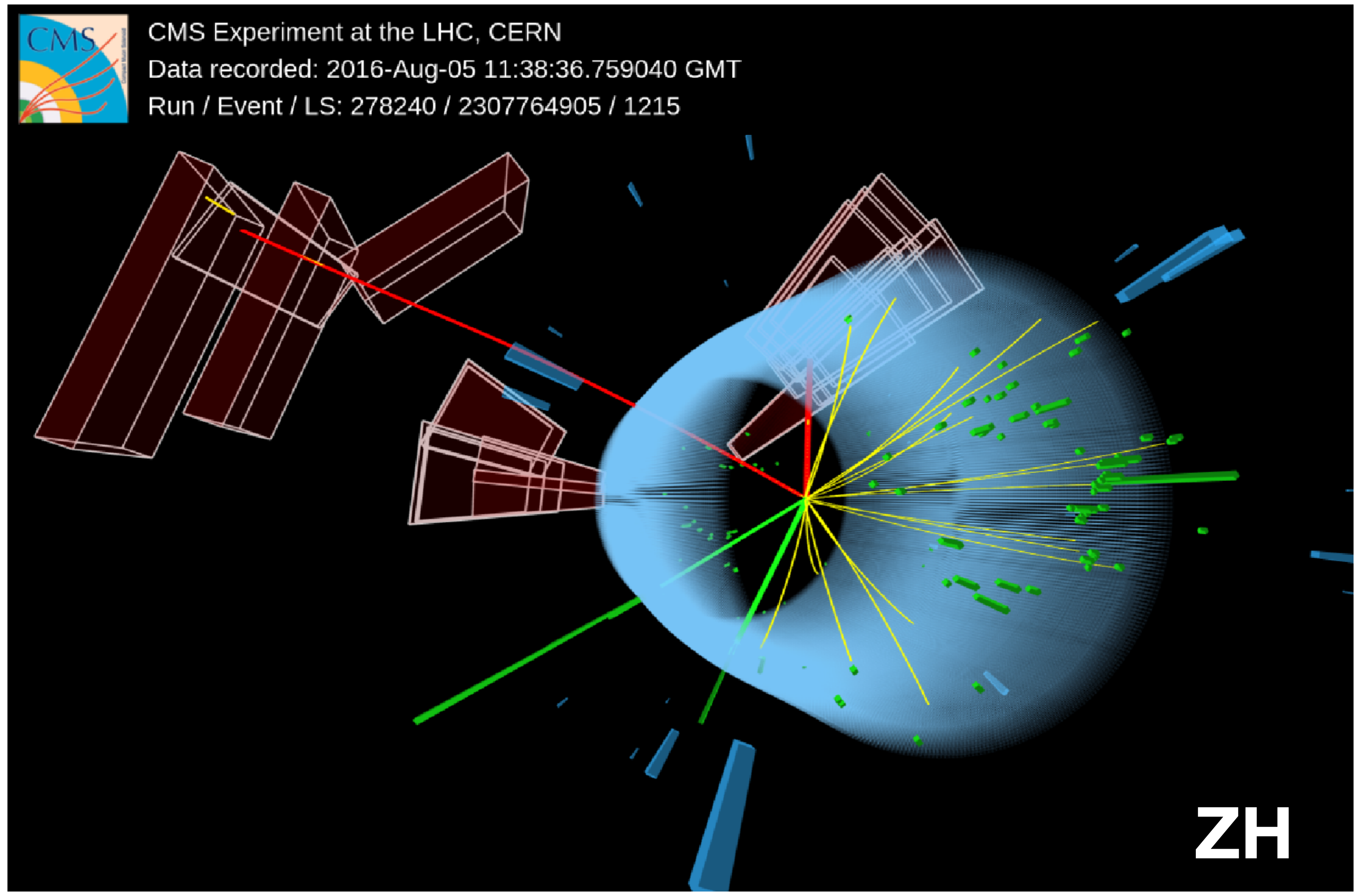
# 3.- Evidences for Rare processes

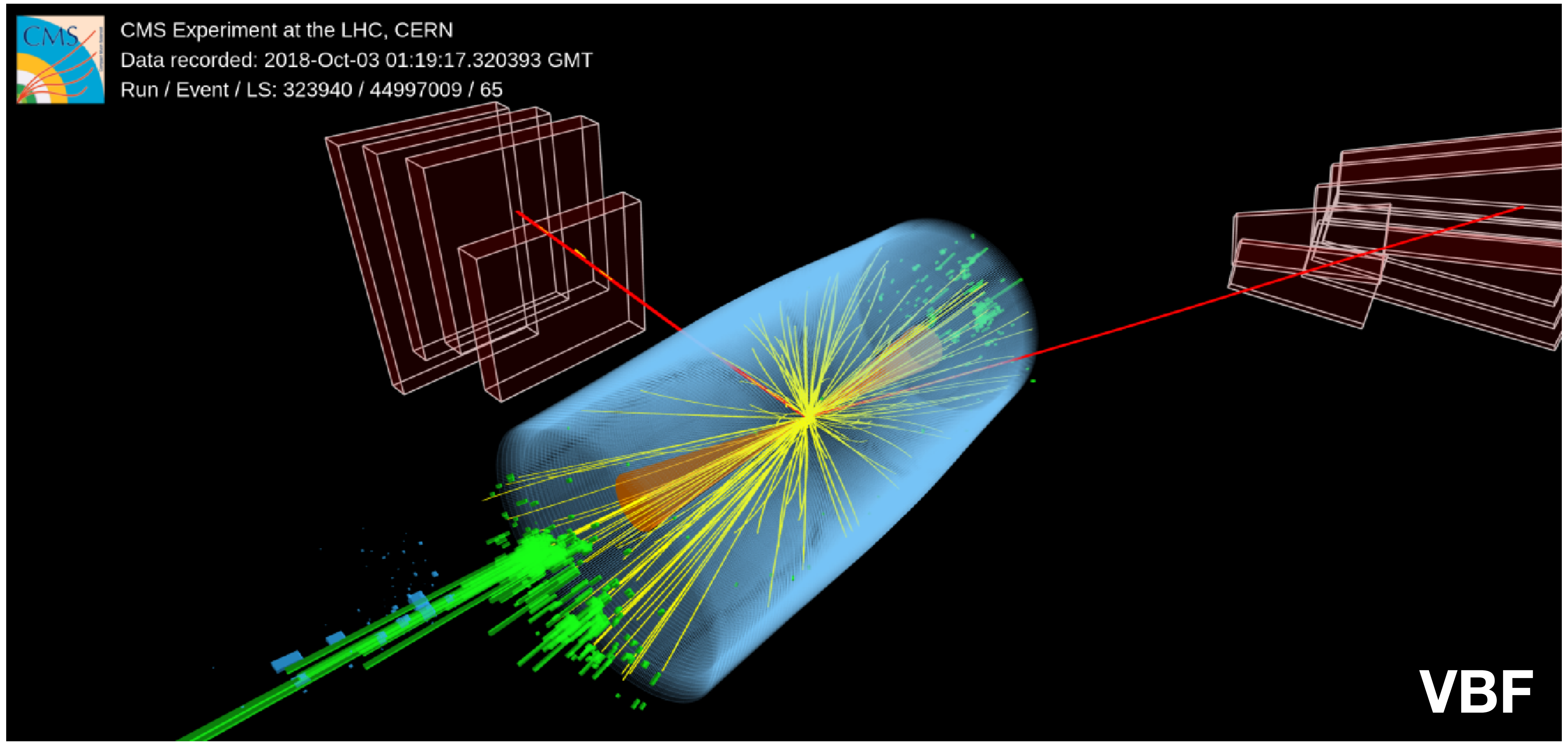
# Evidence for $H \to \mu^+\mu^-$

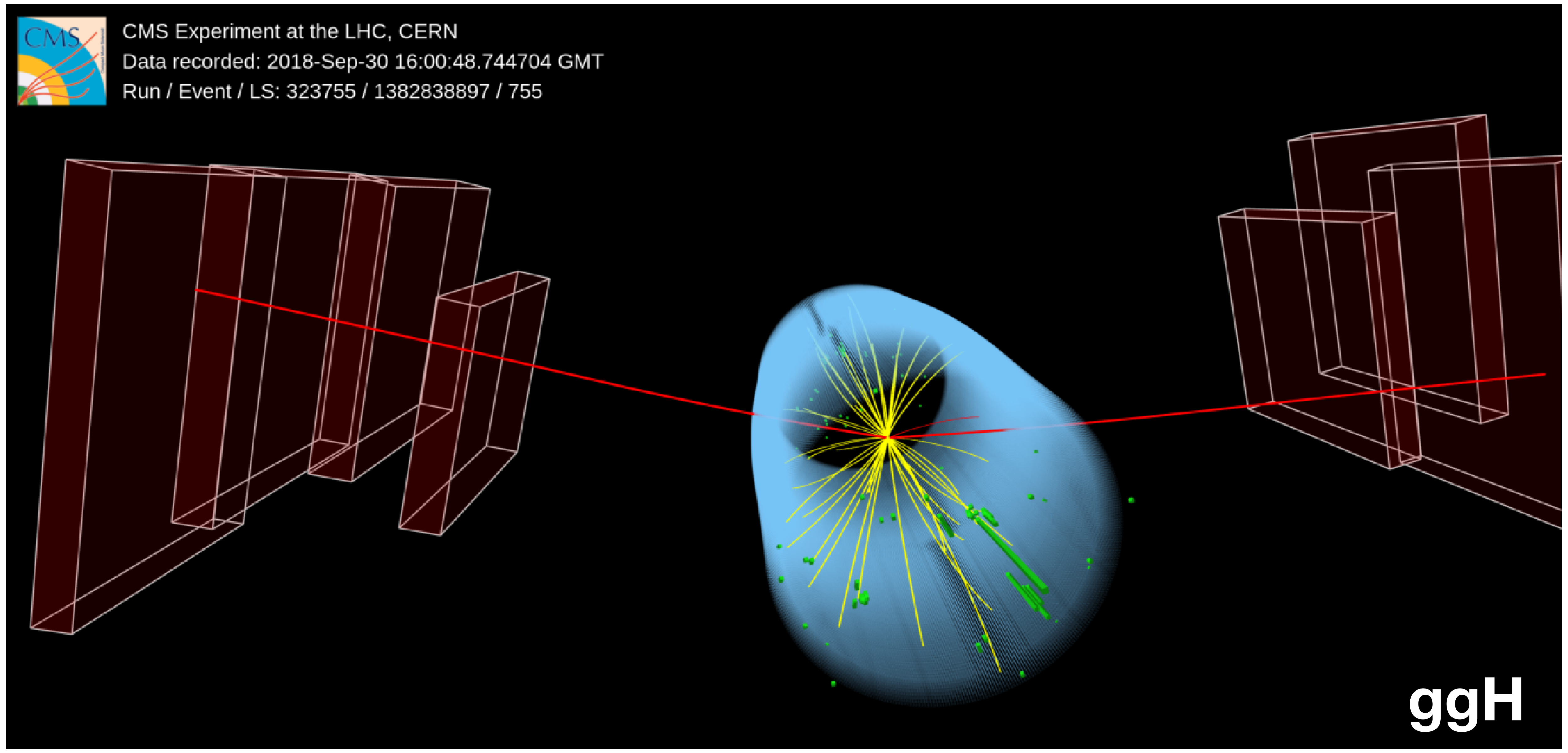




# Evidence for Second Generation Yukawa Coupling

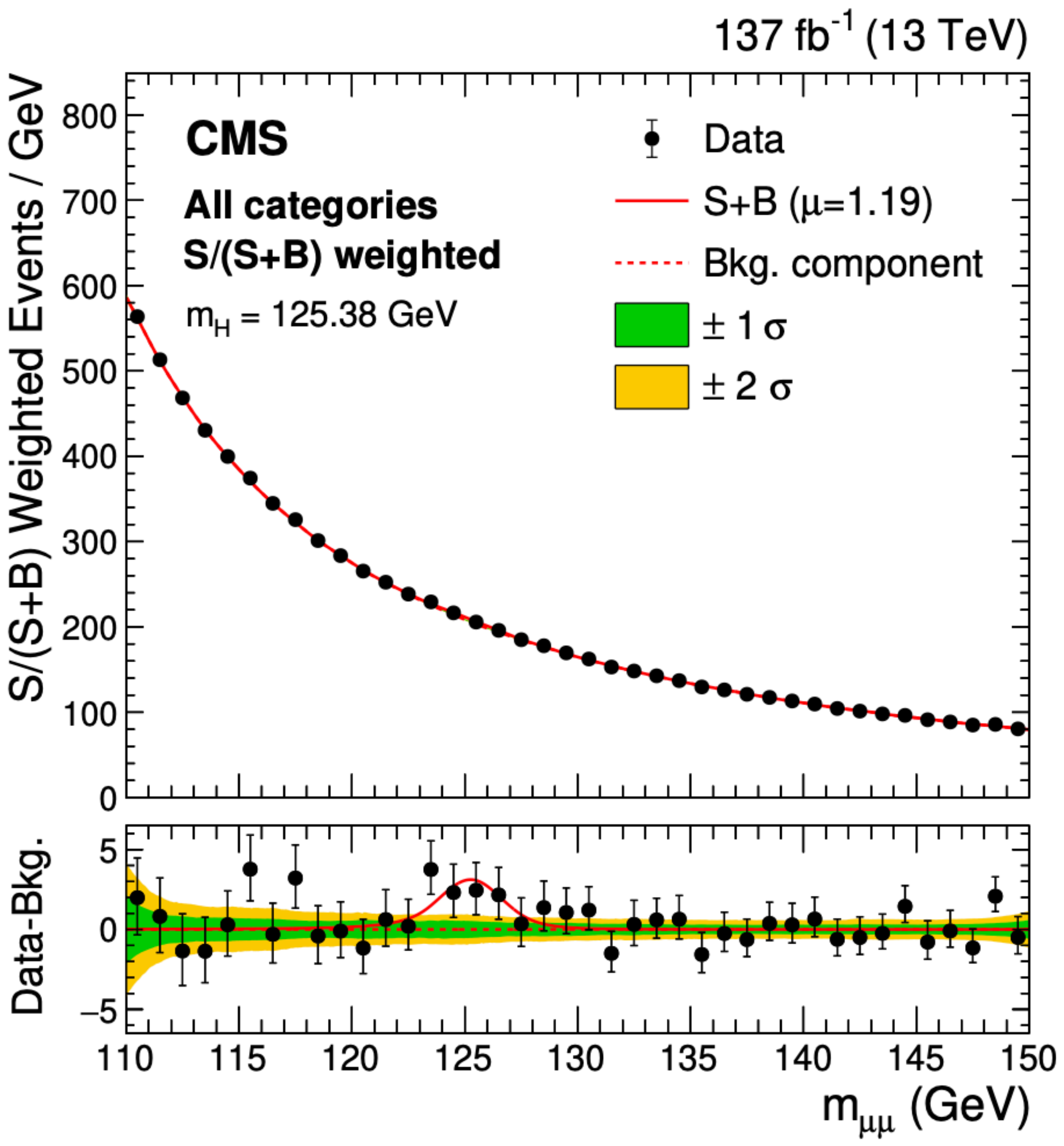
**Very challenging channel!**

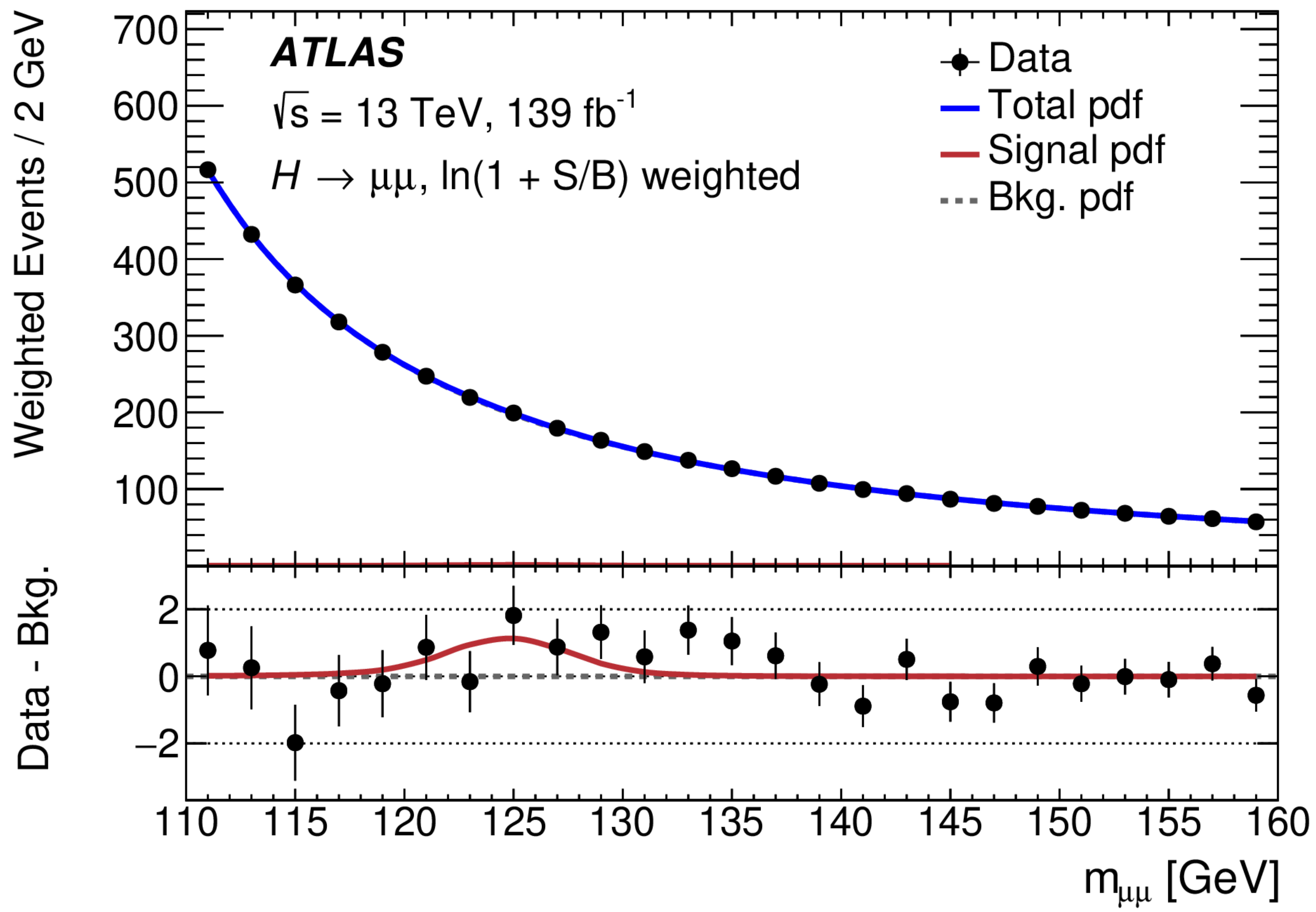
- Approximately 2k events produced but very small signal-to-noise
- Requires a very accurate description of the backgrounds.
- Gain in sensitivity through the separation in production modes.

**Analysis overview**

- All production modes ggF, VBF, VH, ttH
- Improvements in mass resolution through Brem recovery
- DNN/BDT discriminants in all categories / Sideband region used to control backgrounds

**Summary of all categories** Estimate the background parameters through a fit of an analytical form!



# Evidence for Second Generation Yukawa Coupling



## Very challenging channel!

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## Analysis overview

- All production modes ggF, VBF, VH, ttH
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- DNN/BDT discriminants in all categories / Sideband region used to control backgrounds

## Summary of all categories

Estimate the background parameters through a fit of an analytical form!

### CMS Result

Expected $2.5\sigma$

Observed $3.0\sigma$

$$\mu = 1.19 \pm 0.43$$

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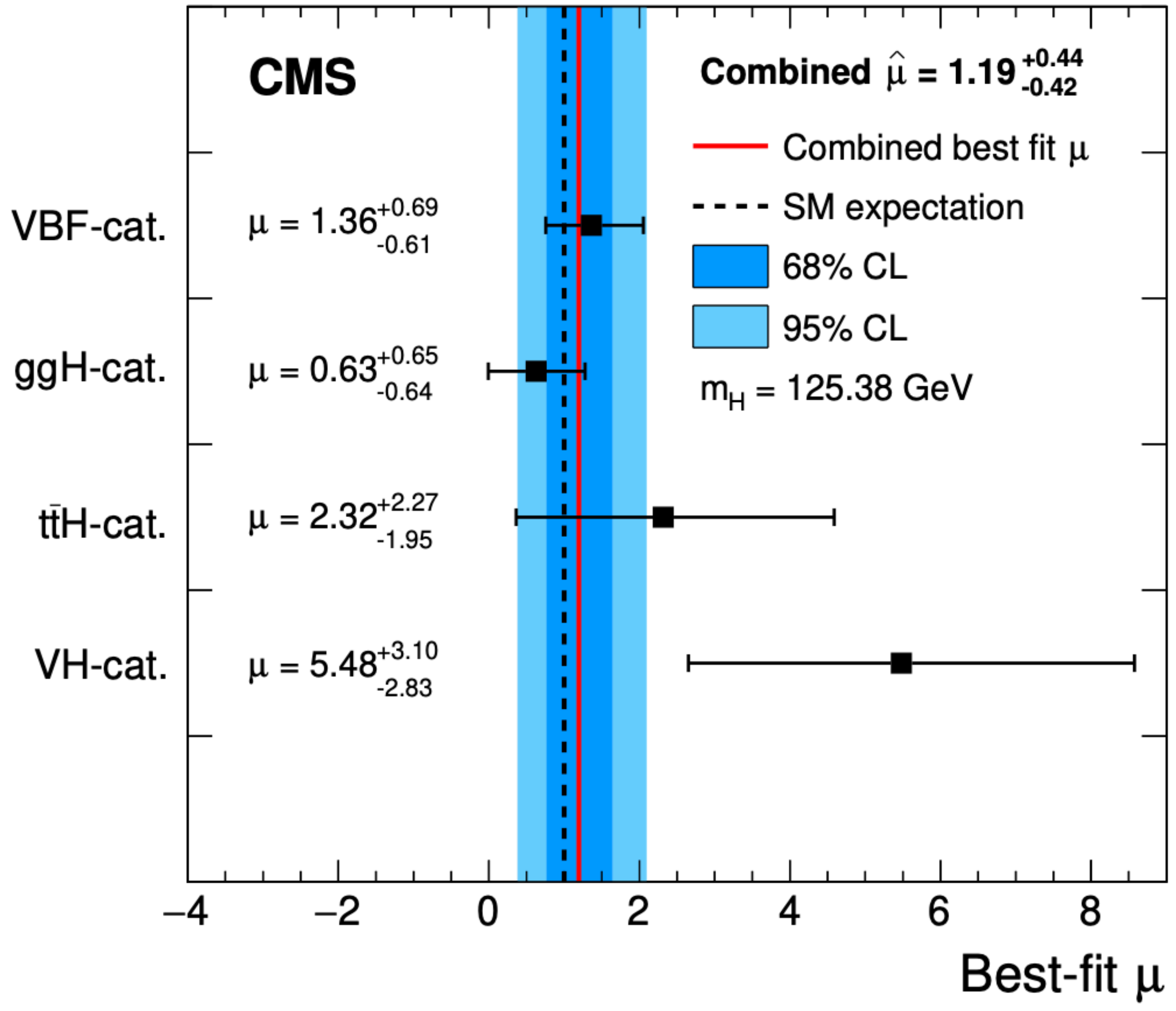
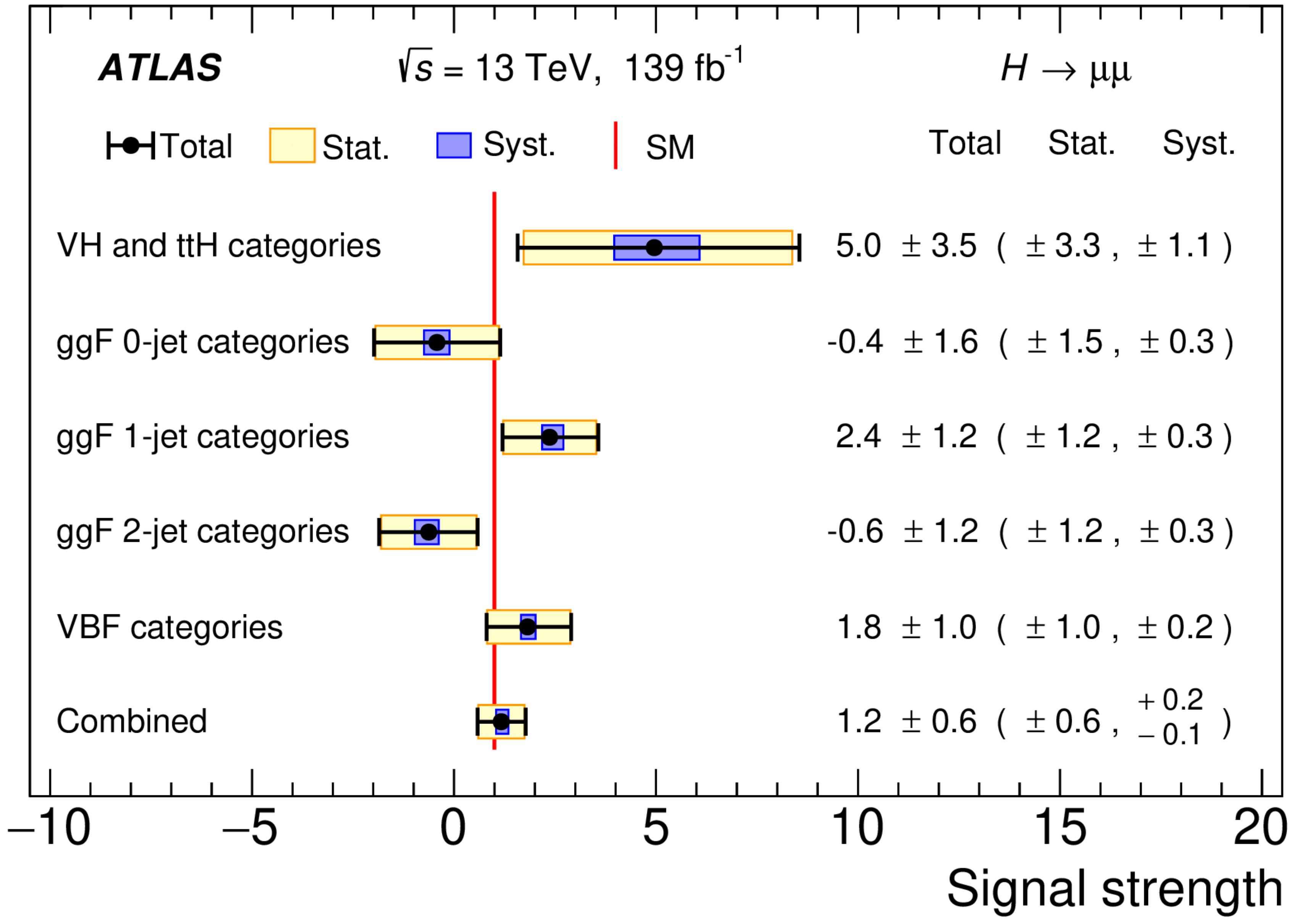



PLB 812




### ATLAS Result

Expected $1.7\sigma$

Observed $2.0\sigma$

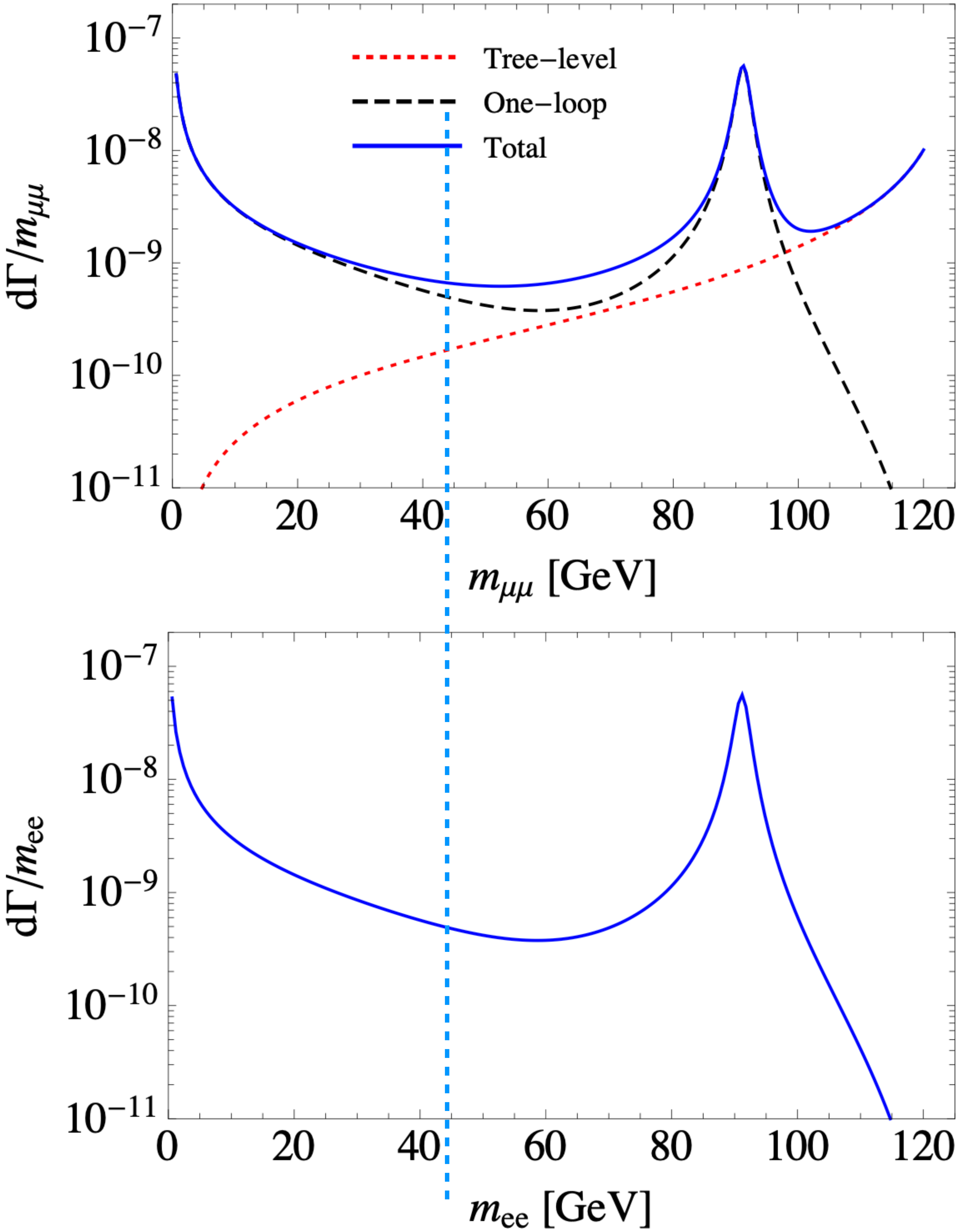
$$\mu = 1.2 \pm 0.6$$

Result dominated by statistical uncertainty, but watch systematics!

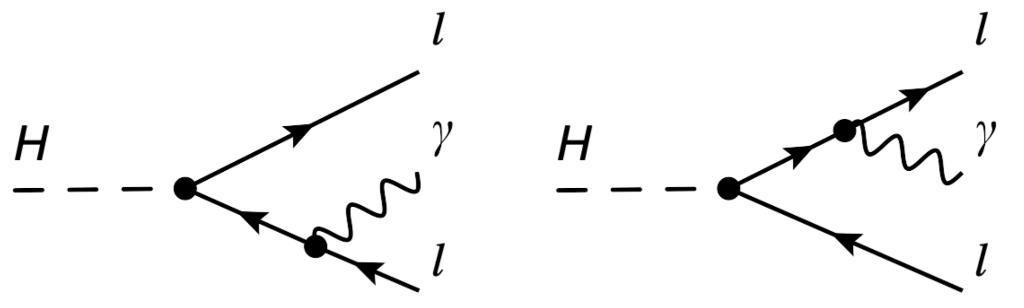
# Evidence for $H \to \gamma\ell^+\ell^-$



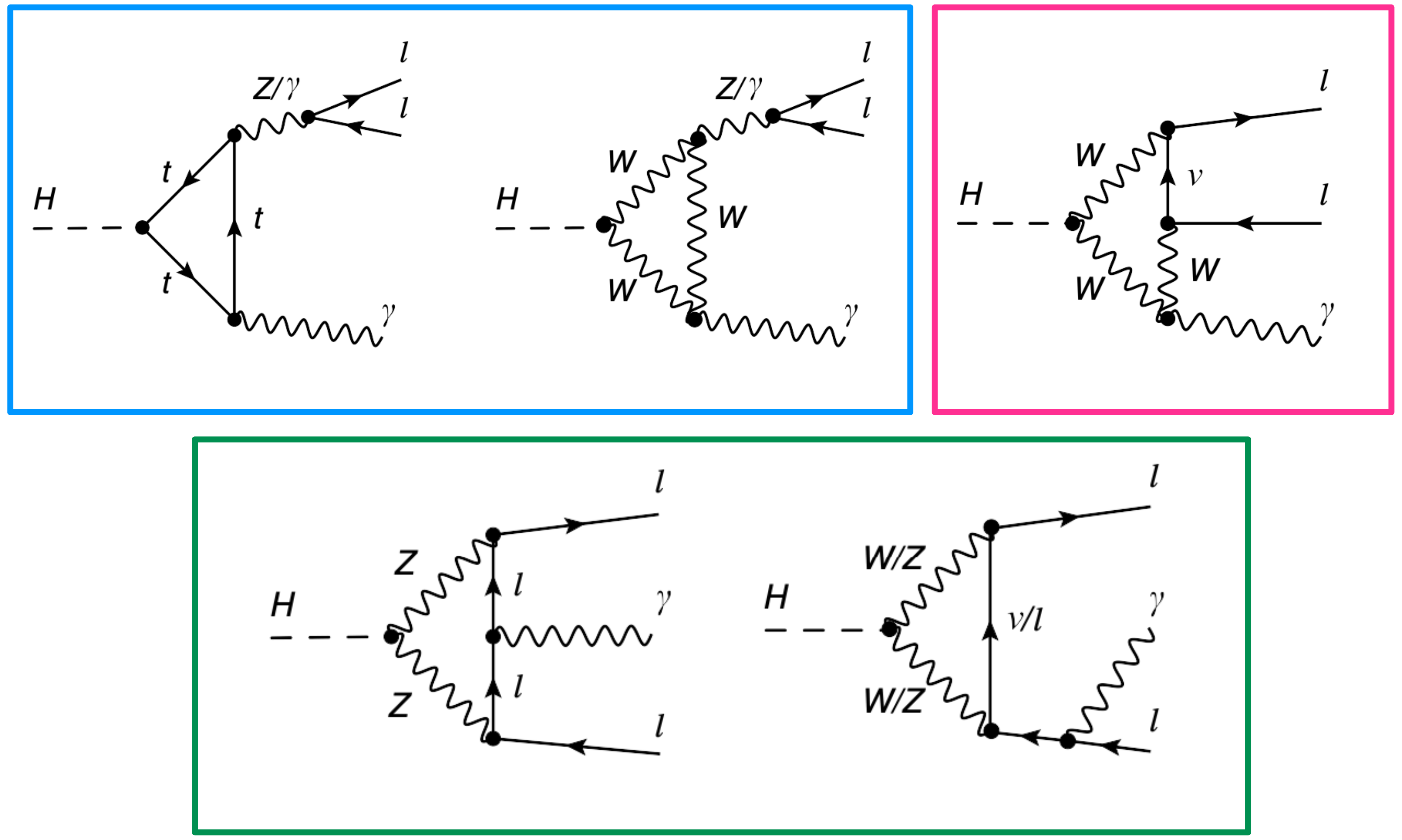
Phys. Rev. D 101, 073003 (2020)




**Tree level** (visible only for muons)



**Loop level** diagrams different types of contributions



A very interesting channel studied in two regimes, at and off the Z resonance ($Z\gamma$ and $\gamma^*\gamma$)

Underlying BSM dynamics that could affect the $R_{K*}$ ratio could also affect the $\ell\ell\gamma$ rate

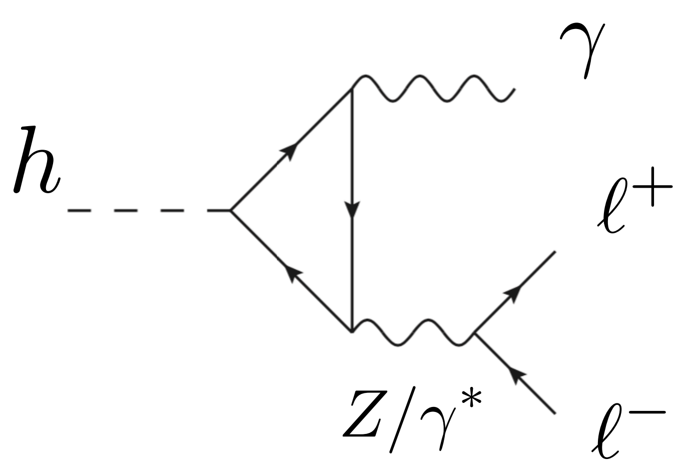
$$R_{K*} \equiv \frac{\text{Br}(B \to K^{(*)}\mu^+\mu^-)}{\text{Br}(B \to K^{(*)}e^+e^-)}$$

Interesting decay observable as a Forward-Backward asymmetry of the lepton w.r.t. flight direction, sensitive to **CP violation** in the interference between the $Z\gamma$ and $\gamma^{(*)}\gamma$ couplings.

Phys. Rev. D 90

# Evidence for $H \rightarrow \gamma\ell^+\ell^-$





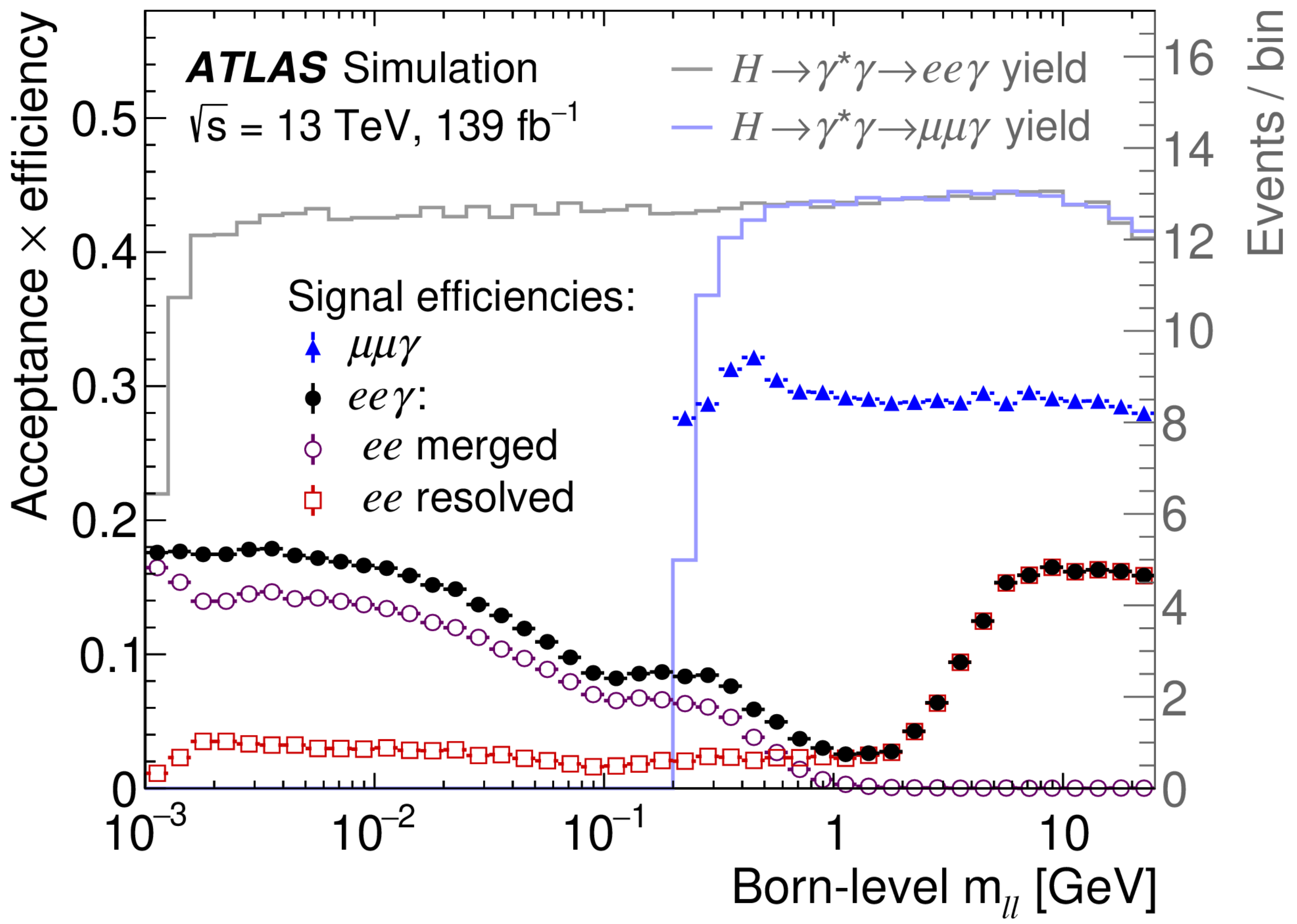

Search initially made in this case in the dimuon channel only (in the low di-lepton mass limit the shower of electrons merge).

~ 1.7% of $Br(\gamma\gamma)$

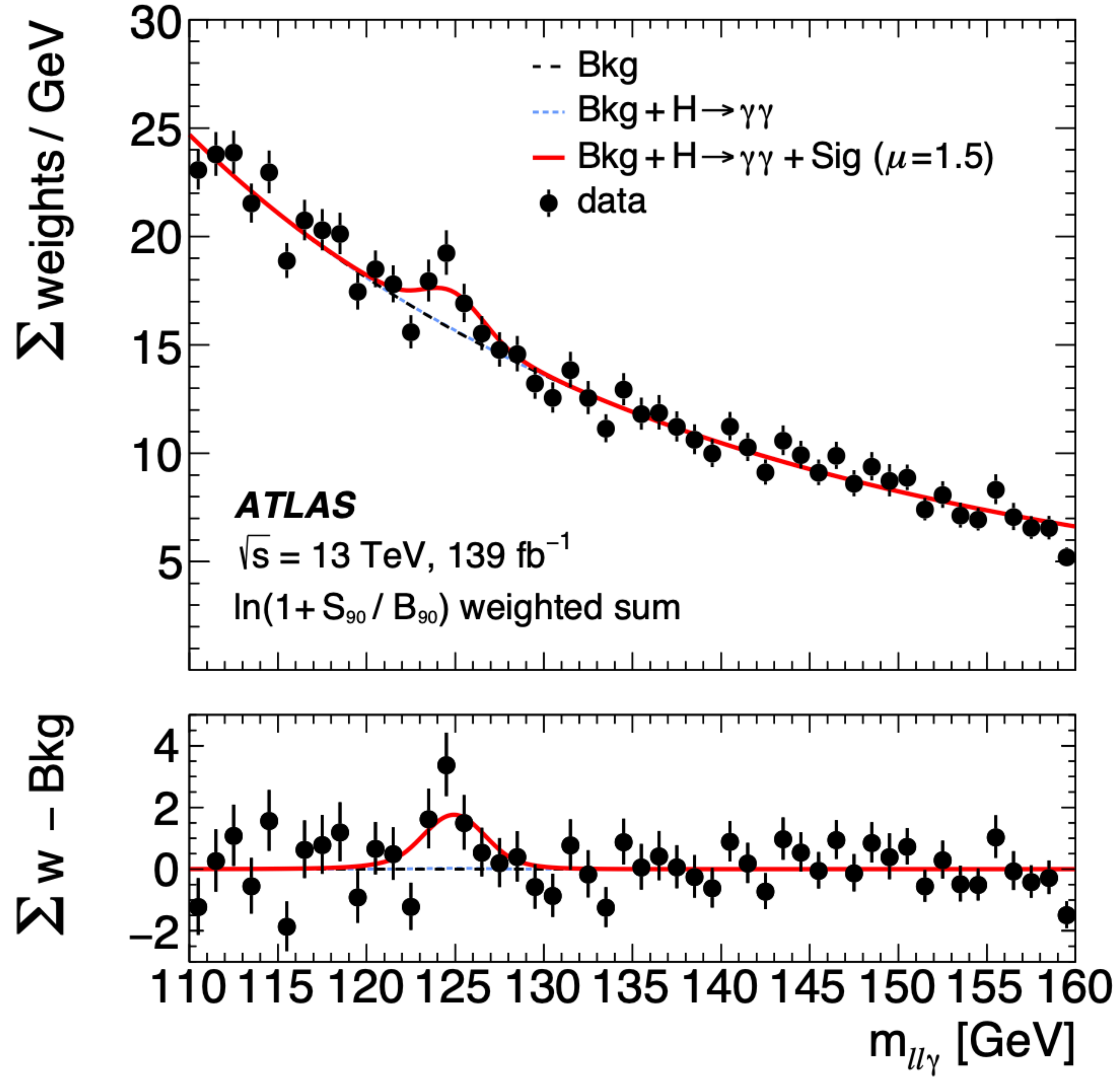
$m_{\ell^+\ell^-} < 50$ GeV

Key experimental challenge is to go to low dilepton mass this required a **new reconstruction technique**:

Merged electron reconstruction where a calorimeter (electron-like) cluster is associated to two tracks and conversions are carefully rejected!




[Phys. Lett. B 819 (2021) 136412]




- 3 x 3 categories (VBF, high pT ggF, low pT ggF) ⊗ (ee resolved, ee merged, $\mu\mu$)
- Contributions from $J/\psi$ are removed with a mass cut

$$\mu = 1.5 \pm 0.5 = 1.5 \pm 0.5\ (\text{stat.})\ ^{+0.2}_{-0.1}\ (\text{syst.})$$

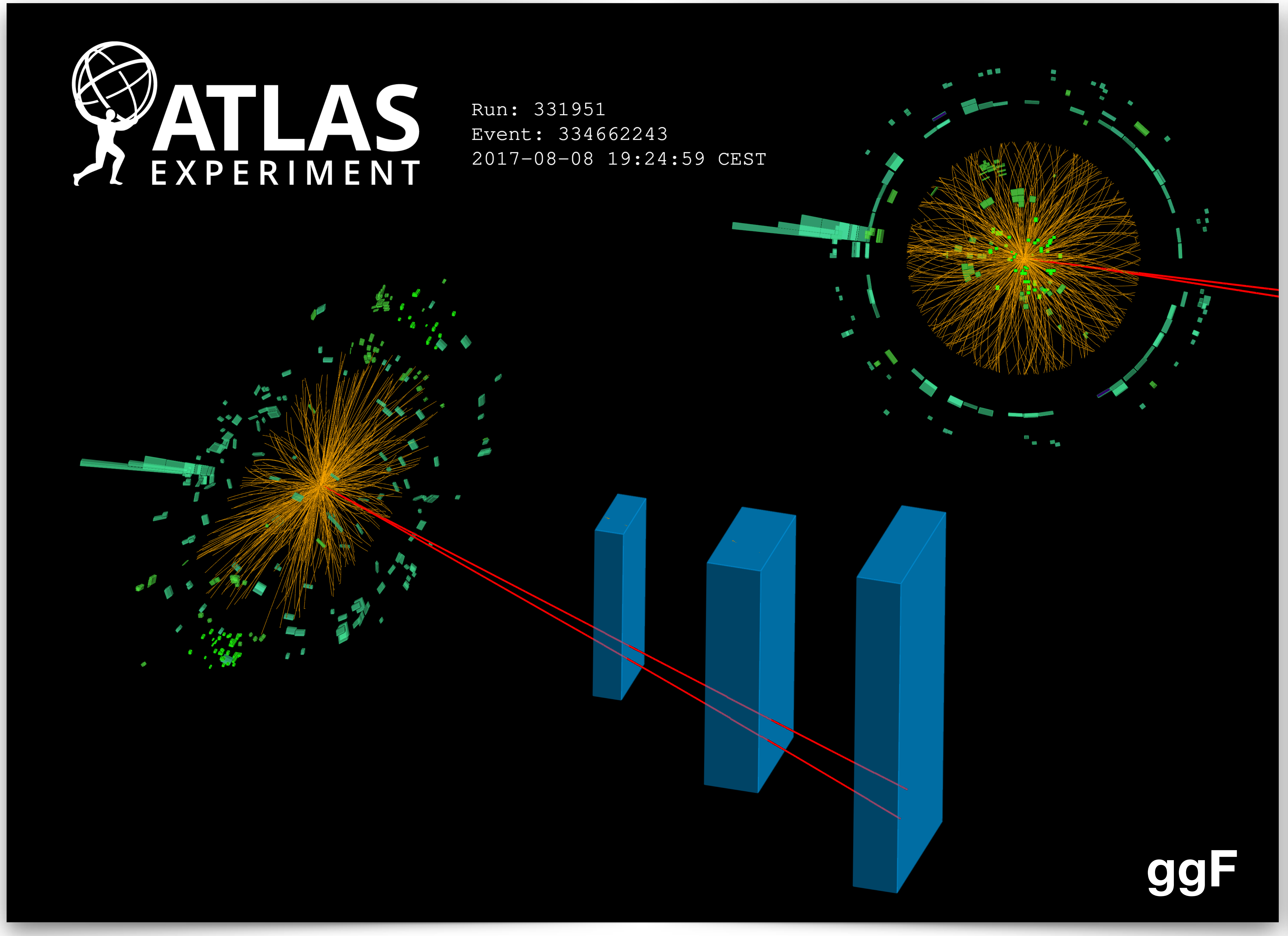
$$\mu_{\text{exp}} = 1.0 \pm 0.5 = 1.0 \pm 0.5\ (\text{stat.})\ ^{+0.2}_{-0.1}\ (\text{syst.})$$

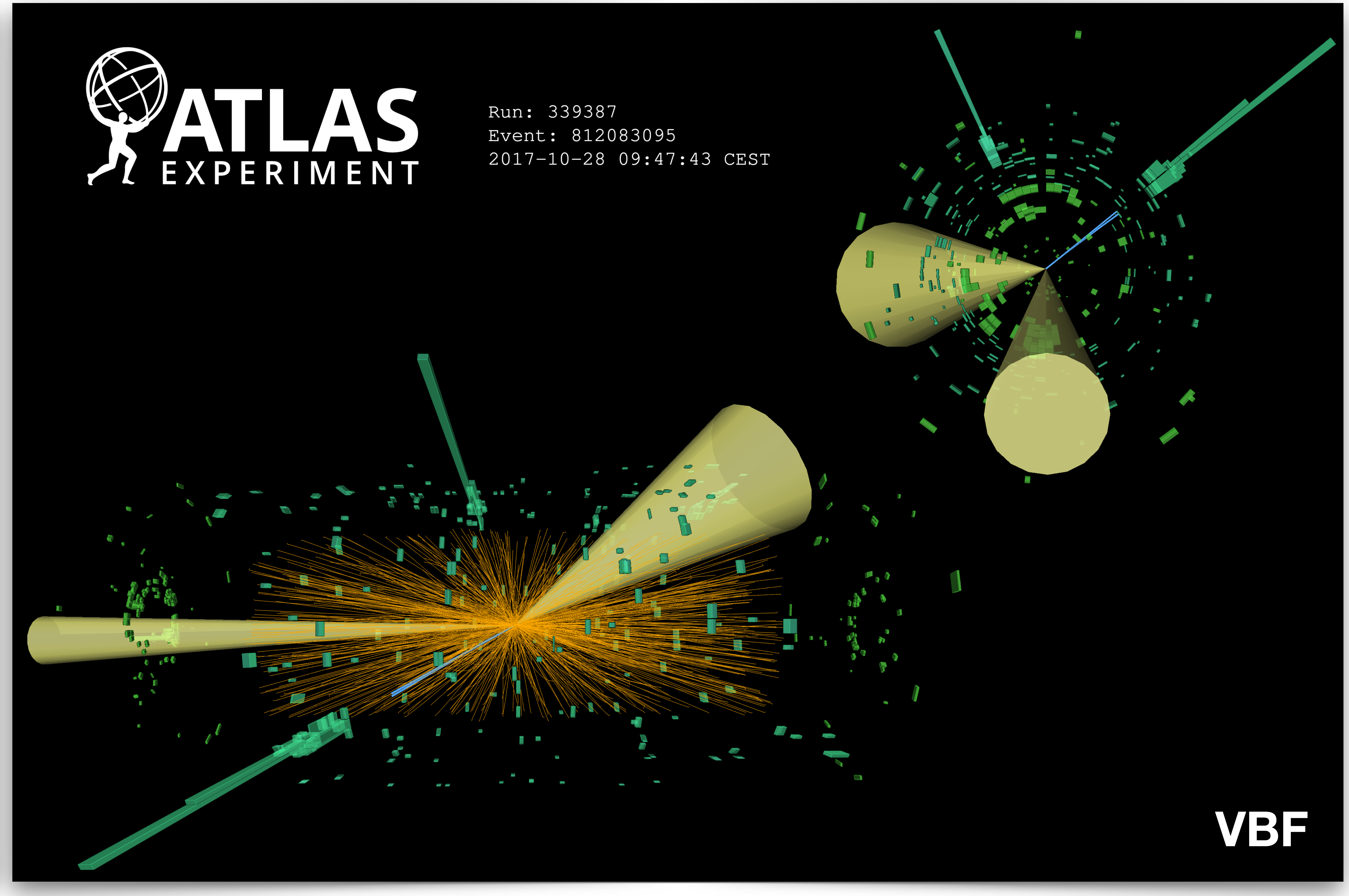
Expected $2.1\sigma$

Observed $3.2\sigma$

# Evidence for $H \rightarrow \gamma\ell^+\ell^-$



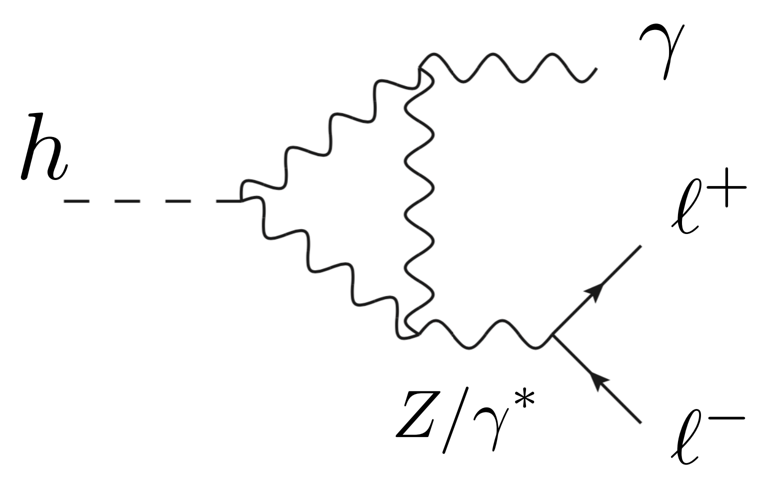


# Searches for the $H \to Z\gamma$ Decay Mode

**Z-photon** $|H^2|W^a_{\mu\nu}W^{\mu\nu a}$

Field tensor coupling not measured yet!




~ 2.3% of $Br(\gamma\gamma)$

A priori straigthforward similar search for a leptonic (electrons and muons) decaying Z and a photon.

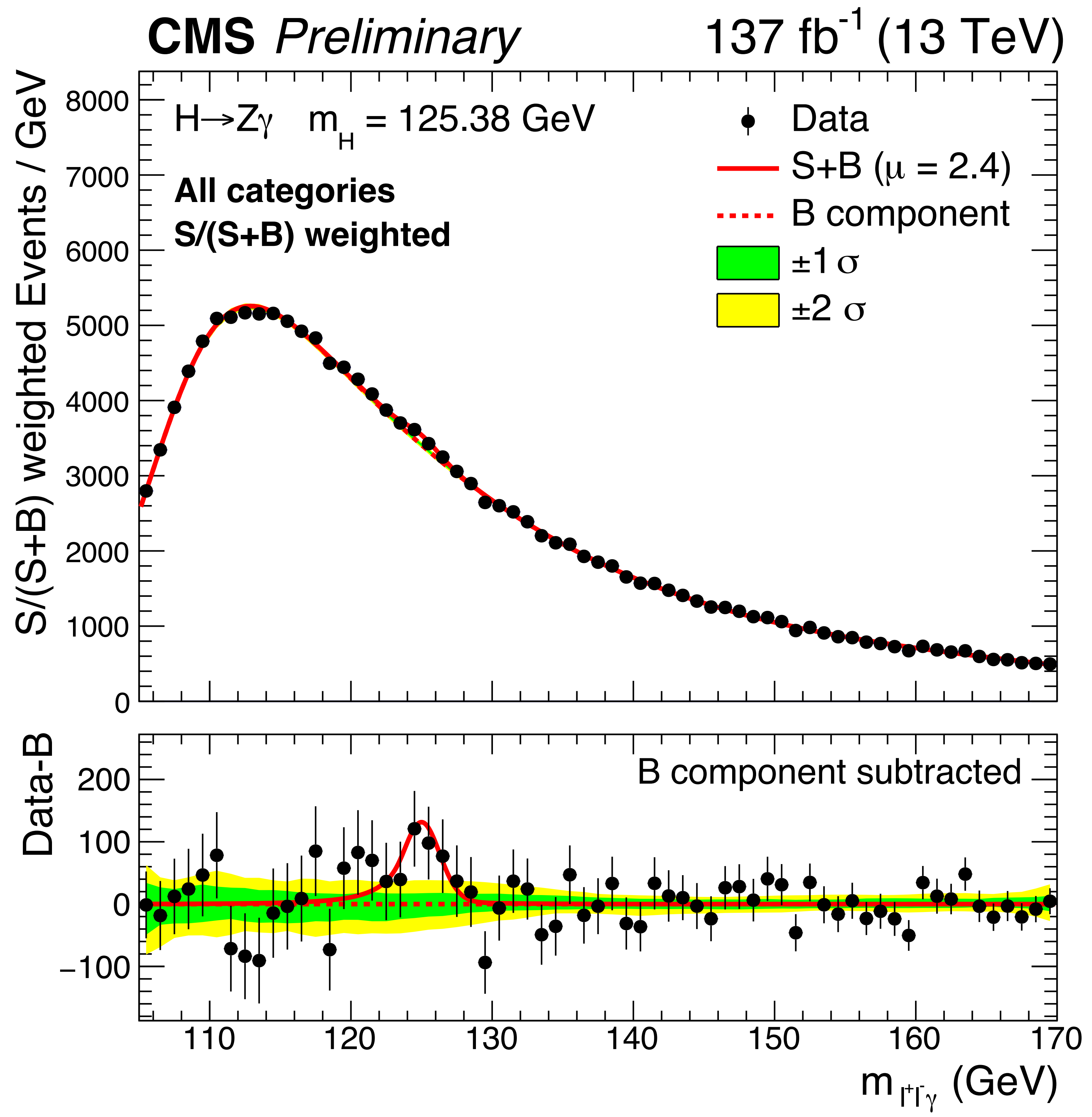
**CMS Result**

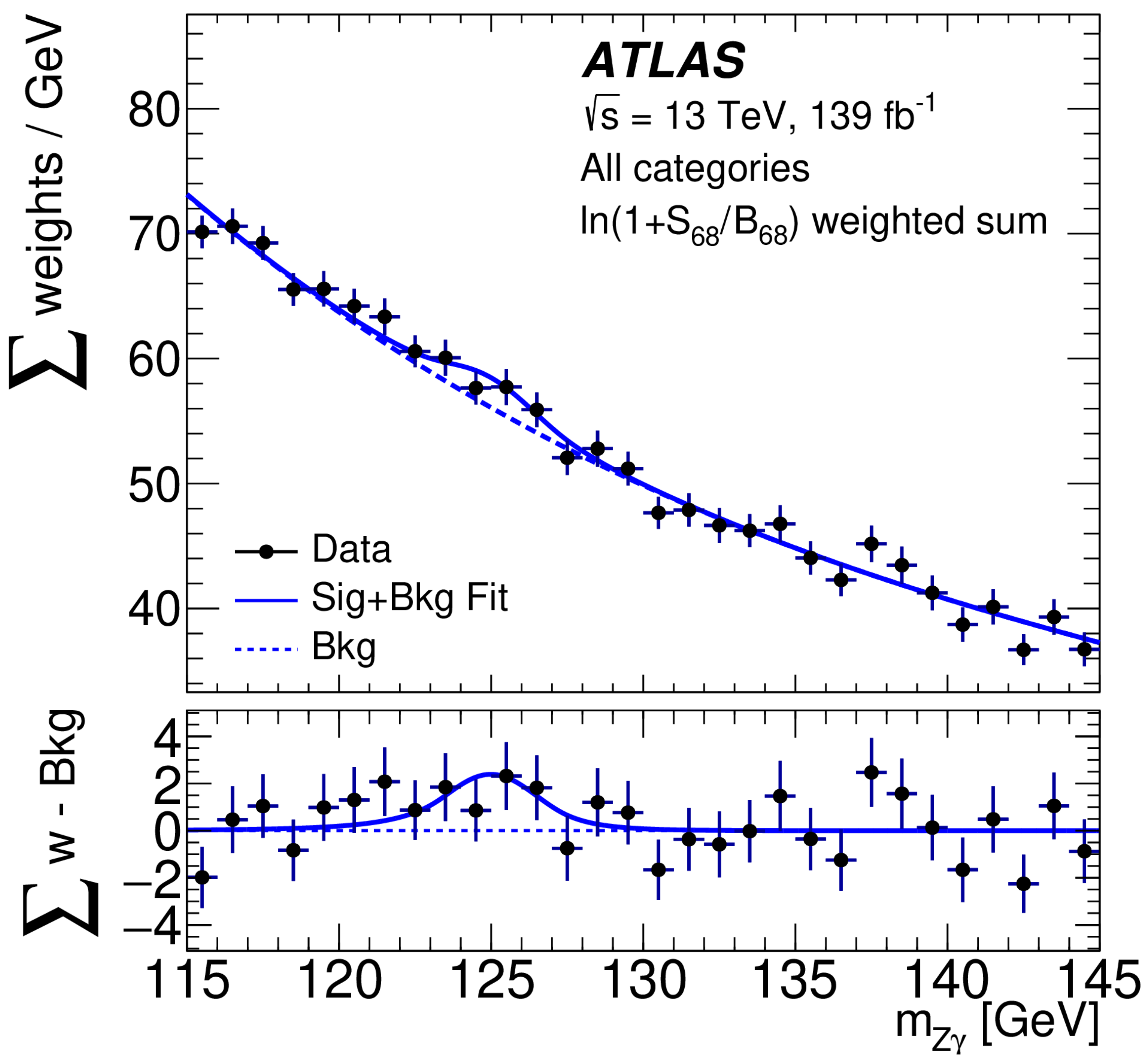
ggF, VBF, VH and ttH enriched channels

$\mu_{Z\gamma} = 2.4 \pm 0.9$

Expected $1.2\sigma$

Observed $2.7\sigma$




**ATLAS Result**

ggF and VBF enriched channels

$\mu_{Z\gamma} = 2.0 \pm 0.9$

Expected $1.2\sigma$

Observed $2.2\sigma$

**To follow closely at Run 3 for first evidence!**

# 4.- Promising constraints

# Cross Sections Definitions



Typically at LHC measurement of number of events in a given dataset, with a set of selection cuts corresponding to a given integrated luminosity L.

**Total cross section** $$\sigma_{tot} = \frac{N_{evts}}{\mathcal{A} \times \varepsilon \times \int \mathcal{L} dt}$$

Where $\sigma_{tot}$ is the total cross section for a given process (which includes the decay branching fractions), A the acceptance of the process, $\varepsilon$ is experimental efficiency (online and offline) and L is the integrated luminosity.

$$\mathcal{A}$$

The acceptance A is derived from the definition of a **fiducial volume** and is the ratio of number of events produced in the fiducial volume to the total number of events. It is an extrapolation factor estimated by theory (typically with Monte Carlo).

**Fiducial cross section** $$\sigma_{fid} = \frac{N_{evts}}{\varepsilon \times \int \mathcal{L} dt}$$

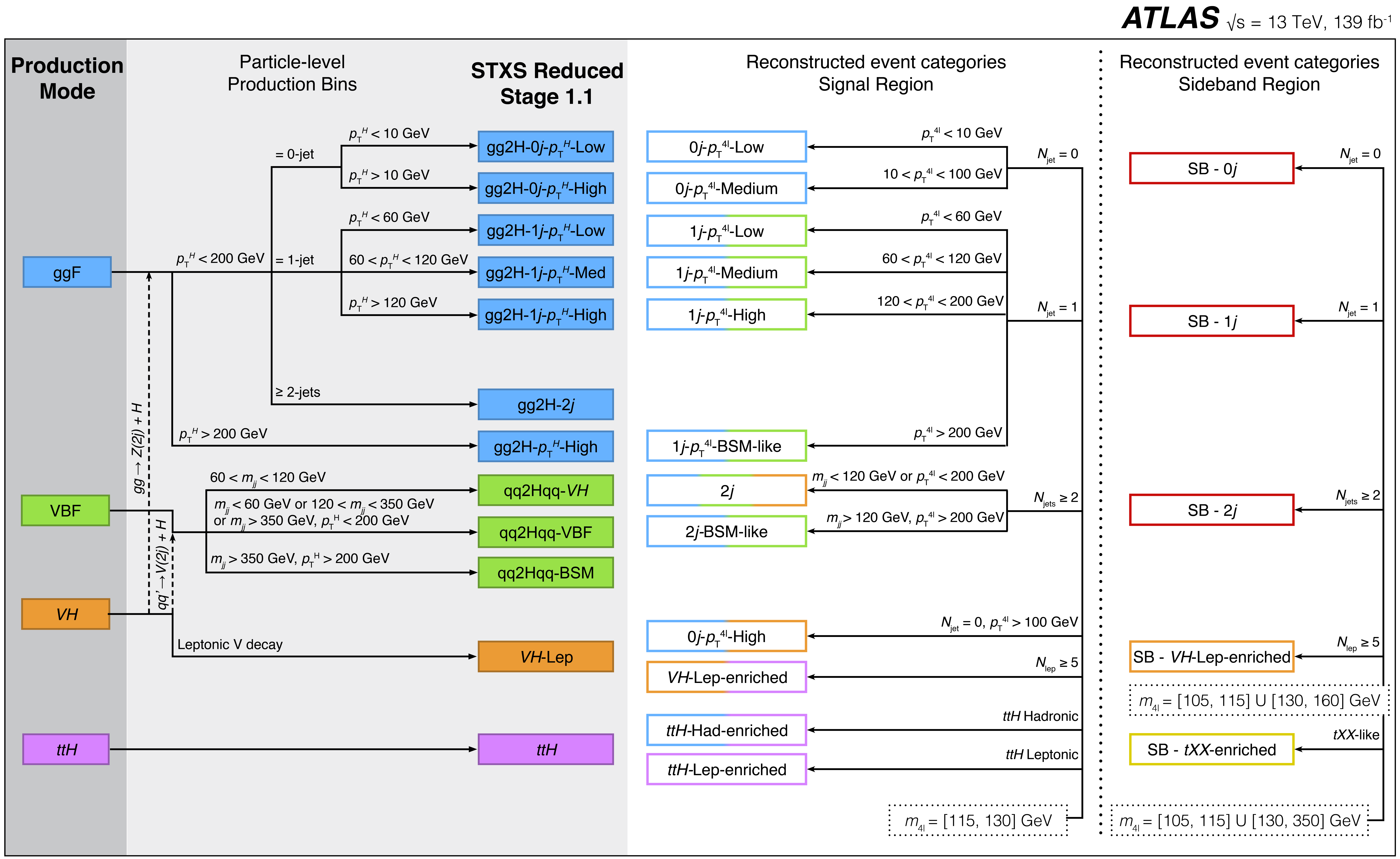
With a proper definition of the fiducial region, ε should bear little model dependence.

# Hybrid Approach: Simplified Template Cross Sections



**Cross section measurements in the four leptons channel**: the goal is to measure as precisely as possible individual production processes (ggF, VBF, VH and ttH) in different regions of phase space.

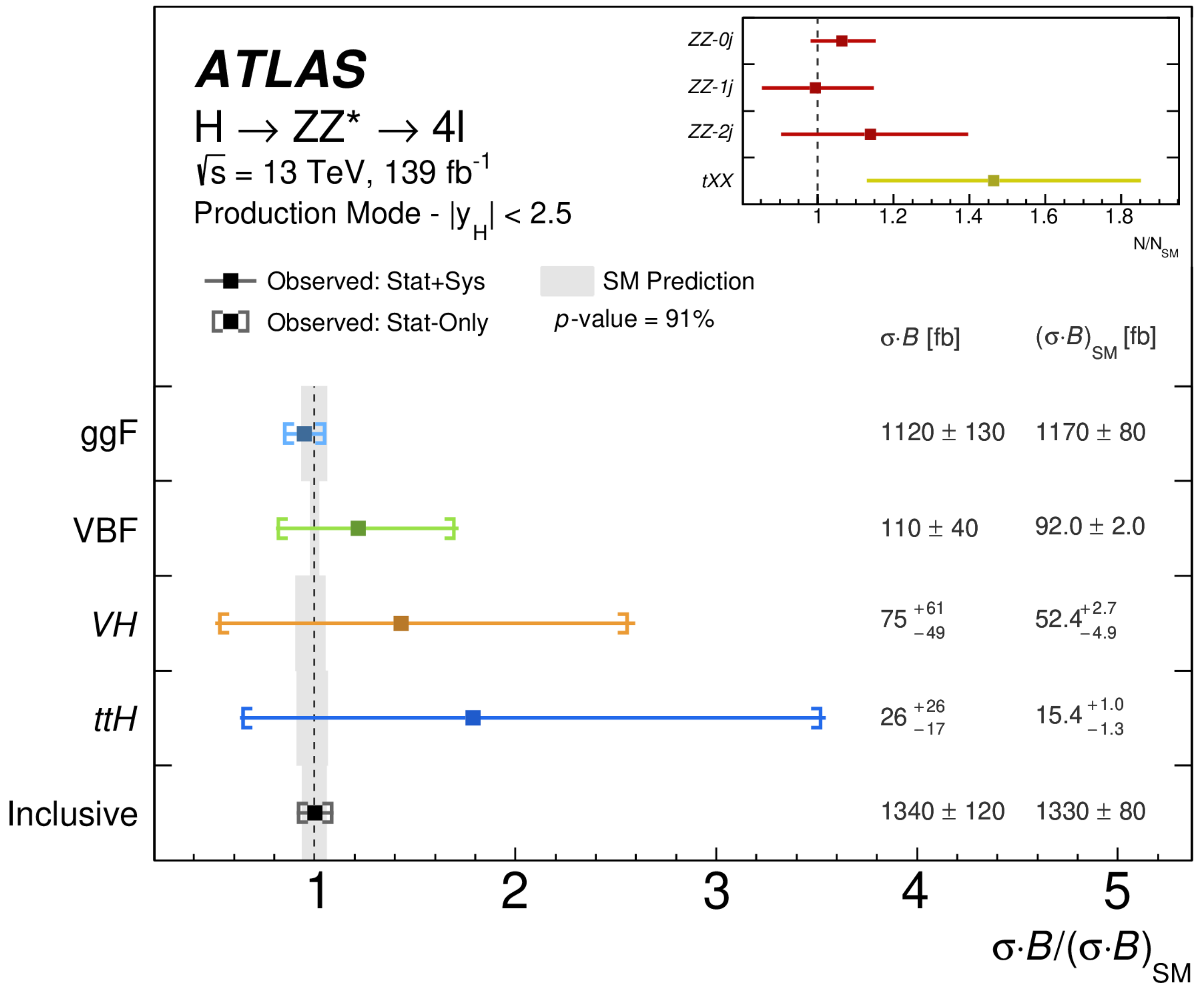
- Define fiducial cuts at truth particle level on Higgs production characteristics (pT, number and kinematics of the additional jets or leptons in the events, etc…)
- Define reconstruction level cuts corresponding to the fiducial volume of interest.
- Integrate over Higgs decays.
- The definition of the fiducial volume is guided both by the TH interest and the experimental capabilities.

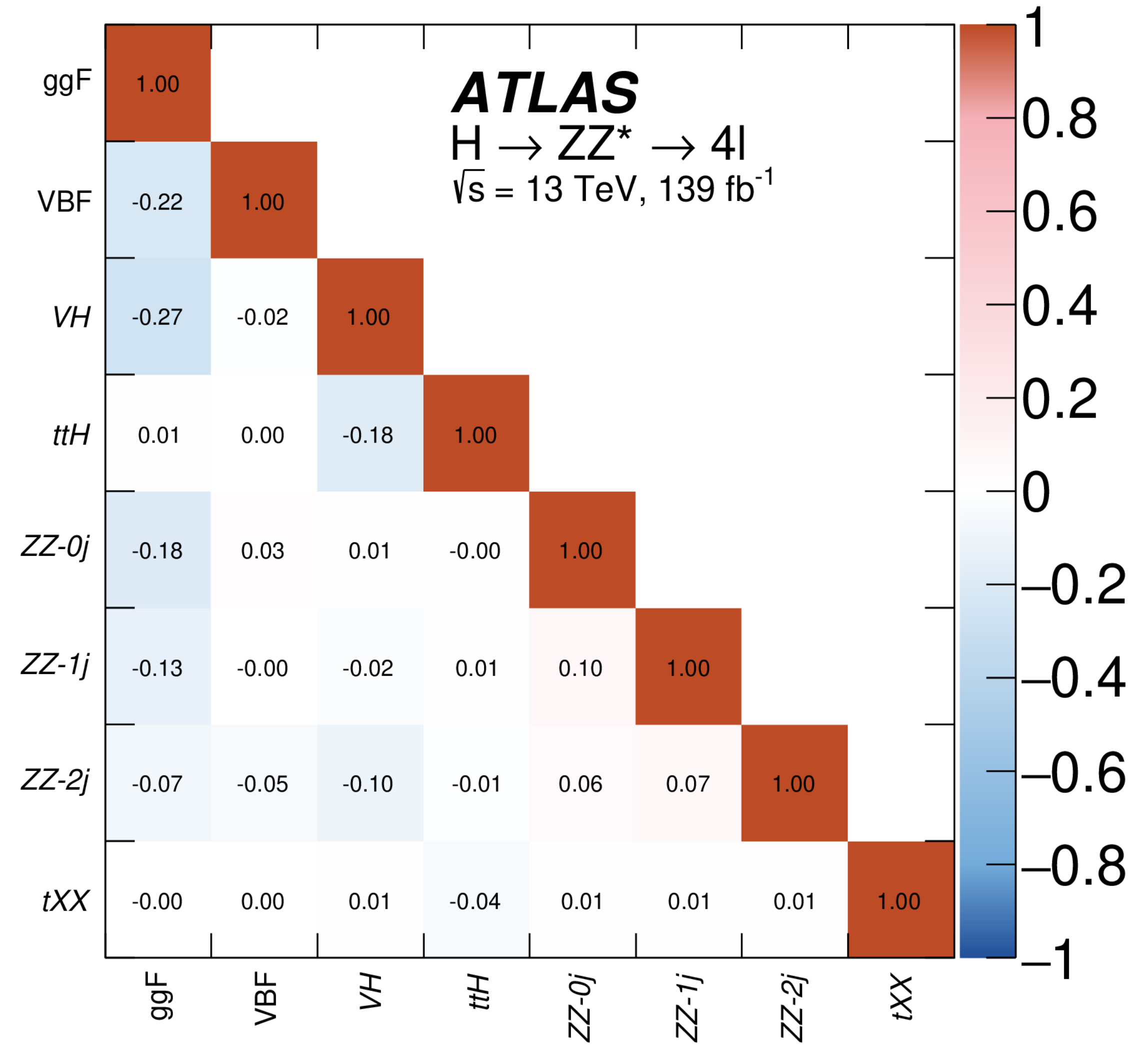


# Hybrid Approach

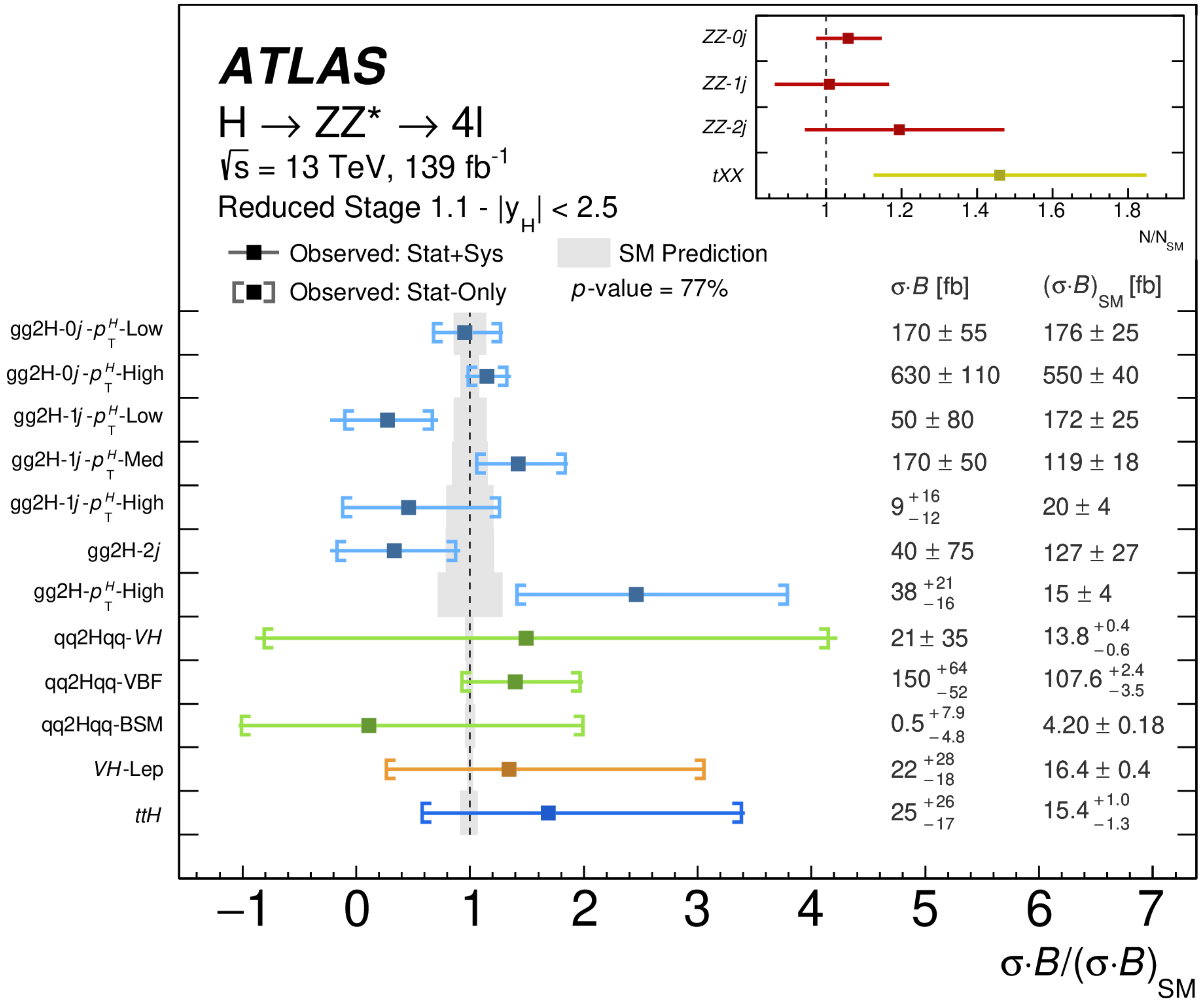
## Four lepton channel example

Specific processes total cross sections are extracted from a global fit




Similar measurements can be done in a more exclusive approach with more fiducial cuts are defined:




These measurements rely on the specific (SM) predicted acceptance of each process and the fact that no additional production processes are present.

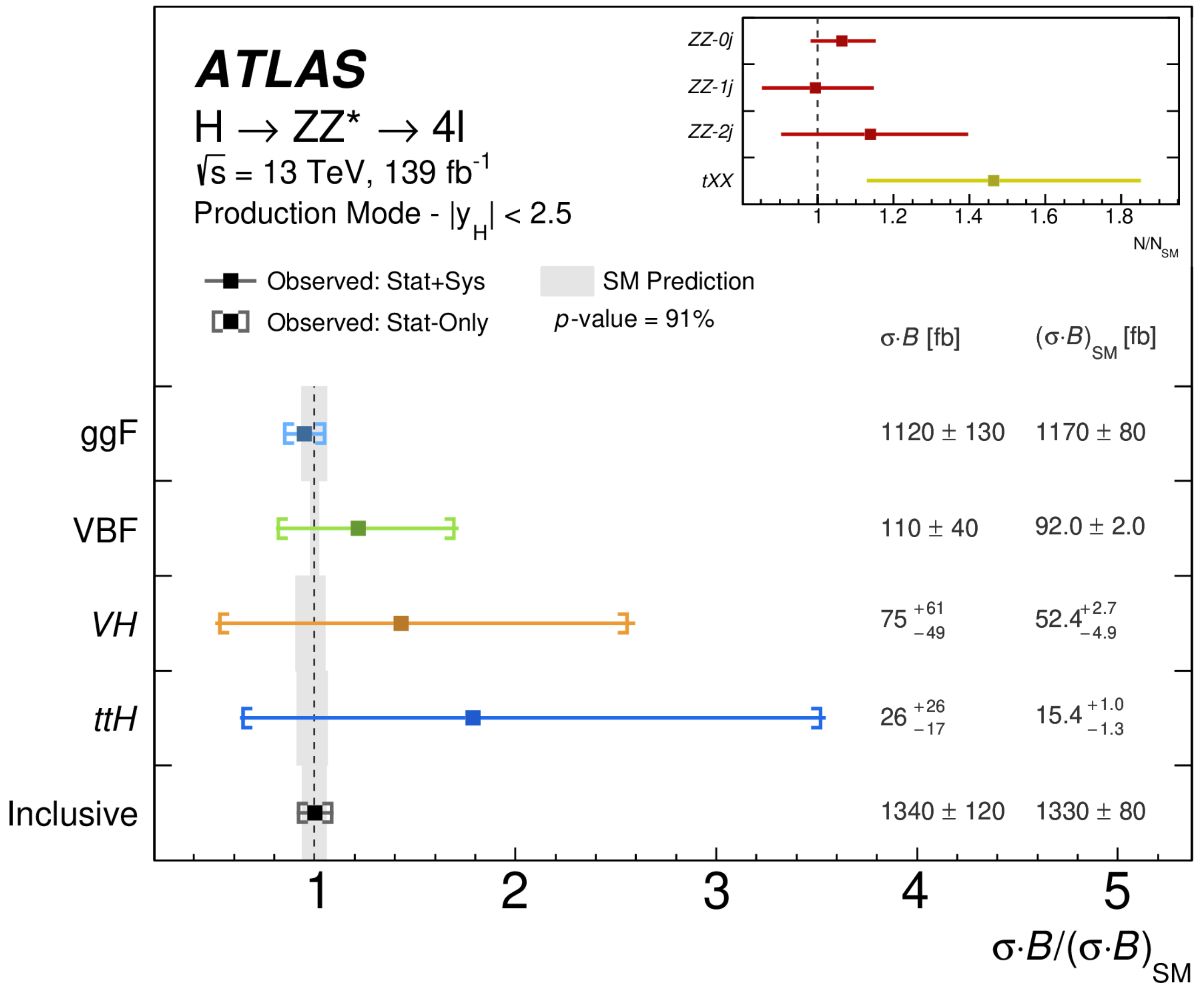
All our couplings measurements are based on this assumption.

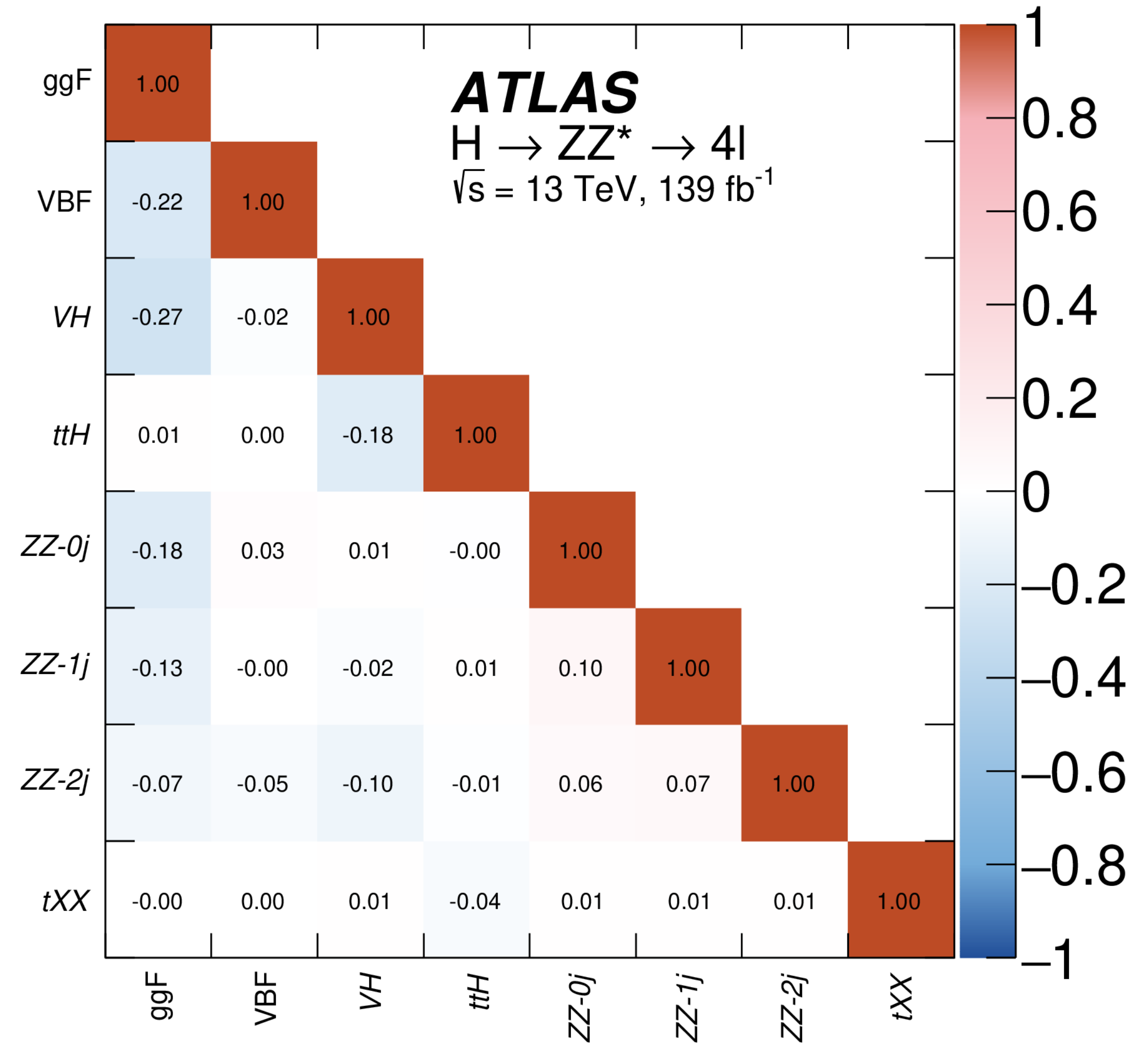
These still rely on assumption of (SM) acceptances but are very useful in the case of an EFT approach.

# Hybrid Approach

## Four lepton channel example

Specific processes total cross sections are extracted from a global fit

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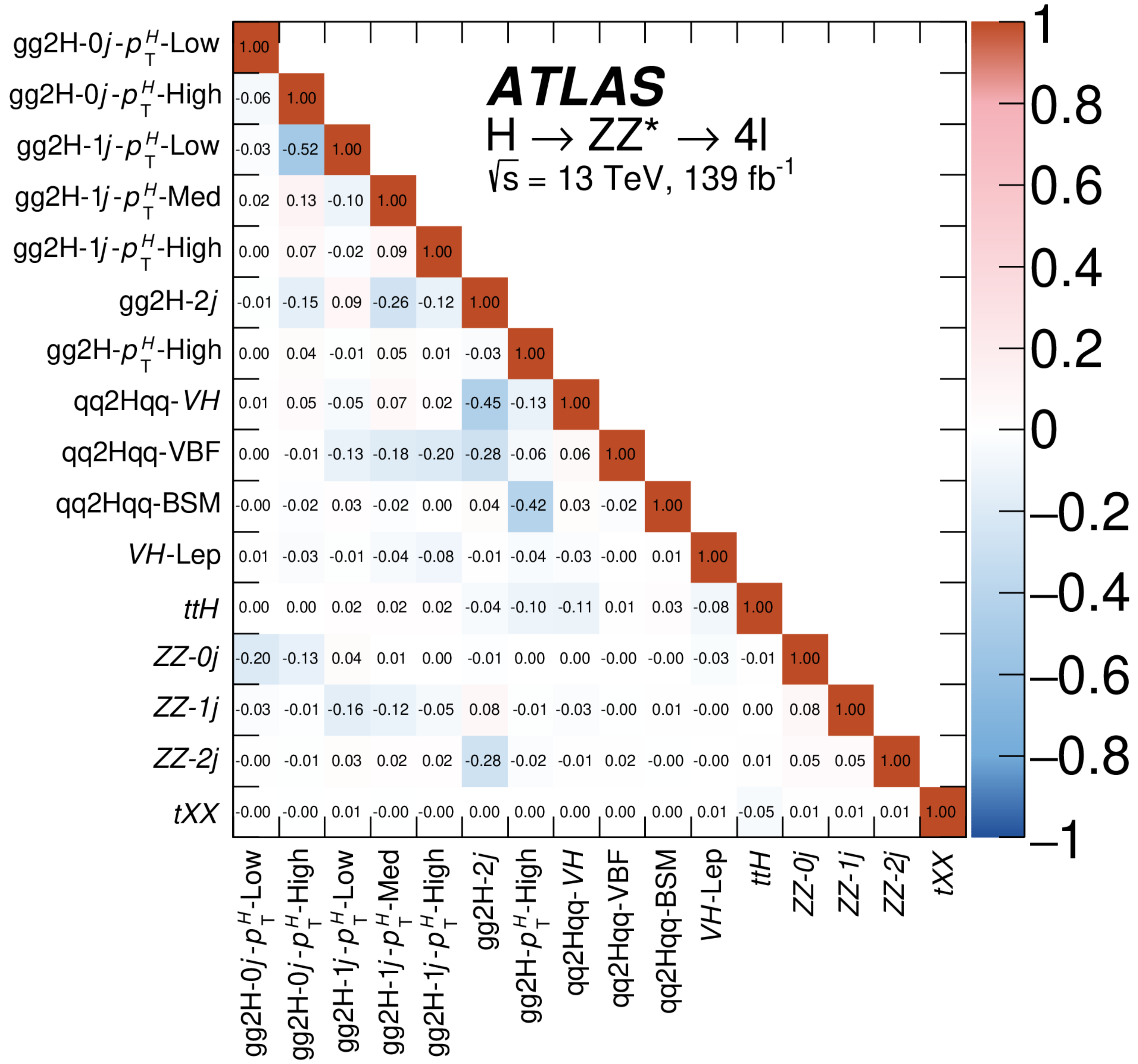



These measurements rely on the specific (SM) predicted acceptance of each process and the fact that no additional production processes are present.

All our couplings measurements are based on this assumption.

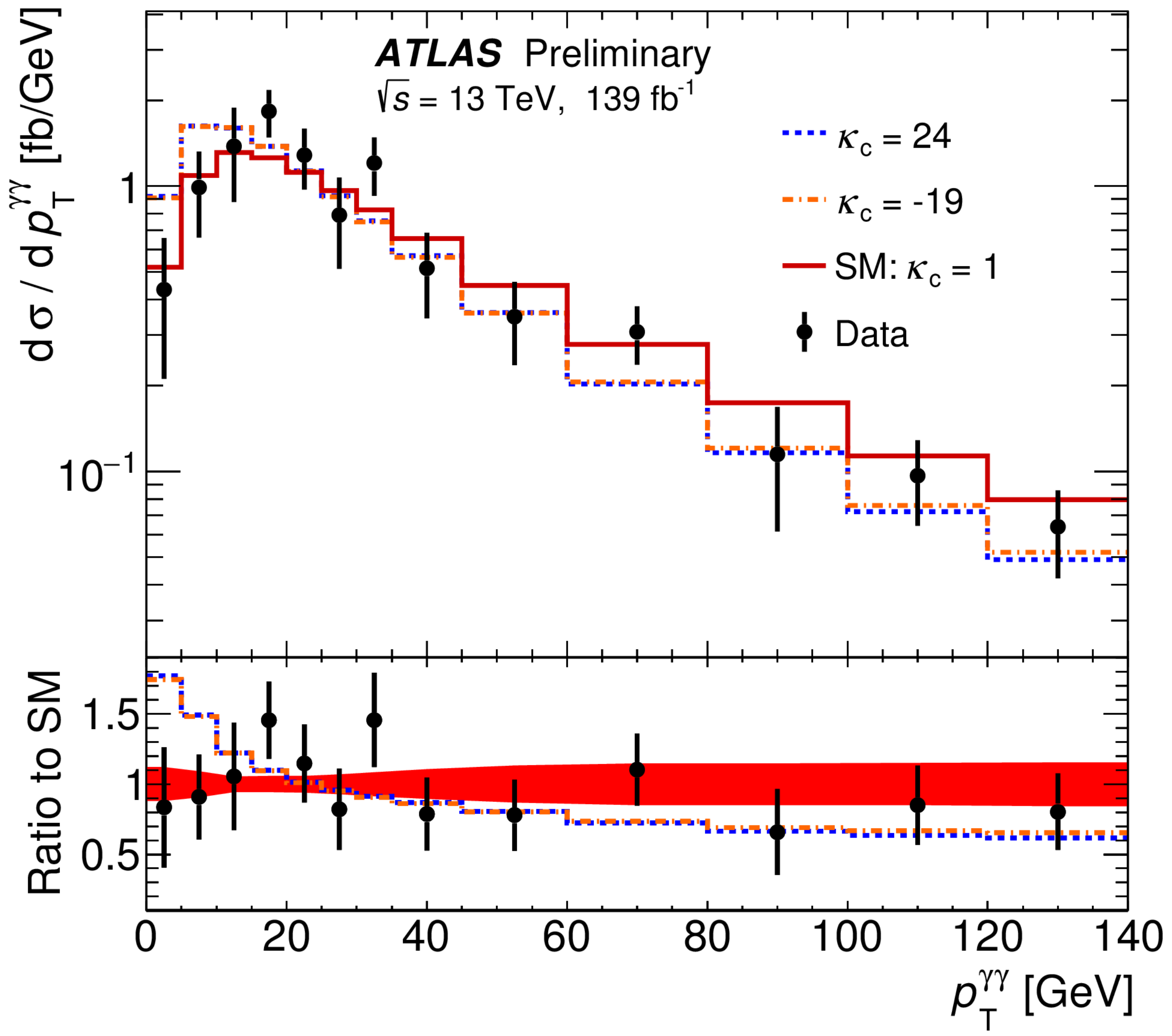
These still rely on assumption of (SM) acceptances but are very useful in the case of an EFT approach.

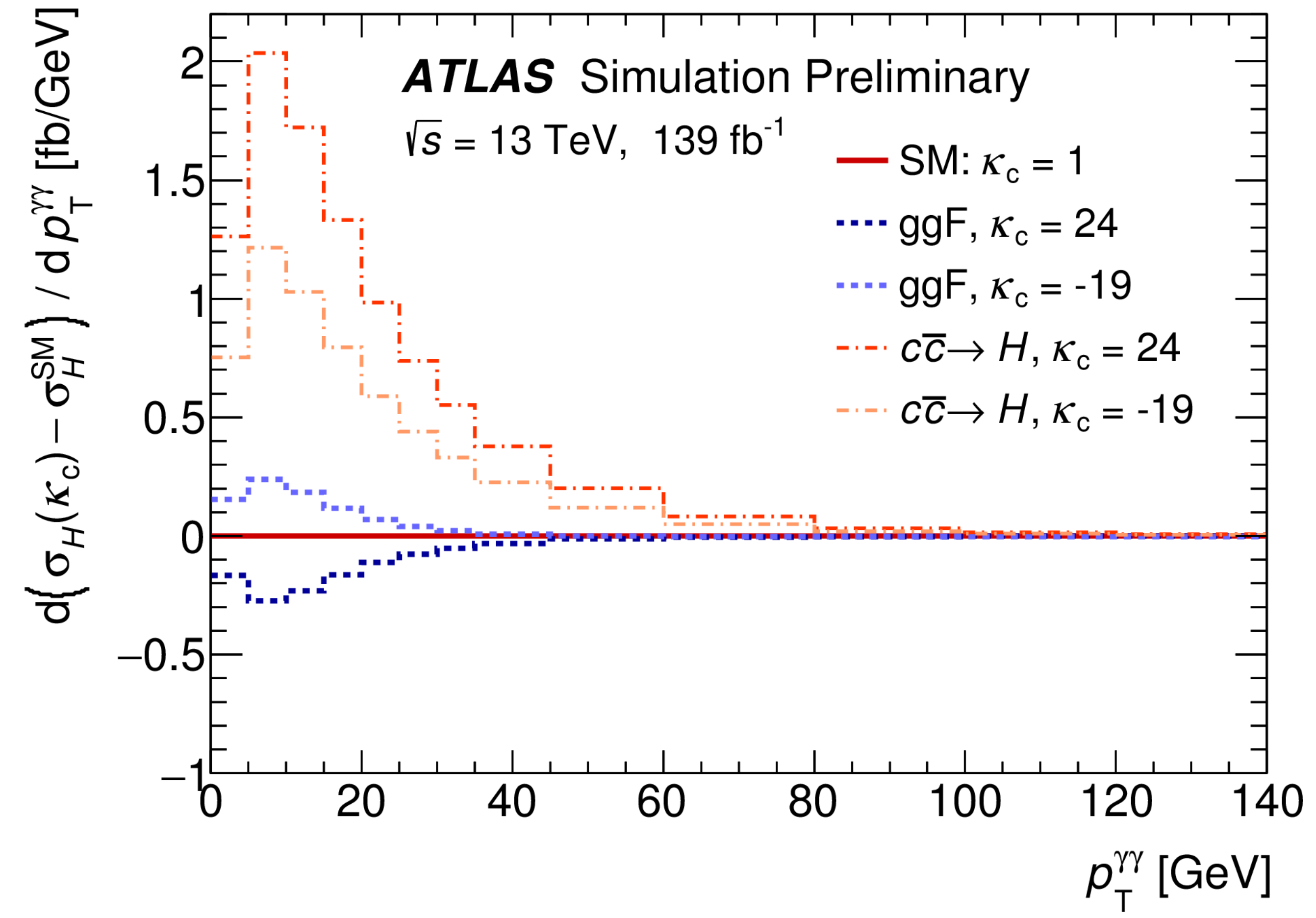
**STXS Measurements done now in most main Higgs channels - Important input to EFT interpretations (discussed by John)**

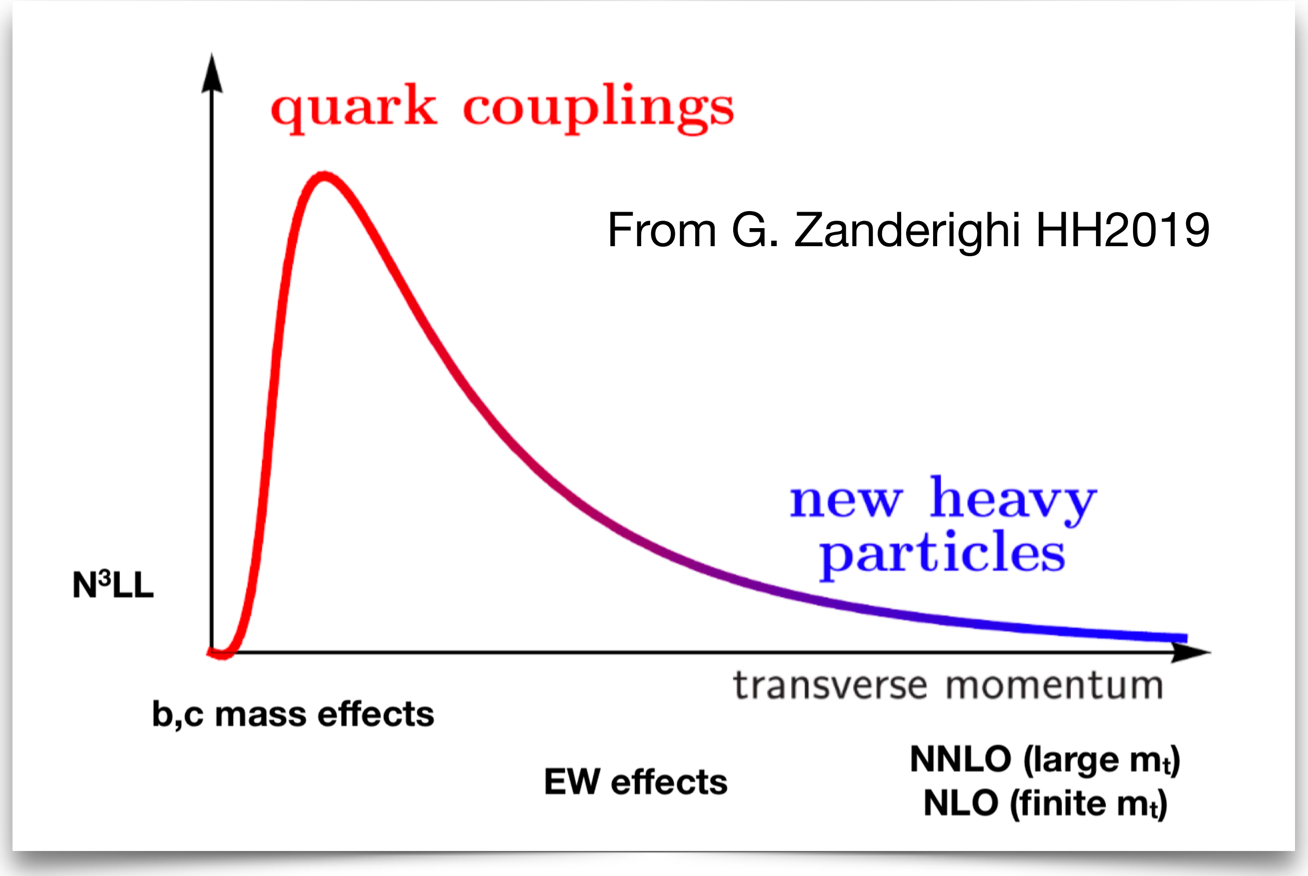
# Differential (fiducial and unfolded) Cross Section Measurements



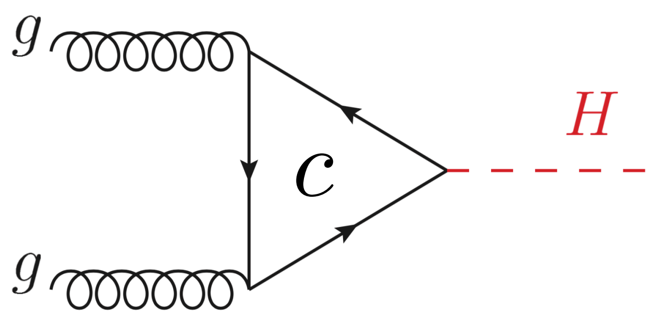
Fiducial and unfolded differential cross section measurement in pT

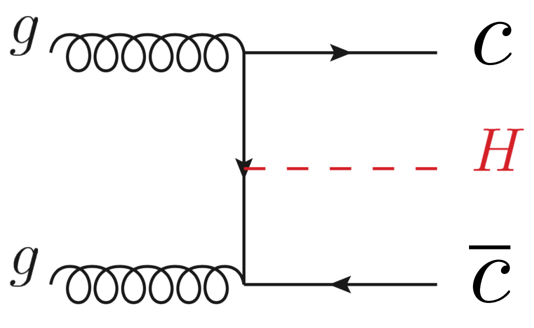


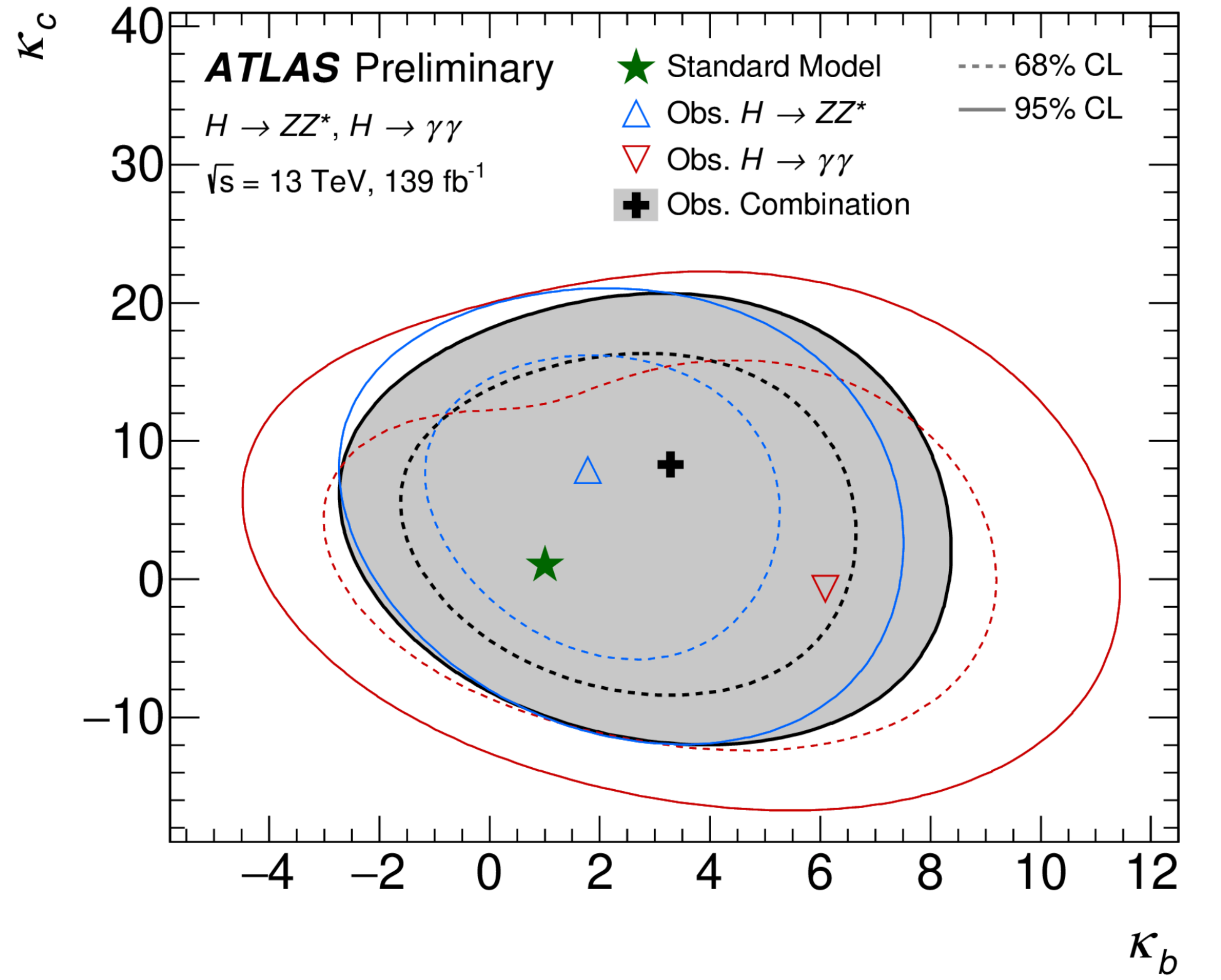




Indirect measurement of the b and c Yukawa couplings through loop:




Significant at large values of $\kappa_c$




| Parameter best-fit | Observed 95% confidence interval | Expected 95% confidence interval |
|---|---|---|
| $\kappa_b = 3.3^{+2.4}_{-4.1}$ | $[-2.1,\ 7.4]$ | $[-2.2,\ 7.4]$ |
| $\kappa_c = 8.3^{+5.5}_{-13.8}$ | $[-10.1,\ 18.3]$ | $[-10.3,\ 16.6]$ |

# CP Properties of Higgs Couplings in  Diboson Channels



Measurement from CMS in the ZZ* (4l) channels in the « untagged », VH (V hadronic) and VBF production modes.

$$f_{a_i} = \frac{|a_i|^2\sigma_i}{\sum_{j=1,2,3}|a_j|^2\sigma_j}, \quad \phi_{a_i} = \arg\left(\frac{a_i}{a_1}\right)$$

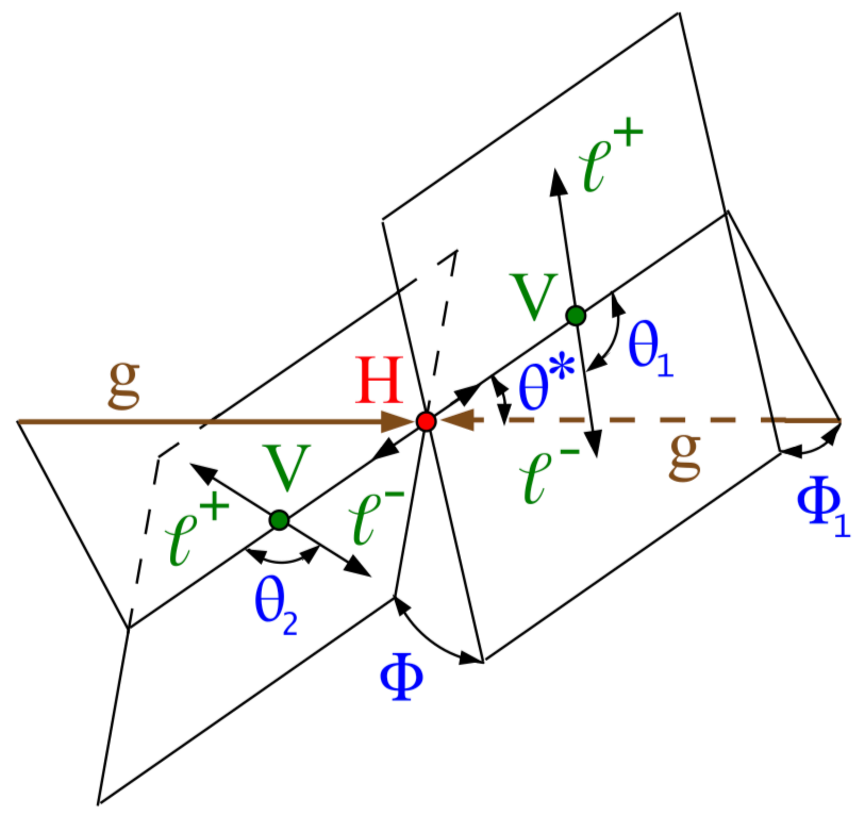
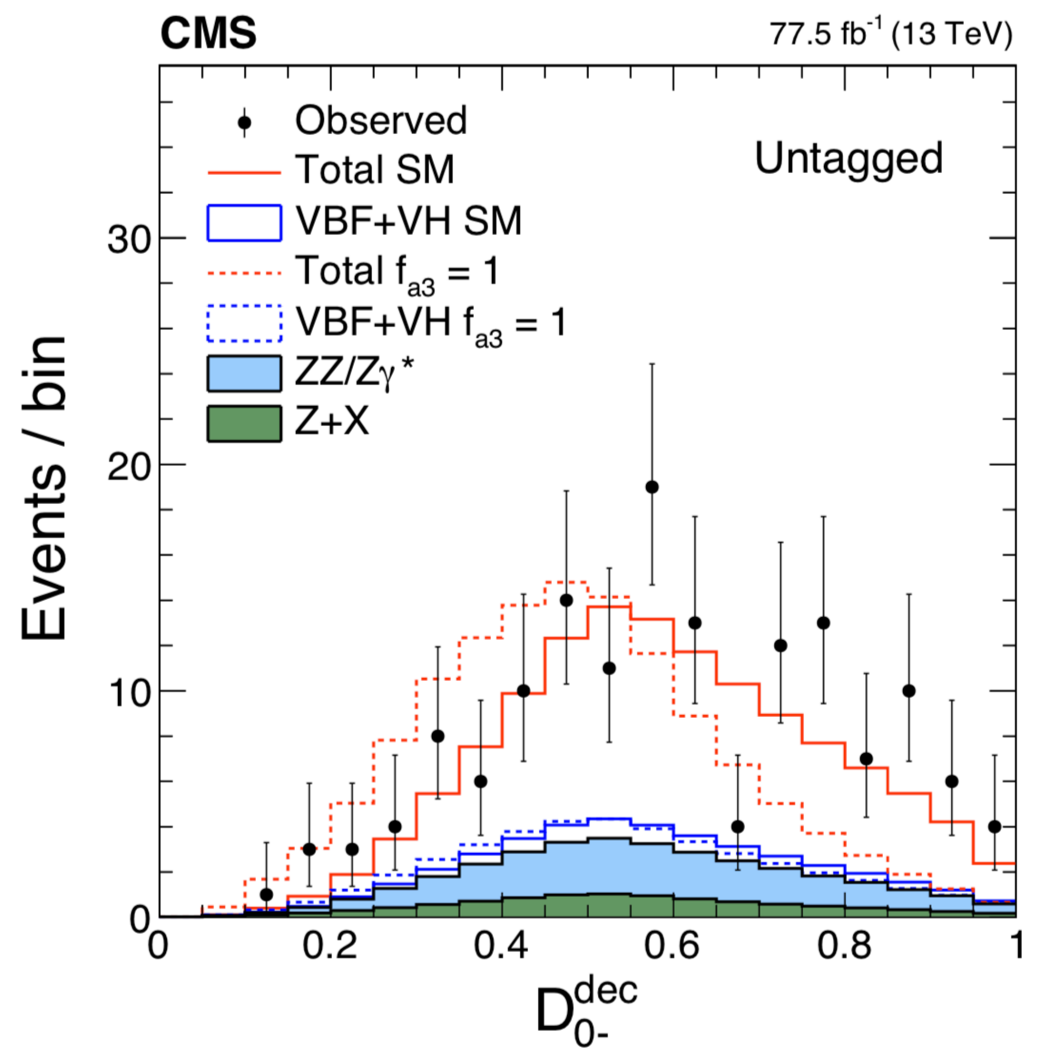
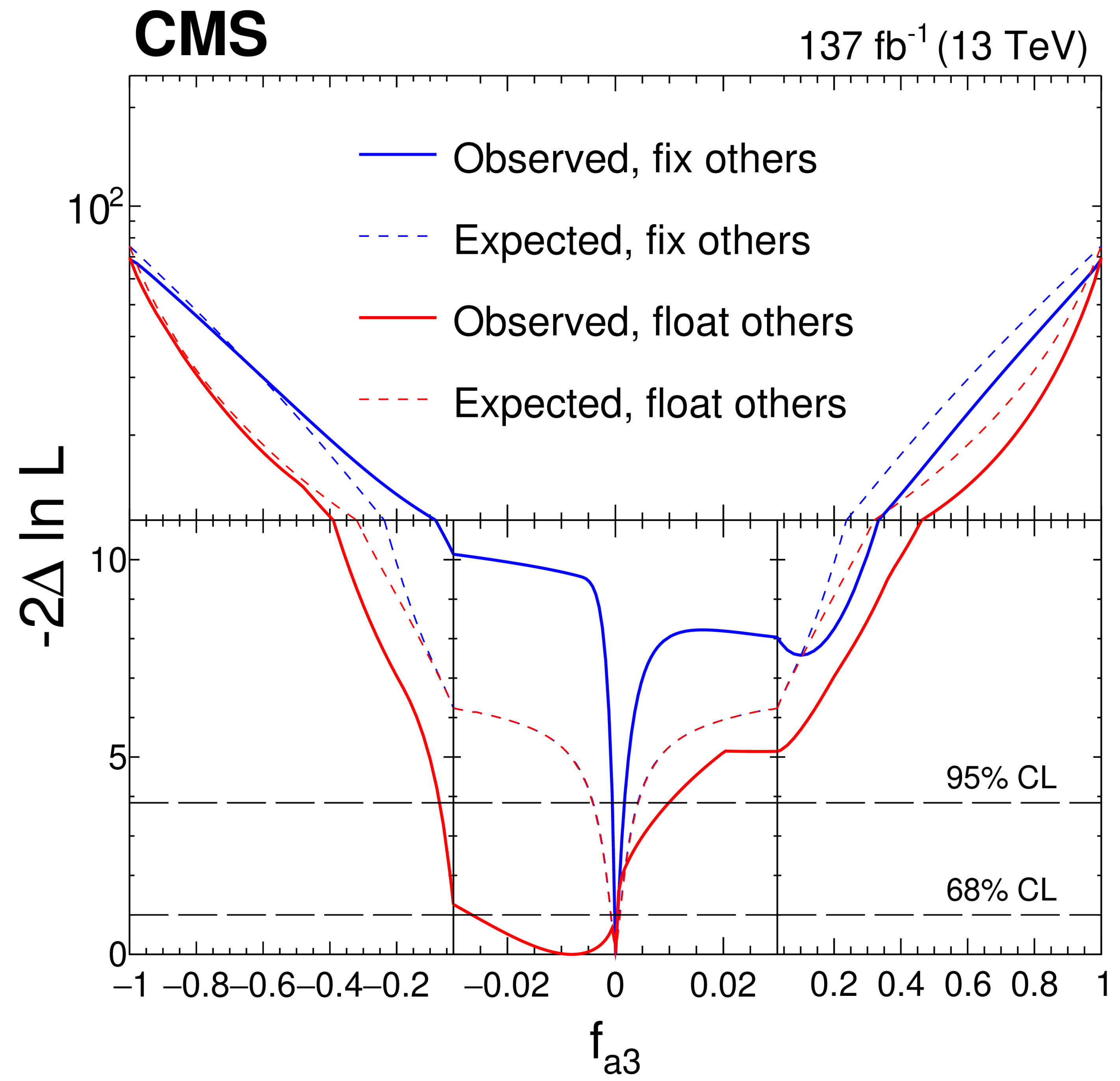



Illustration of 5 production and decay angles for the 4-leptons (most sensitive to the CP mixing)




Analysis based on Matrix Element optimal observables




$$A \sim \left[a_1^{VV} - \frac{\kappa_1^{VV} q_1^2 + \kappa_2^{VV} q_2^2}{(\Lambda_1^{VV})^2} - \frac{\kappa_3^{VV}(q_1+q_2)^2}{(\Lambda_Q^{VV})^2}\right] m_{V_1}^2 \varepsilon_{V_1}^* \varepsilon_{V_2}^*$$

$$+ a_2^{VV} f_{\mu\nu}^{*(1)} f^{*(2)\mu\nu} + a_3^{VV} f_{\mu\nu}^{*(1)} \tilde{f}^{*(2)\mu\nu}$$

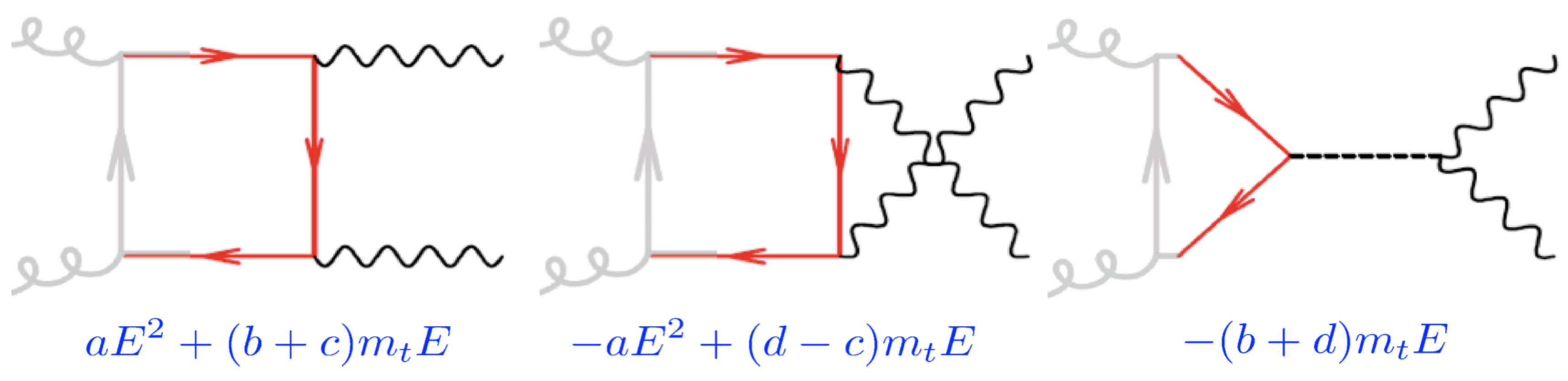
$$f_{\mu\nu}^{*(i)} = \varepsilon_i^\mu q^\nu - \varepsilon_i^\nu q^\mu \qquad \tilde{f}_{\mu\nu}^{*(i)} = \frac{1}{2}\varepsilon_{\mu\nu\rho\sigma} f^{*(i)\rho\sigma}$$

CP violating fraction for a scalar Higgs of ~2% at 68% CL (and ~10-20% at 95% CL)

Higgs couplings to vector bosons is largely CP even!

# Off Shell HVV Couplings and Width

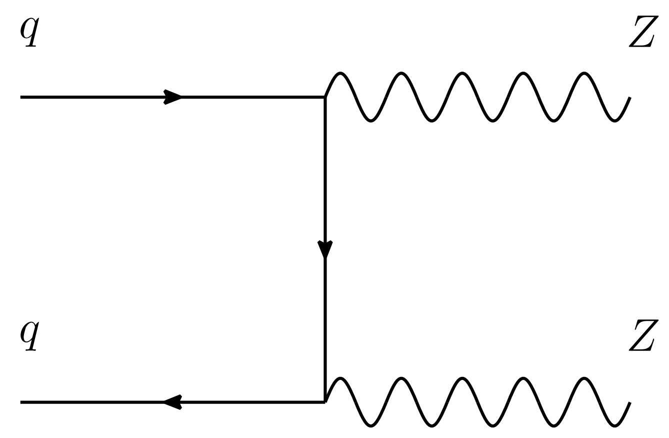
**Higgs as a propagator:** Without the s-channel Higgs unitarity problem!

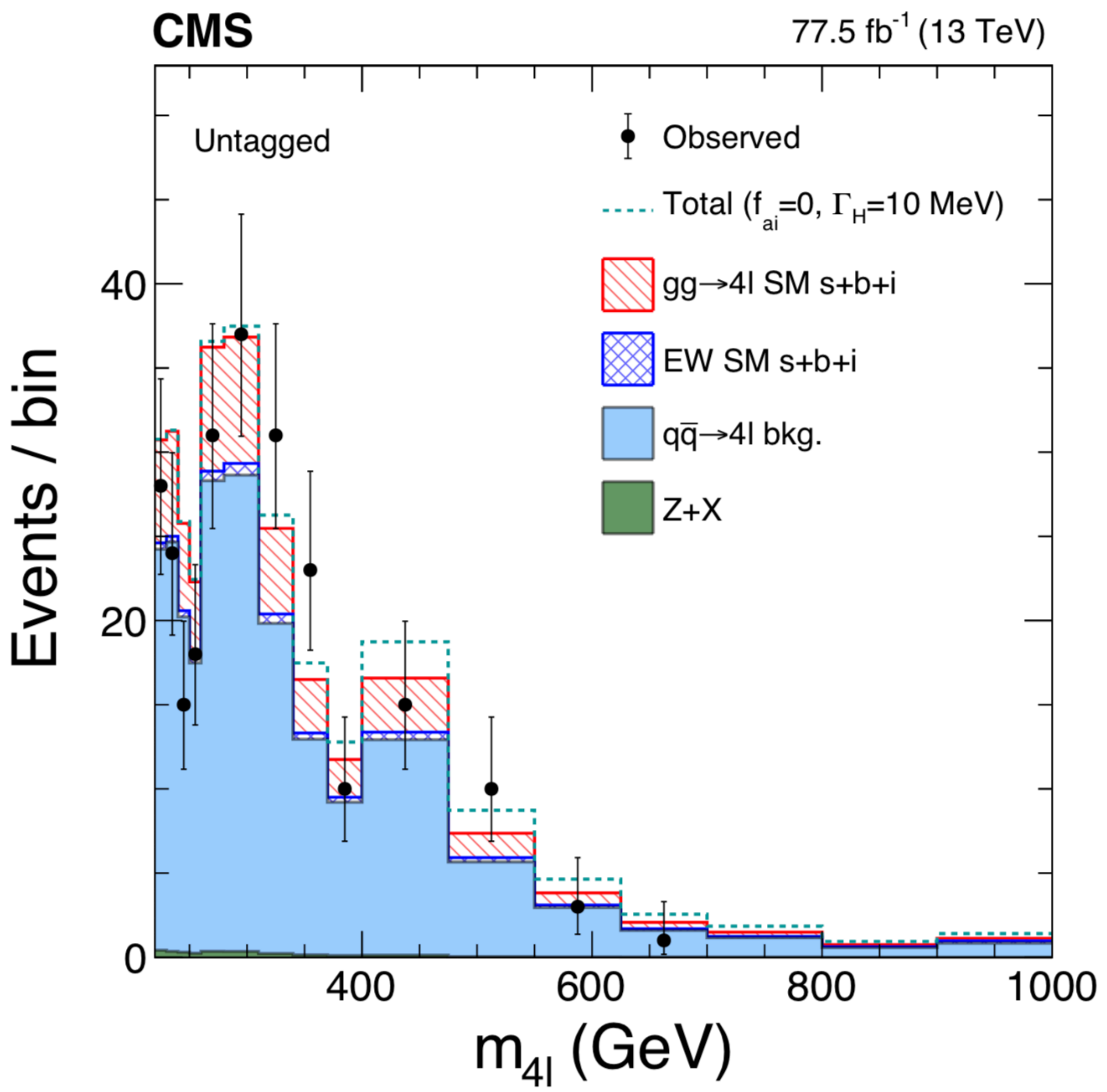


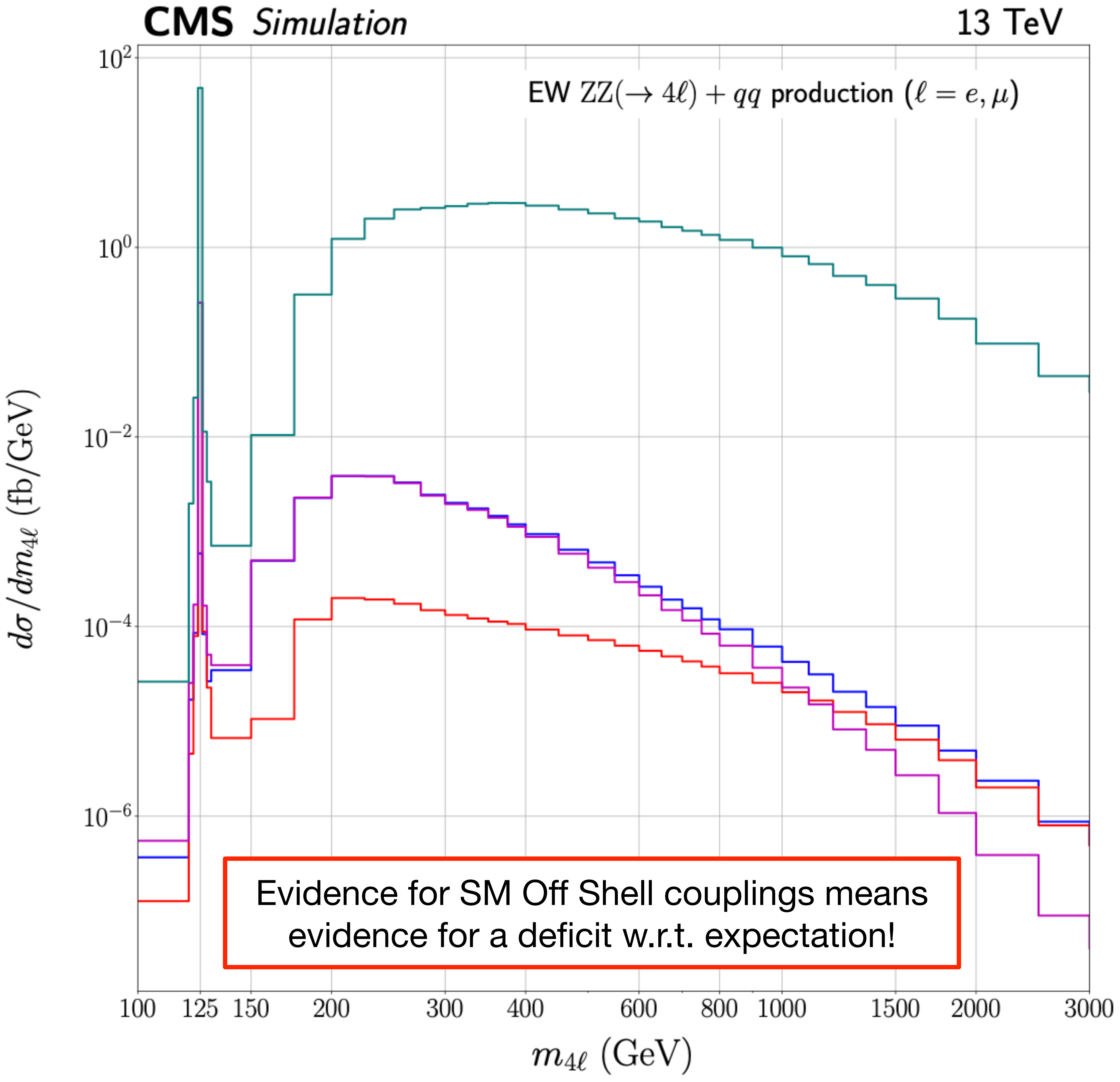

From J. Campbell

Negative interference Higgs signal and $gg \to VV$ background

Highly non trivial also due to large other backgrounds:



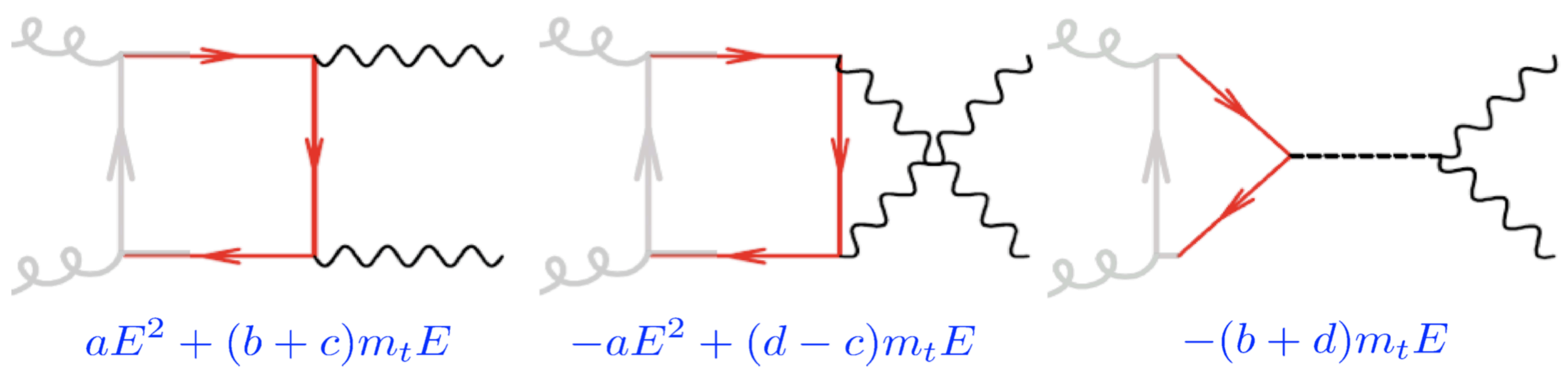




Constraint:

$\mu_{\rm sig}^{\rm on-shell}(gg \to H \to ZZ \to 2e2\mu) = 1$

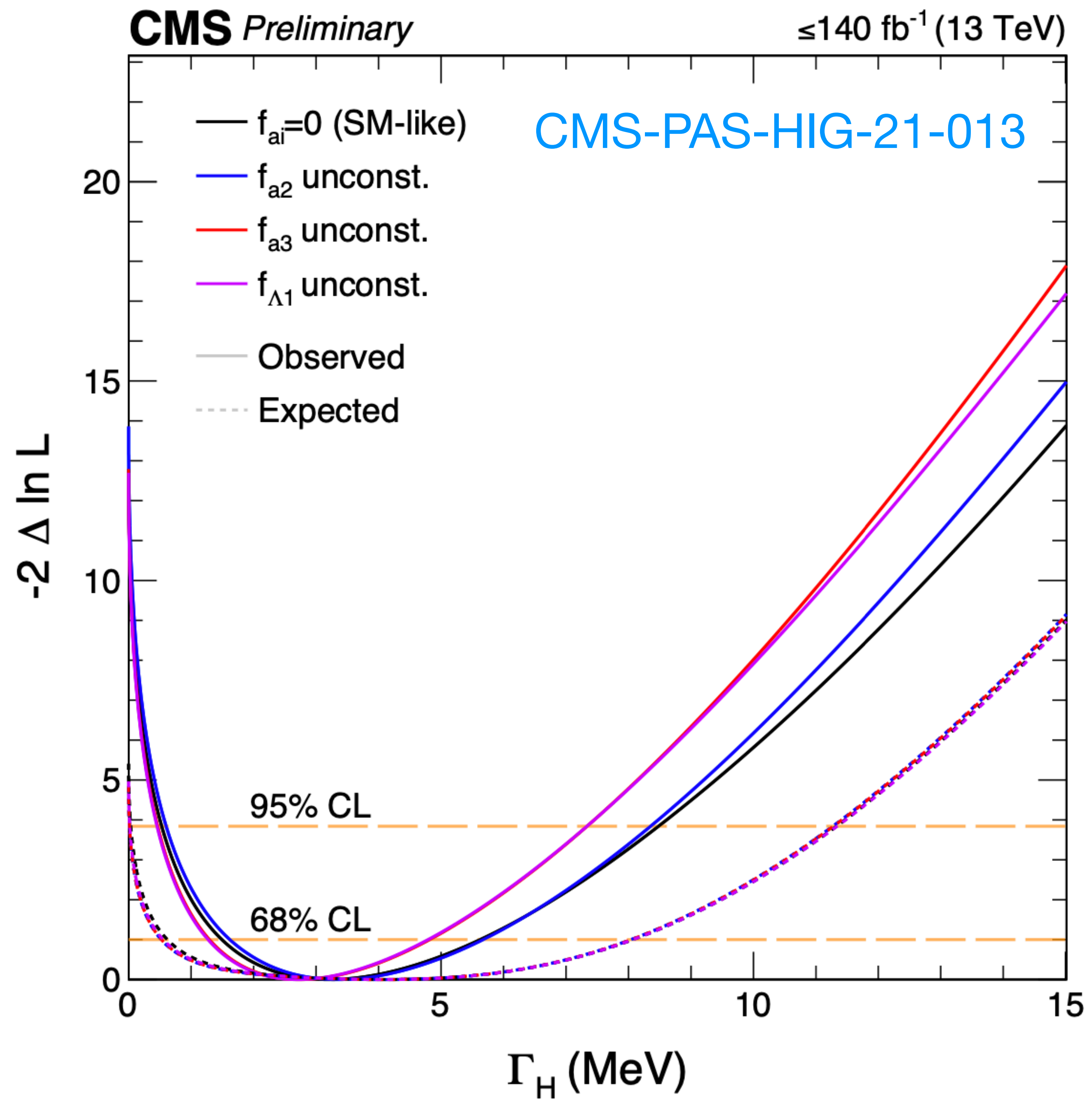
# Off Shell HVV Couplings  and Width

**Higgs as a propagator:** Without the s-channel Higgs unitarity problem!




From J. Campbell

## CMS Combination $4\ell$ with $2\ell 2\nu$




Extraction of the width using ratio between Off Shell and On Shell couplings Assuming that these couplings run as in the Standard Model and measuring them on shell allows for a measurement of the width of the Higgs boson!

$$\Gamma_H = \frac{\mu_{off\ shell}}{\mu_{on\ shell}} \times \Gamma_H^{SM} \qquad (\kappa_t^2 \kappa_V^2)_{on\ shell} = (\kappa_t^2 \kappa_V^2)_{off\ shell}$$

**Partial Run 2 dataset!** PRD 99 (2019):

Expected sensitivity: $\Gamma_H = 4.1^{+5.0}_{-4.0}$ MeV

$$\Gamma_H = 3.2^{+2.8}_{-2.2} \text{ MeV}$$

**Combination with $ZZ \to 2\ell 2\nu$**

$$\Gamma_H = 3.2^{+2.4}_{-1.7} \text{ MeV}$$

Evidence for Off-Shell production at $3.6\sigma$

**Remarkable result to follow closely at Run 3 and at HL-LHC!**

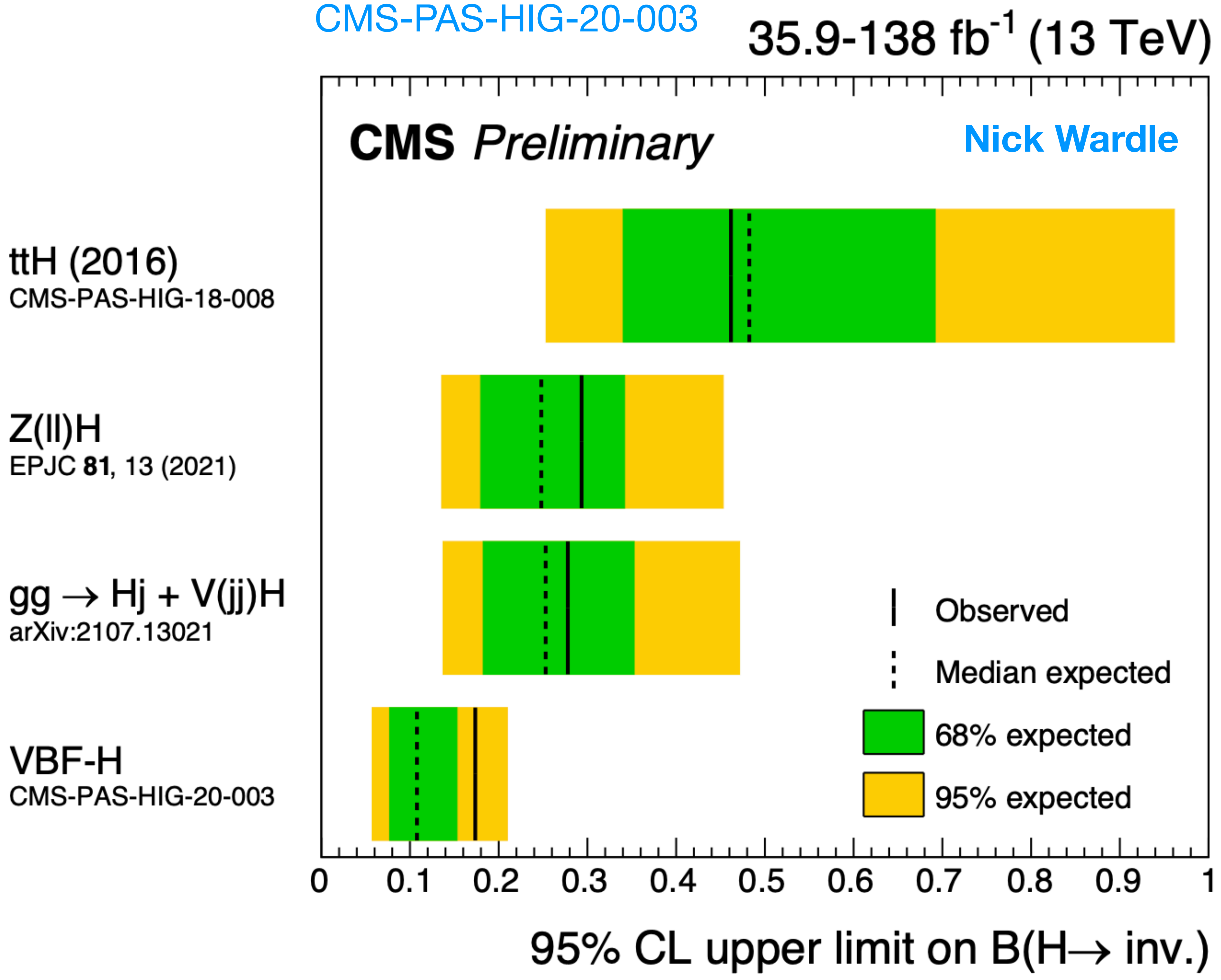
# Invisible decays of the Higgs boson



## CMS New VBF

$Br(\text{inv.}) < 0.17\ (0.11)$

CMS-PAS-HIG-20-003



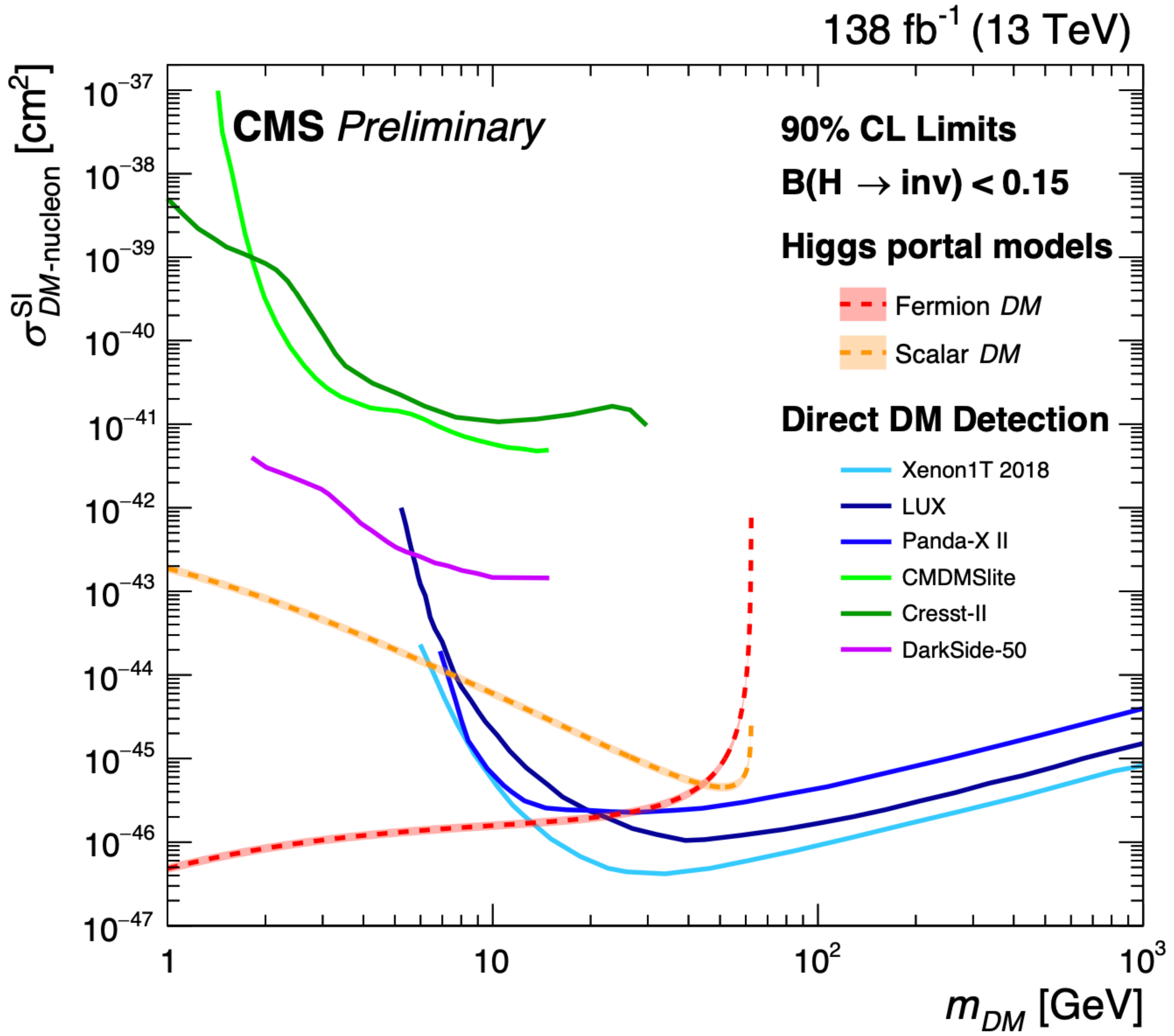

Overall major background is $z \to \nu\bar{\nu}$ (with jets) major challenge to control, but also interesting new measurements from it:

Precision measurement of the invisible Z width from CMS-PAS-CMP-18-014

ATLAS-CONF-2020-052

Limits are now below **9%** on invisible branching at 90% CL

Interpretation in terms of WIMP-Nucleon cross section limits: very nice complementarity with direct searches!



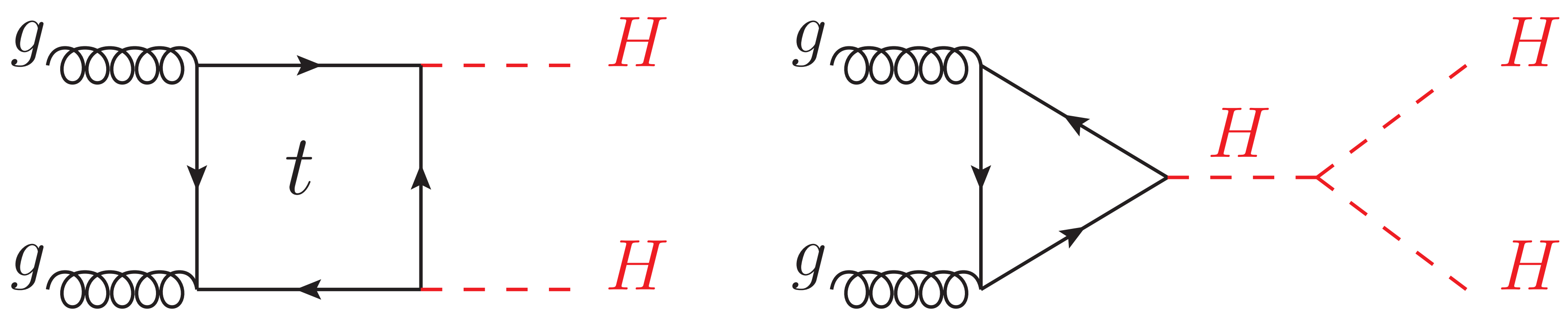

HL-LHC projection $\left(\mu_{\mathrm{VBF},VH} \cdot \mathrm{BR_{inv}}\right)^{\text{HL-LHC}} \leq 2.5\%$

- Control of backgrounds
- Precision on MET and Jet reconstruction and trigger are key!

# Higgs boson self coupling



**The Higgs self coupling is also key to the HL-LHC program!**

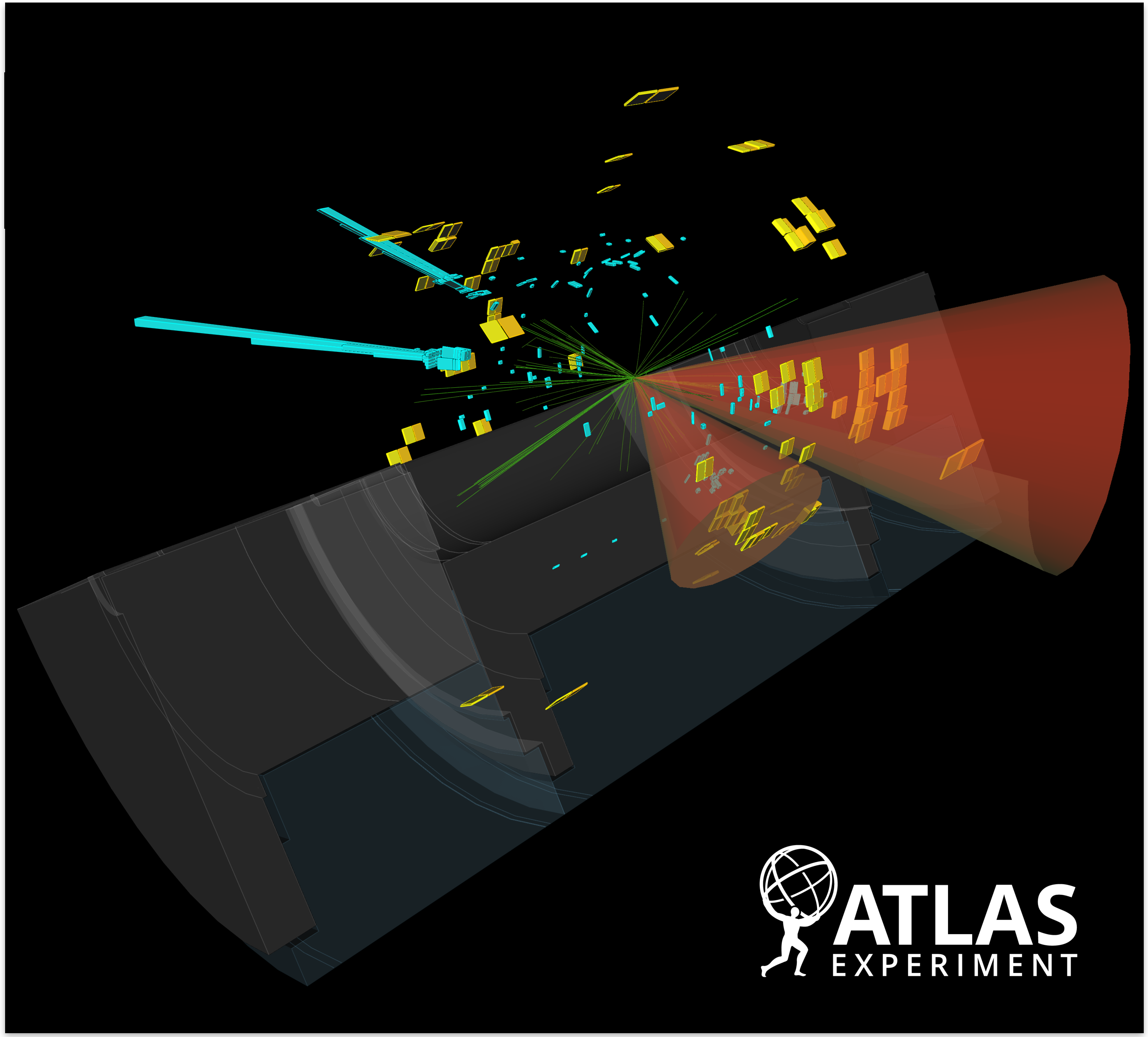



Very similar analysis as the Off-shell Higgs couplings!

Incredibly small cross section ~1000 times smaller than Higgs production!

**Huge challenge!** but still more than 100k event will be produced at HL-LHC!

**Multiple channels investigated:** depending on the both Higgs decays considering (bb, yy, tautau, WW) - All complex topologies!!



# Towards a Measurement of the Higgs Self Coupling

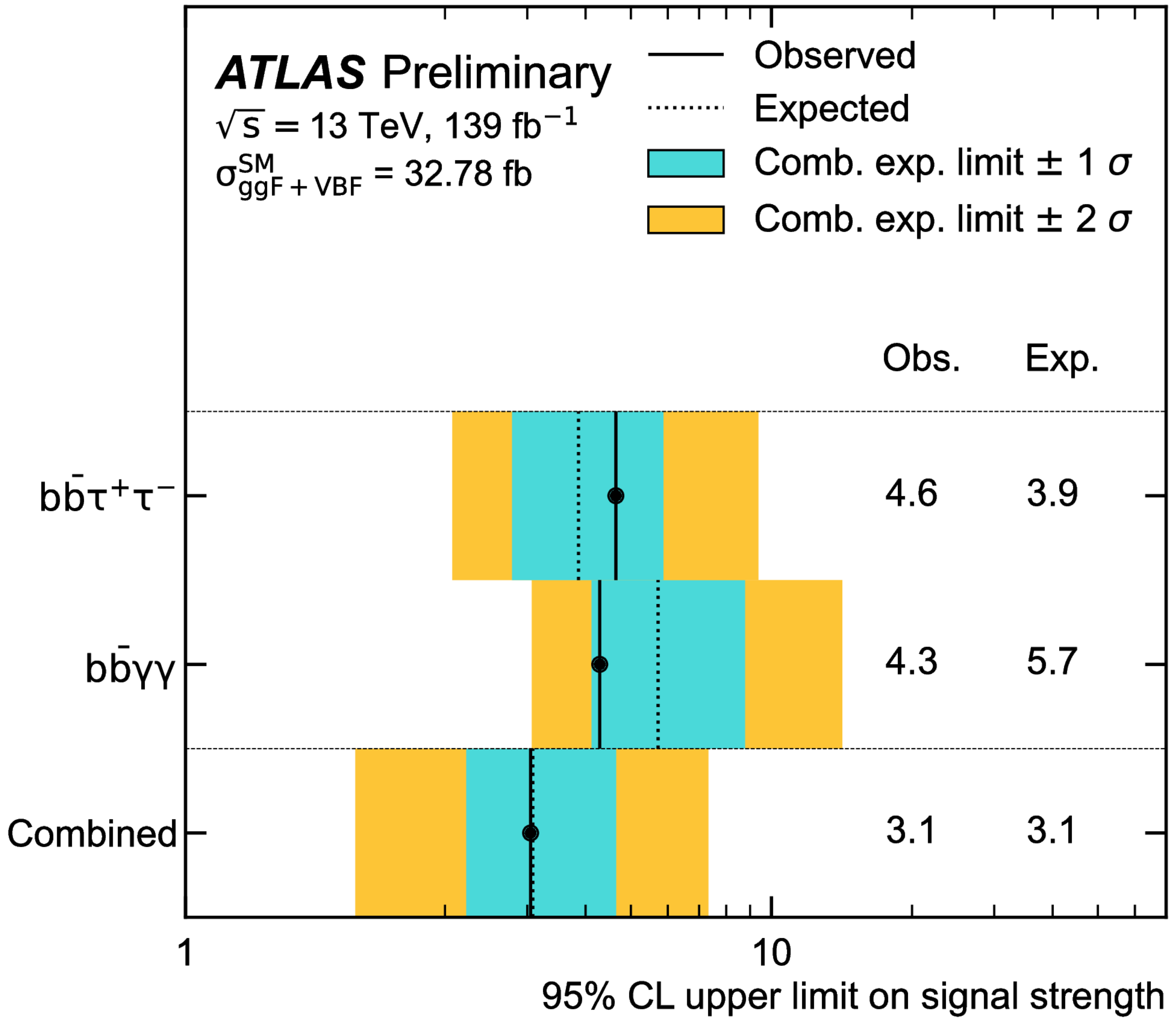


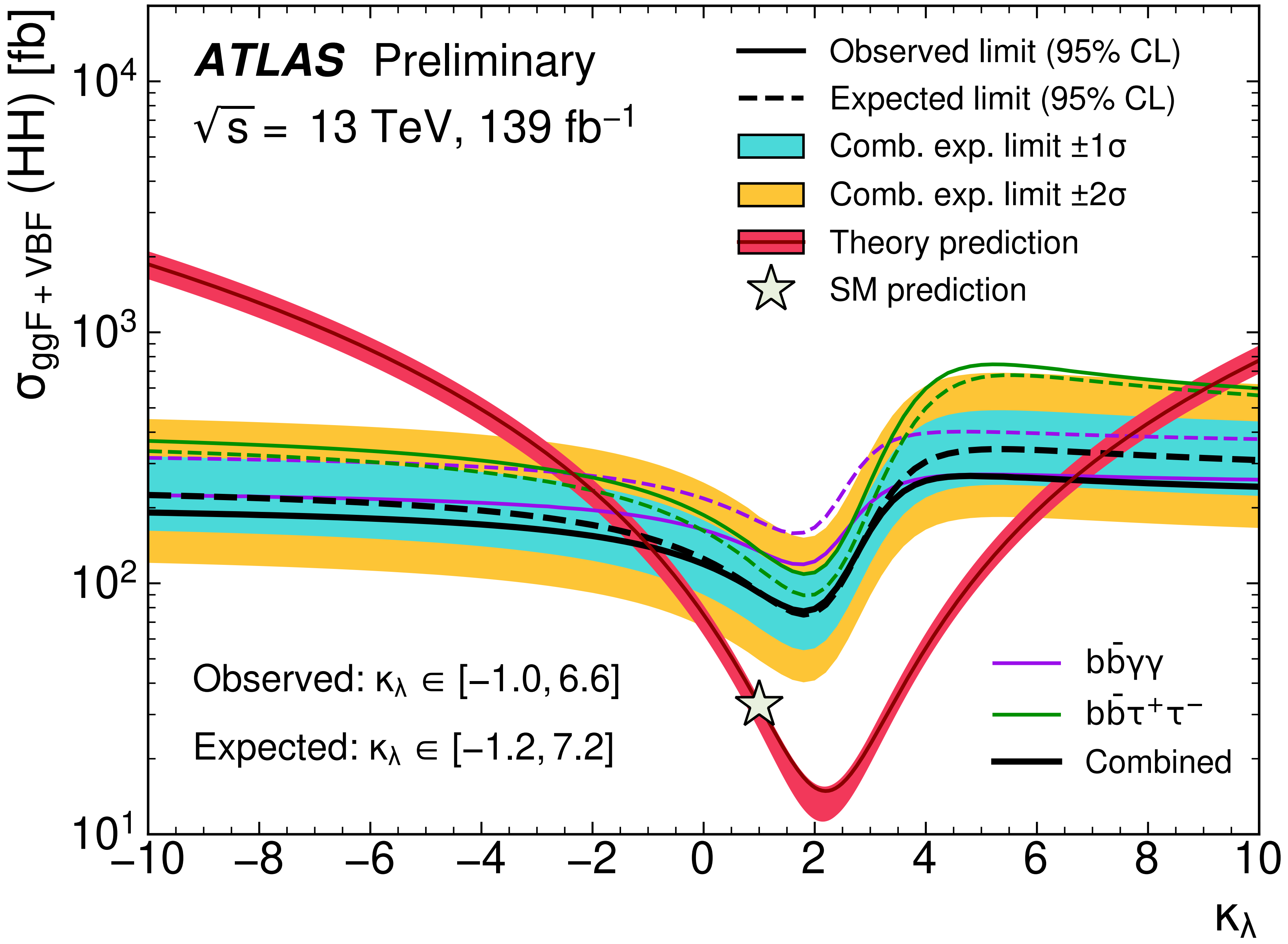
**Summary** in terms of limits on HH production

| exp. | WW $\gamma\gamma$ | bb $\gamma\gamma$ | bb $\tau\tau$ | bbWW | bbbb | bb4l |
|---|---|---|---|---|---|---|
| $\sigma \times \mathrm{Br}$ | 0.1 % | 0.26 % | 7% | 25% | 34% | 1.5%* |
| ATLAS | <747 (386) | **<4.1 (5.5)** | **<4.7 (3.9)** | - | <12.9 (21) | **-** |
| CMS | - | **<7.7 (5.2)** | **<3.3 (5.2)** | <79 (89) | **<3.7 (7.3)** | **30 (37)** |

*without the Z leptonic branching of 3.3% ~4 events expected at HL-LHC high s/b ~ 5

**Full data results in all channels are being finalised and combinations starting!**




**ATLAS Combination of $b\bar{b}\tau\tau$ and $b\bar{b}\gamma\gamma$**
**current best constraint**

Observed constraint on trilinear coupling at 95% CL:

$$-1.0 < \kappa_\lambda < 6.6$$

Expected range:

$$-1.2 < \kappa_\lambda < 7.2$$

Many interesting combinations to appear soon, stay tuned!

**As well as major and exciting challenge for Run 3 - and of course at HL-LHC!**

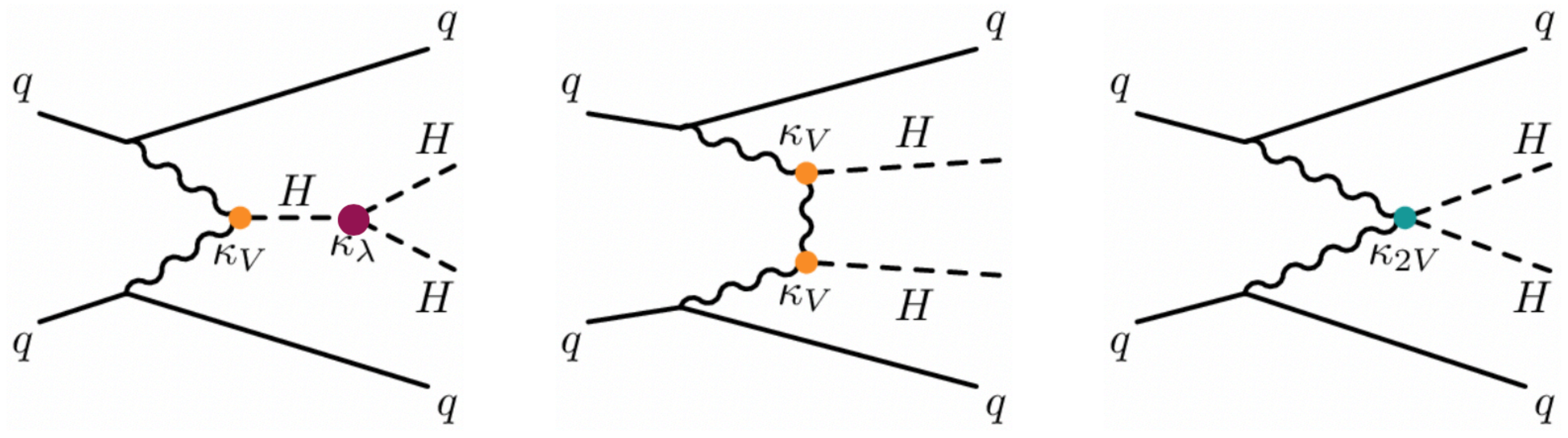
# Towards a Measurement of the Higgs Self Coupling



## Higgs pair production through Vector Boson Fusion

First specific VBF-HH search in the 4b final state, with as main interpretation a limit on the $c_{2V}$

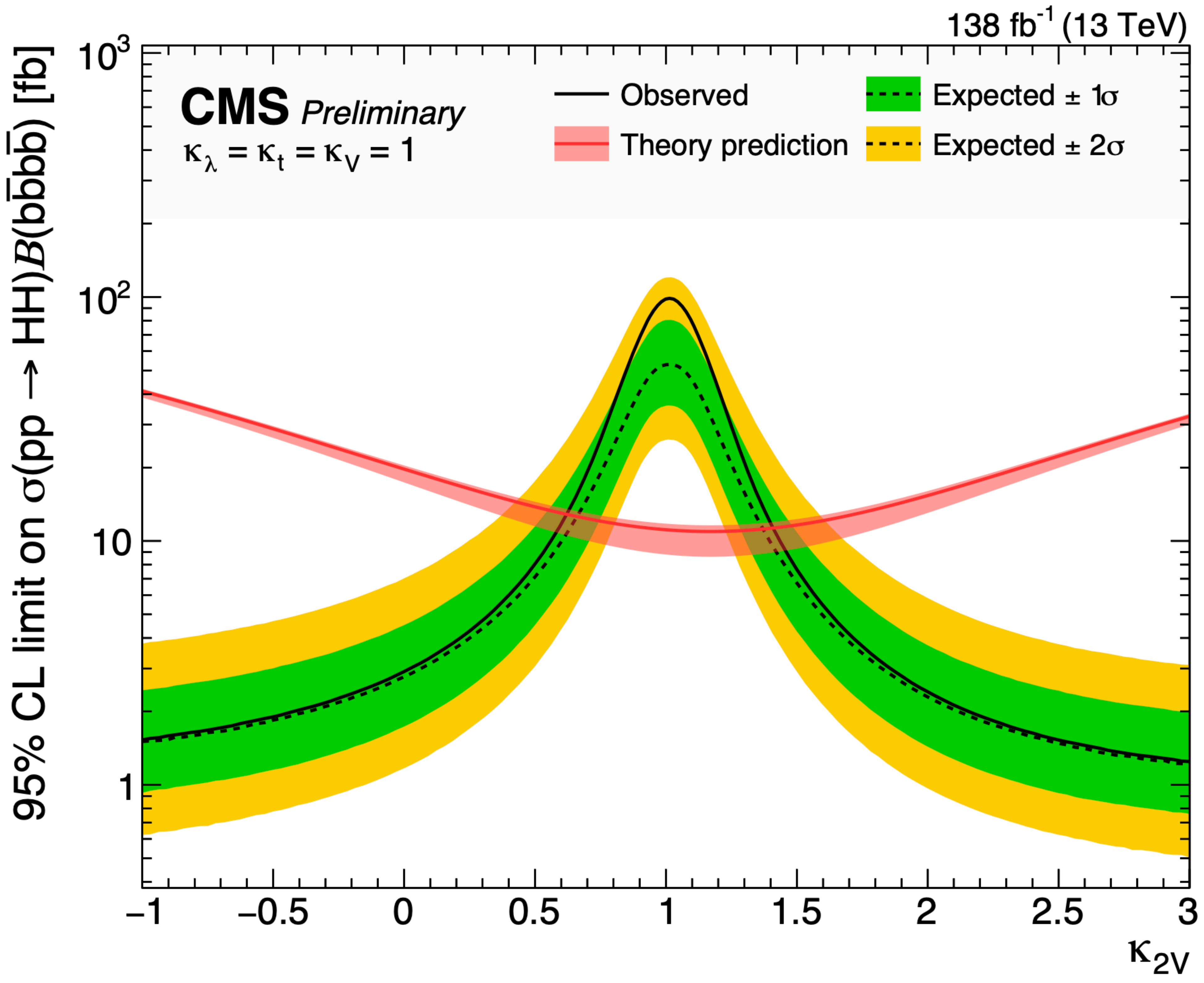
Bishara, Contino, Rojo




Strong variation of cross section (and acceptance) yield quite strong constraints at 95% CL:

$$0.62 < \kappa_{2v} < 1.41$$

**Excludes $\kappa_{2V} = 0$ at 95% CL!**




Uses the latest N3LO-QCD estimate of the VBF-HH cross section!

F. Dreyer and A. Karlberg

# Indirect constraints on Higgs Self Coupling

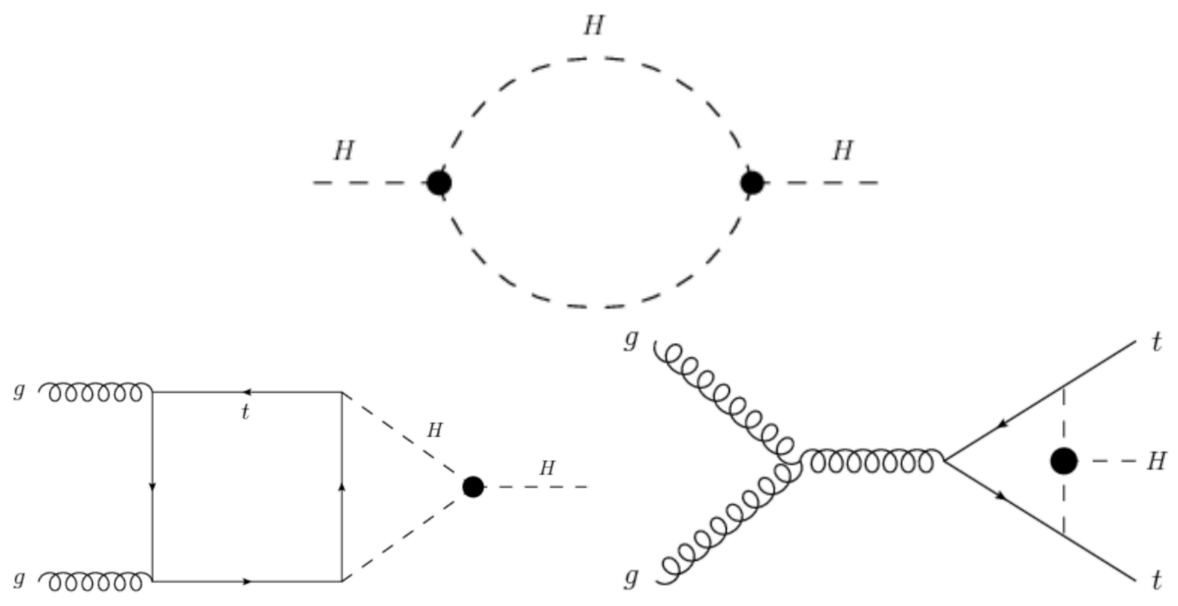


ATLAS-CONF-2019-049

FTR-2018-020

## Indirect constraints from combined STXS

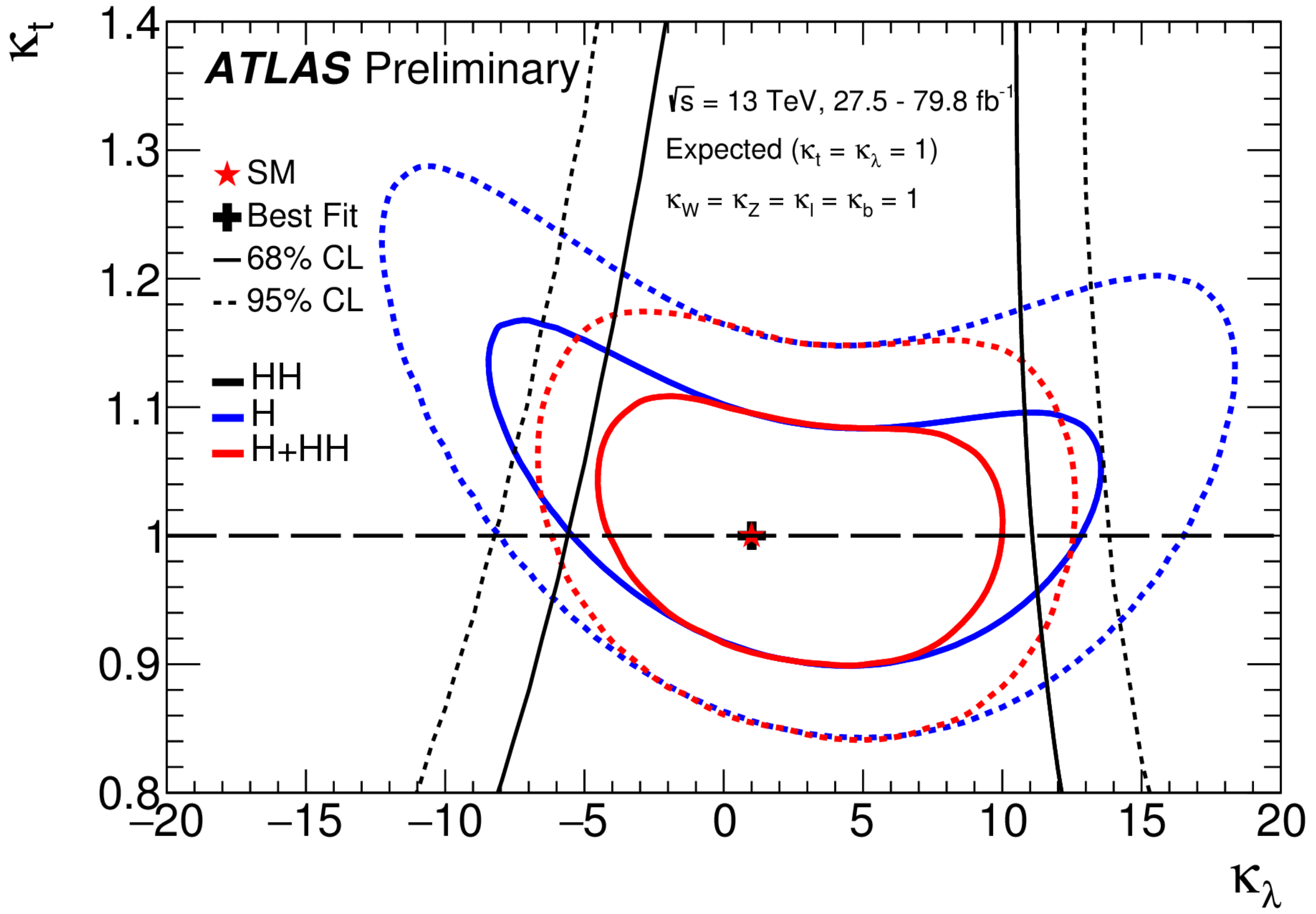
Combination with ATLAS STXSs




- Several production processes (ggF, VBF, VH, tHj)
- Several decay processes (diphoton, ZZ, yy)
- Trilinear coupling on wave function renormalisation

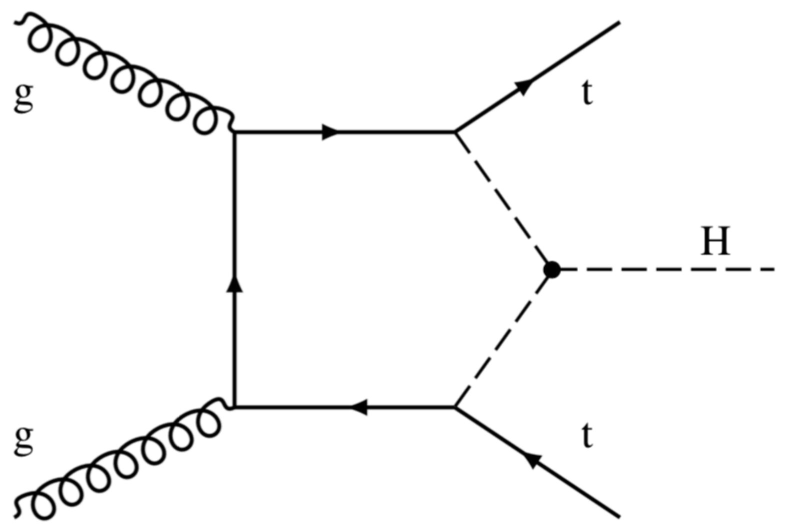
Direct/Indirect currently comparable, direct HH searches will dominate at higher luminosities, but complementarity still necessary to fix $\kappa_t$

$$-2.3 < \kappa_\lambda < 10.3$$

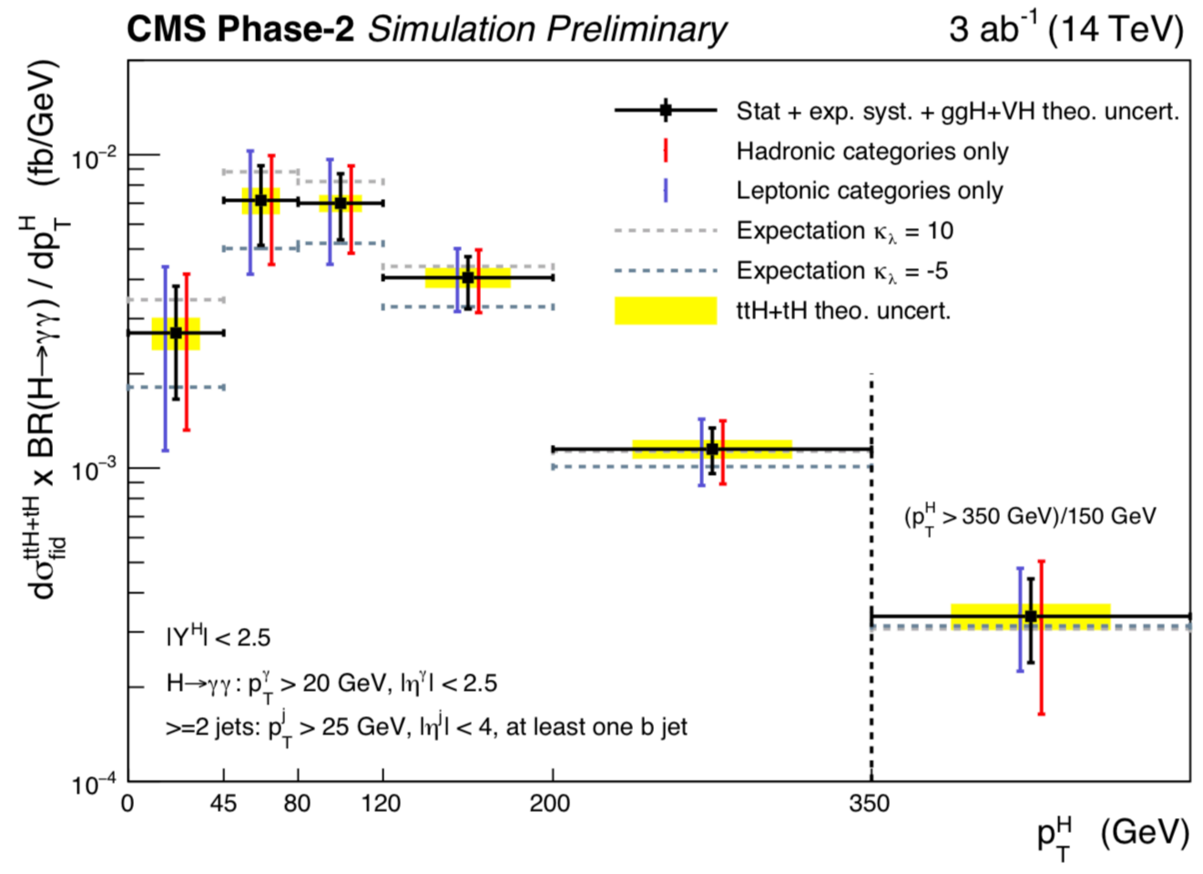



## Indirect constraints from differential measurements (e.g. ttH)

ttH Process (with subsequent decay to diphoton)




$$-4.1 < \kappa_\lambda < 14.1$$




Possible to disentangle effect of trilinear from other coupling modifications from the differential ttH measurements!

## Global fit

S. di Vita, C. Grojean et al.

In a global EFT Flat directions exist in the single-Higgs production (including all relevant operators) and the HH results are necessary to resolve them.

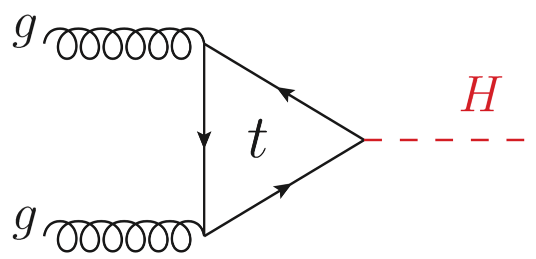
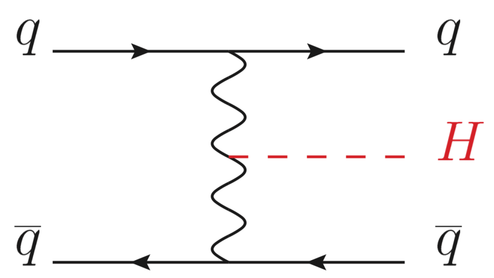
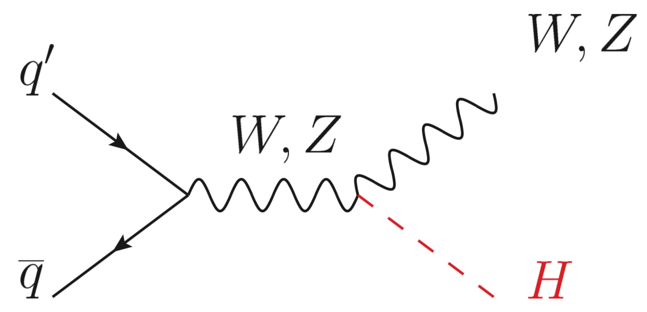
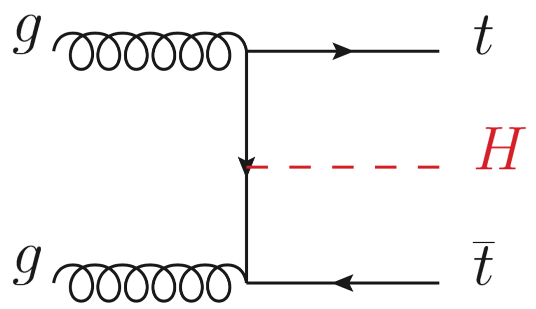
However, the inclusion of single-H differential measurements does not seem improve greatly the trilinear measurement with the full statistics.

# 5.- What have we learned?

# Nano Overview of Main Higgs Analyses at (HL) LHC

Most channels already covered at the Run 2 with only 5% (~150 fb-1) of full HL-LHC dataset!



| | Channel categories | Br | ggF   ~8 M vets produced | VBF   ~600 k vets produced | VH   ~400 k vets produced | ttH   ~80 k evts produced |
|---|---|---|---|---|---|---|
| | Cross Section 13 TeV (8 TeV) | | 48.6 (21.4) pb* | 3.8 (1.6) pb | 2.3 (1.1) pb | 0.5 (0.1) pb |
| Observed modes | γγ | 0.2 % | ✓ | ✓ | ✓ | ✓ |
| | ZZ | 3% | ✓ | ✓ | ✓ | ✓ |
| | WW | 22% | ✓ | ✓ | ✓ | ✓ |
| | ττ | 6.3 % | ✓ | ✓ | ✓ | ✓ |
| | bb | 55% | ✓ | ✓ | ✓ | ✓ |
| Remaining to be observed | Zγ and γγ* | 0.2 % | ✓ | ✓ | ✓ | ✓ |
| | μμ | 0.02 % | ✓ | ✓ | ✓ | ✓ |
| Limits | Invisible | 0.1 % | ✓ (monojet) | ✓ | ✓ | ✓ |

*N3LO

# Where do we Stand in Coupling Properties Measurements?



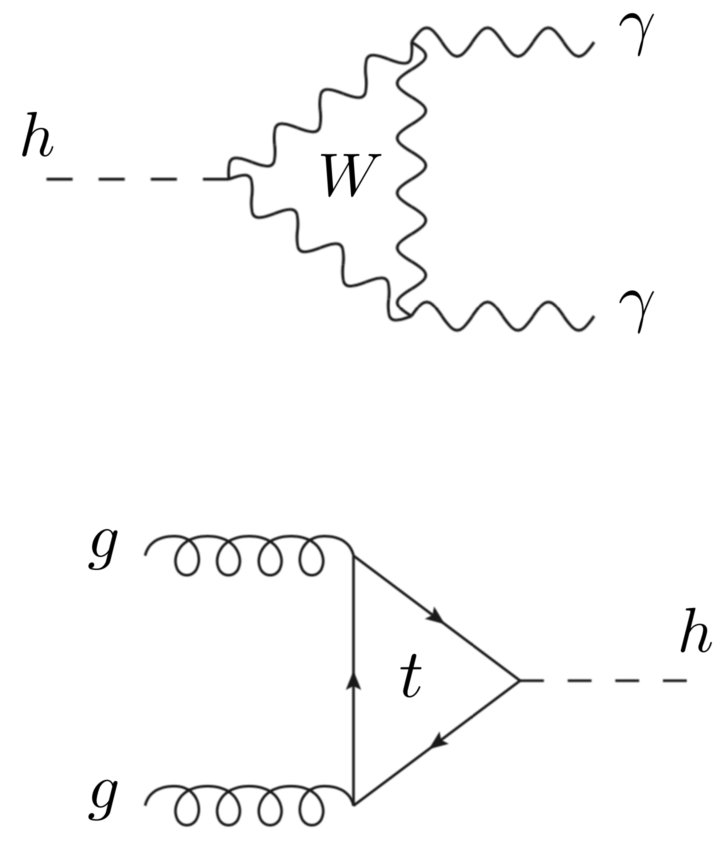
| | ATLAS - CMS Run 1 combination | ATLAS Run 2 | CMS Run 2 | Current precision |
|---|---|---|---|---|
| $\kappa_\gamma$ | 13% | $1.04 \pm 0.06$ | $1.01^{+0.09}_{-0.14}$ | 6% |
| $\kappa_g$ | 14% | $0.92^{+0.07}_{-0.06}$ | $1.16^{+0.12}_{-0.11}$ | 7% |
| $\kappa_Z$ | 11% | $0.99 \pm 0.06$ | $0.96 \pm 0.07$ | 6% |
| $\kappa_W$ | 11% | $1.06 \pm 0.06$ | $-1.11^{+0.14}_{-0.09}$ | 5% |
| $\kappa_t$ | 30% | $0.92 \pm 0.10$ | $1.01 \pm 0.11$ | 11% |
| $\kappa_b$ | 26% | $0.87 \pm 0.11$ | $1.18^{+0.19}_{-0.27}$ | 11% |
| $\kappa_\tau$ | 15% | $0.92 \pm 0.07$ | $0.94 \pm 0.12$ | 8% |

JHEP 08 (2016) 045

ATLAS-CONF-2021-53

CMS-PAS-HIG-19-005

**Probing new particles in the loops**




**Precision largely (but not fully) relying TH uncertainties!**

$$\sigma_{ggF} = 48.68 \pm 3.9\ (\text{scales})\ \pm 1.9\ (\text{PDF})\ \pm 2.6\ (\alpha_S)\ \ \text{Pb}$$

**Still 25 times more data and reduction of a factor of 3 uncertainty!**

Measurements here assume no BSM in Higgs width

# Modelling and predictions - an overarching question!



The dominant systematic uncertainties in a very large number of analysis: modelling and TH systematic uncertainties.

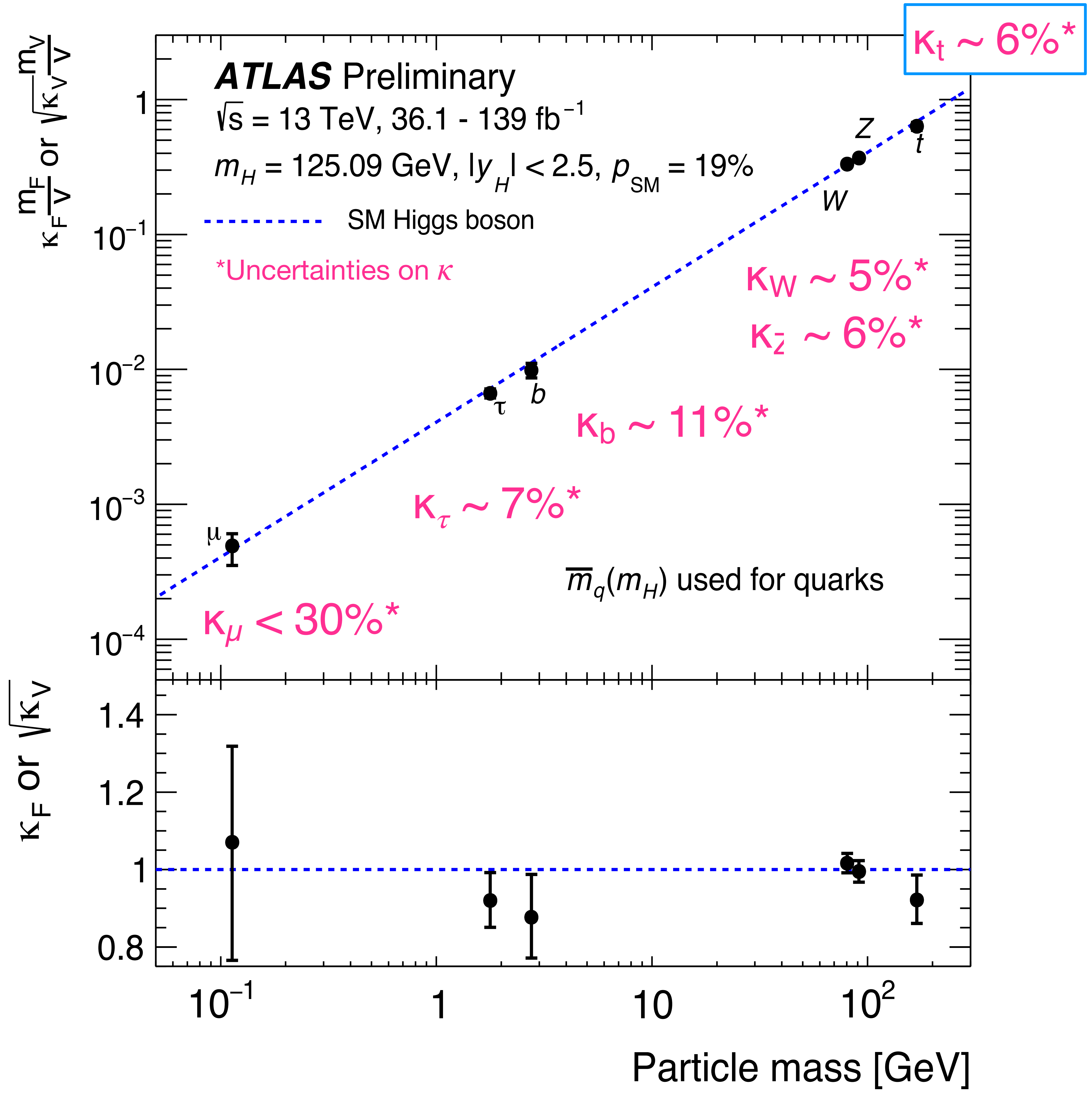
The level of precision reached so far **relies** on a number of **TH breakthroughs**

- The « Next-to… » revolutions, and novel tools for automated calculations at higher orders
- Reaching N3LO-QCD precision (ggF, VBF and VBF-HH)
- NNLO Monte Carlos (requiring NNLO-PS matching!)
- Up to N3LL resummation matched to fixed order
- IR and Colinear safe fast Jet reconstruction algorithms

These are one of the most important **pillars of precision at the LHC**, and Higgs physics in particular.

# Higgs Couplings Overview

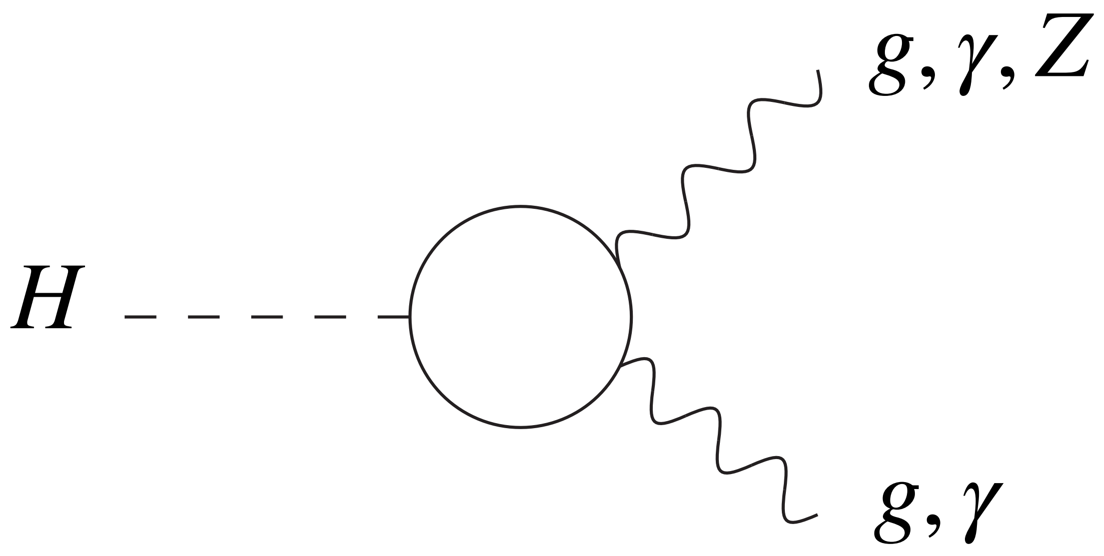





**Effective tree level couplings**

(assuming new particles neither in the decay nor in the loops)

**Effective loop couplings** (assuming $B_i = B_u = 0$)



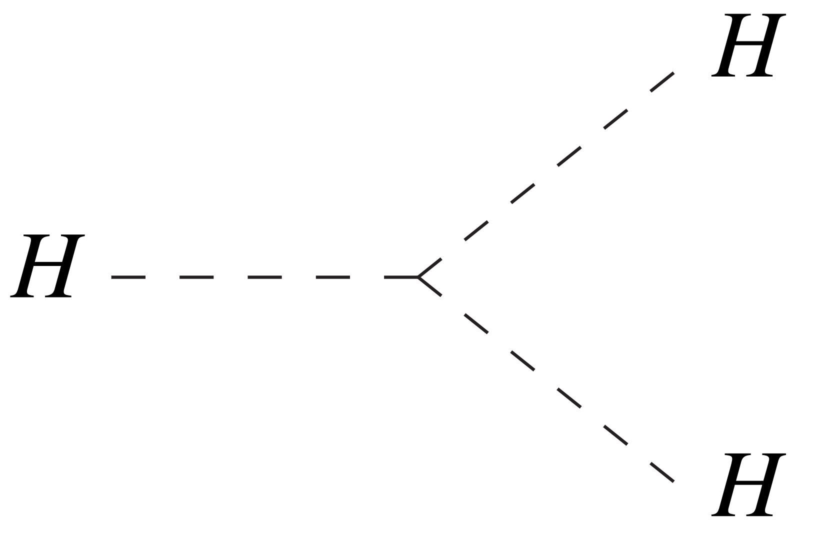

$\kappa_\gamma \sim 1.06 \pm 0.05$

$\kappa_g = 1.00 \pm 0.05$

$\kappa_{Z\gamma} = 1.43^{+0.31}_{-0.38}$

**Effective self coupling**

$-1.0 < \kappa_\lambda < 6.6$ @95% CL




**Invisible branching fraction**

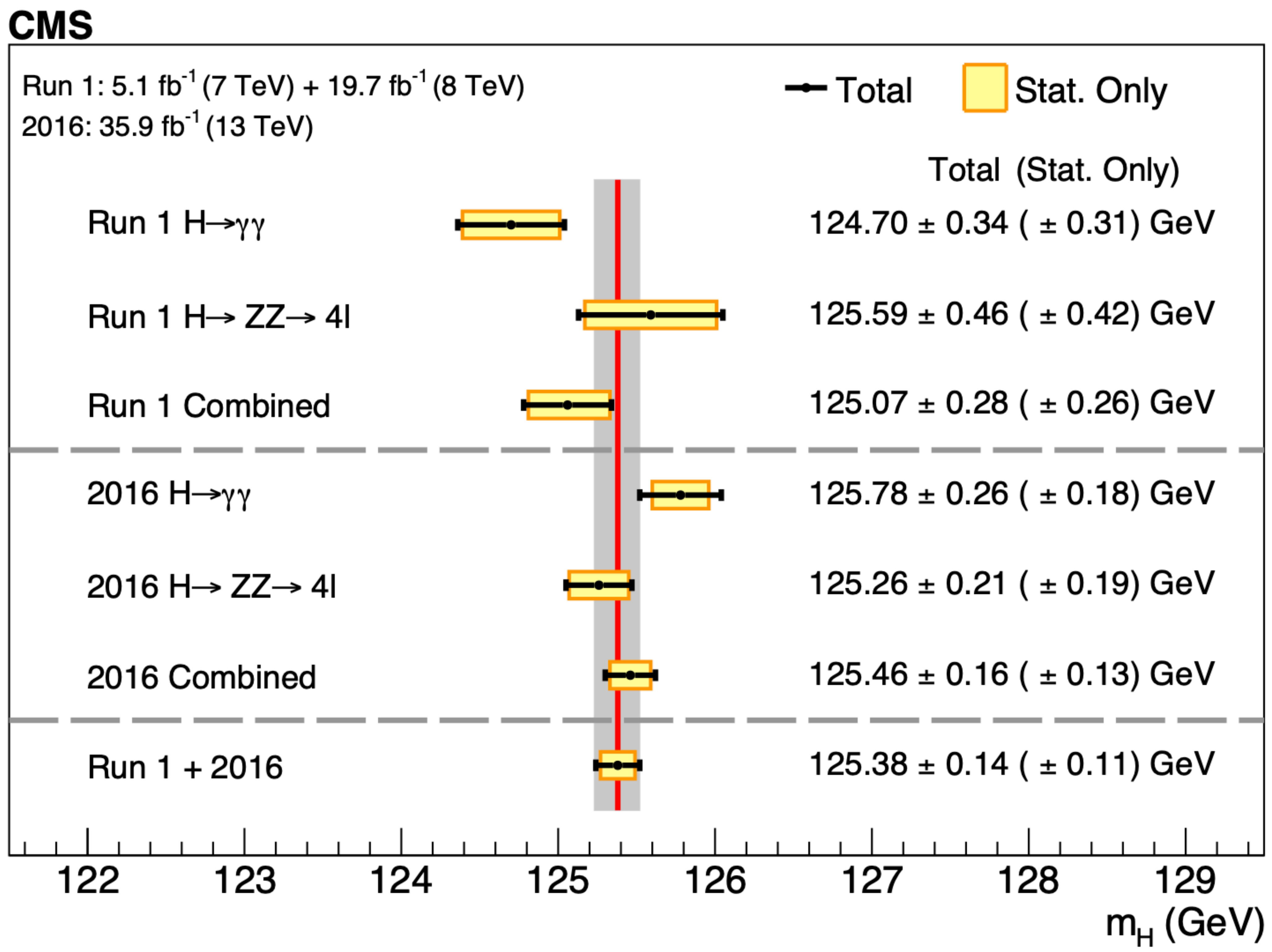
$Br_{inv} < 11\%$ @95% CL

The larger and excellent Run 2 data sample brought many more opportunities…

# Measurement of the Higgs Boson Mass



Latest (and most precise) measurement from CMS:




## Higgs boson mass measurement

- Measurement done exclusively in the diphoton and 4-leptons channel.

- Measurement precision dominated by statistics and **experimental** systematic uncertainties!

- Requires specific and most precise calibration!

Precision is driven by **statistics** but photon, electron and muon scale and resolution systematics will soon become limiting!

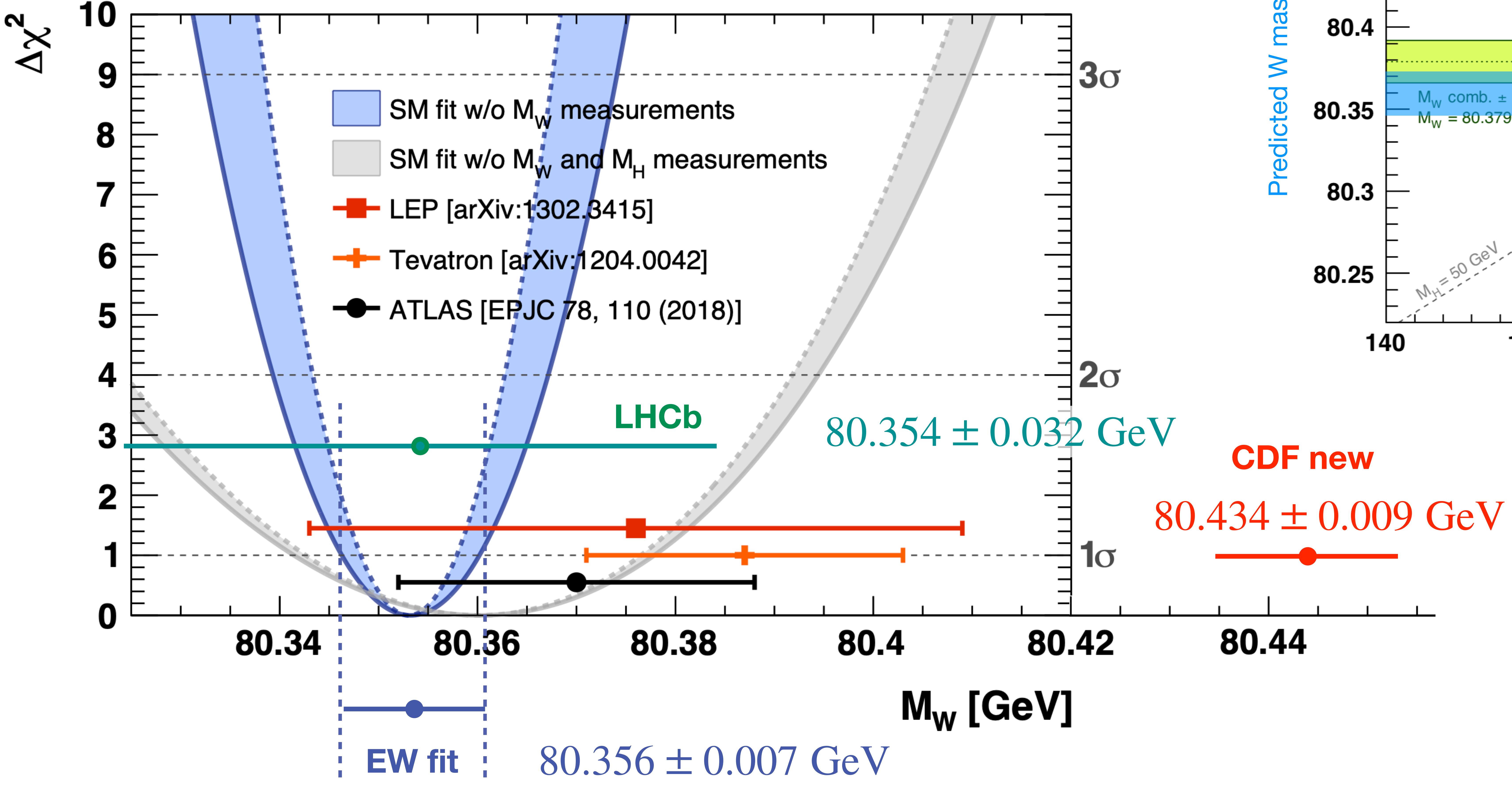
Precision mass measurements could also lead to constraints on the Higgs width through mass shifts from the interference between signal and continuum in the diphoton channel (see backup)

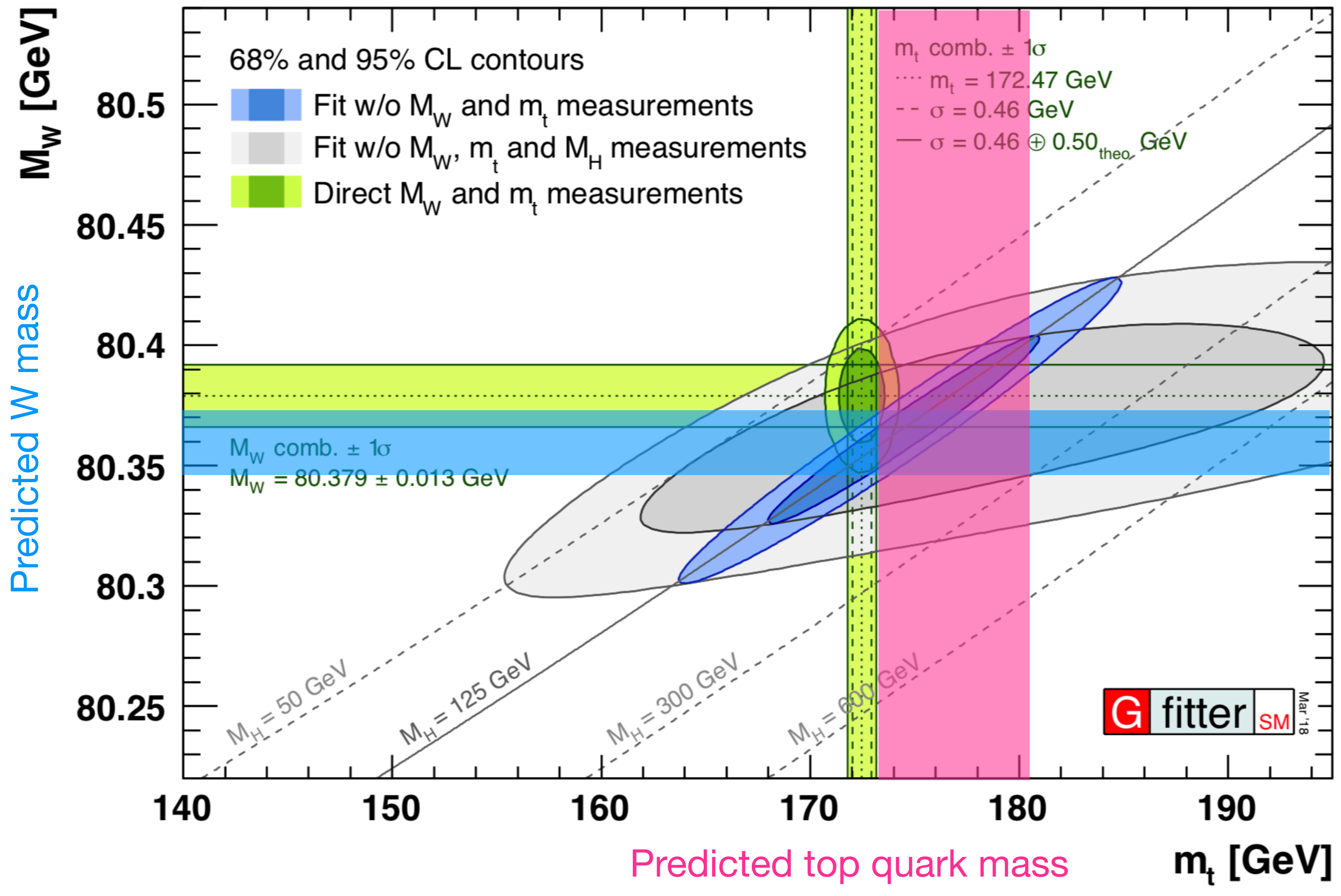
# What have we Learned from Knowing its Mass?



**Precision measurements allow to make predictions!!**

**Assuming the SM,** the top quark mass and Higgs boson mass were (approximately) known before being discovered!




**The knowledge of the Higgs mass has large impact on the precision of indirect measurements!**

The current level of precision on the Higgs mass has little impact on this.

# What have we Learned from Knowing its Mass?



Running of the Higgs self coupling, **assuming SM** only at high scale

$$V(\phi) = -m^2\varphi^\dagger\varphi + \lambda(\varphi^\dagger\varphi)^2$$

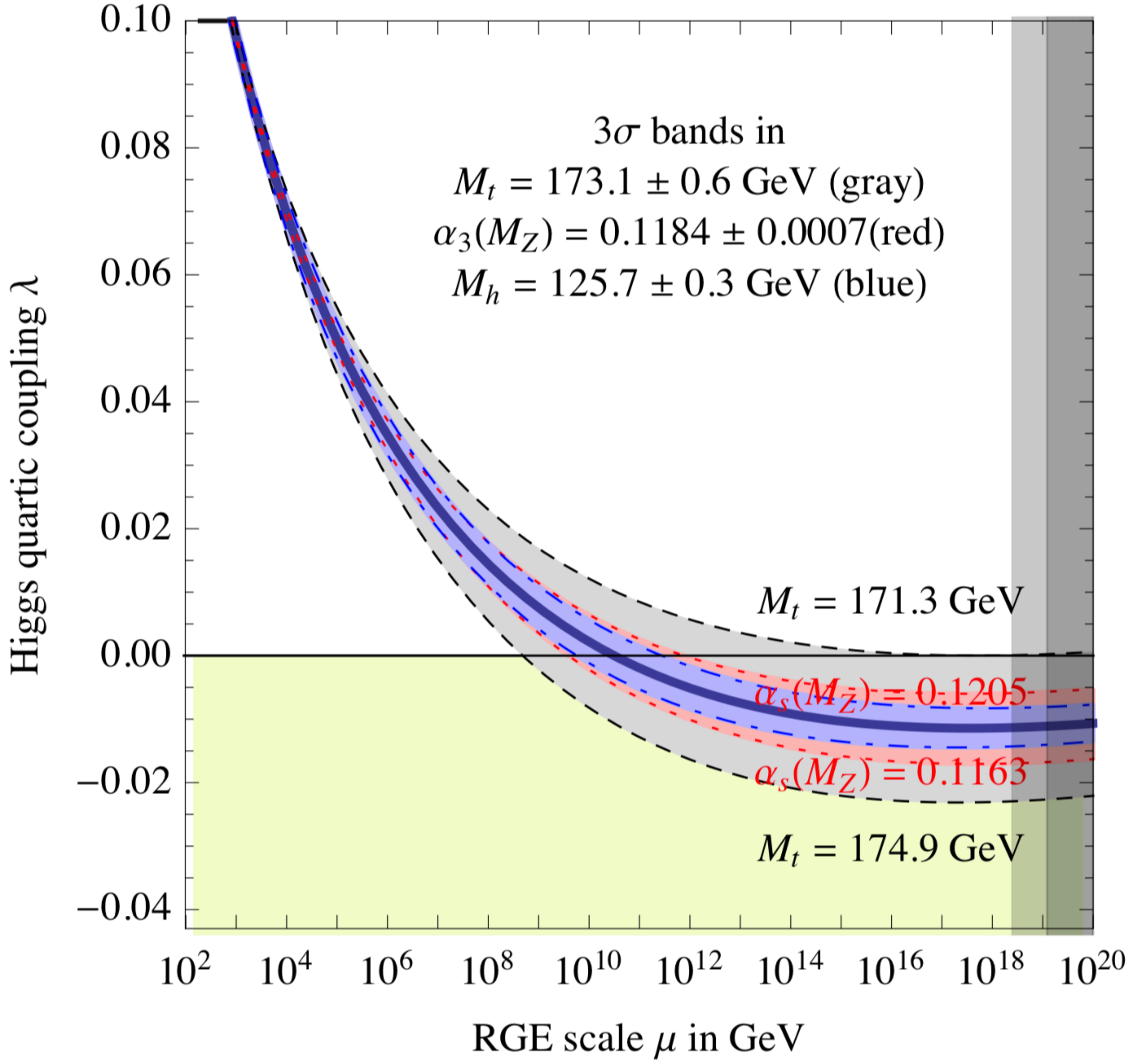
$$m_H = \sqrt{2\lambda}v$$

*With the discovery of the Higgs, for the first time in our history, we have a self-consistent theory that can be extrapolated to exponentially higher energies.*

*Nima Arkani Hamed*

**Vacuum (meta) stability**

Near vanishing coupling at the Planck scale




Interpretation more sensitive to precision on the **top quark** mass is more

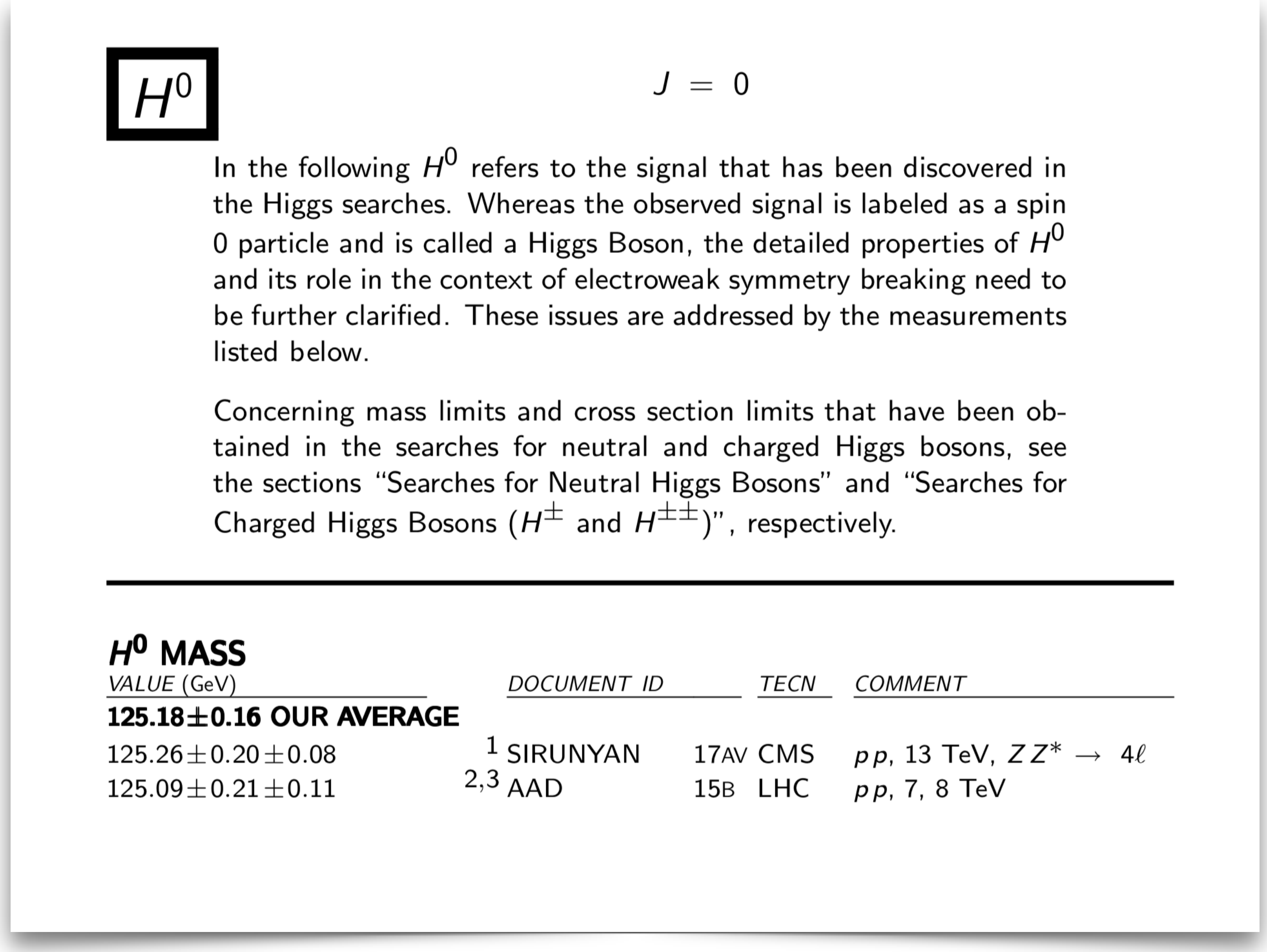
# Higgs Physics Broad Landscape



## Precision
- Mass and width
- Coupling properties
- Quantum numbers (Spin, CP)
- Differential cross sections
- STXS
- Off Shell couplings and width
- Interferometry

## Rare Production
- tH (single top and Higgs)
- FCNC top decays
- Di-Higgs production (and trilinear couplings)

## The Higgs particle



$H^0$ $J = 0$

In the following $H^0$ refers to the signal that has been discovered in the Higgs searches. Whereas the observed signal is labeled as a spin 0 particle and is called a Higgs Boson, the detailed properties of $H^0$ and its role in the context of electroweak symmetry breaking need to be further clarified. These issues are addressed by the measurements listed below.

Concerning mass limits and cross section limits that have been obtained in the searches for neutral and charged Higgs bosons, see the sections "Searches for Neutral Higgs Bosons" and "Searches for Charged Higgs Bosons ($H^{\pm}$ and $H^{\pm\pm}$)", respectively.

**$H^0$ MASS**

| VALUE (GeV) | DOCUMENT ID | | TECN | COMMENT |
|---|---|---|---|---|
| **125.18±0.16 OUR AVERAGE** | | | | |
| 125.26±0.20±0.08 | [1] SIRUNYAN | 17AV | CMS | $pp$, 13 TeV, $ZZ^* \to 4\ell$ |
| 125.09±0.21±0.11 | [2,3] AAD | 15B | LHC | $pp$, 7, 8 TeV |

PDG Listing entry for the Higgs boson

## Rare decays
- $Z\gamma$, $\gamma\gamma*$, Muons $\mu^+\mu^-$
- LFV $\mu\tau$, $e\tau$
- $J/\Psi\gamma$, $Z\Upsilon$, WD, $\phi\gamma$, $\rho\gamma$

## Non minimal Higgs sectors
- 2 HDM searches
- MSSM, NMSSM searches
- Doubly charged Higgs bosons

## Tool for discovery
- Portal to DM (invisible Higgs)
- Portal to hidden sectors
- Portal to BSM physics with $H^0$ in the final state ($ZH^0$, $WH^0$, $H^0H^0$)

# Conclusions and Outlook



CERN 10 years HIGGS boson discovery

- The discovery of the Higgs boson 10 years ago at LHC **Run 1** firmly established the observation of the coupling of the Higgs boson to all gauge bosons (W and Z, g, $\gamma$) and has widely open the field of Higgs physics!

- At **Run 2**, with the high quality and well calibrated large dataset, new ideas, ancillary measurements and remarkable progress in theory predictions and simulations, firmly establishing the coupling of the Higgs boson to fermions (t, b, $\tau$)!

- With only 5% of the entire foreseen LHC project, the achievements reached well beyond expectations with first evidences in rare decay channels $H \to \mu\mu$, $H \to \gamma\gamma^*$ and $H \to Z\gamma$ and very strong limits on the invisible branching fractions, on the total width through Off shell couplings and on CP properties of Higgs couplings to vector bosons and fermions!

- The main couplings of the Higgs boson have been measured to an unprecedented level of precision (5-10%) and are fully compatible with the Higgs boson of the Standard Model!

- This has greatly broaden the landscape of Higgs physics opportunities at LHC and brought **exciting prospects for Higgs physics at Run 3 and HL-LHC!**

**Don't miss Maria's lecture tomorrow!!**