ADVANCING THE FRONTIER OF PERTURBATIVE CALCULATIONS TO N3LO

BERNHARD MISTLBERGER

It is a fantastic honor to receive this award!

I would like to express my deep gratitude to the many people in our field that have made it such an exciting journey to explore the fundamental nature of interactions. In particular, I'd like to thank my friends and colleagues

Babis Anastasiou, Claude Duhr, Johannes Henn,
Lance Dixon and Gavin Salam

SLAC

GUIDO ALTARELLI

1941–2015

A giant of the field

- "Asymptotic Freedom in Parton Language" Evolution of quarks - DGL**A**P
- Perturbative QCD
- Electroweak Precision Physics
- Neutrino Physics
- Small-x physics
- …

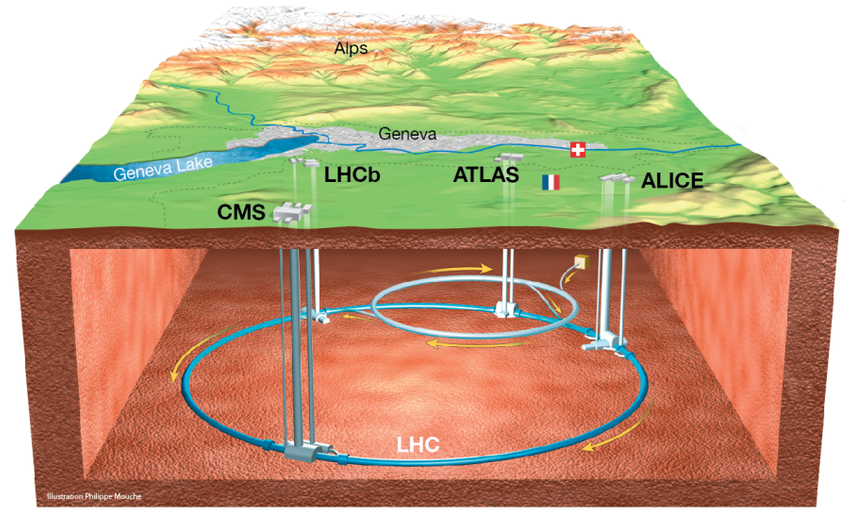
My impression of Alterelli is one of an incredibly intuitive physicist, who knew how to figure out the critical clues towards deepening our understanding of fundamental interactions.

PHYSICS IN THE LHC ERA

Today, nearly all observable physics is described by - or believed to be described by - the Standard Model of particle physics.

However, the description is incomplete!

- Our understanding is insufficient to describe many macroscopic phenomena of the world - and therefor lacking understanding.
- The limitations of this picture are known to us - and we have experiments like the LHC to test and explore them!



Quests in the age of the Higgs:

- **A new interaction: Yukawa!**

- **The mechanism of electro-weak symmetry breaking**

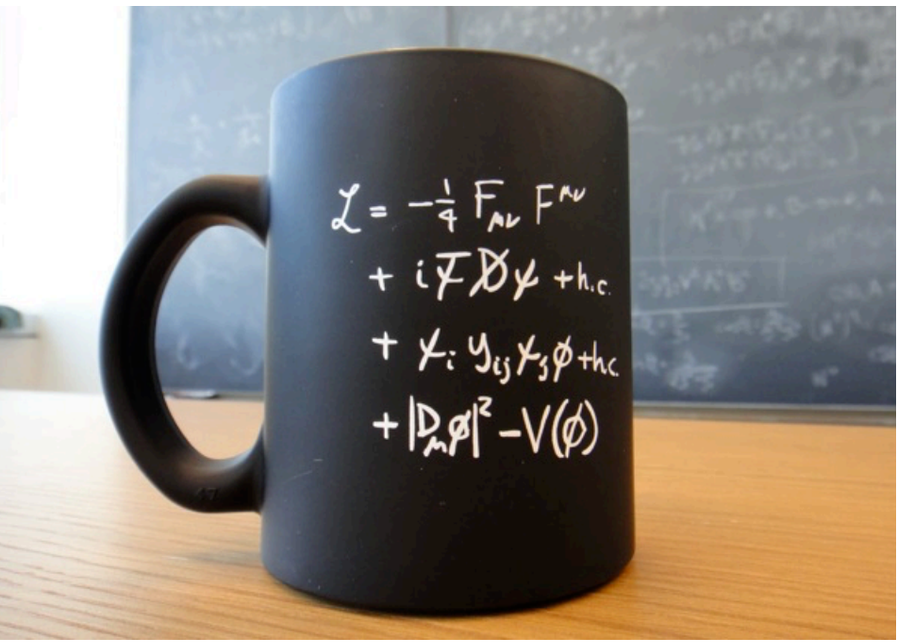
- **Generation of fundamental masses**

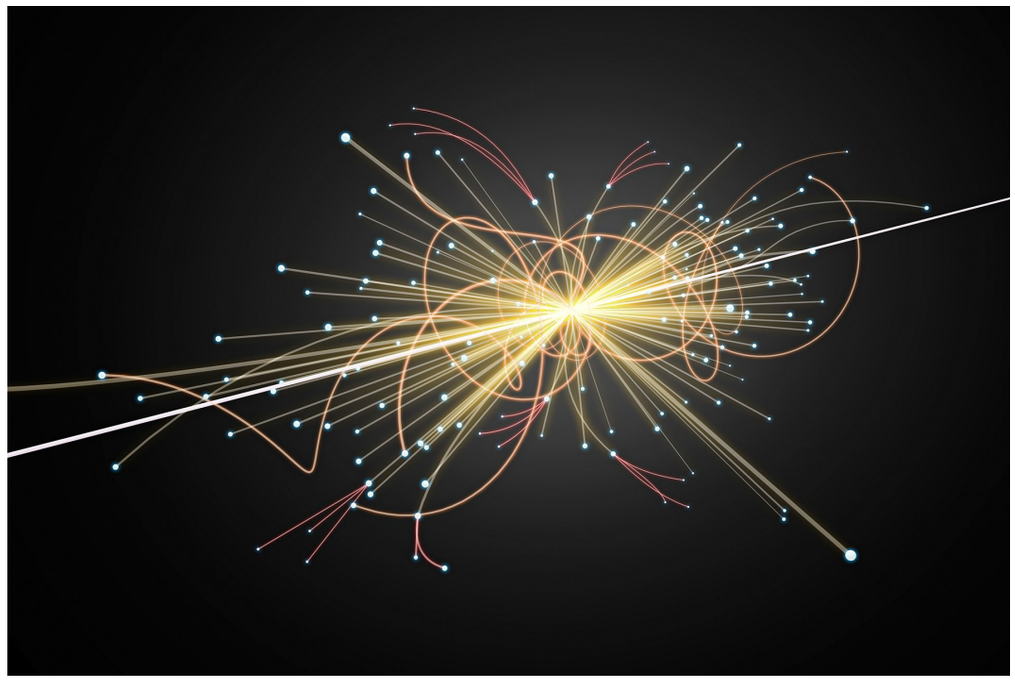
- **Determine couplings / interactions with established matter** $H \heartsuit \mu$?

$W \heartsuit W \heartsuit W \heartsuit W$?

- **Explore the limitations of the Standard Model of particle physics**

EXPLORING THE HIGH ENERGY FRONTIER OF INTERACTIONS





From first principle QFT ... **... to real life measurement**

- Describing the real world starting from the simple, concise formulation of the SM of particle physics is a huge challenge.
- My goal is to sharpen our understanding of fundamental interactions such that the precision in our description of nature allows us to learn from very precise measurements.

Perturbative QCD

- Predict using perturbative QCD

LO **NLO** **NNLO** **N3LO**

$$\hat{\sigma} = \hat{\sigma}^{(0)} + \alpha_S^1 \hat{\sigma}^{(1)} + \alpha_S^2 \hat{\sigma}^{(2)} + \alpha_S^3 \hat{\sigma}^{(3)} + \dots$$

The frontier of perturbative QFT at the LHC

- Complexity of computing high orders in perturbative QFT challenges our methods and understanding.

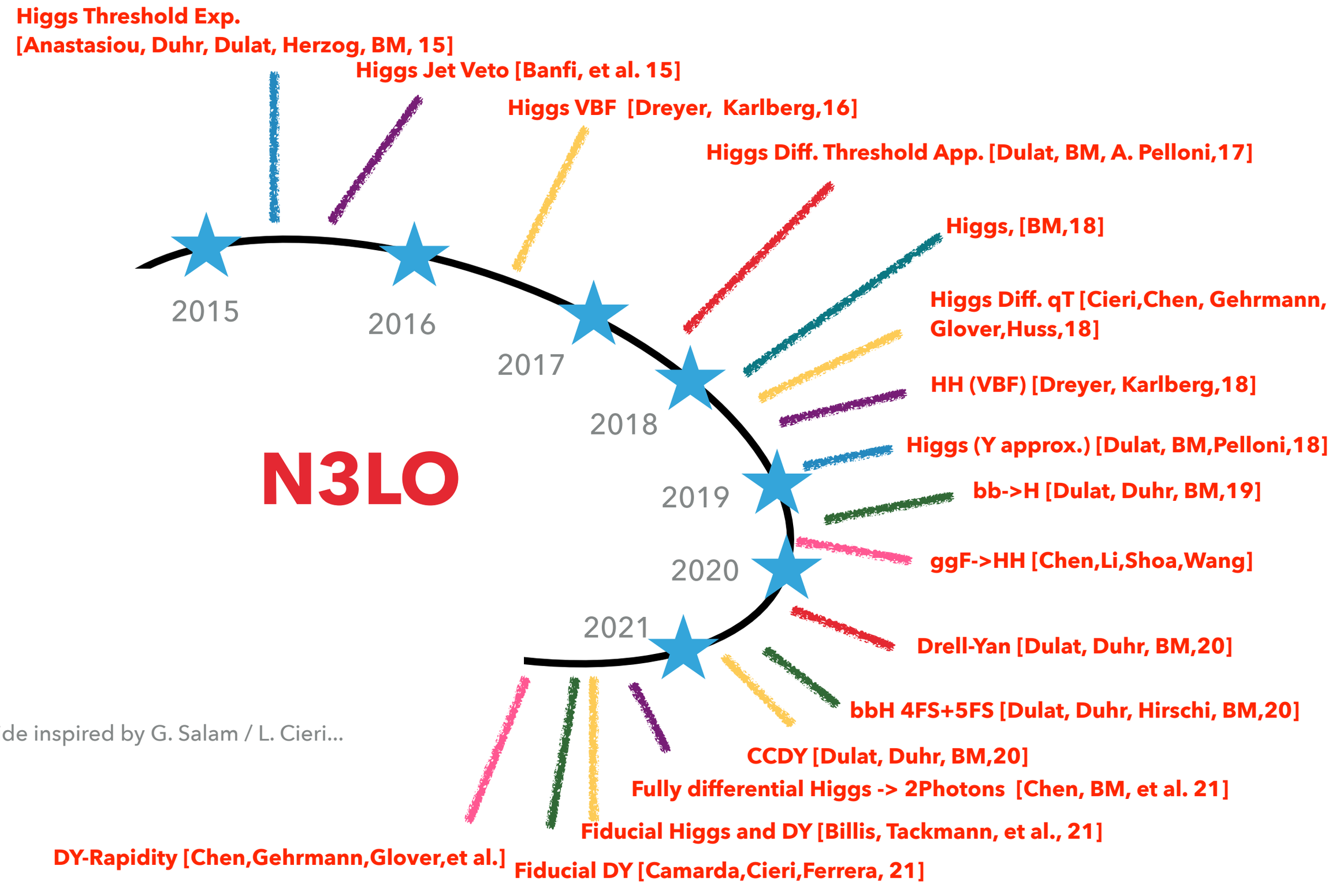
~1,000,000 Feynman Diagrams

New mathematical structures

Vastly growing complexity

N3LO AT THE LHC OVER TIME

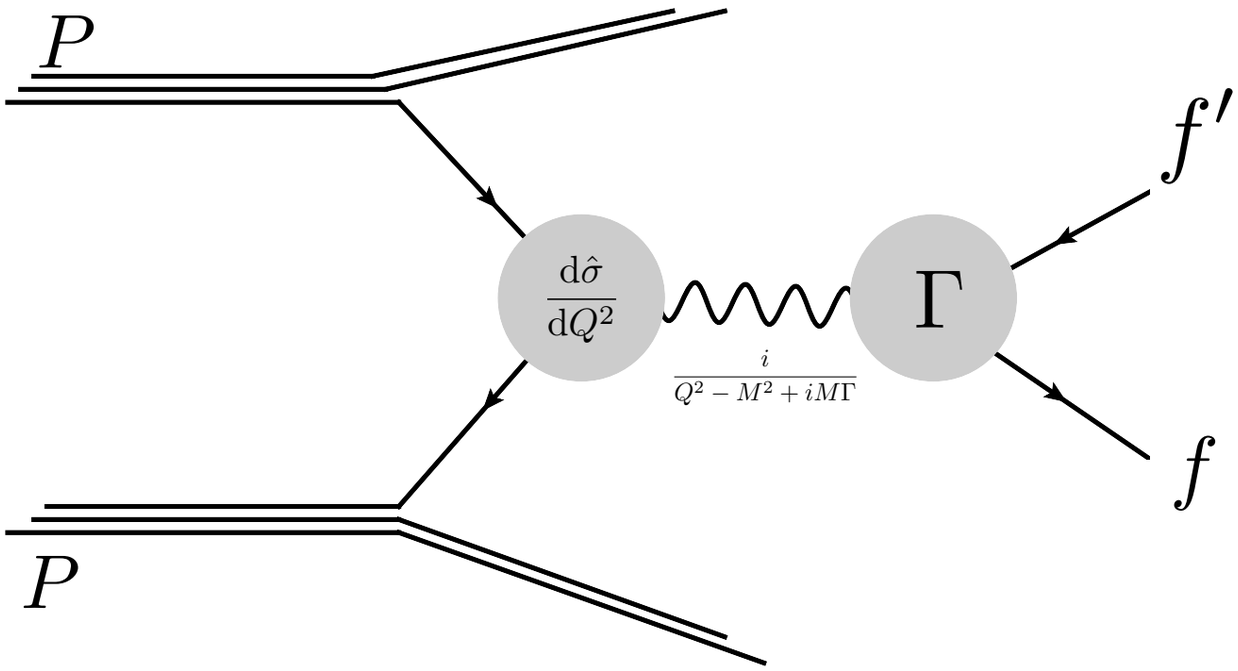
Production Cross Sections



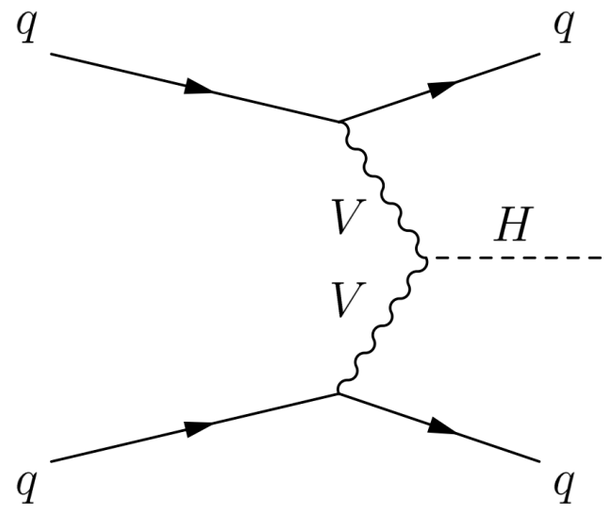
Slide inspired by G. Salam / L. Cieri...

N3LO AT THE LHC RIGHT NOW

Single* Electroweak Boson Production



$\gamma^* \; W \; Z \; H \quad bbH \quad H^* \; G \quad WH \; ZH$



H, HH

- Inclusive cross sections - idealized observables.
- First fully differential predictions for Higgs and DY production

N3LO AT THE LHC RIGHT NOW

Single* Electroweak Boson Production

Predictions for various processes:

	Q [GeV]	K-factor	δ(scale) [%]	δ(PDF + α_S)	δ(PDF-TH)
$gg \to$ Higgs	m_H	1.04	$^{+0.21\%}_{-2.37\%}$	$\pm 3.2\%$	$\pm 1.2\%$
$b\bar{b} \to$ Higgs	m_H	0.978	$^{+3.0\%}_{-4.8\%}$	$\pm 8.4\%$	$\pm 2.5\%$
NCDY	30	0.952	$^{+1.53\%}_{-2.54\%}$	$^{+3.7\%}_{-3.8\%}$	$\pm 2.8\%$
	100	0.979	$^{+0.66\%}_{-0.79\%}$	$^{+1.8\%}_{-1.9\%}$	$\pm 2.5\%$
CCDY(W^+)	30	0.953	$^{+2.5\%}_{-1.7\%}$	$\pm 3.95\%$	$\pm 3.2\%$
	150	0.985	$^{+0.5\%}_{-0.5\%}$	$\pm 1.9\%$	$\pm 2.1\%$
CCDY(W^+)	30	0.950	$^{+2.6\%}_{-1.6\%}$	$\pm 3.7\%$	$\pm 3.2\%$
	150	0.984	$^{+0.6\%}_{-0.5\%}$	$\pm 2\%$	$\pm 2.13\%$

Take-away:

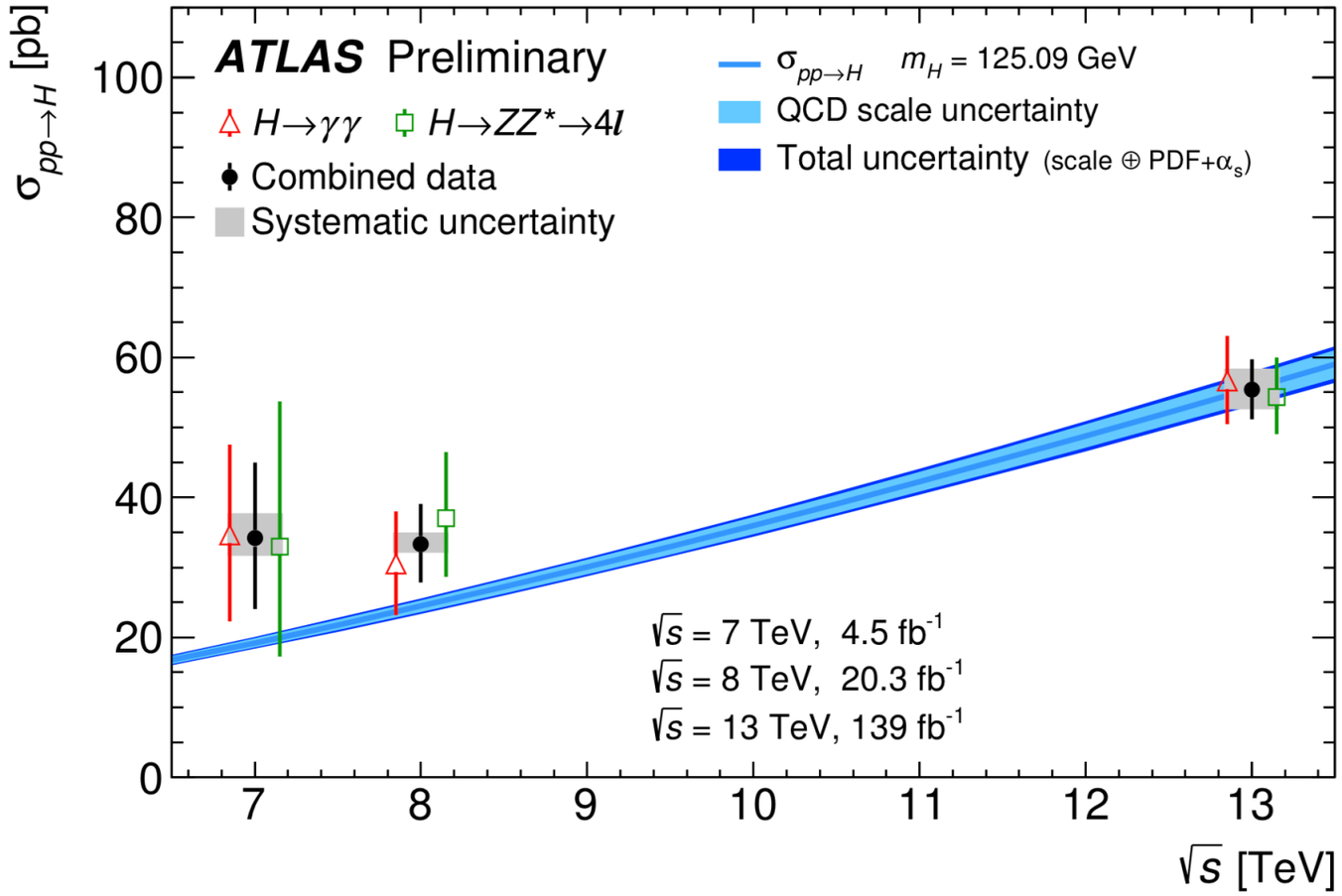
1. N3LO correction: few percent.
2. Residual Uncertainty: percent level.
3. N3LO: Improves predictions and reduces uncertainties.
4. Other uncertainties of comparable size.

N3LO required for target precision for LHC observables

N3LO – THE BENEFITS

How many Higgs bosons are produced at the LHC?

- Testing a central prediction of the SM.
- Probe the properties of the Higgs.



$$\mu = \frac{\sigma_{\text{obs.}}}{\sigma_{\text{SM}}}$$

$\mu = 1.06 \pm 0.07 = 1.06 \pm 0.04(\text{stat}) \pm 0.03(\text{exp.})^{+0.05}_{-0.04}(\text{sig. th.}) \pm 0.02(\text{bkg. th.})$ ATLAS

$\mu = 1.02^{+0.07}_{-0.06} = 1.02 \pm 0.04(\text{stat}) \pm 0.04(\text{exp.}) \pm 0.04(\text{sig.+bkg. th.})$ CMS

THE CHALLENGES AHEAD

$$\sigma = f_1 \circ f_2 \circ \int d\Phi |M|^2 + \mathcal{O}(\Lambda^2/Q^2)$$

1. **Accessibility and User Friendliness:** Creating frameworks that make N^{3}LO (and NNLO) predictions easily accessible for comparison to experimental data.

2. **Corrections beyond QCD:** EWK and masses.

3. **Factorisation Violation at N^{3}LO:** tops, PDFs.

4. **Parton Showers:** Consistent combination of parton showers with fixed order perturbative computations at N^{3}LO.

5. **Resummation:** Complementing N^{3}LO computations and resummation techniques for infrared sensitive observables.

6. **Uncertainties:** Deriving / defining reliable uncertainty estimates for theoretical computations at the percent level.

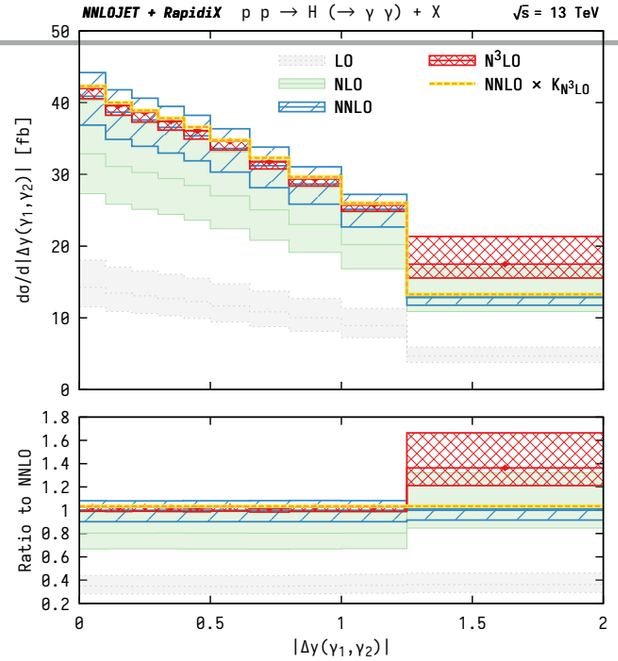
7. **Beyond Leading Power Factorisation:** Exploring the limitations of leading power perturbative descriptions of hadron collision cross sections.

8. ...

My research today

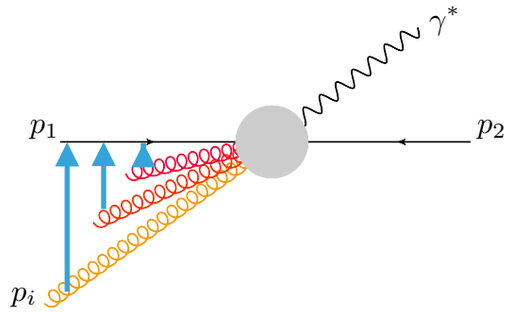
My goal is to find a better understanding of nature to provide answers to our fundamental questions.

- **Develop N3LO predictions to be the backbone for LHC precision phenomenology now and in the future.**



Fully differential predictions for Higgs production at N3LO

- **Create new technology to improve our ability to predict**



Collinear Expansion: New technology to approximate cross sections.

- **Study and learn from the structure of perturbative QFT**

$$\Gamma_{\text{cusp}}\Big|_{\alpha_s^4} = -\left(\frac{\alpha_s N}{\pi}\right)^4 \left[\frac{73\pi^6}{20160} + \frac{\zeta_3^2}{8} + \frac{1}{N^2}\left(\frac{31\pi^6}{5040} + \frac{9\zeta_3^2}{4}\right)\right]$$

Cusp anomalous dimension at 4 loops.

"The beautiful naive parton model of Bjorken, Feynman and others has by now evolved into the QCD improved parton model. This powerful language has become such a familiar and widespread tool for everyday practice in high energy physics that one is led to take all its new successes as granted and in a way obvious." - Guido Altarelli, 1985

Let's follow Altarelli's example and continue to explain the fundamental interactions of nature!

Thank you!