



Highlights from SM Higgs (Higgs to fermions)

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Minoru Hirose (Osaka University)

on behalf of the CMS and ATLAS experiments



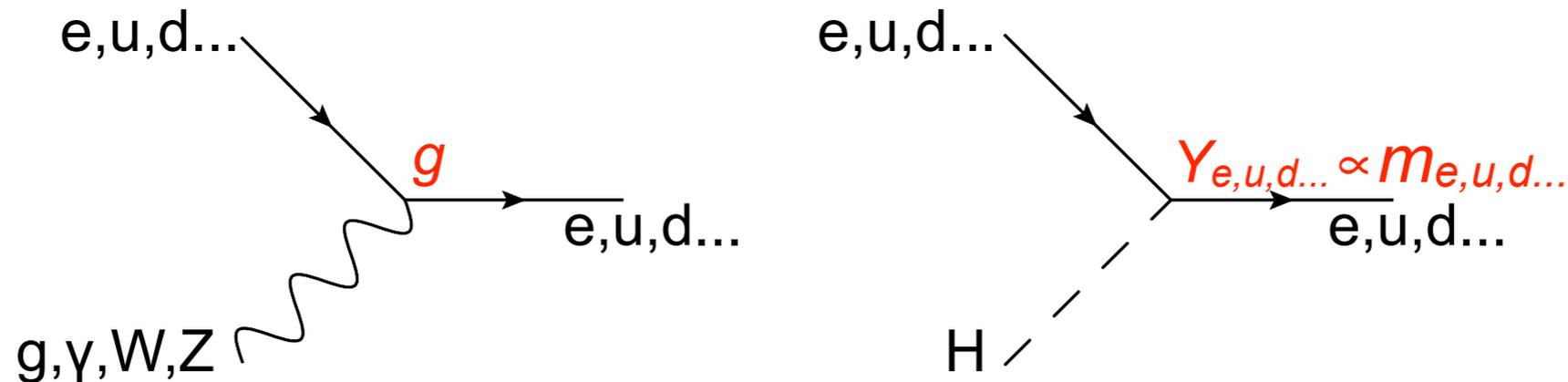
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Introduction

- Higgs sector of the Lagrangian:
 - ➔ The origin of the CKM matrix.
- Standard model Lagrangian parameters:
 - ➔ 4 from the CKM matrix
 - ➔ 11 from the Higgs sector.
 - ➔ Those should be determined by experiments.
- This talk tries to show...
 - ➔ Latest results of Higgs-Fermion coupling measurements.
 - ➔ How well we understand the Higgs sector.

Importance of Higgs-Fermion couplings

- One of the most mysterious parts of the SM Lagrangian.
 - ➔ $\mathcal{L}_{\text{Yukawa}} = -(1 + h/v)\{m_d\bar{d}d + m_u\bar{u}u + m_e\bar{e}e\}$
 - ➔ Coupling constant is proportional to the particle mass. (Non-universal couplings not like the other bosons!!)



- ➔ LHC is the only facility to study this.
 - ✓ CMS and ATLAS are intensively studying it.

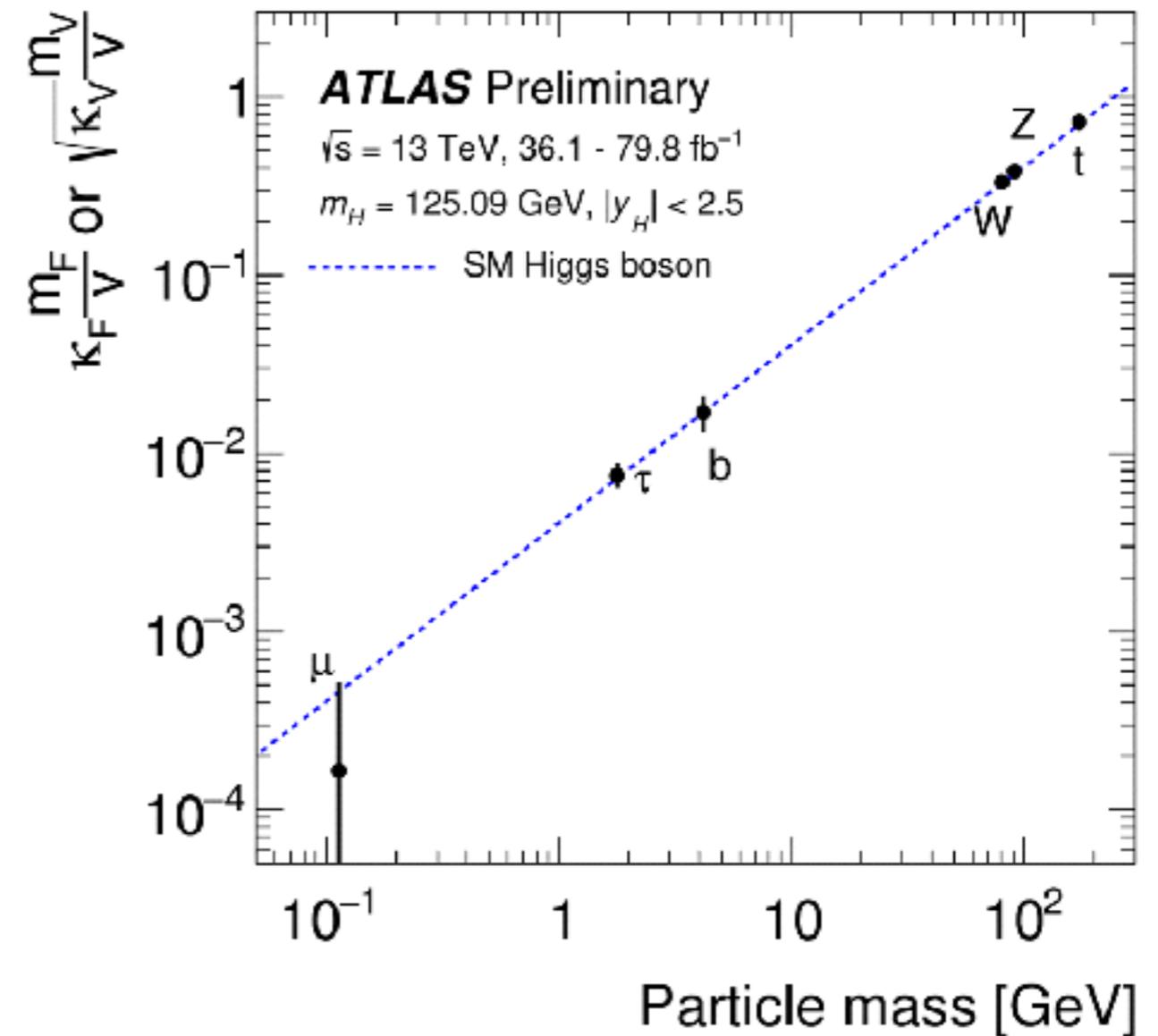
Overview of the Higgs-fermion couplings

- So far, look very SM-like.

1st	2nd	3rd
u	c	t
d	s	b
e	μ	τ

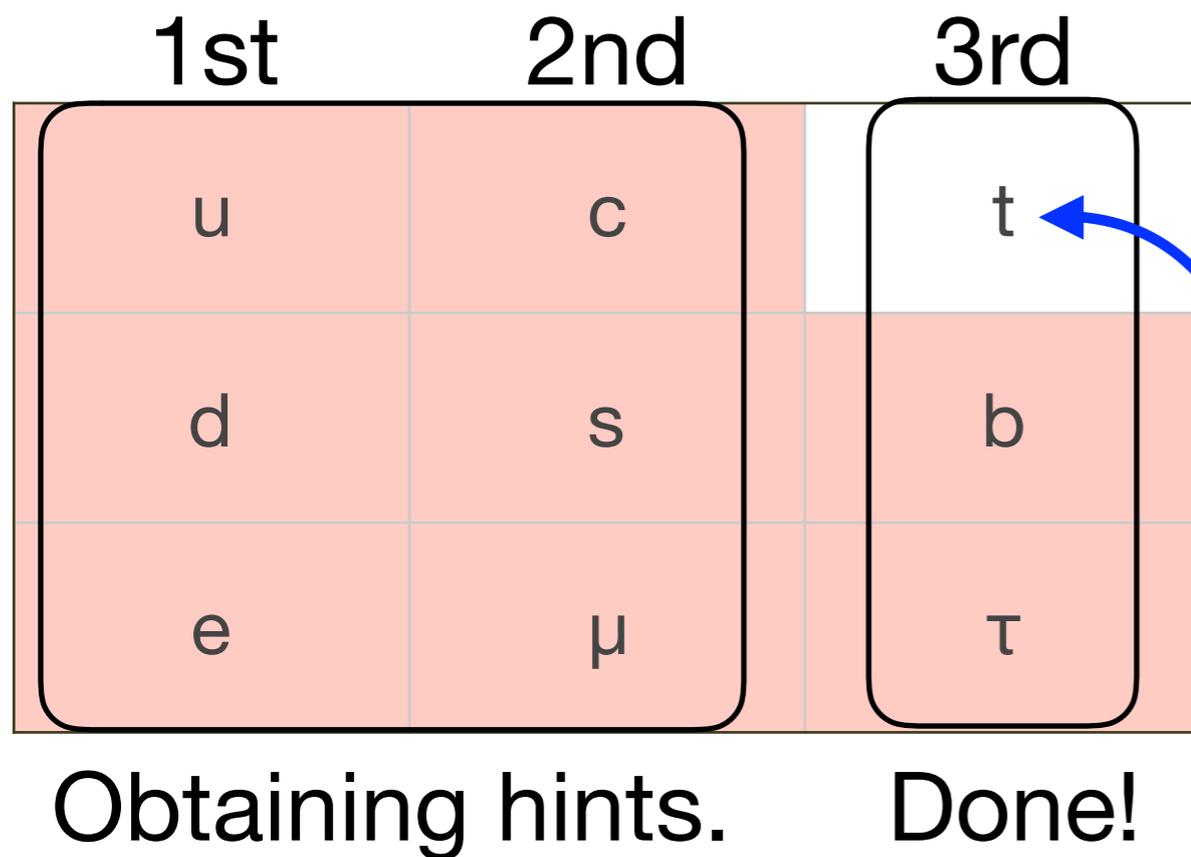
Obtaining hints. Done!

Latest combination of ATLAS Higgs measurements



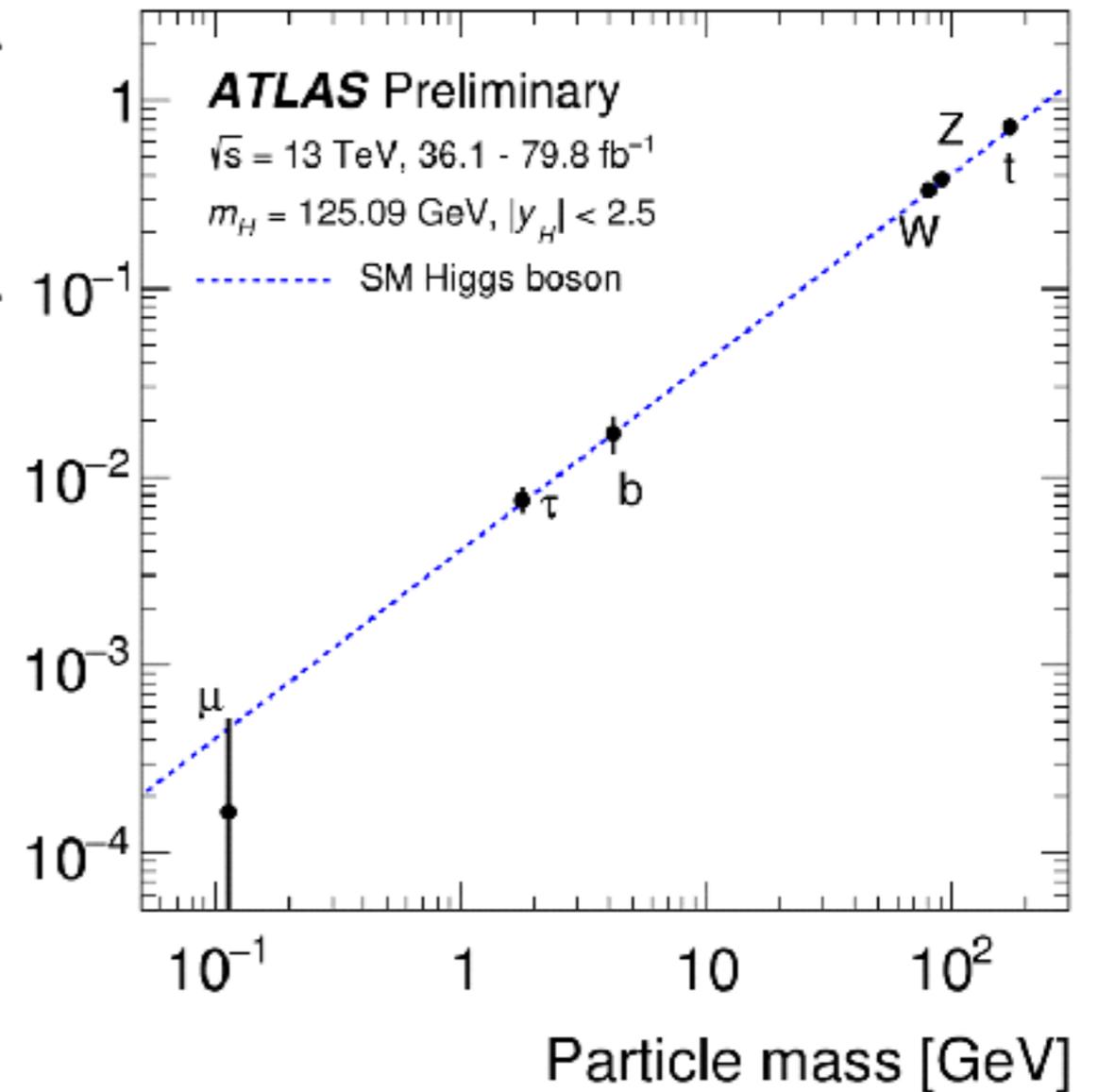
Overview of the Higgs-fermion couplings

- So far, look very SM-like.



$$\frac{m_F}{k_F V} \text{ or } \sqrt{\frac{m_F}{k_V V}}$$

Latest combination of ATLAS Higgs measurements



Recently observed!! Dedicated talk later.

Higgs to bottom and tau

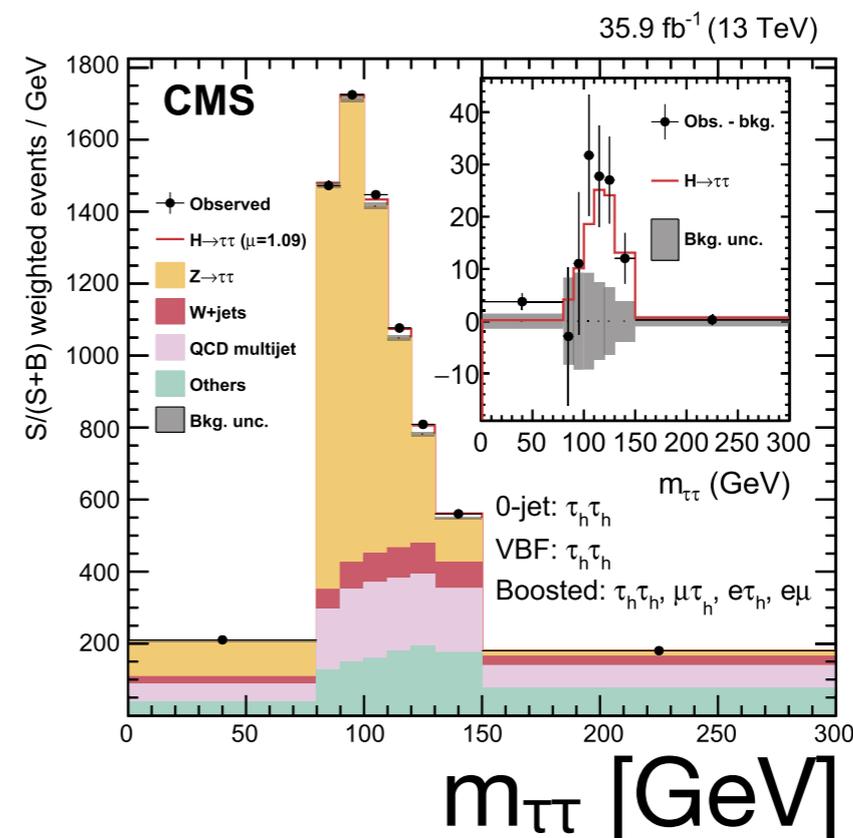
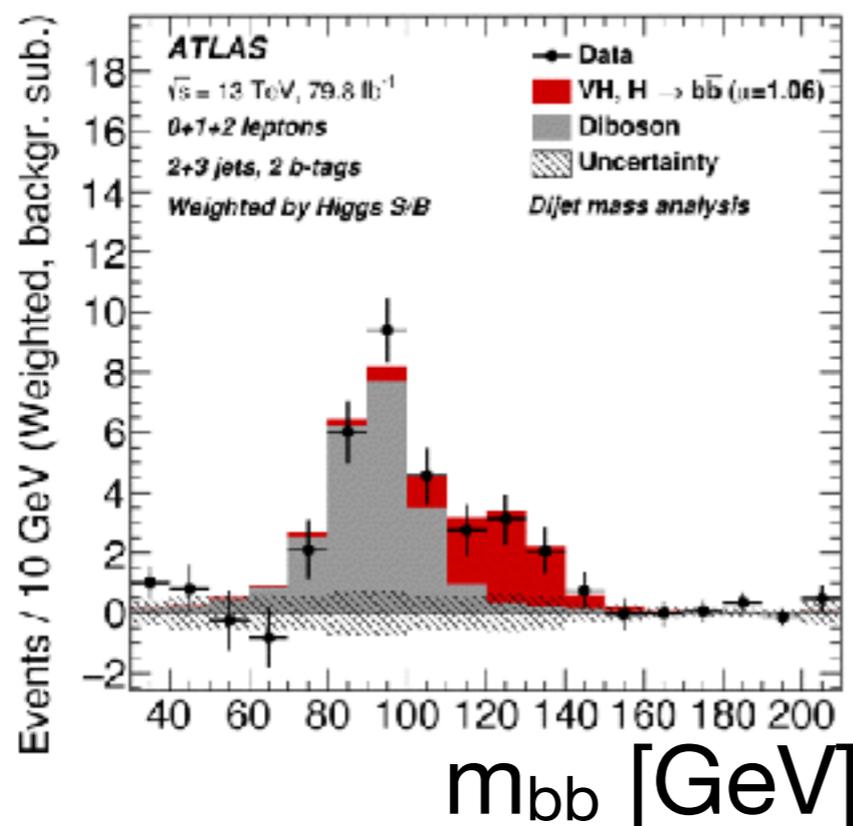
u	c	t
d	s	b
e	μ	τ

$H \rightarrow bb$, $H \rightarrow \tau\tau$

- Third generation, bottom type particles.
 - ➔ Particularly interesting for BSM (e.g. sensitive to a MSSM parameter).
 - ➔ Existence of these processes was already confirmed.

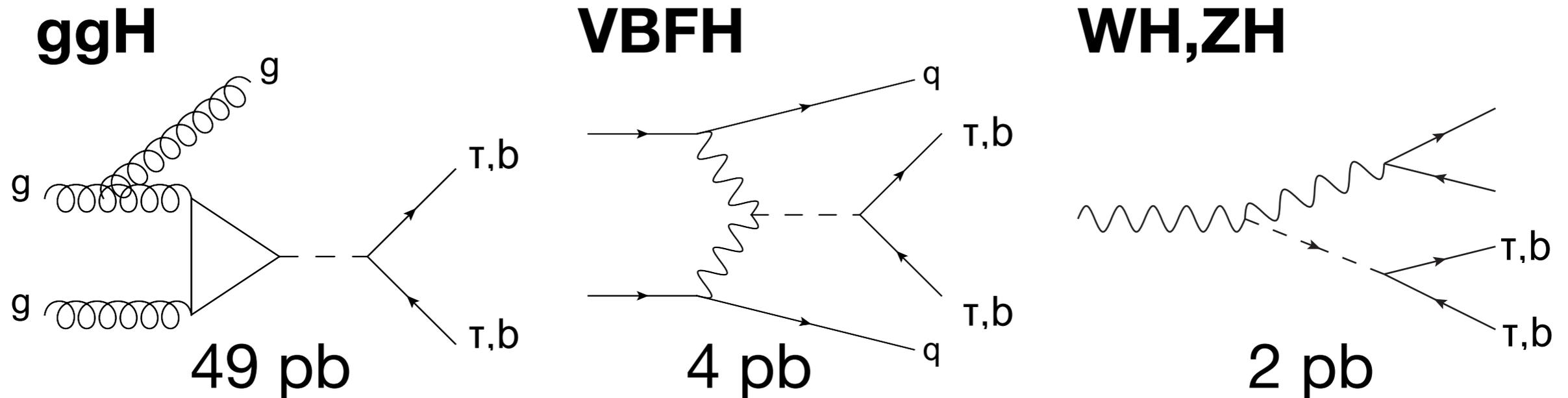
	CMS	ATLAS
$H \rightarrow bb$ (Run 1&2)	5.6σ (5.5σ) New	5.4σ (5.5σ) New
$H \rightarrow \tau\tau$ (Run 1&2)	5.9σ (5.9σ)	6.4σ (5.4σ)

Obs. (Exp.)



$H \rightarrow bb, H \rightarrow \tau\tau$

- Started exploring rarer and/or more difficult processes.

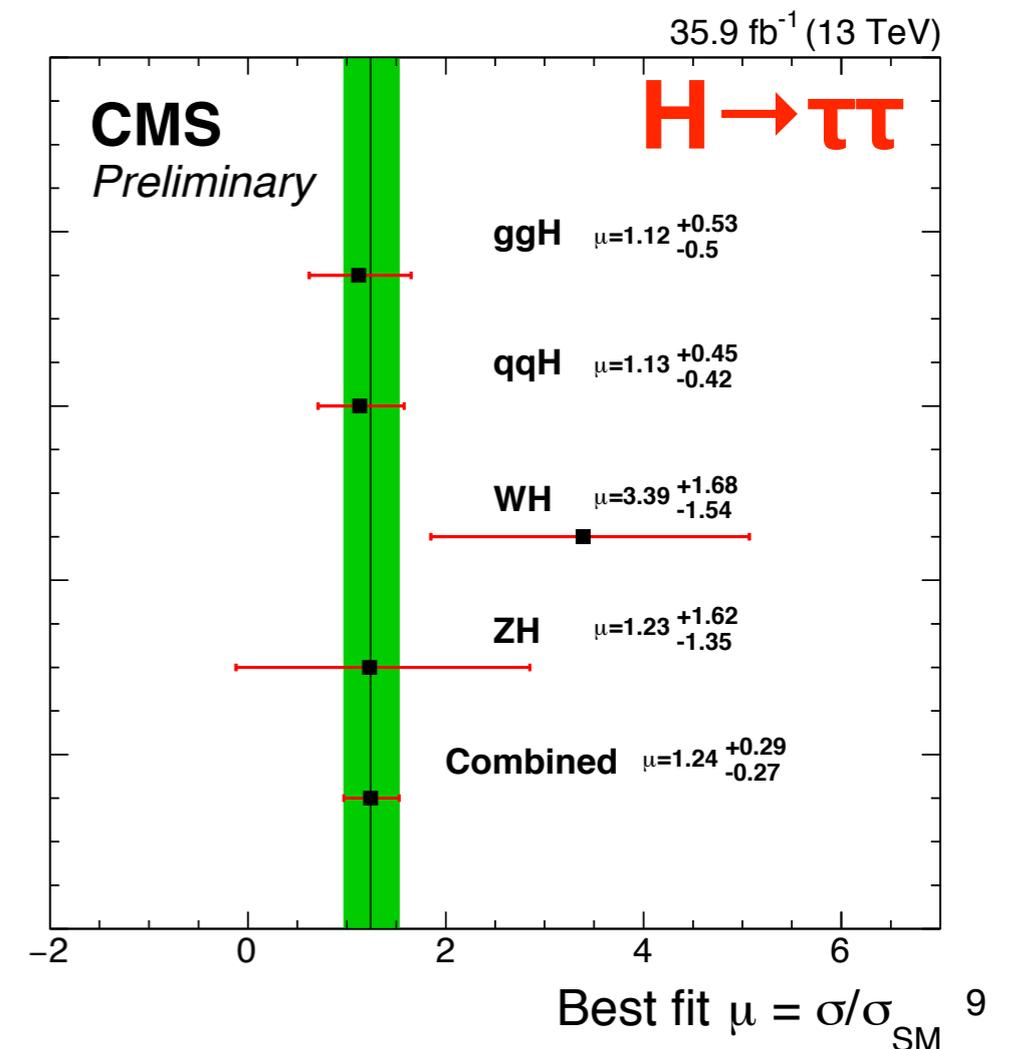
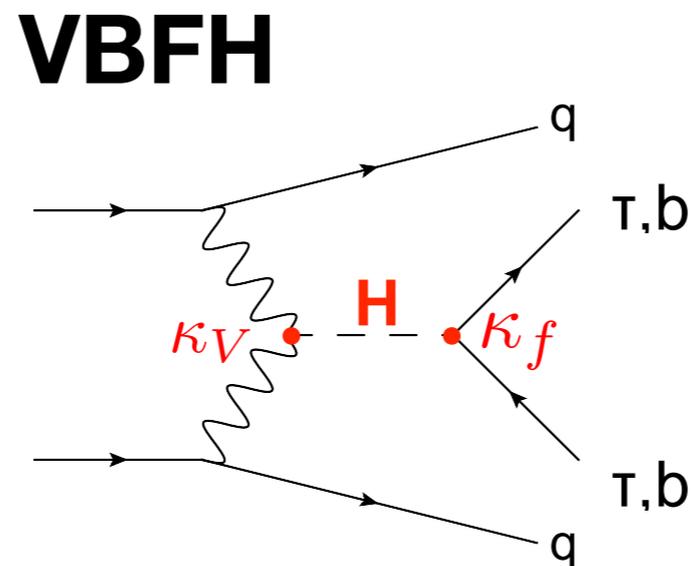
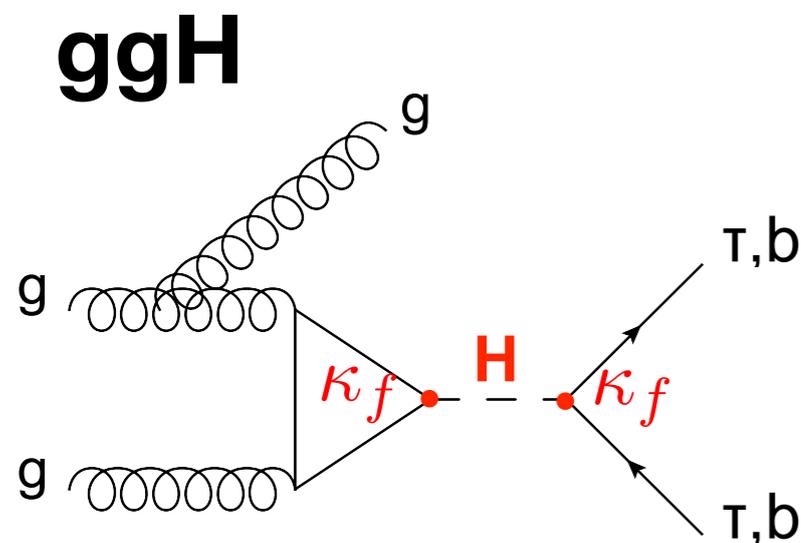


	$H \rightarrow bb$		$H \rightarrow \tau\tau$	
	ATLAS	CMS <i>New</i>	ATLAS	CMS
ggH	- <i>New</i>	1.5σ	○	○
VBFH	1.9σ	2.2σ	○	○
ZH,WH	○	○	$\mu < 5.6(3.5)$ in Run1	2.3σ <i>New</i>

Main production modes for the discoveries

$H \rightarrow bb, H \rightarrow \tau\tau$

- Various μ or $\mu = \sigma_{\text{obs}}/\sigma_{\text{SM}}$ measurement are becoming available.
 - ➔ Of course the precision is not enough, but a nice milestone.
- Good input to constrain the coupling modifier parameters.
 - ➔ Next steps are differential cross section measurements.

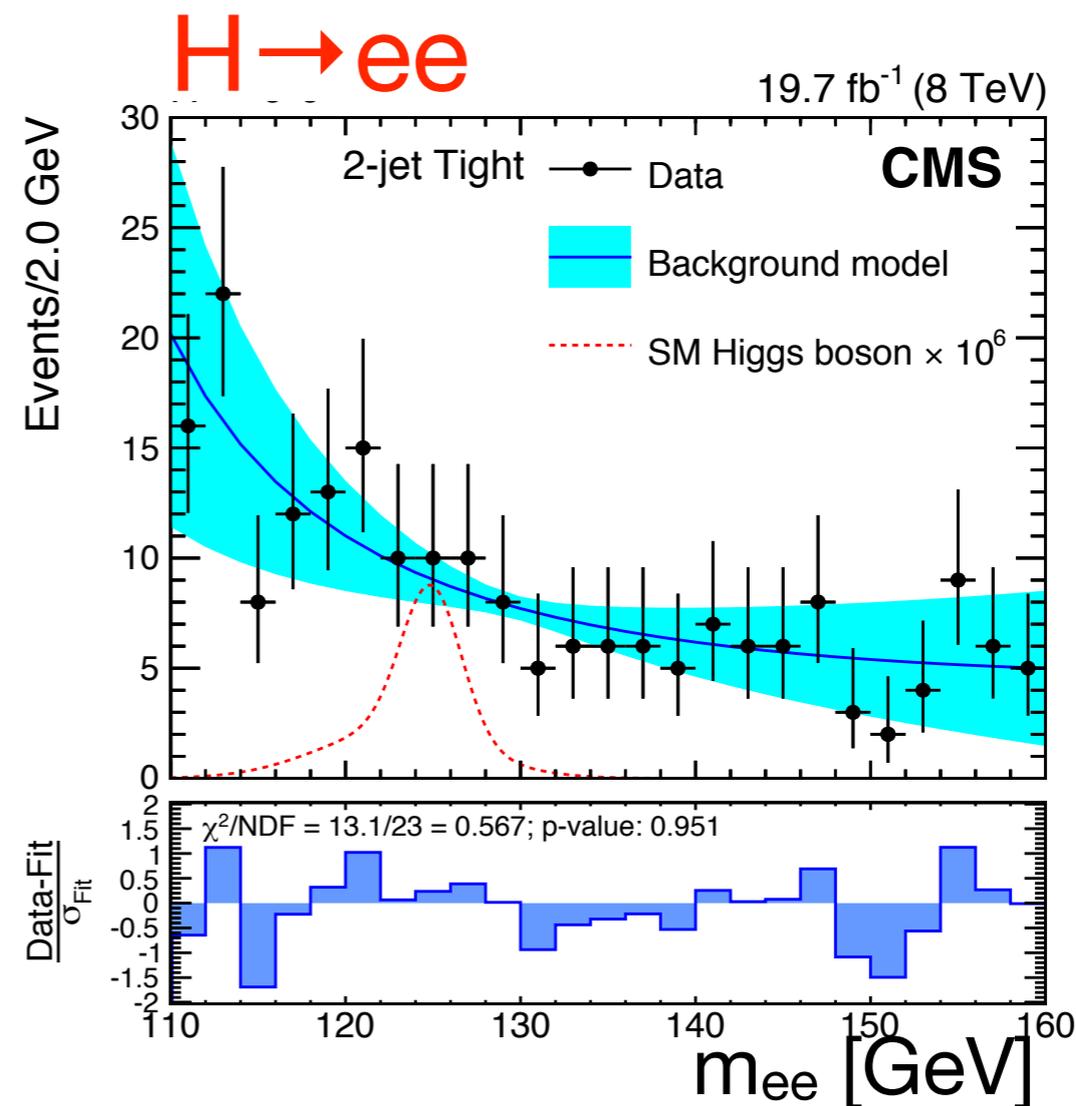
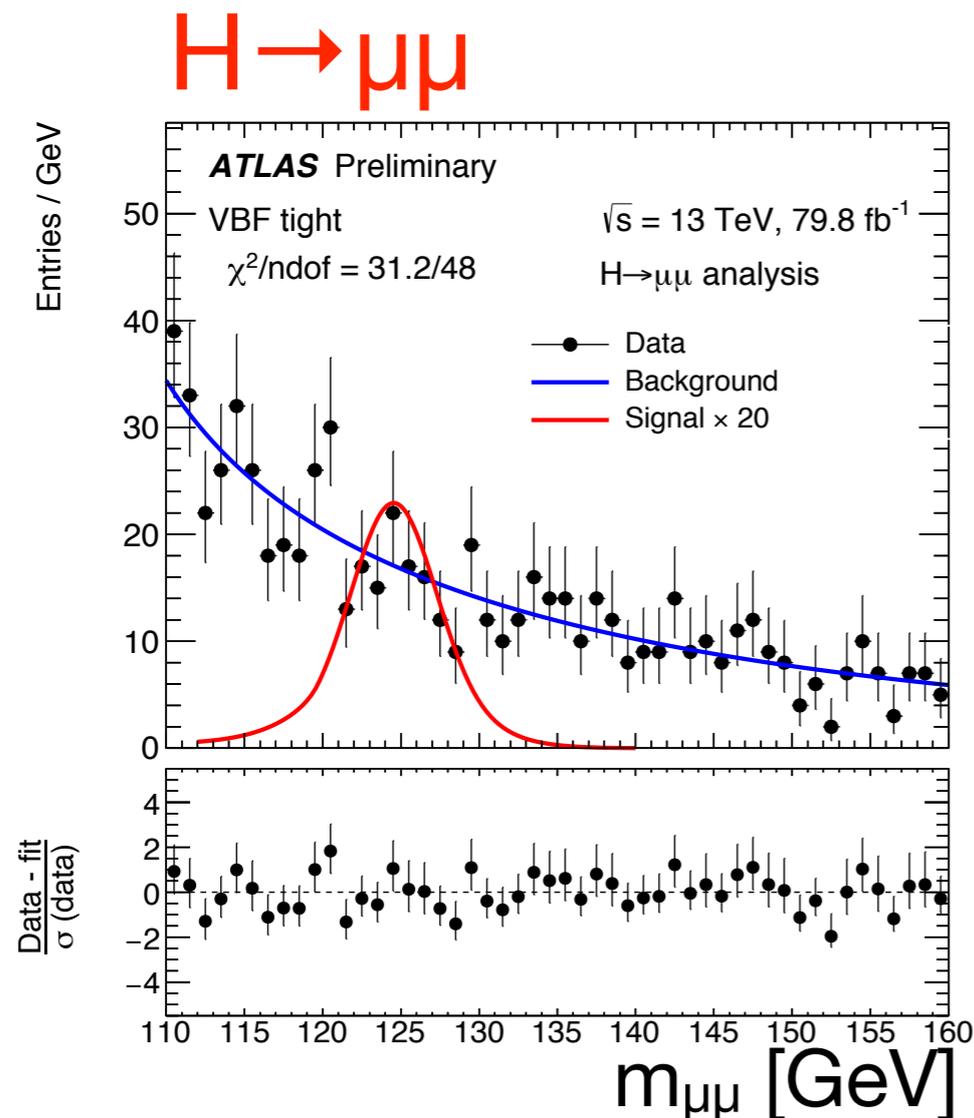


Higgs to electron and muon

u	c	t
d	s	b
e	μ	τ

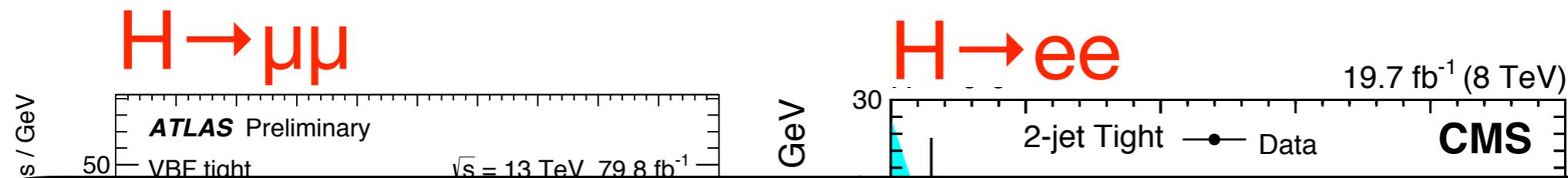
$H \rightarrow \mu\mu/ee$

- Straightforward analysis, but needs enormous amounts of data.
 - ➔ $H \rightarrow \mu\mu$: $\mu < 2.1$ (ATLAS with 80/fb), 2.9 (CMS with 36/fb).
 - ➔ $H \rightarrow ee$: $BR < 0.0019$ (CMS), which is 3.7×10^5 times SM.

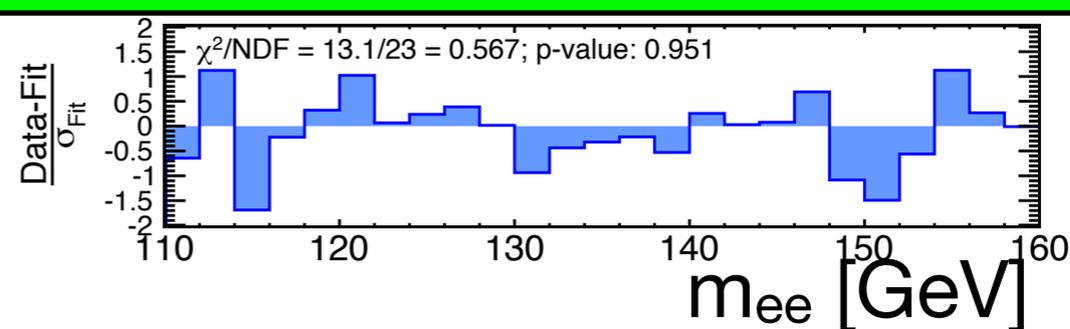
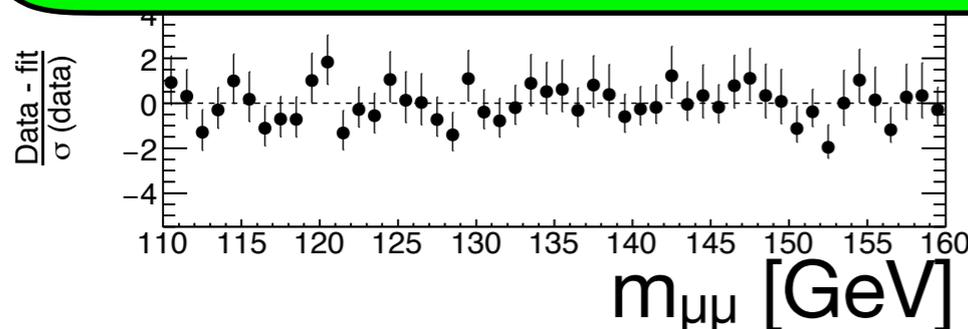


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$H \rightarrow ee$: Hopeless in LHC (or even in HL-LHC)...
 $H \rightarrow \mu\mu$: significance > 9 is expected with 3000/fb by ATLAS.

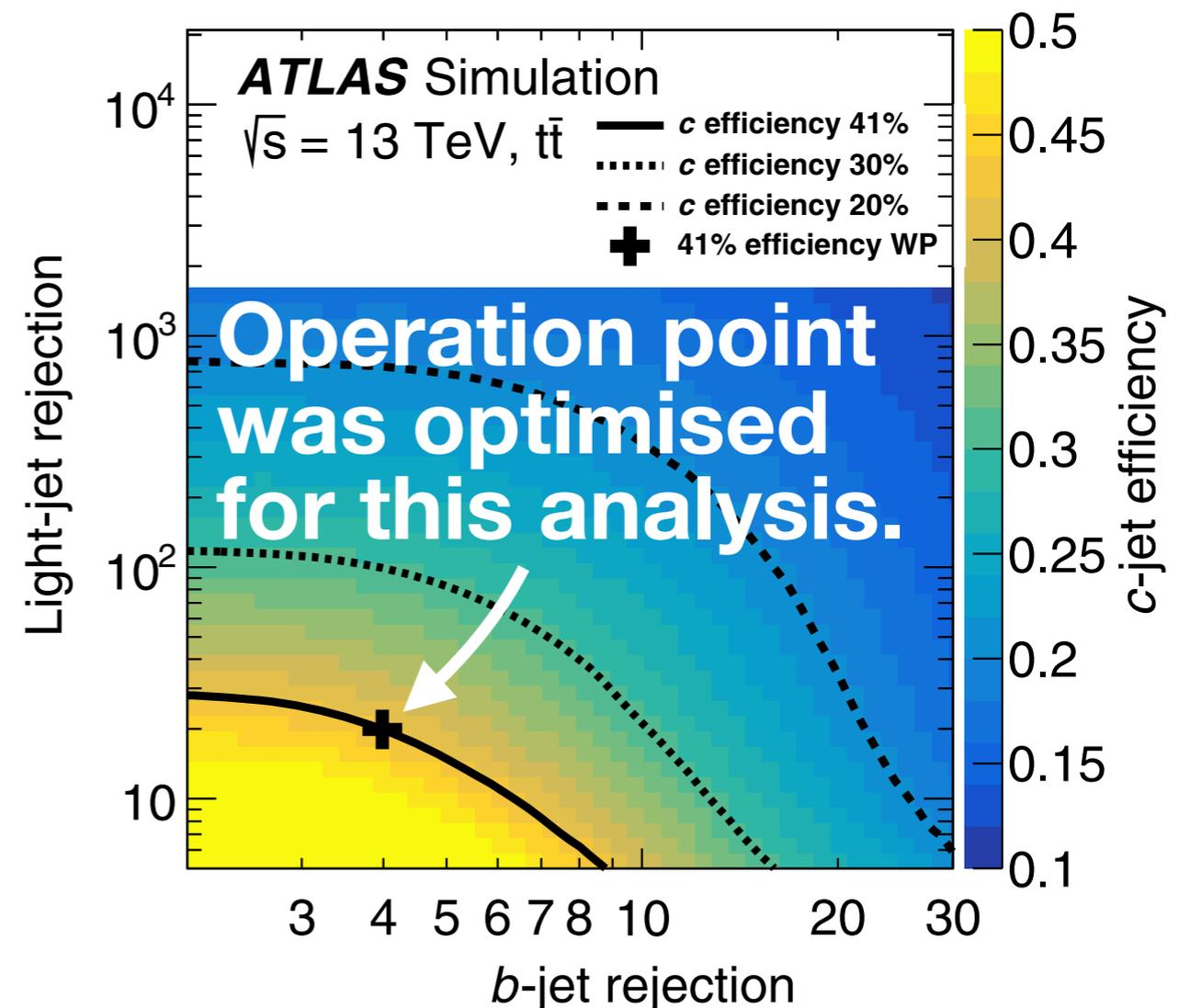


Higgs to charm

u	c	t
d	s	b
e	μ	τ

H → cc

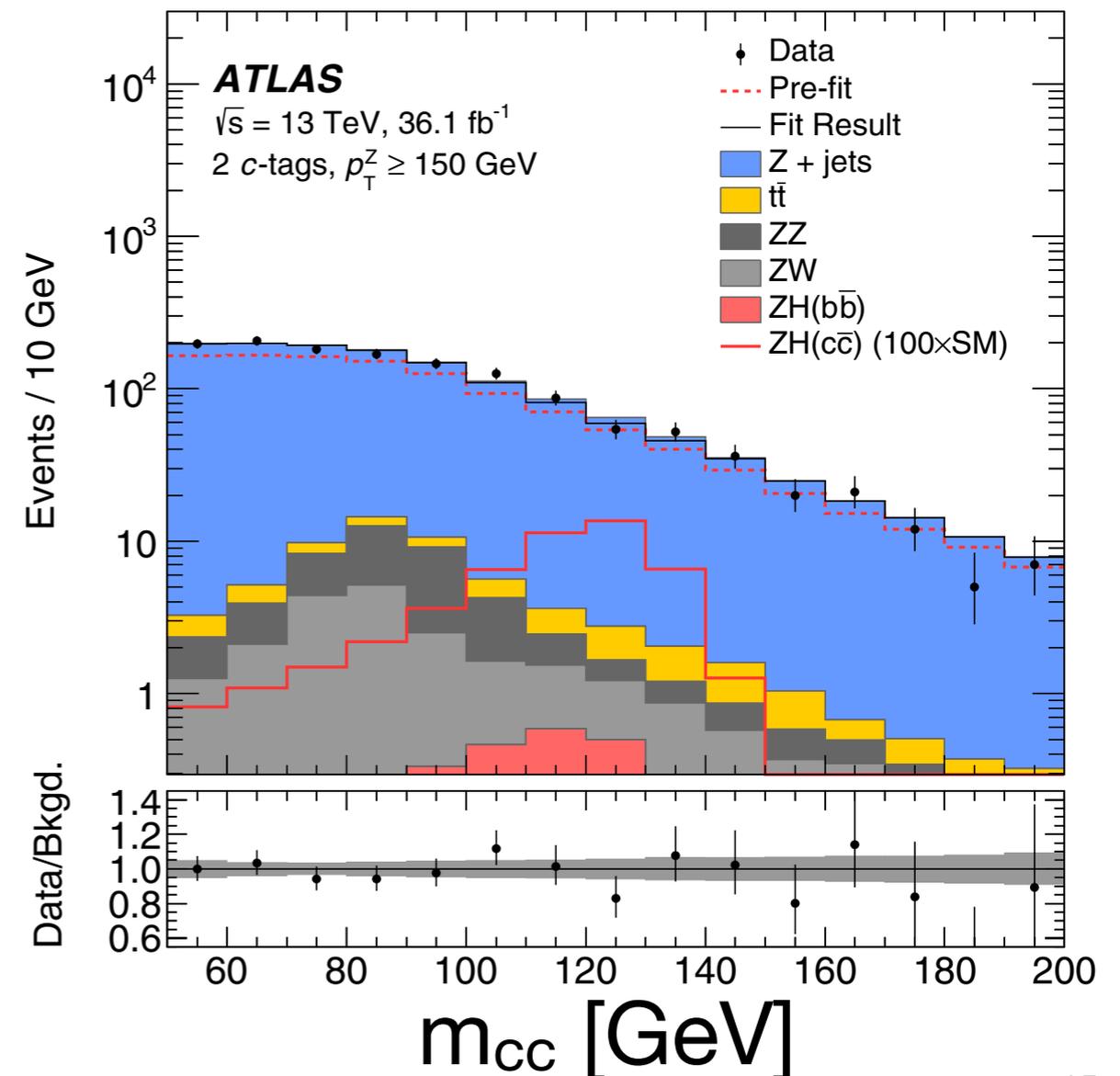
- Important channel for the 2nd generation quark coupling.
- Search for $ZH \rightarrow llcc$ with 2015+2016 data.
 - ➔ c-jets from Higgs decay were attempted to be identified.
 - ➔ c-tagging (efficiency: 41%).
 - ✓ b-jet rejection ~ 4.
 - ✓ l-jet rejection ~ 20.



H → CC

- Upper limit: $\mu < 110$ (obs.), 150_{-40}^{+80} (exp.) with 95% CL.
 ➔ $\sigma_{\text{SM}} = 25.5$ fb.
- Can be improved by better c-jet efficiency calibration? (and worth pursuing!!)

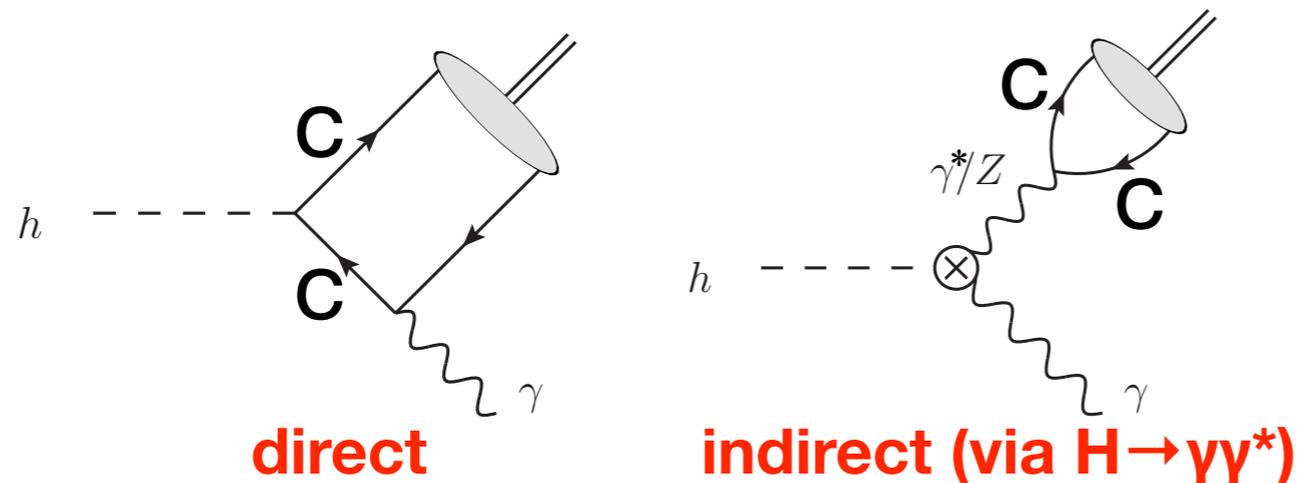
Source	$\sigma / \sigma_{\text{tot}}$
Statistical	49%
Floating Z + jets Normalization	31%
Systematic	87%
Flavor Tagging	73%
Background Modeling	47%
Lepton, Jet and Luminosity	28%
Signal Modeling	28%
MC statistical	6%



Exploration of the Hcc vertex

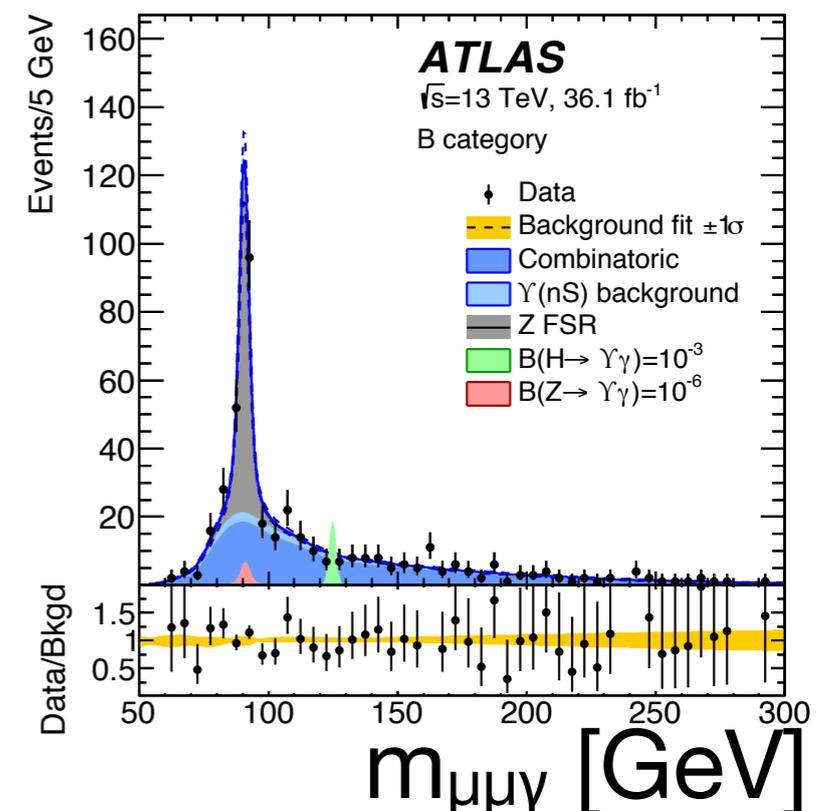
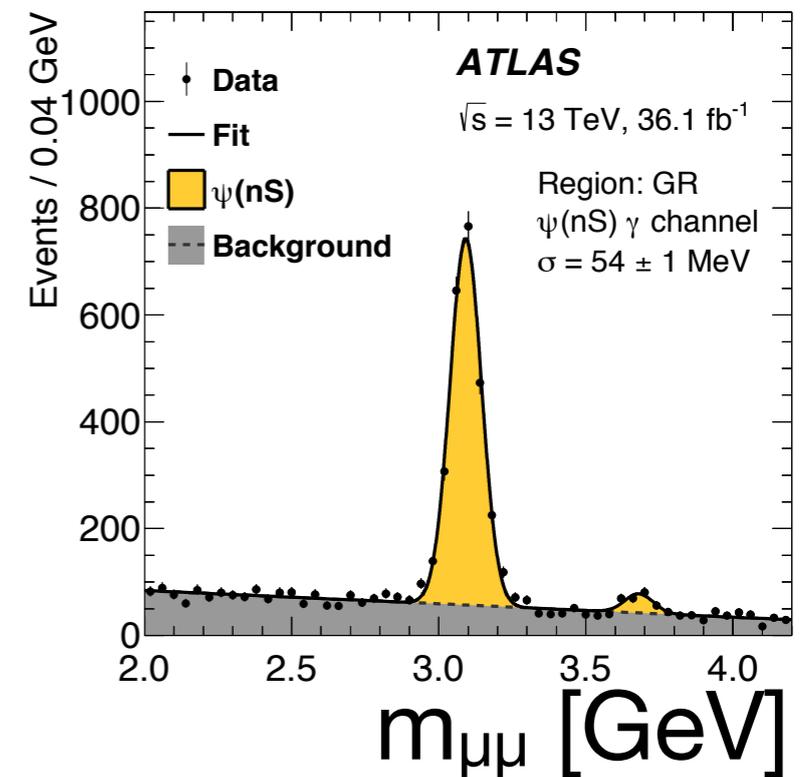
- Identifying charmonium decays.

→ $H \rightarrow J/\psi$ or $\psi(2S) + \gamma$: $\text{BR} = \mathcal{O}(10^{-6})$

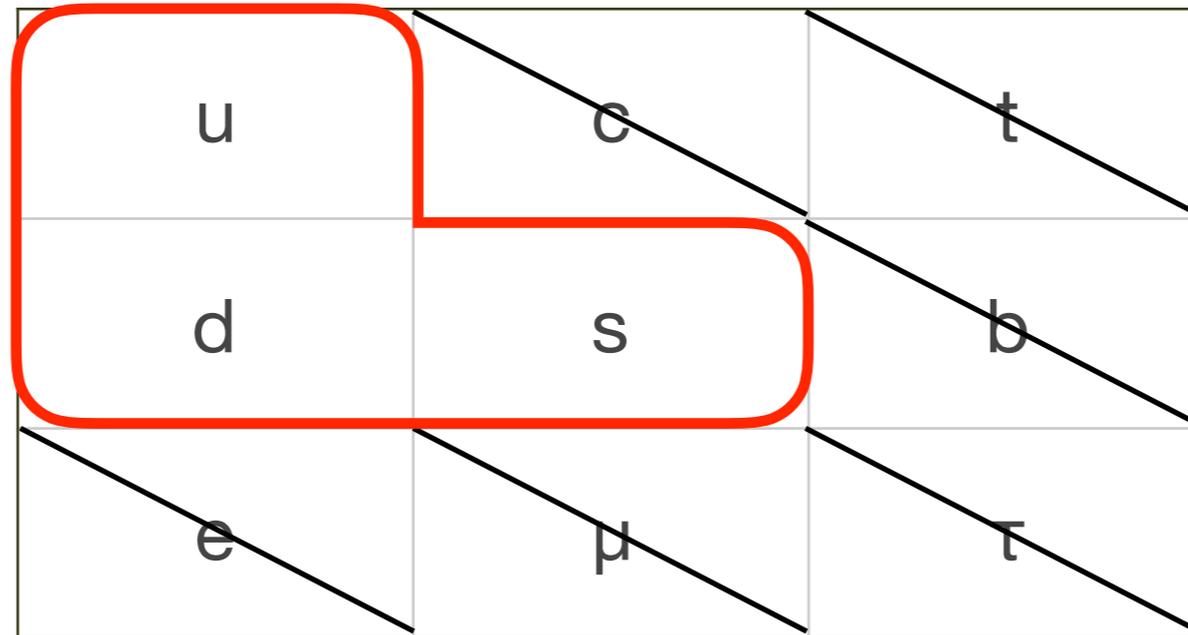


→ Setting limits $\mathcal{O}(10^2)$ above SM.

Branching fraction limit (95% CL)	Expected	Observed
$\mathcal{B}(H \rightarrow J/\psi \gamma) [10^{-4}]$	$3.0^{+1.4}_{-0.8}$	3.5
$\mathcal{B}(H \rightarrow \psi(2S) \gamma) [10^{-4}]$	$15.6^{+7.7}_{-4.4}$	19.8

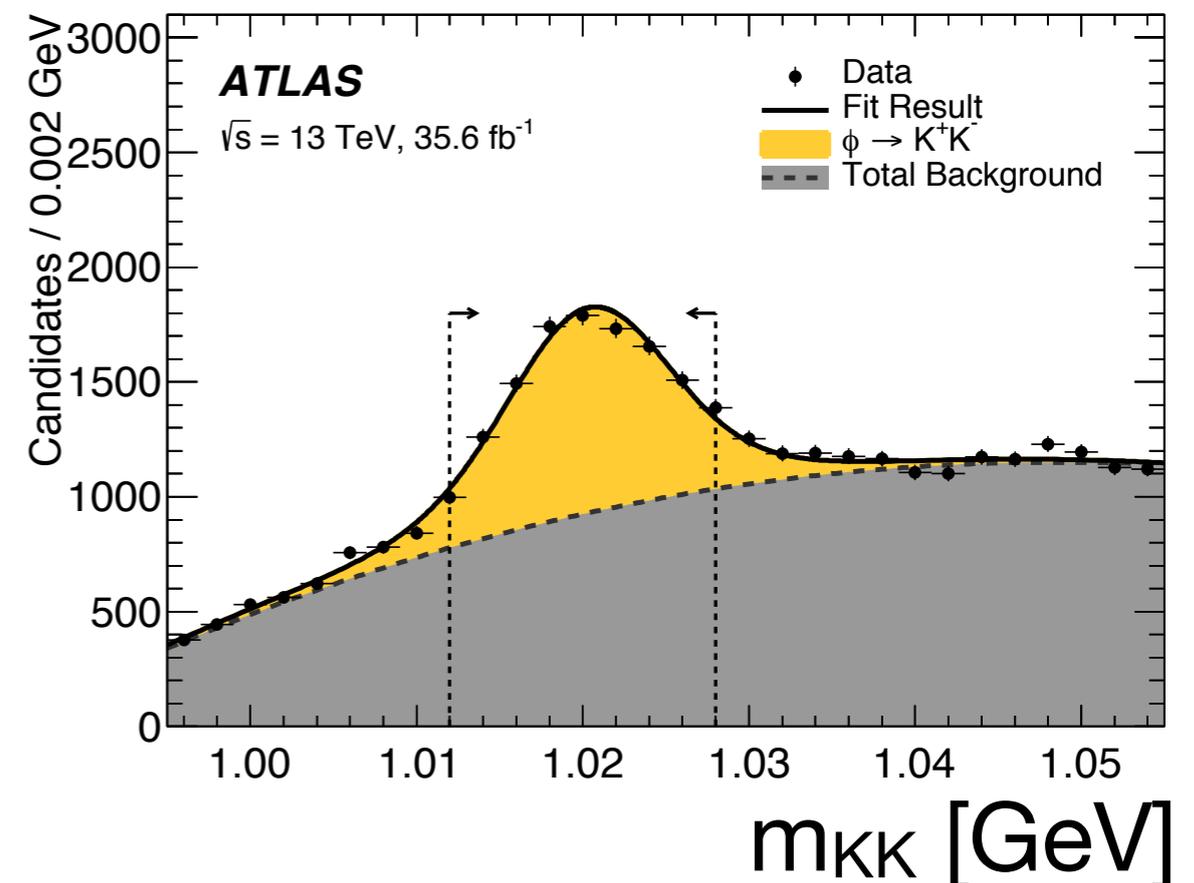


Higgs to light quarks



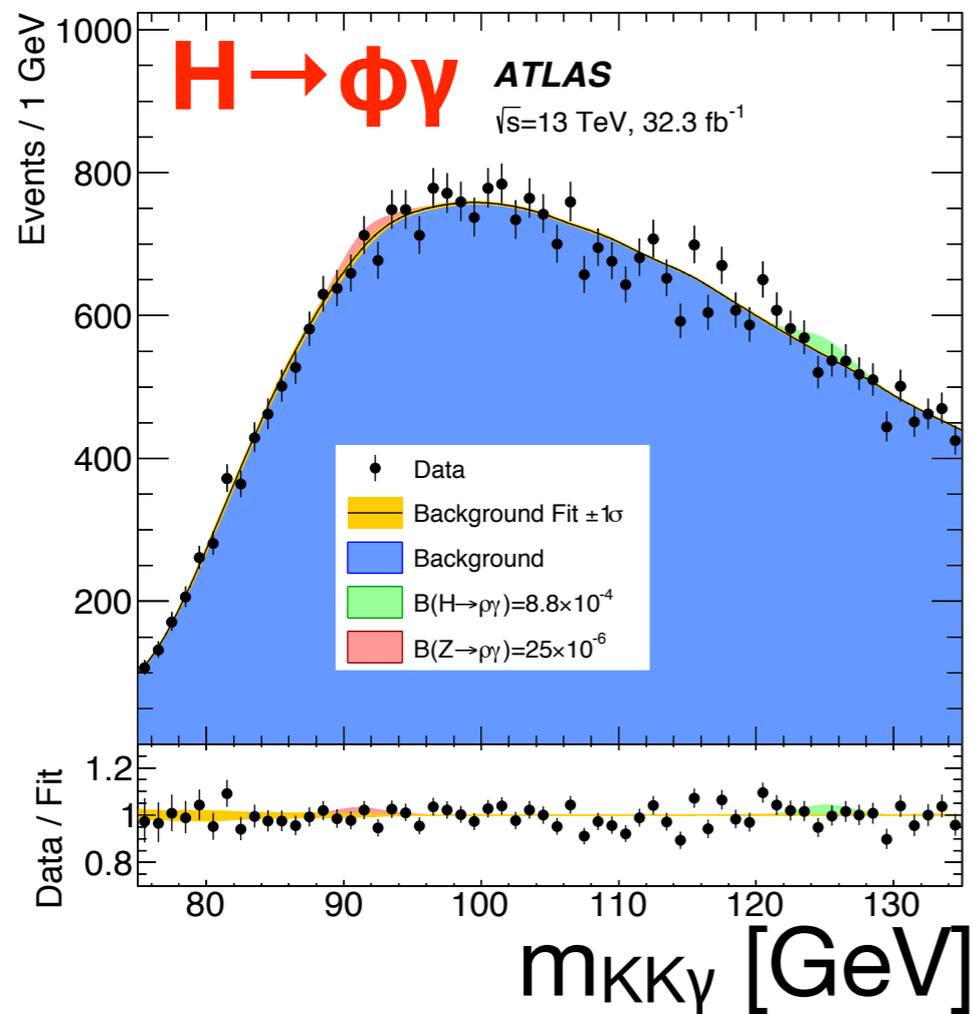
Coupling: light quarks

- Could be probed based on the similar idea as the prev. page.
 - ➔ Studied by Higgs to meson + photon decays.
 - ✓ **s-quark** : ϕ meson
 - ✓ **u-,d-quark**: ρ meson.
- Focusing on large BR channels.
 - ➔ $H \rightarrow \phi \gamma \rightarrow KK\gamma$: $BR(\phi \rightarrow KK) \sim 50\%$
 - ➔ $H \rightarrow \rho \gamma \rightarrow \pi\pi\gamma$: $BR(\rho \rightarrow \pi\pi) \sim 100\%$
- Events are recoded by the dedicated di-track + γ trigger.
- Mesons are identified well by the di-track mass.



Coupling: light quarks

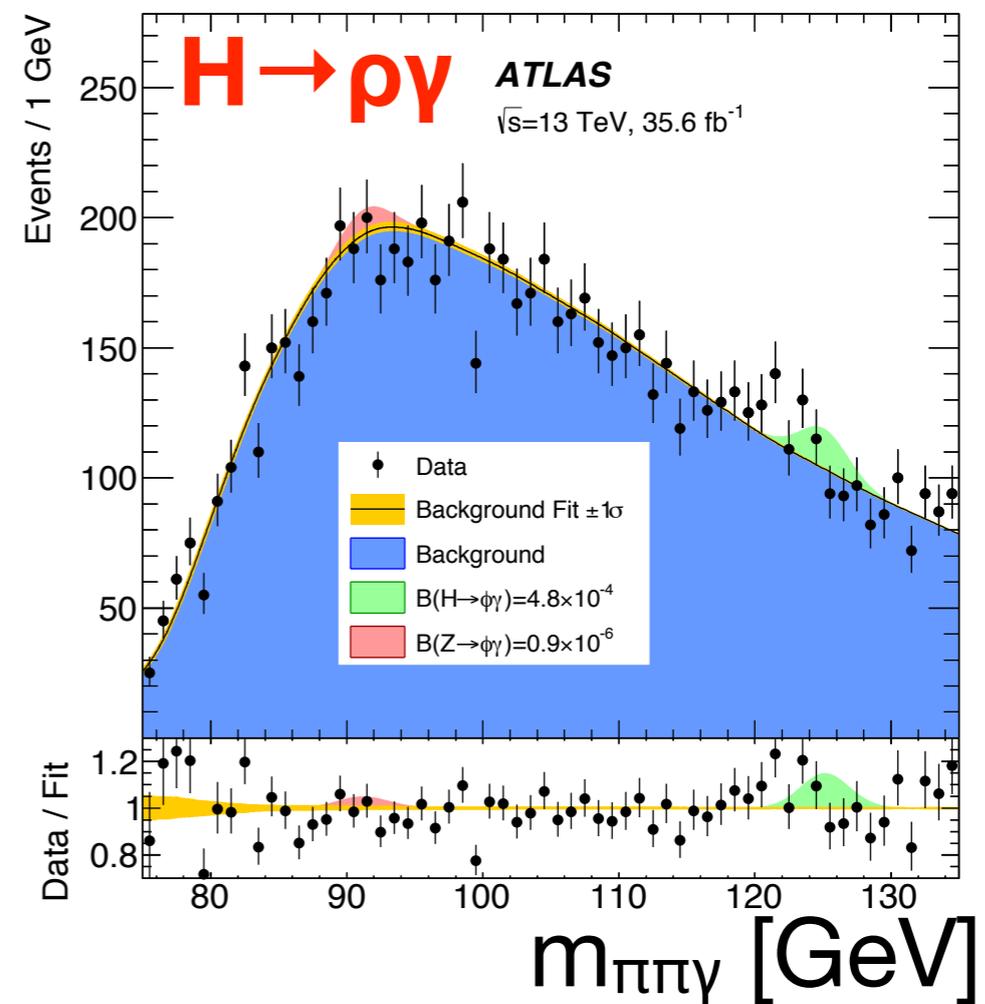
- Higgs mass reconstruction by di-track + γ .



$BR(H \rightarrow \phi\gamma) < 4.8 \times 10^{-4}$ (obs.)

SM prediction:

$$\mathcal{B}(H \rightarrow \phi\gamma) = (2.31 \pm 0.11) \times 10^{-6}$$



$BR(H \rightarrow \rho\gamma) < 8.8 \times 10^{-4}$ (obs.)

SM prediction:

$$\mathcal{B}(H \rightarrow \rho\gamma) = (1.68 \pm 0.08) \times 10^{-5}$$

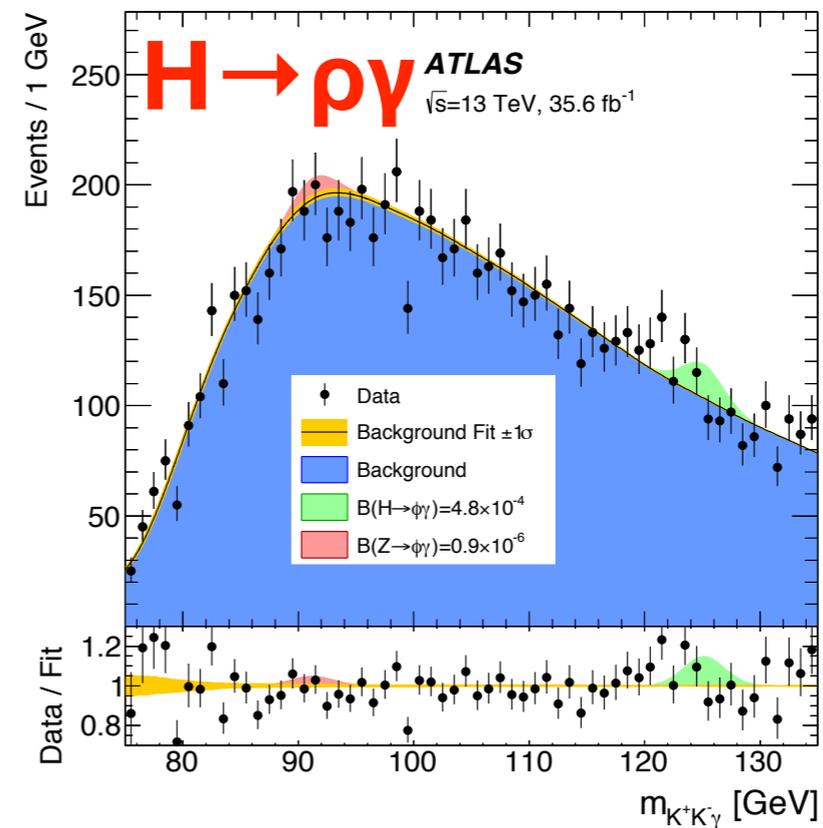
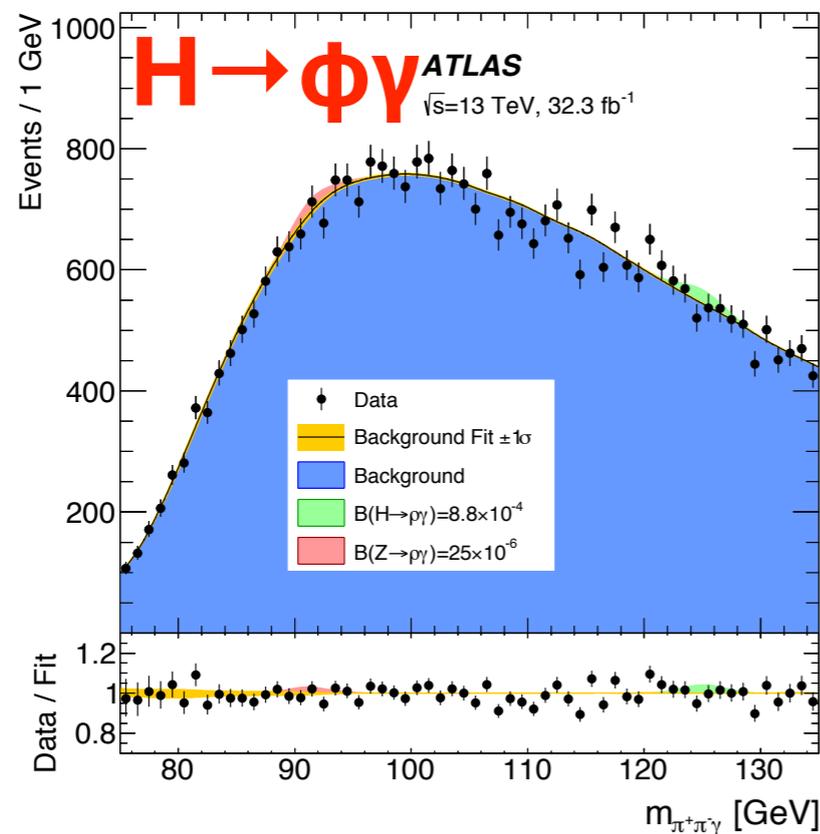
Summary

- Investigation of the Higgs-Fermion couplings
 - ➔ Determination of the SM Lagrangian parameters.
 - ➔ Very important task after the search era of Higgs.
- Higgs coupling measurement status:
 - ➔ 3rd generation:
 - ✓ Started measuring σ for each production mode.
 - ✓ We're entering a new era of trying to do differential cross section measurements.
 - ➔ 2nd and 1st generation:
 - ✓ Started setting upper limits.
 - ✓ $H \rightarrow \mu\mu$ is close to the SM value, but others are far from it.
 - ✓ Need more statistics and new ideas!!

Backup

Coupling: light quarks

- Higgs mass reconstruction by di-track + γ .



- Set upper limits on BR with 95% CL.

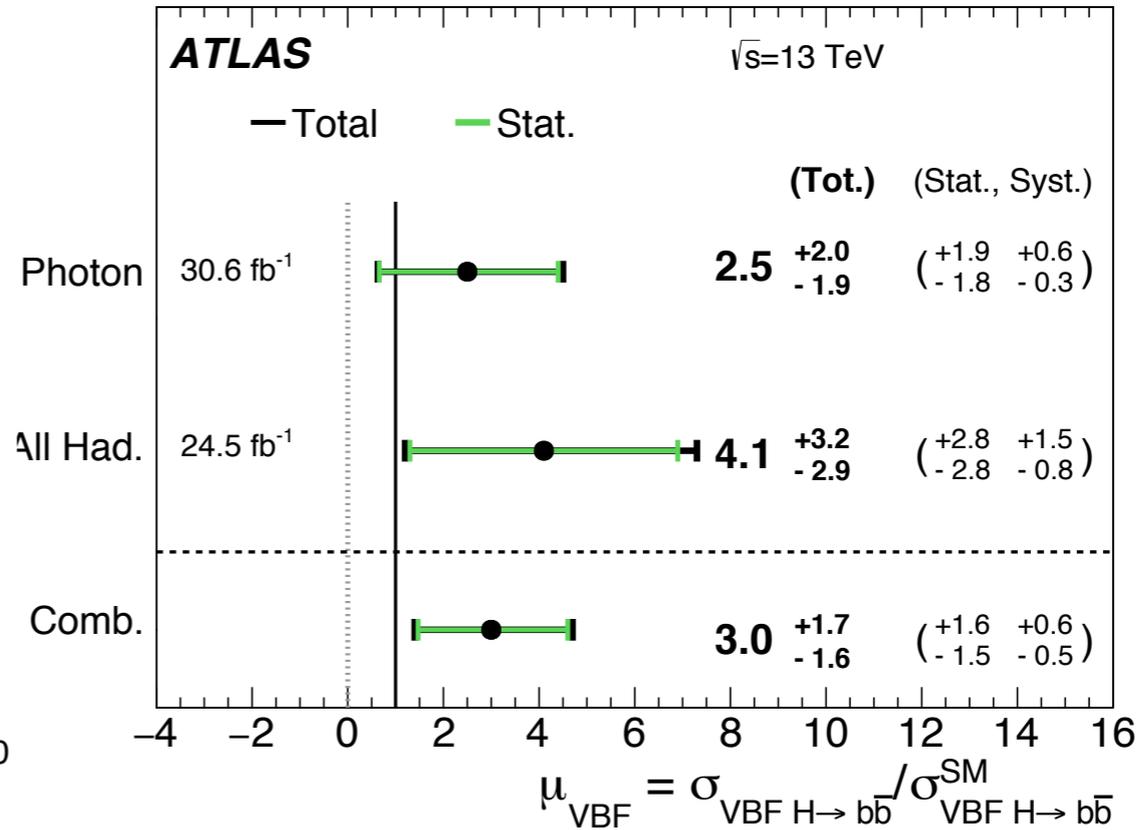
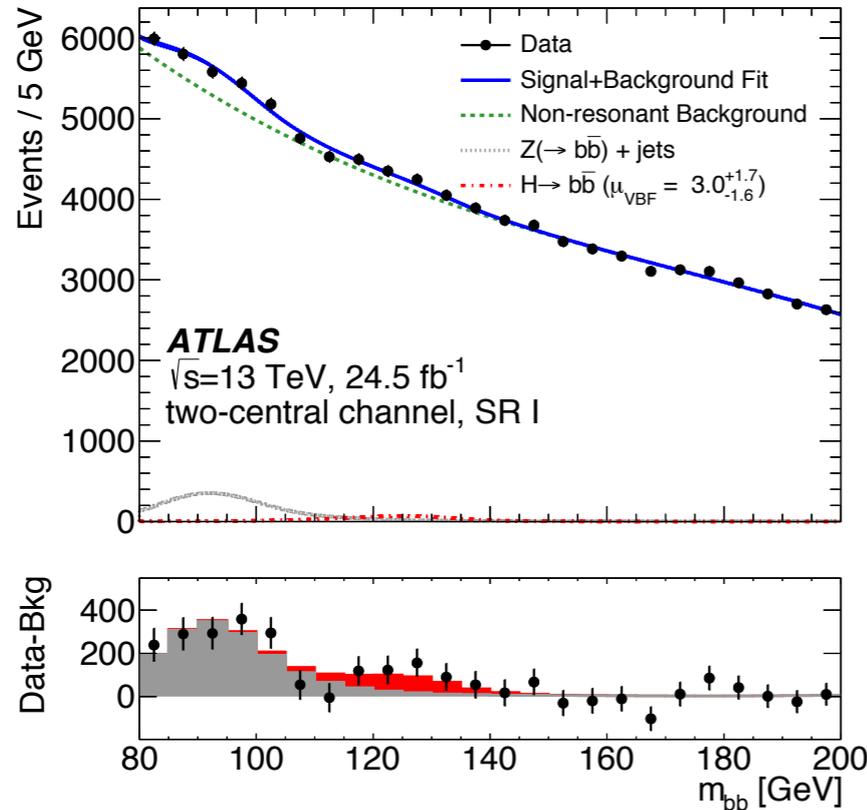
➔ $\text{BR}(H \rightarrow \phi\gamma)[10^{-4}] < 4.2^{+1.8}_{-1.2}$ (exp.), 4.8 (obs.)

✓ SM prediction: $\mathcal{B}(H \rightarrow \phi\gamma) = (2.31 \pm 0.11) \times 10^{-6}$

➔ $\text{BR}(H \rightarrow \rho\gamma)[10^{-4}] < 8.4^{+4.1}_{-2.4}$ (exp.), 8.8 (obs.)

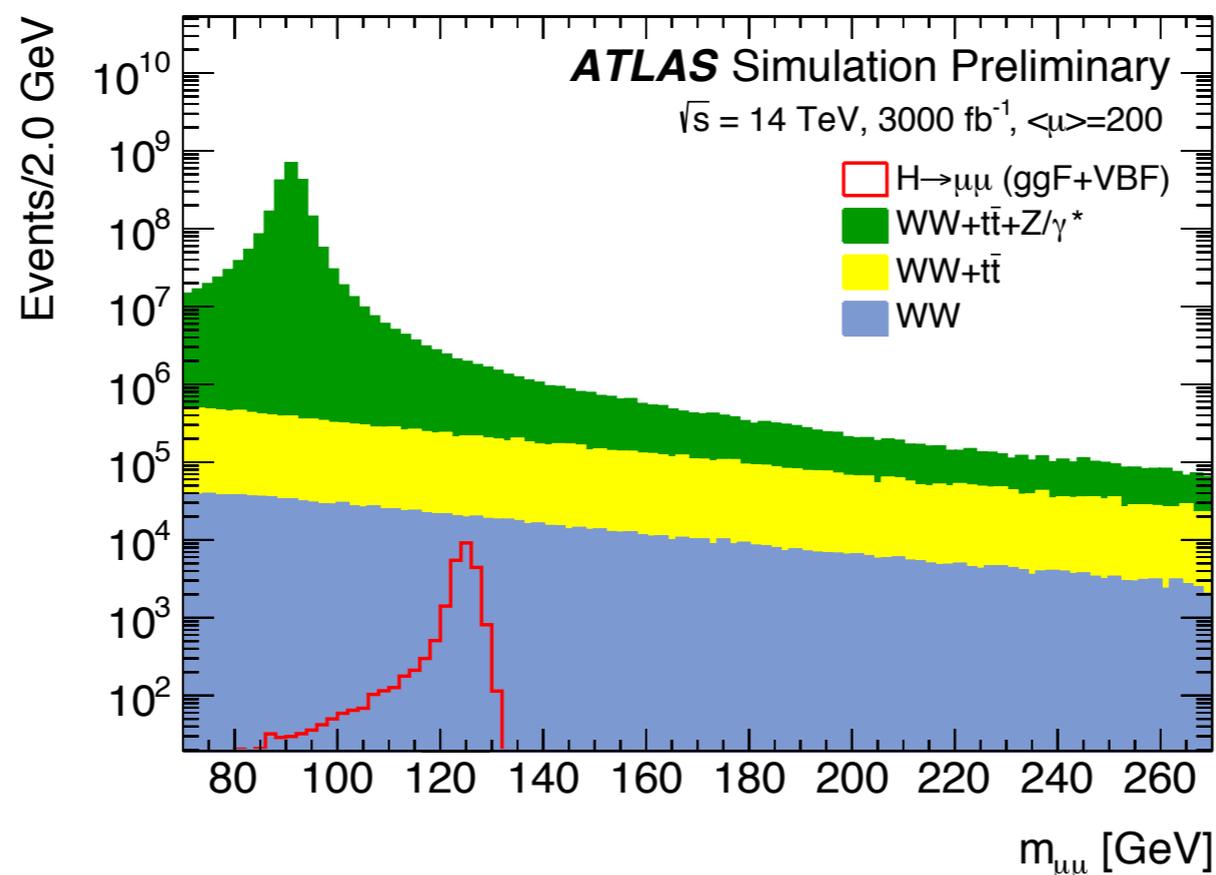
✓ SM prediction: $\mathcal{B}(H \rightarrow \rho\gamma) = (1.68 \pm 0.08) \times 10^{-5}$

VBF $H \rightarrow b\bar{b}$



Results	VBF production		
	<i>All-hadronic</i>	<i>Photon</i>	Combined
Expected significance	0.4 σ	0.6 σ	0.7 σ
Observed significance	1.4 σ	1.4 σ	1.9 σ
Expected limit on signal strength	5.9 ^{+2.6} _{-1.7}	3.7 ^{+1.6} _{-1.0}	3.0 ^{+1.3} _{-0.8}
Observed limit on signal strength	9.7	6.1	5.9
Expected signal strength	1.0 \pm 2.8	1.0 \pm 1.8	1.0 \pm 1.5
Observed signal strength	4.1 ^{+3.2} _{-2.9}	2.5 ^{+2.0} _{-1.9}	3.0 ^{+1.7} _{-1.6}

H → μμ prospects



Category	S	VBF	B	FWHM [GeV]	σ_G [GeV]	$S/\sqrt{S+B}$
VBF-like	386	197	19430	4.37	1.88	2.75
low p_T , central	921	11	350500	3.21	1.37	1.55
med p_T , central	2210	84	300500	3.08	1.32	4.01
hi p_T , central	1810	242	211800	3.50	1.56	3.91
low p_T , non central	2460	28	1740500	4.11	1.79	1.86
med p_T , non central	5860	230	1483600	4.24	1.80	4.80
hi p_T , non central	4380	588	829000	4.70	1.92	4.80
Total	18020	1380	4935500	3.93	1.69	9.53

H → ττ in each production mode and mass

