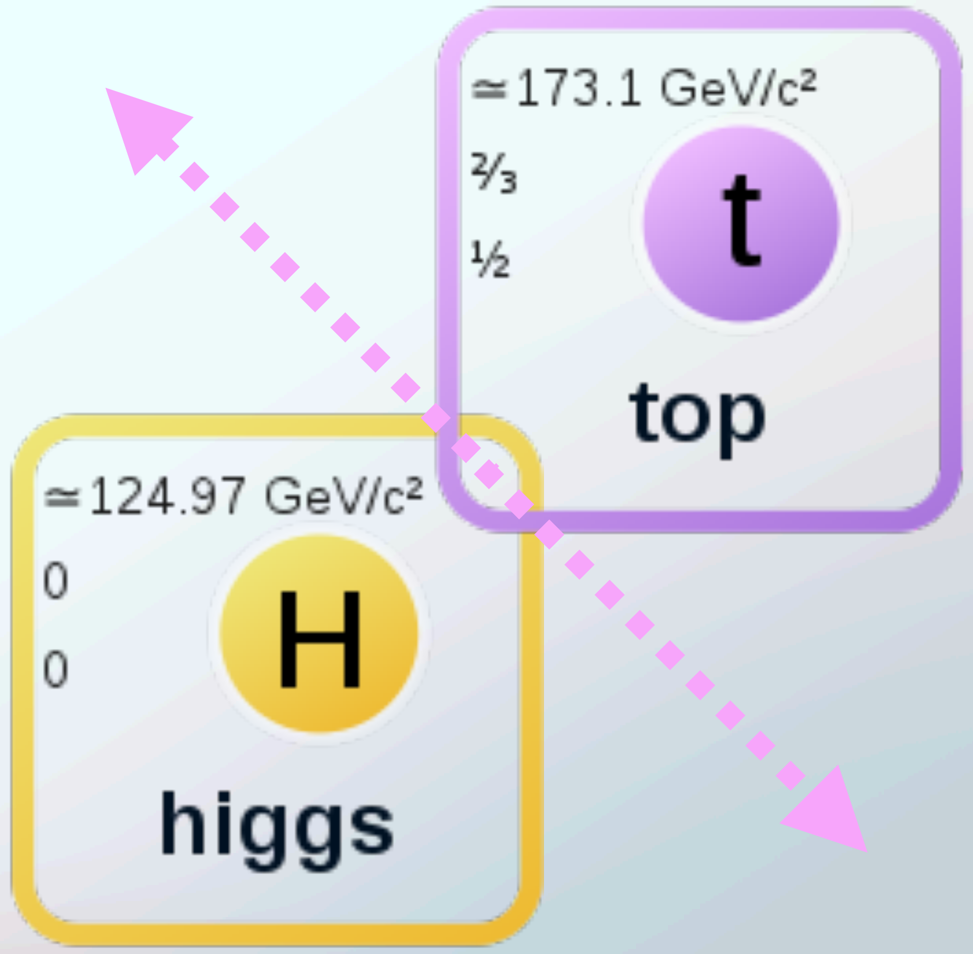
ATLAS
EXPERIMENT

LPC
Particules
pLasmas
Univers
applicationS
Laboratoire de Physique de Clermont

Probing Electroweak Symmetry Breaking with Effective Field Theories

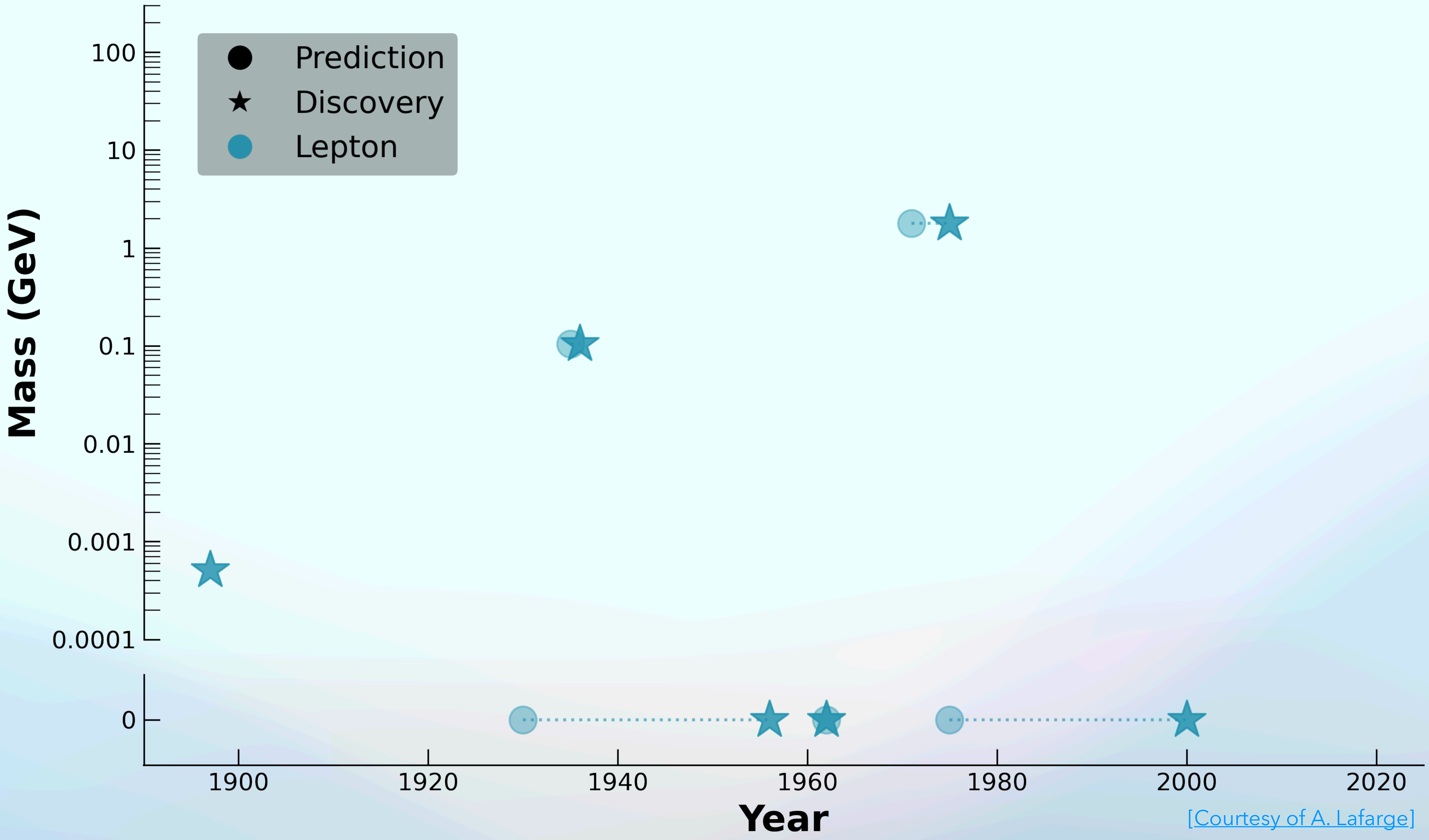
in Top quark and Higgs sectors



LAPP seminar - 17, April 2026

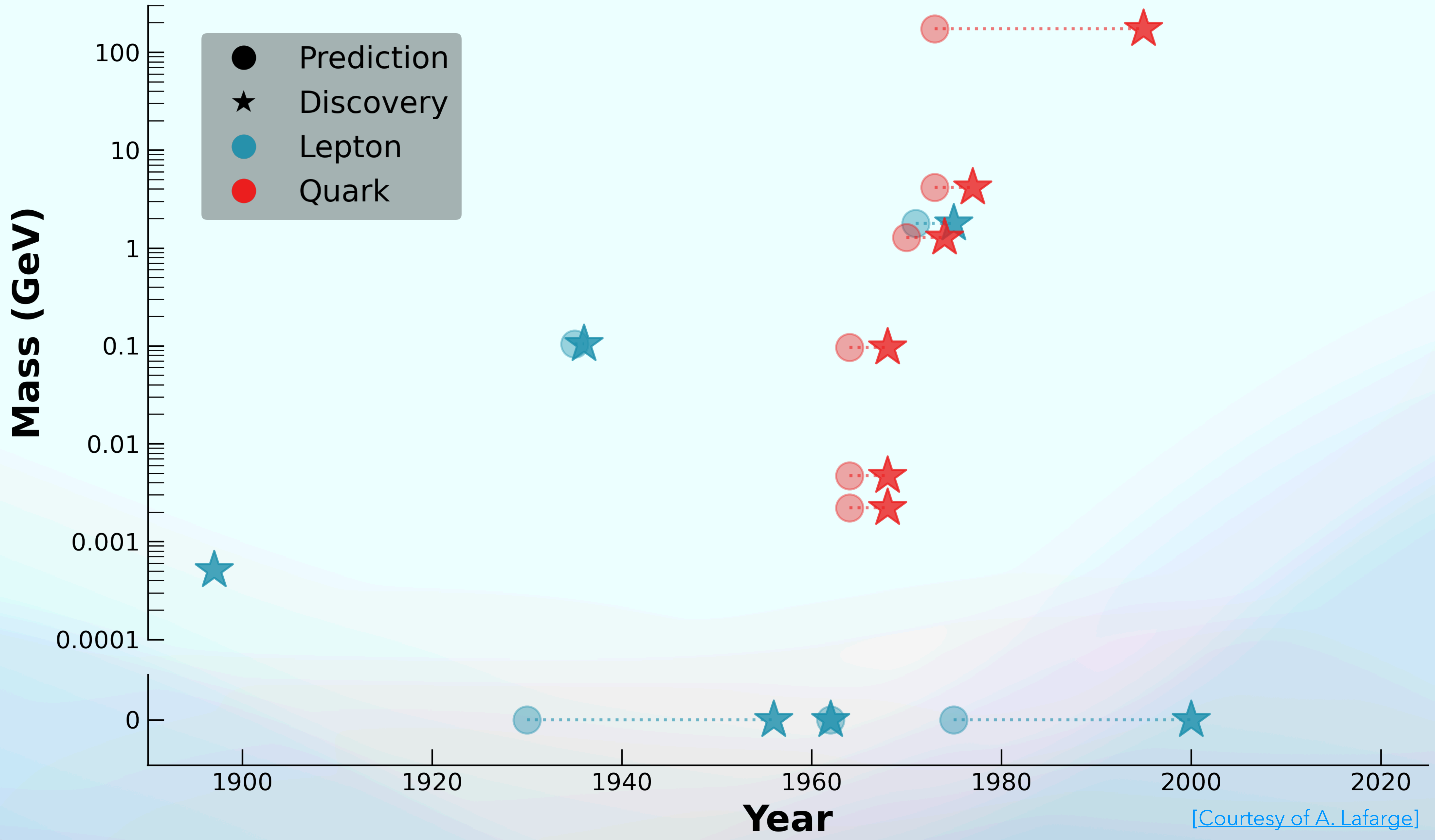
Adrien Auriol

A discovery tale



[Courtesy of A. Lafarge]

A discovery tale



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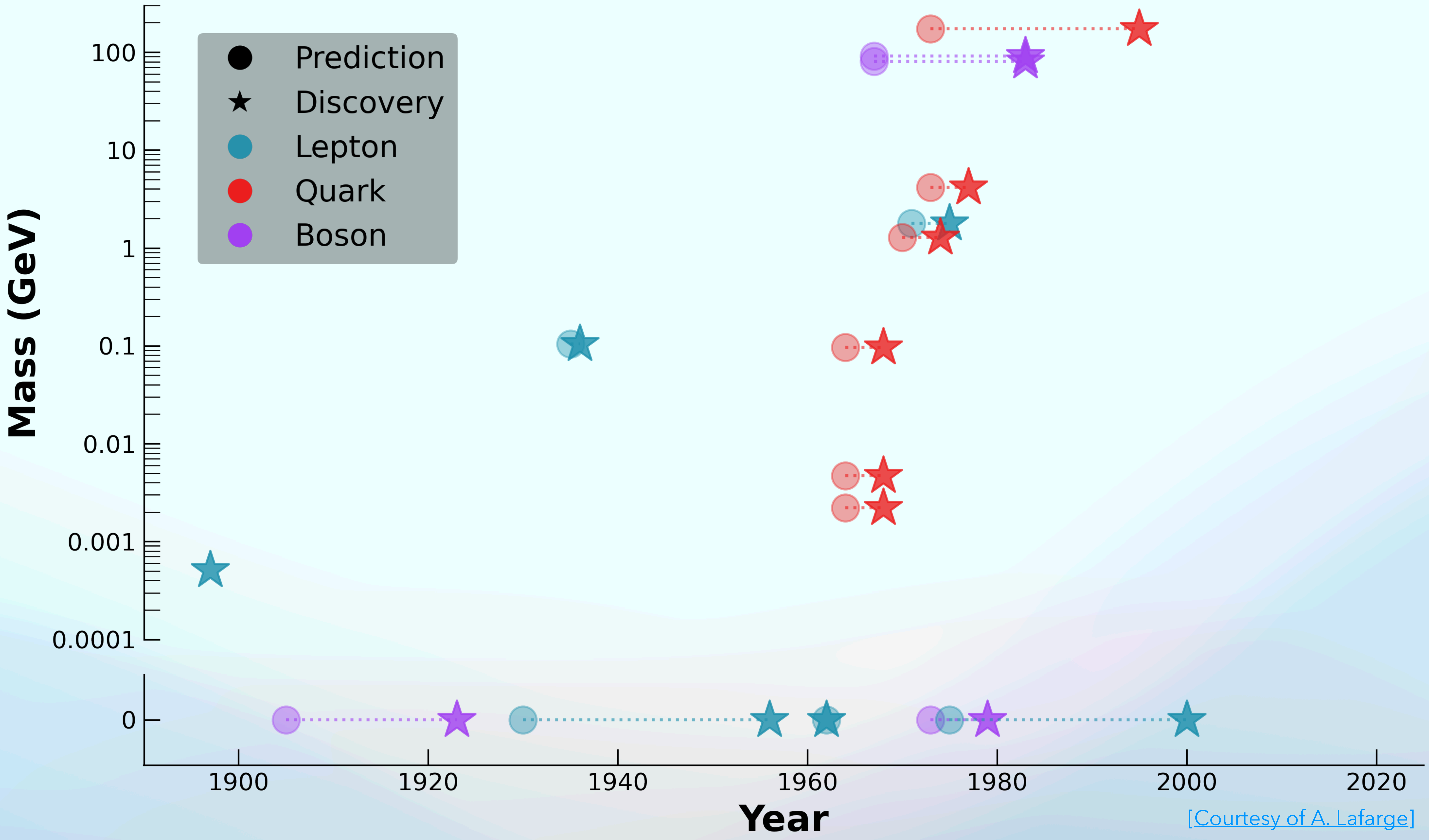

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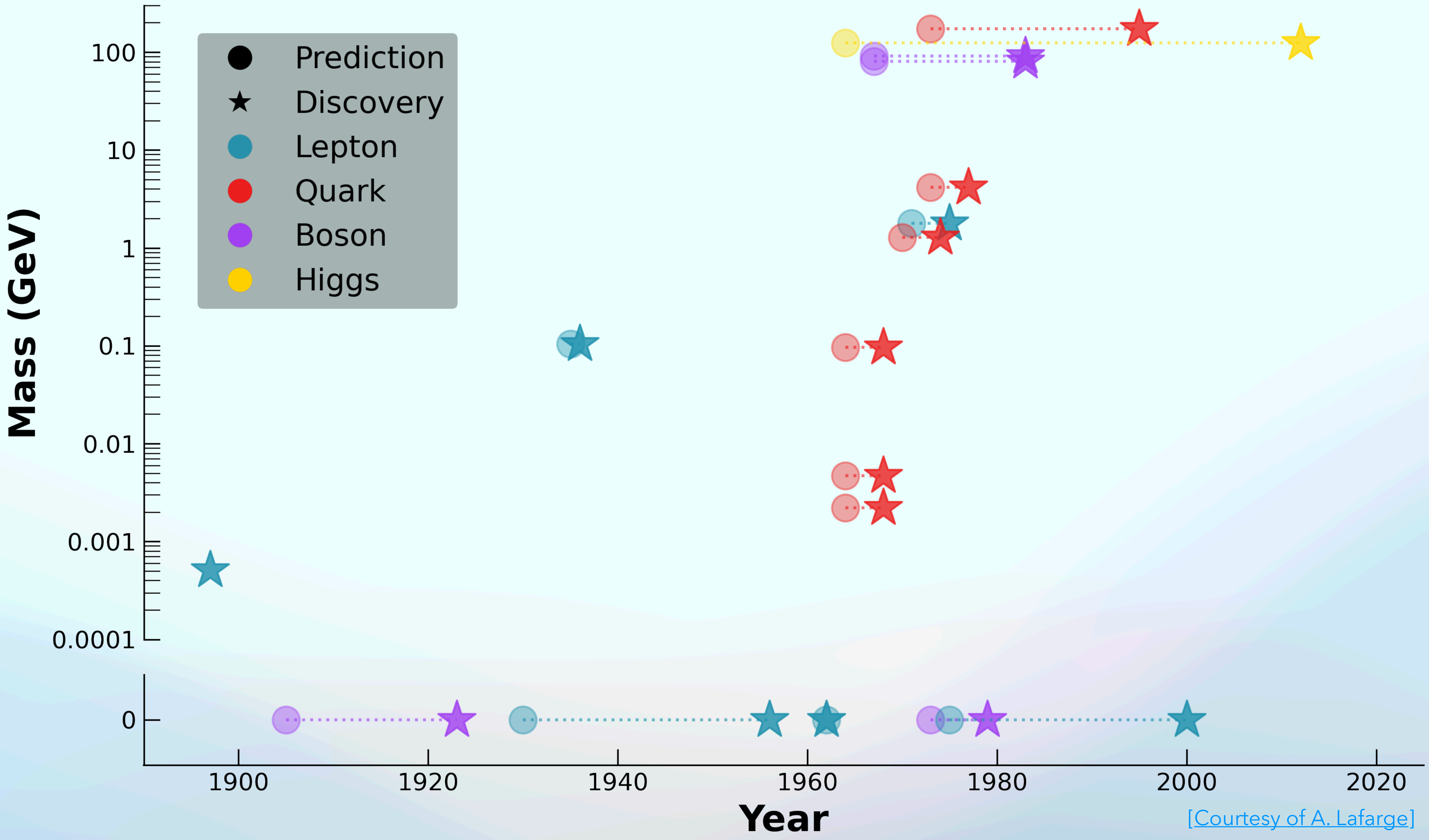
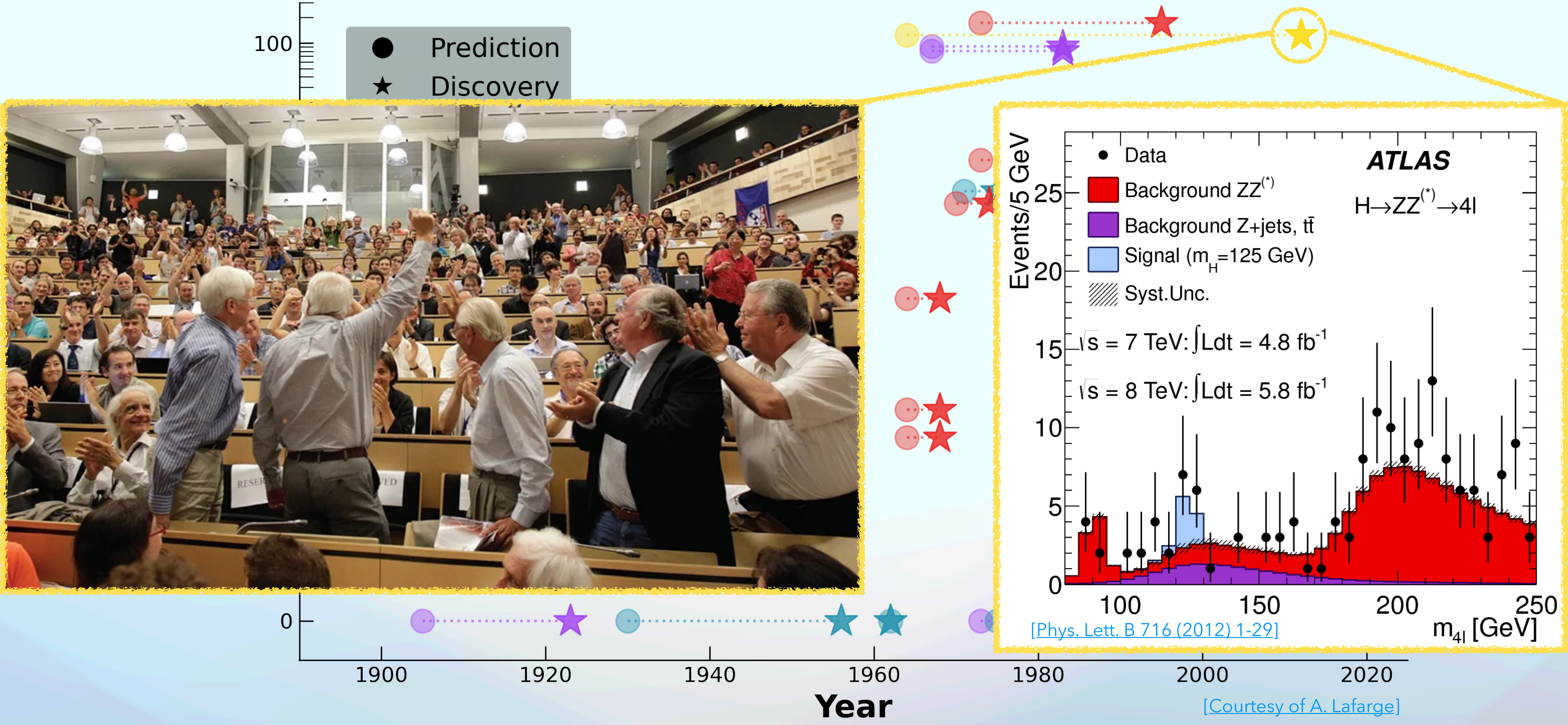
A discovery tale



[Courtesy of A. Lafarge]

A discovery tale

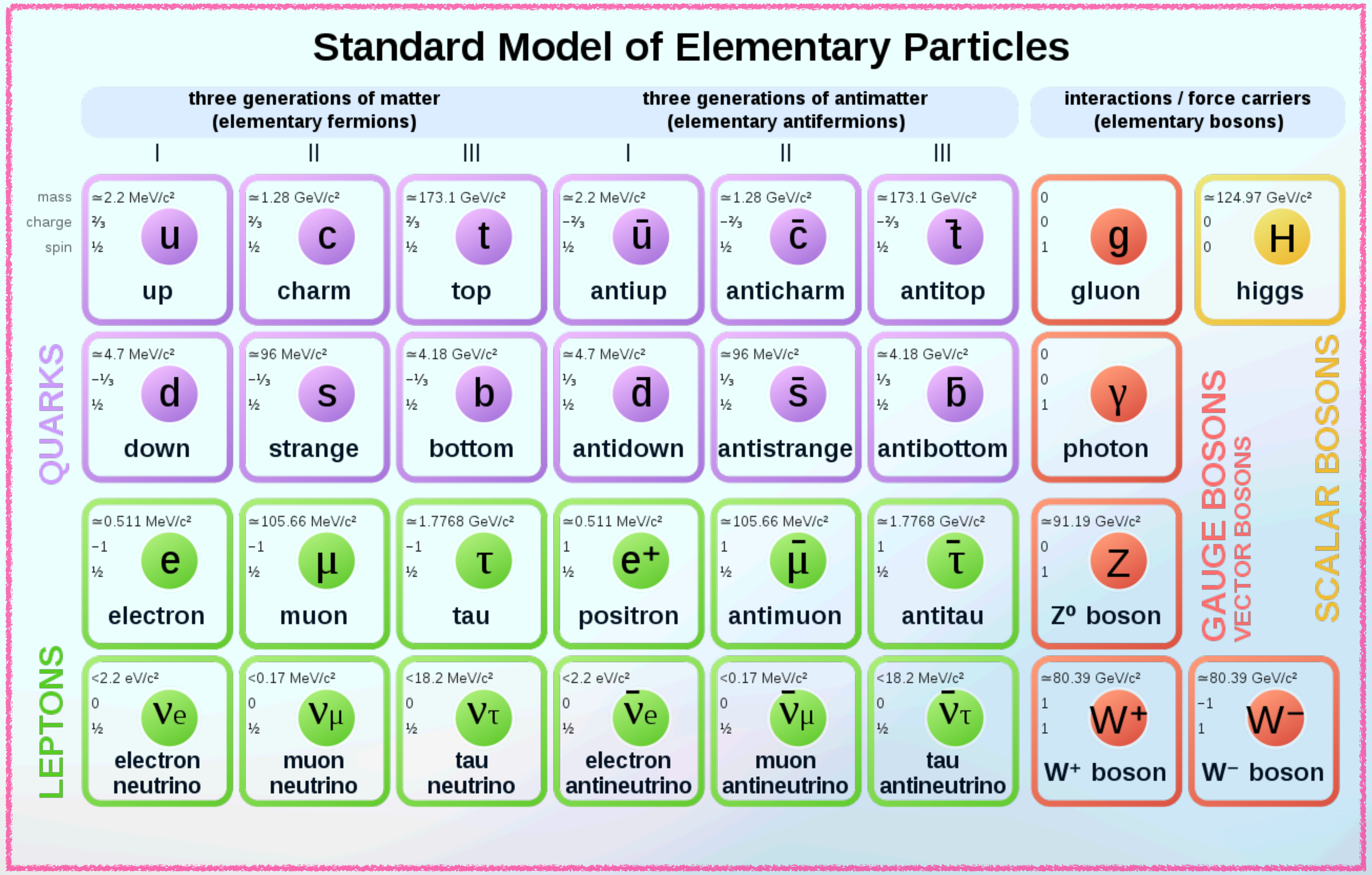


[Phys. Lett. B 716 (2012) 1-29]

[Courtesy of A. Lafarge]

The Standard Model (SM)

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



Standard Model of Elementary Particles

	three generations of matter (elementary fermions) I	II	III	three generations of antimatter (elementary antifermions) I	II	III	interactions / force carriers (elementary bosons)	
mass charge spin	≃2.2 MeV/c² ⅔ ½ u up	≃1.28 GeV/c² ⅔ ½ c charm	≃173.1 GeV/c² ⅔ ½ t top	≃2.2 MeV/c² −⅔ ½ ū antiup	≃1.28 GeV/c² −⅔ ½ c̄ anticharm	≃173.1 GeV/c² −⅔ ½ t̄ antitop	0 0 1 g gluon	≃124.97 GeV/c² 0 0 H higgs
QUARKS	≃4.7 MeV/c² −⅓ ½ d down	≃96 MeV/c² −⅓ ½ s strange	≃4.18 GeV/c² −⅓ ½ b bottom	≃4.7 MeV/c² ⅓ ½ d̄ antidown	≃96 MeV/c² ⅓ ½ s̄ antistrange	≃4.18 GeV/c² ⅓ ½ b̄ antibottom	0 0 1 γ photon	
	≃0.511 MeV/c² −1 ½ e electron	≃105.66 MeV/c² −1 ½ μ muon	≃1.7768 GeV/c² −1 ½ τ tau	≃0.511 MeV/c² 1 ½ e^+ positron	≃105.66 MeV/c² 1 ½ μ̄ antimuon	≃1.7768 GeV/c² 1 ½ τ̄ antitau	≃91.19 GeV/c² 0 1 Z Z^0 boson	
LEPTONS	<2.2 eV/c² 0 ½ νe electron neutrino	<0.17 MeV/c² 0 ½ νμ muon neutrino	<18.2 MeV/c² 0 ½ ντ tau neutrino	<2.2 eV/c² 0 ½ ν̄e electron antineutrino	<0.17 MeV/c² 0 ½ ν̄μ muon antineutrino	<18.2 MeV/c² 0 ½ ν̄τ tau antineutrino	≃80.39 GeV/c² 1 1 W^+ W^+ boson	≃80.39 GeV/c² −1 1 W^- W^- boson

GAUGE BOSONS

VECTOR BOSONS

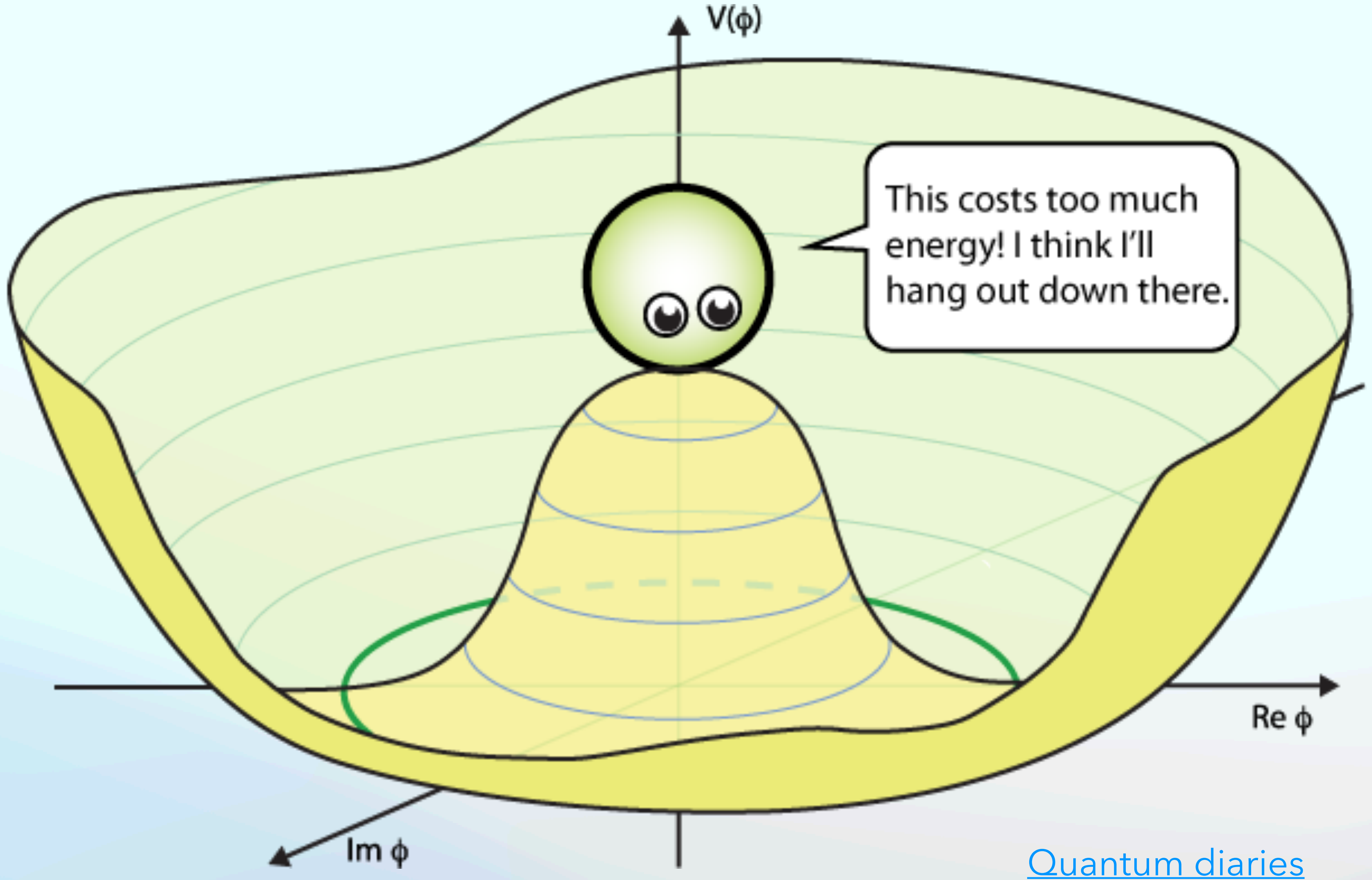
SCALAR BOSONS

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

+

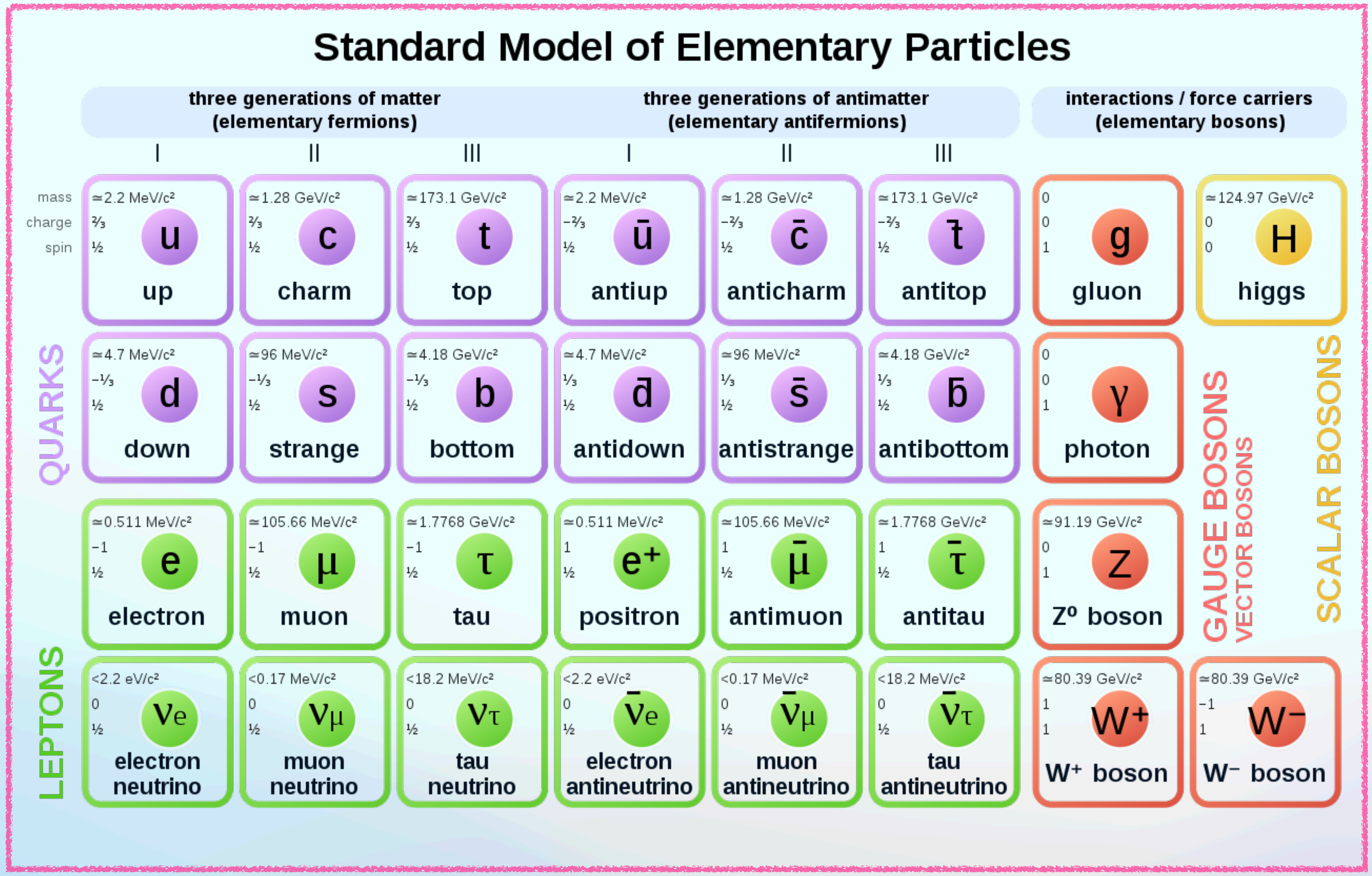
Massive gauge bosons with 3 polarizations

→ **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) ?



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	I	II	III	I	II	III		
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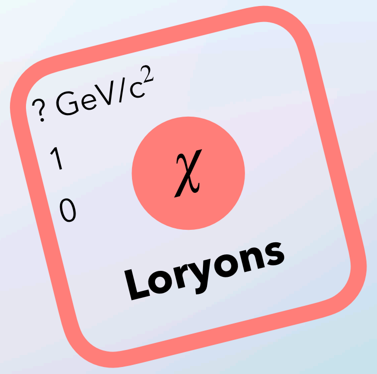
Beyond the SM

Matter-antimatter asymmetry ?

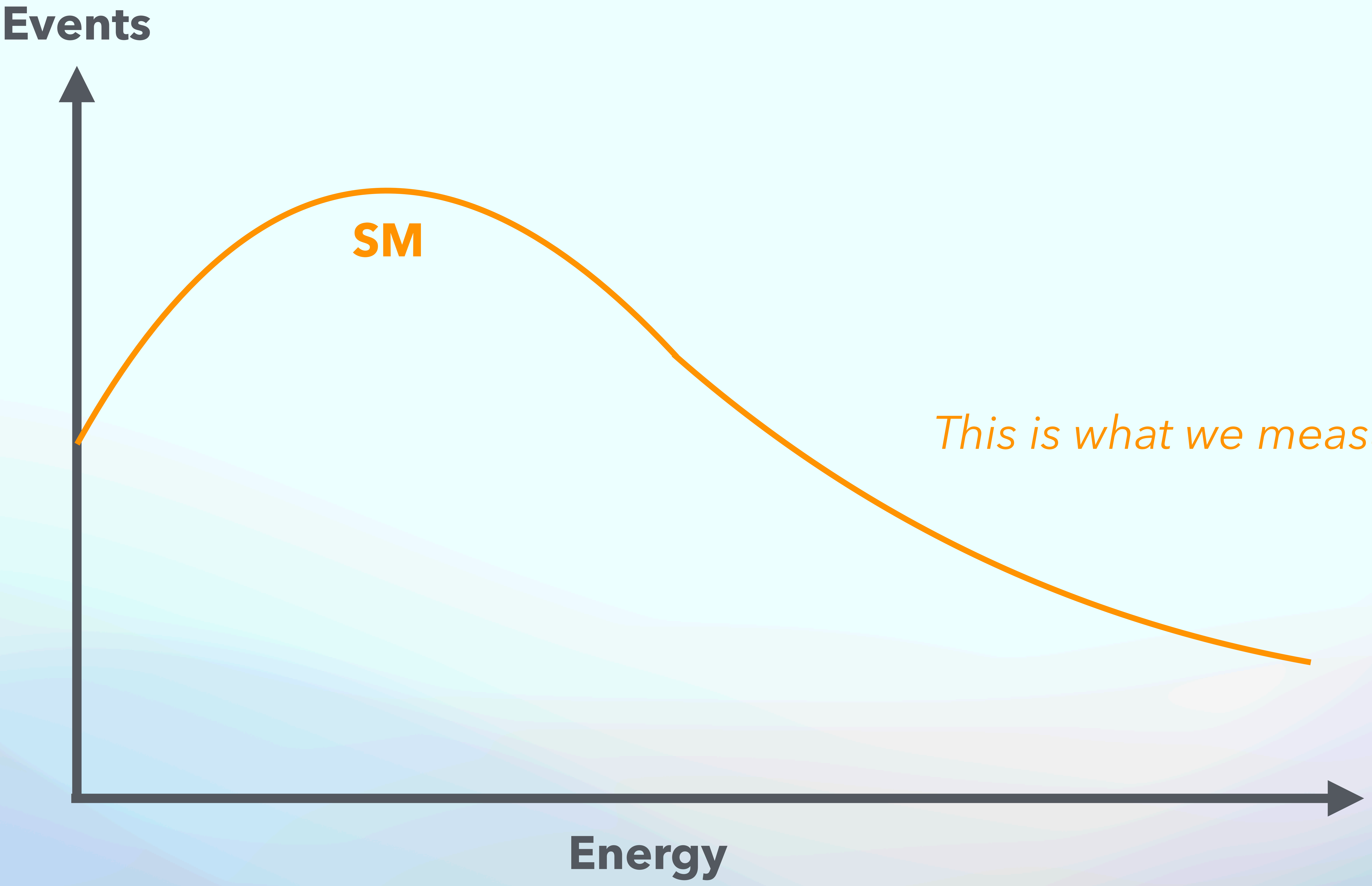
Gravity ?

Shape of Higgs potential ?



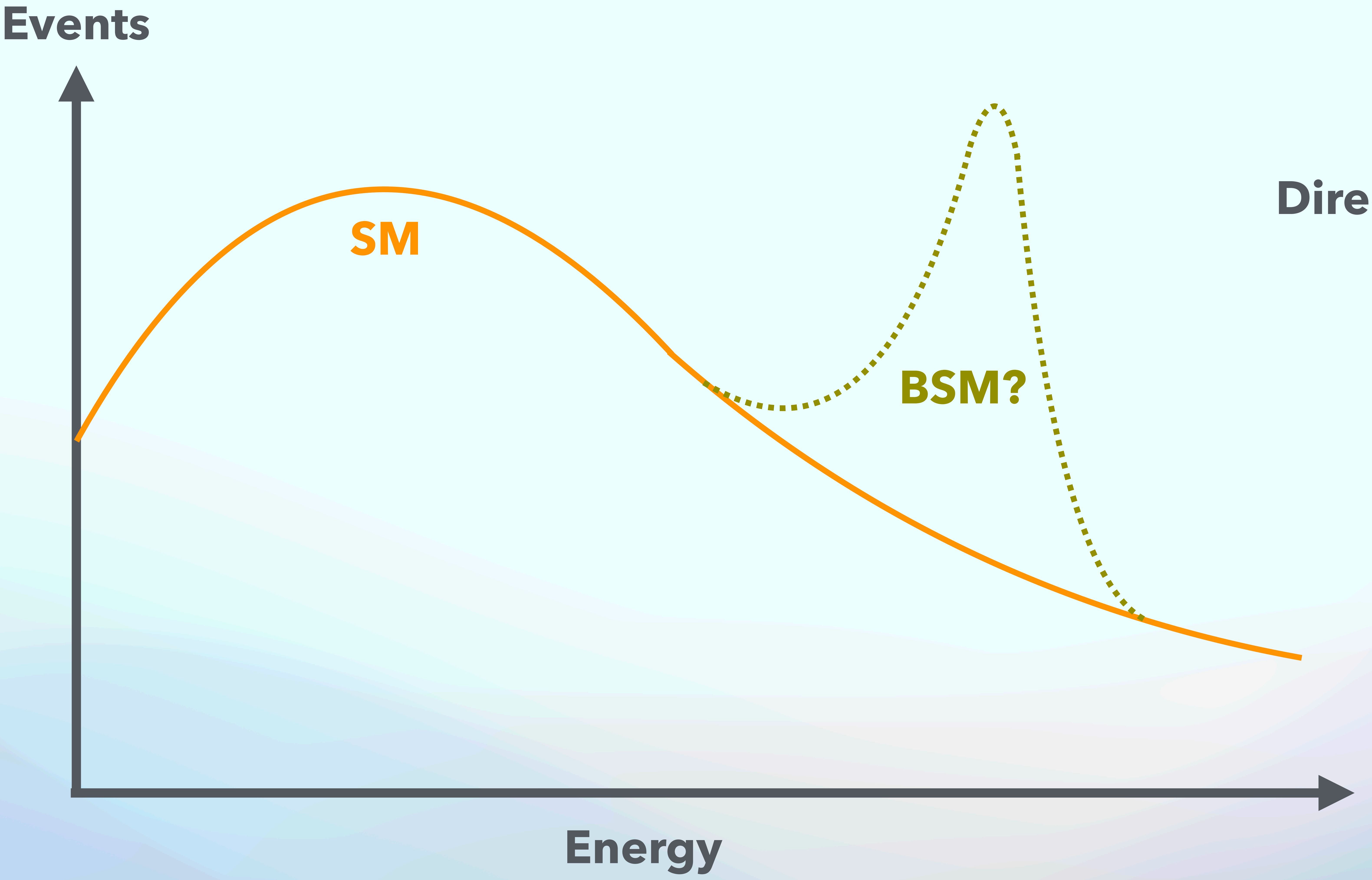
Vacuum stability ?

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"

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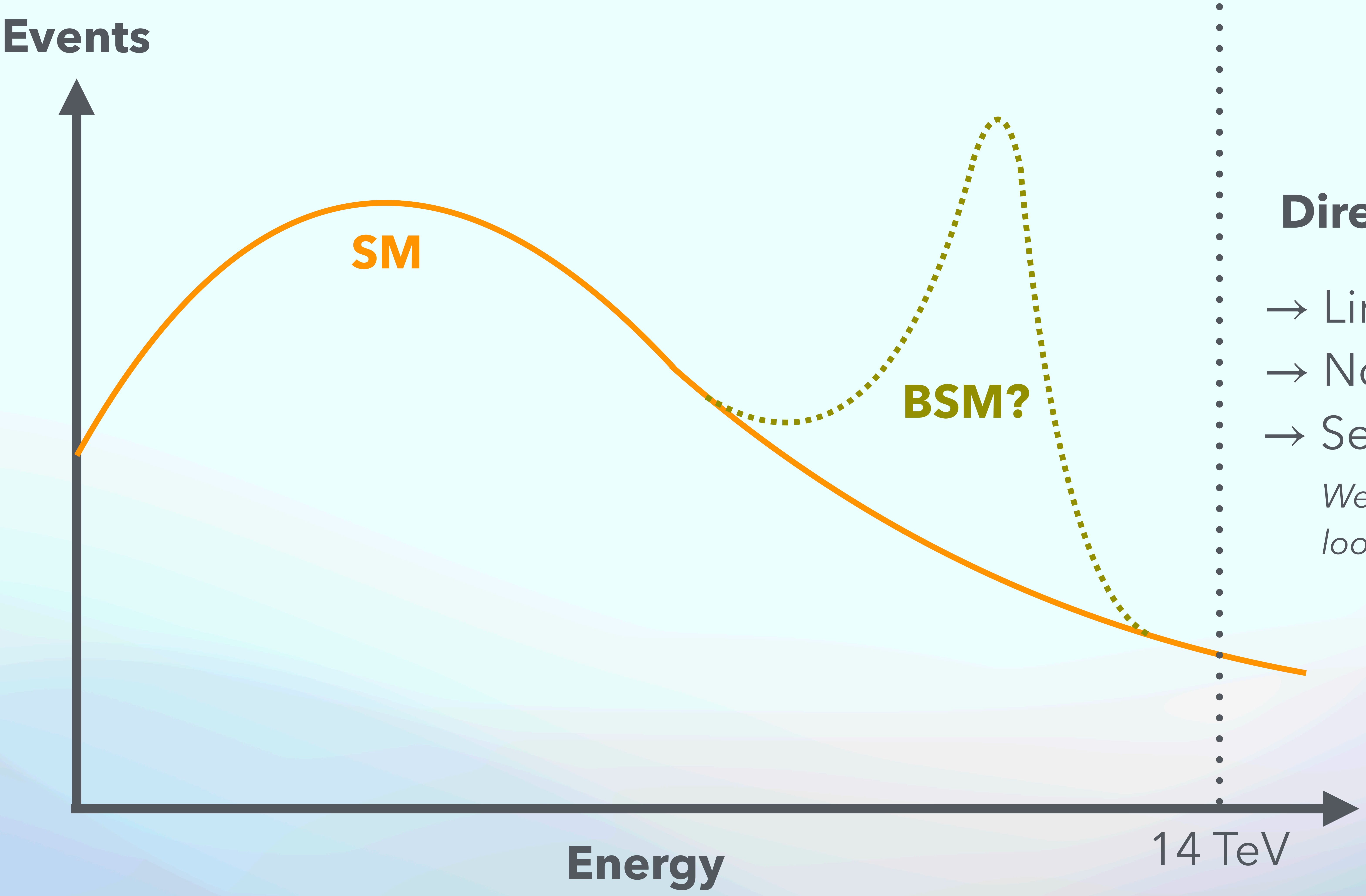
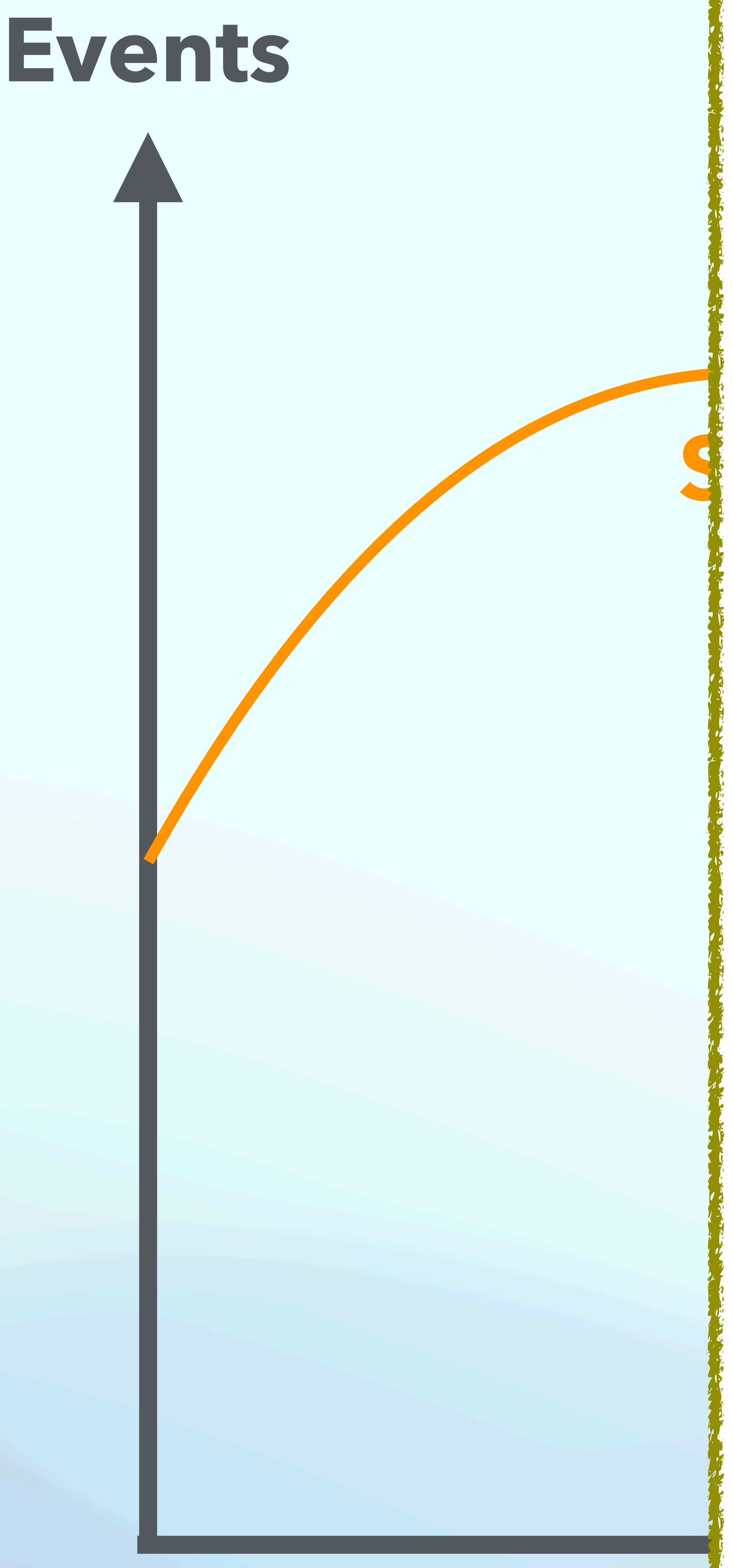


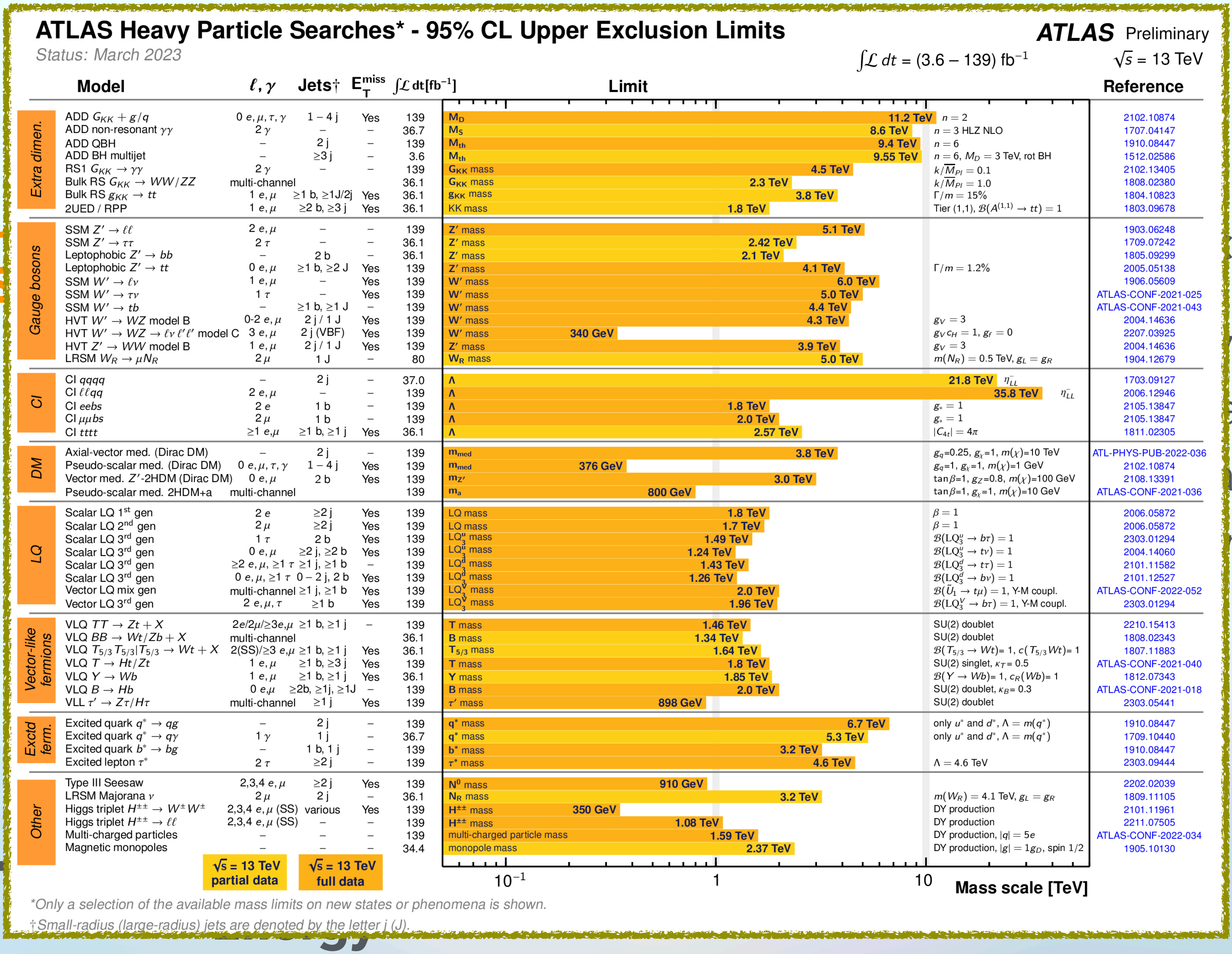
Direct searches, e.g. "bump hunt"

→ 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 ?





ATLAS Heavy Particle Searches* - 95% CL Upper Exclusion Limits

Status: March 2023

ATLAS Preliminary

$\int\mathcal{L}\,dt = (3.6 - 139)\ \mathrm{fb}^{-1}$ $\sqrt{s} = 13$ TeV

	Model	ℓ, γ	Jets†	E_T^{miss}	$\int\mathcal{L}\,dt[\mathrm{fb}^{-1}]$	Limit			Reference
Extra dimen.	ADD $G_{KK} + g/q$	$0\ e, \mu, \tau, \gamma$	$1-4$ j	Yes	139	M_D	11.2 TeV	$n = 2$	2102.10874
	ADD non-resonant $\gamma\gamma$	$2\ \gamma$	–	–	36.7	M_S	8.6 TeV	$n = 3$ HLZ NLO	1707.04147
	ADD QBH	–	2 j	–	139	M_{th}	9.4 TeV	$n = 6$	1910.08447
	ADD BH multijet	–	≥3 j	–	3.6	M_{th}	9.55 TeV	$n = 6$, $M_D = 3$ TeV, rot BH	1512.02586
	RS1 $G_{KK} \to \gamma\gamma$	$2\ \gamma$	–	–	139	G_{KK} mass	4.5 TeV	$k/\overline{M}_{Pl} = 0.1$	2102.13405
	Bulk RS $G_{KK} \to WW/ZZ$	multi-channel			36.1	G_{KK} mass	2.3 TeV	$k/\overline{M}_{Pl} = 1.0$	1808.02380
	Bulk RS $g_{KK} \to tt$	$1\ e, \mu$	≥1 b, ≥1J/2j	Yes	36.1	g_{KK} mass	3.8 TeV	$\Gamma/m = 15\%$	1804.10823
	2UED / RPP	$1\ e, \mu$	≥2 b, ≥3 j	Yes	36.1	KK mass	1.8 TeV	Tier (1,1), $\mathcal{B}(A^{(1,1)} \to tt) = 1$	1803.09678
Gauge bosons	SSM $Z' \to \ell\ell$	$2\ e, \mu$	–	–	139	Z' mass	5.1 TeV		1903.06248
	SSM $Z' \to \tau\tau$	$2\ \tau$	–	–	36.1	Z' mass	2.42 TeV		1709.07242
	Leptophobic $Z' \to bb$	–	2 b	–	36.1	Z' mass	2.1 TeV		1805.09299
	Leptophobic $Z' \to tt$	$0\ e, \mu$	≥1 b, ≥2 J	Yes	139	Z' mass	4.1 TeV	$\Gamma/m = 1.2\%$	2005.05138
	SSM $W' \to \ell\nu$	$1\ e, \mu$	–	Yes	139	W' mass	6.0 TeV		1906.05609
	SSM $W' \to \tau\nu$	$1\ \tau$	–	Yes	139	W' mass	5.0 TeV		ATLAS-CONF-2021-025
	SSM $W' \to tb$	–	≥1 b, ≥1 J	–	139	W' mass	4.4 TeV		ATLAS-CONF-2021-043
	HVT $W' \to WZ$ model B	0-2 e, μ	2 j / 1 J	Yes	139	W' mass	4.3 TeV	$g_V = 3$	2004.14636
	HVT $W' \to WZ \to \ell\nu\,\ell'\ell'$ model C	$3\ e, \mu$	2 j (VBF)	Yes	139	W' mass	340 GeV	$g_V c_H = 1$, $g_f = 0$	2207.03925
	HVT $Z' \to WW$ model B	$1\ e, \mu$	2 j / 1 J	Yes	139	Z' mass	3.9 TeV	$g_V = 3$	2004.14636
	LRSM $W_R \to \mu N_R$	$2\ \mu$	1 J	–	80	W_R mass	5.0 TeV	$m(N_R) = 0.5$ TeV, $g_L = g_R$	1904.12679
CI	CI $qqqq$	–	2 j	–	37.0	Λ	21.8 TeV	η_{LL}^-	1703.09127
	CI $\ell\ell qq$	$2\ e, \mu$	–	–	139	Λ	35.8 TeV	η_{LL}^-	2006.12946
	CI $eebs$	$2\ e$	1 b	–	139	Λ	1.8 TeV	$g_* = 1$	2105.13847
	CI $\mu\mu bs$	$2\ \mu$	1 b	–	139	Λ	2.0 TeV	$g_* = 1$	2105.13847
	CI $tttt$	≥1 e,μ	≥1 b, ≥1 j	Yes	36.1	Λ	2.57 TeV	$\lvert C_{4t}\rvert = 4\pi$	1811.02305
DM	Axial-vector med. (Dirac DM)	–	2 j	–	139	m_{med}	3.8 TeV	g_q=0.25, g_χ=1, $m(\chi)$=10 TeV	ATL-PHYS-PUB-2022-036
	Pseudo-scalar med. (Dirac DM)	$0\ e, \mu, \tau, \gamma$	$1-4$ j	Yes	139	m_{med}	376 GeV	g_q=1, g_χ=1, $m(\chi)$=1 GeV	2102.10874
	Vector med. Z'-2HDM (Dirac DM)	$0\ e, \mu$	2 b	Yes	139	$m_{Z'}$	3.0 TeV	$\tan\beta$=1, g_Z=0.8, $m(\chi)$=100 GeV	2108.13391
	Pseudo-scalar med. 2HDM+a	multi-channel			139	m_a	800 GeV	$\tan\beta$=1, g_χ=1, $m(\chi)$=10 GeV	ATLAS-CONF-2021-036
LQ	Scalar LQ 1st gen	$2\ e$	≥2 j	Yes	139	LQ mass	1.8 TeV	$\beta = 1$	2006.05872
	Scalar LQ 2nd gen	$2\ \mu$	≥2 j	Yes	139	LQ mass	1.7 TeV	$\beta = 1$	2006.05872
	Scalar LQ 3rd gen	$1\ \tau$	2 b	Yes	139	LQ_3^u mass	1.49 TeV	$\mathcal{B}(LQ_3^u \to b\tau) = 1$	2303.01294
	Scalar LQ 3rd gen	$0\ e, \mu$	≥2 j, ≥2 b	Yes	139	LQ_3^u mass	1.24 TeV	$\mathcal{B}(LQ_3^u \to t\nu) = 1$	2004.14060
	Scalar LQ 3rd gen	≥2 e, μ, ≥1 τ	≥1 j, ≥1 b	–	139	LQ_3^d mass	1.43 TeV	$\mathcal{B}(LQ_3^d \to t\tau) = 1$	2101.11582
	Scalar LQ 3rd gen	$0\ e, \mu$, ≥1 τ	$0-2$ j, 2 b	Yes	139	LQ_3^d mass	1.26 TeV	$\mathcal{B}(LQ_3^d \to b\nu) = 1$	2101.12527
	Vector LQ mix gen	multi-channel	≥1 j, ≥1 b	Yes	139	LQ_3^V mass	2.0 TeV	$\mathcal{B}(\tilde{U}_1 \to t\mu) = 1$, Y-M coupl.	ATLAS-CONF-2022-052
	Vector LQ 3rd gen	$2\ e, \mu, \tau$	≥1 b	Yes	139	LQ_3^V mass	1.96 TeV	$\mathcal{B}(LQ_3^V \to b\tau) = 1$, Y-M coupl.	2303.01294
Vector-like fermions	VLQ $TT \to Zt + X$	$2e/2\mu/{\geq}3e,\mu$	≥1 b, ≥1 j	–	139	T mass	1.46 TeV	SU(2) doublet	2210.15413
	VLQ $BB \to Wt/Zb + X$	multi-channel			36.1	B mass	1.34 TeV	SU(2) doublet	1808.02343
	VLQ $T_{5/3}T_{5/3} \vert T_{5/3} \to Wt + X$	2(SS)/≥3 e,μ	≥1 b, ≥1 j	Yes	36.1	$T_{5/3}$ mass	1.64 TeV	$\mathcal{B}(T_{5/3} \to Wt)$= 1, $c(T_{5/3}Wt)$= 1	1807.11883
	VLQ $T \to Ht/Zt$	$1\ e, \mu$	≥1 b, ≥3 j	Yes	139	T mass	1.8 TeV	SU(2) singlet, κ_T= 0.5	ATLAS-CONF-2021-040
	VLQ $Y \to Wb$	$1\ e, \mu$	≥1 b, ≥1 j	Yes	36.1	Y mass	1.85 TeV	$\mathcal{B}(Y \to Wb)$= 1, $c_R(Wb)$= 1	1812.07343
	VLQ $B \to Hb$	$0\ e,\mu$	≥2b, ≥1j, ≥1J	–	139	B mass	2.0 TeV	SU(2) doublet, κ_B= 0.3	ATLAS-CONF-2021-018
	VLL $\tau' \to Z\tau/H\tau$	multi-channel	≥1 j	Yes	139	τ' mass	898 GeV	SU(2) doublet	2303.05441
Exctd ferm.	Excited quark $q^* \to qg$	–	2 j	–	139	q^* mass	6.7 TeV	only u^* and d^*, $\Lambda = m(q^*)$	1910.08447
	Excited quark $q^* \to q\gamma$	$1\ \gamma$	1 j	–	36.7	q^* mass	5.3 TeV	only u^* and d^*, $\Lambda = m(q^*)$	1709.10440
	Excited quark $b^* \to bg$	–	1 b, 1 j	–	139	b^* mass	3.2 TeV		1910.08447
	Excited lepton τ^*	$2\ \tau$	≥2 j	–	139	τ^* mass	4.6 TeV	$\Lambda = 4.6$ TeV	2303.09444
Other	Type III Seesaw	2,3,4 e, μ	≥2 j	Yes	139	N^0 mass	910 GeV		2202.02039
	LRSM Majorana ν	$2\ \mu$	2 j	–	36.1	N_R mass	3.2 TeV	$m(W_R) = 4.1$ TeV, $g_L = g_R$	1809.11105
	Higgs triplet $H^{\pm\pm} \to W^\pm W^\pm$	2,3,4 e, μ (SS)	various	Yes	139	$H^{\pm\pm}$ mass	350 GeV	DY production	2101.11961
	Higgs triplet $H^{\pm\pm} \to \ell\ell$	2,3,4 e, μ (SS)	–	–	139	$H^{\pm\pm}$ mass	1.08 TeV	DY production	2211.07505
	Multi-charged particles	–	–	–	139	multi-charged particle mass	1.59 TeV	DY production, $\lvert q\rvert = 5e$	ATLAS-CONF-2022-034
	Magnetic monopoles	–	–	–	34.4	monopole mass	2.37 TeV	DY production, $\lvert g\rvert = 1g_D$, spin 1/2	1905.10130

*Only a selection of the available mass limits on new states or phenomena is shown.

†Small-radius (large-radius) jets are denoted by the letter j (J).

hes, e.g. "bump hunt"

collider energy reach

article discovered (yet?)

re very model dependent

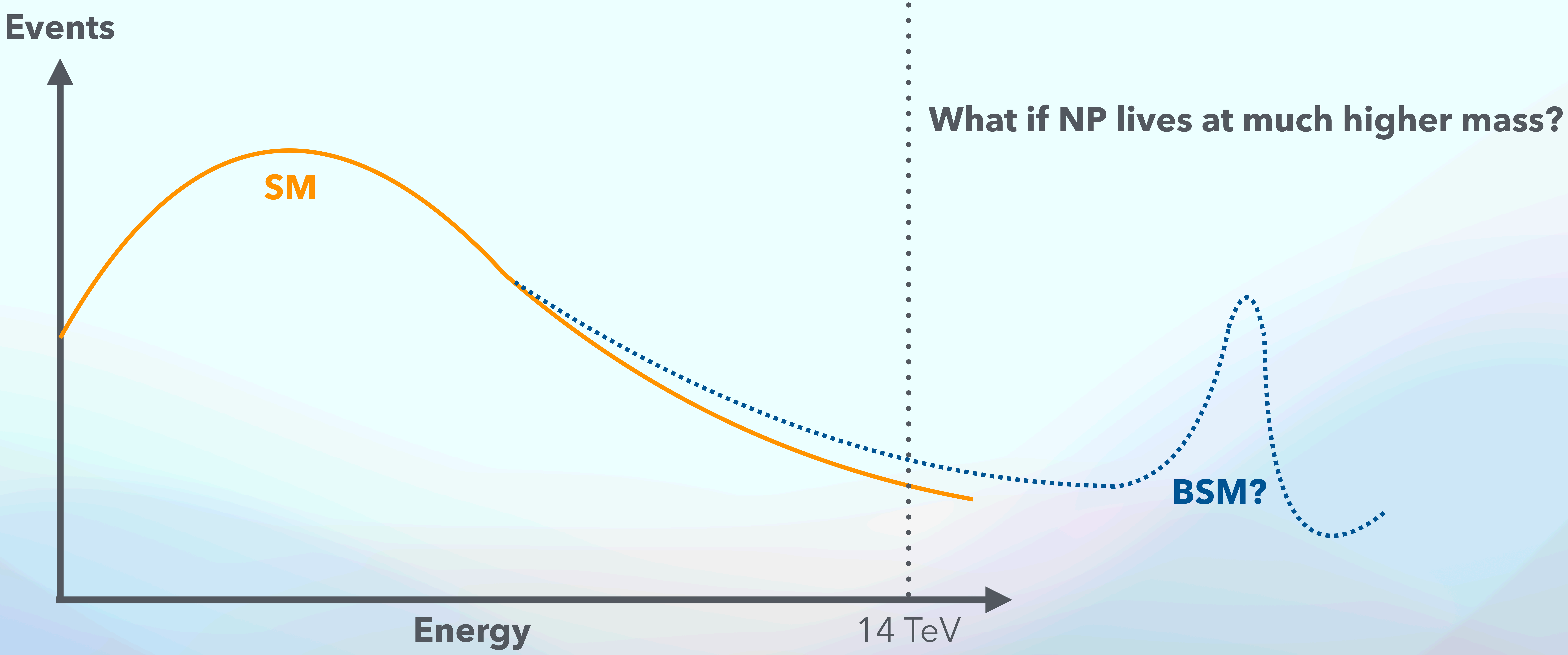
need to roughly know what we are

Nothing so far!

ATL-PHYS-PUB-2024-008

Adrien Auriol - LAPP Seminar

Going beyond the SM - direct or effective ?



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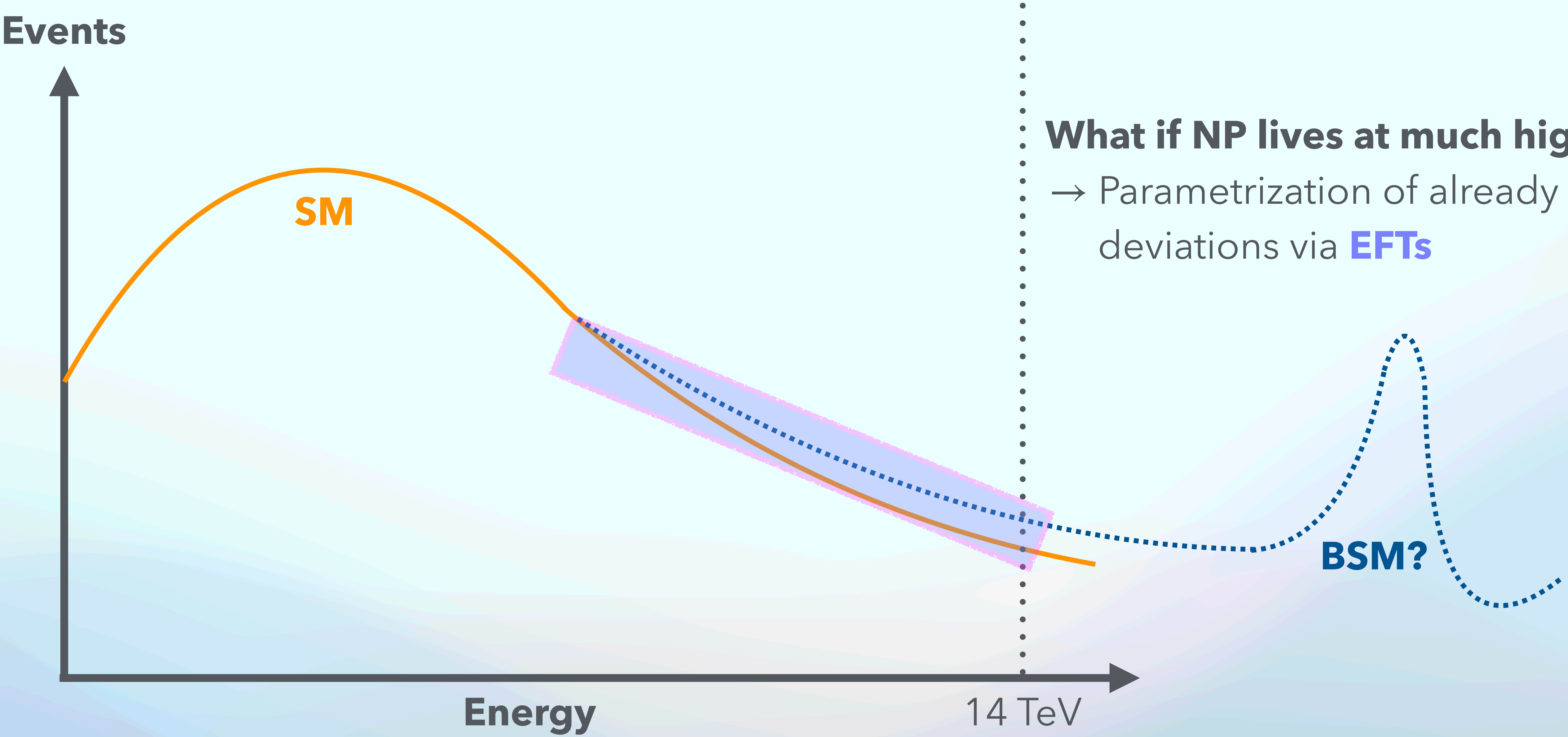
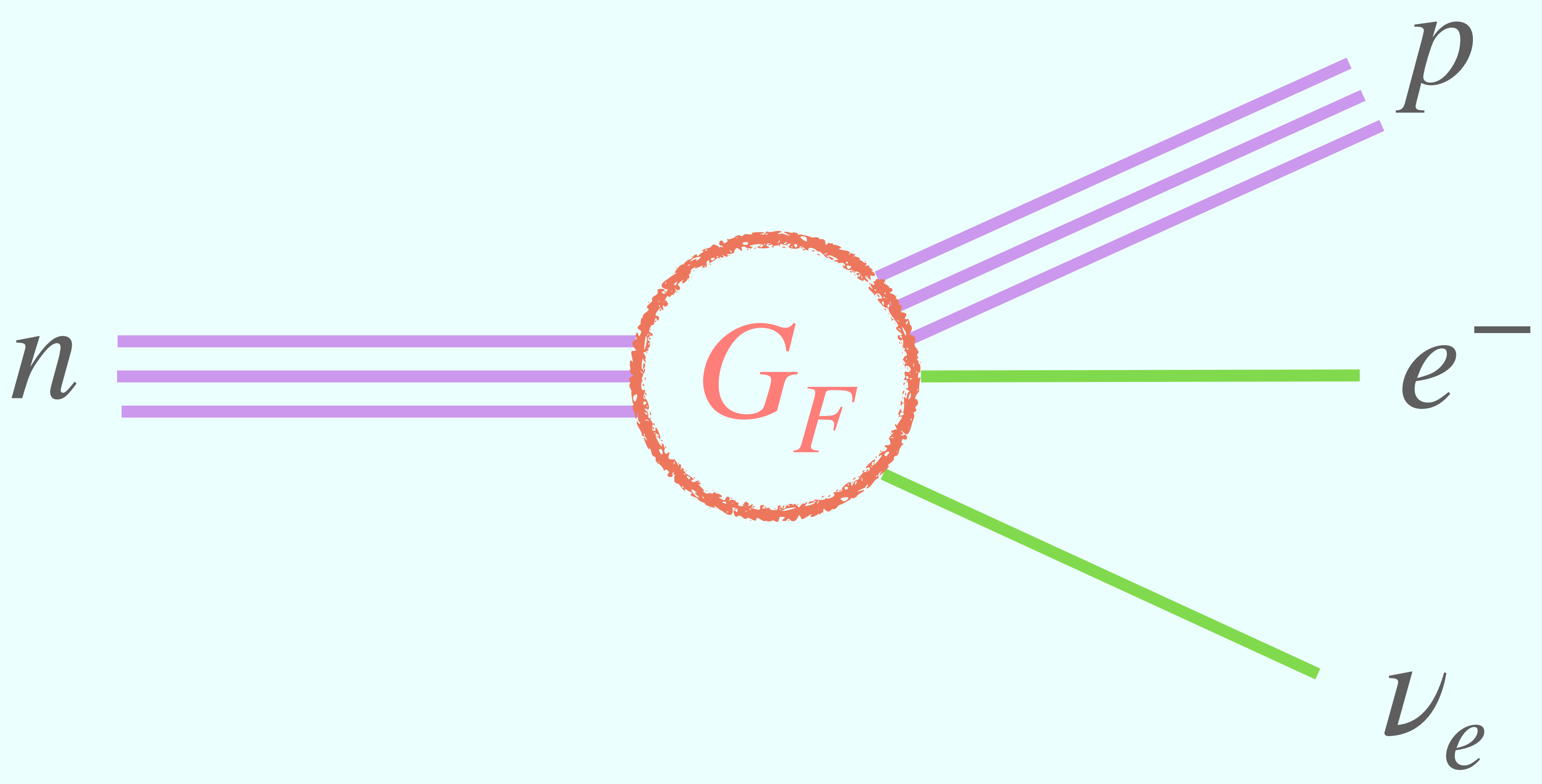


What if NP lives at much higher mass?

→ 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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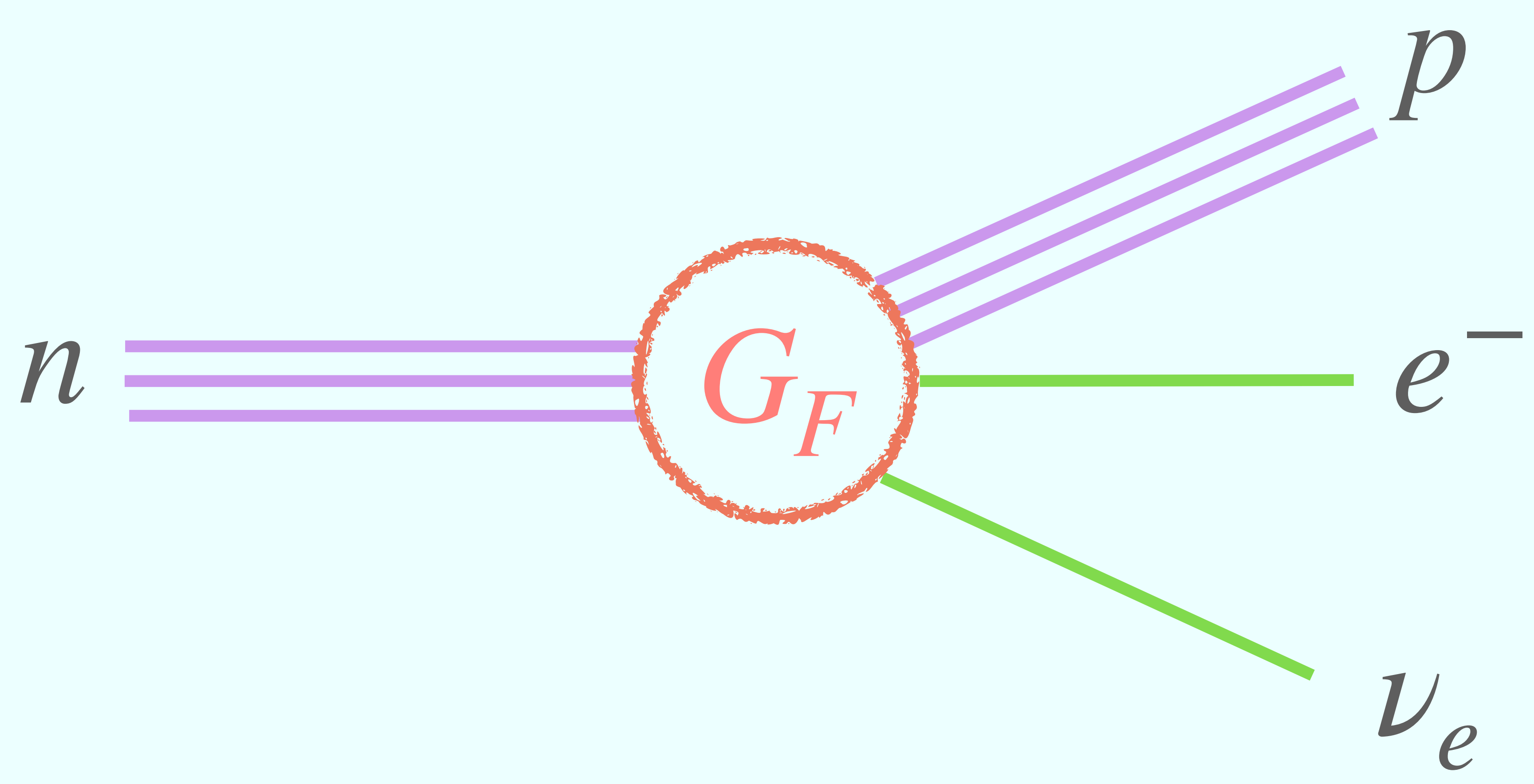

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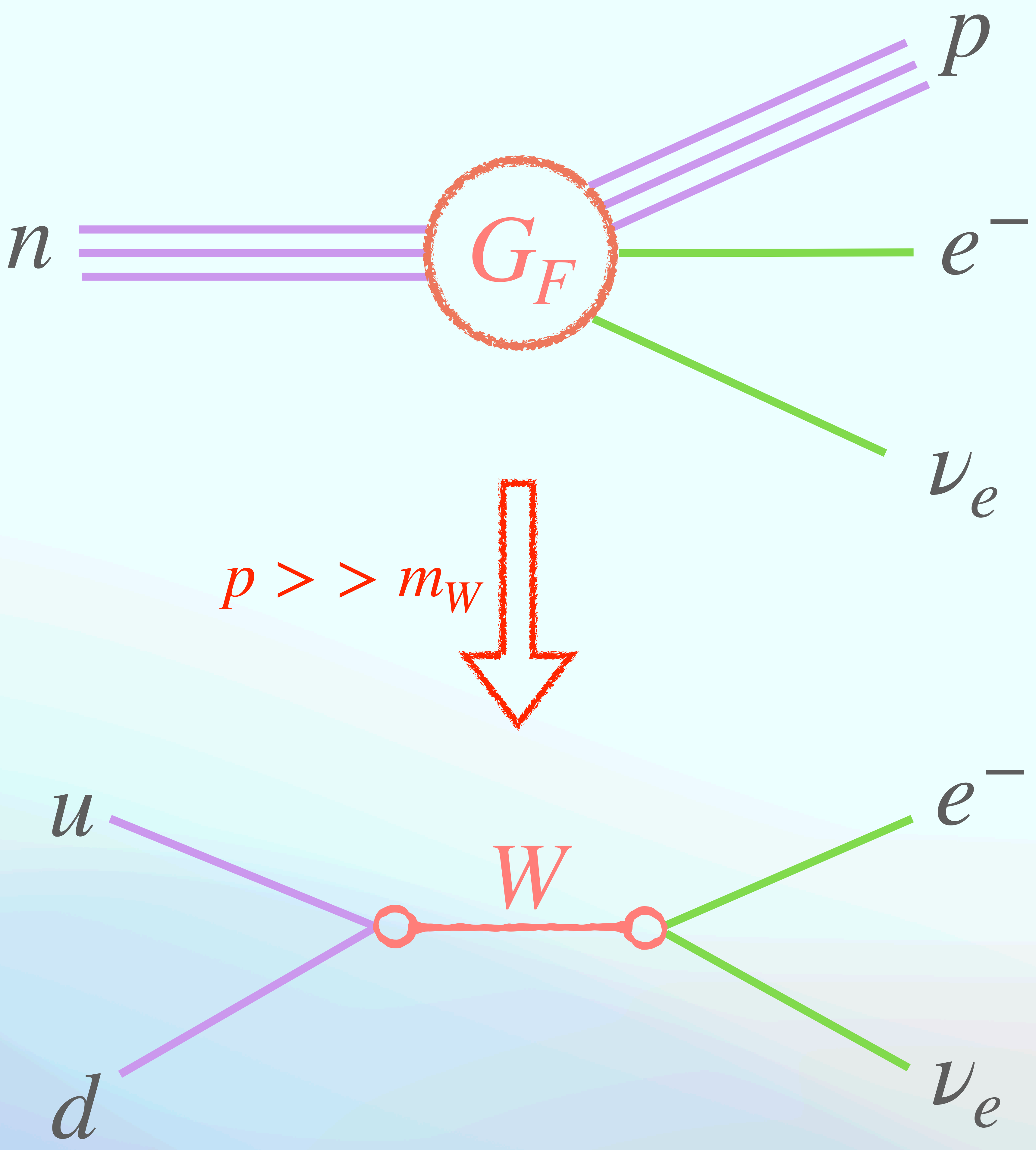
Cross-section grows with s → **Violation of unitarity**

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**

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

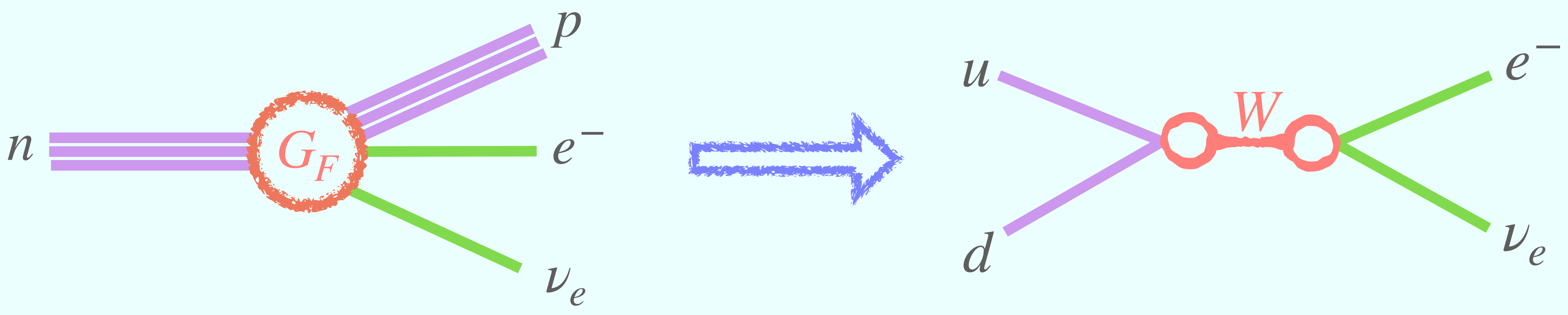
Cross-section grows with s → **Violation of unitarity**

→ 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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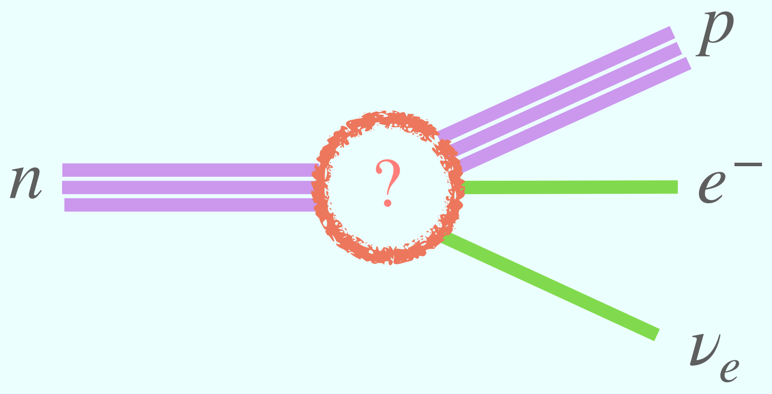
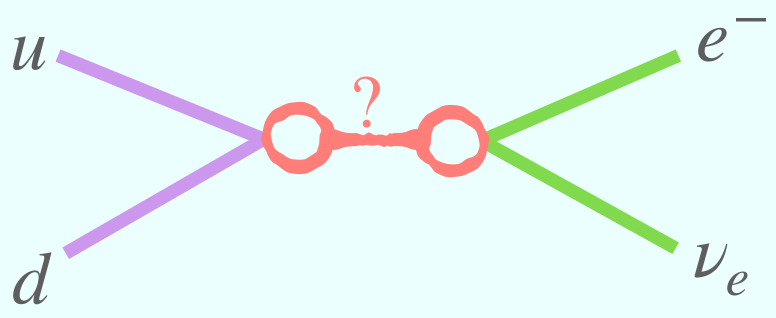


⇐



But can we go the other way?

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

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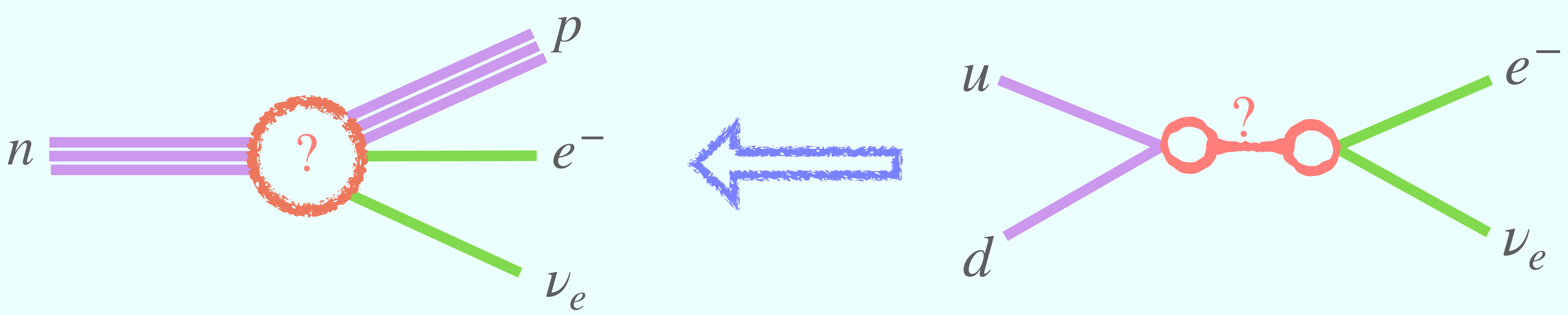

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EFT recipe

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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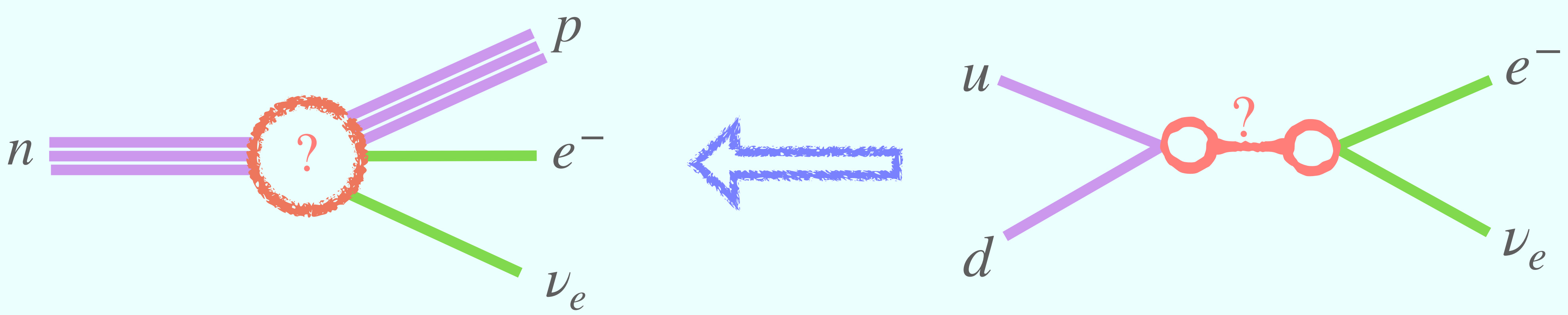

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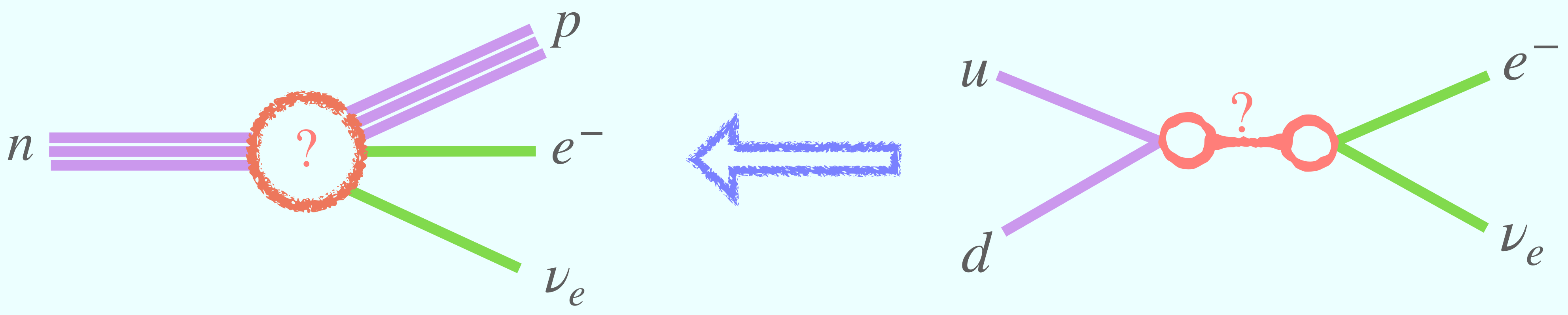

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Step 1 : We fix the field content → SM

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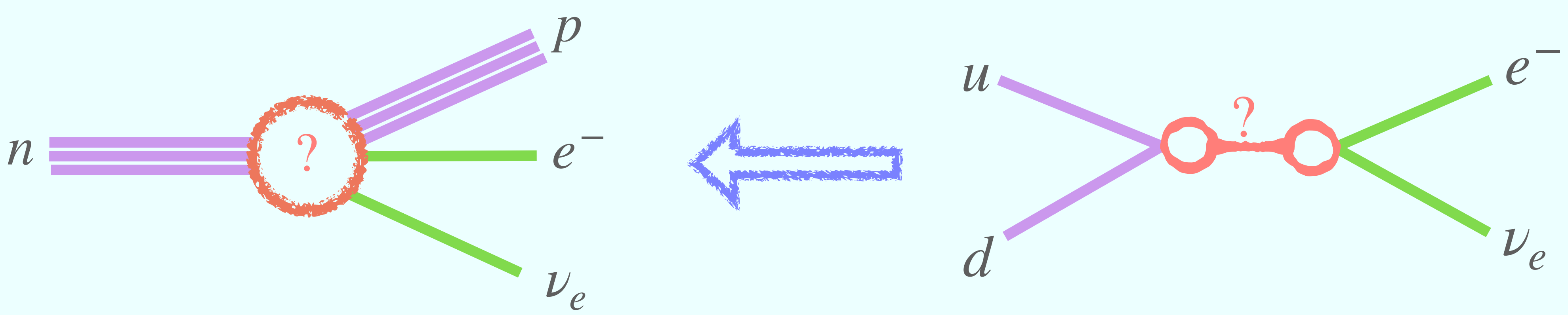

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Step 1 : We fix the field content → SM

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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

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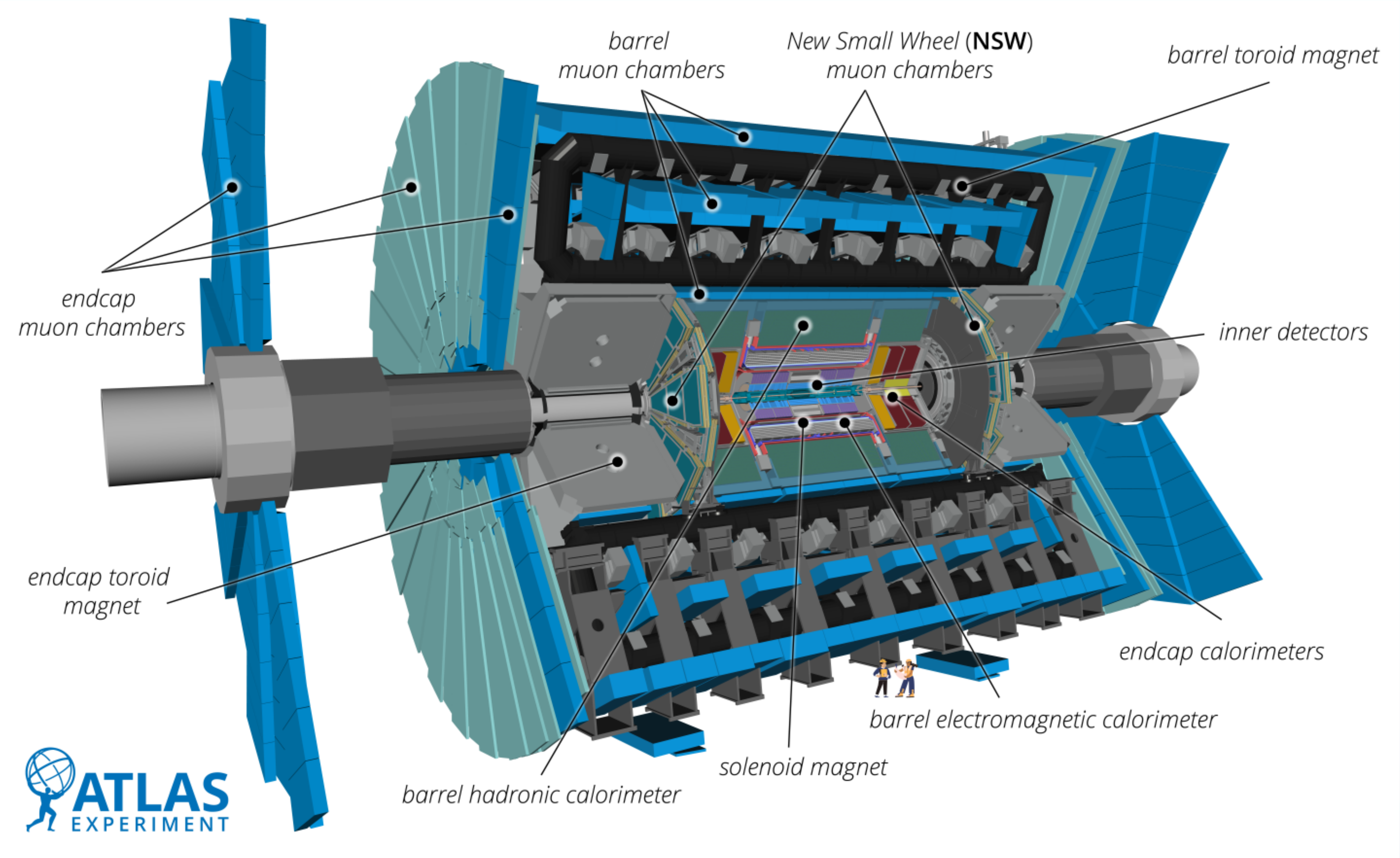
General purpose detectors : ATLAS & CMS



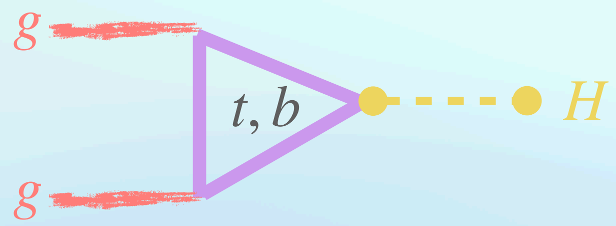
(biased) e.g. ATLAS here, but same main principle for CMS

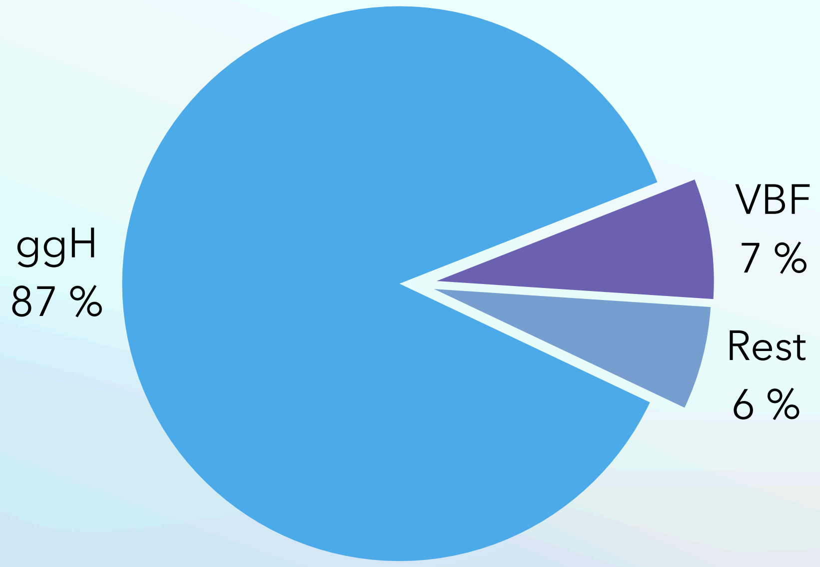
- "**Onion layers**" detector structure
- Various **subsystems** used in combination :
  - Trigger
  - Tracking
  - Calorimetry
  - Particle Identification

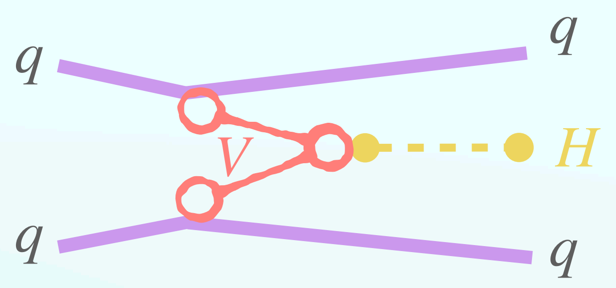
1st protagonist

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







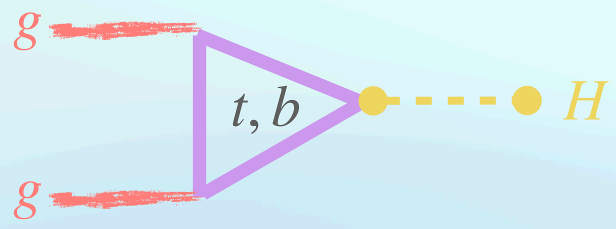
For SM Higgs @ 13 TeV...

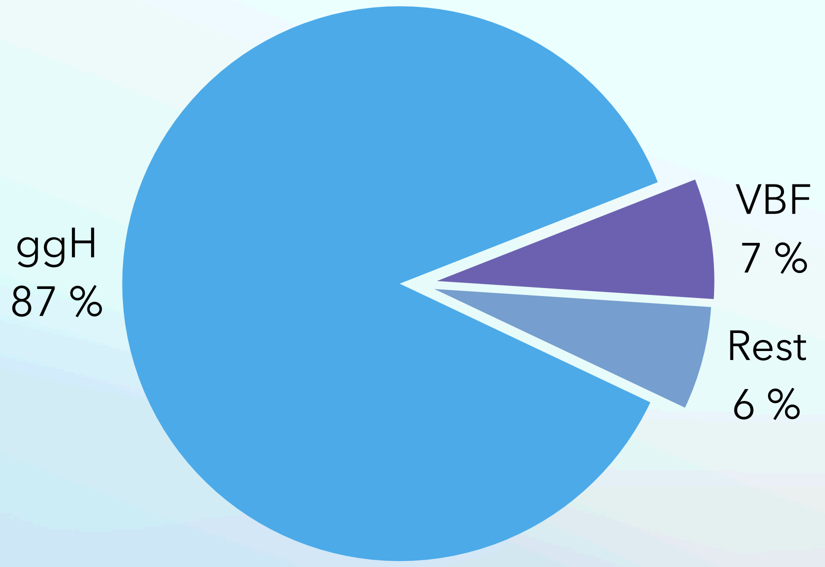
Higgs @ proton collider : prod. and decay

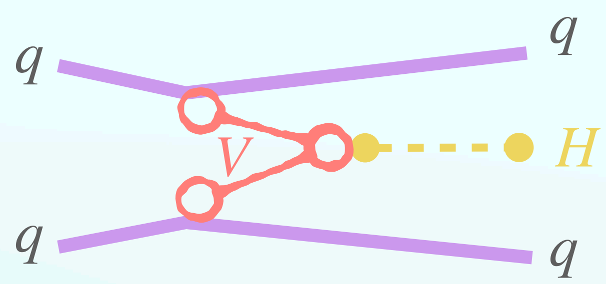
≈124.97 GeV/c²
0
0
H
higgs

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

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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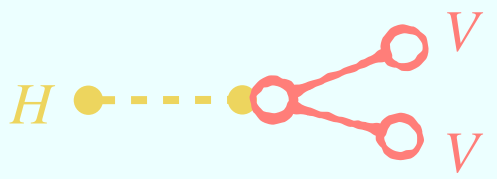
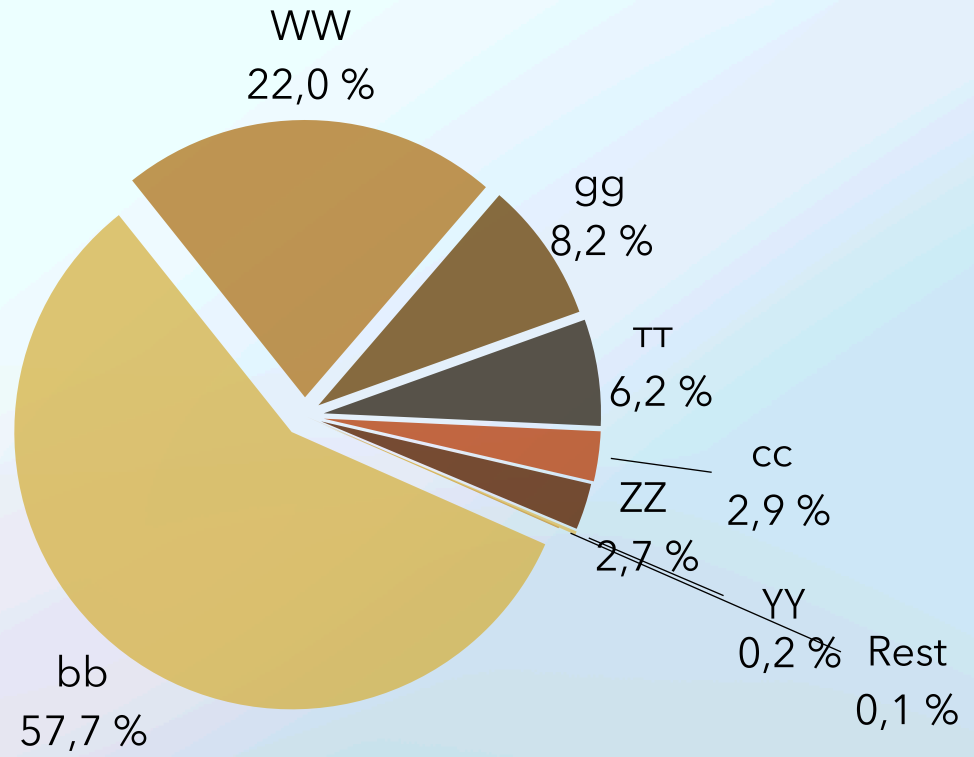
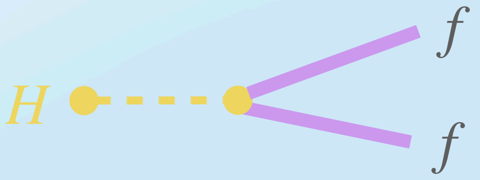
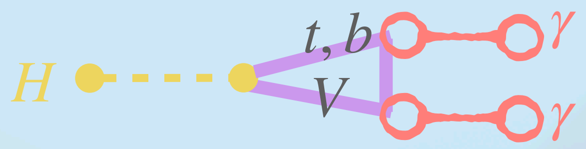




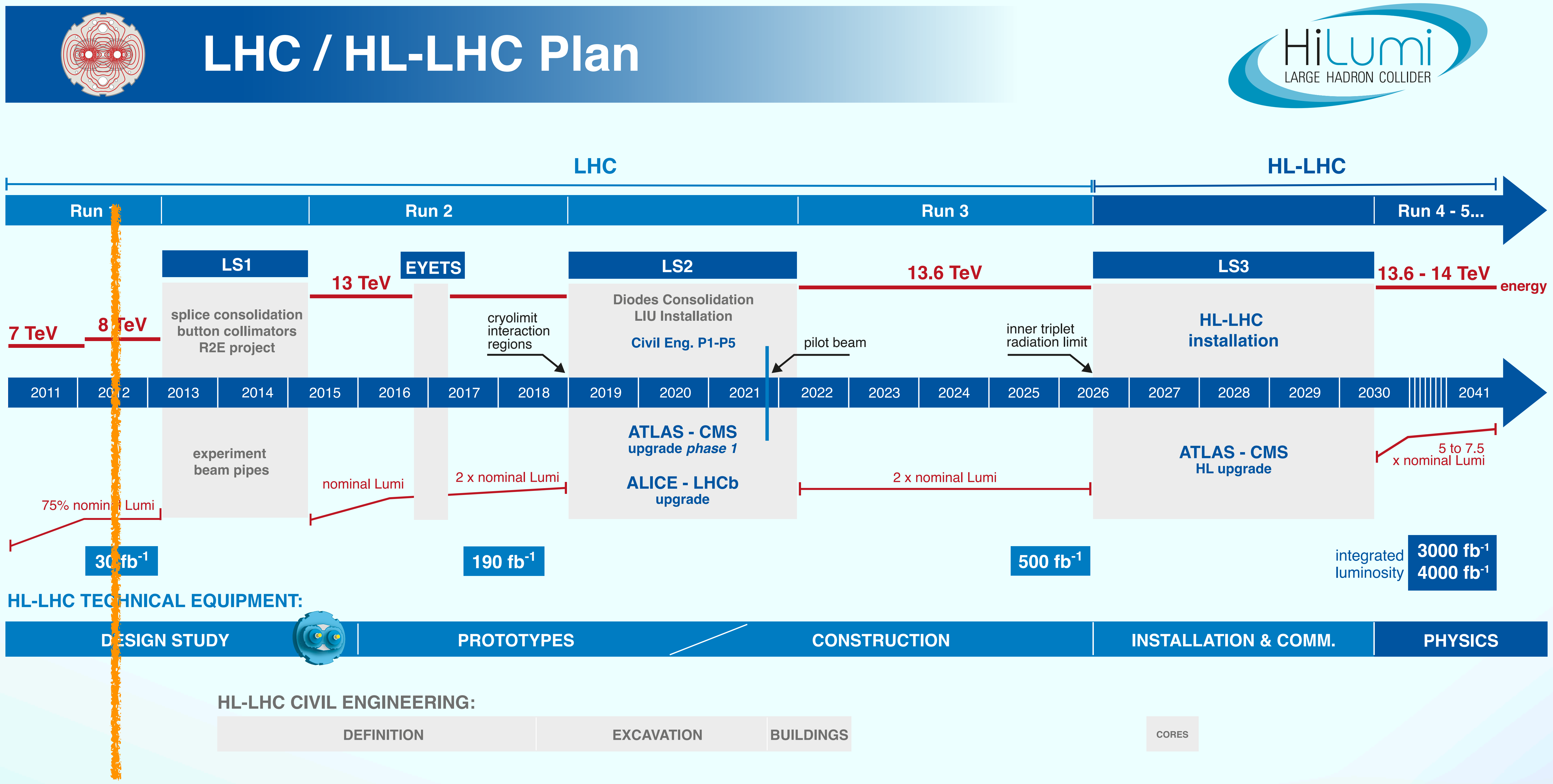




Higgs has narrow width and decays very quickly!

Timeline since discovery

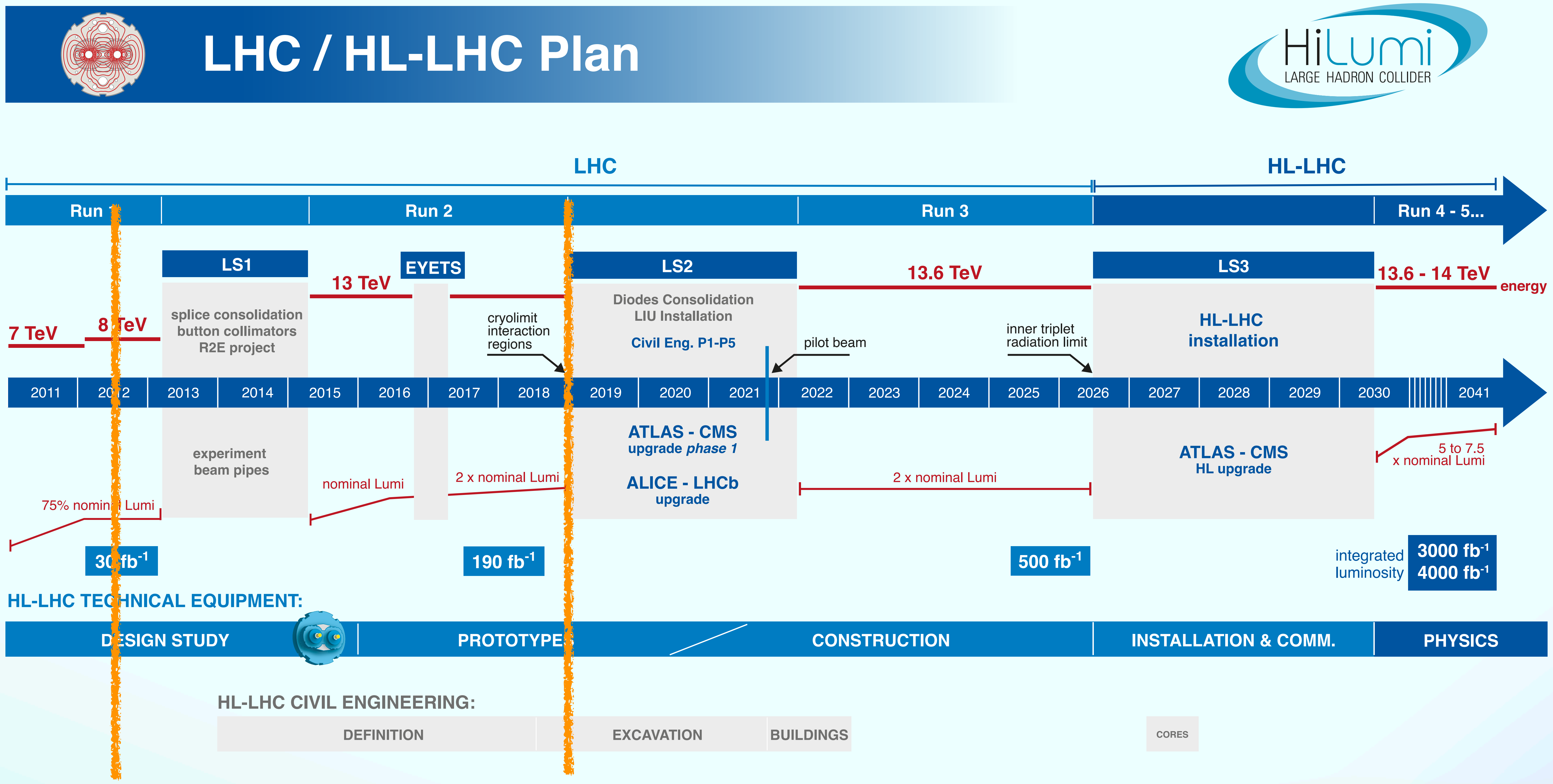
Timeline since discovery



Discovery

~200k Higgs prod.

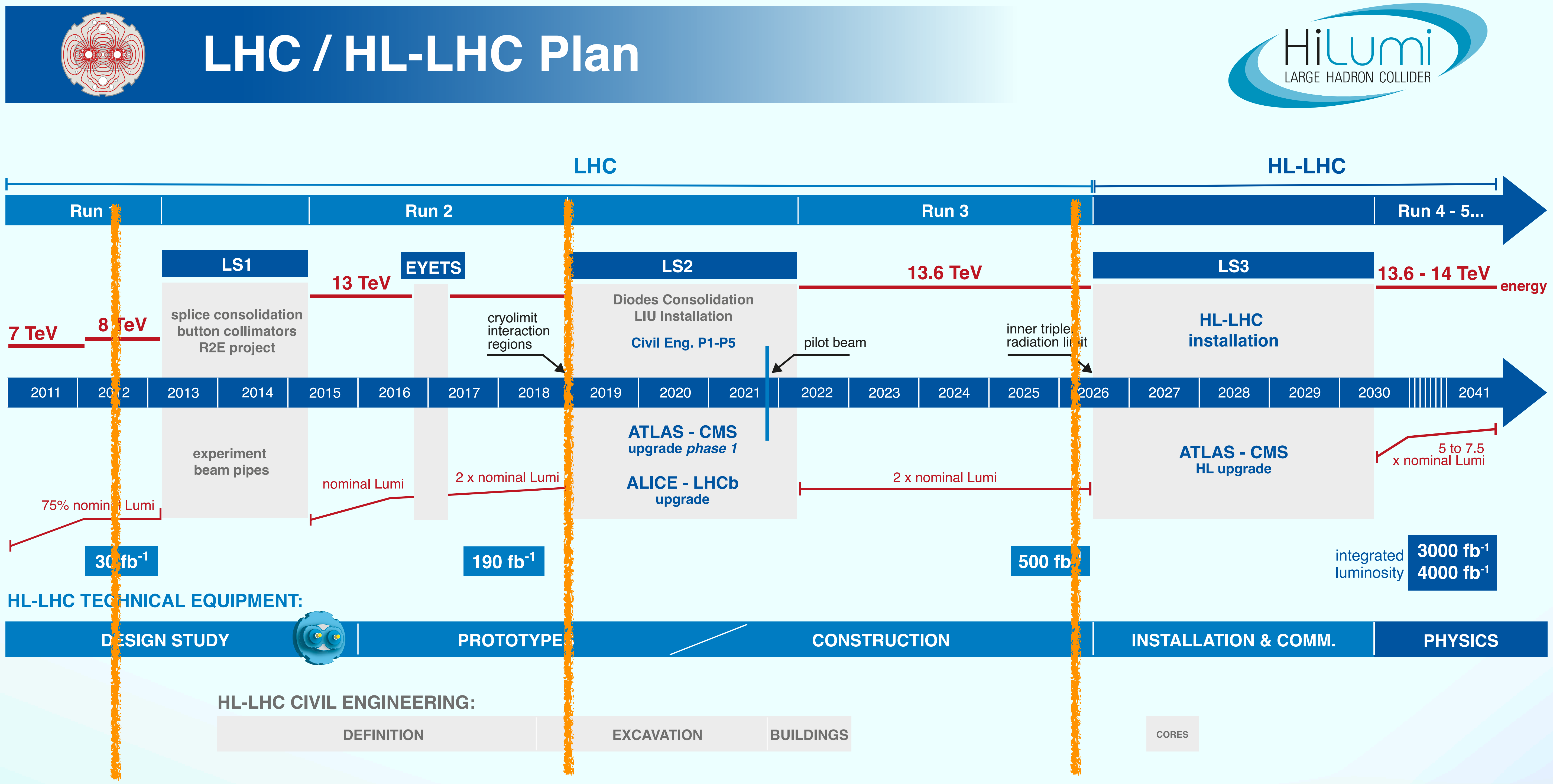
Timeline since discovery



Discovery
~200k Higgs prod.

End of Run 2
~7.7M Higgs prod.

Timeline since discovery



Discovery
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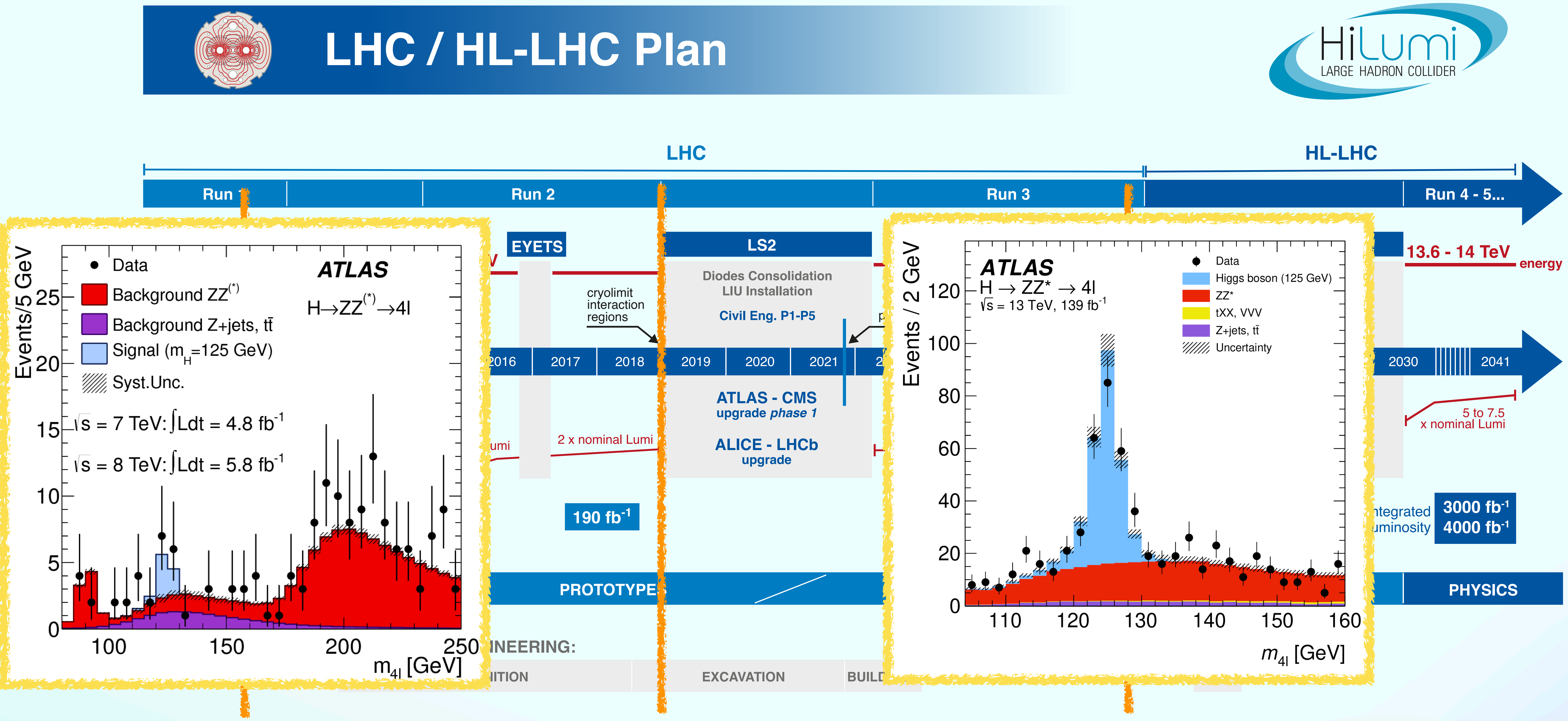
End of Run 2
~7.7M Higgs prod.

Today
~24M Higgs prod.

Timeline since discovery



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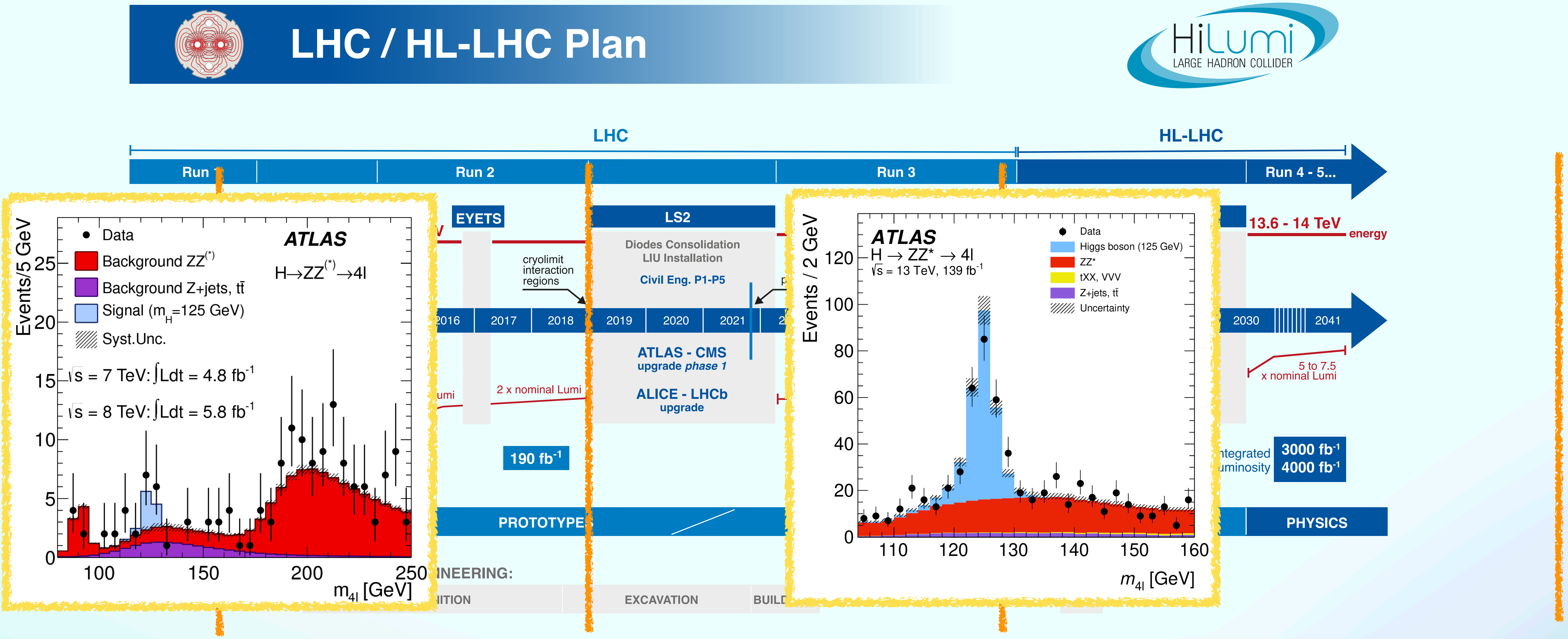


Discovery
~200k Higgs prod.

End of Run 2
~7.7M Higgs prod.

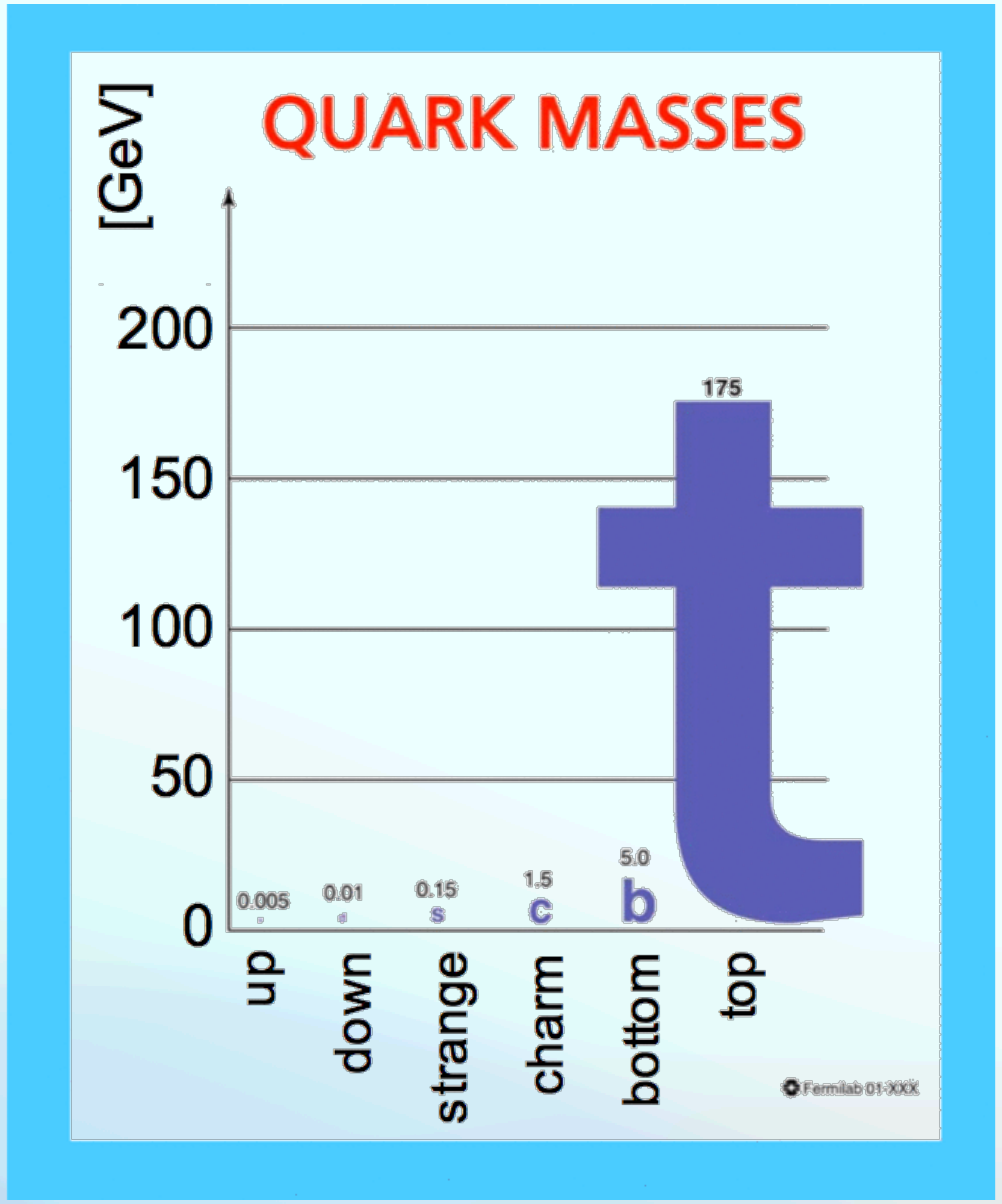
Today
~24M Higgs prod.

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?

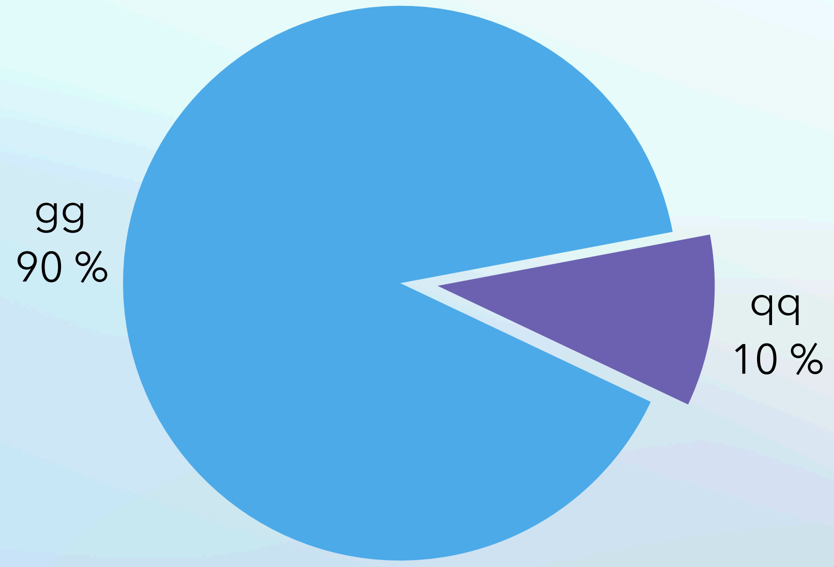
Decays before hadronization

→ Allows to study a "bare" quark

Top @ proton collider : prod. and decay

≈173.1 GeV/c²
⅔
½
t
top

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

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Production mode		Cross-section (pb)
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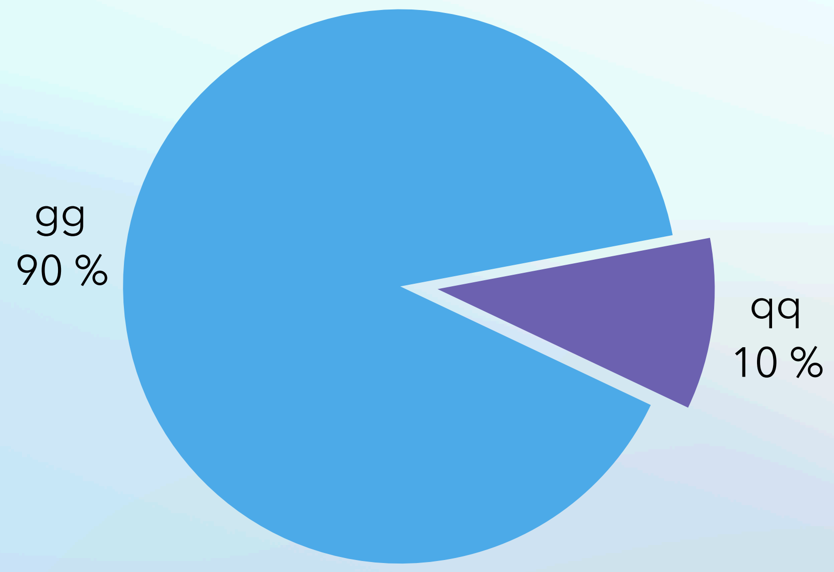
$t\bar{t}W$		0.745
$t\bar{t}Z$		0.811
$t\bar{t}H$		0.529
$t\bar{t}t\bar{t}$		0.015



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Decay Channel	Branching ratio
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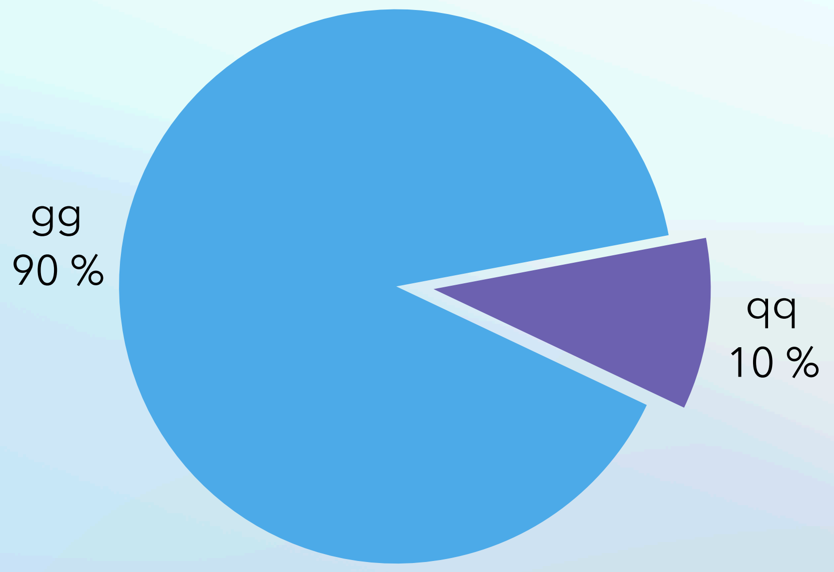

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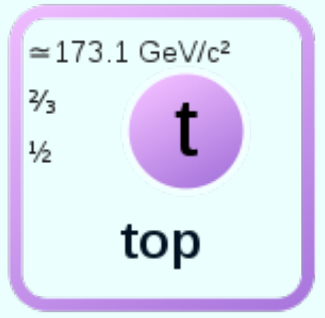

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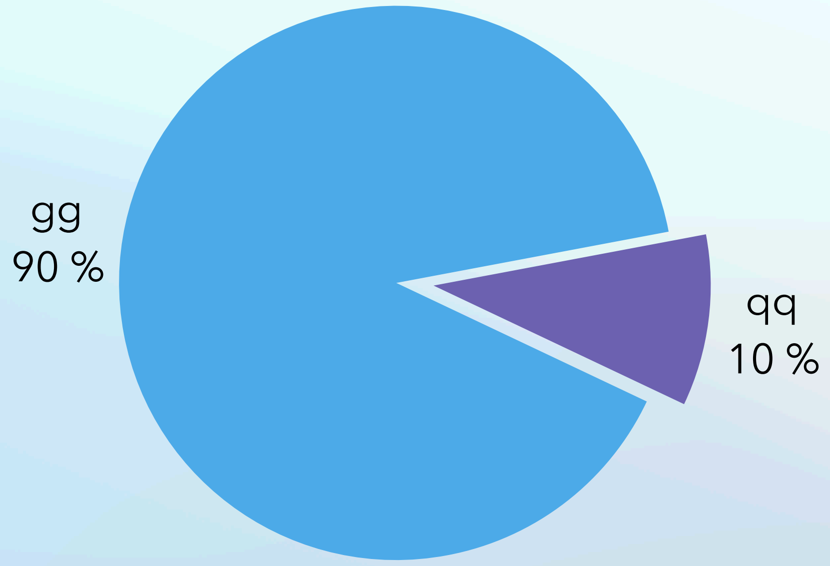

Mostly producted via QCD in $t\bar{t}$ pair

Decay Channel	Branching ratio
$t \to b + W$	99.8

Then, final states from W decays

$t \to b + W(\to q\bar{q})$	66.5
$t \to b + W(\to e\nu_e)$	11
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Top @ proton collider : prod. and decay

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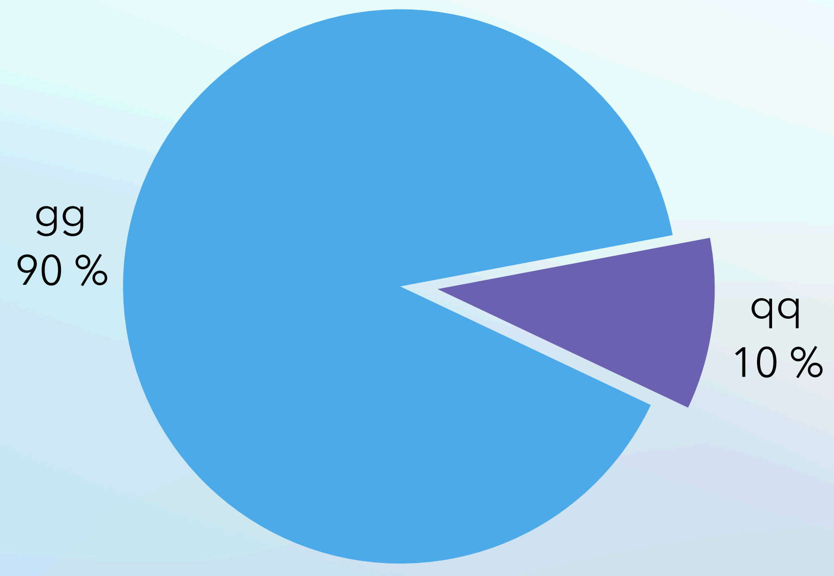

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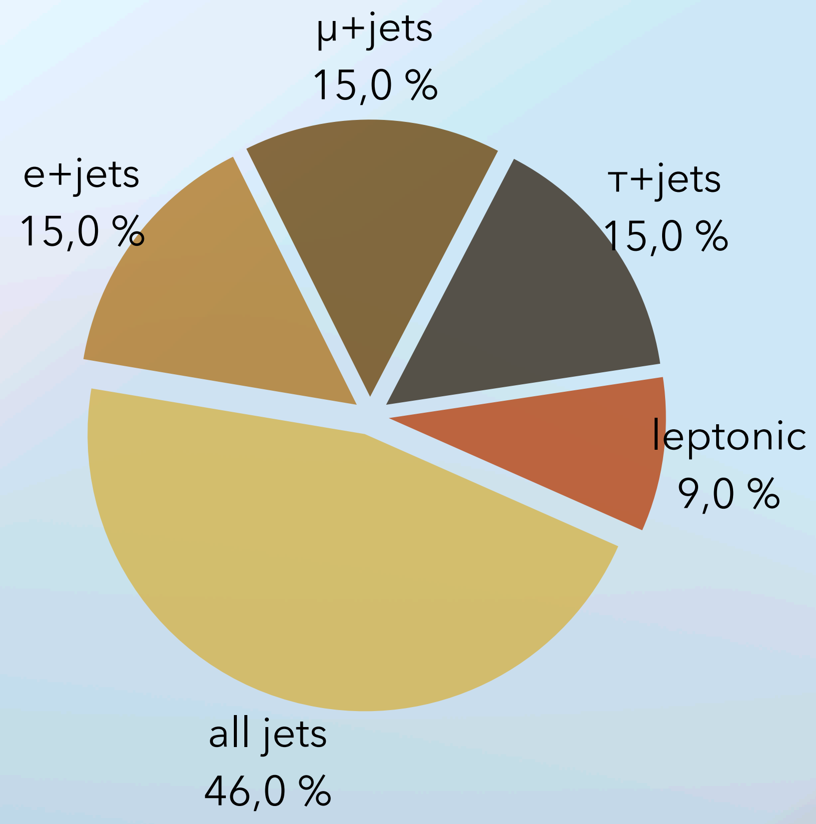
So, for $t\bar{t}$ pair :



LHC is a top quark factory

O(100M) $t\bar{t}$ events produced in Run 2

How to go from theory to measurement?

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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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Event selection

Defining phase space regions rich (and poor) in signal

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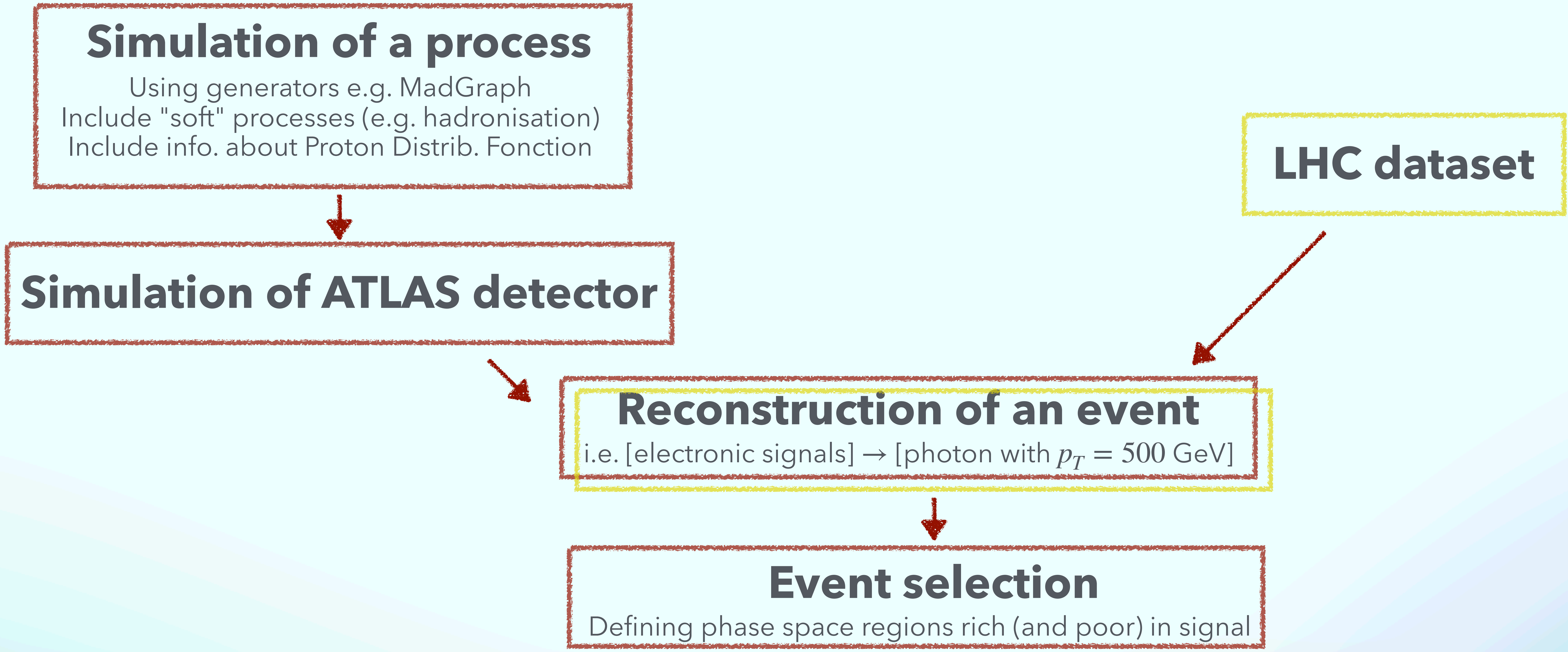

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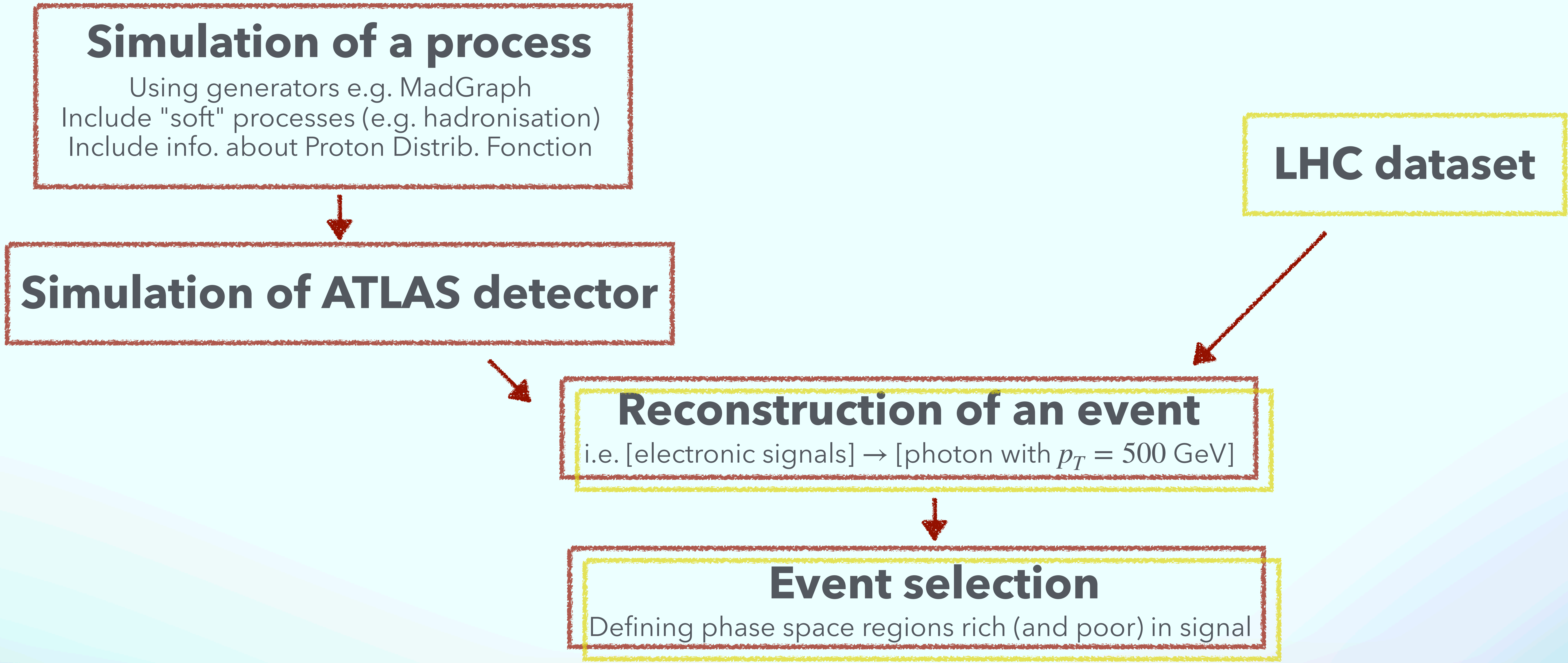

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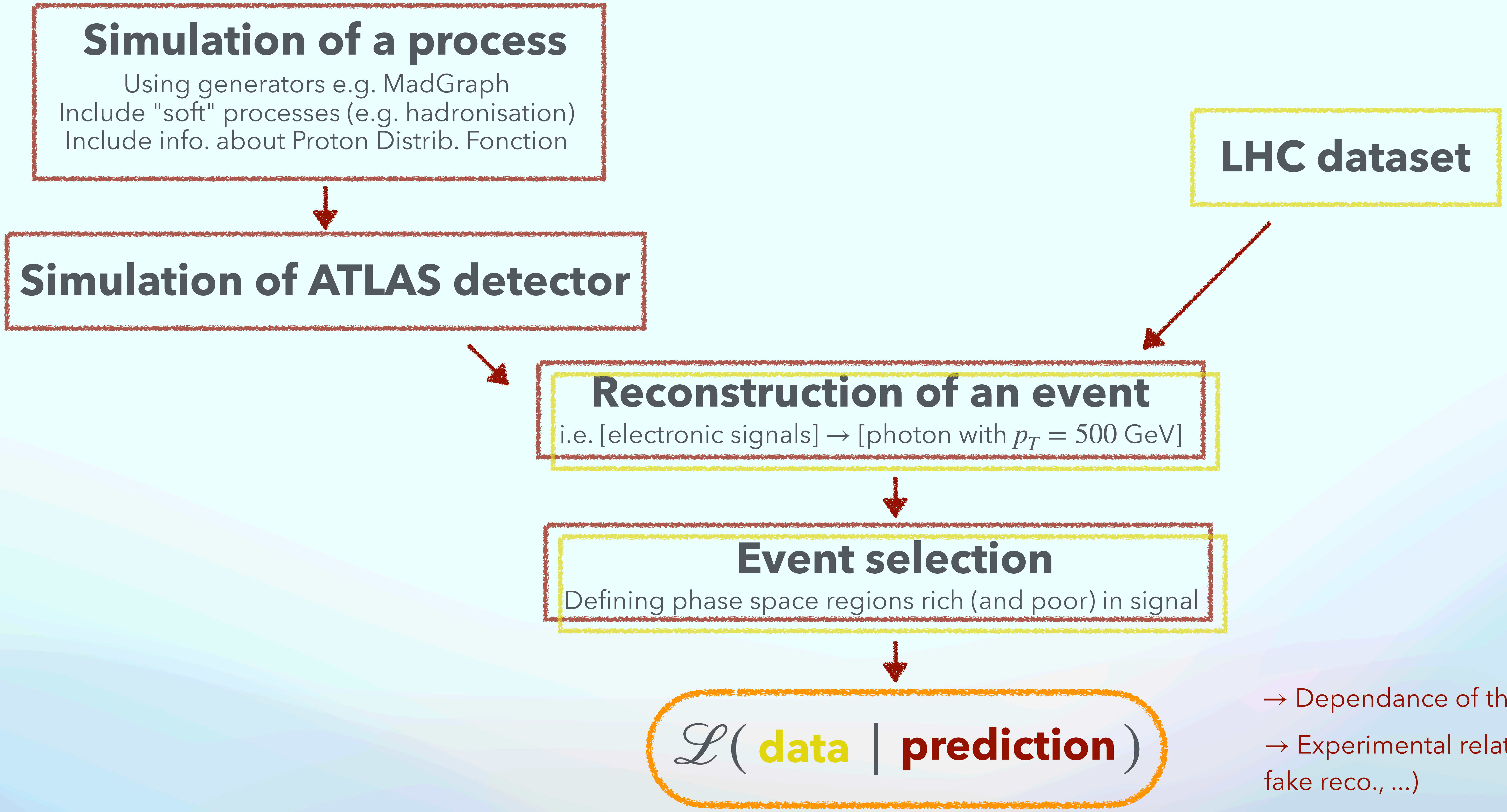

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$\mathscr{L}($ **data** | **prediction** $)$

→ Dependance of theory param. on observables

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

→ Theory uncertainties (PDF, loop calculations)

Recap. so far

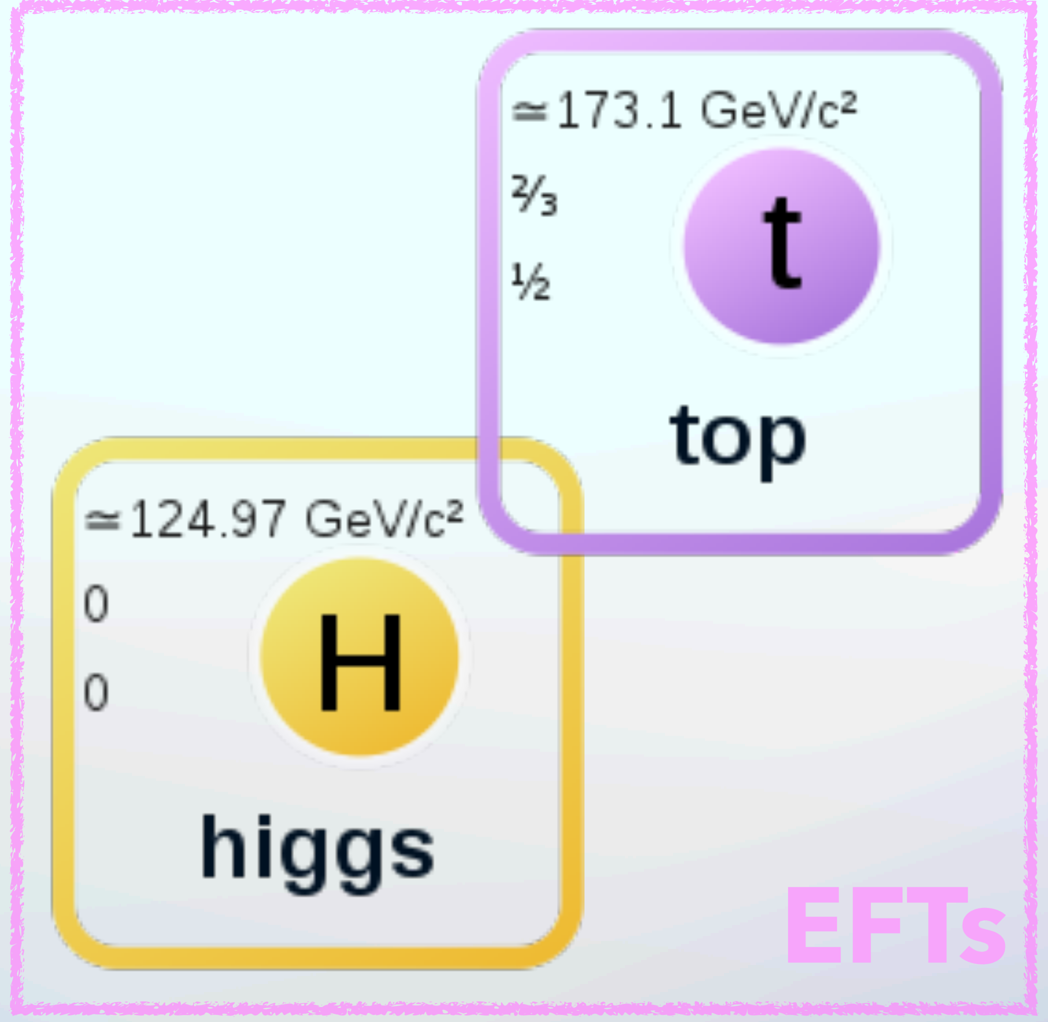
Recap.

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

We have a already *large* dataset to explore
and a 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

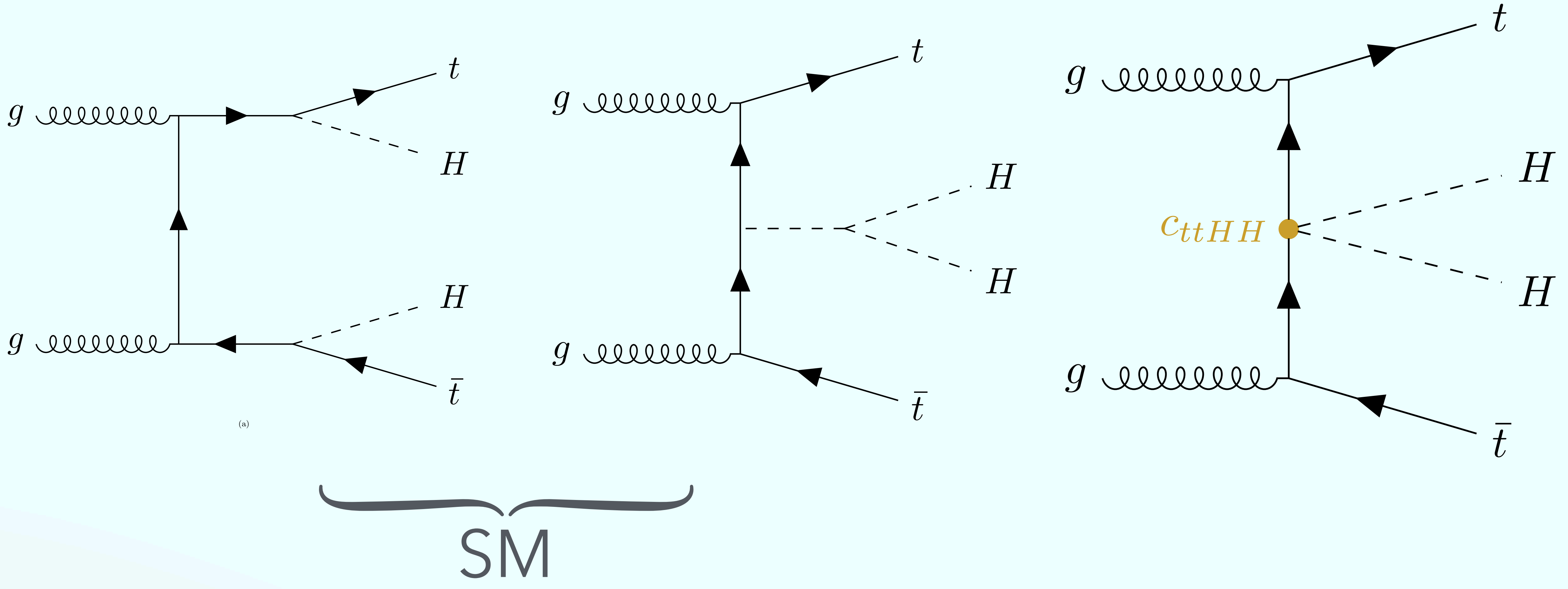


Probing the Top-Higgs Quartic interation

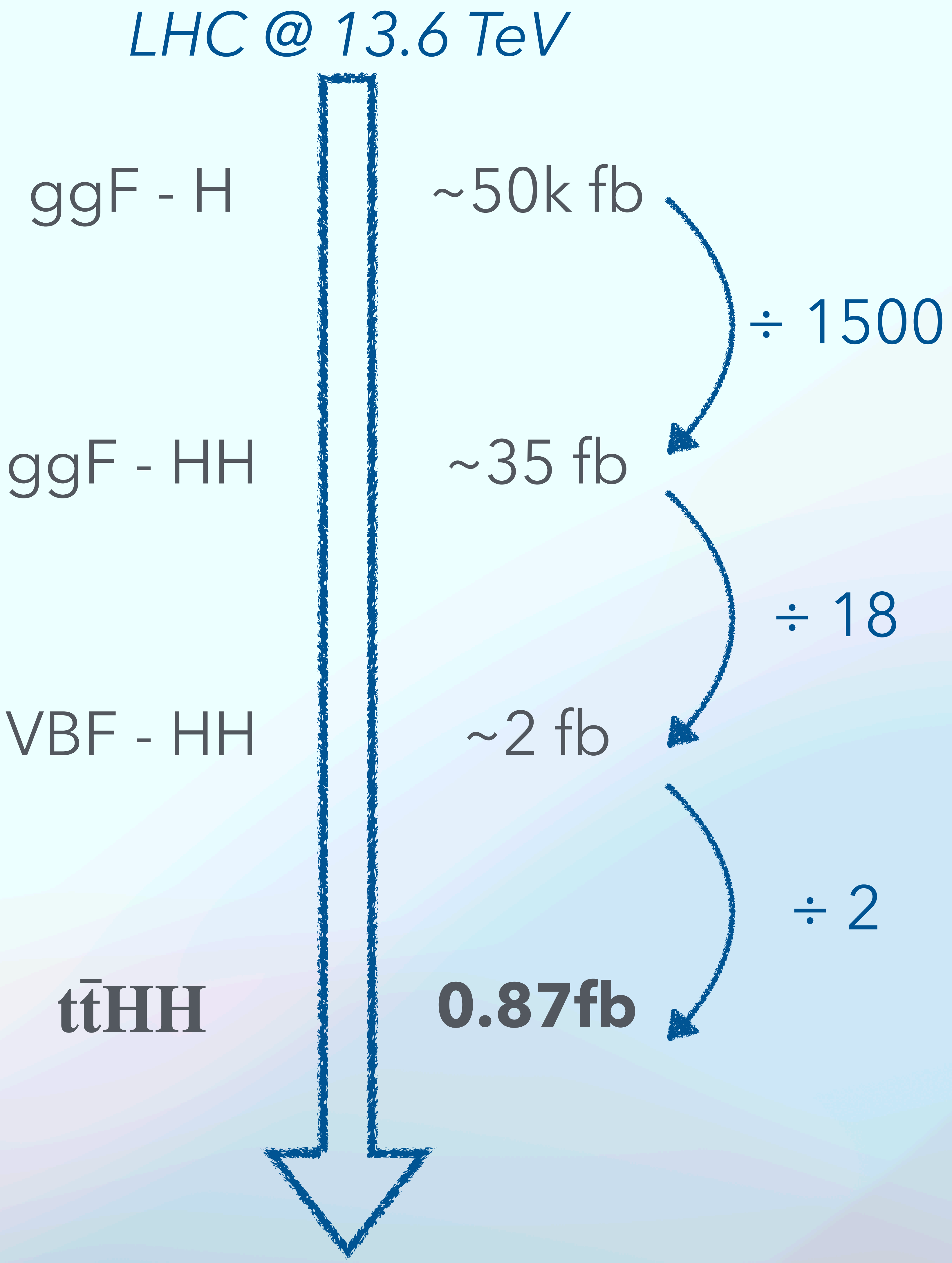
through an EFT interpretation of ttHH production at ATLAS

arXiv:2026.13113

Motivations



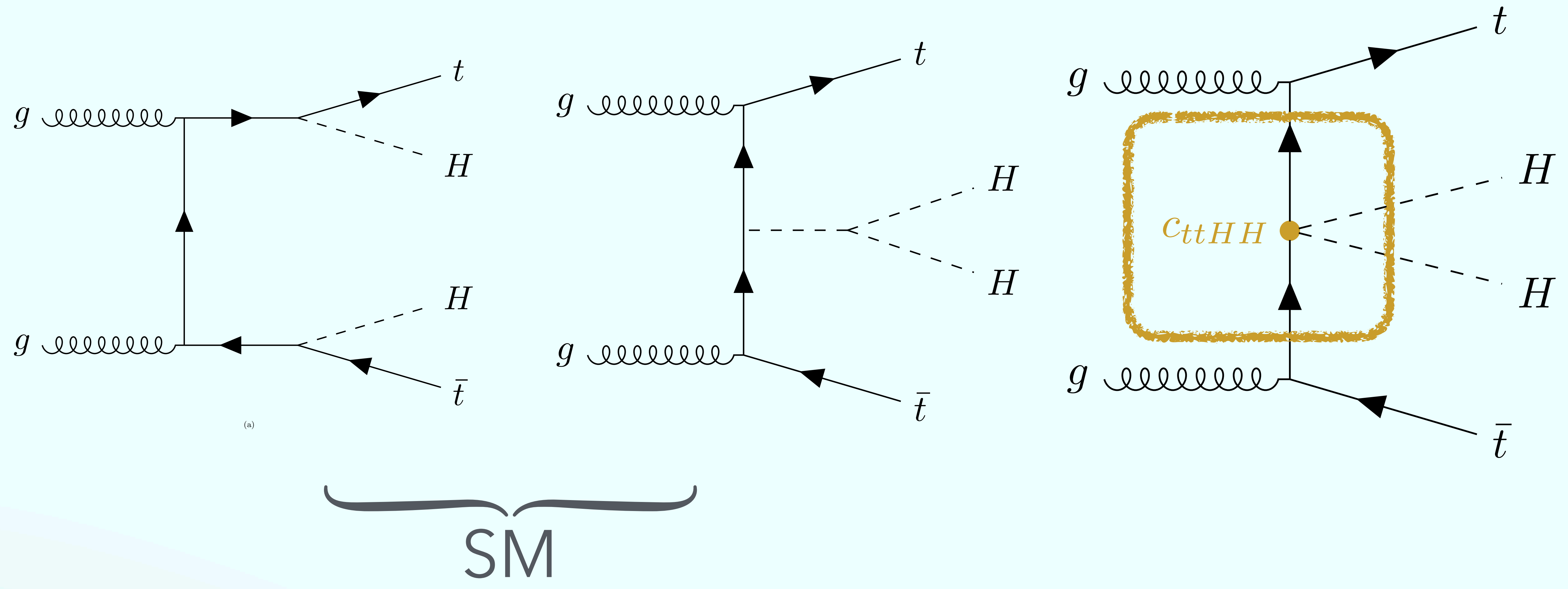
- 3rd leading HH production mode @ LHC



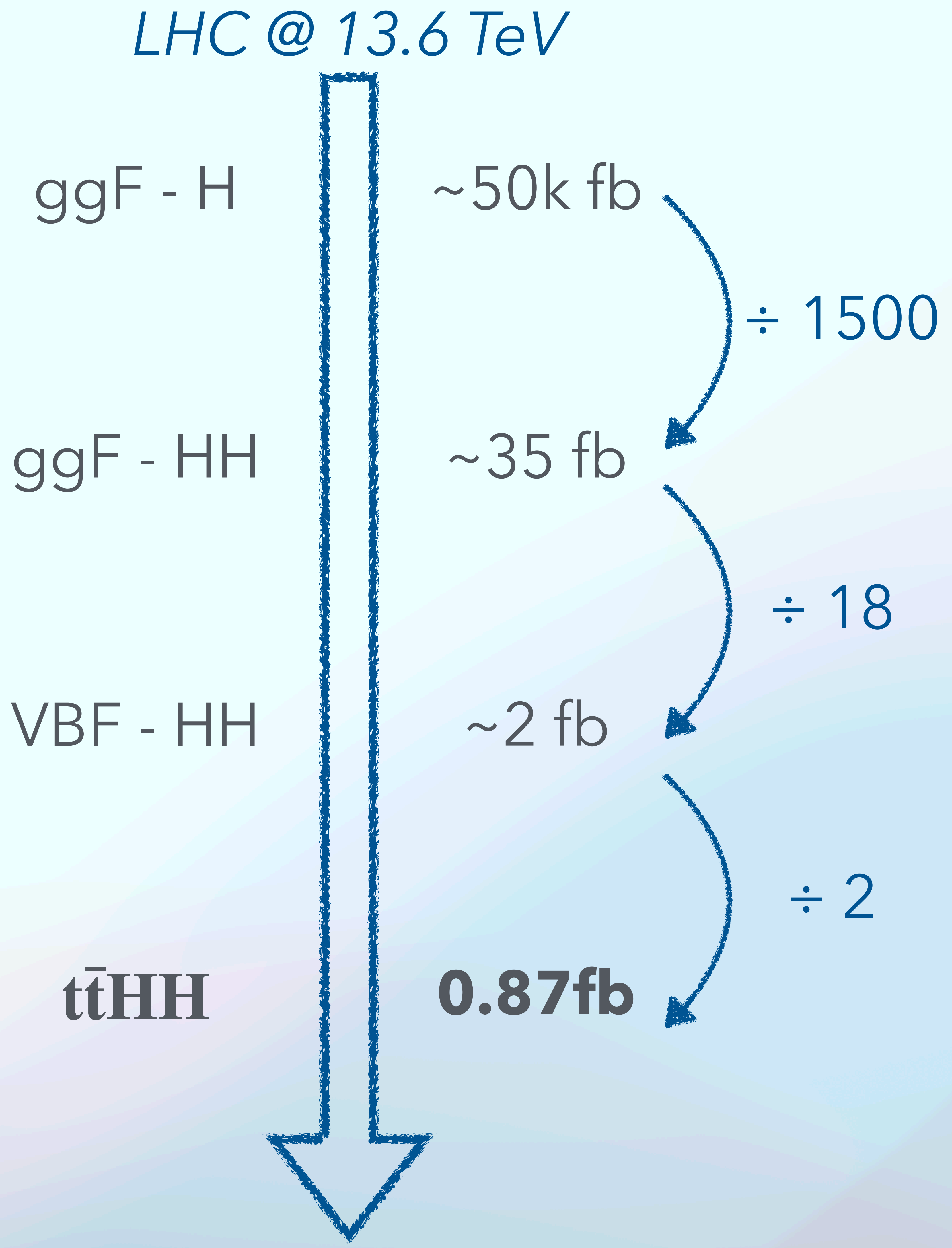
LHC @ 13.6 TeV

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



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VBF - HH ~2 fb

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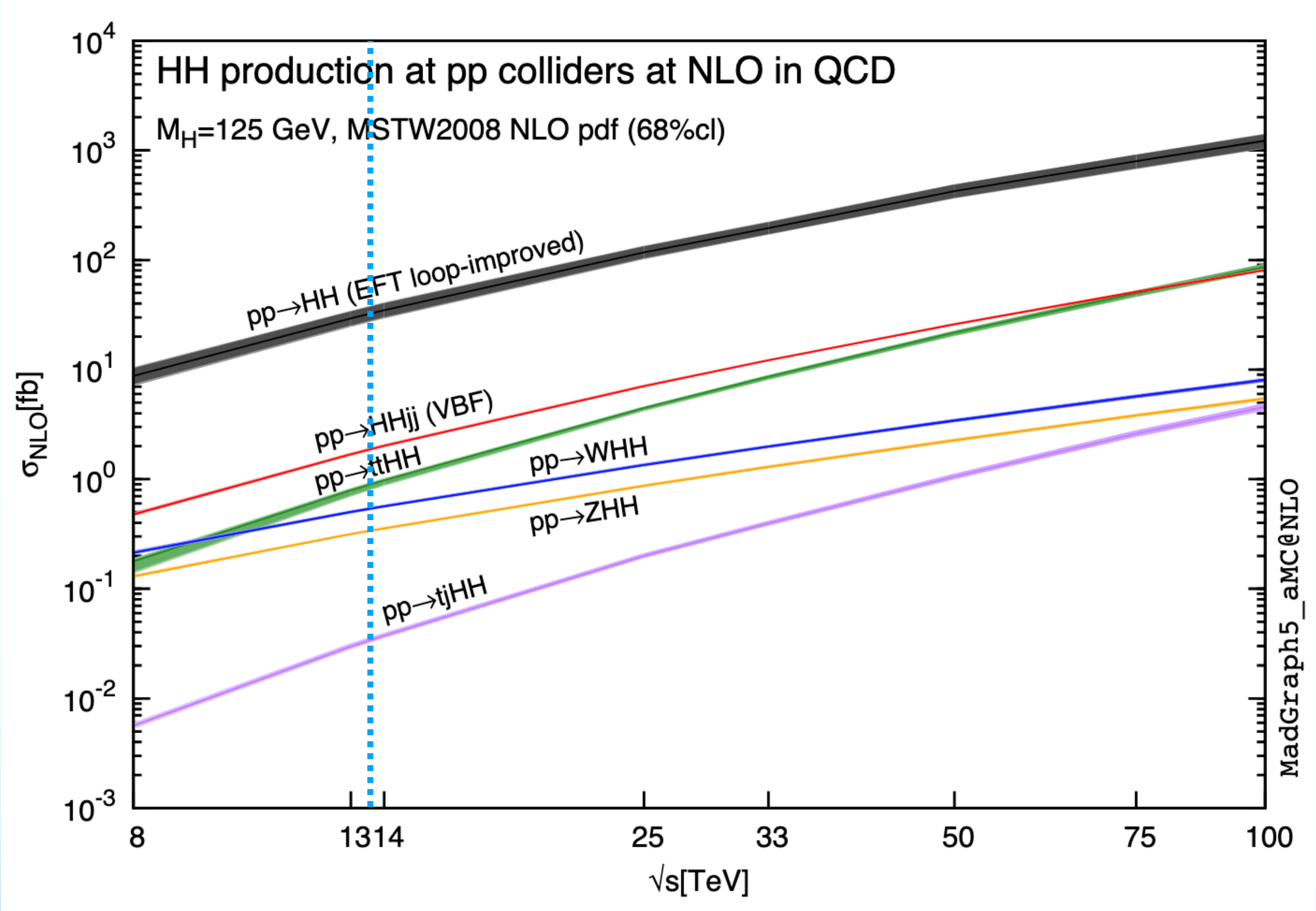
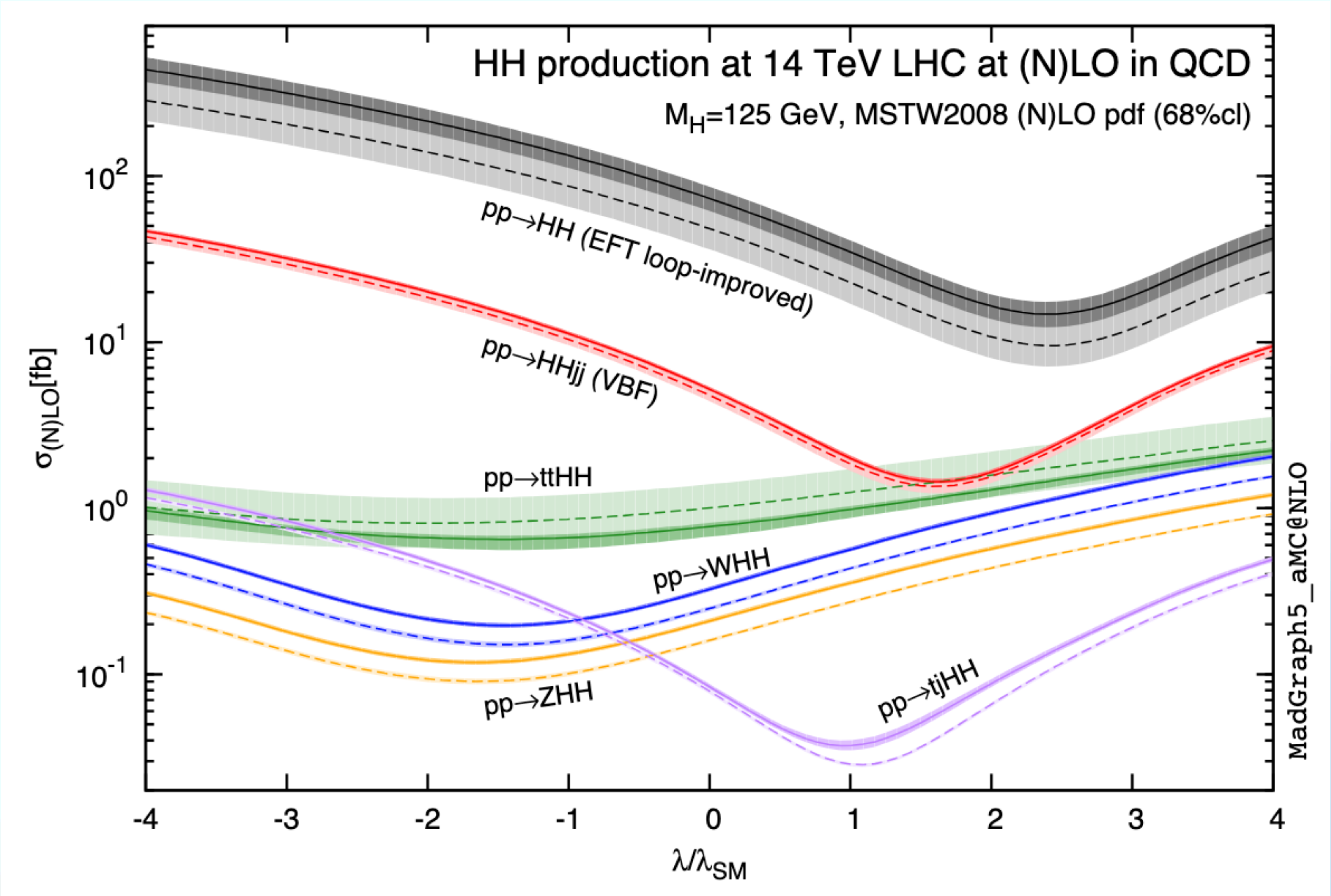
$t\bar{t}$HH **0.87fb**

ttHH production

arXiv:1401.7340

We stand here

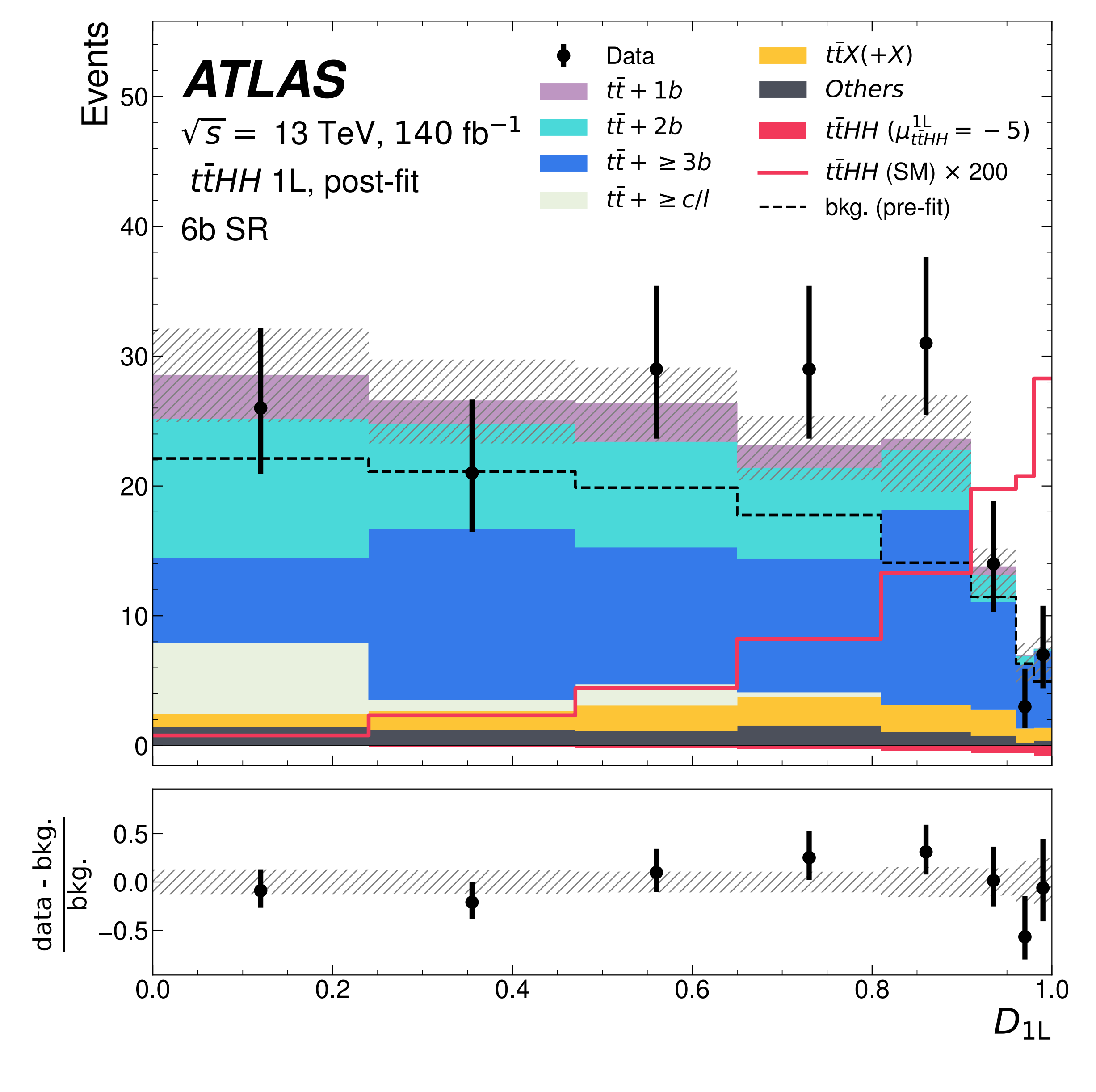




- Cross-section scales faster with $\sqrt{s}$
- Unique interference pattern dependance on κ_λ

  We'll come back to that later...

Strategy

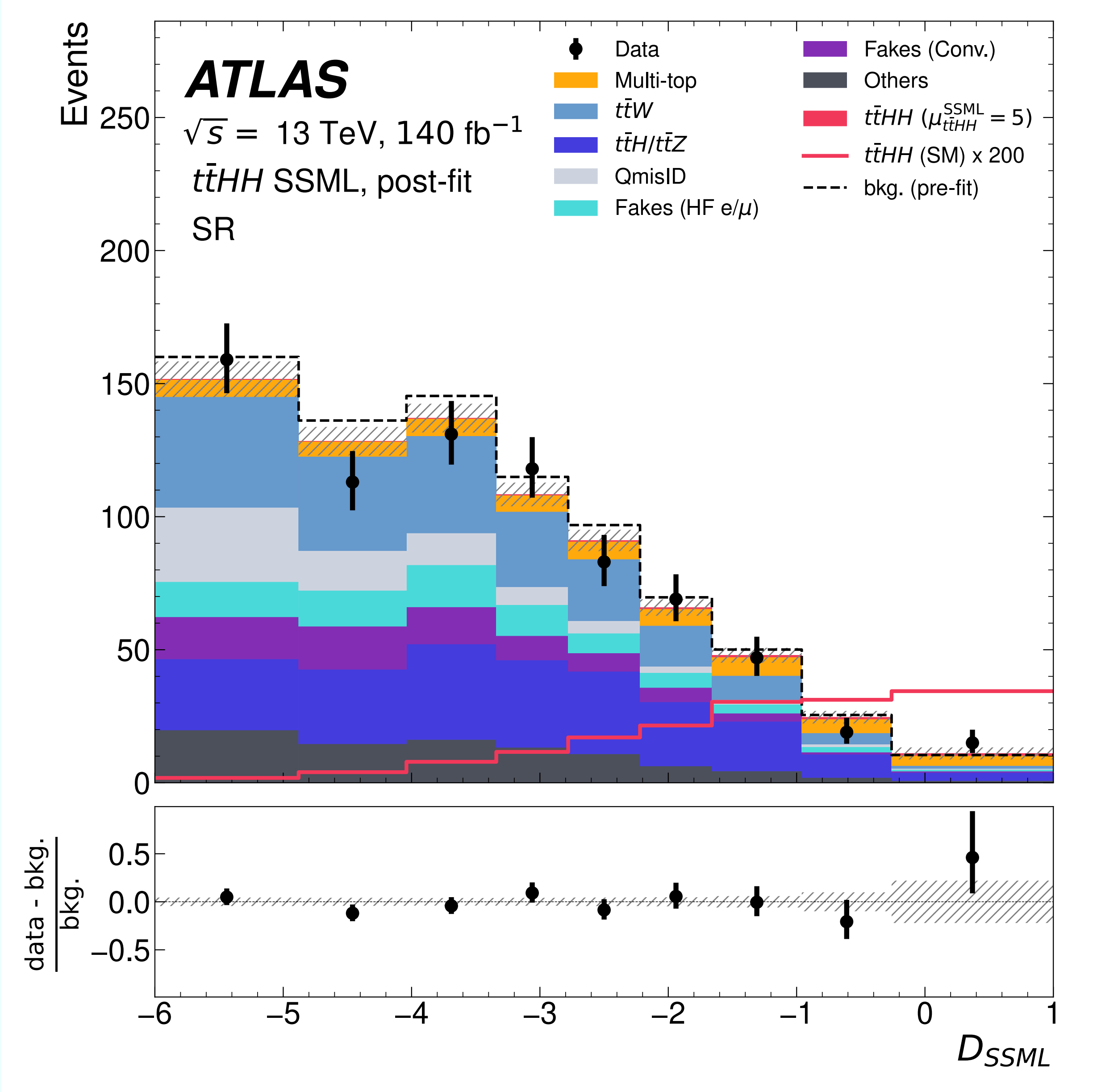


Single lep. channel (1L)

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

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

Obs. limit on μ : **26** x SM



Multi-lep. Channel (ML)

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

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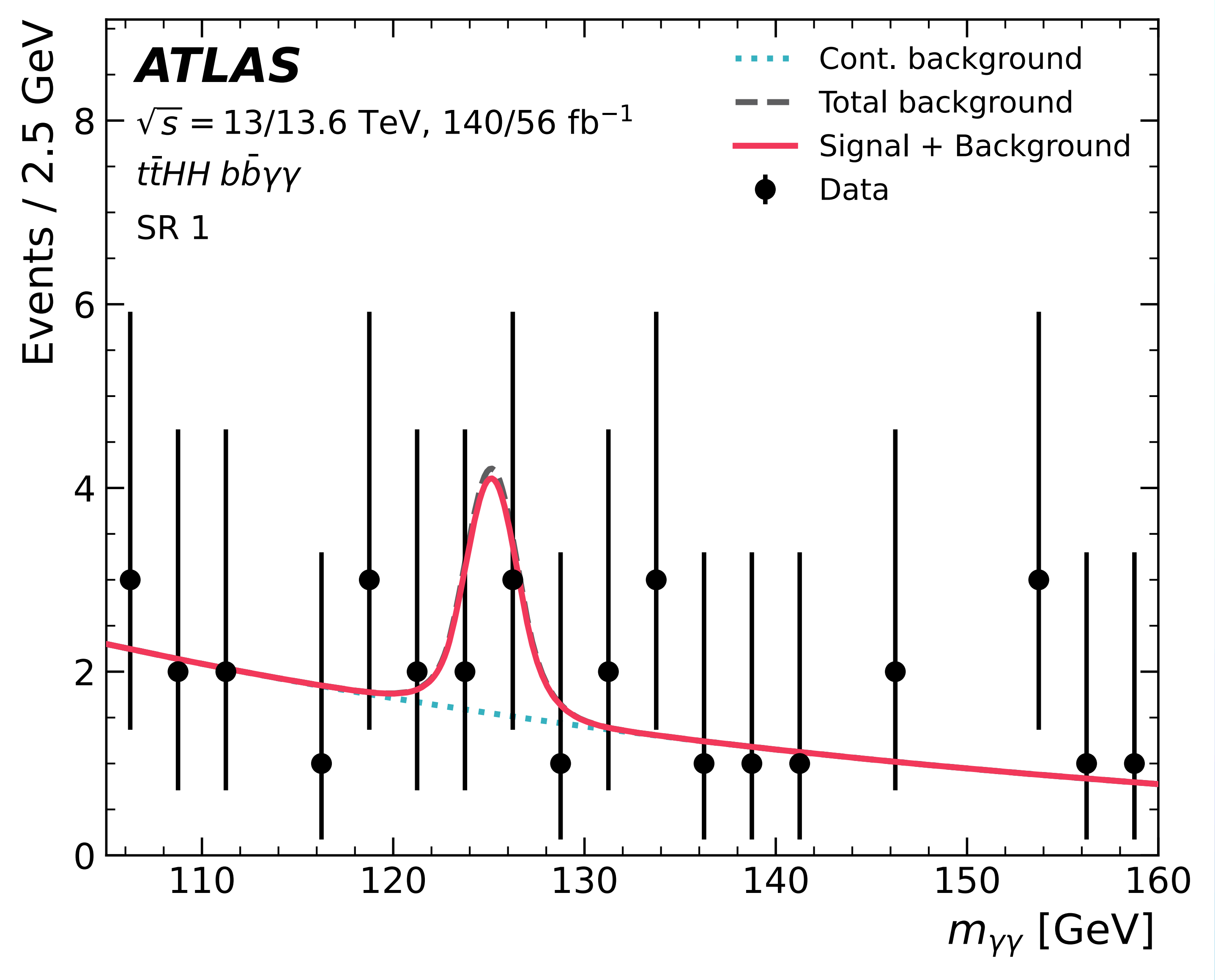
Obs. limit on μ : **40** x SM

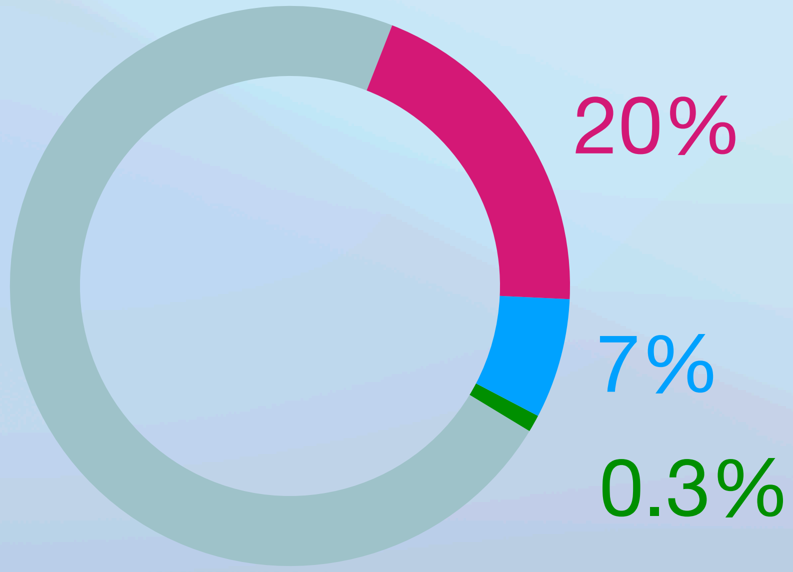


$b\bar{b}\gamma\gamma$ channel

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

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

Obs. limit on μ : **75** x SM



- 1L and ML : Fit Transformer score
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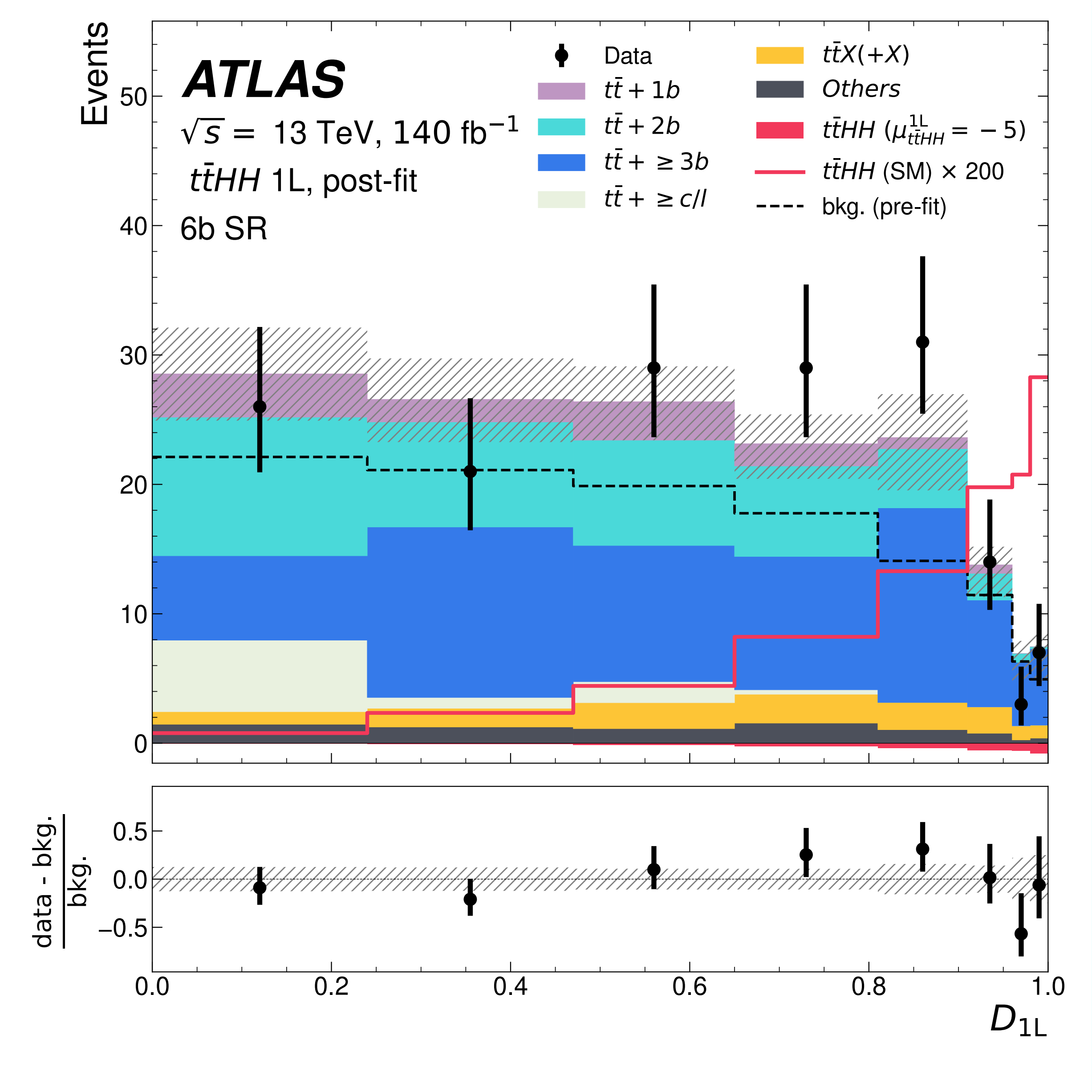
Obs. limit on μ : **20** x SM

Strategy



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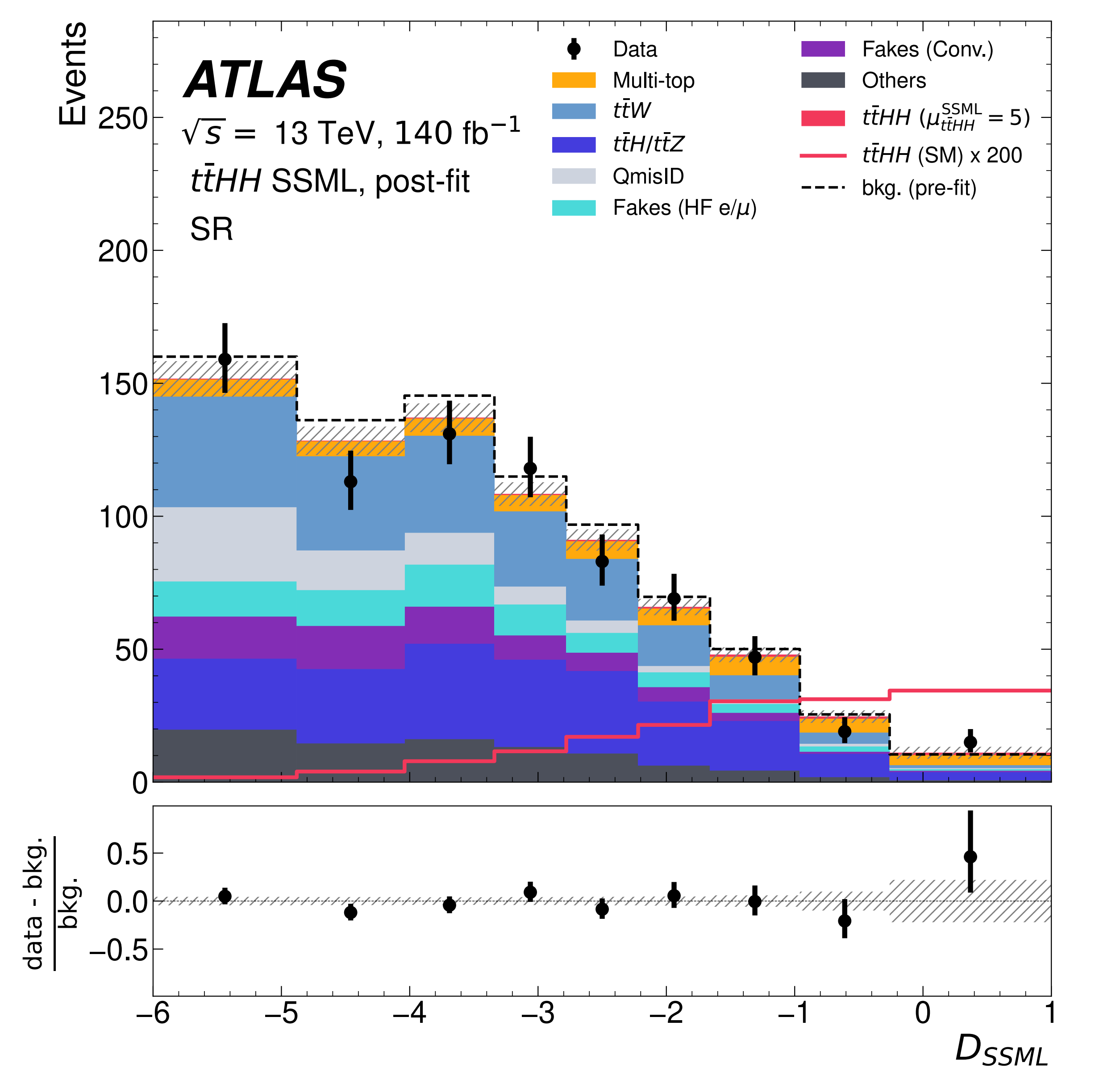

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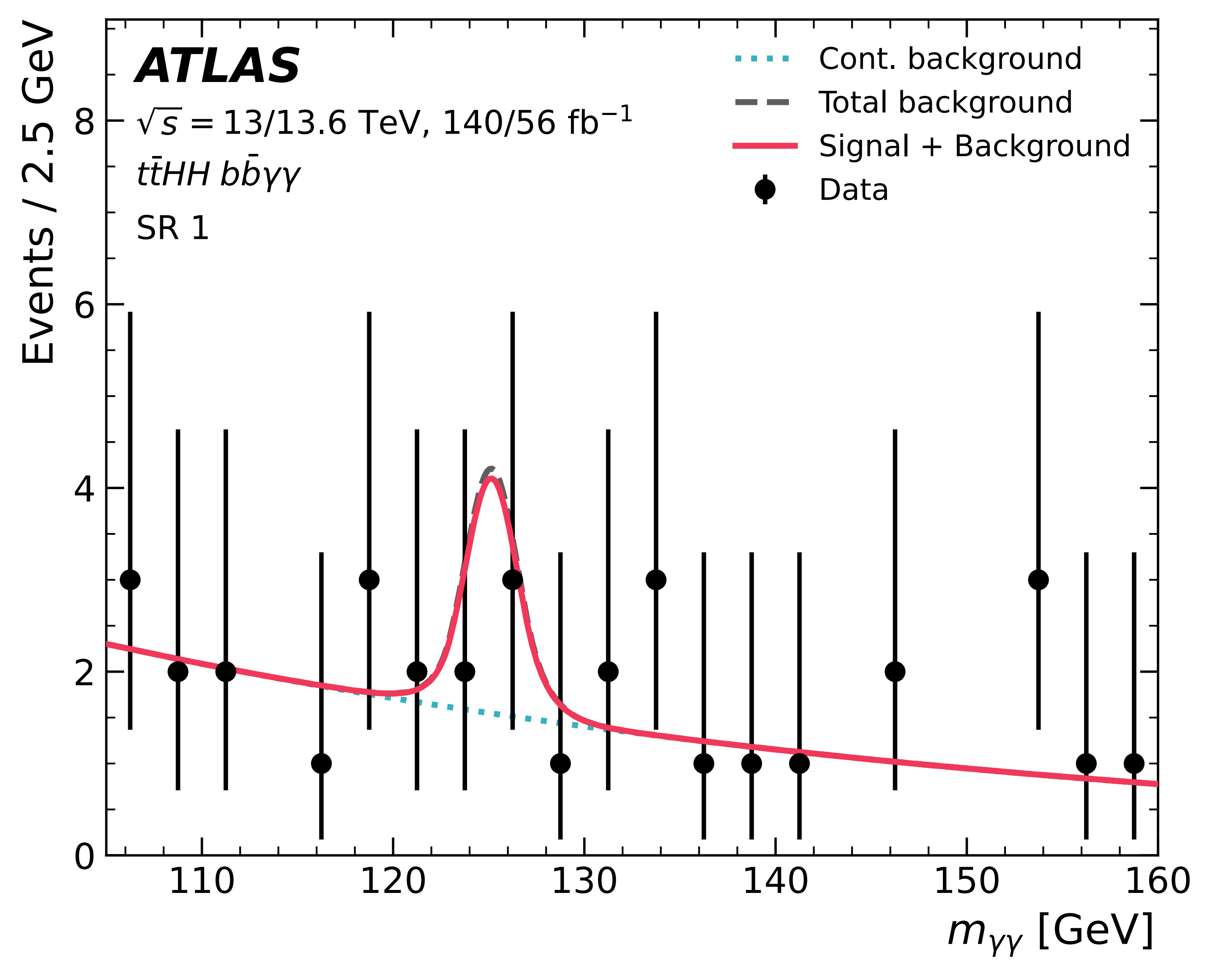

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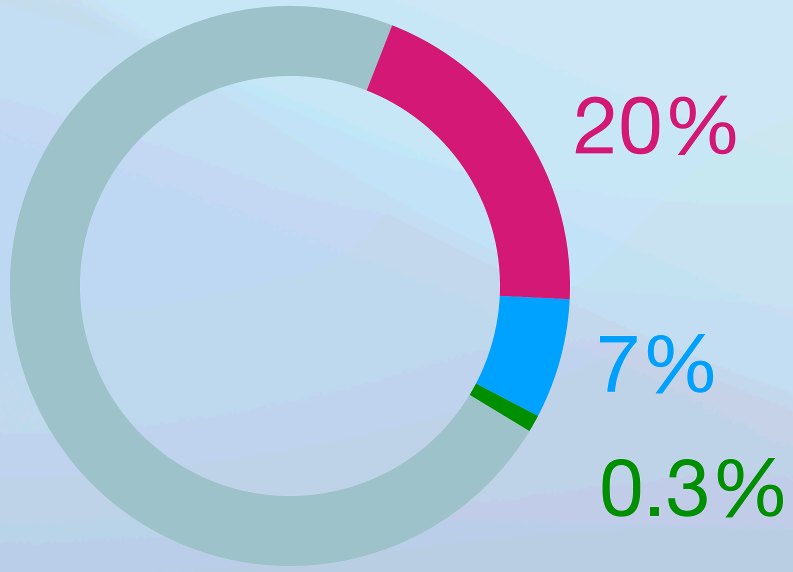

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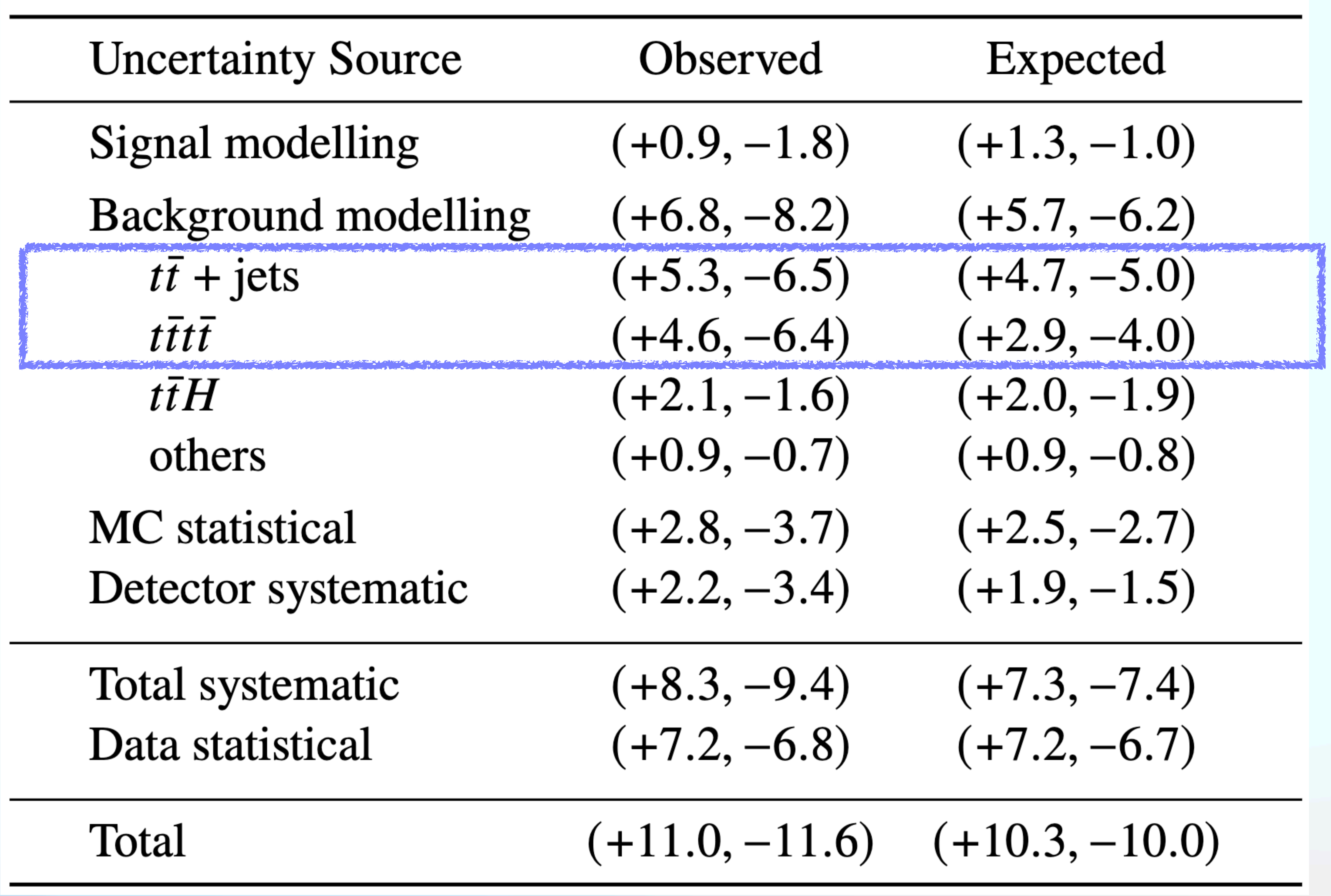
Limitations

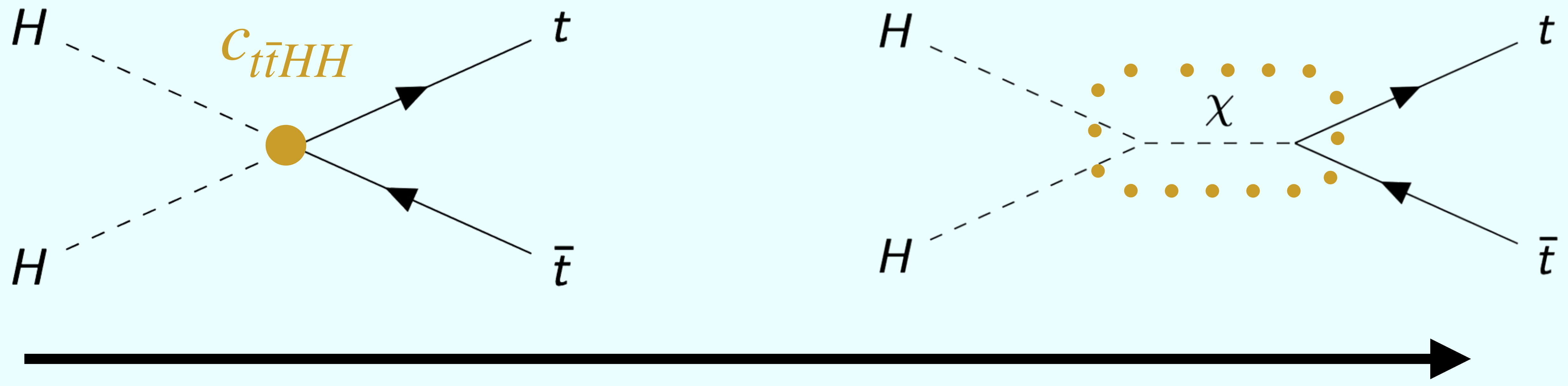


Uncertainty Source	Observed	Expected
Signal modelling	(+0.9, −1.8)	(+1.3, −1.0)
Background modelling	(+6.8, −8.2)	(+5.7, −6.2)
$t\bar{t}$ + jets	(+5.3, −6.5)	(+4.7, −5.0)
$t\bar{t}t\bar{t}$	(+4.6, −6.4)	(+2.9, −4.0)
$t\bar{t}H$	(+2.1, −1.6)	(+2.0, −1.9)
others	(+0.9, −0.7)	(+0.9, −0.8)
MC statistical	(+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} $<<$ $E \sim \Lambda_{NP}$

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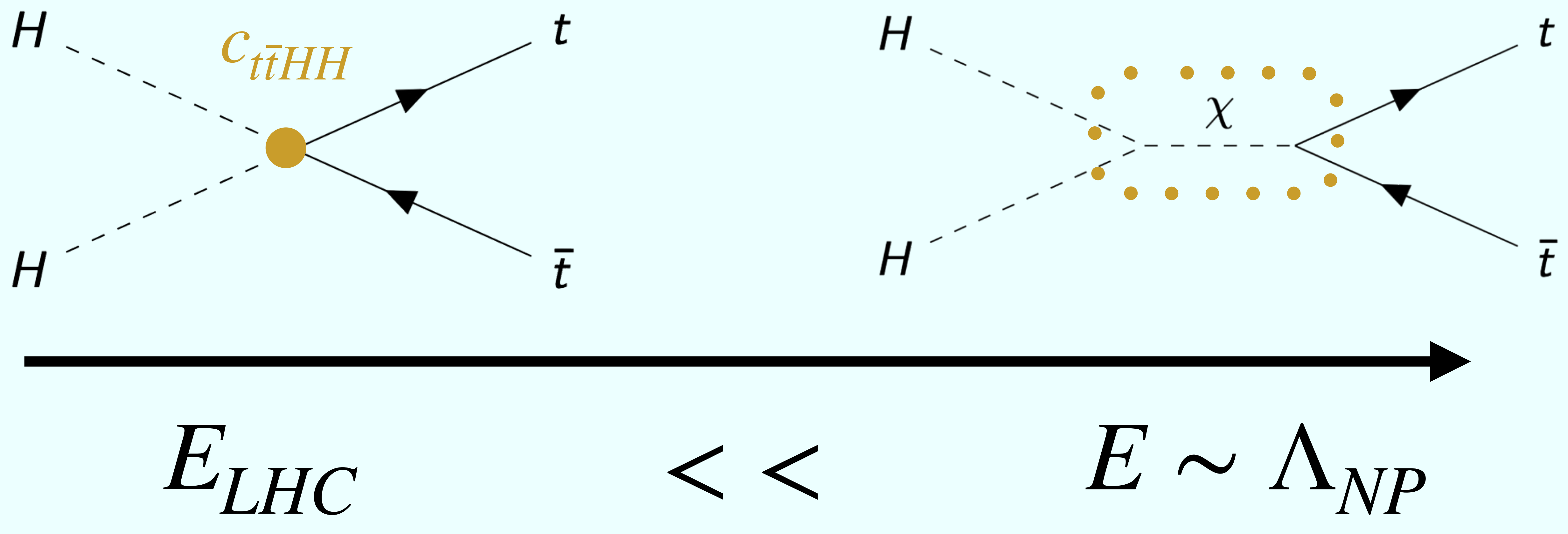

EFT recipe

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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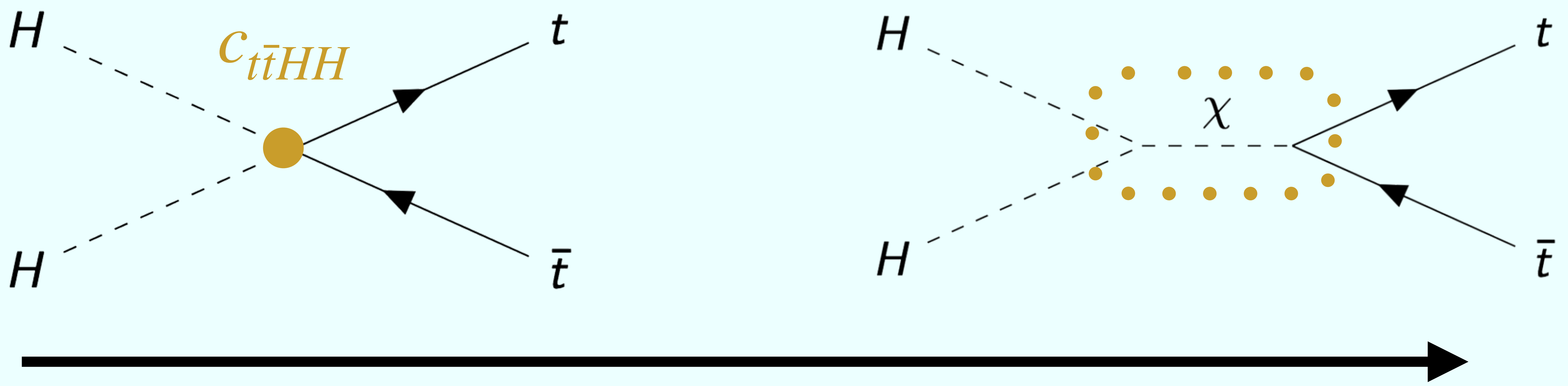

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→ Higgs properties unconstrained by EWSB pattern

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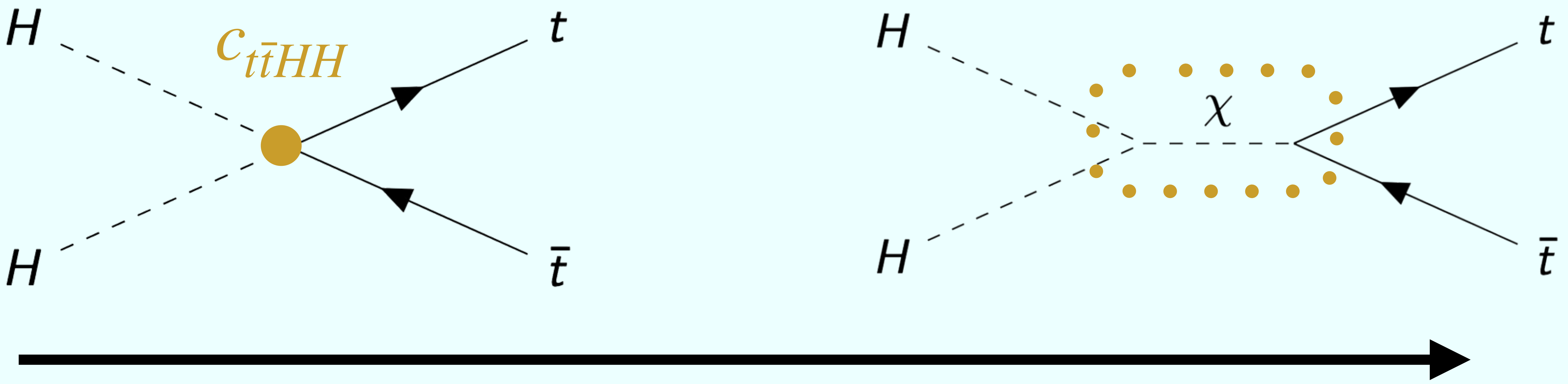

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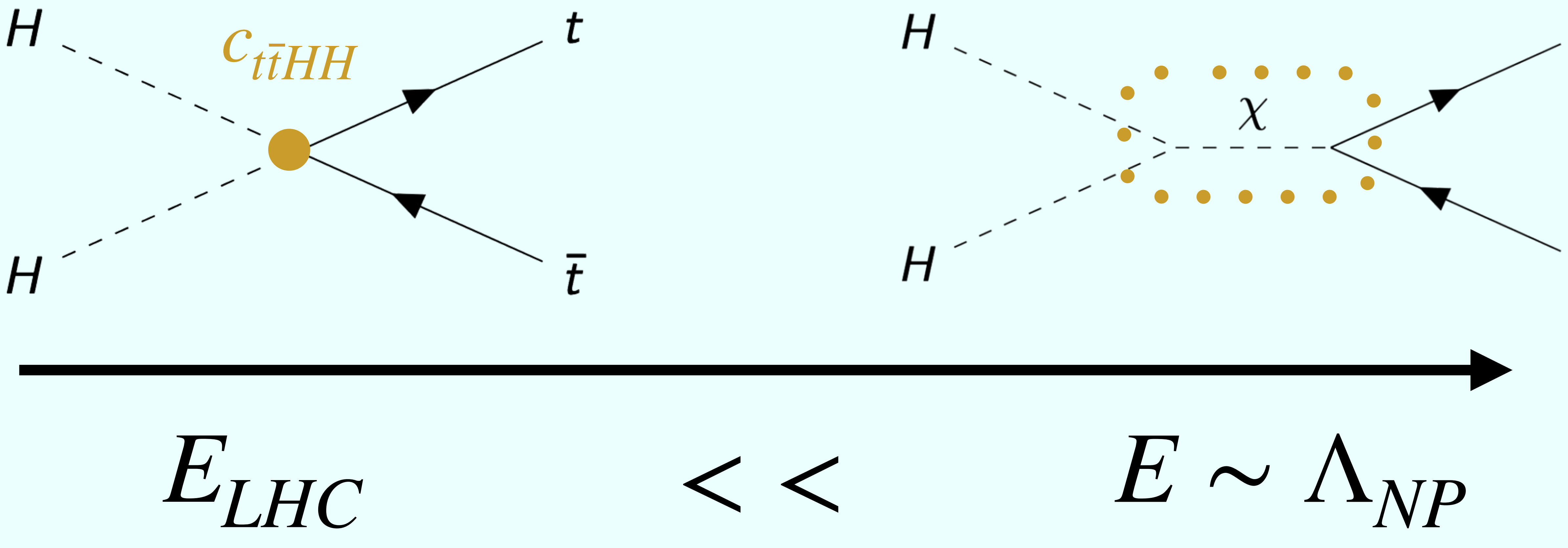

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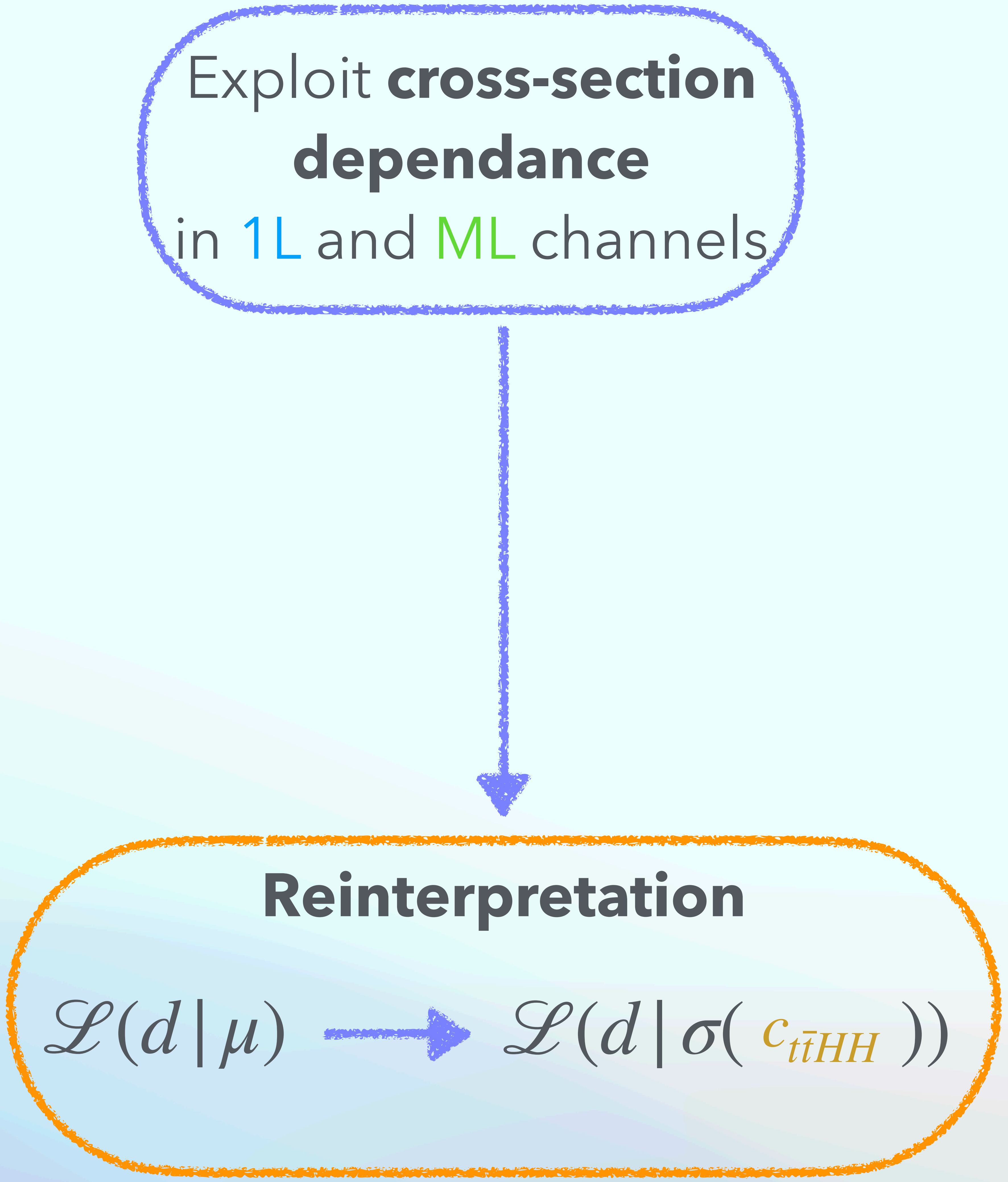
$$\mathscr{L}_{\text{HEFT}} \supset -m_t\left(c_{t\bar{t}H}\frac{h}{v} + c_{t\bar{t}HH}\frac{h^2}{v^2}\right)t\bar{t} - \kappa_\lambda \frac{m_H^2}{2v}h^3$$

Strategy and results



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

Reinterpretation

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

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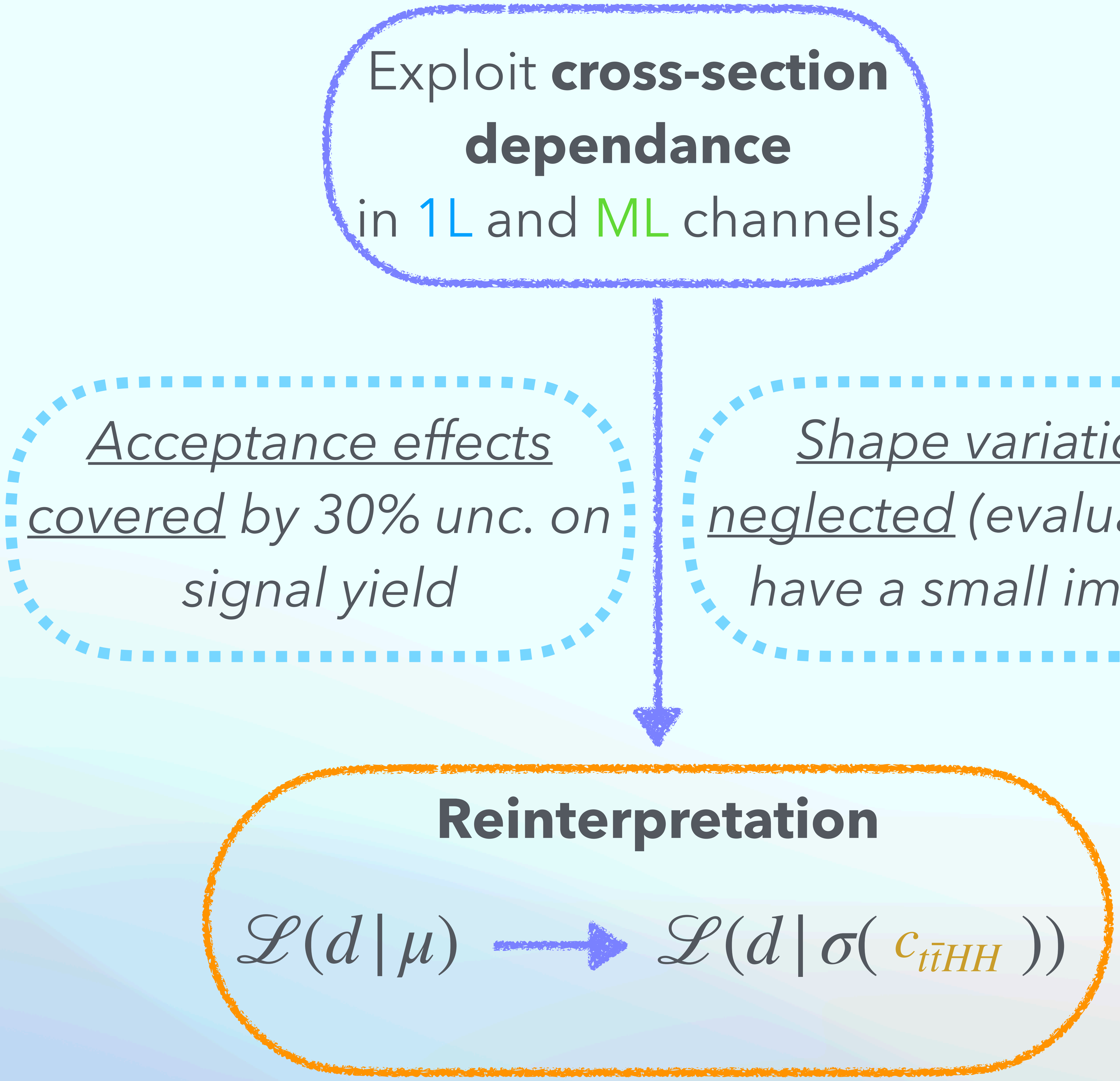

Exploit **cross-section dependance** in 1L and ML channels

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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Sample simulation is **expensive**

in €, in time, and in CO2

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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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arXiv:2304.01968

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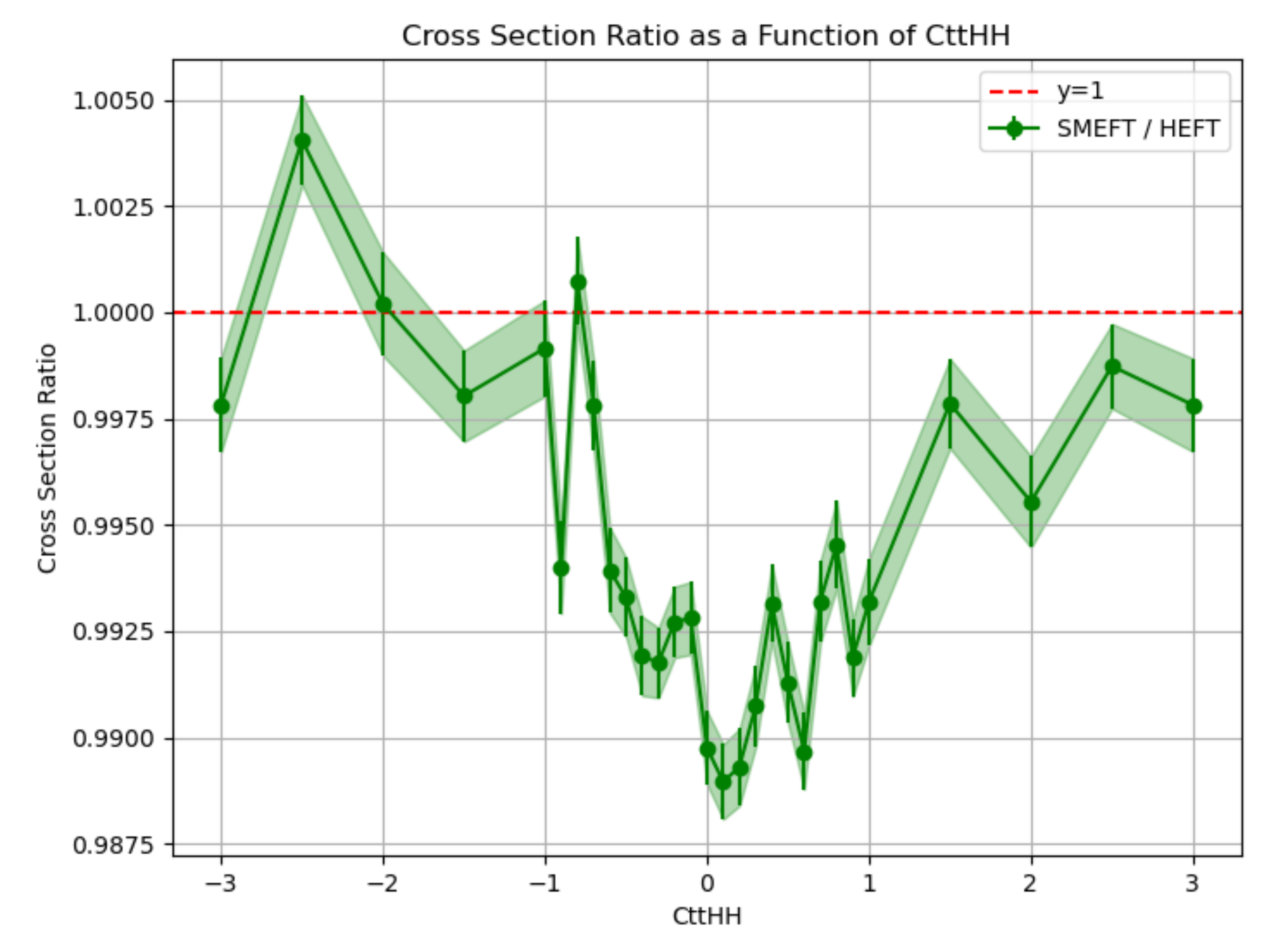

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[arXiv:2304.01968](https://arxiv.org/abs/2304.01968)

→ **Agreement at ~1% level**

A probe for HEFT vs. SMEFT

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\end{aligned}
$$

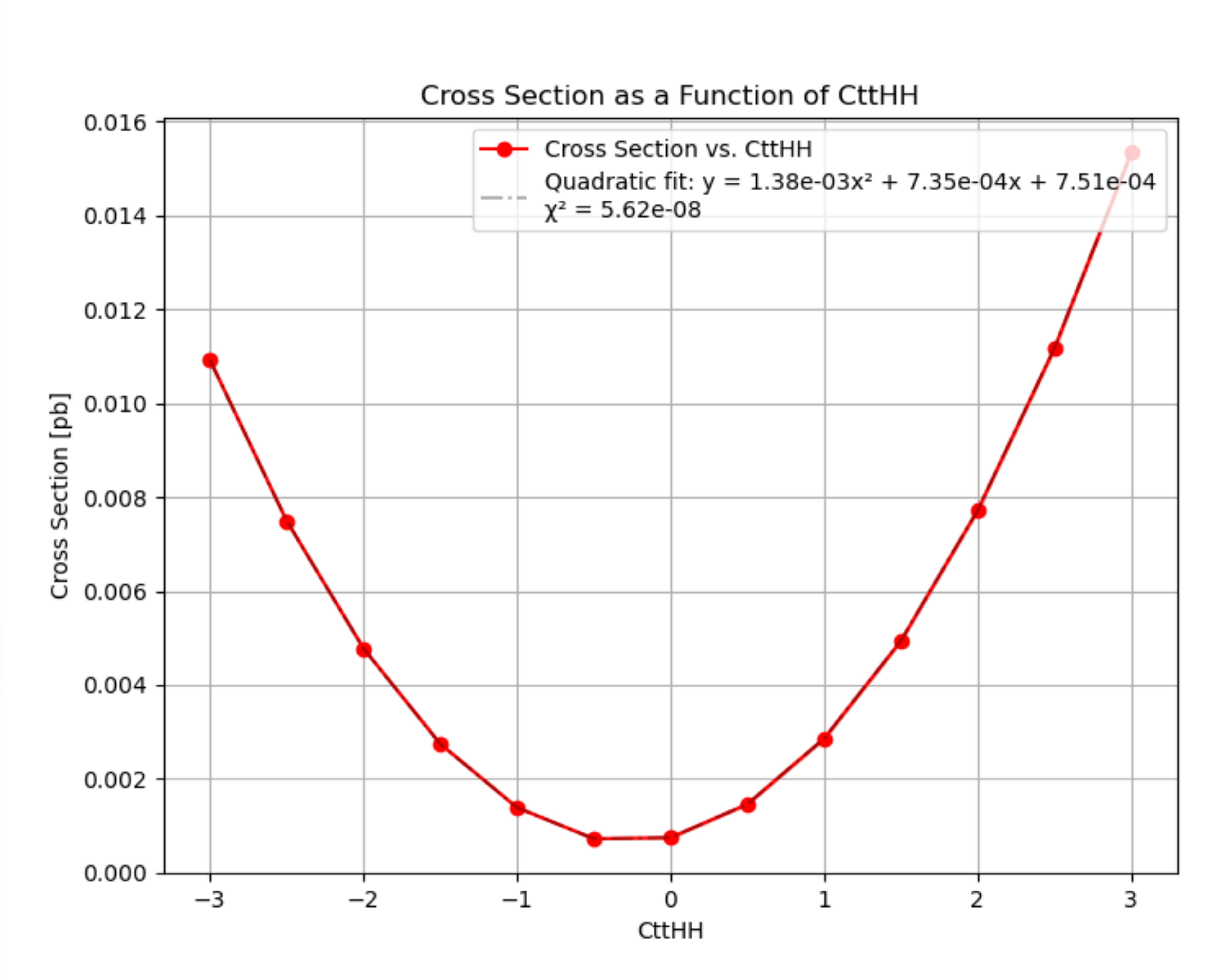
arXiv:2304.01968

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

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

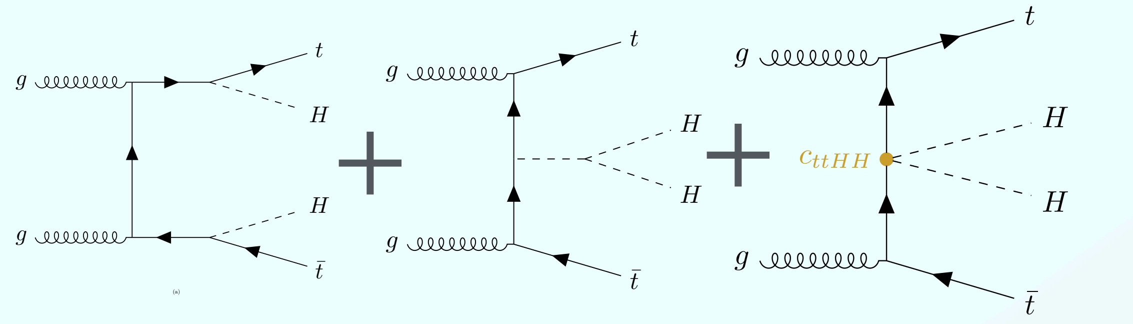
HEFT provides a way to **decorellate them** and study the Higgs mechanism

Cross-section dependance



Quadratic dependance → **Expected**

$\sigma \sim |$



$|^2$

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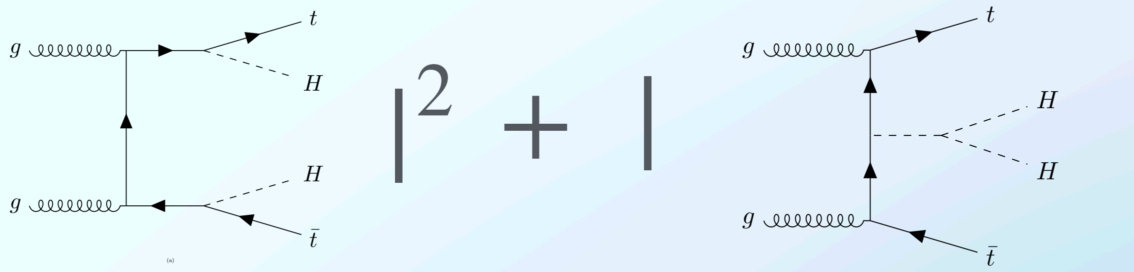
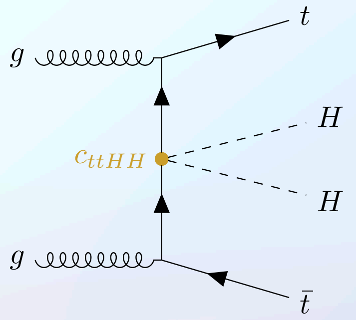


$|^2 + |$ $|^2$

$+ |$



$|^2 +$ cross-terms…

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

How to extract the most kin. information?

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

→ 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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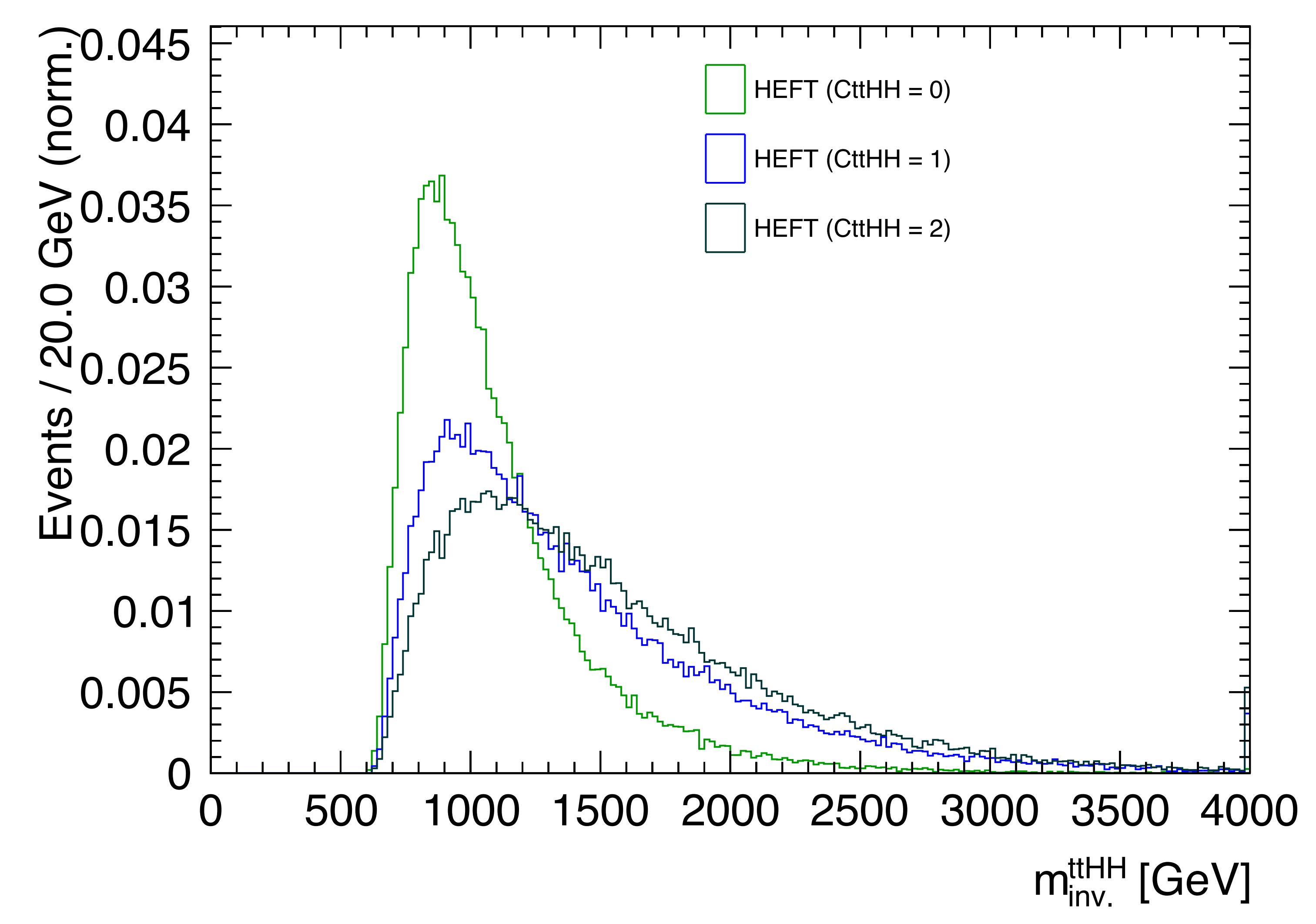

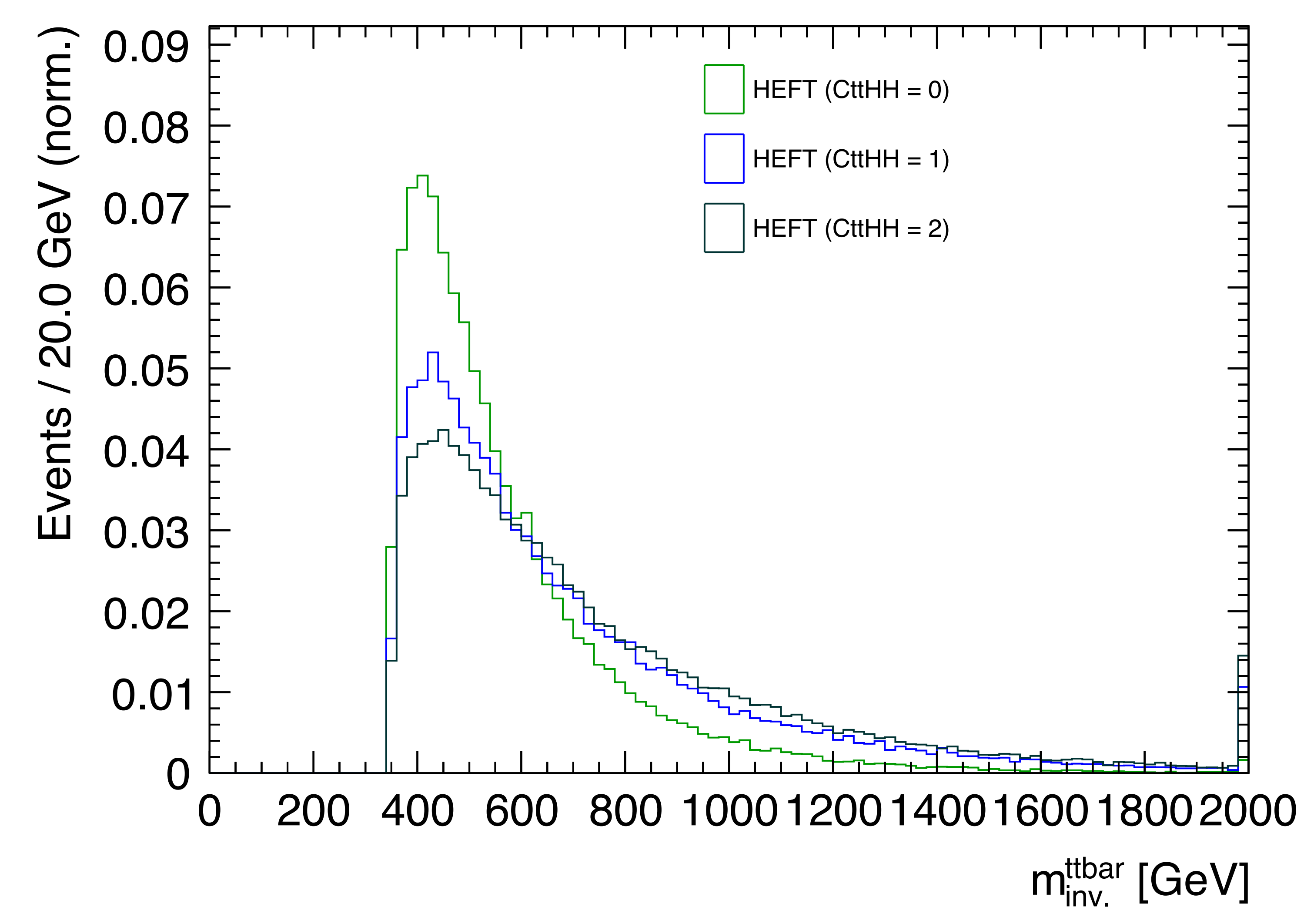

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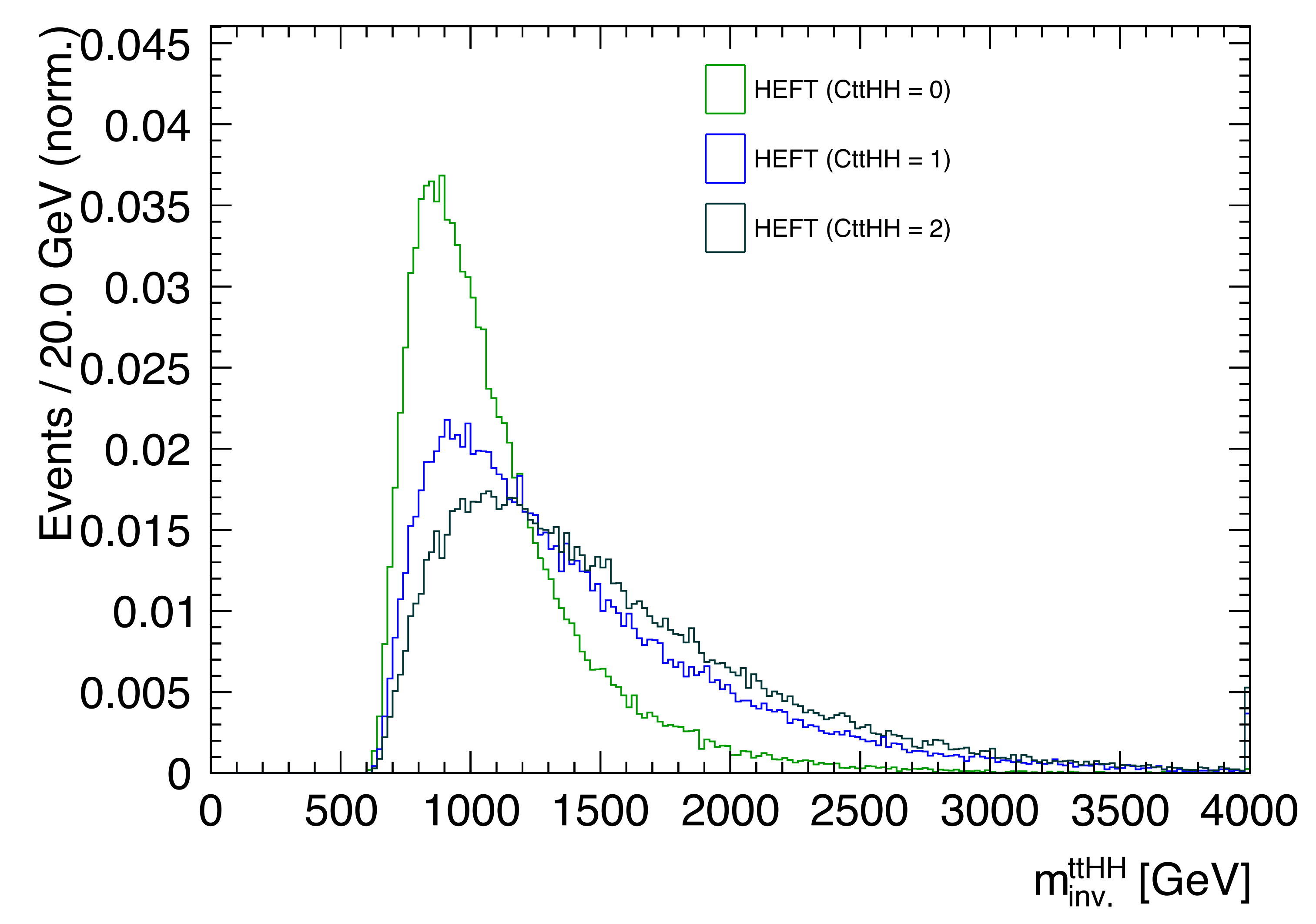

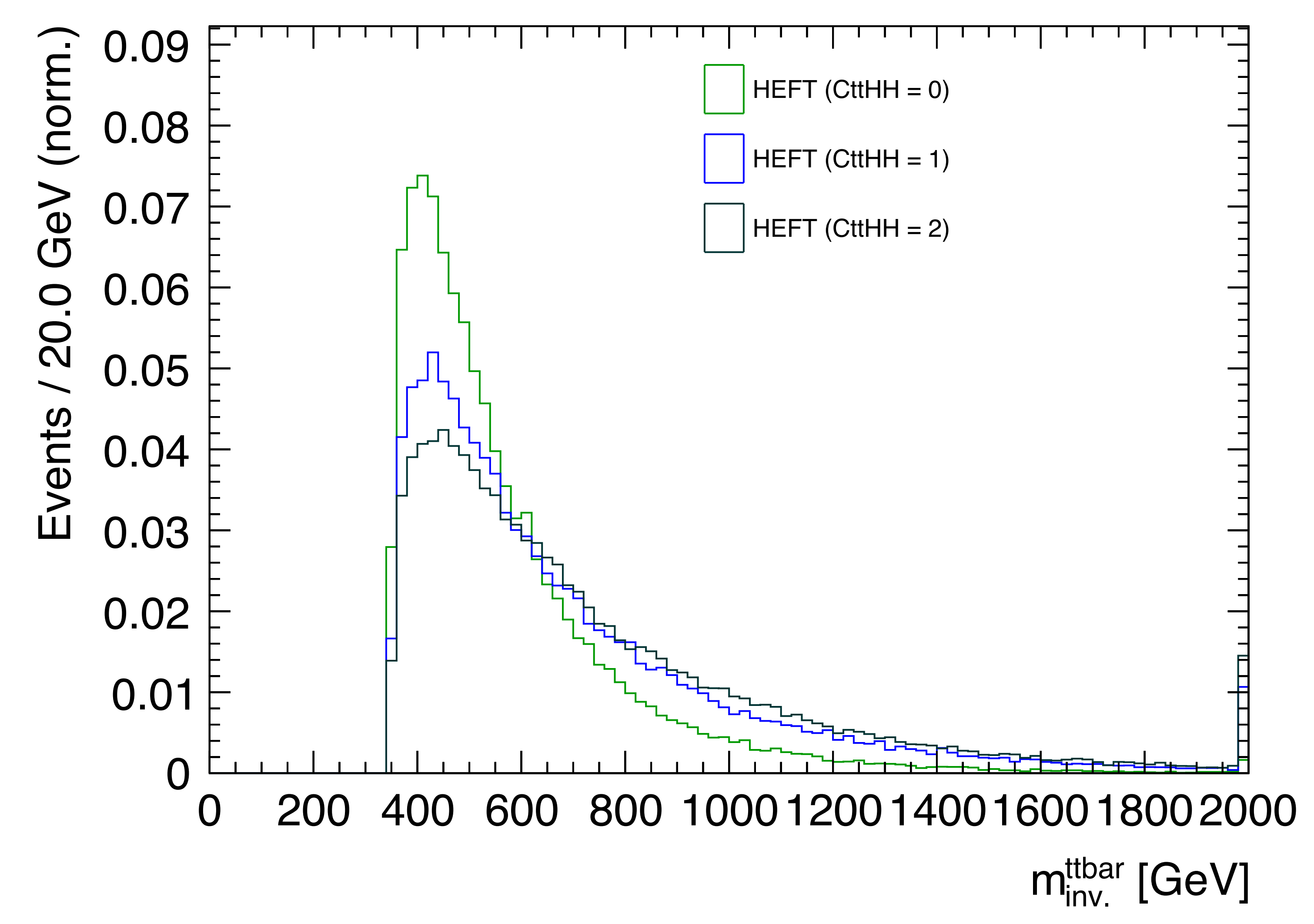

Or even better…

How to extract the most kin. information?

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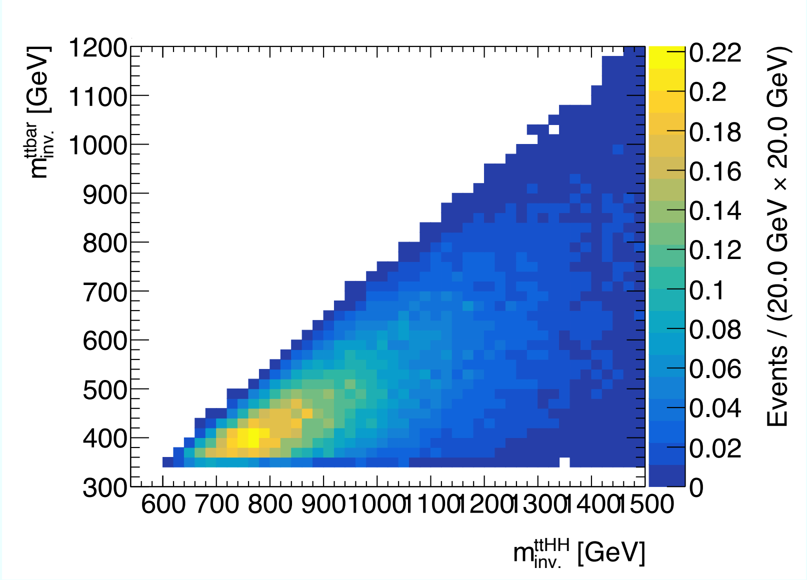
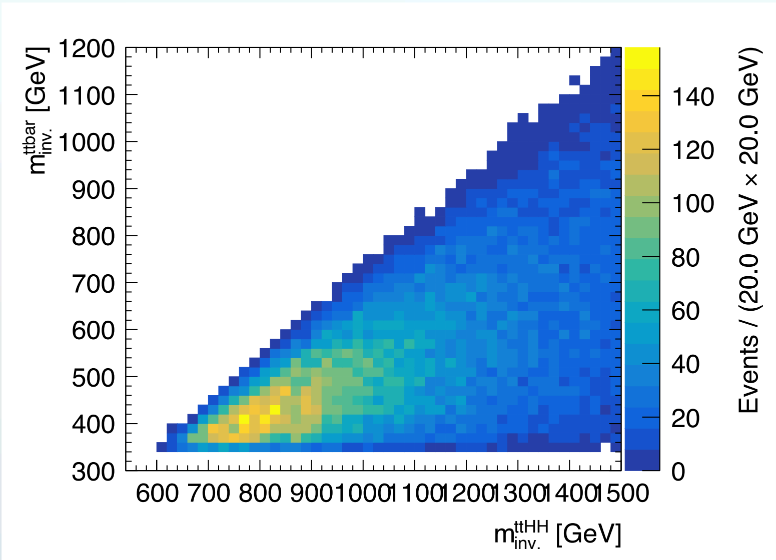
Not possible as no HEFT model existed at the time!

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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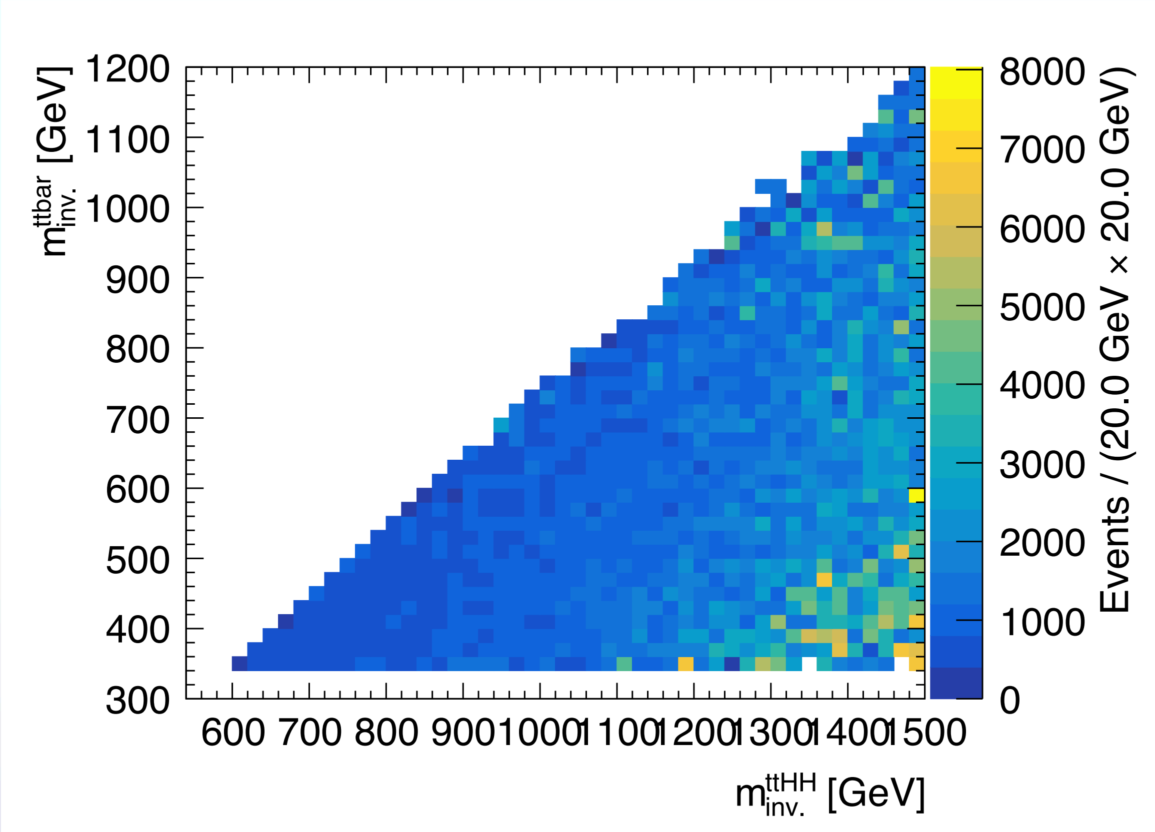
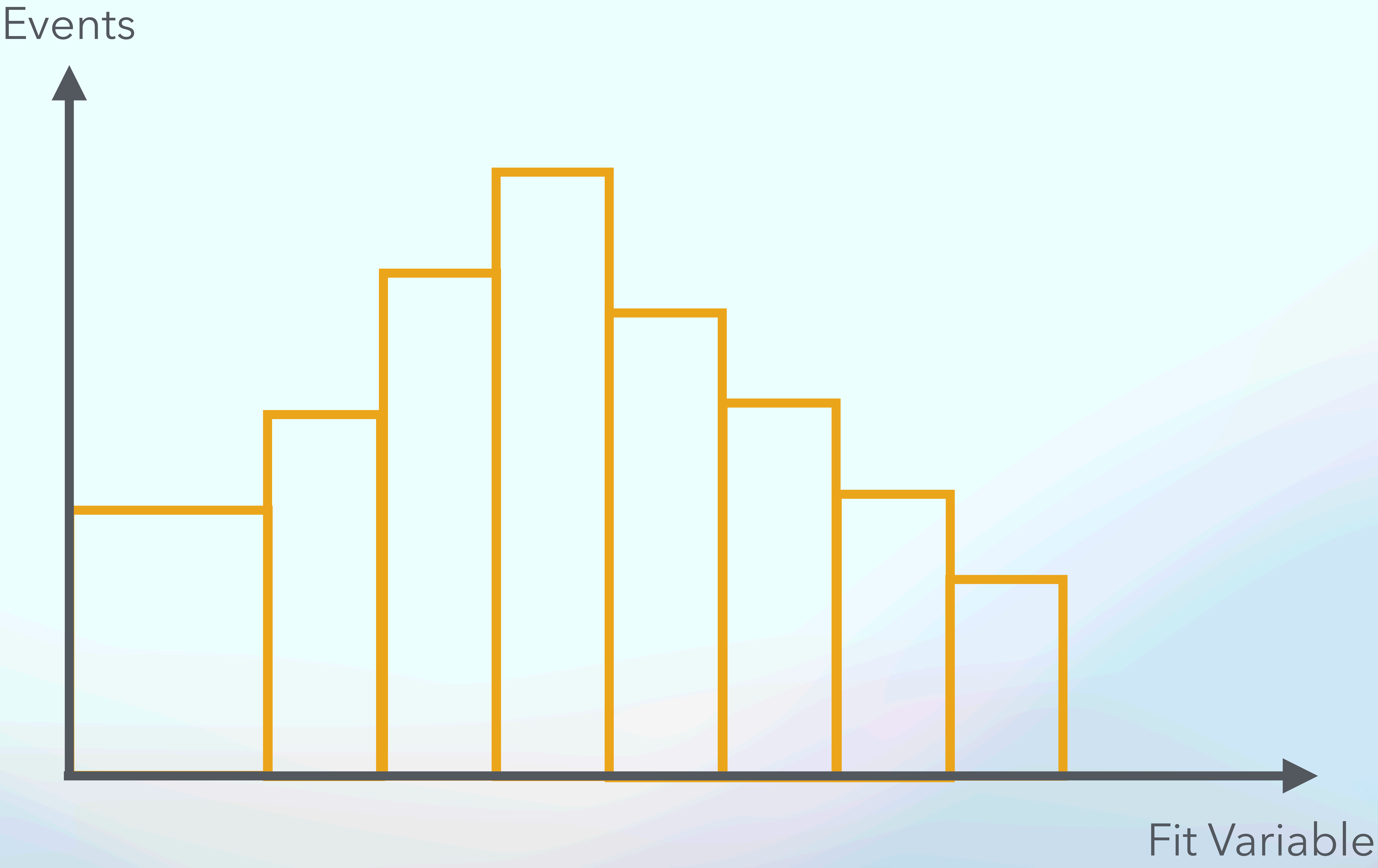


arXiv:2502.20976

answers this question in the context of ggF diHiggs

What effects do we need to take into account?



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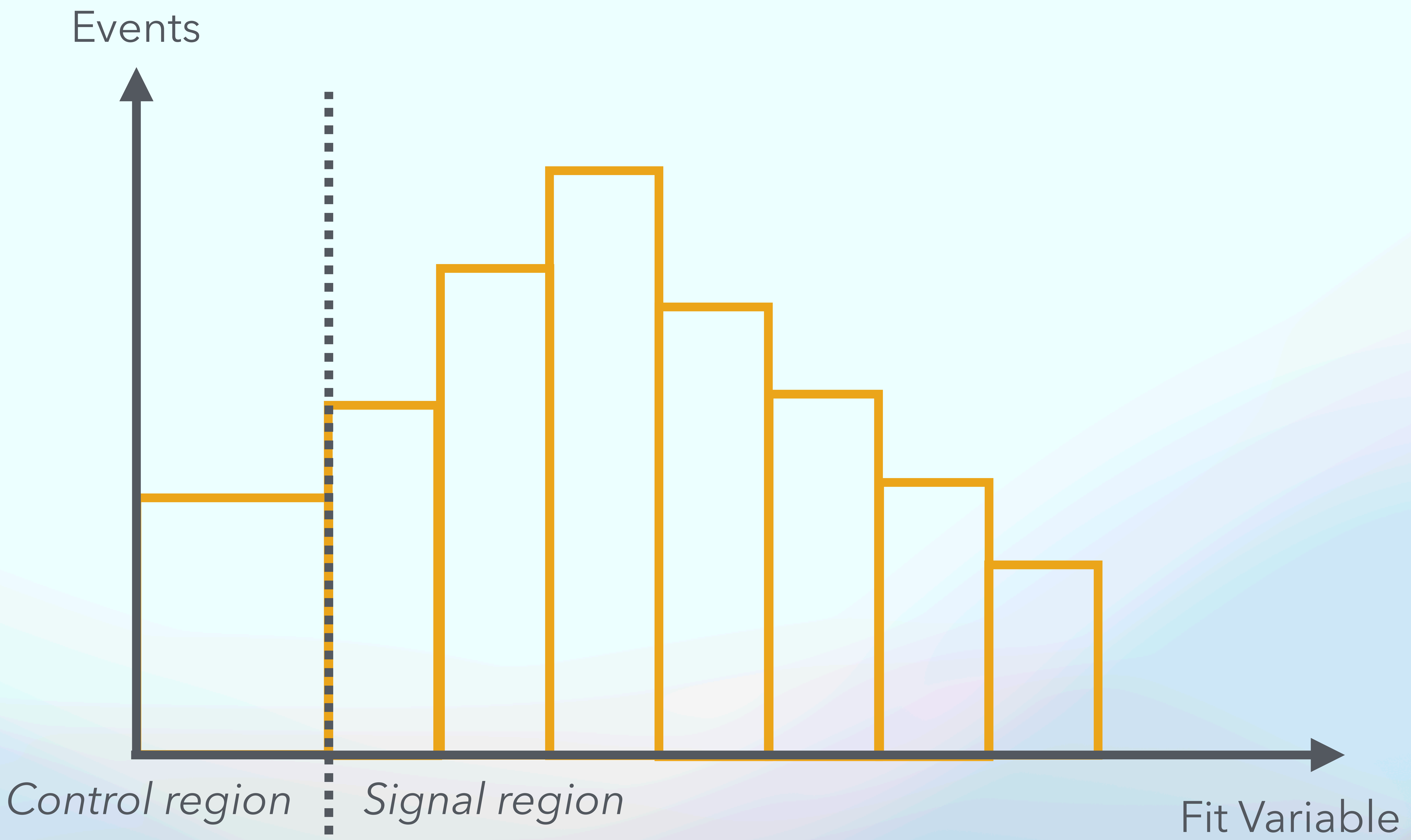

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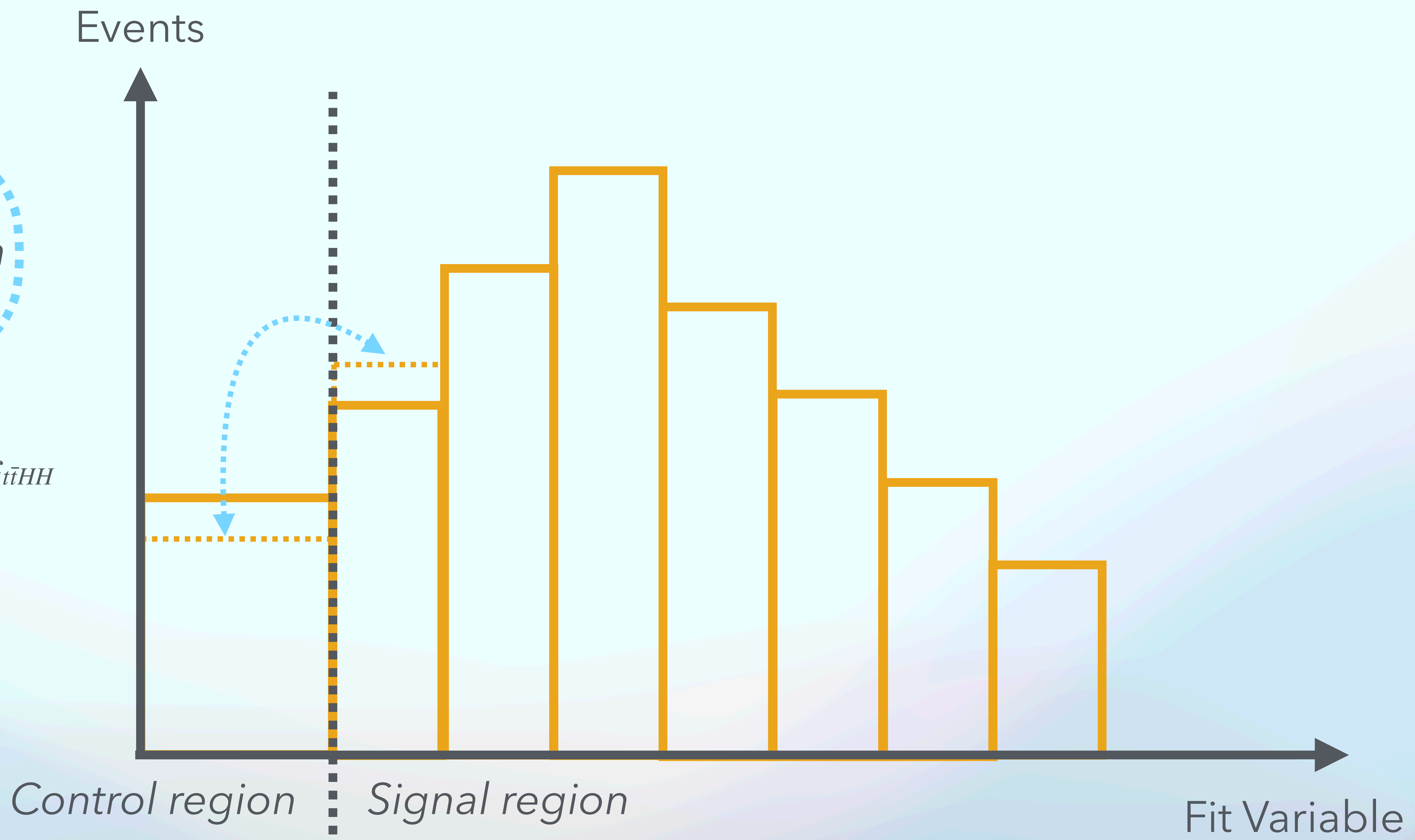


Acceptance effects covered by 30% unc. on signal yield

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?

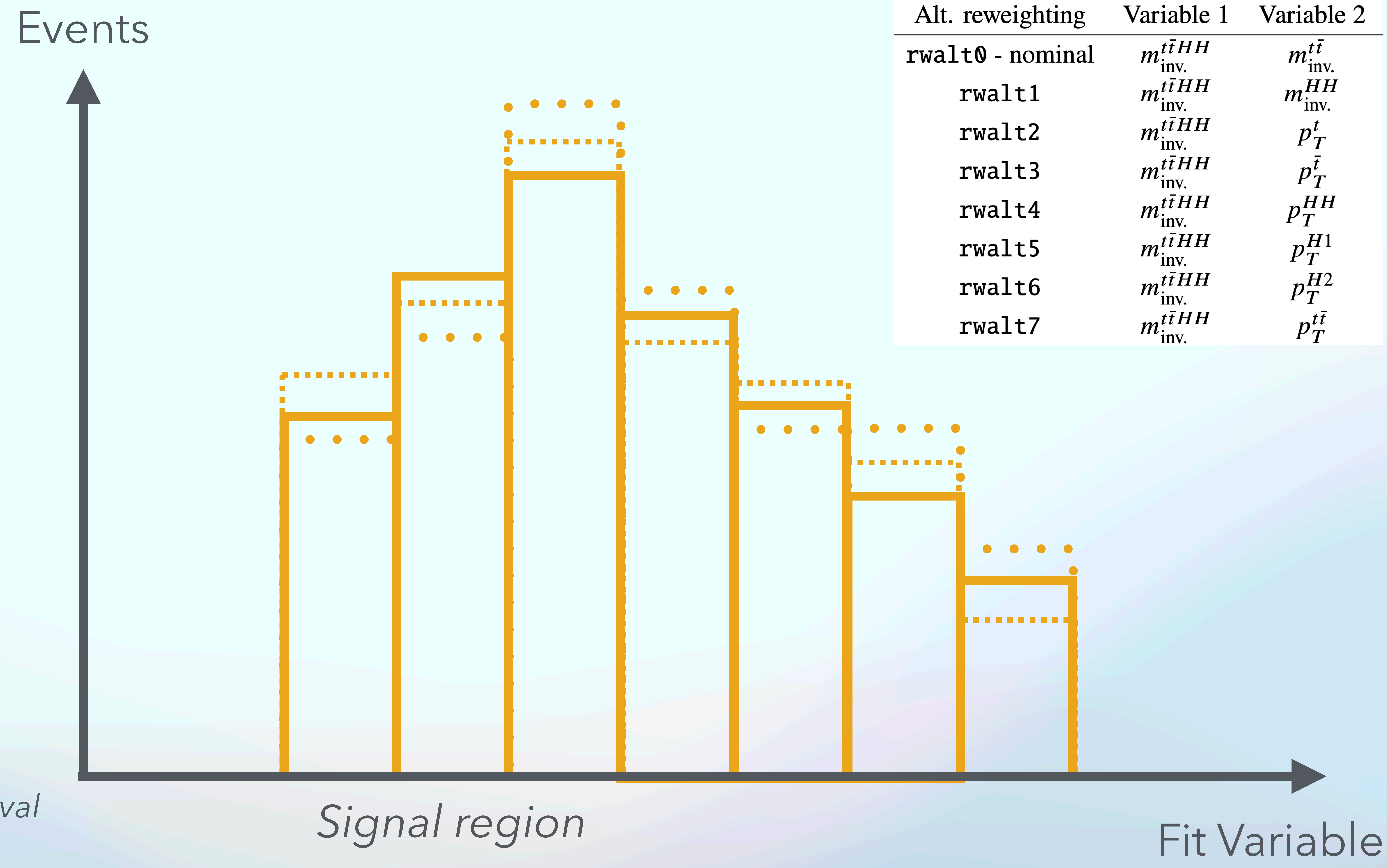
↓

We tested 7 alternative reweightings against no shape variation

↓

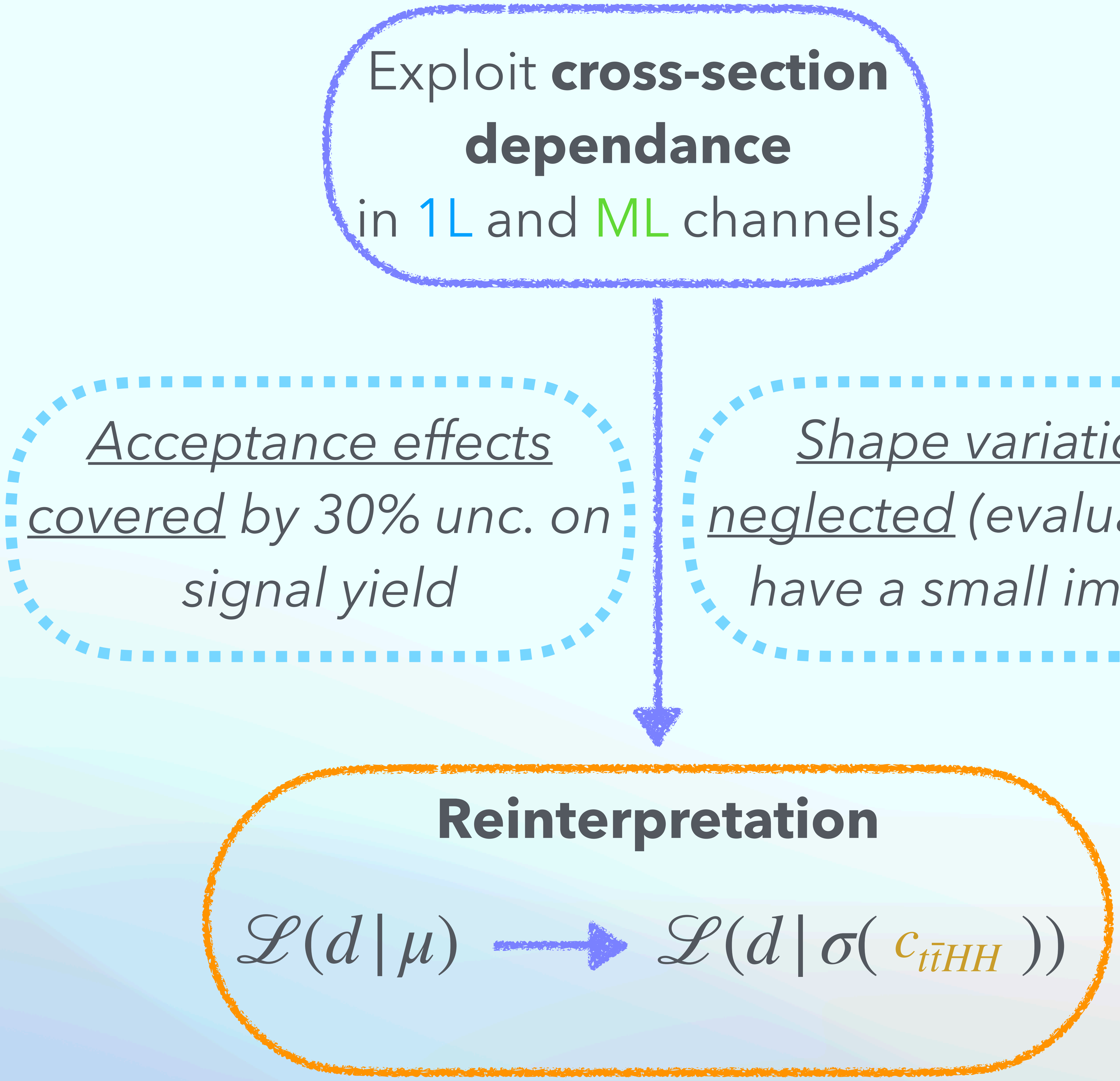
Shape variations neglected (evaluated to have a small impact)

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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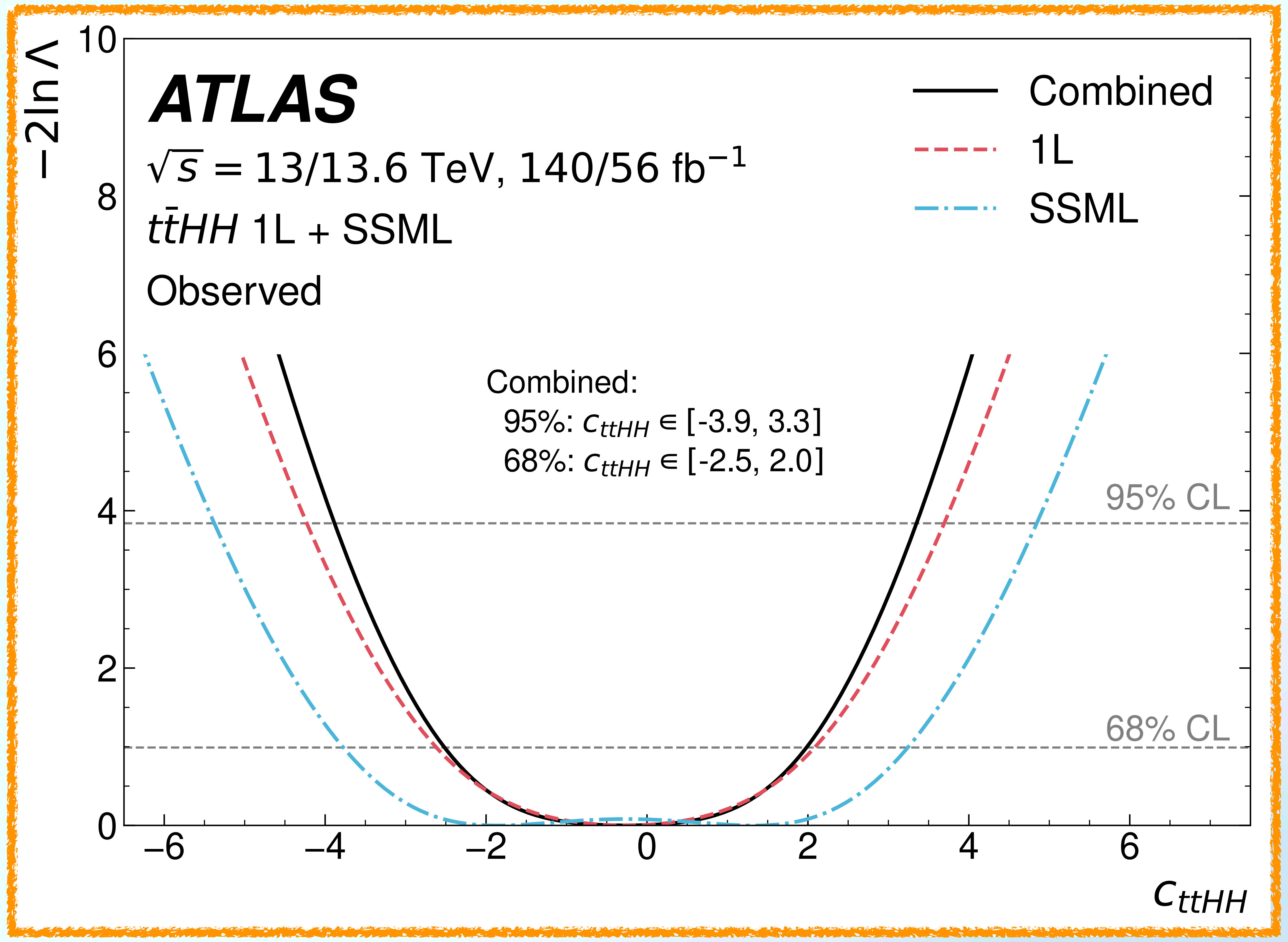

Almost flat likelihood (small degeneracy in ML channel)

→ 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

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

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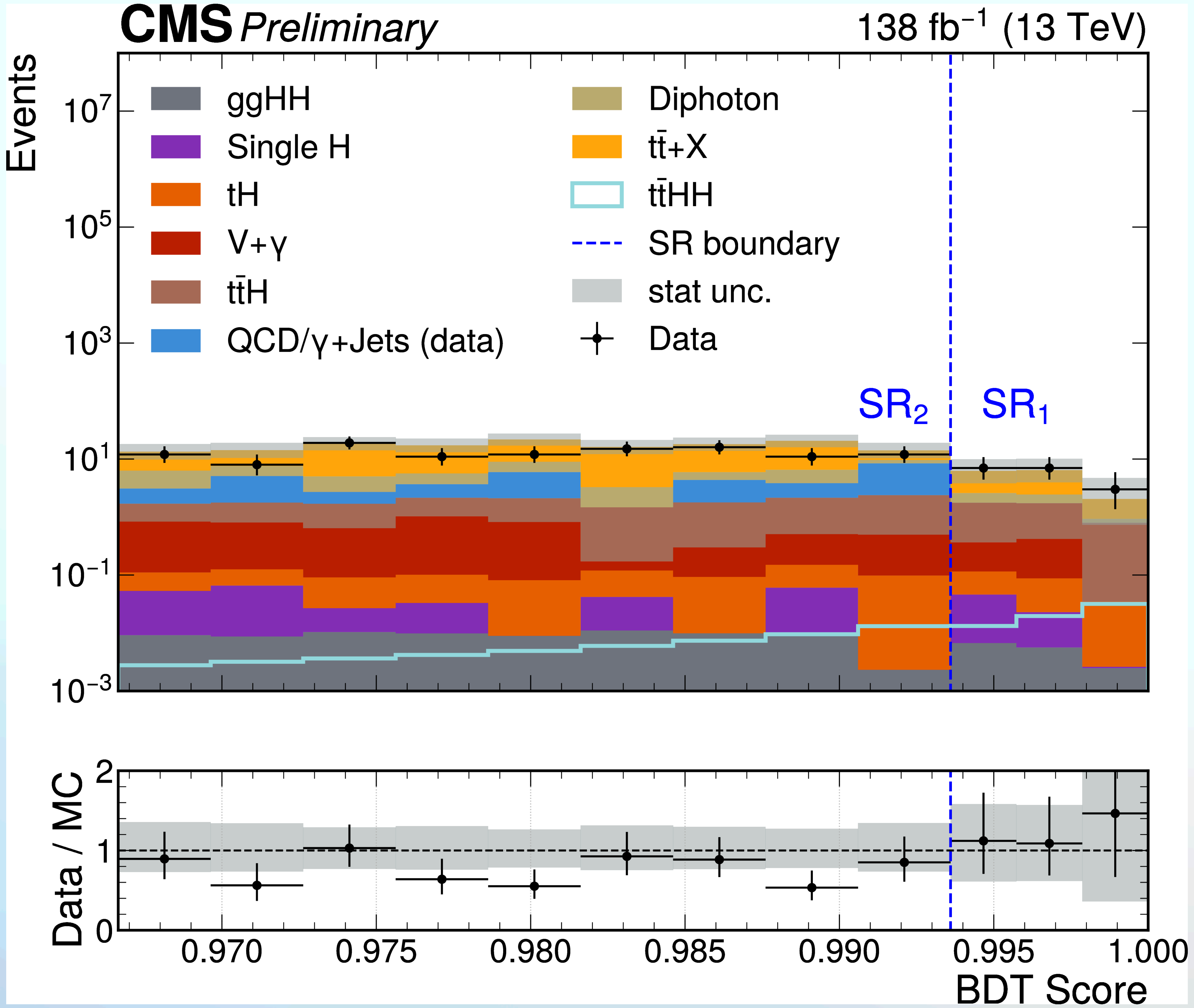
Obs. 95% CL limits on $c_{t\bar{t}HH}$	[-8.0, 7.5]	

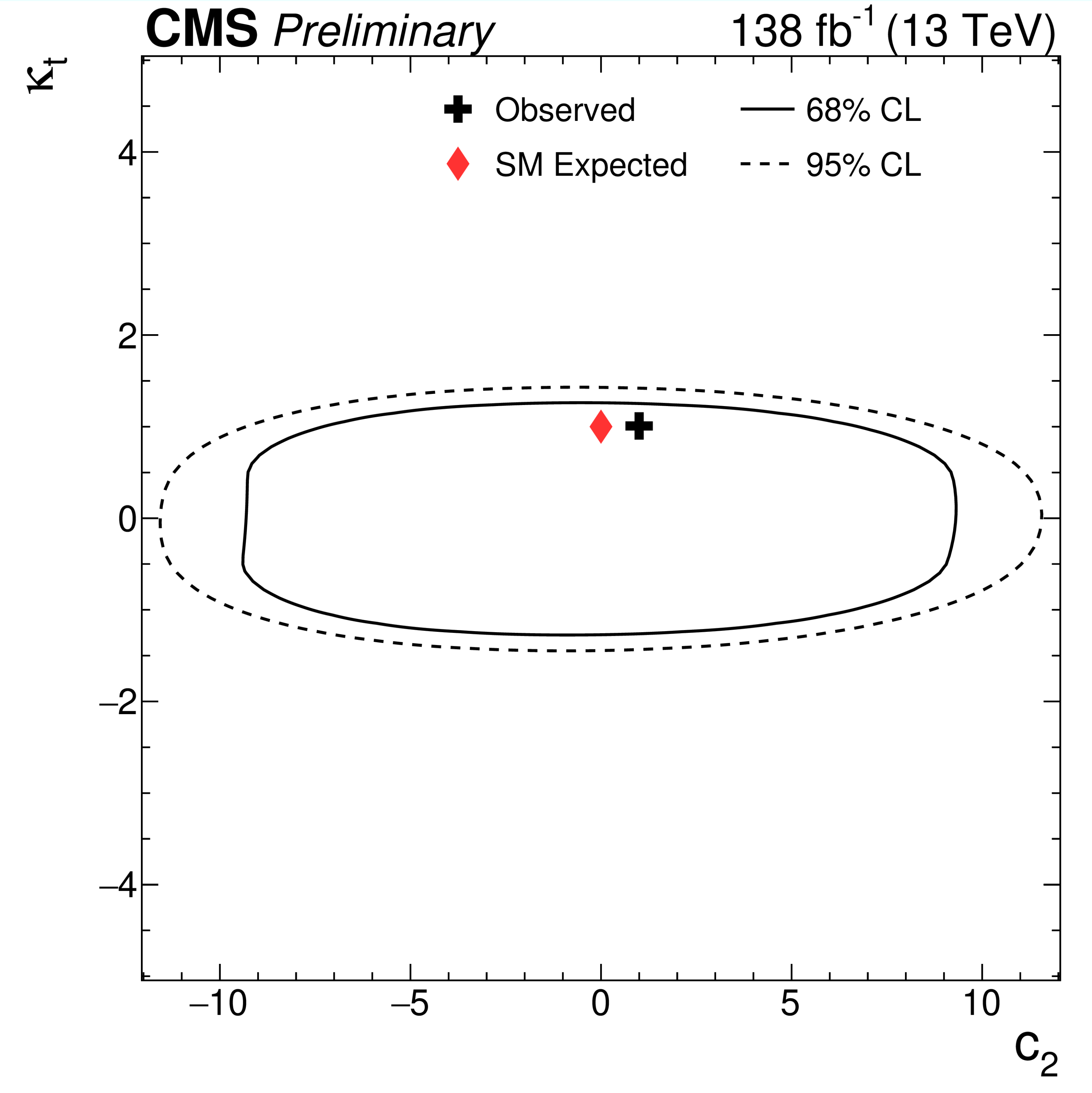
CMS ttHH analysis (1)

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*...*



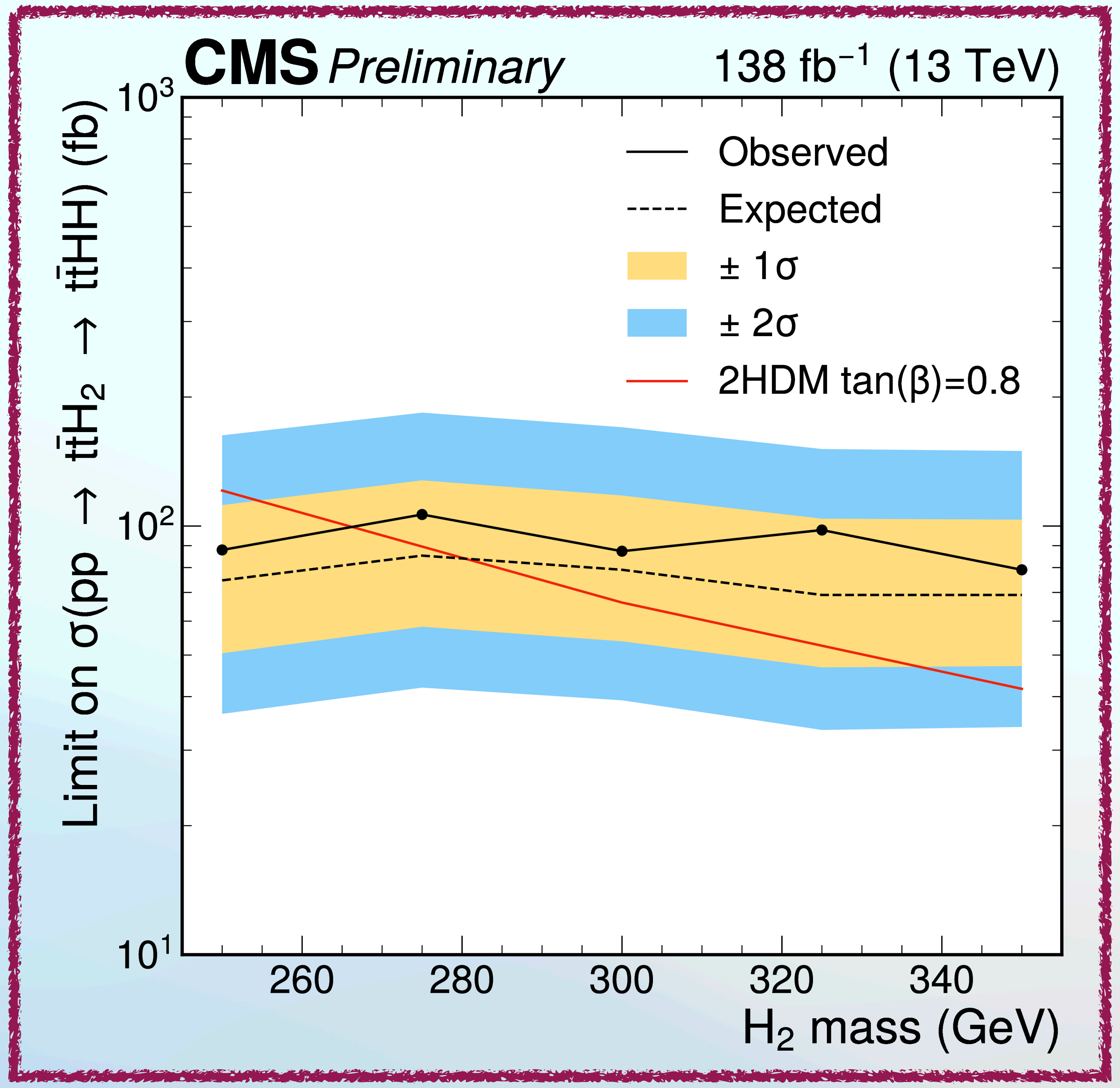


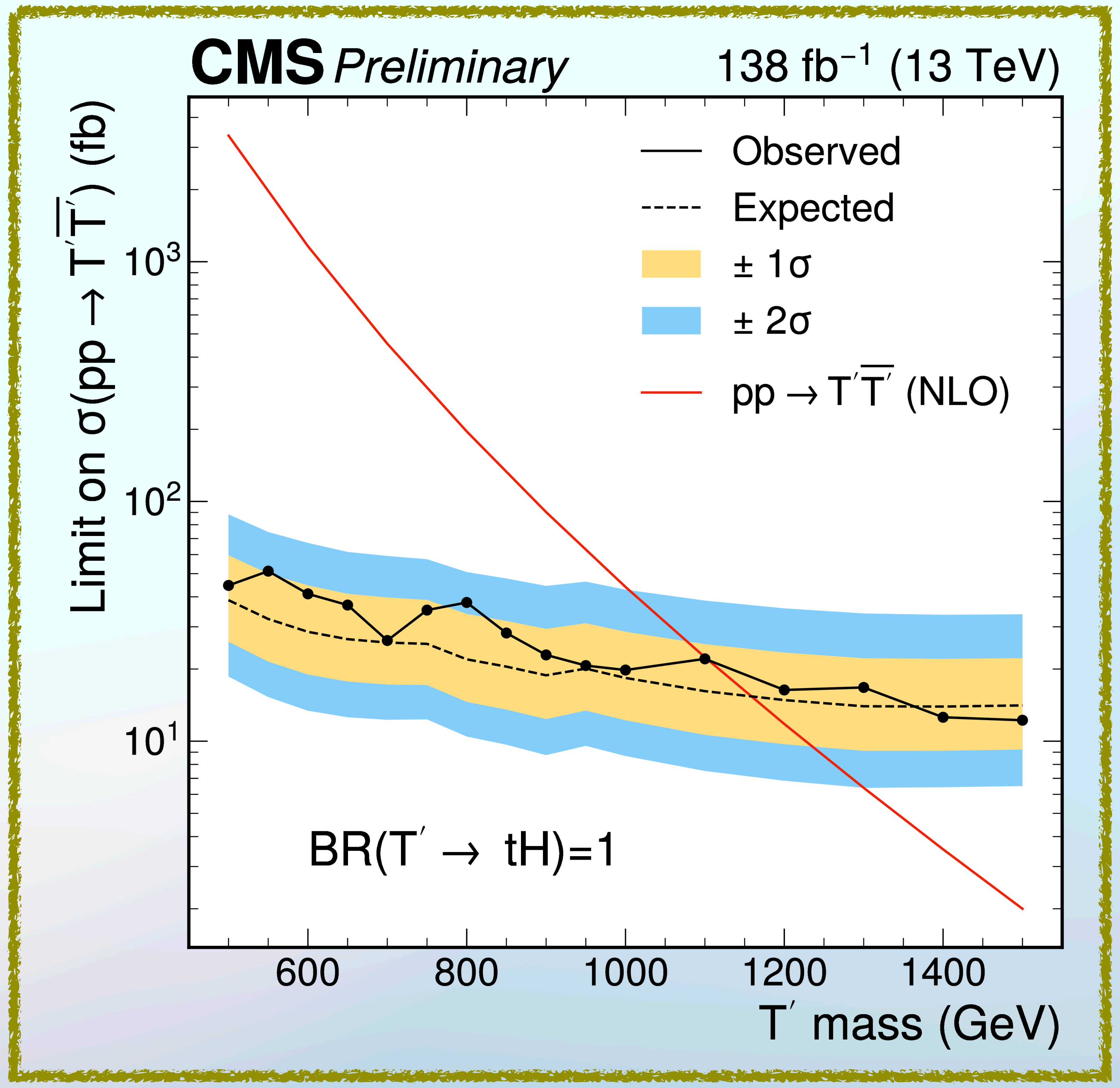
CMS ttHH analysis (2)

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 $T' \to tH$ final state

natural candidate to test HEFT vs. SMEFT





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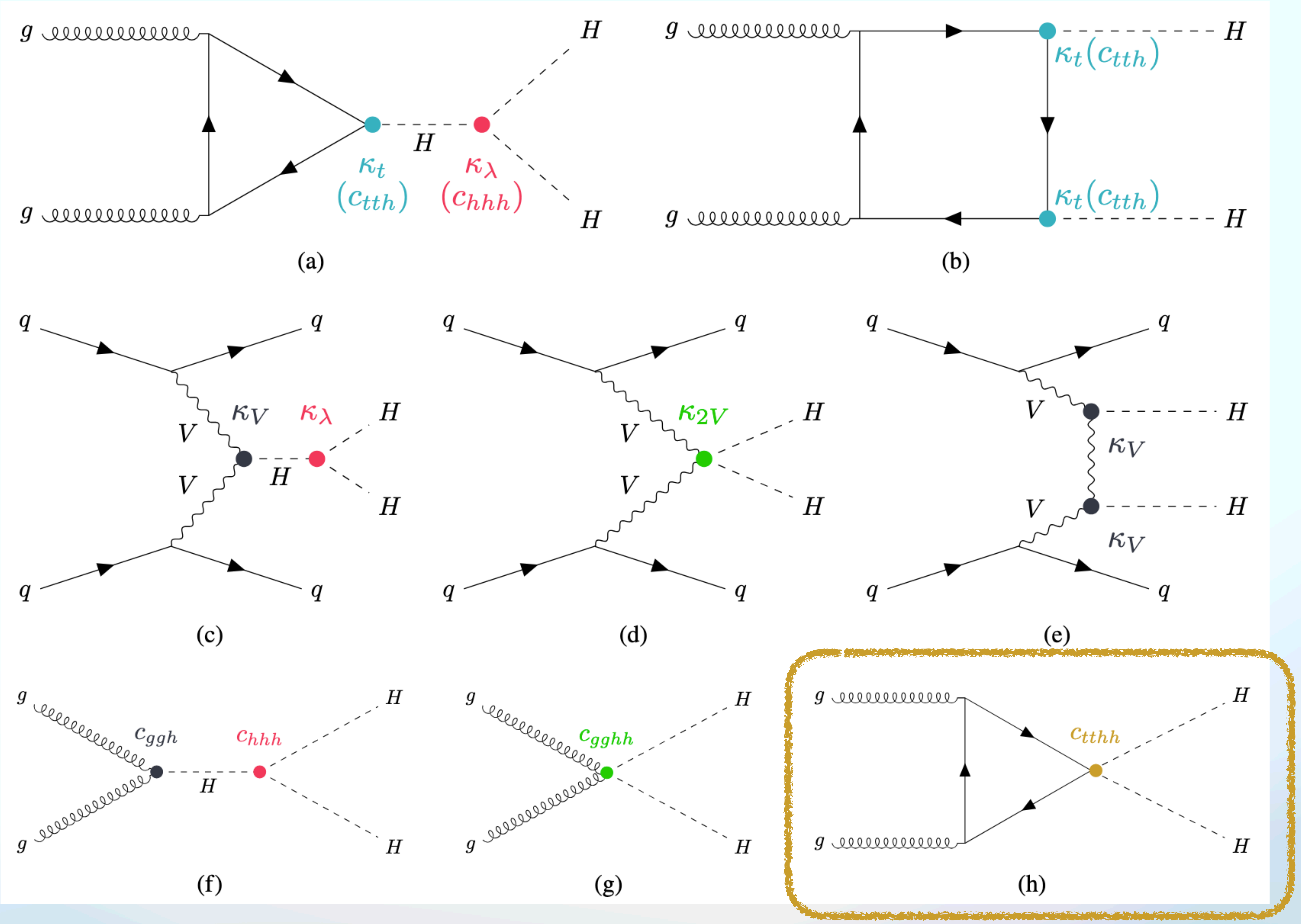
Obs. 95% CL limits on $c_{t\bar{t}HH}$	[-8.0, 7.5]	[-0.19, 0.7]	[-0.29, 0.59]

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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Possible improvements

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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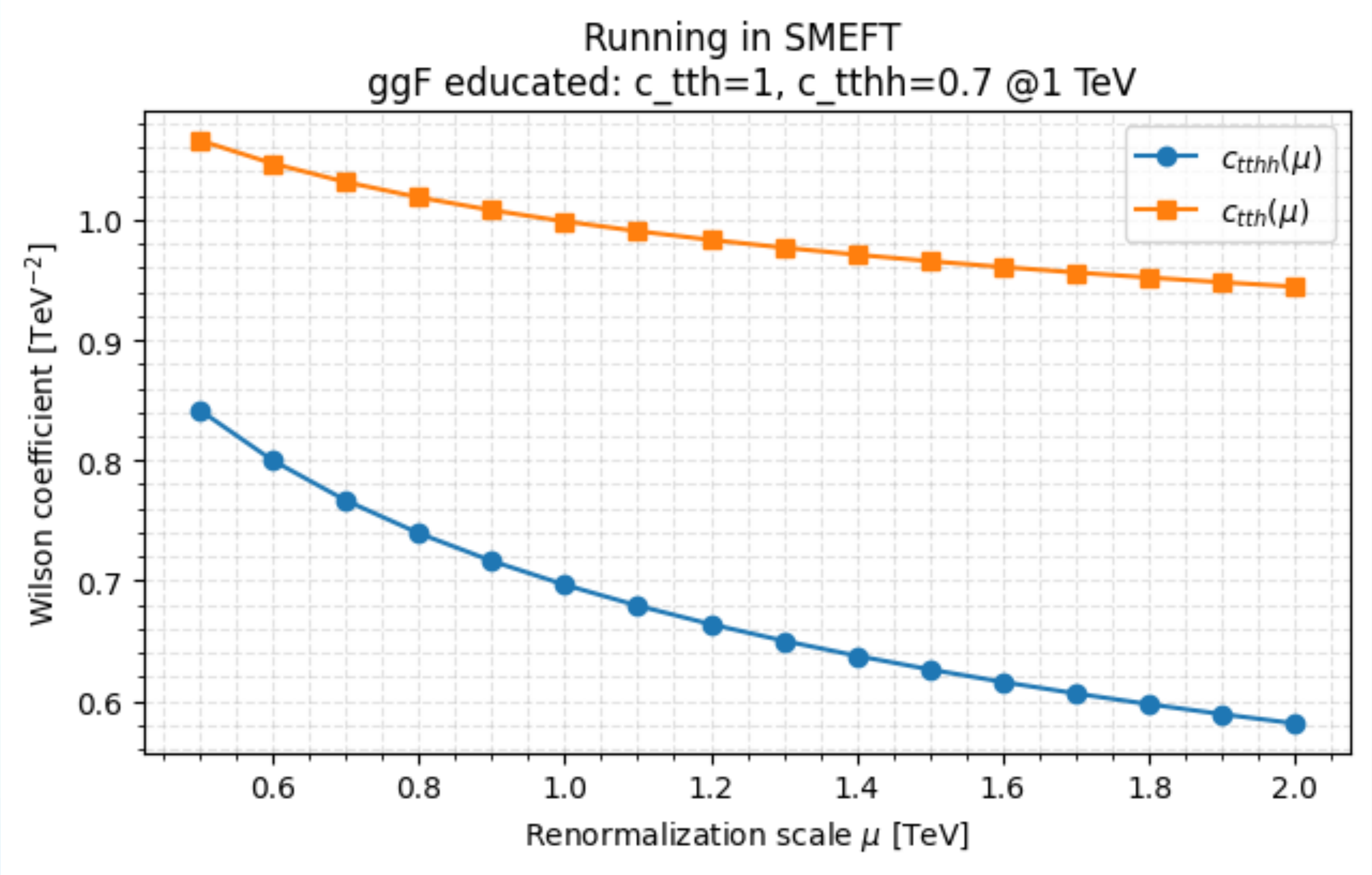

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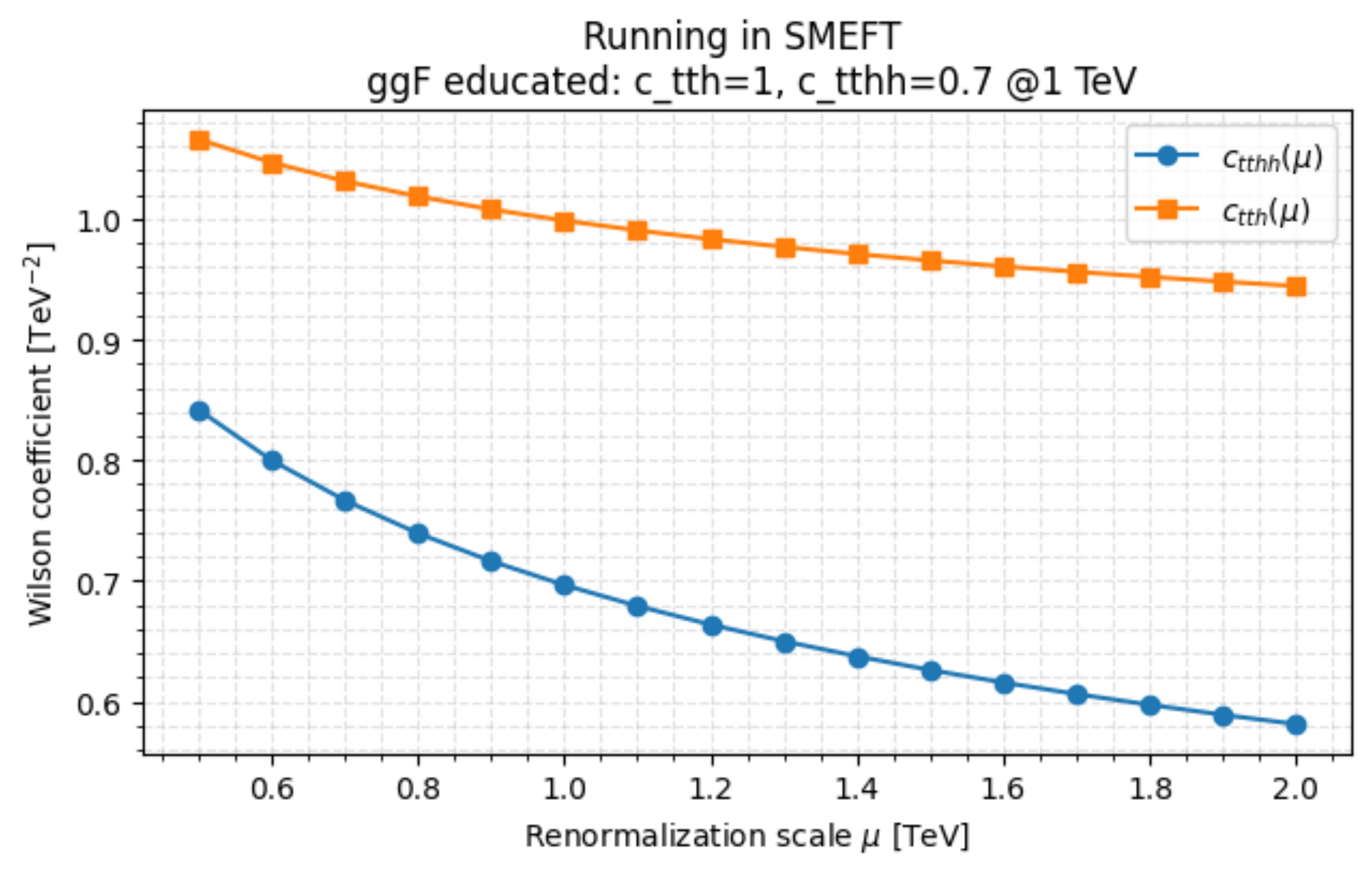

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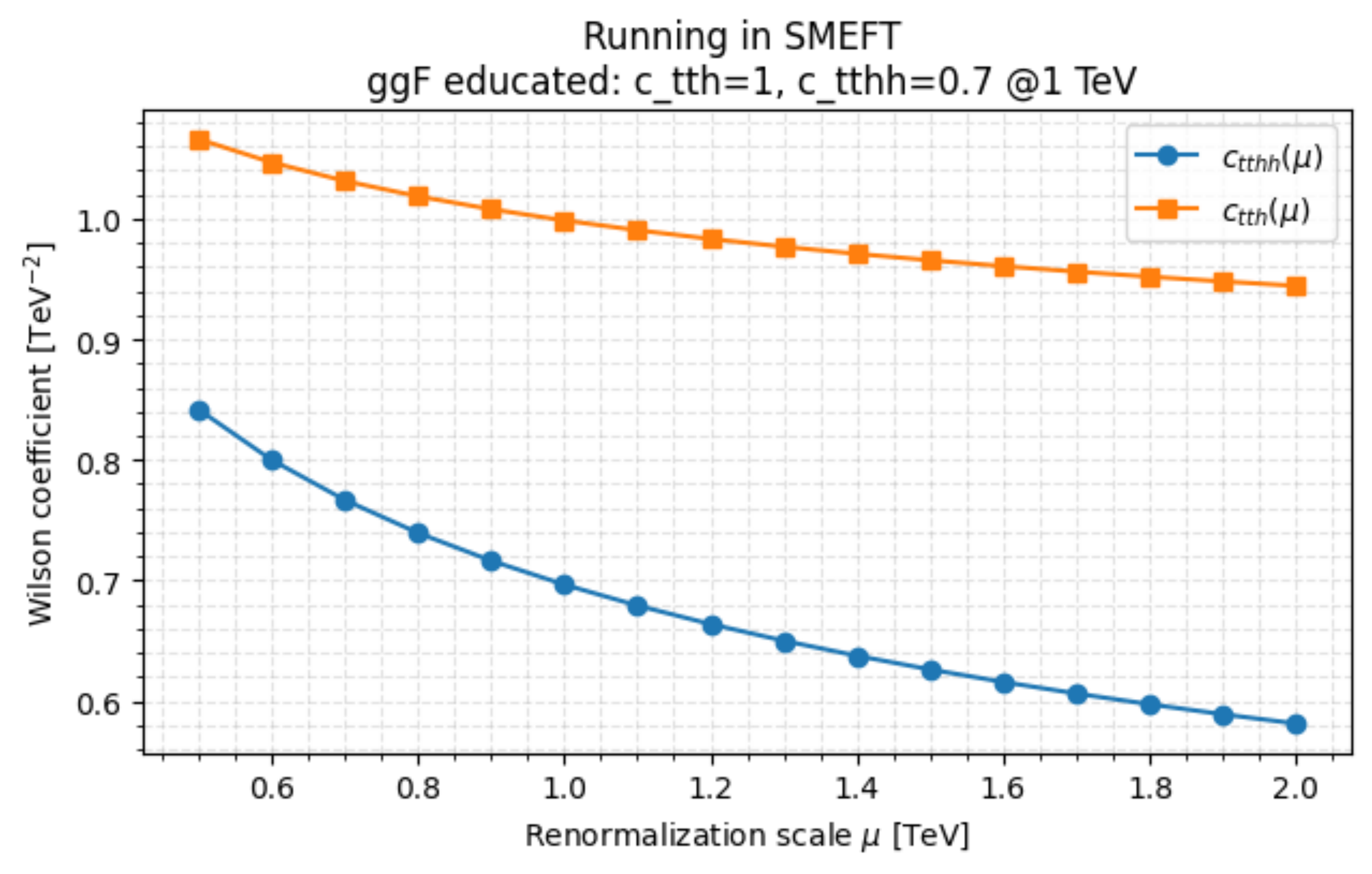

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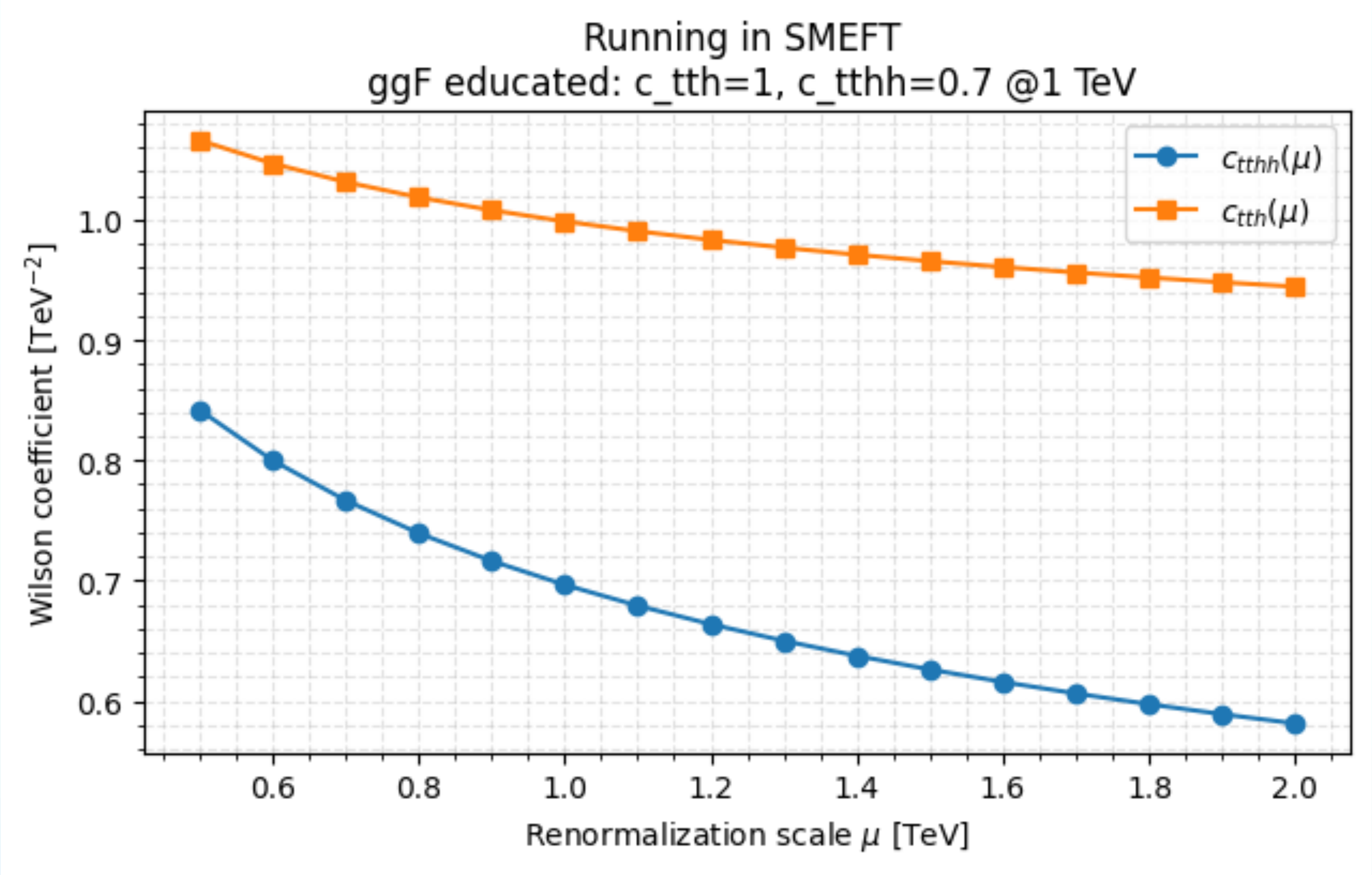

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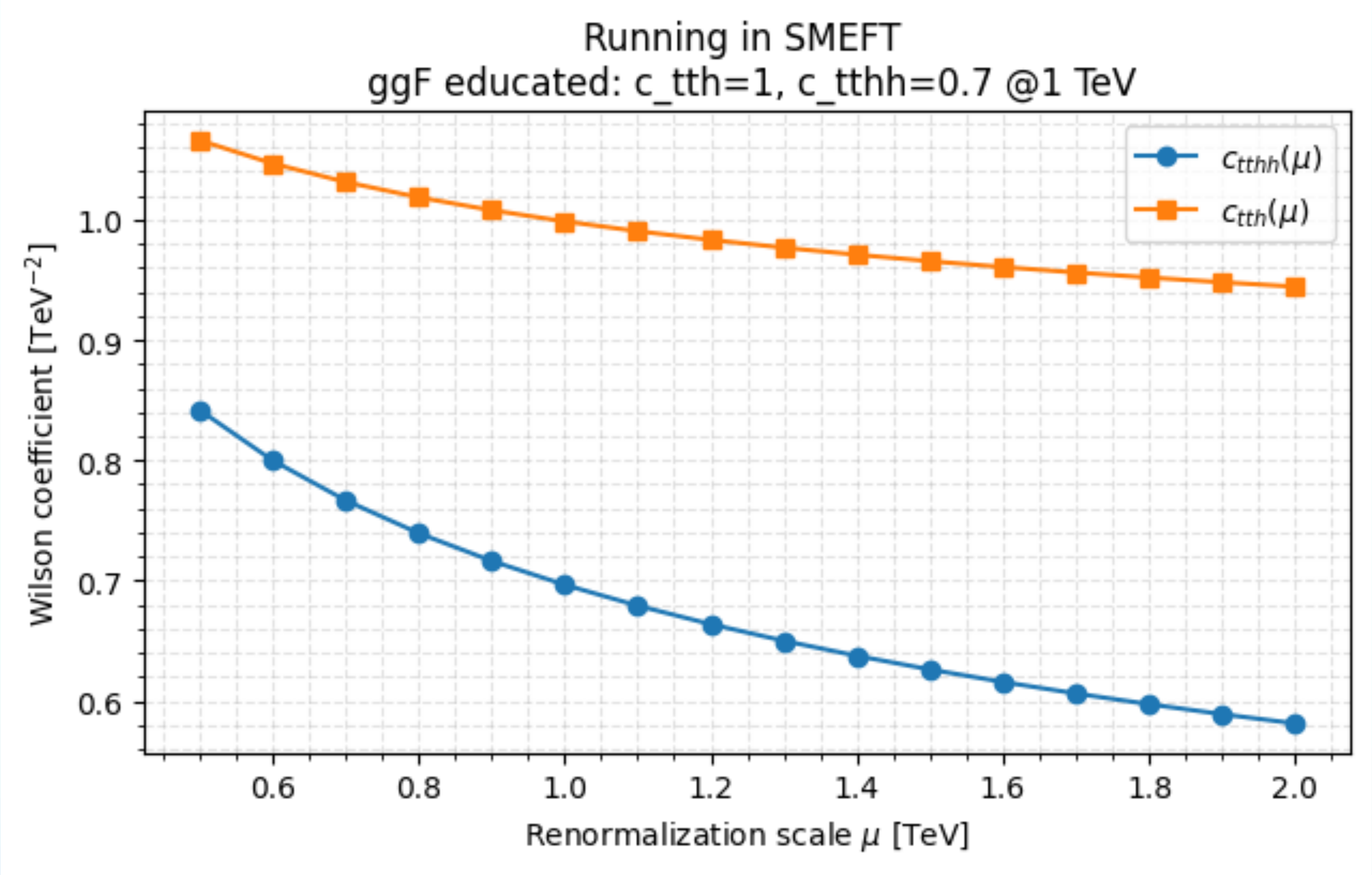

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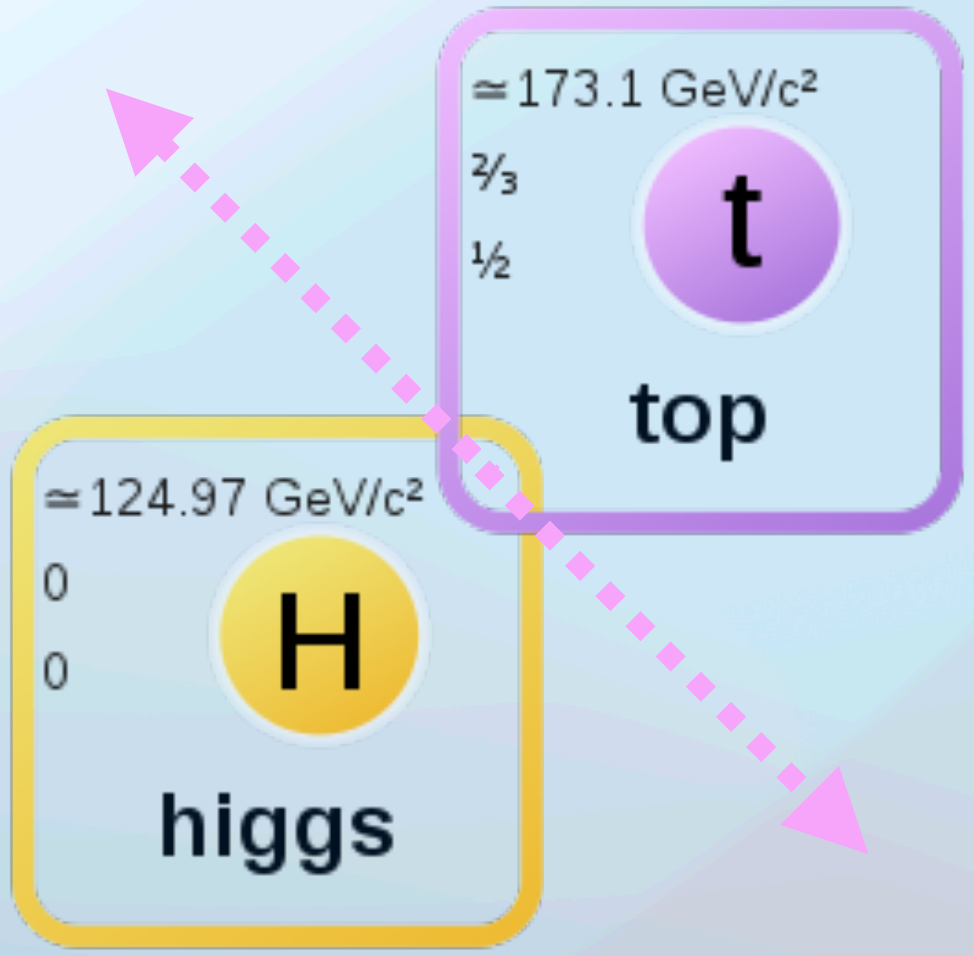
Is this running valid? → proper implementation of HEFT running needed

probably not

Conclusion

Thoughts for the future



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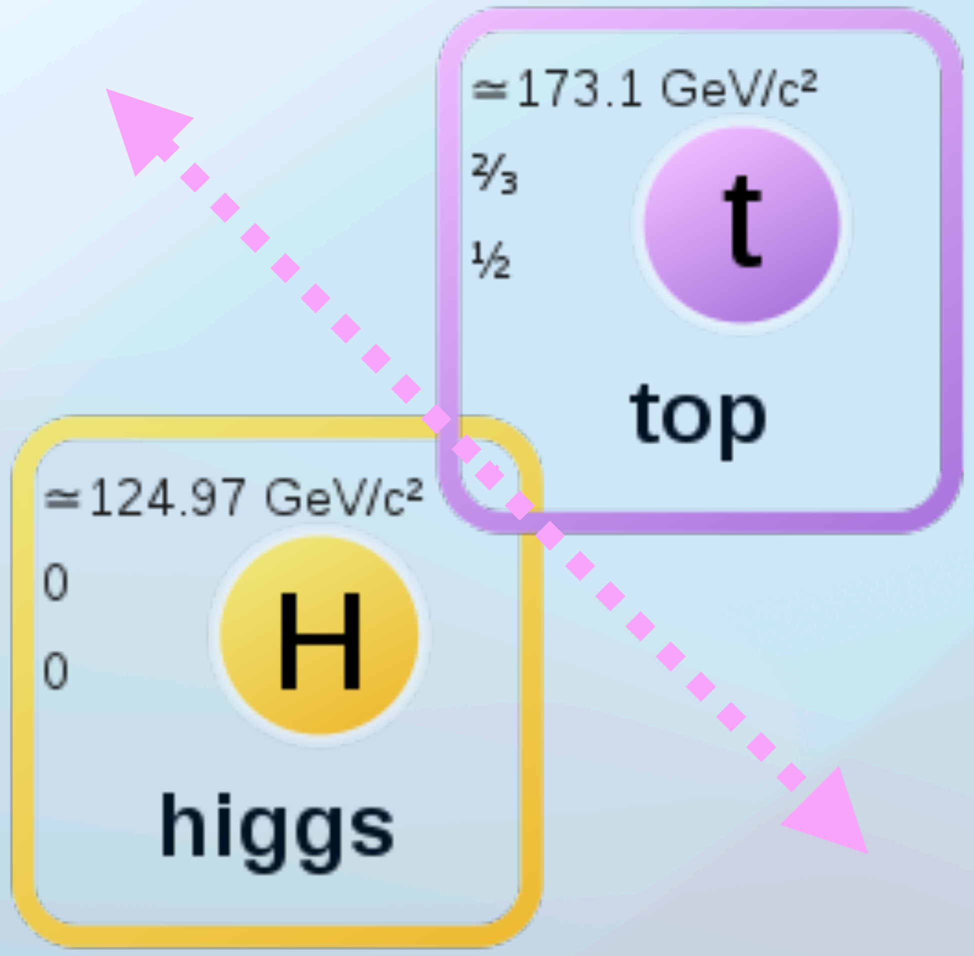
$t\bar{t}HH$ is promising but still limited

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

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



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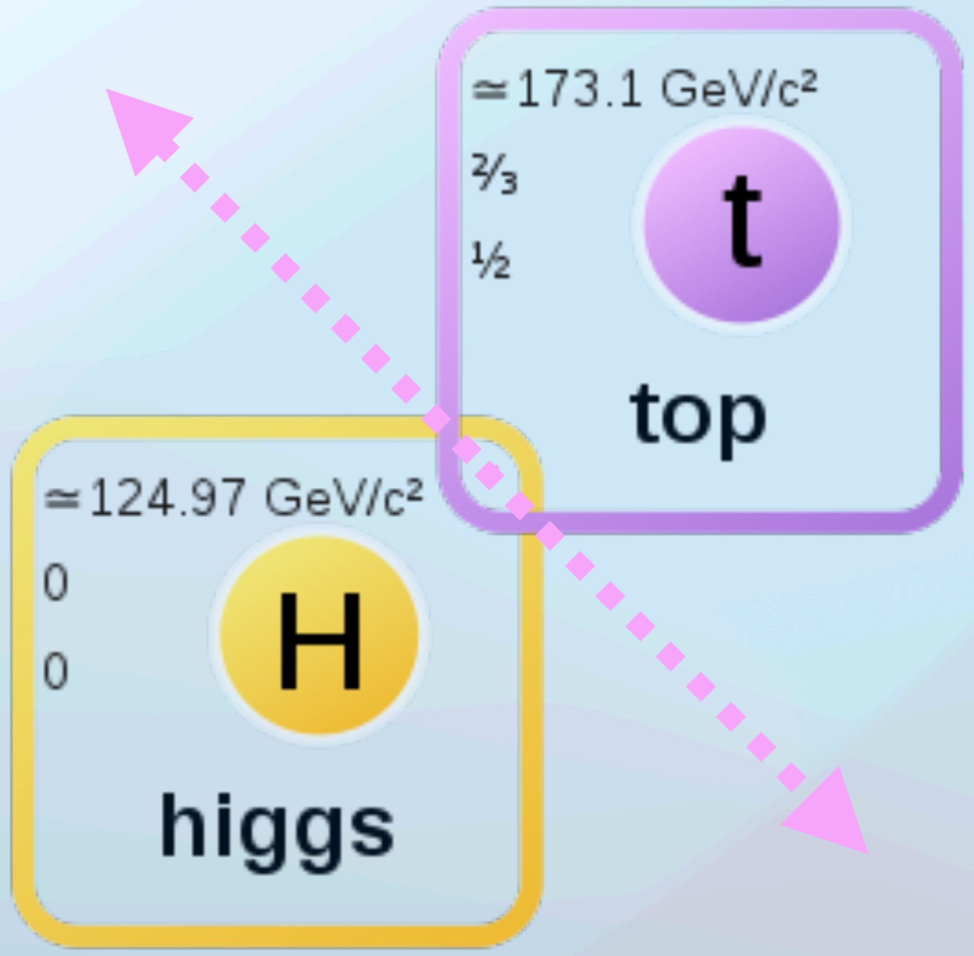

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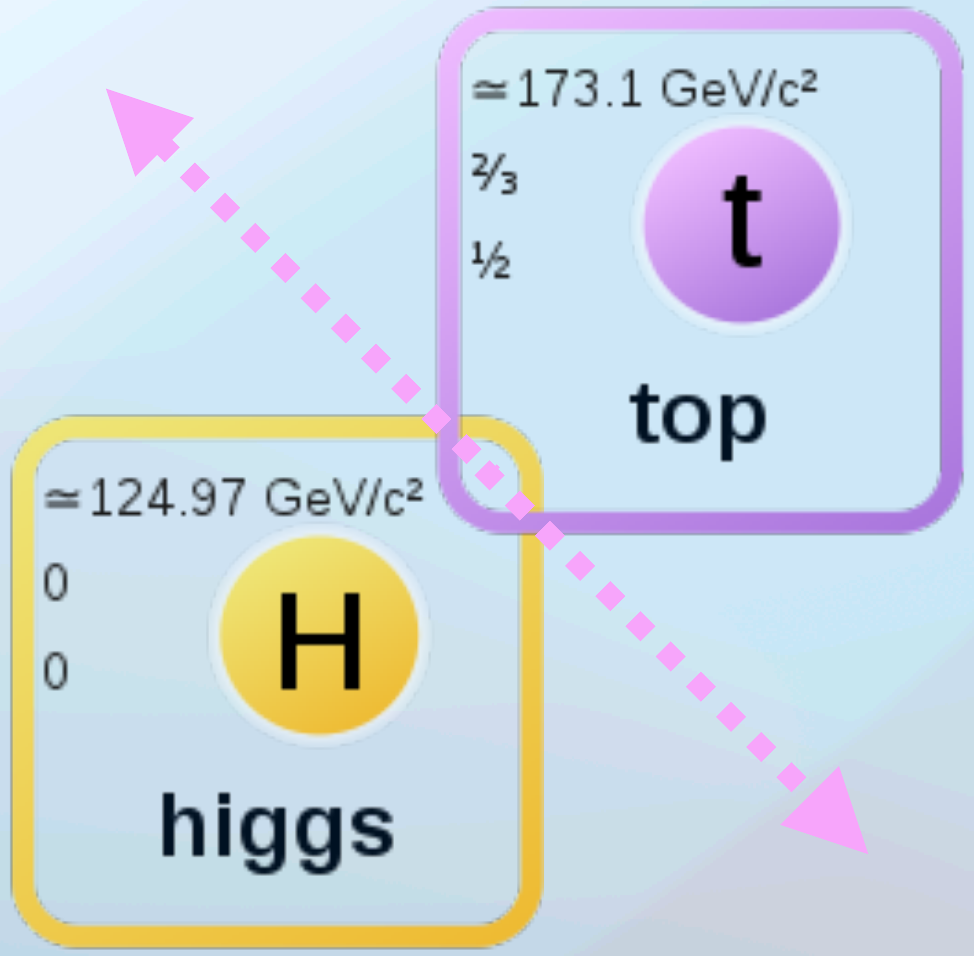
→ Designing analysis specifically for EFT



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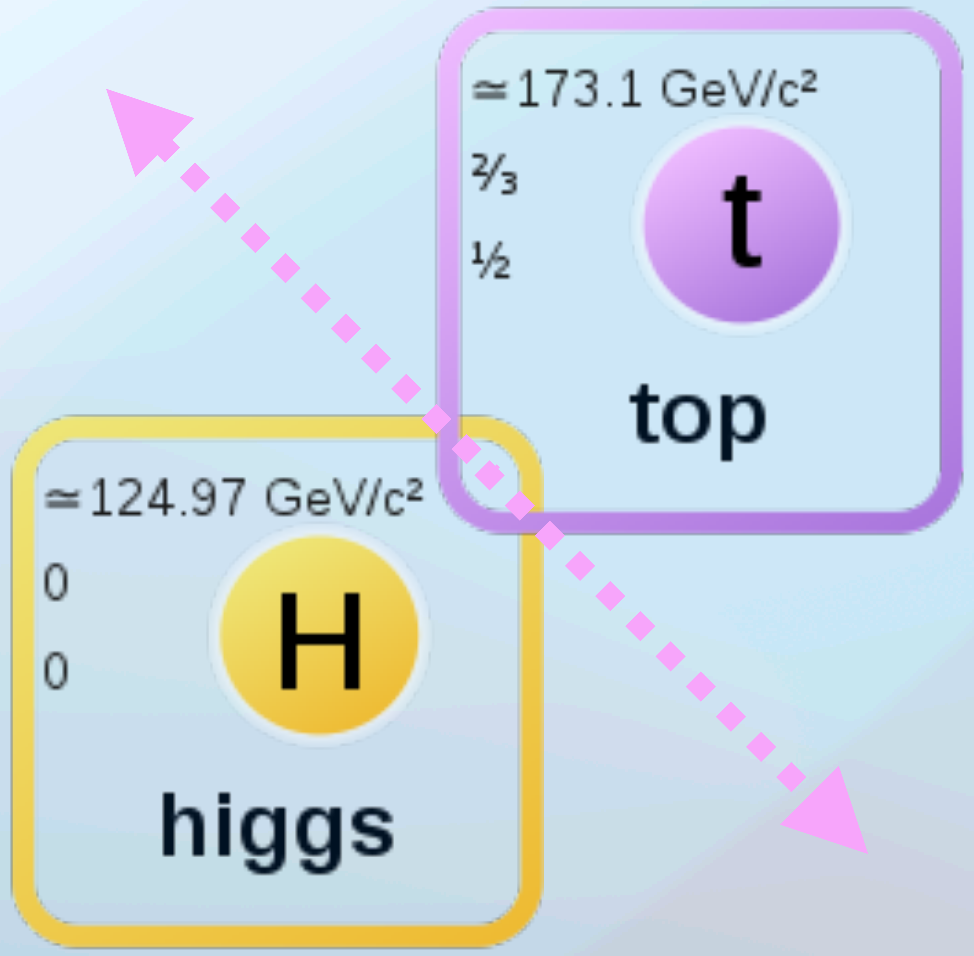
HEFT vs. "*traditional*" **SMEFT** interpretion *when relevant*

What UV model have different predictions in both frameworks?



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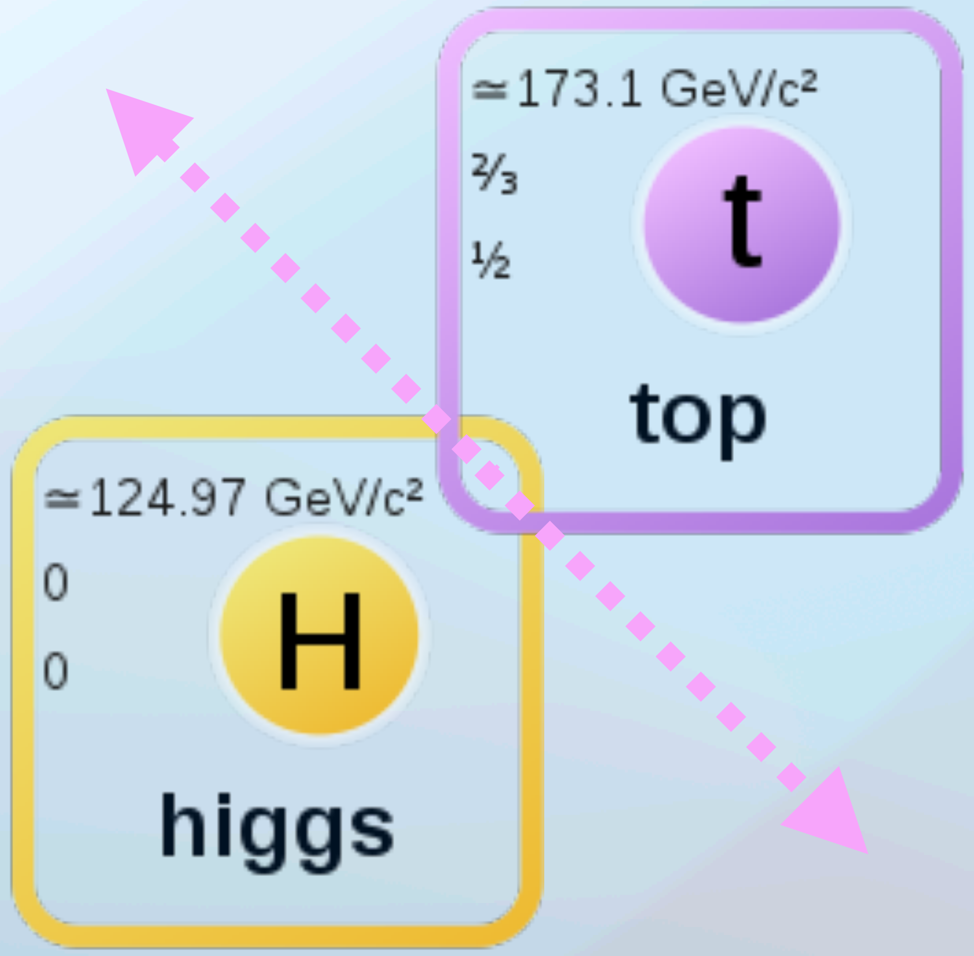


Top and Higgs sectors are **promising probes** for exploring EWSB + connexion to heavy NP

Thank you!

😊

Backup

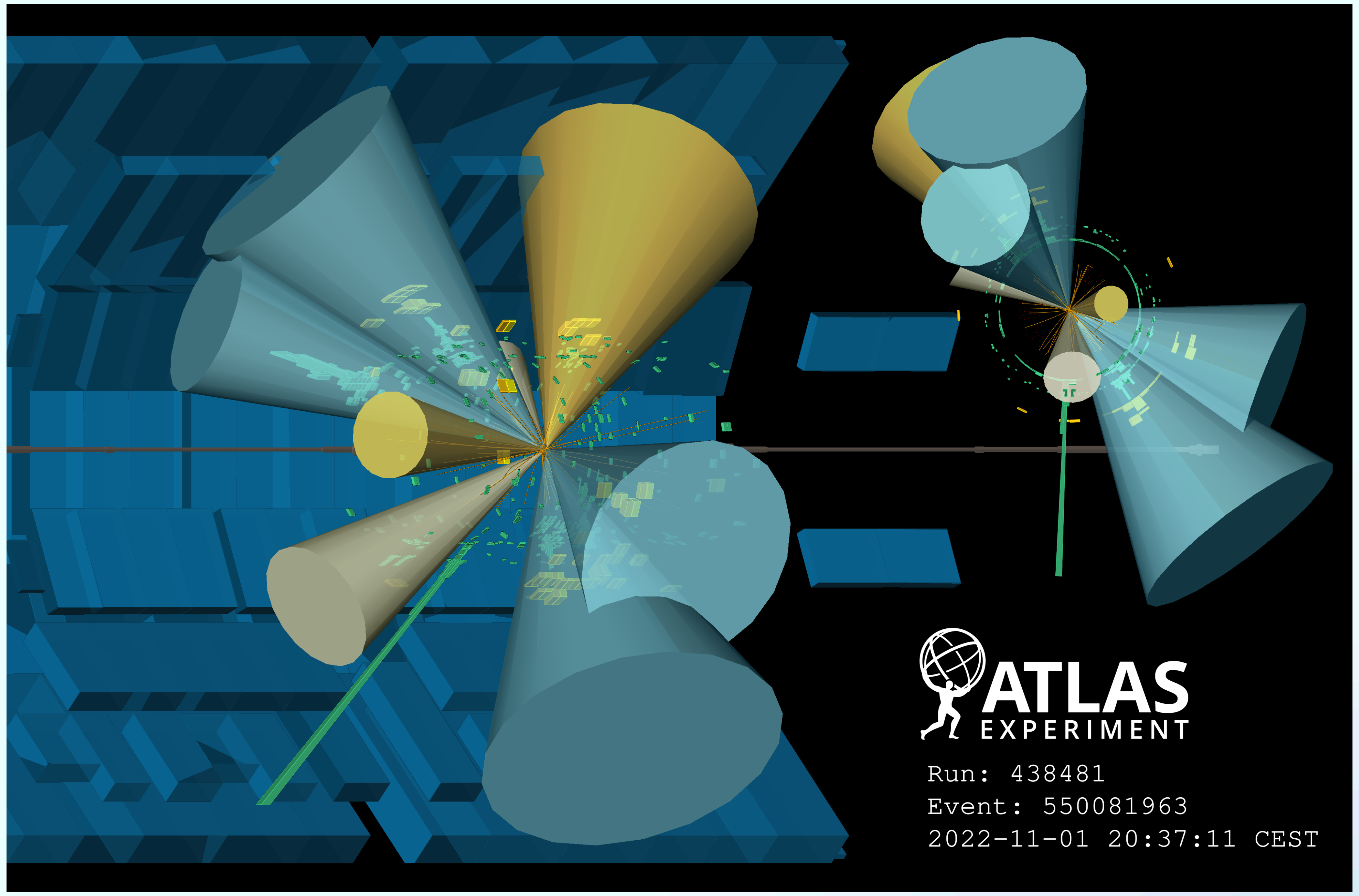
Single-lepton channel

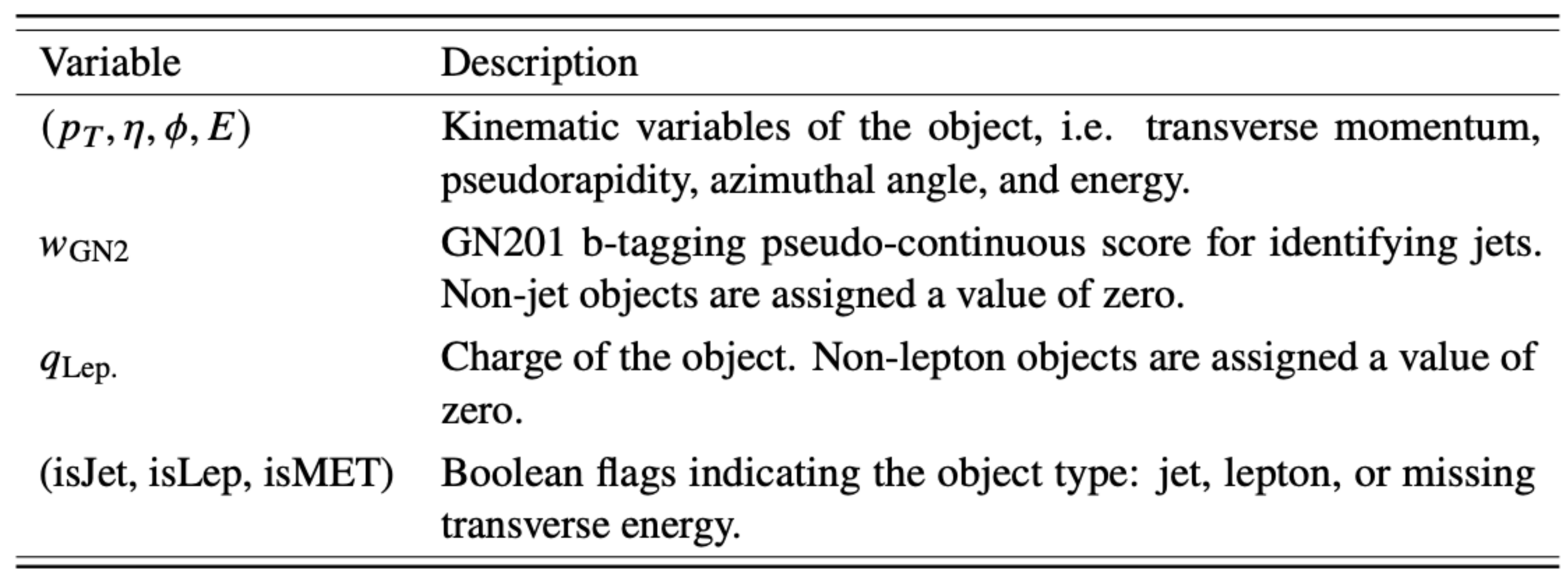
Single lepton from W and $\geq$ 4 b-tagged jets

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

Signal / Background split by jet-multiplicity

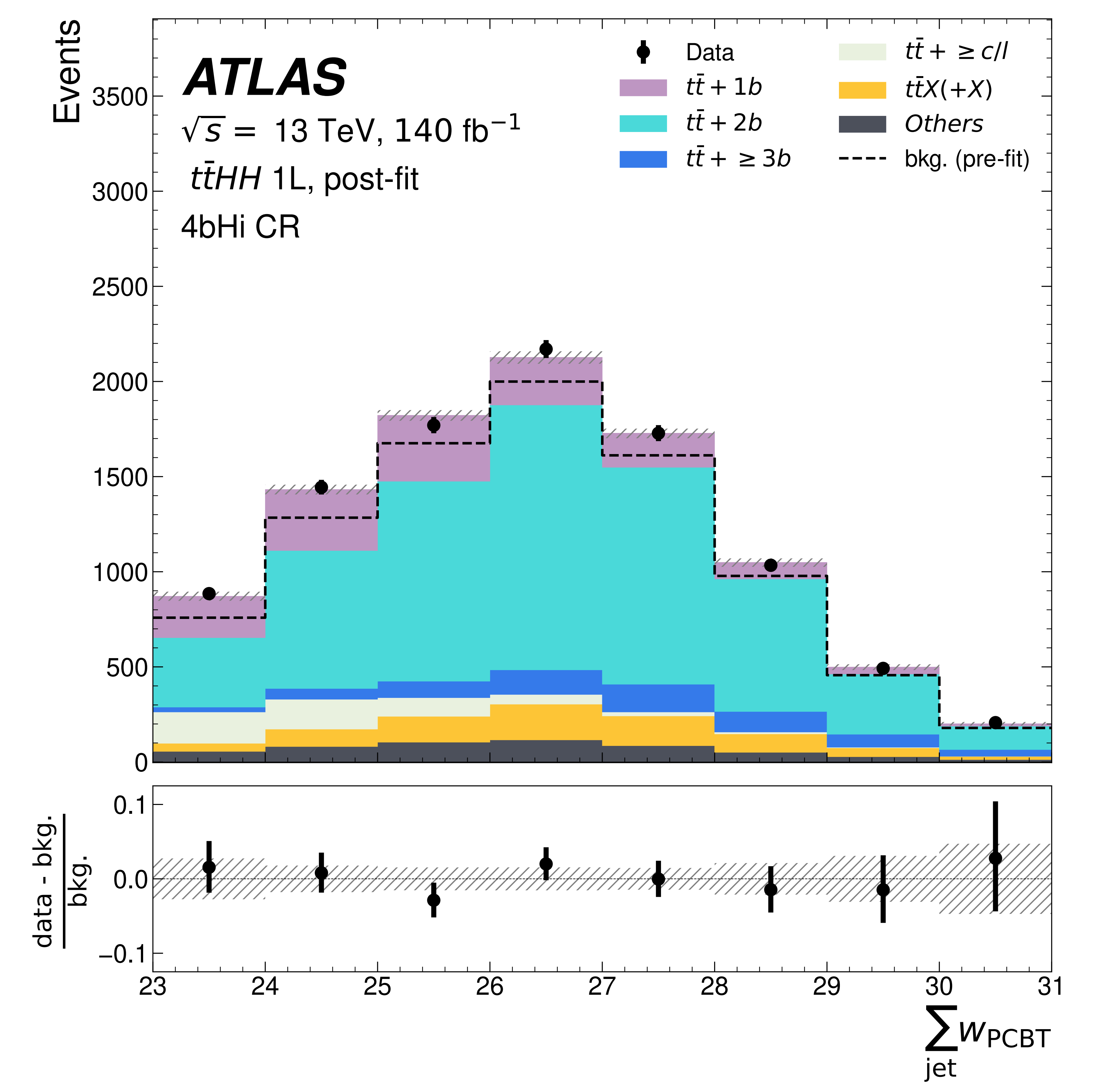
Fit from a GNN score

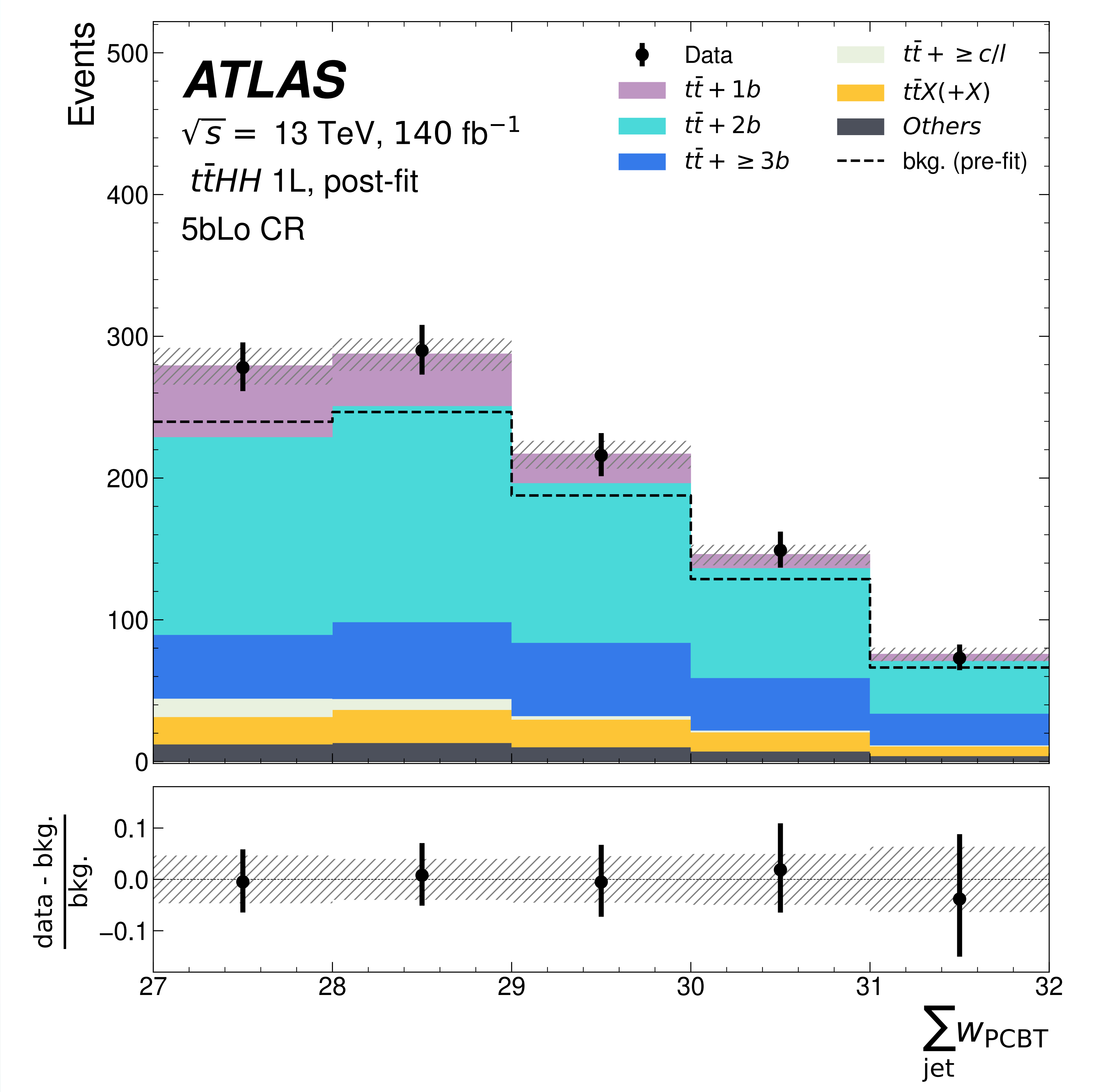




Variable	Description
(p_T, η, ϕ, E)	Kinematic variables of the object, i.e. transverse momentum, pseudorapidity, azimuthal angle, and energy.
w_{GN2}	GN201 b-tagging pseudo-continuous score for identifying jets. Non-jet objects are assigned a value of zero.
$q_{\mathrm{Lep.}}$	Charge of the object. Non-lepton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

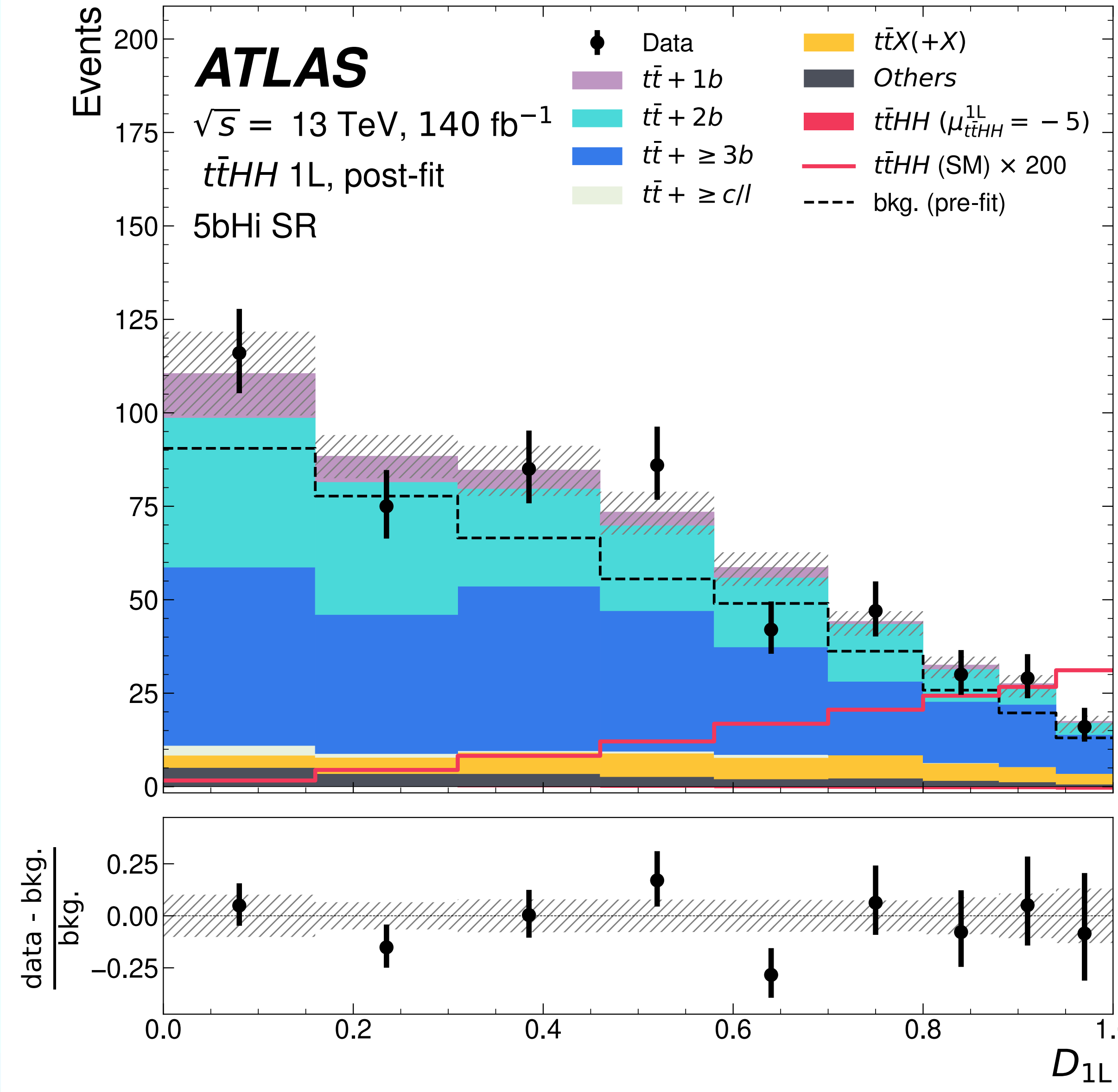
1L Run 2 CR distributions

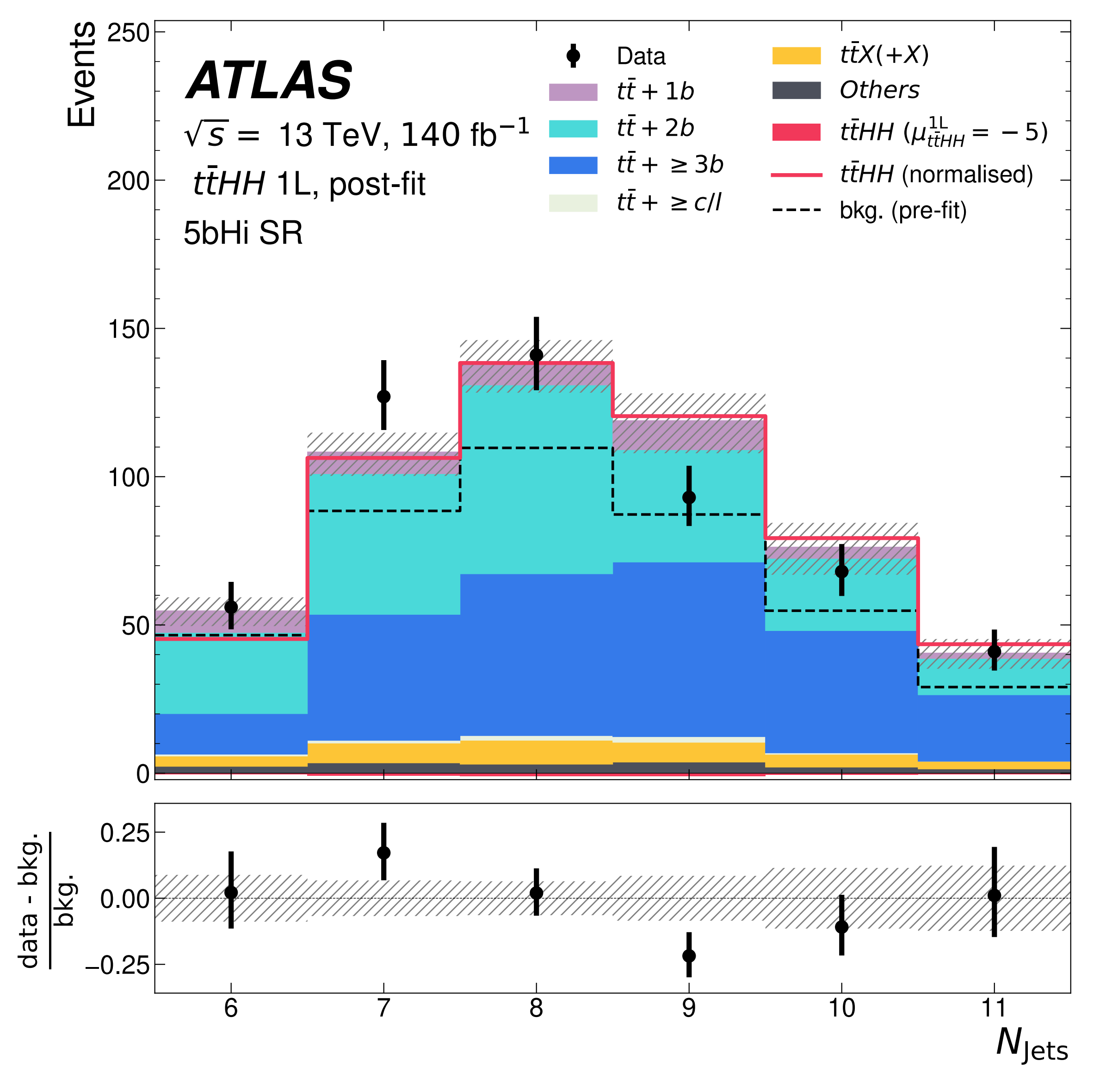


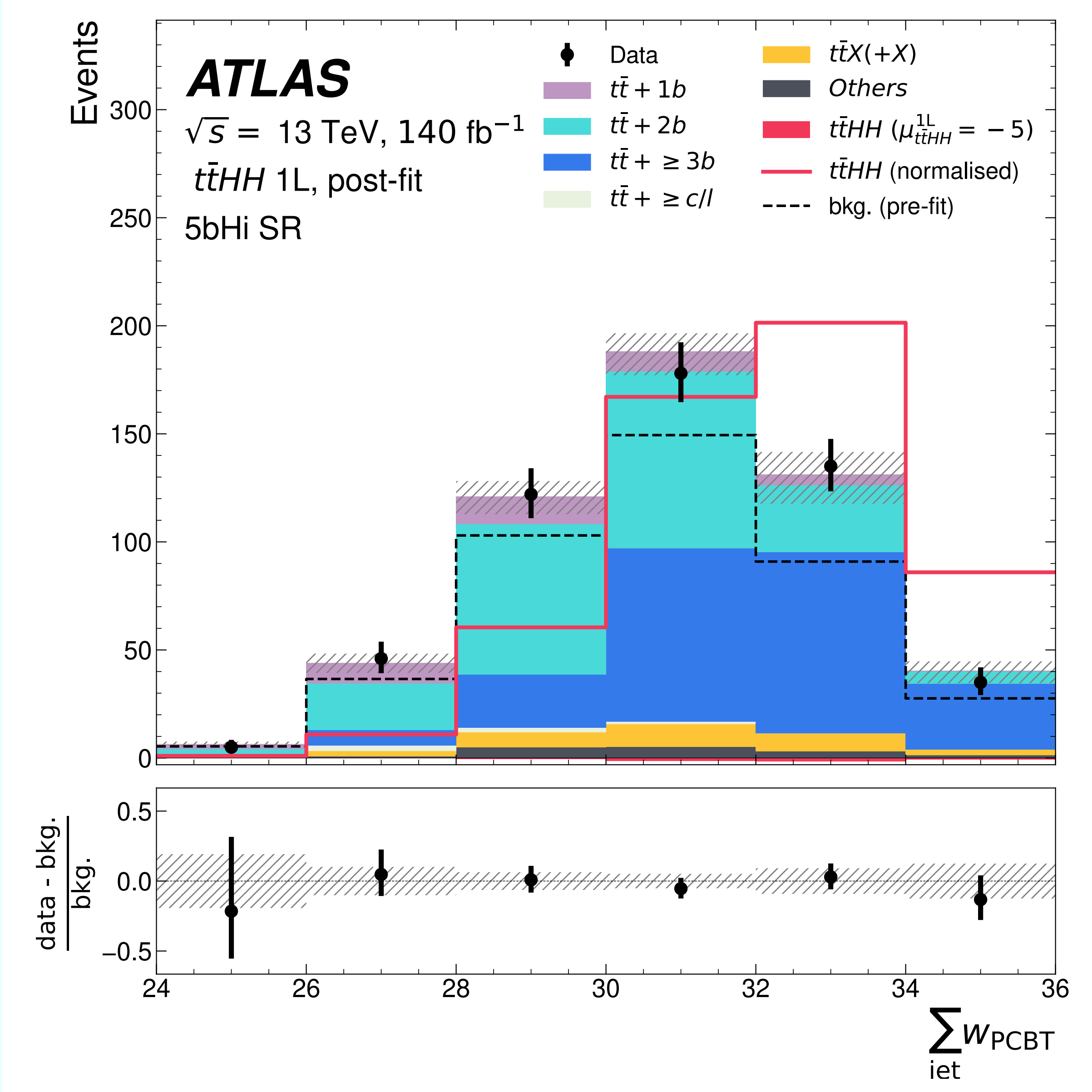


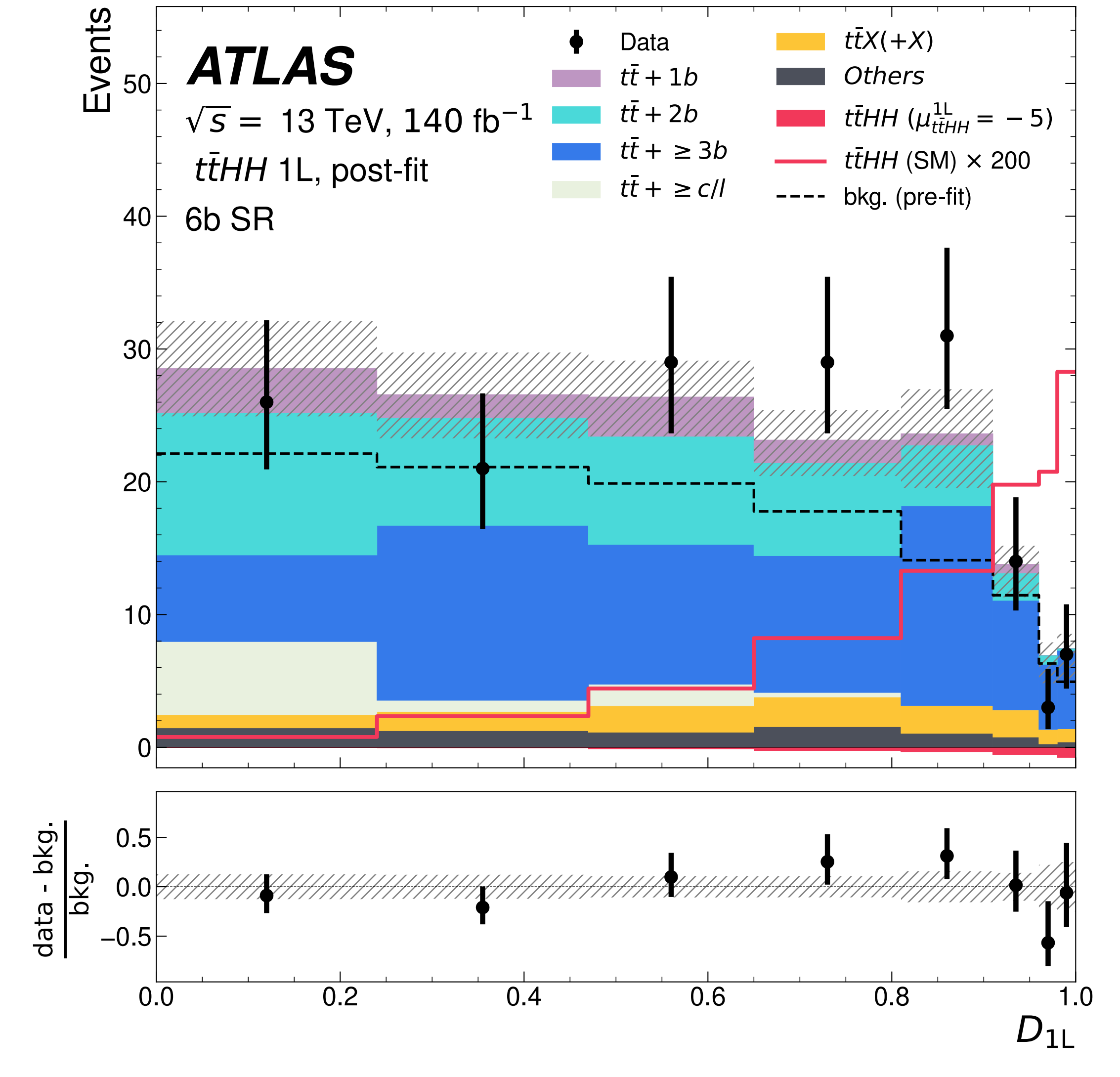
- Signal defined by jet multiplicity
- Well understood background

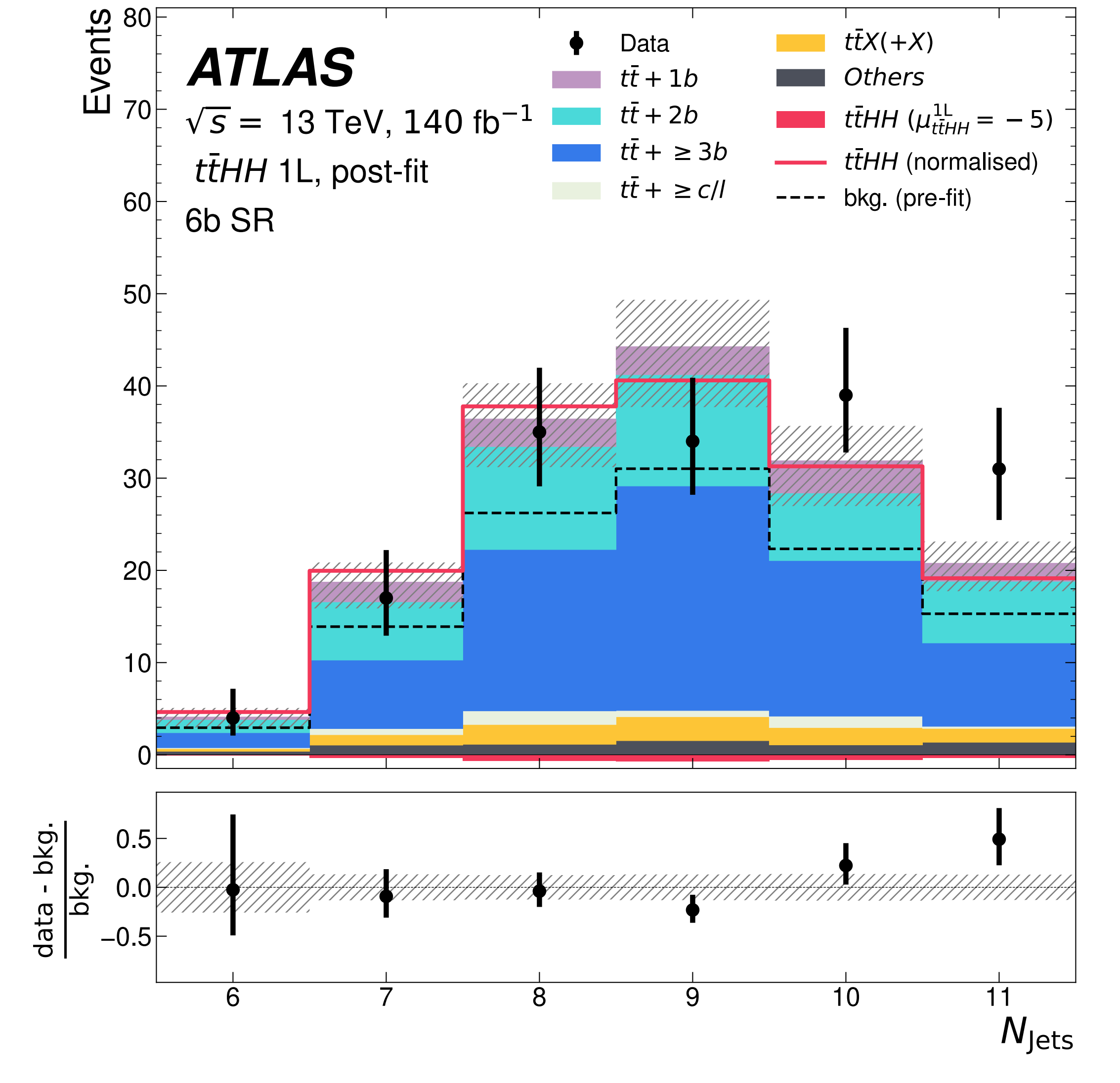
1L Run 2 SR distributions

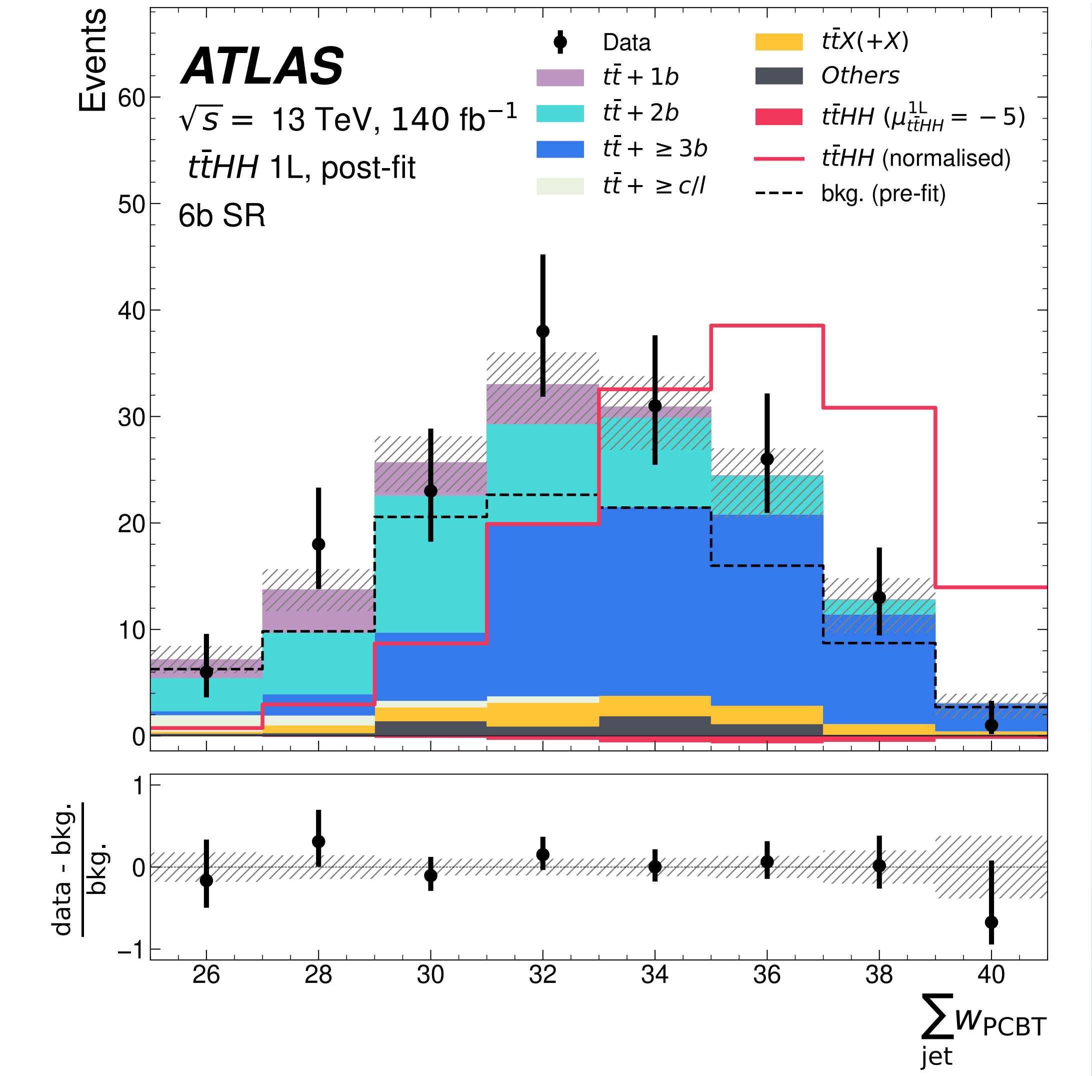




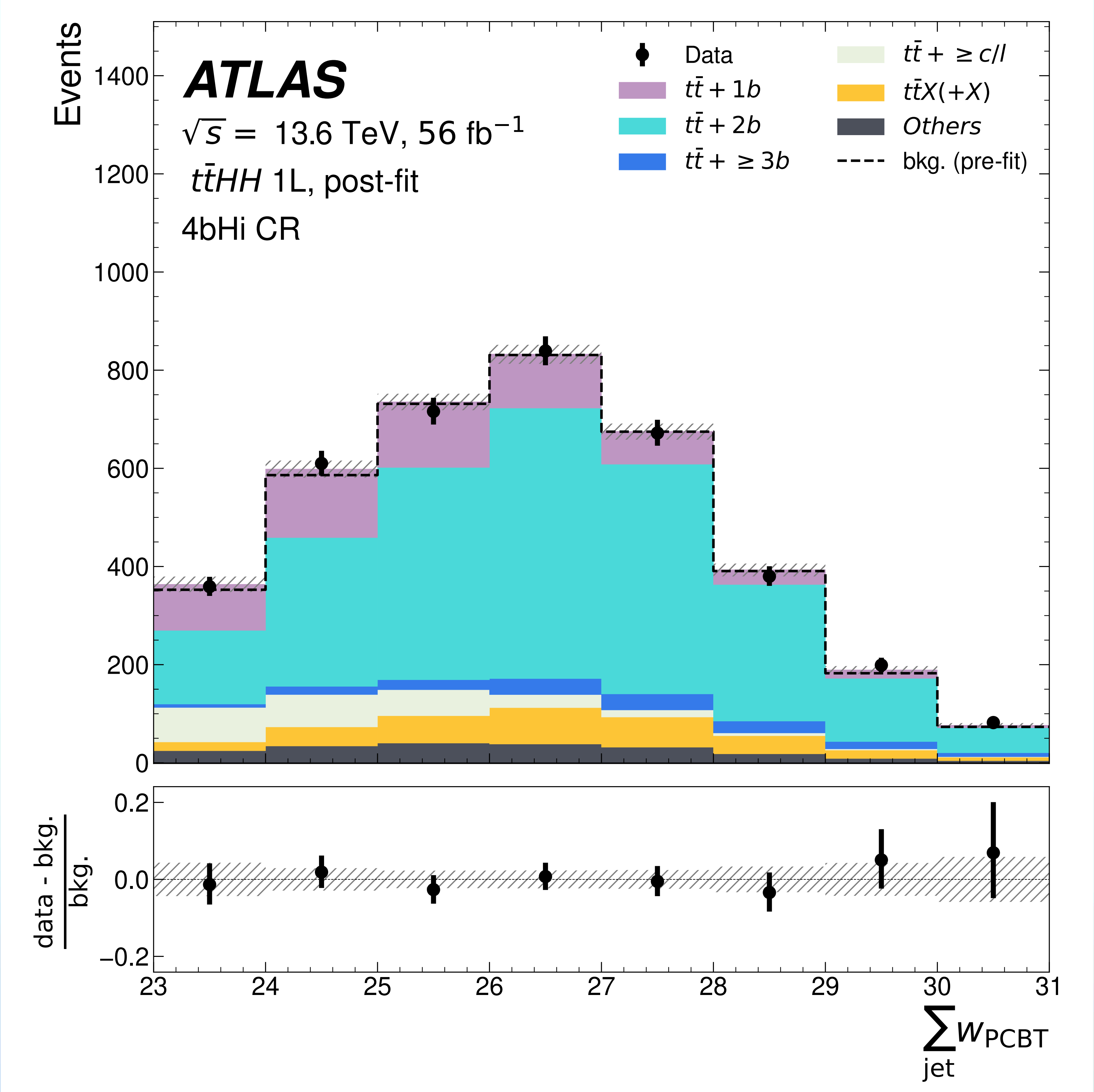


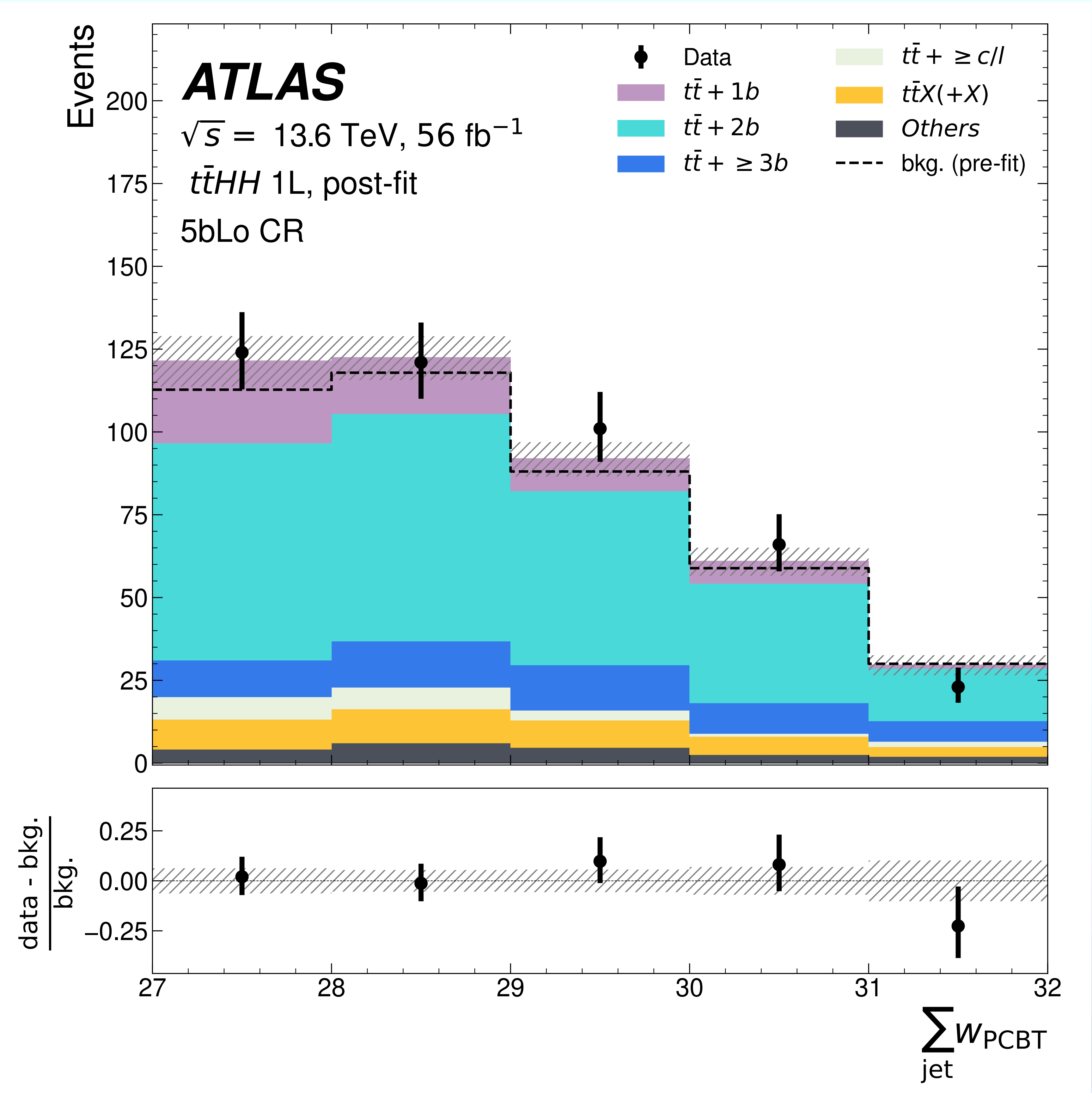






1L Run 3 CR distributions





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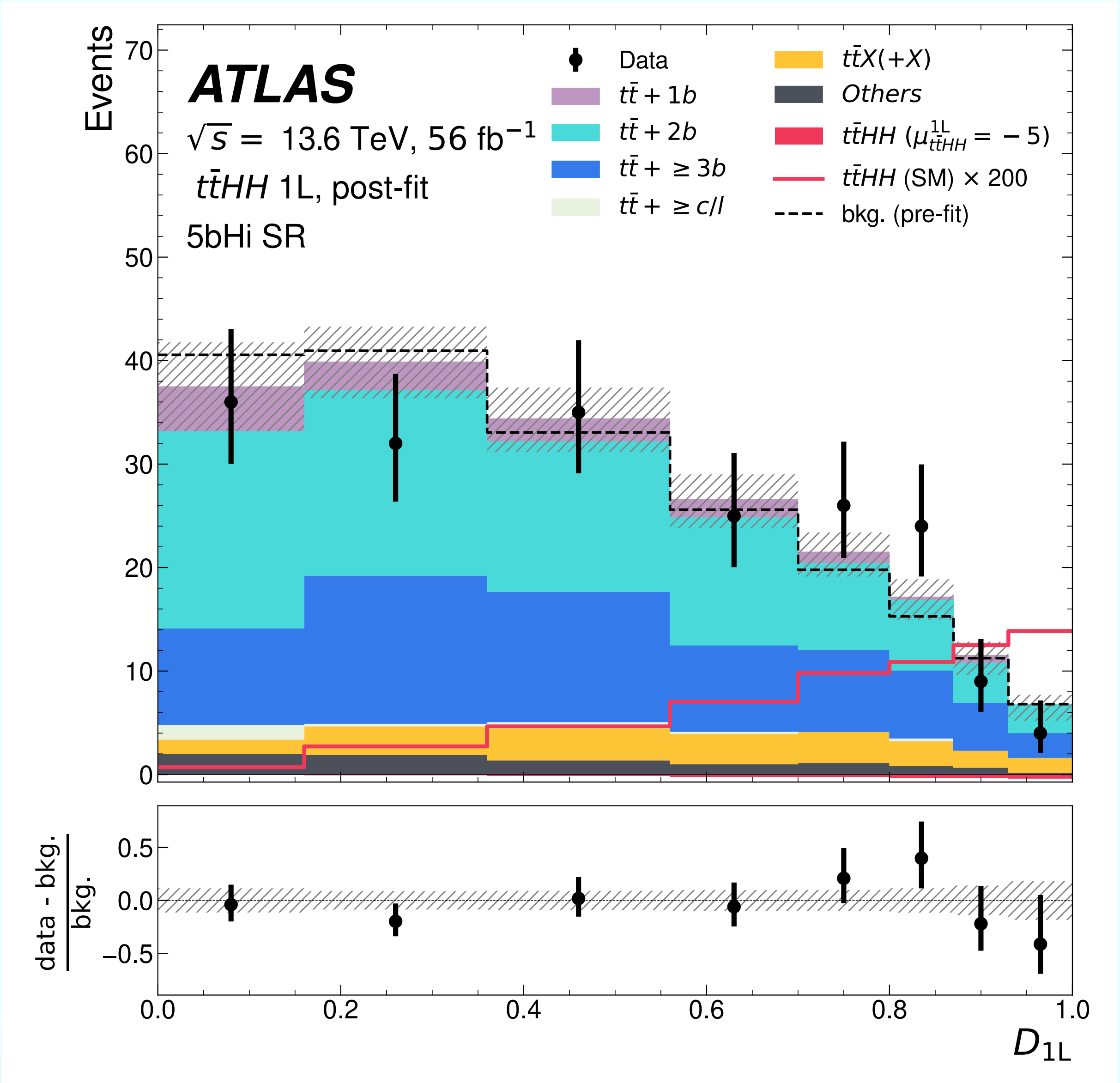
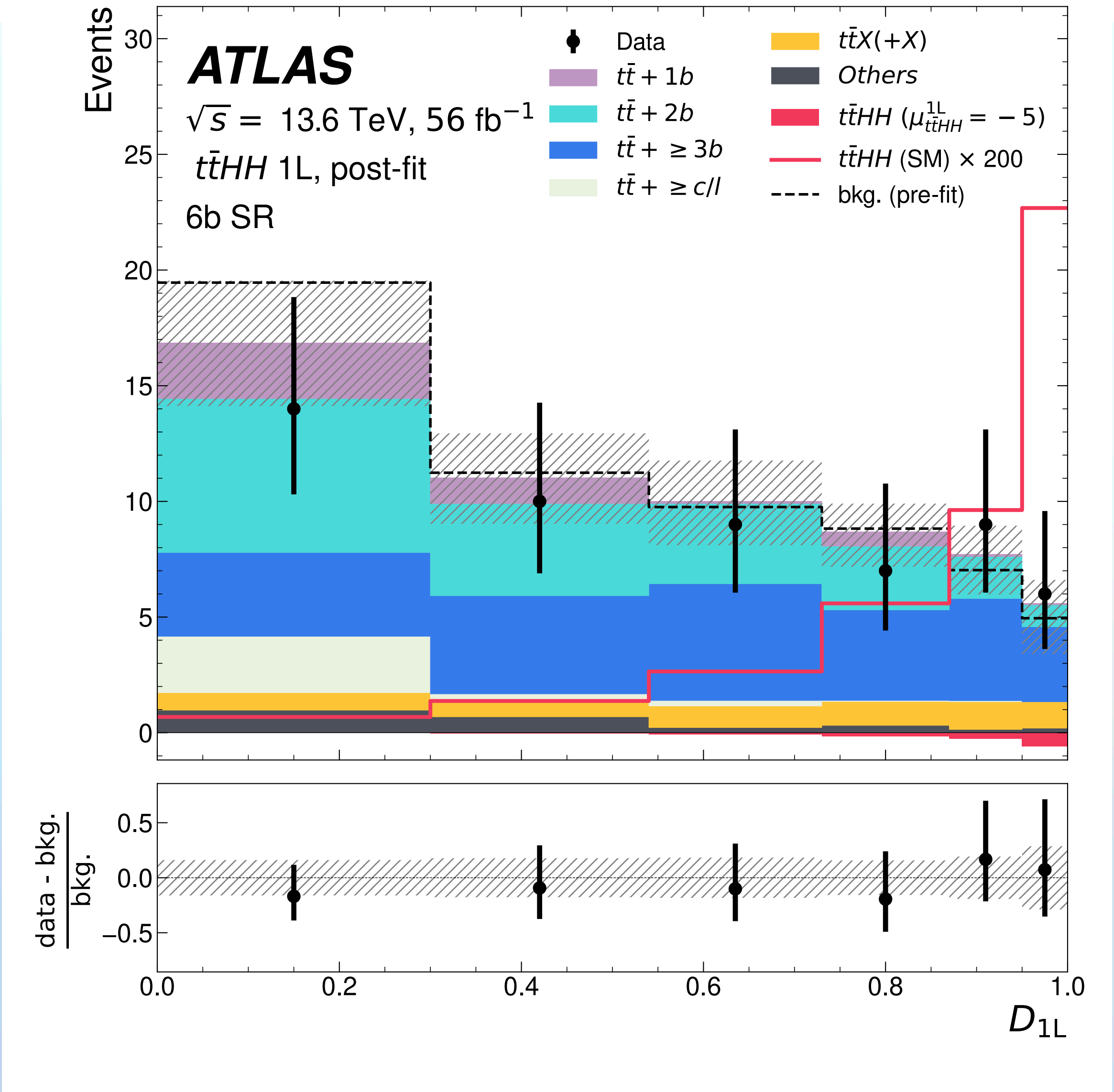
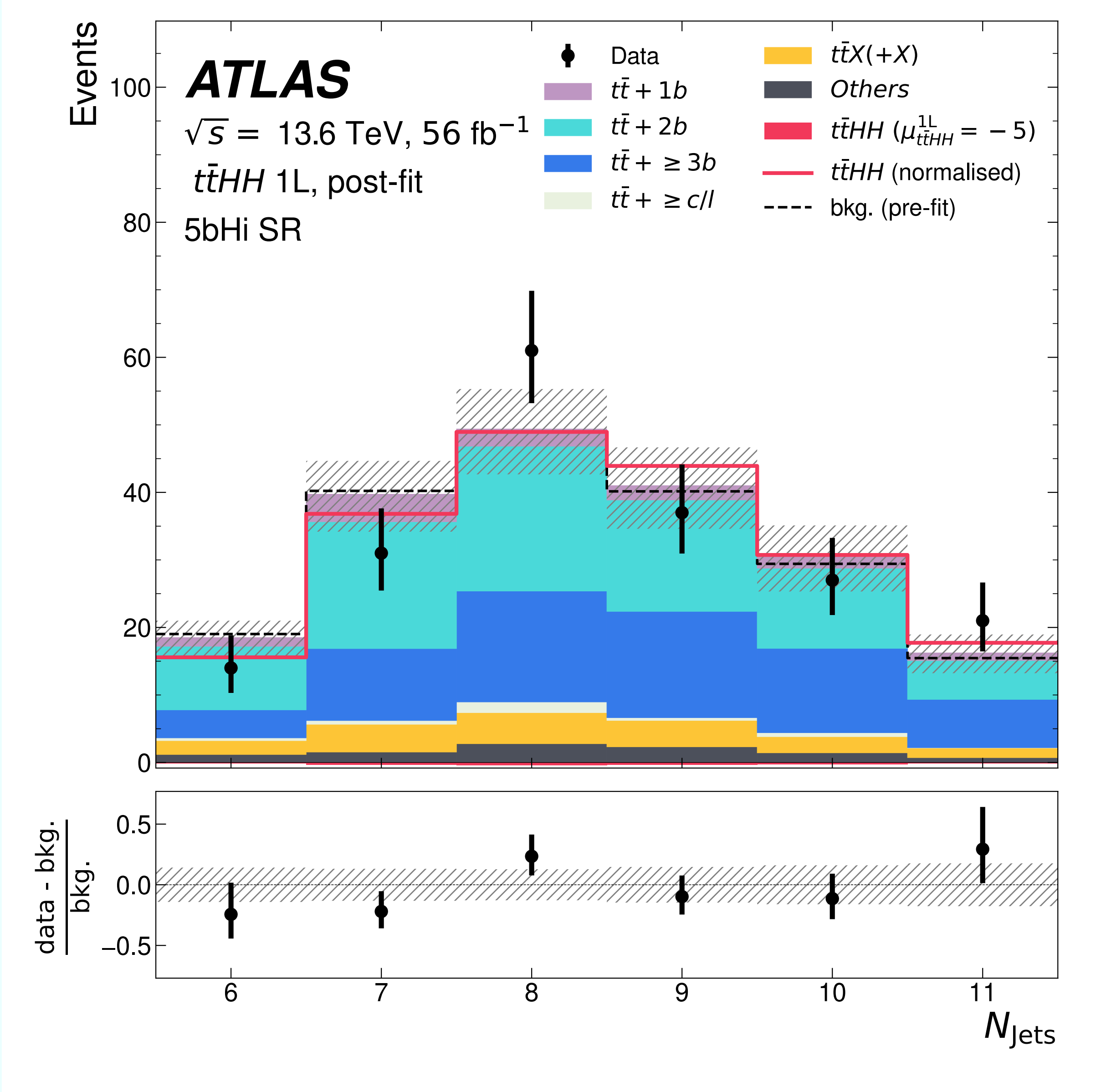
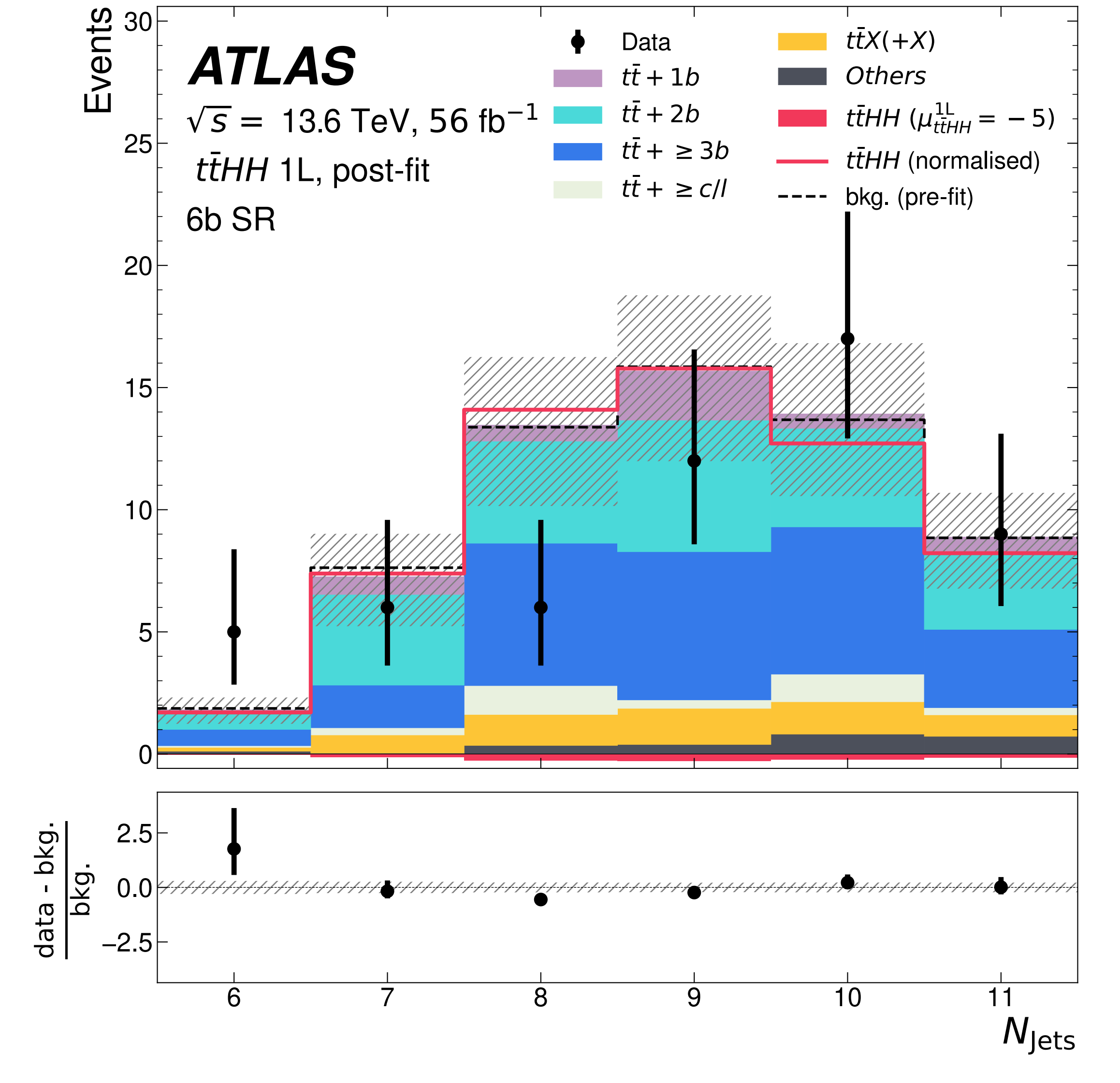
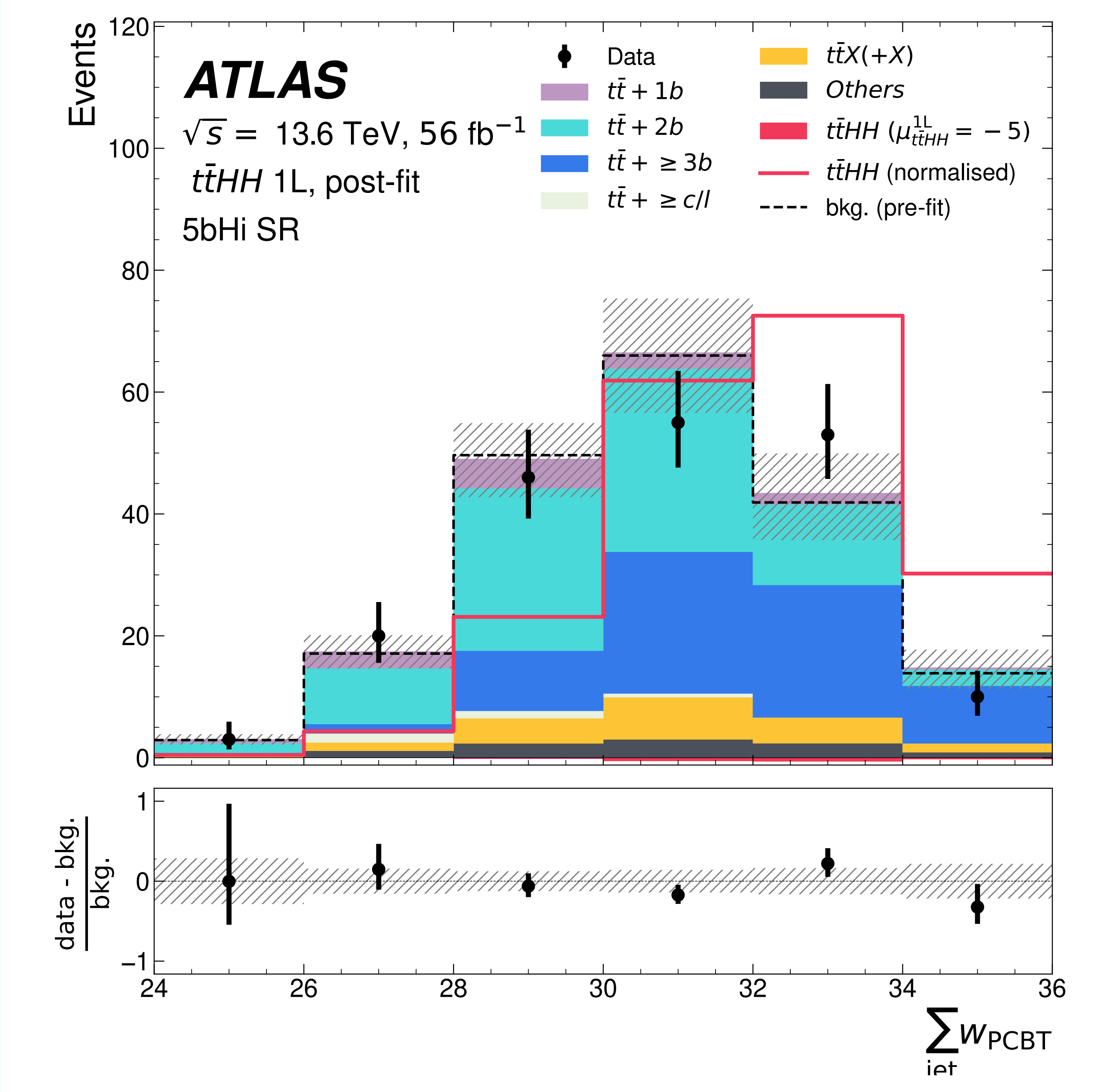
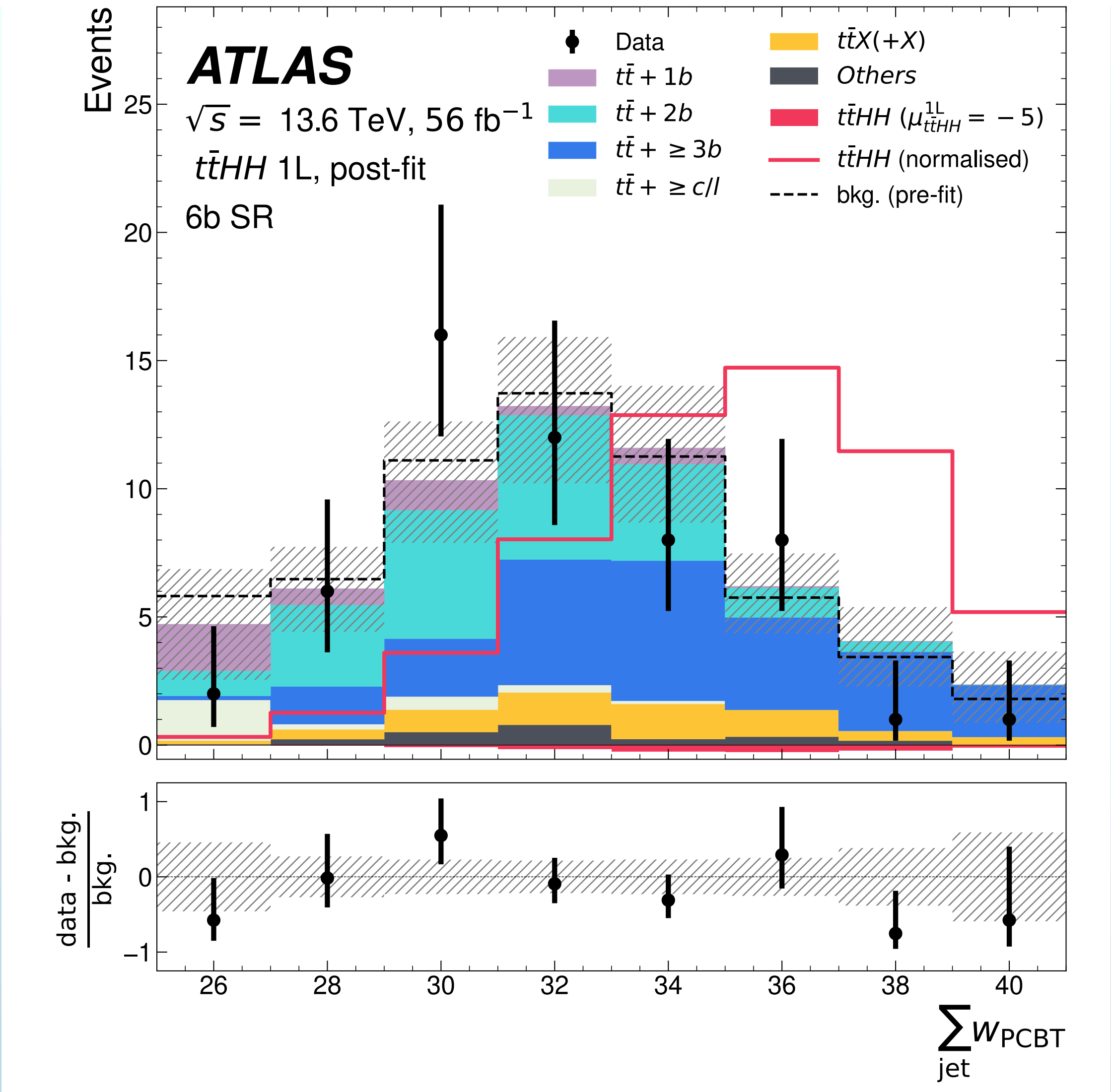












Same-sign multi-lepton channel

$\geq$ 2 b-tagged jets

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

Dominant irreducible backgrounds :

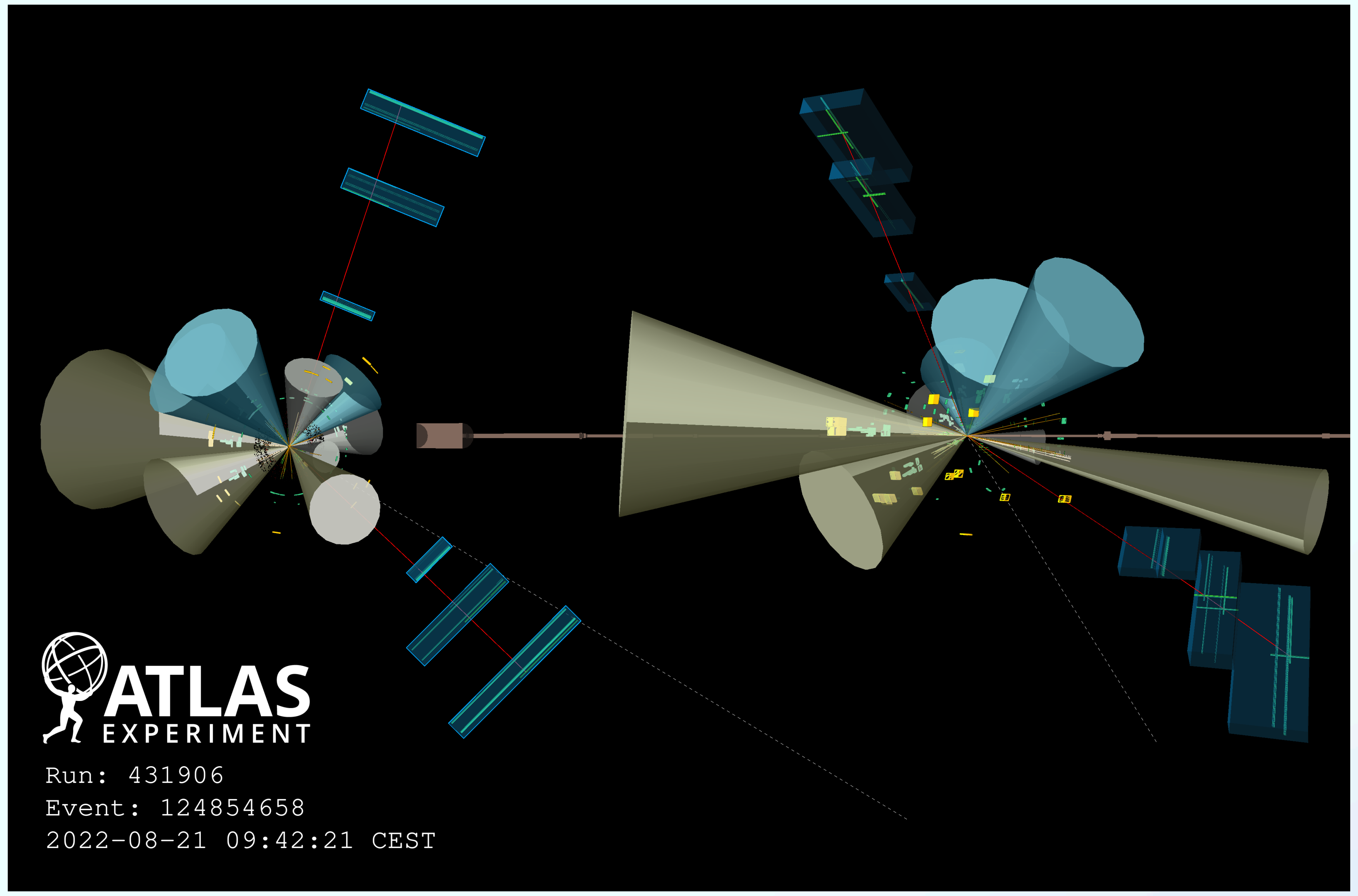
$t\bar{t}W$ and $t\bar{t}t\bar{t}$ normalization

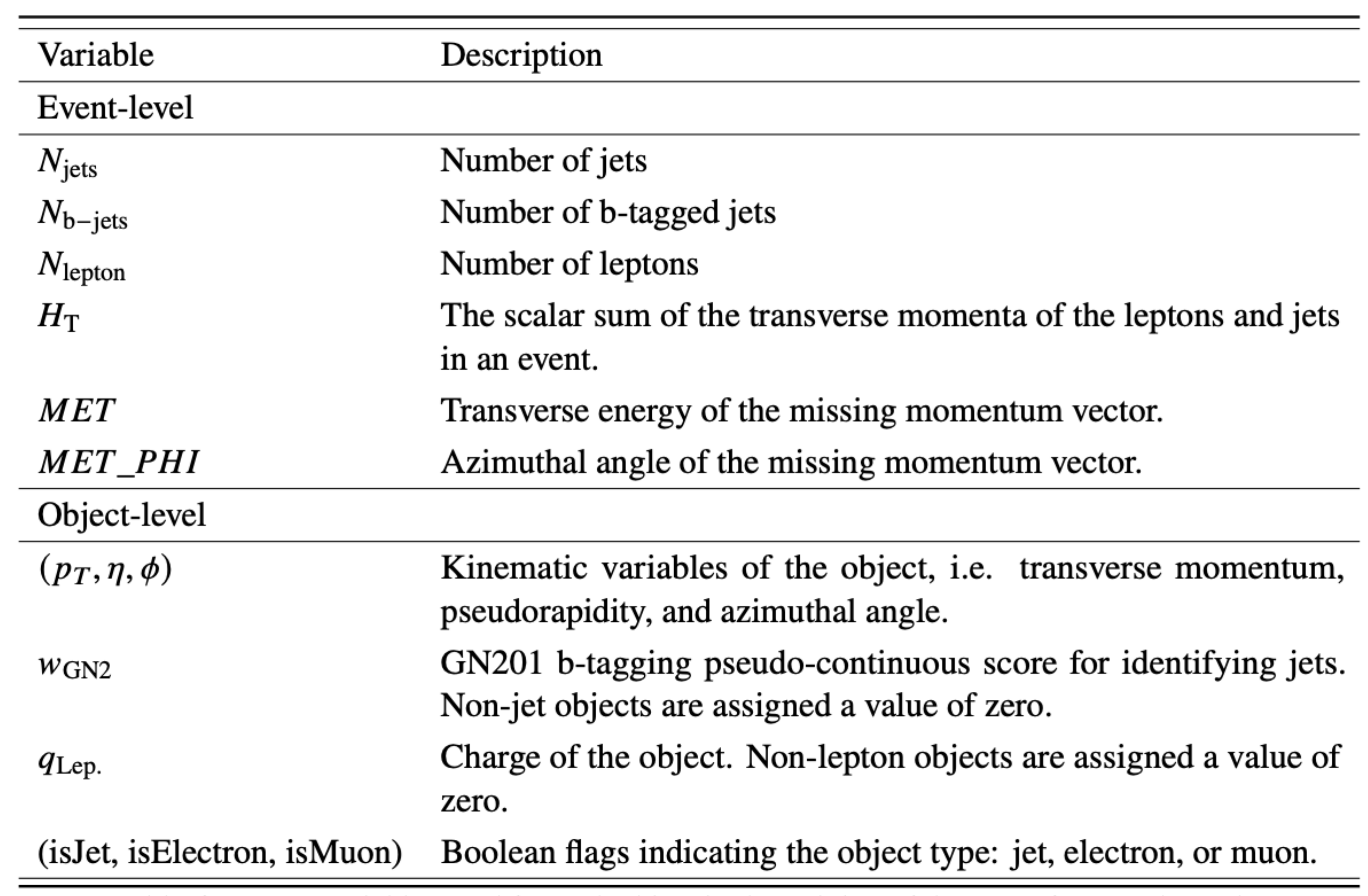
Channel which suffers a lot from instrumental backrounds :

→ Charge mis-identification

→ "Fake" leptons from HF decays or photon conversions

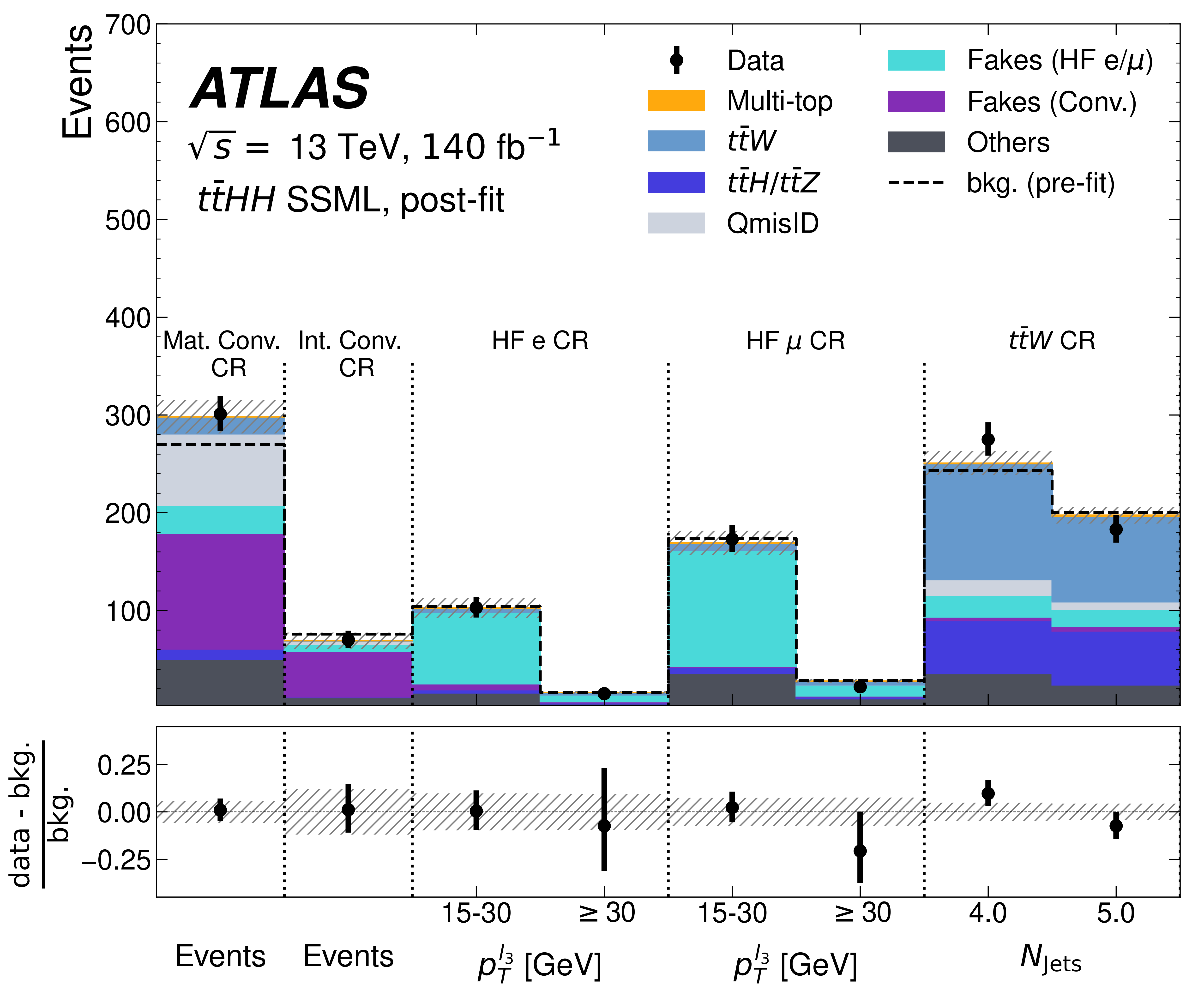
i.e. photons which look like lepton



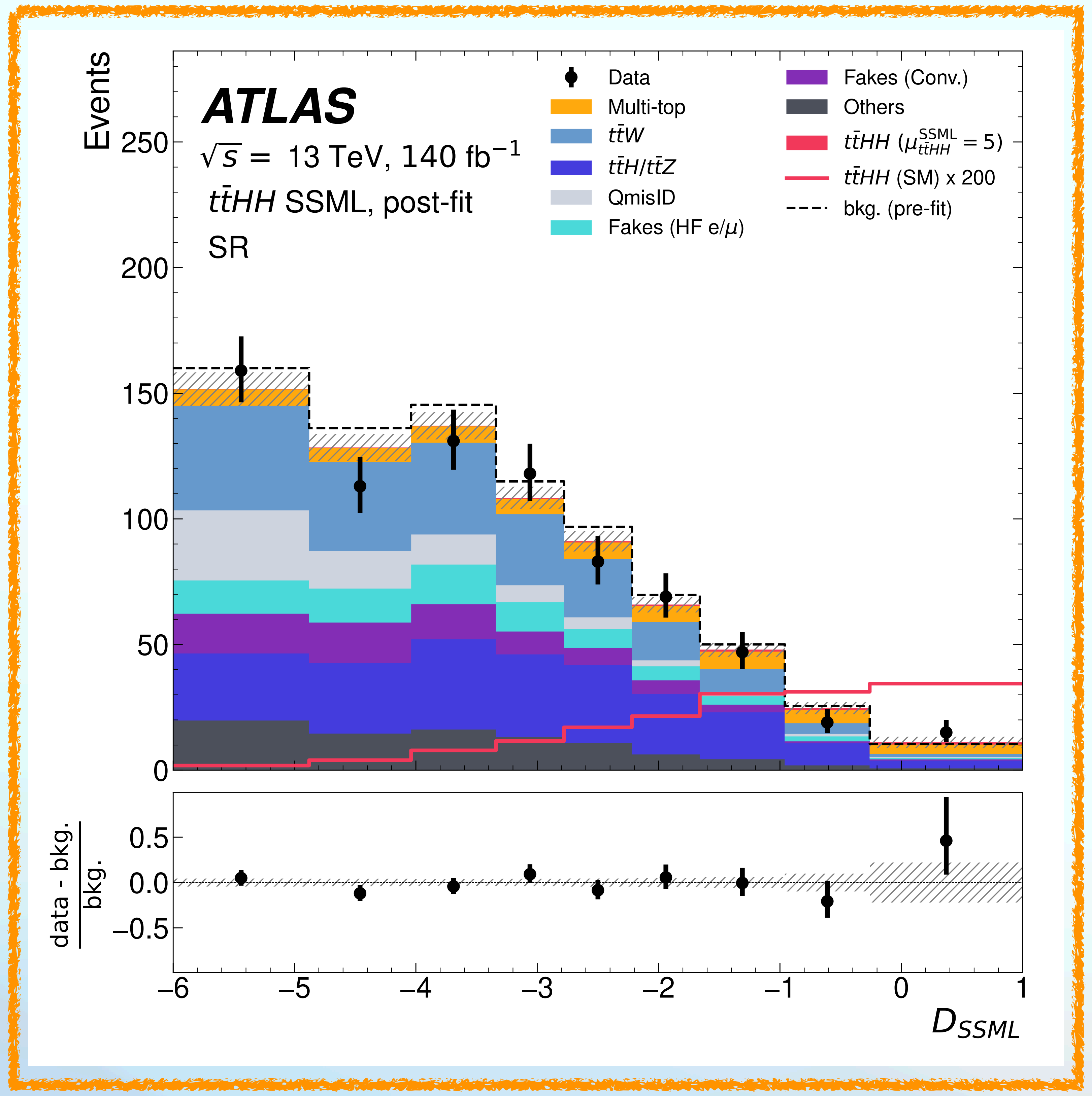


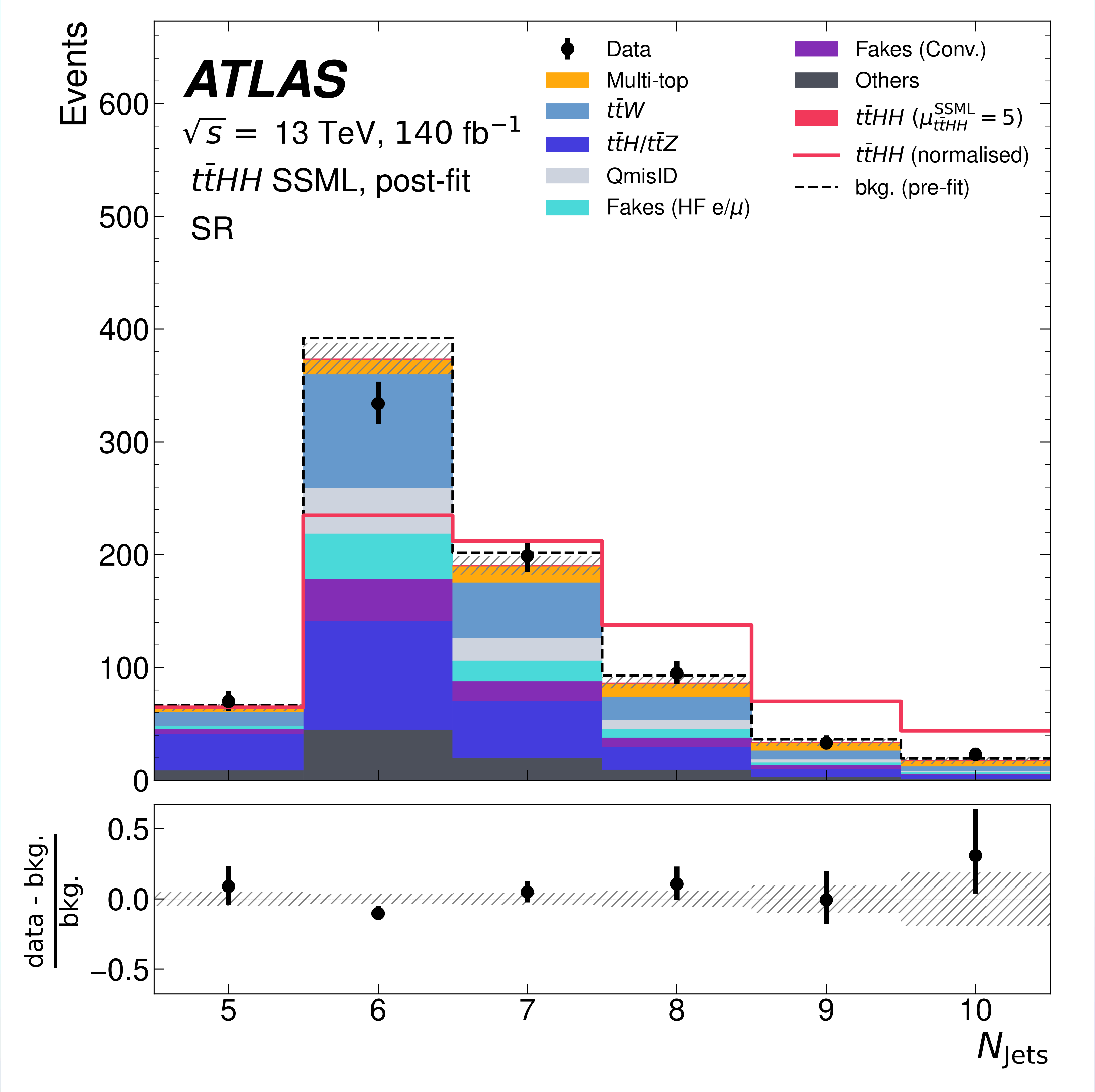
Variable	Description
Event-level	
N_{jets}	Number of jets
$N_{\text{b-jets}}$	Number of b-tagged jets
N_{lepton}	Number of leptons
H_T	The scalar sum of the transverse momenta of the leptons and jets in an event.
MET	Transverse energy of the missing momentum vector.
MET_PHI	Azimuthal angle of the missing 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.

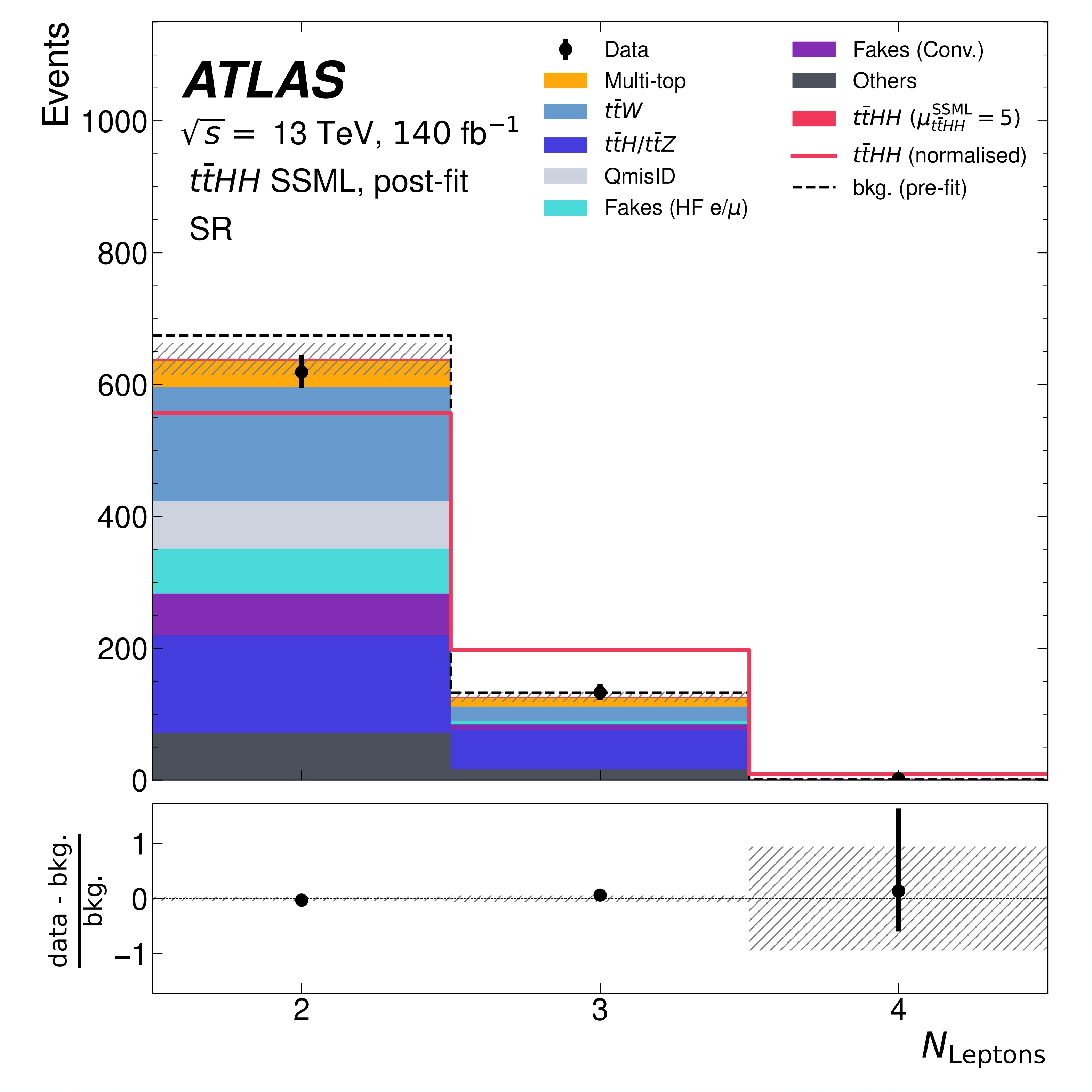
ML Run 2 CR distributions



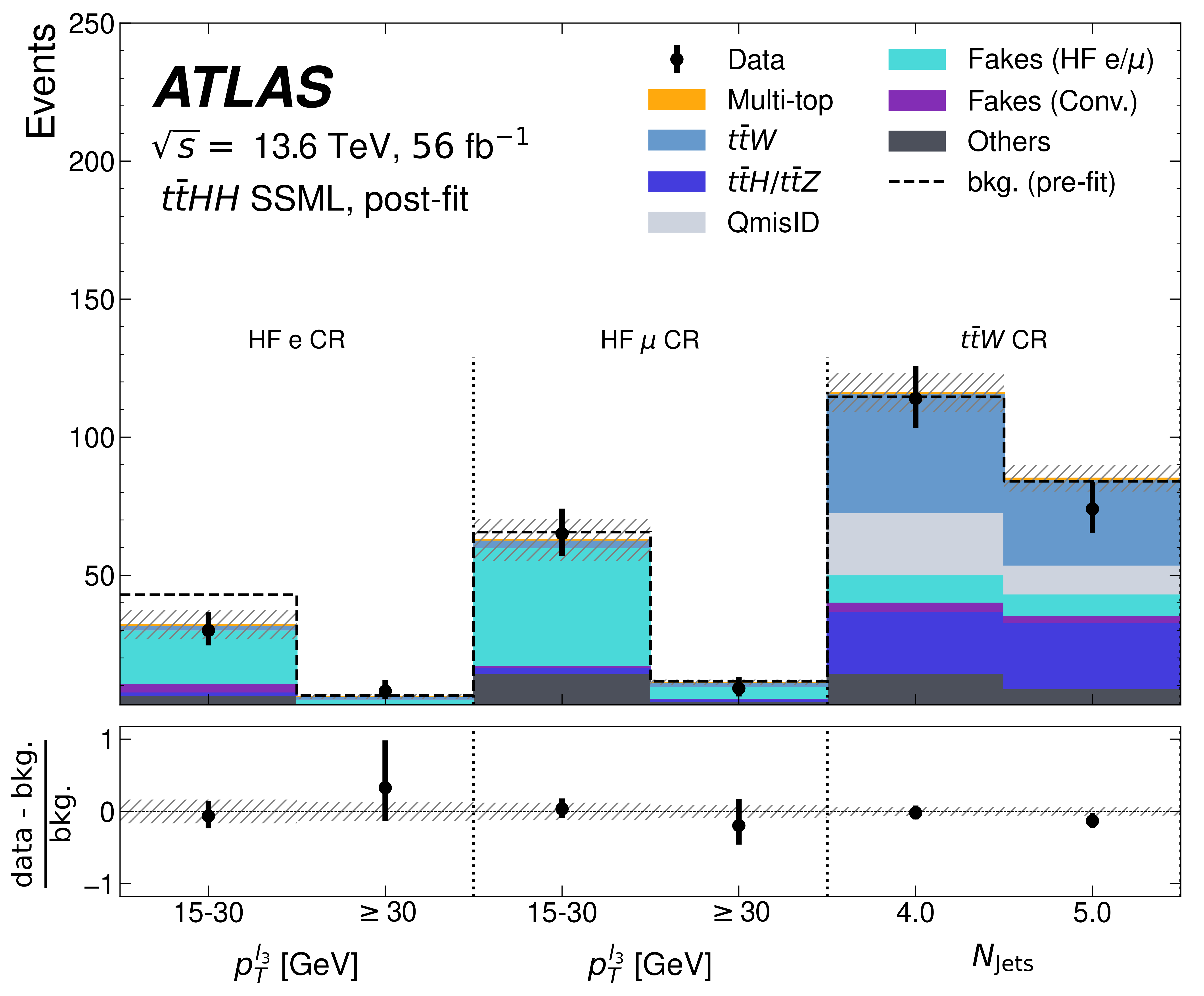
ML Run 2 SR distributions



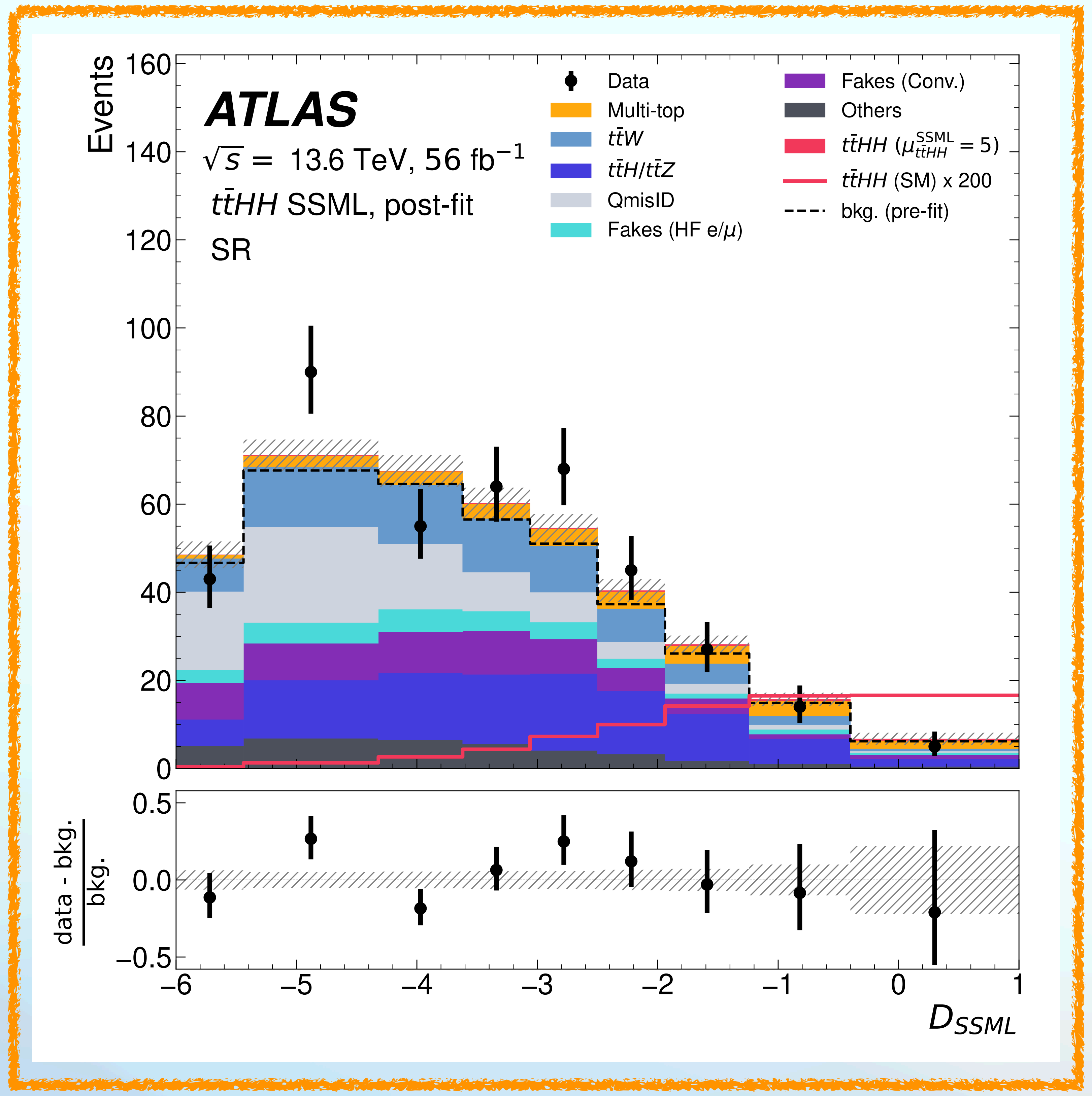


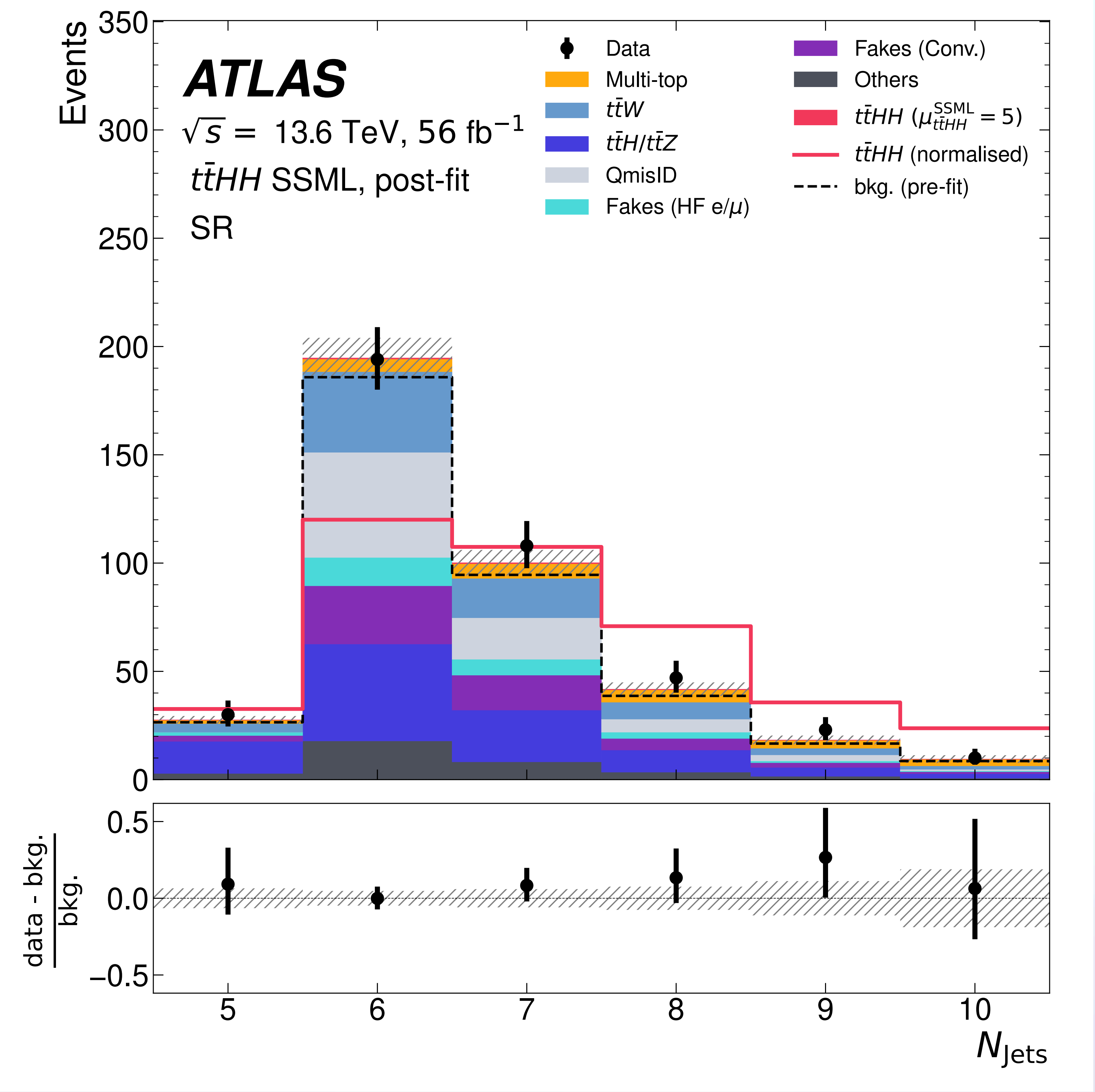


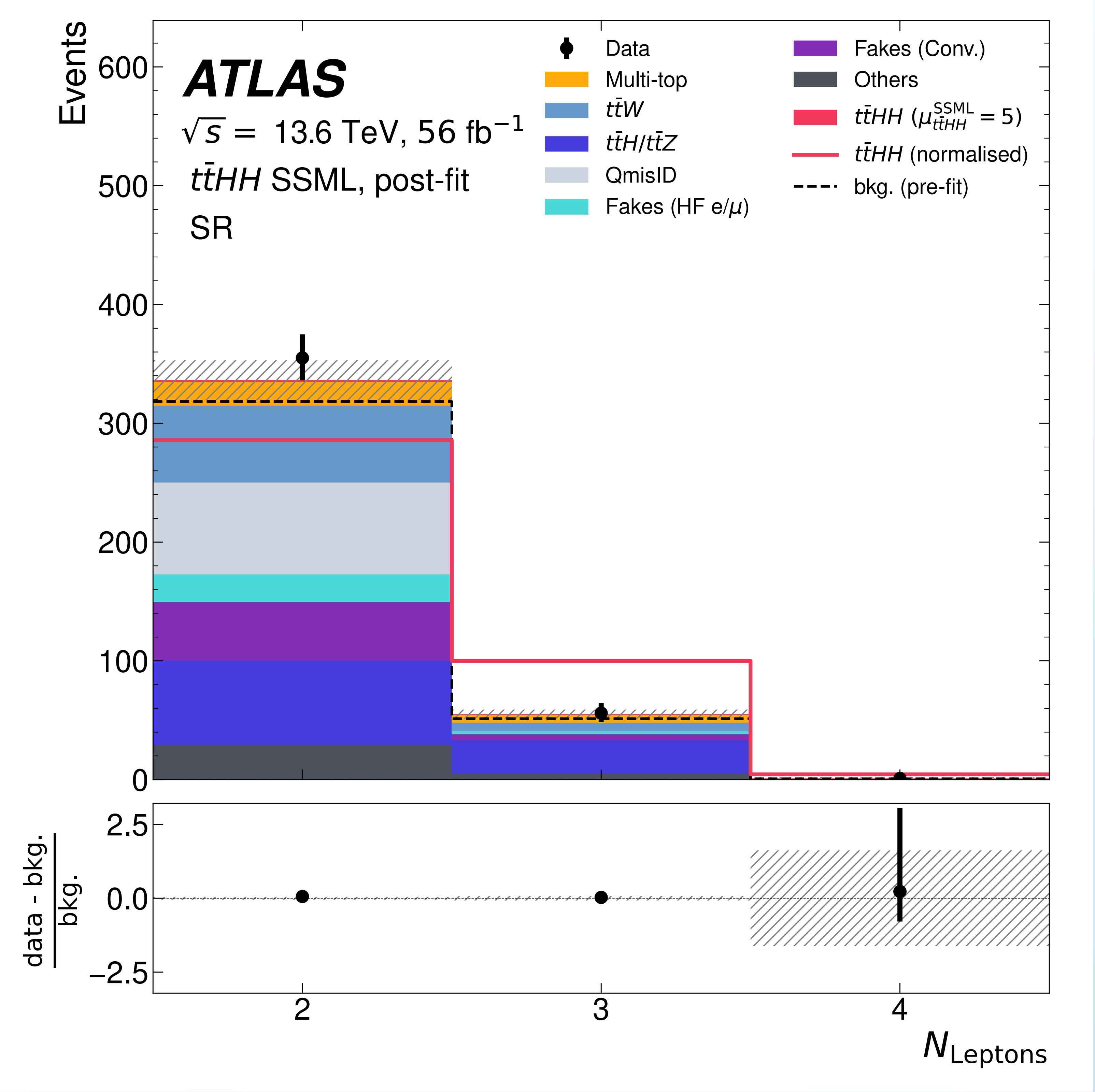
ML Run 3 CR distributions



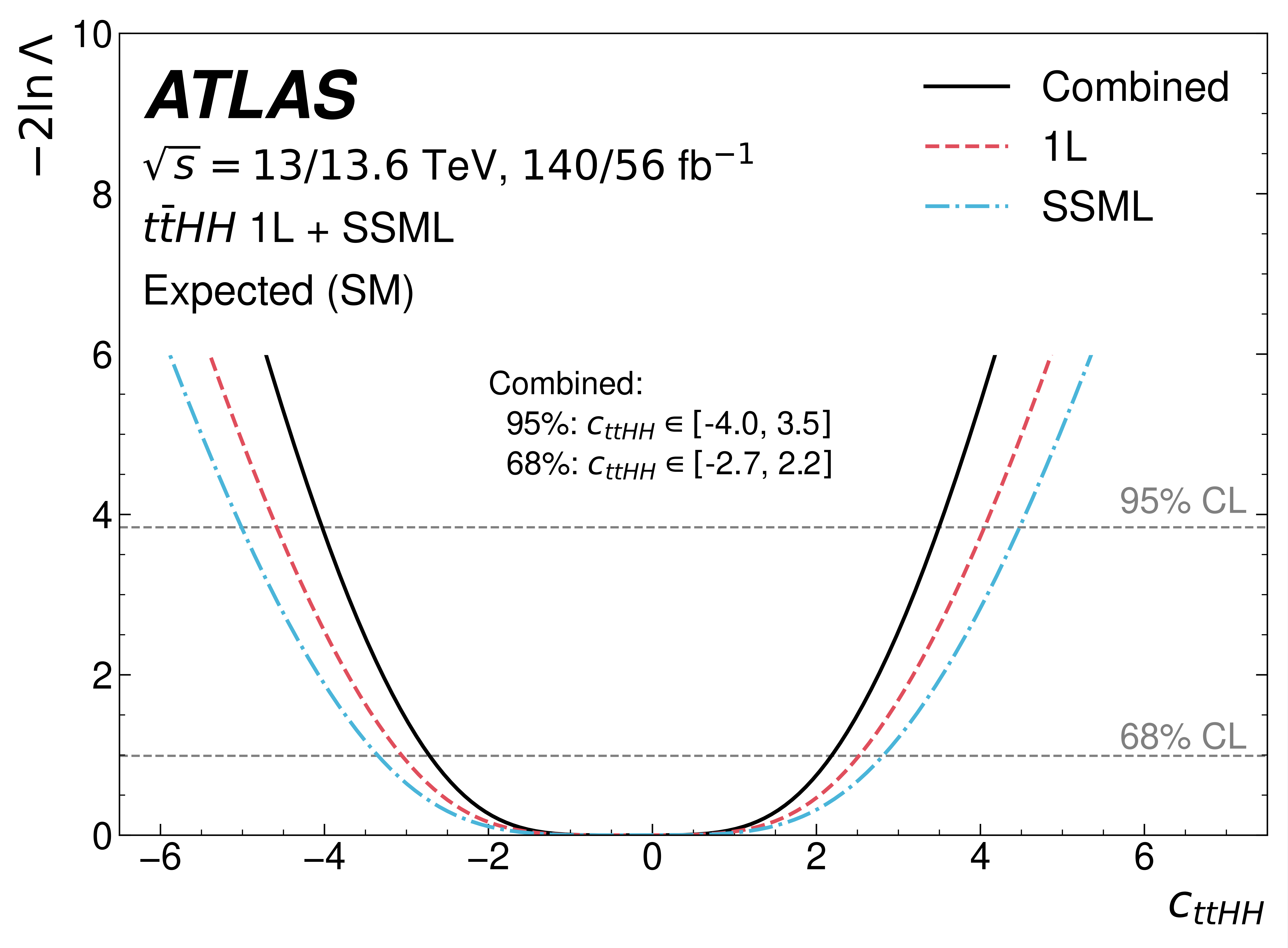
ML Run 3 SR distributions





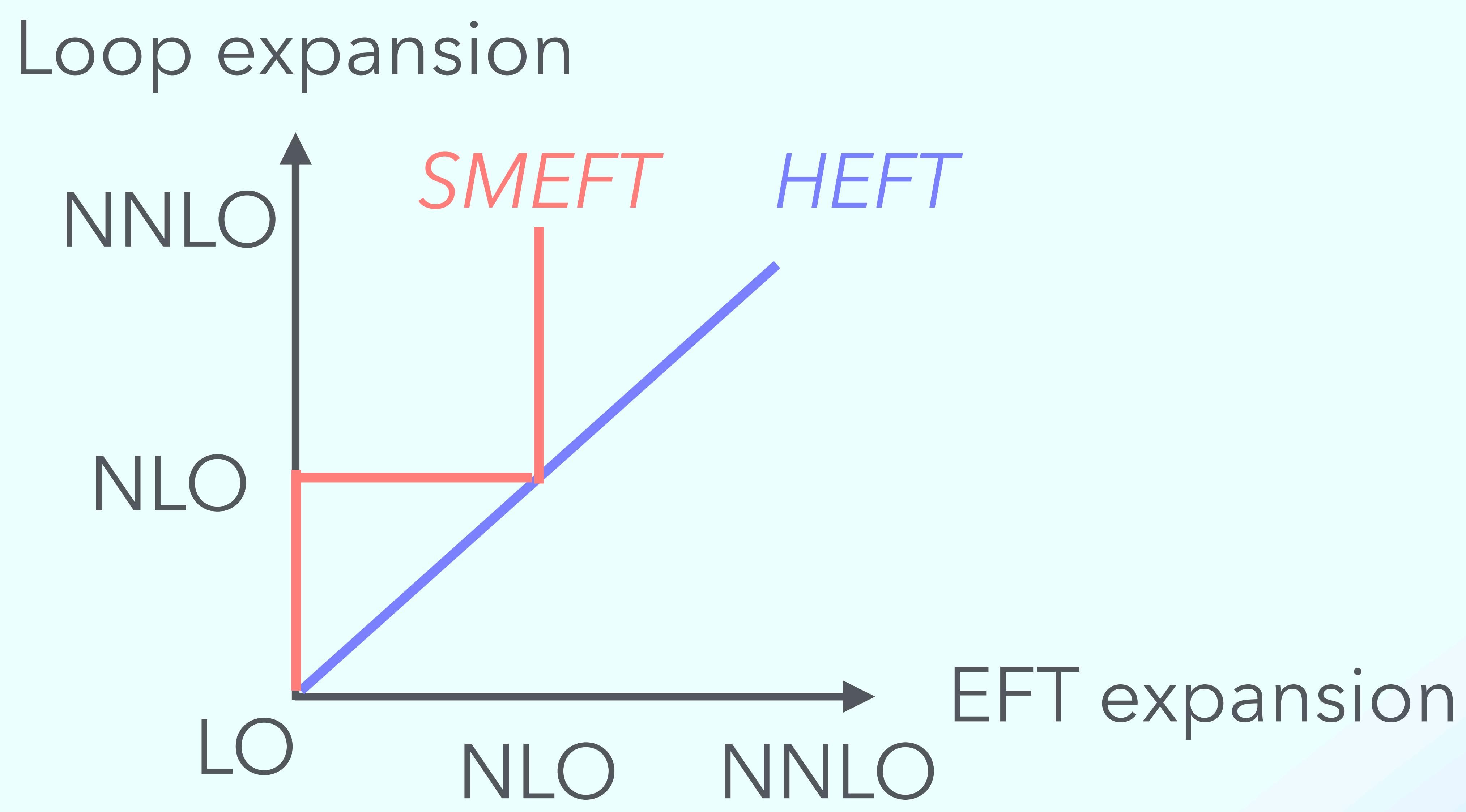


Expected likelihood for EFT fit



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 : $\sigma_{\text{EFT}} \sim |\mathscr{M}_{\text{SM}} + \underset{\textit{One d=6}}{\mathscr{M}_6} + \underset{\textit{Two d=6}}{\mathscr{M}_{6+6}} + \underset{\textit{One d=8}}{\mathscr{M}_8} + \cdots|^2$

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

HEFT vs. SMEFT power counting

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

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

	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

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 : $\sigma_{\text{EFT}} \sim |\mathscr{M}_{\text{SM}} + \underset{\text{One d=6}}{\mathscr{M}_6} + \underset{\text{Two d=6}}{\mathscr{M}_{6+6}} + \underset{\text{One d=8}}{\mathscr{M}_8} + \cdots|^2$

	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}			$+|\mathscr{M}_{6+6}|^2$	$+|\mathscr{M}_8|^2+Re(\mathscr{M}_8 \cdot \mathscr{M}_{6+6})$

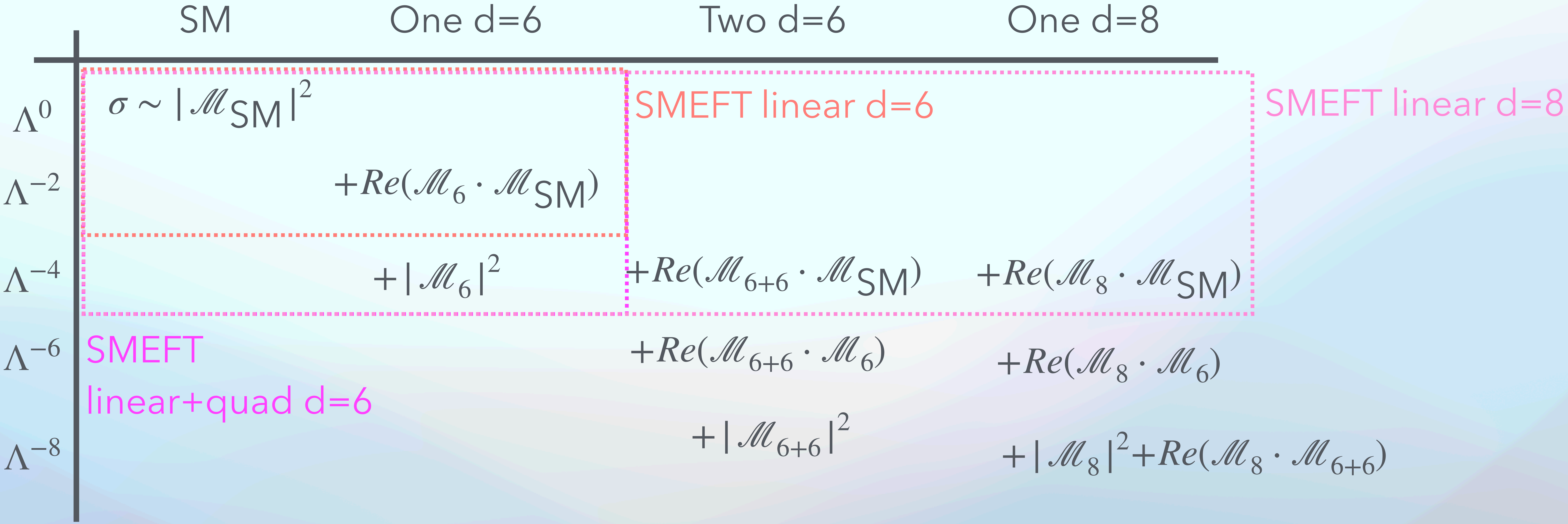
SMEFT linear d=6

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

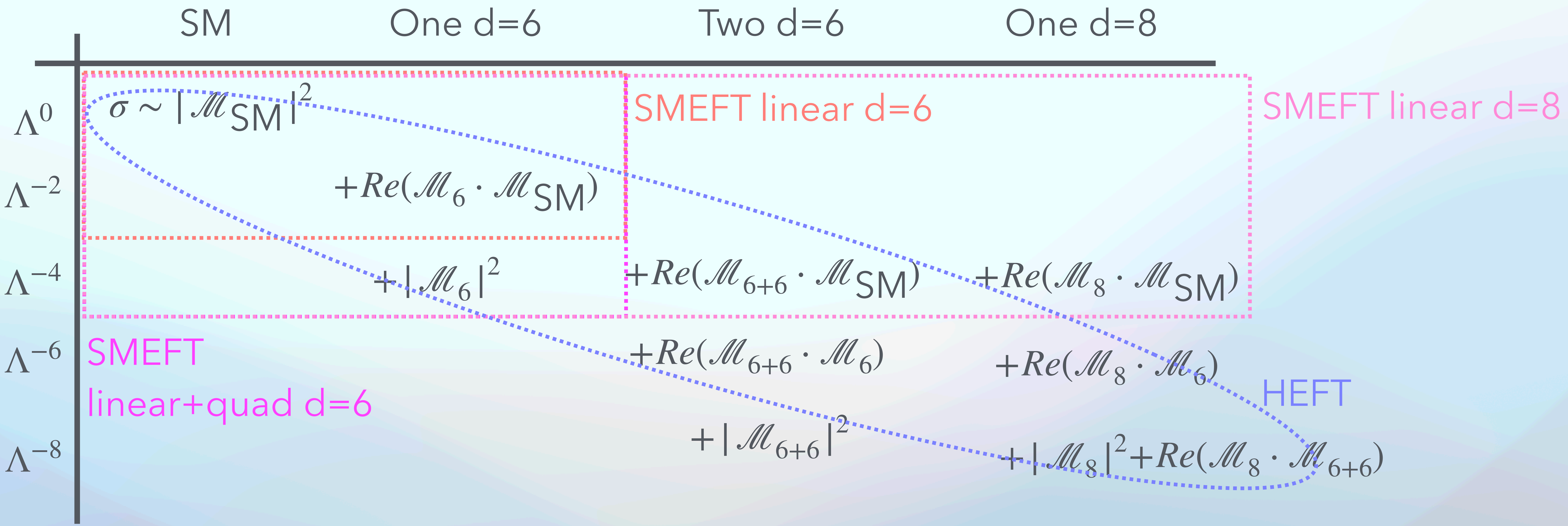


	SM	One d=6	Two d=6	One d=8
Λ^0	$\sigma \sim \|\mathscr{M}_{\text{SM}}\|^2$			
Λ^{-2}		$+Re(\mathscr{M}_6 \cdot \mathscr{M}_{\text{SM}})$		
Λ^{-4}		$+\|\mathscr{M}_6\|^2$	$+Re(\mathscr{M}_{6+6} \cdot \mathscr{M}_{\text{SM}})$	$+Re(\mathscr{M}_8 \cdot \mathscr{M}_{\text{SM}})$
Λ^{-6}			$+Re(\mathscr{M}_{6+6}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

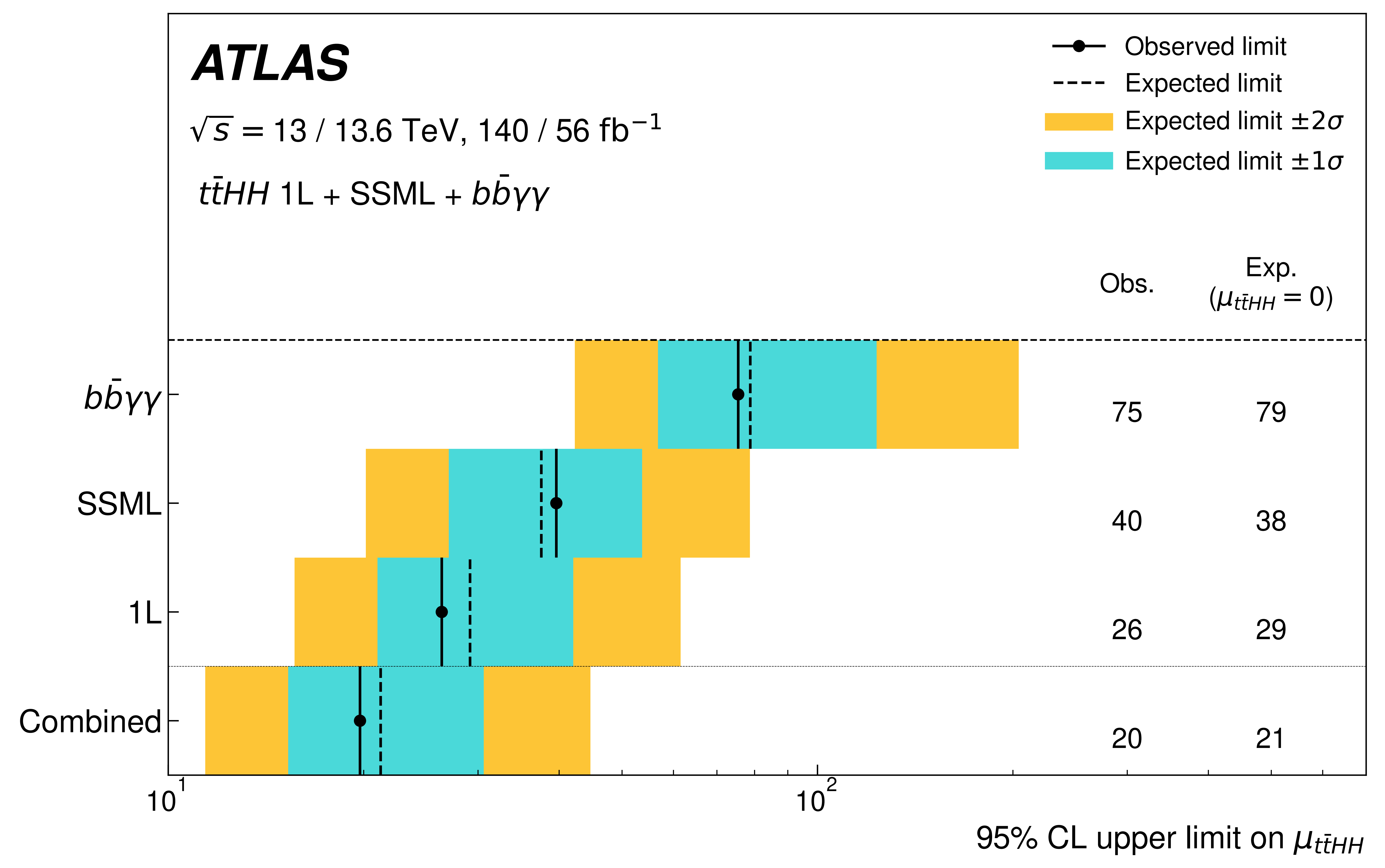
Lagrangian : $\mathscr{L}_{\text{EFT}} = \mathscr{L}_{\text{SM}} + \sum_i \frac{c_i^{(6)}}{\Lambda^2}\mathscr{O}_i^{(6)} + \sum_i \frac{c_i^{(8)}}{\Lambda^4}\mathscr{O}_i^{(8)} + \cdots$

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



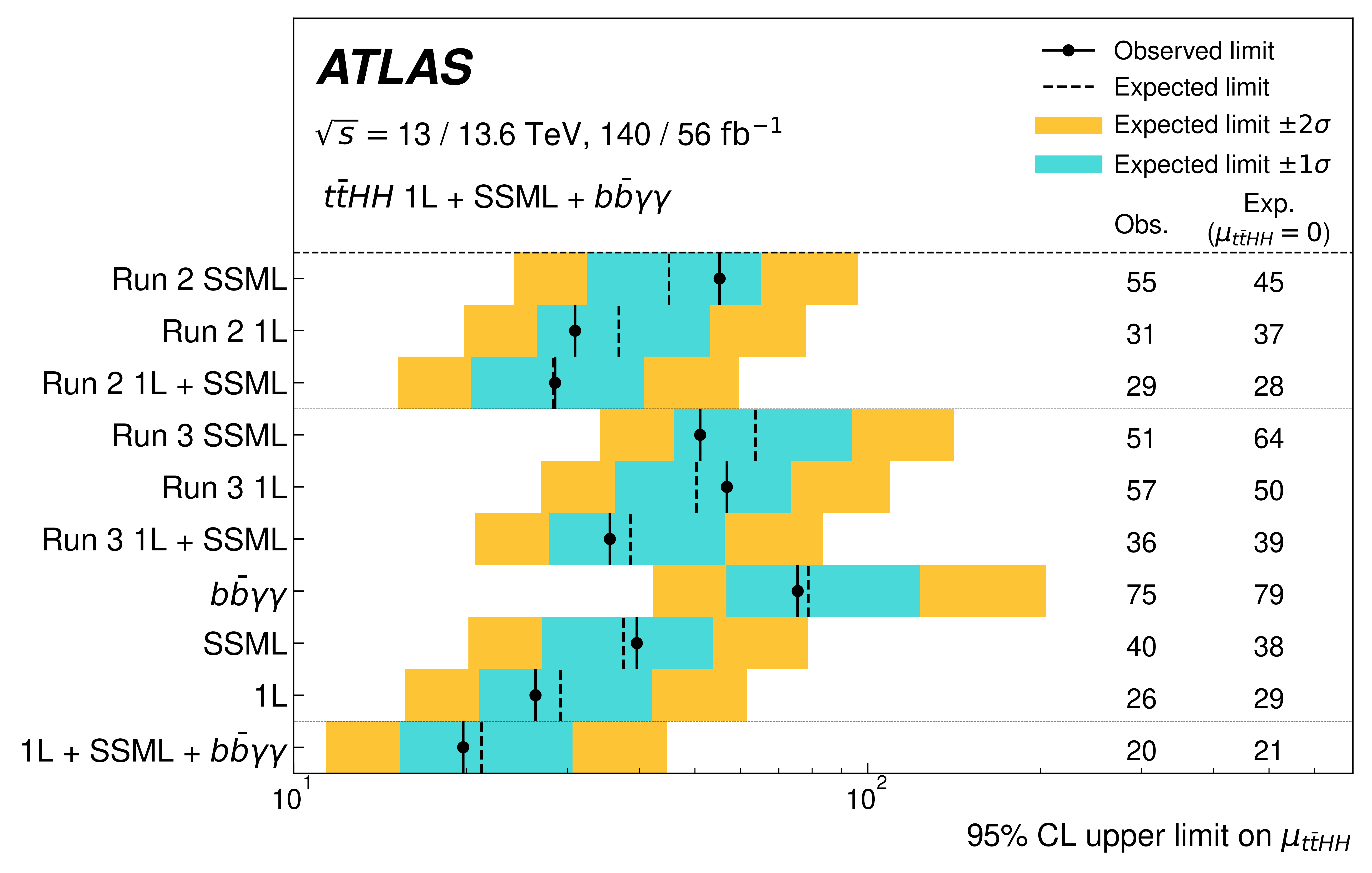
	SM	One d=6	Two d=6	One d=8
Λ^0	$\sigma \sim |\mathscr{M}_{\text{SM}}|^2$			
Λ^{-2}		$+Re(\mathscr{M}_6 \cdot \mathscr{M}_{\text{SM}})$		
Λ^{-4}		$+|\mathscr{M}_6|^2$	$+Re(\mathscr{M}_{6+6} \cdot \mathscr{M}_{\text{SM}})$	$+Re(\mathscr{M}_8 \cdot \mathscr{M}_{\text{SM}})$
Λ^{-6}			$+Re(\mathscr{M}_{6+6}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

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