PRECISION HIGGS PHYSICS: A (PARTIAL) REVIEW

LHCP 2024

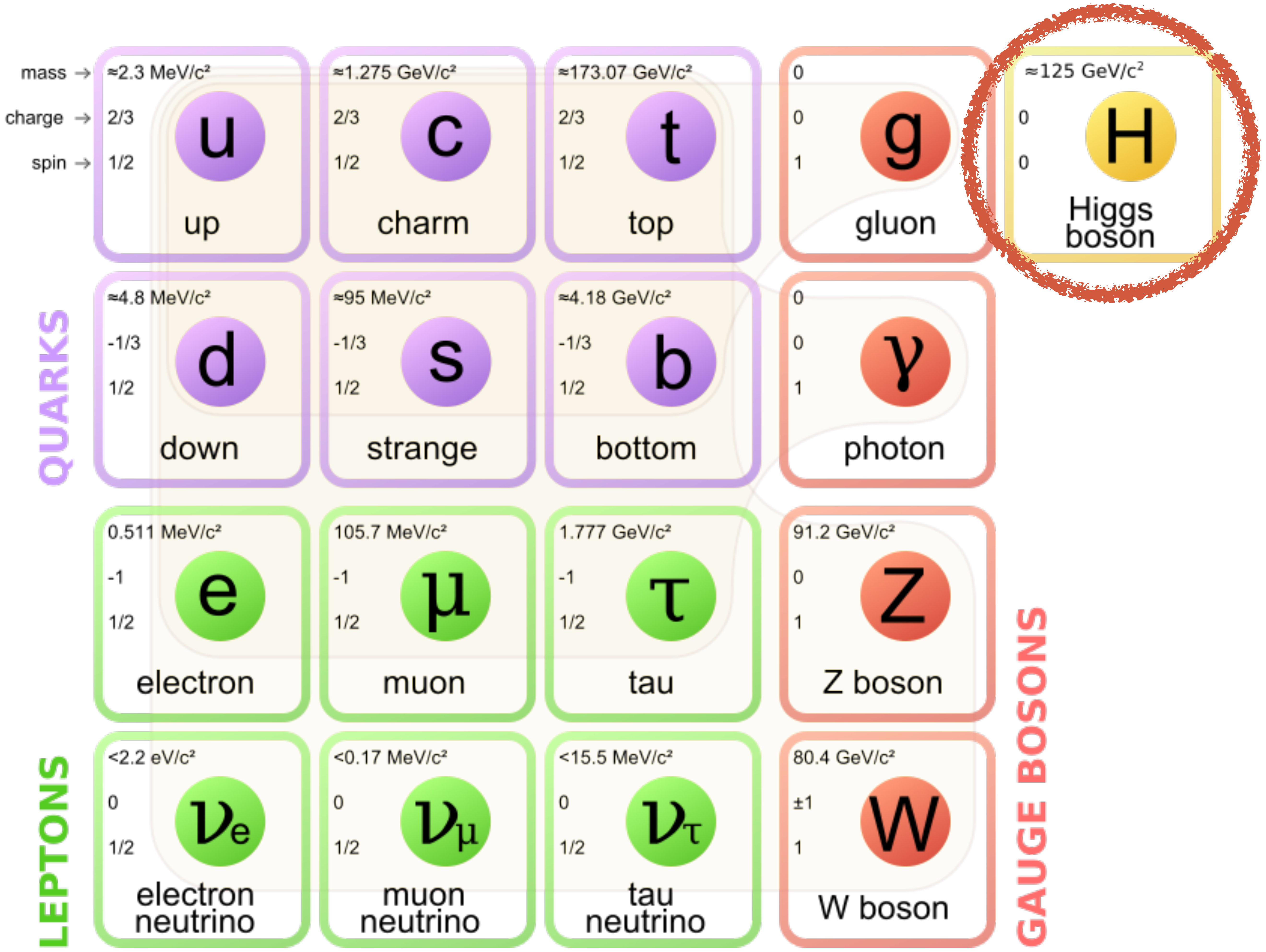
Northeastern University (Boston, USA) – June 6th 2024

Lorenzo Tancredi – Technical University Munich

Technische Universität München

29 May 1929 - 8 April 2024

THE HIGGS BOSON: THE LAST MISSING PIECE

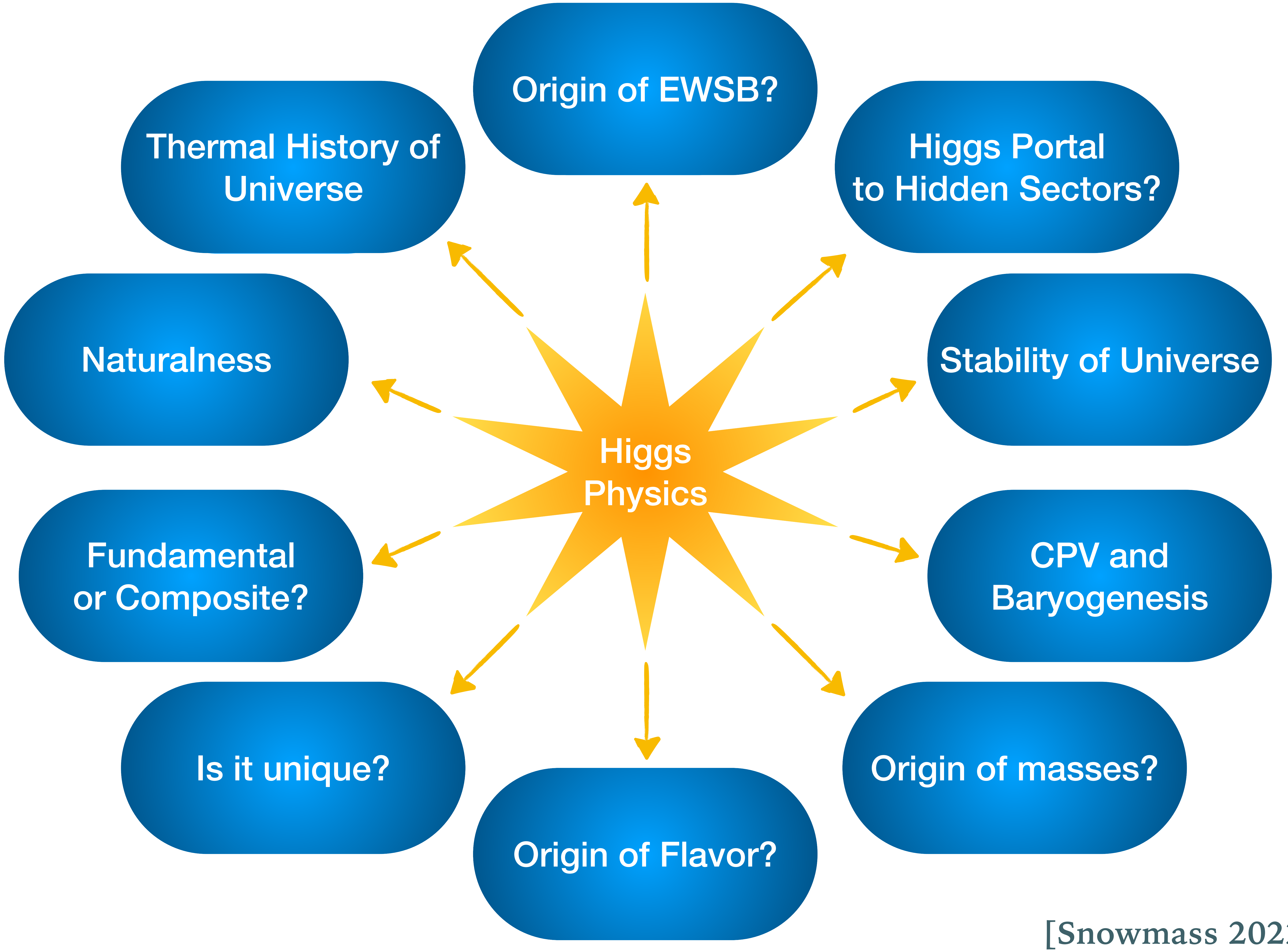


Higgs field "holds SM together"

Out of the 19 free parameters in the SM, 15 are directly connected to the Higgs

Particle masses, mixing parameters, CKM matrix, CP violating phase…

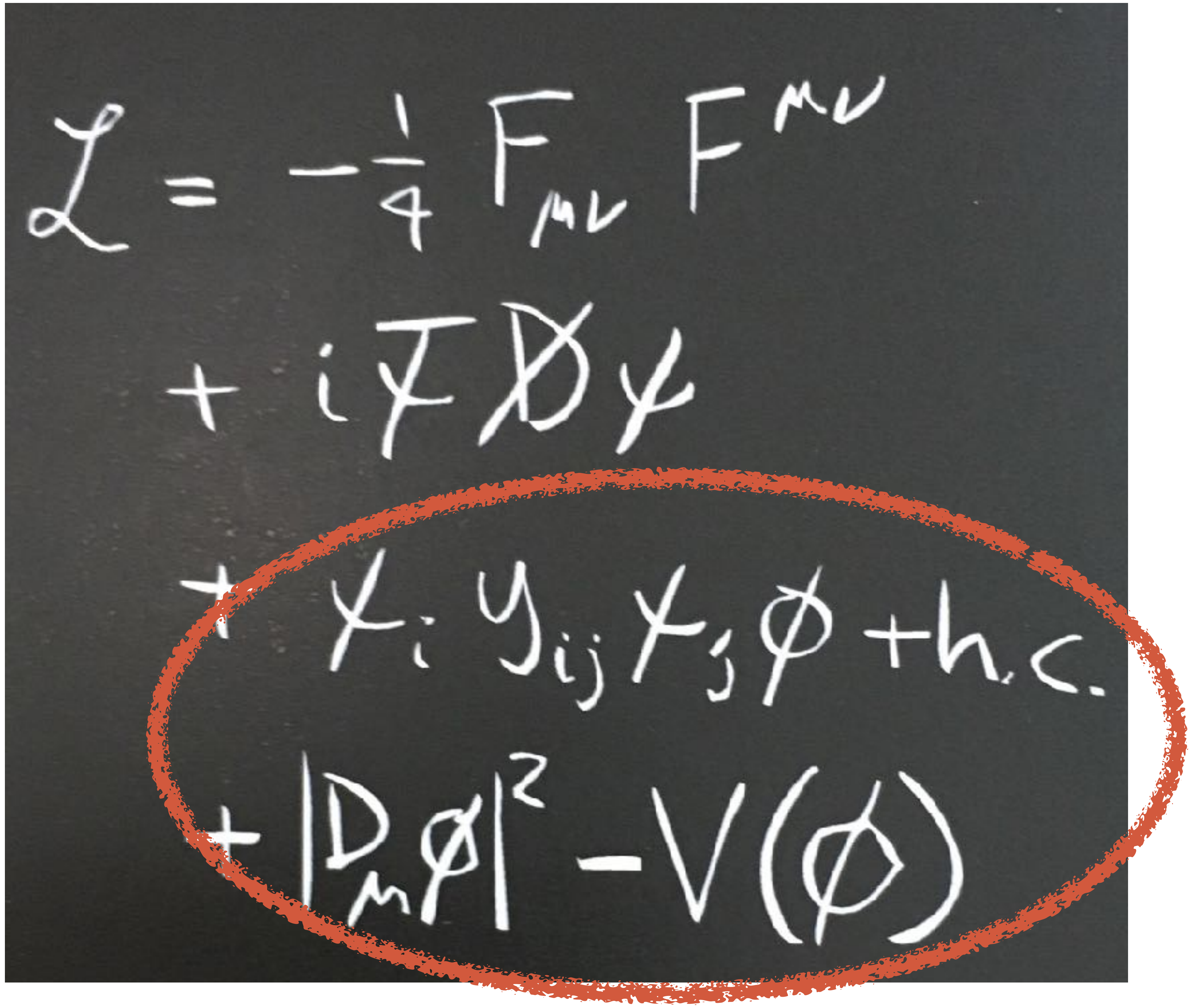
THE HIGGS BOSON: THE COOLEST KID IN THE ROOM



[Snowmass 2022 arXiv:2209.0751]

HIGGS INTERACTIONS AT THE LHC

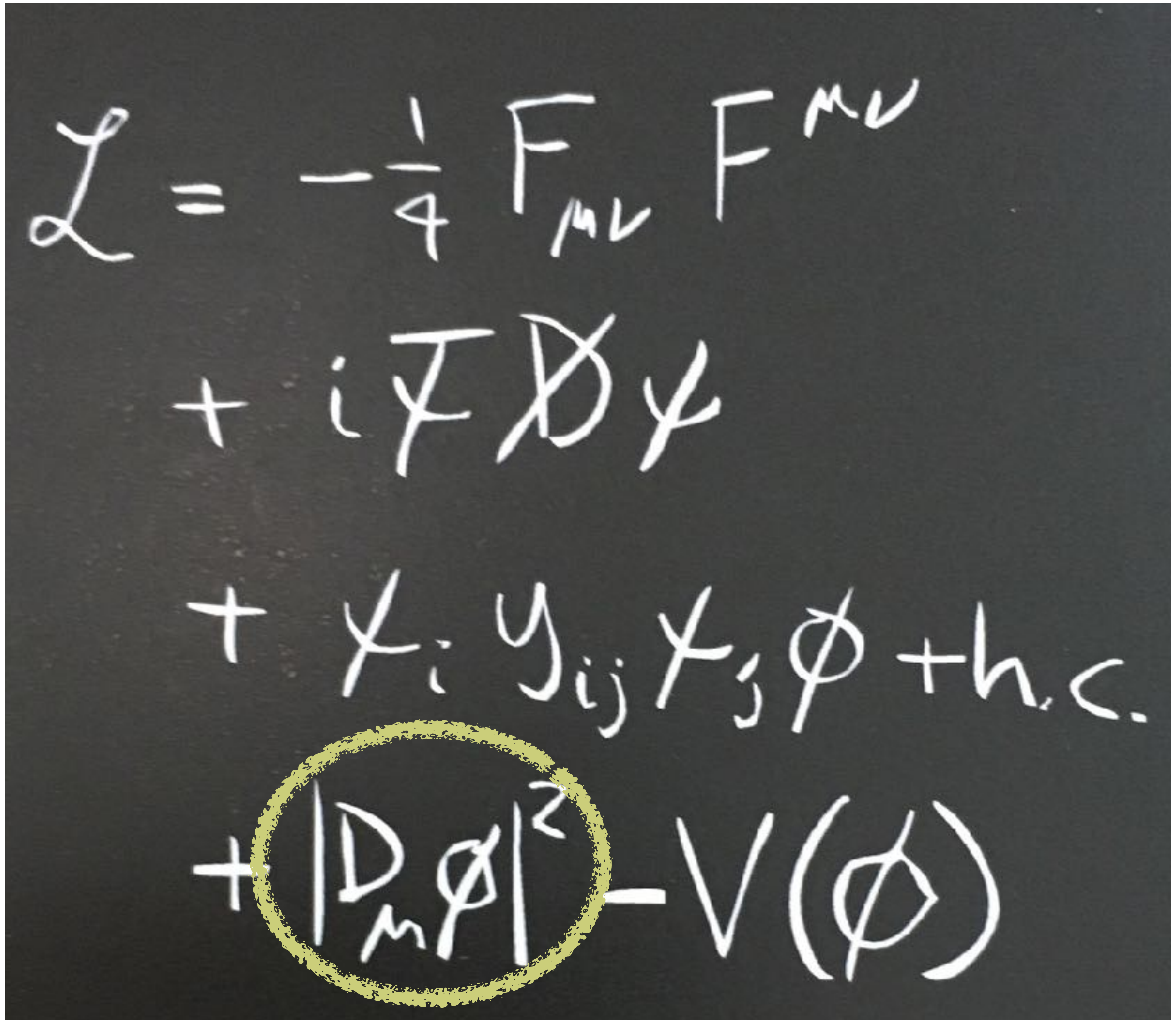
Hints to answer these questions hidden in the **details of Higgs interactions to SM particles**



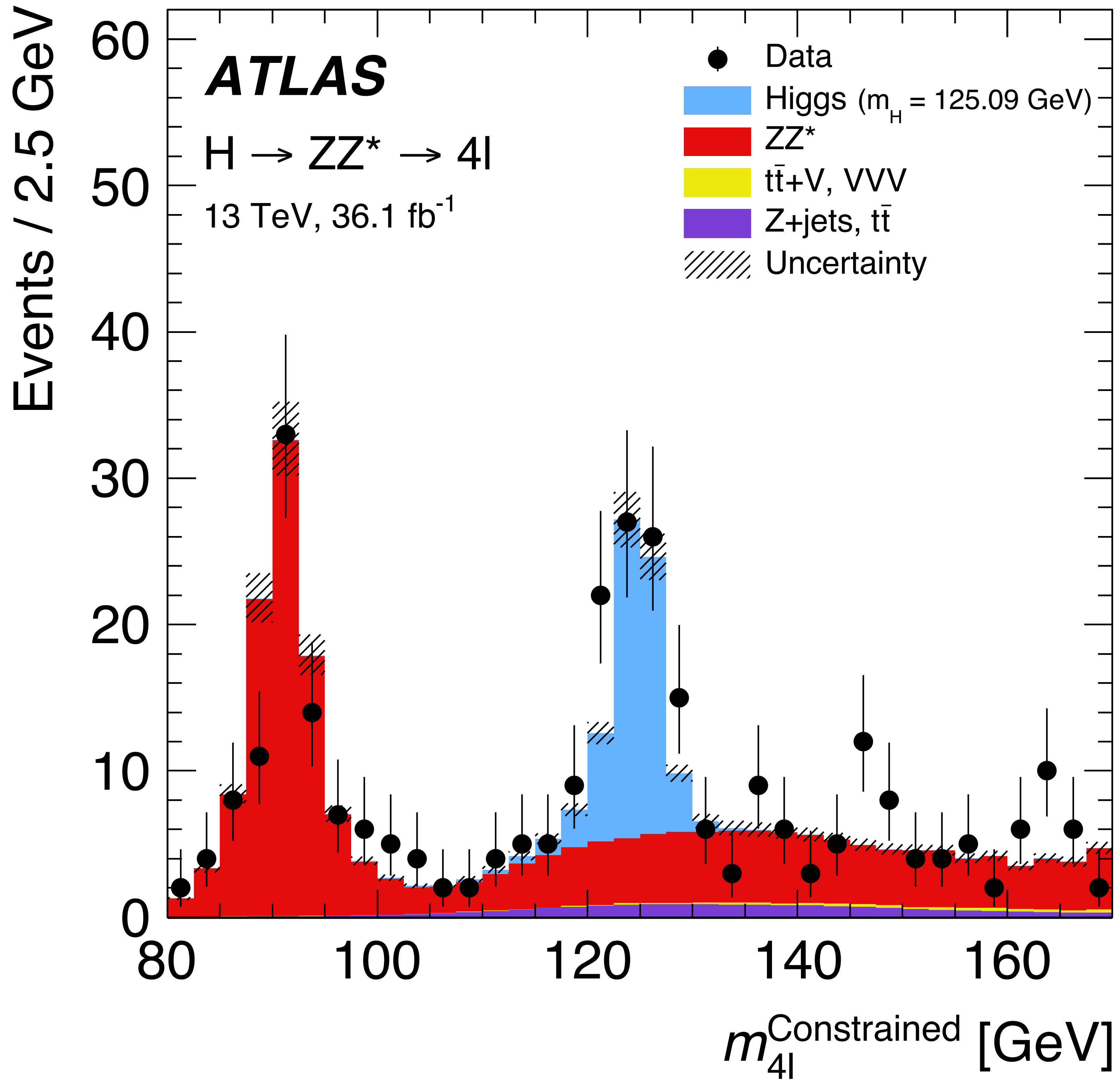
LHC has opened a window for us to peak at Higgs' interactions for the first time !

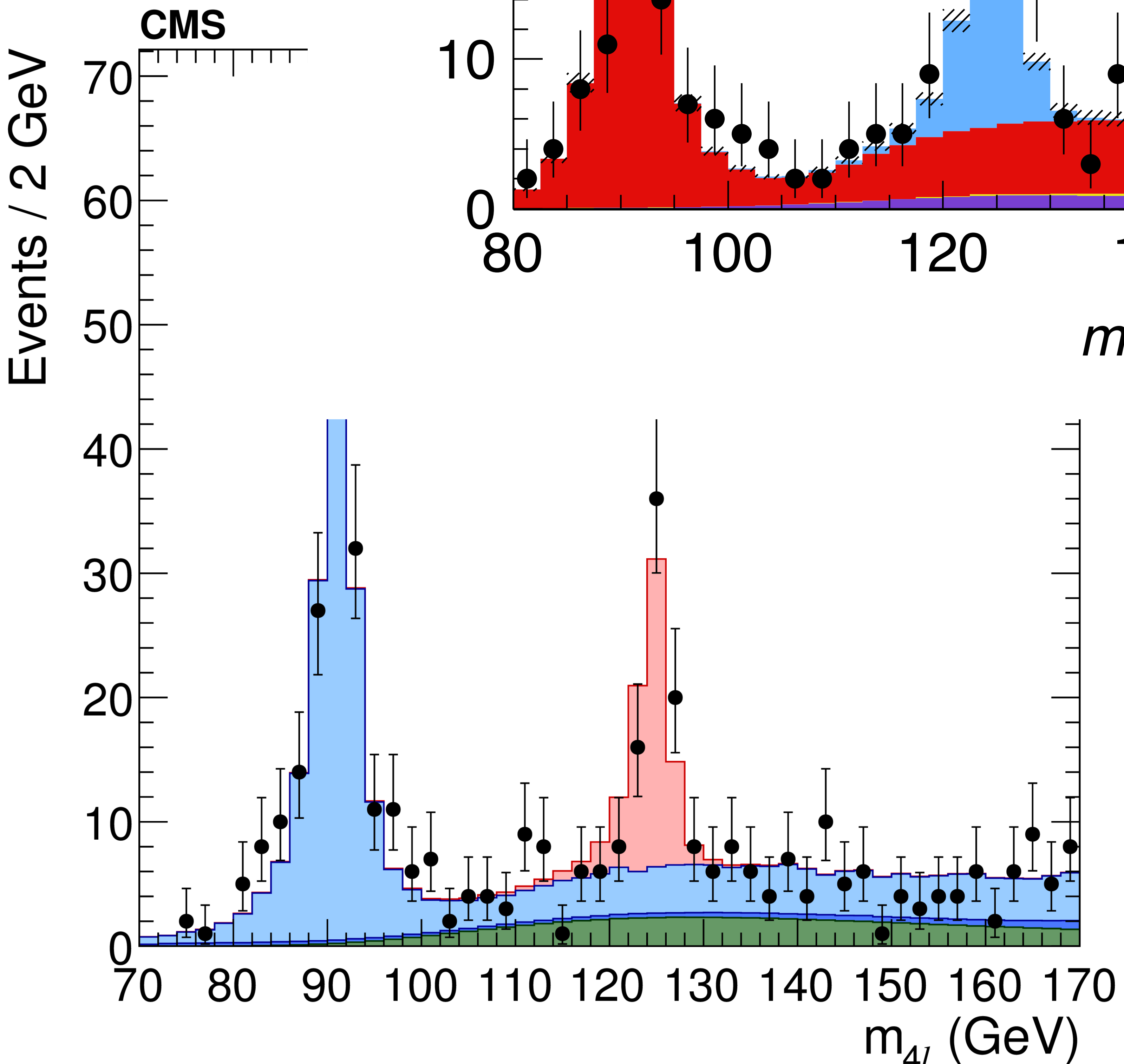
HIGGS INTERACTIONS THE GAUGE SECTOR

Higgs discovery through its **couplings to gauge sector**



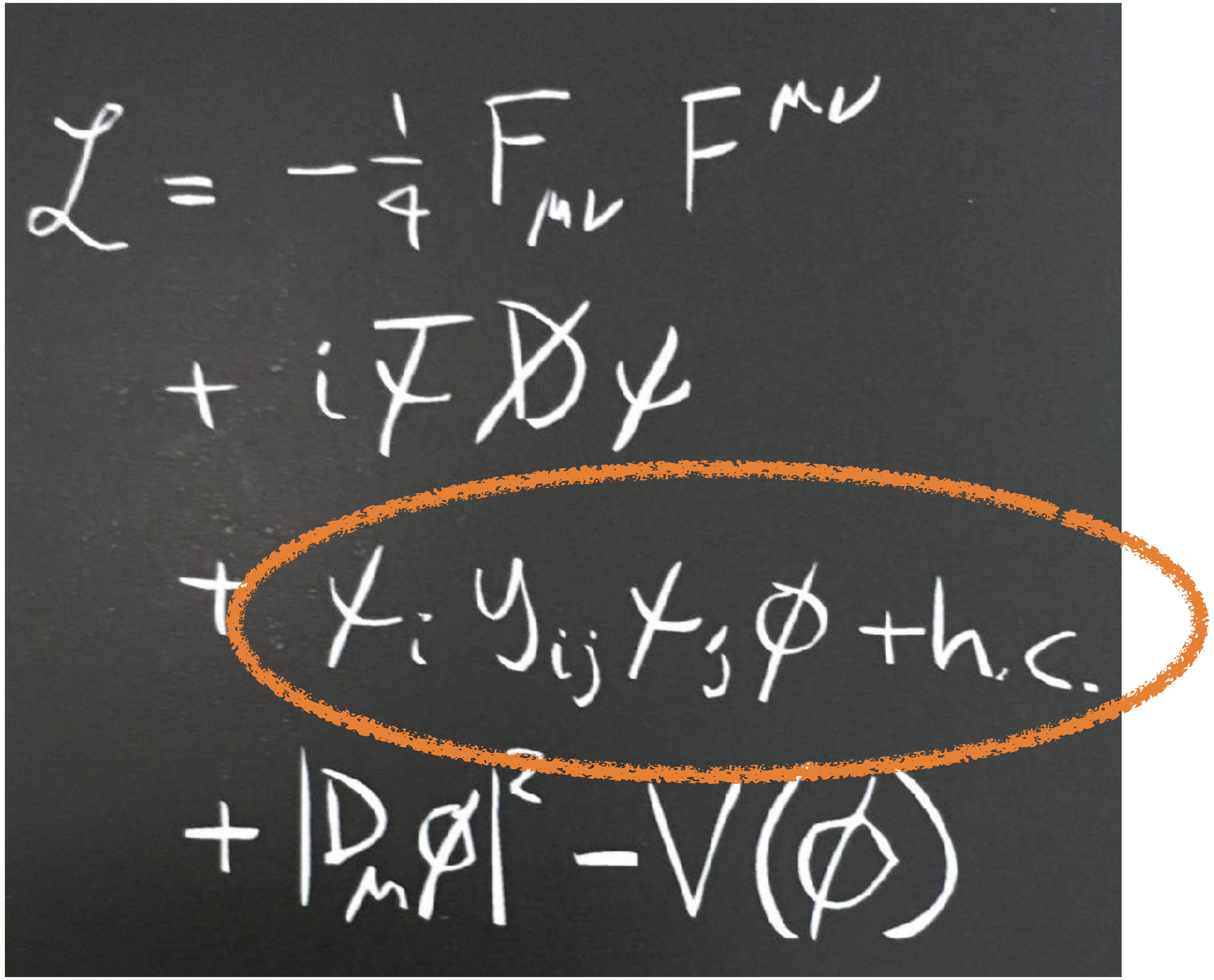
Strongly constrained by **gauge symmetry**

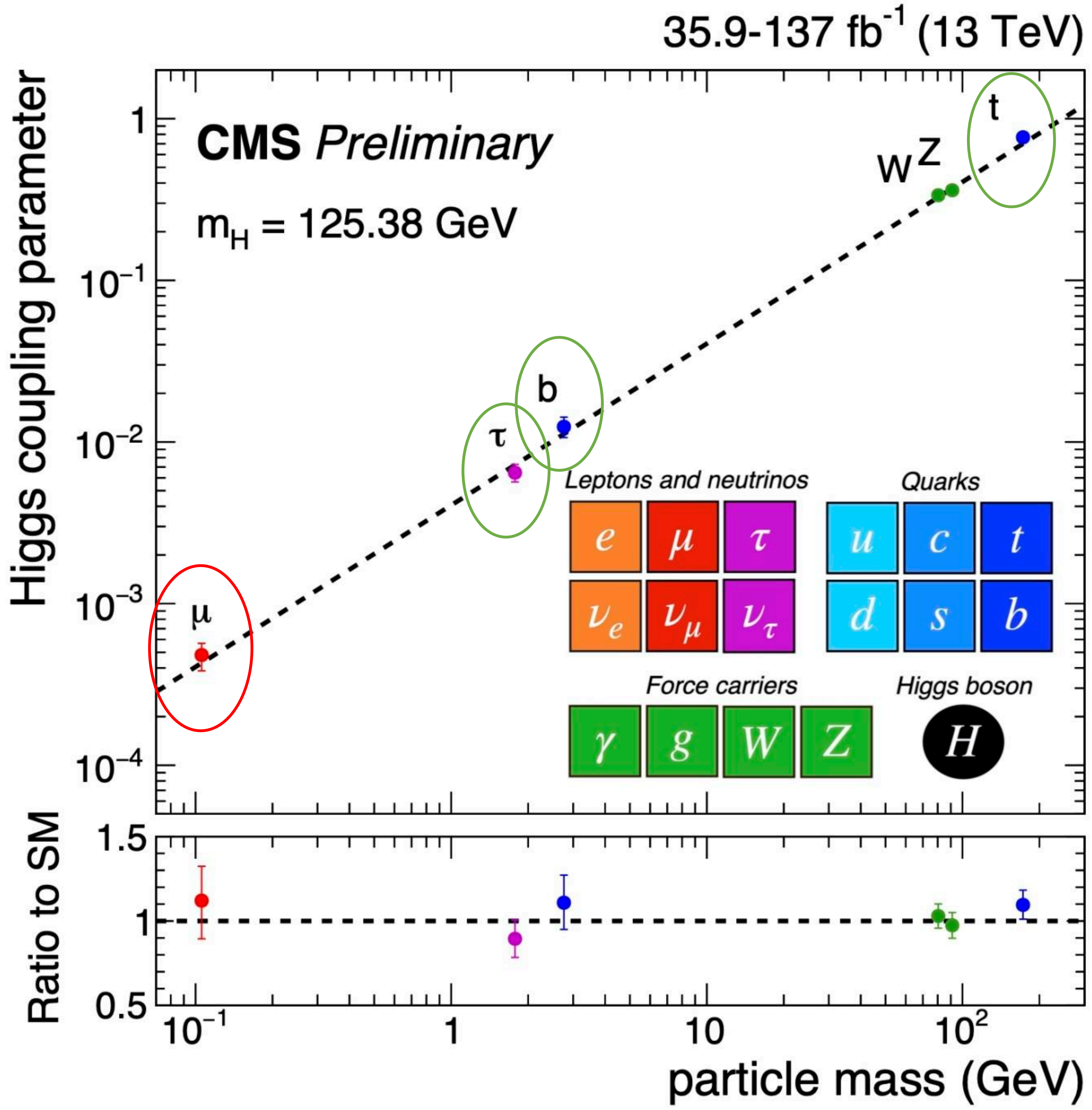


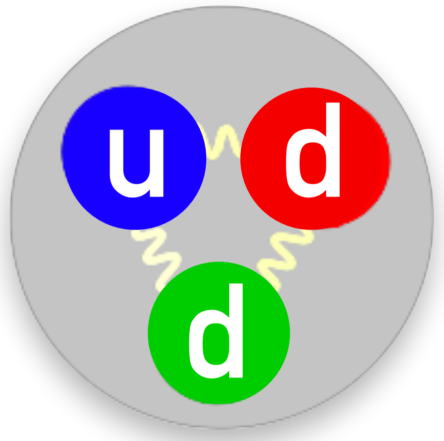


HIGGS INTERACTIONS THE YUKAWA SECTOR

LHC run 2 opened a window on details of **Yukawa sector**

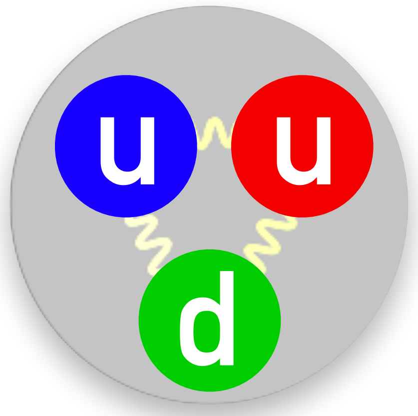






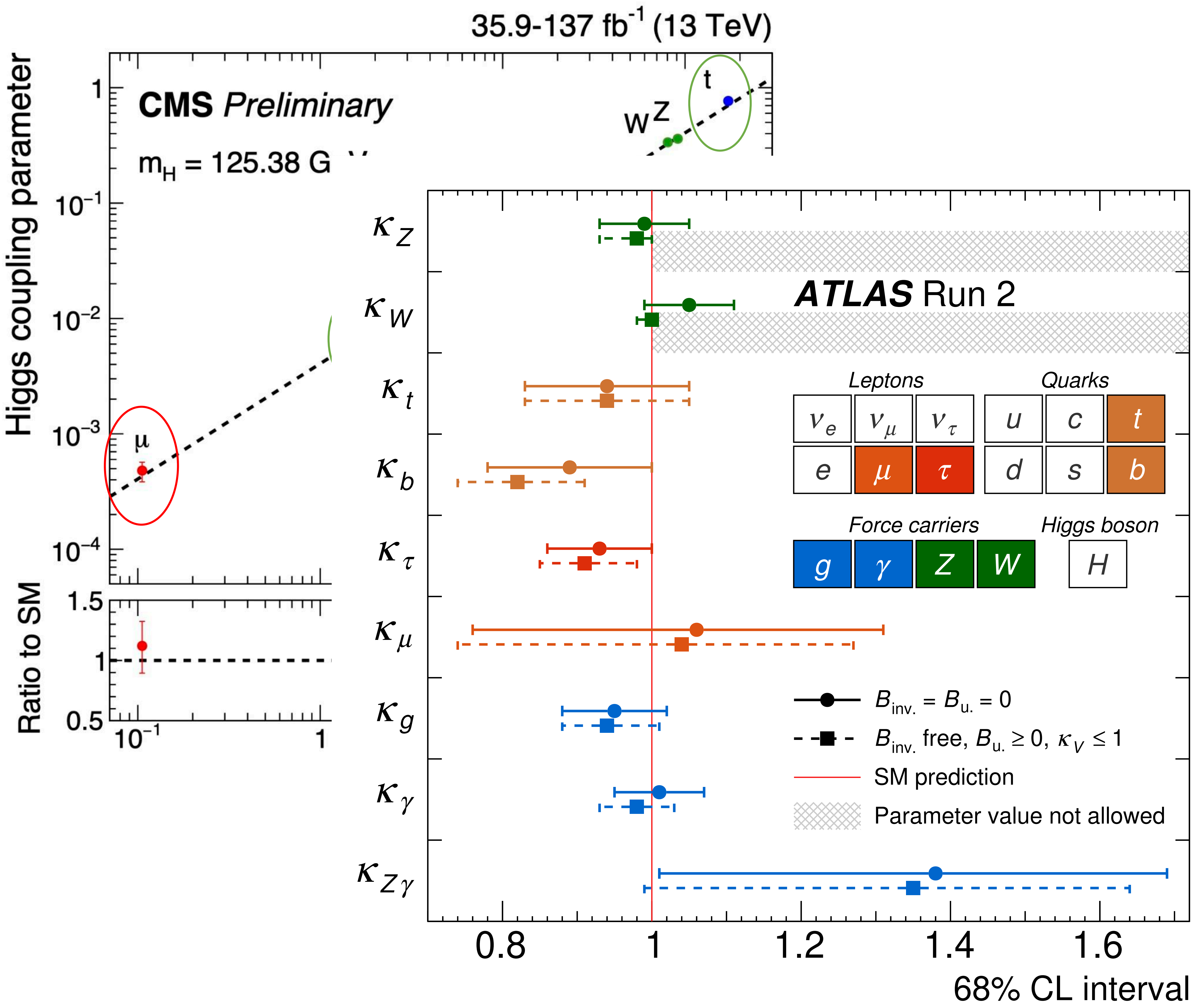
$m_n = 939.6$ MeV

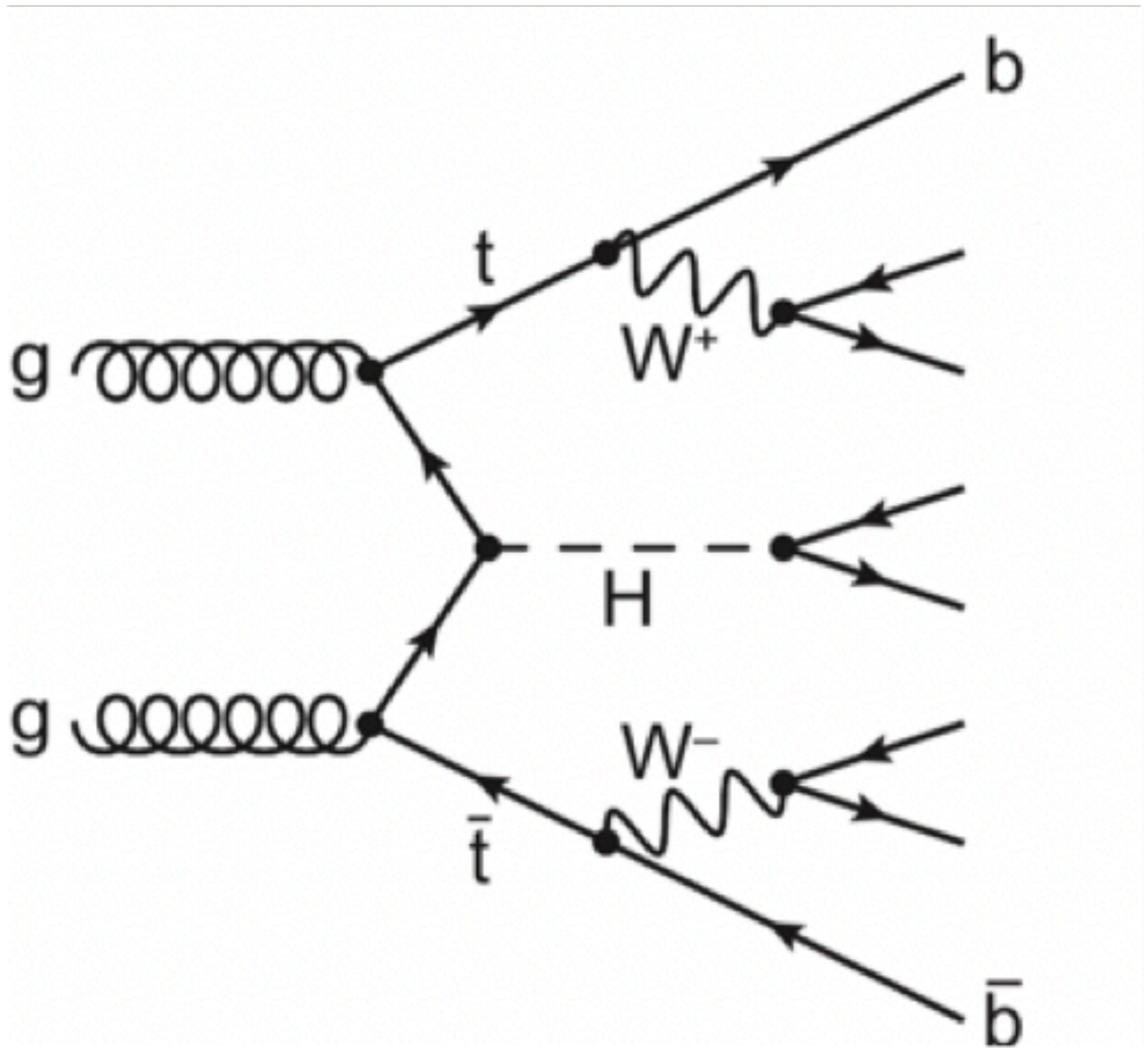
$m_p = 938.3$ MeV



HIGGS INTERACTIONS THE YUKAWA SECTOR

Run 2 direct observation of H coupling to **third family fermions**



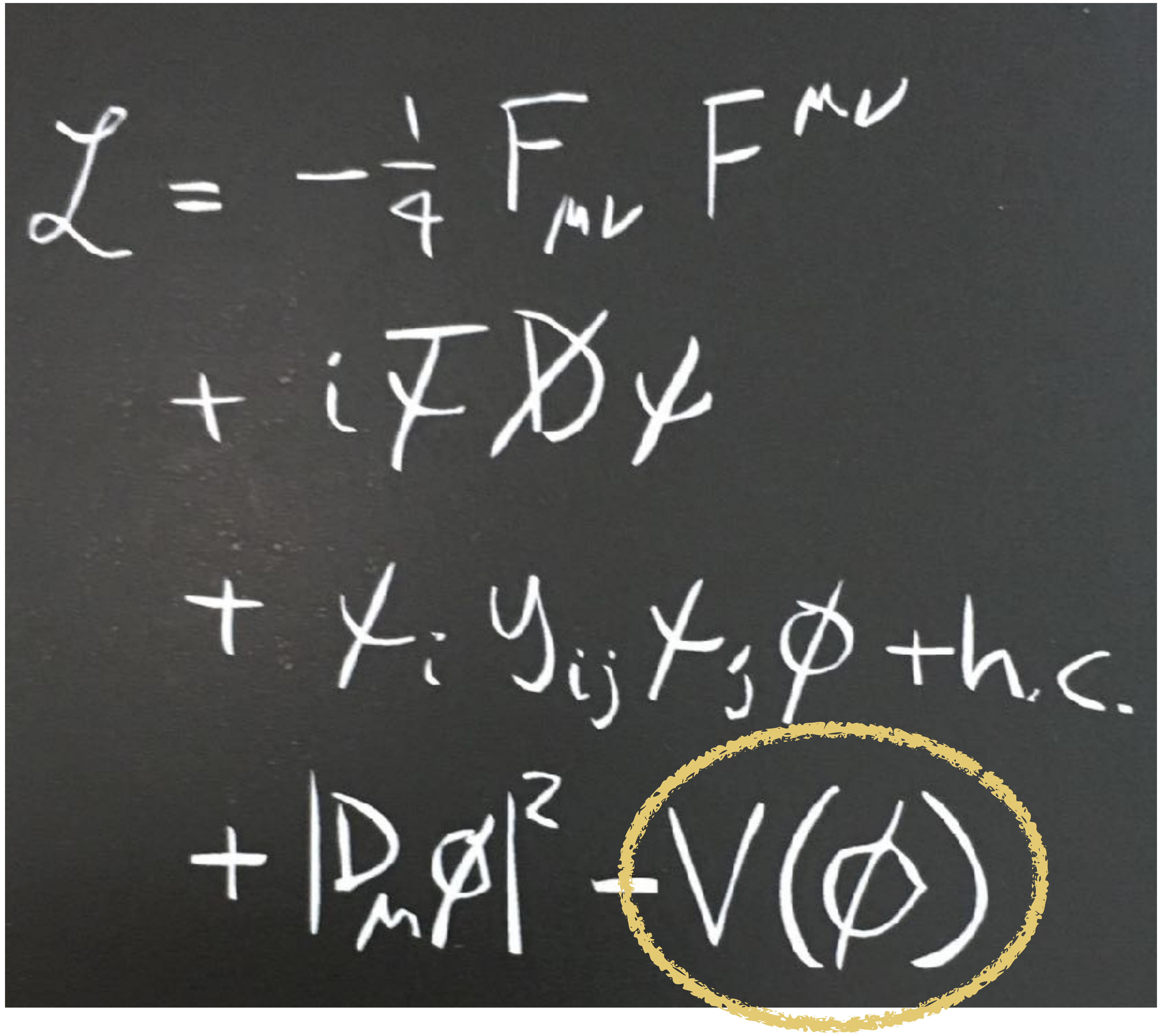


Run 3 and **HL potential**:

1. **Precision** measurements for **third family**
2. **Discovery couplings to second family**!

(at least μ & c !)

HIGGS SELF INTERACTIONS THE MOST MYSTERIOUS?



We have seen the Higgs but

$$V(\phi) = -\mu^2\phi^2 + \frac{\lambda}{4!}\phi^4$$

is a “toy model”!

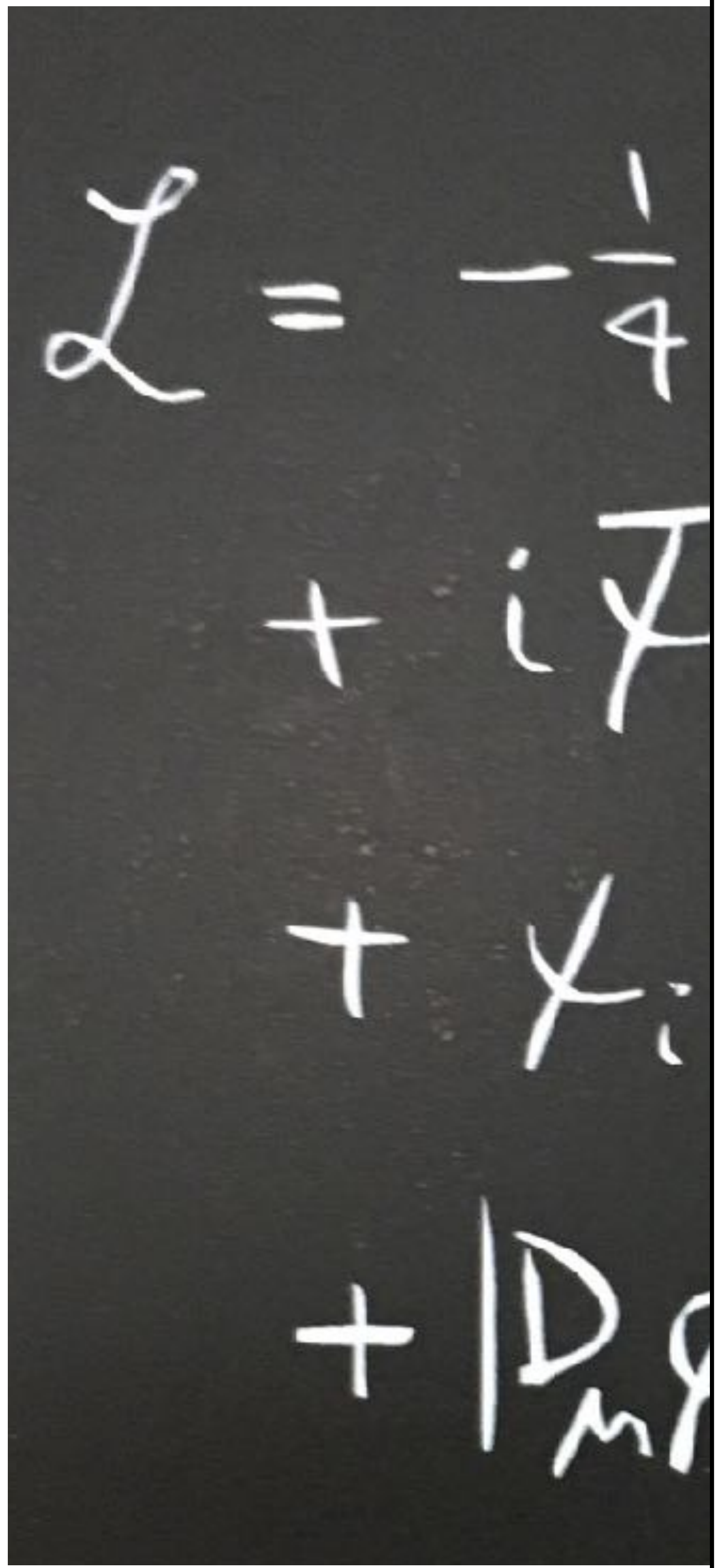
1. more minima?
2. more Higges?
3. microscopic model of SSB?
4. …

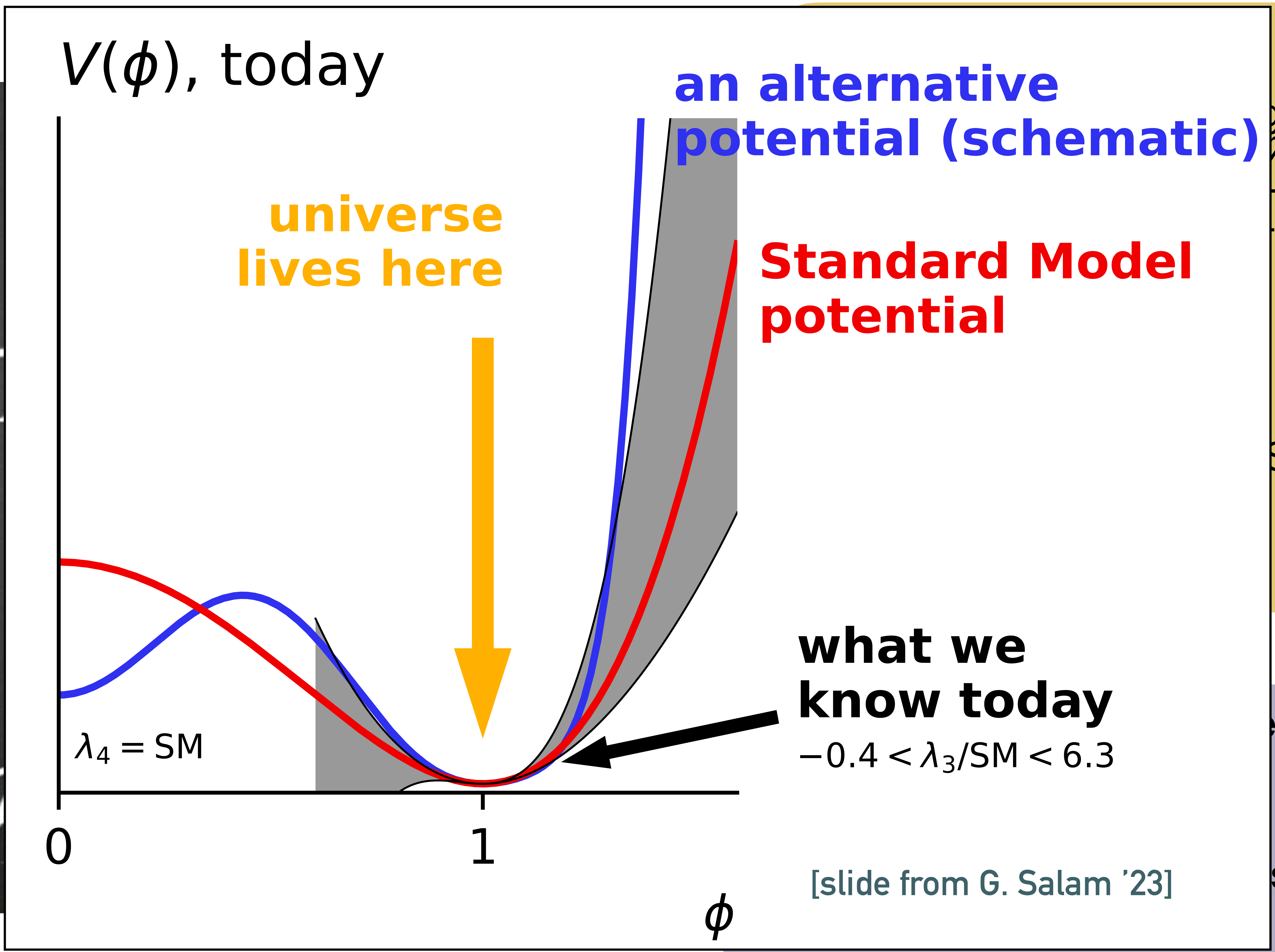
Higgs self coupling extremely difficult to measure.

With current techniques estimate 4σ ATLAS+CMS

HIGGS SELF INTERACTIONS THE MOST MYSTERIOUS?

See also talk by J. Alison





gs but

ϕ^4

SSB?

ly difficult to

stimate 4σ

HIGGS SELF INTERACTIONS THE MOST MYSTERIOUS?

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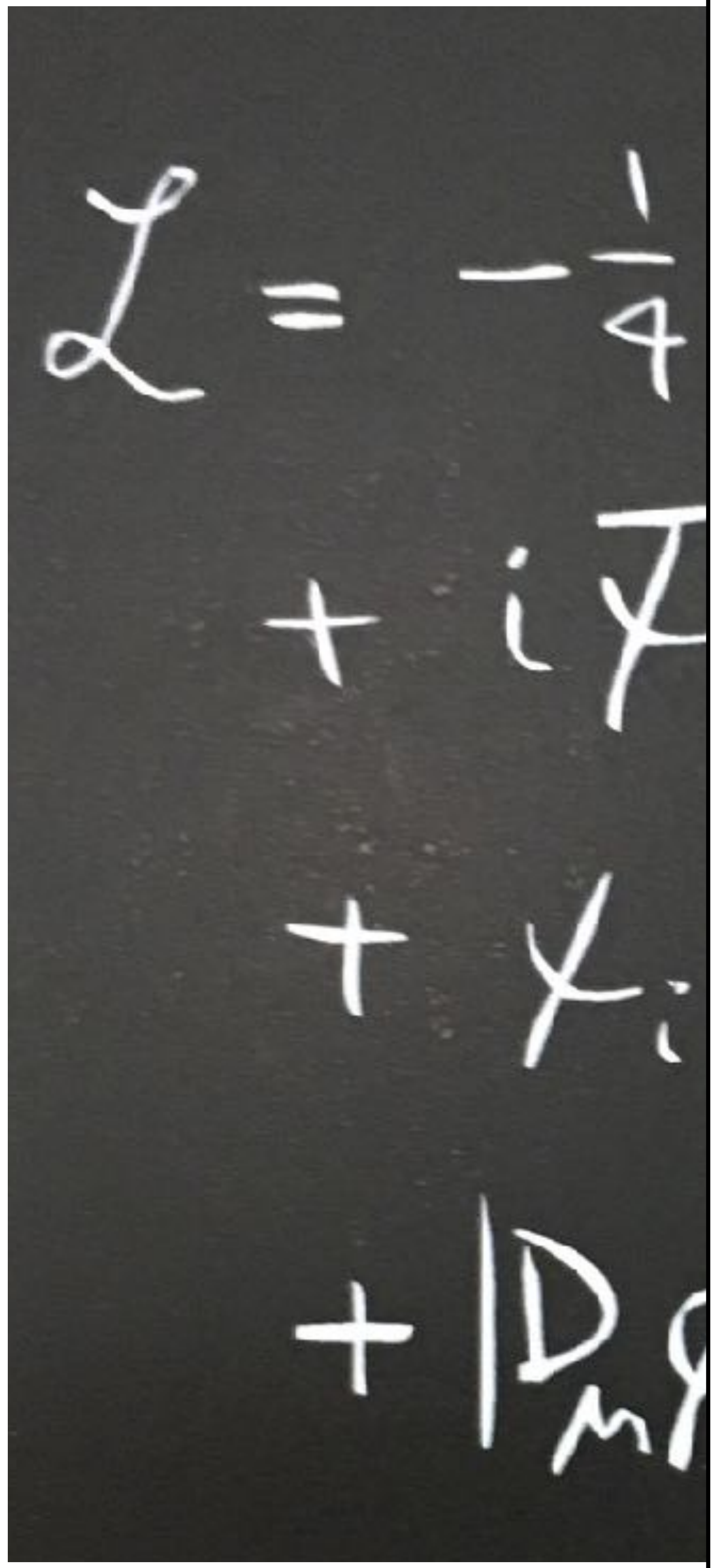

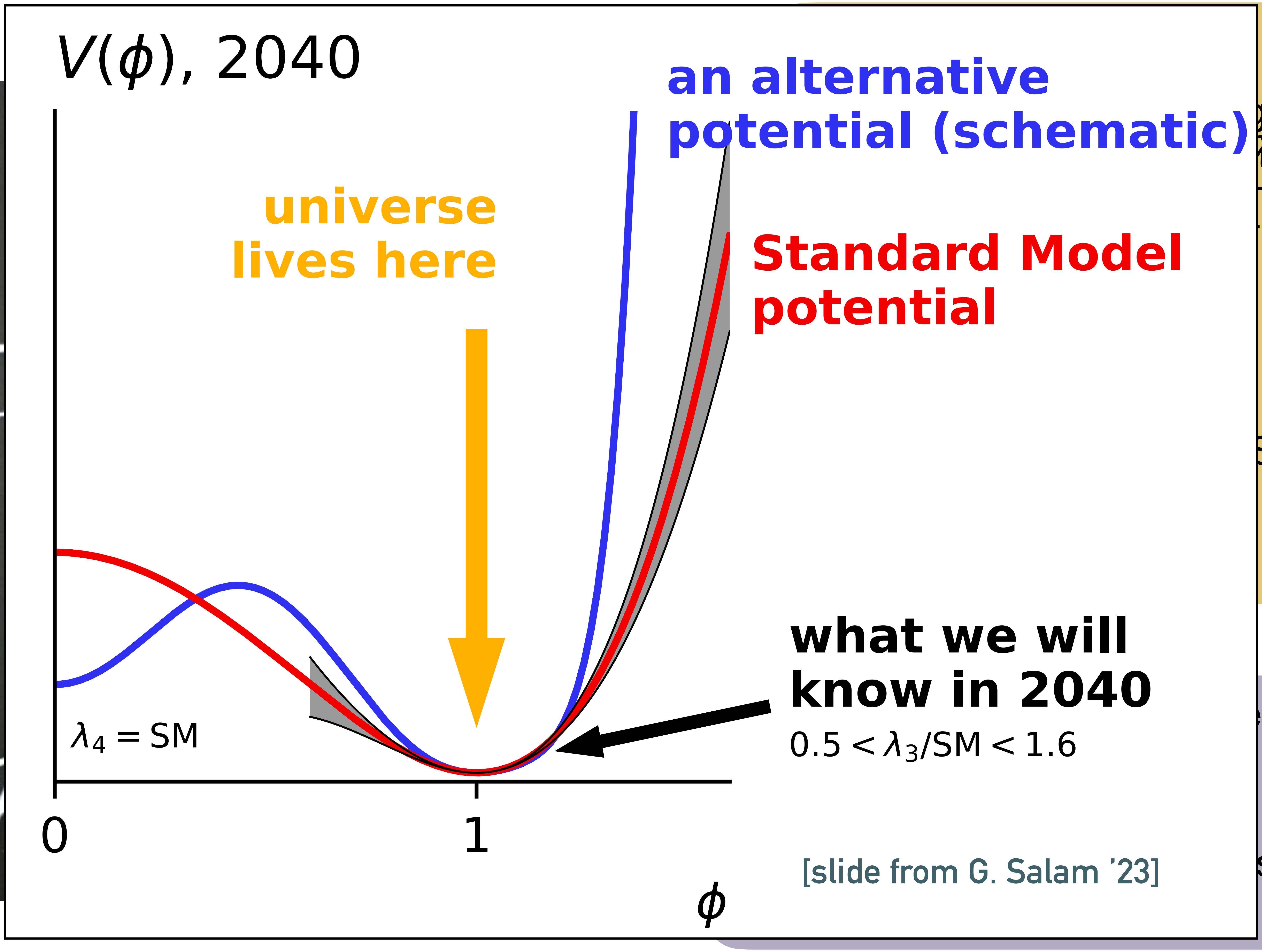

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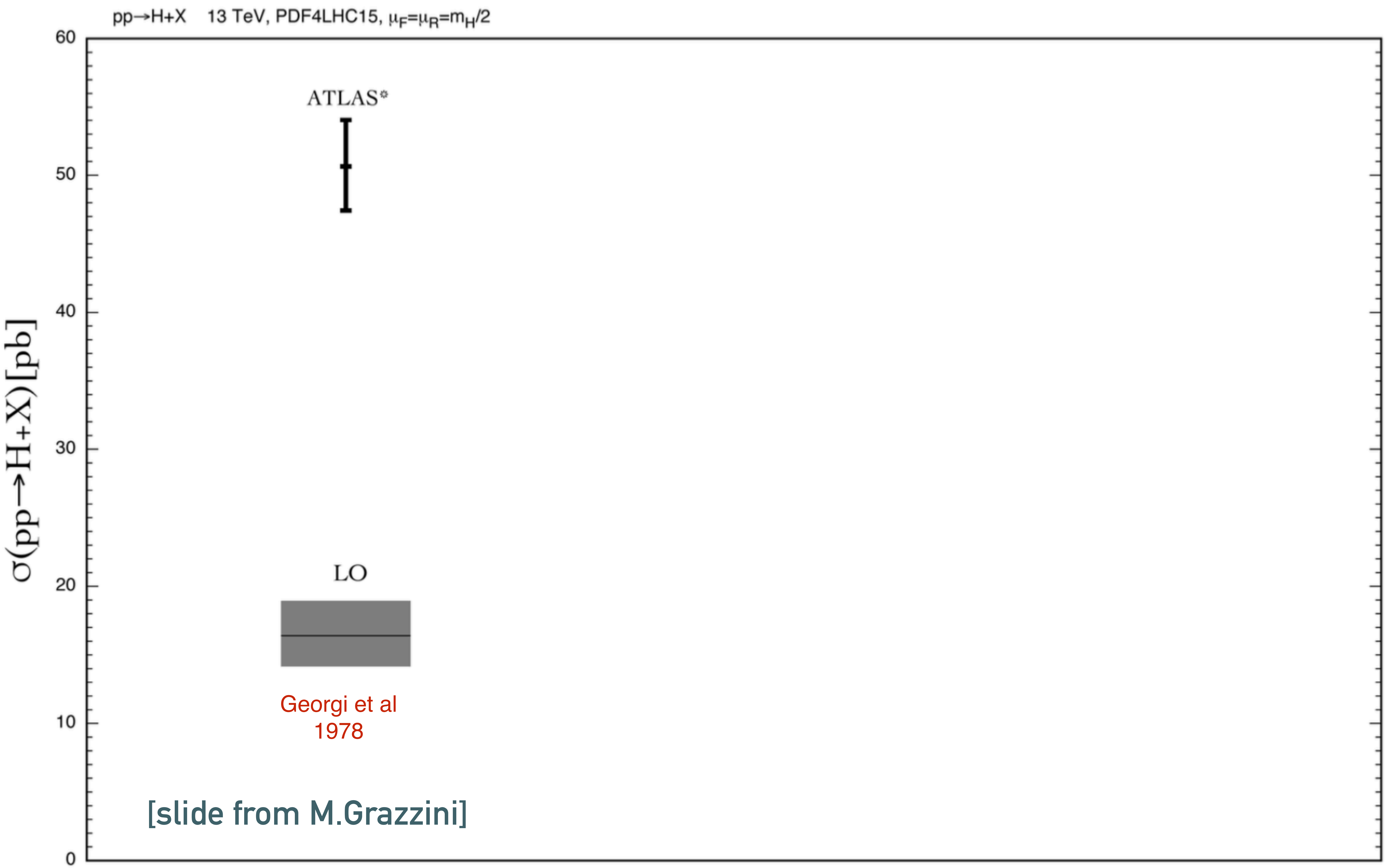
THE NEED OF PRECISION



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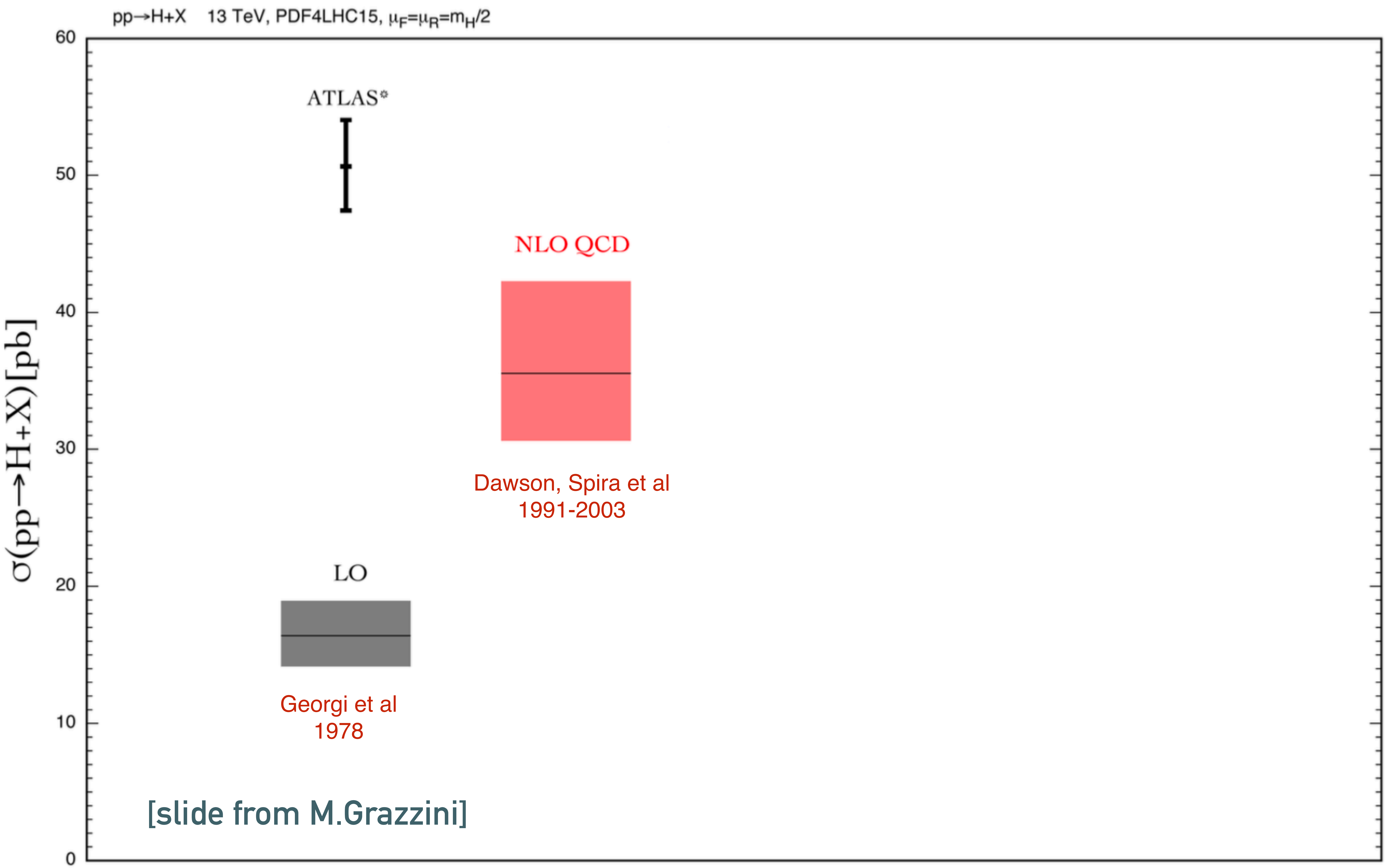
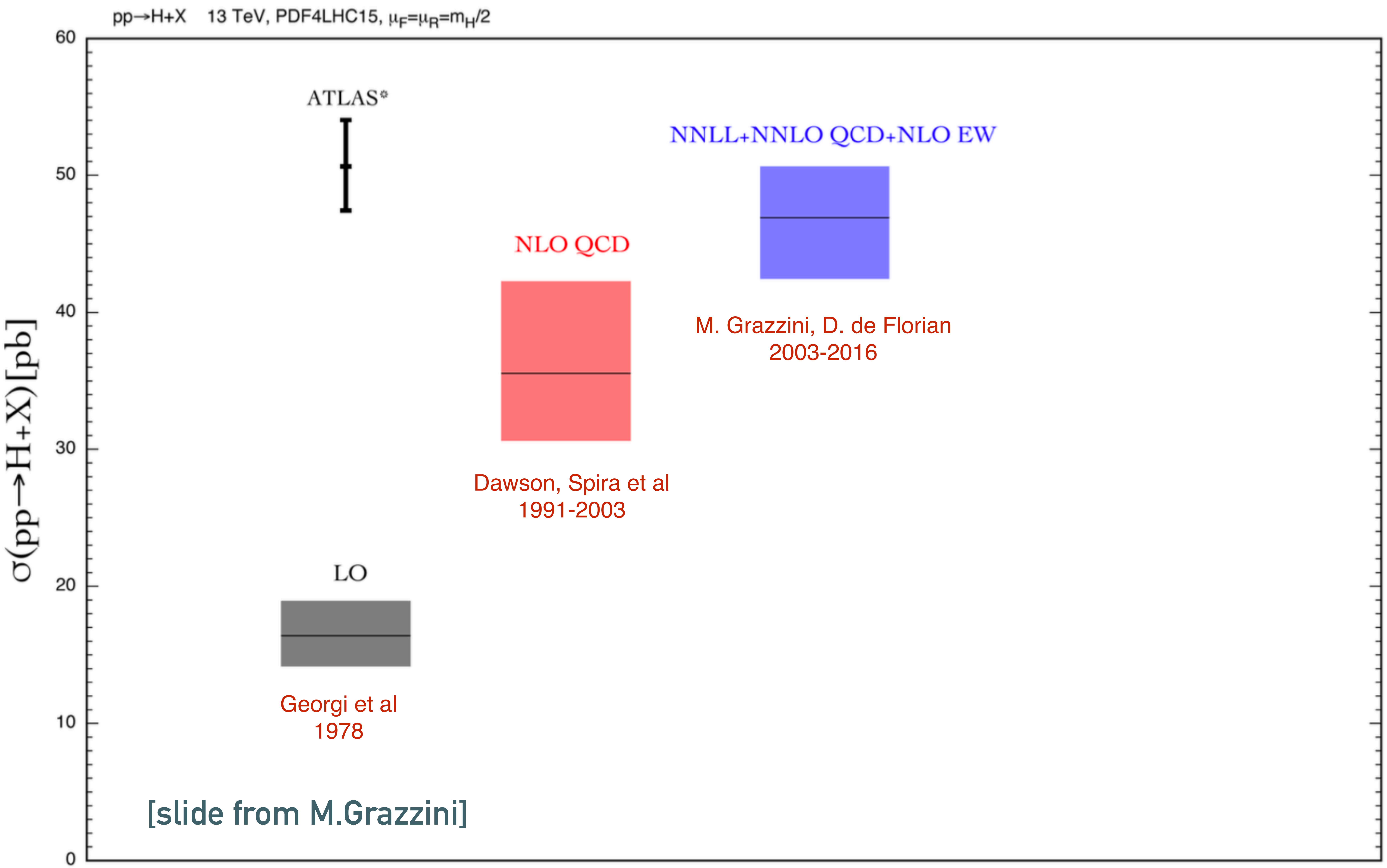


[slide from M.Grazzini]

THE NEED OF PRECISION



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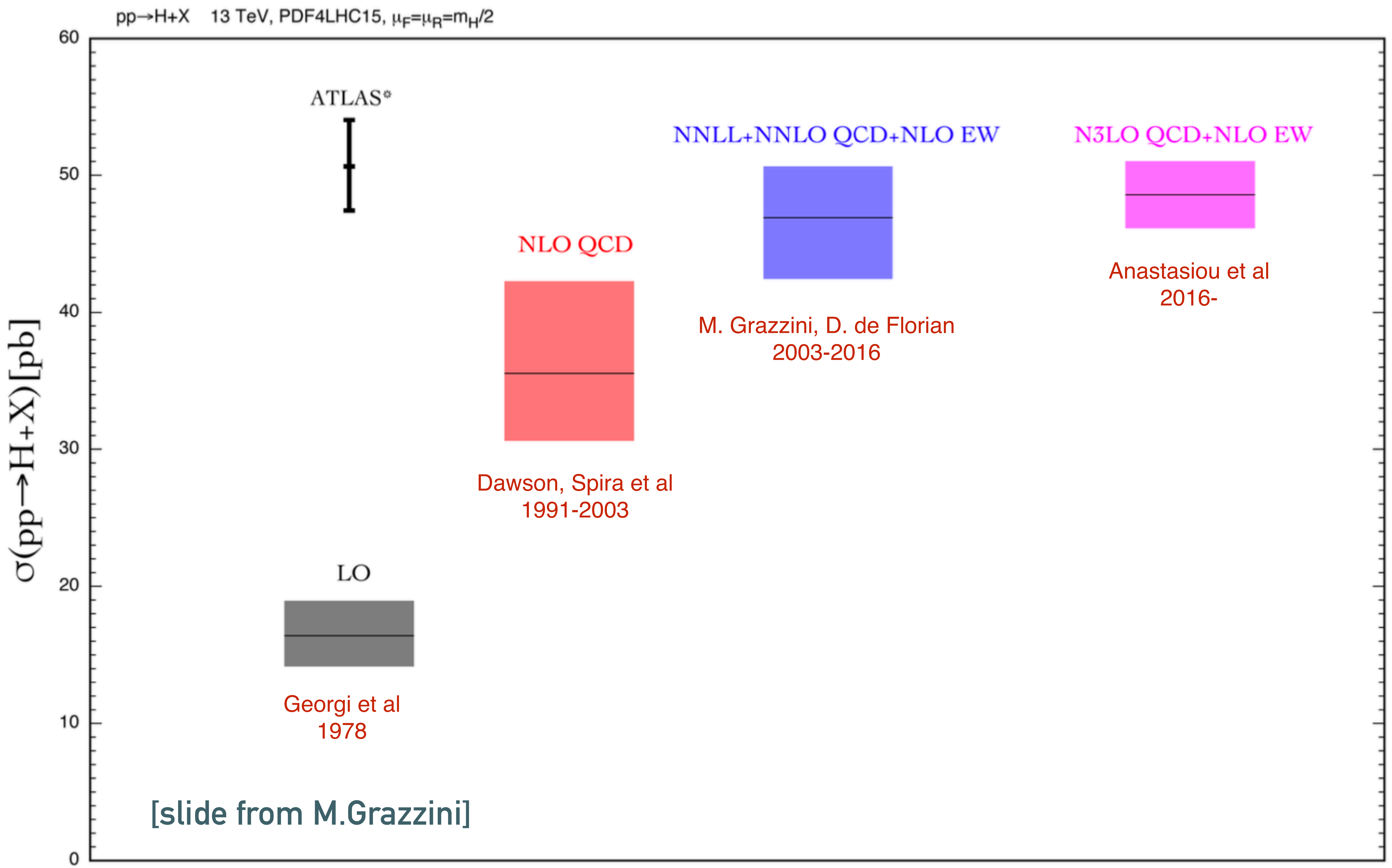

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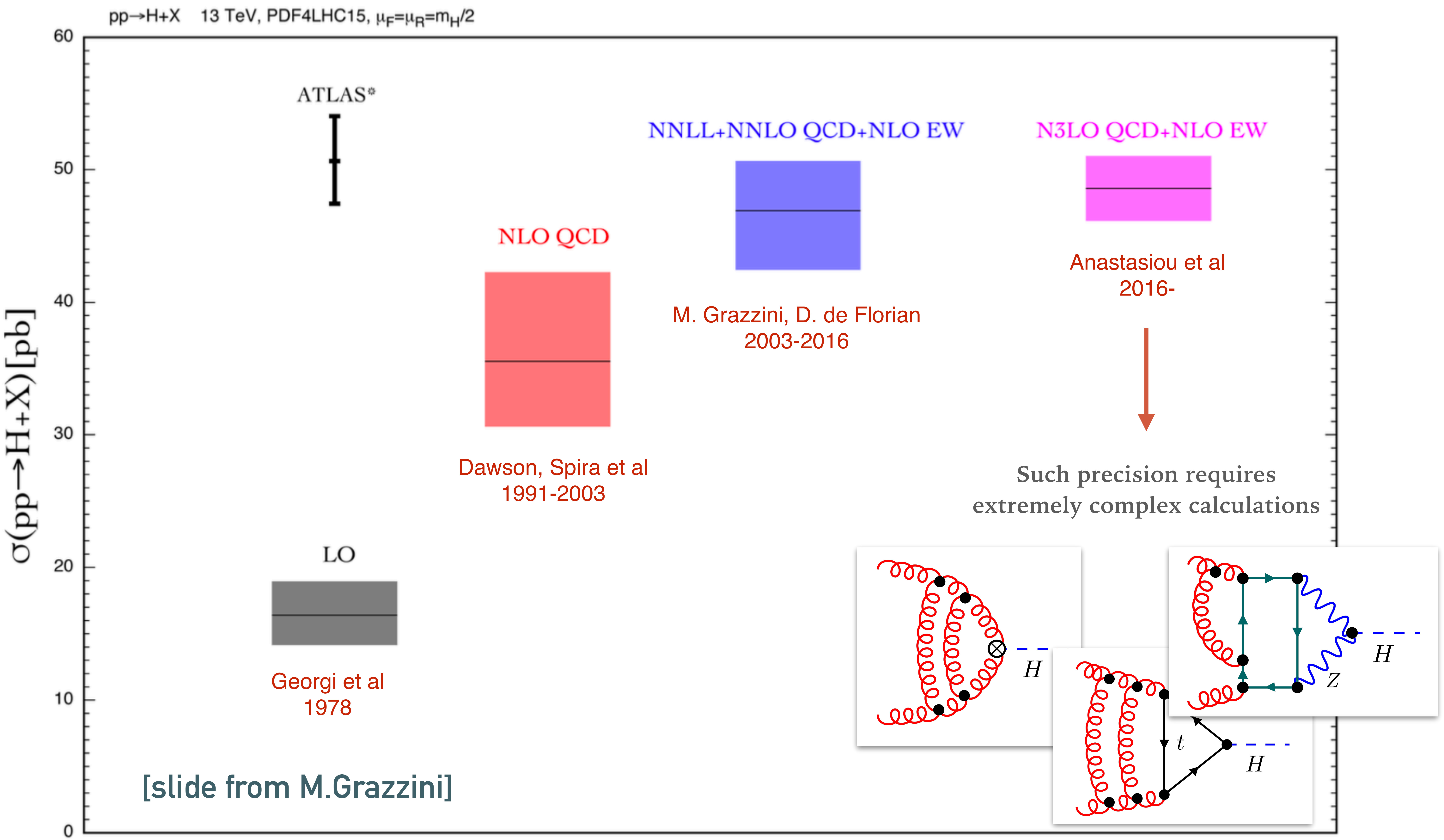
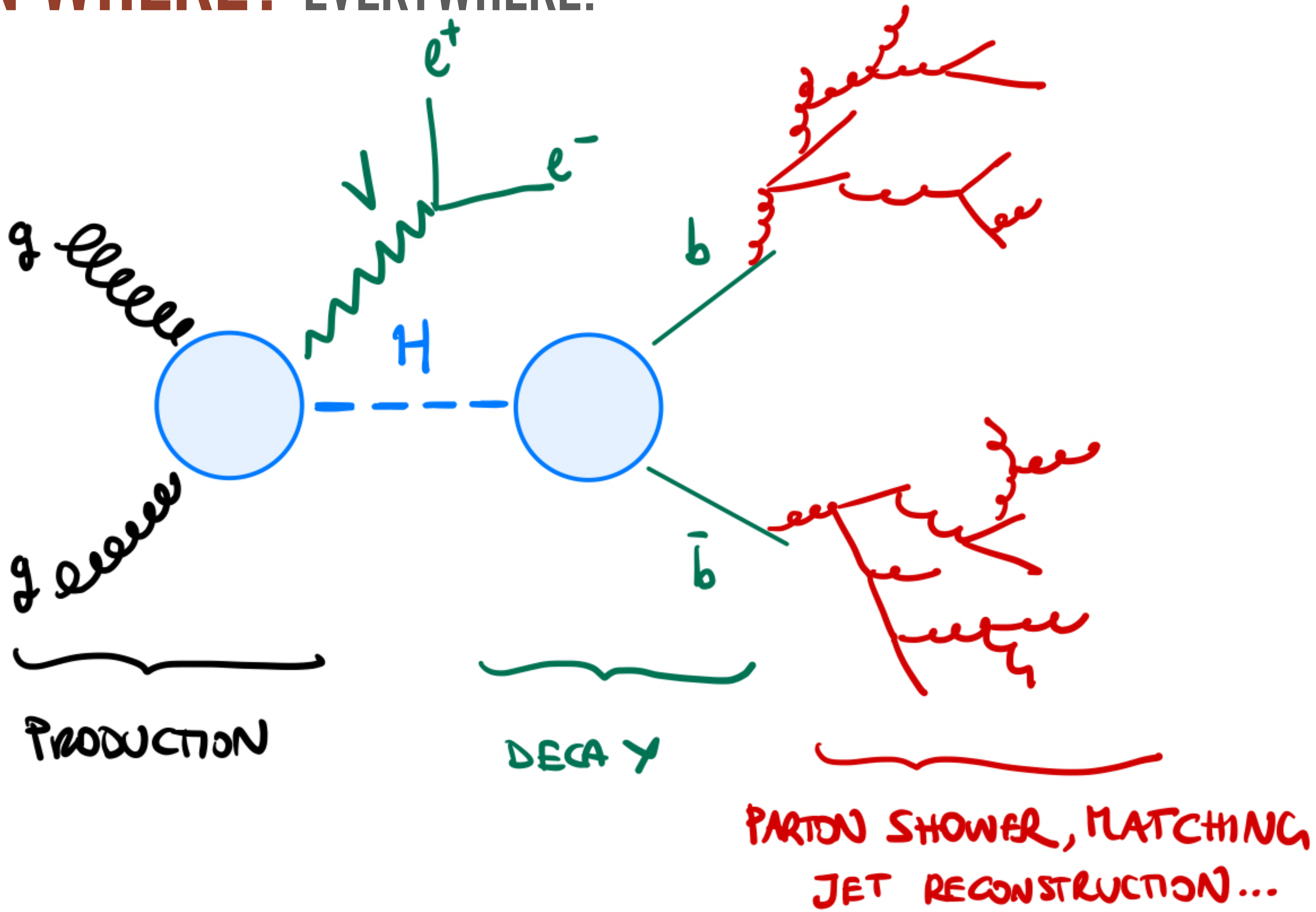


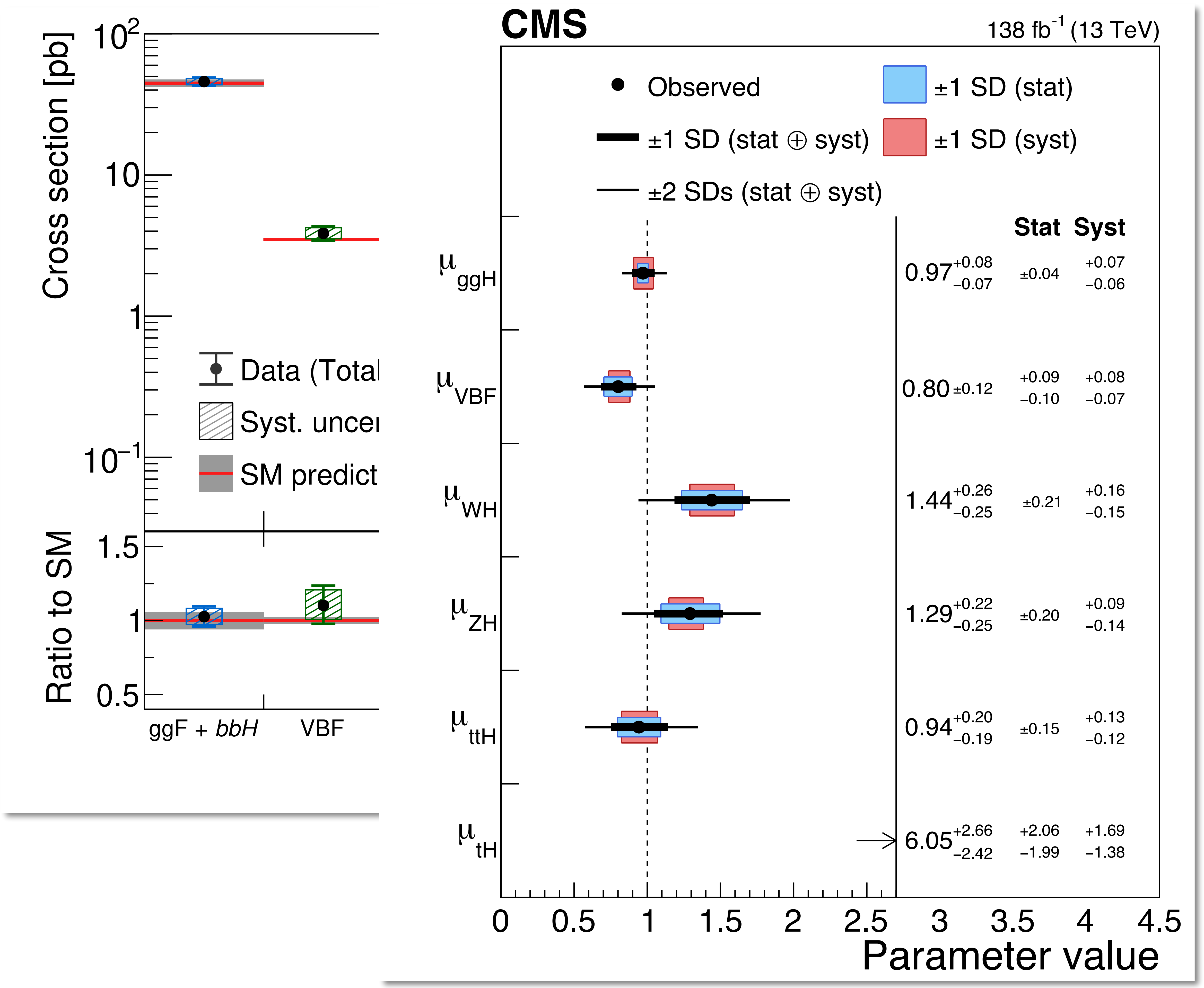
[Diagrams from Harlander LHCP 2023]

PRECISION WHERE? EVERYWHERE!

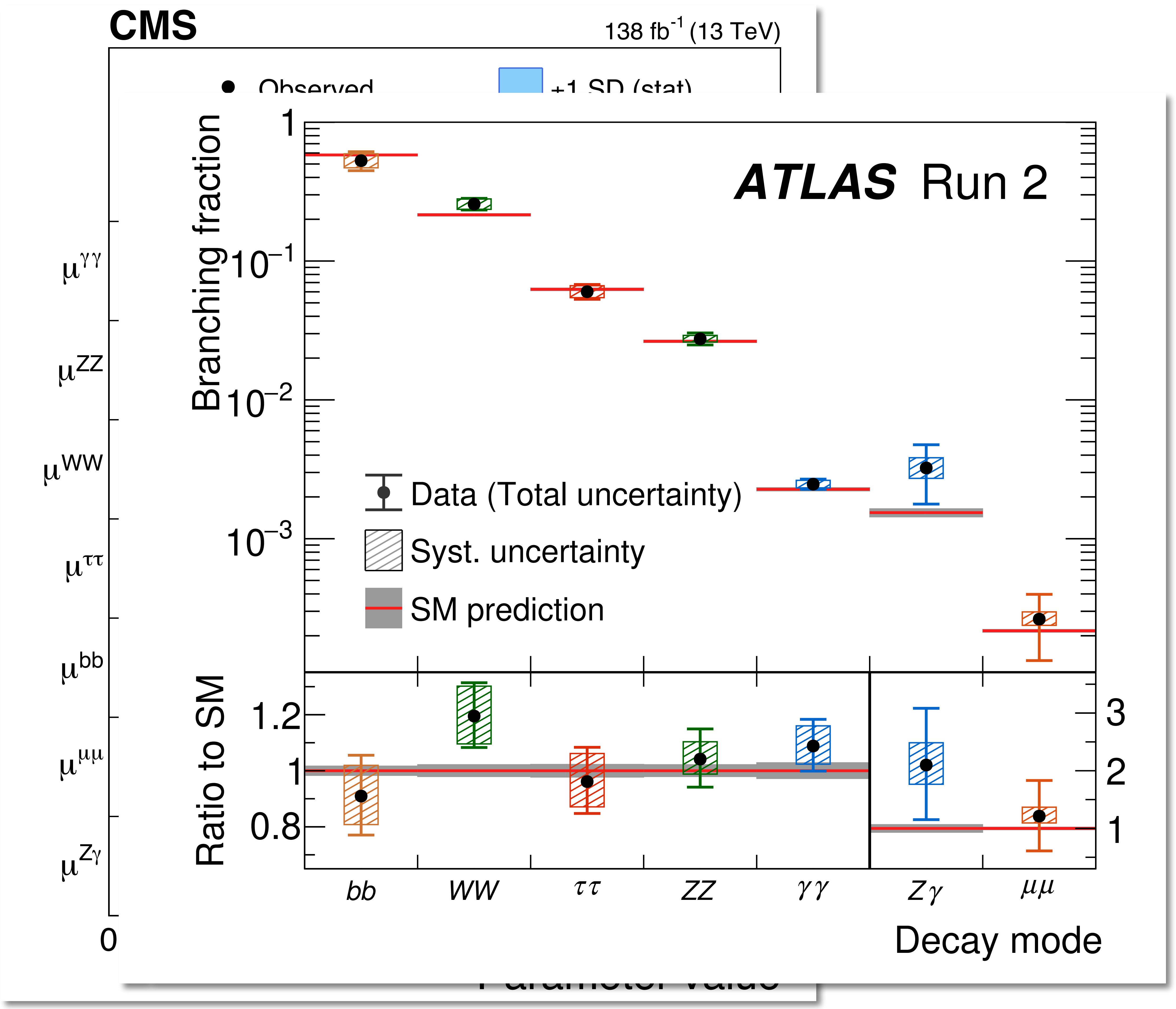


HIGGS PRODUCTION AND DECAYS EXPERIMENTAL ADVANCES

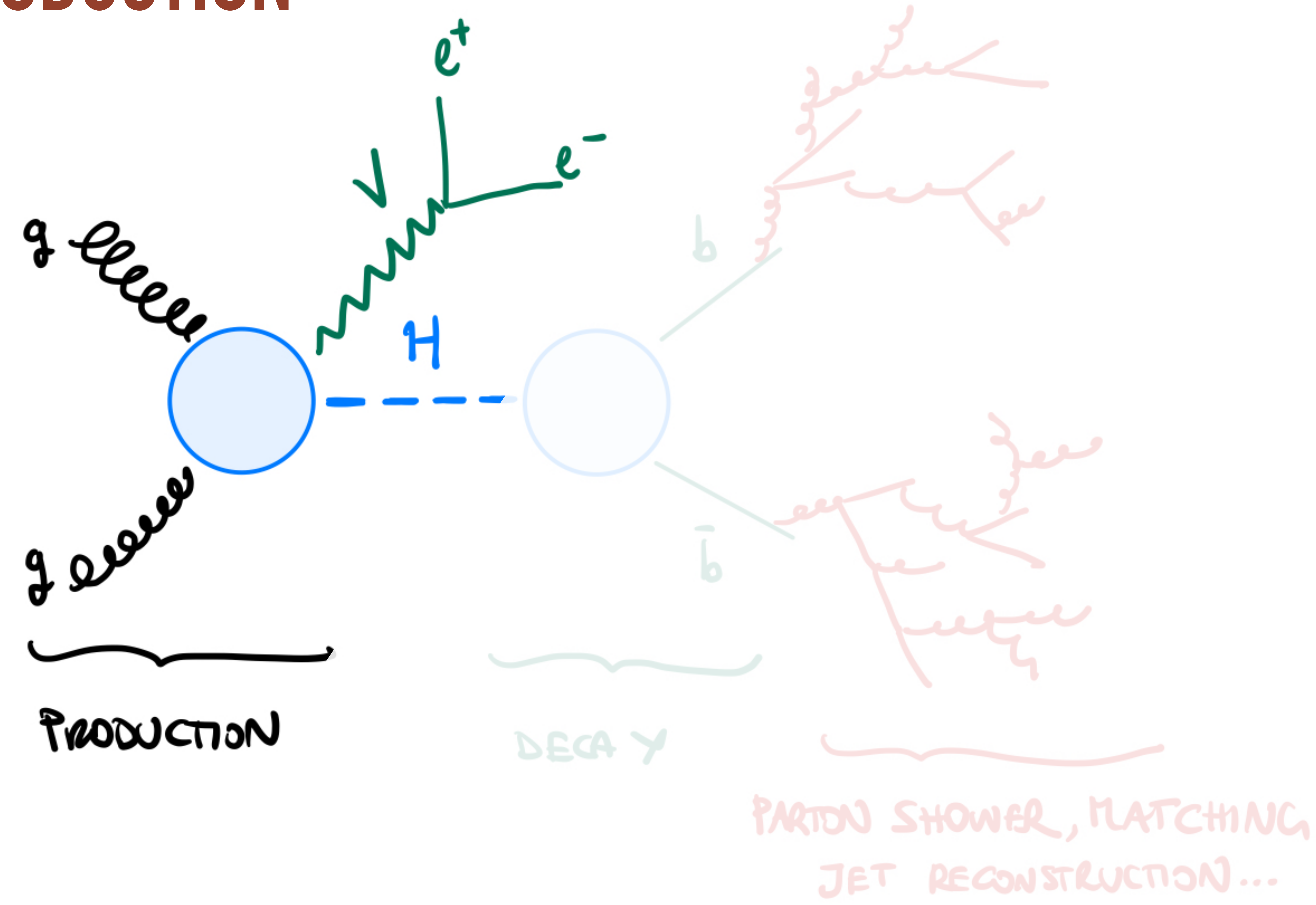
Production channels



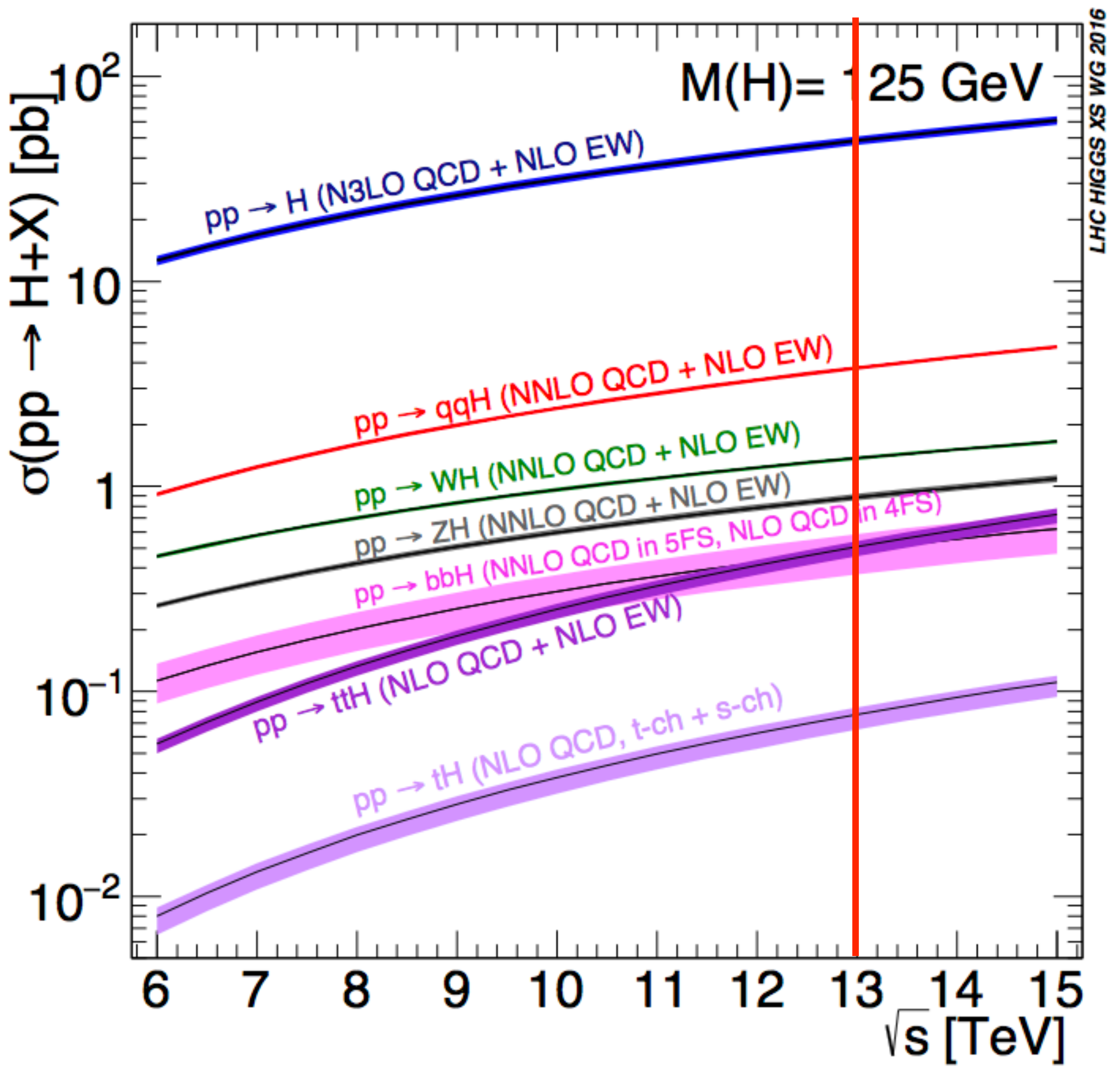
Decay channels



HIGGS PRODUCTION

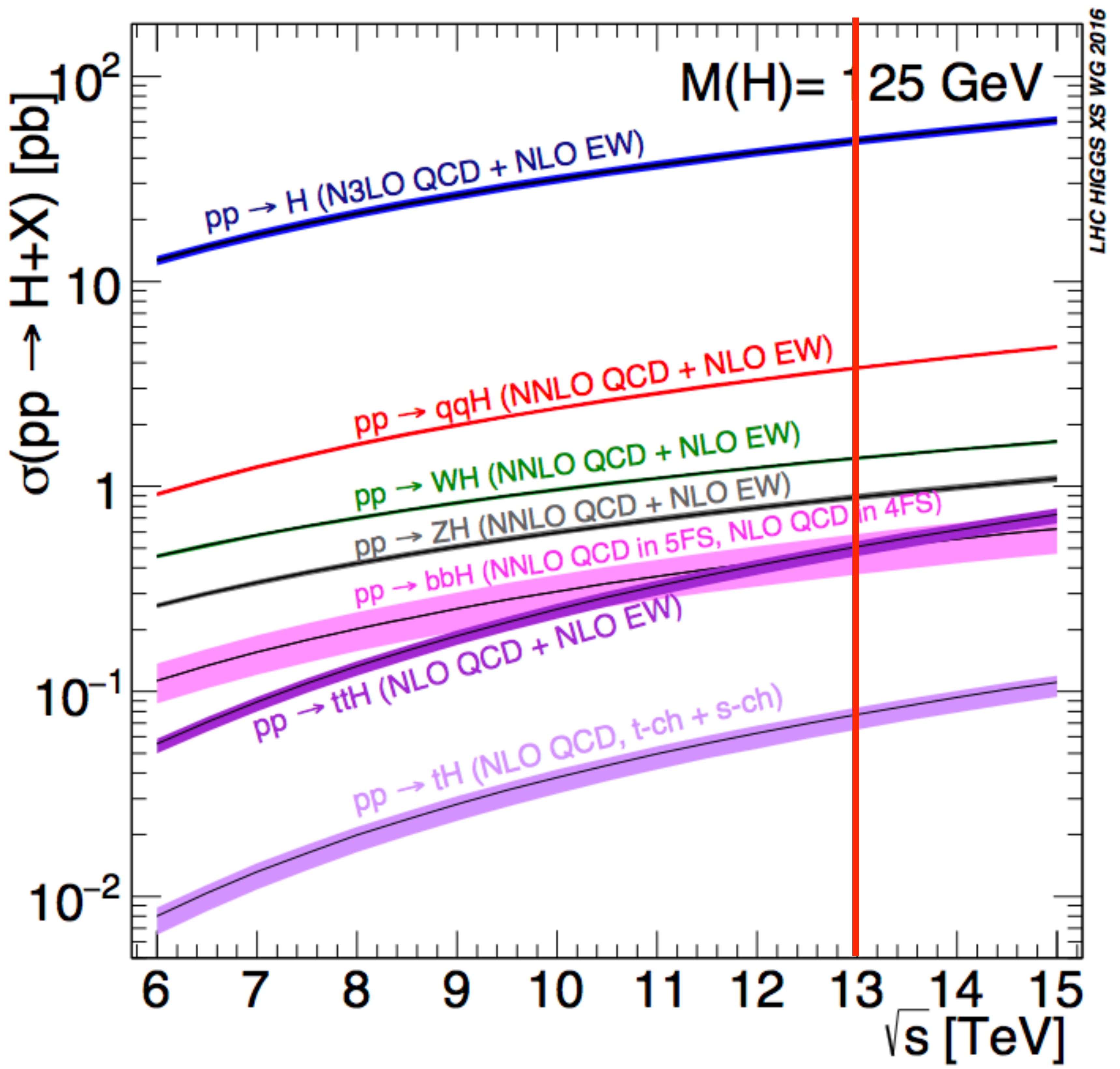


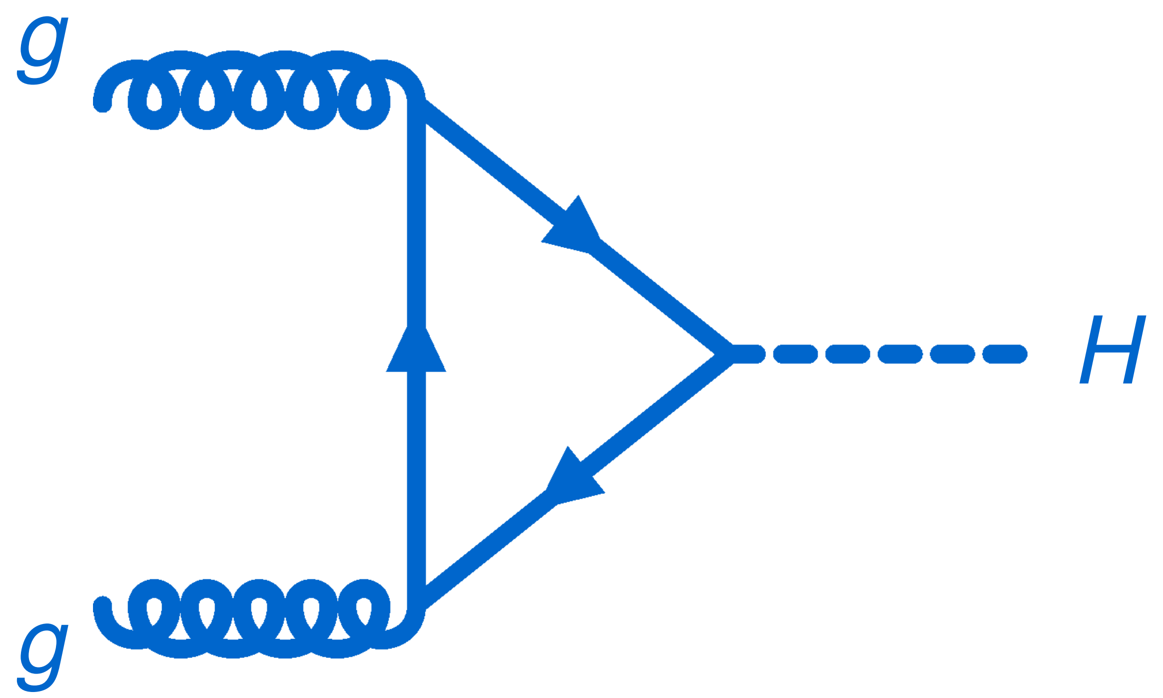
HIGGS PRODUCTION



$\sqrt{s}$ (TeV)	Production cross section (in pb) for $m_H = 125\,\text{GeV}$					
	ggF	VBF	WH	ZH	$t\bar{t}H$	total
13	$48.6^{+5\%}_{-5\%}$	$3.78^{+2\%}_{-2\%}$	$1.37^{+2\%}_{-2\%}$	$0.88^{+5\%}_{-5\%}$	$0.50^{+9\%}_{-13\%}$	55.1

HIGGS PRODUCTION: GLUON FUSION





$\sim 87\%$

ggF main focus

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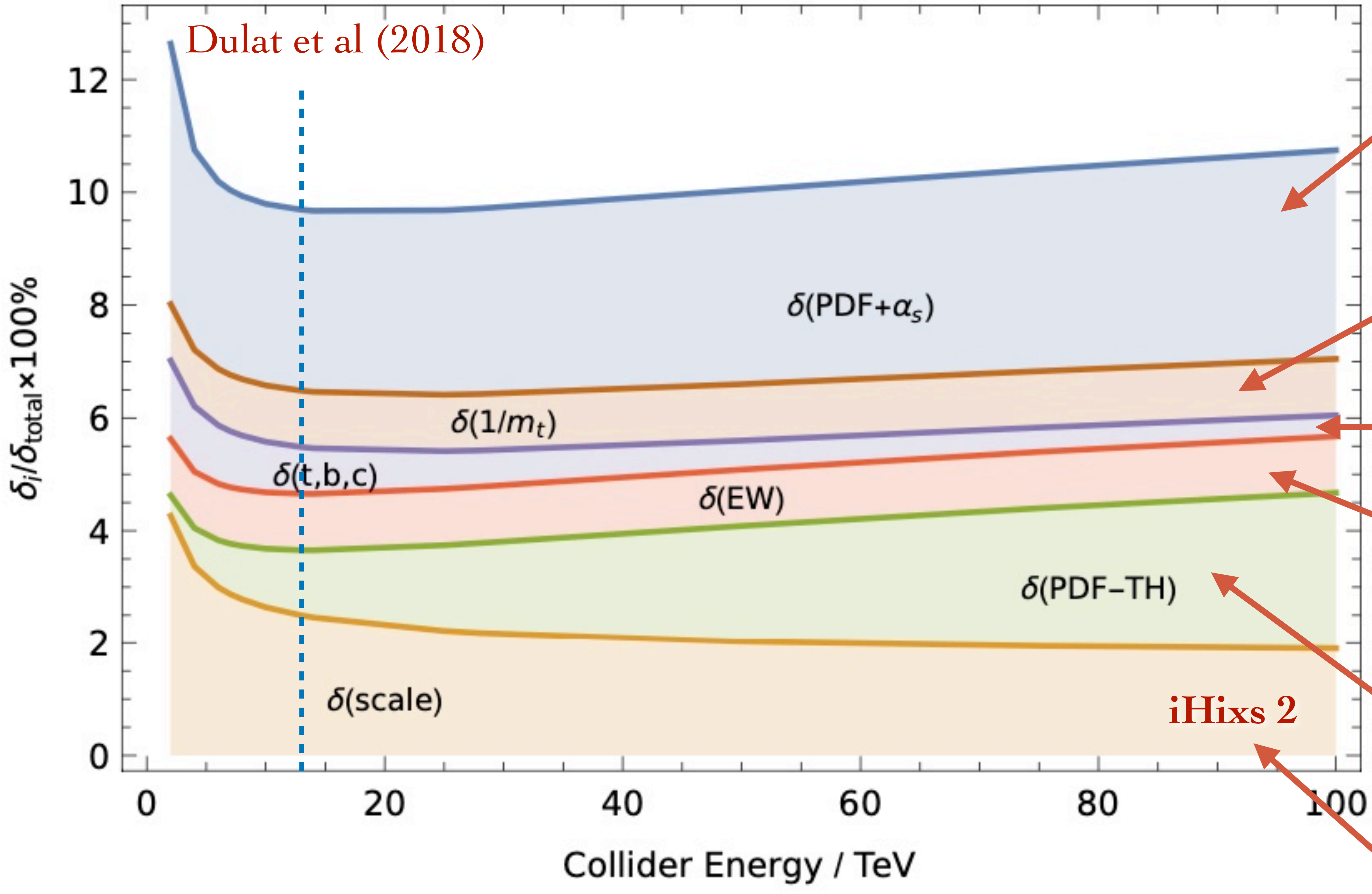
GLUON FUSION THEORY STATUS: UNCERTAINTY BUDGET 2018

[Dulat, Lazopoulos, Mistlberger 1802.00827]



$\alpha_s = 0.118 \pm 0.001 \to \mathcal{O}(2\%)$ uncertainty on x-section

Exact top mass dependence

Bottom mass contribution

QCD+EW mixed contributions

requires N^3LO PDFs

residual scale variation on N^3LO results

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

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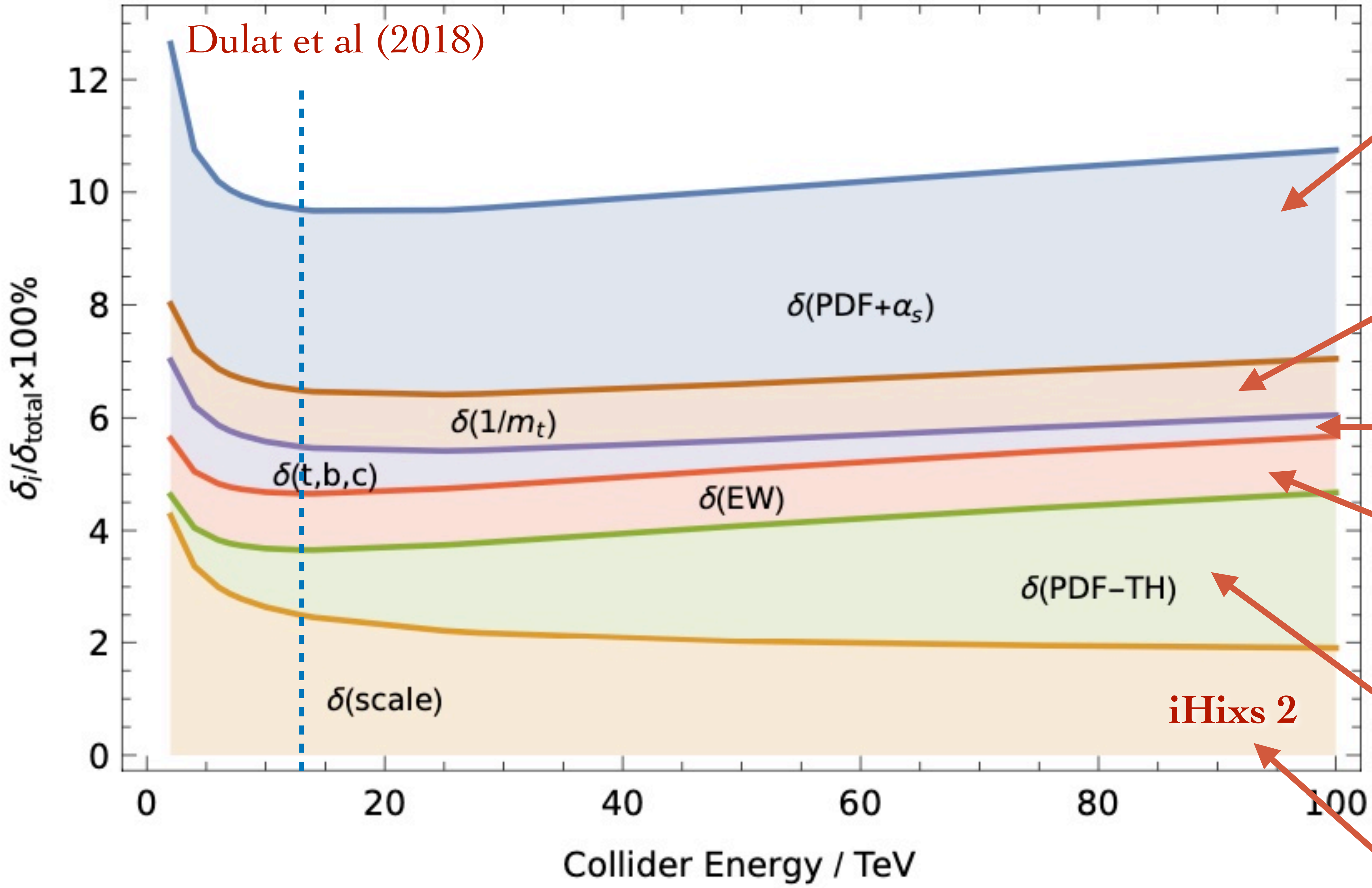

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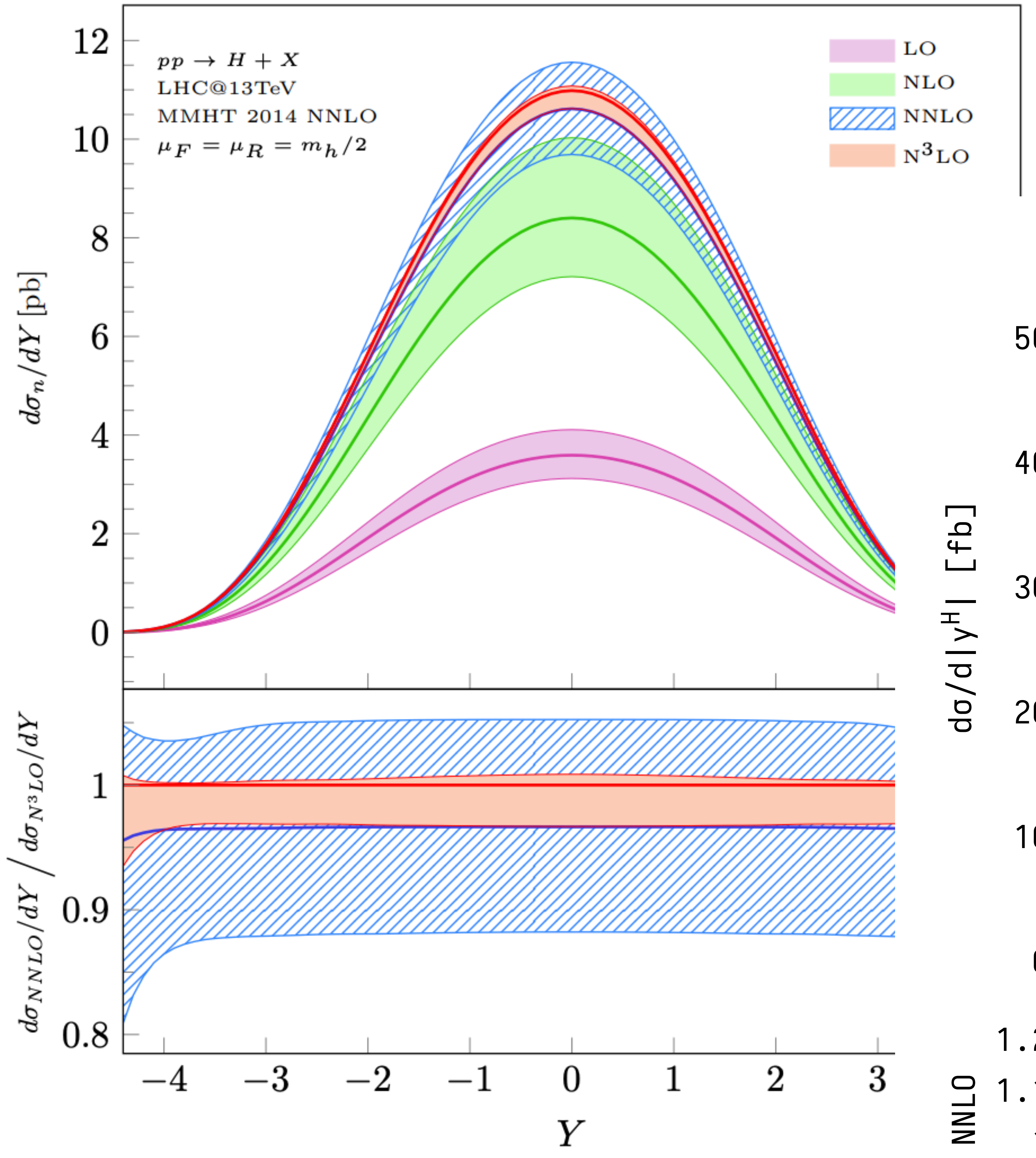
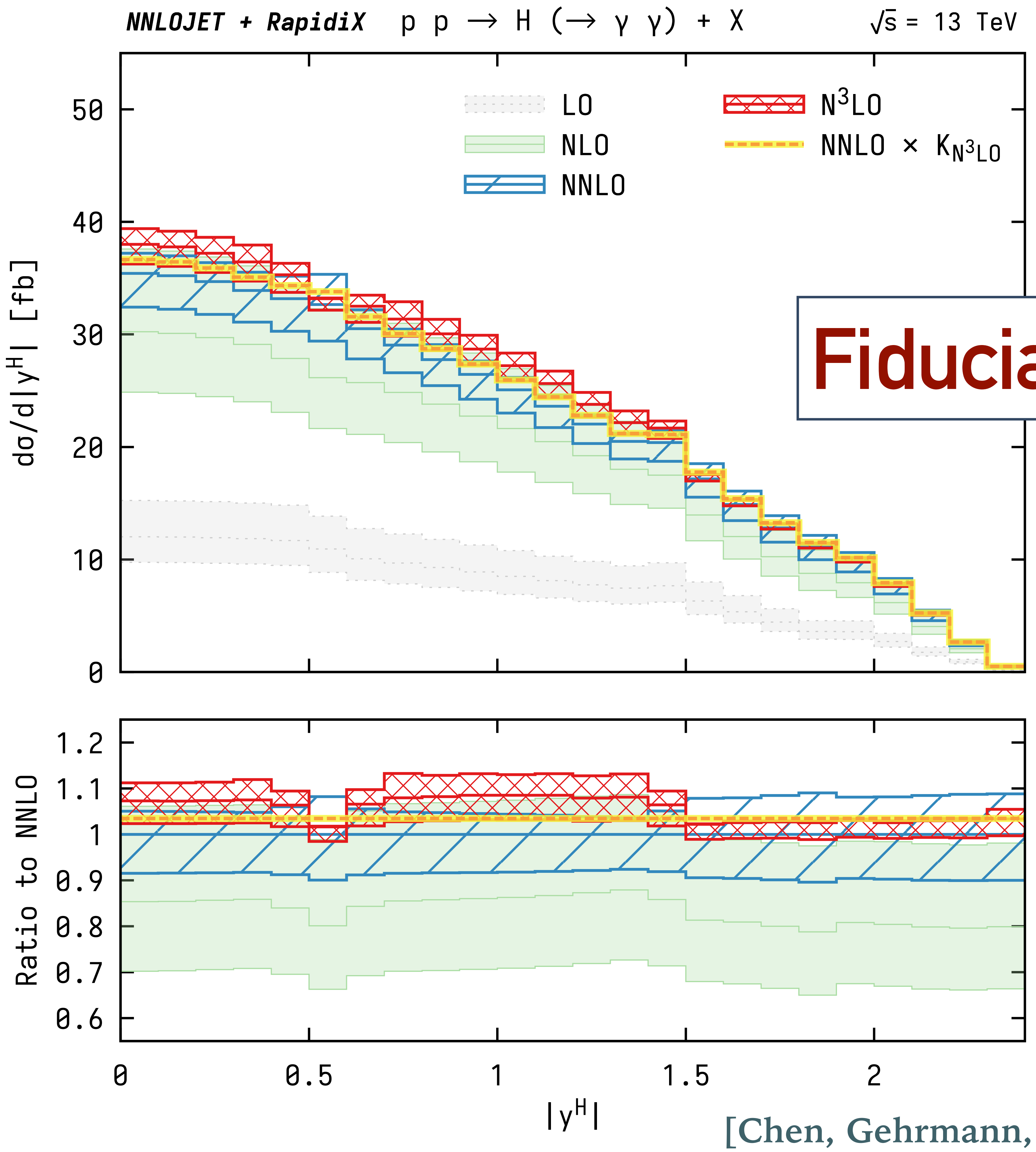
δ(scale)	δ(trunc)	δ(PDF-TH)	δ(EW)	$\delta(t, b, c)$	$\delta(1/m_t)$
$^{+0.10\text{ pb}}_{-1.15\text{ pb}}$	±0.18 pb	±0.56 pb	±0.49 pb	±0.40 pb	±0.49 pb
$^{+0.21\%}_{-2.37\%}$	$\pm0.37\%$	$\pm1.16\%$	$\pm1\%$	$\pm0.83\%$	$\pm1\%$

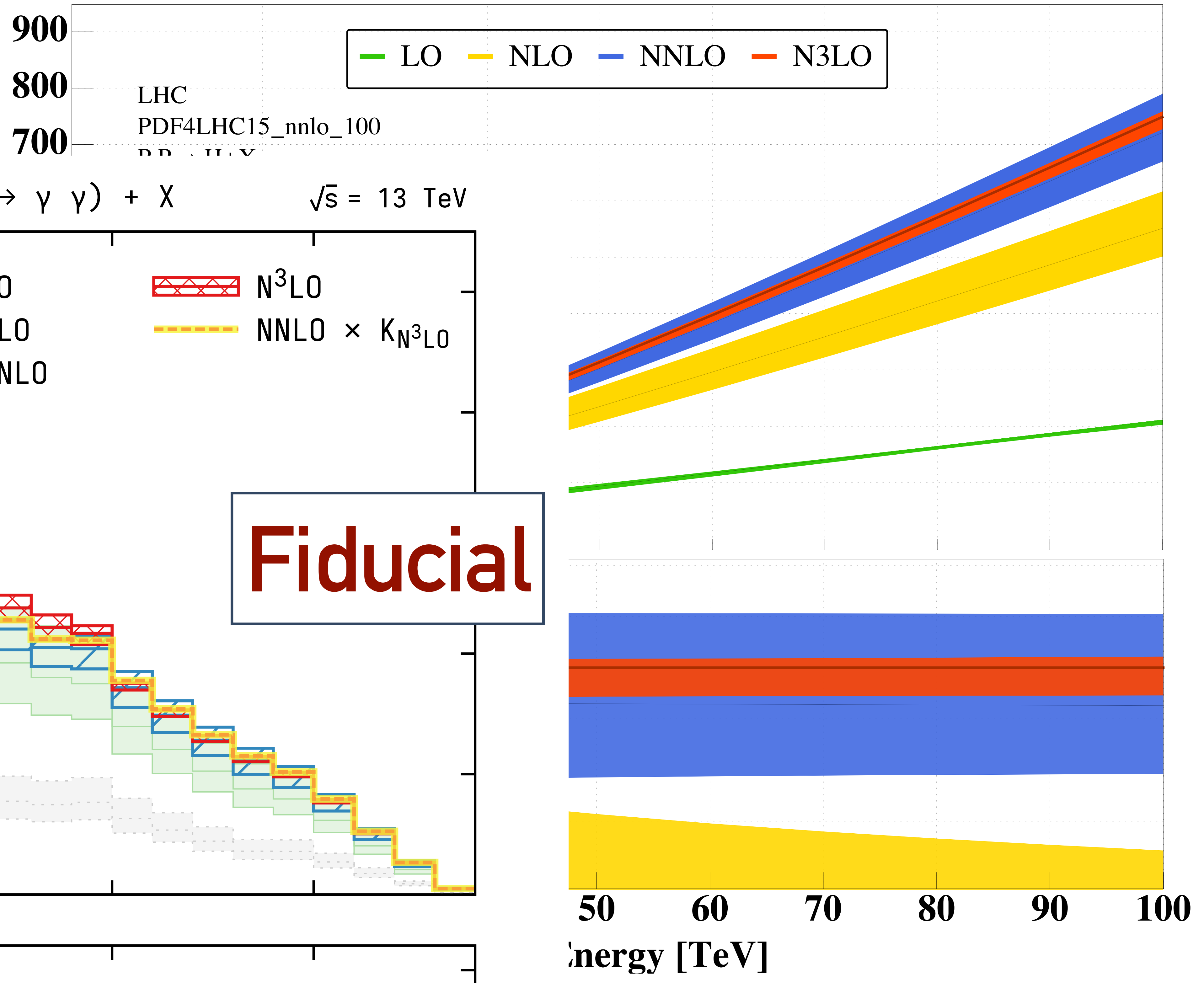
GLUON FUSION TO N3LO: INCLUSIVE AND FULLY DIFFERENTIAL IN HEFT



[Dulat, Mistlberger, Pelloni 2018]



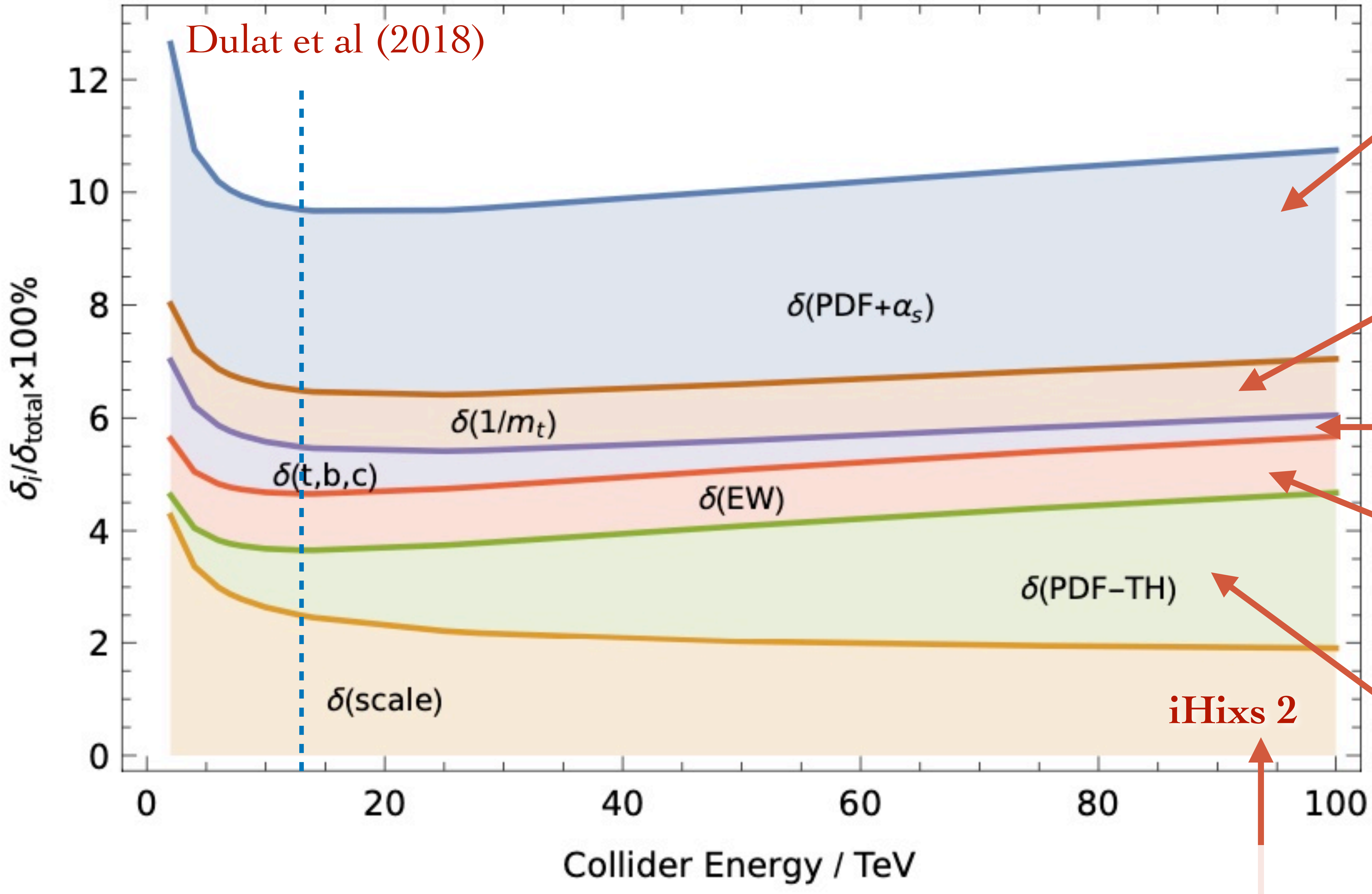
Fiducial



[Mistlberger 2018]
[Baglio, Duhr, Mistlberger, Szafron 2022]

[Chen, Gehrmann, Glover, Huss, Mistlberger, Pelloni 2102.07607]

GLUON FUSION: MASS EFFECTS (TOPS AND BOTTOMS)



[Dulat, Lazopoulos, Mistlberger 1802.00827]

$\alpha_s = 0.118 \pm 0.001 \rightarrow \mathcal{O}(2\%)$ uncertainty on x-section

Exact top mass dependence

[latest that have been lifted]

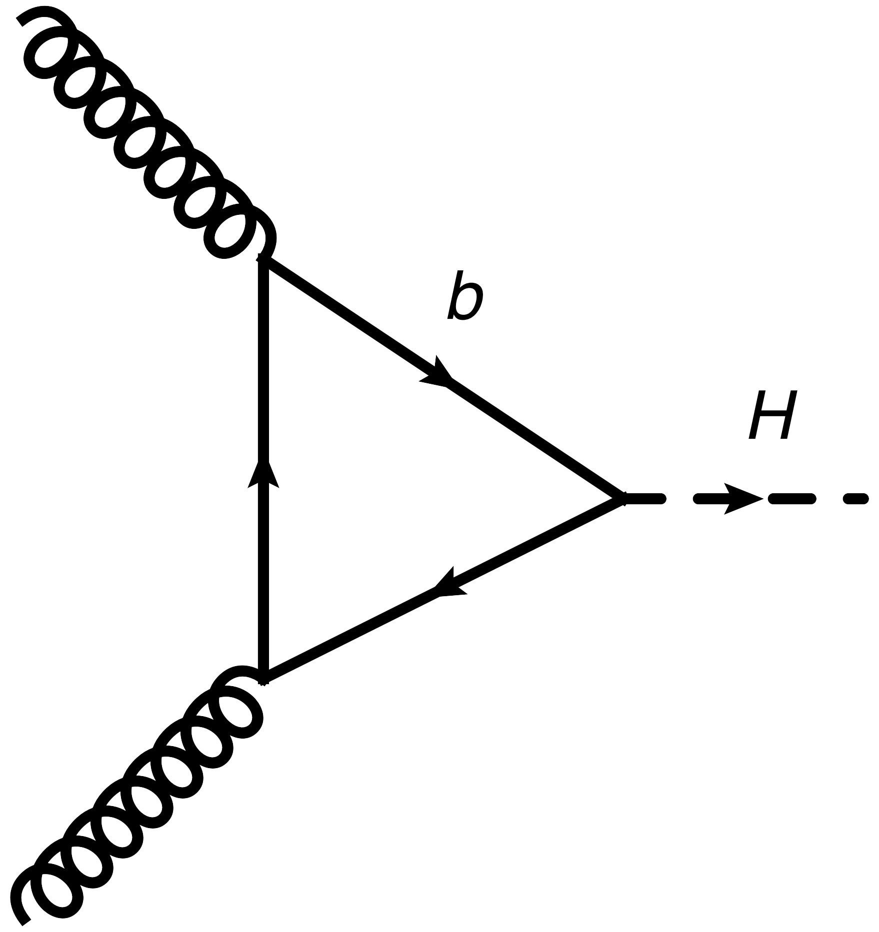
Bottom mass contribution

QCD+EW mixed contributions

requires N^{3}LO PDFs

residual scale variation on N^{3}LO results

BOTTOM MASS EFFECTS: TOP-BOTTOM INTERFERENCE INCLUSIVE



$$\sim -\frac{3}{2}\frac{m_b^2}{m_H^2}\ln^2\frac{m_H^2}{m_b^2}\,\mathcal{M}^t_{gg\to H}$$

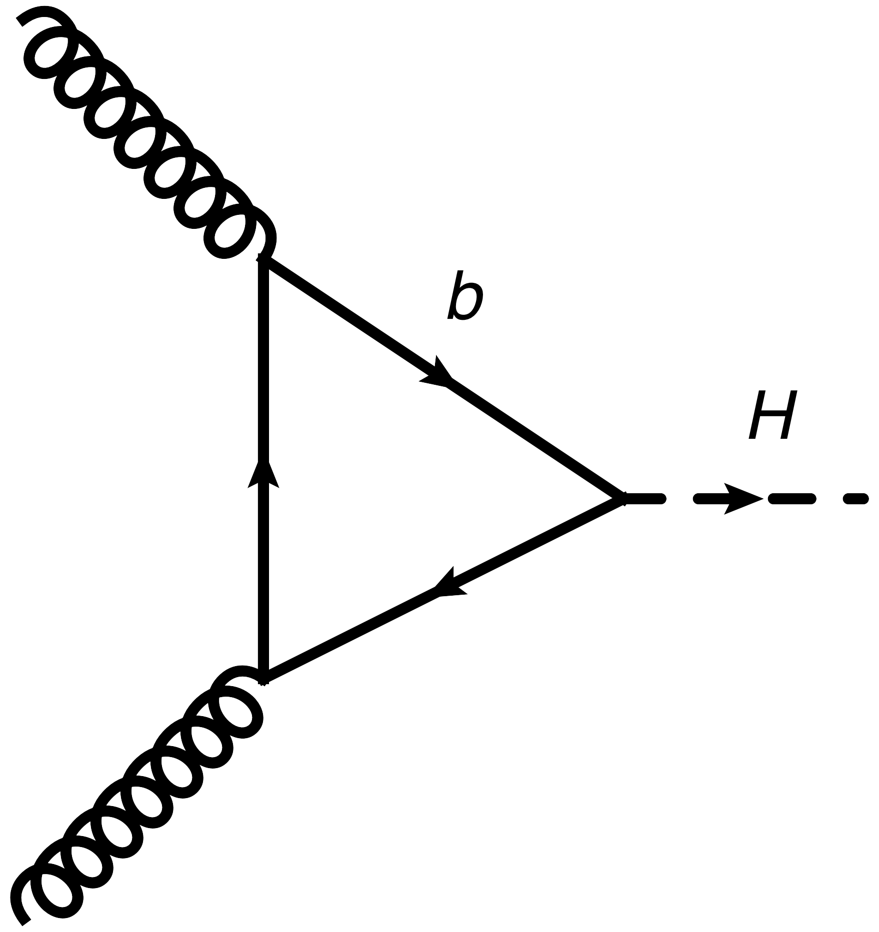
effect of (NL) logarithms at threshold estimated by [Penin, Melnikov ’16; Liu Penin ’17,’18; Anastasiou, Penin ’20]

	LO	NLO	NNLO	N^{3}LO
$\delta\sigma^{\rm LL}_{pp\to H+X}$	-1.420	-1.640	-1.667	-1.670
$\delta\sigma^{\rm NLL}_{pp\to H+X}$	-1.420	-2.048	-2.183	-2.204
$\delta\sigma_{pp\to H+X}$	-1.023	-2.000		

[Anastasiou, Penin 2004.03602]

approx $\delta\sigma^{\rm NNLO}_{pp\to H+X} = -2.18 \pm 0.20\ pb$

BOTTOM MASS EFFECTS: TOP-BOTTOM INTERFERENCE INCLUSIVE



$$\sim -\frac{3}{2}\frac{m_b^2}{m_H^2}\ \ln^2\frac{m_H^2}{m_b^2}\ \mathcal{M}^t_{gg\to H}$$

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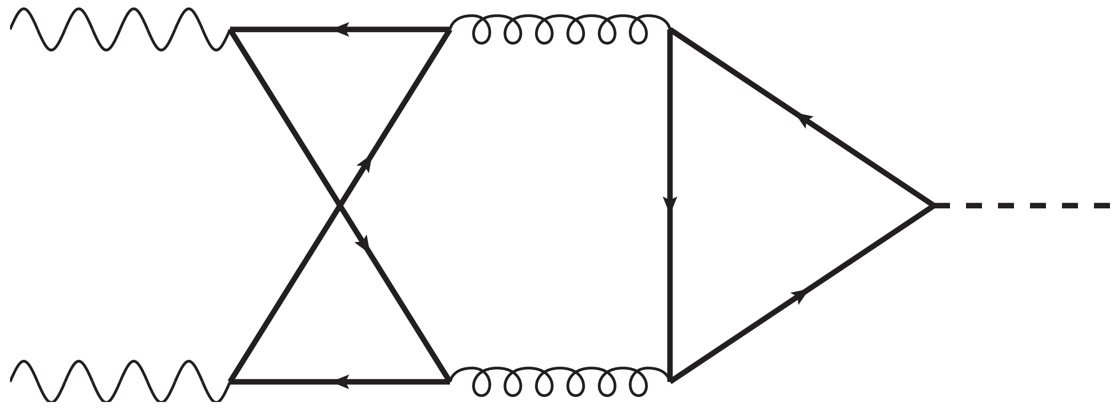
$\delta\sigma_{pp\to H+X}$	-1.023	-2.000	**-1.990**	

[Anastasiou, Penin 2004.03602]

approx $\delta\sigma^{NNLO}_{pp\to H+X} = -2.18 \pm 0.20\ pb$

full $\delta\sigma^{NNLO}_{pp\to H+X} = -1.99^{+0.30}_{-0.15}\ pb$

compatible within errors!

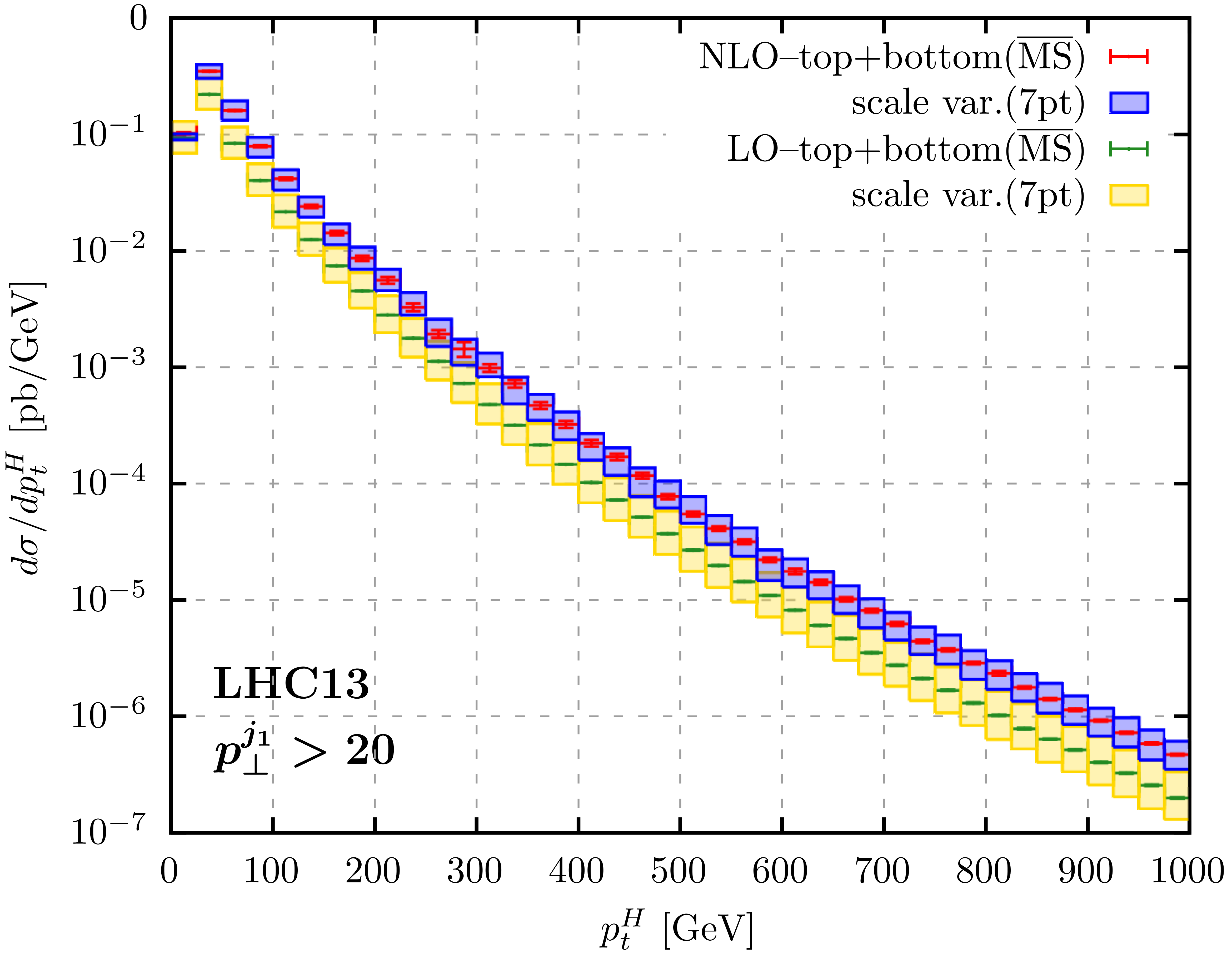


Exact calculation by [Czakon, Eschment, Niggetiedt, Poncelet, Schellenberger 2312.09896]

See also talk by M. Niggetiedt

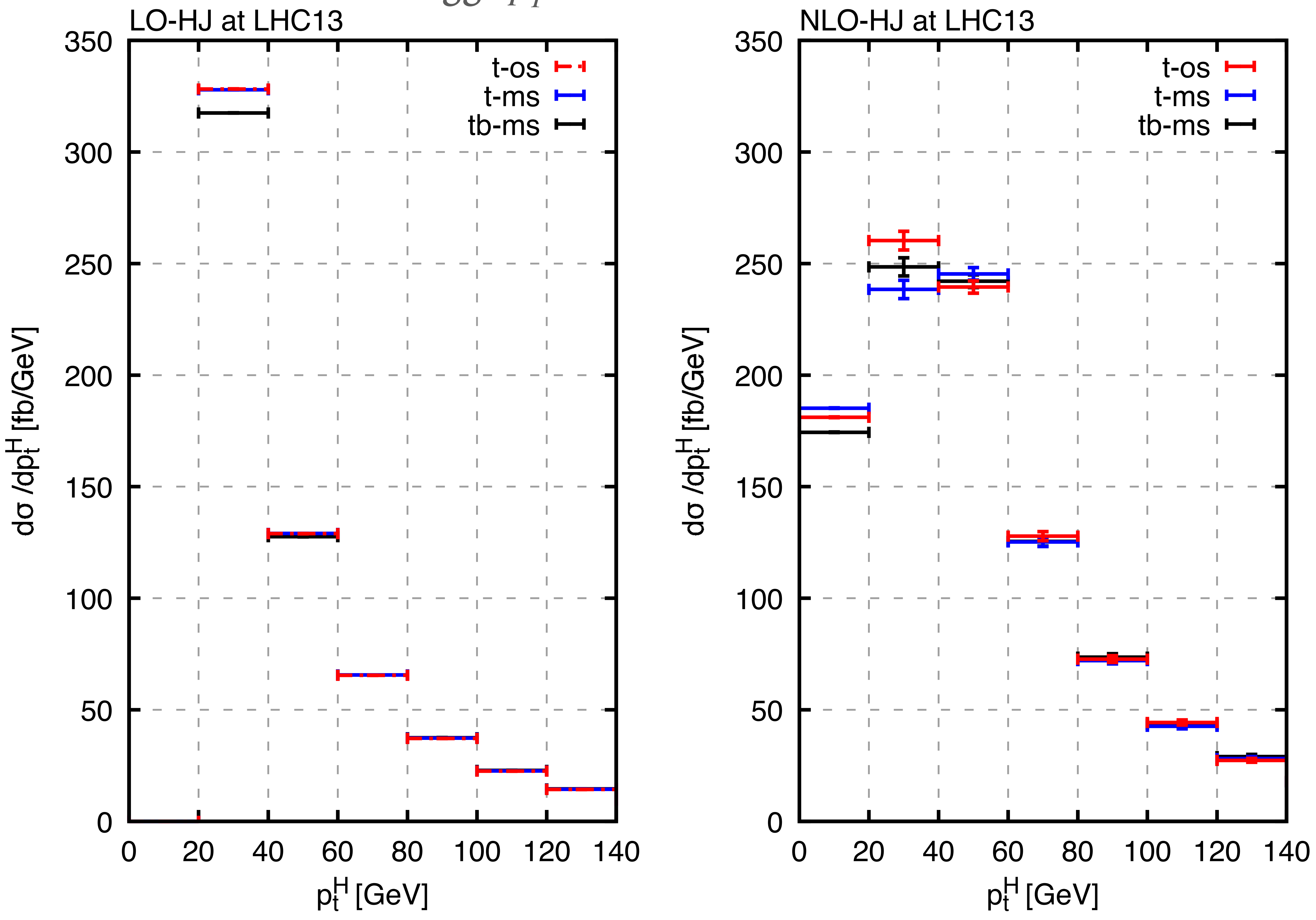
INTERFERENCE EFFECTS: DIFFERENTIAL IN PT @ NLO

Higgs p_T distribution with top and bottom



[Bonciani et al 2206.10490]

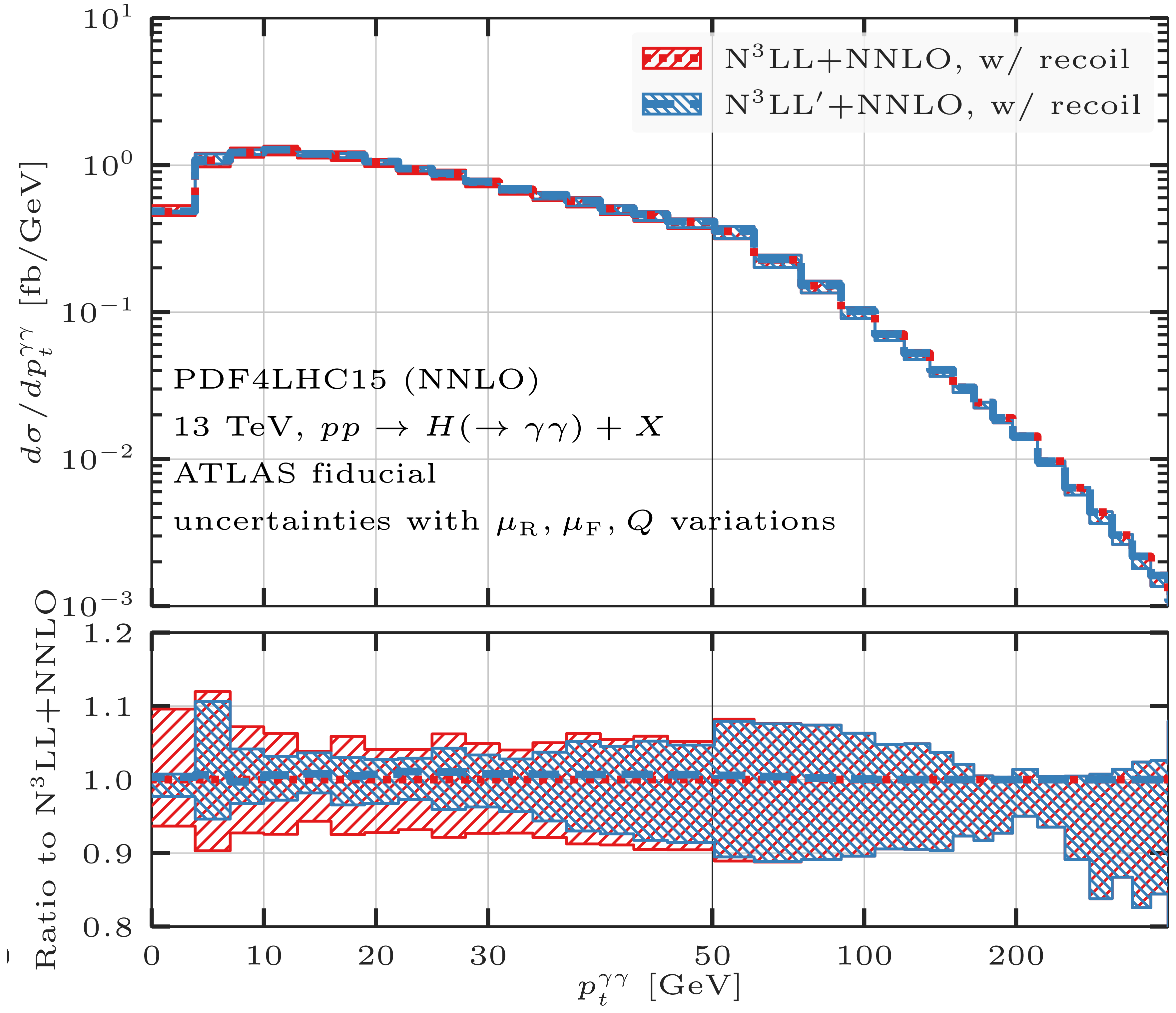
Higgs p_T distribution at LO & NLO



“ We find that within the scale uncertainty the LO contribution of the bottom quark, and thus of the top-bottom interference, to the Higgs boson production is almost erased at inclusive level by the NLO corrections. On the other hand, at the low end of the p_T distribution, the interference induces a non trivial change of shape. ”

OTHER EFFECTS ON PT SPECTRUM

Low p_T under control to N^{3}LL

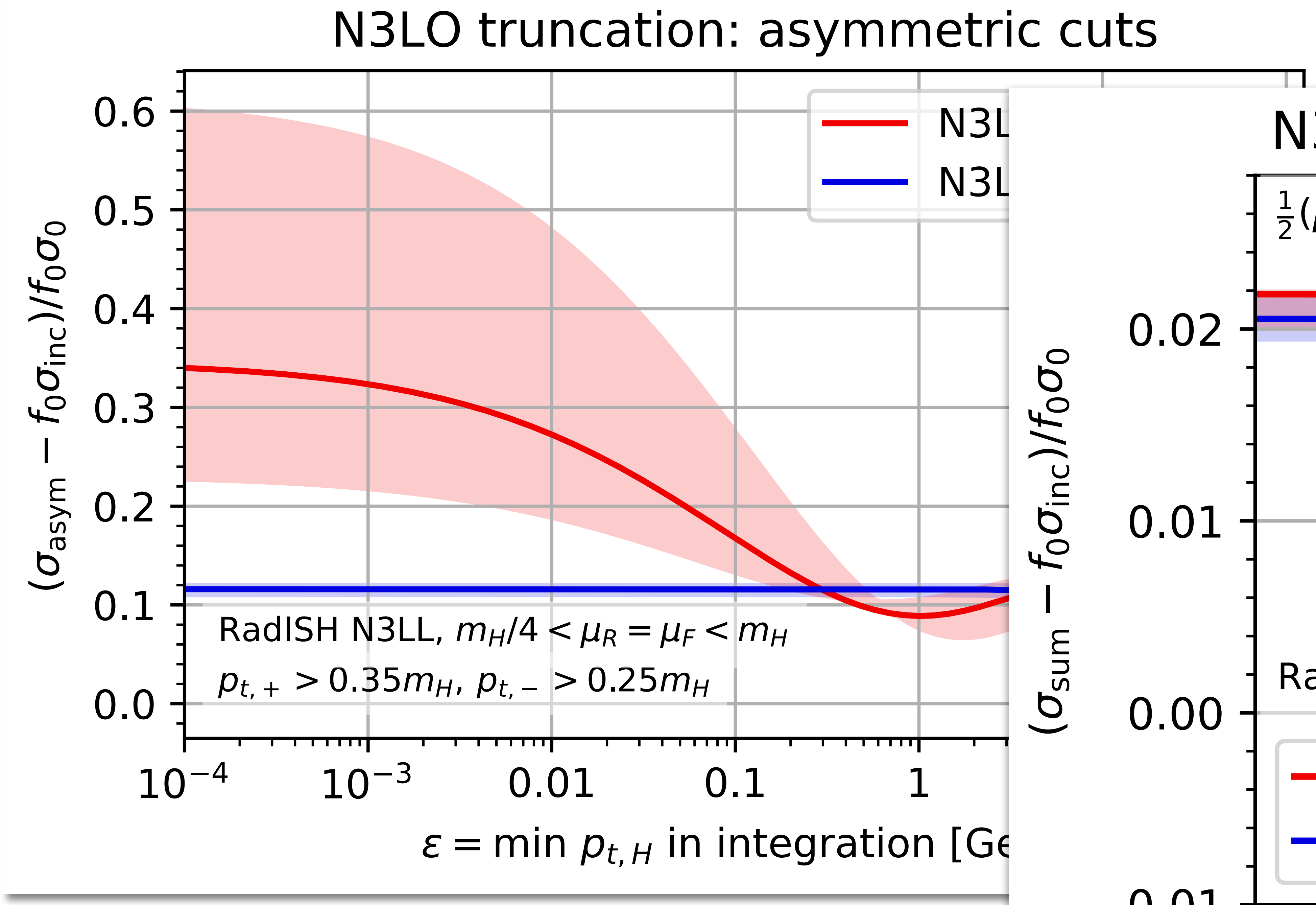


[Re, Rottoli, Torrielli 2104.07509]

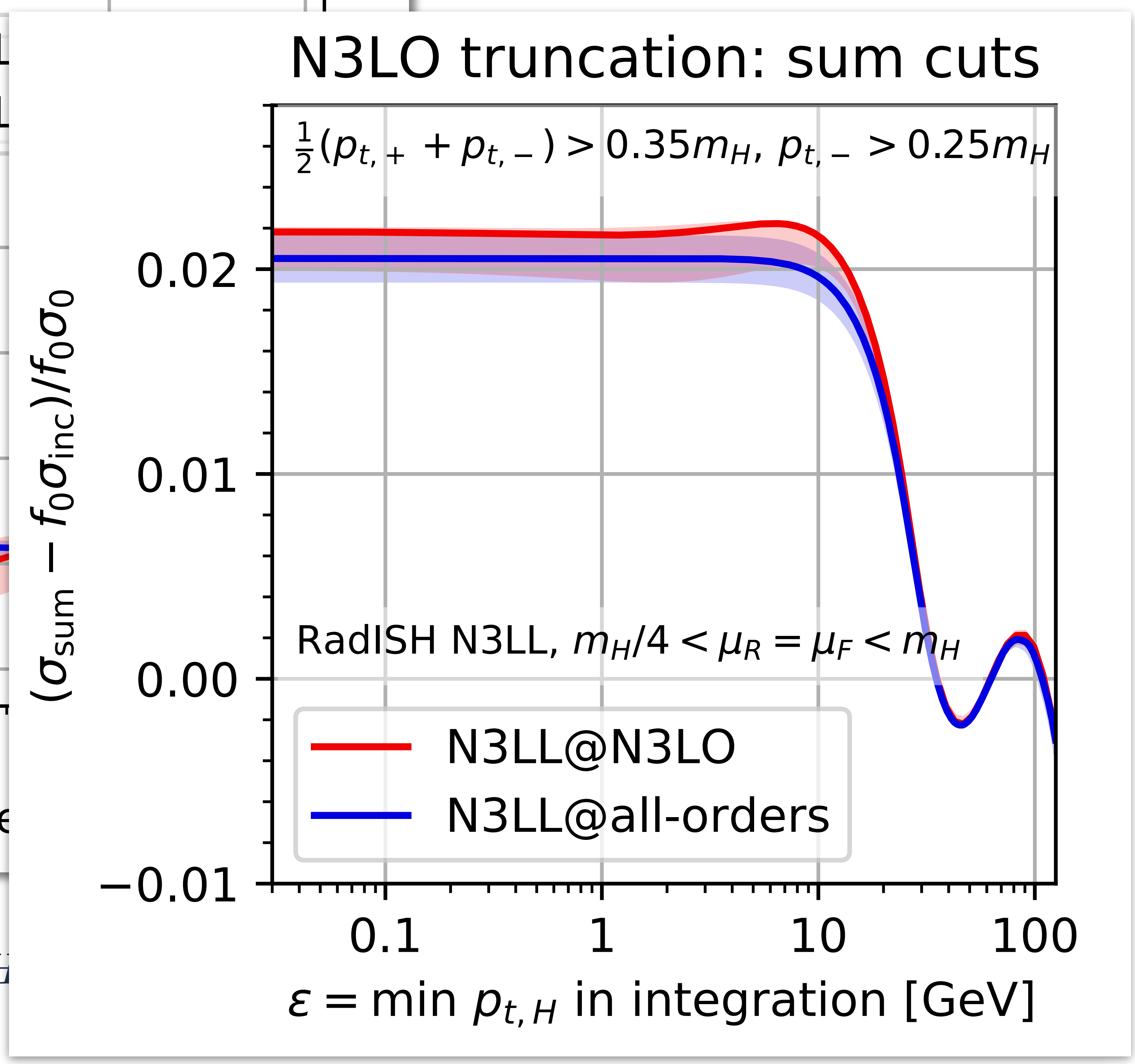
Fixed order calculation suffers of large **spurious effects** when looking at fiducial cuts!

→ ATLAS/CMS cuts **induce IR sensitivity**

New cuts with low IR sensitivity [Salam, Slade 2106.08329]



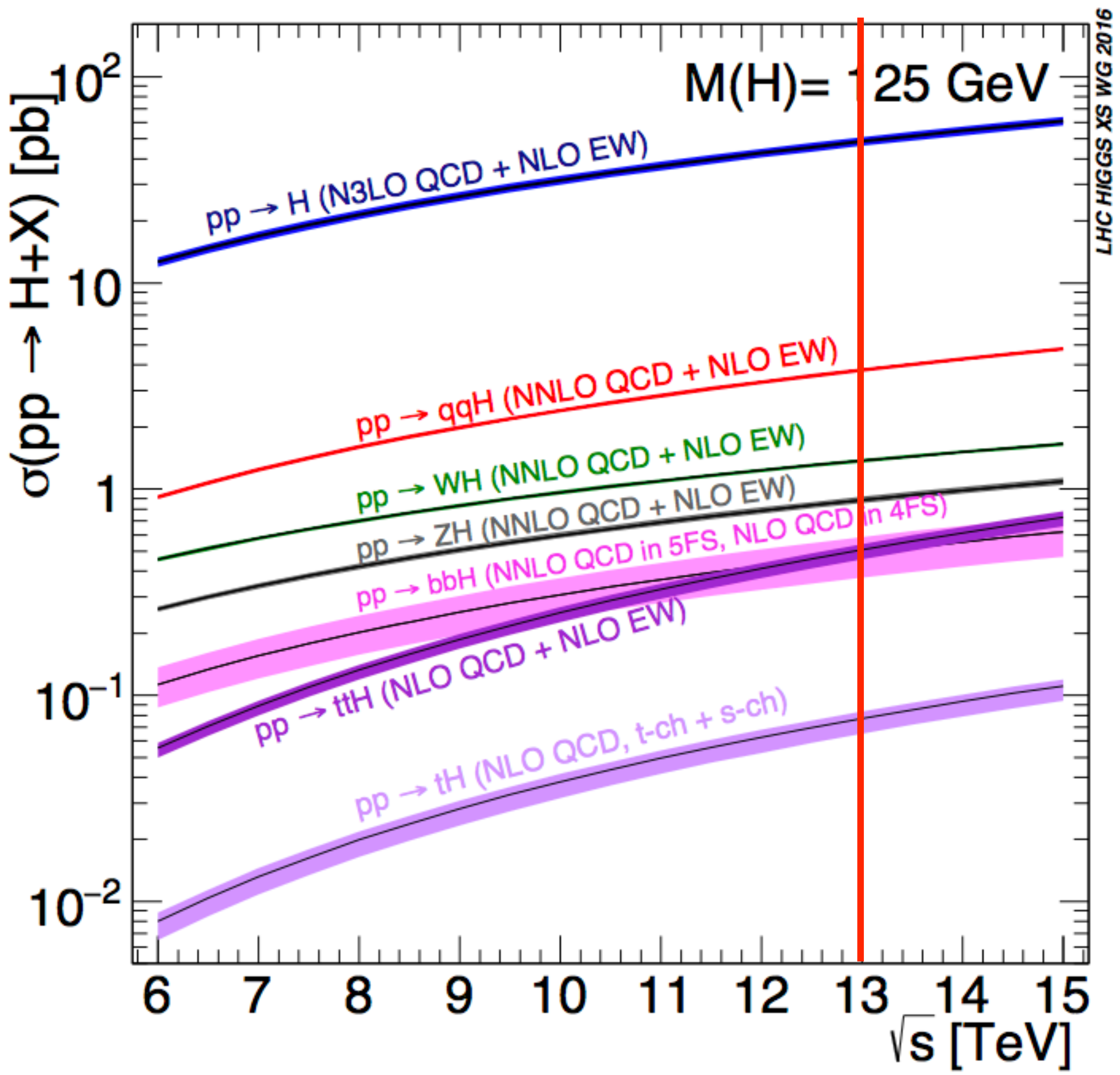
$p_{t,1} > 0.35 m_H, p_{t,2} > 0.25 m_H$

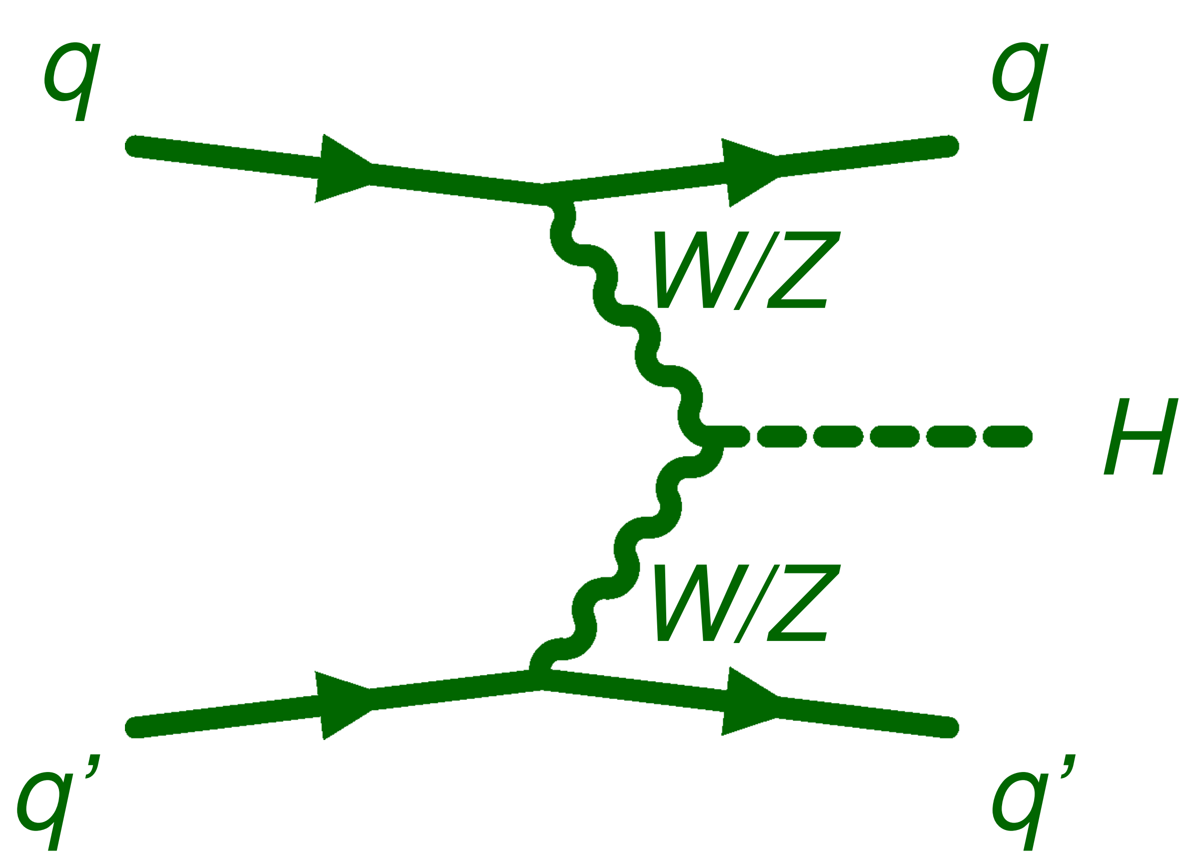


$p_{t,2} > 0.25 m_H, \frac{p_{t,1} + p_{t,2}}{2} > 0.35 m_H$

Also for $bb \to H$ [Cal, Kuk, Lim, Tackmann 2306.16458]

HIGGS PRODUCTION: VECTOR BOSON FUSION





$\sim 7\%$

Second largest channel

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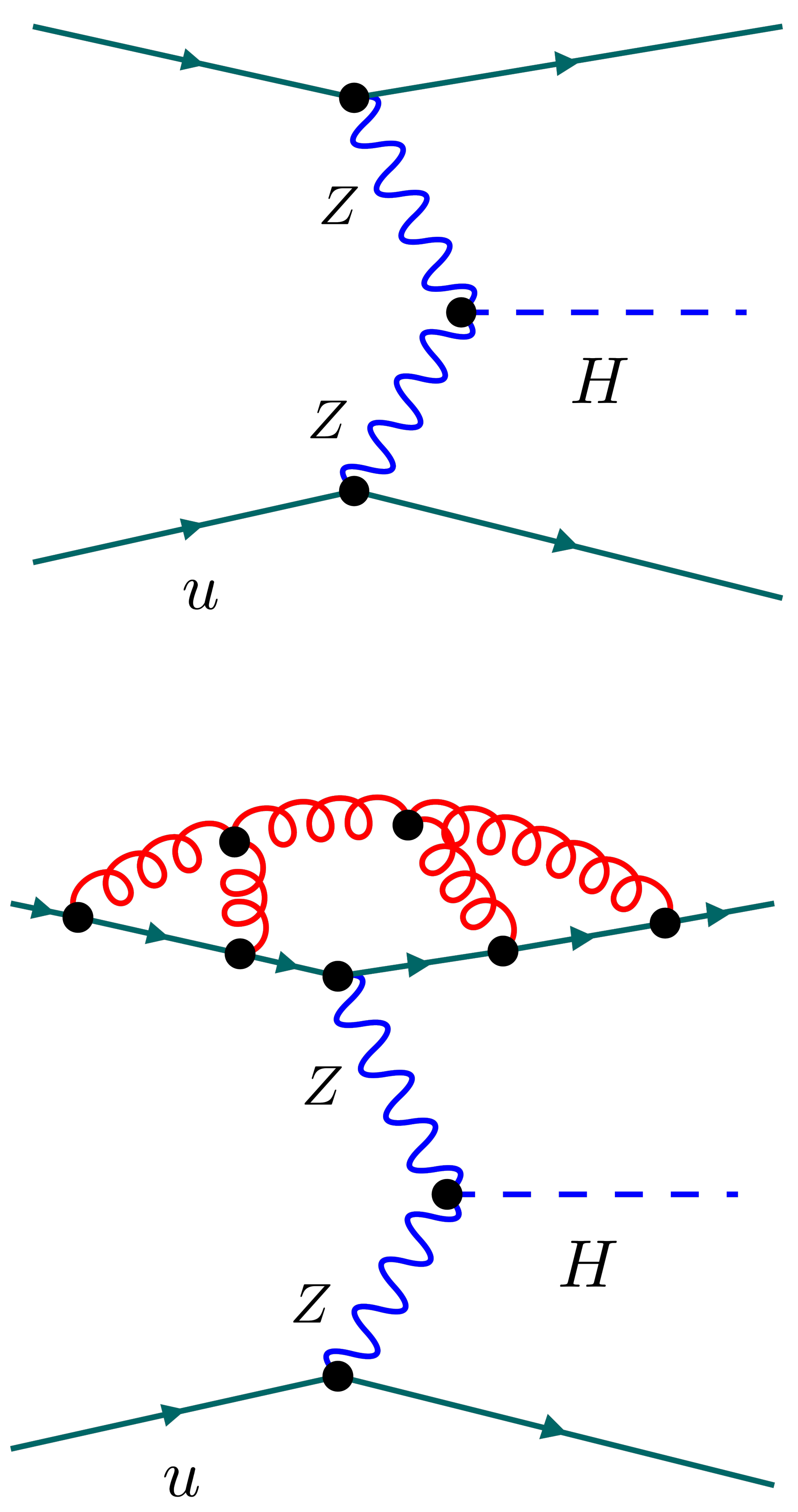
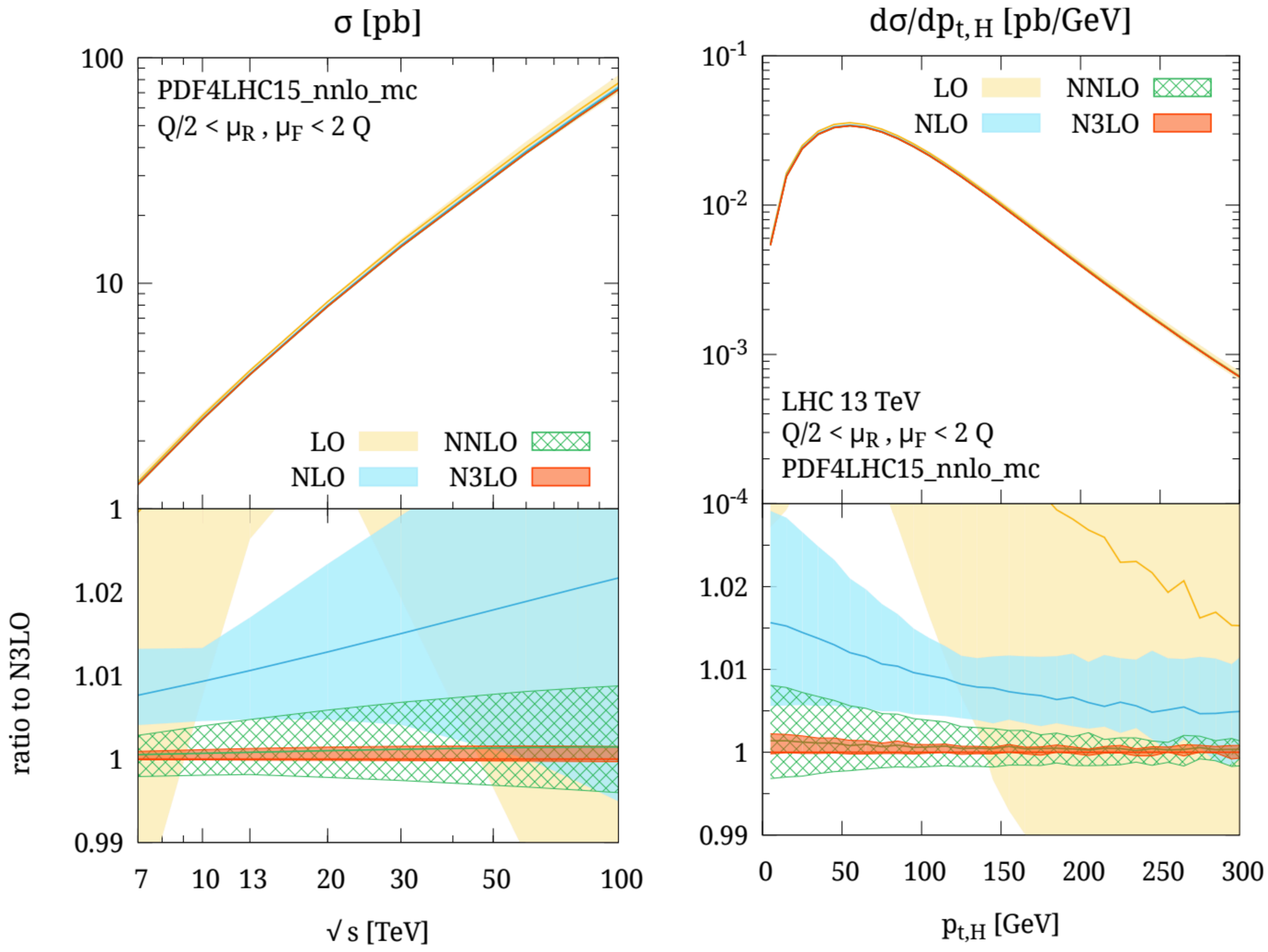
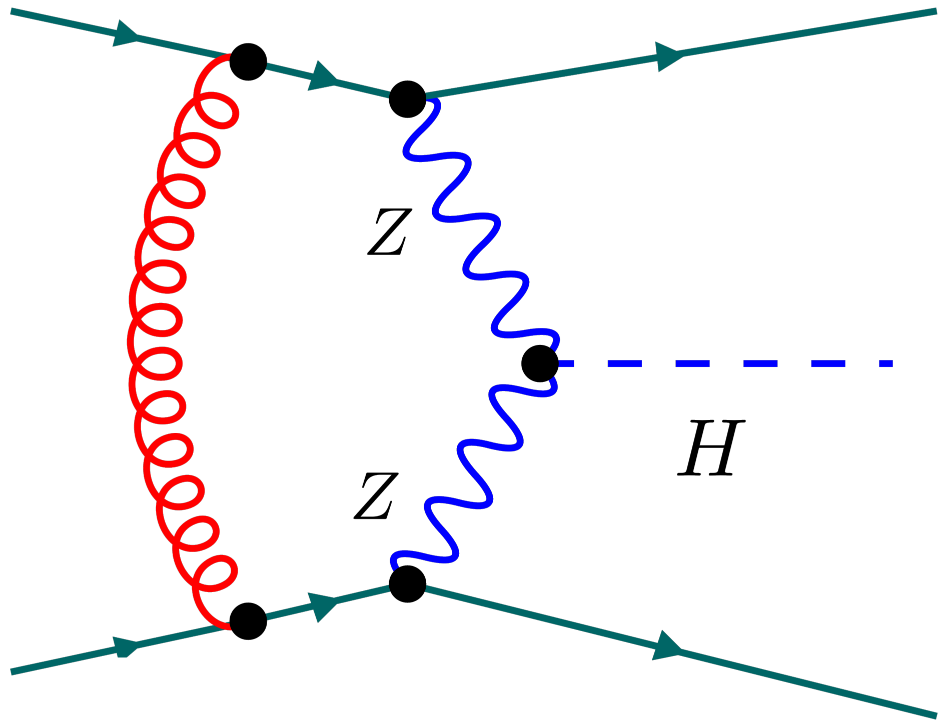
VECTOR BOSON FUSION: FACTORISABLE CORRECTIONS



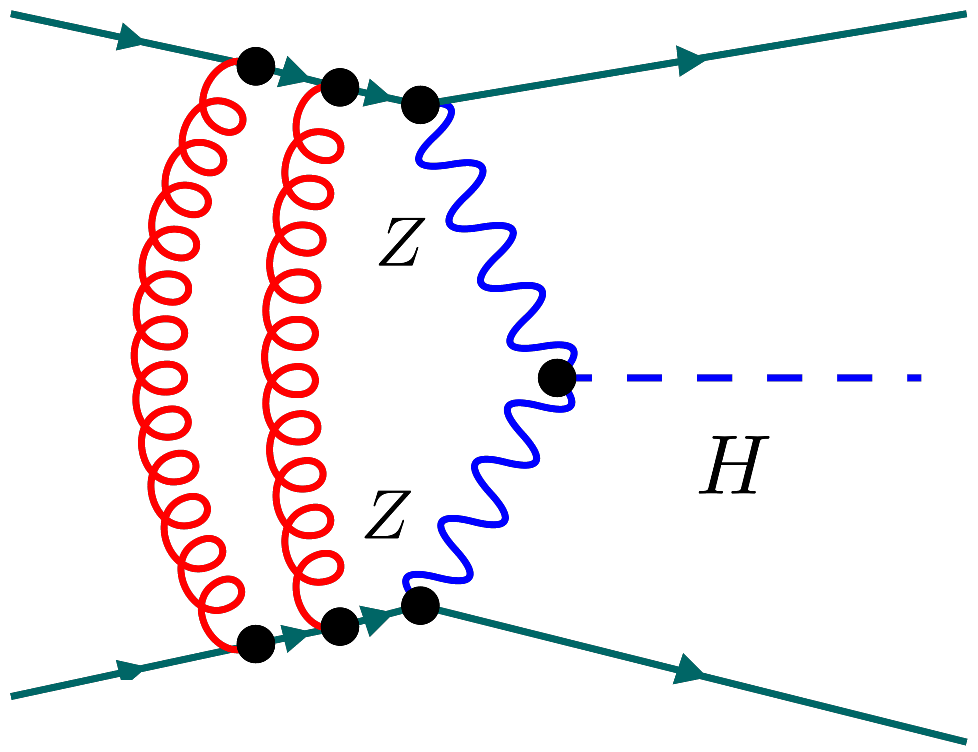


Factorisable corrections known to N^3LO through projection to Born method [Dreyer, Karlberg 1606.00840]

VECTOR BOSON FUSION: NON-FACTORISABLE VS FACTORISABLE



~ 0 @ **NLO due to color**



Up to NNLO gluons have to be color singlet → **color-suppressed**

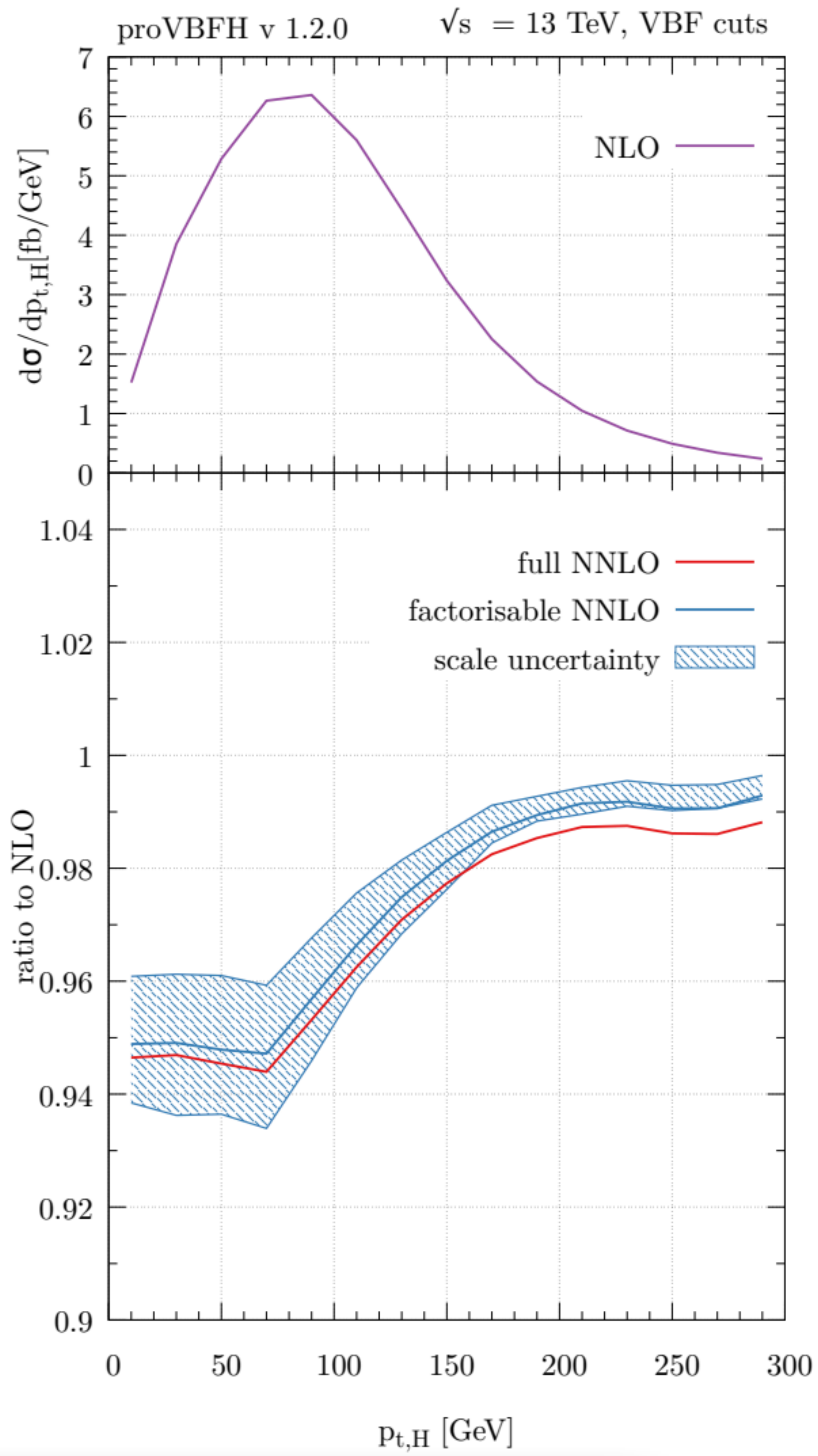
Complicated radiative corrections

Enhanced by **Coulomb phase**

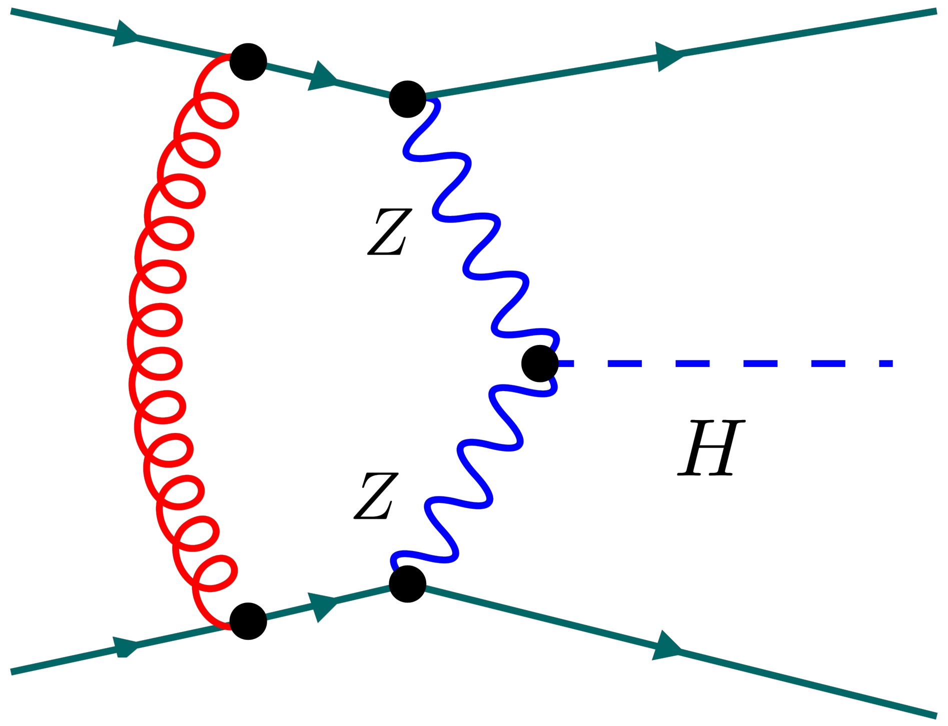
Enhancement estimated in eikonal approximation

[Liu et al. 1906.10899] [Dreyer et al. 2005.11334]

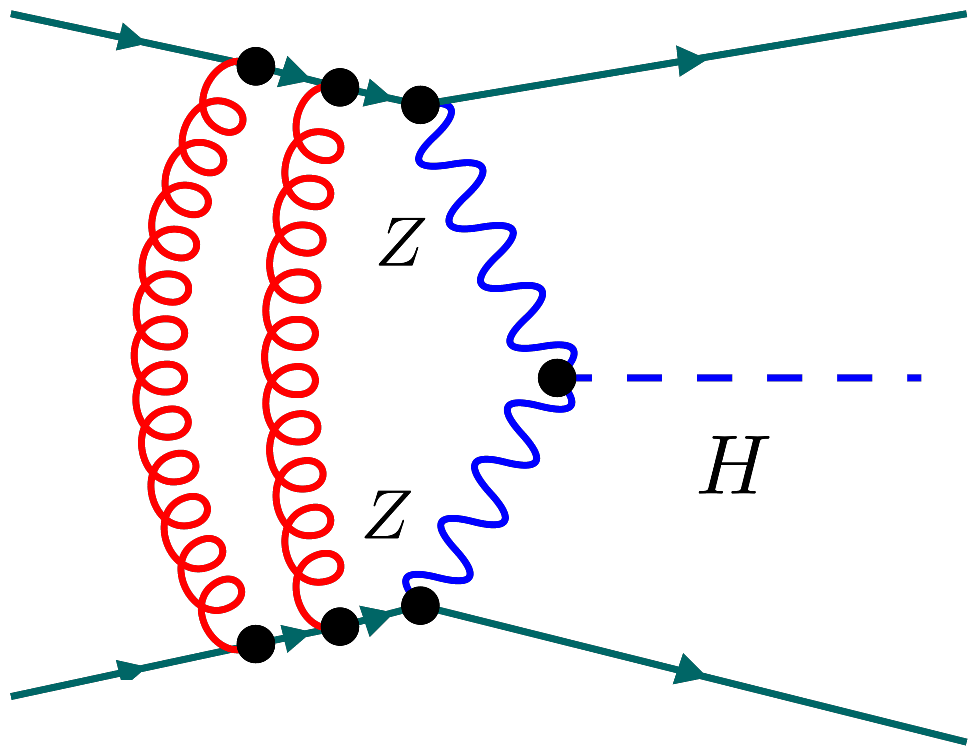
Inclusive $\mathcal{O}(0.5\%)$, but up to few % in high p_T regions



VECTOR BOSON FUSION: NON-FACTORISABLE VS FACTORISABLE



~ 0 **@ NLO due to color**



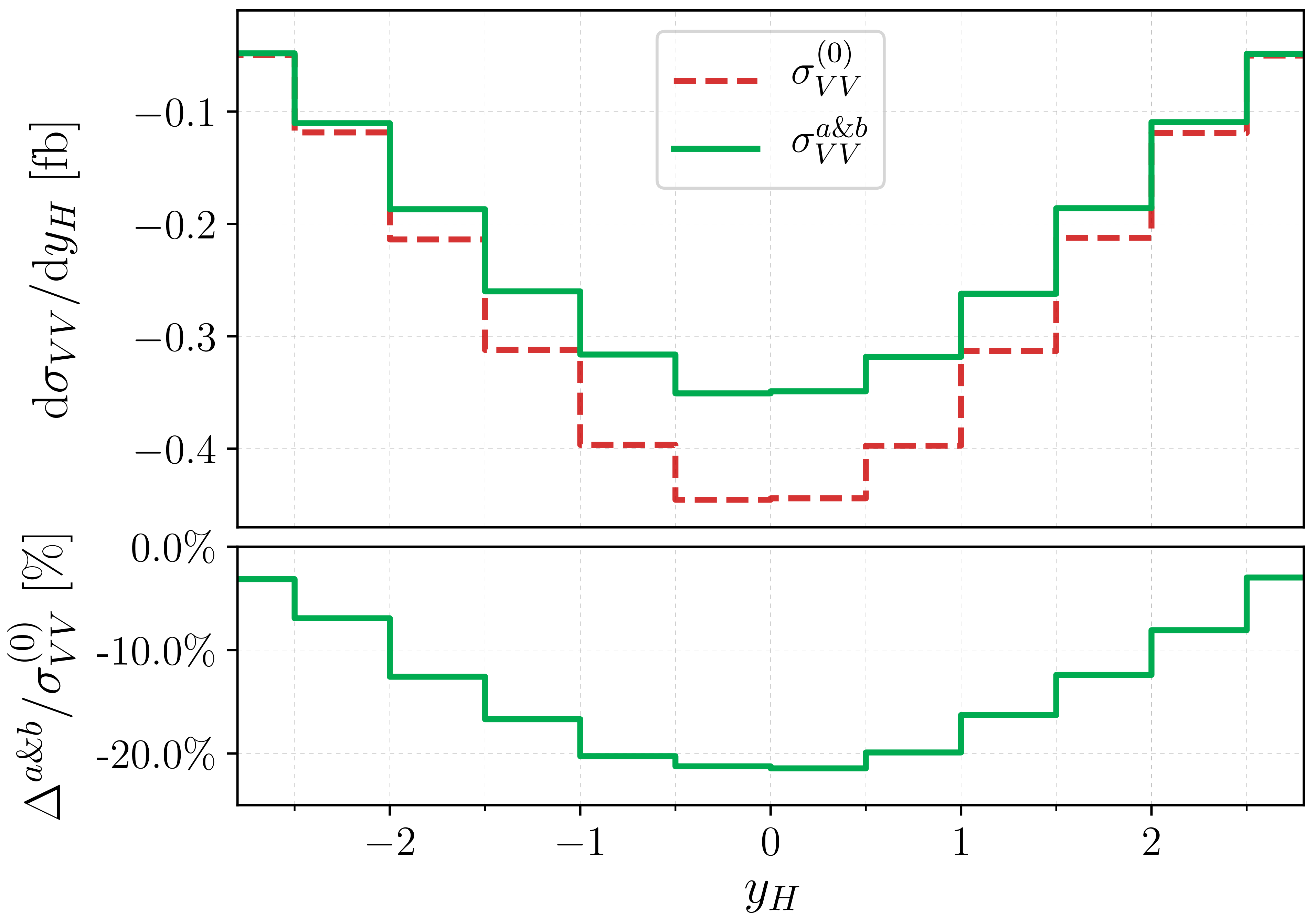
Up to NNLO gluons have to be color singlet → **color-suppressed**

Complicated radiative corrections

Enhanced by **Coulomb phase**

Next-to-eikonal recently computed

[Asteriadis et al. 2305.08016] **[Long et al. 2305.12937]**



Enhancement estimated in eikonal approximation

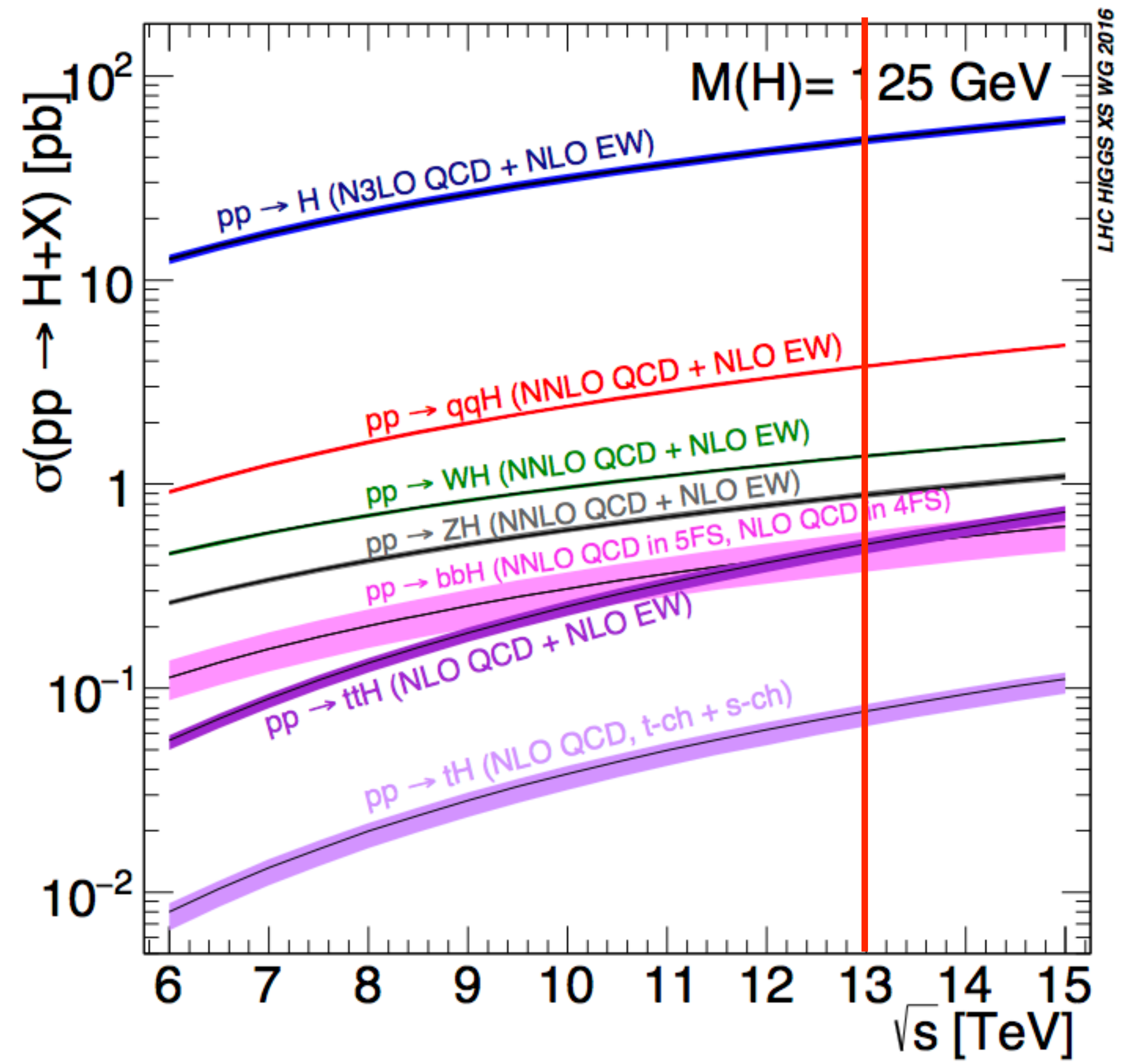
[Liu et al. 1906.10899] **[Dreyer et al. 2005.11334]**

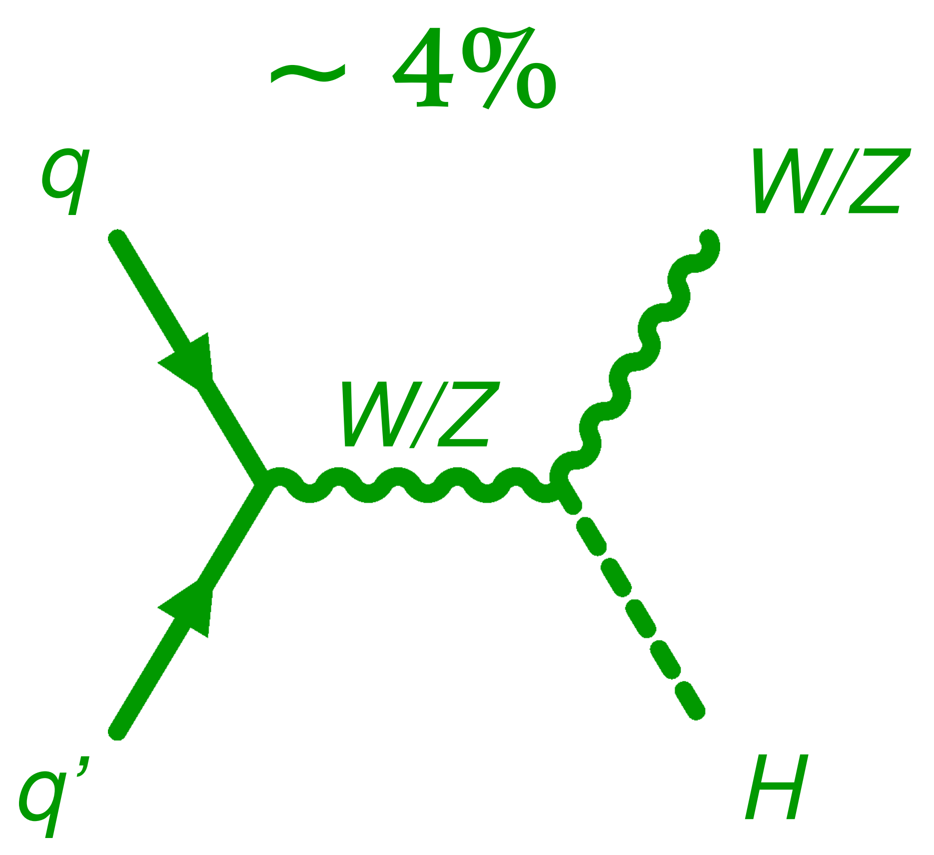
Inclusive $\mathcal{O}(0.5\%)$, but up to few % in high p_T regions →

Sizable corrections **O(20%) of leading eikonal**

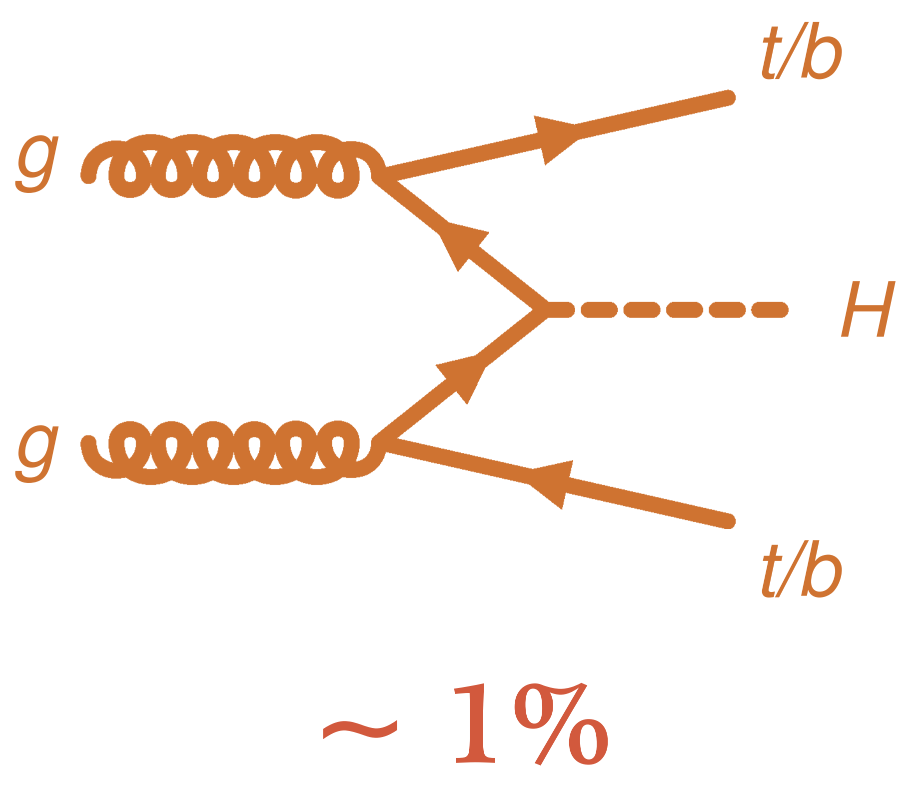
Since NF VBF small, **overall correction unchanged**

ASSOCIATED PRODUCTION



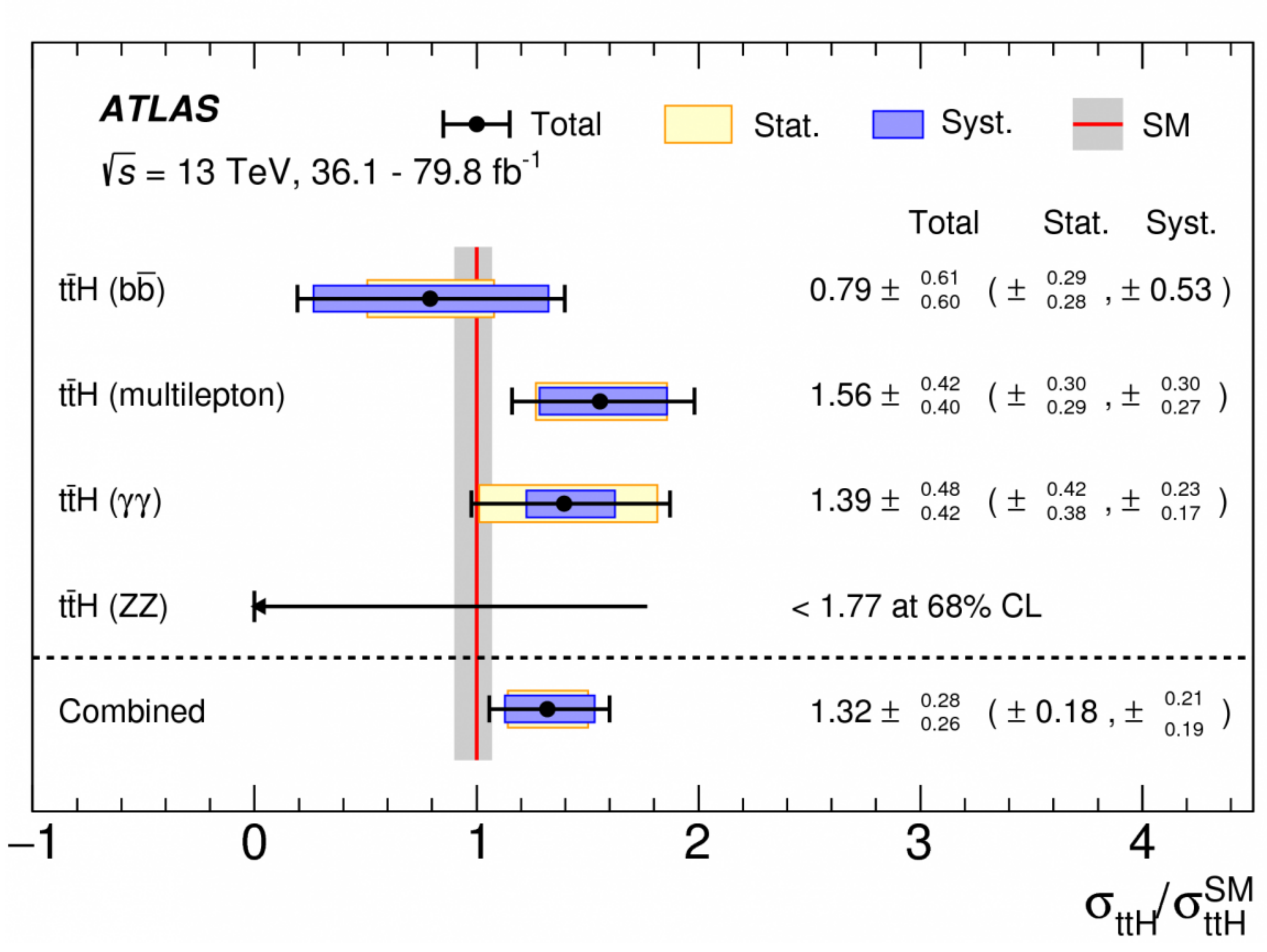


if aiming at % level precision, they are desirable

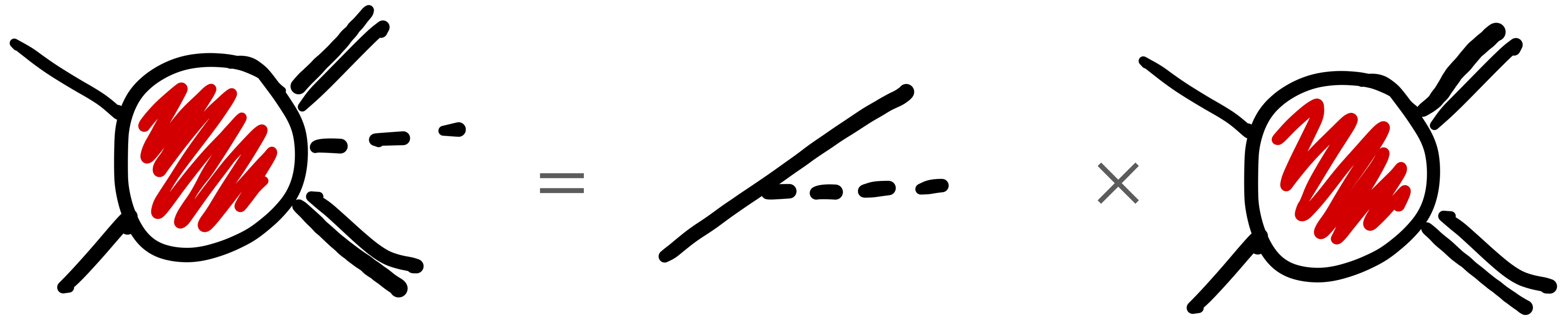


$\sqrt{s}$ (TeV)	Production cross section (in pb) for $m_H = 125\,\text{GeV}$					
	ggF	VBF	WH	ZH	$t\bar{t}H$	total
13	$48.6^{+5\%}_{-5\%}$	$3.78^{+2\%}_{-2\%}$	$1.37^{+2\%}_{-2\%}$	$0.88^{+5\%}_{-5\%}$	$0.50^{+9\%}_{-13\%}$	55.1

ASSOCIATED PRODUCTION: TTH PRODUCTION NNLO IN SOFT APPROX



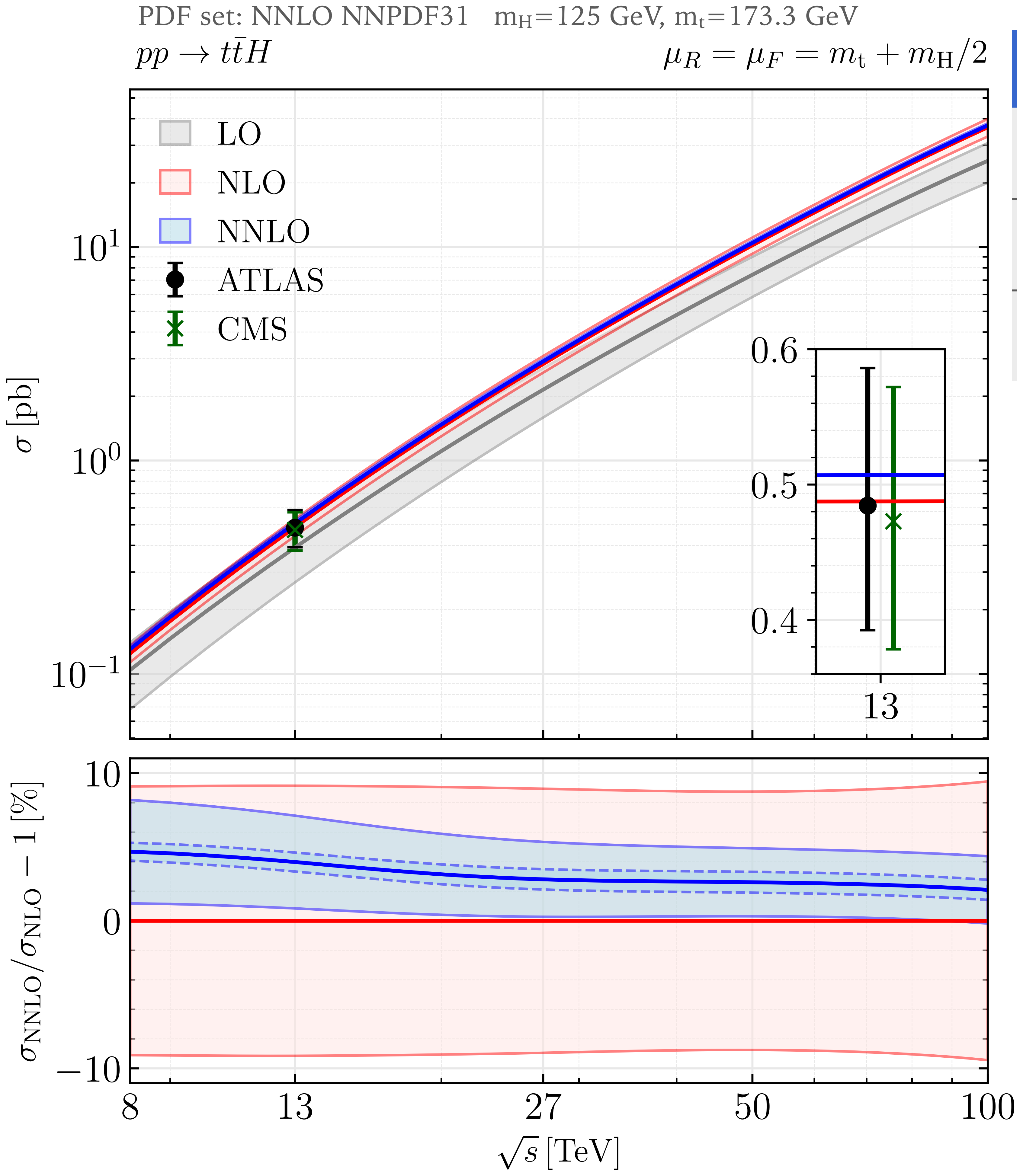
[M.Cepeda et al.: arXiv 1902.00134]



$$\mathcal{M}_{c\bar{c}\to t\bar{t}H}\big(\{p_i\},k\big) \simeq F\big(\alpha_S(\mu_R);m_t/\mu_R\big)\,\frac{m_t}{v}\sum_{i=3,4}\frac{m_t}{p_i\cdot k}\mathcal{M}_{c\bar{c}\to t\bar{t}}\big(\{p_i\}\big)$$

Final uncertainty: • ±15 % on $\Delta\sigma_{\rm NNLO}$ • ±0.6 % on $\sigma_{\rm NNLO}$

Effect on the total cross section modulated by the (small) contribution of the hard factor: about ***1%*** *of the LO cross section in the gg and* ***2-3%*** *in the $q\bar{q}$ channel.*



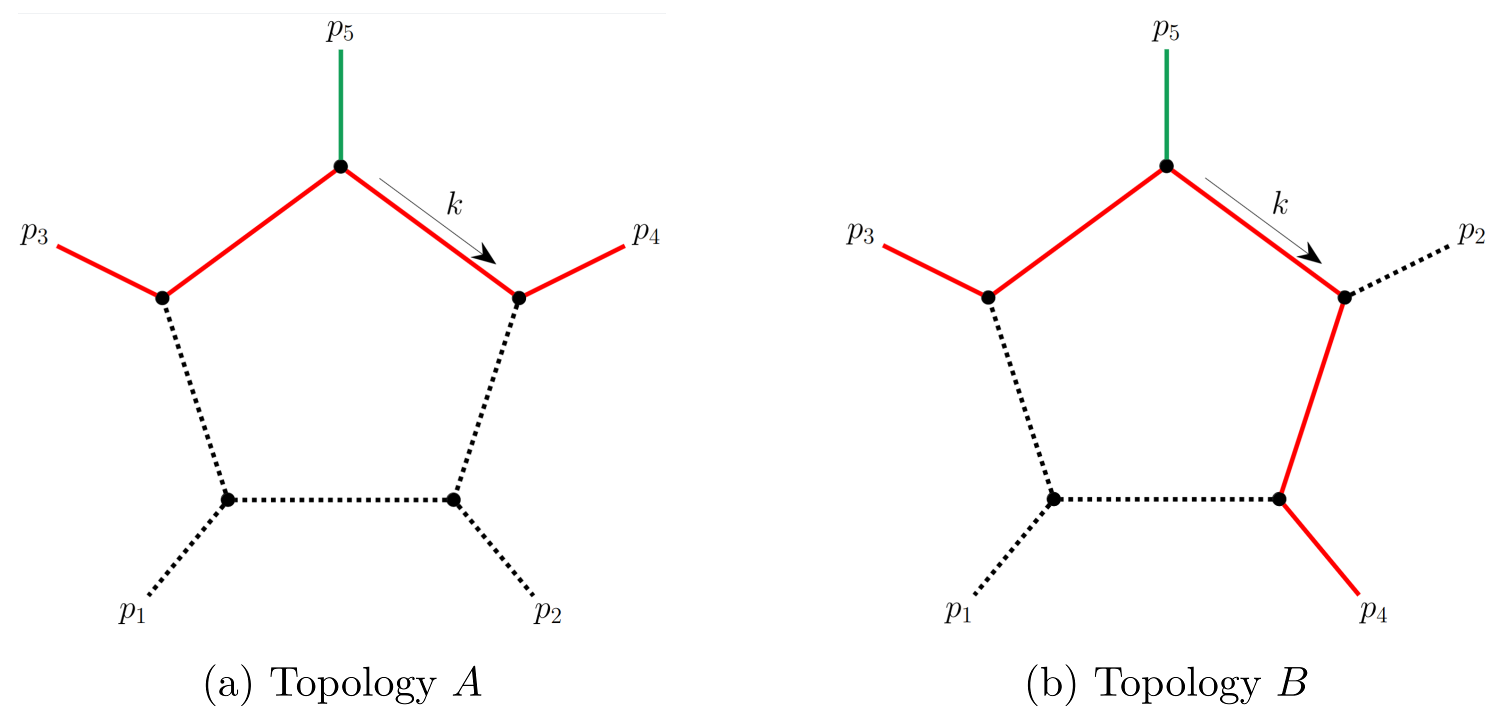
[Catani, Devoto, Grazzini, Kallweit, Mazzitelli, Savoini 2210.07846]

Residual uncertainty $\sim 3\,\%$

more precise assessment of virtual contributions missing

ASSOCIATED PRODUCTION: TTH PRODUCTION GLUON CHANNEL

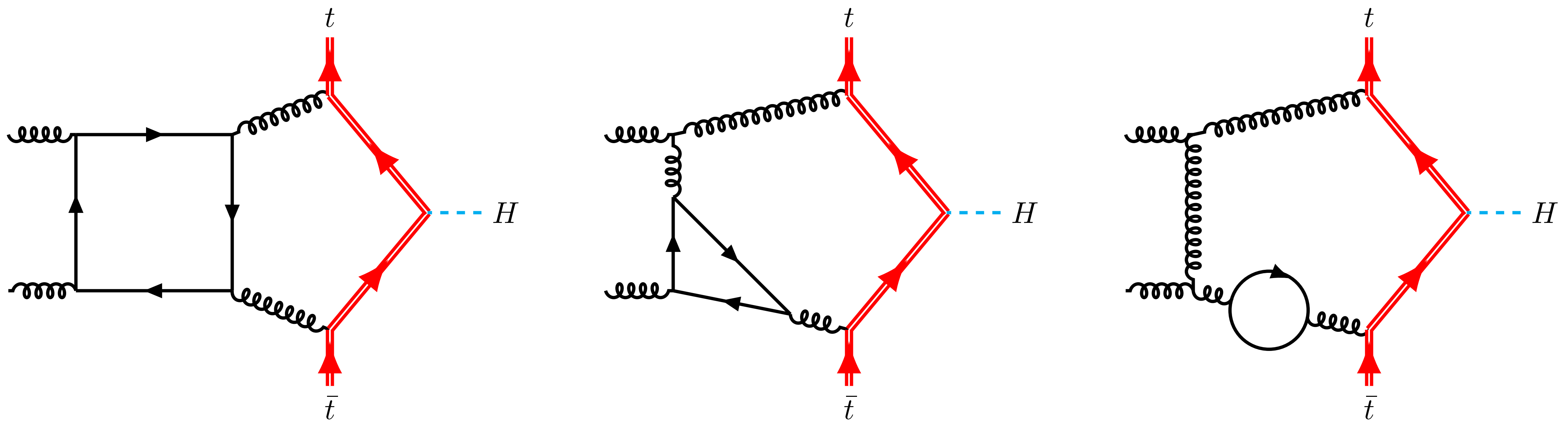
$gg \to t\bar{t}H$ @ 1loop to $\mathcal{O}(\epsilon^2)$



$$2\mathcal{N}\,\mathrm{Re}\left[\overline{\sum}(\mathcal{A}^{(0)})^\dagger\mathcal{A}_{\mathrm{r}}^{(1)}\right] = 2\mathcal{N}\,\mathrm{Re}\left[\overline{\sum}(\mathcal{A}^{(0)})^\dagger\mathcal{A}^{(1)}\right] + 2\mathcal{N}\,\mathrm{Re}\left[\overline{\sum}(\mathcal{A}^{(0)})^\dagger\mathcal{A}_{\mathrm{ct}}^{(1)}\right] =$$
$$= \left(-\frac{0.75348873}{\epsilon^2} + \frac{1.3691456}{\epsilon} + 0.82613668 - 4.9282871\epsilon + 1.5817369\epsilon^2\right) \times 10^{-7}$$

[Buccioni, Kreer, Liu, Tancredi 2312.10015]

Planar master integrals for n_f corrections

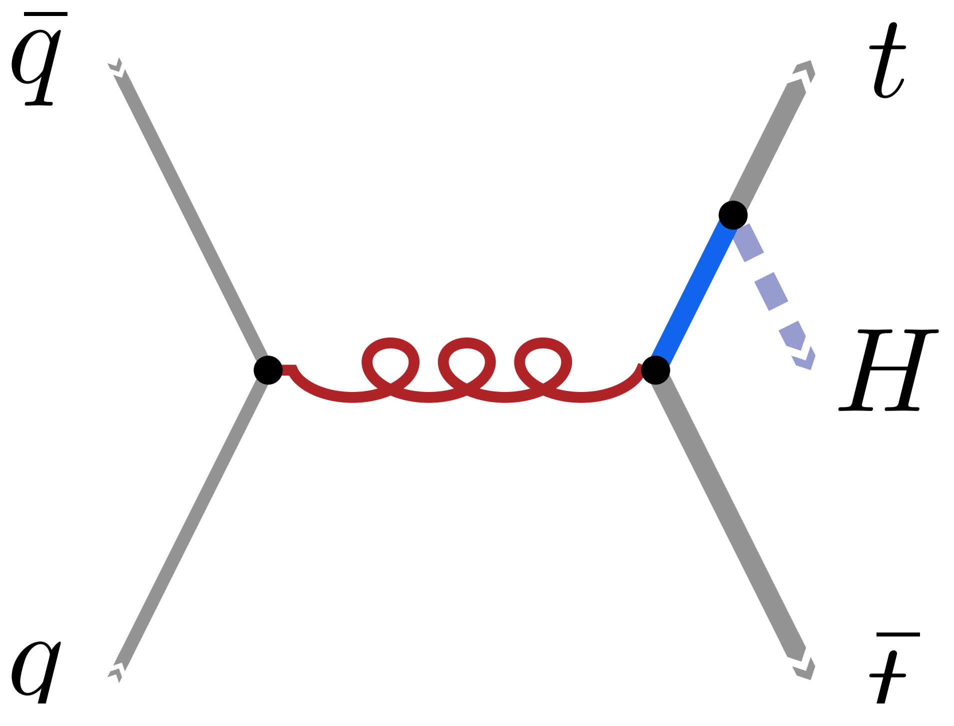


	$\mathcal{O}(\epsilon^0)$	$\mathcal{O}(\epsilon^1)$	$\mathcal{O}(\epsilon^2)$	$\mathcal{O}(\epsilon^3)$	$\mathcal{O}(\epsilon^4)$
$(\vec{I}_1)_{109}$	0	0	0	-3.703380133 $+5.885655074\,i$	2.149576969 $-10.432322830\,i$
$(\vec{I}_1)_{110}$	0	0	0	0	0
$(\vec{I}_1)_{111}$	0	0	-1.306045093 $-12.647039669\,i$	2.05552771 $+25.35139955\,i$	-85.55528965 $-75.93834102\,i$

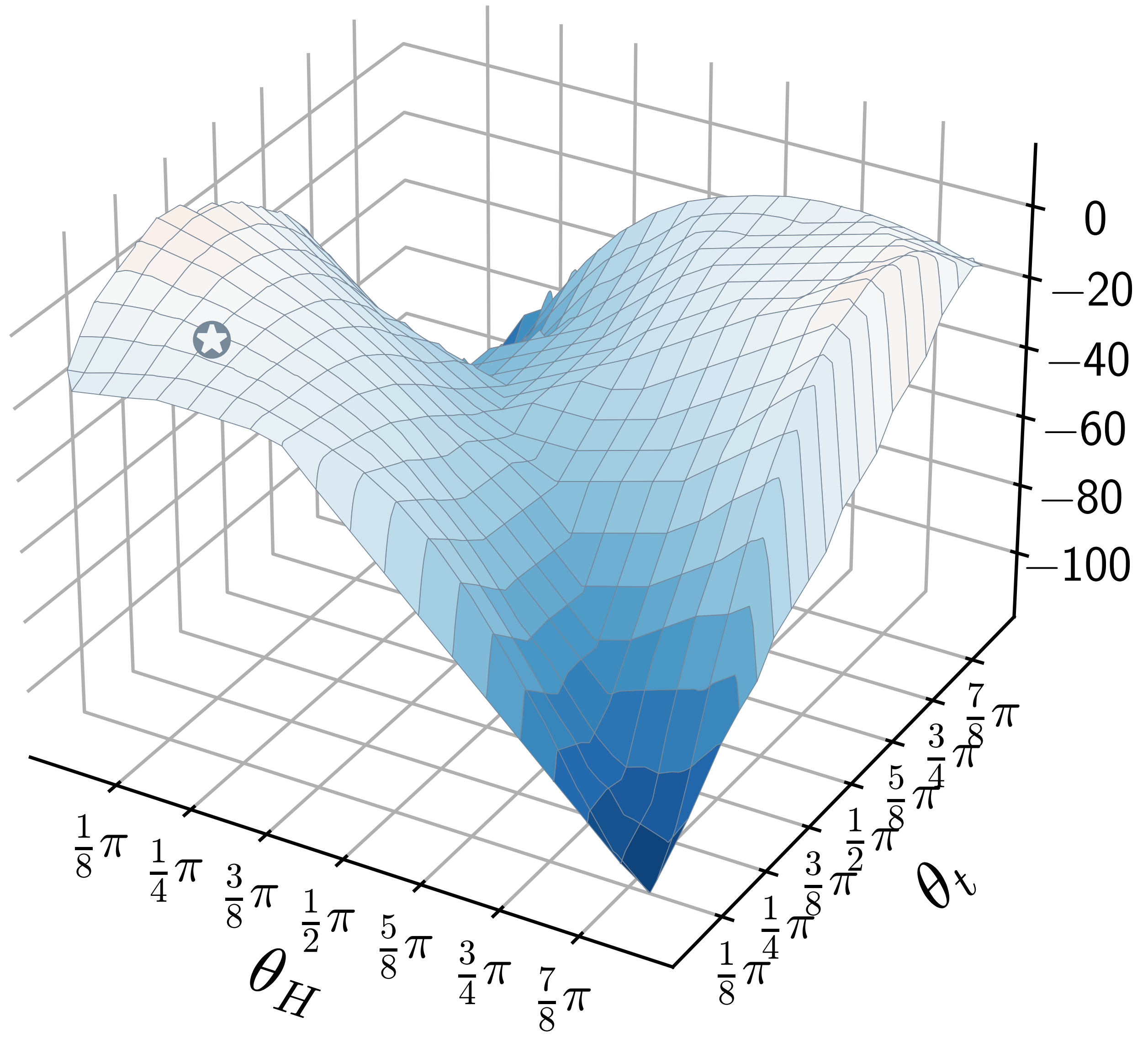
[Cordero, Figueiredo, Kraus, Page, Reina 2312.08131]

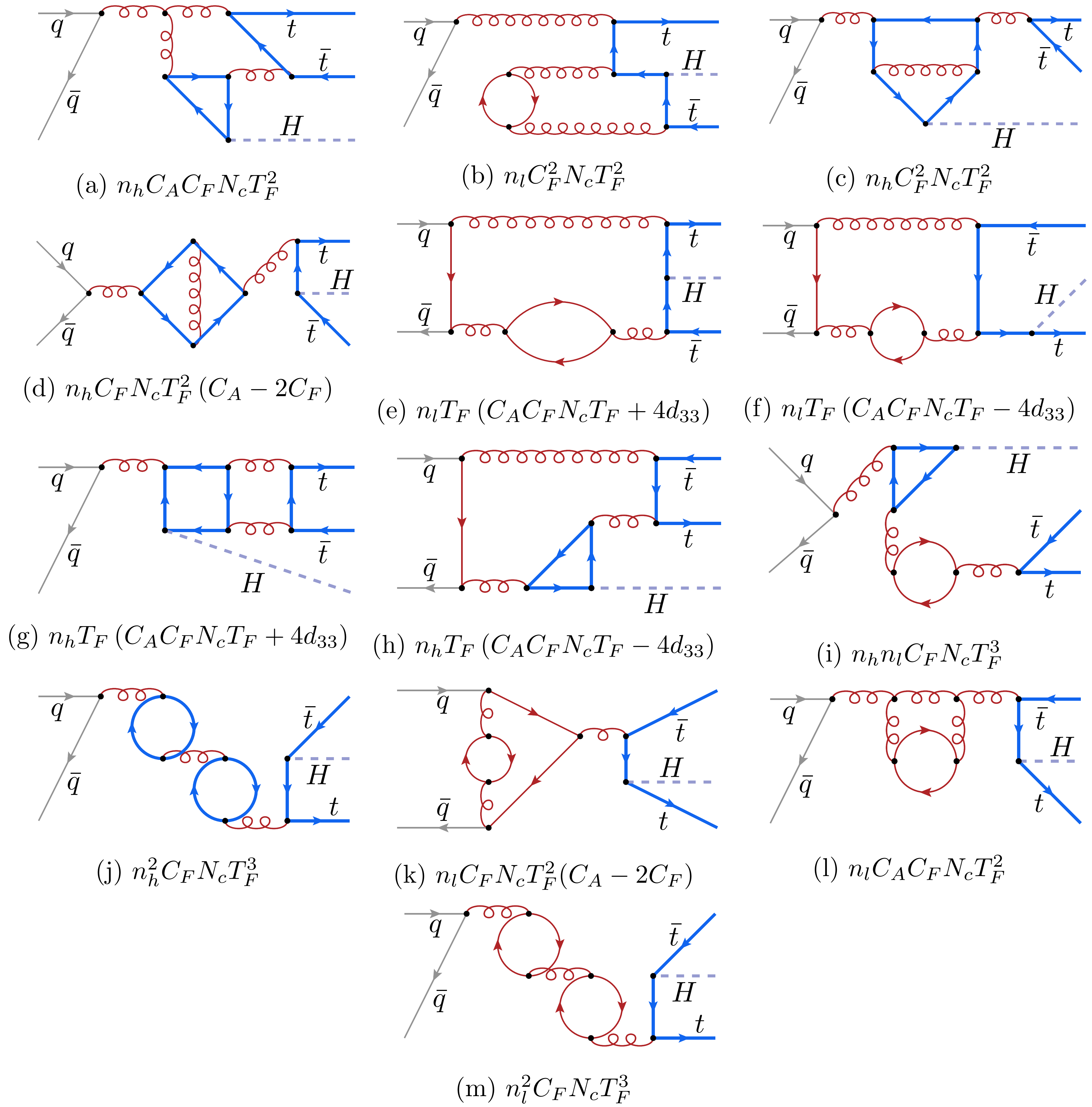
ASSOCIATED PRODUCTION: TTH PRODUCTION QUARK CHANNEL

proof of concept: n_f contribution to $q\bar{q} \to t\bar{t}H$



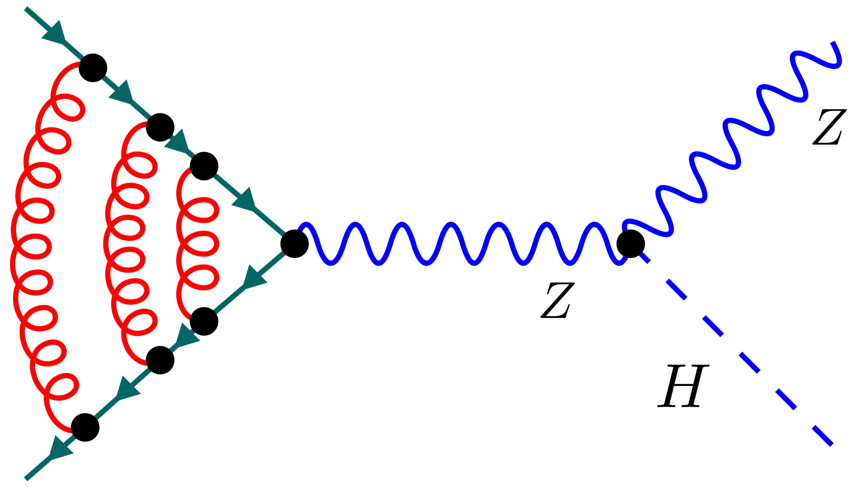
$\mathcal{C}/\mathcal{A}$





Numerical evaluation of the amplitude using **sector decompositon** [Agarwal et al 2402.03301]

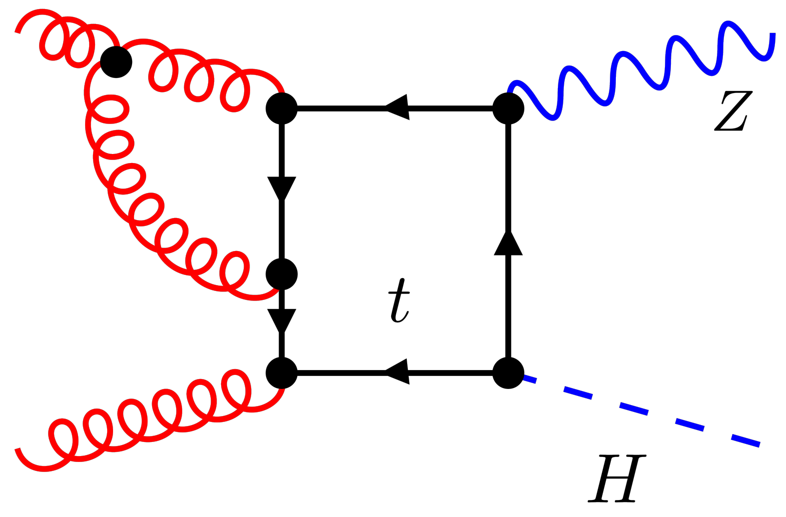
ASSOCIATED PRODUCTION: ZH & WH PRODUCTION

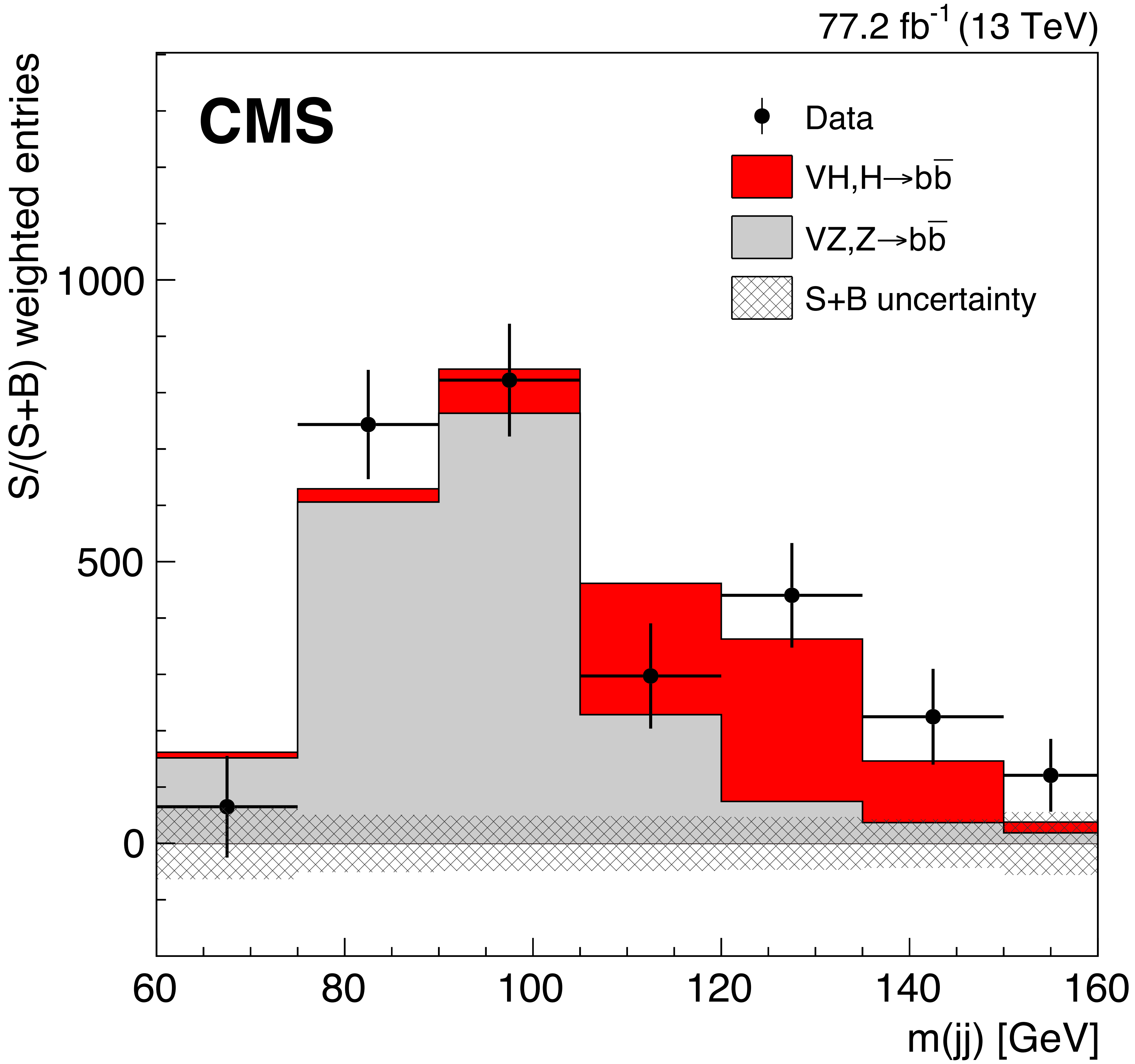


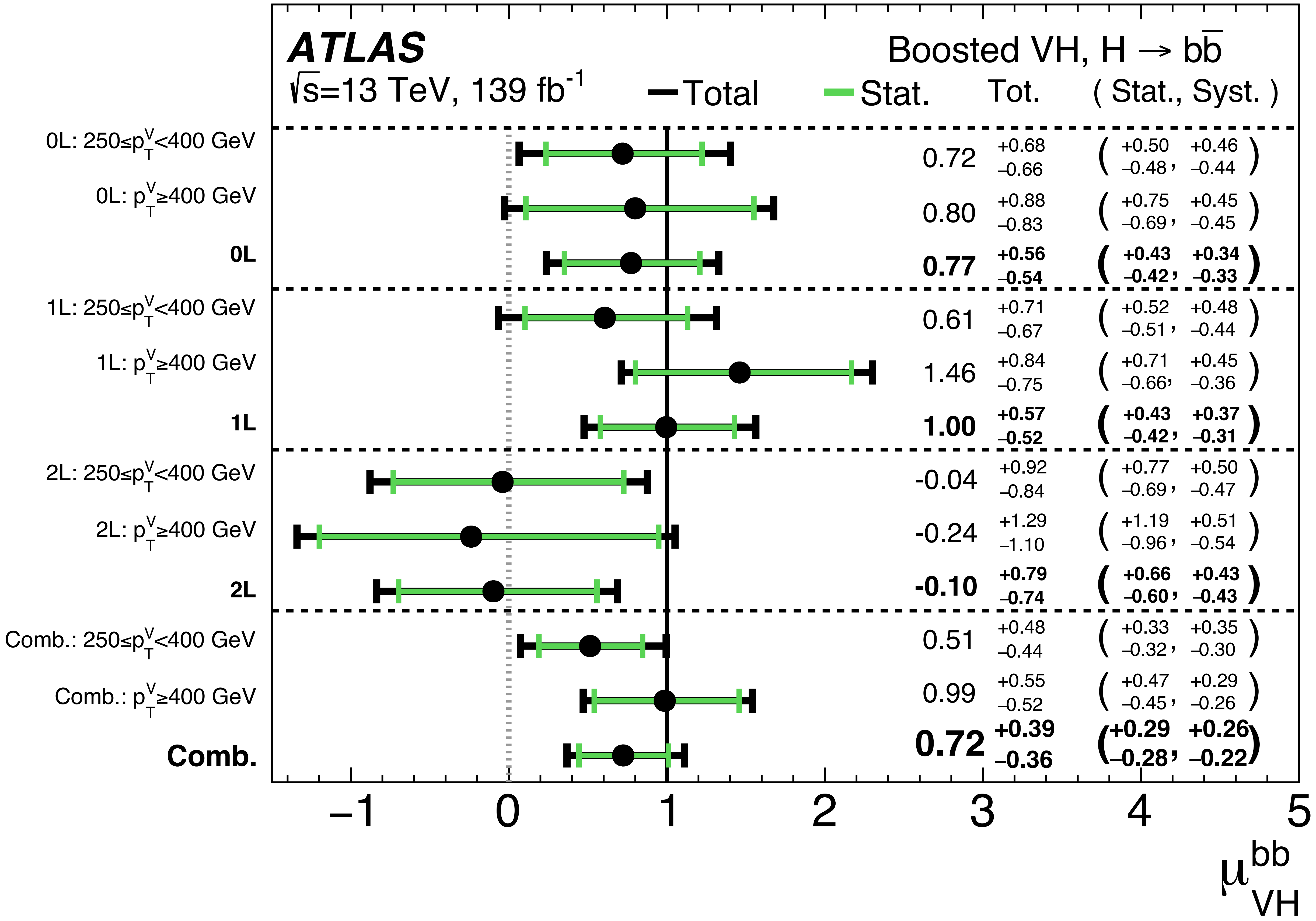
VH probe of Higgs at high pT: **mass effects important**

Important for $H \to b\bar{b}$, bkq can be more easily suppressed

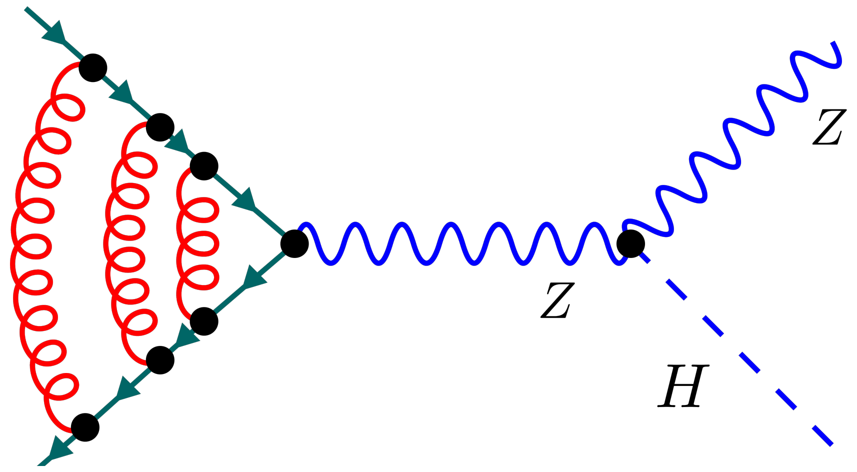
Also indirect probe of **Higgs self-coupling** (many talks here!)







ASSOCIATED PRODUCTION: ZH & WH PRODUCTION



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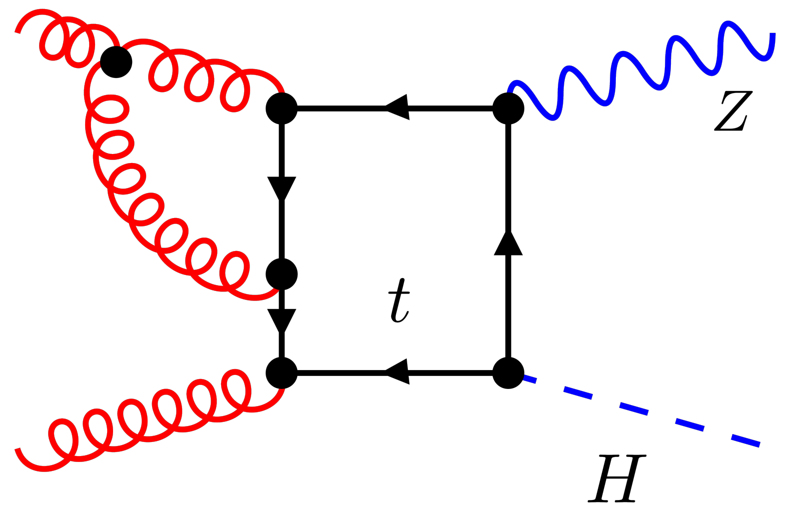
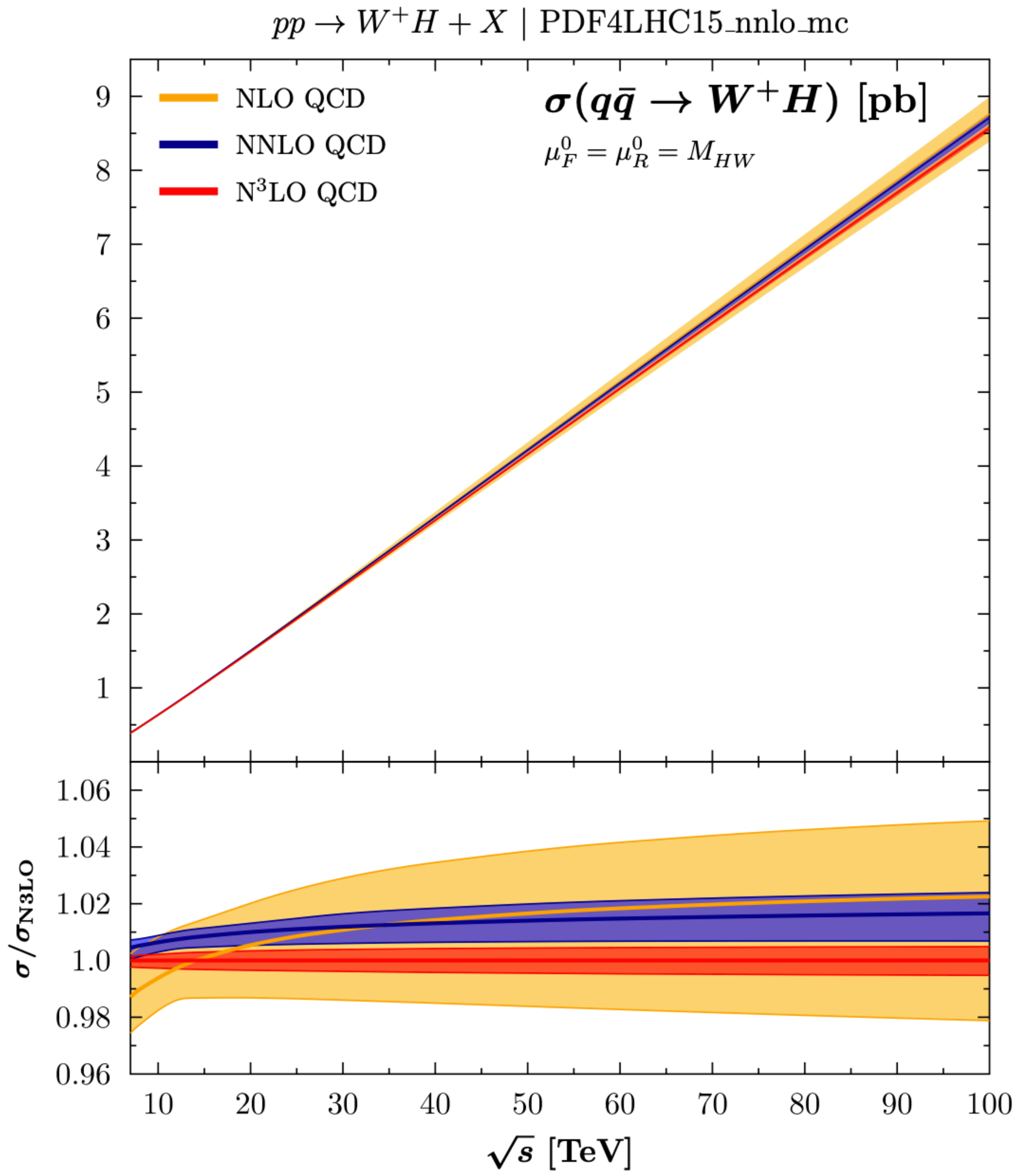


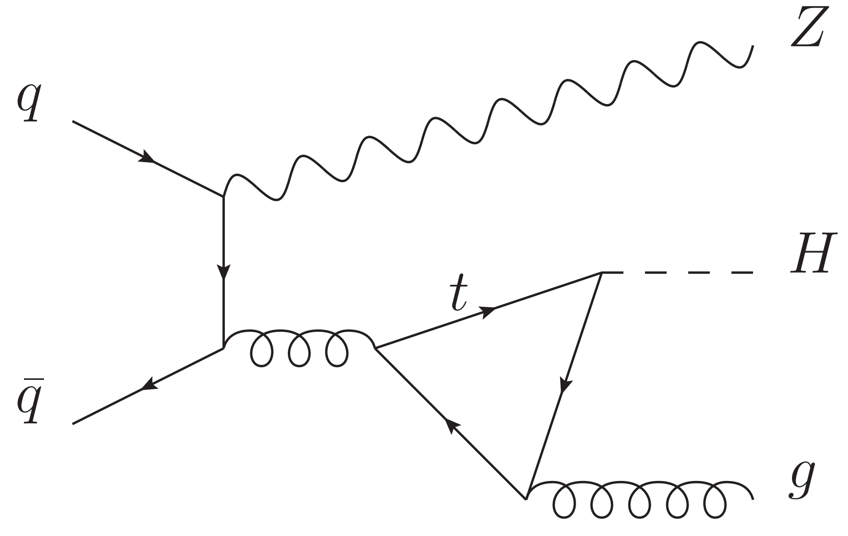


[Baglio, Duhr, Mistlberger, Szafron, 2209.06138]

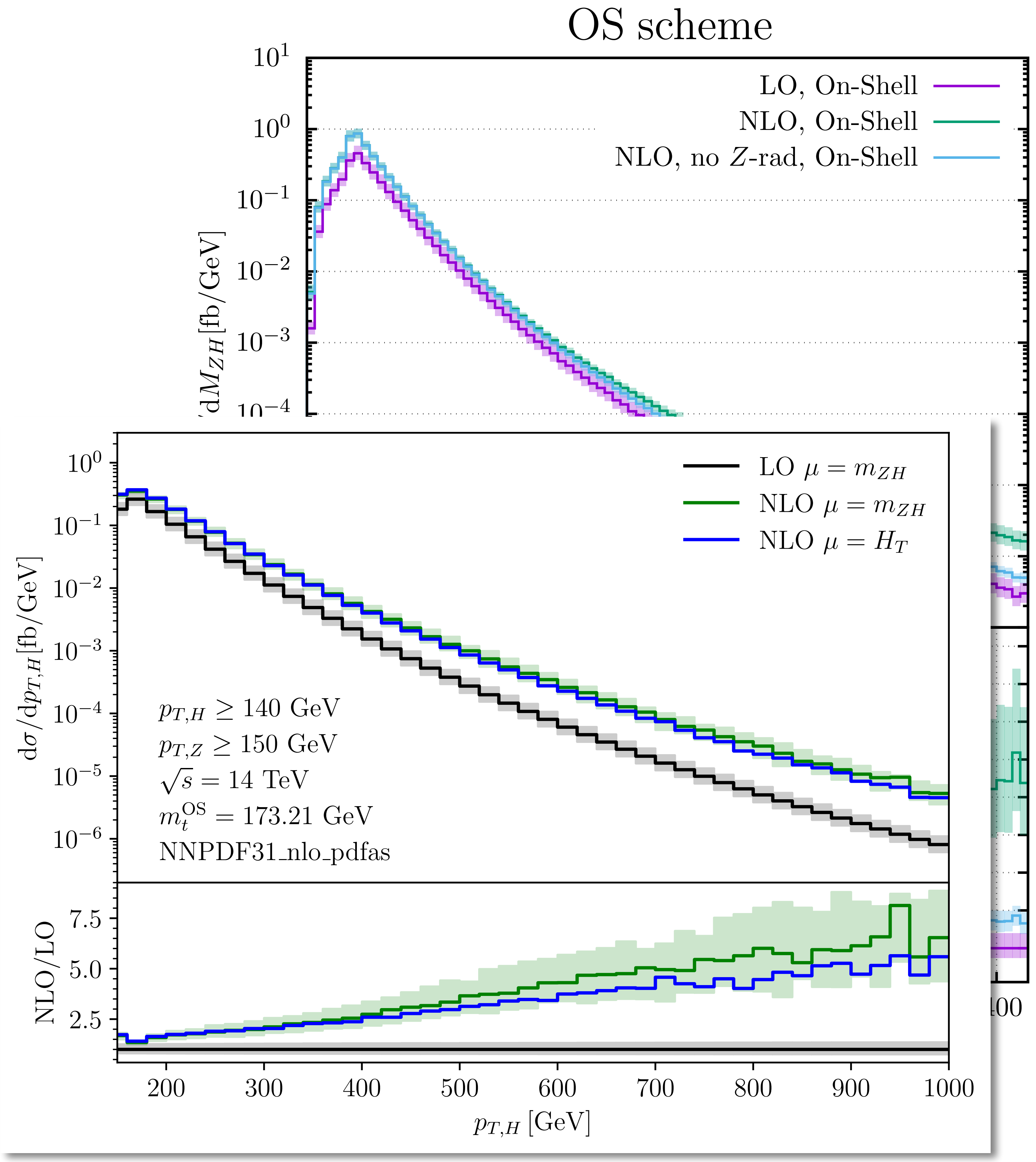
$gg \to ZH$ loop induced, NLO formally N^{3}LO

Uncertainty $\sim 3\%$

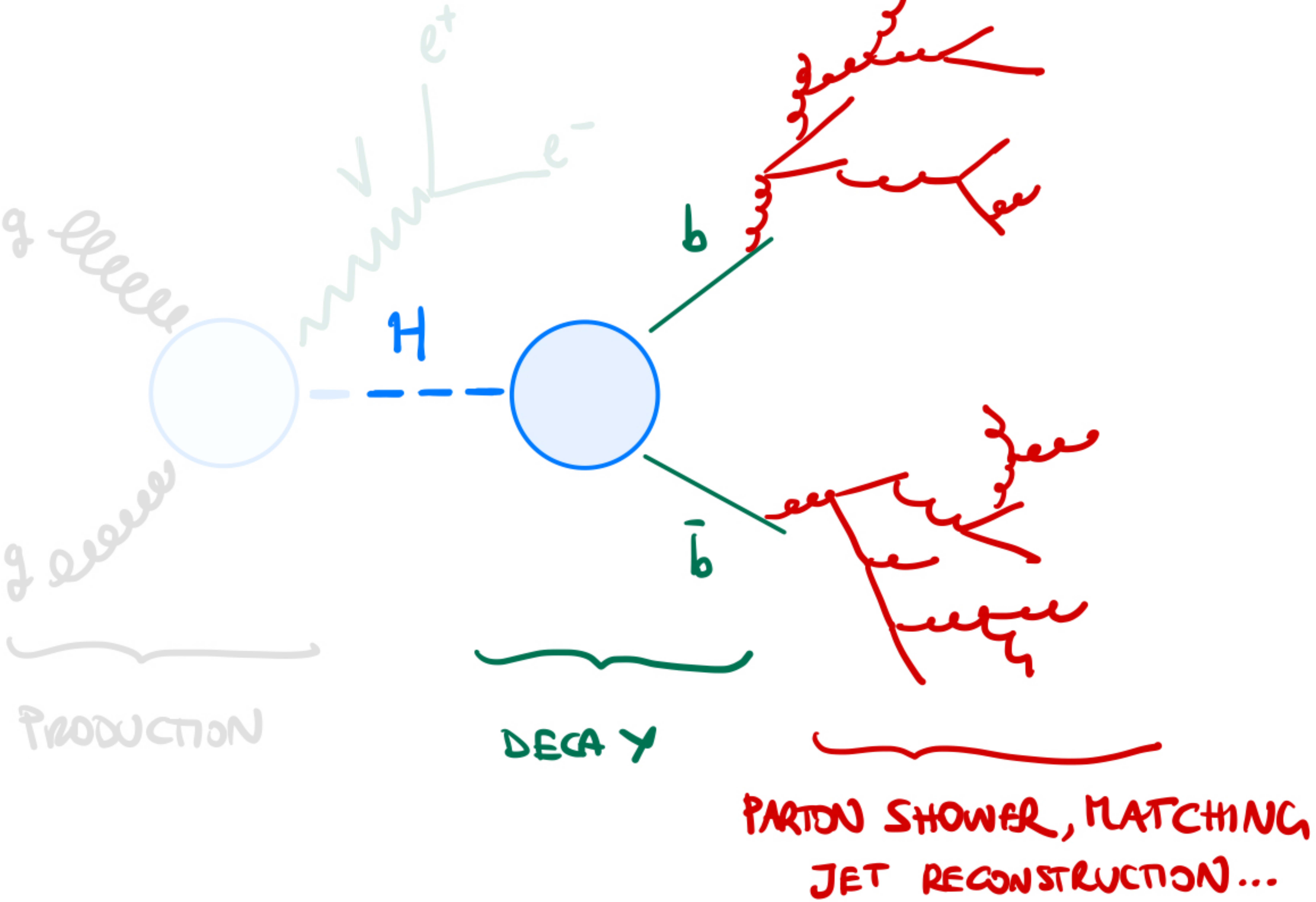
Large $\log \frac{m_Z^2}{m_{ZH}^2}$ in qg channel (qq suppr by PDFs)



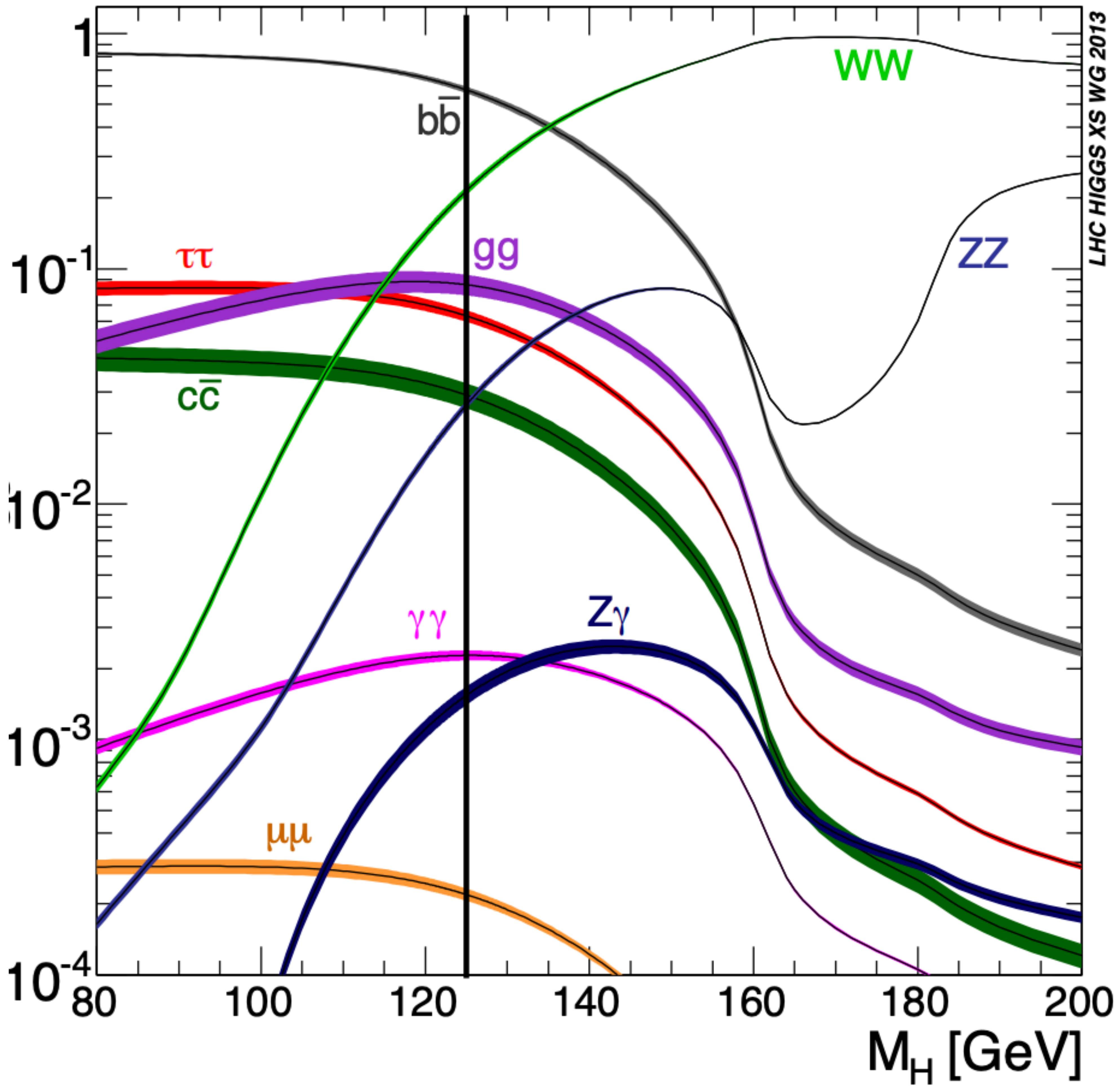
[Hasselhuhn, Luthe, Steinhauser, 1611.05881]
[Wang, Xu, Xu, Yang, 2107.08206]
[Chen, Davies, Jones, Kerner 2204.05225]
[Degrassi, Gröber, Vitti, Zhao, 2205.02769]



HIGGS DECAYS AND MATCHING TO PARTON SHOWERS

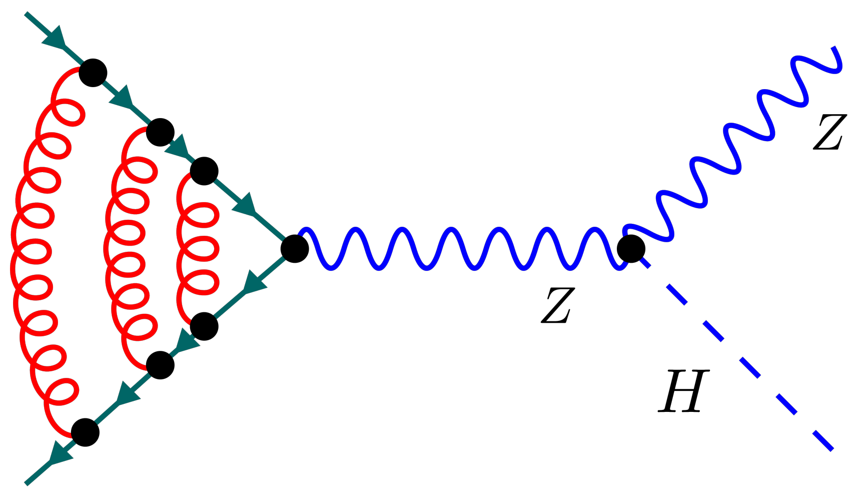


HIGGS DECAYS: FLAVOUR OF DECAY PRODUCTS

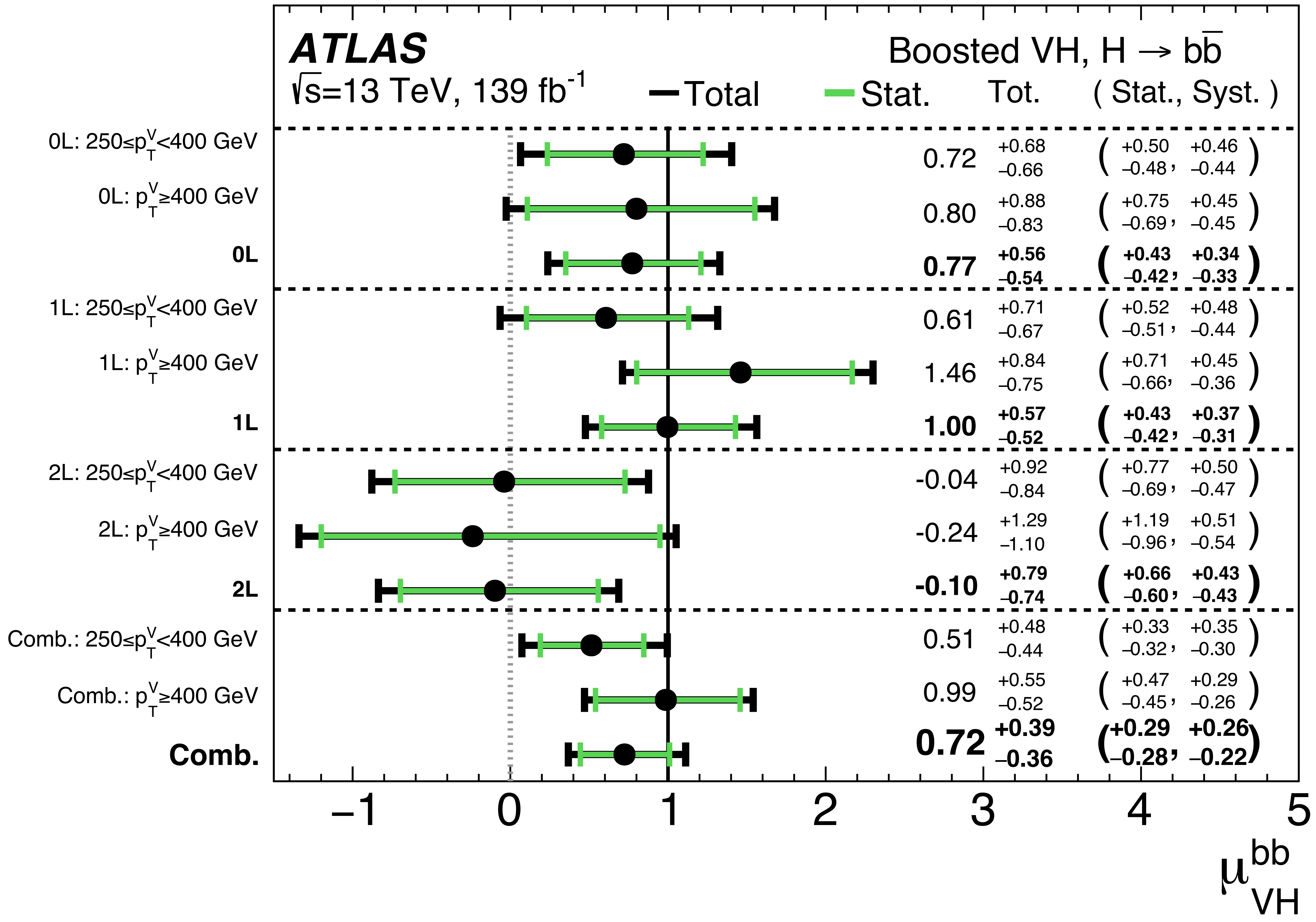


Decay channel	Branching ratio	Rel. uncertainty
$H \to \gamma\gamma$	2.27×10^{-3}	$^{+5.0\%}_{-4.9\%}$
$H \to ZZ$	2.62×10^{-2}	$^{+4.3\%}_{-4.1\%}$
$H \to W^+W^-$	2.14×10^{-1}	$^{+4.3\%}_{-4.2\%}$
$H \to \tau^+\tau^-$	6.27×10^{-2}	$^{+5.7\%}_{-5.7\%}$
$H \to b\bar{b}$	5.84×10^{-1}	$^{+3.2\%}_{-3.3\%}$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

ASSOCIATED PRODUCTION: JET FLAVOUR TAGGING



Reconstructed Higgs spectrum depends on jet algorithm used, **especially for $p_T \geq 300$ GeV**



[Caletti, Larkoski, Marzani, Reichelt 2205.01109]
[Czakon, Mitov, Poncelet 2205.11879]
[Gauld, Huss. Stagnitto 2208.11138]
[Caola, Grabarczyk, Salam, Scyboz, Thaler 2306.07314]

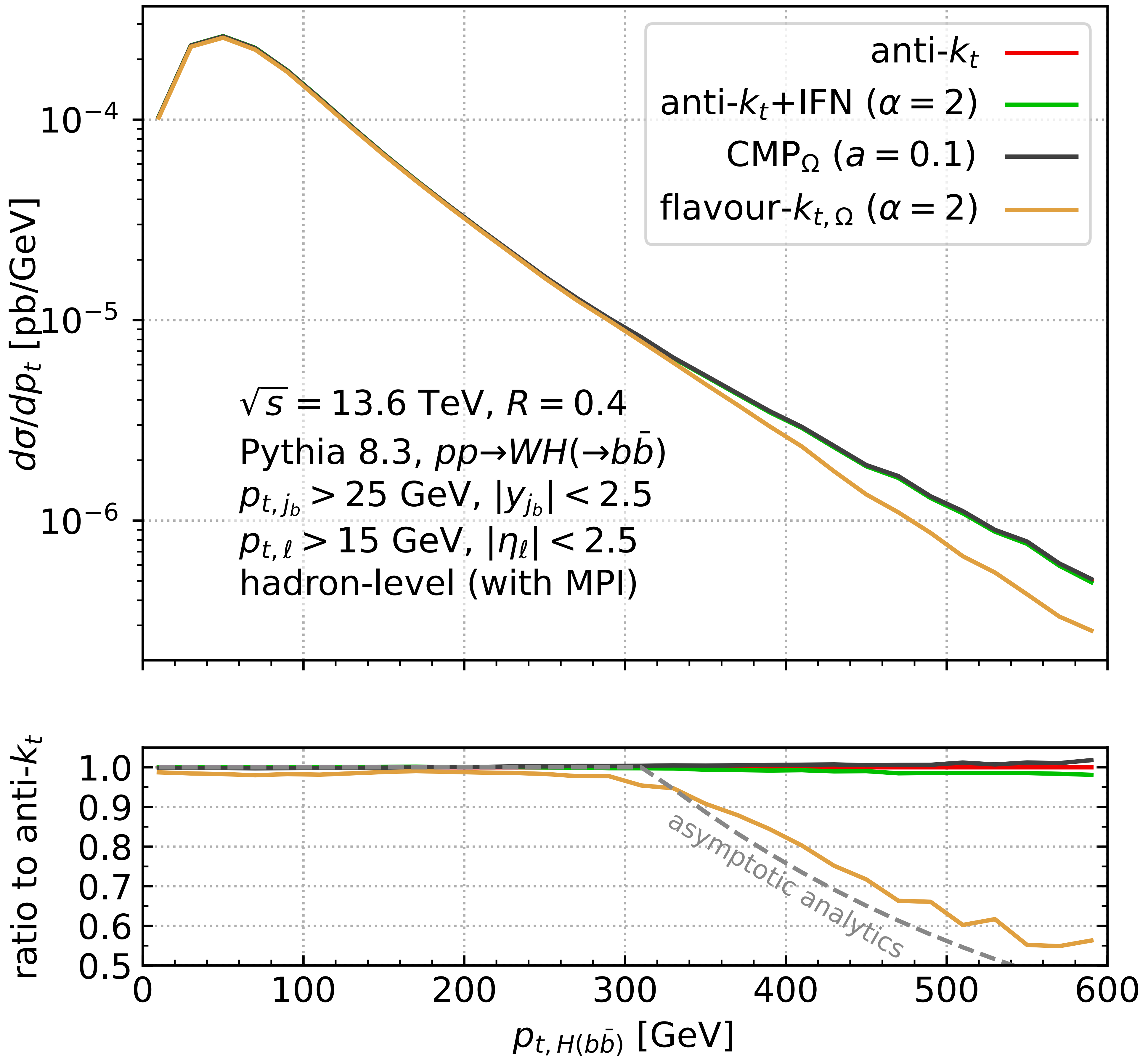
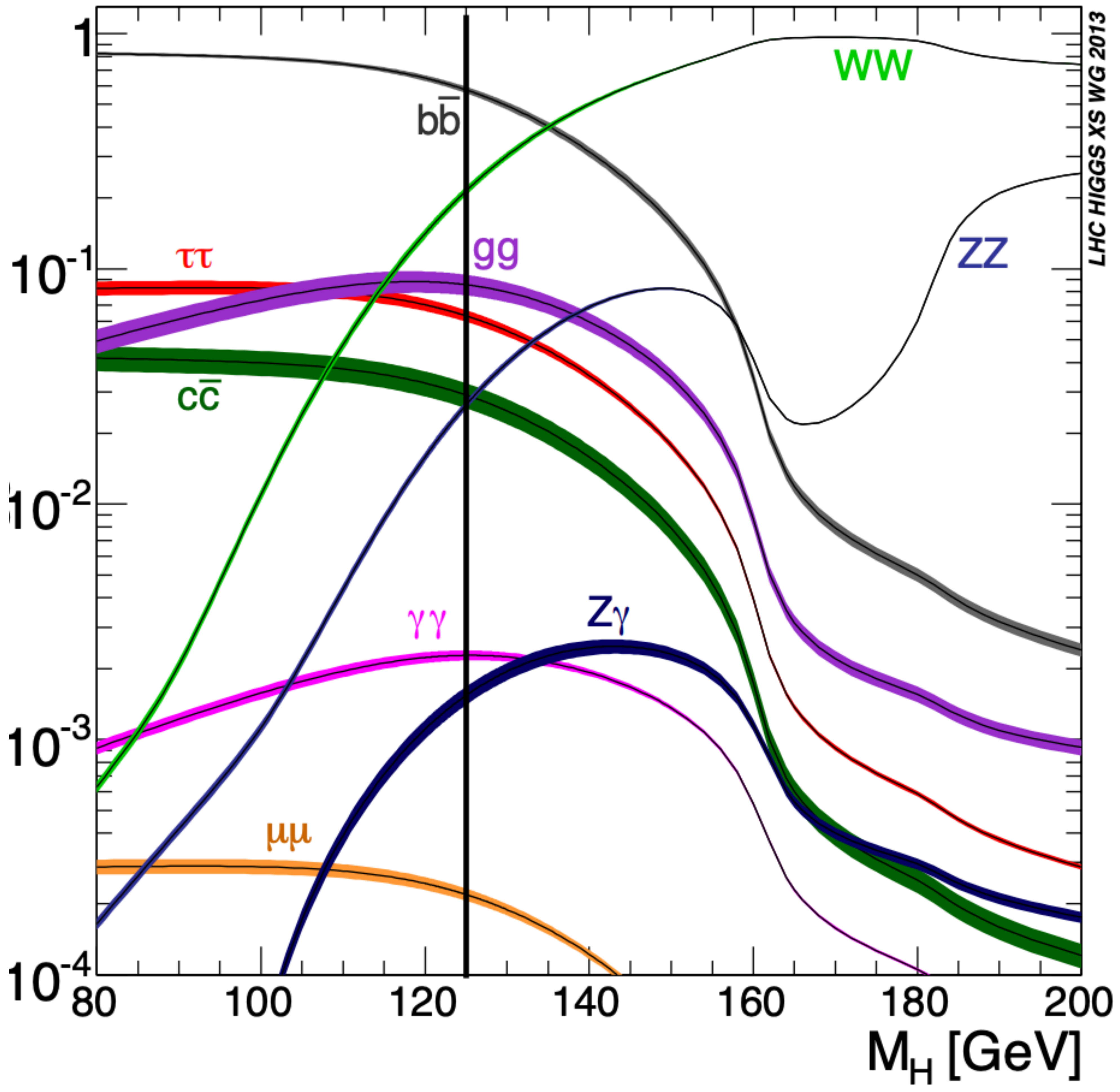


FIG. 8. The transverse momentum spectrum of the reconstructed Higgs boson in $WH(\rightarrow \mu\nu b\bar{b})$ at centre-of-mass energy $\sqrt{s} = 13.6$ TeV, at hadron level (with stable B-hadrons).

HIGGS DECAYS: HIGGS WIDTH AND ALL THAT



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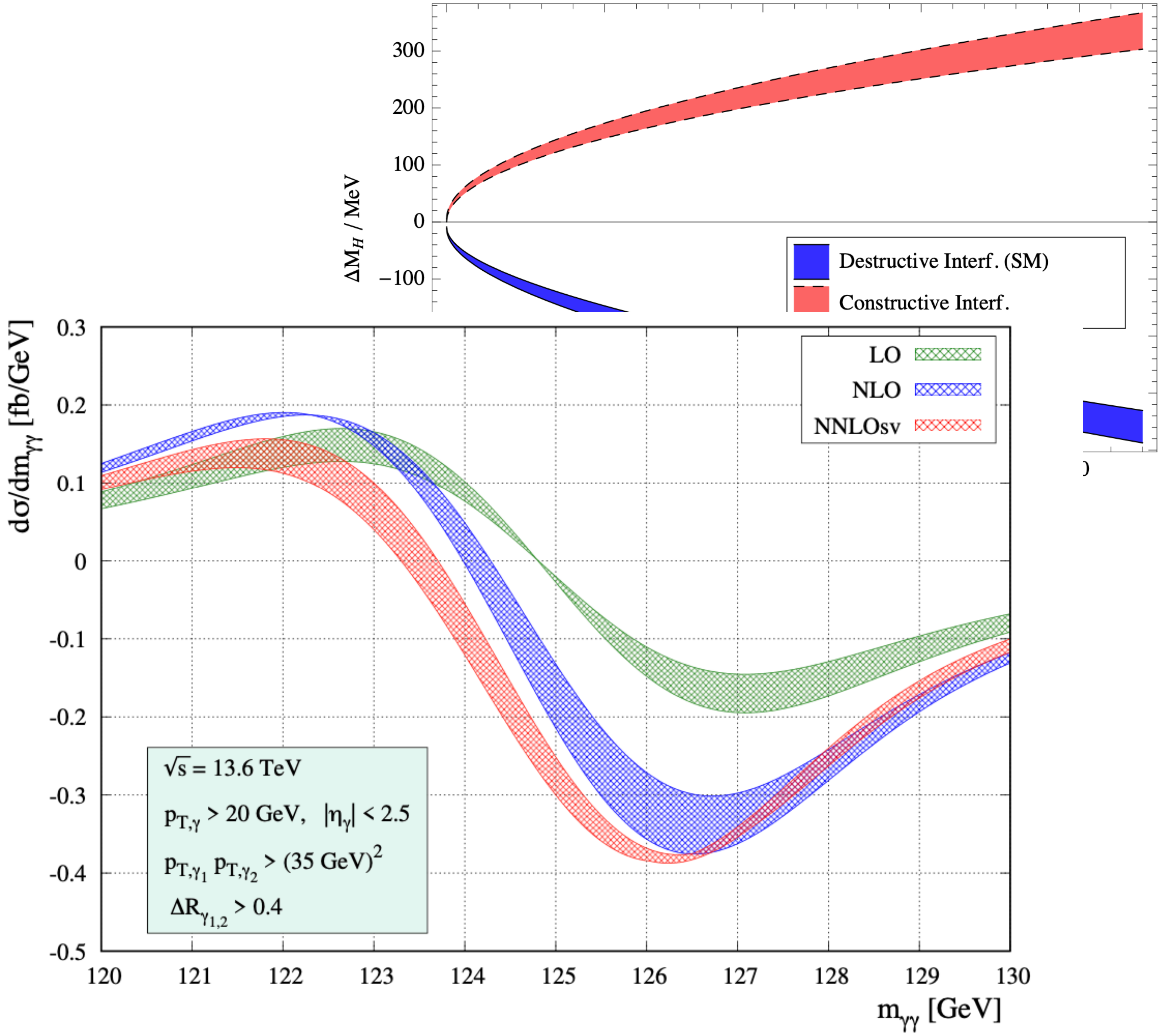
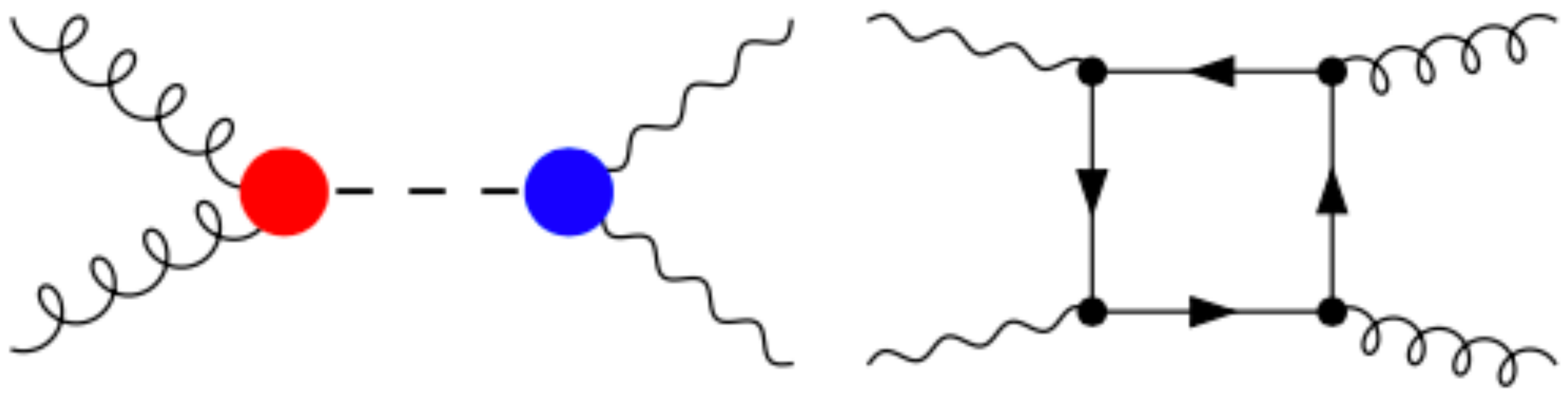
HIGGS DECAYS TO $\gamma\gamma$, $Z\gamma$: INTERFERENCE EFFECTS

$\Gamma_H \sim 4$ MeV in Standard Model LHC direct resolution $\mathcal{O}(GeV)$





Mass peak shift from interference [Martin 1208.1533]

Use for indirect bounds on Higgs width [Dixon, Li 1305.3854]

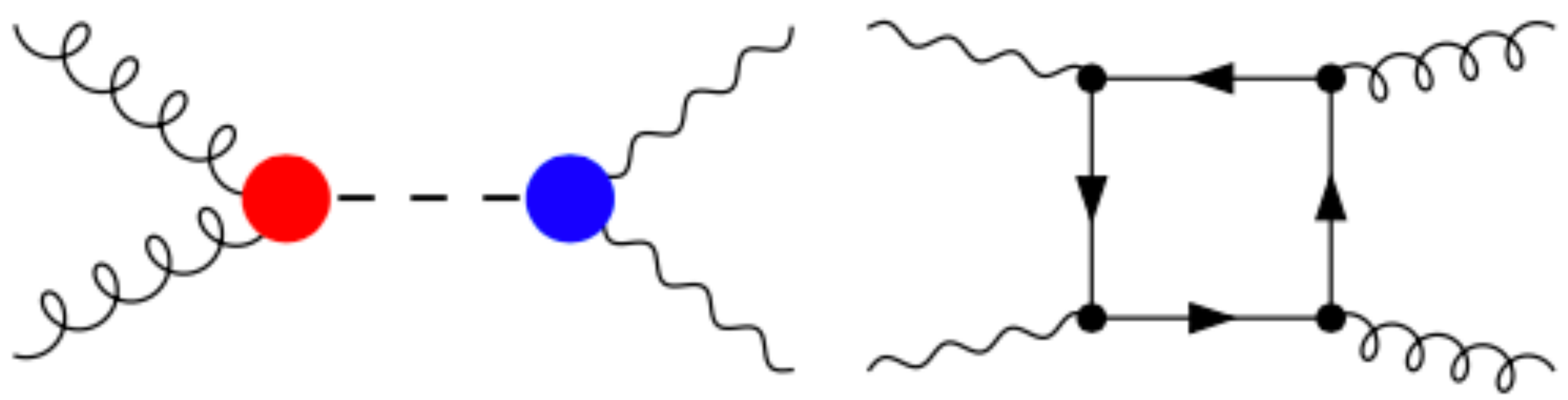
δ(scale)	δ(trunc)	δ(PDF-TH)	δ(EW)	$\delta(t,b,c)$	$\delta(1/m_t)$
$^{+0.10\text{ pb}}_{-1.15\text{ pb}}$	±0.18 pb	±0.56 pb	±0.49 pb	±0.40 pb	±0.49 pb
$^{+0.21\%}_{-2.37\%}$	±0.37%	±1.16%	±1%	±0.83%	±1%

Interference effect on XS must be taken into account: $\mathcal{O}(2\%)$

Interference effects for $H \to \gamma\gamma$ NNLO (SV) decrease mass shift → loosen bound on $\Gamma_H \leq (10-20)\Gamma_{H,SM}$

[Bargiela, Buccioni, Devoto, Caola, von Manteuffel, Tancredi 2212.06287]

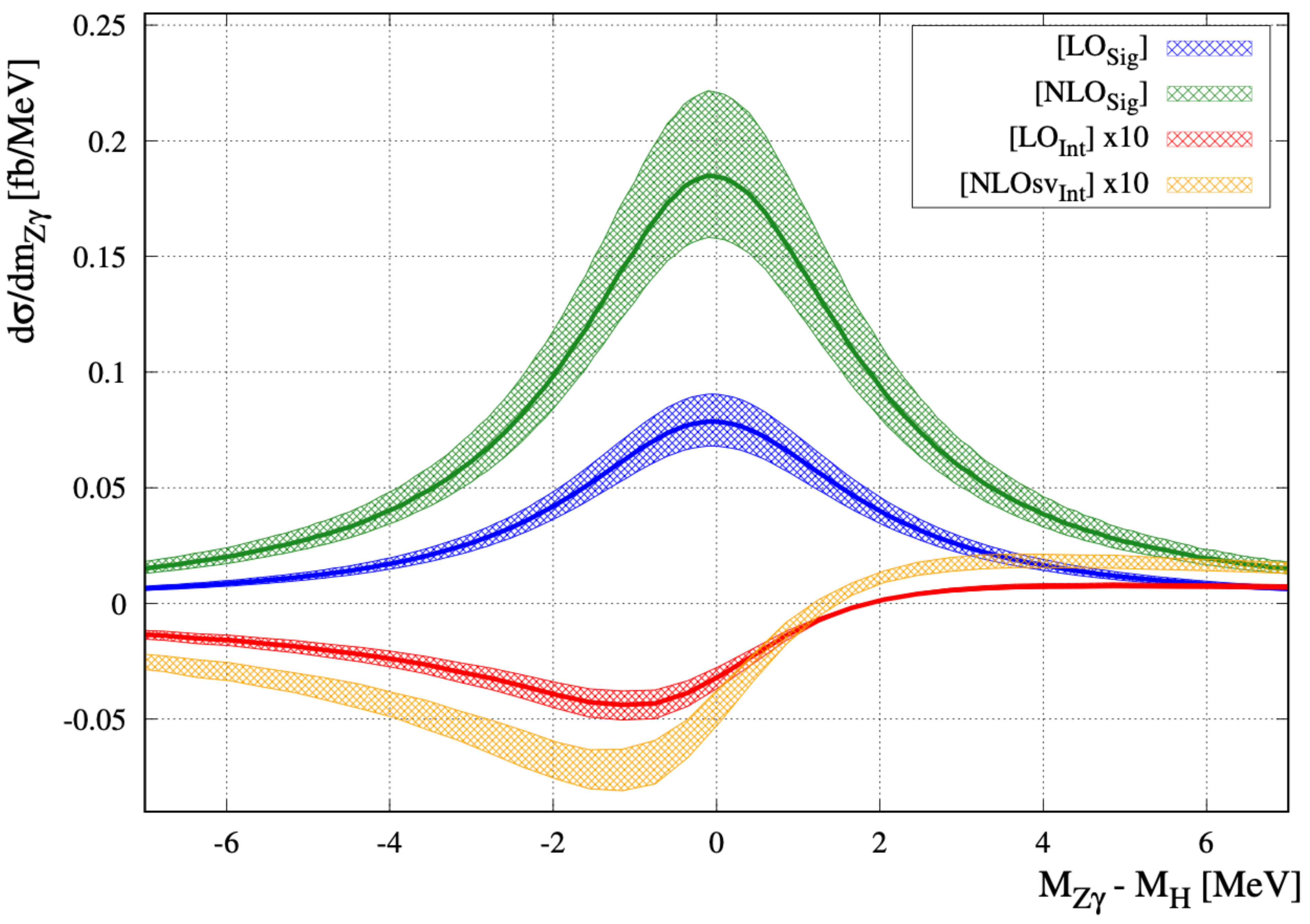
HIGGS DECAYS TO $\gamma\gamma$, $Z\gamma$: INTERFERENCE EFFECTS



Recent evidence for rare decay $H \to Z\gamma$ ATLAS + CMS [Phys.Rev.Lett 132 (2024) 021803]

Signar yield $\mu = 2.2 \pm 0.7 \times$ SM rate $\quad \mathcal{B}_{\rm exp}[H \to Z^0\gamma] = (3.4 \pm 1.1) \times 10^{-3}$

Interference effects for $H \to Z\gamma$ NLO in Soft-Virtual approx [Buccioni, Devoto, Djouadi, Ellis, Quevillon, Tancredi 2312.12384]



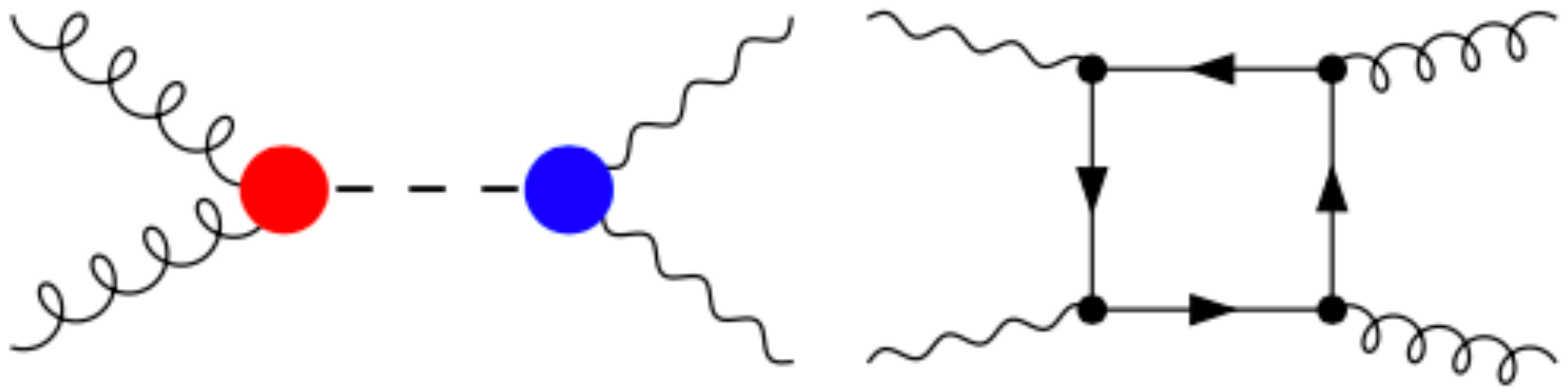
LO interference is non-zero contrary to $H \to \gamma\gamma$

Interference has destructive impact on XS ~ -3%

NLO (sv) effects small, effect **does not resolve apparent tension**

$$\sigma^{\rm NLO}_{\rm Sig} = 1.207^{+20\%}_{-15\%}\ {\rm fb},\ \ \sigma^{\rm NLOsv}_{\rm Int} = -0.0344^{+12\%}_{-12\%}\ {\rm fb}$$

HIGGS DECAYS TO $\gamma\gamma$, $Z\gamma$: INTERFERENCE EFFECTS



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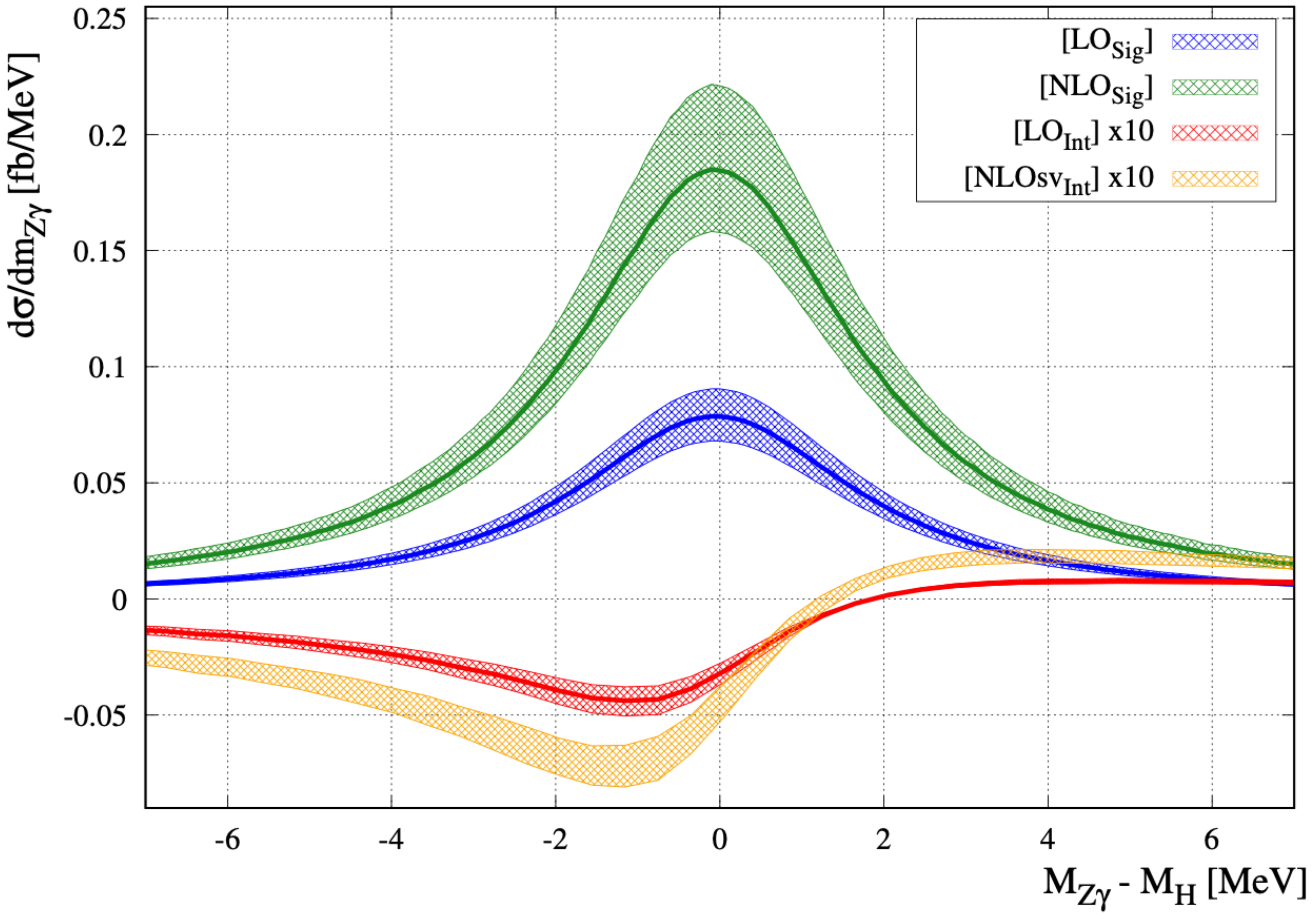

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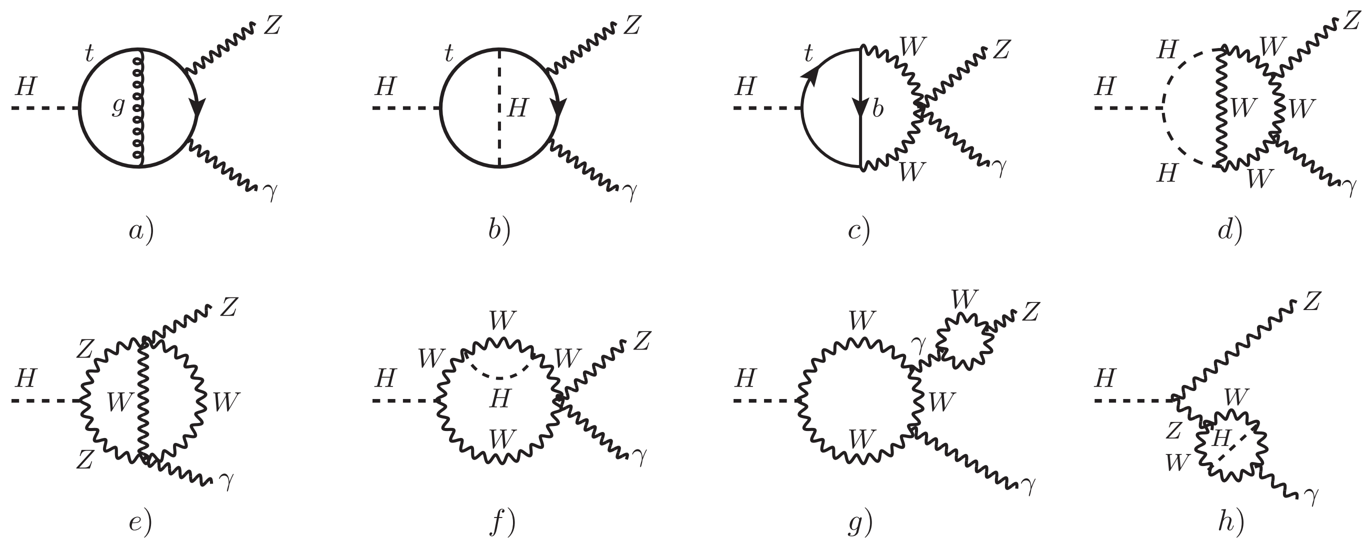
Electroweak corrections [Chen, Chen, Qiao. Zhu 2404.11441] [Sang, Feng, Jia 2405.03464]

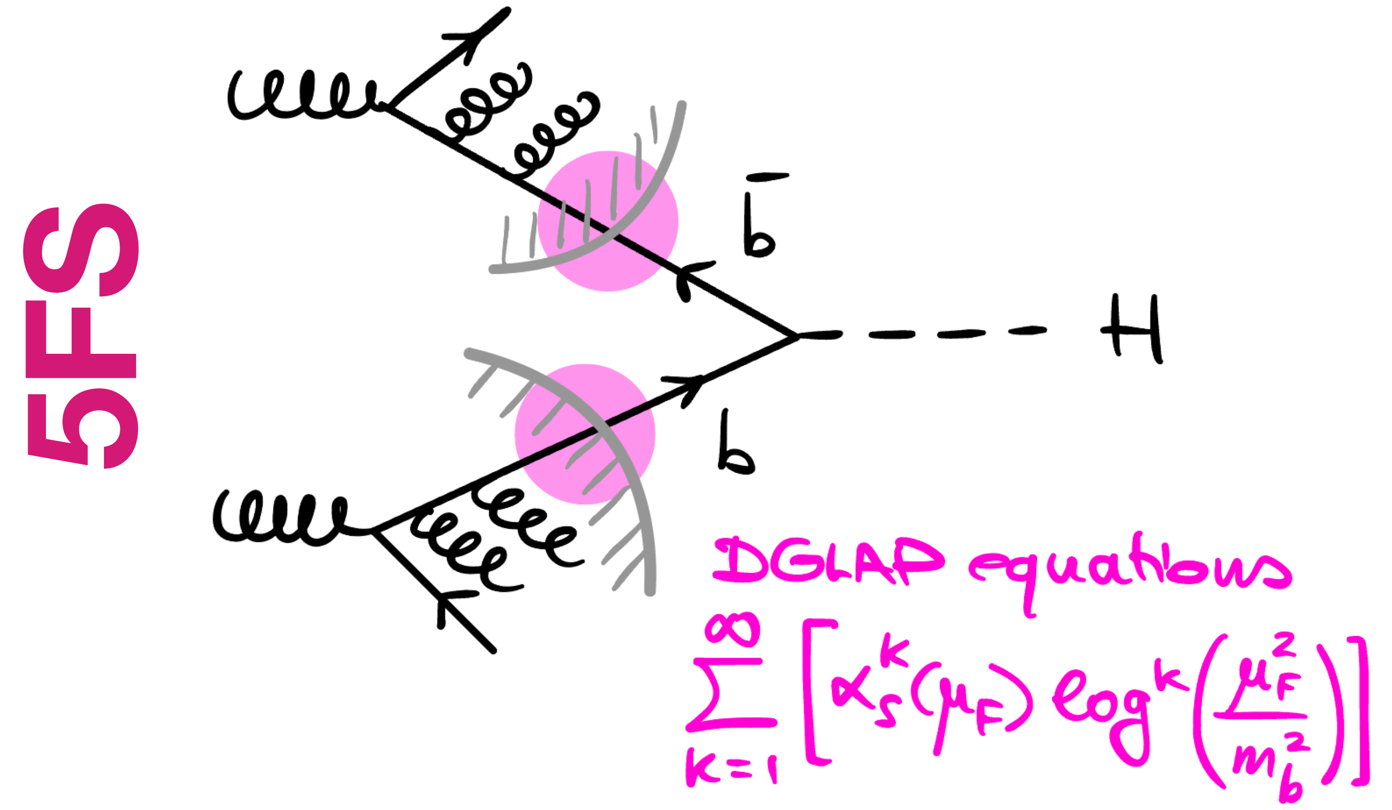


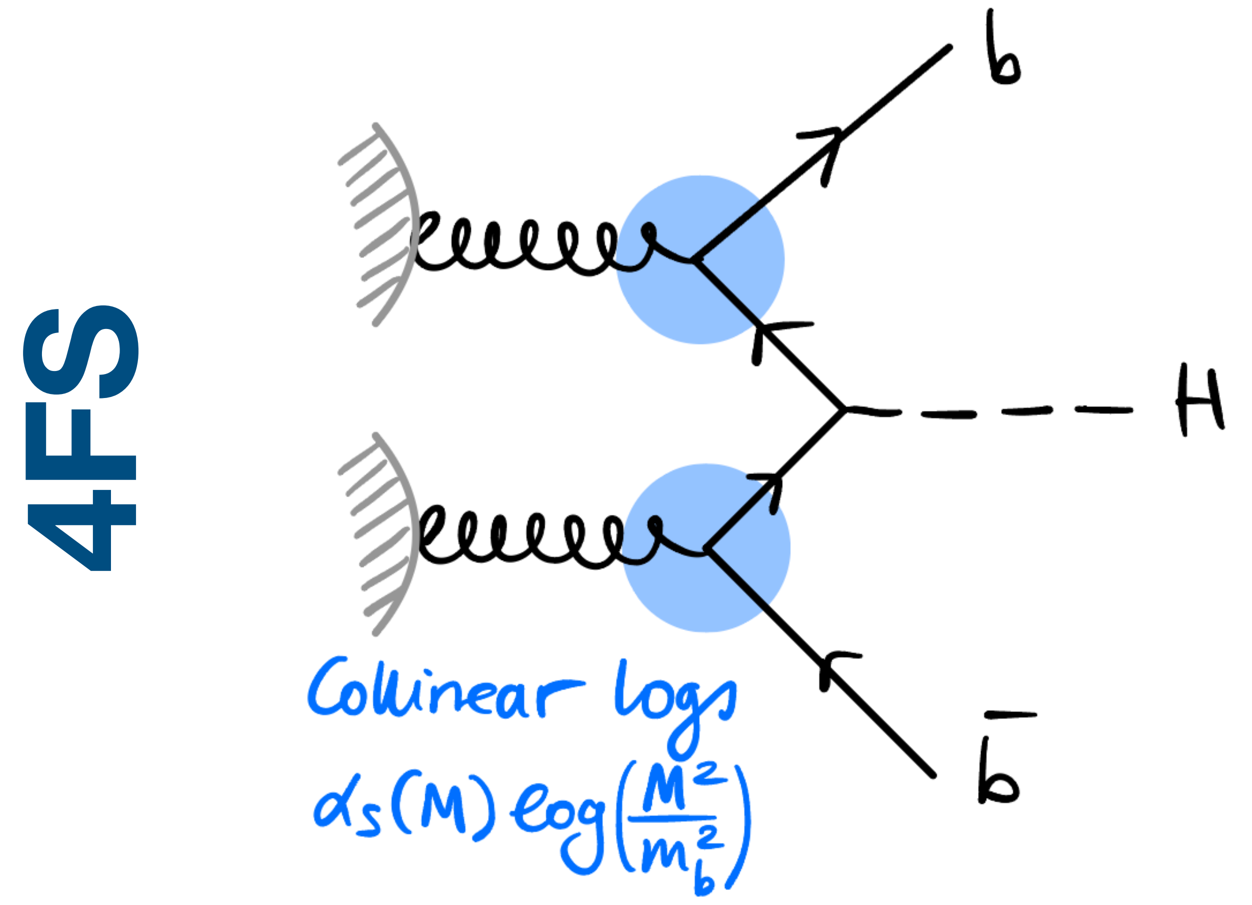
$$\mathcal{B}[H \to Z^0\gamma] = (1.55 \pm 0.06) \times 10^{-3}$$

→ tension might **resolve itself with more statistics!**

HIGGS PRODUCTION WITH B QUARKS: 5FS IN NNLO + PS

[Biello, Sankar, Wiesemann, Zanderighi 2402.04025]





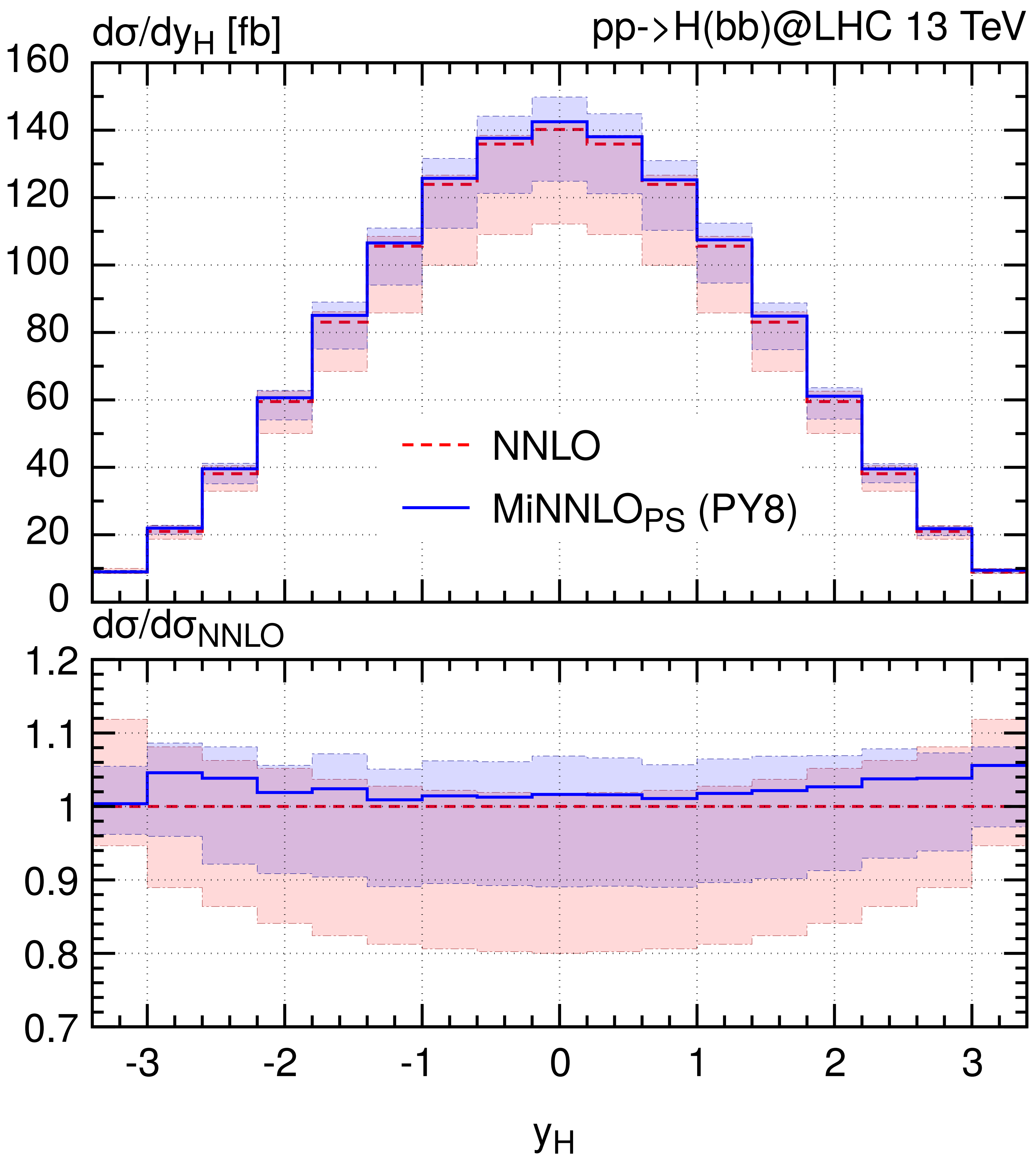
$\mathcal{O}(2\%)$ of the gluon fusion channel

Direct detection at LHC challenging

Most important background for $pp \to HH \to Hb\bar{b}$, especially at HL-LHC

calculations in 4FS more difficult

5-point amplitudes with massive quarks



Drawings from Biello, Moriond '24

NNLO XS reduced by ~ 2%

Process	NLO (SusHi)	NNLO (SusHi)	MiNLO′	MiNNLO$_{PS}$
$b\bar{b} \to H$	$0.646(0)^{+10.4\%}_{-10.9\%}$ pb	$0.518(2)^{+7.2\%}_{-7.5\%}$ pb	$0.571(1)^{+17.4\%}_{-22.7\%}$ pb	$0.509(8)^{+2.9\%}_{-5.3\%}$ pb

CONCLUSIONS

First of all, apologies for all the results I could not talk about:

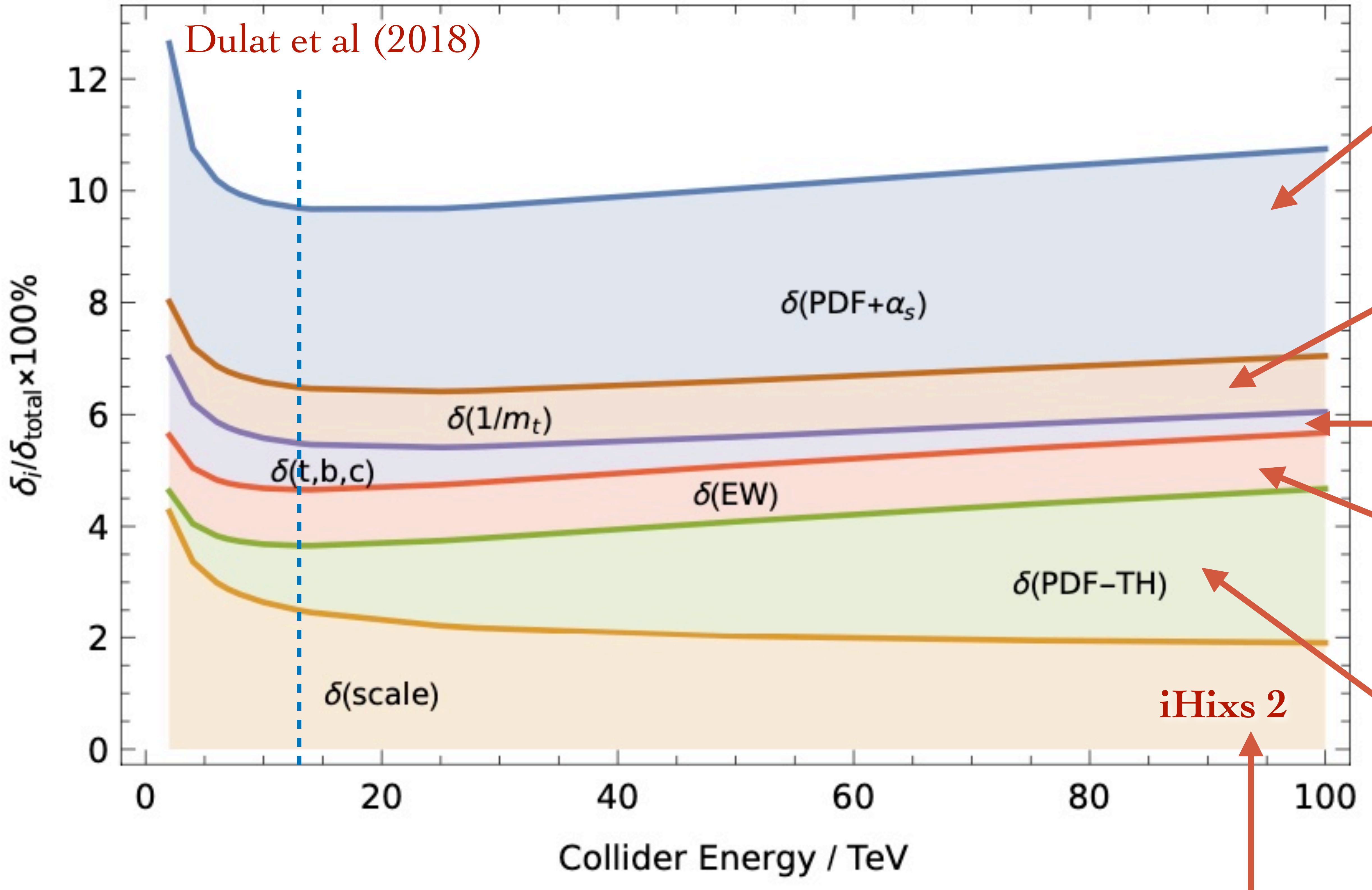
- **QCD-EW effects** (their general importance highlighted by **M. Zaro on Wednesday**)
- **di-Higgs production** **(see also J. Alison's talk on Wednesday)**
- (much) more on **Parton showers and matching**
- (much) more on **Resummation**
- …

Still I hope I could convince you (or maybe just remind you) that:

- **The Higgs is cool**! After its discovery, the LHC (HL-LHC) have started a breathtaking program of its precise characterisation
- This relies on impressive **experimental advances** AND on equally impressive **theoretical calculations**
- The devil is in the details: subtle effects, interference, jet flavour, spurious effects from cuts etc…
- **To truly understand the Higgs boson, concerted effort between theory and experiment!**

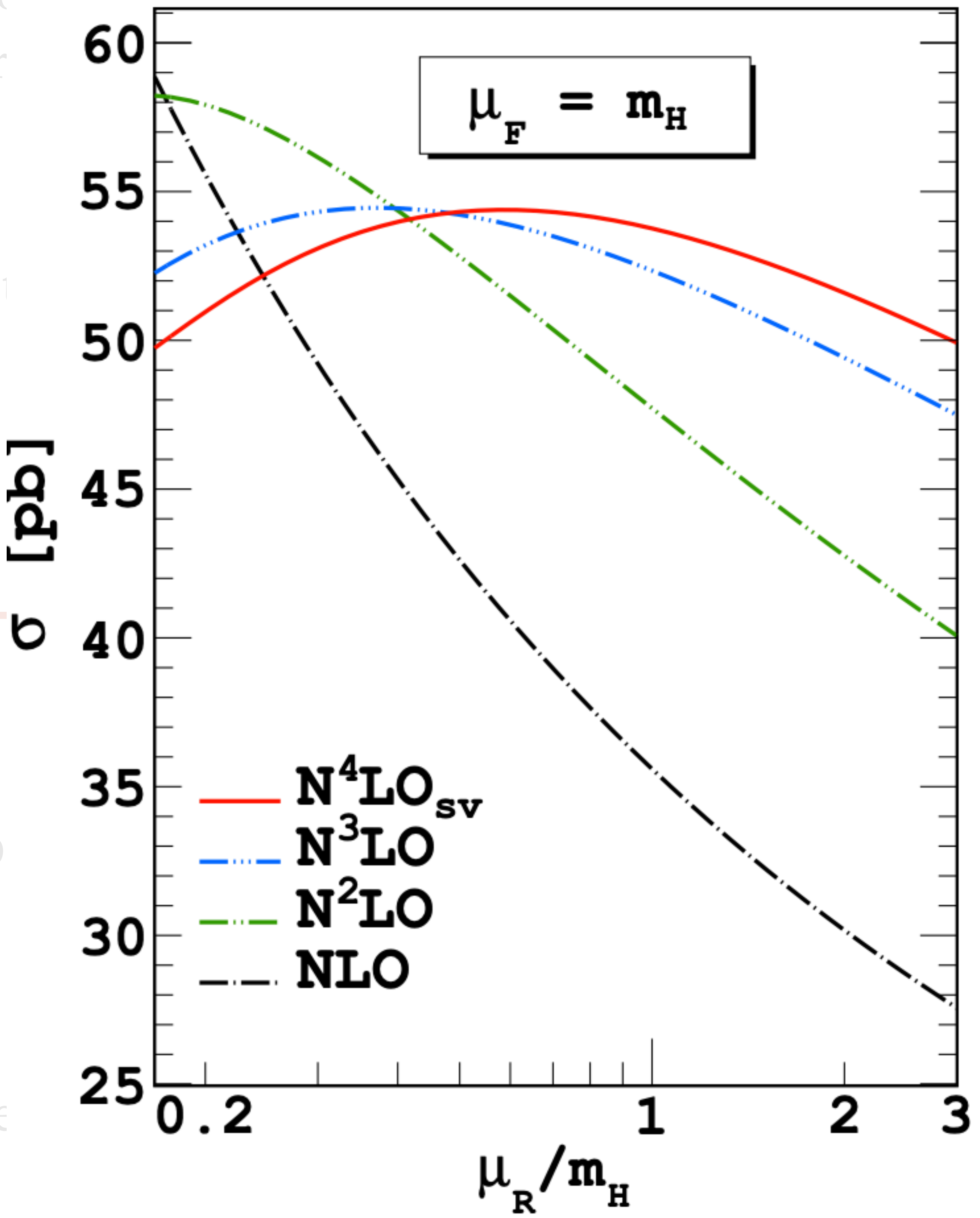
THANK YOU !

GLUON FUSION: BEYOND N3LO HEFT



[Dulat, Lazopoulos, Mistlberger 1802.00827]

Beyond requires N^{4}LO



Soft-virtual N^{4}LO by [Das et al 2004.00563]