Precision physics at the LHC

56. International Meeting on Nuclear Physics, January 2018, Bormio

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- **Precise calculations and measurements of the orbit of Uranus allowed to precisely know where to aim the telescopes and Neptune was found**

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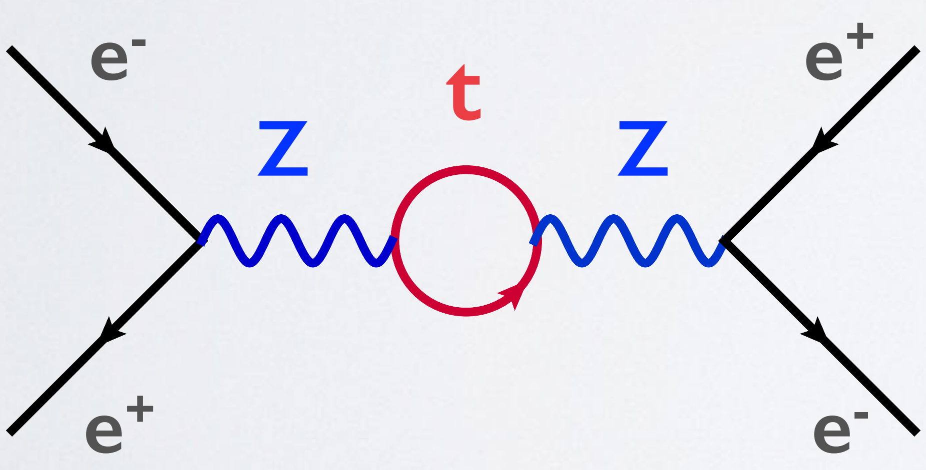
- **Precise calculations and measurements of the orbit of Uranus allowed to precisely know where to aim the telescopes and Neptune was found**
- **Also precision measurements of the orbit of Mercury gave the first evidence for General Relativity much before any gravitational wave was seen**

LEP and the top quark

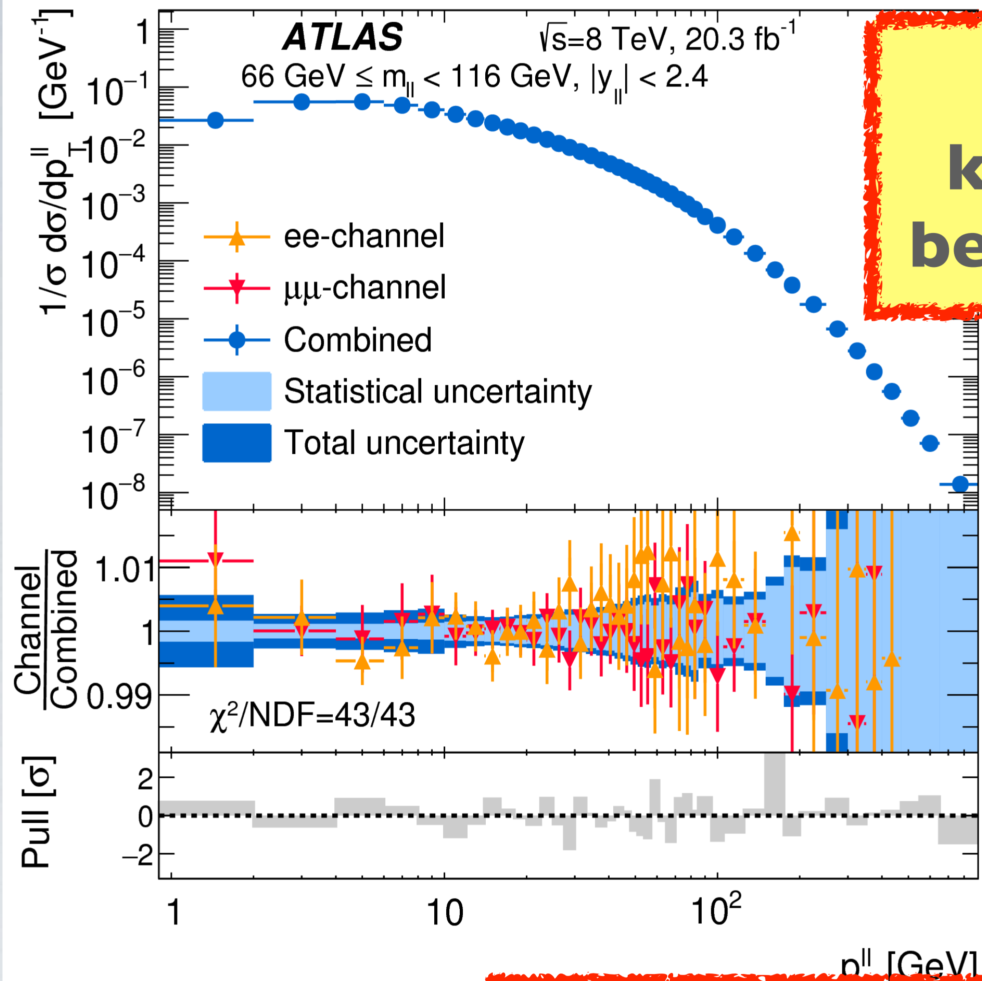
Similarly, precision calculations of e^+e^- collisions, together with the most precise measurements at LEP at CERN allowed us to know about the existence of the top quark, and even to estimate the value of its mass before it was directly discovered at the Tevatron



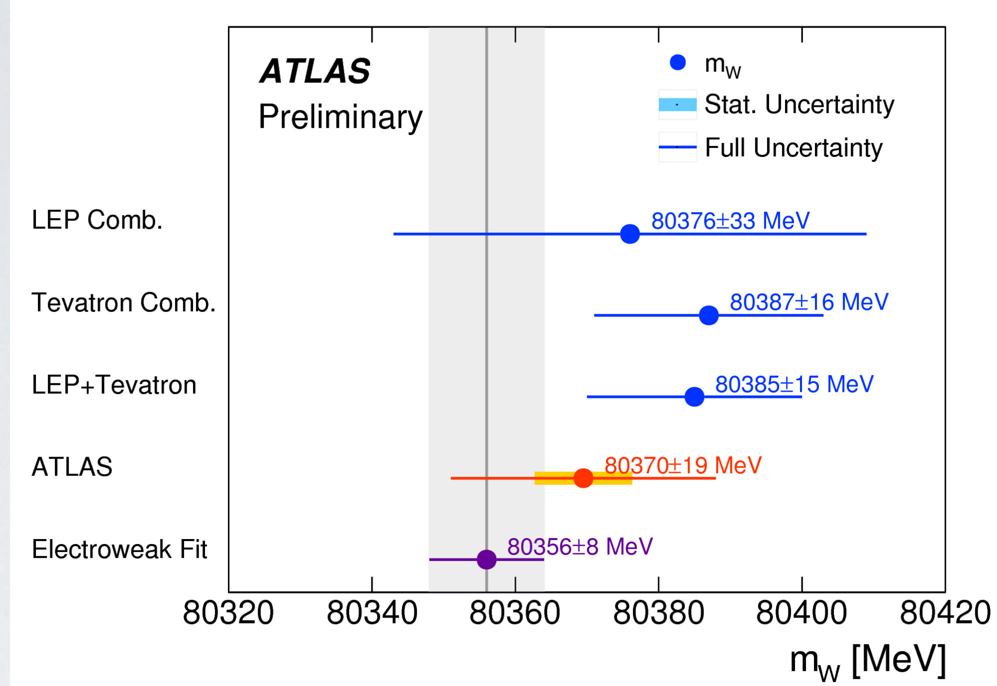
- Mass of the top quark from ***indirect*** determinations at LEPI and SLC in 1993: $m_{top} = (177 \pm 10)$ GeV
- First ***direct*** production at the Tevatron in 1994: $m_{top} = (174 \pm 16)$ GeV

LHC as a precision machine

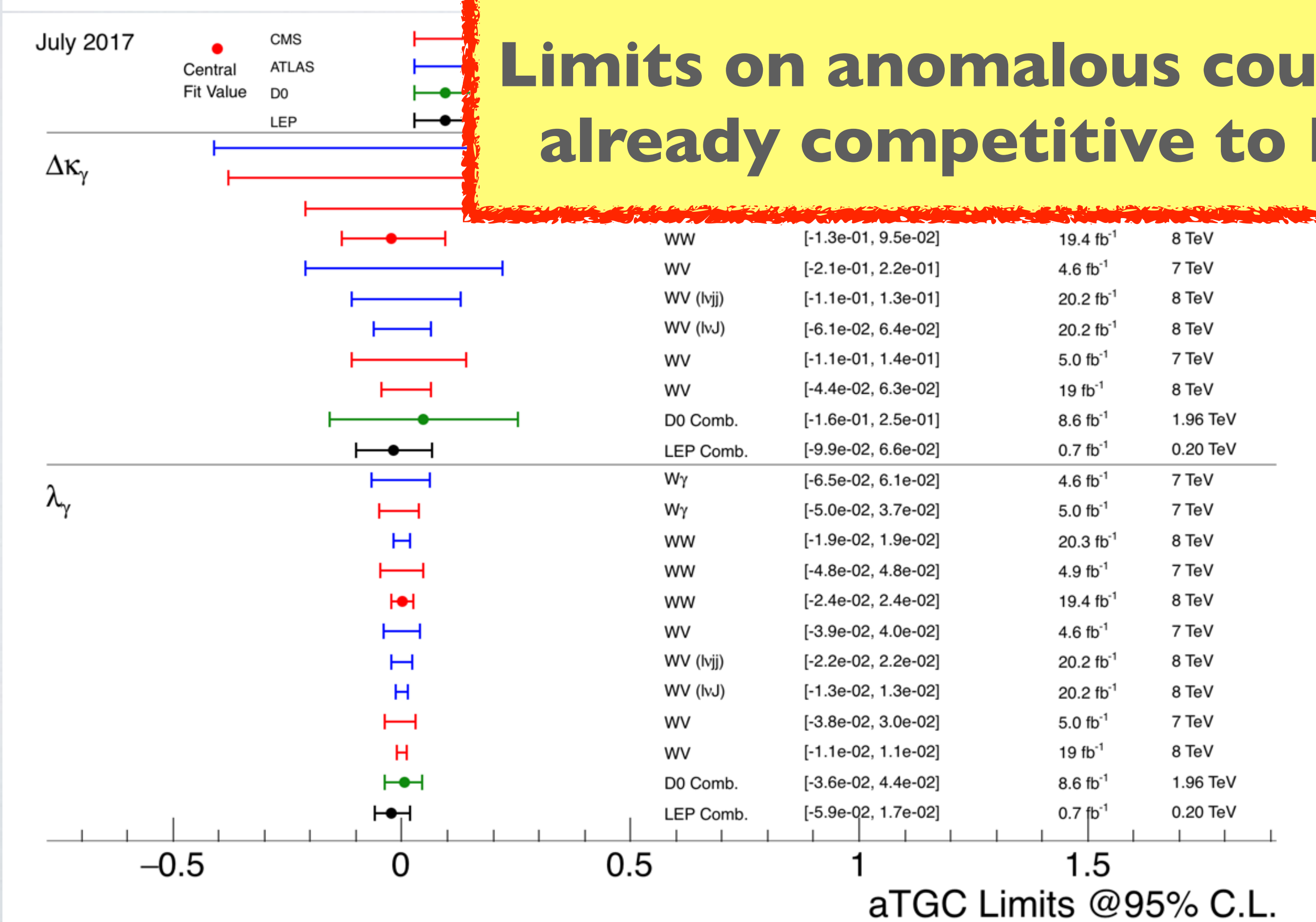
- Traditionally
  - ➡ e^+e^- colliders: precision machines because of clean environment
  - ➡ proton-proton colliders: discovery machines since higher energies are more easily achieved
- First change of perspective with the Tevatron and **revolution with the LHC: hadron collider as a precision machine**



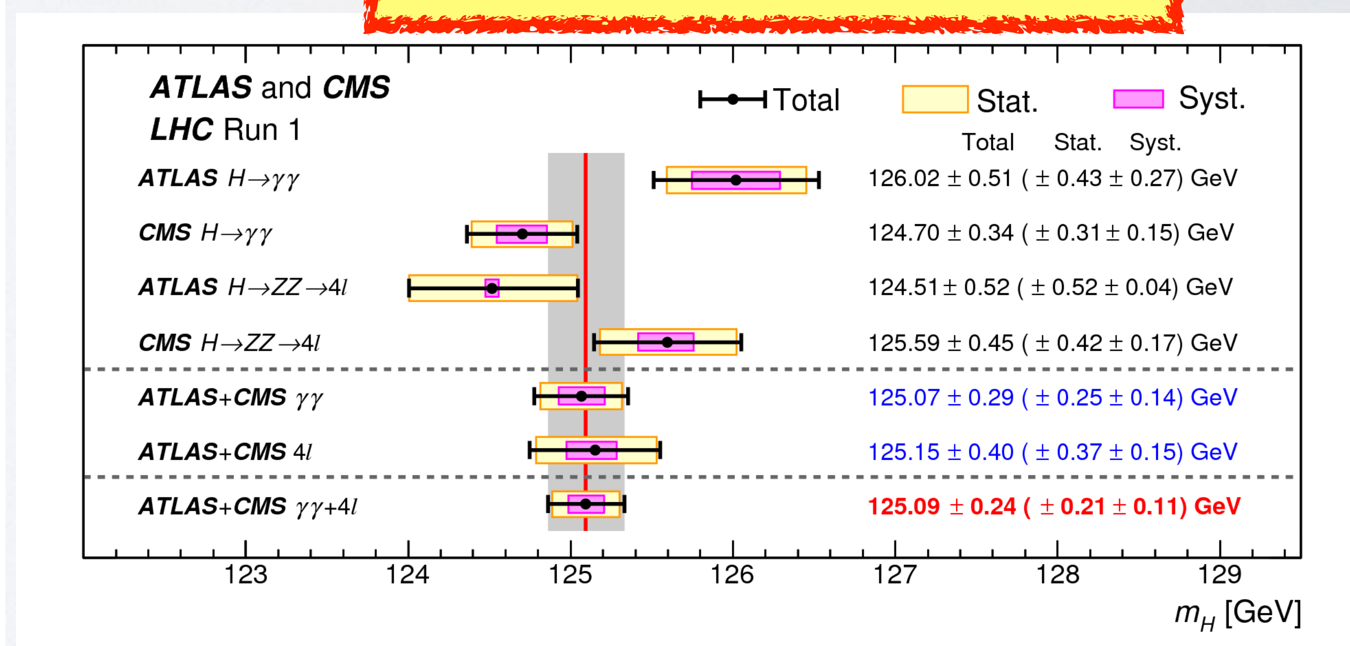
Z-boson kinematics to below a percent



W-boson mass measured with 20 MeV precision (0.02%)



Limits on anomalous coupling already competitive to LEP



Higgs mass measured to 250 MeV (0.2%)

Role of precision theory

- Thanks to accelerator, experiments and computers, precision measurements are already a reality
- This is a game changer which doubles the value of the LHC and HL-LHC
  - when new particles are found directly $\Longrightarrow$ precision measurements of properties, which are needed to understand the new underlying theory (this is happening now for the Higgs boson)
  - but also precision tests bring in new possibilities, complementary to direct searches for new physics (like for Uranus)
- in this endeavour, precise theory predictions crucial to enhance sensitivity

Precision via perturbation

Number of events computed as successive approximations with additional terms that become smaller and smaller.
More terms in the approximation ⇒ improved accuracy

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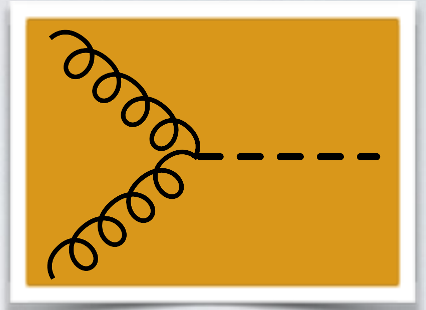
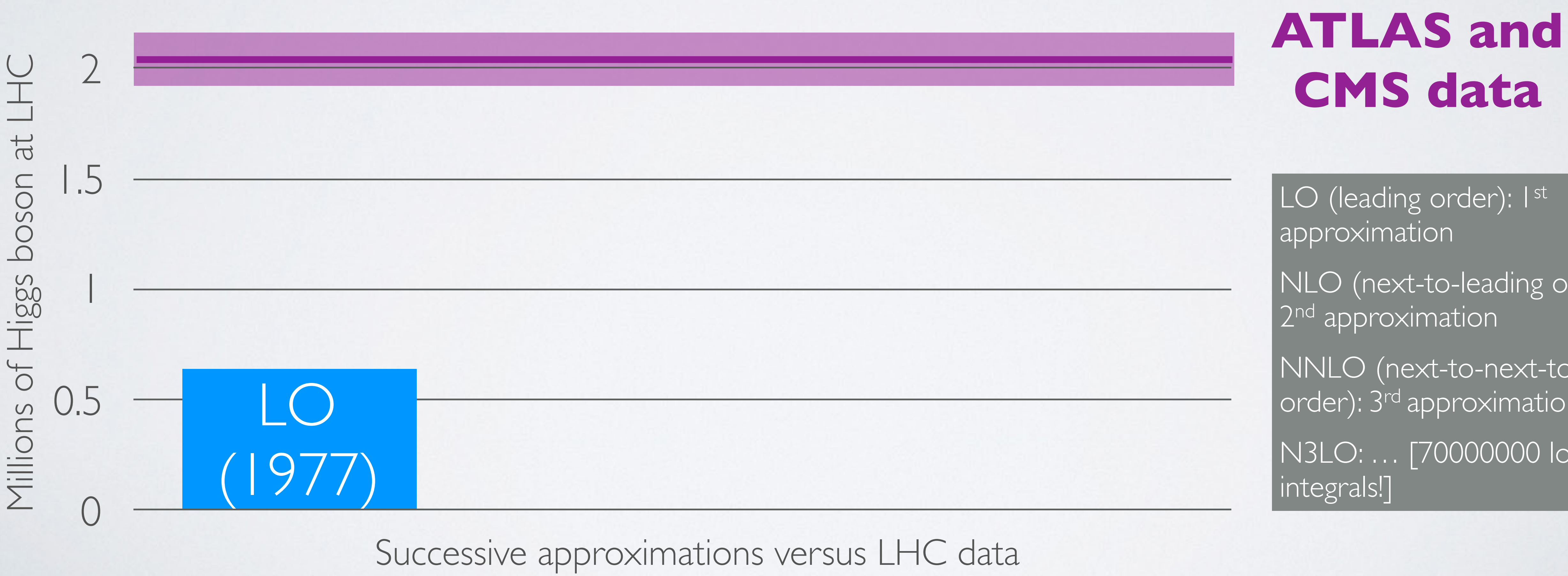


Example: number of Higgs bosons at production in millions (end 2016)



LO (leading order): 1st approximation

NLO (next-to-leading order): 2nd approximation

NNLO (next-to-next-to-leading order): 3rd approximation

N3LO: … [70000000 loop integrals!]

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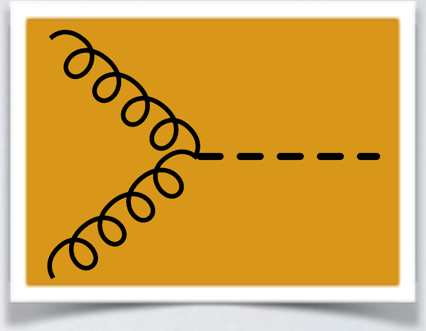

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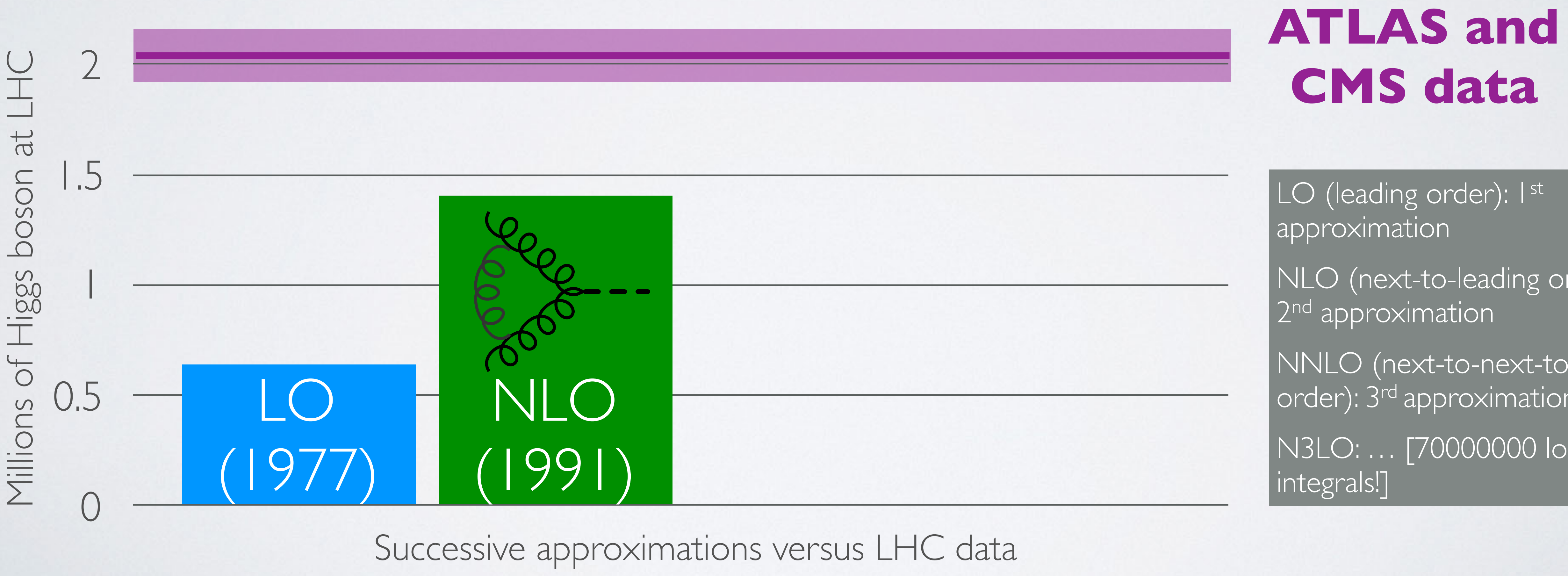

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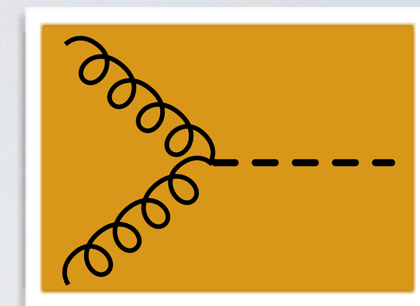

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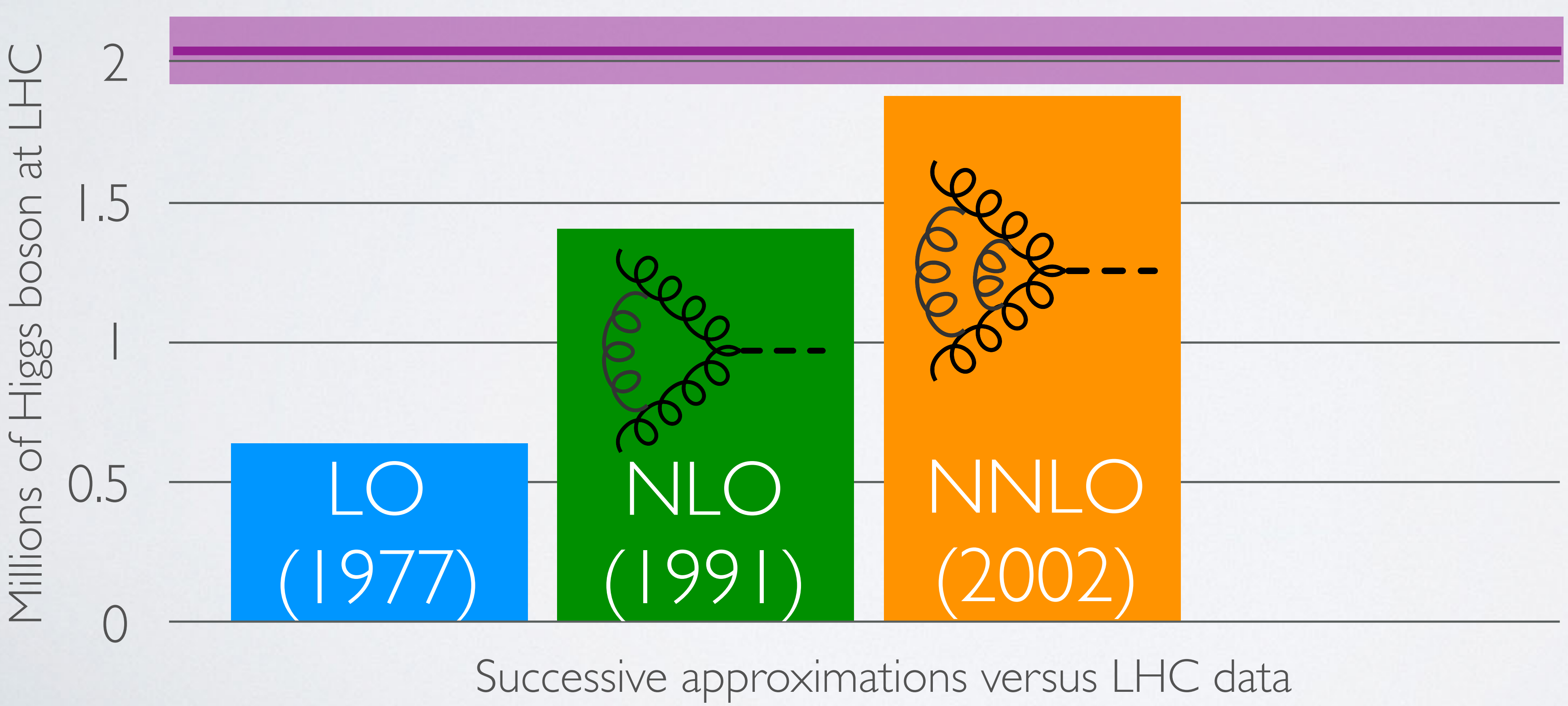

ATLAS and CMS data

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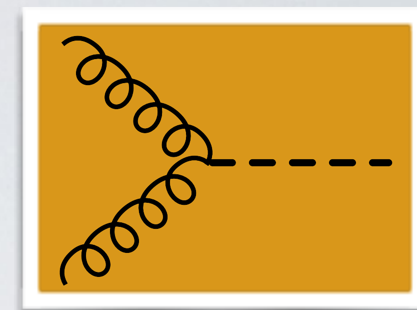

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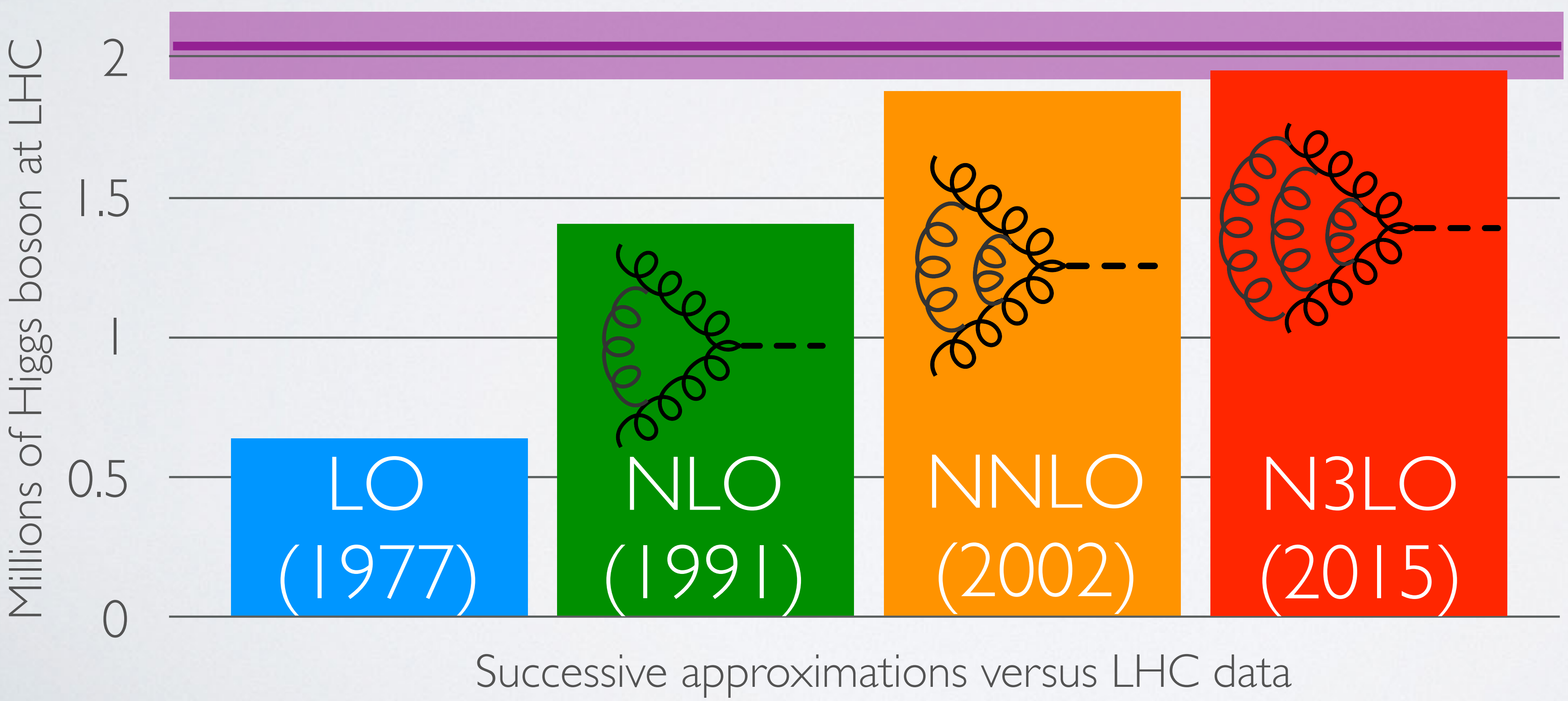

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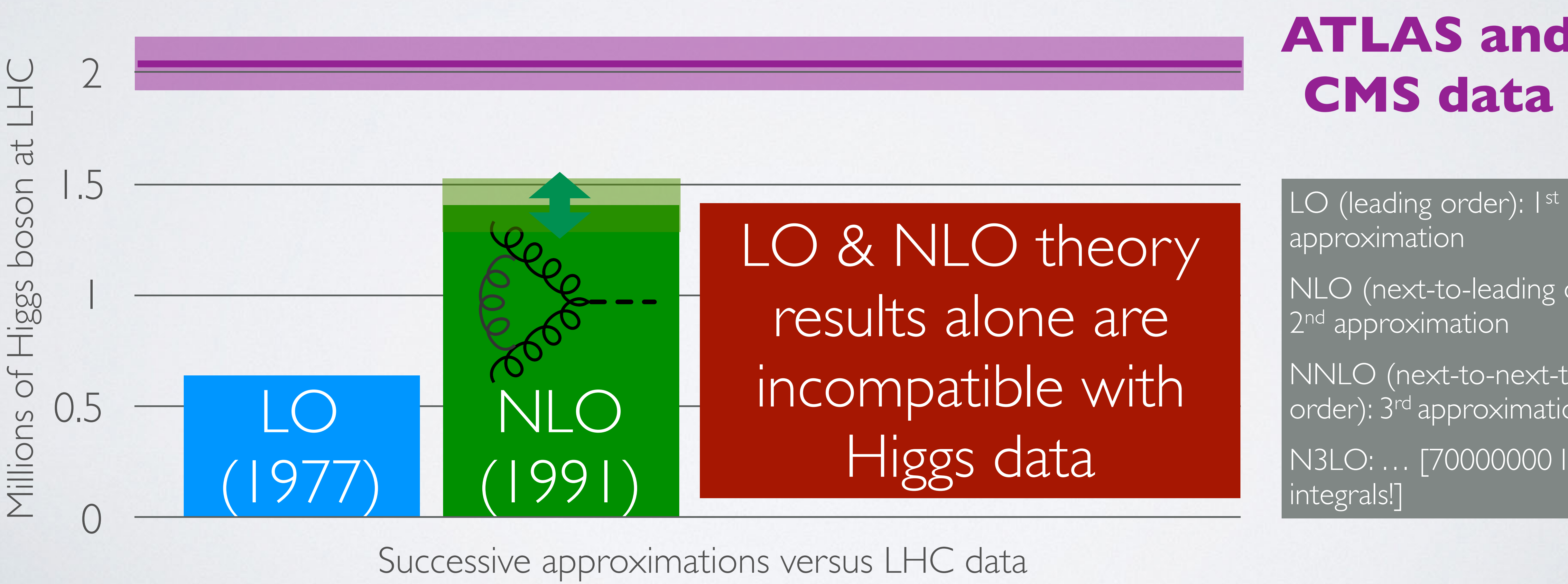
N3LO: … [70000000 loop integrals!]

Precision via perturbation

Without NNLO & N3LO results:

- ➡ we could not perform any precision test of the Higgs boson
- ➡ we would think that we have discovered New Physics!



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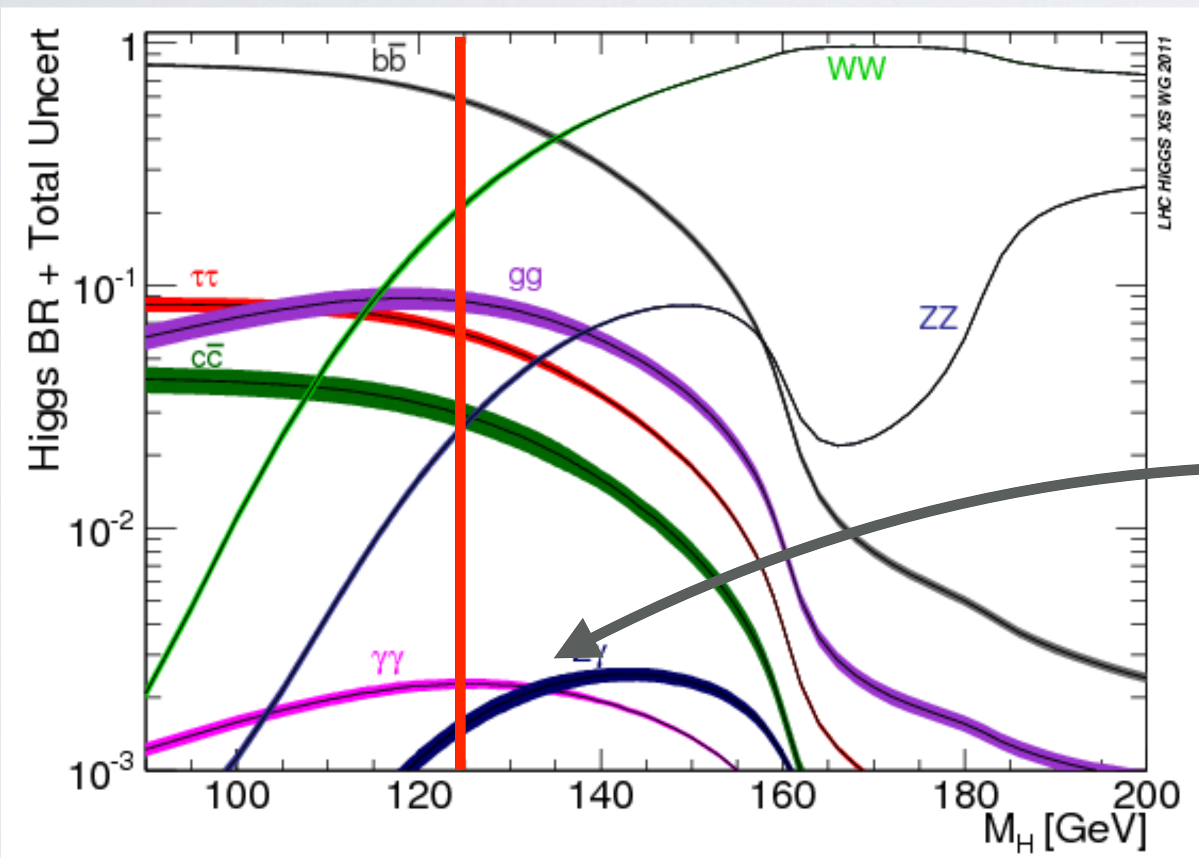
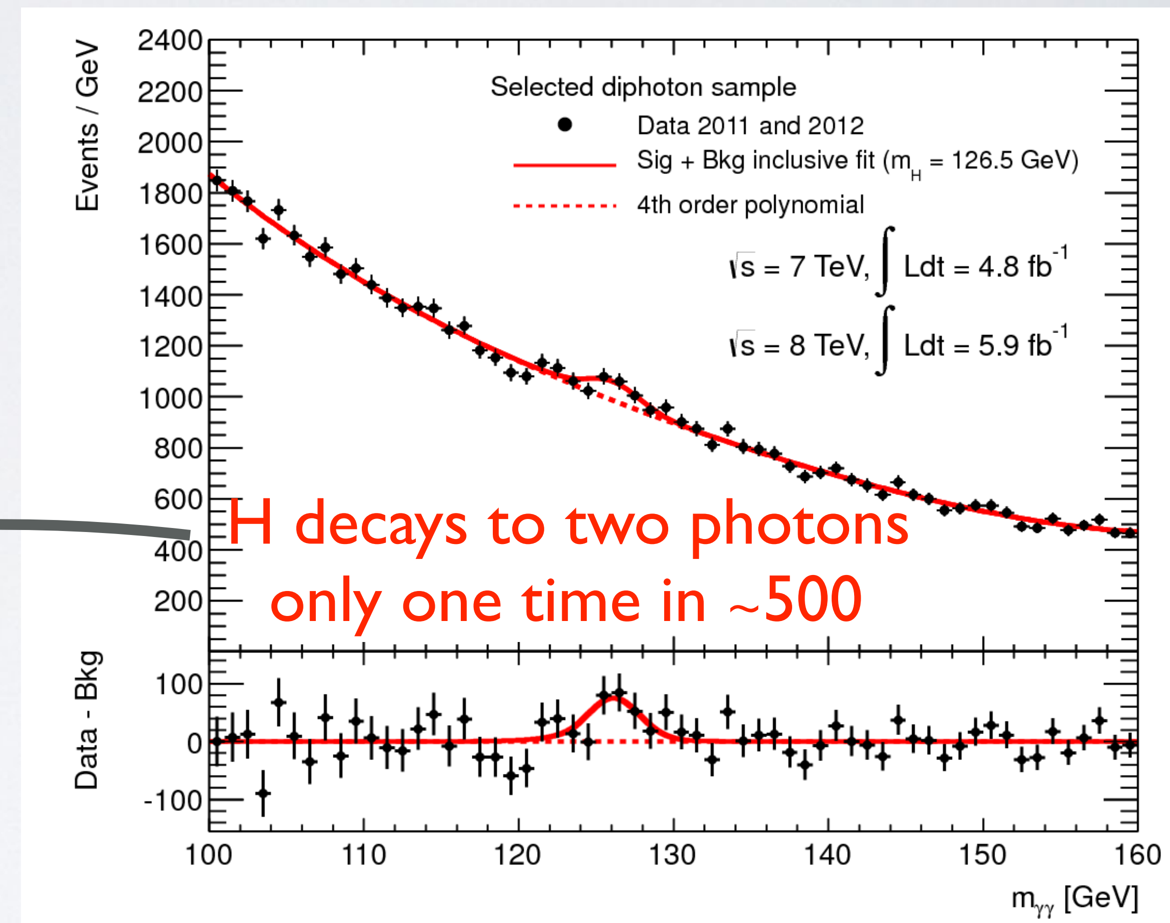
Why do we need millions of H

m_H = 125 GeV



Discovery & mass measurement



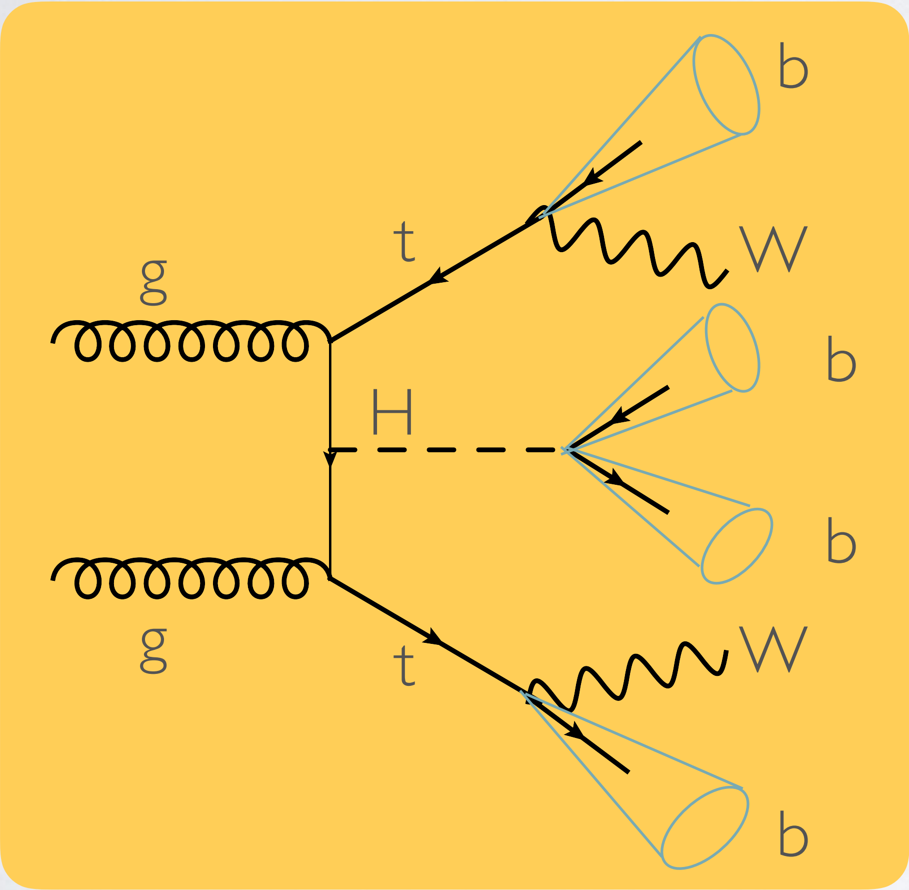
H decays to two photons
only one time in ~500

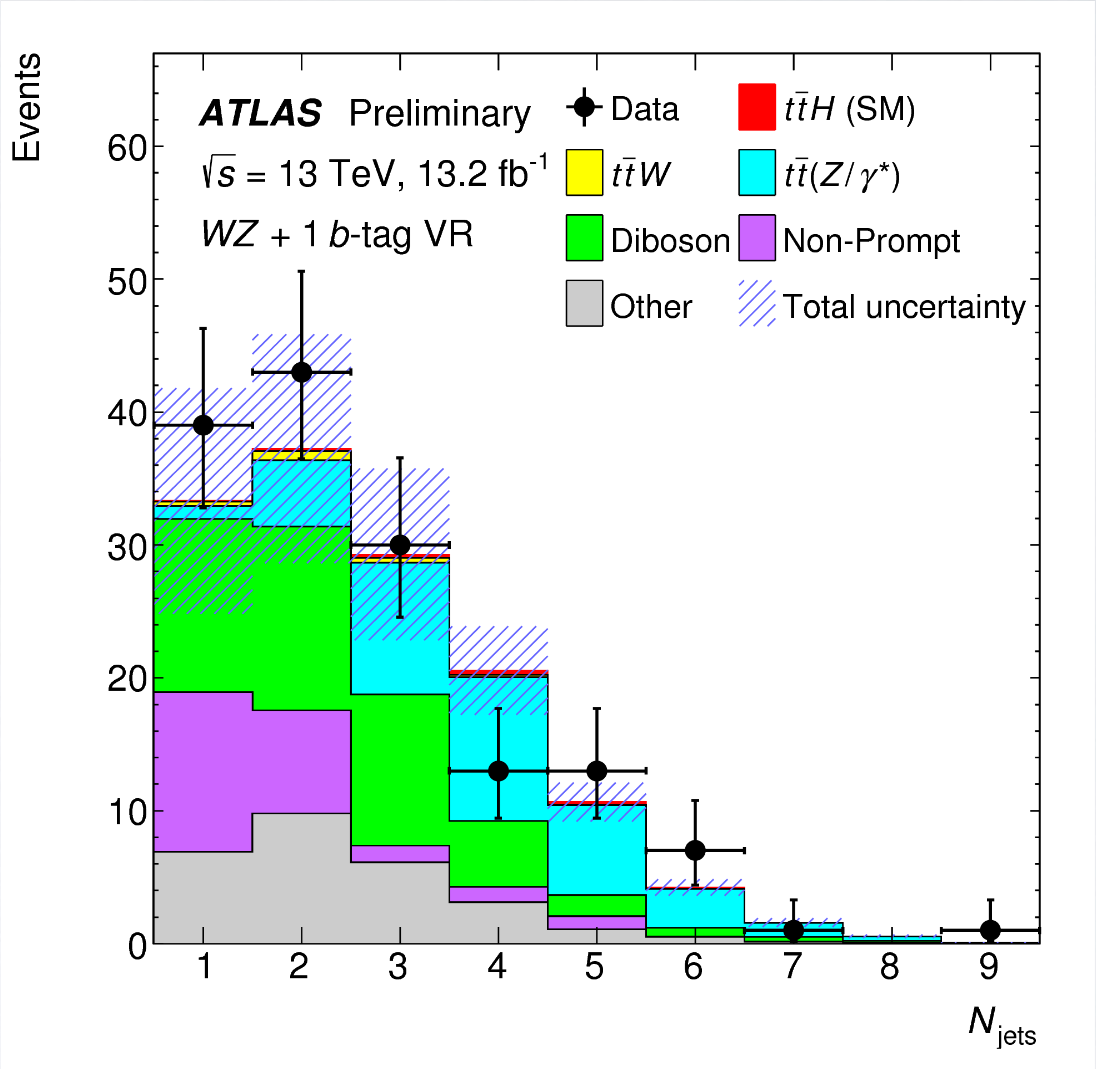
Higgs lies in a fantastic spot where to study the Higgs coupling.
Incredibly rich phenomenology.

Taming backgrounds

Example:

Higgs production in association with top-quarks with H ⟶ bb





Need precision not just for Higgs signals, but also for all SM backgrounds, in particular events involving many jets

Example: 2 gluons → 4 gluons

specific question of interest concerns the QCD four-jet background to the detection of W^+W^- pairs in their nonleptonic decays. The cross sections for the elementary two→four processes have not been calculated, and their complexity is such that they may not be evaluated in the foreseeable future. It is worthwhile to seek estimates of the four-jet cross sections, even if these are only reliable in restricted regions of phase space.

Supercollider physics

(1984)

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K. Lane

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Eichten *et al.* summarize the motivation for exploring the 1-TeV ($=10^{12}$ eV) energy scale in elementary particle interactions and explore the capabilities of proton-(anti)proton colliders with beam energies between 1 and 50 TeV. The authors calculate the production rates and characteristics for a number of conventional processes, and discuss their intrinsic physics interest as well as their role as backgrounds to more exotic phenomena. The authors review the theoretical motivation and expected signatures for several new phenomena which may occur on the 1-TeV scale. Their results provide a reference point for the choice of machine parameters and for experiment design.

TeV. From Fig. 78 we find the corresponding two-jet cross section (at $p_\perp=0.5$ TeV/c) to be about 7×10^{-2} nb/GeV, which is larger by an order of magnitude. Let us next consider the cross section in the neighborhood of the peak in Fig. 102. The integrated cross section in the bin [illegible] 0.4 is approximately 0.1 nb/GeV, with transverse energy [illegible] by $\langle E_T\rangle\approx(1\text{ TeV})\times\langle\cos\theta\rangle=350$ GeV. The [illegible] two-jet cross section, again from Fig. 78, is approximately [illegible] which is larger by 2 orders of magnitude. In fact, we have certainly underestimated $\langle E_T\rangle$ and thus somewhat overestimated the two-jet/three-jet ratio in this second case.

We draw two conclusions from this very casual analysis:

At least at small-to-mod[illegible] values of E_T, two-jet events should [illegible] for most of the cross section.

[illegible] three-jet cross section is large enough that a detailed study of this topology should be possible.

It is apparent that these questions are amenable to detailed investigation with the aid of realistic Monte Carlo simulations. Given the elementary two→three cross sections and reasonable parametrizations of the fragmentation functions, this exercise can be carried out with some degree of confidence.

For multijet events containing more than three jets, the theoretical situation is considerably more primitive. A specific question of interest concerns the QCD four-jet background to the detection of W^+W^- pairs in their nonleptonic decays. The cross sections for the elementary two→four processes have not been calculated, and their complexity is such that they may not be evaluated in the foreseeable future. It is worthwhile to seek estimates of the four-jet cross sections, even if these are only reliable in restricted regions of phase space.

Another background source of four-jet events is double parton scattering, as shown in Fig. 103. If all the parton momentum fractions are small, the two interactions may be treated as uncorrelated. The resulting four-jet cross section with transverse energy E_T may then be approximated by

$$\sigma_4(E_T)=\int_\epsilon^{E_T-\epsilon}dE_{T1}\int_\epsilon^{E_T-\epsilon}dE_{T2}\,\frac{\sigma_2(E_{T1})\sigma_2(E_{T2})\delta(E_{T1}+E_{T2}-E_T)}{\sigma_{\text{total}}}\,, \tag{3.47}$$

where $\sigma_2(E_{T1})$ is the two-jet cross section and ϵ denotes the minimum E_T required for a discernable two-jet event. For a recent study of double parton scattering at $Sp\bar{p}S$ and Tevatron energies, see Paver and Treleani (1983).

In view of the promise that multijet spectroscopy holds, improving our understanding of the QCD background is an urgent priority for further study.

D. Summary

We conclude this section with a brief summary of the ranges of jet energy which are accessible for various beam energies and luminosities. We find essentially no differences between pp and $\bar{p}p$ collisions, so only pp results will be given except at $\sqrt{s}=2$ TeV where $\bar{p}p$ rates are quoted. Figure 104 shows the E_T range which can be explored at the level of at least one event per GeV of E_T per unit rapidity at 90° in the c.m. (compare Figs. 77–79 and 83). The results are presented in terms of the transverse energy per event E_T, which corresponds to twice the transverse momentum $p_\perp$ of a jet. In Fig. 105 we plot the values of E_T that distinguish the regimes in which the two-gluon, quark-gluon, and quark-quark final states are dominant. Comparing with Fig. 104, we find that while the accessible ranges of E_T are impressive, it seems extremely difficult to obtain a clean sample of quark jets. Useful for estimating trigger rates is the total cross section for two jets integrated over $E_T(=2p_\perp)>E_{T_0}$ for both jets in a rapidity interval of -2.5 to $+2.5$. This is shown for pp collisions in Fig. 106.

IV. ELECTROWEAK PHENOMENA

In this section we discuss the supercollider processes associated with the standard model of the weak and electromagnetic interactions (Glashow, 1961; Weinberg, 1967; Salam, 1968). By "standard model" we understand the $SU(2)_L\otimes U(1)_Y$ theory applied to three quark and lepton doublets, and with the gauge symmetry broken by a single complex Higgs doublet. The particles associated with the electroweak interactions are therefore the (left-handed) charged intermediate bosons $W^\pm$, the neutral intermedi-

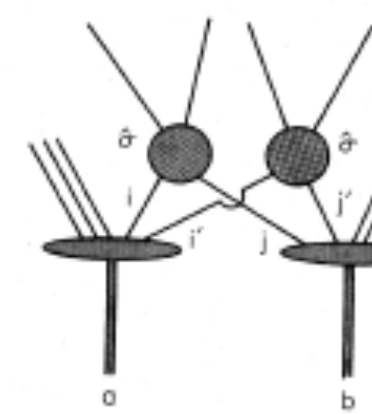
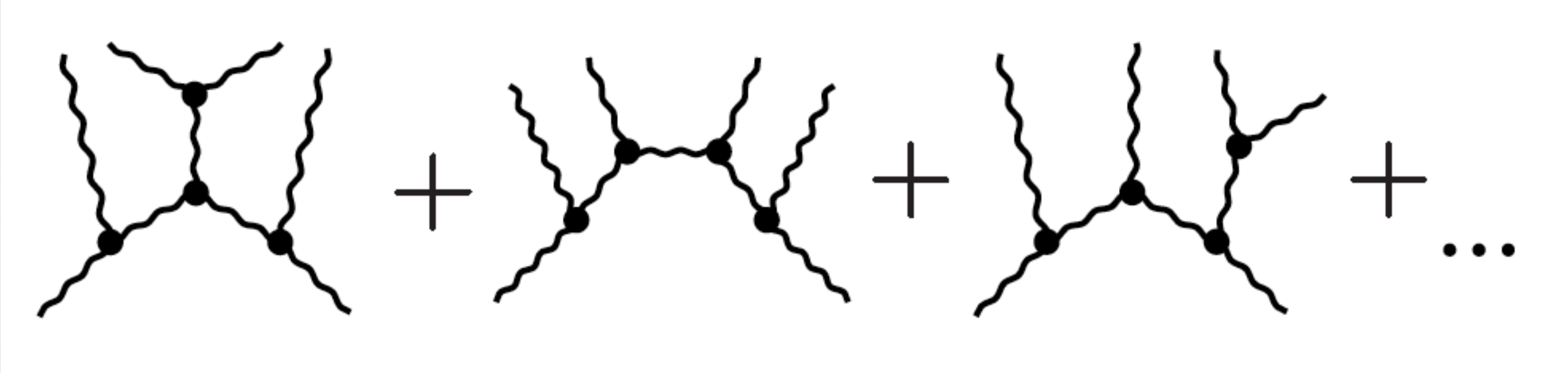


FIG. 103. Four-jet topology arising from two independent parton interactions.

Example: 2 gluons → 4 gluons

Consider the amplitude for two gluons to collide and produce four gluons: gg → gggg.

Before modern computers, this would have been barely tractable even at leading order (LO)



217 diagrams

Example: 2 gluons → 4 gluons

In 1985 Parke and Taylor took up the challenge, using

✓ the most advanced theoretical tools available

✓ the world best computers

they produced a final formula that would fit in **8 pages**

THE CROSS SECTION FOR FOUR-GLUON PRODUCTION BY GLUON–GLUON FUSION

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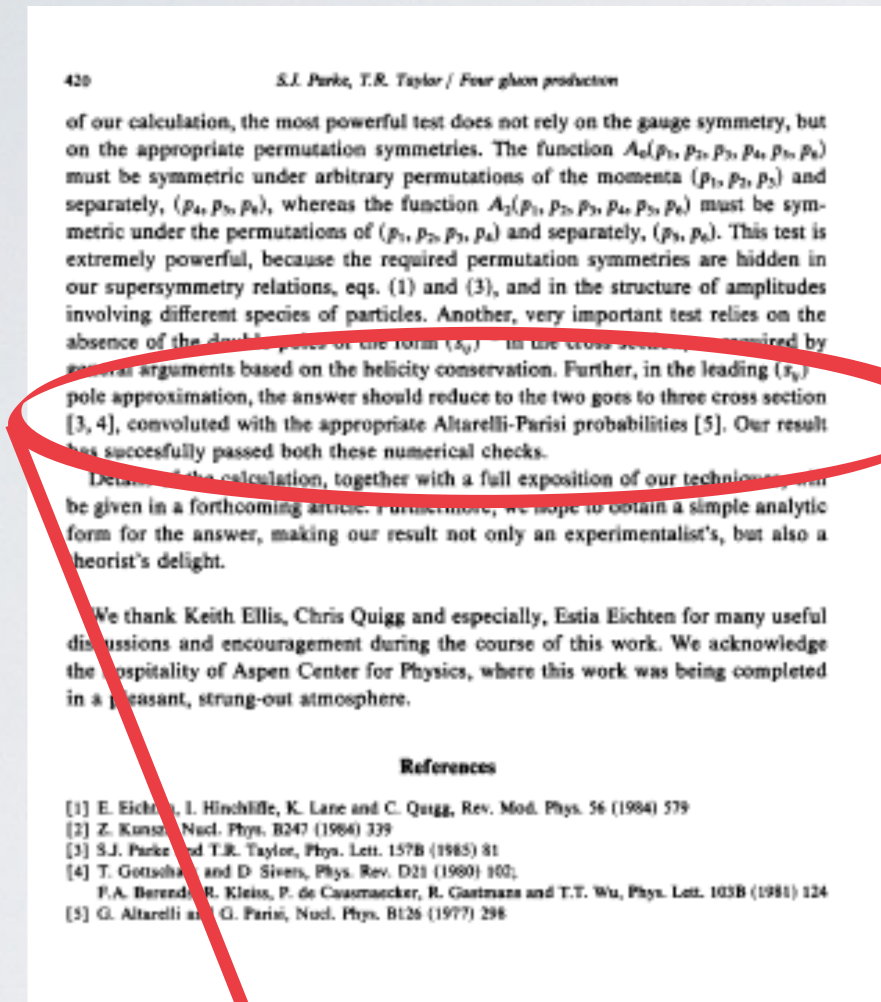
Received 13 September 1985

The cross section for two-gluon to four-gluon scattering is given in a form suitable for fast numerical calculations.

Example: 2 gluons → 4 gluons



of our calculation, the most powerful test does not rely on the gauge symmetry, but on the appropriate permutation symmetries. The function $A_6(p_1, p_2, p_3, p_4, p_5, p_6)$ must be symmetric under arbitrary permutations of the momenta (p_1, p_2, p_3) and separately, (p_4, p_5, p_6), whereas the function $A_3(p_1, p_2, p_3, p_4, p_5, p_6)$ must be symmetric under the permutations of (p_1, p_2, p_3, p_4) and separately, (p_5, p_6). This test is extremely powerful, because the required permutation symmetries are hidden in our supersymmetry relations, eqs. (1) and (3), and in the structure of amplitudes involving different species of particles. Another, very important test relies on the absence of the [illegible] required by [illegible] arguments based on the helicity conservation. Further, in the leading (s_{ij}) pole approximation, the answer should reduce to the two goes to three cross section [3, 4], convoluted with the appropriate Altarelli-Parisi probabilities [5]. Our result [illegible] succesfully passed both these numerical checks.

[illegible] calculation, together with a full exposition of our techniques, [illegible] be given in a forthcoming [illegible] a simple analytic form for the answer, making our result not only an experimentalist's, but also a [illegible]heorist's delight.

[illegible]e thank Keith Ellis, Chris Quigg and especially, Estia Eichten for many useful dis[illegible]ussions and encouragement during the course of this work. We acknowledge the [illegible]ospitality of Aspen Center for Physics, where this work was being completed in a [illegible]easant, strung-out atmosphere.

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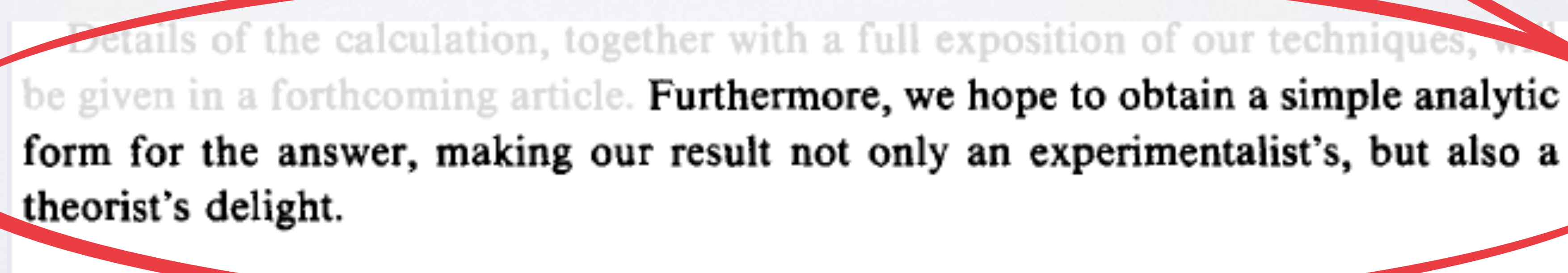
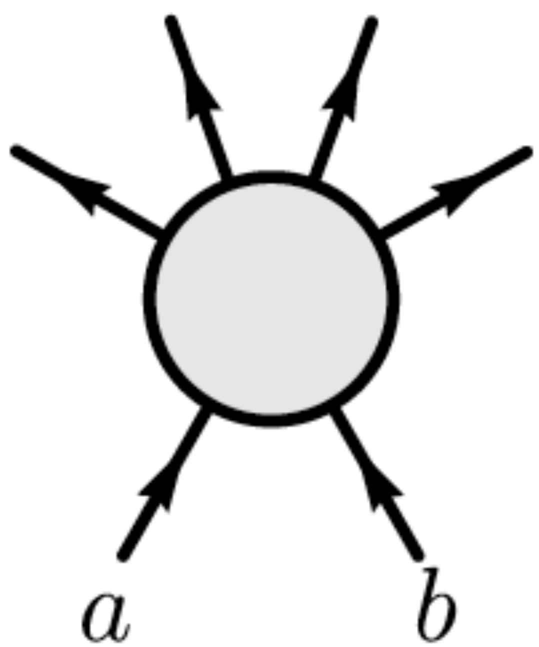


Details of the calculation, together with a full exposition of our techniques, will be given in a forthcoming article. Furthermore, we hope to obtain a simple analytic form for the answer, making our result not only an experimentalist's, but also a theorist's delight.

Finding simplicity

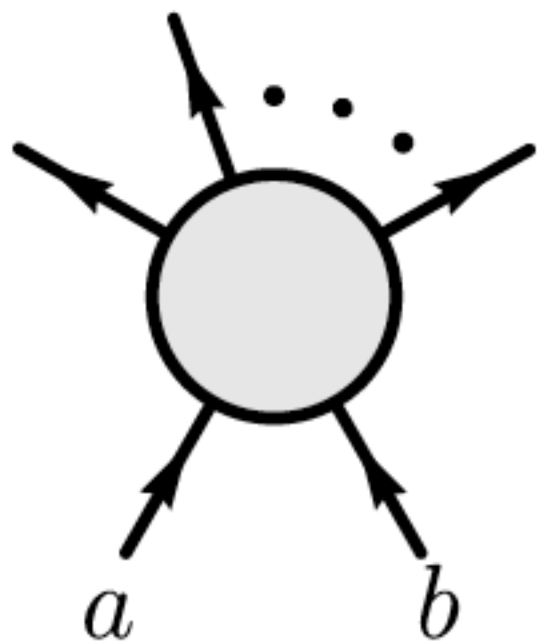
Soon afterwards they could guess an incredible, unanticipated simple form (for a fixed helicity configuration) …



$$= \frac{\langle a\, b\rangle^4}{\langle 1\,2\rangle\langle 2\,3\rangle\langle 3\,4\rangle\langle 4\,5\rangle\langle 5\,6\rangle\langle 6\,1\rangle}$$

Finding simplicity

… which naturally suggested the result for an arbitrary number of gluons



$$= \frac{\langle a\, b\rangle^4}{\langle 1\, 2\rangle\langle 2\, 3\rangle\langle 3\, 4\rangle\langle 4\, 5\rangle \cdots \langle n\, 1\rangle}$$

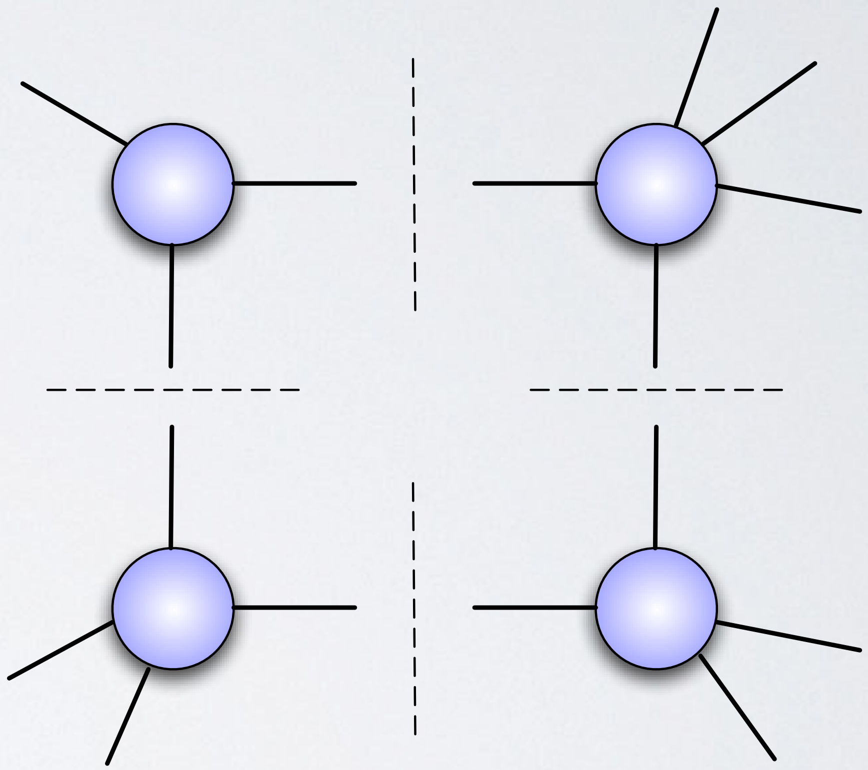
Twenty years later (2004)

- After Parke-Taylor and a number of other results the calculation of LO amplitudes was soon mastered
- Yet, the calculation of NLO QCD corrections remained a big challenge for more than twenty years
- One calculation (article) per process considered
- No automation was in sight

Thirty years later (2014)

Suddenly, **thanks to theoretical conceptual breakthrough ideas**

- connection between NLO amplitudes and LO ones
- input from supersymmetry/string theory
- sophisticated algebraic methods
- connections with formal theory and pure mathematics …



the problem of computing NLO QCD corrections is now solved

Automated NLO

Example: **single Higgs production processes** (similar results available for all SM processes of similar complexity, backgrounds to Higgs studies)

Process Single Higgs production		Syntax	Cross section (pb) LO 13 TeV		NLO 13 TeV	
g.1	$pp \to H$ (HEFT)	`p p > h`	$1.593 \pm 0.003 \cdot 10^{1}$	$^{+34.8\%}_{-26.0\%}$ $^{+1.2\%}_{-1.7\%}$	$3.261 \pm 0.010 \cdot 10^{1}$	$^{+20.2\%}_{-17.9\%}$ $^{+1.1\%}_{-1.6\%}$
g.2	$pp \to Hj$ (HEFT)	`p p > h j`	$8.367 \pm 0.003 \cdot 10^{0}$	$^{+39.4\%}_{-26.4\%}$ $^{+1.2\%}_{-1.4\%}$	$1.422 \pm 0.006 \cdot 10^{1}$	$^{+18.5\%}_{-16.6\%}$ $^{+1.1\%}_{-1.4\%}$
g.3	$pp \to Hjj$ (HEFT)	`p p > h j j`	$3.020 \pm 0.002 \cdot 10^{0}$	$^{+59.1\%}_{-34.7\%}$ $^{+1.4\%}_{-1.7\%}$	$5.124 \pm 0.020 \cdot 10^{0}$	$^{+20.7\%}_{-21.0\%}$ $^{+1.3\%}_{-1.5\%}$
g.4	$pp \to Hjj$ (VBF)	`p p > h j j $$ w+ w- z`	$1.987 \pm 0.002 \cdot 10^{0}$	$^{+1.7\%}_{-2.0\%}$ $^{+1.9\%}_{-1.4\%}$	$1.900 \pm 0.006 \cdot 10^{0}$	$^{+0.8\%}_{-0.9\%}$ $^{+2.0\%}_{-1.5\%}$
g.5	$pp \to Hjjj$ (VBF)	`p p > h j j j $$ w+ w- z`	$2.824 \pm 0.005 \cdot 10^{-1}$	$^{+15.7\%}_{-12.7\%}$ $^{+1.5\%}_{-1.0\%}$	$3.085 \pm 0.010 \cdot 10^{-1}$	$^{+2.0\%}_{-3.0\%}$ $^{+1.5\%}_{-1.1\%}$
g.6	$pp \to HW^{\pm}$	`p p > h wpm`	$1.195 \pm 0.002 \cdot 10^{0}$	$^{+3.5\%}_{-4.5\%}$ $^{+1.9\%}_{-1.5\%}$	$1.419 \pm 0.005 \cdot 10^{0}$	$^{+2.1\%}_{-2.6\%}$ $^{+1.9\%}_{-1.4\%}$
g.7	$pp \to HW^{\pm}j$	`p p > h wpm j`	$4.018 \pm 0.003 \cdot 10^{-1}$	$^{+10.7\%}_{-9.3\%}$ $^{+1.2\%}_{-0.9\%}$	$4.842 \pm 0.017 \cdot 10^{-1}$	$^{+3.6\%}_{-3.7\%}$ $^{+1.2\%}_{-1.0\%}$
g.8*	$pp \to HW^{\pm}jj$	`p p > h wpm j j`	$1.198 \pm 0.016 \cdot 10^{-1}$	$^{+26.1\%}_{-19.4\%}$ $^{+0.8\%}_{-0.6\%}$	$1.574 \pm 0.014 \cdot 10^{-1}$	$^{+5.0\%}_{-6.5\%}$ $^{+0.9\%}_{-0.6\%}$
g.9	$pp \to HZ$	`p p > h z`	$6.468 \pm 0.008 \cdot 10^{-1}$	$^{+3.5\%}_{-4.5\%}$ $^{+1.9\%}_{-1.4\%}$	$7.674 \pm 0.027 \cdot 10^{-1}$	$^{+2.0\%}_{-2.5\%}$ $^{+1.9\%}_{-1.4\%}$
g.10	$pp \to HZj$	`p p > h z j`	$2.225 \pm 0.001 \cdot 10^{-1}$	$^{+10.6\%}_{-9.2\%}$ $^{+1.1\%}_{-0.8\%}$	$2.667 \pm 0.010 \cdot 10^{-1}$	$^{+3.5\%}_{-3.6\%}$ $^{+1.1\%}_{-0.9\%}$
g.11*	$pp \to HZjj$	`p p > h z j j`	$7.262 \pm 0.012 \cdot 10^{-2}$	$^{+26.2\%}_{-19.4\%}$ $^{+0.7\%}_{-0.6\%}$	$8.753 \pm 0.037 \cdot 10^{-2}$	$^{+4.8\%}_{-6.3\%}$ $^{+0.7\%}_{-0.6\%}$
g.12*	$pp \to HW^{+}W^{-}$ (4f)	`p p > h w+ w-`	$8.325 \pm 0.139 \cdot 10^{-3}$	$^{+0.0\%}_{-0.3\%}$ $^{+2.0\%}_{-1.6\%}$	$1.065 \pm 0.003 \cdot 10^{-2}$	$^{+2.5\%}_{-1.9\%}$ $^{+2.0\%}_{-1.5\%}$
g.13*	$pp \to HW^{\pm}\gamma$	`p p > h wpm a`	$2.518 \pm 0.006 \cdot 10^{-3}$	$^{+0.7\%}_{-1.4\%}$ $^{+1.9\%}_{-1.5\%}$	$3.309 \pm 0.011 \cdot 10^{-3}$	$^{+2.7\%}_{-2.0\%}$ $^{+1.7\%}_{-1.4\%}$
g.14*	$pp \to HZW^{\pm}$	`p p > h z wpm`	$3.763 \pm 0.007 \cdot 10^{-3}$	$^{+1.1\%}_{-1.5\%}$ $^{+2.0\%}_{-1.6\%}$	$5.292 \pm 0.015 \cdot 10^{-3}$	$^{+3.9\%}_{-3.1\%}$ $^{+1.8\%}_{-1.4\%}$
g.15*	$pp \to HZZ$	`p p > h z z`	$2.093 \pm 0.003 \cdot 10^{-3}$	$^{+0.1\%}_{-0.6\%}$ $^{+1.9\%}_{-1.5\%}$	$2.538 \pm 0.007 \cdot 10^{-3}$	$^{+1.9\%}_{-1.4\%}$ $^{+2.0\%}_{-1.5\%}$
g.16	$pp \to Ht\bar{t}$	`p p > h t t~`	$3.579 \pm 0.003 \cdot 10^{-1}$	$^{+30.0\%}_{-21.5\%}$ $^{+1.7\%}_{-2.0\%}$	$4.608 \pm 0.016 \cdot 10^{-1}$	$^{+5.7\%}_{-9.0\%}$ $^{+2.0\%}_{-2.3\%}$
g.17	$pp \to Htj$	`p p > h tt j`	$4.994 \pm 0.005 \cdot 10^{-2}$	$^{+2.4\%}_{-4.2\%}$ $^{+1.2\%}_{-1.3\%}$	$6.328 \pm 0.022 \cdot 10^{-2}$	$^{+2.9\%}_{-1.8\%}$ $^{+1.5\%}_{-1.6\%}$
g.18	$pp \to Hb\bar{b}$ (4f)	`p p > h b b~`	$4.983 \pm 0.002 \cdot 10^{-1}$	$^{+28.1\%}_{-21.0\%}$ $^{+1.5\%}_{-1.8\%}$	$6.085 \pm 0.026 \cdot 10^{-1}$	$^{+7.3\%}_{-9.6\%}$ $^{+1.6\%}_{-2.0\%}$
g.19	$pp \to Ht\bar{t}j$	`p p > h t t~ j`	$2.674 \pm 0.041 \cdot 10^{-1}$	$^{+45.6\%}_{-29.2\%}$ $^{+2.6\%}_{-2.9\%}$	$3.244 \pm 0.025 \cdot 10^{-1}$	$^{+3.5\%}_{-8.7\%}$ $^{+2.5\%}_{-2.9\%}$
g.20*	$pp \to Hb\bar{b}j$ (4f)	`p p > h b b~ j`	$7.367 \pm 0.002 \cdot 10^{-2}$	$^{+45.6\%}_{-29.1\%}$ $^{+1.8\%}_{-2.1\%}$	$9.034 \pm 0.032 \cdot 10^{-2}$	$^{+7.9\%}_{-11.0\%}$ $^{+1.8\%}_{-2.2\%}$

Automated NLO

<u>Example</u>: **single Higgs production processes** (similar results available for all SM processes of similar complexity, backgrounds to Higgs studies)

Process		Syntax	Cross section (pb)			
Single Higgs production			LO 13 TeV		NLO 13 TeV	
g.1	$pp \to H$ (HEFT)	`p p > h`	$1.593 \pm 0.003 \cdot 10^{1}$	$^{+34.8\%}_{-26.0\%}$ $^{+1.2\%}_{-1.7\%}$	$3.261 \pm 0.010 \cdot 10^{1}$	$^{+20.2\%}_{-17.9\%}$ $^{+1.1\%}_{-1.6\%}$
g.2	$pp \to Hj$ (HEFT)	`p p > h j`	$8.367 \pm 0.003 \cdot 10^{0}$	$^{+39.4\%}_{-26.4\%}$ $^{+1.2\%}_{-1.4\%}$	$1.422 \pm 0.006 \cdot 10^{1}$	$^{+18.5\%}_{-16.6\%}$ $^{+1.1\%}_{-1.4\%}$
g.3	$pp \to Hjj$ (HEFT)	`p p > h j j`	$3.020 \pm 0.002 \cdot 10^{0}$	$^{+59.1\%}_{-34.7\%}$ $^{+1.4\%}_{-1.7\%}$	$5.124 \pm 0.020 \cdot 10^{0}$	$^{+20.7\%}_{-21.0\%}$ $^{+1.3\%}_{-1.5\%}$
g.4	$pp \to Hjj$ (VBF)	`p p > h j j $$ w+ w- z`	$1.987 \pm 0.002 \cdot 10^{0}$	$^{+1.7\%}_{-2.0\%}$ $^{+1.9\%}_{-1.4\%}$	$1.900 \pm 0.006 \cdot 10^{0}$	$^{+0.8\%}_{-0.9\%}$ $^{+2.0\%}_{-1.5\%}$
g.5	$pp \to Hjjj$ (VBF)	`p p > h j j j $$ w+ w- z`	$2.824 \pm 0.005 \cdot 10^{-1}$	$^{+15.7\%}_{-12.7\%}$ $^{+1.5\%}_{-1.0\%}$	$3.085 \pm 0.010 \cdot 10^{-1}$	$^{+2.0\%}_{-3.0\%}$ $^{+1.5\%}_{-1.1\%}$
g.6	$pp \to HW^{\pm}$	`p p > h wpm`	$1.195 \pm 0.002 \cdot 10^{0}$	$^{+3.5\%}_{-4.5\%}$ $^{+1.9\%}_{-1.5\%}$	$1.419 \pm 0.005 \cdot 10^{0}$	$^{+2.1\%}_{-2.6\%}$ $^{+1.9\%}_{-1.4\%}$
g.7	$pp \to$					$^{+3.6\%}_{-3.7\%}$ $^{+1.2\%}_{-1.0\%}$
g.8*	$pp \to$					$^{+5.0\%}_{-6.5\%}$ $^{+0.9\%}_{-0.6\%}$
g.9	$pp \to$					$^{+2.0\%}_{-2.5\%}$ $^{+1.9\%}_{-1.4\%}$
g.10	$pp \to$					$^{+3.5\%}_{-3.6\%}$ $^{+1.1\%}_{-0.9\%}$
g.11*	$pp \to$					$^{+4.8\%}_{-6.3\%}$ $^{+0.7\%}_{-0.6\%}$
g.12*	$pp \to HW^{+}W^{-}$ (4f)	`p p > h w+ w-`	$8.325 \pm 0.139 \cdot 10^{-3}$	$_{-0.3\%}$ $_{-1.6\%}$	$1.065 \pm 0.003 \cdot 10^{-2}$	$^{+2.5\%}_{-1.9\%}$ $^{+2.0\%}_{-1.5\%}$
g.13*	$pp \to HW^{\pm}\gamma$	`p p > h wpm a`	$2.518 \pm 0.006 \cdot 10^{-3}$	$^{+0.7\%}_{-1.4\%}$ $^{+1.9\%}_{-1.5\%}$	$3.309 \pm 0.011 \cdot 10^{-3}$	$^{+2.7\%}_{-2.0\%}$ $^{+1.7\%}_{-1.4\%}$
g.14*	$pp \to HZW^{\pm}$	`p p > h z wpm`	$3.763 \pm 0.007 \cdot 10^{-3}$	$^{+1.1\%}_{-1.5\%}$ $^{+2.0\%}_{-1.6\%}$	$5.292 \pm 0.015 \cdot 10^{-3}$	$^{+3.9\%}_{-3.1\%}$ $^{+1.8\%}_{-1.4\%}$
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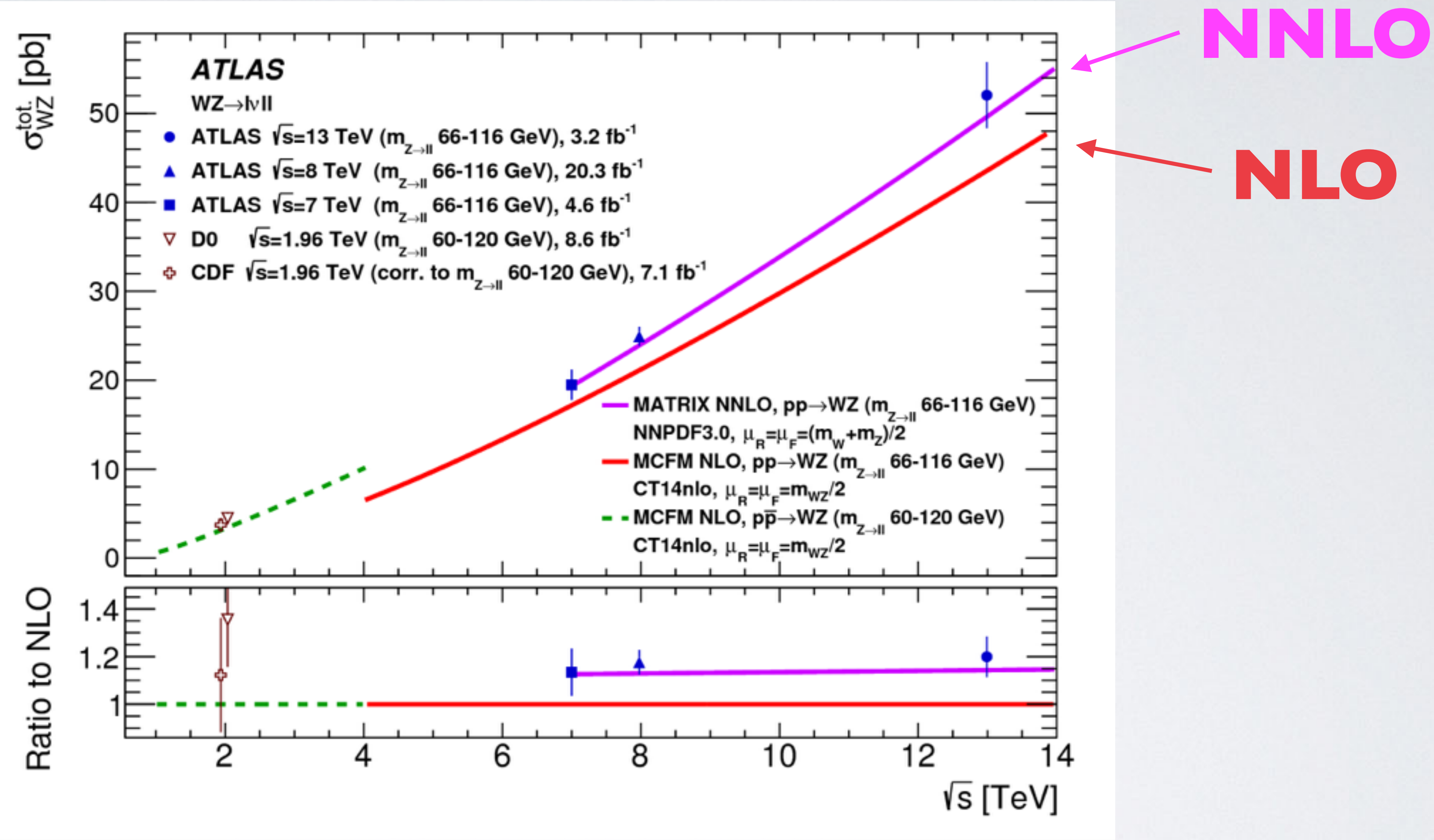
✓A solved problem

NLO & NNLO versus data



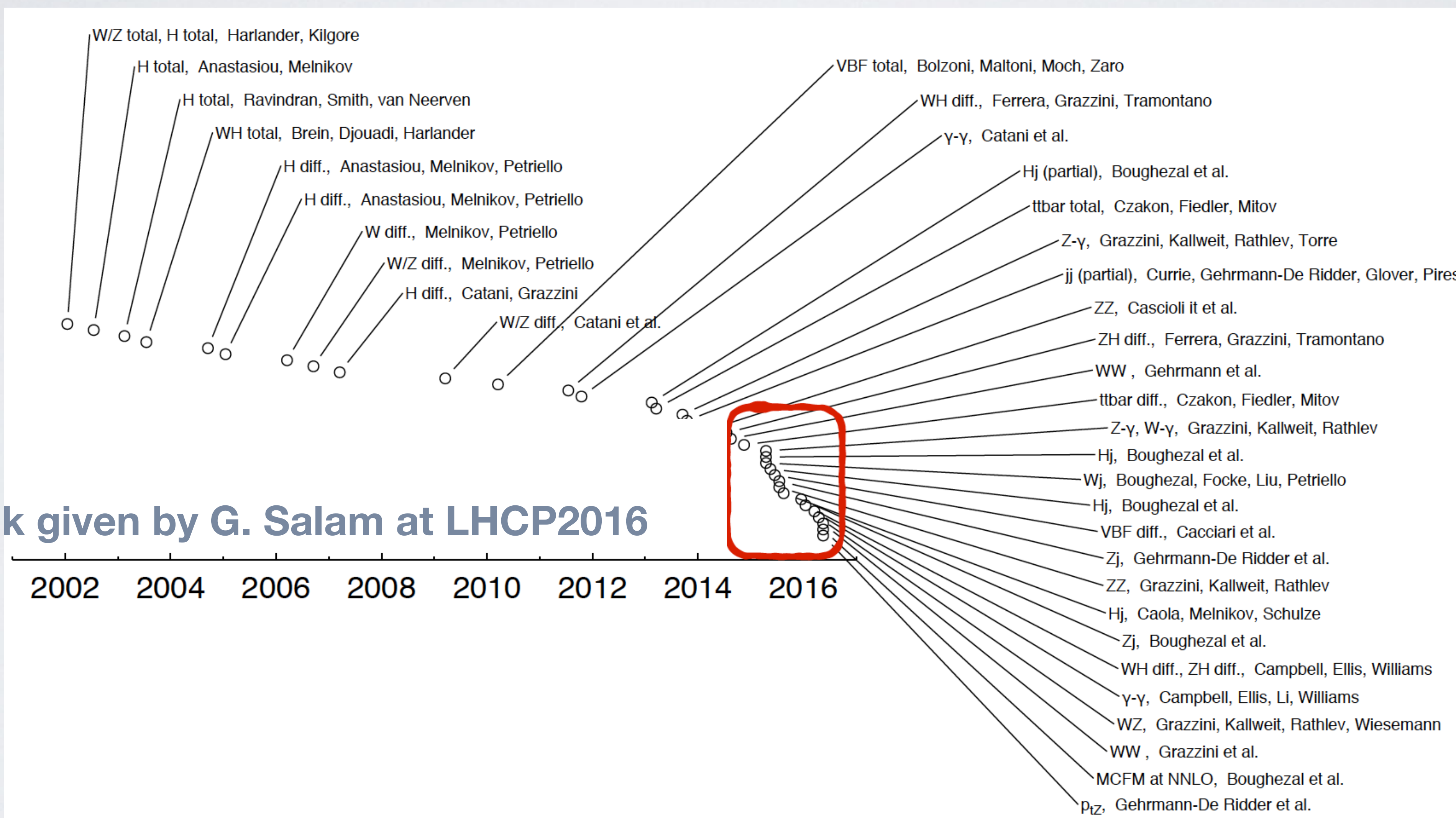
LHC data clearly prefers NNLO

Same conclusion in all measurements examined so far

With more data NLO likely to be insufficient

NNLO: the next challenge

An explosion of NNLO results in the last two years



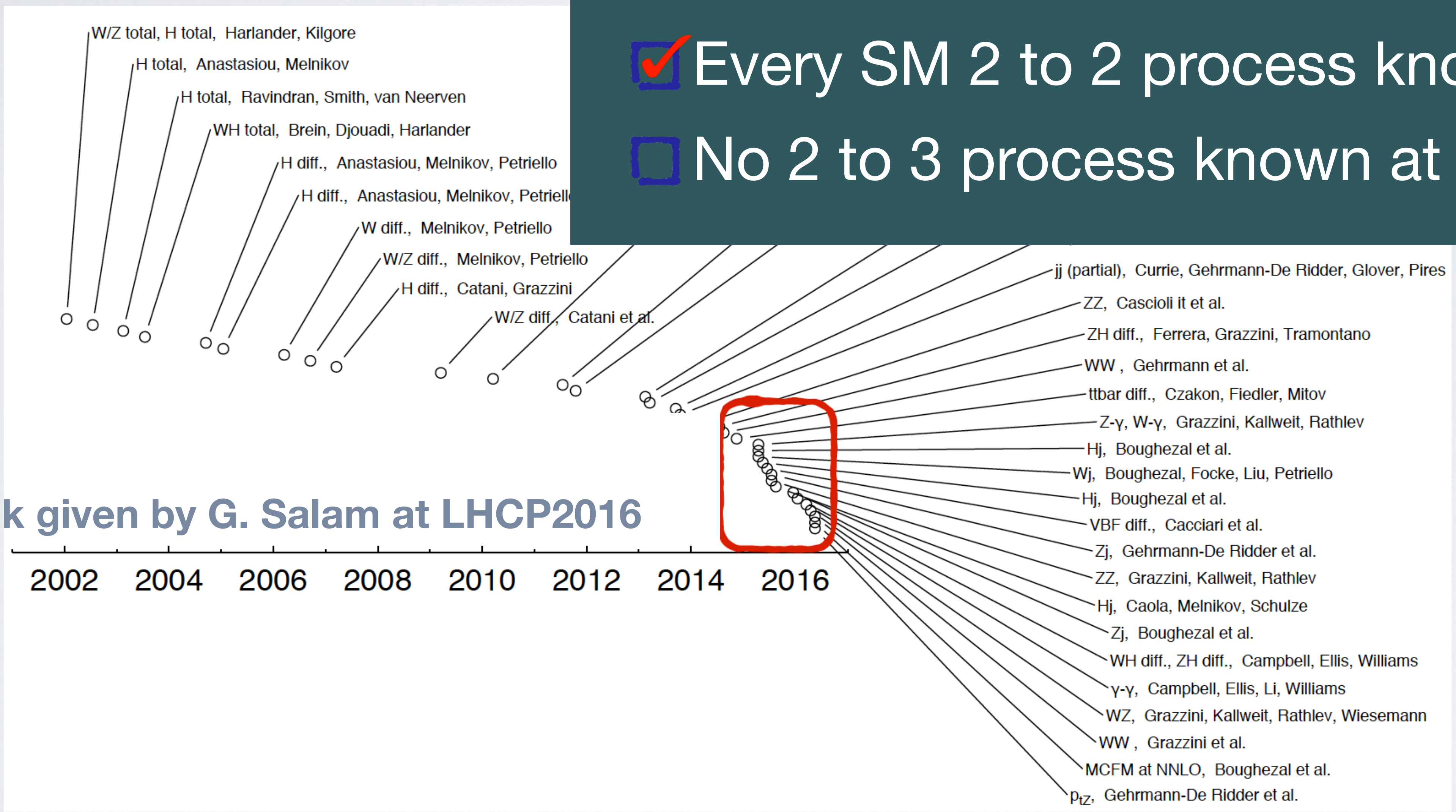
Talk given by G. Salam at LHCP2016

Things are developing rapidly, but **a number of conceptual and technical challenges** remain to be faced

NNLO: the next challenge

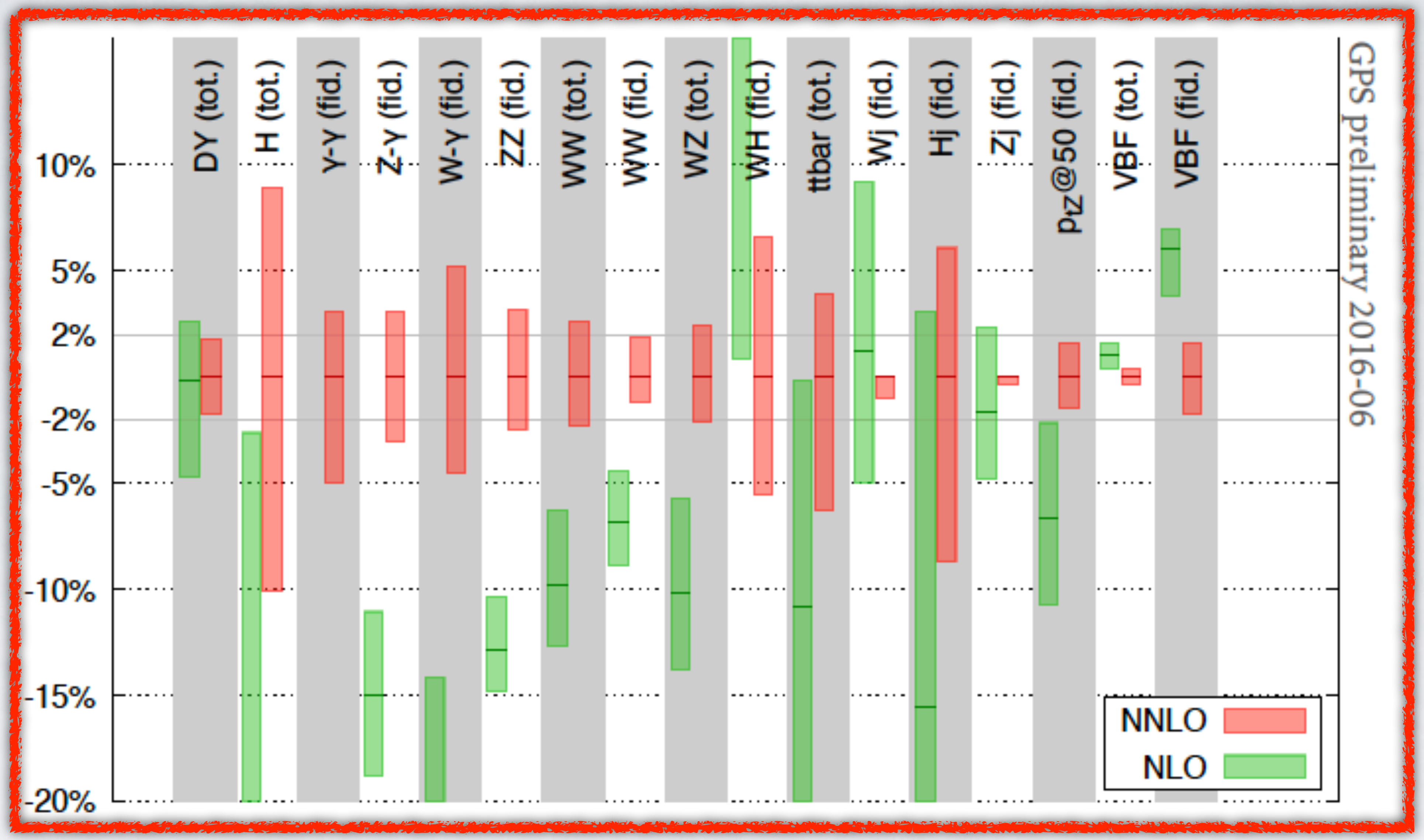
An explosion of NNLO results in the last two years

- ✔ Every SM 2 to 2 process known at NNLO
- ☐ No 2 to 3 process known at NNLO



Things are developing rapidly, but **a number of conceptual and technical challenges** remain to be faced

NNLO: uncertainty ?



NNLO ***scale*** uncertainty bands of 1-2%.
Is the ***theory*** uncertainty indeed 1-2%?

What does precision buy you?

Precision and energy reach

New physics likely heavy ⇒ use effective field theory (EFT)

$$\boxed{\mathcal{L} = \mathcal{L}_{\rm SM} + \sum_i \frac{1}{\Lambda^2} \mathcal{O}_i^{D=6}}$$

scale of new physics

- At low energy, e.g. Higgs couplings

$$\boxed{g = g_{\rm SM}\left(1 + c\frac{v^2}{\Lambda^2}\right)}$$

- At high energy (E), e.g. oblique parameters in $V_L V_L$ scattering (V=W, Z, h)

$$\boxed{g = g_{\rm SM}\left(1 + c\frac{E^2}{\Lambda^2}\right)}$$

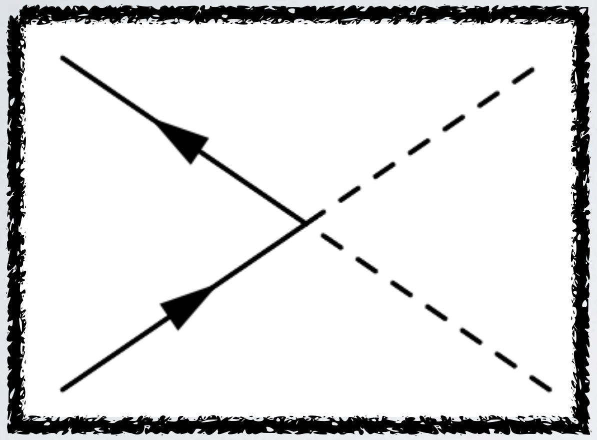
⇒ **Complementarity between precision and energy-reach**

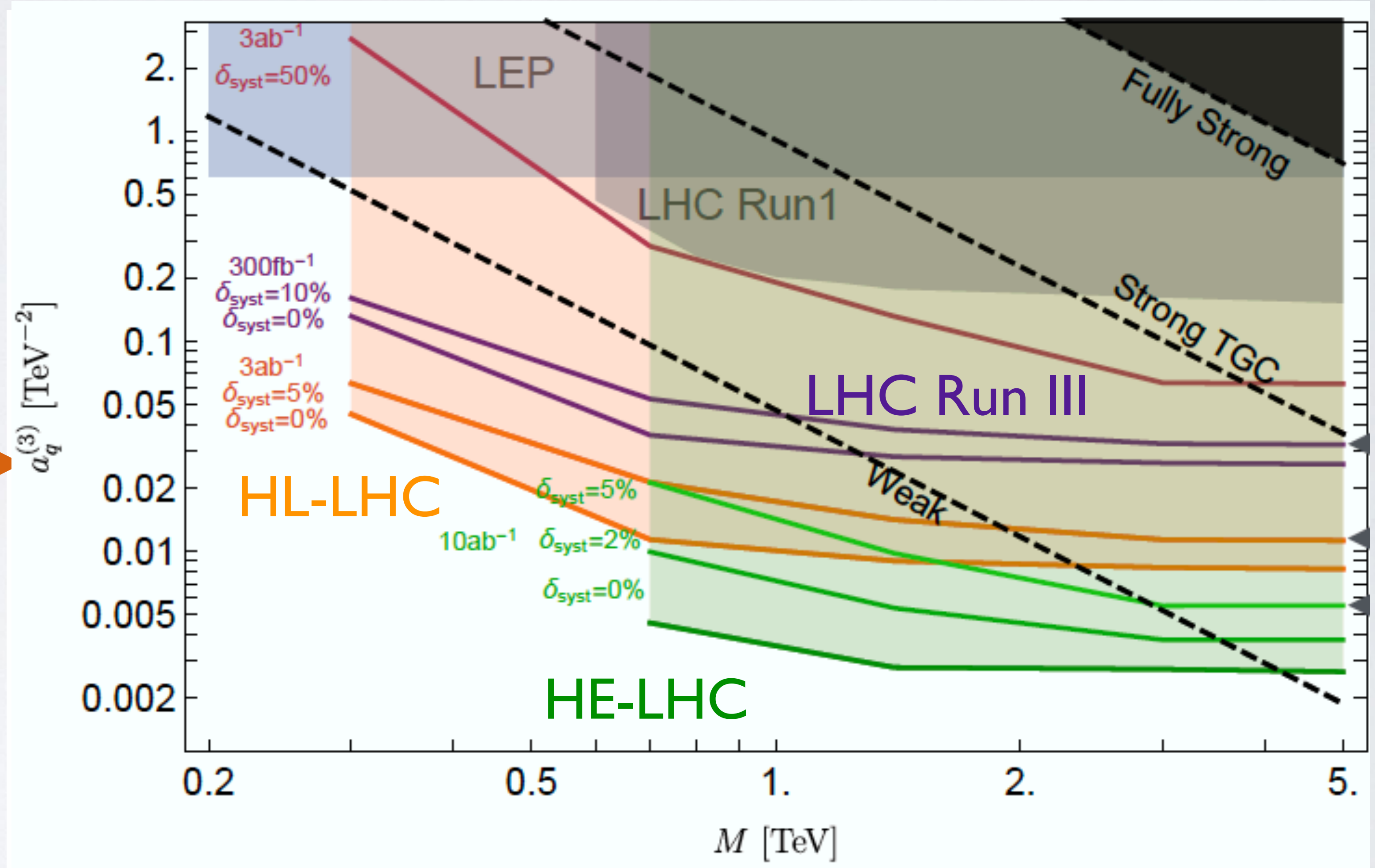
Comparison to Lep benchmark

- High-energy dynamics of longitudinal bosons linked to Higgs physics via Equivalence Theorem
- Only accurate measurements/calculations allow to constrain models that foresee small departures from the SM

per-mille accuracy at LEP	**≈**	**10% accuracy at 1 TeV**
1% accuracy at 1 TeV	**≈**	**10% accuracy at 3 TeV**
0.1% accuracy at 1 TeV	**≈**	**10% accuracy at 10 TeV**

Constraints from di-bosons





$a_q^{(3)} \approx g^{*2}/M^2$: Fermi-constant induced by BSM

M: scale of BSM, identified with highest scale probed experimentally

Higgs studies at the LHC

- The discovery of the Higgs boson at the LHC was a milestone in particle physics
- **Higgs boson is the only fundamental scalar particle ever discovered. Its study at the LHC is new territory**
- It is clear that this will be a long research program at the LHC *[in comparison the b-quark was discovered forty years ago and, Belle II at SuperKEK, will now further study hadrons containing b-quarks]*

An extremely rich program

Precision measurements
- mass, width
- spin, CP, couplings
- off-shell coupling, width interferometry
- differential distributions

H

Rare / beyond SM decays
- $H \to Z\gamma$
- $H \to \mu\mu$
- $H \to cc$
- $H \to \tau\mu$, τe, $e\mu$
- $H \to J/\Psi\gamma$, $Y\gamma$, …

Tool for discovery
- portal to BSM
- portal to hidden sector
- portal to DM

… and much more
- Higgs potential
- di-Higgs
- other FCNC decays
- …

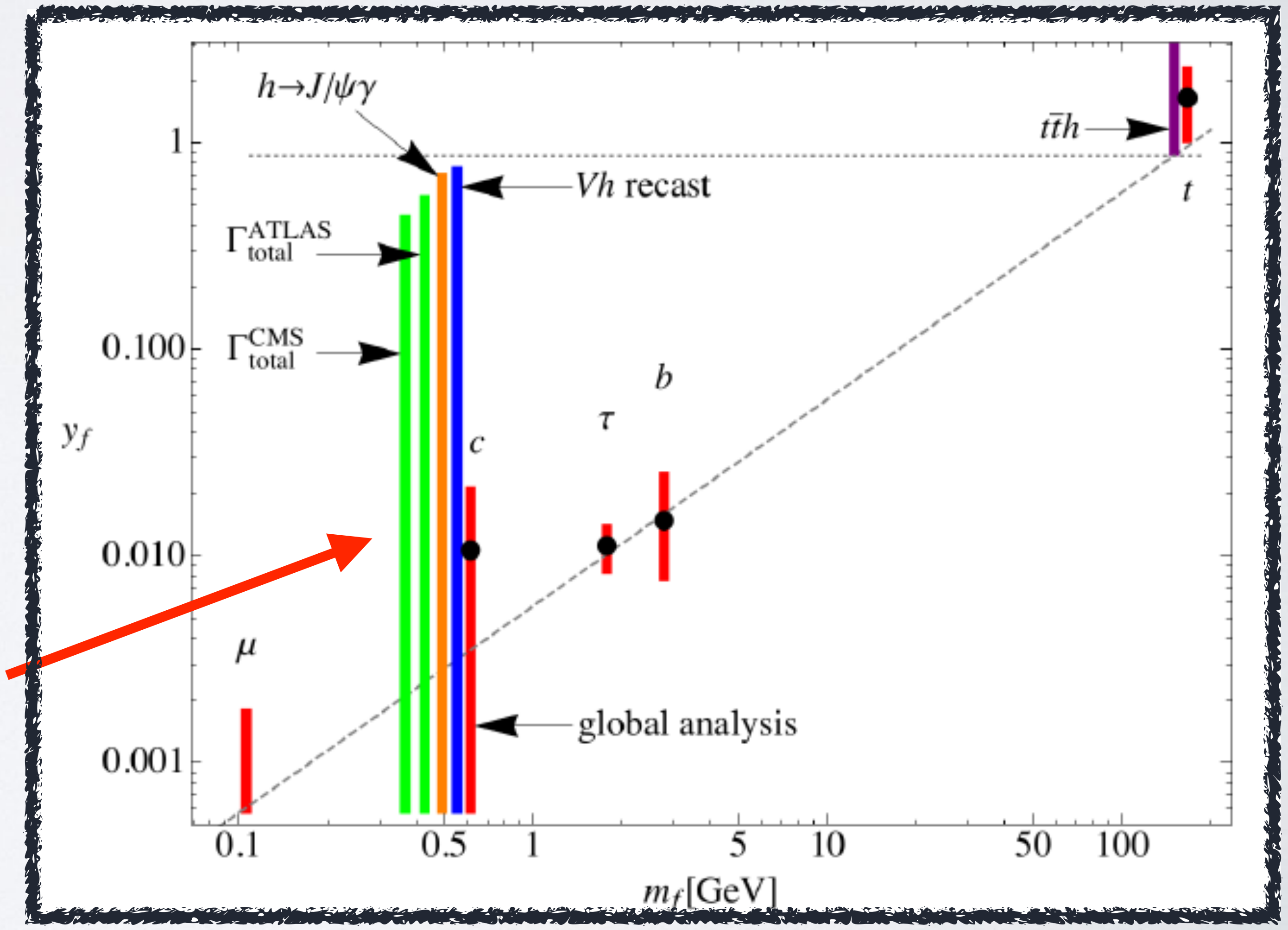
SM minimal or not?
- 2HDM
- MSSM, NMSSM
- extra Higgs states, doubly-charged Higgs

Two examples, out of many, where theoretical precision brings new opportunities in the Higgs sector

1.Higgs coupling to light quarks

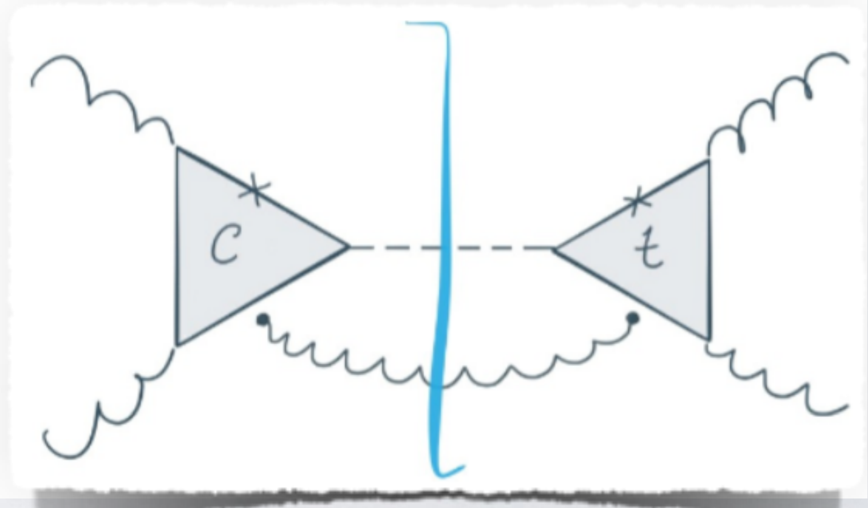
- couplings to 2nd (and 1st) generation notoriously very difficult because they are very small
- a number of ways to constraint the coupling of Higgs to charm:
  - rare exclusive Higgs decays
  - Higgs + charm production
  - constraint from VH (H →bb) including charm mis-tagging
  - constraint from Higgs width

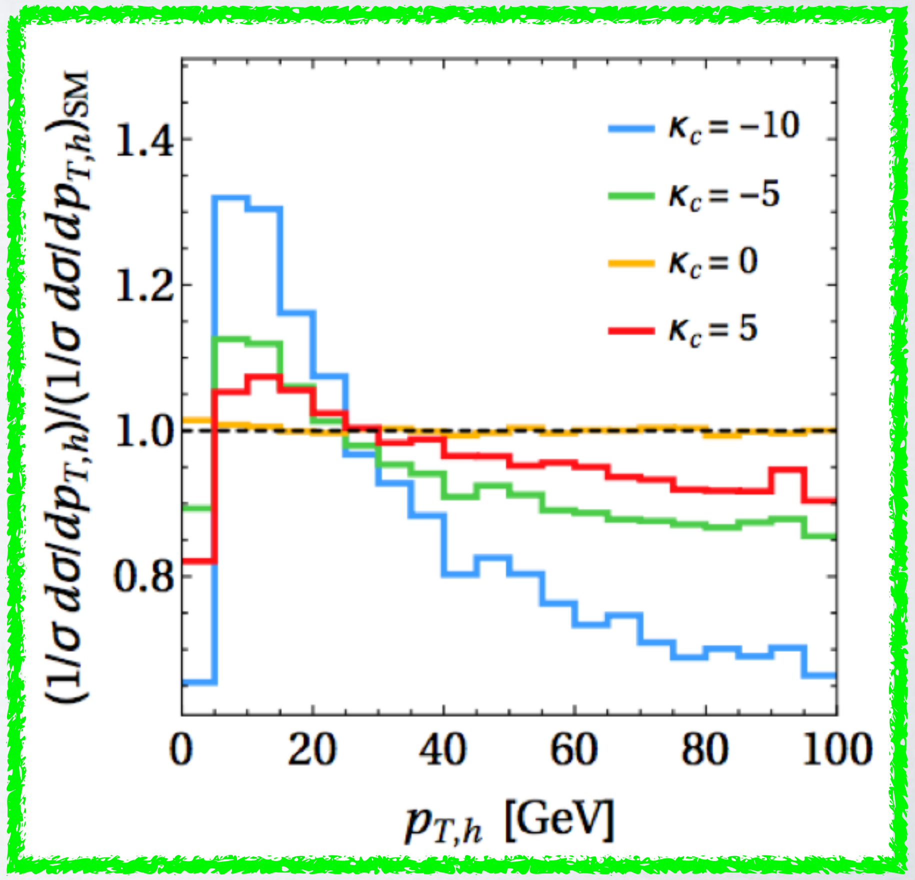
still largely unconstraint



1.Higgs coupling to light quarks

- Higgs produced dominantly via top-quark loop (largest coupling)
- but interference effects with light quarks are not negligible
- provided theoretical predictions are accurate enough (few%?), constraint on charm (and possible strange) Yukawa can be significantly improved





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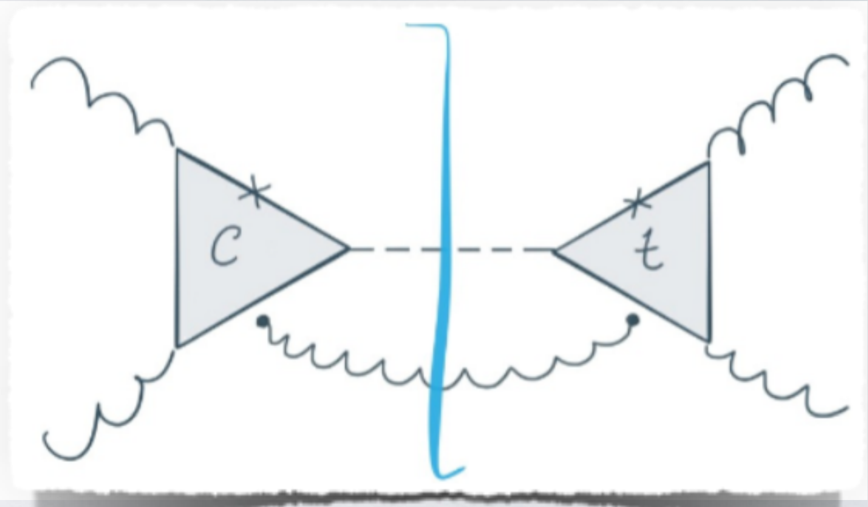
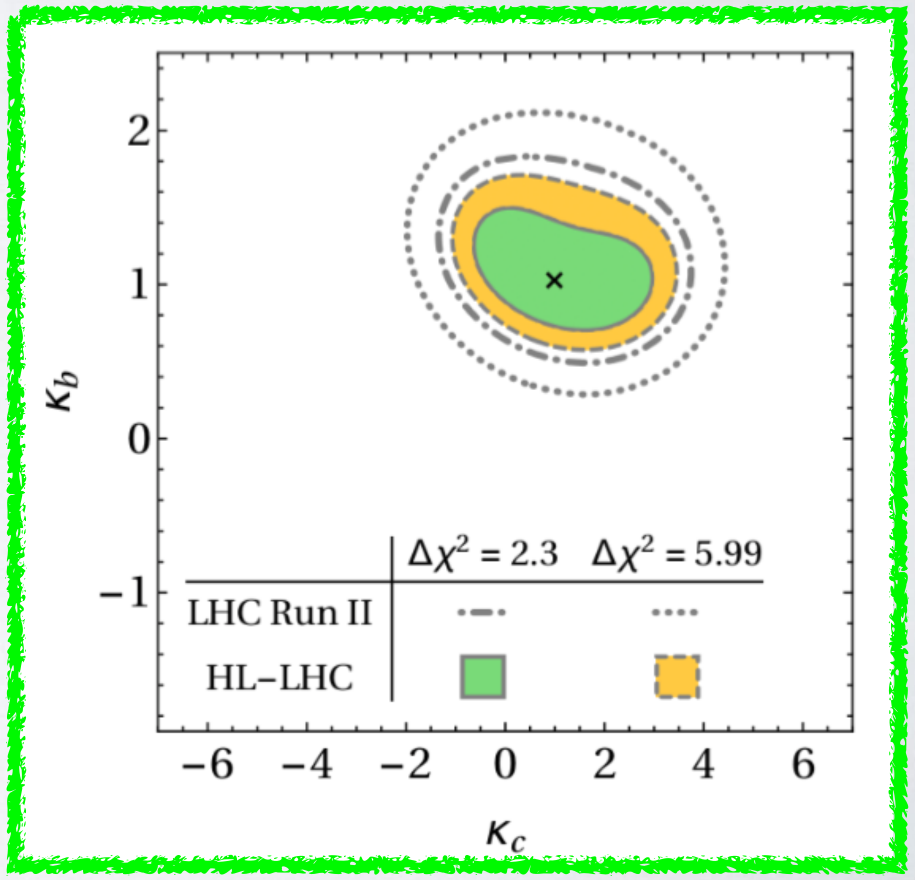
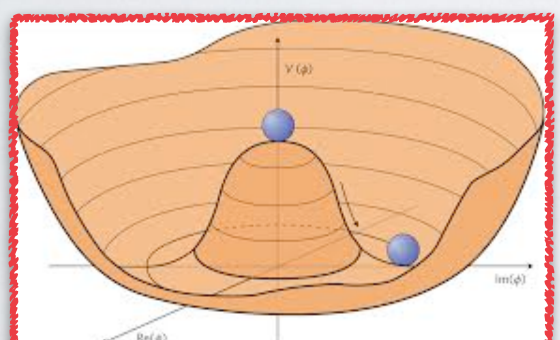




2.The Higgs potential

The Higgs boson is responsible for the masses of all particles we know of. Its potential, linked to the Higgs self coupling, is predicted in the SM, but we have not tested it so far

$$V_{\rm SM} = \frac{m_h}{2} h^2 + \lambda v h^3 + \frac{\lambda}{4} h^4$$

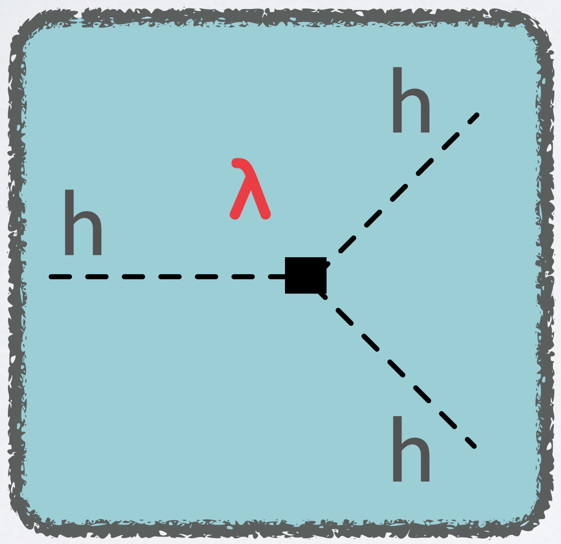


- [x] Single Higgs
  done
  O(45pb)
- [ ] Double Higgs
  very hard
  O(45fb)
- [ ] Triple Higgs
  out of reach
  O(0.1fb)

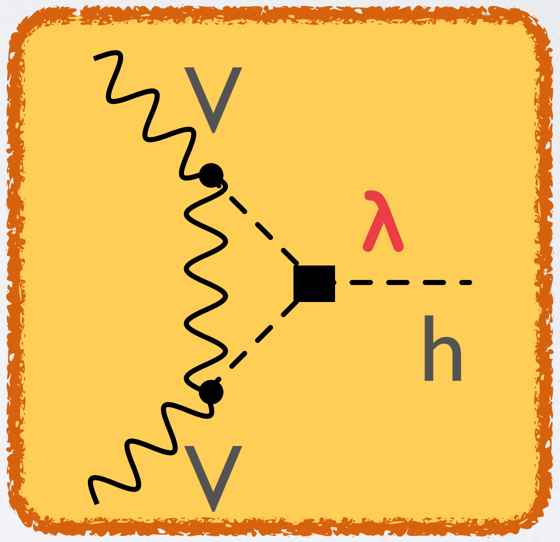
Bounds on λ today from LHC data still very loose (about a factor 10)

2. The Higgs potential

Traditionally: suggested to measure it through the production of two Higgs bosons (but difficult because of very small production rates)



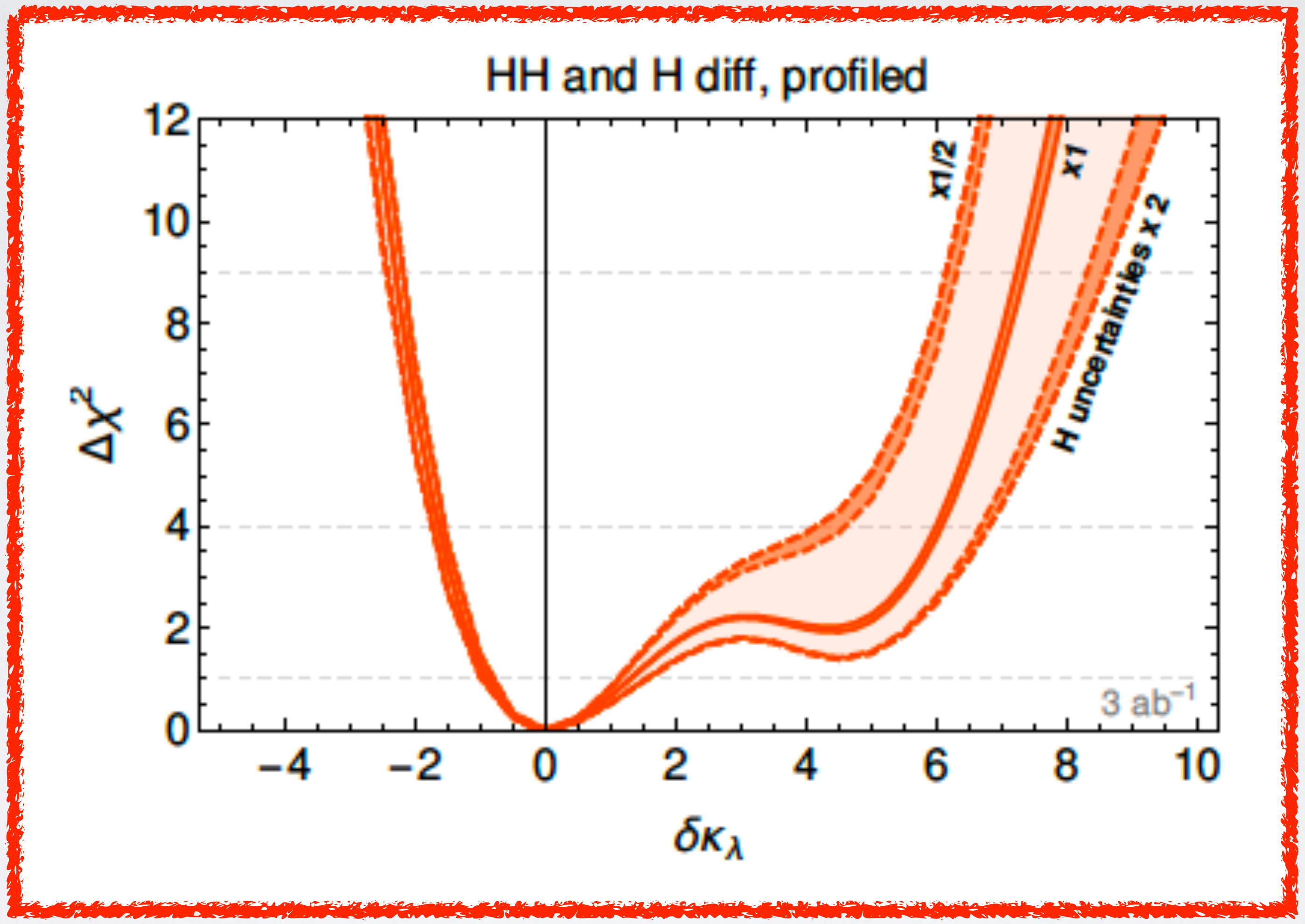
Double Higgs



Single Higgs

New idea: exploit indirect sensitivity to λ of single Higgs production Provides a wealth of new measurements (many production processes, many kinematic distributions), but theory and measurements must be accurate enough

2.The Higgs potential



New idea: exploit indirect sensitivity to λ of single Higgs production Provides a wealth of new measurements (many production processes, many kinematic distributions), but theory and measurements must be accurate enough

Conclusion

- Precision physics at hadron colliders is already there
- Precision Higgs studies in their infancy, much more to come
- Not just precision measurement of couplings but possibility to address key outstanding questions (Higgs potential, minimal Higgs, fine-tuning, portal to hidden sectors, DM…)
- Interplay between precision and energy reach crucial to address these questions