Higgs Hunting 2023

Theory concluding talk

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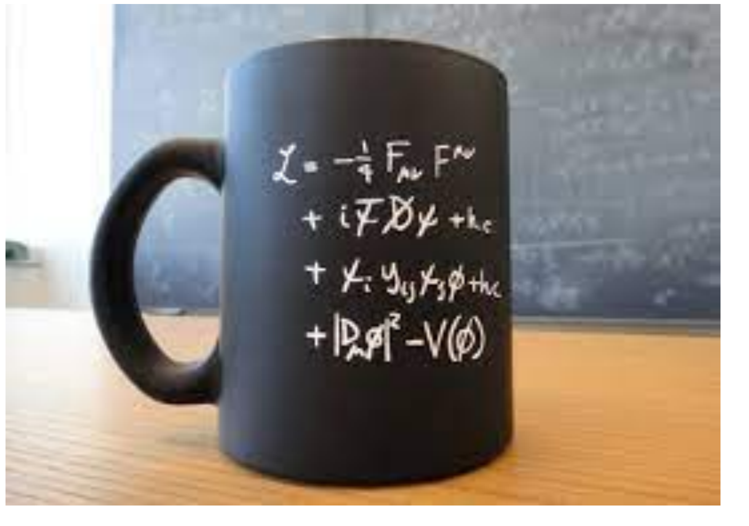
The Standard Model

$$\mathscr{L}_{\text{gauge}} \qquad\qquad \mathscr{L}_{\text{SB}}$$

$$\mathscr{L}_{SM} = -\frac{1}{4}F_{\mu\nu}F^{\mu\nu} + \bar{\psi}i\not{D}\,\psi + (D_\mu\phi)^\dagger(D_\mu\phi) + \mu^2\phi^\dagger\phi - \lambda(\phi^\dagger\phi)^2 + \left(\lambda^{ij}\bar{\psi}_L^i\phi\psi_R^j + \text{h.c.}\right)$$

- natural
- highly symmetric
- precisely tested over the last 50 years
- UV insensitive



The Standard Model

$\mathscr{L}_{\mathrm{SB}}$

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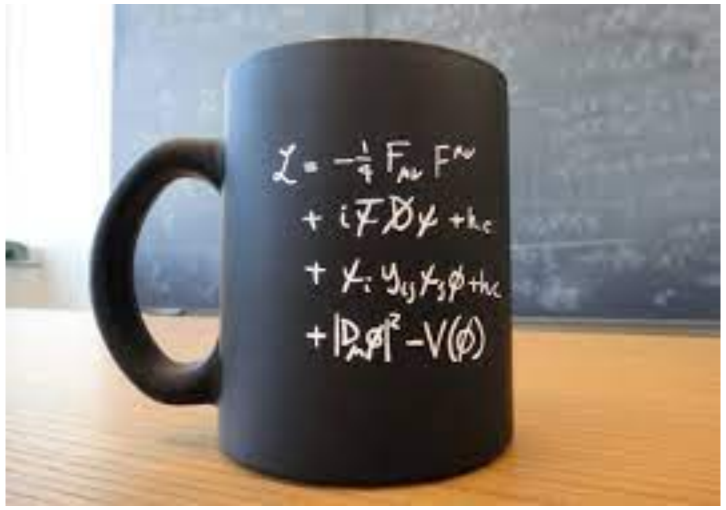
$\Delta\mu^2 \sim \Delta m_H^2 \sim \Lambda^2$

vacuum (meta)stability

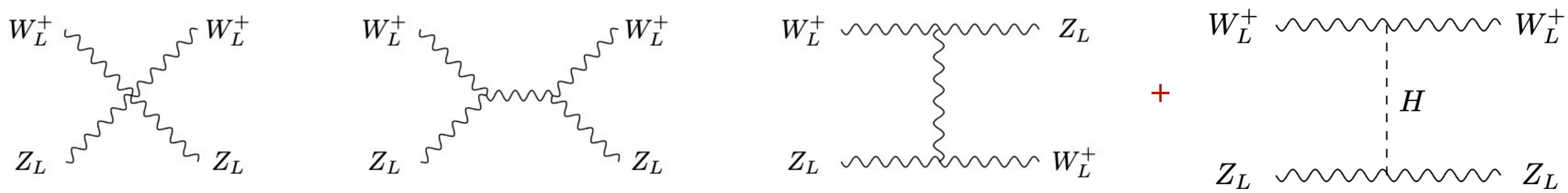
Flavour problem

source of most of the SM problems but at the time the simplest solution providing the necessary ingredients to break the EW symmetry



Higgs, unitarity and Naturalness

In the SM the Higgs boson preserves unitarity in high energy vector boson scattering



➡ No-lose theorem: something had to happen at the TeV scale !

Once the Higgs is in place, the necessity of new physics invoking Naturalness is not a theorem any more !

Or maybe yes ?

Dvali (2021)

Naturalness

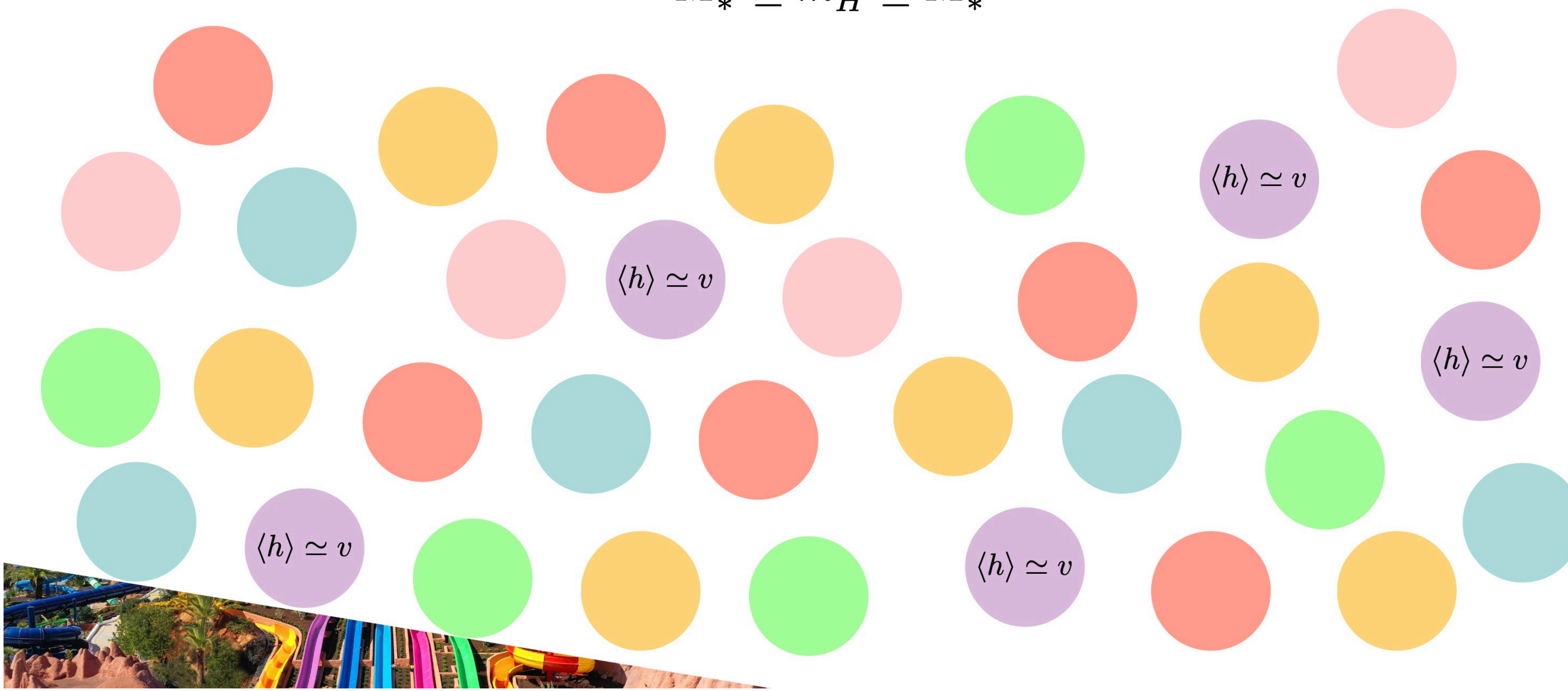
Cosmological solution:

Talk by Tito d'Agnolo

SLIDING NATURALNESS

Landscape of Higgs Masses populated by inflation

$$-M_*^2 \leq m_H^2 \leq M_*^2$$



Naturalness

Cosmological solution:

Talk by Tito d'Agnolo

SLIDING NATURALNESS

After reheating and a time

$$t_c \sim 1/H(\Lambda_{\mathrm{QCD}}) \sim 10^{-5}\ s$$

All patches where the Higgs vev

$\langle h \rangle \simeq v$

$$\langle H^0 \rangle \equiv h$$

$\langle h \rangle \simeq v$

Is outside of a certain range

$$h_{\mathrm{min}} \lesssim h \leq h_{\mathrm{crit}}$$

$\langle h \rangle \simeq v$

crunch

$\langle h \rangle \simeq v$

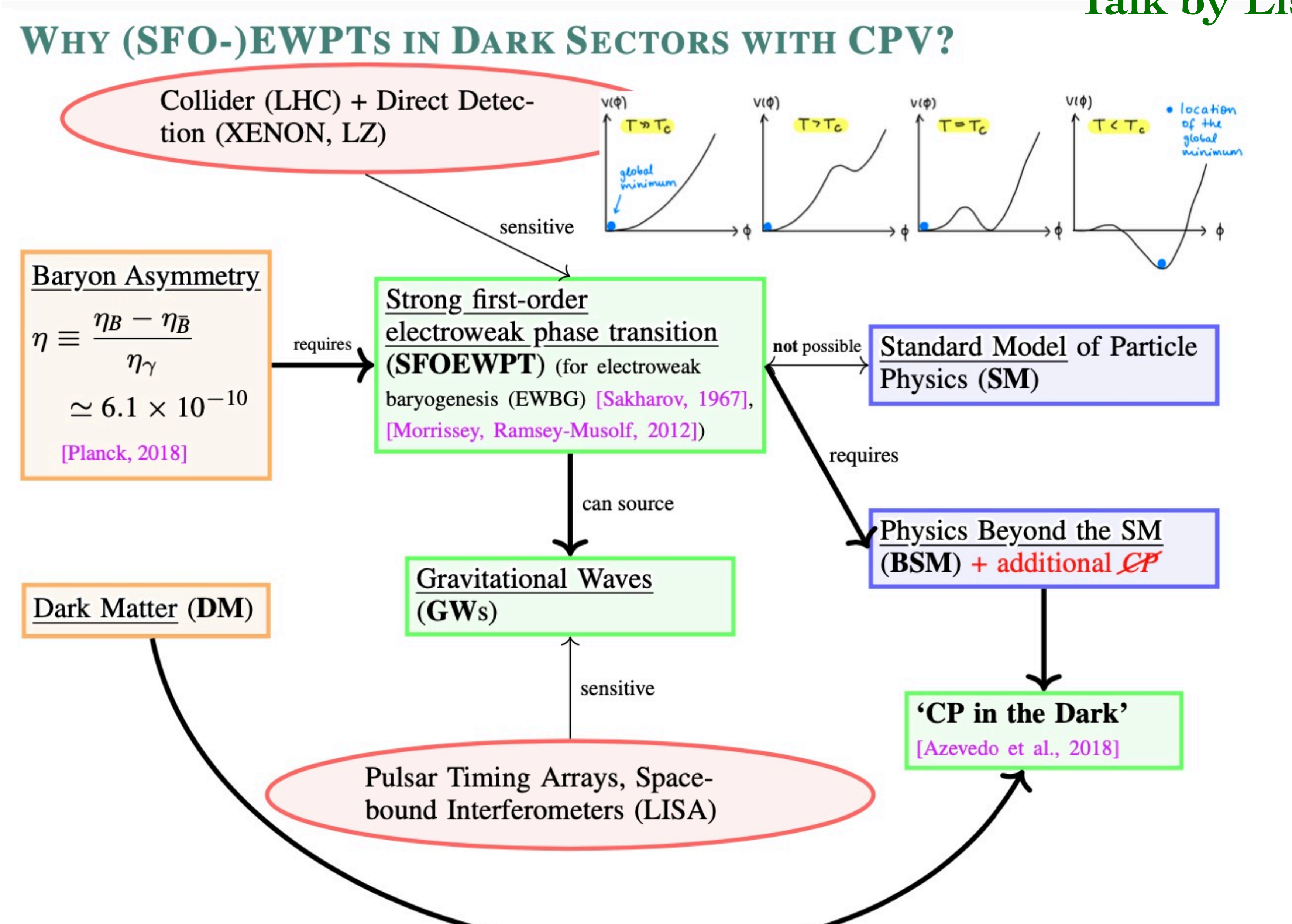
$\langle h \rangle \simeq v$

The role of the Higgs

The Higgs boson can be the key to unlock the mysteries of our Universe

- Extended Higgs sector of N2HDM can provide explicit CP violation, a first order EW phase transition and a stable dark matter candidate

Talk by Lisa Biermann

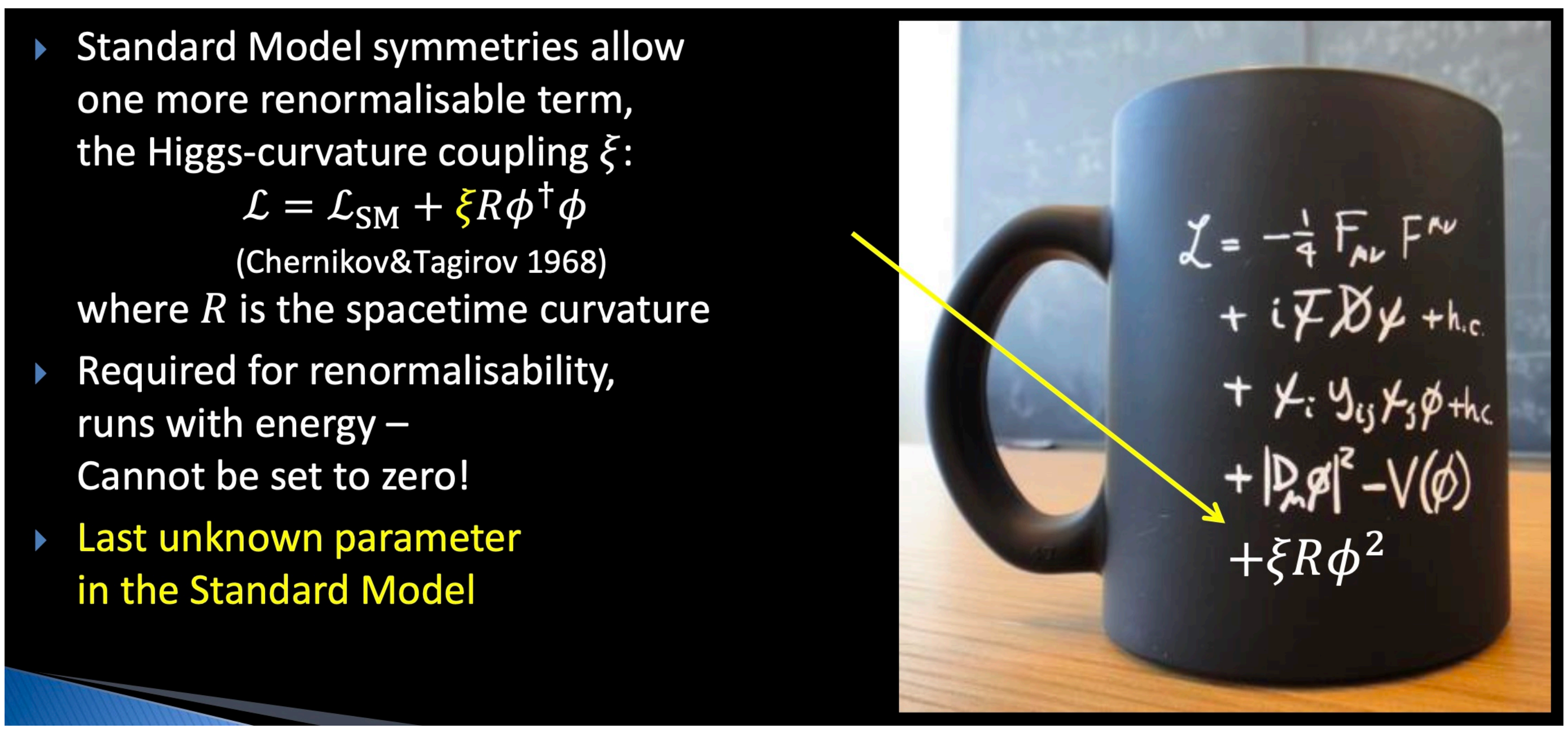


The role of the Higgs

The Higgs boson can be the key to unlock the mysteries of our Universe

- Vacuum metastability allows us to constrain the non-minimal gravitational coupling of the Higgs field….

Talk by Arttu Rajantie



But at the same time the conclusion on metastability requires absence of new-physics up to the Planck scale

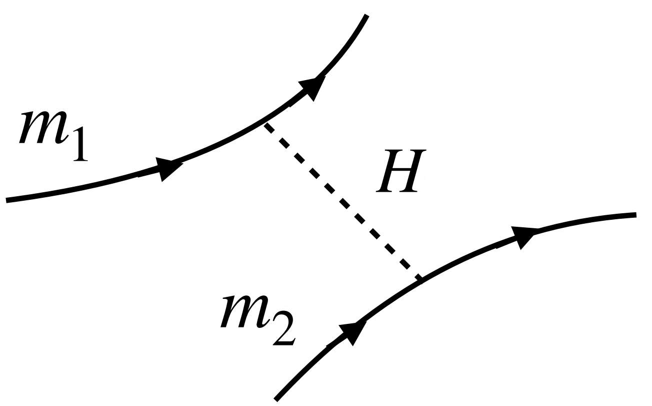
Branchina, Messina (2013)

….and so what ?

The Higgs sector provides an effective description of the symmetry breaking phenomenon, but we miss a deep understanding of the relevant dynamics

- An elementary scalar (for the first time not a gauge boson !) appears to **mediate a new kind of force**, which is proportional to particle masses

  The force mediated by the Higgs Boson is **similar to the gravitational force**, though, contrary to it, it has **short range**



- Or is it composite ?

Composite Higgs

Talk by Andrea Wulzer

We must check if the Higgs is elementary.
If so, it is the first spin-zero elementary particle

The Naturalness Paradox shows that is hard to incorporate such particles in Wilsonian interpretation of QFT

We can formulate fully realistic Composite Higgs models

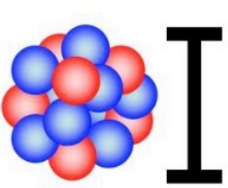
Higgs must be a Goldstone boson of a new symmetry group.

Tuning one single parameter $\xi = \frac{v^2}{f^2} < 1$ we make all its coupling SM-like

Rich phenomenology: Composite sector resonances; Higgs couplings modifications; new EFT interactions of d>4. All this, broadly controlled only by:

$m_* = 1/r_H$
The Higgs inverse size

$g_* = m_*/f$
The coupling-strength of resonances



$r_H = 1/m_*$

Composite Higgs

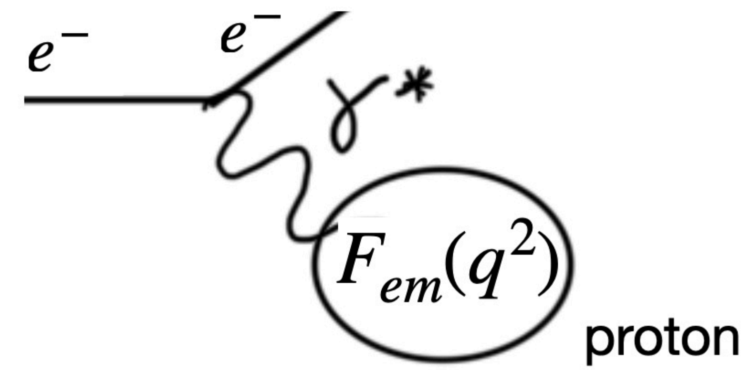
Talk by Andrea Wulzer

What is the "Direct" test of Higgs compositeness ?

Obviously, the one that displays that is not point-like (i.e., not elementary).

Just like for the proton:

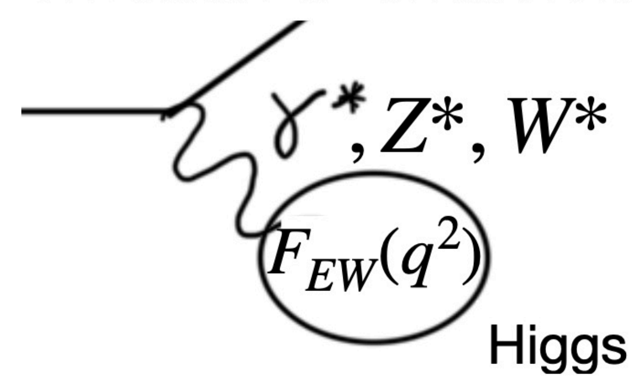
Virtual photon with $E \sim 100$ MeV found to interact with a non-trivial "form-factor", unlike what predicted for the interaction with a point-like proton.



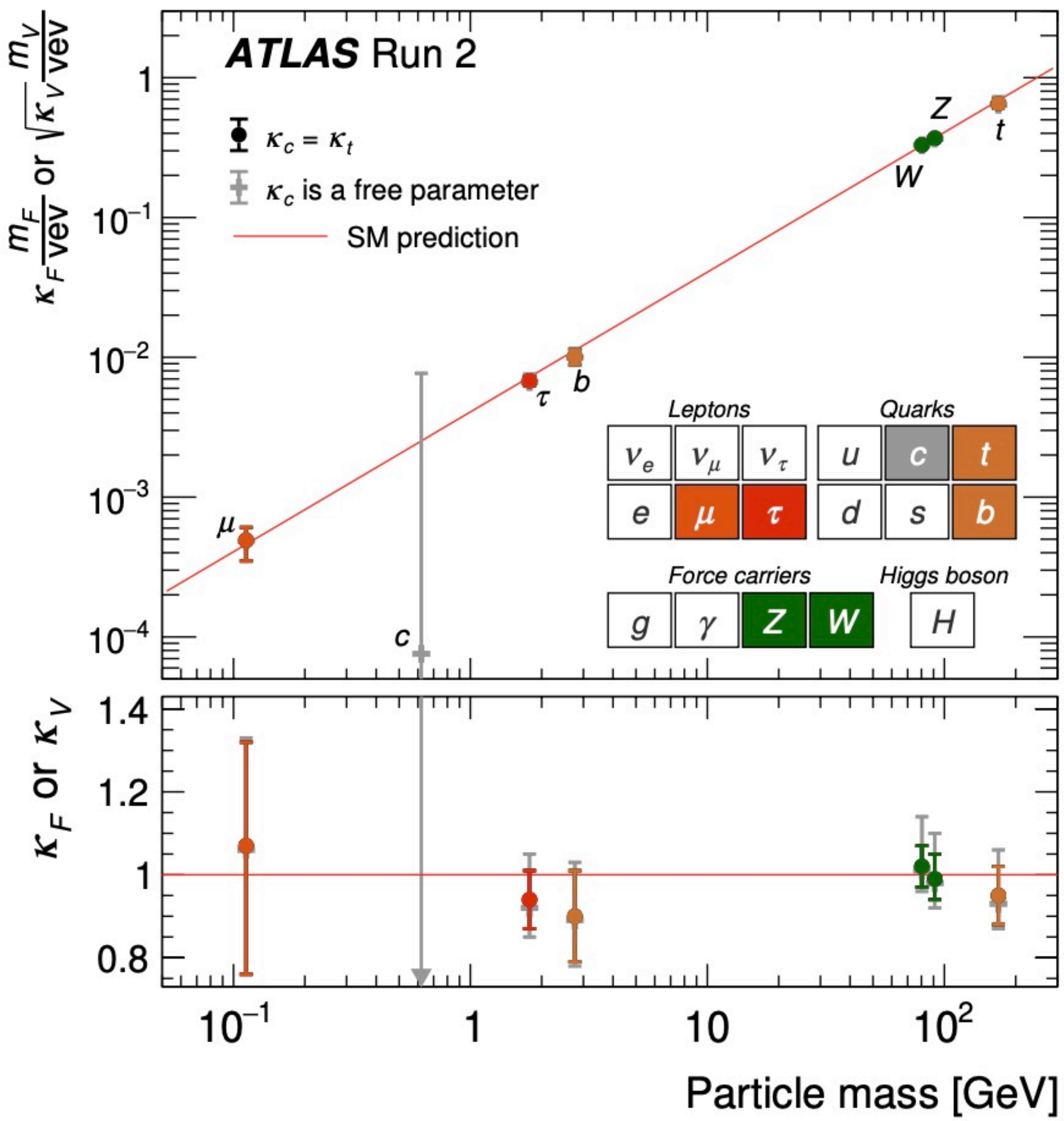
High energy has been essential: $E \lesssim 1/r_p$

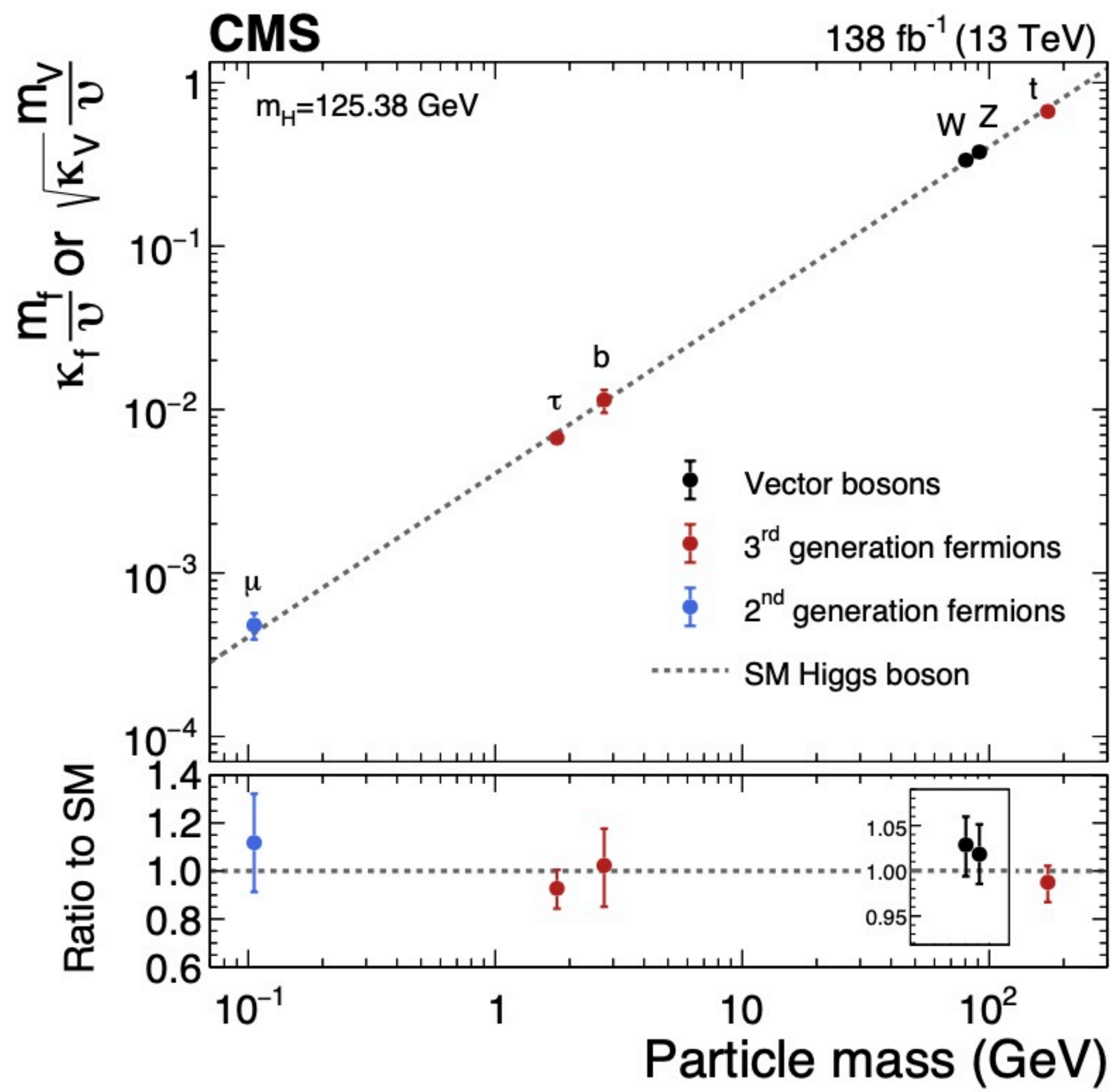
We can probe Higgs Form-Factors by virtual s-channel EW bosons

HZ and HW at cross-section measurement at a very high energy collider



Higgs couplings



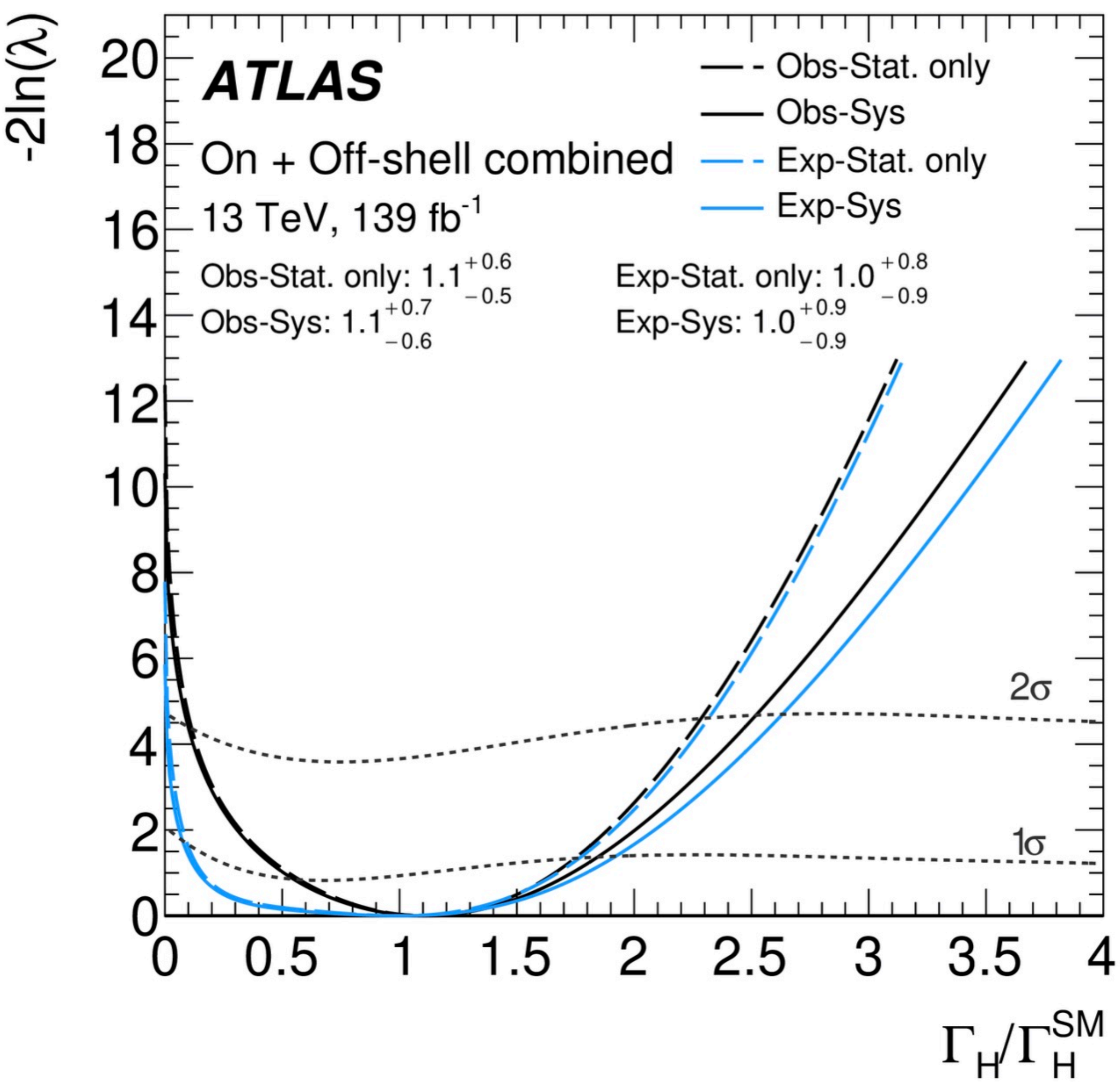


Agreement with SM within three order of magnitude in mass !

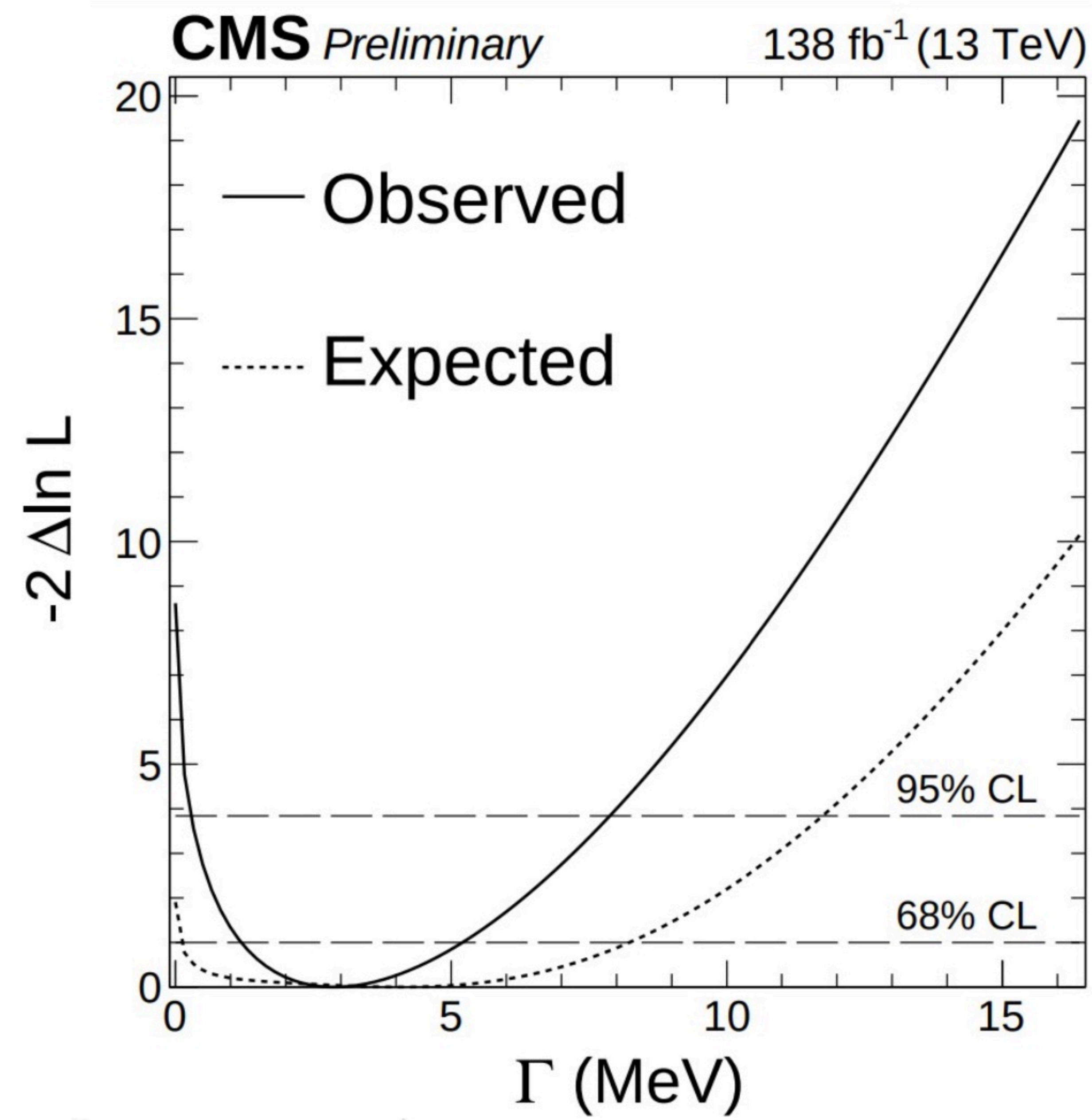
Width

$\Gamma_H = 4.5^{+3.3}_{-2.5}\,\mathrm{MeV}$

$\Gamma_\mathrm{H}\ (\mathrm{MeV}) \;=\; 2.9^{+2.3}_{-1.7}\ [0.3, 7.9]$



Talk by Carsten Burgard



Talk by Savvas Kyriacou

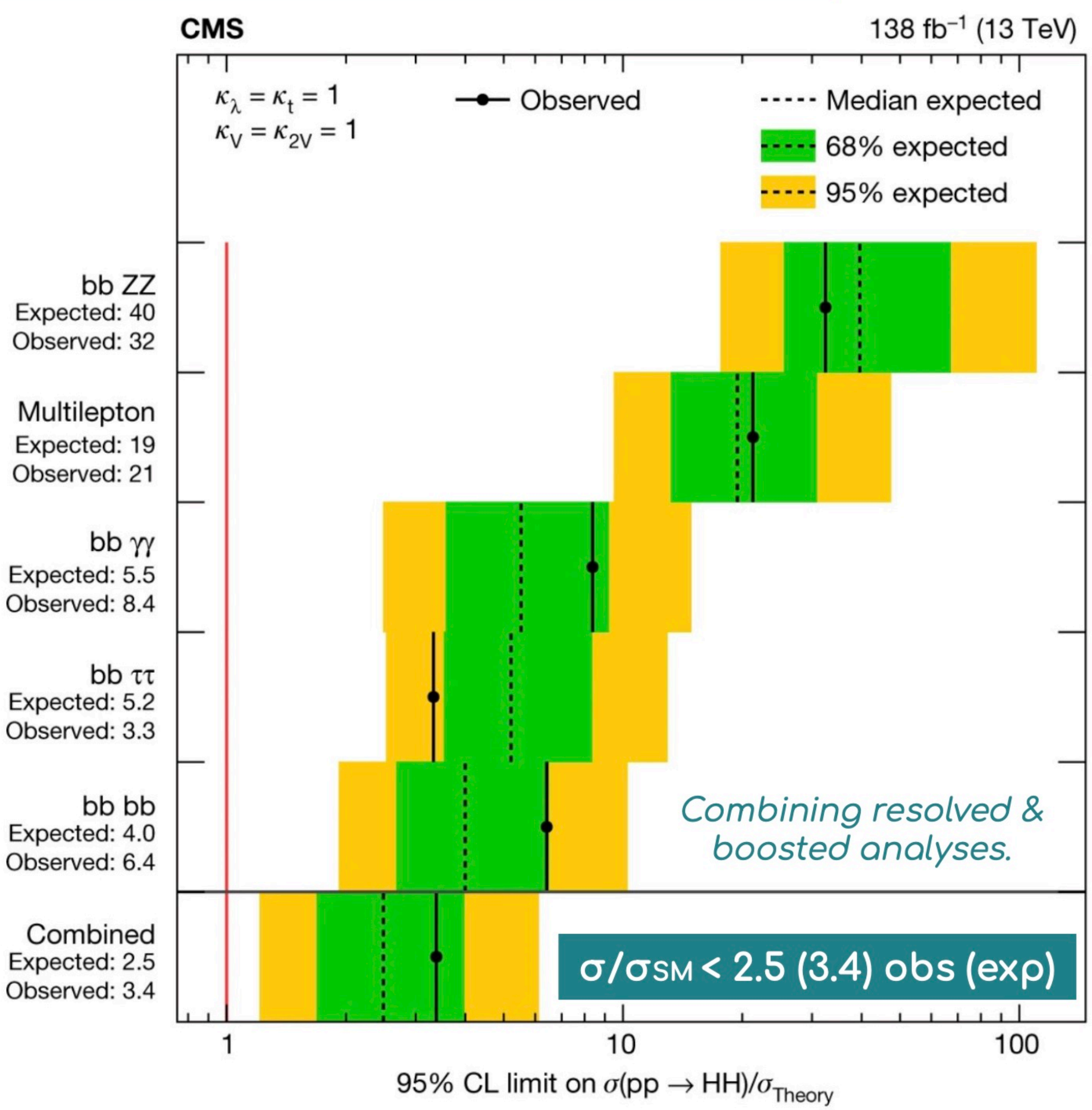
HH

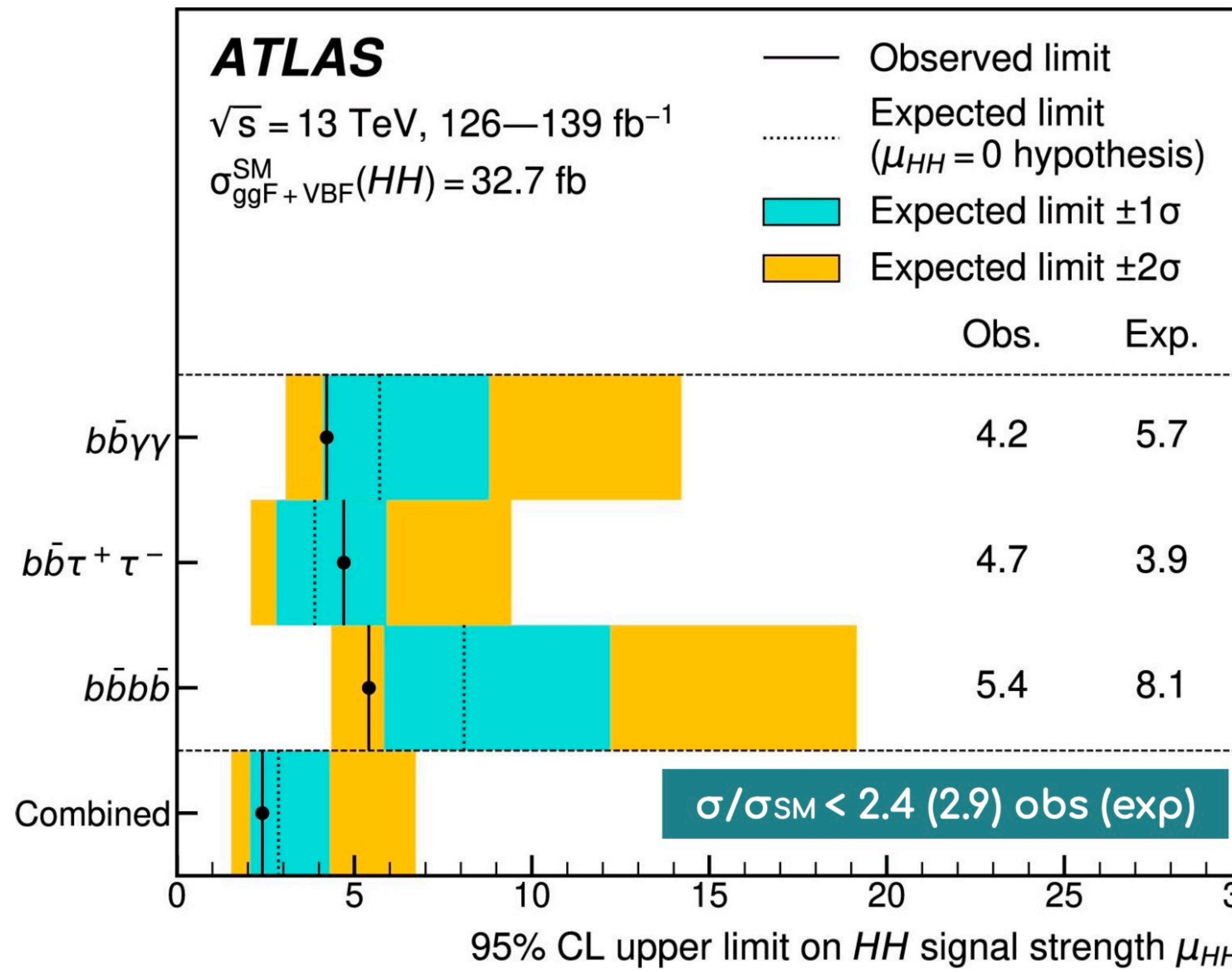
Latest results

(finding the SM HH process)

Best HH combinations from both CMS and ATLAS experiments. Both are very competitive... and approaching the SM.

Results are ~5 better than earlier Run 2 results. *Jona M.*

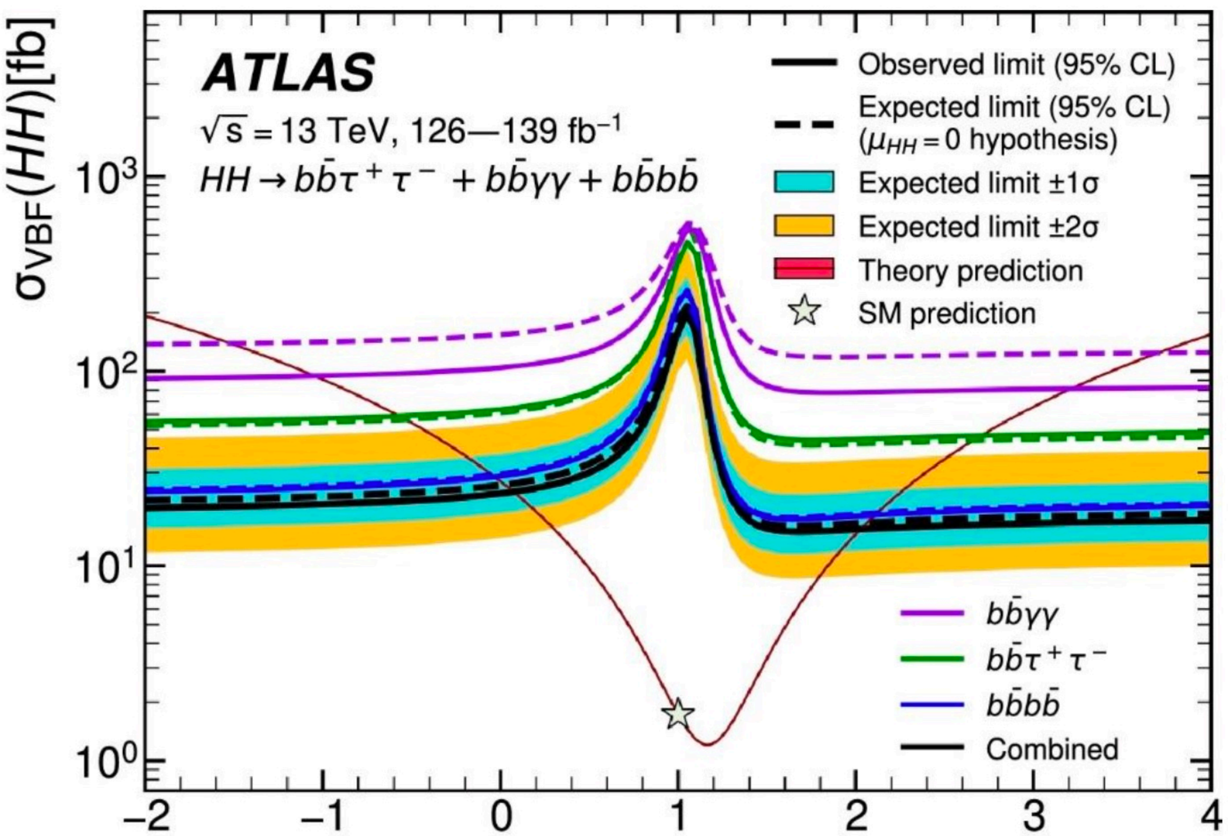




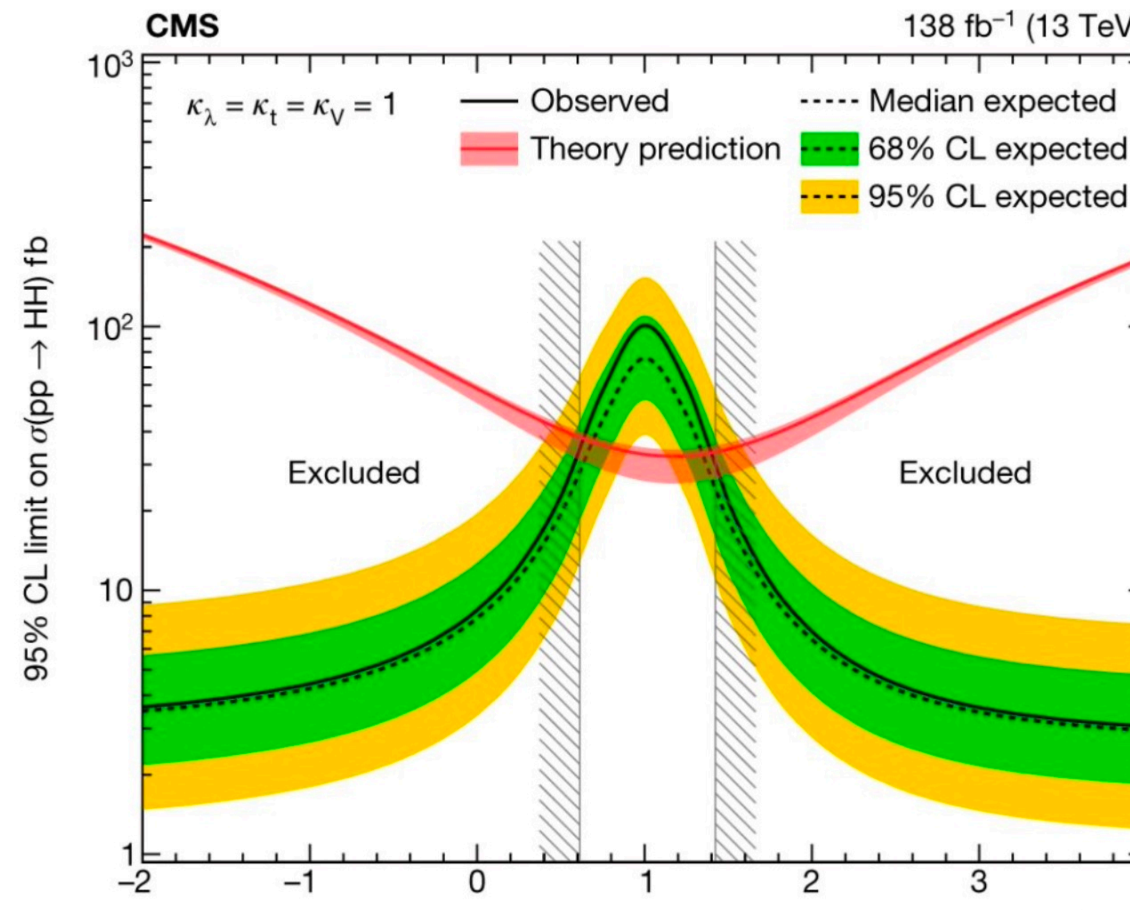
HH

Couplings

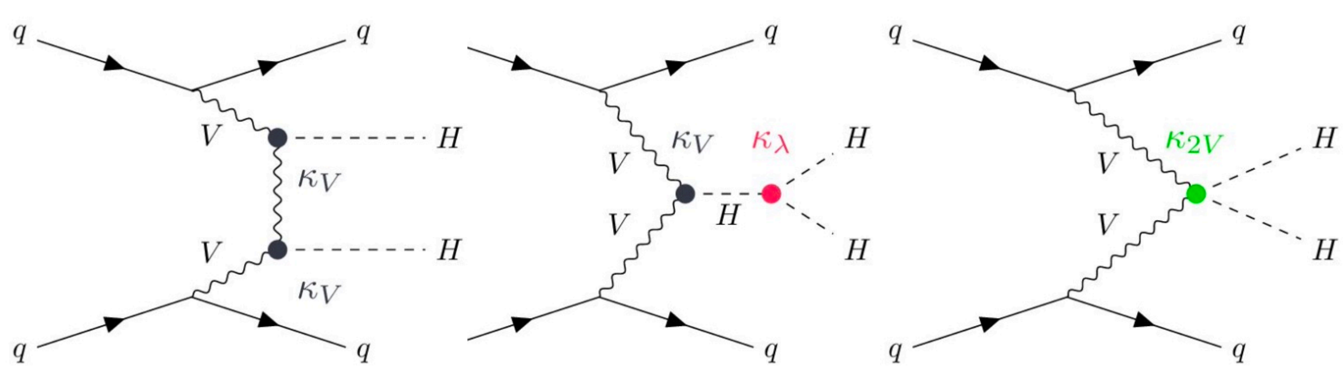
(profiling the HH process)



$\kappa_{2V} \in [0.1, 2.0]$



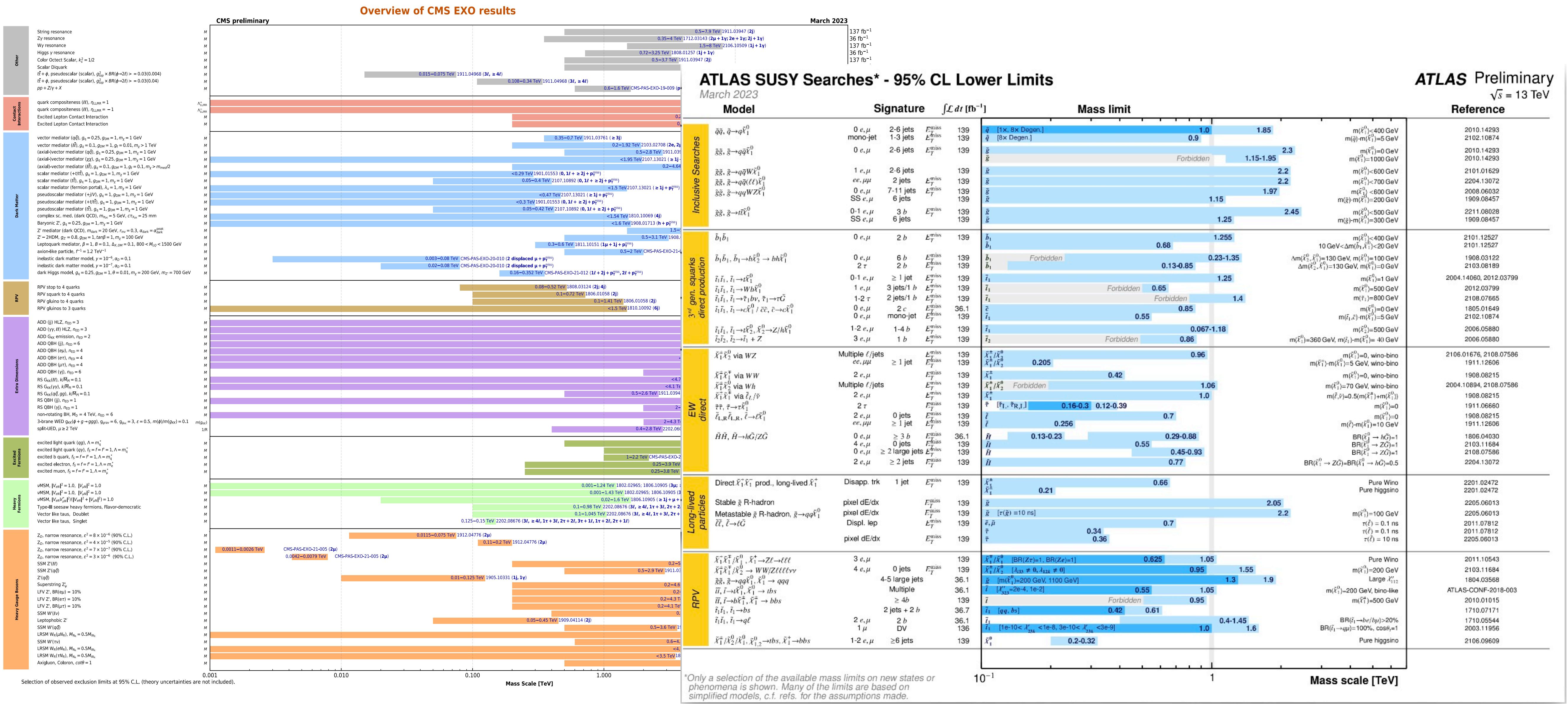
$\kappa_{2V} \in [0.67, 1.38]$



Impressive results from HH→bbbb **boosted** analysis: identifying boosted bb-tagged jets with ParticleNet.

VVHH coupling established at 6.6σ significance level.

…but no sign of New Physics yet

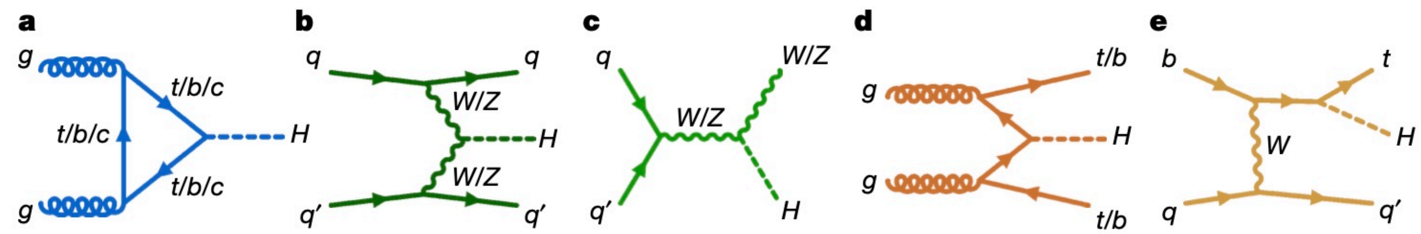


The role of precision theory….

Talk by Aude Gehrmann-De Ridder

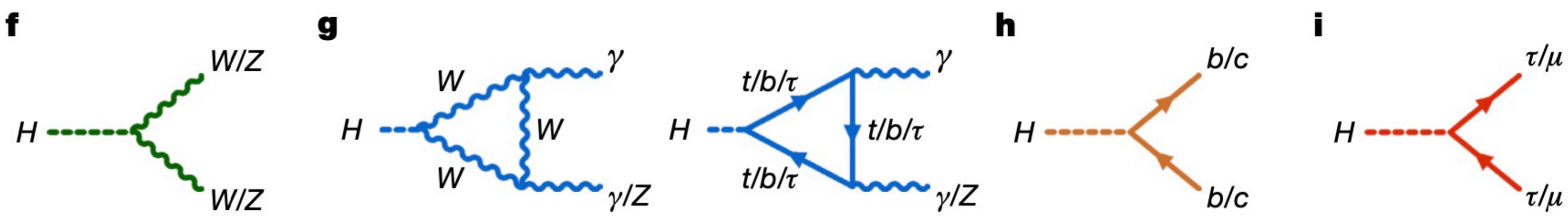
Higgs production and decay

- Higgs production:



  - gluon-gluon fusion dominant: thoroughly studied in theory, precise predictions, mostly in heavy-top EFT

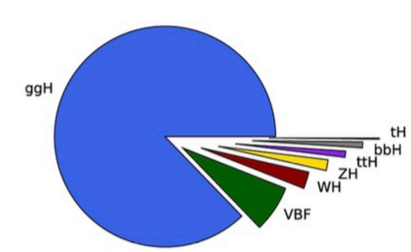
- Higgs Decay:

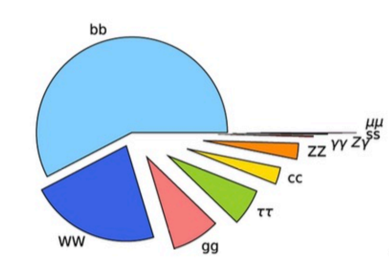


  - Rare loop-induced channels (like $\gamma\gamma$) prefered over dominant modes (e.g. bottom quarks) due to large and irreducible QCD background

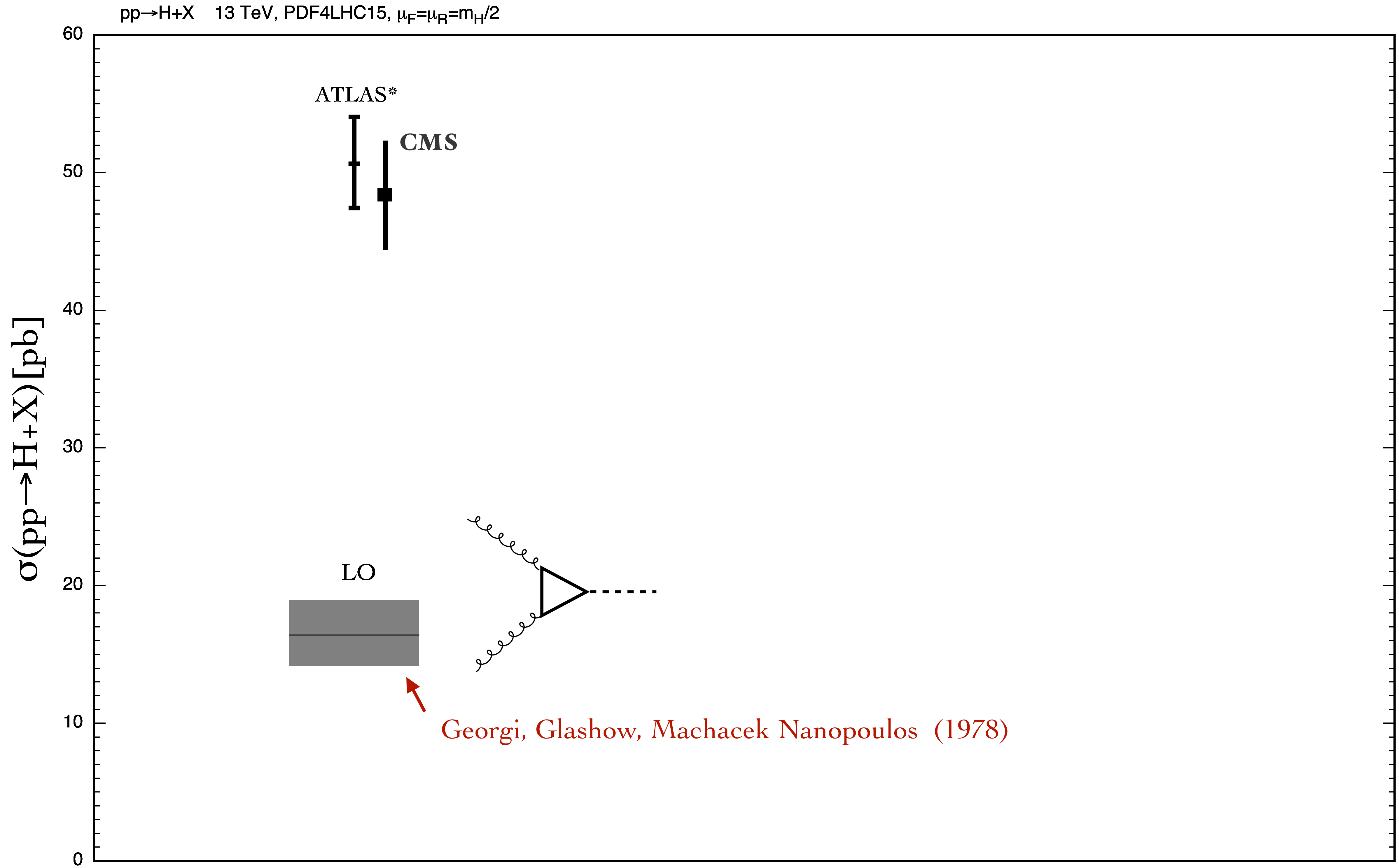
Production mode	Cross section (pb)	Decay channel	Branching fraction (%)
ggH	48.31 ± 2.44	bb	57.63 ± 0.70
VBF	3.771 ± 0.807	WW	22.00 ± 0.33
WH	1.359 ± 0.028	gg	8.15 ± 0.42
ZH	0.877 ± 0.036	$\tau\tau$	6.21 ± 0.09
ttH	0.503 ± 0.035	cc	2.86 ± 0.09
bbH	0.482 ± 0.097	ZZ	2.71 ± 0.04
tH	0.092 ± 0.008	$\gamma\gamma$	0.227 ± 0.005
		$Z\gamma$	0.157 ± 0.009
		ss	0.025 ± 0.001
		$\mu\mu$	0.0216 ± 0.0004

- Higgs signal: need to combine production and decay, challenging for experiment and theory
  - Relative importance of production and decay modes at √s=13 TeV [Higgs Working group (2016): CMS Nature (2022) 2207.00043]





The role of precision theory….



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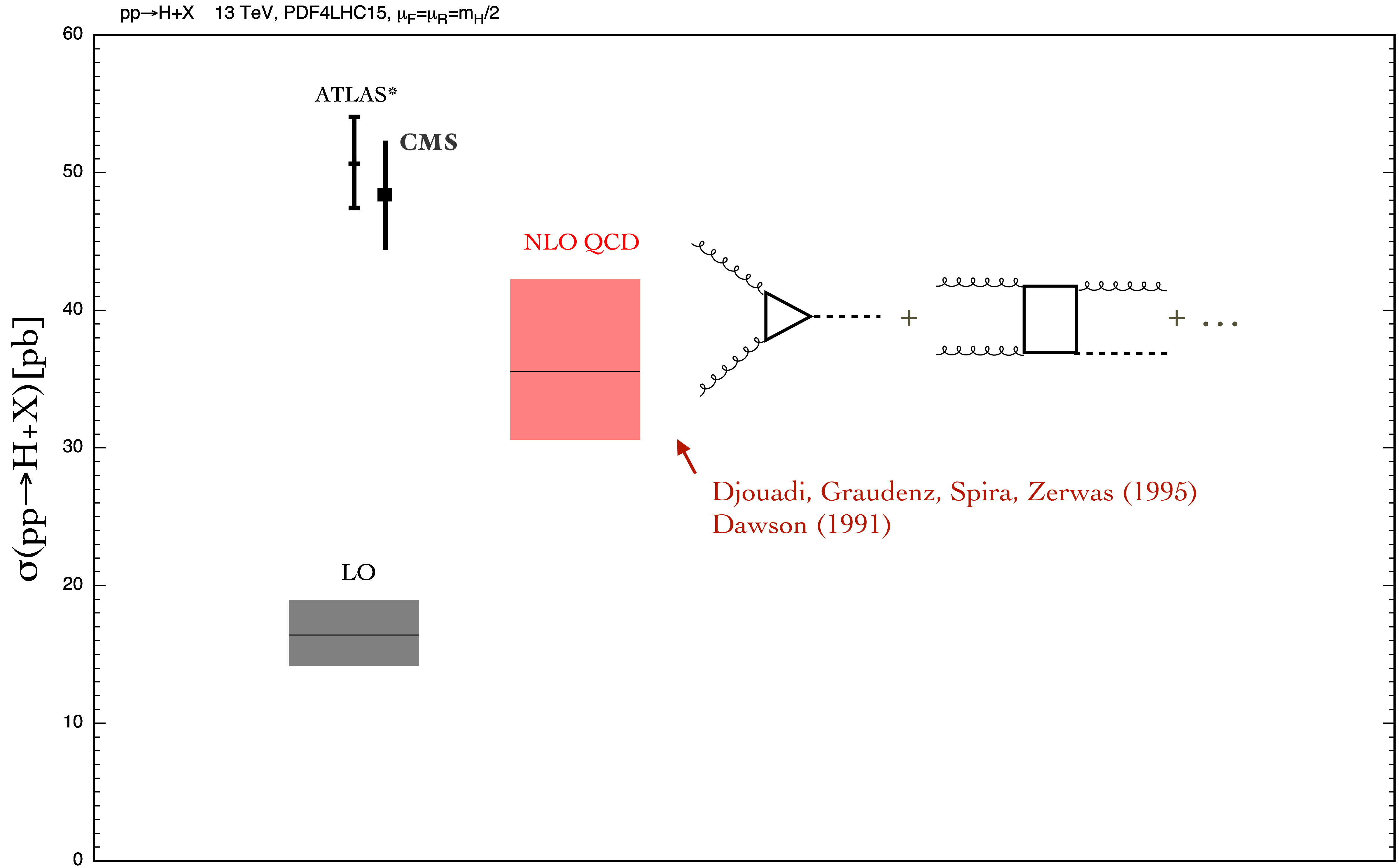

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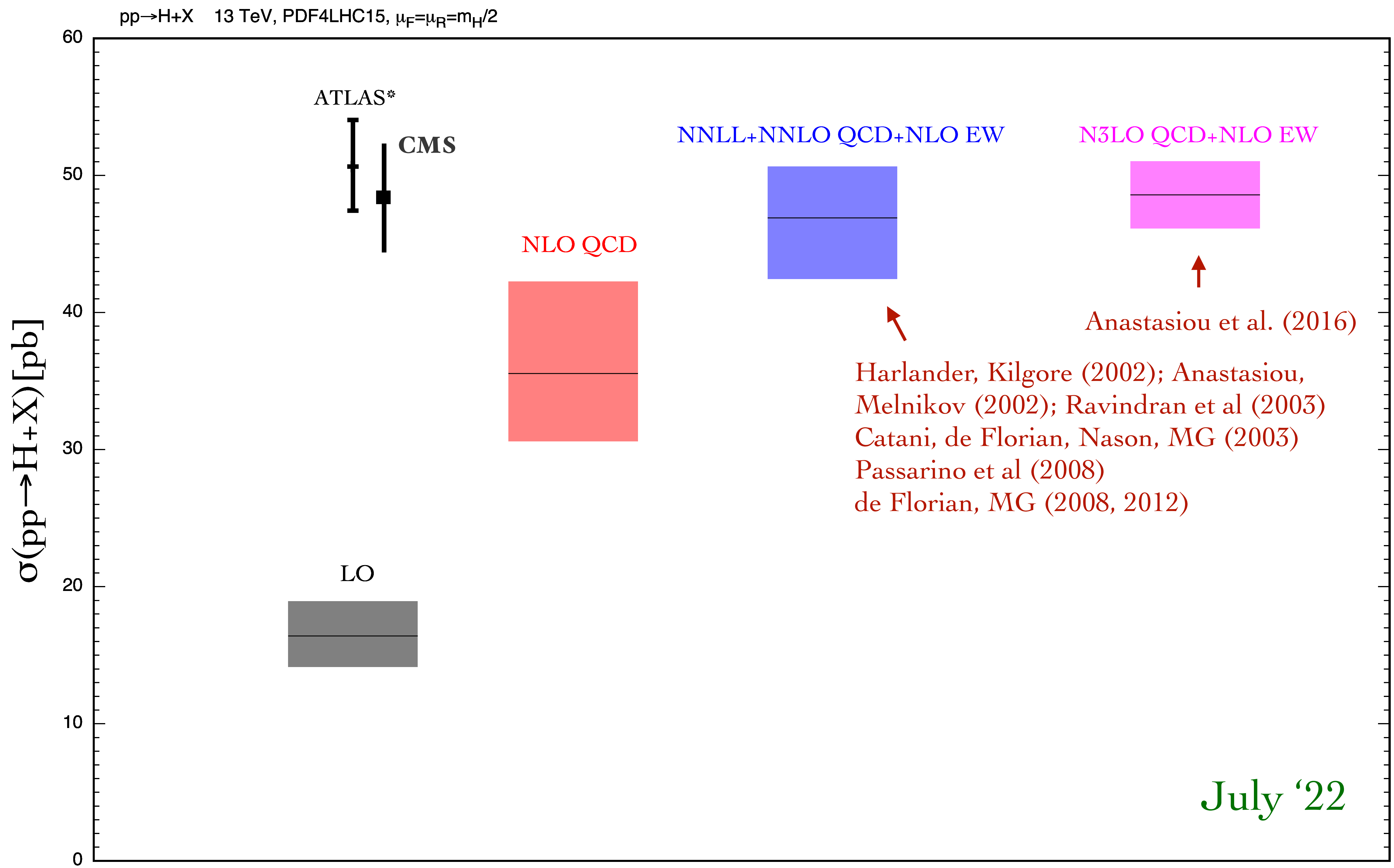
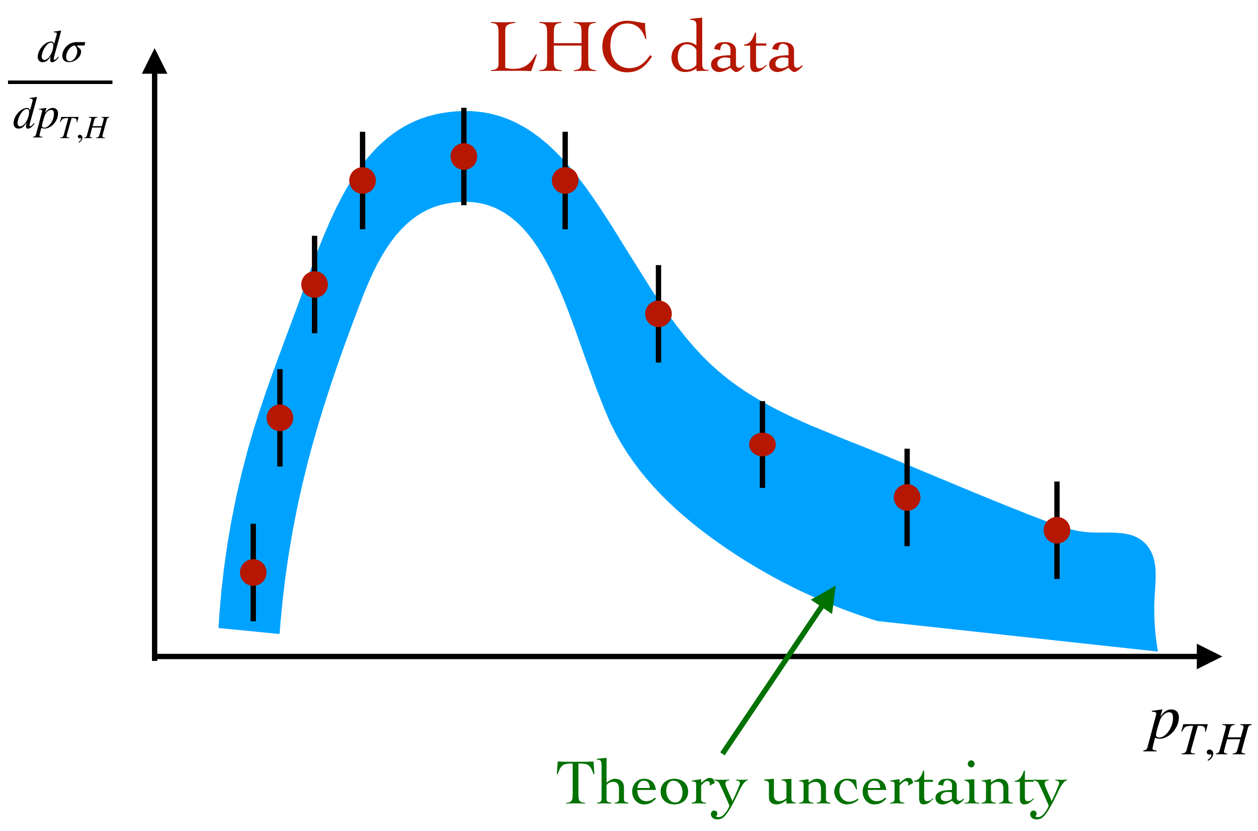
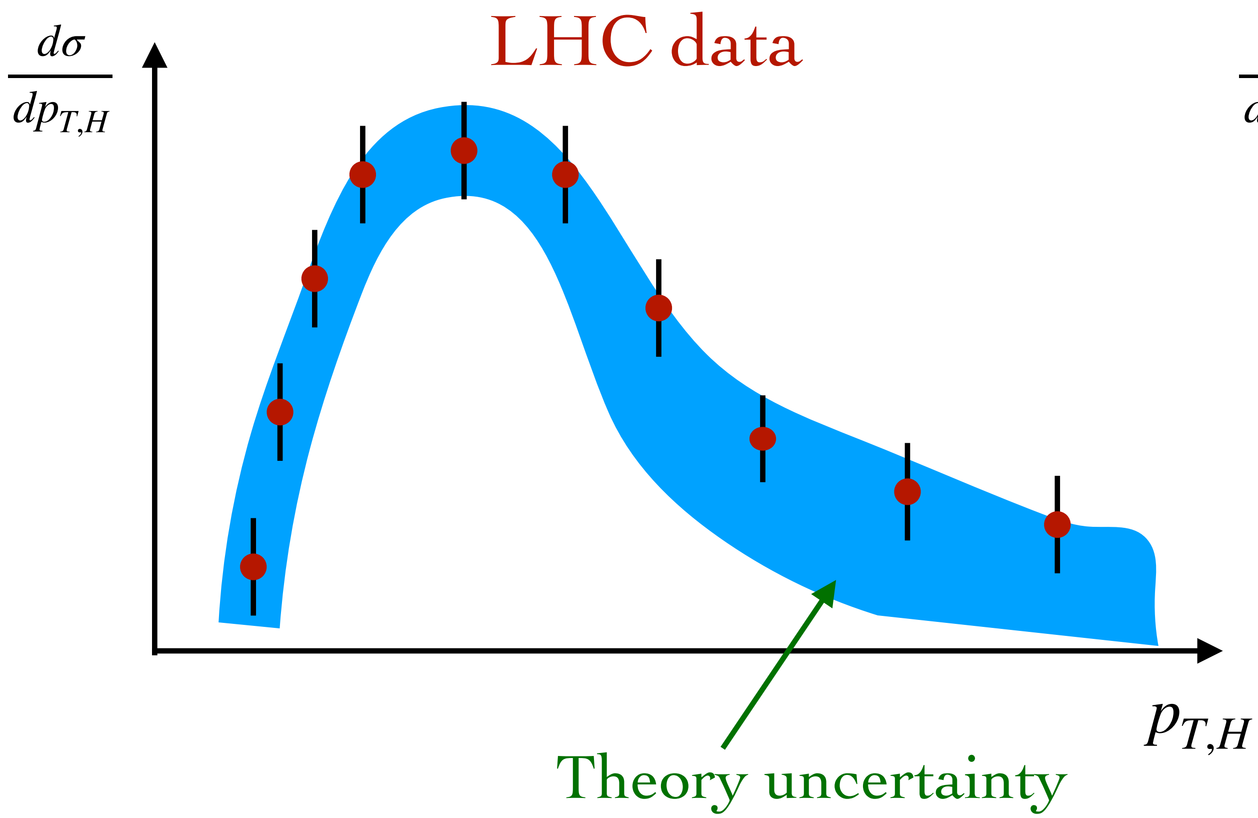
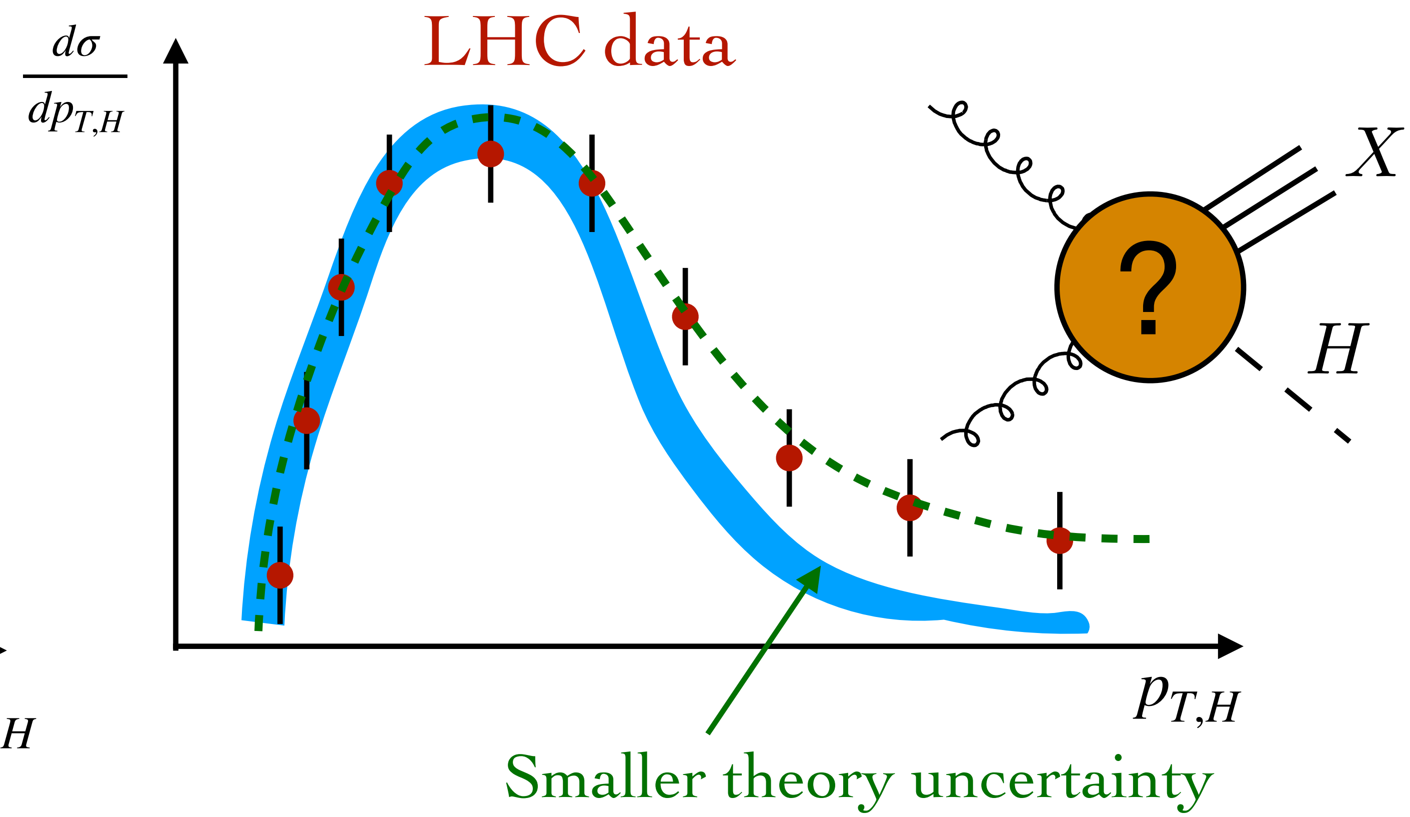


The role of precision theory….

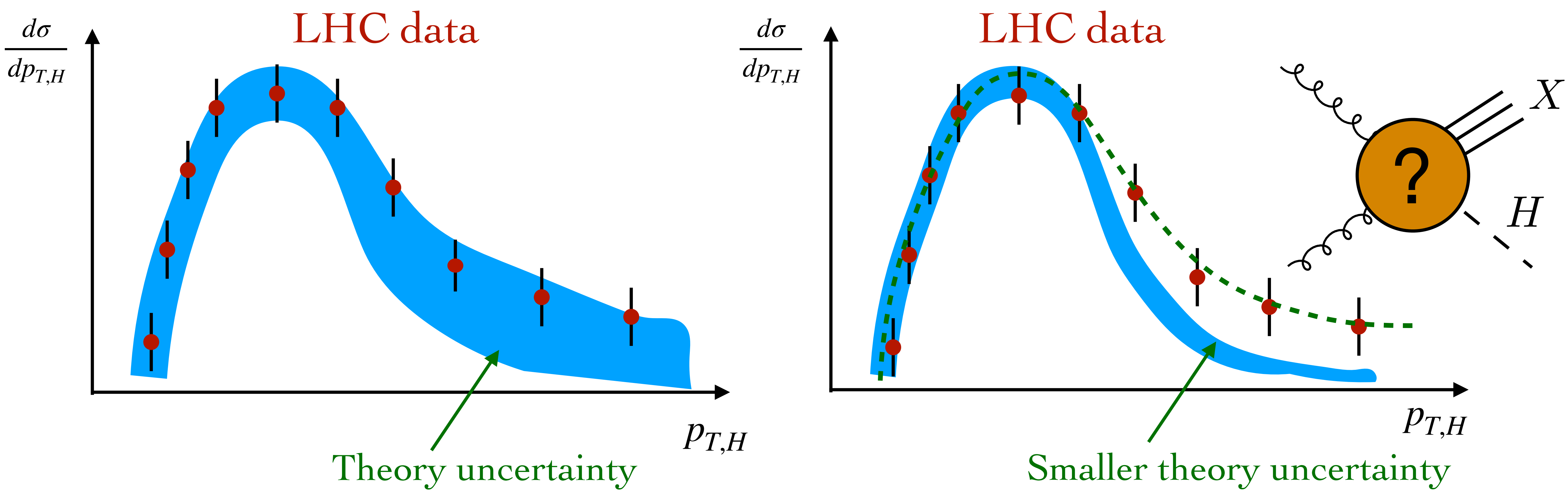


The role of precision theory….



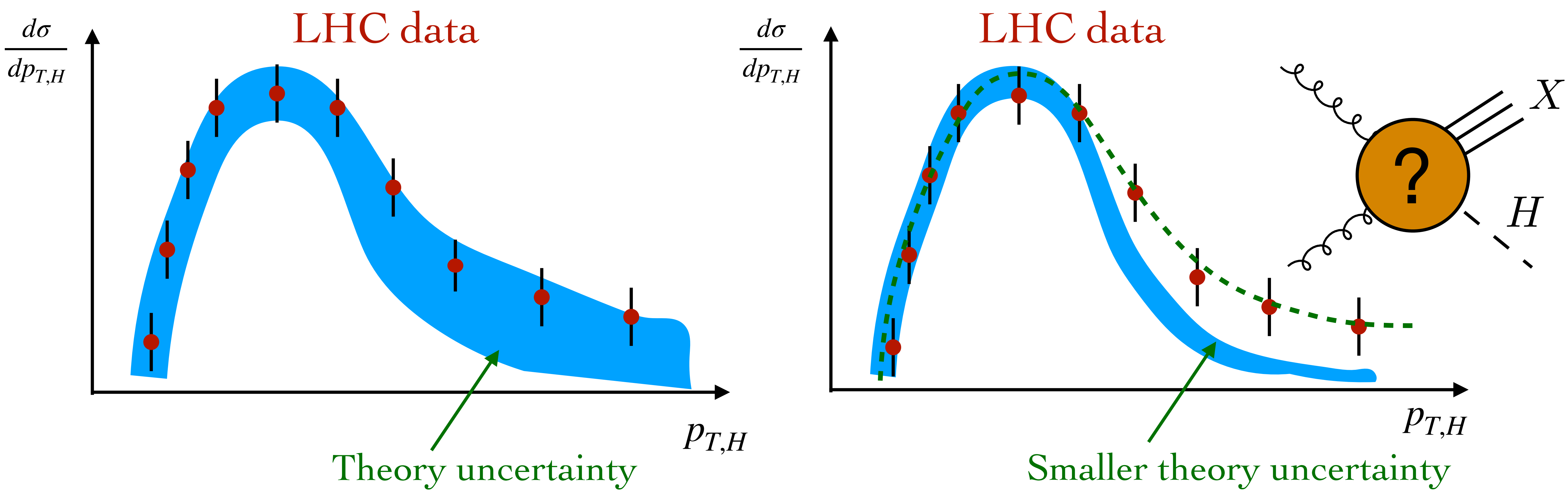


The role of precision theory….



Larger theory uncertainties may lead to miss (or at least delay) new discoveries

The role of precision theory….



Larger theory uncertainties may lead to miss (or at least delay) new discoveries

Exact NLO QCD corrections to Higgs p_T spectrum computed only recently

Jones, Kerner, Luisoni (2018)
Chen, Huss, Jones, Kerner, Lang Lindert, Zhang (2021)
Bonciani et al. (2022)

Combined with NNLO in the EFT

Chen, Cruz-Martinez, Gehrmann, Glover, Jaquier (2016)
Boughezal et al (2015)

→ accurate predictions for boosted analyses

LHCHXSWG-2019-002

The role of precision theory….

Talk by Aude Gehrmann-De Ridder

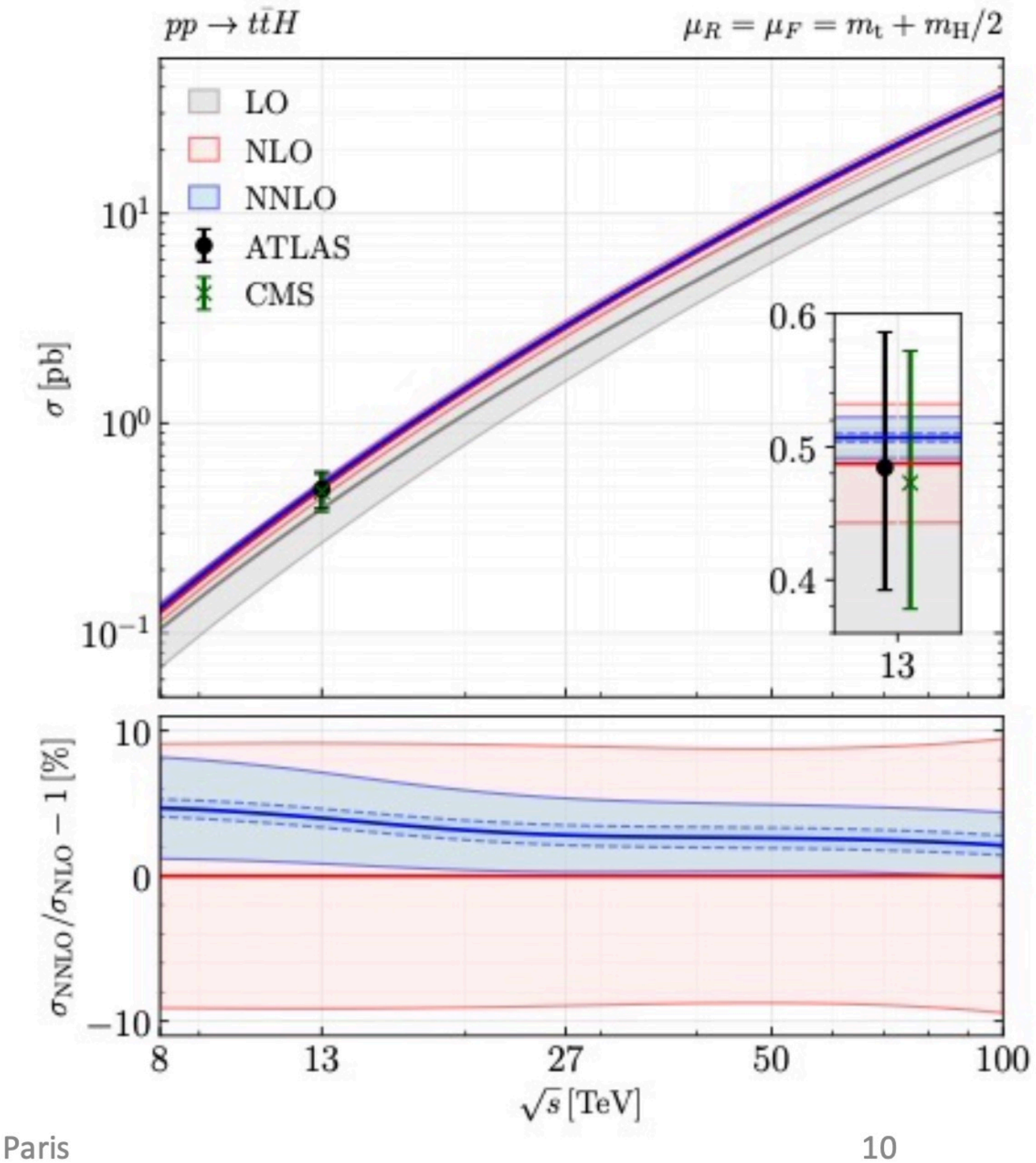
Total cross section for ttH@NNLO

- NNLO calculation versus data at 13 TeV
  [ATLAS: 2207.00092, CMS: 2207.00043]
  [Catani, Devoto, Grazzini,Kallweit, Mazzitelli, Savoini, 2210.07846]

σ [pb]	$\sqrt{s} = 13\,\text{TeV}$	$\sqrt{s} = 100\,\text{TeV}$
σ_{LO}	$0.3910\,^{+31.3\%}_{-22.2\%}$	$25.38\,^{+21.1\%}_{-16.0\%}$
σ_{NLO}	$0.4875\,^{+5.6\%}_{-9.1\%}$	$36.43\,^{+9.4\%}_{-8.7\%}$
σ_{NNLO}	$0.5070\,(31)^{+0.9\%}_{-3.0\%}$	$37.20(25)\,^{+0.1\%}_{-2.2\%}$

  - Error includes scale variation and uncertainty from soft Higgs approximation estimated on exact result at NLO level

- NNLO corrections moderate (2-4 %) with significant reduction of theoretical uncertainty to per-cent level

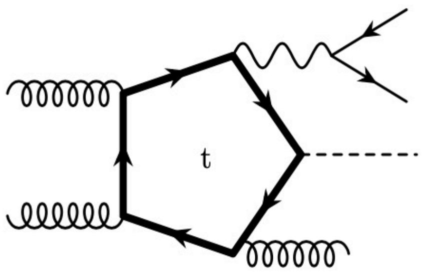


The role of precision theory….

Talk by Aude Gehrmann-De Ridder

ZH + Jet production

- Two types of top-loop contributions
  - qq-induced: at order $\alpha_s^2 y_t$ from interference with Drell-Yan amplitudes (as for W^+, W^-)
  - gg-induced: at order $\alpha_s^3 y_t^2$ from (1-loop-amplitude)^2 (Z only)

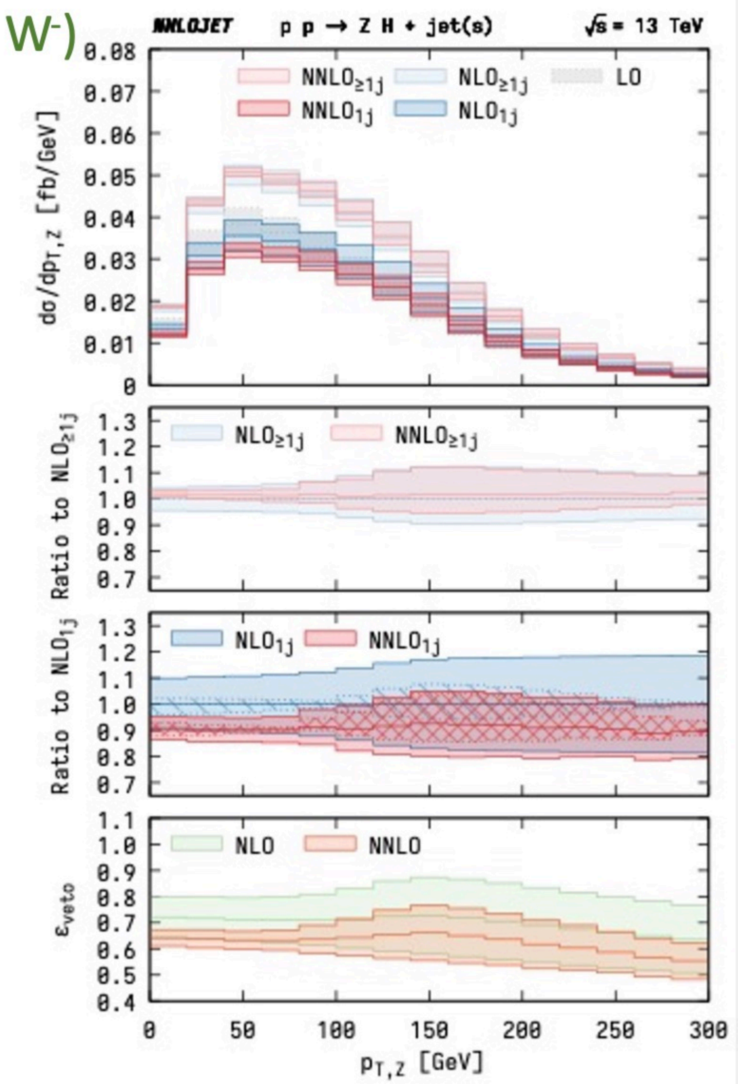


- Fiducial inclusive cross sections: effects of top-loop

σ_{NLO} [fb]	$6.81\,^{+0.22}_{-0.24}$	$6.89\,^{+0.24}_{-0.25}$
σ_{NNLO} [fb]	$6.92\,^{+0.02}_{-0.04}$	$8.04\,^{+0.42}_{-0.32}$
	(without top)	(with top)

  - @ NLO: slight increase of cross section, but no sizeable effect on uncertainty
  - @ NNLO: size of corrections and uncertainties enlarged

- Transverse momentum spectrum of Z boson
  - @ NNLO: Sizeable impact of gg-loop induced contributions
    - 15% in inclusive case and even larger in exclusive mode
    - Large remaining uncertainty band



The role of precision theory….

Signal-background interference in $H \to \gamma\gamma$

Talk by Federica Devoto

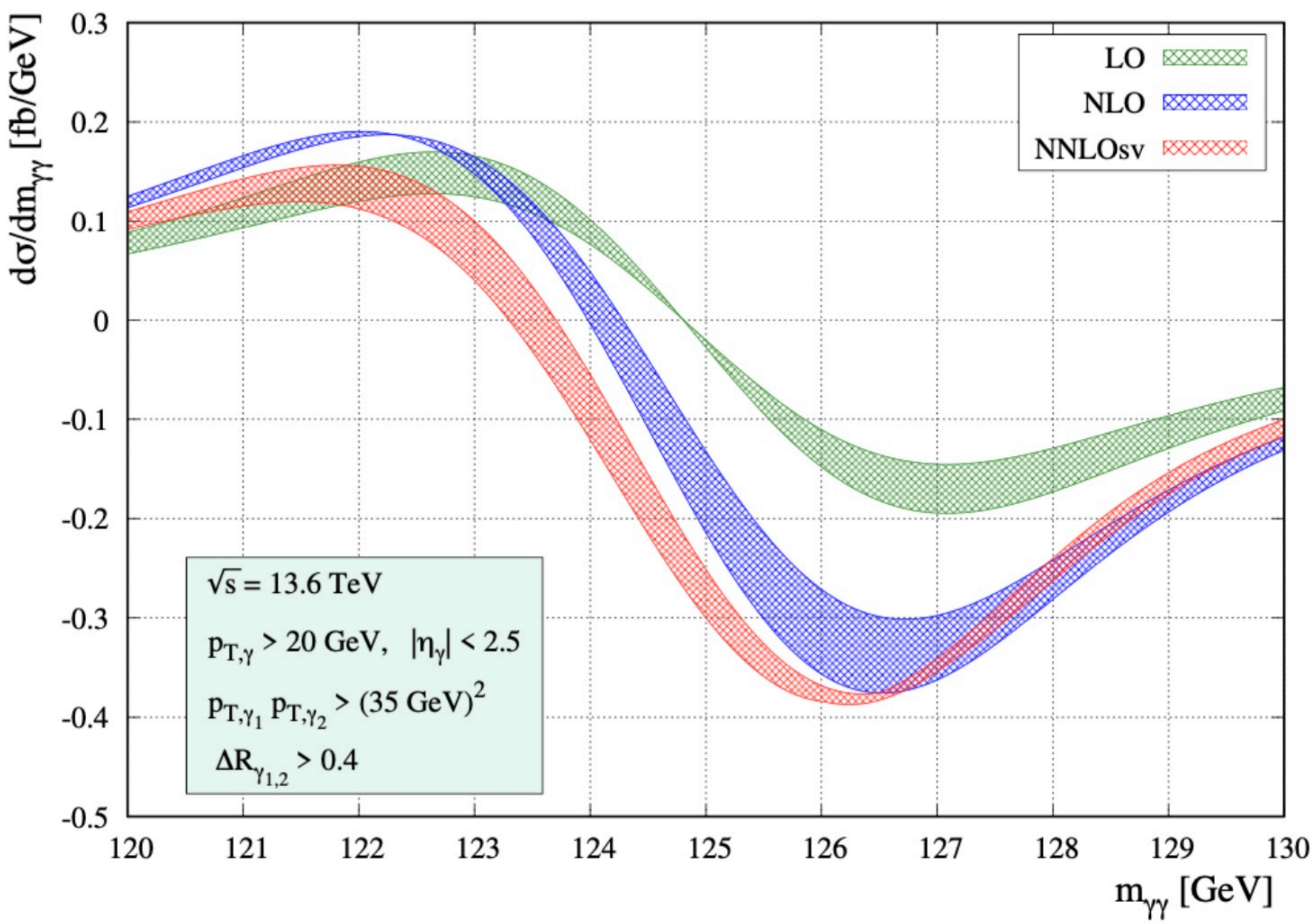


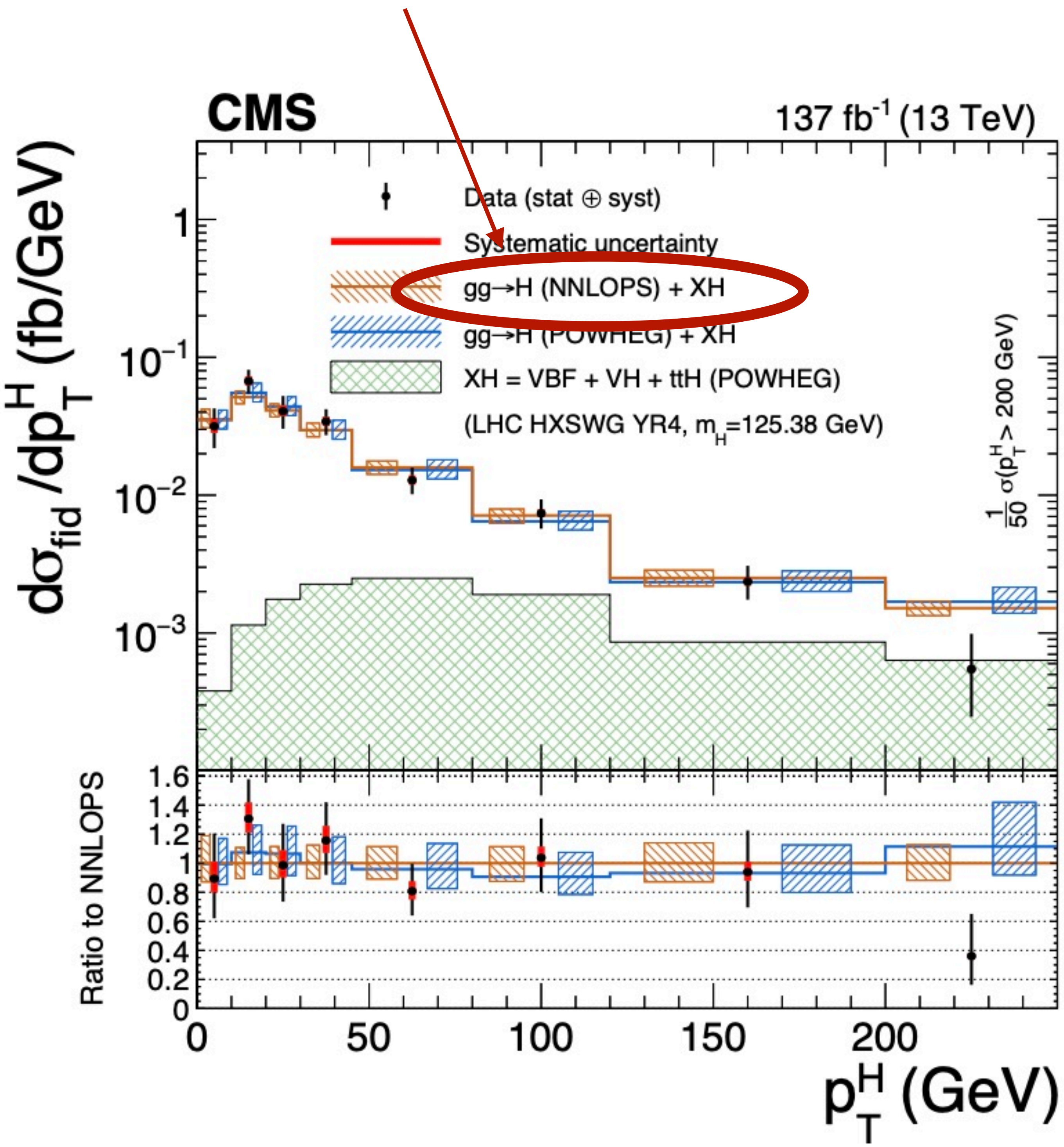
Fig. 4 Signal-background interference contribution to the diphoton invariant mass distribution after Gaussian smearing. Bands represent the envelope given by the scale variation.

- NNLO correction not captured by the NLO scale variation bands…
- …but starting to converge
- Recall this is the sum of real and imaginary part of the interference
- Real part dictates the shape, imaginary part responsible for shift to the left

…and of its MC implementation

default MC: MiNLO+reweighting of the rapidity distribution to HNNLO

Hamilton, Nason, Re, Zanderighi (2013)



Used by CMS to reweight POWHEG sample

…and of its MC implementation

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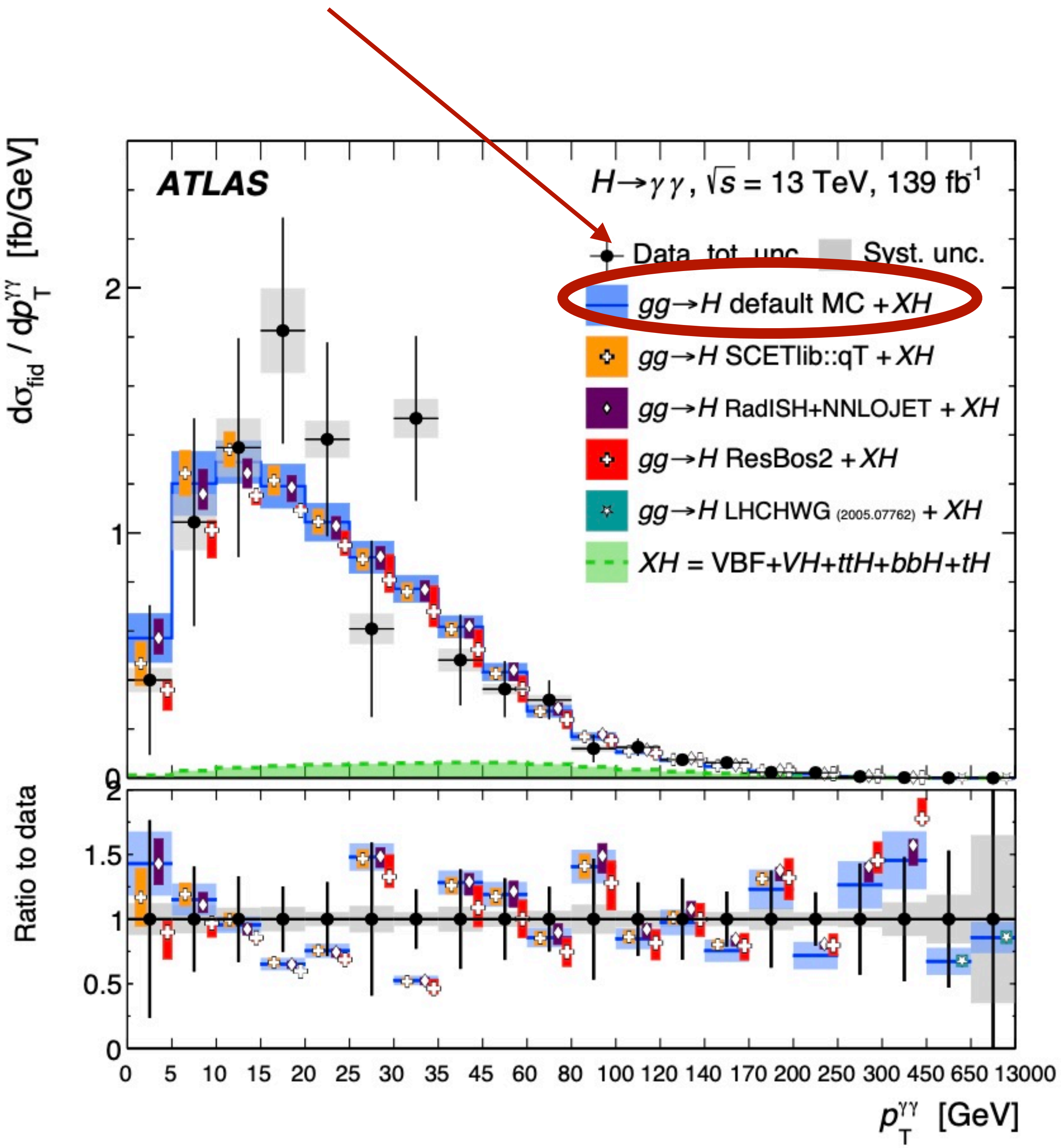


….and by ATLAS as default MC for ggF

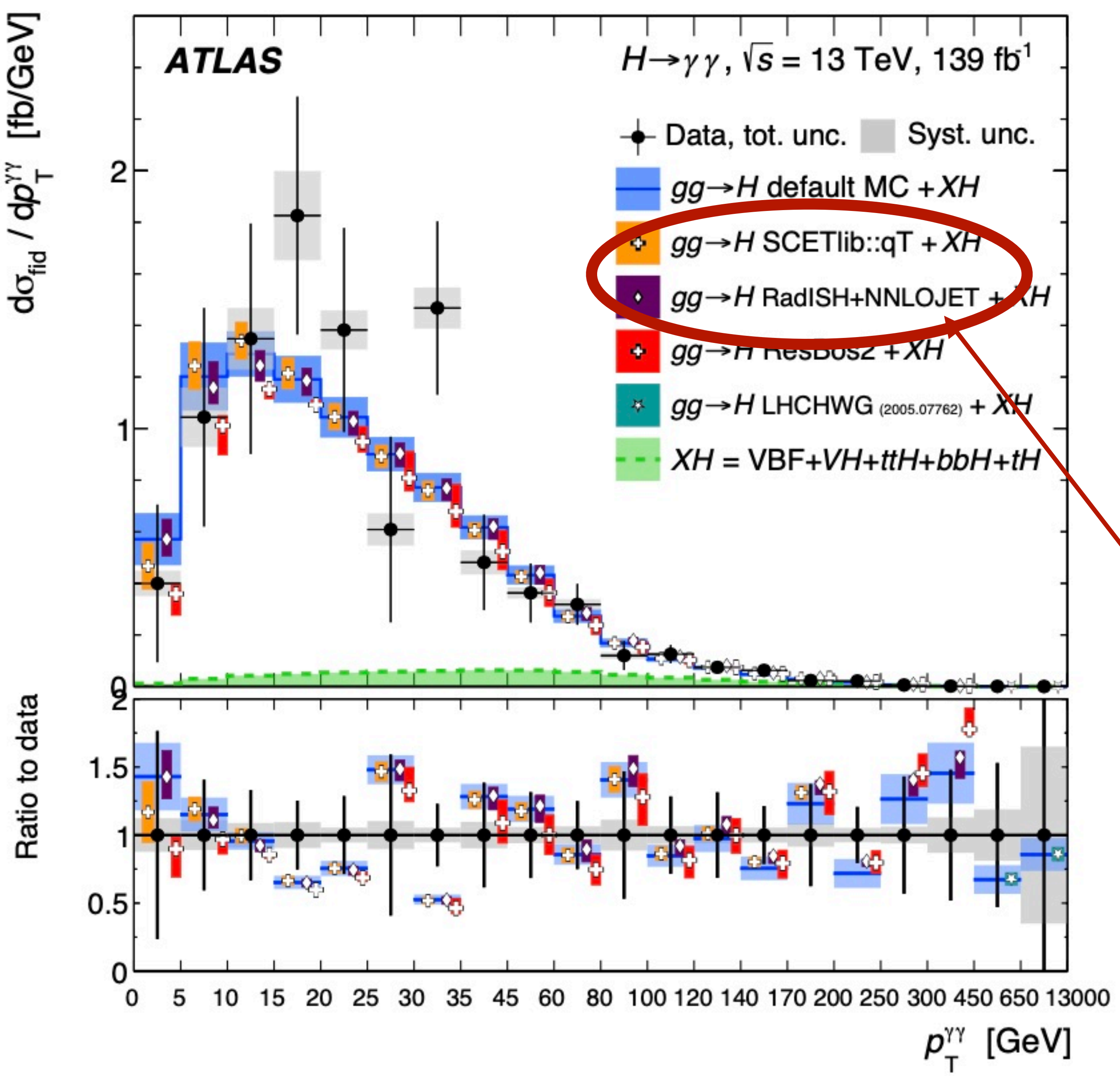
To be eventually replaced by MiNNLOPS (no reweighting)

Monni, Nason, Re, Weisemann, Zanderighi (2019)

…and of its MC implementation

default MC: MiNLO+reweighting of the rapidity distribution to HNNLO

Hamilton, Nason, Re, Zanderighi (2013)



….and by ATLAS as default MC for ggF

To be eventually replaced by MiNNLO$_{PS}$ (no reweighting)

Monni, Nason, Re, Weisemann, Zanderighi (2019)

In nice agreement with most advanced resummed computations*….

Billis, Dehnadi, Ebert, Michel, Tackmann (2021)
Re, Rottoli, Torrielli (2021)
Chen et al (2016)

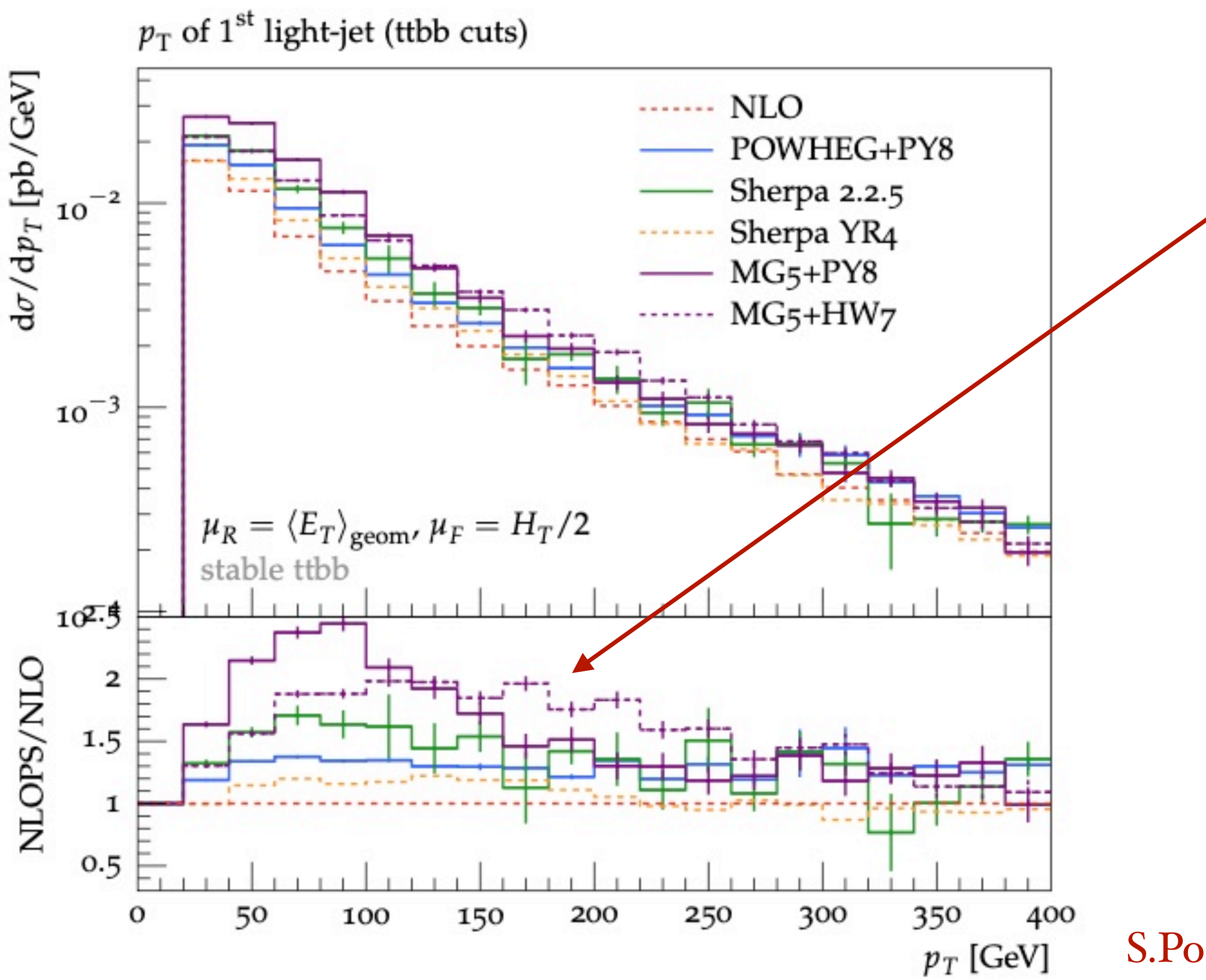
*made possible by recent evaluation of "beam functions" at N^{3}LO

Luo, Yang, Zhu, Zhu (2019)
Ebert, Mistlberger, Vita (2020)

Background modelling

Accuracy in theory predictions is also crucial for the Monte Carlo tools used in the analyses, particularly when background modelling is difficult

Example: $t\bar{t}b\bar{b}$ background to $t\bar{t}H$ with $H \to b\bar{b}$



$\mathcal{O}(100\%)$ differences in p_T of the first light jet

Their origin can be traced back to the large NLOPS effect wrt NLO

Understanding these issues is crucial to assess theory systematics

S.Pozzorini, talk given at HXSWG ttH/tH subgroup meeting, October 2020

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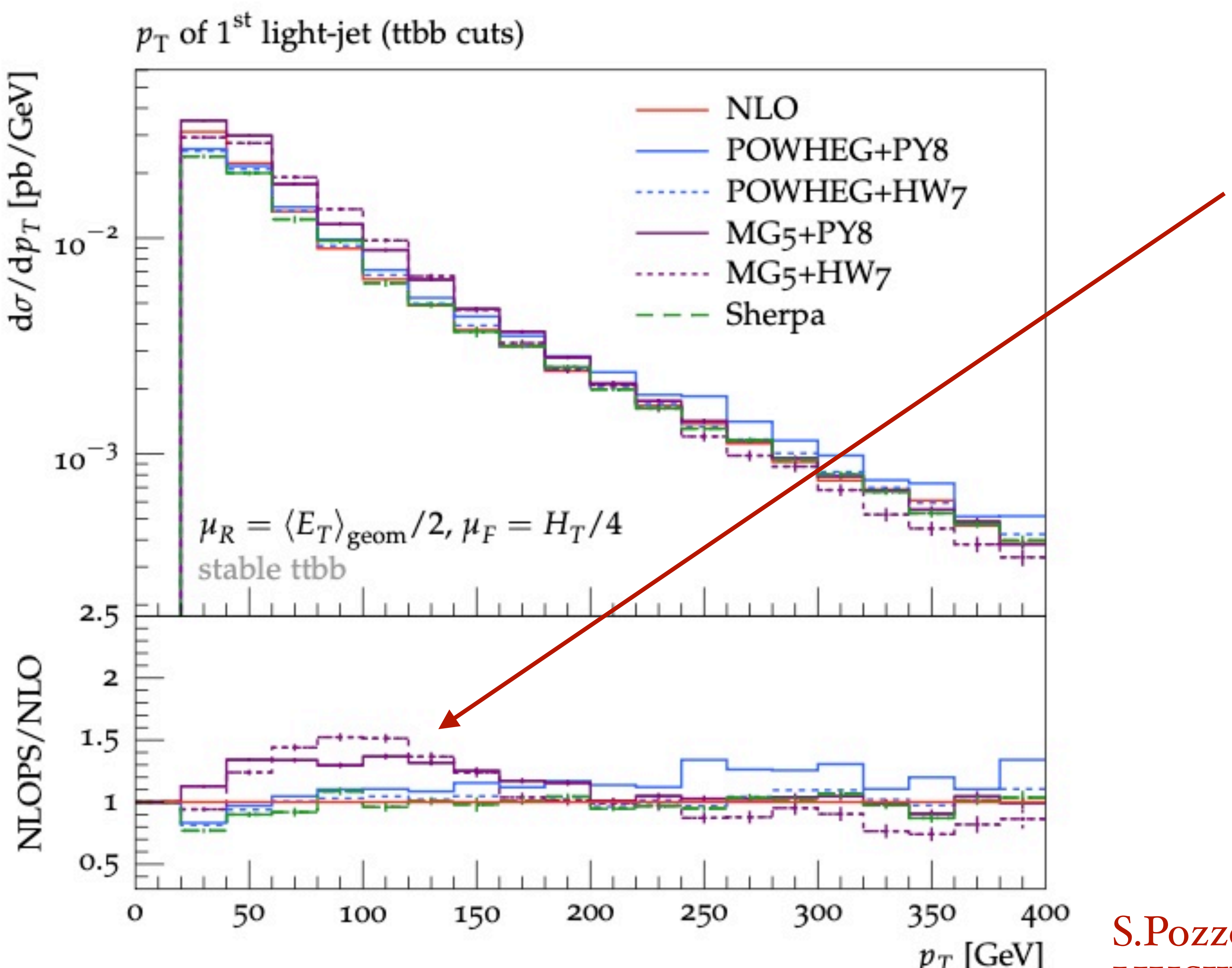

Reduction of default scale significantly reduces the spread between different predictions

Supported by explicit NLO computation of $t\bar{t}b\bar{b}j$

Buccioni, Kallweit, Pozzorini, Zoller (2019)

Ongoing studies within the Higgs WG

S.Pozzorini, talk given at HXSWG ttH/tH subgroup meeting, October 2020

Going beyond the SM

The κ-framework

The failure in finding new physics at the LHC till now has changed our approach: abandon Model Building and go for model independent approaches

LHCHXSWG-2012-001

LHC HXSWG interim recommendations to explore the coupling structure of a Higgs-like particle

LHC Higgs Cross Section Working Group, Light Mass Higgs Subgroup
A. David[1], *A. Denner*[2], *M. Dührssen*[3], *M. Grazzini*[4*], *C. Grojean*[3], *G. Passarino*[5], *M. Schumacher*[6], *M. Spira*[7], *G. Weiglein*[8], *and M. Zanetti*[9].

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Abstract
This document presents an interim framework in which the coupling structure of a Higgs-like particle can be studied. After discussing different options and approximations, recommendations on specific benchmark parametrizations to be used to fit the data are given.

It is interesting to observe that the κ-framework we introduced in 2012 to explore Higgs couplings as "interim recommendation" is still at the basis of the analyses !

The SMEFT paradigm

Talks by Victor Miralles, Maeve Madigan

$$\mathscr{L}_{\text{eff}} = \mathscr{L}_{\text{SM}} + \frac{1}{\Lambda^2}\sum_i C_i O_i + \mathscr{O}\left(\Lambda^{-4}\right)$$

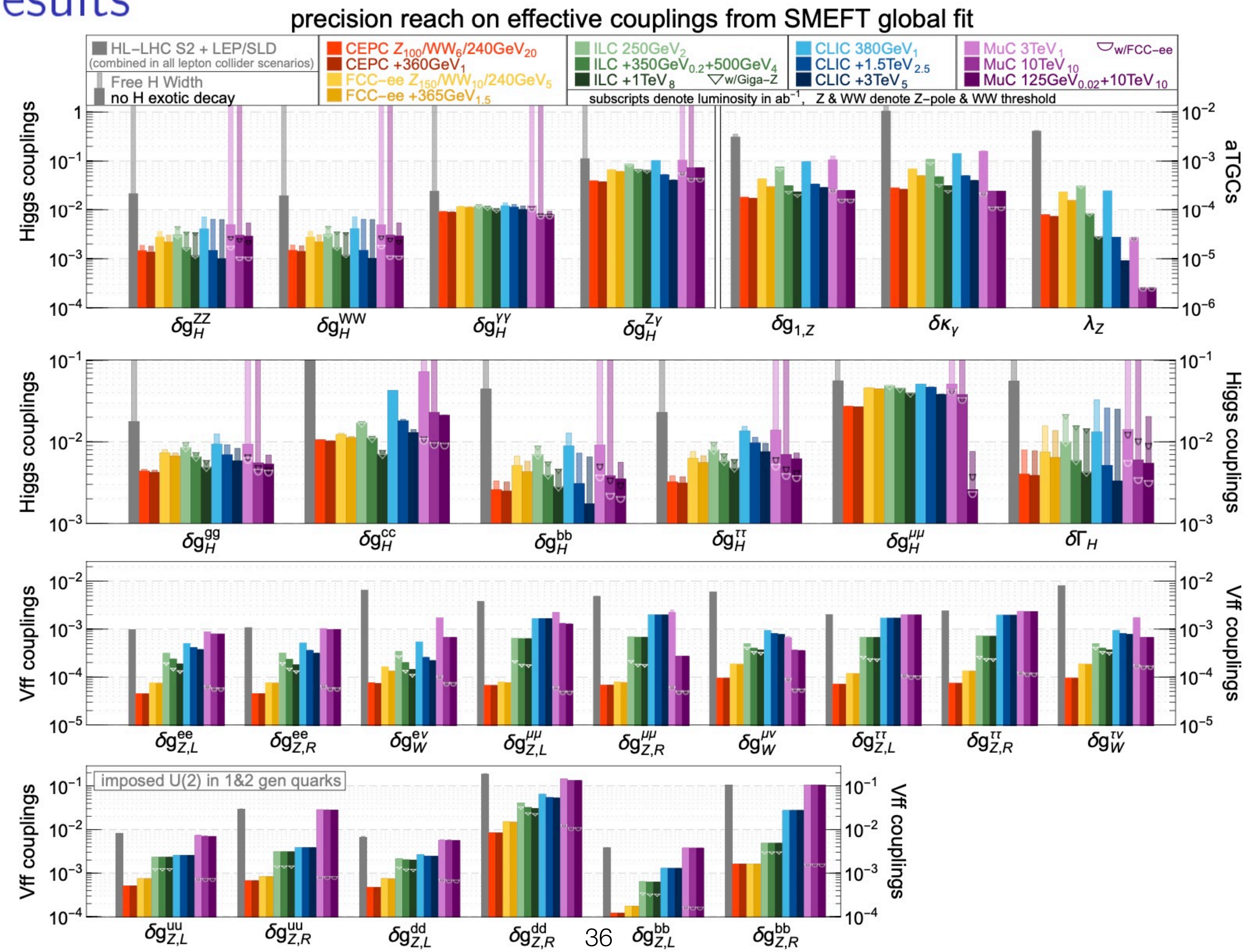
- The Wilson coefficients can be interpreted in terms of NP mediators
- The Lagrangian is expanded up to D6
- The amplitudes include the Λ^{-2} terms from the interference between the SM and D6
- Sometimes the Λ^{-4} operators arising from squaring the D6 are also included
- The double insertions of D6 and the effects of D8 operators, contributing to the same Λ^{-4} order, are usually omitted

$$\sigma = \sigma_{\text{SM}} + \underbrace{\frac{1}{\Lambda^2}\sum C_i O_i}_{\text{SM } \times \text{D6}} + \underbrace{\left(\frac{1}{\Lambda^2}\sum C_i O_i\right)\left(\frac{1}{\Lambda^2}\sum C_j O_j\right)}_{\text{D6}\times\text{D6}} + \underbrace{O(1/\Lambda^4)}_{\text{SM } \times \text{D8}}$$

The SMEFT paradigm

Talk by Victor Miralles

Results

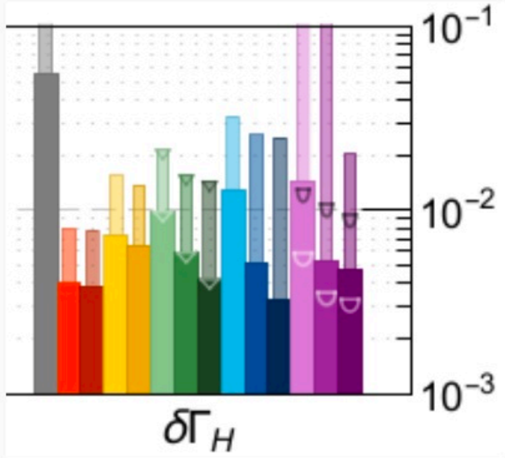


The SMEFT paradigm

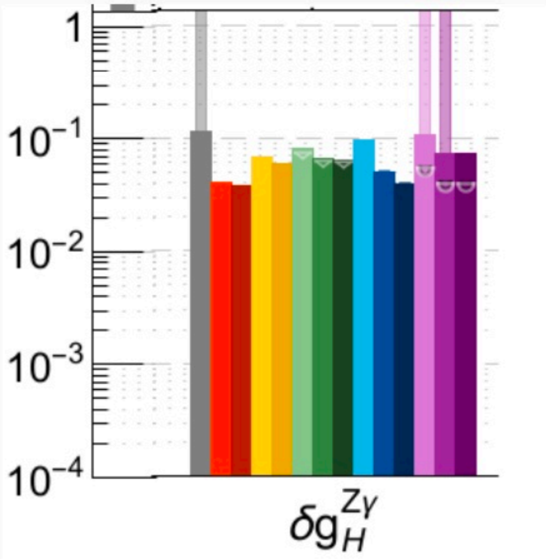
Talk by Victor Miralles

Results: Highlights

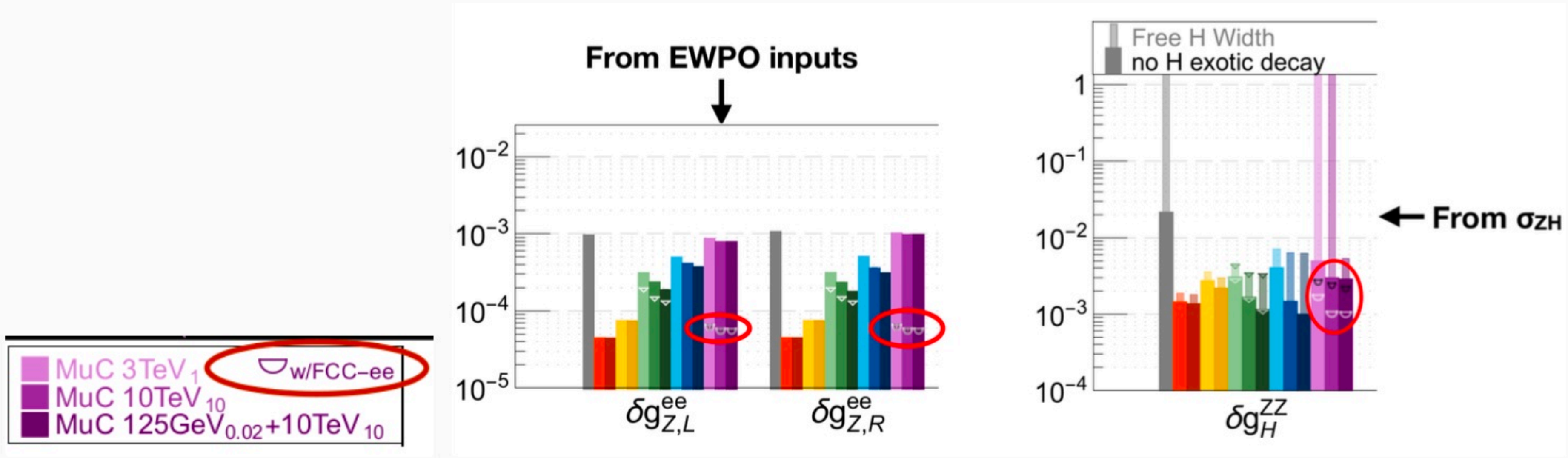
A low energy run accessing $e^+e^- \to HZ$ becomes highly relevant to measure Γ_H



HL-LHC dominates the constraints on rare decays ($\gamma\gamma$, $Z\gamma$, $\mu\mu$)



There is an excellent complementarity between e^+e^- and $\mu^+\mu^-$ colliders



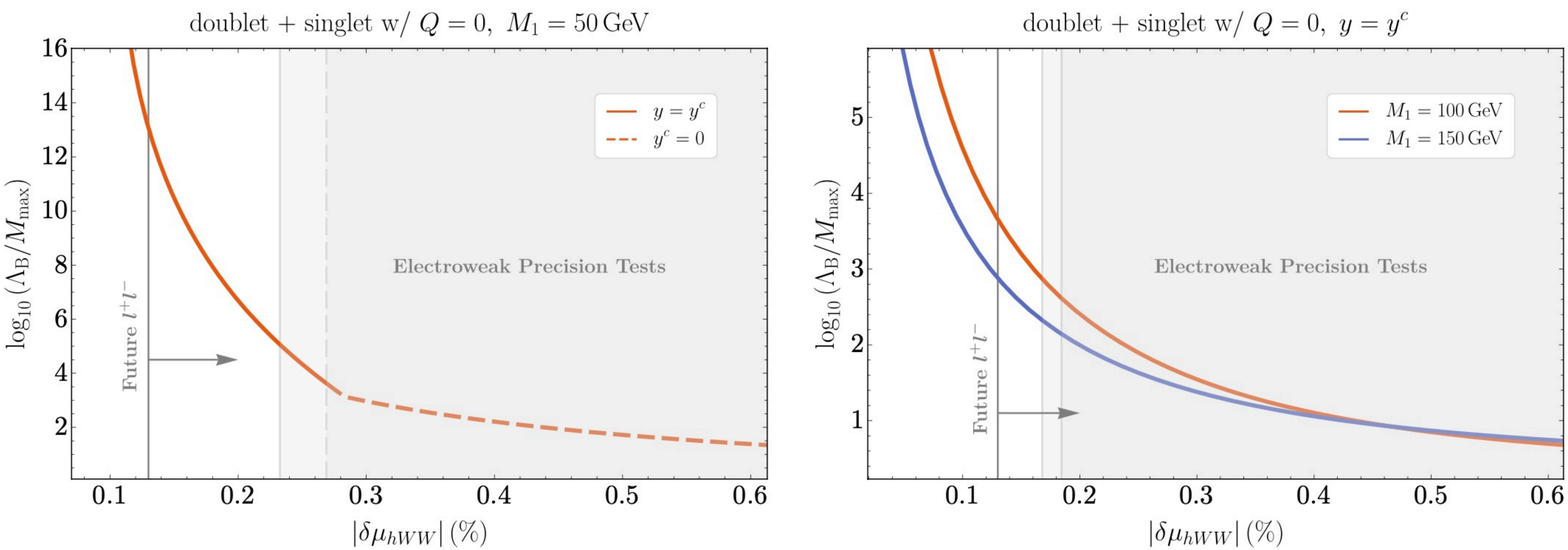
New Physics in Higgs couplings

Talk by Gabriele Rigo

Extend the SM with new fermions that induce observable modifications in HWW and HZZ couplings

Evaluate the ensuing deviations on the HWW and HZZ couplings

Such deviations in turn necessarily imply the existence of new bosons at a scale that can be computed



New Physics in Higgs couplings

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Take-home message:

- Future collider deviation?
- Either light new fermions
- Or new bosons under 100 TeV

How SM-like is the Higgs ?

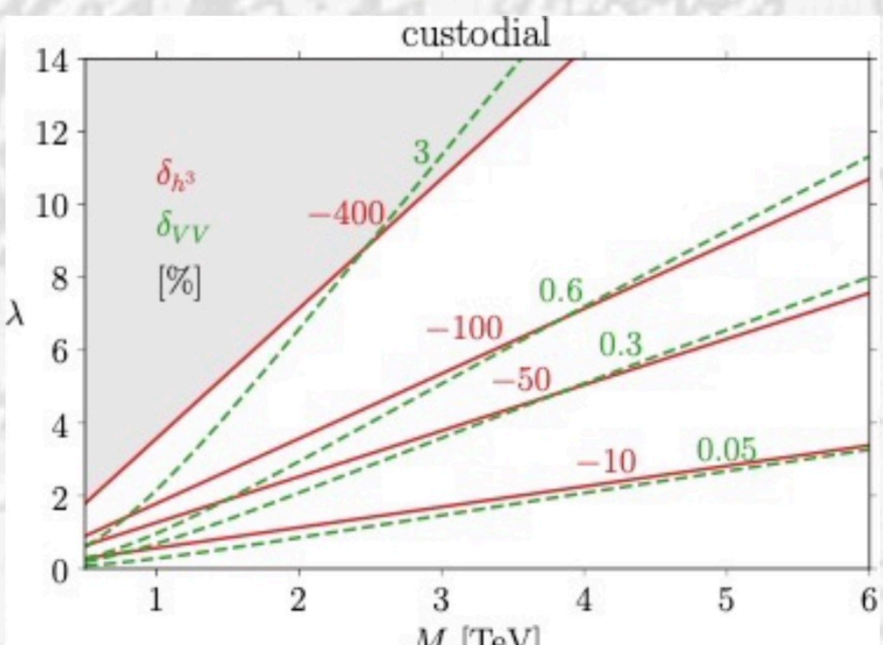
Talk by Matthew McCullough

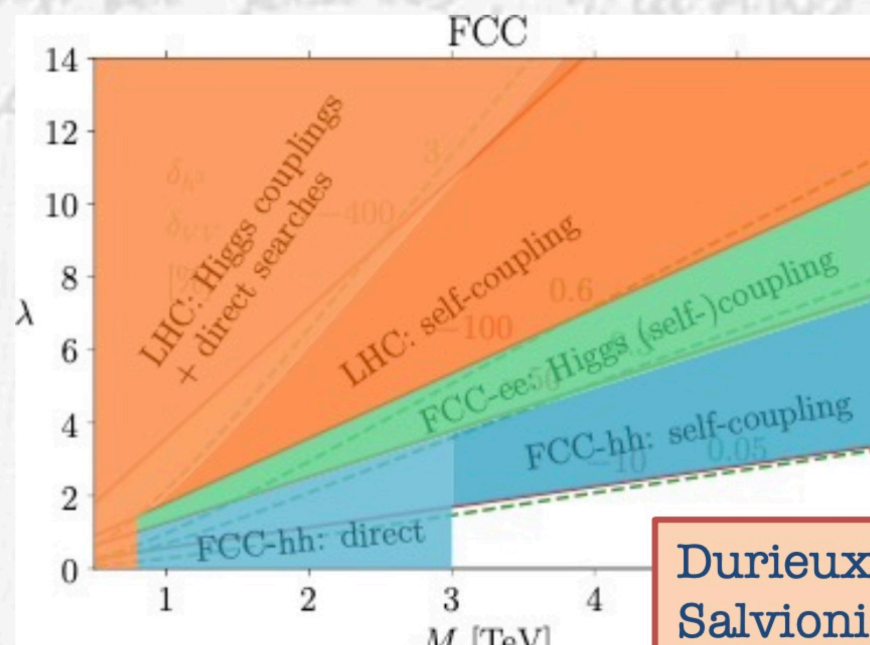
Custodial Quadruplet

Higgs self-coupling is modified at dim-6 at tree-level, all other couplings modified at dim-6 one-loop, or dim-8. All calculable, giving

$$-\frac{\delta_{VV}}{\delta_{h^3}} = 3\left(\frac{m_h}{4\pi v}\right)^2 + \left(\frac{m_h}{M}\right)^2 \approx \frac{1}{200} + \frac{1}{580}\left(\frac{3\ \text{TeV}}{M}\right)^2$$

Remarkably close to NDA estimate!





Durieux, MM, Salvioni. 2022

Can we miss something ?

Talk by Guglielmo Coloretti

- Several hints motivate existence of new scalars at 95 and 152 GeV
- **Real $SU(2)_L$ scalar triplet can naturally explain W mass excess**

Triplet at **95 GeV**
- WW excess

or

- Resonant $\gamma\gamma$ signal (95 GeV)
- **Tension with the bound on $\sigma(pp \to H^{\pm} \to \tau\nu)$ from stau searches**

Triplet at **152 GeV**
- WW excess
- **$t\bar{t}$ differential distribution anomaly with $H \to S(152)\, S'(95) \to WWb\bar{b}$**
- Resonant $\gamma\gamma$ signal (95 GeV) if **$S(152)$ is a triplet and $S'(95)$ is a singlet**

- **Emergence of a model with multiple scalars in a singlet(95)-doublet(125)-doublet(270)-triplet(150) pattern** (work in progress…)

Can we miss something ?

Sven+F. Richard

- With RUN2 data there has been growing evidence for a wide resonance with M=650 GeV and Γtot=100 GeV
- Seen in 3 modes ZZ, WW, h(125)h'(95), each > 3.5 s.d.
- Historically this work started in 2018 *1806.04529* with the mode ZZ, confirmed by *2103.01918*, then came WW *2104.04762* and h(95)h(125) **HIG-21-011**
- Putting them together, one reaches **6 s.d. global** (Fisher method)
- Question: how to interpret this resonance in the context of existing phenomenology ?

F. Richard IJCLab September 2023

Can we miss something ?

Talk by Maeve Madigan
and 2307.10370

Could PDFs completely fit away signs of new physics in the tails of kinematical distributions ?

Before the LHC PDFs were mostly extracted from data collected by fixed-target, HERA and Tevatron experiments, and used as input for LHC predictions

Now (see e.g. NNPDF4.0) about 30% of the data points come from LHC

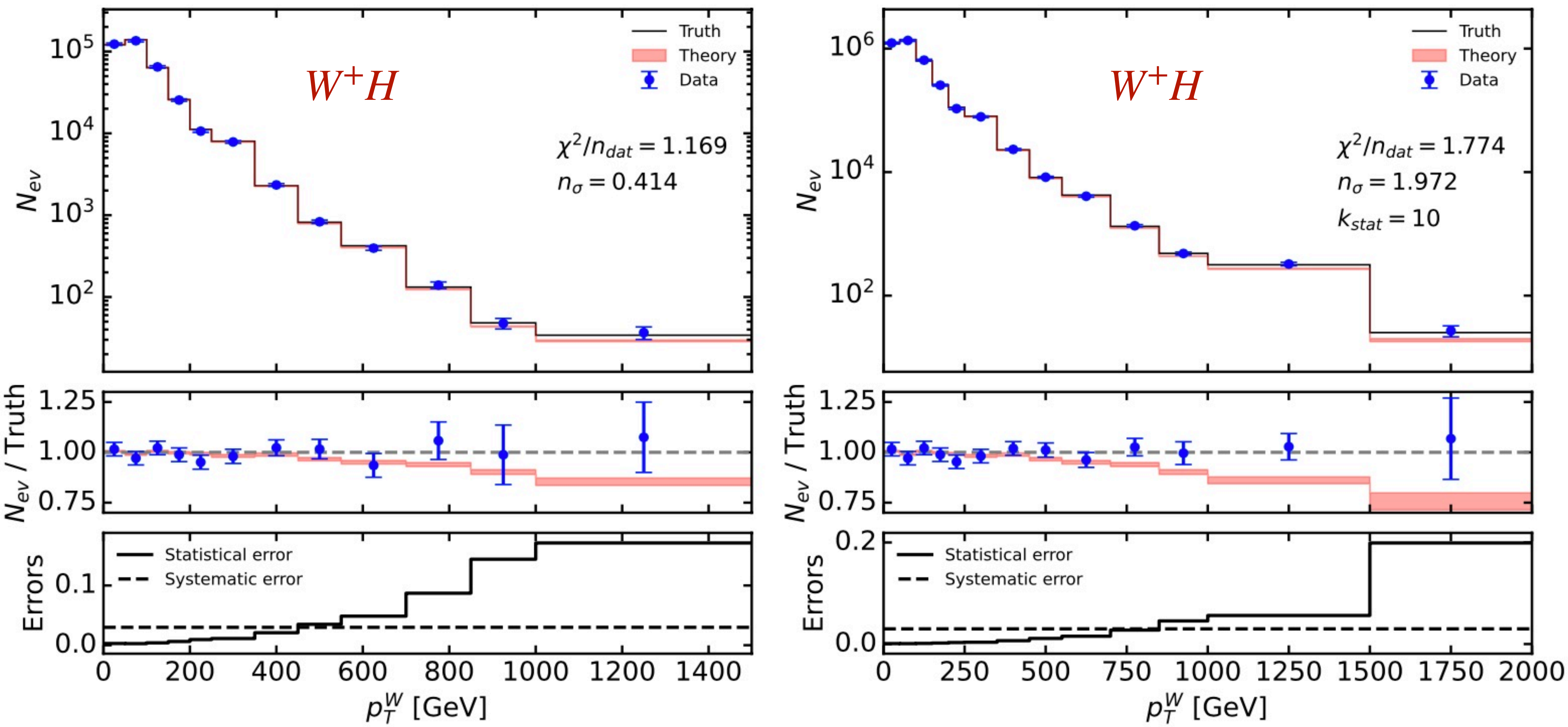
→ Important constraints on high-x gluon (top and jet data) and on quark and antiquark densities at medium and large x

The existence of a flavour universal W' resonance of mass around 10 TeV can contaminate the PDFs we will extract from HL-LHC data still providing a good PDF fit that can accomodate even large deviations from the SM

Can we miss something ?

Talk by Maeve Madigan and 2307.10370

Could PDFs completely fit away signs of new physics in the tails of kinematical distributions ?



The PDF contamination can in turn induce large deviations in other observables

Can we miss something ?

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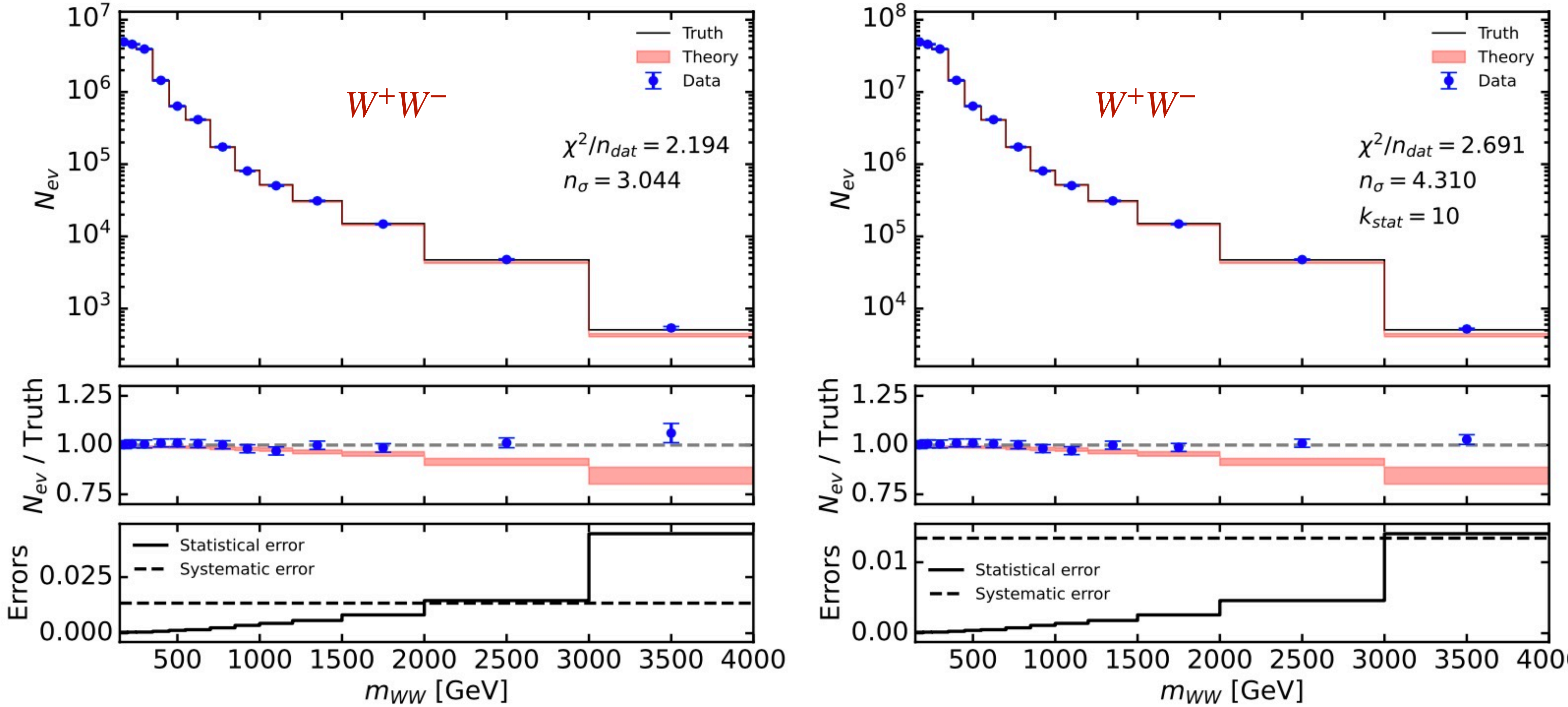


The PDF contamination can in turn induce large deviations in other observables

A bit of history

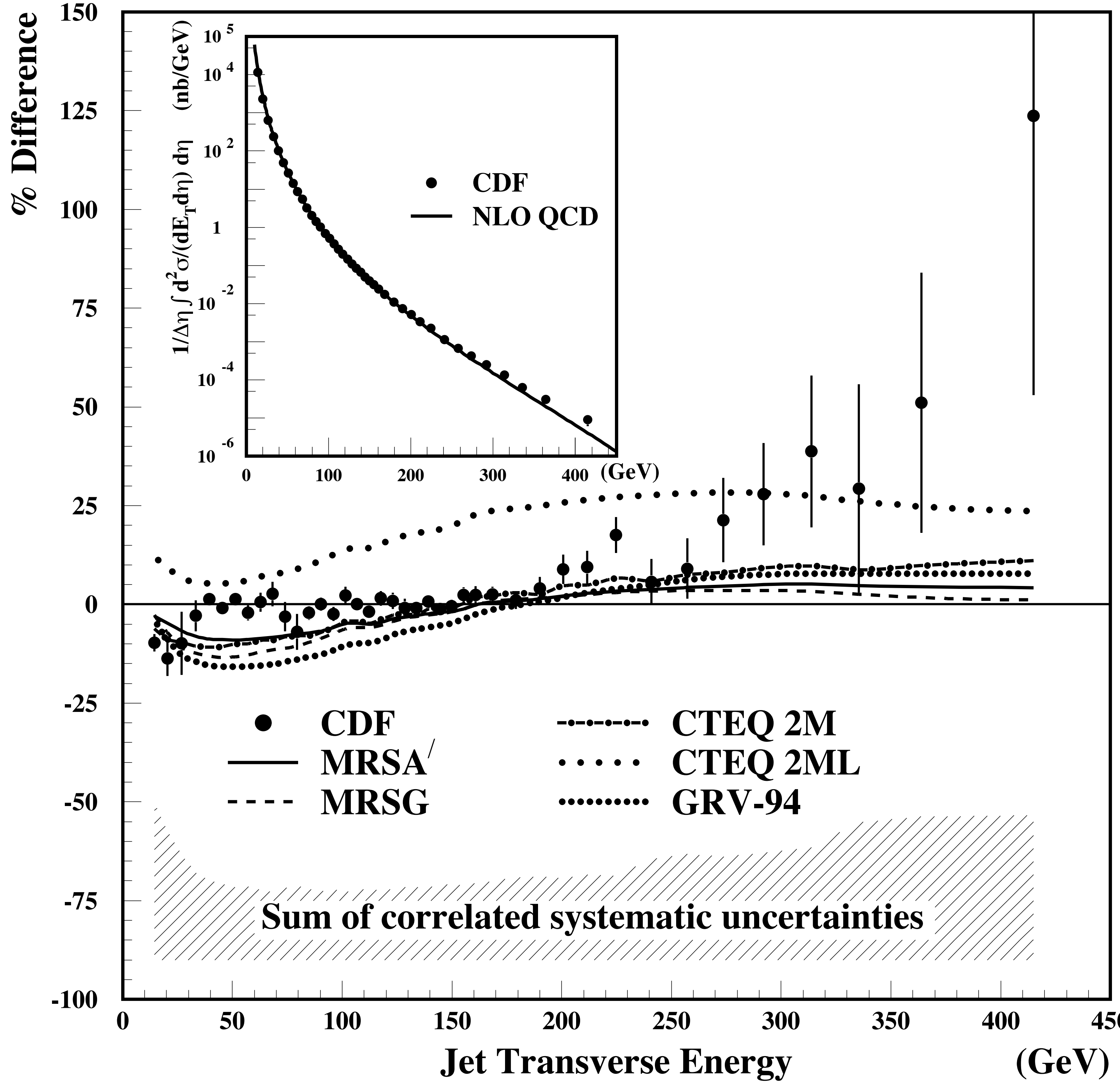
hep-ex/9601008

The measurement of the CDF collaboration at Run I at the Tevatron was historically very important

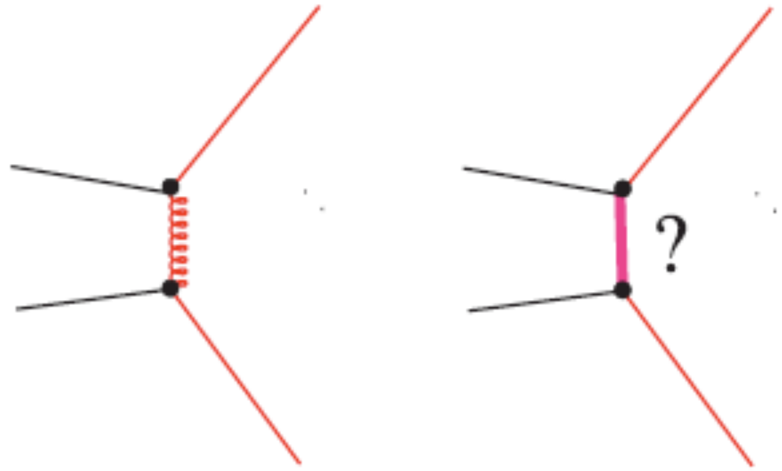
Spectacular agreement of the data with NLO QCD over nine order of magnitude !

At high transverse energies the data showed an excess over the theoretical prediction

Many new physics interpretations were proposed



Quark compositeness typically produces four fermion contact interactions due to the exchange of some heavy new particle of mass M



$$\Delta\mathcal{L} = \frac{f^2}{M^2}\bar{\psi}\gamma^\mu\psi\,\bar{\psi}\gamma_\mu\psi$$

→ should lead to

$$\frac{\text{Data} - \text{Theory}}{\text{Theory}} \sim f^2\frac{E_T^2}{M^2}$$

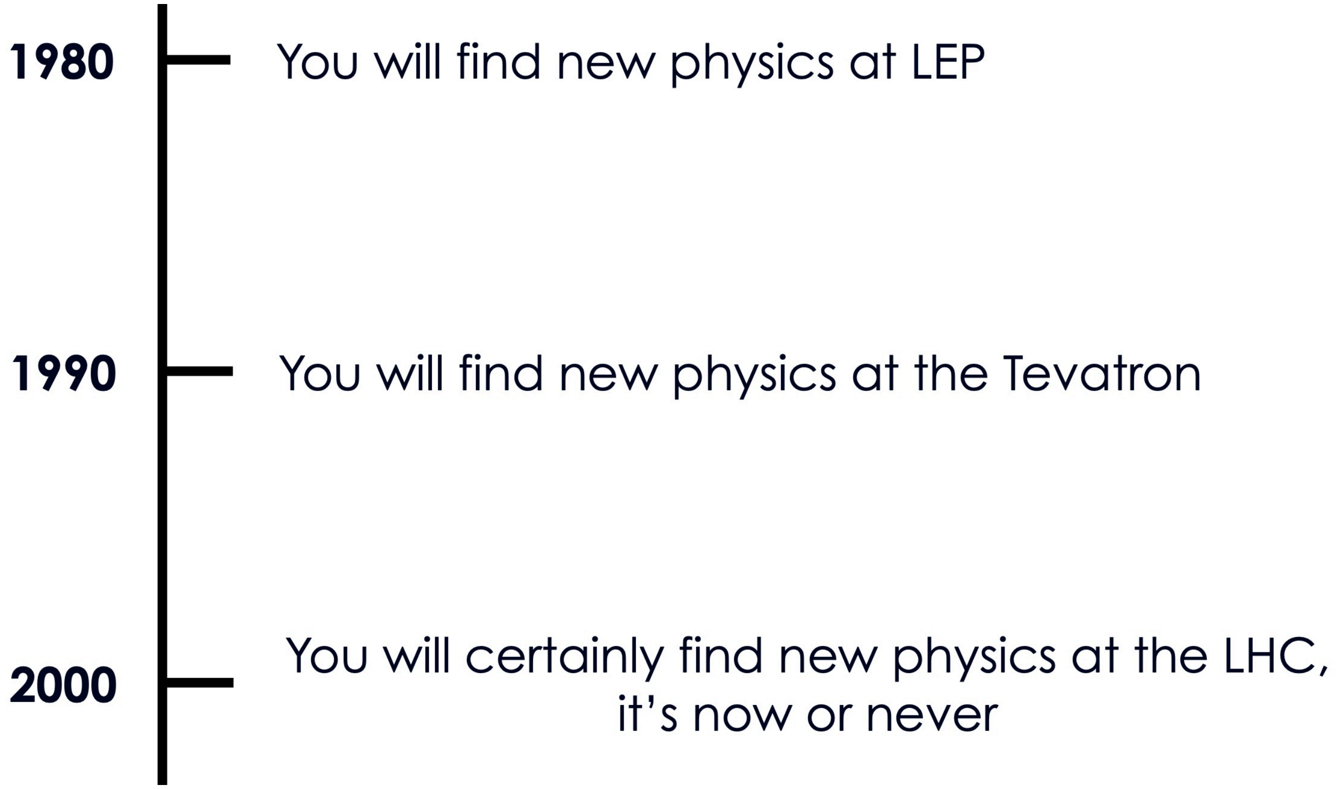
Such interactions however would lead to observable effects in the jet angular distributions

In the end it turned out that the high-E_T excess reported by CDF could be absorbed by allowing for a harder gluon at large x

The Great Depression

Particle physicists ~ 10 years after the Higgs discovery are generally depressed

- No new discovery…
- The Higgs is very SM like…



Maybe this is the theorists' fault ?

Talk by Tito d'Agnolo

I find this attitude largely unjustified !

Up to now only less than 10 % of the expected data set has been analysed and the picture is consistent with the SM but the exploration of the Higgs sector is still in its infancy and surprises are still well possible

The Higgs couplings to W and Z bosons and to third generation fermions are known with precision between 5 and 20 %

This is far from the percent level precision with which we know the strong coupling $\alpha_S(m_Z)$ (not to speak about the QED coupling α !)

More precise determinations of these couplings could uncover differences that might in turn be due to new physics

Despite the prospects for the improvements in the extraction of couplings to vector bosons and third generation fermions, we would ideally like to establish the interactions with electron and up and down quarks, which are those relevant to our everyday life: this is clearly not possible at present

Nonetheless the second generation fermions are much more accessible and we have seen that establishing $H \to \mu^+\mu^-$ is within reach, while recent results suggest that $H \to c\bar{c}$ might also become accessible at HL-LHC

Studying the Higgs potential and establishing if it is the one predicted by the SM is still far in the future and double Higgs production is the best process to access it: SM within reach in Run 3 by combining ATLAS and CMS

This programme has an immense value by itself, regardless on whether we will find New Physics or not !

"We do not measure Higgs couplings precisely with the goal to find deviations from the SM. We measure them to know them, while being ready to detect deviations, if any…" (Michelangelo Mangano, Amplitudes 2023)

Going beyond this we clearly need a new collider

The ~~Standard Model~~ Higgs is very new!

Talk by Andrea Wulzer

- First direct manifestation of massive gauge theory formalism
- First elementary scalar particle
- We must test if it has SM properties, or not, as precisely as we can

Higgs physics is still in its nascence. Pions were discovered in the early 1940's. Their fundamental origin, QCD, was developed theoretically in the early 1970's and only experimentally established in the late 1970's.

Talk by Matthew McCullough

It has been eleven years since the discovery of the Higgs boson.

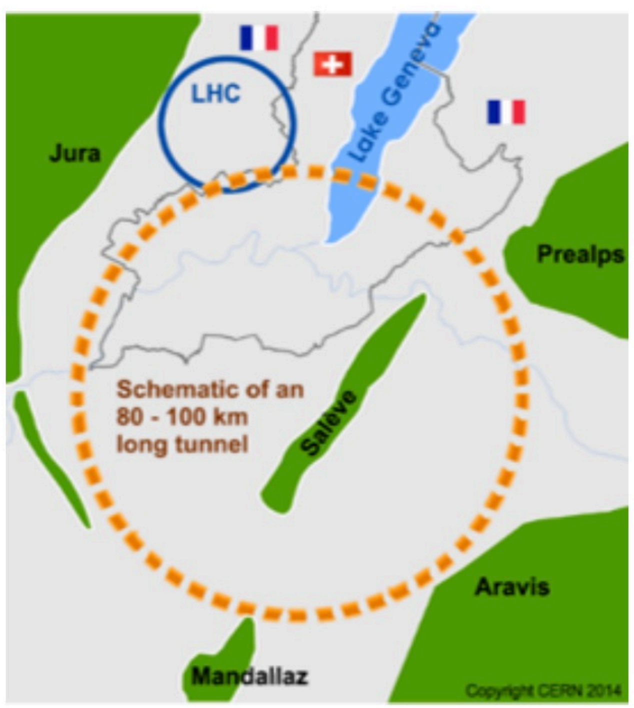
We must be patient and determined to uncover its origins.

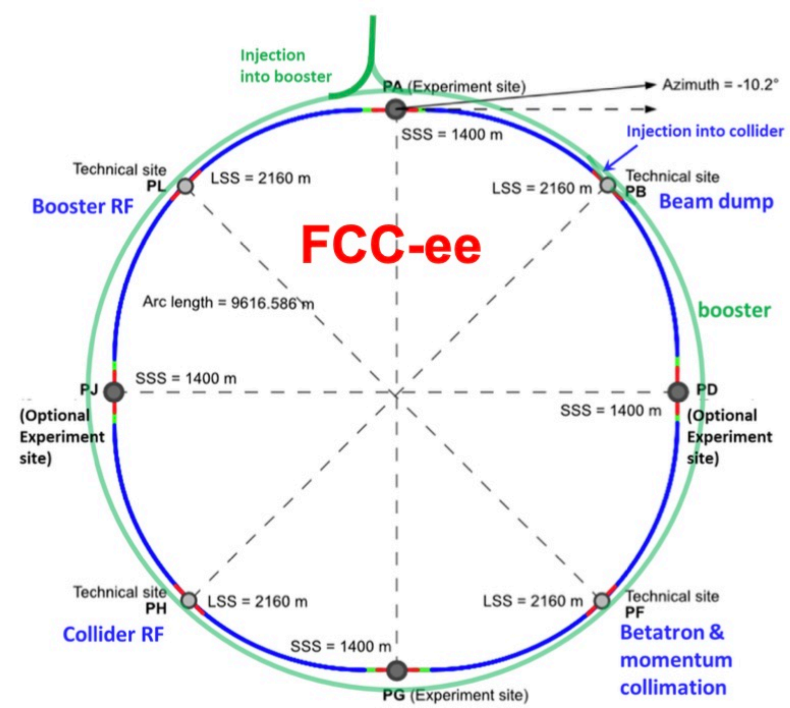
The future is bright….

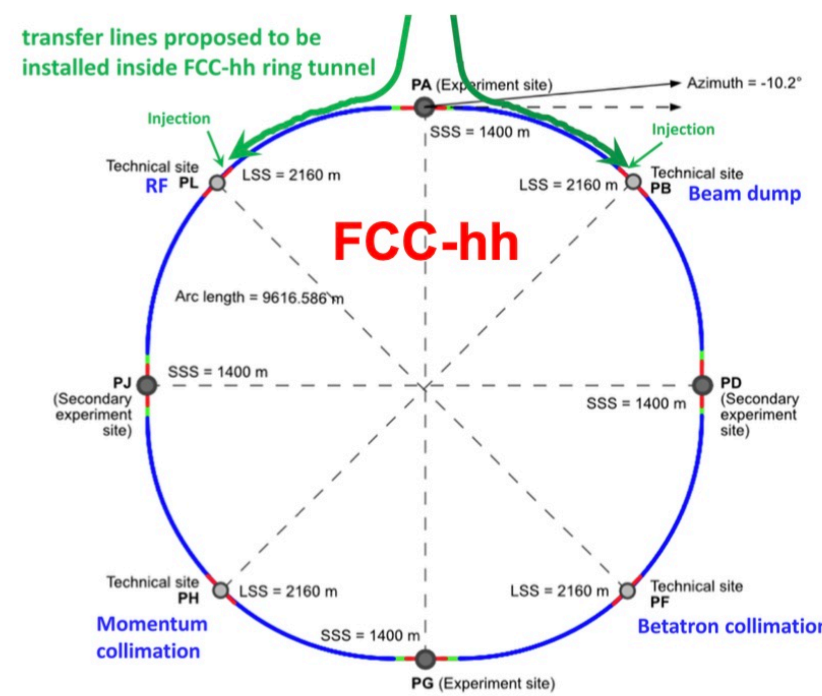
FUTURE CIRCULAR COLLIDER — FCC integrated program 2

comprehensive long-term program maximizing physics opportunities

- **stage 1: FCC-ee (Z, W, H, $t\bar{t}$) as Higgs factory, electroweak & top factory at highest luminosities**
- **stage 2: FCC-hh (~100 TeV) as natural continuation at energy frontier, pp & AA collisions; e-h option**
- highly synergetic and complementary programme boosting the physics reach of both colliders (e.g. model-independent measurements of the Higgs couplings at FCC-hh thanks to input from FCC-ee; and FCC-hh as "energy upgrade" of FCC-ee)
- common civil engineering and technical infrastructures, building on and reusing CERN's existing infrastructure
- FCC integrated project allows the start of a new, major facility at CERN within a few years of the end of HL-LHC







2020 - 2040	2045 - 2063	2070 - 2095

CERN — **Slide from Micheal Benedikt**

Talk by Patrizia Azzi

…but we need to make it happen !

The risk we run is not the one of finding no new physics but the one of dissolving a generation of young and talented researchers and the precious know-how we have accumulated in decades of work

We need to decide what our priority is as a community and we need to do it as soon as possible !

Thanks a lot to all the participants for the nice talks and discussions !