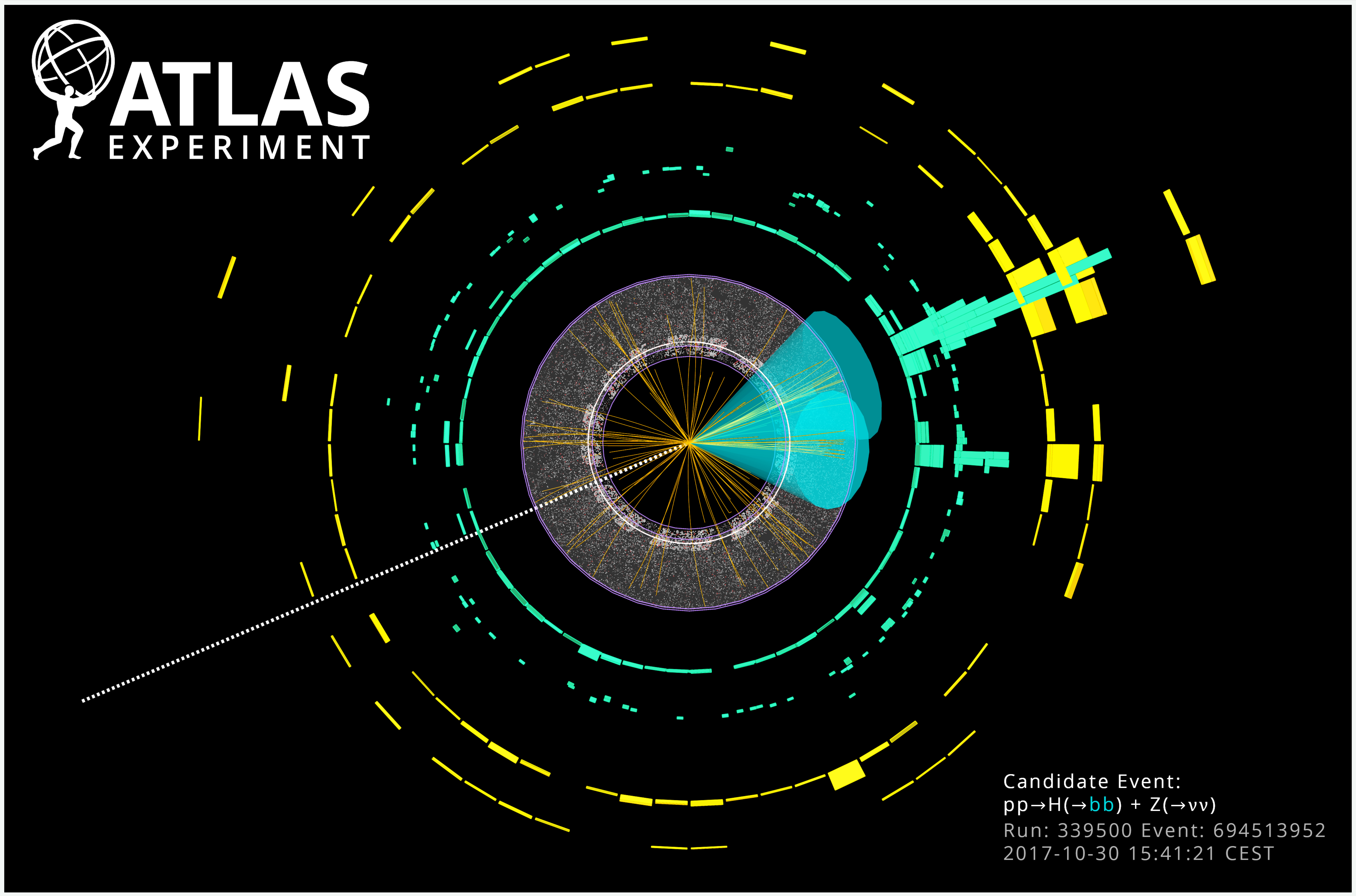
Challenges and Opportunities at the HL-LHC - II



Higgs decaying to b-quarks candidate event in association with a $Z \to \nu\bar{\nu}$

Marumi Kado

Università and INFN, La Sapienza, Rome and LAL IN2P3, Orsay

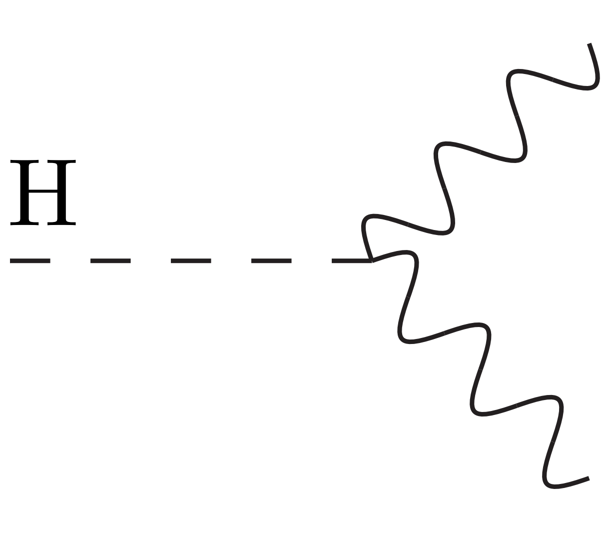
Spaatind 2020, Nordic Conference on Particle Physics - Skeikampen - Norway

The Higgs Boson

All the couplings of the Higgs boson to Standard Model particles (except itself) known well before the discovery…

However, still many more questions!

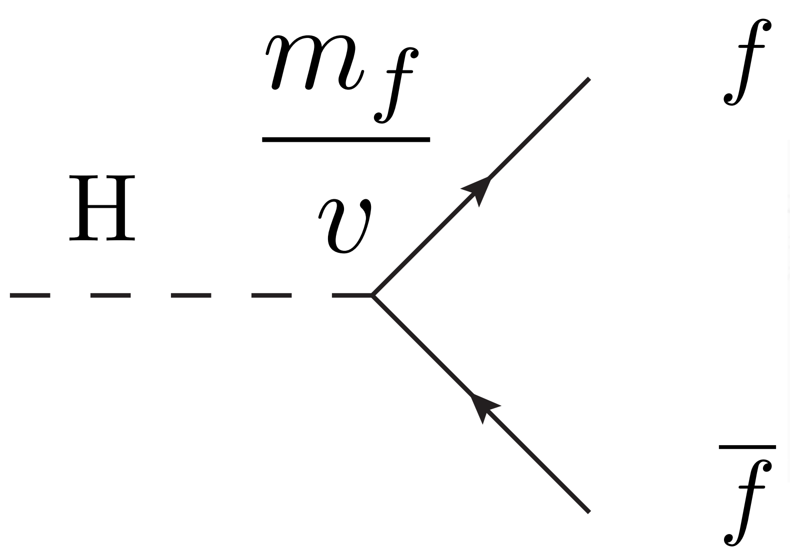
Making the weak interaction short range



$$\frac{2m_V^2}{v}$$

$$|D_\mu \phi|^2$$

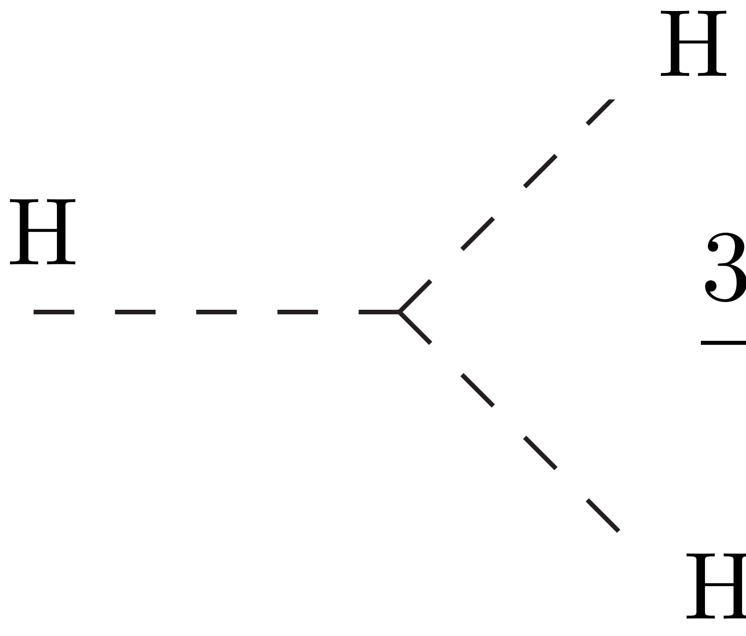
Fundamental non gauge couplings (never seen before)



$$\frac{m_f}{v}$$

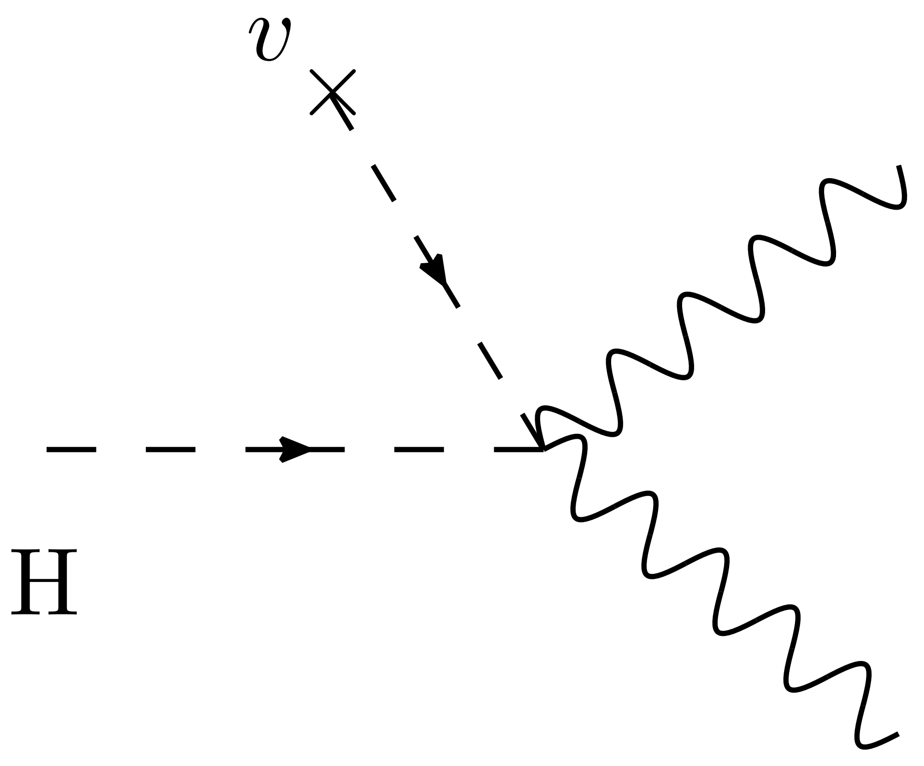
$$\bar{\psi}_i y_{ij} \psi_j \phi$$

Self interactions of a fundamental scalar (never seen before)



$$\frac{3m_H^2}{v}$$

$$V(\phi)$$

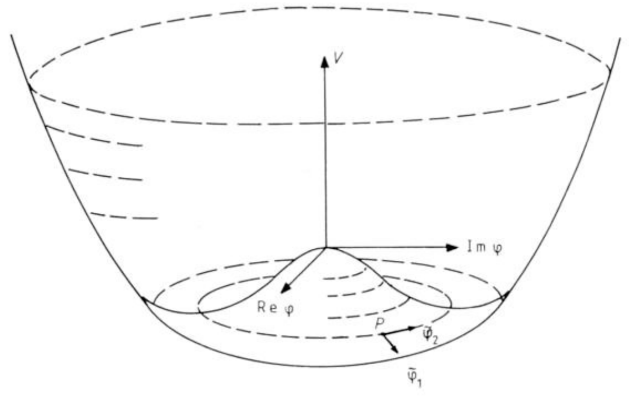


This term could not exist without a vev

$$vHV^\mu V_\mu$$

Proof of condensate !

- Unsolved question of flavour Hierarchy
- Couplings to top critical for the stability of the vacuum
- u and d Yukawa decide the stability of nuclei (from C. Grojean)



- No dynamical explanation in the SM for the shape of the potential
- The self coupling and shape of the potential critical to the EW transition

Measuring Higgs properties is a formidable potential window to physics beyond the Standard Model

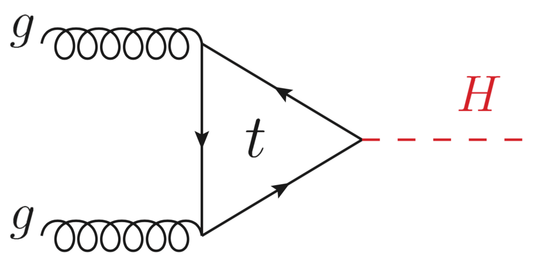
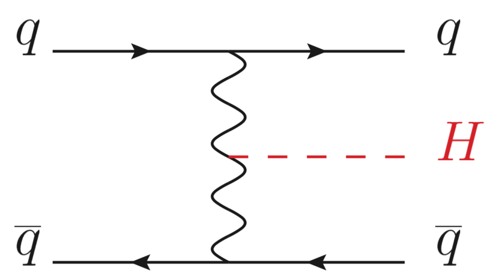
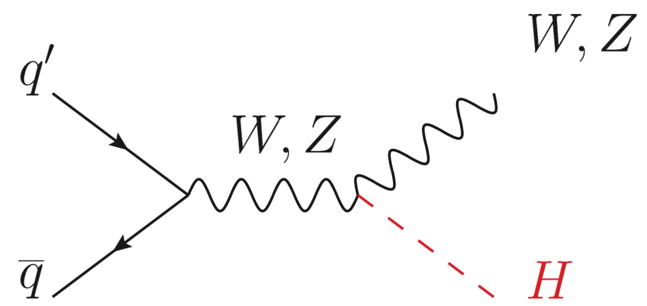
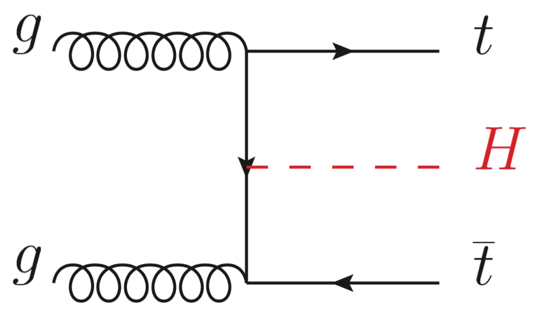
Higgs Physics at the LHC

HL-LHC is a Higgs factory ~160 M Higgs events and ~100 k HH

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

Nano Overview of Main Higgs Analyses at (HL) LHC

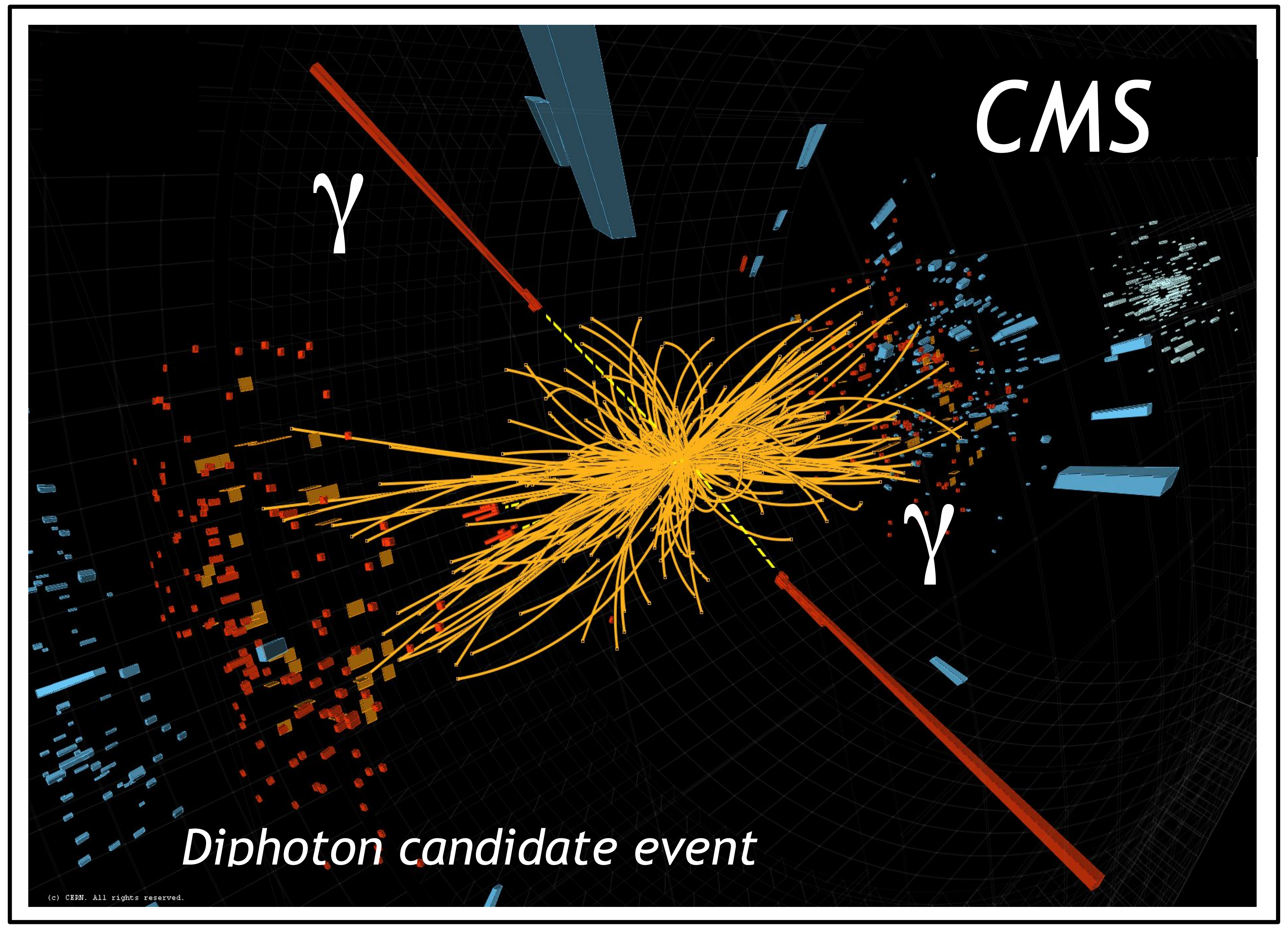
Most channels already covered at the Run 2 with only 3% (80 fb-1) of full HL-LHC dataset!

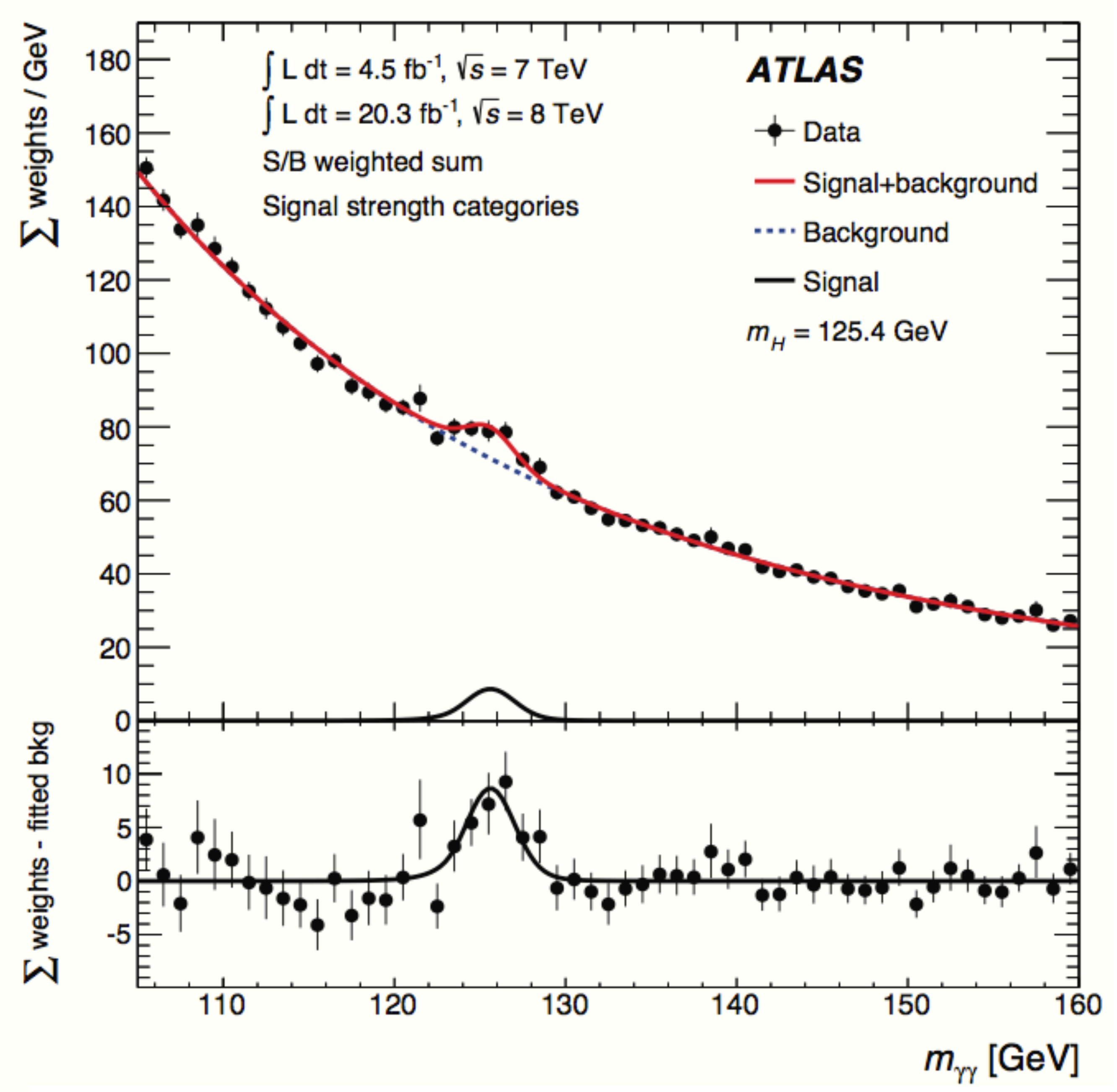
	Channel categories	Br	ggF  ~4 M vets produced	VBF  ~300 k vets produced	VH  ~200 k vets produced	ttH  ~40 k evts produced
	Cross Section 13 TeV (8 TeV)		48.6 (21.4) pb*	3.8 (1.6) pb	2.3 (1.1) pb	0.5 (0.1) pb
Observed modes	γγ	0.2 %	✓	✓	✓	✓
	ZZ	3 %	✓	✓	✓	✓
	WW	22 %	✓	✓	✓	✓
	ττ	6.3 %	✓	✓	✓	✓
	bb	55 %	✓	✓	✓	✓
Remaining to be observed	Zγ and γγ*	0.2 %	✓	✓	✓	✓
	μμ	0.02 %	✓	✓	✓	✓
Limits	Invisible	0.1 %	✓ (monojet)	✓	✓	✓

*N3LO

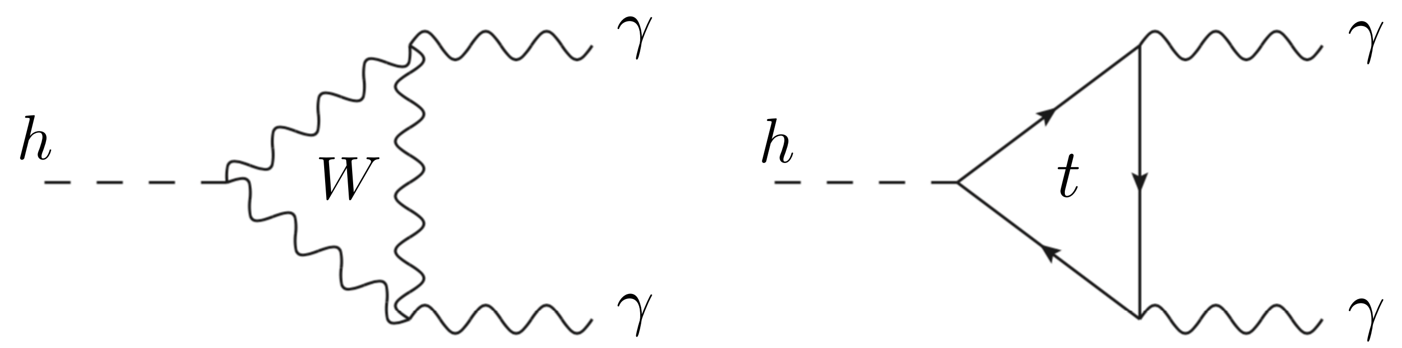
The Discovery Channels

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





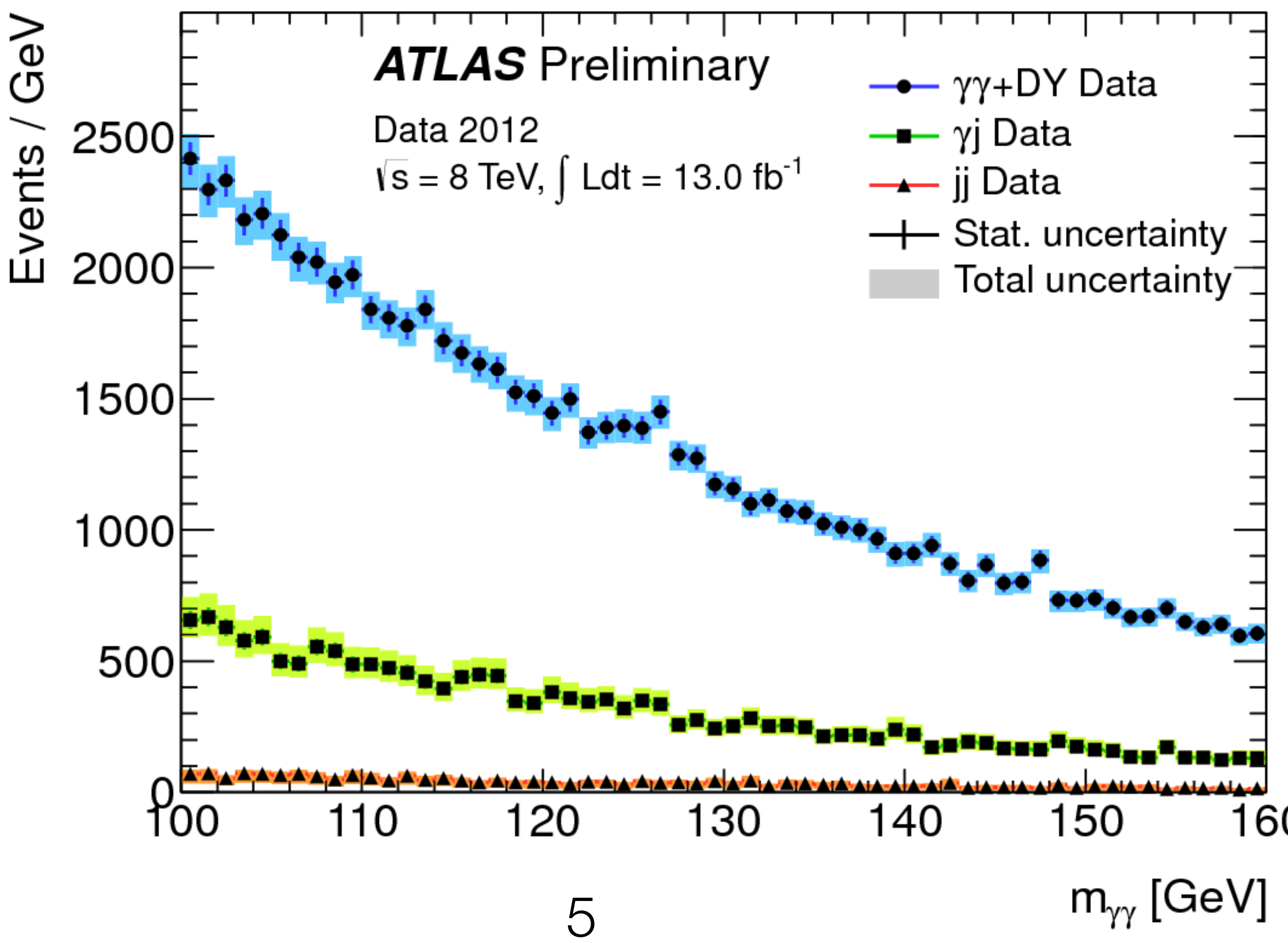
- Main production and decay processes occur through loops :

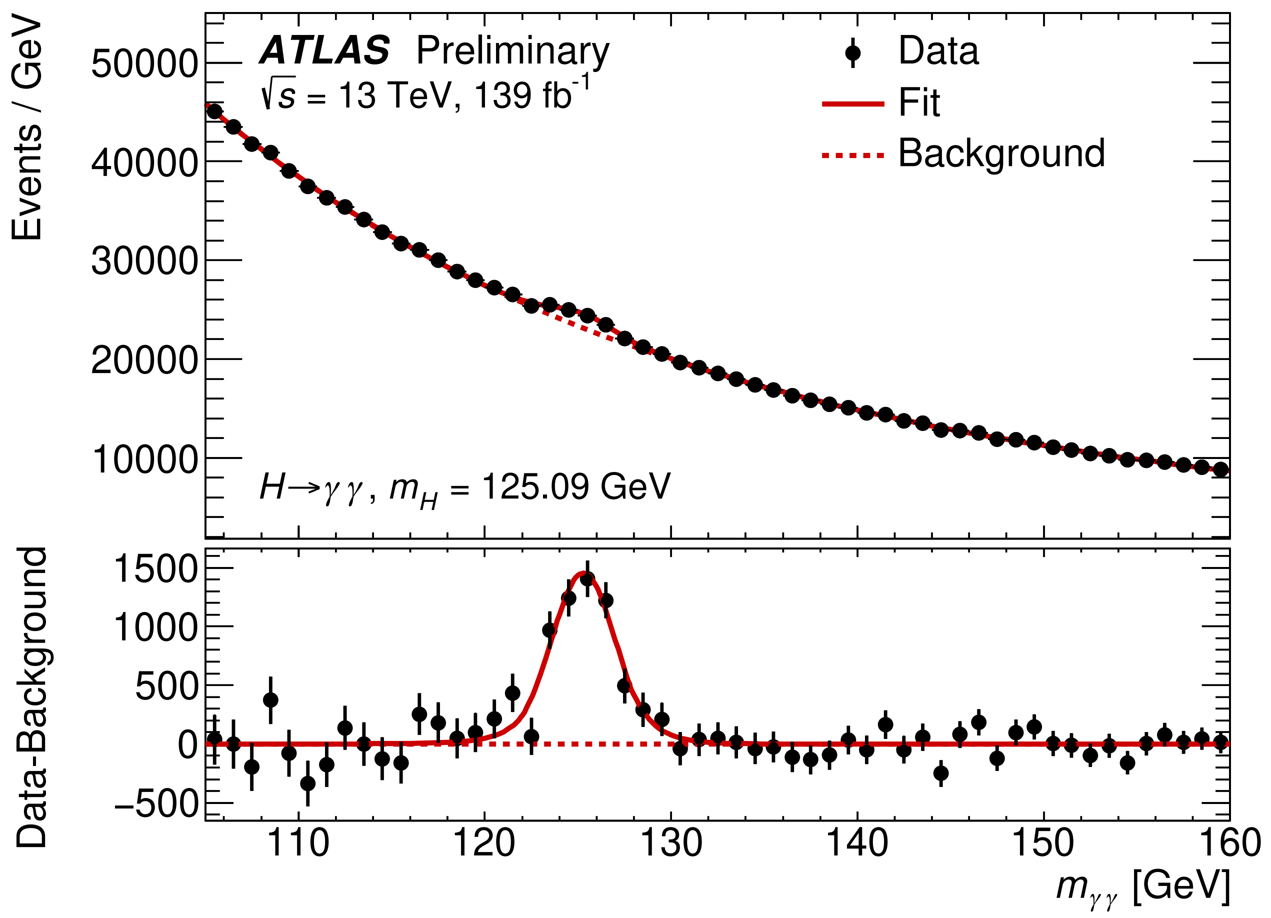


Excellent probe for new physics !

- High mass resolution channel O(1%) allowing data driven estimate of background in the sidebands.
- If observed implies that it does not originate from spin 1 : Landau-Yang theorem

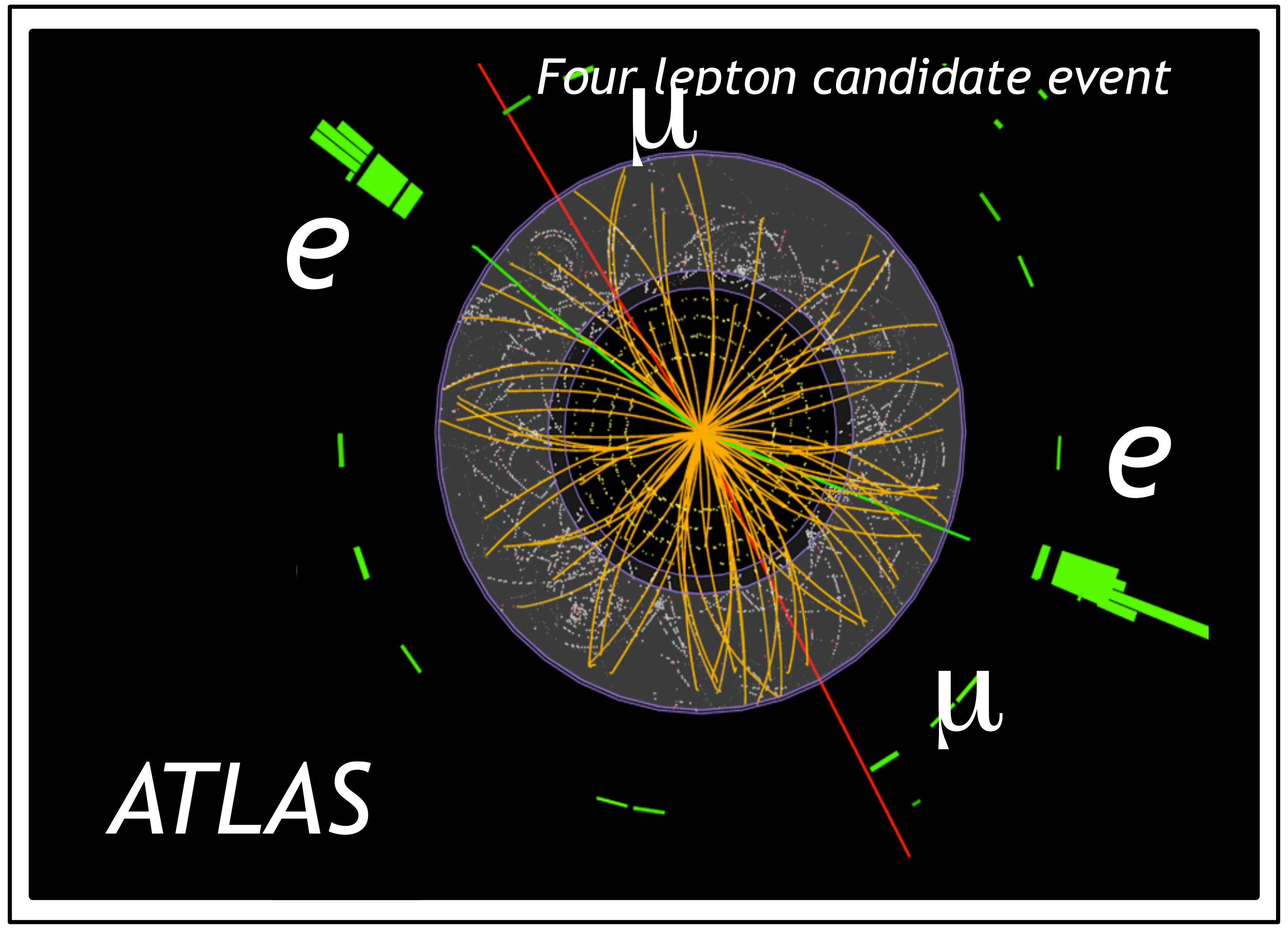
- Low signal over background but overall relatively high statistics of signal (O(300) at Run 1)
- Very simple selection cuts. The essence of the channel relies on the **quality of the detector response** and the **reconstruction**.
- Largest reducible background comes from jets! With another spin-0 particle decaying to a pair of photons: the pi0.

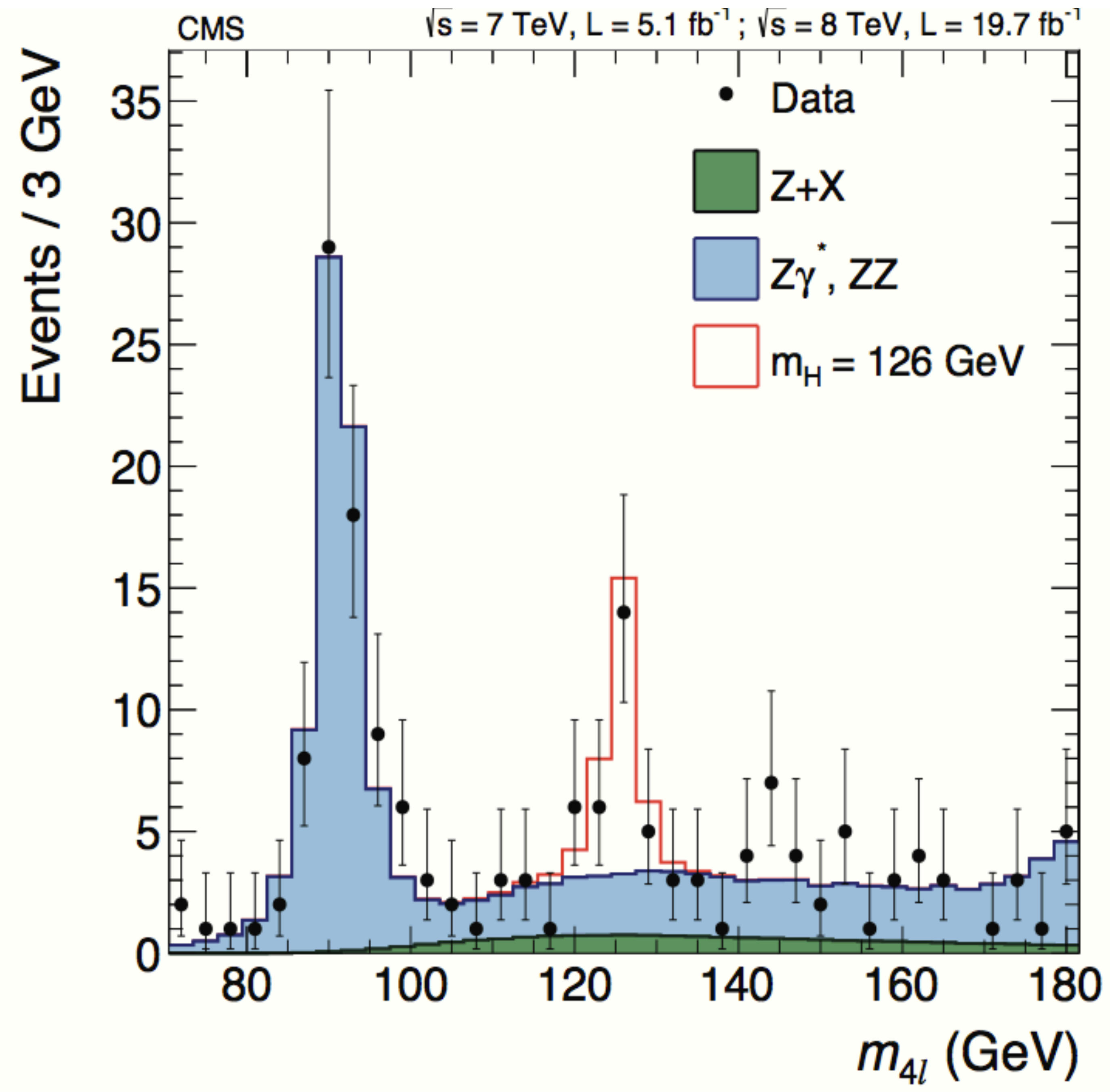




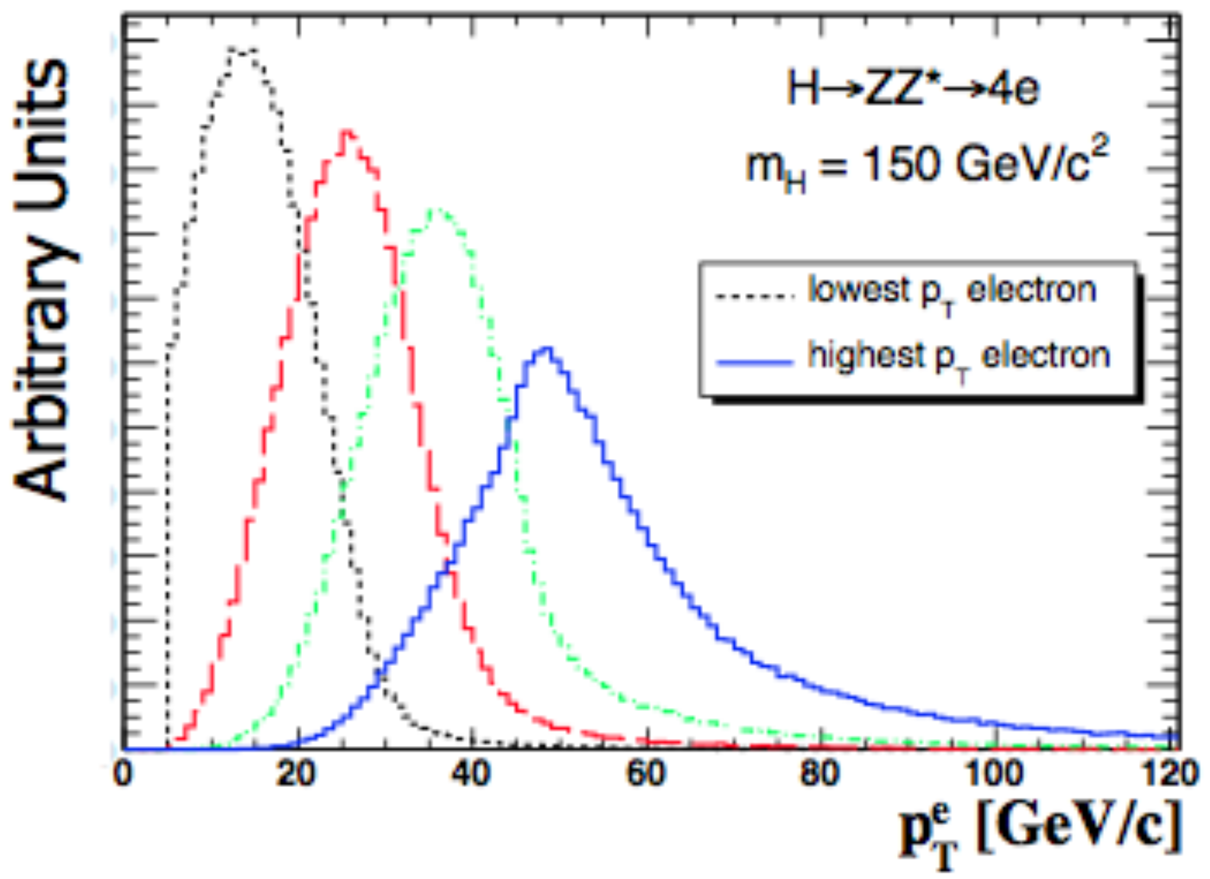
The Discovery Channels

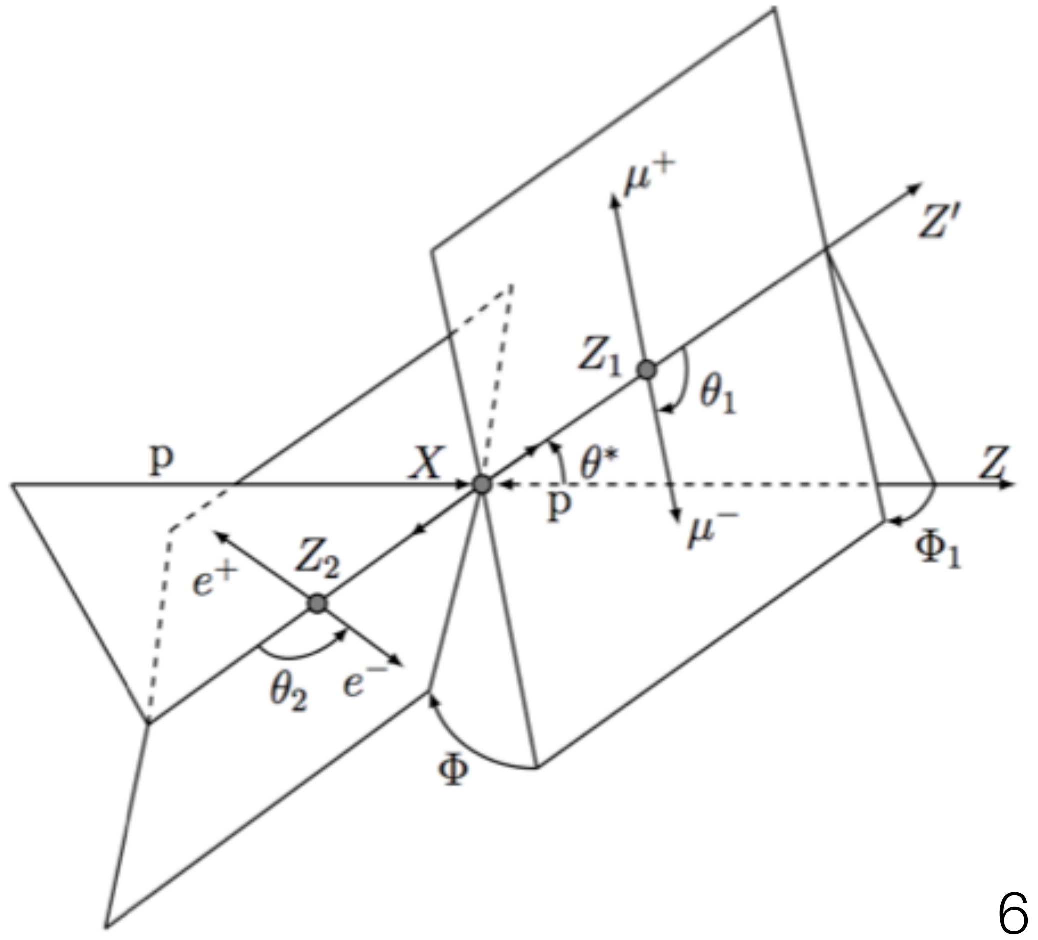
« Bread and Butter » Mass peak signals: the four leptons channel

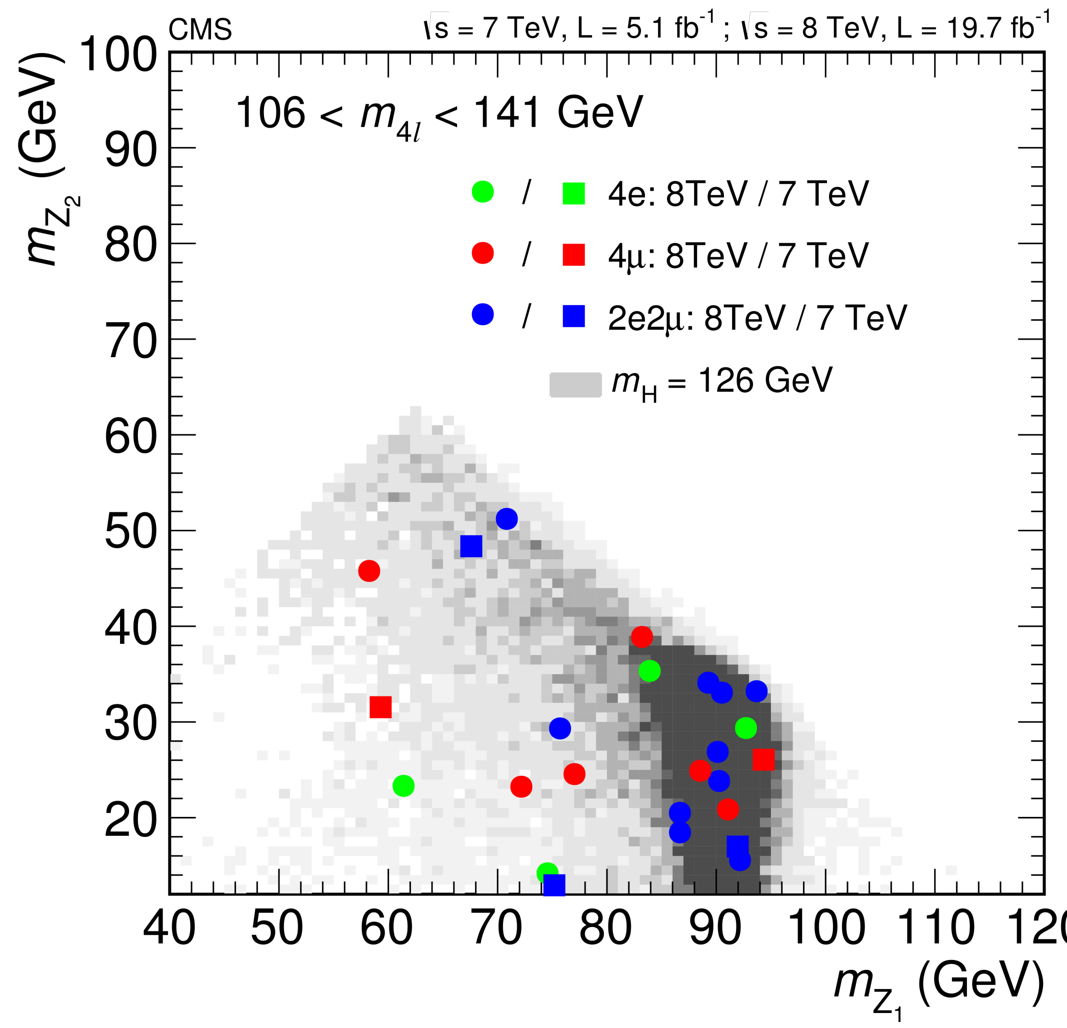


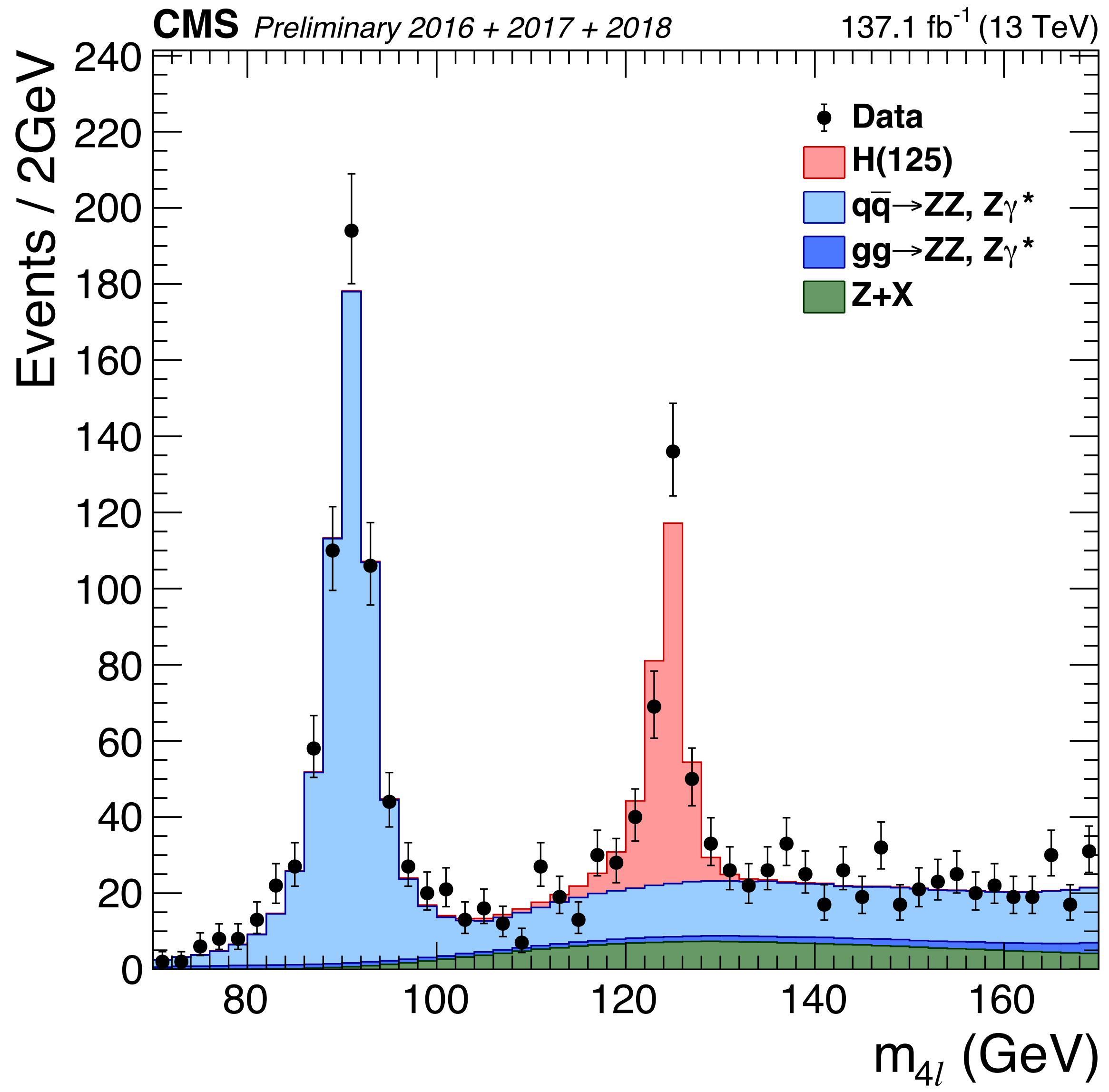


- Channel with High s/b ratio from approximately 2 up to more than 10!
- Backgrounds can be estimated from MC.
- Other important features:
  - Very low rate due to branchings of ZZ and Z to leptons! Efficiency is key!
  - The trailing lepton is at low pT.
  - The polarisation of the two Z can be reconstructed.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



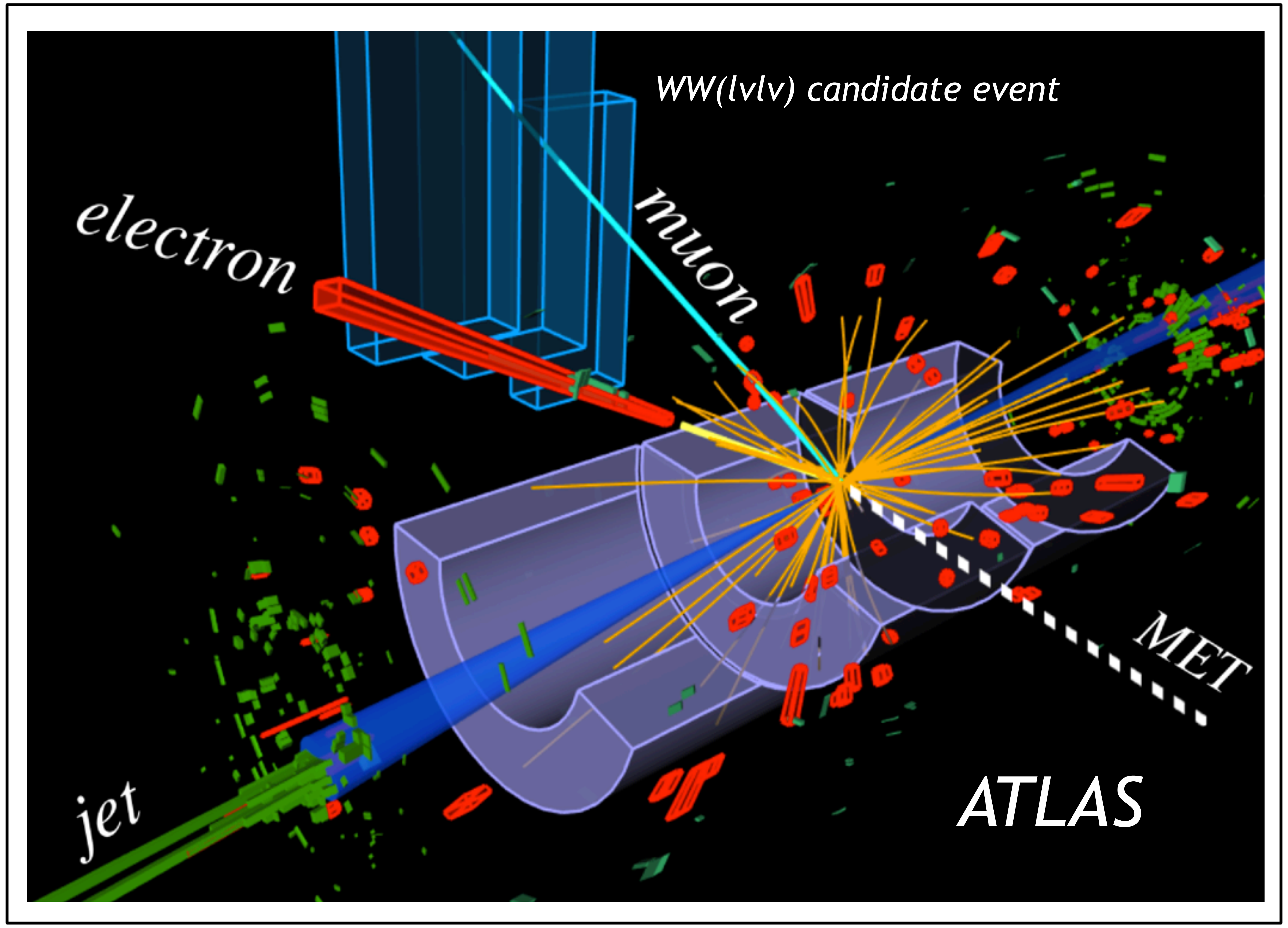






The Discovery Channels

A discovery channel of a different kind: the WW

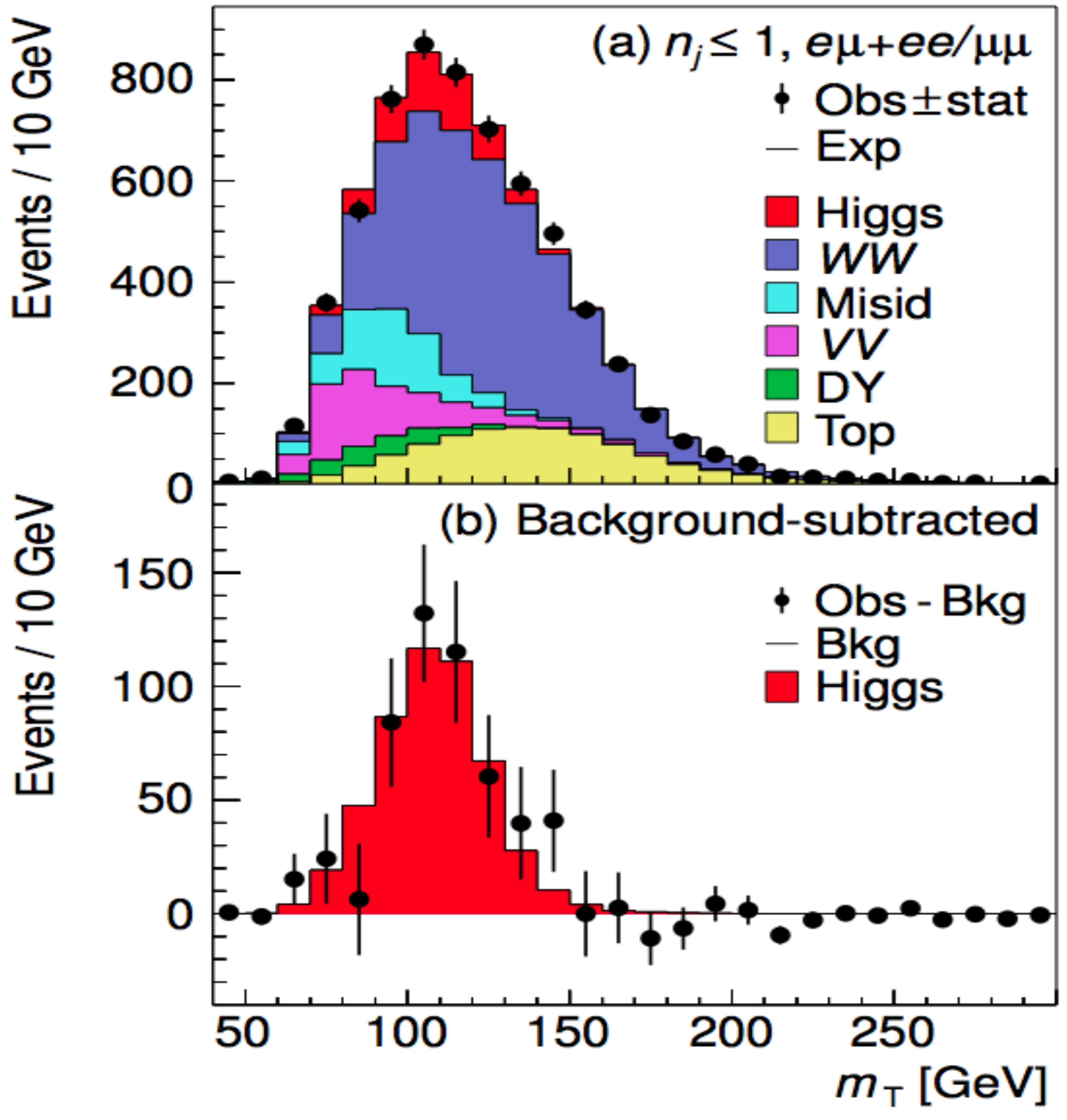


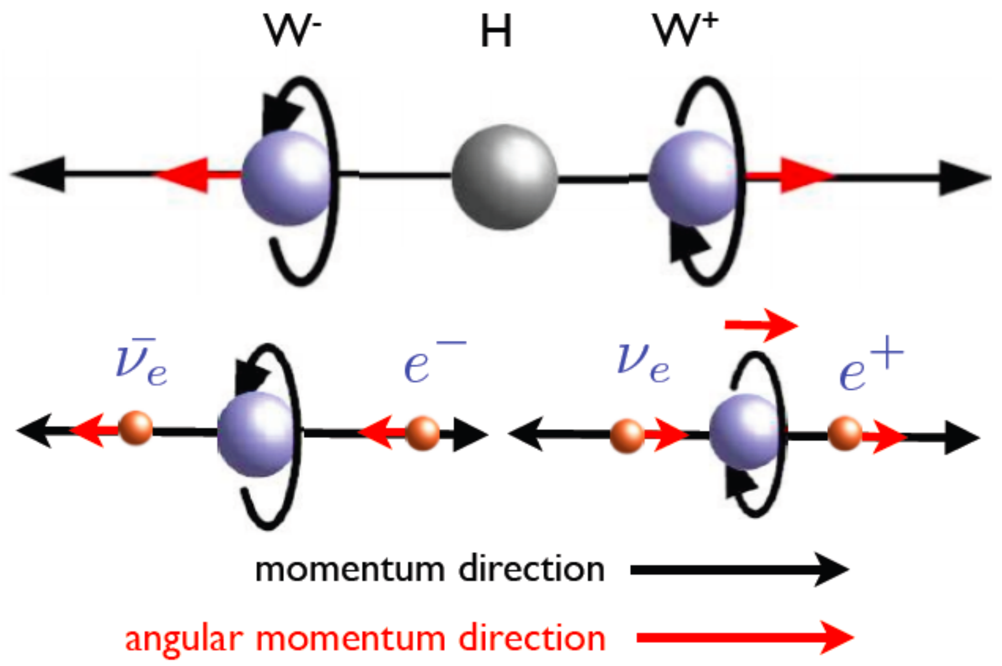
Channel where each of the W decays to leptons, the mass resolution is spoiled by the neutrinos!

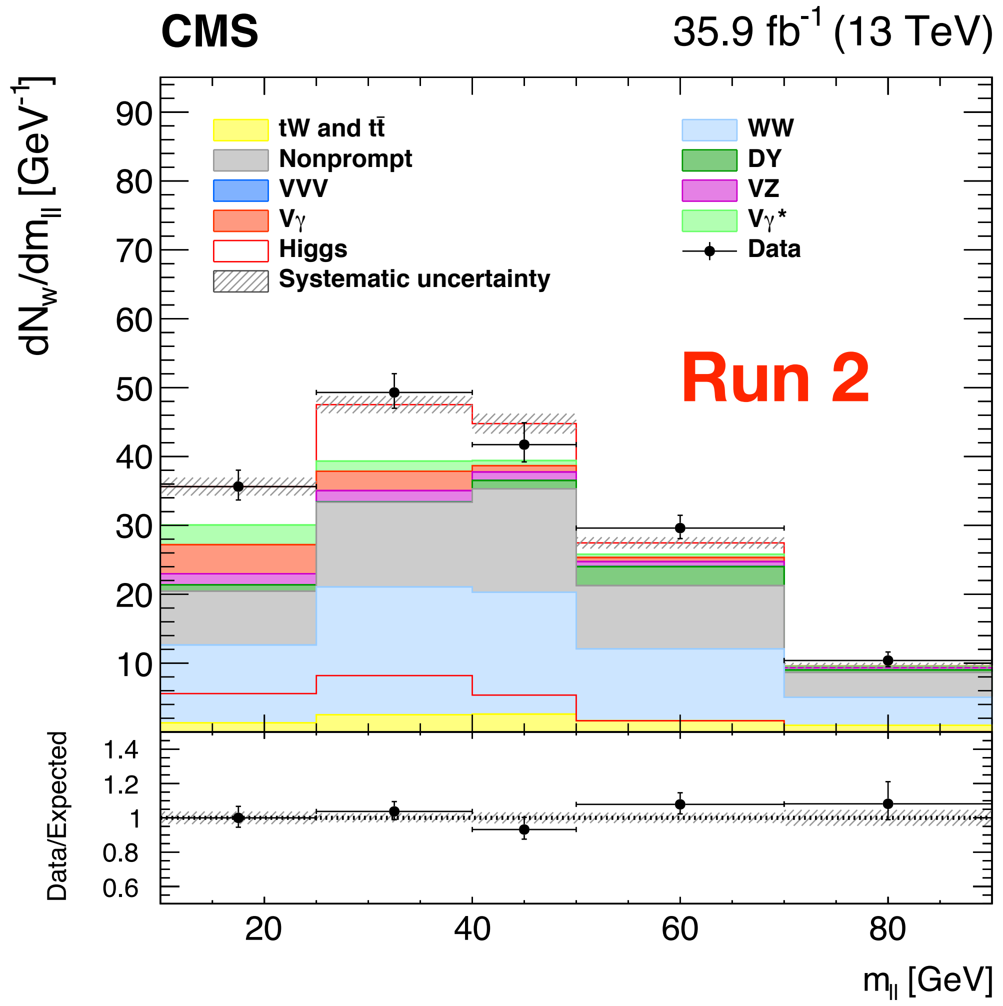
Large event rate, but also large backgrounds from the WW and top production.

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

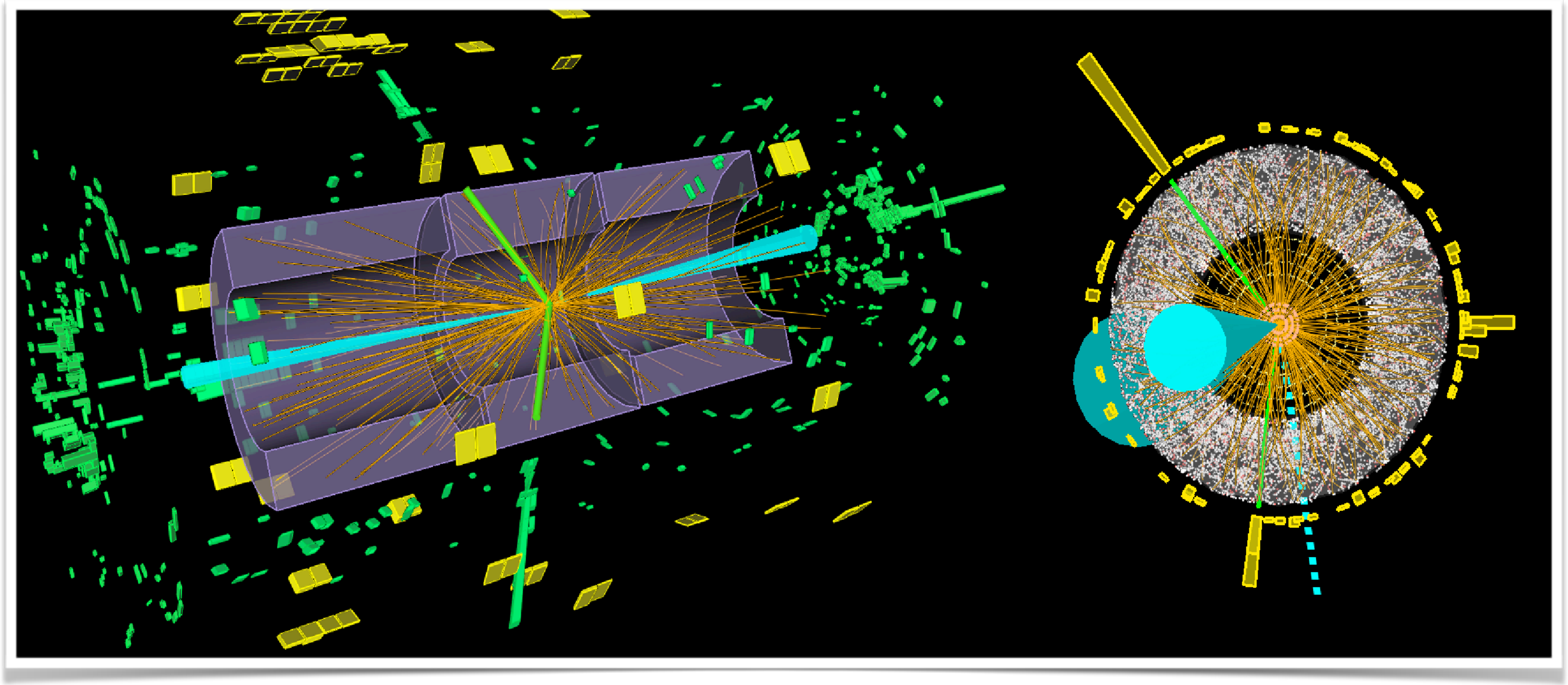
Uses the V-A nature of the W coupling that transfers the W spin correlation to the electrons.

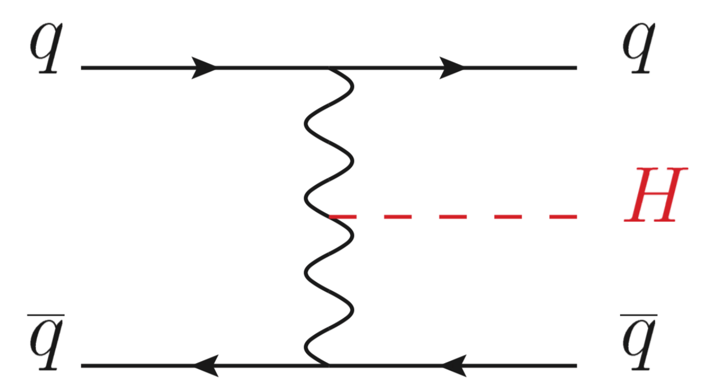






Higgs boson decays to Taus





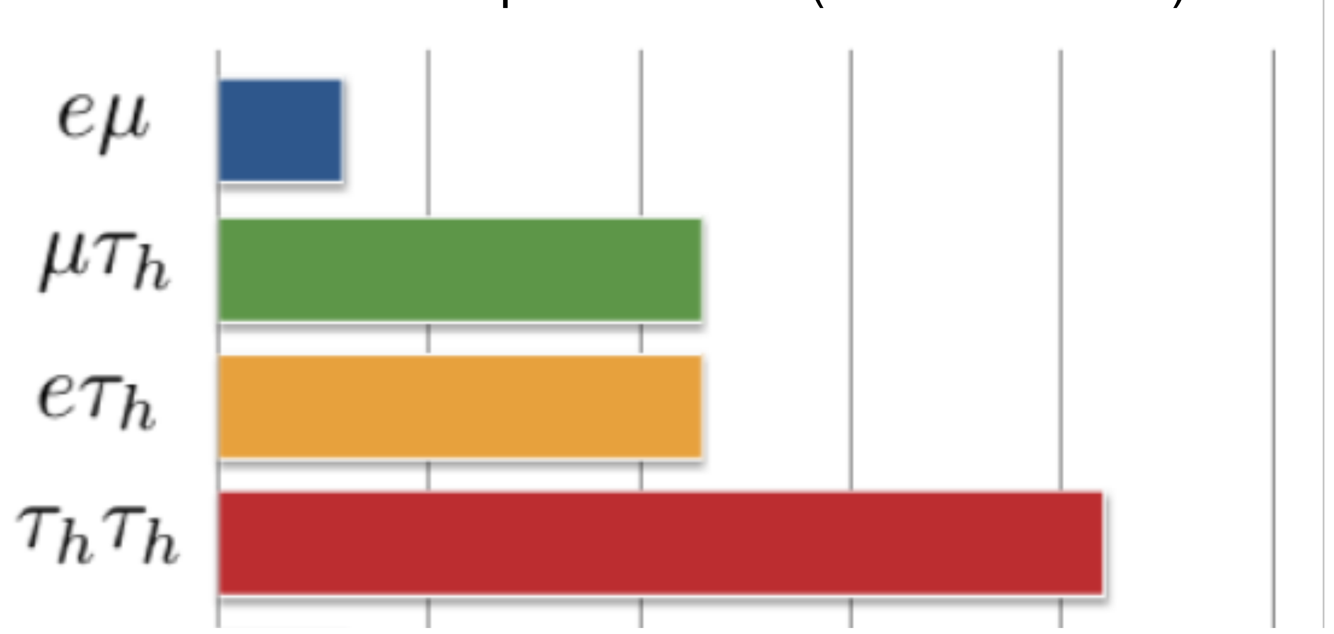
VBF process

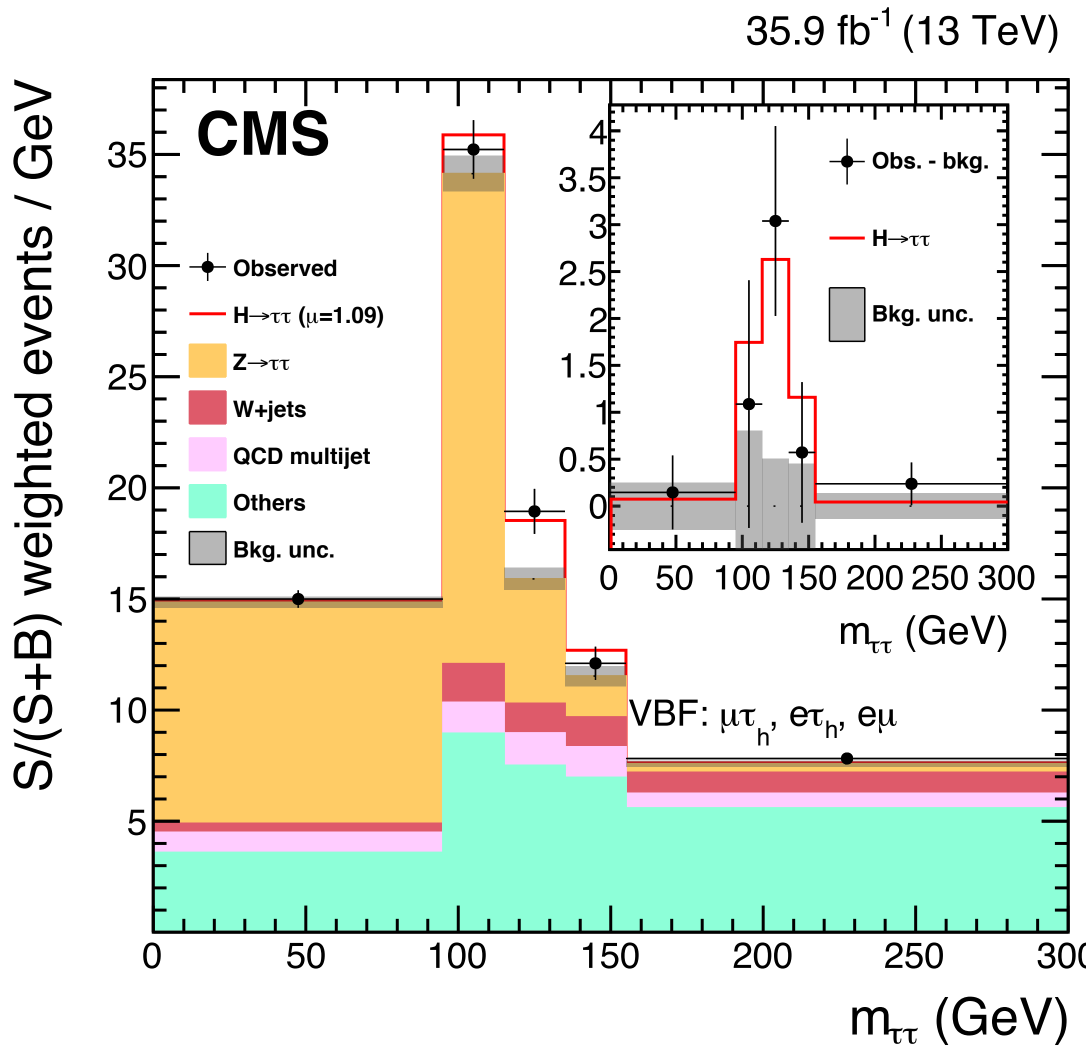
With two forward jets and a large rapidity gap between the jets (due to the color singlet exchange in the t-channel

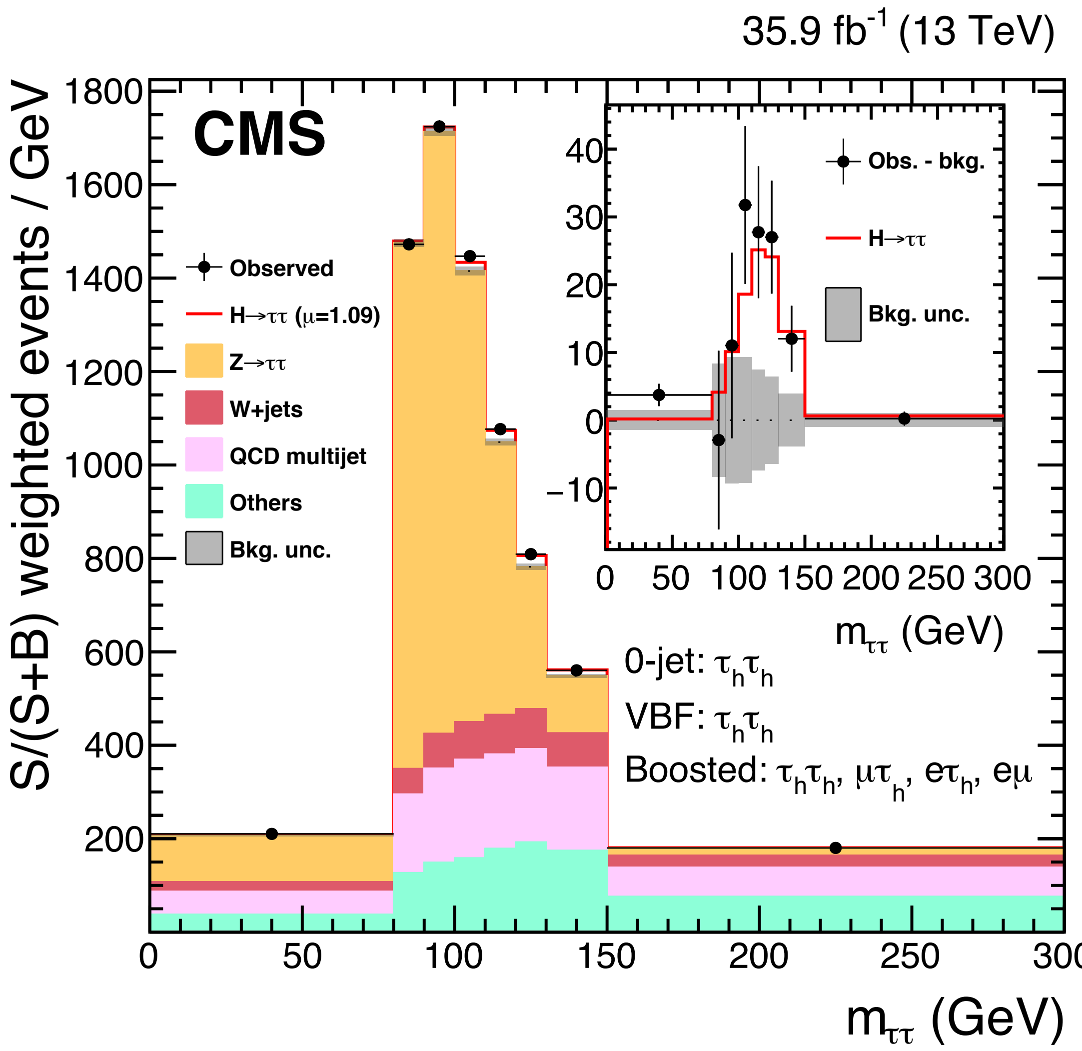
Background is Z production with two jets, in this region of phase space it is difficult to predict!

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

Tau to leptons ~18% (rest is hadrons)





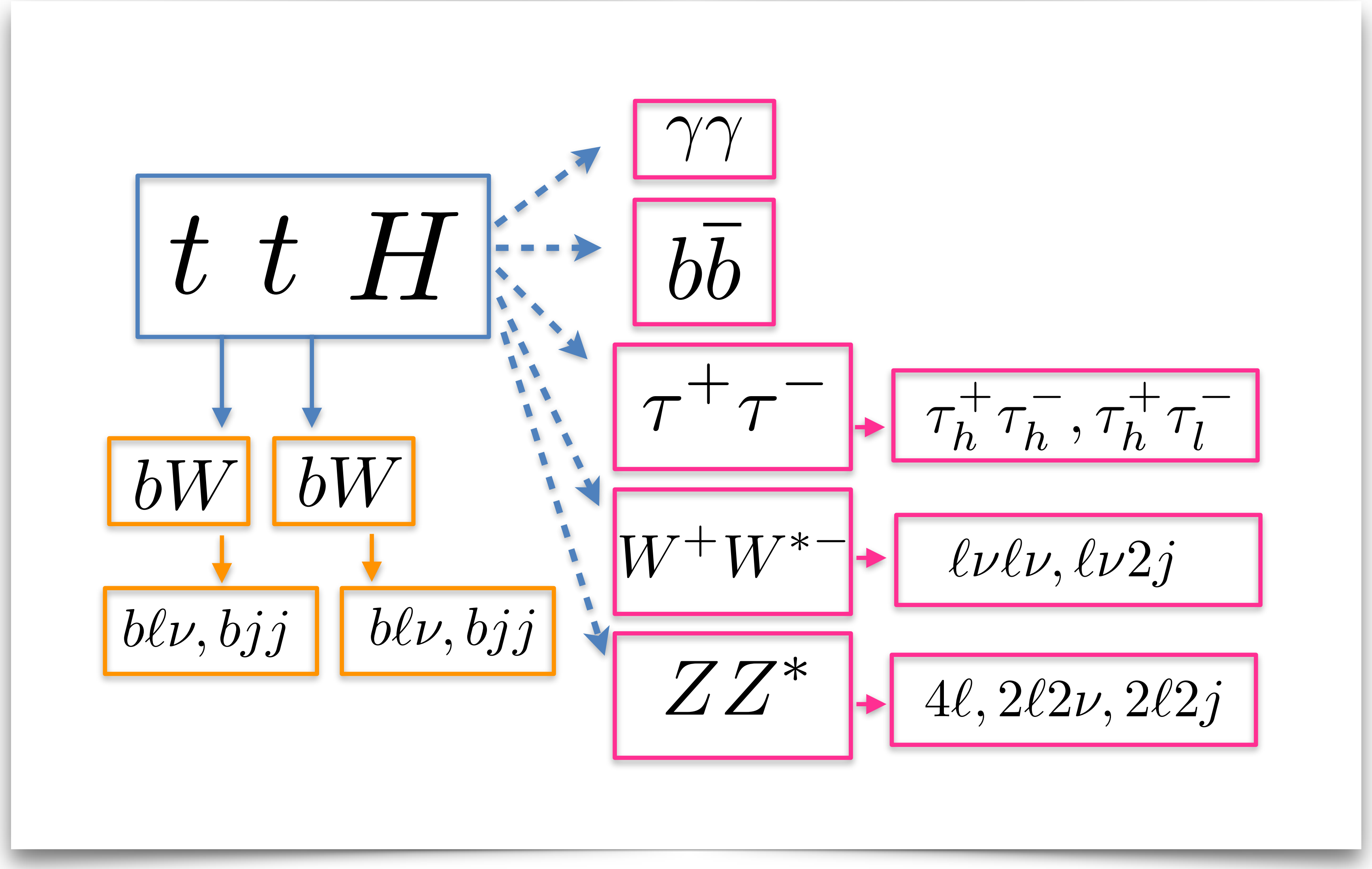


Analysis requires data driven methods to do so: e.g. the embedding of taus in Z to di-muon events.

The tau polarisation can in principle be reconstructed, but this is very difficult and was not done yet.

Direct probe of the top Yukawa coupling

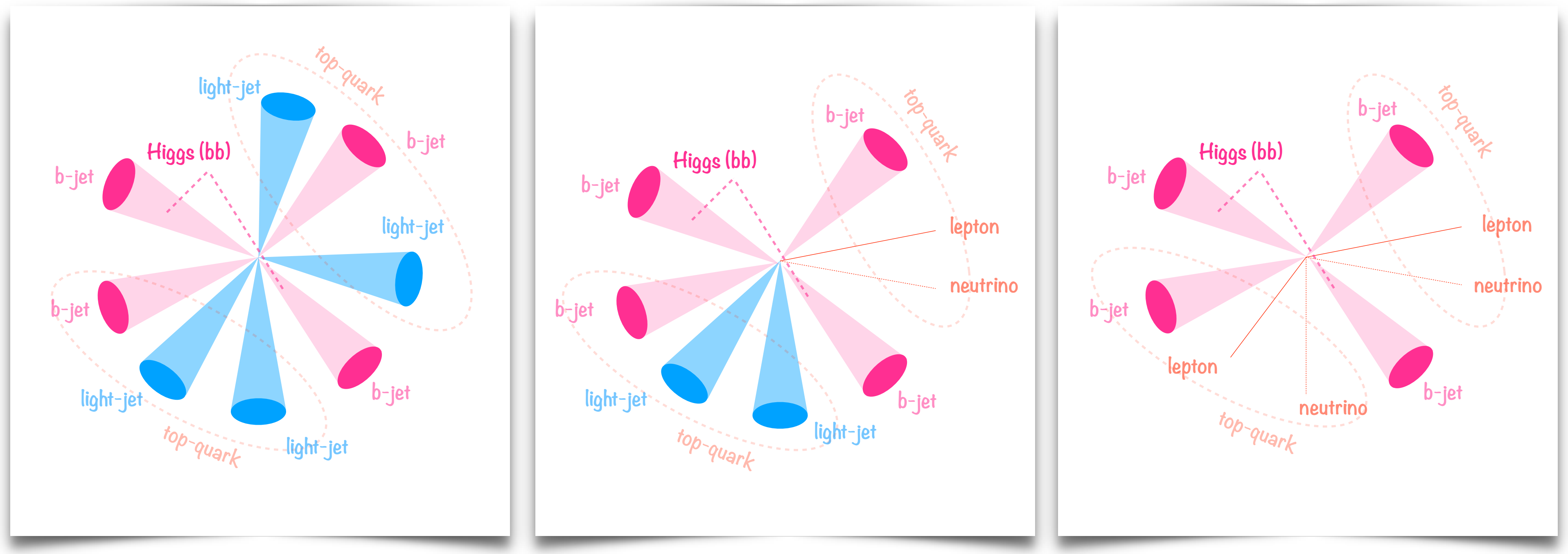
ttH Analyses at LHC: Massively Complex!



- 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!

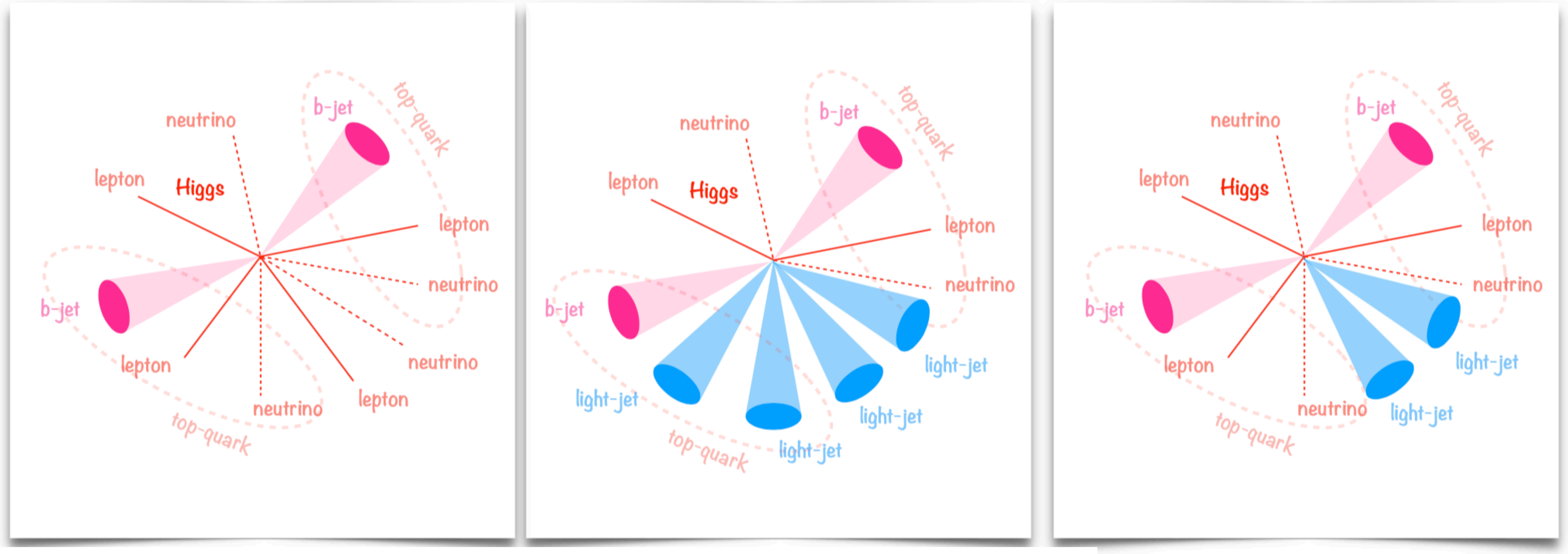
- With the new Run at close to double centre-of-mass energy and increased statistics, changes in leading channels.

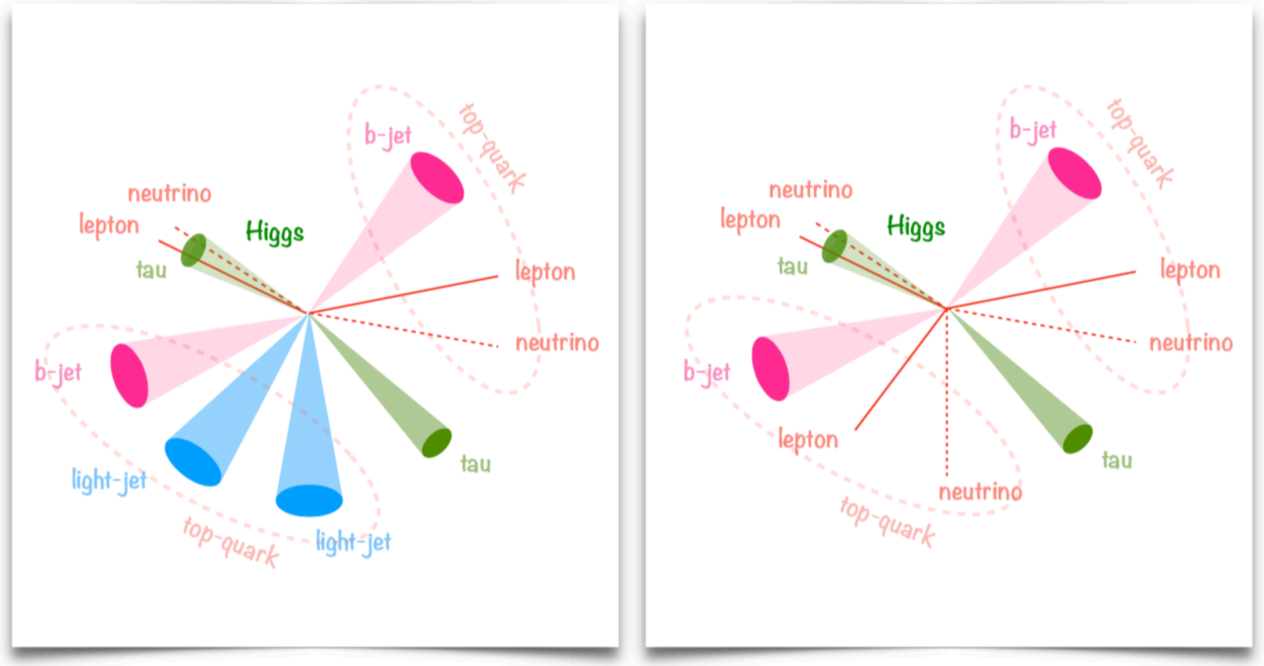


ttH(bb)

Very large backgrounds of top pair production associated with b jets

Dominated by background modelling uncertainties

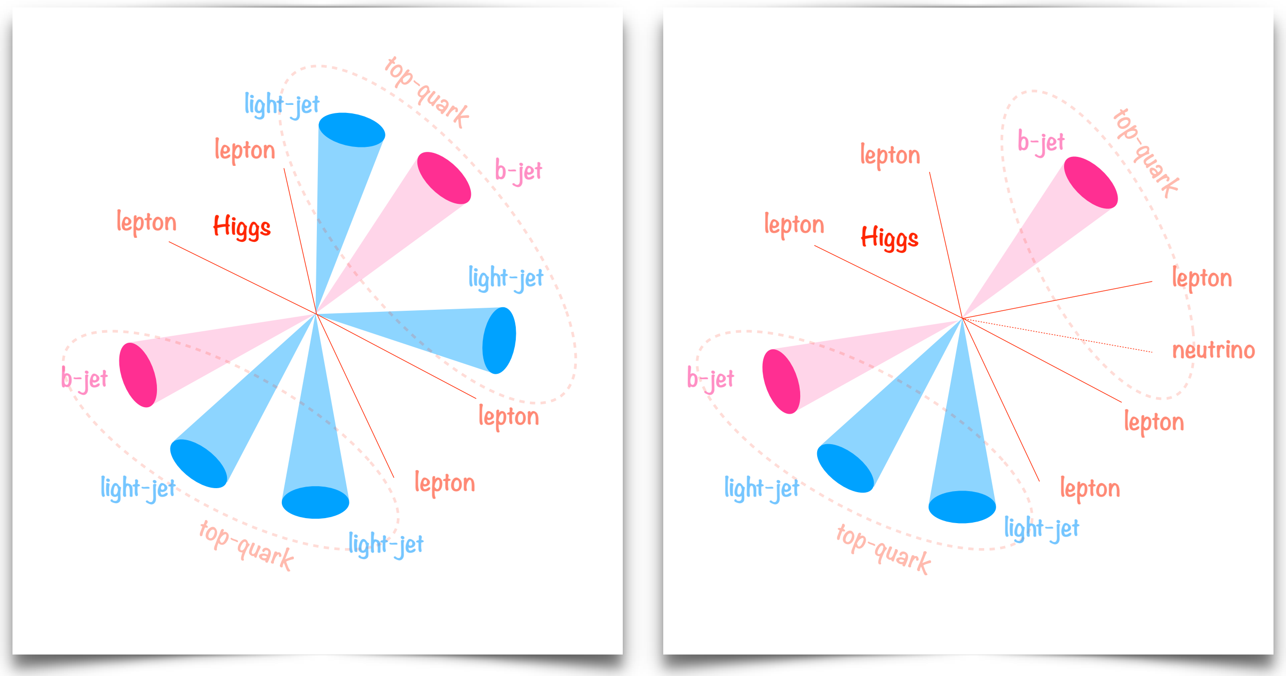




ttH(WW, ZZ and tau tau)

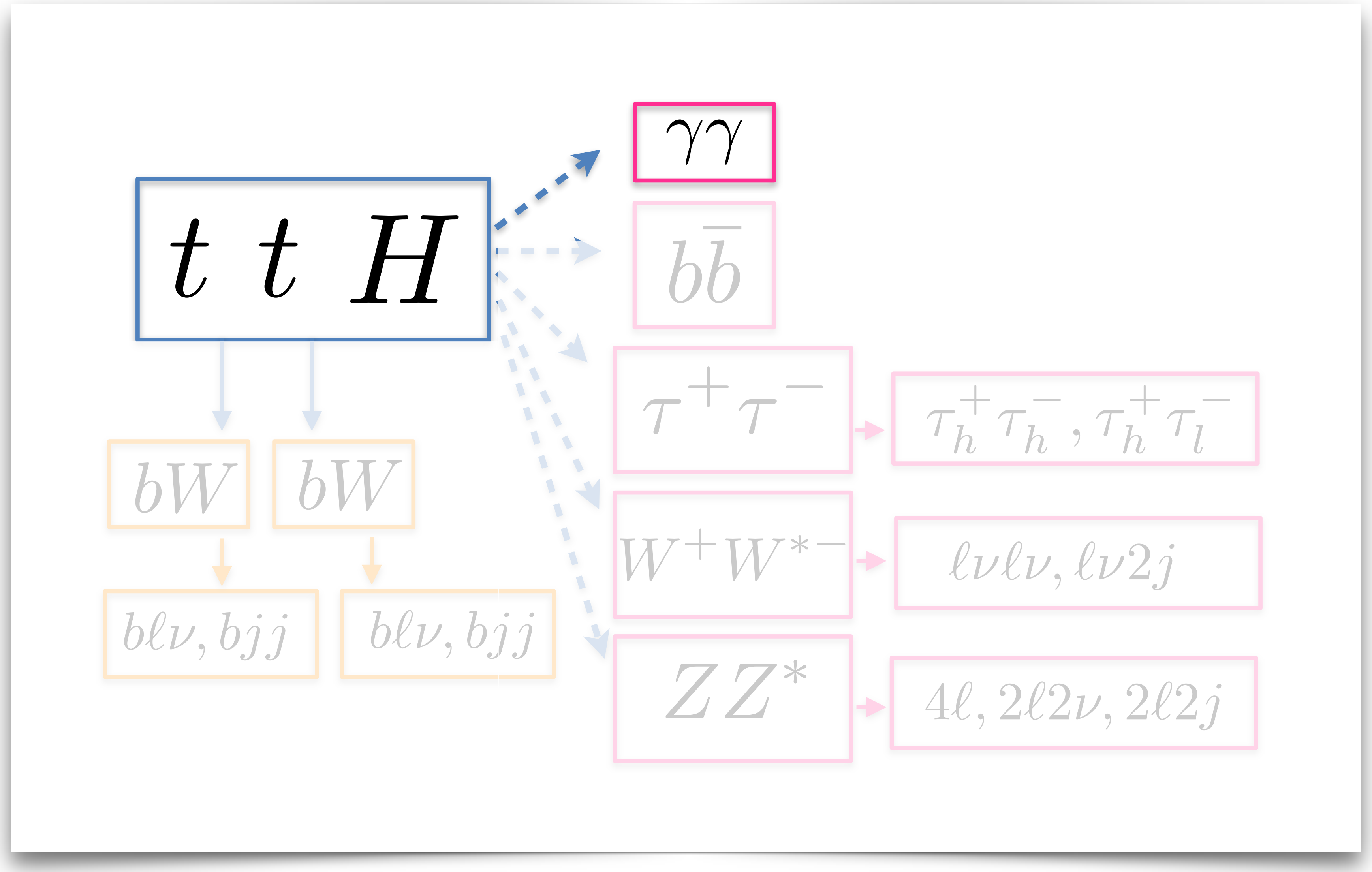
So-called multi-lepton channel

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

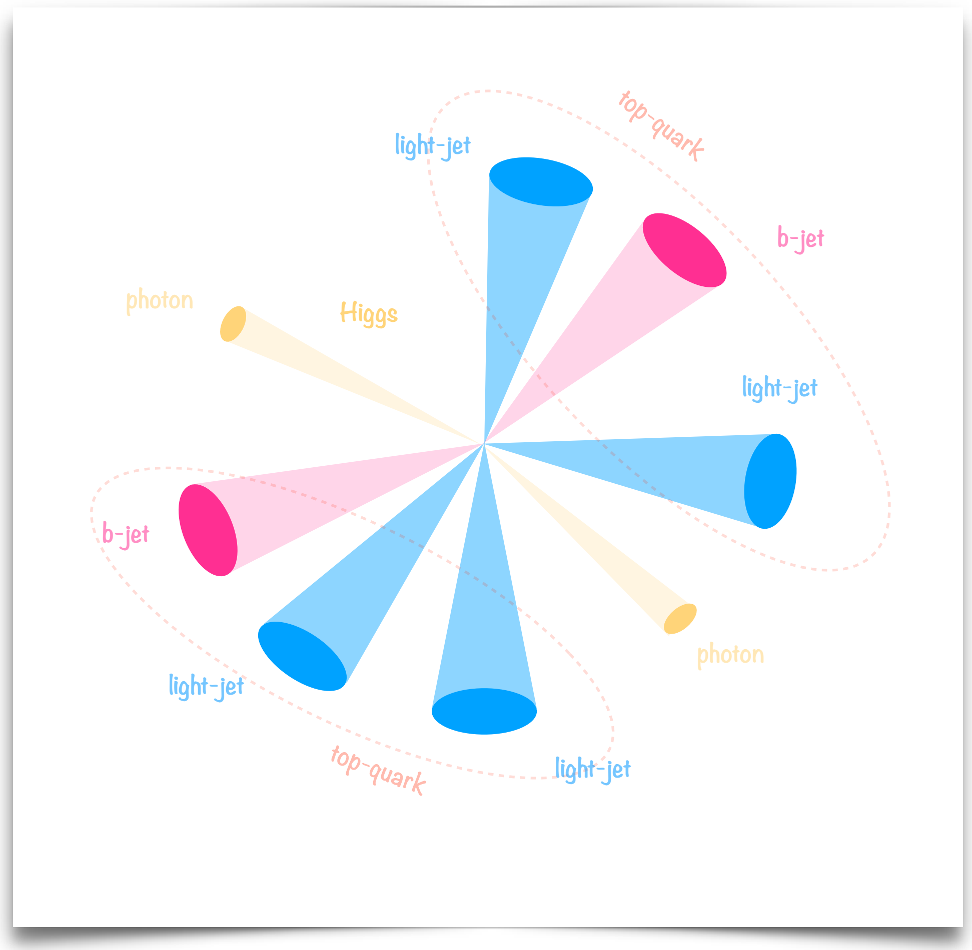


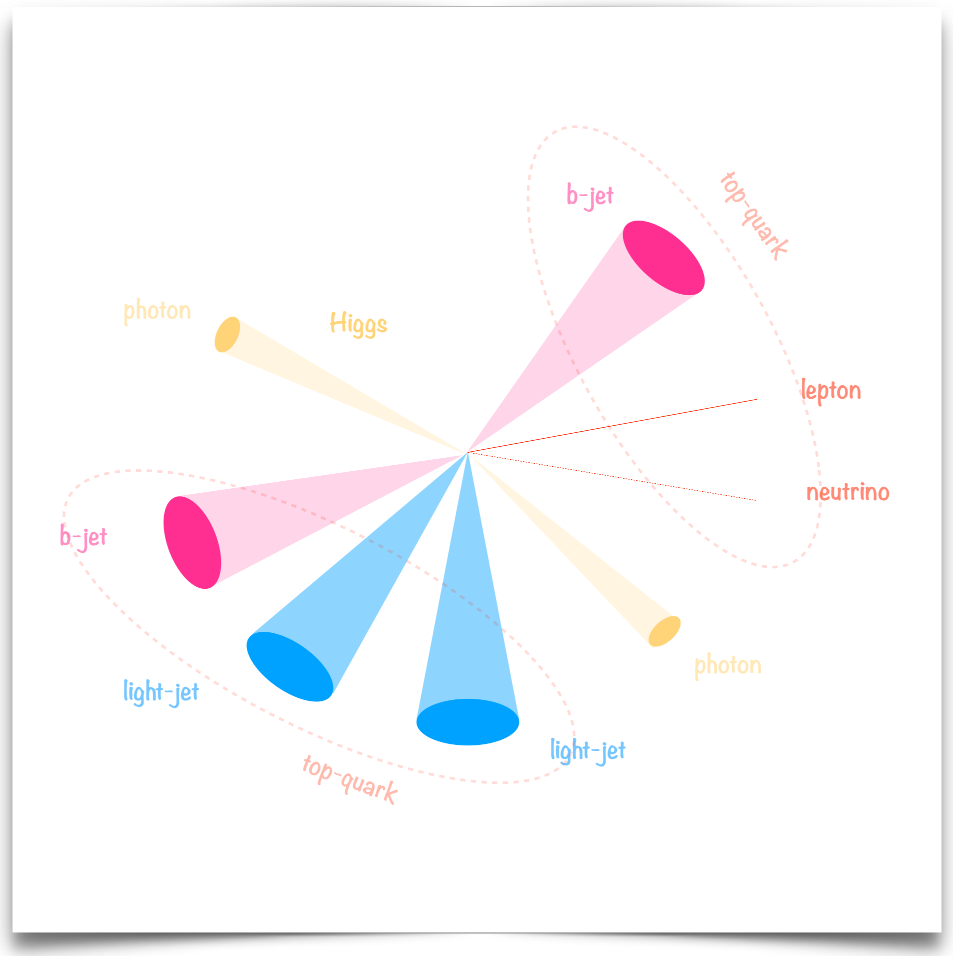
Direct probe of the top Yukawa coupling

ttH Analyses at LHC: Massively Complex!

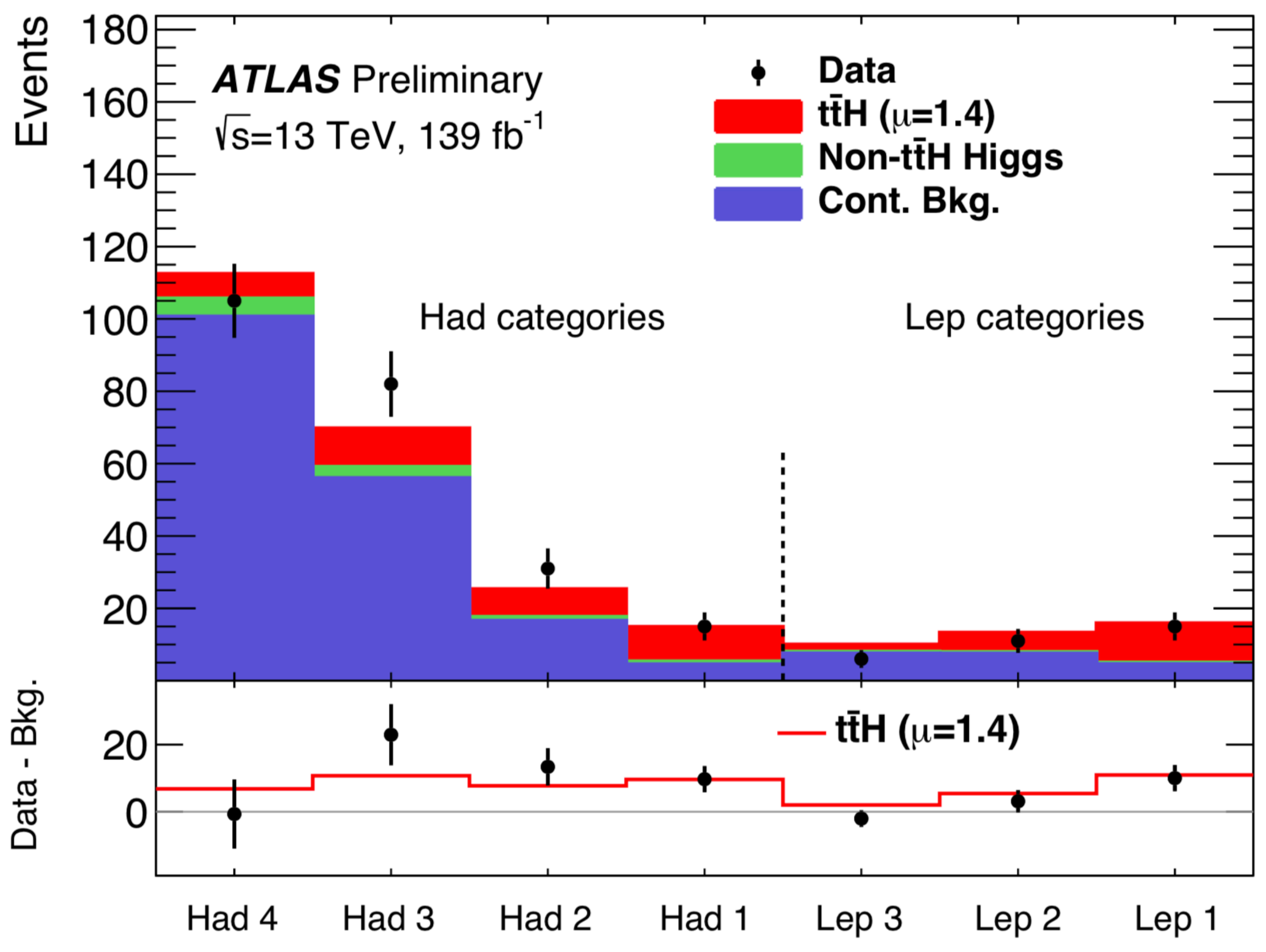


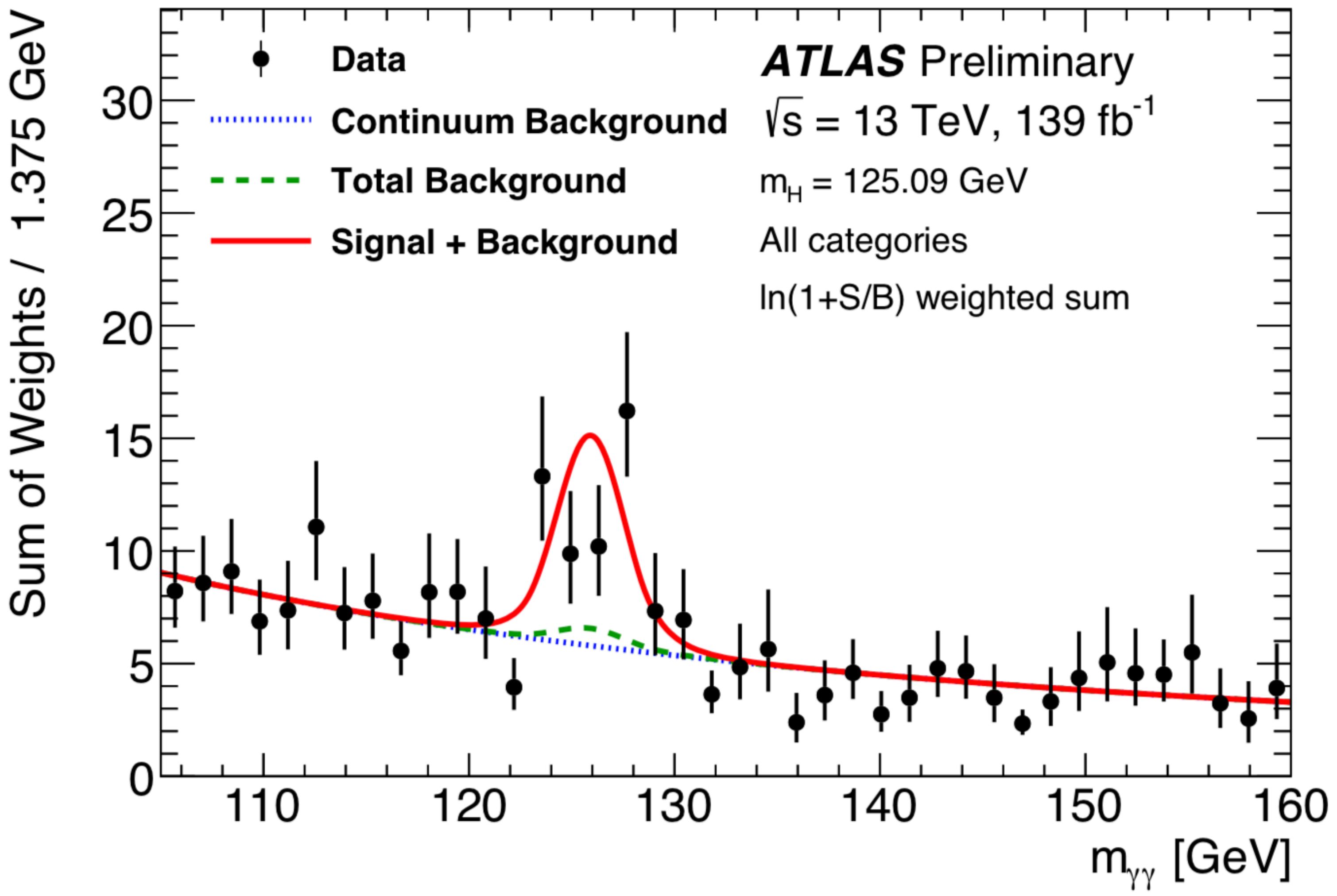
Currently most sensitive channel





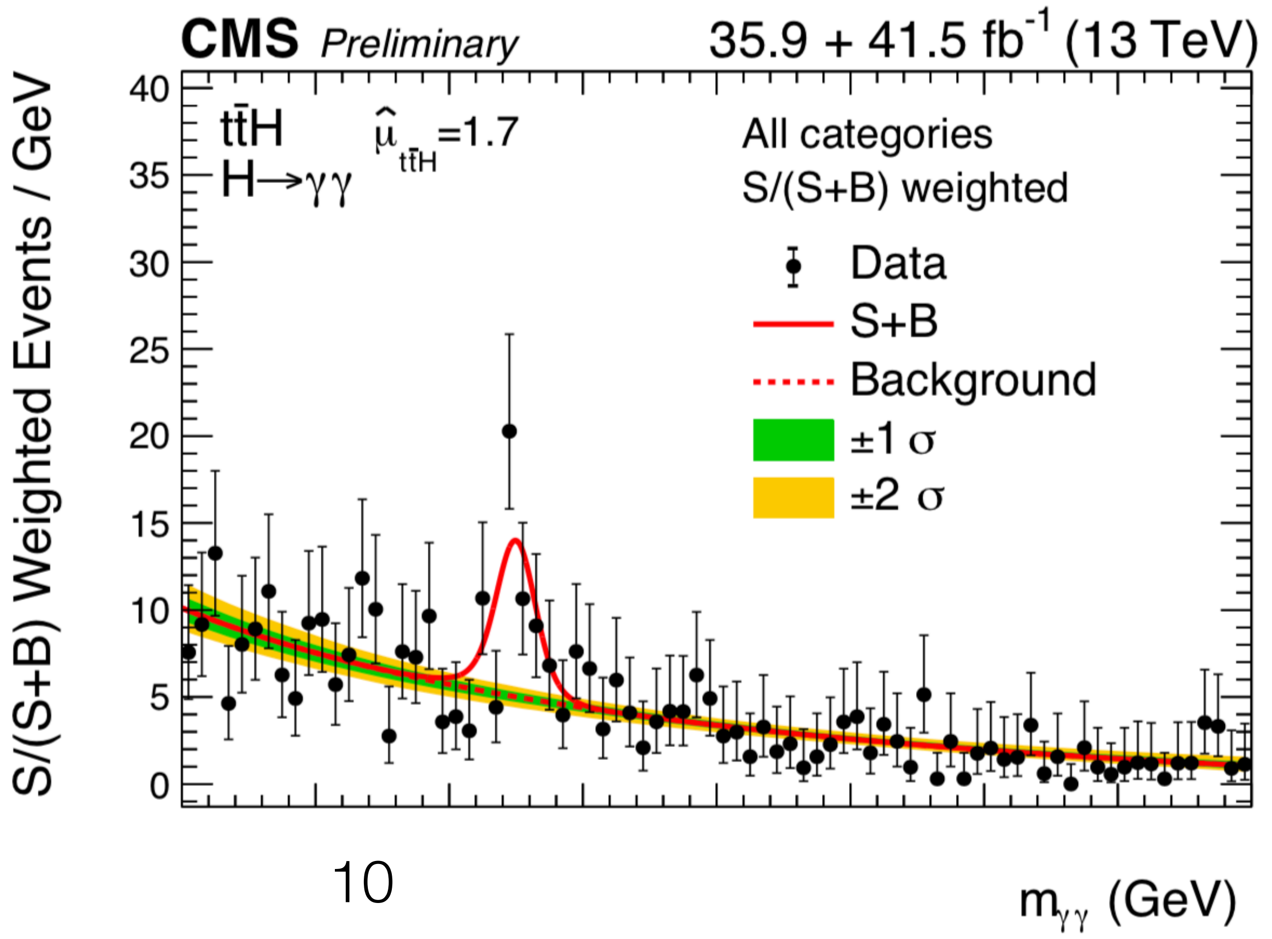
Background and signal modelled using analytic functions.





Cross section dominated by statistical uncertainties:

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



ATLAS	Expected	5.1σ
	Observed	6.3σ

CMS-PAS-HIG-18-018

CMS	Expected	(2.7σ)
	Observed	4.1σ

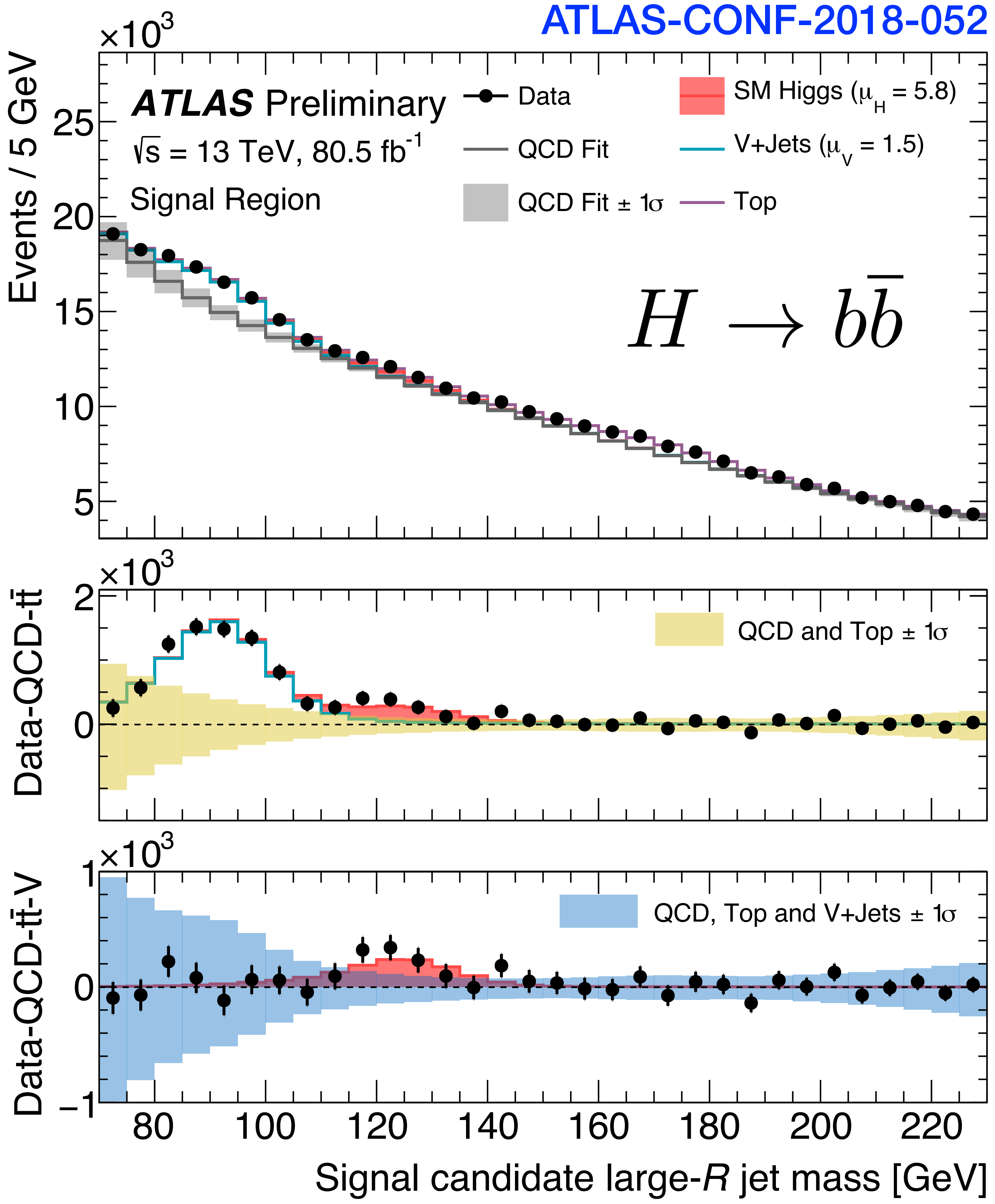
Ratio to SM expectation:

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

Higgs boson decays to b-quarks

Inclusive boosted analysis in bb at highest pT (using jet substructure)

ATLAS-CONF-2018-052



Estimate is tricky as it requires the precise estimate of the fiducial acceptance for the signal

ATLAS

$1.6\sigma\ (obs)$

CMS

$1.5\sigma\ (obs)$

$0.7\sigma\ (exp)$

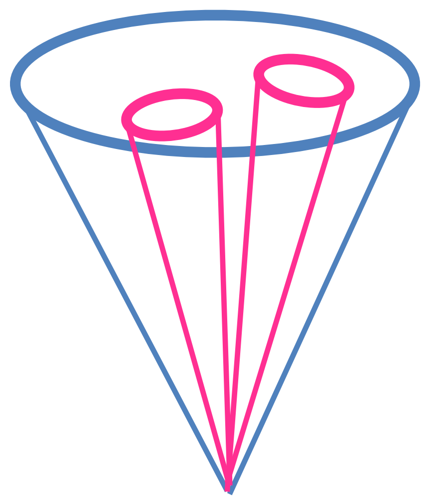
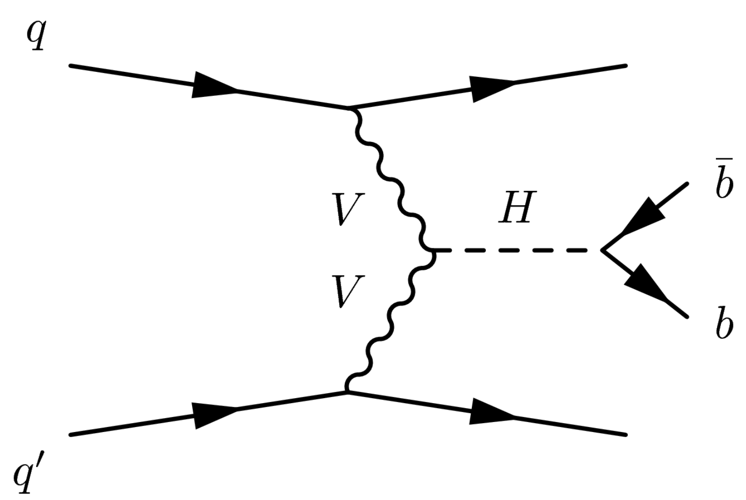
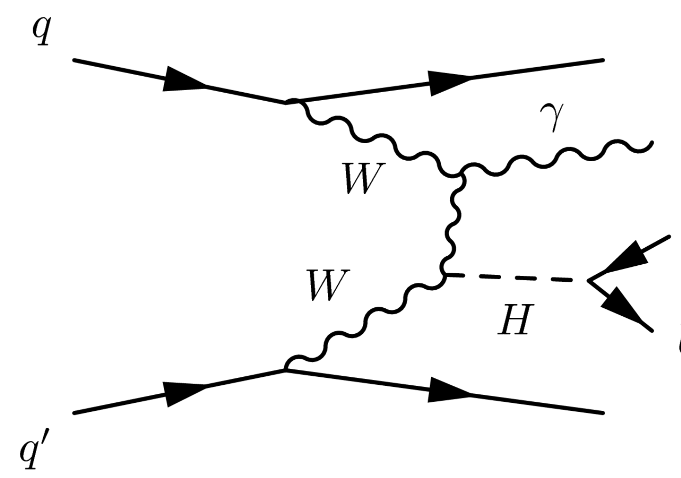


Illustration of the importance of jet substructure reconstruction techniques

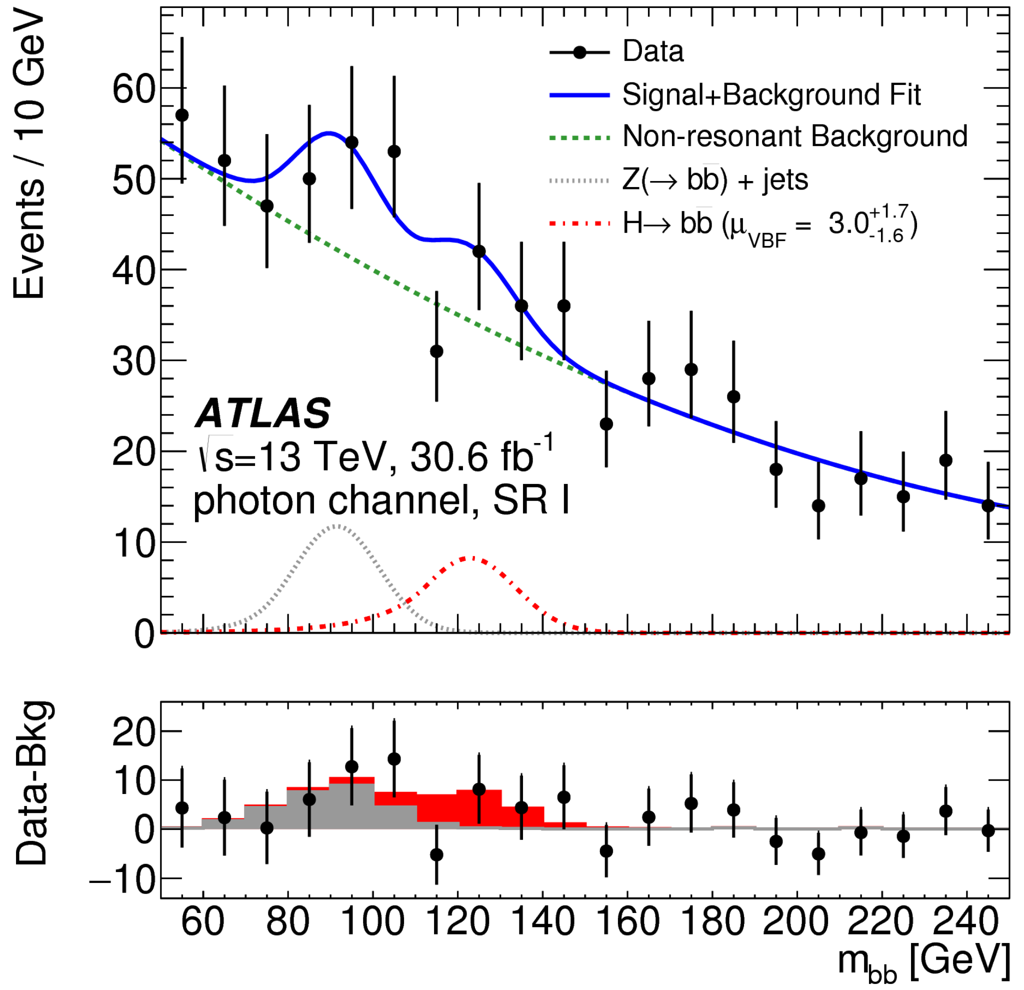
VBF analysis with Higgs in bb including channel with photon

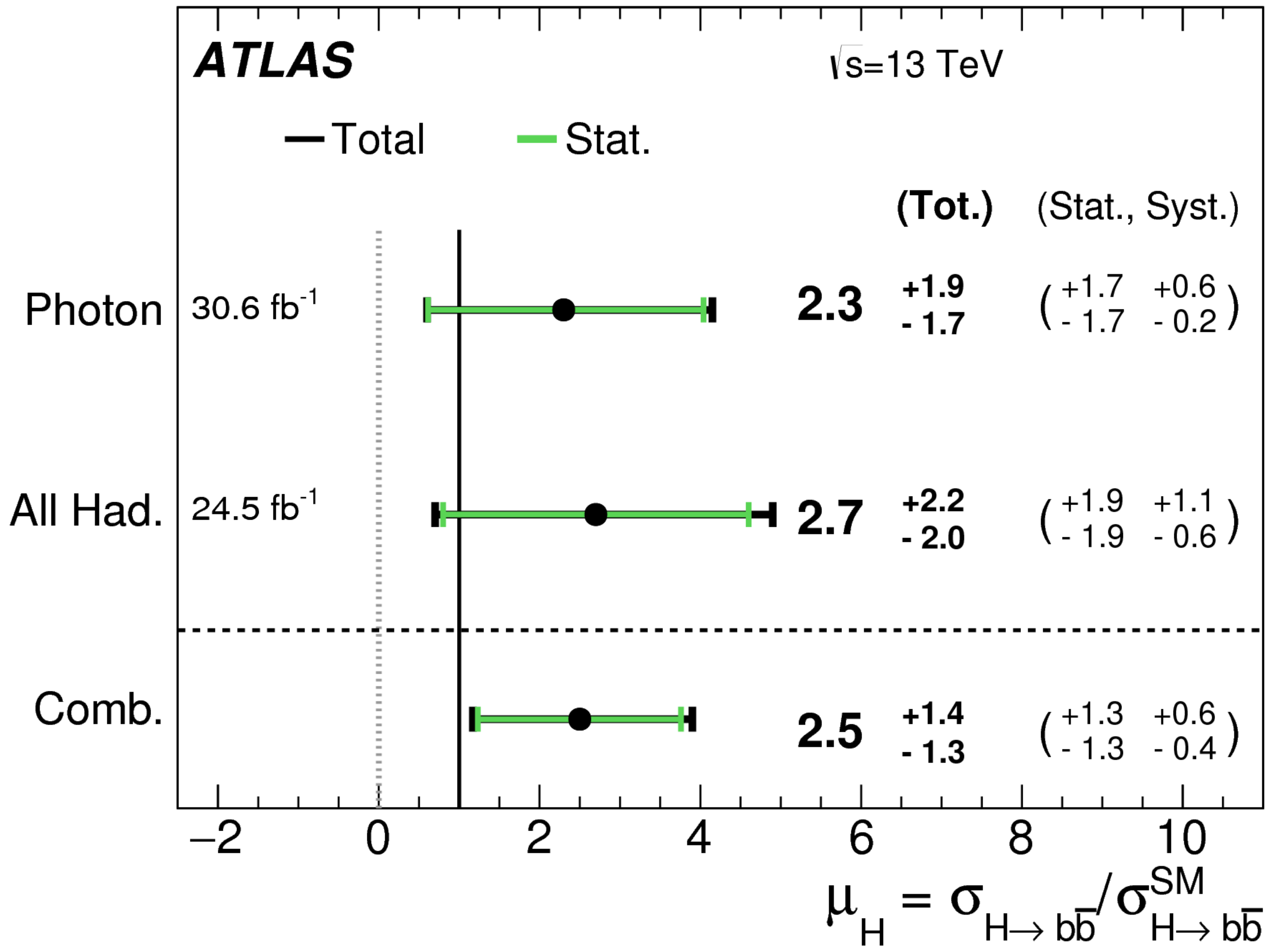




Taking advantage of the VBF with a photon topology which reduces significantly QCD background which has a destructive interference! It is also very useful to trigger on.

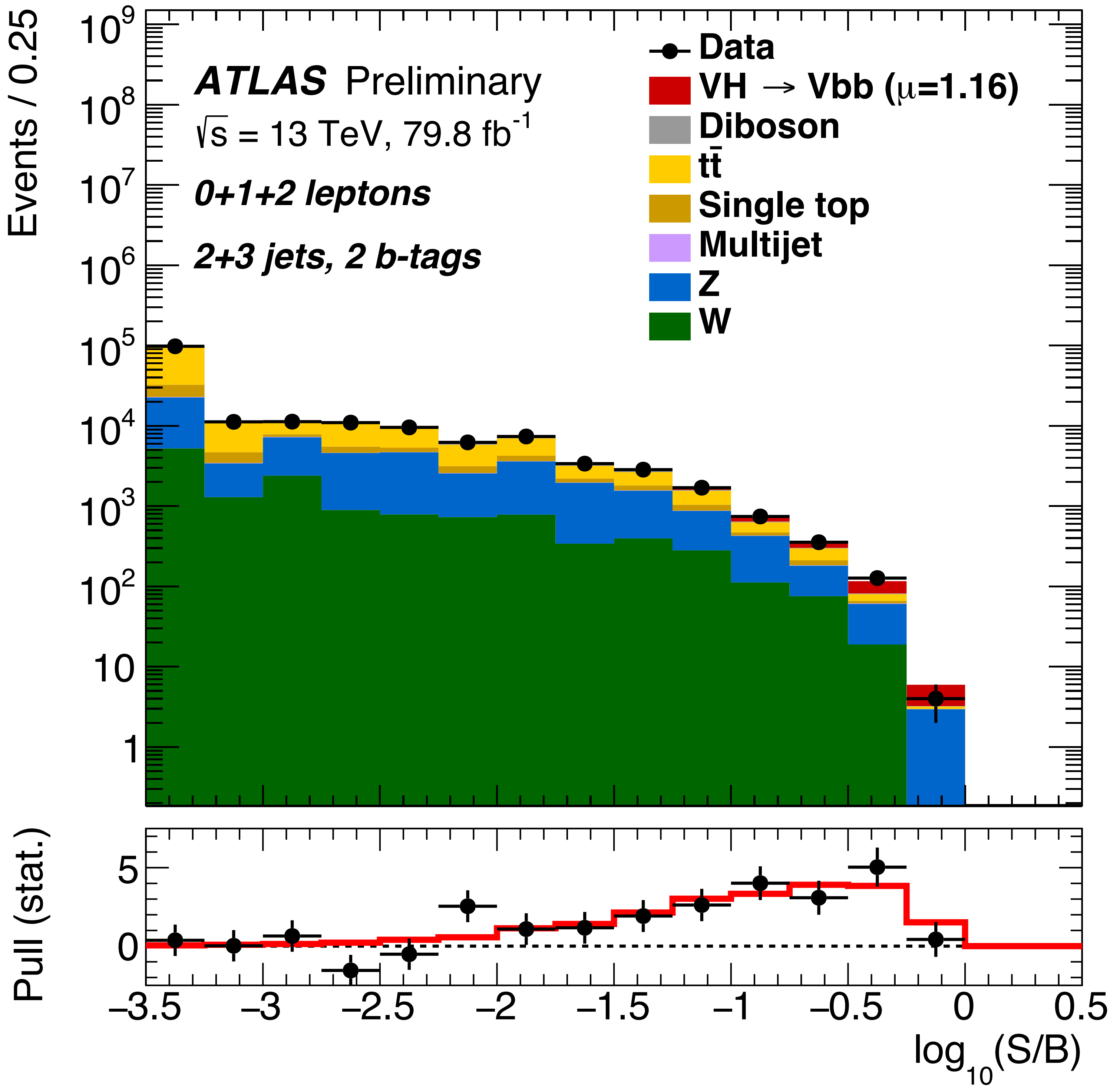
HIGG-2016-30

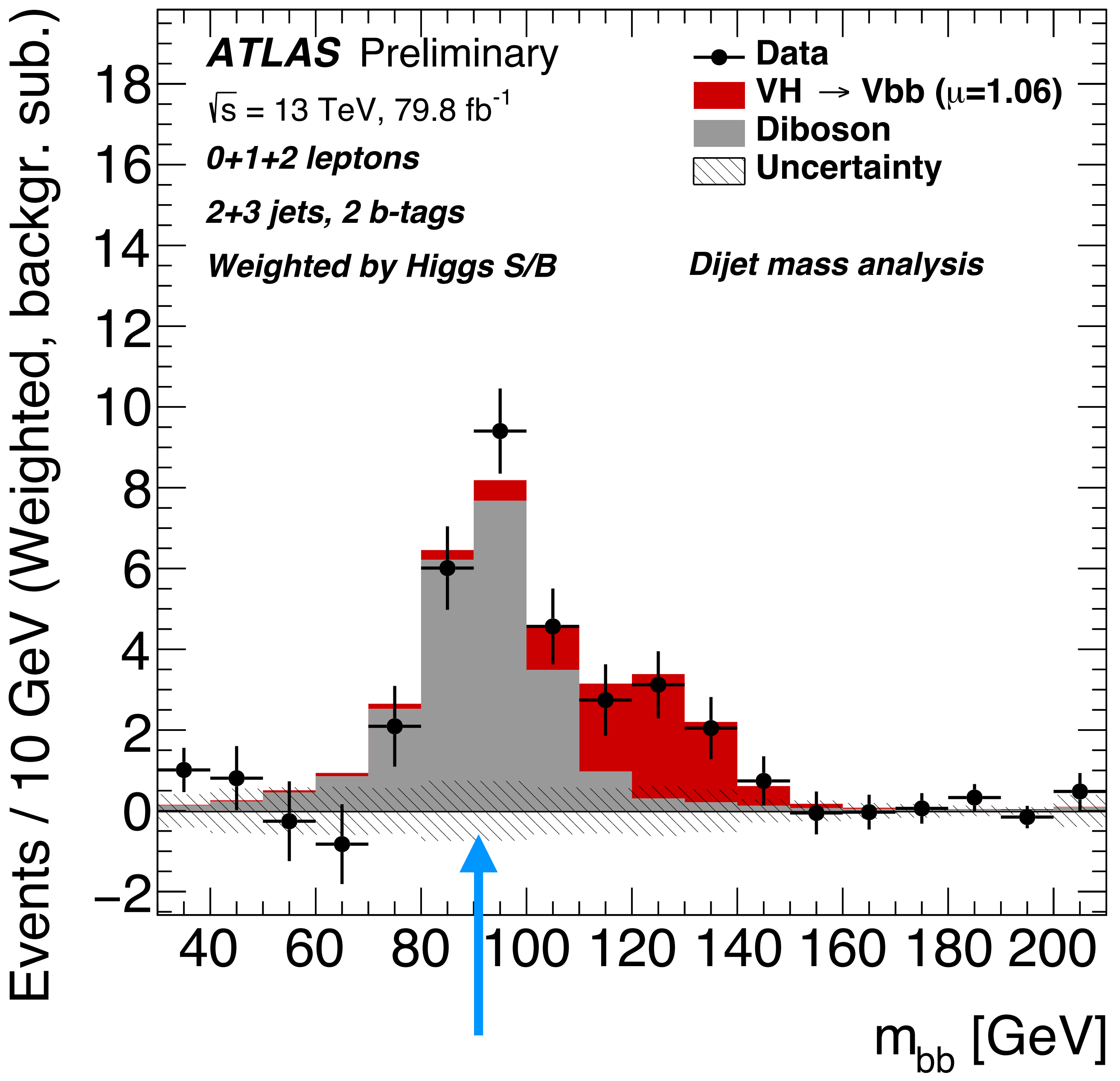




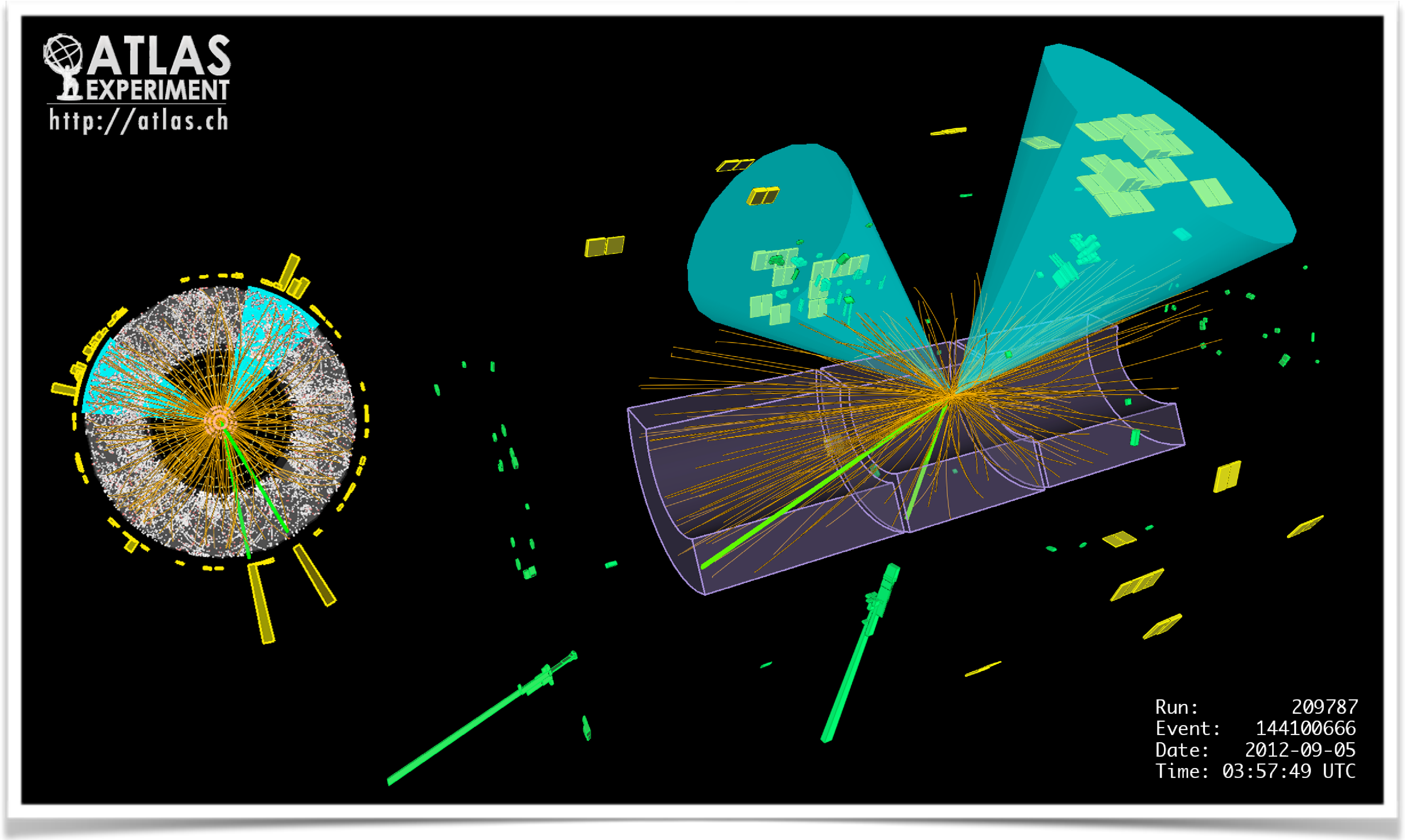
Should start to become single channel sensitive at Run 3.

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	5.4σ	Expected	5.5σ
CMS	Observed	5.5σ	Expected	5.6σ

Run 2 Higgs Headlines

Run 2 Higgs Physics **major milestones** reached: **Third Generation (Charged) Observation Completed!**

Yukawas at LHC		tau	b	top
ATLAS	Exp. Sig.	5.4 σ	5.5 σ	5.1 σ
	Obs. Sig.	6.4 σ	5.4 σ	6.3 σ
	mu	1.09 ± 0.35	1.01 ± 0.20	1.34 ± 0.21 *
CMS	Exp. Sig.	5.9 σ	5.6 σ	4.2 σ
	Obs. Sig.	5.9 σ	5.5 σ	5.2 σ
	mu	1.09 ± 0.27 *	1.04 ± 0.20	1.26 ± 0.26 **

* 13 TeV only derived from cross section measurements

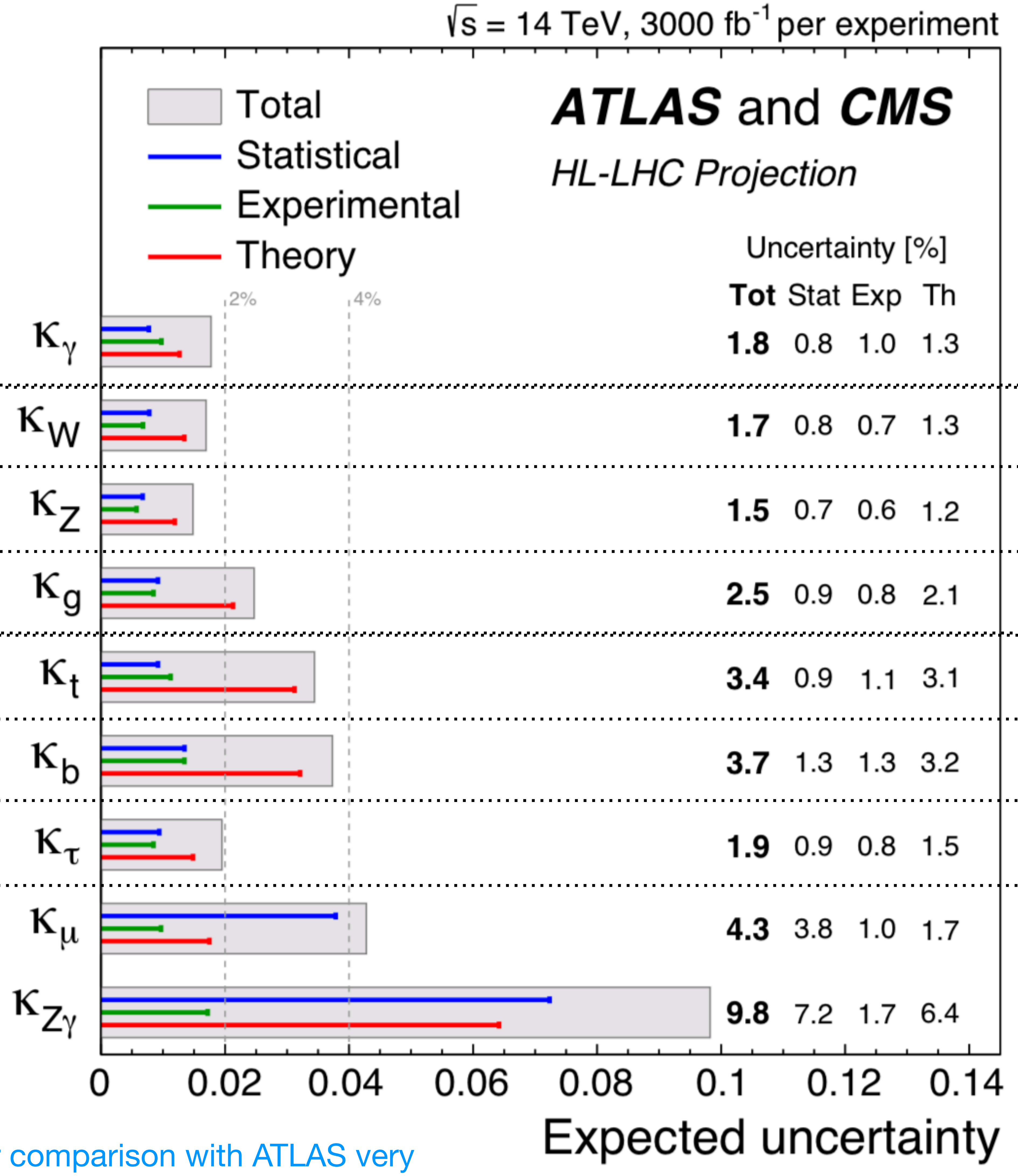
** Lower uncertainty (upper uncertainty 31)

A lot of room for improvement:

- Larger statistics will allow to focus on more specific (and potentially less vulnerable to systematic) regions of phase space.
- Make ancillary measurements for a better control of the backgrounds.

Combination of Main Decay and Production Channels Towards HL-LHC

	ATLAS - CMS Run 1 combination	ATLAS Run 2 (partial)	CMS Run 2 (very early*)
κ_γ	13%	9%	15%
κ_W	11%	8.6%	11%
κ_Z	11%	7.2%	11%
κ_g	14%	11%	11%
κ_t	30%	14%	15%
κ_b	26%	18%	26%
κ_τ	15%	14%	70%
	JHEP 08 (2016) 045	ATLAS-CONF-2019-04	EPJC 79 (2019) 421



Experimental systematics non negligible

Measurements here assume no BSM in Higgs width

Improved TH and PDF uncertainties by a factor of 2 w.r.t. current (motivated from current PDF studies and current TH uncertainties assumptions)

*Unfair comparison with ATLAS very early Run 2 combination

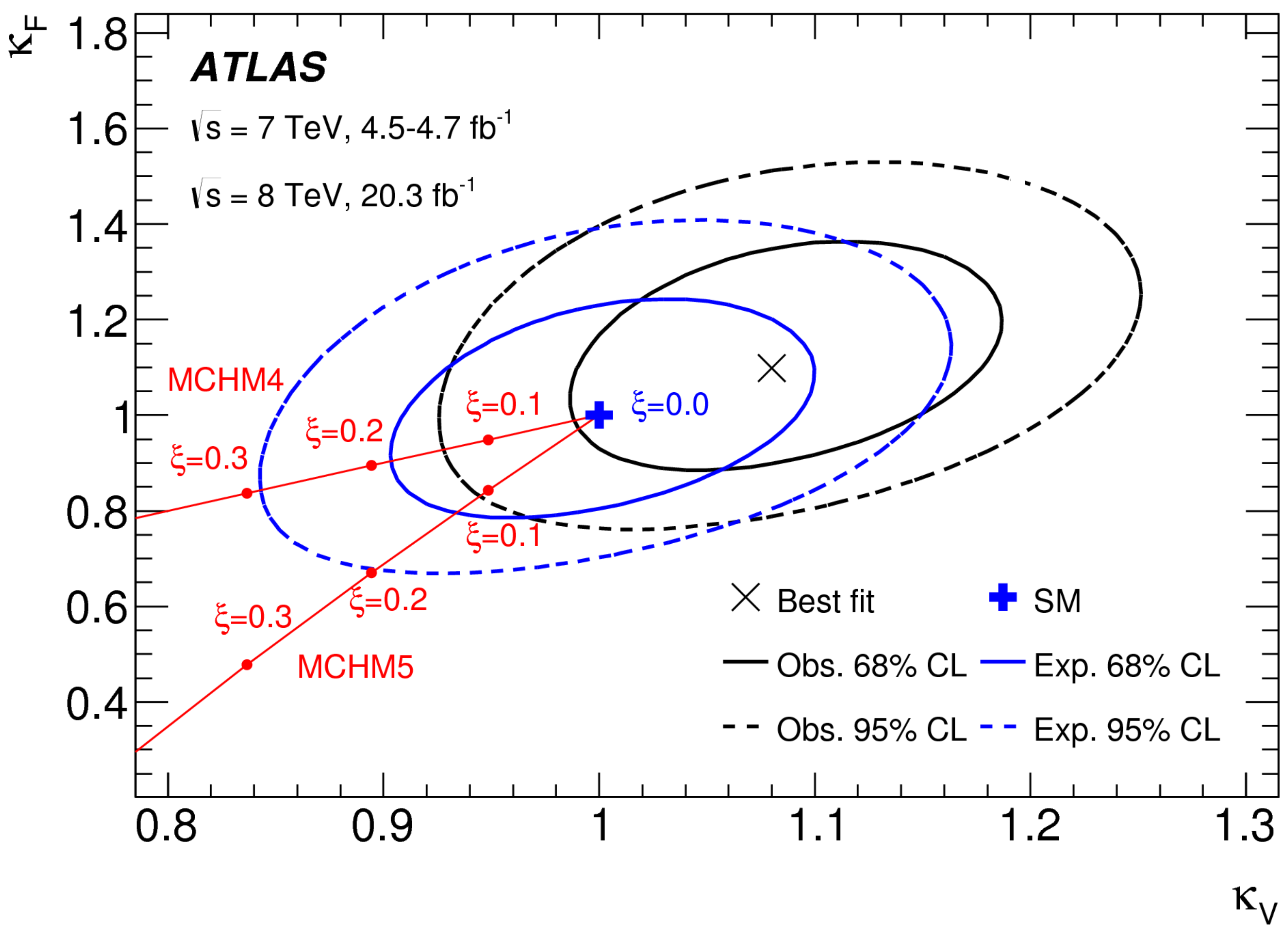
Interpretation of Couplings Measurements

Choosing suitable assumptions to probe interesting new physics scenarios

Probing the Gauge bosons vs fermions

Run 1 results

$$\xi = \frac{\delta g}{g} = \frac{v^2}{f^2}$$

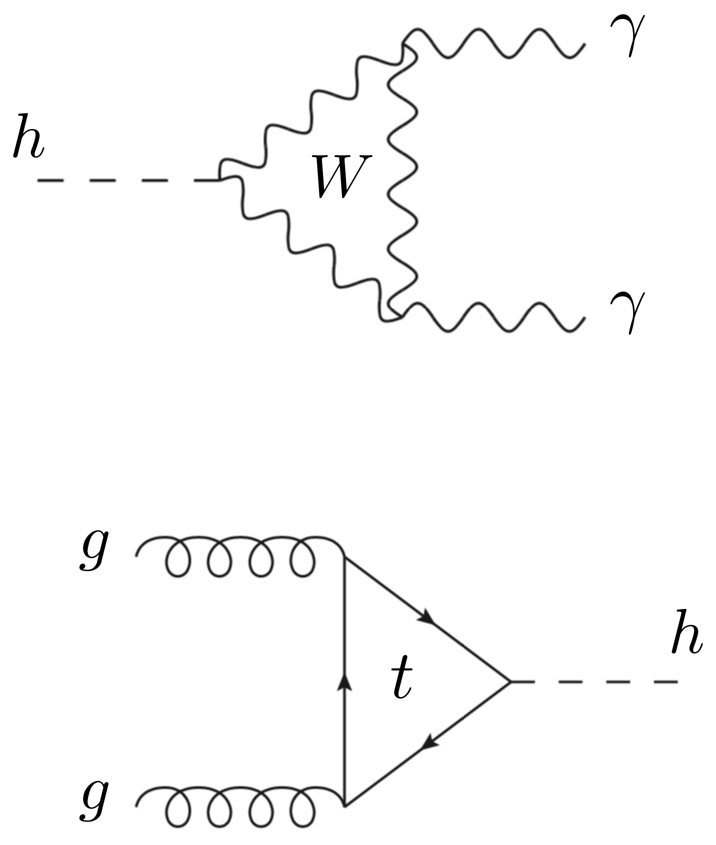


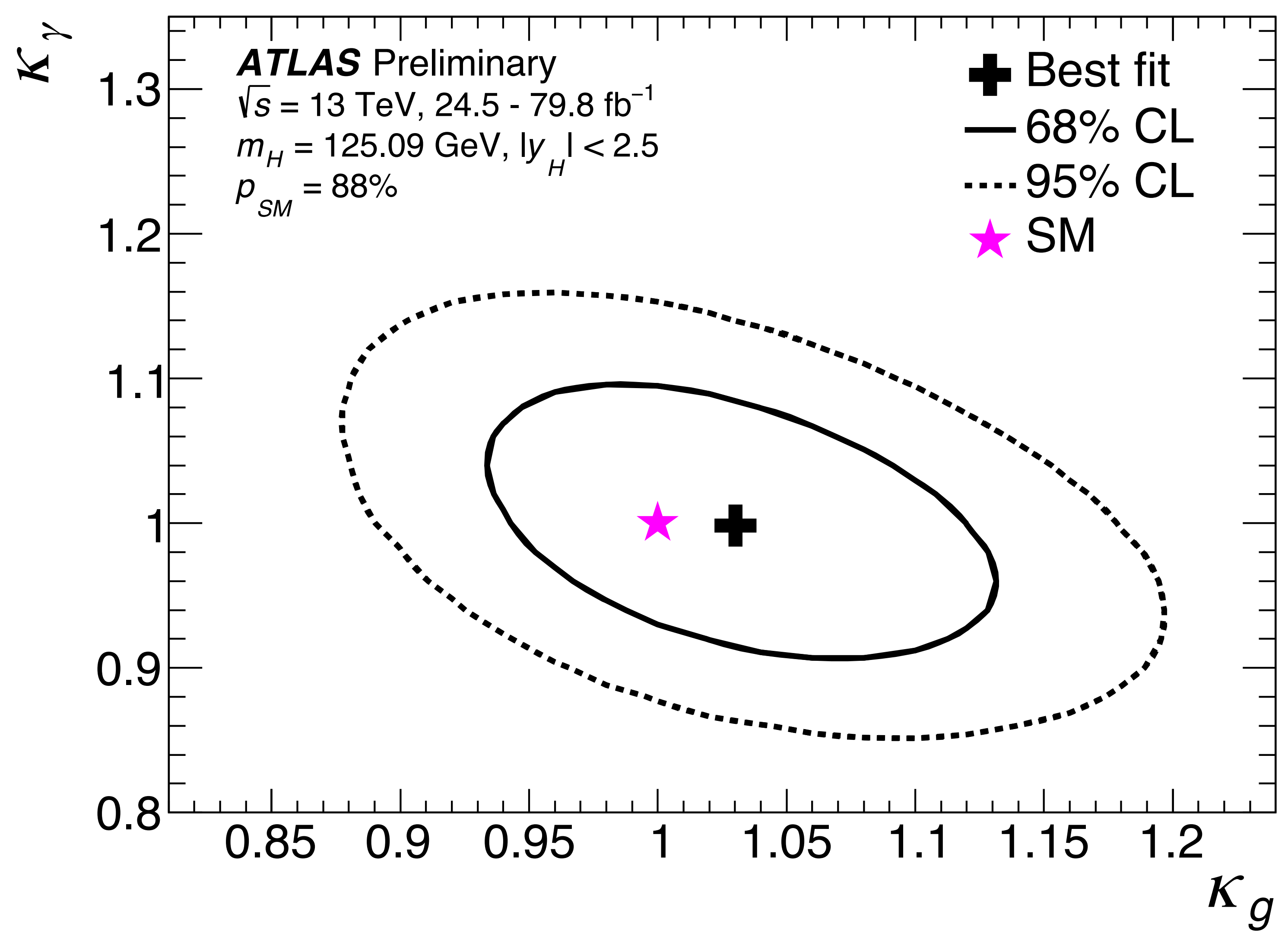
All fermion couplings are fixed to one parameter and similarly for all boson, the couplings to the gluons and the photons are resolved.

Constraining composite Higgs models to **f > 800 GeV**

Probing new particles in the loops

Run 1 results

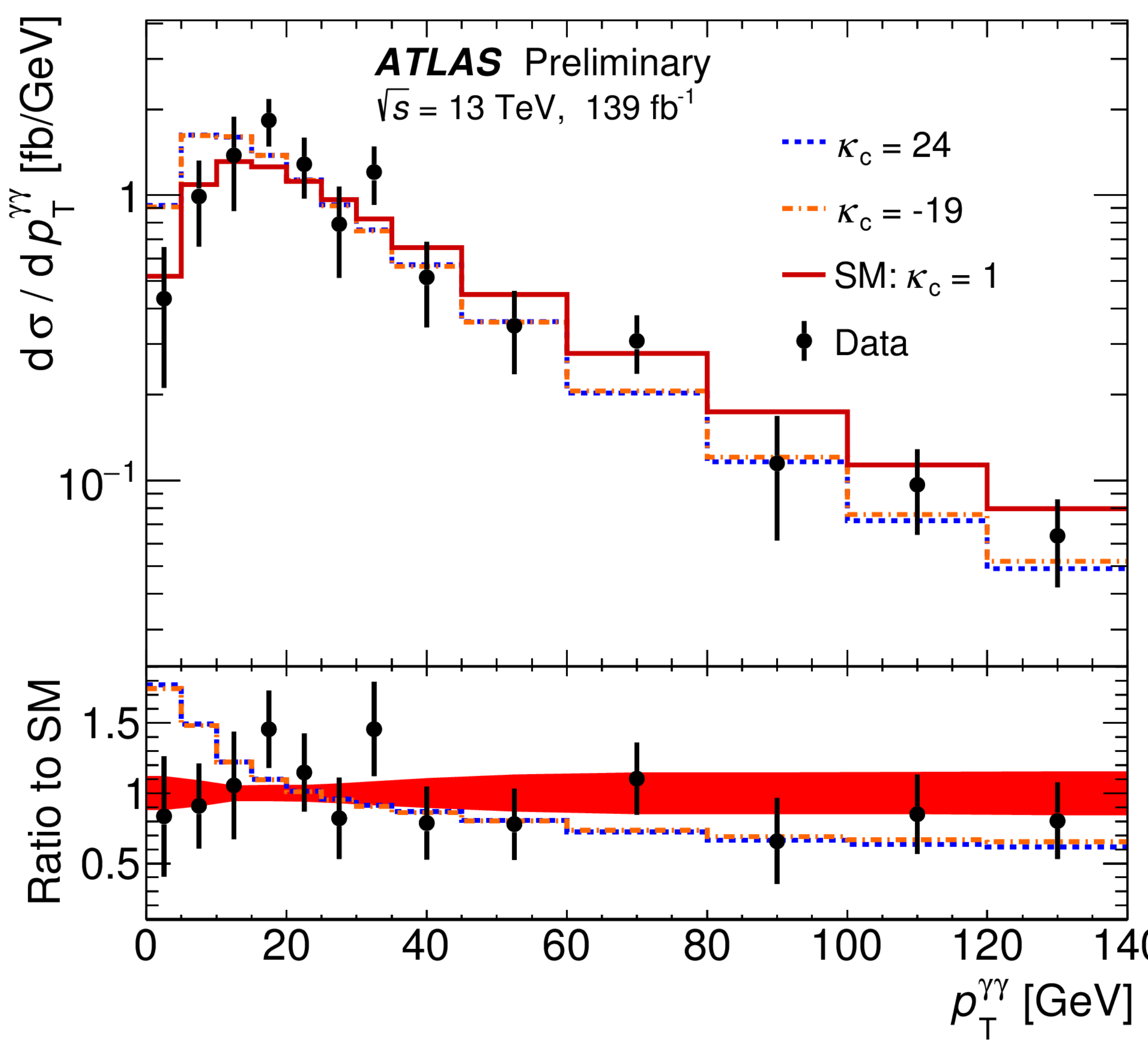


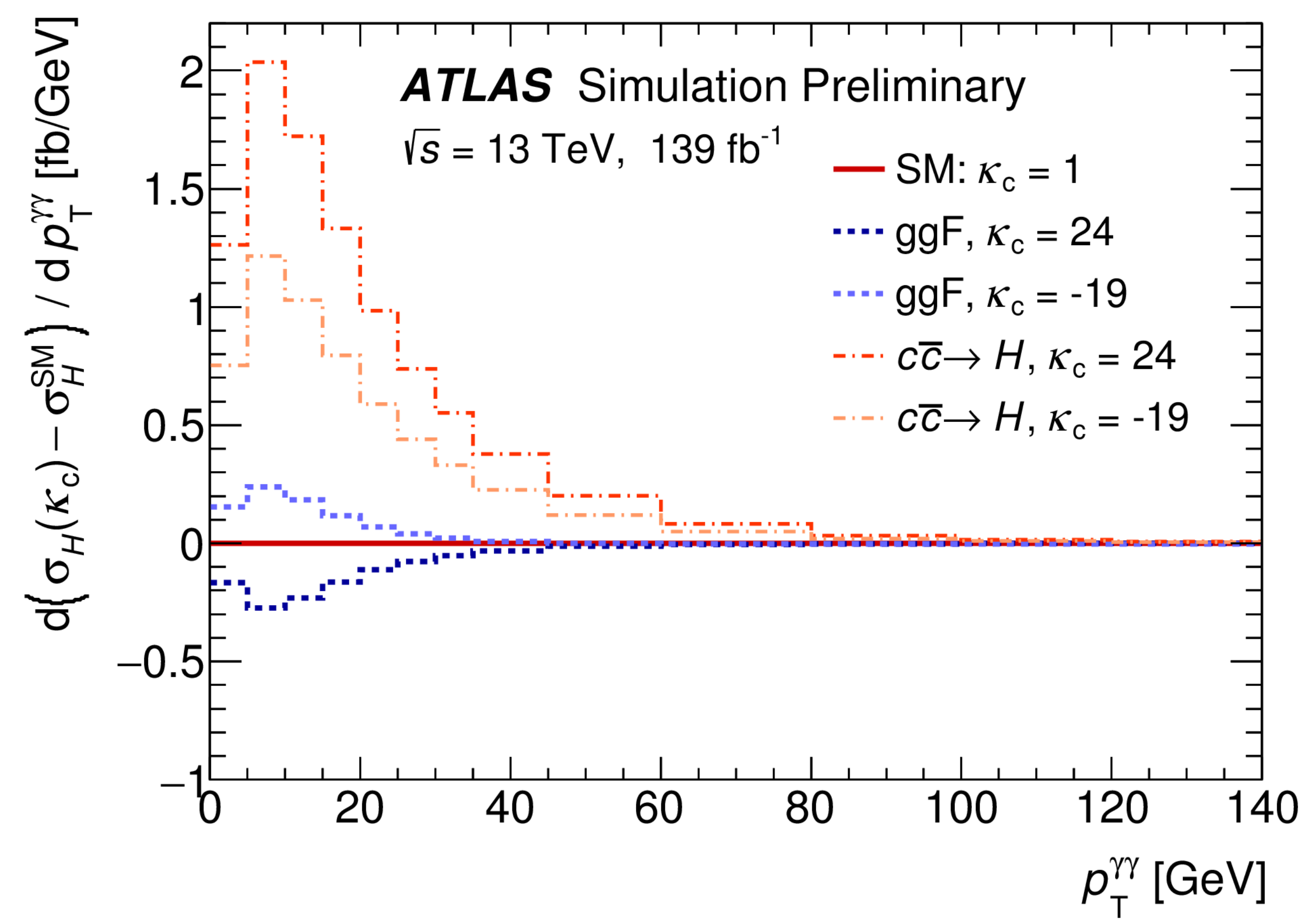


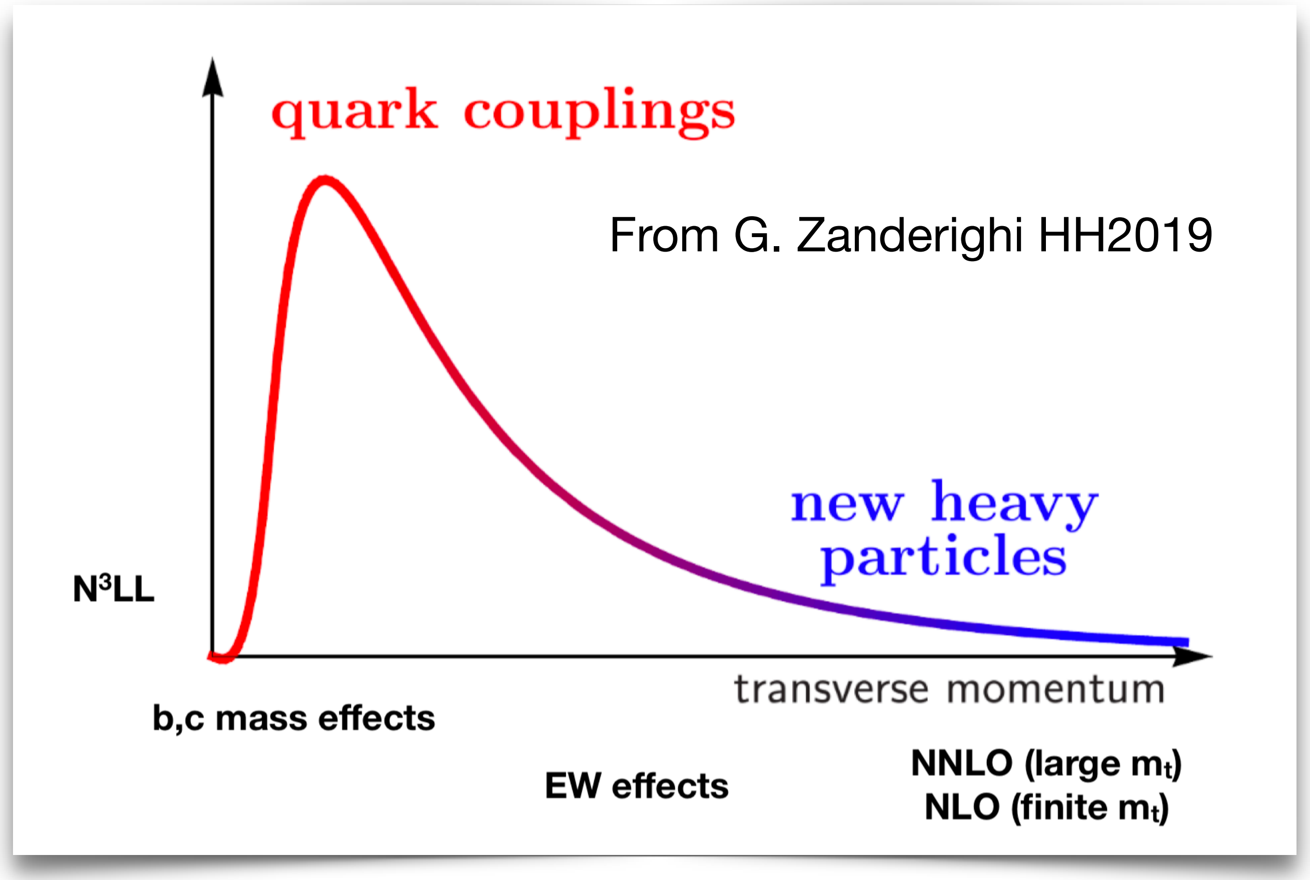
All couplings are set to their Standard Model value except the effective couplings to the photon and the gluon (probing new physics in the loops).

Differential (fiducial and unfolded) Cross Section Measurements

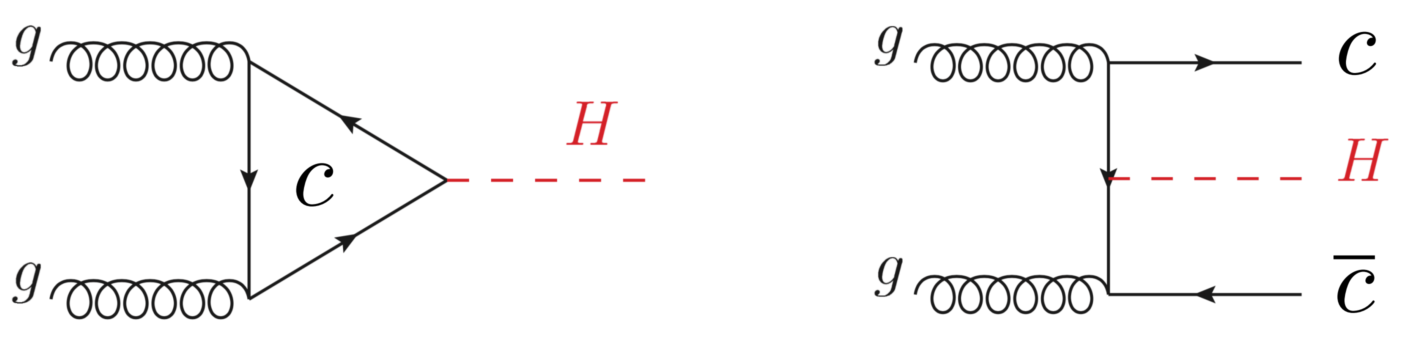
Fiducial and unfolded differential cross section measurement in pT







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



Significant at large values of κ_c

Current 95% CL limits on κ_c:

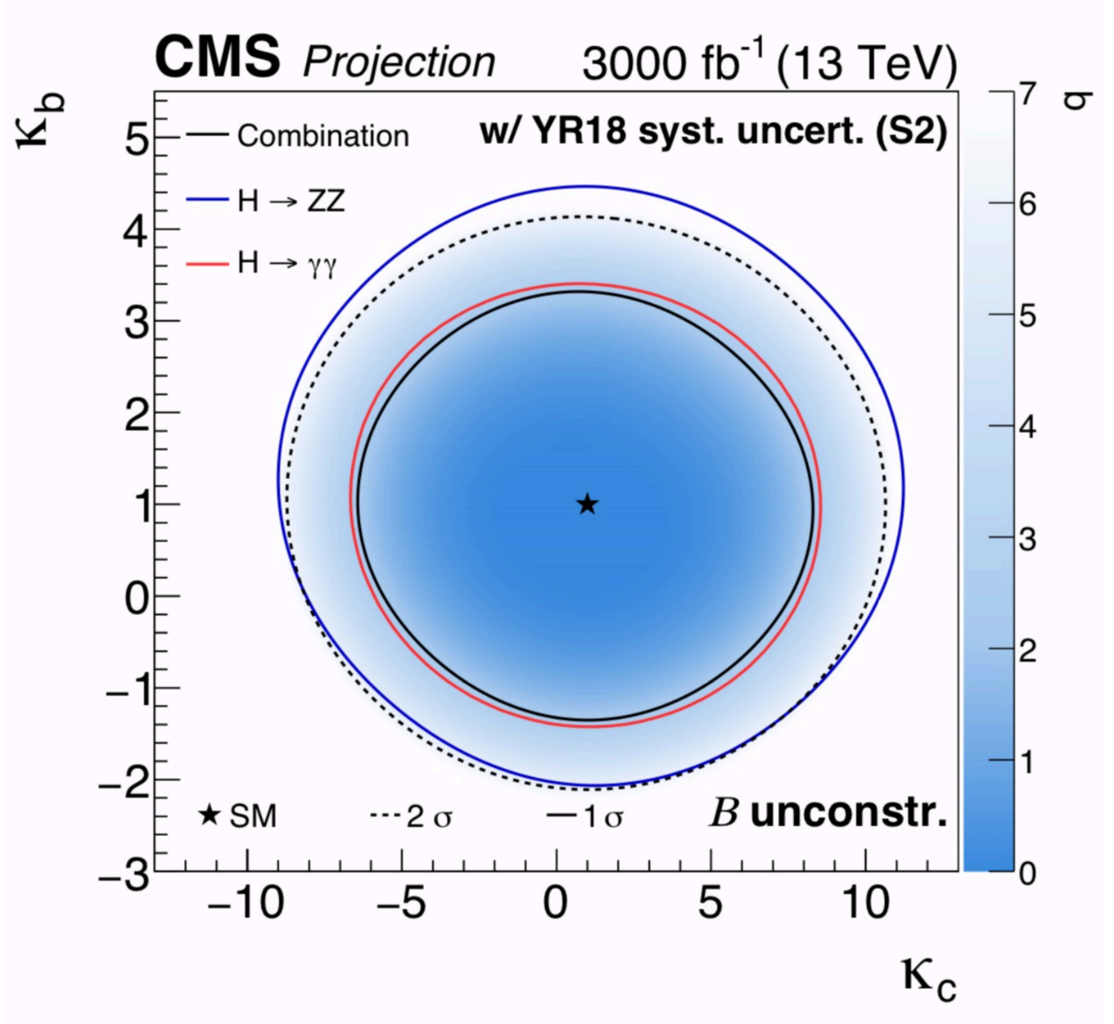
$$-19 < \kappa_c < 24$$

Searches for Higgs production with charm tagged are starting.

CMS HL-LHC projection (see YR)

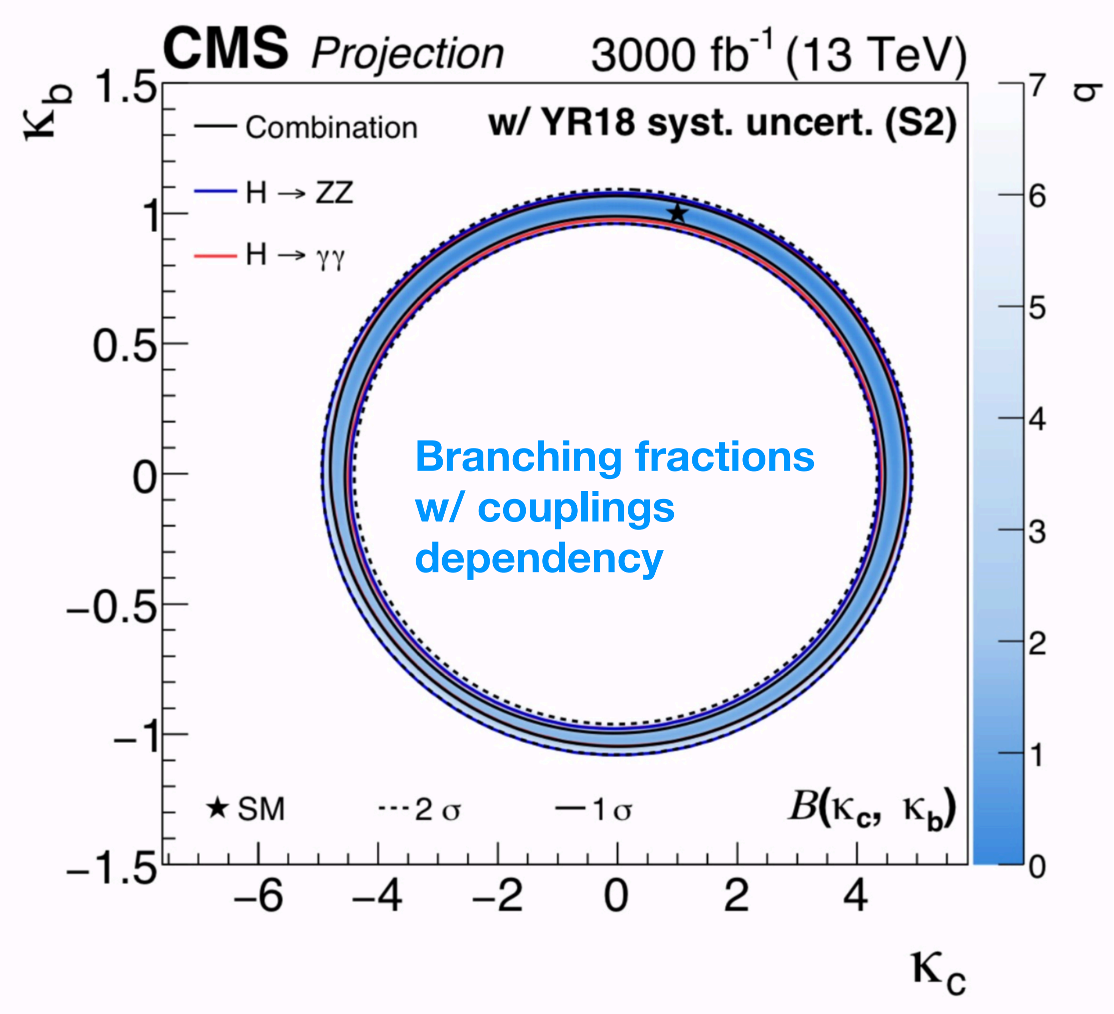
Shape only

~8 x SM



Parametrised branchings

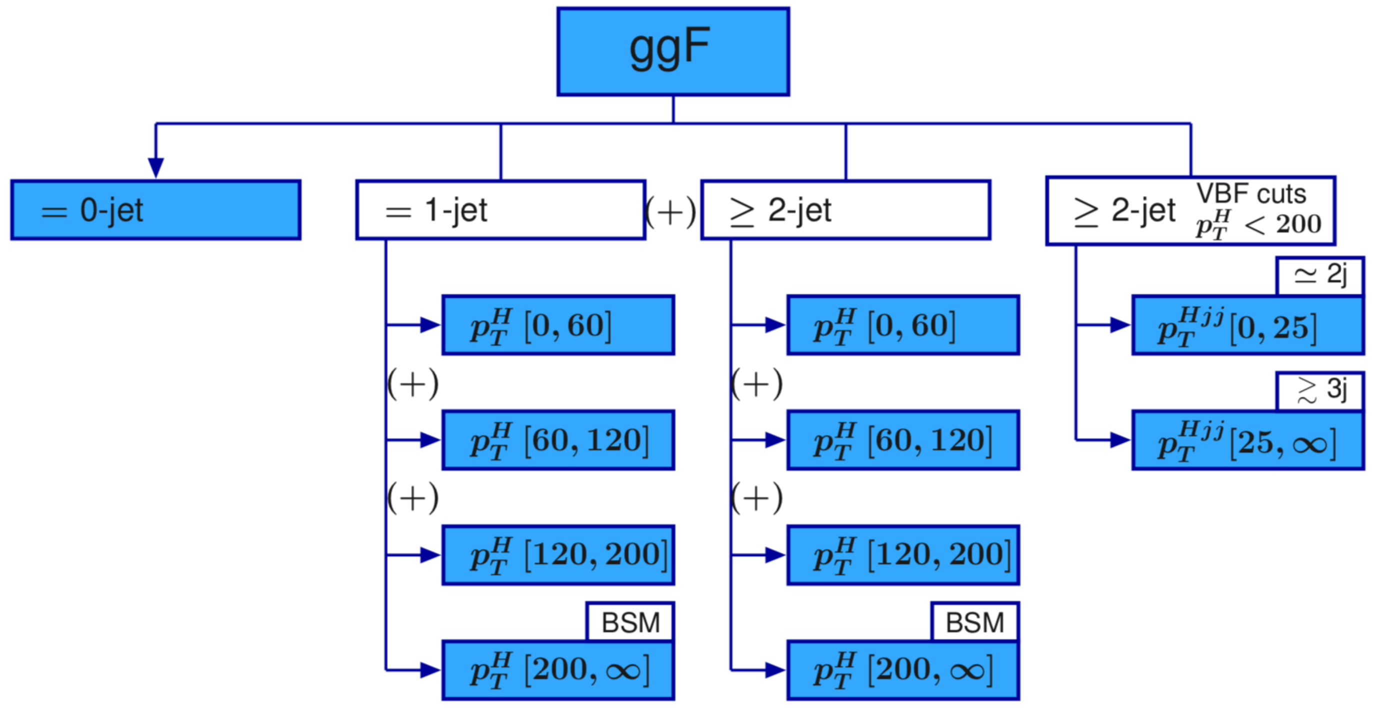
~4 x SM



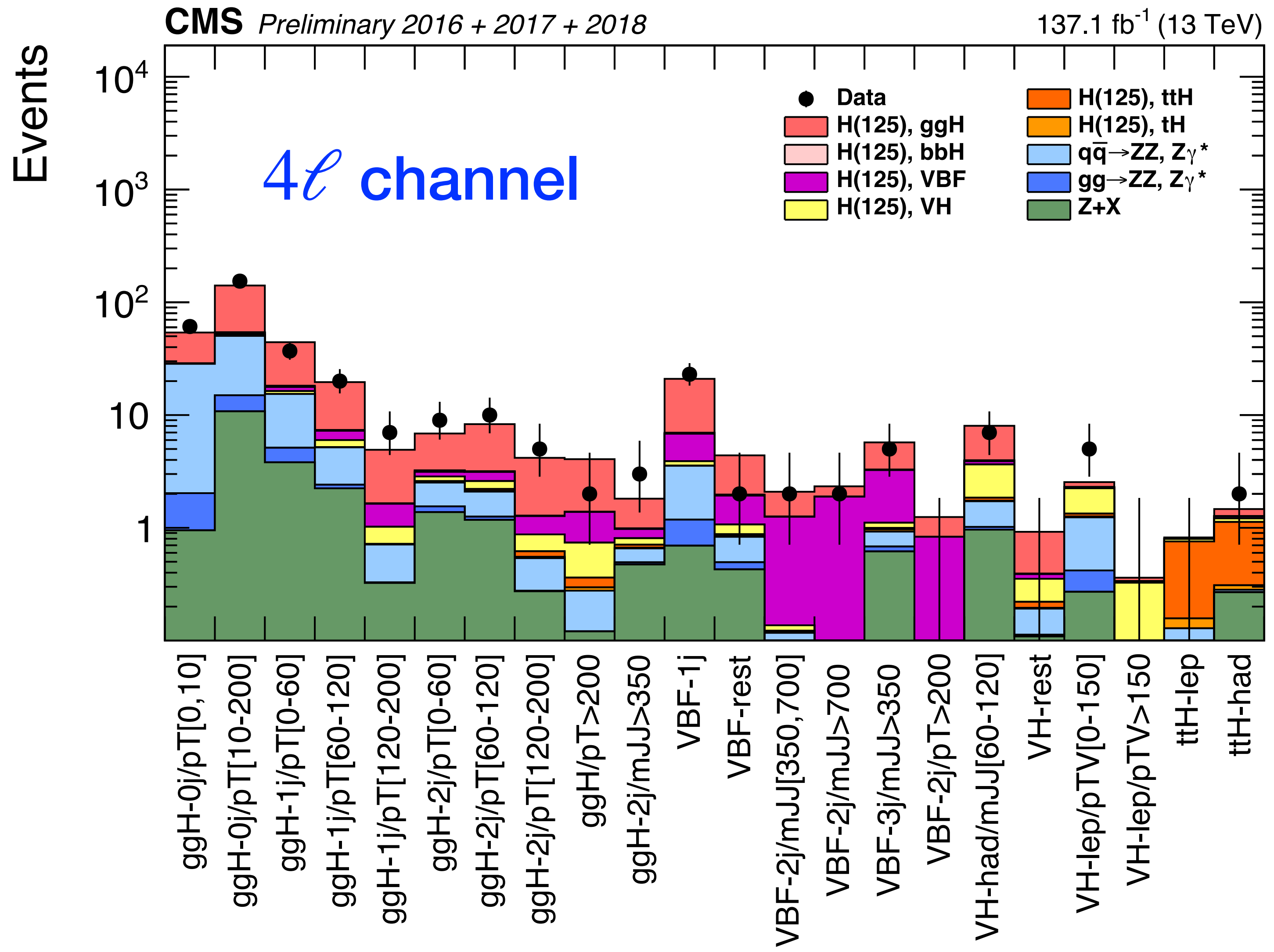
Hybrid Fiducial Approach: Simplified Template Cross Sections

w.r.t. purely fiducial: allows to **combine decay channels** and use **multivariate techniques** in specific channels. **Compromise** as both aspects increase the extrapolation.

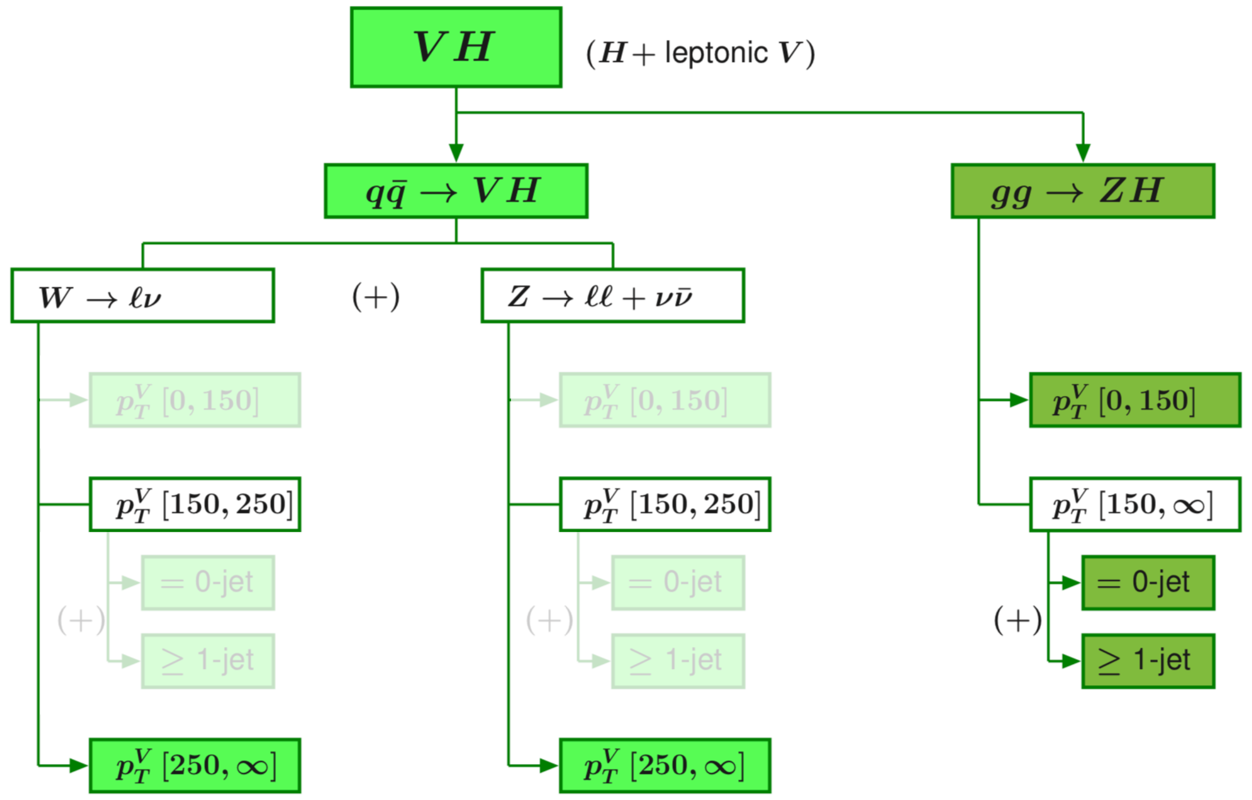
"**Inclusive**" (and most other channels) covered by discovery channels

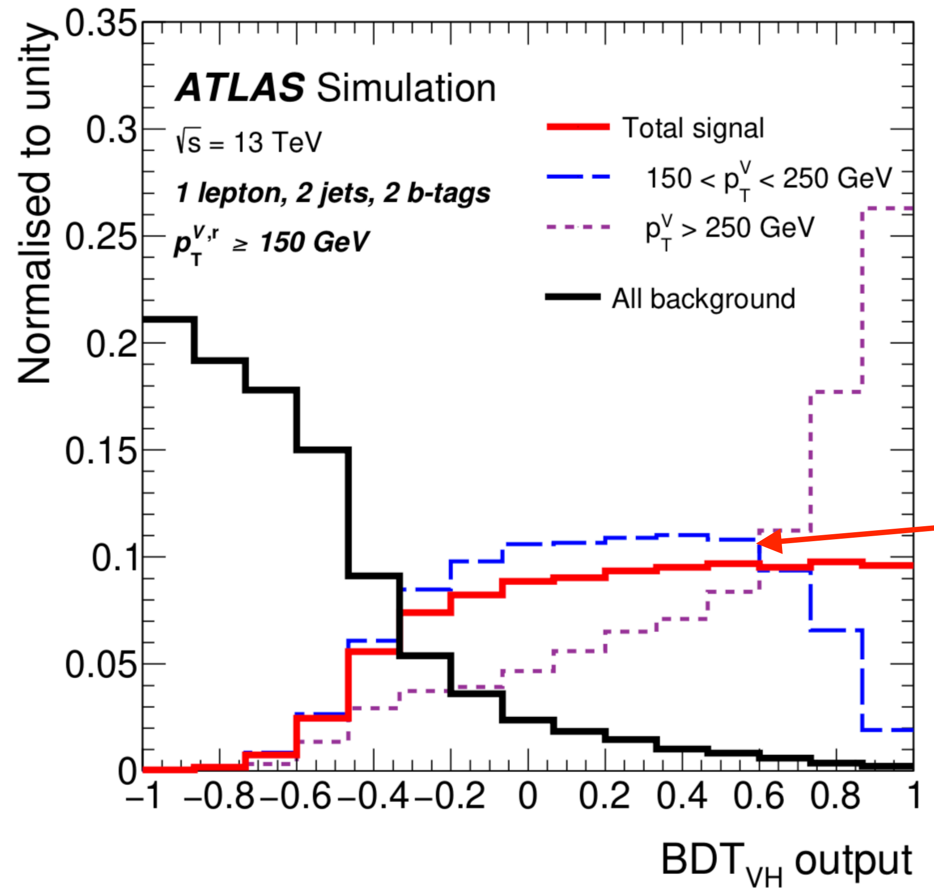


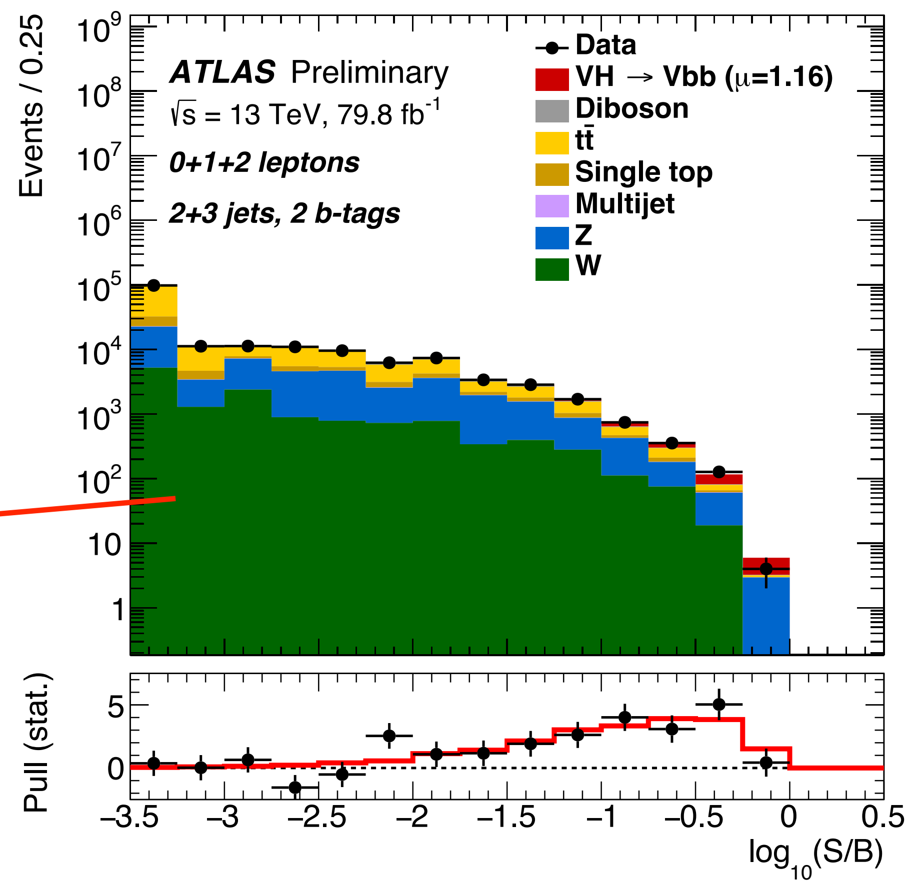
CMS-PAS-HIG-19-001



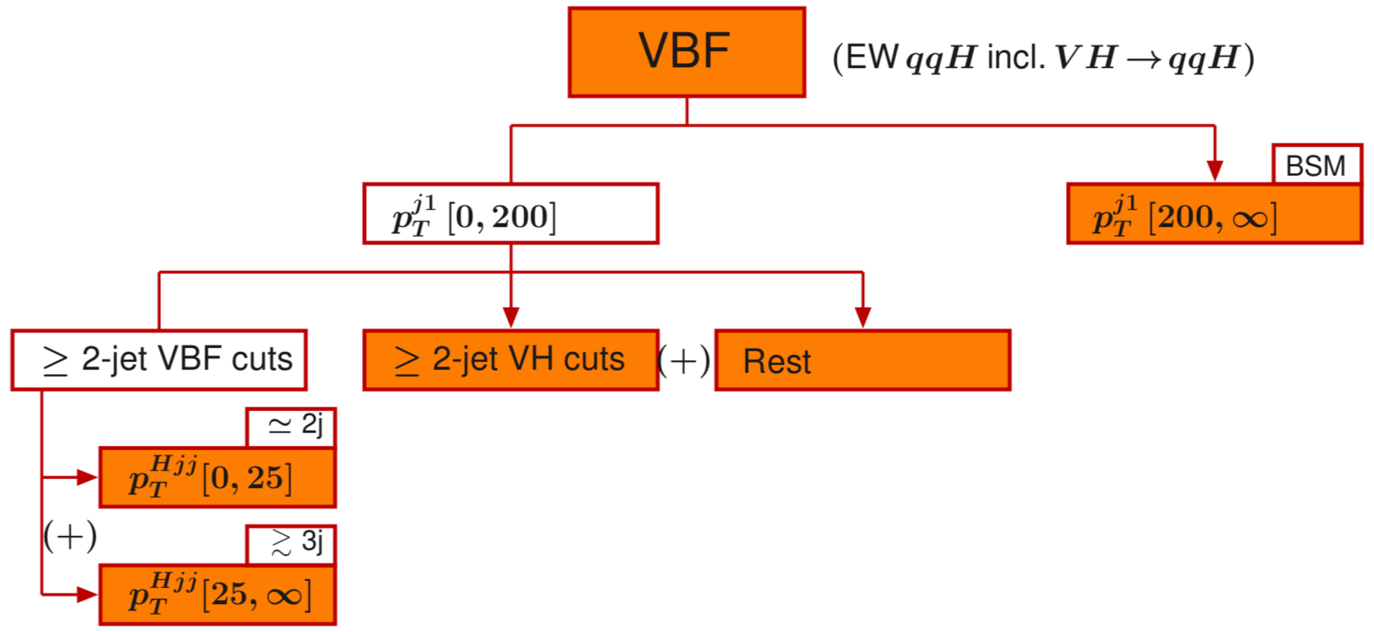
VH covered at high pT also by VH(bb)

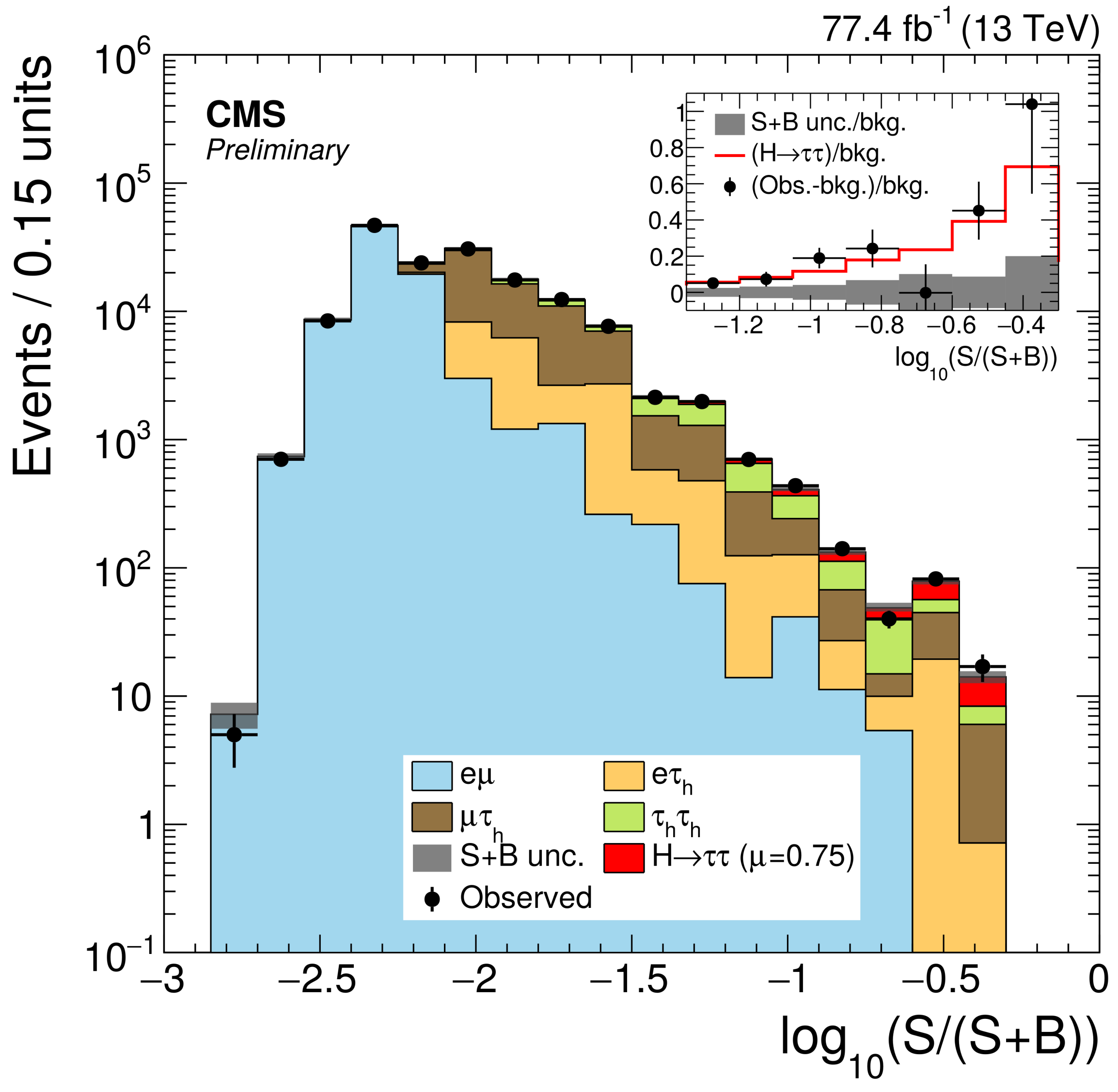


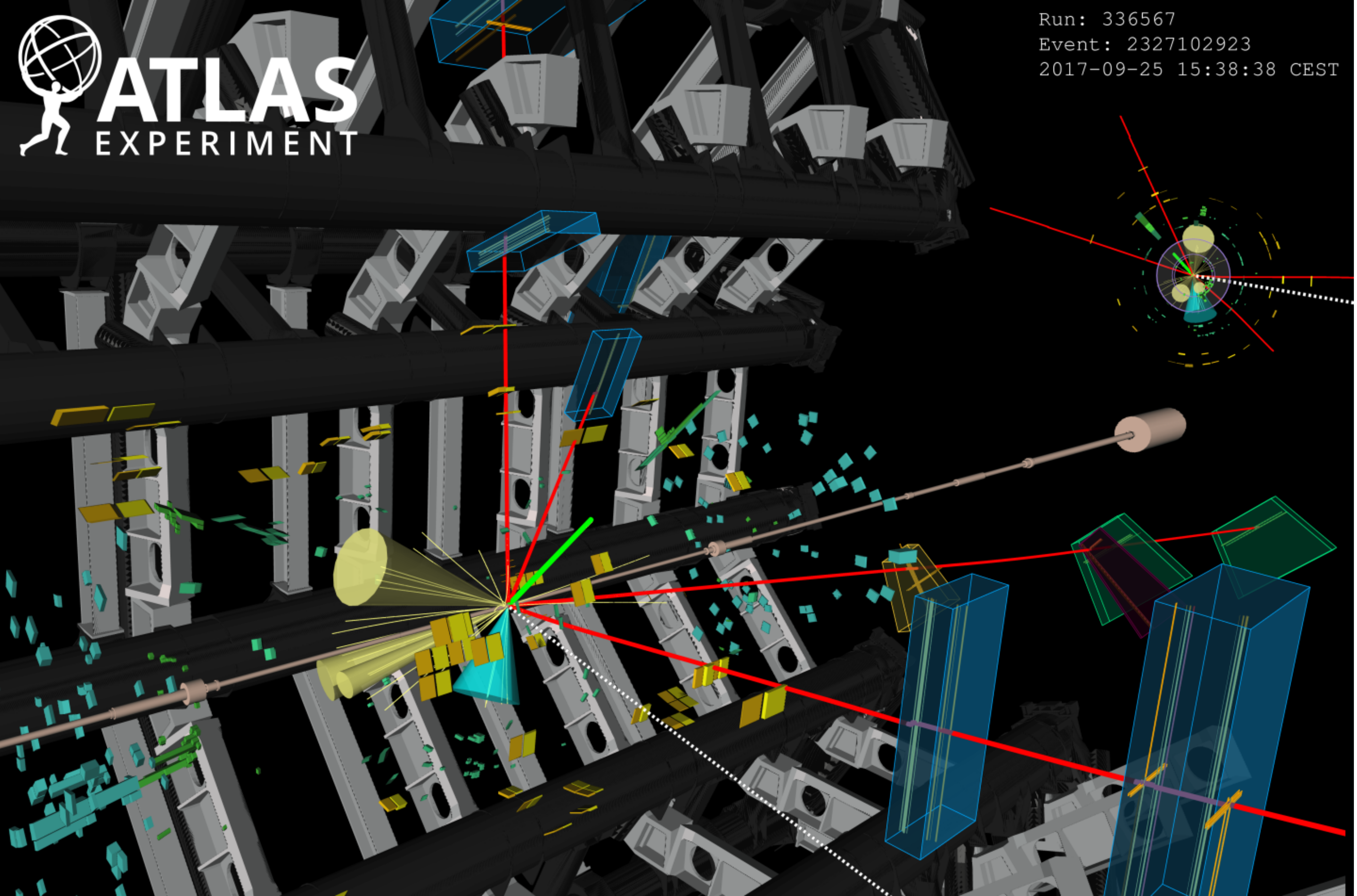




VBF covered at high pT also by VH(tau-tau)







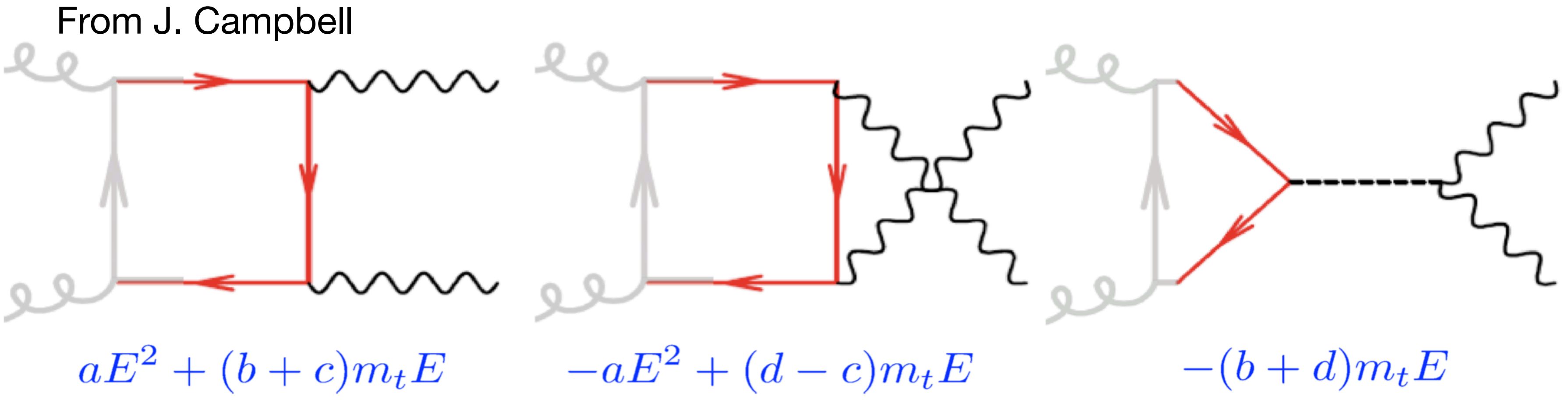
4 muon event with mass 124.4 GeV, one Z mass of 89,3 GeV and the lower mass of 33 GeV, one electron, four jets, lowest pT has tighest b-tagging.

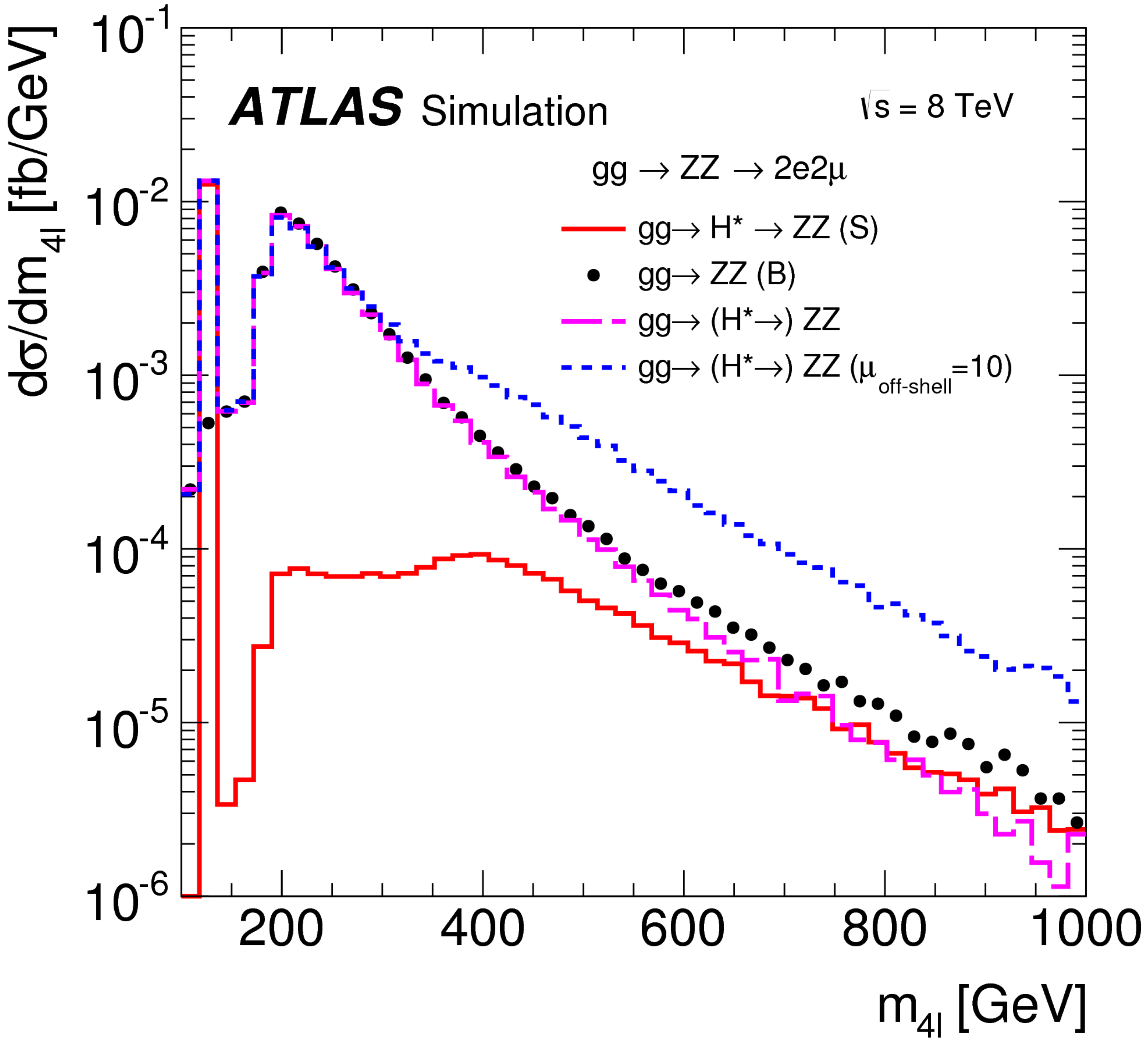
$$s/b \sim 30$$

Off Shell Higgs

Study the Higgs boson as a propagator

Study the 4-leptons spectrum in the high mass regime where the Higgs boson acts as a propagator



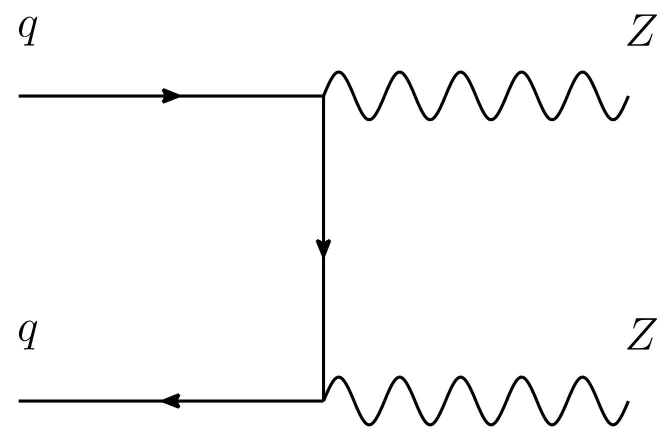


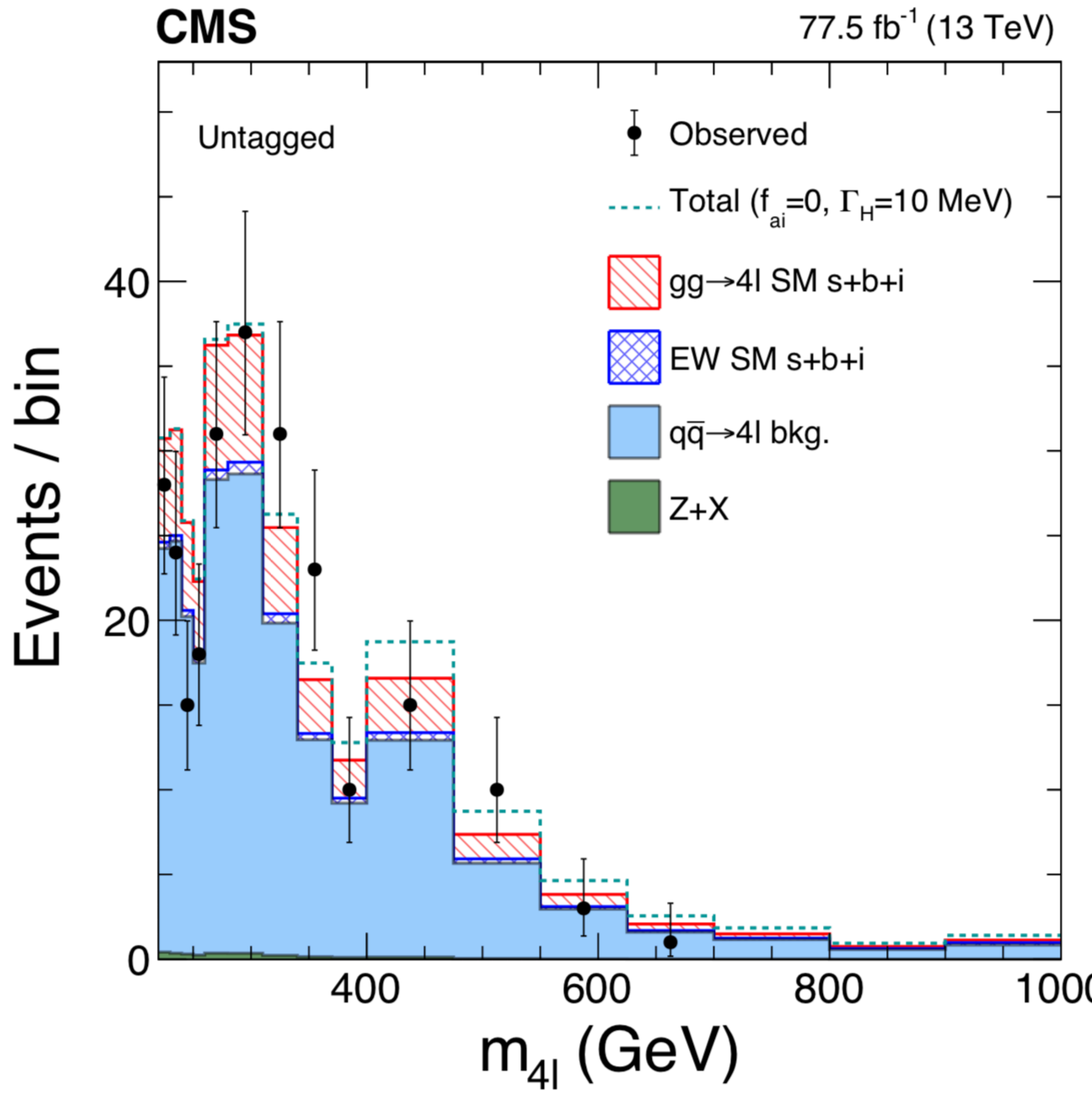
Measuring the Higgs contribution is then independent of the total width of the Higgs boson (sensitive to the product off shell of the Higgs boson to the coupling to the top and Z)

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!

Highly non trivial due to:

- The negative interference
- The large other backgrounds





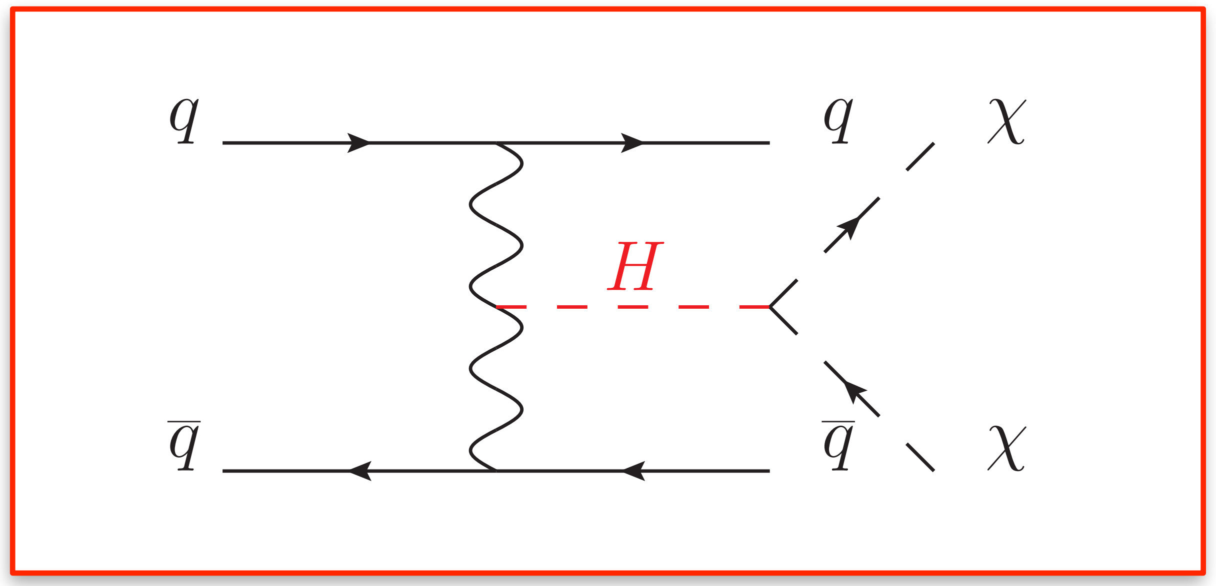
Limits on the total width are currently at approximately **10 MeV** (and exclude 0 at 95% CL).

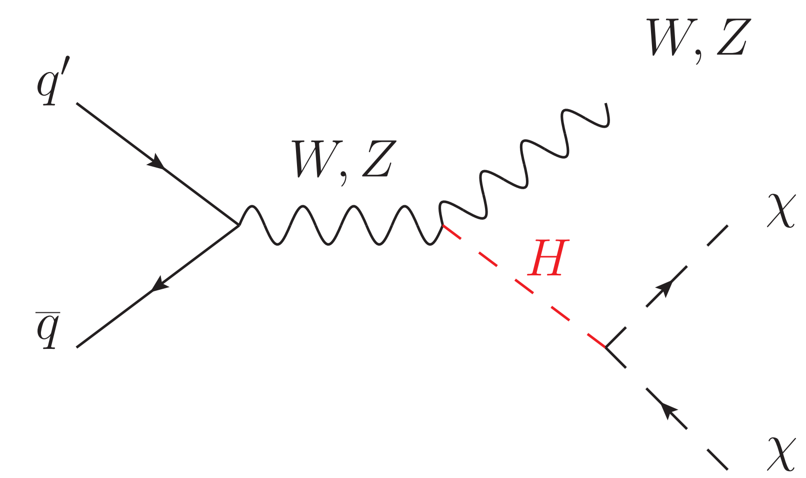
HL-LHC: $\Gamma_H = 4.1^{+1.0}_{-1.1}$ MeV

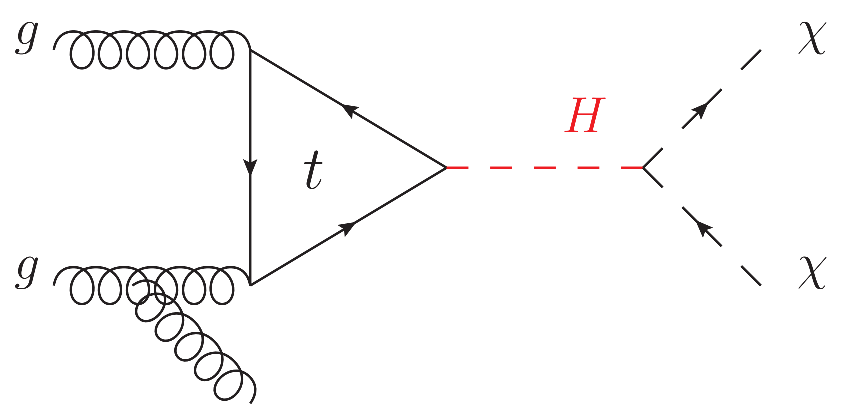
Preliminary HL-LHC results show that a reasonable sensitivity can be obtained with 3 ab^{-1}

Future-ee 0.2%

Invisible decays of the Higgs boson

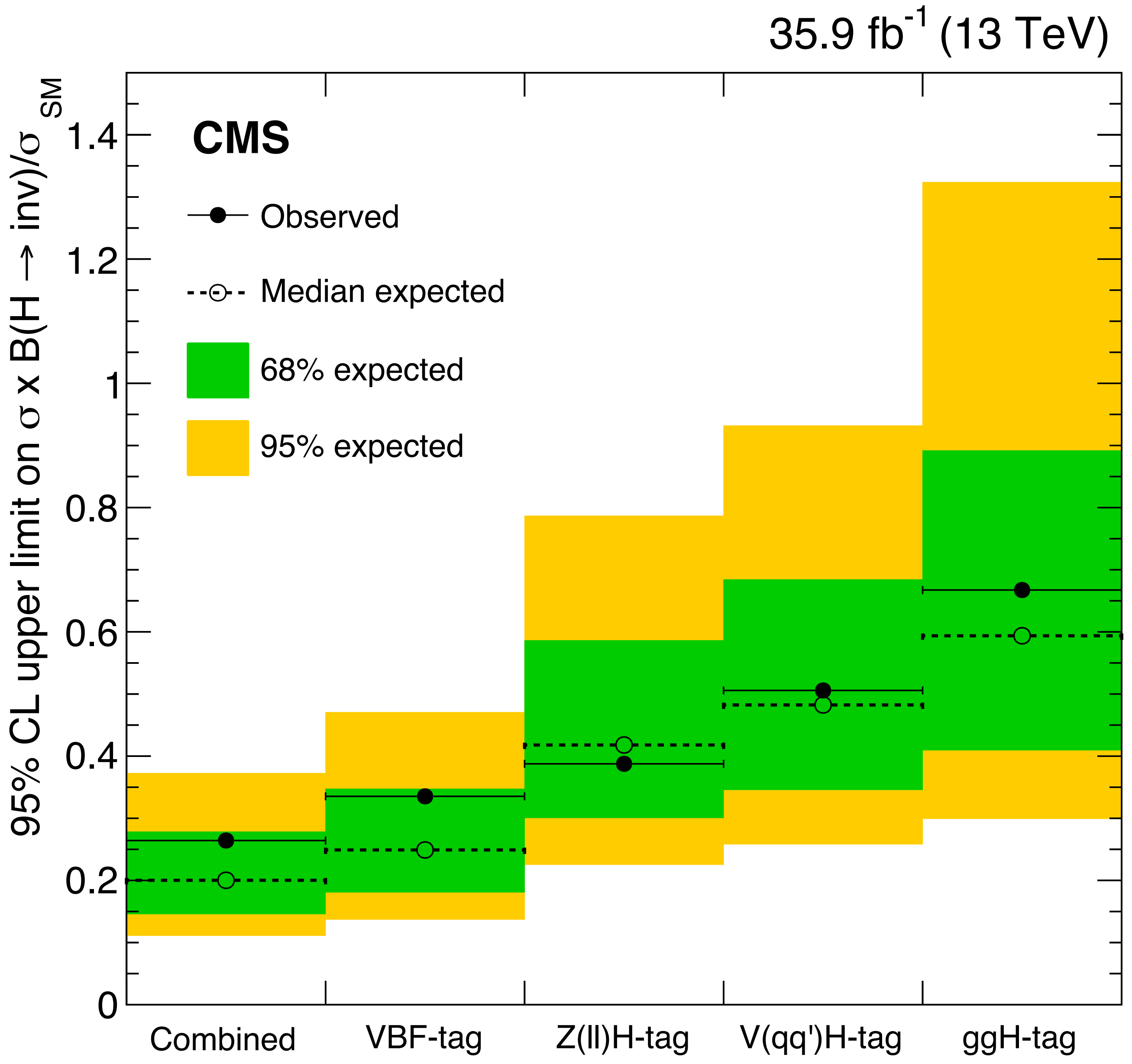




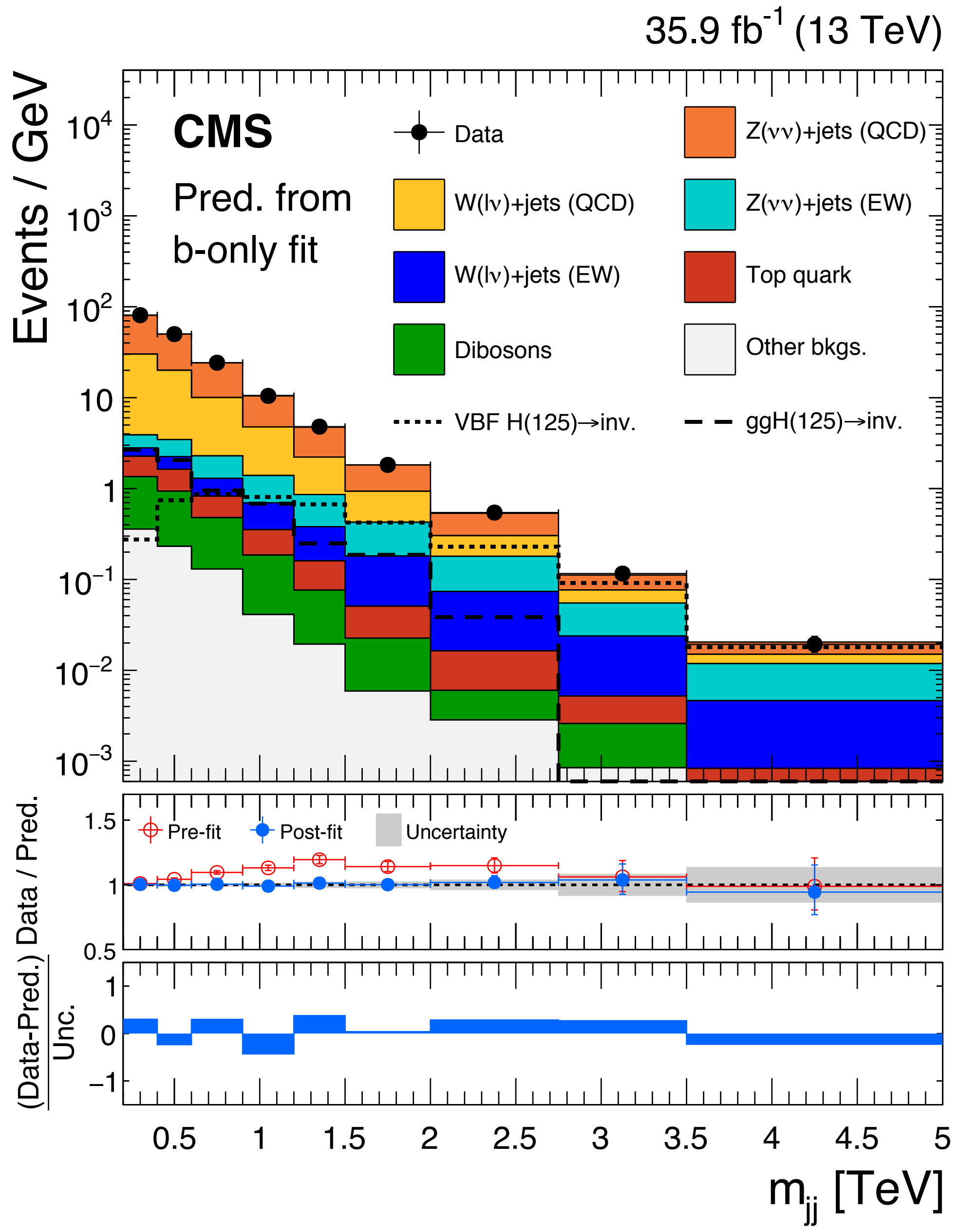


Comprehensive analysis of several channels and several datasets by CMS, to give current level of sensitivity on invisible branching fraction.

- Includes a mono-V hadronic boosted mode
- VBF is the most sensitive channel
- Challenge is the estimate of the V-jets backgrounds: estimated from control regions using W, Z and photon-jet events.
- Recently include ttH (CMS)

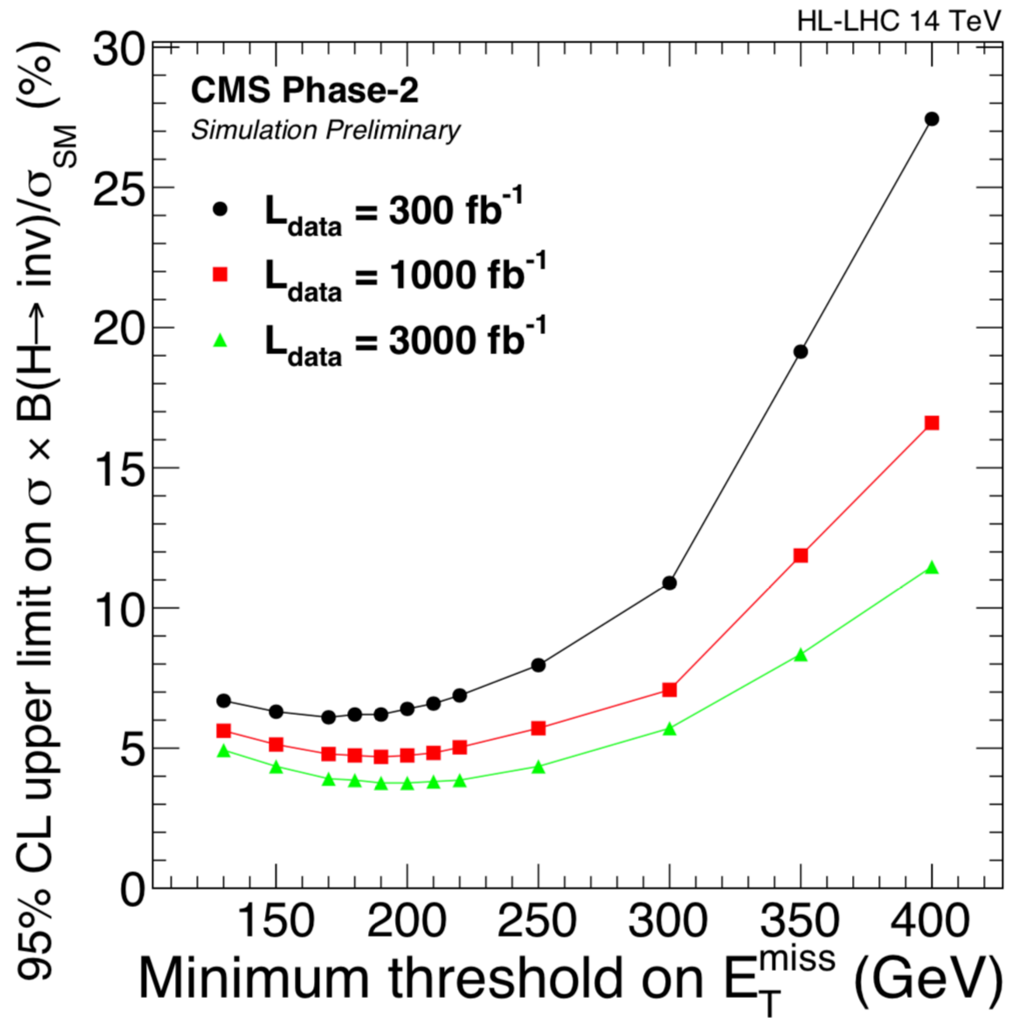


$$\mathrm{Br_{inv.}} < 0.19\ (0.15)$$



These results are still with a **very small Run 2 dataset!**

Projection at HL-LHC in the VBF channel (single experiment):



FTR 18-016

$$Br_{inv} < 3.8\%$$

Combination VH and VBF and consider ATLAS ~ CMS

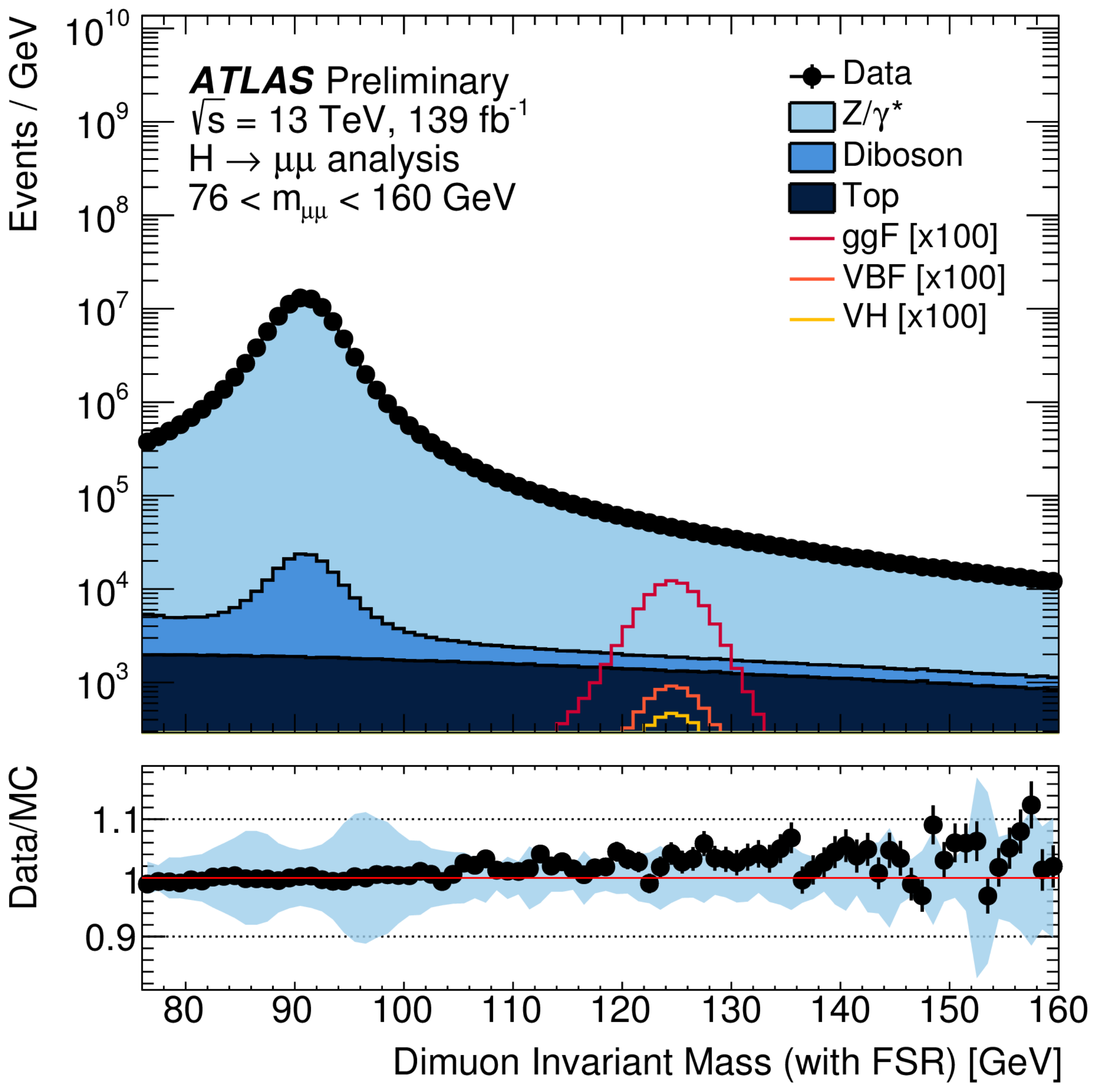
$$Br_{inv} < 2.5\%$$

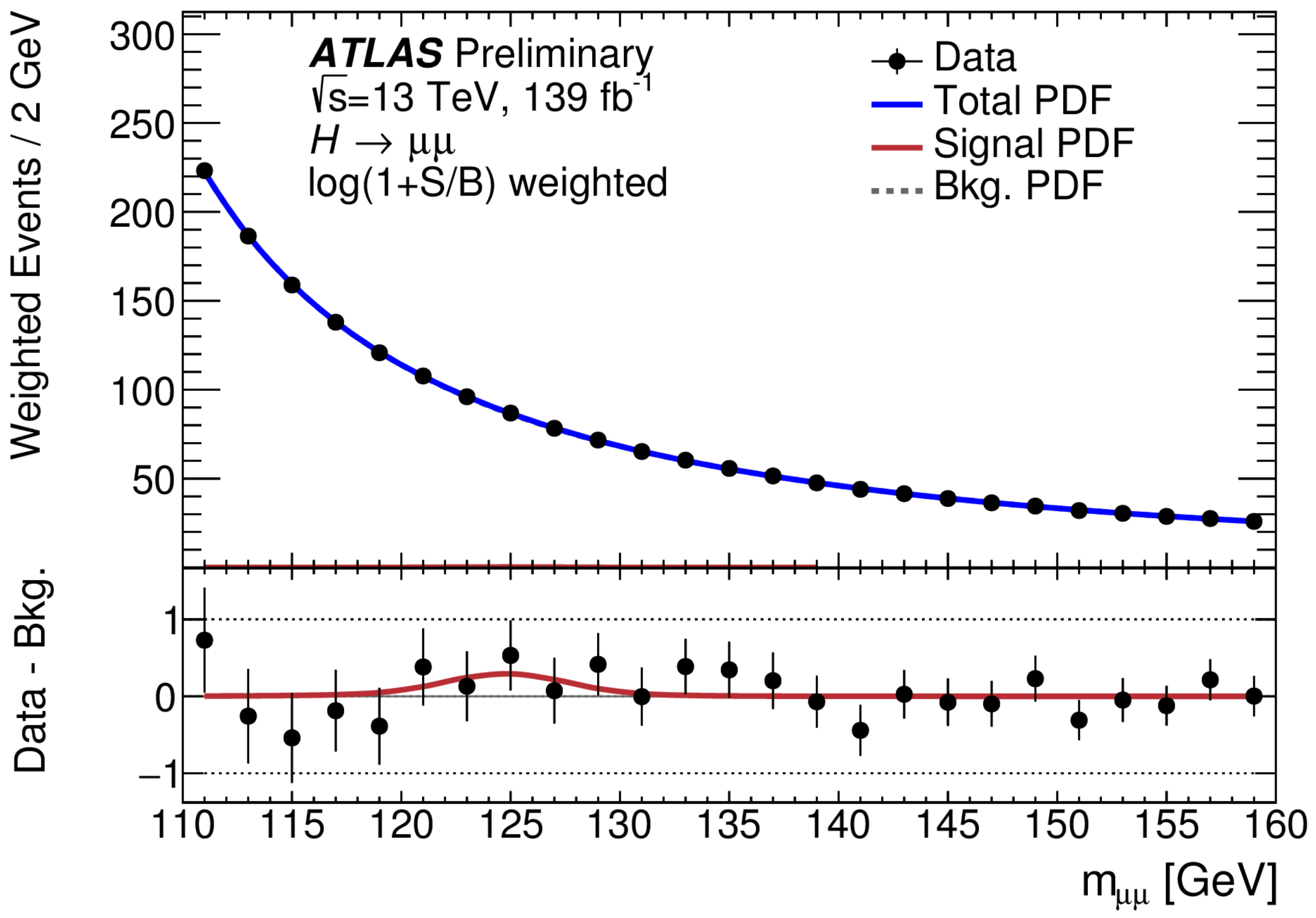
Still room for improvement but sensitivity already slower than pure statistics

Second Generation Yukawa Coupling

The dimuon channel: very challenging, various ways to constrain

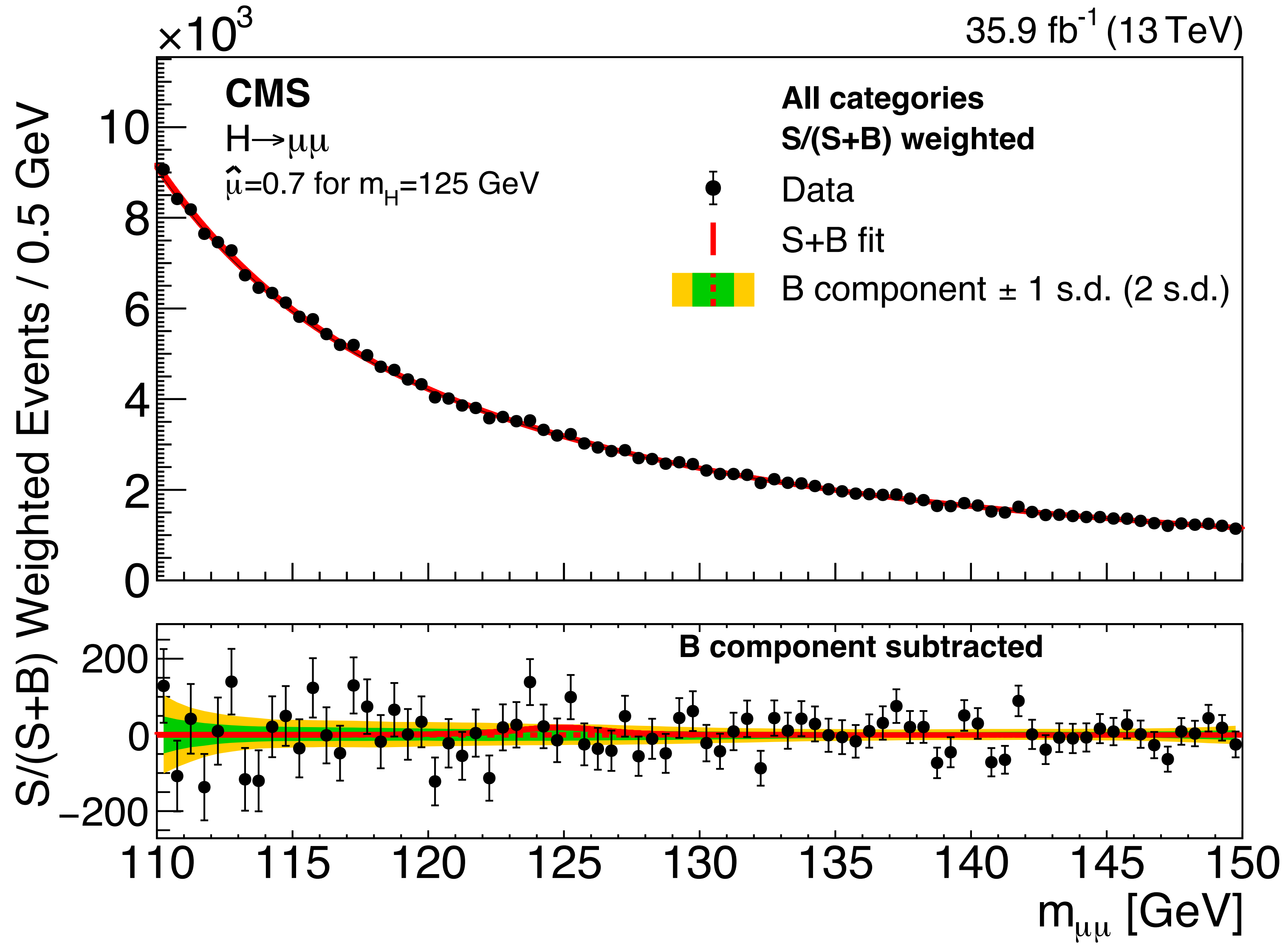
- Approximately 2k events produced but very small signal-to-noise ratio ~0.2% (inclusive)
- Requires a very accurate description of the backgrounds.
- CMS has only analysed 35 fb-1 with a sensitivity of already ~1σ





ATLAS currently ~2 x SM

0.8σ observed (1.5σ exp)



Very rough projection CMS with 140 fb-1 should reach approximately 2σ sensitivity so the combination about 2.5σ

With 300 fb-1 Additional, at Run 3 a combined significance of approximately 4σ should be reachable i.e. a first evidence.

HL-LHC ~5%

More on the 2d Generation (charm) Yukawa Couplings

Very challenging, various ways to constrain

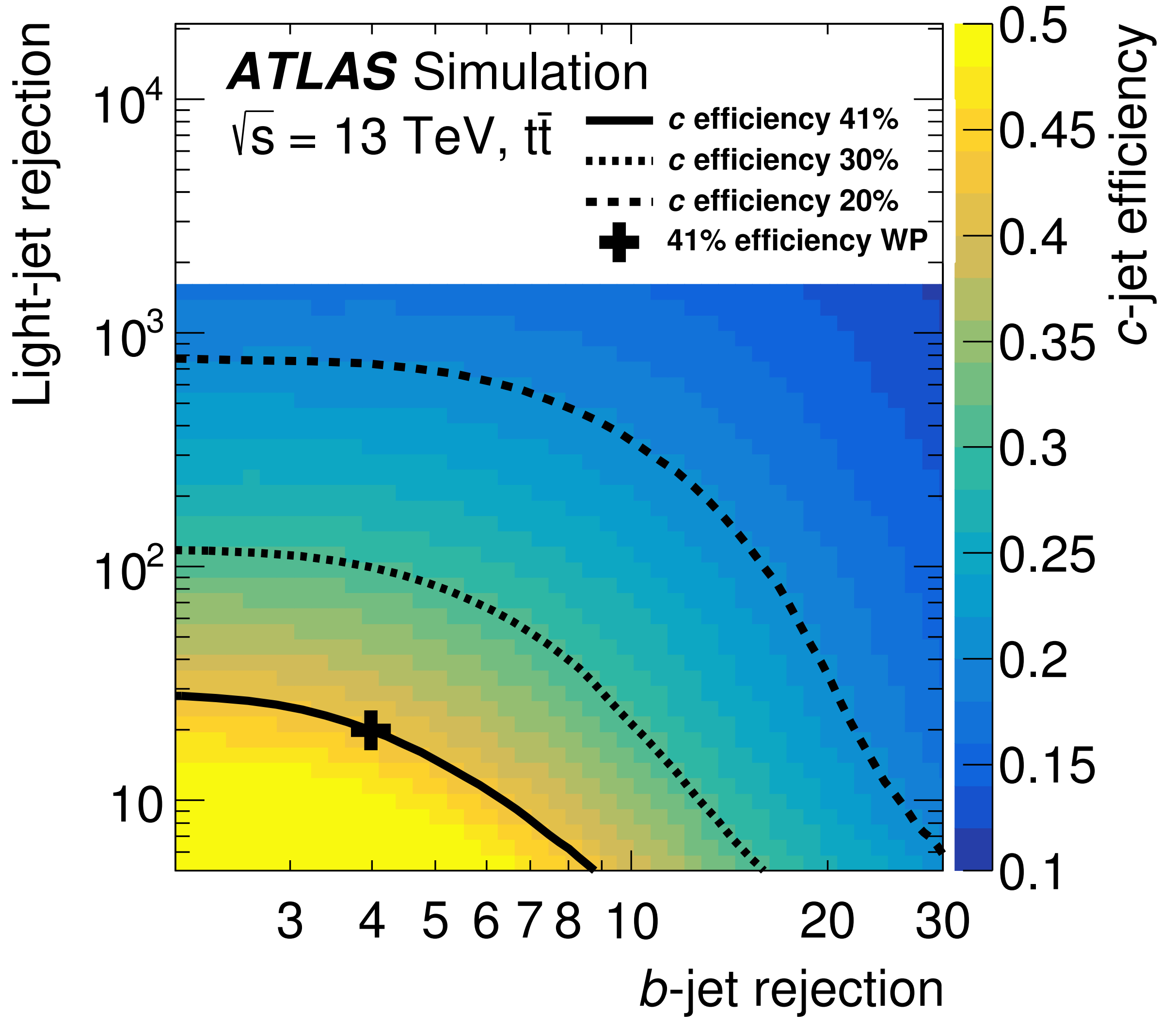
- VH(cc) direct detection, relies on ability to distinguish b and c jets, using charm tagging (based on the charm decay length comprised between b jets and light jets) - based on deep neural network techniques.

- Differential cross sections (as discussed previously in slide 27)

- Charmonium-photon exclusive decays

- WH production charge asymmetry (PDFs)

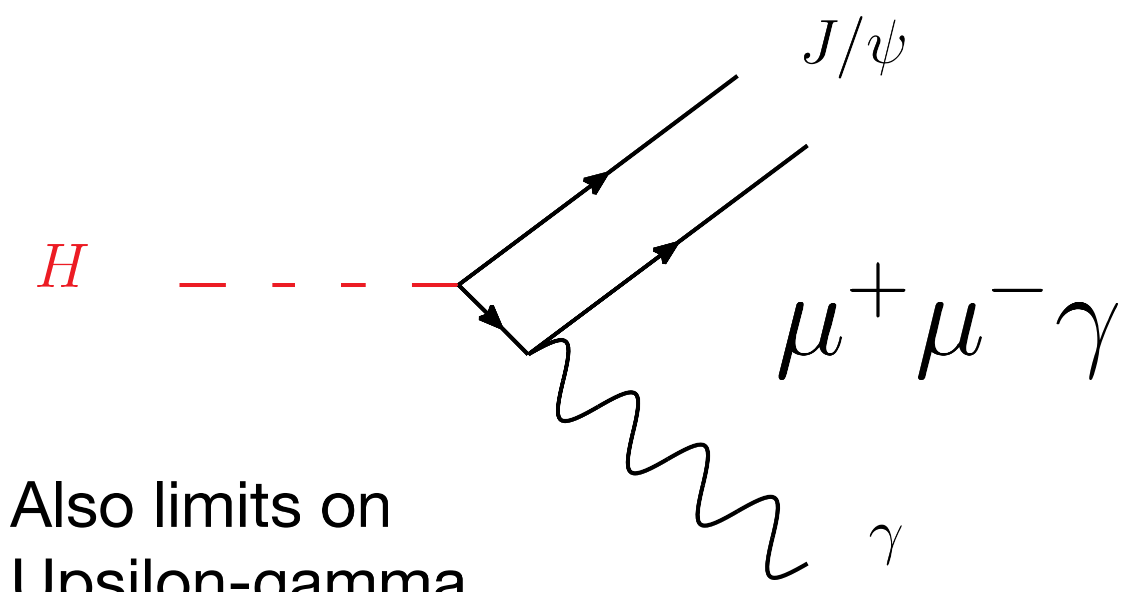
- Total width from the couplings fit (will be discussed in slide 30)



Run 2
(ATLAS and CMS)
<50xSM

HL-LHC
<6xSM

Potentially sensitive to charm Yukawa

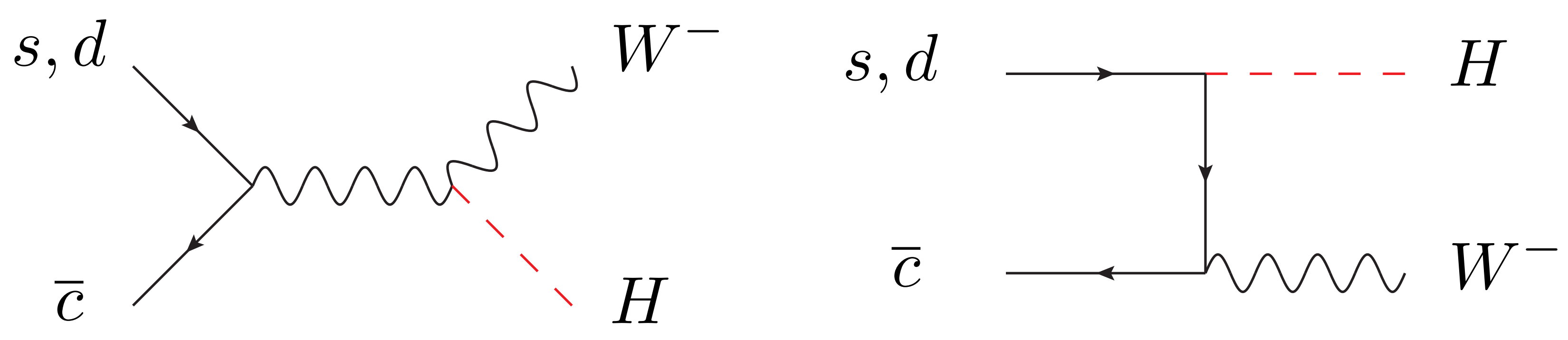


Also limits on Upsilon-gamma

Sensitivity to gamma-gamma* (top loop) and interference

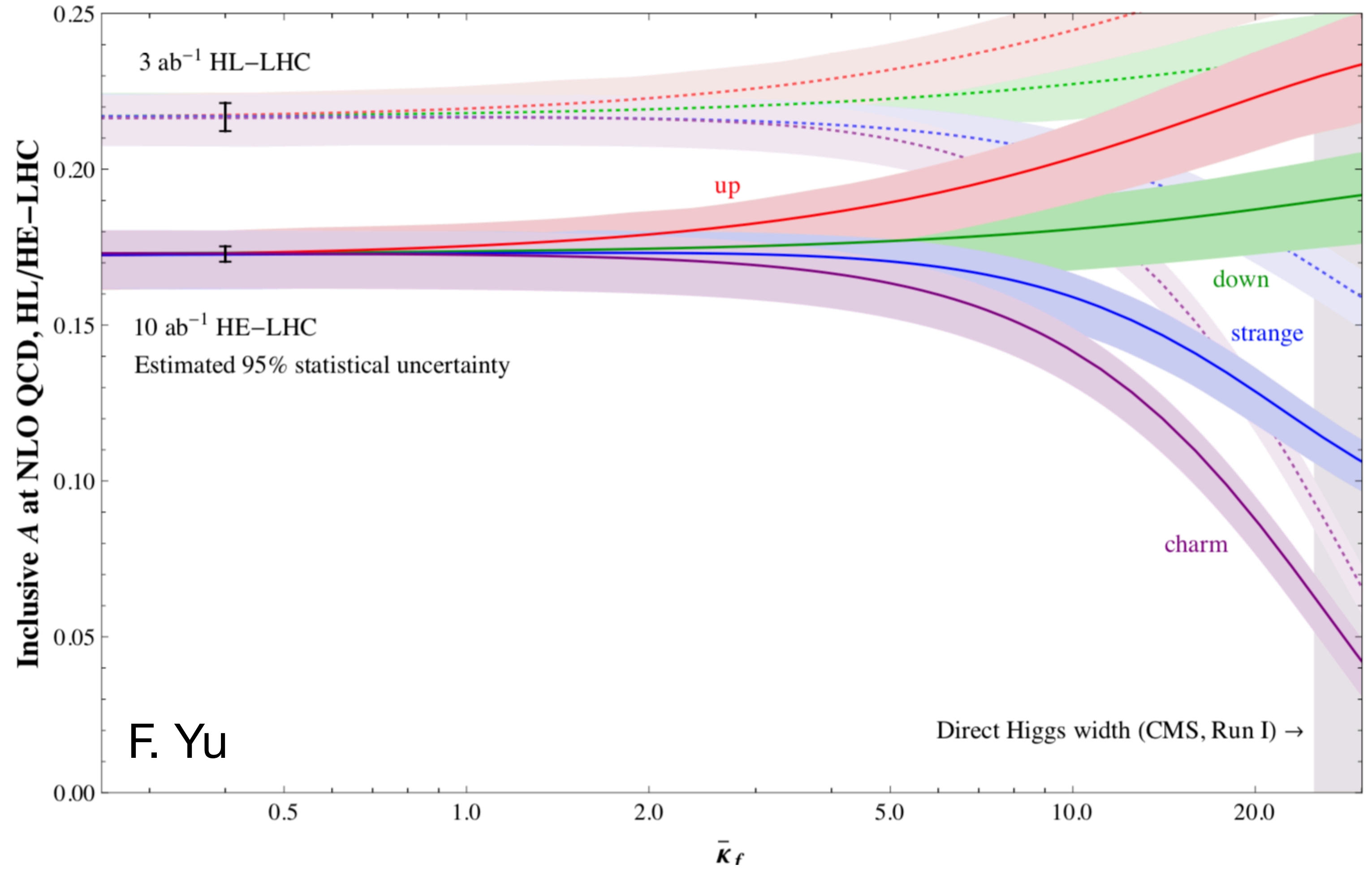
HL-LHC

<15xSM



Based on d anti-d asymmetry in the PDFs

$$A = \frac{\sigma(W^+h) - \sigma(W^-h)}{\sigma(W^+h) + \sigma(W^-h)}$$



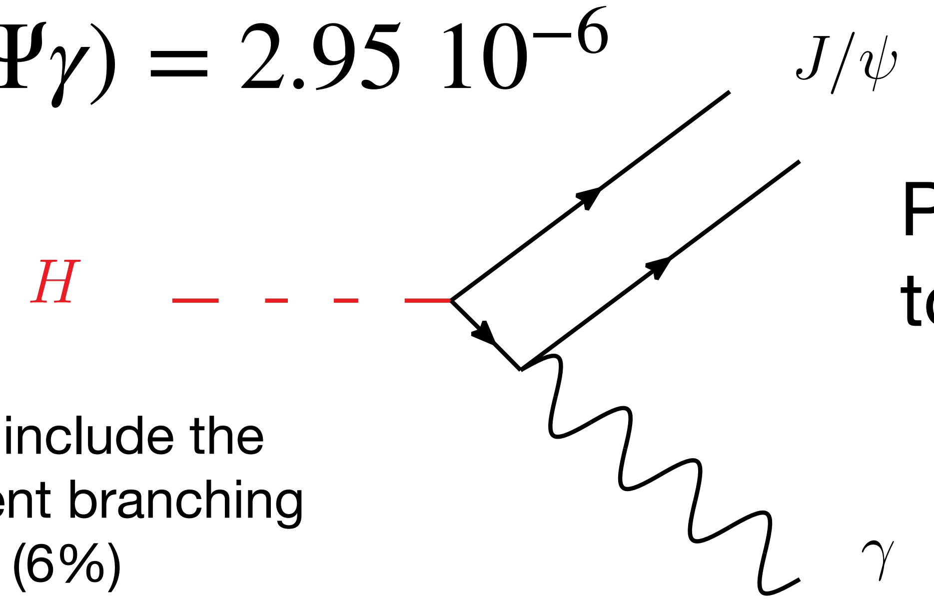
Example of new idea in ratios where many TH uncertainties will cancel, of course in this case sensitive to PDFs.

More Decays with to Quarkonia and a Photon

Current limits

Neubert et al., 2015

$\mathrm{Br}(J/\Psi\gamma) = 2.95\ 10^{-6}$



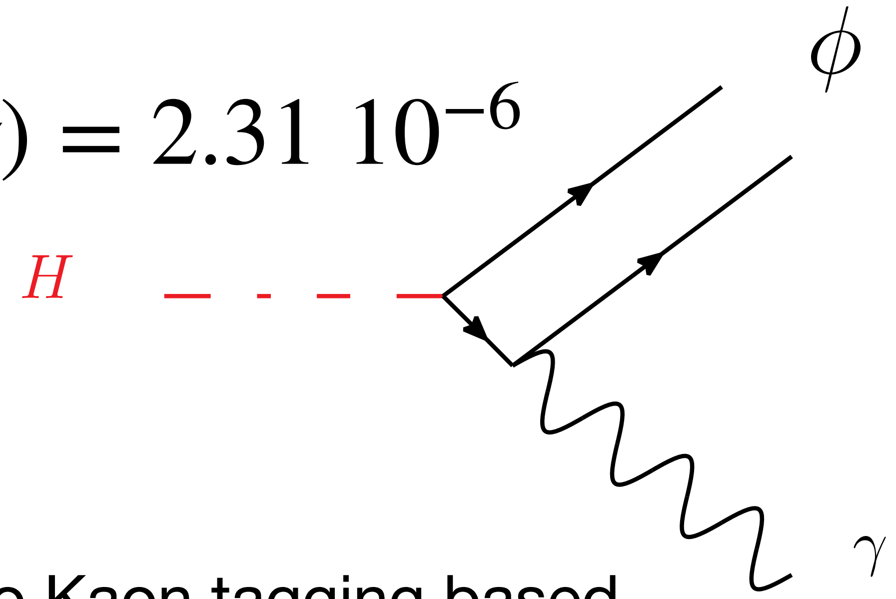
Does not include the subsequent branching to muons (6%)

Potentially sensitive to charm Yukawa

$\mu^+\mu^-\gamma$

~100 x SM

$\mathrm{Br}(\phi\gamma) = 2.31\ 10^{-6}$

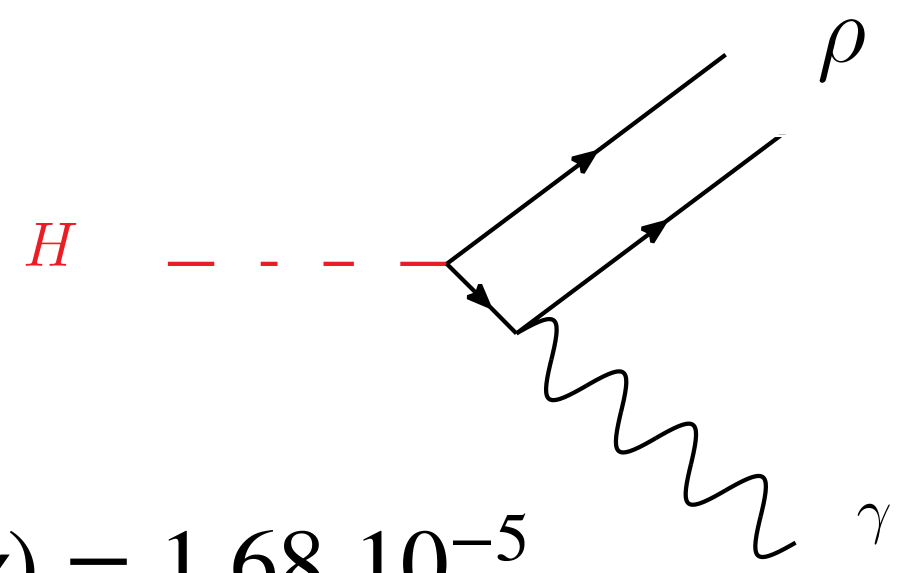


Potentially sensitive to strange Yukawa

$K^+K^-\gamma$

~200 x SM

No Kaon tagging based on the ϕ mass only



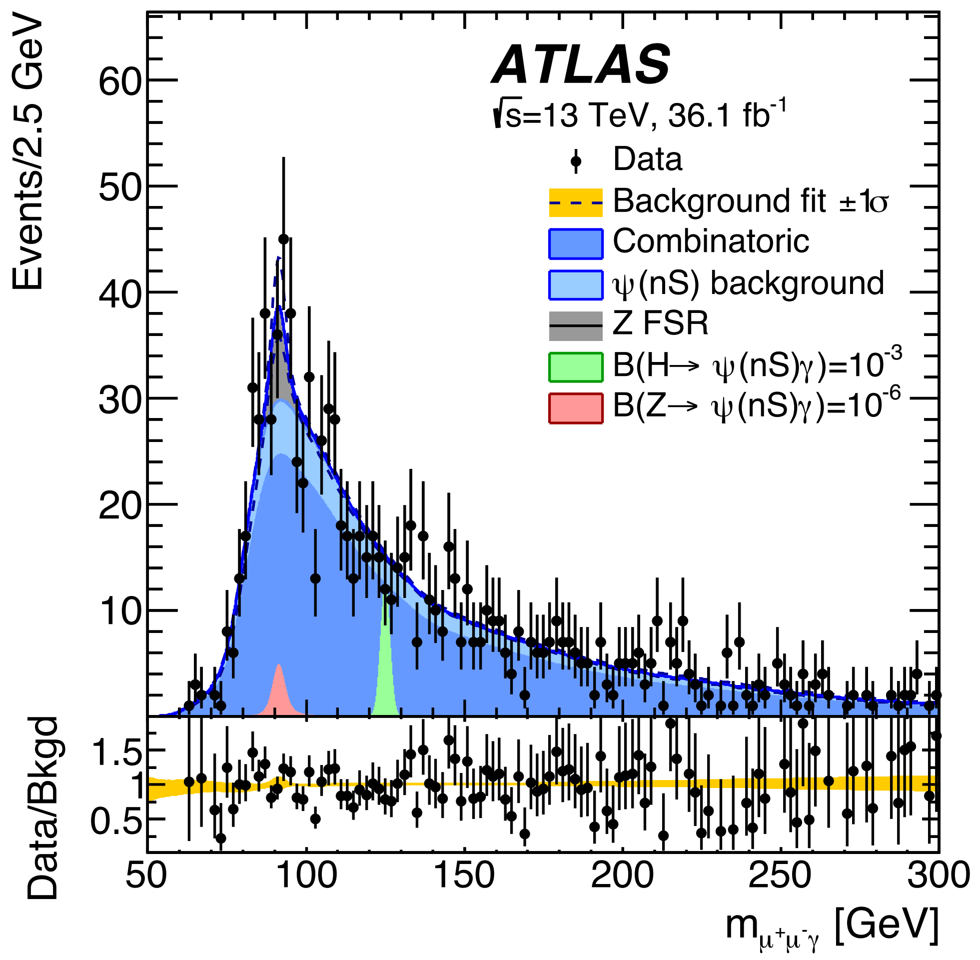
Potentially sensitive to light Yukawa

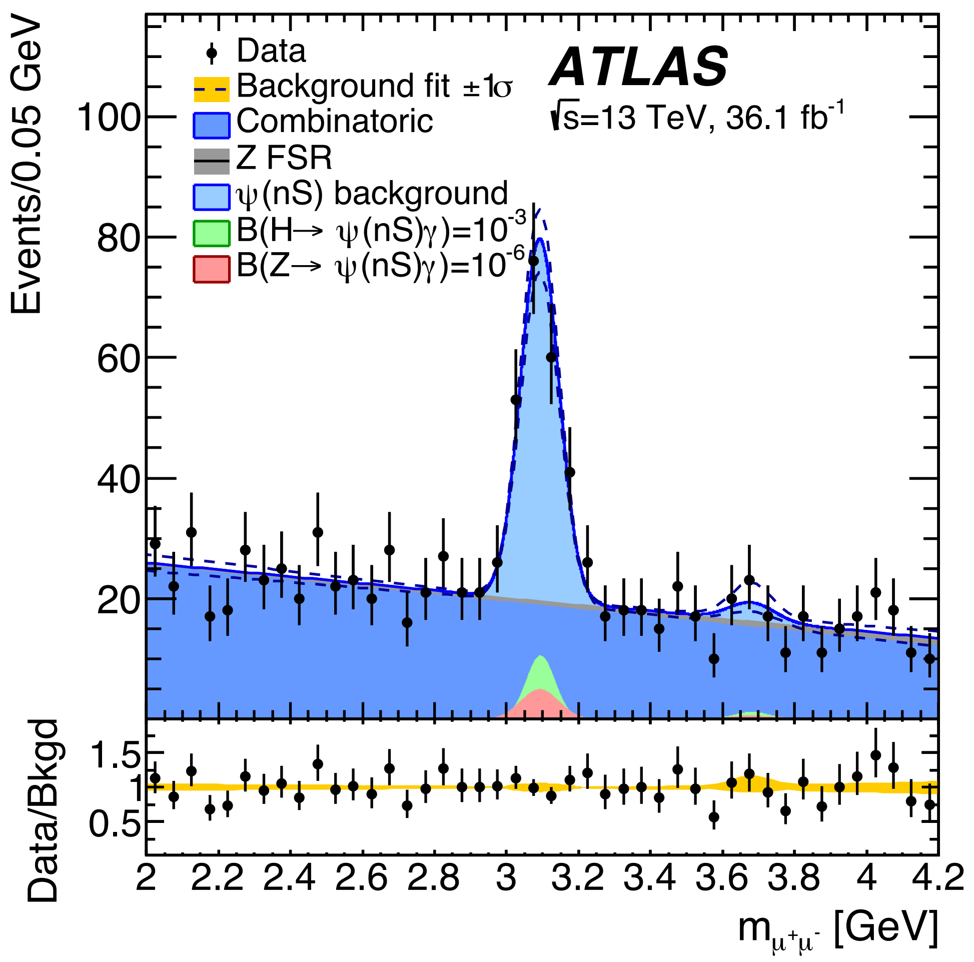
$\pi^+\pi^-\gamma$

~50 x SM

$\mathrm{Br}(\rho\gamma) = 1.68\ 10^{-5}$

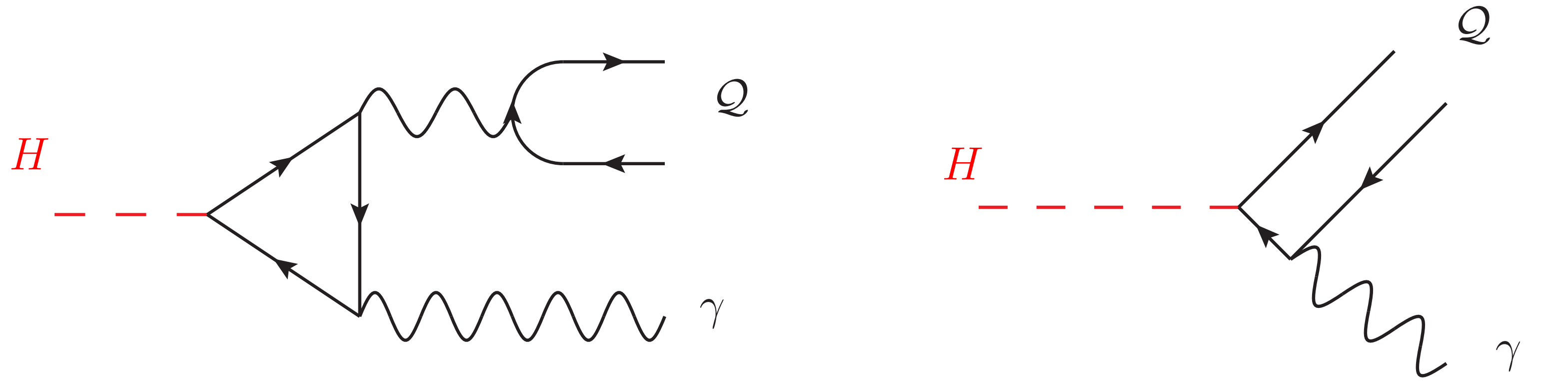
Paradoxically closest limit to SM sensitivity

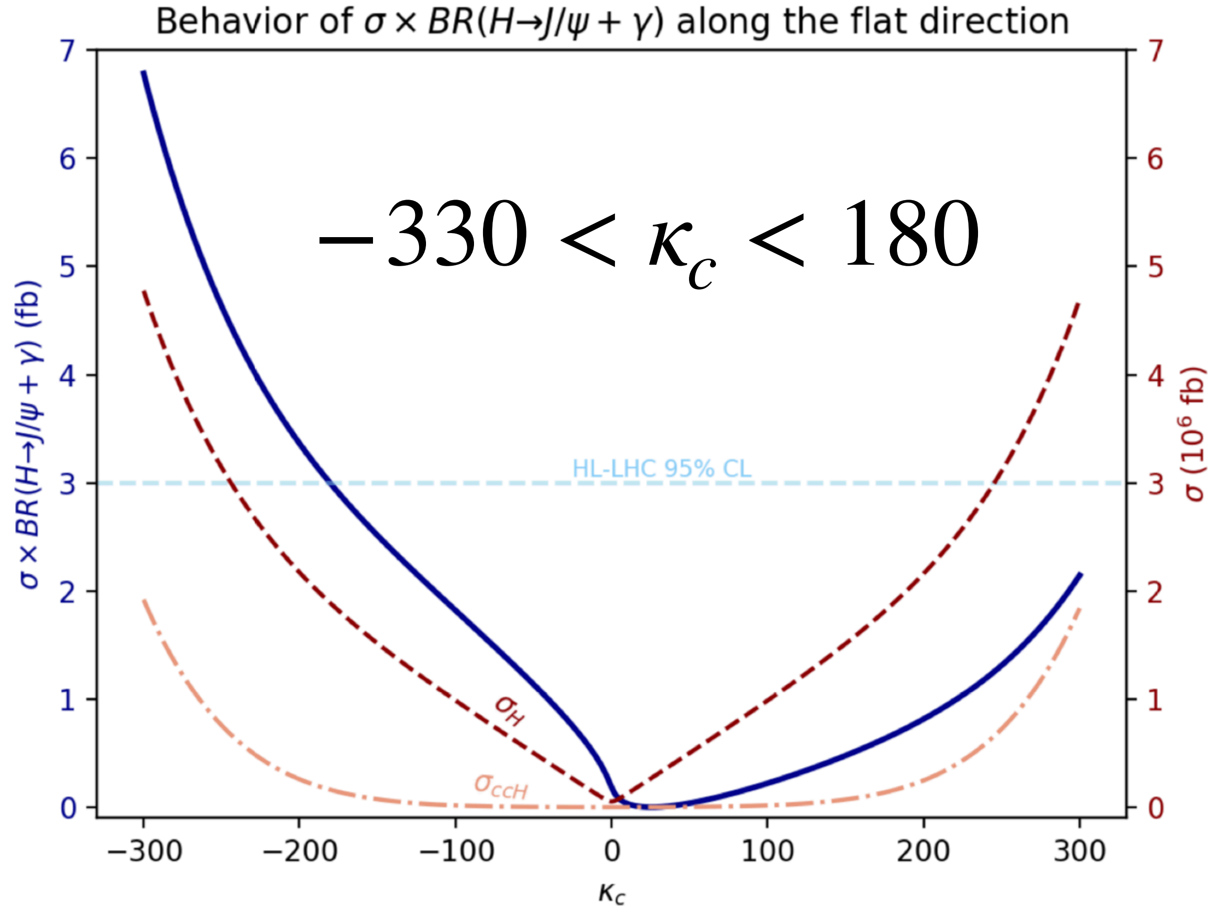




Measuring the Higgs decays to quarkonia and a photon do not give exclusive access to the Yukawa

1905.09360





$$BR(H \to J/\psi + \gamma) \approx \frac{(5|\kappa_c|^{1/2} - 1.04\kappa_c)^2 \times 10^{-10}\ \mathrm{GeV}}{(0.16|\kappa_c| + 0.03\kappa_c^2) \times \Gamma_H^{SM}}$$

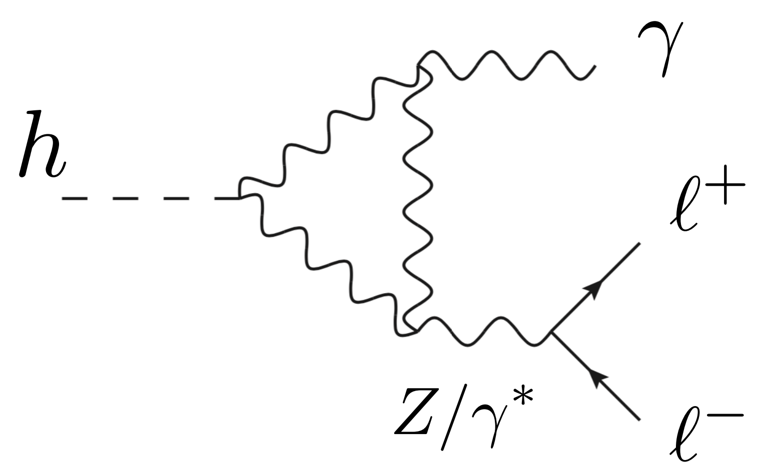
Highly non trivial interpretation as a value of κ_c of ~100 requires a $\kappa_t \sim 20$ i.e. a non perturbative top Yukawa!

More on Rare Decays

Z-photon

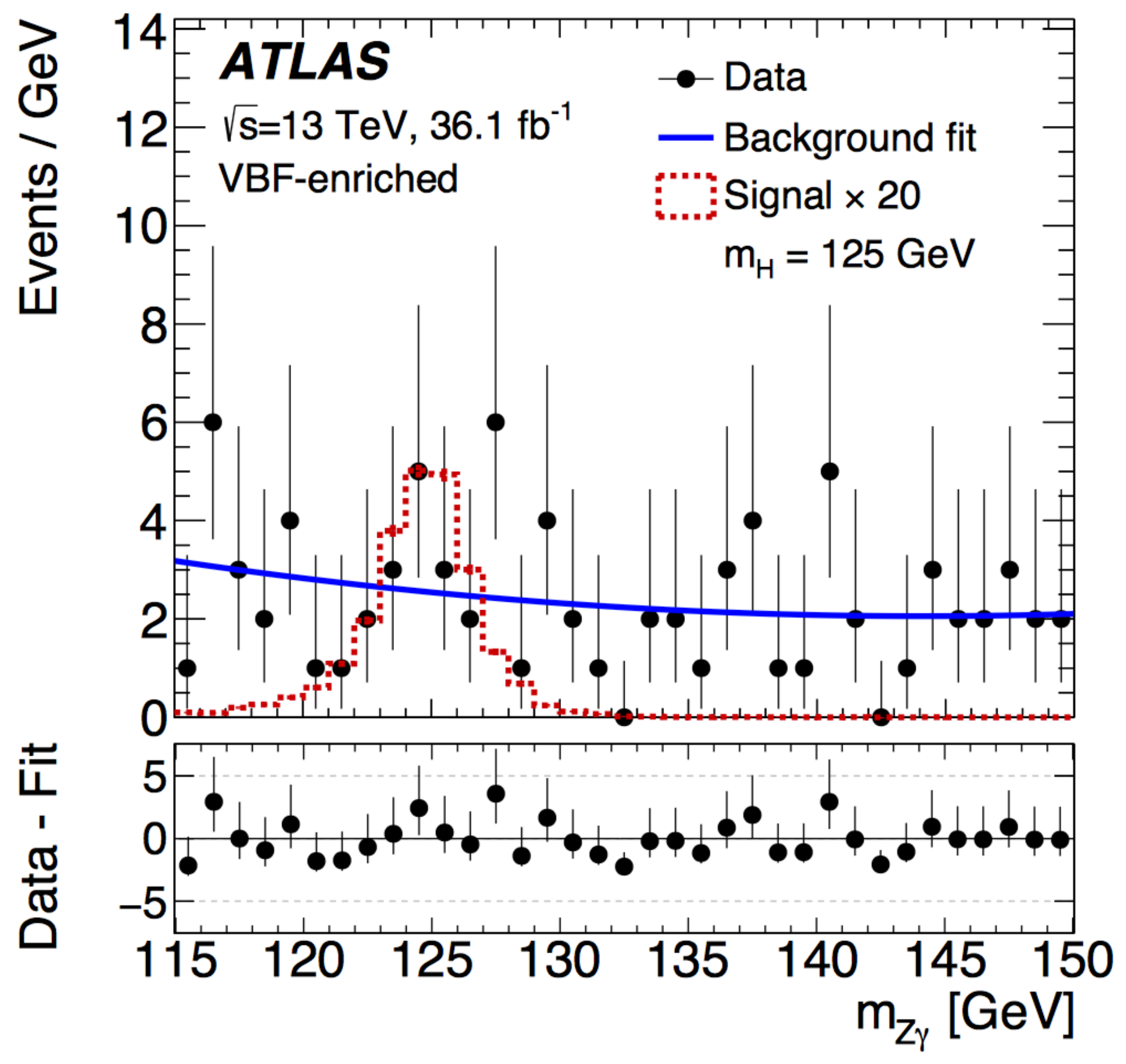
Field tensor coupling not measured yet!

$$|H^2|W^a_{\mu\nu}W^{\mu\nu a}$$



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

Straigthforward search for a leptonic (electrons and muons) decaying Z and a photon.



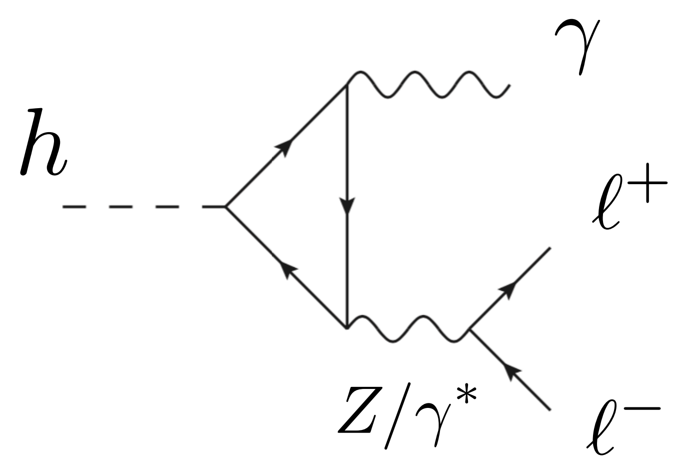
ATLAS and CMS analyses with 36 fb^{-1}:

Limits currently ~6 x SM

Measurable at HL-LHC (Run 3 will be very difficult)

HL-LHC **~10%**

γ^*-photon

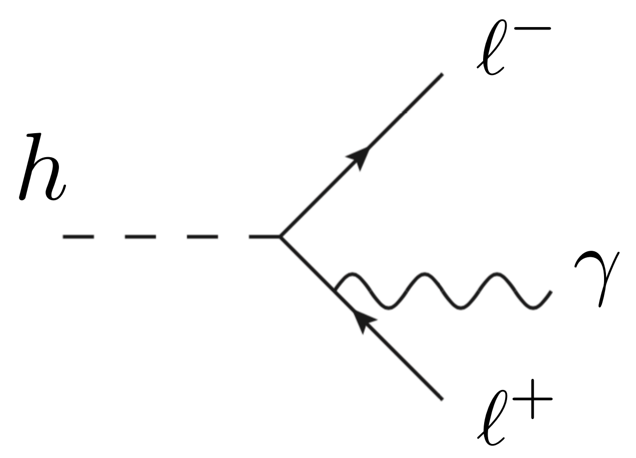


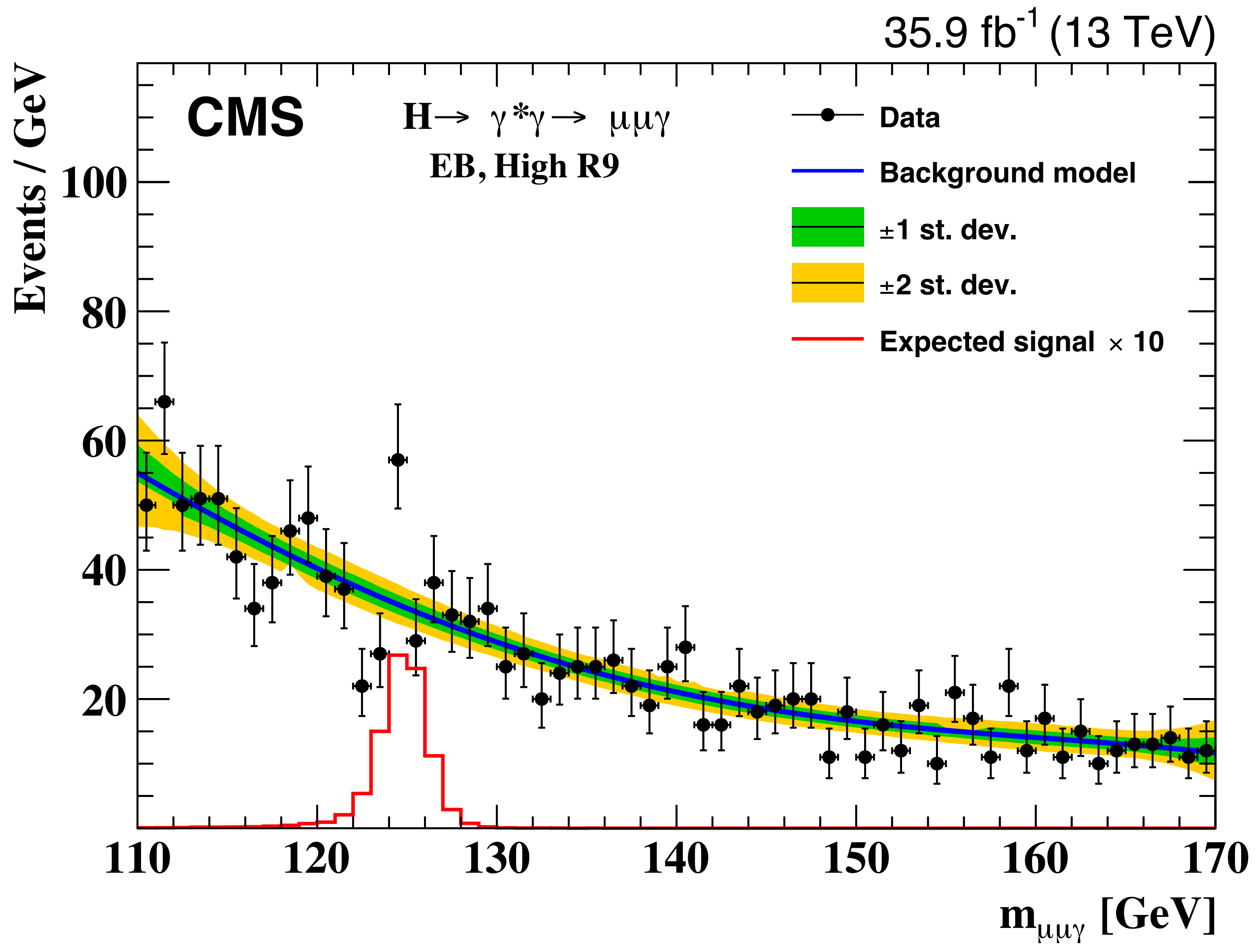
$$m_{\ell^+\ell^-} < 50 \text{ GeV}$$

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

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

… also receives contributions from the muon Yukawa





CMS analyses with 36 fb^{-1}:

Limits currently ~2 x SM

Measurable at HL-LHC (Run 3 be still difficult)

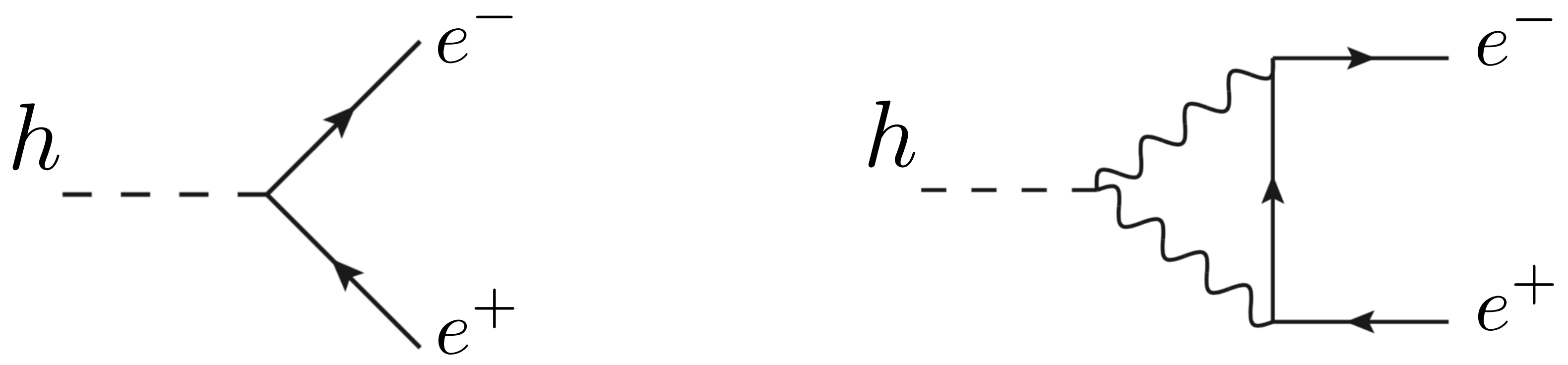
HL-LHC **O(3%)**

From $Z\gamma$ estimate

What about the electron Yukawa?

The soft limit of the photon is covered by the $H \to e^+e^-$ decay channel, sensitive to the electron Yukawa. The Branching fraction in the SM:

$$\mathrm{Br}(H \to e^+e^-) \sim 5\ 10^{-9}$$

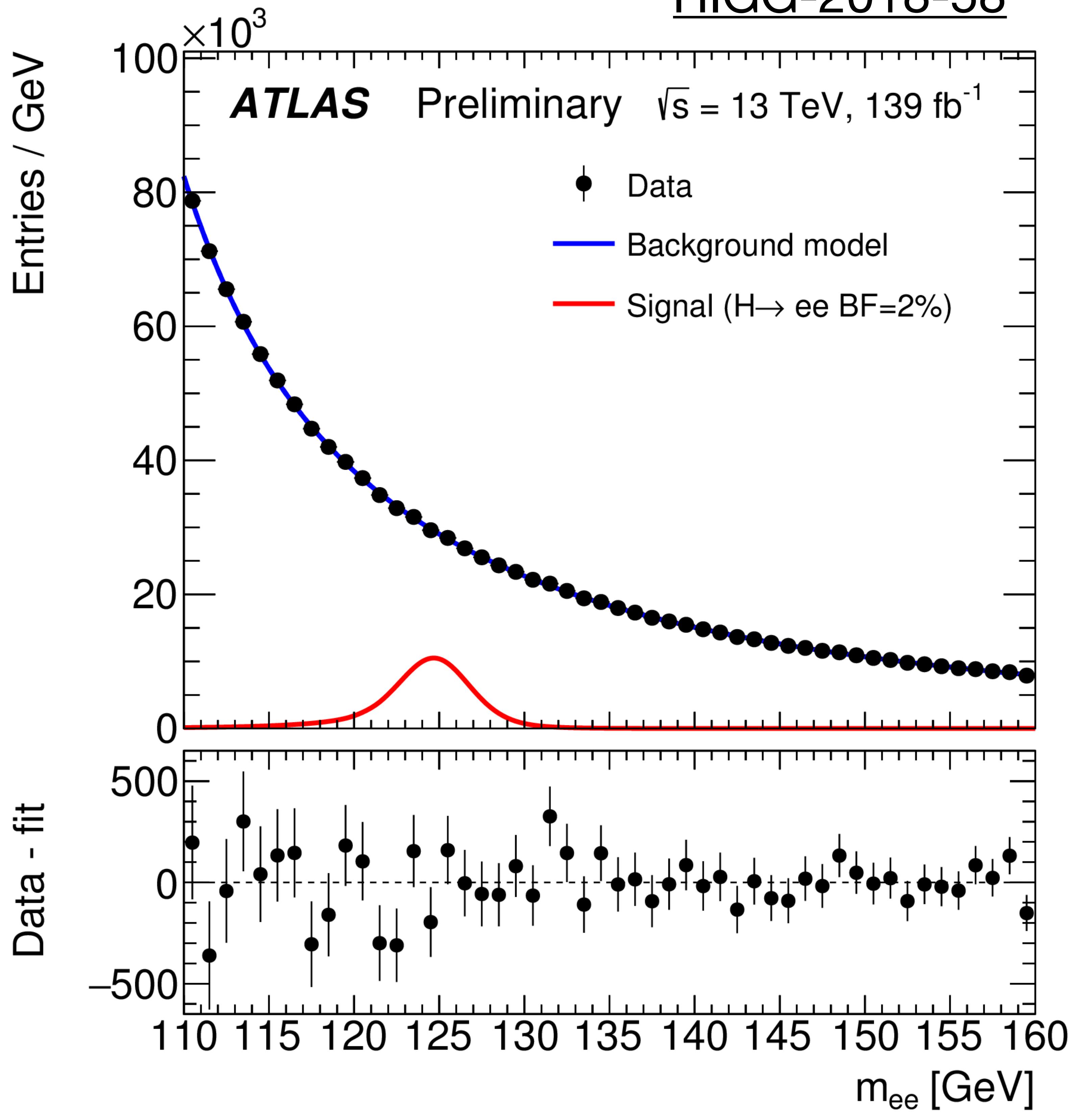


Though one could hope that this would be large, it is suppressed by m_e^2

The limits obtained with a dimuon-like analysis yields a

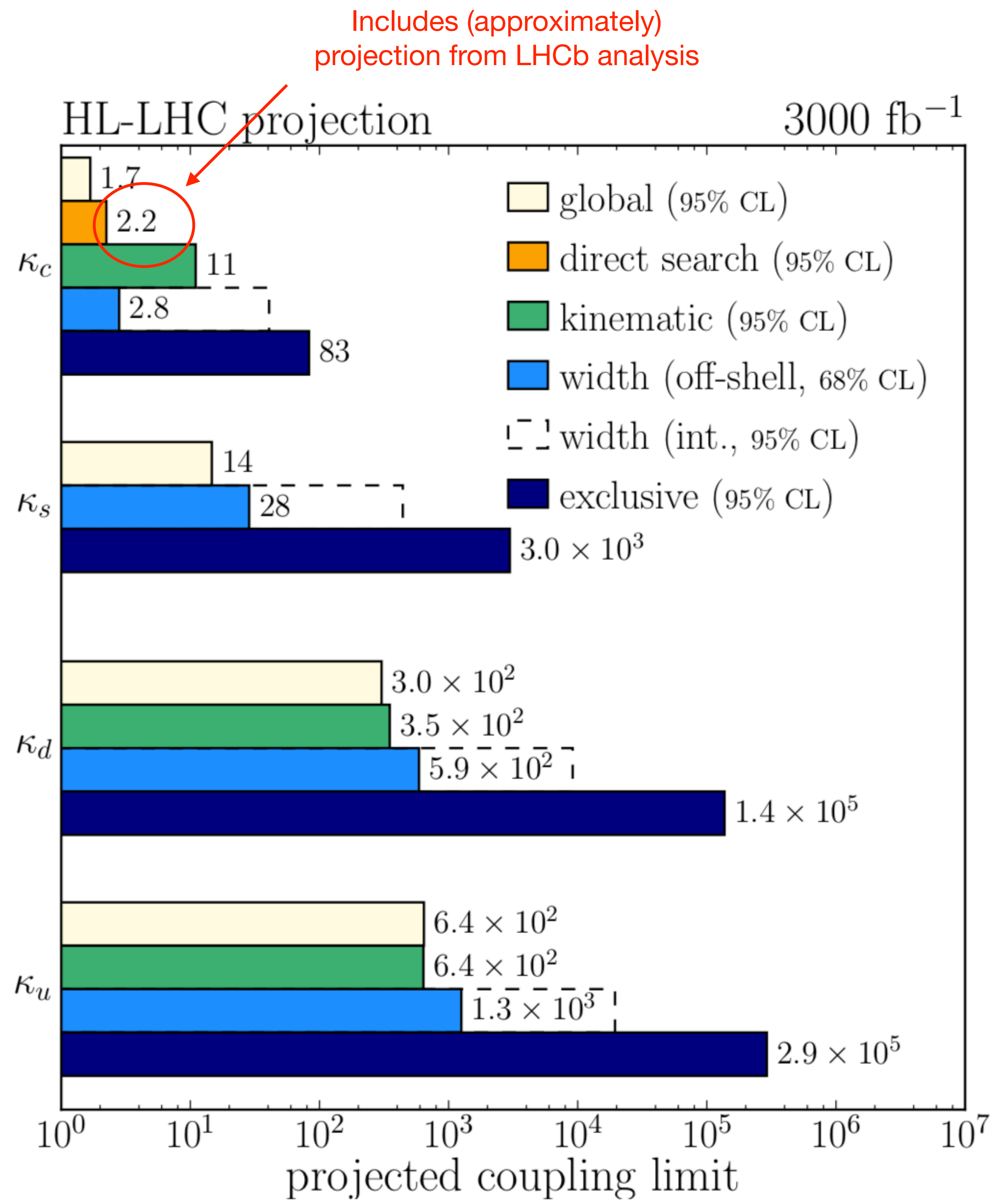
$$\mathrm{Br}(H \to e^+e^-) < 3.4\,10^{-4}$$

[HIGG-2018-58](#)



Perhaps possible at e^+e^- collider in the s-channel $e^+e^- \to h$ (requires special run and monochromatization of beams to compensate for horizontal blow up from Bremstrahlung)

Summary on Flavors
(at HL-LHC with comments on HE-LHC)



First and Second generation Yukawas

- Extremely challenging at HL-LHC (most stringent constraint coming from the couplings fit assuming no BSM width).

- For the charm Yukawa direct search (using charm tagging) is not far behind!

- Then comes sensitivity to coupling combination through width offshell.

- Exclusive searches still only marginally sensitive.

- New emerging ideas to be explored with such large datasets.

CP Properties of Higgs Couplings

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

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

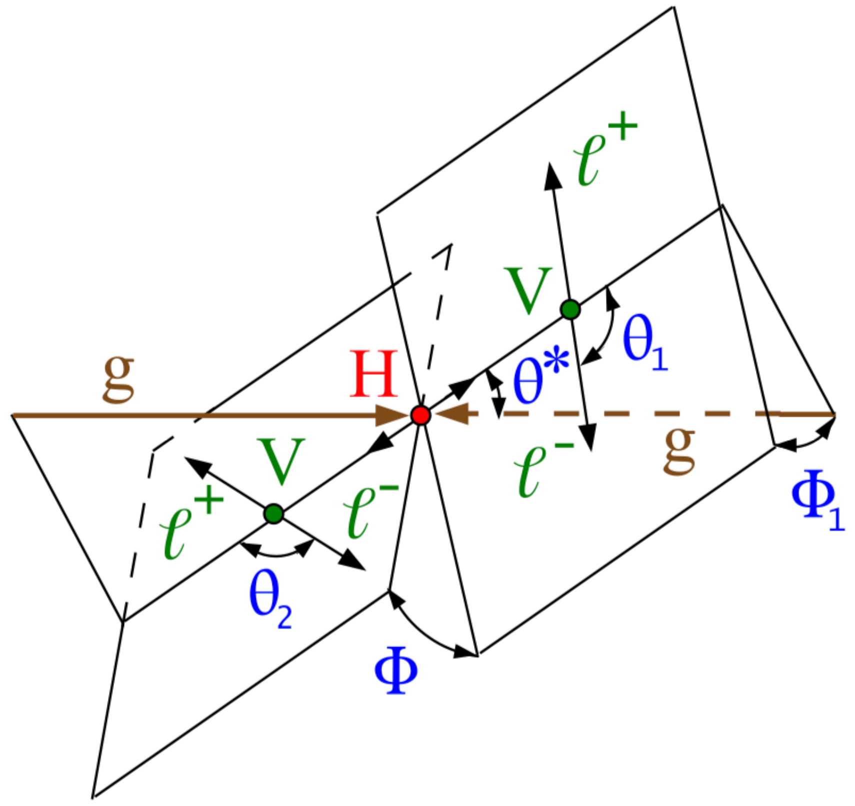
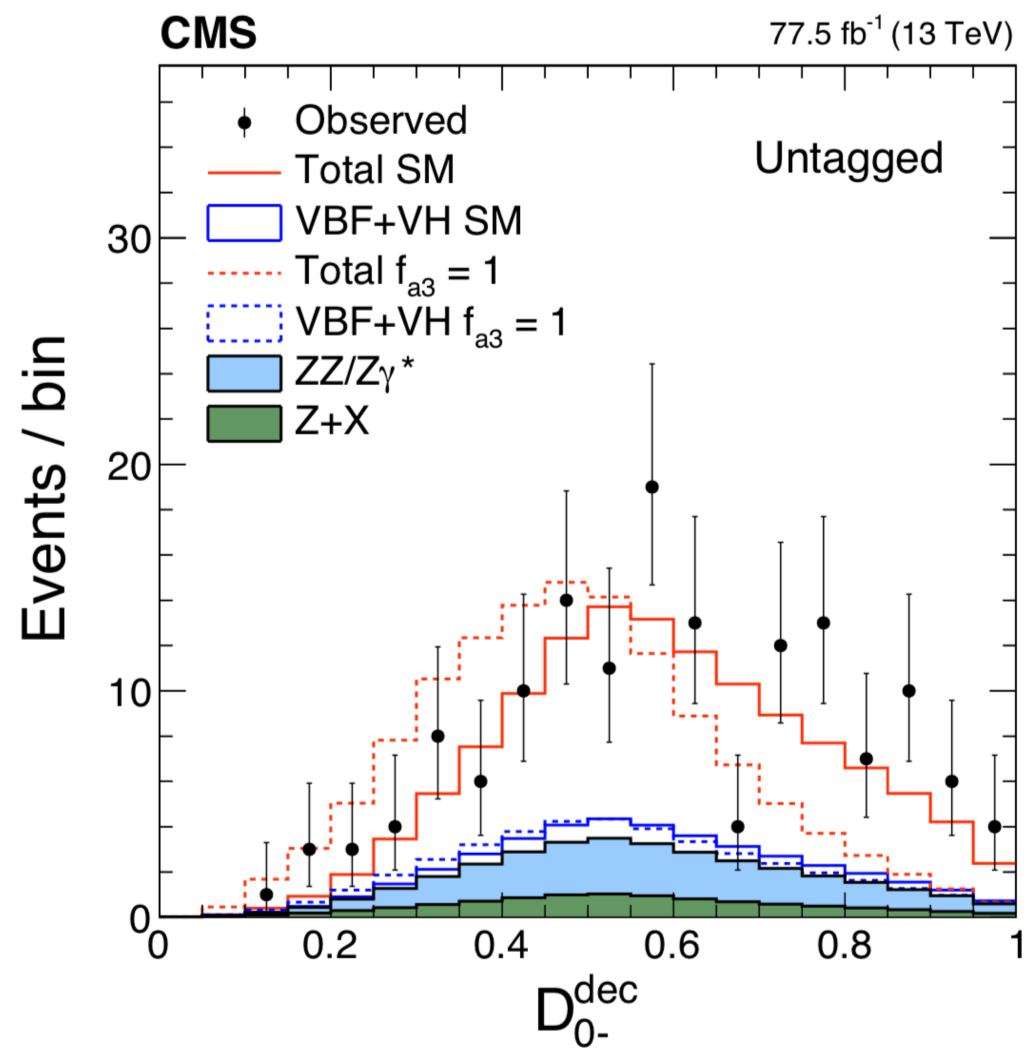
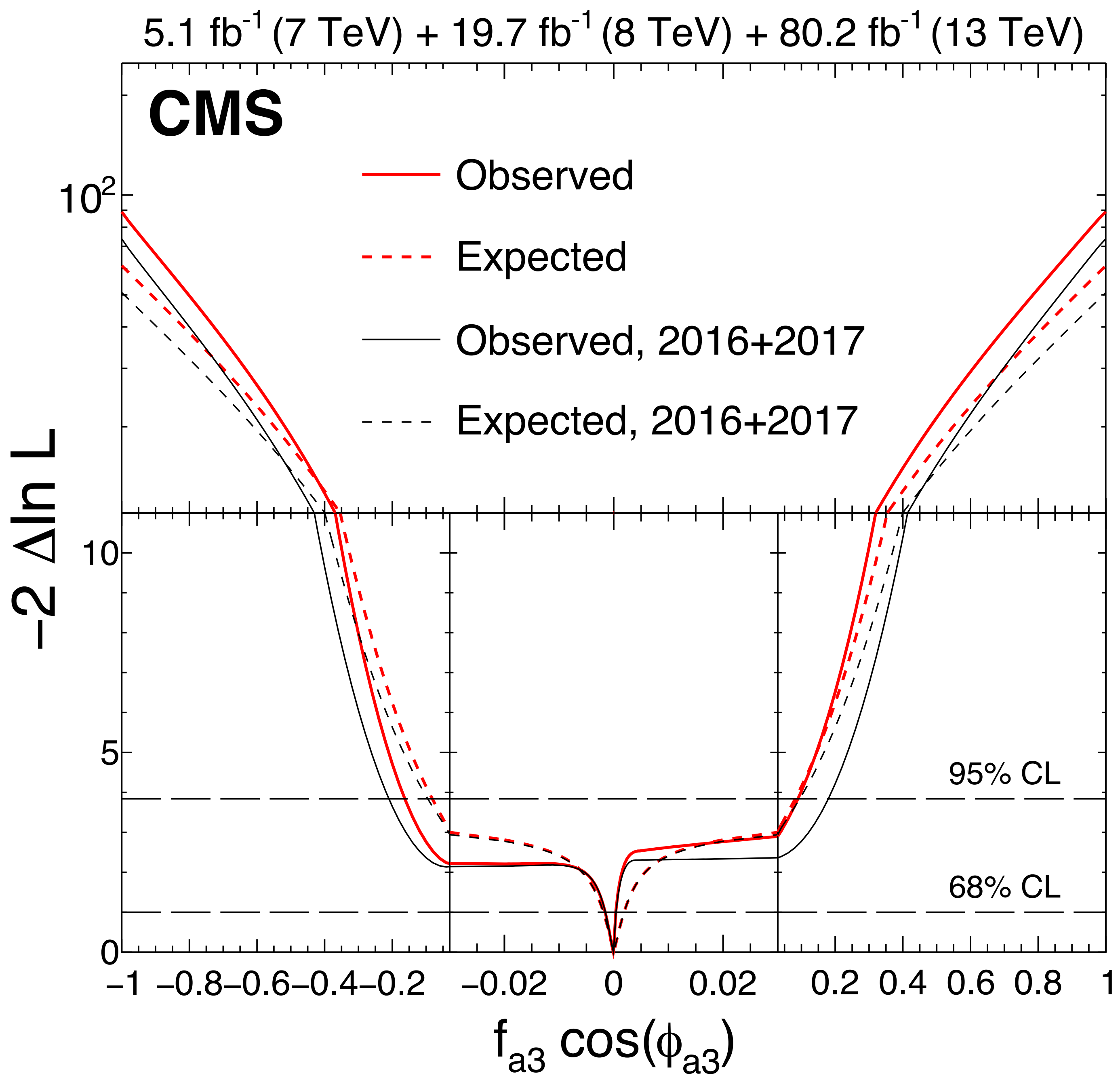


Illustration of 5 production and decay angles for the 4-leptons (most sensitive to the CP mixing)



Analysis based on Matrix Element optimal observables



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

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

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

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

Higgs couplings to vector bosons is CP even

Similar analysis in ATLAS, also using the VBF process in the taut channel

What about the fermion couplings?

The pseudoscalar coupling of the Higgs boson to fermions not probed directly (yet)

$$\frac{\lambda_f}{\sqrt{2}}\left(\kappa_f h\overline{\psi}_f\psi_f + i\tilde{\kappa}_f h\overline{\psi}_f\gamma_5\psi_f\right)$$

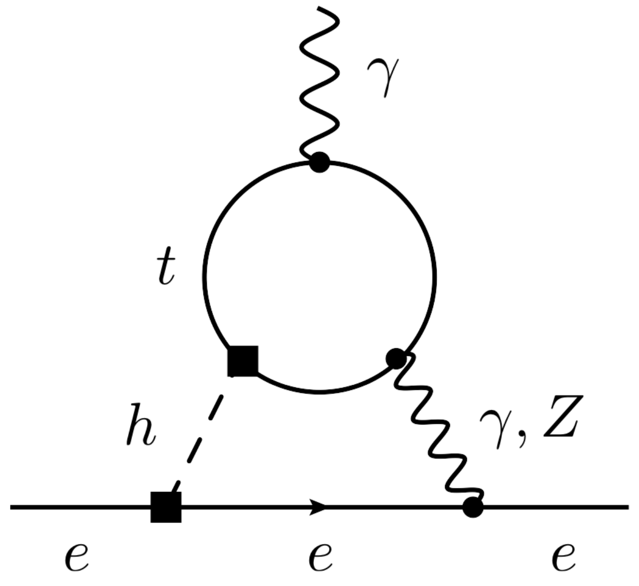
Non zero $\tilde{\kappa}_f$ implies CP violation in the Yukawa interaction

However indirect probes through electron (and neutron) EDM Very suppressed in the SM (where it arises at four loops)

$$d_e/e < 10^{-38}\ \text{cm}$$

Larger if neutrinos are Majorana

A good probe for NP BSM!



From J. Brod., U. Haisch and J. Zupan 2013

$$\frac{d_e}{e} \propto G_F m_e\left[C_1\kappa_e\tilde{\kappa}_t + C_2\tilde{\kappa}_e\kappa_t\right]$$

$$f\left(\frac{m_t^2}{m_h^2}\right)$$

ACME II limit: $\left|\frac{d_e}{e}\right| < 1.1\ 10^{-29}$ cm

Assuming electron Yukawa SM $\tilde{\kappa}_t < 0.001$

It can however be probed directly through ttH angular distributions

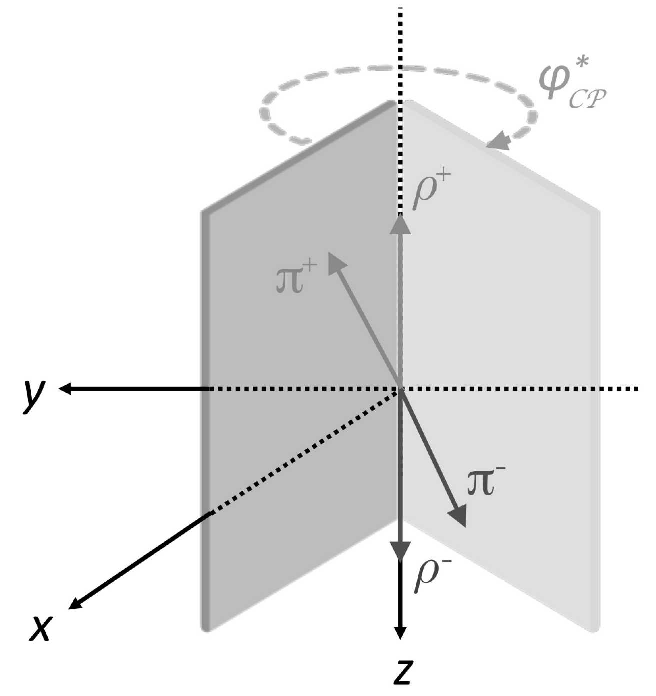
This strong constraint is model dependent, still interesting to probe directly through the ttH production channel.

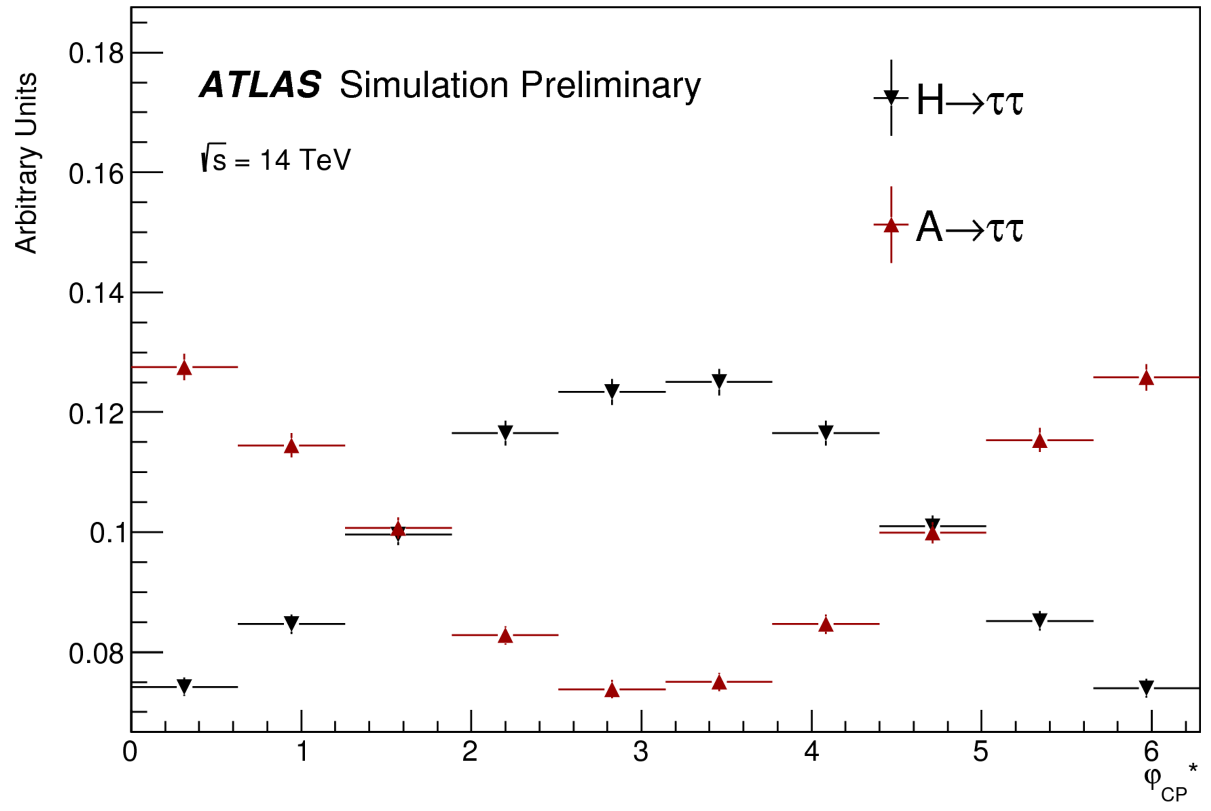
First preliminary study using the $h \to b\bar{b}$ mode and top pair angular variables in the di-leptonic and semi-leptonic modes shows that and exclusion of a pure CP-odd is possible already at Run 3.

The electron EDM constraint is weaker for taus $\tilde{\kappa}_\tau < 0.3$

First attempts to constrain this coupling using tau polarisation observables

$$H \to \tau^+\tau^- \to \rho^+\nu_\tau\rho^-\overline{\nu}_\tau$$





Sensitivity of ~0.3 at 68% CL at HL-LHC

ATLAS-CONF-2019-030

Flavour Changing Neutral Currents

In the **Standard Model** the Yukawa couplings are diagonalised as the mass matrix: **no flavour non-diagonal terms**.

Non diagonal terms can arise in dimension 6 operators in a SM EFT

$$\frac{\phi^\dagger \phi}{\Lambda^2}\left(\lambda_{ij} F_L^i \phi \overline{f^j_d}_R + \lambda_{ij} F_L^i \phi^c \overline{f^j_u}_R\right)$$

In this case the Yukawa-masses relation is broken, and di- and tri-Higgs terms will be generated!

$$Y_{ij} \sim \frac{m_{ij}}{v} + \frac{v^2}{\Lambda^2} c_{ij}$$

As in 2HDMs unless carefully assuming that one Higgs doublet couples to a type of fermion at a time (Natural Flavour Conservation rule - yielding types I - IV 2HDMs)!

Not a necessary condition to match the Kaon, B and muon decays data

Cheng and Sher Ansatz

$$\lambda_{ij} \sim \frac{\sqrt{m_i m_j}}{v}$$

This Ansatz works well with most constraints (light quarks and leptons), but for higher masses the Higgs data can be of interest (experimental goal).

Going beyond this Ansatz requires fine tuning and this is thus called the « Naturalness Limit »

Defines a good experimental goal!

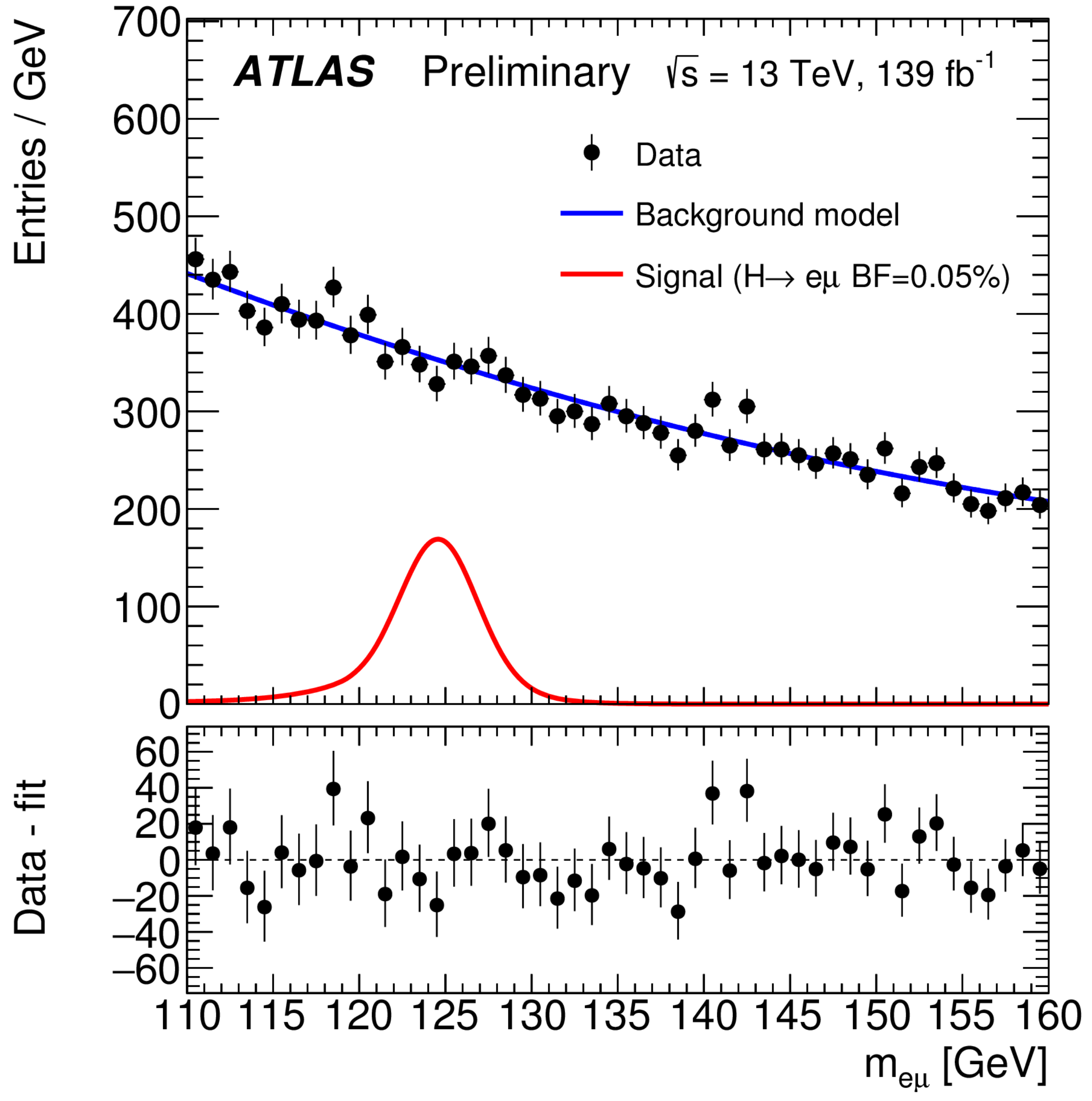
Lepton Flavor Violating Couplings

Simplest channel at the LHC is the $e\mu$ but it is way more constrained by $\mu \to e\gamma$ experiment (MEG)

$$\mathrm{Br}(\mu^+ \to e^+\gamma) < 4.2\ 10^{-13}$$

$$\mathrm{Br}(H \to e\mu) < O(10^{-8})$$

Depending on assumptions on the diagonal e and μ Yukawa

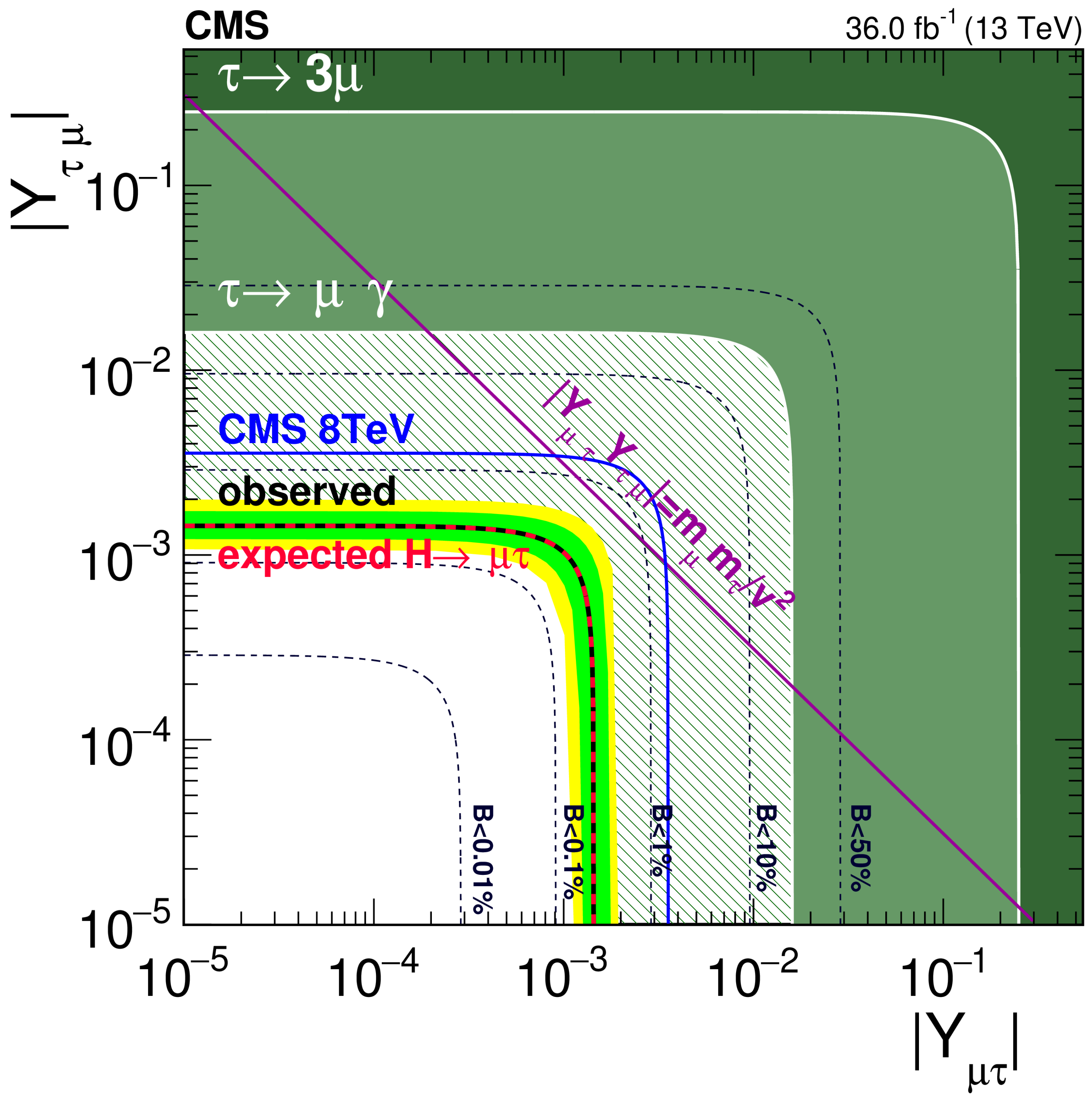


Limit on $e\mu$ LFV Branching at 95%CL:

$\mathrm{Br} < 6.1\ 10^{-5}$ Only factor ~10 from « naturalness » limit

The **Naturalness Limit** in the case of the tau and mu couplings is much larger corresponding to $\mathrm{Br} \sim 0.4\,\%$

τμ channel studied at Run 1 and Run 2 by ATLAS and CMS, with analyses in both the hadronic and leptonic decay channels of the tau (with analyses similar to the $H \to \tau^+\tau^-$ channels).



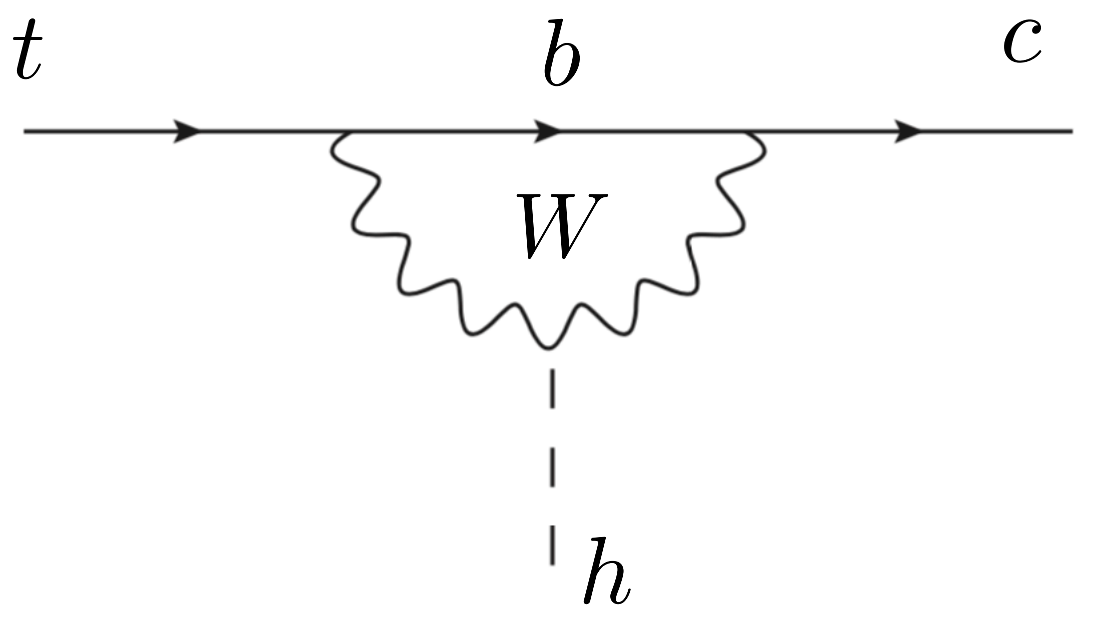
CMS result with 36 fb^{-1}

$$\mathrm{Br}(H \to \tau\mu) < 0.25\%$$

« The raise and fall » of the Cheng and Sher ansatz (see slides)

Rare modes involving top quark

Flavor changing neutral current decays of the top quark is strongly suppressed (by the GIM mechanism)

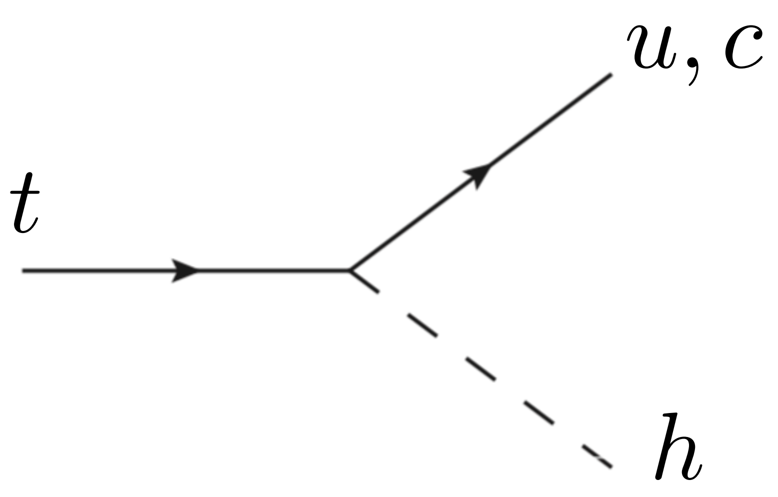


$$\propto m_t \left(\frac{m_b}{m_W}\right)^2$$

$B(t \to Hq)$

SM Branching ~10^{-15}

Therefore an excellent channel to look for New Physics!

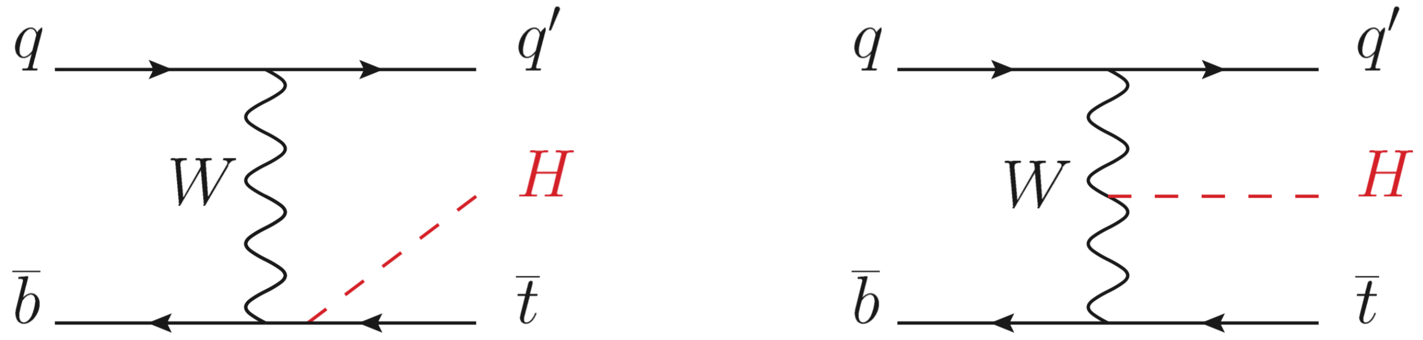


Various decay channels of the Higgs boson ($\gamma\gamma$, bb, WW)

Limits reached with $36\,\mathrm{fb}^{-1}$ at 95% CL (without charm tagging):

$$\mathrm{Br}(t \to Hc) < 0.11\%$$

Tree level interference between top Yukawa and VVH production: single-top and Higgs associated production:

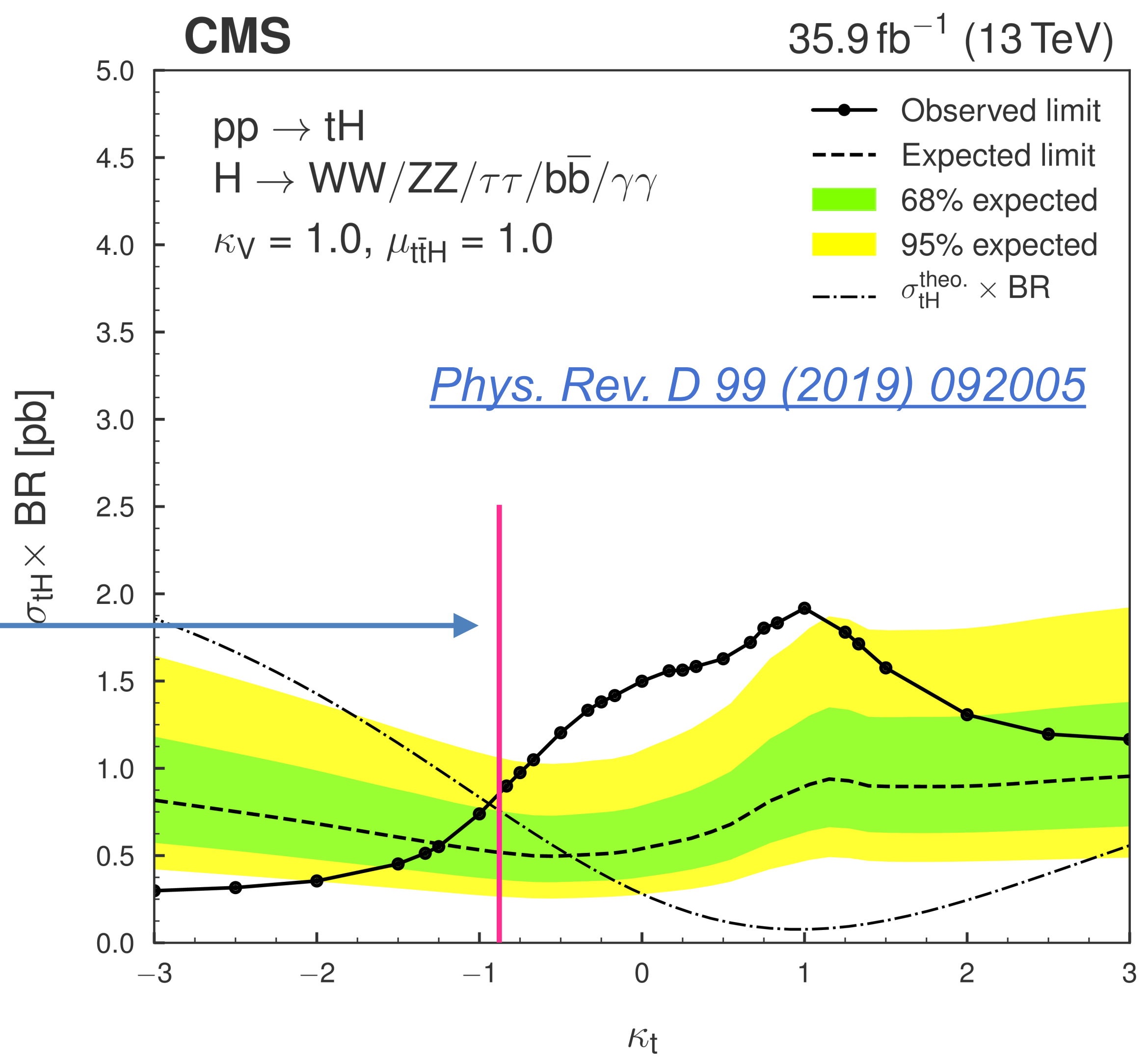


$$\propto 3.3 \times \kappa_W^2 - 5.1\kappa_W\kappa_t + 2.8\kappa_t^2$$

Allows to further constrain the relative sign of the top Yukawa coupling w.r.t. hVV

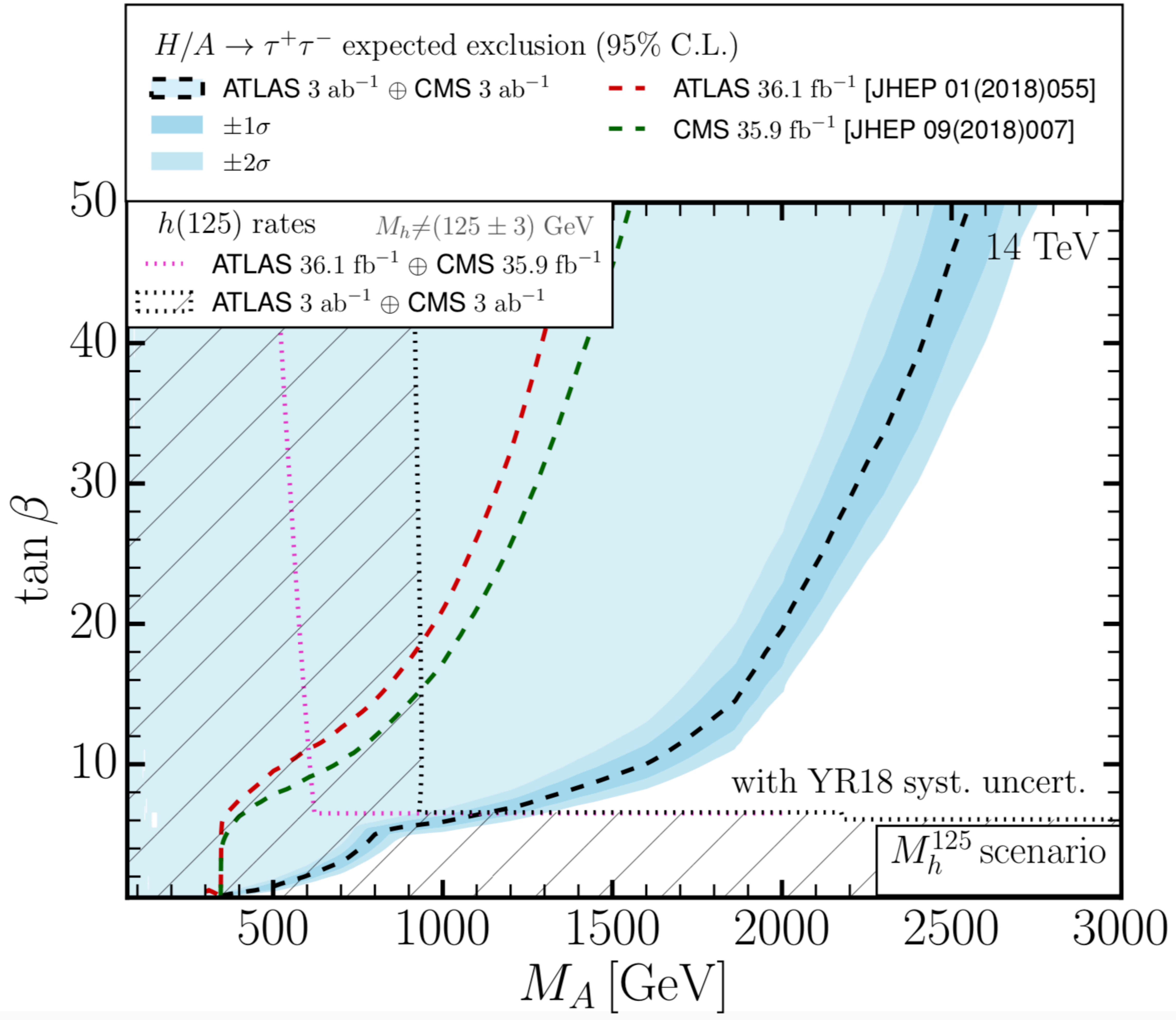
CMS analysis in combination between the multi lepton, bb and $\gamma\gamma$) channels

Excludes values of $\kappa_t < -0.9$ at 95% CL



The discrepancy between observed and expected limits around is caused by the fact that the predicted ttH cross section vanishes while the data favors larger than expected yields for ttH.

BSM Higgs Searches



- Direct **"BSM Higgs searches"** for an extended Higgs sector (MSSM, 2HDM, NMSSM, Georgi-Machacek Triplets, additional singlets, etc…)
- Still large improvement in the sensitivity with the HL ~1 TeV
- Challenge: Extend the direct search coverage in the intermediate tan beta region and high mass requires improving searches such as top-pair (taking into account the interference with the continuum background), no conclusive prospect studies done so far.
- See backup for complete list of searches performed at the LHC.

Complementarity between searches and precision

Measurement of SM processes in the high energy domain

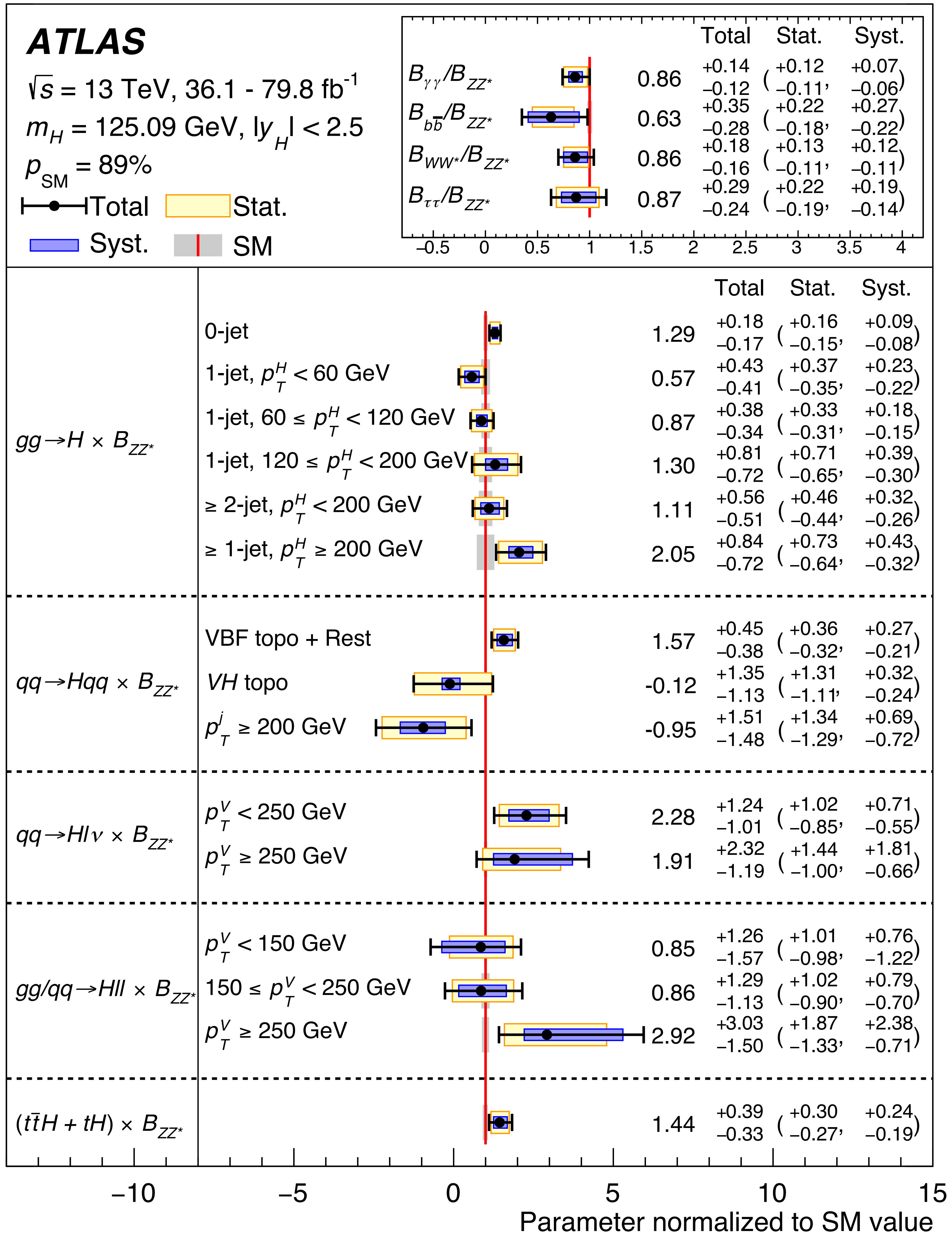
Effective field theory and measurements of non resonant processes at higher energy

$$\frac{\delta c}{c} \sim \frac{g_*^2}{g_{SM}^2}\frac{m_h^2}{\Lambda^2}$$

$$\frac{\delta \mathcal{A}}{\mathcal{A}} \sim \frac{g_*^2}{g_{SM}^2}\frac{E^2}{\Lambda^2}$$

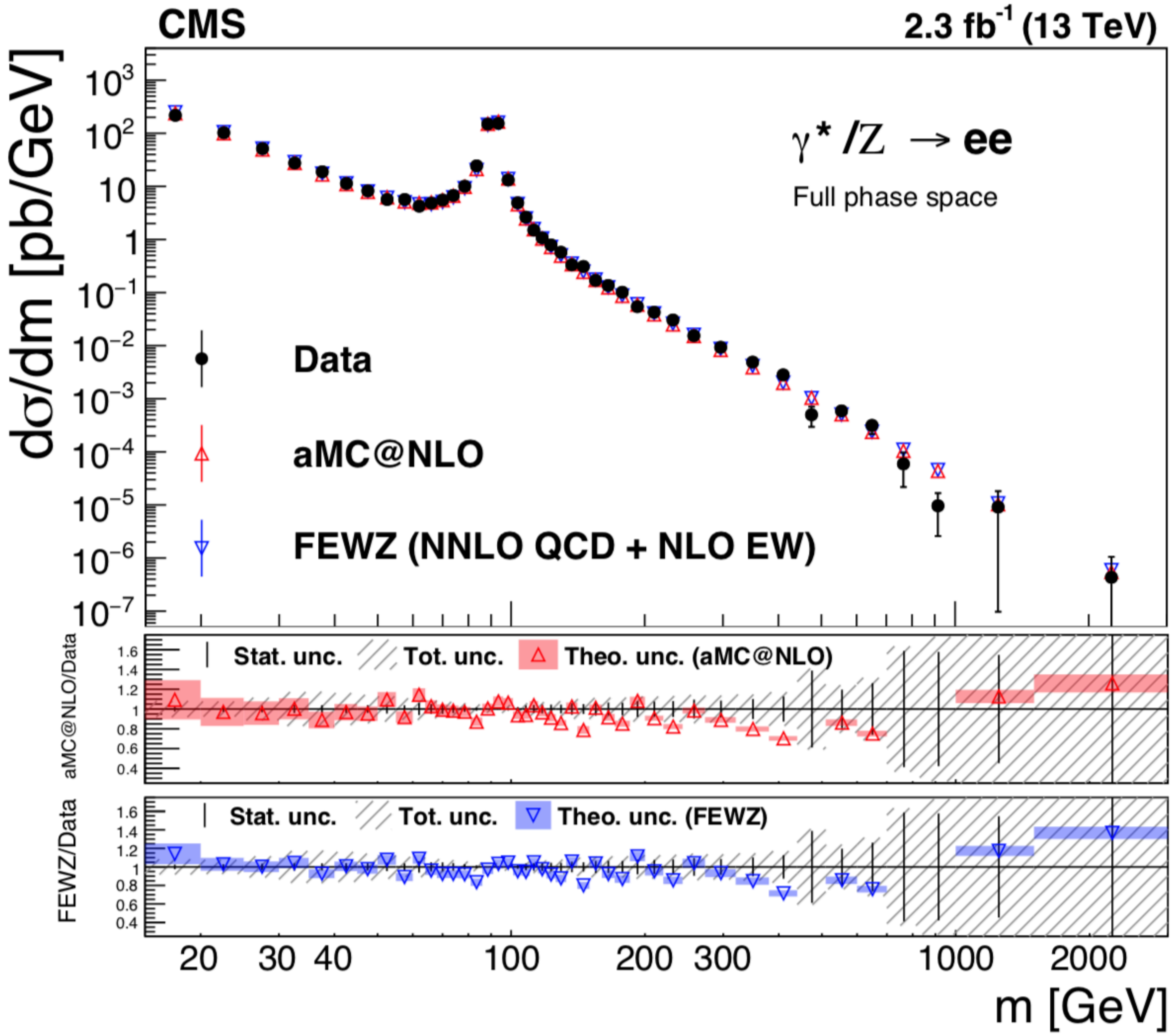
Can reach similar or better sensitivity with less precision using observables which have energy dependence

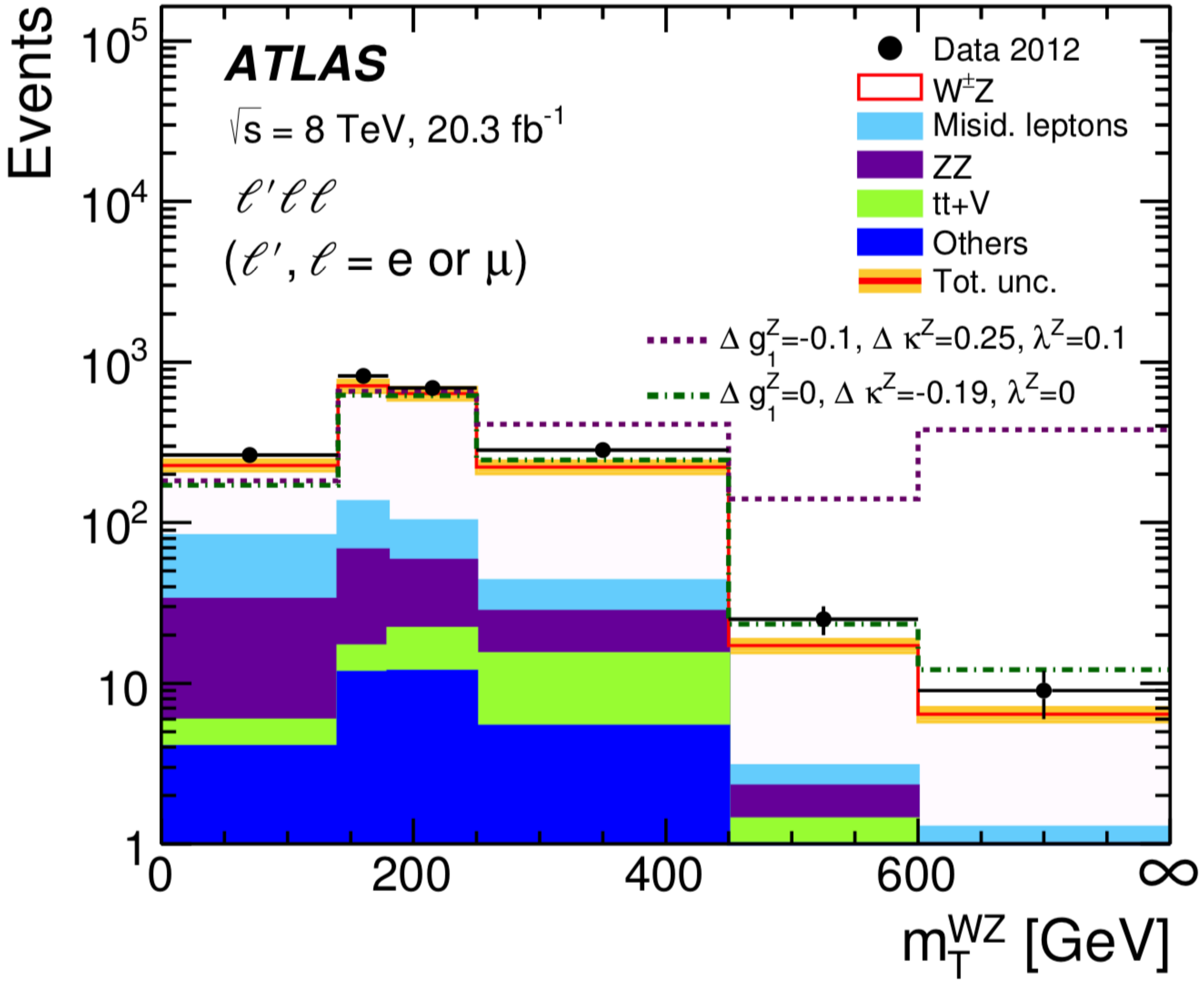
Simplified Template Measurement of Higgs production cross sections (typically) in high transverse momentum regime



ATLAS STXS combined measurement using partial run 2 dataset

Complementarity between searches and precision





Measurement of Higgs production cross sections in high transverse momentum regime

Measurement of di-boson in the high mass regime

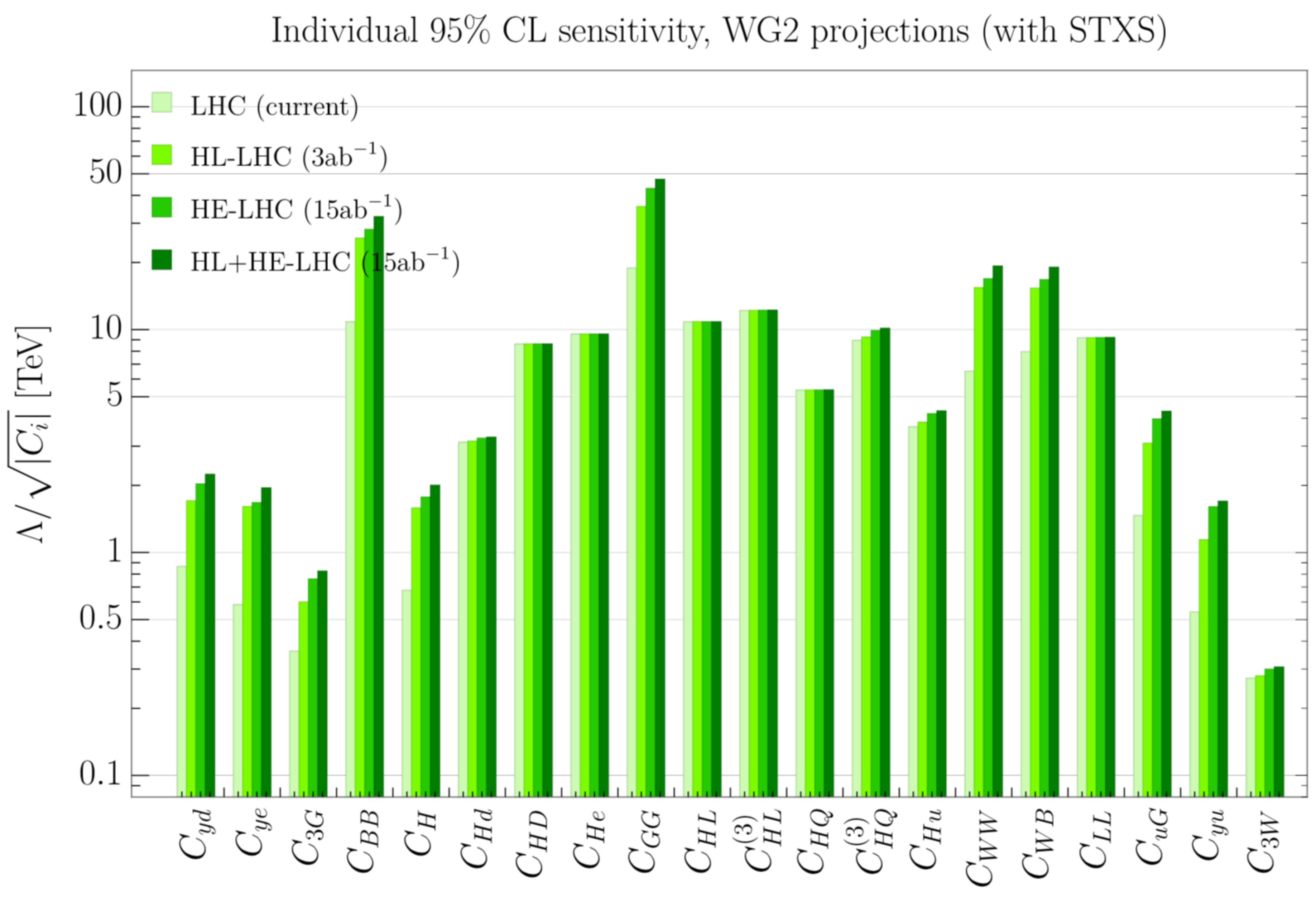
Already yielding constraints stronger than LEP !

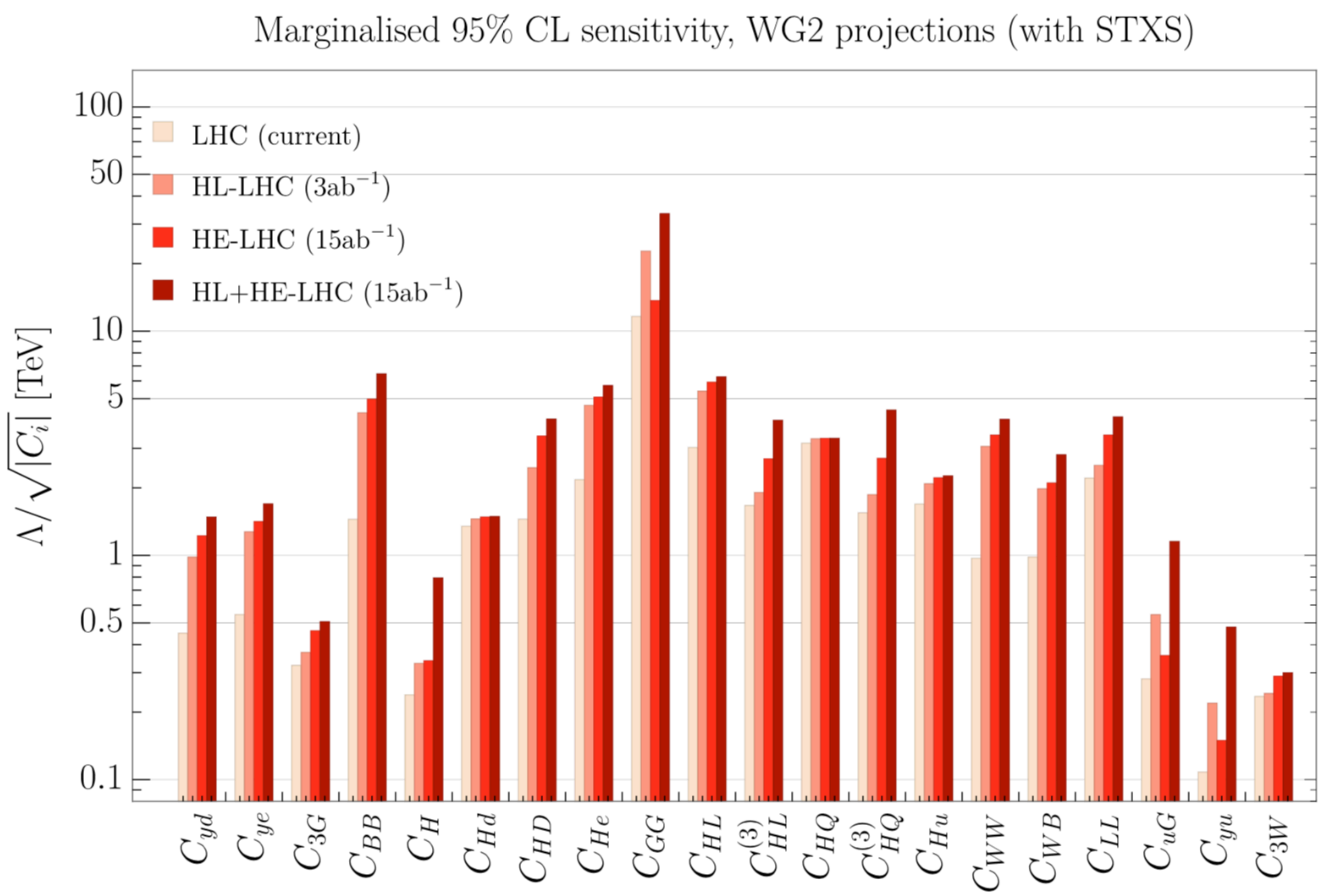
Global EFT Fit (I): Partially Universal EFT fit

- SMEFT with dimension 6 operators in the Warsaw basis

- Reduction of the (2499 baryon number preserving dim-6 Wilson coefficients) using U(3) flavour for the 5 light fermion fields (assuming $U(3)^5$ symmetry), reducing to 76 coefficient among which 20 relevant for di-boson, EWK precision and Higgs physics.

- **Inputs**:
  - Z pole (LEP, SLC) and WW (LEP)
  - LHC Higgs signal strengths (in part VH).
  - LHC WW (with pT>120 GeV)
  - Higgs STXSs





↑ Due to opening of flat direction

Only linear terms in parametrisation taken into account, fair approximation (taking only SM-BSM interference) for precise measurements (BSM small) - observables not growing with energy, less otherwise.

Global EFT Fit (II) for Universal New Physics

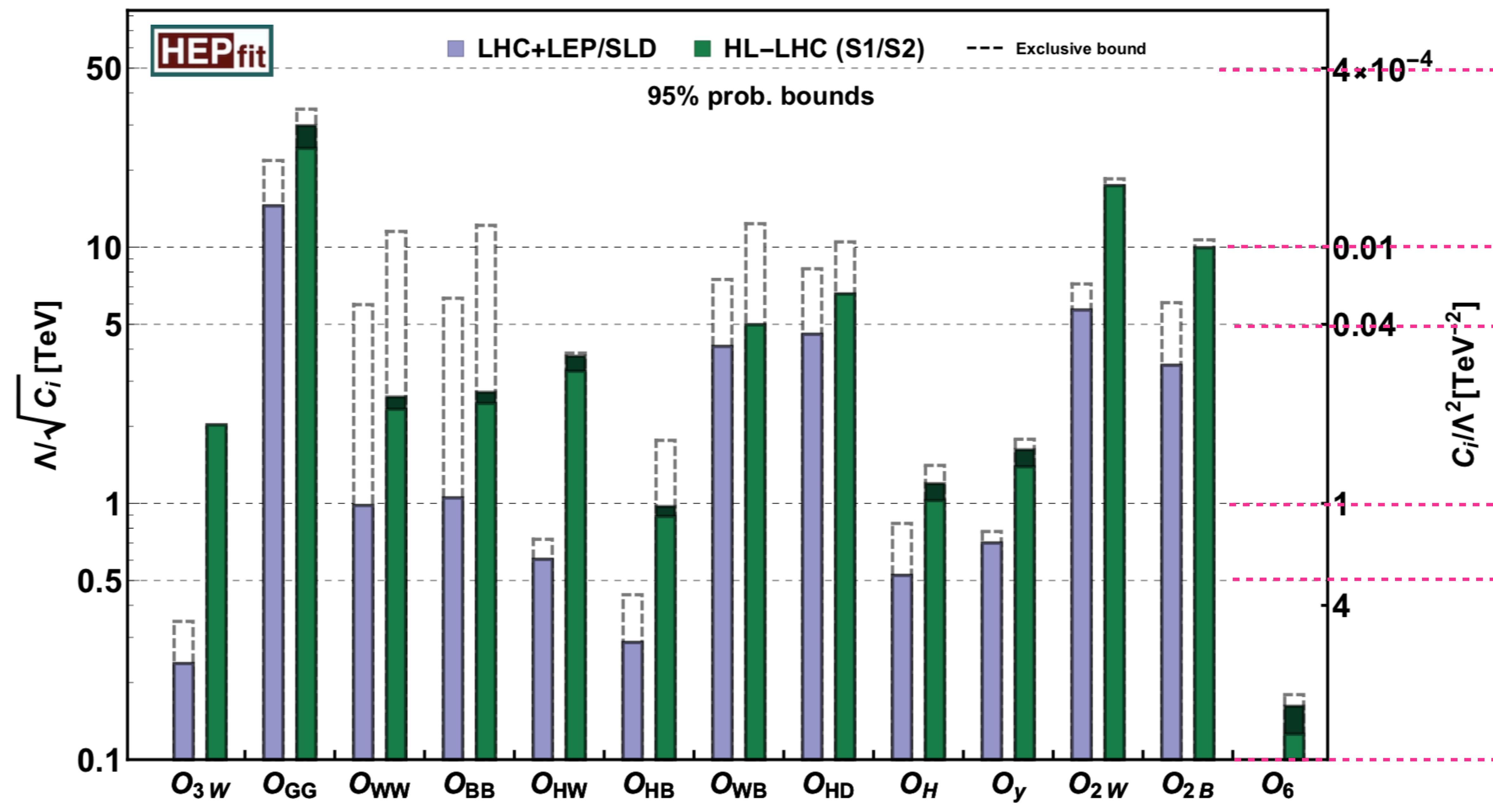
See section 4 of YR

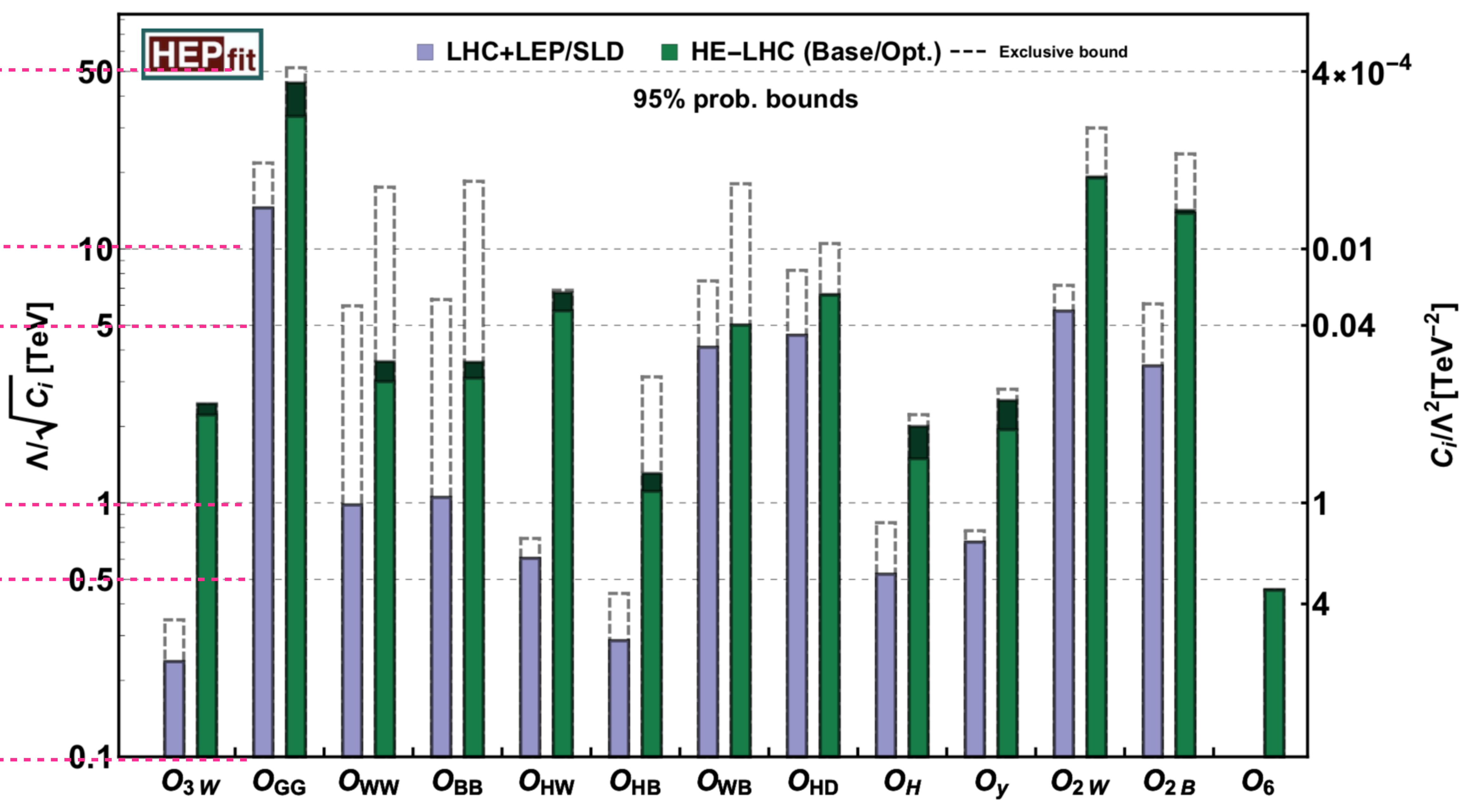
- SMEFT with dimension 6 operators in the Warsaw basis (as well).
- Assuming universality, which results in a slightly simpler model focussing on bosons and the following operators:

$$\{\mathcal{O}_H, \mathcal{O}_{HD}, \mathcal{O}_6, \mathcal{O}_{GG}, \mathcal{O}_{BB}, \mathcal{O}_{WW}, \mathcal{O}_{WB}, \mathcal{O}_{HB}, \mathcal{O}_{HW}, \mathcal{O}_{2B}, \mathcal{O}_{2W}, \mathcal{O}_{3W}, \mathcal{O}_y\}$$

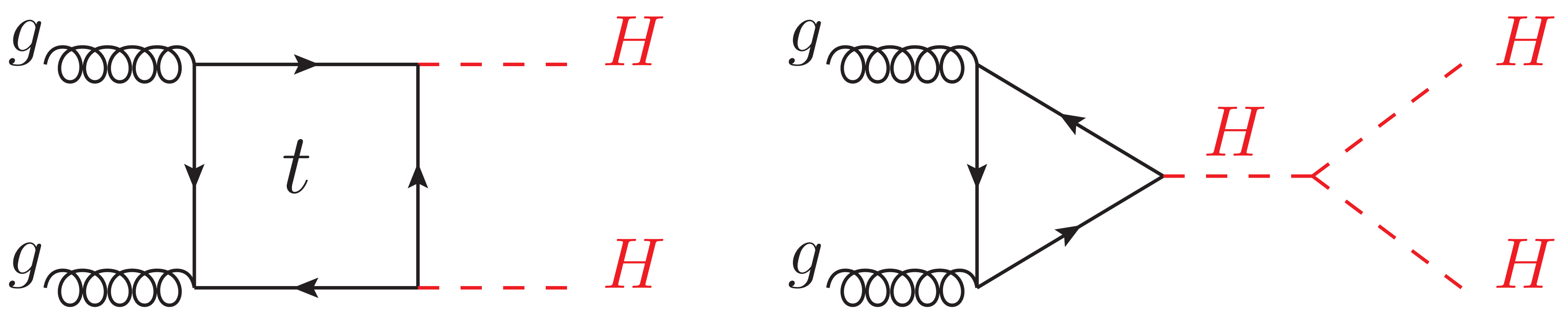
- **Inputs**:
  - LHC Higgs signal strengths (in part VH).
  - HH differential in $b\bar{b}\gamma\gamma$
  - ZH in the high ZH mass regime
  - WZ (better than WW)
  - DY (high mass)

Quadratic terms taken into account where needed.





Double Higgs Production and Higgs Self Coupling



- The total production cross section is very small, huge amount of recent work to improve the prediction at full NLO (differential)!
- **Multiple channels investigated:** depending on the both Higgs decays considering (bb, yy, tautau, WW)
- Evolution of sensitivities has brought interesting surprises.

exp.	WW $\gamma\gamma$	bb $\gamma\gamma$	bb $\tau\tau$	bbWW	bbbb
$\sigma \times B$	0.1 %	0.26 %	7 %	25 %	34 %
ATLAS	<747 (386)	<22 (28)	<13 (15)	-	<13 (21)
CMS	-	<24 (19)	<30 (25)	<79 (89)	<75 (37)

ATLAS combination

$$\sigma_{HH} < 6.9 \times \sigma_{HH}^{SM} \; (10\; exp)$$

$$-5.0 < \kappa_\lambda < 12.0$$

PLB 800 (2020) 135103

(Differential HH taken into account)

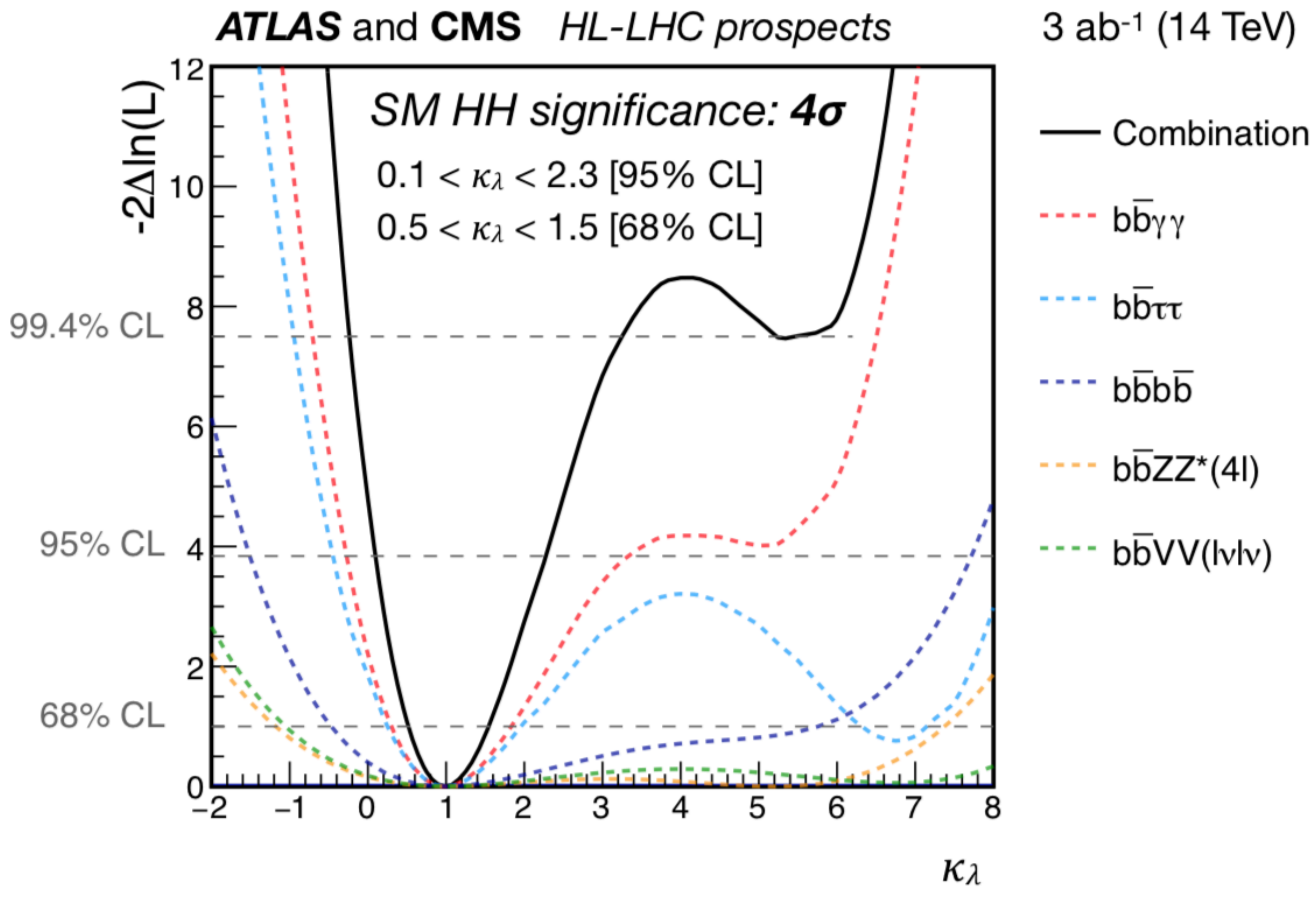
CMS combination

$$\sigma_{HH} < 22.2 \times \sigma_{HH}^{SM} \; (12.8\; exp)$$

$$-11.8 < \kappa_\lambda < 18.8$$

PRL 122 (2019) 121803

At HL-LHC



$$0.5 < \kappa_\lambda < 1.5$$

- Not quite 5σ observation of HH signal.
- significant exclusion of the secondary minimum.
- Closing up on a measurement, though not yet decisive.

In comparison **HE-LHC 10-20%**, **CLIC-3000 10%** and **FCC-hh 5%**

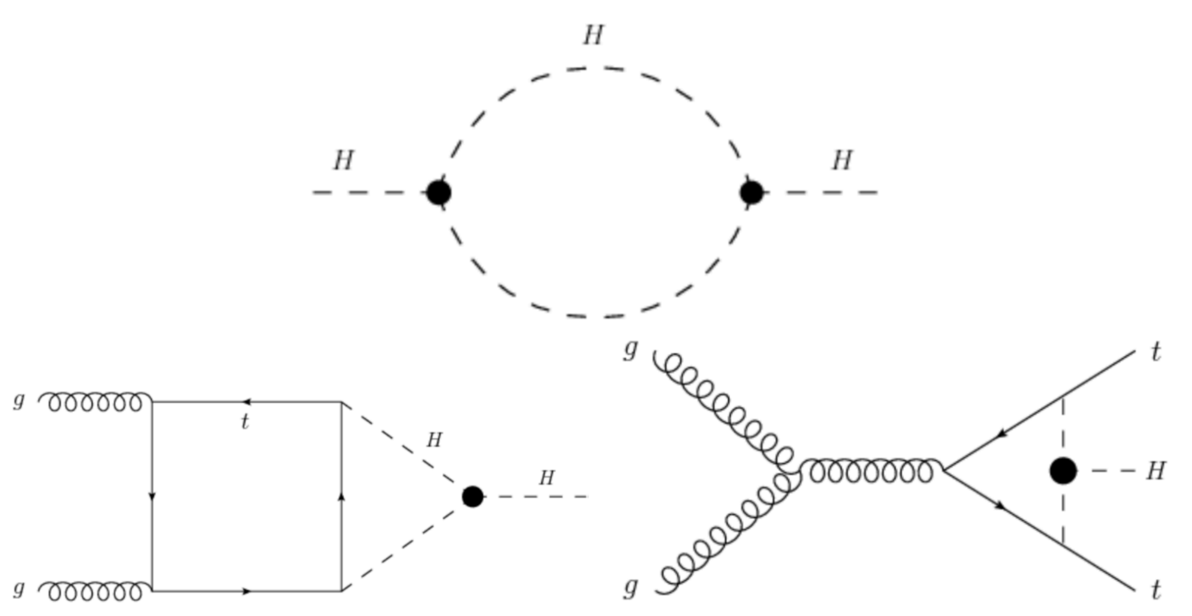
Indirect constraints on Higgs Self Coupling

ATLAS-CONF-2019-049

FTR-2018-020

Indirect constraints from combined STXS

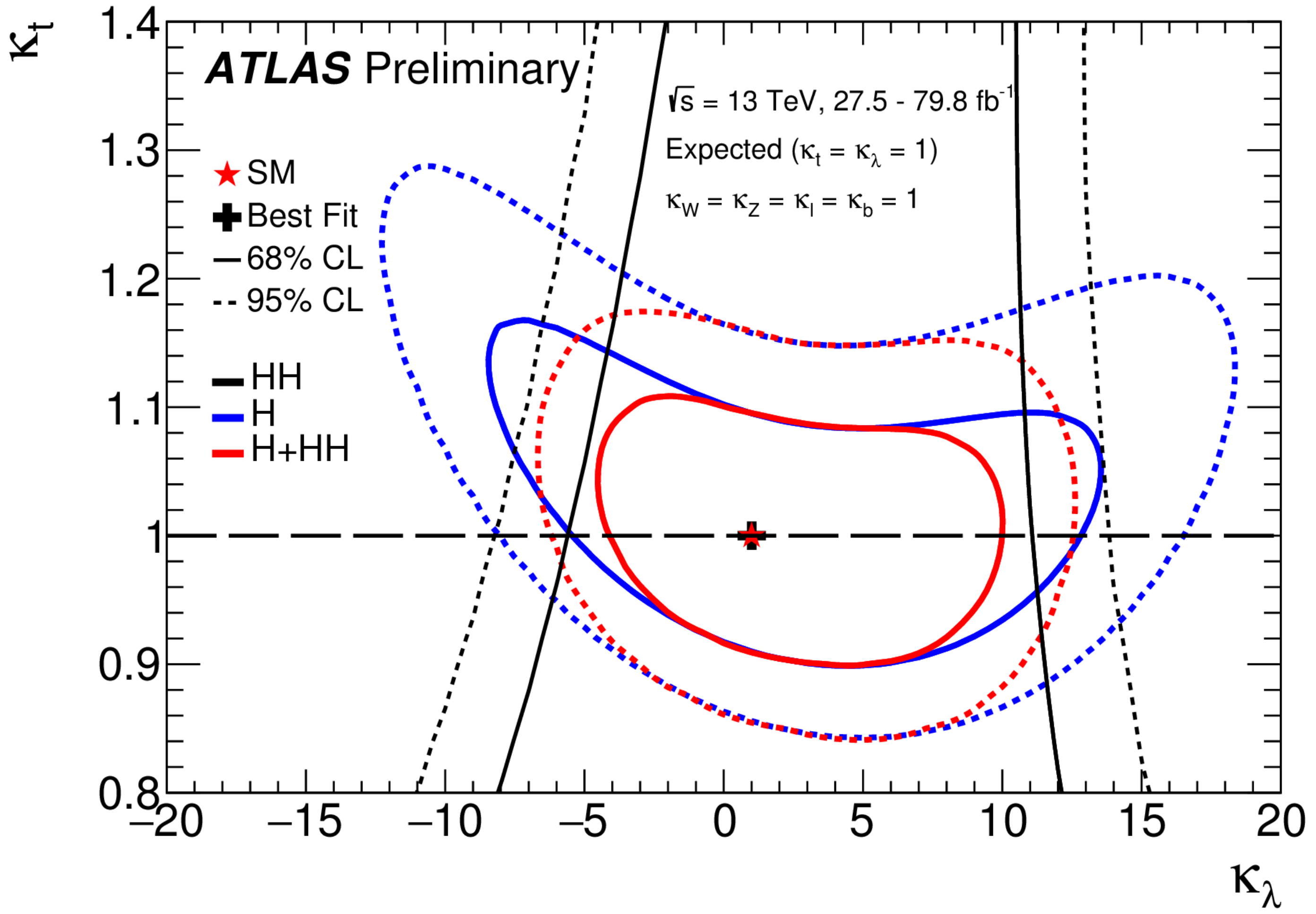
Combination with ATLAS STXSs (discussed slide **33**)



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

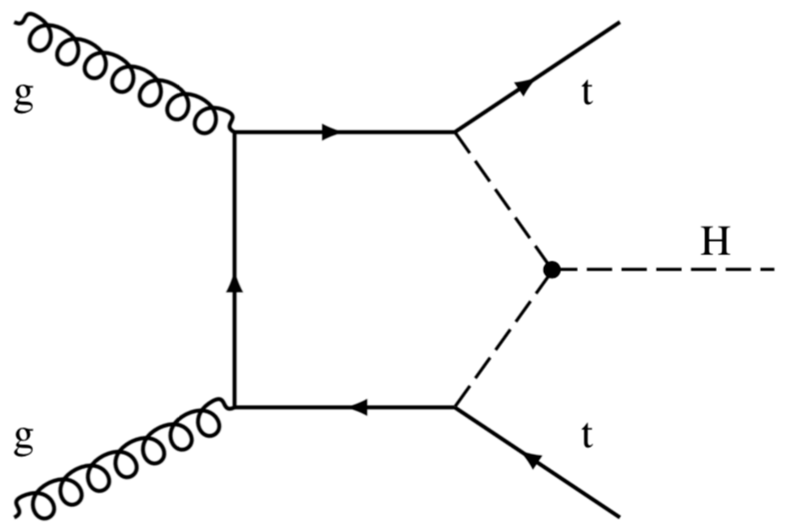
Direct/Indirect currently comparable, direct HH searches will dominate at higher luminosities, but complementarity still necessary to fix κ_t

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

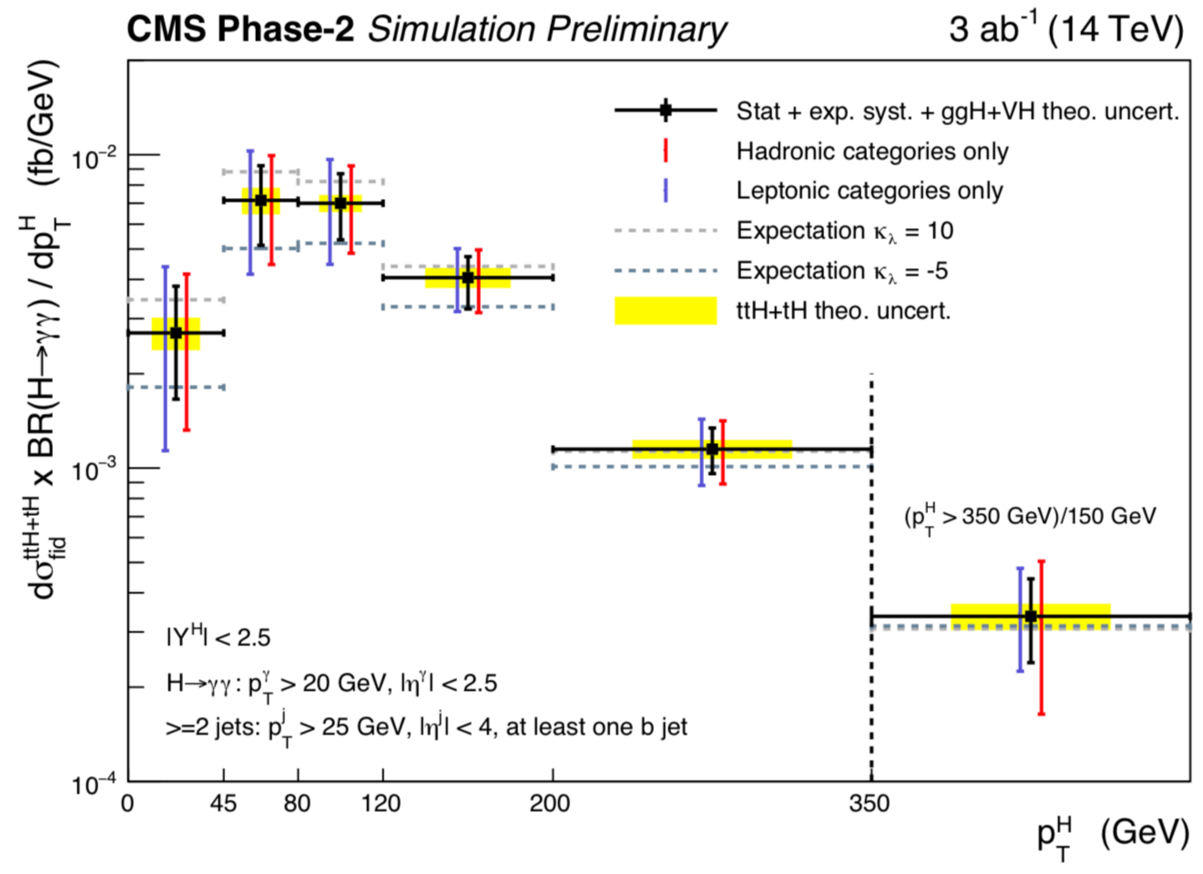


Indirect constraints from differential measurements (e.g. ttH)

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 distribution

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.

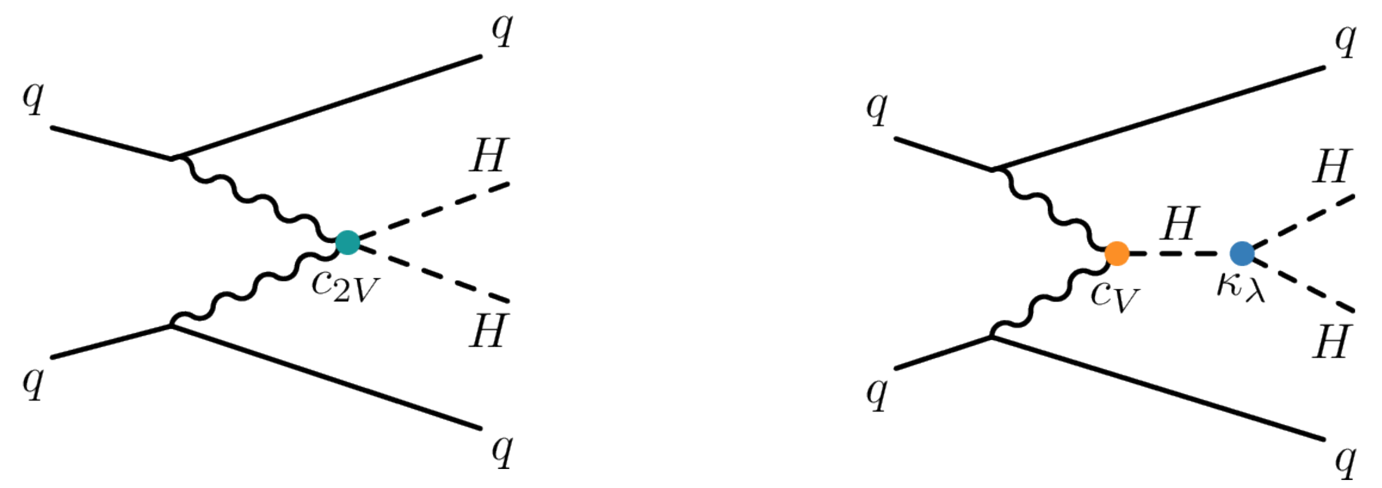
However, the inclusion of single-H differential measurements will not improved greatly the trilinear measurement with the full statistis.

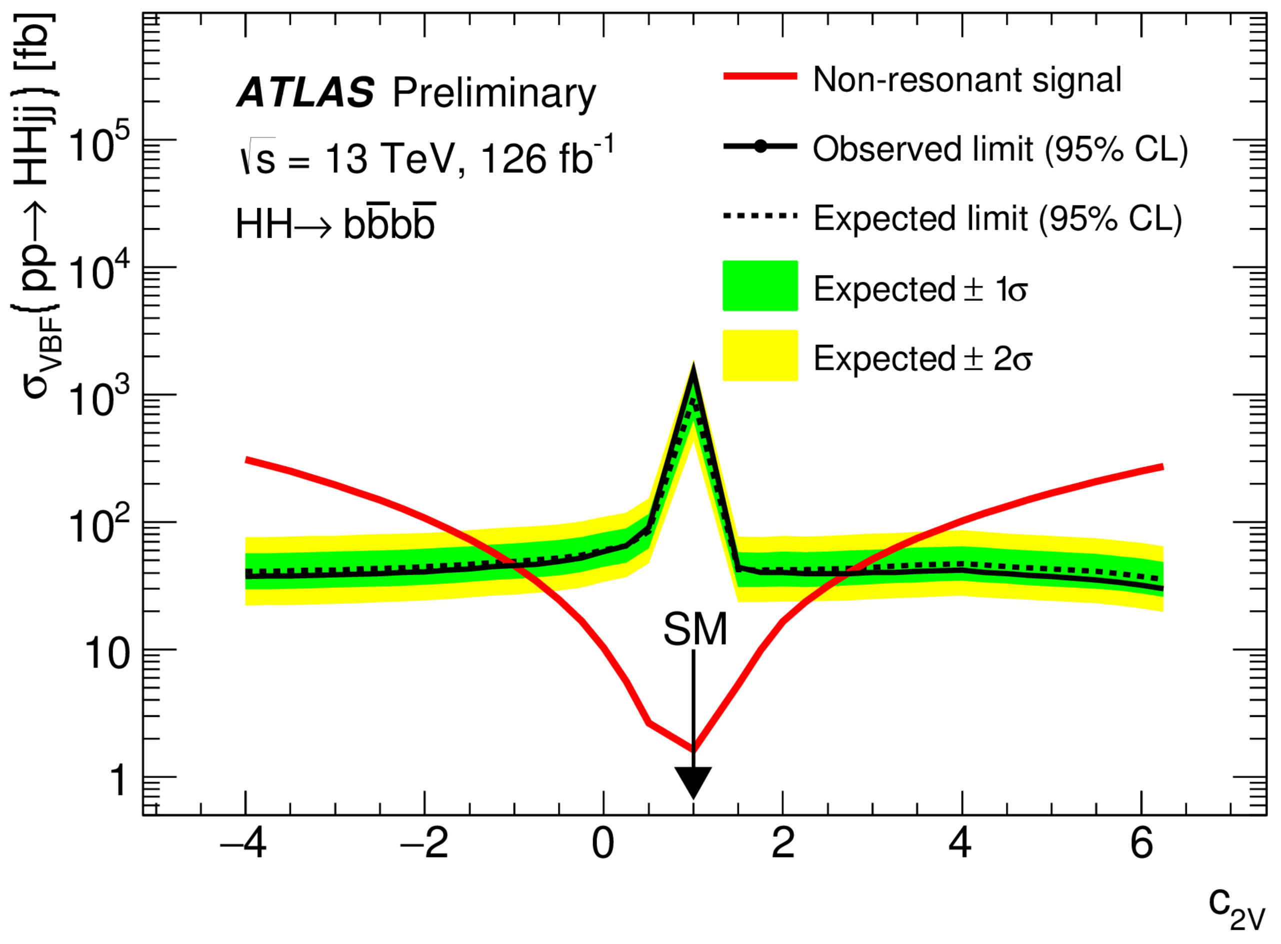
Towards a Measurement of the Higgs Self Coupling

ATLAS-CONF-2019-030

Search for VBF HH production

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





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

F. Dreyer and A. Karlberg

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

$$-1.0 < c_{2V} < 2.7$$

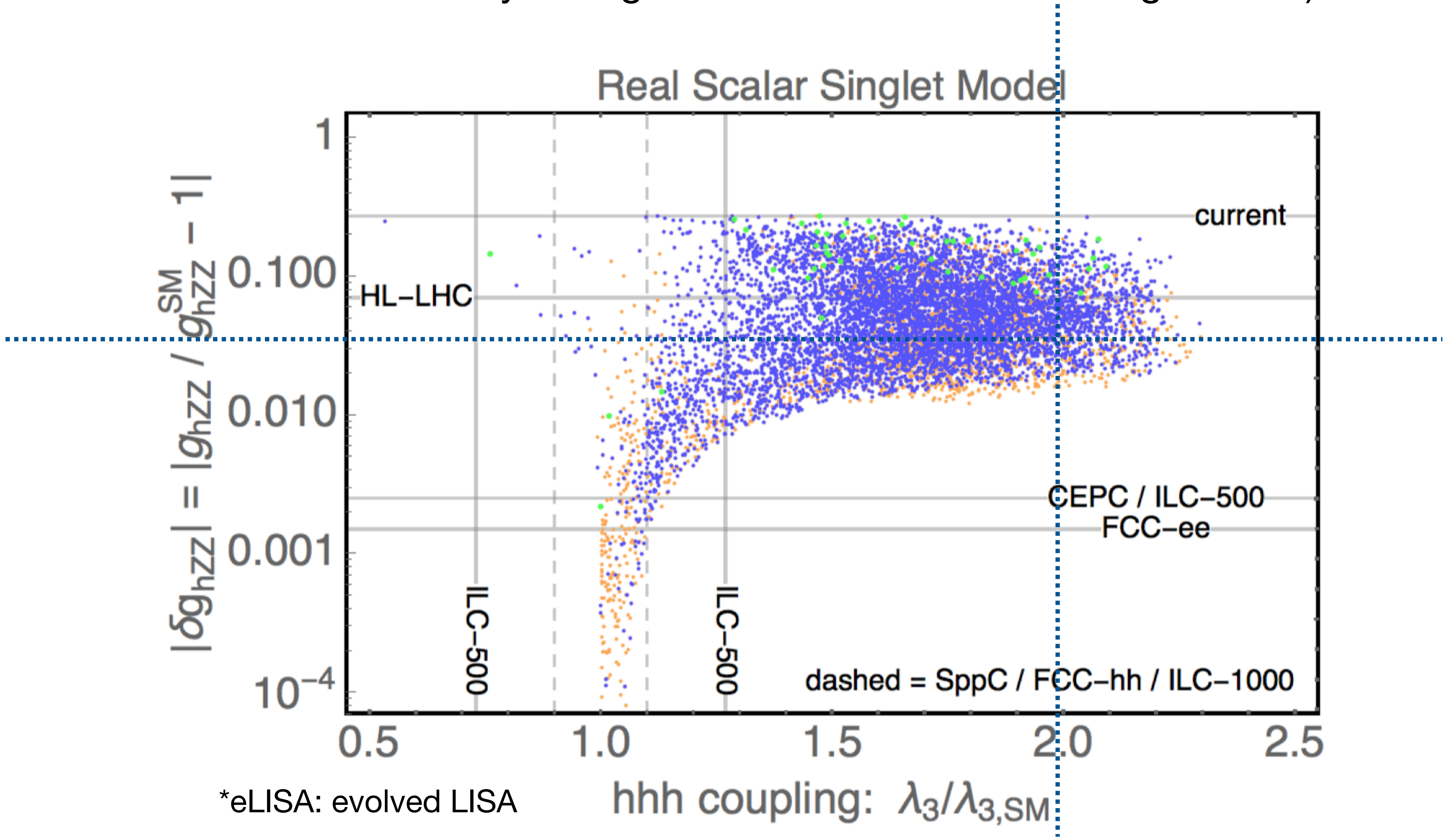
From P. Huang, A. Long and L.-T. Wang

Probing 1st order phase transition and GW signals

A strong 1st order phase transition important for thermal equilibrium violation Sakharov conditions for Baryogenesis.

The sensitivity of HL-LHC to the trilinear coupling could constrain models which would predict strongly first order EW phase transition!

Signals of stochastic background (e.g. collisions of bubbles) in the Phase Tr. could be detected by next generation interferometers e.g. eLISA*)



*eLISA: evolved LISA

Higgs Summary

- While the full run 2 data is still being analysed, major and new landmark results have been achieved in Higgs physics:
    - The direct observation of the Yukawa couplings of the Higgs boson to the third generation fermions (independently by both experiments), and their corresponding couplings measured at the 10-15% level.
    - The precision in the couplings to the EW gauge bosons has reached 7% to 9% (an accomplishment largely due to the increased TH predictions precision)
- Based on the optimised analyses of the higher PU Run 2 data, the prospectives in Higgs measurements at HL-LHC have been reappraised and significantly changed reaching 1.5% precision on the couplings to EW bosons (and 2% to 3.5% on the couplings to third generation fermions).
- Many new ideas have emerged since the discovery expanding immensely the Higgs physics program at the LHC and HL-LHC.
- **Many more hopefully to come!**

Conclusions

- From the first discussions (1977) the LHC program to 20 years to be fully approved (1994), 15 years of construction (2009) and up to now 10 years of running! With the HL-LHC the full program should span approximately 60 years!

- The LHC has provided only about 1/20 of the projected full dataset (1/27 - in case of 4 fb^{-1}) there is still room for discoveries.

- The name of the game is the pursuit of the precision frontier at hadron colliders:
  - Huge progress made in predictions, common TH/EP effort
  - Large number of new ideas investigated development of new tools (e.g. reconstruction and trigger with deep learning technologies)
  - New ideas to reach improved precision and extend our sensitivity reach!

A large amount of exciting challenges and opportunities for the HL-LHC!