Higgs turns ten

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Casa de Zafra, Granada

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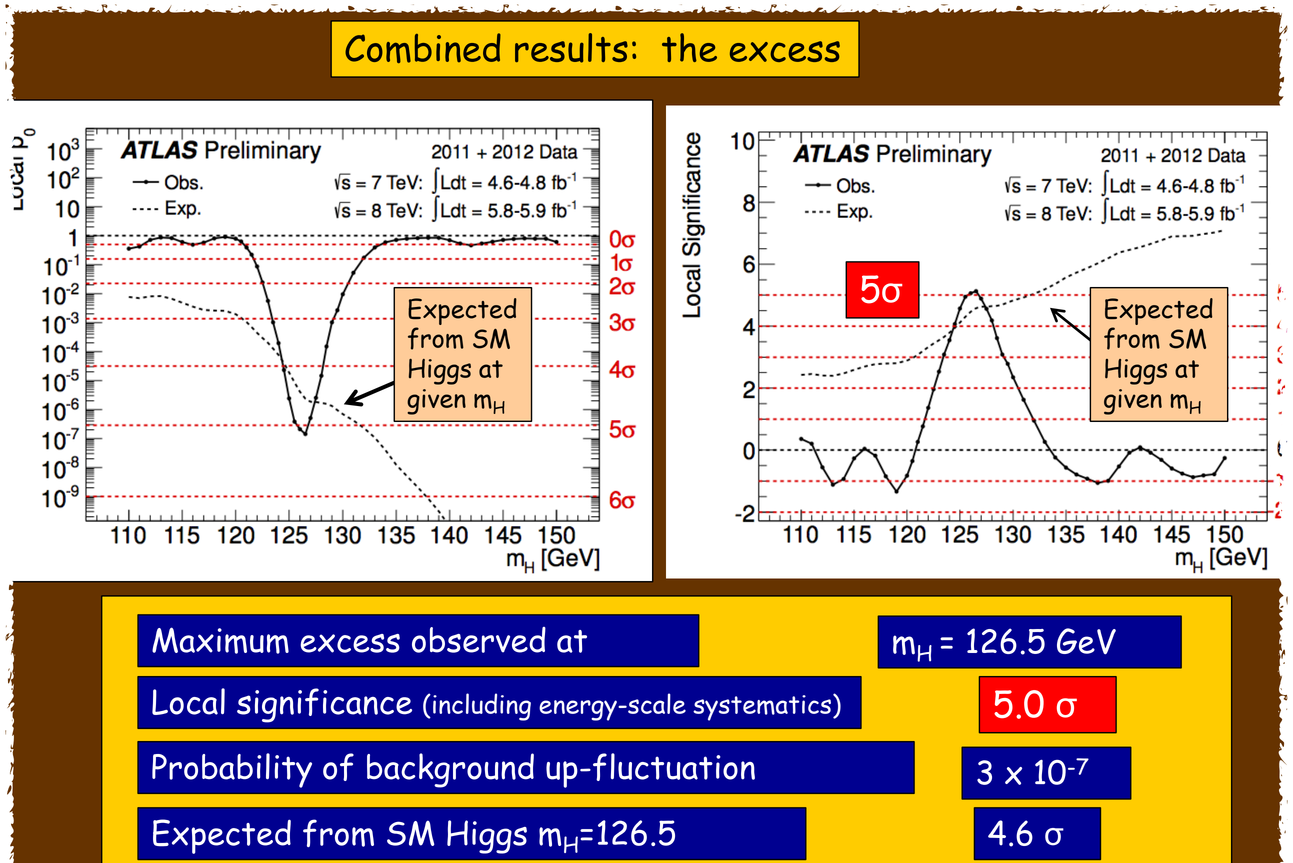
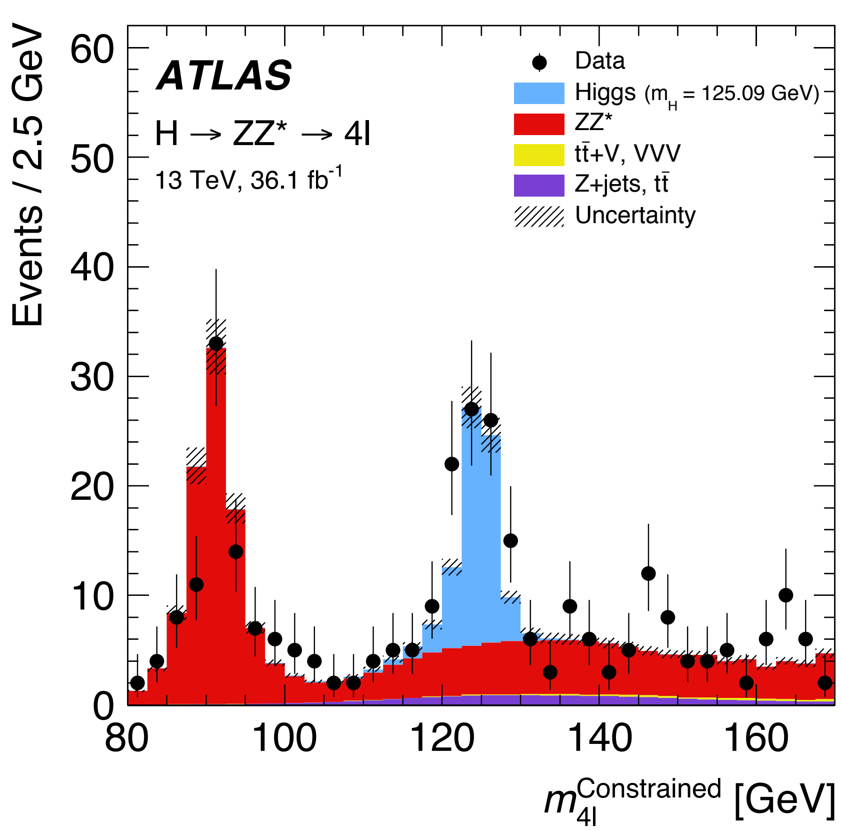
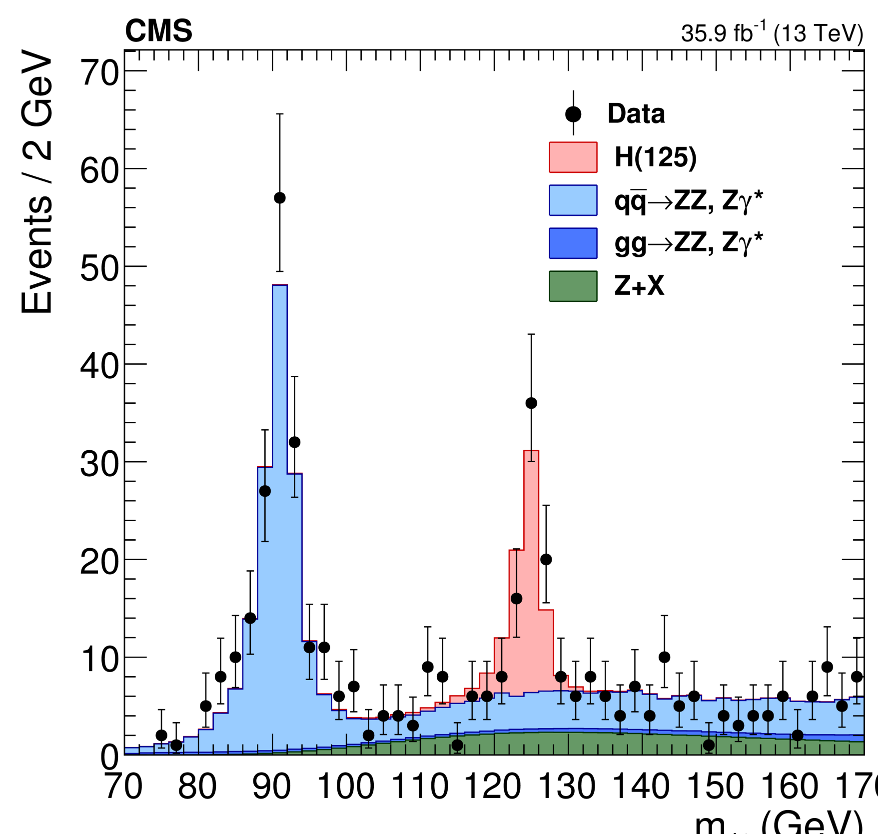
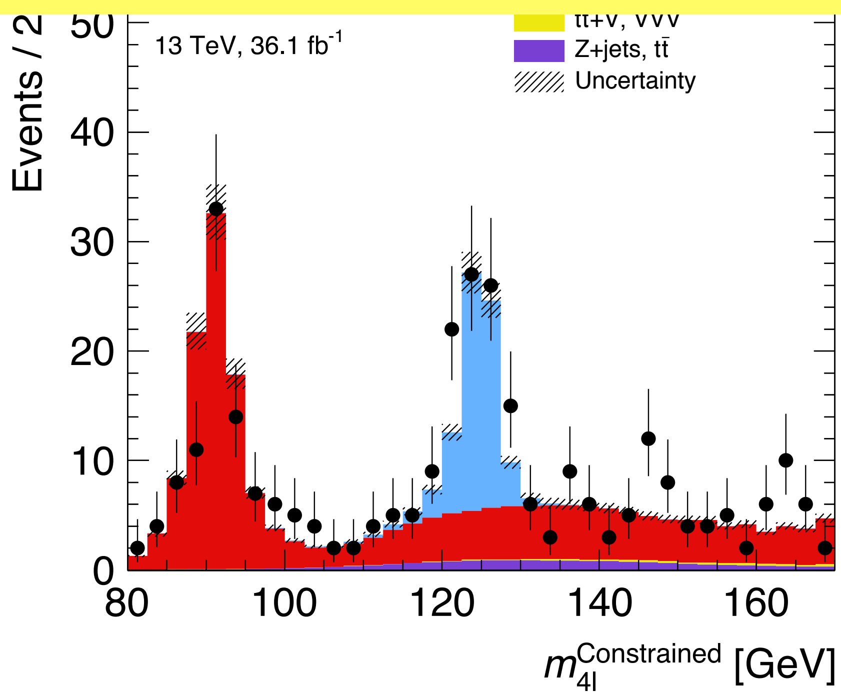
CERN, 4^{th} July 2012

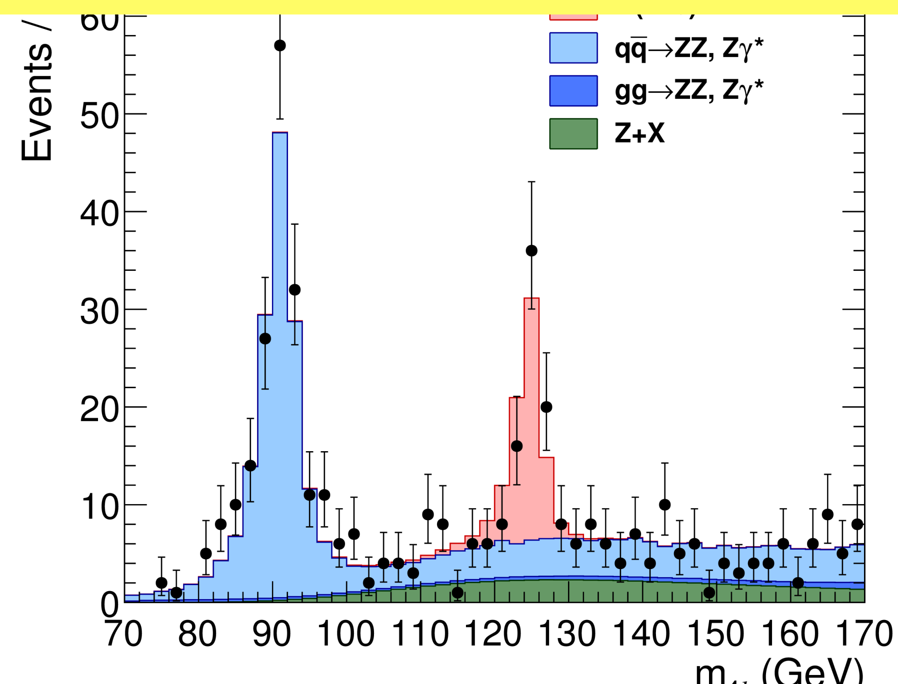



ATLAS
H → ZZ* → 4l
13 TeV, 36.1 fb-1
Data
Higgs (mH = 125.09 GeV)
ZZ*
tt̄+V, VVV
Z+jets, tt̄
Uncertainty
Events / 2.5 GeV
0
10
20
30
40
50
60
80
100
120
140
160
m4l Constrained [GeV]


CMS
35.9 fb-1 (13 TeV)
Data
H(125)
qq̄→ZZ, Zγ*
gg→ZZ, Zγ*
Z+X
Events / 2 GeV
0
10
20
30
40
50
60
70
70
80
90
100
110
120
130
140
150
160
170
m4l (GeV)

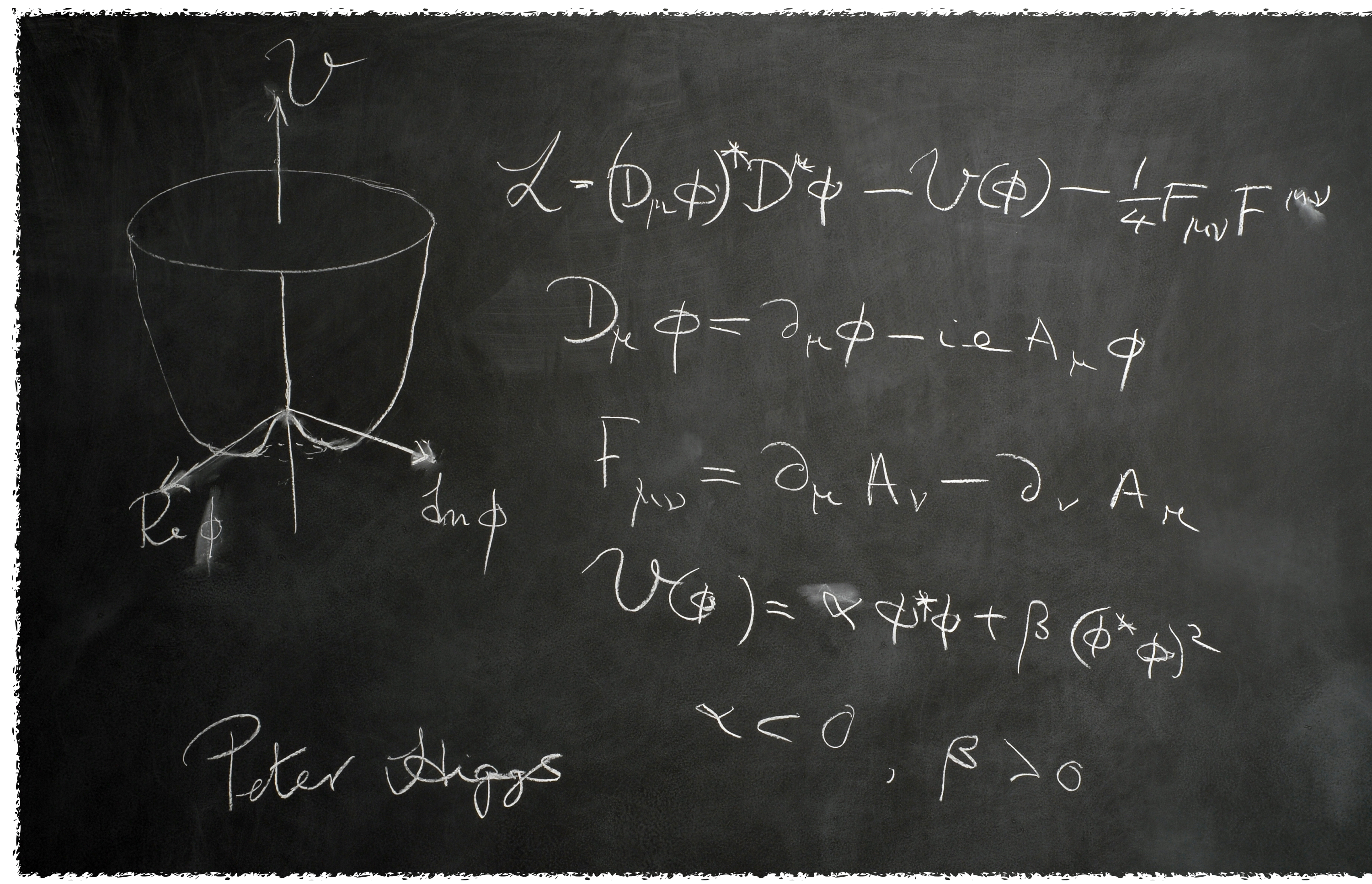
The beginning of a new era!



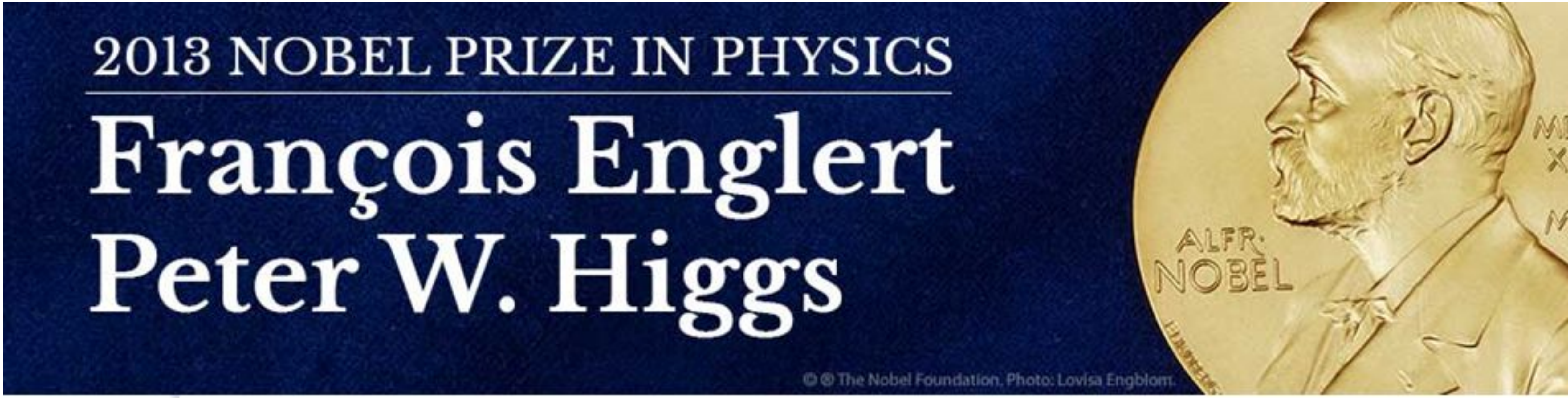


The SM Lagrangian

The discovery was a remarkable confirmation of the simplest and elegant idea postulated in the sixties, i.e. that a Higgs field, with a non-zero vacuum expectation, is responsible to generate masses for Standard Model particles in a consistent way



Higgs Phys. Lett. 12 (1964) 132-133
Englert and Brout Phys. Rev. Lett. 13 (1964) 321-323



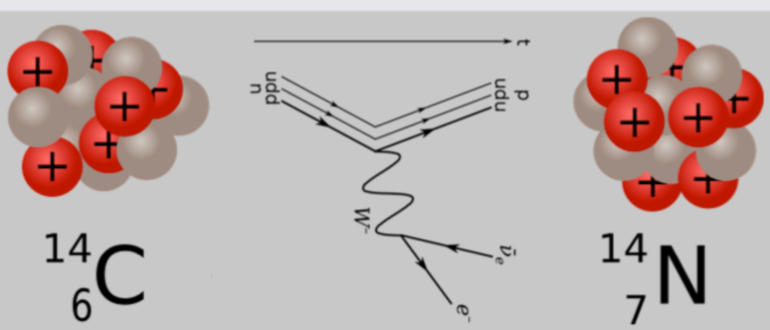
8 October 2013

The Royal Swedish Academy of Sciences has decided to award the Nobel Prize in Physics for 2013 to

François Englert and Peter Higgs

"for the theoretical discovery of a mechanism that contributes to our understanding of the origin of mass of subatomic particles, and which recently was confirmed through the discovery of the predicted fundamental particle, by the ATLAS and CMS experiments at CERN's Large Hadron Collider"

Higgs and everyday life

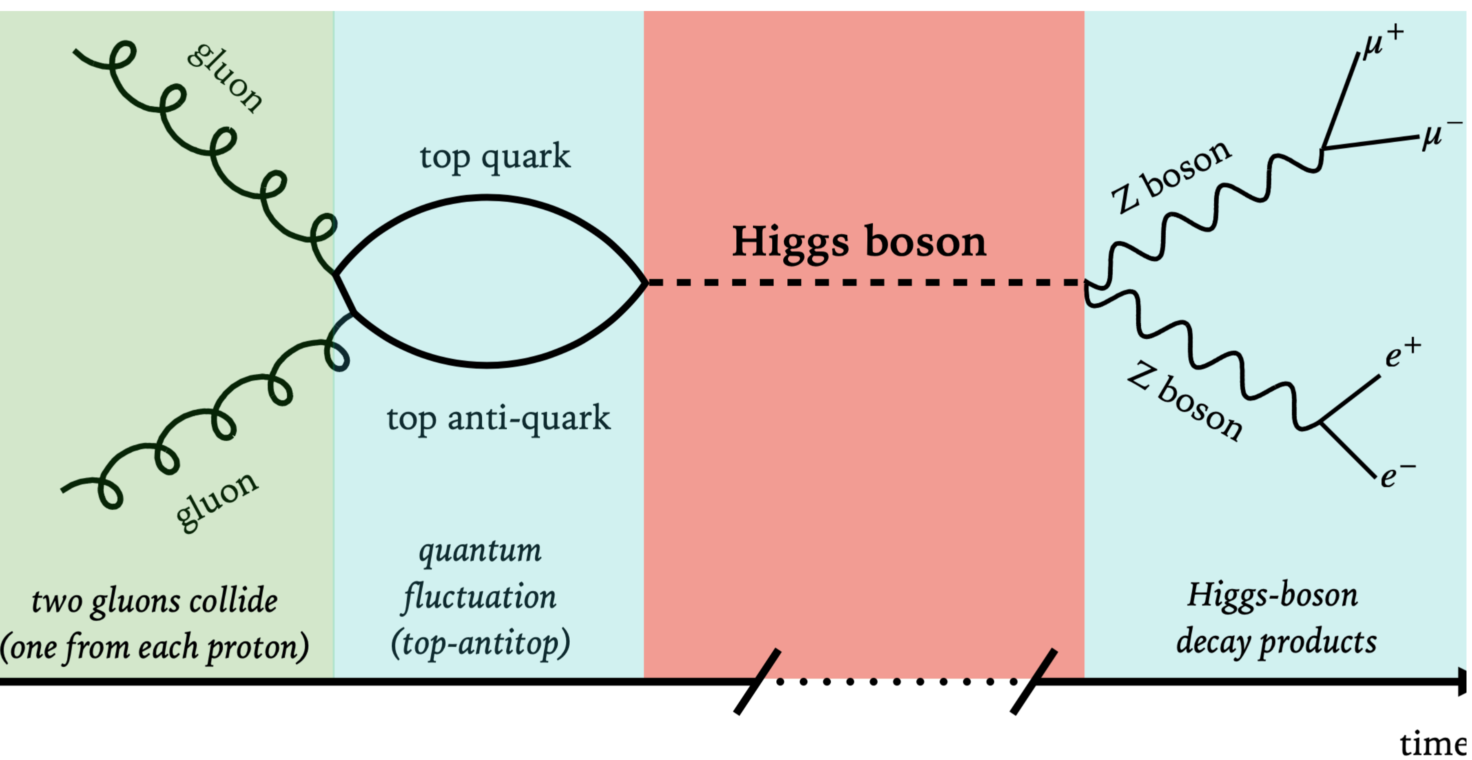
role of fundamental particle masses	consequence in daily life	Higgs role established?
Up quarks (mass ~ 2.2 MeV) lighter than down quarks (~ 4.7 MeV) **proton** (up+up+down): 2.2 + **2.2** + 4.7 + EM+strong force = **938.3** MeV **neutron** (up+down+down): 2.2 + **4.7** + 4.7 + EM+strong force = **939.6** MeV	up & down-quark masses mean protons are **lighter** than neutrons, → protons are stable, giving us hydrogen	**NO**
 atomic radius $\propto \frac{1}{m_e}$	Electron mass (m_e) sets size of atoms & energy levels of chemical reactions	**NO**
 *decay rate* $\propto \frac{1}{m_W^4}$	W-boson mass (m_W) sets rate of radioactive β-decay	**YES**

Why do Higgs interactions matter to everyone?

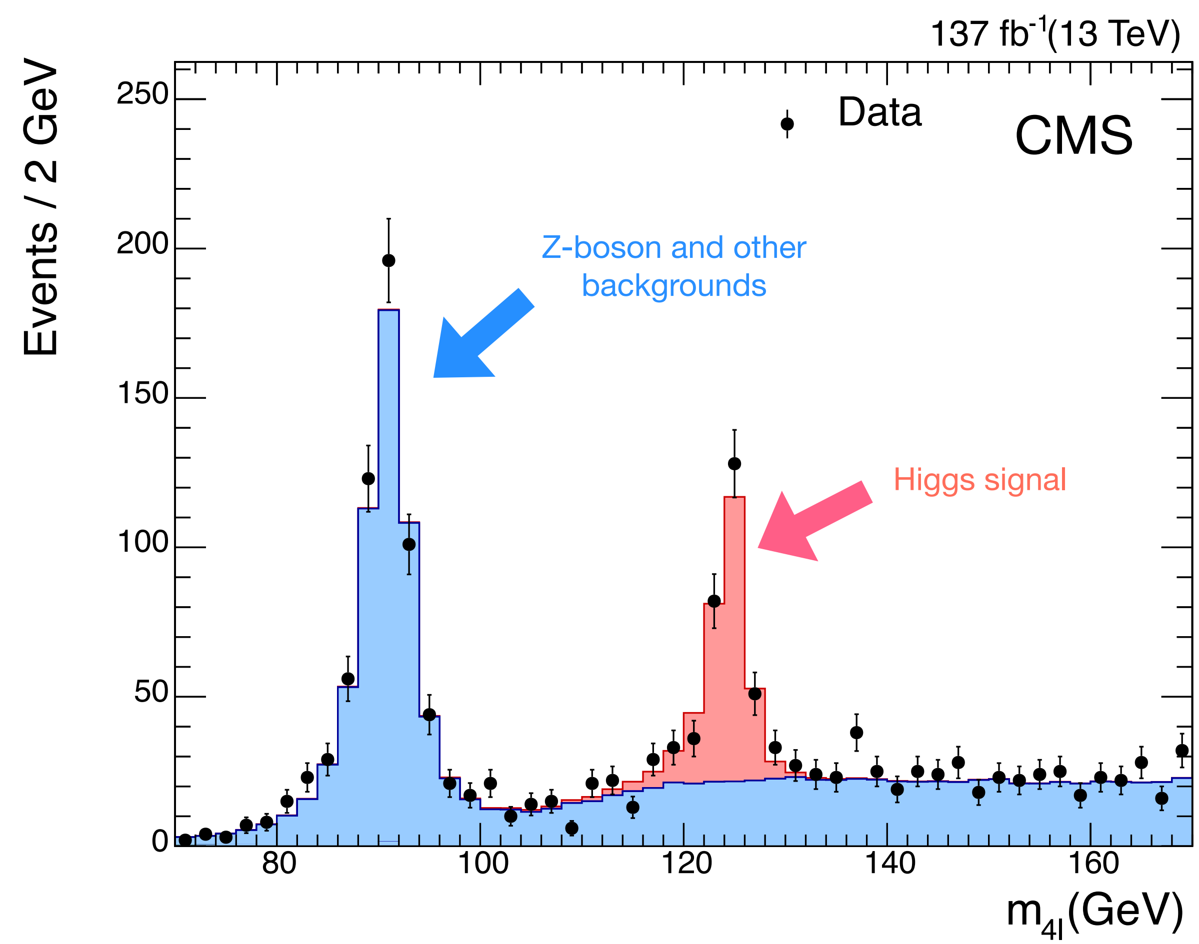
Within the Standard Model of particle physics, they set quark, electron & W masses, with important consequences

Learning about the Higgs

Higgs production and decay



Update of Higgs discovery plot



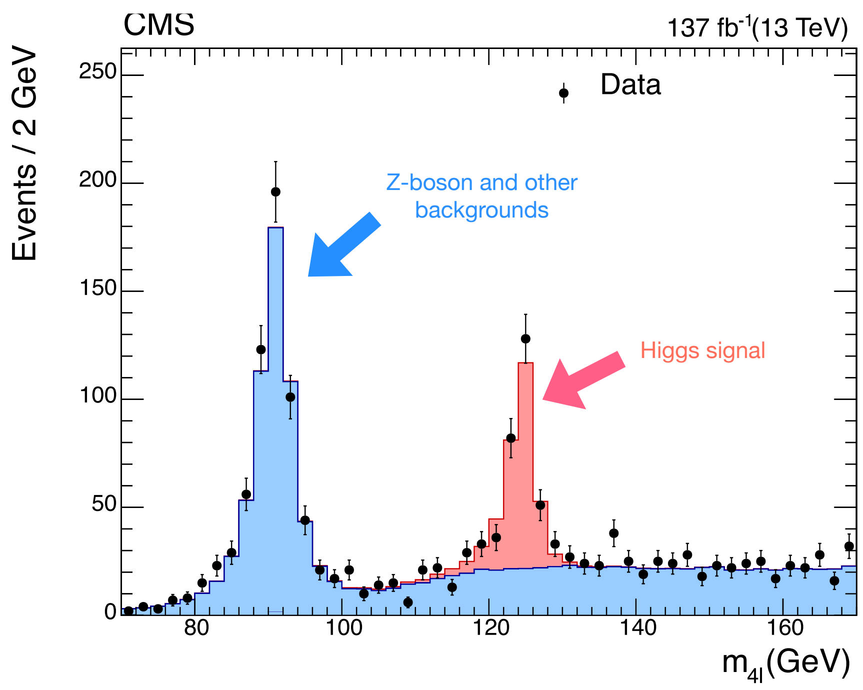
CMS, 2103.04956

[Other crucial discovery channels are the decays to WW and to two photons]

Learning about the Higgs

A lot of information can be extracted

- Existence of the peak: existence of new particle (the Higgs)
- Position of the peak: mass of the Higgs
- Number of events at the peak: information on interaction (the product of) the strength of the Higgs interaction to top and Z bosons
- Angular distributions (not shown) tell us that the Higgs has spin 0

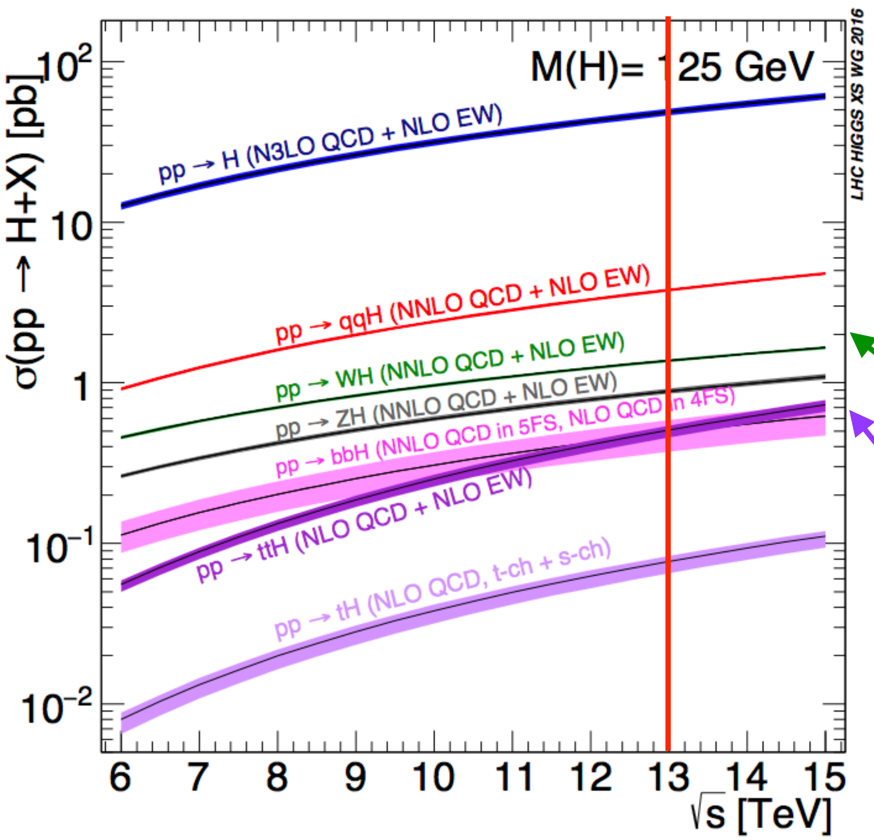


Caveats

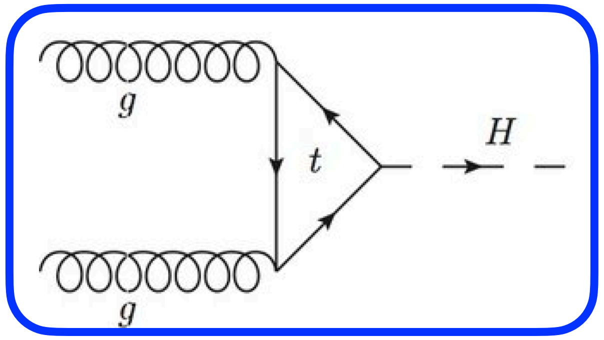
There are a lot of assumptions behind such measurements (e.g. top as quantum fluctuations). Furthermore, only the product of production and decay couplings can be measured.

For this reason, the LHC experiments study a multitude of Higgs production and decay modes, with complementary sensitivities

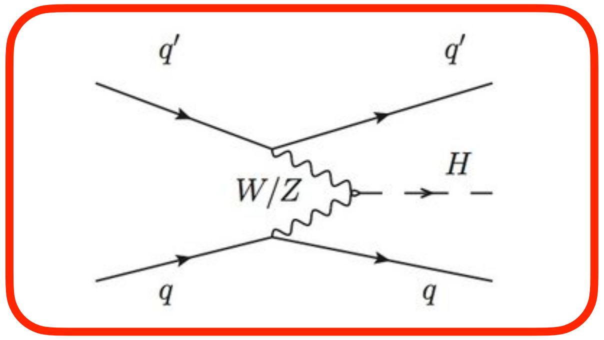
Higgs production



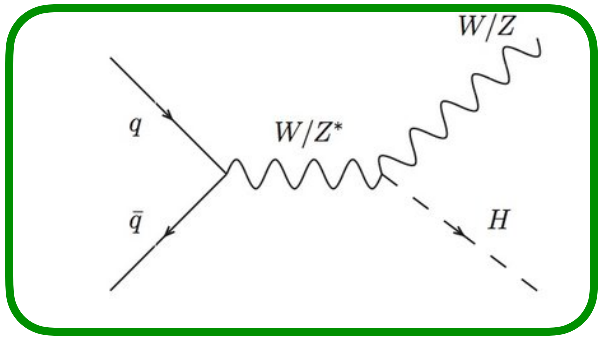
$\sqrt{s}$ (TeV)	Production cross section (in pb) for $m_H = 125\,\mathrm{GeV}$					
	ggF	VBF	WH	ZH	$t\bar{t}H$	total
1.96	$0.95^{+17\%}_{-17\%}$	$0.065^{+8\%}_{-7\%}$	$0.13^{+8\%}_{-8\%}$	$0.079^{+8\%}_{-8\%}$	$0.004^{+10\%}_{-10\%}$	1.23
7	$16.9^{+5\%}_{-5\%}$	$1.24^{+2\%}_{-2\%}$	$0.58^{+3\%}_{-3\%}$	$0.34^{+4\%}_{-4\%}$	$0.09^{+8\%}_{-14\%}$	19.1
8	$21.4^{+5\%}_{-5\%}$	$1.60^{+2\%}_{-2\%}$	$0.70^{+3\%}_{-3\%}$	$0.42^{+5\%}_{-5\%}$	$0.13^{+8\%}_{-13\%}$	24.2
13	$48.6^{+5\%}_{-5\%}$	$3.78^{+2\%}_{-2\%}$	$1.37^{+2\%}_{-2\%}$	$0.88^{+5\%}_{-5\%}$	$0.50^{+9\%}_{-13\%}$	55.1
14	$54.7^{+5\%}_{-5\%}$	$4.28^{+2\%}_{-2\%}$	$1.51^{+2\%}_{-2\%}$	$0.99^{+5\%}_{-5\%}$	$0.60^{+9\%}_{-13\%}$	62.1



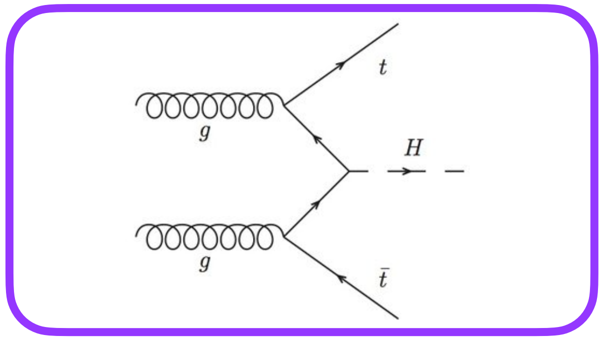
N3LO



N3LO

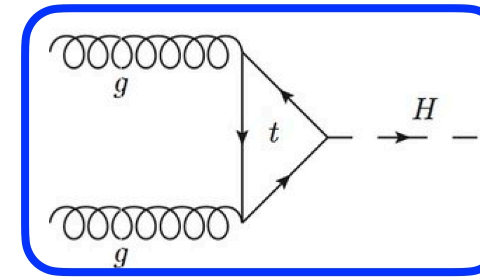


NNLO



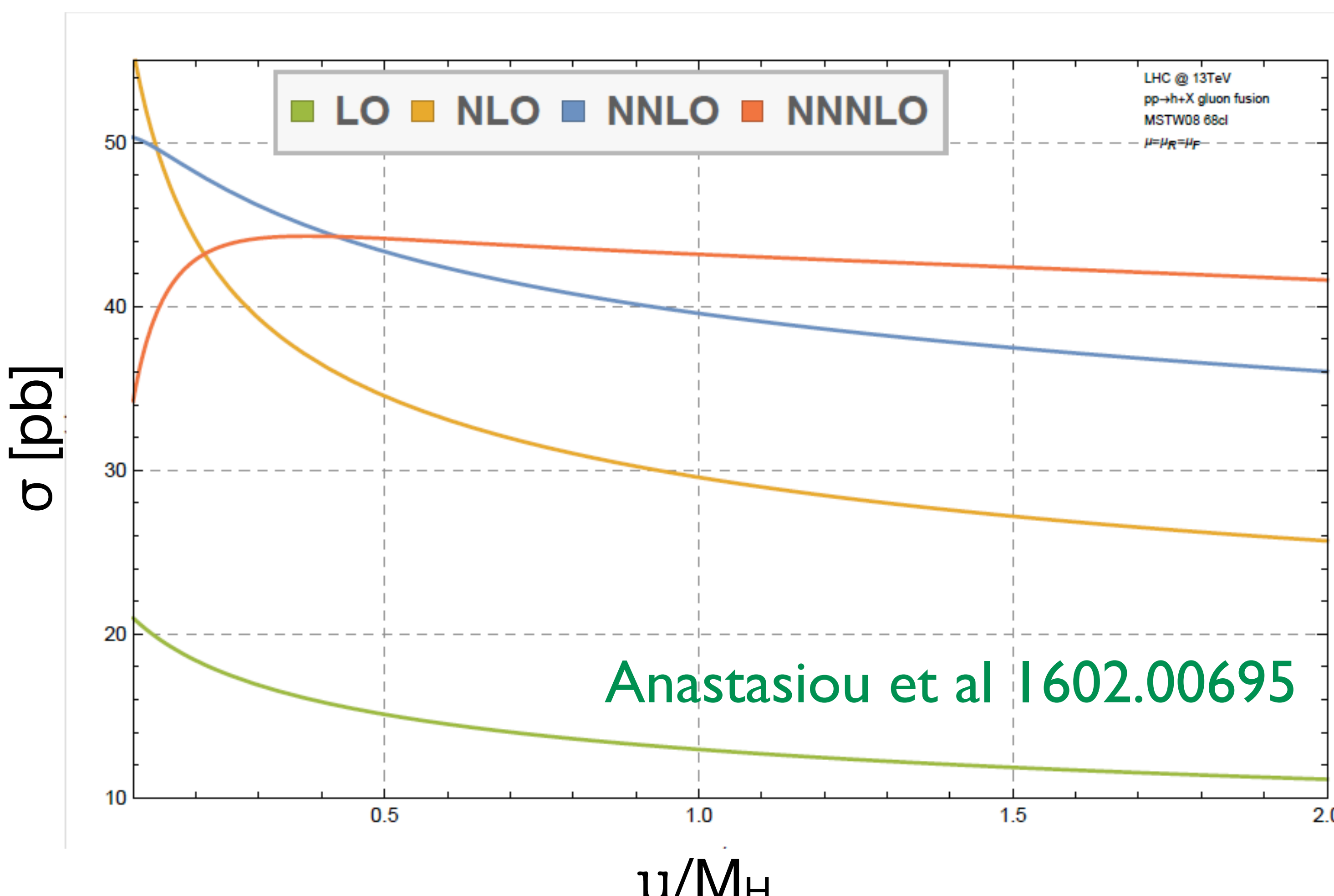
NLO

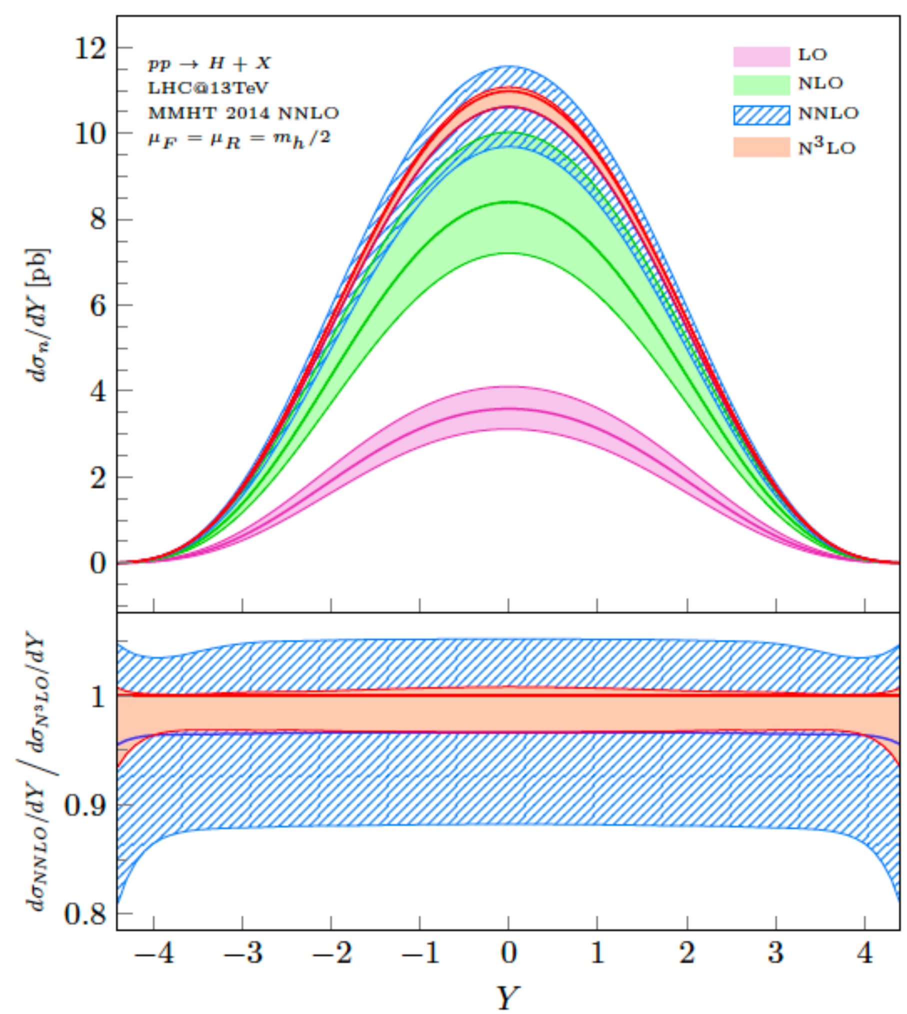
ggF Higgs production



At N³LO:

- O(100000) interference diagrams (1000 at NNLO)
- 68273802 loop and phase space integrals (47000 at NNLO)
- about 1000 master integrals (26 at NNLO)





Dulat et al 1810.09462

Higgs production

$$\sigma = 48.58\,\text{pb}^{+2.22\,\text{pb}\,(+4.56\%)}_{-3.27\,\text{pb}\,(-6.72\%)}\;(\text{theory}) \pm 1.56\,\text{pb}\,(3.20\%)\;(\text{PDF}+\alpha_s)\,.$$

$$\begin{aligned}
48.58\,\text{pb} = \;& 16.00\,\text{pb} & (+32.9\%) & \quad (\text{LO, rEFT}) \\
& + 20.84\,\text{pb} & (+42.9\%) & \quad (\text{NLO, rEFT}) \\
& - \;\; 2.05\,\text{pb} & (-4.2\%) & \quad ((t,b,c),\ \text{exact NLO}) \\
& + \;\; 9.56\,\text{pb} & (+19.7\%) & \quad (\text{NNLO, rEFT}) \\
& + \;\; 0.34\,\text{pb} & (+0.2\%) & \quad (\text{NNLO}, 1/m_t) \\
& + \;\; 2.40\,\text{pb} & (+4.9\%) & \quad (\text{EW, QCD-EW}) \\
& + \;\; 1.49\,\text{pb} & (+3.1\%) & \quad (\text{N}^3\text{LO, rEFT})
\end{aligned}$$

δ(scale)	δ(trunc)	δ(PDF-TH)	δ(EW)	$\delta(t,b,c)$	$\delta(1/m_t)$
$^{+0.10\text{ pb}}_{-1.15\text{ pb}}$	± 0.18 pb	± 0.56 pb	± 0.49 pb	± 0.40 pb	± 0.49 pb
$^{+0.21\%}_{-2.37\%}$	$\pm 0.37\%$	$\pm 1.16\%$	$\pm 1\%$	$\pm 0.83\%$	$\pm 1\%$

⇒ Many effects need to be accounted for to reach high precision

⇒ Many sources of uncertainties contribute to the error budget

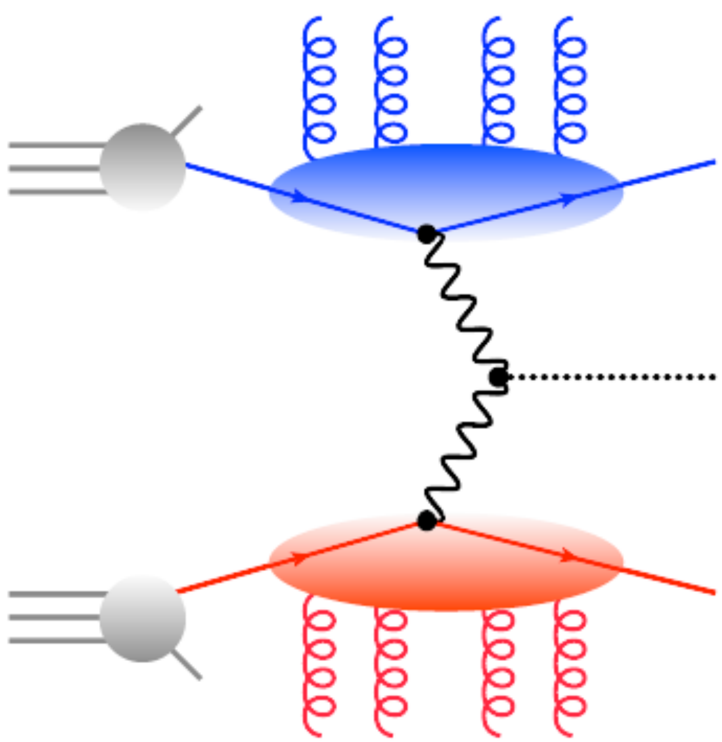
Dominant uncertainties (PDF & α_s) will be reduced by new data and new input from lattice for α_s (PDG error on α_s already reduced from 0.015 to 0.011)

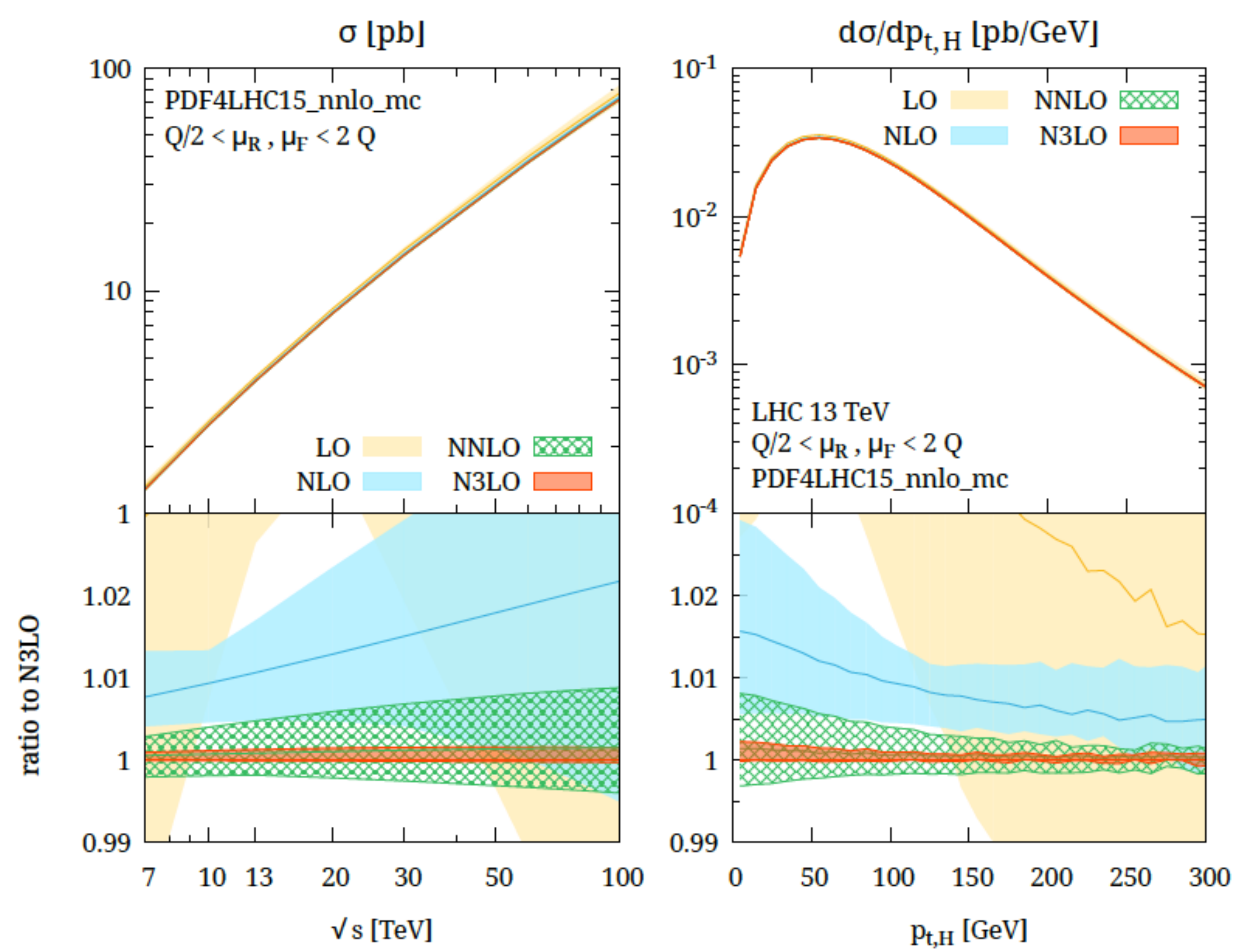
⇒ A reduction of the uncertainty by a factor 2 seems realistic

VBF Higgs at N^{3}LO

Inclusive Vector Boson Fusion Higgs cross-section (DIS approx.)

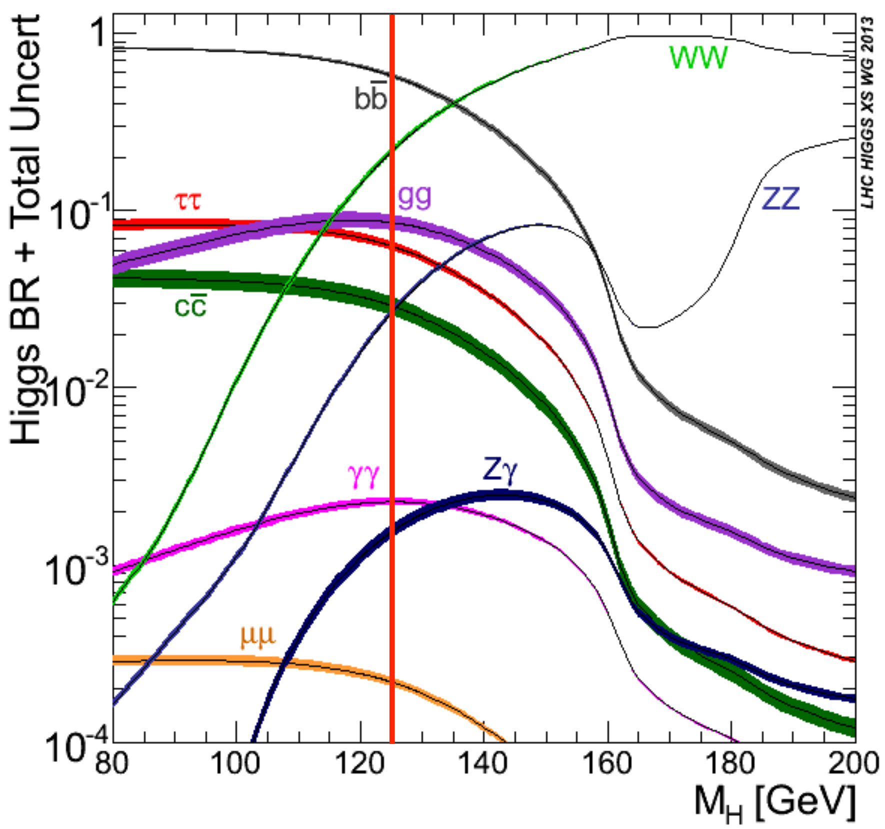
Dreyer & Karlberg 1606.00840





NB: NNLO non-factorizable effects sub-percent
Liu et al. 1906.10899

Higgs decays



Decay channel	Branching ratio	Rel. uncertainty
$H \to \gamma\gamma$	2.27×10^{-3}	$^{+5.0\%}_{-4.9\%}$
$H \to ZZ$	2.62×10^{-2}	$^{+4.3\%}_{-4.1\%}$
$H \to W^+W^-$	2.14×10^{-1}	$^{+4.3\%}_{-4.2\%}$
$H \to \tau^+\tau^-$	6.27×10^{-2}	$^{+5.7\%}_{-5.7\%}$
$H \to b\bar{b}$	5.84×10^{-1}	$^{+3.2\%}_{-3.3\%}$
$H \to Z\gamma$	1.53×10^{-3}	$^{+9.0\%}_{-8.9\%}$
$H \to \mu^+\mu^-$	2.18×10^{-4}	$^{+6.0\%}_{-5.9\%}$

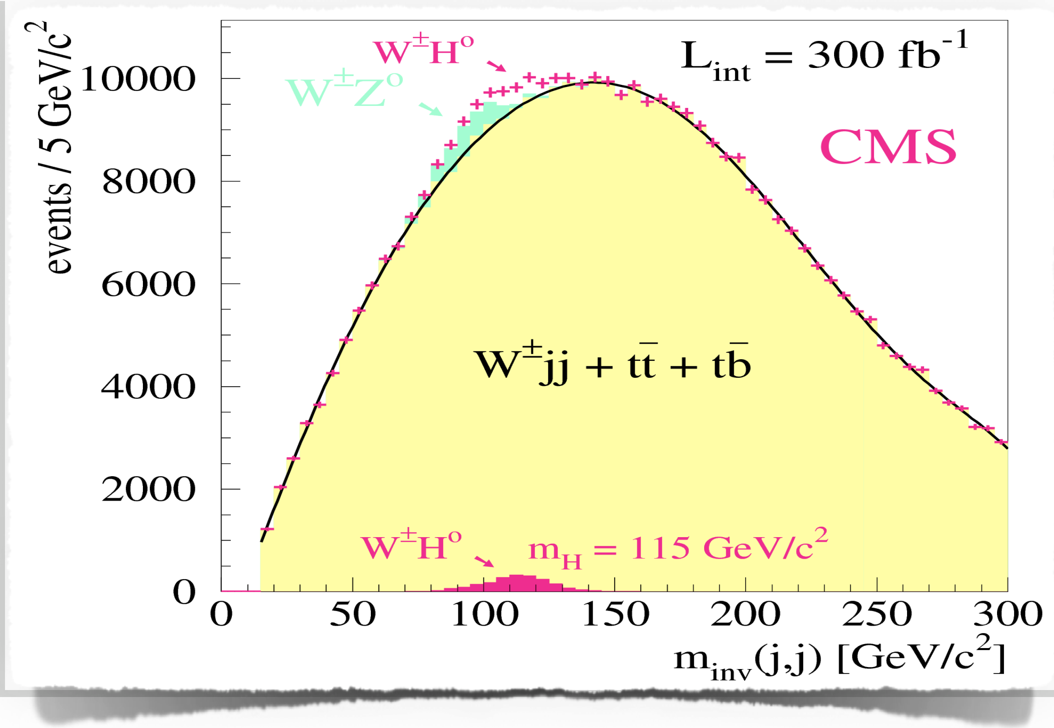
<u>Higgs mass lies in a lucky spot:</u>

- Had the Higgs boson been 50 GeV heavier, it would have been impossible to detect more than just two basic channels (ZZ and WW)
- Had the Higgs been just 10 GeV lighter, the decays to WW and ZZ would have been impossible so far

The value of the Higgs mass chosen by Nature is part of the reason why the LHC could establish much more than originally foreseen in just ten years

Sample unforeseen success

Observation of pp →WH(bb)



Conclusion:

The extraction of a signal from H → bb decays in the WH channel will be very difficult at the LHC even under the most optimistic assumptions [...]

ATLAS Technical Design Report '99

Recall why searching for pp →WH(bb) is hard:

$\sigma(\mathrm{pp} \to WH(bb)) \sim \mathrm{few\ pb}$ $\quad \sigma(\mathrm{pp} \to Wbb) \sim \mathrm{few\ pb}$

$\sigma(\mathrm{pp} \to tt) \sim 800\mathrm{pb}$ $\sigma(\mathrm{pp} \to Wjj) \sim \mathrm{few}\ 10^4\mathrm{pb}$ $\sigma(\mathrm{pp} \to bb) \sim 400\mathrm{pb}$

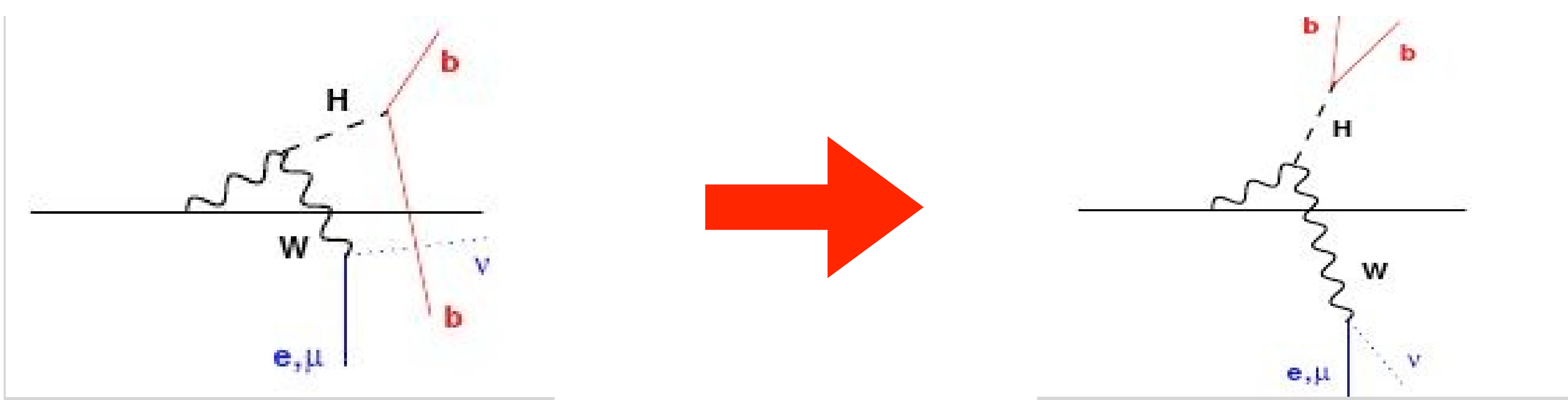
⇒ signal extraction very difficult

Observation of pp →WH(bb)

But ingenious suggestions open up a window of opportunity

Central idea: require high-p_T W and Higgs boson in the event

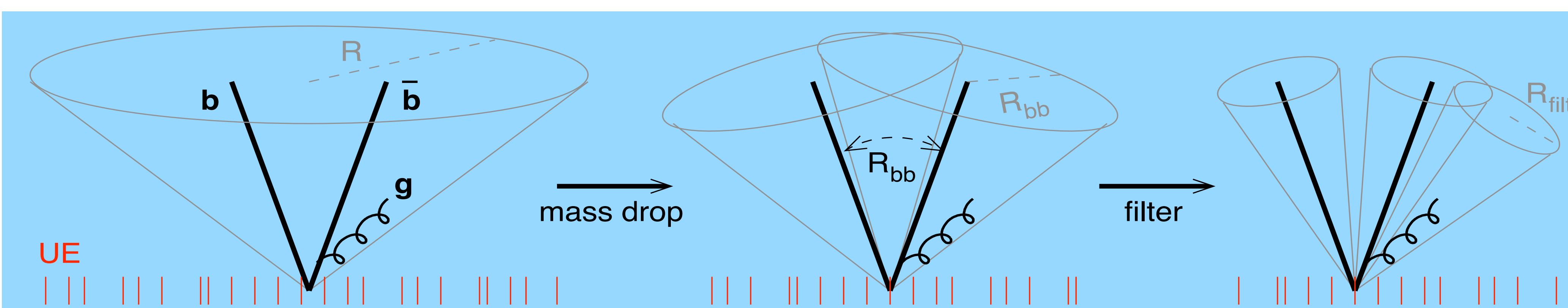
- leads to back-to-back events where two b-quarks are contained within the same jet
- high p_T reduces the signal but reduces the background much more
- improve acceptance and kinematic resolution



Observation of pp →WH(bb)

Then use a jet-algorithm geared to exploit the specific pattern of H → bb versus g → gg, q → qg

- QCD partons prefer soft emissions (hard → hard + soft)
- Higgs decay prefers symmetric splitting
- try to beat down contamination from underlying event
- try to capture most of the perturbative QCD radiation



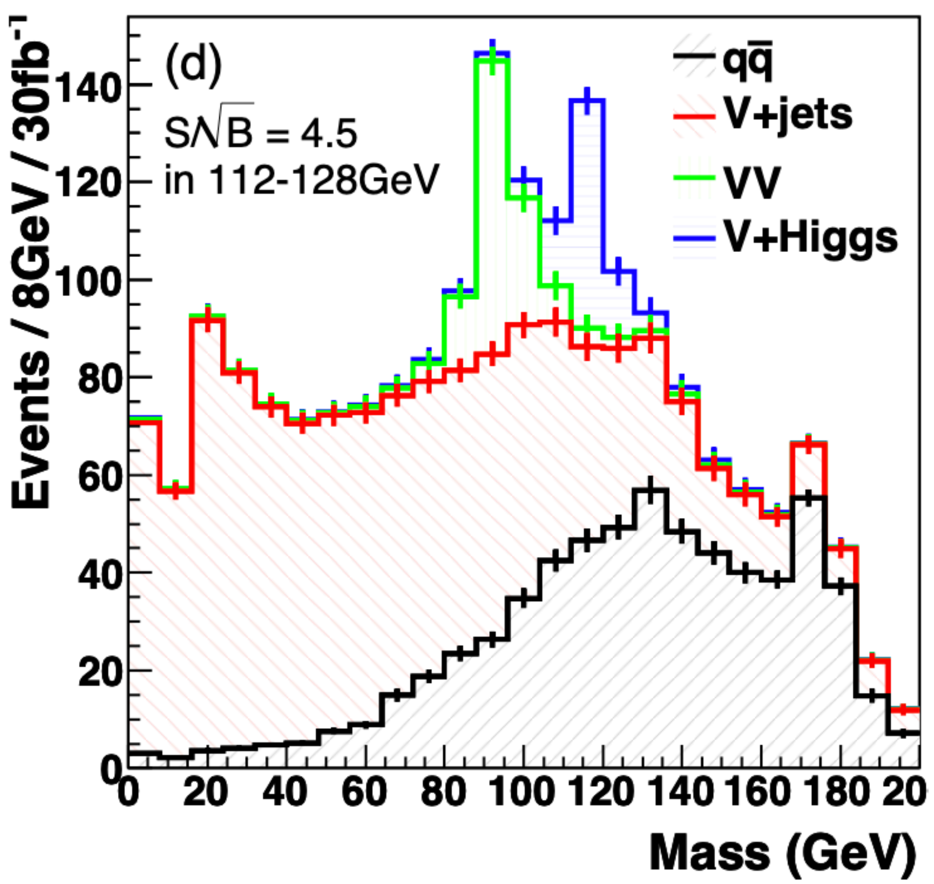
1. cluster the event with jet algorithm large R

2. undo last recombination: large mass drop + symmetric + b tags

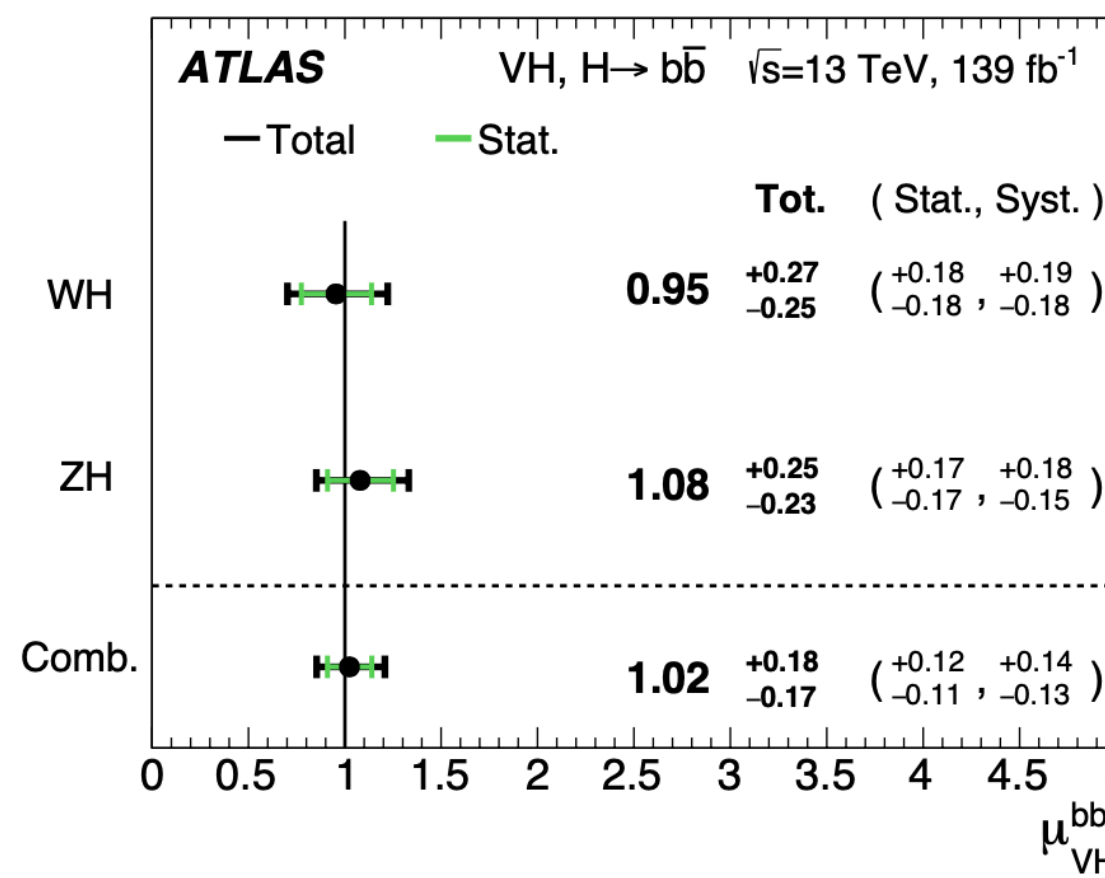
3. filter away the UE: take only the 3 hardest sub-jets

Observation of pp →WH(bb)

Mass of the three hardest sub-jets:



Butterworth et al. 0802.2470

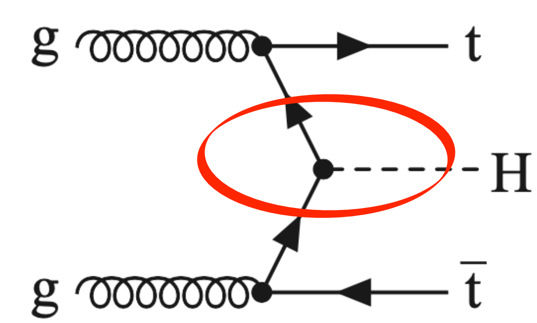


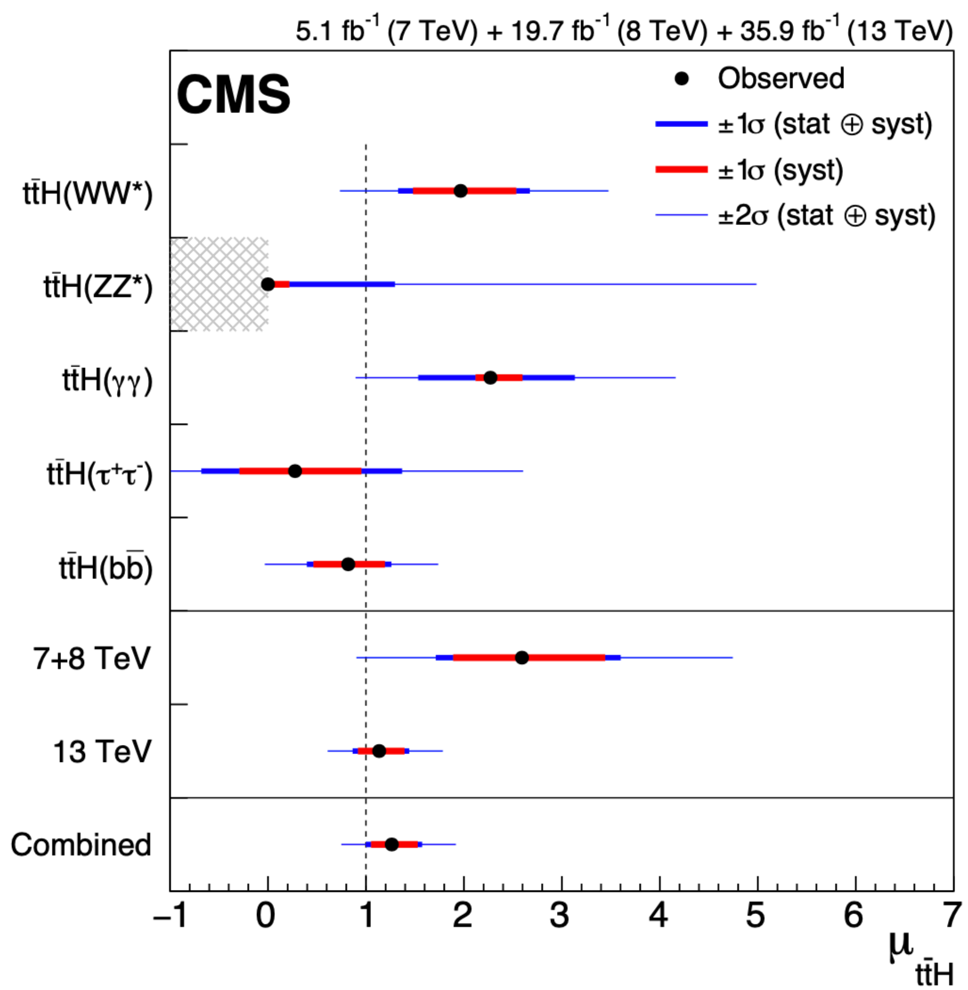
ATLAS 2007.02873

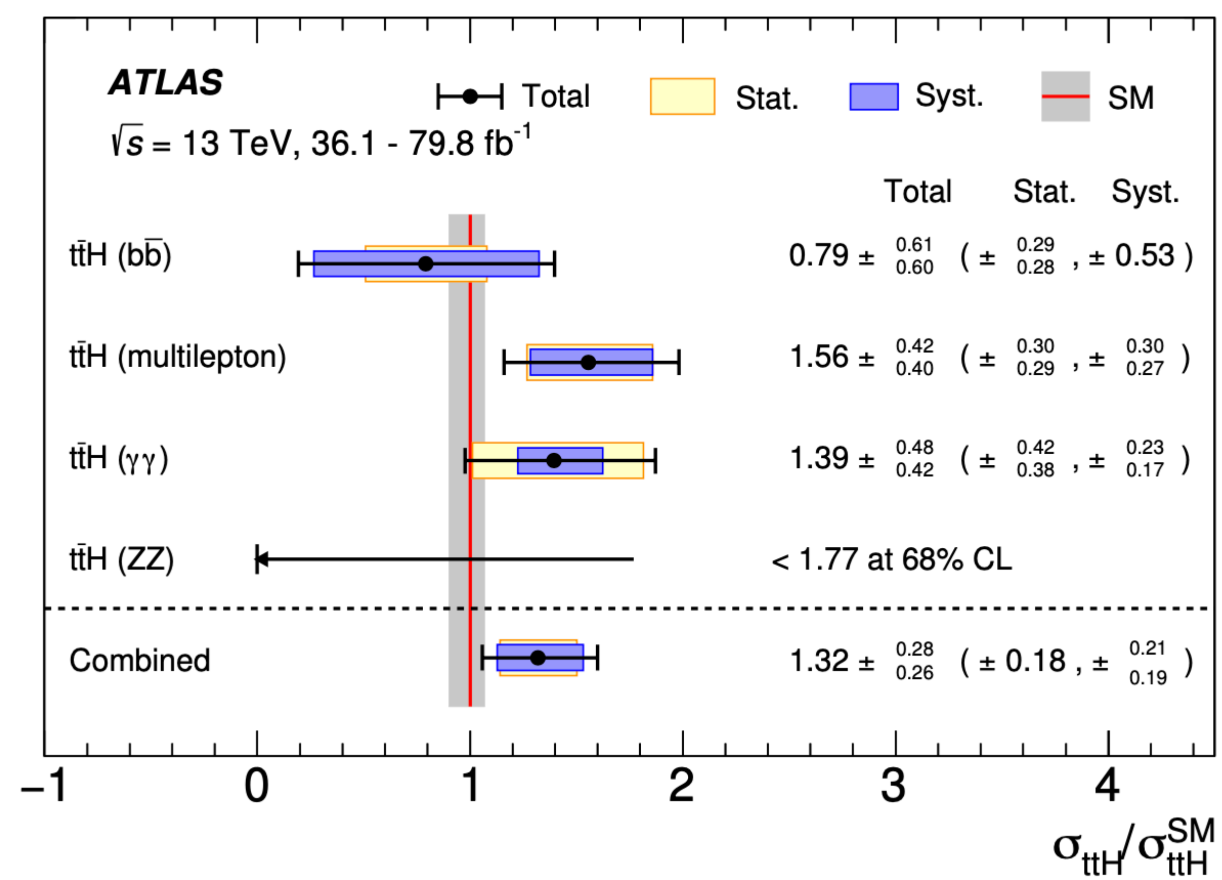
This and other work opened the new field of jet-substructure, widely used today in Higgs physics and BSM searches

Recent highlights: ttH

Not just one more process, but a direct evidence of a new fundamental interaction, a fifth force (the Yukawa interaction)



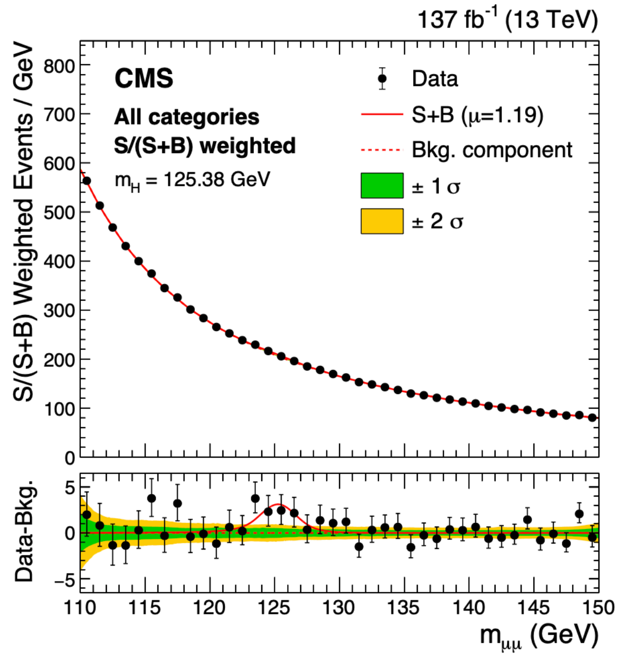


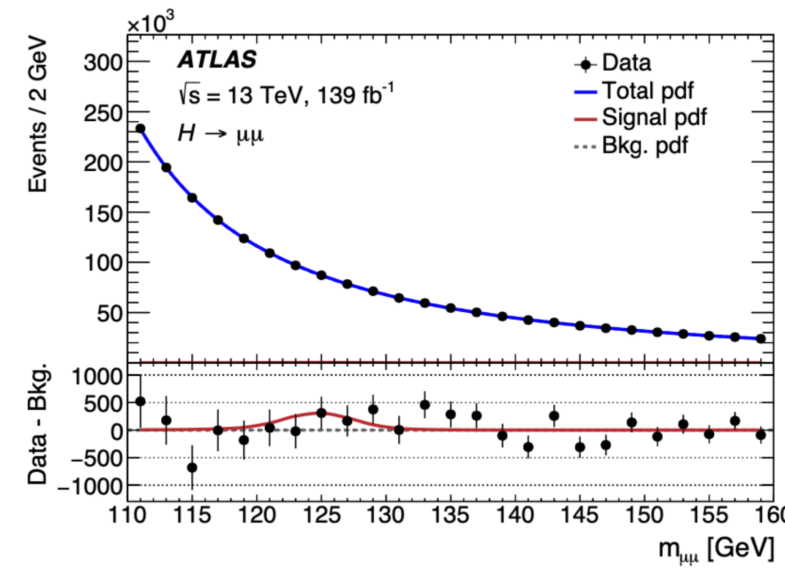


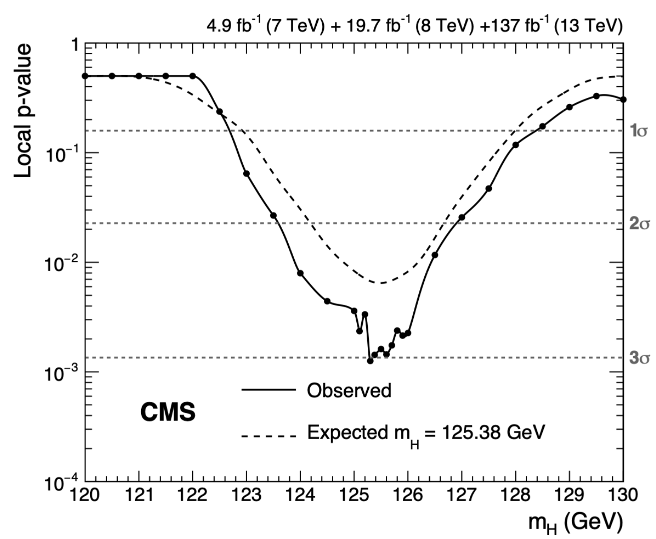
CMS, 1804.02610

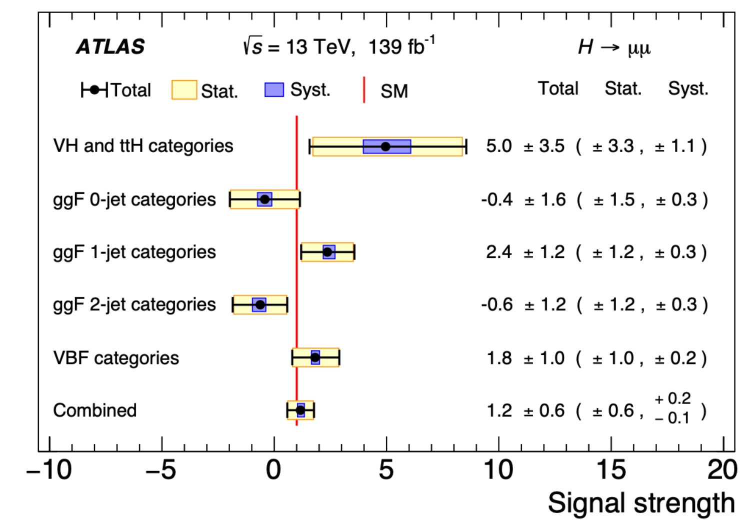
ATLAS, 1806.00425

Recent highlights: H→μμ







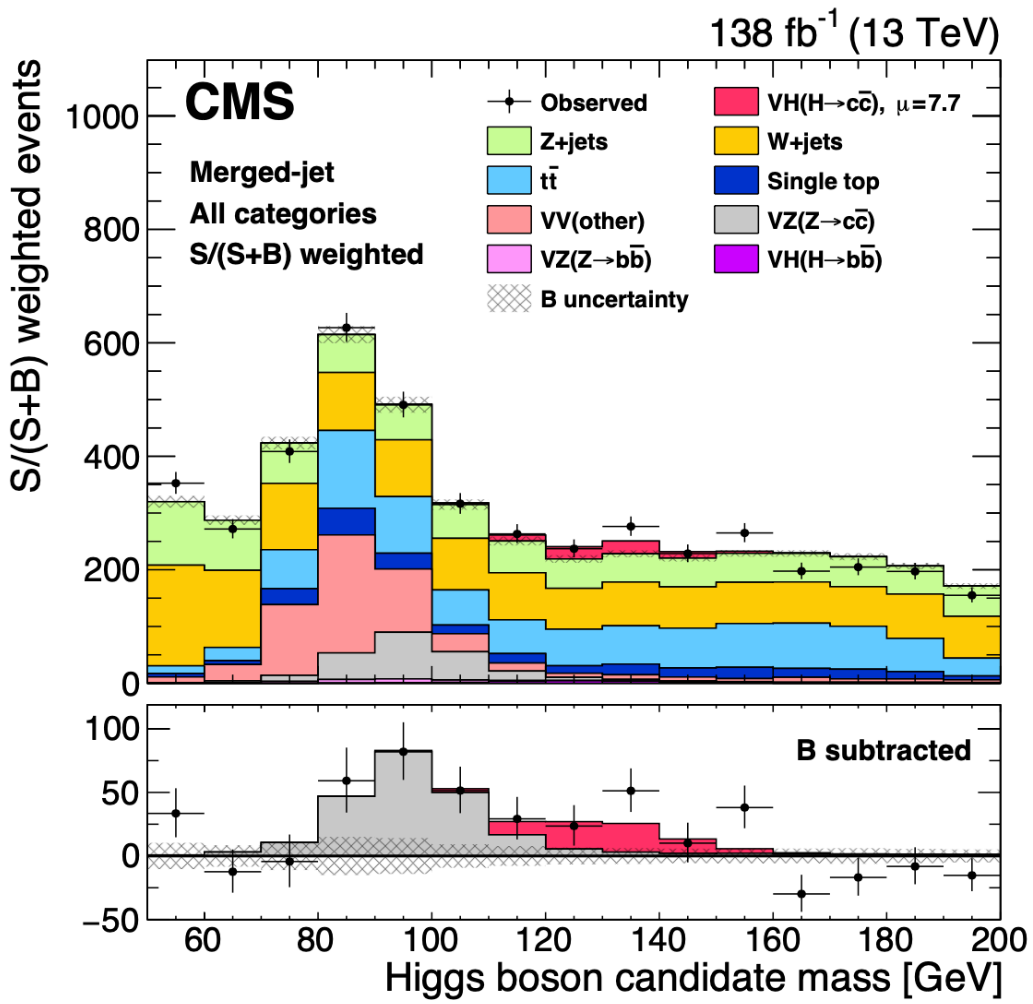


CMS, 2205.05550

ATLAS, 2007.07830

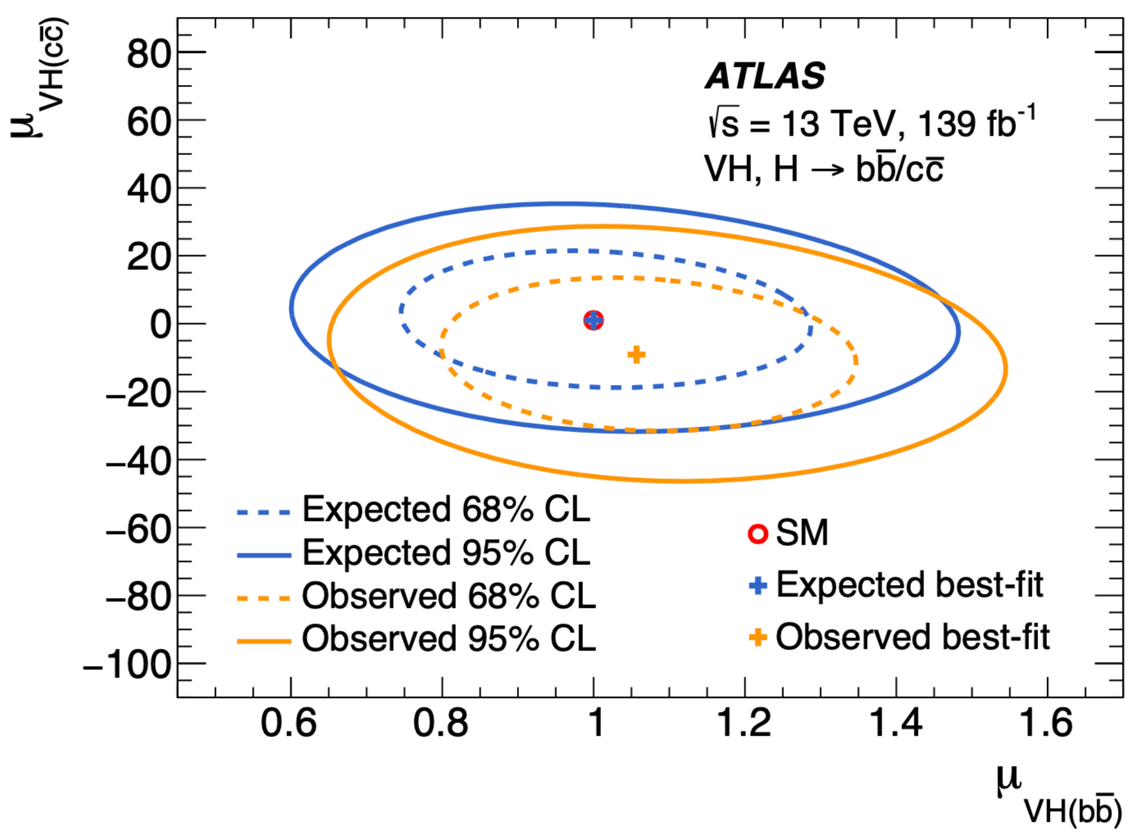
Role of precision theory predictions rather limited

Recent highlights: H→cc



$1.1 < |\kappa_c| < 5.5\ (|\kappa_c| < 3.4)$

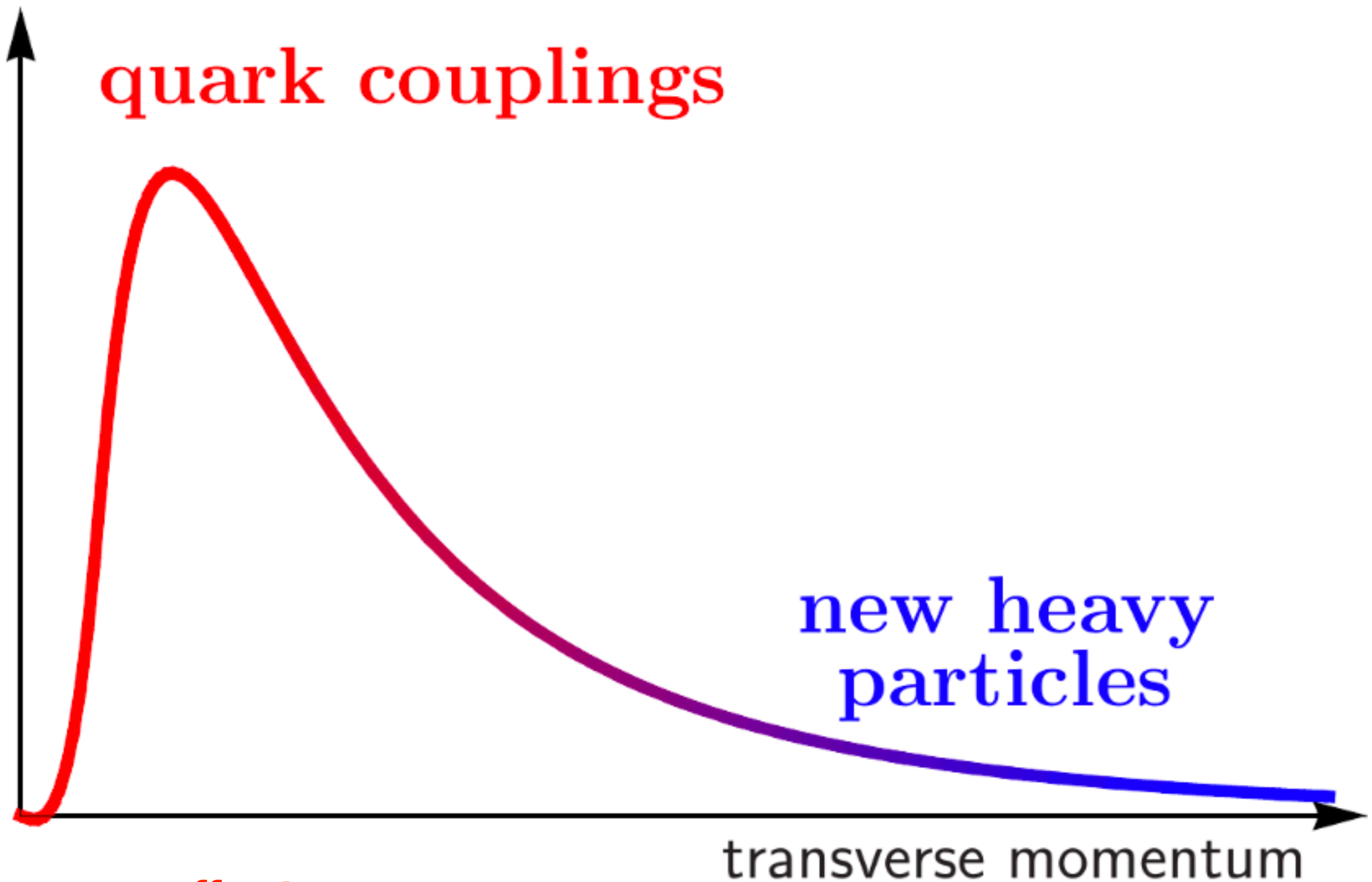
CMS, 2205.05550



ATLAS, 2201.11428

Crucial role of precision theory predictions for the prediction and simulation of background processes

Higgs p_t and light Yukawas



N^{3}LL

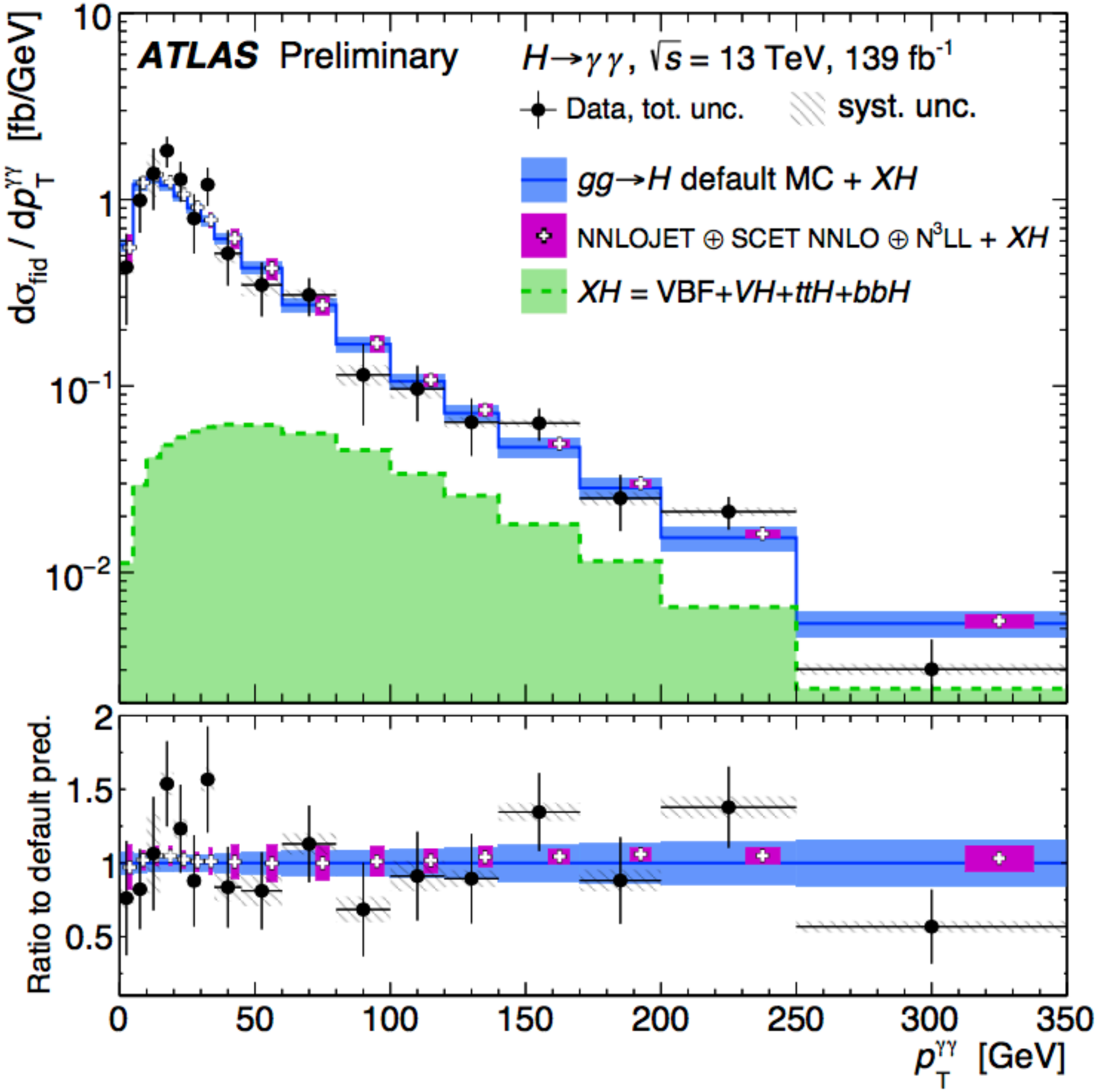
b,c mass effects

Bishara et al 1606.09253

EW effects

NNLO (large m_t)
NLO (finite m_t)

Higgs p_t

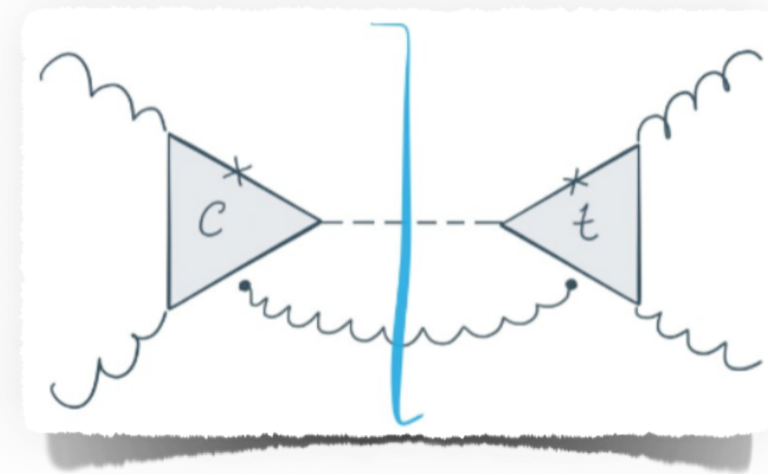


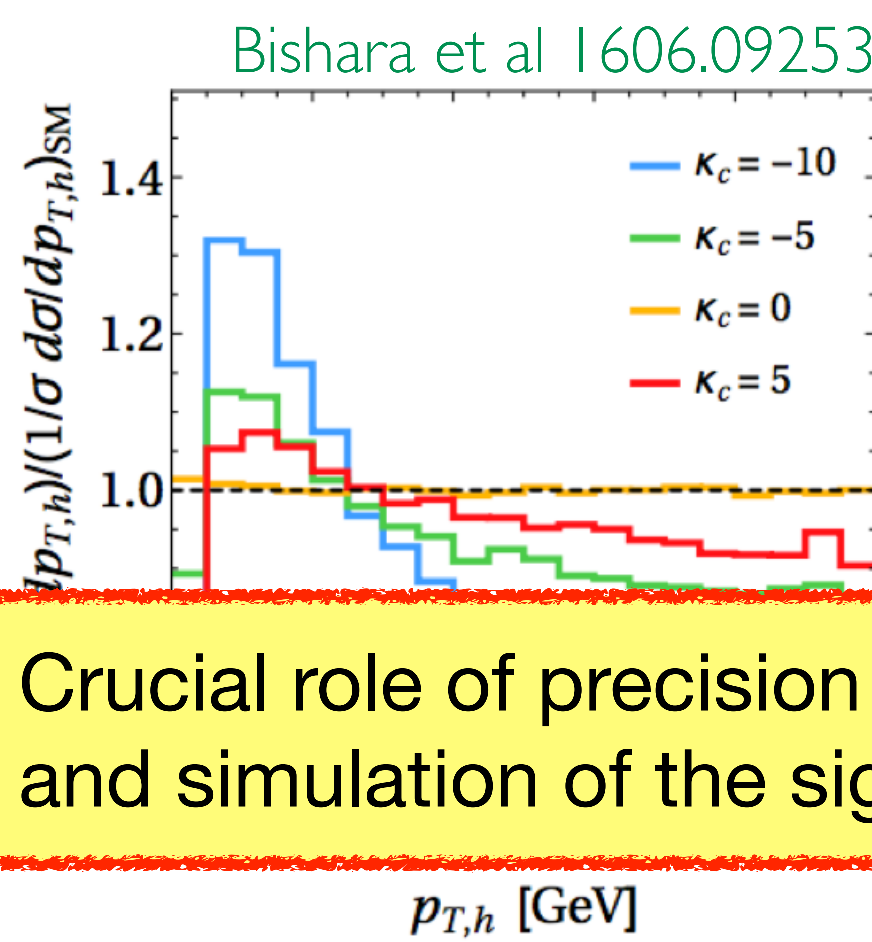
Today impressive level of sophistication (NNLO+N^{3}LL), still theory uncertainty about 10-20%

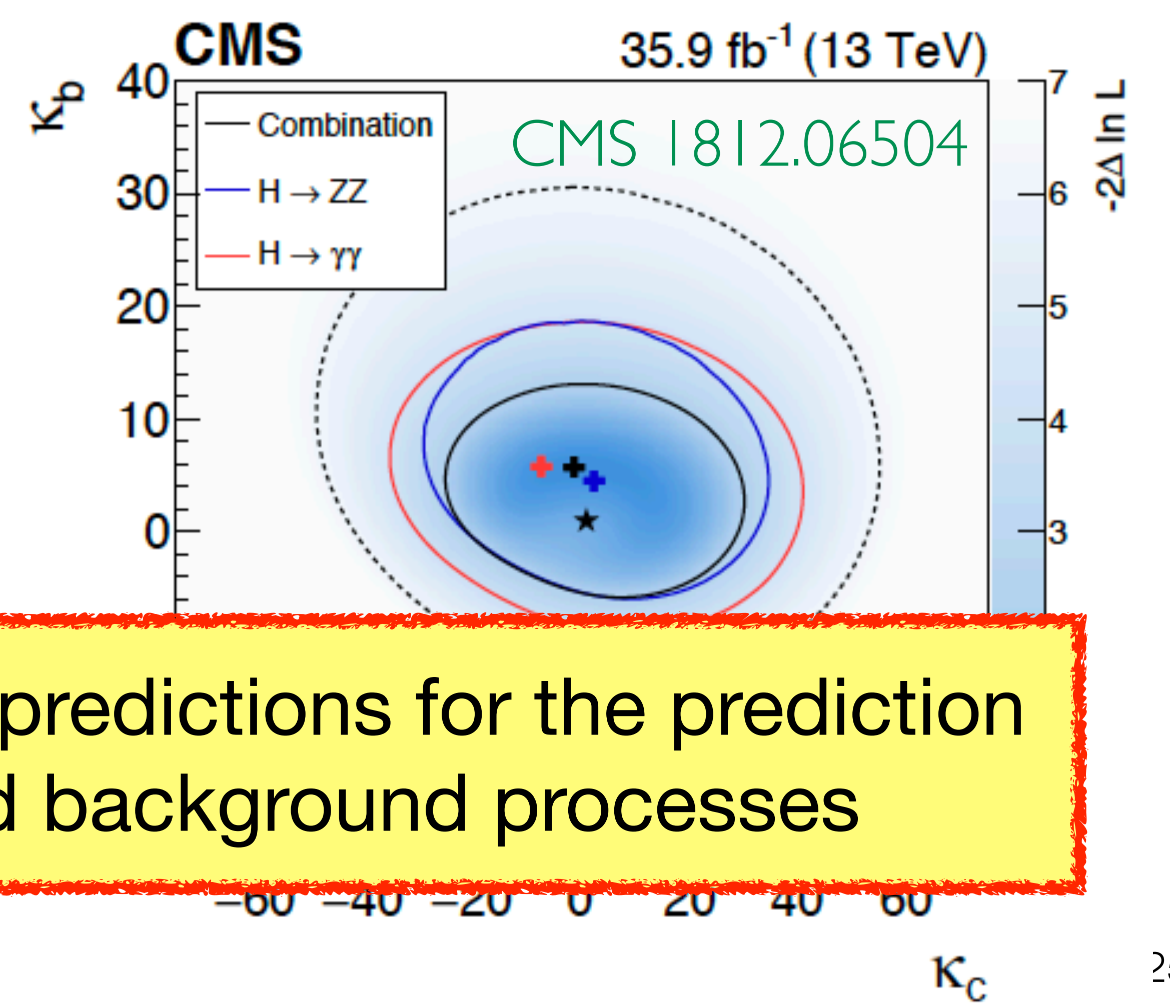
Charm Yukawa through $p_{t,H}$

Interference between top and charm loops create a distortion of the Higgs transverse momentum (at low pt)

⇒ sensitivity to charm Yukawa coupling



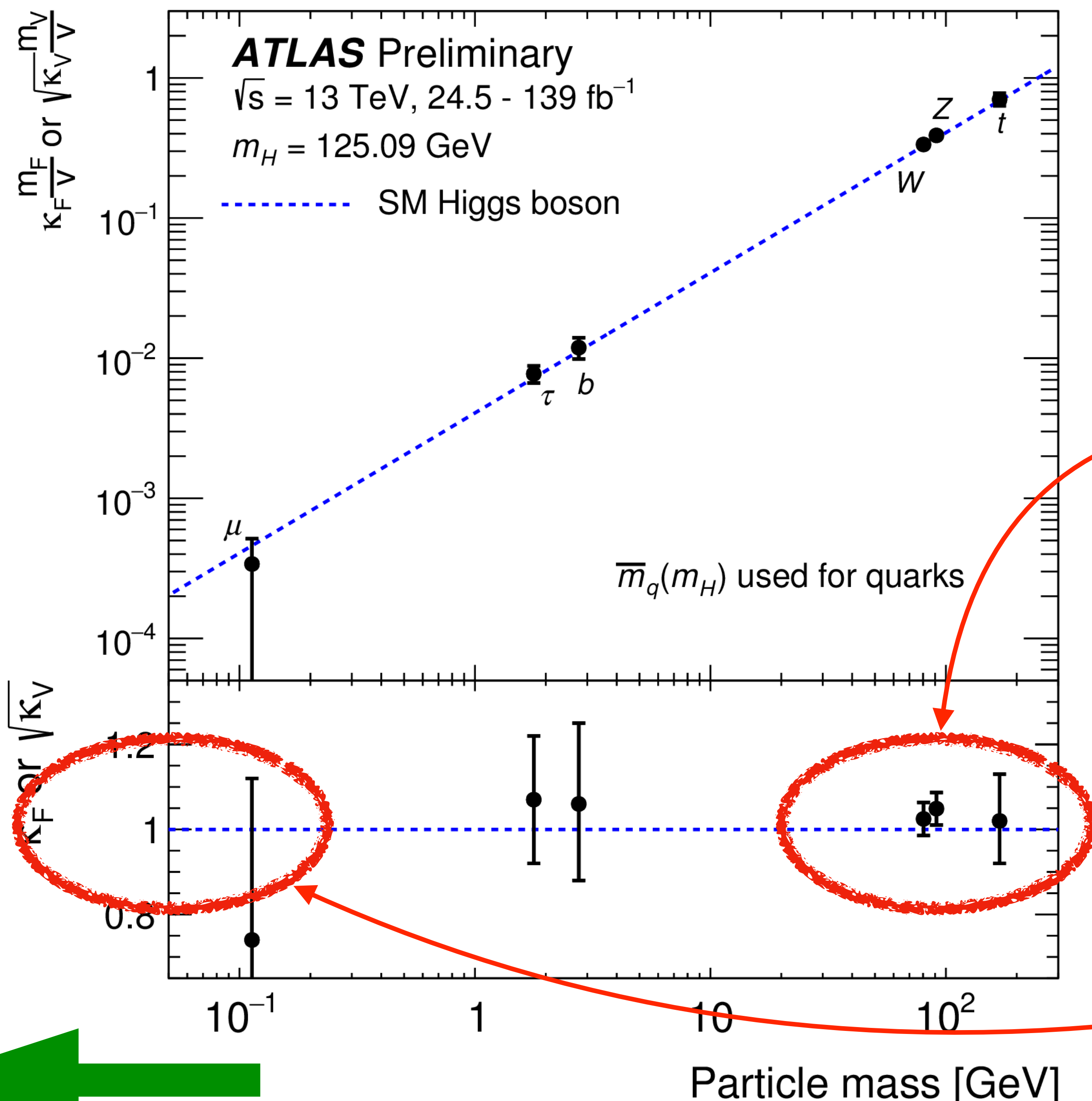




Crucial role of precision theory predictions for the prediction and simulation of the signal and background processes

Status of Higgs couplings

Footprint of SM Higgs: mass versus coupling correlation



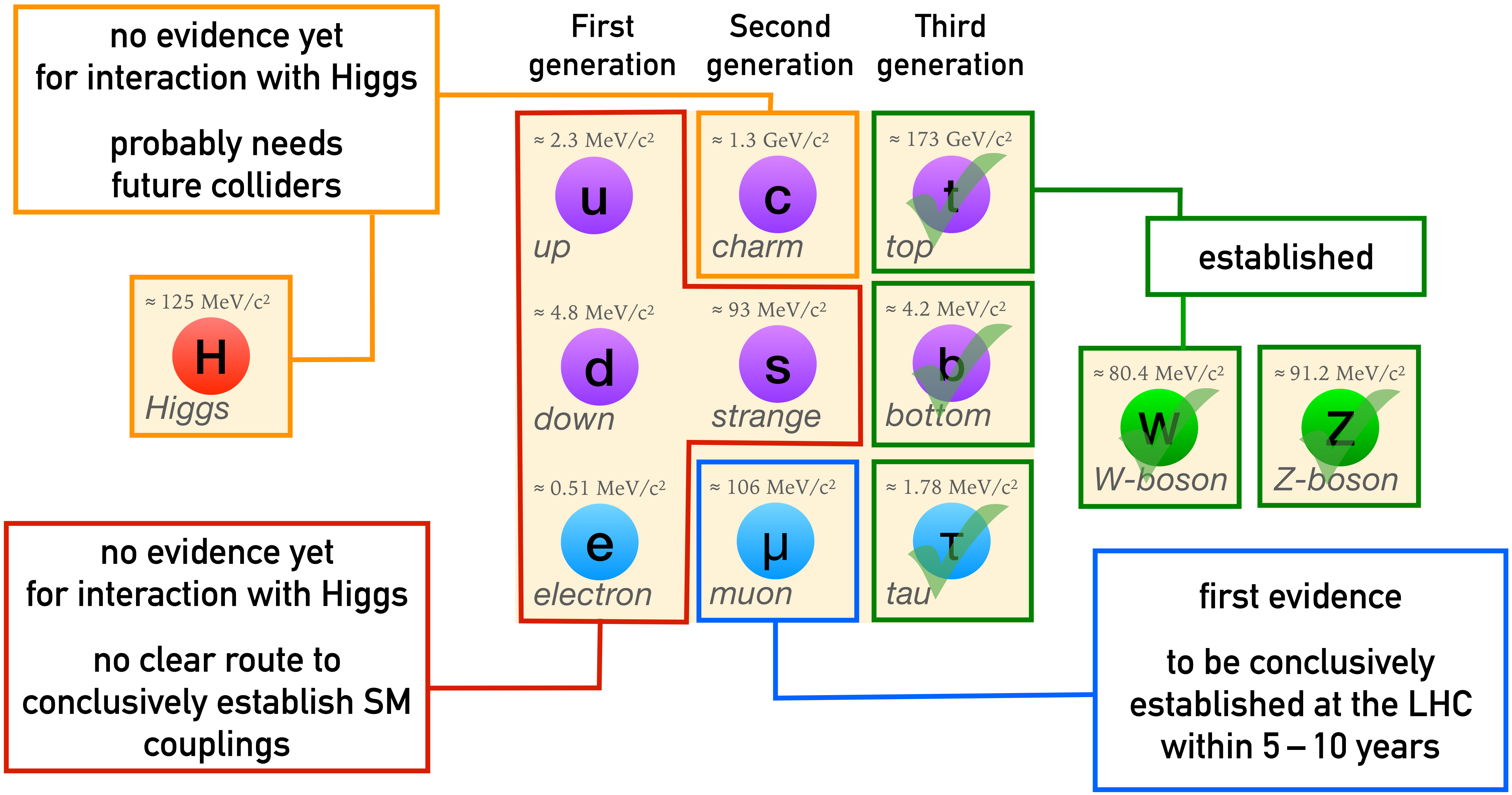
SM predictions for the couplings of heavier particles (gauge bosons, 3rd generation fermions) tested to about 10%

No stringent tests for lighter particles yet (1st and 2nd generation fermions)

Electron, light quarks, neutrinos

Higgs interactions

Status and prospects of our knowledge of Higgs interactions with known particles



Wang, Salam, GZ, Nature perspective to appear

Higgs and New Physics

Seeds of New Physics in the Higgs Lagrangian:

$$\mathcal{L}(\phi) = (D_\mu \phi)^\dagger (D^\mu \phi) - \mu_0^2 |\phi|^2 + \lambda |\phi|^4 + Y_{ij} \bar{\psi}_L^i \psi_R^j \phi$$

Gauge invariant mass generation of gauge bosons in the SM

The Higgs mass terms. Connected to the naturalness problem

The Higgs quartic self-interaction. Connected to the question of the stability of the potential

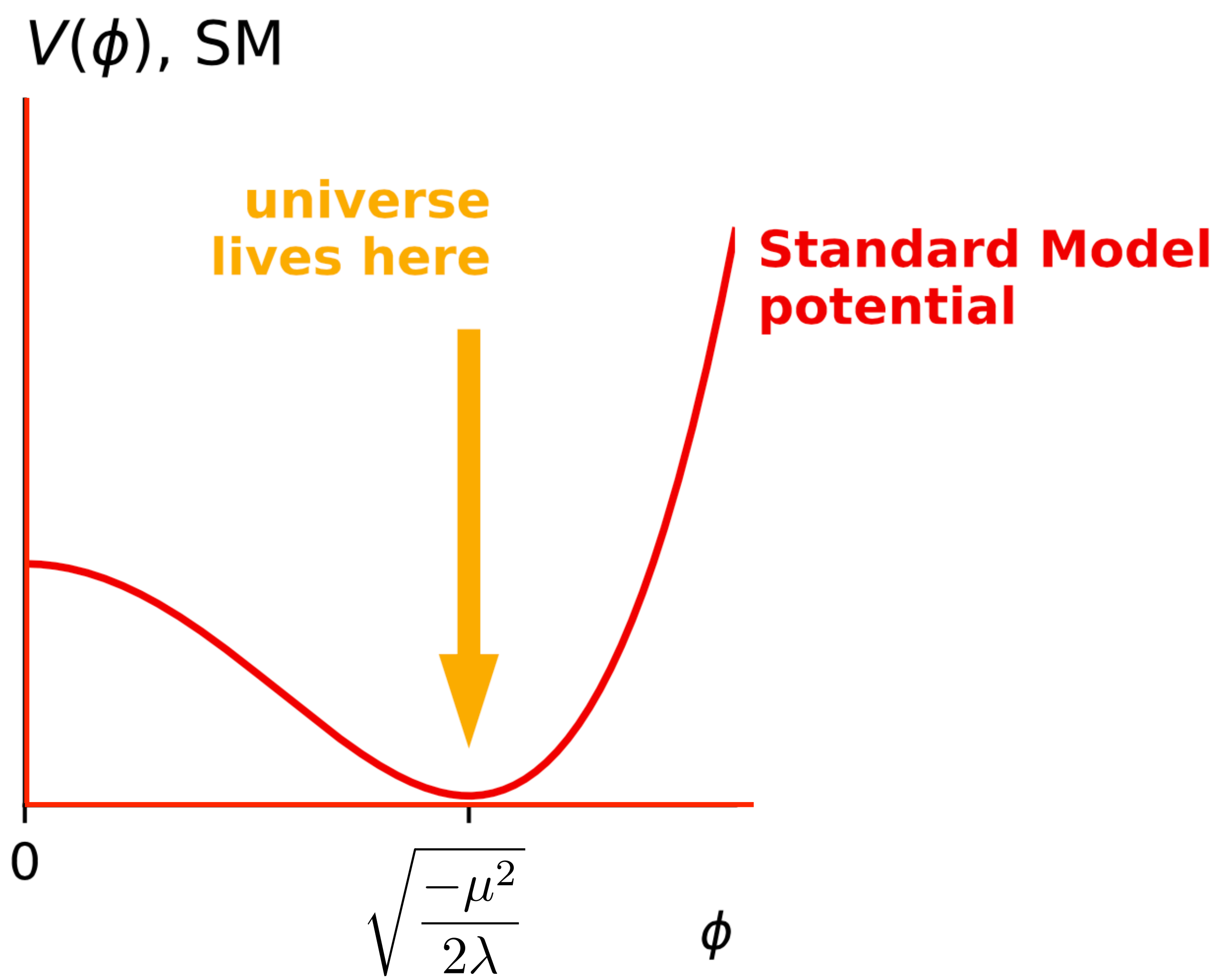
Yukawas give mass to fermions. Connected to flavour/CP problem

The Higgs potential

$$V(\phi) = \mu^2|\phi|^2 + \lambda|\phi|^4$$

Theorist's assumption

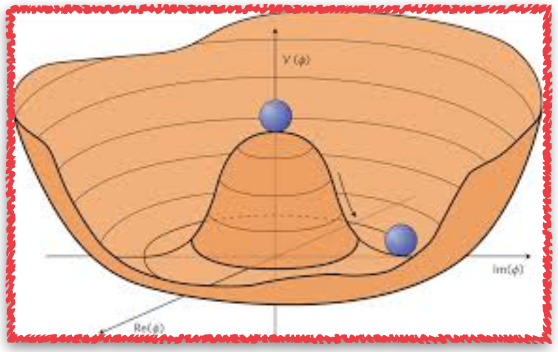
the cornerstone of the SM, also connects with the stability of the universe



The Higgs boson is responsible for the masses of all particles. Its potential, linked to the Higgs self-coupling, is predicted in the SM, but we have not tested it so far

Establishing this assumption is a big answerable question, a guaranteed pay-off

The Higgs potential



After electroweak symmetry breaking:

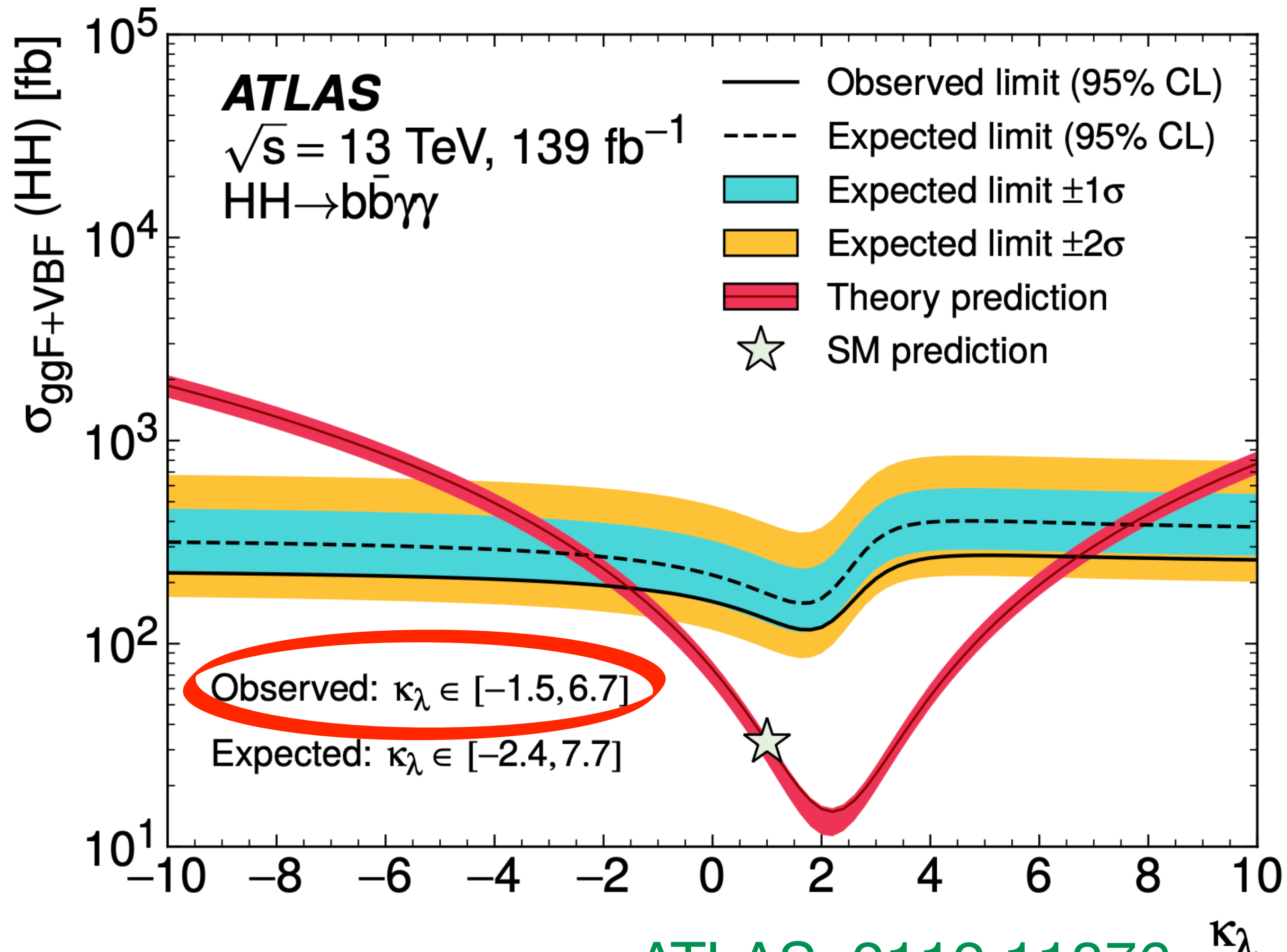
$$V_{\rm SM} = \frac{m_h}{2} h^2 + \lambda v h^3 + \frac{\lambda}{4} h^4$$

Single Higgs (✔)	Double Higgs (☐)	Triple Higgs (☐)
done	very hard	out of reach
O(7 millions)	O(7000)	O(15)

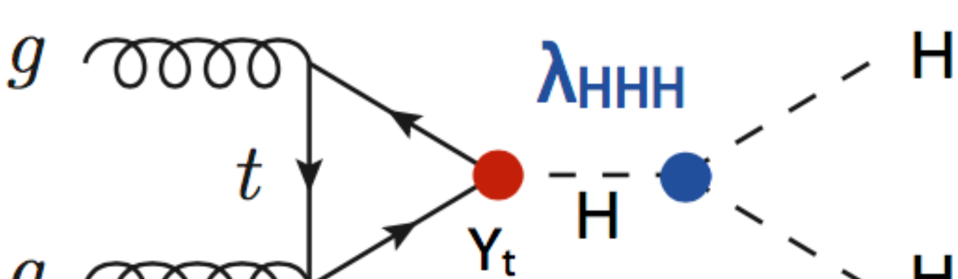
events produced so far

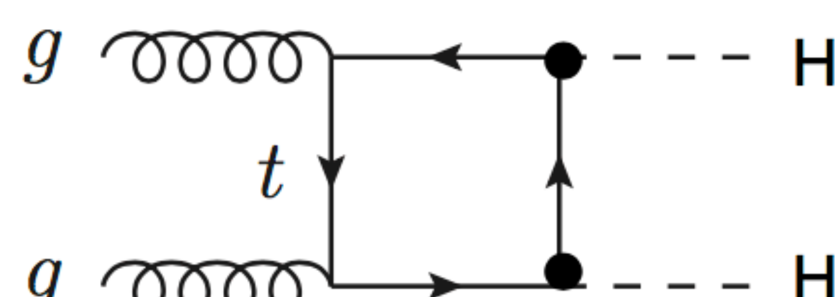
The Higgs self-coupling

- Double-Higgs production is directly sensitive to the self-coupling
- Sensitivity limited also because of destructive interference



ATLAS, 2112.11876

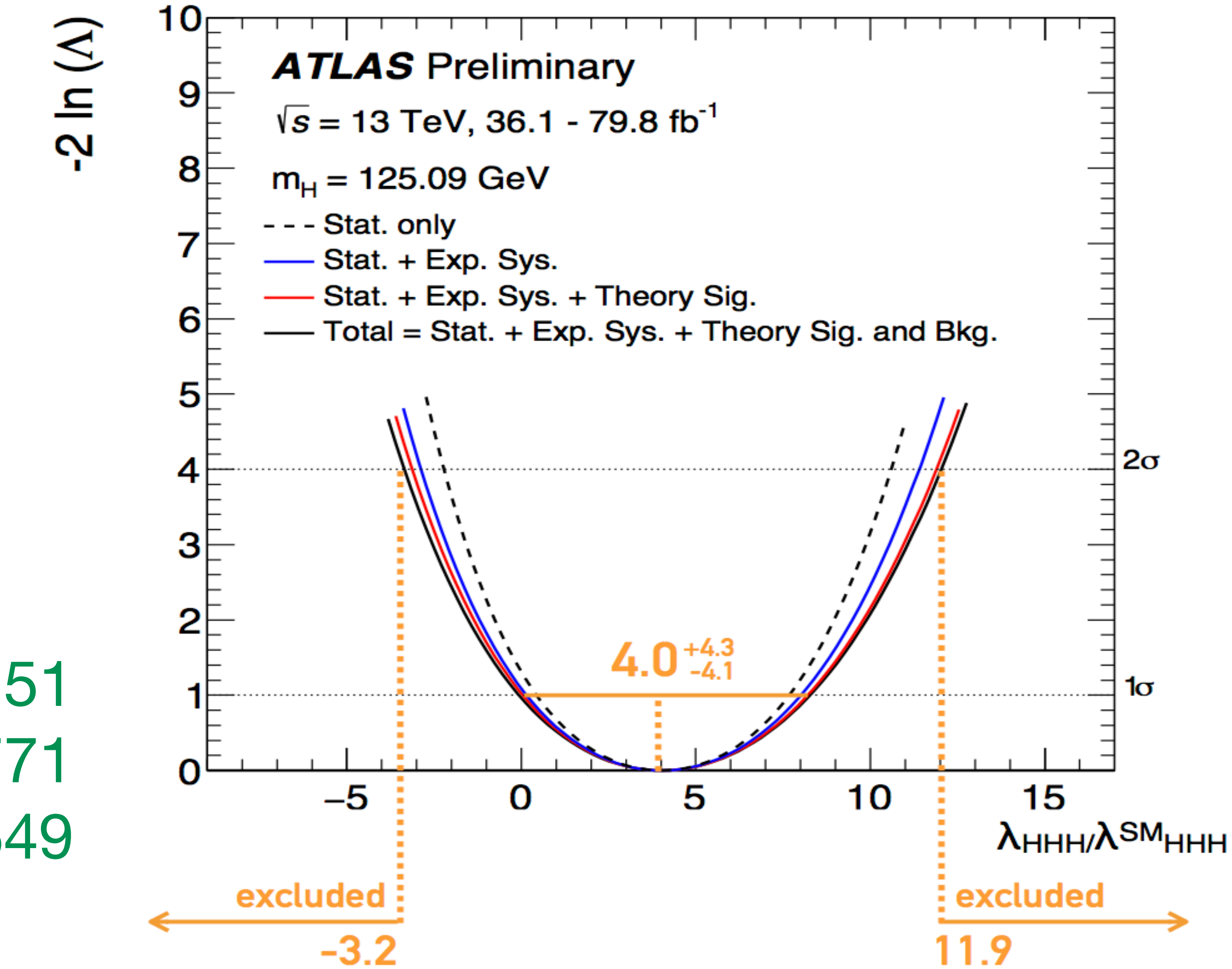


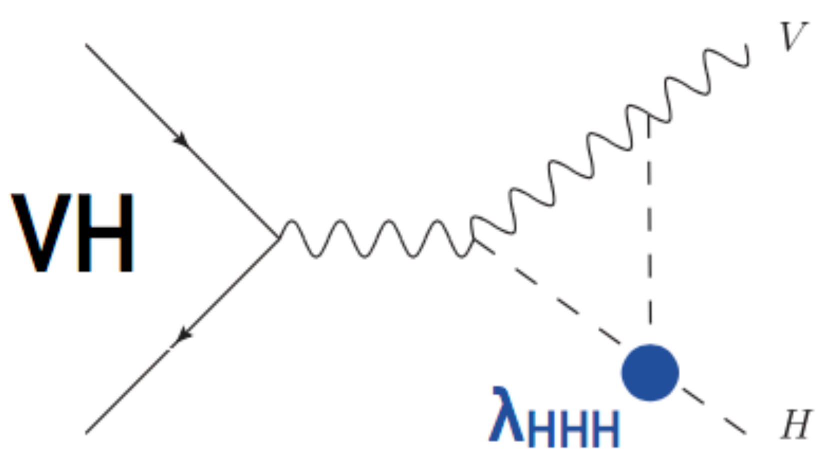


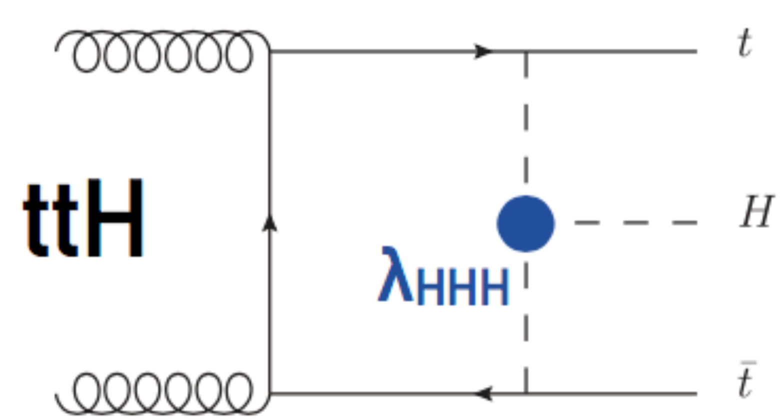
The Higgs self-coupling

- Single-Higgs production modes indirectly sensitive to the self-coupling through electro-weak effects
- Precision theory predictions absolutely crucial

De Grassi et al 1607.04251
Bizon et al 1610.05771
Maltoni et al 1709.08649

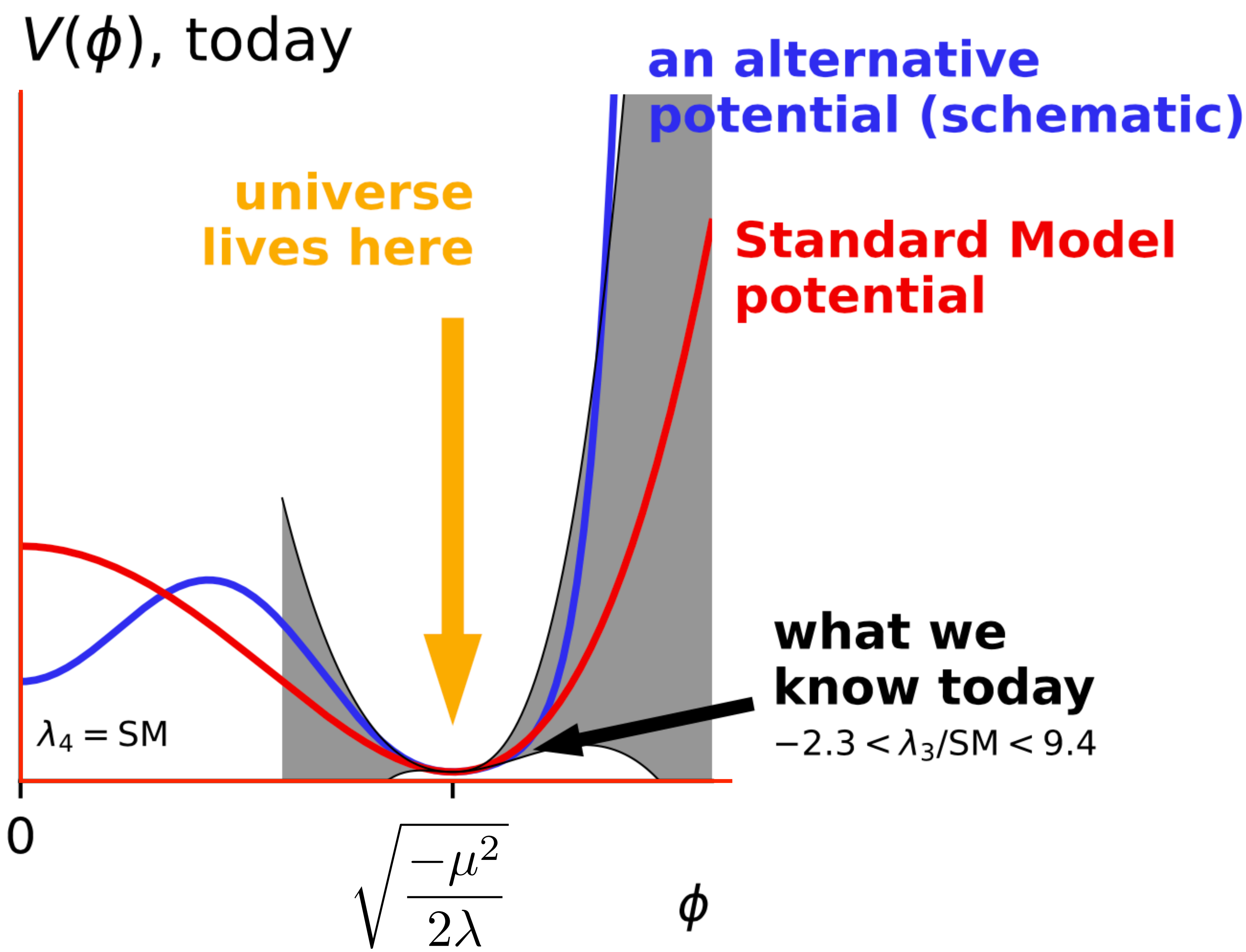






The Higgs potential

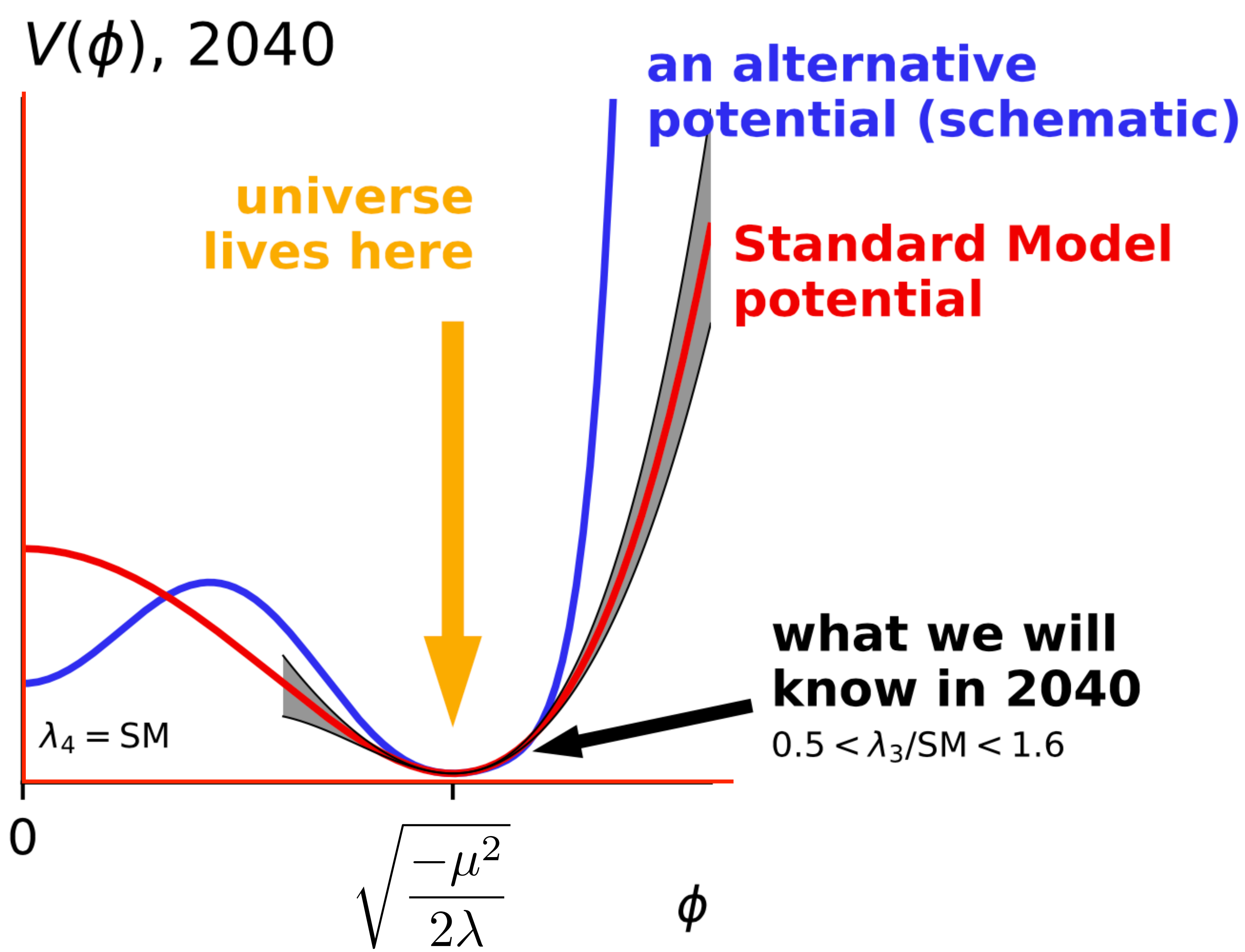
What did we establish so far?



Adapted from Wang, Salam, GZ, Nature perspective to appear

The Higgs potential

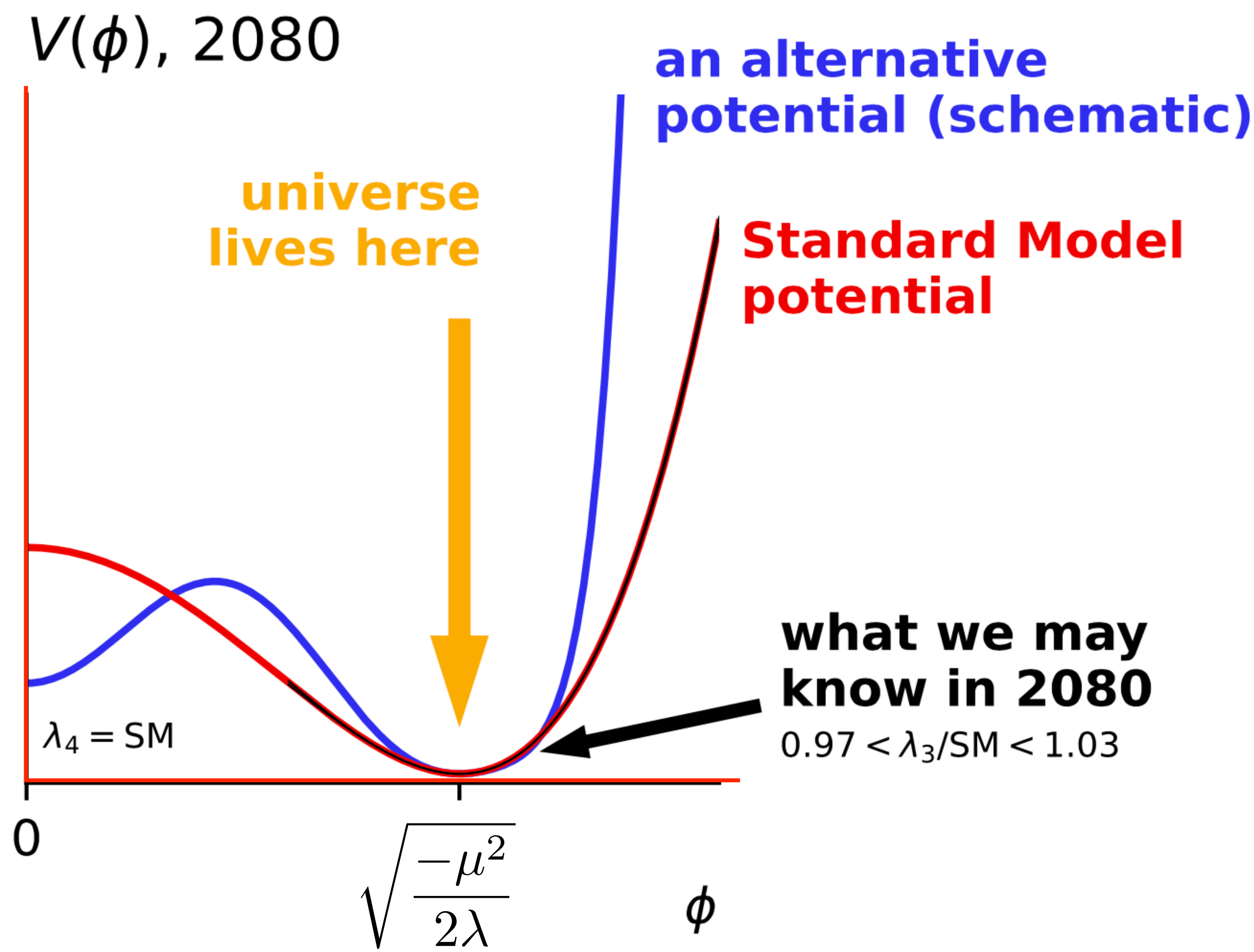
What are the prospects in the next twenty years?



Adapted from Wang, Salam, GZ, Nature perspective to appear

The Higgs potential

What are the prospects after a possible FCC ?



Adapted from Wang, Salam, GZ, Nature perspective to appear

Higgs and New Physics

New physics likely heavy ⇒ use effective field theory (EFT)

$$\mathcal{L} = \mathcal{L}_{\text{SM}} + \sum_i \frac{1}{\Lambda^2} \mathcal{O}_i^{D=6}$$

scale of new physics

Results in a modification of the SM couplings (or in the presence of new couplings)

At low energy, e.g. Higgs couplings:

$$g = g_{\text{SM}} \left(1 + c \frac{v^2}{\Lambda^2} \right)$$

At high energy, e.g. $V_L V_L$ scattering:

$$g = g_{\text{SM}} \left(1 + c \frac{E^2}{\Lambda^2} \right)$$

Higgs and New Physics

New physics likely heavy ⇒ use effective field theory (EFT)

$$\mathcal{L} = \mathcal{L}_{\rm SM} + \sum_i \frac{1}{\Lambda^2} \mathcal{O}_i^{D=6}$$

scale of new physics

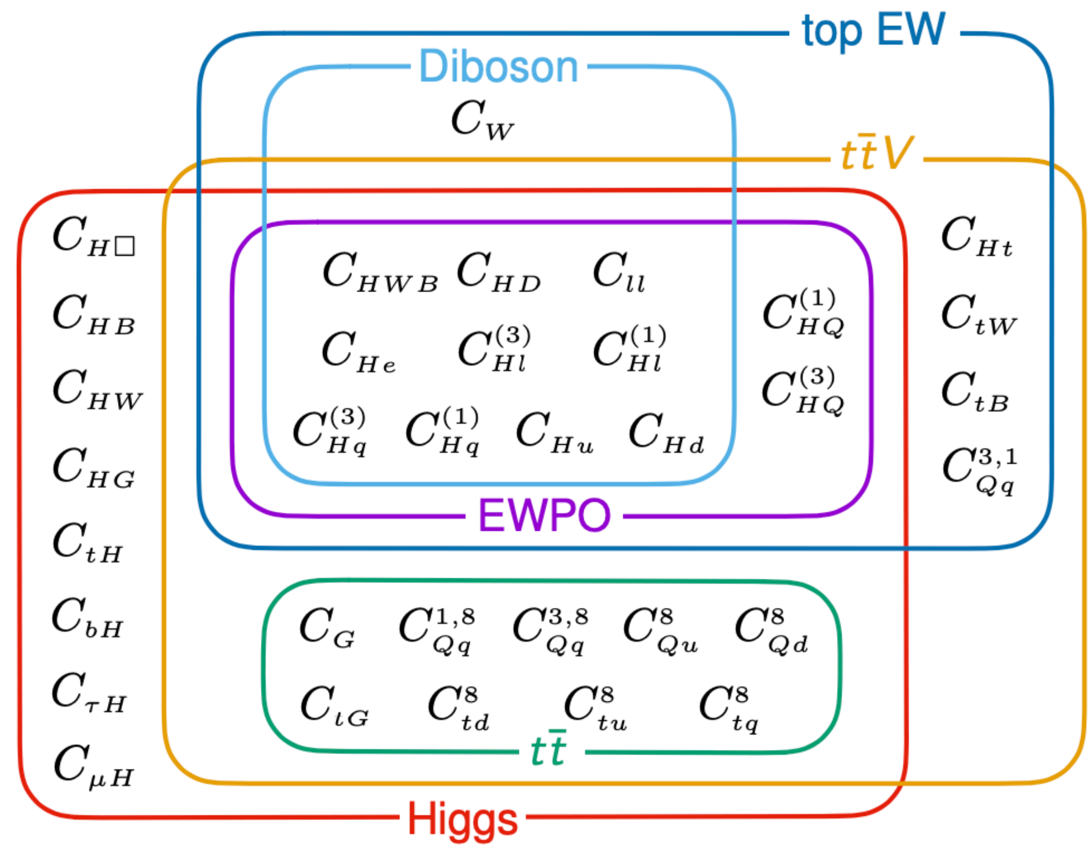
per-mille accuracy at LEP ≈ 10% accuracy at 1 TeV
1% accuracy at 1 TeV ≈ 10% accuracy at 3 TeV
0.1% accuracy at 1 TeV ≈ 10% accuracy at 10 TeV

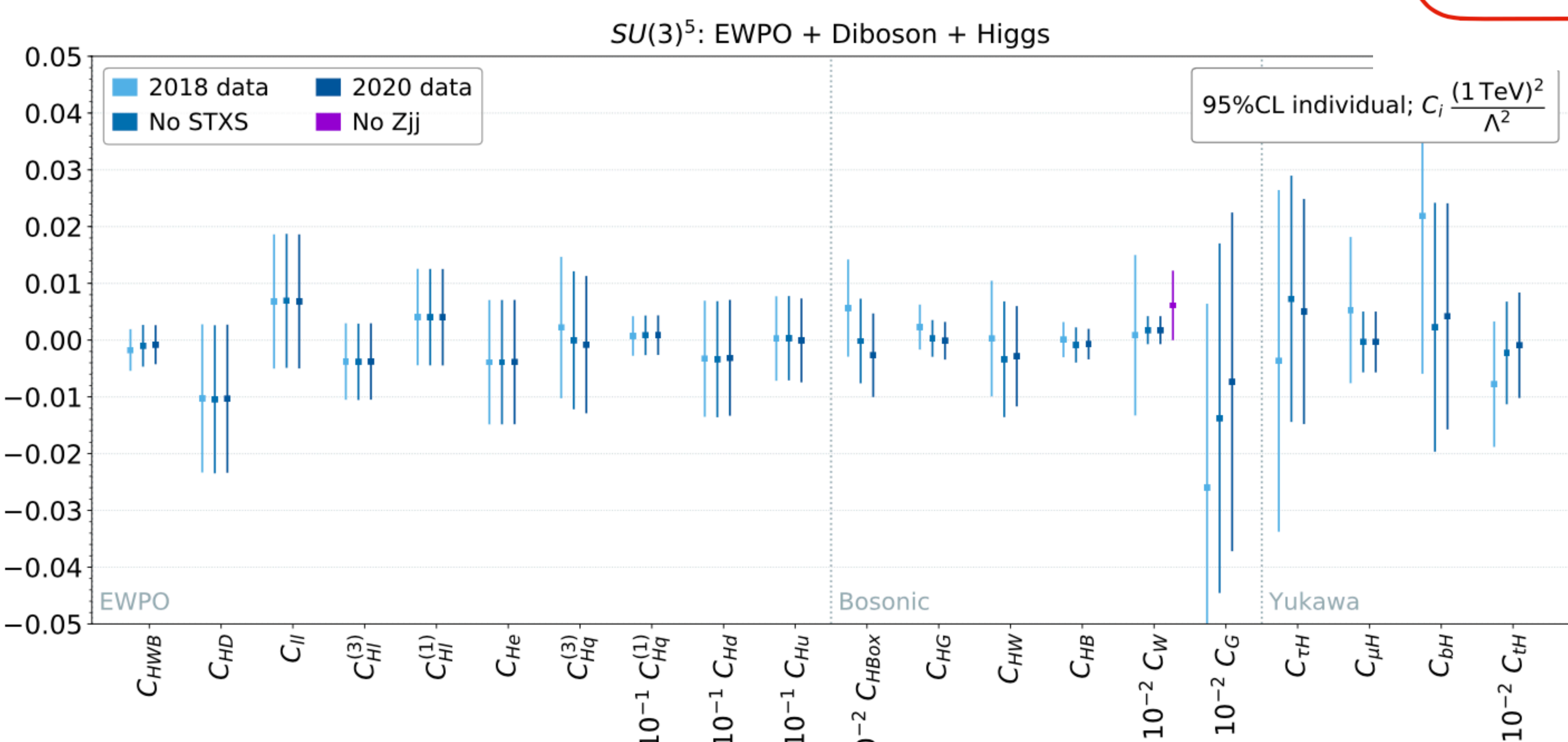
$$g = g_{\rm SM}\left(1 + c\frac{v^2}{\Lambda^2}\right)$$

$$g = g_{\rm SM}\left(1 + c\frac{E^2}{\Lambda^2}\right)$$

Higgs and New Physics

Sample global constraints on coefficients of D=6 operators





Ellis et al 2012.02779

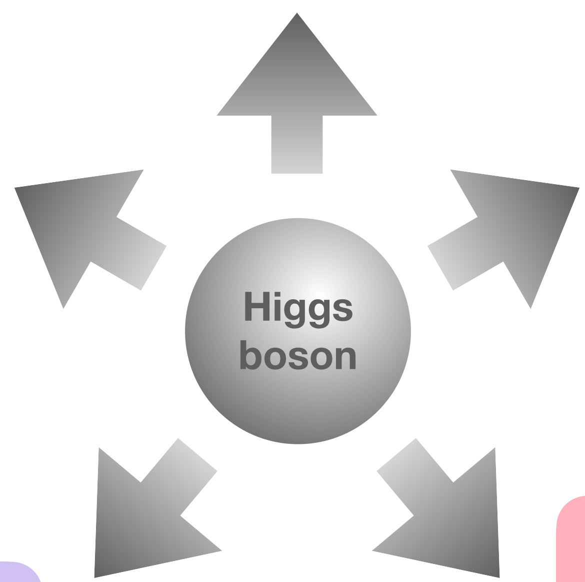
Possible connections of the Higgs to major open questions

What is the origin of the early-universe inflation?

- Is the Higgs connected to the mechanism that drives inflation?
- Are there any imprints in cosmological observations?

What is the origin of the vast range of quark and lepton masses in the Standard Model?

- Are there modified interactions to the Higgs boson and known particles?
- Does the Higgs decay into pairs of quarks and leptons with distinct flavours (for example, $H \rightarrow \mu^{+}\tau^{-}$)?



Why is the electroweak interaction so much stronger than gravity?

- Are there new particles close to the mass of the Higgs boson?
- Is the Higgs boson elementary or made of other particles?
- Are there anomalies in the interactions of the Higgs with the W and Z?

What is dark matter?

- Can the Higgs provide a portal to dark matter or a dark sector?
- Is the Higgs lifetime consistent with the Standard Model?
- Are there new decay modes of the Higgs?

Why is there more matter than antimatter in the universe?

- Are there charge-parity violating Higgs decays?
- Are there anomalies in the Higgs self-coupling that would imply a strong first-order early-universe electroweak phase transition?
- Are there multiple Higgs sectors?

Wang, Salam, GZ, Nature perspective to appear

Conclusions

- Higgs studies are just out of their infancy. So far, the Higgs looks very much Standard Model like
- The scalar sector is connected to profound questions (naturalness, vacuum stability, flavour)
- The discovery allows us to explore a new sector with a broad experimental program that will extend over decades
- Thanks to the excellent performance of experiments, to theory and computational developments, much more was achieved at LHC compared to expectations
- Much more will be learnt in the years to come