

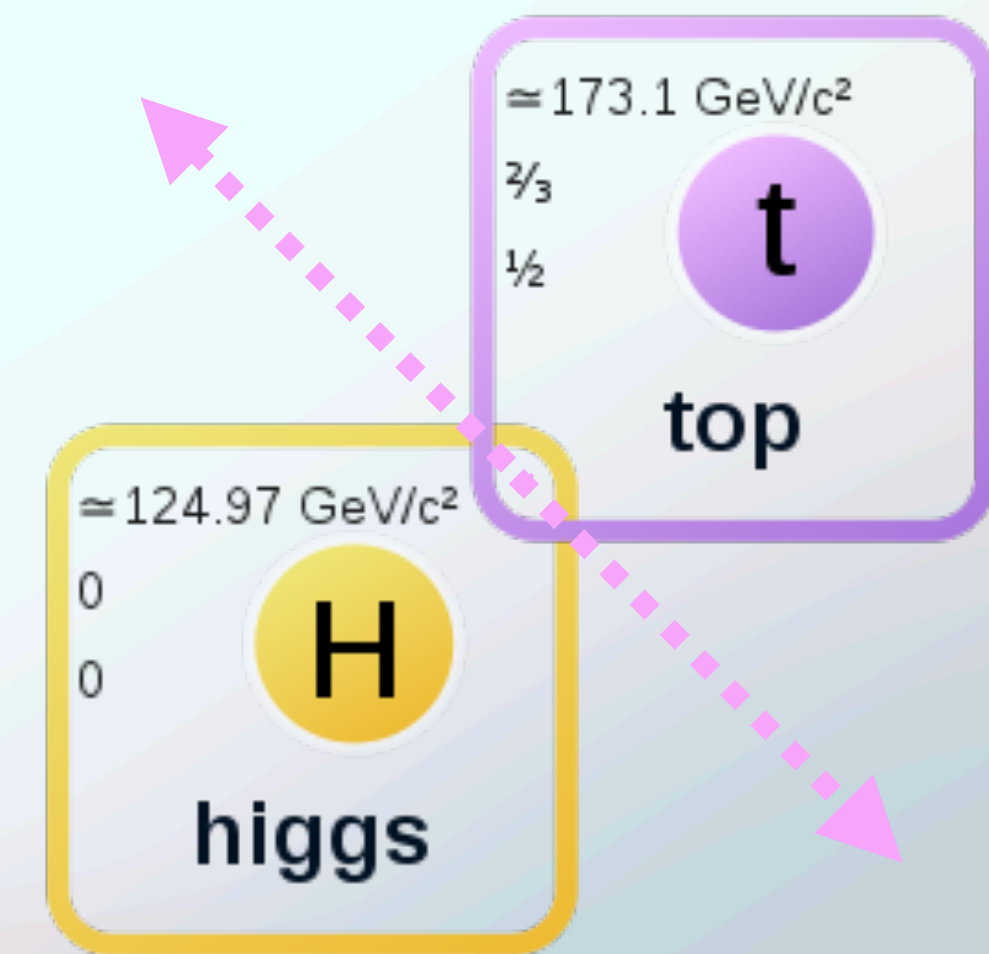


# Probing Electroweak Symmetry Breaking with Effective Field Theories

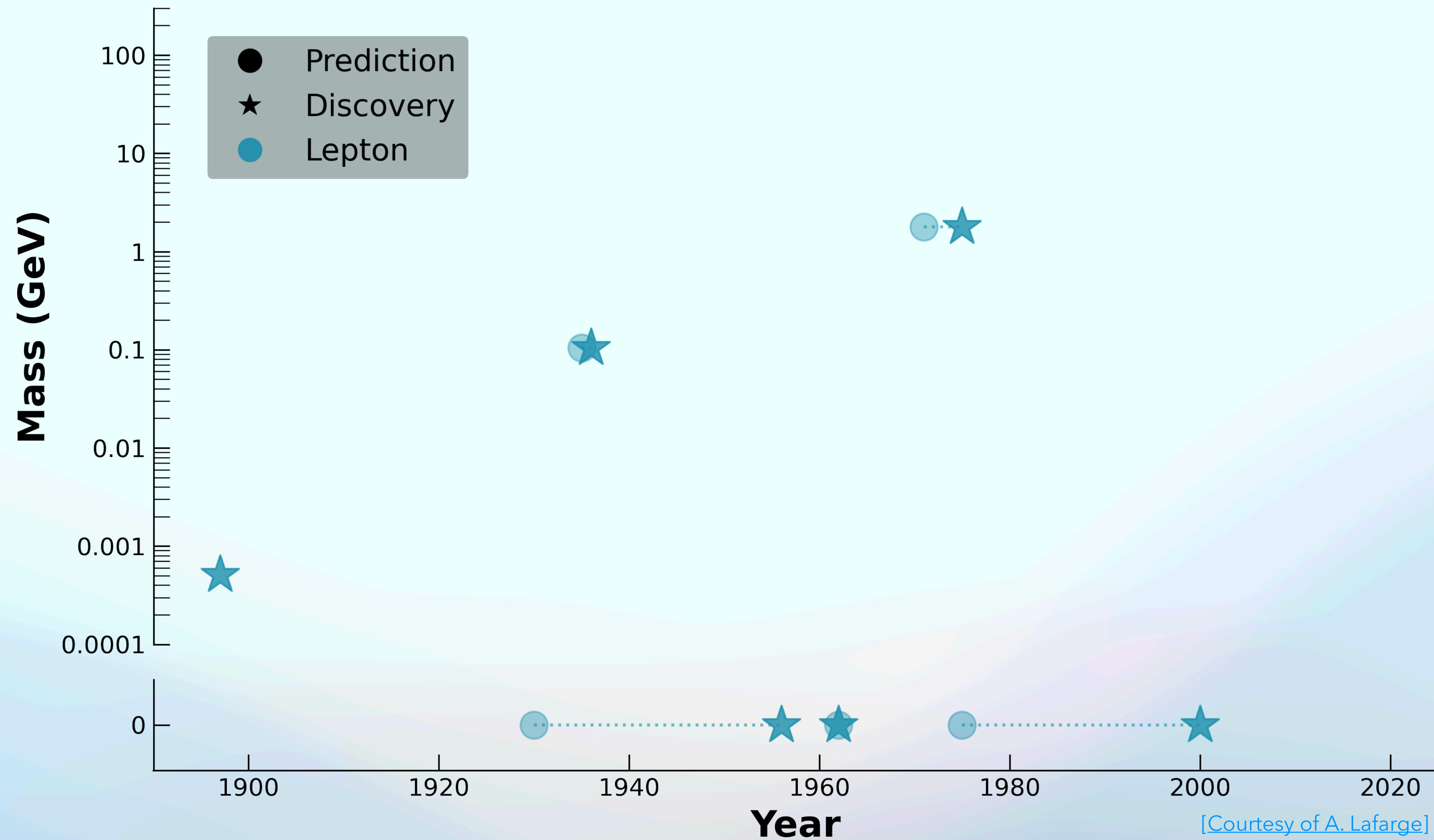
in Top quark and Higgs sectors

LPCA seminar - 30, April 2026

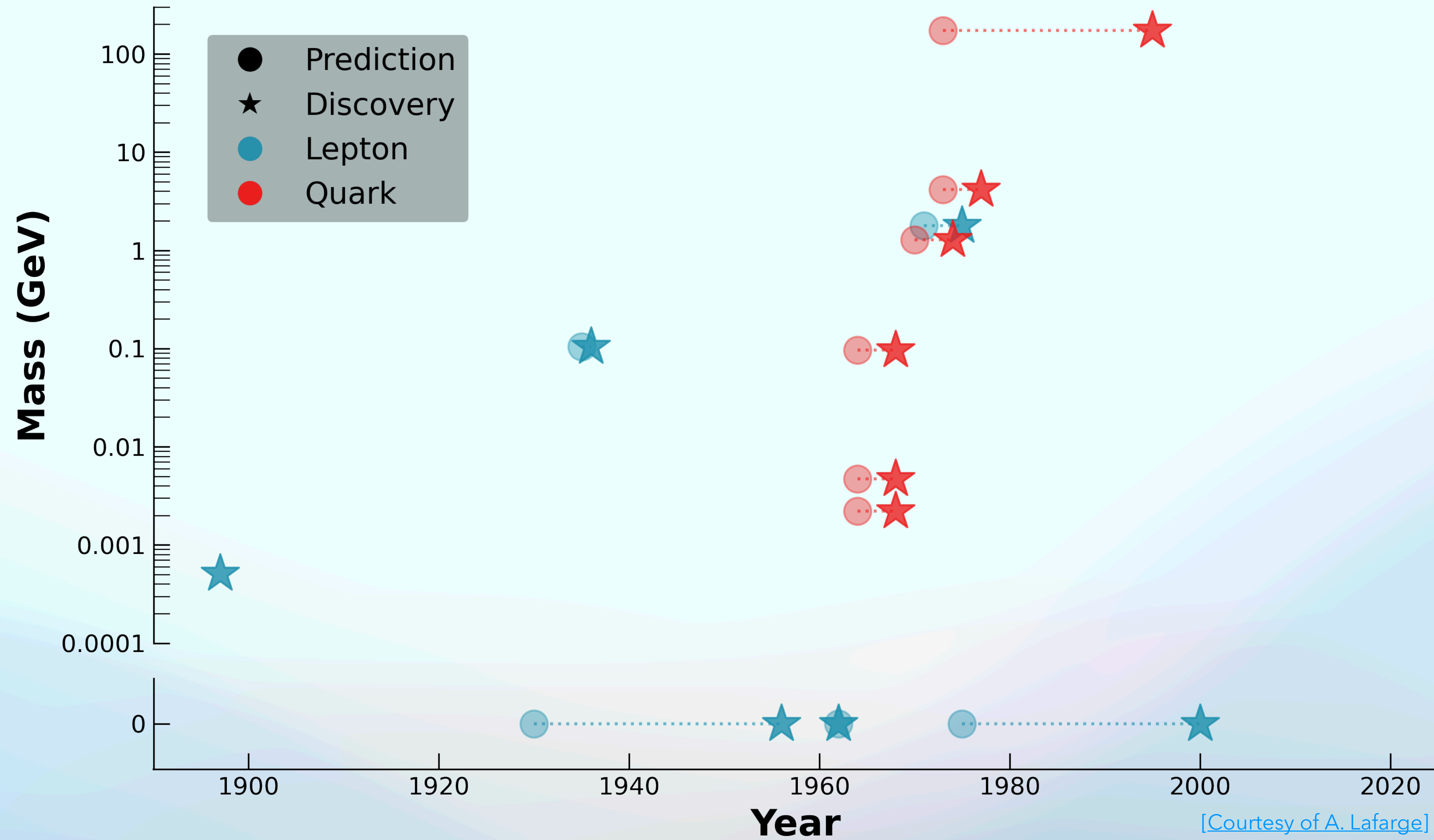
Adrien Auriol



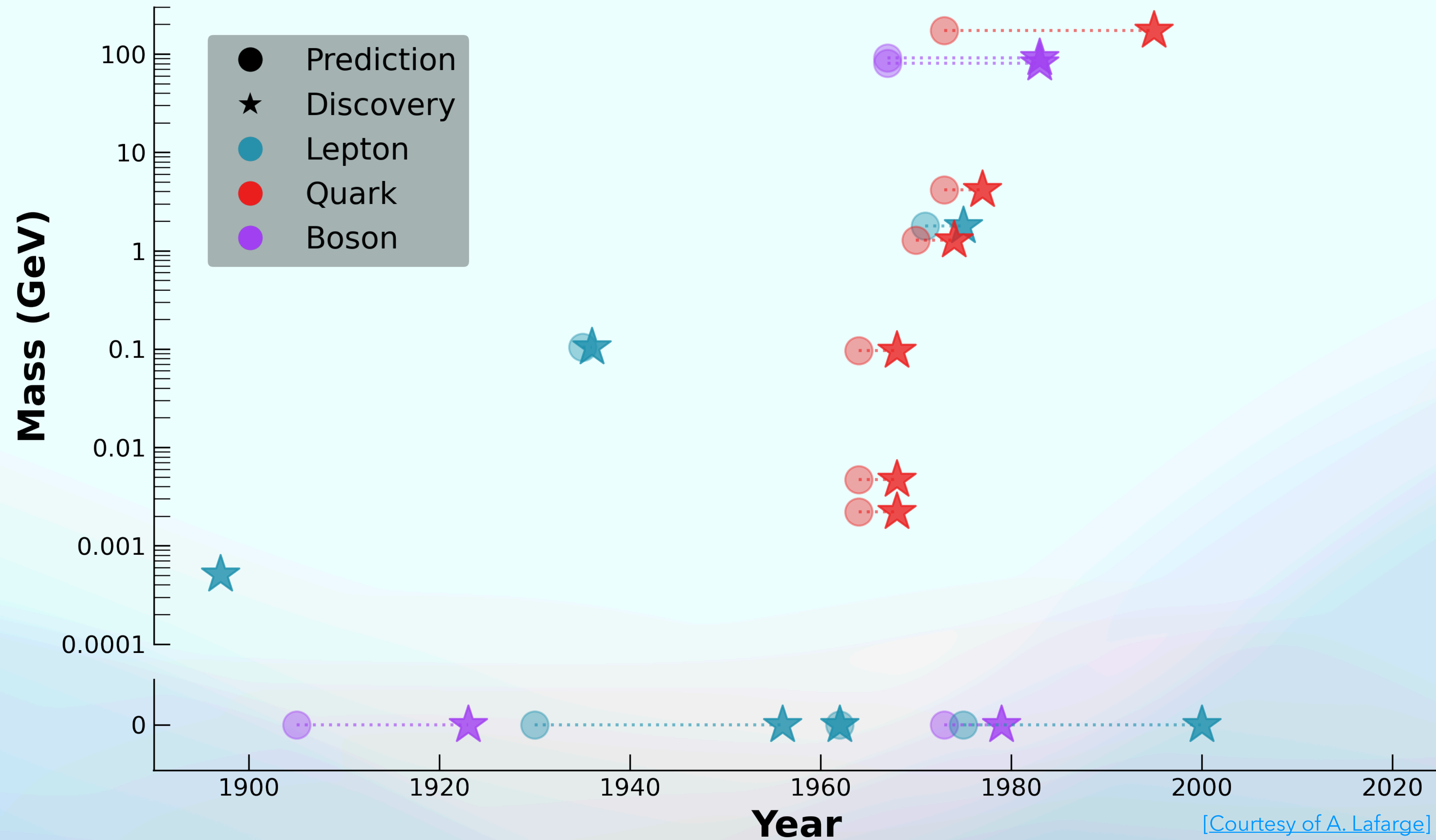
# A discovery tale



# A discovery tale

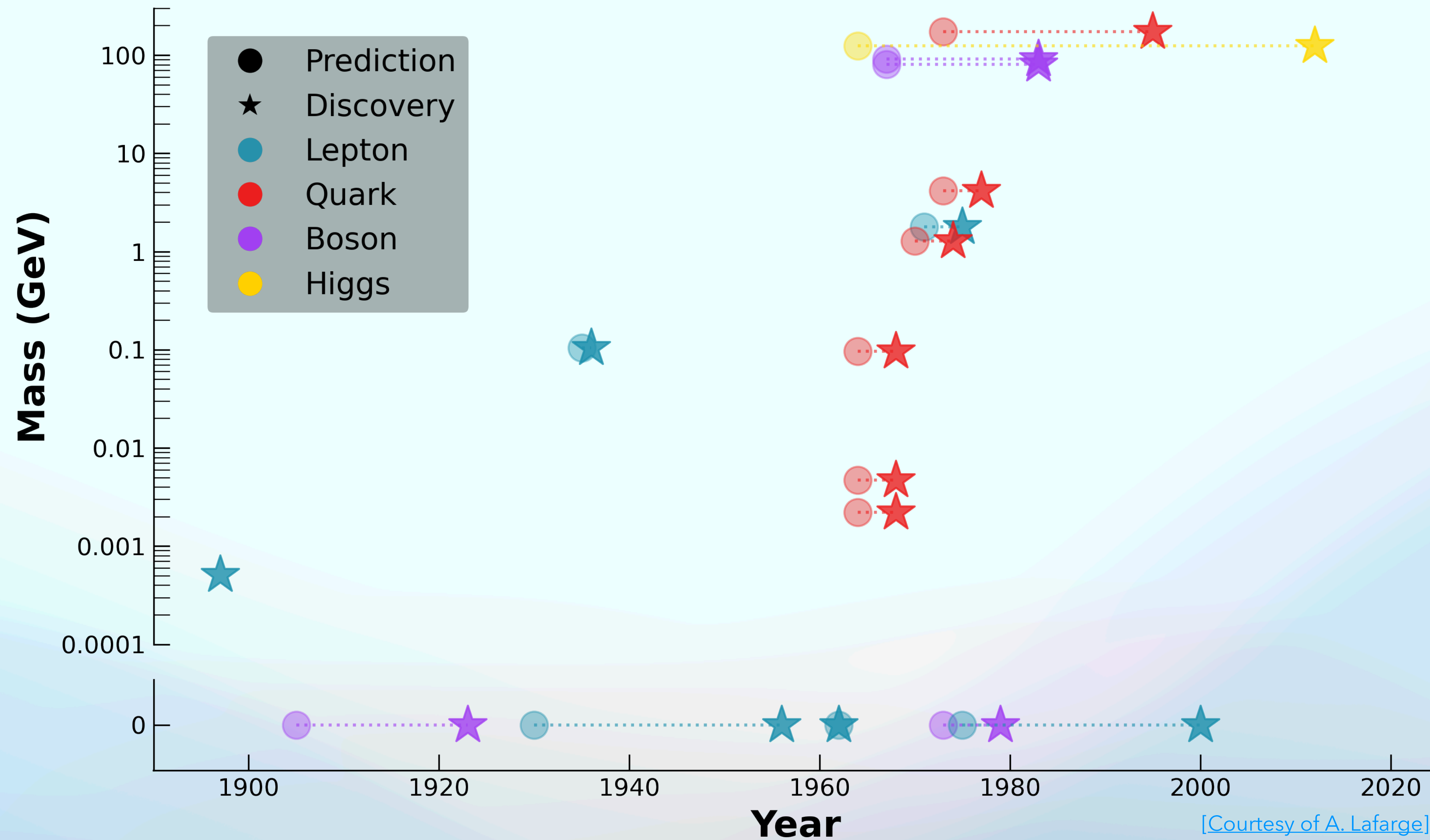


# A discovery tale



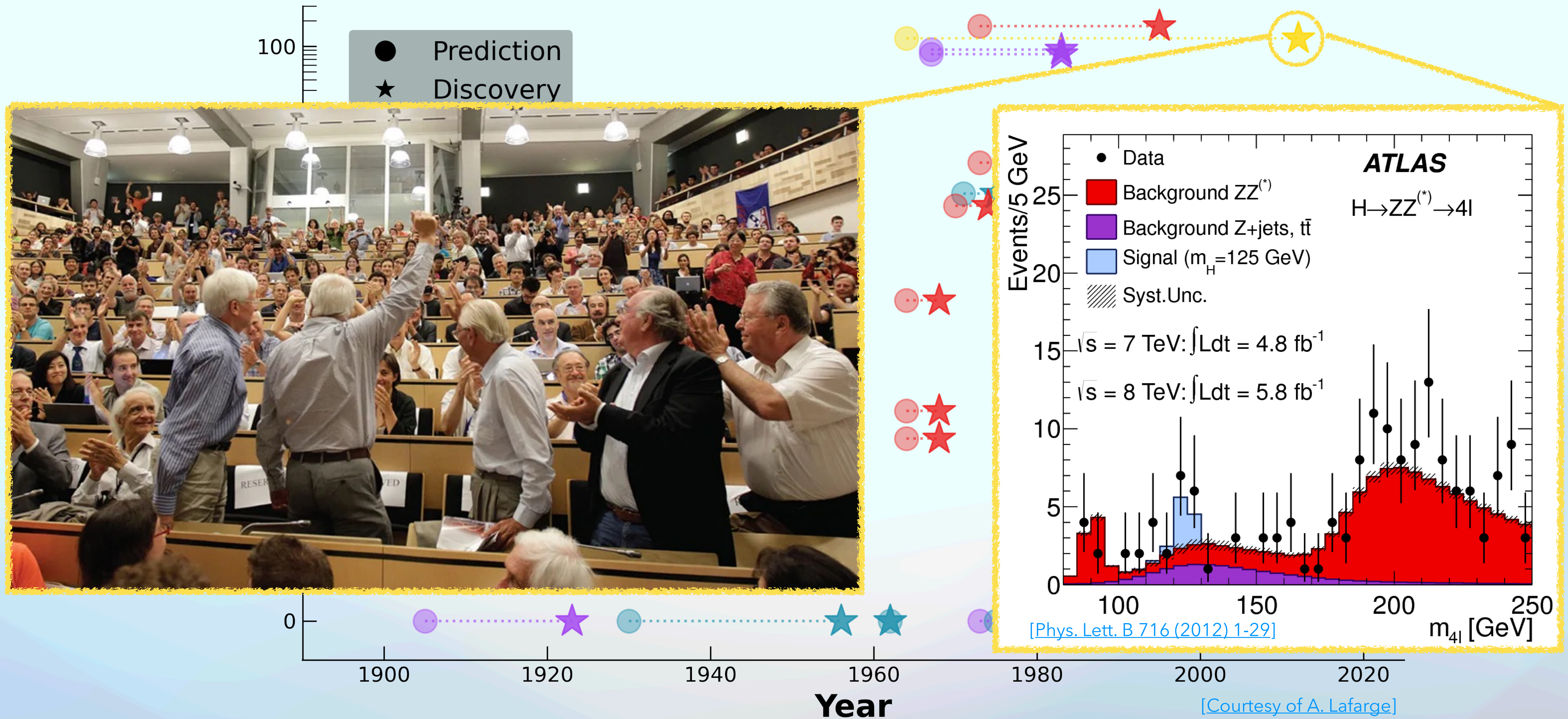
[Courtesy of A. Lafarge]

# A discovery tale



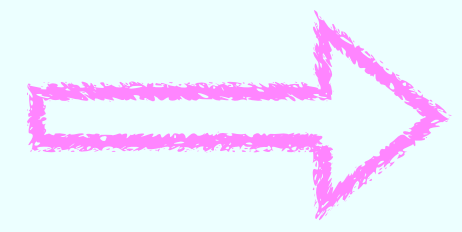
[Courtesy of A. Lafarge]

# A discovery tale



# The Standard Model (SM)

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



### Standard Model of Elementary Particles

	three generations of matter (elementary fermions)			three generations of antimatter (elementary antifermions)			interactions / force carriers (elementary bosons)	
	I	II	III	I	II	III		
mass	≈ 2.2 MeV/c <sup>2</sup>	≈ 1.28 GeV/c <sup>2</sup>	≈ 173.1 GeV/c <sup>2</sup>	≈ 2.2 MeV/c <sup>2</sup>	≈ 1.28 GeV/c <sup>2</sup>	≈ 173.1 GeV/c <sup>2</sup>	0	≈ 124.97 GeV/c <sup>2</sup>
charge	2/3	2/3	2/3	-2/3	-2/3	-2/3	0	0
spin	1/2	1/2	1/2	1/2	1/2	1/2	1	0
	<b>u</b> up	<b>c</b> charm	<b>t</b> top	<b>ū</b> antiup	<b>c̄</b> anticharm	<b>t̄</b> antitop	<b>g</b> gluon	<b>H</b> higgs
	<b>d</b> down	<b>s</b> strange	<b>b</b> bottom	<b>d̄</b> antidown	<b>s̄</b> antistrange	<b>b̄</b> antibottom	<b>γ</b> photon	
	<b>e</b> electron	<b>μ</b> muon	<b>τ</b> tau	<b>e<sup>+</sup></b> positron	<b>μ̄</b> antimuon	<b>τ̄</b> antitau	<b>Z</b> Z <sup>0</sup> boson	
	<b>ν<sub>e</sub></b> electron neutrino	<b>ν<sub>μ</sub></b> muon neutrino	<b>ν<sub>τ</sub></b> tau neutrino	<b>ν̄<sub>e</sub></b> electron antineutrino	<b>ν̄<sub>μ</sub></b> muon antineutrino	<b>ν̄<sub>τ</sub></b> tau antineutrino	<b>W<sup>+</sup></b> W <sup>+</sup> boson	<b>W<sup>-</sup></b> W <sup>-</sup> boson

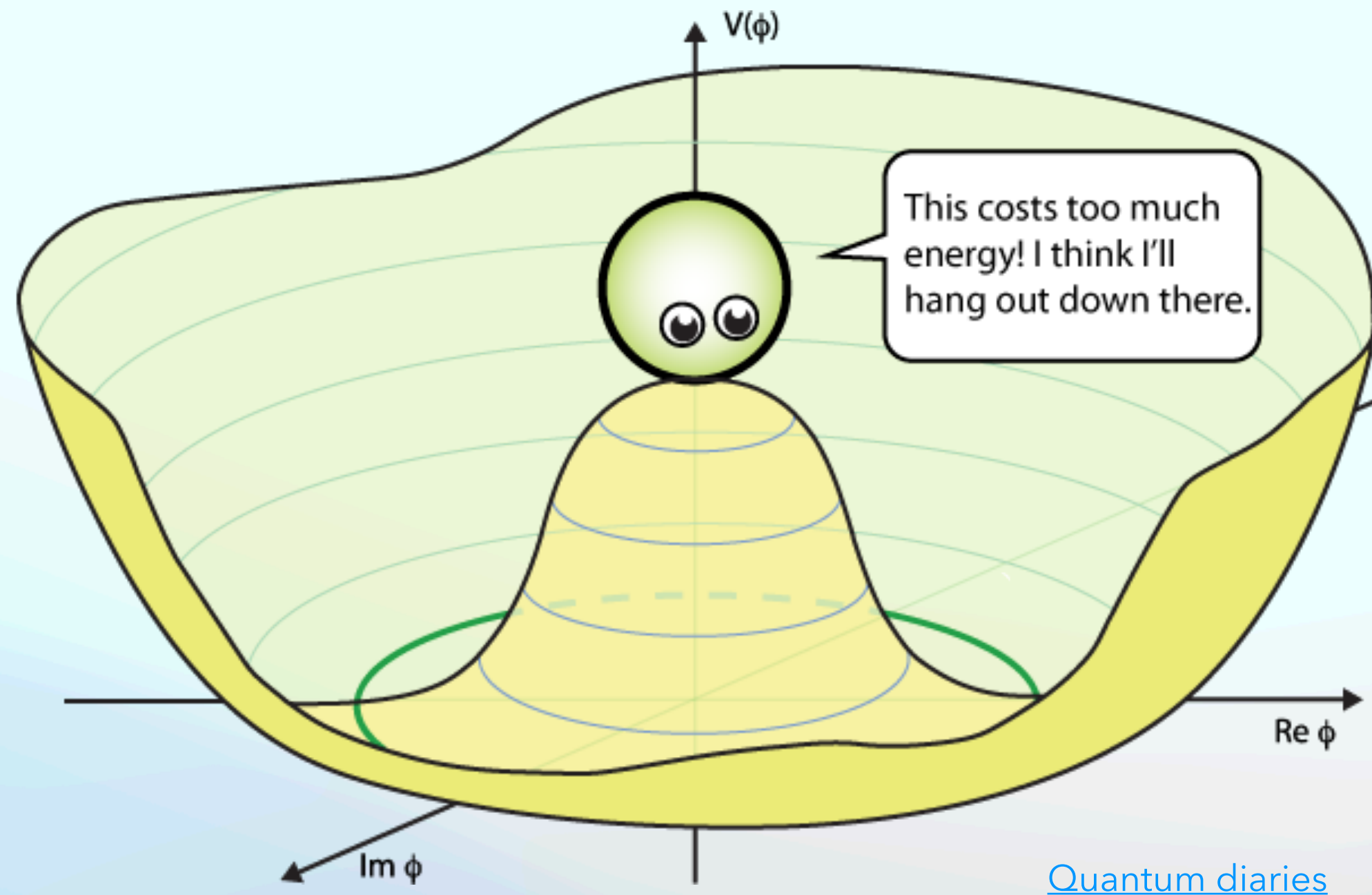
QUARKS  
LEPTONS  
GAUGE BOSONS  
VECTOR BOSONS  
SCALAR BOSONS

# Generalities about the Higgs boson in the SM

**SM** introduce a spin-0 Higgs field  $\phi$

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

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



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

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

# The Higgs mechanism in the SM

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

$SU(2)_L$  doublet



## Broken phase

1 Higgs scalar  $h$   
3 Goldstone bosons

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

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

# The Higgs mechanism in the SM

## Unbroken phase

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

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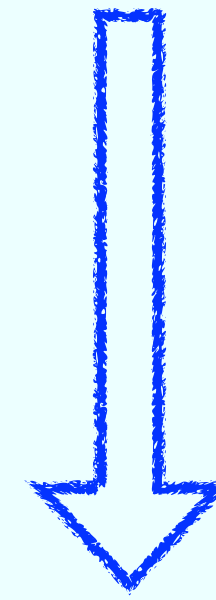


## Broken phase

1 Higgs scalar  $h$   
3 Goldstone bosons

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

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



## Gauge Interaction

Goldstone are eaten  
Become longitudinal polarization of  $W^\pm, Z^0$

$\approx 91.19 \text{ GeV}/c^2$  <b>Z<sup>0</sup> boson</b>	$\approx 124.97 \text{ GeV}/c^2$  <b>higgs</b>	<p>1 physical Higgs boson</p> <p>+</p> <p>Massive gauge bosons with 3 polarizations</p>	<ul style="list-style-type: none"> <li>→ <b>1</b> d.o.f. from Higgs scalar</li> <li>→ <b>3x3</b> d.o.f. from Vector Bosons</li> <li>→ <b>2</b> d.o.f. from Photon</li> </ul>
$\approx 80.39 \text{ GeV}/c^2$  <b>W<sup>+</sup> boson</b>			

# Beyond the Standard Model (BSM) ?

### Standard Model of Elementary Particles

	three generations of matter (elementary fermions)			three generations of antimatter (elementary antifermions)			interactions / force carriers (elementary bosons)	
	I	II	III	I	II	III		
mass	$\approx 2.2 \text{ MeV}/c^2$	$\approx 1.28 \text{ GeV}/c^2$	$\approx 173.1 \text{ GeV}/c^2$	$\approx 2.2 \text{ MeV}/c^2$	$\approx 1.28 \text{ GeV}/c^2$	$\approx 173.1 \text{ GeV}/c^2$	0	$\approx 124.97 \text{ GeV}/c^2$
charge	$\frac{2}{3}$	$\frac{2}{3}$	$\frac{2}{3}$	$-\frac{2}{3}$	$-\frac{2}{3}$	$-\frac{2}{3}$	0	0
spin	$\frac{1}{2}$	$\frac{1}{2}$	$\frac{1}{2}$	$\frac{1}{2}$	$\frac{1}{2}$	$\frac{1}{2}$	1	0
	<b>u</b> up	<b>c</b> charm	<b>t</b> top	<b><math>\bar{u}</math></b> antiup	<b><math>\bar{c}</math></b> anticharm	<b><math>\bar{t}</math></b> antitop	<b>g</b> gluon	<b>H</b> higgs
	<b>d</b> down	<b>s</b> strange	<b>b</b> bottom	<b><math>\bar{d}</math></b> antidown	<b><math>\bar{s}</math></b> antistrange	<b><math>\bar{b}</math></b> antibottom	<b><math>\gamma</math></b> photon	
	<b>e</b> electron	<b><math>\mu</math></b> muon	<b><math>\tau</math></b> tau	<b><math>e^+</math></b> positron	<b><math>\bar{\mu}</math></b> antimuon	<b><math>\bar{\tau}</math></b> antitau	<b>Z</b> Z <sup>0</sup> boson	
	<b><math>\nu_e</math></b> electron neutrino	<b><math>\nu_\mu</math></b> muon neutrino	<b><math>\nu_\tau</math></b> tau neutrino	<b><math>\bar{\nu}_e</math></b> electron antineutrino	<b><math>\bar{\nu}_\mu</math></b> muon antineutrino	<b><math>\bar{\nu}_\tau</math></b> tau antineutrino	<b>W<sup>+</sup></b> W <sup>+</sup> boson	<b>W<sup>-</sup></b> W <sup>-</sup> boson

**QUARKS** (rows 1-3)  
**LEPTONS** (rows 4-5)  
**GAUGE BOSONS VECTOR BOSONS** (columns 7-8)  
**SCALAR BOSONS** (column 9)

### Beyond the SM

Matter-antimatter asymmetry ?

Gravity ?

Shape of Higgs potential ?

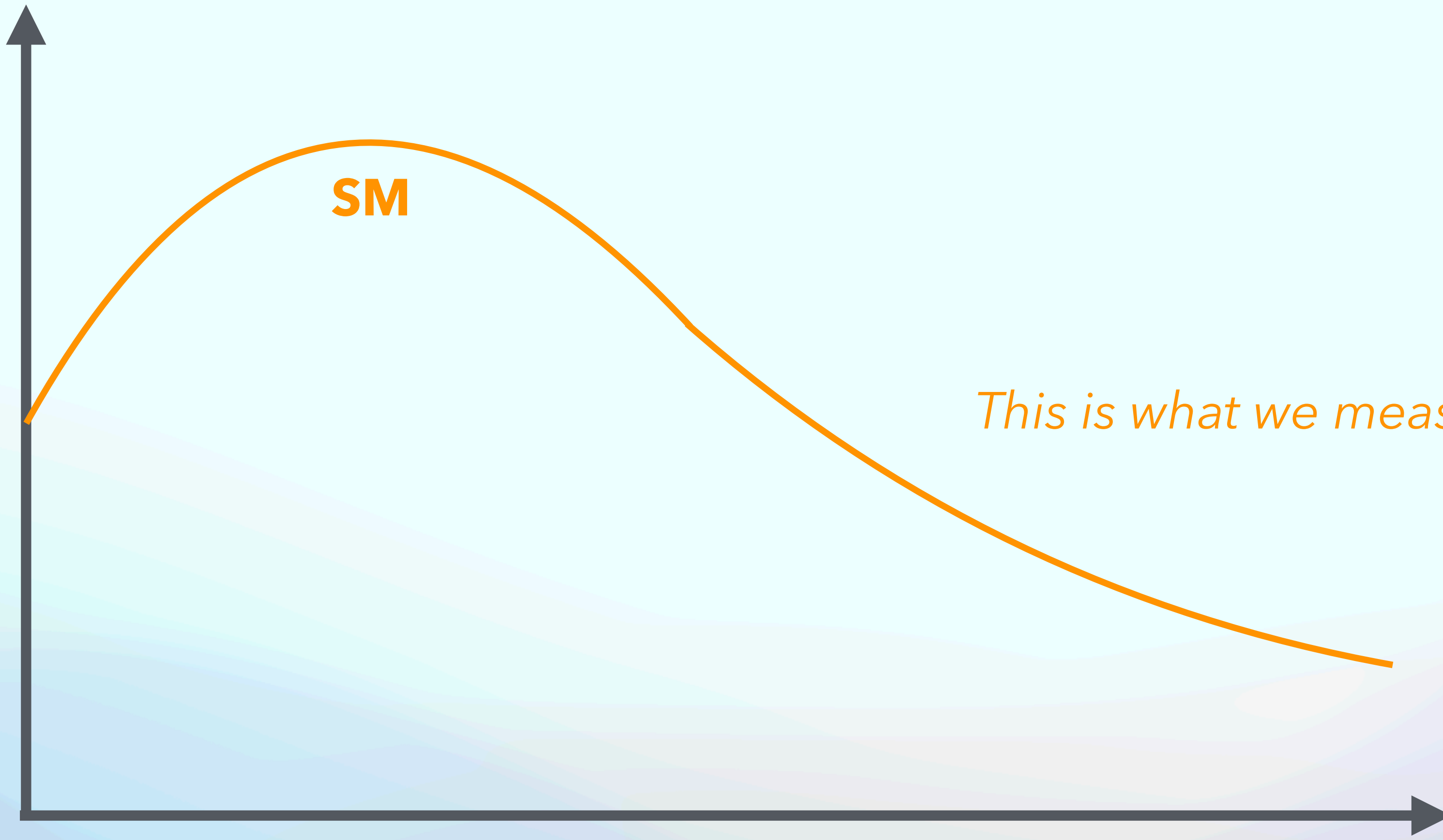
Vacuum stability ?

$\begin{matrix} 0 \\ 0 \\ 2 \end{matrix}$   
**g**  
 Graviton

$\begin{matrix} ? \text{ GeV}/c^2 \\ 1 \\ 0 \end{matrix}$   
 **$\chi$**   
 Loryons

# Going beyond the SM - **direct** or **effective** ?

**Events**



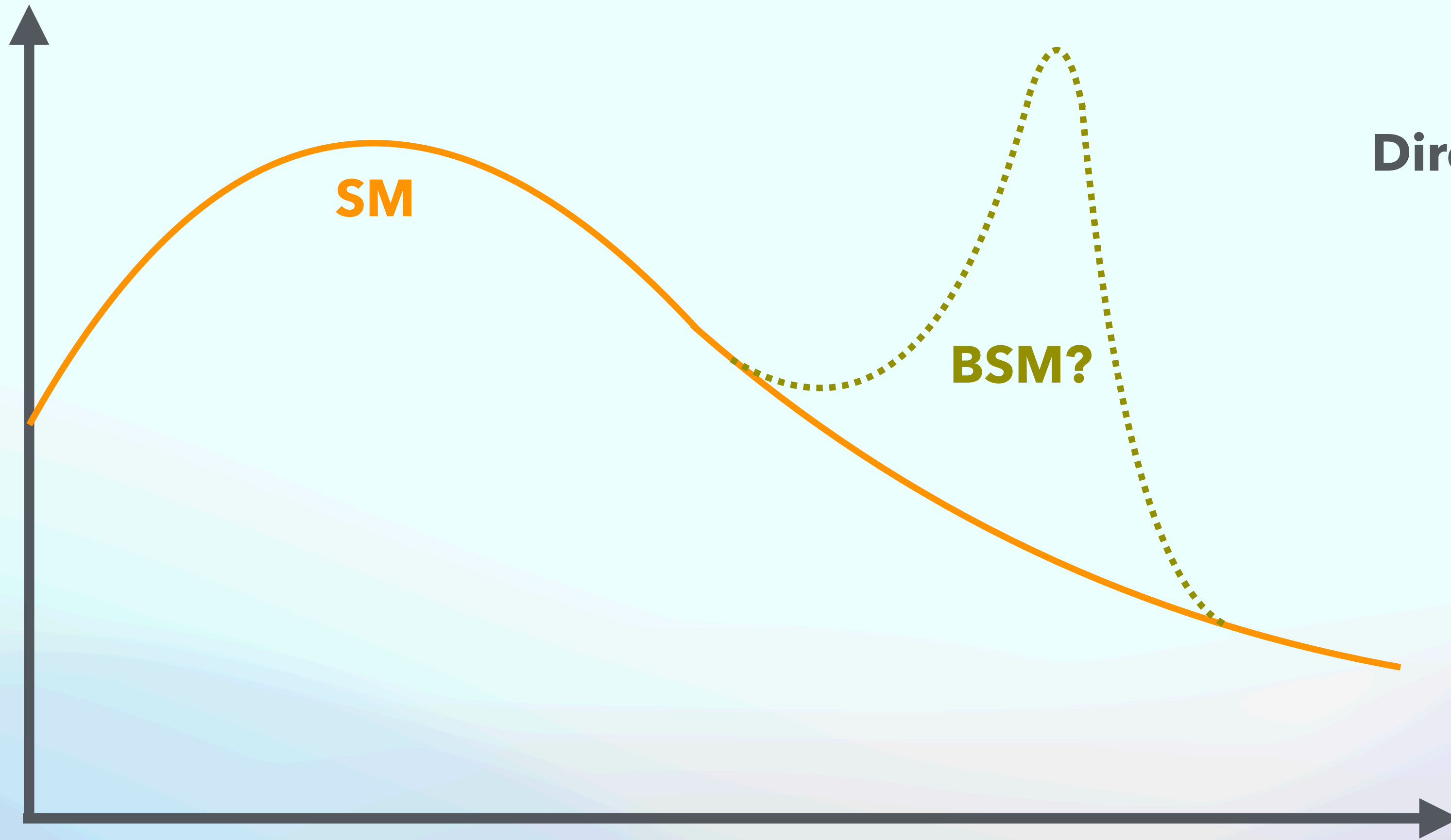
**SM**

*This is what we measure if SM is realized in nature*

**Energy**

# Going beyond the SM - **direct** or effective ?

**Events**



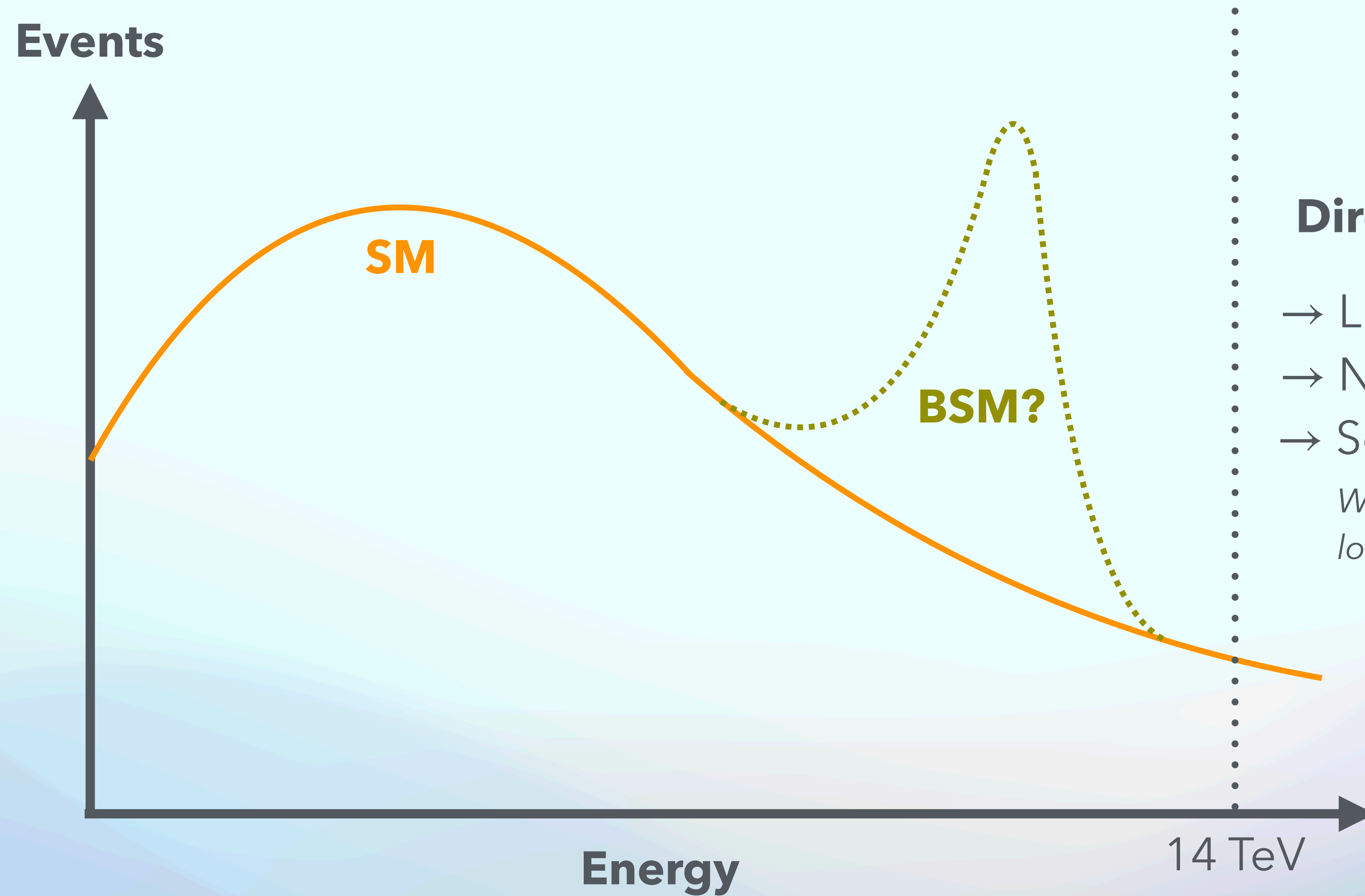
**SM**

**BSM?**

**Direct searches**, e.g. "bump hunt"

**Energy**

# Going beyond the SM - **direct** or effective ?



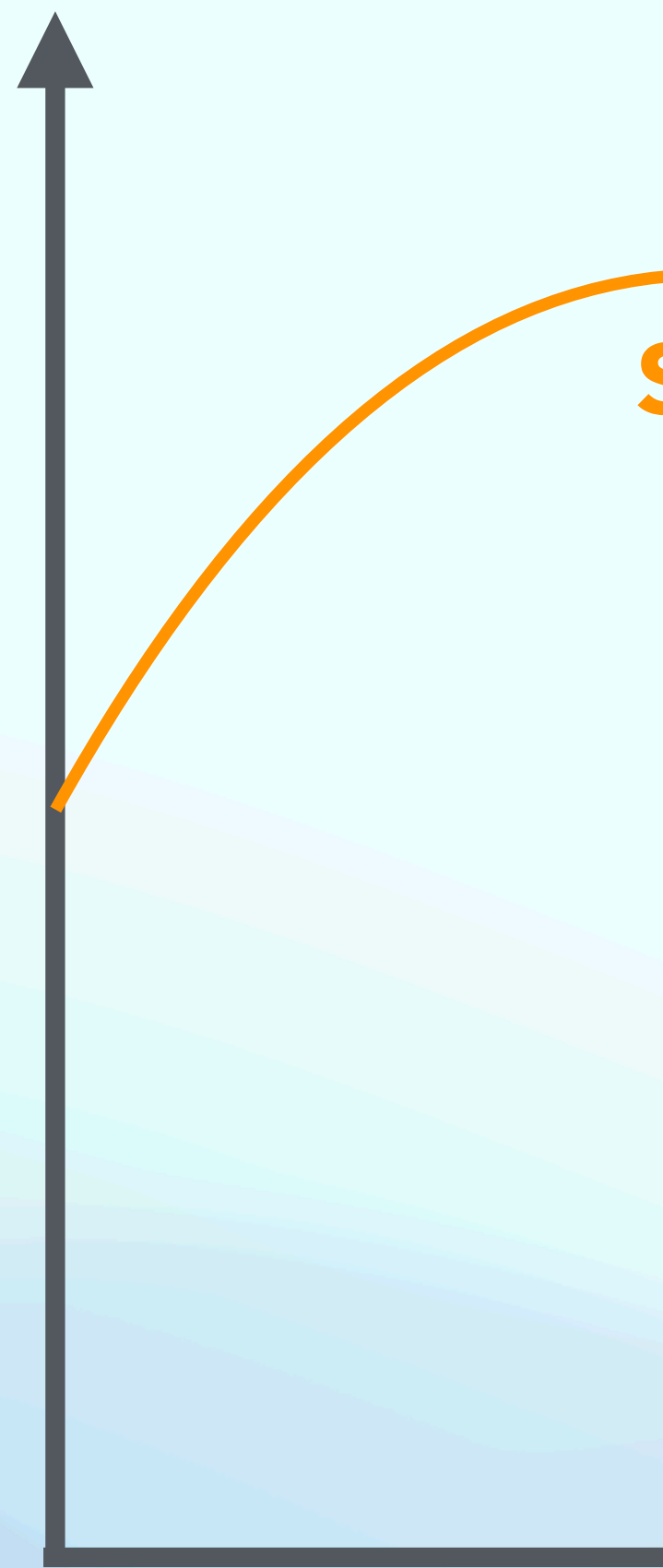
**Direct searches**, e.g. "bump hunt"

- 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 ?

Events



**ATLAS Heavy Particle Searches\* - 95% CL Upper Exclusion Limits** ATLAS Preliminary  
 Status: March 2023  $\int \mathcal{L} dt = (3.6 - 139) \text{ fb}^{-1}$   $\sqrt{s} = 13 \text{ TeV}$

Model	$\ell, \gamma$	Jets <sup>†</sup>	$E_T^{\text{miss}}$	$\int \mathcal{L} dt [\text{fb}^{-1}]$	Limit	Reference
<b>Extra dimen.</b>	ADD $G_{KK} + g/q$	$0 e, \mu, \tau, \gamma$	$1-4 j$	Yes	139	$M_D$ 11.2 TeV $n=2$
	ADD non-resonant $\gamma\gamma$	$2 \gamma$	-	-	36.7	$M_S$ 8.6 TeV $n=3$ HLZ NLO
	ADD QBH	-	$2 j$	-	139	$M_{hh}$ 9.4 TeV $n=6$
	ADD BH multijet	-	$\geq 3 j$	-	3.6	$M_{hh}$ 9.55 TeV $n=6, M_D = 3 \text{ TeV, rot BH}$
	RS1 $G_{KK} \rightarrow \gamma\gamma$	$2 \gamma$	-	-	139	$G_{KK}$ mass 4.5 TeV $k/\overline{M}_{Pl} = 0.1$
	Bulk RS $G_{KK} \rightarrow WW/ZZ$	multi-channel	-	-	36.1	$G_{KK}$ mass 2.3 TeV $k/\overline{M}_{Pl} = 1.0$
	Bulk RS $g_{KK} \rightarrow tt$	$1 e, \mu$	$\geq 1 b, \geq 1 J/2 j$	Yes	36.1	$g_{KK}$ mass 3.8 TeV $\Gamma/m = 15\%$
	2UED / RPP	$1 e, \mu$	$\geq 2 b, \geq 3 j$	Yes	36.1	KK mass 1.8 TeV Tier (1,1), $\mathcal{B}(A^{(1,1)} \rightarrow tt) = 1$
<b>Gauge bosons</b>	SSM $Z' \rightarrow \ell\ell$	$2 e, \mu$	-	-	139	$Z'$ mass 5.1 TeV
	SSM $Z' \rightarrow \tau\tau$	$2 \tau$	-	-	36.1	$Z'$ mass 2.42 TeV
	Leptophobic $Z' \rightarrow bb$	-	$2 b$	-	36.1	$Z'$ mass 2.1 TeV
	Leptophobic $Z' \rightarrow tt$	$0 e, \mu$	$\geq 1 b, \geq 2 J$	Yes	139	$Z'$ mass 4.1 TeV $\Gamma/m = 1.2\%$
	SSM $W' \rightarrow \ell\nu$	$1 e, \mu$	-	Yes	139	$W'$ mass 6.0 TeV
	SSM $W' \rightarrow \tau\nu$	$1 \tau$	-	Yes	139	$W'$ mass 5.0 TeV
	SSM $W' \rightarrow tb$	-	$\geq 1 b, \geq 1 J$	-	139	$W'$ mass 4.4 TeV
	HVT $W' \rightarrow WZ$ model B	$0-2 e, \mu$	$2 j / 1 J$	Yes	139	$W'$ mass 4.3 TeV $g_V = 3$
	HVT $W' \rightarrow WZ \rightarrow \ell\nu \ell' \ell'$ model C	$3 e, \mu$	$2 j$ (VBF)	Yes	139	$W'$ mass 340 GeV $g_V c_W = 1, g_T = 0$
	HVT $Z' \rightarrow WW$ model B	$1 e, \mu$	$2 j / 1 J$	Yes	139	$Z'$ mass 3.9 TeV $g_V = 3$
	LRSM $W_R \rightarrow \mu N_R$	$2 \mu$	$1 J$	-	80	$W_R$ mass 5.0 TeV $m(N_R) = 0.5 \text{ TeV, } g_L = g_R$
<b>CI</b>	CI $qqqq$	-	$2 j$	-	37.0	$\Lambda$ 21.8 TeV $\eta_{LL}$
	CI $\ell\ell qq$	$2 e, \mu$	-	-	139	$\Lambda$ 35.8 TeV $\eta_{LL}$
	CI $e e b s$	$2 e$	$1 b$	-	139	$\Lambda$ 1.8 TeV $g_s = 1$
	CI $\mu\mu b s$	$2 \mu$	$1 b$	-	139	$\Lambda$ 2.0 TeV $g_s = 1$
	CI $tttt$	$\geq 1 e, \mu$	$\geq 1 b, \geq 1 j$	Yes	36.1	$\Lambda$ 2.57 TeV $ C_{4i}  = 4\pi$
<b>DM</b>	Axial-vector med. (Dirac DM)	-	$2 j$	-	139	$m_{\text{med}}$ 3.8 TeV $g_a = 0.25, g_s = 1, m(\chi) = 10 \text{ TeV}$
	Pseudo-scalar med. (Dirac DM)	$0 e, \mu, \tau, \gamma$	$1-4 j$	Yes	139	$m_{\text{med}}$ 376 GeV $g_a = 1, g_s = 1, m(\chi) = 1 \text{ GeV}$
	Vector med. $Z'$ -2HDM (Dirac DM)	$0 e, \mu$	$2 b$	Yes	139	$m_{Z'}$ 3.0 TeV $\tan\beta = 1, g_2 = 0.8, m(\chi) = 100 \text{ GeV}$
	Pseudo-scalar med. 2HDM+a	multi-channel	-	-	139	$m_a$ 800 GeV $\tan\beta = 1, g_s = 1, m(\chi) = 10 \text{ GeV}$
<b>LQ</b>	Scalar LQ 1 <sup>st</sup> gen	$2 e$	$\geq 2 j$	Yes	139	LQ mass 1.8 TeV $\beta = 1$
	Scalar LQ 2 <sup>nd</sup> gen	$2 \mu$	$\geq 2 j$	Yes	139	LQ mass 1.7 TeV $\beta = 1$
	Scalar LQ 3 <sup>rd</sup> gen	$1 \tau$	$2 b$	Yes	139	LQ mass 1.49 TeV $\mathcal{B}(LQ_3^+ \rightarrow b\tau) = 1$
	Scalar LQ 3 <sup>rd</sup> gen	$0 e, \mu$	$\geq 2 j, \geq 2 b$	Yes	139	LQ mass 1.24 TeV $\mathcal{B}(LQ_3^+ \rightarrow t\nu) = 1$
	Scalar LQ 3 <sup>rd</sup> gen	$\geq 2 e, \mu, \geq 1 \tau$	$\geq 1 j, \geq 1 b$	-	139	LQ mass 1.43 TeV $\mathcal{B}(LQ_3^+ \rightarrow t\tau) = 1$
	Scalar LQ 3 <sup>rd</sup> gen	$0 e, \mu, \geq 1 \tau$	$0-2 j, 2 b$	Yes	139	LQ mass 1.26 TeV $\mathcal{B}(LQ_3^+ \rightarrow b\nu) = 1$
	Vector LQ mix gen	multi-channel	$\geq 1 j, \geq 1 b$	Yes	139	LQ mass 2.0 TeV $\mathcal{B}(L_1^+ \rightarrow t\mu) = 1, \text{Y-M coupl.}$
	Vector LQ 3 <sup>rd</sup> gen	$2 e, \mu, \tau$	$\geq 1 b$	Yes	139	LQ mass 1.96 TeV $\mathcal{B}(LQ_3^+ \rightarrow b\tau) = 1, \text{Y-M coupl.}$
<b>Vector-like fermions</b>	VLQ $TT \rightarrow Zt + X$	$2e/2\mu \geq 3e, \mu$	$\geq 1 b, \geq 1 j$	-	139	T mass 1.46 TeV SU(2) doublet
	VLQ $BB \rightarrow Wt/Zb + X$	multi-channel	-	-	36.1	B mass 1.34 TeV SU(2) doublet
	VLQ $T_{5/3} T_{5/3} T_{5/3} \rightarrow Wt + X$	$2(SS) \geq 3 e, \mu$	$\geq 1 b, \geq 1 j$	Yes	36.1	$T_{5/3}$ mass 1.64 TeV $\mathcal{B}(T_{5/3} \rightarrow Wt) = 1, c(T_{5/3} Wt) = 1$
	VLQ $T \rightarrow Ht/Zt$	$1 e, \mu$	$\geq 1 b, \geq 3 j$	Yes	139	T mass 1.8 TeV SU(2) singlet, $\kappa_T = 0.5$
	VLQ $Y \rightarrow Wb$	$1 e, \mu$	$\geq 1 b, \geq 1 j$	Yes	36.1	Y mass 1.85 TeV $\mathcal{B}(Y \rightarrow Wb) = 1, c_Y(Wb) = 1$
	VLQ $B \rightarrow Hb$	$0 e, \mu$	$\geq 2b, \geq 1j, \geq 1J$	-	139	B mass 2.0 TeV SU(2) doublet, $\kappa_B = 0.3$
	VLL $\tau \rightarrow Z\tau/H\tau$	multi-channel	$\geq 1 j$	Yes	139	$\tau'$ mass 898 GeV SU(2) doublet
<b>Excited ferm.</b>	Excited quark $q^* \rightarrow qg$	-	$2 j$	-	139	$q^*$ mass 6.7 TeV only $u^*$ and $d^*, \Lambda = m(q^*)$
	Excited quark $q^* \rightarrow q\gamma$	$1 \gamma$	$1 j$	-	36.7	$q^*$ mass 5.3 TeV only $u^*$ and $d^*, \Lambda = m(q^*)$
	Excited quark $b^* \rightarrow bg$	-	$1 b, 1 j$	-	139	$b^*$ mass 3.2 TeV $\Lambda = 4.6 \text{ TeV}$
	Excited lepton $\tau^*$	$2 \tau$	$\geq 2 j$	-	139	$\tau^*$ mass 4.6 TeV
<b>Other</b>	Type III Seesaw	$2, 3, 4 e, \mu$	$\geq 2 j$	Yes	139	$N^0$ mass 910 GeV
	LRSM Majorana $\nu$	$2 \mu$	$2 j$	-	36.1	$N_R$ mass 3.2 TeV
	Higgs triplet $H^{\pm\pm} \rightarrow W^\pm W^\pm$	$2, 3, 4 e, \mu$ (SS)	various	Yes	139	$H^{\pm\pm}$ mass 350 GeV
	Higgs triplet $H^{\pm\pm} \rightarrow \ell\ell$	$2, 3, 4 e, \mu$ (SS)	-	-	139	$H^{\pm\pm}$ mass 1.08 TeV
	Multi-charged particles	-	-	-	139	multi-charged particle mass 1.59 TeV
	Magnetic monopoles	-	-	-	34.4	monopole mass 2.37 TeV

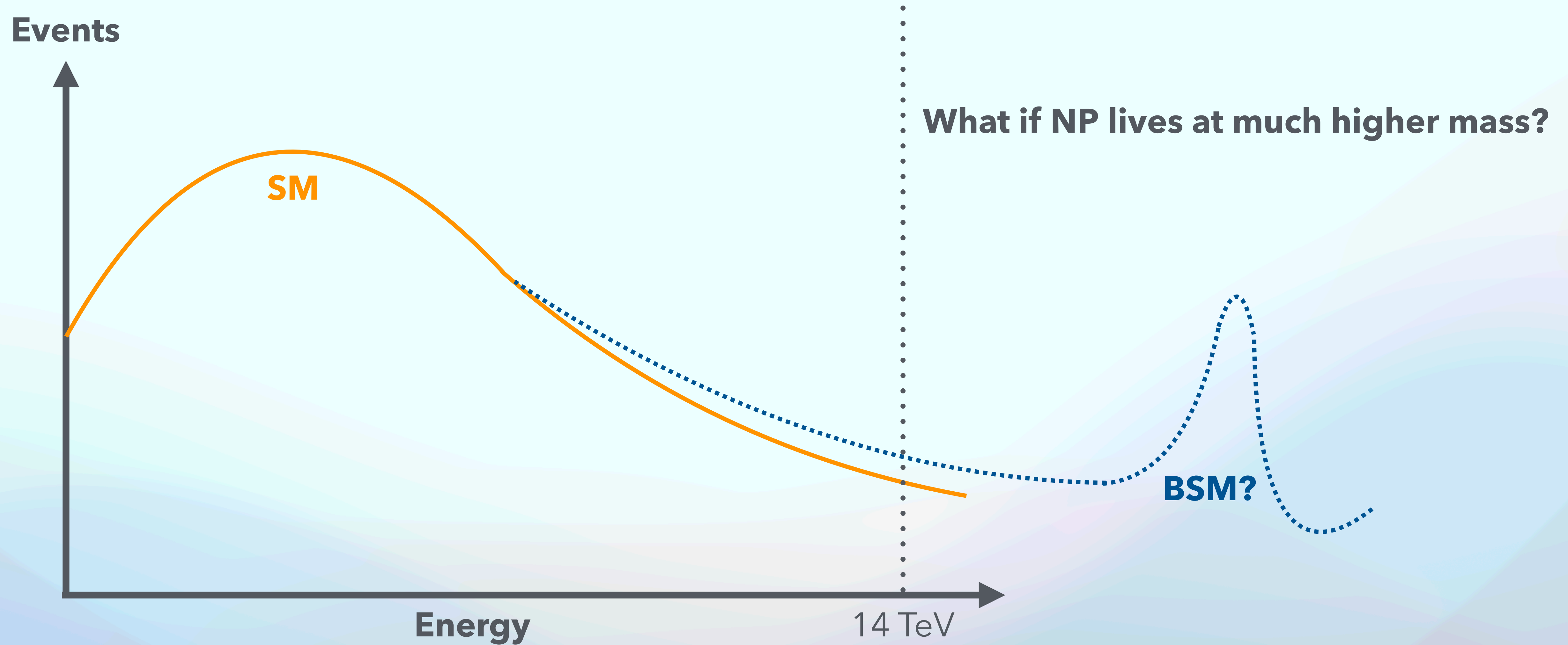
*\*Only a selection of the available mass limits on new states or phenomena is shown.  
<sup>†</sup>Small-radius (large-radius) jets are denoted by the letter j (J).*

Searches, e.g. "bump hunt"  
 As collider energy reach  
 particle discovered (yet?)  
 are very model dependent  
 need to roughly know what we are

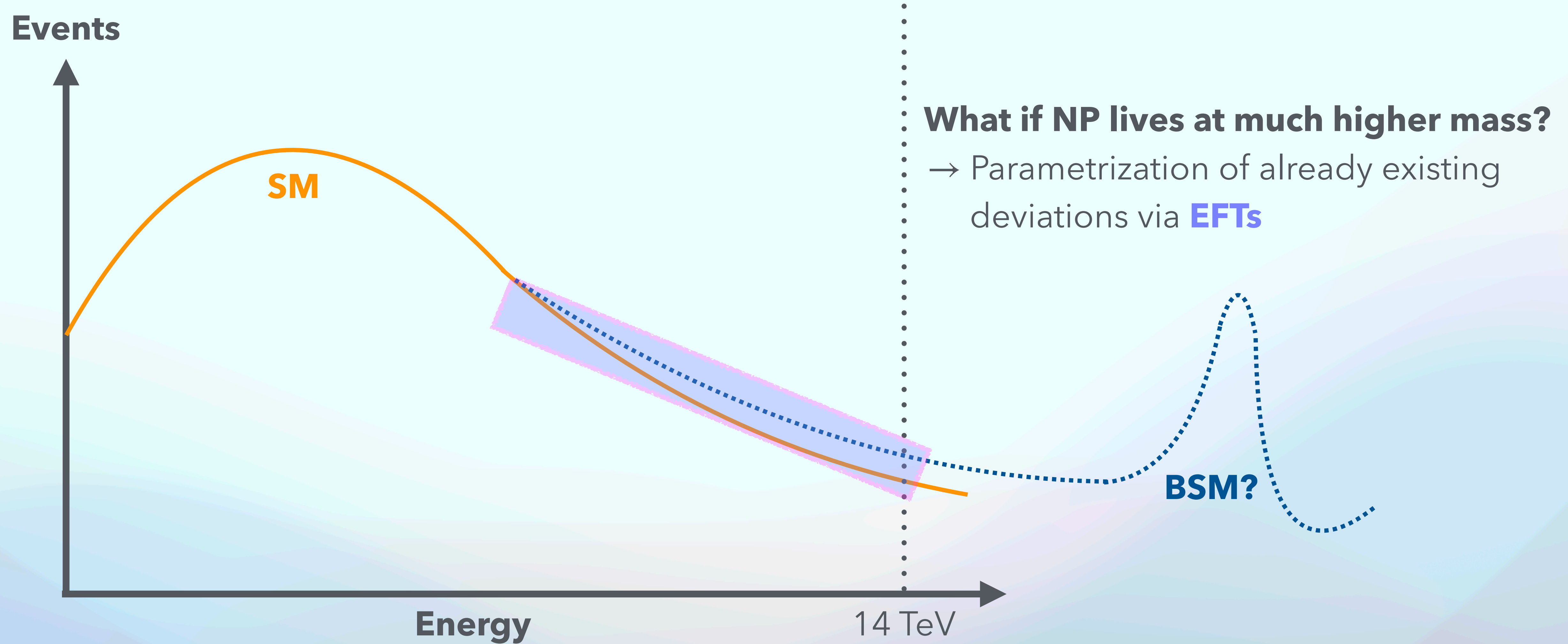
Nothing so far!

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# Going beyond the SM - **direct** or **effective** ?



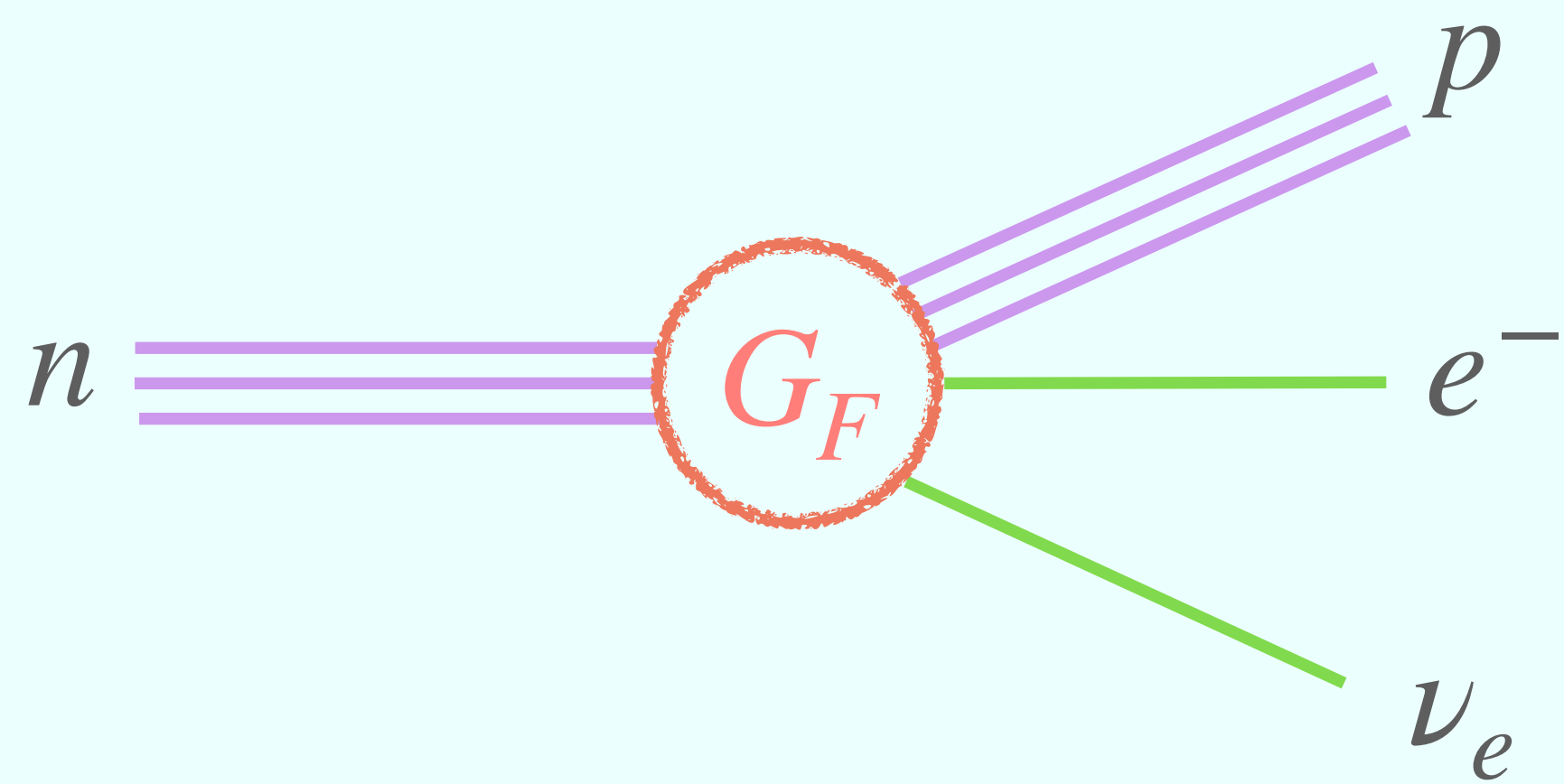
# Going beyond the SM - **direct** or **effective** ?



# Before SM was even Standard...

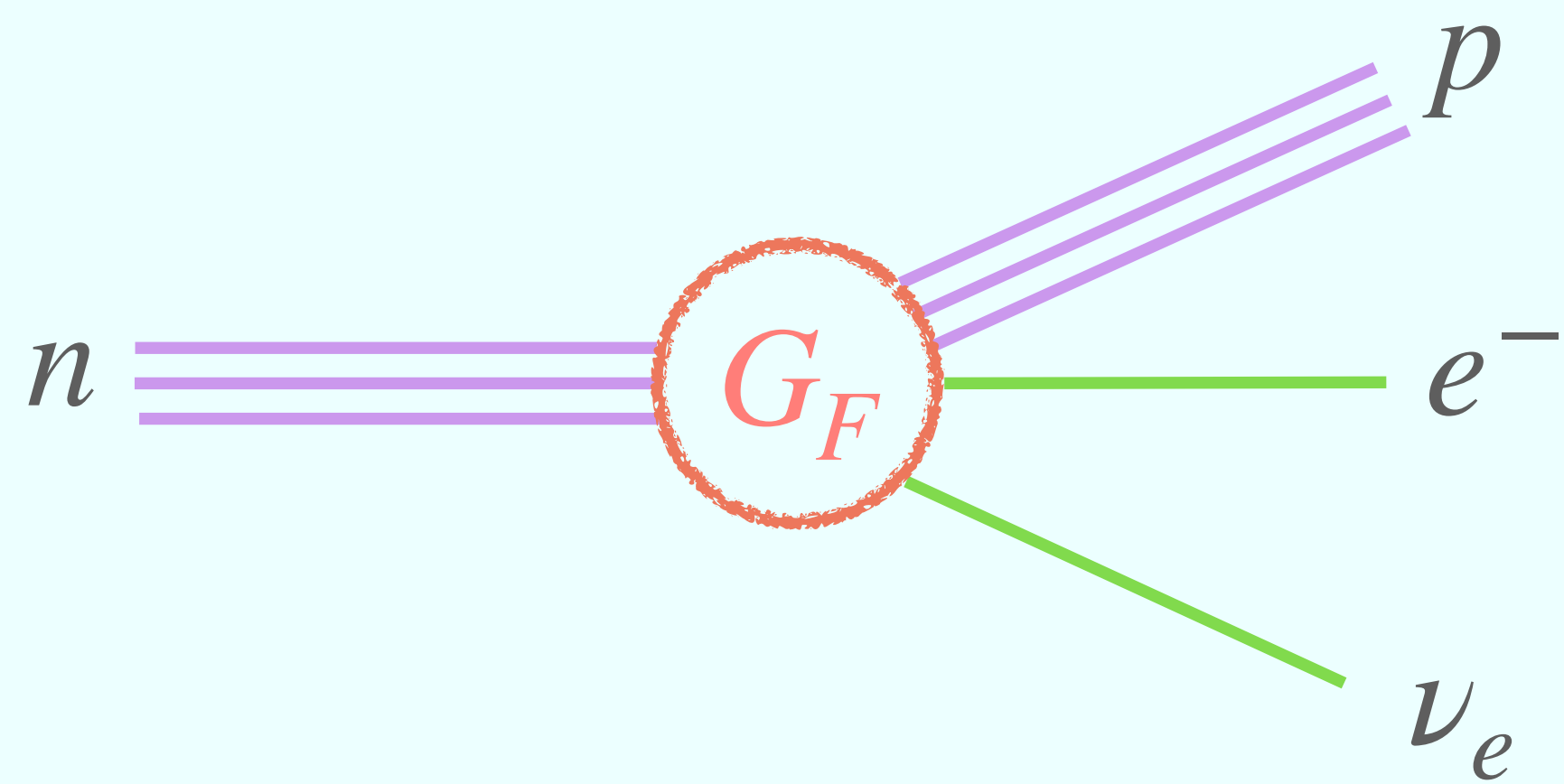
Proposal by E. Fermi to explain  $\beta$  decay during early stage of weak interaction theory development

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



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

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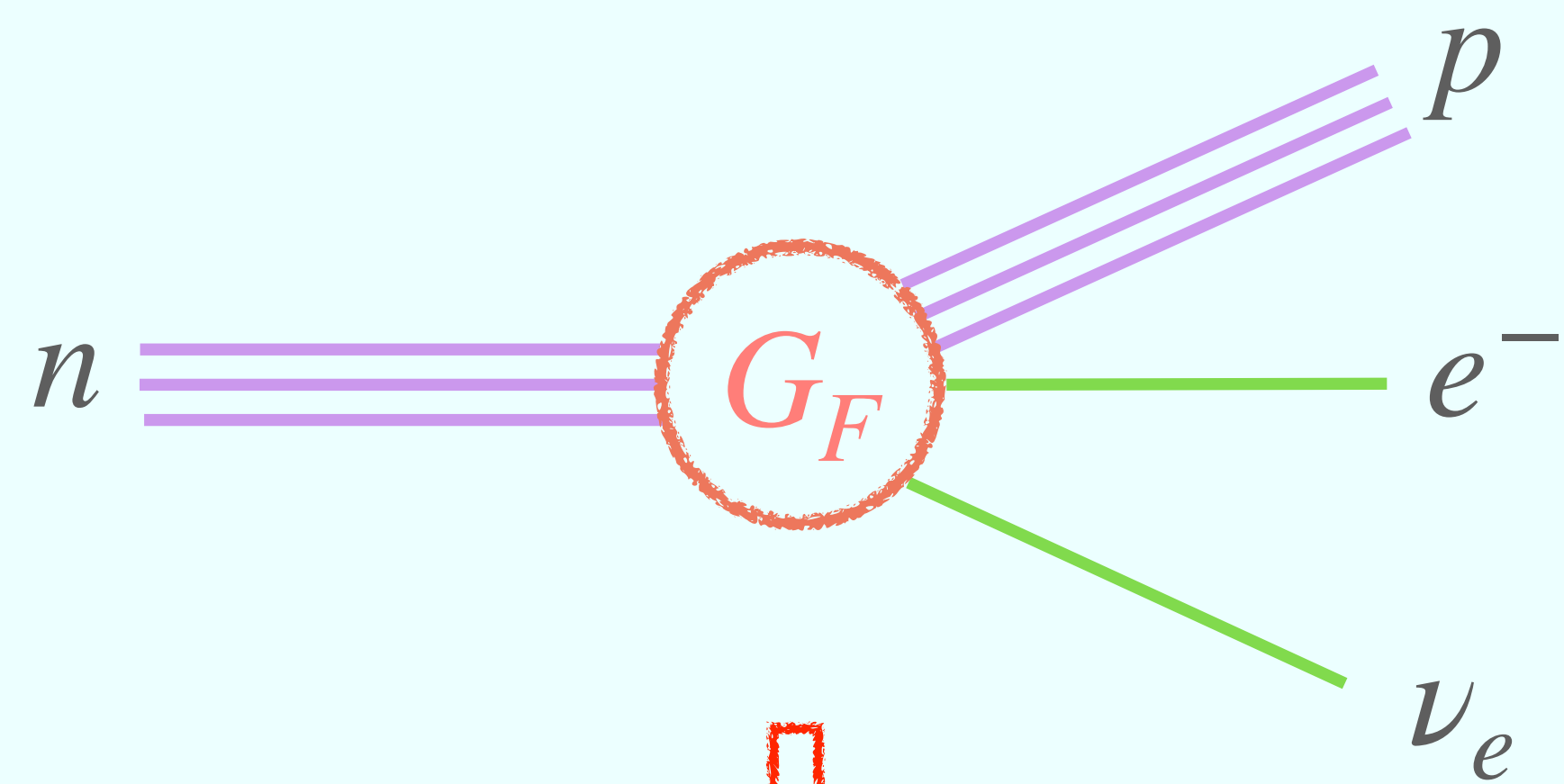
$$\sigma = \frac{G_F^2}{\pi} s$$

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

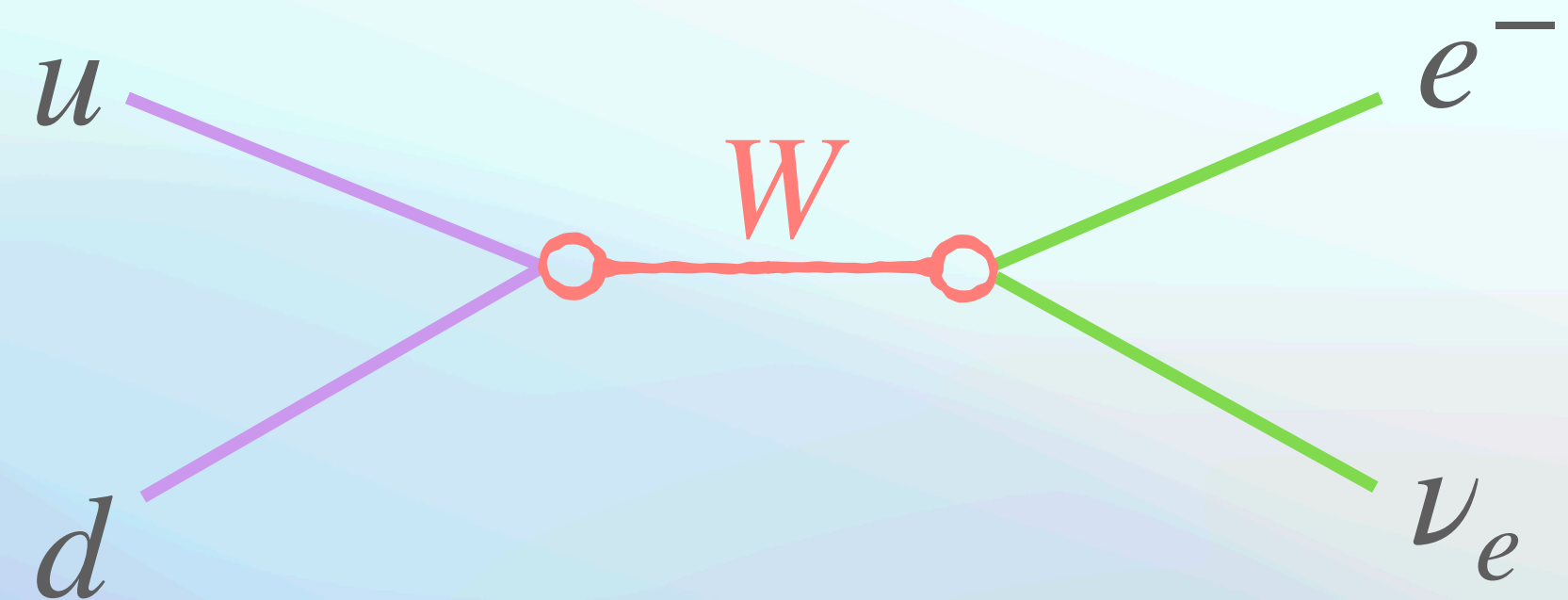
# Before SM was even Standard...

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

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



$p \gg m_W$



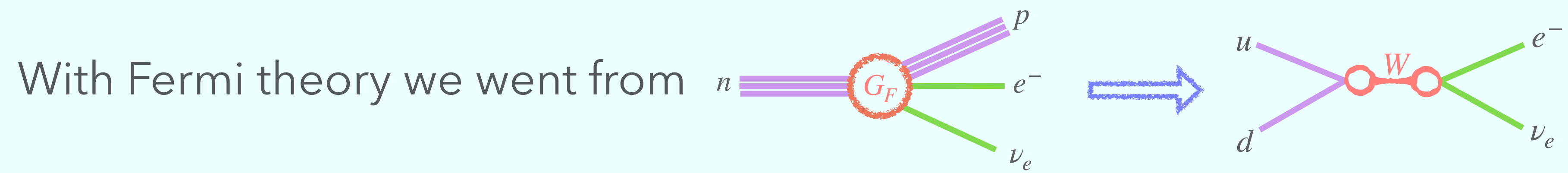
$$\sigma = \frac{G_F^2 s}{\pi}$$

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

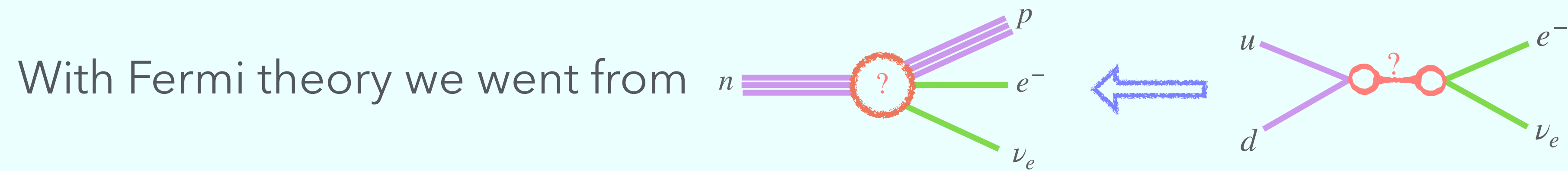
→ Valid for energies  $\ll 100$  GeV

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

# How to build an Effective theory?

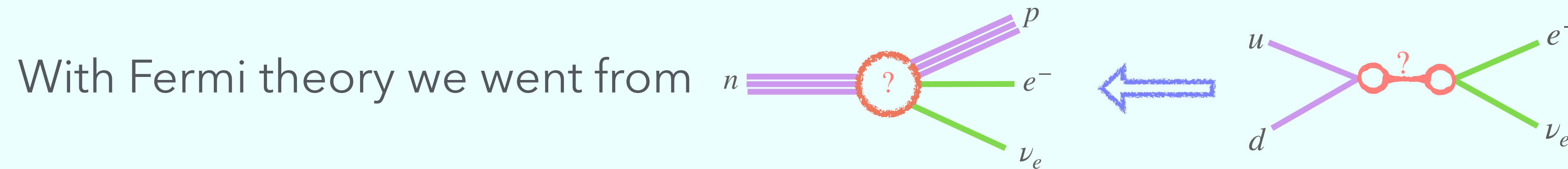


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i.e. infer New Physics by parametrizing "low" energy*

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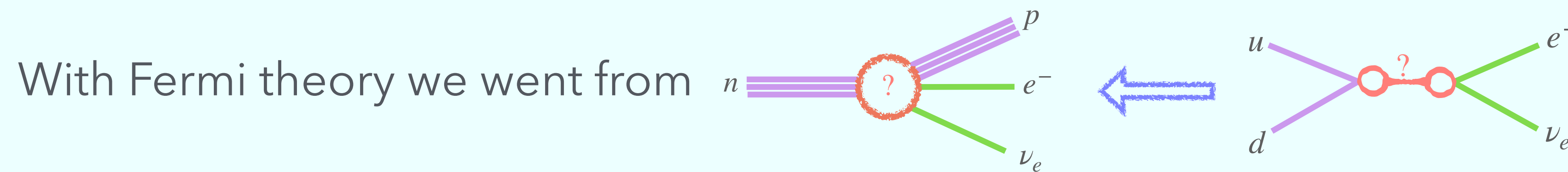
*EFT recipe*

**Step 1** : We fix the field content

**Step 2** : We fix the symmetries

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

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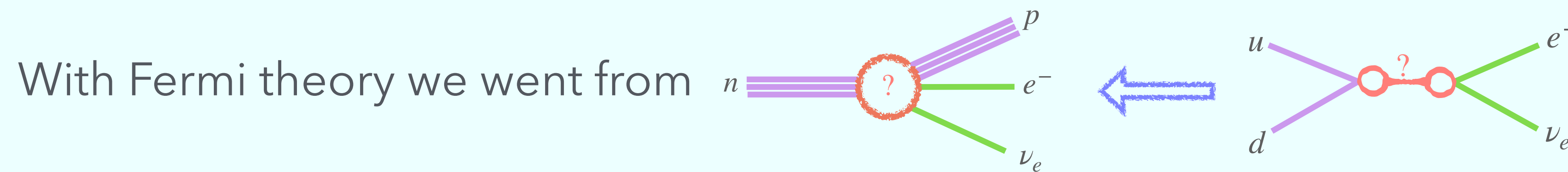
*EFT recipe*

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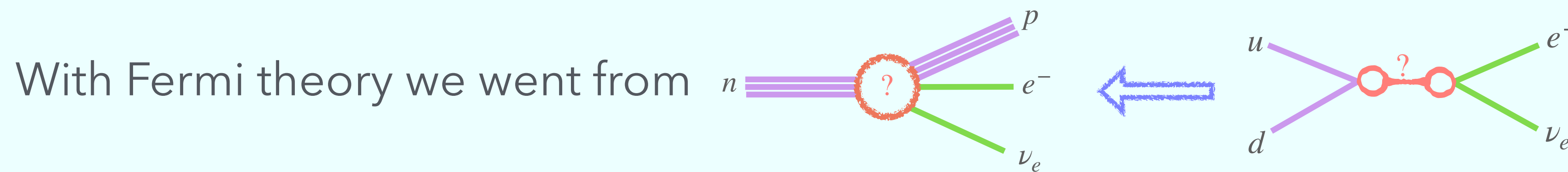
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**Step 3** : We write an exhaustive list of allowed interactions at a fixed order

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

# Effective field theory approach

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

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

**EFTs** provide :

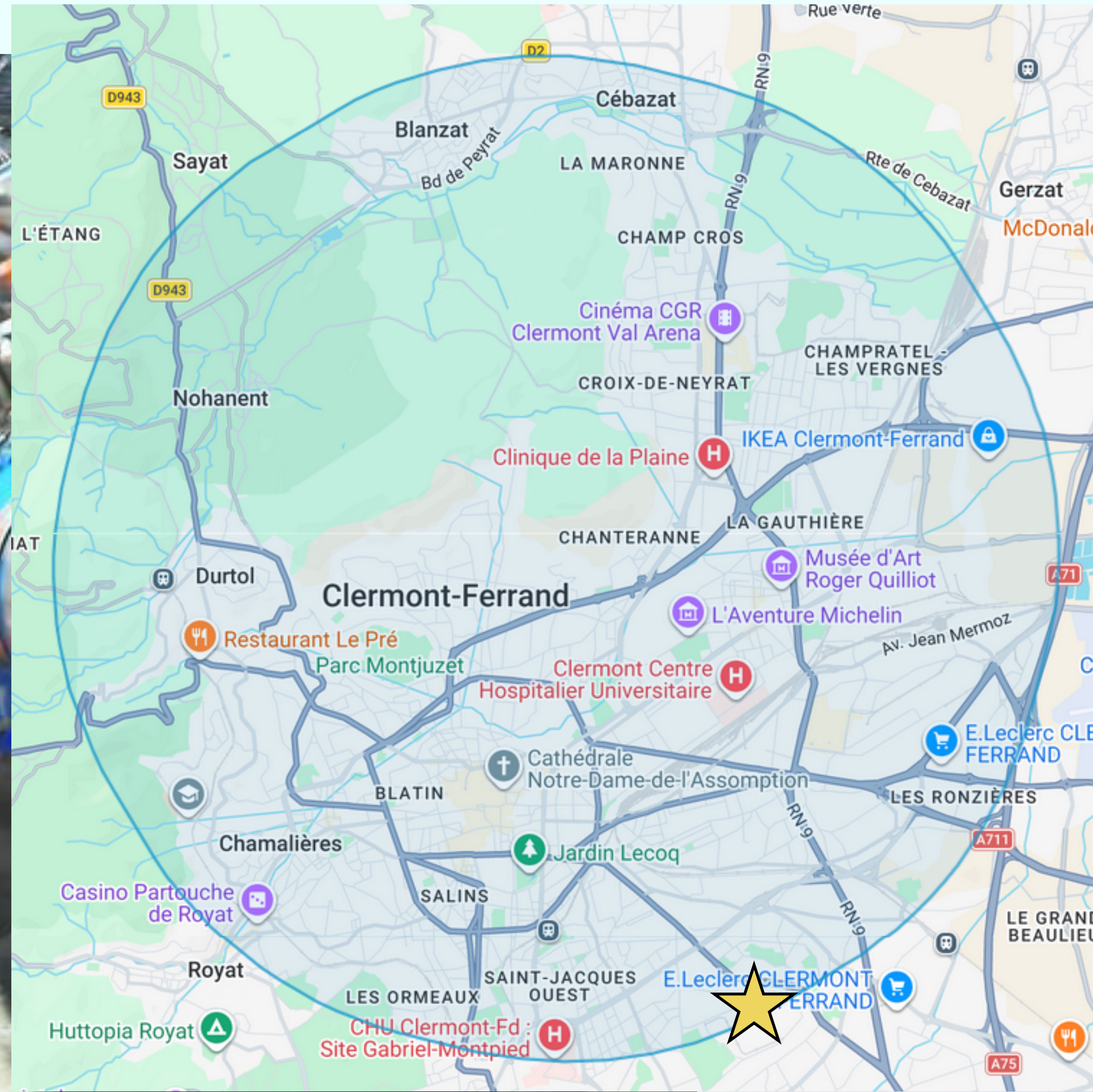
- Fairly model-agnostic approach
- Way to integrate out heavy degrees of freedom
- Only considers SM content (exhaustive list of fields)
- Treats all SM sectors equivalently

# 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

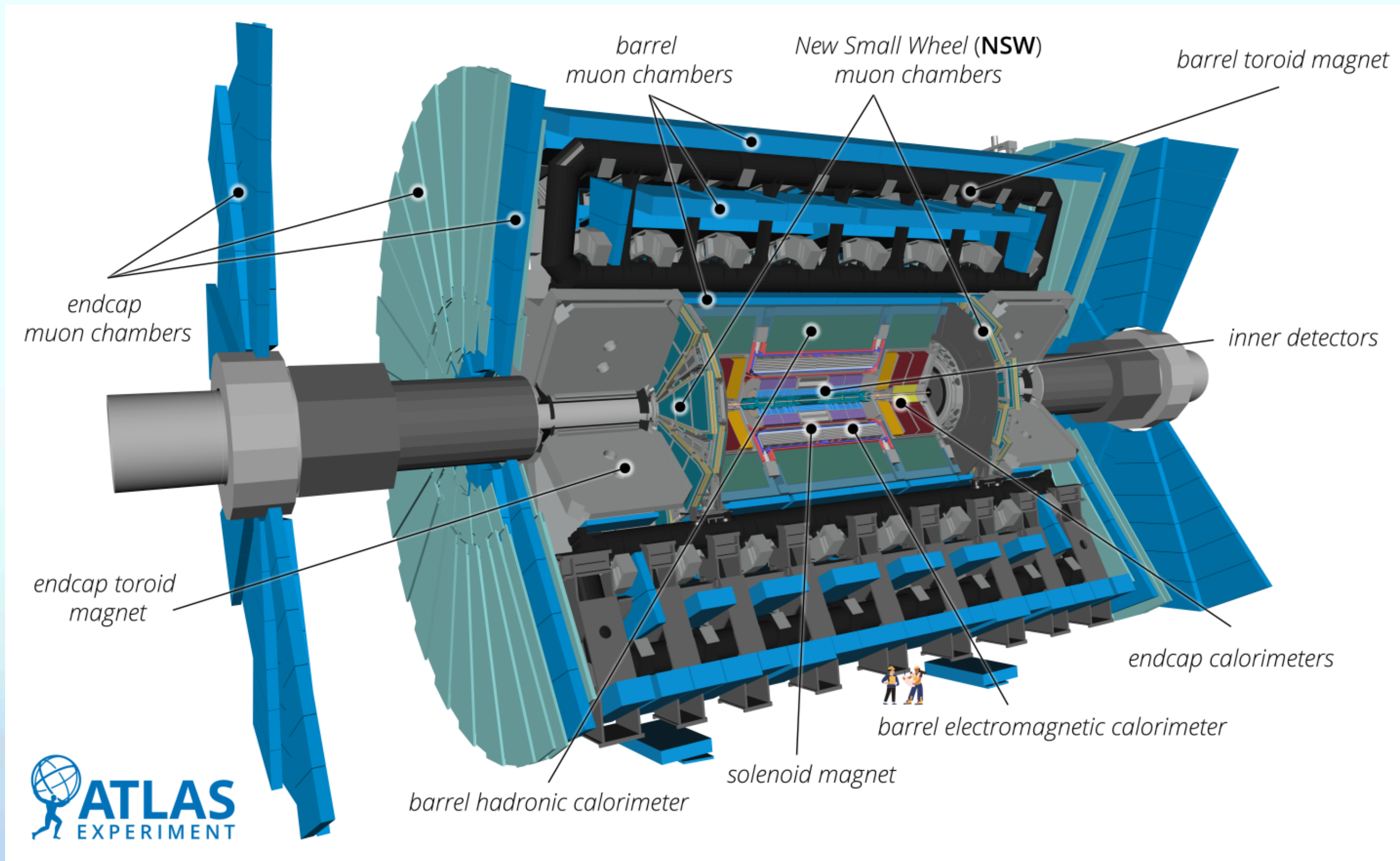


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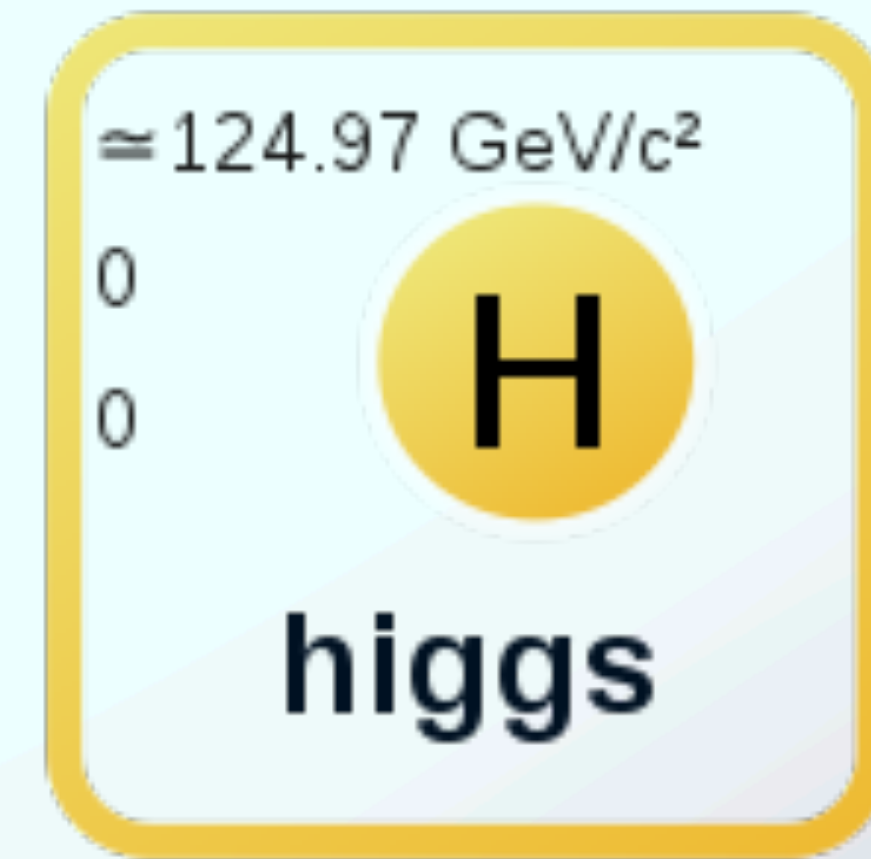
# General purpose detectors : ATLAS & CMS



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

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

1st protagonist

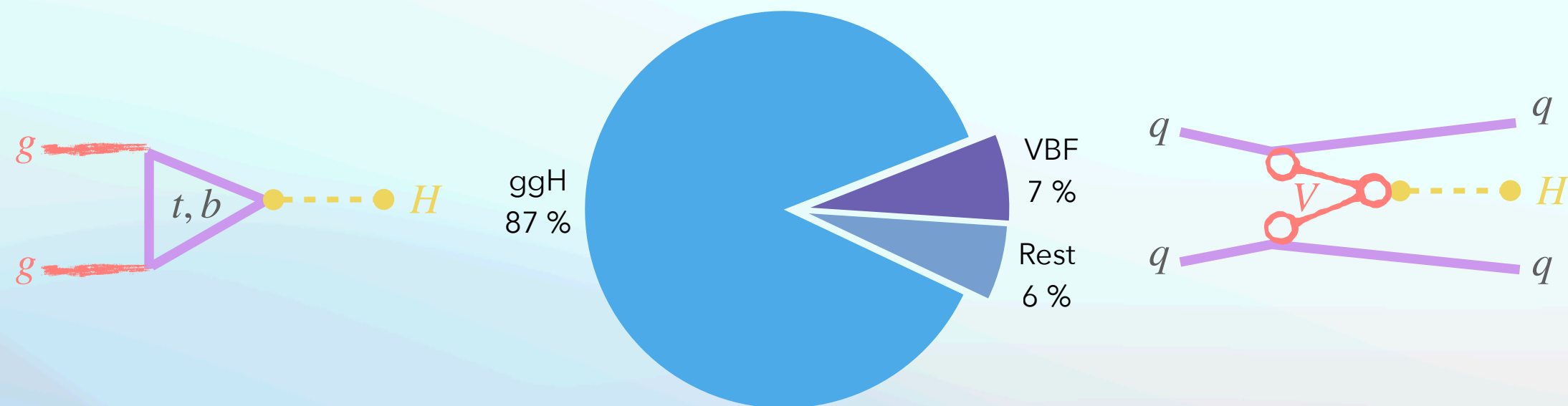


# Higgs @ proton collider : prod. and decay



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



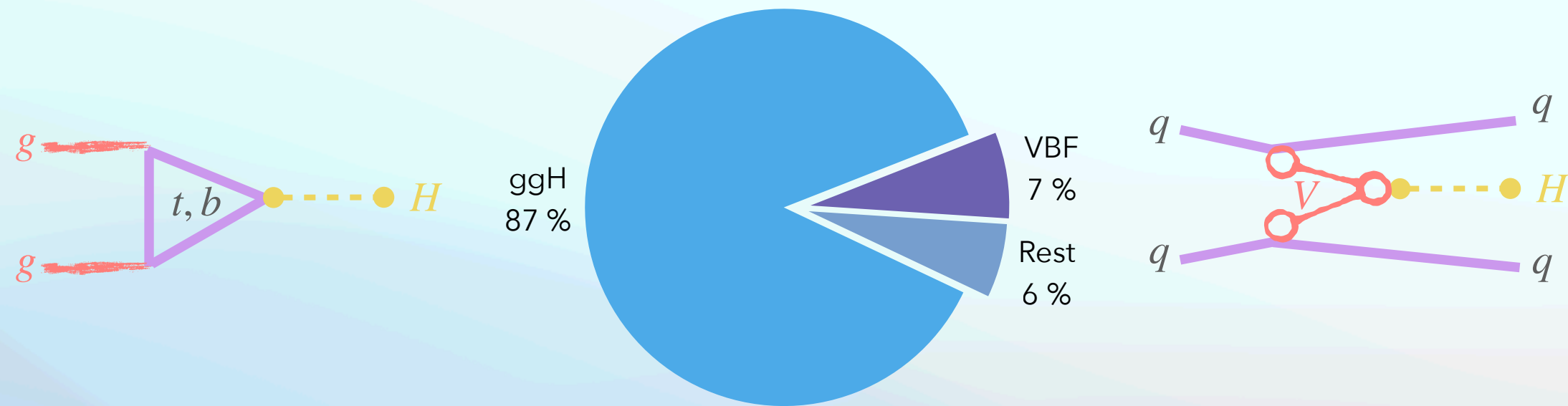
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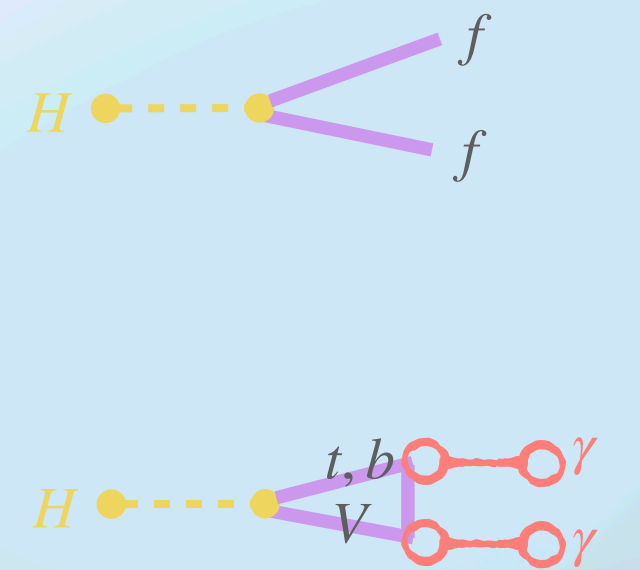
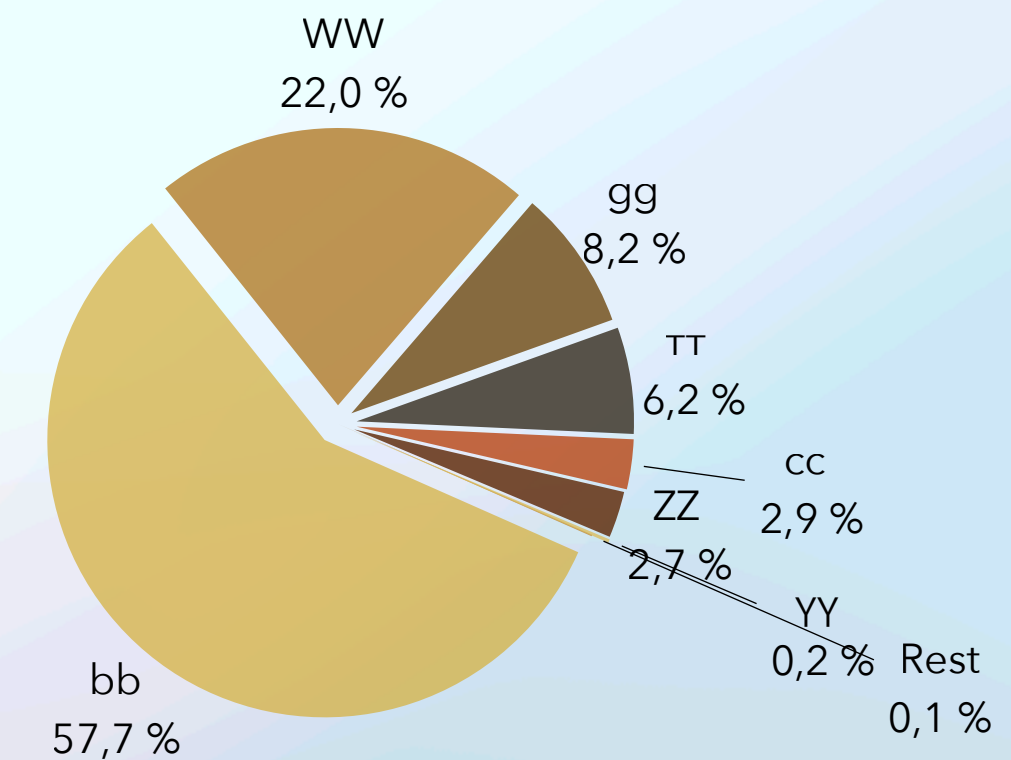
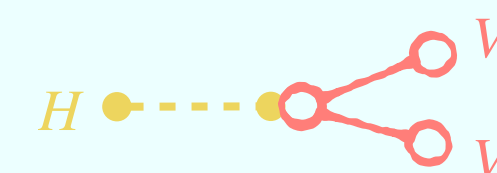
Decay Channel

Branching ratio

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

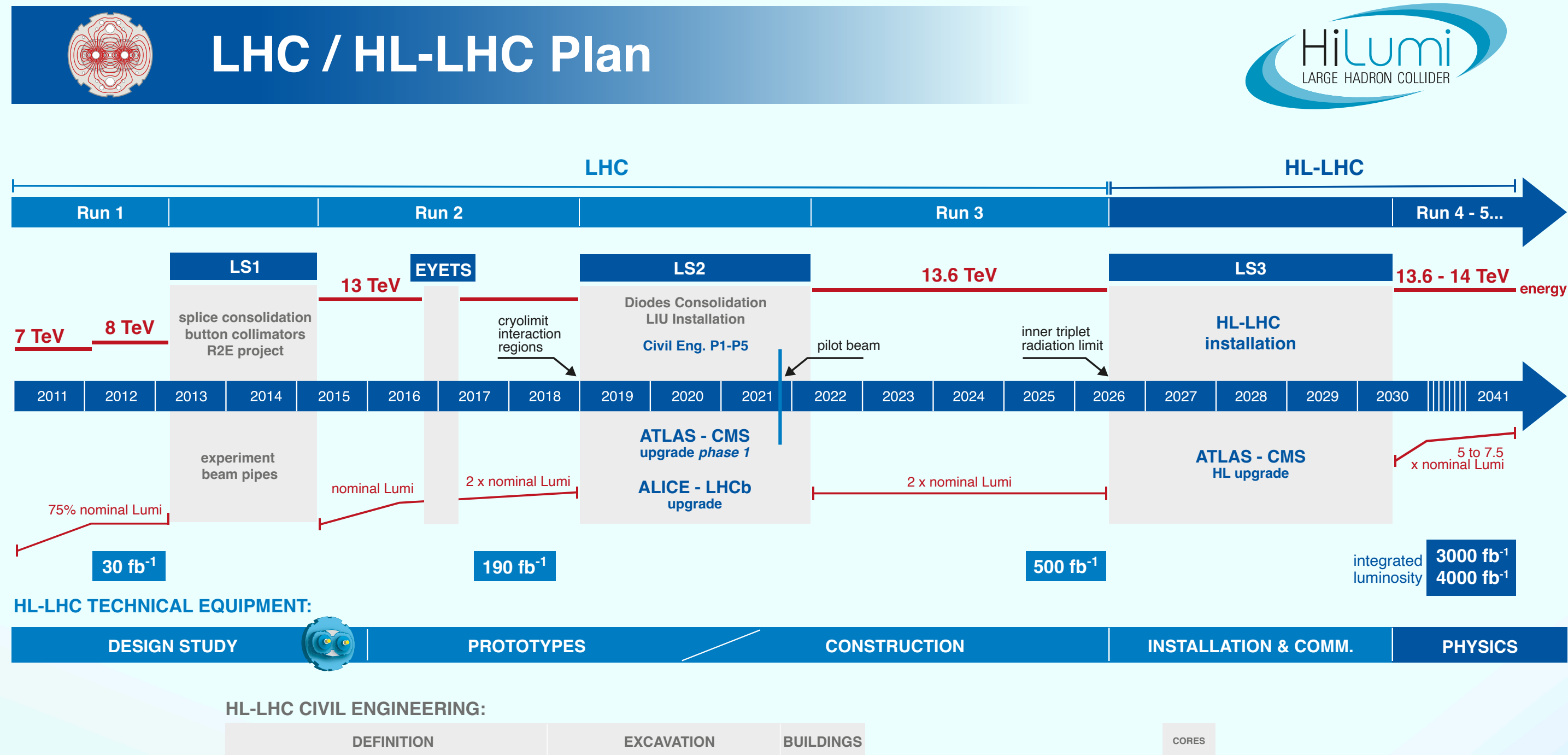


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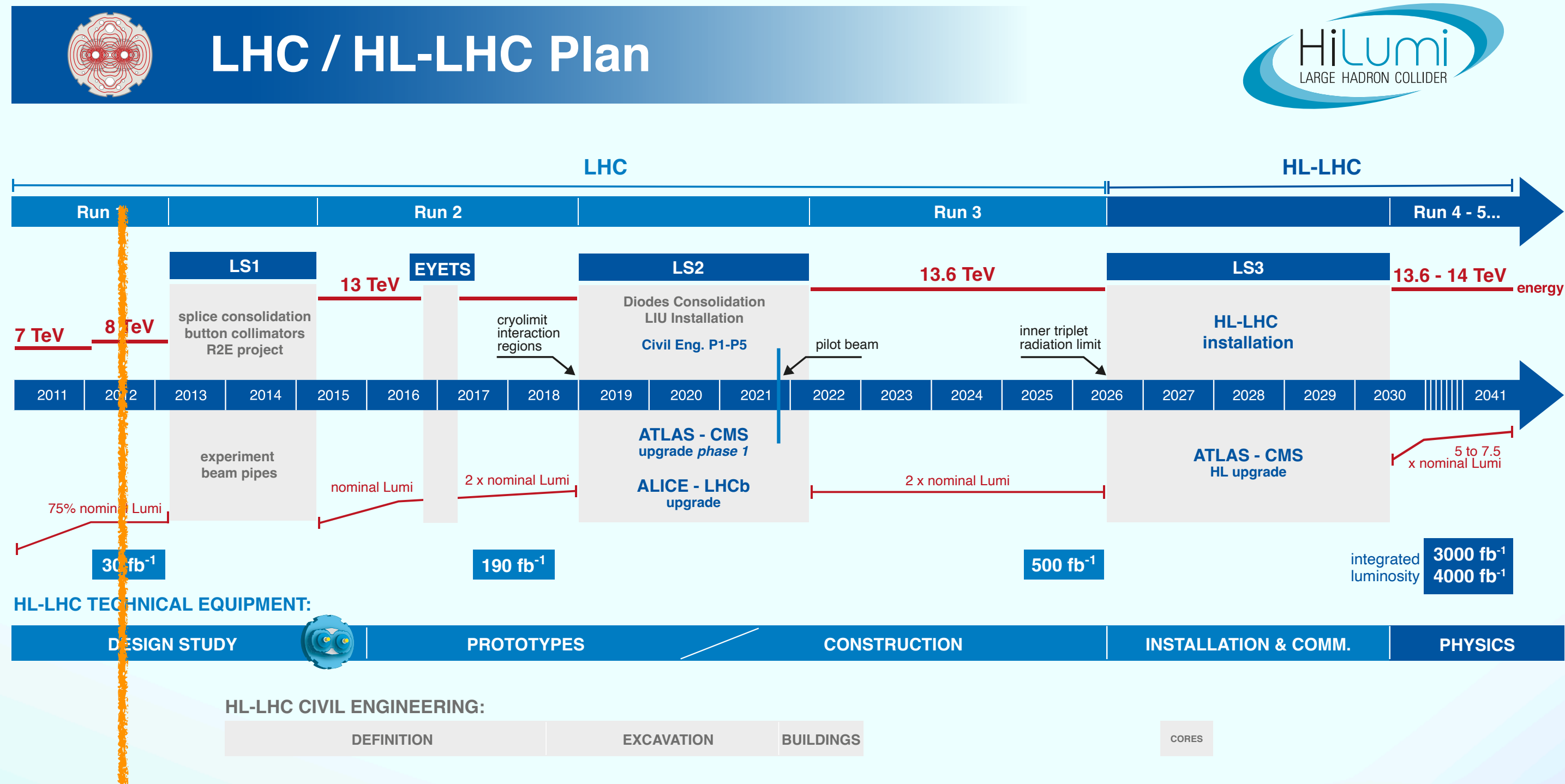


Higgs has narrow width and decays very quickly!

# Timeline since discovery

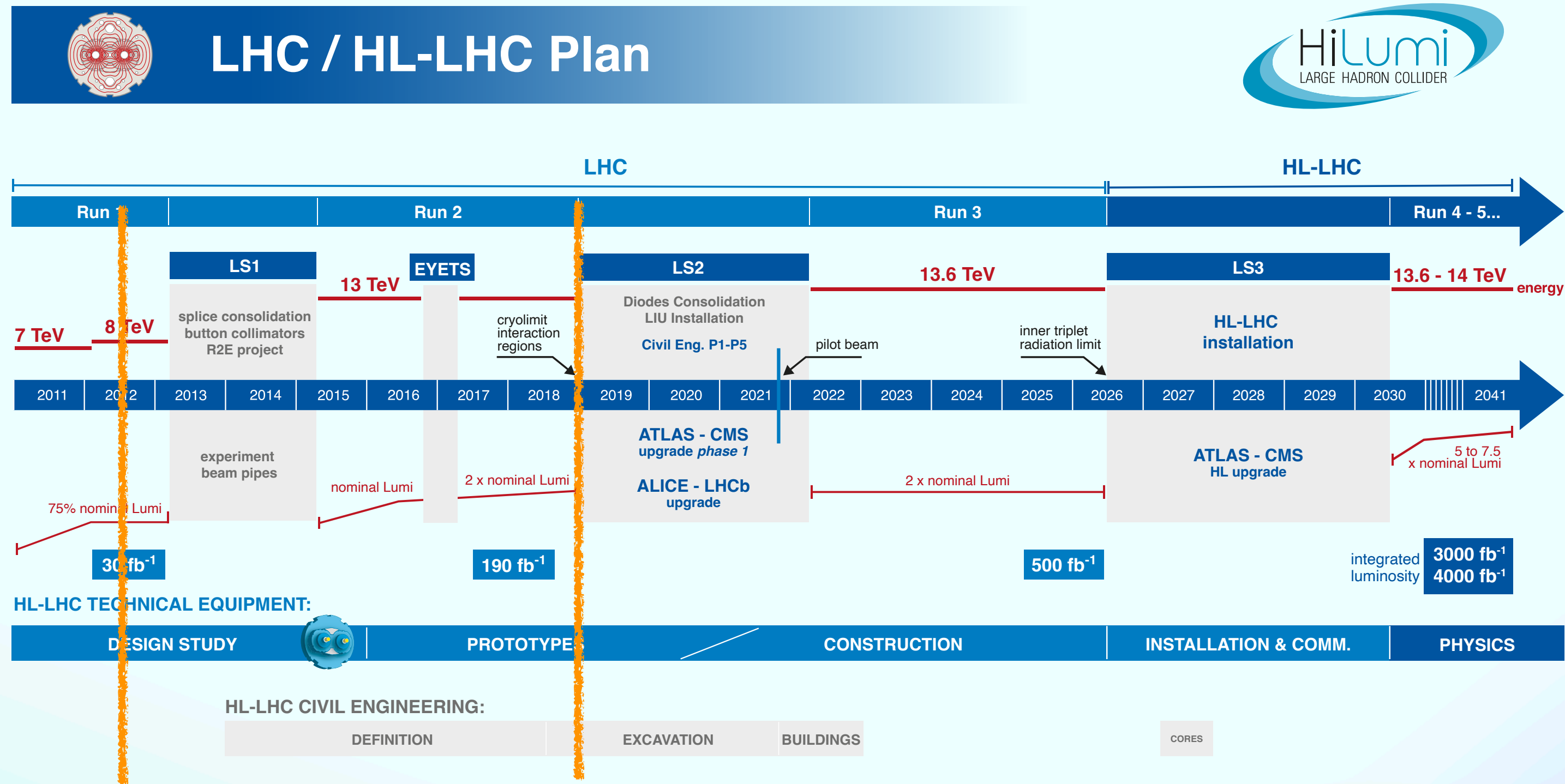


# Timeline since discovery



**Discovery**  
~200k Higgs prod.

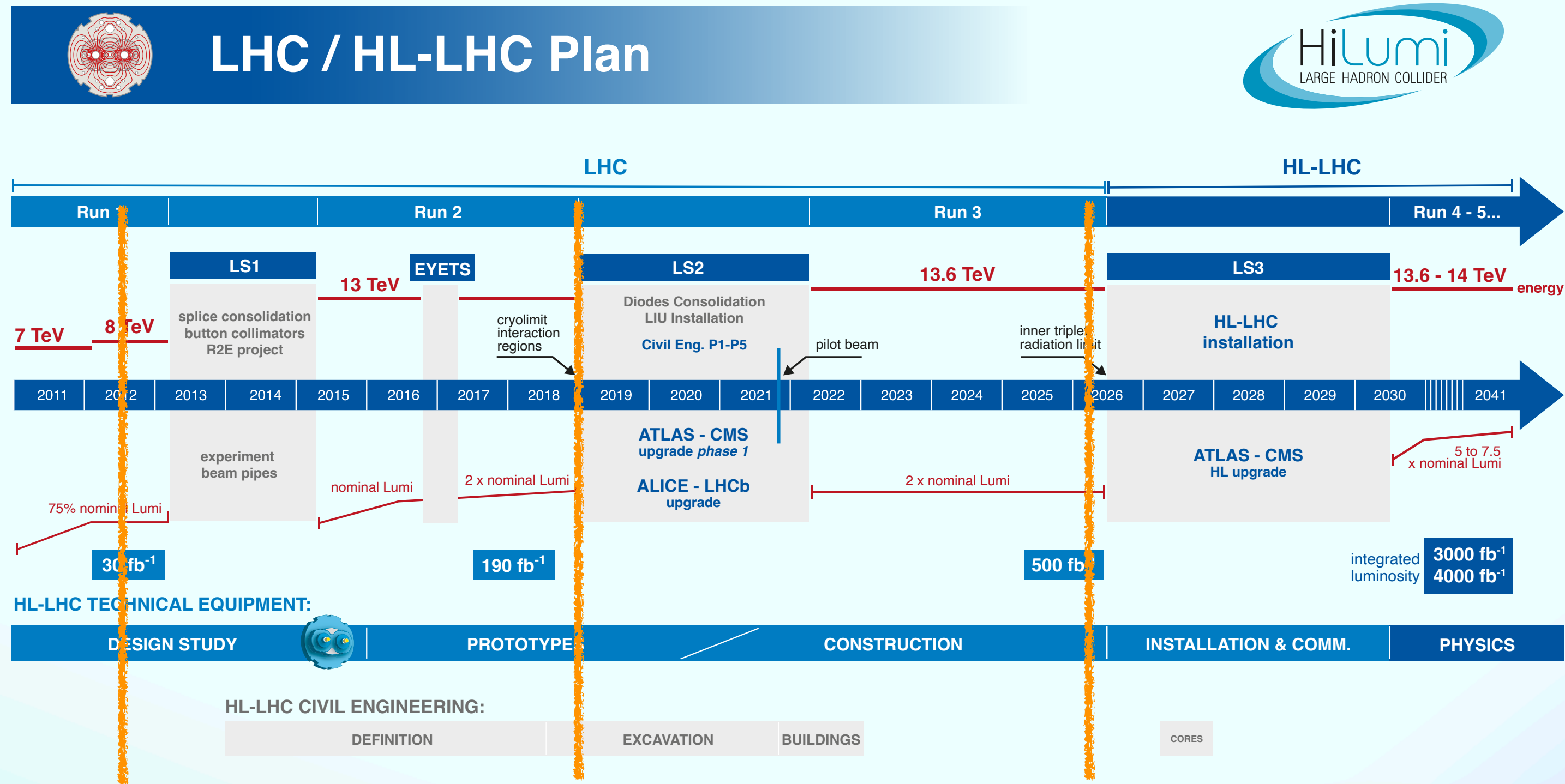
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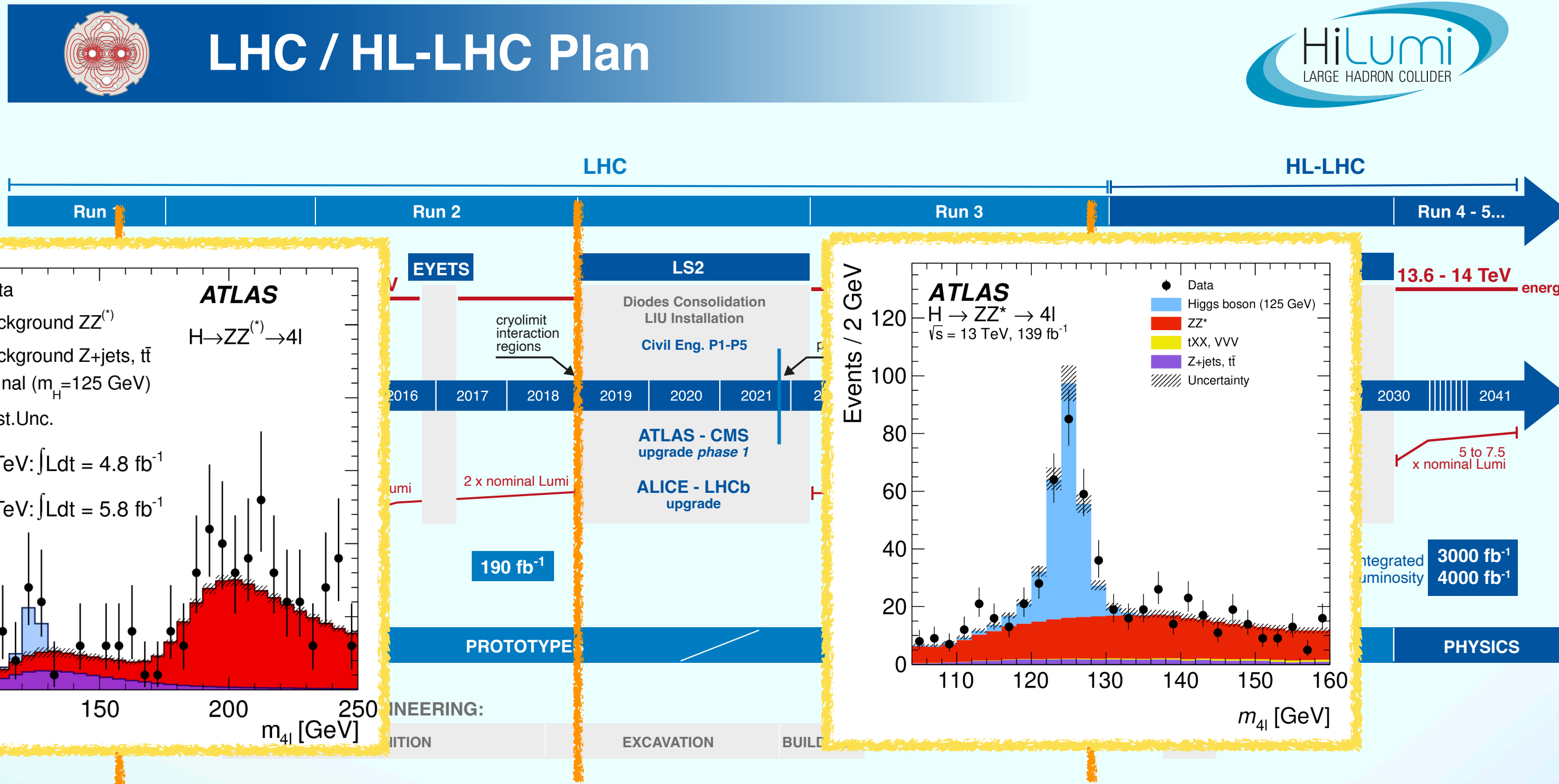
**End of Run 2**  
~7.7M Higgs prod.

# Timeline since discovery



**Discovery** ~200k Higgs prod.      **End of Run 2** ~7.7M Higgs prod.      **Today** ~24M Higgs prod.

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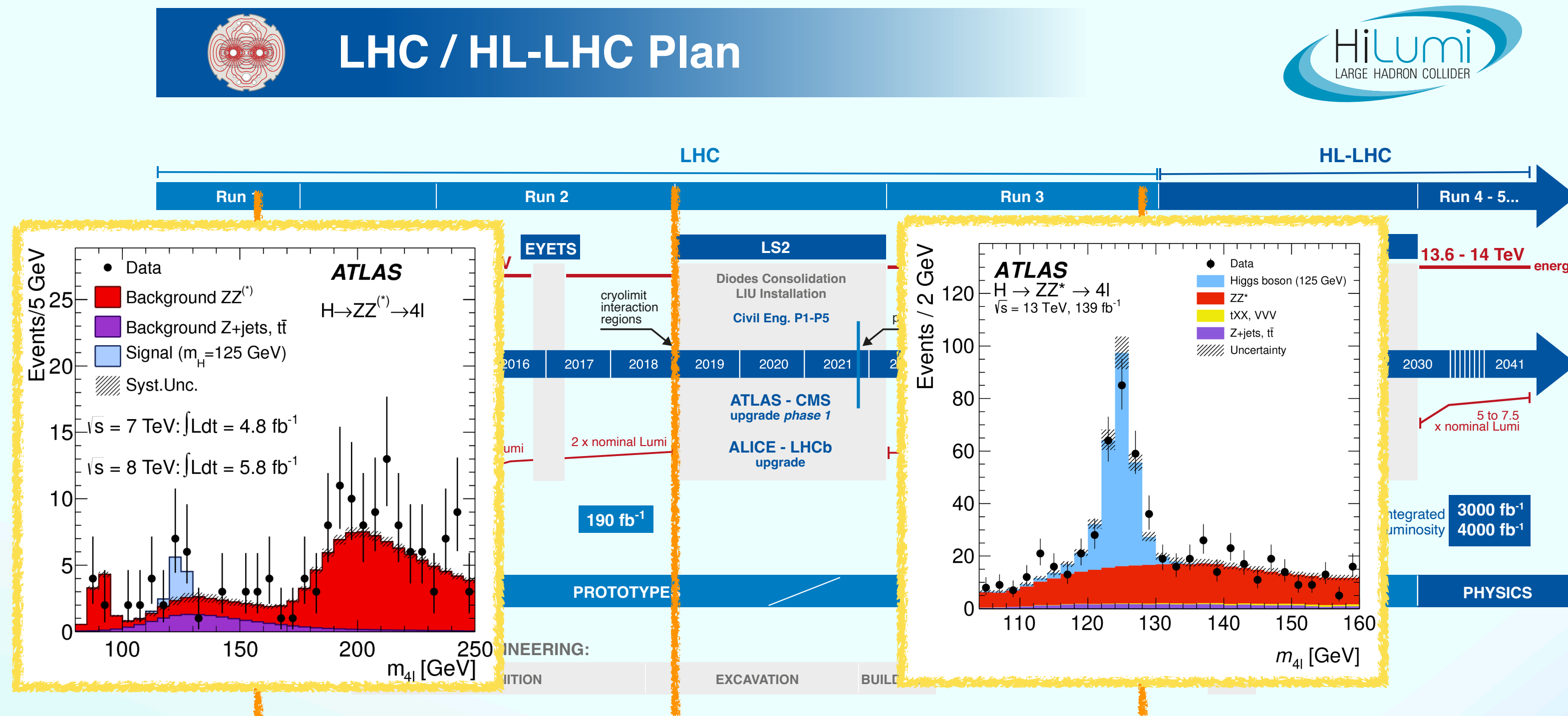


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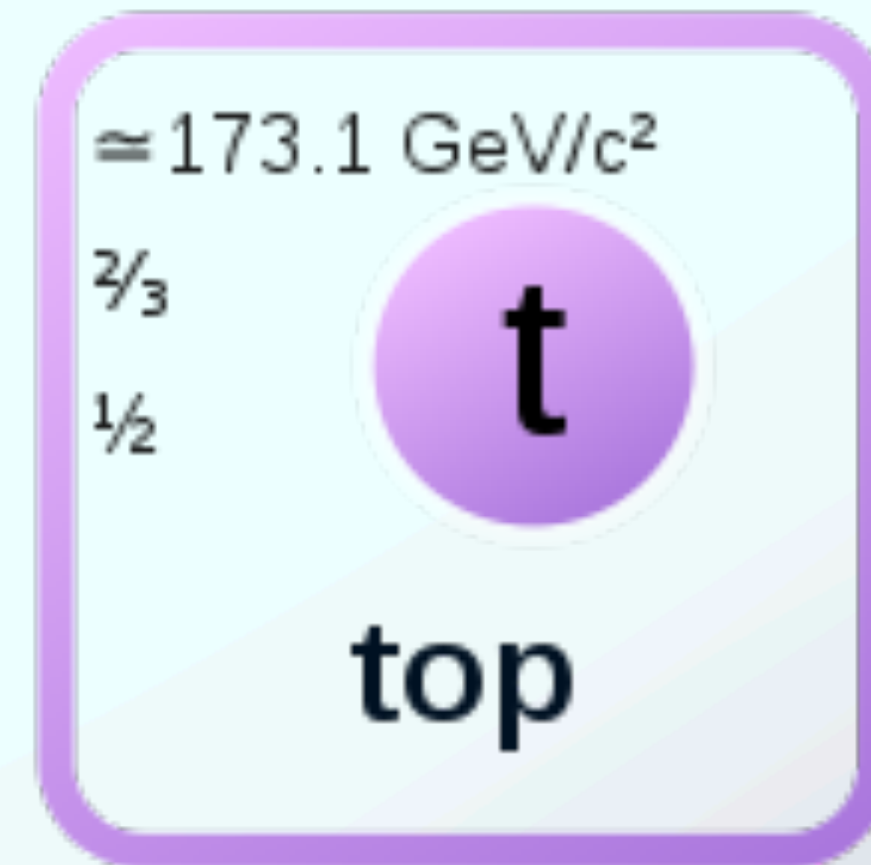
**End of Run 2**  
~7.7M Higgs prod.

**Today**  
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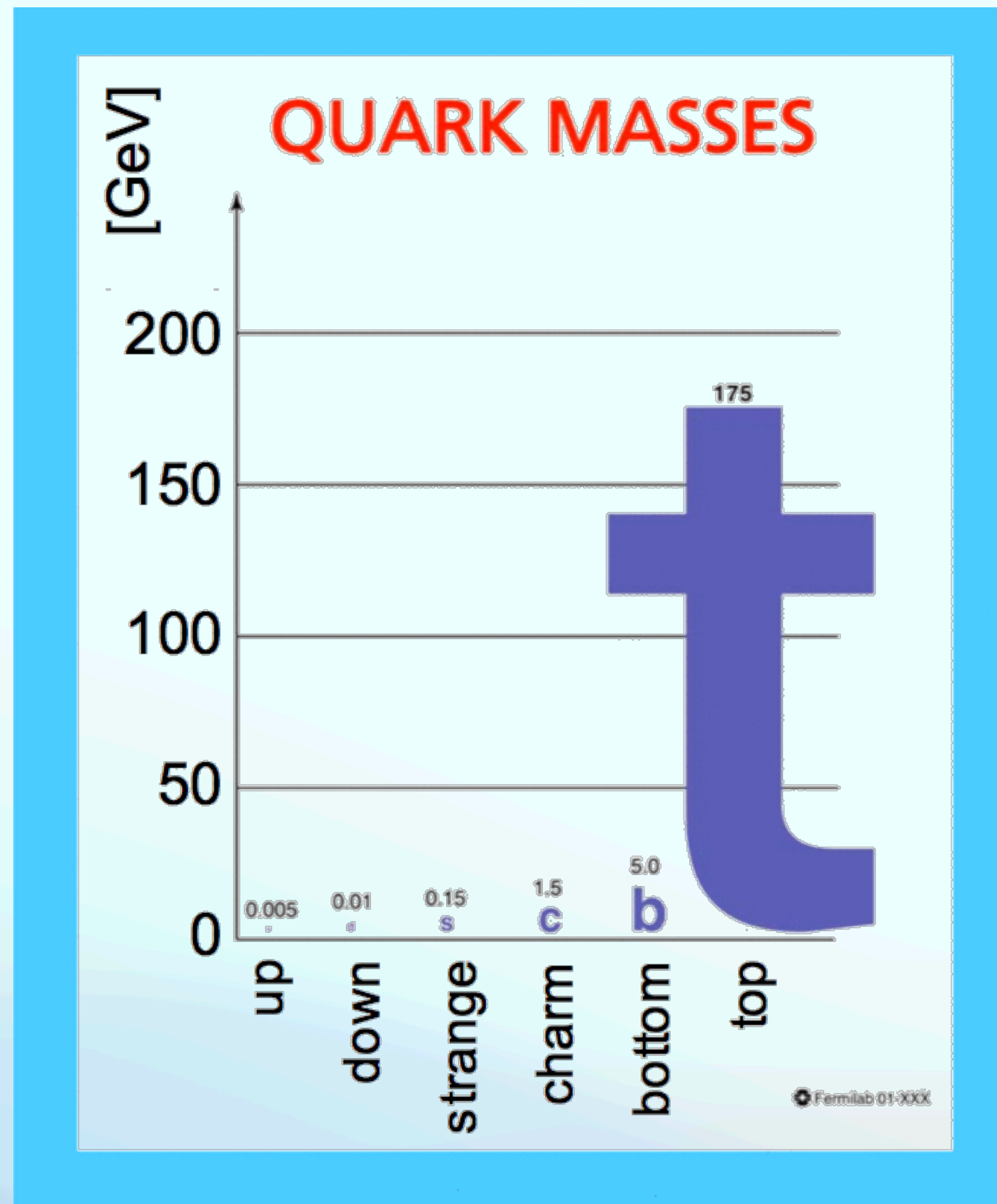
**End of HL-LHC**  
~170M Higgs prod.

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

2nd protagonist



# The Top quark as a probe for new physics



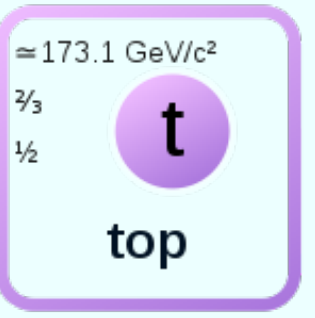
**Heaviest** particle in the SM  
*why?*

- Strongest coupling to Higgs sector
- Particular connection to Heavy New Sector?

**Decays** before hadronization

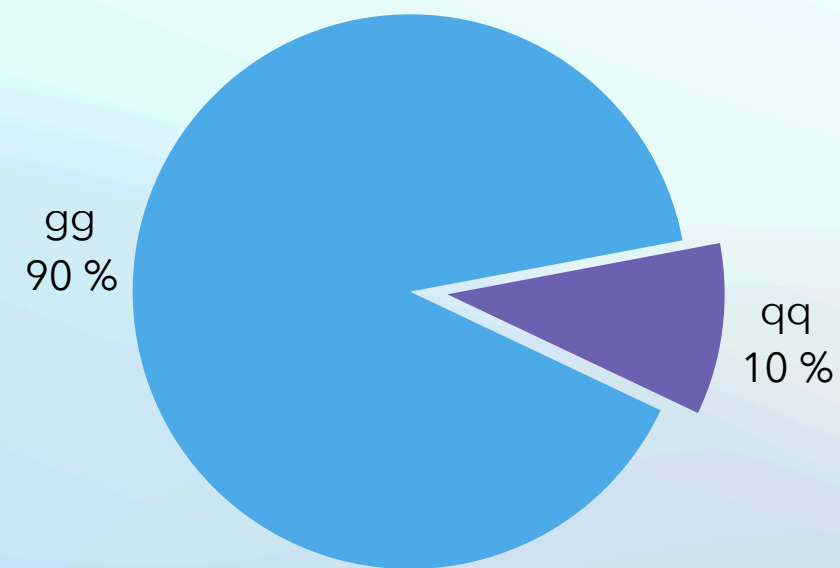
- Allows to study a "bare" quark

# Top @ proton collider : prod. and decay



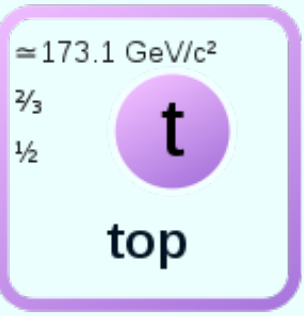
Production mode      Cross-section (pb)

$gg \rightarrow t\bar{t}$	} $\sim 90\%$	833.9
$qq \rightarrow t\bar{t}$		



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

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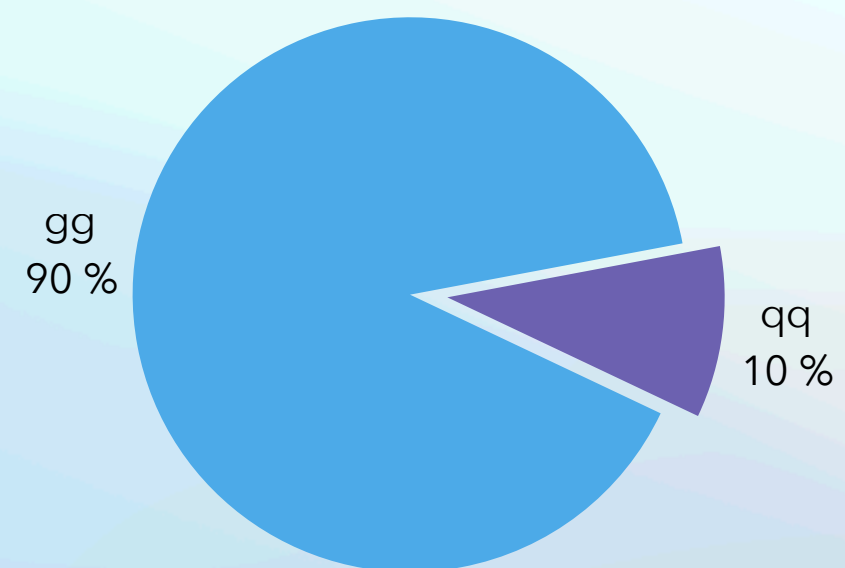
$gg \rightarrow t\bar{t}$       } ~90%  
 $qq \rightarrow t\bar{t}$       } ~10%      833.9

$t\bar{t}W$       0.745

$t\bar{t}Z$       0.811

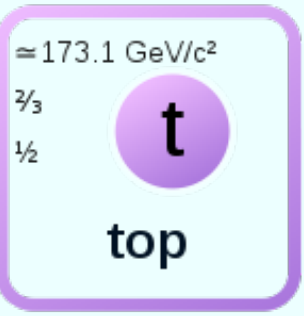
$t\bar{t}H$       0.529

$t\bar{t}t\bar{t}$       0.015



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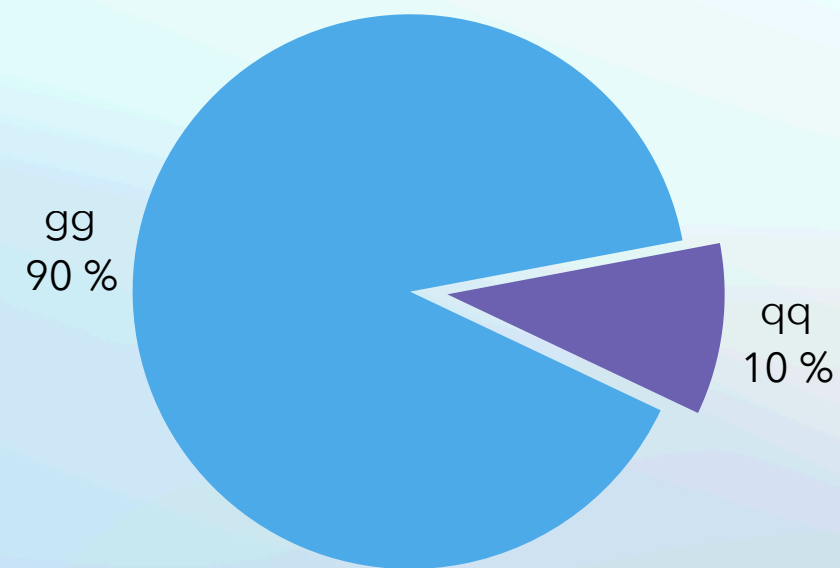
# Top @ proton collider : prod. and decay



Production mode	Cross-section (pb)	Decay Channel	Branching ratio
-----------------	--------------------	---------------	-----------------

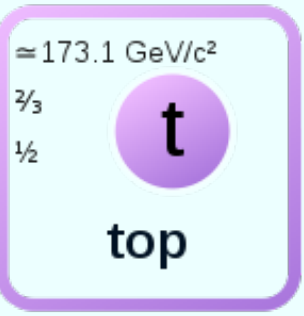
$gg \rightarrow t\bar{t}$ $qq \rightarrow t\bar{t}$	$\left. \begin{array}{l} \sim 90\% \\ \sim 10\% \end{array} \right\}$ 833.9	$t \rightarrow b + W$	99.8
--	--	-----------------------	------

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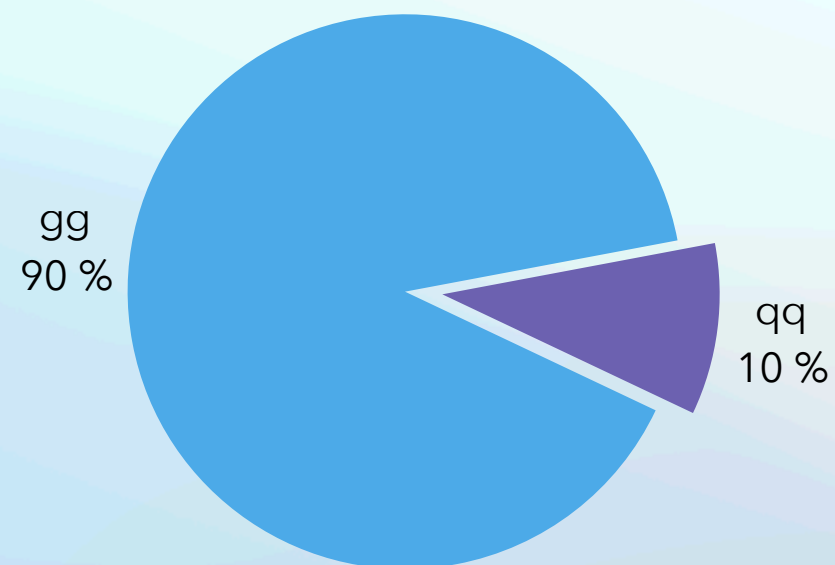
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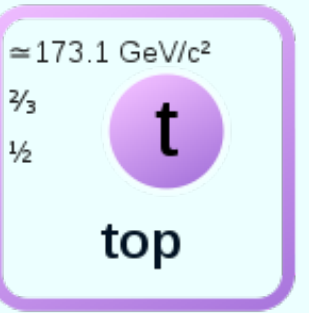
Then, final states from  $W$  decays

$t \rightarrow b + W(\rightarrow q\bar{q})$	66.5
$t \rightarrow b + W(\rightarrow e\nu_e)$	11
$t \rightarrow b + W(\rightarrow \mu\nu_\mu)$	11
$t \rightarrow b + W(\rightarrow \tau\nu_\tau)$	11

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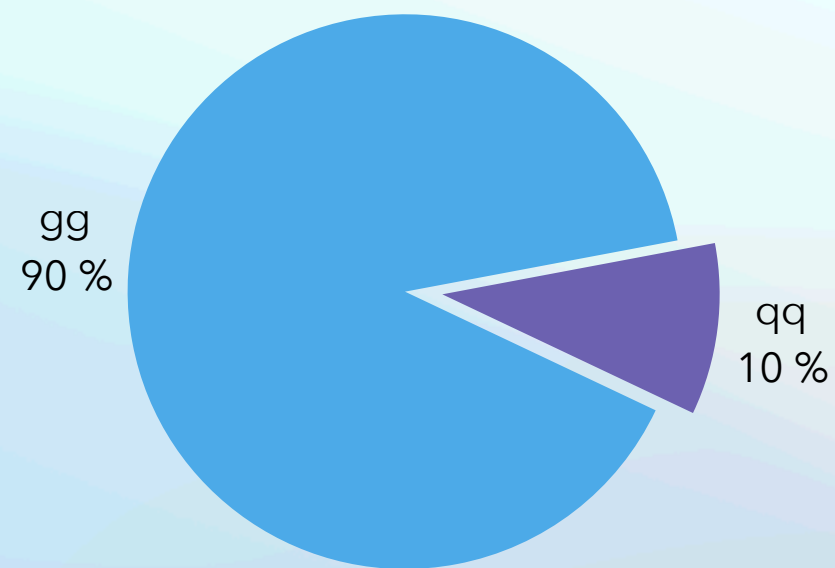


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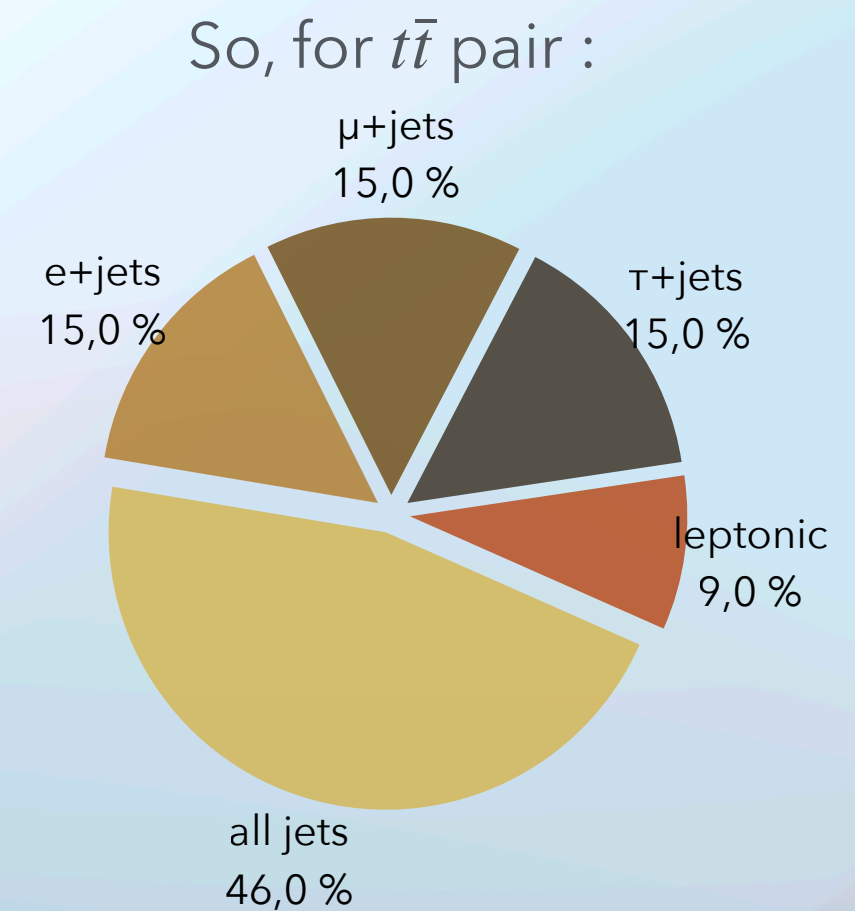
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Mostly produced via QCD in  $t\bar{t}$  pair

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



# How to go from theory to measurement?

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## **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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## Simulation of ATLAS detector



## Reconstruction of an event

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

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## Simulation of ATLAS detector



## Reconstruction of an event

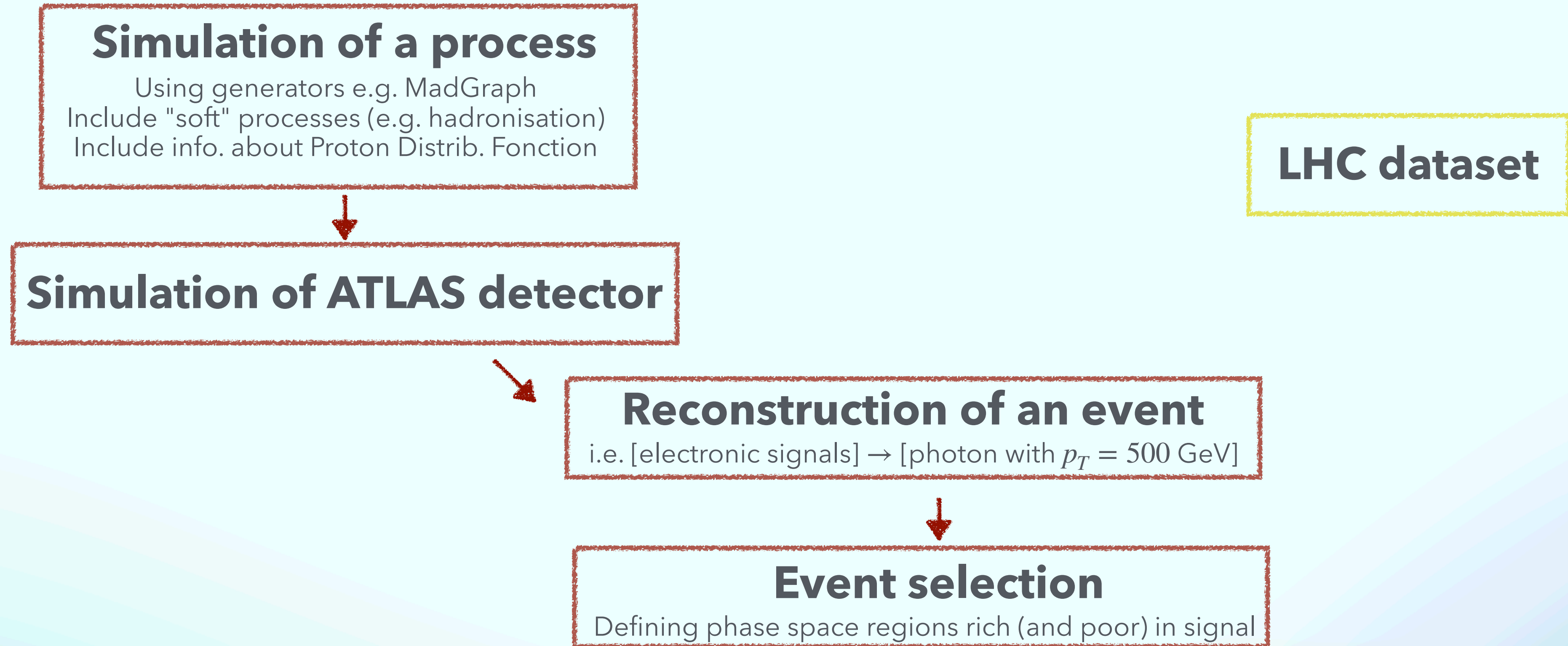
i.e. [electronic signals] → [photon with  $p_T = 500$  GeV]



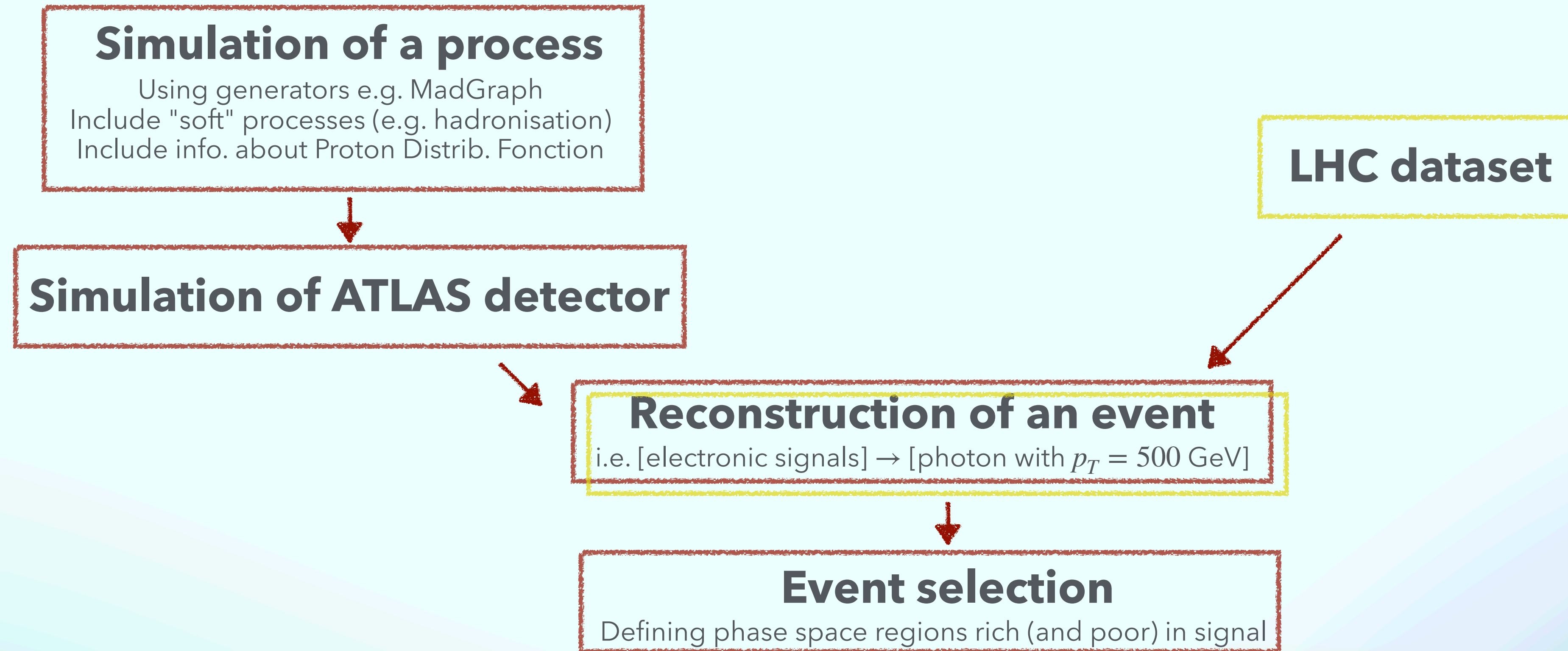
## Event selection

Defining phase space regions rich (and poor) in signal

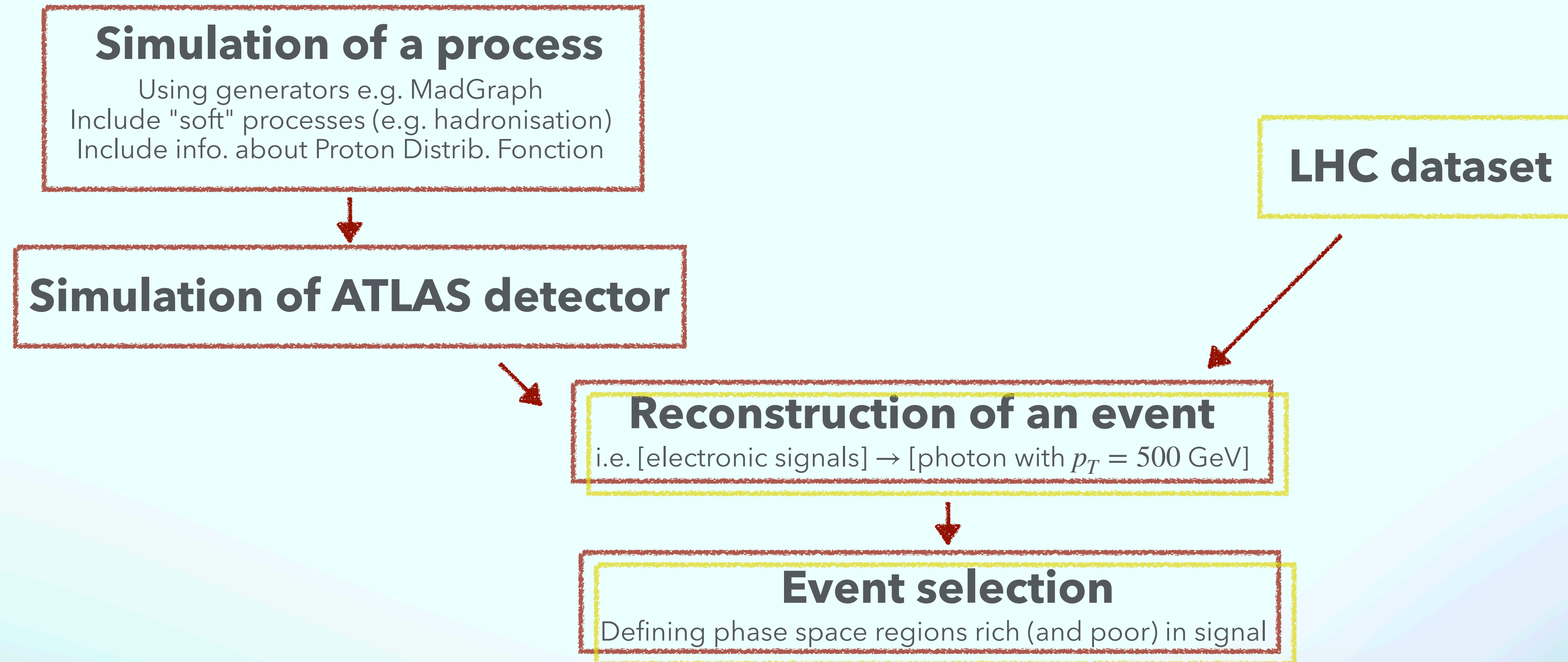
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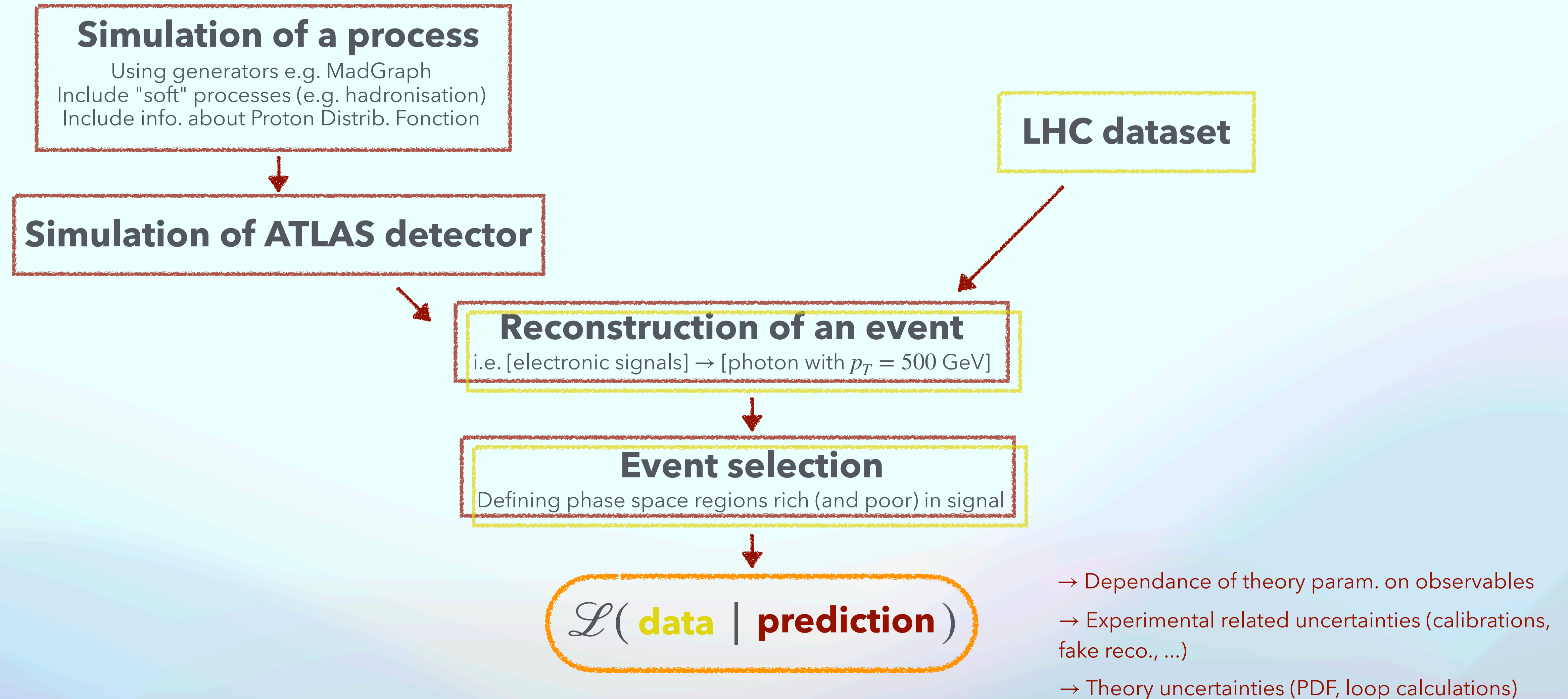
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# How to go from theory to measurement?



Recap. so far

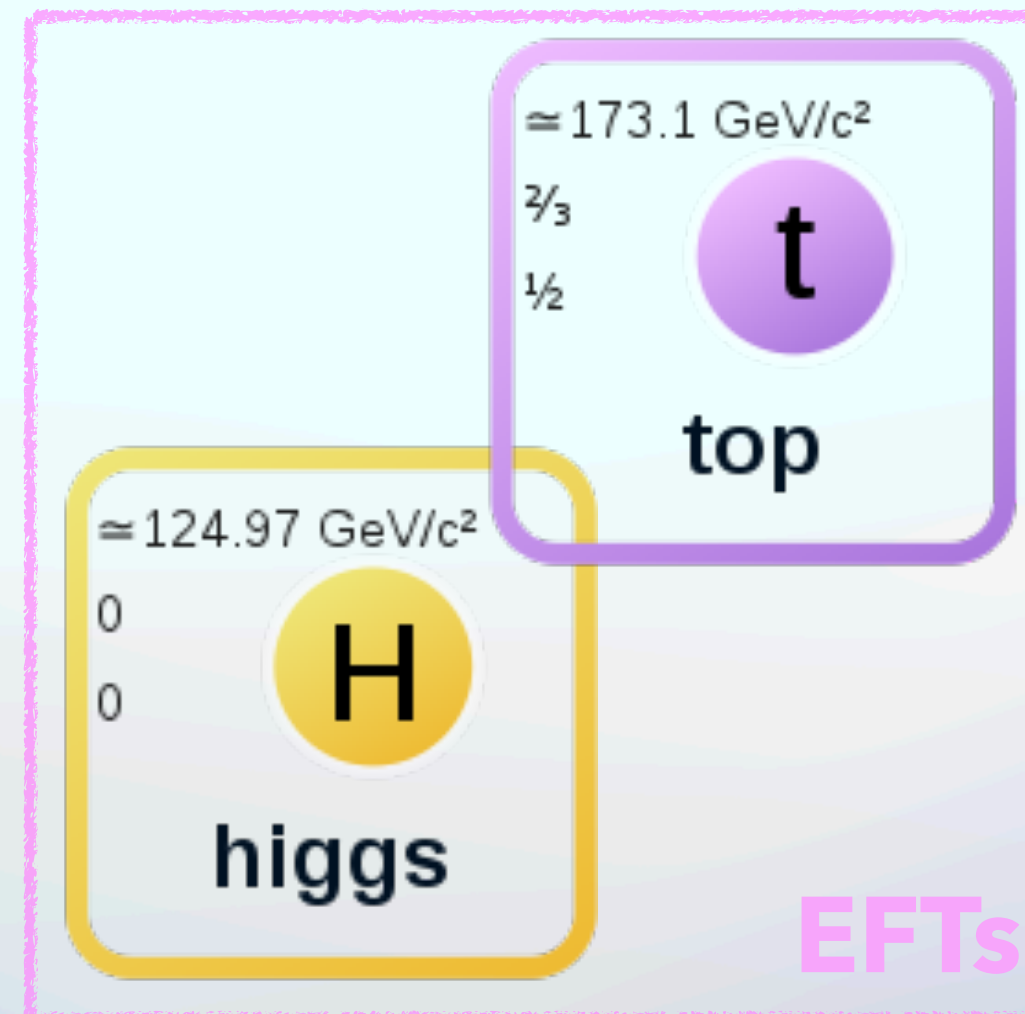
# Recap.

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

We have a already *large* dataset to explore  
and a even larger one 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

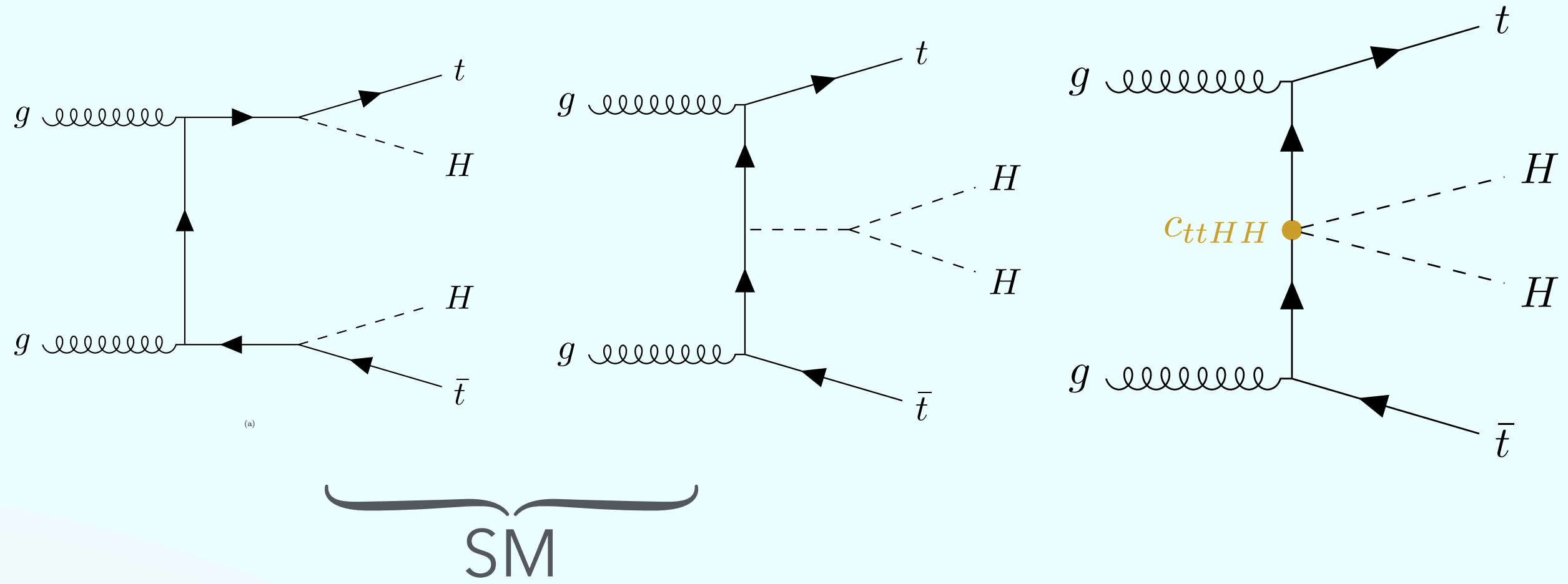


# Probing the Top-Higgs Quartic interaction

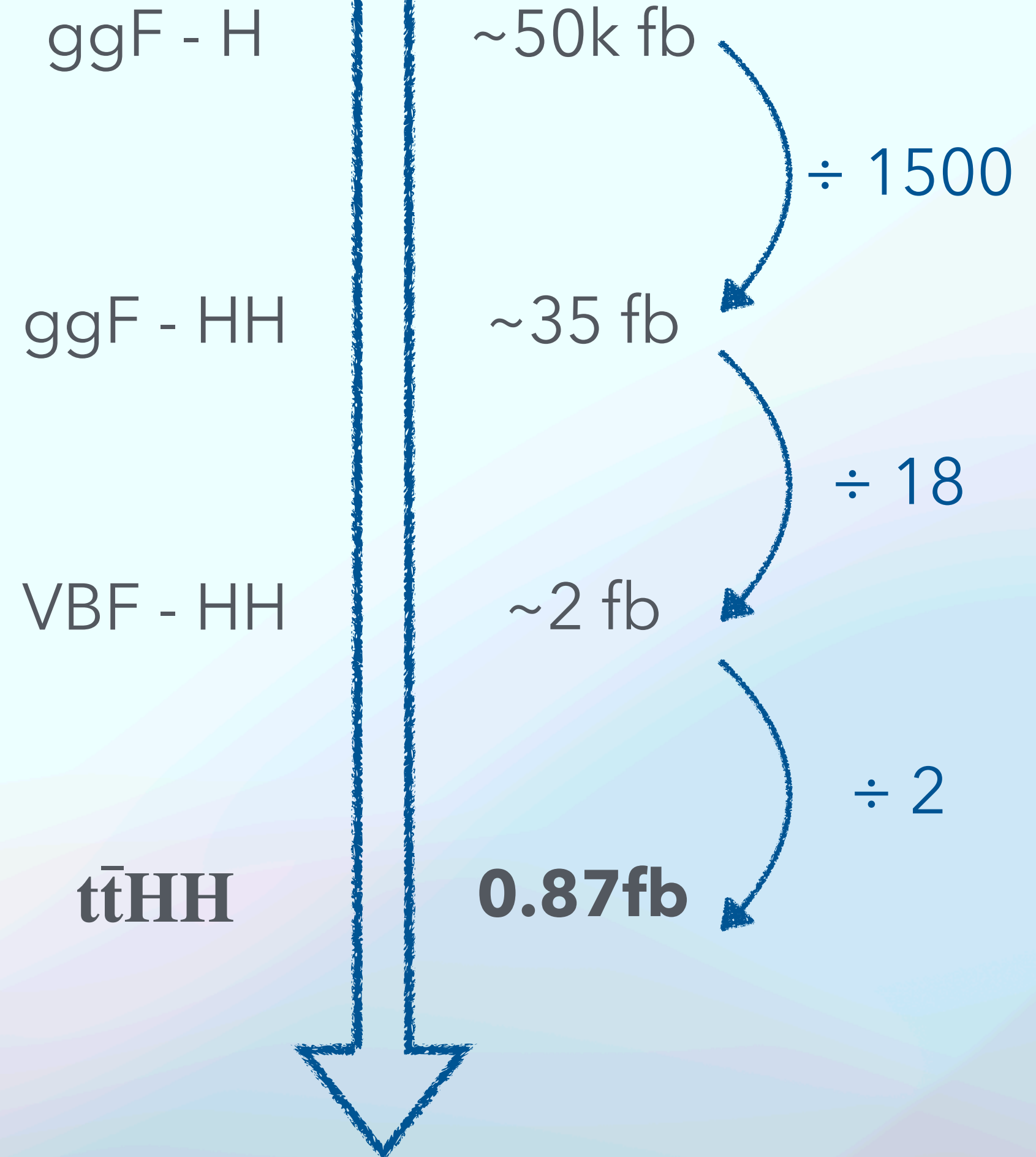
through an EFT interpretation of  $t\bar{t}HH$  production at ATLAS

[arXiv:2026.13113](https://arxiv.org/abs/2026.13113)

# Motivations

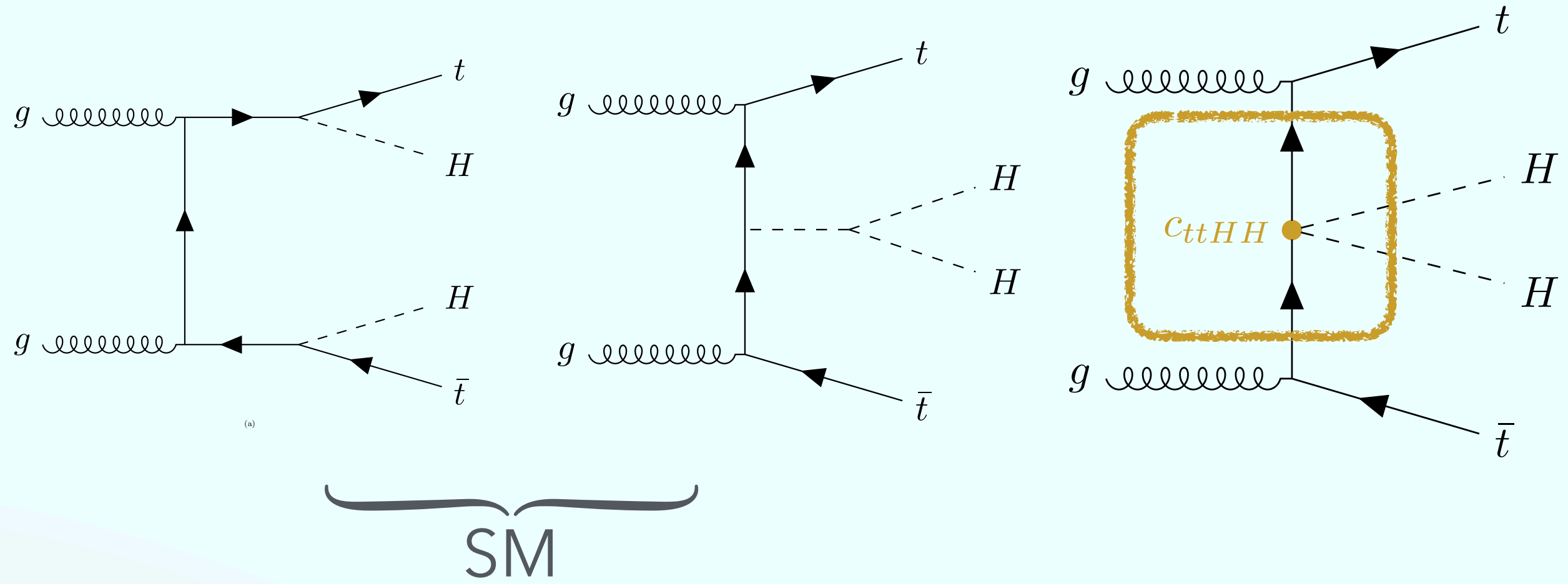


LHC @ 13.6 TeV

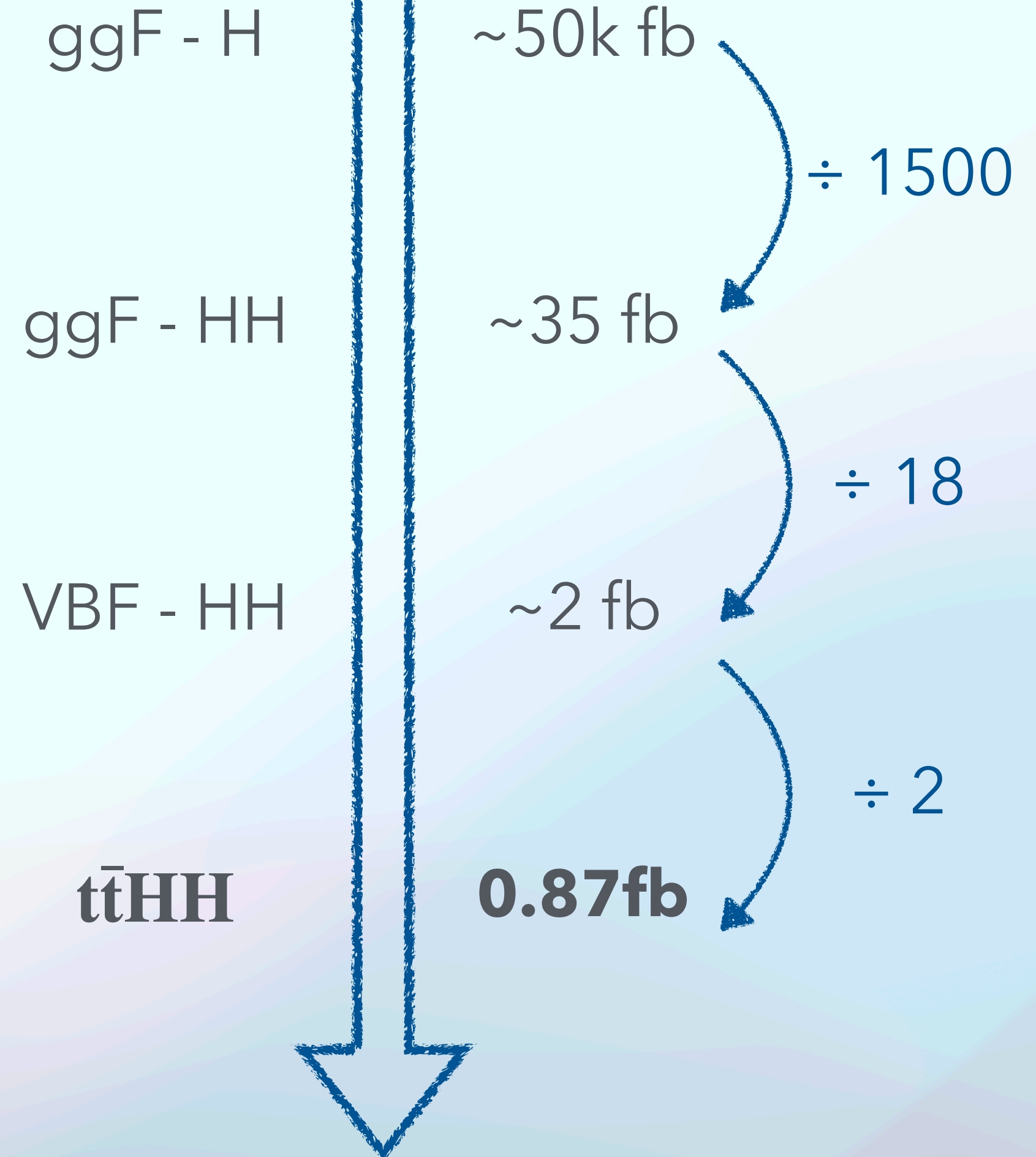


- 3rd leading HH production mode @ LHC

# Motivations



LHC @ 13.6 TeV

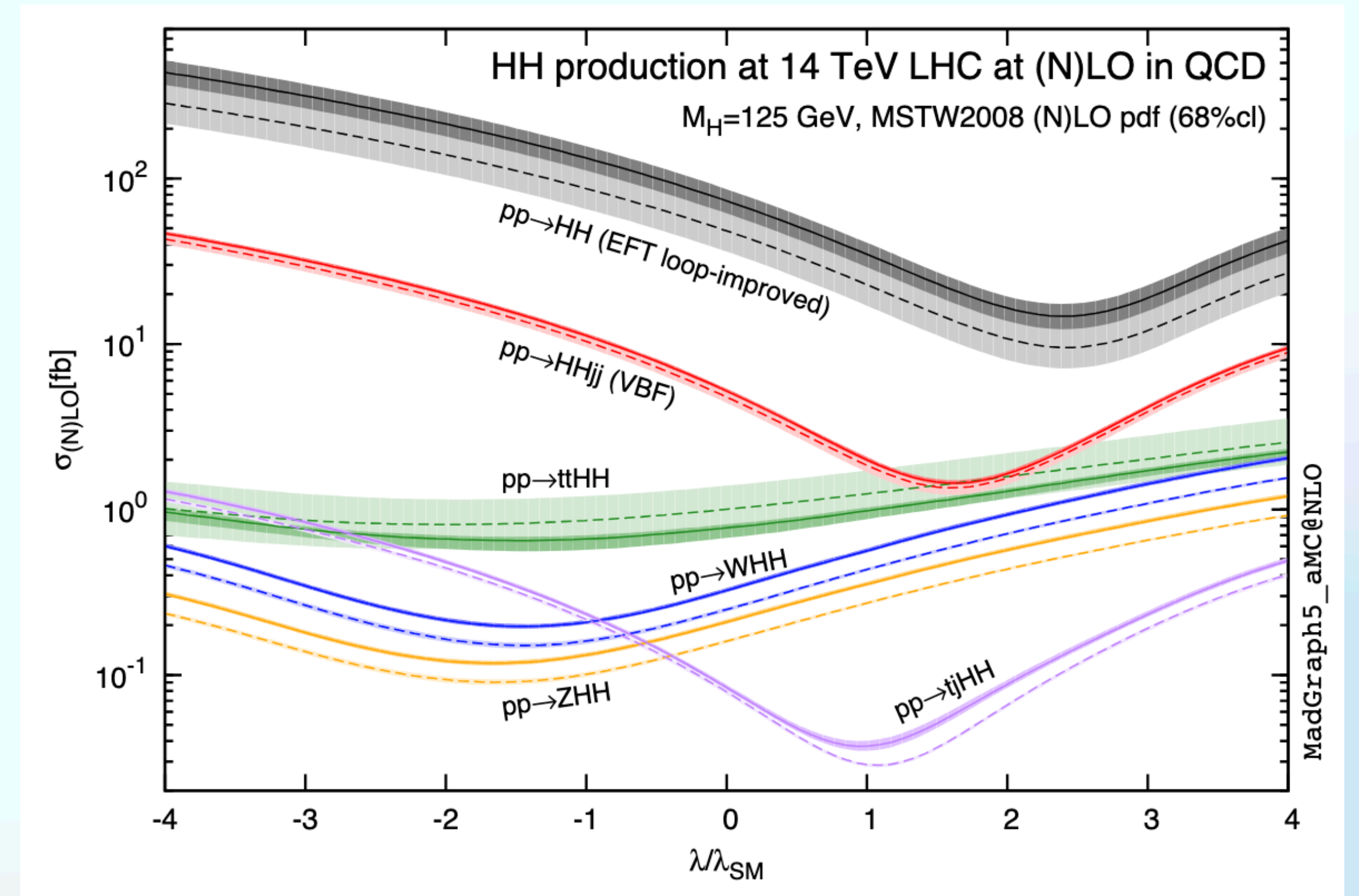
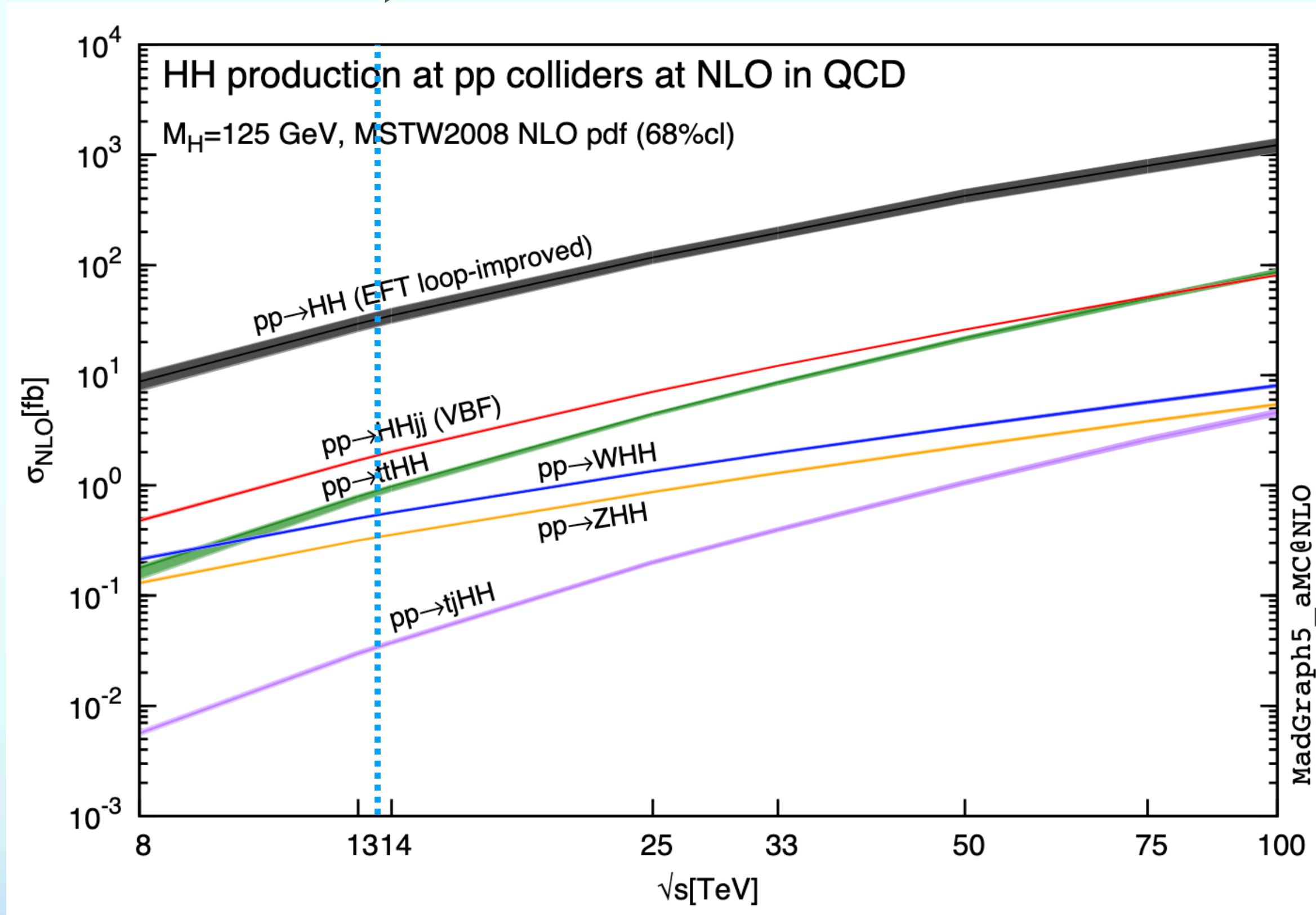


- 3rd leading HH production mode @ LHC
- Gives **direct** access to  $t\bar{t}HH$  quartic interaction

# ttHH production

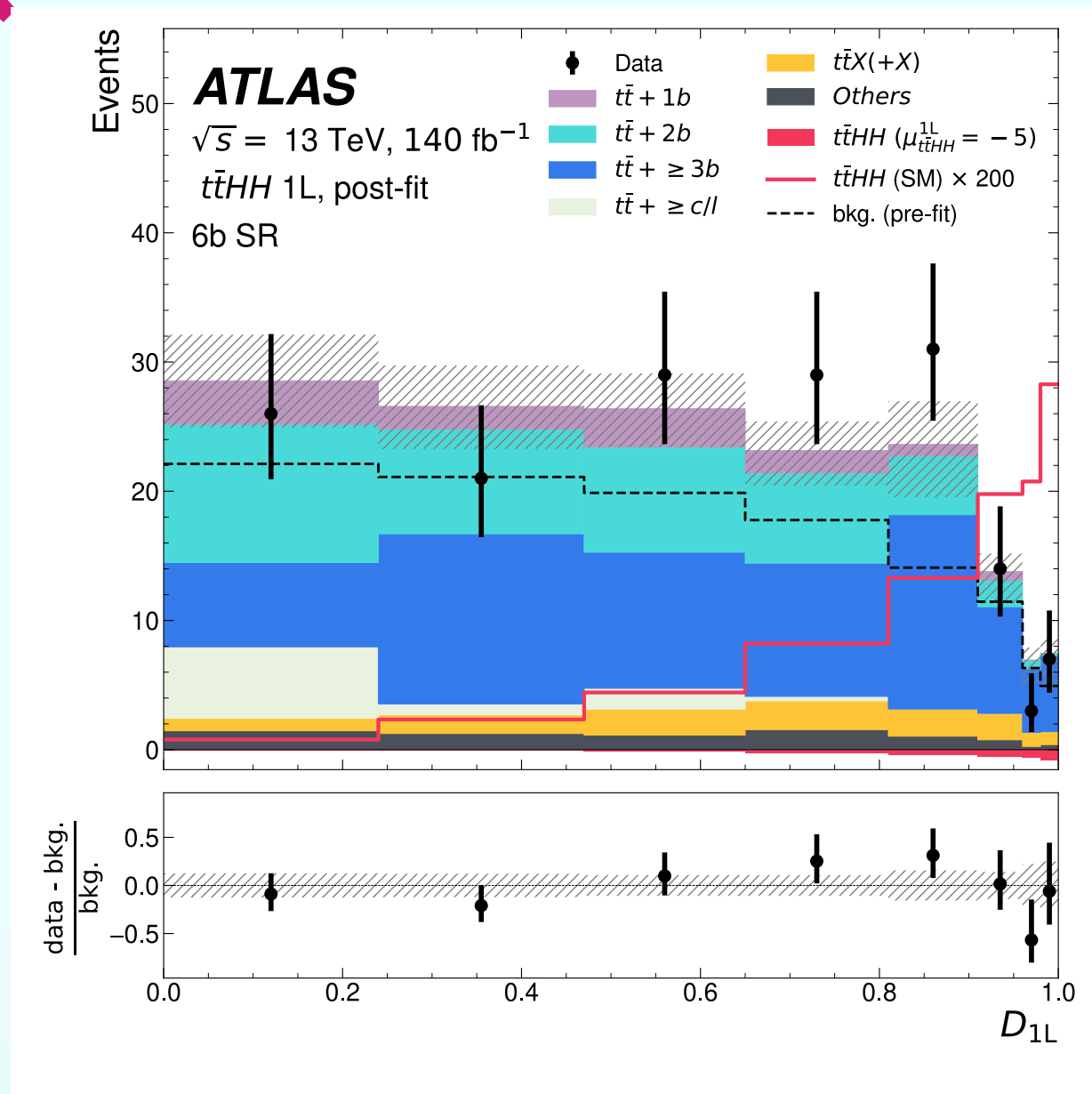
[arXiv:1401.7340](https://arxiv.org/abs/1401.7340)

*We stand here*



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

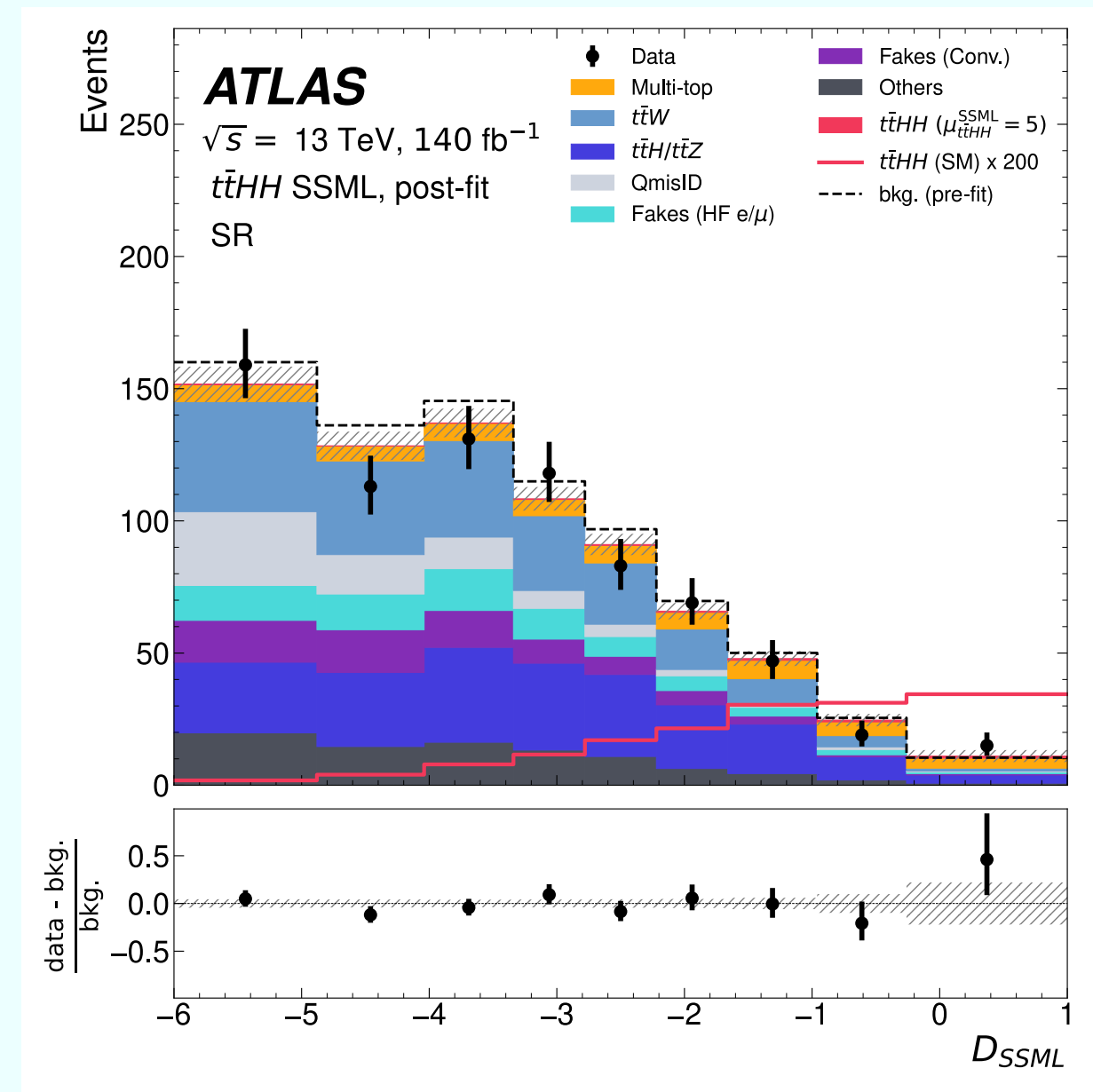
# Strategy



## Single lep. channel (1L)

$HH \rightarrow 4b$  and semileptonic  $t\bar{t}$   
dom. bkg :  $t\bar{t}$  + jets

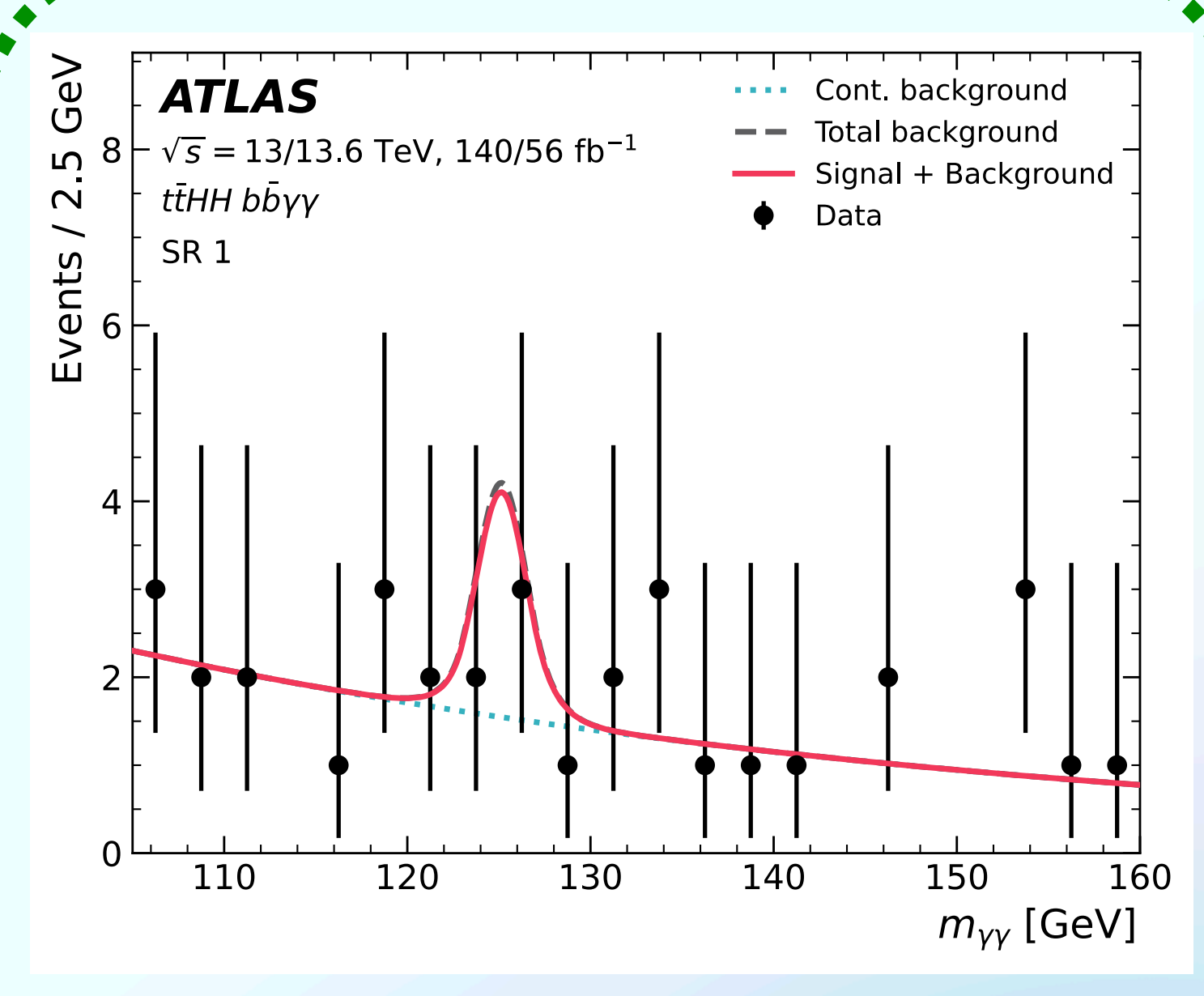
Obs. limit on  $\mu$  : **26** x SM



## Multi-lep. Channel (ML)

$HH \rightarrow b\bar{b}WW, b\bar{b}\tau\tau, \dots$   
dom. bkg :  $t\bar{t}W, t\bar{t}t\bar{t}, QmidID$

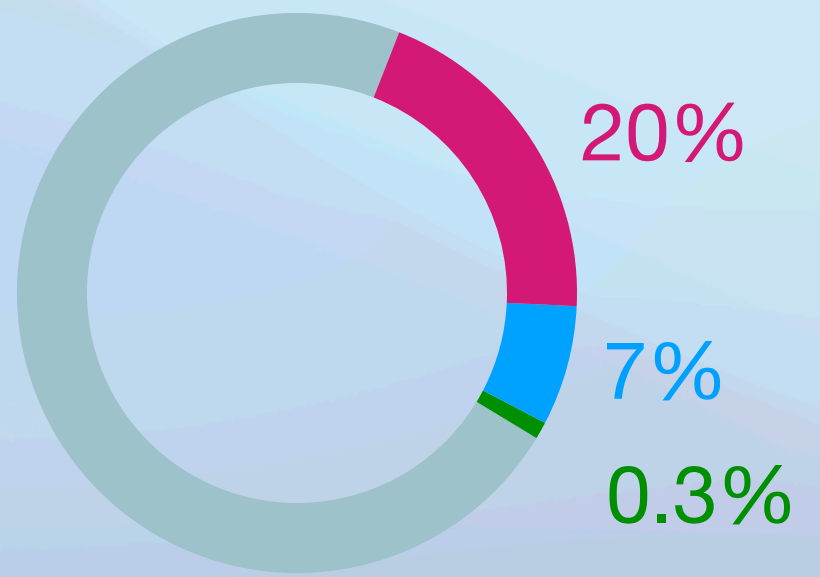
Obs. limit on  $\mu$  : **40** x SM



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

$HH \rightarrow b\bar{b}\gamma\gamma$   
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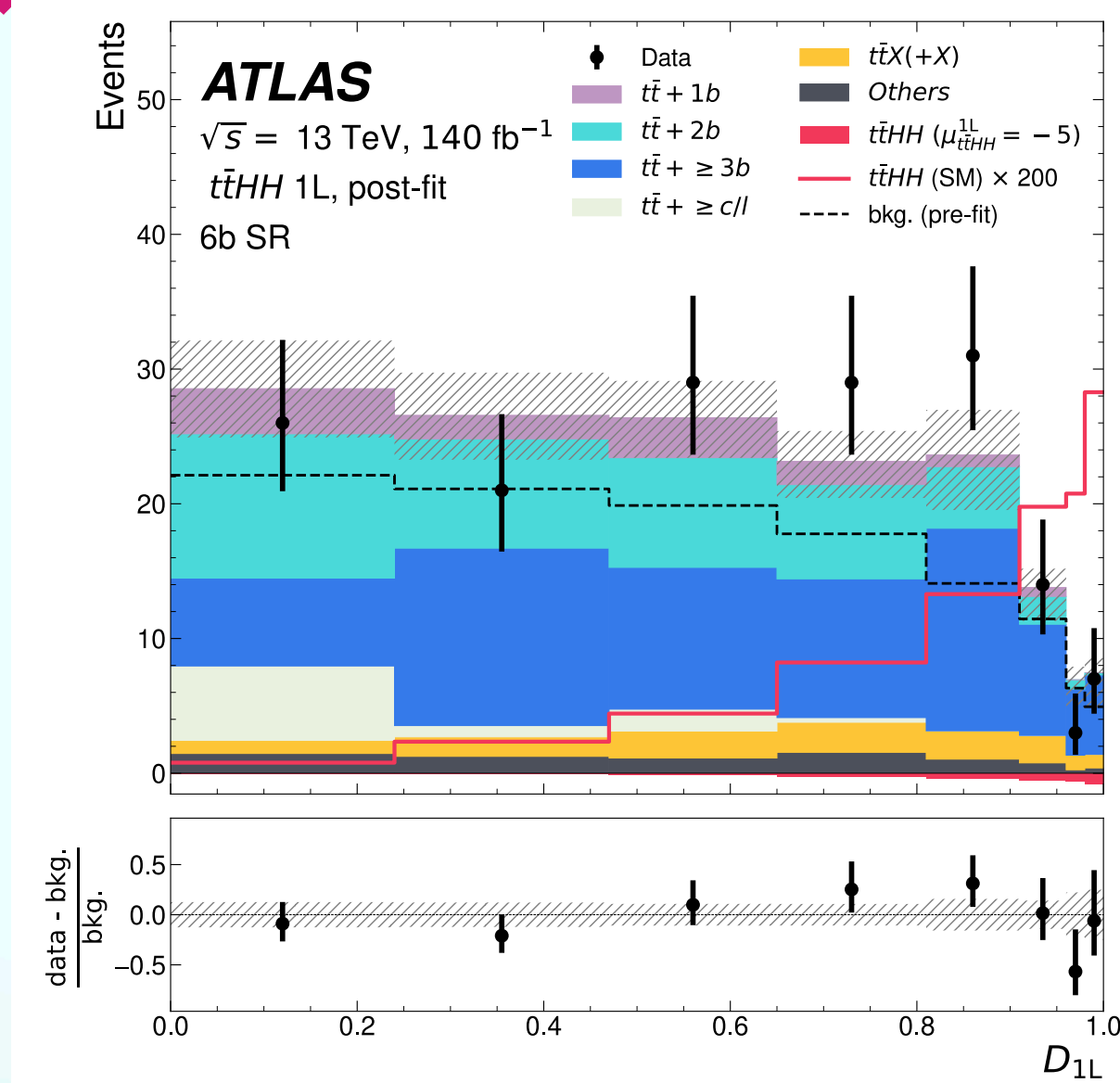
Obs. limit on  $\mu$  : **75** x SM



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

Obs. limit on  $\mu$  : **20** x SM

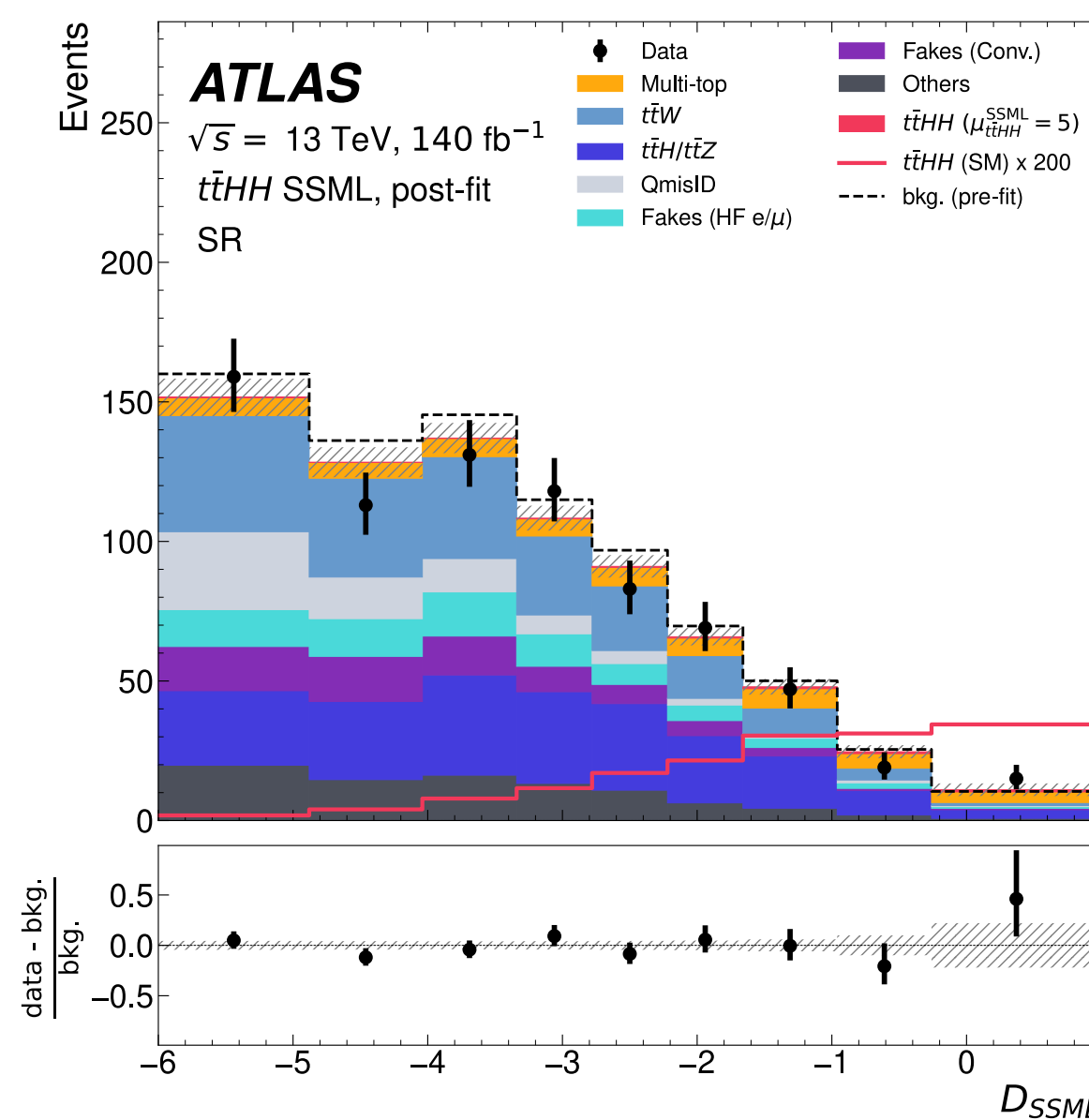
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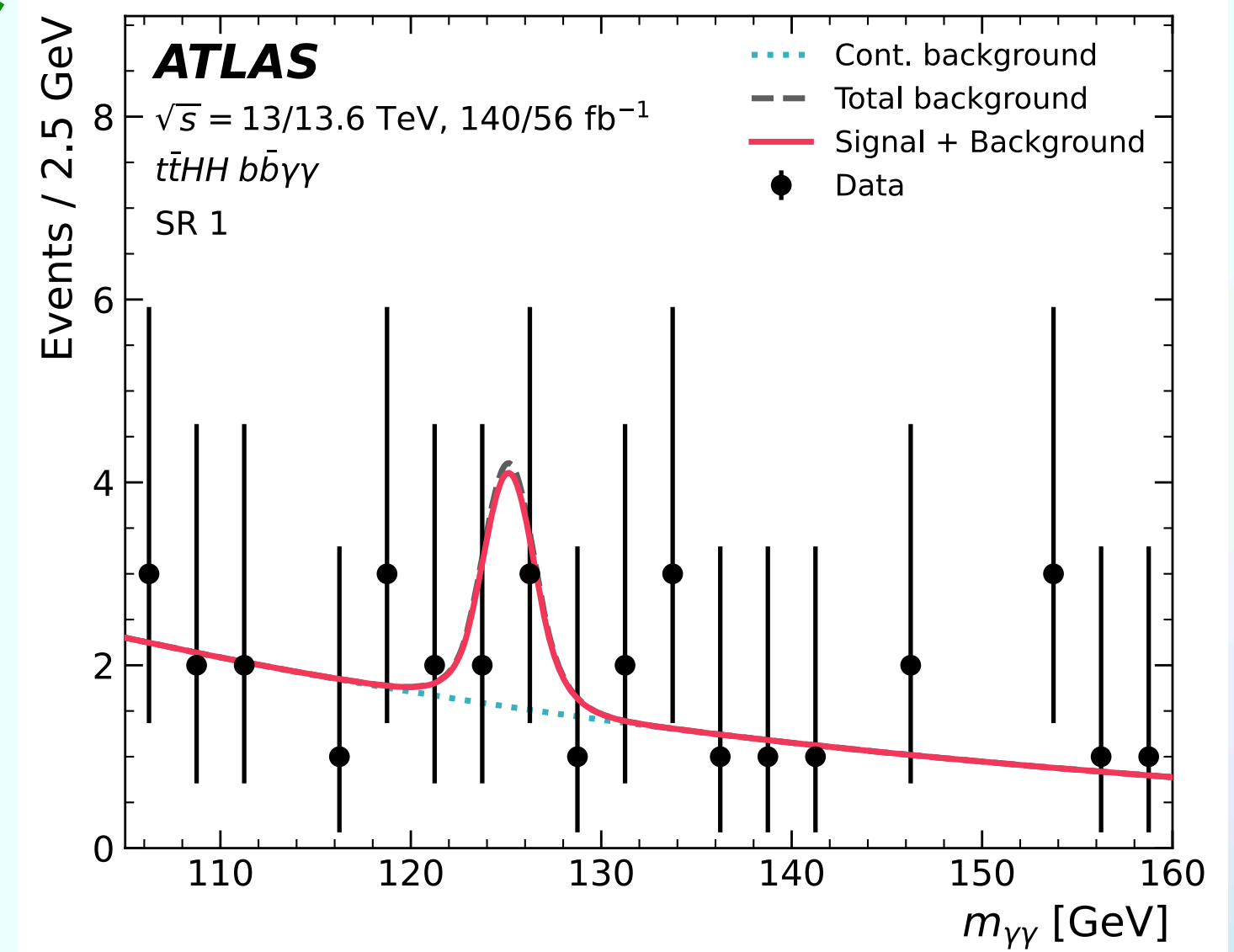
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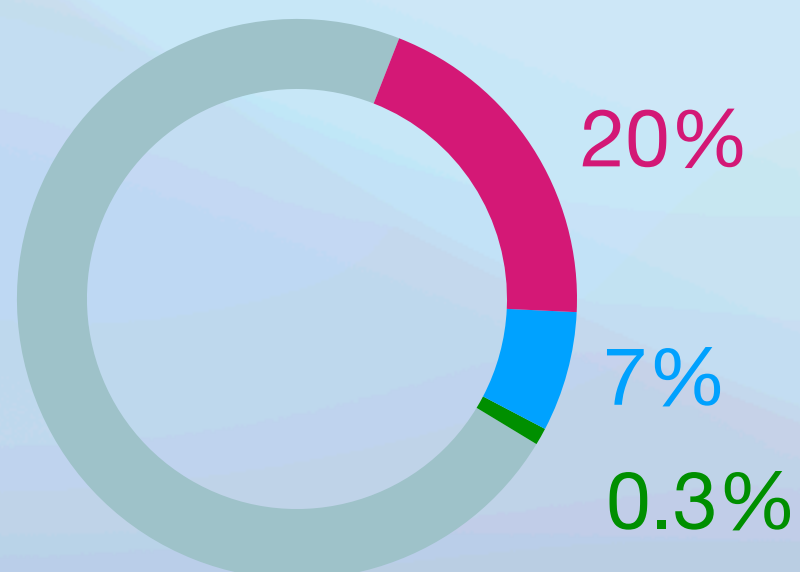
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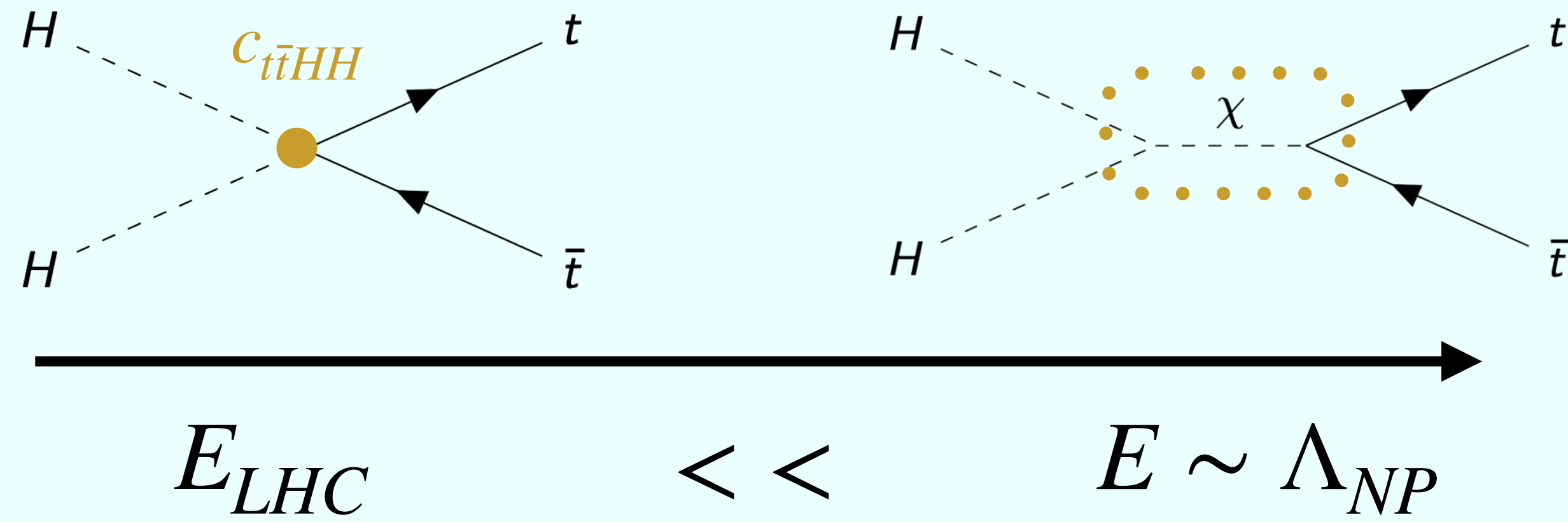
# Limitations

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)
$t\bar{t}\bar{t}\bar{t}$	(+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)

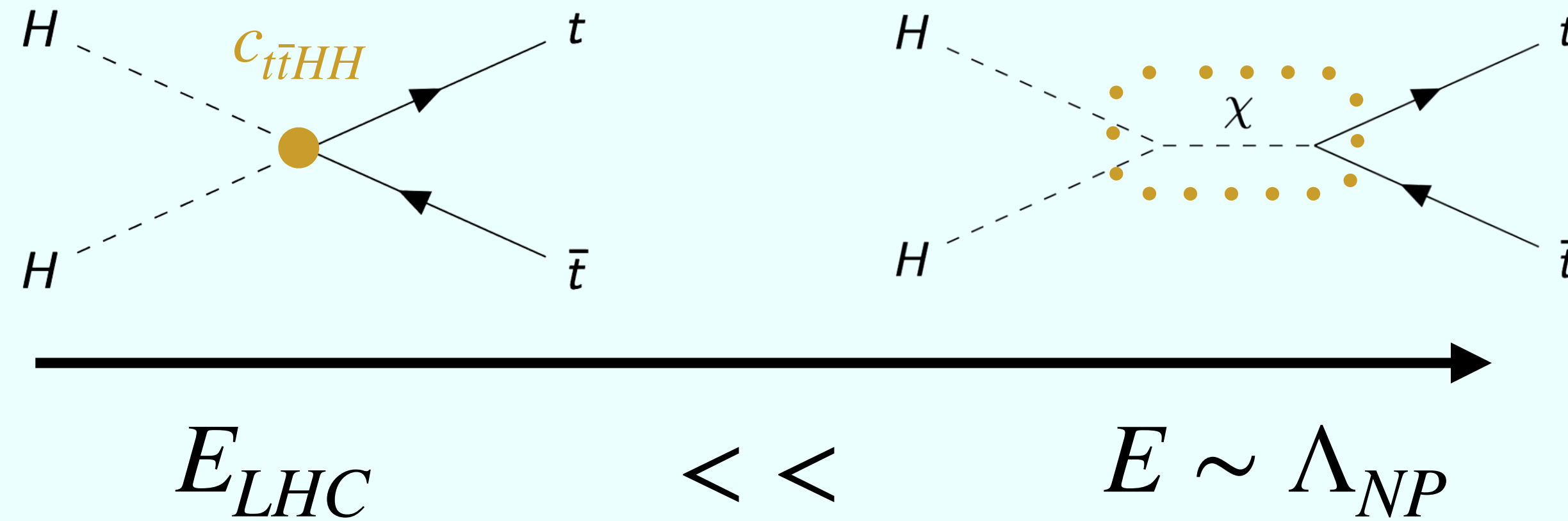
**Dominant systematic unc. :**  
heavy flavour modelling and 4 tops

**Overall** → Balance between stat. and modelling

# Higgs Effective Field Theory



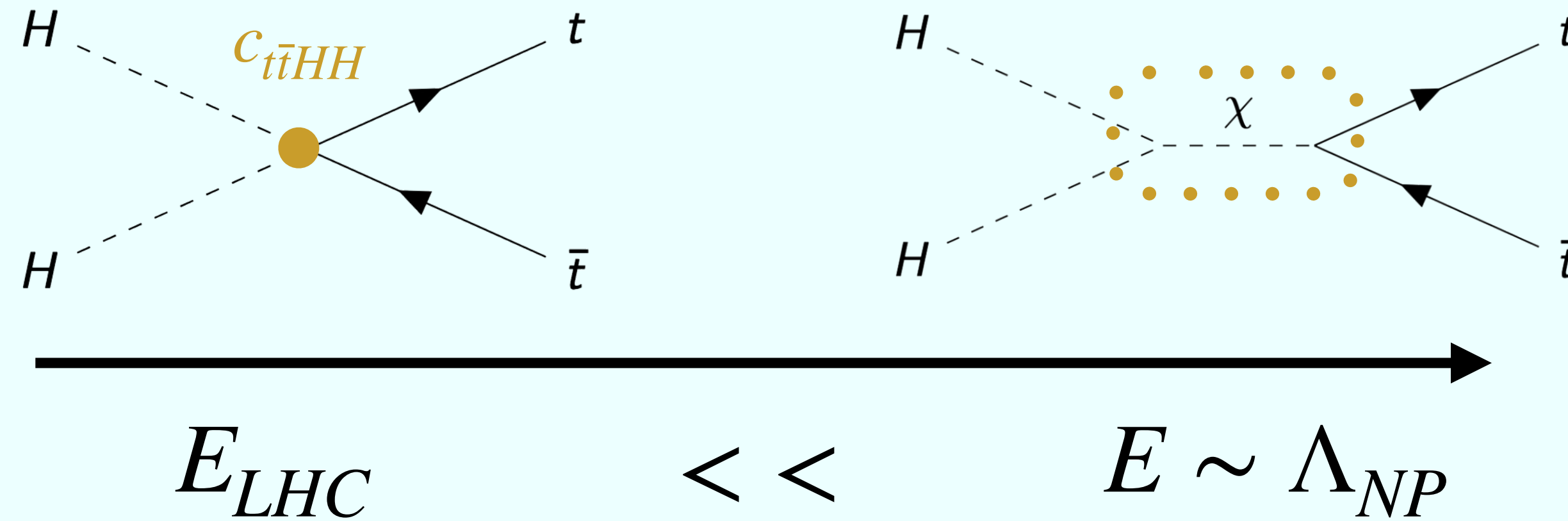
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## *EFT recipe*

- 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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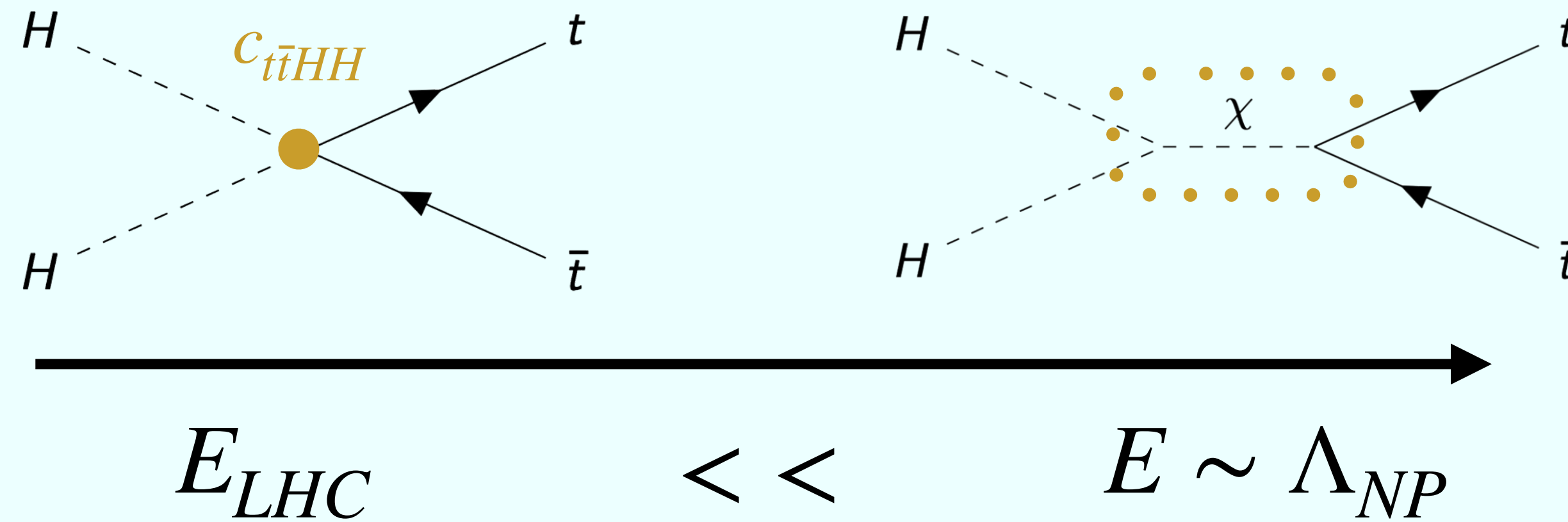
HEFT relaxes the assumption that the physical Higgs boson  $h$  is part of a  $SU(2)_L$  doublet

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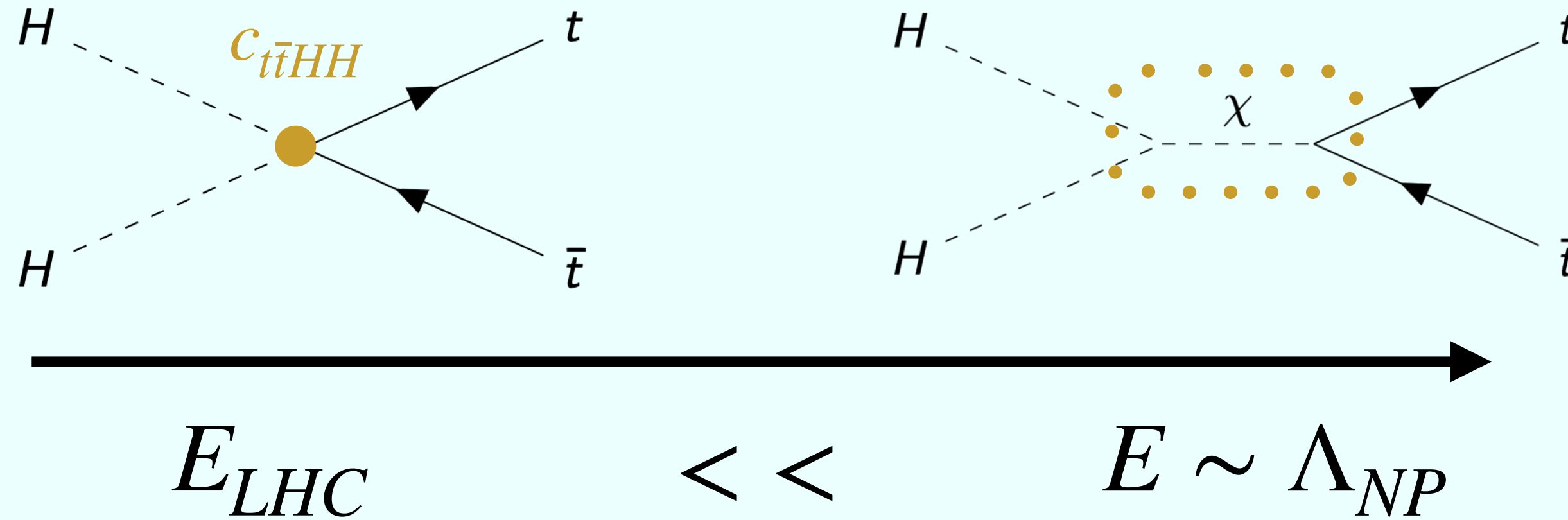
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$$\mathcal{L}_{\text{HEFT}} \supset -m_t \left( c_{t\bar{t}H} \frac{h}{v} + c_{t\bar{t}HH} \frac{h^2}{v^2} \right) t\bar{t} - \kappa_\lambda \frac{m_H^2}{2v} h^3$$

# Strategy and results

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



**Reinterpretation**

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

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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  $\sim$ 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](https://github.com/Ryczek/CttHH)
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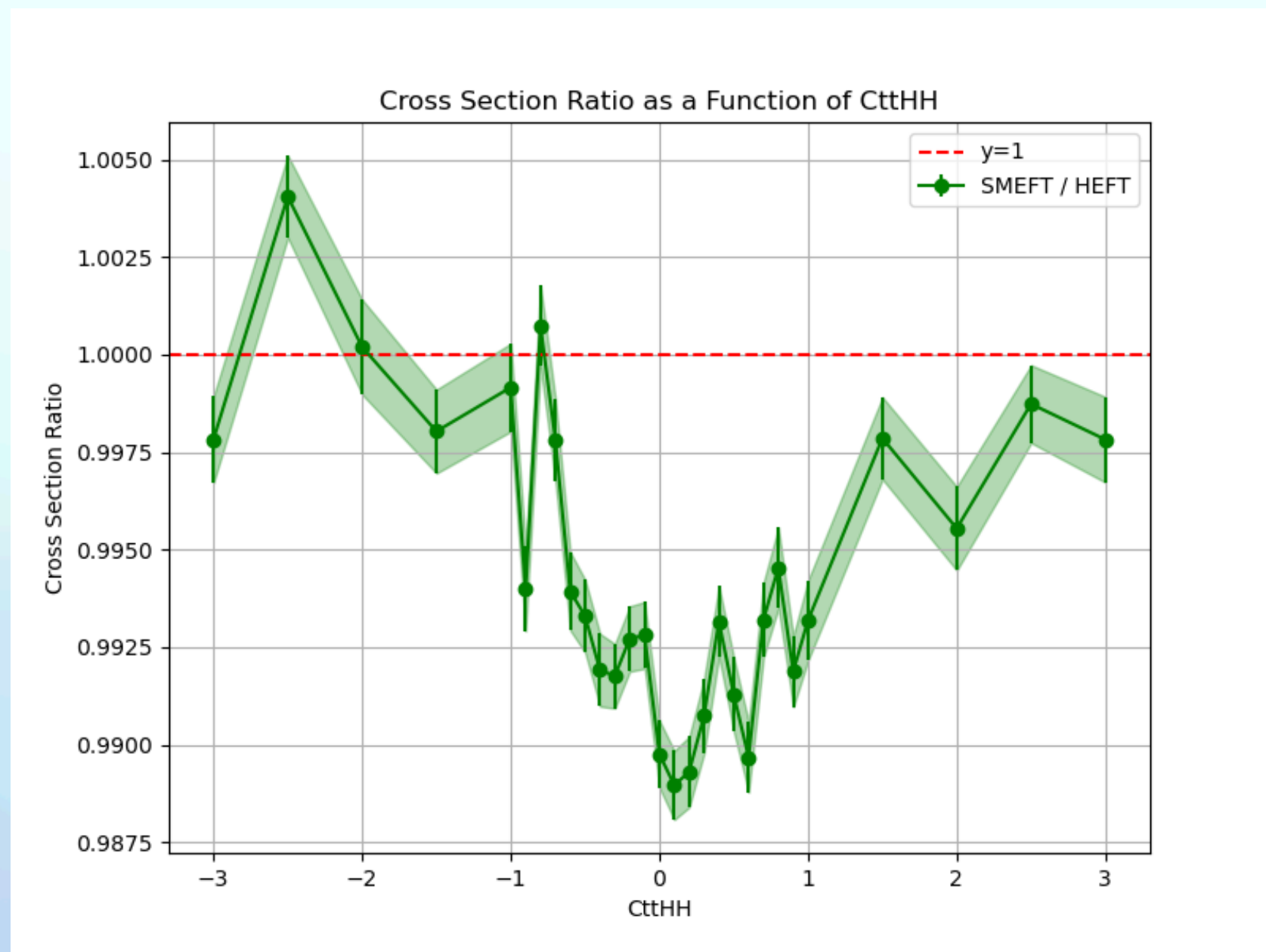
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[arXiv:2304.01968](https://arxiv.org/abs/2304.01968)

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→ Agreement at ~1% level

# A probe for HEFT vs. SMEFT

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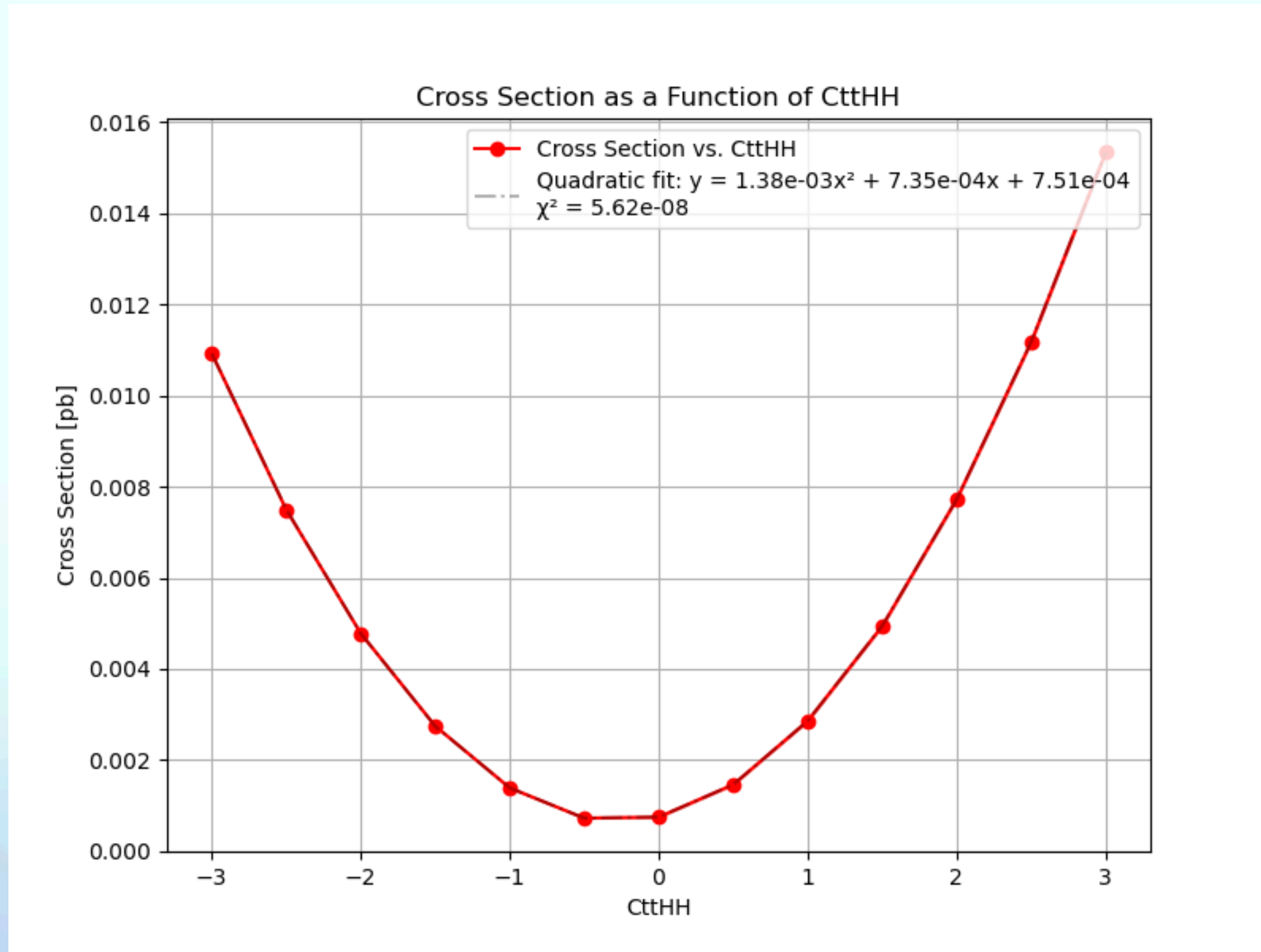
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Connects HEFT and SMEFT in  $t\bar{t}HH$

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

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

# Cross-section dependance



Quadratic dependance → **Expected**

$$\sigma \sim \left| \begin{array}{c} g \text{ wavy} \rightarrow t \\ \uparrow \\ g \text{ wavy} \rightarrow \bar{t} \\ \uparrow \\ H \text{ dashed} \\ \uparrow \\ H \text{ dashed} \end{array} + \begin{array}{c} g \text{ wavy} \rightarrow t \\ \uparrow \\ g \text{ wavy} \rightarrow \bar{t} \\ \uparrow \\ H \text{ dashed} \\ \uparrow \\ H \text{ dashed} \end{array} + C_{ttHH} \begin{array}{c} g \text{ wavy} \rightarrow t \\ \uparrow \\ g \text{ wavy} \rightarrow \bar{t} \\ \uparrow \\ H \text{ dashed} \\ \uparrow \\ H \text{ dashed} \end{array} \right|^2$$

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

# How to extract the most kin. information?

Ideally :  $\sim \frac{\mathcal{M}_{SM}}{\mathcal{M}_{BSM}}$  → optimal as long as phase-space is ~comparable  
*not trivial as we probe heavy-mass*

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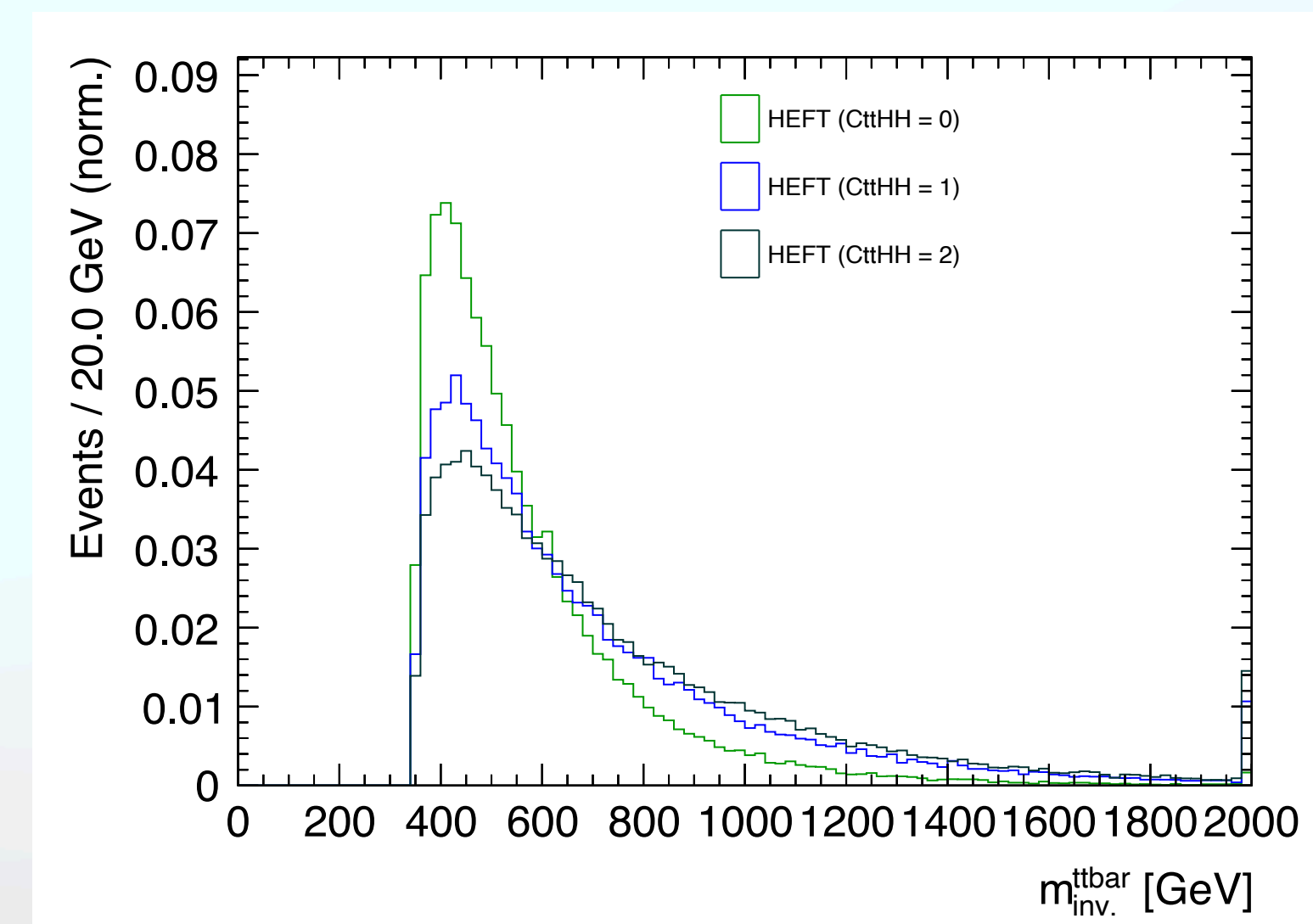
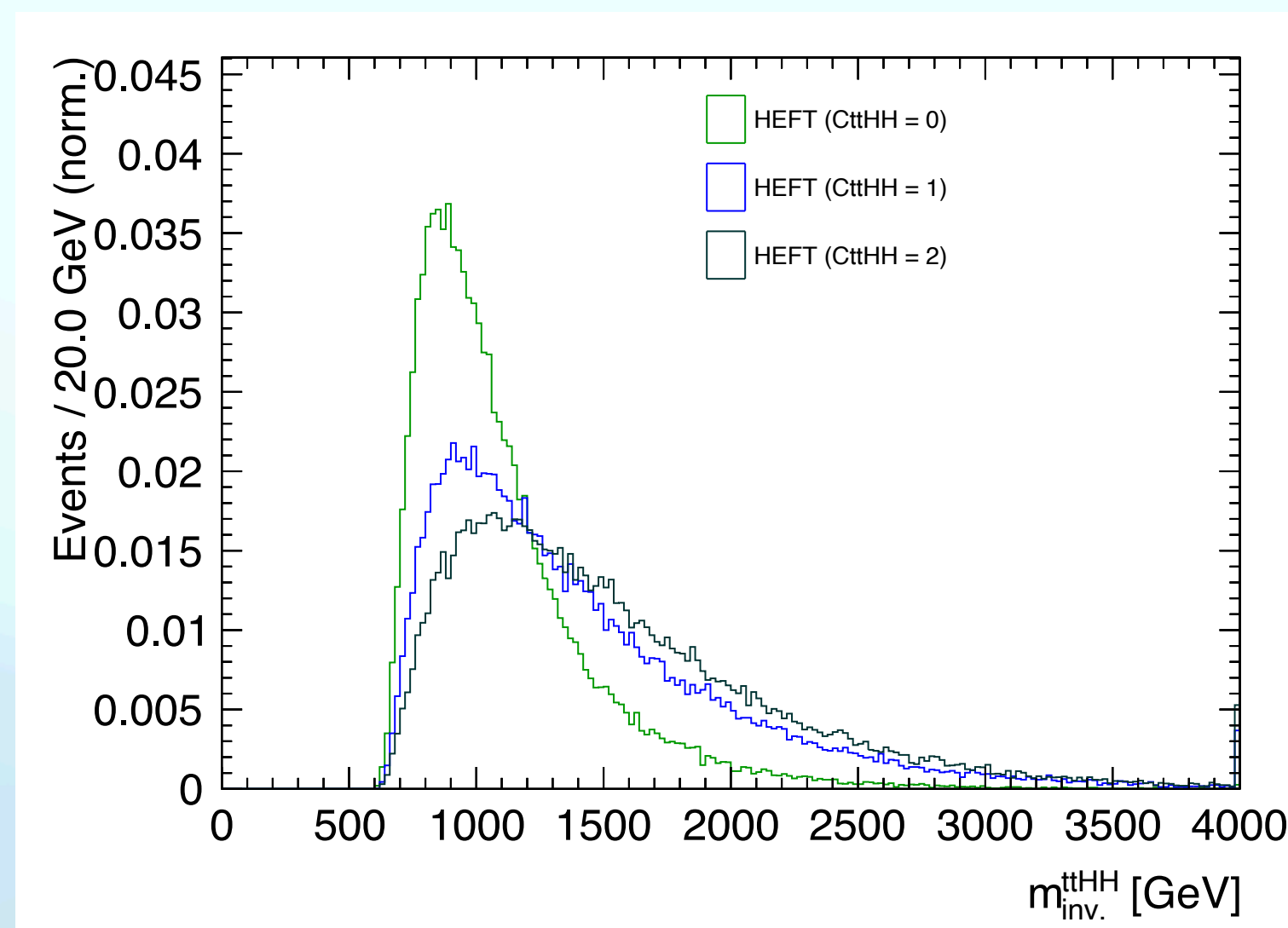
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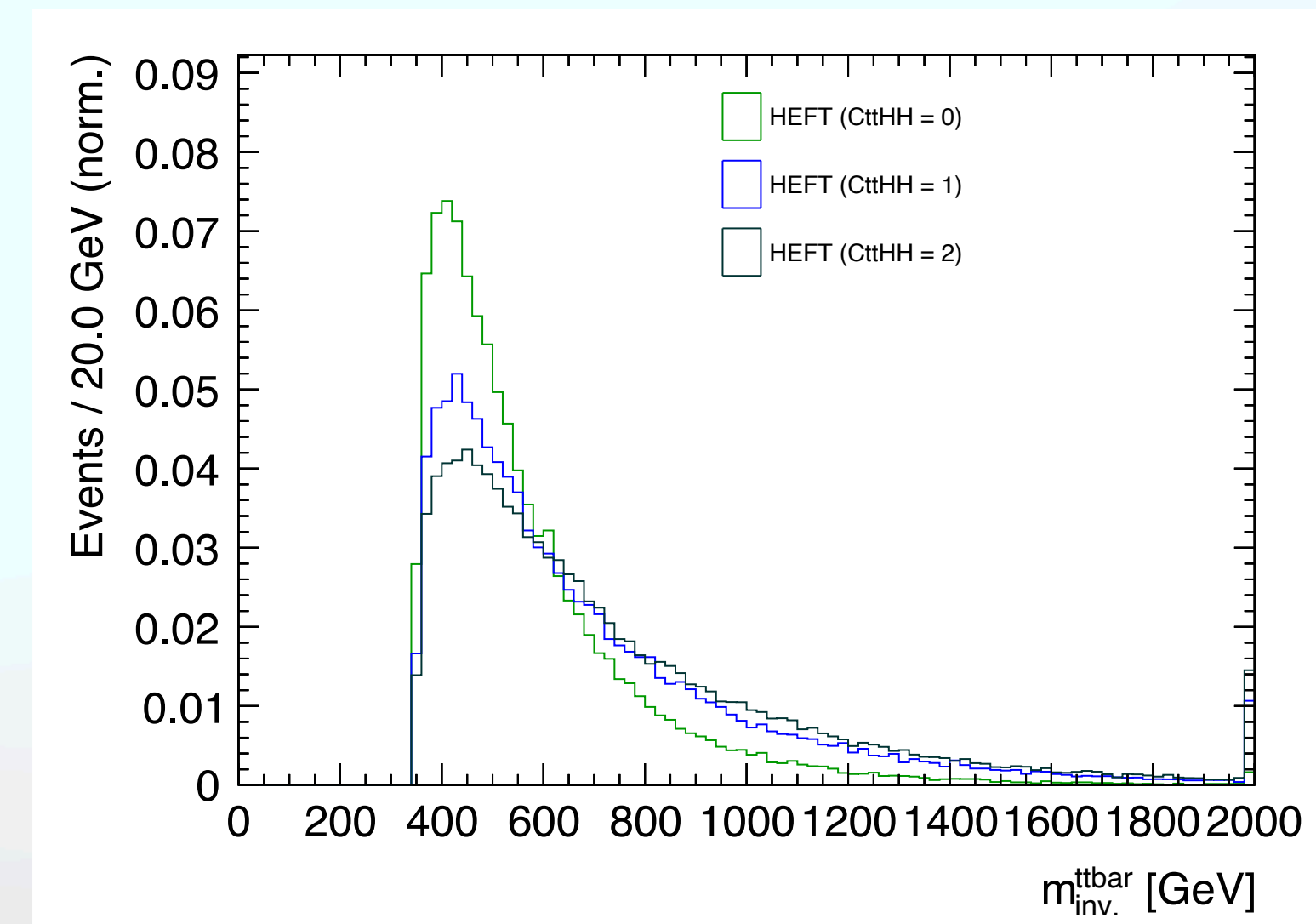
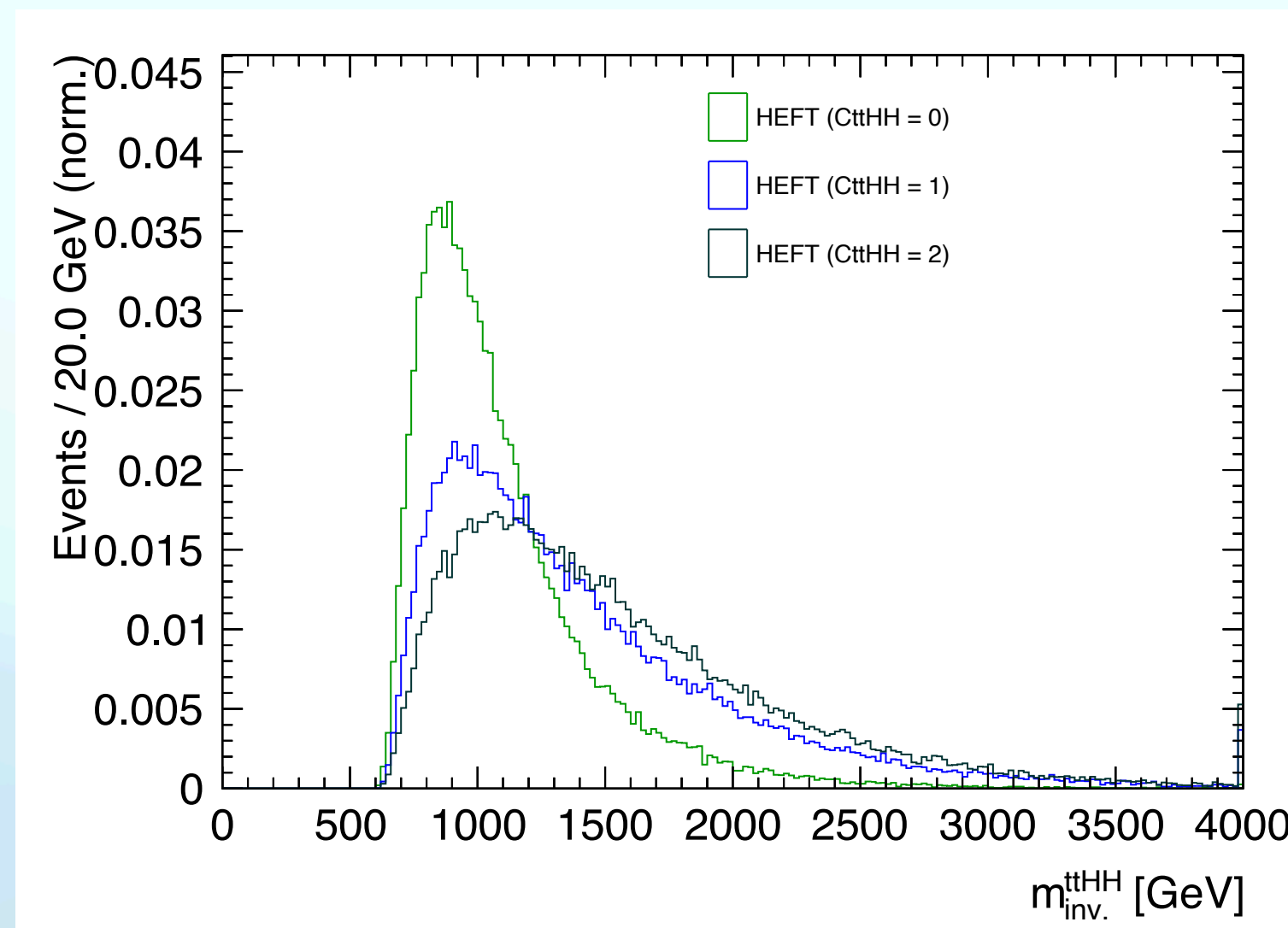


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**Or even better...**

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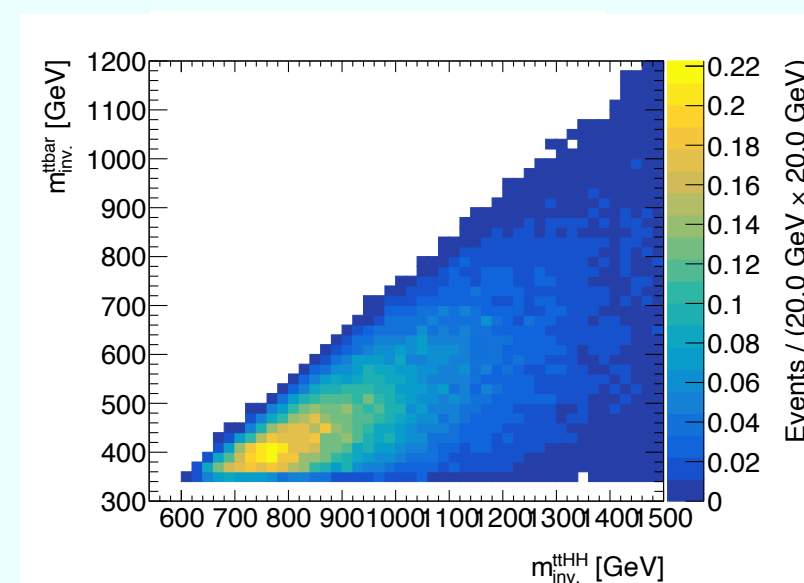
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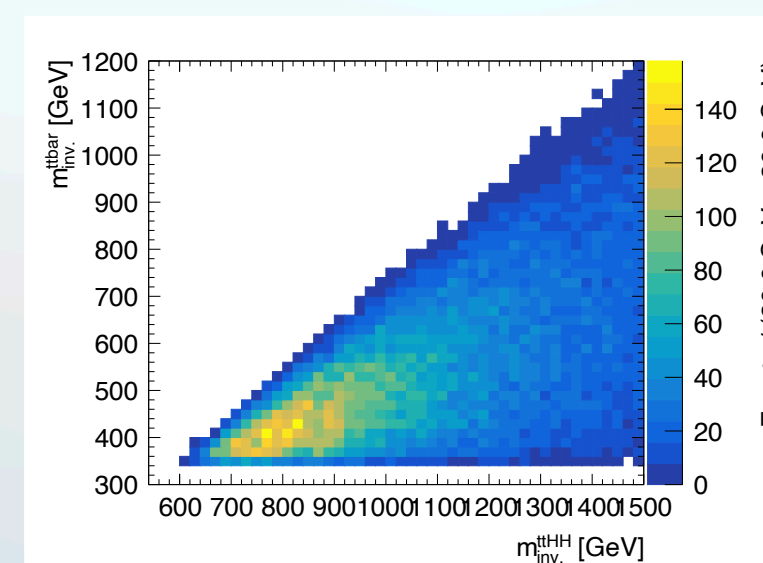
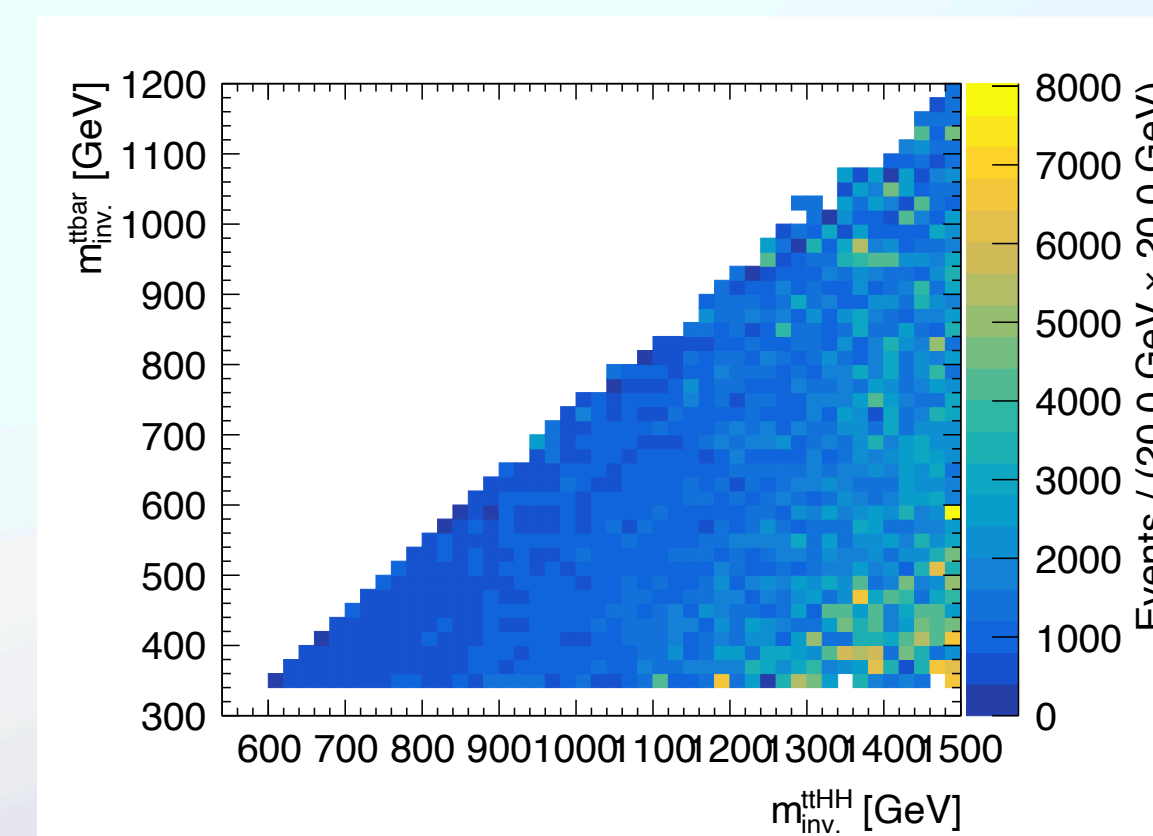
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We can take a **2D** distribution:

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



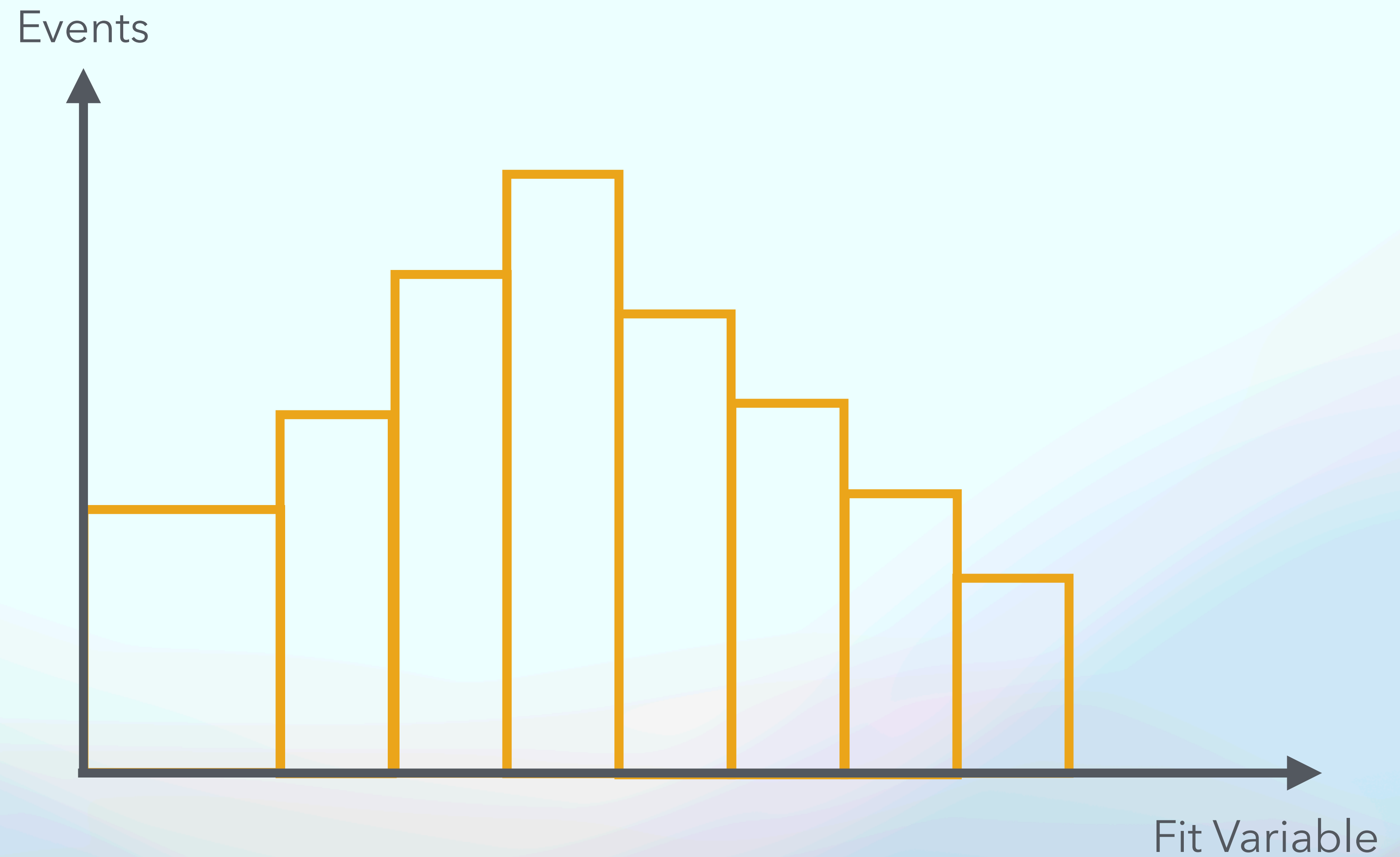
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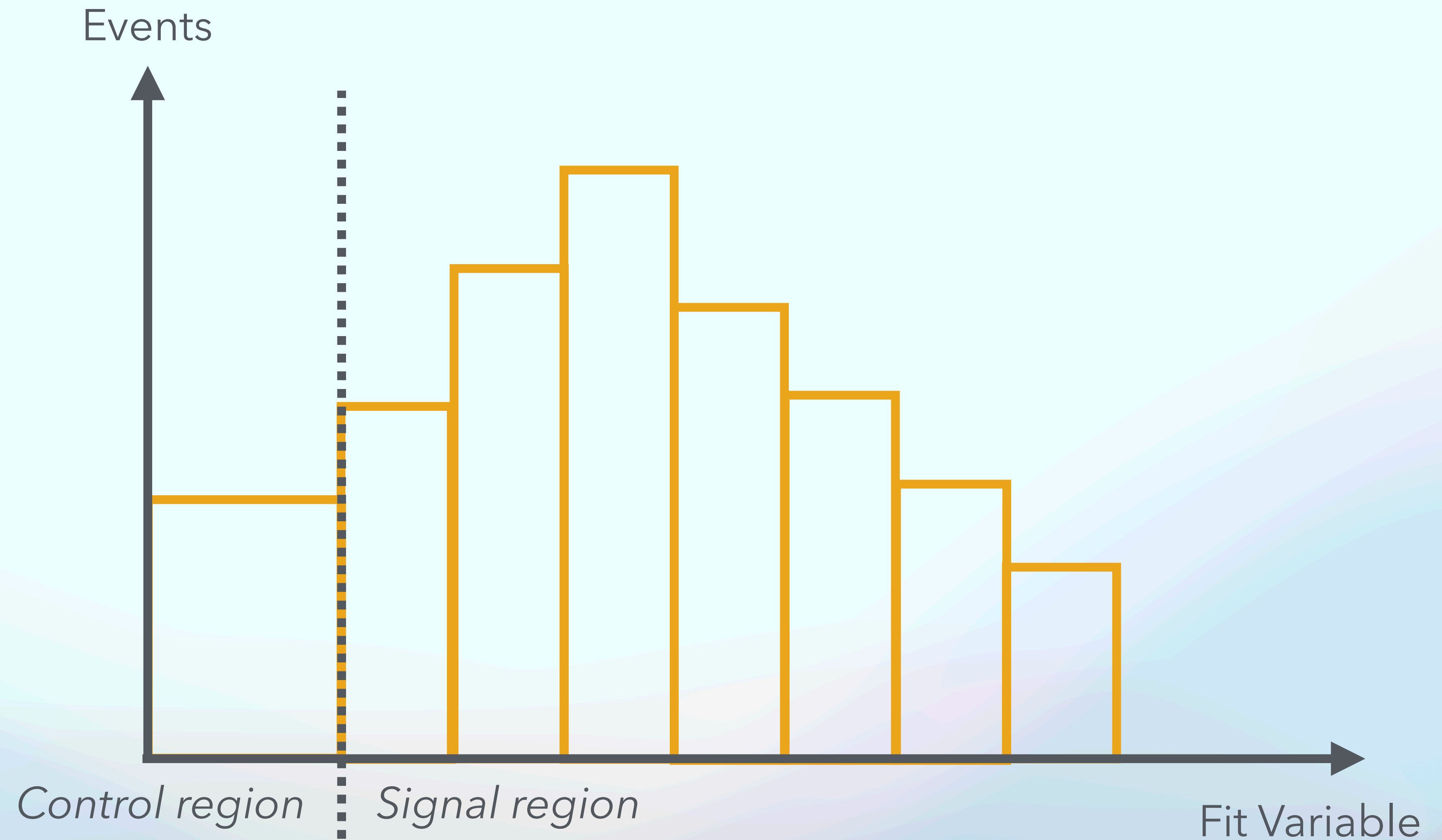
[arXiv:2502.20976](https://arxiv.org/abs/2502.20976)

answers this question in the context of ggF diHiggs

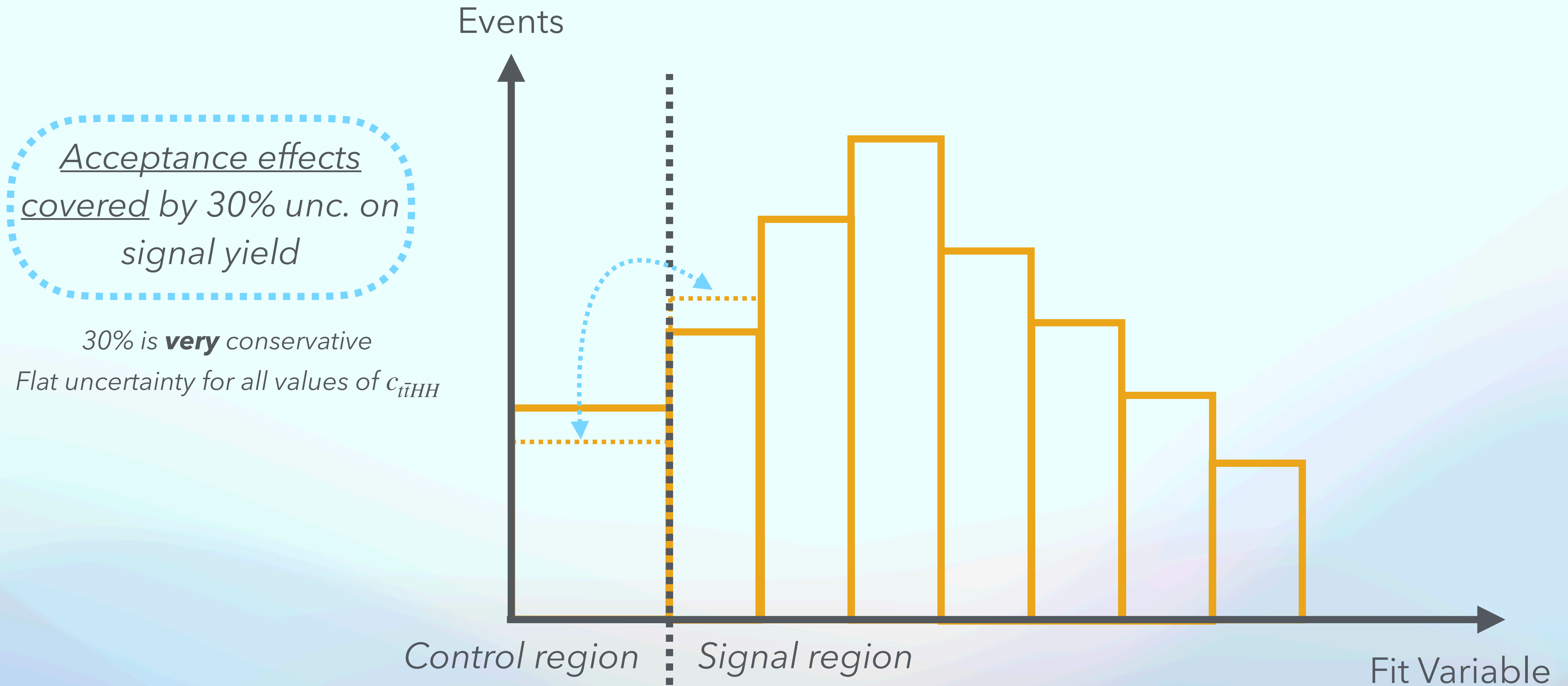
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Does the shapes have an impact on the sensitivity?

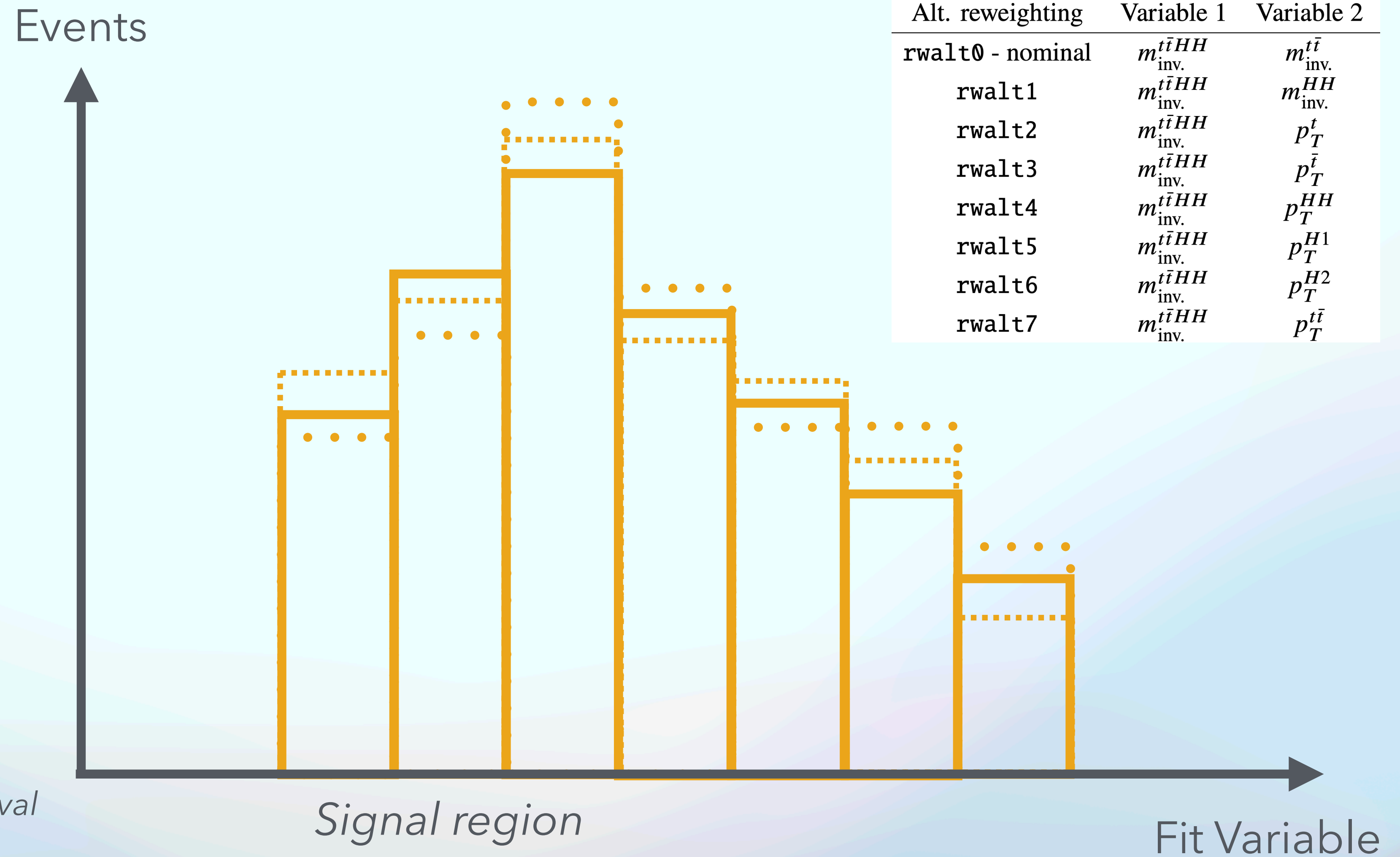


We tested 7 alternative reweightings against no shape variation



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

At most 10% impact on 95% CL interval



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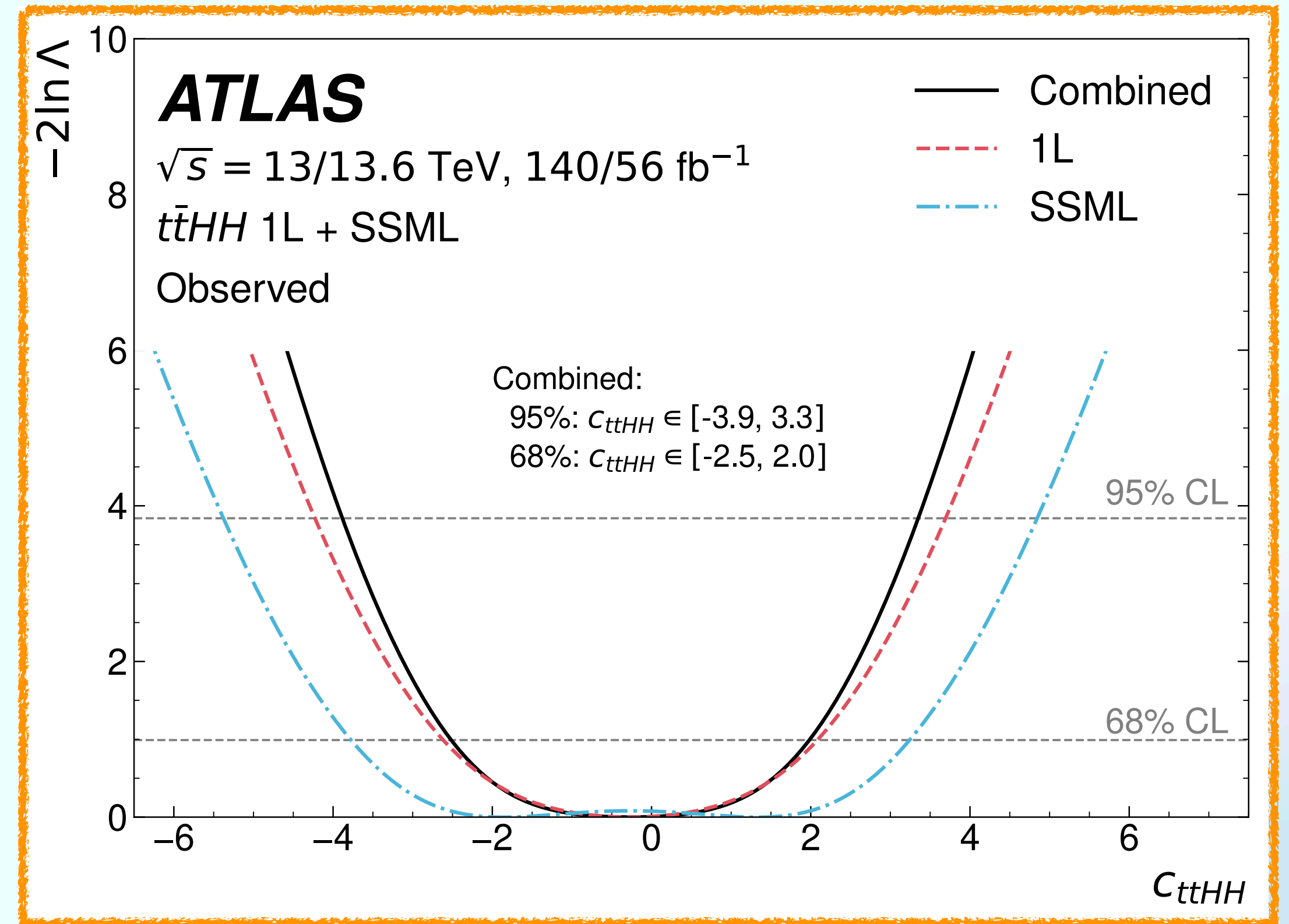
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Almost flat likelihood  
 (small degeneracy in ML channel)  
 → Not sensible to sign

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

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

# Outlook of ATLAS analysis

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→ Most stringent **direct limits** on  $c_{t\bar{t}HH}$

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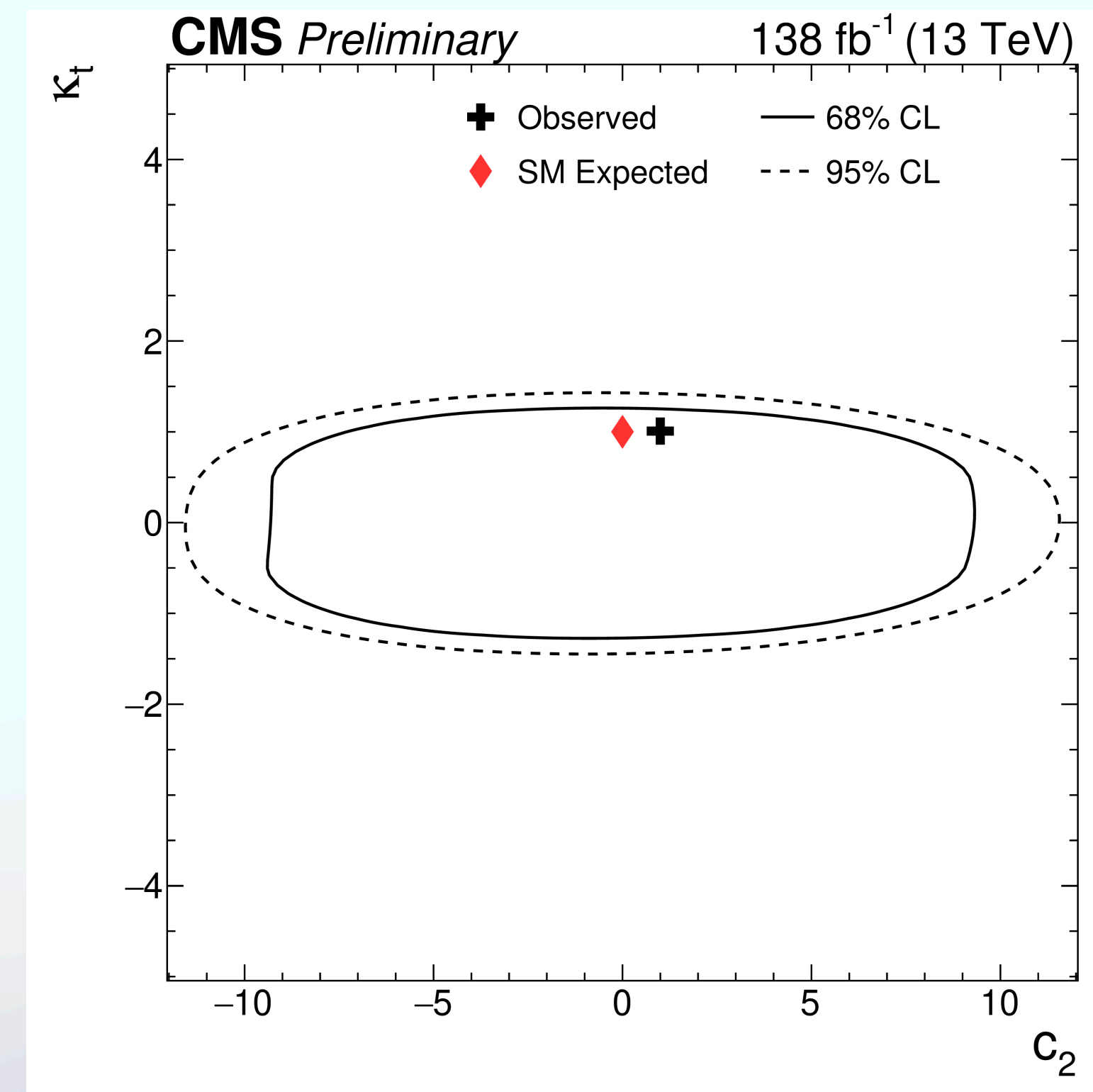
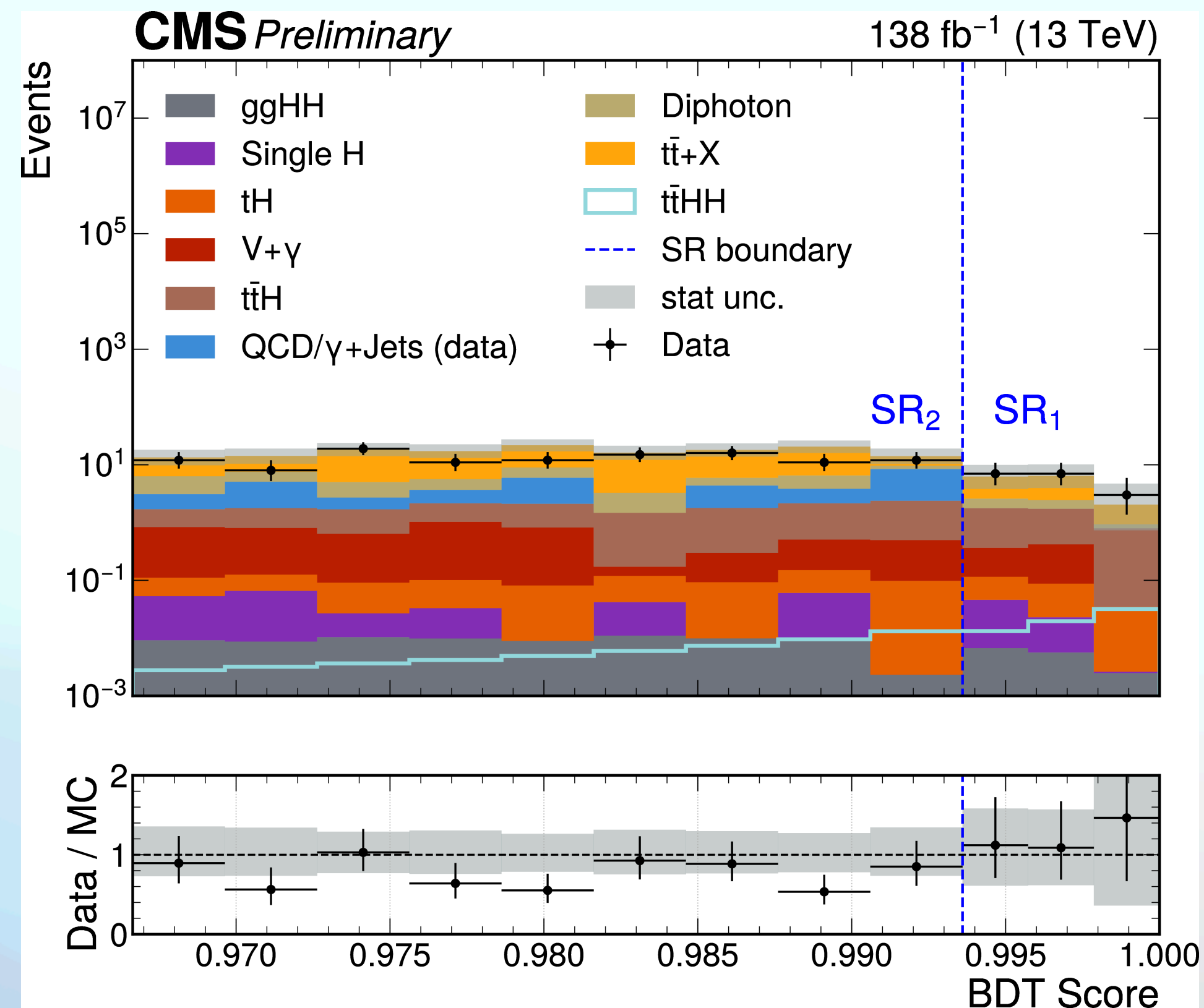
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	<b>CMS <math>t\bar{t}HH</math></b> <a href="#">[CMS-PAS-HIG-23-004]</a>
Obs. 95% CL limits on $c_{t\bar{t}HH}$	[-8.0, 7.5]

# CMS ttHH analysis (1)

CMS-PAS-HIG-23-004

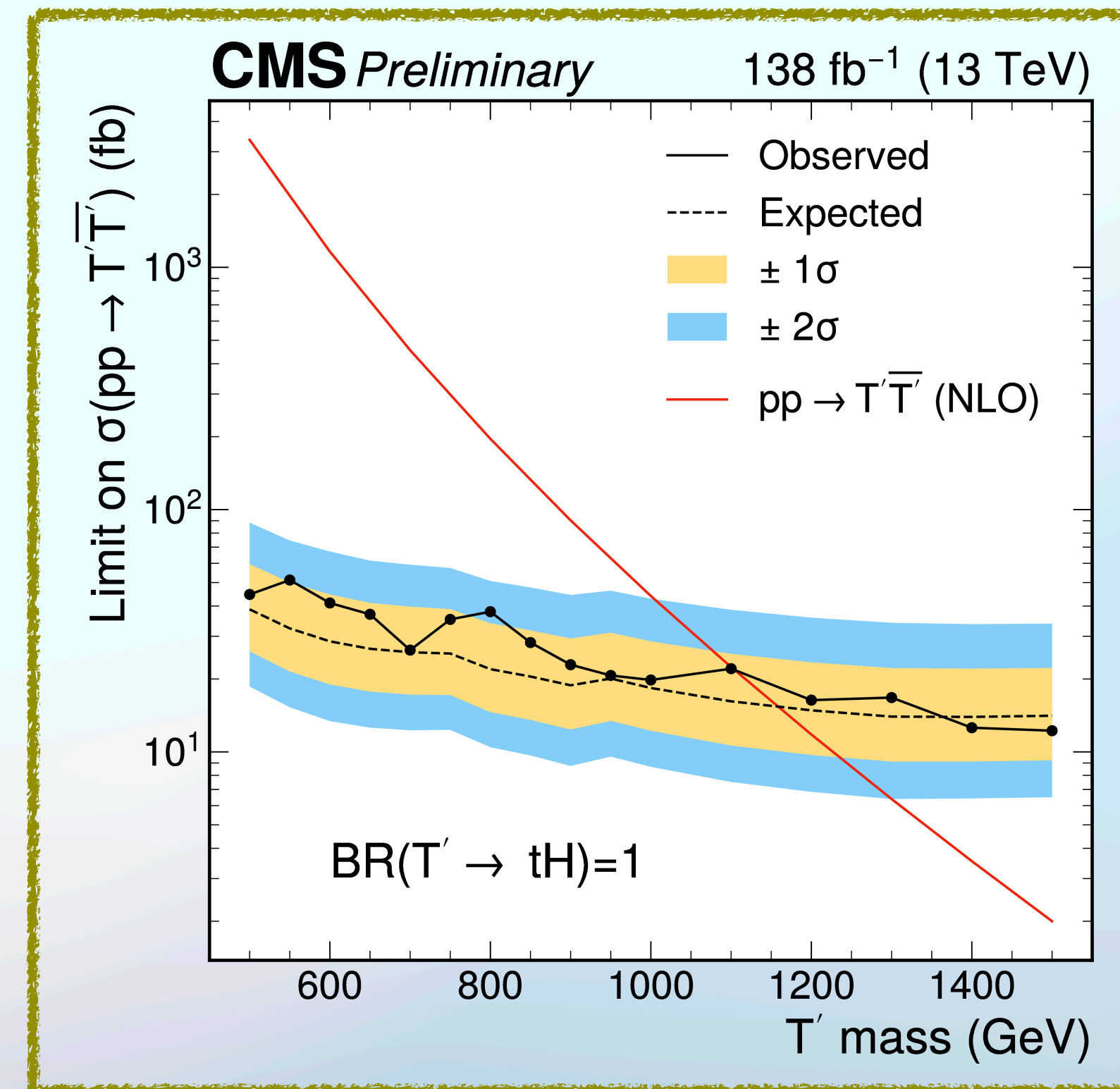
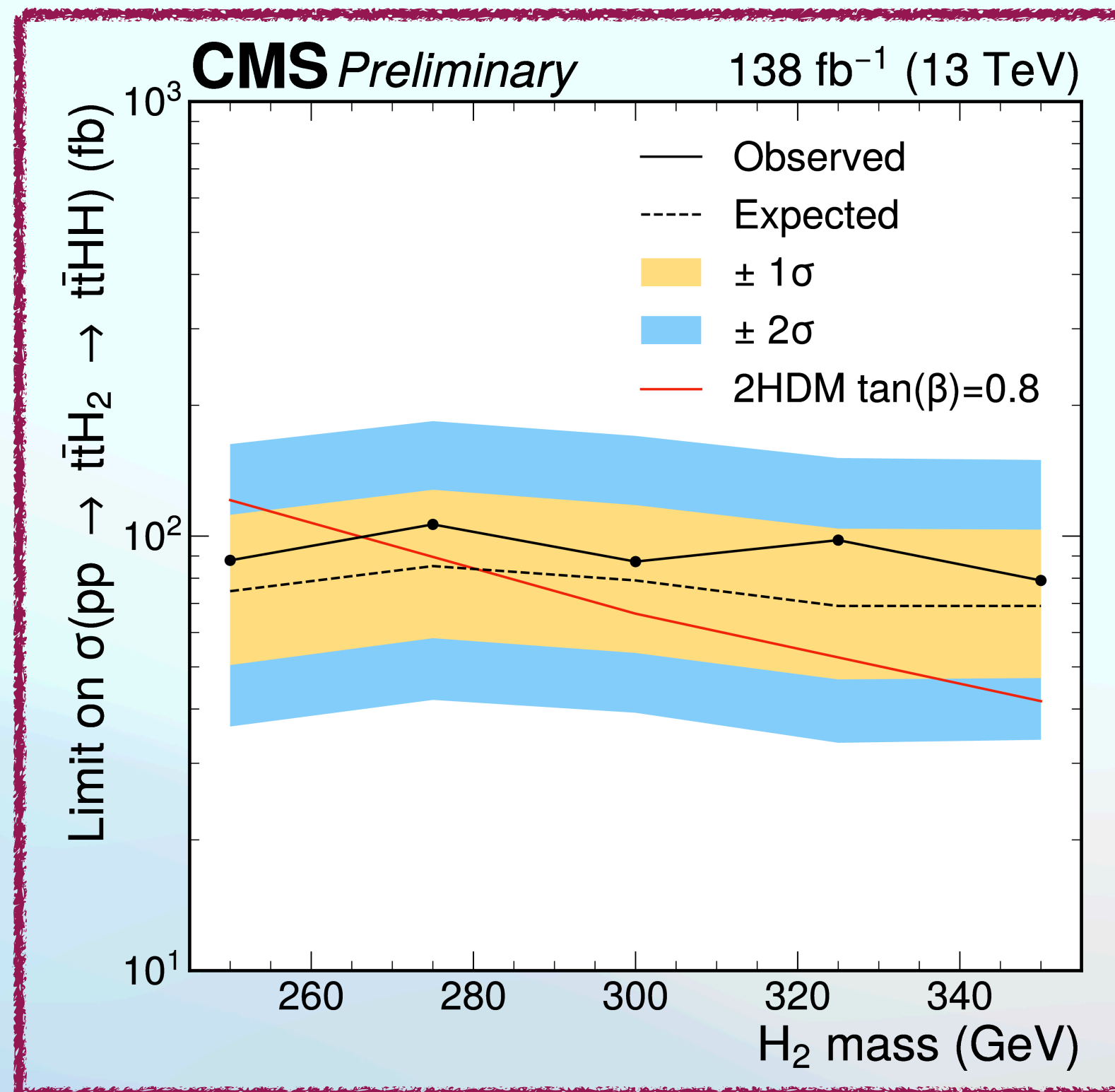
- **Targets**  $\gamma\gamma + X$  with  $X \in [b, W^\pm, \tau^\pm]$  with **Run 2 data**
- Similar modelling strategy as ATLAS (MVA discriminant)
- **Both**  $c_{t\bar{t}HH}$  and  $c_{tHH}$  probed (called resp.  $c_2$  and  $\kappa_t$ )  
*Not  $\kappa_\lambda...$*



# 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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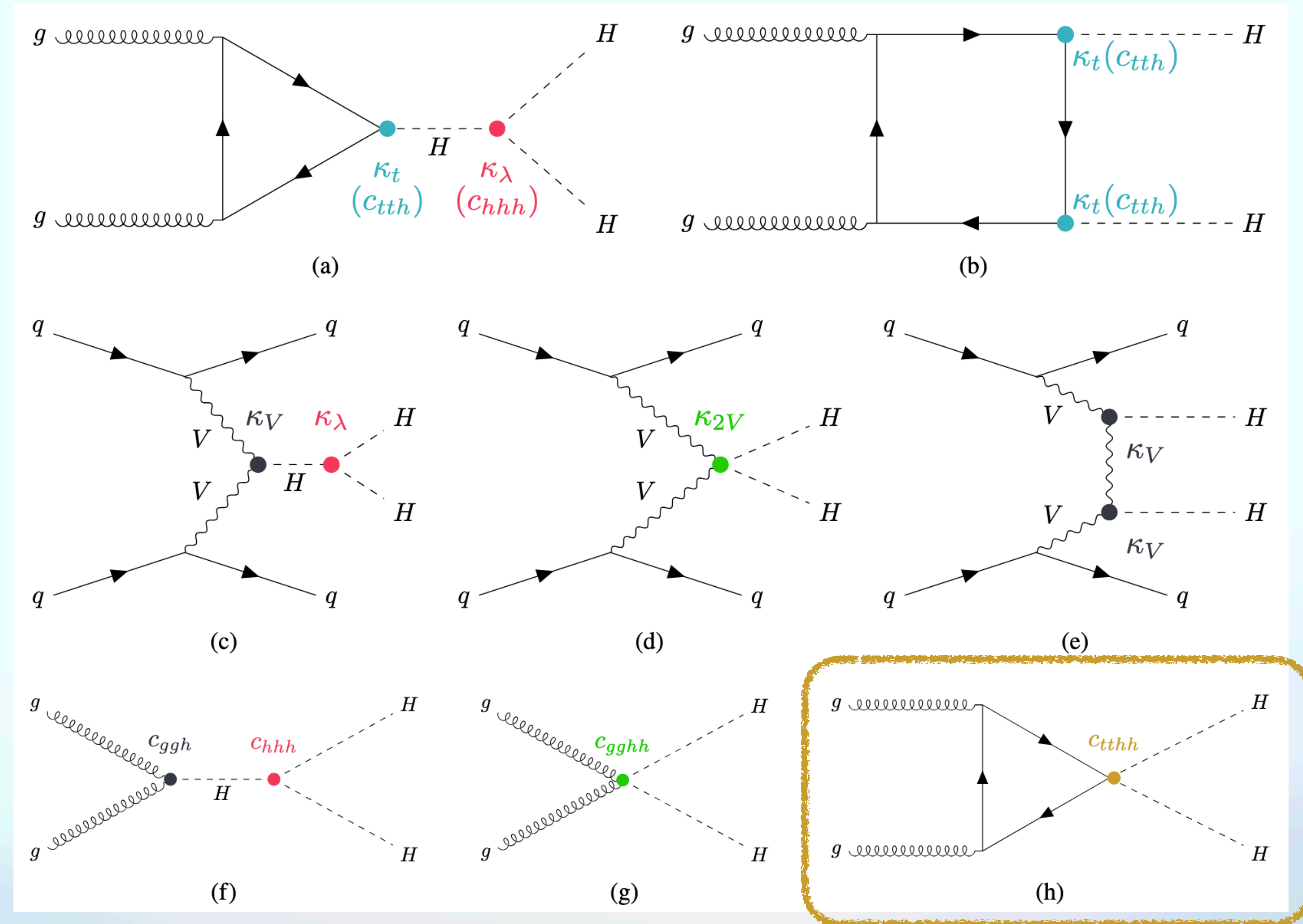
# Outlook of ATLAS analysis

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

- **First search** for  $t\bar{t}HH$  done by ATLAS  
→ Most stringent **direct limits** on  $c_{t\bar{t}HH}$

	<b>CMS <math>t\bar{t}HH</math></b> <small>[CMS-PAS-HIG-23-004]</small>	<b>ATLAS HH comb.</b> <small>[arXiv:2406.09971]</small>	<b>CMS HH comb.</b> <small>[arXiv:2510.07527]</small>
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

	<b>CMS <math>t\bar{t}HH</math></b> <small>[CMS-PAS-HIG-23-004]</small>	<b>ATLAS HH comb.</b> <small>[arXiv:2406.09971]</small>	<b>CMS HH comb.</b> <small>[arXiv:2510.07527]</small>
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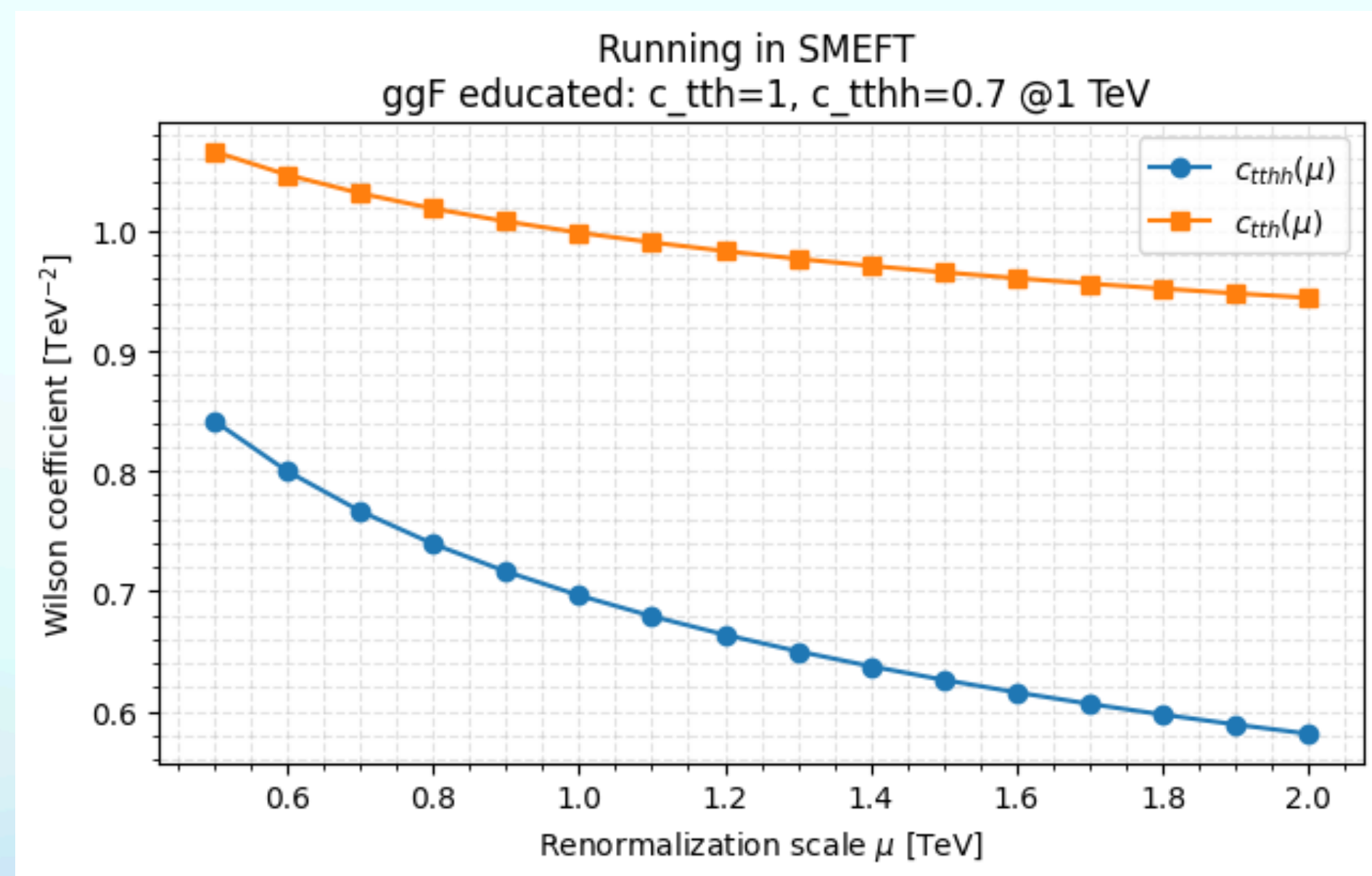
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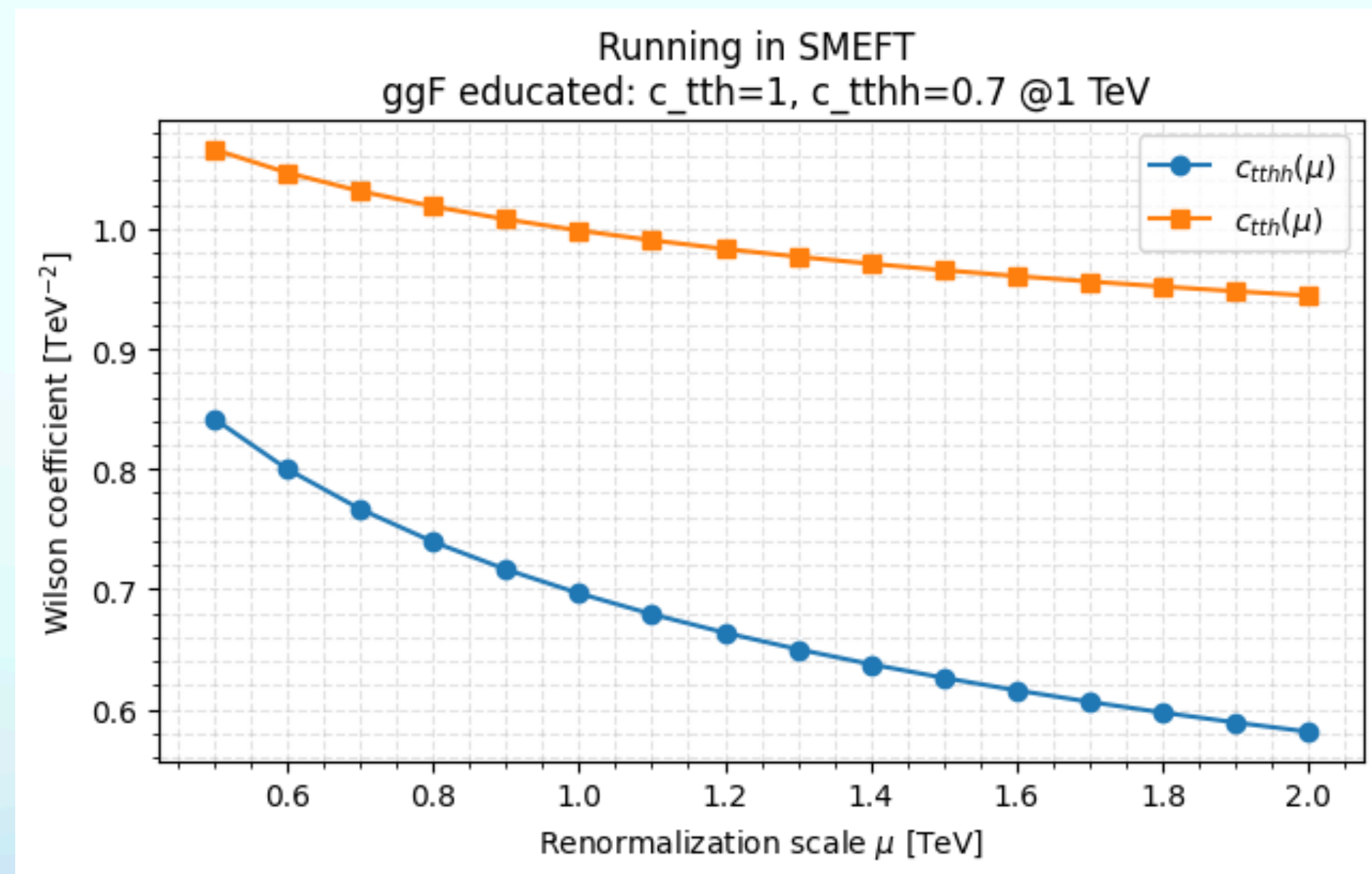
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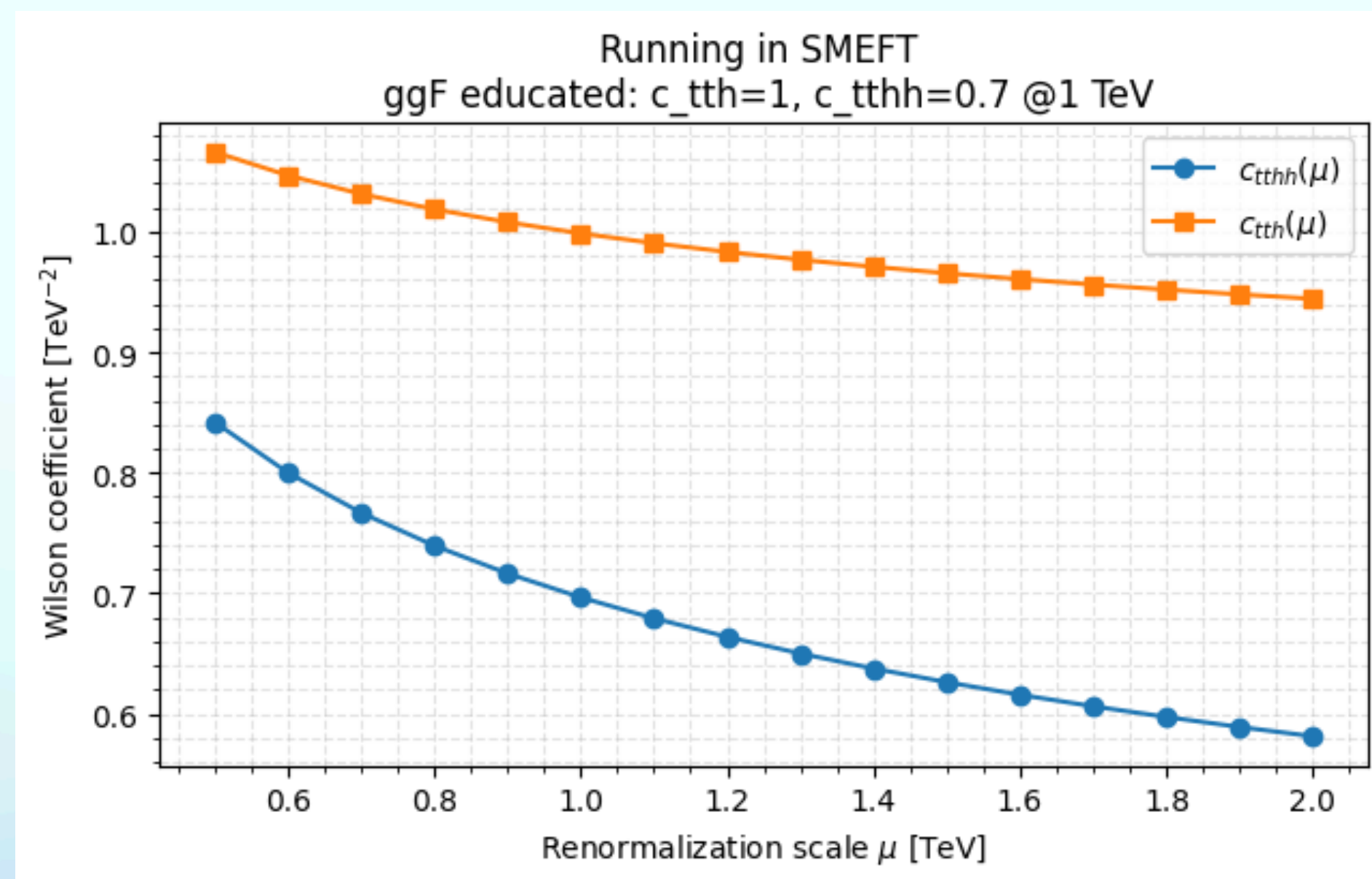
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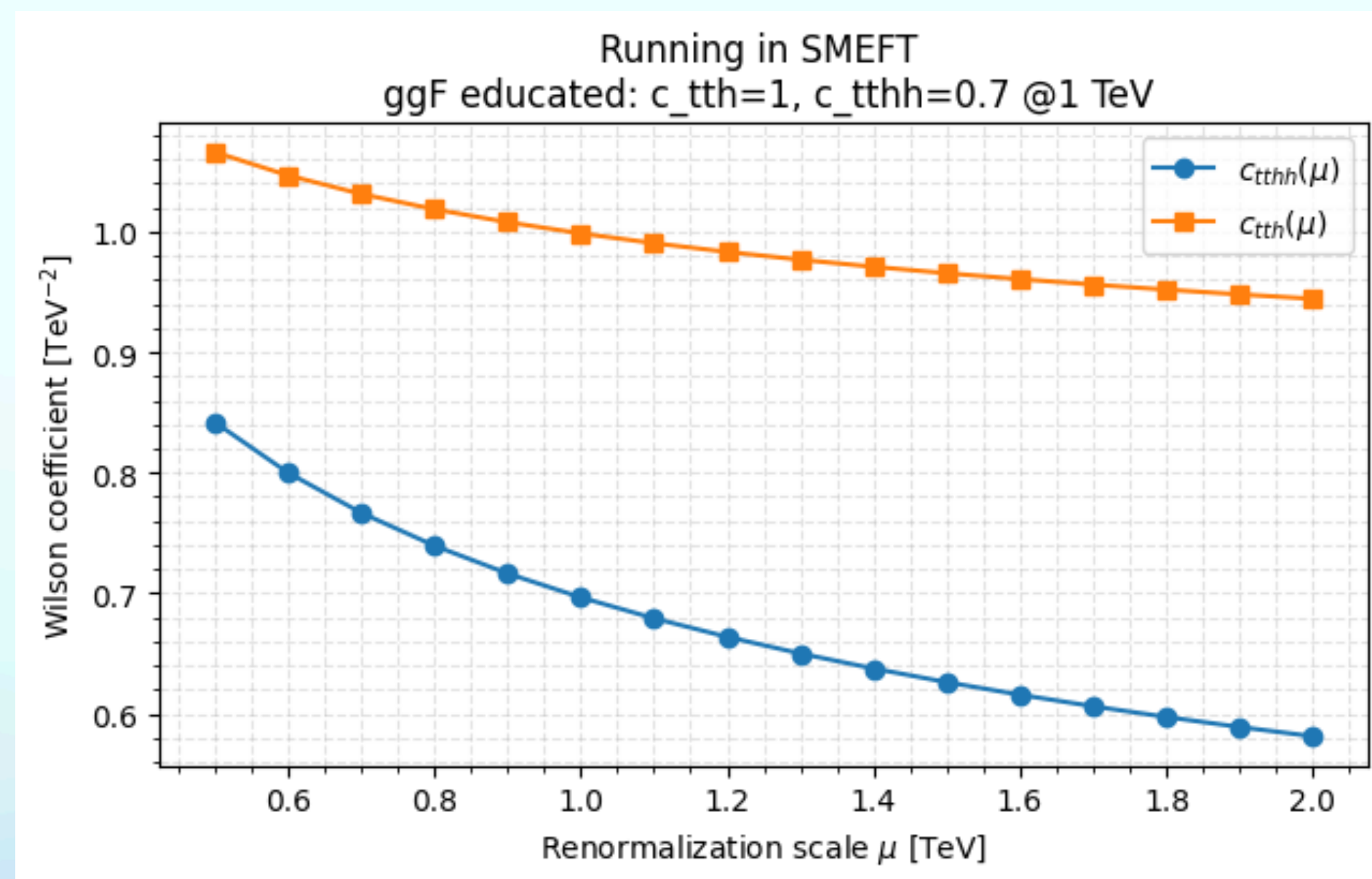
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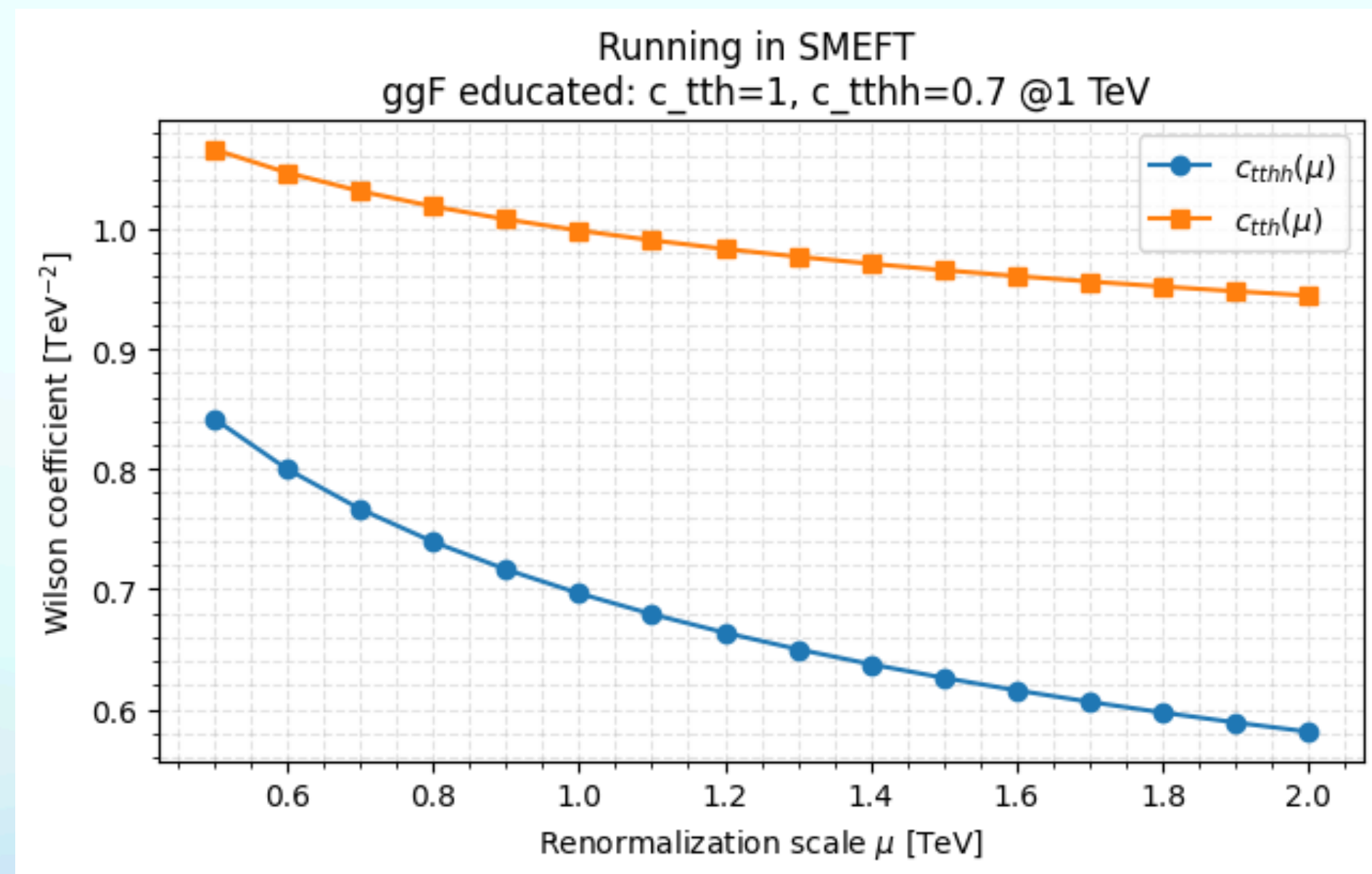
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Is this running valid? → proper implementation of HEFT running needed  
*probably not*

Conclusion

# Thoughts for the future



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

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

→ Factor  $\sim 2$  of size of 95%CL interval by the end of Run 4



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- *Higher order effects* to be taken into account (running of the coeffs)
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*What UV model have different predictions in both frameworks?*

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



Thank you!



Backup

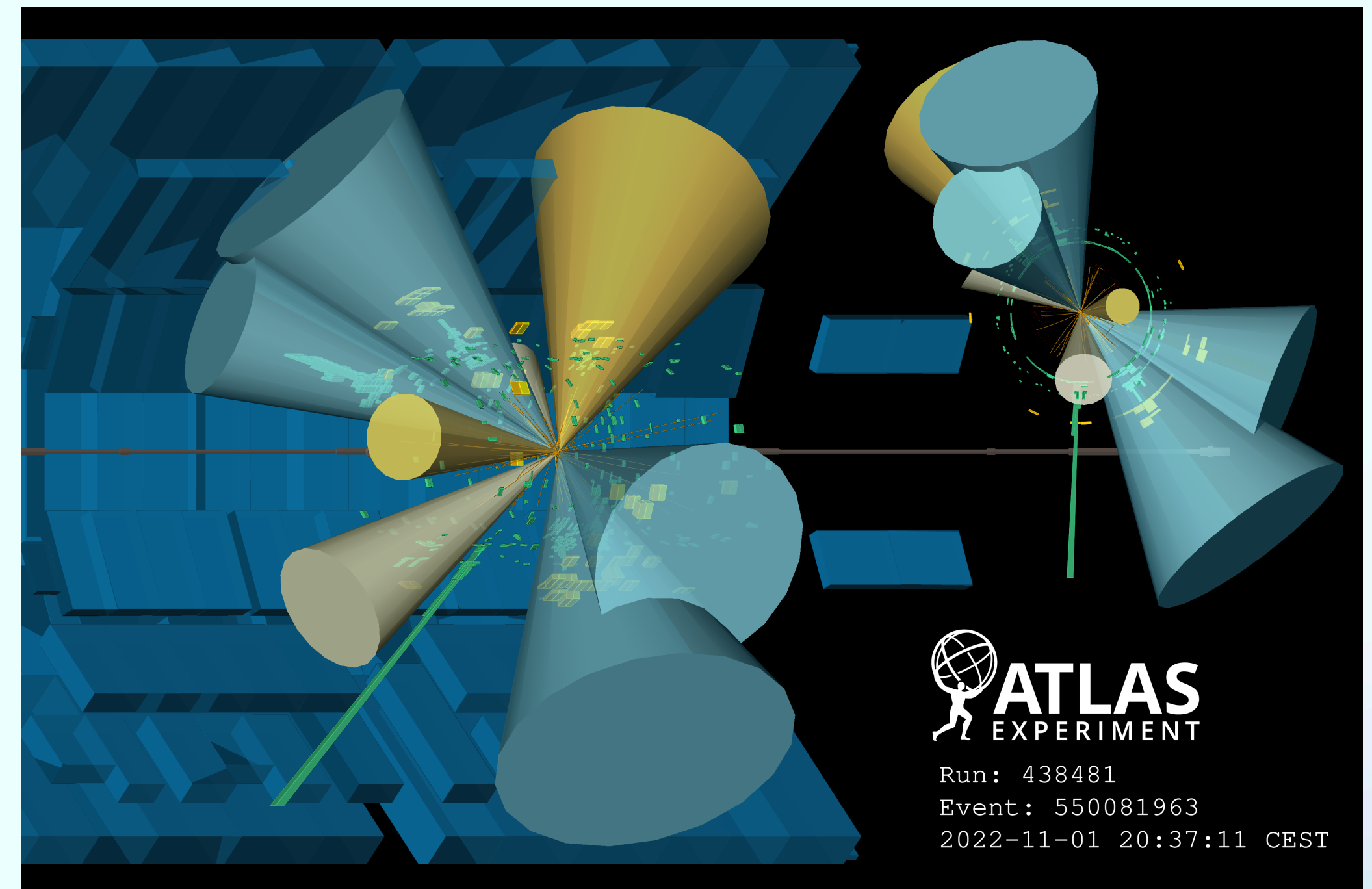
# Single-lepton channel

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

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

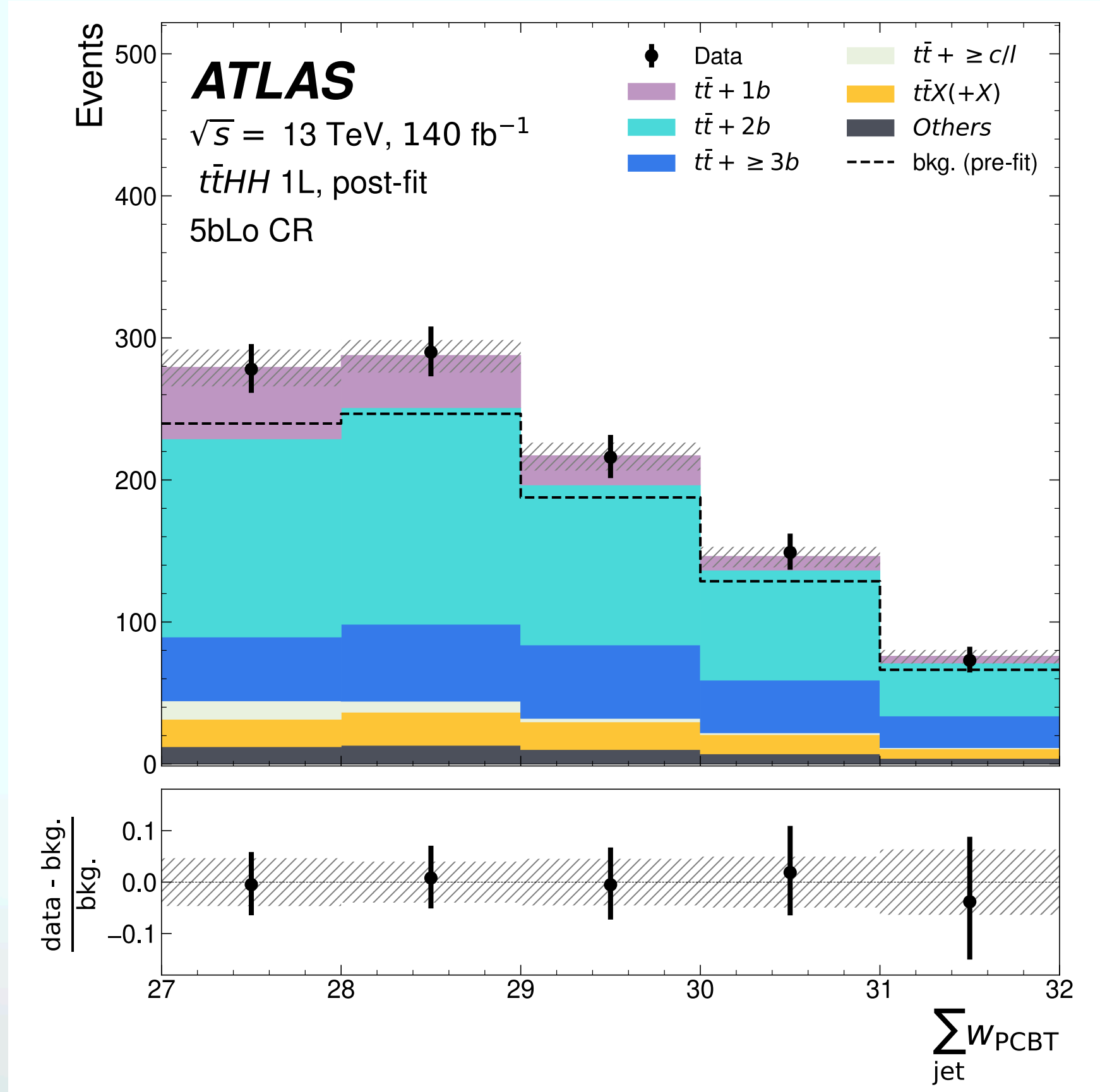
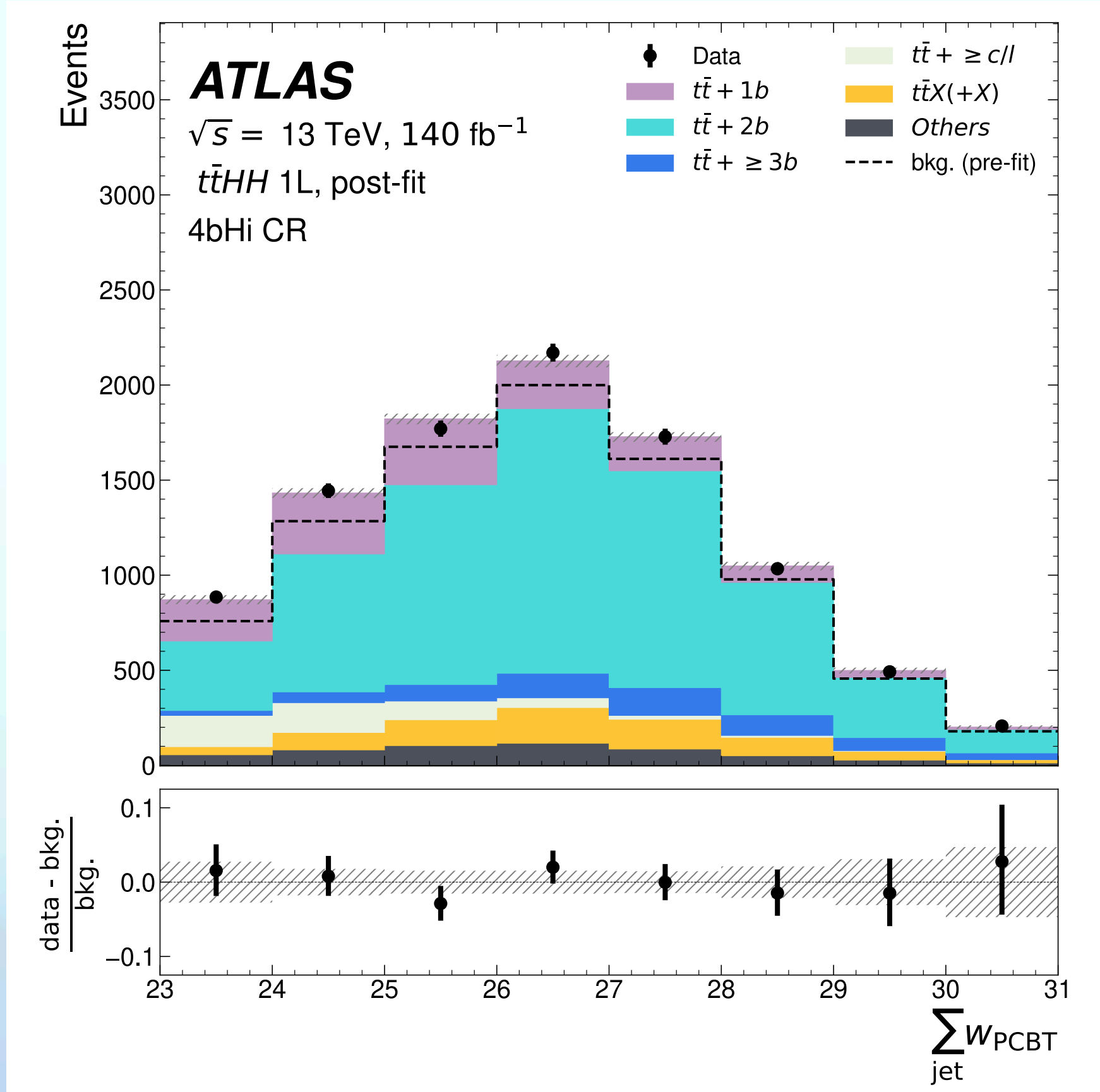
Signal / Background split by jet-multiplicity

Fit from a GNN score



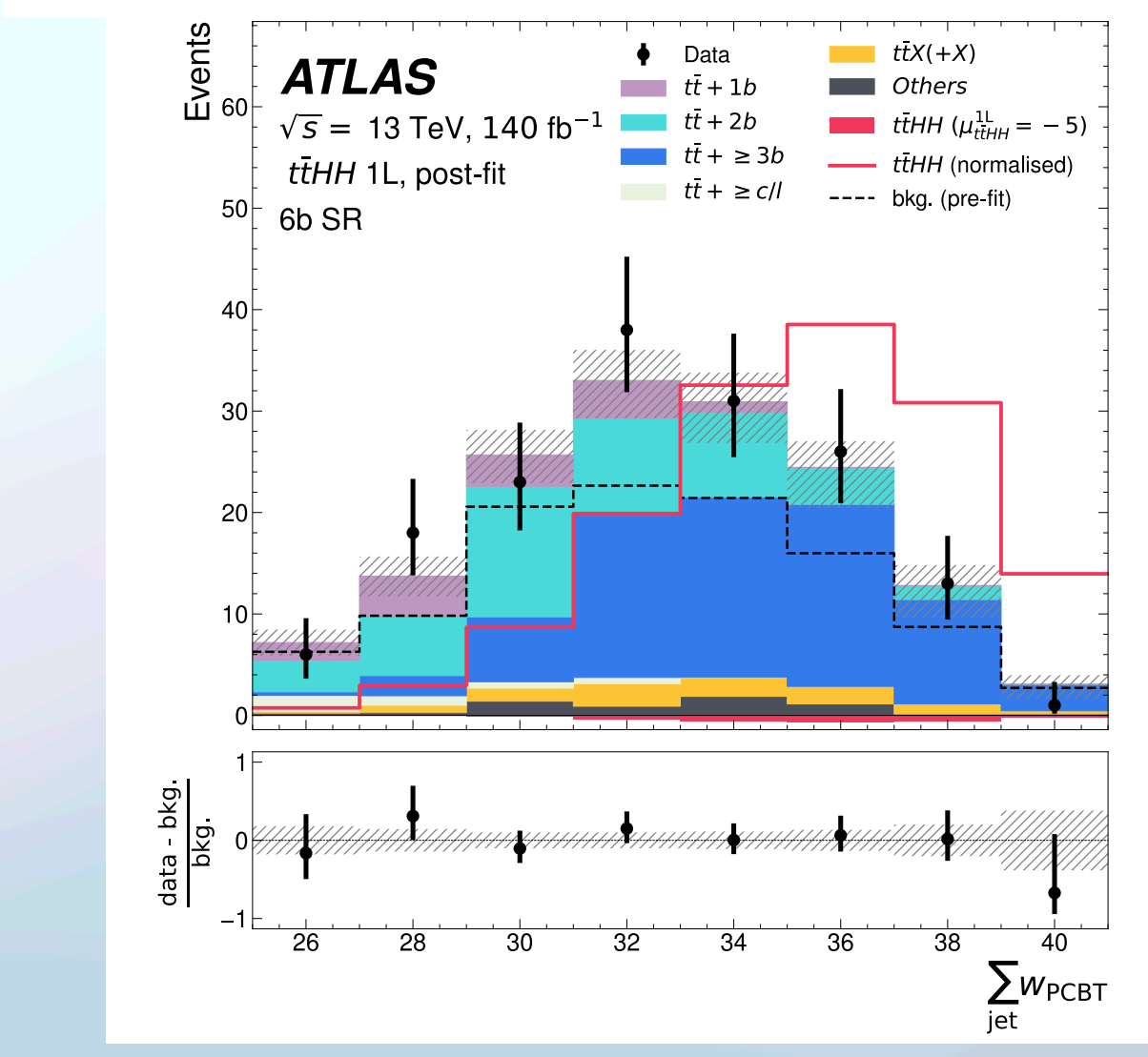
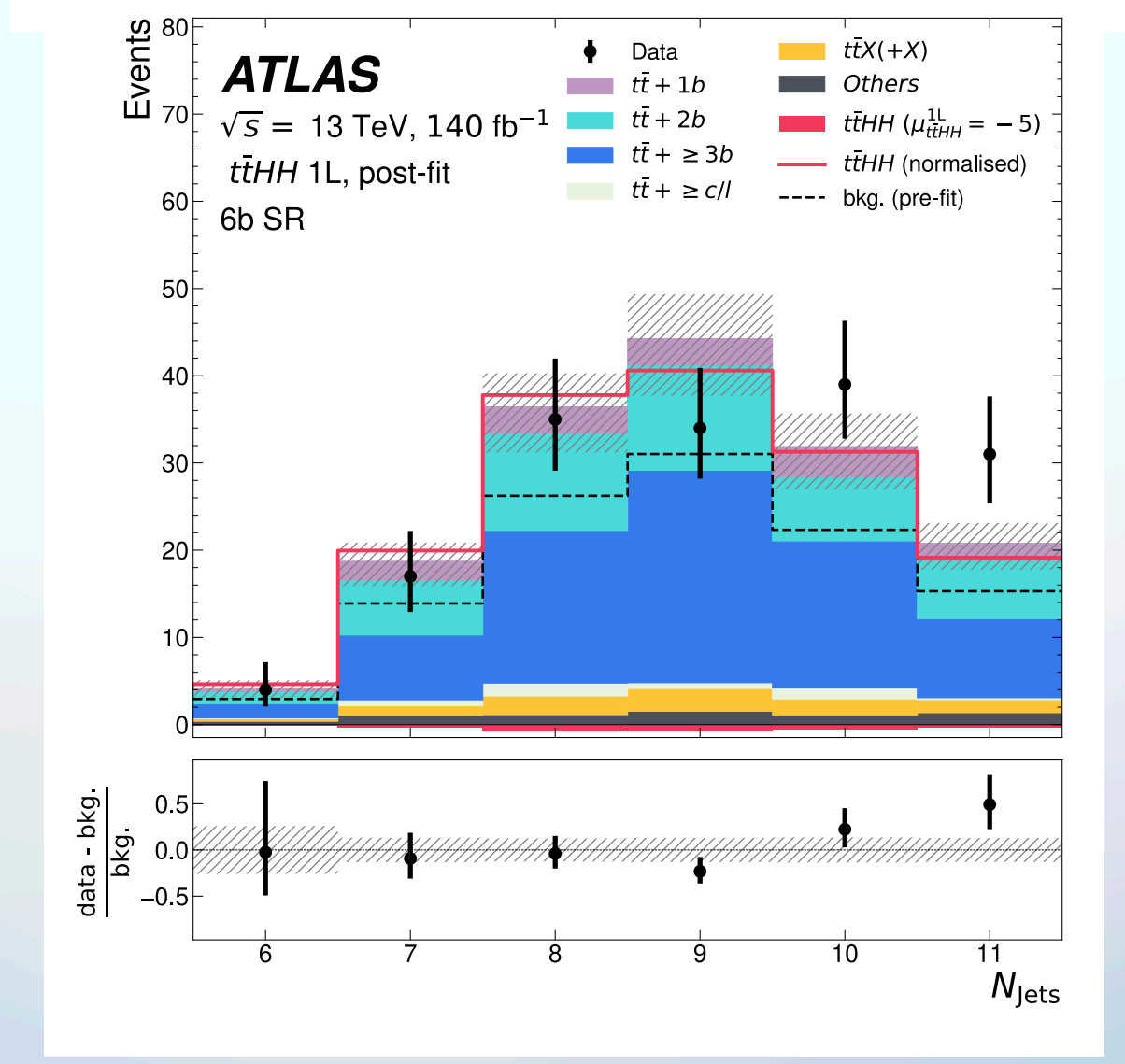
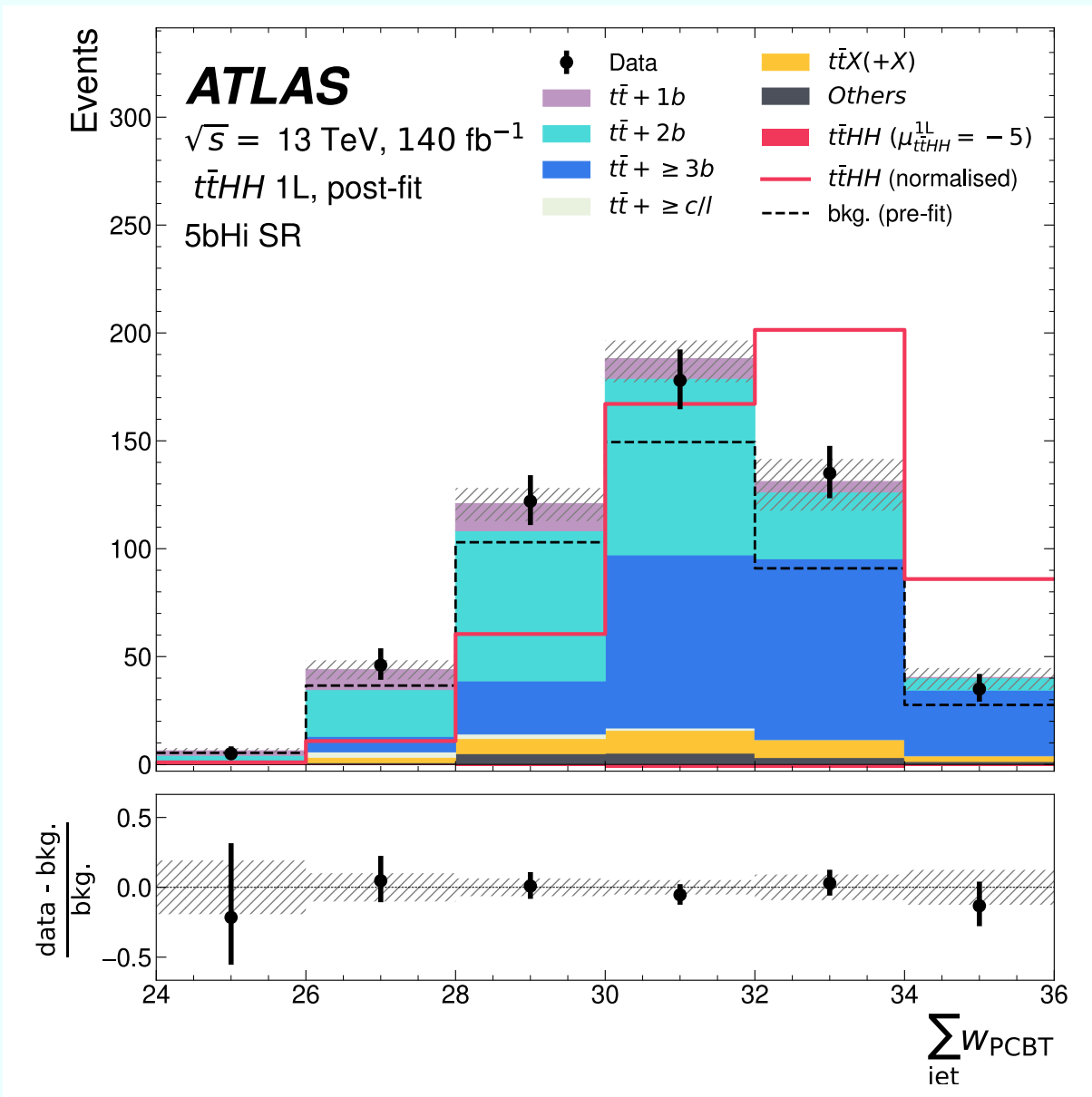
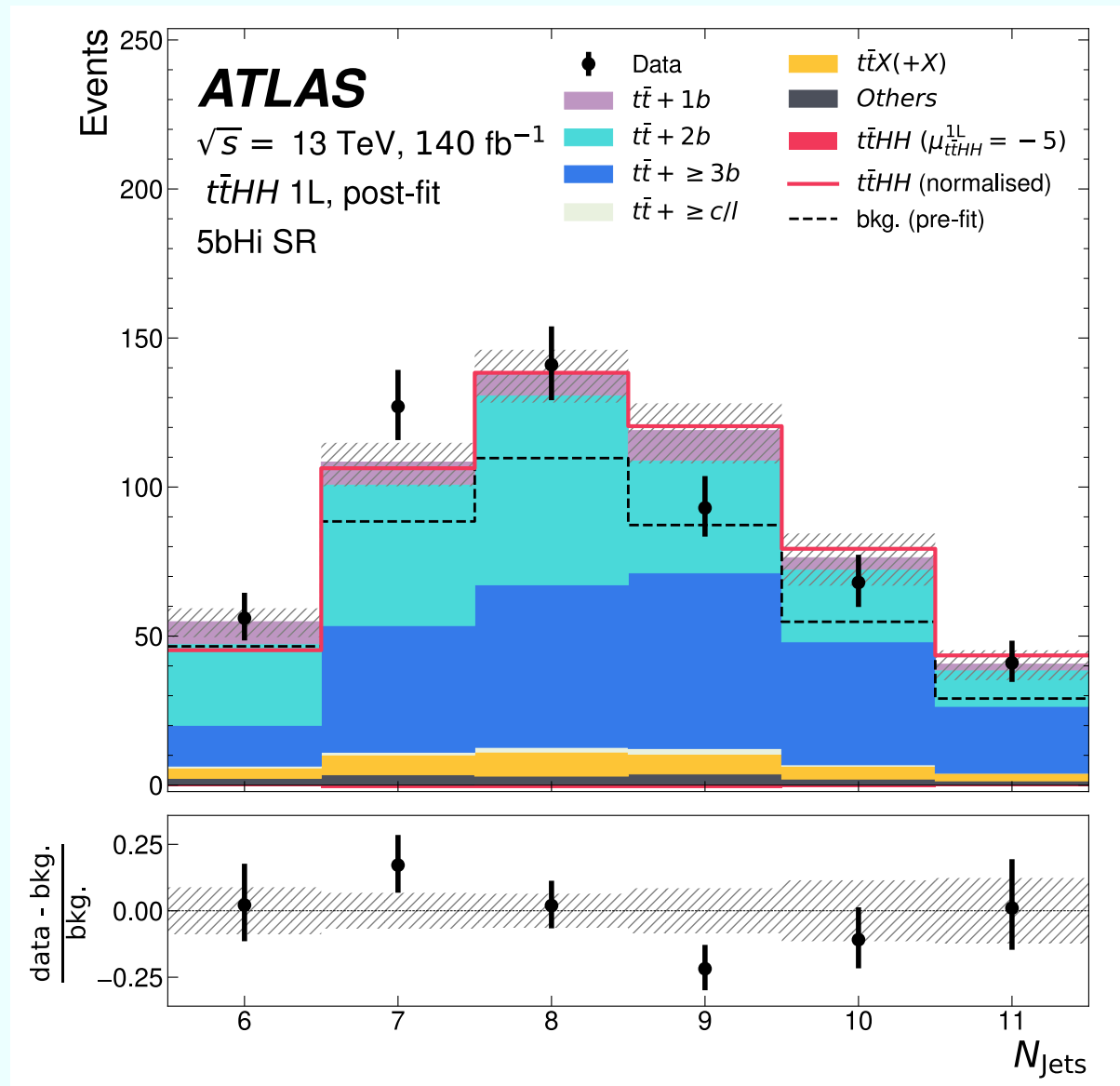
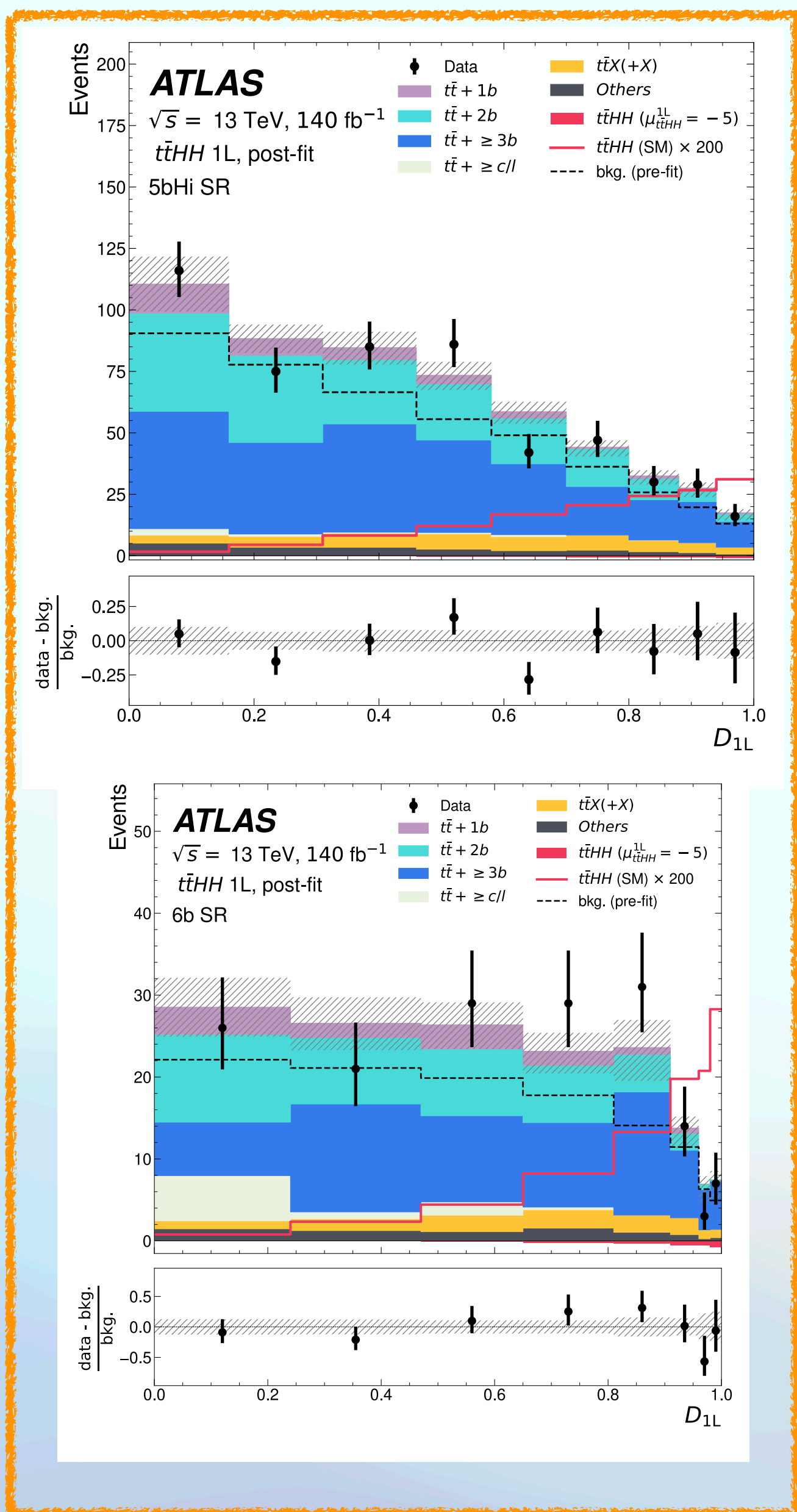
Variable	Description
$(p_T, \eta, \phi, E)$	Kinematic variables of the object, i.e. transverse momentum, pseudorapidity, azimuthal angle, and energy.
$w_{GN2}$	GN201 b-tagging pseudo-continuous score for identifying jets. Non-jet objects are assigned a value of zero.
$q_{Lep.}$	Charge of the object. 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

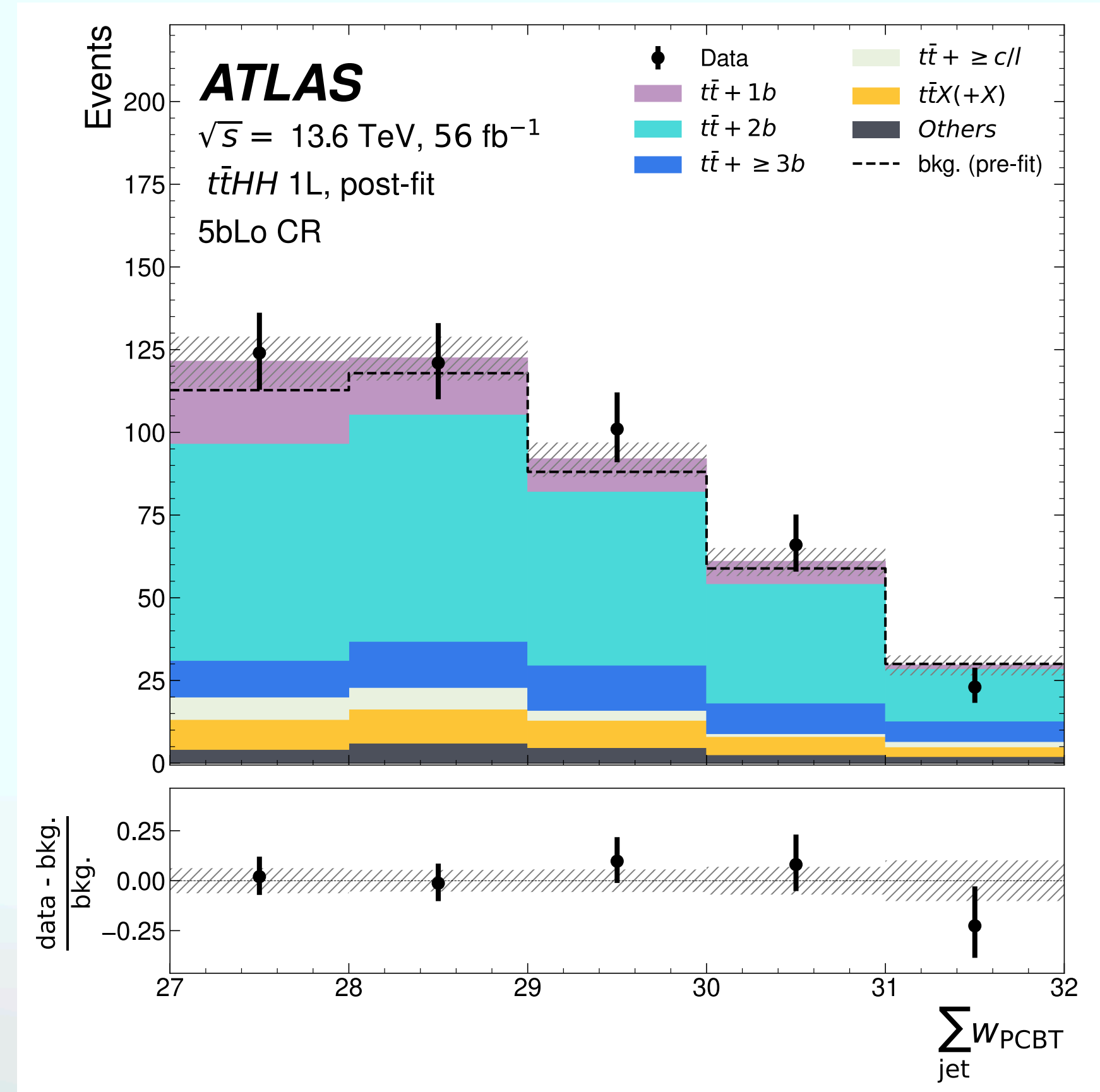
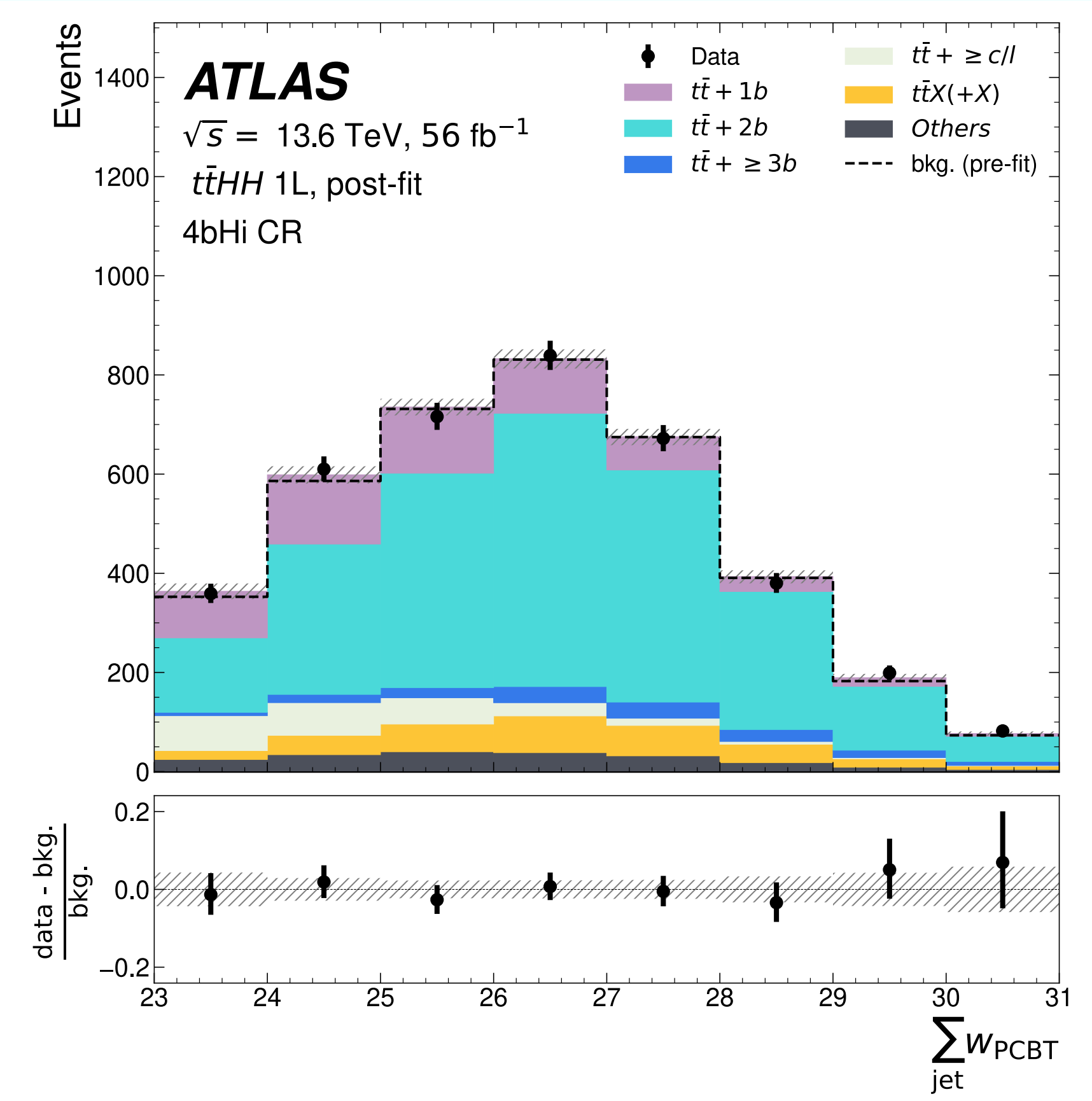


- Signal defined by jet multiplicity
- Well understood background

# 1L Run 2 SR distributions

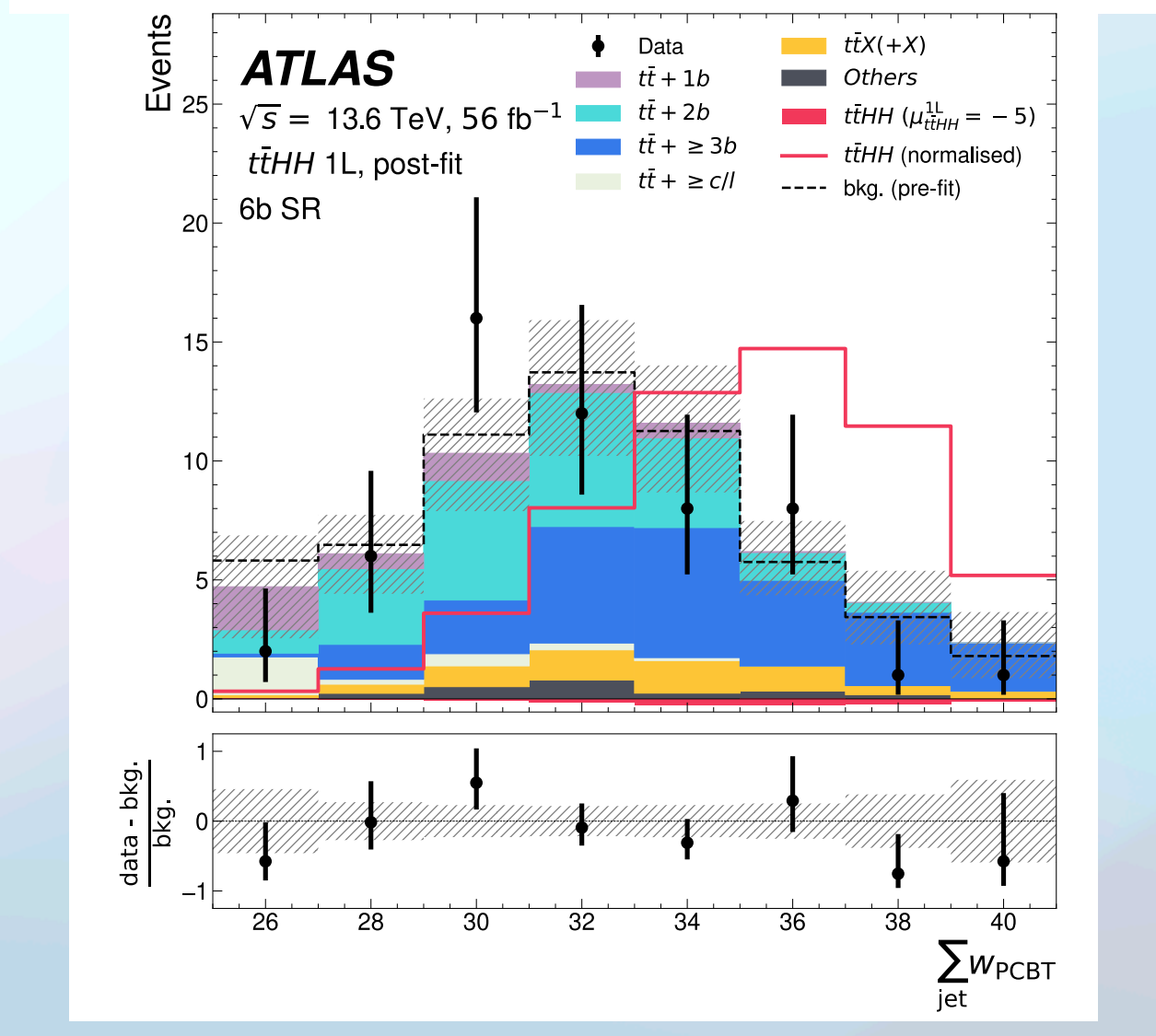
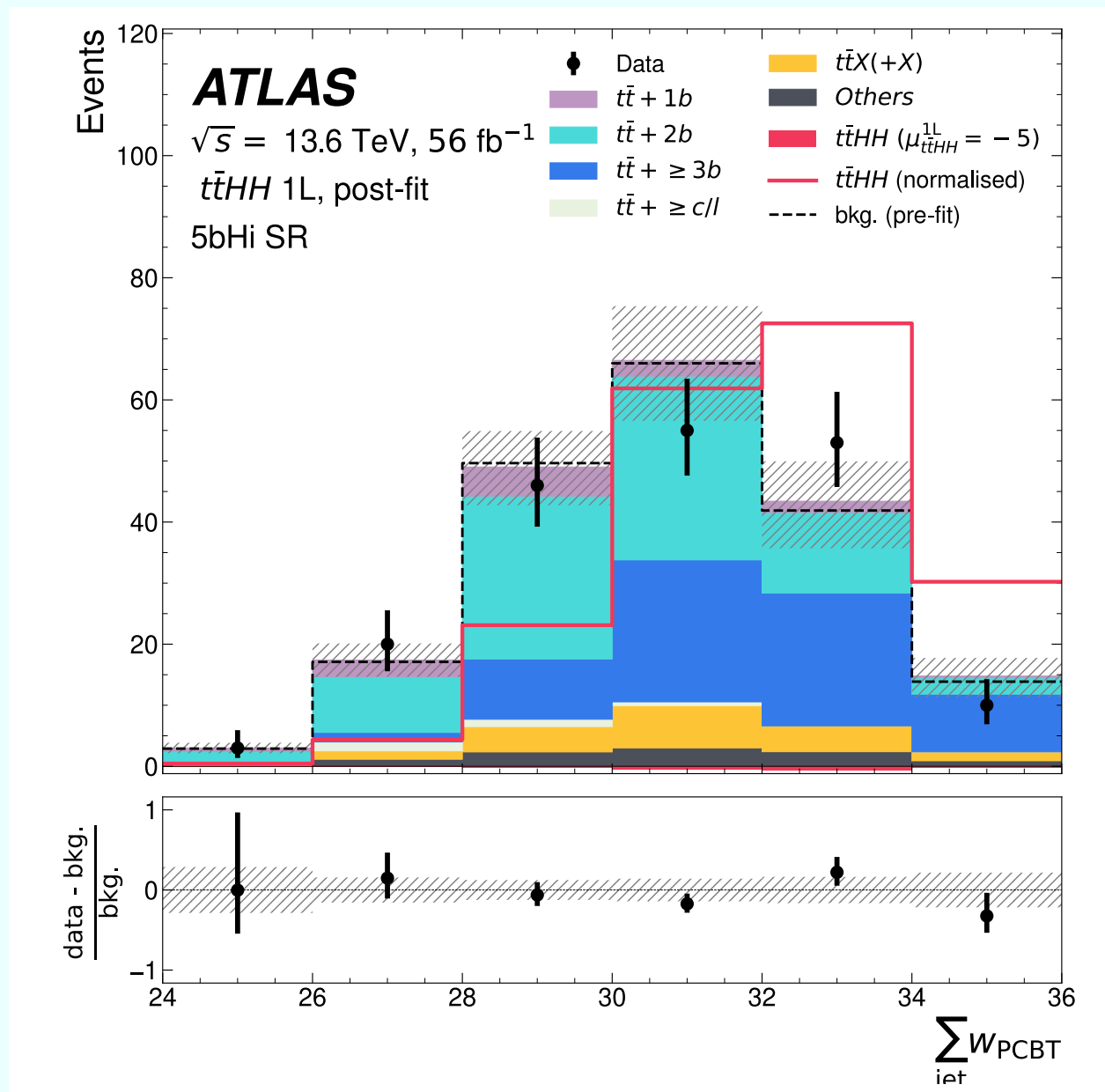
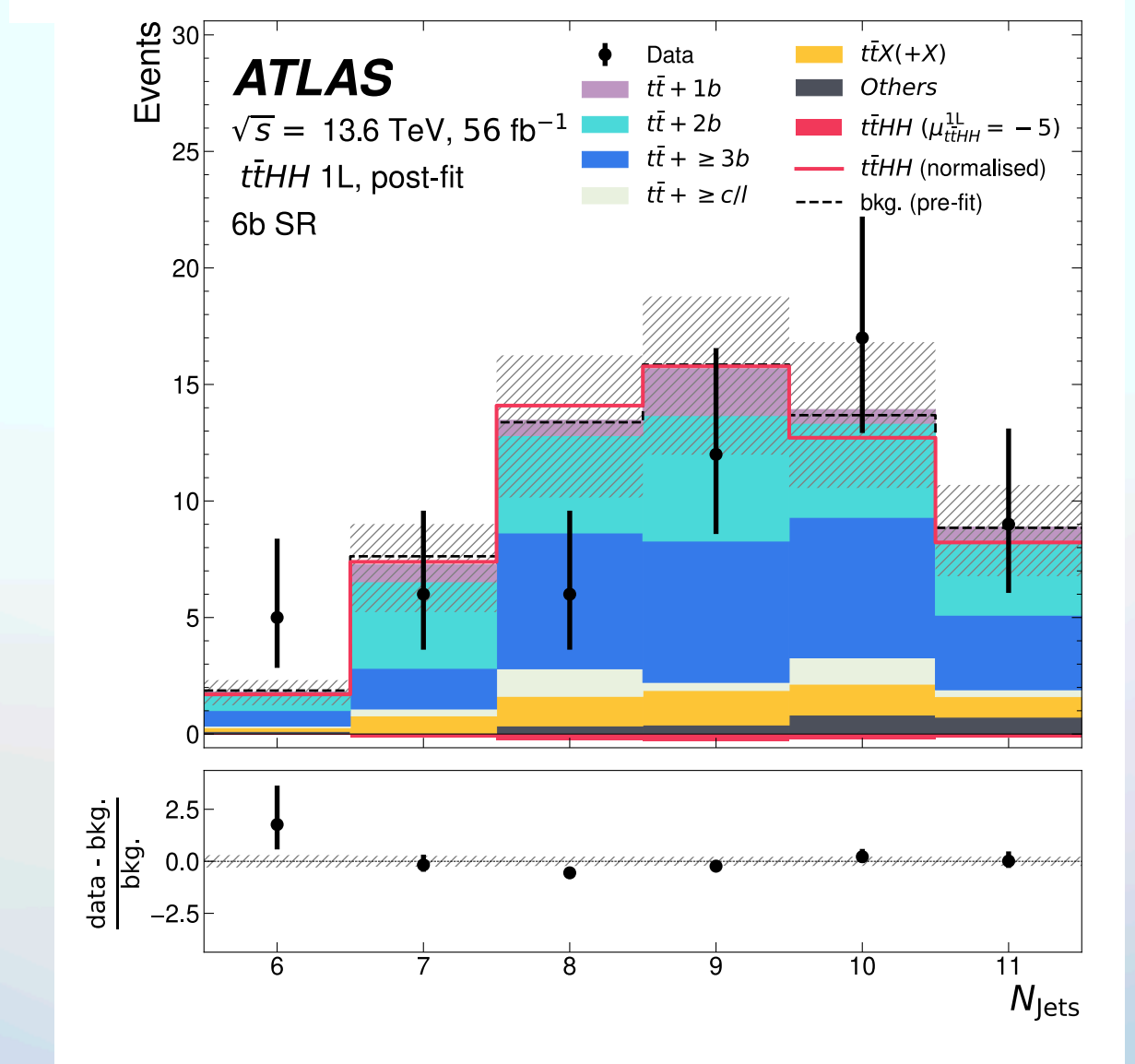
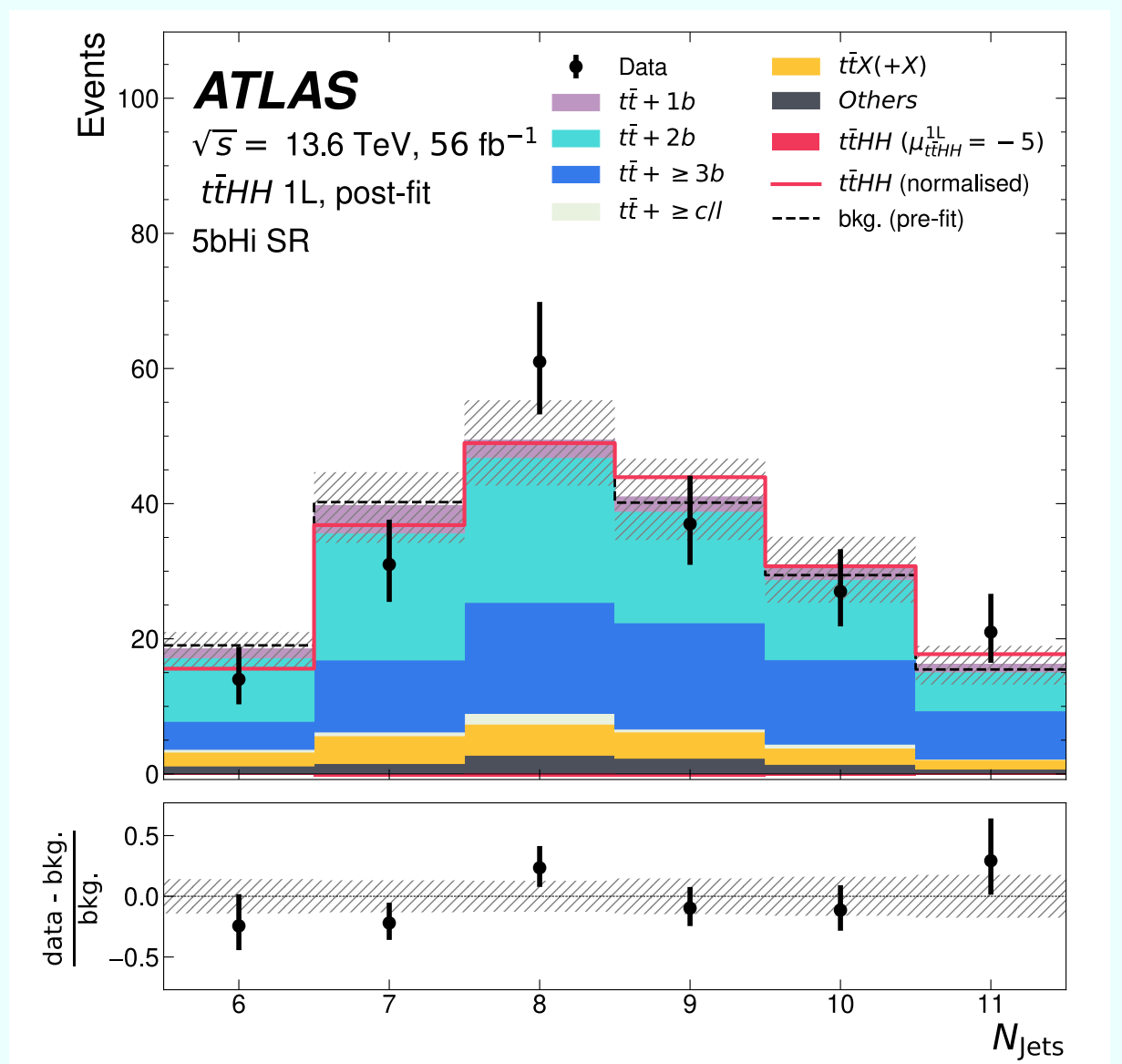
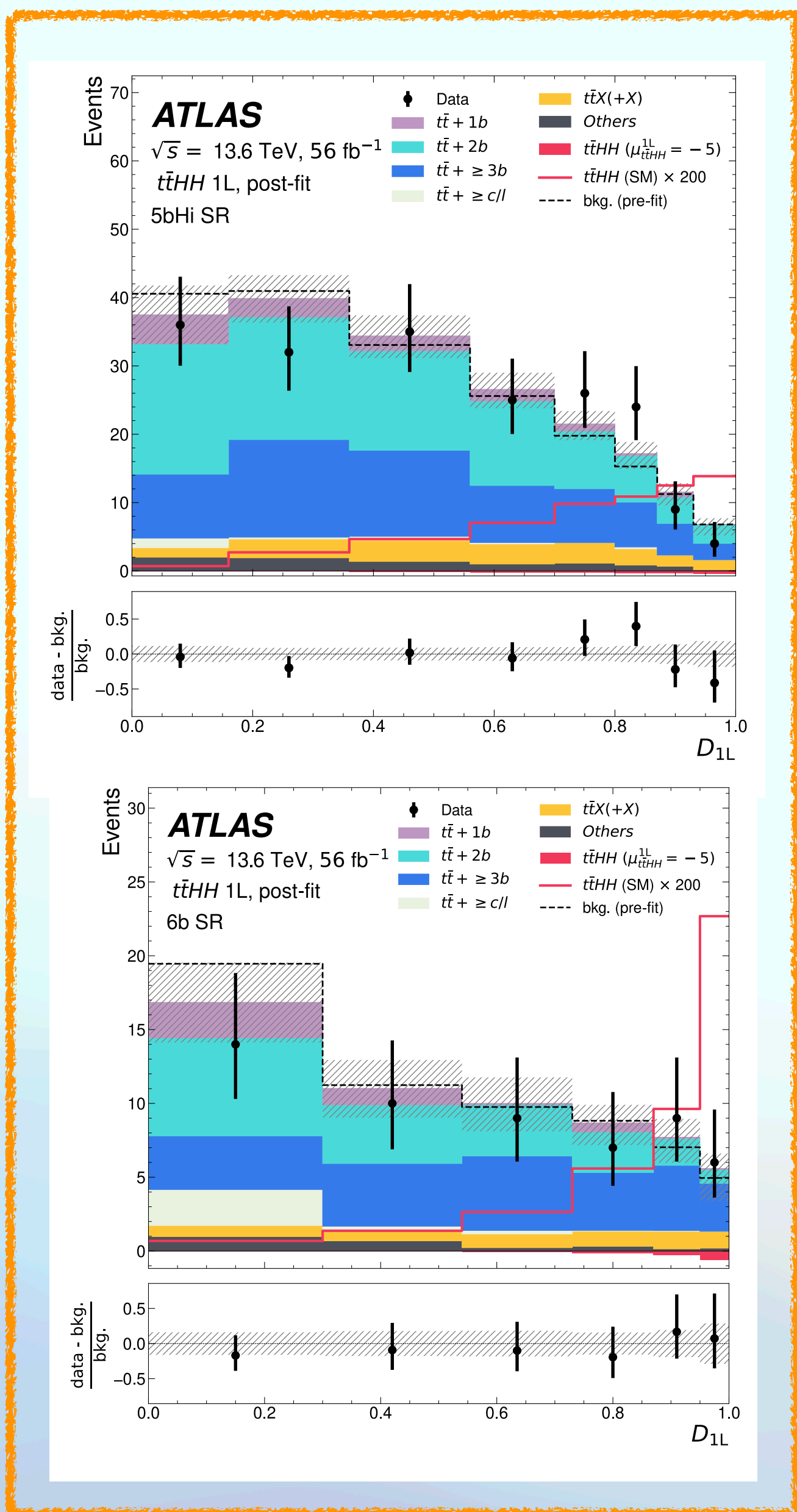


# 1L Run 3 CR distributions



- 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 :

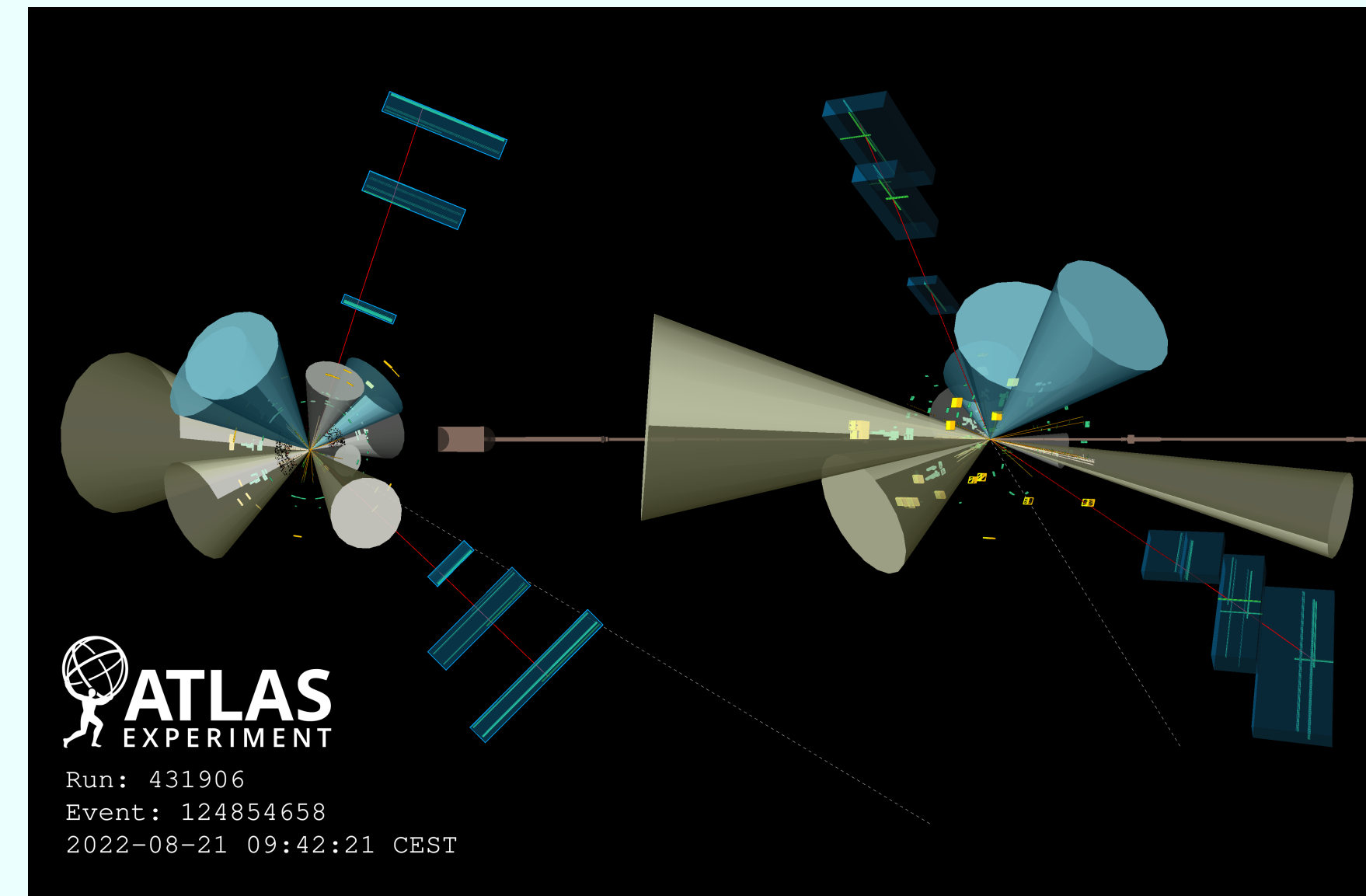
$t\bar{t}W$  and  $t\bar{t}t\bar{t}$  normalization

Channel which suffers a lot from instrumental backgrounds :

→ Charge mis-identification

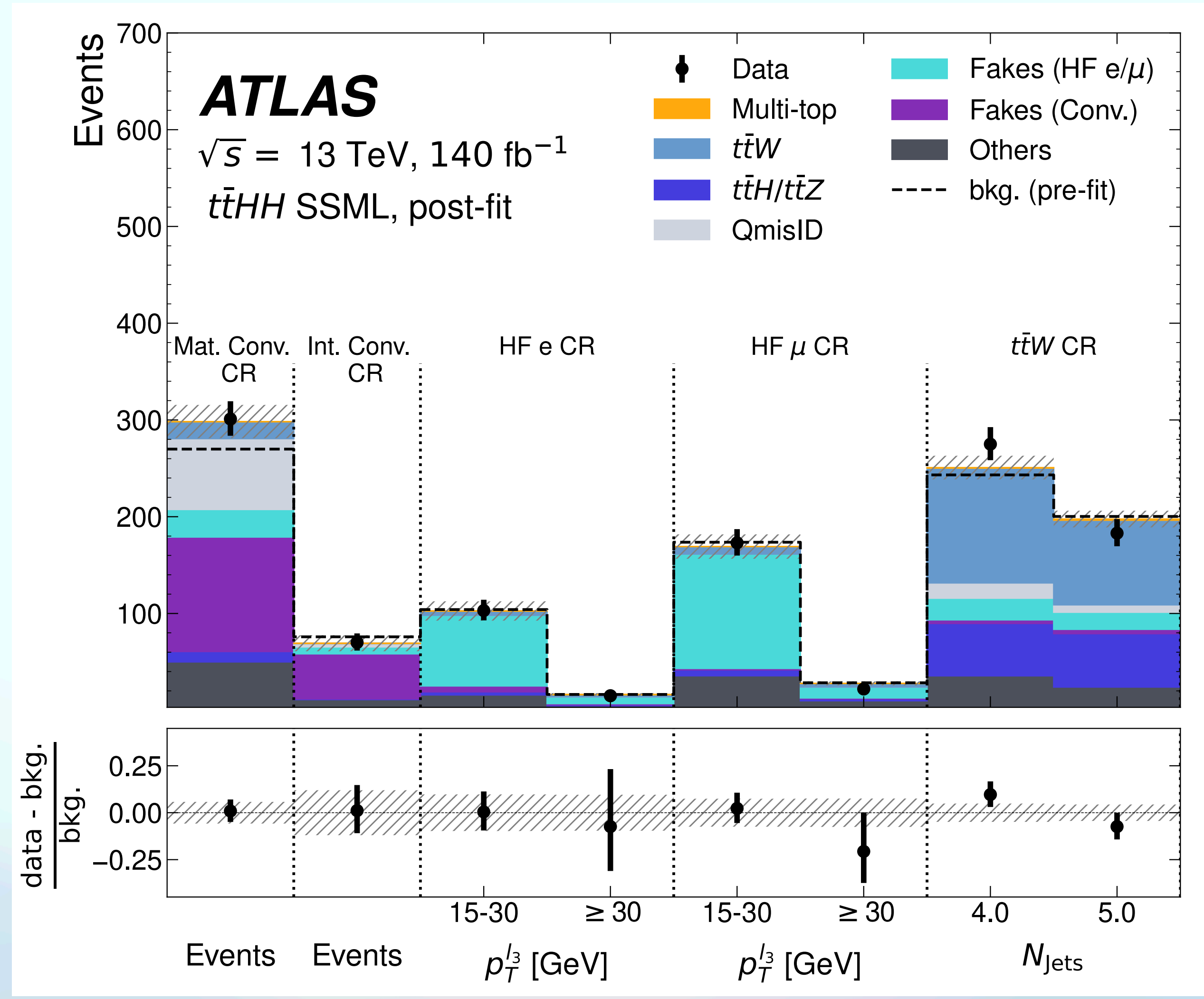
→ "Fake" leptons from HF decays or photon conversions

*i.e. photons which look like lepton*

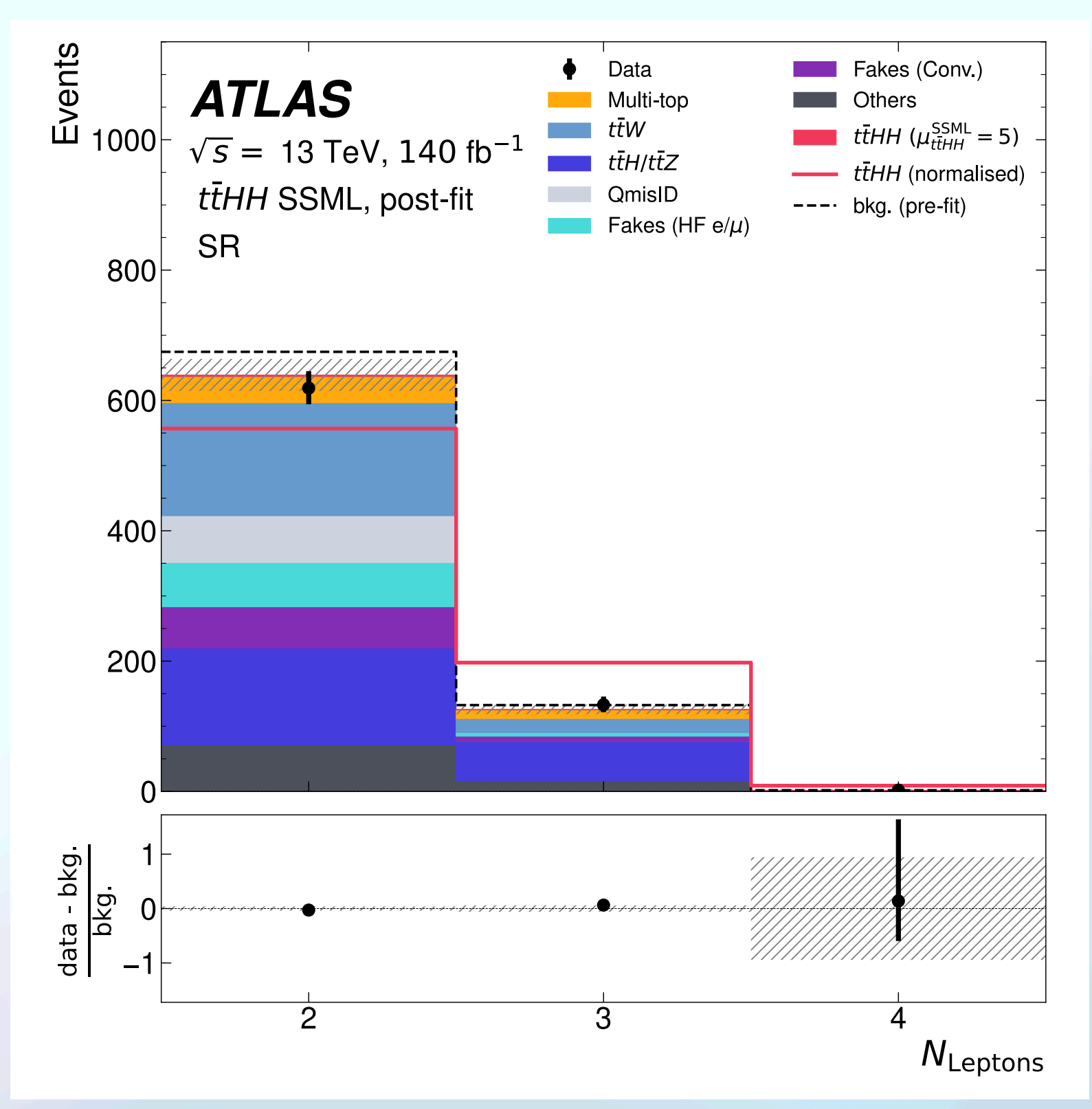
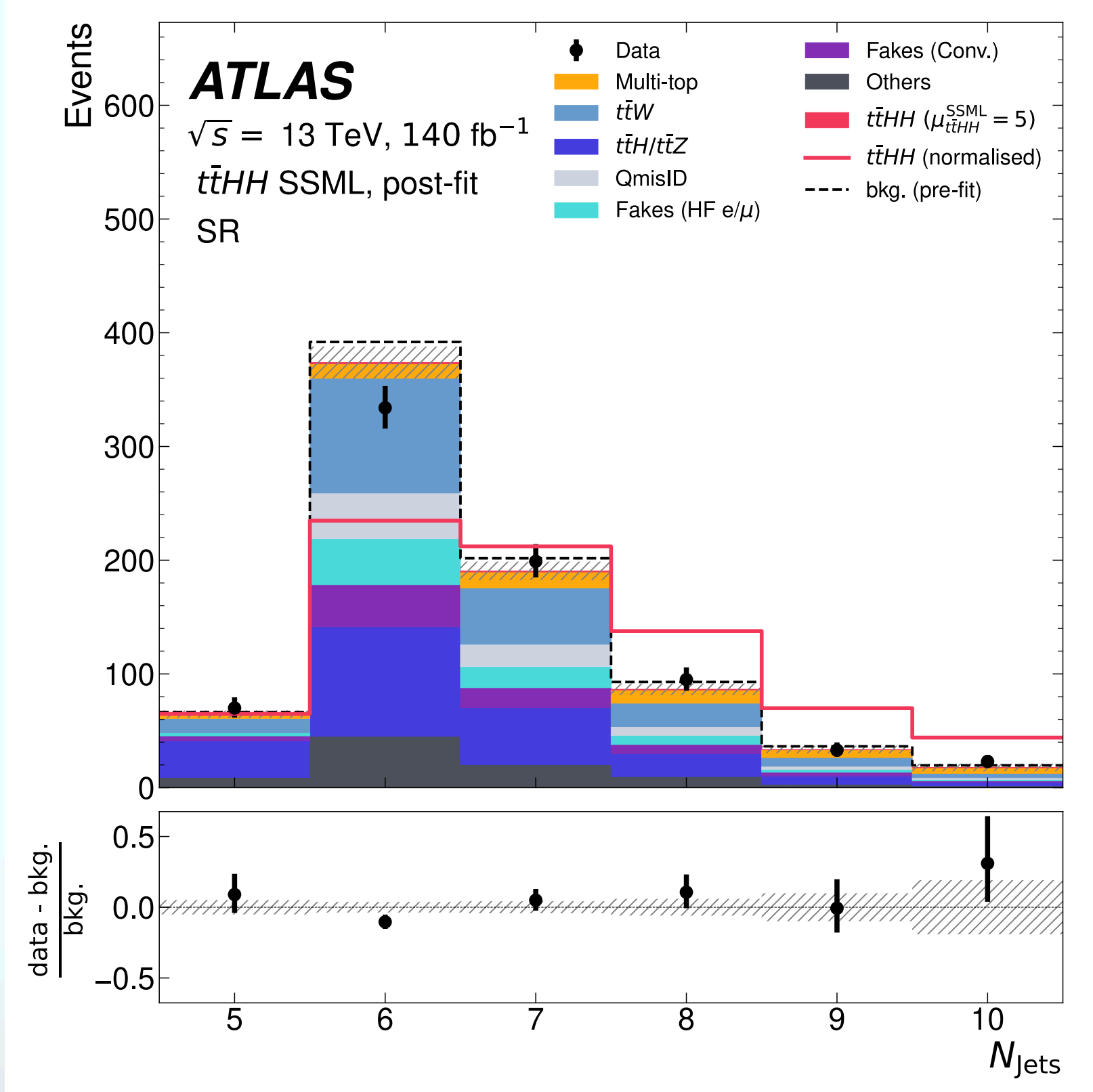
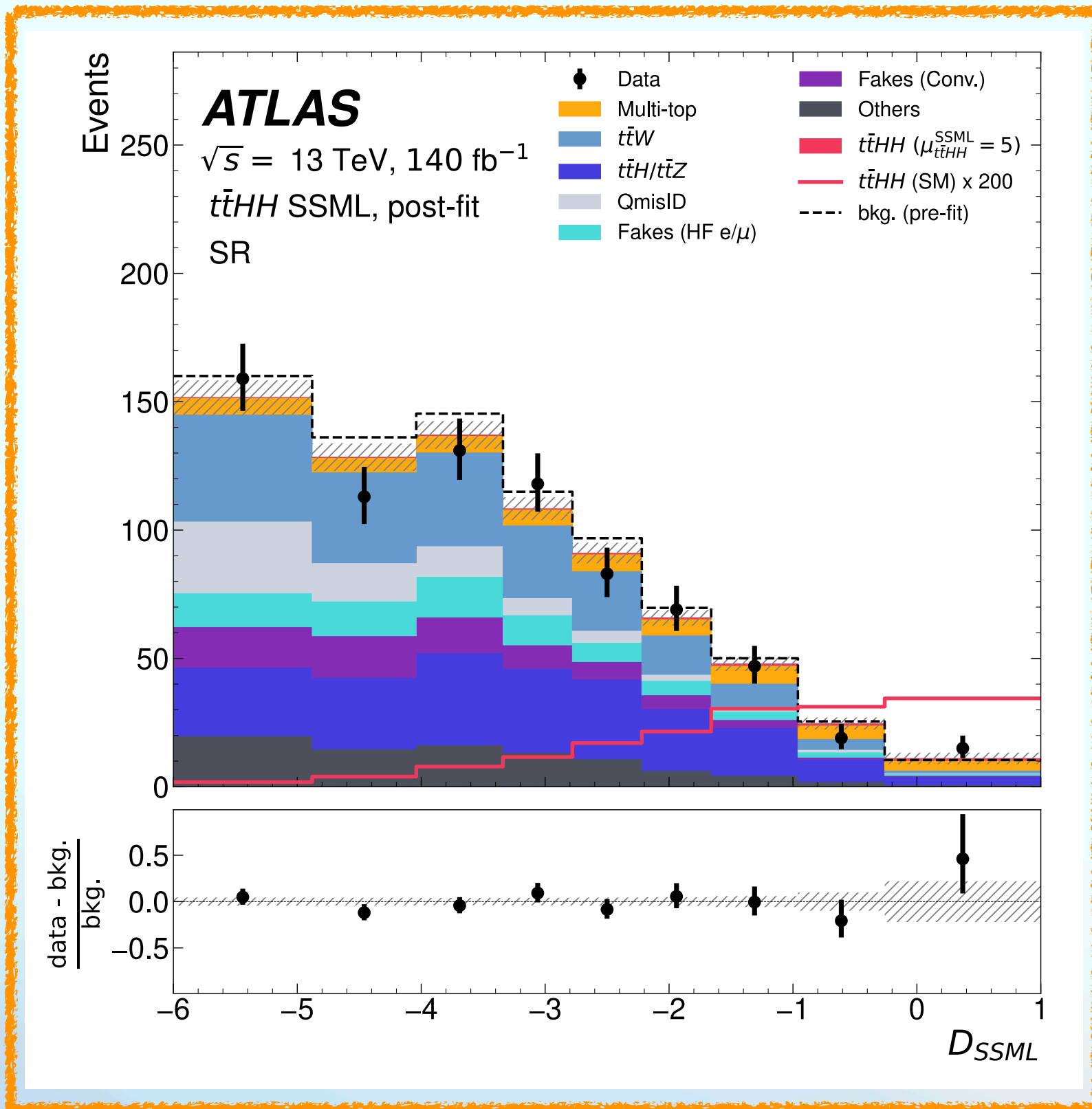


Variable	Description
Event-level	
$N_{\text{jets}}$	Number of jets
$N_{\text{b-jets}}$	Number of b-tagged jets
$N_{\text{lepton}}$	Number of leptons
$H_{\text{T}}$	The scalar sum of the transverse momenta of the leptons and jets in an event.
$MET$	Transverse energy of the missing momentum vector.
$MET\_PHI$	Azimuthal angle of the missing momentum vector.
Object-level	
$(p_{\text{T}}, \eta, \phi)$	Kinematic variables of the object, i.e. transverse momentum, pseudorapidity, and azimuthal angle.
$w_{\text{GN2}}$	GN201 b-tagging pseudo-continuous score for identifying jets. Non-jet objects are assigned a value of zero.
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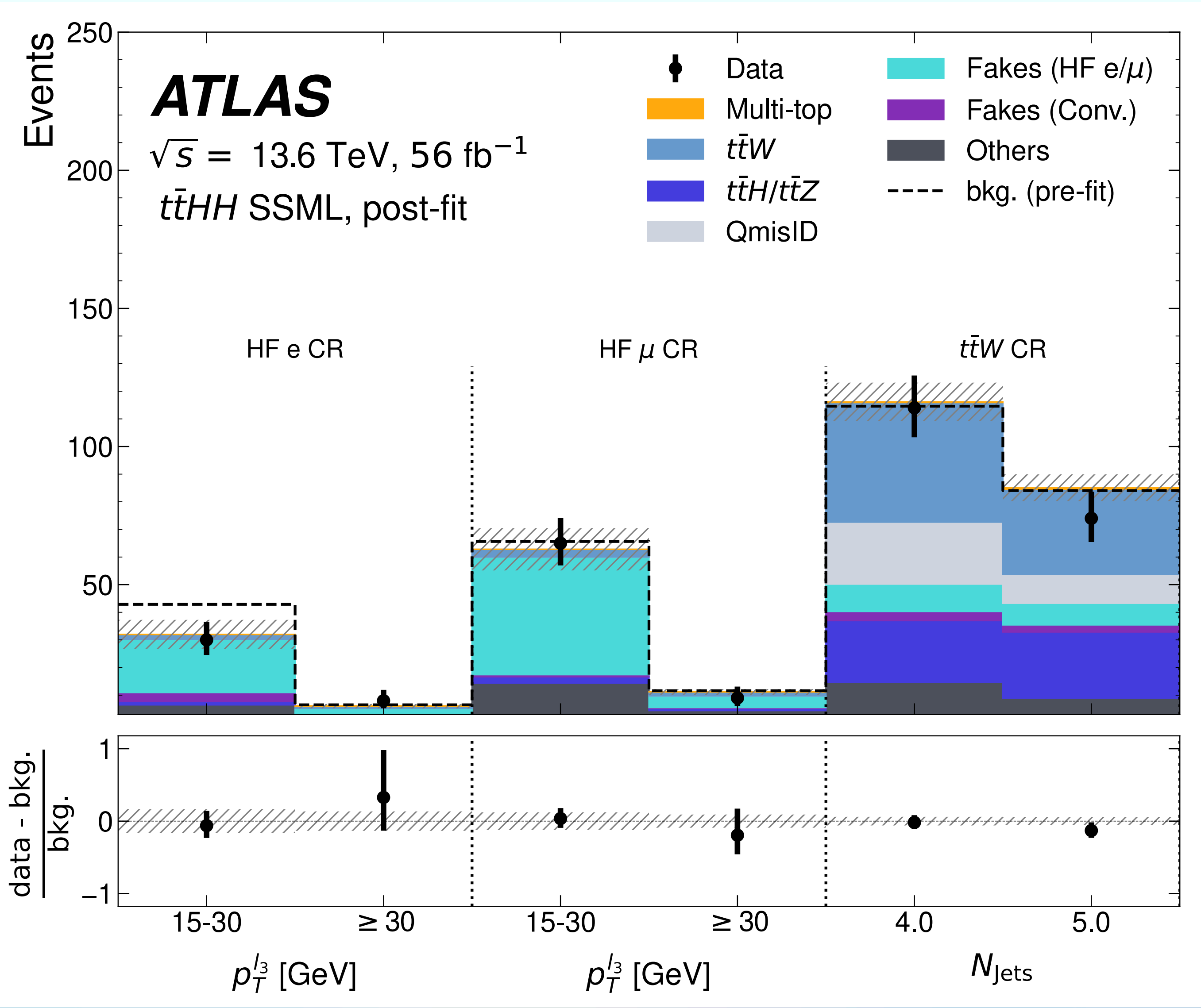
# ML Run 2 CR distributions



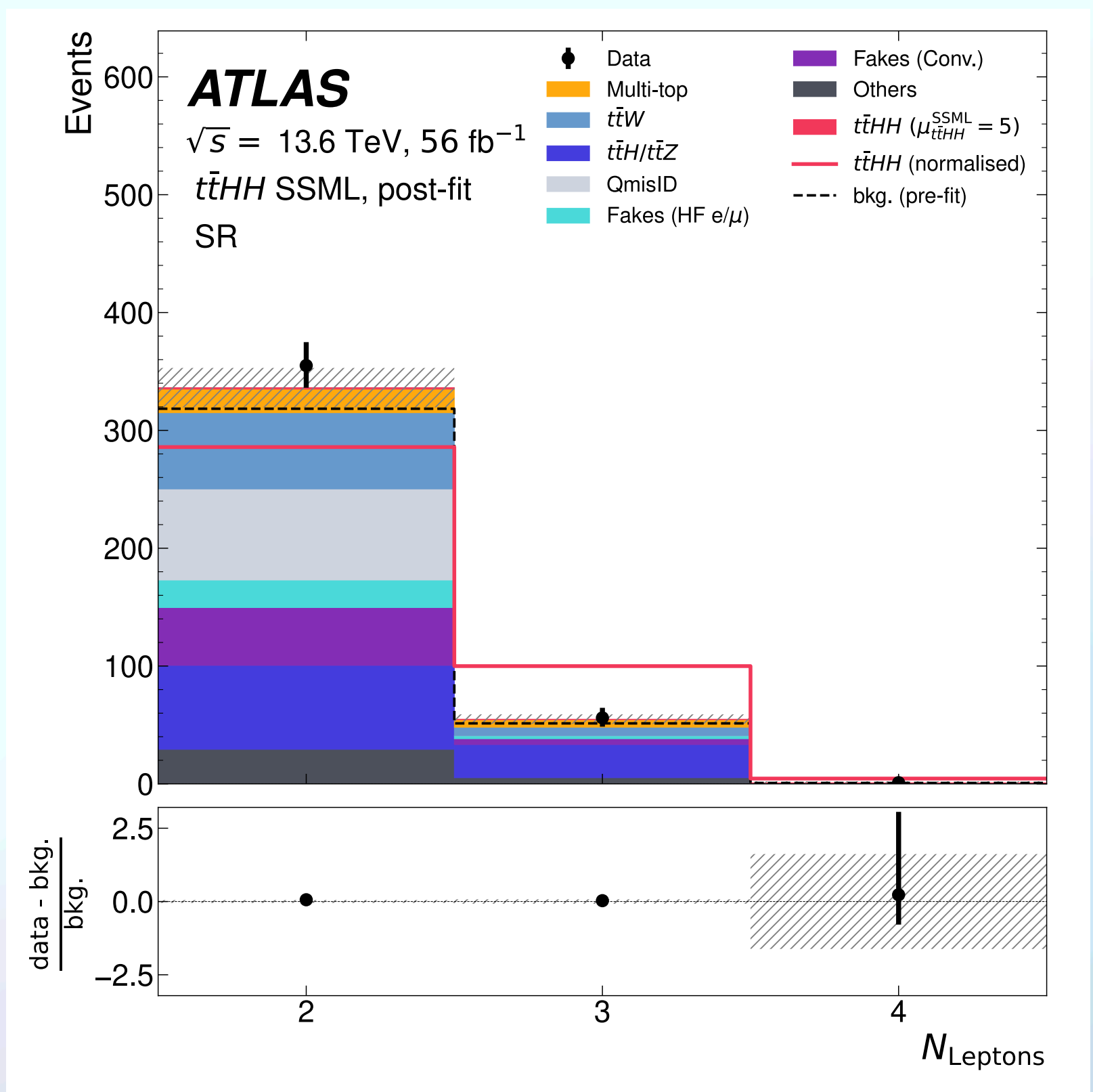
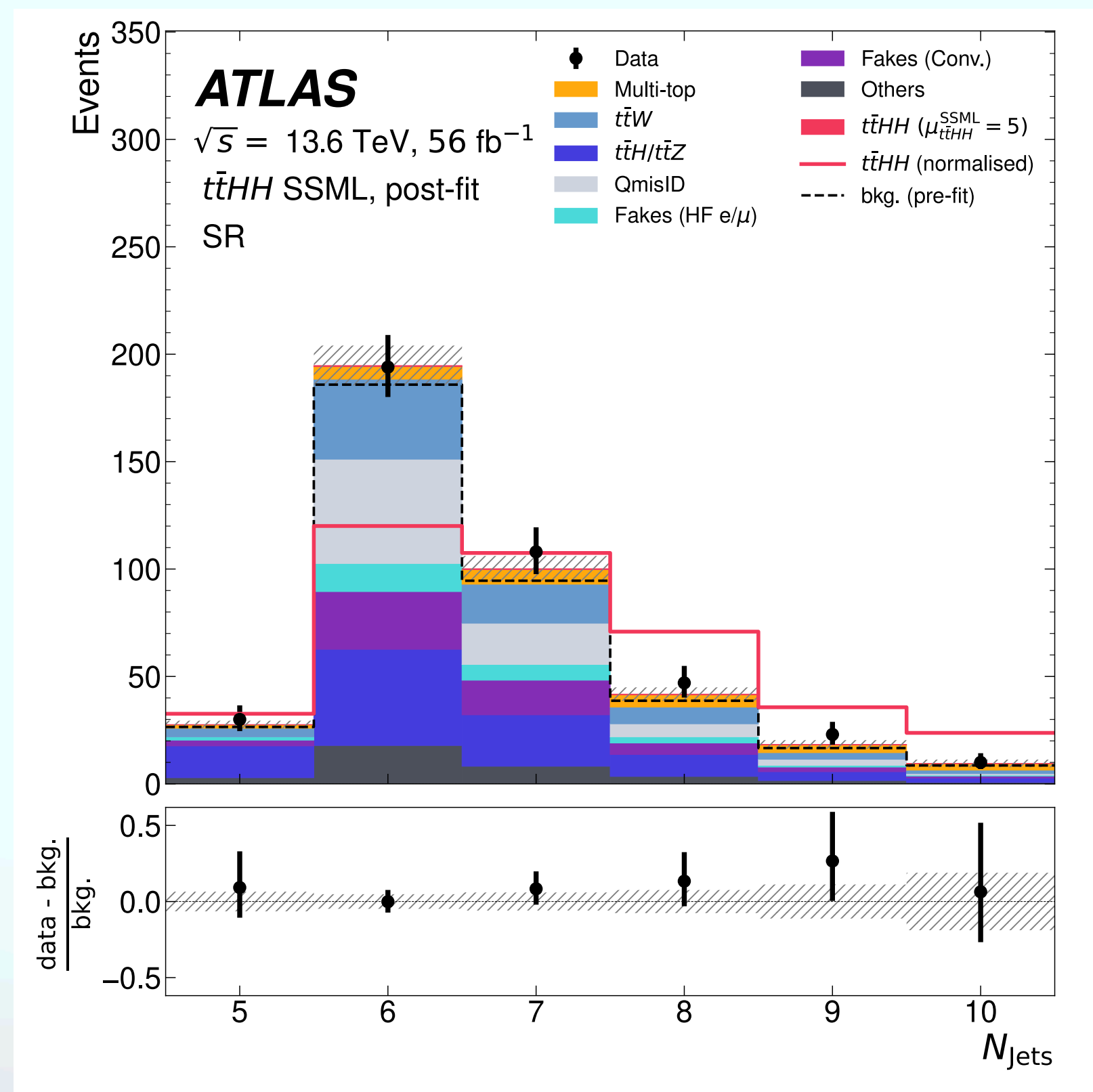
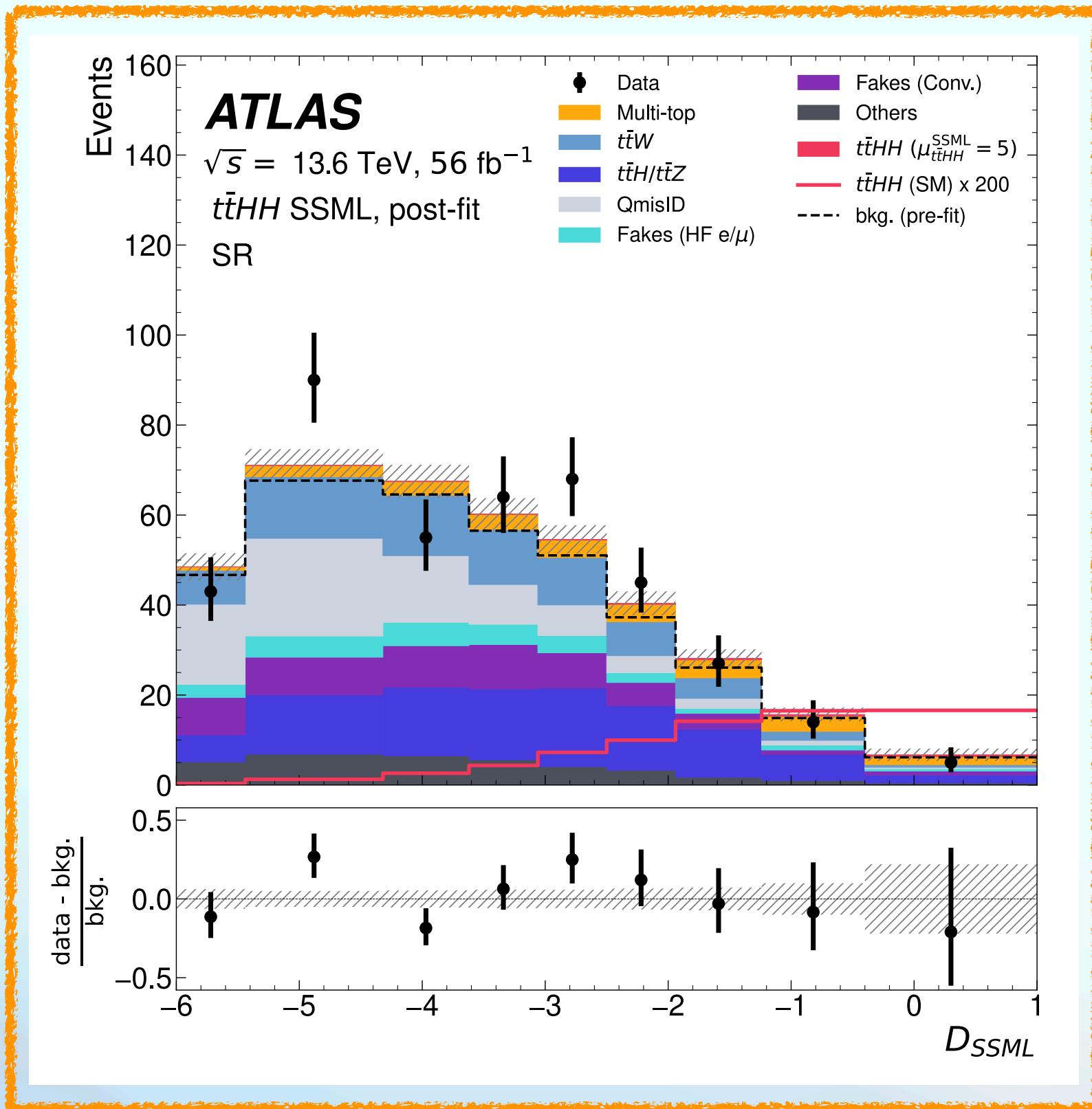
# ML Run 2 SR distributions



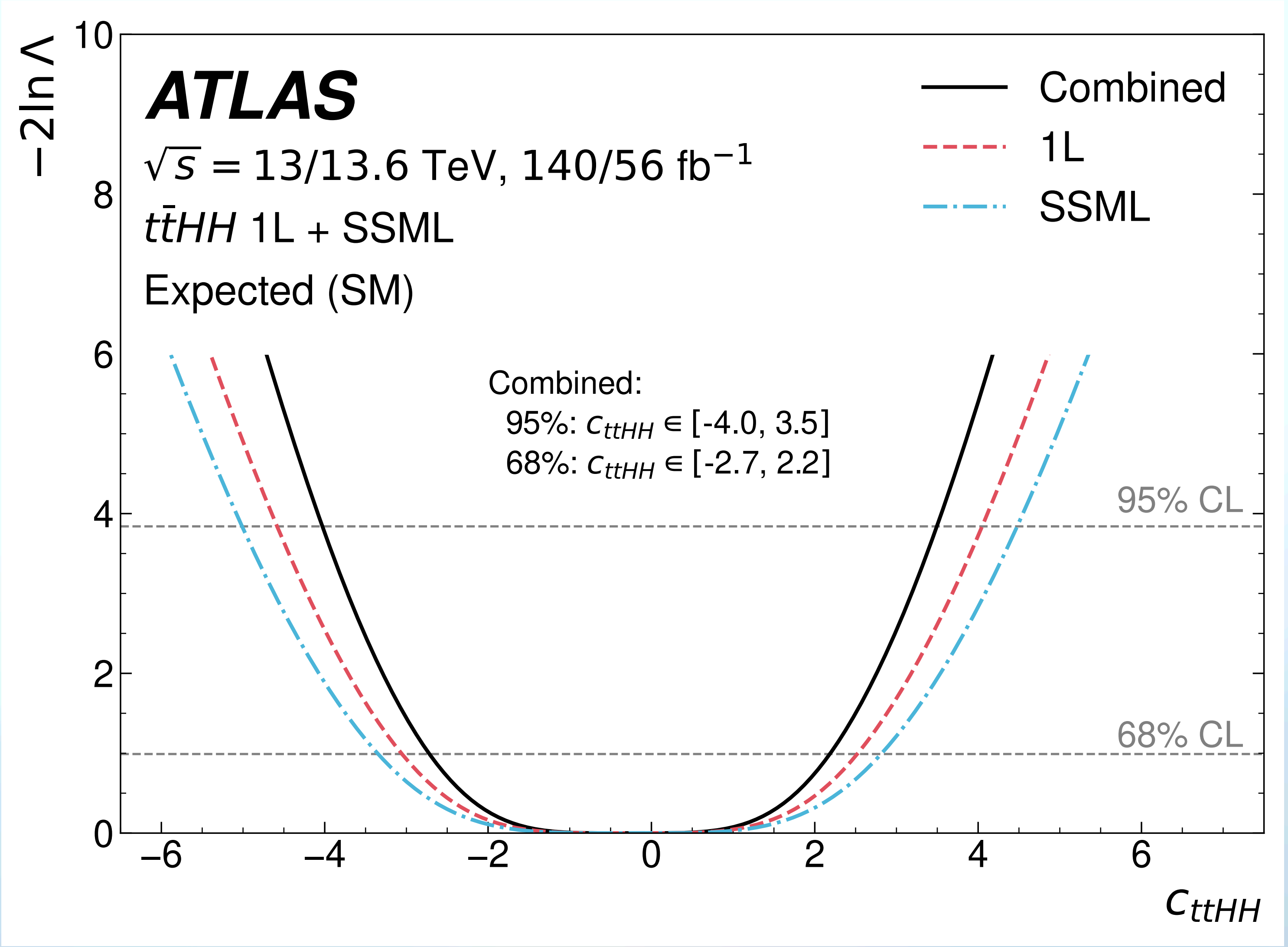
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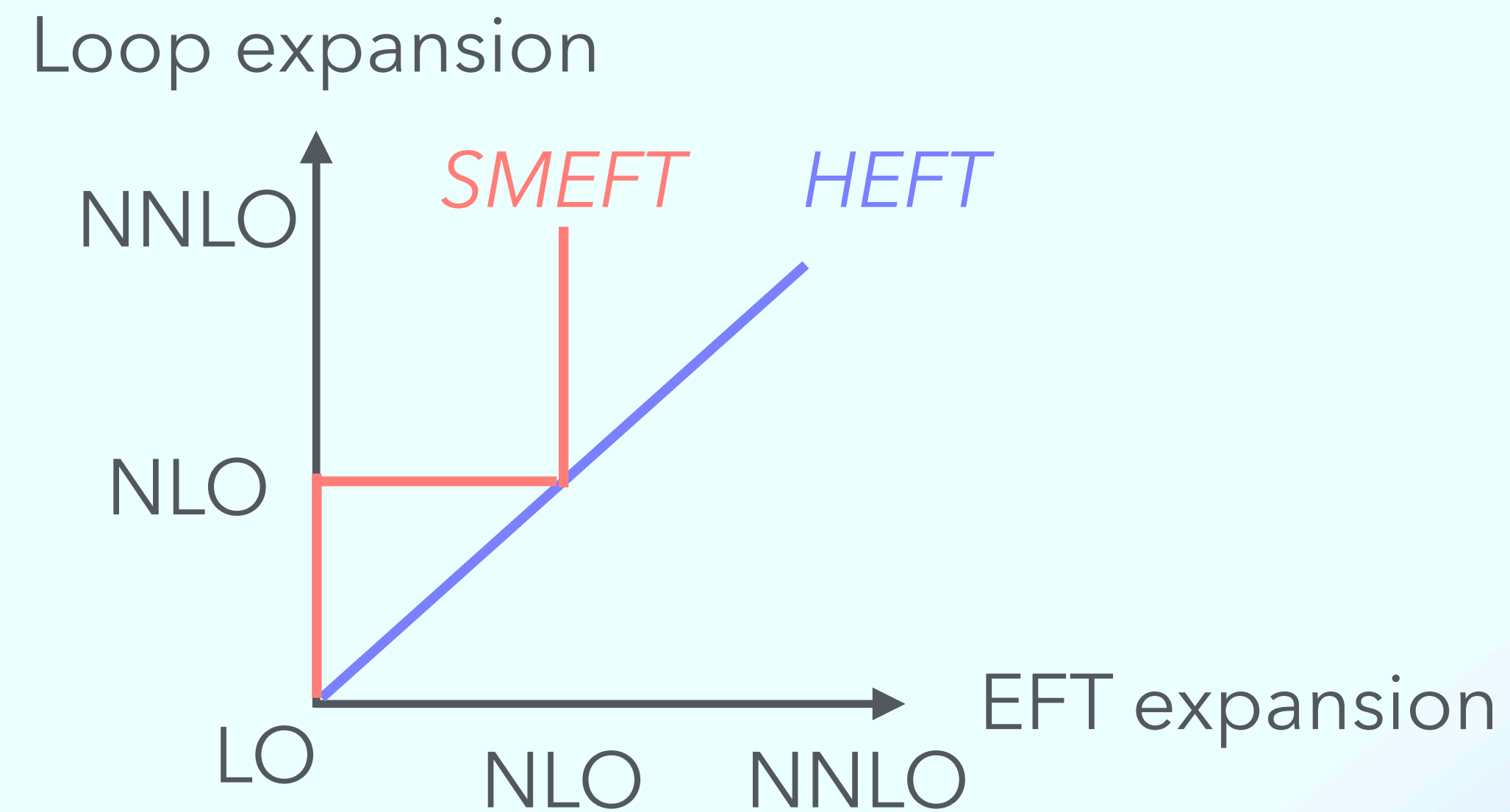


# Expected likelihood for EFT fit



# HEFT vs. SMEFT power counting

[arXiv:[2511.23410](https://arxiv.org/abs/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 :  $\mathcal{L}_{\text{EFT}} = \mathcal{L}_{\text{SM}} + \sum_i \frac{c_i^{(6)}}{\Lambda^2} \mathcal{O}_i^{(6)} + \sum_i \frac{c_i^{(8)}}{\Lambda^4} \mathcal{O}_i^{(8)} + \dots$

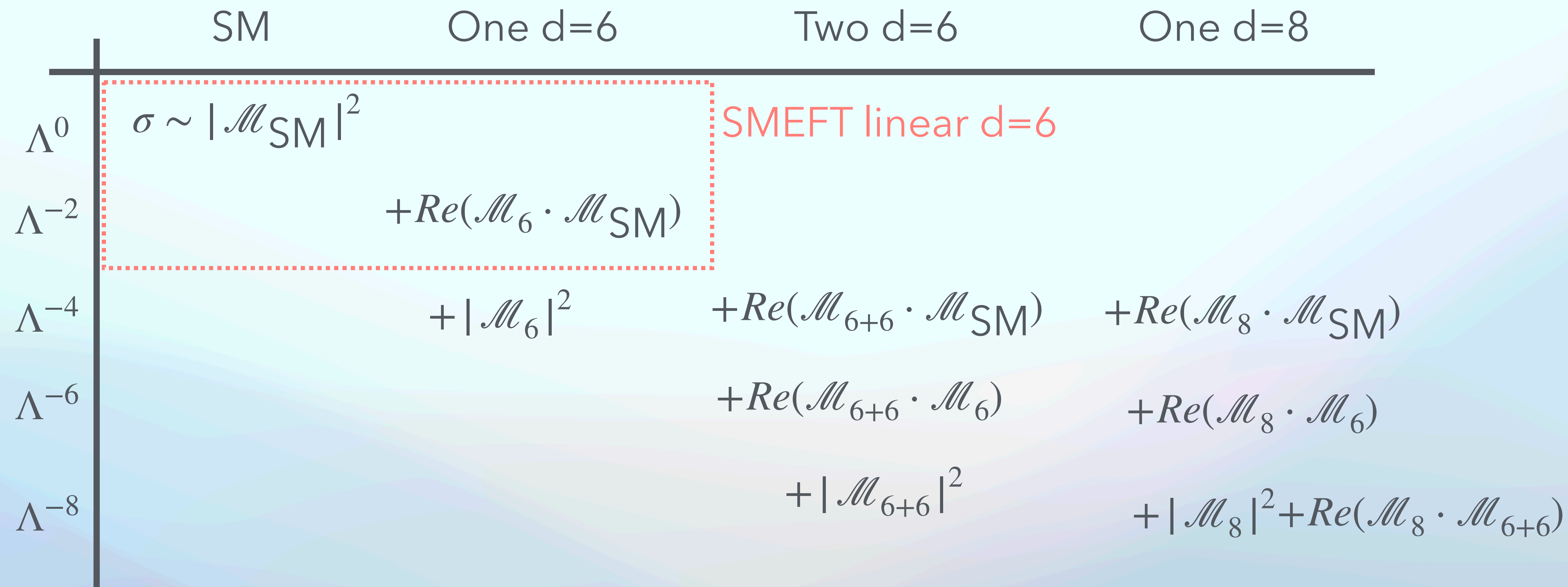
Event rates :  $\sigma_{\text{EFT}} \sim |\mathcal{M}_{\text{SM}} + \underbrace{\mathcal{M}_6}_{\text{One } d=6} + \underbrace{\mathcal{M}_{6+6}}_{\text{Two } d=6} + \underbrace{\mathcal{M}_8}_{\text{One } d=8} + \dots|^2$

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

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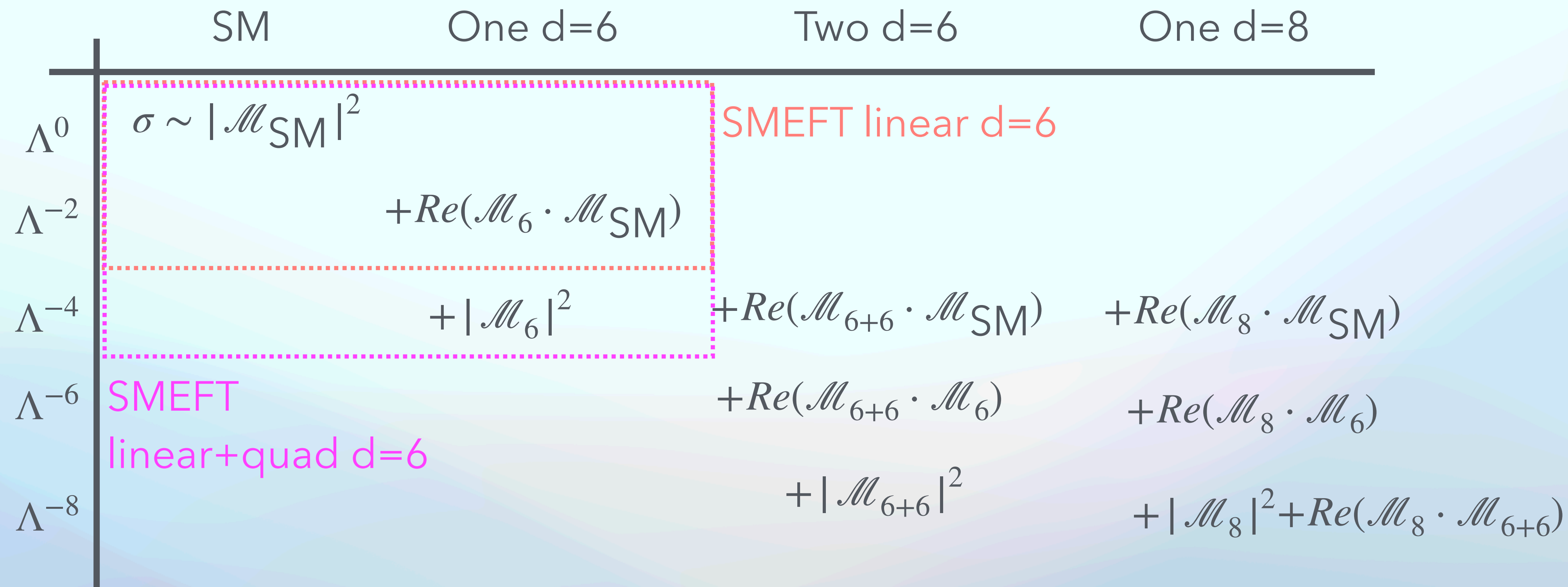
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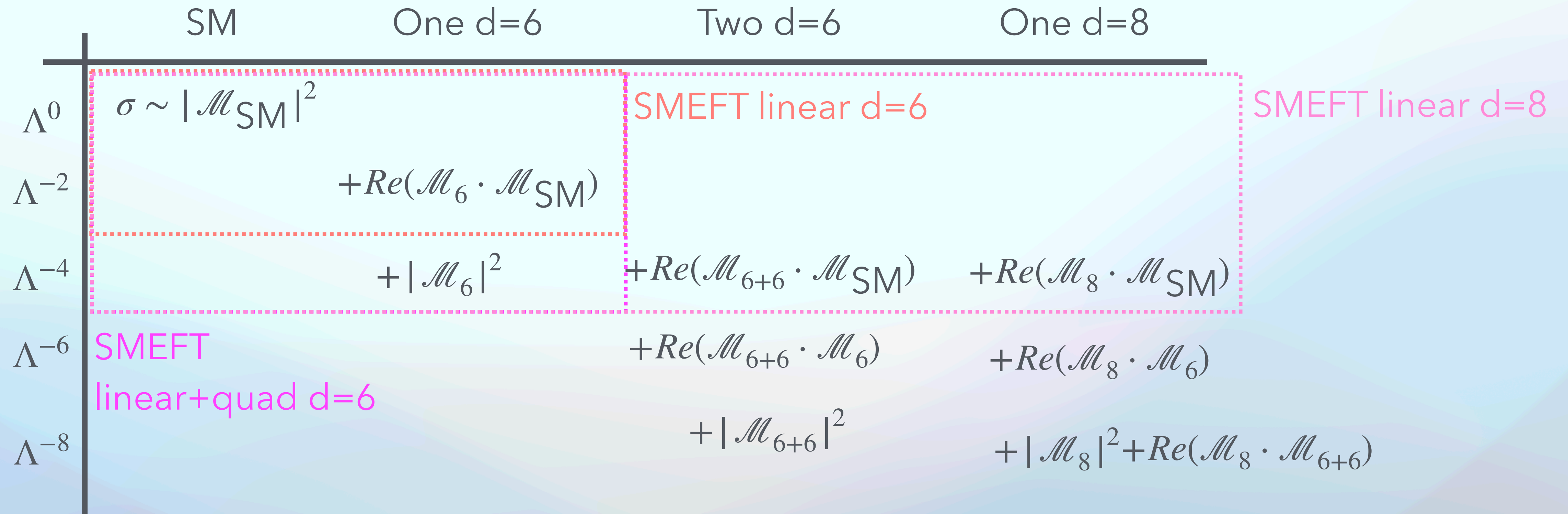
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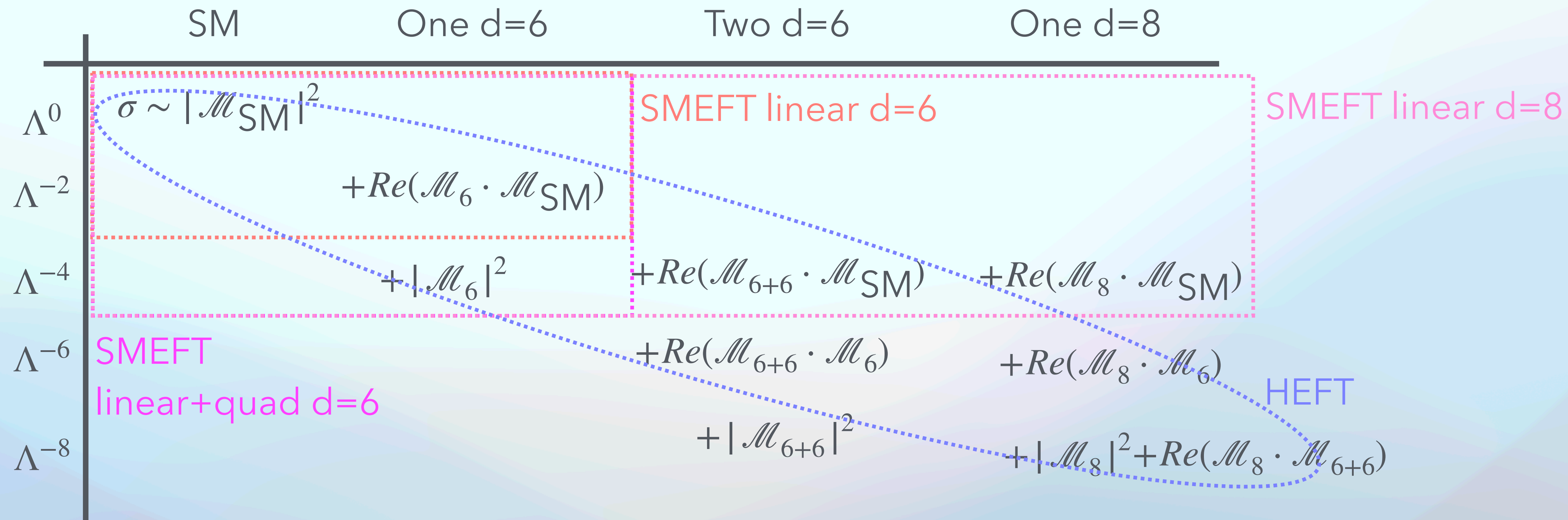
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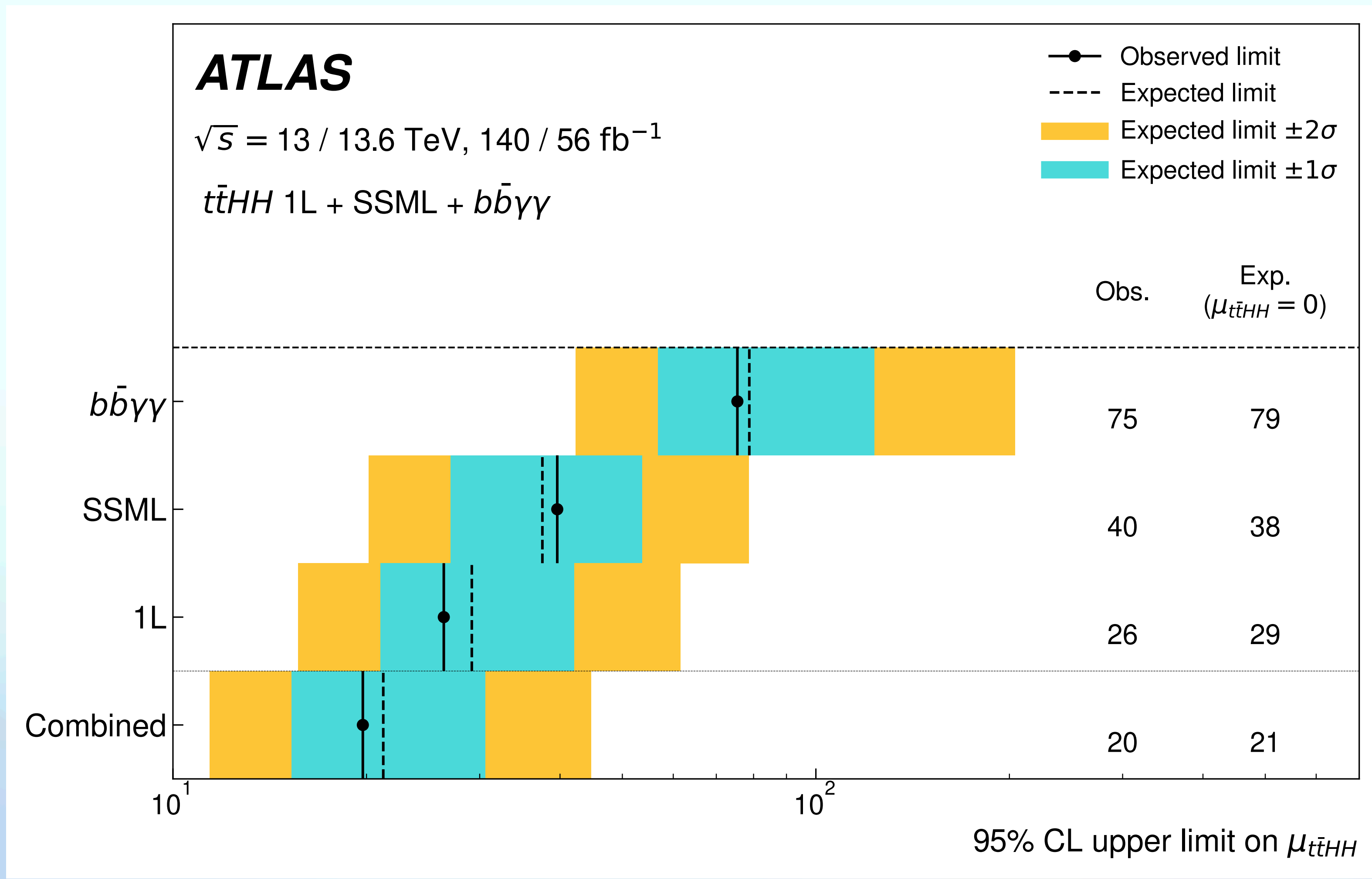
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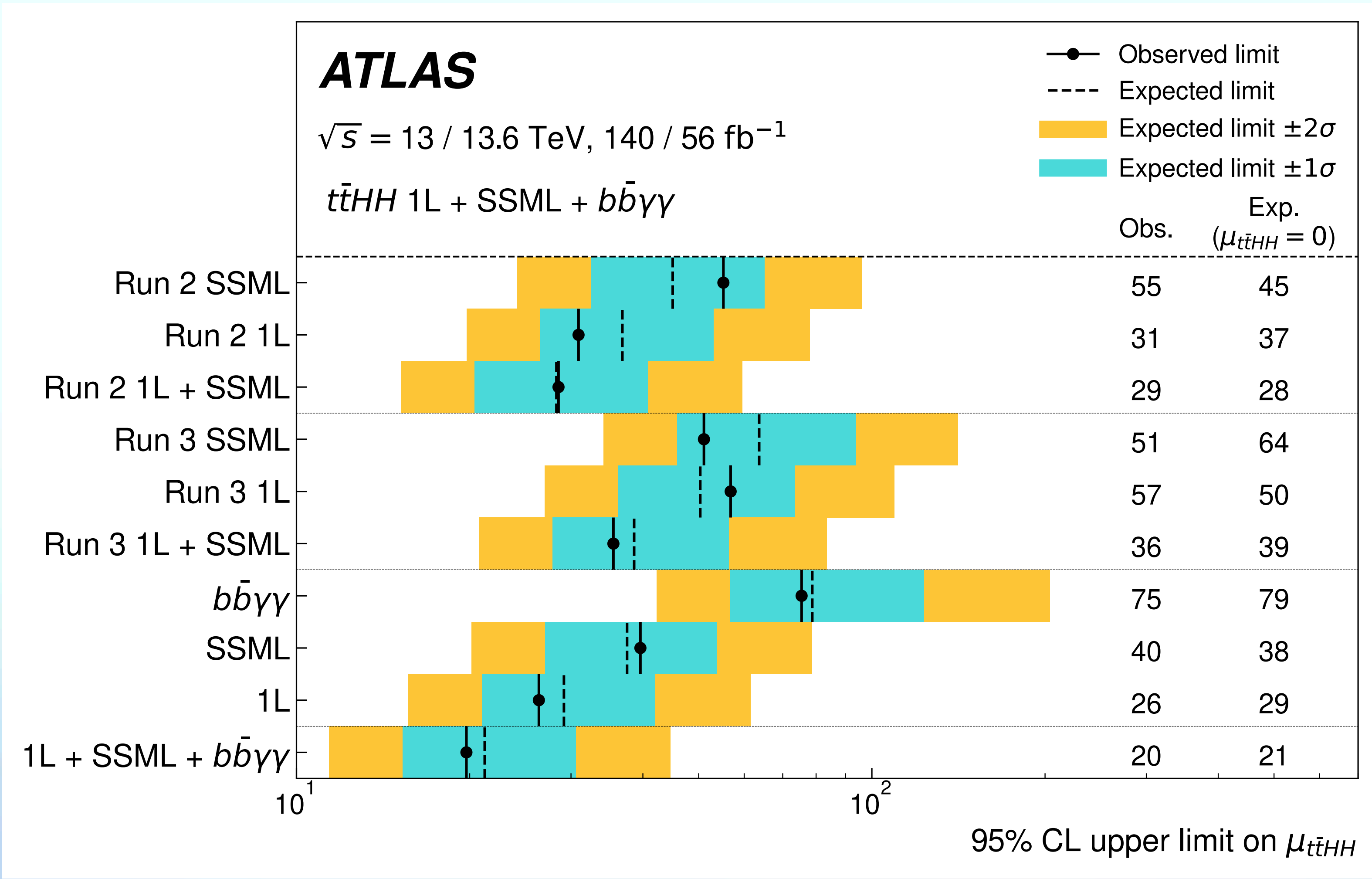


# Results on signal strength



- 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*