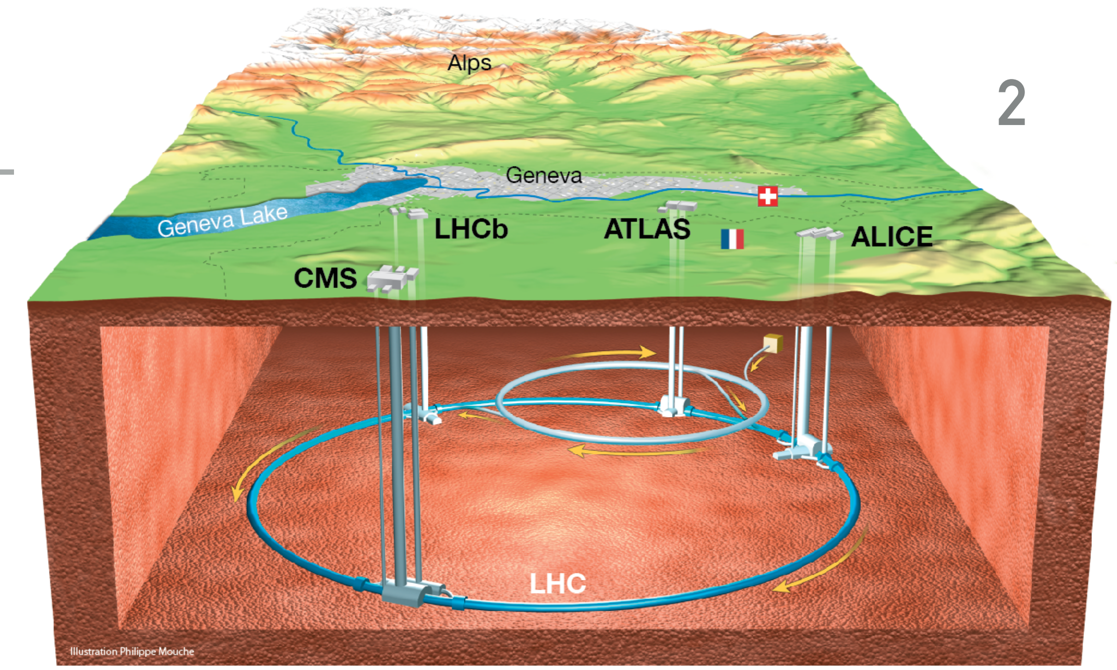
BERNHARD MISTLBERGER

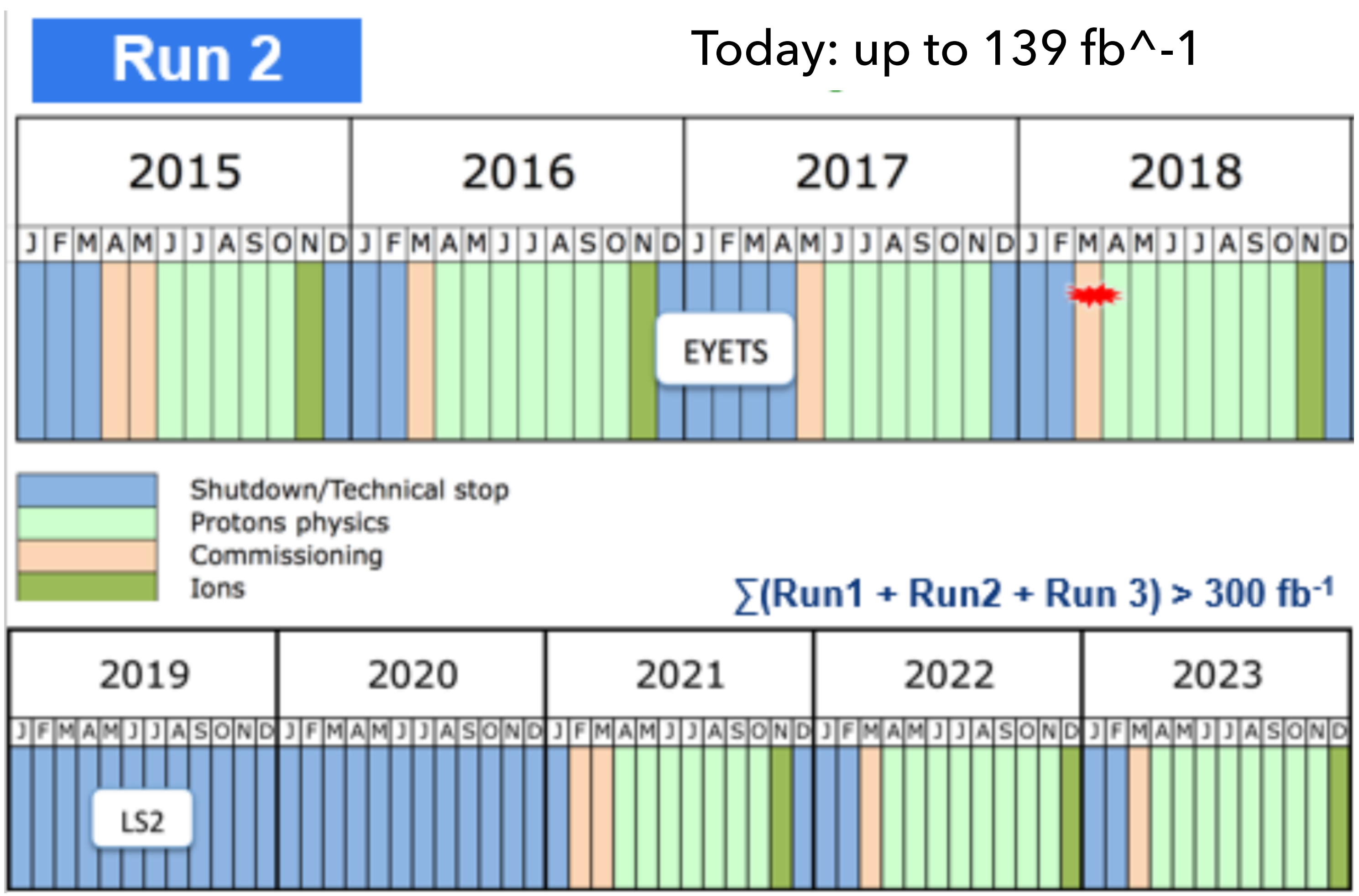
PREDICTING CROSS SECTIONS FOR HIGGS BOSON PHYSICS AT N3LO IN QCD

THE LHC – AN INCREDIBLE SUCCESS

- Running since 2009
- Experimental performance excellent and exceeding expectations!



Period	Integrated Luminosity [fb^{-1}]
Run 1	29.2
Run 2: 2015	4.2
Run 2: 2016	39.7
Run 2: 2017	50.2
Run 2: 2018	66.0
Total Run1 + Run 2	189.3

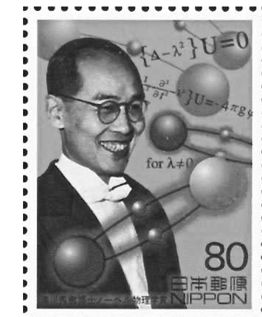


- **We are still at the beginning of LHC physics!**
- **300 fb^-1 until end of 2023**
- **3000 fb^-1 in HL - LHC**

THE LHC – AN INCREDIBLE SUCCESS

- 4th of July 2012: **The Higgs Age begins!**

The quest p.H.



* **Explore a never before observed interaction: Yukawa!**

* **Gain insight in the mechanism of electro-weak symmetry breaking**

* **Investigate the 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.**

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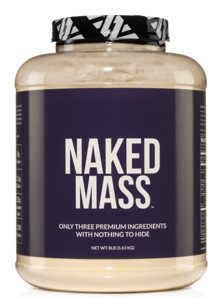
THE LHC - AN INCREDIBLE SUCCESS



H ♡ μ ?

W ♡ W ♡ W ♡ W ?

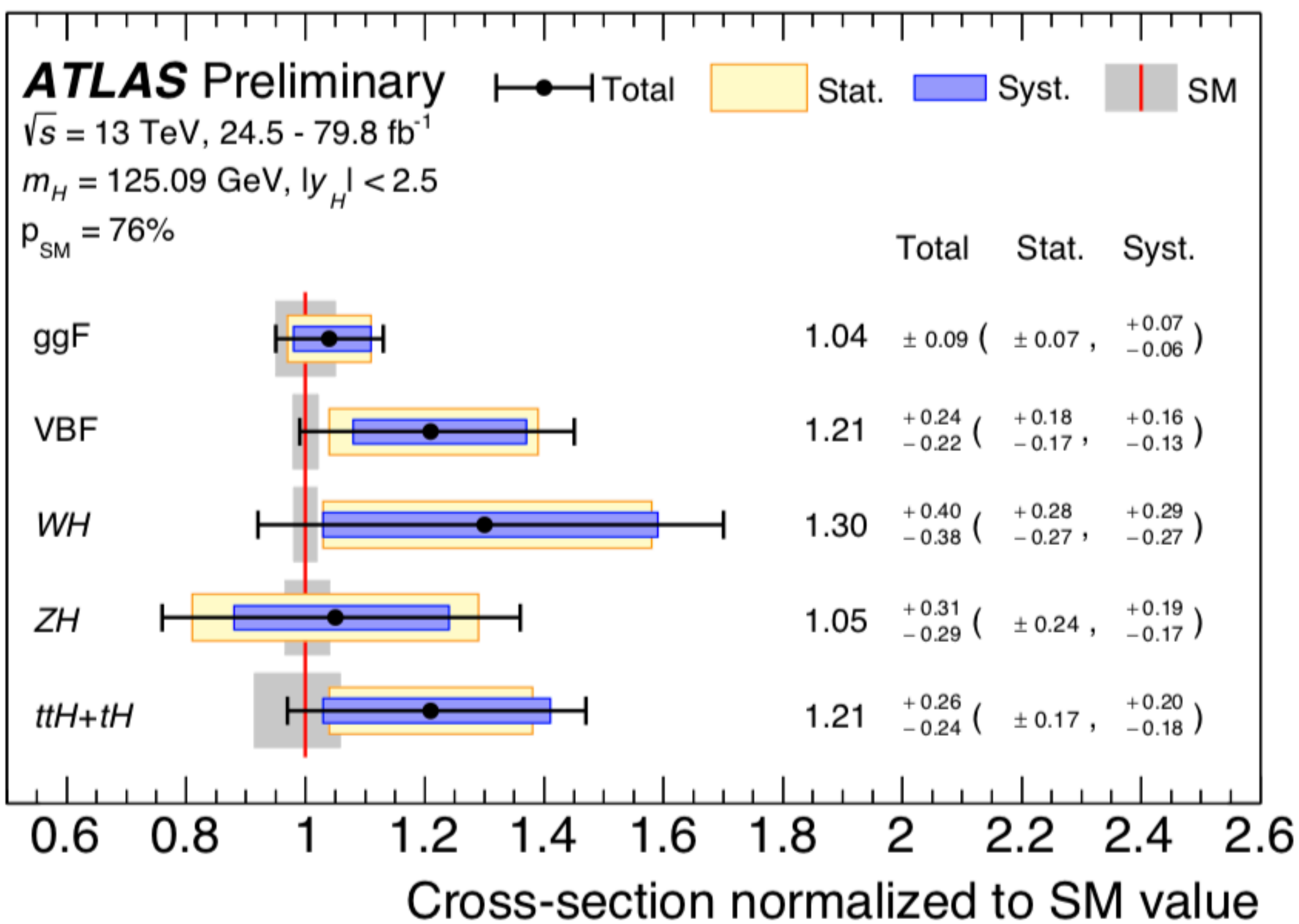
The Method: Predict & Compare.

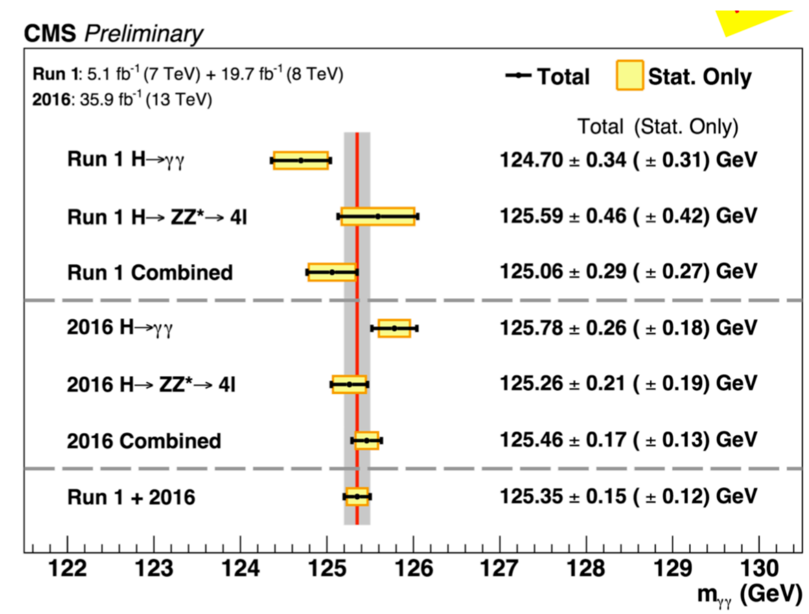
Precision is key!

Inclusive Production Cross Section of the Higgs Boson

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

Physics at 10 % level





$$m_h = 125.35 \pm 0.15 GeV$$

Inclusive Production Cross Section of the Higgs Boson AT 3000 FB^-1

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

Relative uncertainty	Total	Stat	Exp.
S1	3.5%	0.6%	1.6%
S2	2.4%	0.6%	1.3%

- Luminosity at 1%
- Couplings better then 5%
- Differential cross sections get precise

Inclusive Production Cross Section of the Higgs Boson AT 3000 FB^-1

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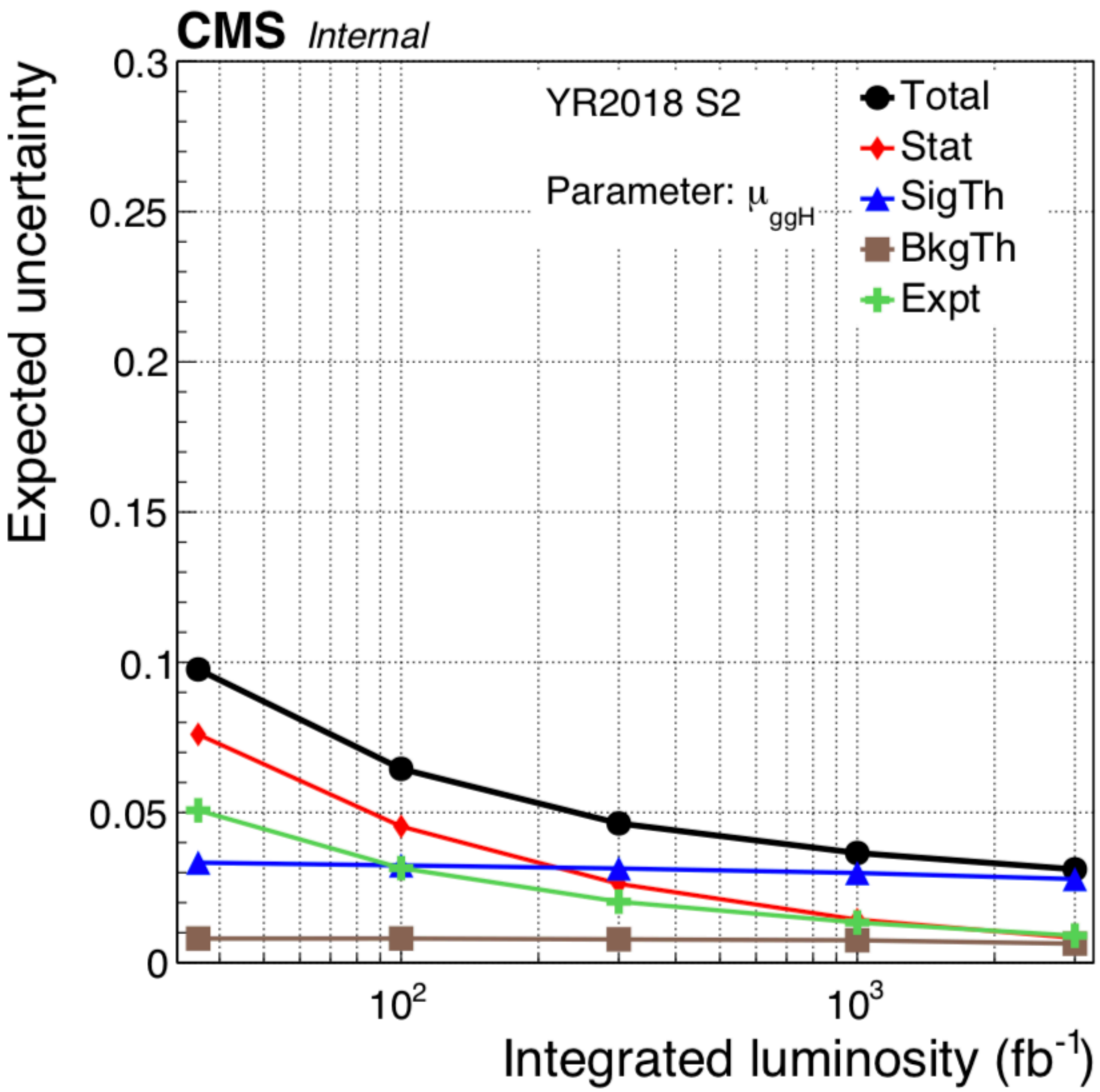

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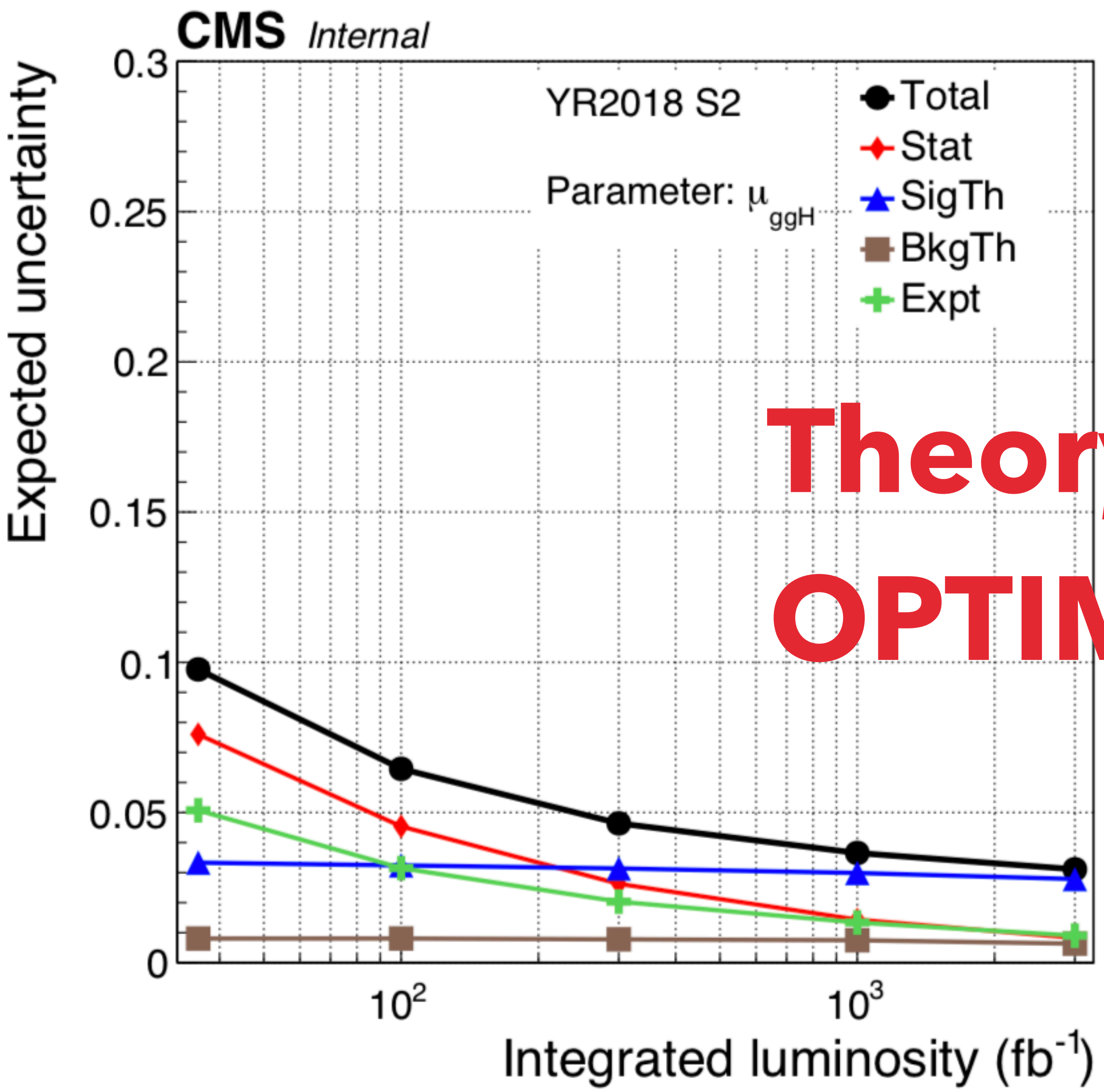
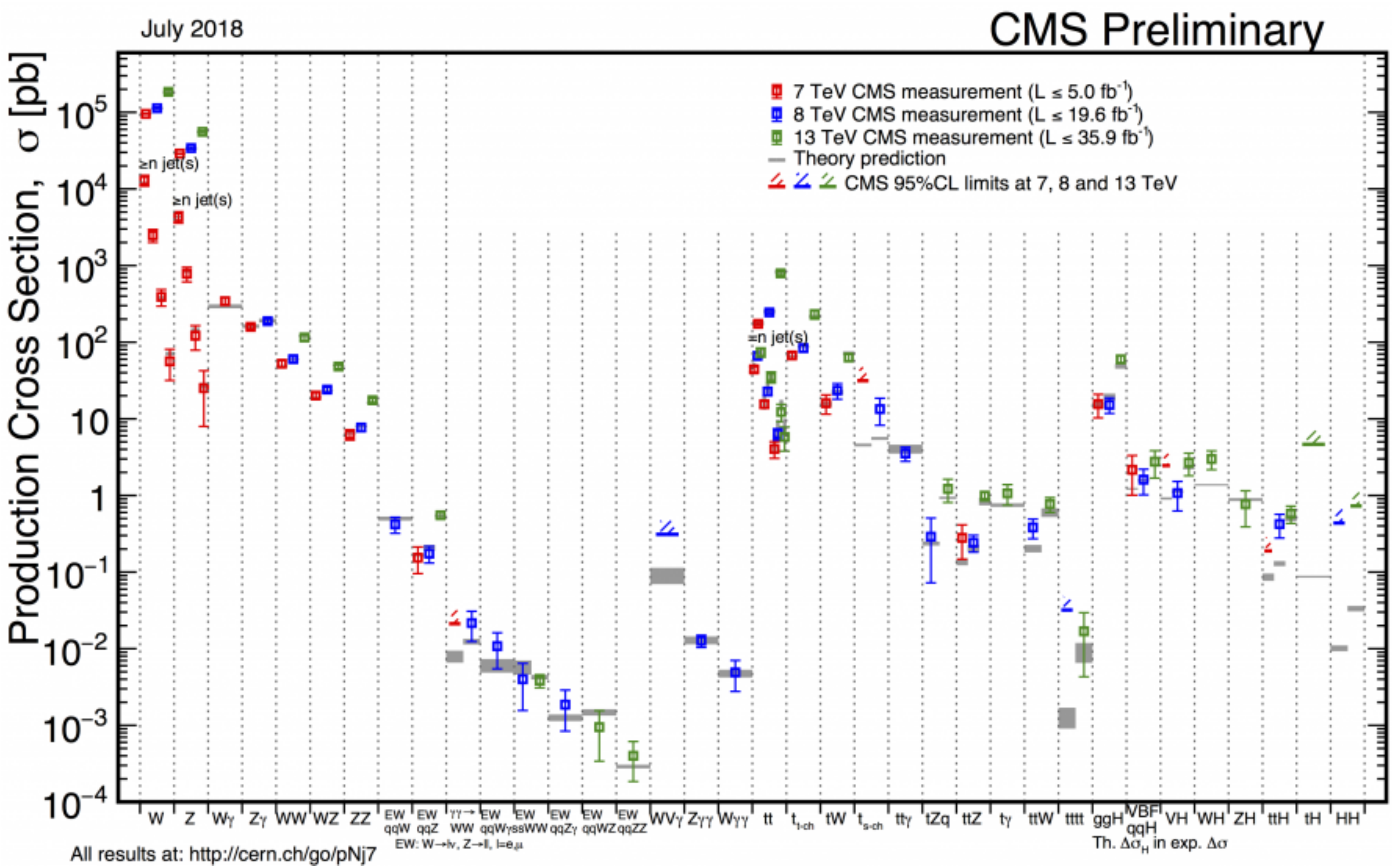
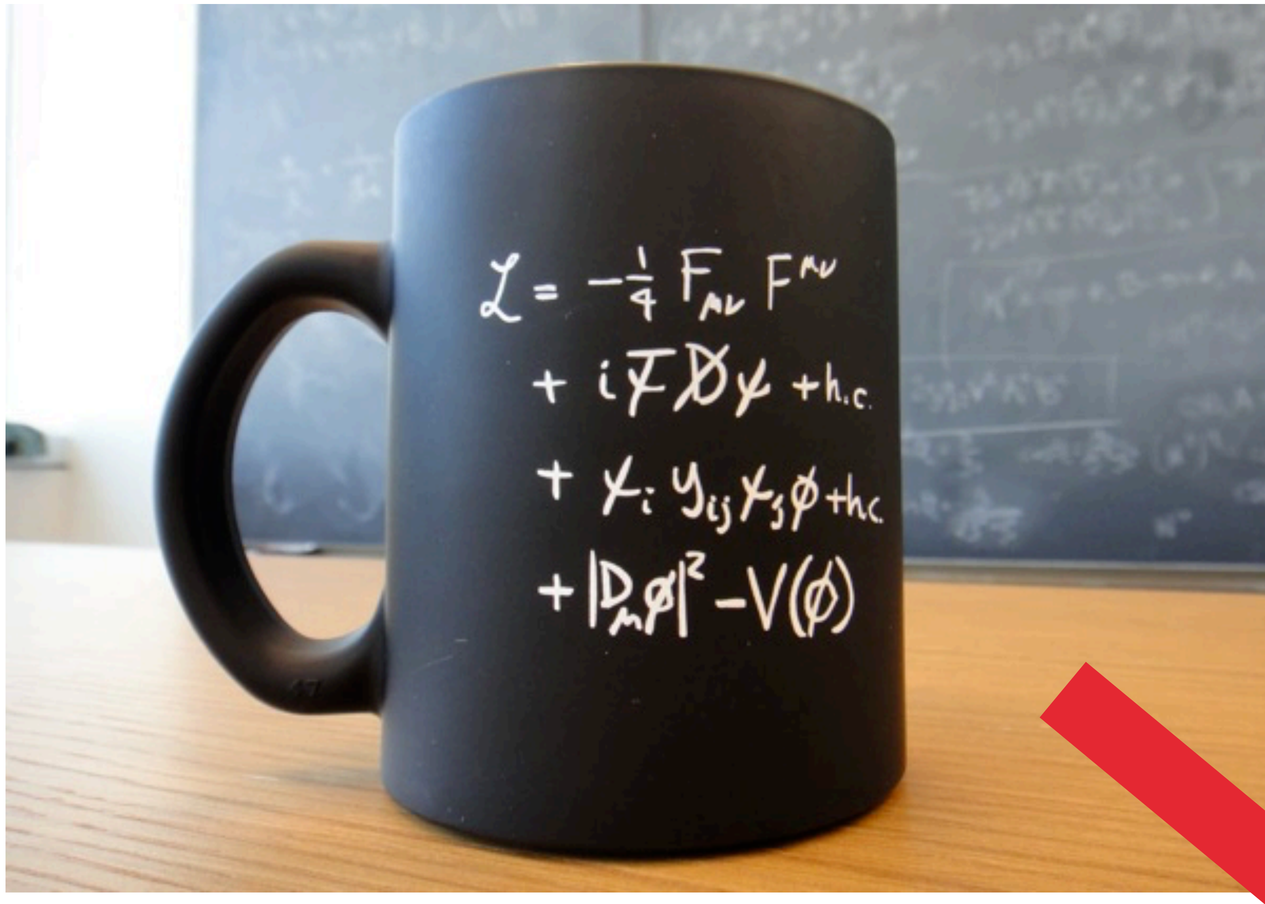


Theory uncertainties: OPTIMISTIC scenario!!!

LHC PROCESSES

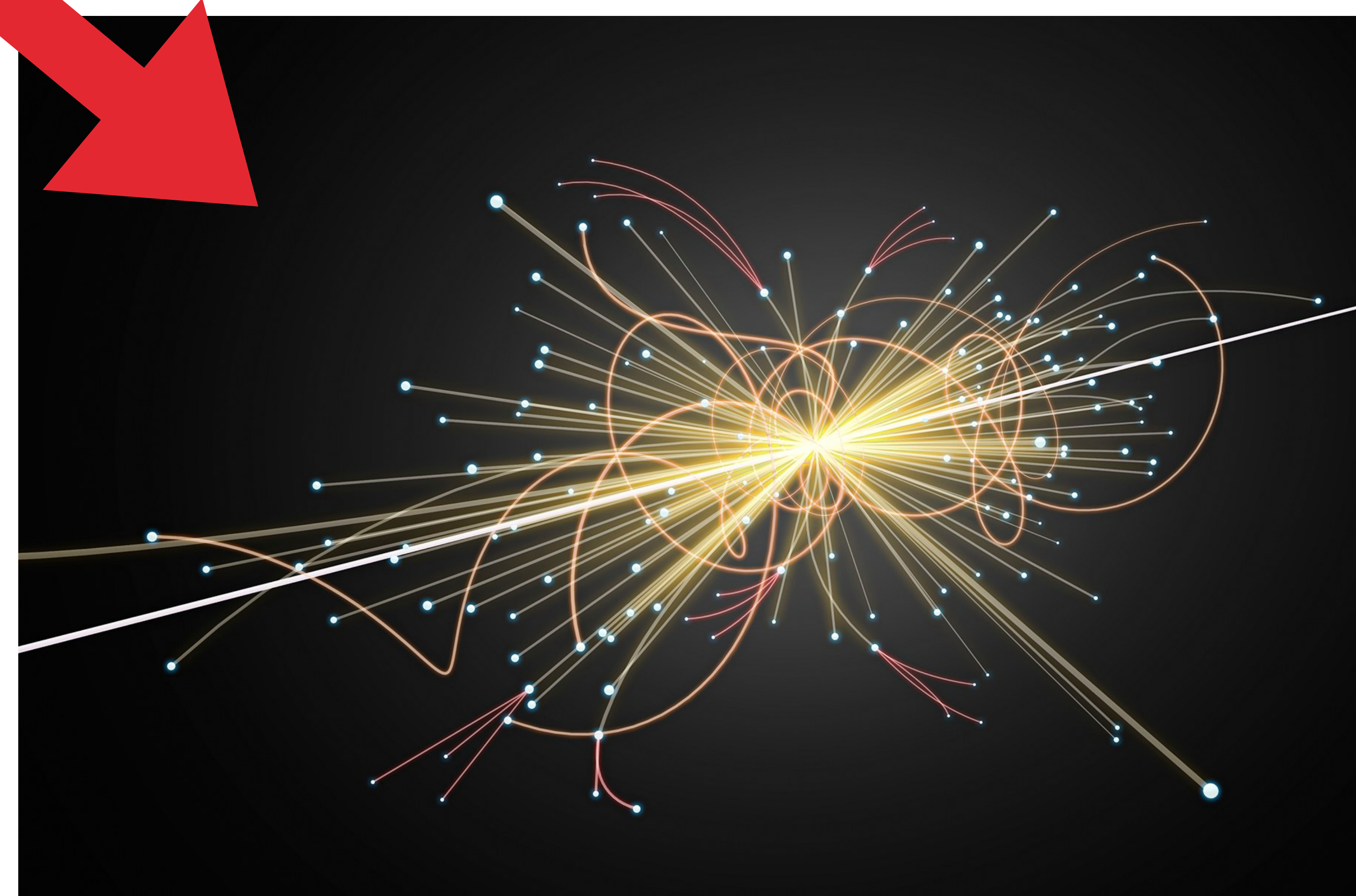


FROM THE STANDARD MODEL TO REAL LIFE OBSERVABLES

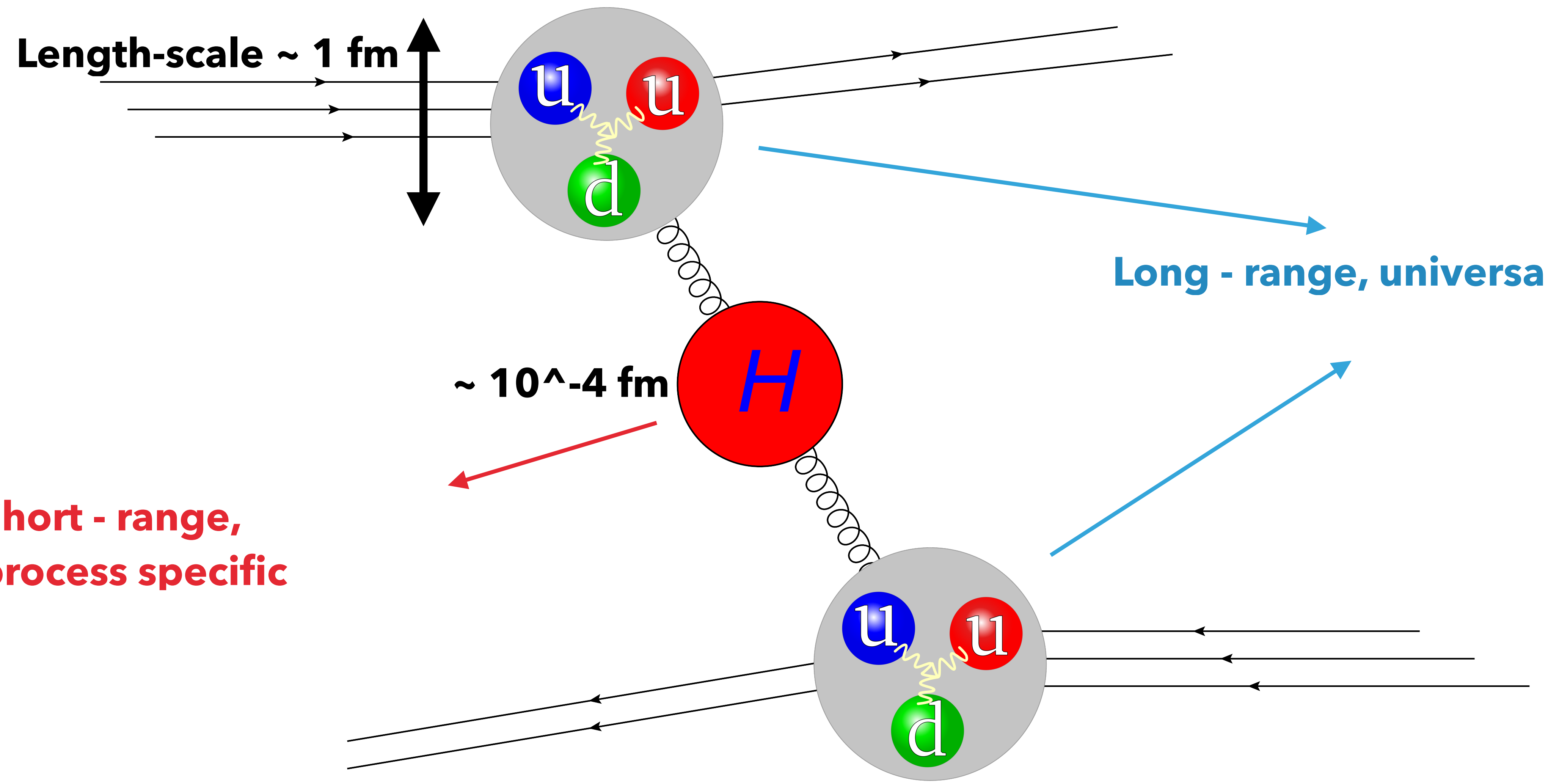


From first principle QFT ...

... to real life measurement



THE WAY TO PRECISION LHC PREDICTIONS

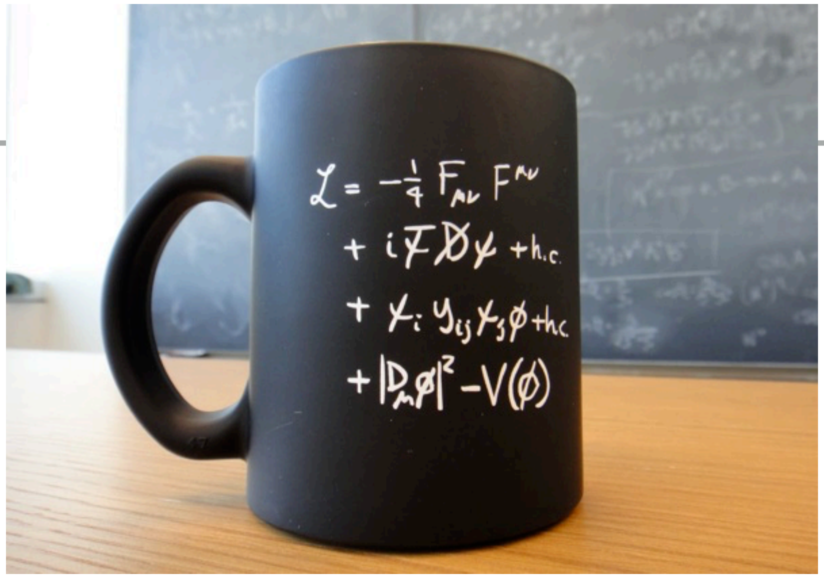


FACTORISATION

$$\sigma \sim \int dx dy f(x) f(y) \hat{\sigma} + \mathcal{O}\left(\frac{\Lambda}{Q}\right)$$

- Intrinsic limitation = level of target precision?

THE WAY TO PRECISION LHC PREDICTIONS



$$\sigma \sim \int dx dy f(x) f(y) \hat{\sigma} + \mathcal{O}\left(\frac{\Lambda}{Q}\right)$$

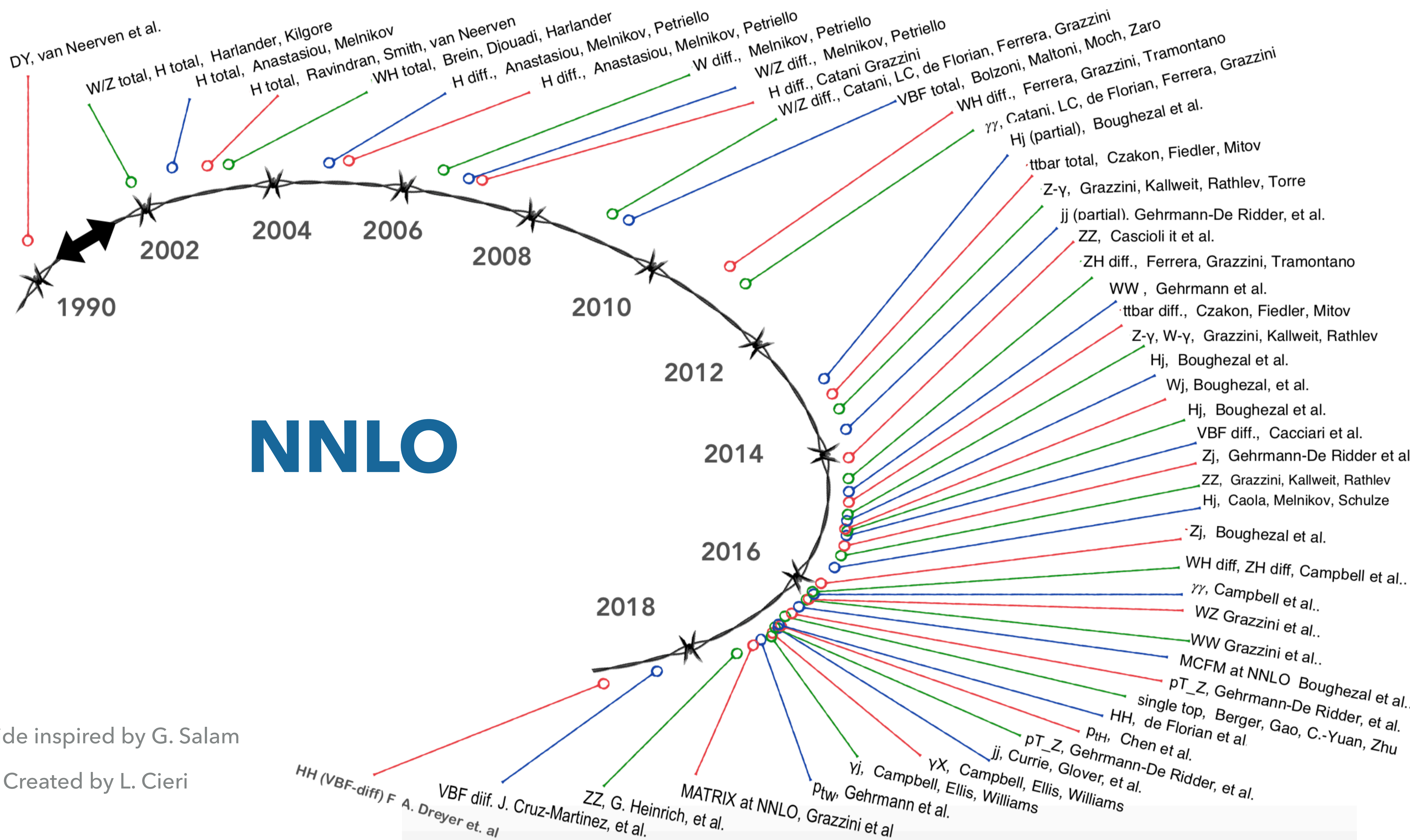
- Perturbative partonic cross sections
- QCD perturbation theory is dominant $\alpha_S = 0.118$
- Naively:

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

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

10% 1% 0.1%

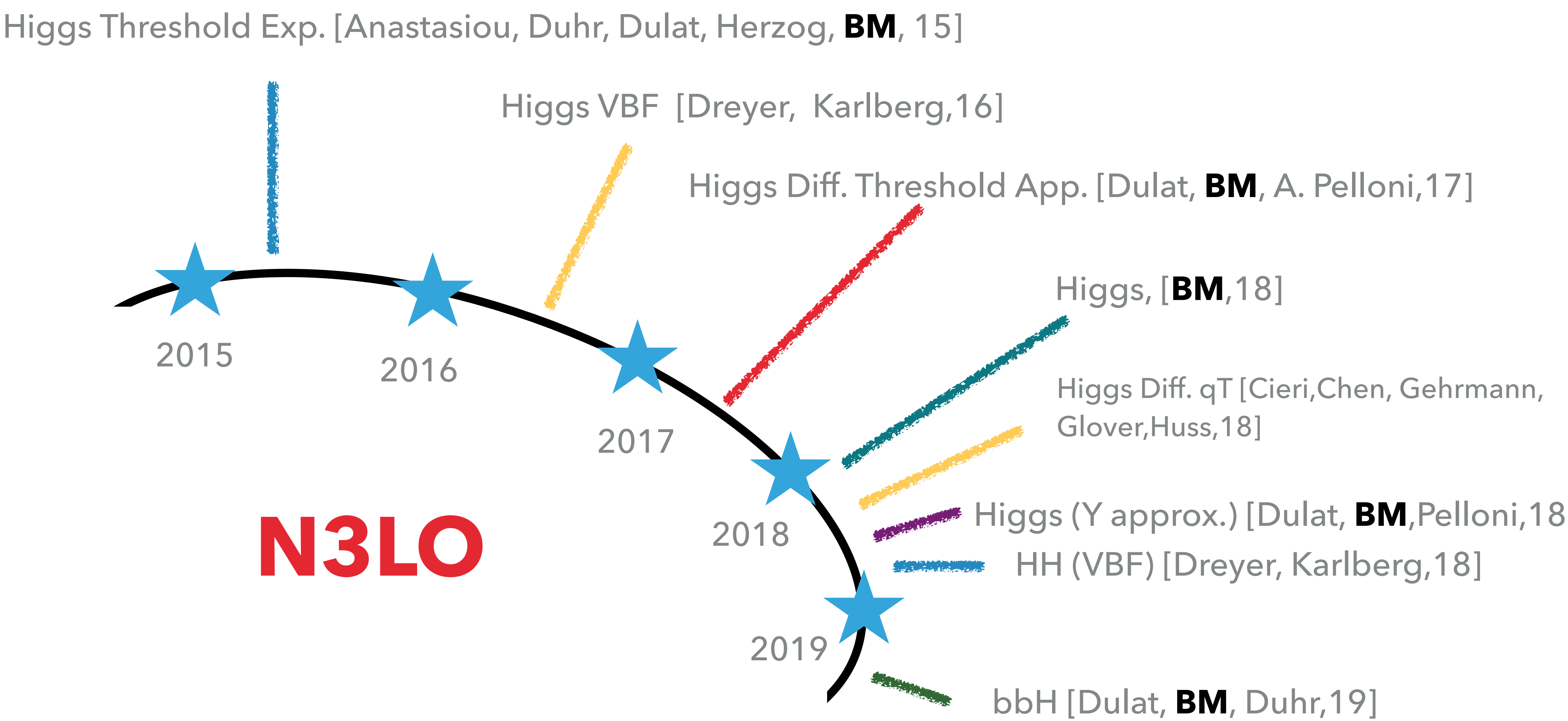
NNLO OVER TIME



Slide inspired by G. Salam

Created by L. Cieri

N3LO OVER TIME



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

HOW MANY HIGGS BOSONS ARE PRODUCED BY THE LHC?

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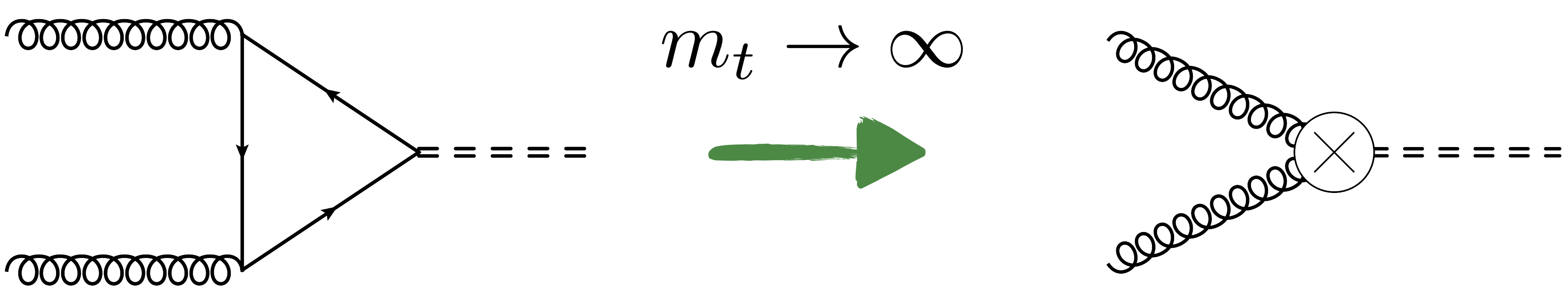
LO **NLO** **NNLO** **N3LO**

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

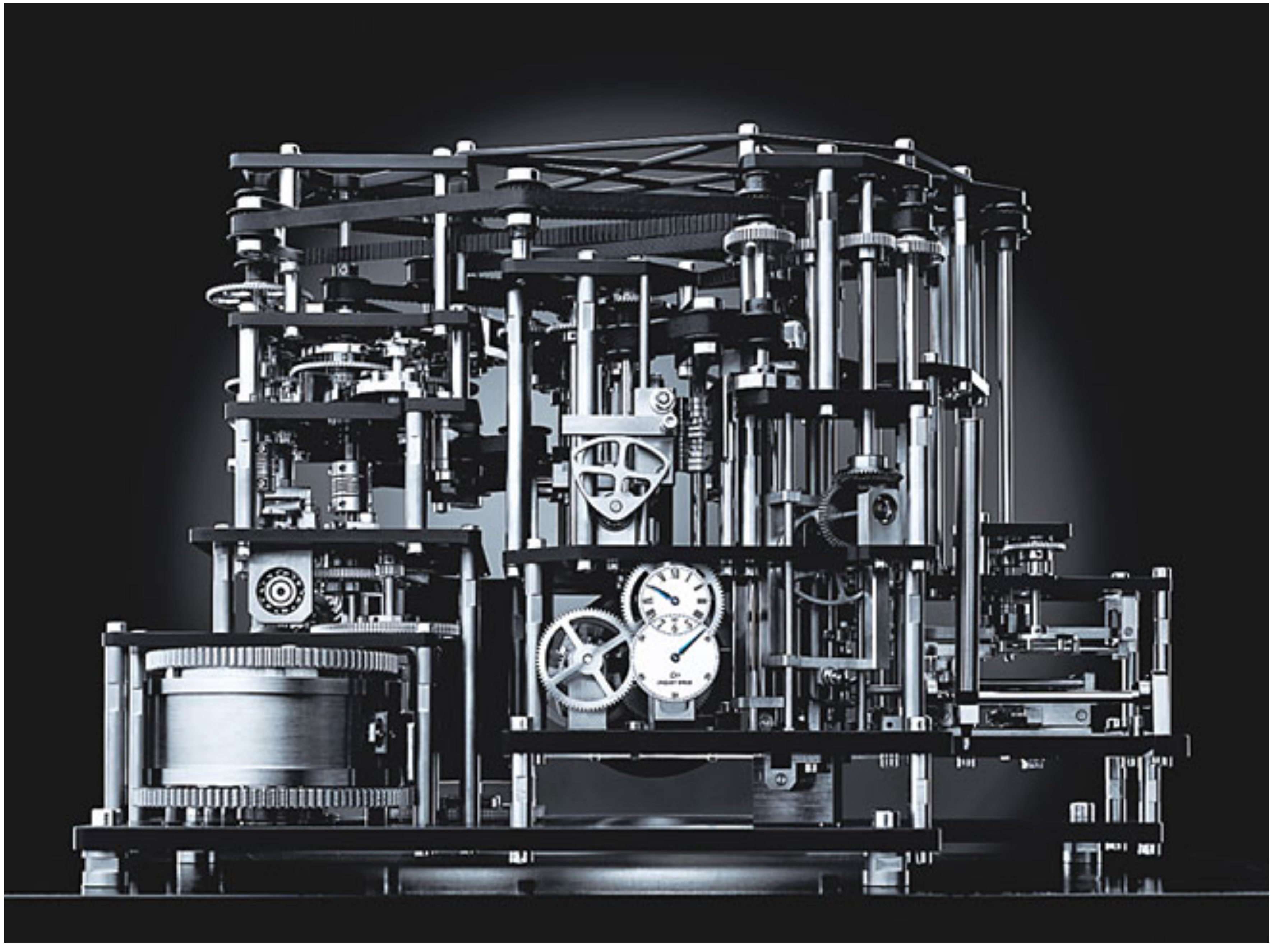
- Perturbative partonic cross sections

Gluon Fusion ~90% of all Higgs bosons

- Integrate out the top quark



THE CROSS SECTION CALCULATION MACHINE



1. Diagrams and Integrals
2. Approximating Integrals
3. Computing Integrals

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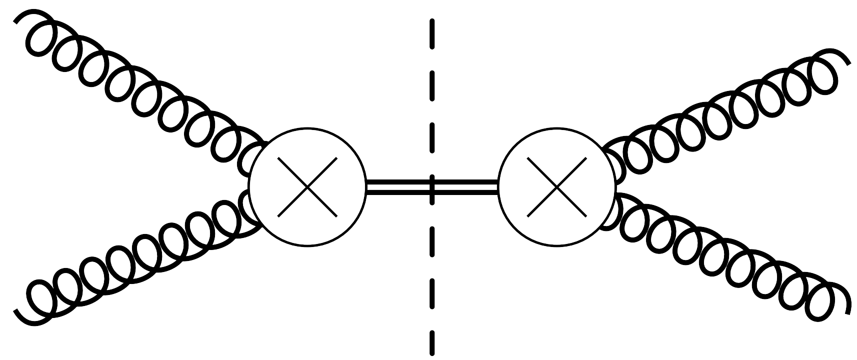
DIAGRAMS AND INTEGRALS

LO

$\sigma^{(0)}$

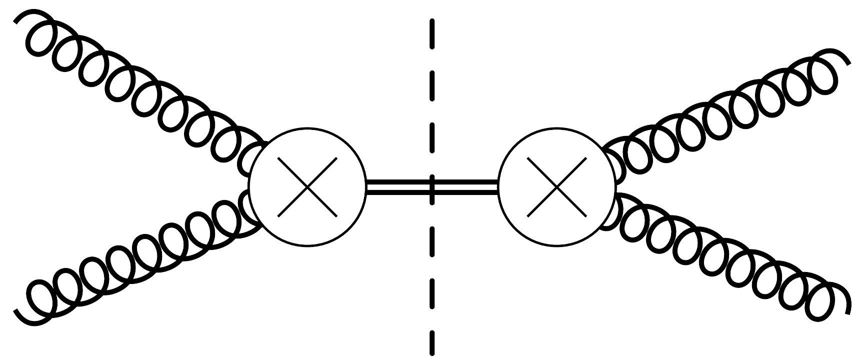


1 Diagram

DIAGRAMS AND INTEGRALS

LO

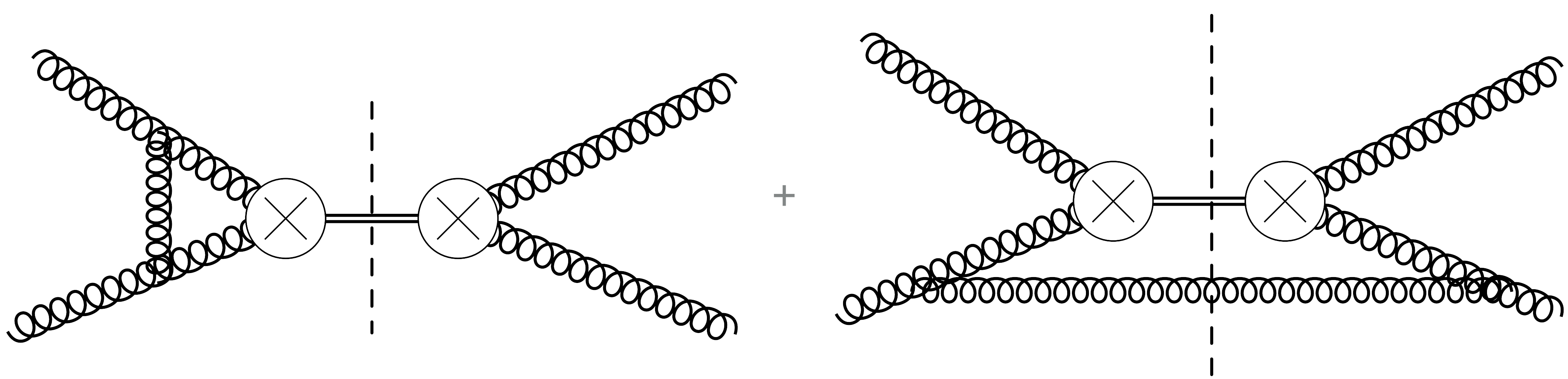
$\sigma^{(0)}$



1 Diagram

NLO

$+\alpha_S^1 \sigma^{(1)}$

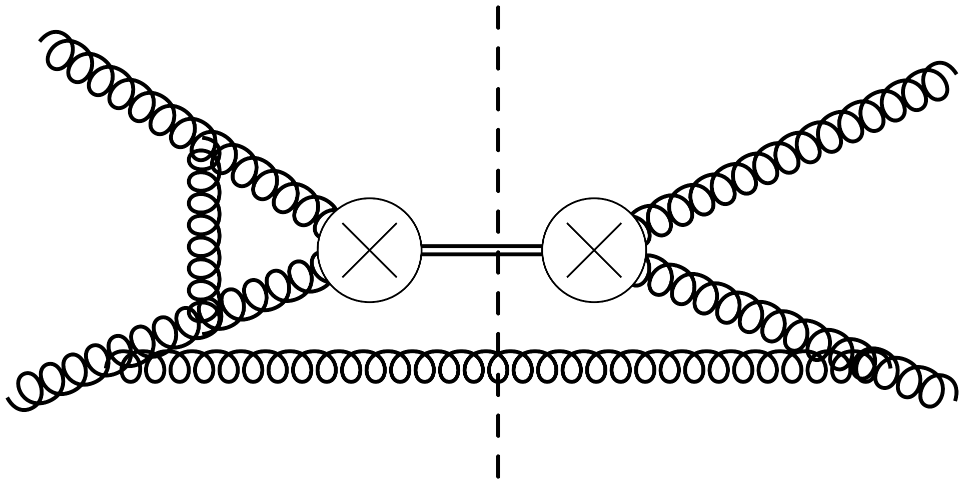


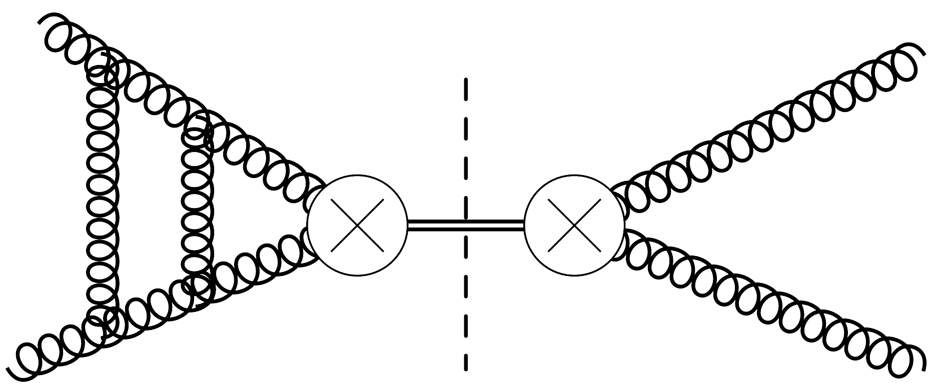
~10 Diagrams

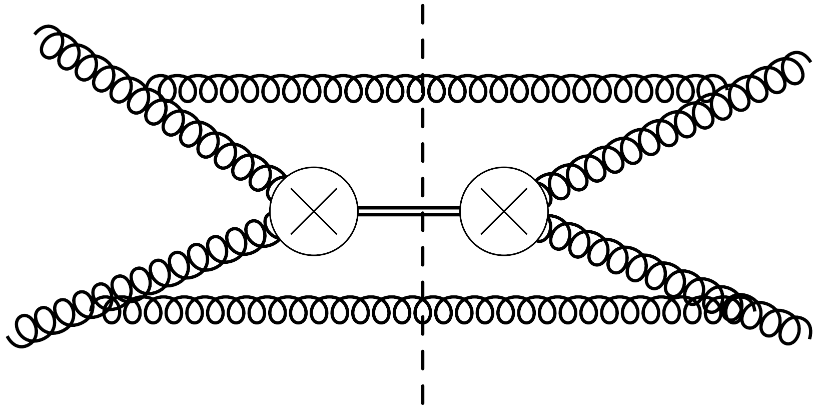
DIAGRAMS AND INTEGRALS

NNLO

$$+\alpha_S^2 \sigma^{(2)}$$





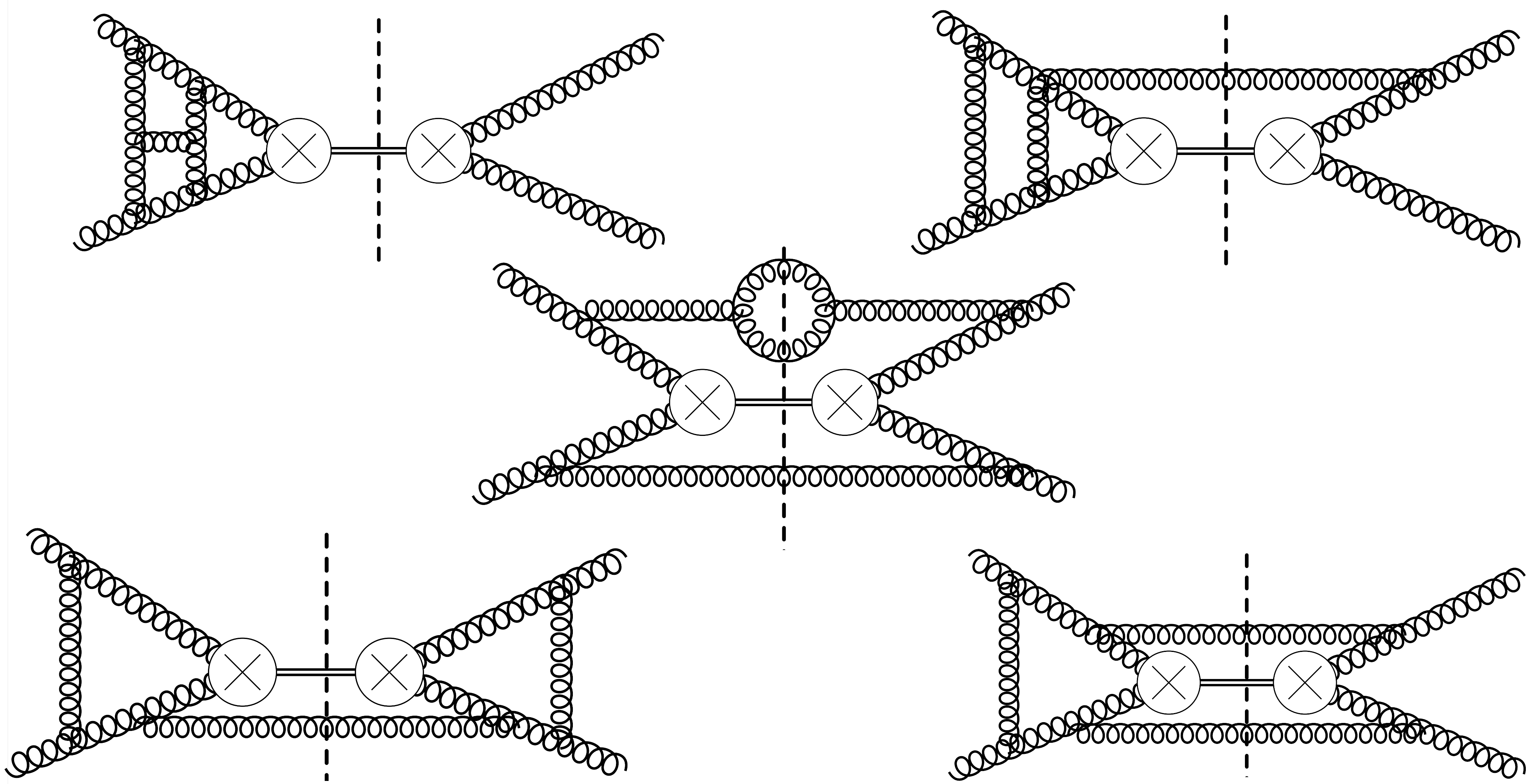


~1000 Diagrams

DIAGRAMS AND INTEGRALS

$+\alpha_S^3 \sigma^{(3)}$

N3LO



100 000 diagrams

Feynman diagrams lead to Feynman integrals

Order	Integrals
0	1
1	~100
2	~50000
3	517531178

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0	1
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- Luckily they are related!

$$c_1 I_1 + c_2 I_2 + \cdots = 0$$

DIAGRAMS AND INTEGRALS

Feynman diagrams lead to Feynman integrals

Order	Integrals	After Relations
0	1	1
1	~100	2
2	~50000	27
3	517531178	1027

[Anastasiou, Duhr, Dulat,Herzog,**BM**,16]

- Luckily they are related!

$$c_1 I_1 + c_2 I_2 + \cdots = 0$$

- Reverse unitarity, IBPs, Laporta, …

Based on [Anastasiou, Dixon, Melnikov, Petriello,… , 2000+]

$$c_1 I_1 + c_2 I_2 + \cdots = 0$$

★ Checking for zeros:

$$c(t) = t - t + t - t + t - t + t - t \cdots + t - t + t = 0?$$

- Analytically: slow
- Numerically: faster $\quad t = 13$
- Machine-sized numerically: fast!

Finite field arithmetics: $t = 27\%13 = 1$

Based on [Manteuffel,Schabinger]

★ Reconstructing polynomials:

$c(t) = ?$ ➡ $c(13) = 13$ ➡ $c(t) = t$

DIAGRAMS AND INTEGRALS – 1 COEFFICIENT

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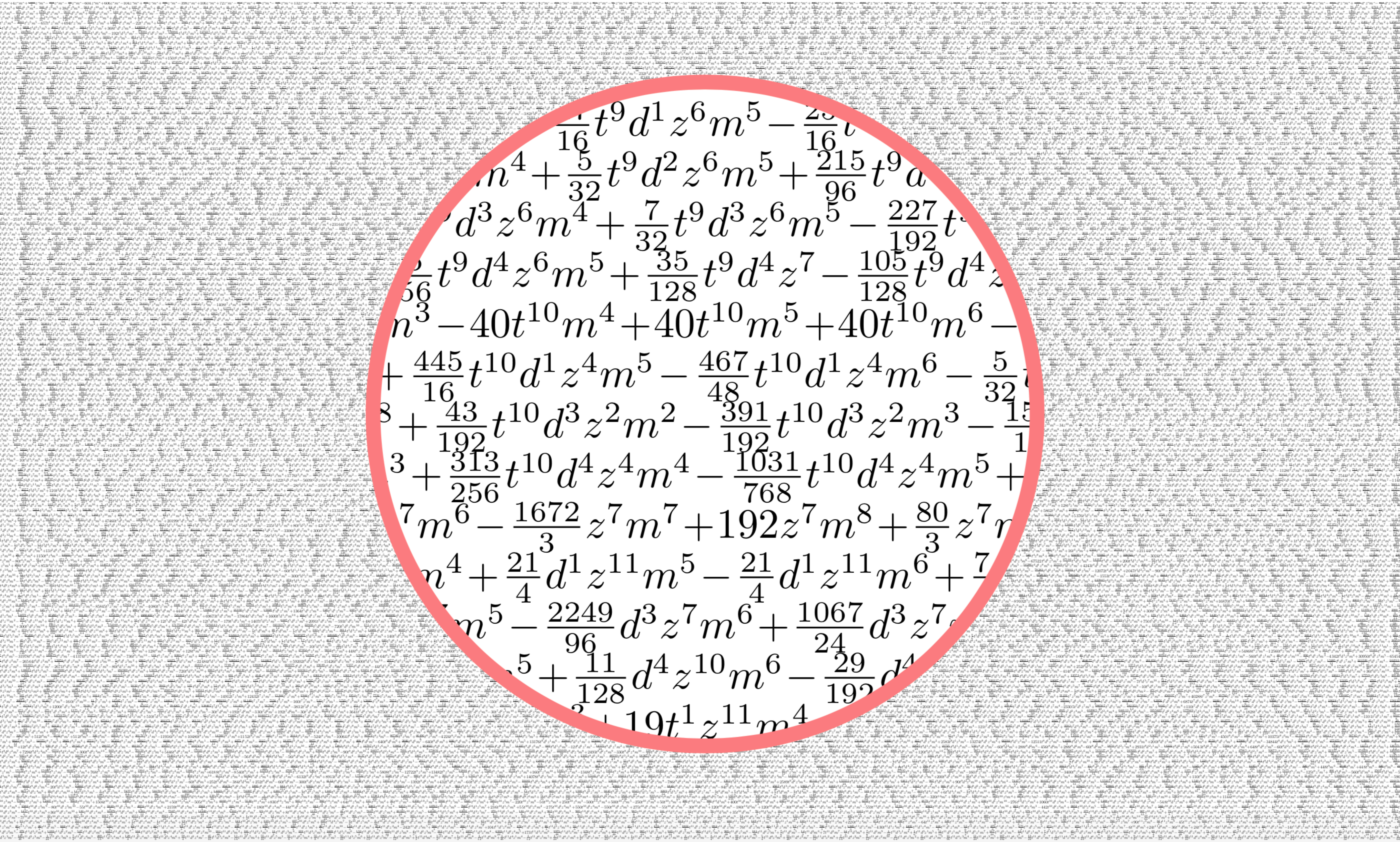

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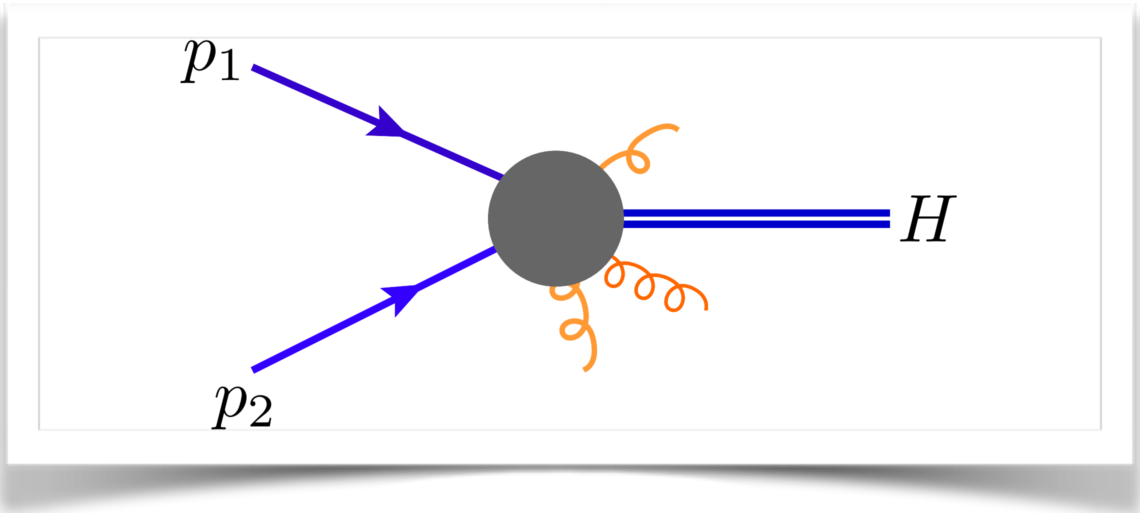
APPROXIMATING INTEGRALS

1027 integrals to compute at N3LO

They are difficult! - Can we approximate them?

Expand around the production threshold

$$\bar{z} = 1 - \frac{m_h^2}{s}$$



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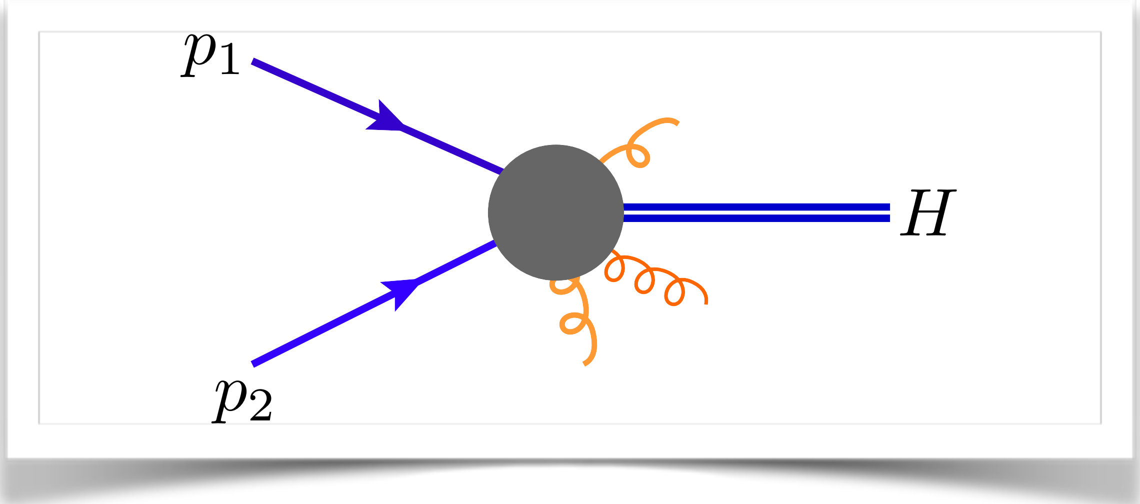

$$\hat{\sigma}^{(3)} = \hat{\sigma}^{(3,-1)} + \mathcal{O}(\bar{z}^0).$$

- New methods to expand real diagrams [Anastasiou, Dulat, Duhr, **BM**,13]
- New methods to expand virtual diagrams [Anastasiou, Dulat, Duhr, Herzog, **BM**,13,15]
- Universal limit

[Anastasiou, Dulat, Duhr, Furlan, Gehrmann, Herzog,**BM**,14]
[Li,Manteuffel,Schabinger,Zhu]

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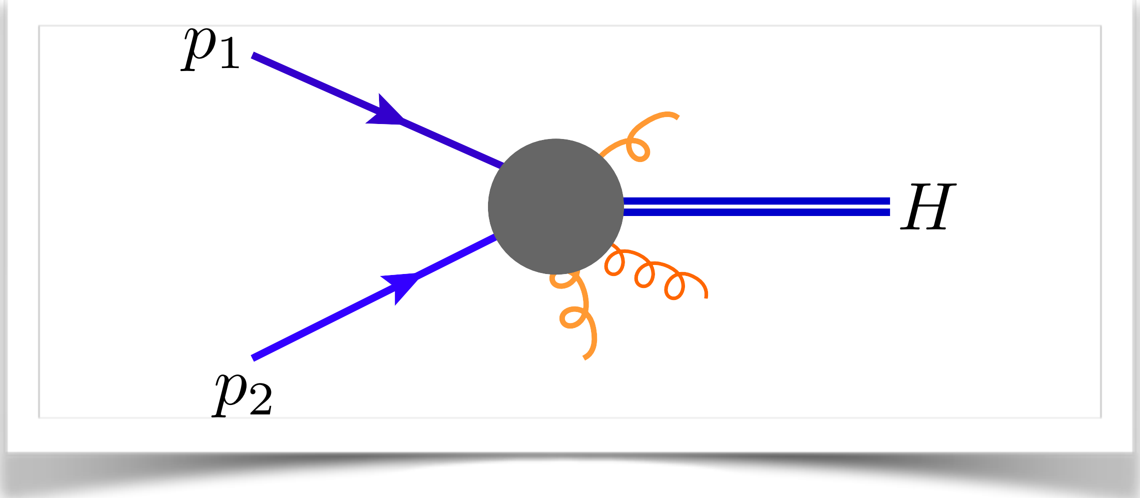

$$\hat{\sigma}^{(3)} = \hat{\sigma}^{(3,-1)} + \bar{z}^0 \hat{\sigma}^{(3,0)} + \mathcal{O}(\bar{z}^1).$$

- Systematic expansion of Feynman diagrams at the integrand level

[Anastasiou, Dulat, Duhr, Furlan, Gehrmann, Herzog, **BM**,14]

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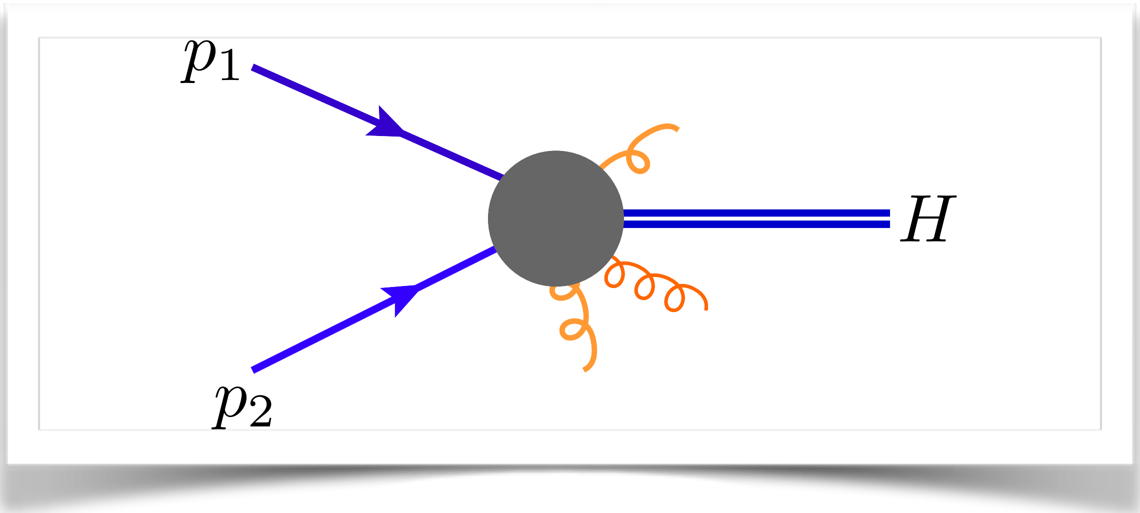

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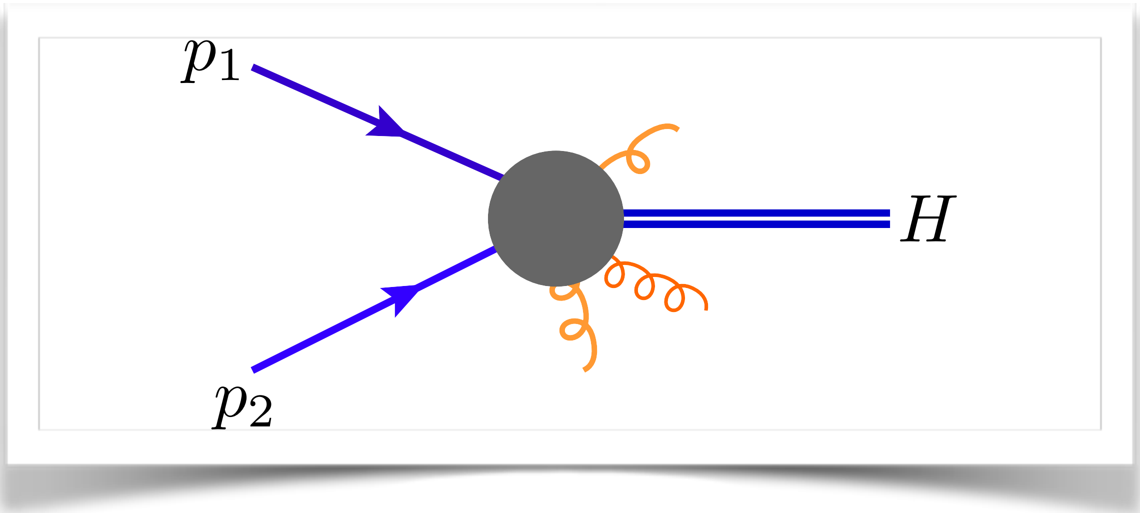

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$$+\bar{z}^3 \hat{\sigma}^{(3,3)} + \bar{z}^4 \hat{\sigma}^{(3,4)} + \bar{z}^5 \hat{\sigma}^{(3,5)} + \bar{z}^6 \hat{\sigma}^{(3,6)} + \bar{z}^7 \hat{\sigma}^{(3,7)} + \bar{z}^8 \hat{\sigma}^{(3,8)} + \bar{z}^9 \hat{\sigma}^{(3,9)} +$$

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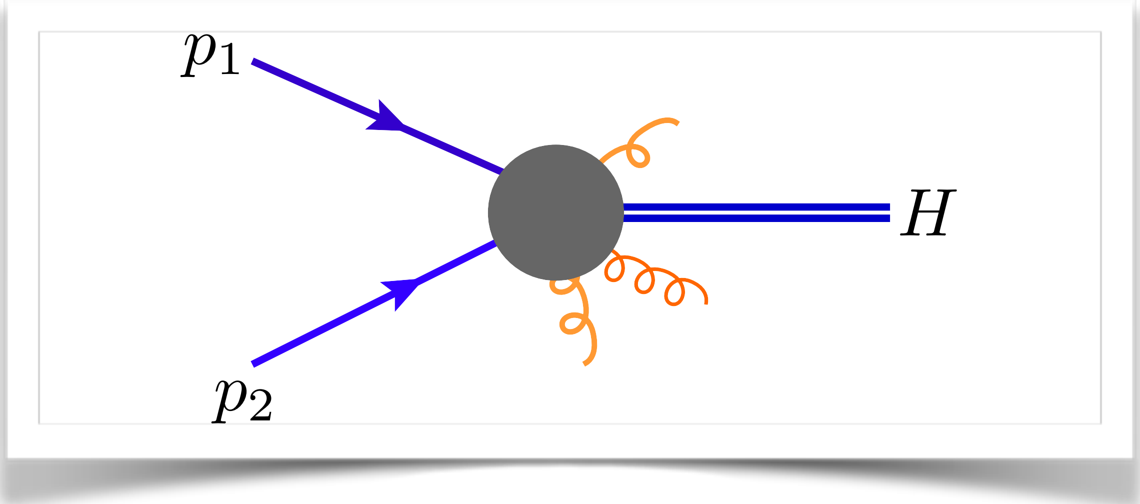

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$$+\bar{z}^{10}\hat{\sigma}^{(3,10)} + \bar{z}^{11}\hat{\sigma}^{(3,11)} + \bar{z}^{12}\hat{\sigma}^{(3,12)} + \bar{z}^{13}\hat{\sigma}^{(3,13)} + \bar{z}^{14}\hat{\sigma}^{(3,14)} + \bar{z}^{15}\hat{\sigma}^{(3,15)} + \bar{z}^{16}\hat{\sigma}^{(3,16)} + \bar{z}^{17}\hat{\sigma}^{(3,17)}$$

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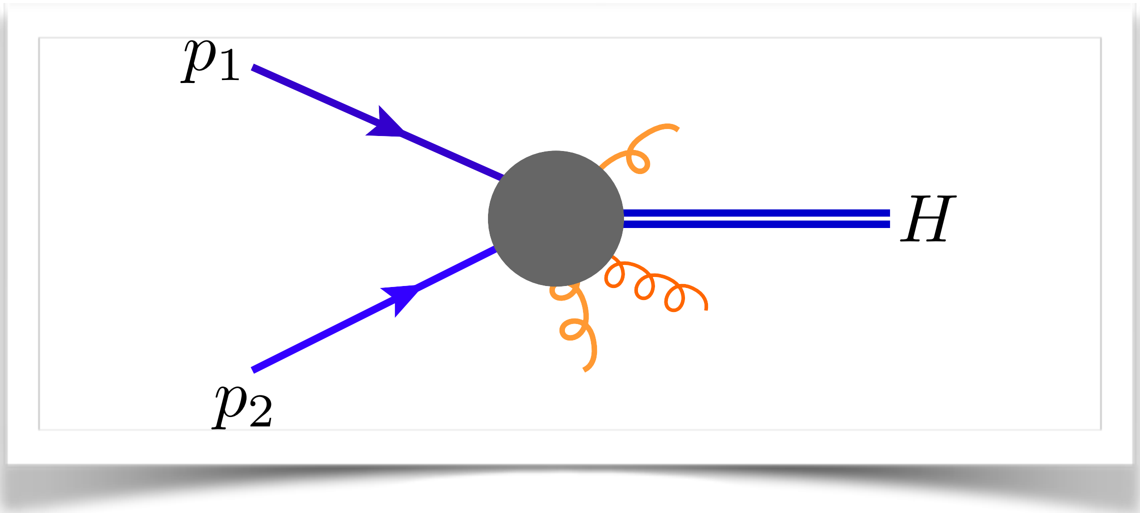

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$$+\bar{z}^{18}\hat{\sigma}^{(3,18)} + \bar{z}^{19}\hat{\sigma}^{(3,19)} + \bar{z}^{20}\hat{\sigma}^{(3,20)} + \bar{z}^{21}\hat{\sigma}^{(3,21)} + \bar{z}^{22}\hat{\sigma}^{(3,22)} + \bar{z}^{23}\hat{\sigma}^{(3,23)} + \bar{z}^{24}\hat{\sigma}^{(3,24)} + \bar{z}^{25}\hat{\sigma}^{(3,25)}$$

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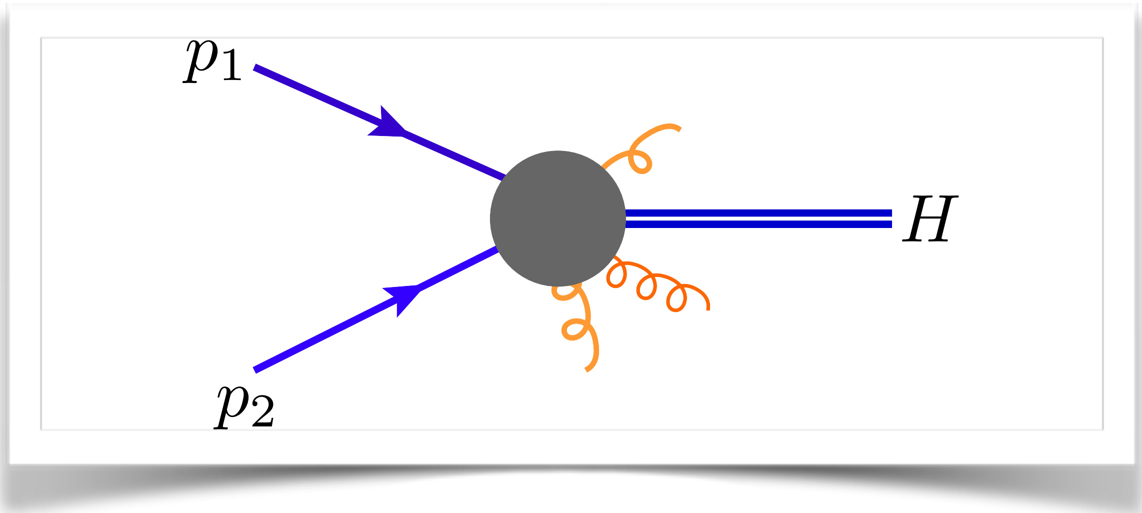

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$$+\bar{z}^{26}\hat{\sigma}^{(3,26)} + \bar{z}^{27}\hat{\sigma}^{(3,27)} + \bar{z}^{28}\hat{\sigma}^{(3,28)} + \bar{z}^{29}\hat{\sigma}^{(3,29)} + \bar{z}^{30}\hat{\sigma}^{(3,30)} + \mathcal{O}(\bar{z}^{31})$$

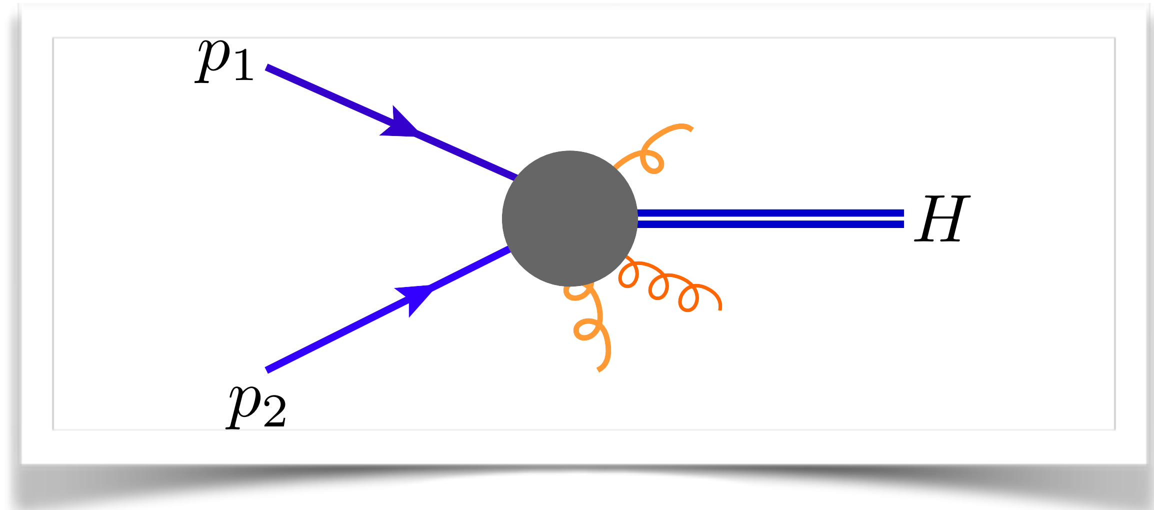
APPROXIMATING INTEGRALS

1027 integrals to compute at N3LO

They are difficult! - Can we approximate them?

Expand around the production threshold

$$\bar{z} = 1 - \frac{m_h^2}{s}$$



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$$+\bar{z}^{10} \hat{\sigma}^{(3,10)} + \bar{z}^{11} \hat{\sigma}^{(3,11)} + \bar{z}^{12} \hat{\sigma}^{(3,12)} + \bar{z}^{13} \hat{\sigma}^{(3,13)} \cdots$$
$$+\bar{z}^{18} \hat{\sigma}^{(3,18)} + \bar{z}^{19} \hat{\sigma}^{(3,19)} + \bar{z}^{20} \hat{\sigma}^{(3,20)} + \bar{z}^{21} \hat{\sigma}^{(3,21)} + \bar{z}^{22} \hat{\sigma}^{(3,22)} + \bar{z}^{23} \hat{\sigma}^{(3,23)} + \bar{z}^{24} \hat{\sigma}^{(3,24)} + \bar{z}^{25} \hat{\sigma}^{(3,25)}$$
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- Combine with differential equations

  [Dulat, **BM**,14]

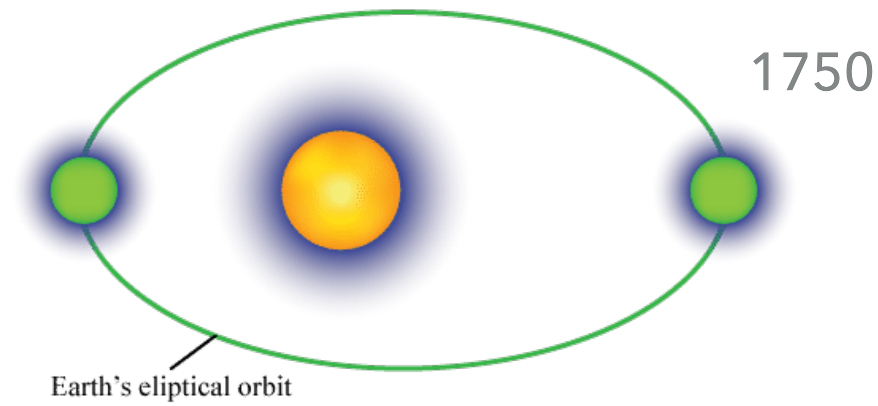
  [Anastasiou, Duhr, Dulat, Furlan, Gehrmann, Herzog, Lazopoulos, **BM**,16]

1. Diagrams and Integrals
2. Approximating Integrals
3. Computing Integrals

Complication: A **new** class of functions at N3LO

Elliptic Integral: ~ period of the planet

$$\psi(z) = \int^{z} \frac{dt}{\sqrt{(1-t^2)(1-at^2)}}$$



Iterated Elliptic Integral:

$$I(a,b,\ldots,c,z) = \int^{z} \frac{dt_n}{t_n - c} \cdots \int^{t_2} \frac{dt_1}{t_1 - b} \psi(t_1)$$

- How to relate them?
- How to evaluate them?
- How to expand them around different points?
- ....

Iterated Elliptic Integral:

- How to relate them?

$$c_1 I_1 + c_2 I_2 + c_3 I_3 = 0?$$

- We know already how to expand around $\bar{z} = 0$

$$I_i = a_{i0} + \bar{z} a_{i1} + \bar{z}^2 a_{i2} + \dots$$

- Equations:

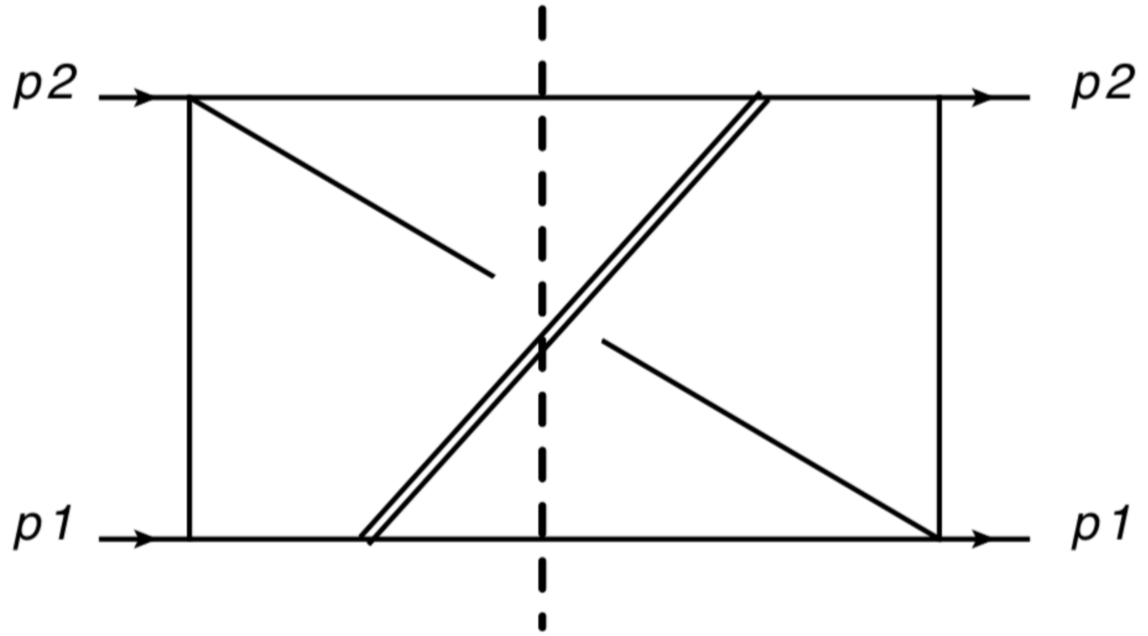
$$(a_{10} c_1 + a_{20} c_2 + a_{30} c_3) + \bar{z}(a_{11} c_1 + a_{21} c_2 + a_{31} c_3) + \dots = 0?$$

- Find a solution for any power in $\bar{z}$?

$$I_1 = -\frac{1}{c_1}(c_2 I_2 + c_3 I_3)$$

- ~10000 relations with up to 77 integrals per relation.

COMPUTING INTEGRALS



Iterated Elliptic Integral:

- How to relate them? ✓
- How to evaluate them? ✓
- How to expand them around different points? ✓
- …. ✓

First analytic partonic LHC cross section at N3LO

[**BM**,18]

HOW MANY HIGGS BOSONS ARE PRODUCED BY THE LHC?

PRODUCING HIGGS BOSONS

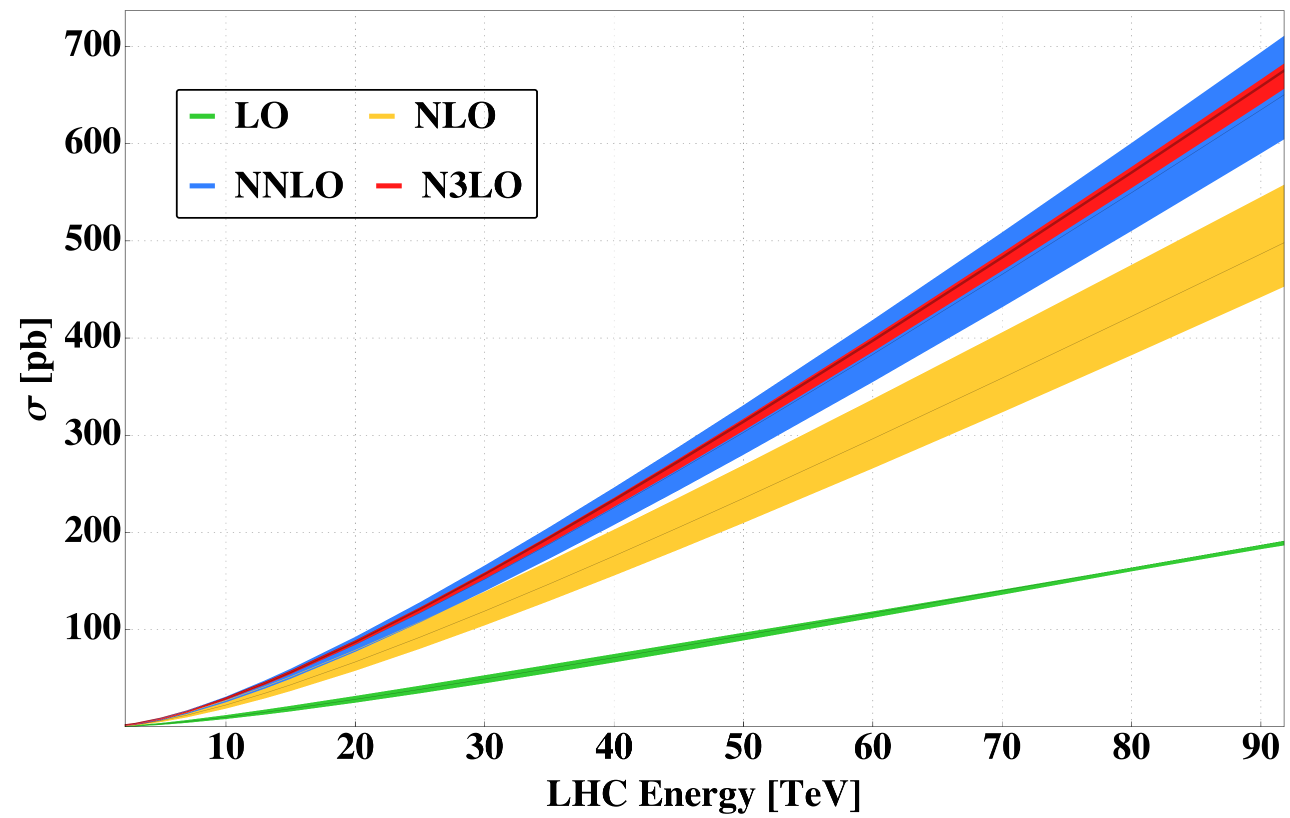
@ 13 TeV in 2018

$$\sigma = \sigma^{(0)}$$ 900 000 Higgs Bosons

$$+\alpha_S^1 \sigma^{(1)}$$ +1 100 000 Higgs Bosons

$$+\alpha_S^2 \sigma^{(2)}$$ +500 000 Higgs Bosons

$$+\alpha_S^3 \sigma^{(3)}$$ +100 000 Higgs Bosons



- Large corrections at low orders
- N3LO seems to stabilise the predictions

PREDICTIONS FOR THE LHC

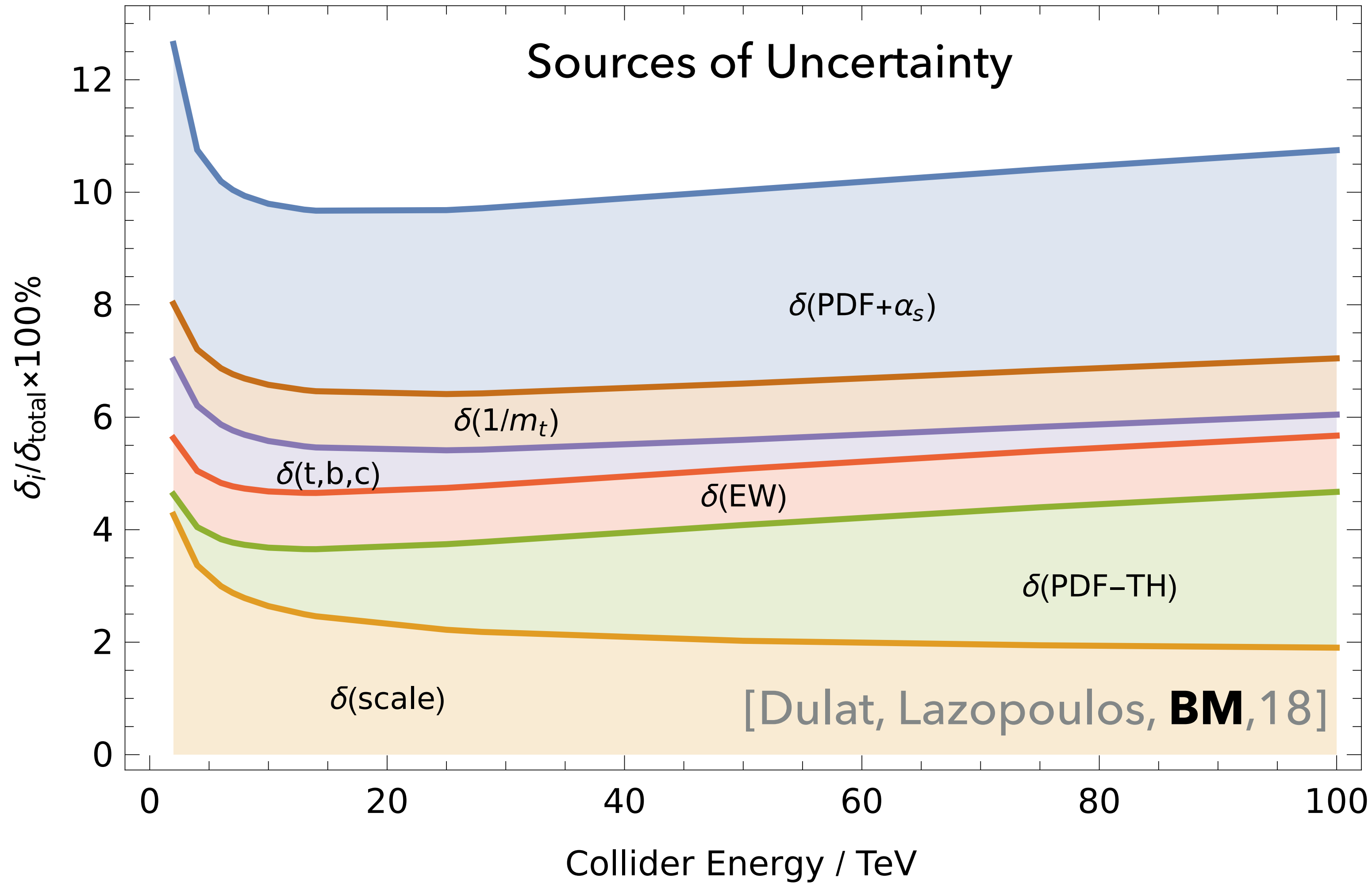
Much more than QCD corrections

- Electro-weak corrections.
- Neglected quark mass effects.
- Coupling to bottom, charm quarks.
- Estimate uncertainties.

  Truncation of perturbative series

  PDF, α_S

- …



PREDICTIONS FOR THE LHC

Much more than QCD corrections

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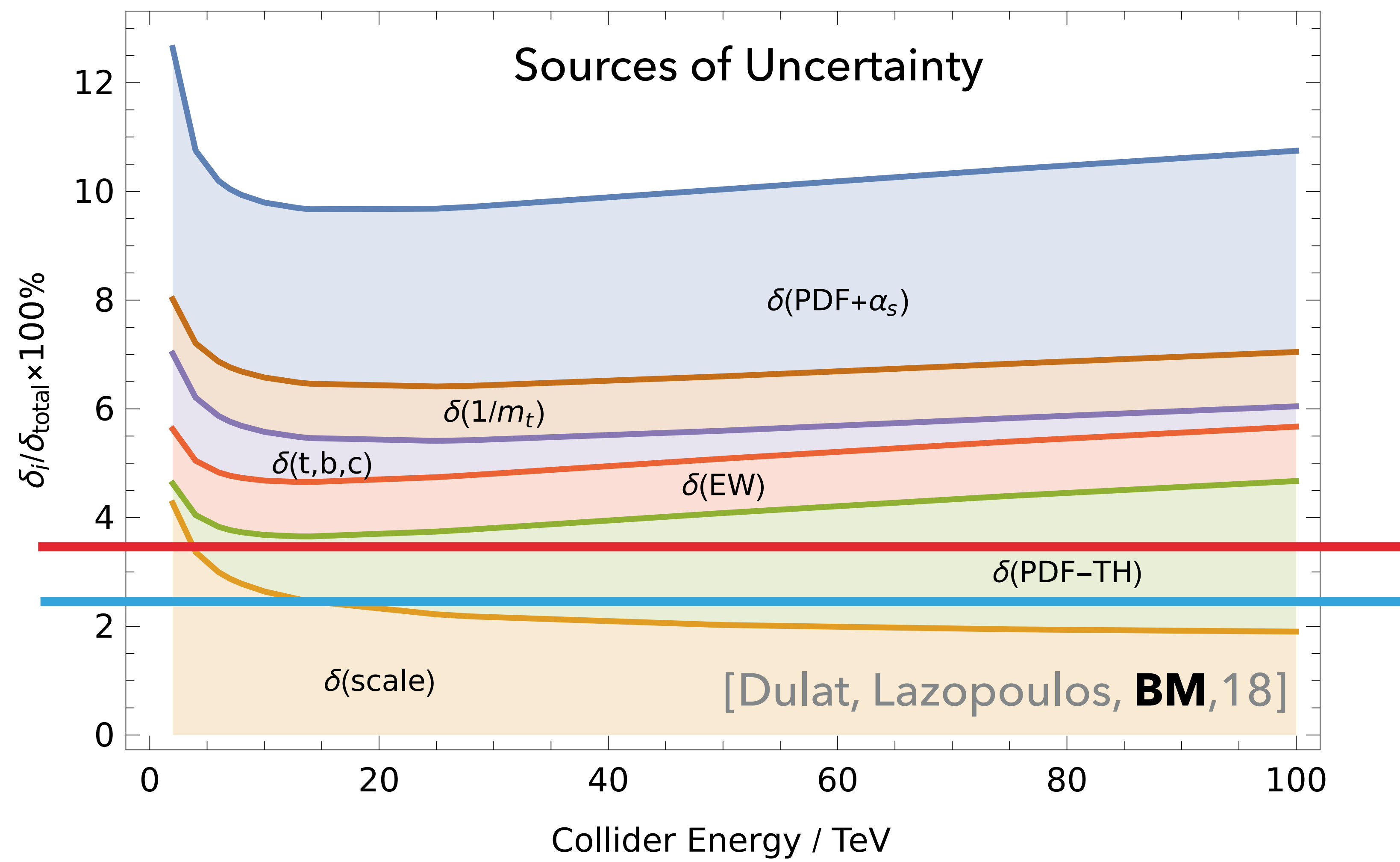
  PDF, α_S

- …

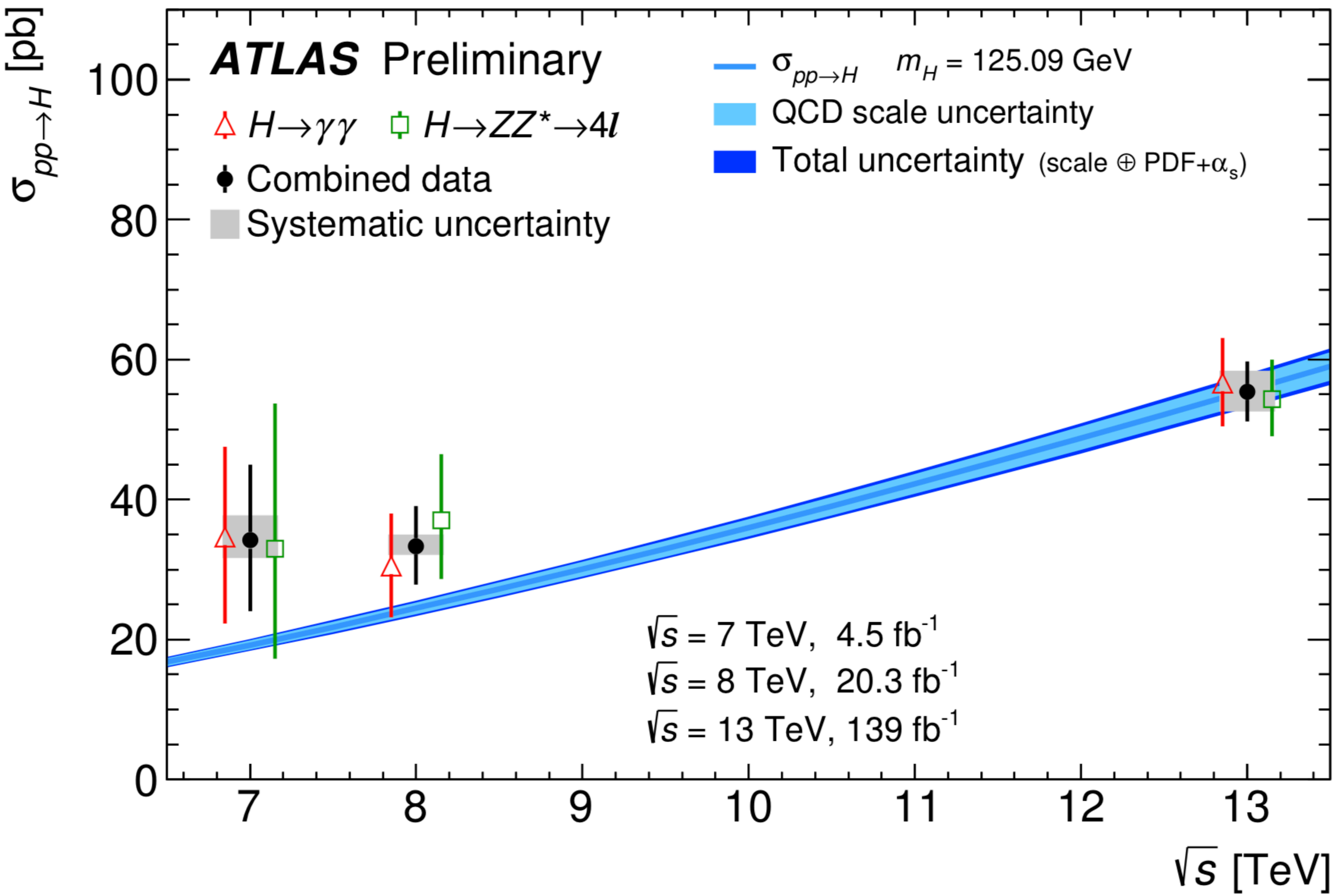
HL-LHC

Pessimistic scenario

Optimistic scenario



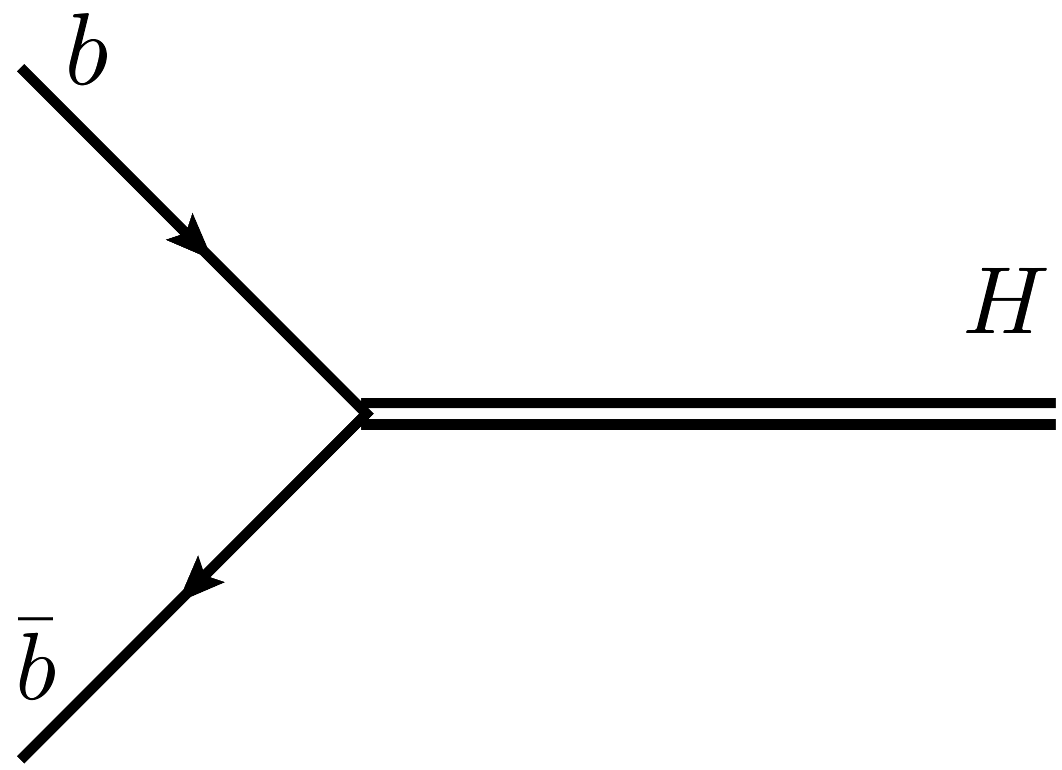
THE HIGGS BOSON CROSS SECTION



HIGHER ORDER COMPUTATION

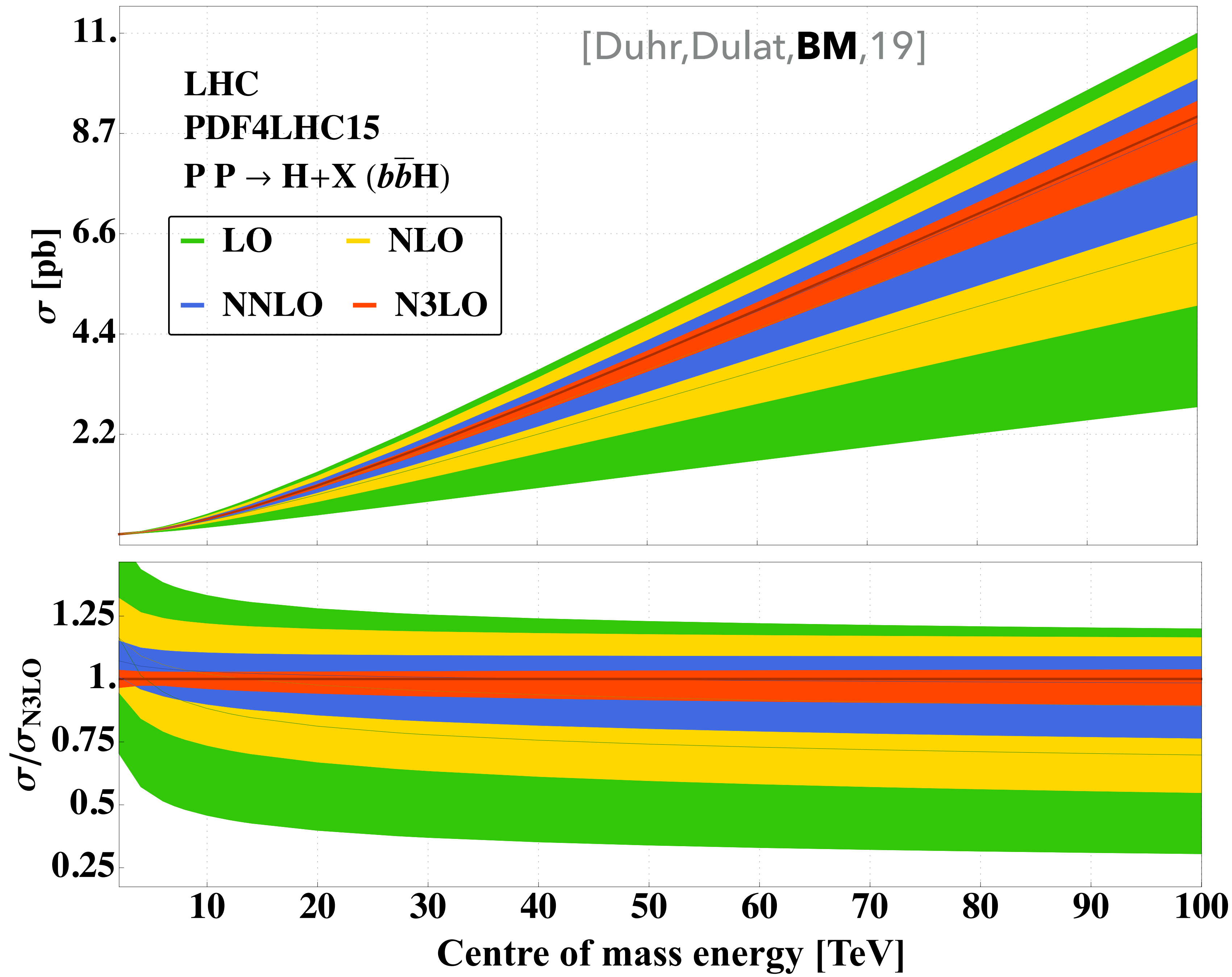
For other processes

Fusion of two bottom quarks to produce a Higgs boson

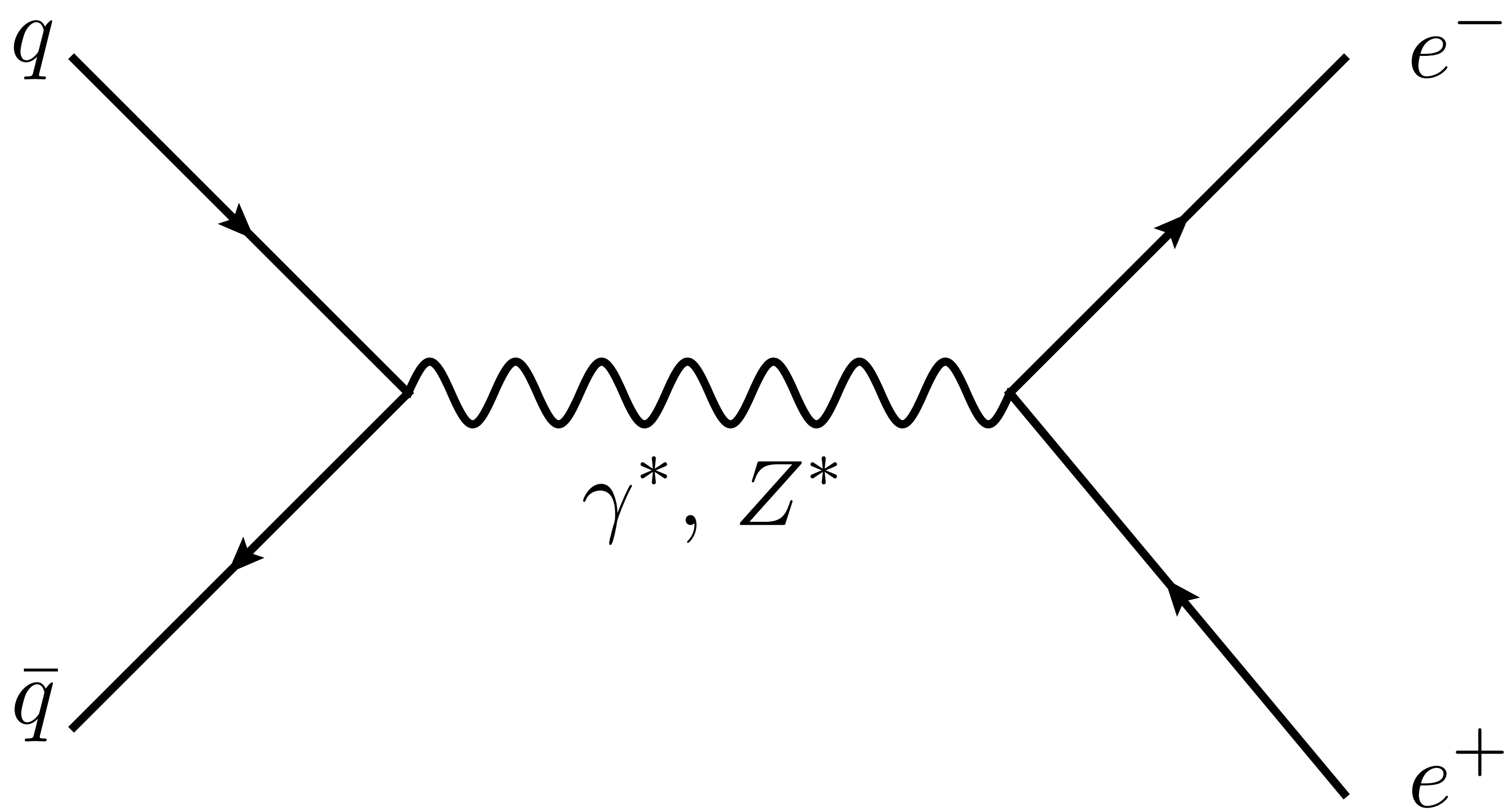


- Test of the bottom quark Yukawa coupling
- Bottom quarks treated as part of the proton

Fusion of two bottom quarks to produce a Higgs boson

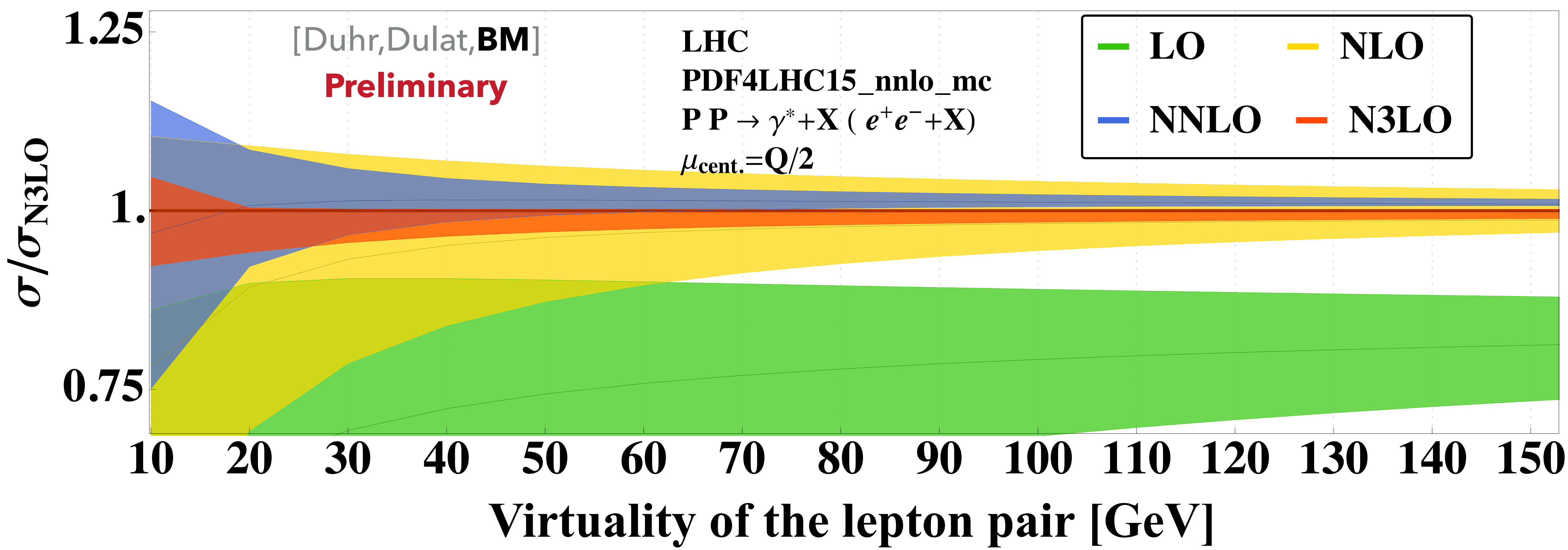


The probability to produce a $e^+ e^-$ pair



- The standard candle process at the LHC
- Parton distribution functions

The probability to produce a $e^+ e^-$ pair



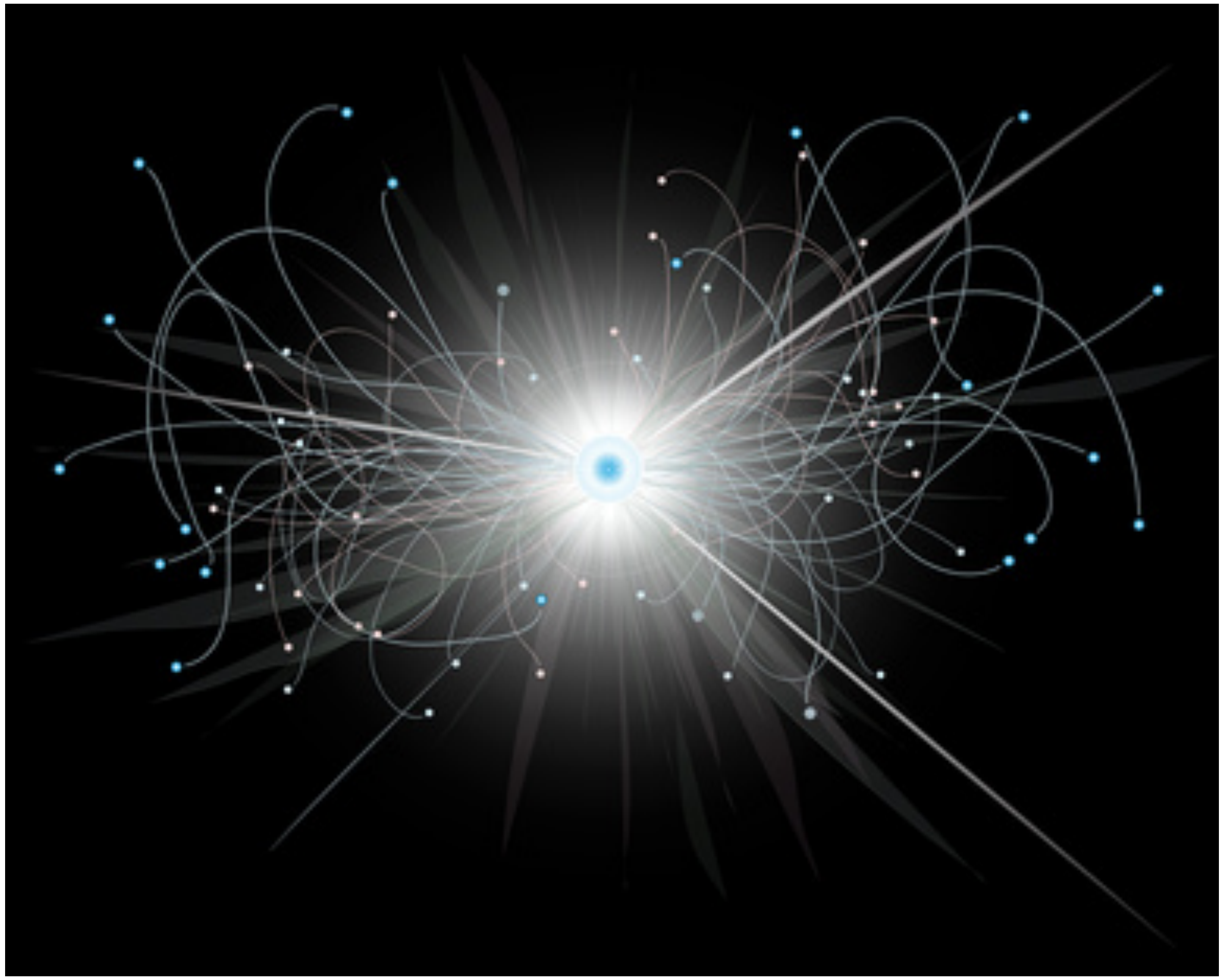
- Currently only photon exchange.
- Interesting perturbative development!

HIGHER ORDER COMPUTATION

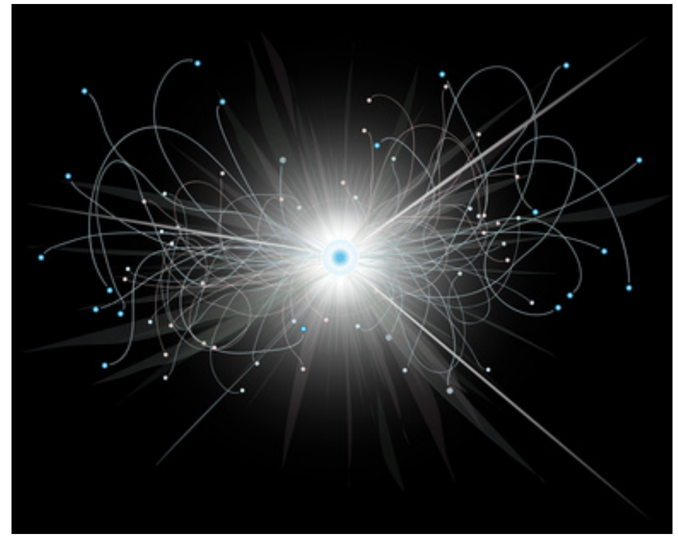
For realistic final states

DIFFERENTIAL CROSS SECTIONS

- Inclusive cross sections are idealised observables.
- Finite detector volumes and resolution.
- Exploring kinematic regimes can enhance a signal we are interested in.



DIFFERENTIAL CROSS SECTIONS

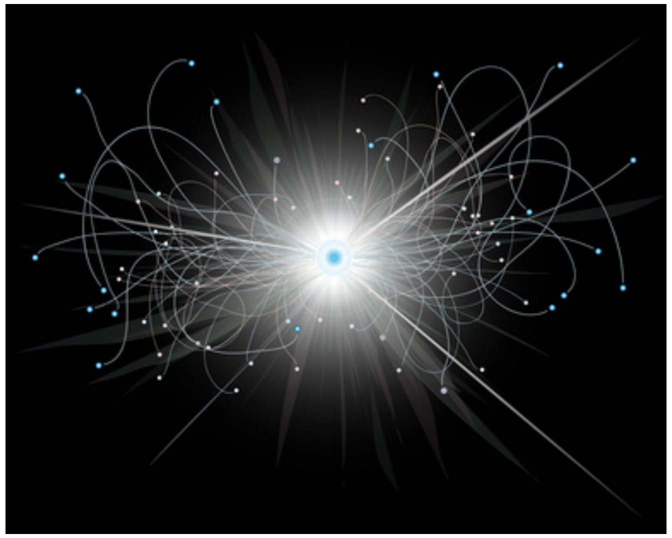


- Current understanding of the infrared structure is one limiting factor.

NNLO:

Inclusive Higgs ~ **CPU seconds**

DIFFERENTIAL CROSS SECTIONS

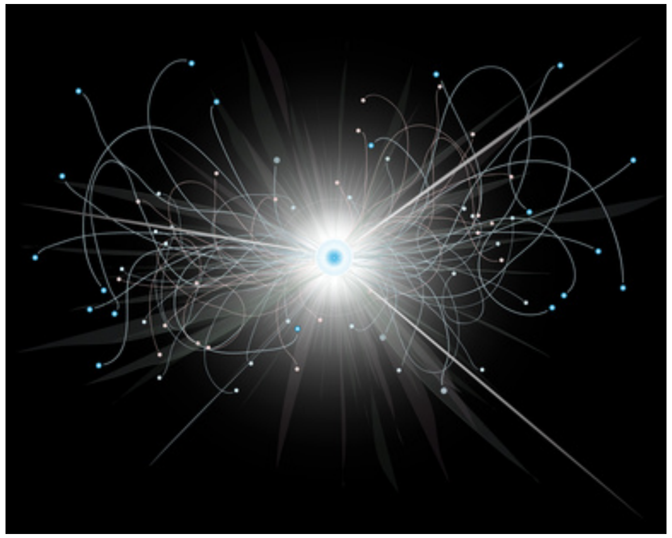


- Current understanding of the infrared structure is one limiting factor.

NNLO:

Inclusive Higgs	**~ CPU seconds**
Differential Higgs (pT, Y, etc.)	**~ 10-100 CPU hours**

DIFFERENTIAL CROSS SECTIONS



- Current understanding of the infrared structure is one limiting factor.

NNLO:

Inclusive Higgs ~ CPU seconds

Differential Higgs (pT, Y, etc.) ~ 10-100 CPU hours

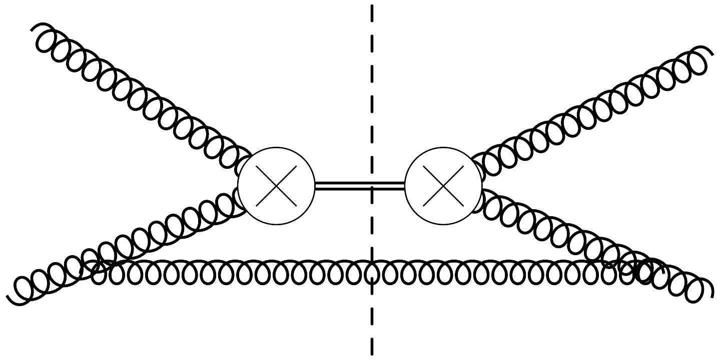
Differential Higgs+Jet (pT-H) ~ 10^5- 10^6 CPU hours

~1 CPU century

DIFFERENTIAL CROSS SECTIONS

- IR Divergences:

$$\int d^4p_h d^4p_g$$

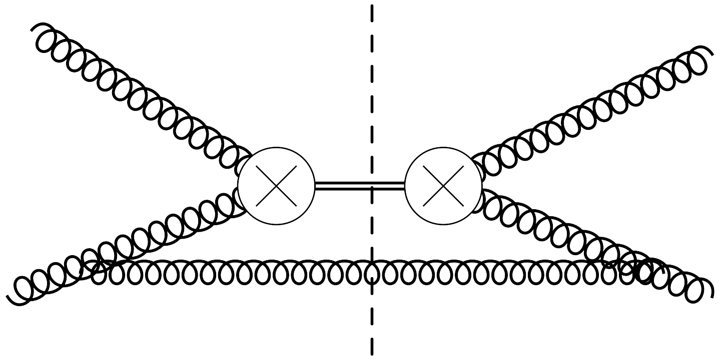


$$\sim \int \frac{dE_g}{E_g} \frac{d\cos\phi_{1g}}{1-\cos\phi_{1g}} F(E_g, \cos(\phi_{1g}))$$

DIFFERENTIAL CROSS SECTIONS

- IR Divergences:

$$\int d^4p_h d^4p_g$$

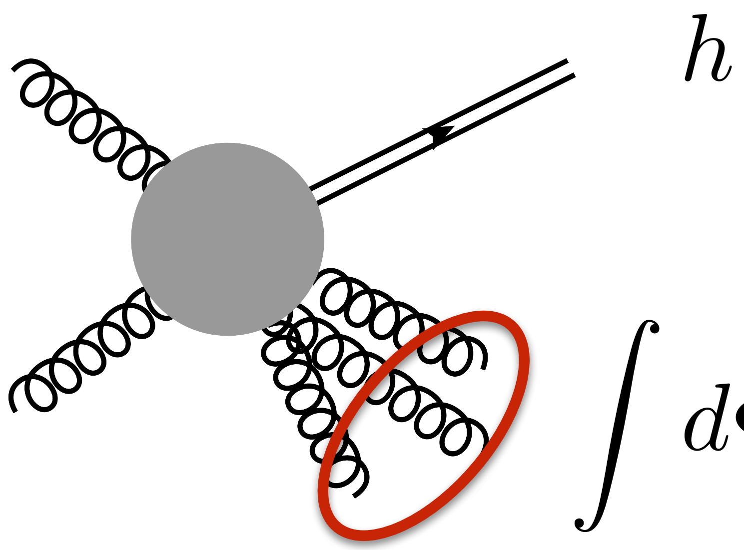


$$\sim \int \frac{dE_g}{E_g} \frac{d\cos\phi_{1g}}{1-\cos\phi_{1g}} F(E_g, \cos(\phi_{1g}))$$

- Dimensional Regularisation:

$$\int_0^1 dE_g E_g^{-1-\epsilon} = \frac{1}{-\epsilon}$$

DIFFERENTIAL CROSS SECTIONS



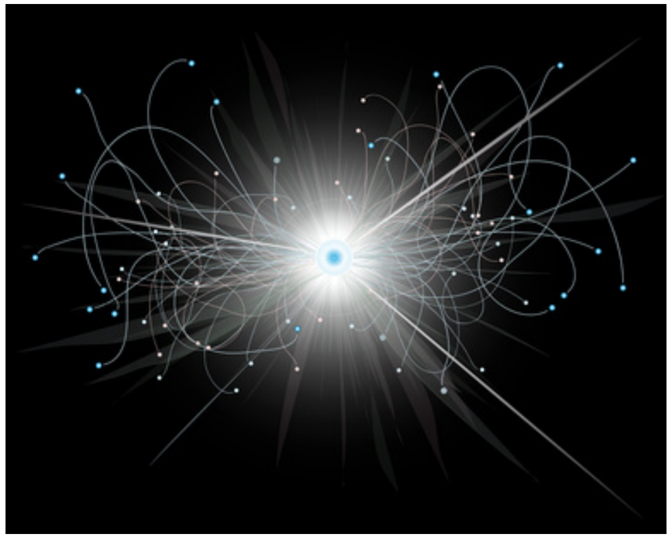
$$\int d\Phi_n$$

- Let's analytically integrate over radiation
  [Dulat,**BM**,Pelloni, 17]
  [Dulat,Lionetti,**BM**,Pelloni,Specchia, 17]

- Formulae depend on:

$$p_h = \begin{pmatrix} E \\ p_x \\ p_y \\ p_z \end{pmatrix} = \begin{pmatrix} \sqrt{p_T^2 + m_h^2} \cosh Y \\ p_T \cos\phi \\ p_T \sin\phi \\ \sqrt{p_T^2 + m_h^2} \sinh Y \end{pmatrix}$$

DIFFERENTIAL CROSS SECTIONS

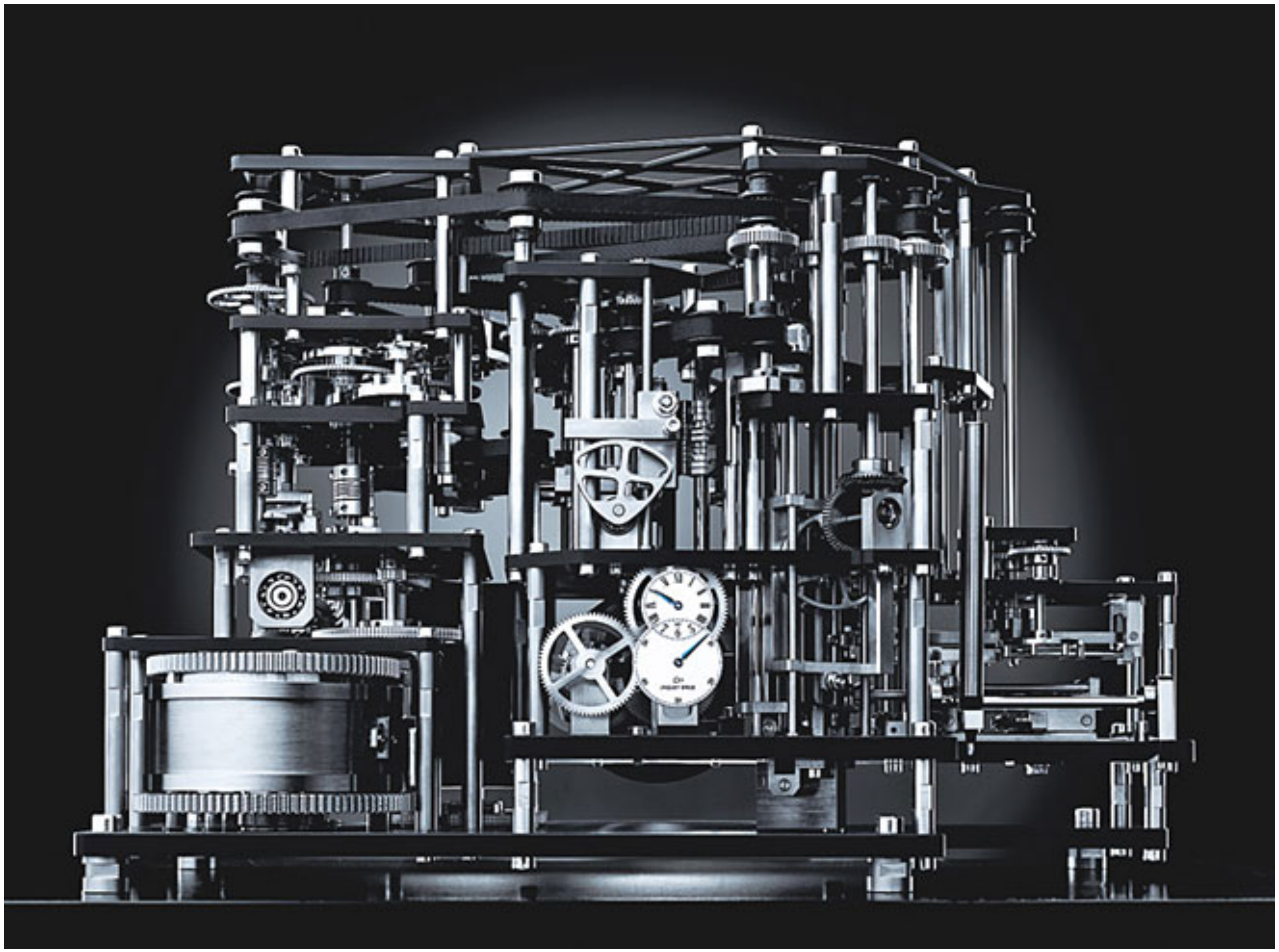


Rapidity of the Higgs boson:

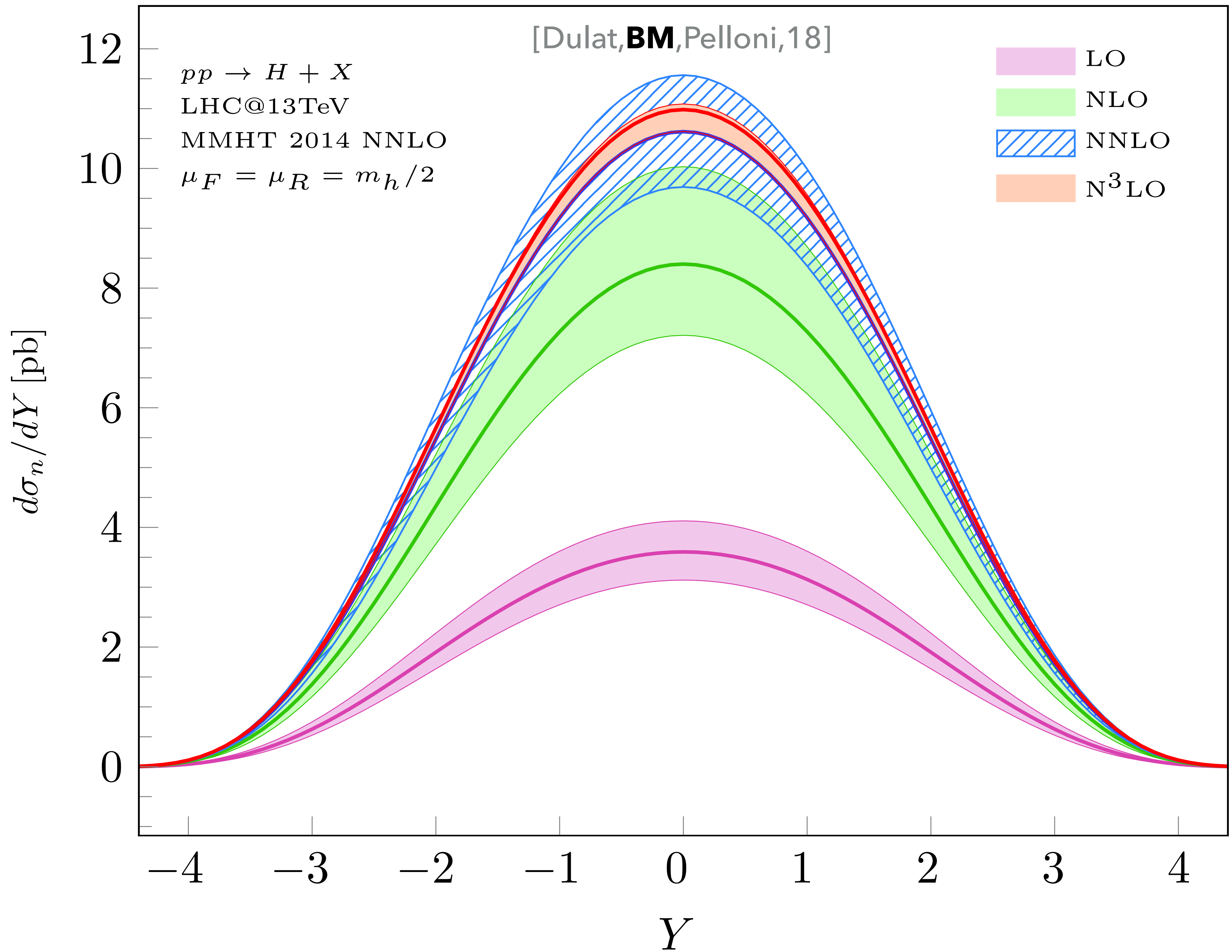
$$Y = \frac{1}{2}\log\left(\frac{2P_1 p_h}{2P_2 p_h}\right)$$

Build on **N3LO** technology

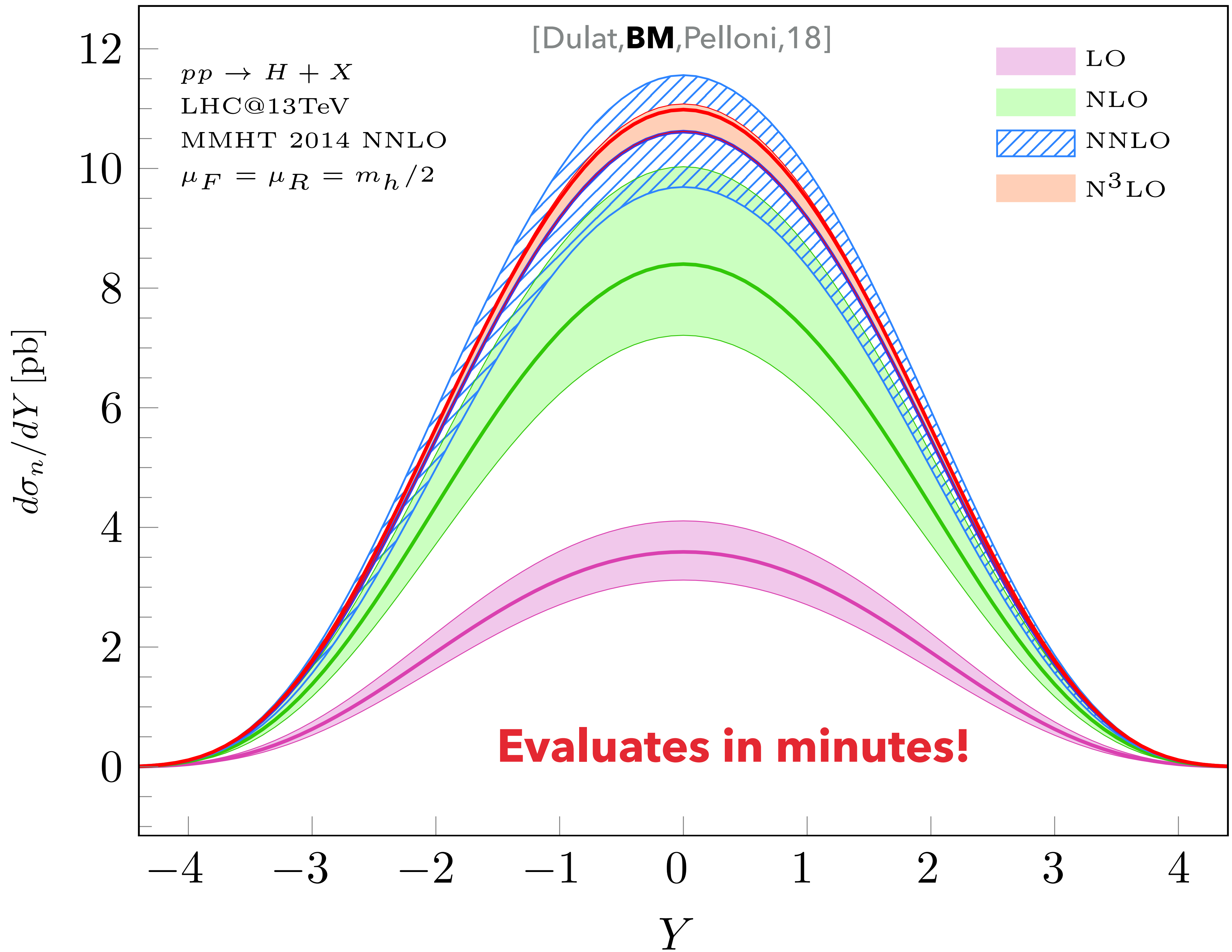
SO WE USE OUR CROSS SECTION MACHINE AND COMPUTE!



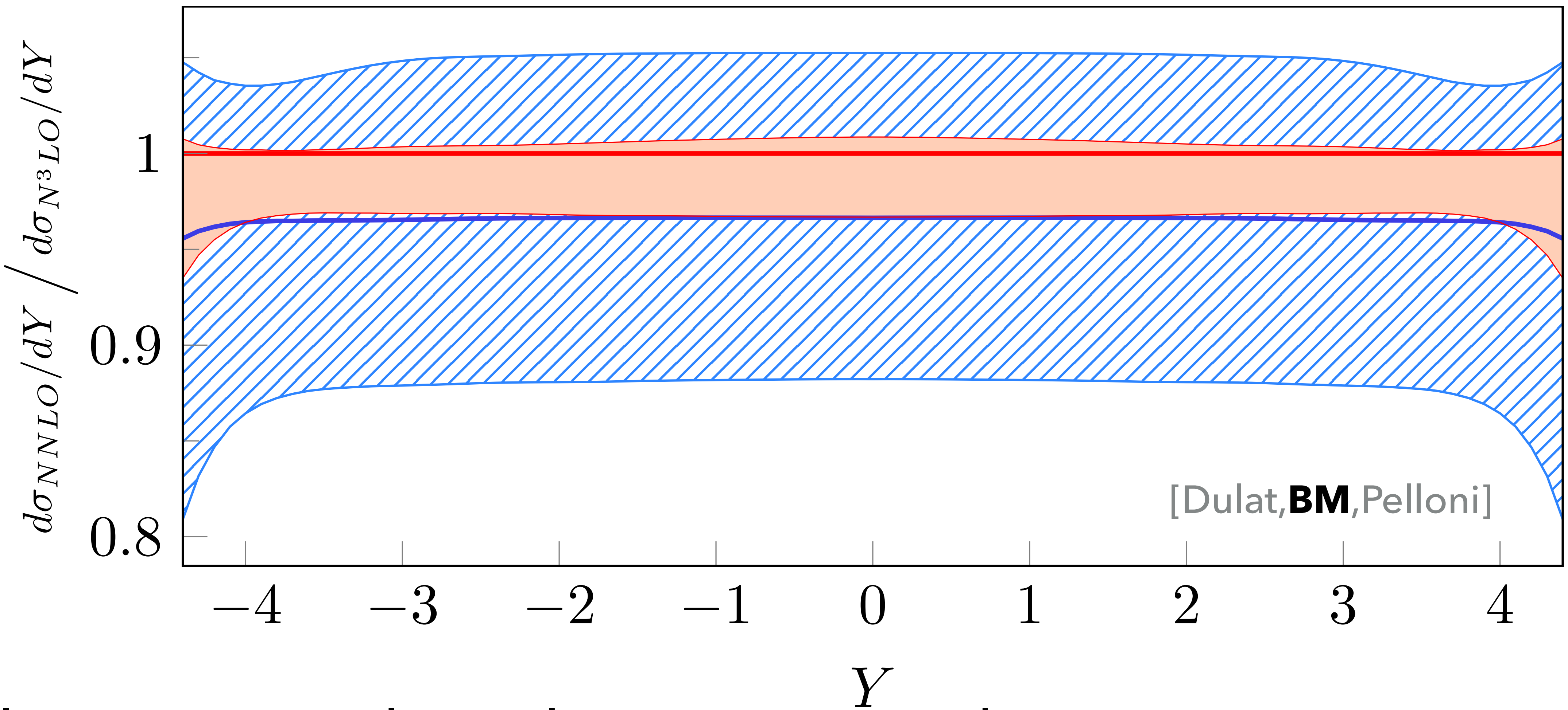
HIGGS BOSON RAPIDITY



HIGGS BOSON RAPIDITY



HIGGS BOSON RAPIDITY - RATIO



- Flat correction throughout entire rapidity range.
- Significant reduction in scale uncertainty.

SUBTRACTION ALGORITHMS

Fully Differential Cross Sections

Typical treatment of singularities in fixed order perturbation theory:
Example:

$$\sigma \sim \int_0^{q^2} dp_\perp^2 \frac{1}{(p_\perp^2)^{1+\epsilon}} \left(M(p_\perp^2) - \tilde{M}(0) \right)$$

+Integrated Counter Term

Divergence

Local Counter Term

Matrix Element

SUBTRACTION ALGORITHMS

Fully Differential Cross Sections

Typical treatment of singularities in fixed order perturbation theory:
More general example:

Measurement Function

$$\sigma_J \sim \int d\phi_n (M(\phi_n, \phi_{\text{Born}}) J(\phi_n, \phi_{\text{Born}}) - \tilde{M}(\phi_n, \phi_{\text{Born}}) J(0, \phi_{\text{Born}}))$$

Integrate over n-partons

+Integrated Counter Term

Divergence

Local Counter Term

IRC - Safety: $J(\phi_n, \phi_{\text{Born}}) \to J(0, \phi_{\text{Born}})$ in singular limits

SUBTRACTION ALGORITHMS – PROJECTION TO BORN

[Cacciari,Dreyer,Karlberg,Salam,Zanderighi]

→ **Fully Differential Cross Sections**

The perfect subtraction algorithm!

$$\sigma_J \sim \int d\phi_n (M(\phi_n, \phi_{\text{Born}}) J(\phi_n, \phi_{\text{Born}}) - \tilde{M}(\phi_n, \phi_{\text{Born}}) J(0, \phi_{\text{Born}}))$$

+Integrated Counter Term

SUBTRACTION ALGORITHMS – PROJECTION TO BORN

[Cacciari,Dreyer,Karlberg,Salam,Zanderighi]

→ **Fully Differential Cross Sections**

The perfect subtraction algorithm!

$$\sigma_J \sim \int d\phi_n M(\phi_n, \phi_{\text{Born}}) \left[J(\phi_n, \phi_{\text{Born}}) - J(0, \phi_{\text{Born}}) \right]$$

+Integrated Counter Term

$$\tilde{M}(\phi_n, \phi_{\text{Born}}) = M(\phi_n, \phi_{\text{Born}})$$

SUBTRACTION ALGORITHMS - PROJECTION TO BORN

[Cacciari,Dreyer,Karlberg,Salam,Zanderighi]

Fully Differential Cross Sections

The perfect subtraction algorithm!

$$\sigma_J \sim \int d\phi_n M(\phi_n, \phi_{\text{Born}}) \Big[J(\phi_n, \phi_{\text{Born}}) - J(0, \phi_{\text{Born}}) \Big]$$

+Integrated Counter Term

$$\tilde{M}(\phi_n, \phi_{\text{Born}}) = M(\phi_n, \phi_{\text{Born}})$$

- **Fully local subtraction**
- **No large numerical discrepancy between local CT and matrix element possible**
- **Successfully used in DIS - like processes (VBF H / HH @ N3LO, differential DIS)**
- **Need to know Integrated Counter Term exactly. Hard!!**

SUBTRACTION ALGORITHMS – PROJECTION TO BORN

[Cacciari,Dreyer,Karlberg,Salam,Zanderighi]

→ **Fully Differential Cross Sections**

The perfect subtraction algorithm!

$$\sigma_J \sim \int d\phi_n M(\phi_n, \phi_{\text{Born}}) \Big[J(\phi_n, \phi_{\text{Born}}) - J(0, \phi_{\text{Born}}) \Big]$$

+Integrated Counter Term

For Higgs Boson Production:

$$\phi_{\text{Born}} = \{z, Y\}$$

Integrated Counter Term → $\frac{d\sigma}{dz dY}$

CURRENTLY TESTING AT NNLO

- Projection-To-Born

$$Y_H \quad \infty \quad H + J$$

$$P\,P \to H + X \to \gamma\gamma + X$$

- Define a fiducial volume

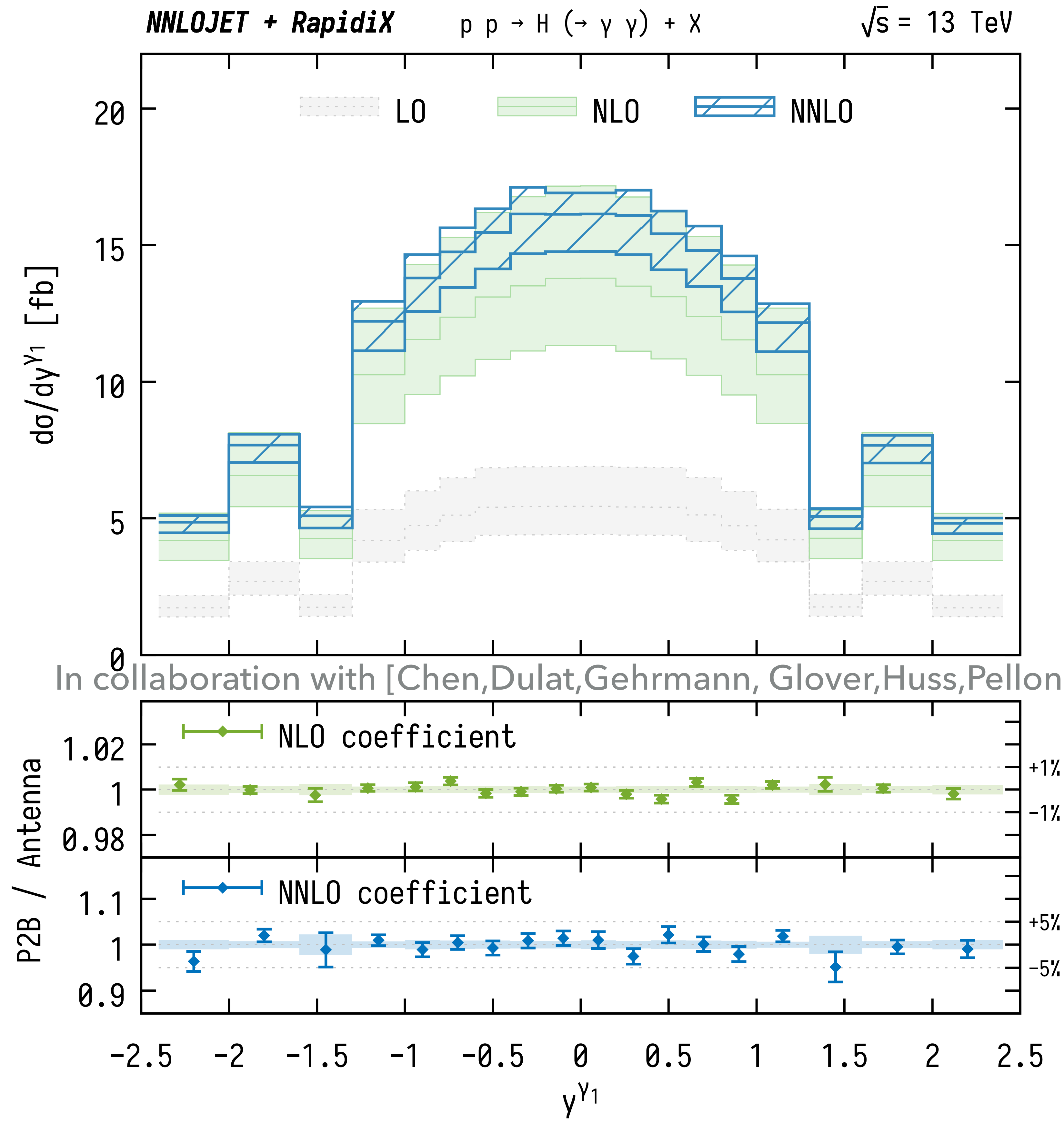
$$p_{\mathrm{T}}^{\gamma_1} > 0.35 \times m_{\gamma\gamma}, \qquad p_{\mathrm{T}}^{\gamma_2} > 0.25 \times m_{\gamma\gamma},$$
$$|\eta^\gamma| < 2.37 \ \text{ excluding } \ 1.37 < |\eta^\gamma| < 1.52,$$

+Photon Isolation

HIGGS BOSON DIFFERENTIAL CROSS SECTIONS

$$H \to \gamma\gamma$$

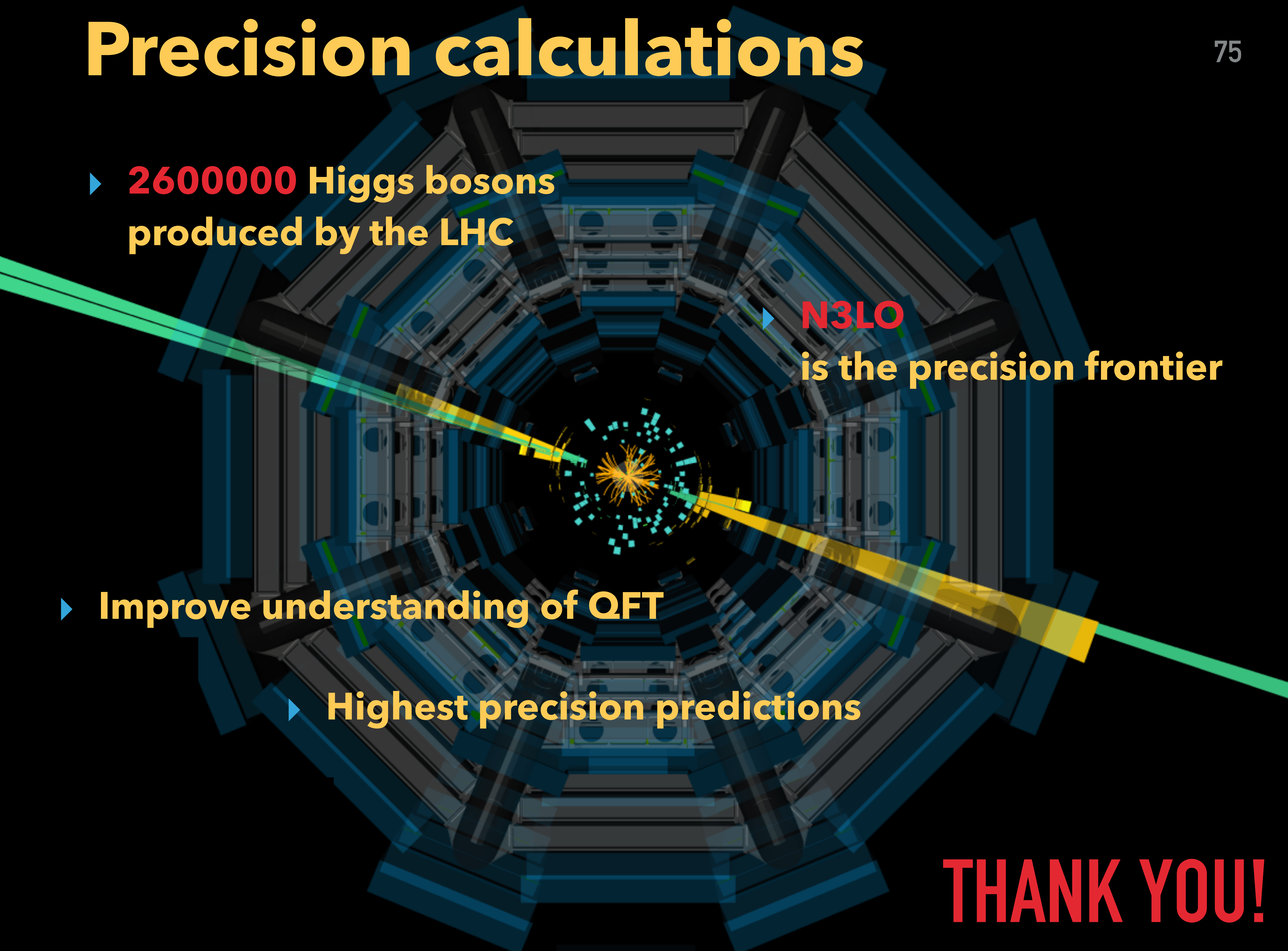
- Leading Photon Y
- Extension to N3LO in progress
- Combination with other uncertainties required!



In collaboration with [Chen,Dulat,Gehrmann, Glover,Huss,Pelloni]

Precision calculations

- 2600000 Higgs bosons produced by the LHC
- N3LO is the precision frontier
- Improve understanding of QFT
- Highest precision predictions



THANK YOU!