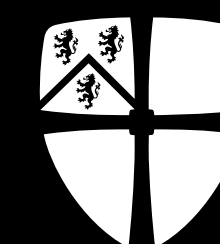


YETI, Durham, July 14th 2026

The Higgs Precision Programme

Stephen Jones

IPPP Durham / Royal Society URF



Durham
University

THE
ROYAL
SOCIETY

Photo Credit: ATLAS

Outline

Goal of this Talk

Primer for the LHC → HL-LHC Era

Motivation

Why study the Higgs sector?

How can we study the Higgs sector?

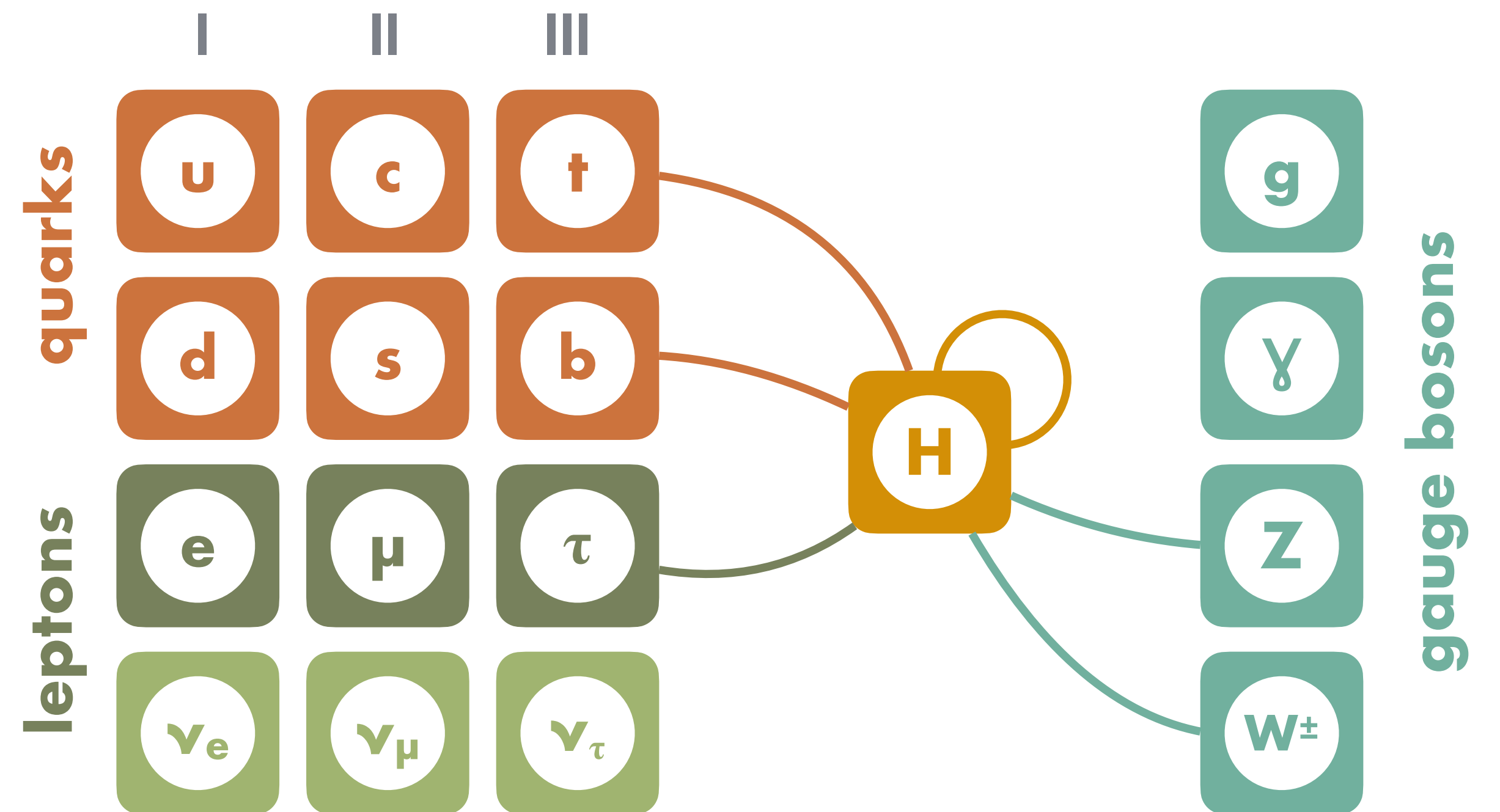
Higgs Production & Higgs Decay

Review

Selected Highlights

Challenges

Future Directions



Introduction

Straw Poll

Theory

Q1: Who is working on theory involving SM/BSM Higgs bosons?

Q2: Who is working on precision calculations?

Experiment

Q3: Who is working on a measurement related to Higgs Physics?

Q4: Who is working on precision measurements?

Why Study the Higgs Sector?

The Role of the Higgs Field in the Standard Model

$$\mathcal{L}_{\text{SM}} = \mathcal{L}_{\text{gauge}} + \mathcal{L}_{\text{Fermion}} + \mathcal{L}_{\text{Higgs}} + \mathcal{L}_{\text{Yukawa}} + \mathcal{L}_{\text{GF}} + \mathcal{L}_{\text{Ghost}}$$



Q: What are these?
What do they do?

The Role of the Higgs Field in the Standard Model

$$\mathcal{L}_{\text{SM}} = \mathcal{L}_{\text{gauge}} + \mathcal{L}_{\text{Fermion}} + \mathcal{L}_{\text{Higgs}} + \mathcal{L}_{\text{Yukawa}} + \mathcal{L}_{\text{GF}} + \mathcal{L}_{\text{Ghost}}$$

The Higgs field plays a central role in the SM

It provides mass to $W^\pm/Z$ bosons via Electroweak symmetry breaking and leptons via Yukawa couplings

$$\mathcal{L}_{\text{Higgs}} = \left(D_\mu \Phi \right)^\dagger D_\mu \Phi + \mu^2 \Phi^\dagger \Phi - \lambda \left(\Phi^\dagger \Phi \right)^2$$

$$\Phi = \begin{bmatrix} \varphi^+ \\ \frac{v + H + i\varphi_Z}{\sqrt{2}} \end{bmatrix}.$$

$$\widetilde{\Phi} = i\sigma_2 \Phi^*$$

Complex SU(2) doublet

$$\mathcal{L}_{\text{Yukawa}} = -\bar{L}_L Y_l \Phi \ell_R - \bar{Q}'_L Y_d \Phi d'_R - \bar{Q}'_L Y_u \widetilde{\Phi} u'_R + \text{h.c.}$$

↑
**Left-handed
SU(2) doublets**

↑
**Right-handed
singlets**

↑
**Complex 3x3
matrices in flavour**

The Role of the Higgs Field in the Standard Model

$$\mathcal{L}_{\text{SM}} = \mathcal{L}_{\text{gauge}} + \mathcal{L}_{\text{Fermion}} + \mathcal{L}_{\text{Higgs}} + \mathcal{L}_{\text{Yukawa}} + \mathcal{L}_{\text{GF}} + \mathcal{L}_{\text{Ghost}}$$

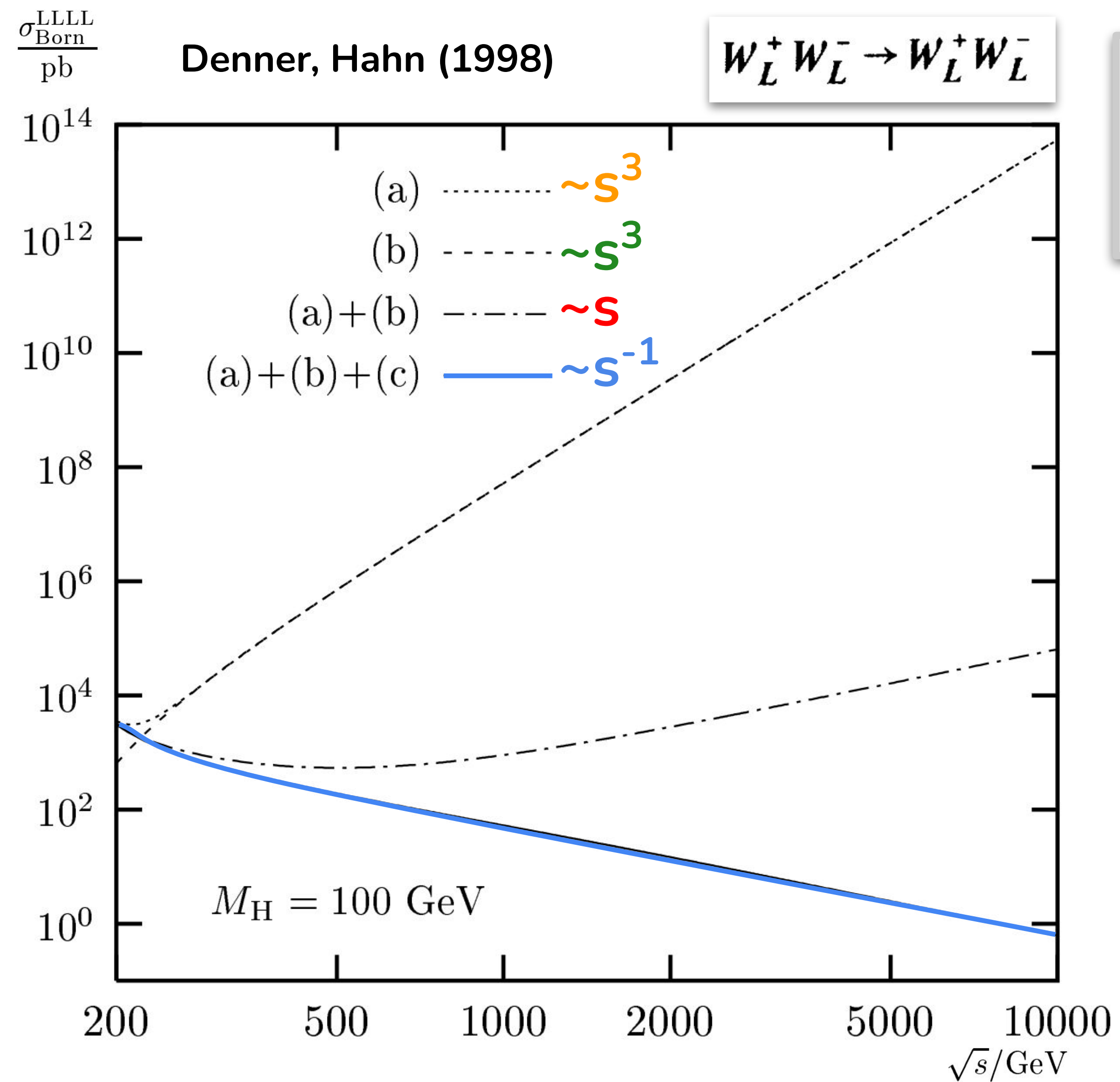
And yet... almost every problem of the Standard Model originates from Higgs interactions!

$$\mathcal{L}_{\text{Higgs}} = \left(D_\mu \Phi \right)^\dagger D_\mu \Phi + \overset{\text{naturalness}}{\downarrow} \mu^2 \Phi^\dagger \Phi - \overset{\text{stability}}{\downarrow} \lambda \left(\Phi^\dagger \Phi \right)^2 - \overset{\text{cosmological constant}}{\downarrow} V_0$$

$$\mathcal{L}_{\text{Yukawa}} = -\bar{L}_L Y_l \Phi \ell_R - \bar{Q}'_L Y_d \Phi d'_R - \bar{Q}'_L Y_u \widetilde{\Phi} u'_R + \text{h.c.},$$

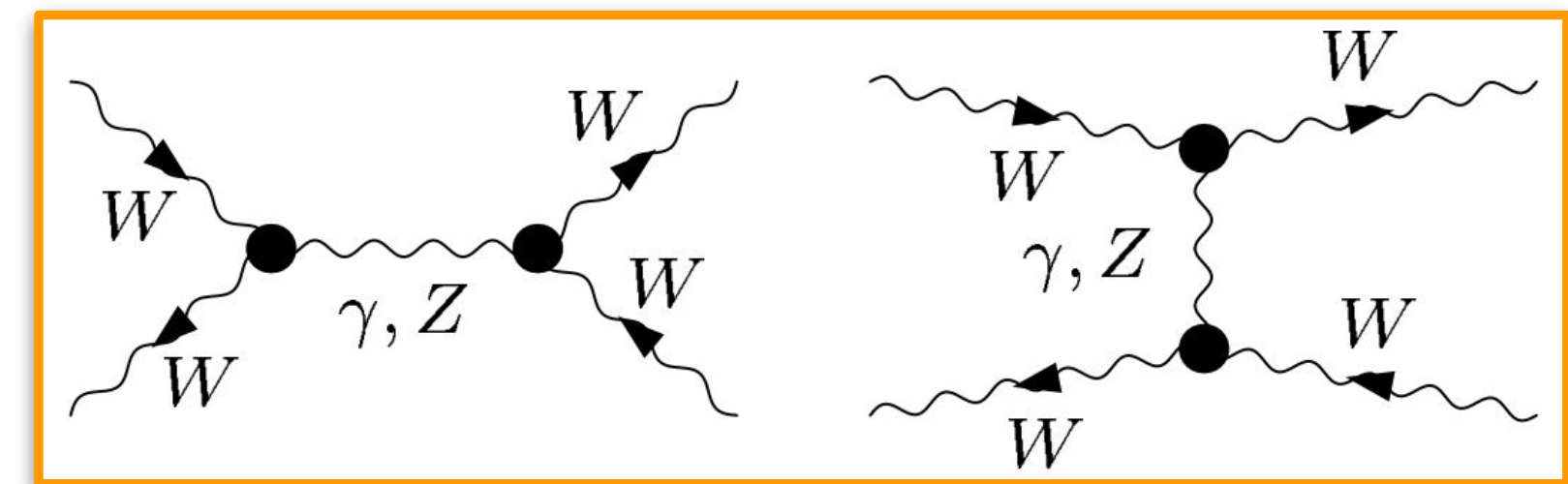
$\uparrow$
flavour

The No-Lose Theorem

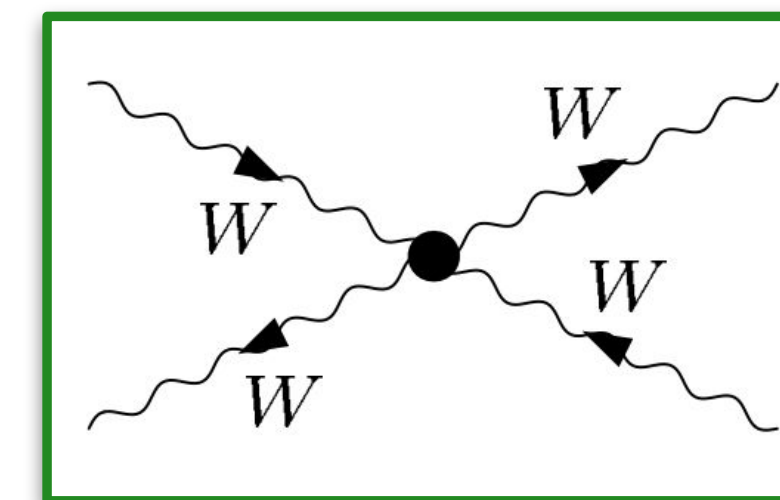


The SM Higgs boson ($4.5 \text{ GeV} < m_h < \sim 2m_W$) cancels the energy growth of purely-bosonic $V_L V_L \rightarrow V_L V_L$ scattering, preserving unitarity.

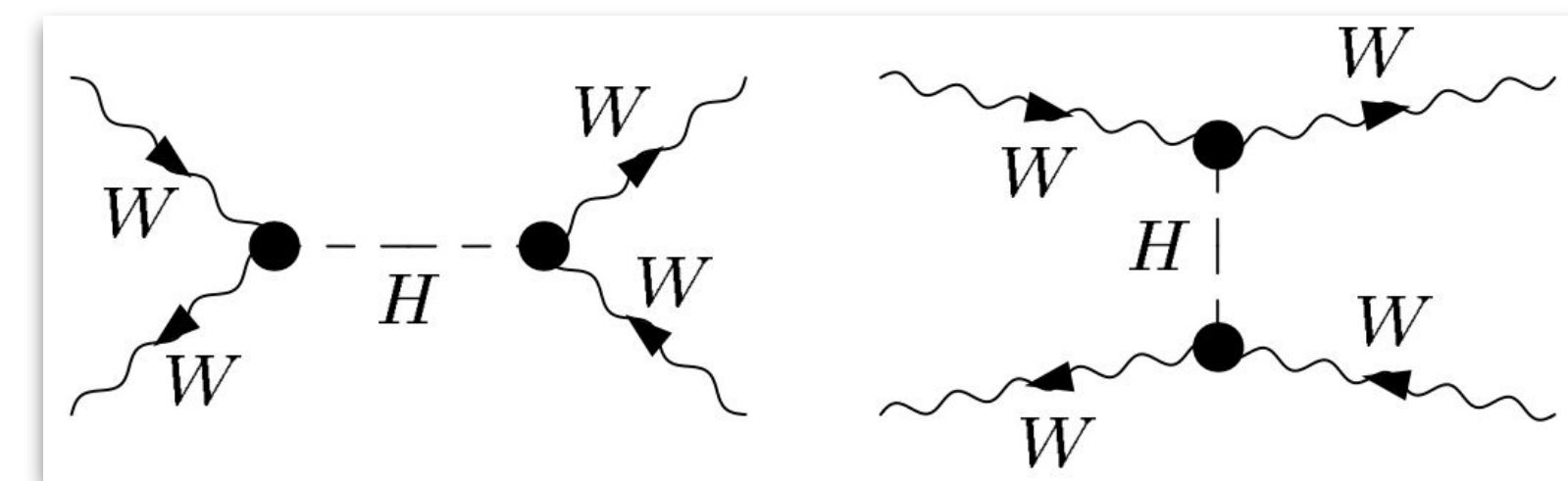
(a)



(b)



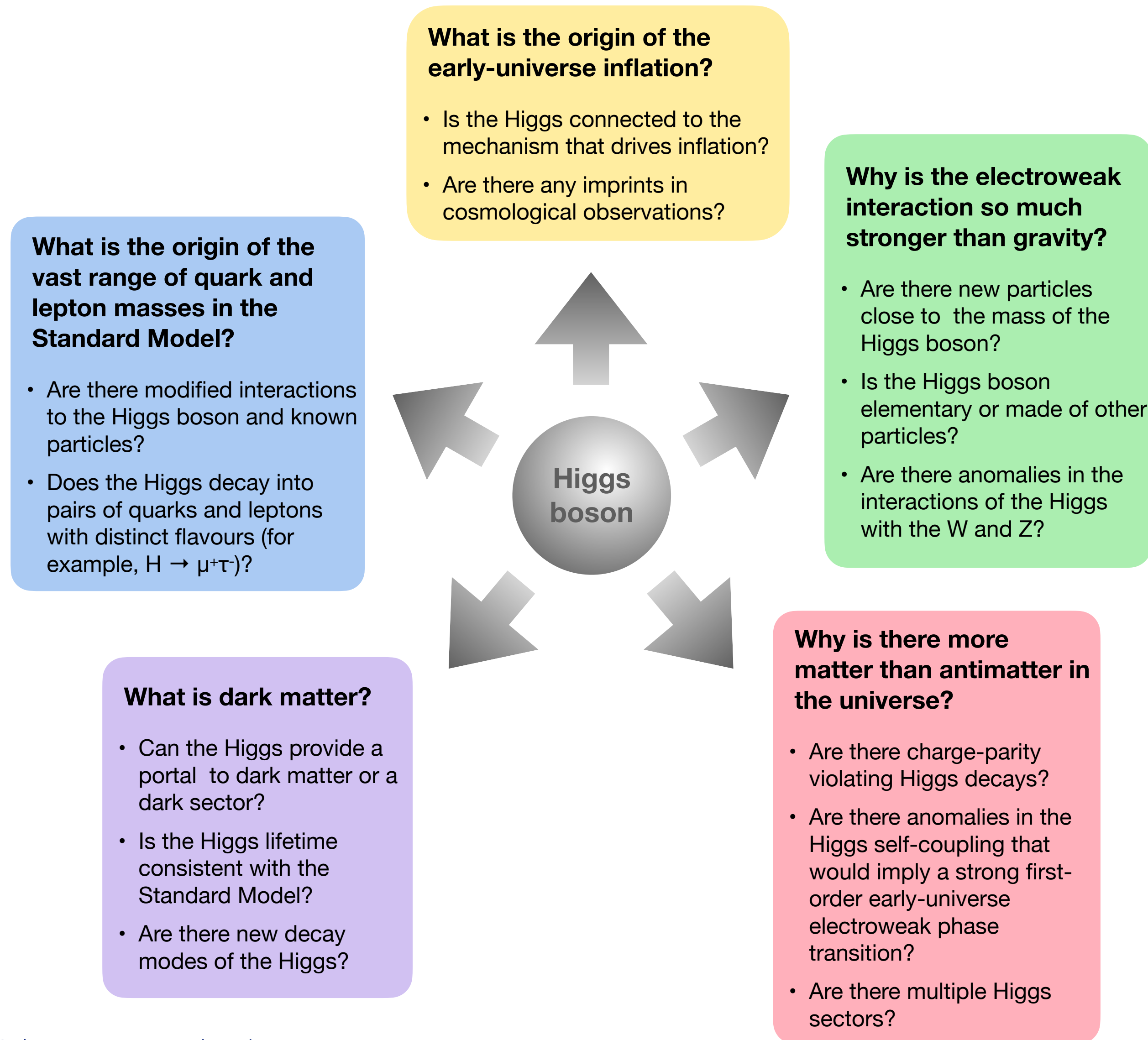
(c)



Fundamental Role

Particle whose mass is set by the interaction with the Higgs field	Role of the particle masses	Impact on everyday life	Has the Higgs-particle interaction been experimentally confirmed?
Up quark ($m_{\text{up}} \sim 2.2 \text{ MeV}/c^2$) Down quark ($m_{\text{down}} \sim 4.7 \text{ MeV}/c^2$)	Affects the mass of the proton and neutron	Differences in quark masses ($m_{\text{up}} < m_{\text{down}}$) contribute to protons (made of two up and one down quarks) being lighter than neutrons (made of one up and two down quarks). As a result, protons are stable, as required for the existence of hydrogen.	No
Electron	Atomic radius $\propto 1/m_e$	A different value of the electron mass would modify the energy levels and chemical reactions of all known elements.	No
W boson	Radioactive beta decay rate $\propto 1/m_W^4$	Many radioactive decays, and the fusion reactions that power the sun, involve the W boson. The W mass affects the rate of all of these reactions.	Yes

Open Questions



The Higgs as a candle in the dark...

- Does the Higgs couple to the 2nd/3rd generation fermions as the SM predicts?
- What else does the Higgs couple to? What is hiding in the tails of boosted Higgs production?
- Is the Higgs potential as the SM predicts?

Suddenly we are able to explore a new sector of the SM Lagrangian, there is much left to measure and surprises are not ruled out!

How Can We Study the Higgs Sector?

Phenomenology & Precision

Goal

Theory → concrete, testable predictions

Experimental observations → parameters, interactions, dynamics

Precise predictions require a detailed understanding of the theory

Fixed order amplitudes and subtraction schemes (QCD & EW)

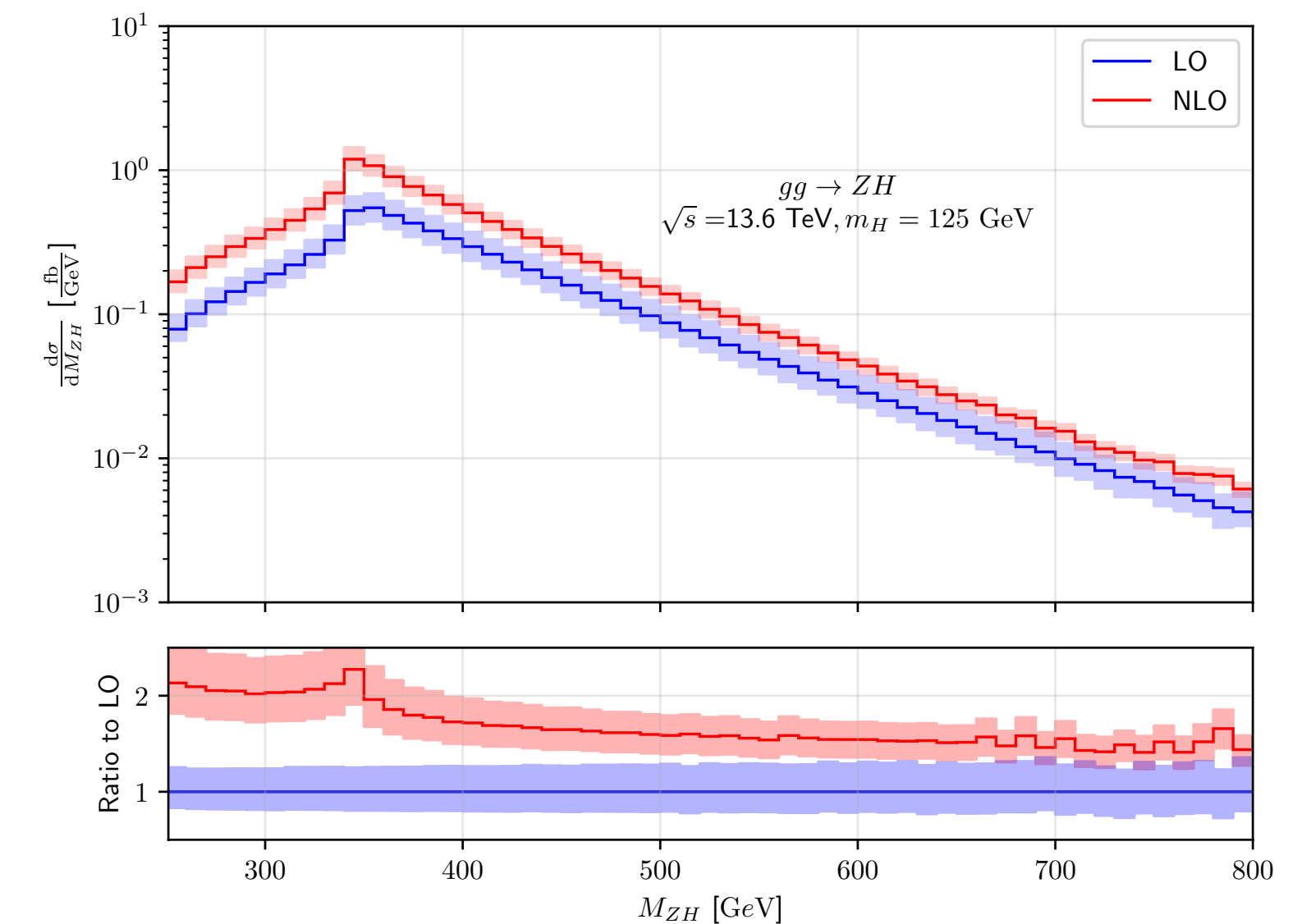
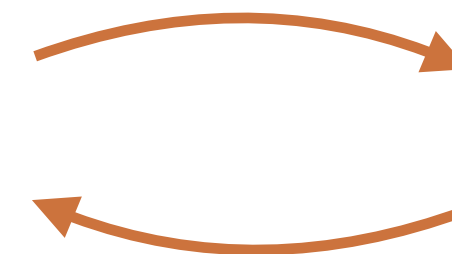
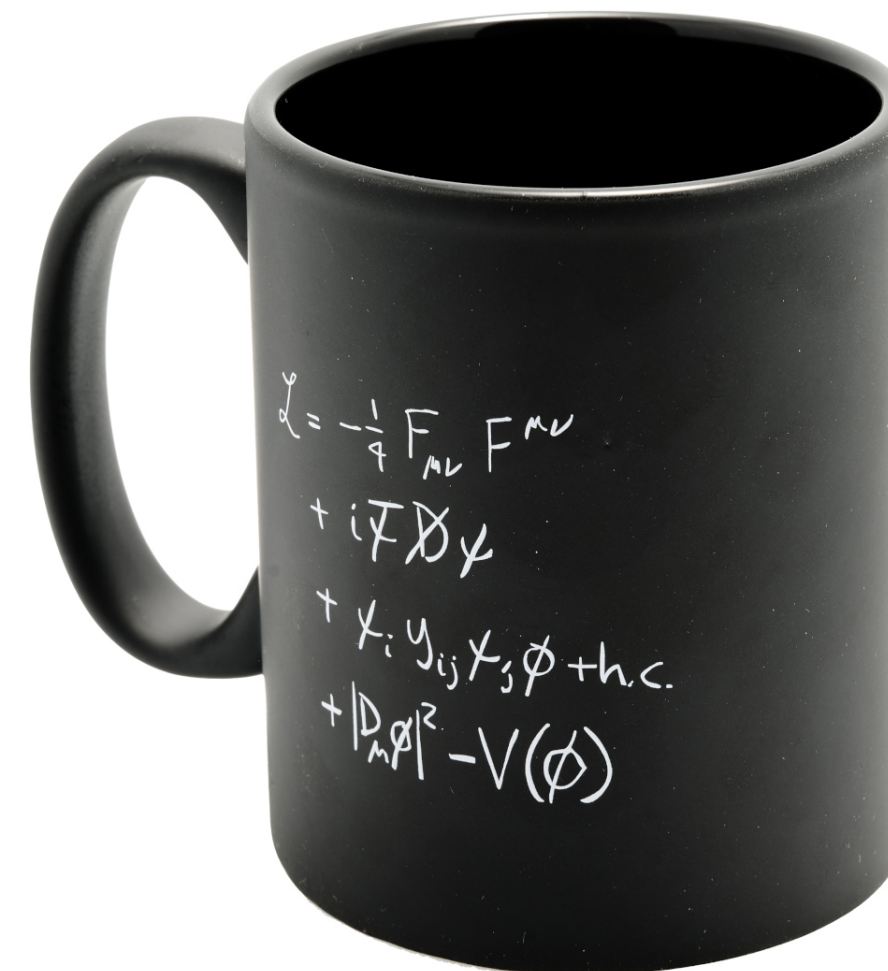
Parton Distribution Functions

Jets/Flavour

Parton Showers/Resummation

Non-perturbative aspects

For production process & backgrounds



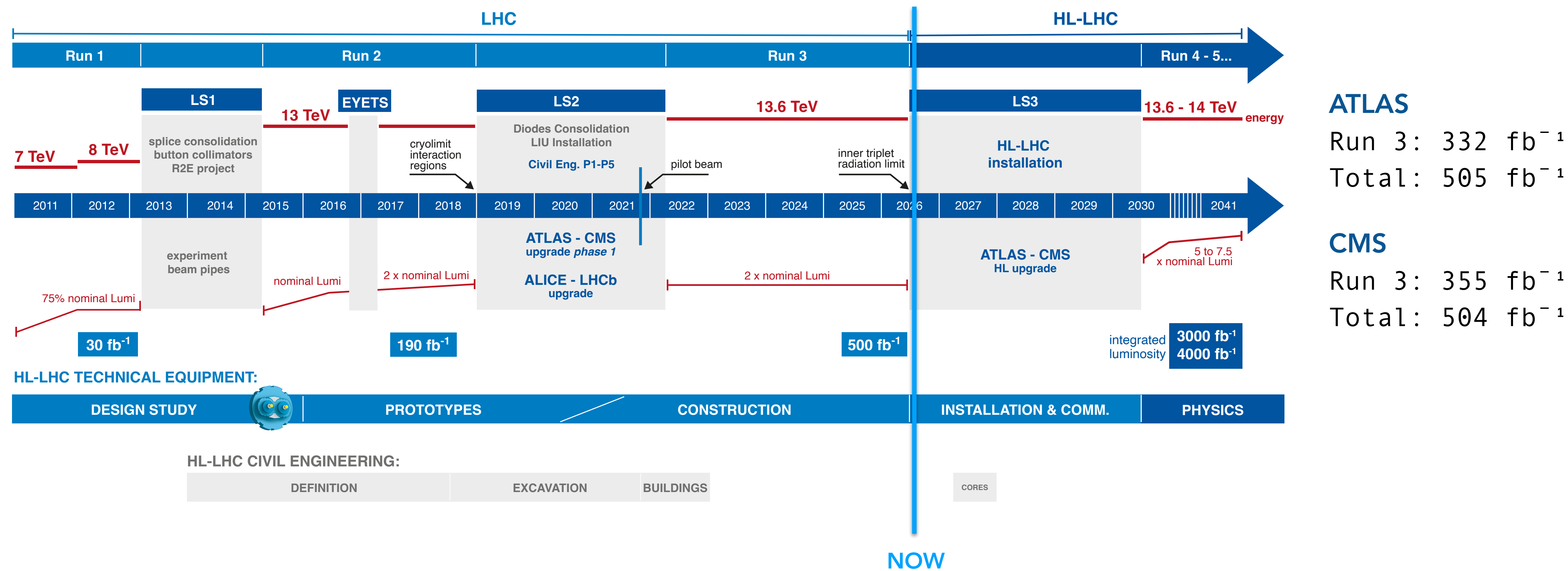
LHCHWG: Updated $gg \rightarrow ZH$ Prediction

Aveleira, Chen, Davies, Degraasi, Giardino, Gröber, Heinrich, SPJ, Kerner, Schlenk, Steinhauser, Vitti 25

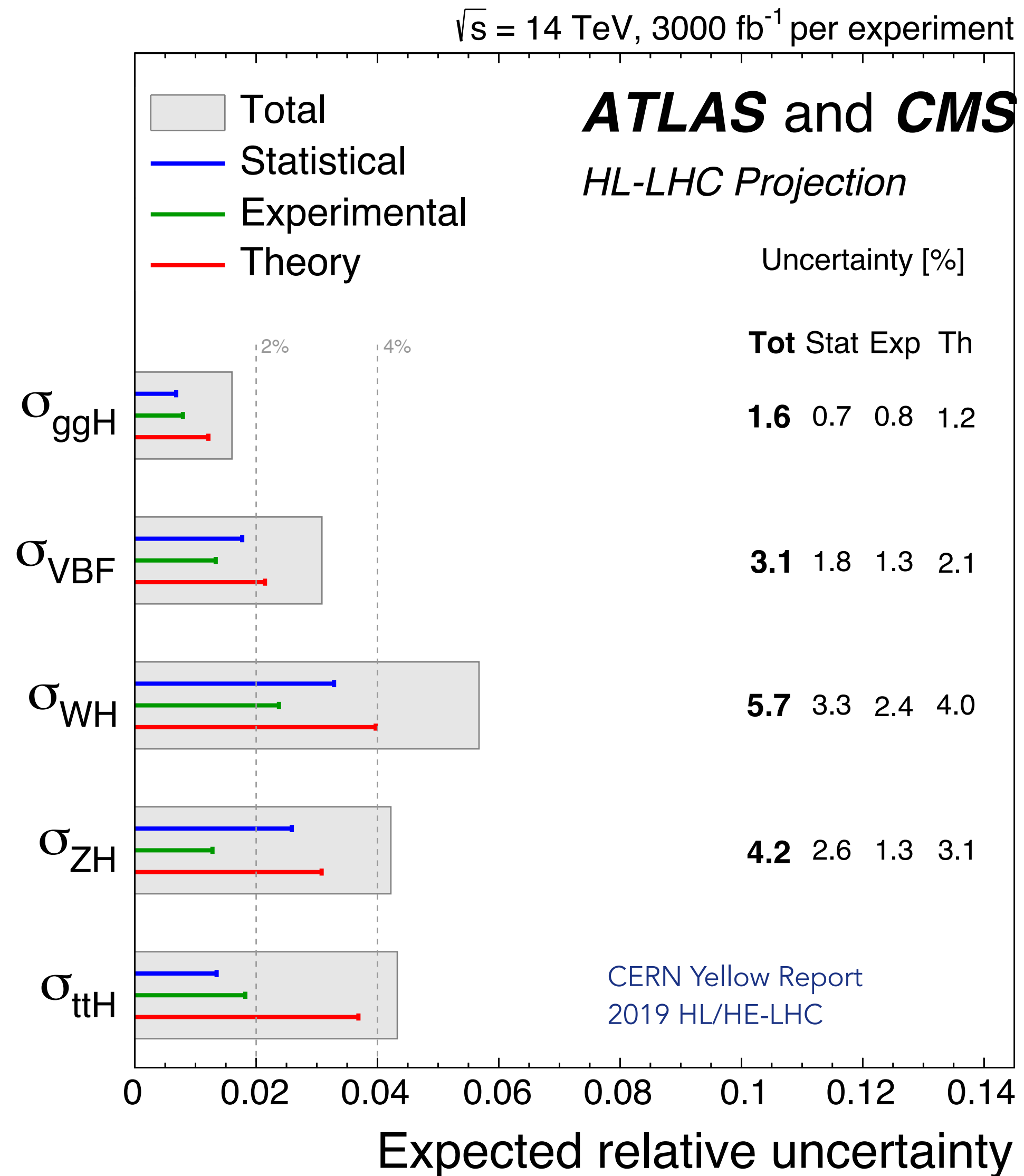
Phenomenology is the melting pot of our best description of nature and the interface between theory and experiment

LHC & HL-LHC

At 05:52 on 27 June 2026, the final protons of the Large Hadron Collider's 3rd data-taking period circulated...



So long LHC, and thanks for all the Higgs!



HL-LHC construction now underway
~10x integrated luminosity of LHC
(LHC ~0.5 ab⁻¹, HL-LHC: 3-4 ab⁻¹)

- 1) Experimental projection is pessimistic considering current performance
- 2) Plot shown assumes reduction by factor 2 of today's uncertainties

Theory uncertainty is expected to dominate HL-LHC Higgs physics

Higgs Interactions

QCD to Standard Model

Working with the full SM is significantly more cumbersome (and error prone) than we are used to in the QCD community

QCD Vertices

```
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[ bbar , b , g         ; gs='1', gw='0']
```



SM Vertices (R_ξ Gauge)

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Technical Challenges

New diagram topologies

Many mass scales

QCD/EW effects potentially relevant

Wider Conceptual Challenges

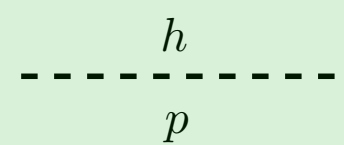
γ_5 with higher-order EW corrections

E.G: von Manteuffel, Stöckinger, Weißwange 25; Stöckinger, Weißwange 23

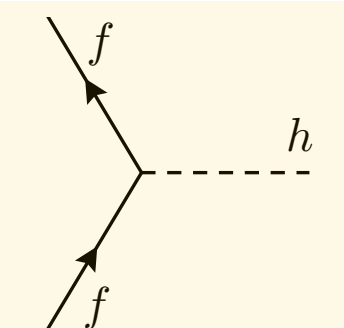
EW Input Schemes

Tadpole Schemes

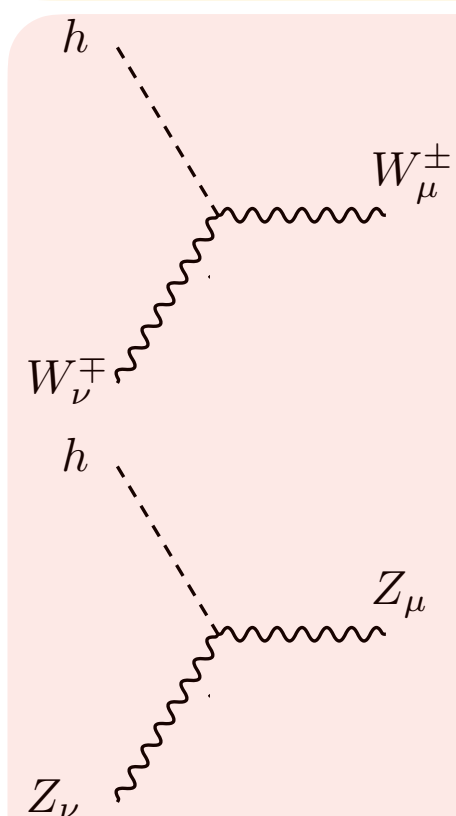
Feynman Rules

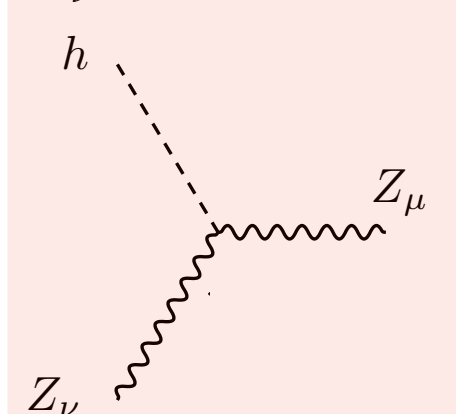


$$\frac{i}{p^2 - m_h^2 + i\epsilon}$$

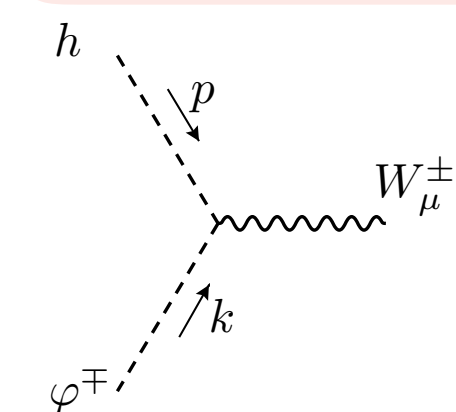


$$-i \frac{g}{2} \frac{m_f}{m_W}$$

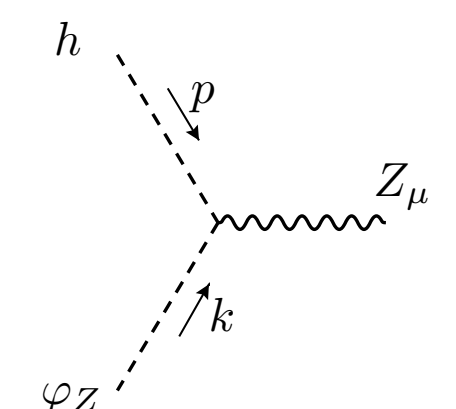


$$ig m_W g_{\mu\nu}$$


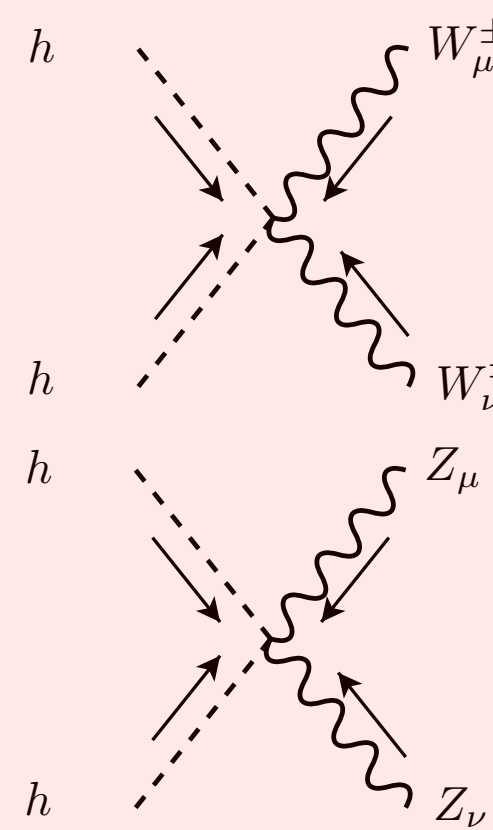
$$i \frac{g}{\cos \theta_W} m_Z g_{\mu\nu}$$

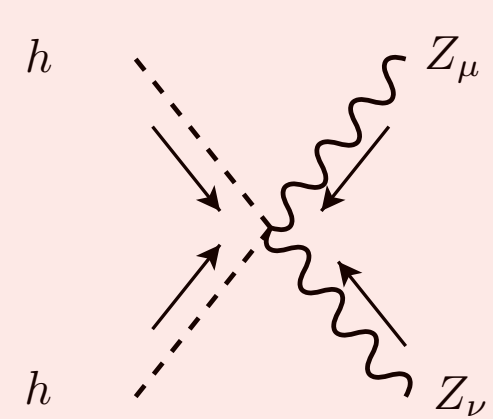


$$\pm \frac{i}{2} \eta g (k - p)_\mu$$

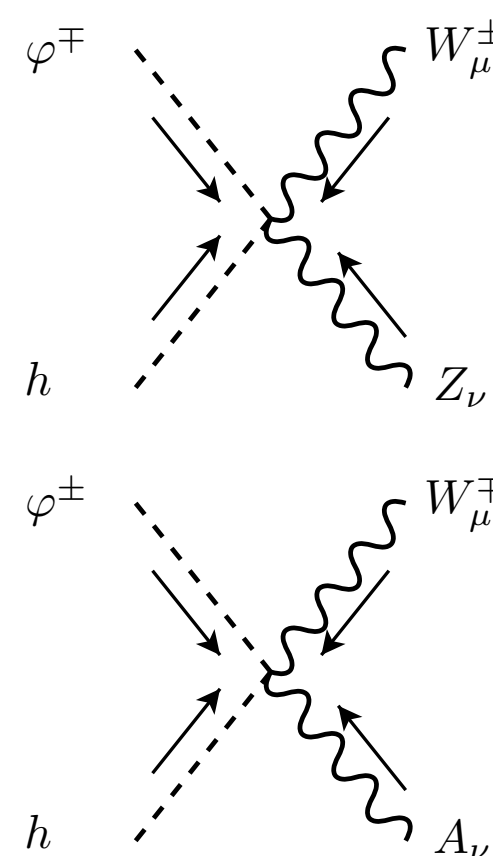


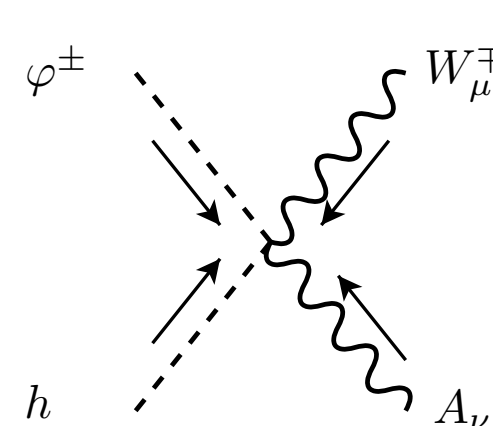
$$- \eta \eta_Z \frac{g}{2 \cos \theta_W} (k - p)_\mu$$



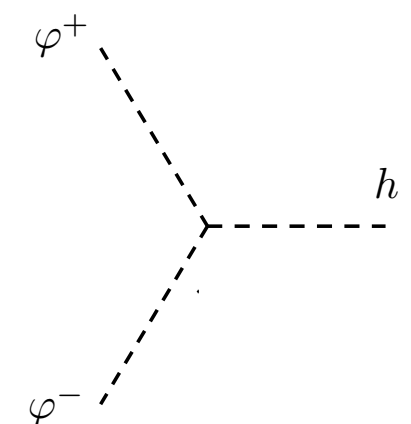
$$\frac{i}{2} g^2 g_{\mu\nu}$$


$$\frac{i}{2 \cos^2 \theta_W} g^2 g_{\mu\nu}$$

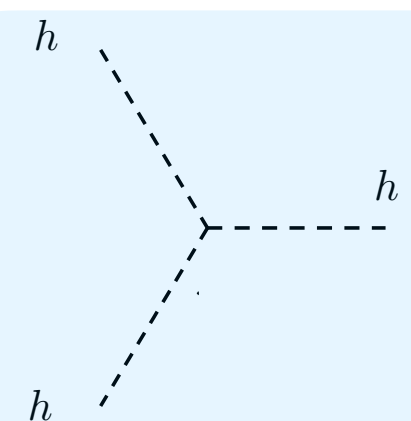


$$-i \eta_Z g^2 \frac{\sin^2 \theta_W}{2 \cos \theta_W} g_{\mu\nu}$$


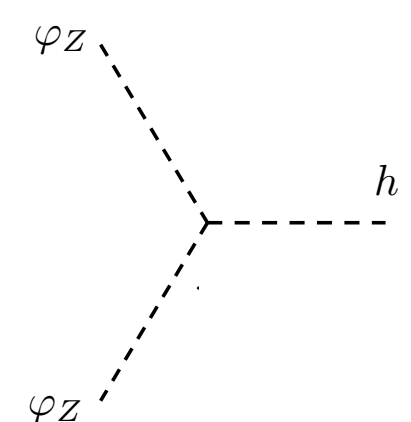
$$\frac{i}{2} \eta_e \eta e g g_{\mu\nu}$$



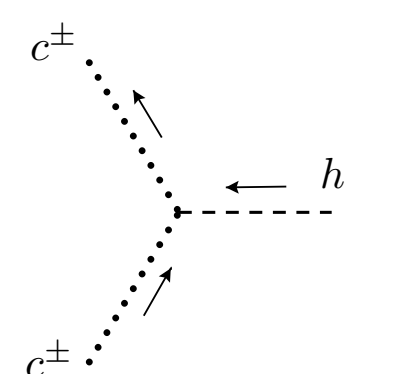
$$-\frac{i}{2} g \frac{m_h^2}{m_W}$$



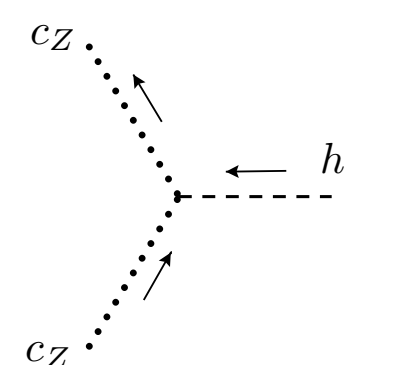
$$-\frac{3}{2} i g \frac{m_h^2}{m_W}$$



$$-\frac{i}{2} g \frac{m_h^2}{m_W}$$

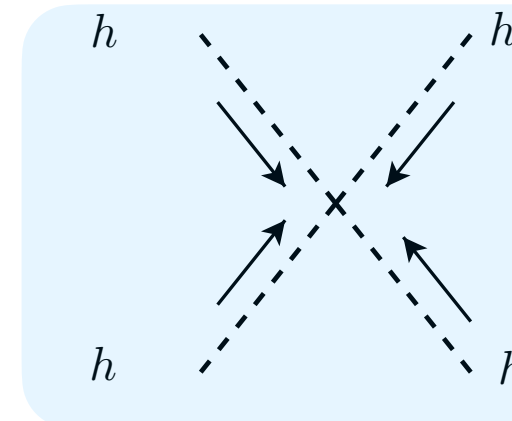


$$-\frac{i}{2} \eta_G g \xi_W m_W$$

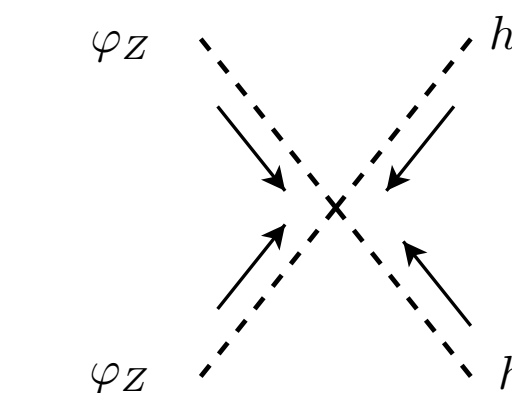


$$- \eta_G \frac{ig}{2 \cos \theta_W} \xi_Z m_Z$$

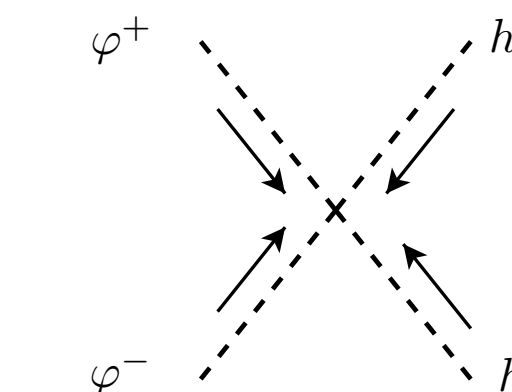
$$g = 2 \frac{m_W}{v}$$



$$-\frac{3}{4} i g^2 \frac{m_h^2}{m_W^2}$$

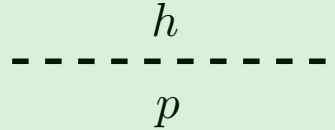


$$-\frac{i}{4} g^2 \frac{m_h^2}{m_W^2}$$

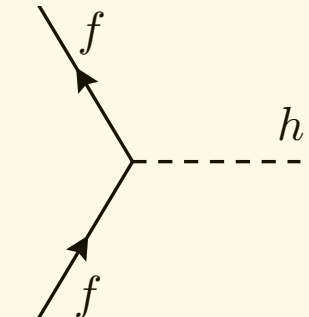


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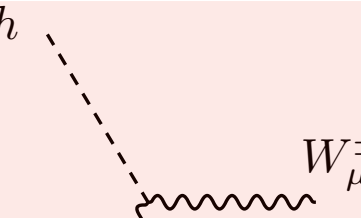
Feynman Rules

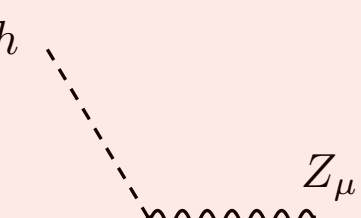


$$\frac{i}{p^2 - m^2 + i\epsilon}$$

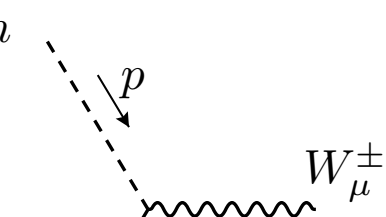


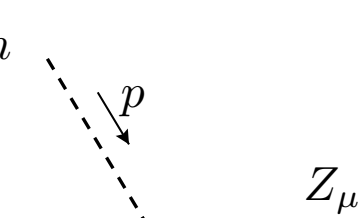
$$-i \frac{g}{2} \frac{m_f}{m_W}$$



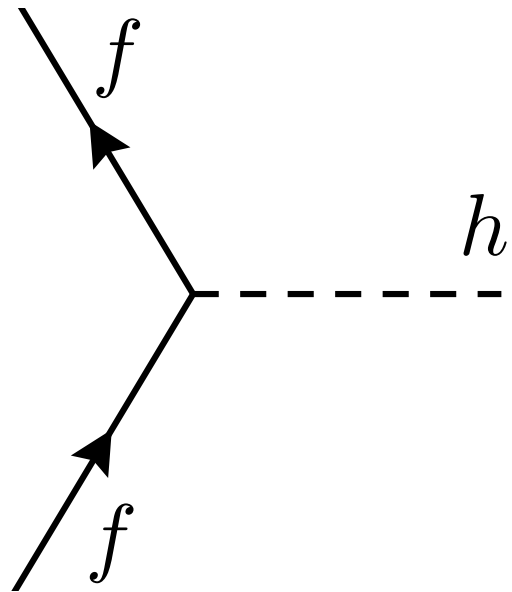
$$ig m_f$$


$$i \frac{g}{\cos \theta_W}$$



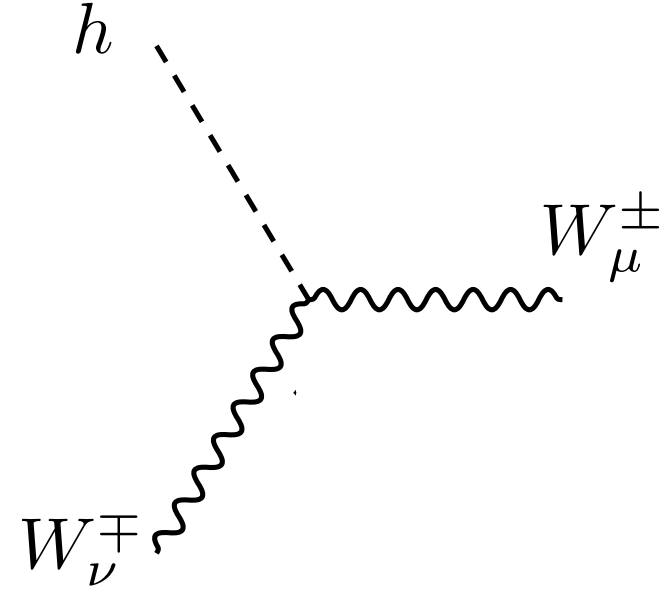
$$\pm \frac{i}{2} \eta g$$


$$- \eta \eta_Z \frac{g}{2 \cos \theta_W}$$



$$-i \frac{g}{2} \frac{m_f}{m_W} = -i \frac{m_f}{v}$$

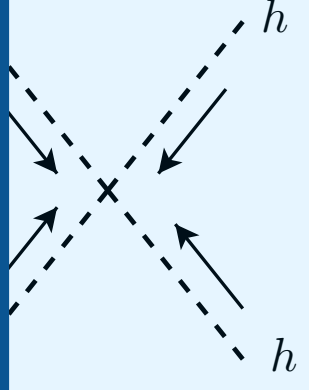
Proportional to quark mass !



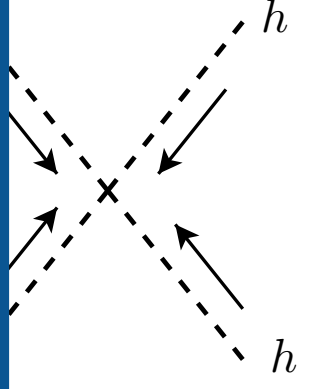
$$ig m_W g_{\mu\nu} = i 2 \frac{m_W^2}{v} g_{\mu\nu}$$

Proportional to boson mass² !

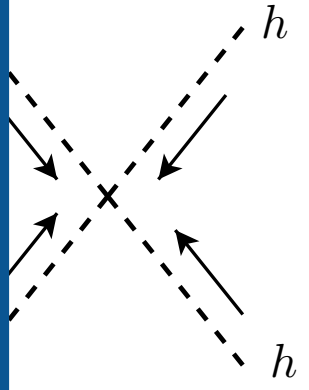
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$$- \frac{3}{4} i g^2 \frac{m_h^2}{m_W^2}$$

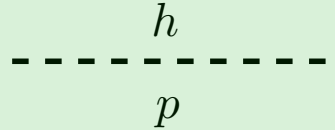


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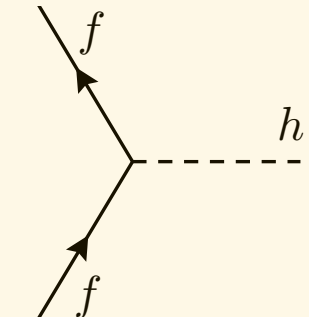


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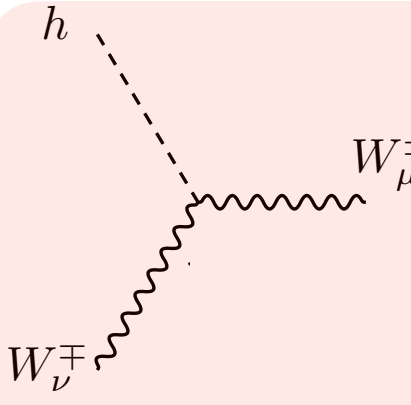
Feynman Rules

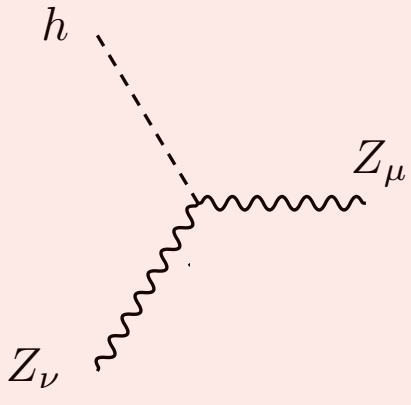


$$\frac{i}{p^2 - m_h^2 + i\epsilon}$$

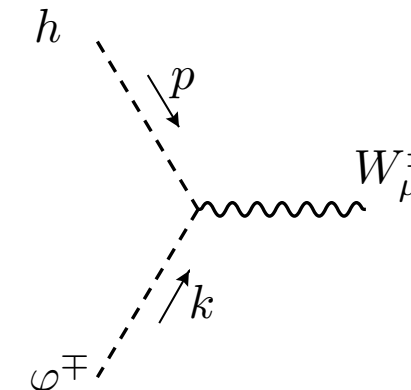


$$-i \frac{g}{2} \frac{m_f}{m_h}$$

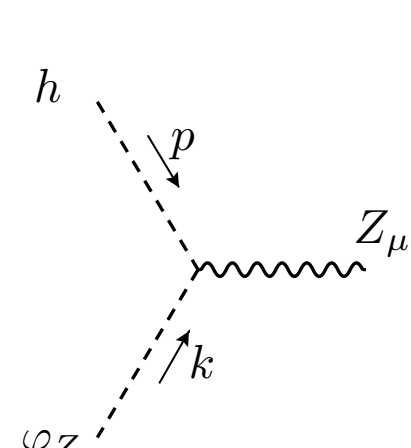


$$ig m_W$$


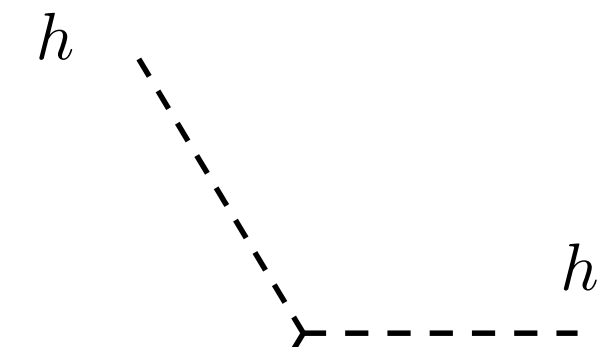
$$i \frac{g}{\cos \theta_W}$$



$$\pm \frac{i}{2} \eta g$$

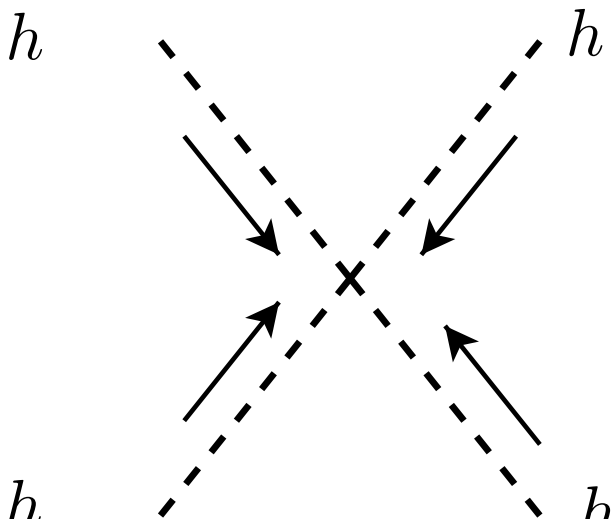


$$- \eta \eta_Z \frac{g}{2 \cos \theta_W}$$



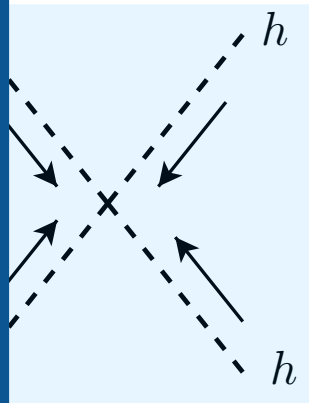
$$-\frac{3}{2} ig \frac{m_h^2}{m_W} = -3i \frac{m_h^2}{v}$$

**In the SM:
determined by
Higgs mass and vev!**

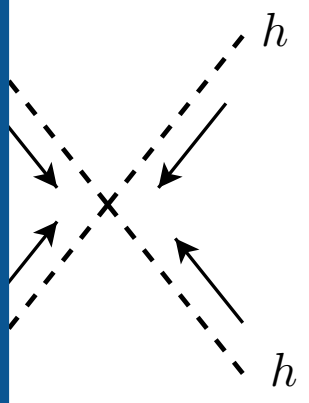


$$-\frac{3}{4} ig^2 \frac{m_h^2}{m_W^2} = -3i \frac{m_h^2}{v^2}$$

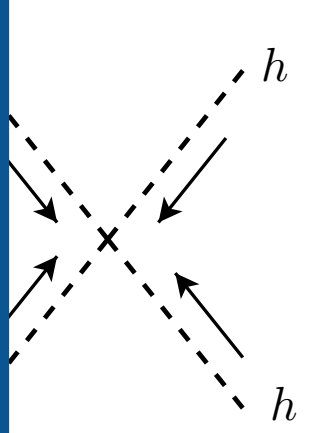
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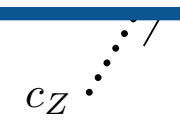
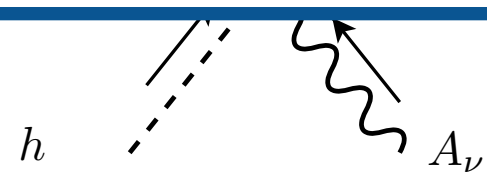
$$-\frac{3}{4} i g^2 \frac{m_h^2}{m_W^2}$$



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Higgs Couplings

Let's consider what freedom we have in the Higgs sector of the Standard Model

$$D_\mu \Phi = \left[\partial_\mu + i\eta \frac{g}{\sqrt{2}} (\tau^+ W_\mu^+ + \tau^- W_\mu^-) + i\eta \frac{g}{2} \tau_3 W_\mu^3 + i\eta' \frac{g'}{2} B_\mu \right] \Phi$$

$$\mathcal{L}_{\text{Higgs}} = \left(D_\mu \Phi \right)^\dagger D_\mu \Phi - V(\Phi)$$

$$V(\Phi) = -\mu^2 \Phi^\dagger \Phi + \lambda (\Phi^\dagger \Phi)^2$$

EW symmetry
breaking

$$\mu^2 = \frac{m_h^2}{2}, \quad \lambda = \frac{1}{2} \frac{m_h^2}{v^2}$$

Higgs self-coupling is not a free parameter!

$$V(\Phi) = -\frac{m_h^2}{2} H^2 + \frac{m_h^2}{2v} H^3 + \frac{m_h^2}{8v^2} H^4$$

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Couplings fixed by gauge invariance $(g, g') \leftrightarrow (m_W, m_Z)$

$$\left(D_\mu \Phi \right)^\dagger D_\mu \Phi$$

$$\frac{1}{8} g^2 v^2 W_\mu^3 W^{\mu 3} + \frac{1}{8} g'^2 v^2 B_\mu B^\mu - \frac{1}{4} \eta \eta' g g' v^2 W_\mu^3 B^\mu + \dots$$

$$\sim g m_W W^{+\mu} W_\mu^- H + g \frac{m_Z}{\cos \theta_W} Z^\mu Z_\mu H$$

No free parameters!

Q: What happens if we try to adjust the HVV or HHVV couplings (i.e. κ framework)?

Higgs Couplings

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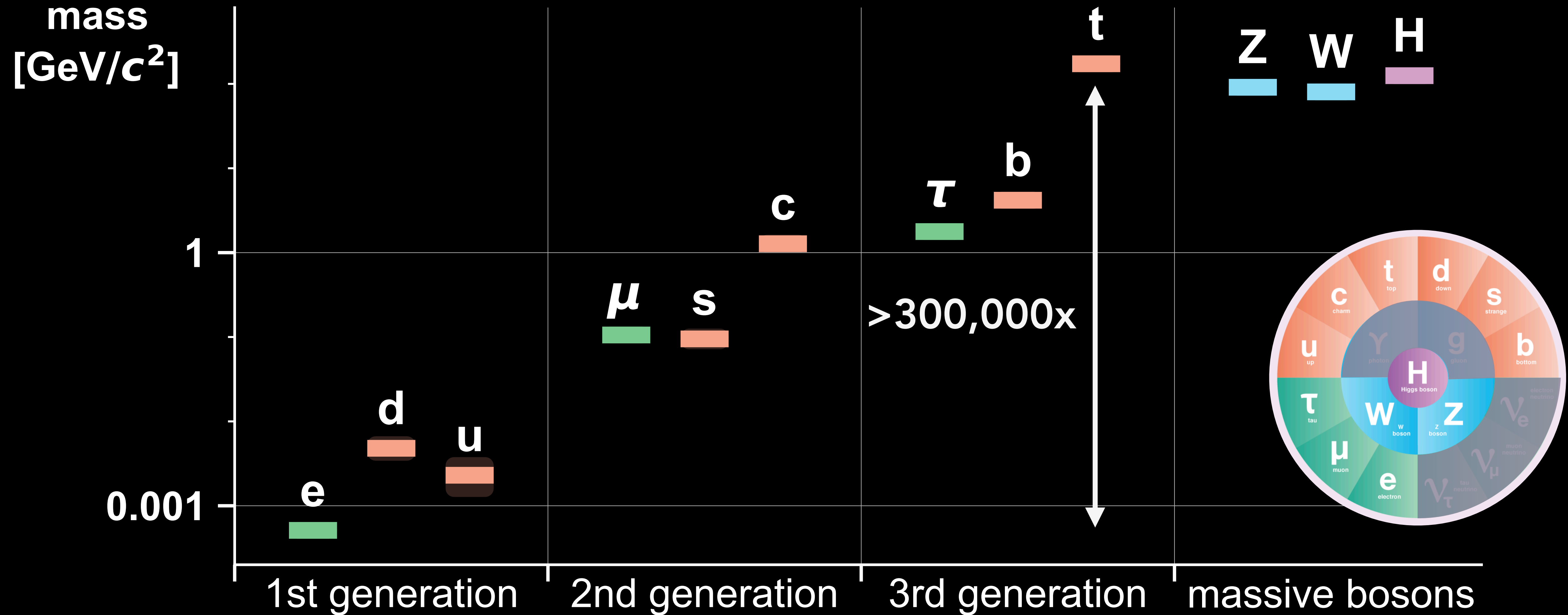
$$\sim g m_W W^{+\mu} W_\mu^- H + g \frac{m_Z}{\cos \theta_W} Z^\mu Z_\mu H$$

No free parameters!

Q: What happens if we try to adjust the HVV or HHVV couplings (i.e. κ framework)?

A: Breaks local gauge invariance (and also renormalisability of EW corrections)

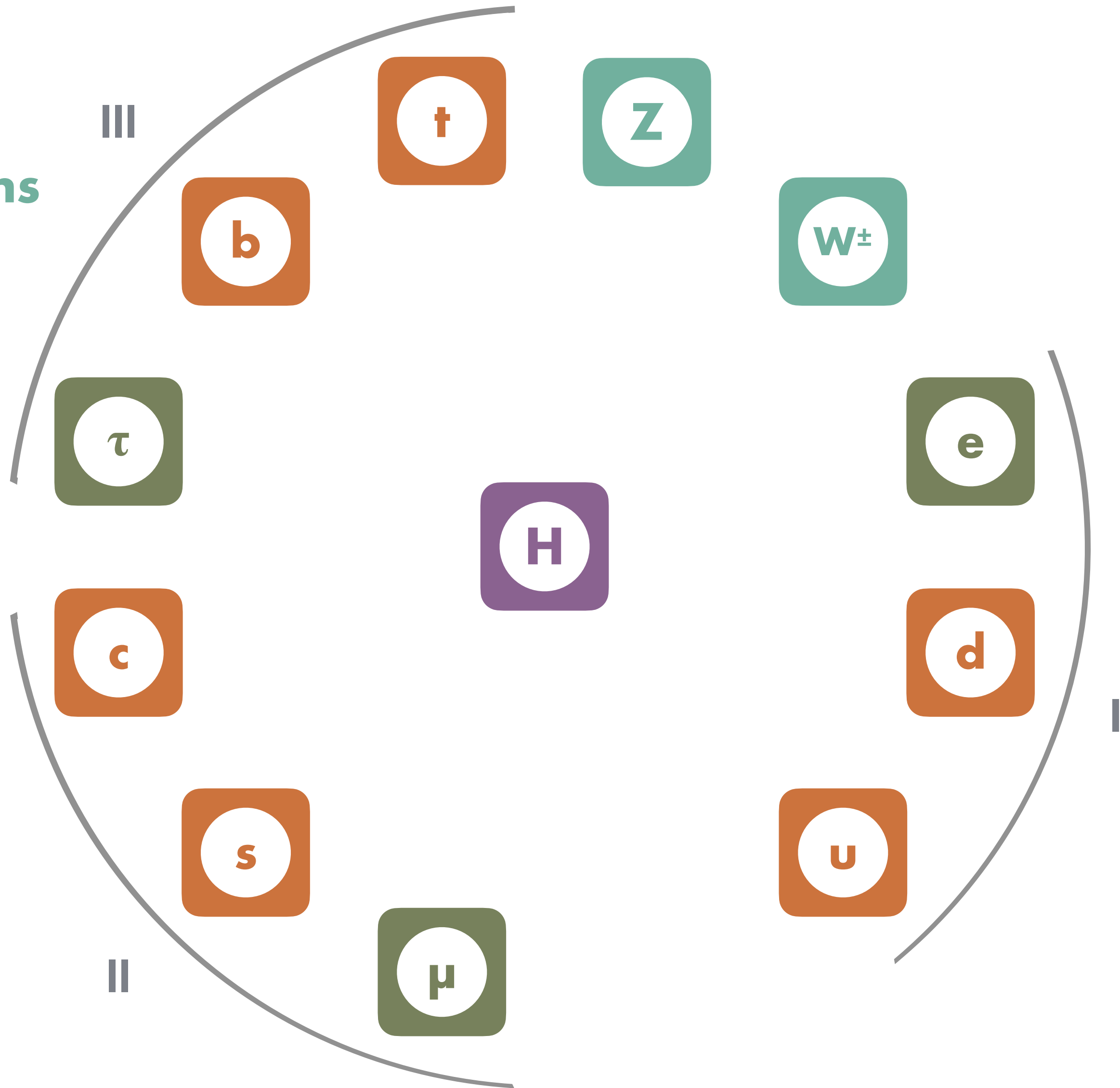
Standard Model massive particles (except ν)



quarks

leptons

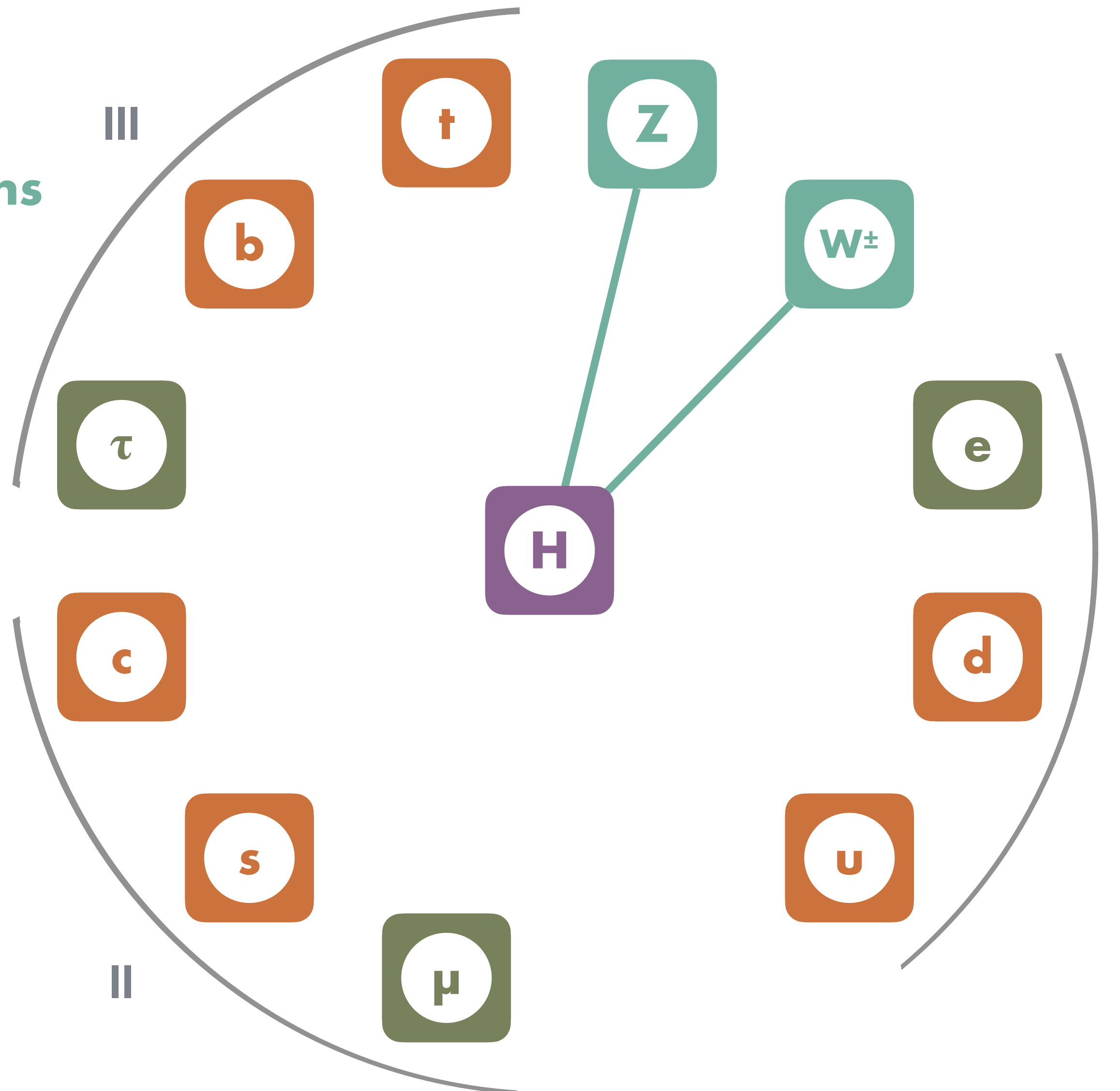
gauge bosons



quarks

leptons

gauge bosons



$\mathcal{L} =$

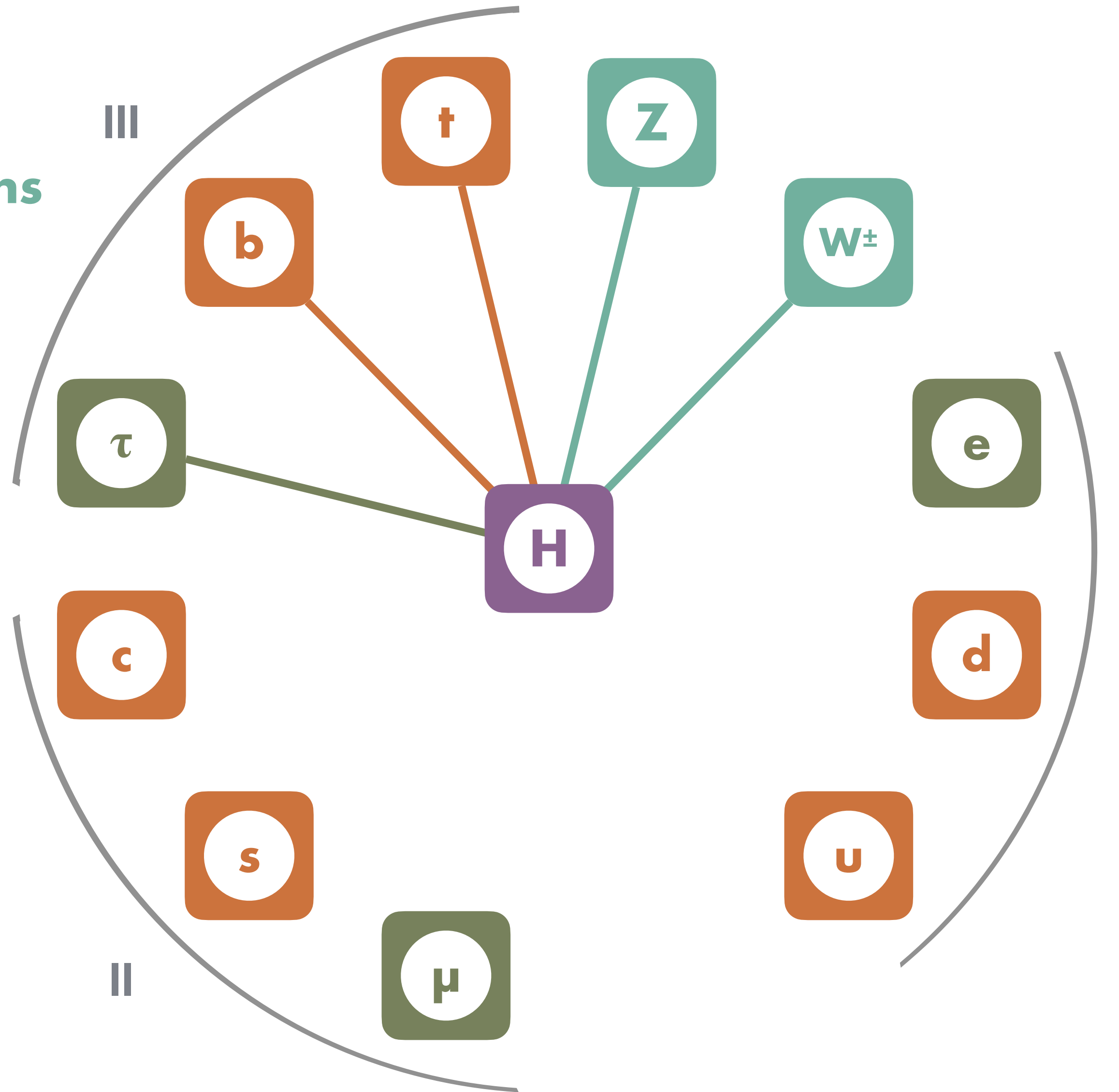
$+ |D_\mu \phi|^2$ **Gauge Interactions**

~5-10% @ Run 2 LHC

quarks

leptons

gauge bosons



$\mathcal{L} =$

$+ |D_\mu \phi|^2$ **Gauge Interactions**

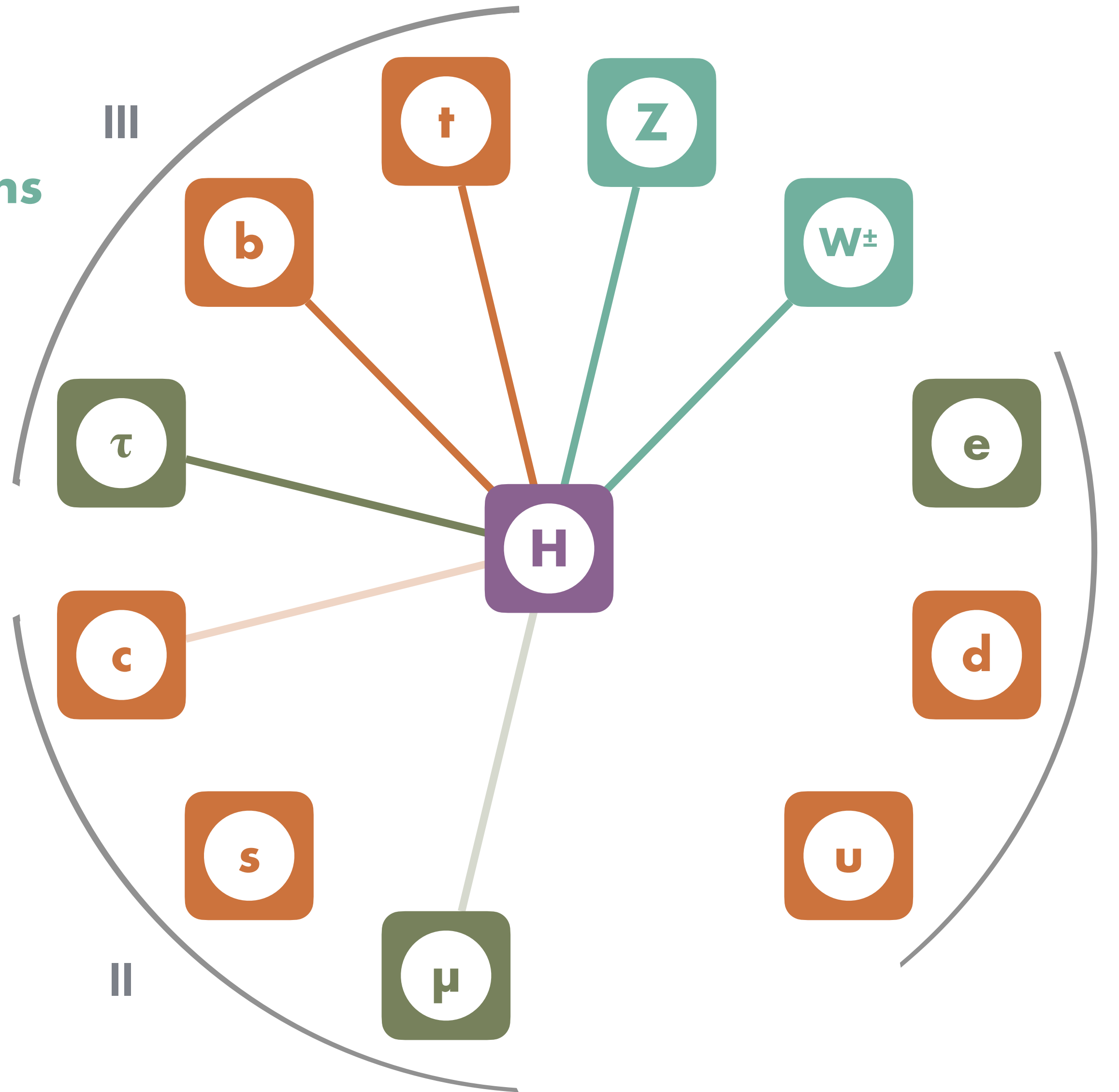
$+ \psi_i y_{ij} \psi_j \phi$ **Yukawa Interactions**
fermion masses $\leftrightarrow$ flavour

III ~10-20% @ Run 2 LHC

quarks

leptons

gauge bosons



$\mathcal{L} =$

$+ |D_\mu \phi|^2$ **Gauge Interactions**

$+ \psi_i y_{ij} \psi_j \phi$ **Yukawa Interactions**
fermion masses ↔ flavour

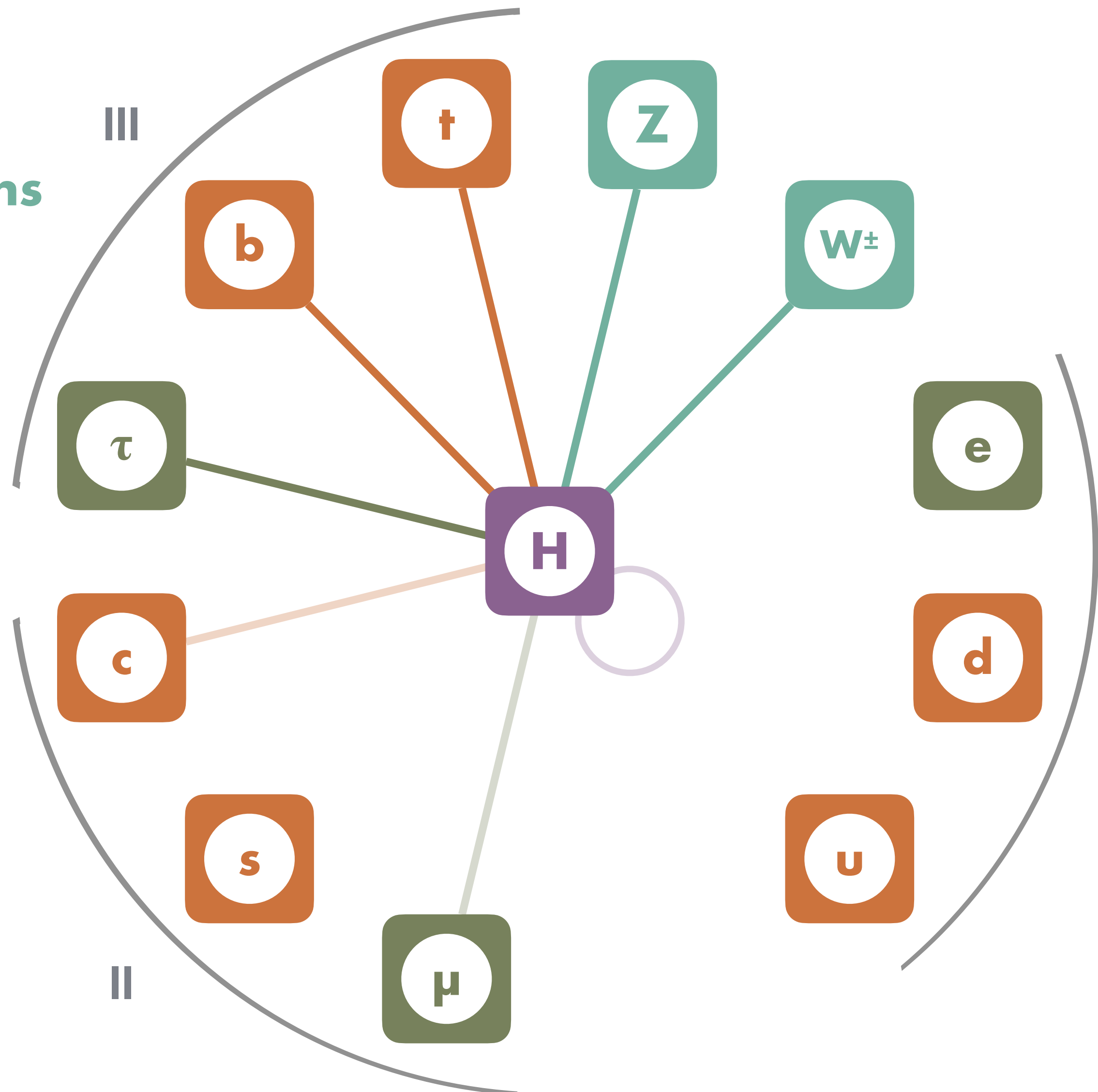
III ~10-20% @ Run 2 LHC

II ~60% / first hints

quarks

leptons

gauge bosons



$$\mathcal{L} =$$

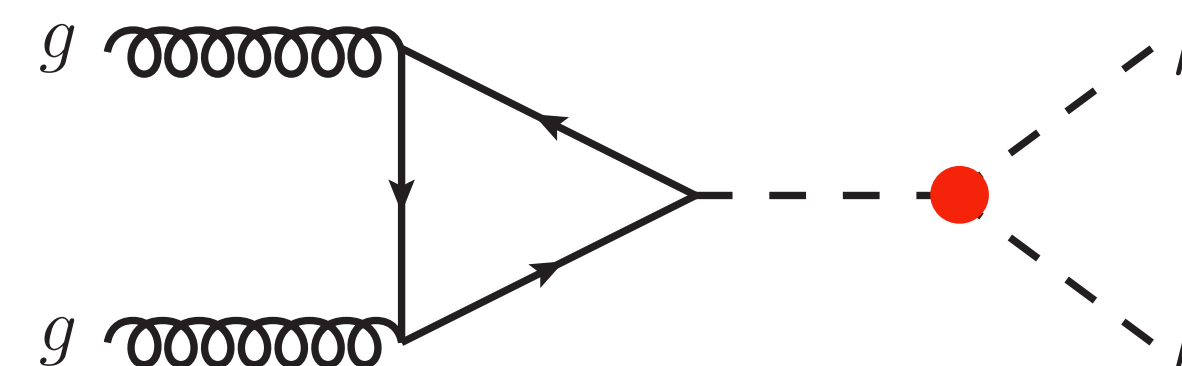
$$+ |D_\mu \phi|^2 \quad \text{Gauge Interactions}$$

$$+ \psi_i y_{ij} \psi_j \phi \quad \text{Yukawa Interactions}$$

fermion masses ↔ flavour

$$- V(\phi) \quad \text{Higgs Potential}$$

self-coupling ↔ vacuum stability

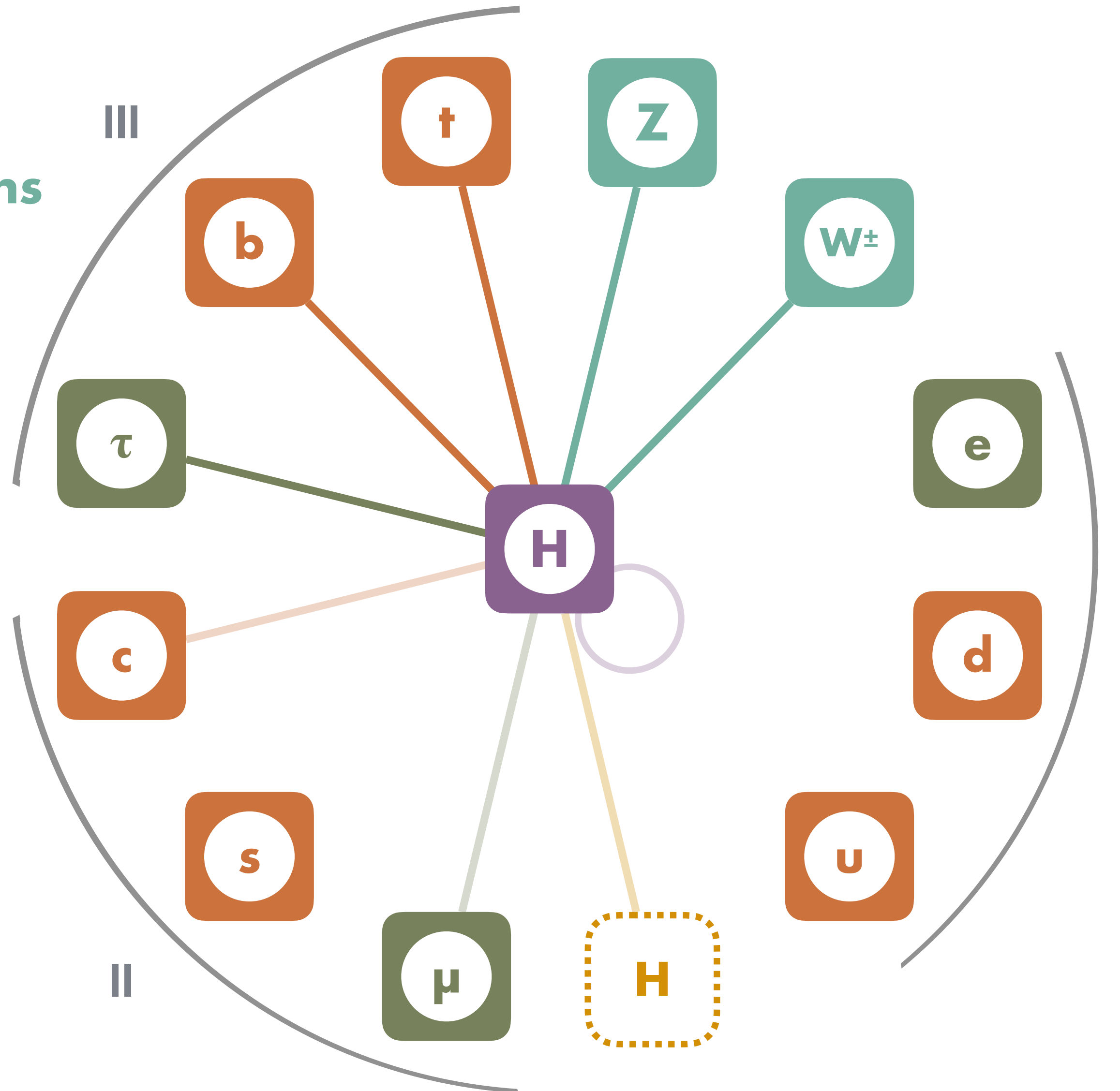


Direct measurement of the Higgs self-coupling would be a fundamental discovery

quarks

leptons

gauge bosons



$\mathcal{L} =$

$+ |D_\mu \phi|^2$ **Gauge Interactions**

$+ \psi_i y_{ij} \psi_j \phi$ **Yukawa Interactions**
fermion masses ↔ flavour

$- V(\phi)$ **Higgs Potential**
self-coupling ↔ vacuum stability

$+ \dots$ **Surprises**



Precision

Introduction to Precision

Fixed Order Calculations

→ Marco (Today)

Integral Reduction

Computing Integrals

Sampling Phase-space

Subtraction

Process Simulation & Modelling

→ Christian (Yesterday)

Resummation

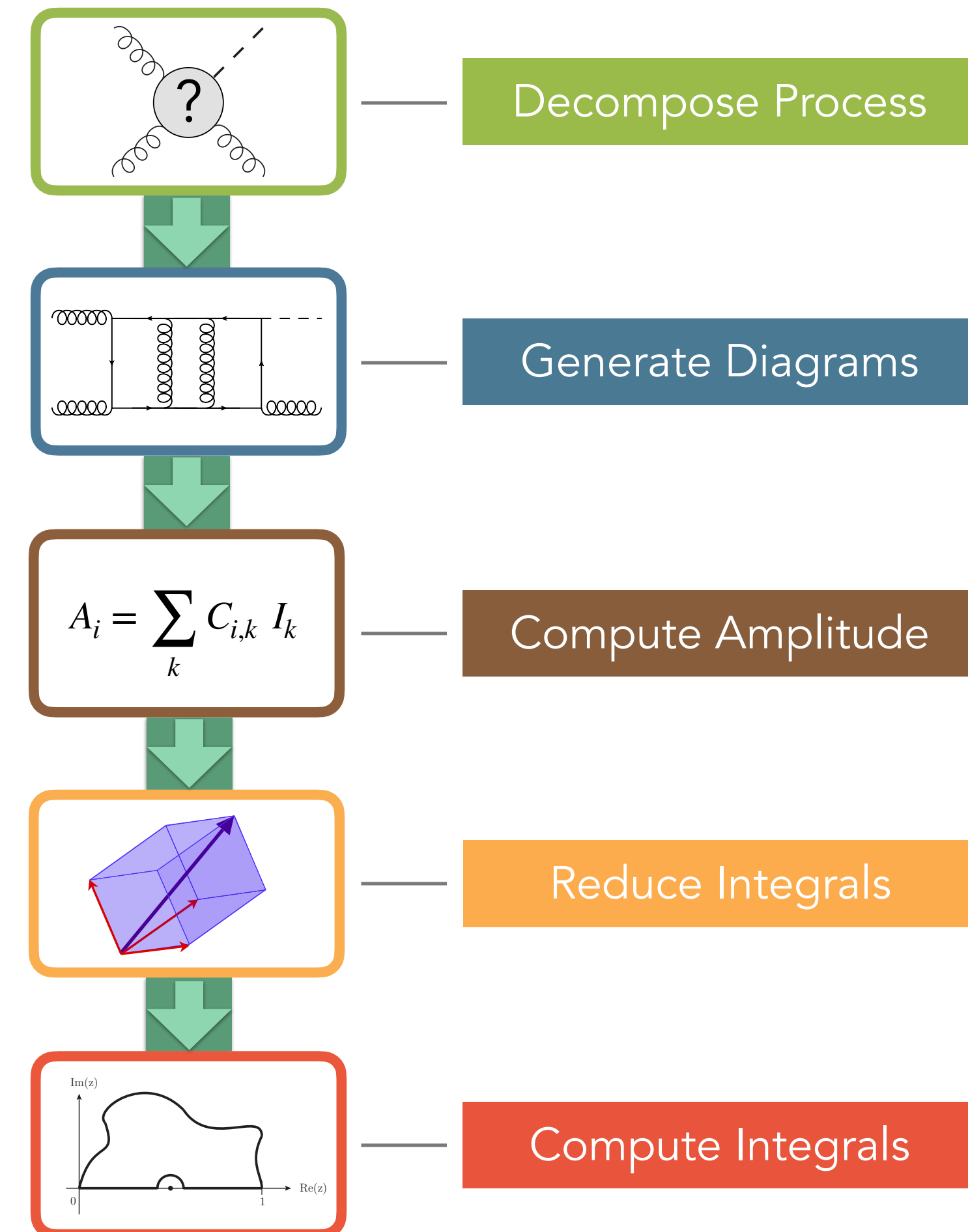
Parton Showers

Negative Events

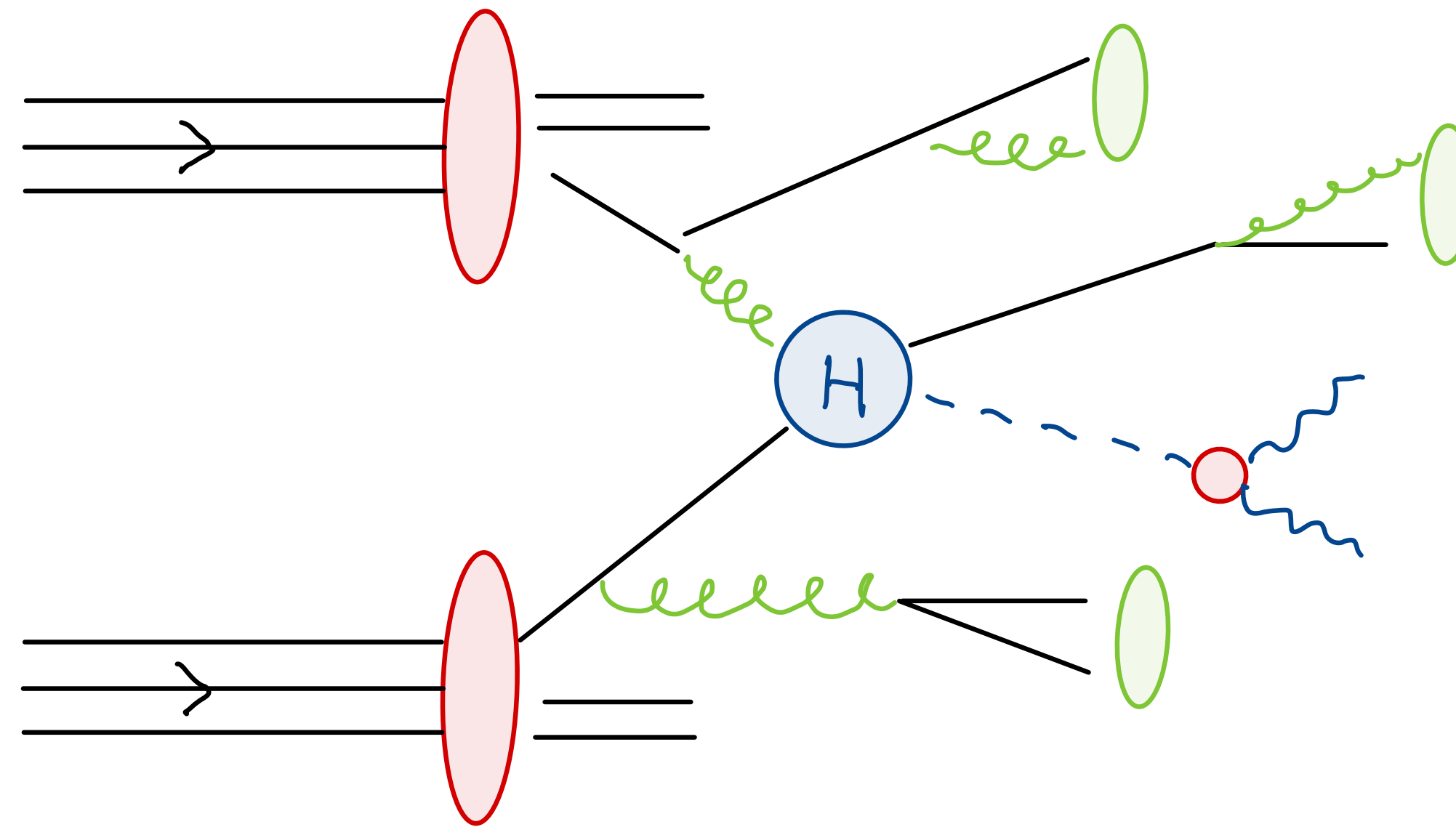
Building Predictions

Parton Distribution Functions (PDFs) → Thomas (Yesterday)

Estimating Uncertainties



Improving Precision



- + Parton Shower
- + Resummation
- + Hadronisation
- + Underlying Event

$$d\sigma = \int dx_a dx_b f_a(x_a) f_b(x_b) d\hat{\sigma}_{ab}(x_a, x_b) F_J + \mathcal{O}((\Lambda/Q)^m)$$

↑

Parton Distribution
Functions (PDFs)

↑

Hard Scattering
Matrix Element

↑

Non-perturbative
effects ~ few %

With $\alpha_s \sim 0.1$, expect: NLO ~ 10% correction, NNLO ~ 1% correction

Higgs channels are important exceptions, receive much larger corrections!

Perturbation Theory

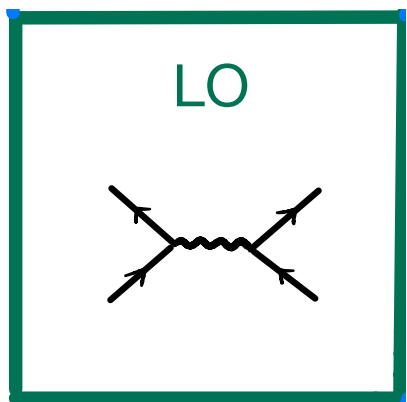
At sufficiently high energies $\alpha_s \sim 0.1$ can expand

$$\sigma = \alpha^j \alpha_s^k \left(\sigma^{LO} + \alpha_s \sigma^{NLO} + \alpha_s^2 \sigma^{NNLO} + \alpha_s^3 \sigma^{N3LO} + \dots + \alpha \sigma^{\text{NLO (EW)}} + \dots + \alpha \alpha_s \sigma^{\text{NNLO (QCD-EW)}} \right)$$

↑ loops

$\alpha \sim 0.01$ EW effects can be enhanced (thresholds/high-energy)

$$\sigma^{LO} = \int_n d\sigma^B$$



(unresolved) real radiation →

Figure ($e^+e^- \rightarrow \text{jets}$) : G. Heinrich

Perturbation Theory

At sufficiently high energies $\alpha_s \sim 0.1$ can expand

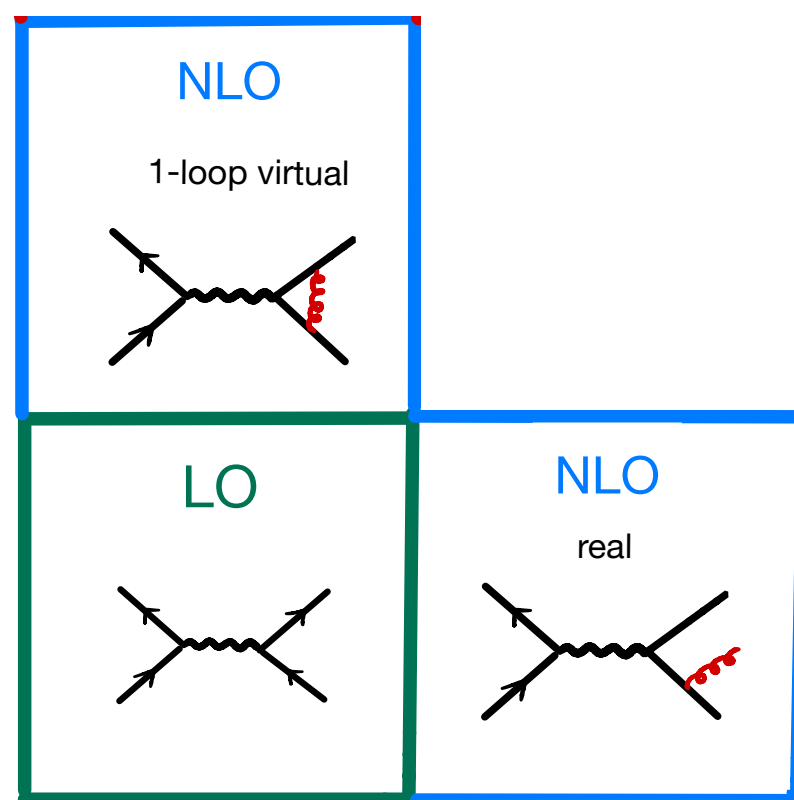
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$$\sigma^{NLO} = \int_n d\sigma^V + \int_{n+1} d\sigma^R$$



(unresolved) real radiation →

Figure ($e^+e^- \rightarrow \text{jets}$) : G. Heinrich

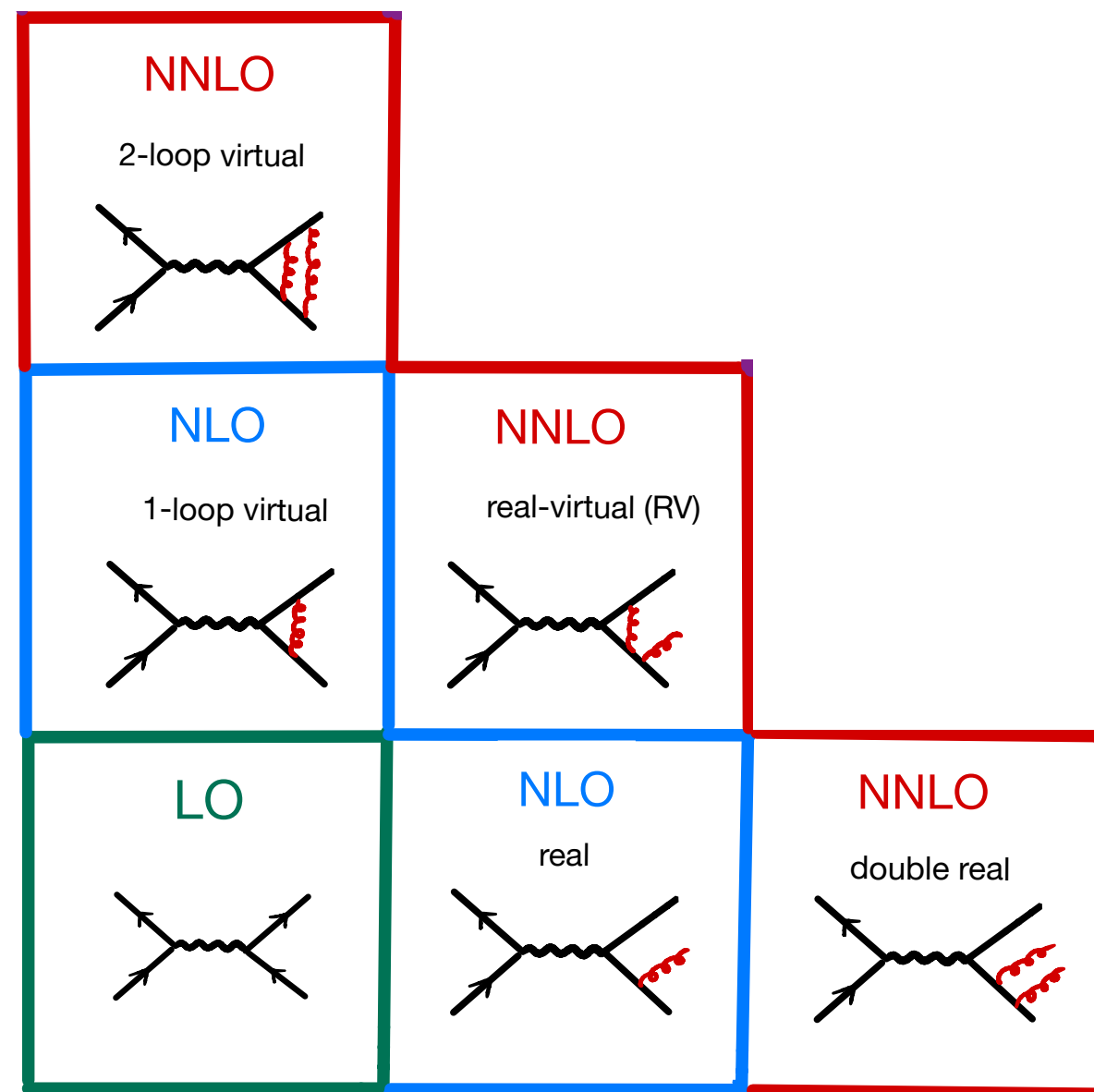
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$$\sigma^{LO} = \int_n d\sigma^B$$

$$\sigma^{NLO} = \int_n d\sigma^V + \int_{n+1} d\sigma^R$$

$$\sigma^{NNLO} = \int_n d\sigma^{VV} + \int_{n+1} d\sigma^{RV} + \int_{n+2} d\sigma^{RR}$$

Figure ($e^+e^- \rightarrow \text{jets}$) : G. Heinrich

Perturbation Theory

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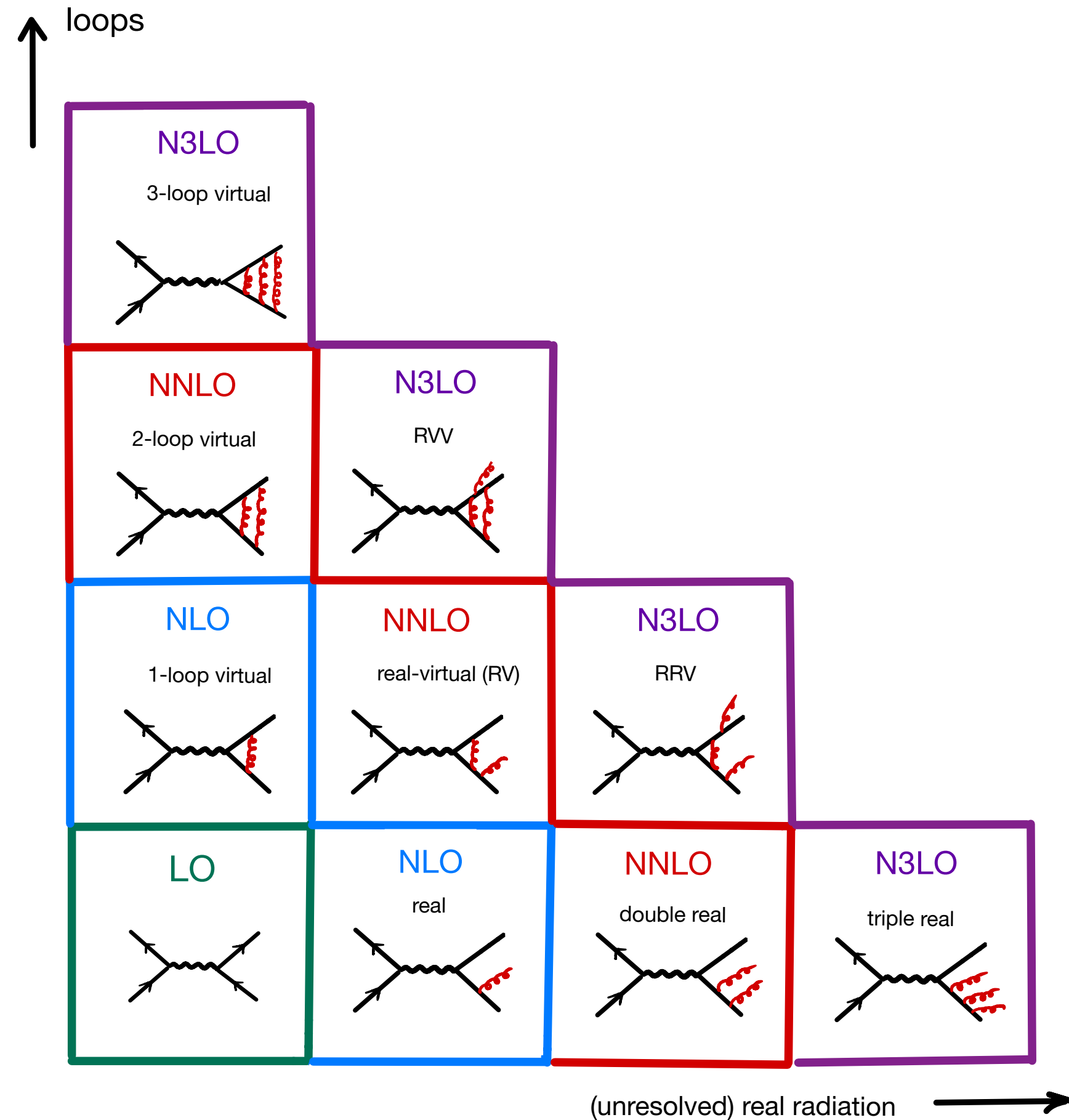


Figure ($e^+e^- \rightarrow \text{jets}$) : G. Heinrich

$$\begin{aligned} \sigma^{LO} &= \int_n d\sigma^B \\ \sigma^{NLO} &= \int_n d\sigma^V + \int_{n+1} d\sigma^R \\ \sigma^{NNLO} &= \int_n d\sigma^{VV} + \int_{n+1} d\sigma^{RV} + \int_{n+2} d\sigma^{RR} \\ &\vdots \end{aligned}$$

Beyond LO each piece separately Infrared (IR) divergent

$$d = 4 - 2\epsilon$$

Q: What about the UV divergences?

Why is Precision Important?

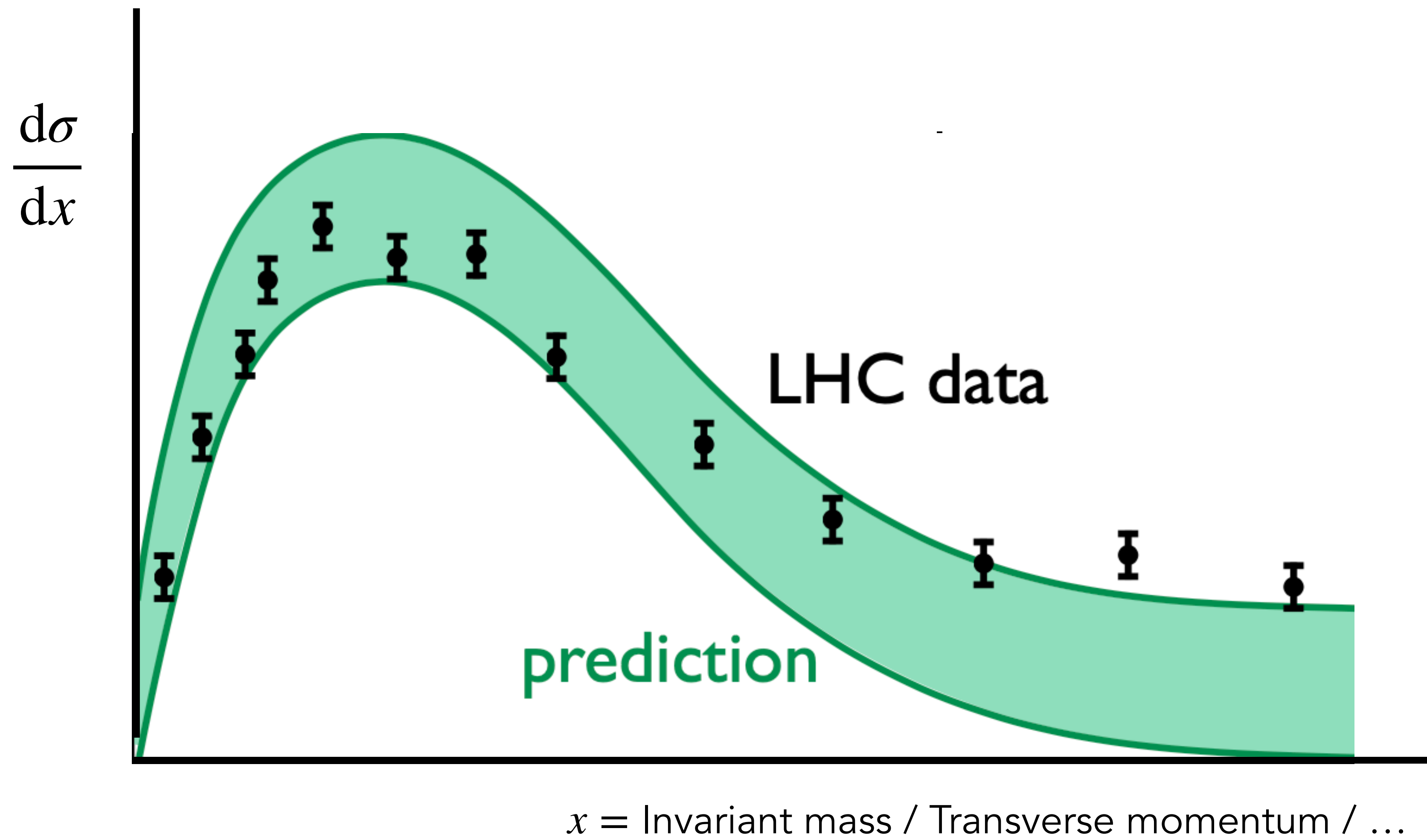


Figure: G. Zanderighi / M. Wiesemann

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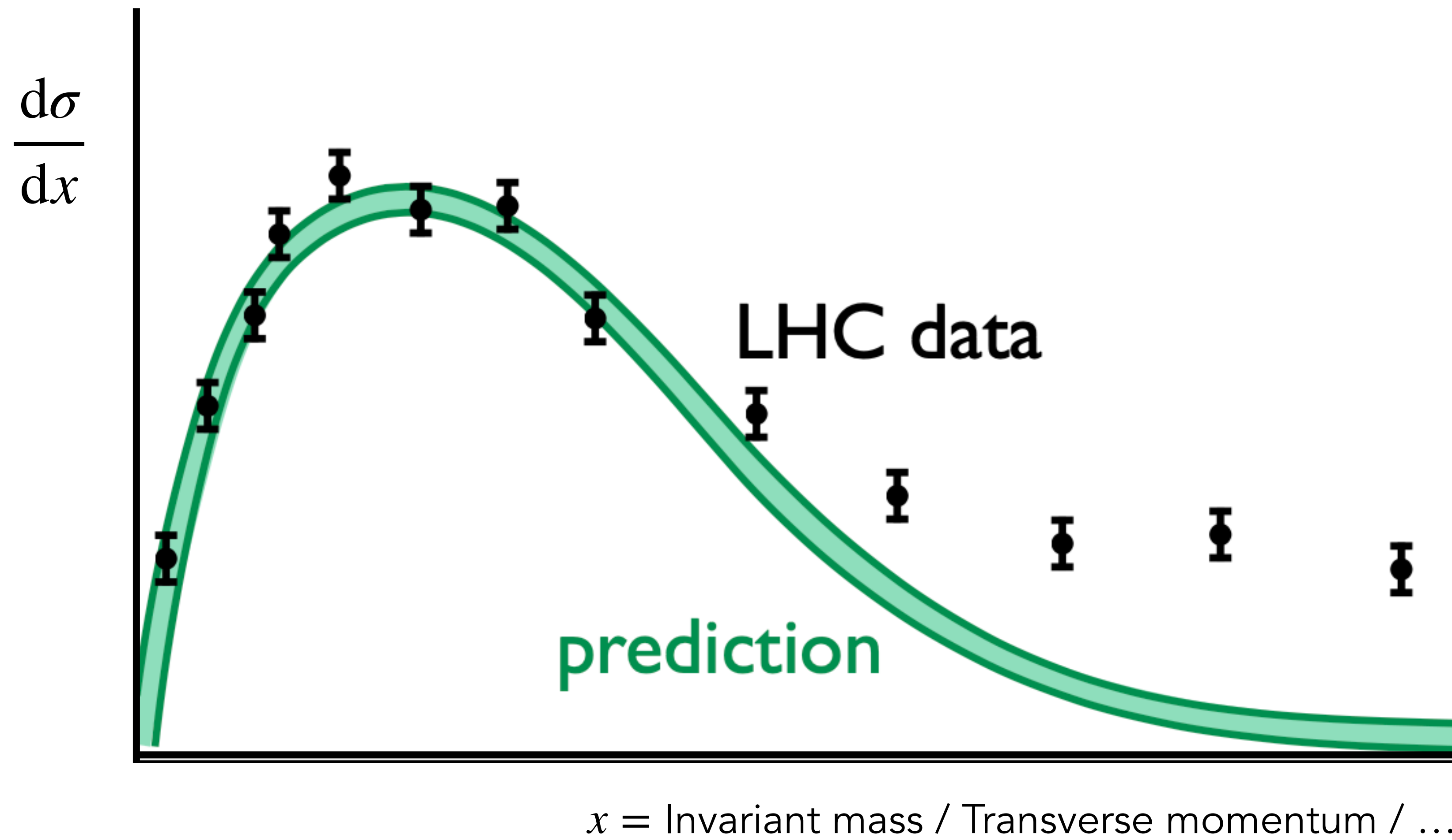


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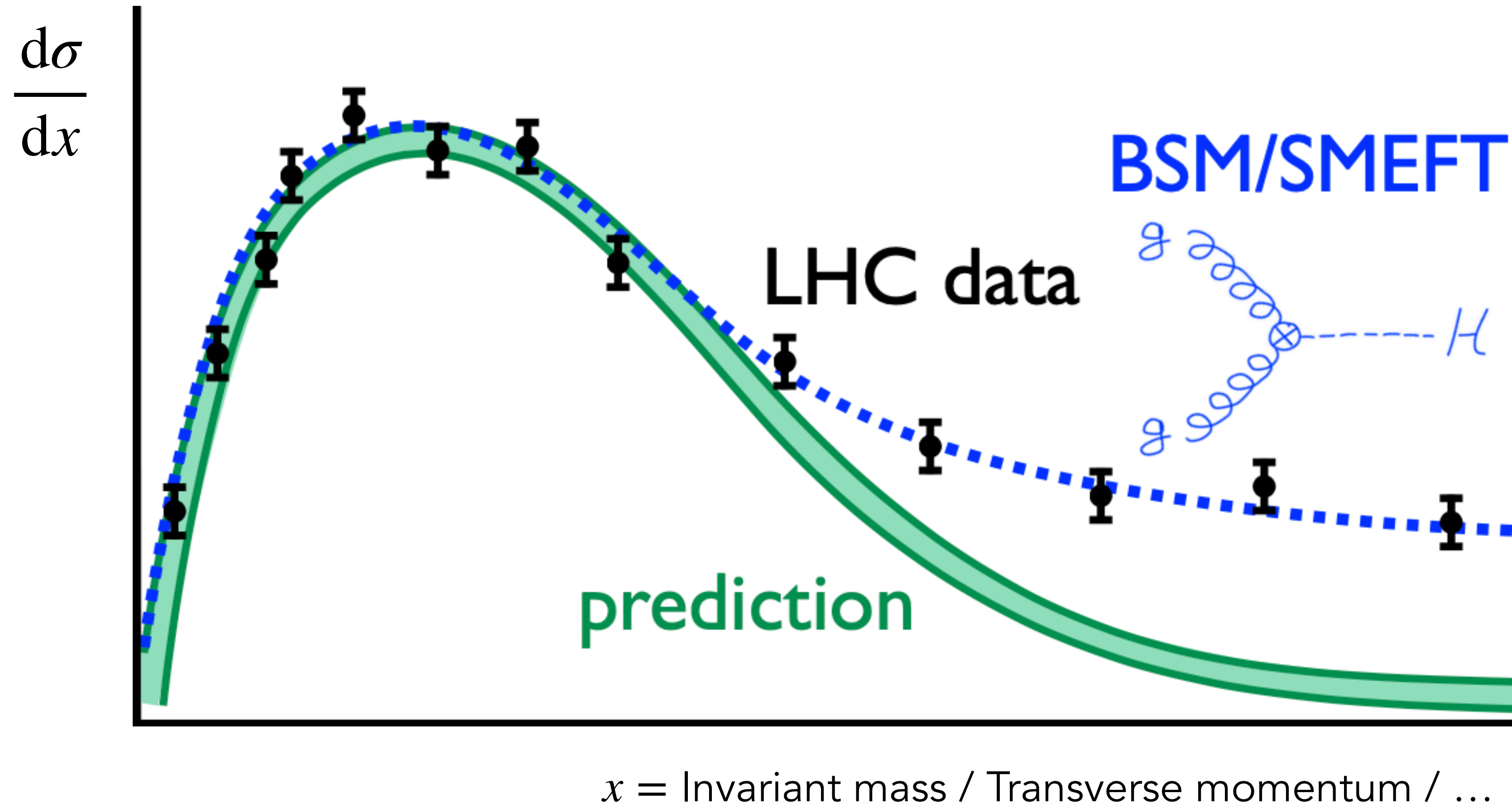


Figure: G. Zanderighi / M. Wiesemann

Higgs Production

Experimental Measurement of Higgs Production

$$R_{if} = \sigma_i \times B_f$$

R_{if} - rate of production via process i with decay into final state f

σ_i - cross section for production process i

B_f - branching ratio into final state f

Signal Strength

$$\mu_{if} = (\sigma_i \times B_f) / (\sigma_i^{\text{SM}} \times B_f^{\text{SM}})$$

μ_{if} - signal strength for production via i and decay into f

Global Signal Strength

Global fit of all production and decay processes

**Theory errors are already
dominating with Run 2 data!**

$$\mu = 1.023 \pm 0.028 \text{ (stat.) } {}^{+0.026}_{-0.025} \text{ (exp.) } {}^{+0.039}_{-0.036} \text{ (sig. th.) } \pm 0.012 \text{ (bkg. th.)}$$

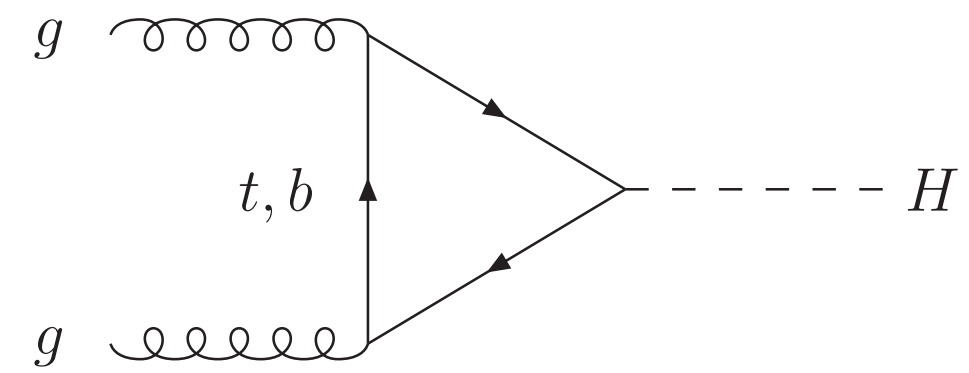
Overview

σ [pb] @ 13 TeV / # Higgs in 140 fb^{-1}

Q: What is the dominant Higgs boson production channel at the LHC/HL-LHC?

Overview

σ [pb] @ 13 TeV / # Higgs in 140 fb⁻¹

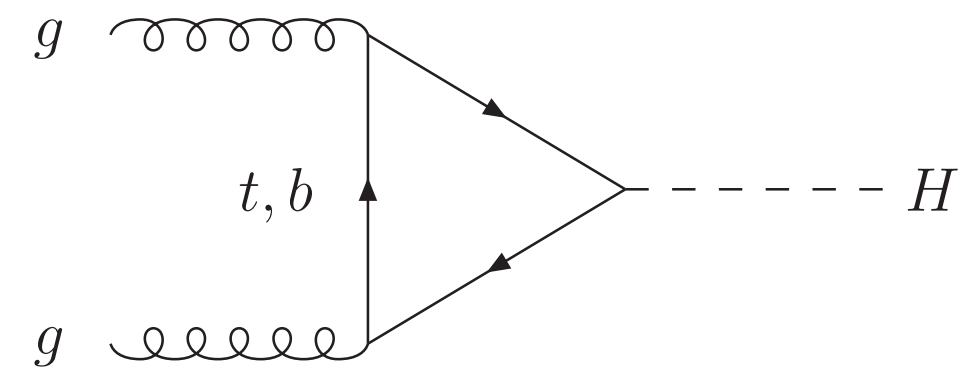


49 pb / 6.9M

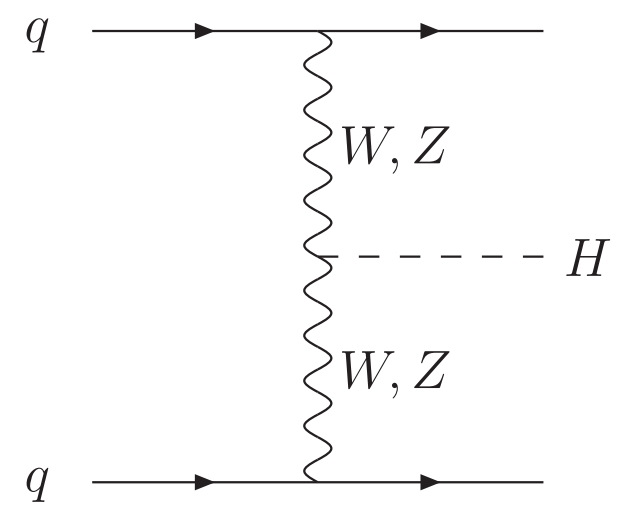
Q: Why does this channel dominate?

Overview

σ [pb] @ 13 TeV / # Higgs in 140 fb⁻¹



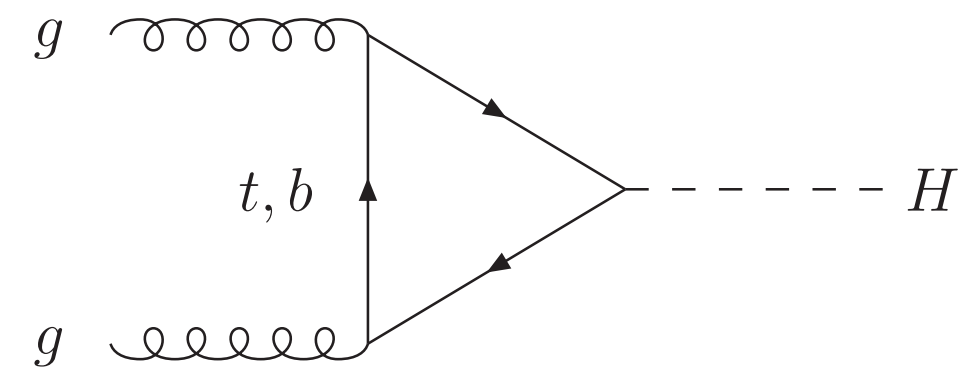
49 pb / 6.9M



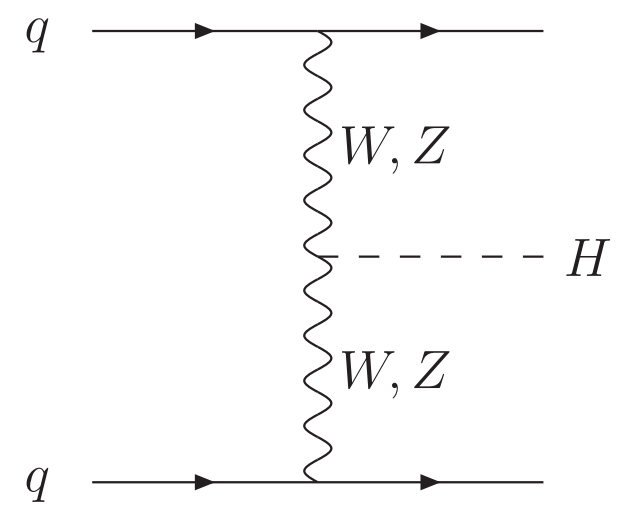
3.8 pb / 520k

Overview

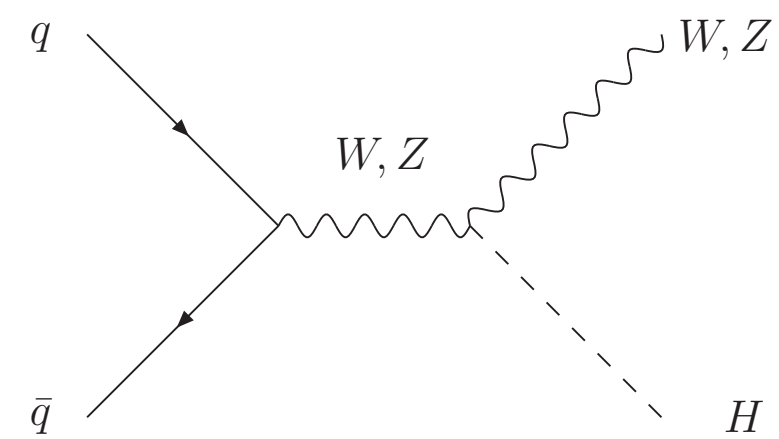
σ [pb] @ 13 TeV / # Higgs in 140 fb⁻¹



49 pb / 6.9M



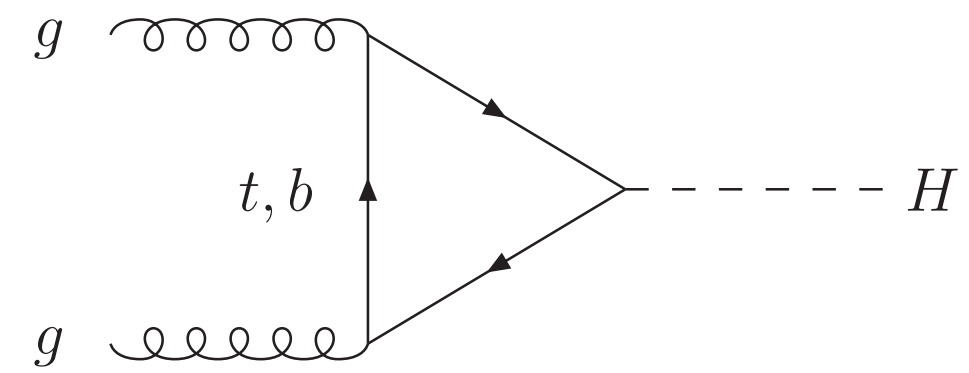
3.8 pb / 520k



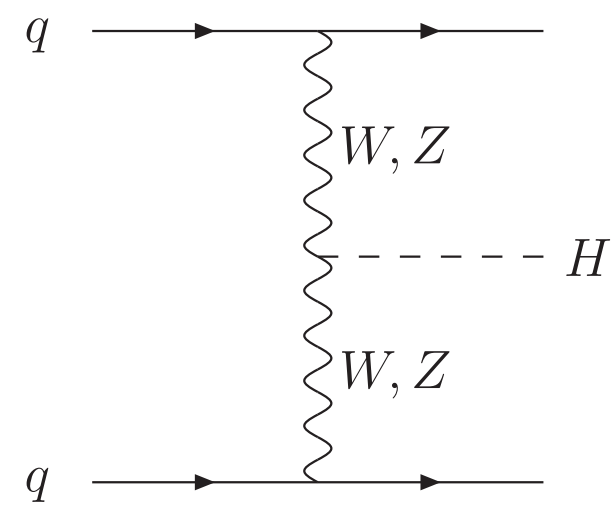
2.3 pb / 320k

Overview

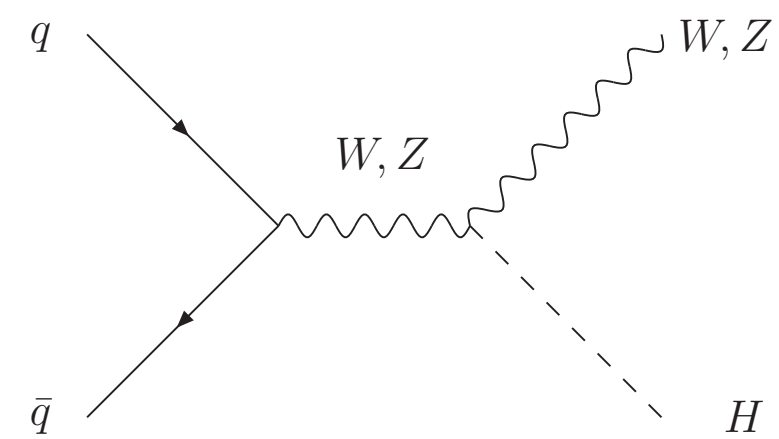
σ [pb] @ 13 TeV / # Higgs in 140 fb⁻¹



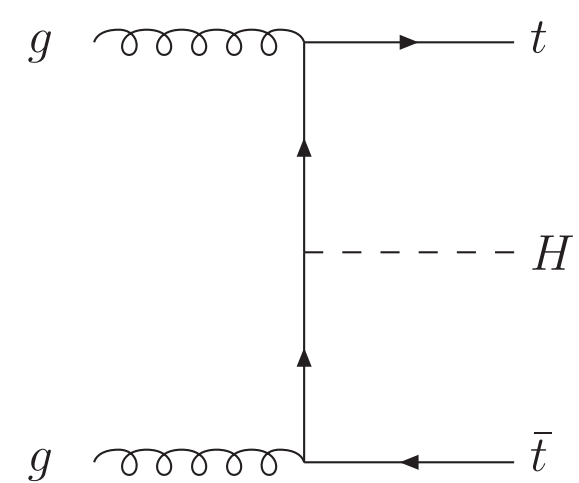
49 pb / 6.9M



3.8 pb / 520k



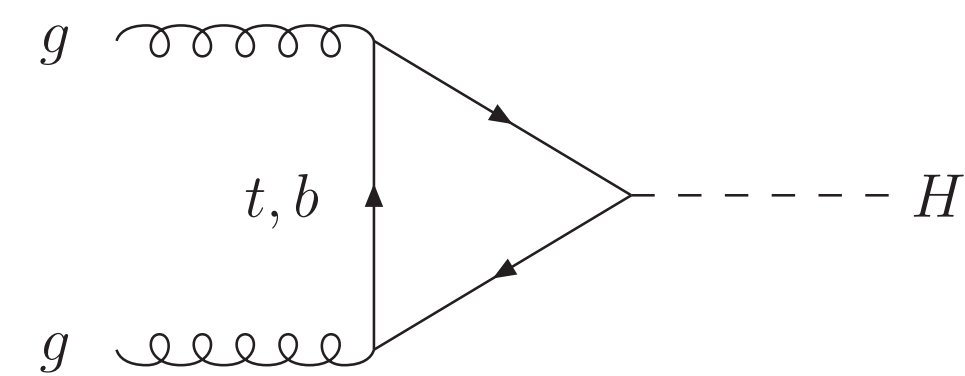
2.3 pb / 320k



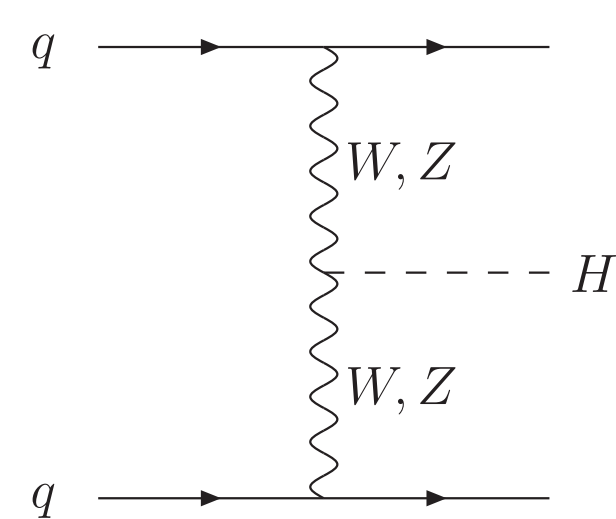
0.5 pb / 70k

Overview

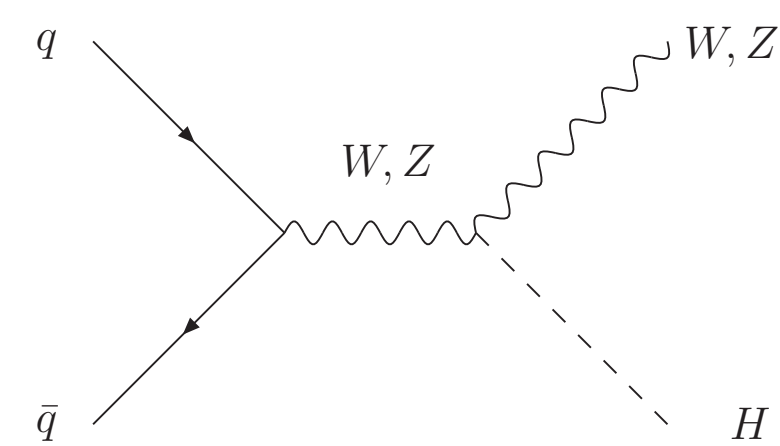
σ [pb] @ 13 TeV / # Higgs in 140 fb⁻¹



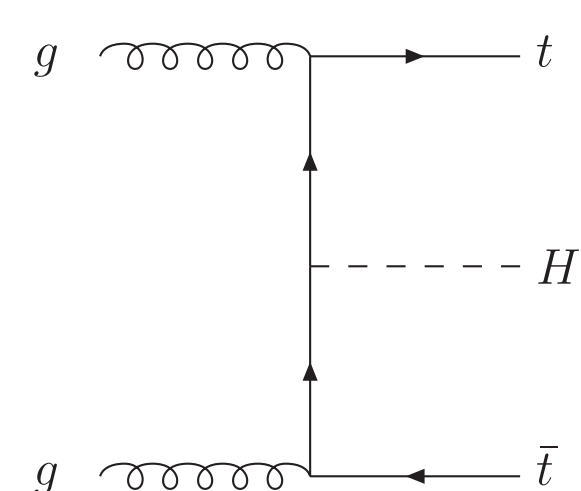
49 pb / 6.9M



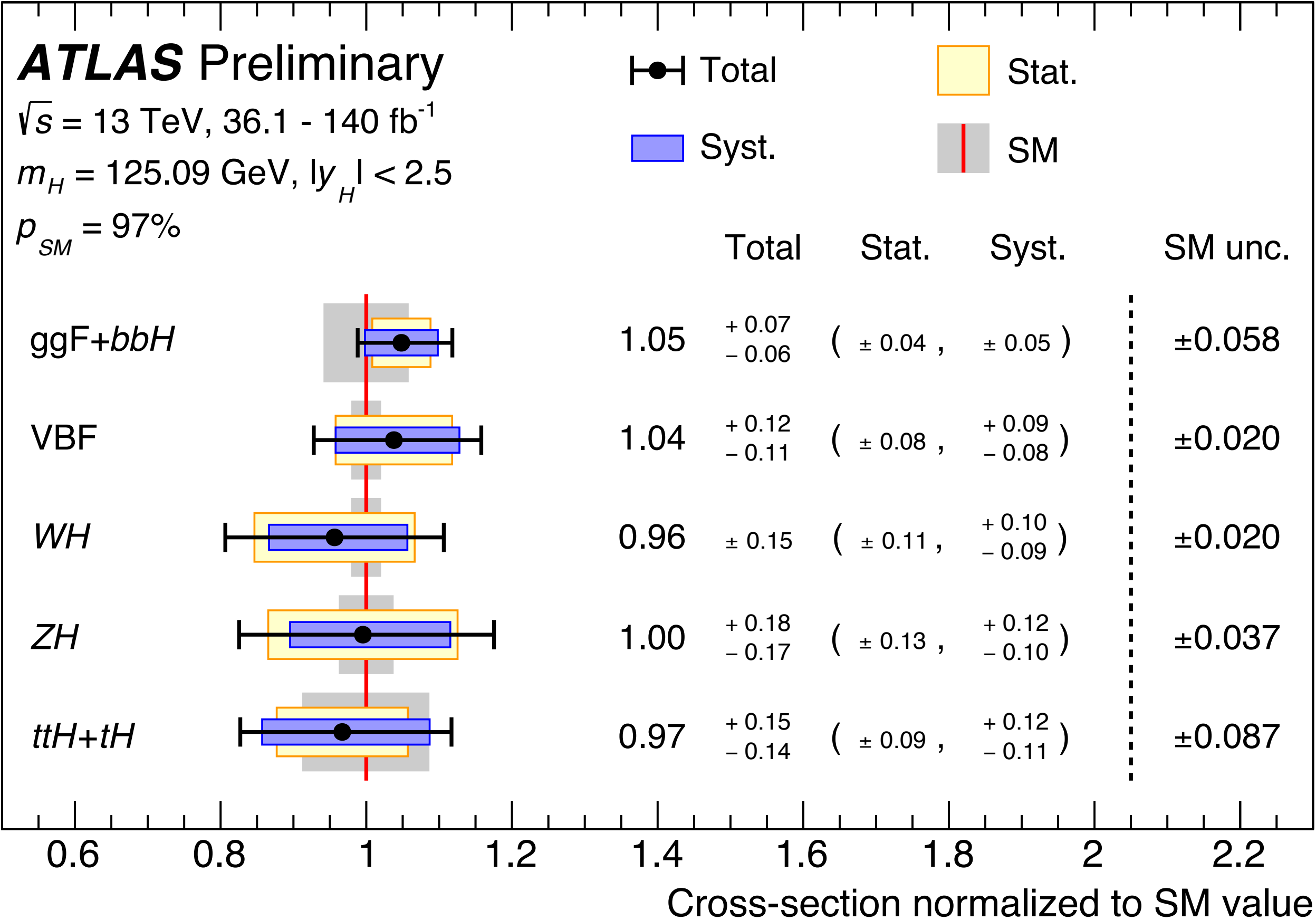
3.8 pb / 520k



2.3 pb / 320k

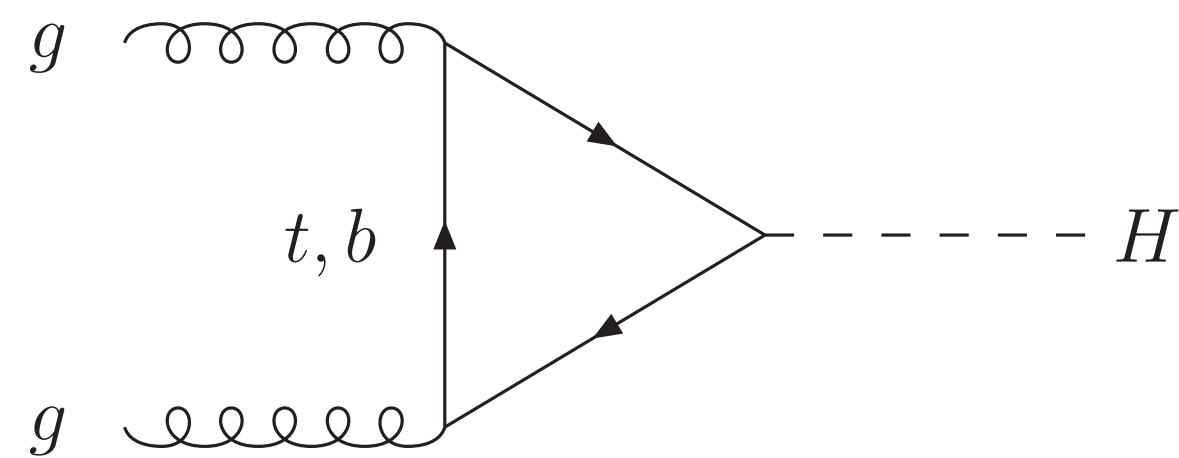


0.5 pb / 70k

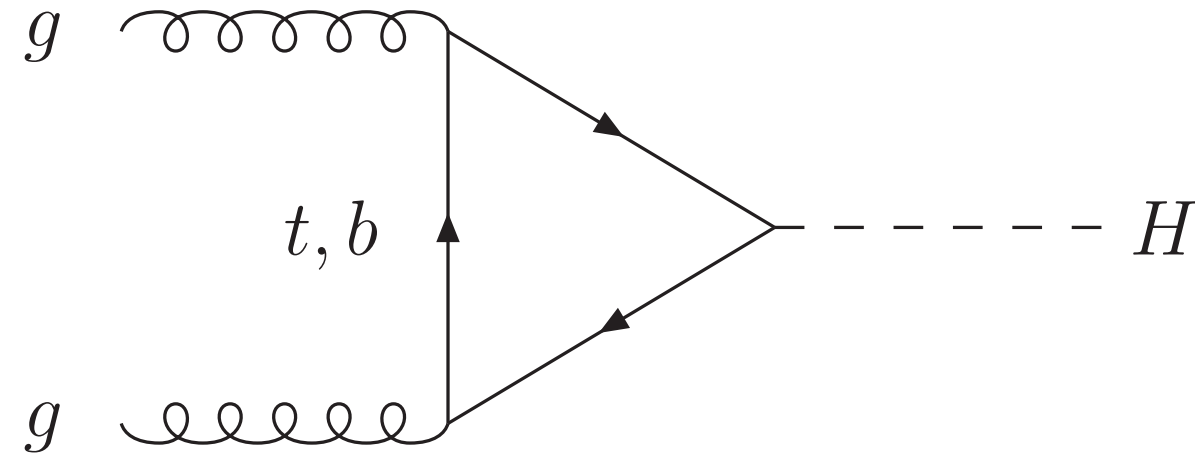


ATLAS-CONF-2025-006

Higgs Production: Gluon Fusion



Gluon Fusion



Factorisation formula

$$\sigma(H + X) = \sum_{i,j} \int dx_1 f_i(x_1, \mu_F) \int dx_2 f_j(x_2, \mu_F) \times \hat{\sigma}_{ij \rightarrow H+X}(s, m_H, \mu_F, \mu_R)$$

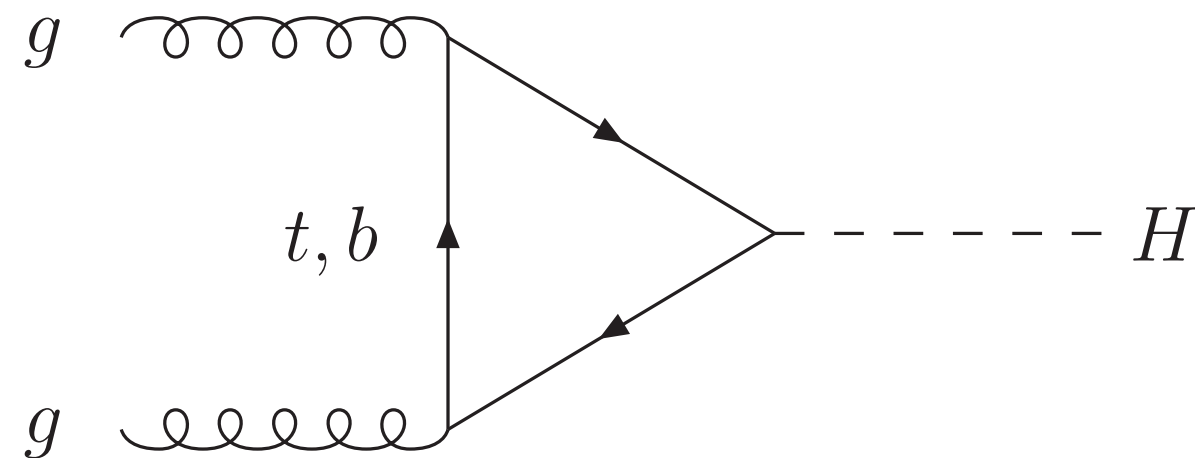
Total Cross Section

$$\sigma_{LO}(pp \rightarrow H) = \sigma_0 \tau_H \frac{d\mathcal{L}^{gg}}{d\tau_H}$$

Gluon luminosity

$$\frac{d\mathcal{L}^{gg}}{d\tau} = \int_{\tau}^1 \frac{dx}{x} g(x, \mu_F^2) g(\tau/x, \mu_F^2)$$

Gluon Fusion



Factorisation formula

$$\sigma(H + X) = \sum_{i,j} \int dx_1 f_i(x_1, \mu_F) \int dx_2 f_j(x_2, \mu_F) \times \hat{\sigma}_{ij \rightarrow H+X}(s, m_H, \mu_F, \mu_R)$$

Total Cross Section

$$\sigma_{LO}(pp \rightarrow H) = \sigma_0 \tau_H \frac{d\mathcal{L}^{gg}}{d\tau_H}$$

Gluon luminosity

$$\frac{d\mathcal{L}^{gg}}{d\tau} = \int_{\tau}^1 \frac{dx}{x} g(x, \mu_F^2) g(\tau/x, \mu_F^2)$$

Coefficient Function / Squared Matrix Element

$$\sigma_0 = \frac{\pi^2}{8M_H^3} \Gamma_{LO}(H \rightarrow gg) = \frac{G_F \alpha_s^2(\mu_R)}{288\sqrt{2}\pi} \left| \sum_Q A_Q^H(\tau_Q) \right|^2$$

$$\tau_H = M_H^2/s$$

$$\tau_Q = 4M_Q^2/M_H^2$$

$$A_Q^H(\tau) = \frac{3}{2}\tau \left[1 + (1 - \tau)f(\tau) \right]$$

$$f(\tau) = \arcsin^2 \frac{1}{\sqrt{\tau}} \quad \tau \geq 1$$

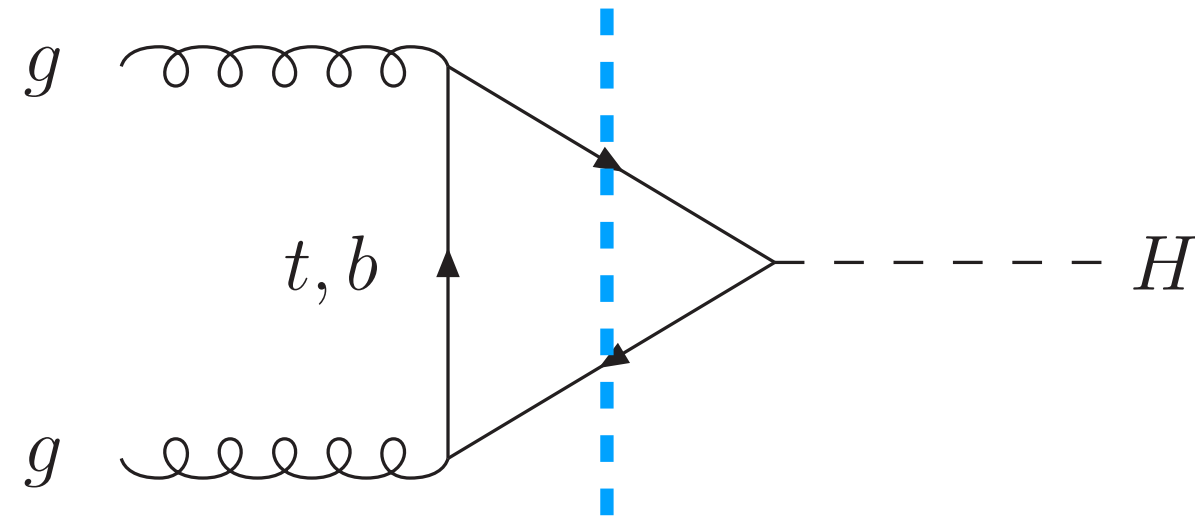
$$f(\tau) = -\frac{1}{4} \left[\log \frac{1 + \sqrt{1 - \tau}}{1 - \sqrt{1 - \tau}} - i\pi \right]^2 \quad \tau < 1$$

Q: What happens as we cross $\tau_Q = 1$?

Graudenz, Spira, Zerwas 93;

Spira Djouadi, Graudenz, Zerwas 95;

Gluon Fusion



Factorisation formula

$$\sigma(H + X) = \sum_{i,j} \int dx_1 f_i(x_1, \mu_F) \int dx_2 f_j(x_2, \mu_F) \times \hat{\sigma}_{ij \rightarrow H+X}(s, m_H, \mu_F, \mu_R)$$

Total Cross Section

$$\sigma_{LO}(pp \rightarrow H) = \sigma_0 \tau_H \frac{d\mathcal{L}^{gg}}{d\tau_H}$$

Gluon luminosity

$$\frac{d\mathcal{L}^{gg}}{d\tau} = \int_{\tau}^1 \frac{dx}{x} g(x, \mu_F^2) g(\tau/x, \mu_F^2)$$

A: Enough energy for both quark propagators to go on-shell

Coefficient Function / Squared Matrix Element

$$\sigma_0 = \frac{\pi^2}{8M_H^3} \Gamma_{LO}(H \rightarrow gg) = \frac{G_F \alpha_s^2(\mu_R)}{288\sqrt{2}\pi} \left| \sum_Q A_Q^H(\tau_Q) \right|^2$$

$$A_Q^H(\tau) = \frac{3}{2} \tau [1 + (1 - \tau)f(\tau)]$$

$$f(\tau) = \arcsin^2 \frac{1}{\sqrt{\tau}} \quad \tau \geq 1$$

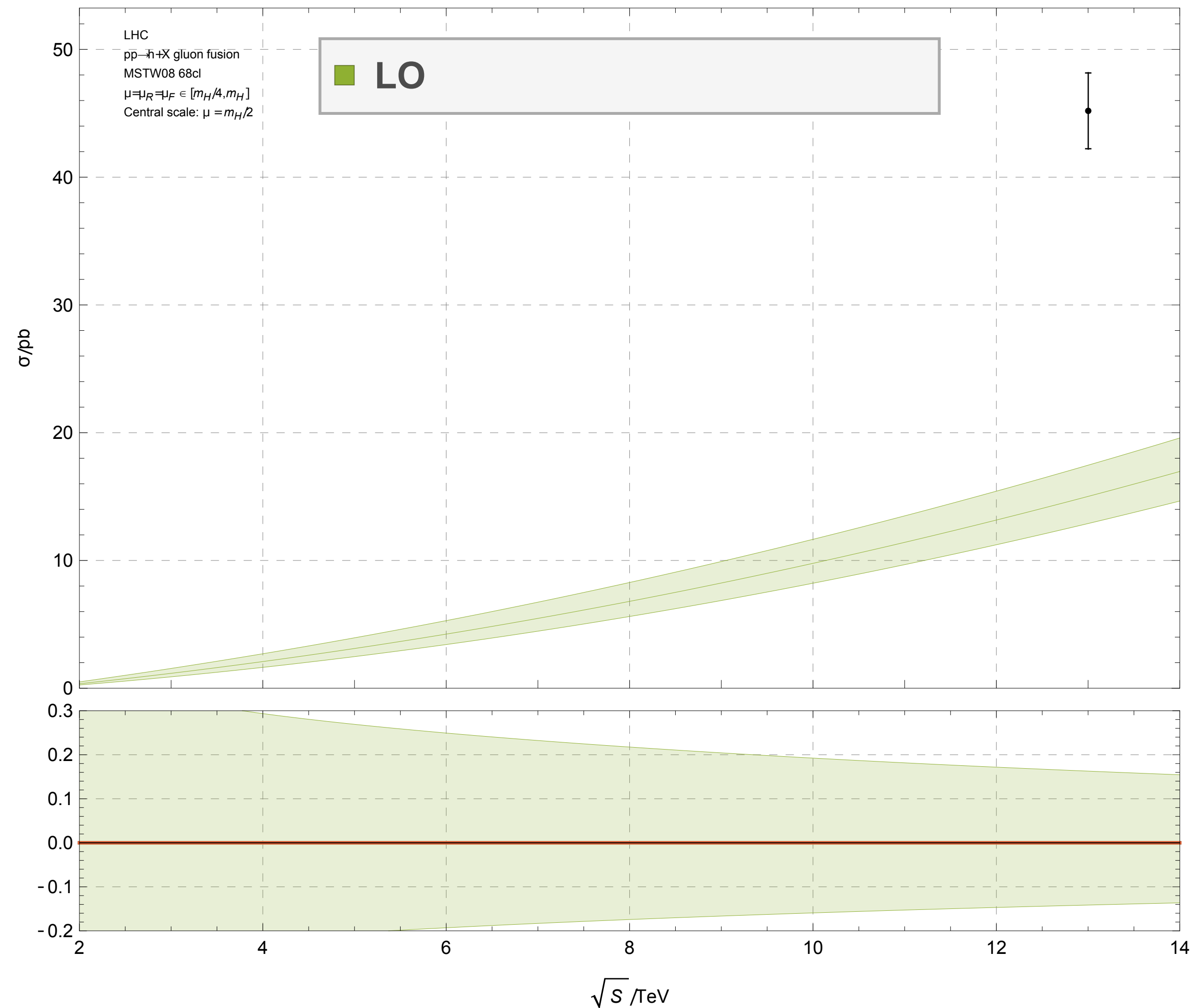
$$f(\tau) = -\frac{1}{4} \left[\log \frac{1 + \sqrt{1 - \tau}}{1 - \sqrt{1 - \tau}} - i\pi \right]^2 \quad \tau < 1$$

Graudenz, Spira, Zerwas 93;

Spira Djouadi, Graudenz, Zerwas 95;

How Important is Precision?

Let's take current experimental results for $gg \rightarrow H$ and compare it to this theory prediction



“ATLAS-CONF-2021-053”

Q: Did we just find BSM physics?

*Warning: just a cartoon, don't trust data/theory from this plot!

NLO Corrections

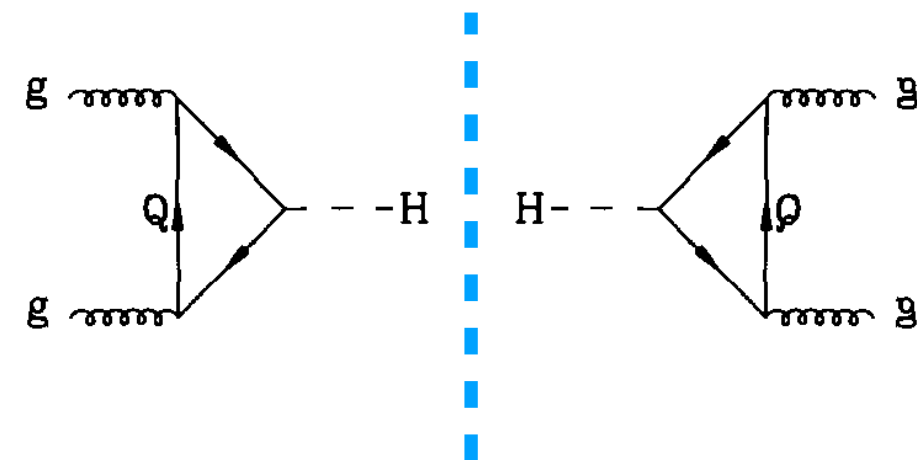
How do we improve the perturbative precision?

$$\sigma(H + X) = \sum_{i,j} \int dx_1 f_i(x_1, \mu_F) \int dx_2 f_j(x_2, \mu_F) \times \hat{\sigma}_{ij \rightarrow H+X}(s, m_H, \mu_F, \mu_R)$$

$$\hat{\sigma}(ij \rightarrow H + X) = \hat{\sigma}^{(0)}(ij \rightarrow H) + \hat{\sigma}^{(1)}(ij \rightarrow H + 0/1 \text{ partons}) + \hat{\sigma}^{(2)}(ij \rightarrow H + 0/1/2 \text{ partons}) + \dots$$

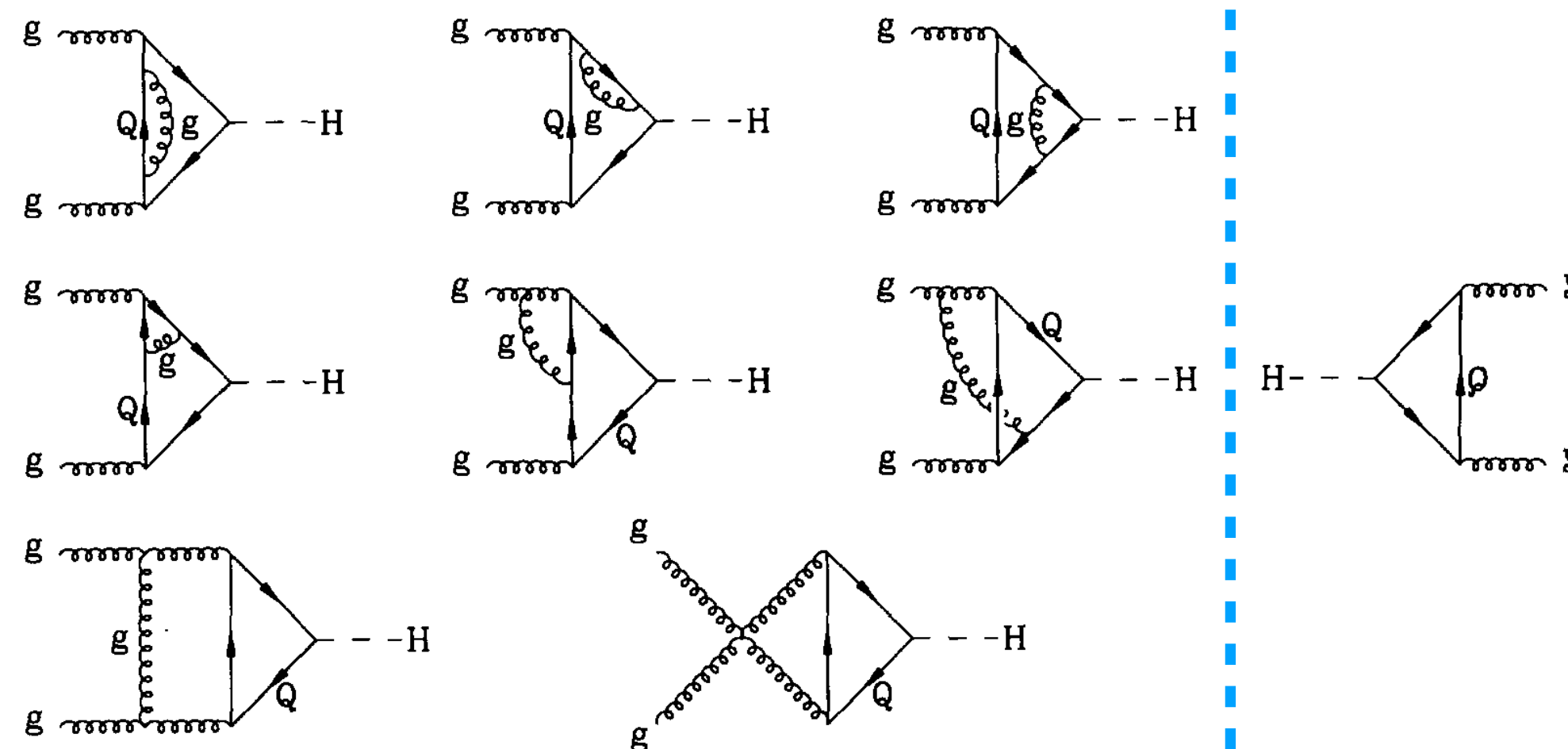
Born α_s^2

$$\hat{\sigma}^{(0)}(ij \rightarrow H)$$



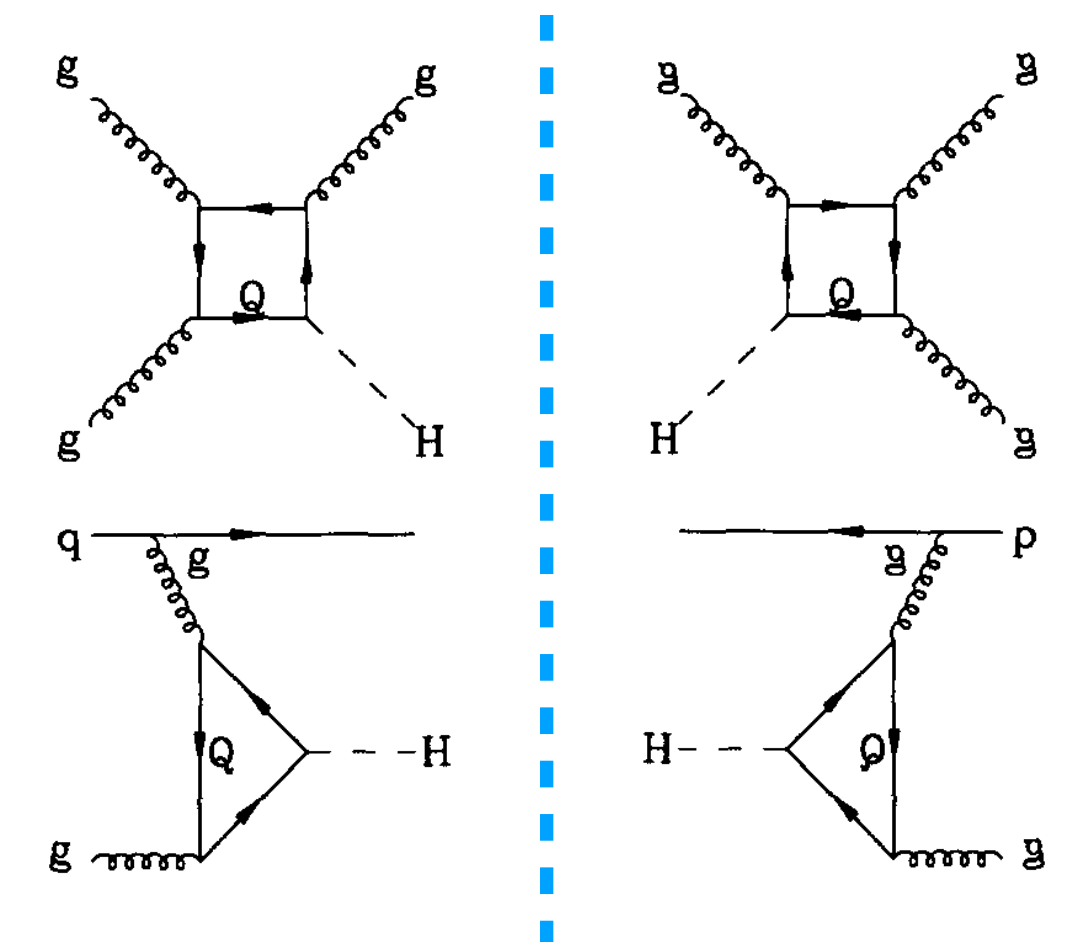
Virtual α_s^3

$$\hat{\sigma}^{(1)}(ij \rightarrow H + 0 \text{ partons})$$



Real α_s^3

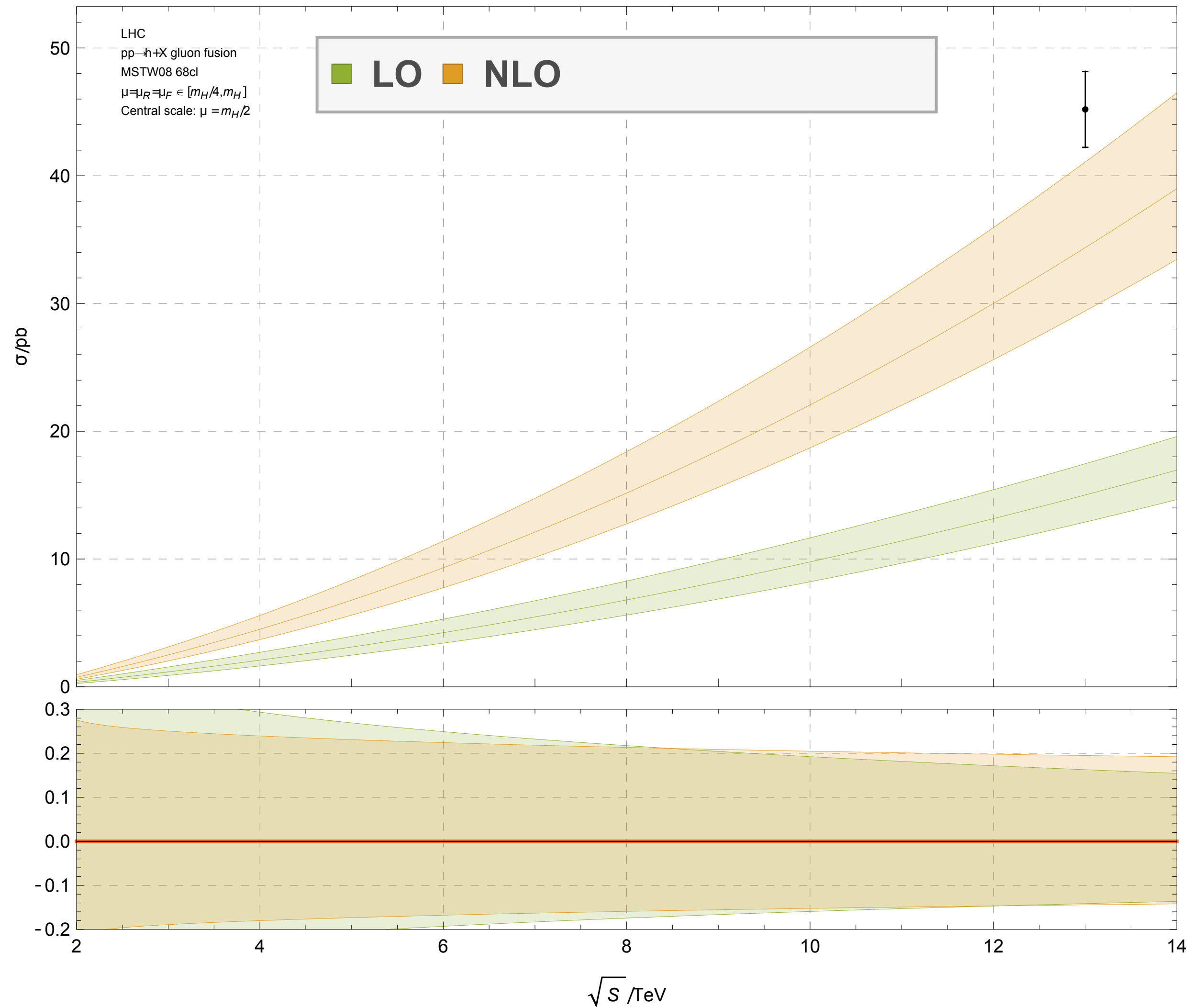
$$\hat{\sigma}^{(1)}(ij \rightarrow H + 1 \text{ partons})$$



New production channels!

How Important is Precision?

Imagine we had current experimental results for $gg \rightarrow H$, but only NLO theory...

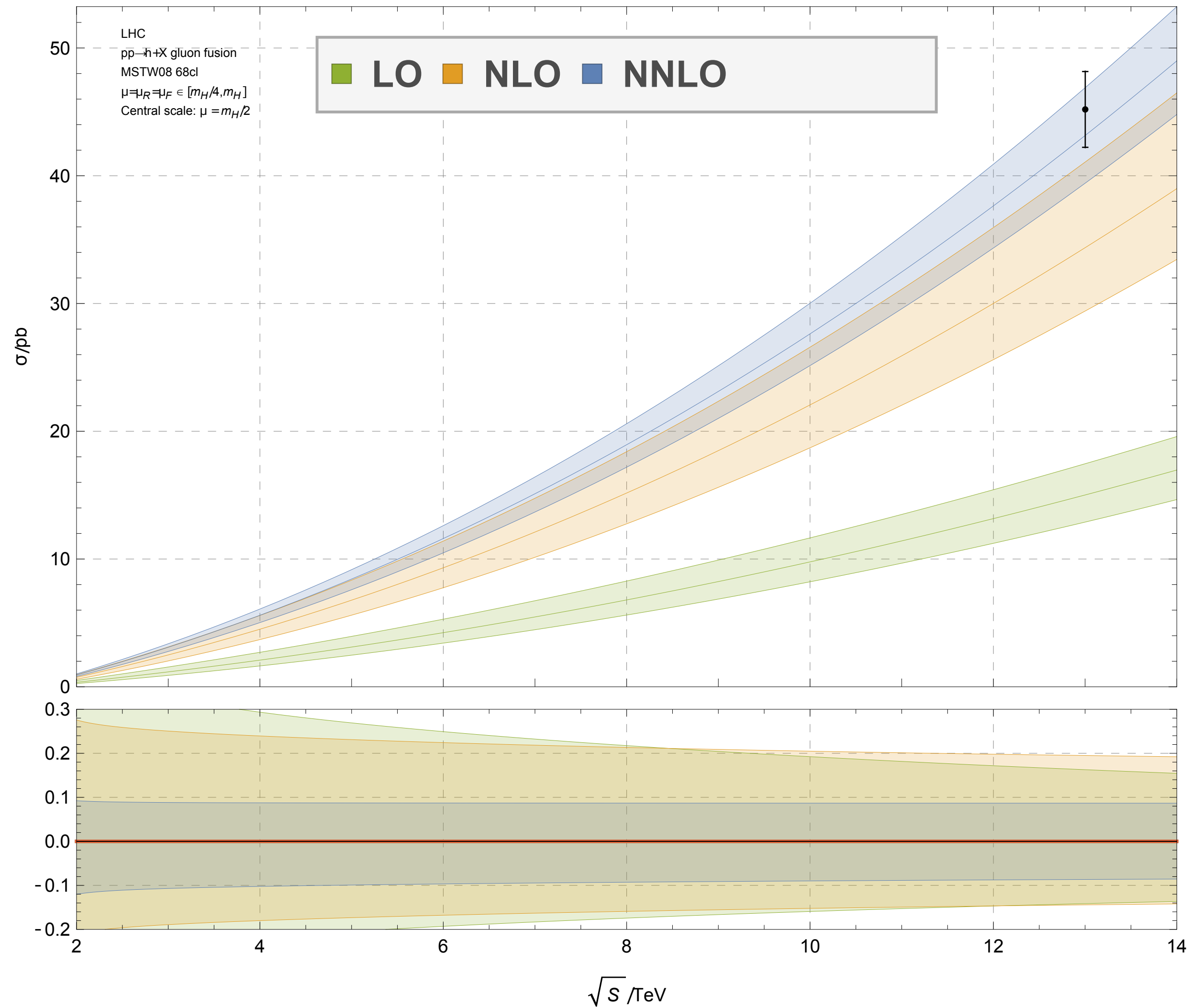


Graudenz, Spira, Zerwas 93;
Spira, Djouadi, Graudenz, Zerwas 95;

*Warning: just a cartoon, don't
trust data/theory from this plot!

How Important is Precision?

Imagine we had current experimental results for $gg \rightarrow H$, but only NNLO theory...

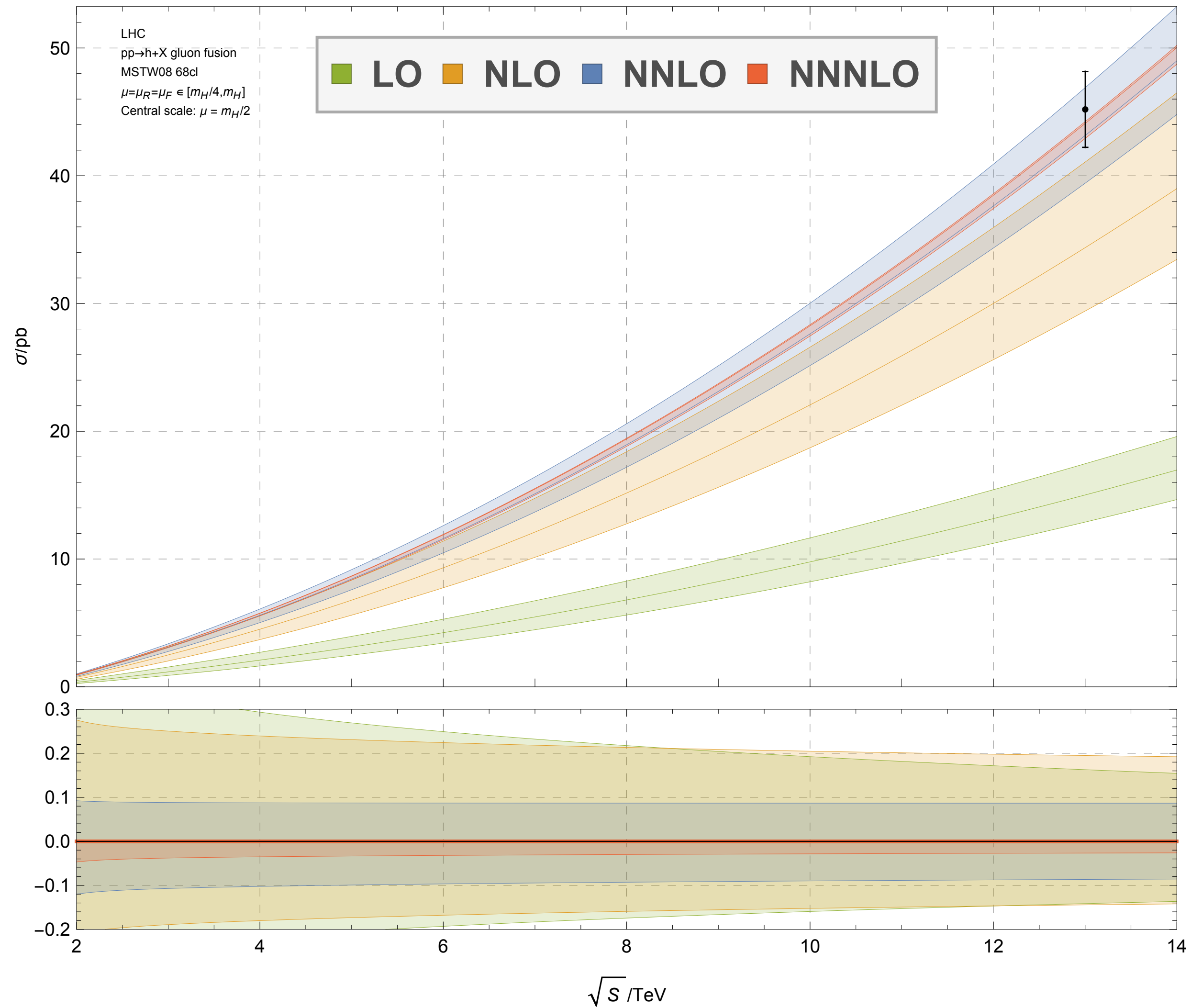


Anastasiou, Melnikov 02;
Harlander, Kilgore 02;
Ravindran, Smith, van
Neerven 03;

*Warning: just a cartoon, don't
trust data/theory from this plot!

How Important is Precision?

Imagine we had current experimental results for $gg \rightarrow H$, but only N3LO theory...



Anastasiou, Duhr, Dulat,
(Furlan), (Gehrmann),
Herzog, Mistlberger 16;
Mistlberger 18;

*Warning: just a cartoon, don't
trust data/theory from this plot!

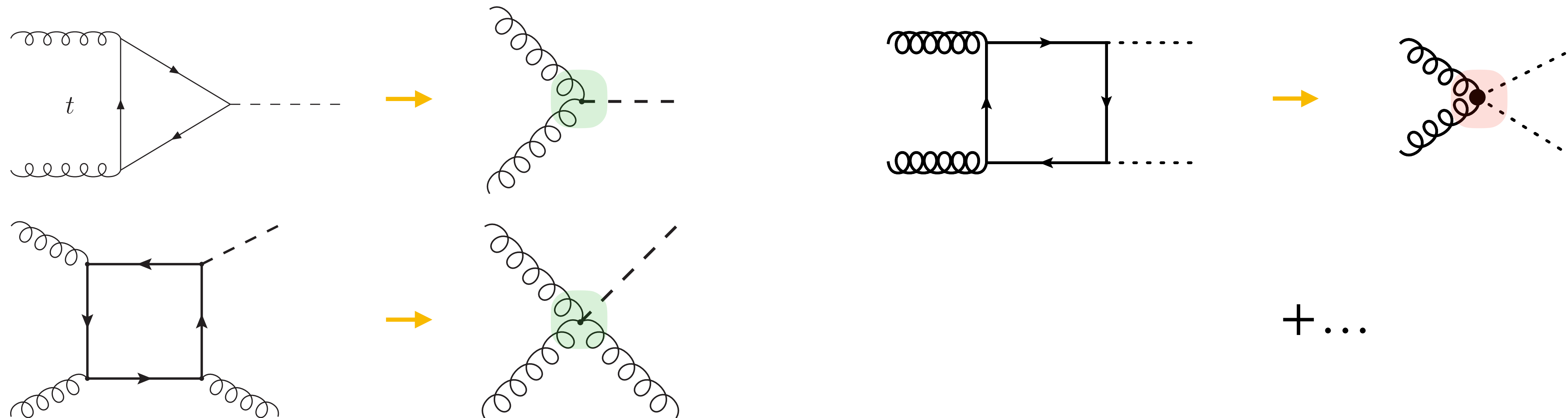
Heavy Top Limit (HTL)

It is very difficult to calculate higher order corrections ← **Q: Why?**

Can simplify our work by making an approximation that works well when m_t can be treated as a very large parameter

We can introduce an effective field theory description which couples gluons to Higgs bosons

$$\mathcal{L}_{\text{eff}} = -C_H \left(\frac{H}{v} \right) \frac{1}{4} G_{\mu\nu}^a G^{\mu\nu,a} + \frac{C_{HH}}{2} \left(\frac{H}{v} \right)^2 \frac{1}{4} G_{\mu\nu}^a G^{\mu\nu,a} + \dots$$

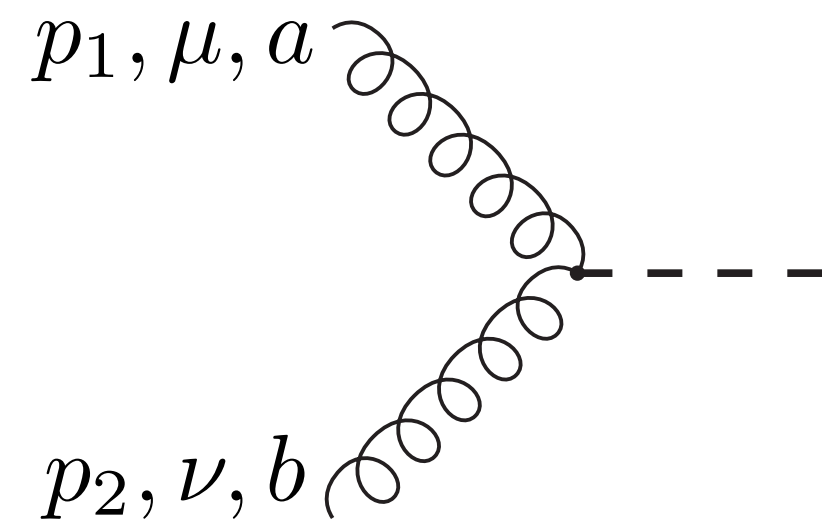


Reduces the number of loops by 1, avoid loop integrals depending on the scale m_t !

Heavy Top Limit (HTL)

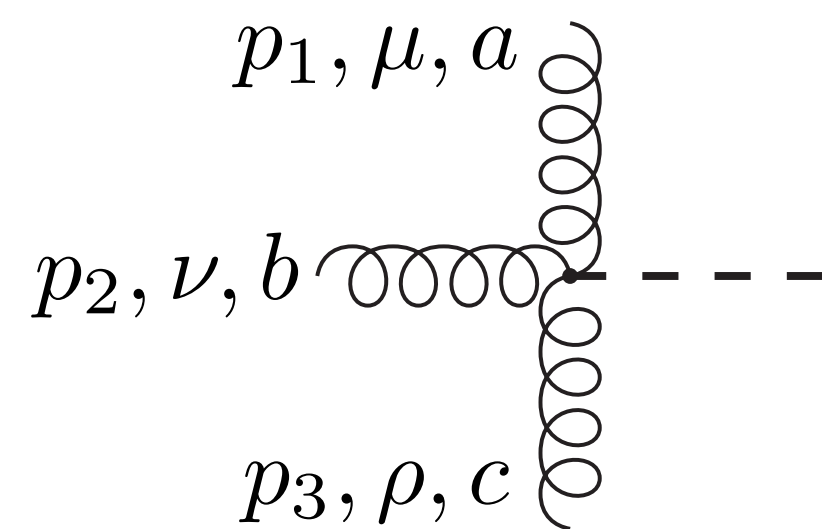
Can derive Feynman rules for our new effective theory

$$\mathcal{L}_{\text{eff}} \supset -\frac{1}{4} \frac{C_H}{v} H G_{\mu\nu}^a G^{\mu\nu,a}$$



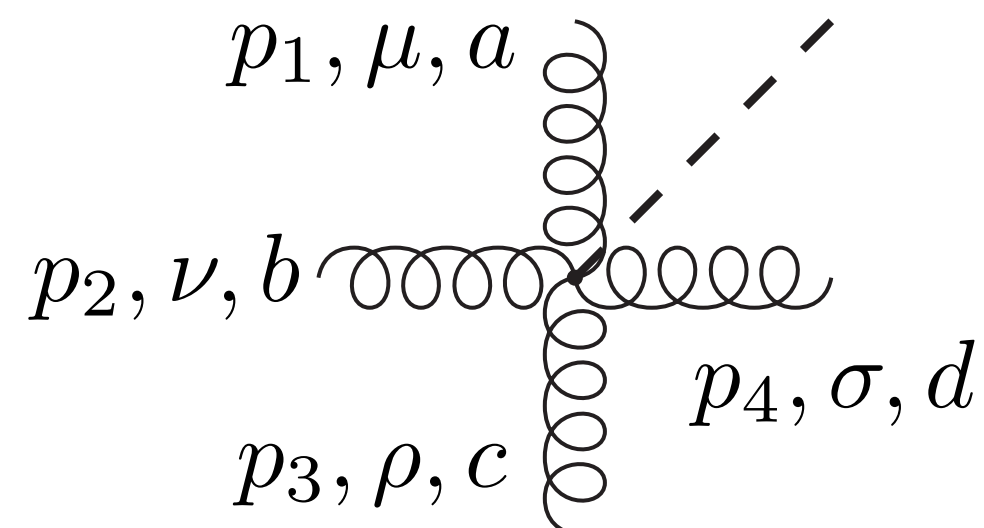
$$= i \frac{C_H}{v} \delta^{ab} H^{\mu\nu}(p_1, p_2)$$

$$H^{\mu\nu}(p_1, p_2) = -g^{\mu\nu} p_1 \cdot p_2 + p_2^\mu p_1^\nu$$



$$= -\frac{C_H}{v} g_s f^{abc} V^{\mu\nu\rho}(p_1, p_2, p_3)$$

$$\begin{aligned} V^{\mu\nu\rho}(p_1, p_2, p_3) = & \\ & + g^{\mu\nu} (p_1 - p_2)^\rho \\ & + g^{\nu\rho} (p_2 - p_3)^\mu \\ & + g^{\rho\mu} (p_3 - p_1)^\nu \end{aligned}$$



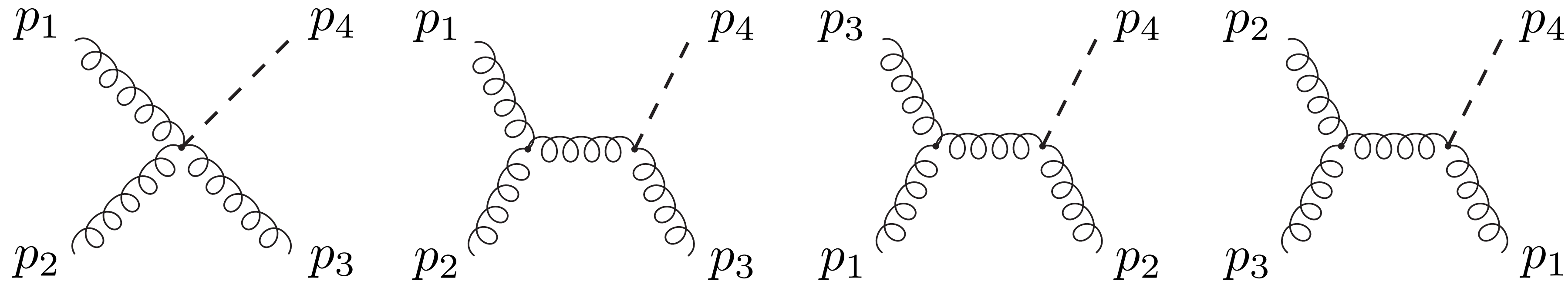
$$= -i \frac{C_H}{v} g_s^2 X_{\mu\nu\rho\sigma}^{abcd}$$

$$X_{\mu\nu\rho\sigma}^{abcd} = \dots$$

Need to fix the coefficient C_H ← How?

HTL Diagrams

Consider $gg \rightarrow Hg$ at leading order in this theory



This is a tree level calculation in the HTL effective theory

$$s = (p_1 + p_2)^2, \quad t = (p_1 + p_3)^2, \quad u = (p_2 + p_3)^2$$

$$N_A = N_c^2 - 1$$

$$|M_{\text{HTL}}|^2 = C_A N_A 4\pi\alpha_s \left(\frac{C_H}{v} \right)^2 \frac{(m_H^8 + s^4 + t^4 + u^4)(1 - 2\epsilon) + \epsilon/2(m_H^4 + s^2 + t^2 + u^2)^2}{stu}$$

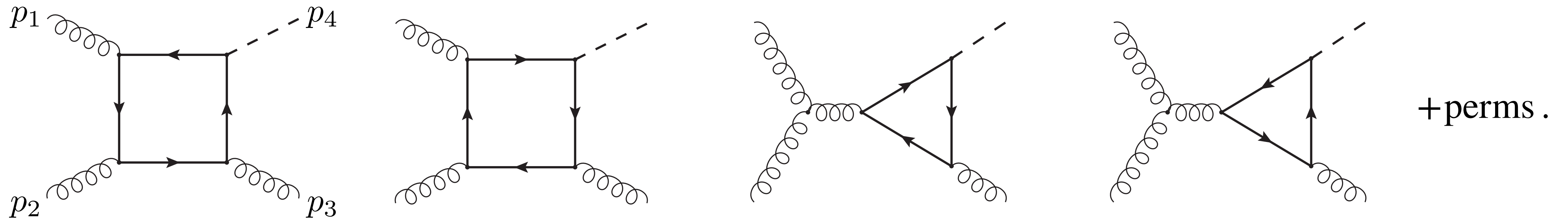
Depends on the Wilson coefficient C_H

Q: What is ϵ here?

Full Theory Diagrams

For the purpose of determining C_H we also need a computation of **any quantity** that depends on it in the full theory

Chetyrkin, Kniehl,
Steinhauser 97



Have to compute 1-loop integrals then **expand them in the large m_t limit**

$$|M_{\text{full}, m_t \rightarrow \infty}|^2 = \frac{4C_A N_A}{9} \frac{\alpha_s^3}{\pi v^2} \frac{(m_H^8 + s^4 + t^4 + u^4)(1 - 2\epsilon) + \epsilon/2(m_H^4 + s^2 + t^2 + u^2)^2}{stu}$$

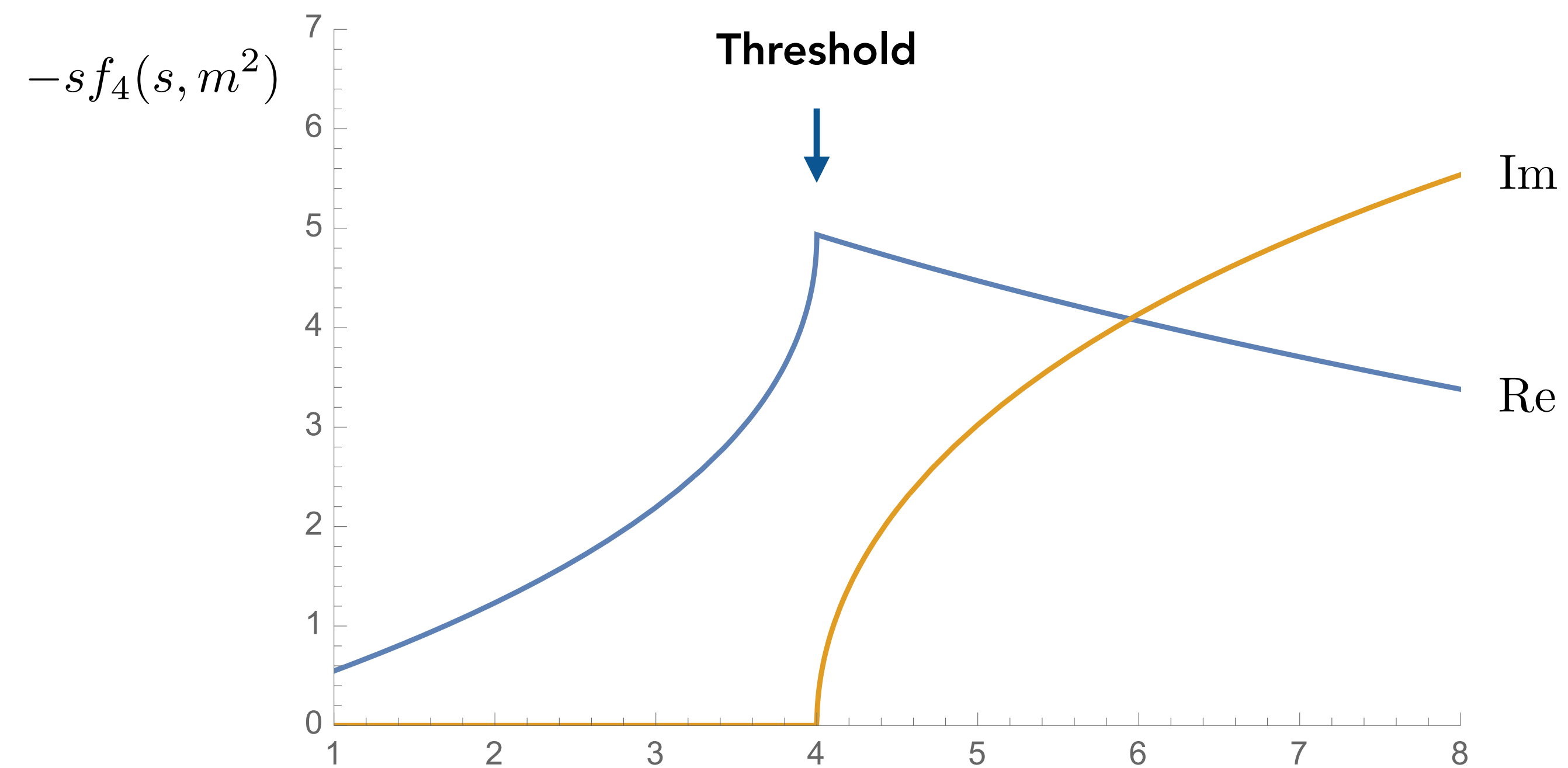
$$C_H = \frac{\alpha_s}{3\pi} + \mathcal{O}(\alpha_s^2) \quad \updownarrow$$

$$|M_{\text{HTL}}|^2 = C_A N_A 4\pi\alpha_s \left(\frac{C_H}{v}\right)^2 \frac{(m_H^8 + s^4 + t^4 + u^4)(1 - 2\epsilon) + \epsilon/2(m_H^4 + s^2 + t^2 + u^2)^2}{stu}$$

Expanding Integrals

$$\begin{array}{c} \text{---}s \end{array} \begin{array}{c} \diagup \\ | \\ \diagdown \end{array} \begin{array}{c} s \end{array} = -\frac{1}{2} \ln^2 \left(-\frac{1-\beta}{1+\beta} \right) \qquad \beta = \sqrt{1 - \frac{4m^2}{s}}$$

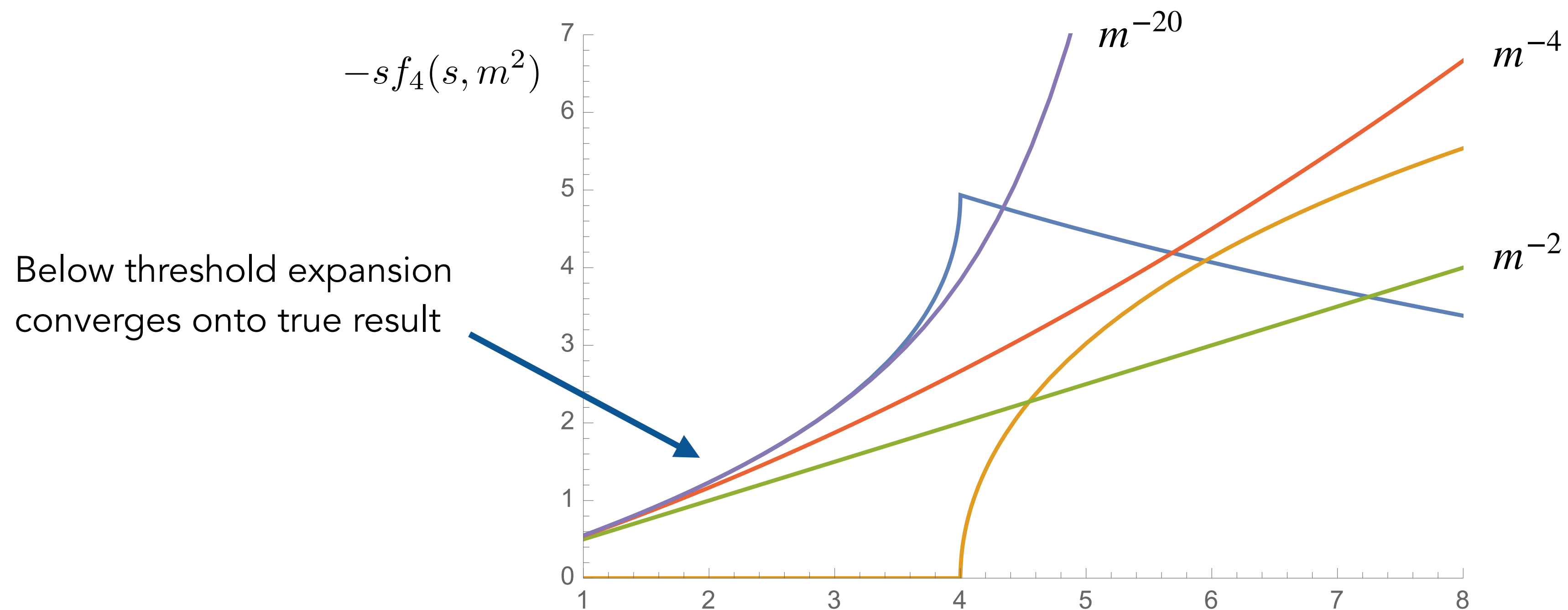
Threshold: for $s > 4m^2$ propagators can be on-shell, integral has a branch point and develops an imaginary part



Expanding Integrals

$$\begin{array}{c} \text{---}s \\ \text{---} \end{array} \begin{array}{c} \diagup \\ | \\ \diagdown \end{array} \begin{array}{c} \text{---}s \\ \text{---} \end{array} = -\frac{1}{2} \ln^2 \left(-\frac{1-\beta}{1+\beta} \right) = \frac{s}{2m^2} + \frac{s^2}{24m^4} + \frac{s^3}{180m^6} + \dots$$

Threshold: for $s > 4m^2$ propagators can be on-shell, integral has a branch point and develops an imaginary part



Q: What does this imply about where we can trust HTL results?

Q: What implication does this have for

$gg \rightarrow H$?

$gg \rightarrow Hj$?

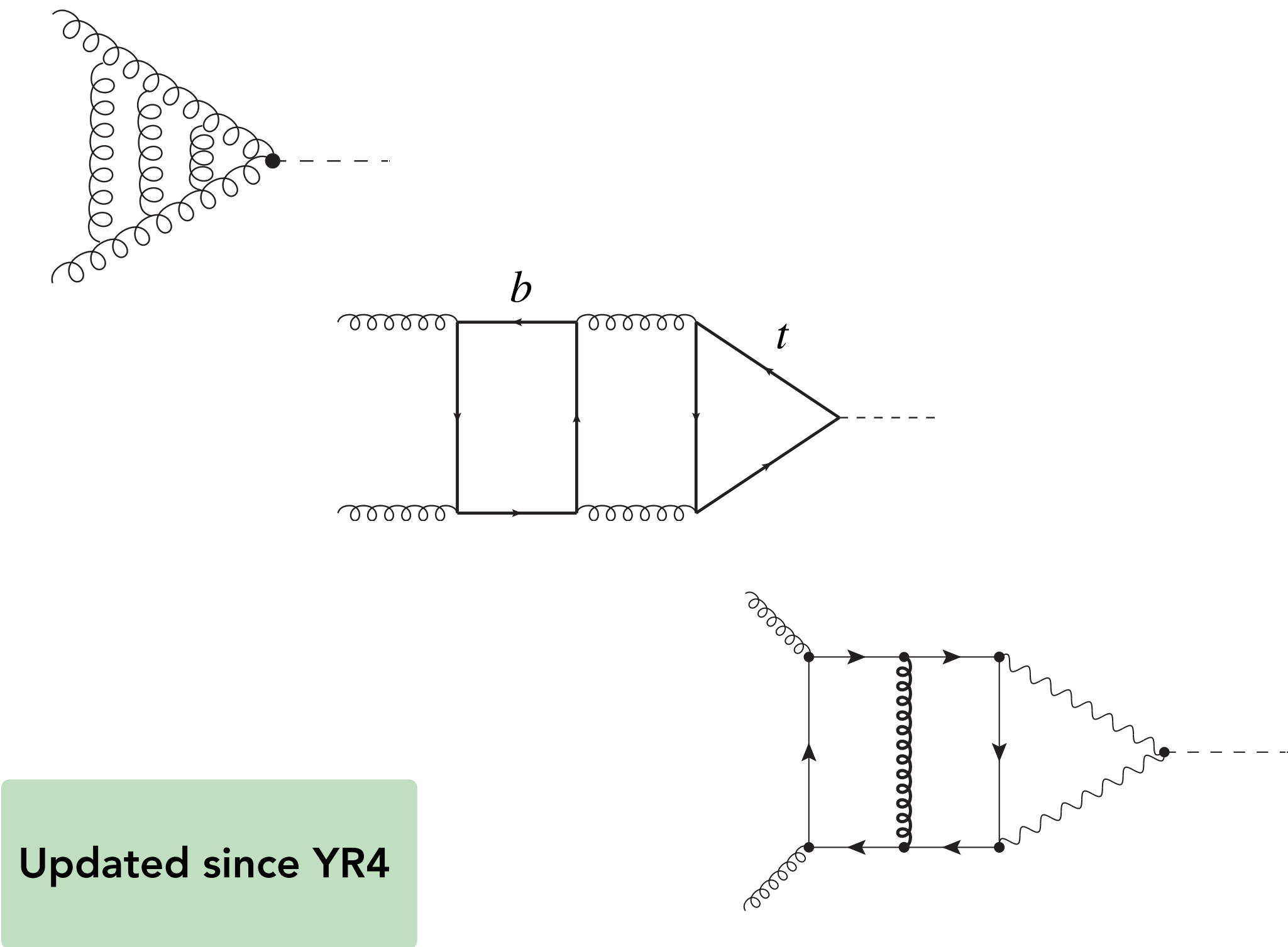
Higgs Production in Gluon Fusion

LHCHWG ggF (Report 5)

Theoretical uncertainties dominate experimental sys/stat even for σ_{tot} , **it is critically important that we improve theory precision**

ATLAS-CONF-2025-006; CMS-PAS-HIG-21-018

Calculations	References
Approximate N ⁴ LO HTL QCD	[1]
N ³ LO HTL QCD	[2,3,4]
NNLO HTL QCD	[5,6,7]
NLO HTL QCD	[8,9]
NNLO QCD	[10,11,12,13]
NLO QCD	[14,15]
EW & Mixed QCD-EW Corrections	[16,17,18,19]
N ³ LL Threshold Resummation	[20,21]
PDFs	References
Approximate N ³ LO PDFs	[22,23,24,25]
QED Evolution PDFs	[26,27,28,29,30,31,32]
NNLO PDFs	[33,34,35,36,37]
Codes	References
N ³ LO QCD	[38]



[1] Das, Moch, Vogt 20; [2,3] Anastasiou, Duhr, Dulat, (Furlan, Gehrmann), Herzog, (Lazopoulos), Mistlberger 15, (16); [4] Mistlberger 18; [5] Anastasiou, Melnikov 02; [6] Harlander, Kilgore 02; [7] Ravindran, Smith, van Neerven 03; [8] Dawson 91; [9] Djouadi, Spira, Zerwas 91; [10] Czakon, Niggetiedt 20; [11] Czakon, Harlander, Klappert, Niggetiedt 21; [12,13] Czakon Eschment, Niggetiedt (Poncelet, Schellenberger) 24 (24); [14] Graudenz, Spira, Zerwas 93; [15] Spira Djouadi, Graudenz, Zerwas 95; [16,17] Actis, Passarino, Sturm, Uccirati 08, 09; [18] Aglietti, Bonciani, Degrassi, Vicini 04; [19] Becchetti, Bonciani, Del Duca, Hirschi, Moriello, Schweitzer 21; [20] Bonvini, Marzani 14; [21] Catani, Cieri, de Florian, Ferrera, Grazzini 14; [22] MSHT 22; [23] NNPDF 24; [24] Benchmarking 24; [25] MSHT+NNPDF 25; [26,27] Manohar, Nason, Salam Zanderighi 16, 17; [28,29] NNPDF 18, 24; [30,31] MSHT 19, 22, 24; [32] CTEQ 22; [33] PDF4LHC21; [34] CTEQ 21; [35] MSHT 21; [36] ABM 17; [37] NNPDF 17; [38] iHixs 2 18

Quark Mass Corrections Overview

Main Formula

$$\sigma_{ij} = R_{\text{LO}} C^2 \left(\sigma_{ij}^{\text{LO,HTL}} + \sigma_{ij}^{\text{NLO,HTL}} + \sigma_{ij}^{\text{NNLO,HTL}} + \sigma_{ij}^{\text{N}^3\text{LO,HTL}} \right) + \delta\sigma_{ij}^{\text{LO,(t,b,c)}} + \delta\sigma_{ij}^{\text{NLO,(t,b,c)}} + \delta\sigma_{ij}^{\text{NNLO,(t,b,c)}}$$

Mass Corrections

$$\delta\sigma_{ij}^{\text{N}^n\text{LO,(t,b,c)}} = \delta\sigma_{ij}^{\text{N}^n\text{LO,(t)}} + \sigma_{ij}^{\text{N}^n\text{LO,(b)}} + \sigma_{ij}^{\text{N}^n\text{LO,(c)}} + \delta\sigma_{ij}^{\text{N}^n\text{LO,(t}\times\text{b)}} + \sigma_{ij}^{\text{N}^n\text{LO,(t}\times\text{c)}} + \sigma_{ij}^{\text{N}^n\text{LO,(b}\times\text{c)}}$$

$$\delta\sigma_{ij}^{\text{N}^n\text{LO,(t)}} = \sigma_{ij}^{\text{N}^n\text{LO,(t)}} - \left[C_{\text{QCD}}^2 R_{\text{LO}} \sigma_{ij}^{\text{HTL}} \right]_{\alpha_s^{n+2}},$$

Dominant Contributions

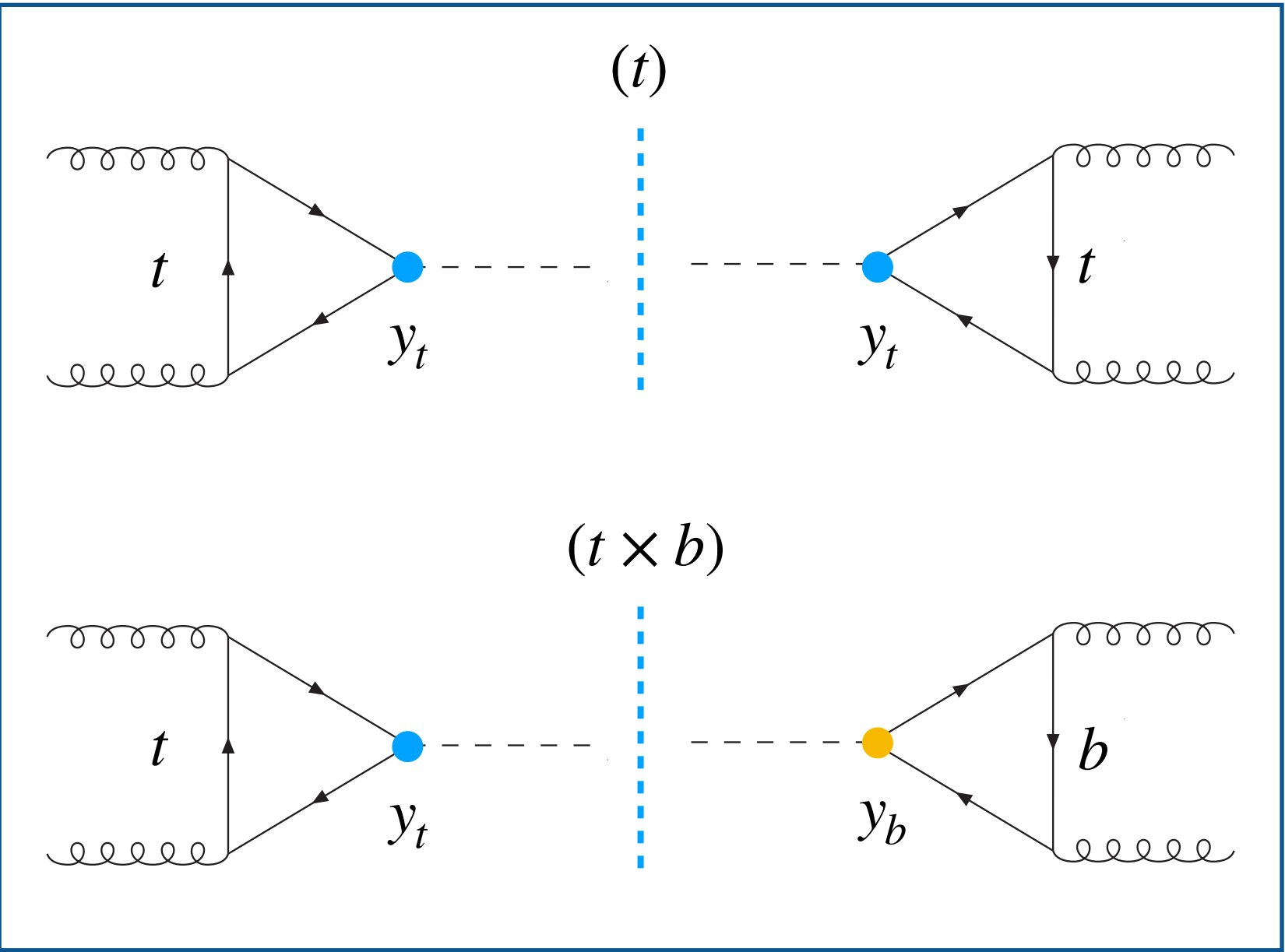
$$M_t^{\text{OS}} = 172.5 \text{ GeV}, M_b^{\overline{\text{MS}}}(M_b^{\overline{\text{MS}}}) = 4.18 \text{ GeV}, M_c^{\overline{\text{MS}}}(3\text{GeV}) = 0.986 \text{ GeV}$$

$\sqrt{s} = 13.6 \text{ TeV}$							
	$\sigma^{(t,b,c)}$ [pb]	$\sigma^{(t)}$ [pb]	$\sigma^{(b)}$ [pb]	$\sigma^{(c)}$ [pb]	$\sigma^{(t\times b)}$ [pb]	$\sigma^{(t\times c)}$ [pb]	$\sigma^{(b\times c)}$ [pb]
σ^{LO}	+15.865	+17.115	+0.045	+0.000	-1.172	-0.131	+0.008
σ^{NLO}	+21.347	+22.035	+0.063	+0.001	-0.673	-0.101	+0.012
σ^{NNLO}	—	+10.103	—	—	+0.04	—	—
Total	—	+49.253	—	—	-1.805	—	—

LHCHWG Summary Report 25

NNLO Numbers: Czakon, Niggetiedt, Harlander, Klappert, Eschment, Poncelet, Schellenberger

Based on: Czakon, Niggetiedt 20; Czakon, Harlander, Klappert, Niggetiedt 21; Czakon Eschment, Niggetiedt (Poncelet, Schellenberger) 24 (24);



We can estimate missing higher order effects for mass corrections via **scale variations** and **scheme uncertainties**

Higgs Production in Gluon Fusion (Report 5)

Final result receives contributions from many sources, biggest challenge is to assess uncertainties related to combining these results

$$\delta(\text{theory}) = \delta(\text{scale}) + \delta(\text{EWK}) + \delta(t, b, c)$$

$$\delta(t, b, c) = \delta^{\text{scheme}}(t) + \delta^{\text{MHOU}}(t) + \delta^{\text{scheme}}(t \times b) + \delta^{\text{MHOU}}(t \times b) + \delta^{\text{MHOU}}(b, c, t \times c, b \times c)$$

$\pm 0.01\%$ $\pm 0.17\%$ $\pm 0.09\%$ $\pm 0.17\%$ $\pm 0.06\%$

$$\delta(\text{PDF} + \alpha_s) = \sqrt{\delta(\text{PDF})^2 + \delta(\alpha_s)^2}$$

NNLO PDF: PDF4LHC21
aN³LO PDF: MSHT20xNNPDF40

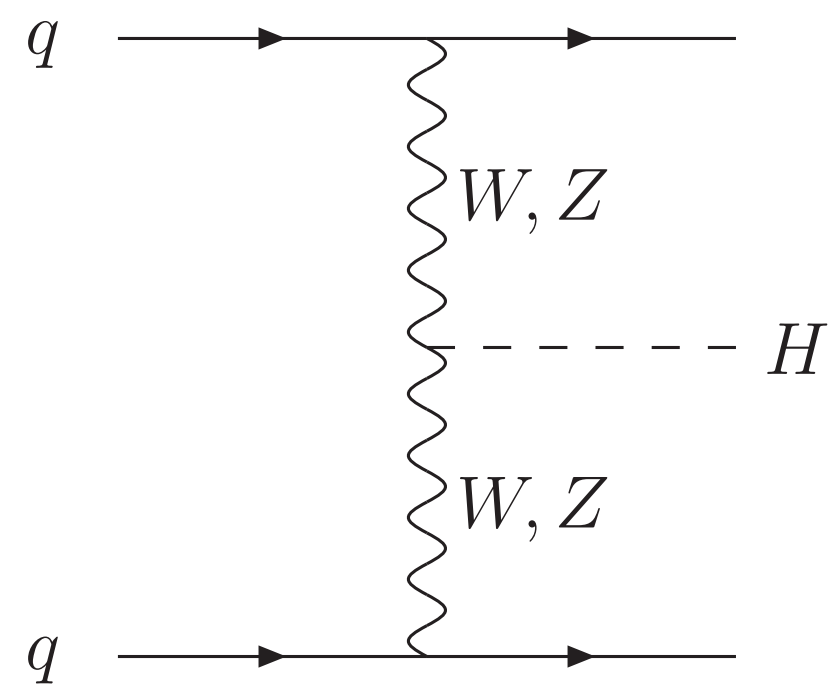
$$\delta(\text{PDF} - \text{TH}) = \pm |\sigma^{(2),\text{HTL,NNLO}} - \sigma^{(2),\text{HTL,NLO}}|$$

Table 4: Total ggH cross sections in the SM for a LHC CM energy of $\sqrt{s} = 13.6$ TeV.

$\sqrt{s} = 13.6$ TeV						NNLO PDF				aN ³ LO PDF				
M_{H} [GeV]	σ [pb]	$\delta(\text{theory})$	$\delta(\text{scale})$	$\delta(\text{EWK})$	$\delta(\text{t, b, c})$	$\delta(\text{PDF} + \alpha_s)$	$\delta(\text{PDF})$	$\delta(\alpha_s)$	$\delta(\text{PDF-TH})$	Δ [pb]	$\delta(\text{PDF} + \alpha_s)$	$\delta(\text{Gauss})$	$\delta(\text{Total})$	$\delta(\text{Total(Gauss)})$
120.00	55.54	$^{+1.65}_{-4.66}\%$	$^{+0.31}_{-3.32}\%$	$\pm 1.00\%$	$\pm 0.34\%$	$\pm 2.48\%$	$^{+1.65}_{-1.65}\%$	$\pm 1.85\%$	$\pm 2.42\%$	-2.56	$^{+1.73}_{-1.73}\%$	$\pm 4.09\%$	$^{+4.76}_{-7.50}\%$	$\pm 4.78\%$
122.00	53.97	$^{+1.66}_{-4.65}\%$	$^{+0.32}_{-3.31}\%$	$\pm 1.00\%$	$\pm 0.34\%$	$\pm 2.47\%$	$^{+1.65}_{-1.65}\%$	$\pm 1.84\%$	$\pm 2.40\%$	-2.49	$^{+1.73}_{-1.73}\%$	$\pm 4.07\%$	$^{+4.75}_{-7.47}\%$	$\pm 4.76\%$
124.00	52.46	$^{+1.65}_{-4.65}\%$	$^{+0.31}_{-3.31}\%$	$\pm 1.00\%$	$\pm 0.34\%$	$\pm 2.46\%$	$^{+1.64}_{-1.64}\%$	$\pm 1.84\%$	$\pm 2.37\%$	-2.43	$^{+1.74}_{-1.74}\%$	$\pm 4.05\%$	$^{+4.71}_{-7.44}\%$	$\pm 4.74\%$
124.60	52.02	$^{+1.65}_{-4.65}\%$	$^{+0.31}_{-3.31}\%$	$\pm 1.00\%$	$\pm 0.34\%$	$\pm 2.46\%$	$^{+1.64}_{-1.64}\%$	$\pm 1.84\%$	$\pm 2.36\%$	-2.41	$^{+1.74}_{-1.74}\%$	$\pm 4.05\%$	$^{+4.70}_{-7.43}\%$	$\pm 4.74\%$
124.80	51.87	$^{+1.65}_{-4.65}\%$	$^{+0.31}_{-3.31}\%$	$\pm 1.00\%$	$\pm 0.34\%$	$\pm 2.46\%$	$^{+1.64}_{-1.64}\%$	$\pm 1.83\%$	$\pm 2.36\%$	-2.41	$^{+1.74}_{-1.74}\%$	$\pm 4.05\%$	$^{+4.70}_{-7.43}\%$	$\pm 4.73\%$
125.00	51.72	$^{+1.65}_{-4.65}\%$	$^{+0.31}_{-3.31}\%$	$\pm 1.00\%$	$\pm 0.34\%$	$\pm 2.46\%$	$^{+1.64}_{-1.64}\%$	$\pm 1.83\%$	$\pm 2.36\%$	-2.40	$^{+1.74}_{-1.74}\%$	$\pm 4.05\%$	$^{+4.70}_{-7.43}\%$	$\pm 4.73\%$
125.09	51.66	$^{+1.65}_{-4.65}\%$	$^{+0.31}_{-3.31}\%$	$\pm 1.00\%$	$\pm 0.34\%$	$\pm 2.46\%$	$^{+1.64}_{-1.64}\%$	$\pm 1.83\%$	$\pm 2.36\%$	-2.40	$^{+1.74}_{-1.74}\%$	$\pm 4.05\%$	$^{+4.70}_{-7.43}\%$	$\pm 4.73\%$
125.20	51.58	$^{+1.65}_{-4.65}\%$	$^{+0.31}_{-3.31}\%$	$\pm 1.00\%$	$\pm 0.34\%$	$\pm 2.46\%$	$^{+1.64}_{-1.64}\%$	$\pm 1.83\%$	$\pm 2.35\%$	-2.39	$^{+1.74}_{-1.74}\%$	$\pm 4.04\%$	$^{+4.69}_{-7.42}\%$	$\pm 4.73\%$
125.30	51.51	$^{+1.65}_{-4.64}\%$	$^{+0.31}_{-3.30}\%$	$\pm 1.00\%$	$\pm 0.34\%$	$\pm 2.46\%$	$^{+1.64}_{-1.64}\%$	$\pm 1.83\%$	$\pm 2.35\%$	-2.39	$^{+1.74}_{-1.74}\%$	$\pm 4.04\%$	$^{+4.69}_{-7.41}\%$	$\pm 4.72\%$
125.38	51.45	$^{+1.65}_{-4.64}\%$	$^{+0.31}_{-3.30}\%$	$\pm 1.00\%$	$\pm 0.34\%$	$\pm 2.46\%$	$^{+1.64}_{-1.64}\%$	$\pm 1.83\%$	$\pm 2.35\%$	-2.39	$^{+1.74}_{-1.74}\%$	$\pm 4.04\%$	$^{+4.69}_{-7.41}\%$	$\pm 4.72\%$
125.60	51.29	$^{+1.65}_{-4.64}\%$	$^{+0.31}_{-3.30}\%$	$\pm 1.00\%$	$\pm 0.34\%$	$\pm 2.46\%$	$^{+1.64}_{-1.64}\%$	$\pm 1.83\%$	$\pm 2.35\%$	-2.38	$^{+1.74}_{-1.74}\%$	$\pm 4.04\%$	$^{+4.69}_{-7.41}\%$	$\pm 4.72\%$
126.00	51.01	$^{+1.65}_{-4.64}\%$	$^{+0.31}_{-3.30}\%$	$\pm 1.00\%$	$\pm 0.34\%$	$\pm 2.46\%$	$^{+1.64}_{-1.64}\%$	$\pm 1.83\%$	$\pm 2.34\%$	-2.37	$^{+1.74}_{-1.74}\%$	$\pm 4.03\%$	$^{+4.69}_{-7.40}\%$	$\pm 4.72\%$
128.00	49.62	$^{+1.64}_{-4.63}\%$	$^{+0.30}_{-3.29}\%$	$\pm 1.00\%$	$\pm 0.34\%$	$\pm 2.45\%$	$^{+1.64}_{-1.64}\%$	$\pm 1.83\%$	$\pm 2.32\%$	-2.31	$^{+1.74}_{-1.74}\%$	$\pm 4.01\%$	$^{+4.66}_{-7.37}\%$	$\pm 4.70\%$
130.00	48.28	$^{+1.64}_{-4.62}\%$	$^{+0.30}_{-3.28}\%$	$\pm 1.00\%$	$\pm 0.34\%$	$\pm 2.45\%$	$^{+1.64}_{-1.64}\%$	$\pm 1.82\%$	$\pm 2.30\%$	-2.25	$^{+1.74}_{-1.74}\%$	$\pm 4.00\%$	$^{+4.64}_{-7.34}\%$	$\pm 4.69\%$

$$\delta(\text{Gauss}) = (\max[|\delta(\text{theory})|] + \delta(+\text{PDF} - \text{TH})]/\sqrt{3}, \quad \delta(\text{Total}) = \sqrt{(\delta(\text{theory}) + \delta(\text{PDF} - \text{TH}))^2 + \delta(\text{PDF} + \alpha_s)^2}, \quad \delta(\text{Total}(\text{Gauss})) = \sqrt{\delta(\text{Gauss})^2 + \delta(\text{PDF} + \alpha_s)^2}$$

Higgs Production: Vector Boson Fusion (VBF)

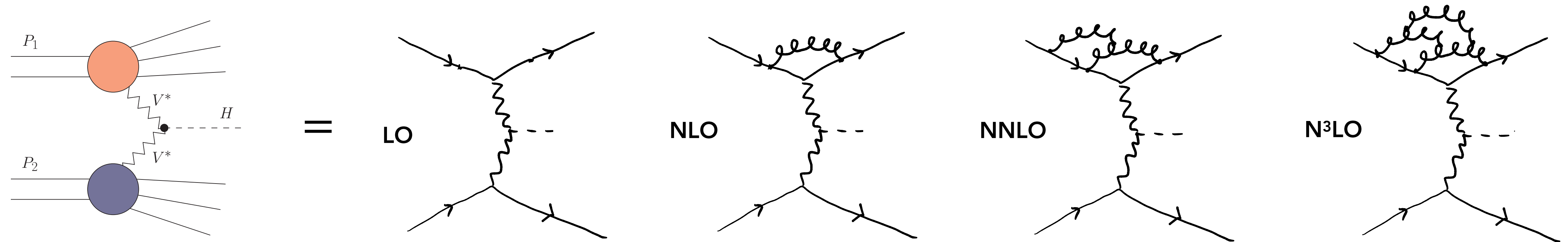


Vector Boson Fusion (VBF)

$pp \rightarrow Hjj$ with **fiducial** cuts to enhance VBF component: 2 jets, $p_{T,j} > 30 \text{ GeV}$, $m_{jj} > 300 \text{ GeV}$, $|\Delta y_{jj}| > 2$

Known to exclusively (inclusively) to NNLO (N3LO) in the **structure function / DIS approximation**

Dreyer, Karlberg 16; Cacciari, Dreyer, Karlberg, Salam, Zanderighi 15,18; Cruz-Martinez, Gehrmann, Glover, Huss 18



NLO: **non-factorisable** virtual contribution vanishes due to colour conservation

NNLO: get colour suppressed **non-factorisable** contribution



Vector Boson Fusion (VBF)

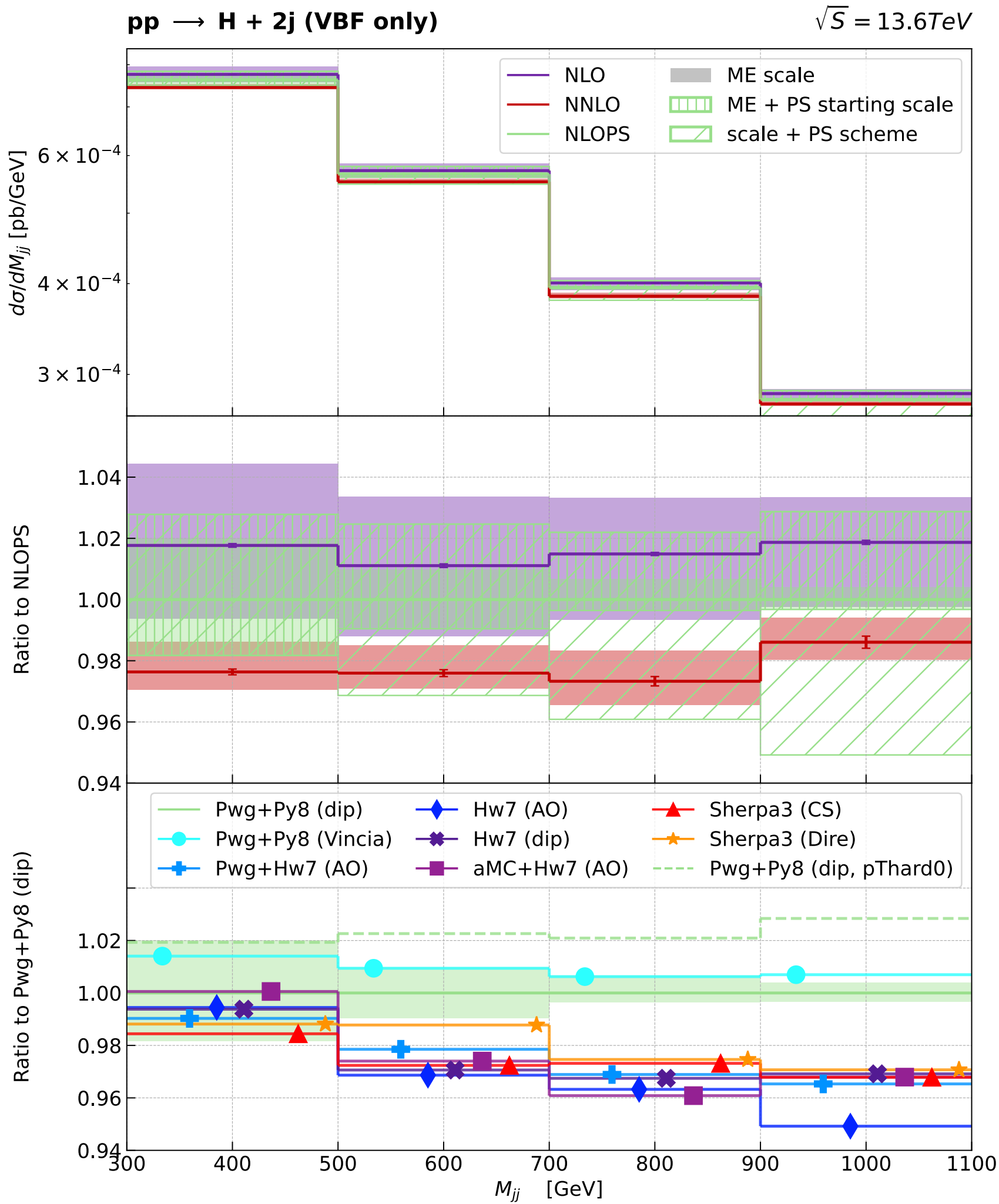
Significant theoretical effort to produce state-of-the-art predictions for this channel

Need fiducial predictions combining many different pieces and approximations

A. Buckley, et al 21; LHCHWG-2025-003

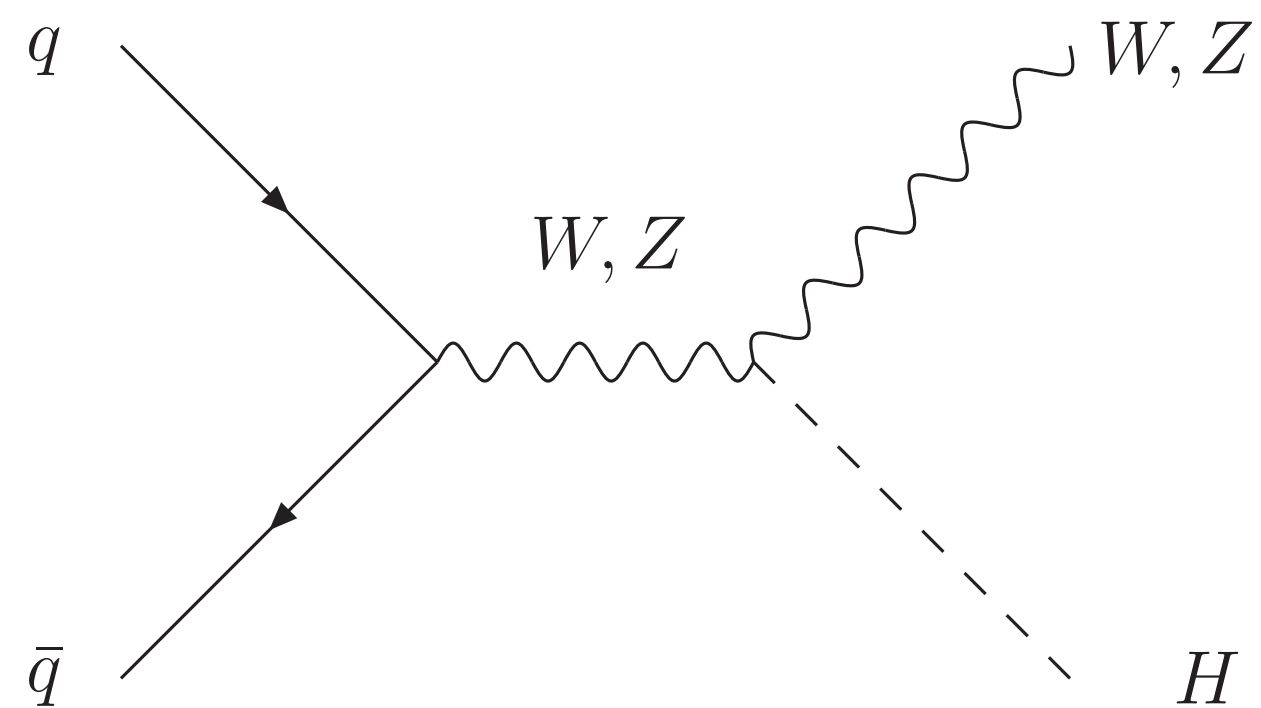
Order	σ [pb]	δ [%]
VBF approx.		
LO [α^3]	2.479(1)	-
NLO QCD [$\alpha^3\alpha_s$]	-0.300(3)	-12.1
NNLO QCD [$\alpha^3\alpha_s^2$]	-0.088(7)	-3.55
NNLO QCD non-fact. [$\alpha^3\alpha_s^2$]	-0.0053766(7)	-0.22
Full		
LO [α^3]	2.4772(1)	-
NLO QCD [$\alpha^3\alpha_s$]	-0.2648(10)	-10.7
NLO EW [α^4]	-0.14759(5)	-5.95
Photon induced [α^4]	0.021286(2)	+0.86
Loop induced int. [$\alpha^2\alpha_s^2$]	-0.003301(1)	-0.01
Loop induced squ. [$\alpha\alpha_s^4$]	0.136403(9)	5.5
LO ggF [$\alpha\alpha_s^4$]	1.7751(6)	71.5
$g\gamma \rightarrow ggH$ [$\alpha^2\alpha_s^3$]	$4.3(1) \times 10^{-6}$	0.0
Best prediction		
pp $\rightarrow$ Hjj	2.041(9)	-17.6

Treatment of irreducible backgrounds (e.g. gluon-fusion) also involved



(b) $120\text{ GeV} < p_{T,H} < 260\text{ GeV}$

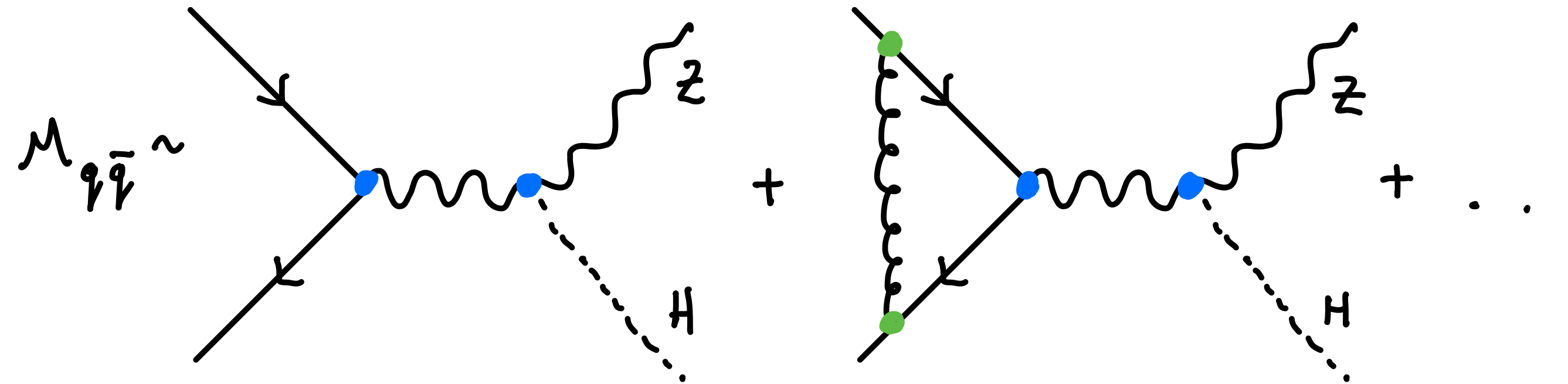
Higgs Production: W/Z Associated Production



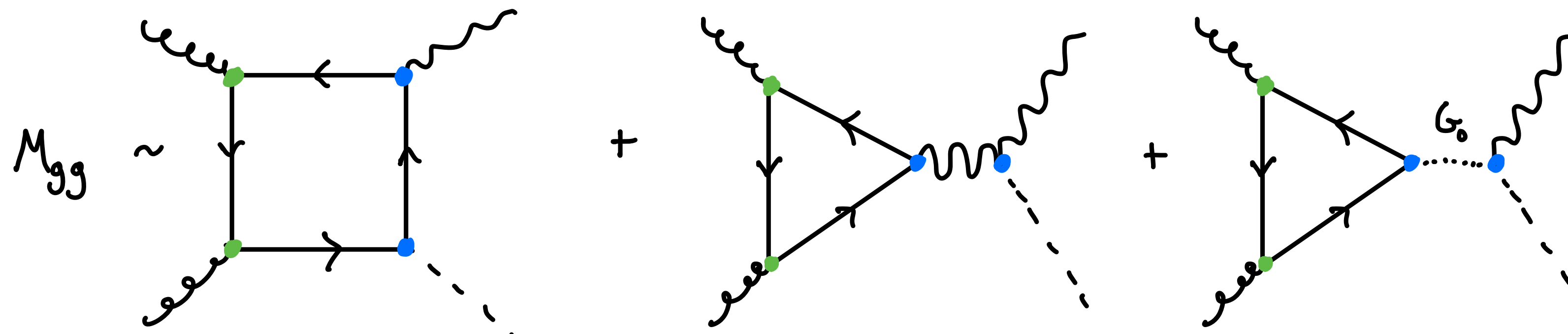
$pp \rightarrow ZH$

Production of ZH provides an interesting example of a channel where higher-order corrections can be suddenly enhanced

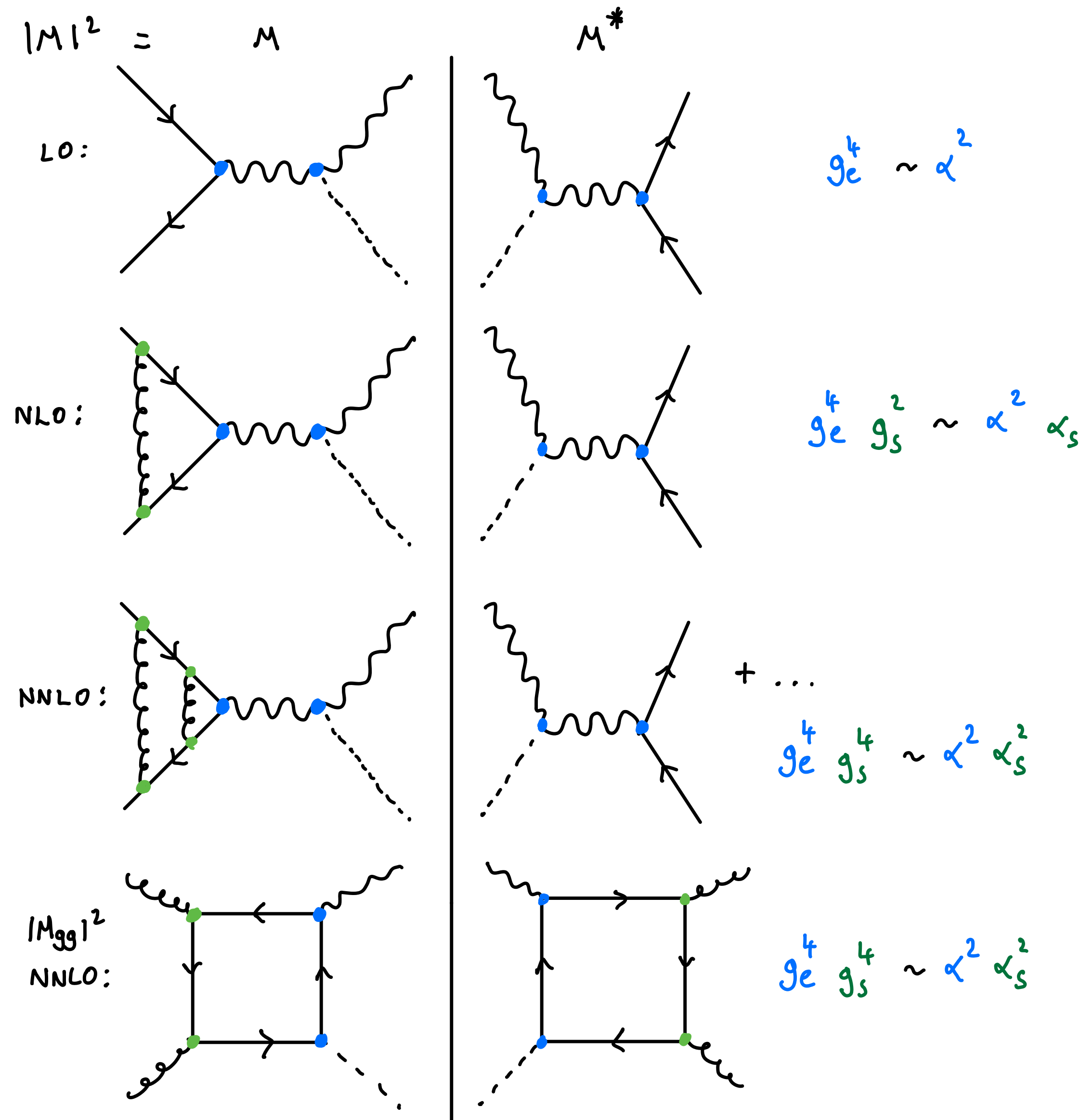
Consider the matrix element for $pp \rightarrow ZH$ with QCD corrections



As we consider higher orders, eventually we encounter a loop-induced (i.e. LO in this channel is 1-loop) $gg \rightarrow ZH$ channel



$pp \rightarrow ZH$



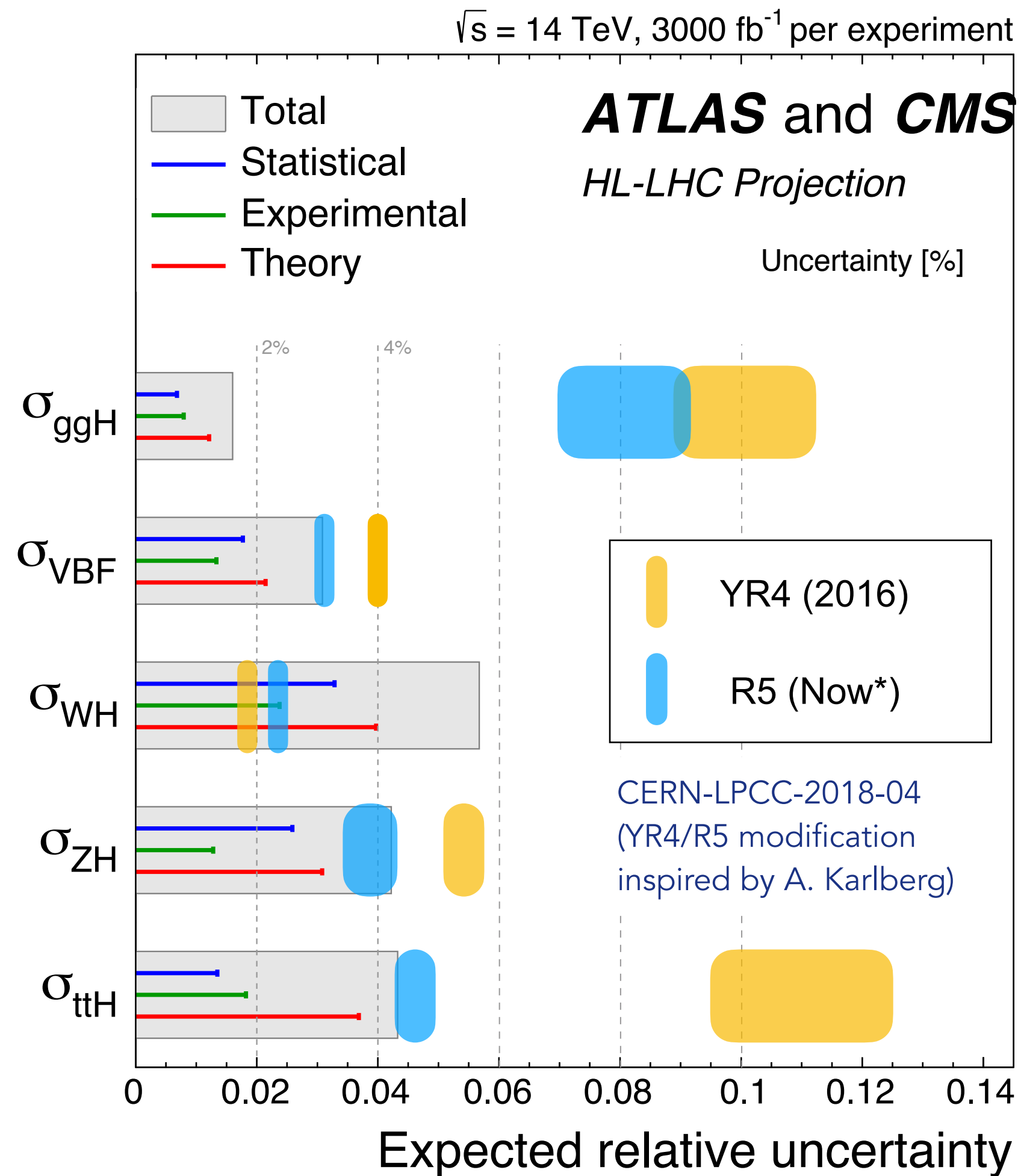
The $gg \rightarrow ZH$ channel contributes to $pp \rightarrow ZH$ starting at NNLO in QCD

However due the large gluon-gluon luminosity at the LHC it contributes significantly ($\sim 10\%$) to the total cross section

Furthermore as a loop-induced Higgs process, the higher-order corrections are large (about 100%), meaning even gluon-induced N3LO corrections are significant! Even more severe for distributions.

Q: Does the gg channel contribute to WH production? Why?

Higgs Working Group Summary



Community effort to stimulate TH and encourage EXP/TH communication

ggH: heavy-top @ $N^3\text{LO}$ + finite quark mass effects @ NNLO

Mistlberger 18; Czakon, Niggetiedt 20; Czakon, Harlander, Klappert, Niggetiedt 21; Czakon Eschment, Niggetiedt (Poncelet, Schellenberger) 24 (24);

ZH: $gg \rightarrow ZH$ @ NLO

Aveleira, Chen, Davies, Degrassi, Giardino, Gröber, Heinrich, SPJ, Kerner, Schlenk, Steinhauser, Vitti 25

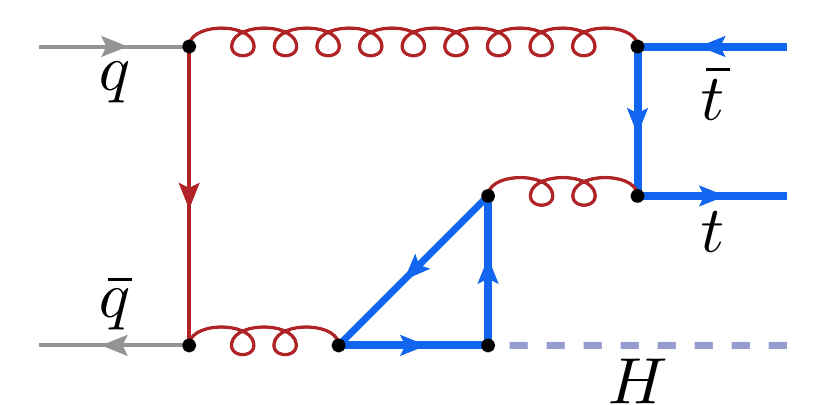
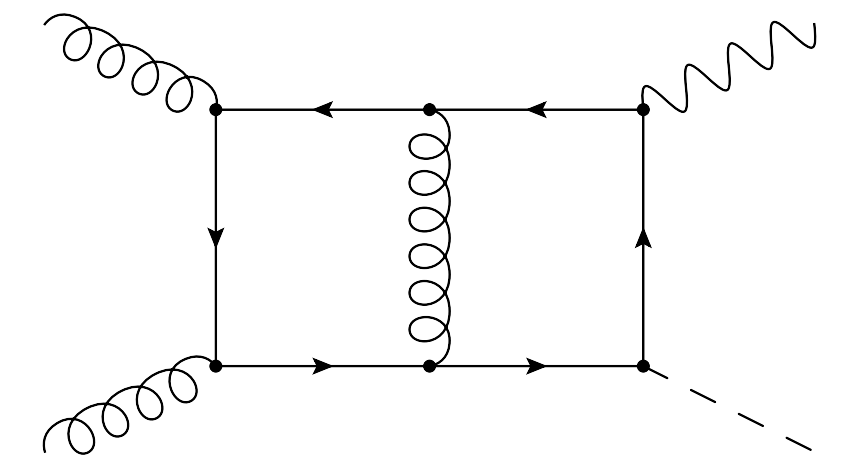
$t\bar{t}H$: approximate $t\bar{t}H$ @ NNLO

Catani, Devoto, Grazzini, Kallweit, Mazzitelli, Savoini 22; Wang, Xia, Lin Yang, Ye 24

Ongoing efforts to compute missing corrections

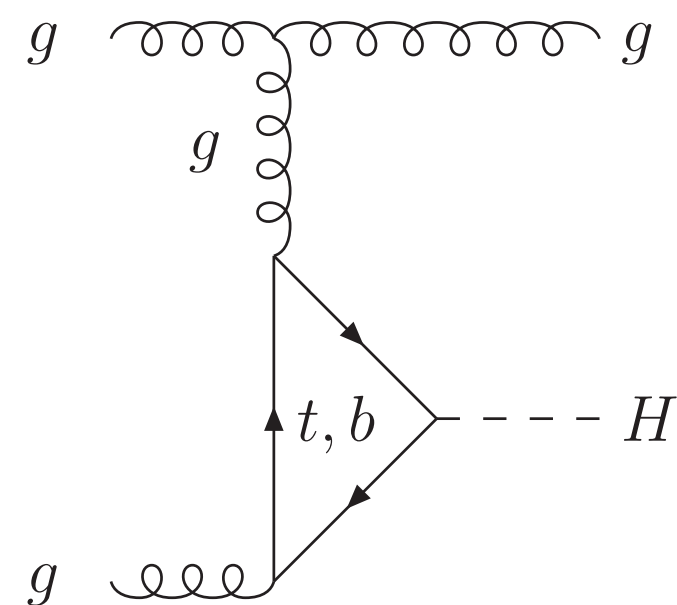
Febres Cordero, Figueiredo, Kraus, Page, Reina 23

Agarwal, Heinrich, SPJ, Kerner, Klein, Lang, Magerya, Olsson 24



This glosses over the (perhaps) more interesting differential measurements which allow us to probe higher energies

Boosted Higgs

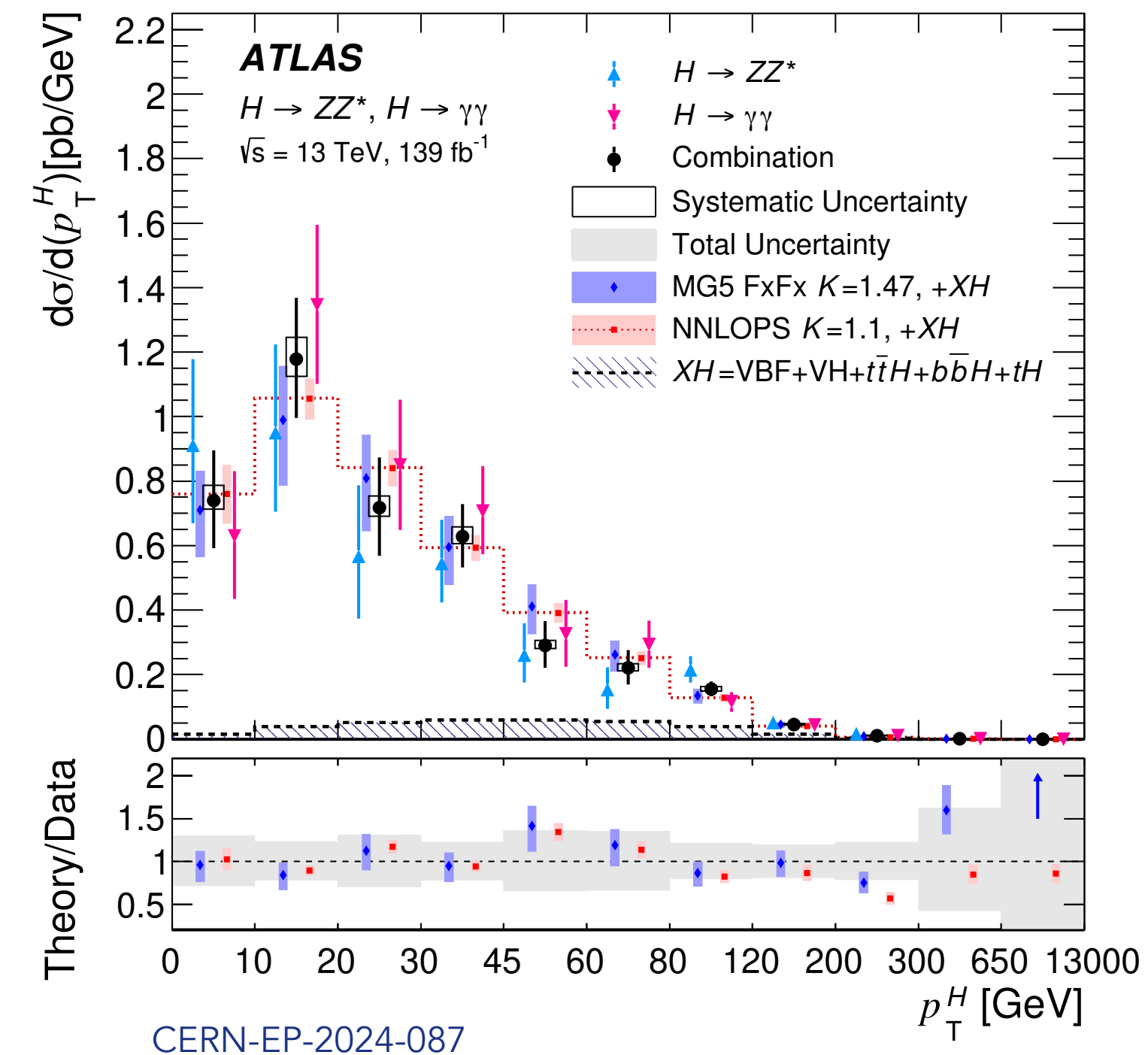
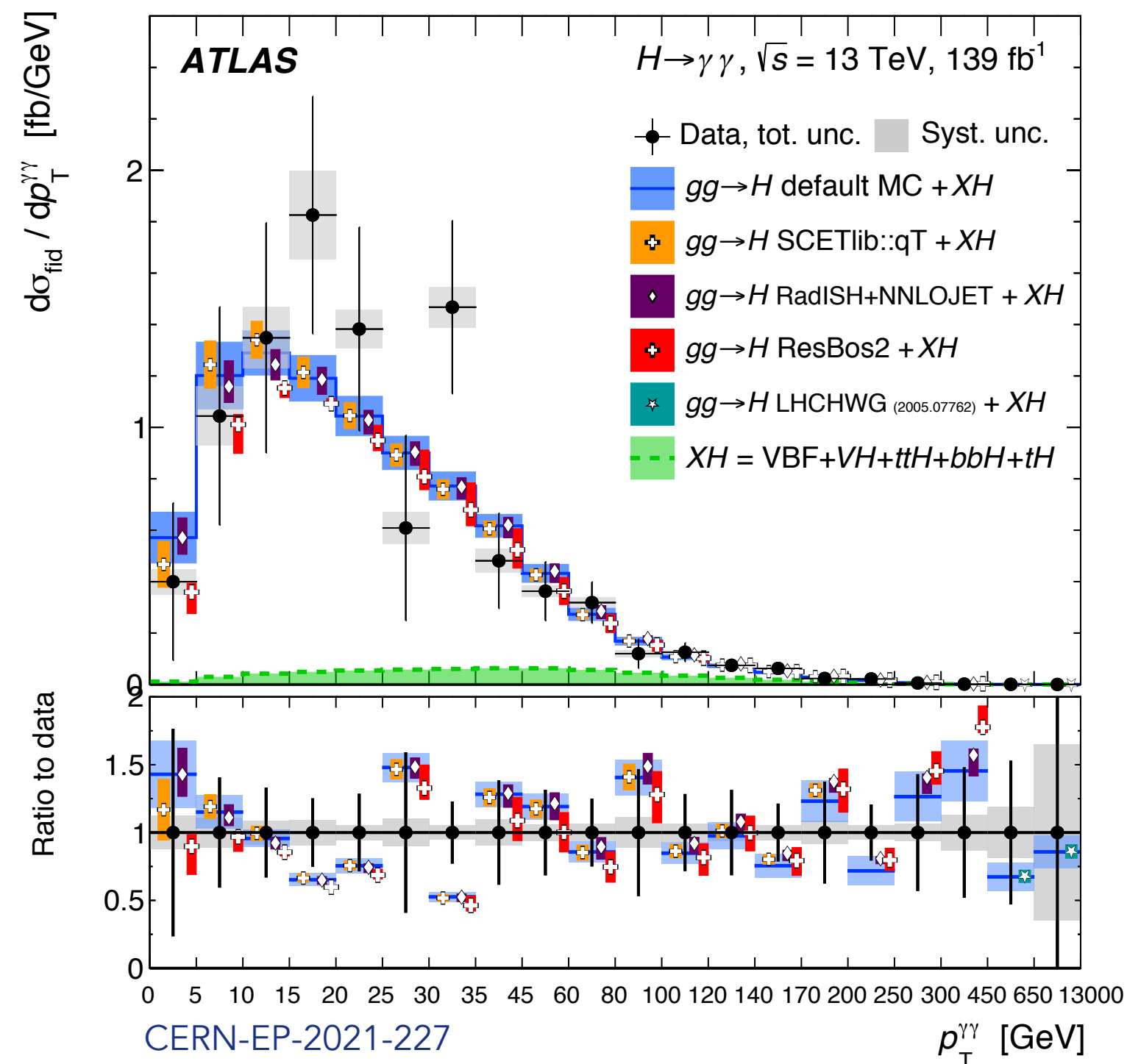
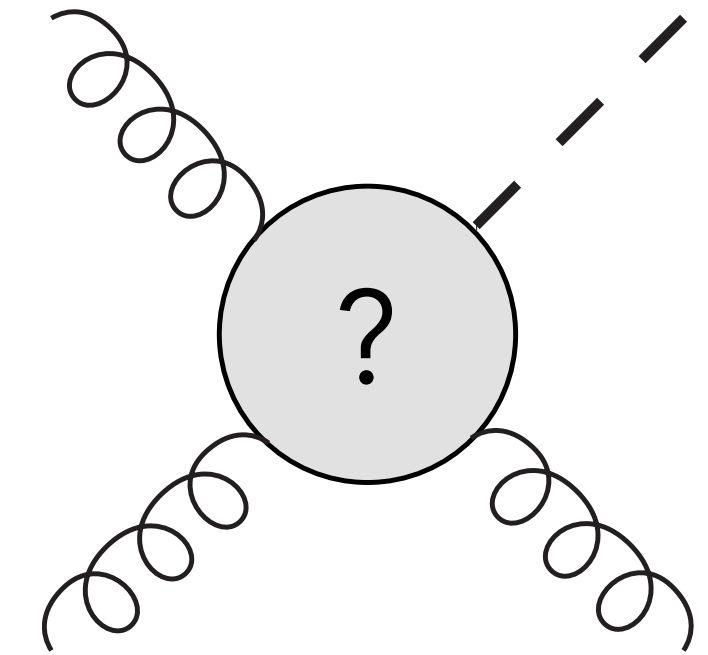


Boosted Higgs

Why might we want to study boosted (high- p_T) Higgs production?

At moderate/large p_T :

- Particles in the loop can be resolved
- May disentangle modified top quark Yukawa coupling from (BSM) point-like ggH coupling
- As we cross the top threshold, top mass becomes important!



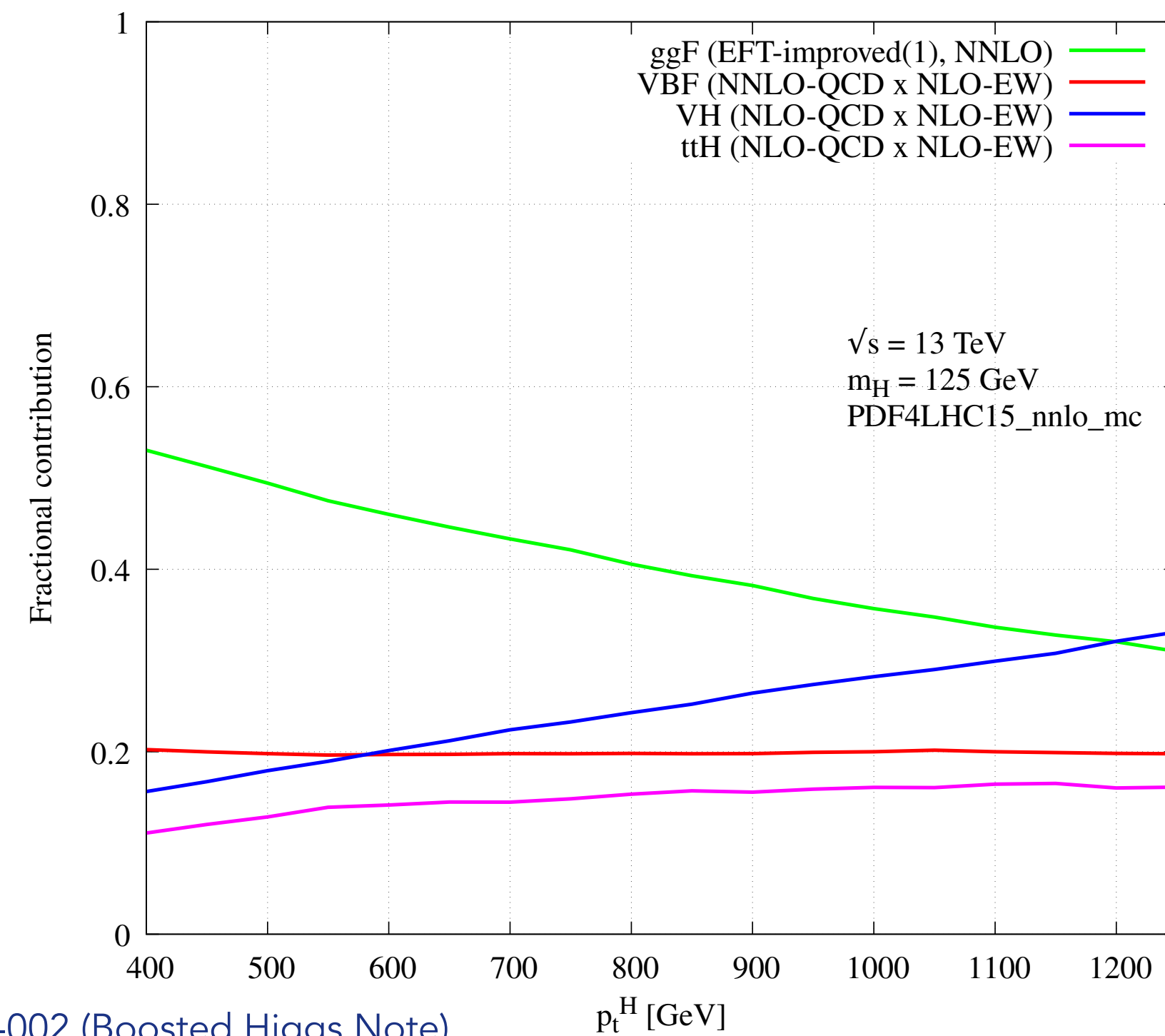
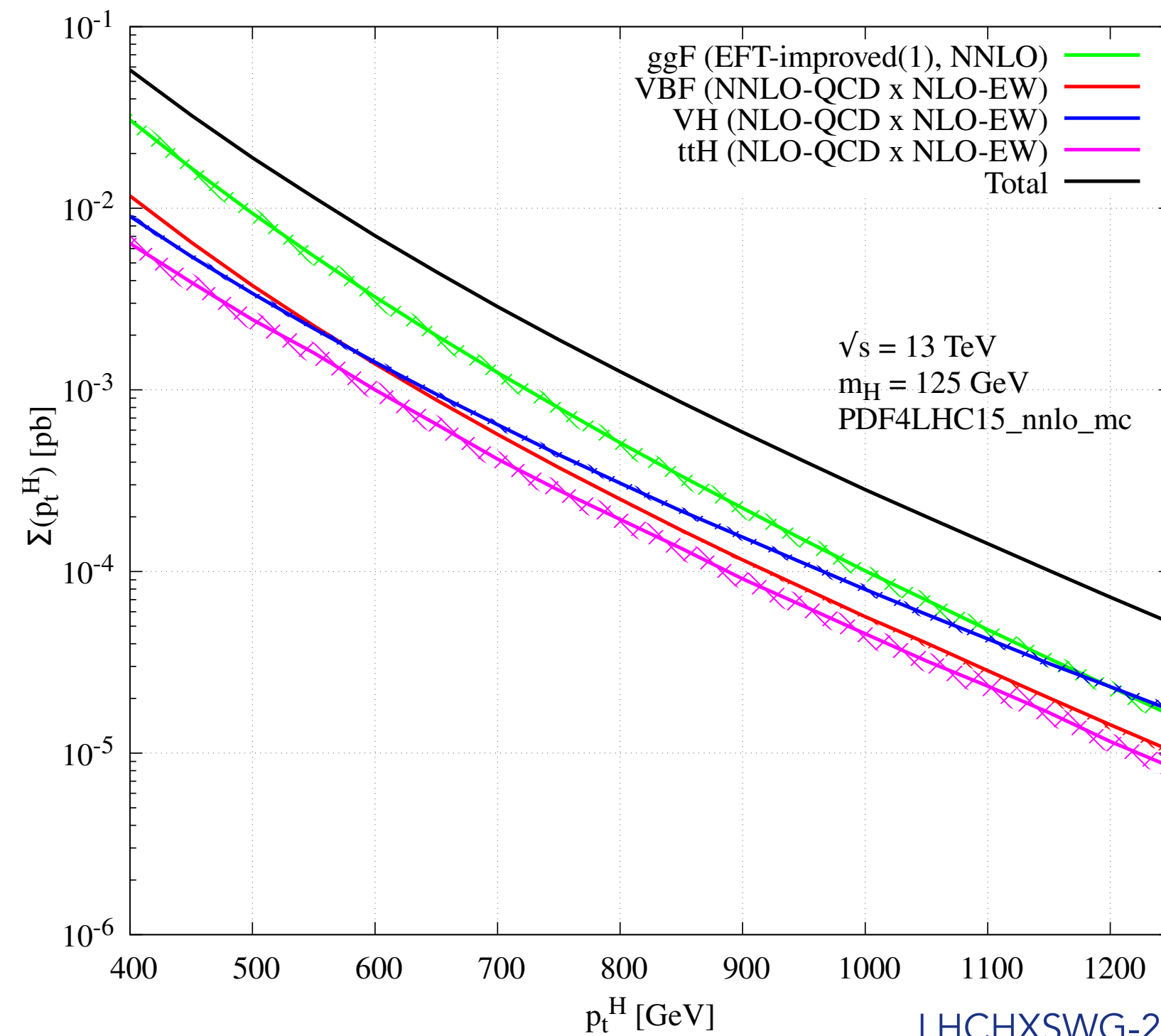
Boosted Higgs Contamination

Complicated interplay of channels relevant for high- p_T^H predictions

Fractional contribution of VBF approximately constant with p_T^H

+ ggF contamination decreases for boosted H

+ VH contamination increases for boosted H

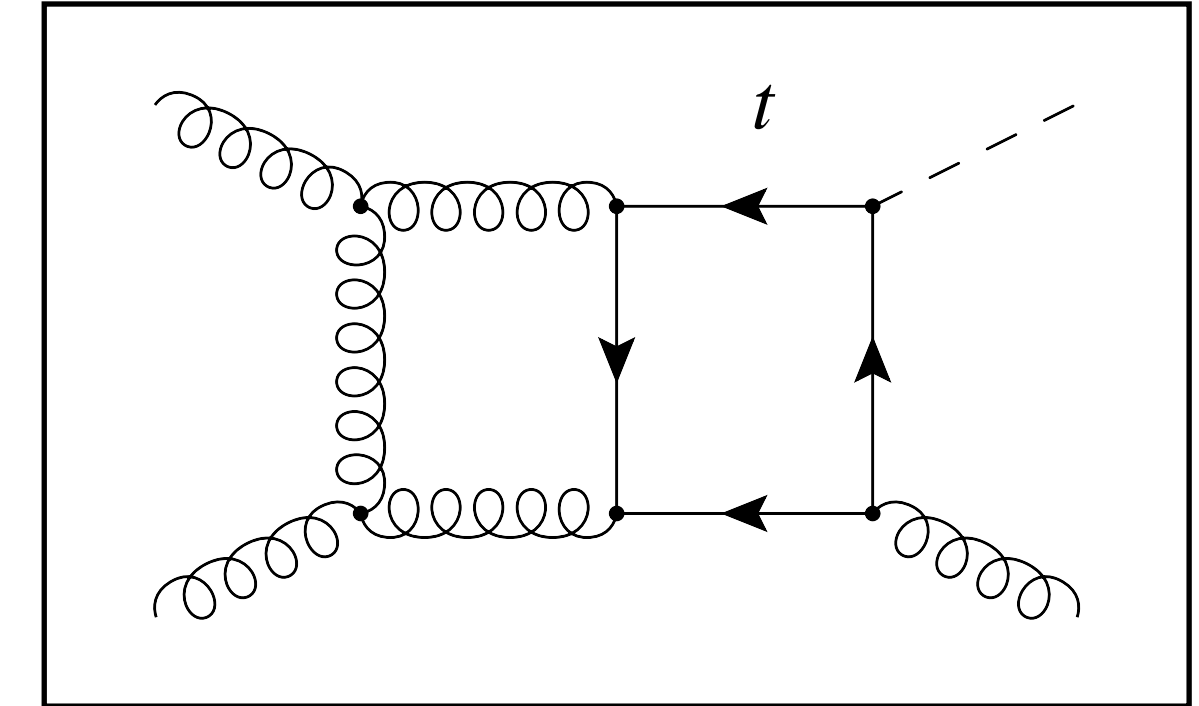
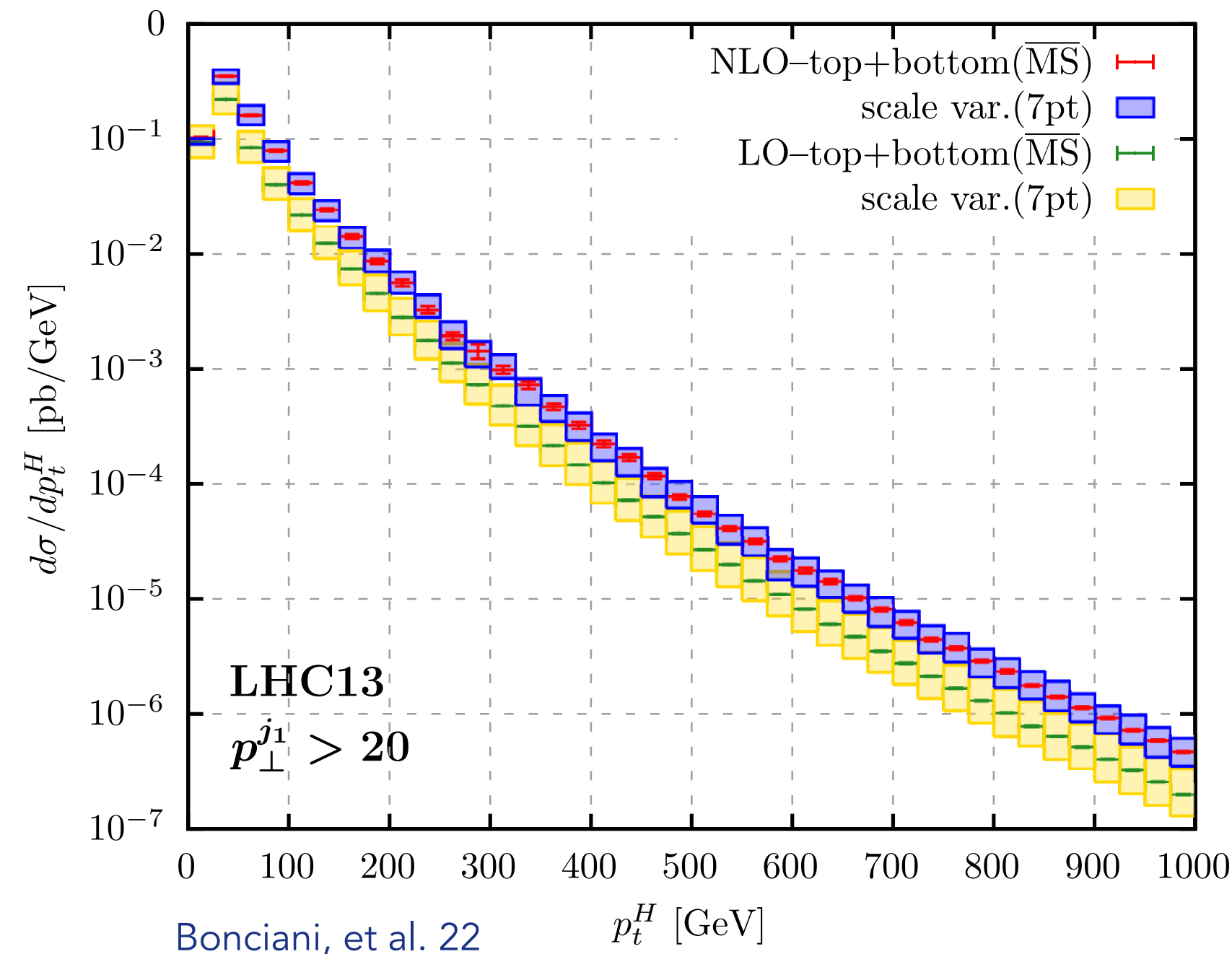


Future update on boosted Higgs requires input from several working groups

Boosted Higgs: NLO H+j

HTL not valid for $p_T \gtrsim m_t$: (b,t)-quark mass effects known for H+j at NLO

Bonciani, Del Duca, Frellesvig, Hidding, Hirschi, Moriello, Salvatori, Somogyi, Tramontano 22; Kudashkin, Melnikov, Wever, Lindert/ Neumann/ Chen, Huss, SPJ, Kerner, Lang, Luisoni, Zhang 18-21



renormalisation of internal masses	σ_{LO} [pb]	σ_{NLO} [pb]
top+bottom-($\overline{\text{MS}}$)	$12.318^{+4.711}_{-3.117}$	$19.89(8)^{+2.84}_{-3.19}$
top-($\overline{\text{MS}}$)	$12.538^{+4.822}_{-3.183}$	$19.90(8)^{+2.66}_{-2.85}$
top-(OS)	$12.551^{+4.933}_{-3.244}$	$20.22(8)^{+3.06}_{-3.09}$

Full NLO Result

Enhances cross-section by $\sim 1.6x$

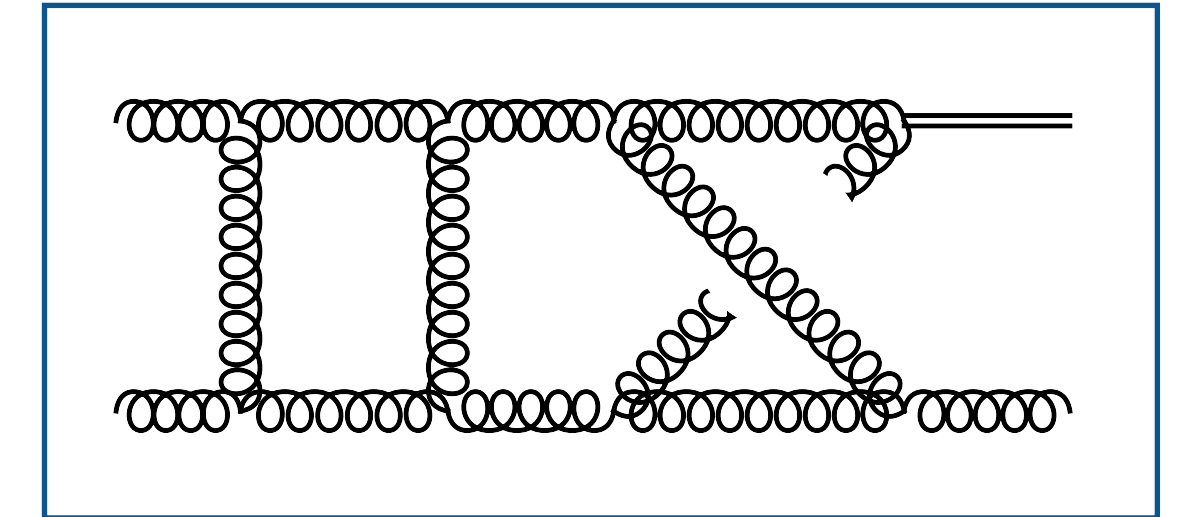
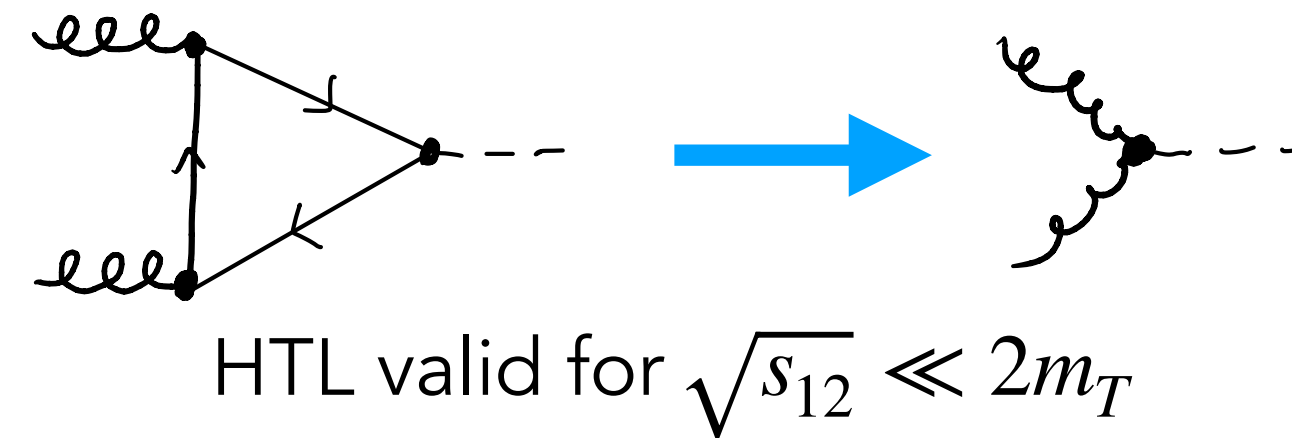
Significantly reduces scale uncertainty

Top quark mass scheme uncertainty reduced but comparable to scale uncertainty

Higgs + Jet @ $N^3\text{LO}_{\text{HTL}}$

Work in the Heavy Top Limit (HTL)

$$\mathcal{L}_{eff} = \mathcal{L}_{SM,5} - \frac{C^0}{4} H G_a^{\mu\nu} G_{a,\mu\nu}$$



Chen, Guan, Mistlberger 25

Virtual amplitudes for Higgs + Jet @ 3 Loop

Generalised leading colour $\{N_c^6, N_c^5 n_f, N_c^4 n_f^2, N_c^3 n_f^3\}$

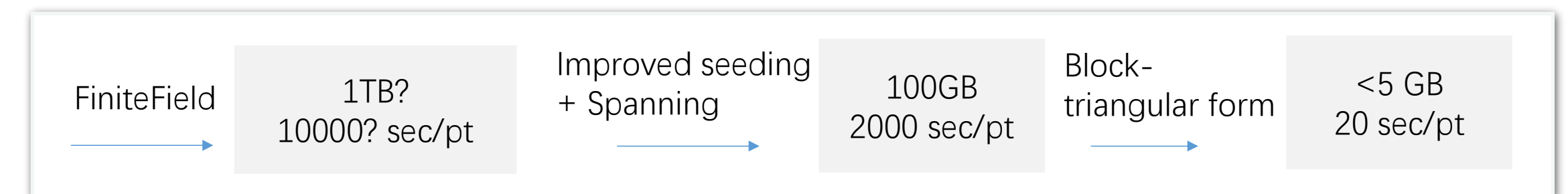
Reduction

Very challenging calculation involving difficult IBP reduction

Non-planar, Rank 6, 305 master integrals per family

Blade (+improved seeding $\rightarrow$ seed with different ranks in different sectors)

Guan, Liu, Ma, Wu 24; Liu, Ma 18; Guan, Liu, Ma 20; Driesse, Jakobsen, Mogull, Plefka, Sauer, Usovitsch 24



Guan (QCD@LHC 2025)

Master Integrals

3-loop massless + one off-shell leg

Planar + non-planar result expressed in terms of GPLs

Many sectors in literature, remaining 2 computed

Further topologies required to obtain sub-leading colour

Vita, Mastrolia, Schubert, Yundin 14

Canko, Syrrakos 21, 23

Henn, Lim, Torres Bobadilla 23

Gehrmann, Henn, Jakubcik, Lim, Mella, Syrrakos, Tancredi, Torres Bobadilla 24

Higgs + Jet @ NLO_{EW}

Two independent calculations of EW corrections to HJ

Kira + Fire + Blade → 3600 Master Integrals

Klappert, Lange, Maierhöfer, Usovitsch 08; Smirnov 15; Guan, Liu, Ma, Wu 24;

Find basis with d and invariants factorising & at most linear in d

Boundary conditions for master integrals using AMFlow Liu, Ma, Wang 18;
Liu, Ma 23;

Solve differential equations numerically

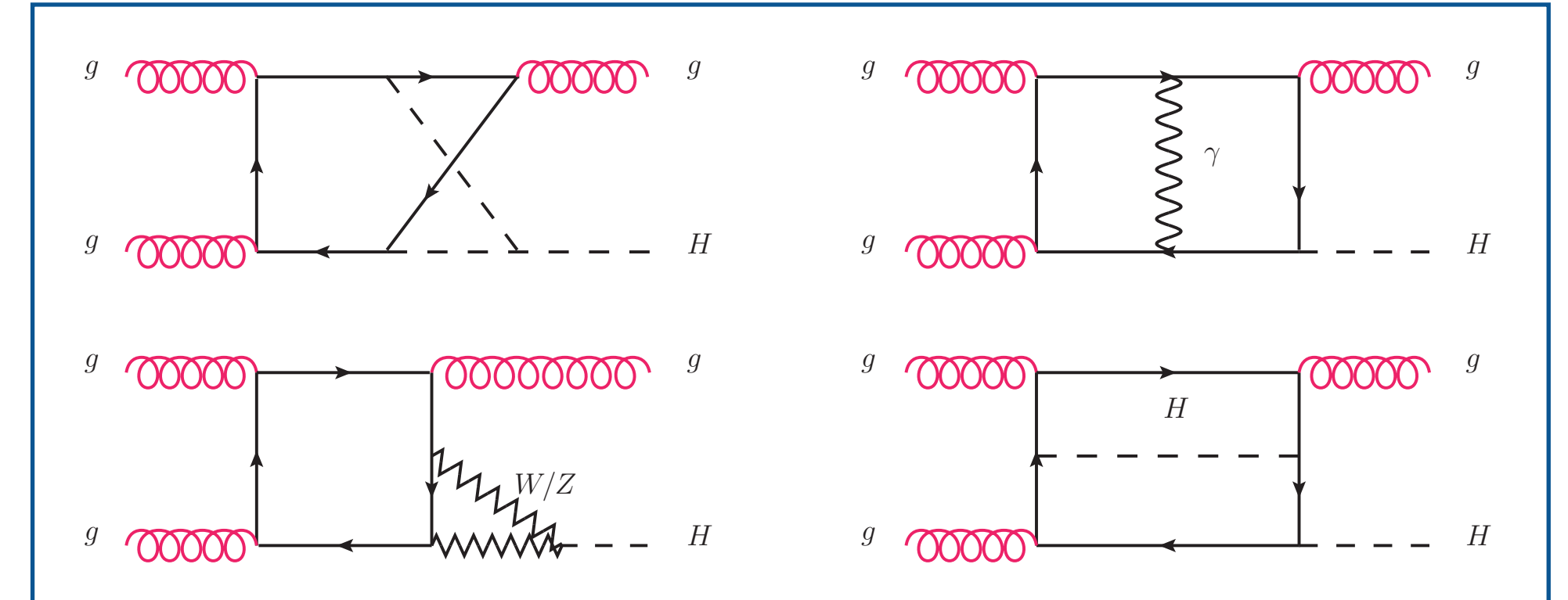
Chen, Li, Sang 25

Blade + FiniteFlow fixing ϵ numerically Peraro 19

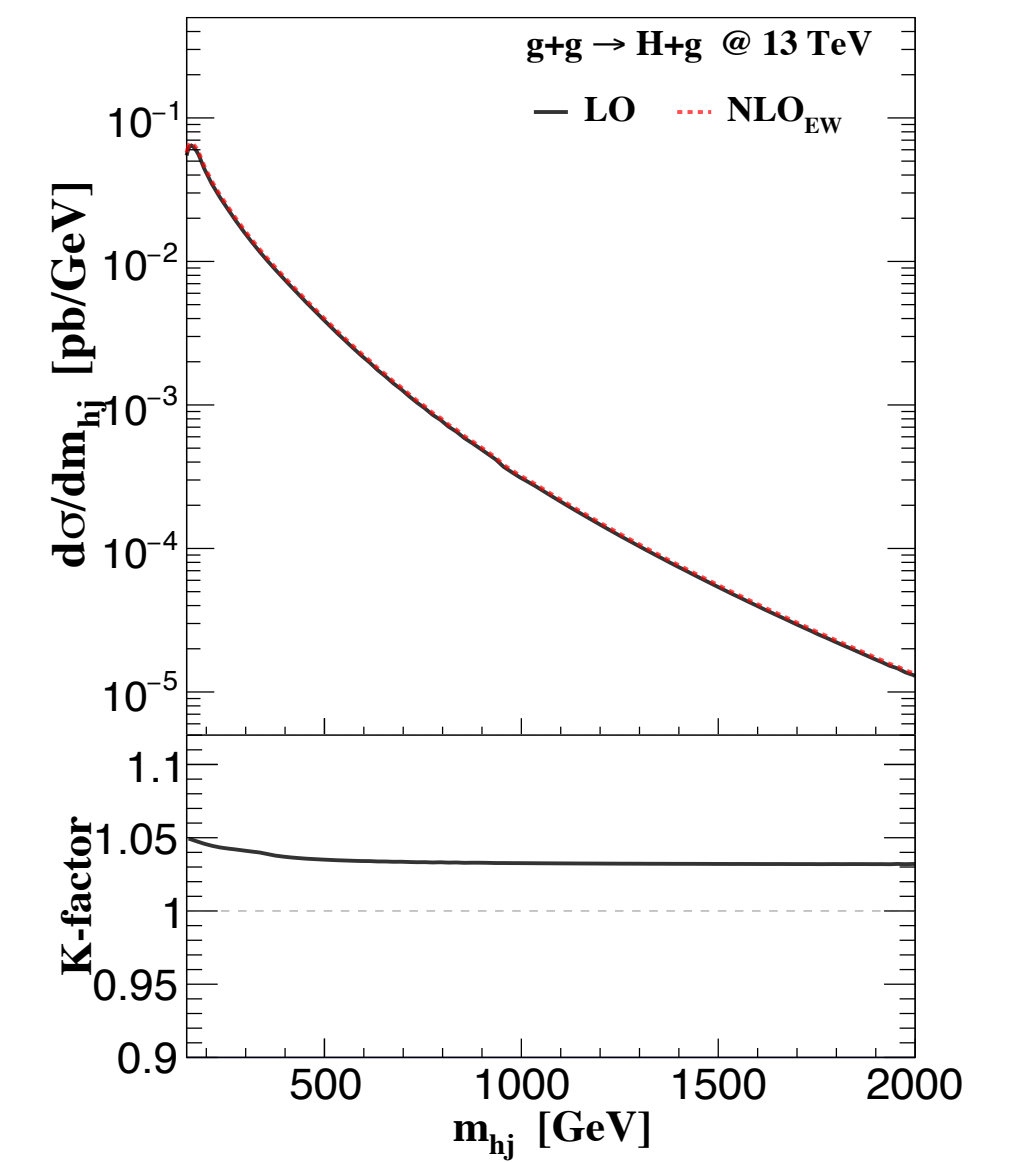
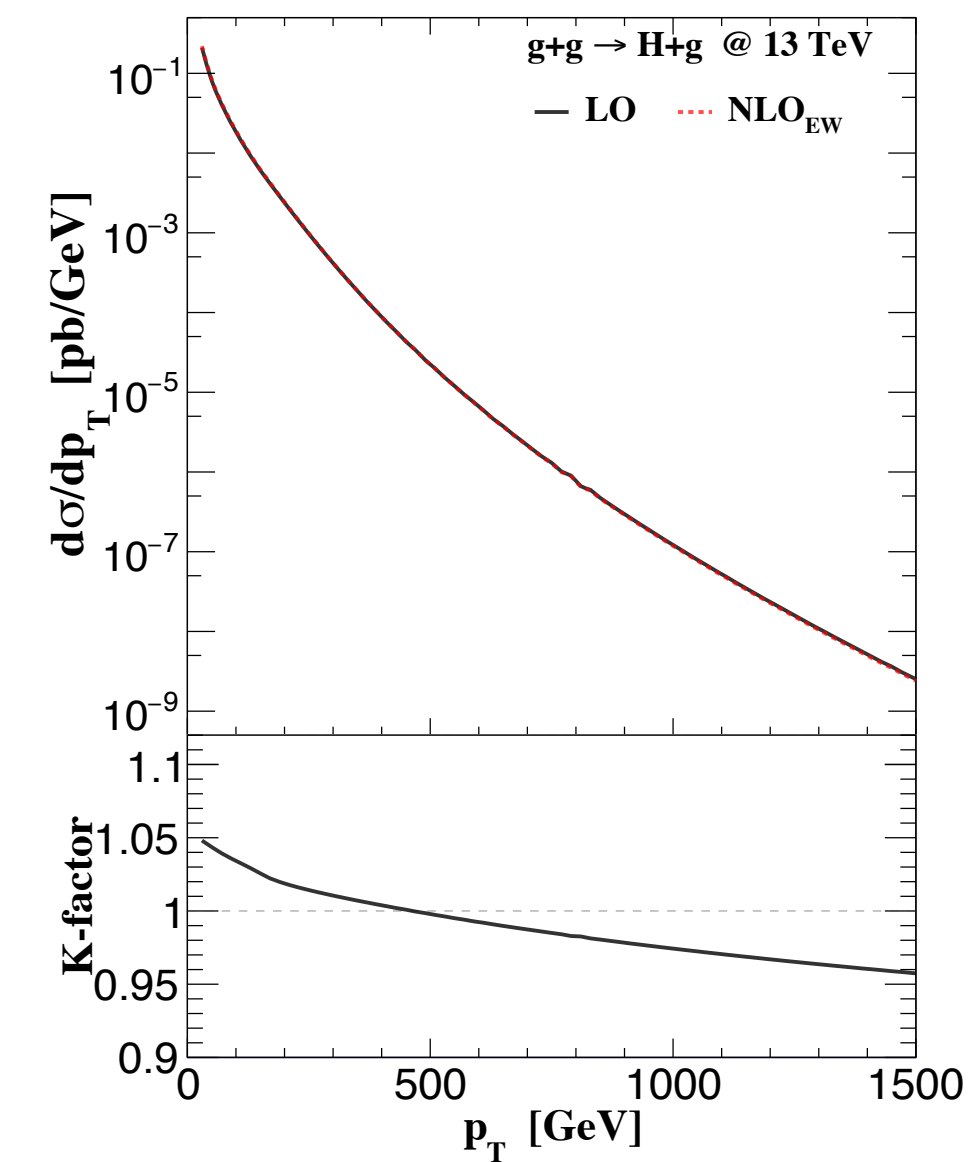
Compute master integrals using AMFlow

Bi, Ma, Mu 25

Both groups find that the EW corrections enhance the cross-section by around 4-5%, K-factor depends on p_T



Bi, Ma, Mu 25; Chen, Li, Sang 25;



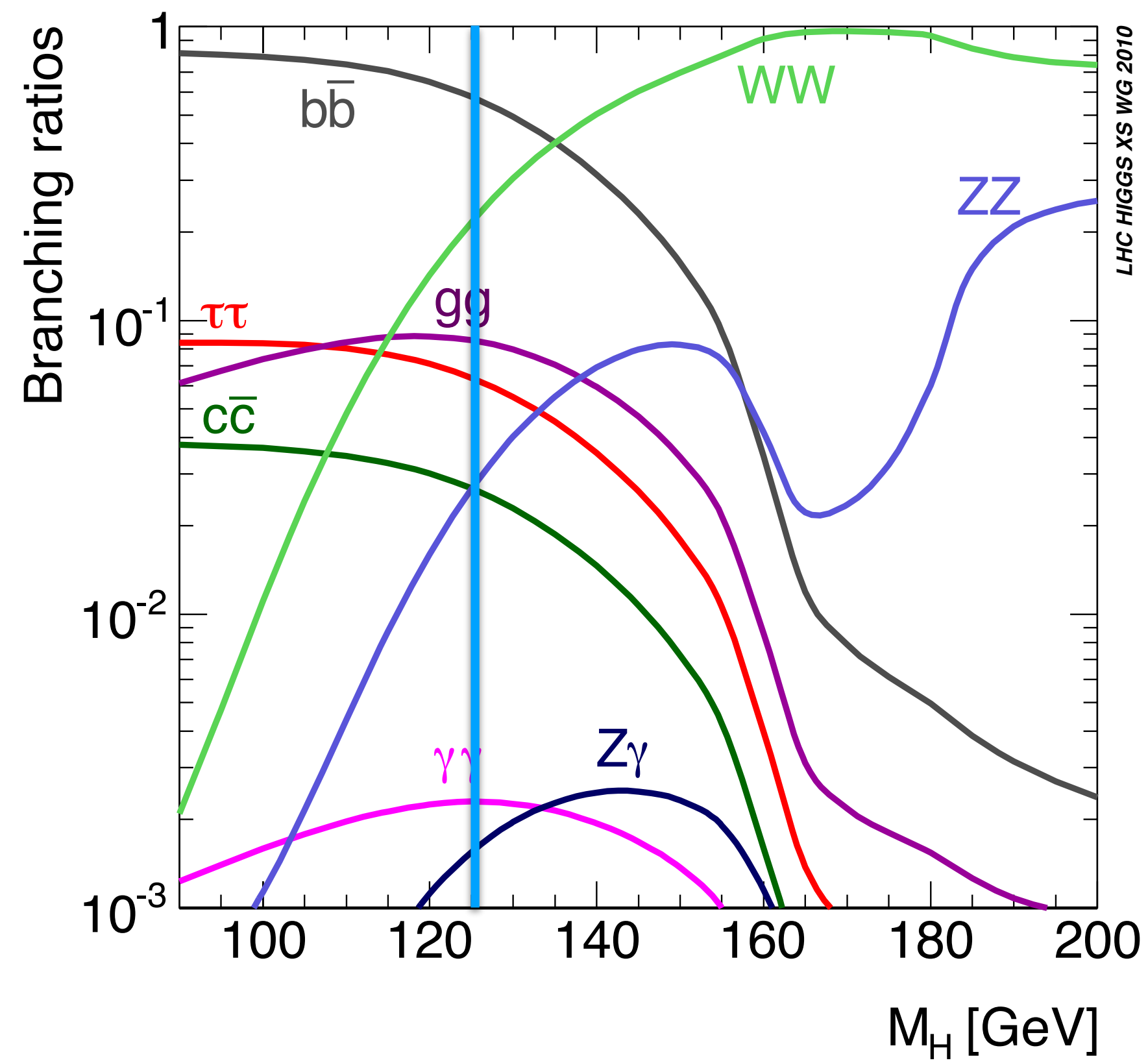
Chen, Li, Sang 25;

Higgs Decays & Couplings

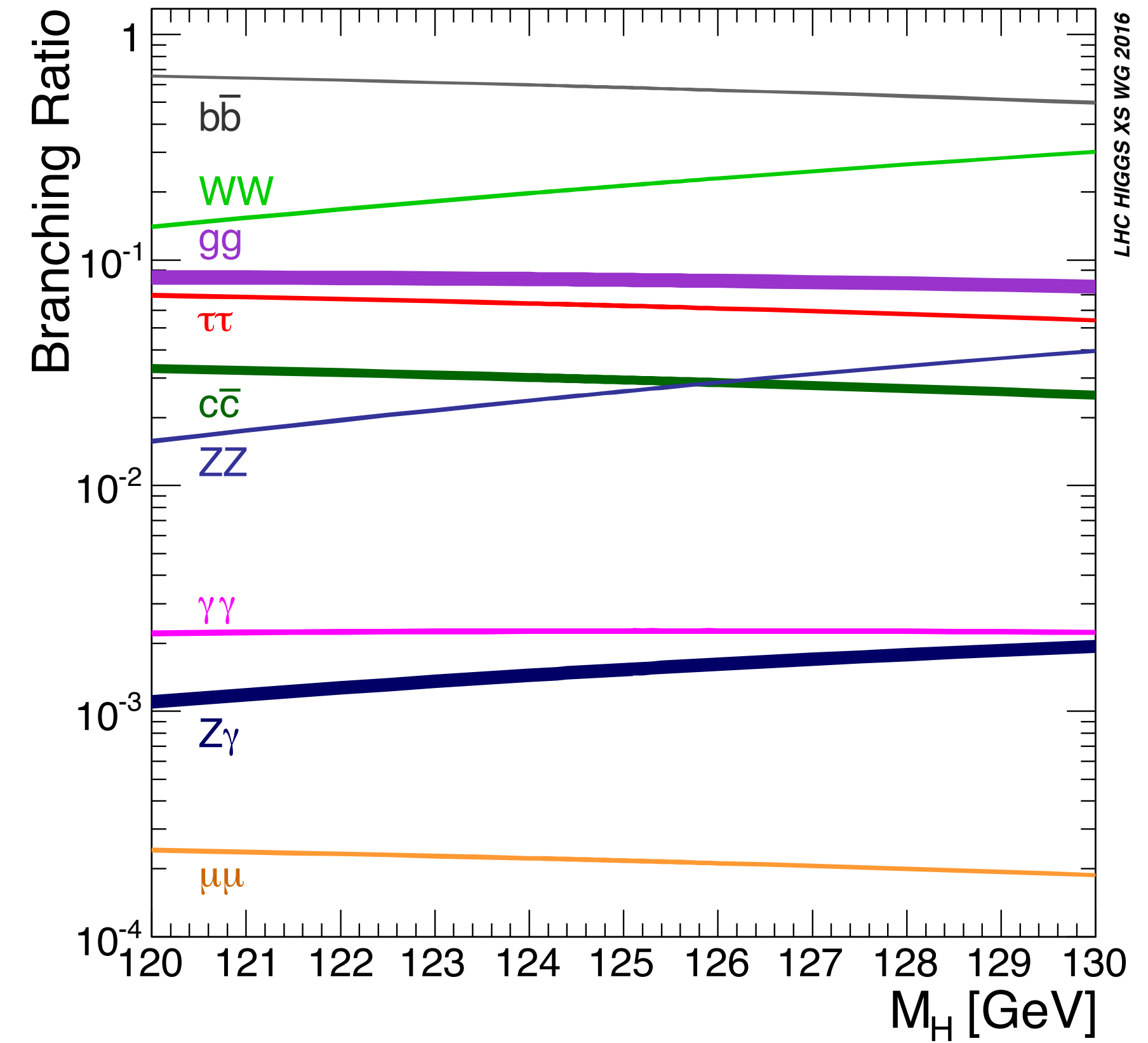
Higgs Decay

The value of the Higgs boson mass means that many decays are possible in the SM

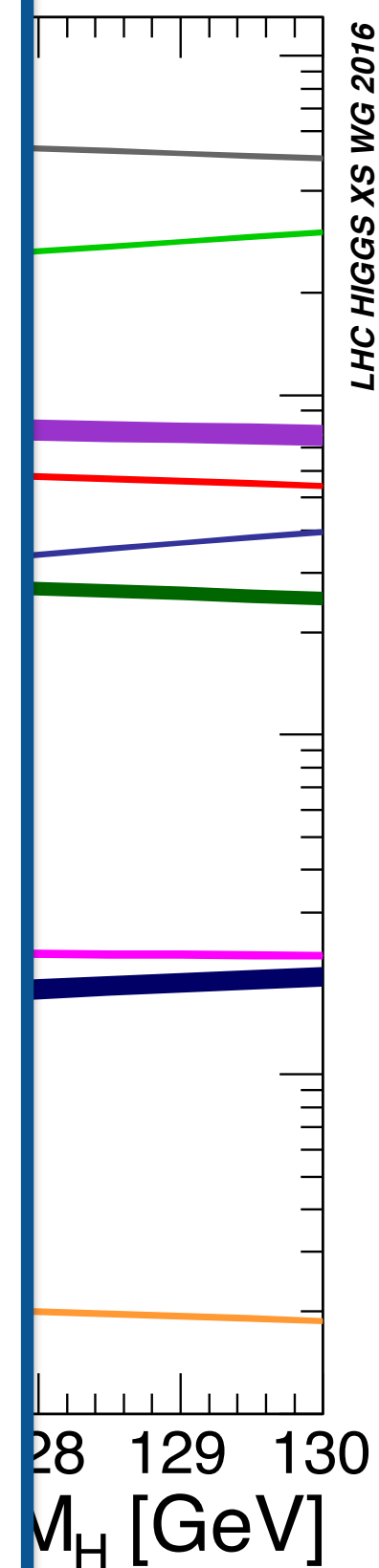
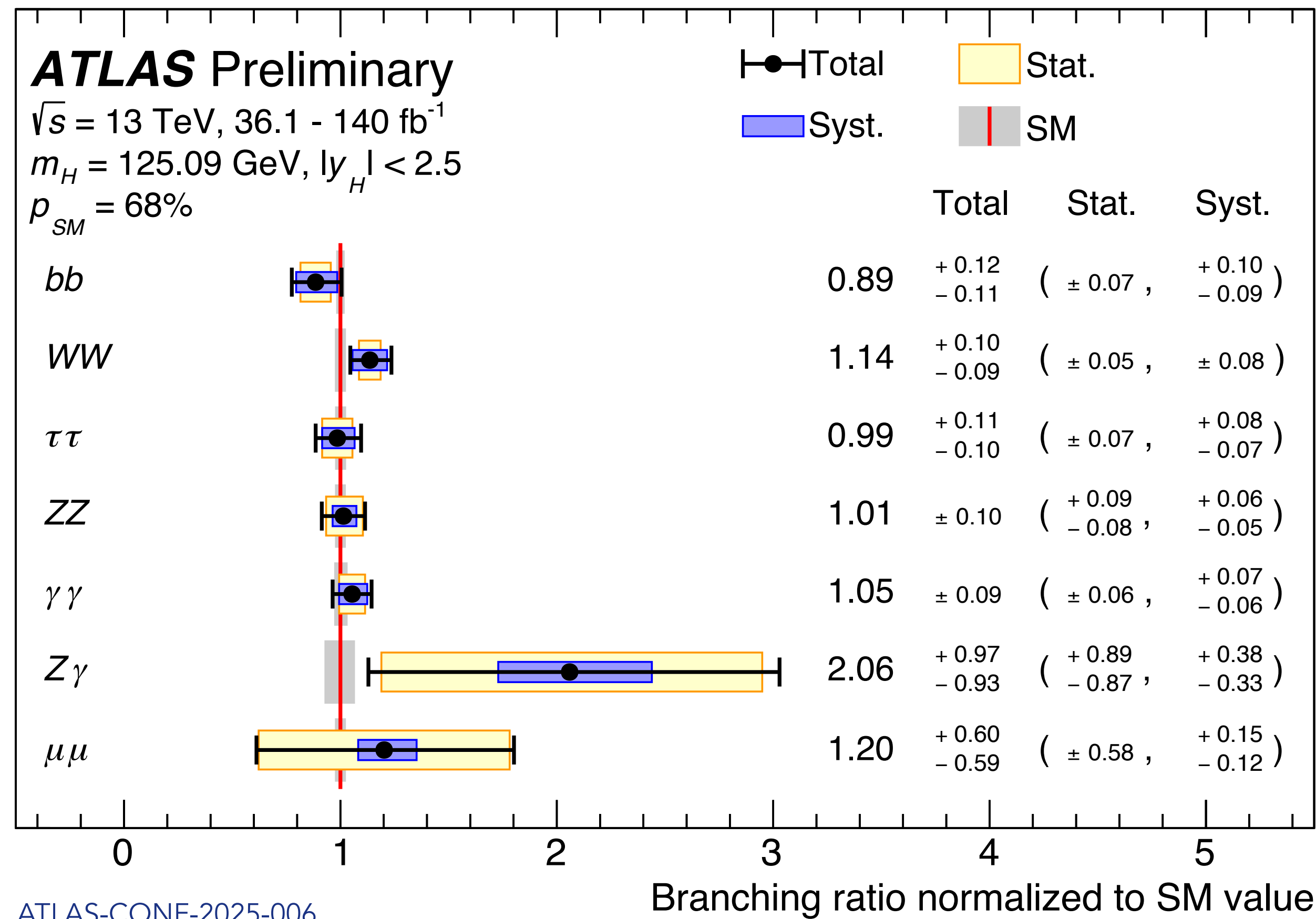
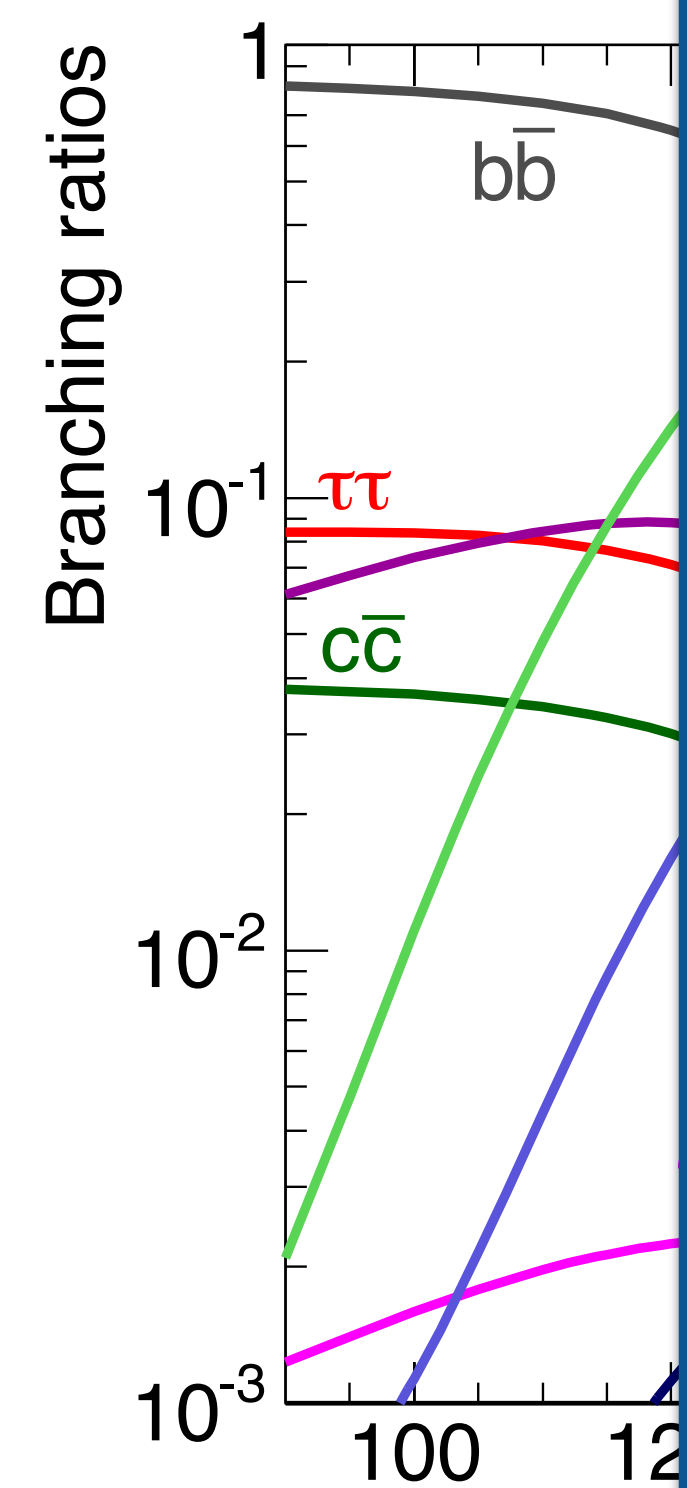
This makes the study of Higgs decays very rich!



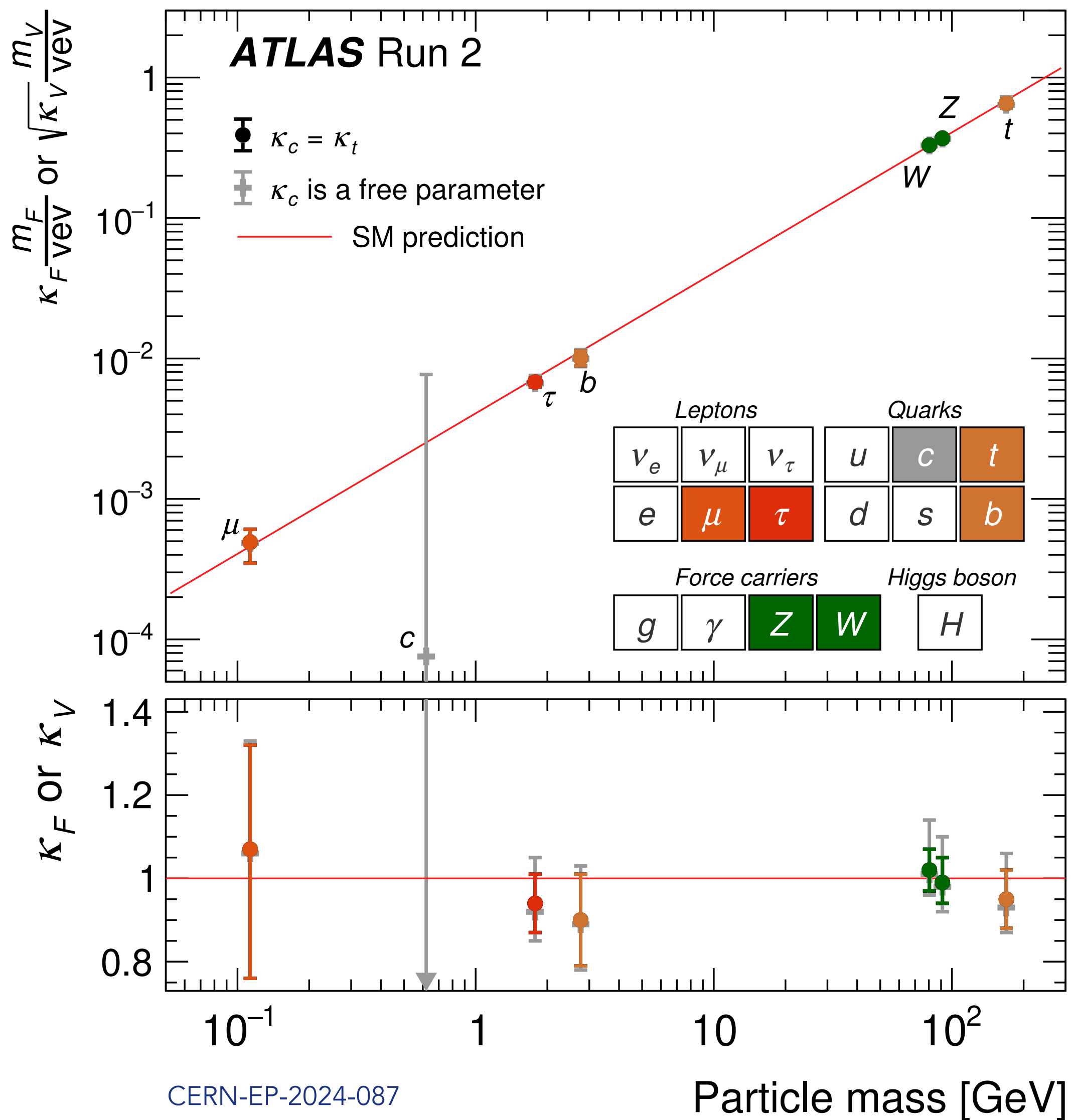
Handbook of LHC Higgs Cross Sections [1101.0593]



Higgs Decay



Higgs Couplings



Can compare the extracted values to the SM prediction in this beautiful way

$$= -i \frac{m_f}{v}$$

Proportional to quark mass

$$= i2 \frac{m_W^2}{v} g_{\mu\nu}$$

Proportional to boson mass²

Tempting to think that we have confirmed the SM but we are only just beginning to scratch the surface

$H \rightarrow \mu\mu$

A direct probe of Higgs coupling to 2nd generation fermions!

Run 2 140 fb⁻¹ @ $\sqrt{s} = 13$ TeV
+ **Run 3** 165 fb⁻¹ @ $\sqrt{s} = 13.6$ TeV

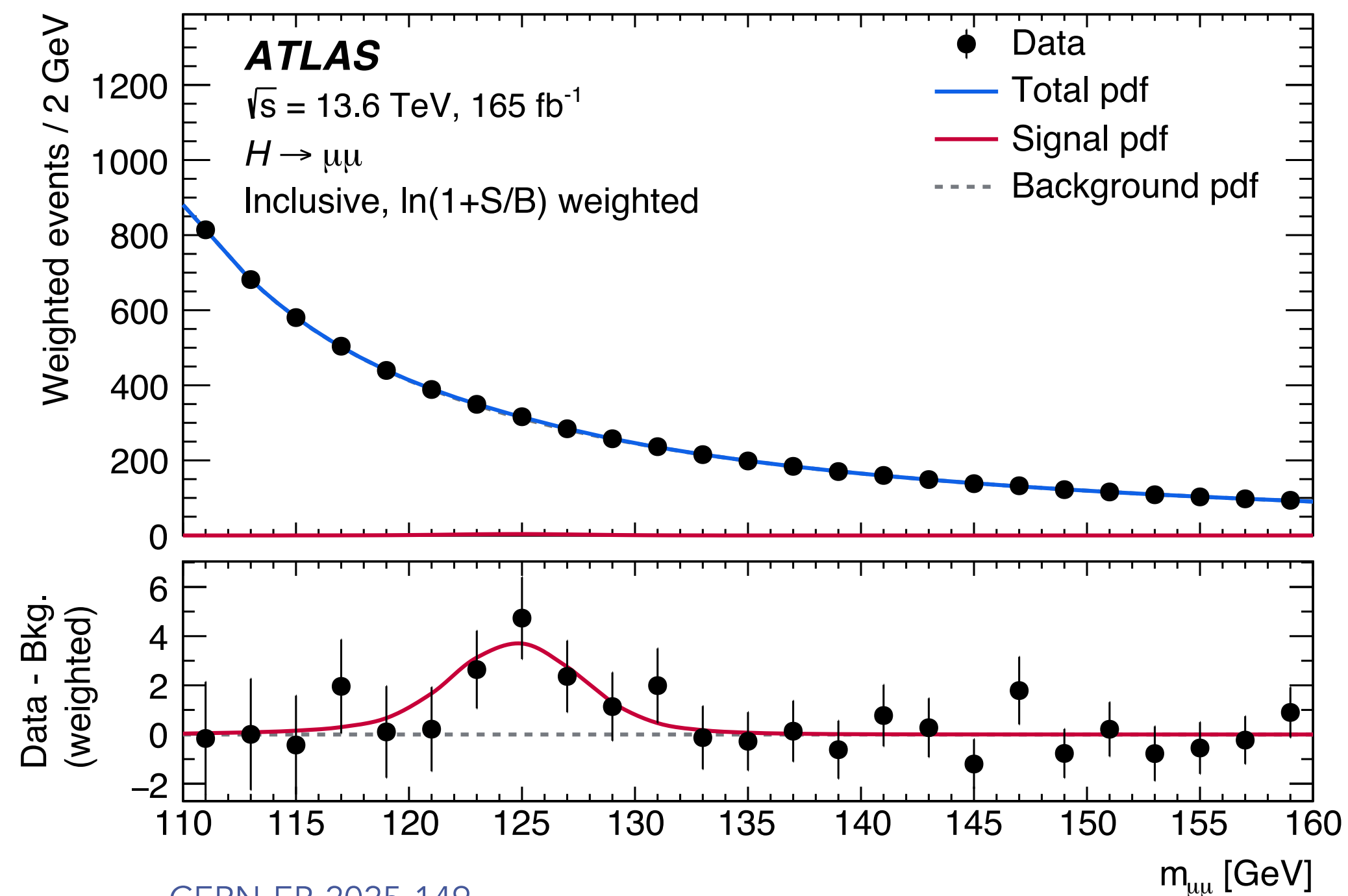
Signal Strength

$\mu = 1.4 \pm 0.4$ 3.4 σ (2.5 σ)

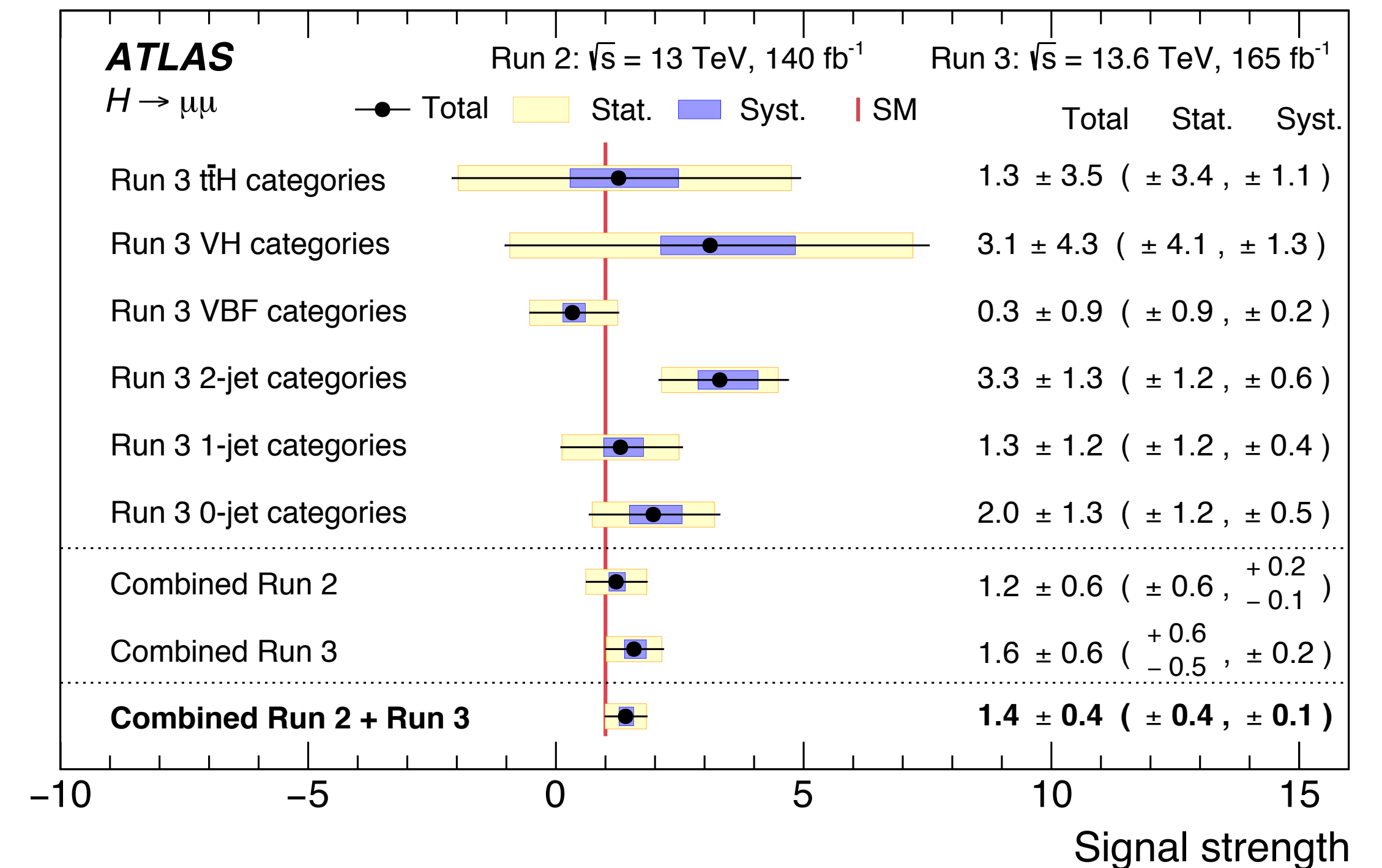
Statistically limited

(systematic uncertainties 5% of total)

Incredibly close to discovery...



CERN-EP-2025-149



Outlook & Challenges

Higgs Discoveries

The LHC has delivered incredible discoveries in the Higgs sector beyond discovering the Higgs boson

2018 ($t\bar{t}H$): Direct observation of a Yukawa coupling

[CMS 1804.02610/ ATLAS 1806.00425](#)

2020 ($H \rightarrow \mu\mu$): Direct evidence that Higgs field is responsible for mass of 2nd gen. leptons

[CMS 2009.04363 / ATLAS 2007.07830](#)

2022 ($H \rightarrow c\bar{c}$): Hints that Higgs field is responsible for mass of 2nd gen. quarks

[2205.05550 / ATLAS 2201.11428](#)

2023 ($H \rightarrow Z\gamma$): Evidence of a rare decay

[CERN-EP-2023-157](#)

I believe that we can and should celebrate this more than we do!

Fixed Order Progress

Impressive progress made in recent years venturing into very difficult territory (beyond MPLs, internal masses, 2→3)

Higgs

process	known	desired
$pp \rightarrow H$	N^3LO_{HTL}	N^4LO_{HTL} (incl.)
	$NNLO_{QCD}^{(t,t \times b)}$	
	$N^{(1,1)}LO_{QCD \otimes EW}^{(HTL)}$	
	NLO_{QCD}	
$pp \rightarrow H + j$	$NNLO_{HTL}$	$NNLO_{HTL} \otimes NLO_{QCD} + NLO_{EW}$
	NLO_{QCD}	N^3LO_{HTL}
	$N^{(1,1)}LO_{QCD \otimes EW}$	$NNLO_{QCD}$
$pp \rightarrow H + 2j$	$NLO_{HTL} \otimes LO_{QCD}$	$NNLO_{HTL} \otimes NLO_{QCD} + NLO_{EW}$
	$N^3LO_{QCD}^{(VBF^*)}$ (incl.)	$N^3LO_{QCD}^{(VBF^*)}$
	$NNLO_{QCD}^{(VBF^*)}$	$NNLO_{QCD}^{(VBF)}$
	$NLO_{EW}^{(VBF)}$	NLO_{QCD}
$pp \rightarrow H + 3j$	NLO_{HTL}	$NLO_{QCD} + NLO_{EW}$
	$NLO_{QCD}^{(VBF)}$	$NNLO_{QCD}^{(VBF^*)}$
$pp \rightarrow VH$	N^3LO_{QCD} (incl.) + NLO_{EW}	N^3LO_{QCD}
	$NLO_{gg \rightarrow HZ}^{(t,b)}$	$N^{(1,1)}LO_{QCD \otimes EW}$
$pp \rightarrow VH + j$	$NNLO_{QCD}$	$NLO_{QCD} + NLO_{EW}$
$pp \rightarrow HH$	$N^3LO_{HTL} \otimes NLO_{QCD}$	$NNLO_{QCD}$
	NLO_{EW}	
$pp \rightarrow HH + 2j$	$N^3LO_{QCD}^{(VBF^*)}$ (incl.)	NLO_{QCD}
	$NNLO_{QCD}^{(VBF^*)}$	
	$NLO_{EW}^{(VBF)}$	
$pp \rightarrow HHH$	$NNLO_{HTL}$	NLO_{QCD}
$pp \rightarrow H + t\bar{t}$	$NLO_{QCD} + NLO_{EW}$	$NNLO_{QCD}$
	$NNLO_{QCD}$ (approx.)	
$pp \rightarrow H + t/\bar{t}$	$NLO_{QCD} + NLO_{EW}$	$NNLO_{QCD}$

Vector Bosons

process	known	desired
$pp \rightarrow V$	$N^3LO_{QCD} + N^{(1,1)}LO_{QCD \otimes EW}$	N^2LO_{EW}
	NLO_{EW}	
$pp \rightarrow VV'$	$NNLO_{QCD} + NLO_{EW}$	Full NLO_{QCD}
	+ Full NLO_{QCD} ($gg \rightarrow ZZ$),	(gg channel, w/ massive loops)
	approx. NLO_{QCD} ($gg \rightarrow WW$)	$N^{(1,1)}LO_{QCD \otimes EW}$
$pp \rightarrow V + j$	$NNLO_{QCD} + NLO_{EW}$	hadronic decays
$pp \rightarrow V + 2j$	$NLO_{QCD} + NLO_{EW}$ (QCD component)	$NNLO_{QCD}$
	$NLO_{QCD} + NLO_{EW}$ (EW component)	
$pp \rightarrow V + b\bar{b}$	NLO_{QCD}	$NNLO_{QCD} + NLO_{EW}$
$pp \rightarrow W + b\bar{b}$	$NNLO_{QCD}$	
$pp \rightarrow VV' + 1j$	$NLO_{QCD} + NLO_{EW}$	$NNLO_{QCD}$
$pp \rightarrow VV' + 2j$	NLO_{QCD} (QCD component)	Full $NLO_{QCD} + NLO_{EW}$
	$NLO_{QCD} + NLO_{EW}$ (EW component)	
$pp \rightarrow W^+W^+ + 2j$	Full $NLO_{QCD} + NLO_{EW}$	$NLO_{QCD} + NLO_{EW}$ (off-shell)
$pp \rightarrow W^+W^- + 2j$	$NLO_{QCD} + NLO_{EW}$ (EW component)	
$pp \rightarrow W^+Z + 2j$	$NLO_{QCD} + NLO_{EW}$ (EW component)	
$pp \rightarrow ZZ + 2j$	Full $NLO_{QCD} + NLO_{EW}$	
$pp \rightarrow VV'V''$	$NLO_{QCD} + NLO_{EW}$ (w/ decays)	$NLO_{QCD} + NLO_{EW}$ (off-shell)
$pp \rightarrow WWW$	$NLO_{QCD} + NLO_{EW}$ (off-shell)	
$pp \rightarrow W^+W^+(V \rightarrow jj)$	$NLO_{QCD} + NLO_{EW}$ (off-shell)	$NLO_{QCD} + NLO_{EW}$ (off-shell)
$pp \rightarrow WZ(V \rightarrow jj)$	$NLO_{QCD} + NLO_{EW}$ (off-shell)	
$pp \rightarrow \gamma\gamma$	$NNLO_{QCD} + NLO_{EW}$	N^3LO_{QCD}
$pp \rightarrow \gamma + j$	$NNLO_{QCD} + NLO_{EW}$	N^3LO_{QCD}
$pp \rightarrow \gamma\gamma + j$	$NNLO_{QCD} + NLO_{EW}$	N^3LO_{QCD}
	+ NLO_{QCD} (gg channel)	
$pp \rightarrow \gamma\gamma\gamma$	$NNLO_{QCD}$	NLO_{EW}

Top

process	known	desired
$pp \rightarrow t\bar{t}$	$NNLO_{QCD} + NLO_{EW}$ (w/o decays)	N^3LO_{QCD}
	$NLO_{QCD} + NLO_{EW}$ (off-shell)	
	$NNLO_{QCD}$ (w/ decays)	
$pp \rightarrow t\bar{t} + j$	NLO_{QCD} (off-shell effects)	$NNLO_{QCD} + NLO_{EW}$ (w decays)
	NLO_{EW} (w/o decays)	
$pp \rightarrow t\bar{t} + 2j$	NLO_{QCD} (w/o decays)	$NLO_{QCD} + NLO_{EW}$ (w decays)
$pp \rightarrow t\bar{t} + V'$	$NLO_{QCD} + NLO_{EW}$ (w decays)	$NNLO_{QCD} + NLO_{EW}$ (w decays)
$pp \rightarrow t\bar{t} + \gamma$	NLO_{QCD} (off-shell)	$NNLO_{QCD} + NLO_{EW}$ (w decays)
$pp \rightarrow t\bar{t} + Z$	$NLO_{QCD} + NLO_{EW}$ (off-shell)	
$pp \rightarrow t\bar{t} + W$	$NLO_{QCD} + NLO_{EW}$ (off-shell)	
$pp \rightarrow t/\bar{t}$	$NNLO_{QCD}^*$ (w decays)	$NNLO_{QCD} + NLO_{EW}$ (w decays)
	NLO_{EW} (w/o decays)	
$pp \rightarrow tZj$	$NLO_{QCD} + NLO_{EW}$ (off shell)	$NNLO_{QCD} + NLO_{EW}$ (w/o decays)
$pp \rightarrow t\bar{t}t\bar{t}$	NLO_{QCD} (w decay)	$NLO_{QCD} + NLO_{EW}$ (off-shell)
	NLO_{EW} (w/o decays)	$NNLO_{QCD}$

Jets

process	known	desired
$pp \rightarrow 2\text{jets}$	$NNLO_{QCD}$	$N^3LO_{QCD} + NLO_{EW}$
	$NLO_{QCD} + NLO_{EW}$	
$pp \rightarrow 3\text{jets}$	$NNLO_{QCD} + NLO_{EW}$	

Fixed Order Progress

Impressive progress made in recent years venturing into very difficult territory (beyond MPLs, internal masses, 2→3)

Higgs

process	known	desired
$pp \rightarrow H$	N^3LO_{HTL}	N^4LO_{HTL} (incl.)
	$NNLO_{QCD}^{(t,t \times b)}$	
	$N^{(1,1)}LO_{QCD \otimes EW}^{(HTL)}$	
	NLO_{QCD}	
$pp \rightarrow H + j$	$NNLO_{HTL}$	$NNLO_{HTL} \otimes NLO_{QCD} + NLO_{EW}$
	NLO_{QCD}	N^3LO_{HTL}
	$N^{(1,1)}LO_{QCD \otimes EW}$	$NNLO_{QCD}$
$pp \rightarrow H + 2j$	$NLO_{HTL} \otimes LO_{QCD}$	$NNLO_{HTL} \otimes NLO_{QCD} + NLO_{EW}$
	$N^3LO_{QCD}^{(VBF^*)}$ (incl.)	$N^3LO_{QCD}^{(VBF^*)}$
	$NNLO_{QCD}^{(VBF^*)}$	$NNLO_{QCD}^{(VBF)}$
	$NLO_{EW}^{(VBF)}$	NLO_{QCD}
$pp \rightarrow H + 3j$	NLO_{HTL}	$NLO_{QCD} + NLO_{EW}$
	$NLO_{QCD}^{(VBF)}$	$NNLO_{QCD}^{(VBF^*)}$
$pp \rightarrow VH$	N^3LO_{QCD} (incl.) + NLO_{EW}	N^3LO_{QCD}
	$NLO_{gg \rightarrow HZ}^{(t,b)}$	$N^{(1,1)}LO_{QCD \otimes EW}$
$pp \rightarrow VH + j$	$NNLO_{QCD}$	
	$NLO_{QCD} + NLO_{EW}$	
$pp \rightarrow HH$	$N^3LO_{HTL} \otimes NLO_{QCD}$	$NNLO_{QCD}$
	NLO_{EW}	
$pp \rightarrow HH + 2j$	$N^3LO_{QCD}^{(VBF^*)}$ (incl.)	NLO_{QCD}
	$NNLO_{QCD}^{(VBF^*)}$	
	$NLO_{EW}^{(VBF)}$	
$pp \rightarrow HHH$	$NNLO_{HTL}$	NLO_{QCD}
$pp \rightarrow H + t\bar{t}$	$NLO_{QCD} + NLO_{EW}$	$NNLO_{QCD}$
	$NNLO_{QCD}$ (approx.)	
$pp \rightarrow H + t/\bar{t}$	$NLO_{QCD} + NLO_{EW}$	$NNLO_{QCD}$

Vector Bosons

process	known	desired
$pp \rightarrow V$	$N^3LO_{QCD} + N^{(1,1)}LO_{QCD \otimes EW}$	N^2LO_{EW}
	NLO_{EW}	
$pp \rightarrow VV'$	$NNLO_{QCD} + NLO_{EW}$	Full NLO_{QCD}
	+ Full NLO_{QCD} ($gg \rightarrow ZZ$), approx. NLO_{QCD} ($gg \rightarrow WW$)	(gg channel, w/ massive loops) $N^{(1,1)}LO_{QCD \otimes EW}$
$pp \rightarrow V + j$	$NNLO_{QCD} + NLO_{EW}$	hadronic decays
$pp \rightarrow V + 2j$	$NLO_{QCD} + NLO_{EW}$ (QCD component)	$NNLO_{QCD}$
	$NLO_{QCD} + NLO_{EW}$ (EW component)	
$pp \rightarrow V + b\bar{b}$	NLO_{QCD}	$NNLO_{QCD} + NLO_{EW}$
$pp \rightarrow W + b\bar{b}$	$NNLO_{QCD}$	
$pp \rightarrow VV' + 1j$	$NLO_{QCD} + NLO_{EW}$	$NNLO_{QCD}$
$pp \rightarrow VV' + 2j$	NLO_{QCD} (QCD component)	Full $NLO_{QCD} + NLO_{EW}$
	$NLO_{QCD} + NLO_{EW}$ (EW component)	
$pp \rightarrow W^+W^+ + 2j$	Full $NLO_{QCD} + NLO_{EW}$	
$pp \rightarrow W^+W^- + 2j$	$NLO_{QCD} + NLO_{EW}$ (EW component)	
$pp \rightarrow W^+Z + 2j$	$NLO_{QCD} + NLO_{EW}$ (EW component)	
$pp \rightarrow ZZ + 2j$	Full $NLO_{QCD} + NLO_{EW}$	$NLO_{QCD} + NLO_{EW}$ (off-shell)
$pp \rightarrow VV'V''$	$NLO_{QCD} + NLO_{EW}$ (w/ decays)	
$pp \rightarrow WWW$	$NLO_{QCD} + NLO_{EW}$ (off-shell)	
$pp \rightarrow W^+W^+(V \rightarrow jj)$	$NLO_{QCD} + NLO_{EW}$ (off-shell)	
$pp \rightarrow WZ(V \rightarrow jj)$	$NLO_{QCD} + NLO_{EW}$ (off-shell)	
$pp \rightarrow \gamma\gamma$	$NNLO_{QCD} + NLO_{EW}$	N^3LO_{QCD}
$pp \rightarrow \gamma + j$	$NNLO_{QCD} + NLO_{EW}$	N^3LO_{QCD}
$pp \rightarrow \gamma\gamma + j$	$NNLO_{QCD} + NLO_{EW}$	
	+ NLO_{QCD} (gg channel)	
$pp \rightarrow \gamma\gamma\gamma$	$NNLO_{QCD}$	NLO_{EW}

Top

process	known	desired
$pp \rightarrow t\bar{t}$	$NNLO_{QCD} + NLO_{EW}$ (w/o decays)	N^3LO_{QCD}
	$NLO_{QCD} + NLO_{EW}$ (off-shell)	
	$NNLO_{QCD}$ (w/ decays)	
$pp \rightarrow t\bar{t} + j$	NLO_{QCD} (off-shell effects)	$NNLO_{QCD} + NLO_{EW}$ (w decays)
	NLO_{EW} (w/o decays)	
$pp \rightarrow t\bar{t} + 2j$	NLO_{QCD} (w/o decays)	$NLO_{QCD} + NLO_{EW}$ (w decays)
$pp \rightarrow t\bar{t} + V'$	$NLO_{QCD} + NLO_{EW}$ (w decays)	$NNLO_{QCD} + NLO_{EW}$ (w decays)
$pp \rightarrow t\bar{t} + \gamma$	NLO_{QCD} (off-shell)	
$pp \rightarrow t\bar{t} + Z$	$NLO_{QCD} + NLO_{EW}$ (off-shell)	
$pp \rightarrow t\bar{t} + W$	$NLO_{QCD} + NLO_{EW}$ (off-shell)	$NNLO_{QCD} + NLO_{EW}$ (w decays)
$pp \rightarrow t/\bar{t}$	$NNLO_{QCD}^*$ (w decays)	
	NLO_{EW} (w/o decays)	
$pp \rightarrow tZj$	$NLO_{QCD} + NLO_{EW}$ (off shell)	$NNLO_{QCD} + NLO_{EW}$ (w/o decays)
$pp \rightarrow t\bar{t}t\bar{t}$	NLO_{QCD} (w decay)	$NLO_{QCD} + NLO_{EW}$ (off-shell)
	NLO_{EW} (w/o decays)	$NNLO_{QCD}$

Jets

process	known	desired
$pp \rightarrow 2\text{jets}$	$NNLO_{QCD}$	$N^3LO_{QCD} + NLO_{EW}$
	$NLO_{QCD} + NLO_{EW}$	
$pp \rightarrow 3\text{jets}$	$NNLO_{QCD} + NLO_{EW}$	

- completed since 2021
- progress since 2021

Fixed Order Progress

Impressive progress made in recent years venturing into very difficult territory (beyond MPLs, internal masses, $2 \rightarrow 3$)

Higgs

process	known	desired
$pp \rightarrow H$	$\text{N}^3\text{LO}_{\text{HTL}}$	$\text{N}^4\text{LO}_{\text{HTL}}$ (incl.)
	$\text{NNLO}_{\text{QCD}}^{(t,t \times b)}$	
	$\text{N}^{(1,1)}\text{LO}_{\text{QCD} \otimes \text{EW}}^{(\text{HTL})}$	
	NLO_{QCD}	
$pp \rightarrow H + j$	NNLO_{HTL}	$\text{NNLO}_{\text{HTL}} \otimes \text{NLO}_{\text{QCD}} + \text{NLO}_{\text{EW}}$
	NLO_{QCD}	$\text{N}^3\text{LO}_{\text{HTL}}$
	$\text{N}^{(1,1)}\text{LO}_{\text{QCD} \otimes \text{EW}}$	NNLO_{QCD}
$pp \rightarrow H + 2j$	$\text{NLO}_{\text{HTL}} \otimes \text{LO}_{\text{QCD}}$	$\text{NNLO}_{\text{HTL}} \otimes \text{NLO}_{\text{QCD}} + \text{NLO}_{\text{EW}}$
	$\text{N}^3\text{LO}_{\text{QCD}}^{(\text{VBF}^*)}$ (incl.)	$\text{N}^3\text{LO}_{\text{QCD}}^{(\text{VBF}^*)}$
	$\text{NNLO}_{\text{QCD}}^{(\text{VBF}^*)}$	$\text{NNLO}_{\text{QCD}}^{(\text{VBF})}$
	$\text{NLO}_{\text{EW}}^{(\text{VBF})}$	NLO_{QCD}
$pp \rightarrow H + 3j$	NLO_{HTL}	$\text{NLO}_{\text{QCD}} + \text{NLO}_{\text{EW}}$
	$\text{NLO}_{\text{QCD}}^{(\text{VBF})}$	$\text{NNLO}_{\text{QCD}}^{(\text{VBF}^*)}$
$pp \rightarrow VH$	$\text{N}^3\text{LO}_{\text{QCD}}$ (incl.)+ NLO_{EW}	$\text{N}^3\text{LO}_{\text{QCD}}$
	$\text{NLO}_{qq \rightarrow HZ}^{(t,b)}$	$\text{N}^{(1,1)}\text{LO}_{\text{QCD} \otimes \text{EW}}$

$pp \rightarrow VH + j$	NNLO_{QCD}	
	$\text{NLO}_{\text{QCD}} + \text{NLO}_{\text{EW}}$	
$pp \rightarrow HH$	$\text{N}^3\text{LO}_{\text{HTL}} \otimes \text{NLO}_{\text{QCD}}$	NNLO_{QCD}
	NLO_{EW}	
$pp \rightarrow HH + 2j$	$\text{N}^3\text{LO}_{\text{QCD}}^{(\text{VBF}^*)}$ (incl.)	NLO_{QCD}
	$\text{NNLO}_{\text{QCD}}^{(\text{VBF}^*)}$	
	$\text{NLO}_{\text{EW}}^{(\text{VBF})}$	
$pp \rightarrow HHH$	NNLO_{HTL}	NLO_{QCD}
$pp \rightarrow H + t\bar{t}$	$\text{NLO}_{\text{QCD}} + \text{NLO}_{\text{EW}}$	NNLO_{QCD}
	NNLO_{QCD} (approx.)	
$pp \rightarrow H + t/\bar{t}$	$\text{NLO}_{\text{QCD}} + \text{NLO}_{\text{EW}}$	NNLO_{QCD}

Future Directions

Current Status

Incredible performance by the LHC: discovery → precision era of Higgs physics

Theory uncertainties limit our ability to explore the Higgs sector

It is critically important to have a robust fixed-order programme alongside precision developments in parton showers and analysis techniques

Future Community Goals

Extremely exciting times ahead... (can we claim discovery of $H\mu\mu$ coupling? obtain evidence of HHH ?)

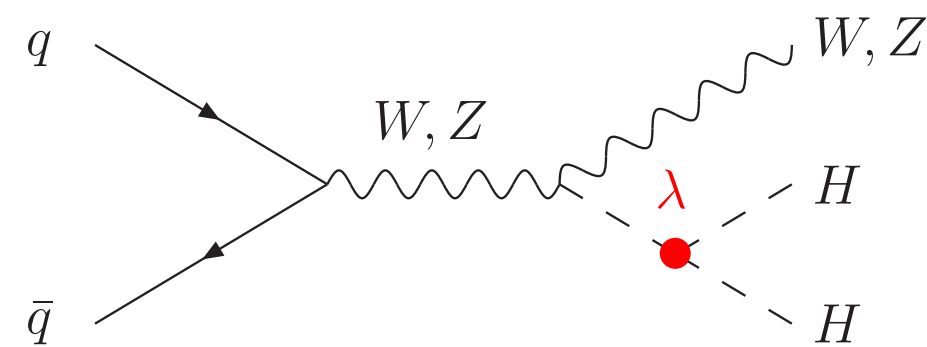
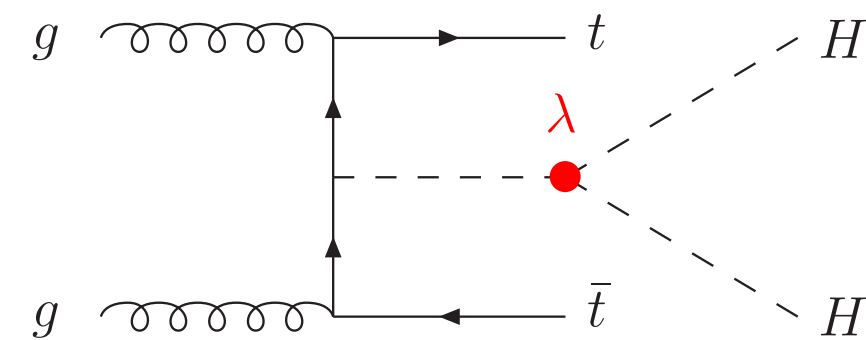
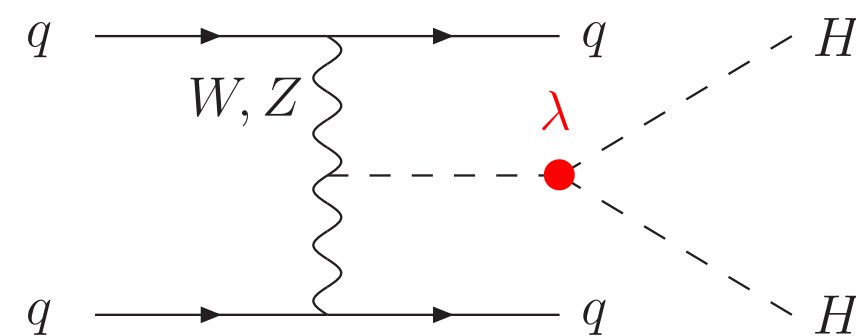
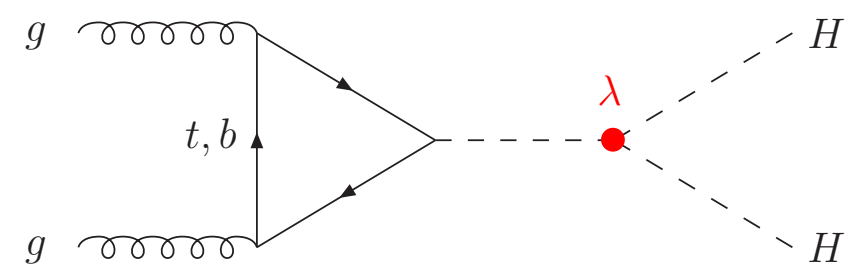
Lift standard candle processes and interesting final states to N^3LO making this the new standard

Refine tools/techniques for multi-loop electroweak corrections, with two-loop electroweak becoming a new standard (also in prep for FCC-ee)

Thank you for listening!

Backup

Higgs Production: HH Production



$$\sigma(pp \rightarrow HH) \sim \frac{\sigma(pp \rightarrow H)}{1000}$$

Experimental Progress

Experimental Limits (Run 2) @ 95% CL

ATLAS: $-1.2(-1.6) < \kappa_3 < 7.2(7.2)$ $\sigma \leq 2.9 \text{ (2.4)} \times \sigma_{SM}$

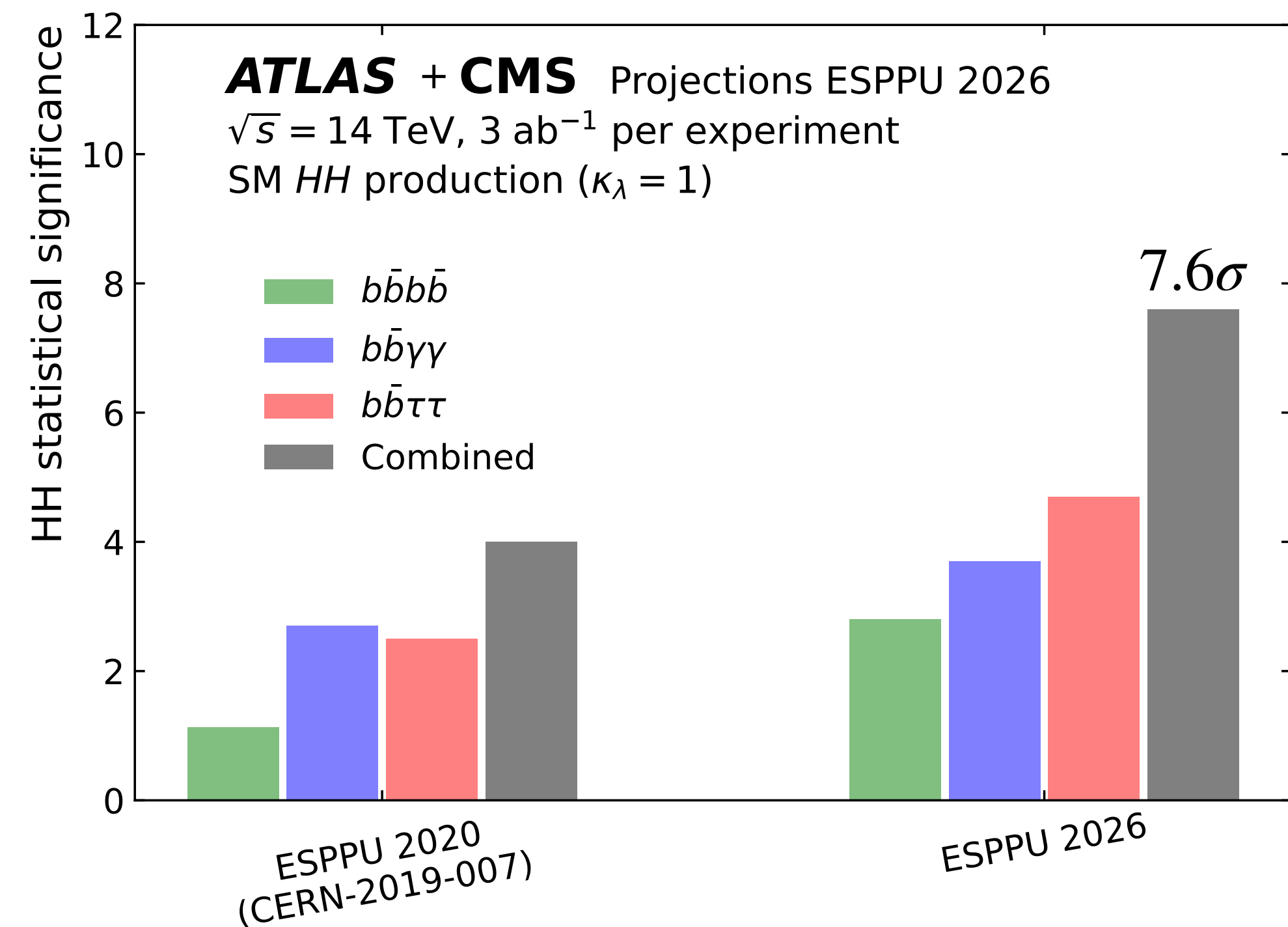
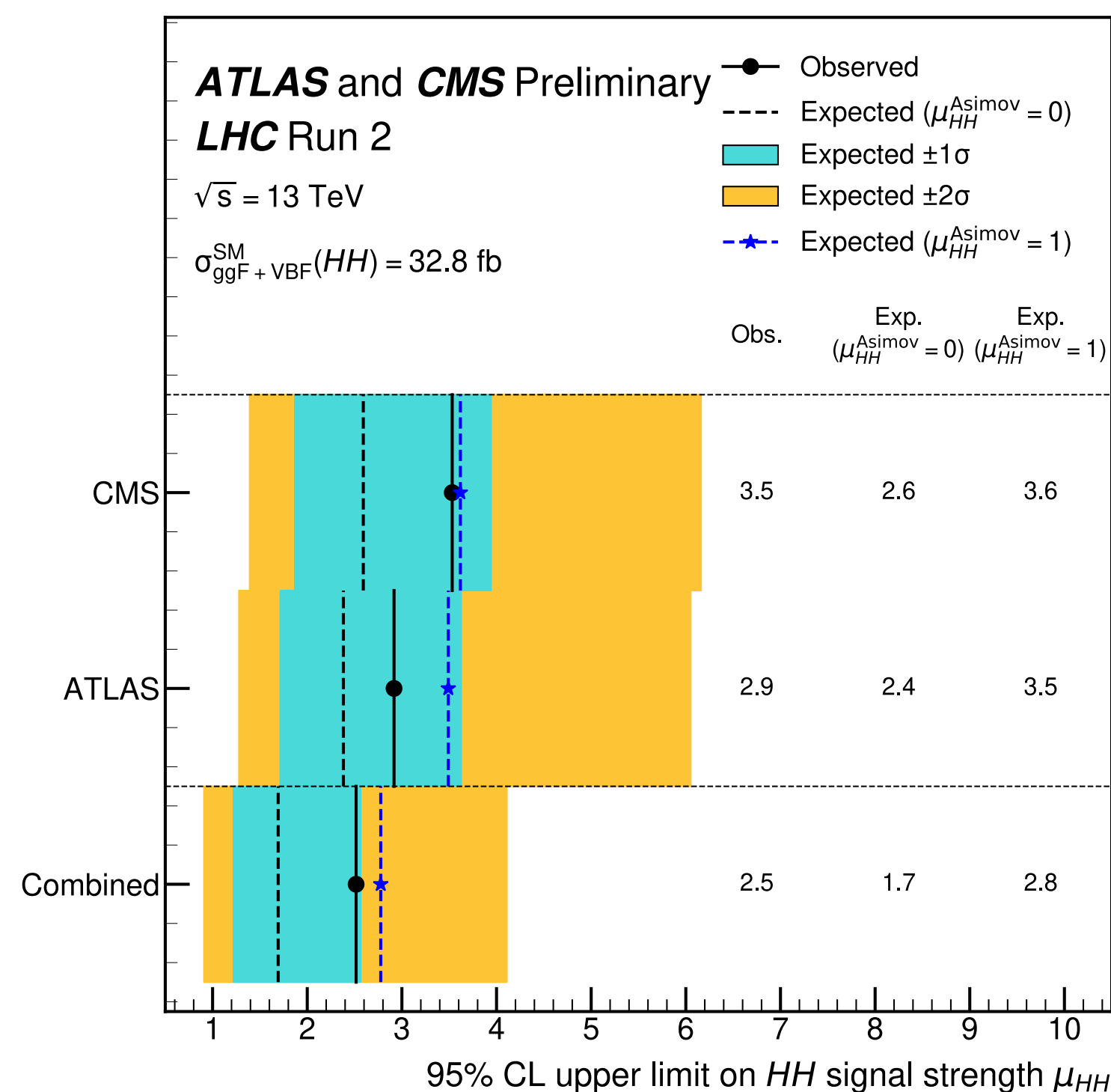
ATLAS CERN-EP-2024-160

CMS: $-1.39(-1.02) < \kappa_3 < 7.02(7.19)$ $\sigma \leq 3.5 \text{ (2.5)} \times \sigma_{SM}$

CMS-PAS-HIG-20-011

A+C: $-0.71(-1.3) < \kappa_3 < 6.1(6.7)$ $\sigma \leq 2.5 \text{ (1.7)} \times \sigma_{SM}$

ATLAS-CONF-2025-012



ATL-PHYS-PUB-2025-018 / CMS-HIG-25-002

Projections for HL-LHC (European Strategy 2026)

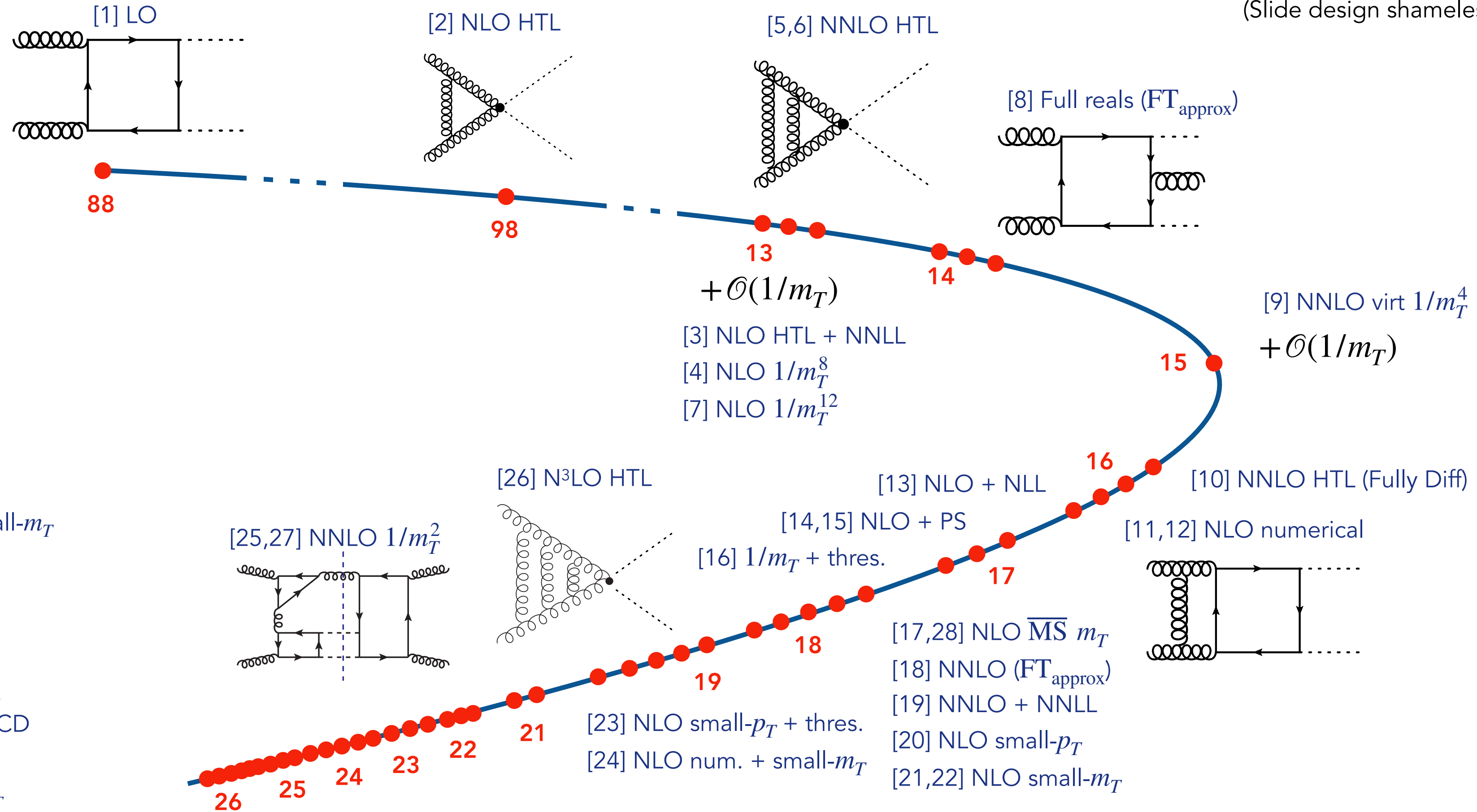
Expected measurement of κ_3 with uncertainty $< 30 \%$

Potential for further analysis improvements

Theory Progress

(Slide design shamelessly stolen from G. Salam)

- [29] NLO small- p_T + small- m_T
- [30] EW: leading Yukawa vs λ_3^{eff}
- [31] EW: leading Yukawa
- [32] N³LO + N³LL + NLO m_T
- [33] NLO small- t + small- m_T
- [34] NNLO: n_f contrib.
- [35] EW: $1/m_T$
- [36] NLO comb expansions
- [37] NLO EW corrections
- [38] NLO + $b\bar{b}\gamma\gamma$ decays
- [39] NNLO: reducible
- [40] EW: Yukawa/self-coupling
- [41] EW: self-coupling
- [42] EW: Factorizable
- [43] EW: Yukawa/self-coupling small- m_T
- [44] NNLO + PS with m_T effects
- [45] NNLO: Large- N_c small- p_T
- [46] EW: Light quark induced
- [47] NLO comb expansions
- [48] EW: Top-Yukawa + light-quark
- [49] EW: Quark-induced + NLO QCD
- [50] N³LO fully diff + NLO m_T
- [51] NLO EW corrections, small- m_T



[1] Glover, van der Bij 88; [2] Dawson, Dittmaier, Spira 98; [3] Shao, Li, Li, Wang 13; [4] Grigo, Hoff, Melnikov, Steinhauser 13; [5] de Florian, Mazzitelli 13; [6] Grigo, Melnikov, Steinhauser 14; [7] Grigo, Hoff 14; [8] Maltoni, Vryonidou, Zaro 14; [9] Grigo, Hoff, Steinhauser 15; [10] de Florian, Grazzini, Hanga, Kallweit, Lindert, Maierhöfer, Mazzitelli, Rathlev 16; [11] Borowka, Greiner, Heinrich, SPJ, Kerner, Schlenk, Schubert, Zirke 16; [12] Borowka, Greiner, Heinrich, SPJ, Kerner, Schlenk, Zirke 16; [13] Ferrera, Pires 16; [14] Heinrich, SPJ, Kerner, Luisoni, Vryonidou 17; [15] SPJ, Kuttimalai 17; [16] Gröber, Maier, Rauh 17; [17] Baglio, Campanario, Glaus, Mühlleitner, Spira, Streicher 18; [18] Grazzini, Heinrich, SPJ, Kallweit, Kerner, Lindert, Mazzitelli 18; [19] de Florian, Mazzitelli 18; [20] Bonciani, Degrandi, Giardino, Gröber 18; [21] Davies, Mishima, Steinhauser, Wellmann 18, 18; [22] Mishima 18; [23] Gröber, Maier, Rauh 19; [24] Davies, Heinrich, SPJ, Kerner, Mishima, Steinhauser, David Wellmann 19; [25] Davies, Steinhauser 19; [26] Chen, Li, Shao, Wang 19, 19; [27] Davies, Herren, Mishima, Steinhauser 19, 21; [28] Baglio, Campanario, Glaus, Mühlleitner, Ronca, Spira 21; [29] Bellafronte, Degrandi, Giardino, Gröber, Vitti 22; [30] Mühlleitner, Schlenk, Spira 22; [31] Davies, Mishima, Schönwald, Steinhauser, Zhang 22; [32] Ajjath, Shao 22; [33] Davies, Mishima, Schönwald, Steinhauser 23; [34] Davies, Schönwald, Steinhauser 23; [35] Davies, Schönwald, Steinhauser, Zhang 23; [36] Bagnaschi, Degrandi, Gröber 23; [37] Bi, Huang, Huang, Ma Yu 23; [38] Li, Si, Wang, Zhang, Zhao 24; [39] Davies, Schönwald, Steinhauser, Vitti 24; [40] Heinrich, SPJ, Kerner, Stone, Vestner 24; [41] Li, Si, Wang, Zhang, Zhao 24; [42] Davies, Schönwald, Steinhauser, Zhang 24; [43] Davies, Schönwald, Steinhauser, Zhang 25; [44] Alioli, Marinelli, Napolitano; [45] Davies, Schönwald, Steinhauser 25; [46] Bonetti, Rendler, Bobadilla 25; [47] Davies, Schönwald, Stremmer 25; [48] Bhattacharya, Campanario, Carlotti, Chang, Mazzitelli, Mühlleitner, Ronca, Spira 25; [49] Bonetti, Heinrich, Rendler, Torres Bobadilla 26; [50] Chen, Dai, Tao Li, Li, Shao, Wang 26; [51] Davies, Schönwald, Steinhauser, Zhang 26;