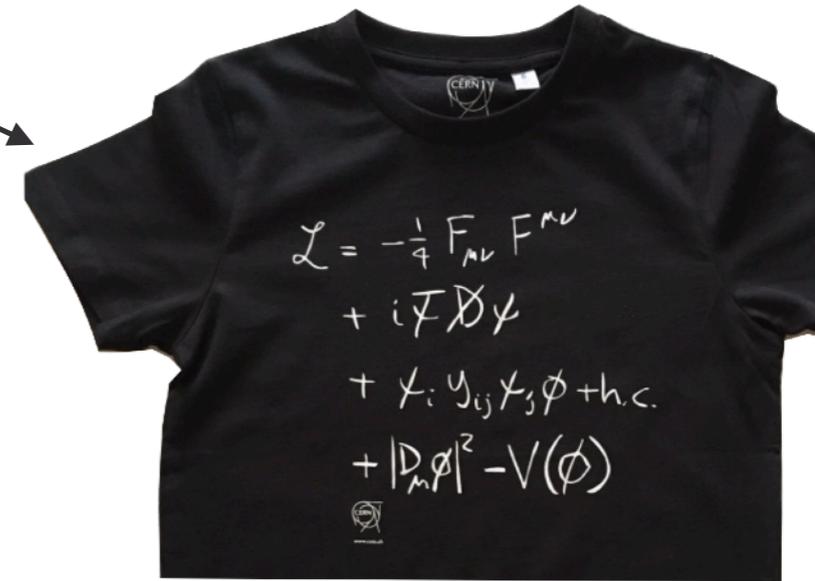
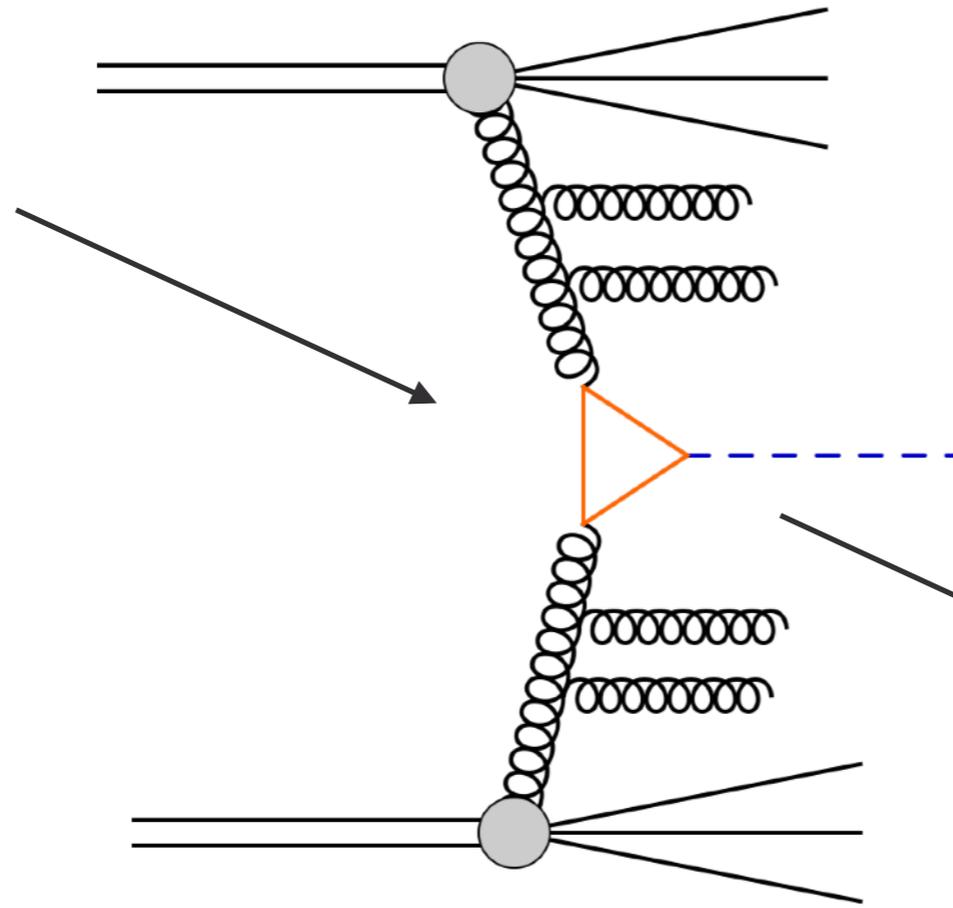
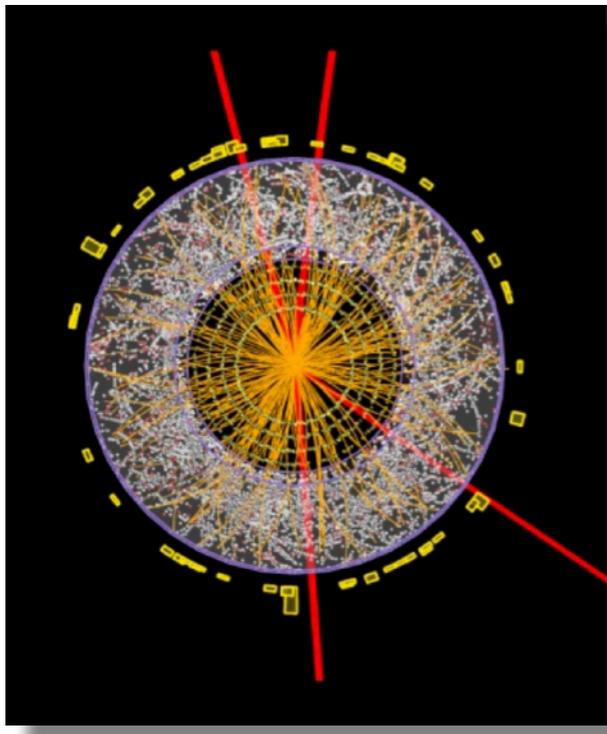


# ... from collisions to the Higgs boson

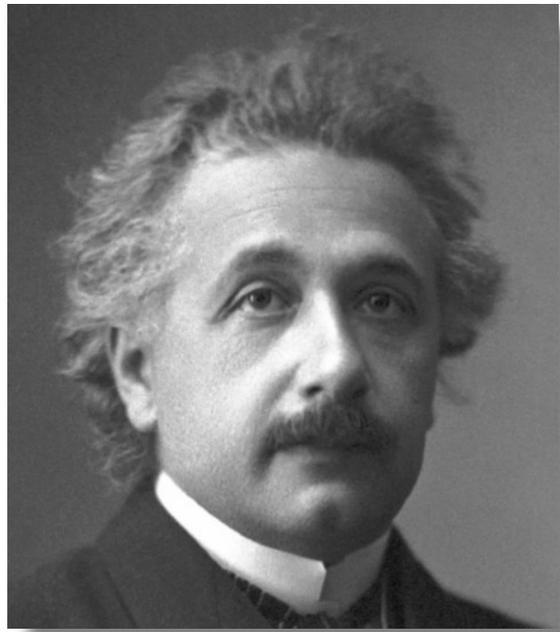
Fabrizio Caola

*Rudolf Peierls Centre for Theoretical Physics & Wadham College*

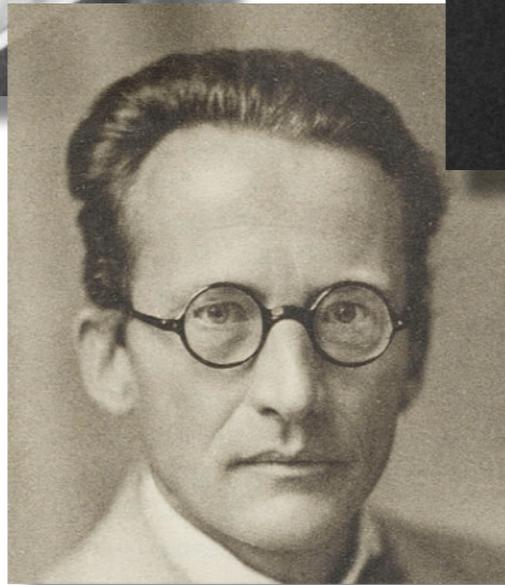


or: *how do quark and gluons interact and create a Higgs?*

# *The subatomic world at high energies*



+



=

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*special relativity*

*quantum mechanics*

- Structure of fundamental interactions: very constrained
- Only freedom  $\sim$  particle content and symmetries

→ *first principles calculations*

# Quantum chromodynamics

To study any process at the LHC:  
*we need to understand how quark and gluons interact*

$$\begin{aligned}\mathcal{L} = & -\frac{1}{4} F_{\mu\nu} F^{\mu\nu} \\ & + i\bar{\psi} \not{D} \psi \\ & + \bar{\psi}_i Y_{ij} \psi_j \phi + \text{h.c.} \\ & + |D_\mu \phi|^2 - V(\phi)\end{aligned}$$

Quantum field theory for  
strong interactions →  
**quantum chromodynamics (QCD)**

A well-defined, well-established theory...

# Quantum chromodynamics

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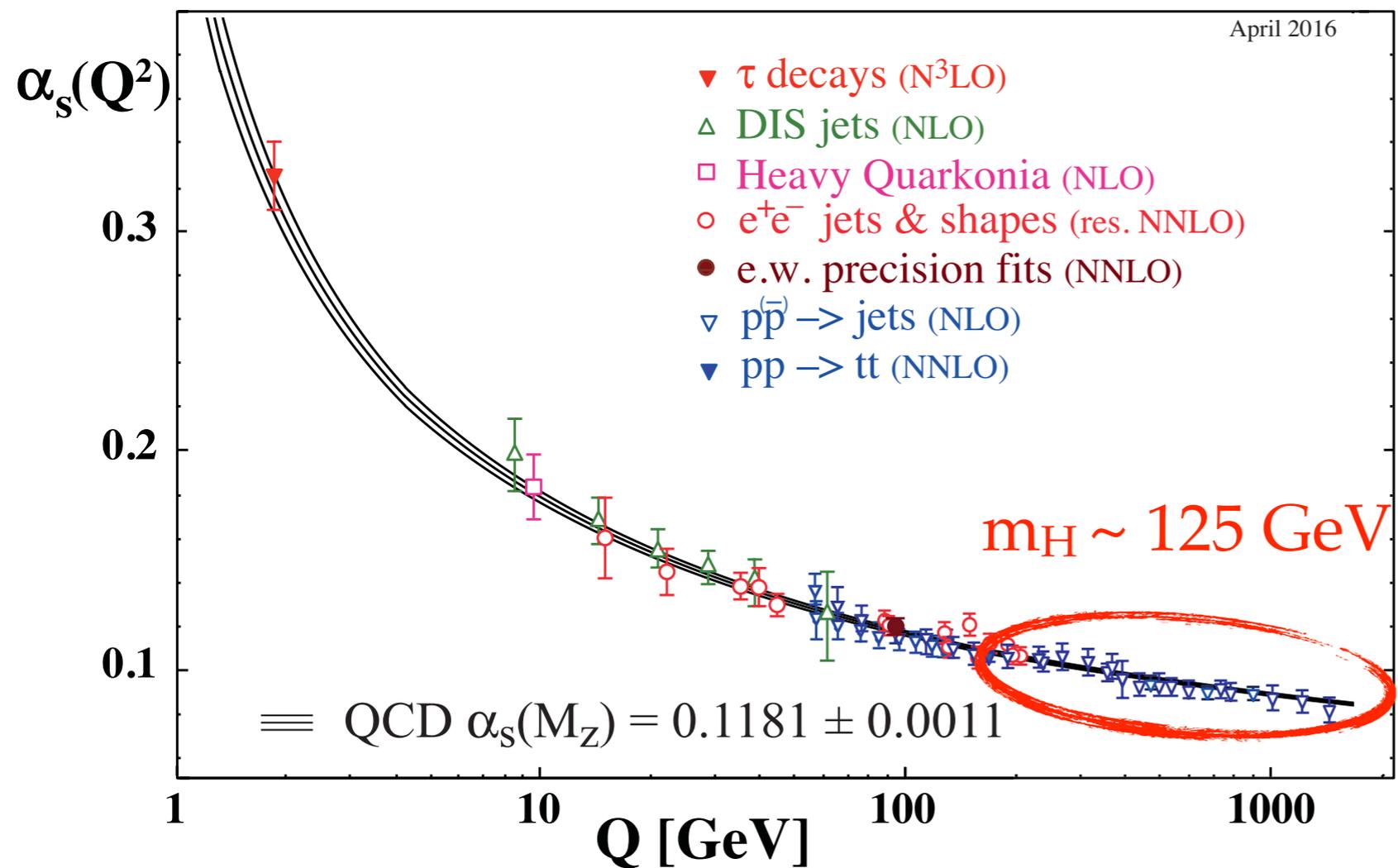
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Quantum field theory for  
strong interactions →  
**quantum chromodynamics (QCD)**

A well-defined, well-established theory...  
**extremely hard to deal with**

# QCD for Higgs studies: weakly coupled

At high energies, QCD becomes weakly coupled



$$\alpha_s(m_P) \gg 1$$

$$\alpha_s(m_H) \sim 0.1$$

*Study interactions as perturbation around theory of free quarks/gluons*

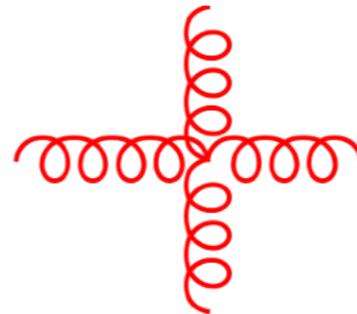
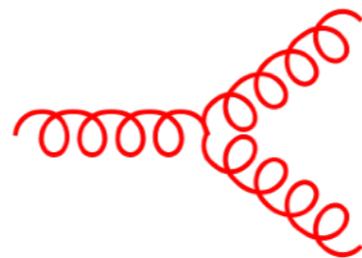
$\sigma = \sigma_0 + \alpha_s \sigma_1 + \alpha_s^2 \sigma_2 + \dots \rightarrow$  **perturbative QFT: Feynman diagrams**

# Perturbation theory and Feynman diagrams

$$I \rightarrow F \quad \sigma = \sigma_0 + \alpha_s \sigma_1 + \alpha_s^2 \sigma_2 + \dots$$

- For a given QFT  $\rightarrow$  set of basic building blocks

*QCD, only gluons*

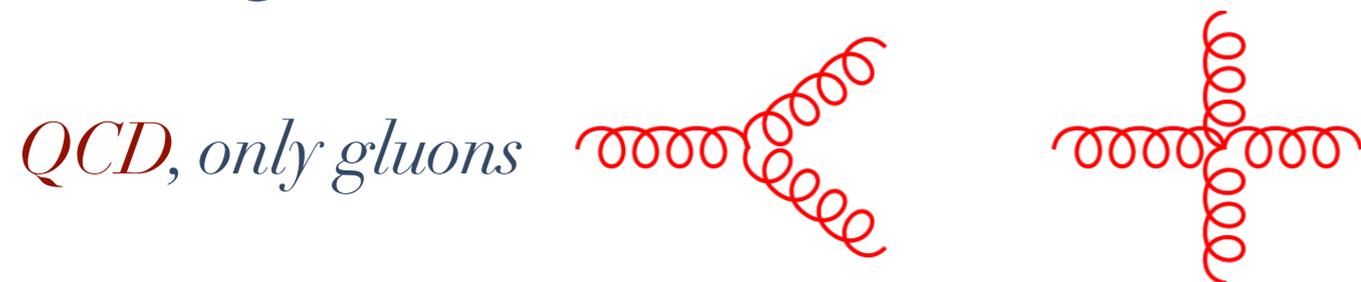


# Perturbation theory and Feynman diagrams

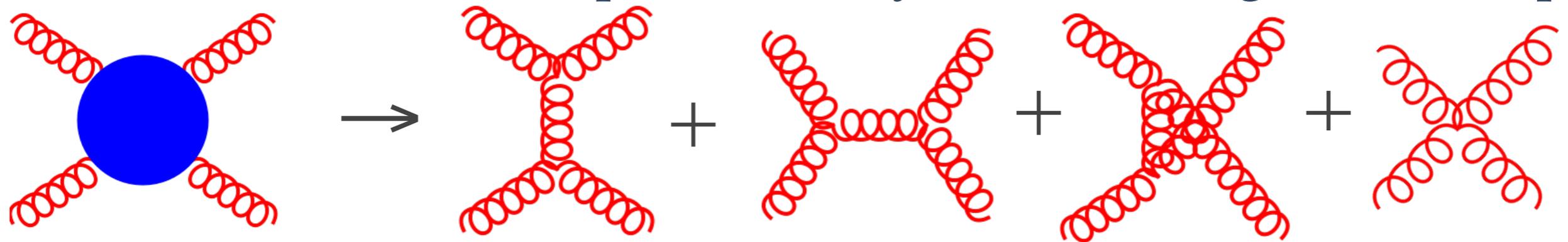
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- $\sigma_0$ : connect  $I$  to  $F$ , in all possible ways, minimising closed loops

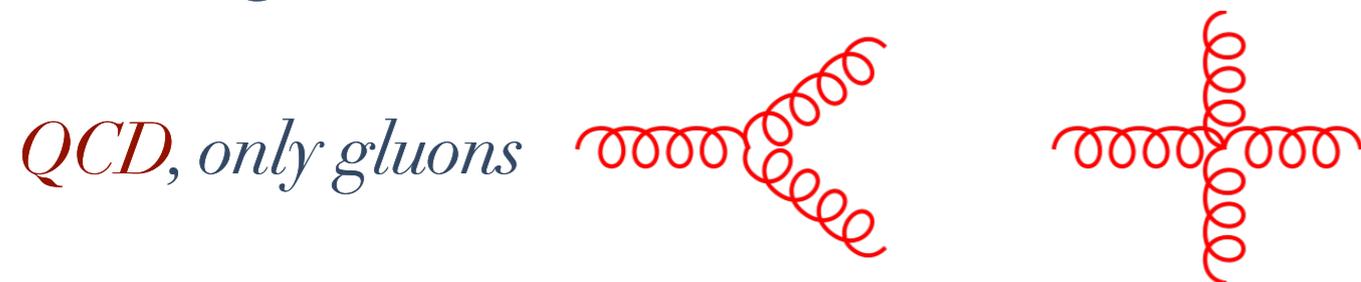


# Perturbation theory and Feynman diagrams

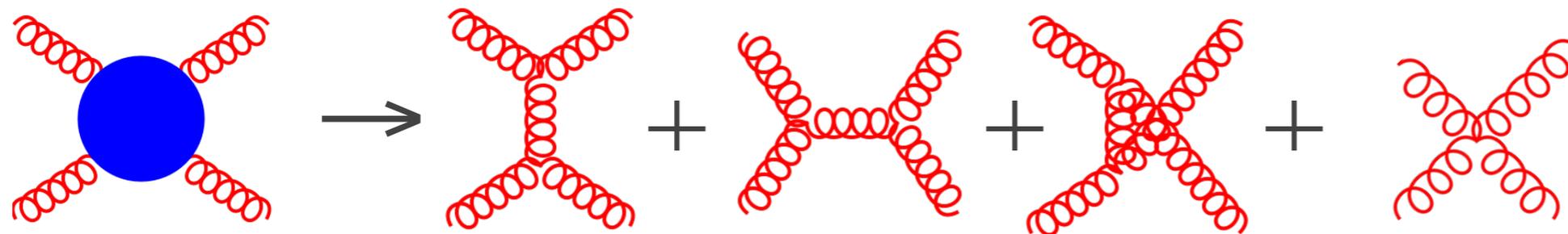
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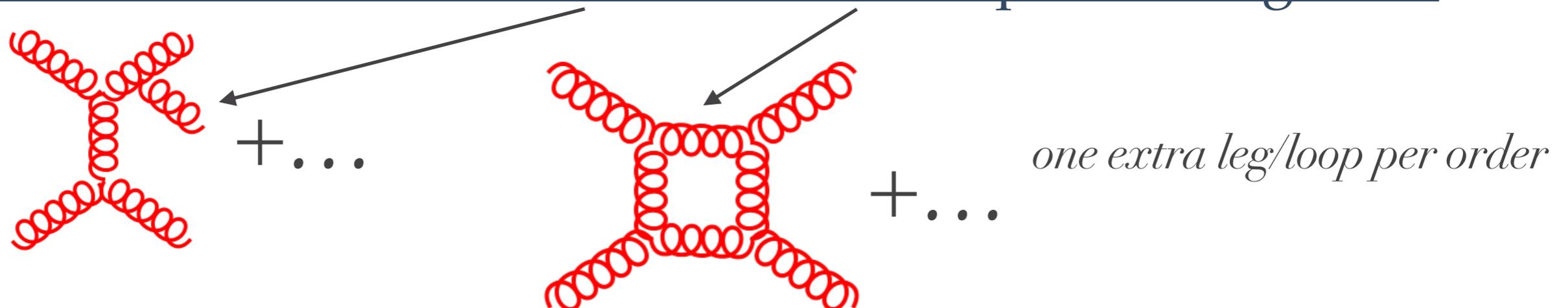
- For a given QFT  $\rightarrow$  set of basic building blocks



- $\sigma_0$ : connect  $I$  to  $F$ , in all possible ways, minimising closed loops



- Higher orders: dress with real and virtual quark and gluons

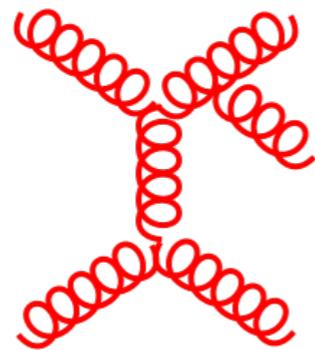


# Perturbation theory and Feynman diagrams

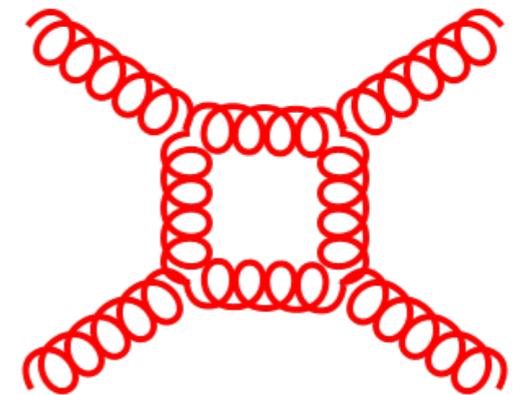
$$\sigma = \sigma_0 + \alpha_s \sigma_1 + \alpha_s^2 \sigma_2 + \dots$$



- *Feynman rules*: associate to each diagram an analytic formula



*“Tree” diagrams: simple rational functions of momenta / polarisations*



*“Loop”: must integrate over momenta of particles in the loop → non trivial transcendental functions*

- Very well-understood procedure since the `60s
- Fully algorithmic

# The punch-line:

To compute any precise theoretical prediction for any LHC process →  
*need to compute Feynman diagrams with many legs/loops*

## How many?

- We want to test Higgs interactions at the few percent...

$$\sigma = \sigma_0 + \alpha_s \sigma_1 + \alpha_s^2 \sigma_2 + \dots, \alpha_s \sim 0.1$$



*Leading Order (LO) → very imprecise*

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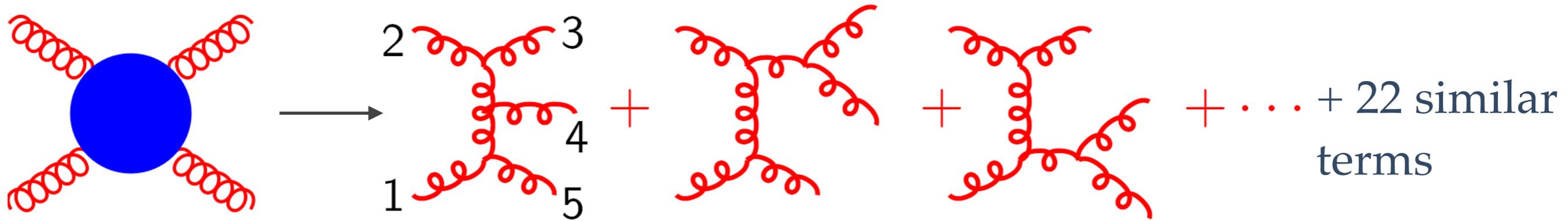
*Next-to-Leading Order (NLO) → ~ 10%*

*Need Next-to-next-to-leading order (NNLO) and beyond for precision*

...in principle: compute a bunch of diagrams with extra legs/loops

# ... in practice: back to our example

Dress with one real gluon



amp =

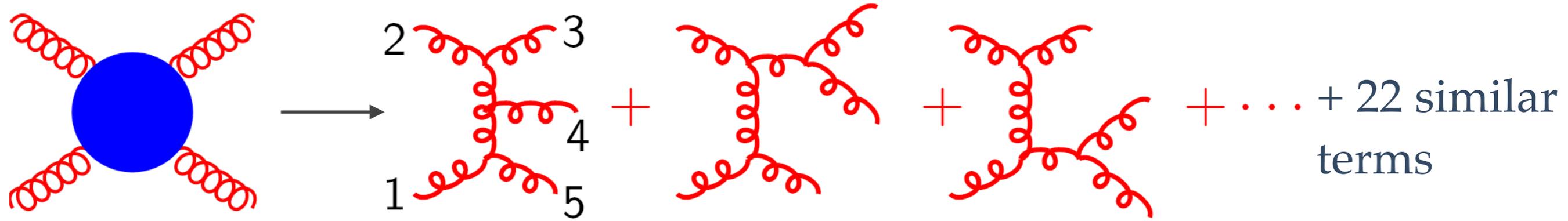
$$\begin{aligned}
 &+ F(\text{CiE1}, \text{Ci2}, \text{CiE4}) * F(\text{CiE2}, \text{Ci2}, \text{CiXX}) * F(\text{CiE3}, \text{CiE5}, \text{CiXX}) * ( \\
 &\quad - e1.e3*e2.e5*e4.p1*s14^{-1} \\
 &\quad - 1/2*e1.e3*e2.e5*e4.p4*s14^{-1} \\
 &\quad - 1/2*e1.e4*e2.e3*e5.p1*s14^{-1} \\
 &\quad + 1/2*e1.e4*e2.e3*e5.p4*s14^{-1} \\
 &\quad + 1/2*e1.e4*e2.e5*e3.p1*s14^{-1} \\
 &\quad - 1/2*e1.e4*e2.e5*e3.p4*s14^{-1} \\
 &\quad + e1.e5*e2.e3*e4.p1*s14^{-1} \\
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 &\quad - 1/2*e1.p1*e2.e3*e4.e5*s14^{-1} \\
 &\quad + 1/2*e1.p1*e2.e5*e3.e4*s14^{-1} \\
 &\quad - e1.p4*e2.e3*e4.e5*s14^{-1} \\
 &\quad + e1.p4*e2.e5*e3.e4*s14^{-1} \\
 &\quad )
 \end{aligned}$$

$$\begin{aligned}
 &+ F(\text{CiE1}, \text{Ci2}, \text{CiE4}) * F(\text{CiE2}, \text{Ci2}, \text{Ci4}) * F(\text{CiE3}, \text{CiE5}, \text{Ci4}) * ( \\
 &\quad - 2*e1.e2*e3.e5*e4.p1*p1.p3*s14^{-1}*s124^{-1} \\
 &\quad - 2*e1.e2*e3.e5*e4.p1*p1.p4*s14^{-1}*s124^{-1} \\
 &\quad + 2*e1.e2*e3.e5*e4.p1*p2.p3*s14^{-1}*s124^{-1} \\
 &\quad - 2*e1.e2*e3.e5*e4.p1*p3.p4*s14^{-1}*s124^{-1} \\
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 &\quad + 3*e1.e2*e3.p2*e4.p1*e5.p1*s14^{-1}*s124^{-1}
 \end{aligned}$$

*Rational function of momenta  
and polarisations*

# ... in practice: back to our example

Dress with one real gluon



```

- 1/2*e1.e3*e2.e4*e5.p4*s134^-1
- 1/2*e1.e3*e2.e5*e4.p1*s134^-1
- e1.e3*e2.e5*e4.p2*s134^-1
- 1/2*e1.e3*e2.e5*e4.p3*s134^-1
- 1/2*e1.e3*e2.e5*e4.p4*s134^-1
+ e1.e3*e2.p1*e4.e5*s134^-1
+ 1/2*e1.e3*e2.p2*e4.e5*s134^-1
+ e1.e3*e2.p3*e4.e5*s134^-1
+ e1.e3*e2.p4*e4.e5*s134^-1
- e1.e5*e2.p1*e3.e4*s134^-1
- 1/2*e1.e5*e2.p2*e3.e4*s134^-1
- e1.e5*e2.p3*e3.e4*s134^-1
- e1.e5*e2.p4*e3.e4*s134^-1
+ 1/2*e1.p1*e2.e5*e3.e4*s134^-1
+ e1.p2*e2.e5*e3.e4*s134^-1
+ 1/2*e1.p3*e2.e5*e3.e4*s134^-1
+ 1/2*e1.p4*e2.e5*e3.e4*s134^-1
)

```

98 pages analytic formula!

```

+ F(CiE1,CiXX,CiE4)*F(CiE3,CiE2,Ci2)*F(CiE5,Ci2,CiXX) * (
+ e1.e2*e3.p2*e4.e5*s23^-1
+ 1/2*e1.e2*e3.p3*e4.e5*s23^-1
- 1/2*e1.e3*e2.p2*e4.e5*s23^-1
- e1.e3*e2.p3*e4.e5*s23^-1
+ 1/2*e1.e5*e2.e3*e4.p2*s23^-1
- 1/2*e1.e5*e2.e3*e4.p3*s23^-1
- e1.e5*e2.e4*e3.p2*s23^-1
- 1/2*e1.e5*e2.e4*e3.p3*s23^-1
+ 1/2*e1.e5*e2.p2*e3.e4*s23^-1
+ e1.e5*e2.p3*e3.e4*s23^-1
- 1/2*e1.p2*e2.e3*e4.e5*s23^-1
+ 1/2*e1.p3*e2.e3*e4.e5*s23^-1
);

```

# More legs...

Final state gluons	2	3	4	5	6	...
# diagrams	4	25	220	2485	34300	...

Explosion of  
terms

Supercollider physics

(1984) 617

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.

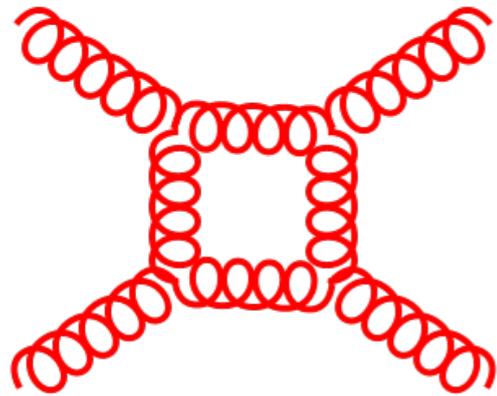
For multijet events containing more than three jets, the theoretical situation is considerably more primitive. A specific question of interest concerns the QCD four-jet background to the detection of  $W^+W^-$  pairs in their nonleptonic decays.

**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.

Prospect for  
theoretical  
calculations 30y ago

# Loops?



- Very difficult integrals...
- ... when you compute them you get infinity!

in principle, last century  
physics tells us what to do...

... in practice, we don't go very far

# Typical expectation: hopeless

My first interaction with a Nobel Prize winner...

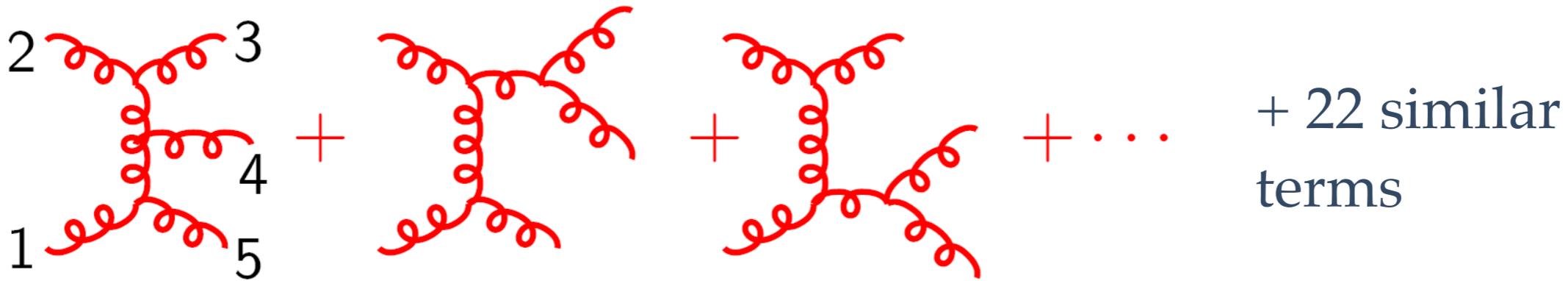
- Him, to friend A: *what are you working on?*
- My friend: *X and Y [...]*
- Him: *Fascinating [...]* *Keep on the good work!*

Similar pattern with friend B, C... until it is my turn

- Him: *and you, what are you doing?*
- Me: *I am trying to do precision physics at the LHC*
- Him, genuinely worried for me: *my dear boy, no! You should change topic, the LHC is a messy environment, we are going to discover stuff but we cannot do precision physics there!*

*if we kept relying on '70s understanding of QFT, he had a point...*

# ... but in the meantime



amp =

$$\begin{aligned}
 &+ F(\text{CiE1}, \text{Ci2}, \text{CiE4}) * F(\text{CiE2}, \text{Ci2}, \text{CiXX}) * F(\text{CiE3}, \text{CiE5}, \text{CiXX}) * ( \\
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 &+ 3*e1.e2*e3.p2*e4.p1*e5.p1*s14^{-1}*s124^{-1} \\
 & )
 \end{aligned}$$

Massive simplification!

$$A_5^{\text{tree}}(1^\pm, 2^+, 3^+, 4^+, 5^+) = 0$$

$$A_5^{\text{tree}}(1^-, 2^-, 3^+, 4^+, 5^+) = i \frac{\langle 12 \rangle^4}{\langle 12 \rangle \langle 23 \rangle \langle 34 \rangle \langle 45 \rangle \langle 51 \rangle}$$

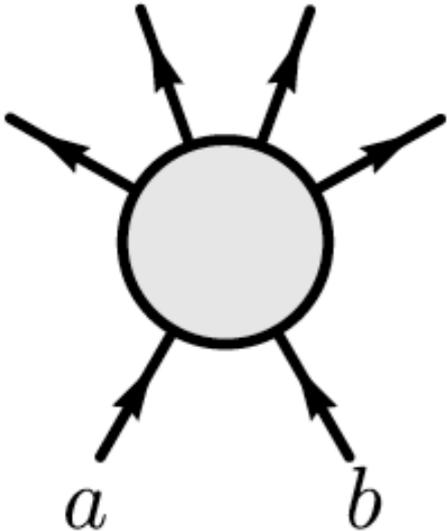
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Same physical content

# Massive simplifications in tree amplitudes

Similar simplification persist at higher multiplicity

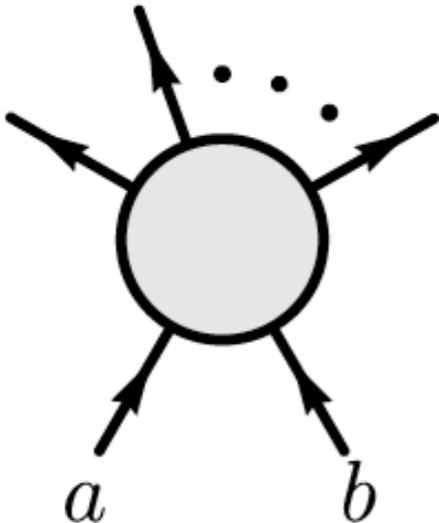
Simplest helicity configuration:



A Feynman diagram representing a 6-point tree amplitude. It consists of a central grey circle with six external lines. Two lines at the bottom are labeled 'a' and 'b'. The other four lines are arranged in two pairs at the top, each pair pointing away from the circle. The diagram is equated to a fraction: the numerator is  $\langle ab \rangle^4$  and the denominator is the product of six spinor brackets:  $\langle 12 \rangle \langle 23 \rangle \langle 34 \rangle \langle 45 \rangle \langle 56 \rangle \langle 61 \rangle$ .

$$= \frac{\langle ab \rangle^4}{\langle 12 \rangle \langle 23 \rangle \langle 34 \rangle \langle 45 \rangle \langle 56 \rangle \langle 61 \rangle}$$

Sum of 220 Feynman diagrams!



A Feynman diagram representing an n-point tree amplitude. It consists of a central grey circle with n external lines. Two lines at the bottom are labeled 'a' and 'b'. The other n-2 lines are arranged in a semi-circle at the top, with three dots between the top-most and top-right-most lines to indicate continuation. The diagram is equated to a fraction: the numerator is  $\langle ab \rangle^4$  and the denominator is the product of n spinor brackets:  $\langle 12 \rangle \langle 23 \rangle \langle 34 \rangle \langle 45 \rangle \dots \langle n1 \rangle$ .

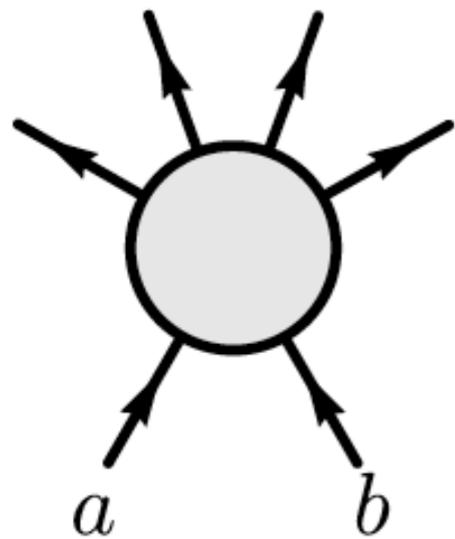
$$= \frac{\langle ab \rangle^4}{\langle 12 \rangle \langle 23 \rangle \langle 34 \rangle \langle 45 \rangle \dots \langle n1 \rangle}$$

Sum of  $\sim n!$  diagrams

# Massive simplifications in tree amplitudes

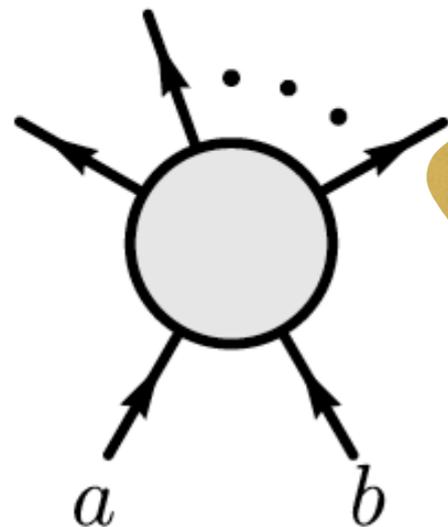
Similar simplification persist at higher multiplicity

Simplest helicity configuration:



$$= \frac{\langle ab \rangle^4}{\langle 12 \rangle \langle 23 \rangle \langle 34 \rangle \langle 45 \rangle \langle 56 \rangle}$$

220 Feynman diagrams!



$$\frac{\langle ab \rangle^4}{\langle 12 \rangle \langle 23 \rangle \langle 34 \rangle \langle 45 \rangle \cdots \langle n1 \rangle}$$

Sum of  $\sim n!$  diagrams

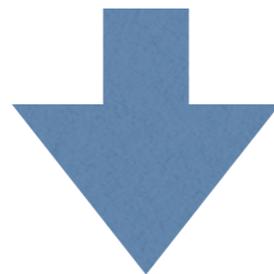
**What is going on?**

# QFT in the XXI century

Structure of QFT extremely rigid  $\rightarrow$  very much constrained by special relativity and quantum mechanics

- Special relativity: *everything is local*  $\rightarrow$  tree-level results can only have a well-defined set of simple singularities
- Quantum mechanics: *unitarity*  $\rightarrow$  what happens at singular points entirely determined by trees with **lower multiplicity**

Completely hidden in Feynman diagrams!



Trees have a natural recursive nature, that can be fully exploited to reconstruct the result for  $n+1$  legs from the  $n$ -leg one.

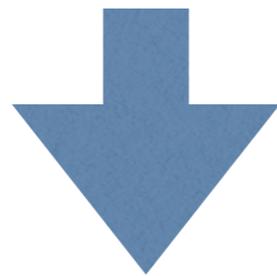
# QFT in the XXI century

Structure of QFT extremely rigid  $\rightarrow$  very much constrained by special relativity and quantum mechanics

- Special relativity: *everything is local*  $\rightarrow$  tree-level diagrams have a well-defined set of simple singular points
- Quantum mechanics: *unitarity*  $\rightarrow$  singular points entirely determined by tree-level diagrams **multiplicity**

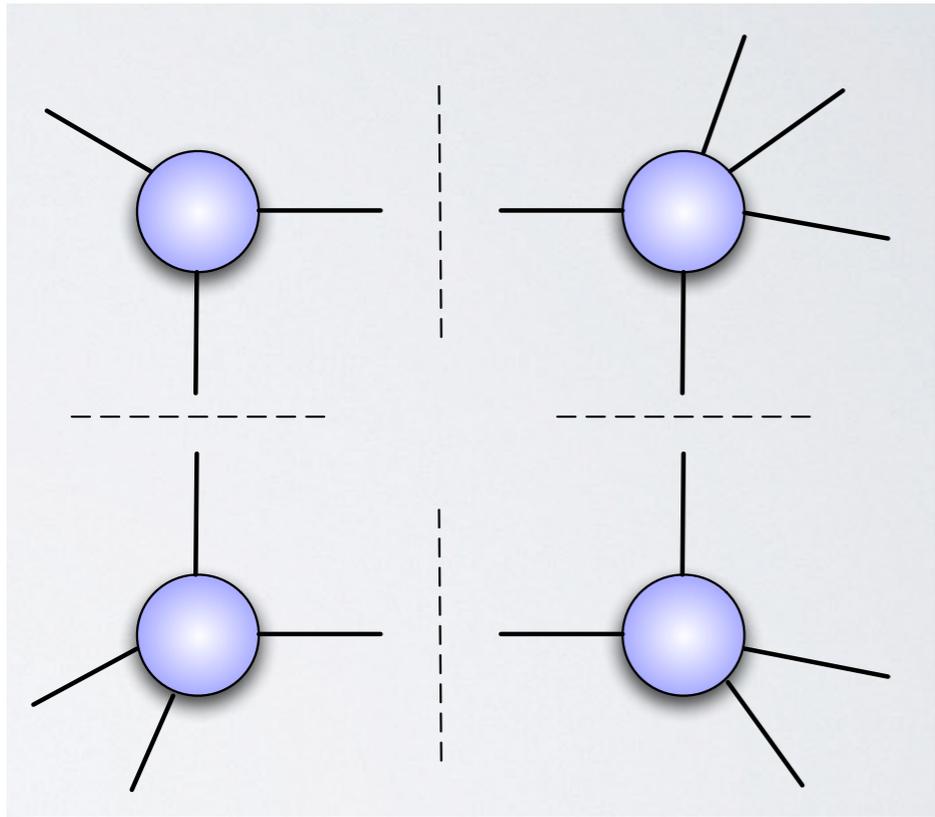
Completely hidden in the diagrams!

**Trees: problem solved**



Trees have a natural recursive nature, that can be fully exploited to reconstruct the result for  $n+1$  legs from the  $n$ -leg one. *Any process.*

# ... what about loops?

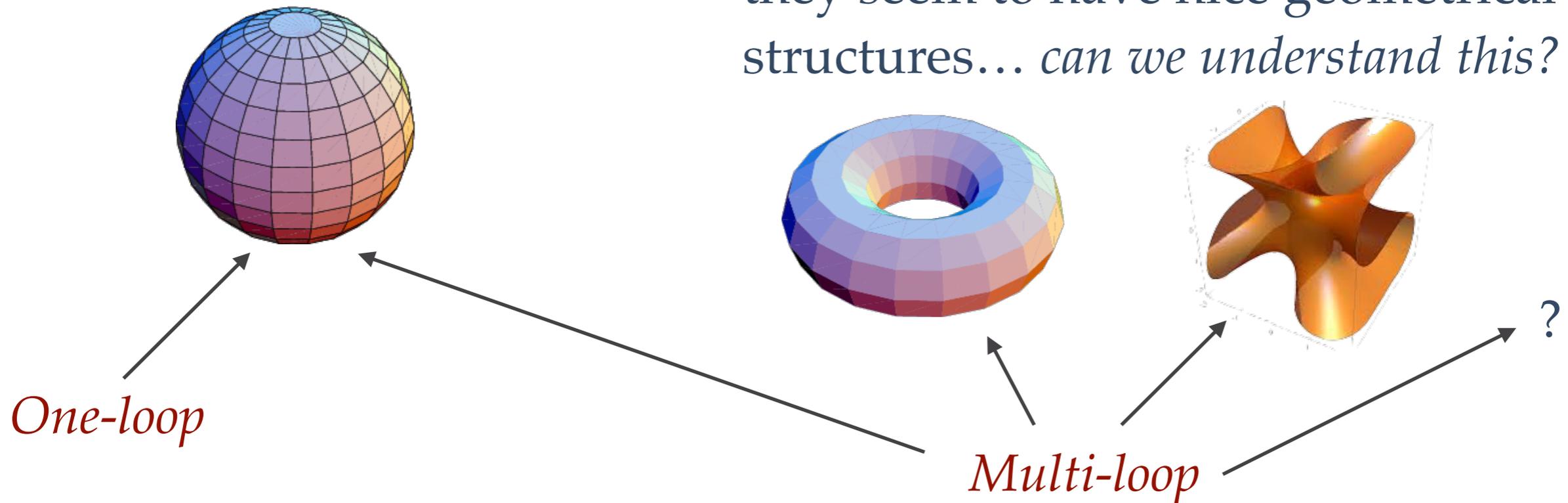


Similar ideas:

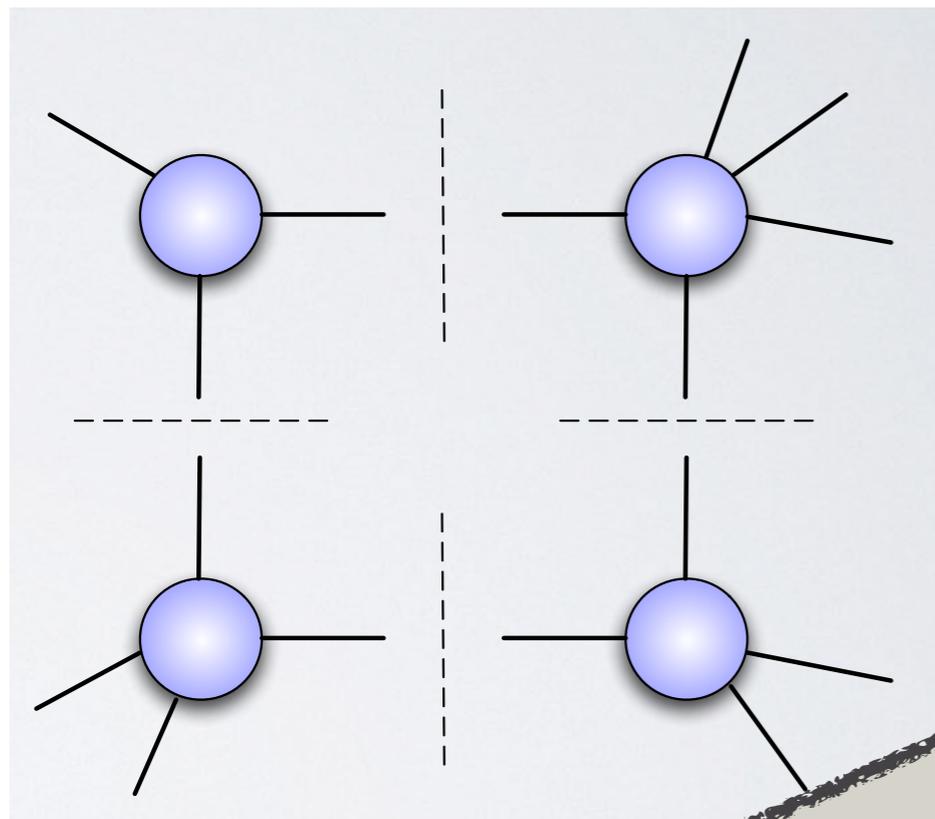
- “cut open a loop”  $\rightarrow$  tree
- use smart trees  $\rightarrow$  simplify dramatically the function to integrate

Integrals?

- one loop  $\rightarrow$  solved long time ago
- higher loop  $\rightarrow$  very complicated, but they seem to have nice geometrical structures... *can we understand this?*



# ... what about loops?



Similar ideas:

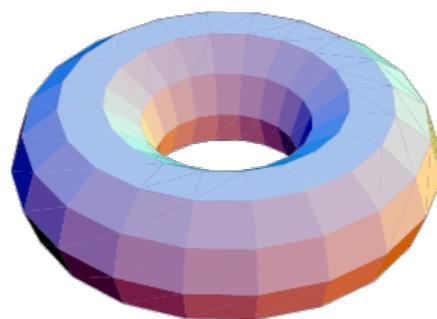
- "cut open a loop"  $\rightarrow$  tree
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Integrate

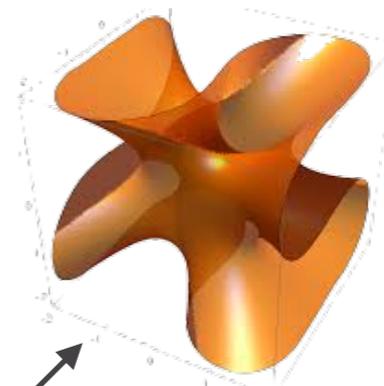
**A lot of progress**

discovered long time ago  
loop  $\rightarrow$  very complicated, but  
they seem to have nice geometrical  
structures... *can we understand this?*

*One-loop*



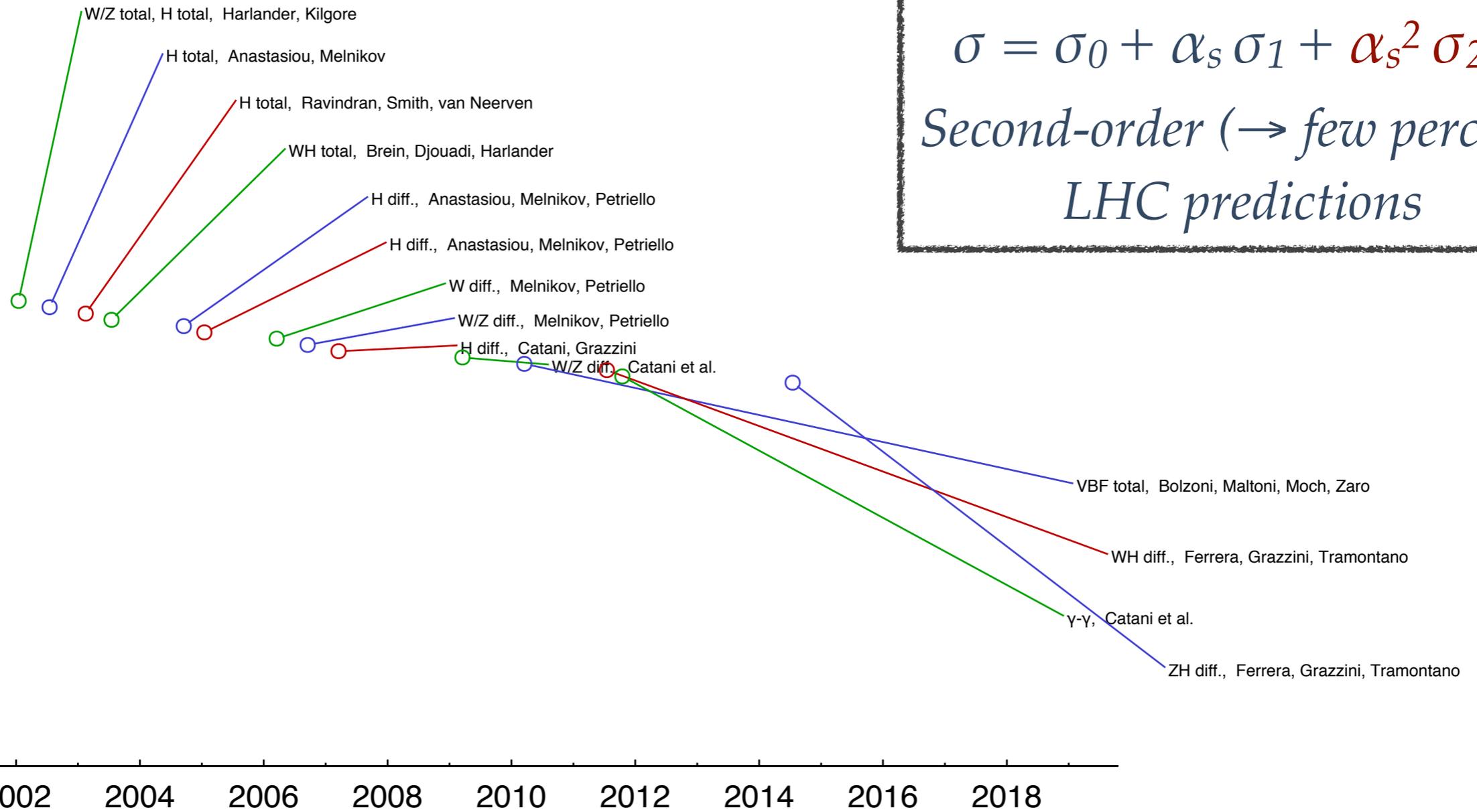
*Multi-loop*



?

# Precision physics at the LHC: timeline

[thanks to Gavin for the graphics]

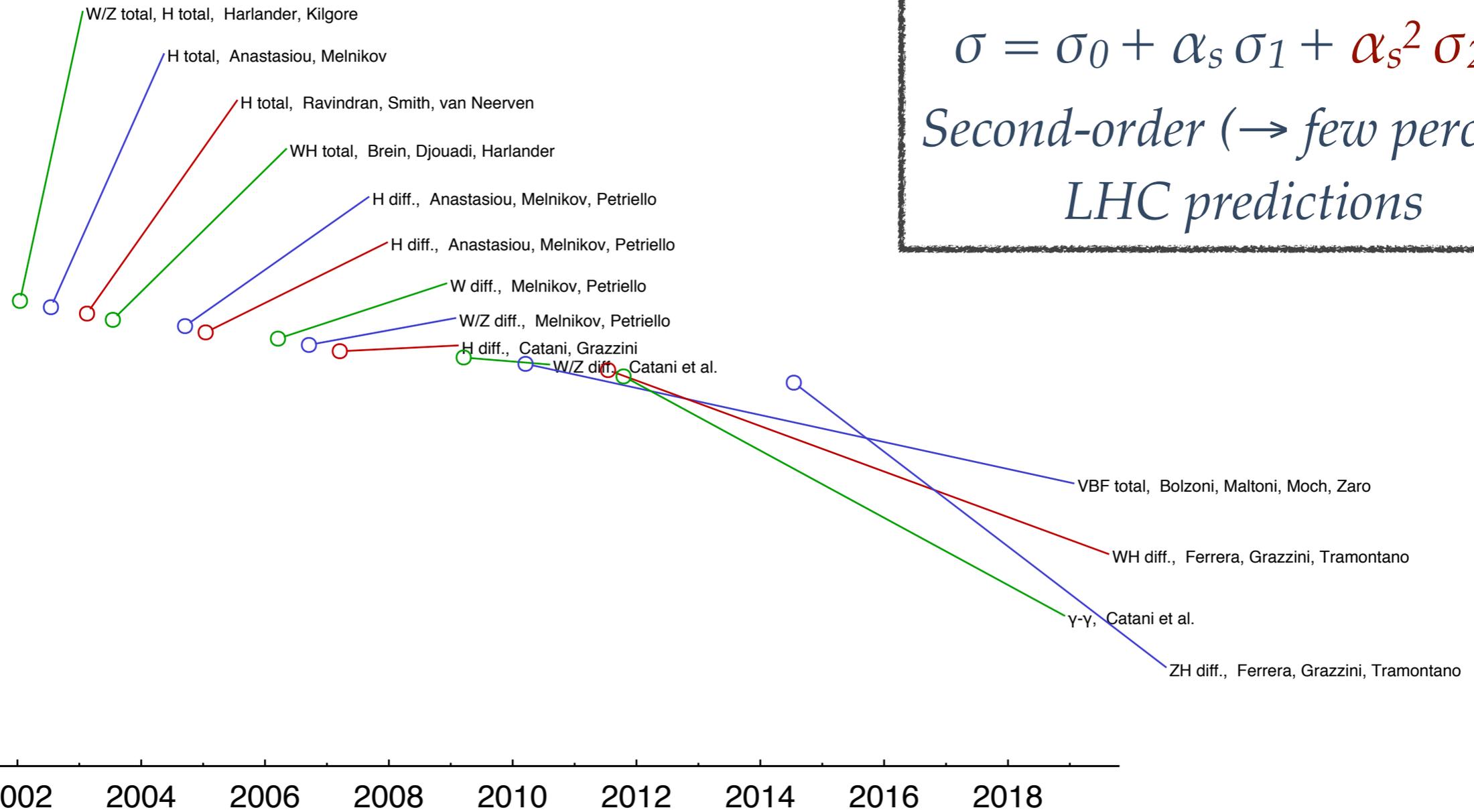


$$\sigma = \sigma_0 + \alpha_s \sigma_1 + \alpha_s^2 \sigma_2 + \dots$$

Second-order ( $\rightarrow$  few percent)  
LHC predictions

# Precision physics at the LHC: timeline

[thanks to Gavin for the graphics]



$$\sigma = \sigma_0 + \alpha_s \sigma_1 + \alpha_s^2 \sigma_2 + \dots$$

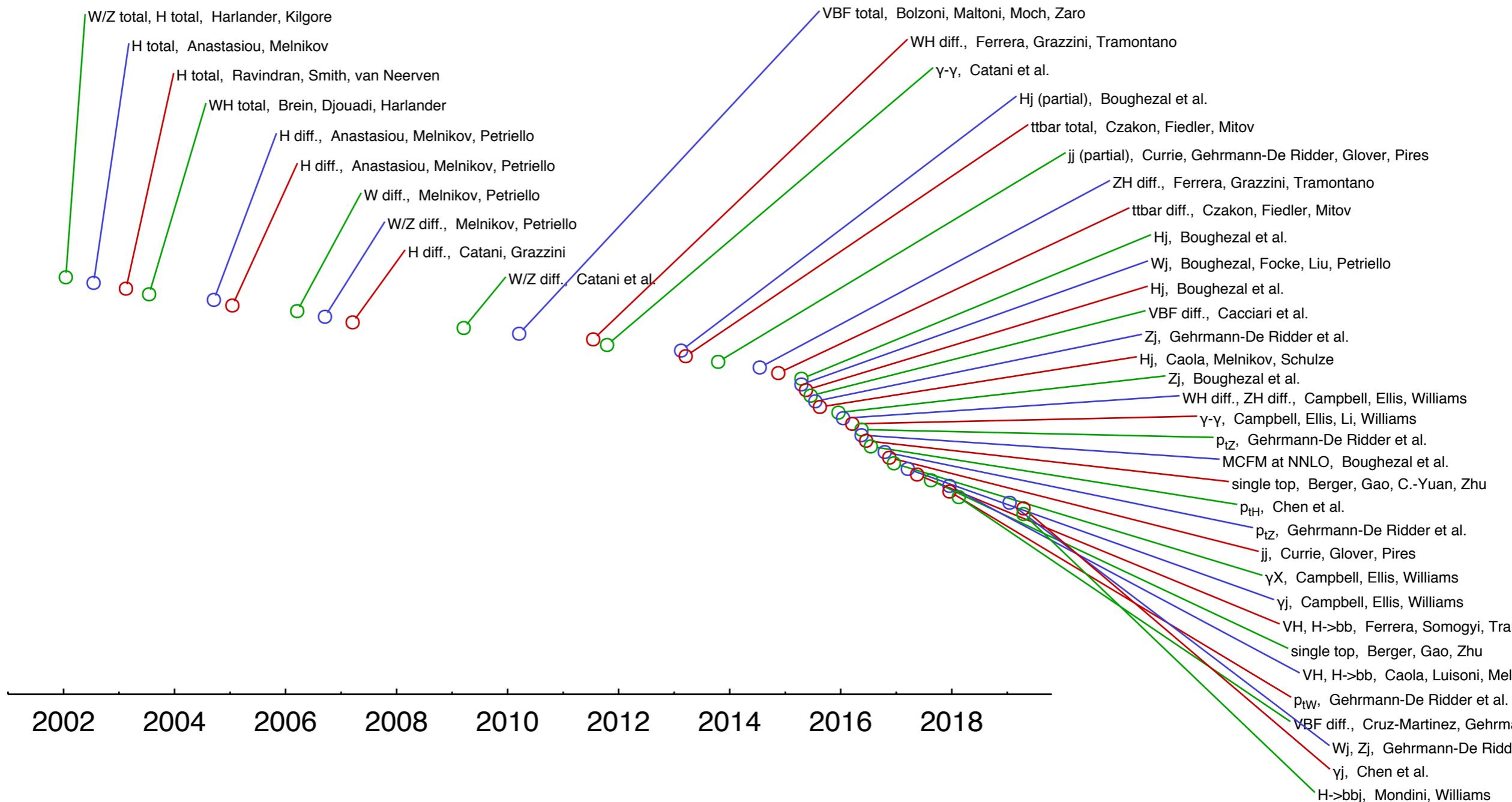
Second-order ( $\rightarrow$  few percent)  
 LHC predictions

First steps towards dealing with infinities in generic processes

New ideas for 2-loop

# Precision physics at the LHC: timeline

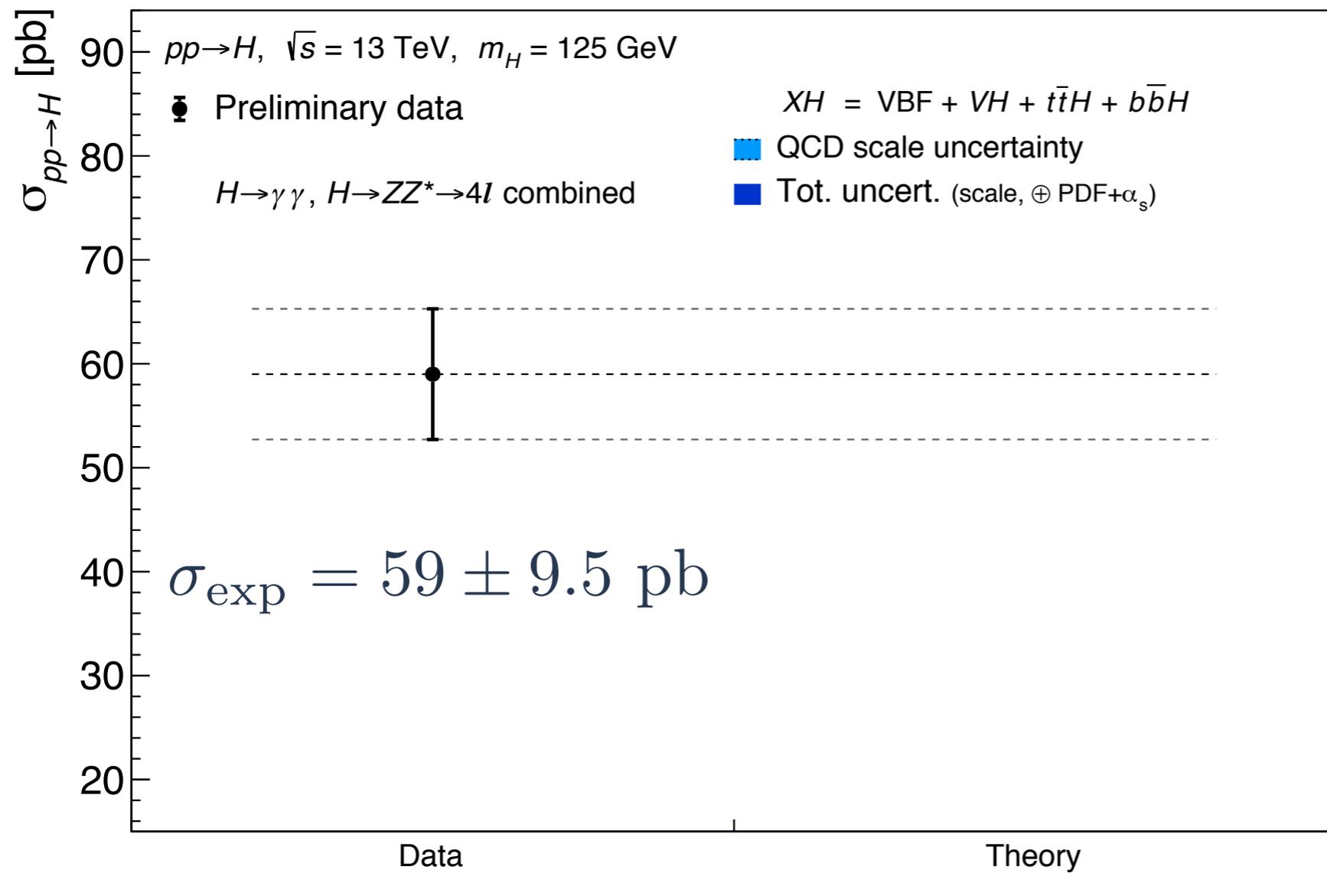
[thanks to Gavin for the graphics]



Explosion of higher order results  
**precision physics at the LHC is possible**

# Precision and the Higgs

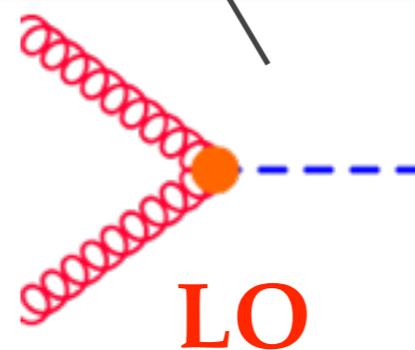
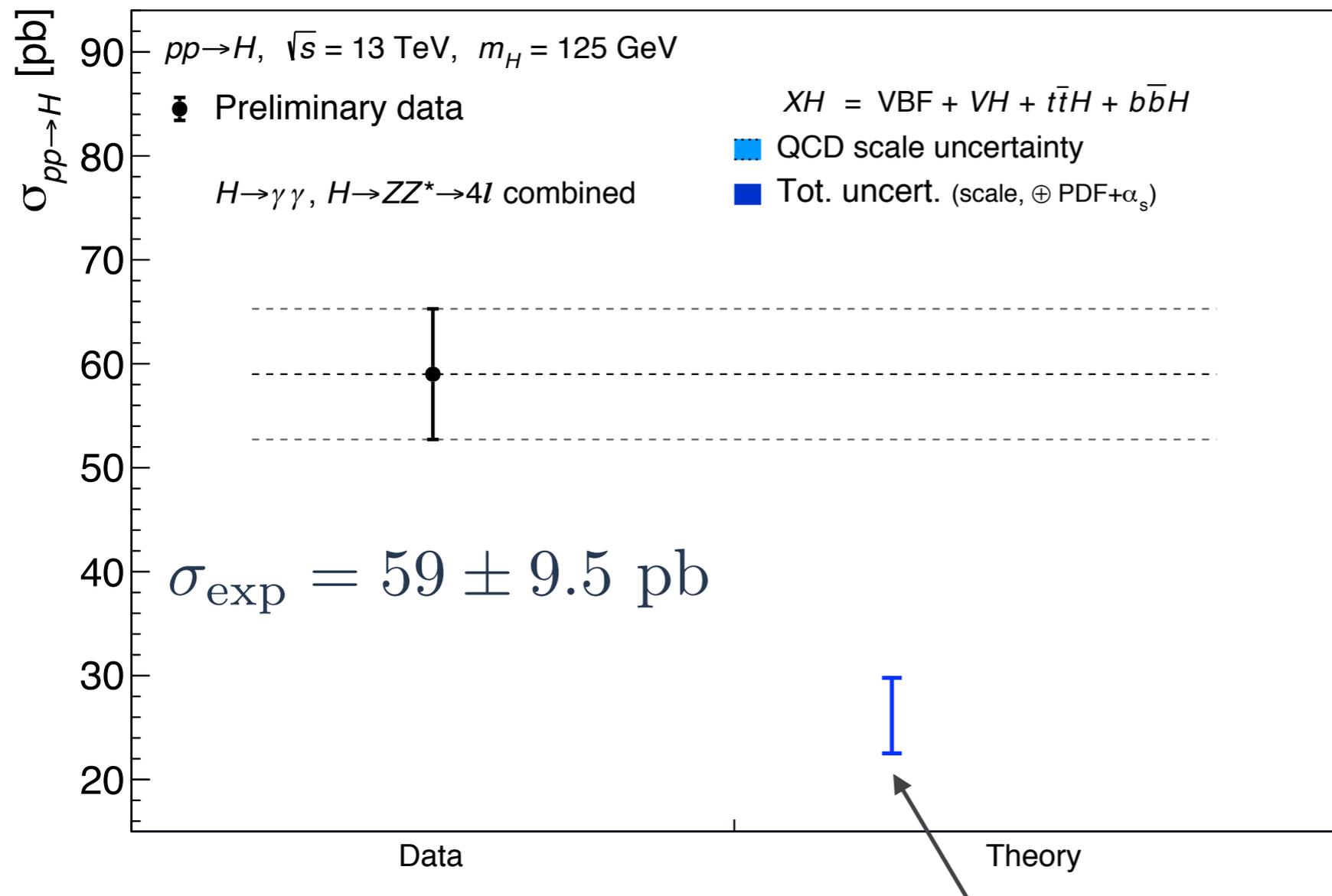
## *Higgs boson production: today*



# Precision and the Higgs

*Higgs boson production: today*

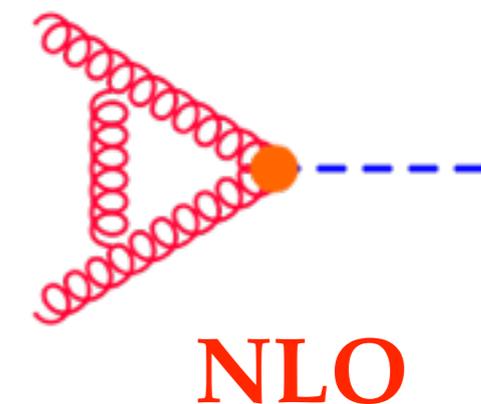
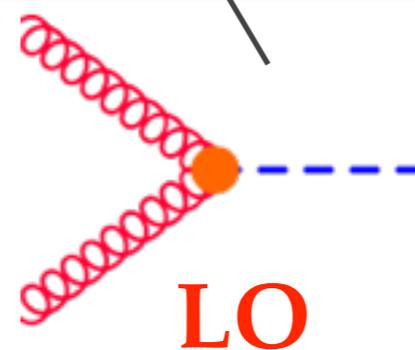
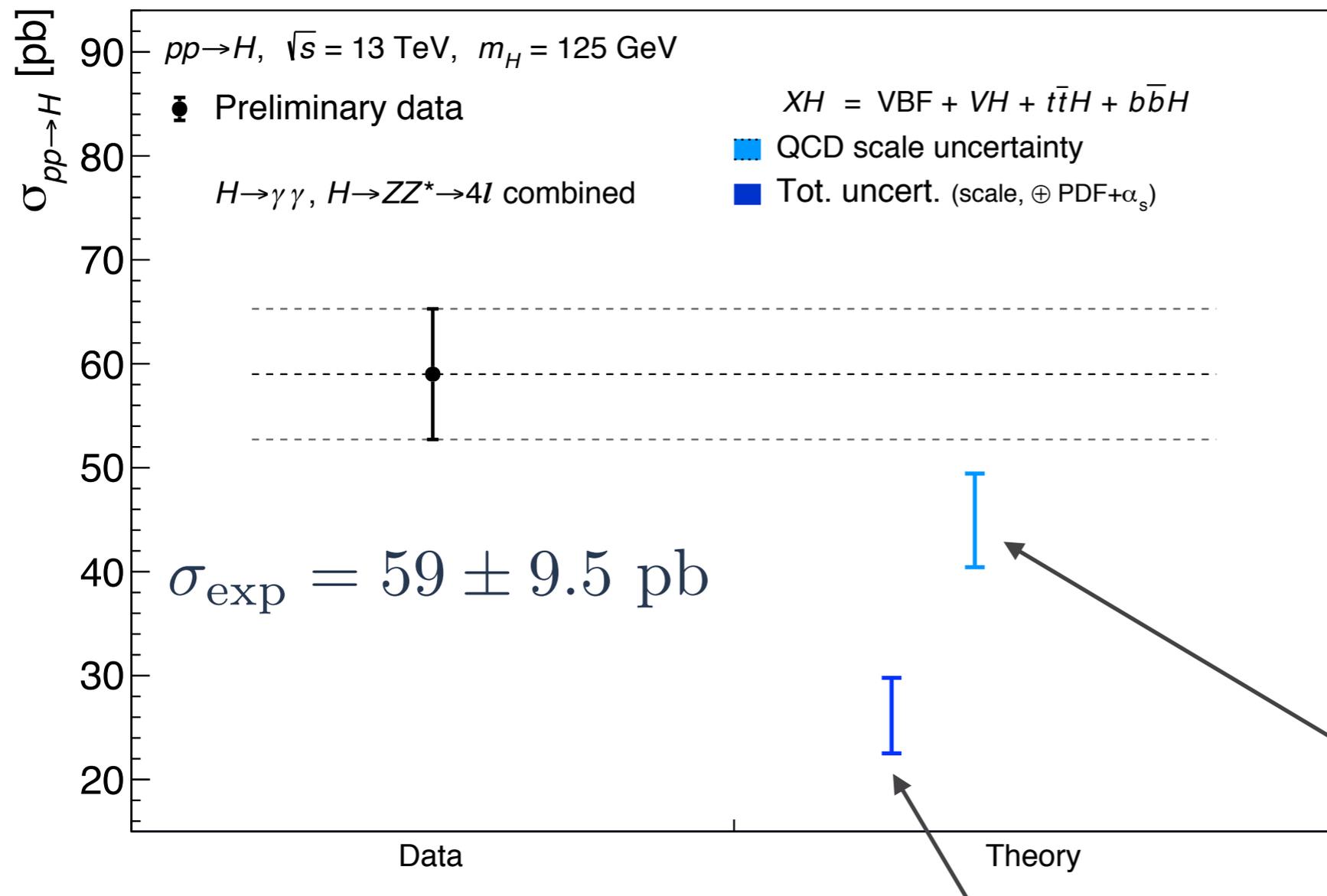
$$\sigma = \sigma_0$$



# Precision and the Higgs

Higgs boson production: today

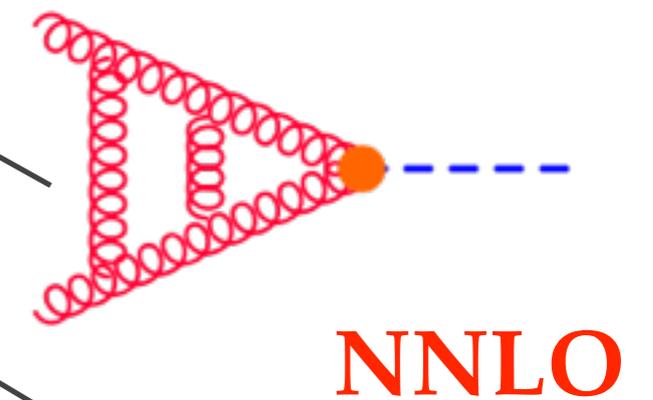
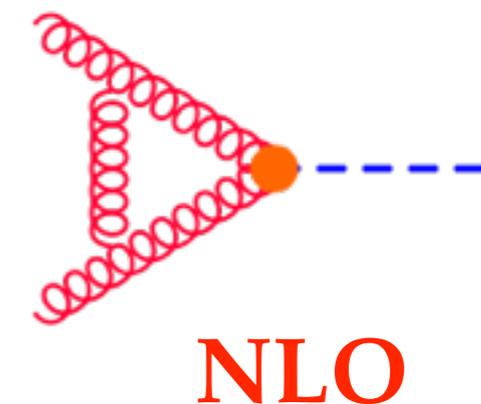
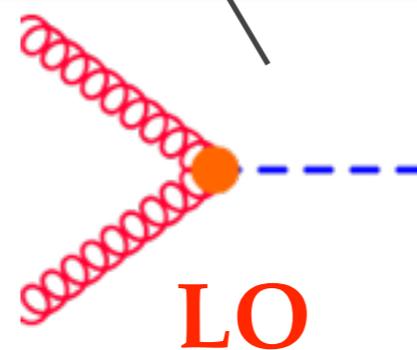
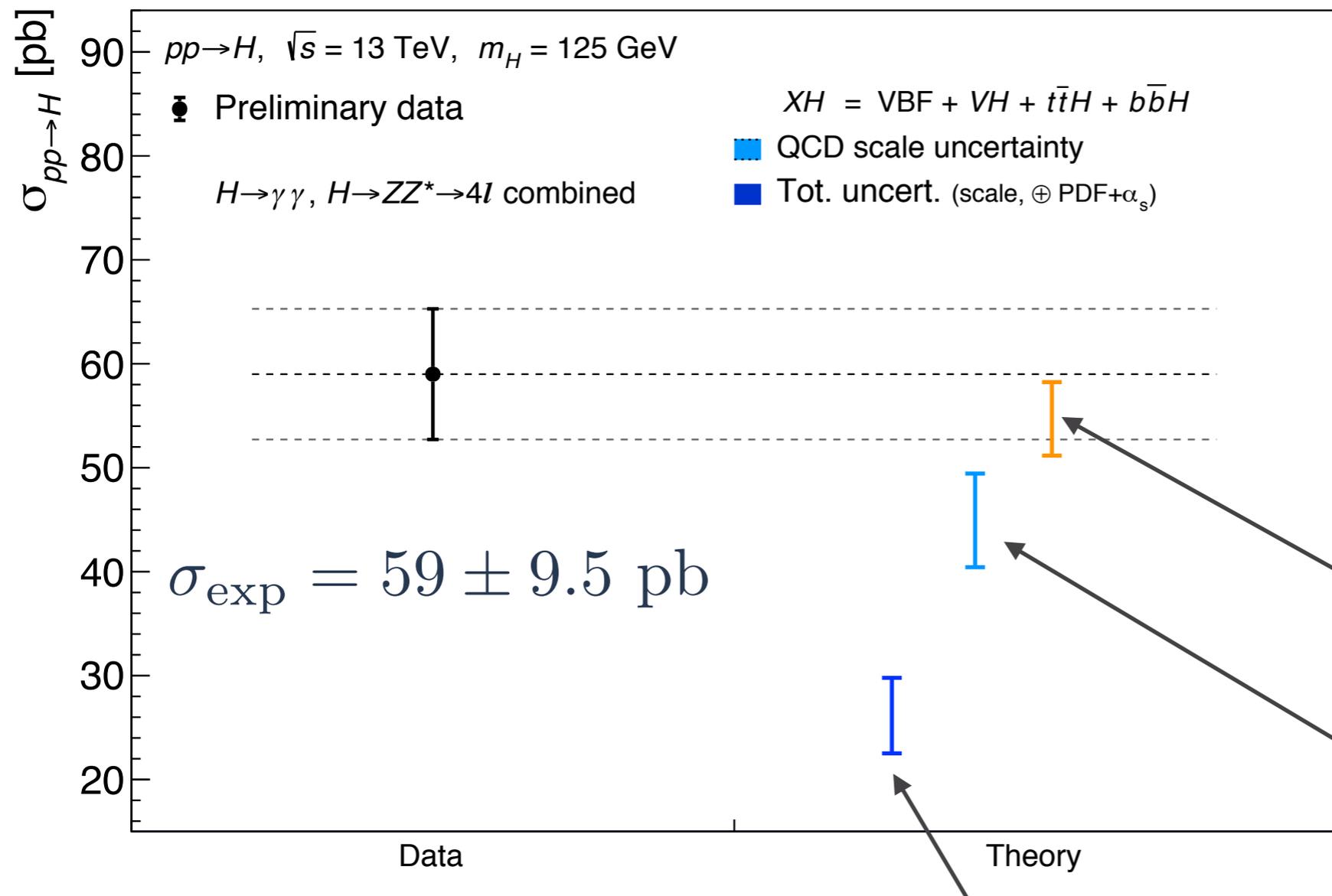
$$\sigma = \sigma_0 + \alpha_s \sigma_1$$



# Precision and the Higgs

*Higgs boson production: today*

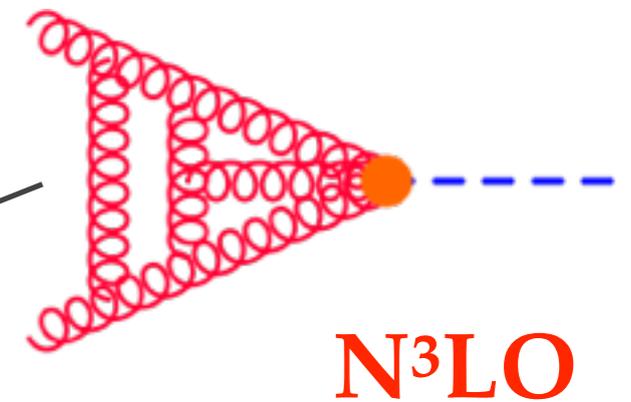
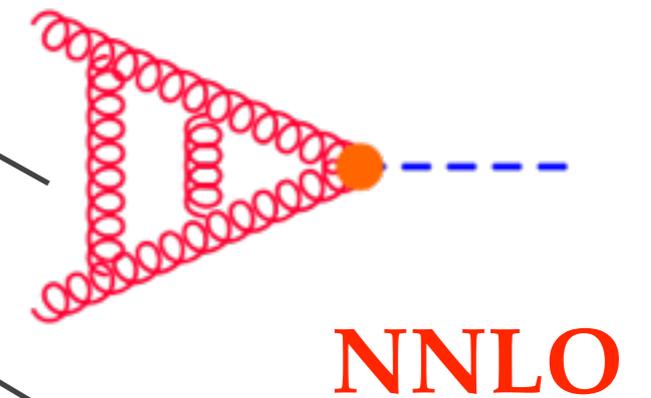
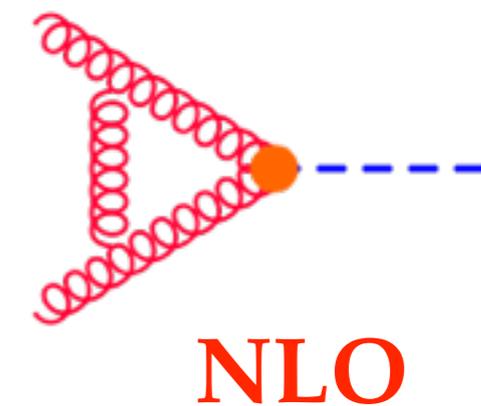
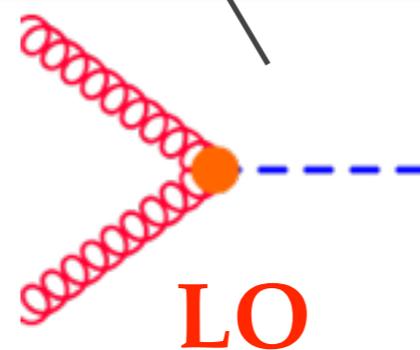
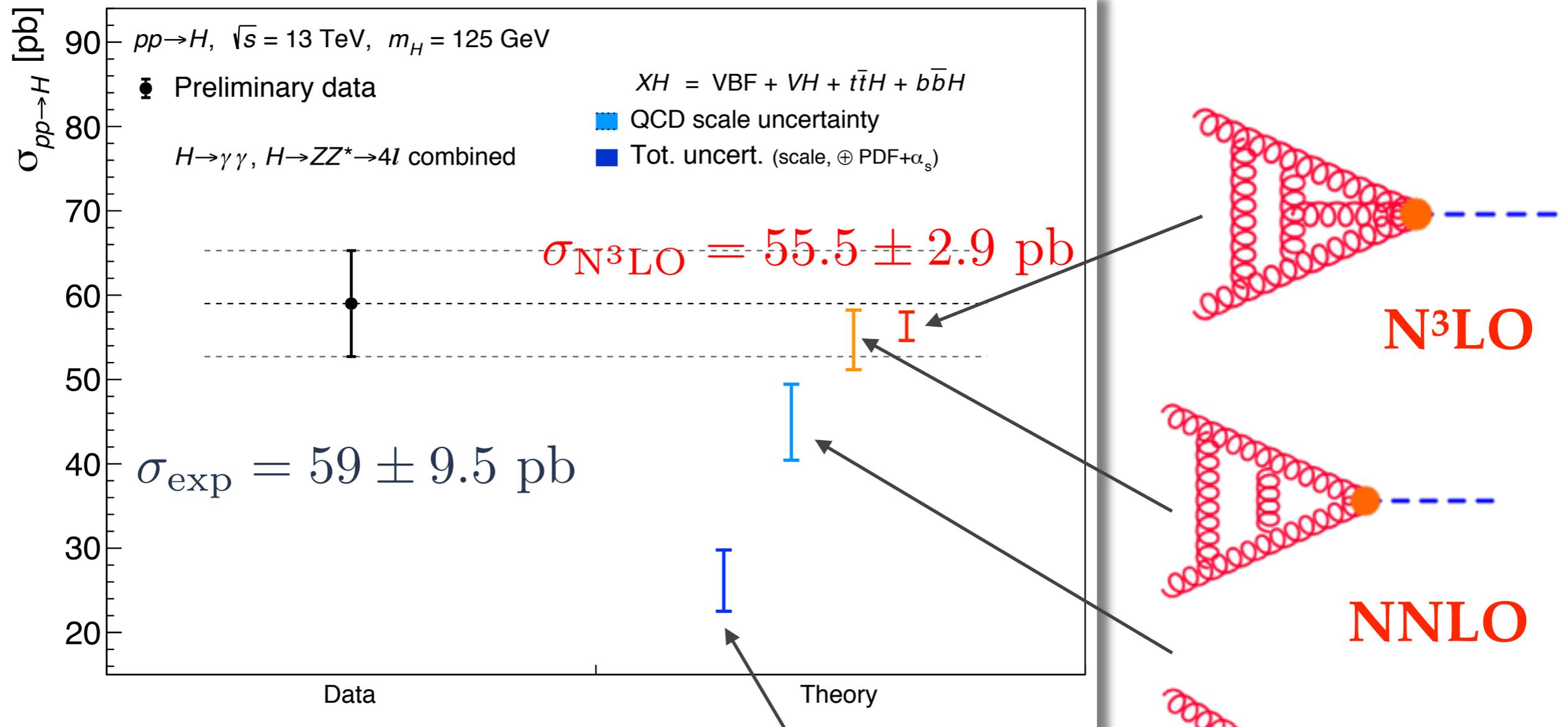
$$\sigma = \sigma_0 + \alpha_s \sigma_1 + \alpha_s^2 \sigma_2$$



# Precision and the Higgs

*Higgs boson production: today*

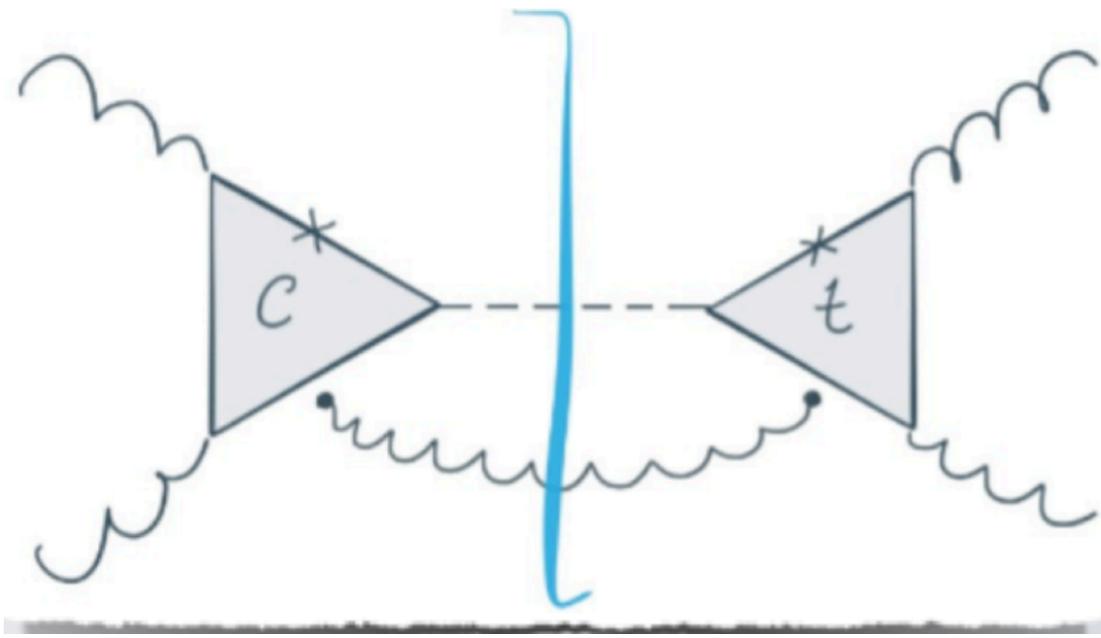
$$\sigma = \sigma_0 + \alpha_s \sigma_1 + \alpha_s^2 \sigma_2 + \alpha_s^3 \sigma_3$$



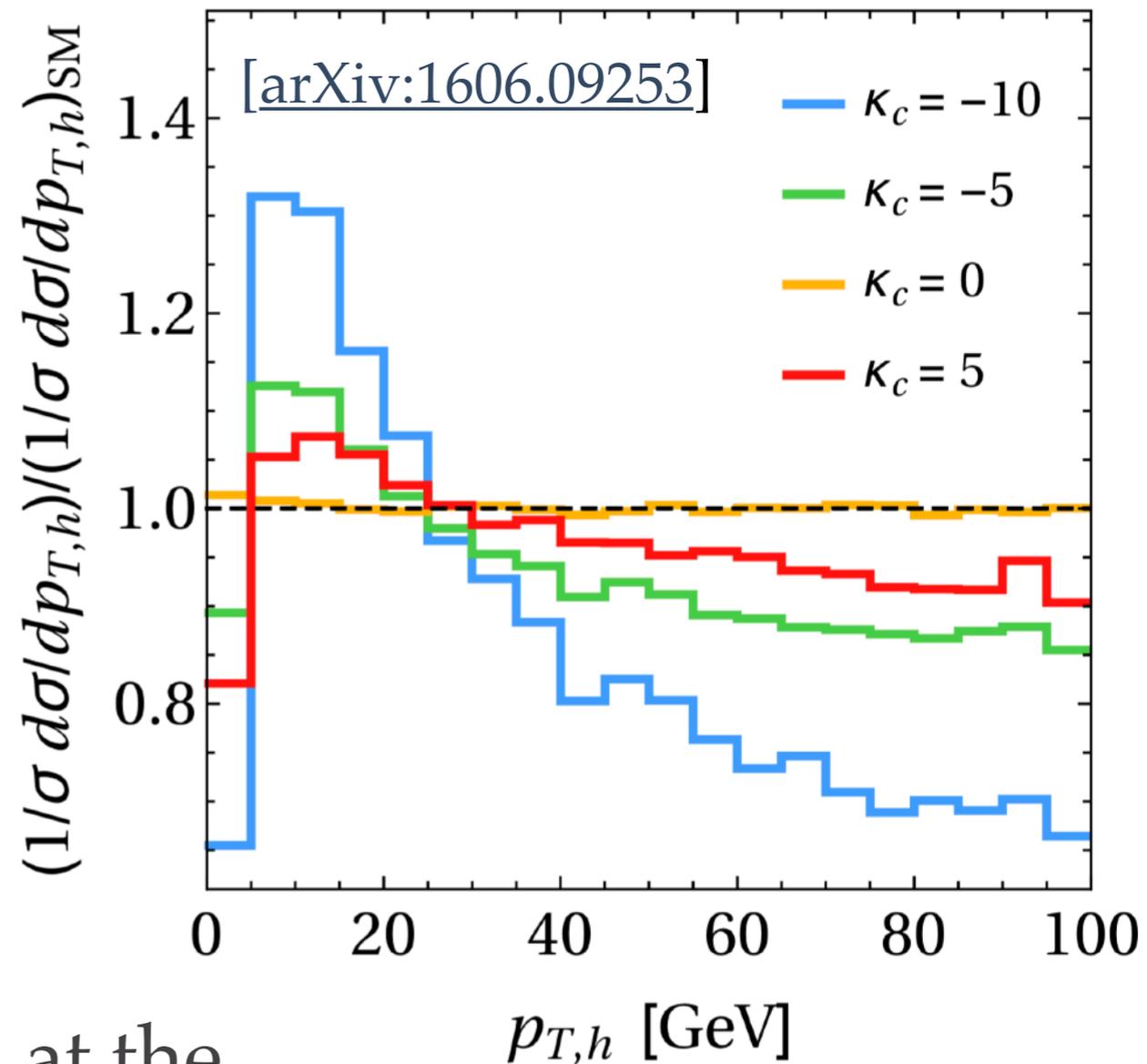
*Very high orders required to test the Higgs sector!*

# Extracting Yukawa interactions

*Use gluon as a probe to look inside Higgs interactions...*

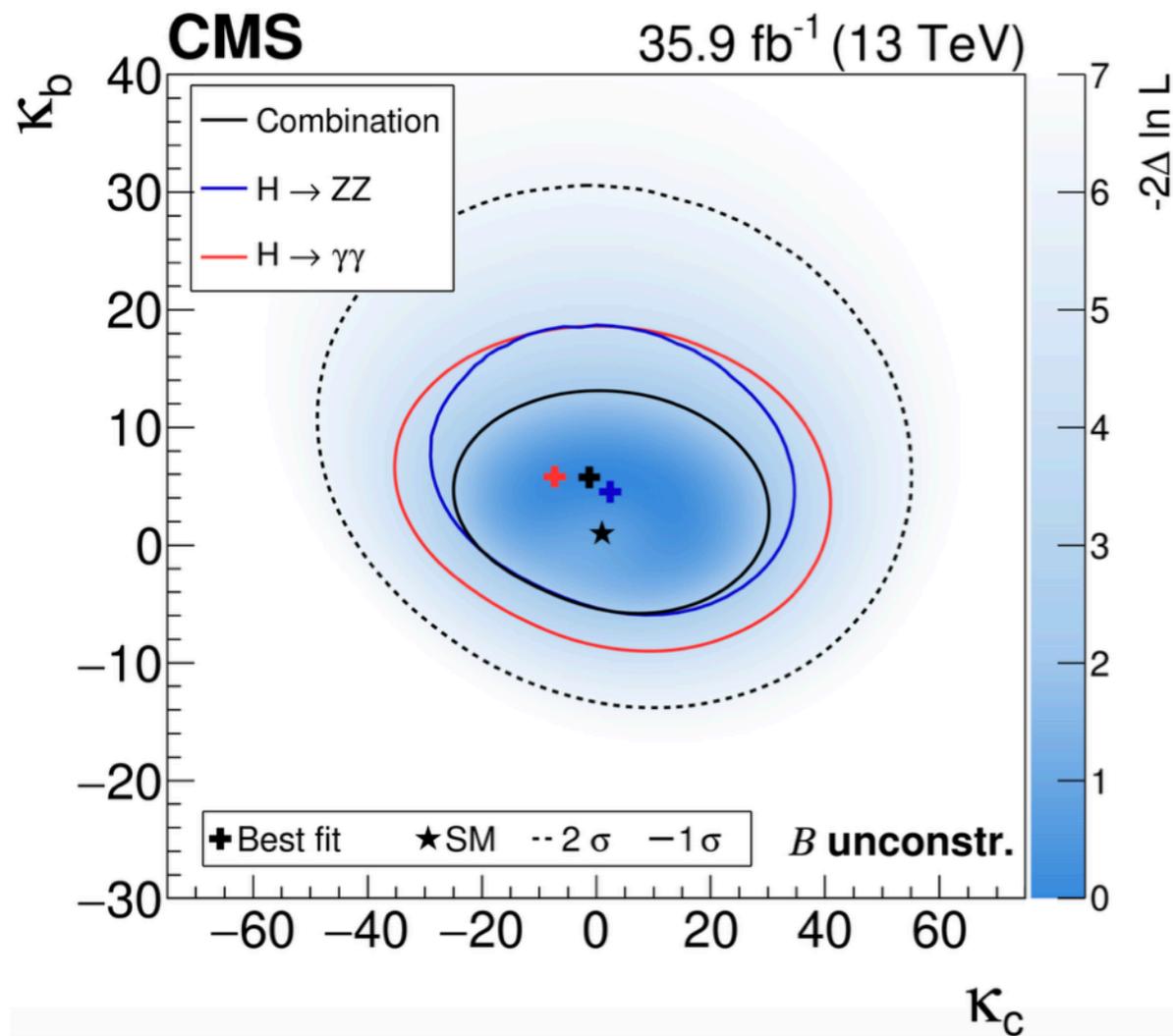


- “1”: Standard Model
- Curves: Higgs is not as predicted by the Standard Model
- If we control theoretical predictions at the few percent  $\rightarrow$  **can disentangle**

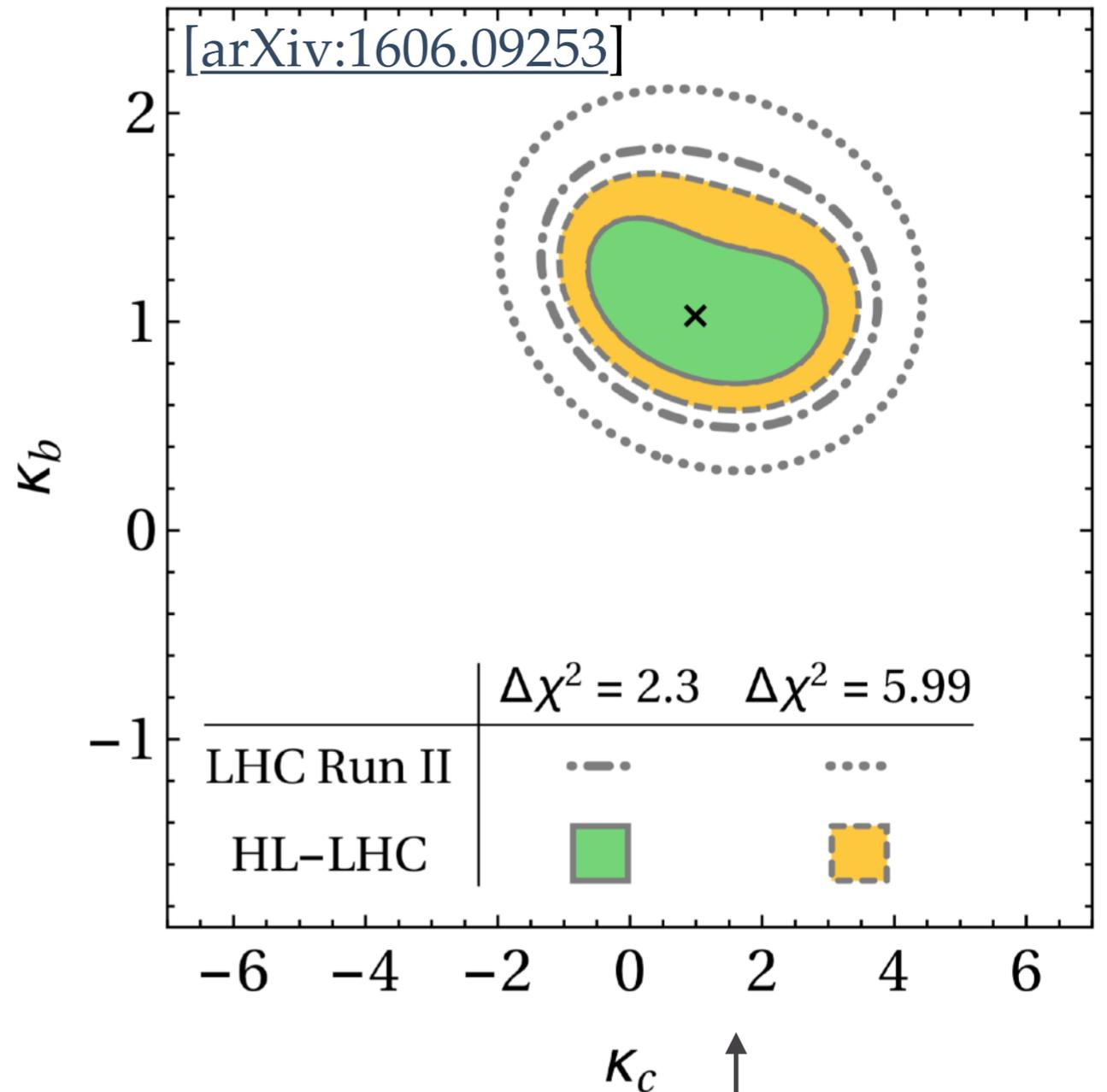


# Extracting Yukawa interactions

*Already interesting results*



[arXiv:1606.09253]



*Could improve dramatically in the future*

# Conclusions

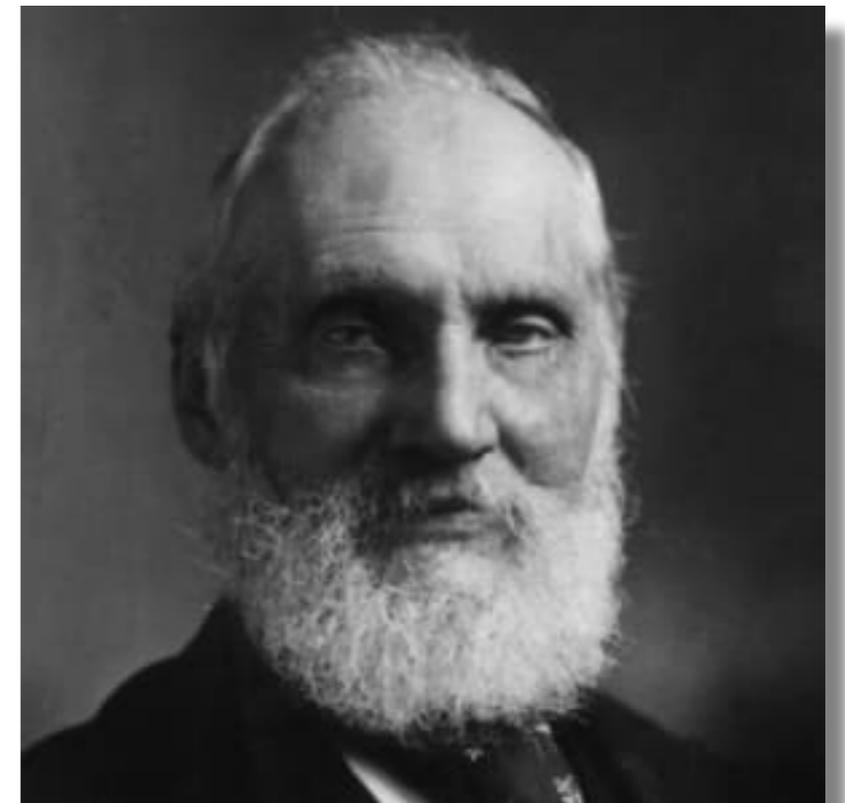
- Higgs studies at the LHC require very good control on QCD
- Although QCD is known since last century, a lot of exciting new progress
- Did cover only a tiny fraction of what is going on...
- A new way of looking at QCD, we keep learning interesting new stuff, and can apply it for high precision studies at the LHC
- Already know we can do a lot...
- ... but in the precision program the best is yet to come: more data, better theory understanding
- LHC is the beginning of the Higgs story
- With precision, we can explore the very core of Higgs interactions

# High precision Higgs studies

- With the Higgs, the Standard Model may be a complete theory. What is the point of looking at the next decimal digit?

“physics is complete, all we need to do is to measure some known quantities to a great degree of precision”

*Lord Kelvin, ca 1900*



*5 years later: special relativity.*

*Less than 30 years later: quantum mechanics, general relativity*

*Thank you very much*

*...fatti non foste a viver come bruti, ma per seguir virtue e canoscenza*

*[...you were not born to live like brutes, but to follow virtue and knowledge]*