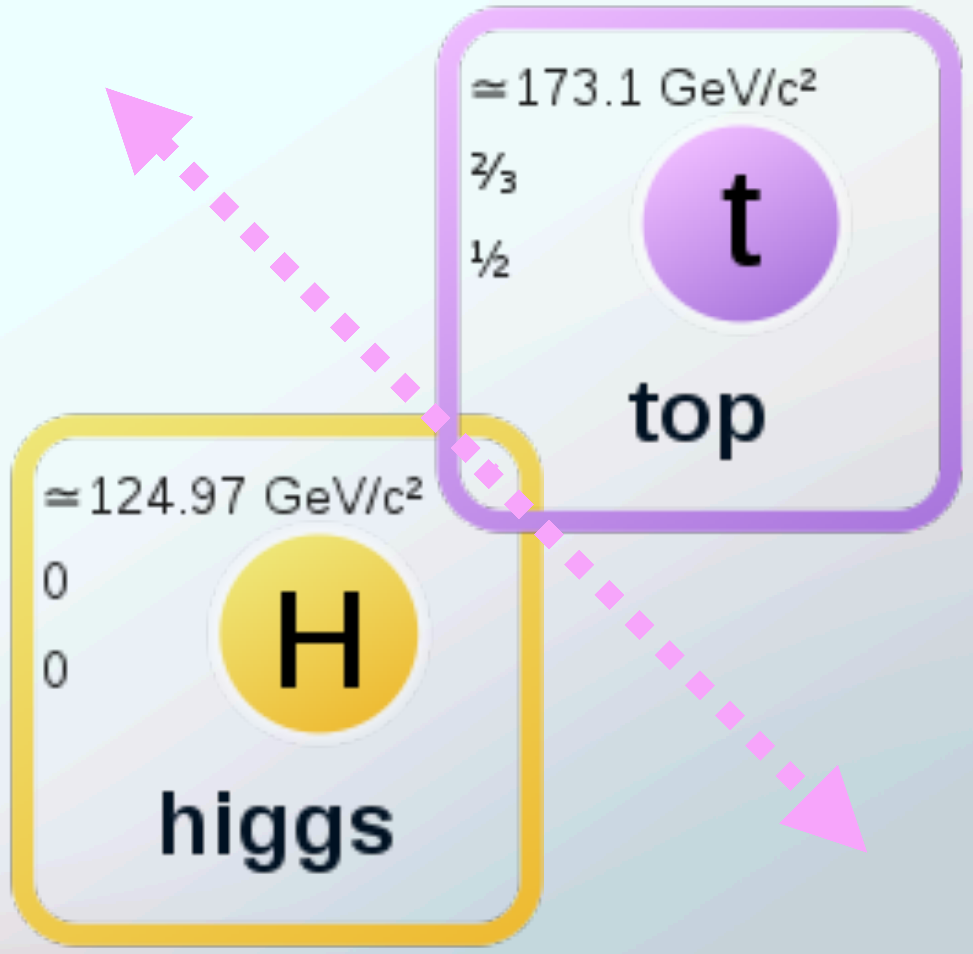
Probing Electroweak Symmetry Breaking with Effective Field Theories

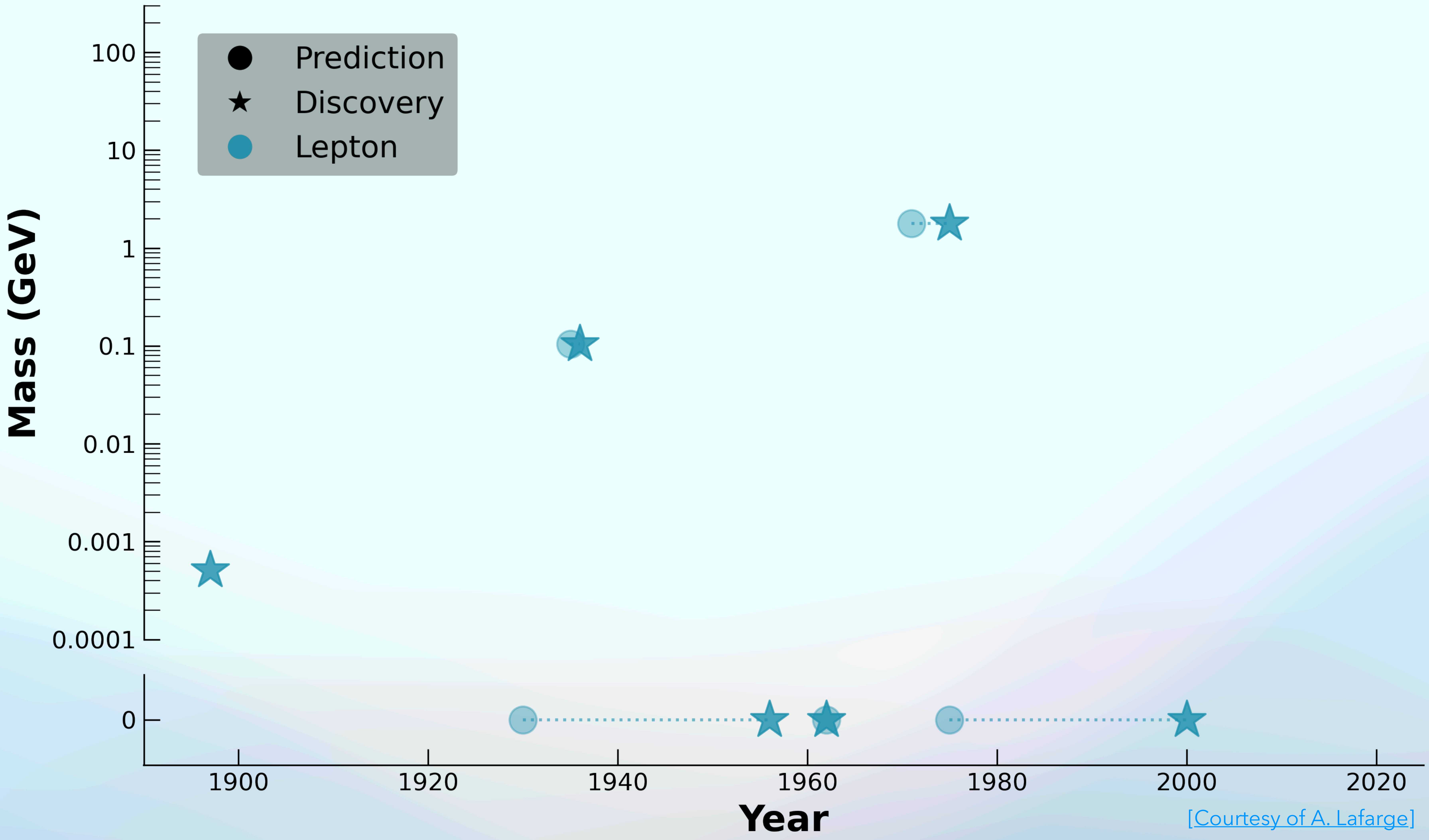
in Top quark and Higgs sectors



IPHC seminar - 30, March 2026

Adrien Auriol

A discovery tale



[Courtesy of A. Lafarge]

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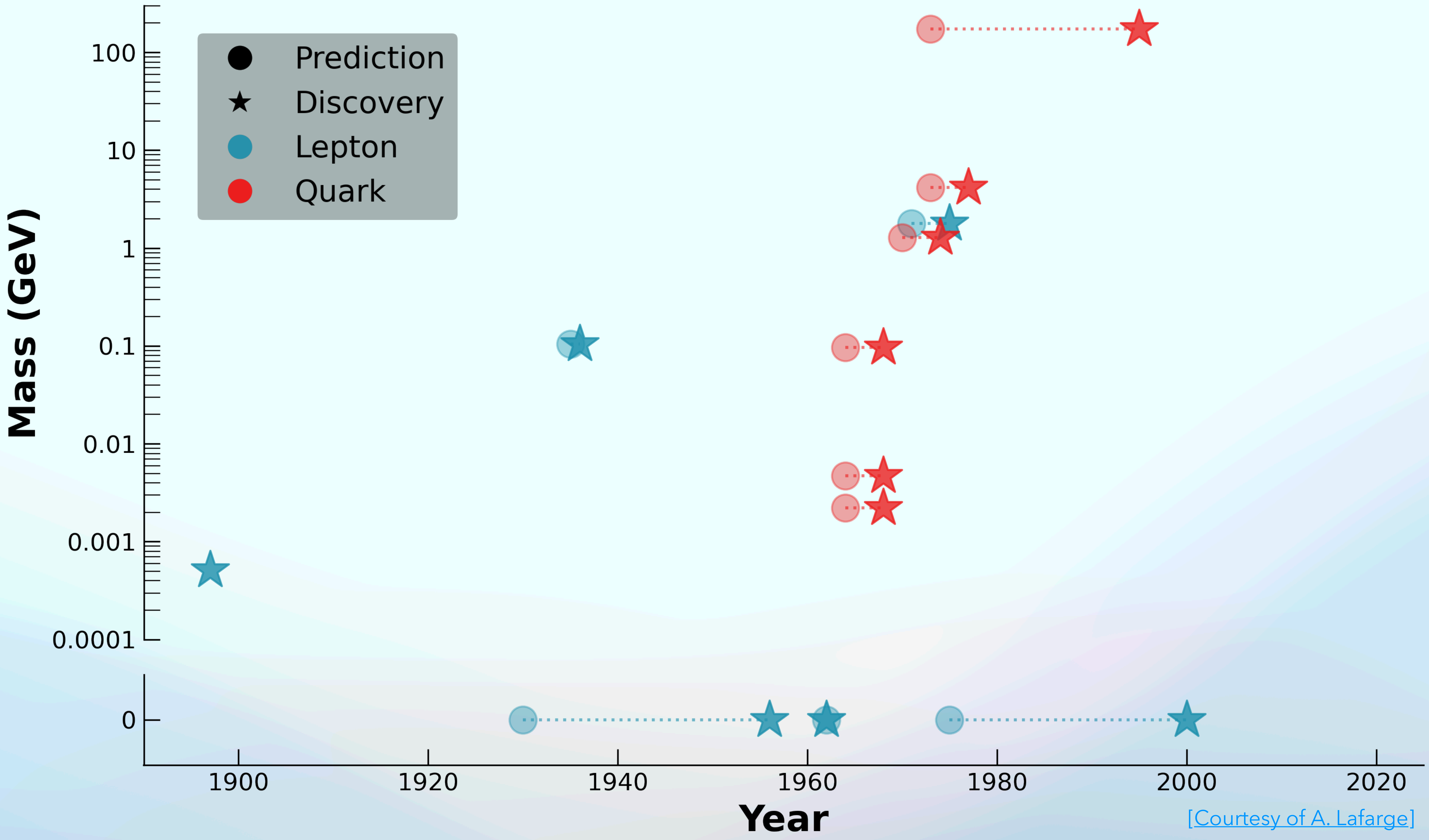

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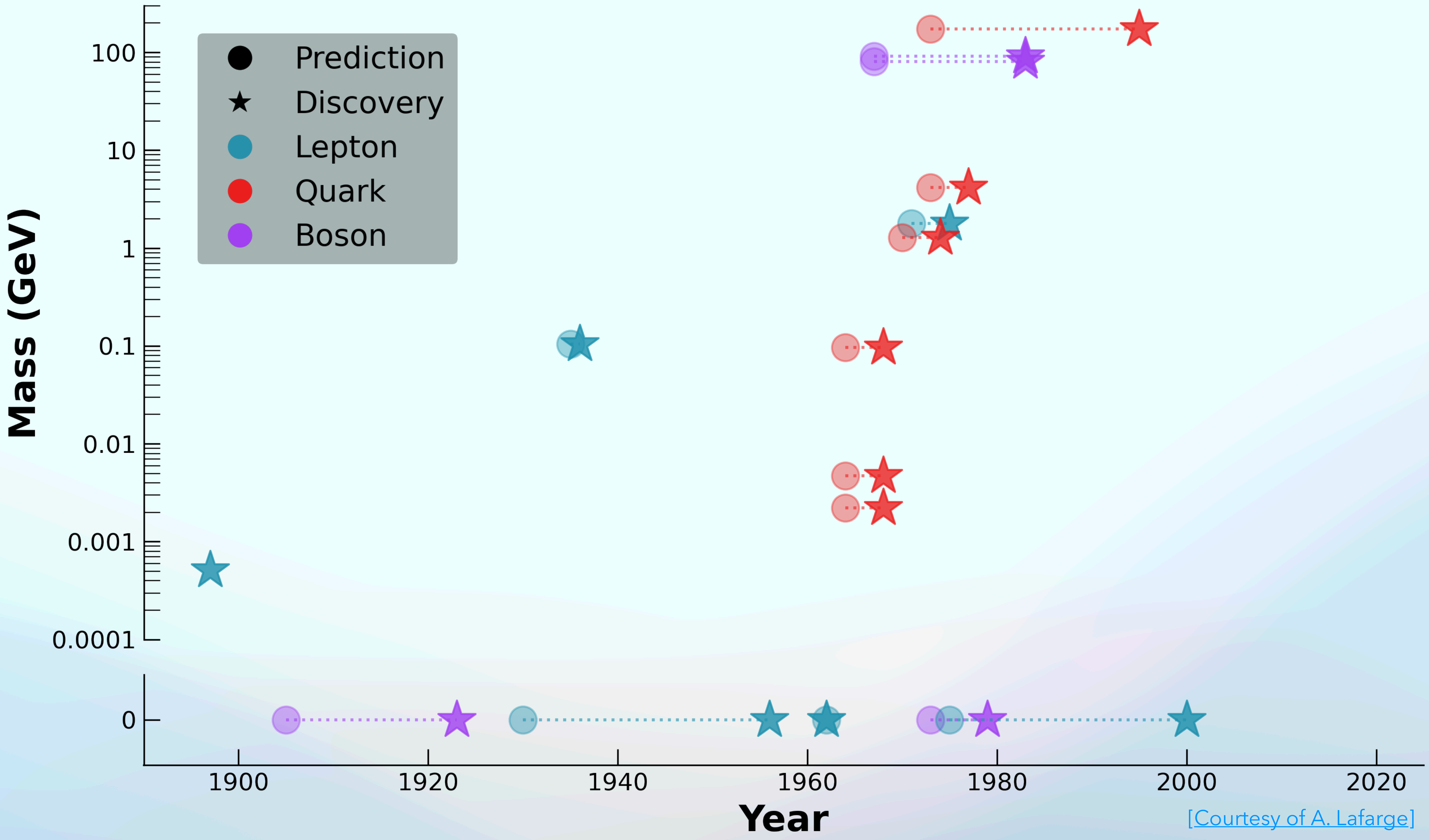

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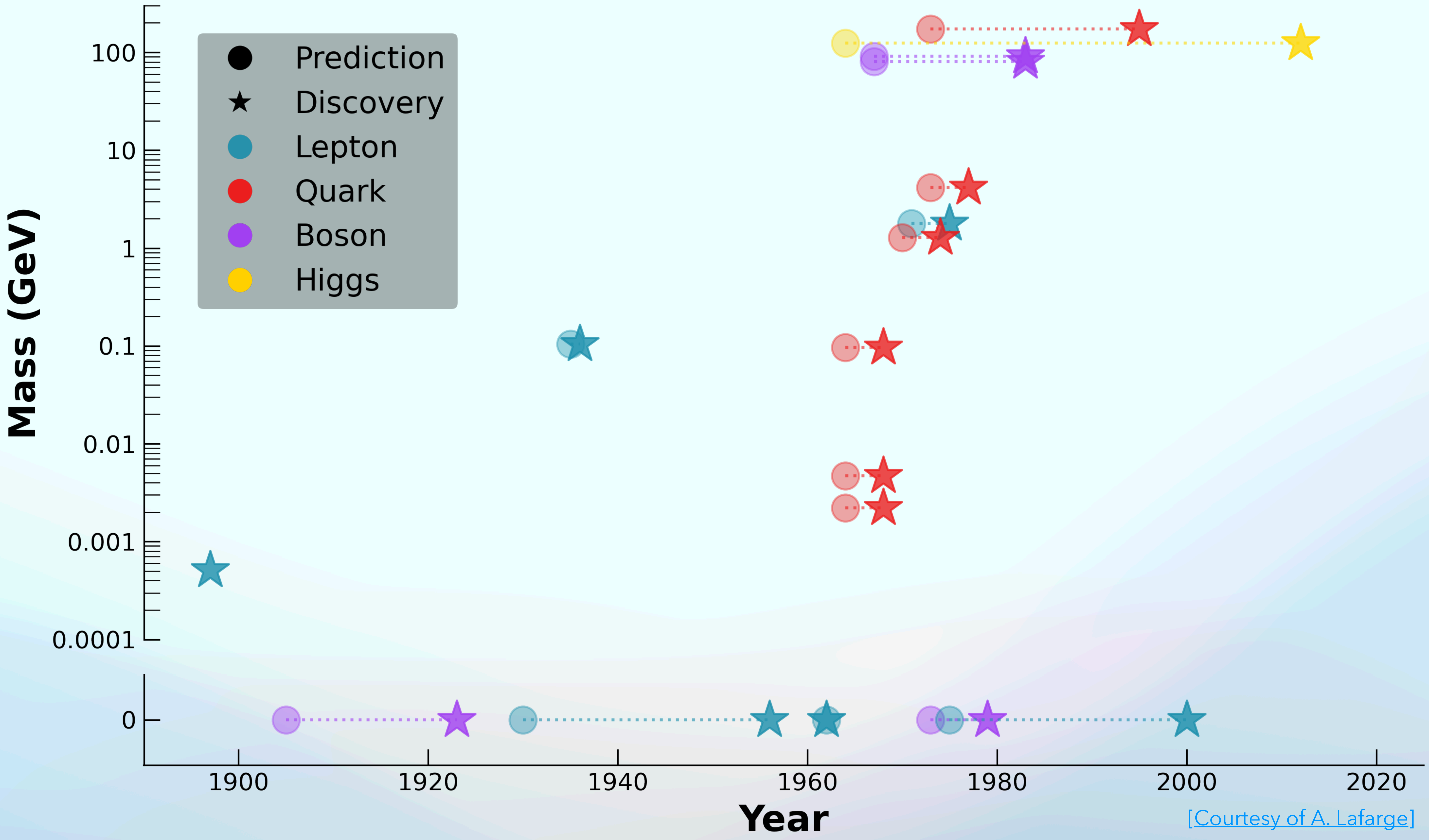

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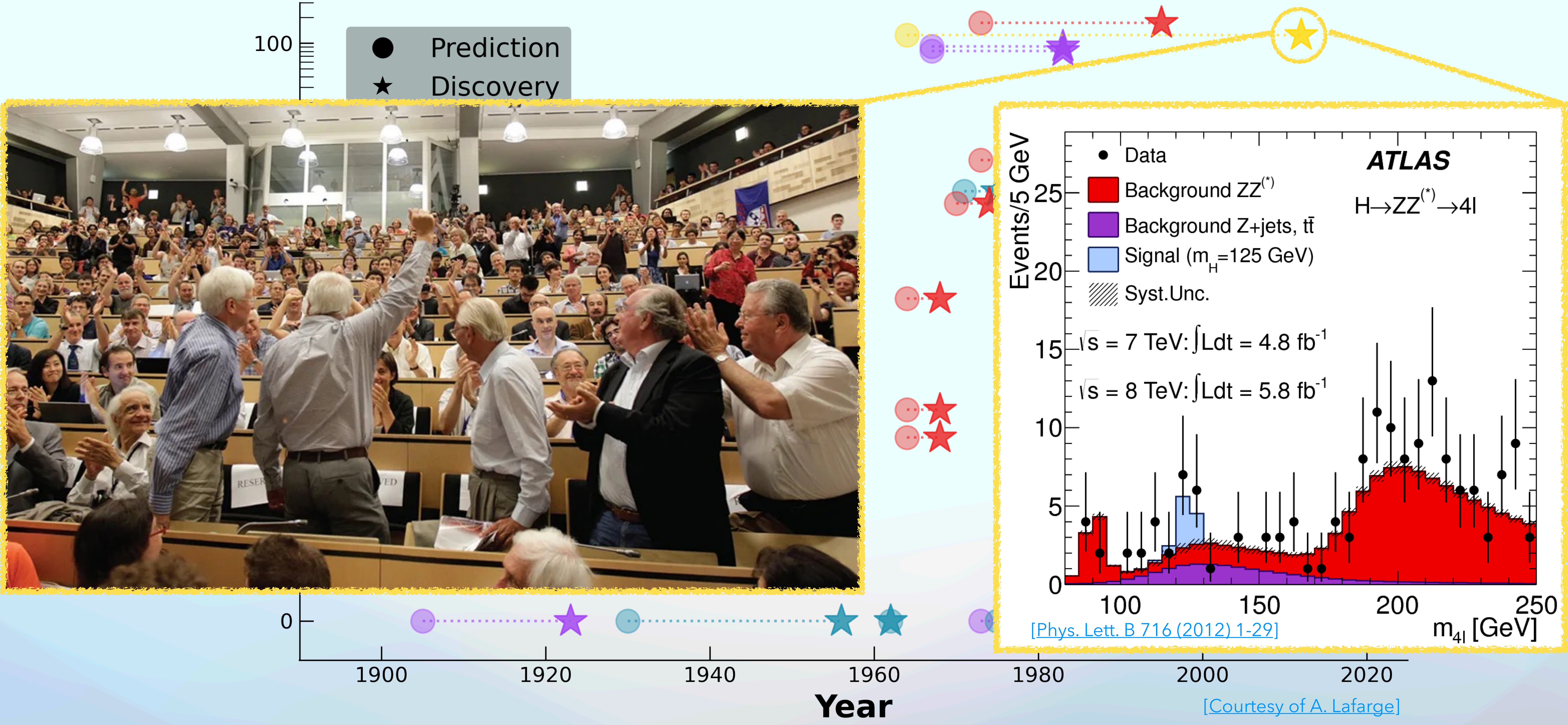
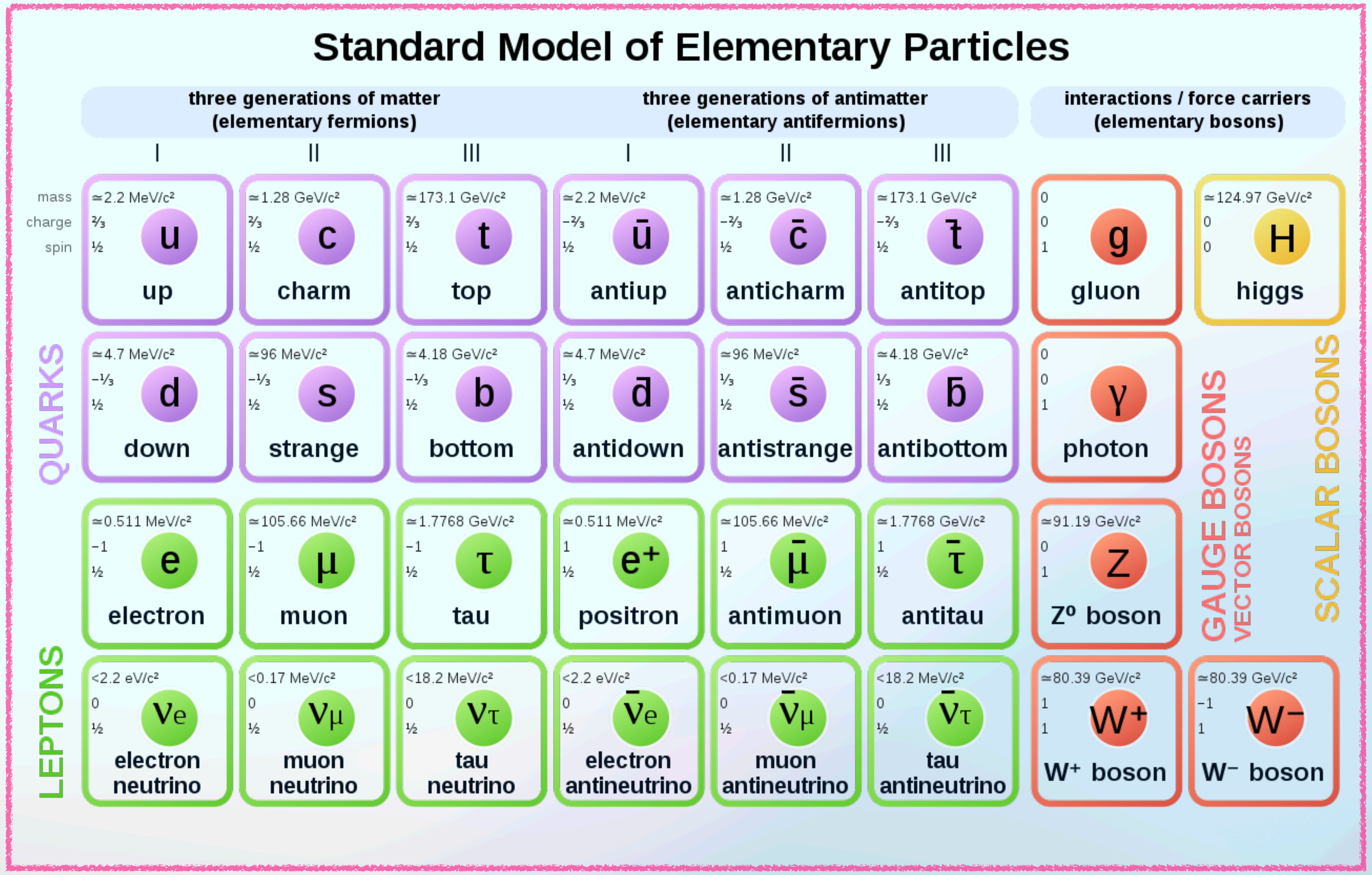


[Courtesy of A. Lafarge]

The Standard Model (SM)

$$
\begin{aligned}
\mathscr{L}_{SM} = &-\frac{1}{4}G^{A}_{\mu\nu}G^{A\mu\nu} - \frac{1}{4}W^{I}_{\mu\nu}W^{I\mu\nu} - \frac{1}{4}B_{\mu\nu}B^{\mu\nu} \\
&+ \sum_{\psi=q_L,\,u_R,\,d_R,\,\ell_L,\,e_R} \bar{\psi}\, i\gamma^{\mu}D_{\mu}\psi + (D_{\mu}H)^{\dagger}(D^{\mu}H) \\
&-\mu^2 H^{\dagger}H - \lambda(H^{\dagger}H)^2 \\
&-\left(\bar{q}_L Y_u \tilde{H}\, u_R + \bar{q}_L Y_d H\, d_R + \bar{\ell}_L Y_e H\, e_R + \text{h.c.}\right).
\end{aligned}
$$

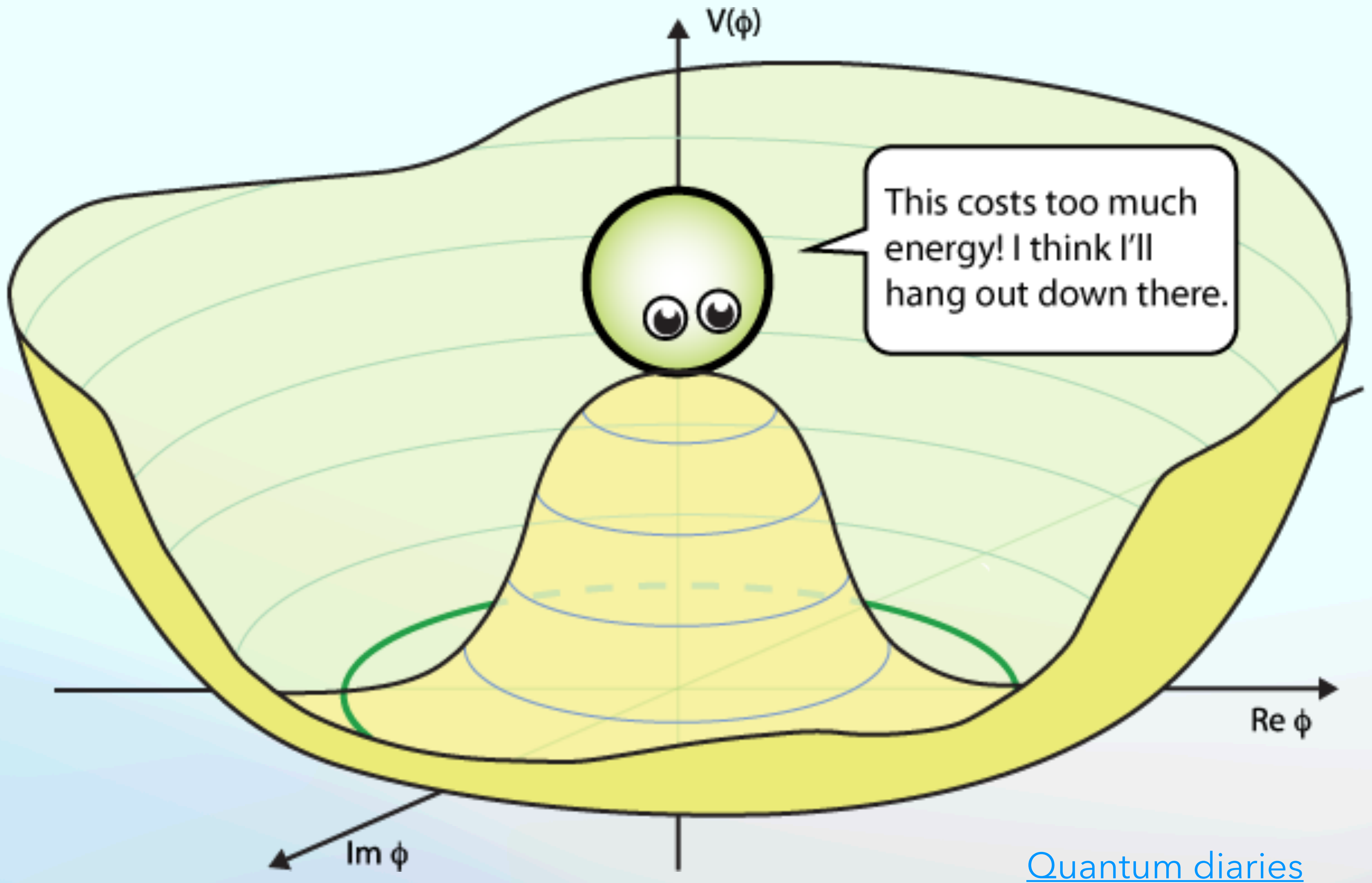


Generalities about the Higgs boson in the SM

SM introduce a spin-0 Higgs field ϕ

- **EWSB** : Explains how W and Z bosons aquire mass
- **Yukawa couplings** : Explains how fermions aquire mass

After EWSB, remaining degree of freedom : **Higgs Boson**



Quantum diaries

$$V(H) = \frac{1}{2}m_H^2 H^2 + \lambda v H^3 + \frac{\lambda}{4}H^4$$

In SM, **Higgs Boson** properties are **tied** to the EWSB mechanism

The Higgs mechanism in the SM

Unbroken phase

$$\phi = \begin{pmatrix} \phi^+ = \phi_1 + i\phi_2 \\ \phi^0 = \phi_3 + i\phi_4 \end{pmatrix}$$

$SU(2)_L$ doublet

→ **4** *real* d.o.f. from Higgs doublet
→ **4x2** *real* d.o.f. from Gauge bosons

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SSB

Vacuum picks a direction

Broken phase

1 Higgs scalar h

3 Goldstone bosons

$$< \phi > = \frac{1}{\sqrt{2}} \begin{pmatrix} 0 \\ v + h \end{pmatrix}$$

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Gauge Interaction

Goldstone are eaten

Become longitudinal polarization of $W^{\pm}, Z^0$

1 physical Higgs boson

+

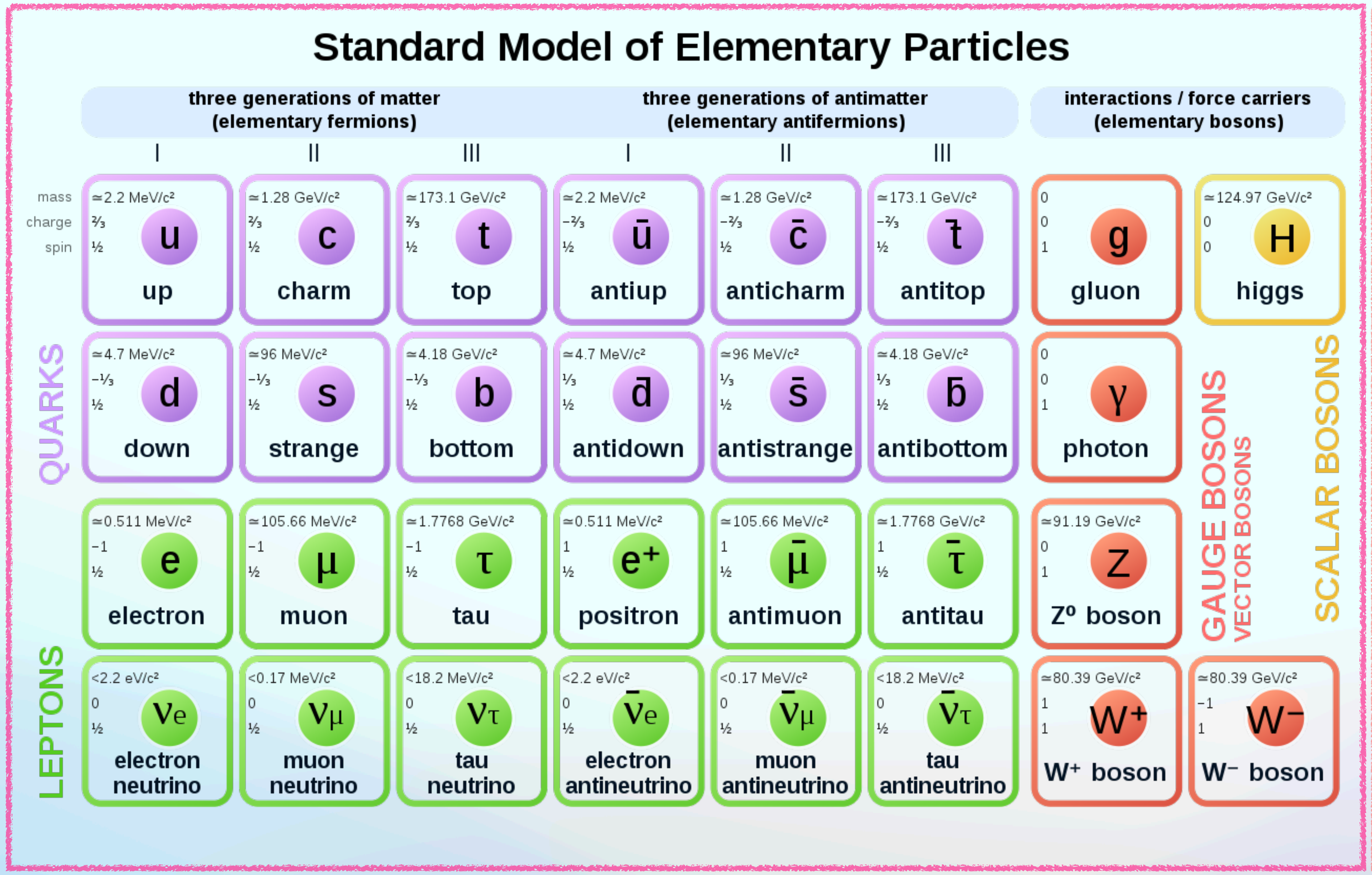
Massive gauge bosons with 3 polarizations

→ **1** d.o.f. from Higgs scalar

→ **3x3** d.o.f. from Vector Bosons

→ **2** d.o.f. from Photon

Beyond the Standard Model (BSM) ?

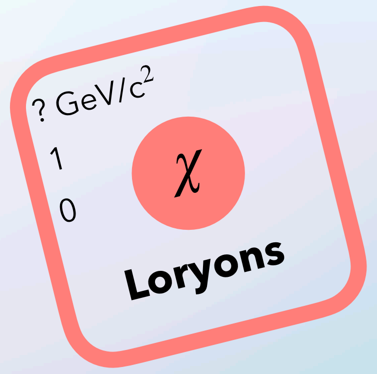


Beyond the SM

Matter-antimatter asymmetry ?

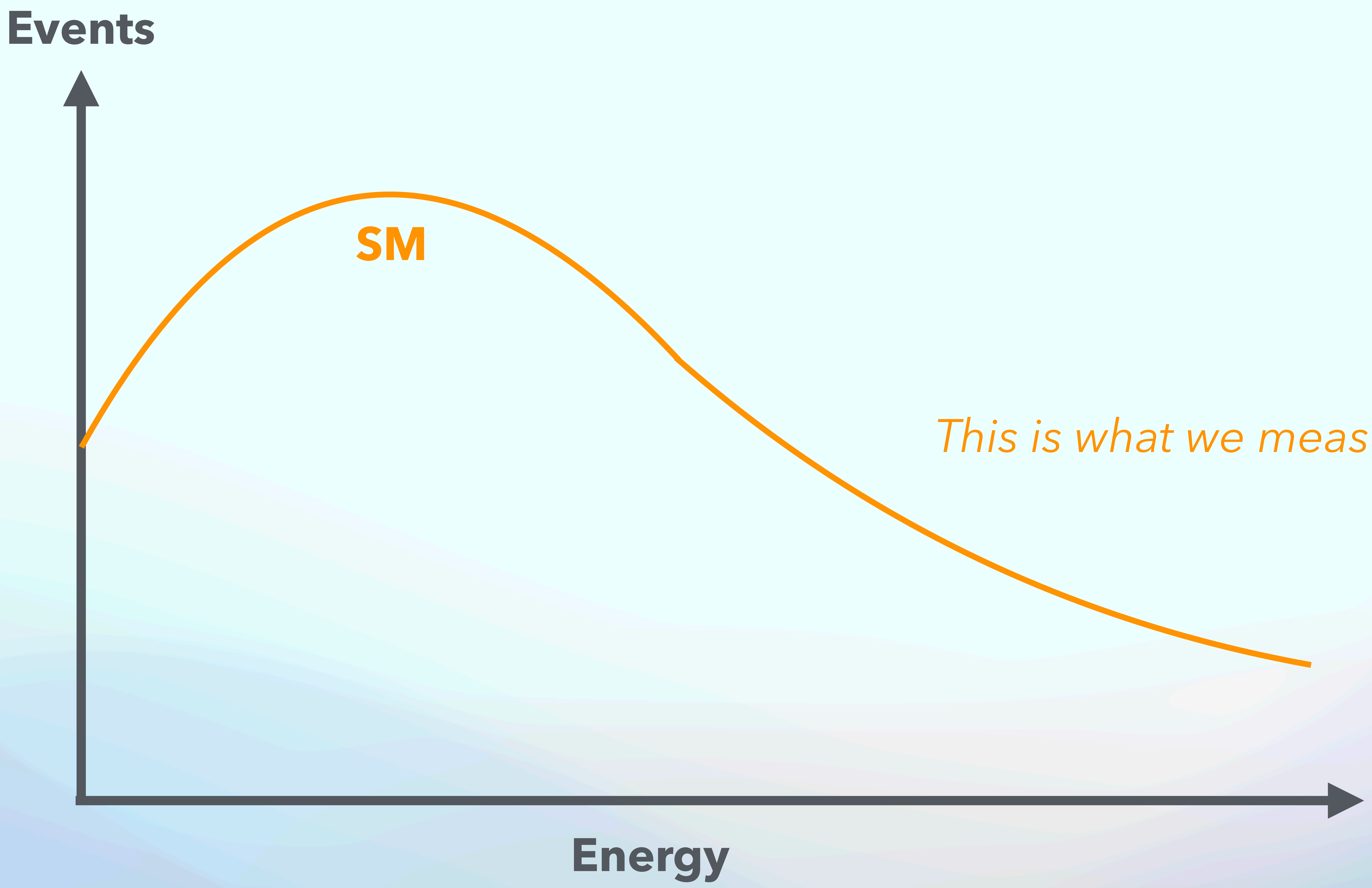
Gravity ?

Shape of Higgs potential ?



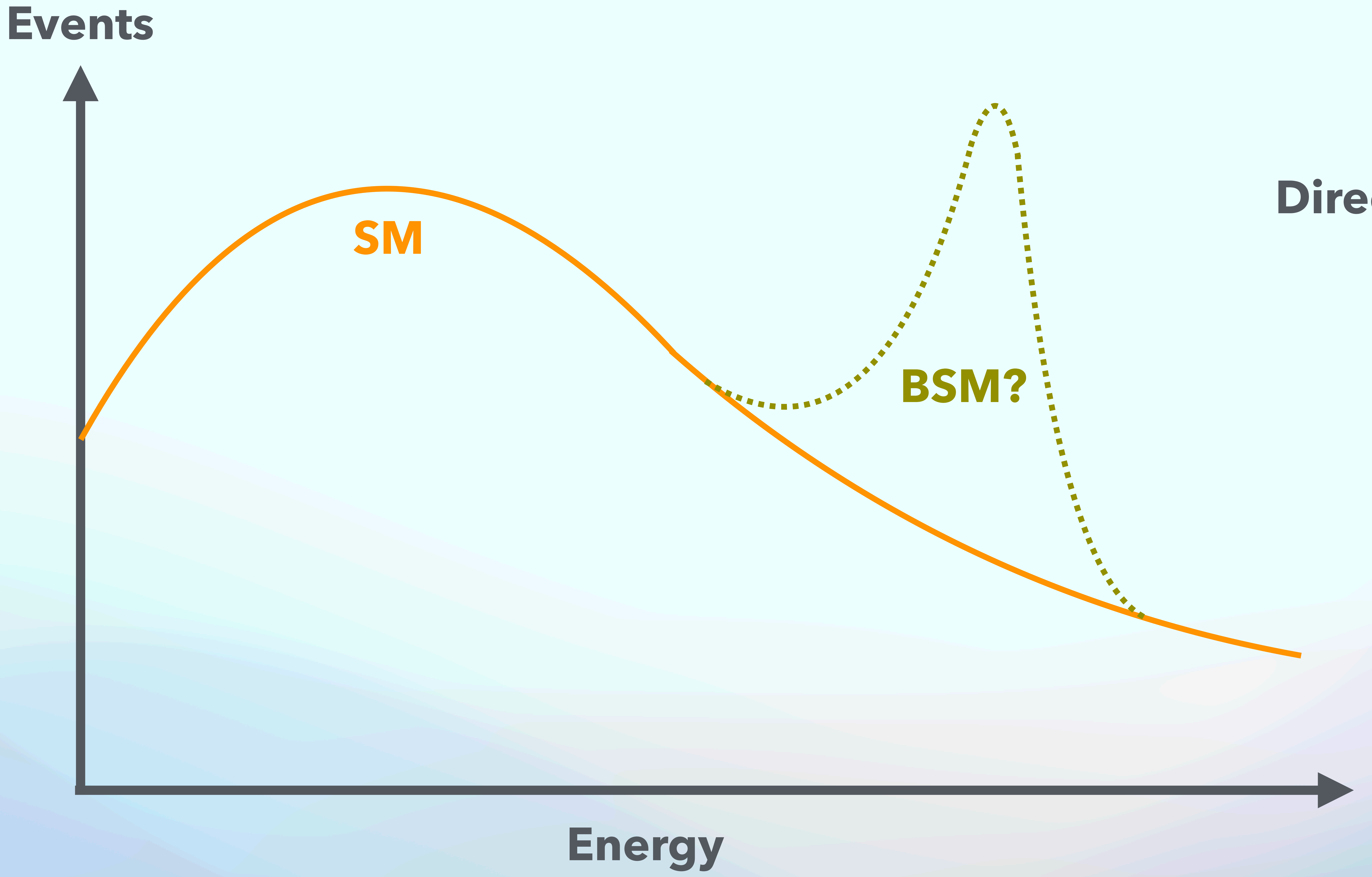
Vacuum stability ?

Going beyond the SM - direct or effective ?



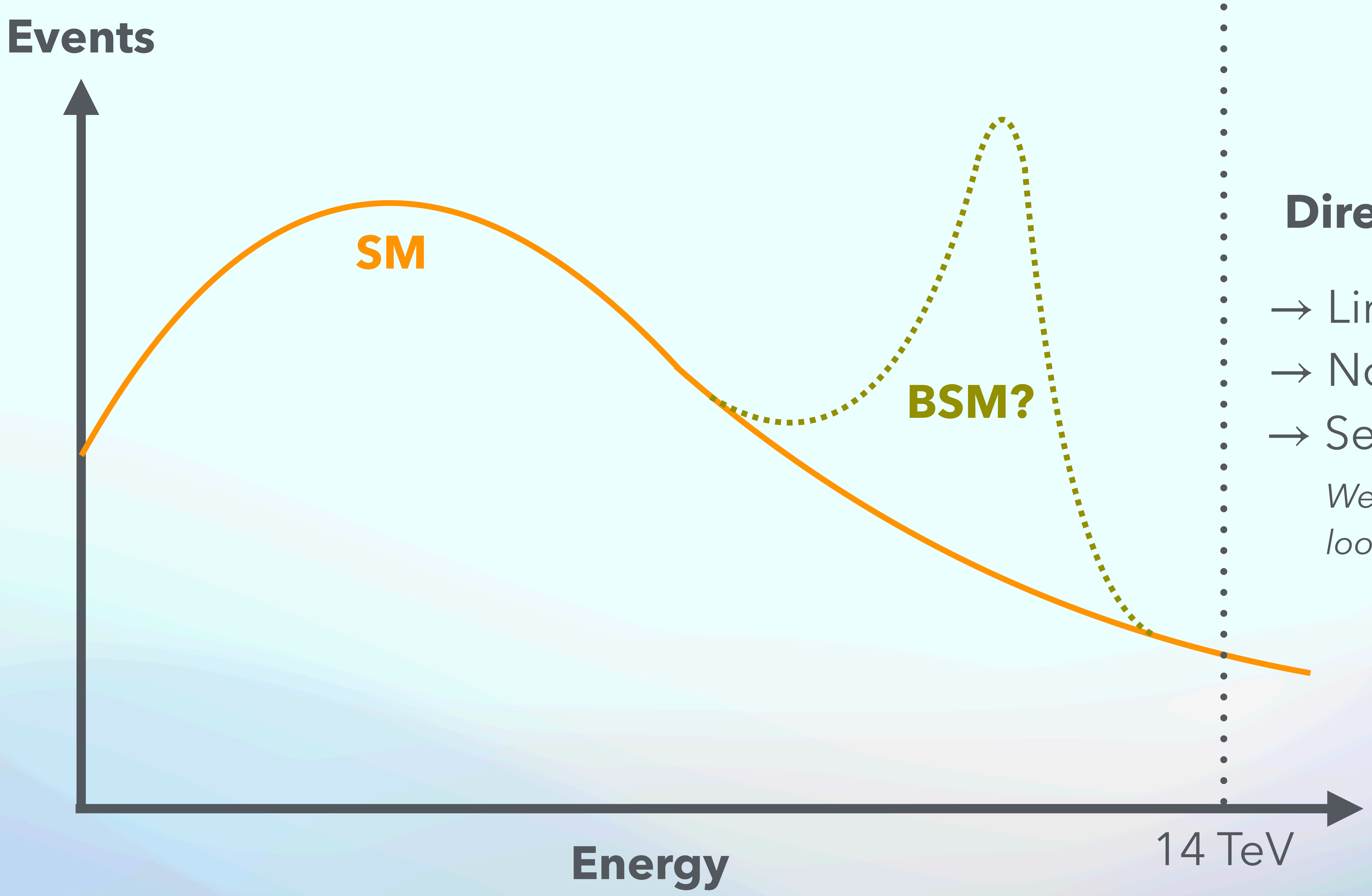
This is what we measure if SM is realized in nature

Going beyond the SM - direct or effective ?



Direct searches, e.g. "bump hunt"

Going beyond the SM - direct or effective ?

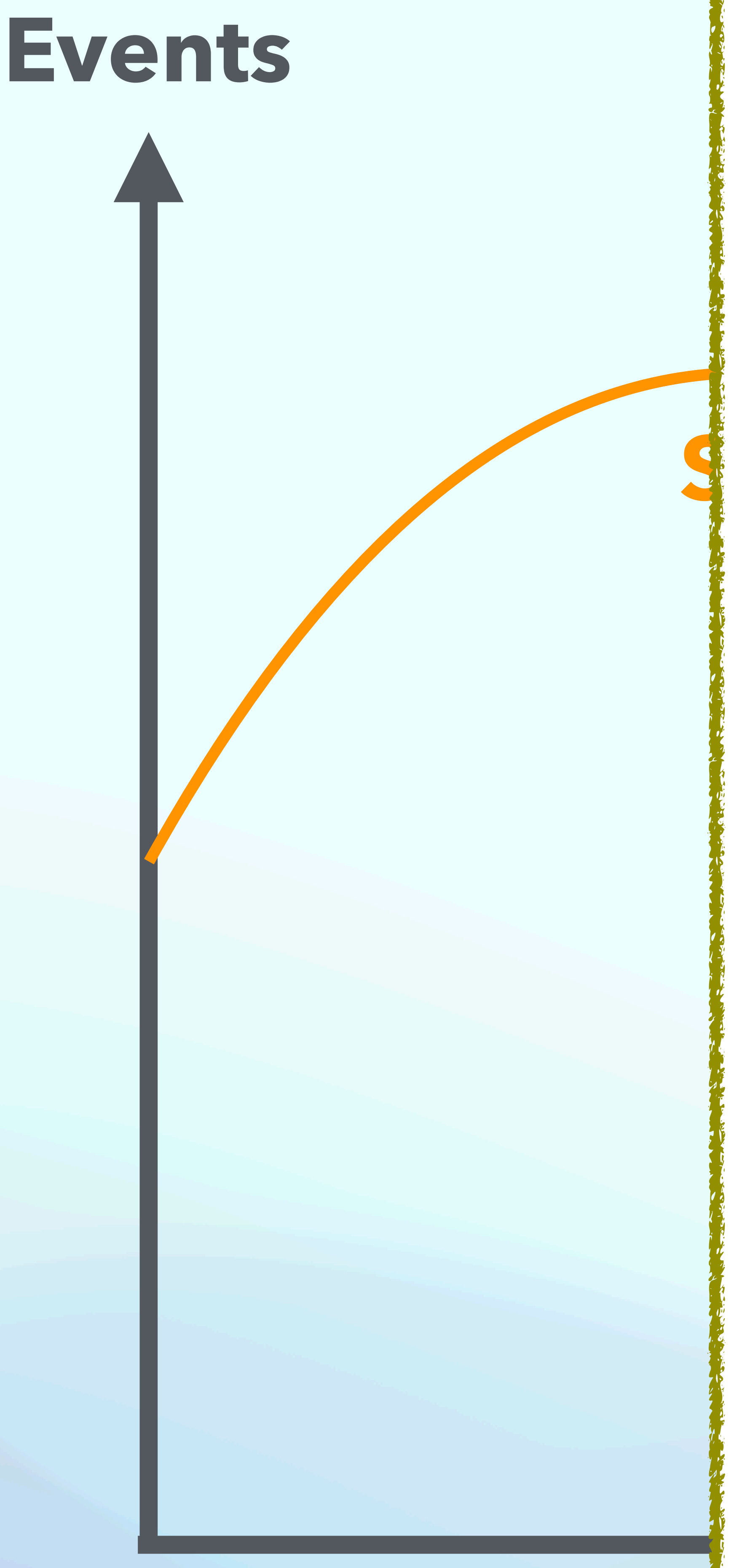


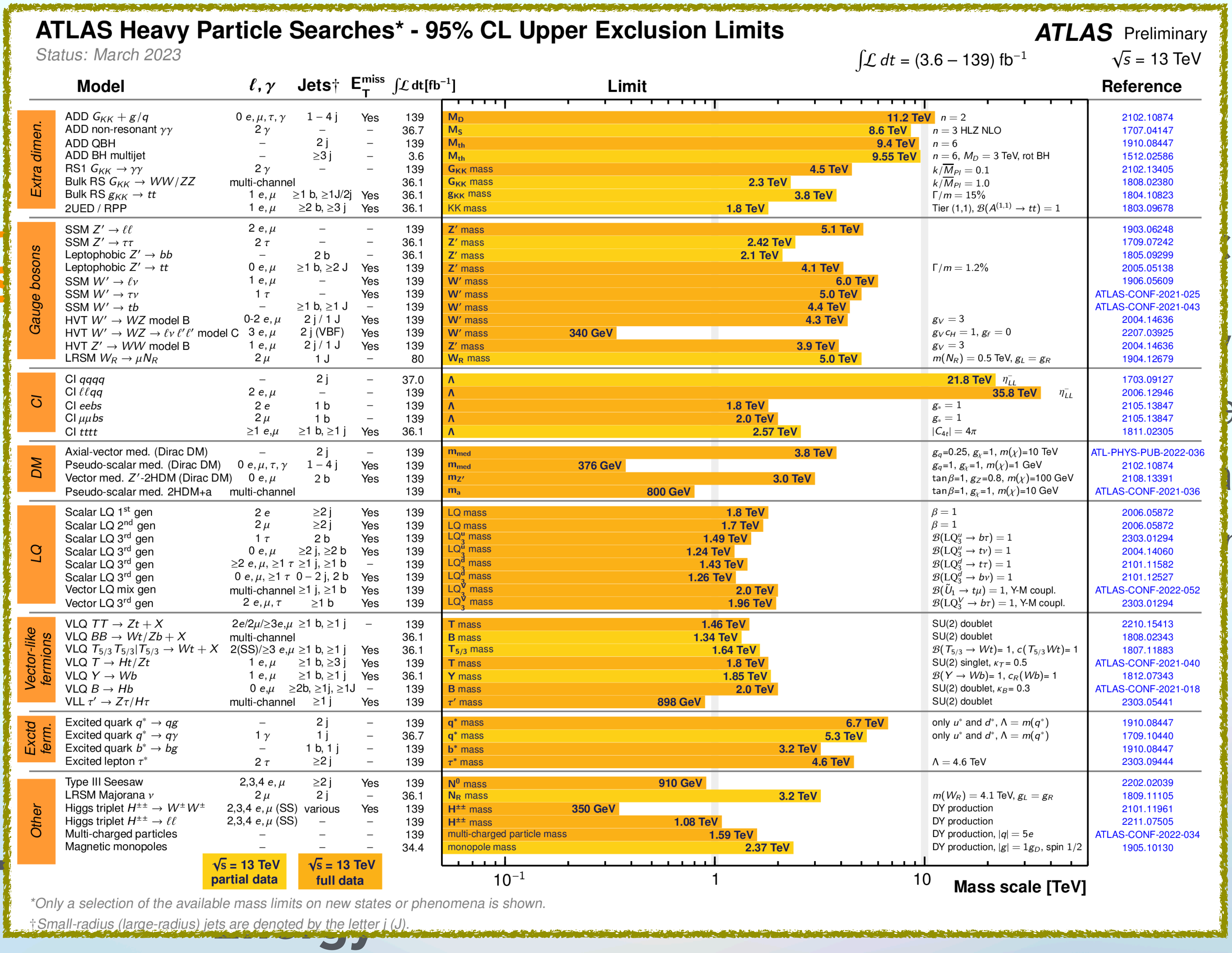
Direct searches, e.g. "bump hunt"

→ Limited by collider energy reach
→ No new particle discovered (yet?)
→ Searches are very model dependent

We somehow need to roughly know what we are looking for…

Going beyond the SM - direct or effective ?





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Nothing so far!

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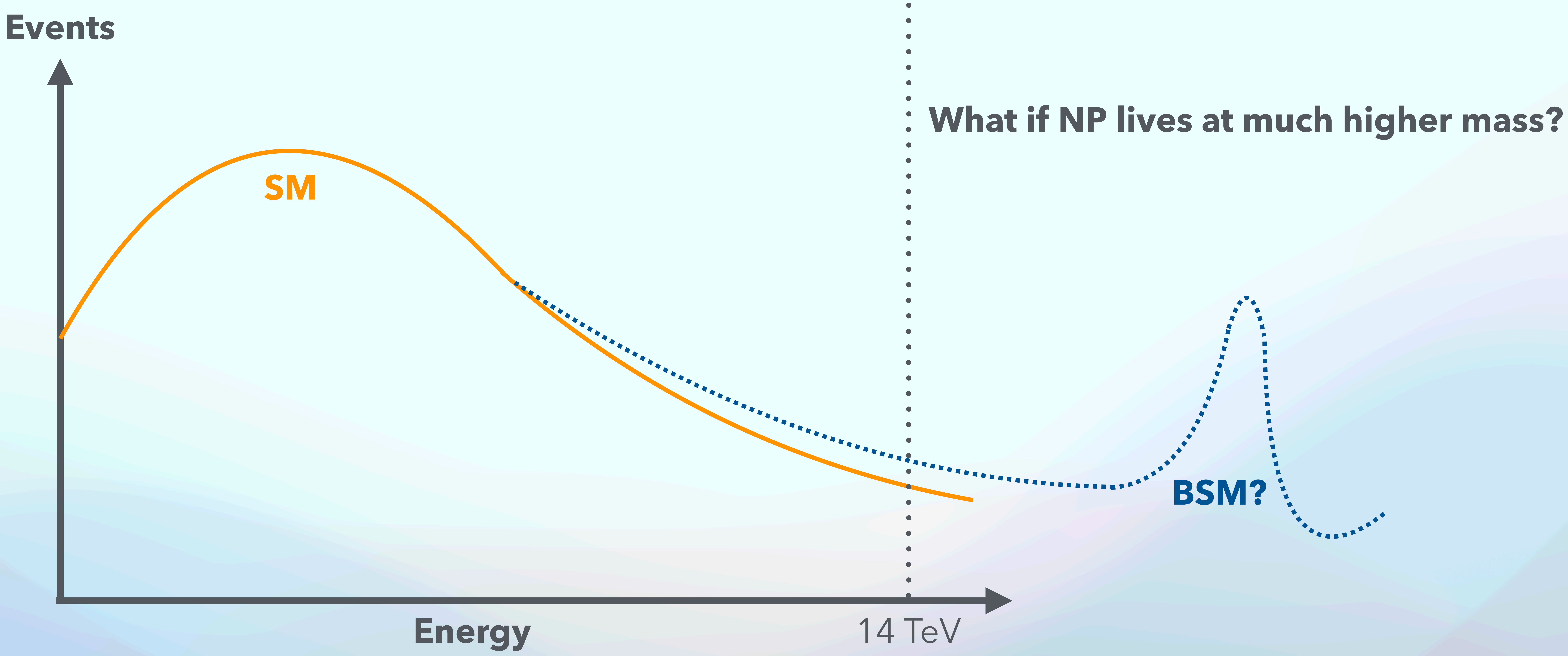
Going beyond the SM - direct or effective ?



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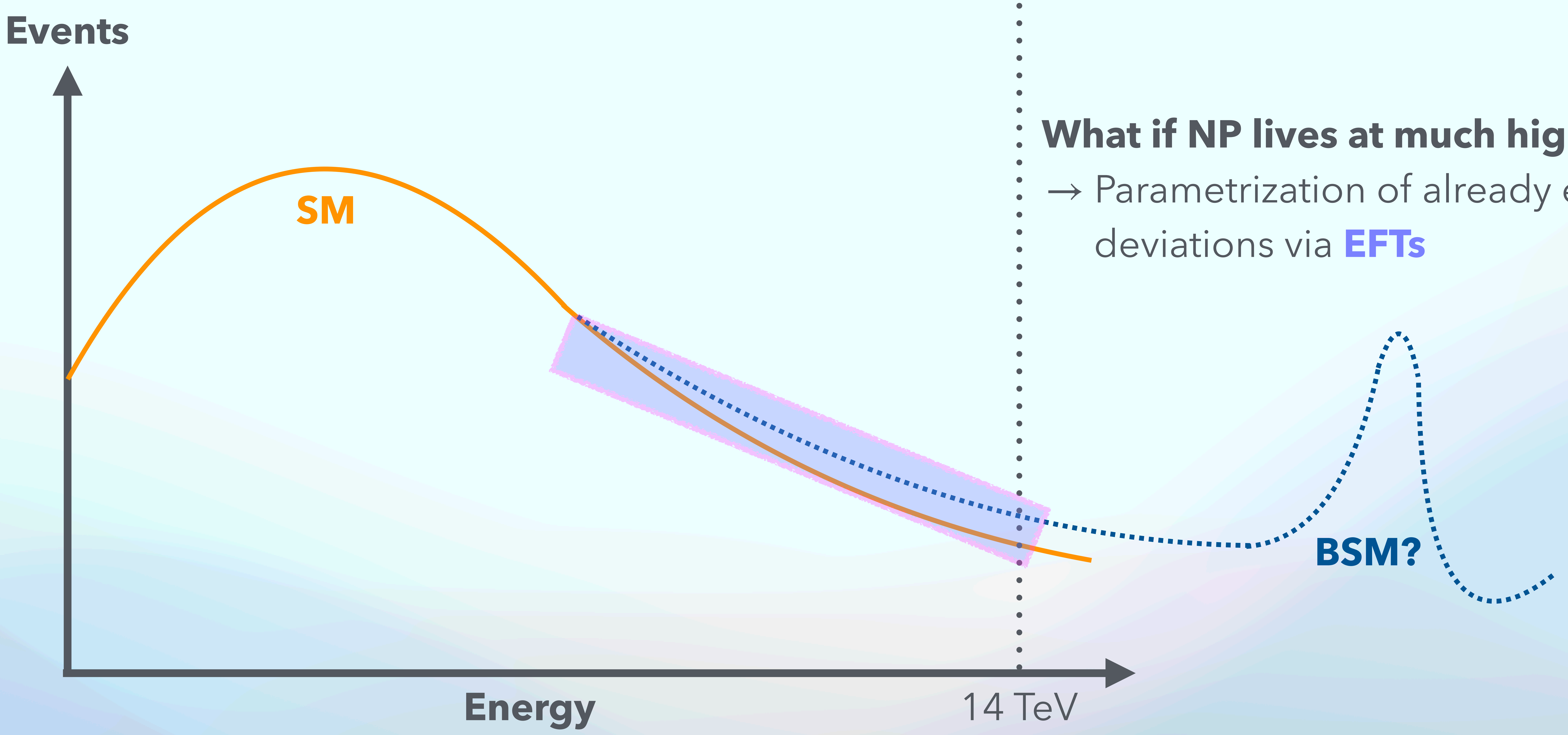
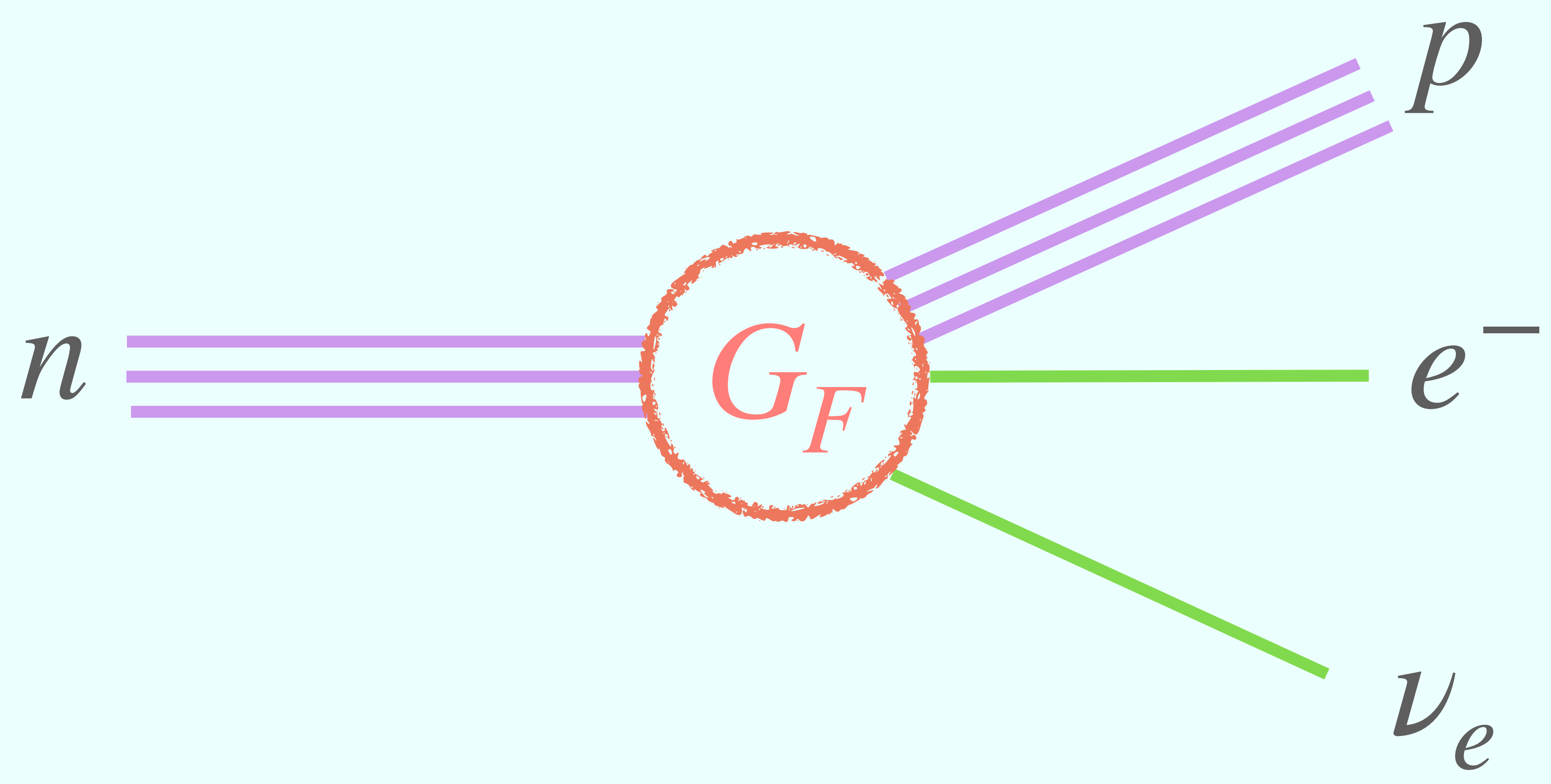


What if NP lives at much higher mass?

→ Parametrization of already existing deviations via **EFTs**

Before SM was even Standard...



Proposal by E. Fermi to explain β decay during early stage of weak interaction theory development

→ Point-like interaction
→ Describes well the weak interaction **but**

$$\sigma = \frac{G_F^2}{\pi} s$$

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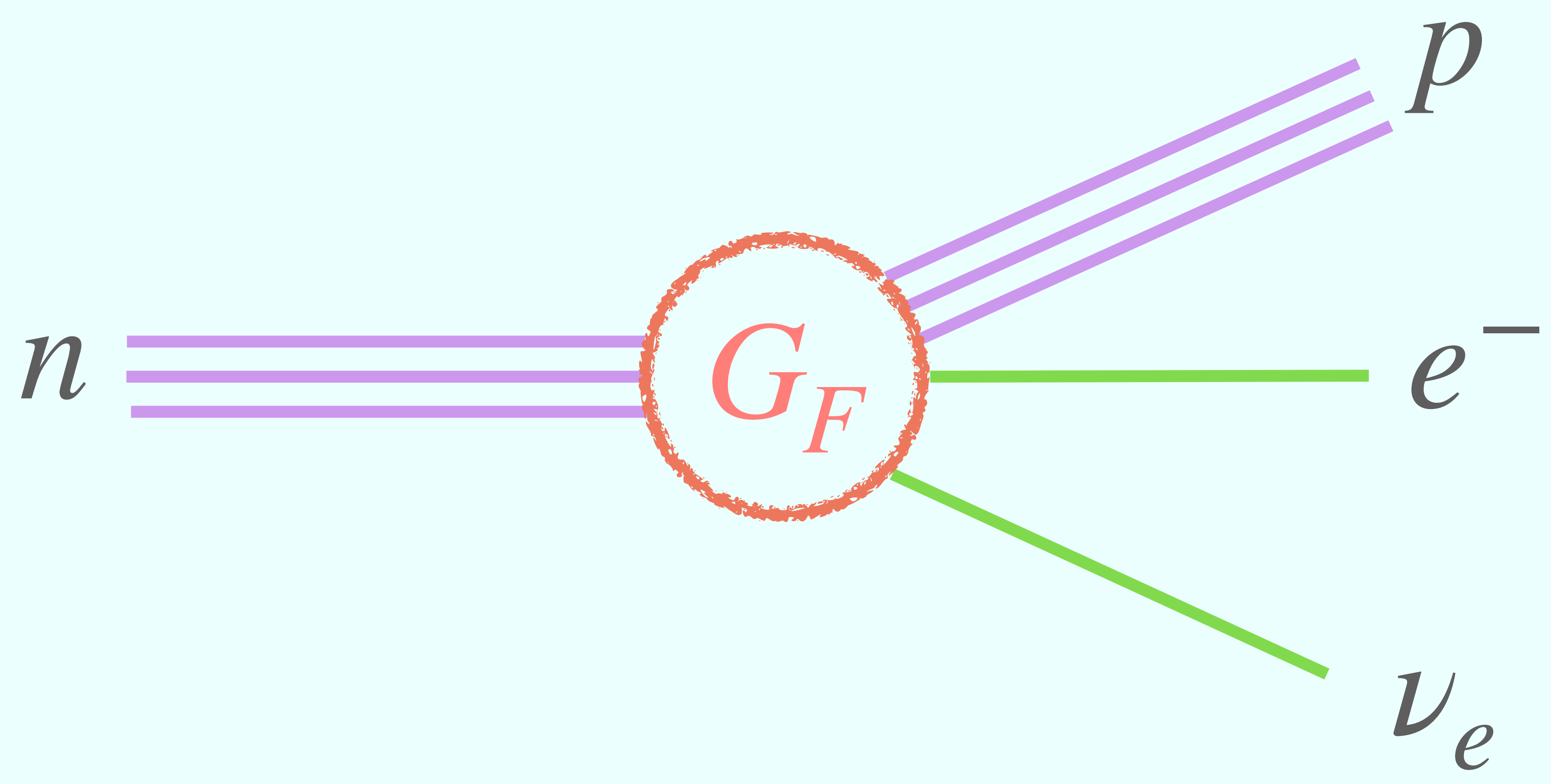

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Cross-section grows with s → **Violation of unitarity**

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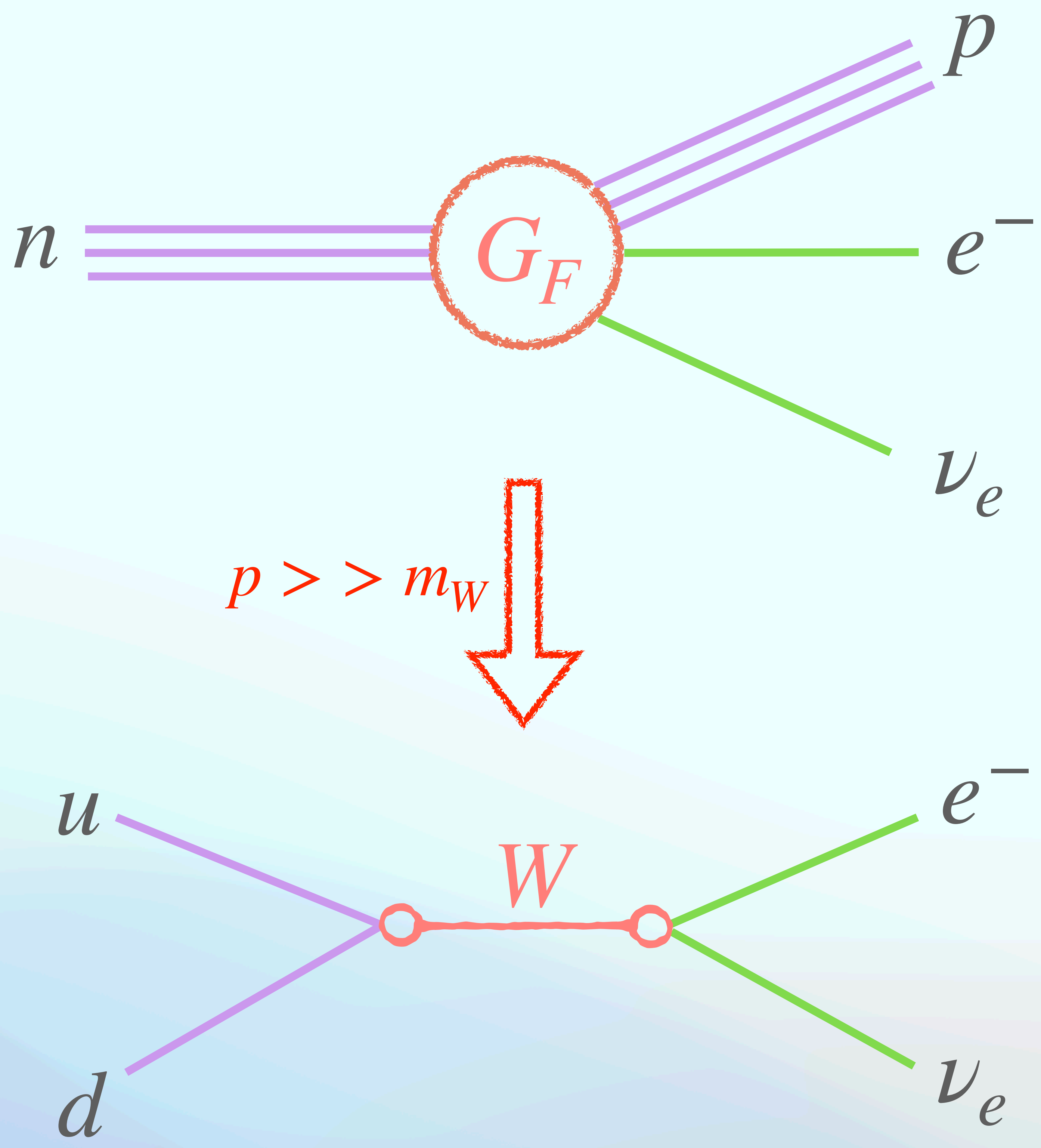

Proposal by E. Fermi to explain β decay during early stage of weak interaction theory development

→ Point-like interaction

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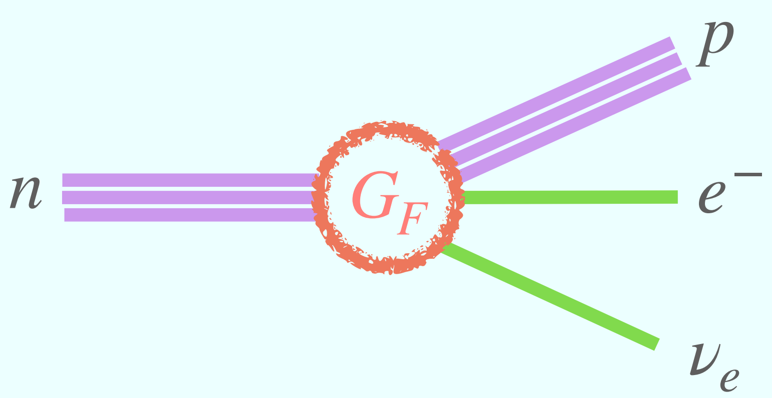
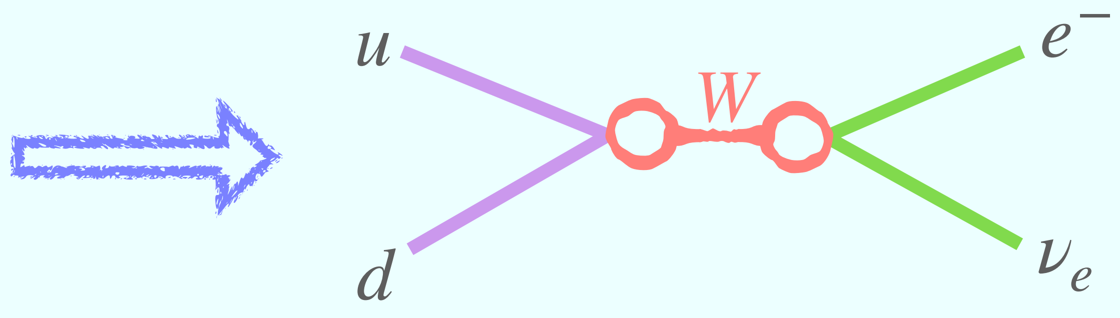
$$\sigma = \frac{G_F{}^2}{\pi} s$$

Cross-section grows with s → **Violation of unitarity**

→ Valid for energies << 100 GeV

→ Later developments determined the correct tensor structure + two massive bosons

How to build an Effective theory?

With Fermi theory we went from  

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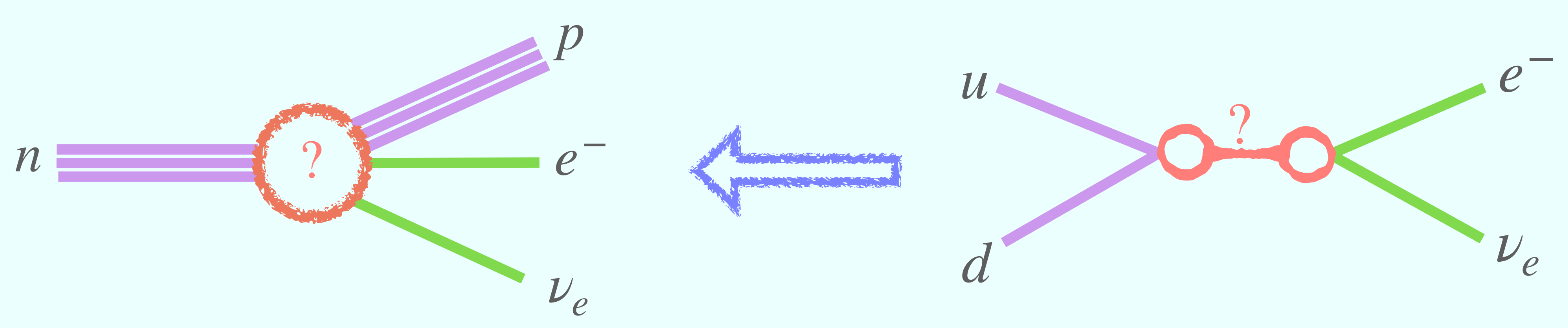
With Fermi theory we went from 

But can we go the other way?

i.e. infer New Physics by parametrizing "low" energy

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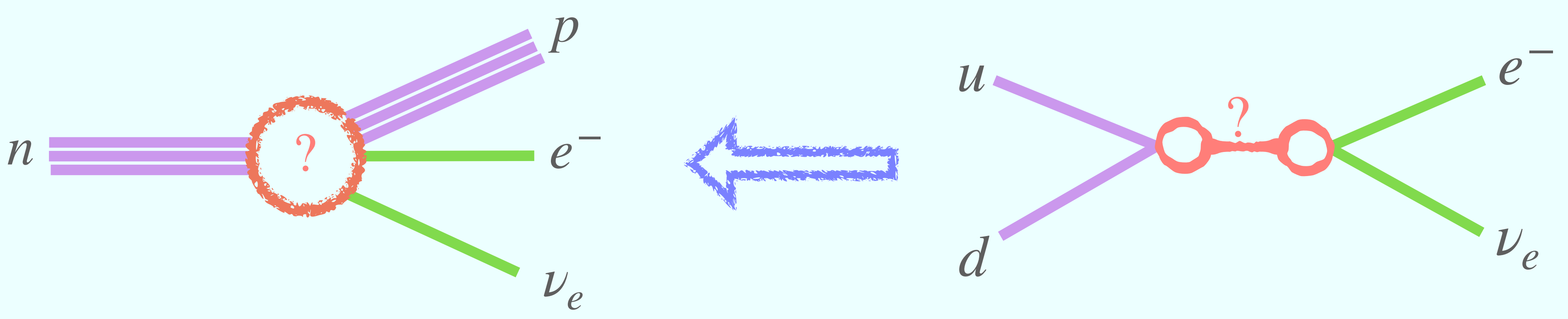
With Fermi theory we went from 

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EFT recipe

Step 1 : We fix the field content

Step 2 : We fix the symmetries

Step 3 : We write an <u>exhaustive list</u> of allowed interactions at a fixed order

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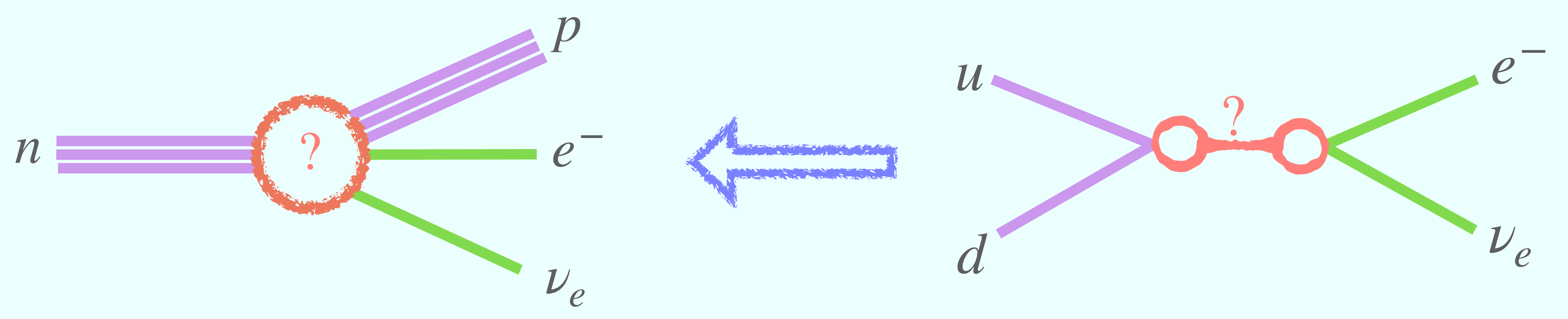
With Fermi theory we went from 

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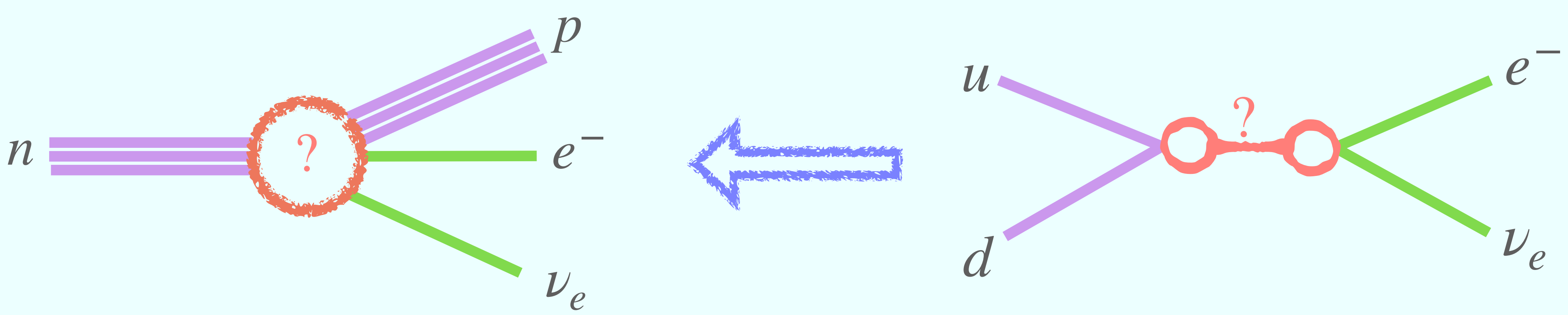
With Fermi theory we went from 

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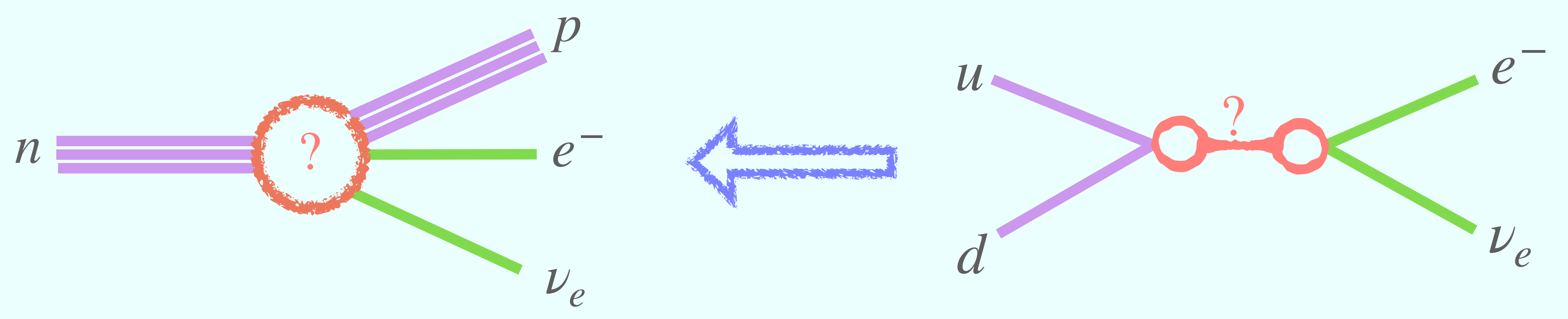
With Fermi theory we went from 

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Step 3 : We write an exhaustive list of allowed interactions at a fixed order

$$\rightarrow \mathscr{L}_{\text{SMEFT}} = \mathscr{L}_{\text{SM}} + \sum_{d=5}^{\infty} \sum_{i} \frac{c_{i,d}}{\Lambda^{d-4}} \mathcal{O}_i^{(d)}$$

Effective field theory approach

Current data tends to incate that NP lives at (very) **high energy scale**

New heavy particles beyond the reach of LHC could distord "low" energy physics

EFTs provide :

→ Fairly model-agnostic approach

→ Way to integrate out heavy degrees of freedom

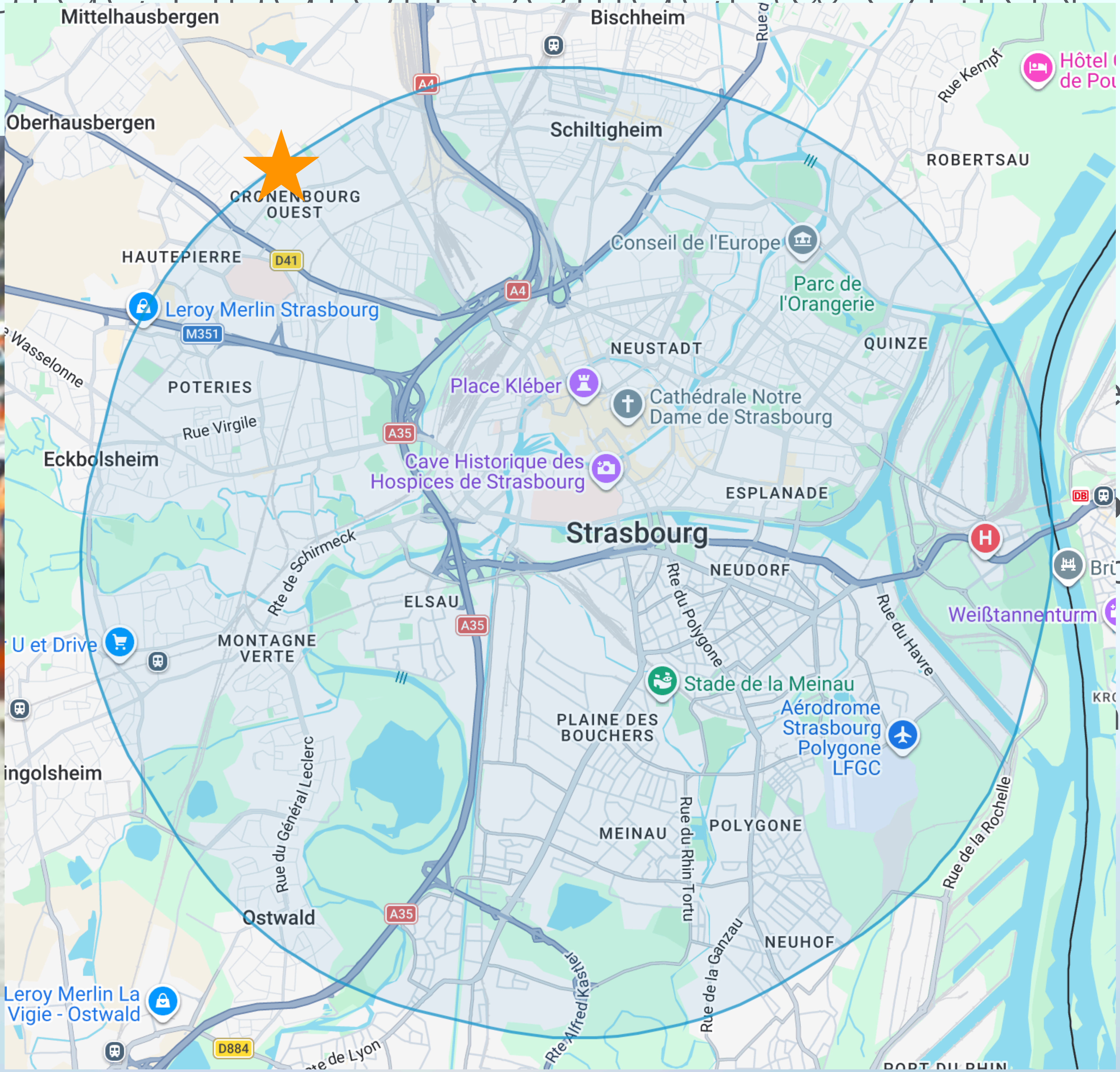
→ Only considers SM content (exhaustive list of fields)

→ Treats all SM sectors equivalently

Our toolbox : Large Hadron Collider @ CERN

- **27 km** circumference accelerator
- Accelerates **protons** and heavy-ions to nearly speed of light
- **Four collisions points**, each with a detector designed for specific purpose

Our toolbox : Large Hadron Collider @ CERN



…erence accelerator

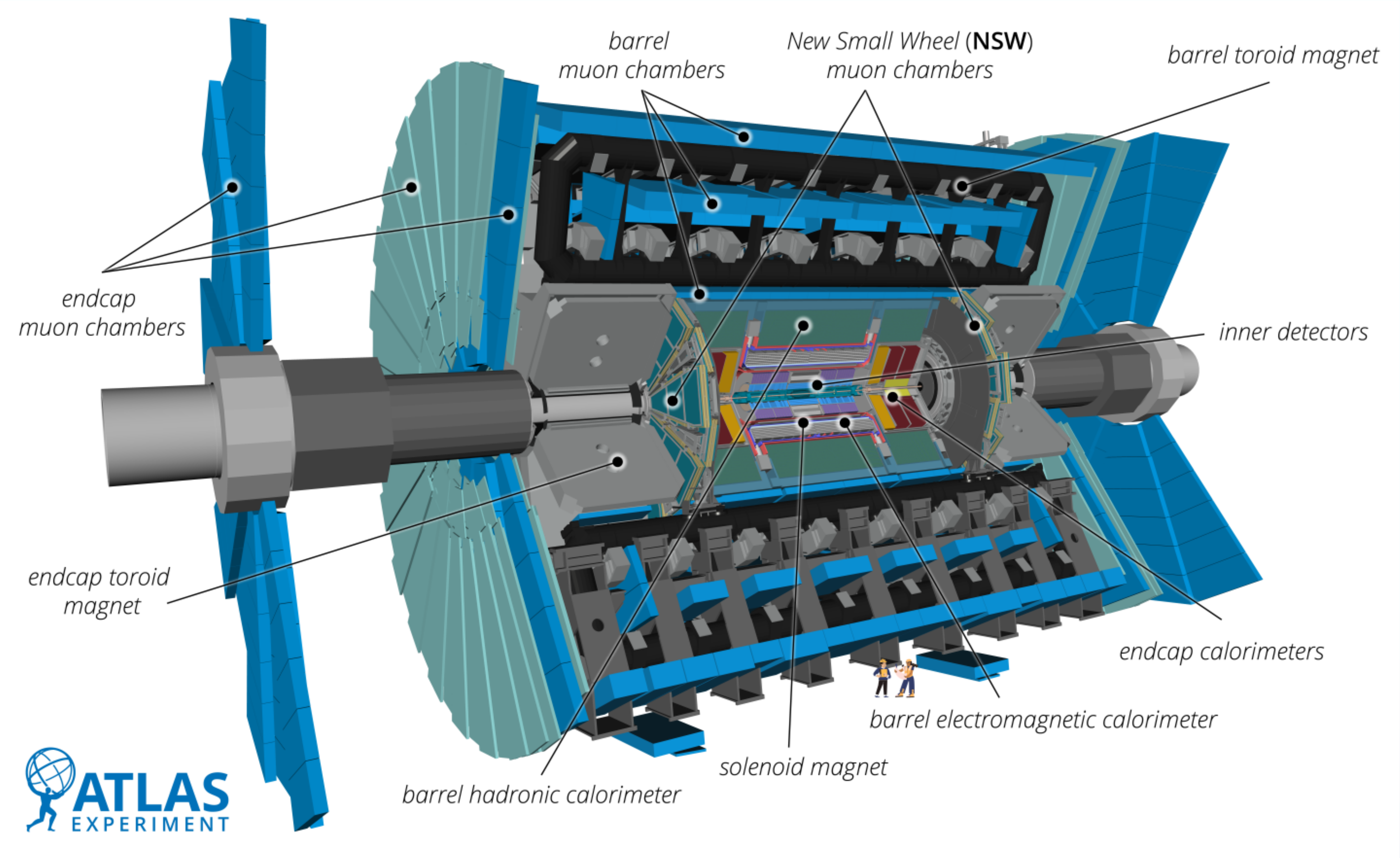
…tons and heavy-

…peed of light

…points, each with a

…ed for specific

General purpose detectors : ATLAS & CMS

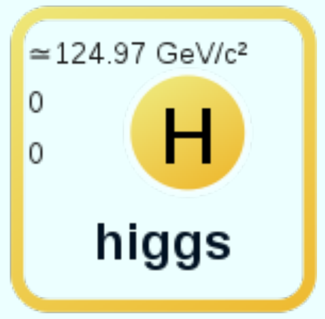


(biased) e.g. ATLAS here, but same main principle for CMS

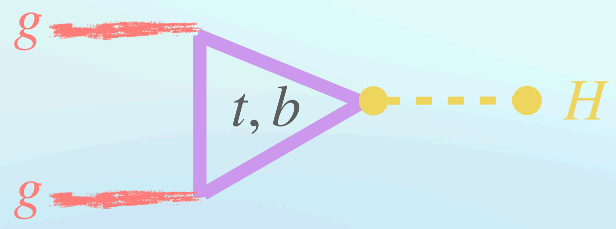
- "**Onion layers**" detector structure
- Various **subsystems** used in combination :
  - Trigger
  - Tracking
  - Calorimetry
  - Particle Identification

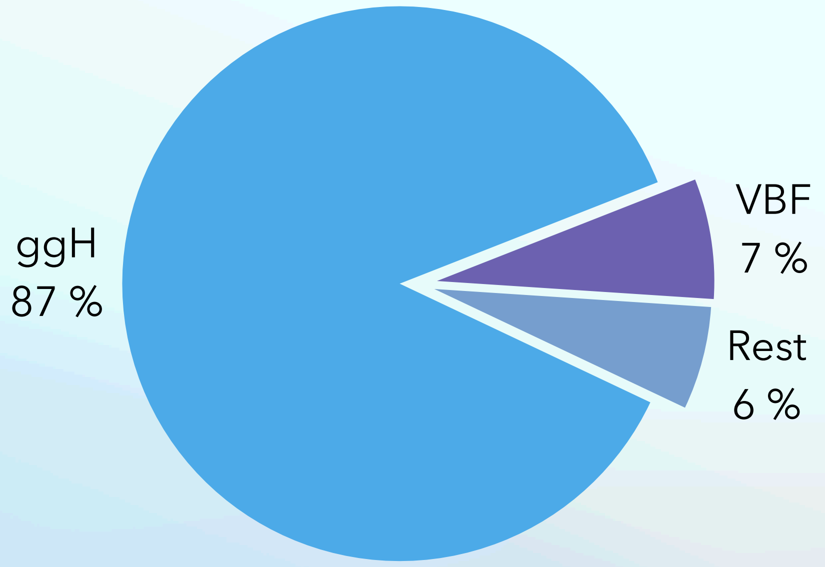
1st protagonist

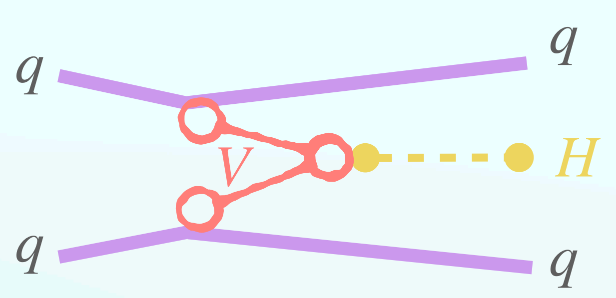
Higgs @ proton collider : prod. and decay



Production mode	Cross-section (pb)
ggH	48.31
VBF	3.771
WH	1.359
ZH	0.877
ttH	0.503
bbH	0.482
tH	0.092

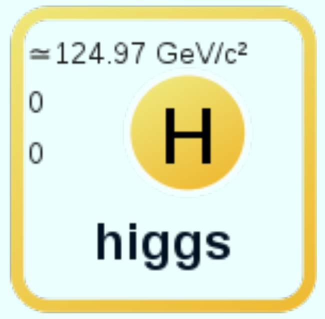






For SM Higgs @ 13 TeV…

Higgs @ proton collider : prod. and decay



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ggH	48.31
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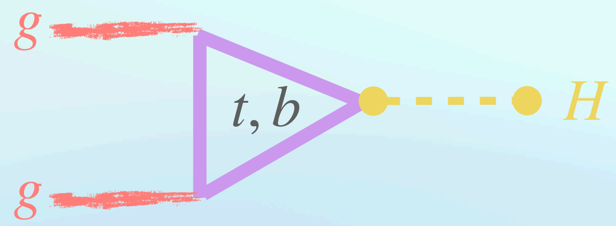
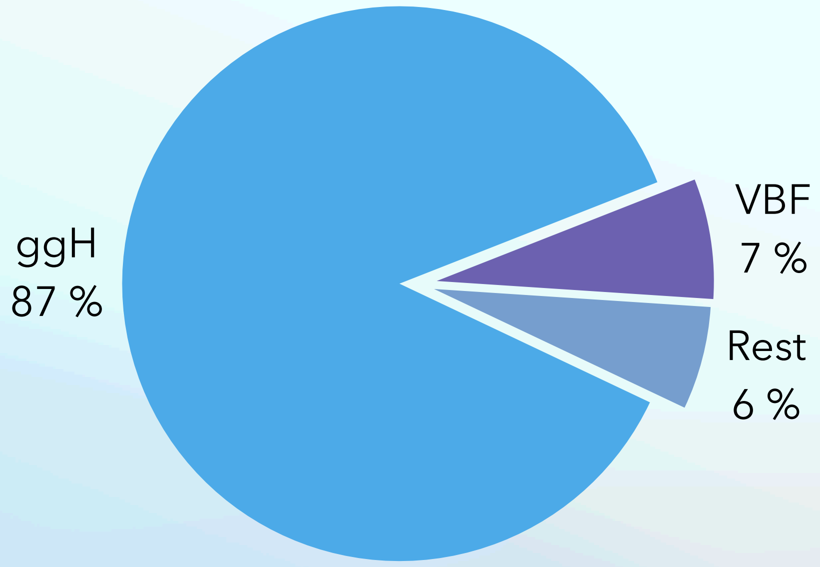
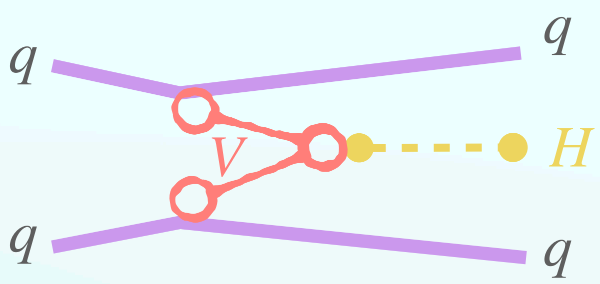
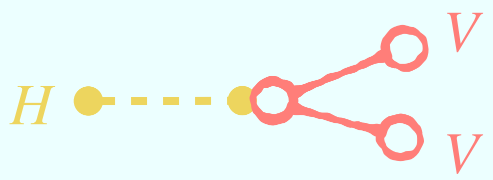
tH	0.092

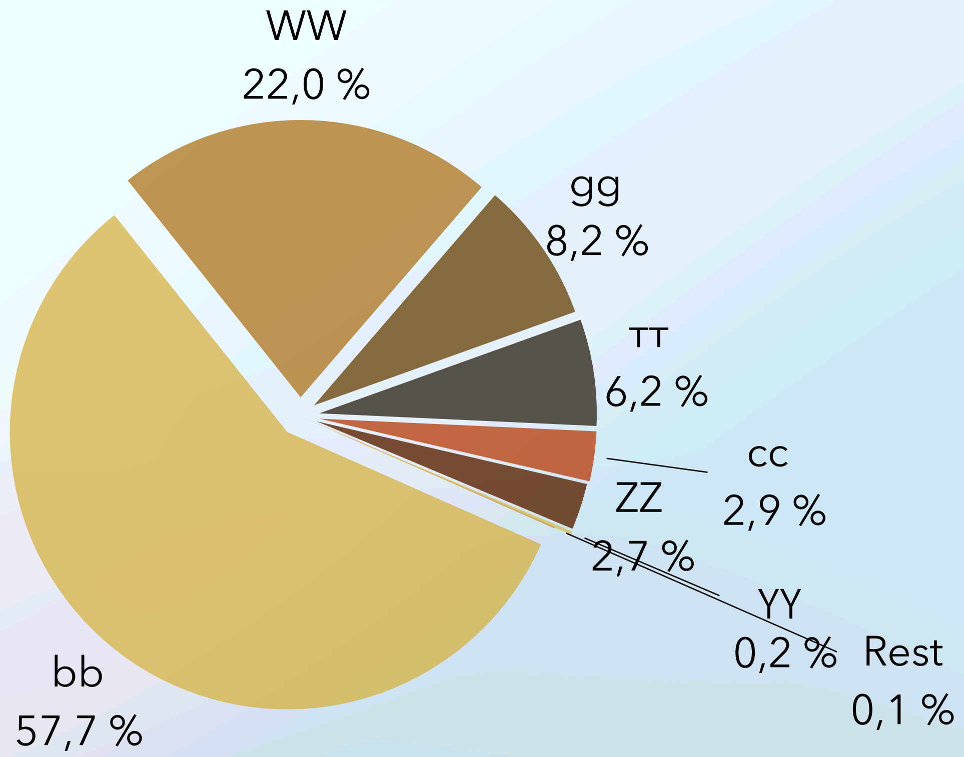
Decay Channel	Branching ratio
bb	57.63
WW	22
gg	8.15
$\tau\tau$	6.21
cc	2.86
ZZ	2.71
$\gamma\gamma$	0.227

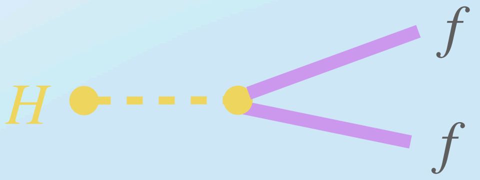


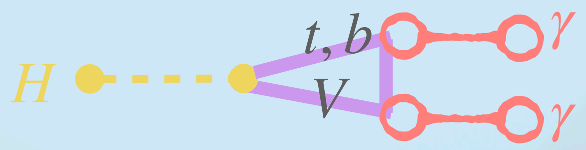








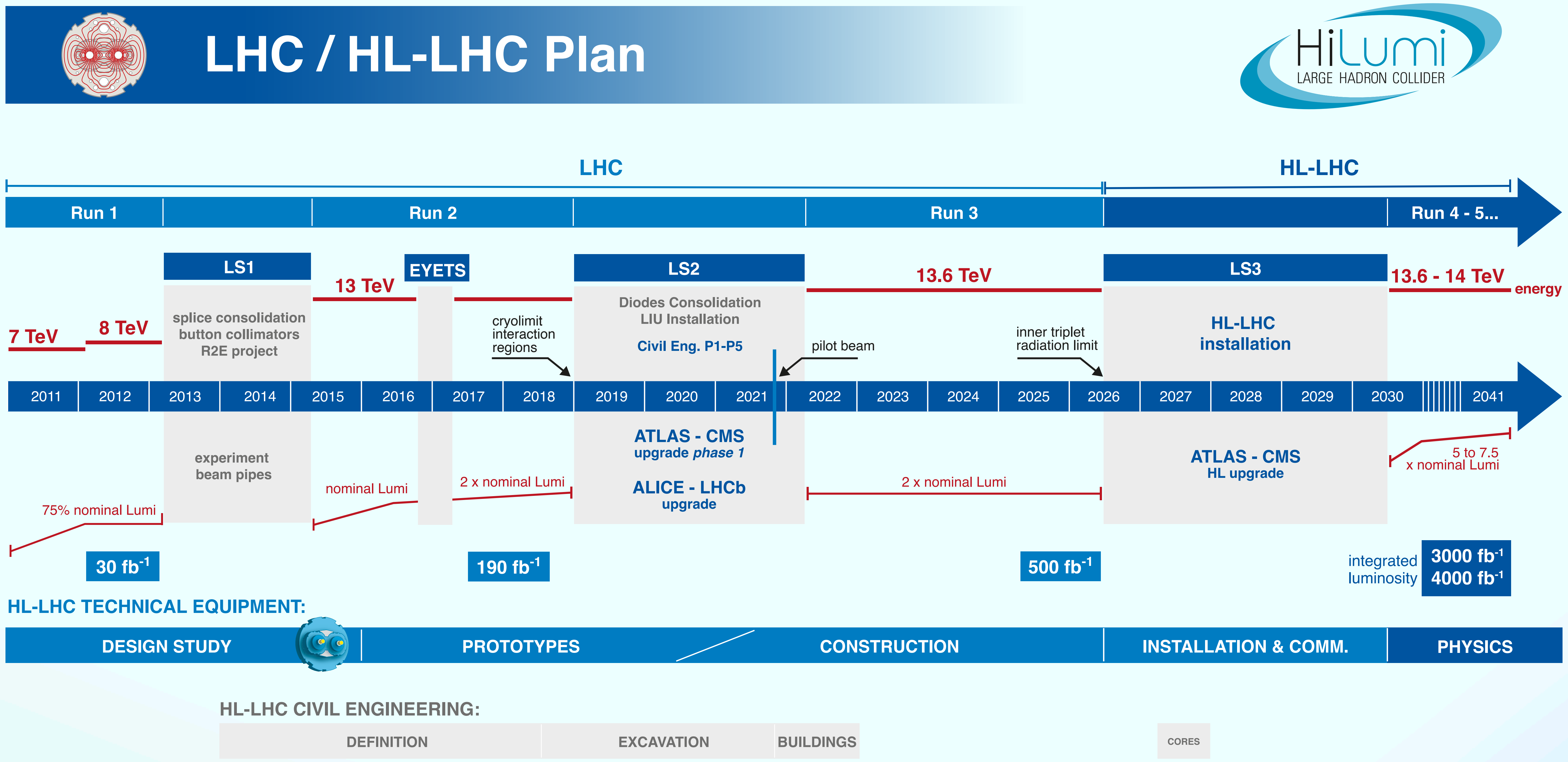




For SM Higgs @ 13 TeV…

Higgs has narrow width and decays very quickly!

Timeline since discovery

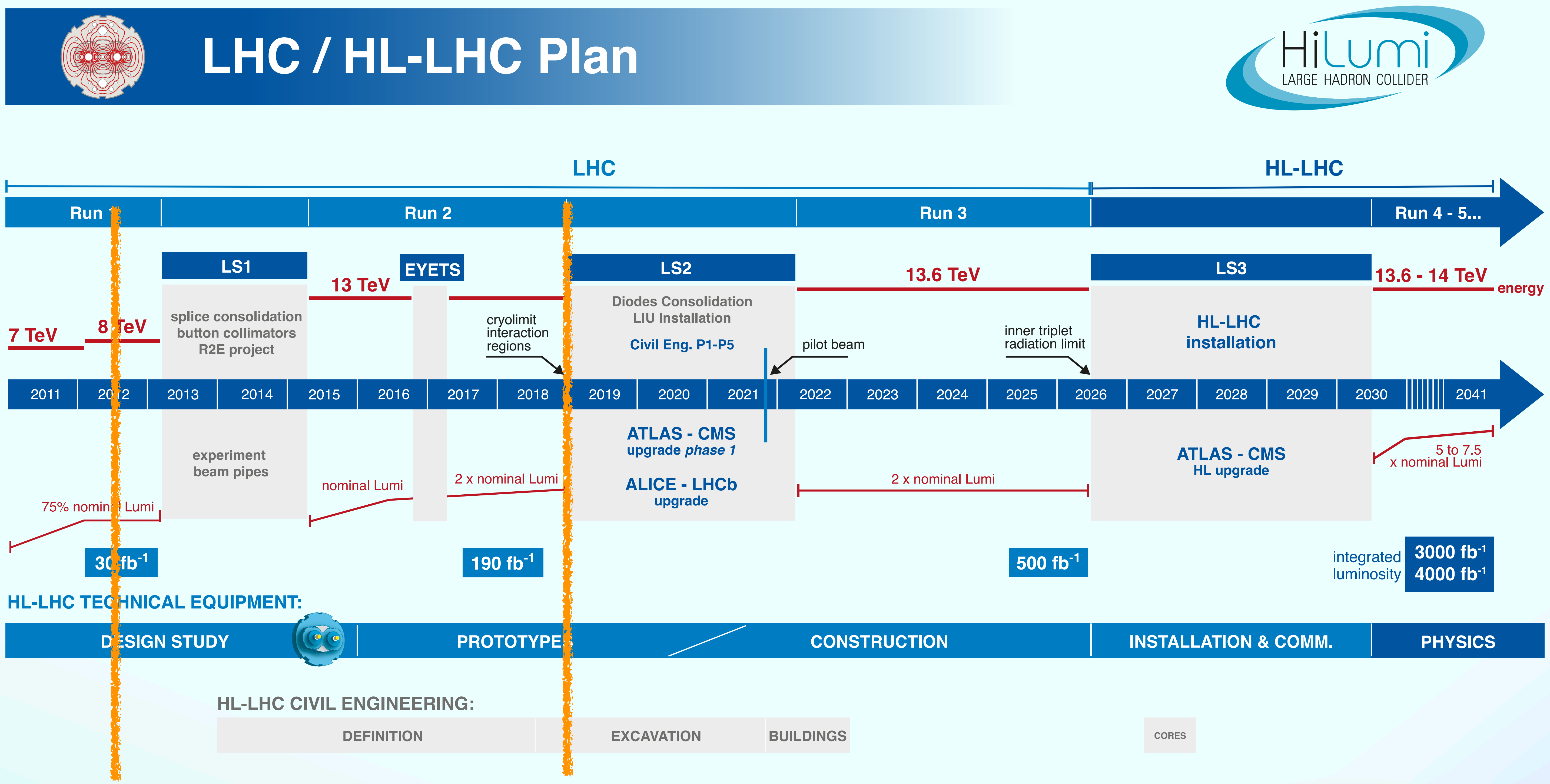


Timeline since discovery

Discovery

~200k Higgs prod.

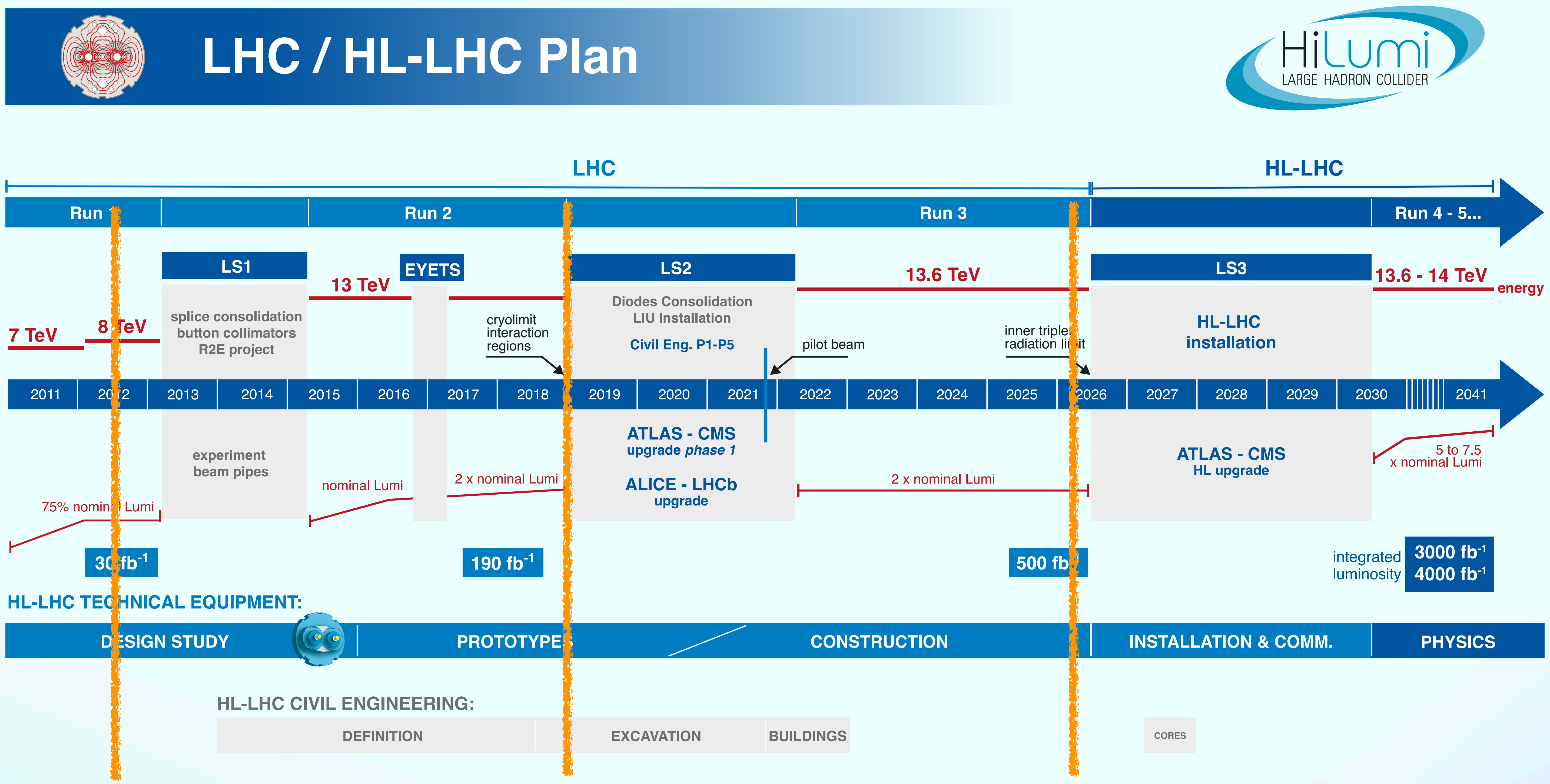
Timeline since discovery



Discovery
~200k Higgs prod.

End of Run 2
~7.7M Higgs prod.

Timeline since discovery

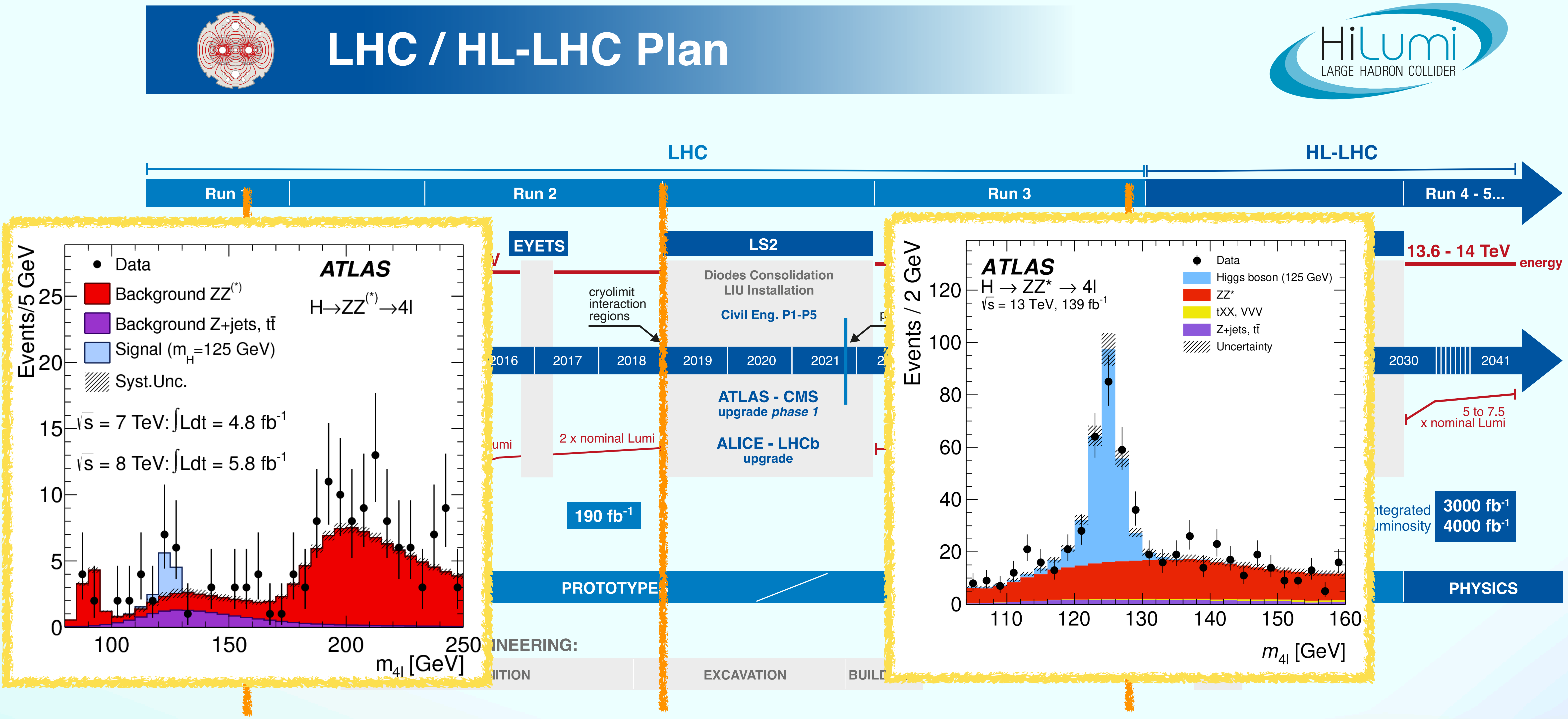


Discovery
~200k Higgs prod.

End of Run 2
~7.7M Higgs prod.

Today
~24M Higgs prod.

Timeline since discovery



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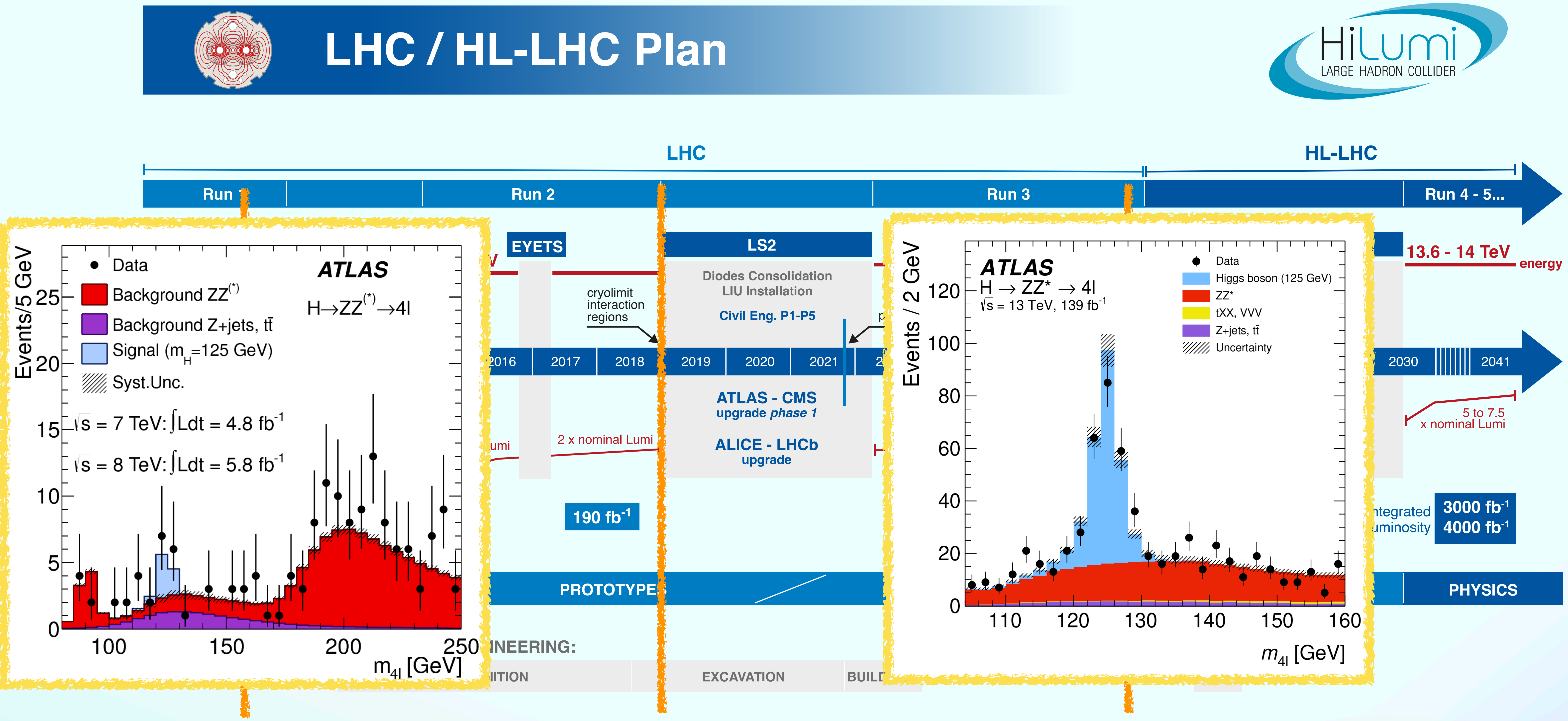
End of Run 2
~7.7M Higgs prod.

Today
~24M Higgs prod.

Timeline since discovery



Discovery
~200k Higgs prod.

End of Run 2
~7.7M Higgs prod.

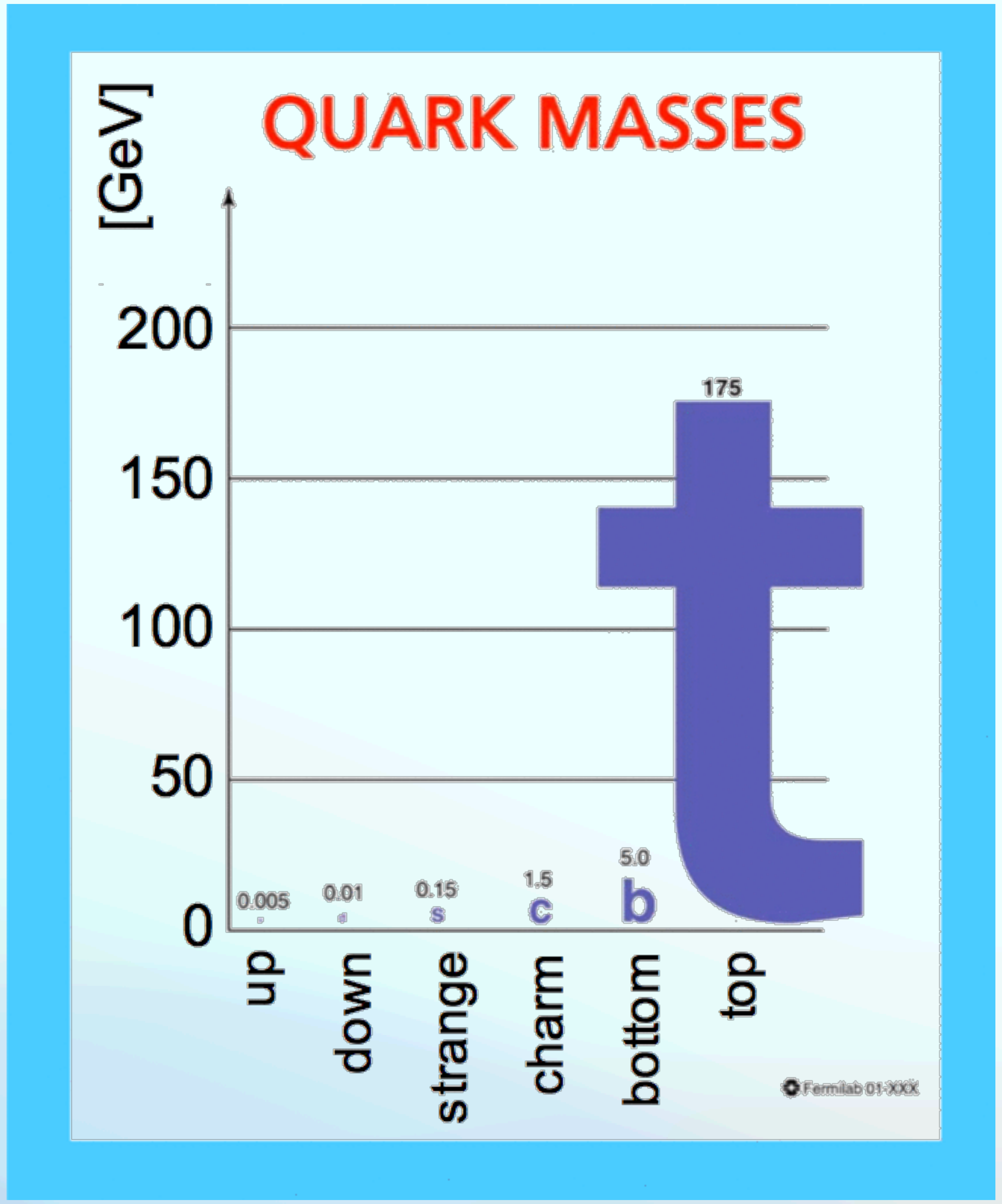
Today
~24M Higgs prod.

End of HL-LHC
~170M Higgs prod.

We analysed **barely ~5%** of the (HL)LHC dataset!

2nd protagonist

The Top quark as a probe for new physics



Heaviest particle in the SM

why?

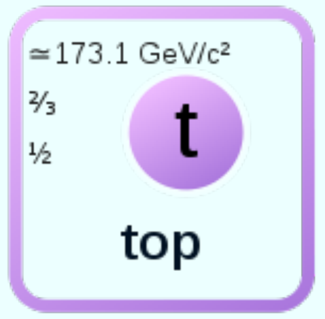
→ Strongest coupling to Higgs sector

→ Particuliar connection to Heavy New Sector?

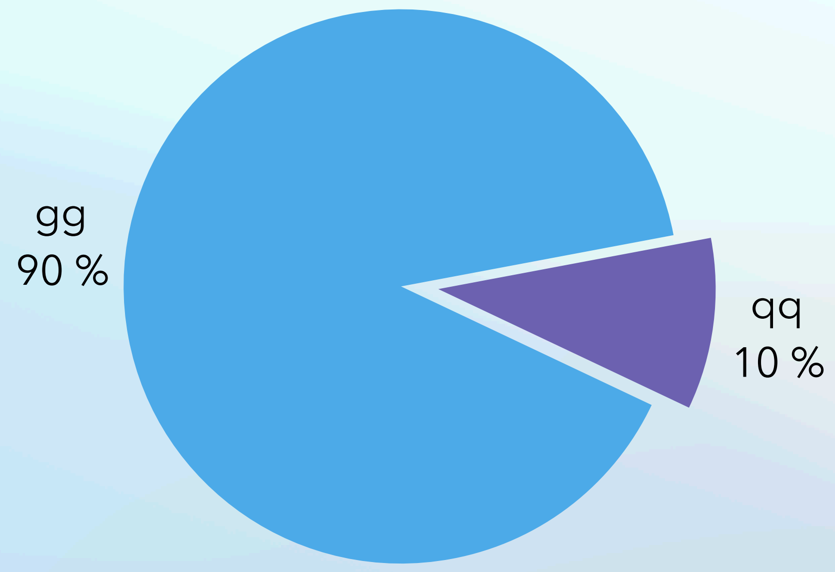
Decays before hadronization

→ Allows to study a "bare" quark

Top @ proton collider : prod. and decay

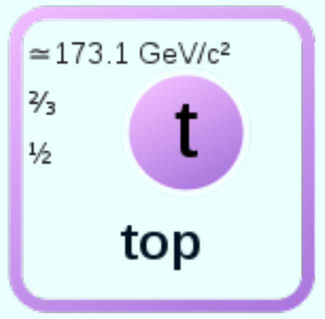


Production mode		Cross-section (pb)
$gg \to t\bar{t}$	~90%	833.9
$qq \to t\bar{t}$	~10%	

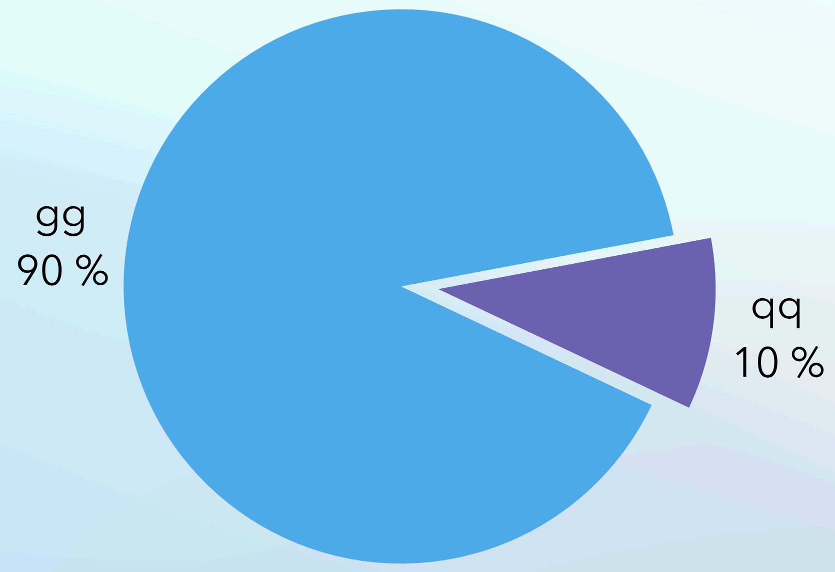


Mostly producted via QCD in $t\bar{t}$ pair

Top @ proton collider : prod. and decay



Production mode		Cross-section (pb)
$gg \rightarrow t\bar{t}$	~90%	833.9
$qq \rightarrow t\bar{t}$	~10%	
$t\bar{t}W$		0.745
$t\bar{t}Z$		0.811
$t\bar{t}H$		0.529
$t\bar{t}t\bar{t}$		0.015



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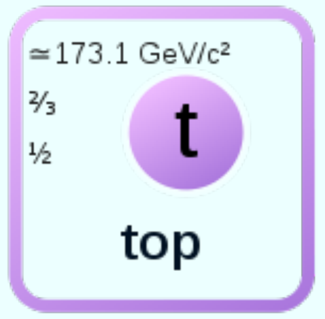

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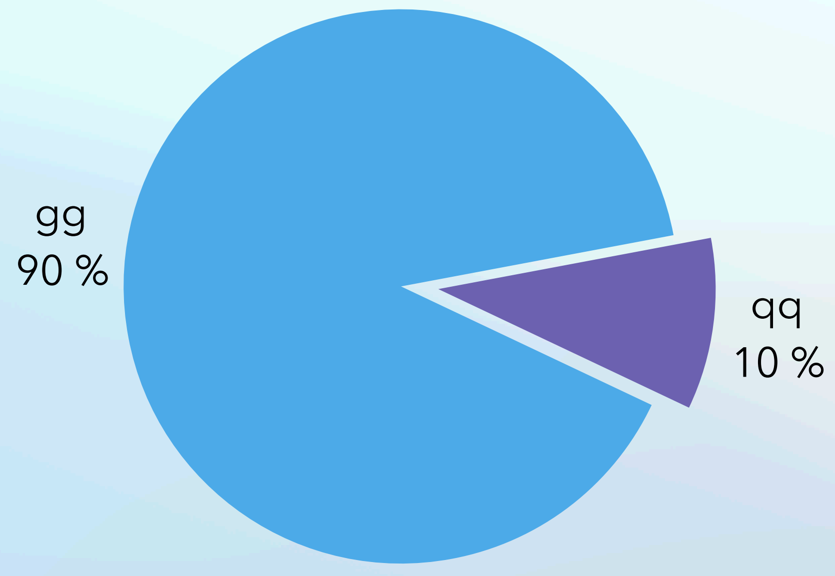

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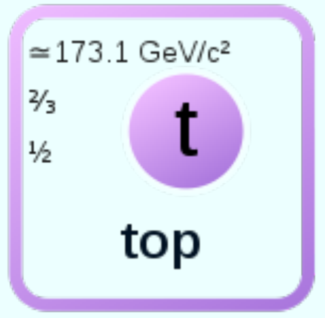

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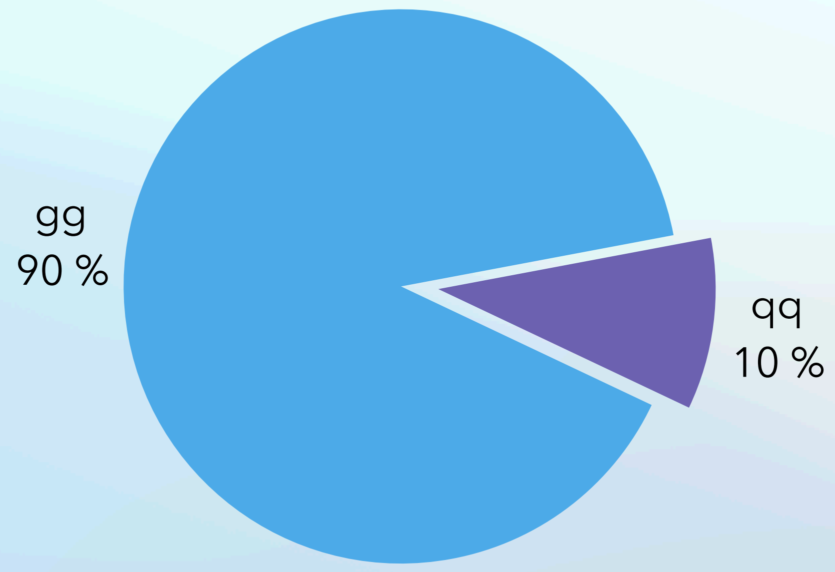

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Then, final states from W decays

$t \to b + W(\to q\bar{q})$	66.5
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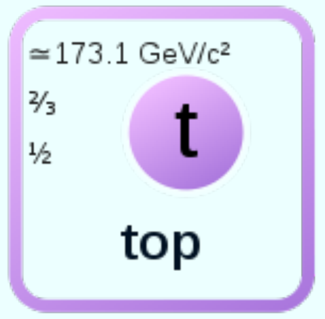

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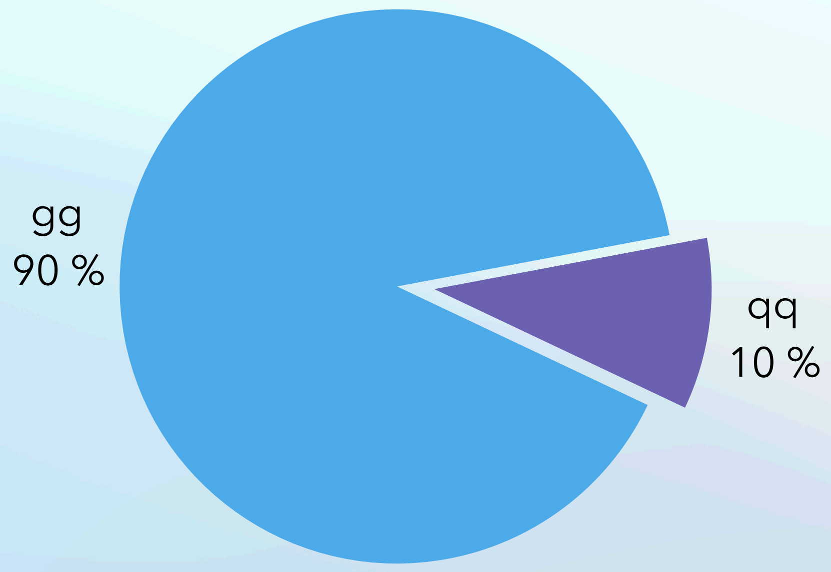

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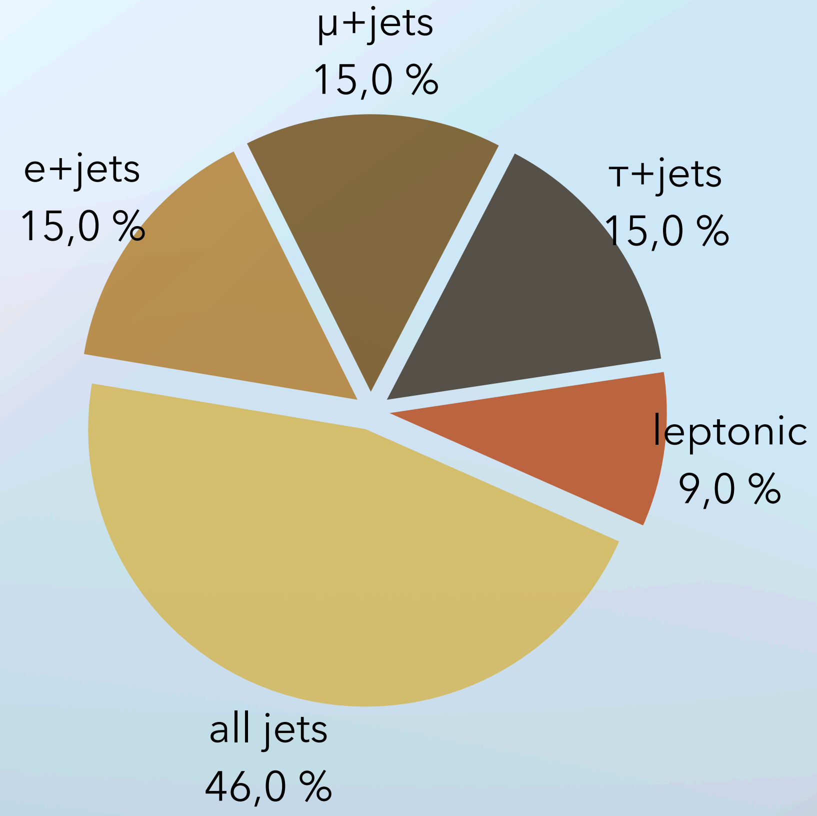
So, for $t\bar{t}$ pair :



LHC is a top quark factory
O(100M) $t\bar{t}$ events produced in Run 2

How to go from theory to measurement?

Simulation of a process

Using generators e.g. MadGraph
Include "soft" processes (e.g. hadronisation)
Include info. about Proton Distrib. Fonction

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Reconstruction of an event

i.e. [electronic signals] → [photon with $p_T = 500$ GeV]

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↓

$\mathscr{L}($ **data** | **prediction** $)$

→ Dependance of theory param. on observables

→ Experimental related uncertainties (calibrations, fake reco., ...)

→ Theory uncertainties (PDF, loop calculations)

Recap. so far

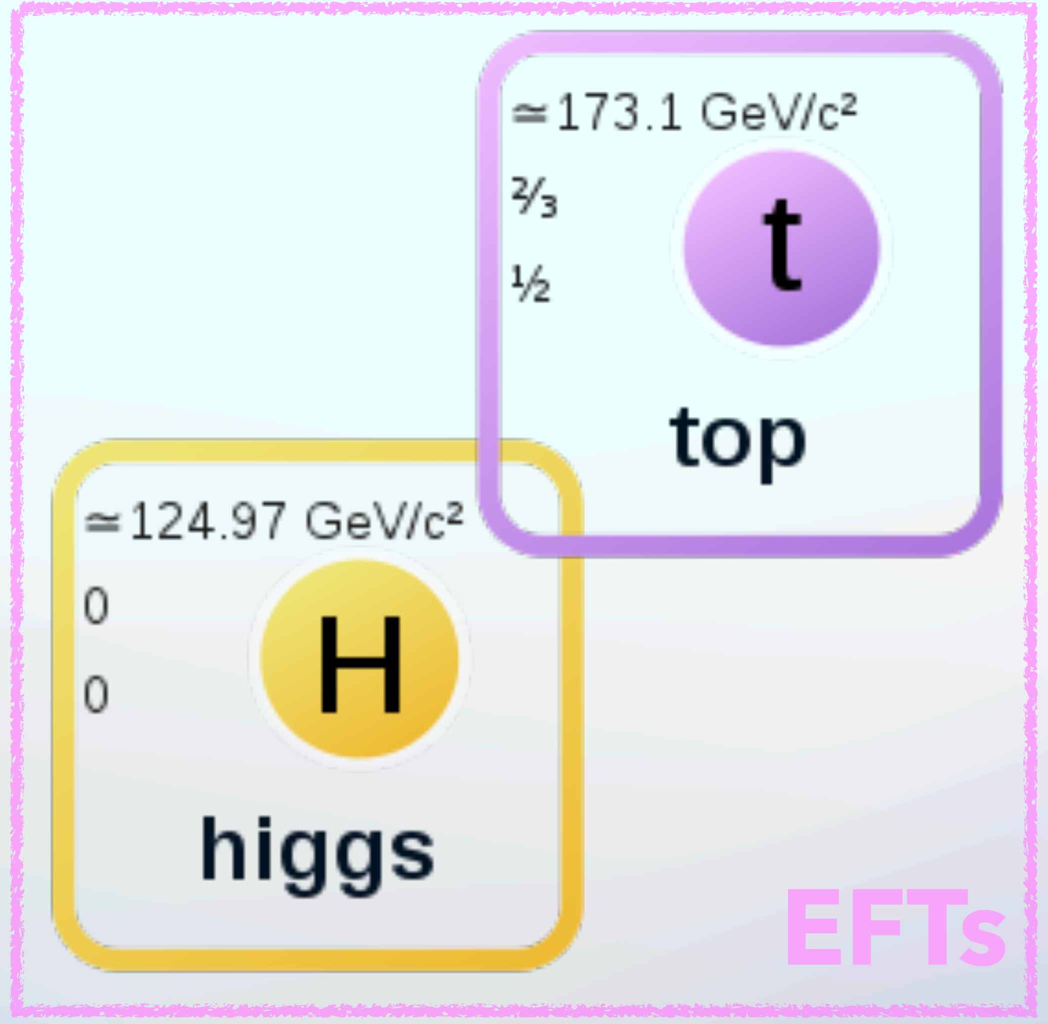
Recap.

SM is heathlier than ever → we need to go **beyond**

We have a already *large* dataset to explore
and a <u>even larger one</u> yet to explore

Higgs boson and **Top quark** seems to be the most promising probes of NP at LHC

Current data tends to incate that NP lives at (very) **high energy scale**
→ Effective approach is needed

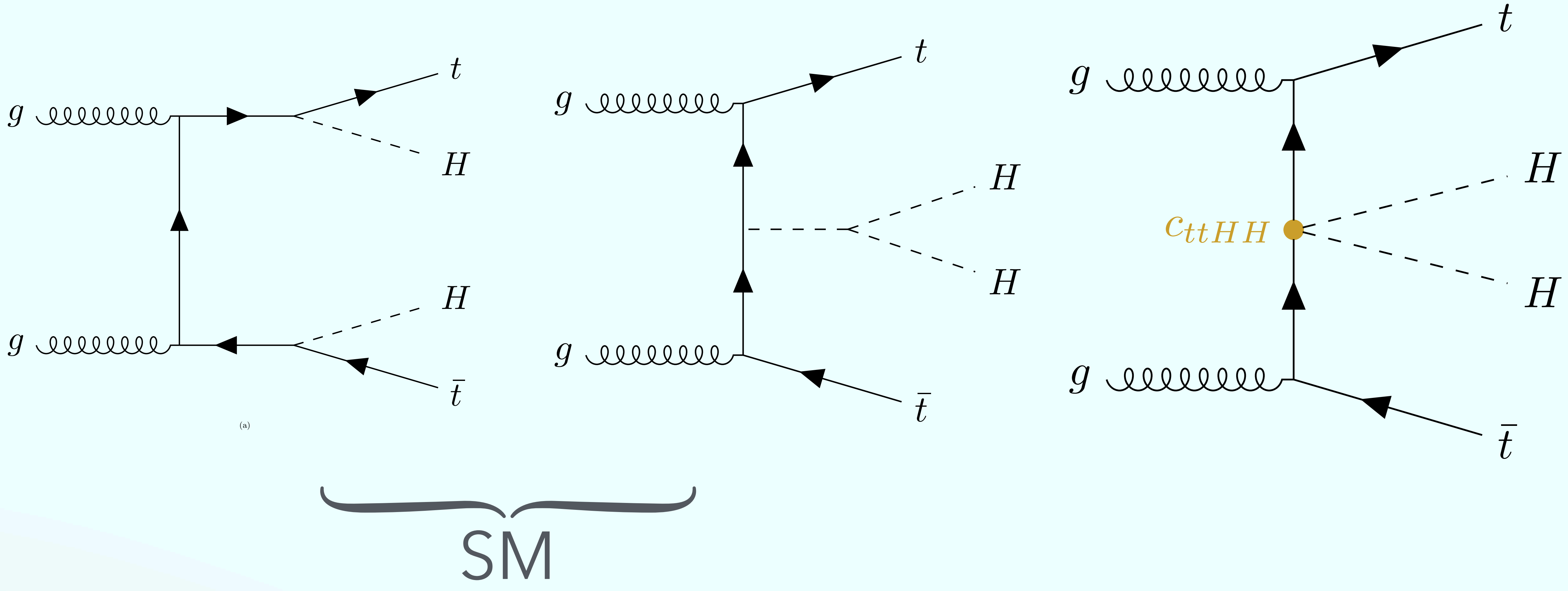


Probing the Top-Higgs Quartic interation

through an EFT interpretation of ttHH production at ATLAS

arXiv:2026.13113

Motivations

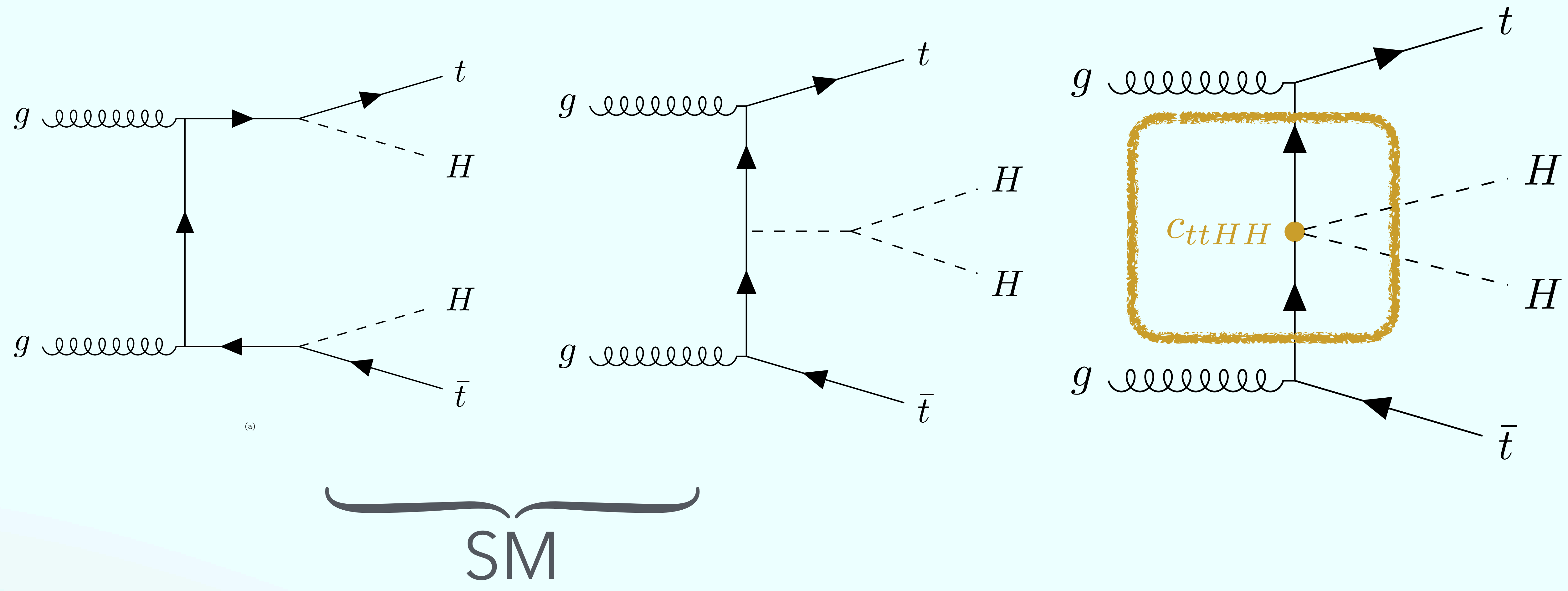


- <u>3rd leading</u> HH production mode @ LHC

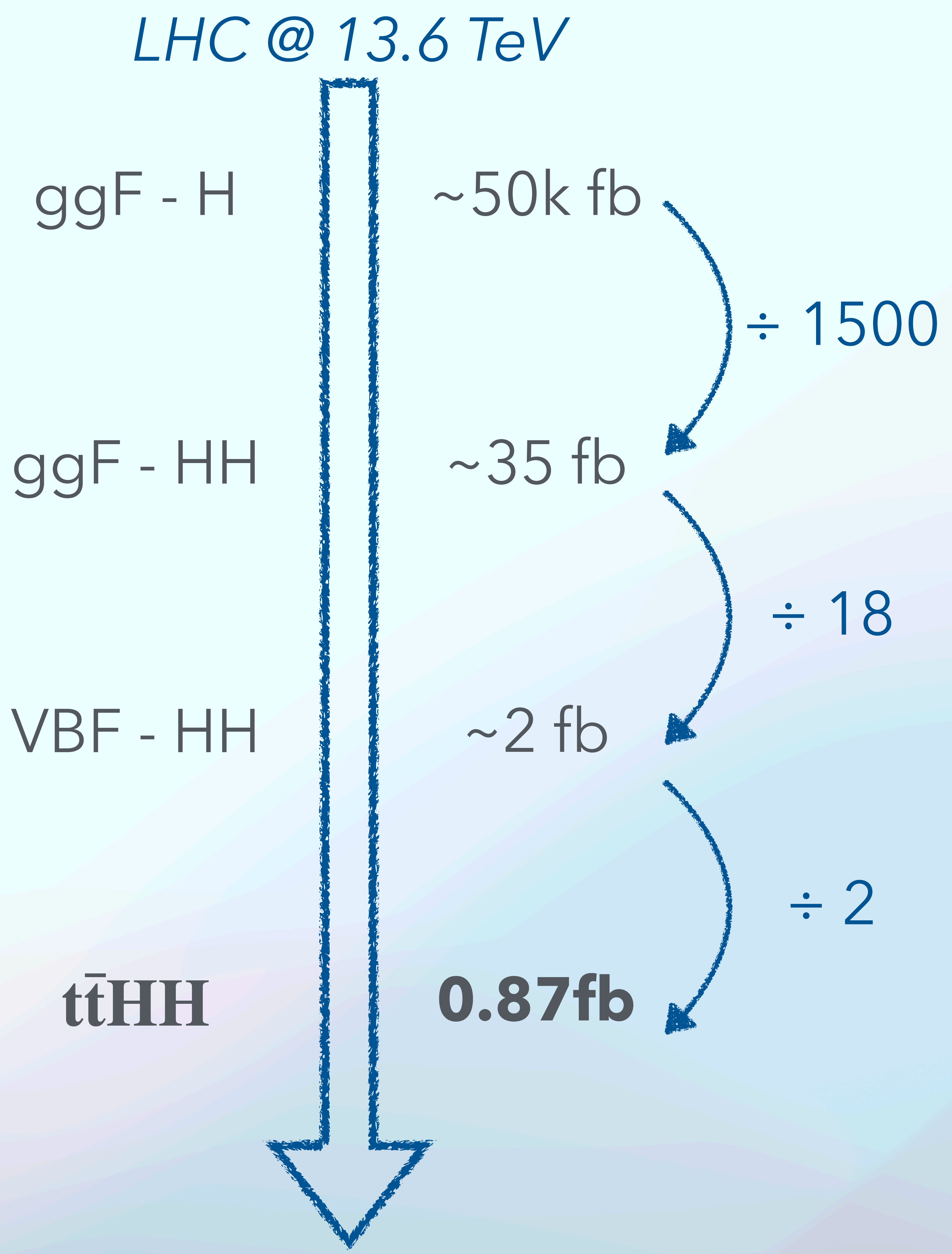
LHC @ 13.6 TeV

ggF - H	~50k fb	
		÷ 1500
ggF - HH	~35 fb	
		÷ 18
VBF - HH	~2 fb	
		÷ 2
$t\bar{t}$HH	**0.87fb**	

Motivations



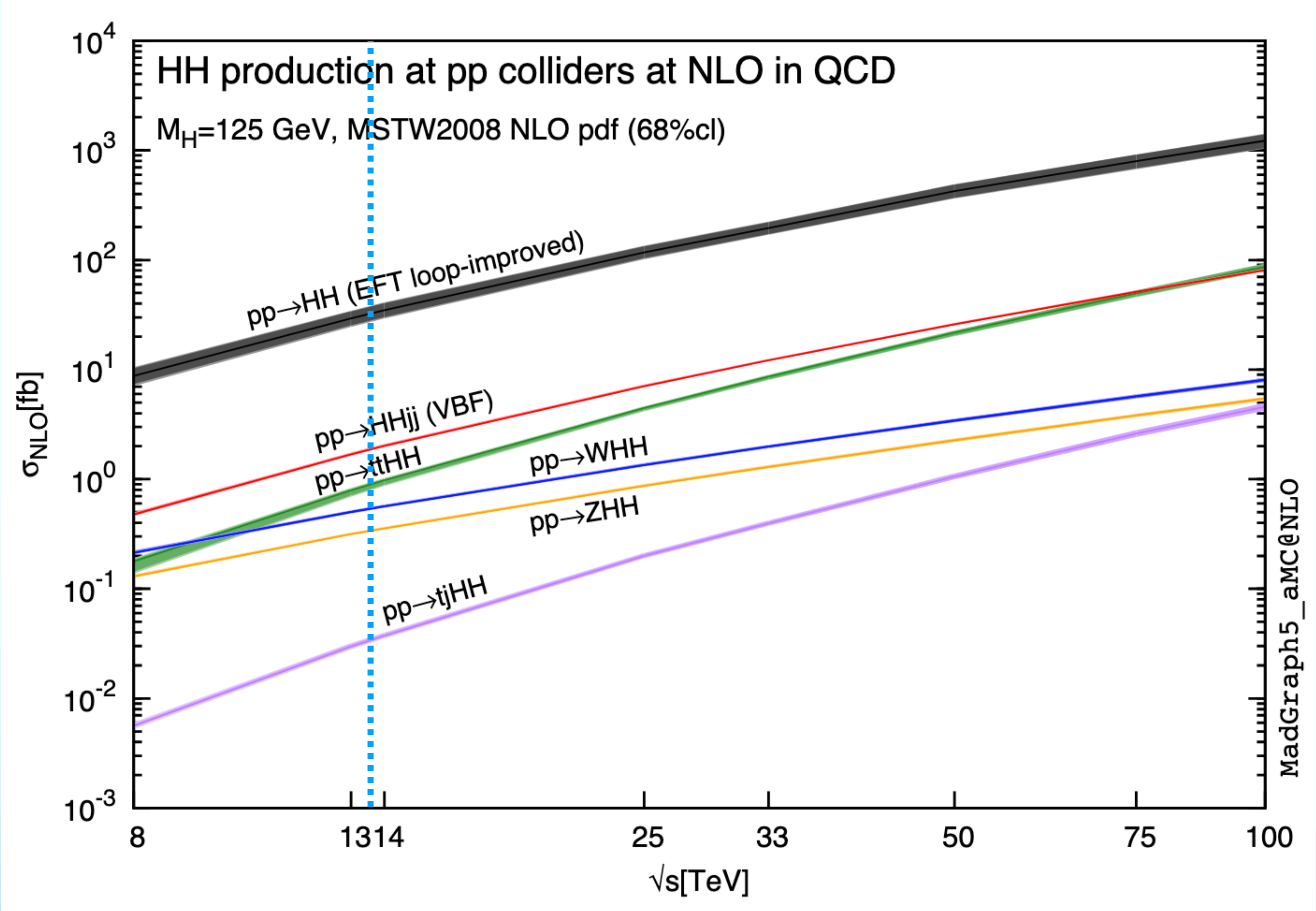
- 3rd leading HH production mode @ LHC
- Gives **direct** access to $t\bar{t}HH$ quartic interaction

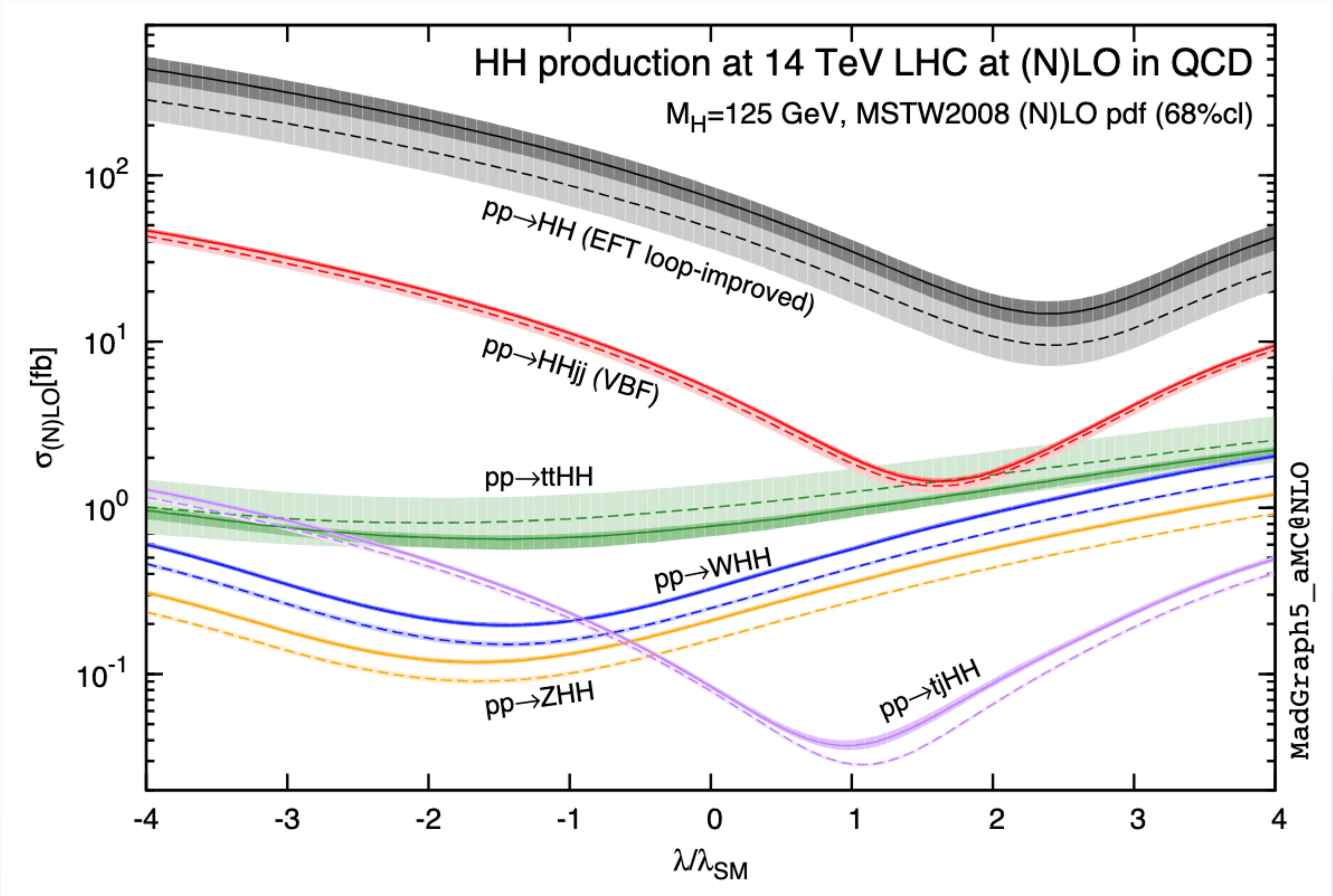


ttHH production

arXiv:1401.7340

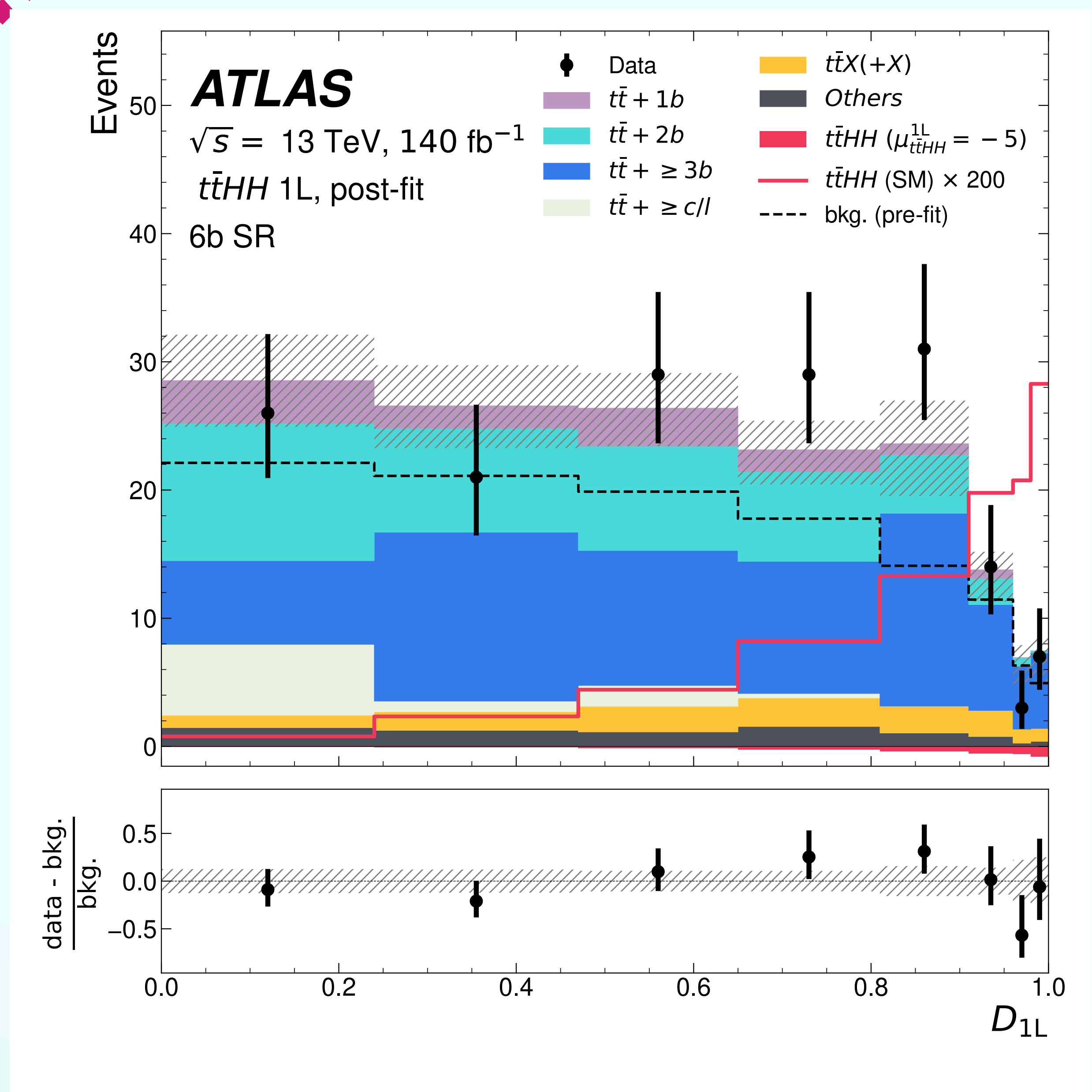
We stand here





- Cross-section scales faster with $\sqrt{s}$
- Unique interference pattern dependance on κ_λ
  We'll come back to that later...

Strategy

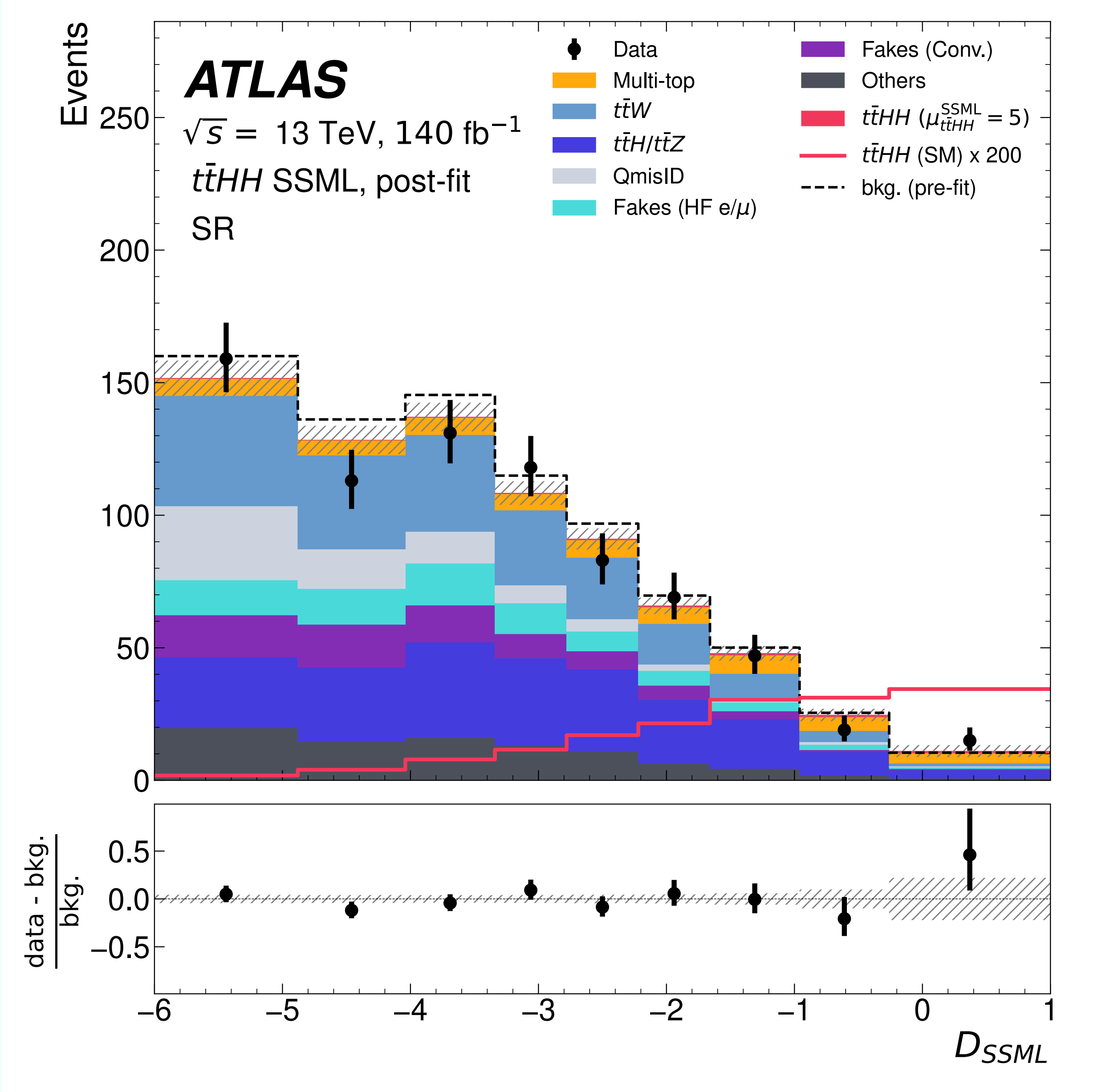


Single lep. channel (1L)

$HH \to 4b$ and semileptonic $t\bar{t}$

dom. bkg : $t\bar{t}$ + jets

Obs. limit on μ : **26** x SM

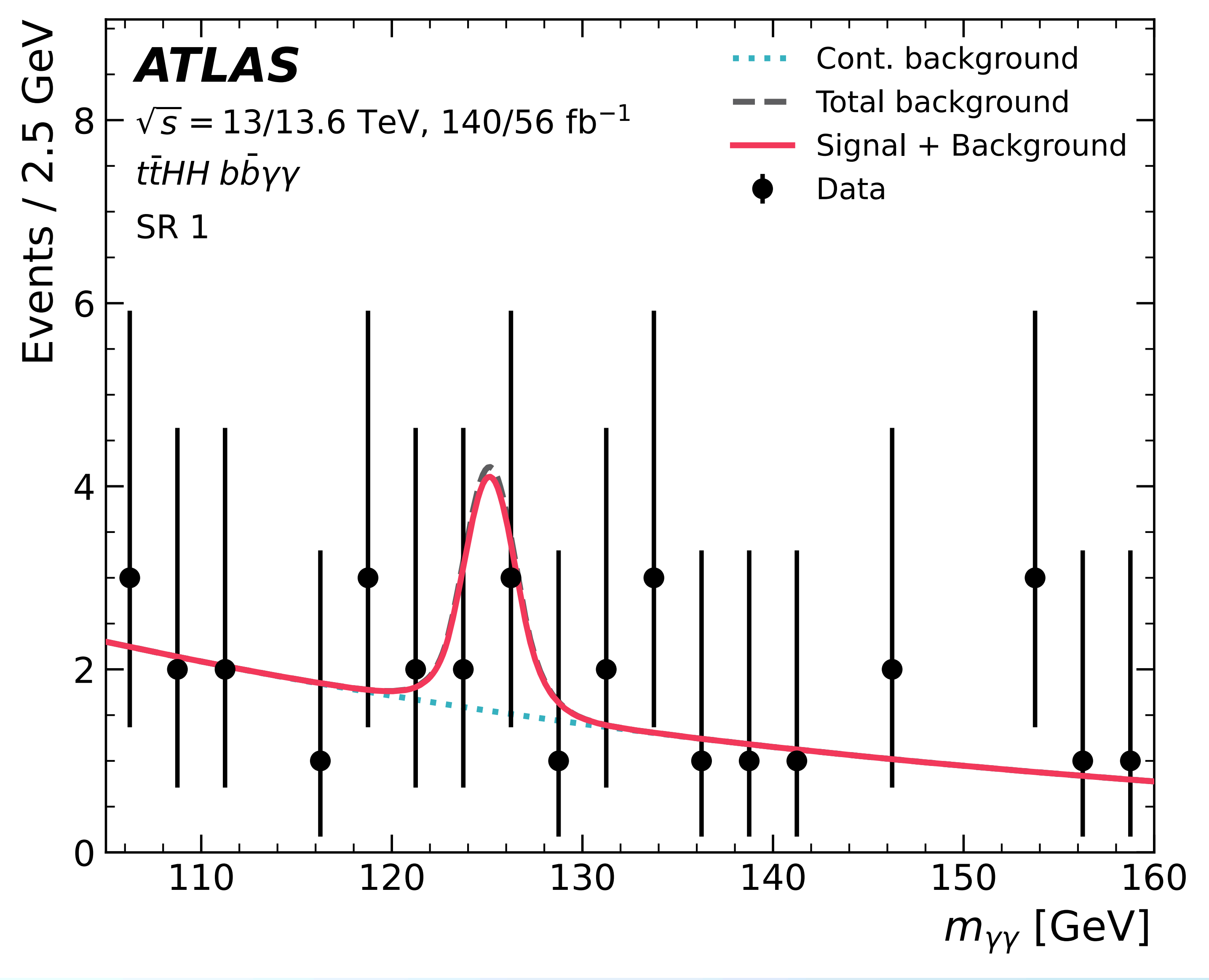


Multi-lep. Channel (ML)

$HH \to b\bar{b}WW, b\bar{b}\tau\tau, \ldots$

dom. bkg : $t\bar{t}W$, $t\bar{t}t\bar{t}$, QmidID

Obs. limit on μ : **40** x SM

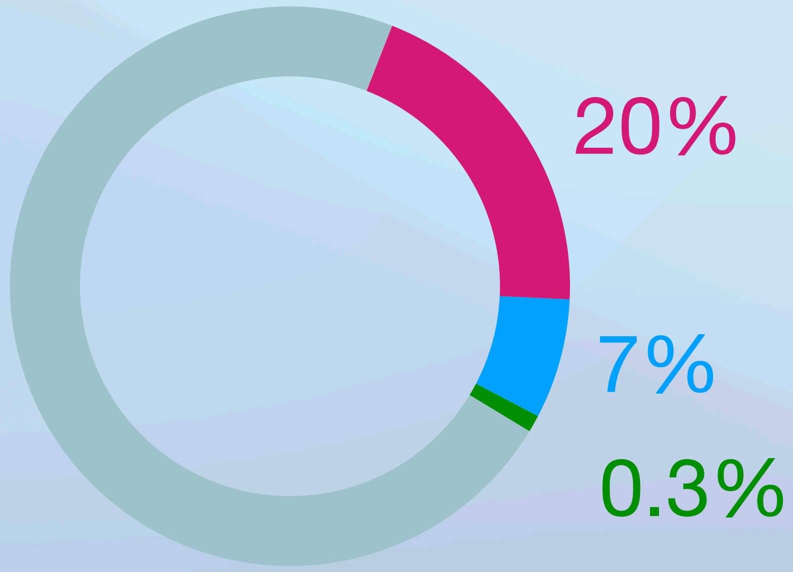


$b\bar{b}\gamma\gamma$ channel

$HH \to b\bar{b}\gamma\gamma$

dom. bkg : $\gamma\gamma$ + jets continuum

Obs. limit on μ : **75** x SM



- 1L and ML : Fit Transformer score
- $b\bar{b}\gamma\gamma$: Fit on $m_{\gamma\gamma}$ after BDT selection

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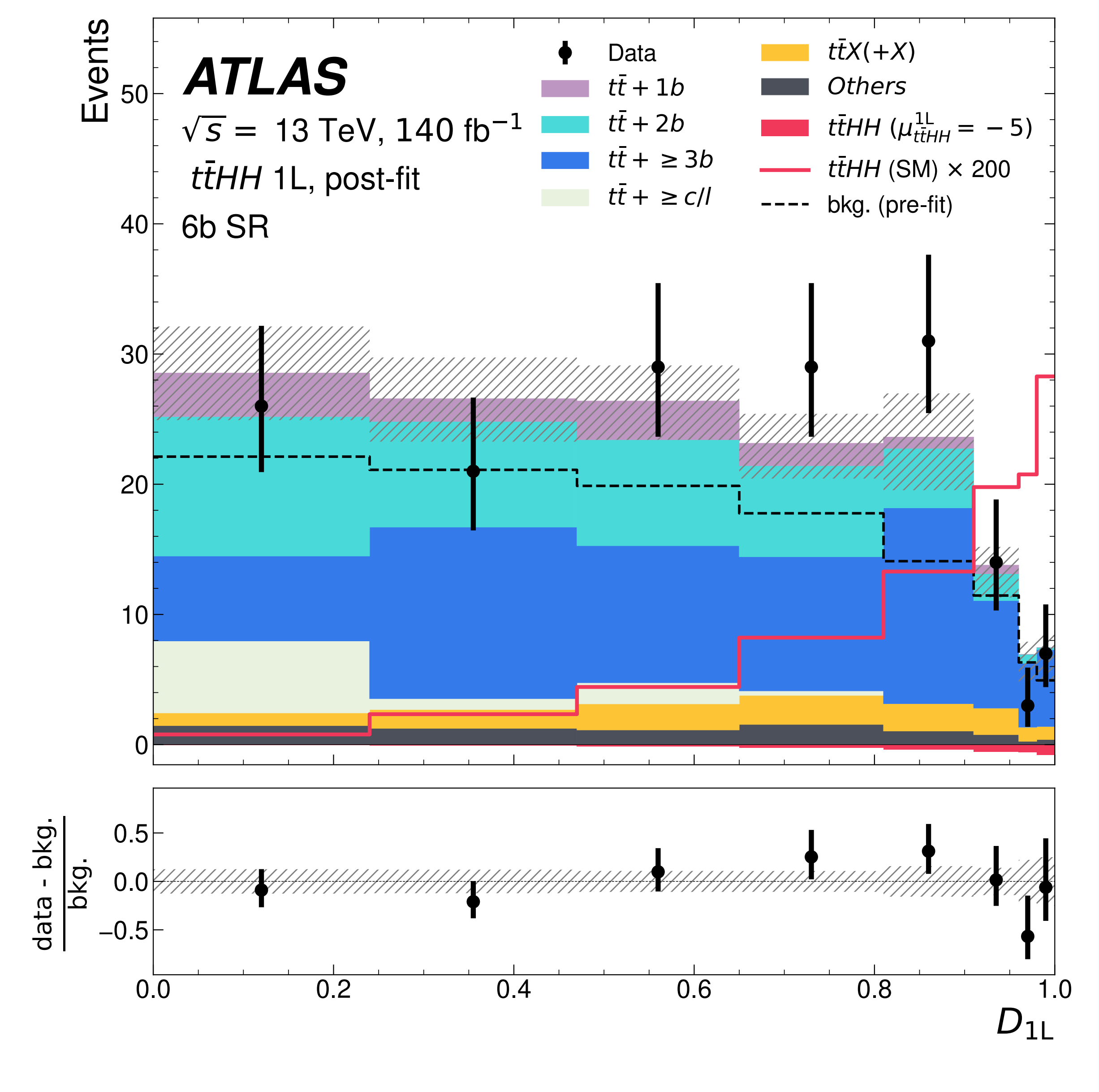
Strategy



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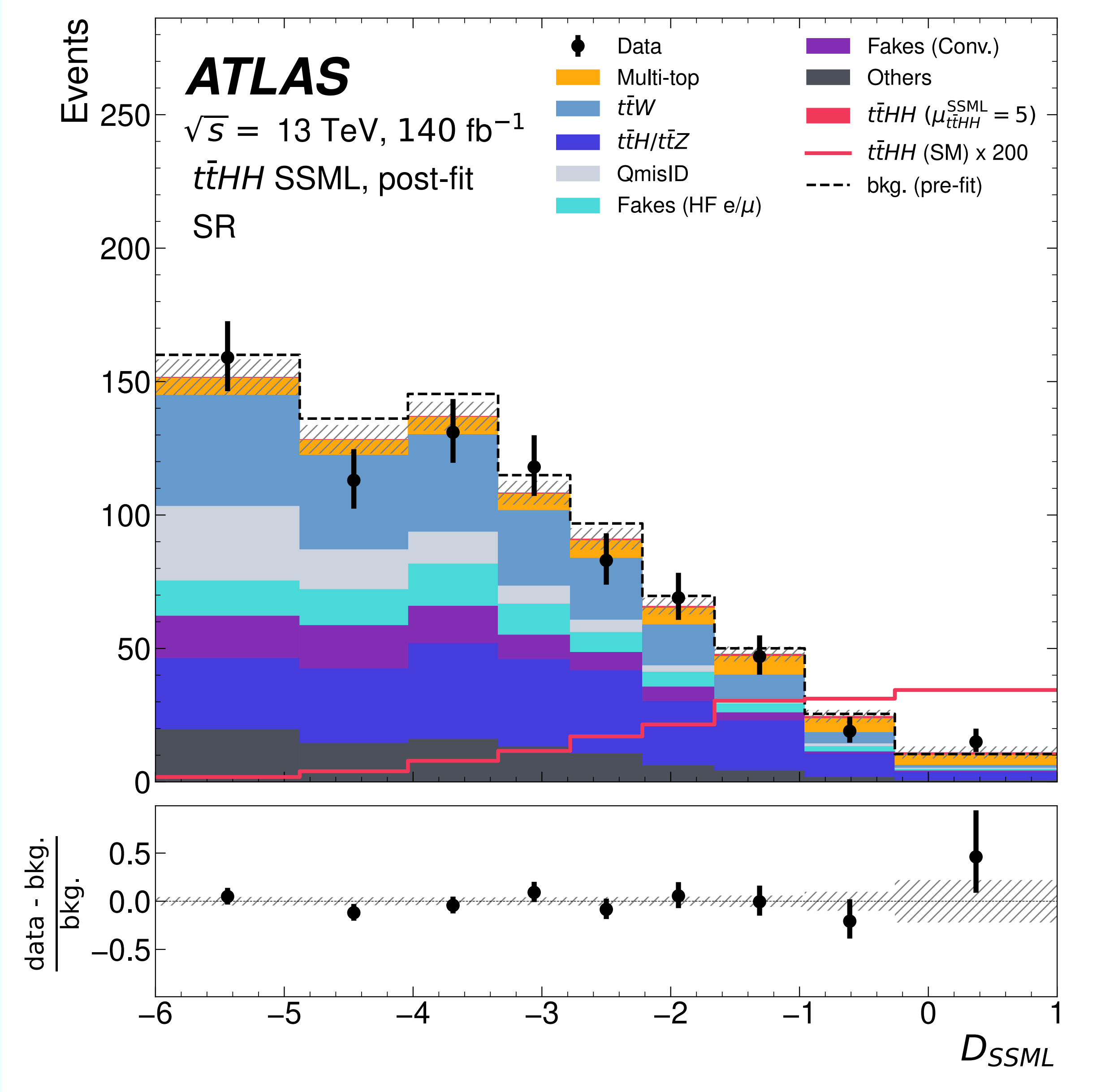

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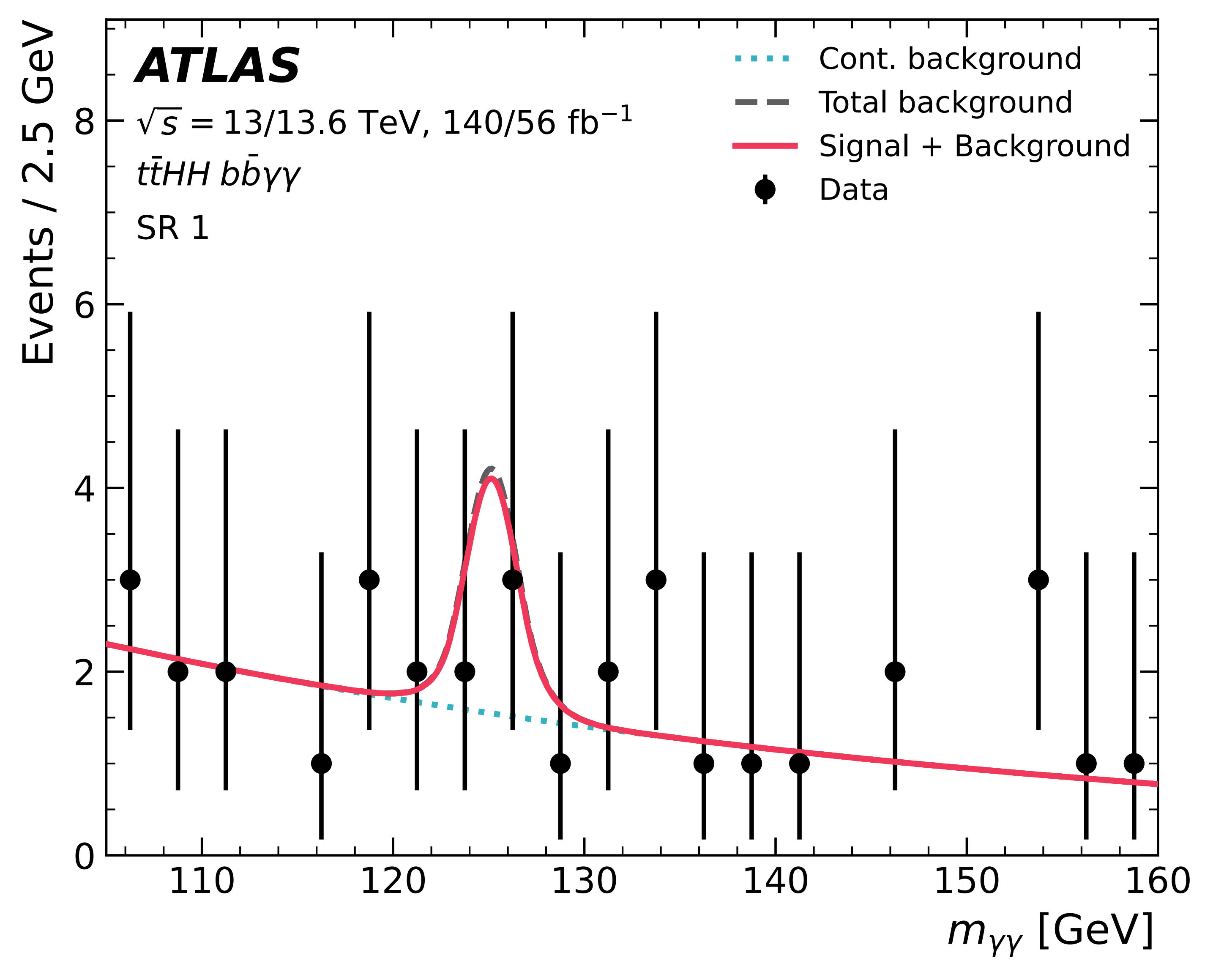

$b\bar{b}\gamma\gamma$ **channel**

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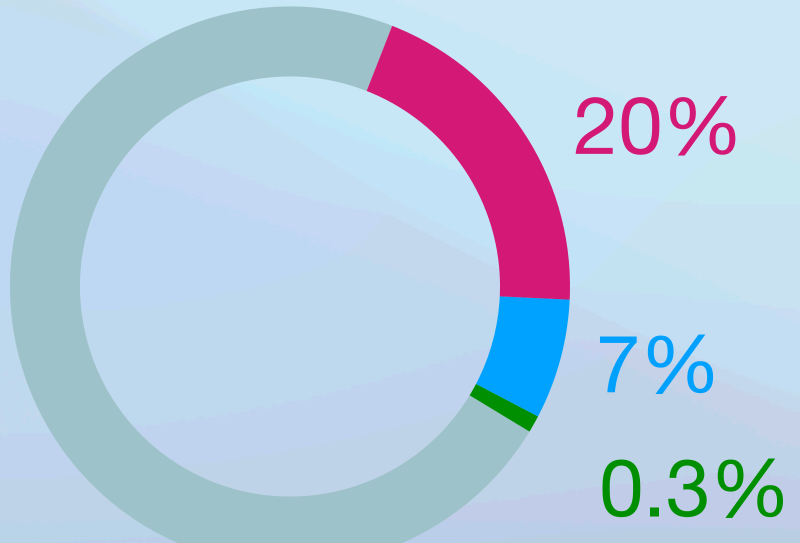

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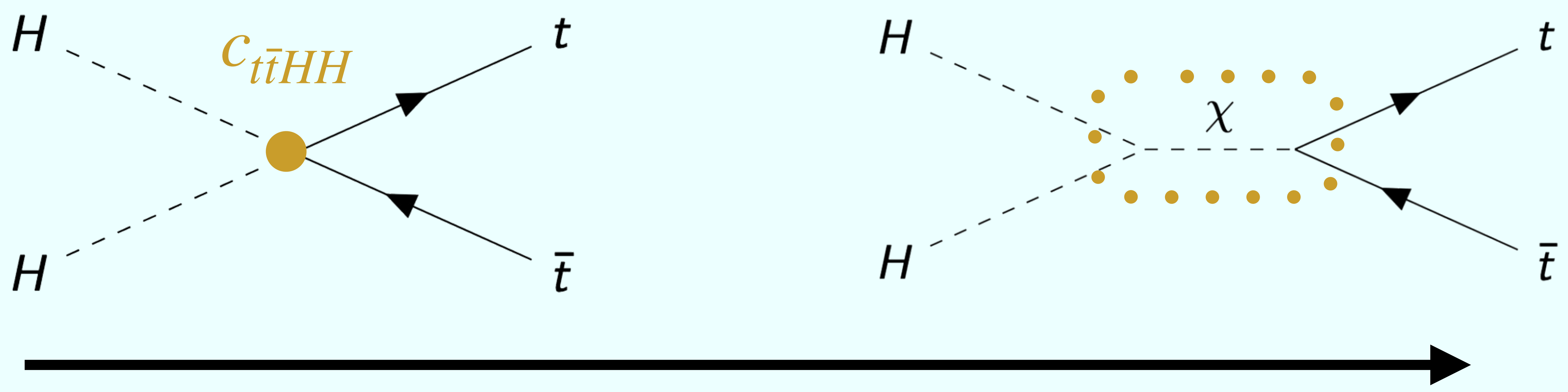
Limitations

Uncertainty Source	Observed	Expected
Signal modelling	(+0.9, −1.8)	(+1.3, −1.0)
Background modelling	(+6.8, −8.2)	(+5.7, −6.2)
$t\bar{t}$ + jets	(+5.3, −6.5)	(+4.7, −5.0)
$t\bar{t}t\bar{t}$	(+4.6, −6.4)	(+2.9, −4.0)
$t\bar{t}H$	(+2.1, −1.6)	(+2.0, −1.9)
others	(+0.9, −0.7)	(+0.9, −0.8)
MC statistical	(+2.8, −3.7)	(+2.5, −2.7)
Detector systematic	(+2.2, −3.4)	(+1.9, −1.5)
Total systematic	(+8.3, −9.4)	(+7.3, −7.4)
Data statistical	(+7.2, −6.8)	(+7.2, −6.7)
Total	(+11.0, −11.6)	(+10.3, −10.0)

Dominant systematic unc. :
heavy flavour modelling and 4 tops

Overall → Balance between stat. and modelling

Higgs Effective Field Theory



$$E_{LHC} \quad << \quad E \sim \Lambda_{NP}$$

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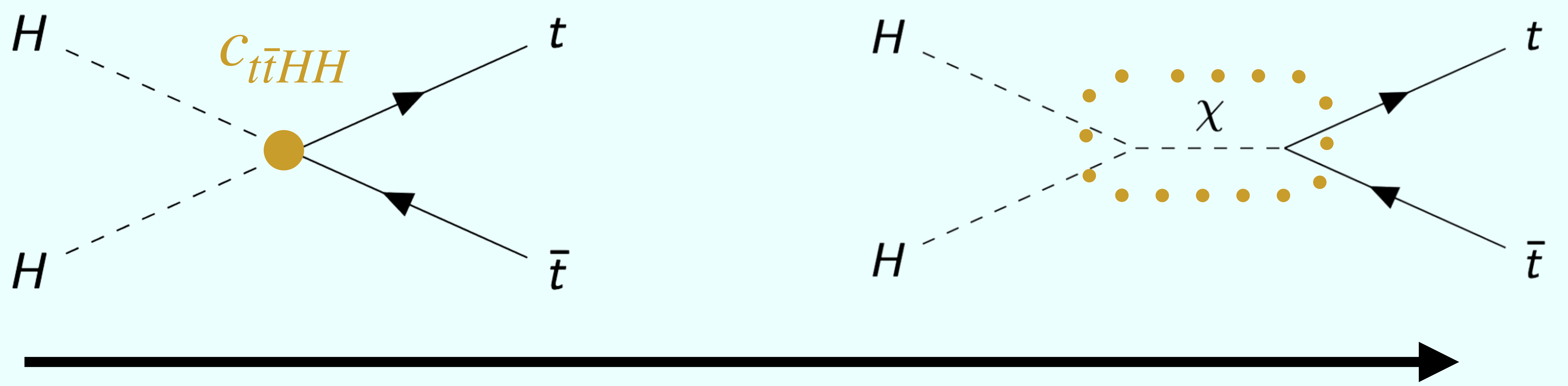

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Step 1 : We fix the field content
Step 2 : We fix the symmetries
Step 3 : We write an exhaustive list of allowed interactions at given order

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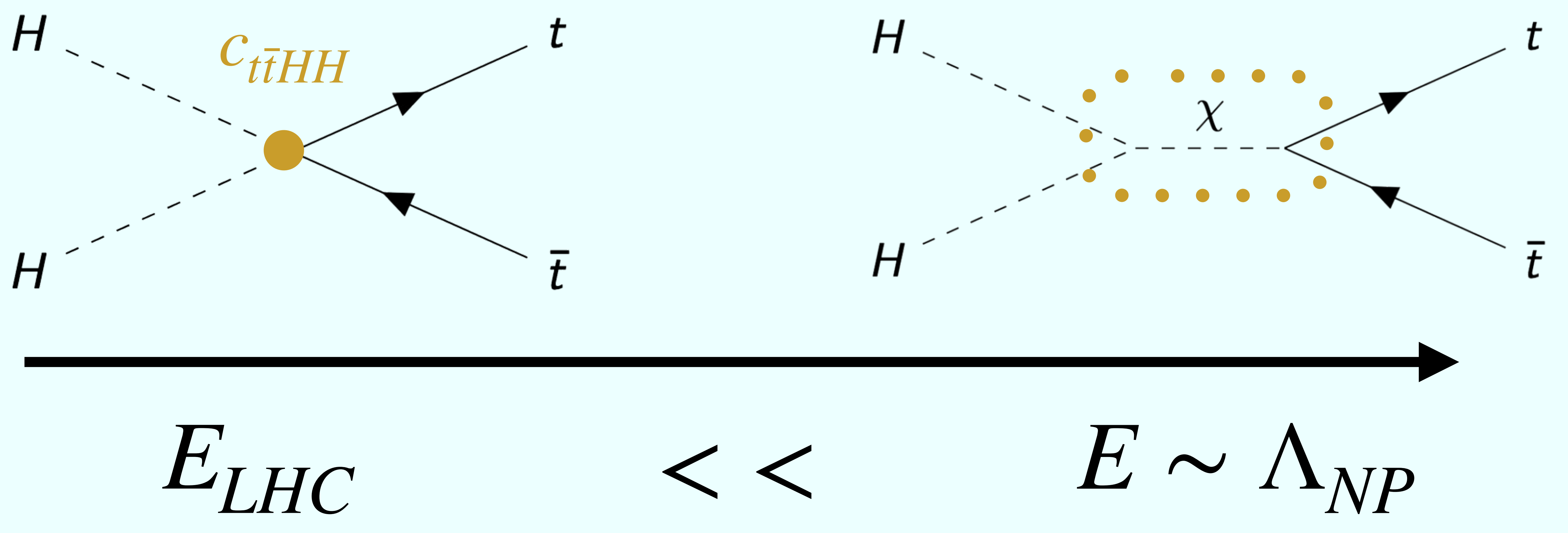

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→ Higgs properties unconstrained by EWSB pattern

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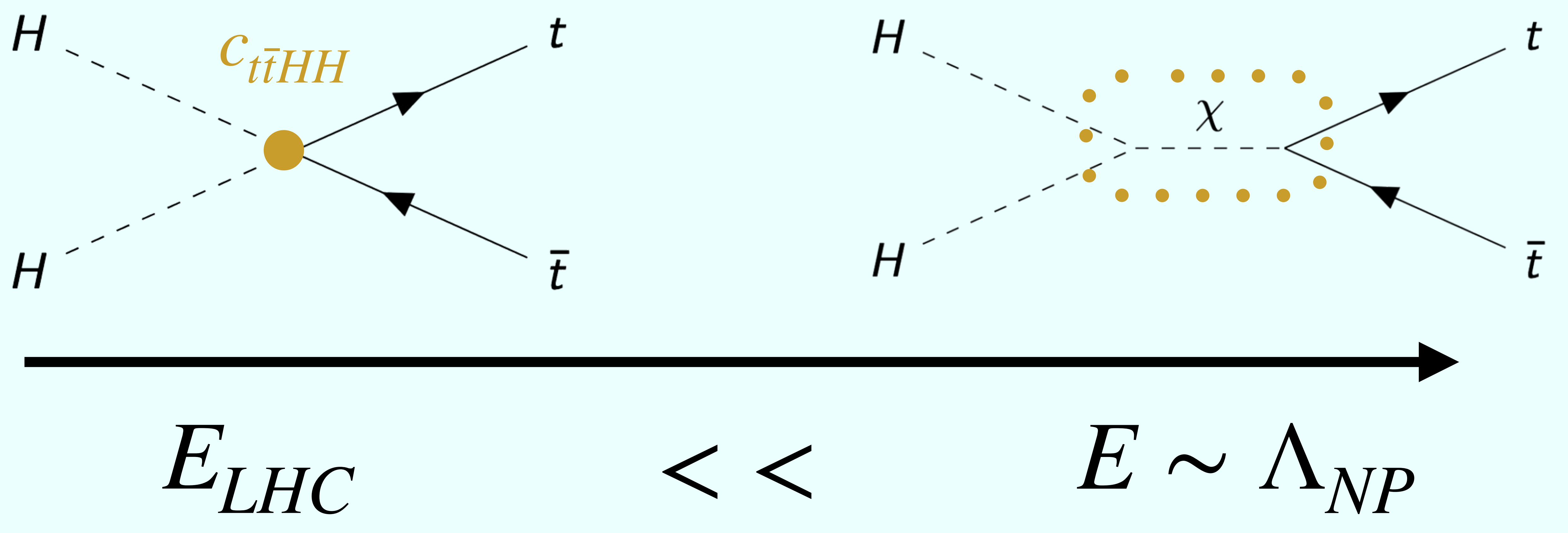

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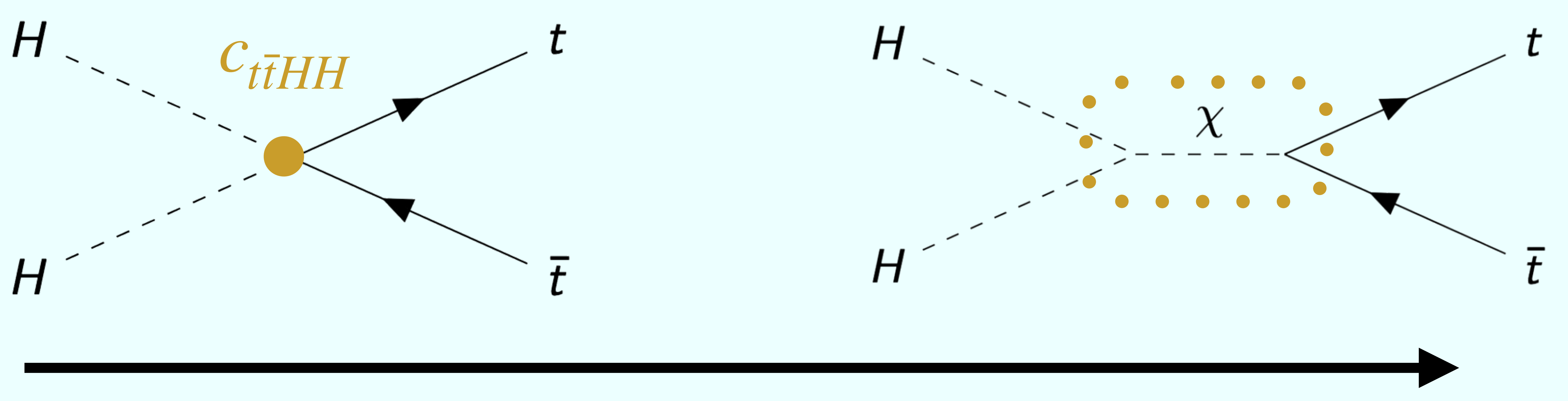

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$$\mathscr{L}_{\text{HEFT}} \supset -m_t\left(c_{t\bar{t}H}\frac{h}{v} + c_{t\bar{t}HH}\frac{h^2}{v^2}\right)t\bar{t} - \kappa_\lambda \frac{m_H^2}{2v}h^3$$

Strategy and results

Exploit **cross-section dependance** in 1L and ML channels

↓

Reinterpretation

$$\mathscr{L}(d\,|\,\mu) \longrightarrow \mathscr{L}(d\,|\,\sigma(\,c_{t\bar{t}HH}\,))$$

Strategy and results

Exploit **cross-section dependance** in 1L and ML channels

Acceptance effects covered *by 30% unc. on signal yield*

Shape variations neglected *(evaluated to have a small impact)*

Reinterpretation

$$\mathscr{L}(d|\mu) \longrightarrow \mathscr{L}(d|\sigma(c_{t\bar{t}HH}))$$

Aparte : EFT modelling

Sample simulation is **expensive**

in €, in time, and in CO_2

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It's cheap!

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Pros :

It's cheap!

Cons :

How can we be sure that we capture well the dependances for the variable we fit?

We can't, but we can estimate that the effect is ~small

First : we need a model!

- Modification of the SM Lagrangian with additional vertices $c_{t\bar{t}HH}, c_{t\bar{t}H}, \kappa_\lambda$
- Implemented by M. Ryczkowski & R. Groeber using FeynRules UFO model format. Can be found on github.com/Ryczek/CttHH
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$$c_{t\bar{t}HH} = -\frac{3v^3}{2\sqrt{2}\Lambda^2 m_t} c_{uH} + \frac{v^2}{\Lambda^2} c_{H\Box} - \frac{v^2}{4\Lambda^2} c_{HD}$$

$$c_{HHH} = 1 - \frac{v^2}{\Lambda^2}\left(2\frac{v^2}{m_H^2} c_H - 3c_{H\Box} + \frac{3}{4} c_{HD}\right)$$

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arXiv:2304.01968

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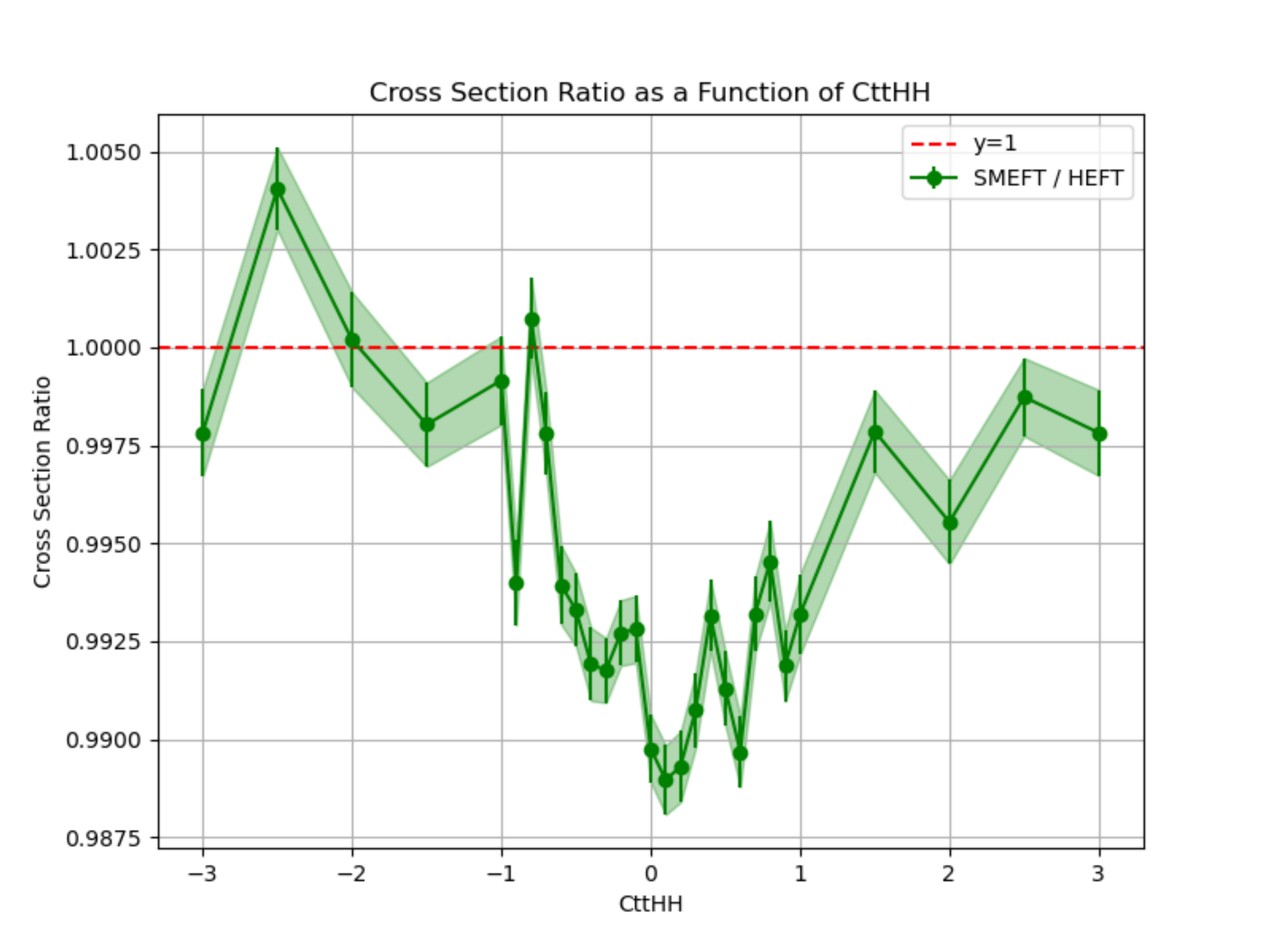

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arXiv:2304.01968

→ **Agreement at ~1% level**

A probe for HEFT vs. SMEFT

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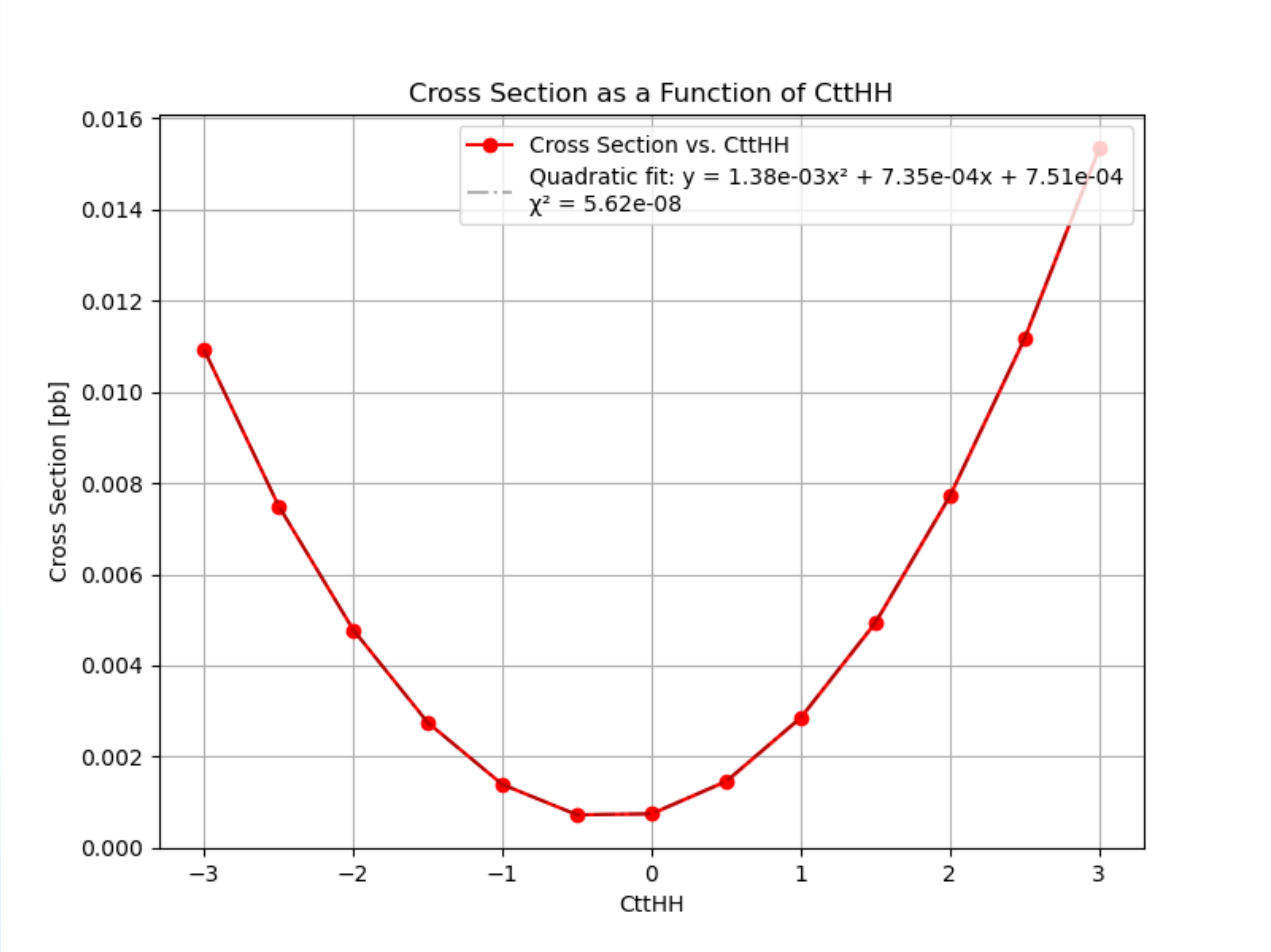
arXiv:2304.01968

Connects HEFT and SMEFT in $t\bar{t}HH$

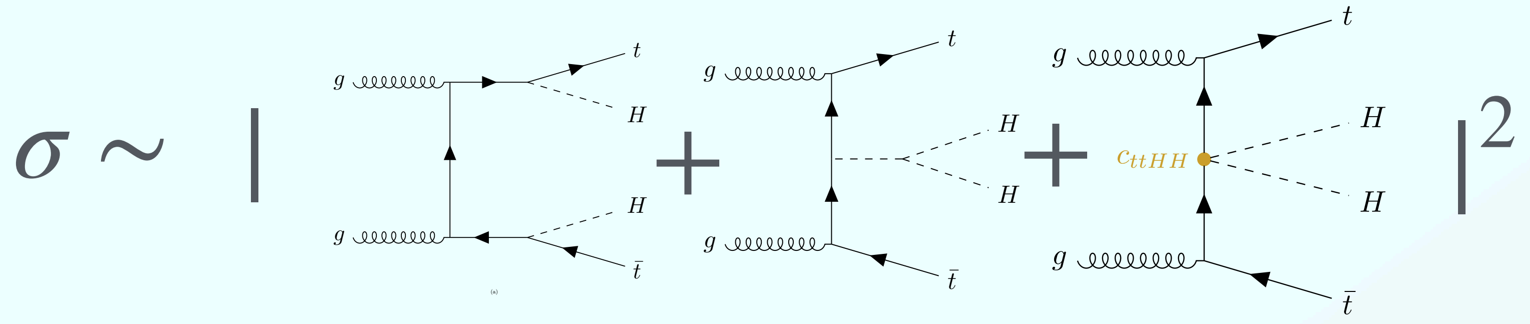
In SMEFT, $t\bar{t}HH$ and $t\bar{t}H$ processes are **bound together**

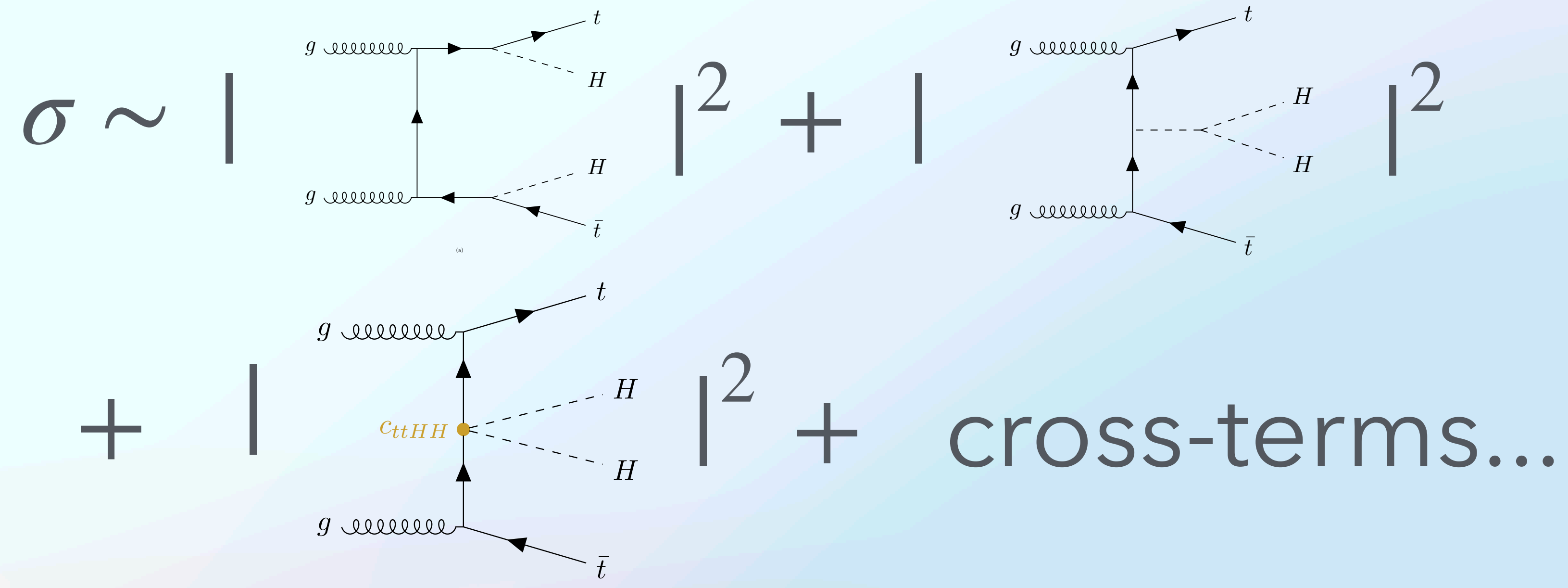
HEFT provides a way to **decorellate them** and study the Higgs mechanism

Cross-section dependance



Quadratic dependance → **Expected**





This also tells us that the cross-terms are small wrt. quad. terms

How to extract the most kin. information?

Ideally : $\sim \dfrac{\mathcal{M}_{SM}}{\mathcal{M}_{BSM}}$

→ optimal as long as phase-space is ~comparable

not trivial as we proble heavy-mass

→ but require to define the Wilson coefficient space to be probed

i.e. you need to know your plan in advance
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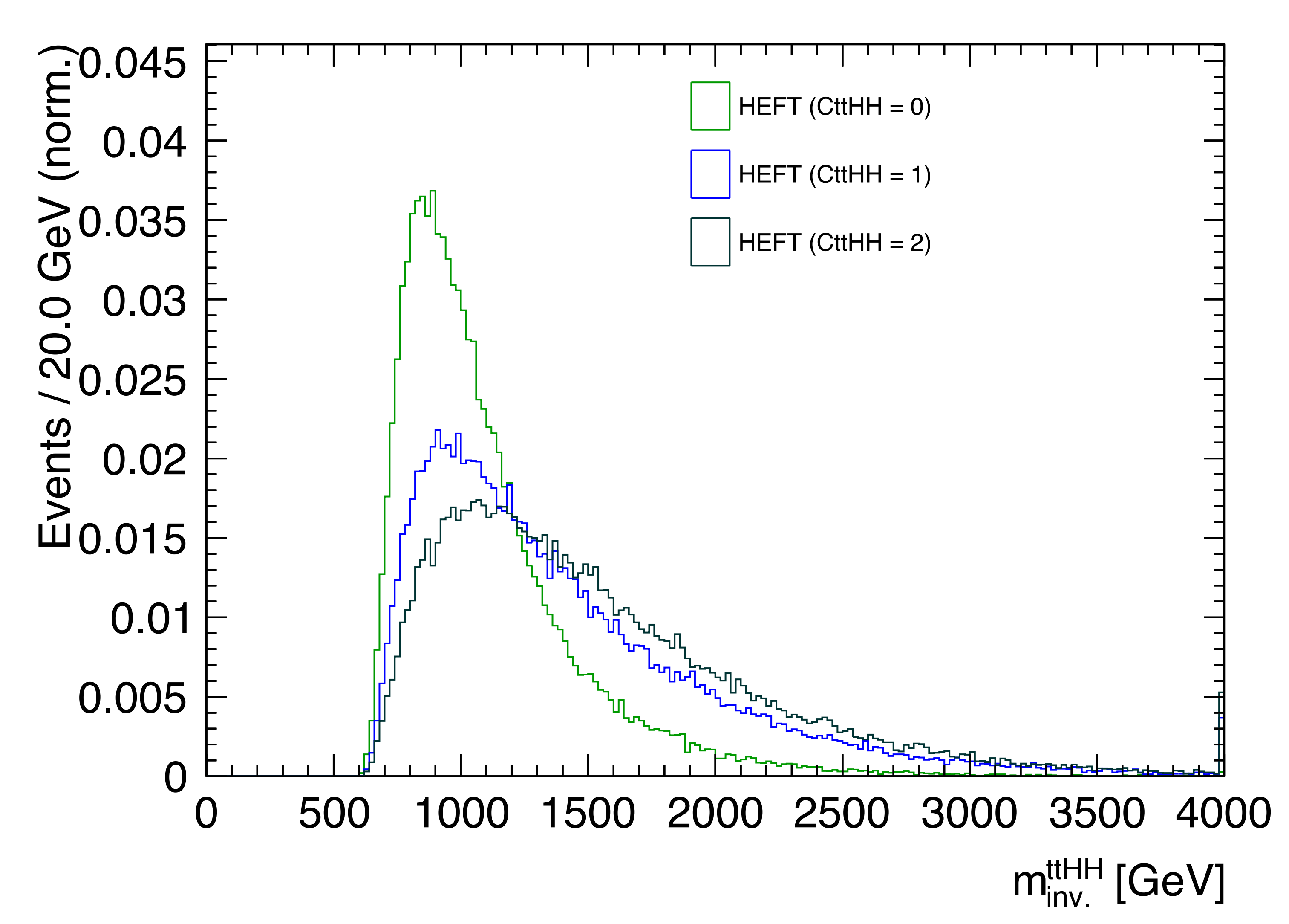
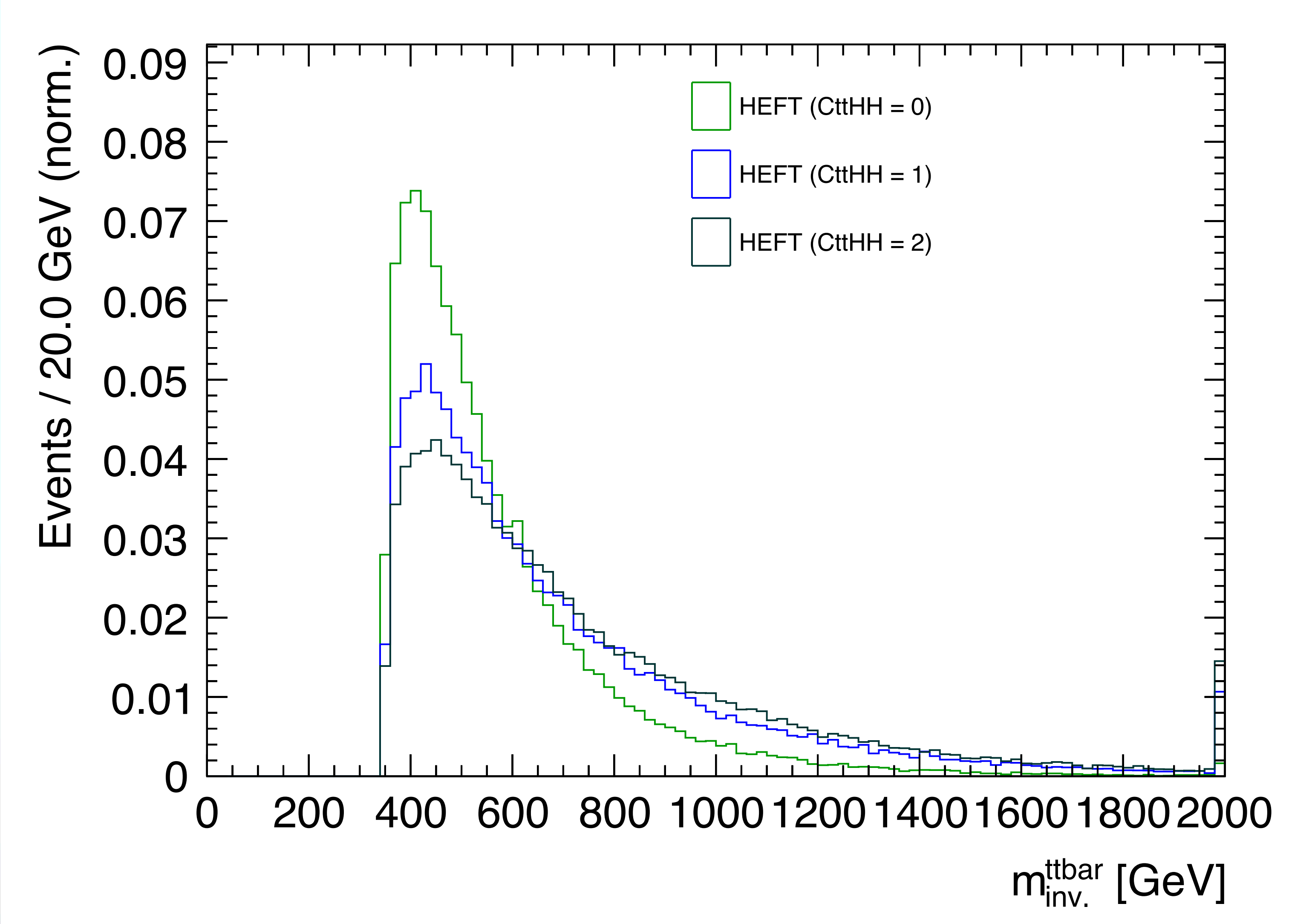
Instead we can take a sensitive distribution





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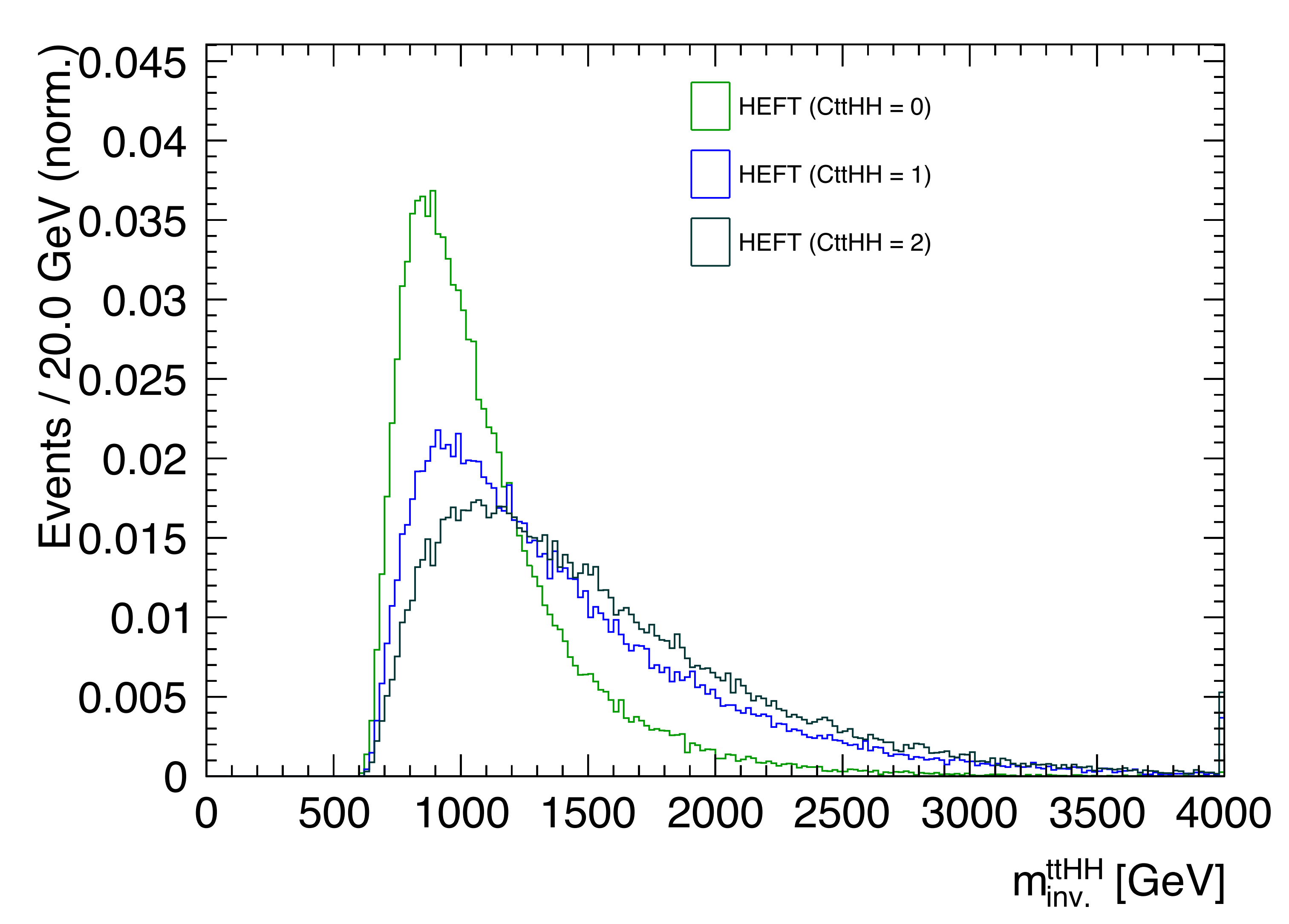

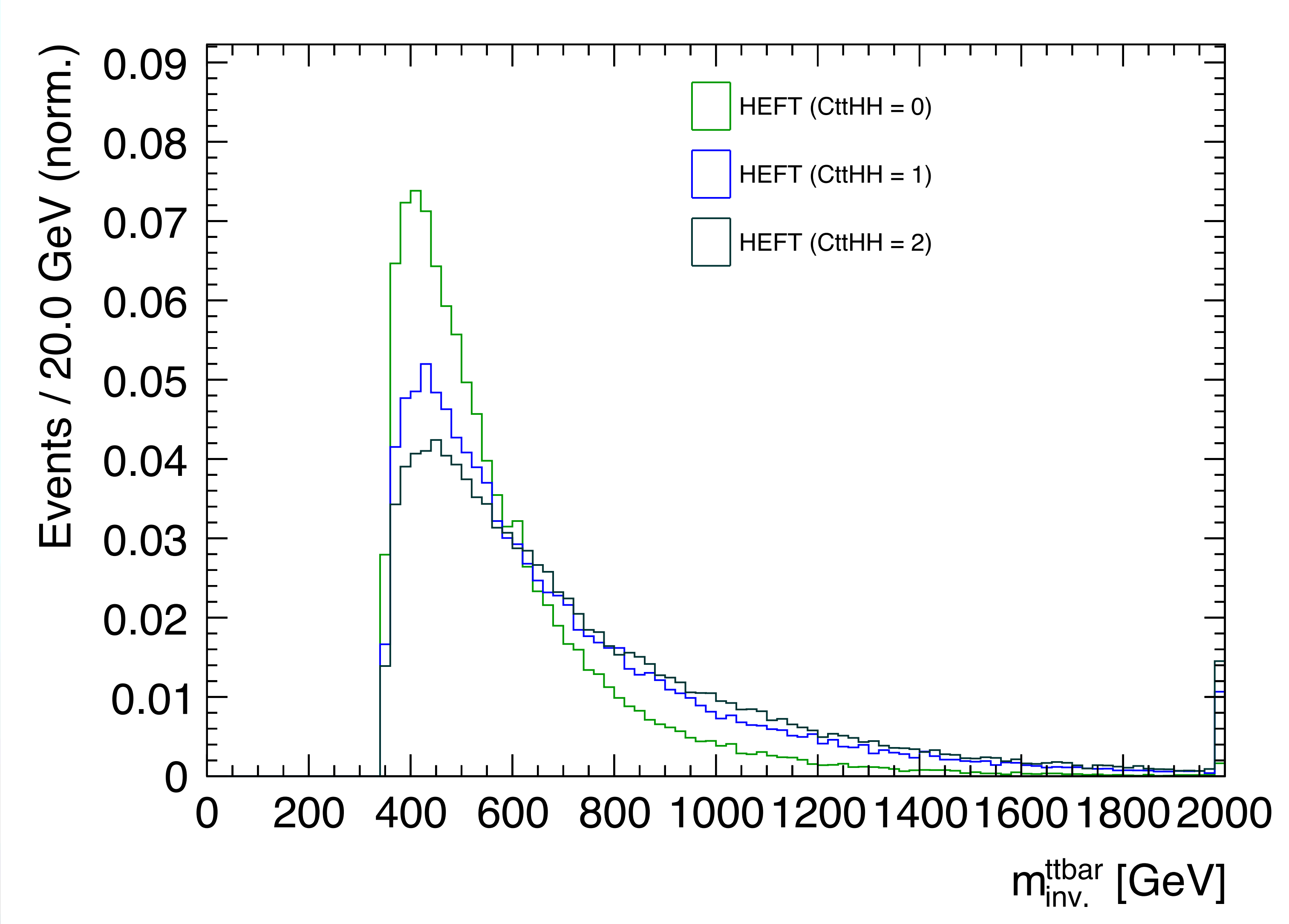

Or even better…

How to extract the most kin. information?

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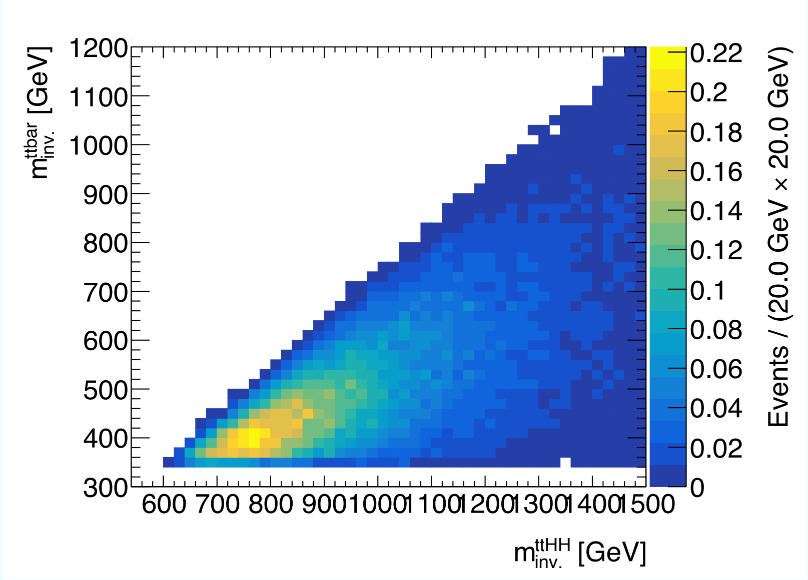
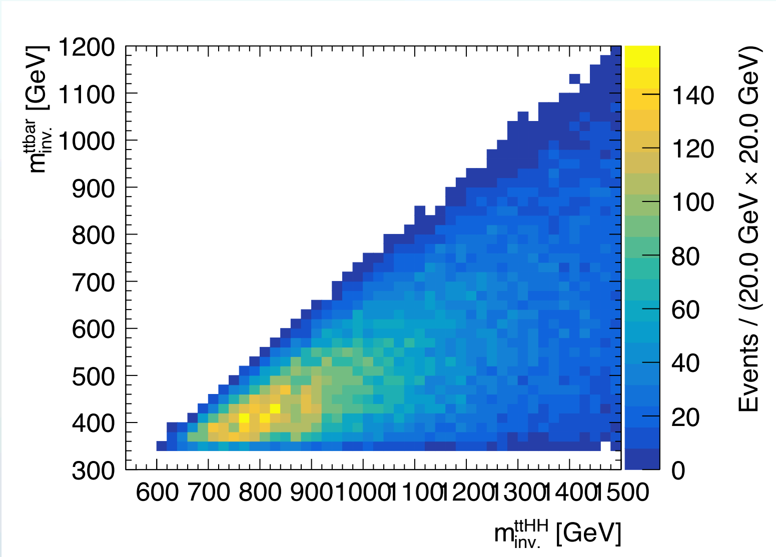
We can take a **2D** distribution:

$$\frac{(m_{\text{inv.}}^{t\bar{t}HH}, m_{\text{inv.}}^{t\bar{t}})_{SM}}{(m_{\text{inv.}}^{t\bar{t}HH}, m_{\text{inv.}}^{t\bar{t}})_{BSM}} \rightarrow$$





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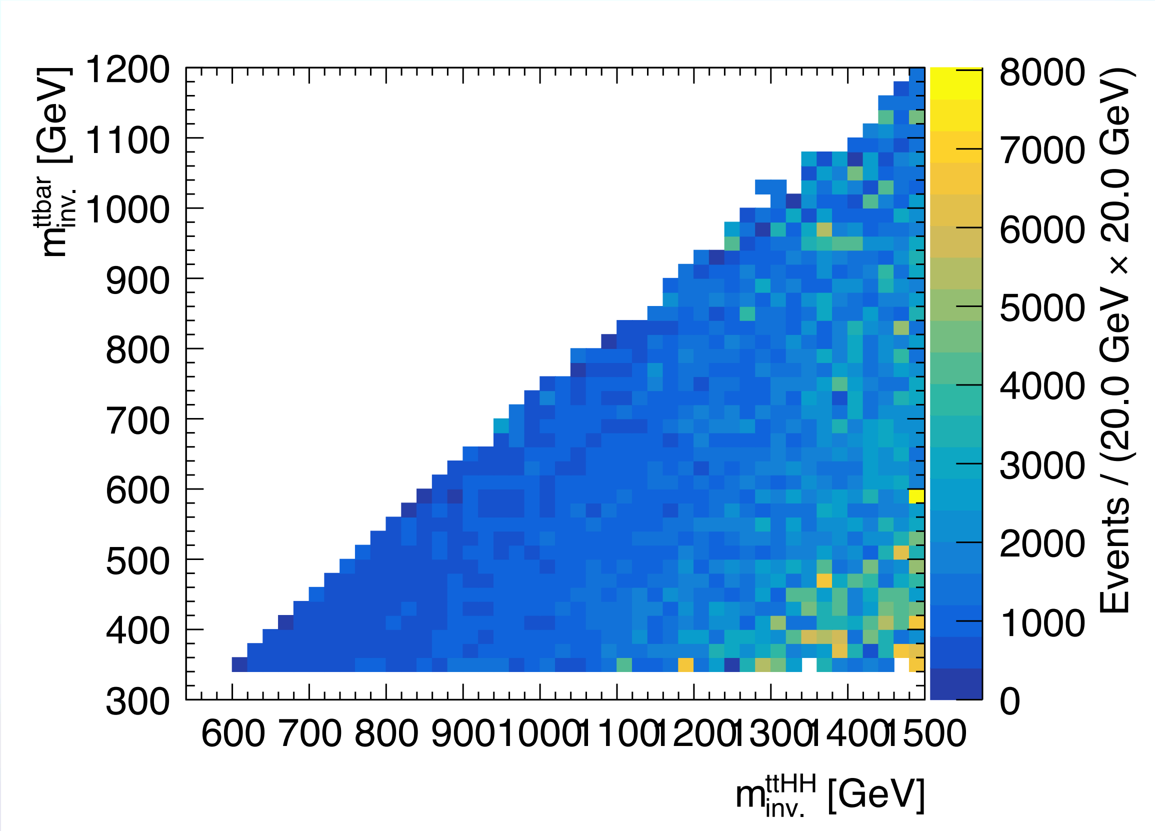
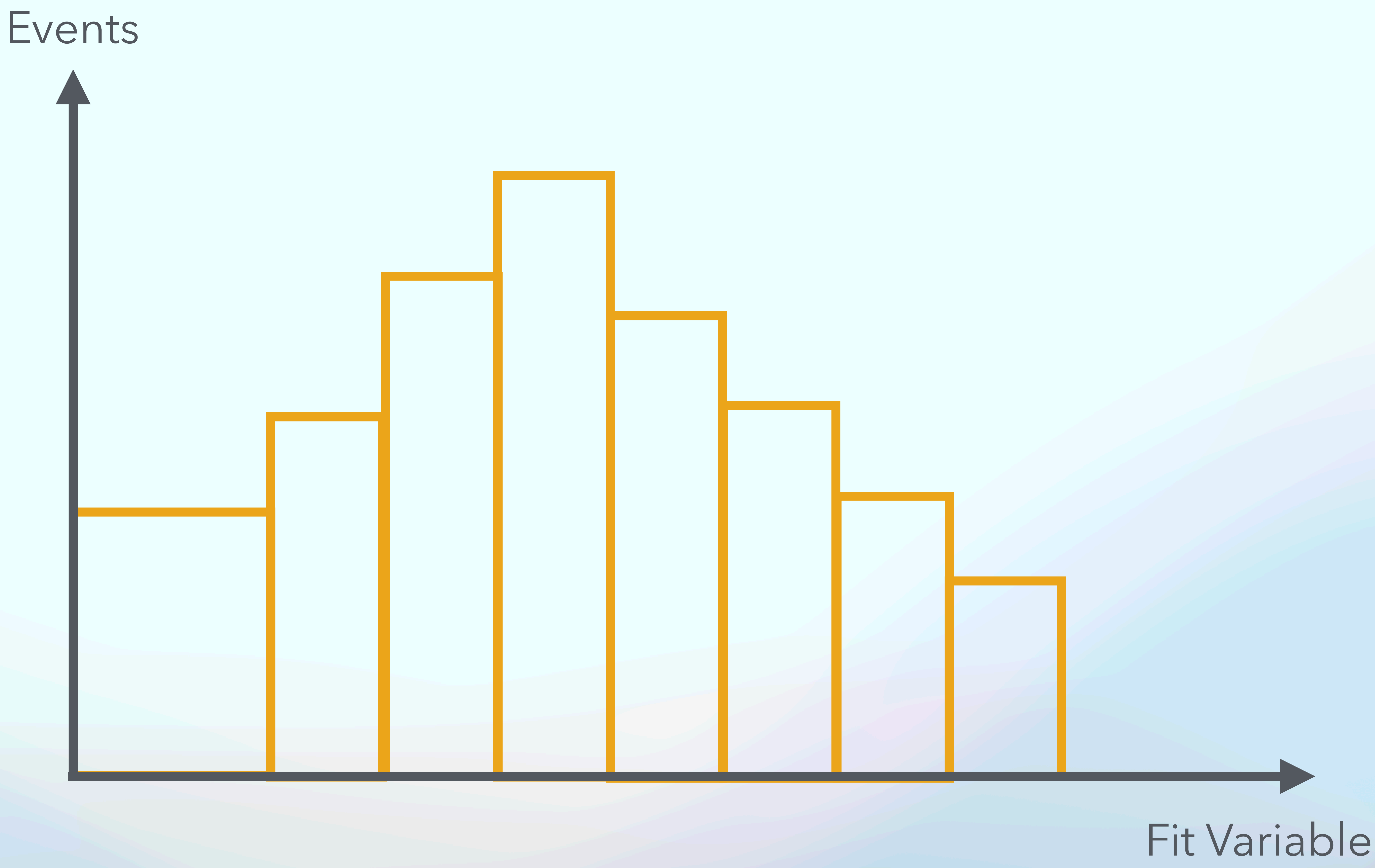


arXiv:2502.20976

answers this question in the context of ggF diHiggs

What effects do we need to take into account?



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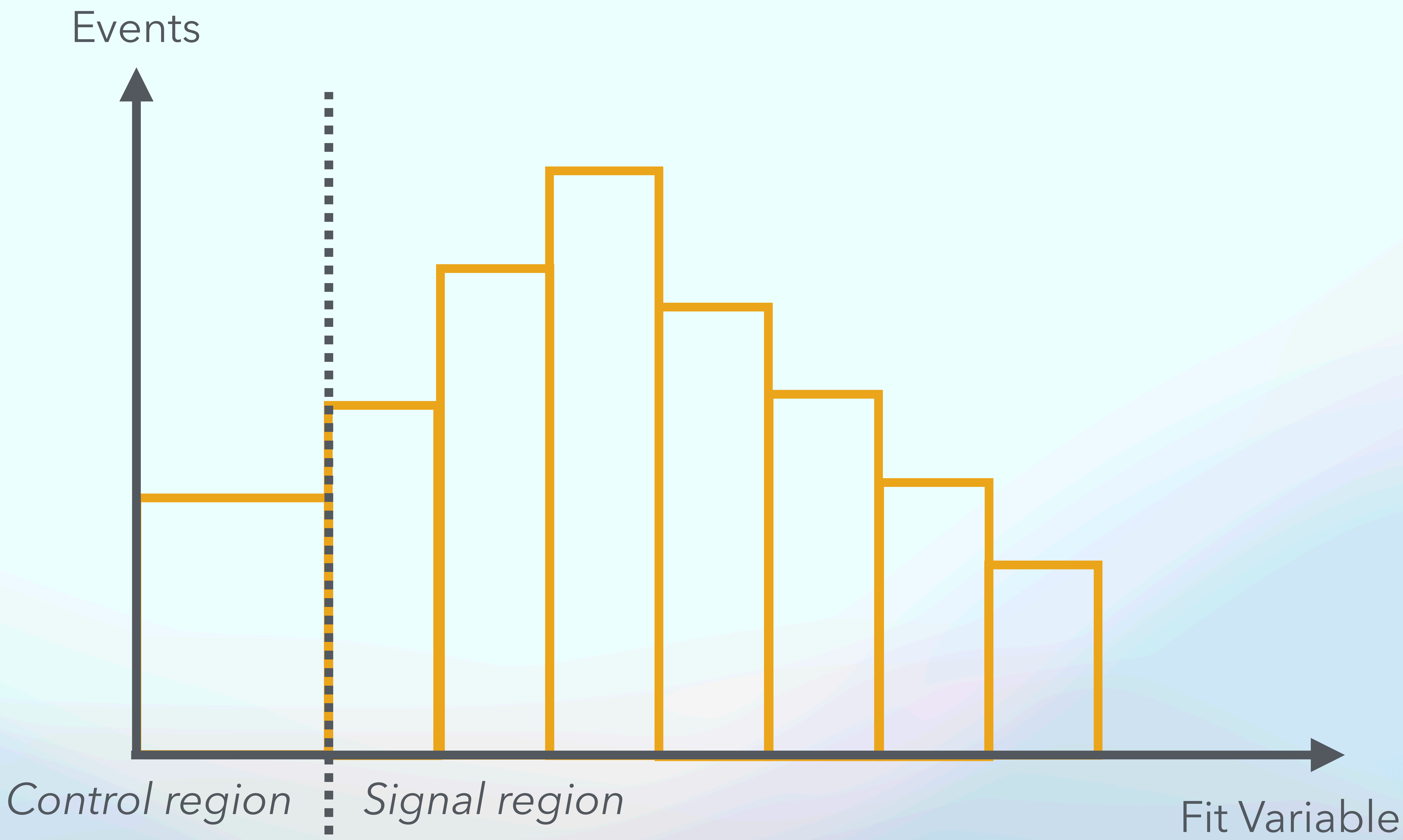
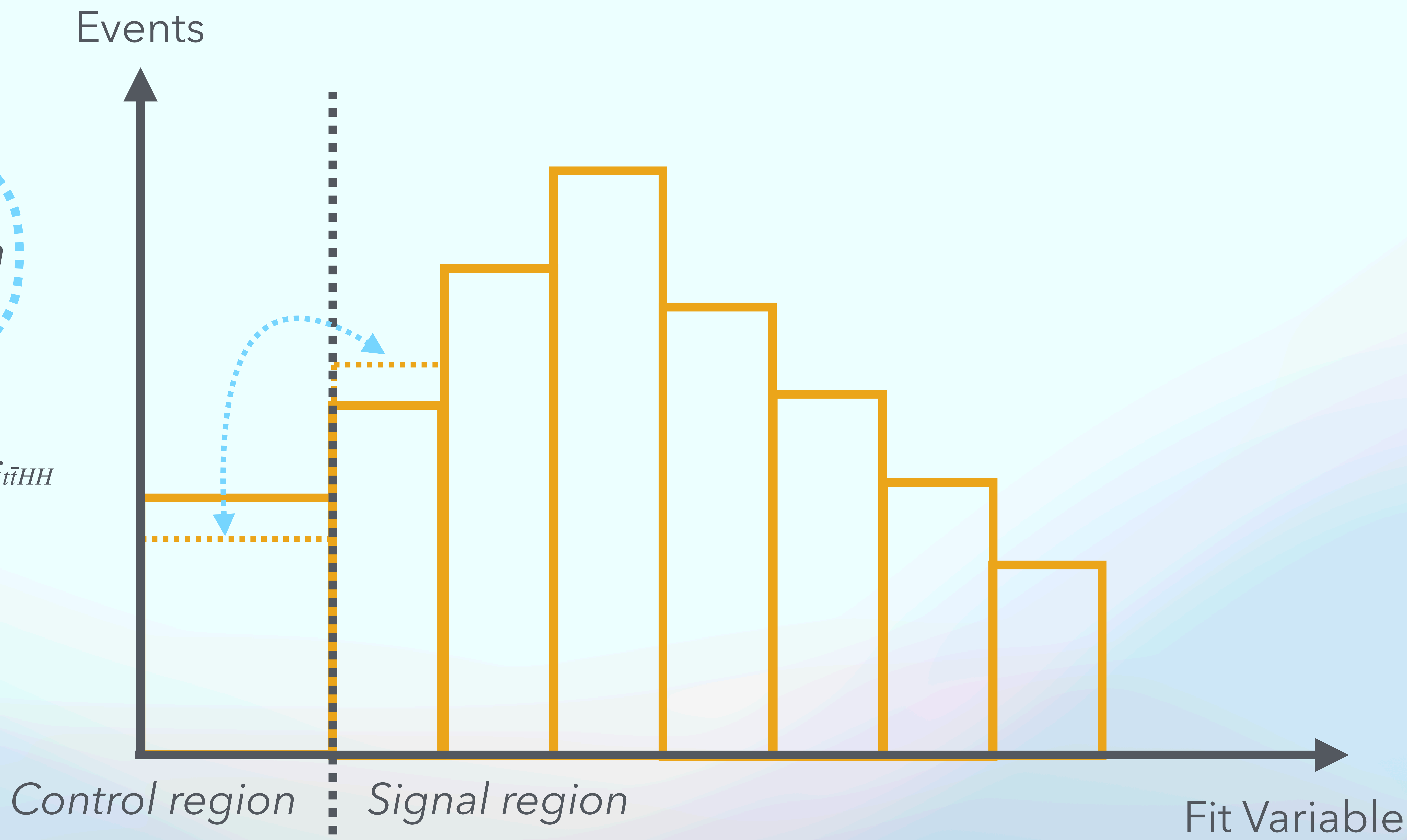


What effects do we need to take into account?

<u>Acceptance effects covered</u> by 30% unc. on signal yield

*30% is **very** conservative*

Flat uncertainty for all values of $c_{t\bar{t}HH}$



What effects do we need to take into account?

Does the shapes have an impact on the sensitivity?

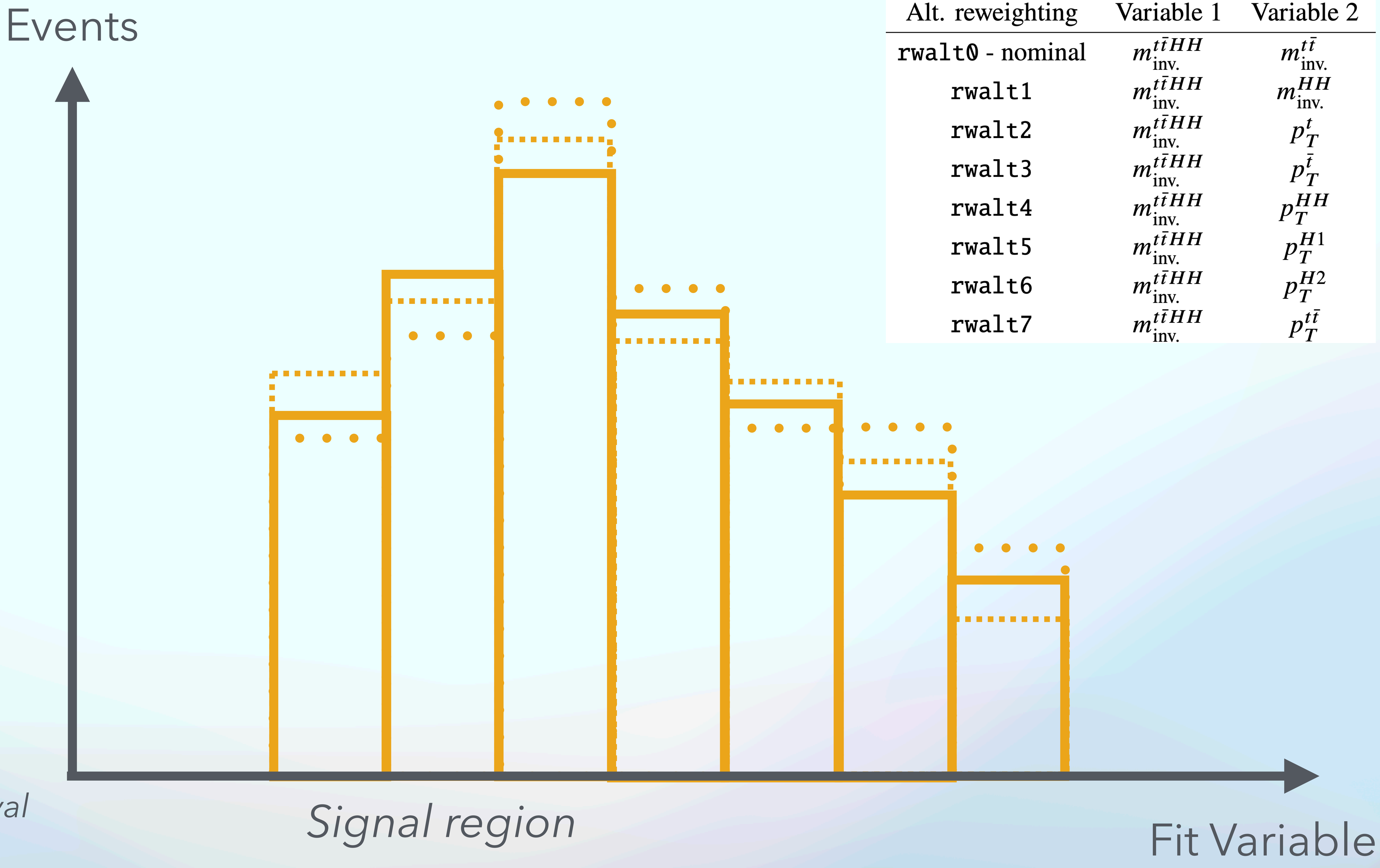
↓

We tested 7 alternative reweightings against <u>no shape variation</u>

↓

Shape variations neglected (evaluated to have a small impact)

At most 10% impact on 95% CL interval



Alt. reweighting	Variable 1	Variable 2
rwalt0 - nominal	$m_{\text{inv.}}^{t\bar{t}HH}$	$m_{\text{inv.}}^{t\bar{t}}$
rwalt1	$m_{\text{inv.}}^{t\bar{t}HH}$	$m_{\text{inv.}}^{HH}$
rwalt2	$m_{\text{inv.}}^{t\bar{t}HH}$	p_T^{t}
rwalt3	$m_{\text{inv.}}^{t\bar{t}HH}$	$p_T^{\bar{t}}$
rwalt4	$m_{\text{inv.}}^{t\bar{t}HH}$	p_T^{HH}
rwalt5	$m_{\text{inv.}}^{t\bar{t}HH}$	p_T^{H1}
rwalt6	$m_{\text{inv.}}^{t\bar{t}HH}$	p_T^{H2}
rwalt7	$m_{\text{inv.}}^{t\bar{t}HH}$	$p_T^{t\bar{t}}$

Strategy and results

Exploit **cross-section dependance** in 1L and ML channels

Acceptance effects covered by 30% unc. on signal yield

Shape variations neglected (evaluated to have a small impact)

Reinterpretation

$$\mathscr{L}(d\,|\,\mu) \longrightarrow \mathscr{L}(d\,|\,\sigma(\,c_{t\bar{t}HH}\,))$$

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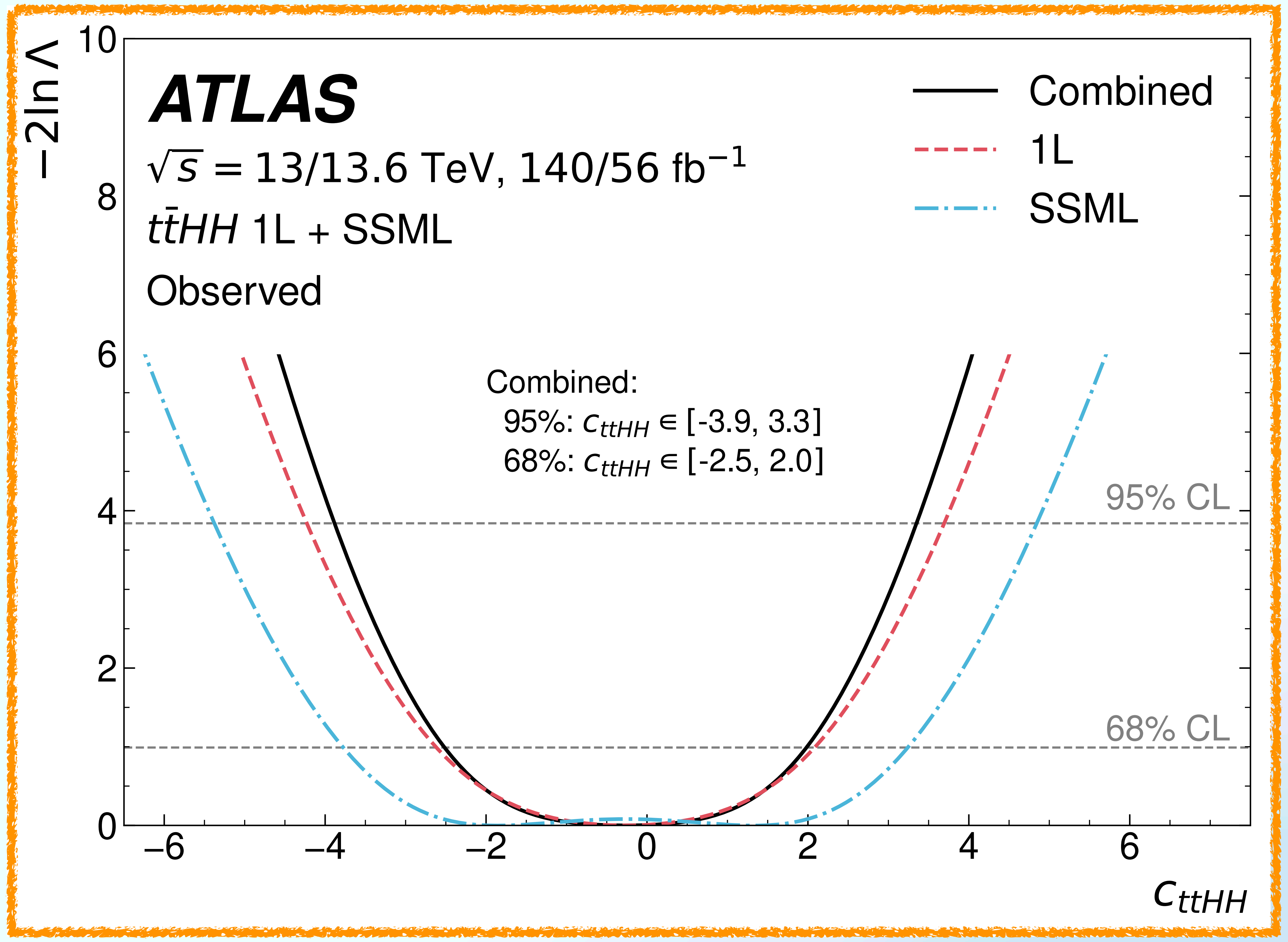

Almost flat likelihood (small degeneracy in ML channel)

→ Not sensible to sign

Exp. : $c_{t\bar{t}HH} \in [-4.1, 3.5]$ @ 95 % CL

Obs. : $c_{t\bar{t}HH} \in [-3.9, 3.3]$ @ 95 % CL

Outlook of ATLAS analysis

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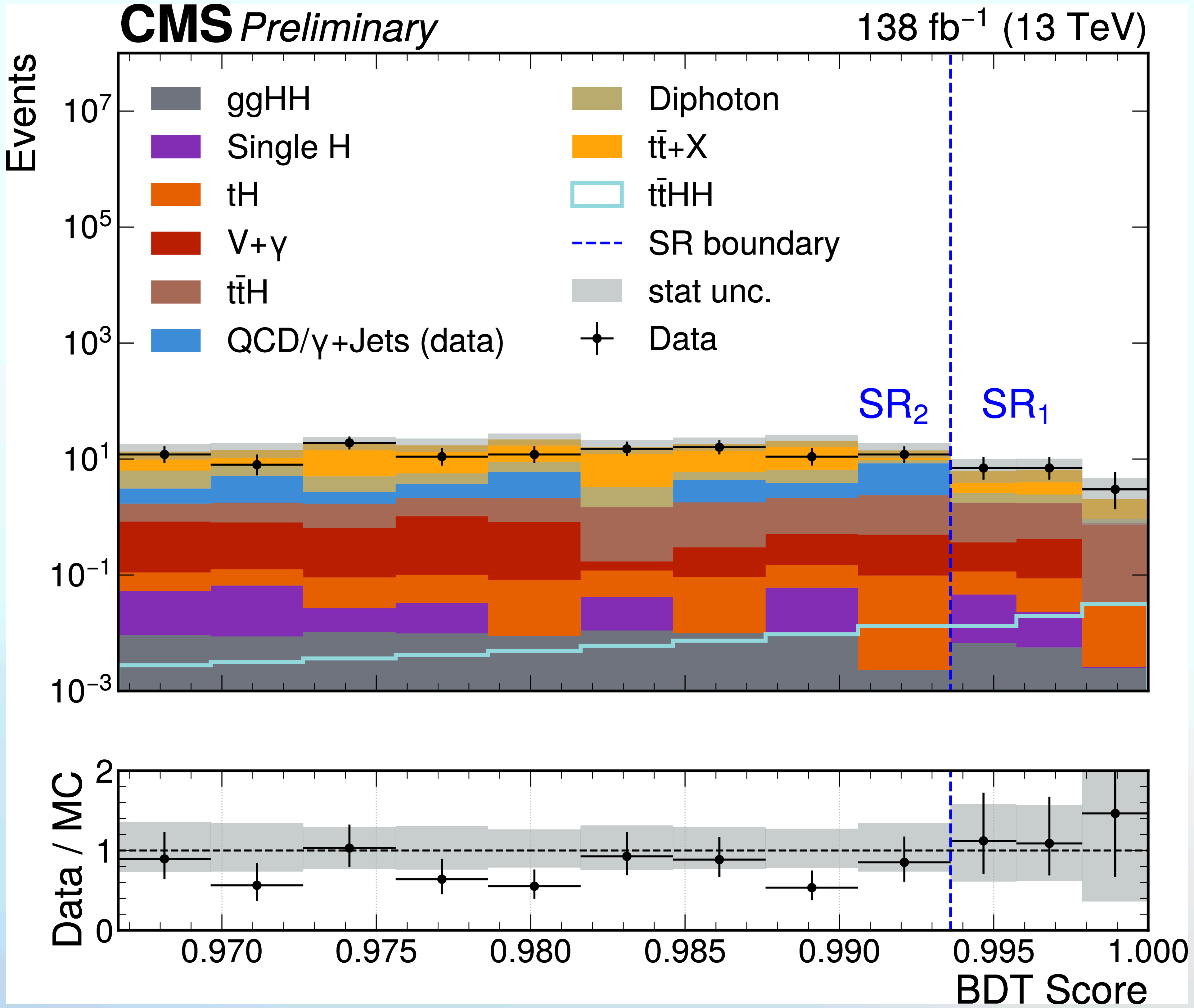
	CMS $t\bar{t}HH$ [CMS-PAS-HIG-23-004]	
Obs. 95% CL limits on $c_{t\bar{t}HH}$	[-8.0, 7.5]	

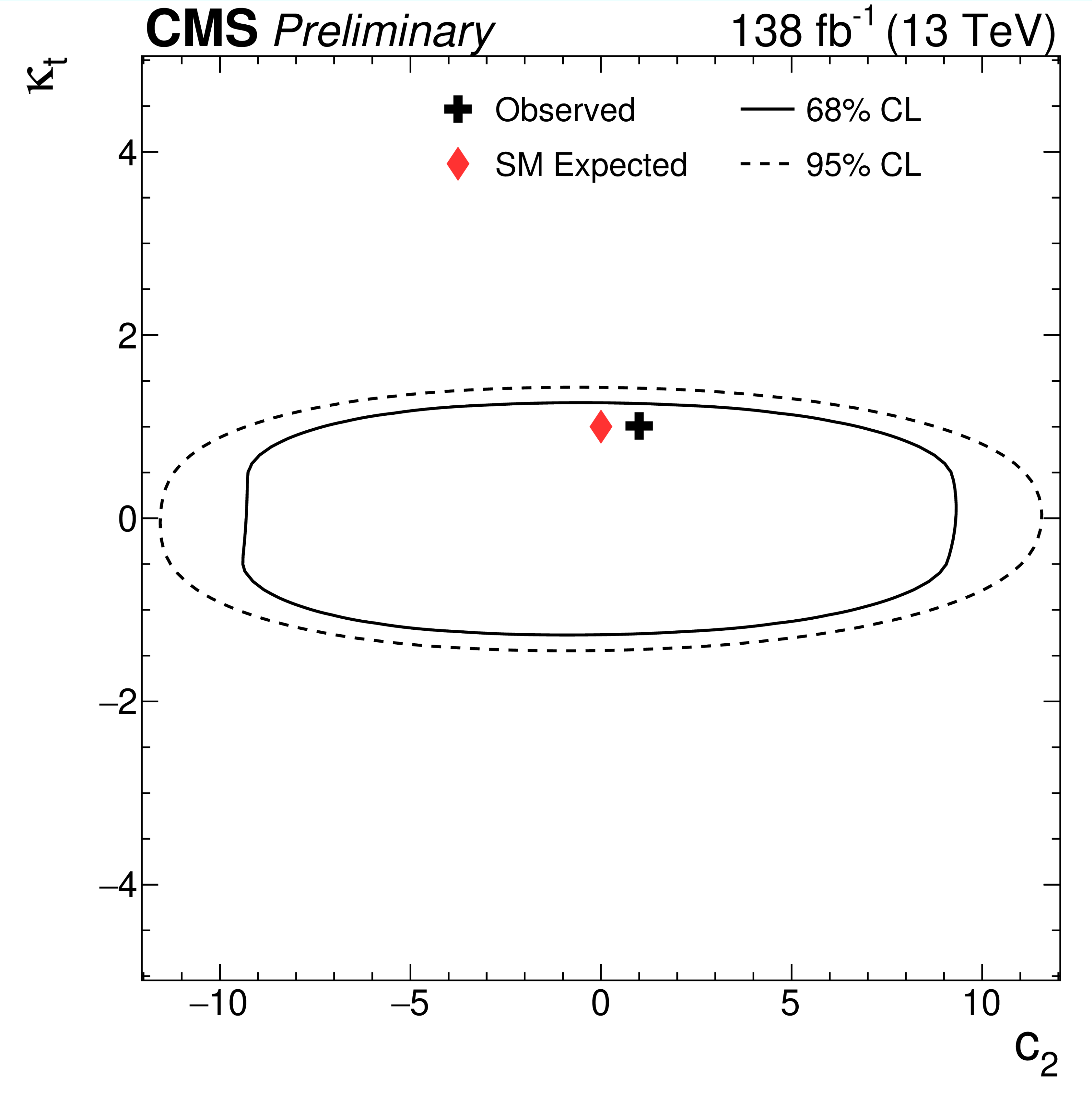
CMS ttHH analysis (1)

CMS-PAS-HIG-23-004

- **Targets** $\gamma\gamma + X$ with $X \in [b, W^{\pm}, \tau^{\pm}]$ with **Run 2 data**
- Similar modelling strategy as ATLAS (MVA discriminant)
- **Both** $c_{t\bar{t}HH}$ and c_{tHH} probed (called resp. c_2 and κ_t)

Not κ_λ...



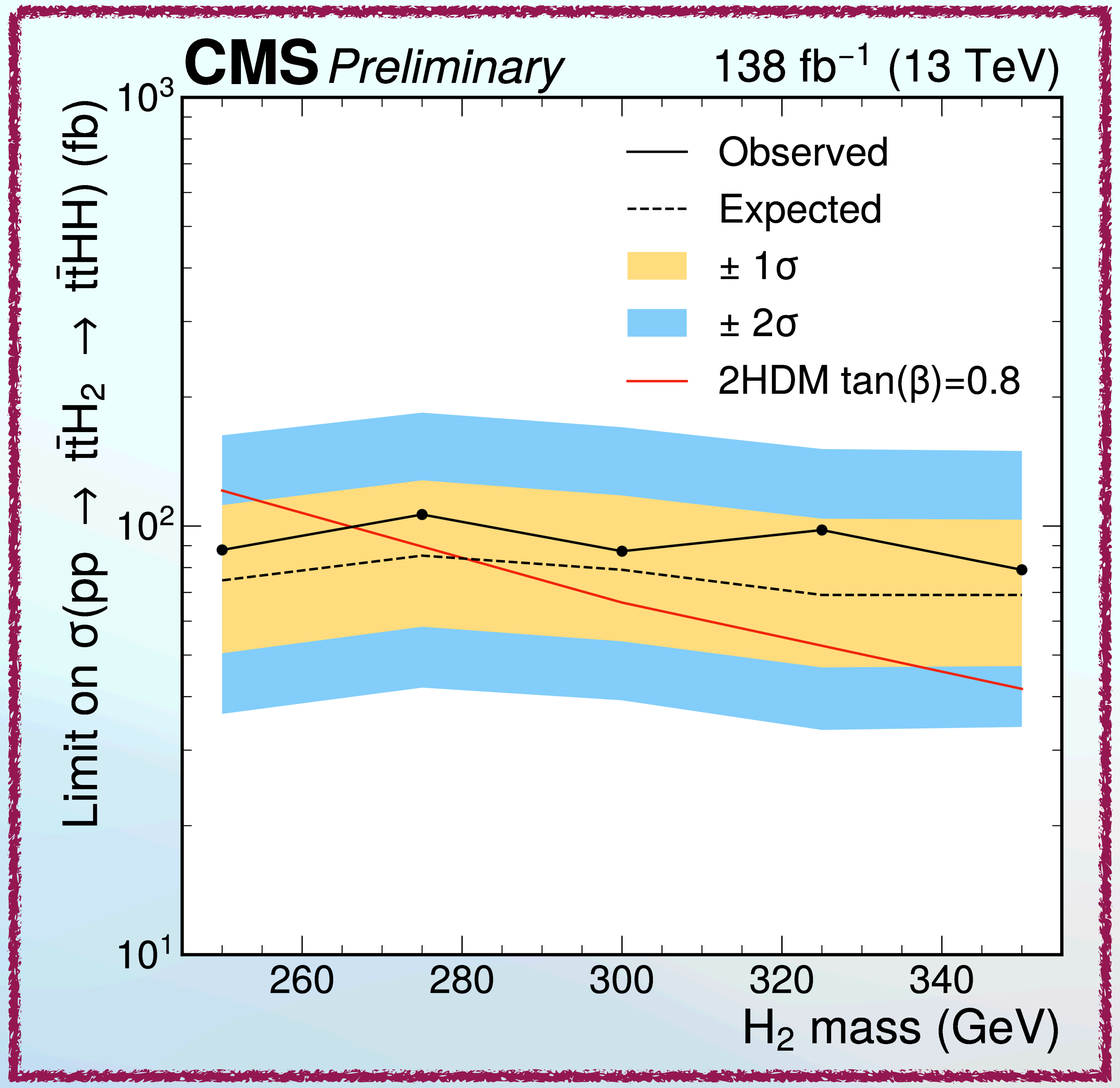


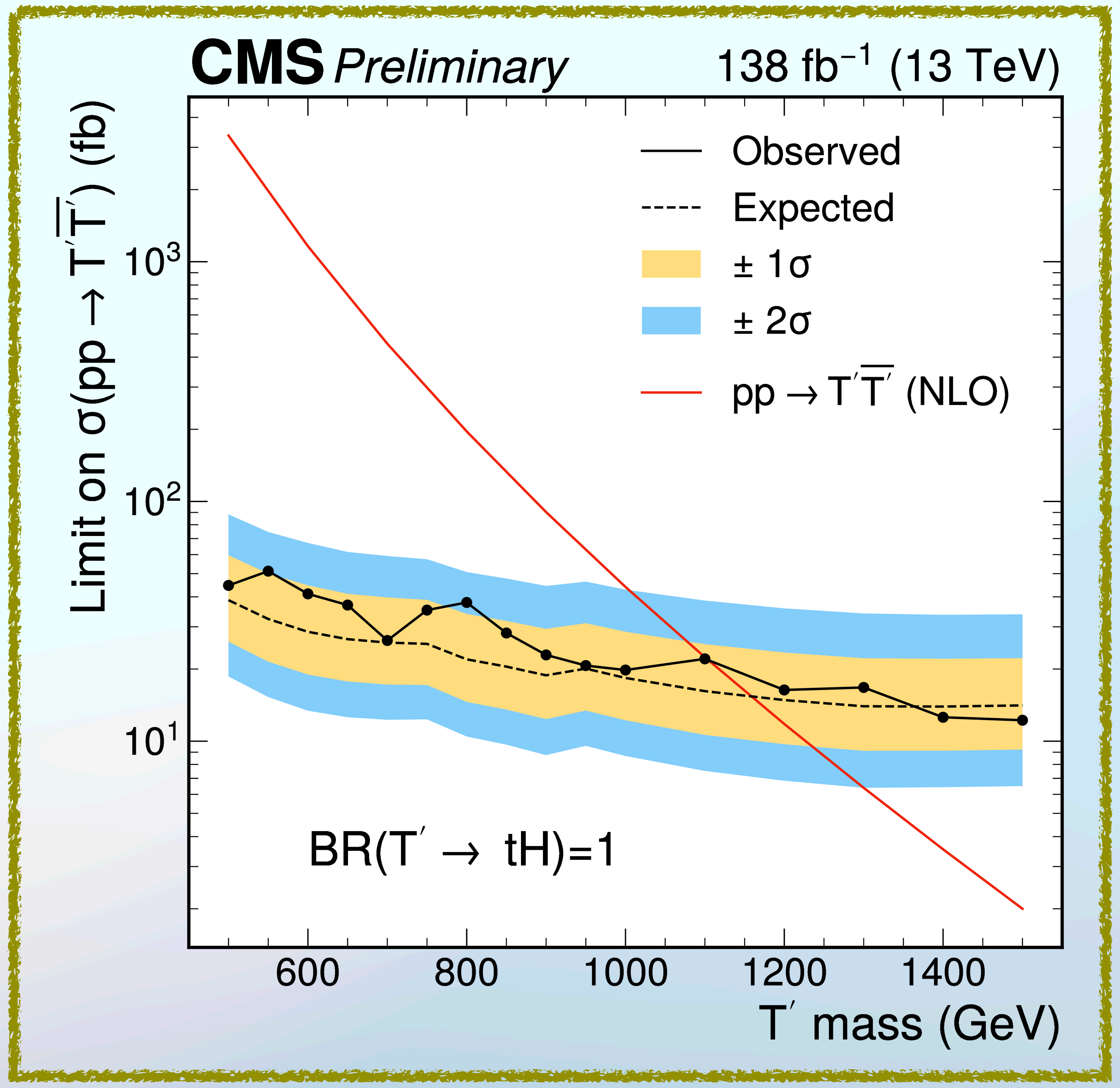
CMS ttHH analysis (2)

CMS-PAS-HIG-23-004

Limits on **resonant production** of CP-even **heavy neutral scalar** (H_2) in the context of **type-II 2HDM** and **heavy VLQ T' pair production** in the $T' \rightarrow tH$ final state

natural candidate to test HEFT vs. SMEFT





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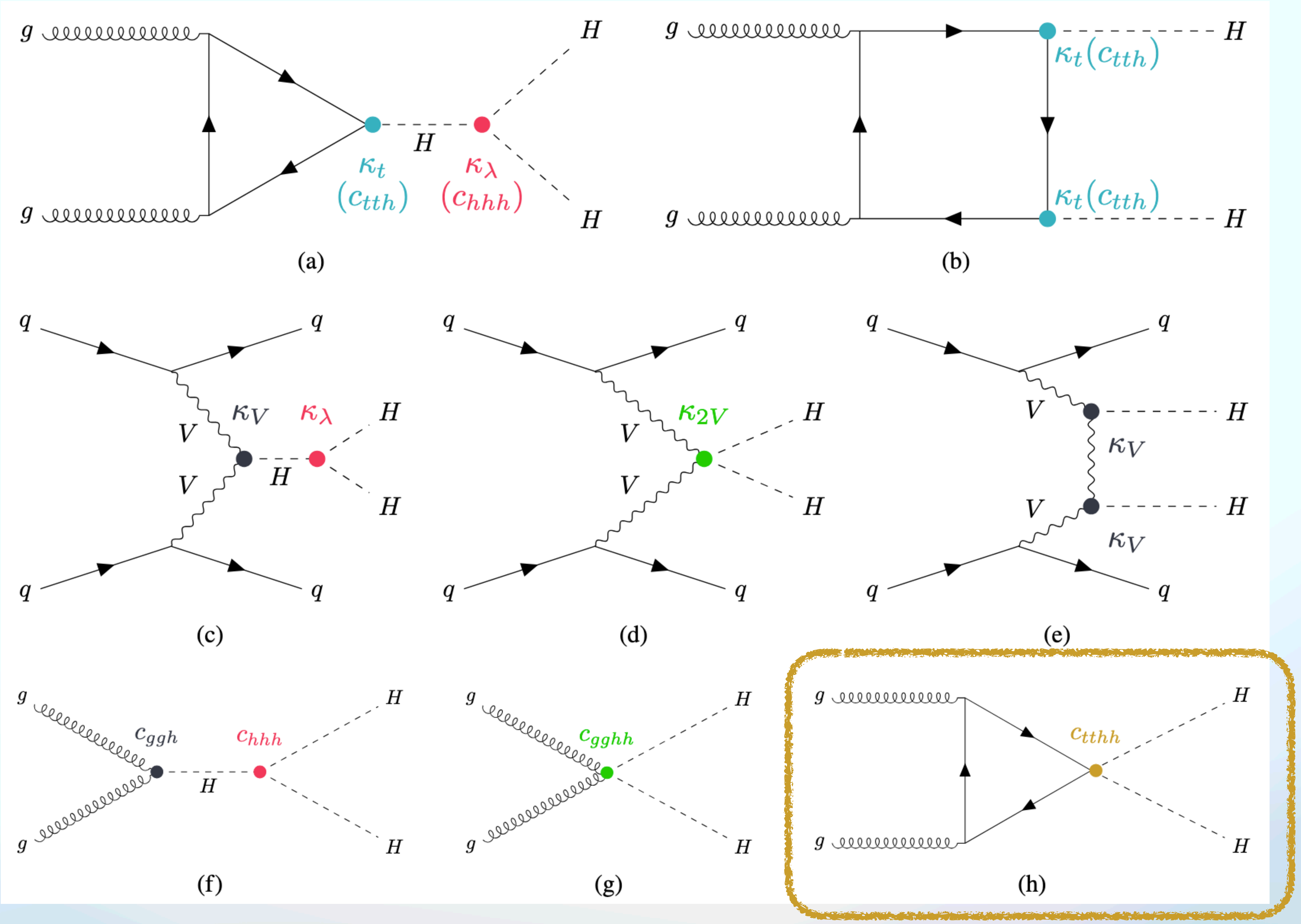
Obs. 95% CL limits on $c_{t\bar{t}HH}$	[-8.0, 7.5]	[-0.19, 0.7]	[-0.29, 0.59]

Comparison with ggF - HH



Parametrised with **more** couplings

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- **First search** for $t\bar{t}HH$ done by ATLAS
  - → Most stringent **direct limits** on $c_{t\bar{t}HH}$
- ggF more sensitive, but parametrised with two additional Higgs-gluon couplings : c_{ggH} and c_{ggHH}
  - → In $t\bar{t}HH$, these enter at higher loop order
  - → More challenging in ggF unless further assumptions imposed

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We set limits on Wilson coefficients at a **given scale**

Effect of running? *~1TeV @ LHC*

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In effective theories : **operators mixing depends on Λ**

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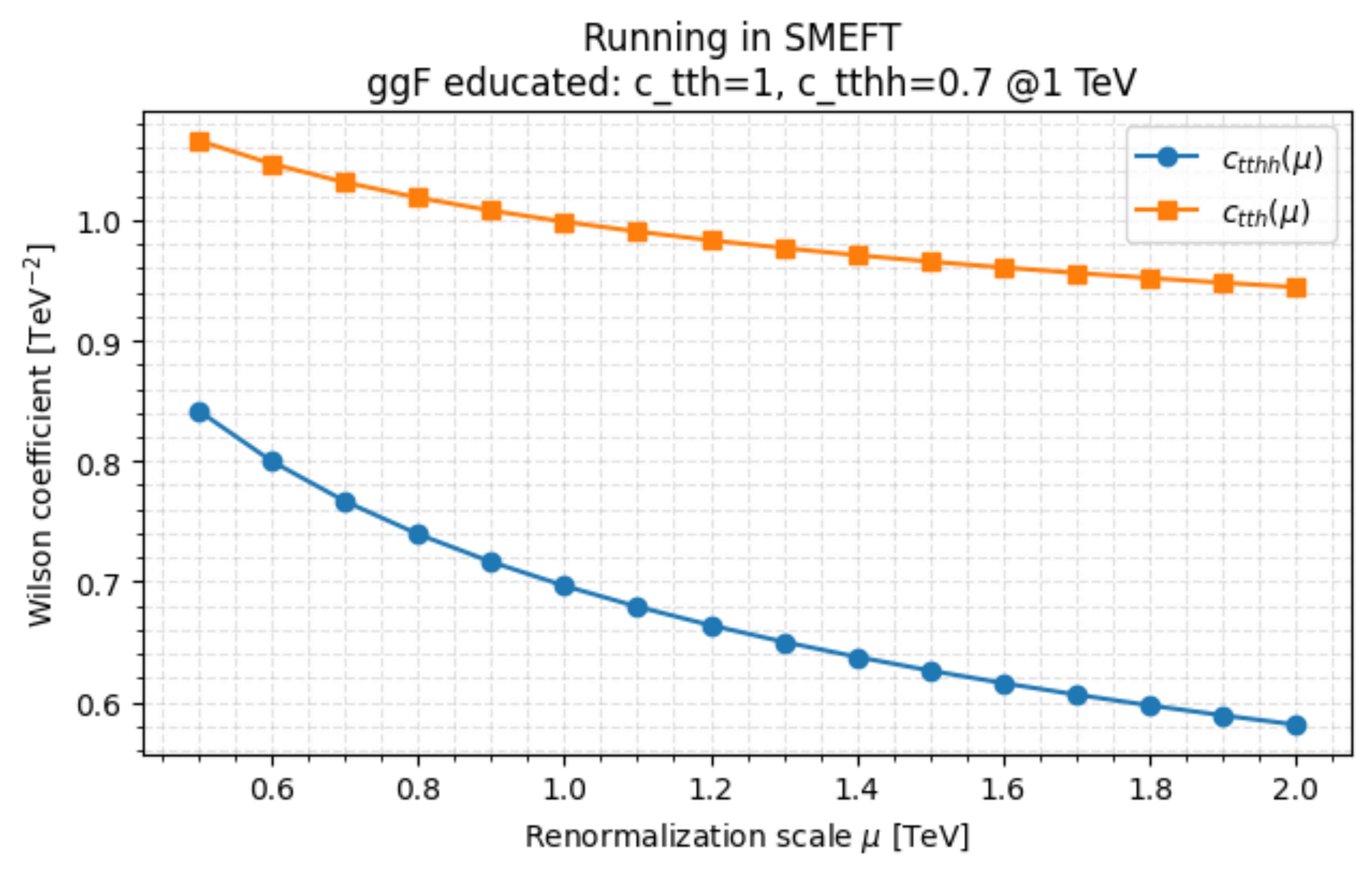

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renormalization group eqs

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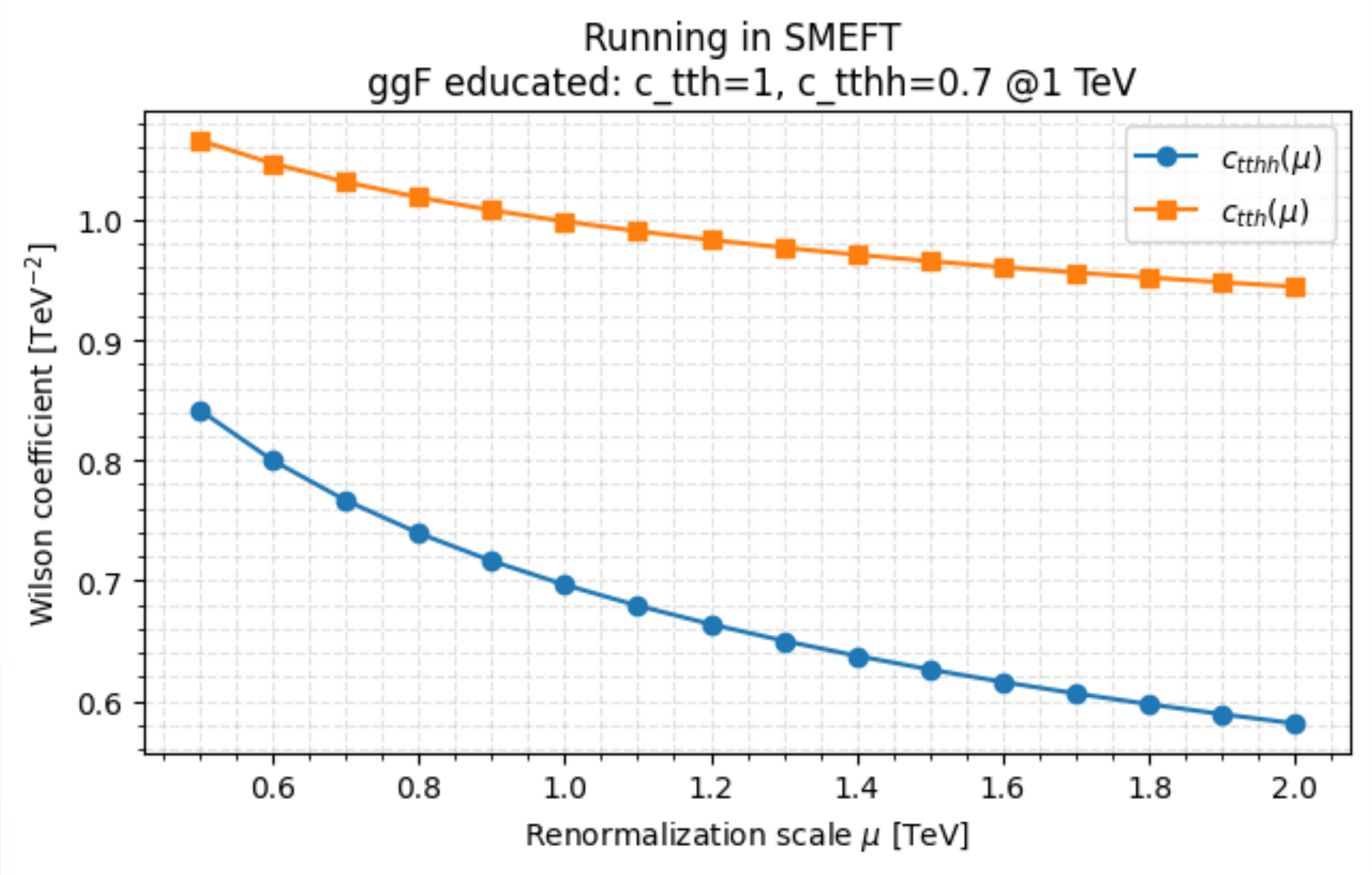

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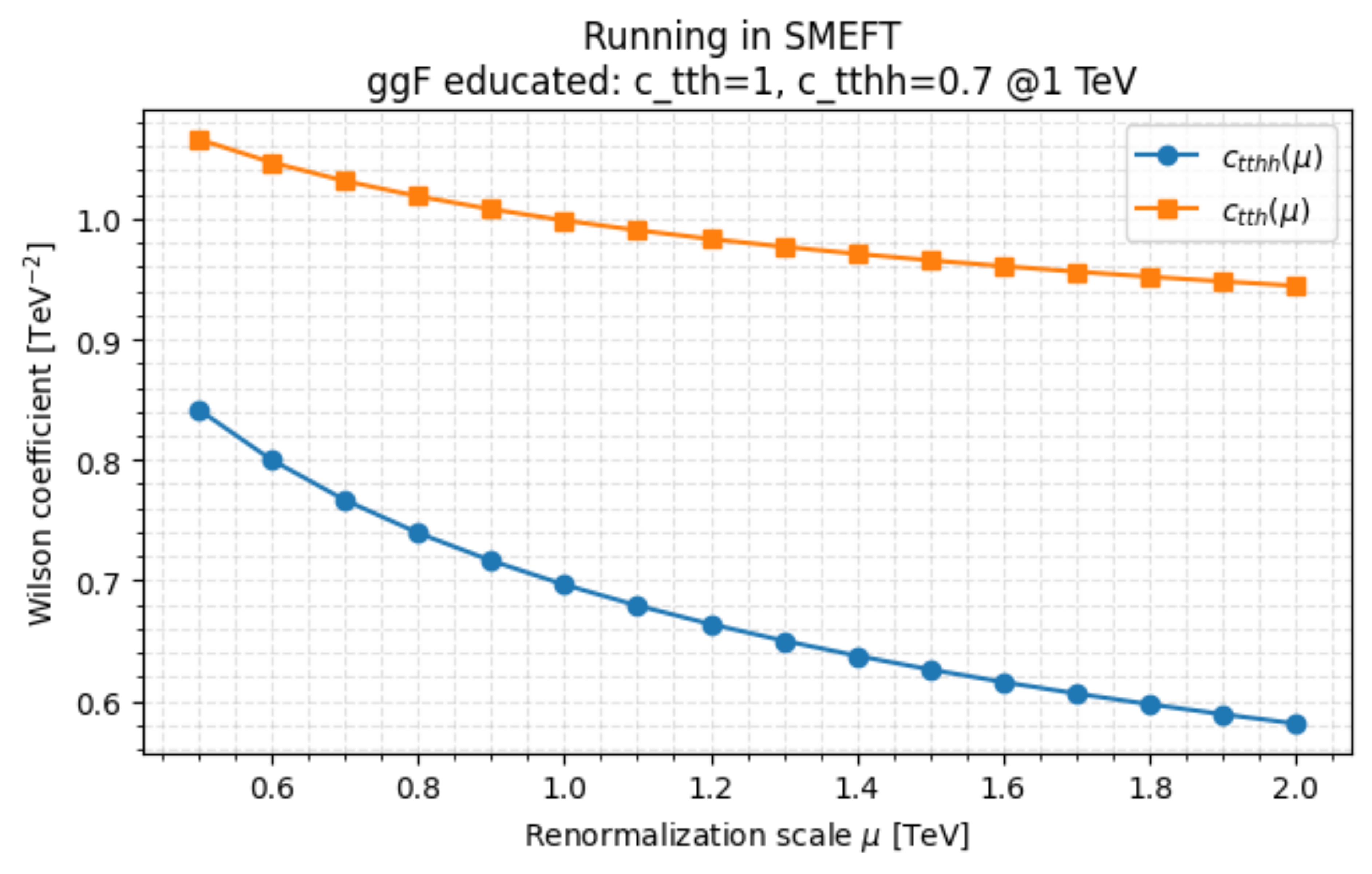

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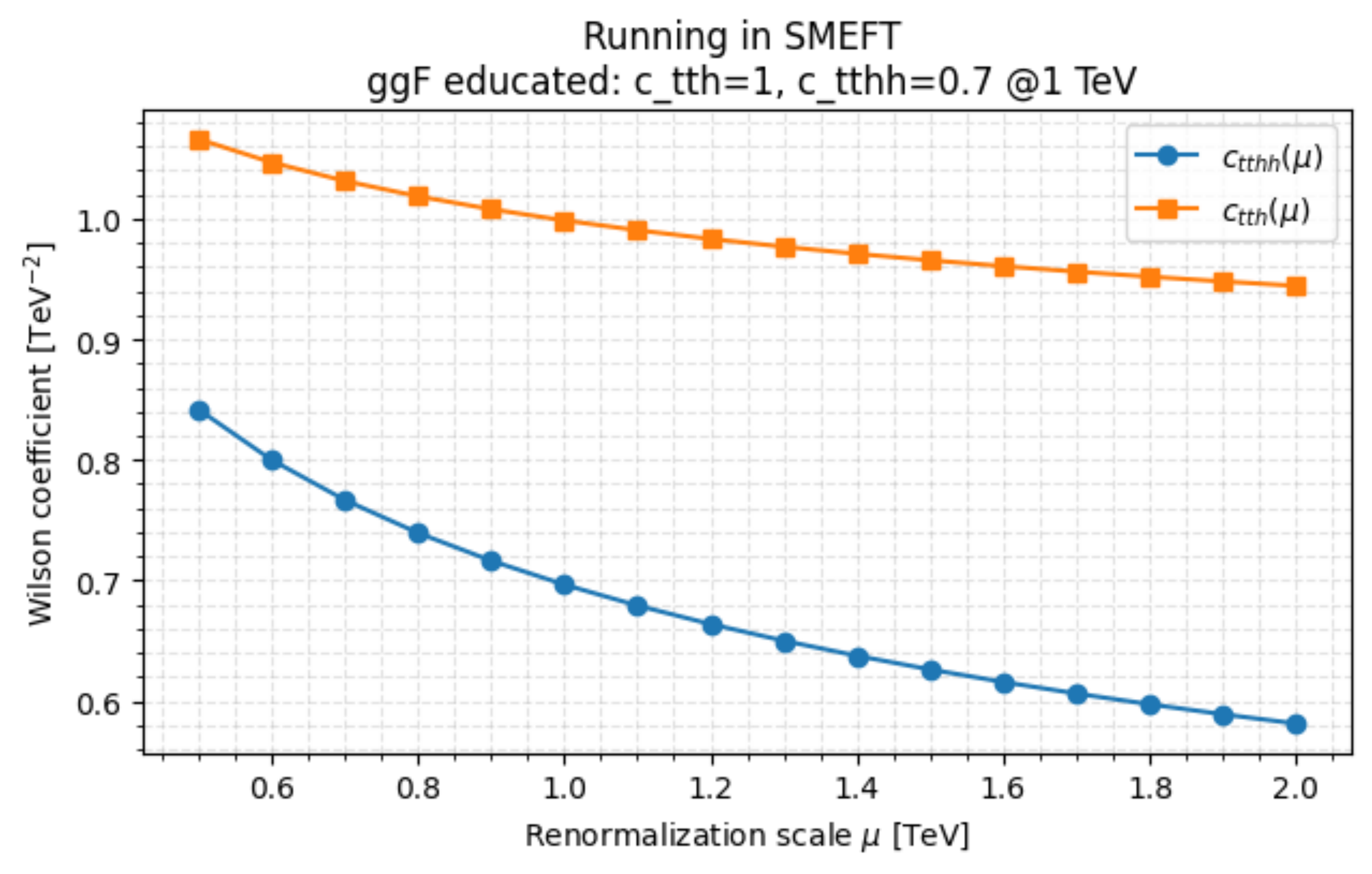

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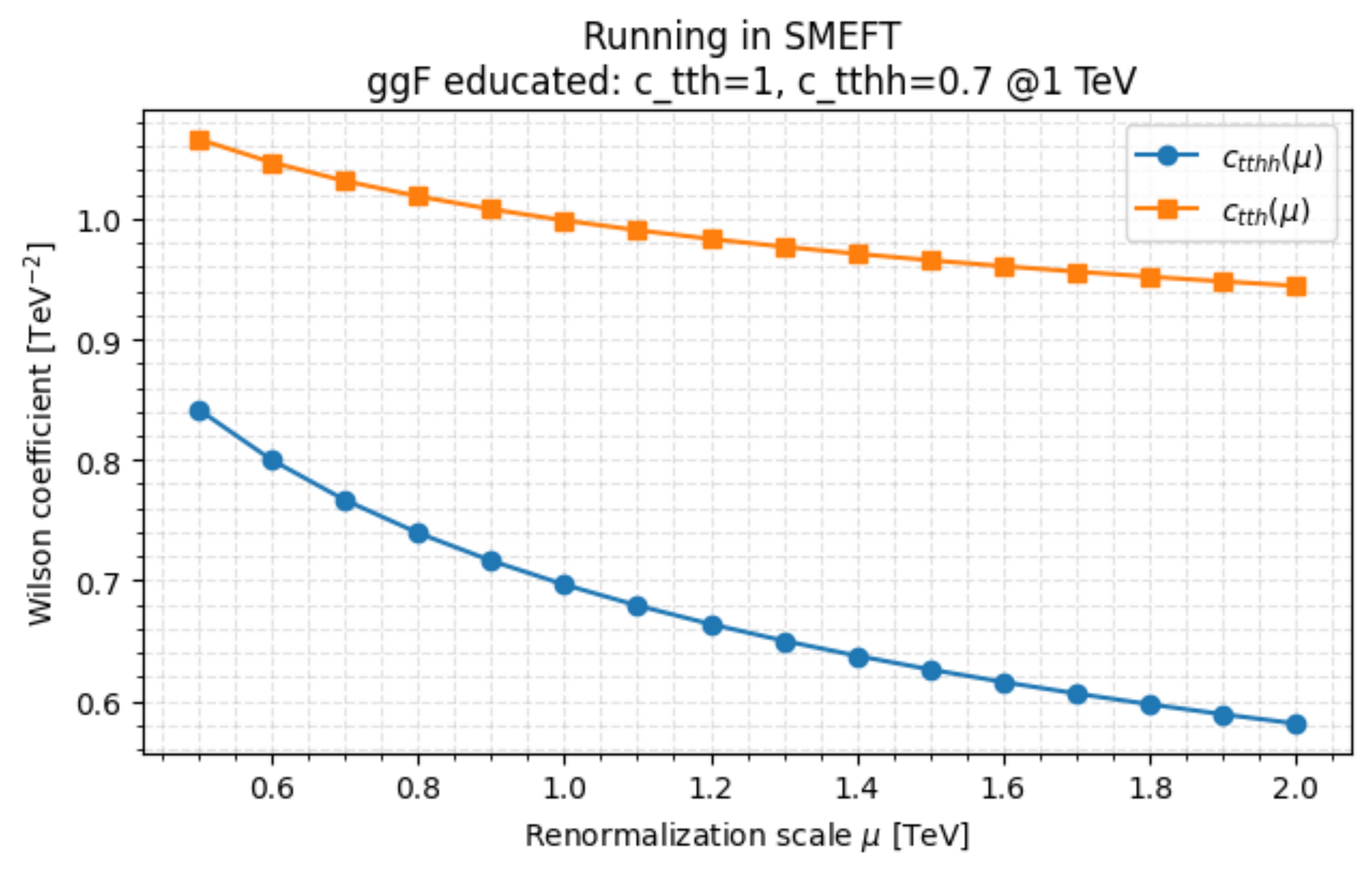

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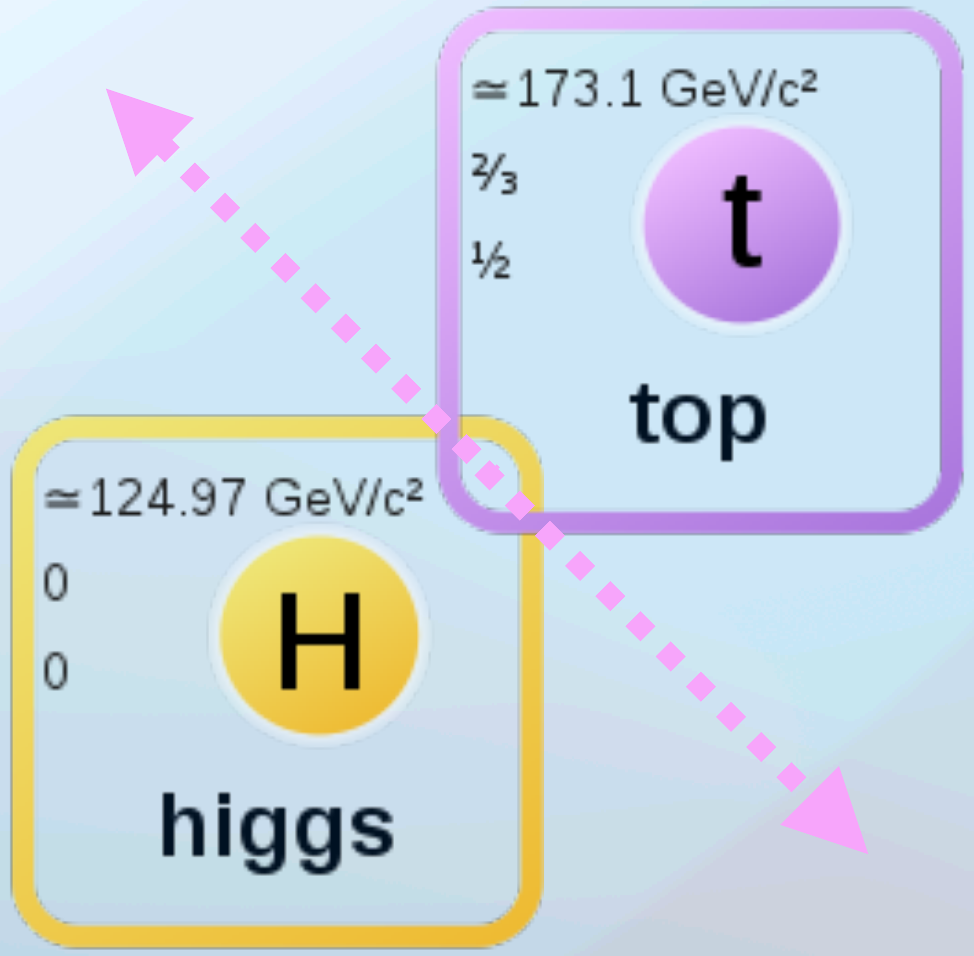
Is this running valid? → proper implementation of HEFT running needed
probably not

Conclusion

Thoughts for the future

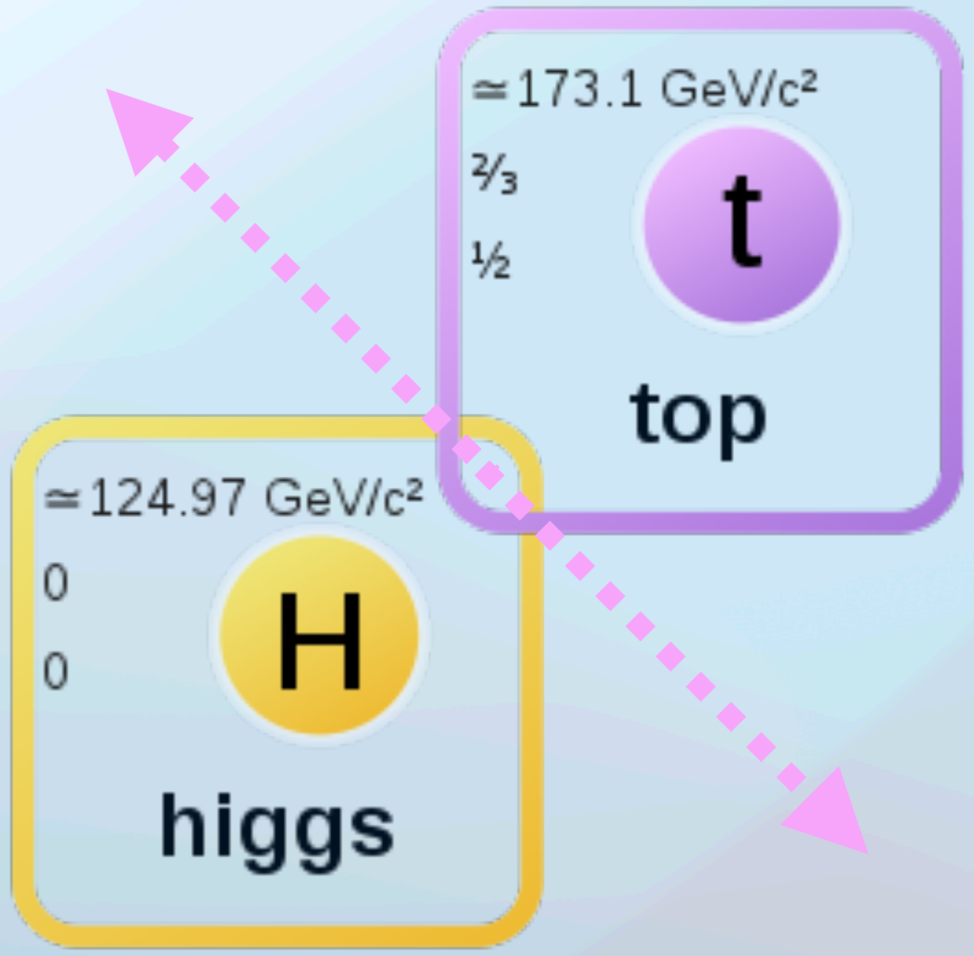


Thoughts for the future

$t\bar{t}HH$ is promising but still limited

→ Importance of processes such as $t\bar{t}t\bar{t}$, $t\bar{t}H$

→ Factor ~2 of size of 95%CL interval by the end of Run 4



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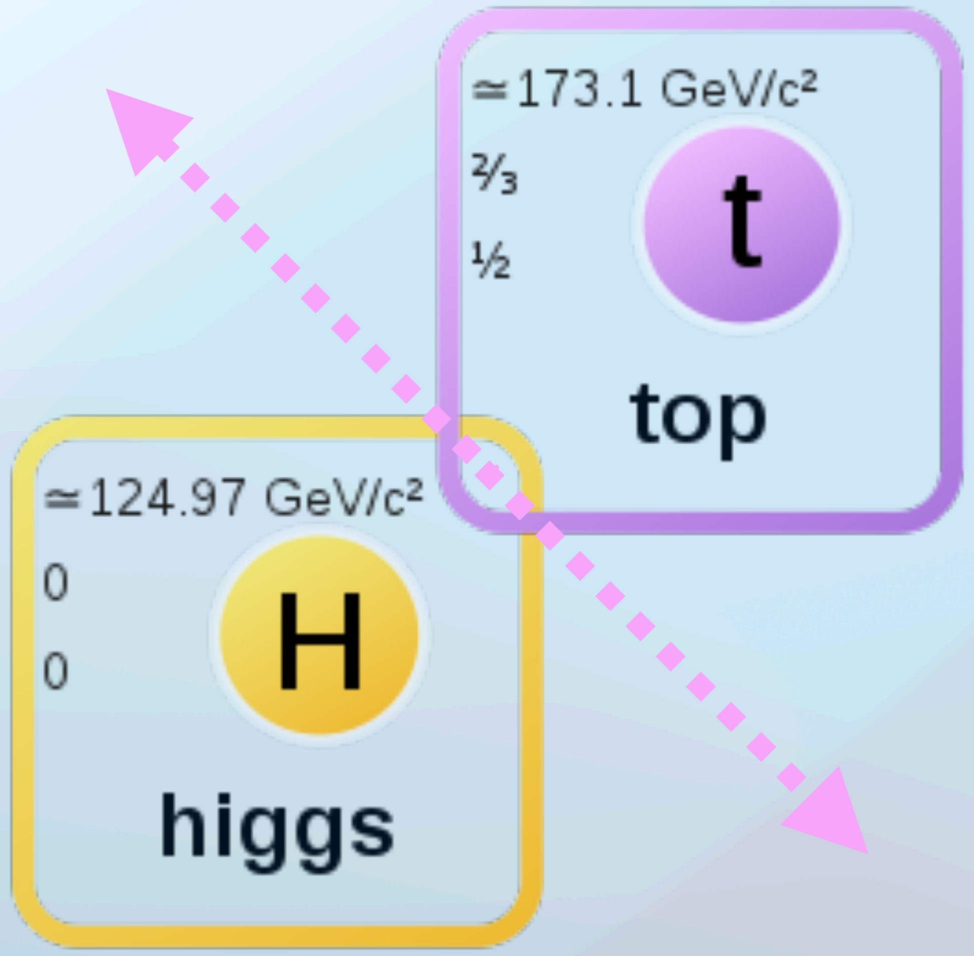

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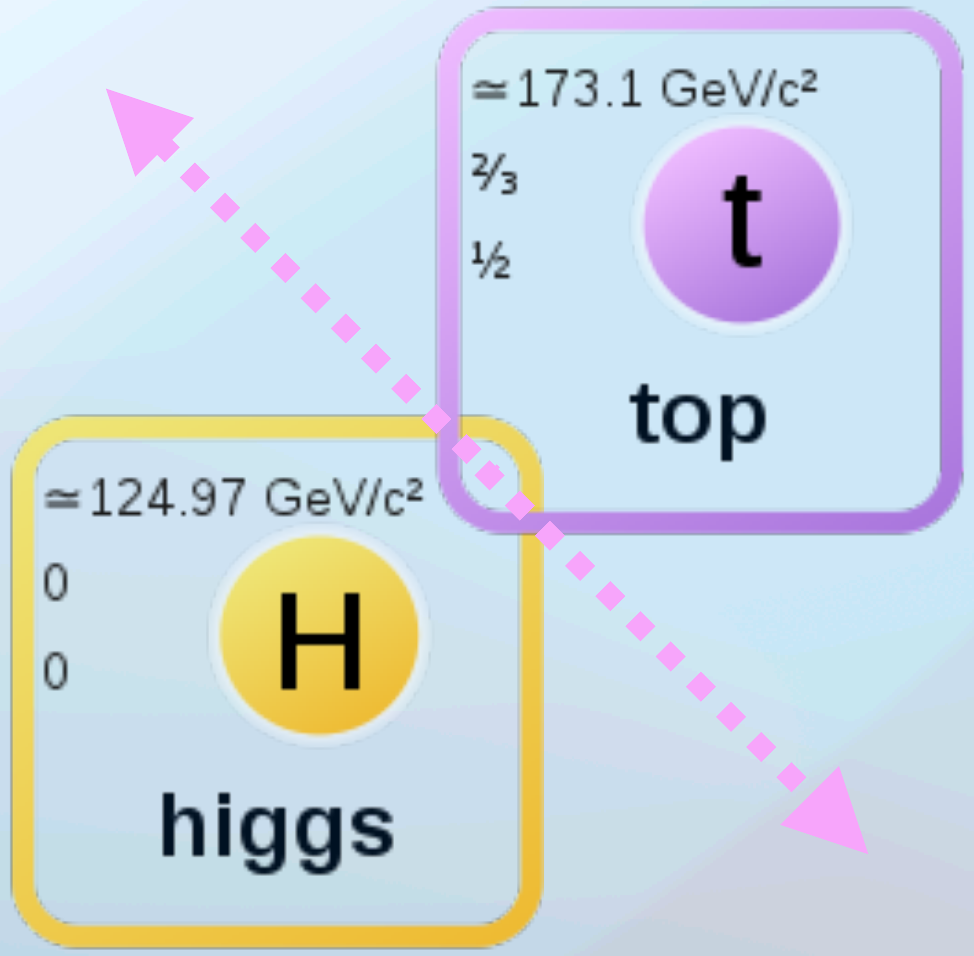
EFT approach is a **powerful tool** to probe BSM, in particular heavy physics

Still **a lot** of room for improvement

→ Combinations, between analysis, and between experiments

→ *Higher order effets* to be taken into account (running of the coeffs)

→ Designing analysis specifically for EFT



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We are already in the SM **precision era**, even though ~95% of the LHC dataset yet to be analyzed

EFT approach is a **powerful tool** to probe BSM, in particular heavy physics

Still **a lot** of room for improvement

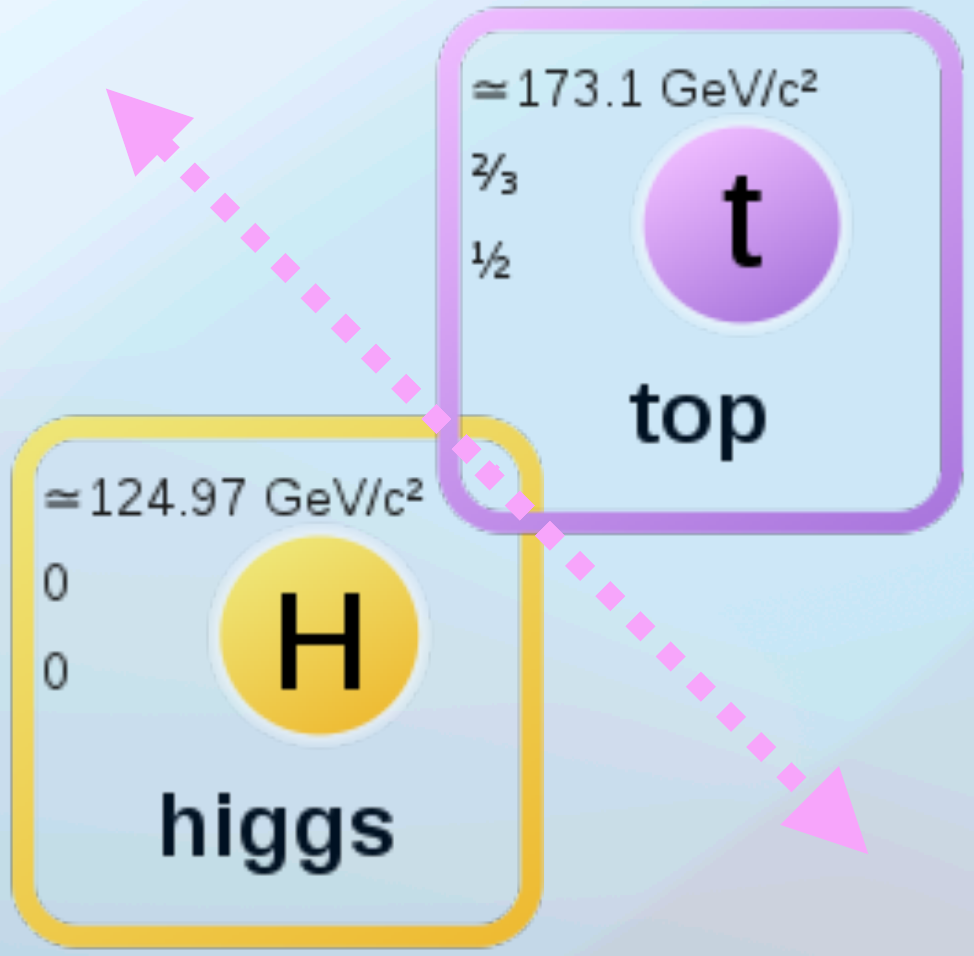
→ Combinations, between analysis, and between experiments

→ *Higher order effets* to be taken into account (running of the coeffs)

→ Designing analysis specifically for EFT

HEFT vs. "*traditional*" **SMEFT** interpretion *when relevant*

What UV model have different predictions in both frameworks?



Thoughts for the future

$t\bar{t}HH$ is promising but still limited

→ Importance of processes such as $t\bar{t}t\bar{t}$, $t\bar{t}H$

→ Factor ~2 of size of 95%CL interval by the end of Run 4

We are already in the SM **precision era**, even though ~95% of the LHC dataset yet to be analyzed

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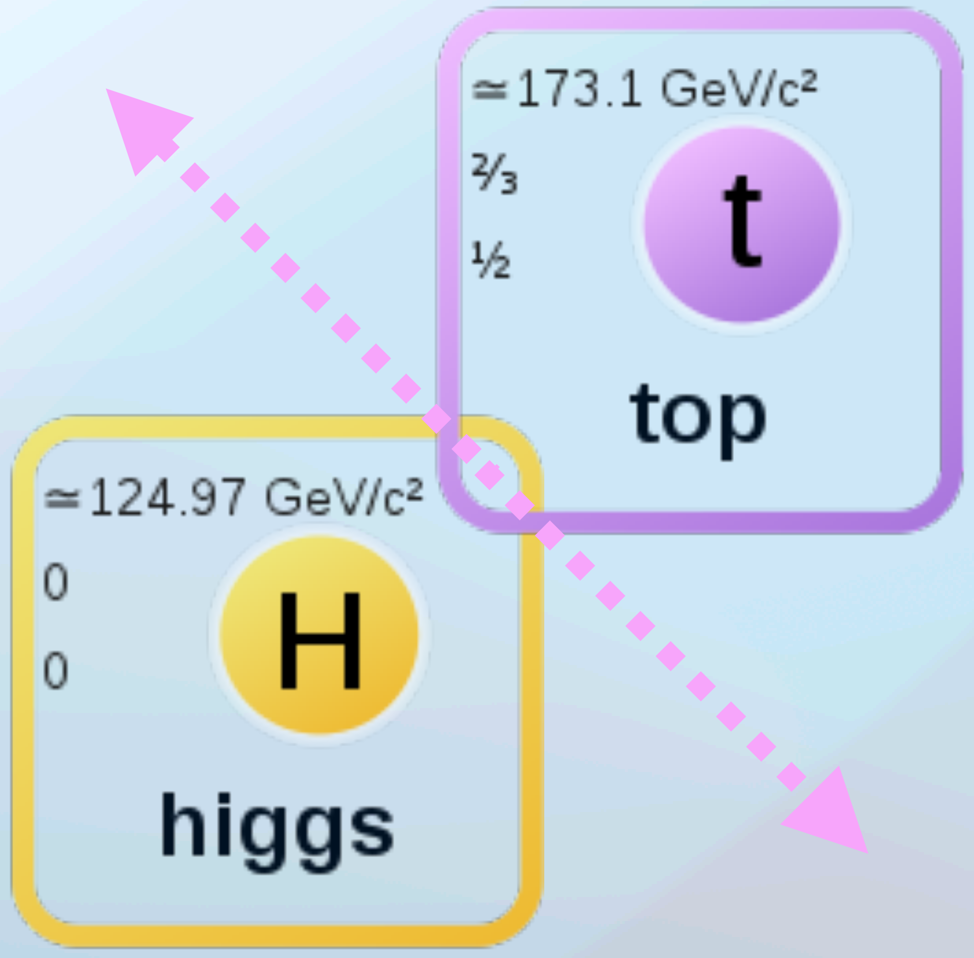


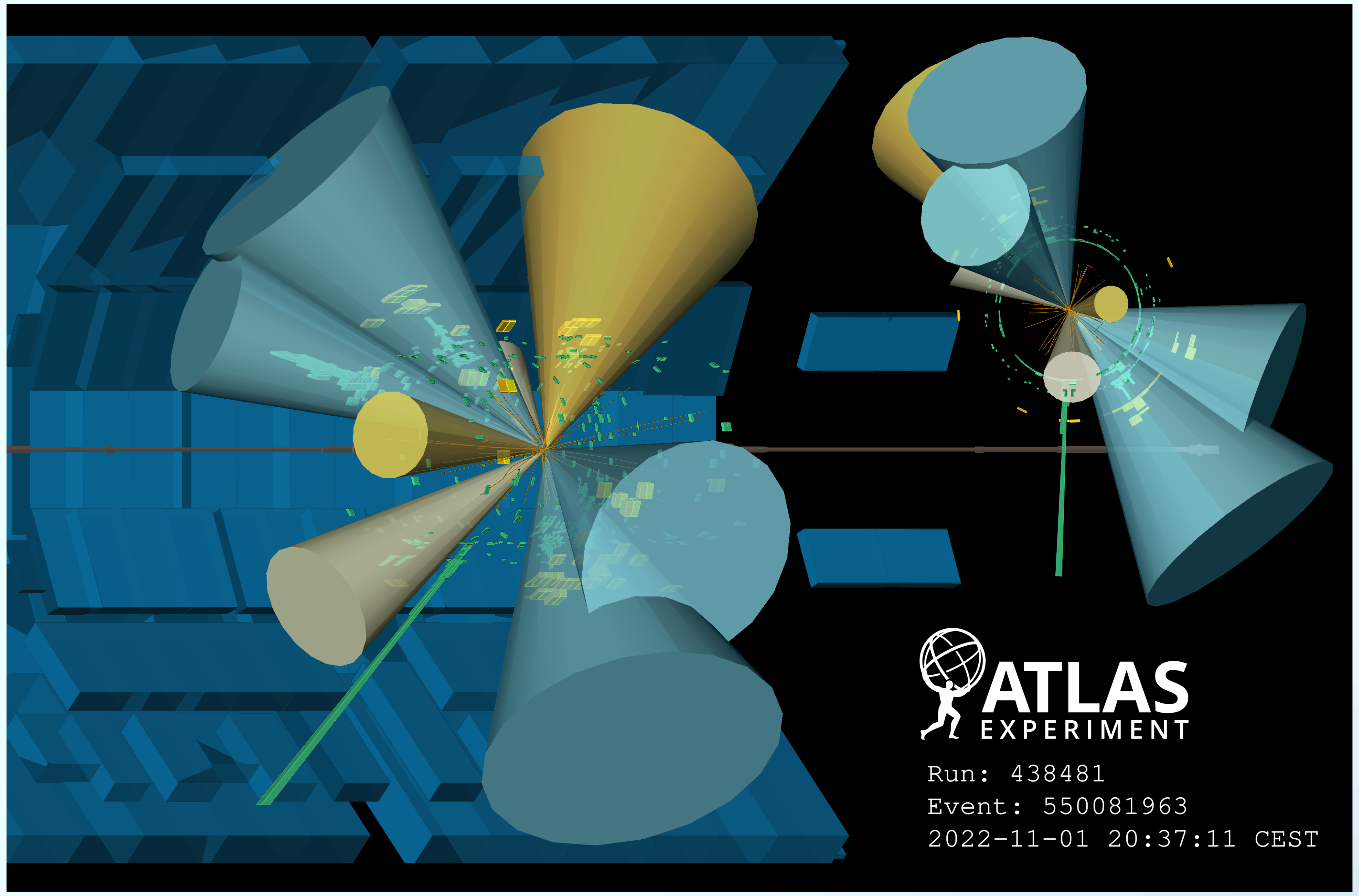
Top and Higgs sectors are **promissing probes** for exploring EWSB + connexion to heavy NP

Thank you!

😊

Backup

Single-lepton channel



Single lepton from W and $\geq$ 4 b-tagged jets

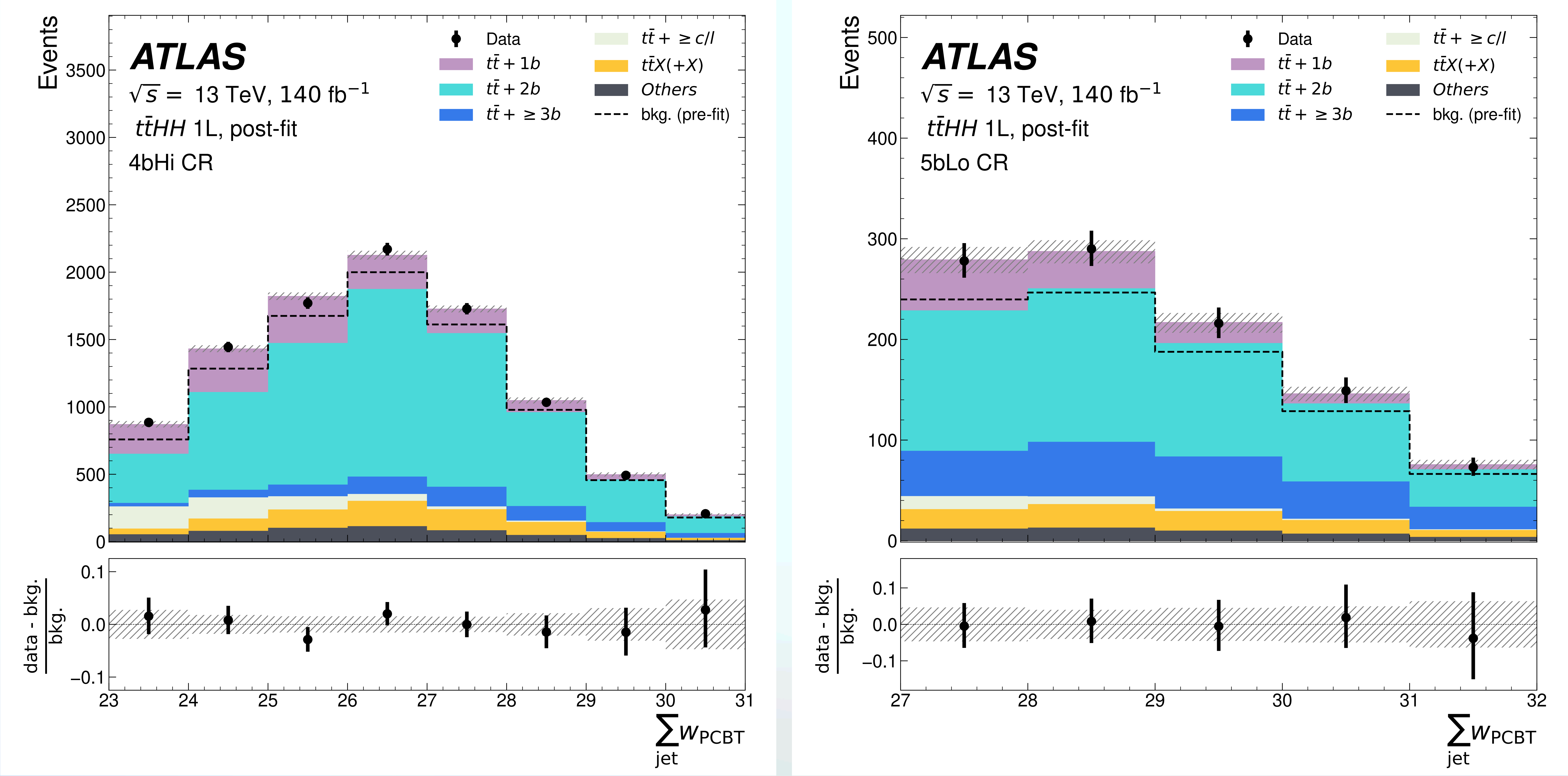
Dominant background : $t\bar{t} + jets$

Signal / Background split by jet-multiplicity

Fit from a GNN score

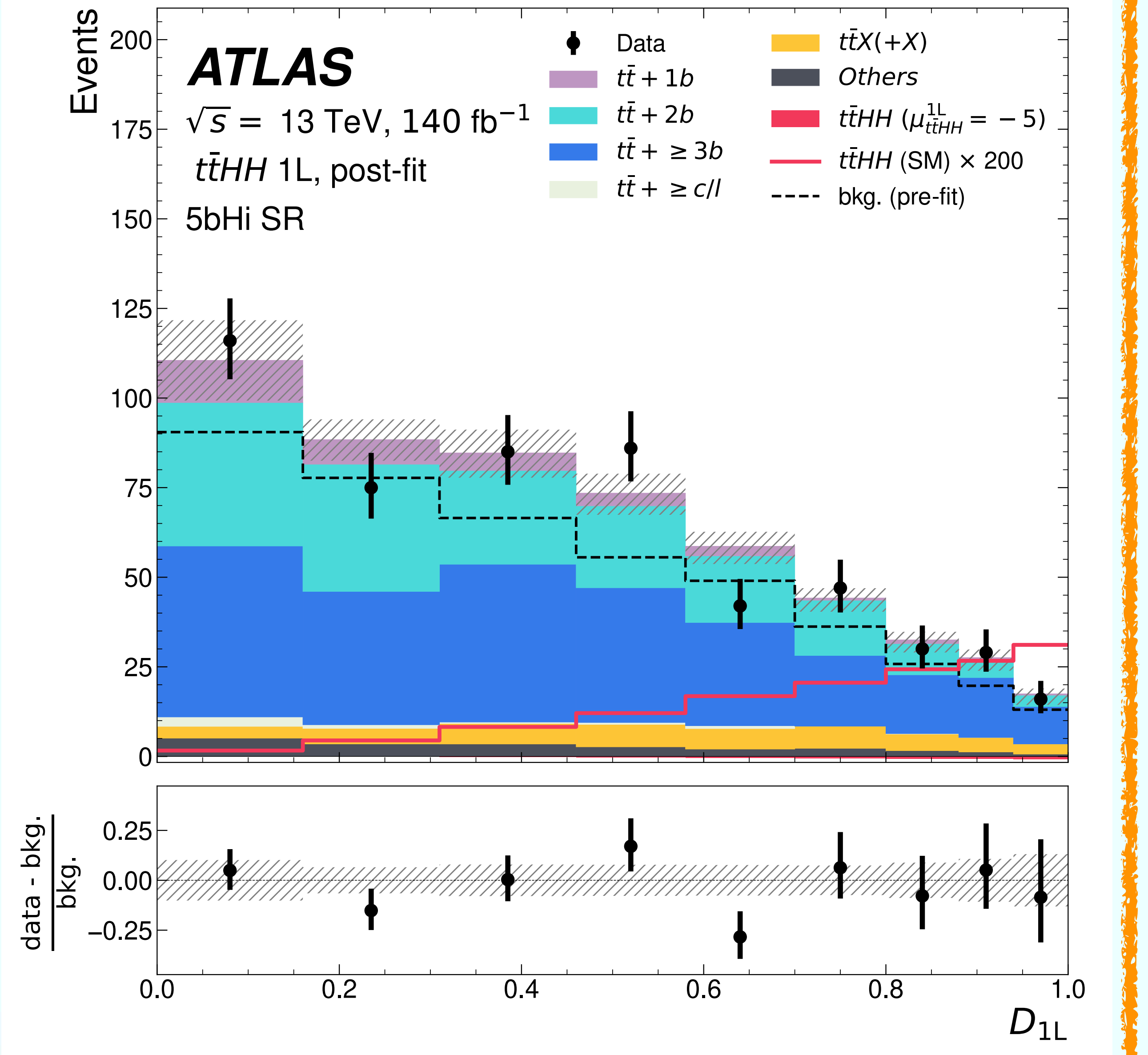
Variable	Description
(p_T, η, ϕ, E)	Kinematic variables of the object, i.e. transverse momentum, pseudorapidity, azimuthal angle, and energy.
w_{GN2}	GN201 b-tagging pseudo-continuous score for identifying jets. Non-jet objects are assigned a value of zero.
$q_{\text{Lep.}}$	Charge of the object. Non-lepton objects are assigned a value of zero.
(isJet, isLep, isMET)	Boolean flags indicating the object type: jet, lepton, or missing transverse energy.

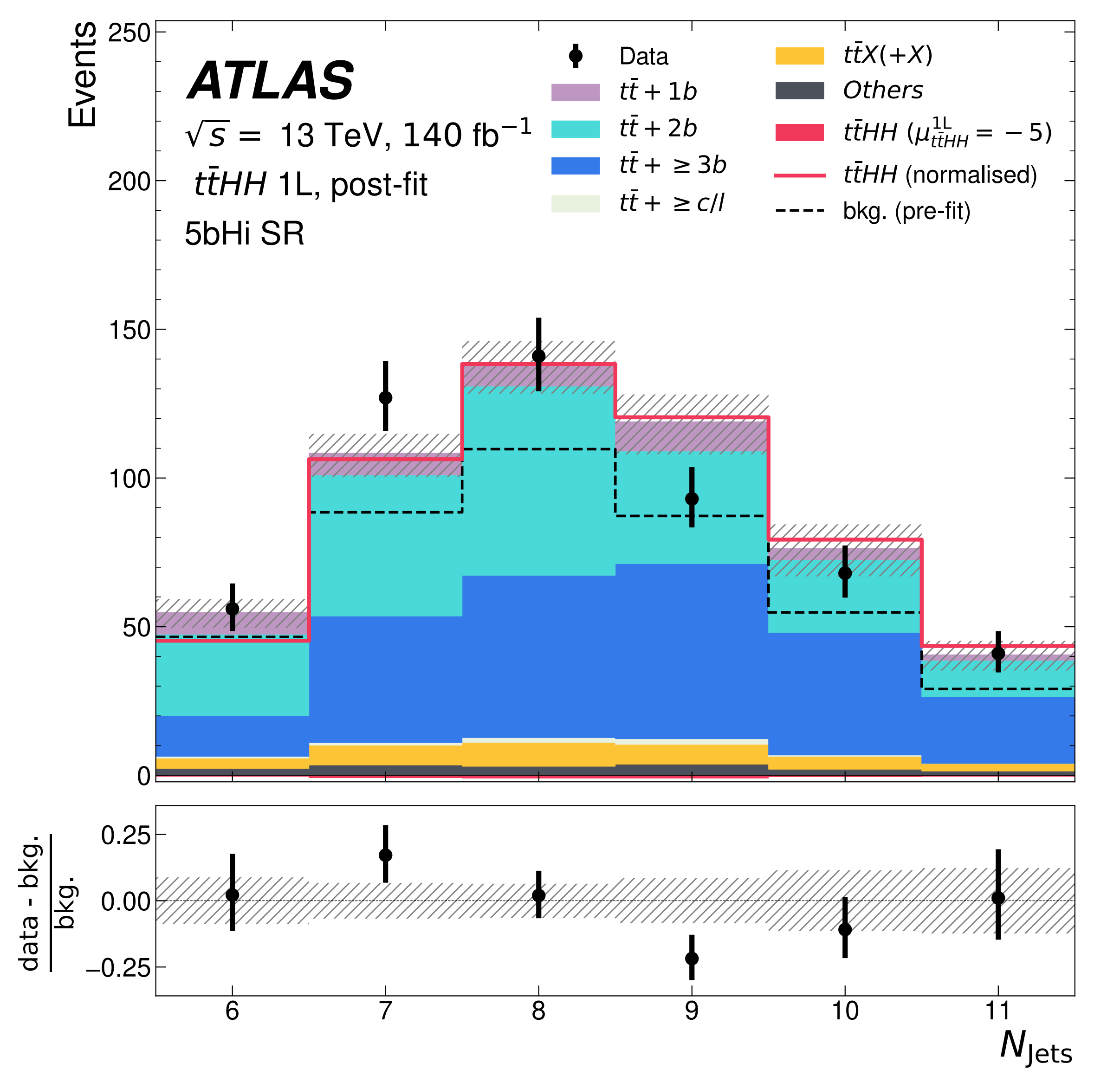
1L Run 2 CR distributions

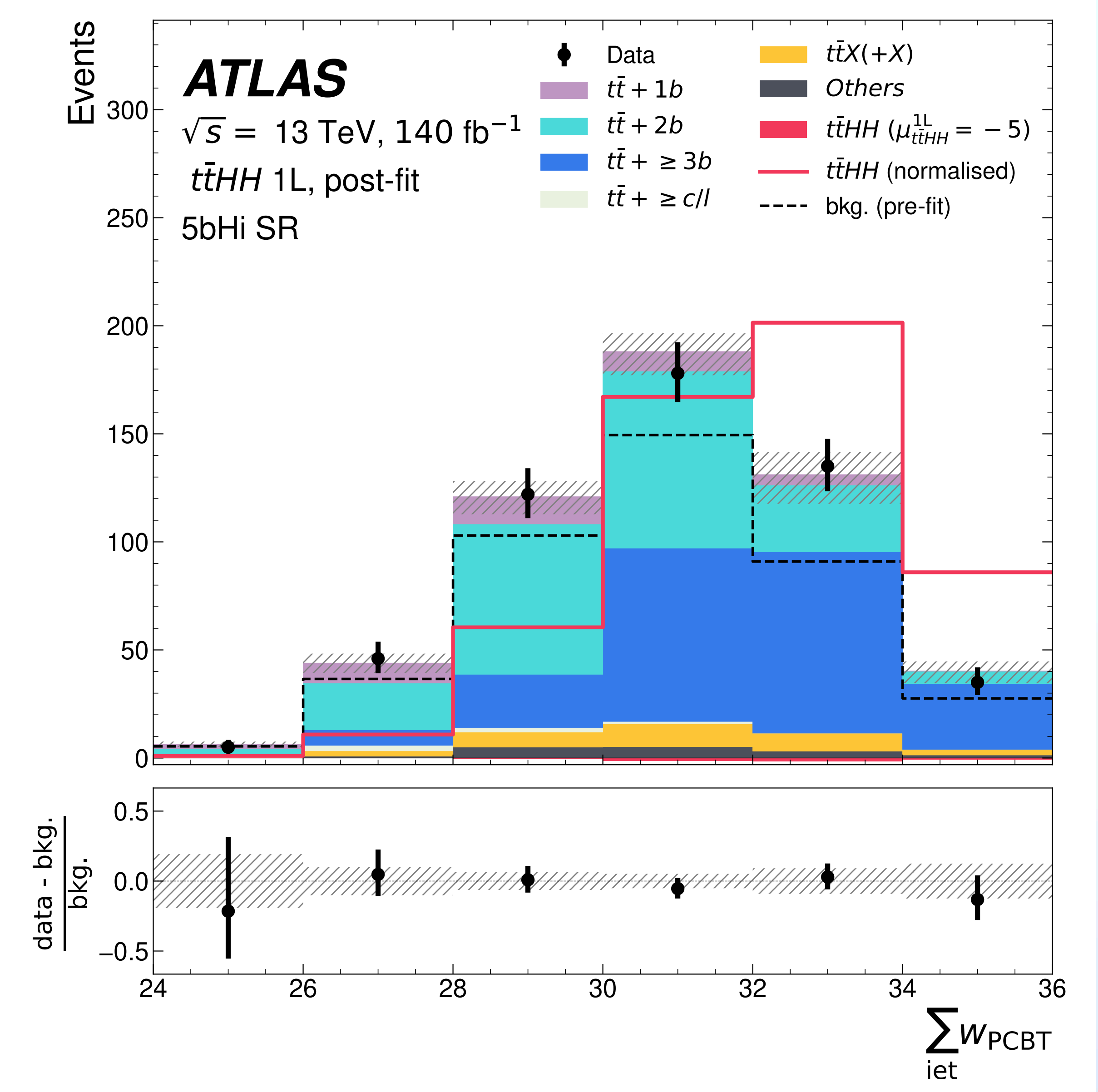


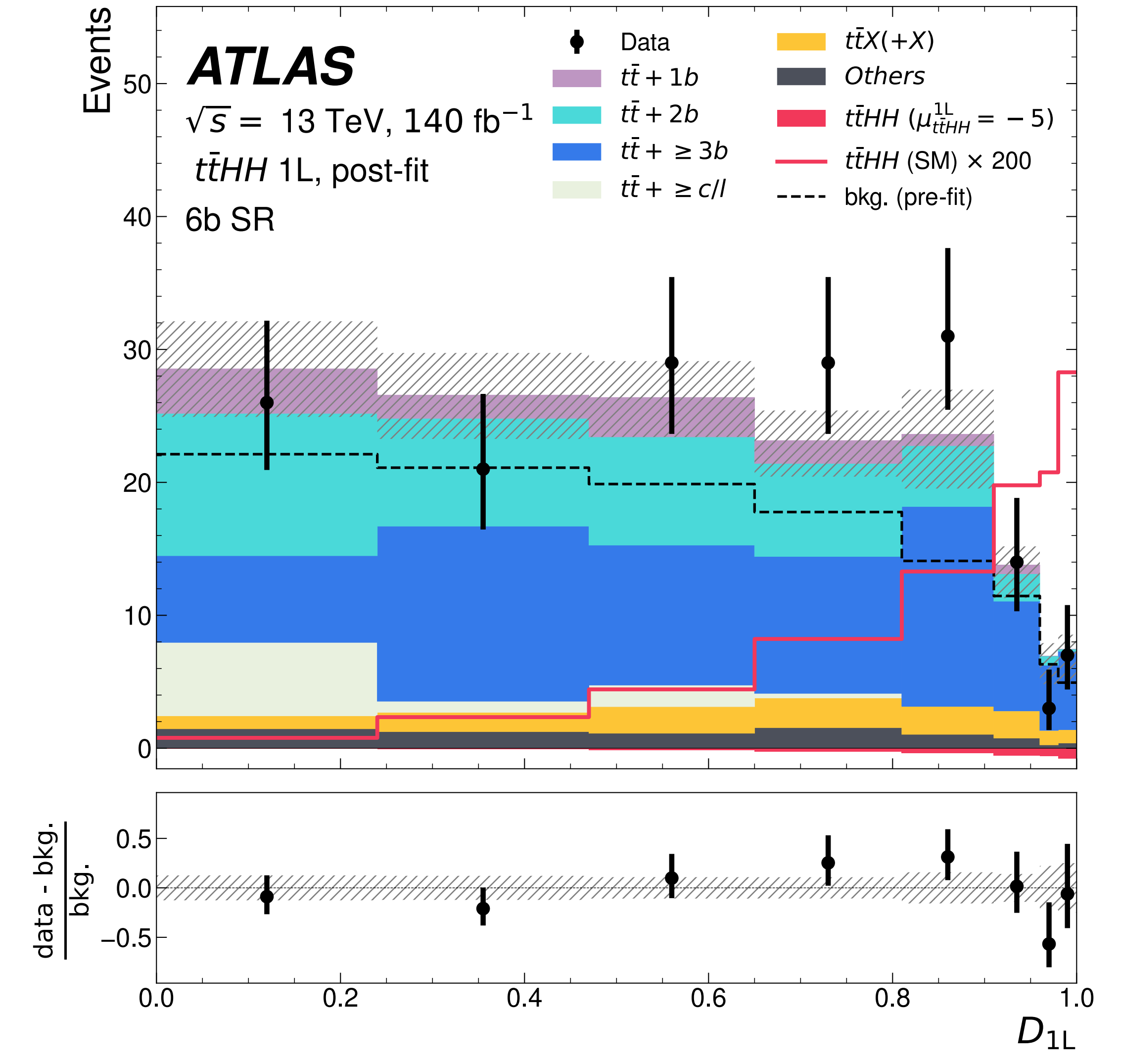
- Signal defined by jet multiplicity
- Well understood background

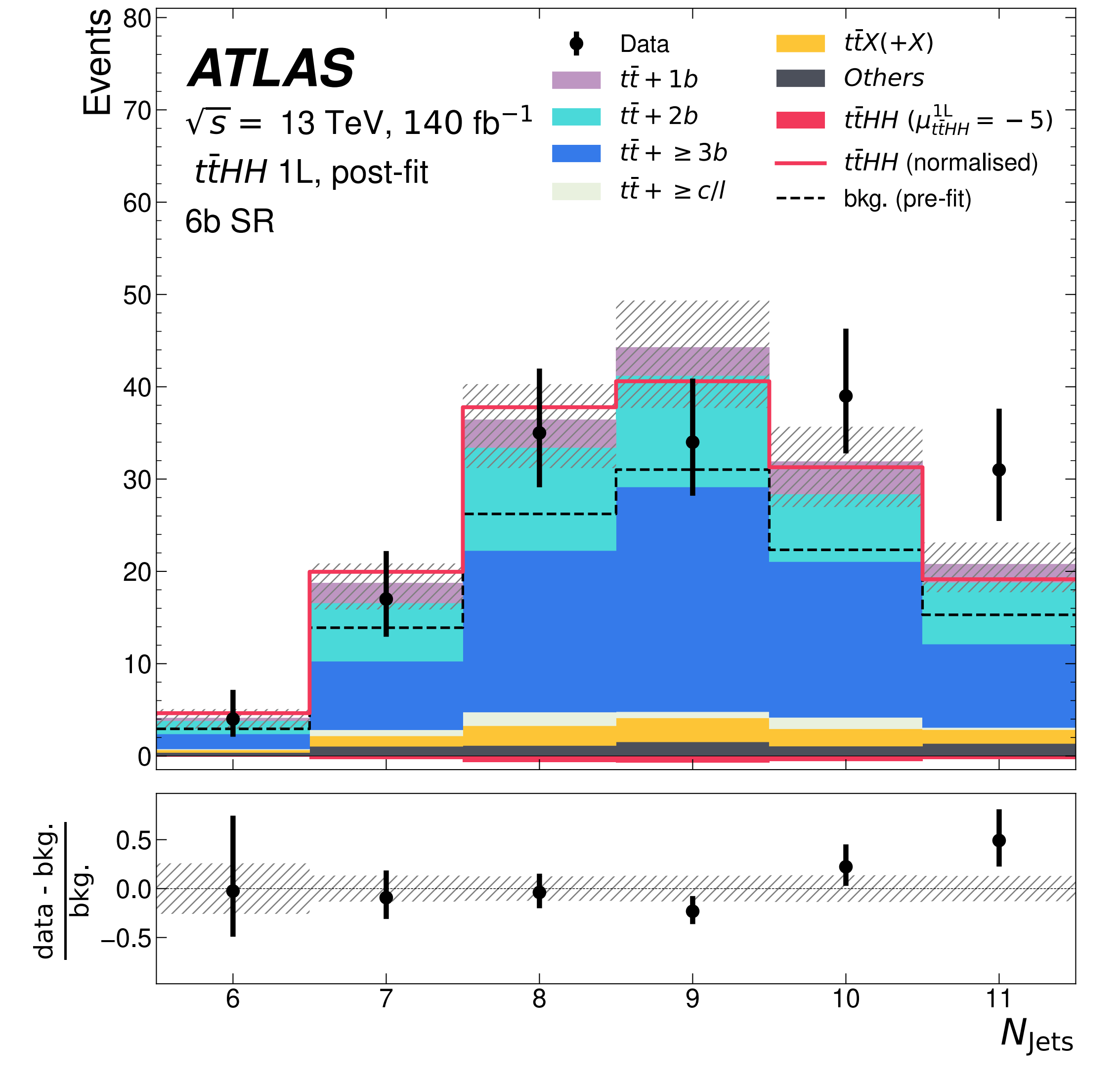
1L Run 2 SR distributions

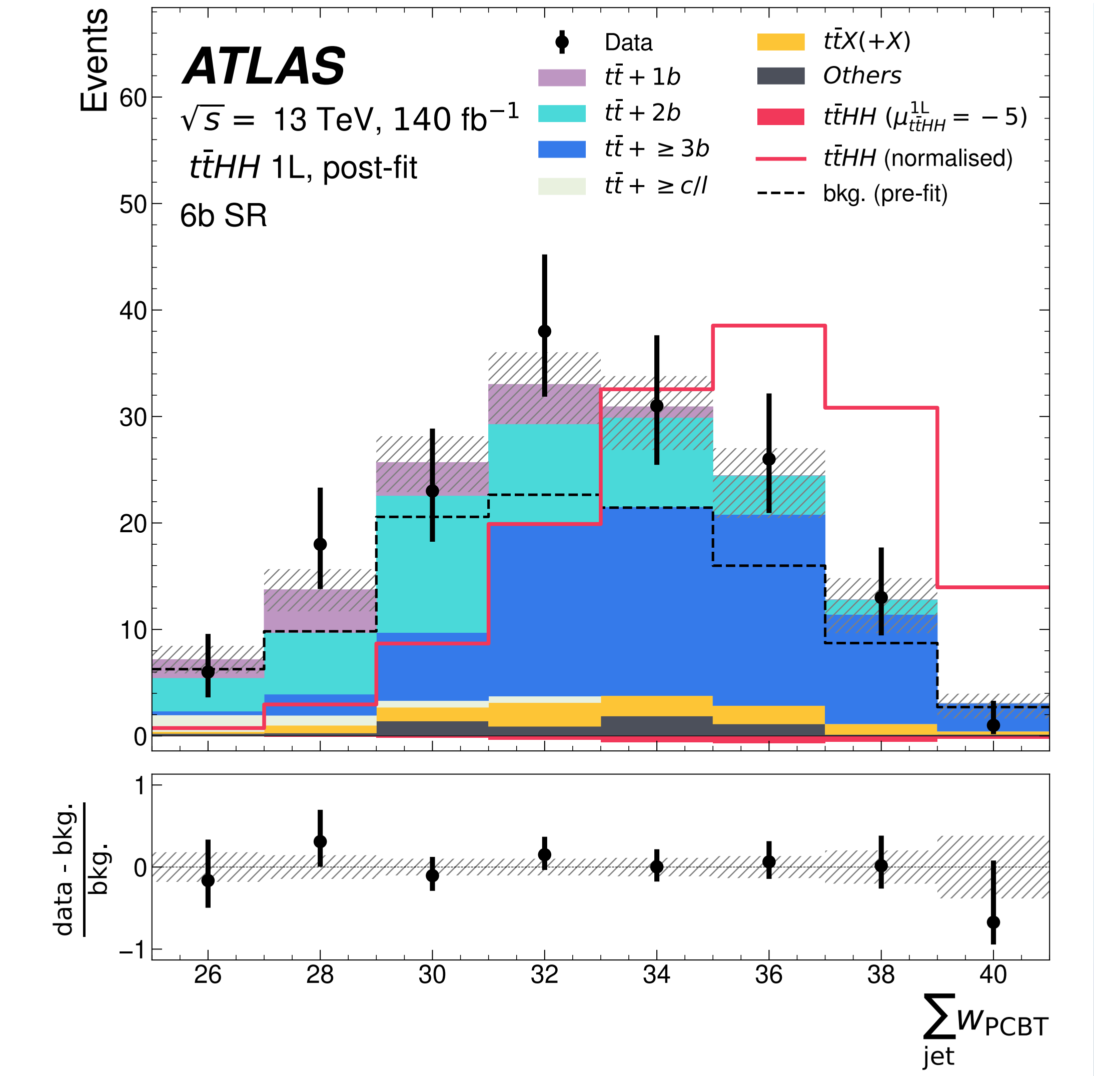




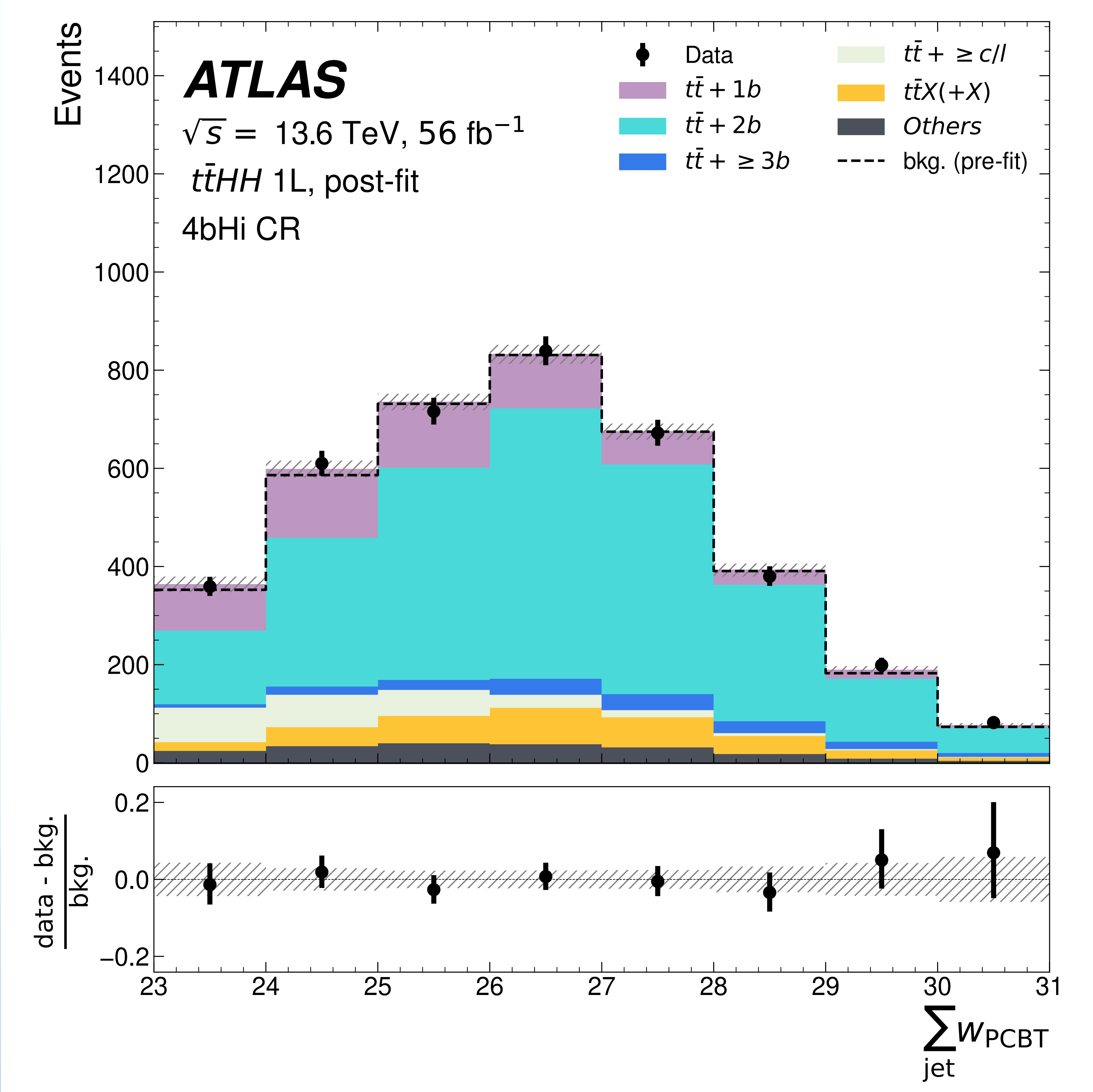


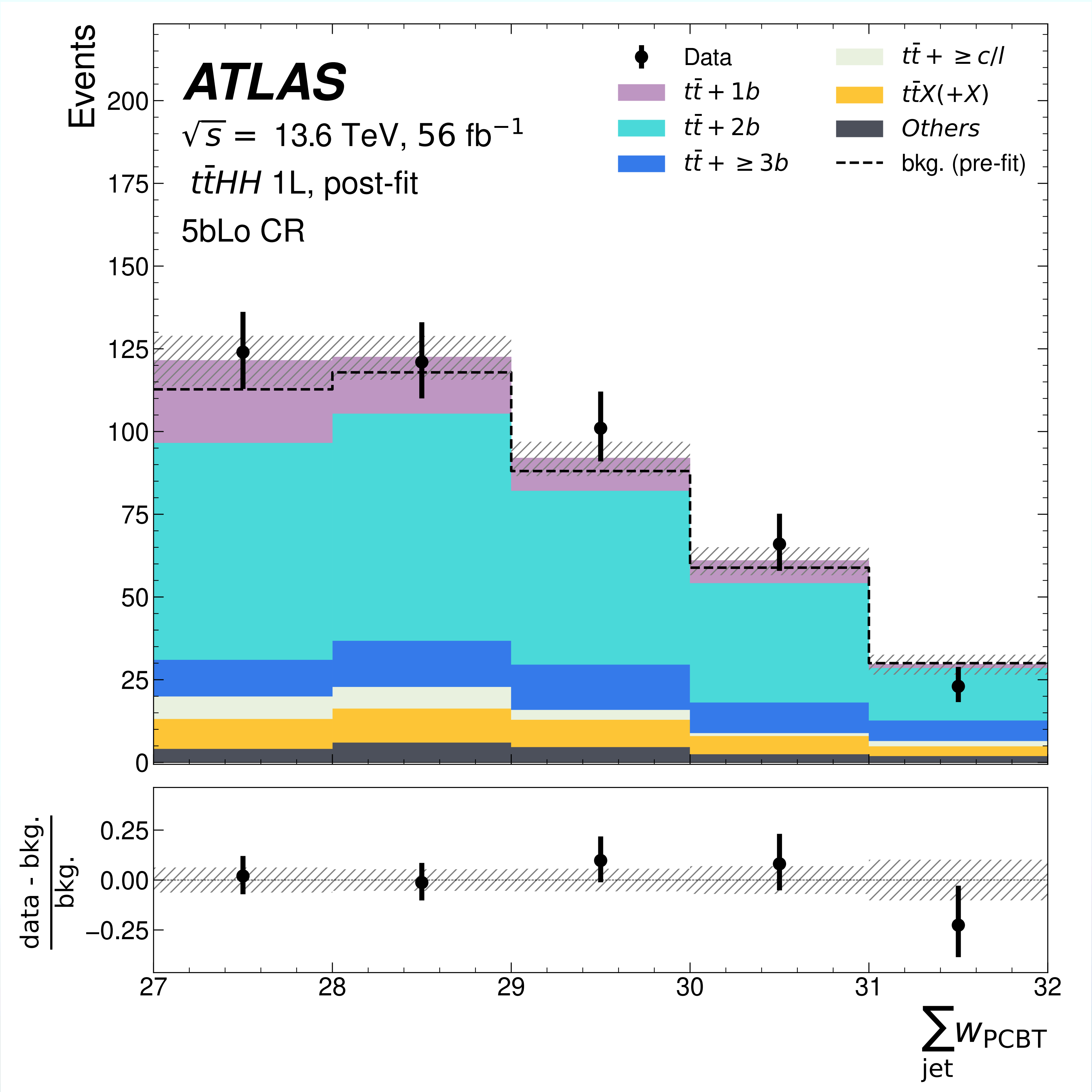






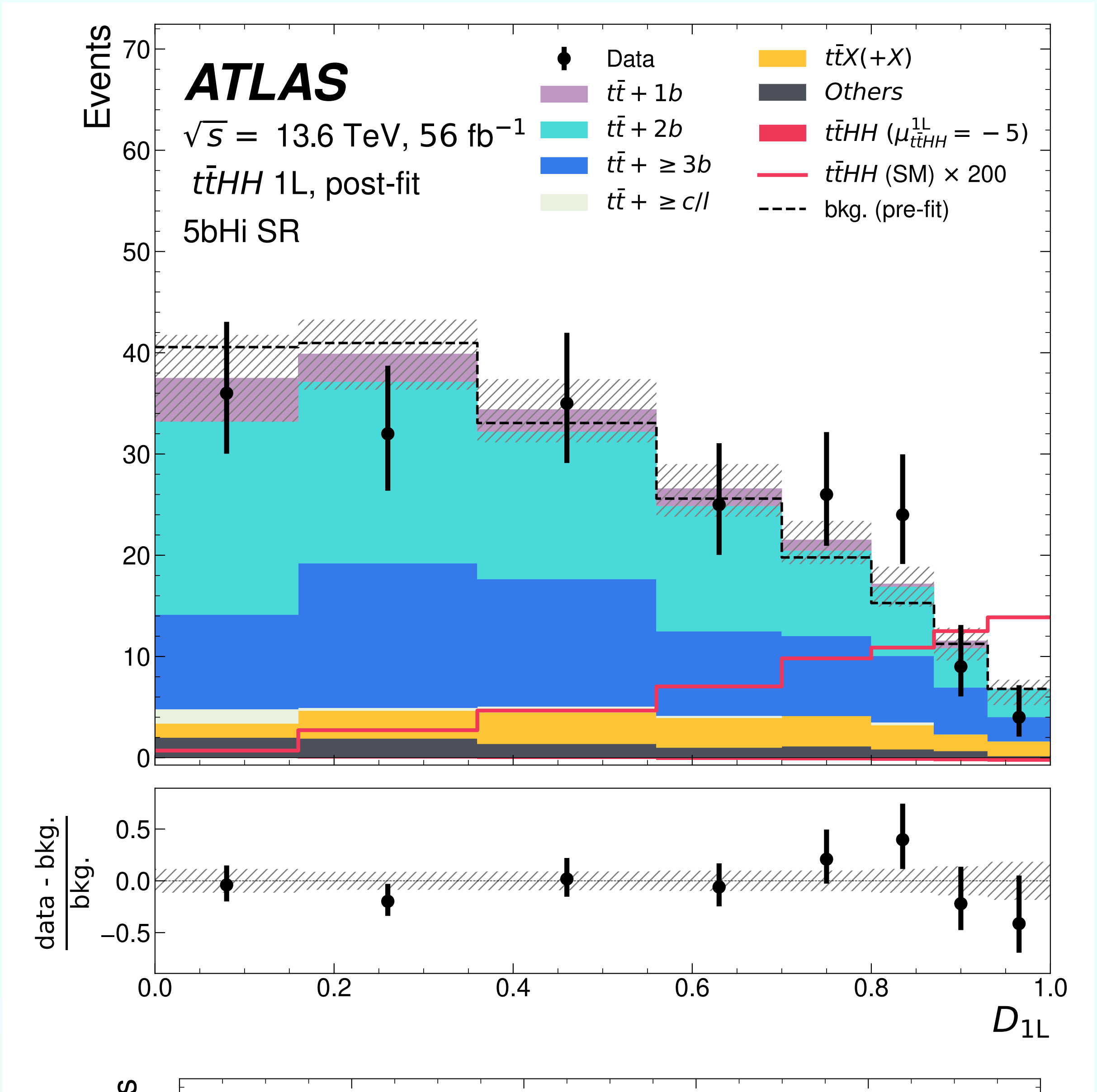
1L Run 3 CR distributions

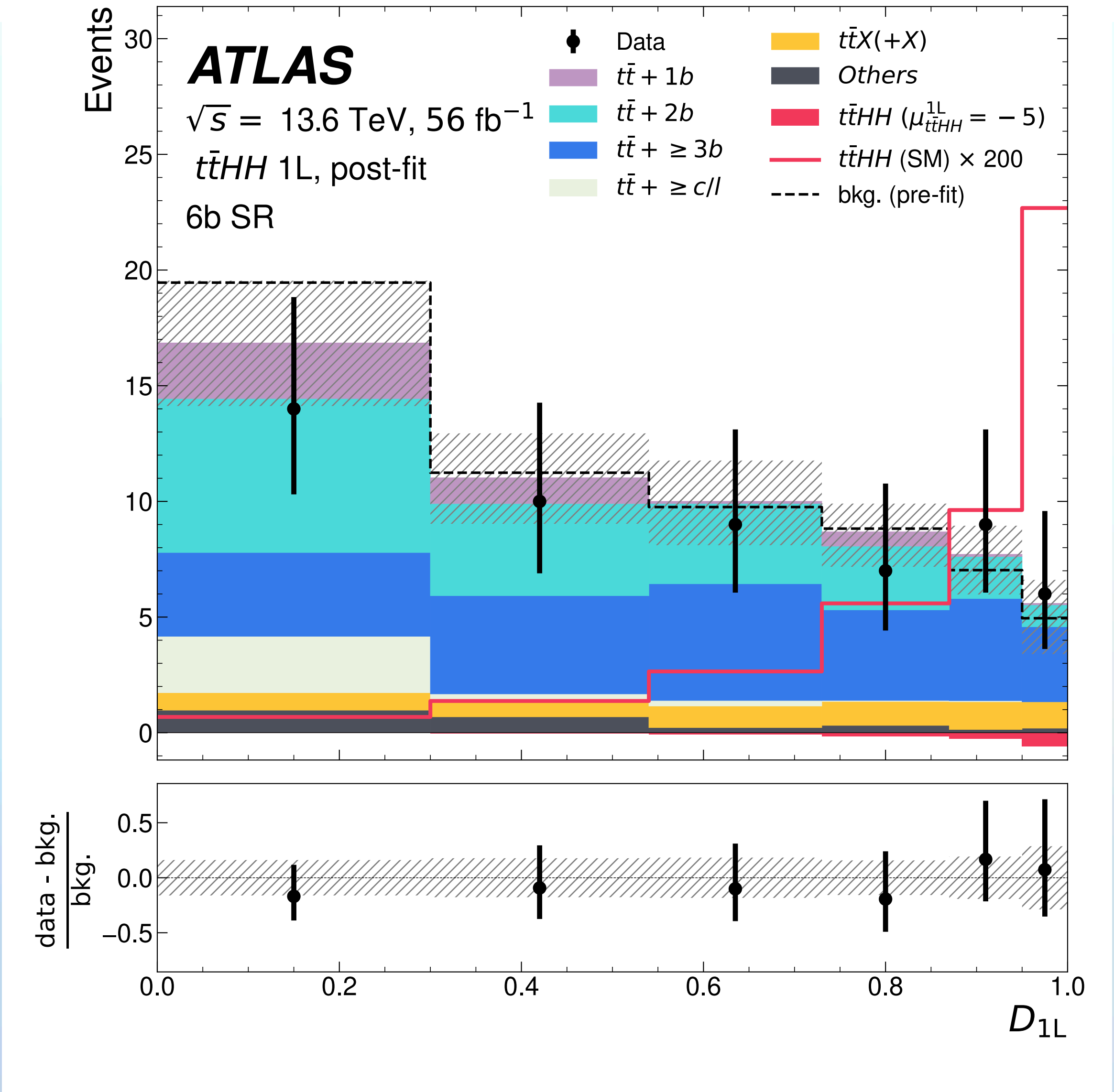


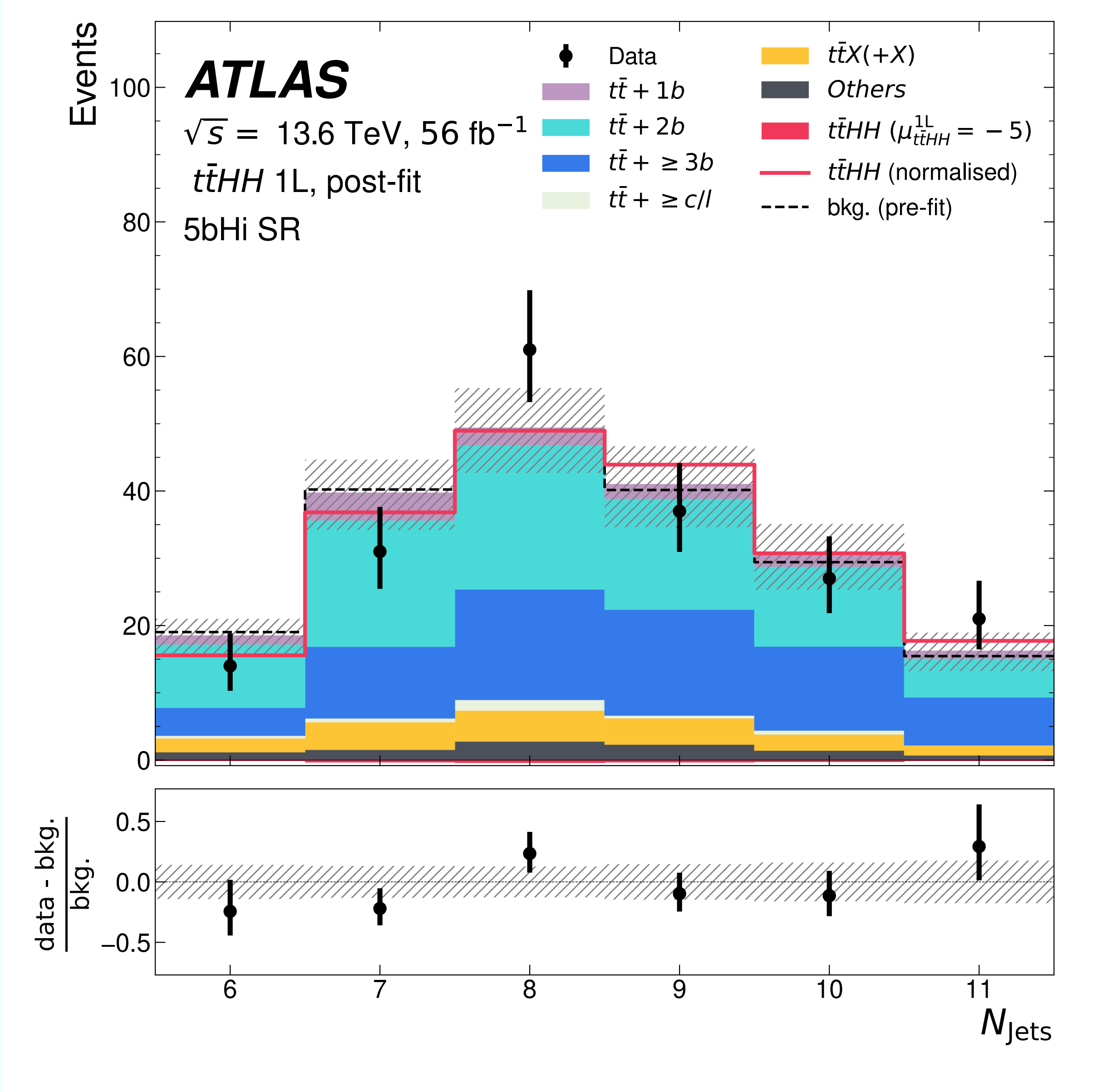


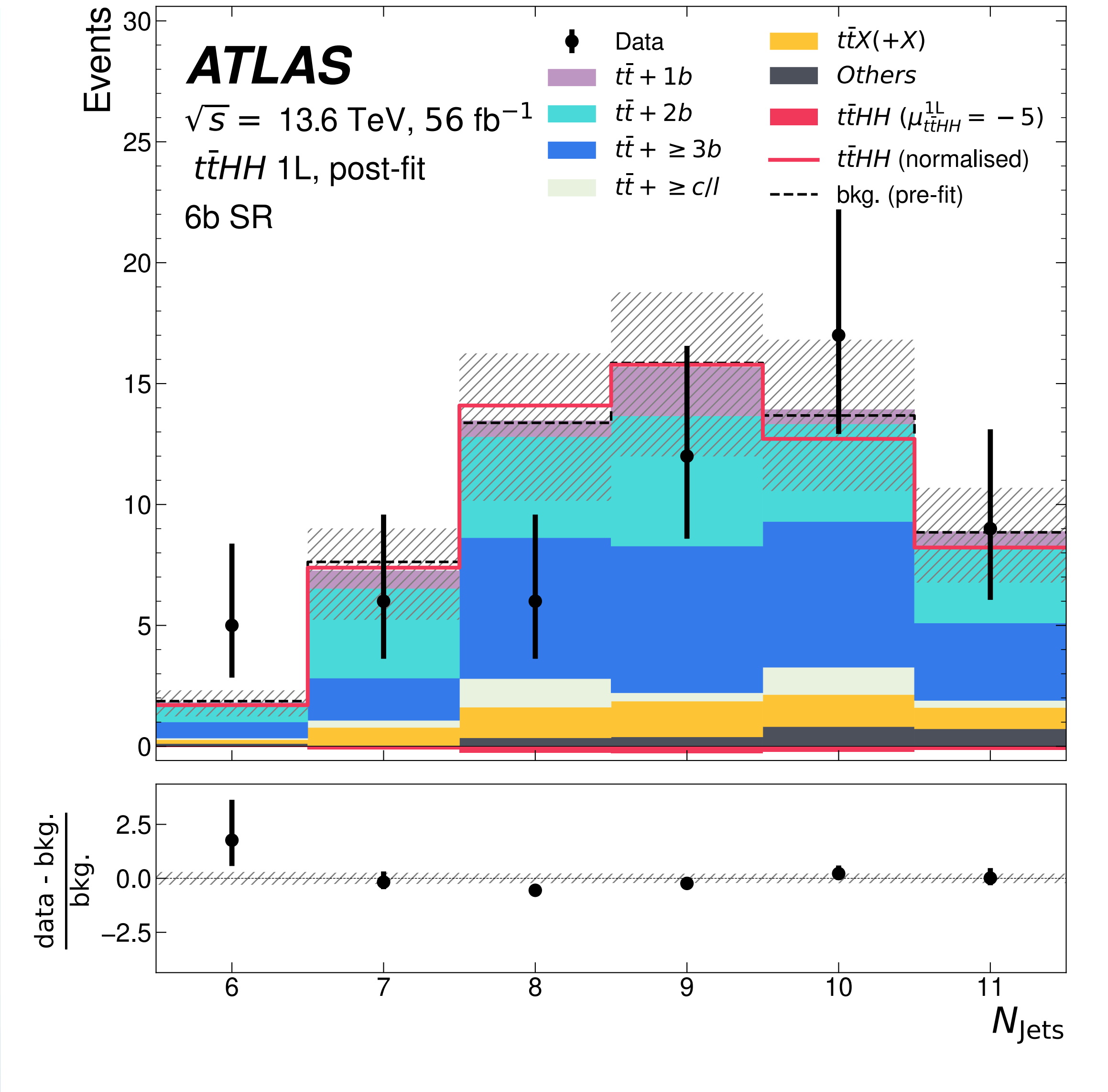
- Signal defined by jet multiplicity
- Well understood background

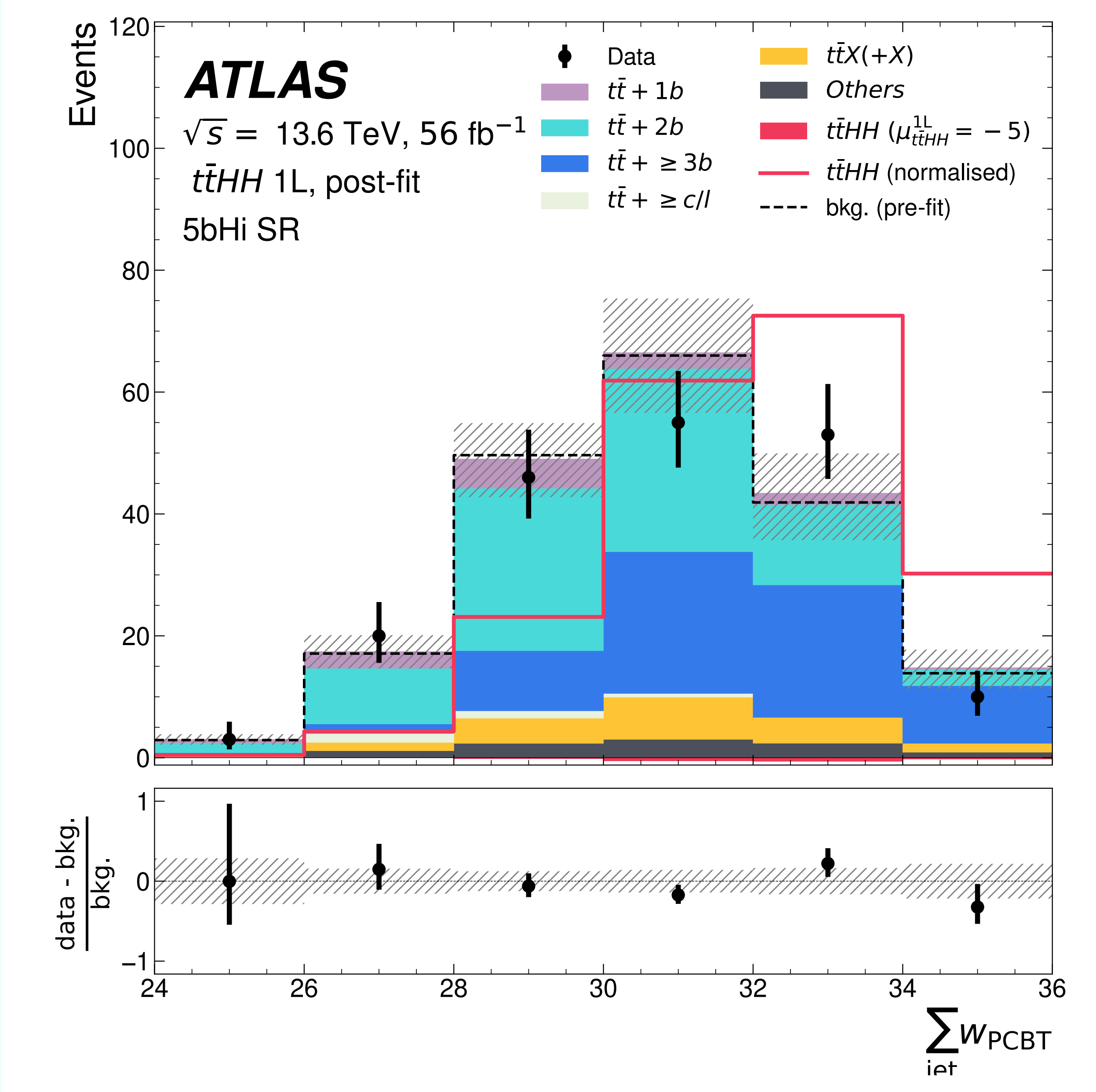
1L Run 3 SR distributions

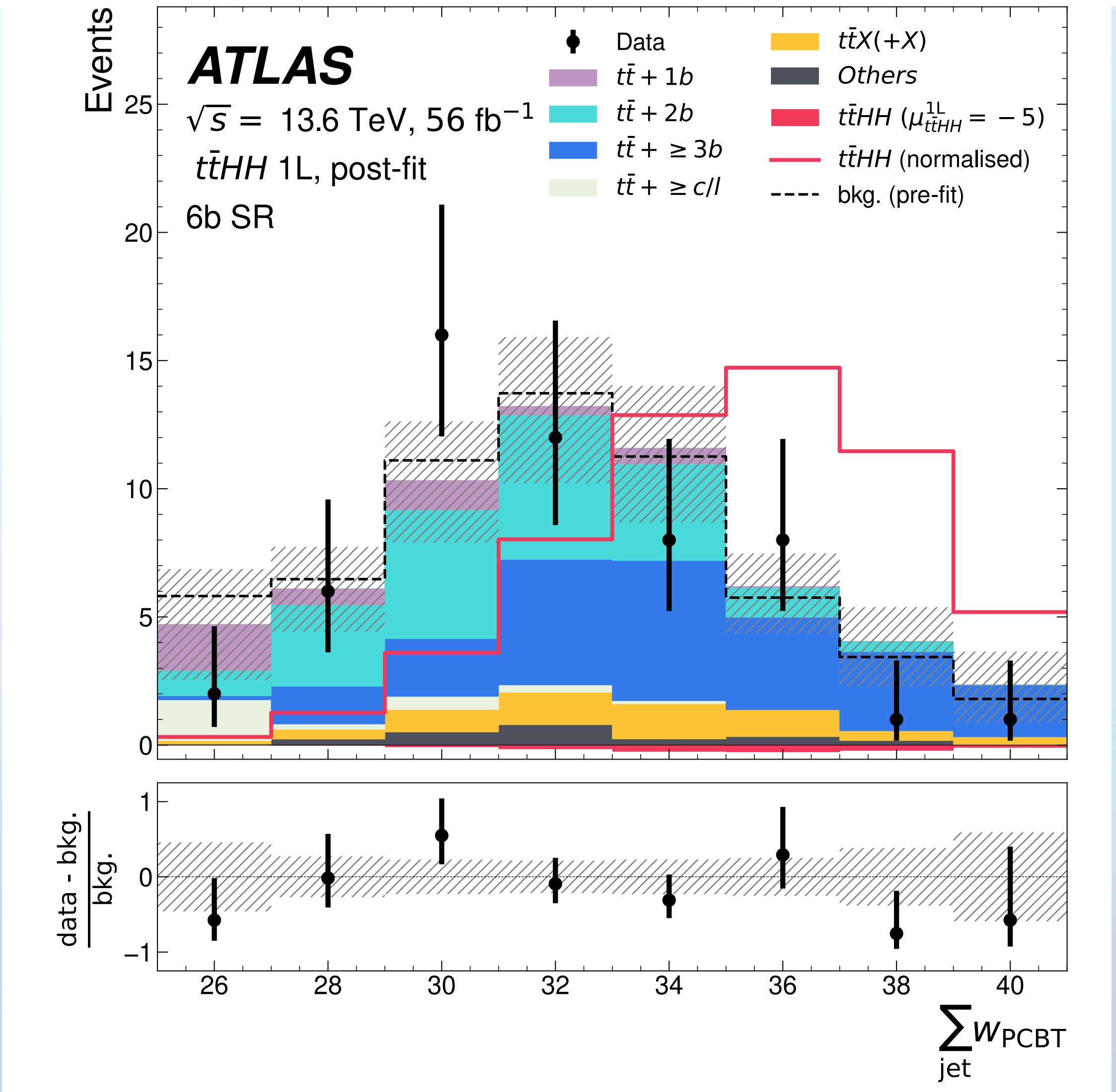












Same-sign multi-lepton channel

$\geq$ 2 b-tagged jets

$\geq$ 2 same-sign leptons from top and Higgs

Dominant irreducible backgrounds :

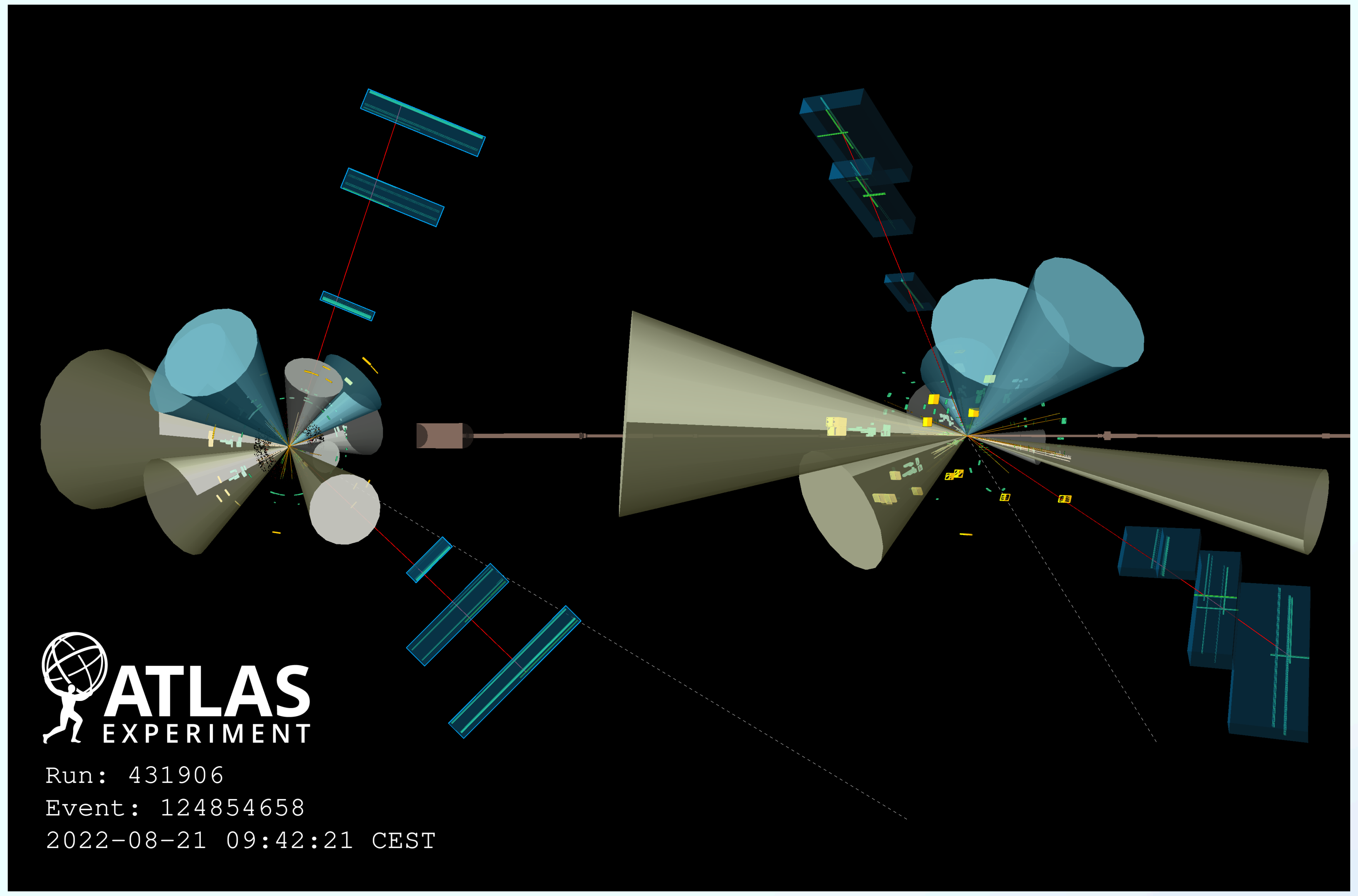
$t\bar{t}W$ and $t\bar{t}t\bar{t}$ normalization

Channel which suffers a lot from instrumental backrounds :

→ Charge mis-identification

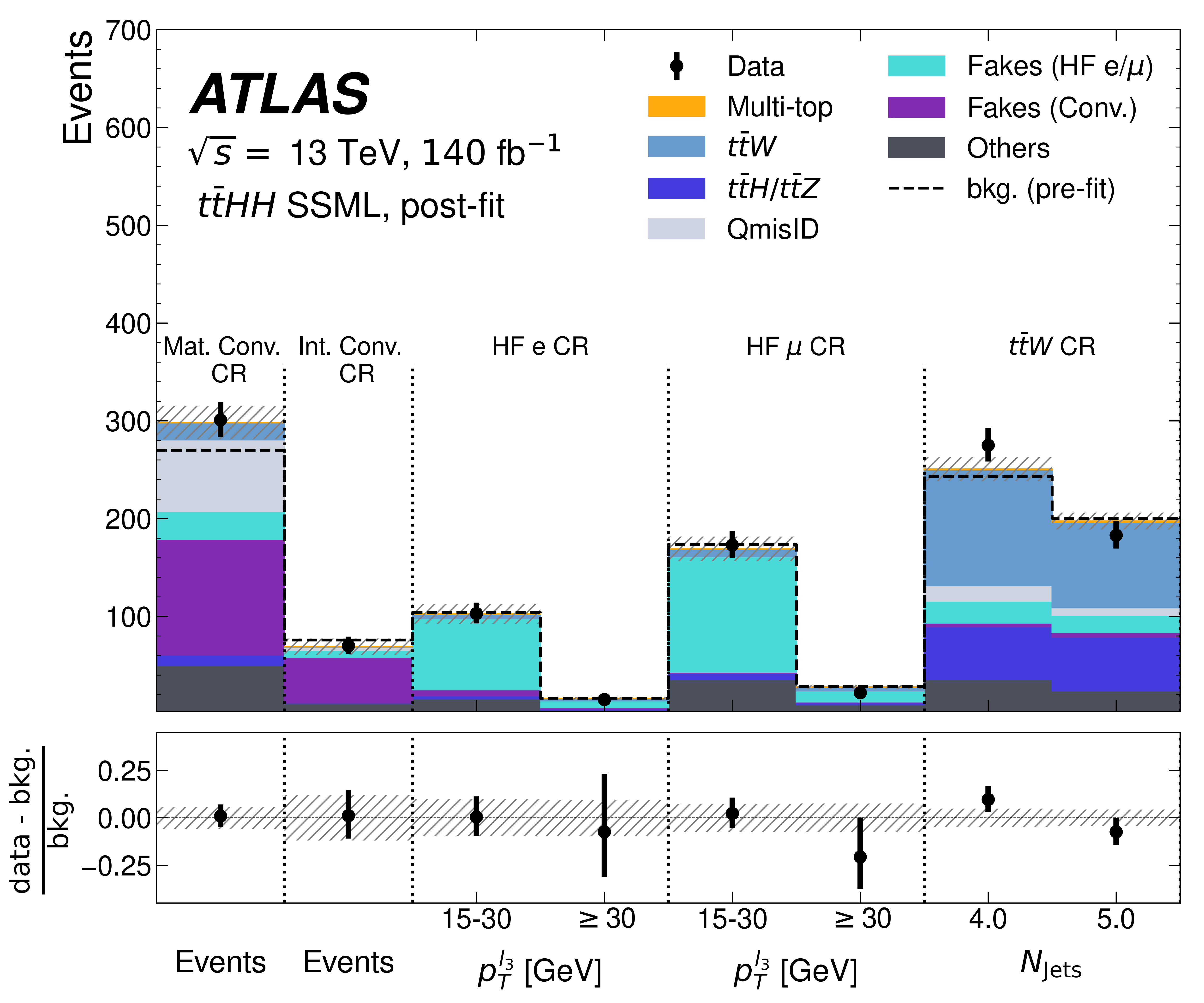
→ "Fake" leptons from HF decays or photon conversions

i.e. photons which look like lepton

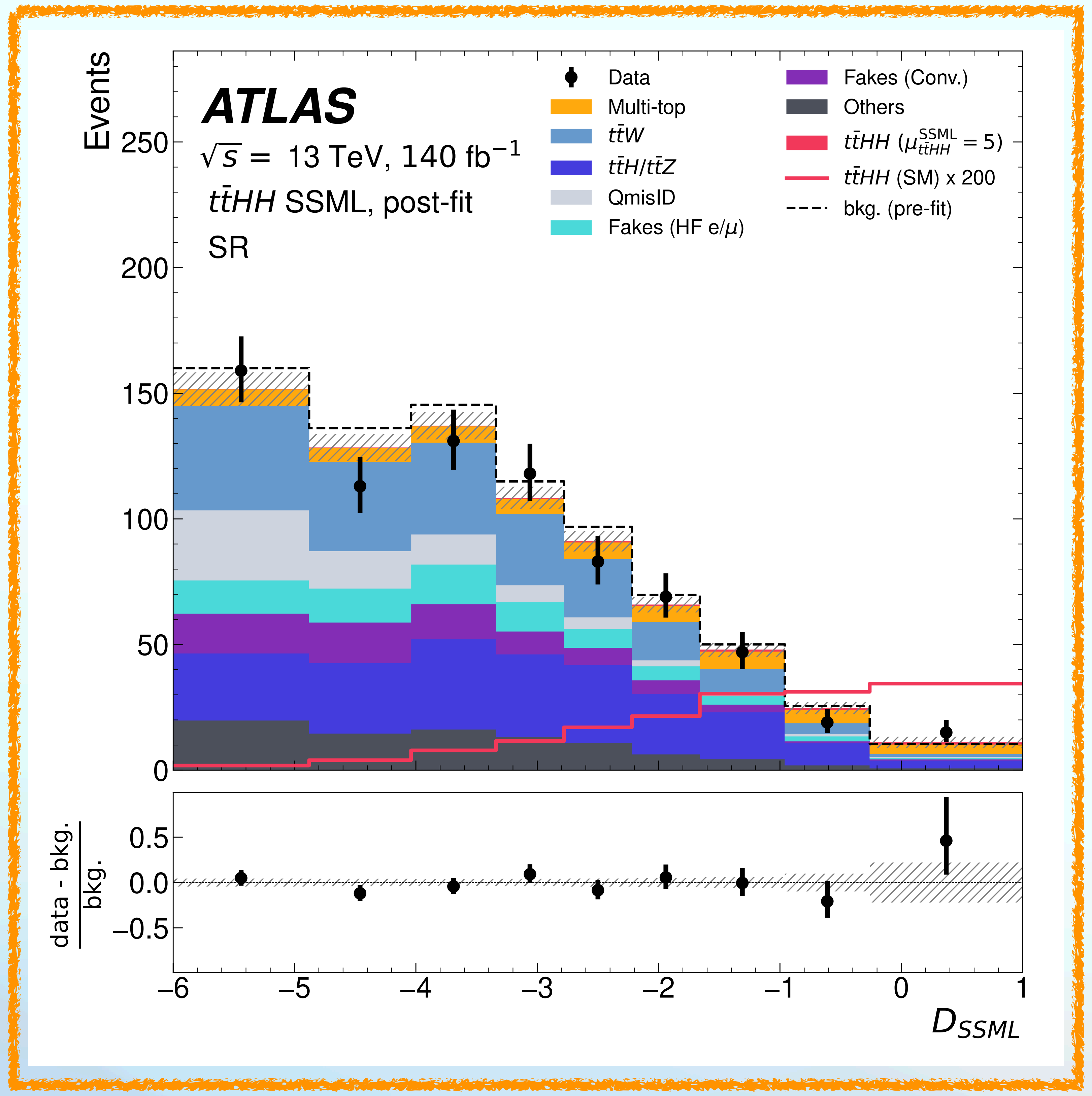


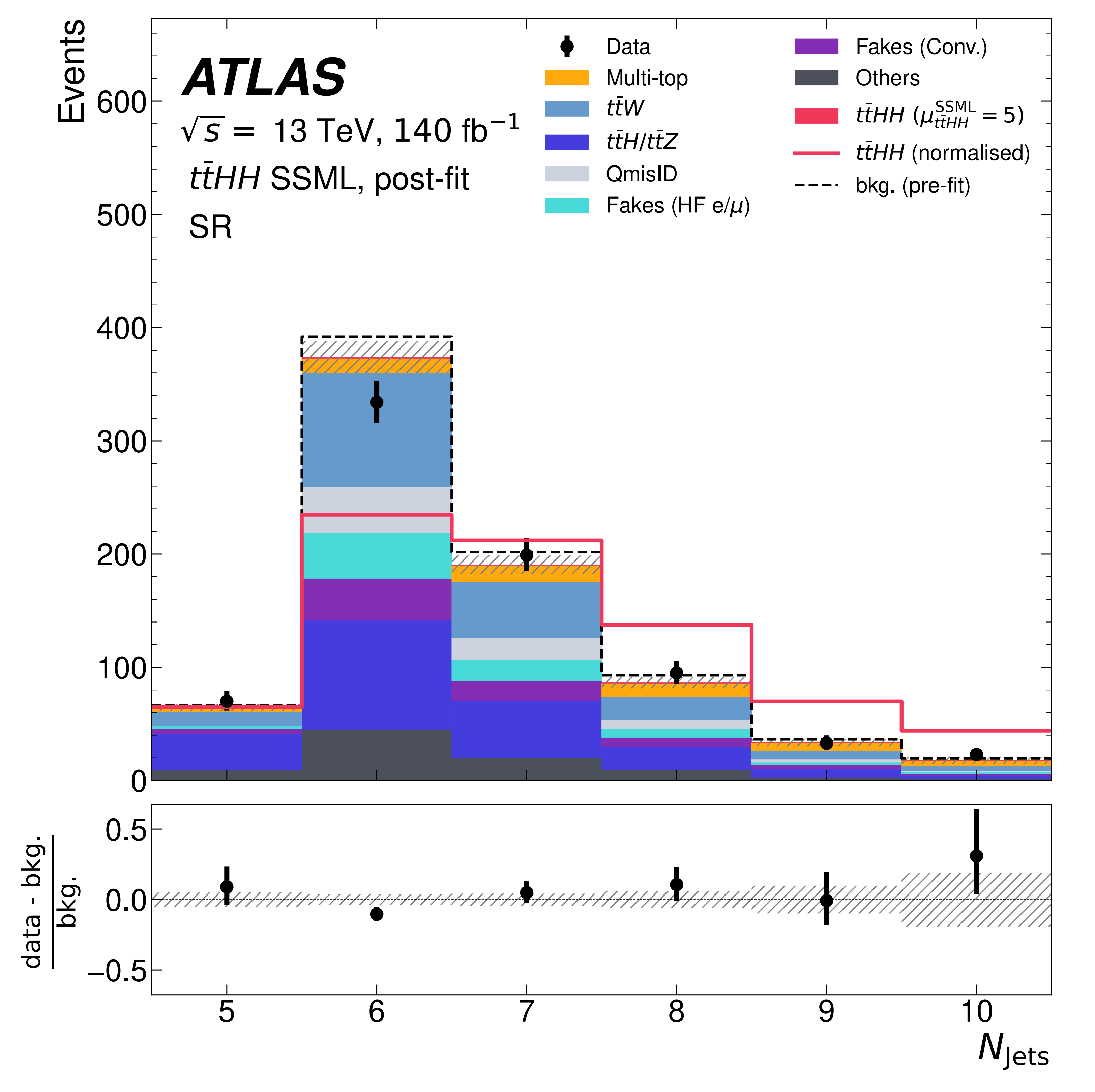
Variable	Description
Event-level	
N_{jets}	Number of jets
$N_{\text{b-jets}}$	Number of b-tagged jets
N_{lepton}	Number of leptons
H_T	The scalar sum of the transverse momenta of the leptons and jets in an event.
MET	Transverse energy of the missing momentum vector.
MET_PHI	Azimuthal angle of the missing momentum vector.
Object-level	
(p_T, η, ϕ)	Kinematic variables of the object, i.e. transverse momentum, pseudorapidity, and azimuthal angle.
w_{GN2}	GN201 b-tagging pseudo-continuous score for identifying jets. Non-jet objects are assigned a value of zero.
$q_{\text{Lep.}}$	Charge of the object. Non-lepton objects are assigned a value of zero.
(isJet, isElectron, isMuon)	Boolean flags indicating the object type: jet, electron, or muon.

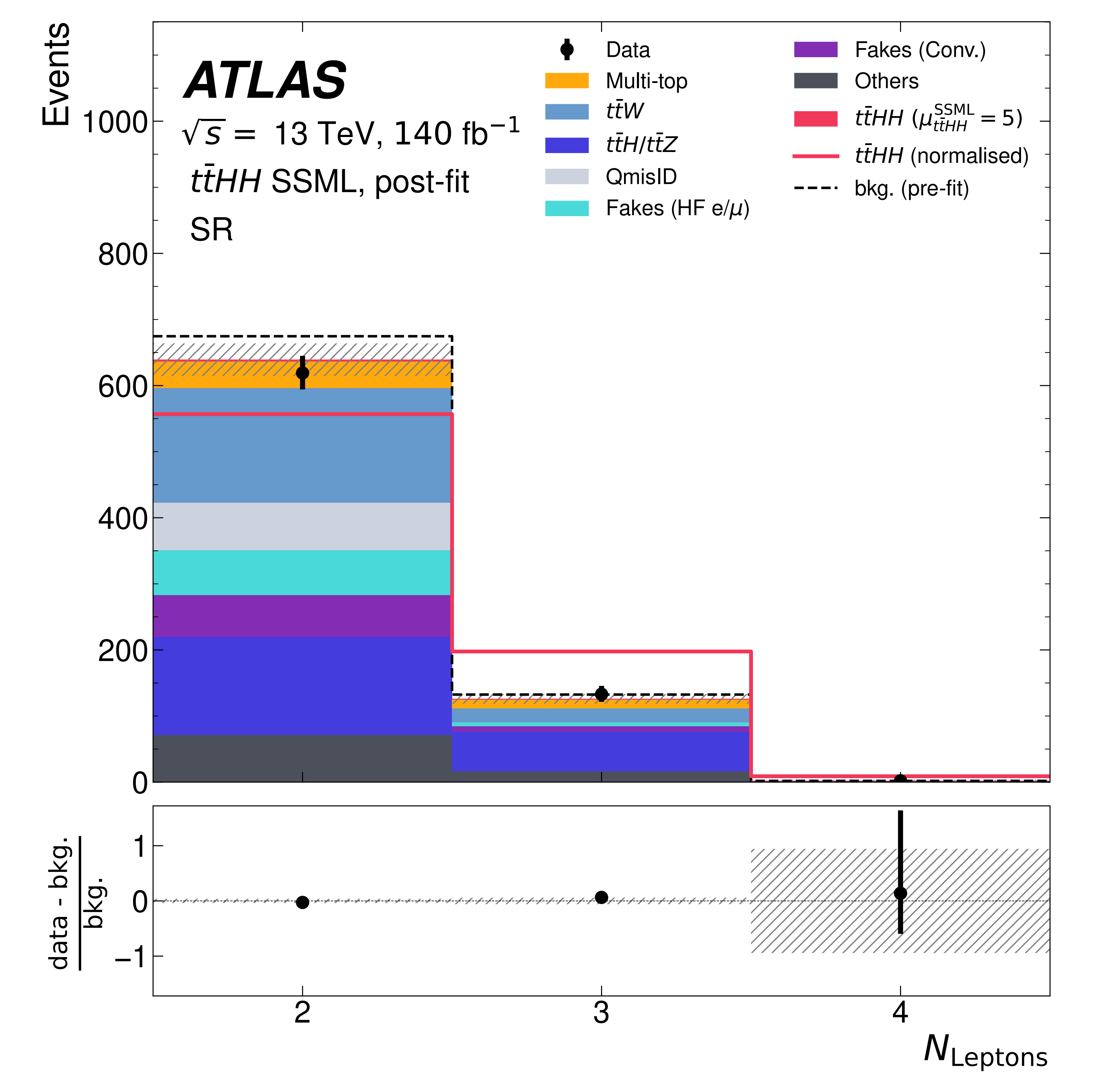
ML Run 2 CR distributions



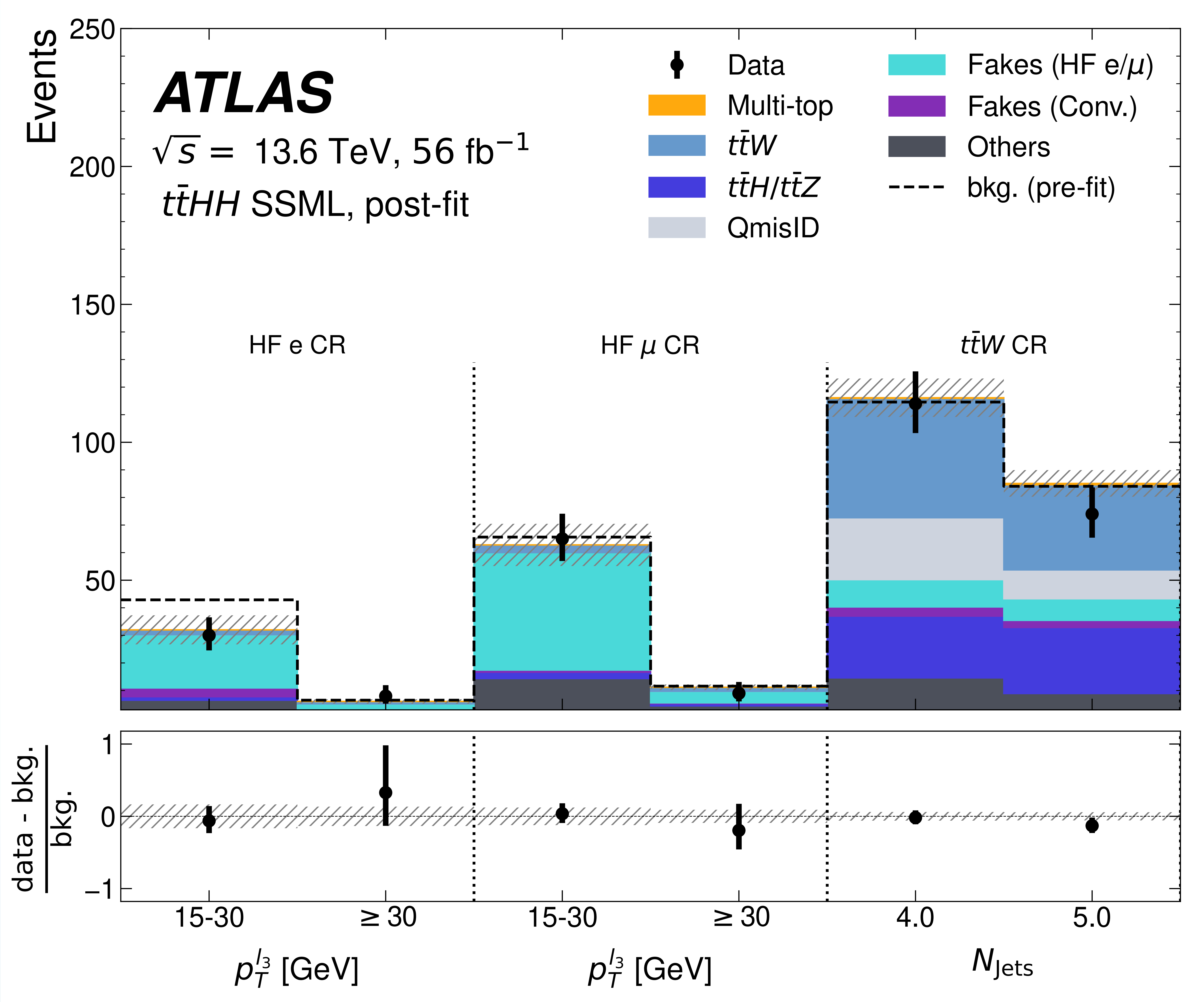
ML Run 2 SR distributions



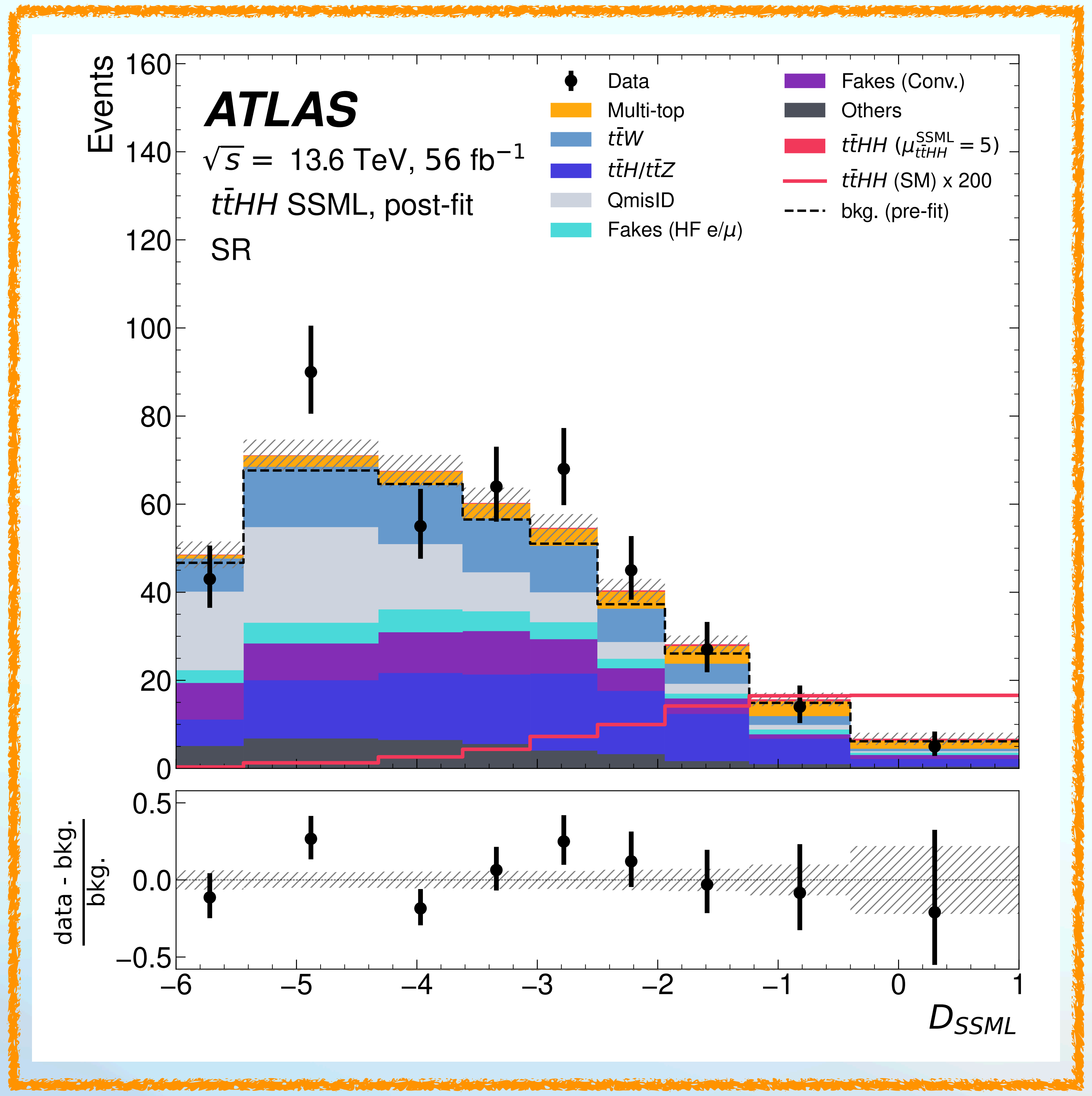


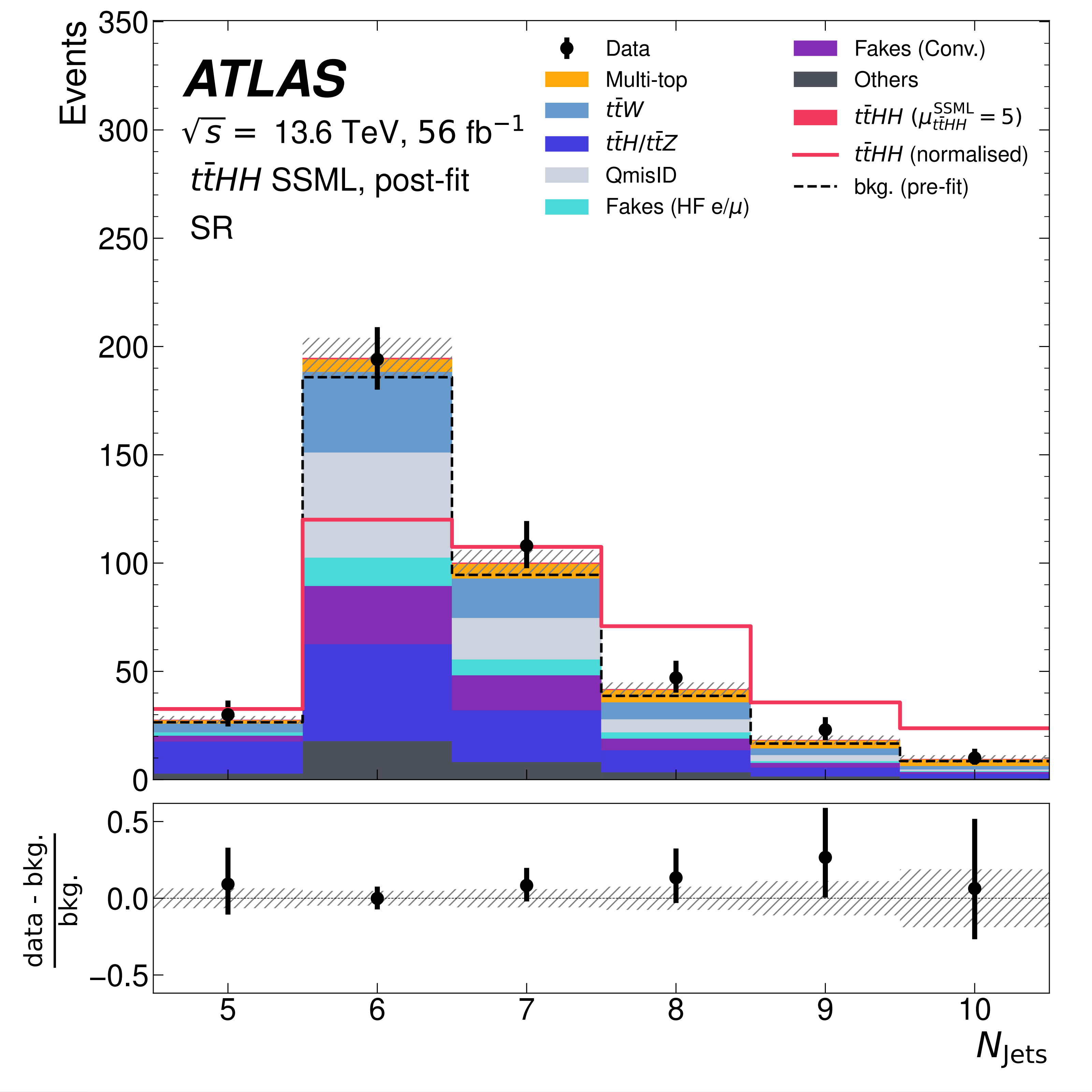


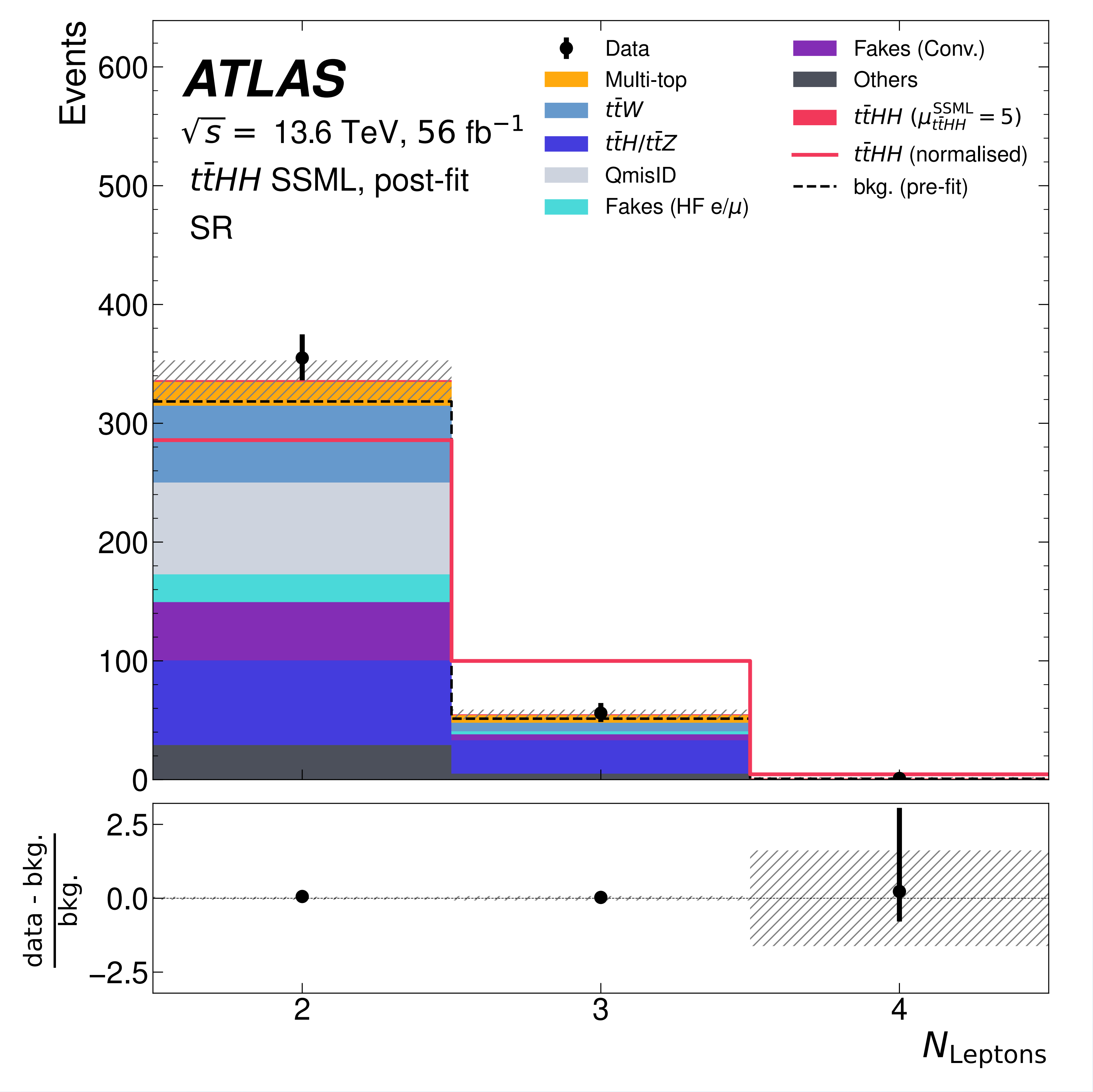
ML Run 3 CR distributions



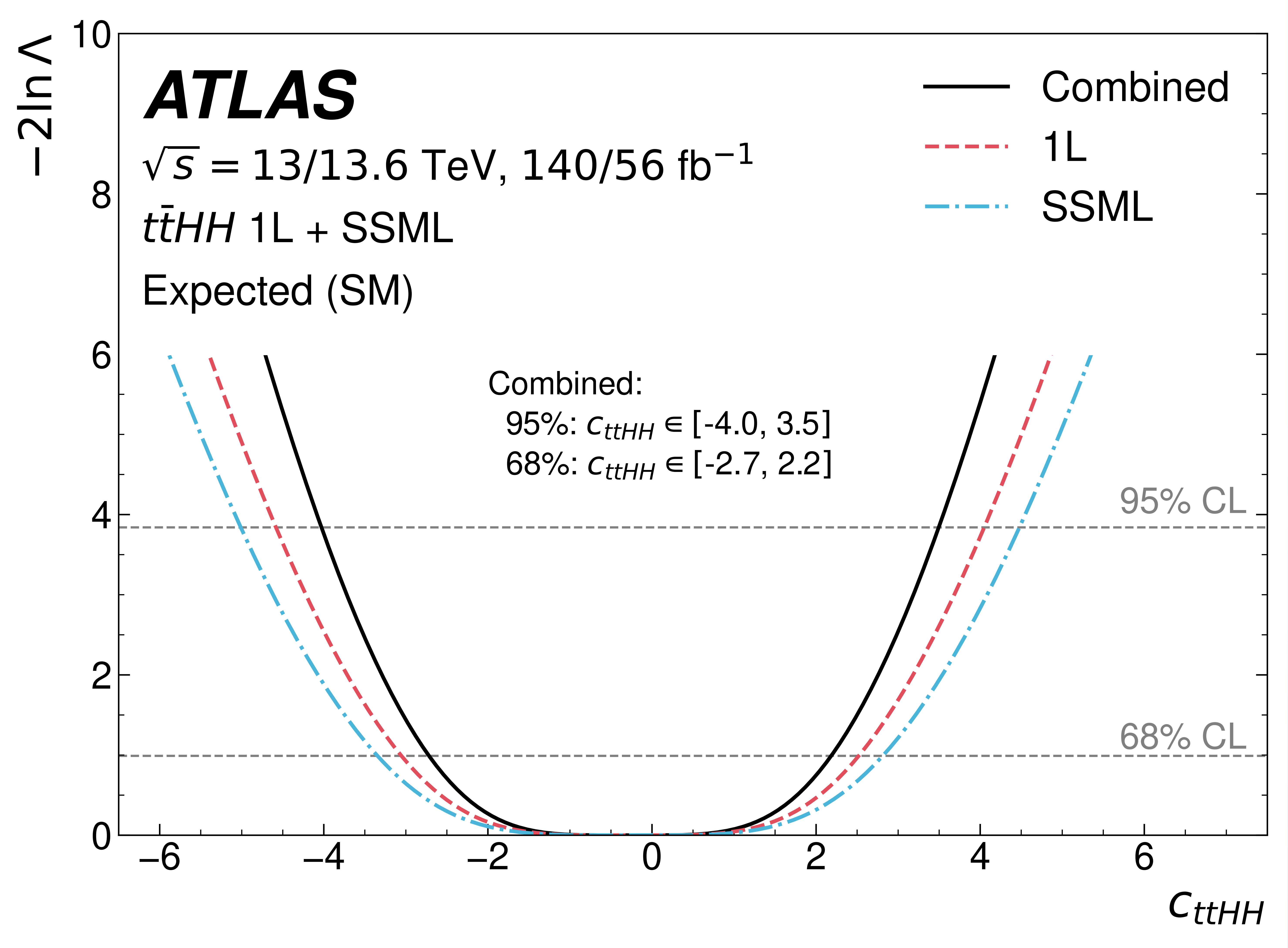
ML Run 3 SR distributions





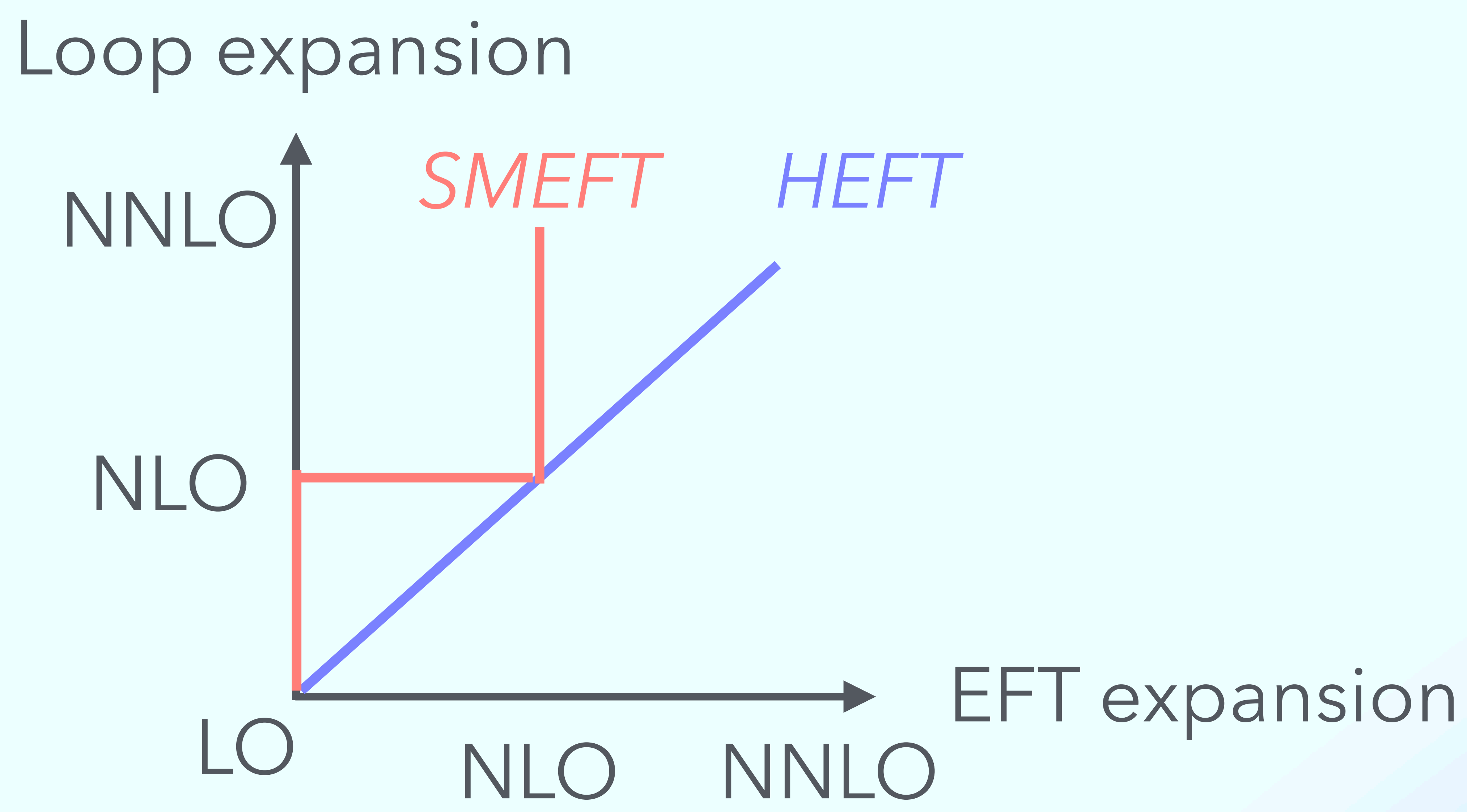


Expected likelihood for EFT fit



HEFT vs. SMEFT power counting

[arXiv:2511.23410]



SMEFT power counting keeps EFT independent of loop expansion

HEFT power counting counts loops, so one is constrained on the diagonal

HEFT vs. SMEFT power counting

Lagrangian : $\mathscr{L}_{\text{EFT}} = \mathscr{L}_{\text{SM}} + \sum_i \frac{c_i^{(6)}}{\Lambda^2}\mathcal{O}_i^{(6)} + \sum_i \frac{c_i^{(8)}}{\Lambda^4}\mathcal{O}_i^{(8)} + \cdots$

Event rates : $\sigma_{\text{EFT}} \sim |\mathscr{M}_{\text{SM}} + \mathscr{M}_6 + \mathscr{M}_{6+6} + \mathscr{M}_8 + \cdots|^2$

One d=6 ($\mathscr{M}_6$), *Two d=6* ($\mathscr{M}_{6+6}$), *One d=8* ($\mathscr{M}_8$)

	SM	One d=6	Two d=6	One d=8
Λ^0	$\sigma \sim |\mathscr{M}_{\text{SM}}|^2$			
Λ^{-2}		$+Re(\mathscr{M}_6 \cdot \mathscr{M}_{\text{SM}})$		
Λ^{-4}		$+|\mathscr{M}_6|^2$	$+Re(\mathscr{M}_{6+6} \cdot \mathscr{M}_{\text{SM}})$	$+Re(\mathscr{M}_8 \cdot \mathscr{M}_{\text{SM}})$
Λ^{-6}			$+Re(\mathscr{M}_{6+6} \cdot \mathscr{M}_6)$	$+Re(\mathscr{M}_8 \cdot \mathscr{M}_6)$
Λ^{-8}			$+|\mathscr{M}_{6+6}|^2$	$+|\mathscr{M}_8|^2 + Re(\mathscr{M}_8 \cdot \mathscr{M}_{6+6})$

HEFT vs. SMEFT power counting

Lagrangian : $\mathscr{L}_{\text{EFT}} = \mathscr{L}_{\text{SM}} + \sum_i \frac{c_i^{(6)}}{\Lambda^2}\mathcal{O}_i^{(6)} + \sum_i \frac{c_i^{(8)}}{\Lambda^4}\mathcal{O}_i^{(8)} + \cdots$

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One d=6 ($\mathscr{M}_6$), *Two d=6* ($\mathscr{M}_{6+6}$), *One d=8* ($\mathscr{M}_8$)

	SM	One d=6	Two d=6	One d=8
Λ^0	$\sigma \sim \lvert\mathscr{M}_{\text{SM}}\rvert^2$			
Λ^{-2}		$+Re(\mathscr{M}_6 \cdot \mathscr{M}_{\text{SM}})$		
Λ^{-4}		$+\lvert\mathscr{M}_6\rvert^2$	$+Re(\mathscr{M}_{6+6} \cdot \mathscr{M}_{\text{SM}})$	$+Re(\mathscr{M}_8 \cdot \mathscr{M}_{\text{SM}})$
Λ^{-6}			$+Re(\mathscr{M}_{6+6} \cdot \mathscr{M}_6)$	$+Re(\mathscr{M}_8 \cdot \mathscr{M}_6)$
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SMEFT linear d=6

HEFT vs. SMEFT power counting

Lagrangian : $\mathscr{L}_{\text{EFT}} = \mathscr{L}_{\text{SM}} + \sum_i \frac{c_i^{(6)}}{\Lambda^2}\mathcal{O}_i^{(6)} + \sum_i \frac{c_i^{(8)}}{\Lambda^4}\mathcal{O}_i^{(8)} + \cdots$

Event rates : $\sigma_{\text{EFT}} \sim |\mathscr{M}_{\text{SM}} + \mathscr{M}_6 + \mathscr{M}_{6+6} + \mathscr{M}_8 + \cdots|^2$

One d=6 ($\mathscr{M}_6$), *Two d=6* ($\mathscr{M}_{6+6}$), *One d=8* ($\mathscr{M}_8$)

	SM	One d=6	Two d=6	One d=8
Λ^0	$\sigma \sim |\mathscr{M}_{\text{SM}}|^2$			
Λ^{-2}		$+Re(\mathscr{M}_6 \cdot \mathscr{M}_{\text{SM}})$		
Λ^{-4}		$+|\mathscr{M}_6|^2$	$+Re(\mathscr{M}_{6+6} \cdot \mathscr{M}_{\text{SM}})$	$+Re(\mathscr{M}_8 \cdot \mathscr{M}_{\text{SM}})$
Λ^{-6}			$+Re(\mathscr{M}_{6+6} \cdot \mathscr{M}_6)$	$+Re(\mathscr{M}_8 \cdot \mathscr{M}_6)$
Λ^{-8}			$+|\mathscr{M}_{6+6}|^2$	$+|\mathscr{M}_8|^2 + Re(\mathscr{M}_8 \cdot \mathscr{M}_{6+6})$

SMEFT linear d=6 (box: rows Λ^0 and Λ^{-2}, columns SM and One d=6)

SMEFT linear+quad d=6 (box: rows Λ^0 to Λ^{-4}, columns SM and One d=6)

HEFT vs. SMEFT power counting

Lagrangian : $\mathscr{L}_{\text{EFT}} = \mathscr{L}_{\text{SM}} + \sum_i \frac{c_i^{(6)}}{\Lambda^2}\mathscr{O}_i^{(6)} + \sum_i \frac{c_i^{(8)}}{\Lambda^4}\mathscr{O}_i^{(8)} + \cdots$

Event rates : $\sigma_{\text{EFT}} \sim |\mathscr{M}_{\text{SM}} + \mathscr{M}_6 + \mathscr{M}_{6+6} + \mathscr{M}_8 + \cdots|^2$

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Λ^{-4}		$+\lvert\mathscr{M}_6\rvert^2$	$+Re(\mathscr{M}_{6+6} \cdot \mathscr{M}_{\text{SM}})$	$+Re(\mathscr{M}_8 \cdot \mathscr{M}_{\text{SM}})$
Λ^{-6}			$+Re(\mathscr{M}_{6+6} \cdot \mathscr{M}_6)$	$+Re(\mathscr{M}_8 \cdot \mathscr{M}_6)$
Λ^{-8}			$+\lvert\mathscr{M}_{6+6}\rvert^2$	$+\lvert\mathscr{M}_8\rvert^2+Re(\mathscr{M}_8 \cdot \mathscr{M}_{6+6})$

SMEFT linear d=6

SMEFT linear d=8

SMEFT linear+quad d=6

HEFT vs. SMEFT power counting

Lagrangian : $\mathscr{L}_{\text{EFT}} = \mathscr{L}_{\text{SM}} + \sum_i \frac{c_i^{(6)}}{\Lambda^2}\mathcal{O}_i^{(6)} + \sum_i \frac{c_i^{(8)}}{\Lambda^4}\mathcal{O}_i^{(8)} + \cdots$

Event rates : $\sigma_{\text{EFT}} \sim |\mathscr{M}_{\text{SM}} + \mathscr{M}_6 + \mathscr{M}_{6+6} + \mathscr{M}_8 + \cdots|^2$

One d=6 ($\mathscr{M}_6$), *Two d=6* ($\mathscr{M}_{6+6}$), *One d=8* ($\mathscr{M}_8$)

	SM	One d=6	Two d=6	One d=8
Λ^0	$\sigma \sim |\mathscr{M}_{\text{SM}}|^2$			
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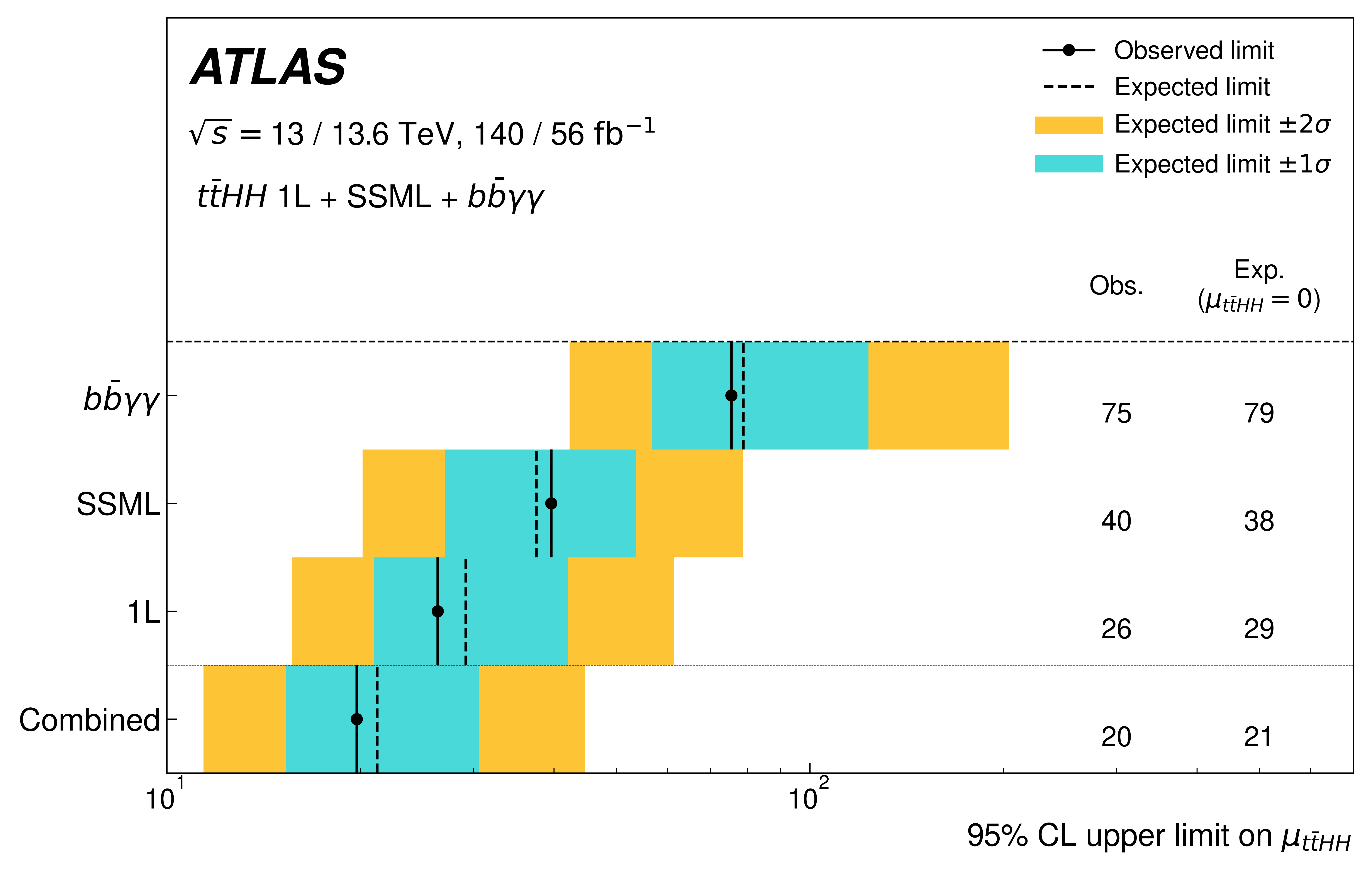
SMEFT linear d=6

SMEFT linear d=8

SMEFT linear+quad d=6

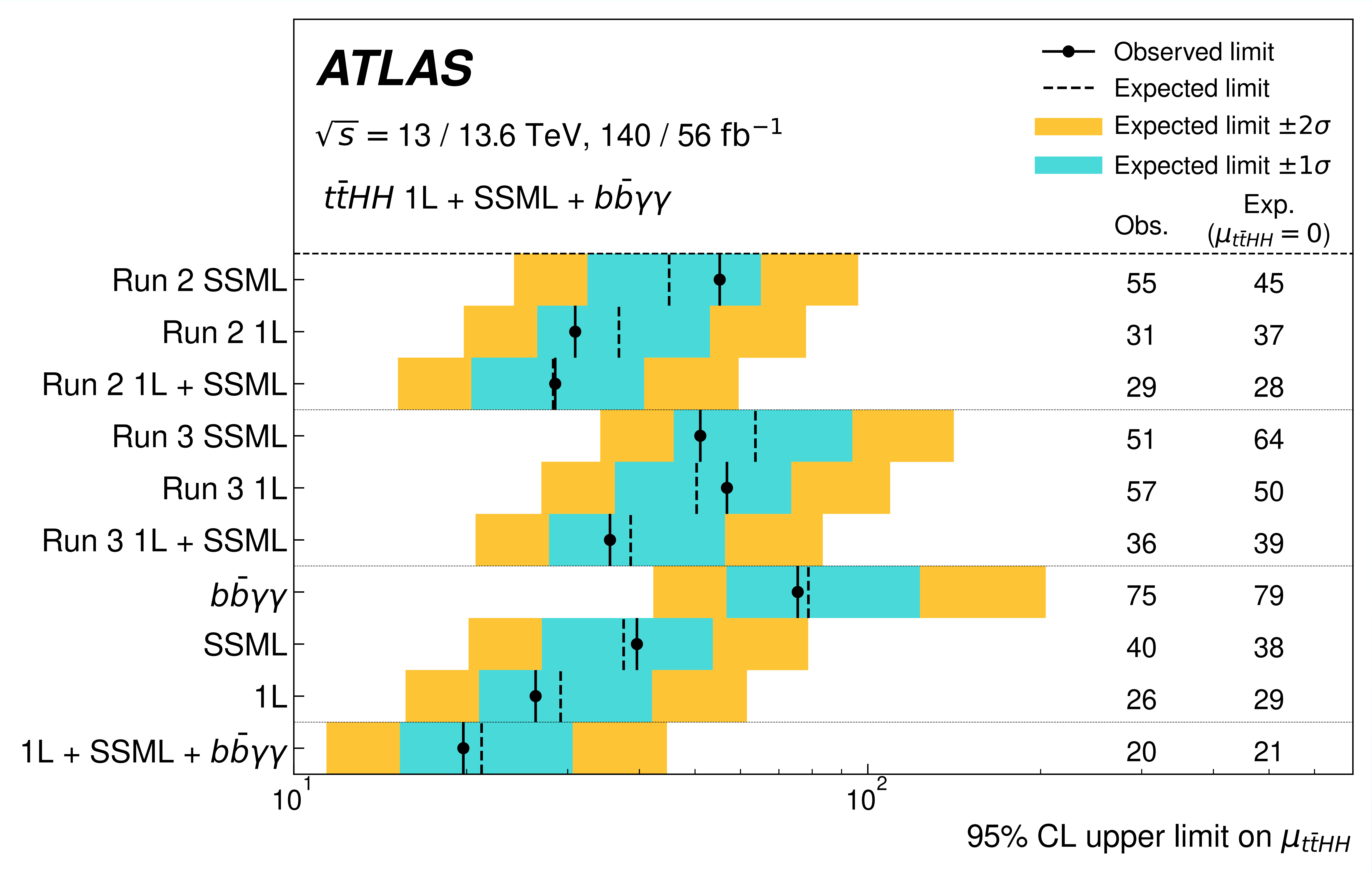
HEFT

Results on signal stength



- No excess observed
- 95% CL Upper Limits : **20 (21) x SM**
- Most stringent limits to date

Signal strength results split by channels



- 1L and ML are the most sensitive channels

Ressources

Most of the results / figures presented in this seminar are sourced, but here is a list of other **very good presentations** I've used as reference while preparing it

Arthur Lafarge's Ph.D. defense

What the double production of the Higgs boson with a two-photon signature in ATLAS reveals about the stability of our universe and how a chronometer will illuminate our understanding?

→ *Overview of di-Higgs physics*

Rahul Balasubramanian's seminar @ LAPP

Effectively going beyond the Standard Model with the ATLAS experiment

→ *Overview of Standard Model Effective field theory in ATLAS*

Jonathon Langford's seminar @ CERN

Combined measurements and interpretations of Higgs boson production and decay in CMS

→ Overview of Higgs boson physics in CMS (and LHC in general)

Tina Ojeda's talk @ Moriond EW

Search for deviations within the EFT framework at ATLAS and CMS

→ Overview of EFT landscape, highlighting the current problems with this tool