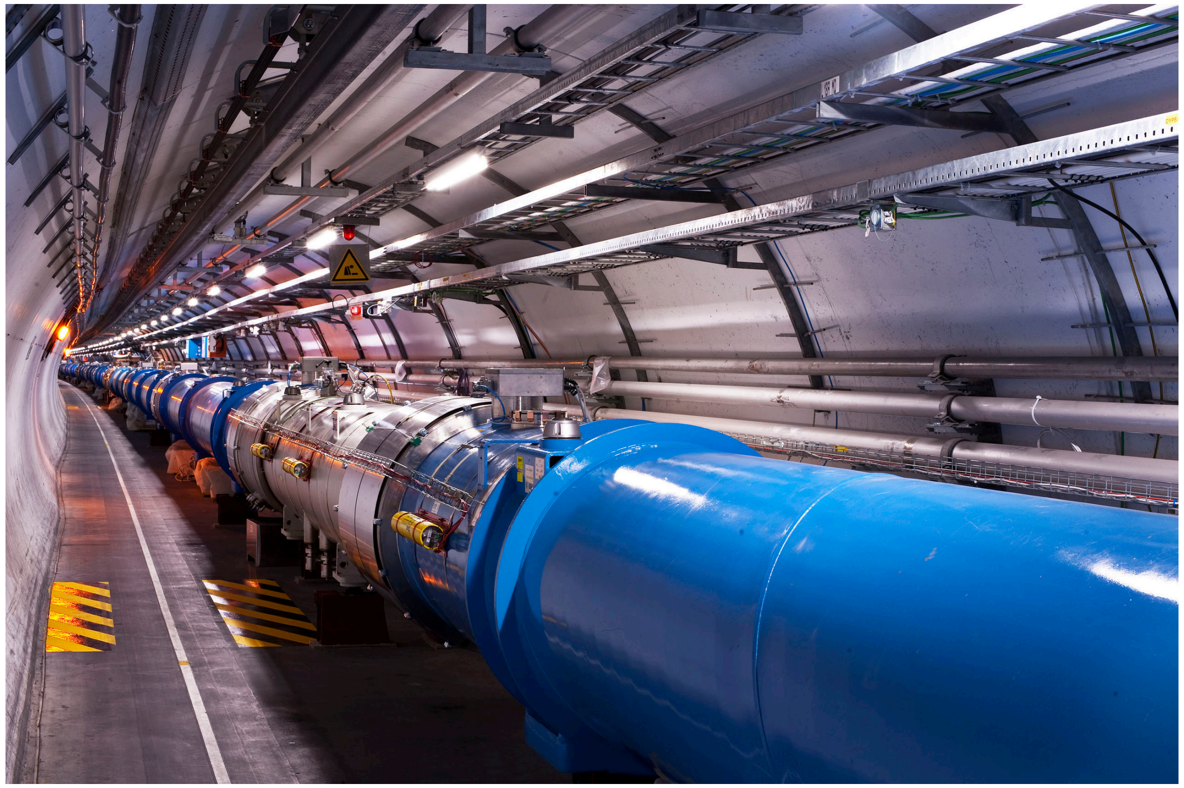
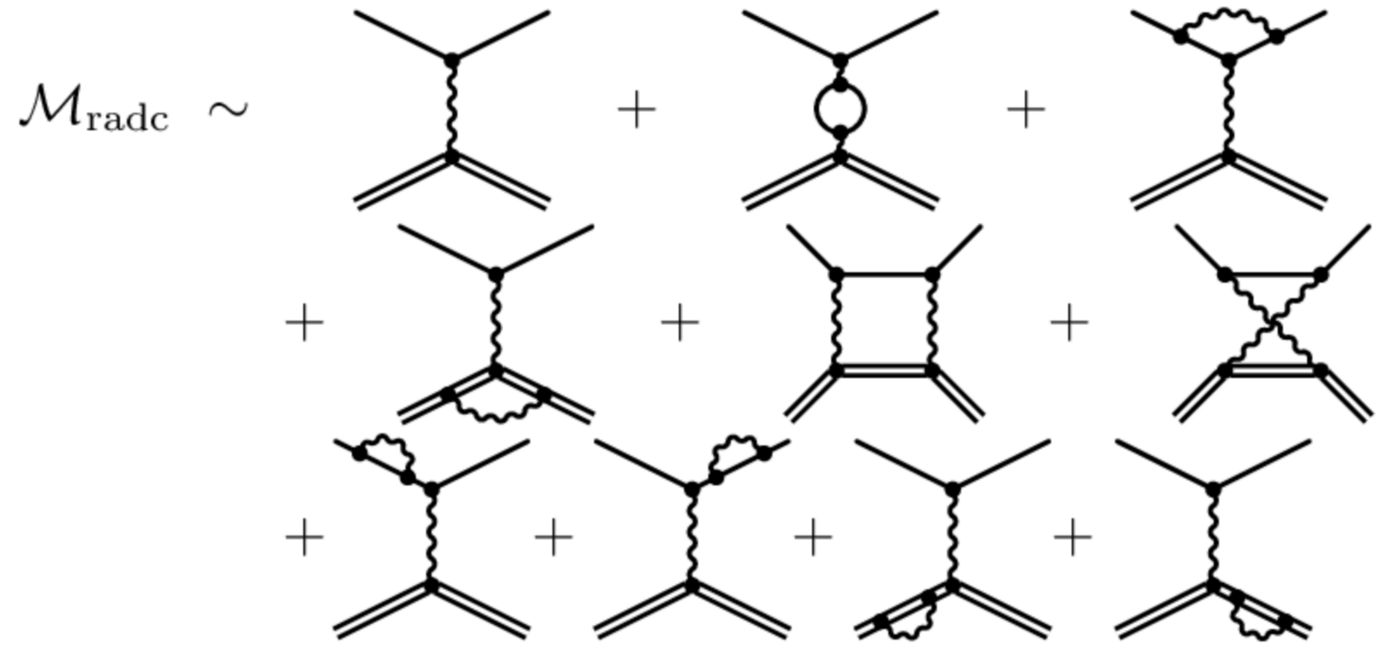




CONFRONTING THEORY AND EXPERIMENT AT THE LARGE HADRON COLLIDER

João Pires

LIP

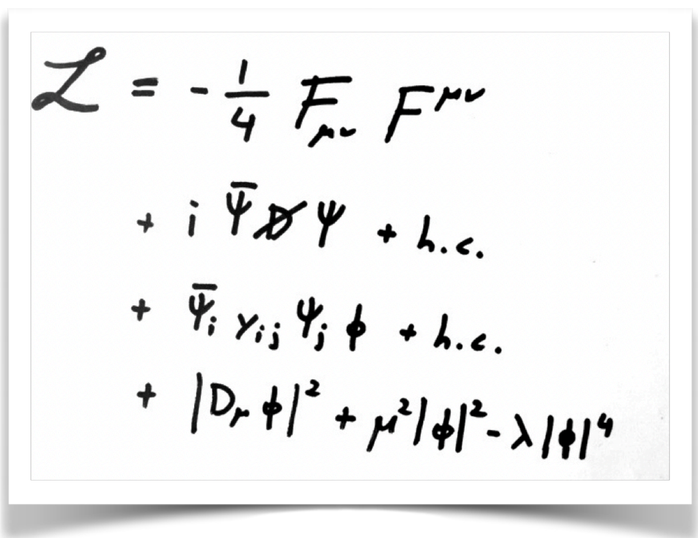
PARTICLE PHYSICS PHENOMENOLOGY

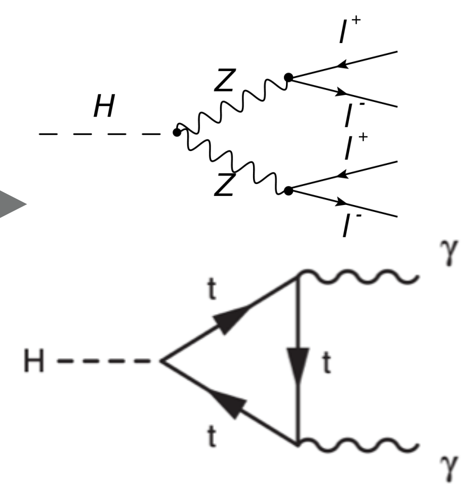
- Phenomenology research sits at the interface between theoretical particle physics and experiments with particle colliders using first principle calculations in Quantum Field Theory
- Practical example: The Standard Model Higgs at the LHC

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

PARTICLE PHYSICS PHENOMENOLOGY

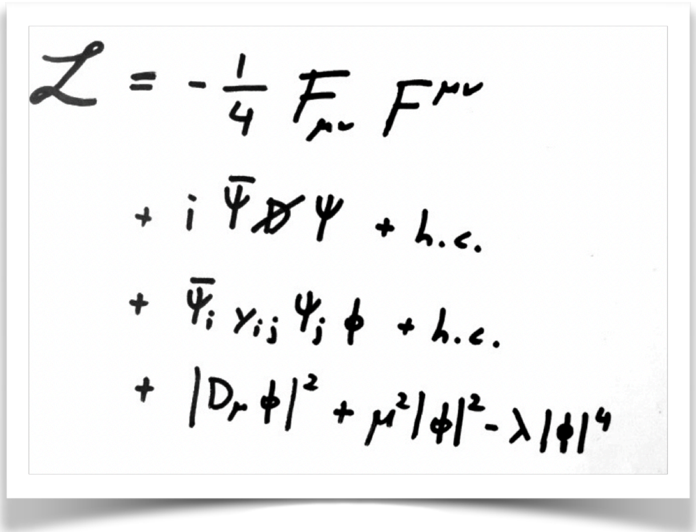
- Phenomenology research sits at the interface between theoretical particle physics and experiments with particle colliders using first principle calculations in Quantum Field Theory
- Practical example: The Standard Model Higgs at the LHC

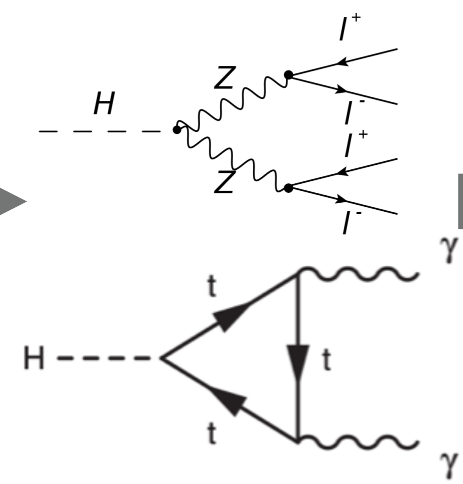




PARTICLE PHYSICS PHENOMENOLOGY

- Phenomenology research sits at the interface between theoretical particle physics and experiments with particle colliders using first principle calculations in Quantum Field Theory
- Practical example: The Standard Model Higgs at the LHC



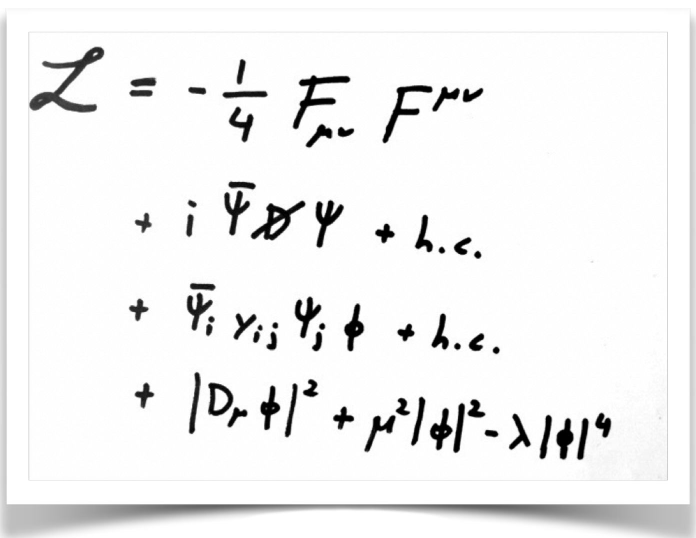


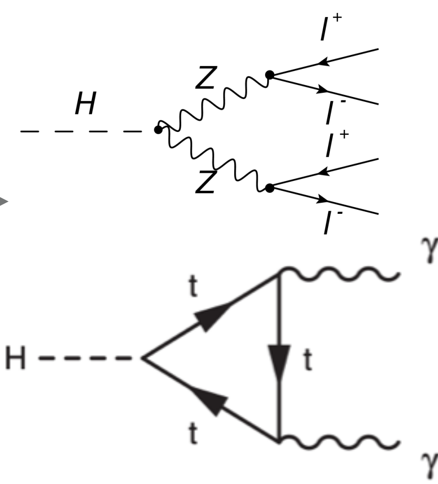
$$\Gamma(h^0 \to \gamma\gamma) = \frac{\alpha_{em}^3 m_h^3}{144\pi^2 m_W^2 \sin^2\theta_w} |\sum_f Q_f^2 N_c(f) I_f(\tau_f) - I_W(\tau_W)|^2$$

$$\Gamma(H \to ZZ) = \frac{1}{8\pi} \frac{M_Z^4}{M_H v^2} \left(1 - \frac{4M_Z^2}{M_H^2}\right)^{1/2} \left(3 + \frac{1}{4}\frac{M_H^4}{M_Z^4} - \frac{M_H^2}{M_Z^2}\right)$$

PARTICLE PHYSICS PHENOMENOLOGY

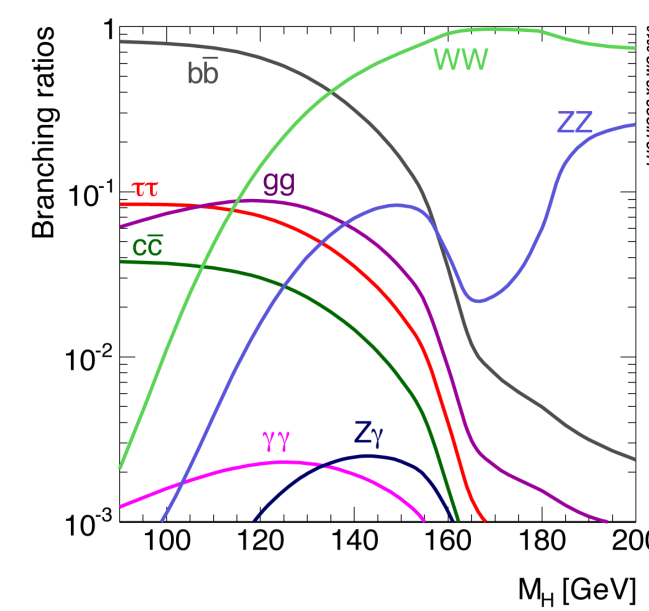
- Phenomenology research sits at the interface between theoretical particle physics and experiments with particle colliders using first principle calculations in Quantum Field Theory
- Practical example: The Standard Model Higgs at the LHC





$$\Gamma(h^0 \to \gamma\gamma) = \frac{\alpha_{em}^3 m_h^3}{144\pi^2 m_W^2 \sin^2\theta_w} \Big|\sum_f Q_f^2 N_c(f) I_f(\tau_f) - I_W(\tau_W)\Big|^2$$

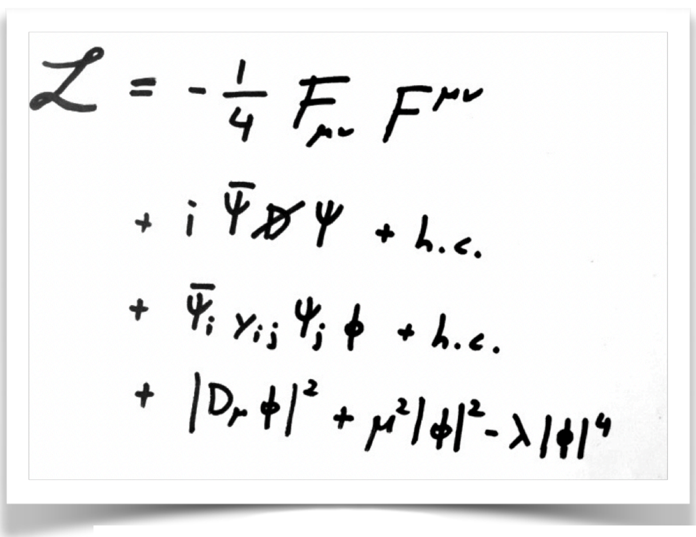
$$\Gamma(H \to ZZ) = \frac{1}{8\pi}\frac{M_Z^4}{M_H v^2}\left(1 - \frac{4M_Z^2}{M_H^2}\right)^{1/2}\left(3 + \frac{1}{4}\frac{M_H^4}{M_Z^4} - \frac{M_H^2}{M_Z^2}\right)$$

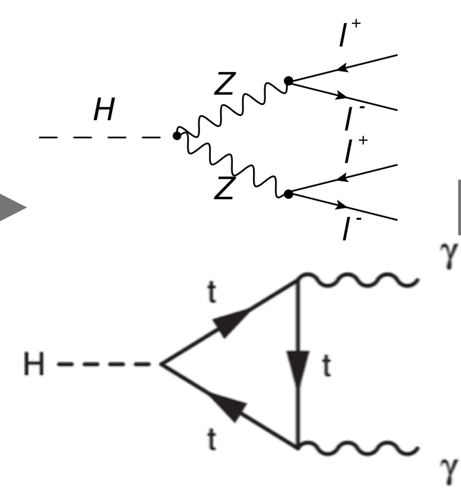


Higgs decay modes as function of M_H (Standard Model theory)

PARTICLE PHYSICS PHENOMENOLOGY

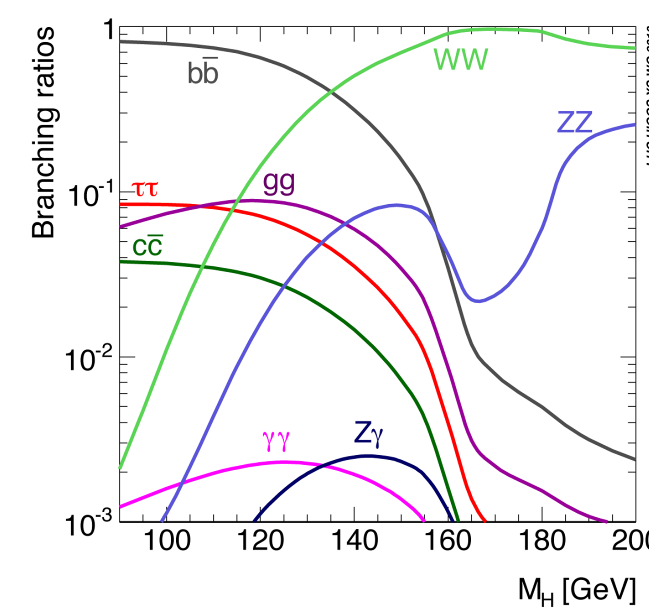
- Phenomenology research sits at the interface between theoretical particle physics and experiments with particle colliders using first principle calculations in Quantum Field Theory
- Practical example: The Standard Model Higgs at the LHC



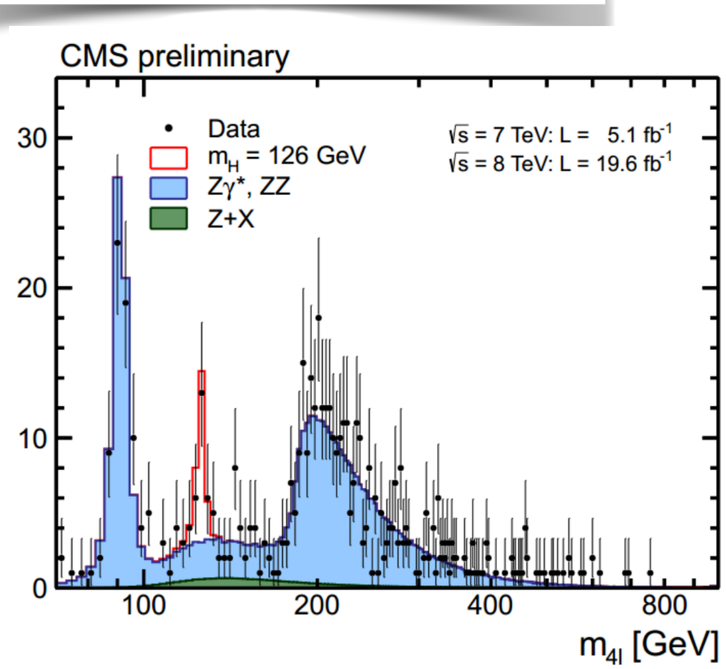


$$\Gamma(h^0 \to \gamma\gamma) = \frac{\alpha_{em}^3 m_h^3}{144\pi^2 m_W^2 \sin^2\theta_w} \left|\sum_f Q_f^2 N_c(f) I_f(\tau_f) - I_W(\tau_W)\right|^2$$

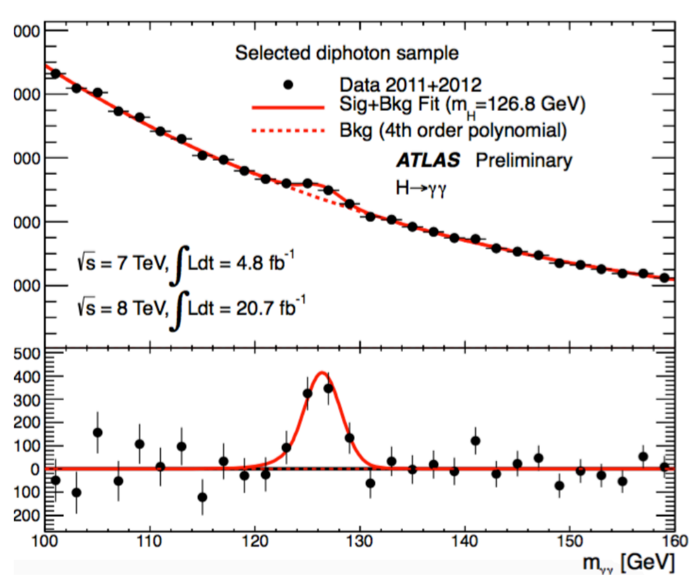
$$\Gamma(H \to ZZ) = \frac{1}{8\pi} \frac{M_Z^4}{M_H v^2} \left(1 - \frac{4M_Z^2}{M_H^2}\right)^{1/2} \left(3 + \frac{1}{4}\frac{M_H^4}{M_Z^4} - \frac{M_H^2}{M_Z^2}\right)$$



Higgs decay modes as function of M_H (Standard Model theory)



Higgs discovery plot in ZZ (CMS experiment at the LHC)



Higgs discovery plot in γγ (ATLAS experiment at the LHC)

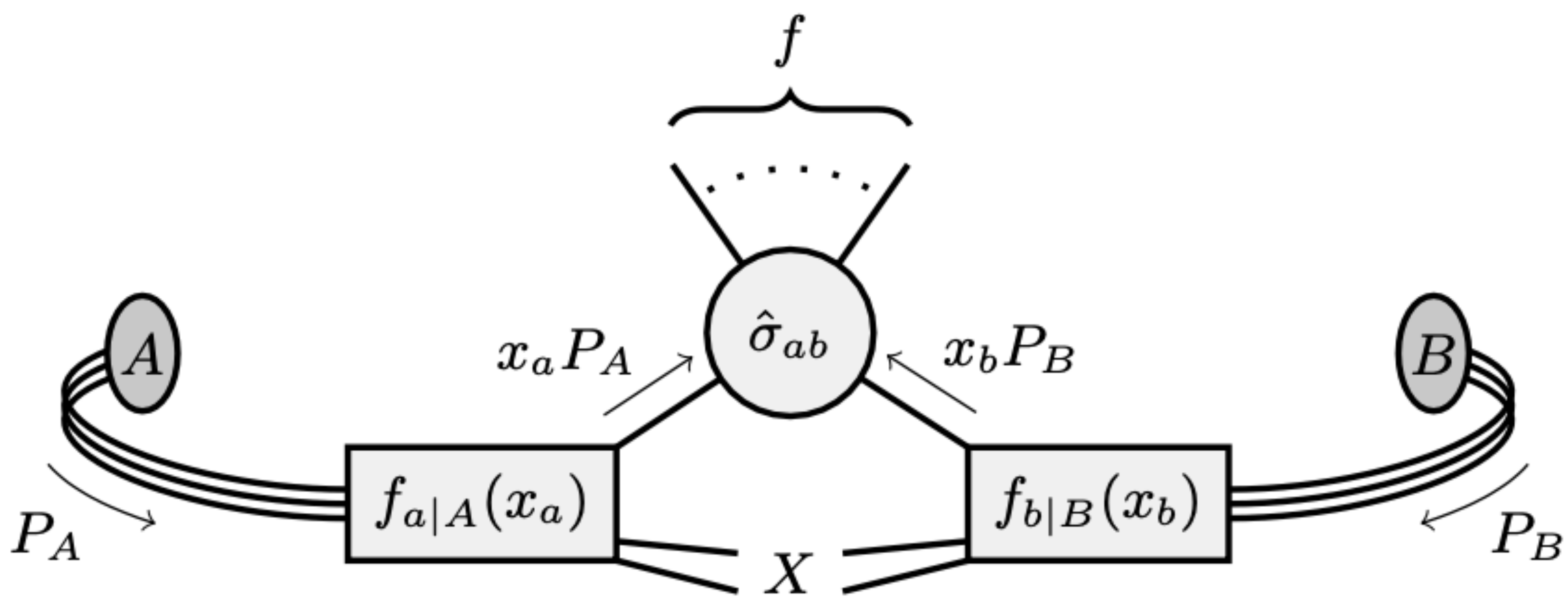
PARTICLE PHYSICS PHENOMENOLOGY

- Aim of the proposal:

> Establish a new standard of theoretical precision in the description of physical observables at the LHC and other particle collider experiments, thereby leading to a more precise extraction of fundamental physics parameters, such as the couplings of the Higgs boson to other fundamental particles

QCD FACTORIZATION AT THE LHC

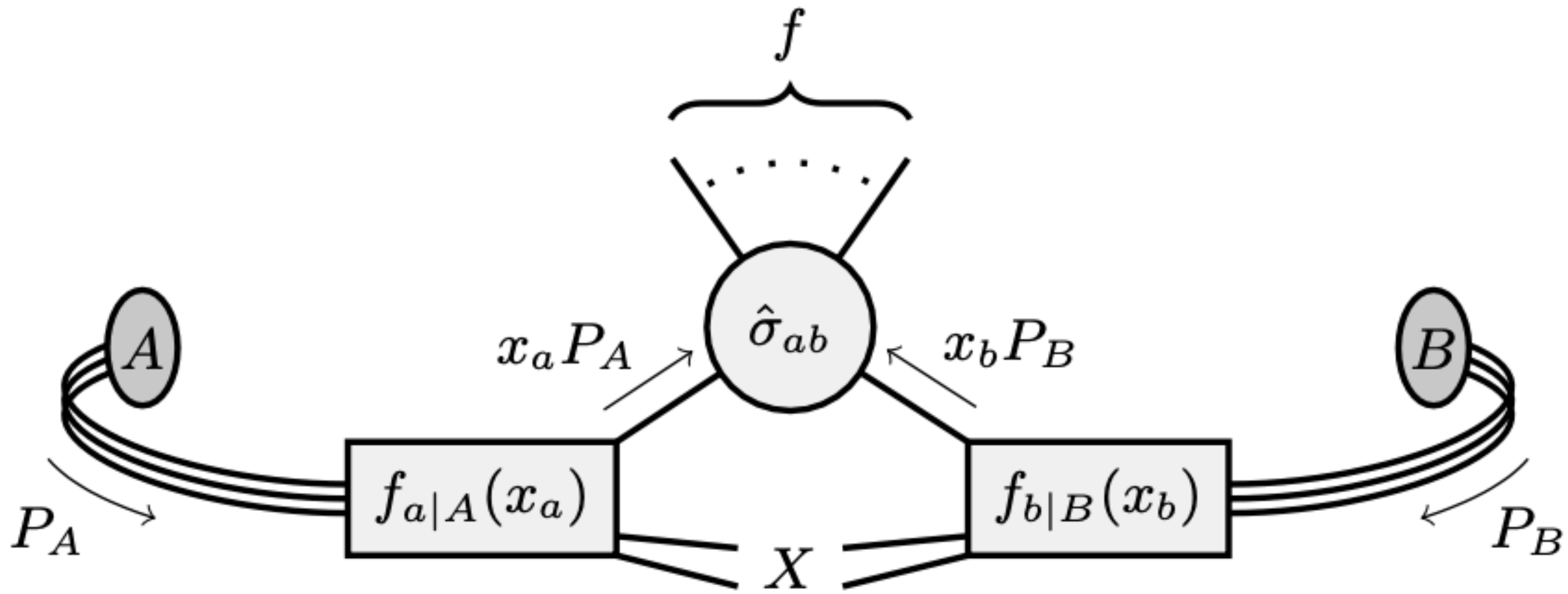
- Inclusive cross section formula for hard scattering process initiated by two hadrons



$$\sigma(P_A, P_B) = \sum_{ab} \int \mathrm{d}x_1 \mathrm{d}x_2 f_{a|A}(x_a, \mu_F^2) f_{b|B}(x_b, \mu_F^2) \hat{\sigma}_{ab}(p_a, p_b, \alpha_s(\mu_R^2), s/\mu_R^2, s/\mu_F^2)$$

QCD FACTORIZATION AT THE LHC

- Inclusive cross section formula for hard scattering process initiated by two hadrons



$$\sigma(P_A, P_B) = \sum_{ab} \int dx_1 dx_2 f_{a|A}(x_a, \mu_F^2) f_{b|B}(x_b, \mu_F^2) \hat{\sigma}_{ab}(p_a, p_b, \alpha_s(\mu_R^2), s/\mu_R^2, s/\mu_F^2)$$

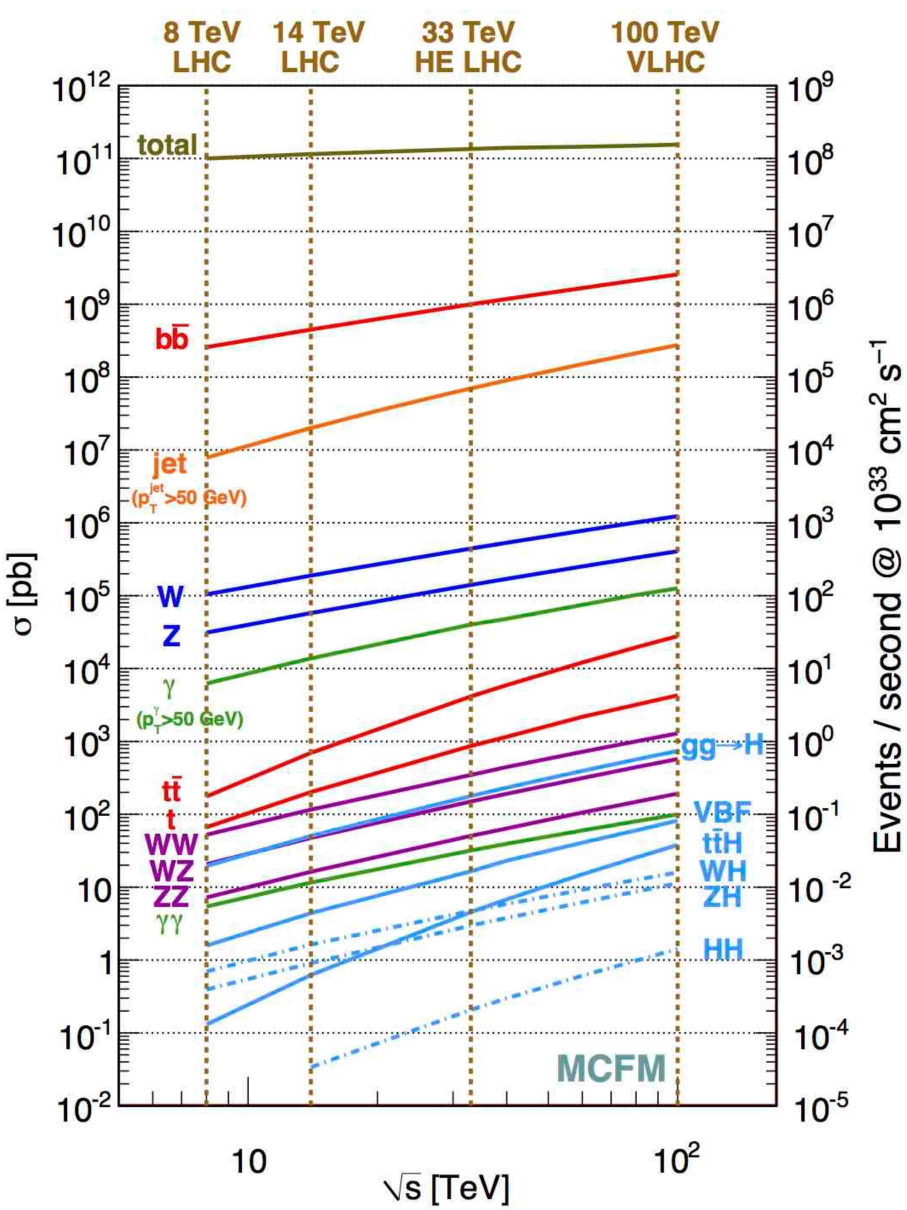
parton distribution functions
(non-perturbative, universal)

hard scattering
(perturbation theory)

- Final state F will typically contain QCD colored particles which will fragment and form a radiation pattern described by a parton shower and at low scales hadronize into final state hadrons which we observe in the LHC detectors

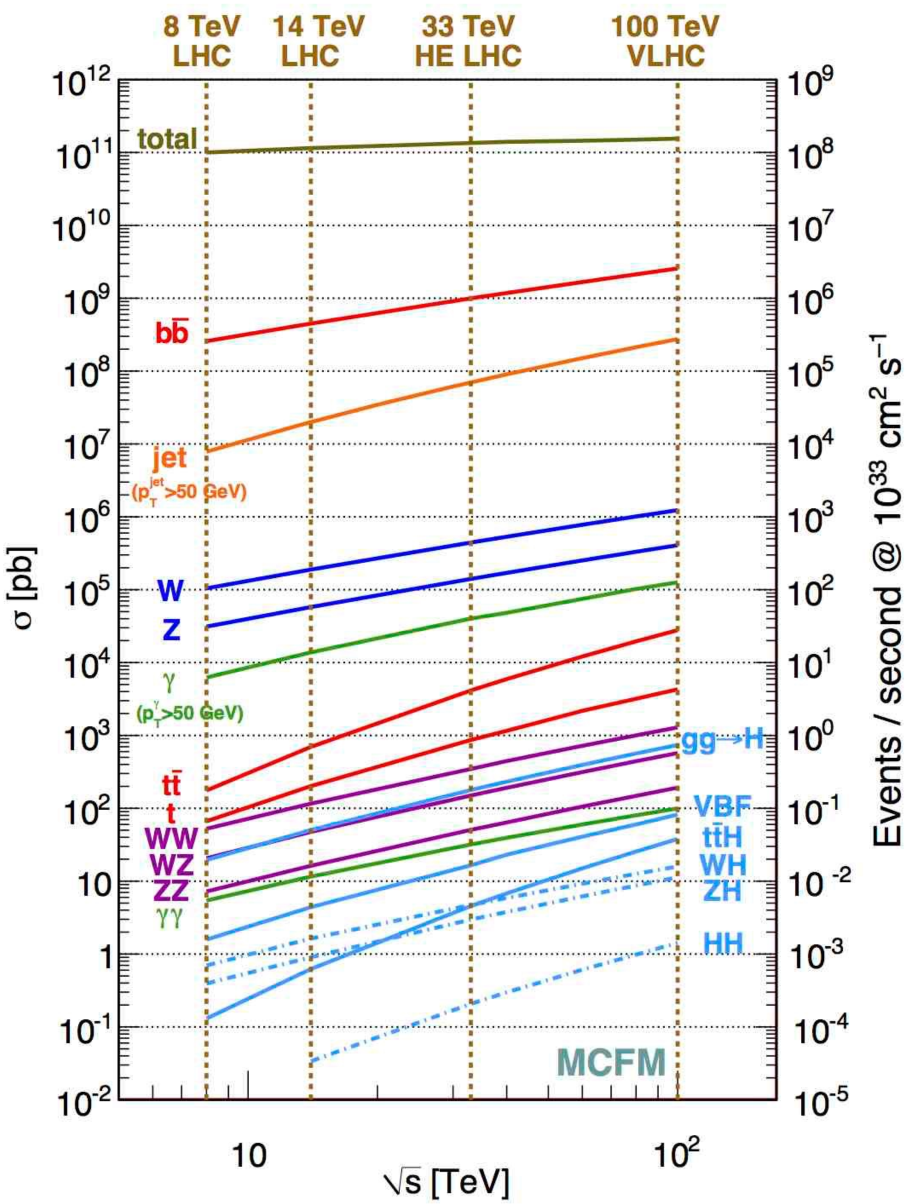
THEORETICAL UNCERTAINTIES

$$\sigma(P_A, P_B) = \sum_{ab} \int \mathrm{d}x_1 \mathrm{d}x_2 f_{a|A}(x_a, \mu_F^2) f_{b|B}(x_b, \mu_F^2) \hat{\sigma}_{ab}(p_a, p_b, \alpha_s(\mu_R^2), s/\mu_R^2, s/\mu_F^2)$$



THEORETICAL UNCERTAINTIES

$$\sigma(P_A, P_B) = \sum_{ab} \int \mathrm{d}x_1 \mathrm{d}x_2 f_{a|A}(x_a, \mu_F^2) f_{b|B}(x_b, \mu_F^2) \hat{\sigma}_{ab}(p_a, p_b, \alpha_s(\mu_R^2), s/\mu_R^2, s/\mu_F^2)$$

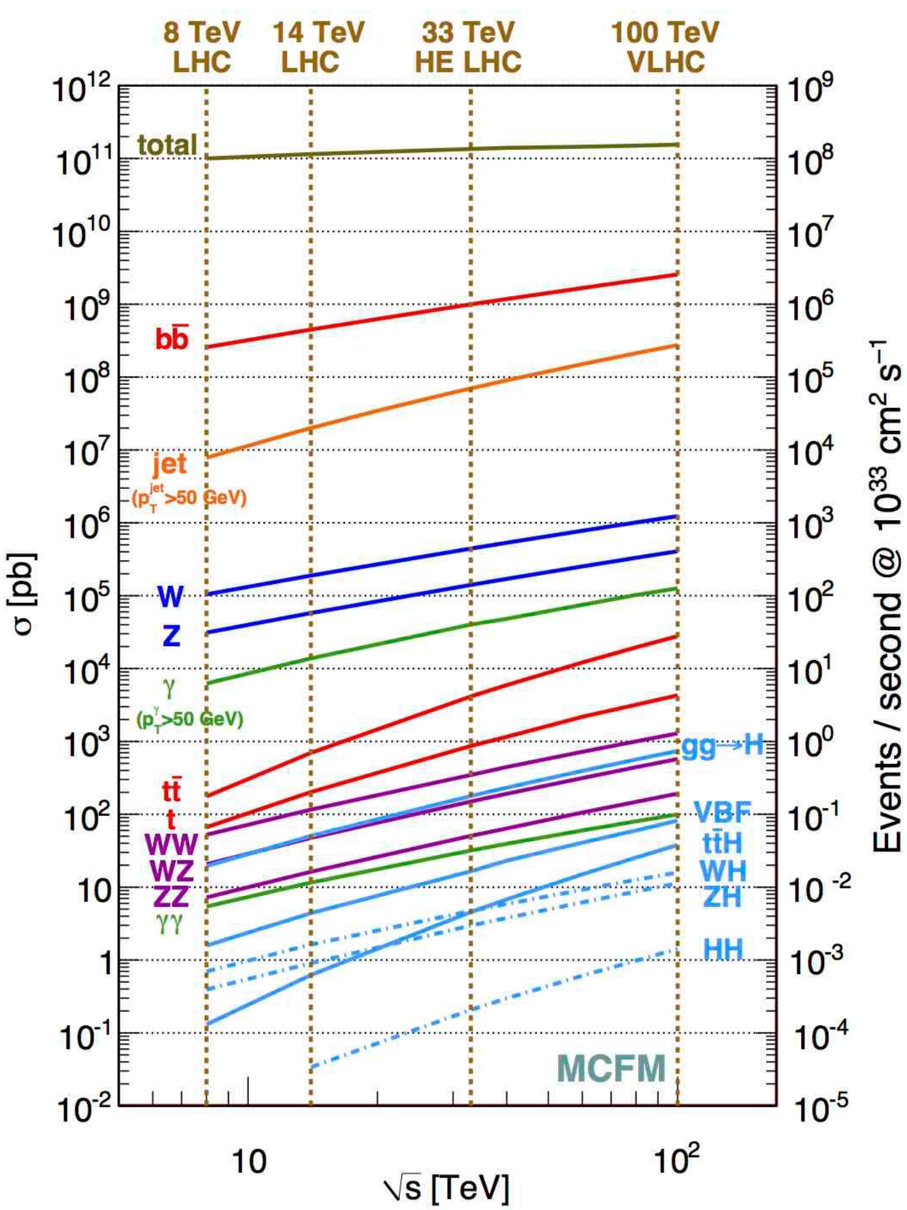


Theoretical uncertainties:

- *Parton distributions (PDF uncertainty)* probability distribution of quarks and gluons in the proton with fraction *x of* proton momentum → ***universal but non perturbative***

THEORETICAL UNCERTAINTIES

$$\sigma(P_A, P_B) = \sum_{ab} \int \mathrm{d}x_1 \mathrm{d}x_2 f_{a|A}(x_a, \mu_F^2) f_{b|B}(x_b, \mu_F^2) \hat{\sigma}_{ab}(p_a, p_b, \alpha_s(\mu_R^2), s/\mu_R^2, s/\mu_F^2)$$



Theoretical uncertainties:

- ***Parton distributions (PDF uncertainty)*** probability distribution of quarks and gluons in the proton with fraction *x of* proton momentum → ***universal but non perturbative***

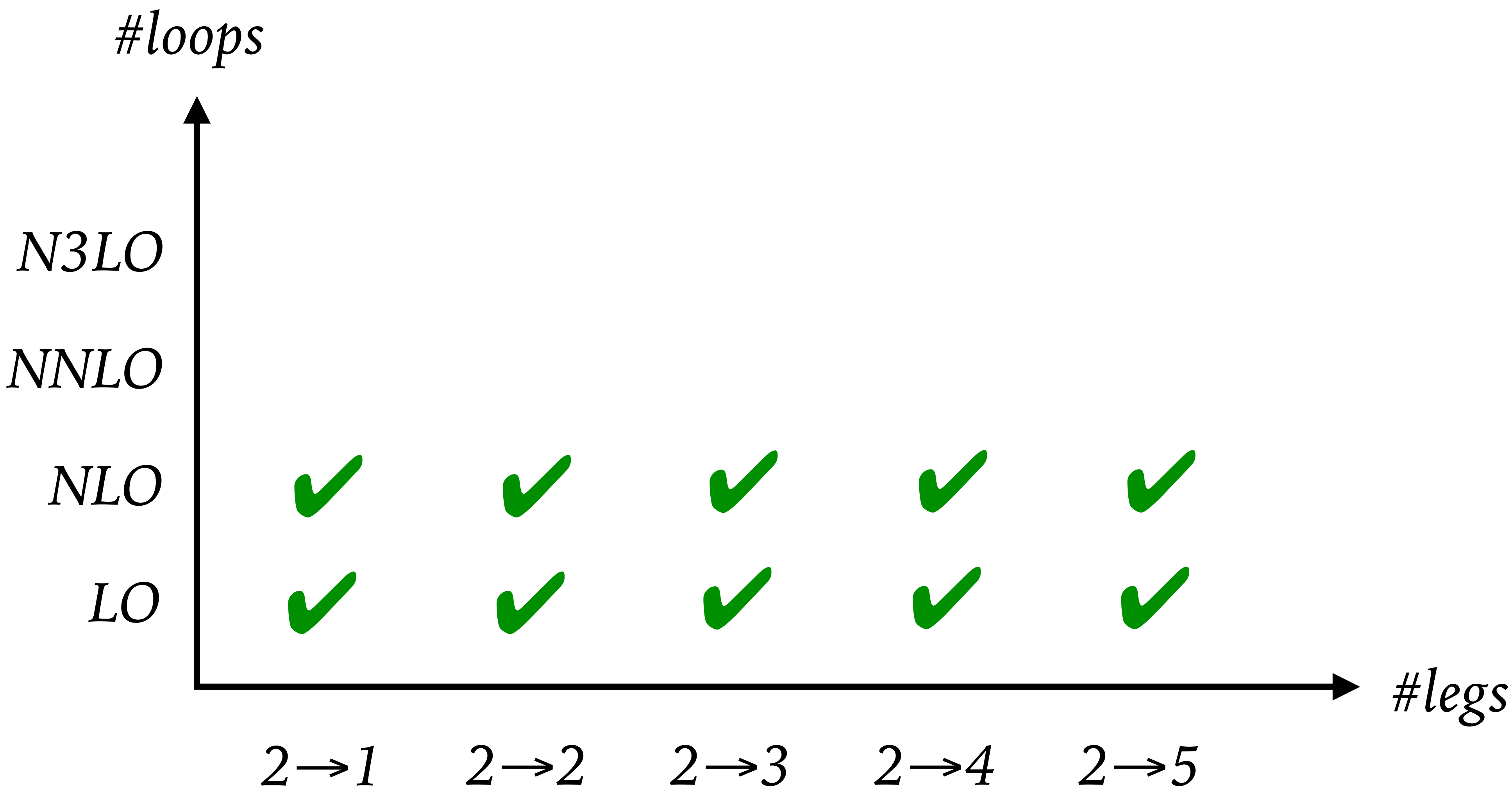
- ***Hard partonic cross section (scale uncertainty)*** process dependent contribution → ***computable in perturbation theory***

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

LO *NLO* *NNLO* *N3LO*

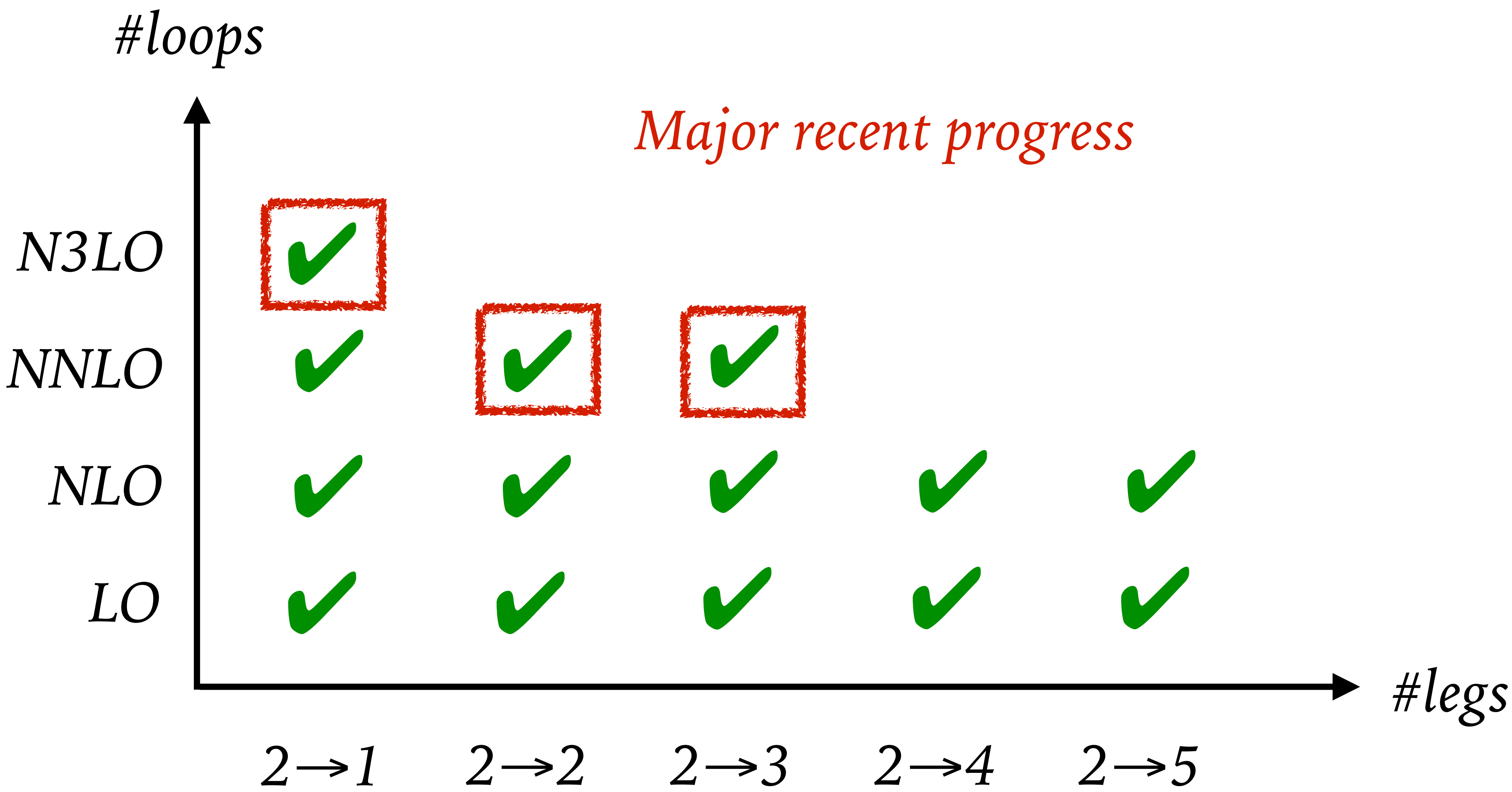
- Truncated series leads to a residual dependence (uncertainty) of the theory prediction on the renormalization and factorization scales μ_R and μ_F

QCD FIXED-ORDER COUPLING EXPANSION: STATE OF THE ART



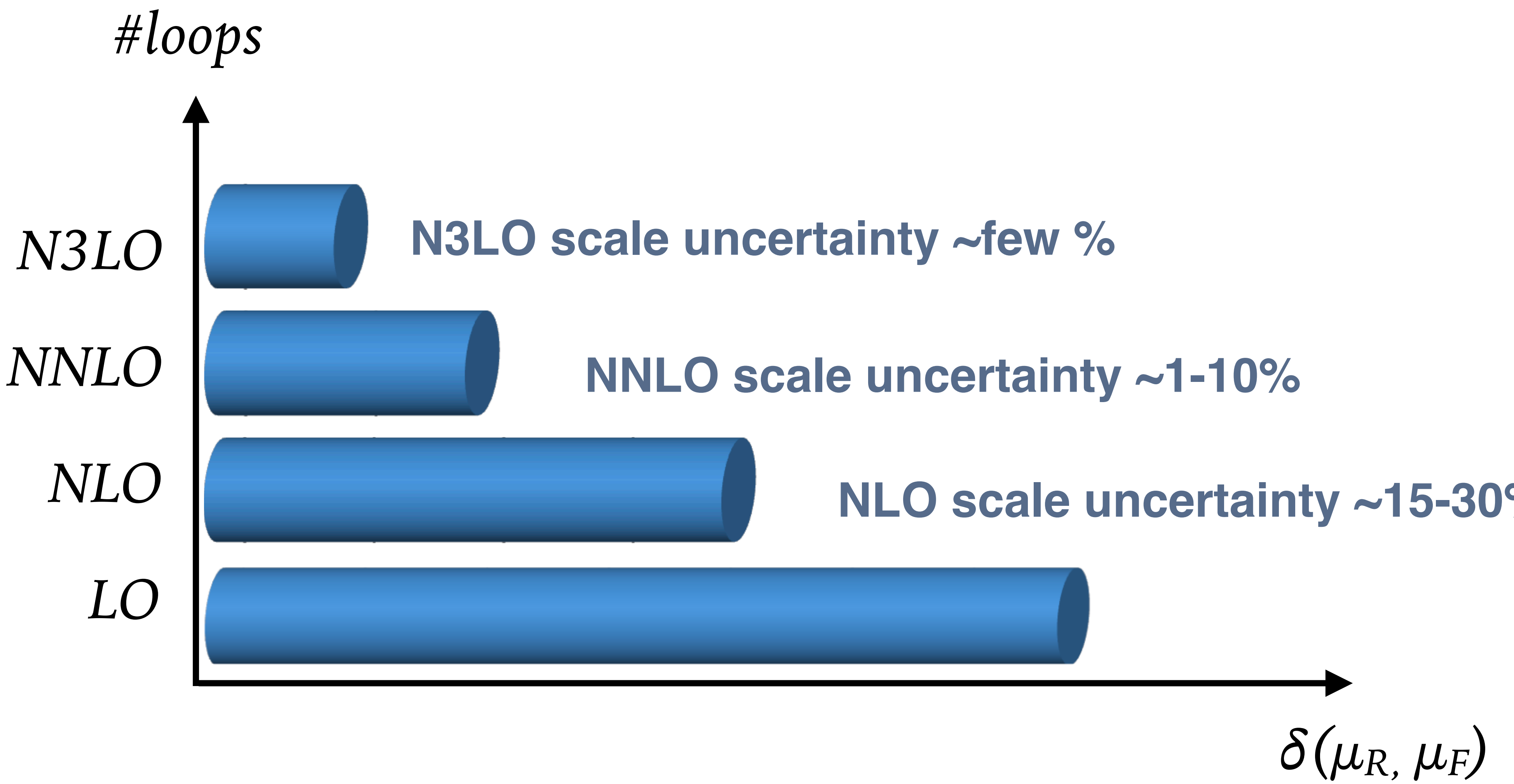
- LO and NLO predictions can be generated automatically: MadGraph and aMC@NLO, POWHEG, SHERPA Monte Carlo generators

QCD FIXED-ORDER COUPLING EXPANSION: STATE OF THE ART



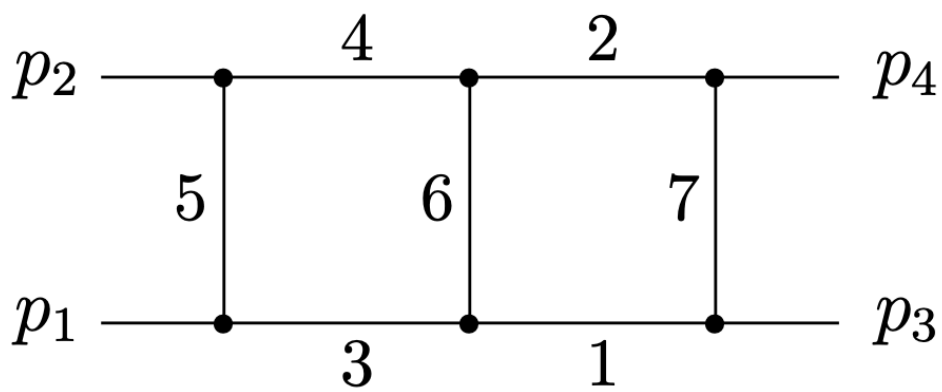
- LO and NLO predictions can be generated automatically: MadGraph and aMC@NLO, POWHEG, SHERPA Monte Carlo generators
- Complexity of the calculations increases with the number of loops and legs: no automated tools at NNLO (2->3 with massless fermions)

QCD FIXED-ORDER COUPLING EXPANSION: STATE OF THE ART



- LO and NLO predictions can be generated automatically: MadGraph and aMC@NLO, POWHEG, SHERPA Monte Carlo generators
- Complexity of the calculations increases with the number of loops and legs: no automated tools at NNLO (2->3 with massless fermions)
- Trade-off is the reduction in the theory uncertainty

2→2 MASSLESS SCATTERING IN QCD AT TWO-LOOPS



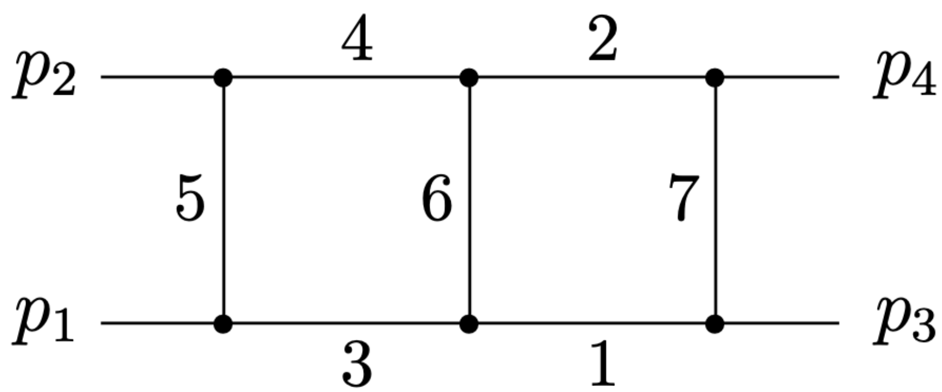
$p_i^2 = 0, \; i{=}1{,}2{,}3{,}4$

$s = (p_1 + p_2)^2 \qquad t = (p_1 + p_3)^2$

- Massless double box two loop integral

$$\int\!\!\int \frac{\mathrm{d}^d k \mathrm{d}^d l}{(k^2 + 2p_1 k)(k^2 - 2p_2 k)k^2(k-l)^2(l^2 + 2p_1 l)(l^2 - 2p_2 l)(l - p_1 - p_3)} \equiv \frac{\left(i\pi^{d/2} \mathrm{e}^{-\gamma_{\mathrm{E}}\epsilon}\right)^2}{(-s)^{2+2\epsilon}(-t)} K(t/s, \epsilon)$$

2→2 MASSLESS SCATTERING IN QCD AT TWO-LOOPS



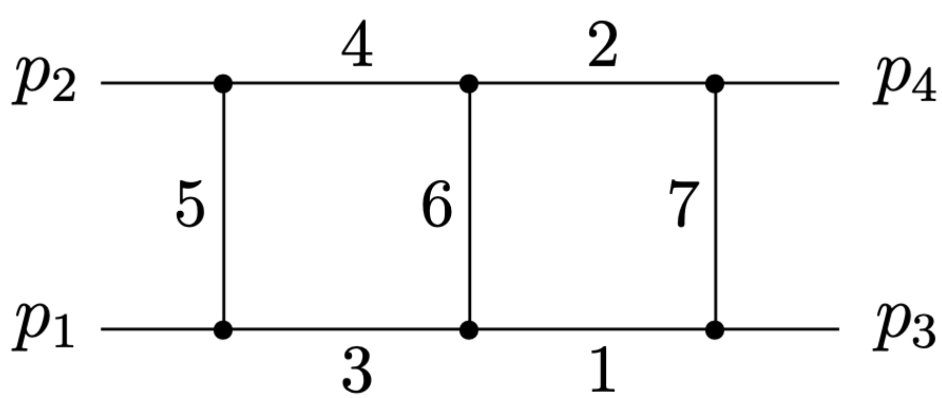
$$p_i^2 = 0, \; i{=}1,2,3,4$$

$$s = (p_1 + p_2)^2 \qquad t = (p_1 + p_3)^2$$

- Massless double box two loop integral

$$\begin{aligned}
K(t/s, \epsilon) \;=\; & -\frac{4}{\epsilon^4} + \frac{5\ln x}{\epsilon^3} - \left(2\ln^2 x - \frac{5}{2}\pi^2\right)\frac{1}{\epsilon^2} \\
& -\left(\frac{2}{3}\ln^3 x + \frac{11}{2}\pi^2 \ln x - \frac{65}{3}\zeta(3)\right)\frac{1}{\epsilon} + \frac{4}{3}\ln^4 x + 6\pi^2 \ln^2 x - \frac{88}{3}\zeta(3)\ln x + \frac{29}{30}\pi^4 \\
& - \left[2\mathrm{Li}_3(-x) - 2\ln x \mathrm{Li}_2(-x) - \left(\ln^2 x + \pi^2\right)\ln(1+x)\right]\frac{2}{\epsilon} \\
& -4\left(S_{2,2}(-x) - \ln x S_{1,2}(-x)\right) + 44\mathrm{Li}_4(-x) - 4\left(\ln(1+x) + 6\ln x\right)\mathrm{Li}_3(-x) \\
& +2\left(\ln^2 x + 2\ln x \ln(1+x) + \frac{10}{3}\pi^2\right)\mathrm{Li}_2(-x) \\
& + \left(\ln^2 x + \pi^2\right)\ln^2(1+x) - \frac{2}{3}\left(4\ln^3 x + 5\pi^2 \ln x - 6\zeta(3)\right)\ln(1+x) \;,
\end{aligned}$$

2→2 MASSLESS SCATTERING IN QCD AT TWO-LOOPS



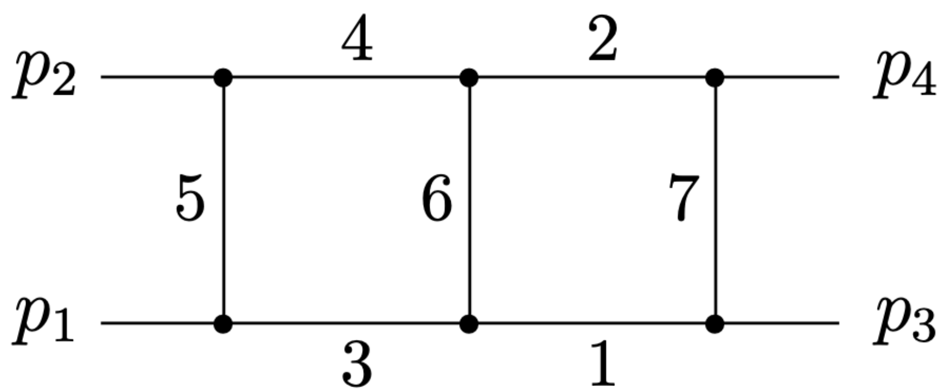
$$p_i^2 = 0, \; i{=}1{,}2{,}3{,}4$$

$$s = (p_1 + p_2)^2 \qquad t = (p_1 + p_3)^2$$

- Massless double box two loop integral

$$K(t/s,\epsilon) = -\frac{4}{\epsilon^4} + \frac{5\ln x}{\epsilon^3} - \left(2\ln^2 x - \frac{5}{2}\pi^2\right)\frac{1}{\epsilon^2}$$
$$-\left(\frac{2}{3}\ln^3 x + \frac{11}{2}\pi^2\ln x - \frac{65}{3}\zeta(3)\right)\frac{1}{\epsilon} + \frac{4}{3}\ln^4 x + 6\pi^2\ln^2 x - \frac{88}{3}\zeta(3)\ln x + \frac{29}{30}\pi^4$$
$$-\left[2\mathrm{Li}_3(-x) - 2\ln x\,\mathrm{Li}_2(-x) - \left(\ln^2 x + \pi^2\right)\ln(1+x)\right]\frac{2}{\epsilon}$$
$$-4\left(S_{2,2}(-x) - \ln x\, S_{1,2}(-x)\right) + 44\mathrm{Li}_4(-x) - 4\left(\ln(1+x) + 6\ln x\right)\mathrm{Li}_3(-x)$$
$$+2\left(\ln^2 x + 2\ln x\ln(1+x) + \frac{10}{3}\pi^2\right)\mathrm{Li}_2(-x)$$
$$+\left(\ln^2 x + \pi^2\right)\ln^2(1+x) - \frac{2}{3}\left(4\ln^3 x + 5\pi^2\ln x - 6\zeta(3)\right)\ln(1+x)\,,$$

- IR-singularities regulated by 1/ε poles
- Explicit result in terms of polylogarithms



$$p_i^2 = 0, \ i{=}1,2,3,4$$

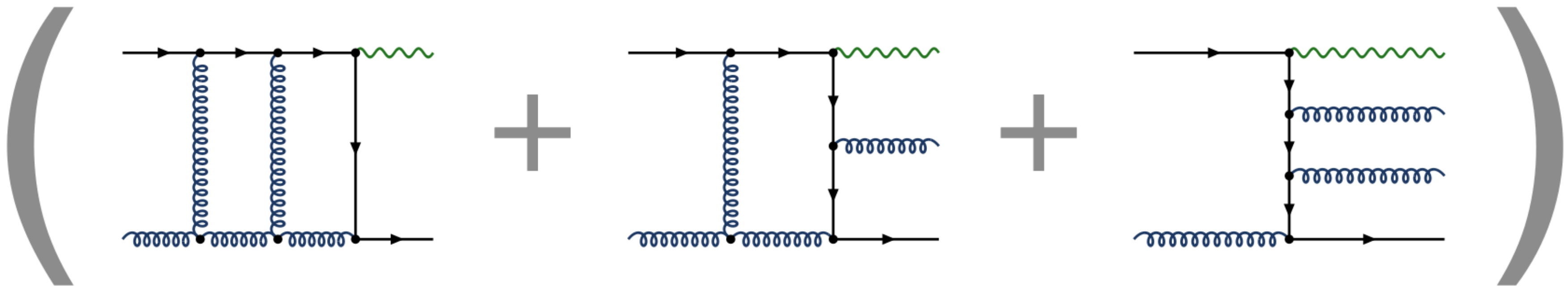
$$s = (p_1 + p_2)^2 \qquad t = (p_1 + p_3)^2$$

- Massless double box two loop integral

$$
\begin{aligned}
K(t/s,\epsilon) = & -\frac{4}{\epsilon^4} + \frac{5\ln x}{\epsilon^3} - \left(2\ln^2 x - \frac{5}{2}\pi^2\right)\frac{1}{\epsilon^2} \\
& -\left(\frac{2}{3}\ln^3 x + \frac{11}{2}\pi^2 \ln x - \frac{65}{3}\zeta(3)\right)\frac{1}{\epsilon} + \frac{4}{3}\ln^4 x + 6\pi^2\ln^2 x - \frac{88}{3}\zeta(3)\ln x + \frac{29}{30}\pi^4 \\
& - \left[2\mathrm{Li}_3(-x) - 2\ln x \mathrm{Li}_2(-x) - \left(\ln^2 x + \pi^2\right)\ln(1+x)\right]\frac{2}{\epsilon} \\
& -4\left(S_{2,2}(-x) - \ln x S_{1,2}(-x)\right) + 44\mathrm{Li}_4(-x) - 4\left(\ln(1+x) + 6\ln x\right)\mathrm{Li}_3(-x) \\
& +2\left(\ln^2 x + 2\ln x \ln(1+x) + \frac{10}{3}\pi^2\right)\mathrm{Li}_2(-x) \\
& + \left(\ln^2 x + \pi^2\right)\ln^2(1+x) - \frac{2}{3}\left(4\ln^3 x + 5\pi^2 \ln x - 6\zeta(3)\right)\ln(1+x) ,
\end{aligned}
$$

- IR-singularities regulated by $1/\varepsilon$ poles
- Explicit result in terms of polylogarithms

ANTENNA SUBTRACTION



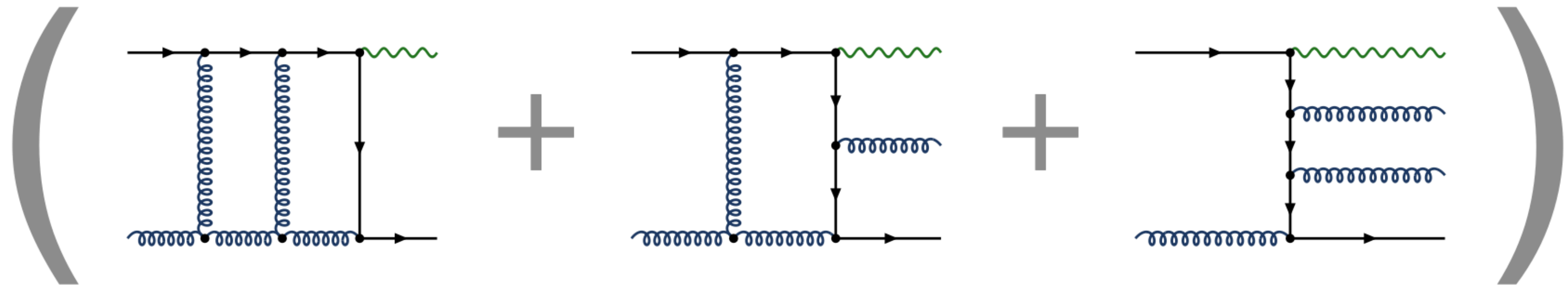
“double virtual” “real-virtual” “double real”

- *$1/\varepsilon^4$, $1/\varepsilon^3$, $1/\varepsilon^2$, $1/\varepsilon$*

- *$1/\varepsilon^2$, $1/\varepsilon$*
- *single unresolved*

- *double unresolved*
- *single unresolved*

ANTENNA SUBTRACTION



"double virtual" — "real-virtual" — "double real"

"double virtual"

- *$1/\varepsilon^4$, $1/\varepsilon^3$, $1/\varepsilon^2$, $1/\varepsilon$*

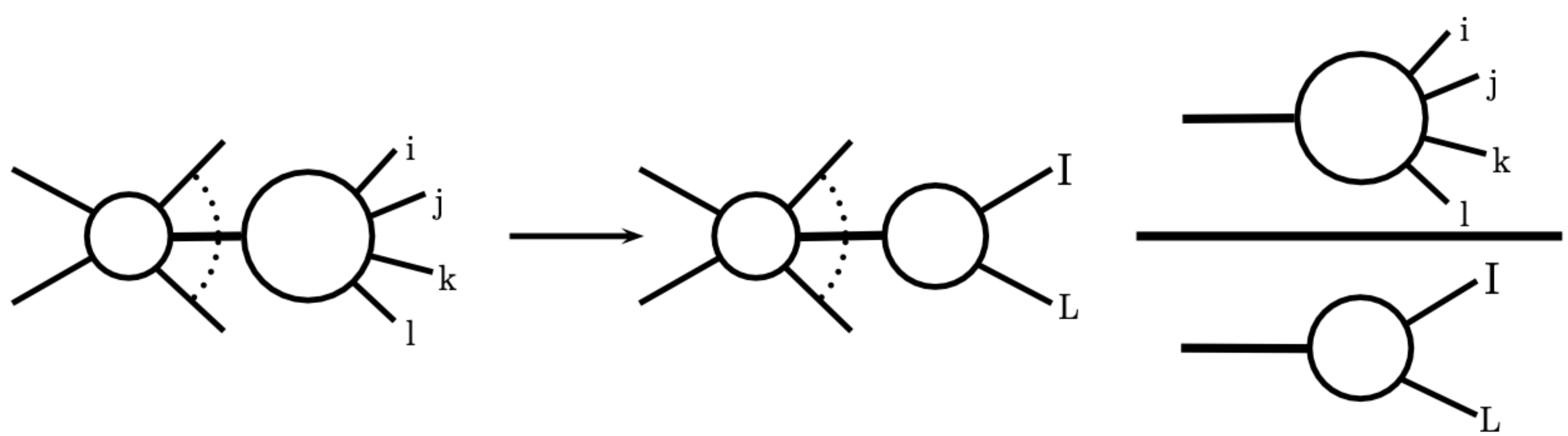
"real-virtual"

- *$1/\varepsilon^2$, $1/\varepsilon$*
- *single unresolved*

"double real"

- *double unresolved*
- *single unresolved*

➤ Cancellation of final and initial state IR-singularities making use of Universal factorization properties of QCD amplitudes in soft and collinear limits:

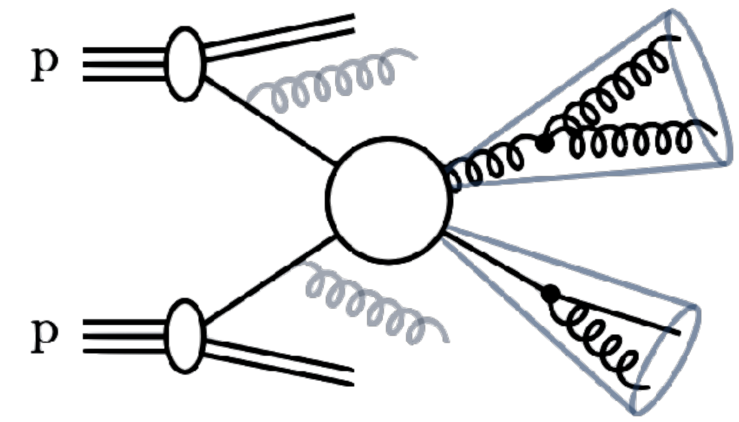


Double real Amplitude — *Reduced matrix element* — *Antenna Function*

[N. Glover, JP '10] [A.Gehrmann, N. Glover, JP '11] [A.Gehrmann, T.Gehrmann, N. Glover, JP '11]

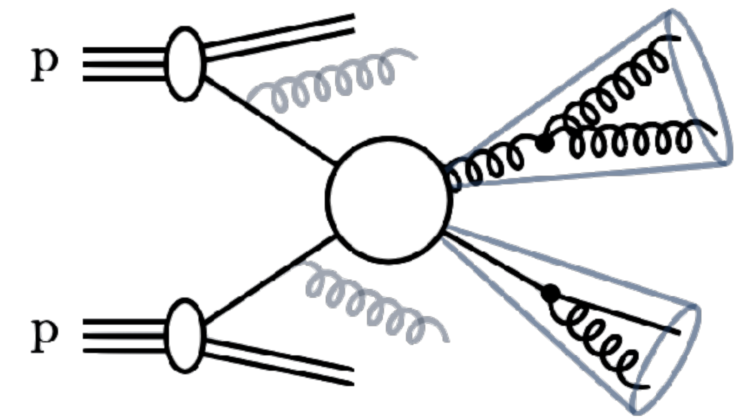
DIJET PRODUCTION AT THE LHC

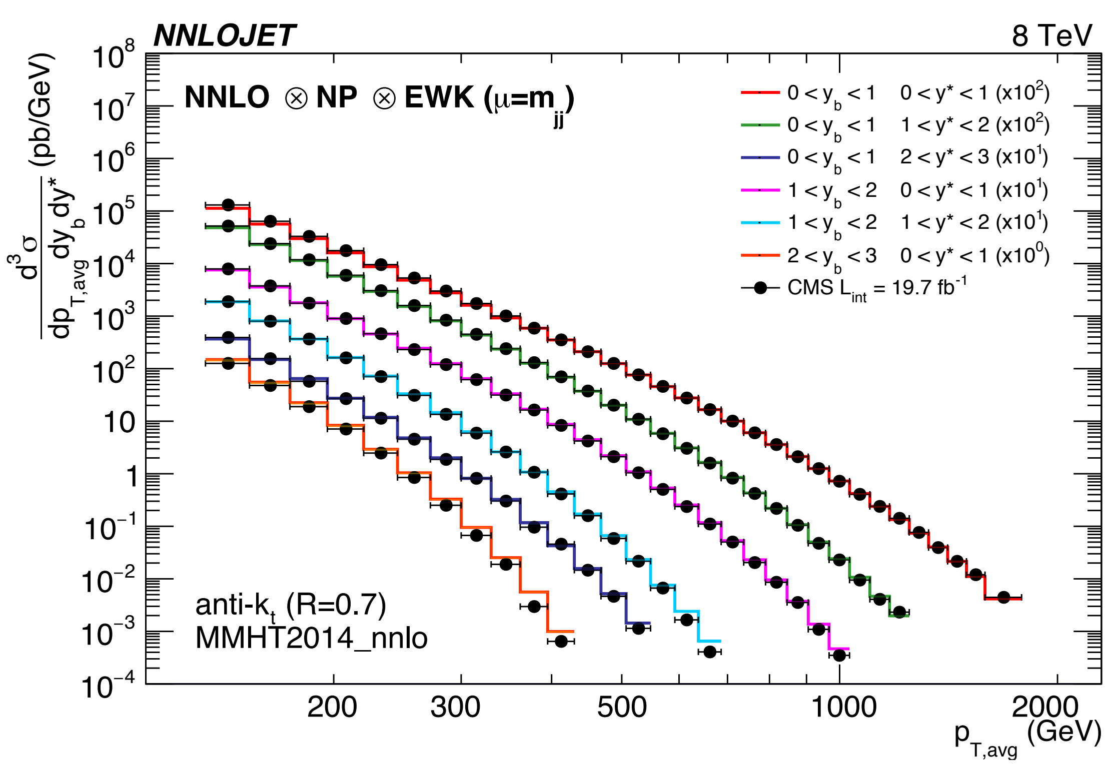
- Dijet cross section: *pp→2jets+X*
  - Triple differential measurement by CMS at 8 TeV [arXiv:1705.02628] as a function of
    - *Average p_T* $$p_{T,\mathrm{avg}} = (p_{T,1} + p_{T,2})/2$$
    - *Rapidity separation* $$y^* = |y_1 - y_2|/2$$
    - *Boost of the dijet system* $$y_b = |y_1 + y_2|/2$$



DIJET PRODUCTION AT THE LHC

- Dijet cross section: *pp→2jets+X*
  - Triple differential measurement by CMS at 8 TeV [arXiv:1705.02628] as a function of
    - *Average p_T* $$p_{T,\mathrm{avg}} = (p_{T,1} + p_{T,2})/2$$
    - *Rapidity separation* $$y^* = |y_1 - y_2|/2$$
    - *Boost of the dijet system* $$y_b = |y_1 + y_2|/2$$

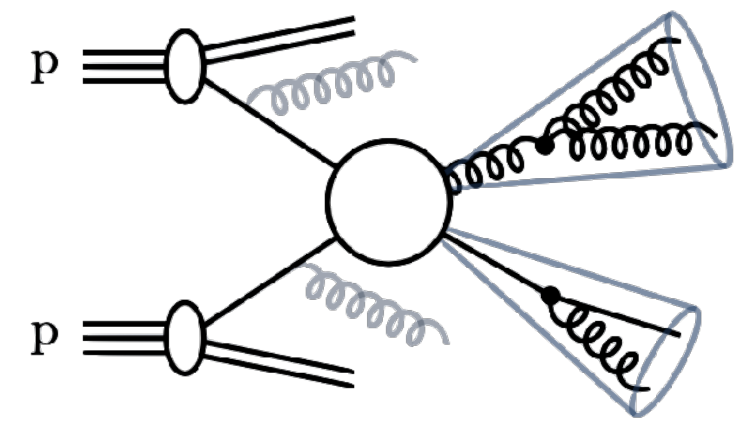


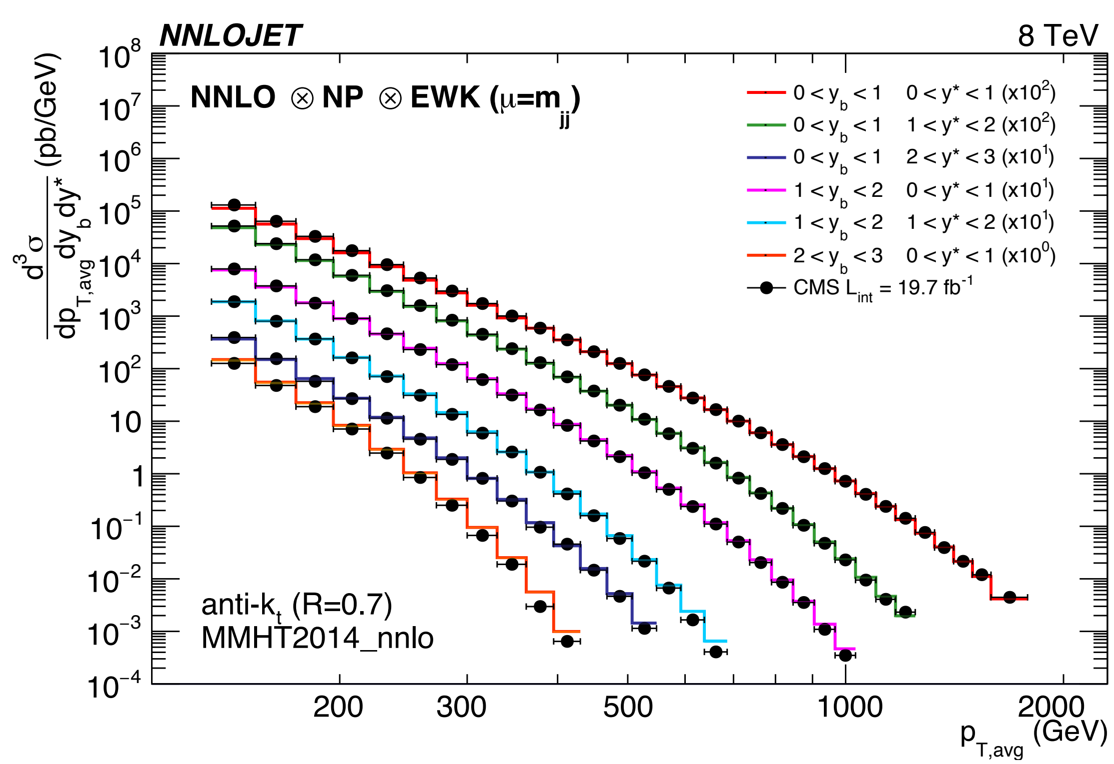


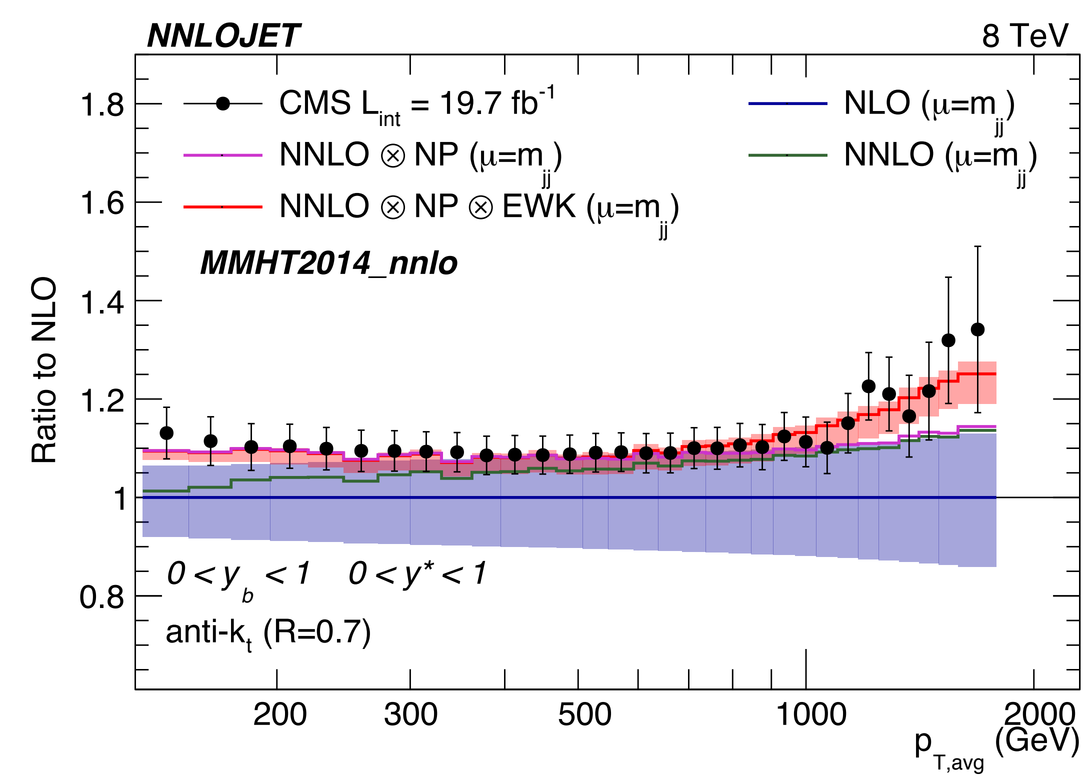
Gehrmann-De Ridder, Gehrmann, Glover, Huss, JP ***[arXiv: 1905.09047] Phys. Rev. Lett. 123, 102001 (2019)***

DIJET PRODUCTION AT THE LHC

- Dijet cross section: *$pp \to 2jets + X$*
  - Triple differential measurement by CMS at 8 TeV [arXiv:1705.02628] as a function of
    - *Average p_T* $$p_{T,\mathrm{avg}} = (p_{T,1} + p_{T,2})/2$$
    - *Rapidity separation* $$y^* = |y_1 - y_2|/2$$
    - *Boost of the dijet system* $$y_b = |y_1 + y_2|/2$$

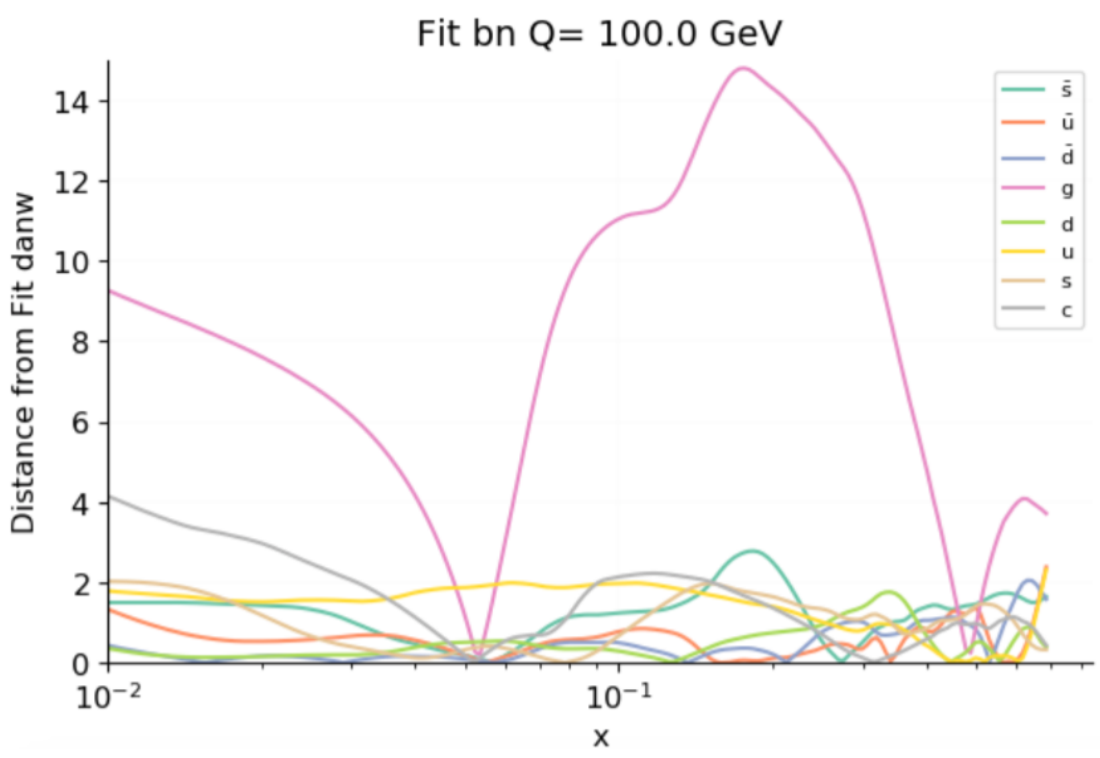






Gehrmann-De Ridder, Gehrmann, Glover, Huss, JP ***[arXiv: 1905.09047] Phys. Rev. Lett. 123, 102001 (2019)***

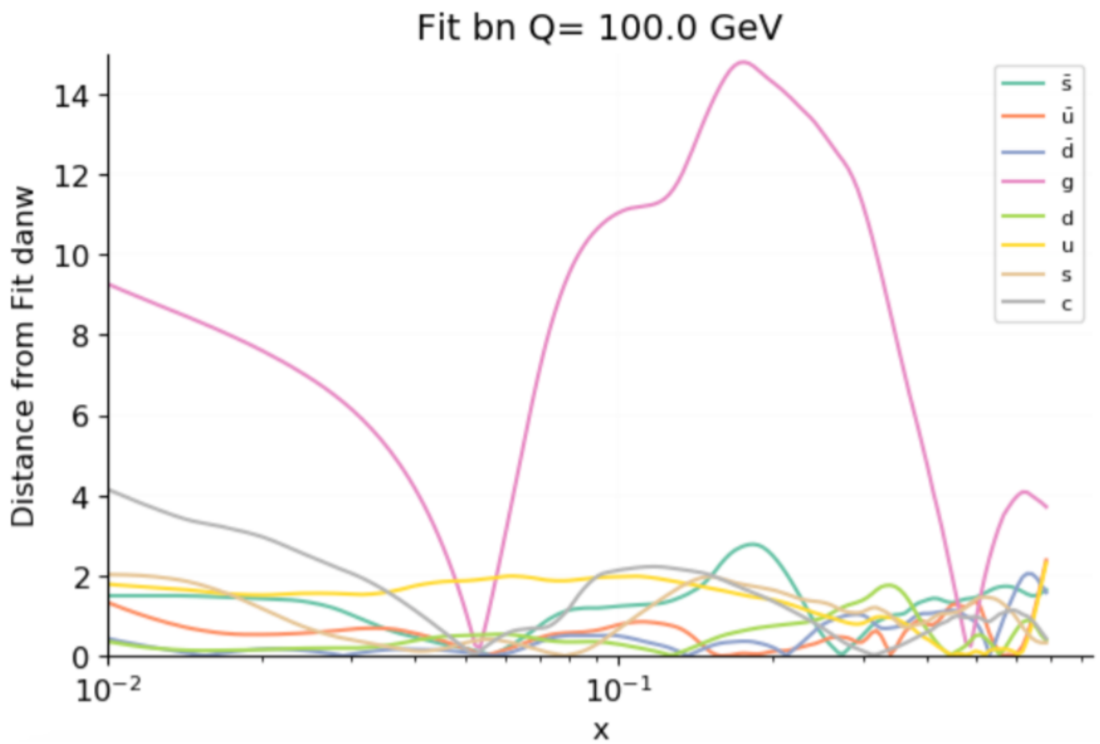
PDF FITS WITH DIJET DATA AT NNLO IN NNPDF DETERMINATION



Dataset	$n_{\rm dat}$	b	bn	d8	d8n	d8nw
CMS 8 TeV	122	[5.60]	[3.81]	3.69	1.59	1.68

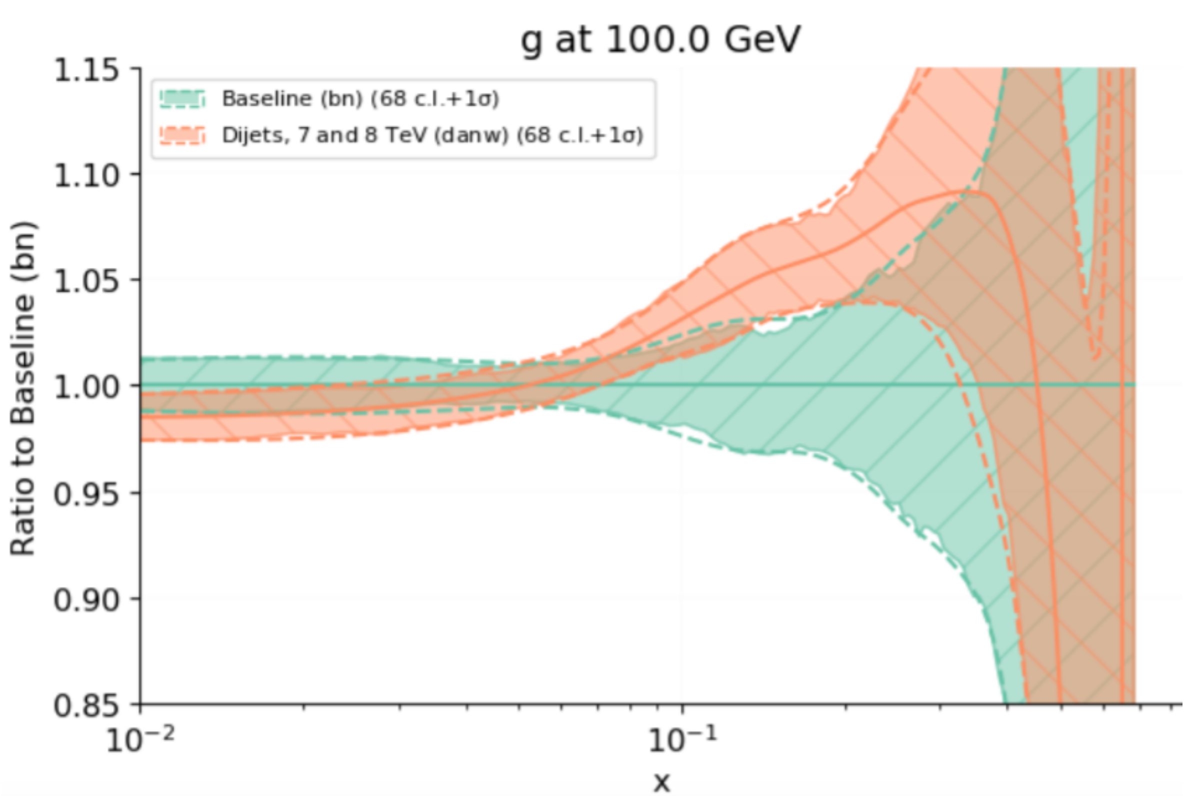
- reduction in $\chi 2$ per data point NLO → NNLO
- only gluon PDF is affected by the dijet data

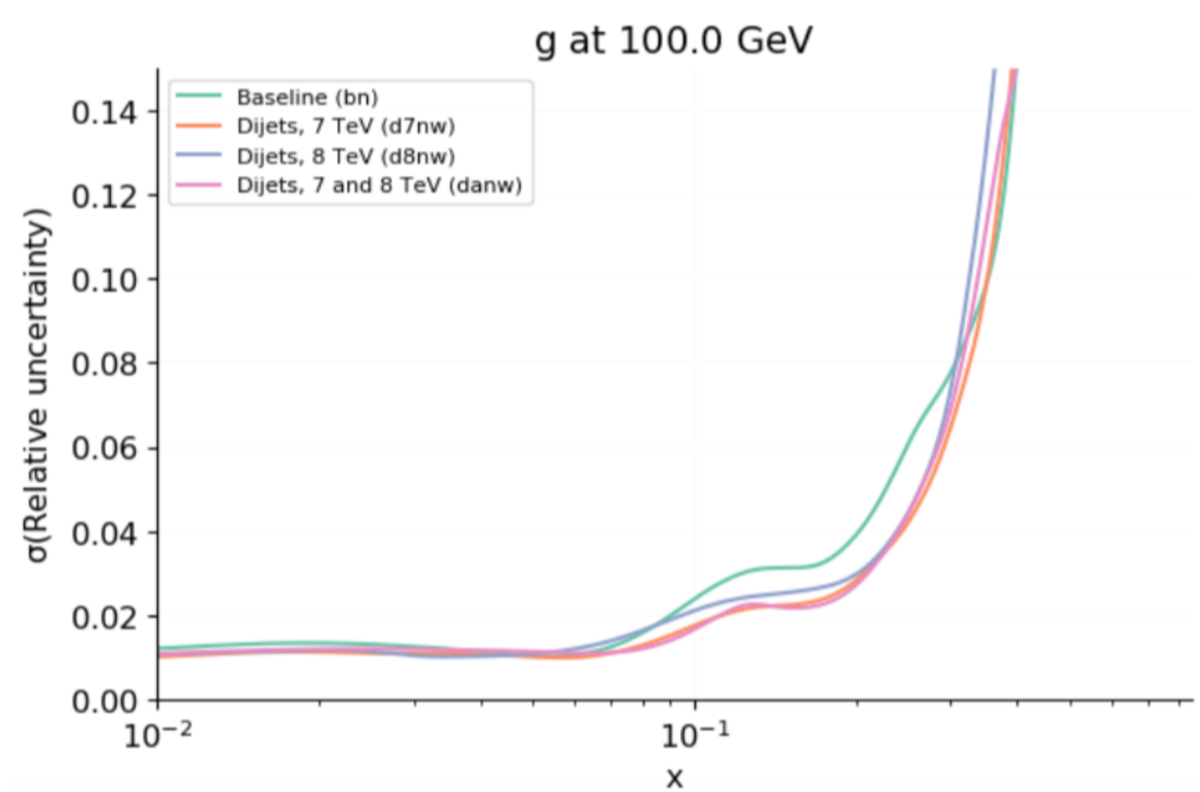
PDF FITS WITH DIJET DATA AT NNLO IN NNPDF DETERMINATION



Dataset	$n_{\rm dat}$	b	bn	d8	d8n	d8nw
CMS 8 TeV	122	[5.60]	[3.81]	3.69	1.59	1.68

- reduction in $\chi 2$ per data point NLO → NNLO
- only gluon PDF is affected by the dijet data
- gluon suppressed by 2% in the small x-region and enhanced by 10% at x~0.3 (1.5σ shift)
- reduction of gluon uncertainty at x≃0.2 to 3%





[Khalek, Forte, Gehrmann, Gehrmann-De Ridder, Giani, Glover, Huss, Nocera, JP, Rojo, Stagnitto]

***[arXiv: 2005.11327] Eur.Phys.J.C* 80 (2020) 8, 79**

NNLO INTERPOLATION GRIDS

- Full 2→2 @NNLO calculation: O(100k) CPUh
  - prohibitive in applications such as PDF + α_S fits

NNLO INTERPOLATION GRIDS

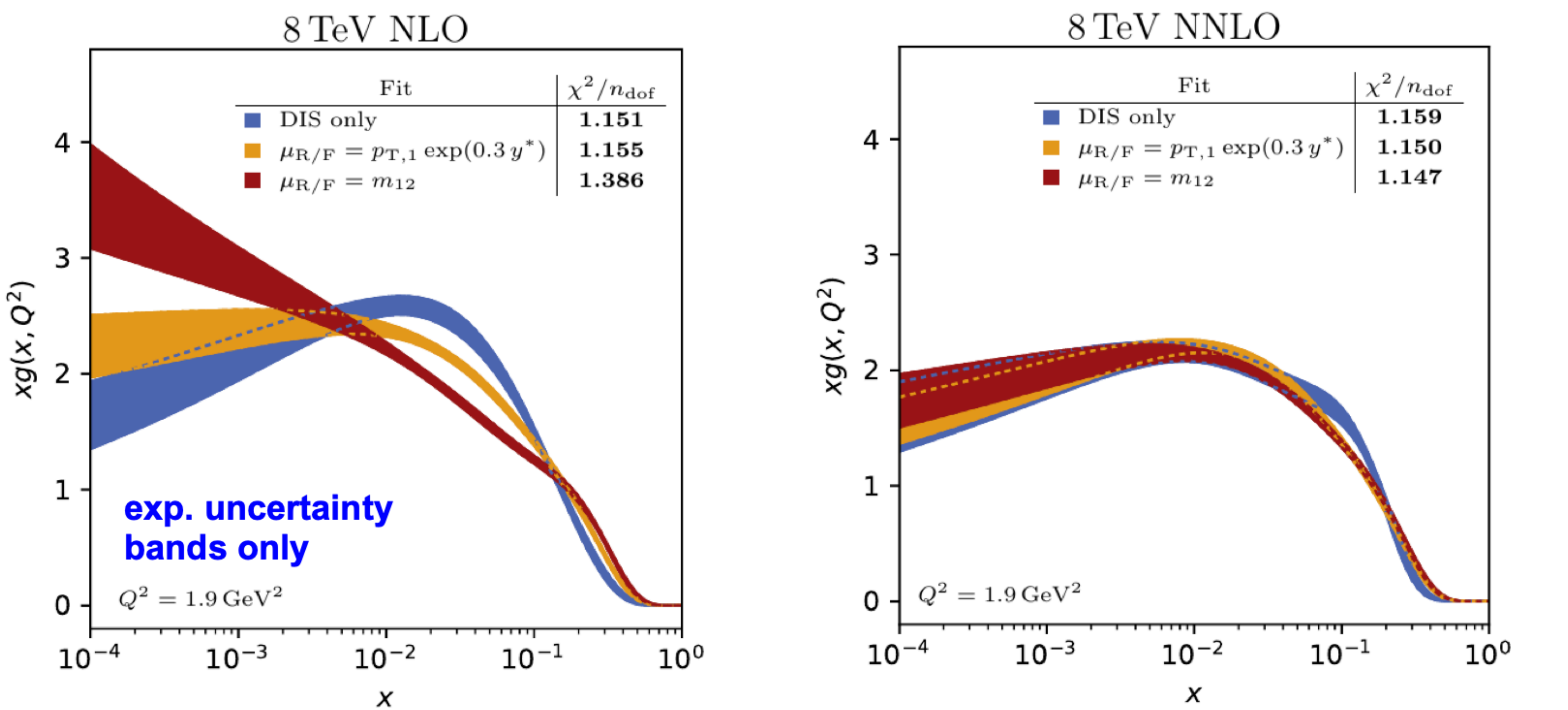
- Full 2→2 @NNLO calculation: O(100k) CPUh
  - prohibitive in applications such as PDF + α_S fits
- New interpolation grids for numerous jet datasets at the LHC computed for ATLAS&CMS
  - Partonic cross sections stripped of α_S and PDF dependence stored once in a high statistics run
  - Grid size: few GB ; NNLO cross section evaluation time: few minutes

```
$fnlo-tk-cppread 2jet.NNLO.fnl3832_yb0_ys0_ptavgj12.tab.gz NNPDF31_nnlo_as_0118 _ LHAPDF
```

  - Publicly available at: *https://ploughshare.web.cern.ch/ploughshare/*

PDF + α_S FITS WITH DIJET DATA

- Gluon from 13-parameter PDF fit with xfitter for two central scale choices



- At NLO (left) Significant differences between theory scale definitions
- At NNLO (right) Much improvement agreement between scales & better fit quality

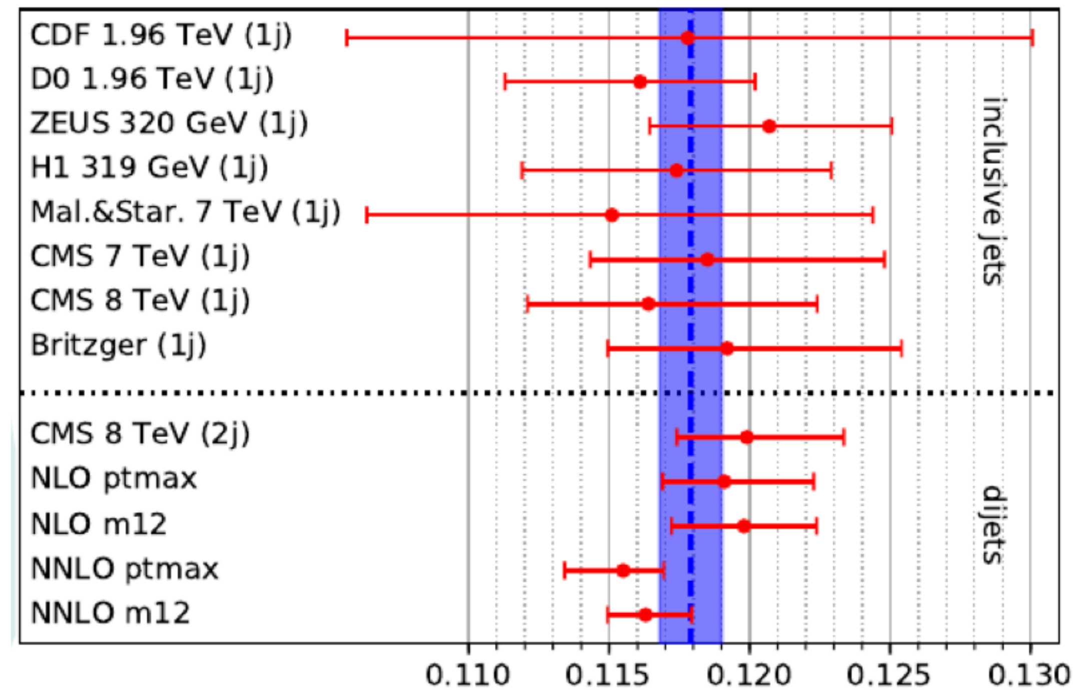
[Britzger, Gehrmann, Gehrmann-De Ridder, Glover, Gwenlan, Huss, JP, Rabbertz, Saviou, Sutton, Stark]

***[arXiv: 2207.13735] Eur.Phys.J.C* 82 (2022) 10, 930**

FITTED α_S VALUES

Fitted $\alpha_S(M_Z)$ values

NLO	$\mu = p_{T,1} e^{0.3y^*}$	$0.1191 \pm 0.0015(\text{exp})^{+0.0028}_{-0.0016}(\text{scale})$
	$\mu = m_{12}$	$0.1198 \pm 0.0015(\text{exp})^{+0.0021}_{-0.0021}(\text{scale})$
NNLO	$\mu = p_{T,1} e^{0.3y^*}$	$0.1155 \pm 0.0012(\text{exp})^{+0.0008}_{-0.0017}(\text{scale})$
	$\mu = m_{12}$	$0.1163 \pm 0.0013(\text{exp})^{+0.0010}_{-0.0004}(\text{scale})$



- Smaller α_S values at NNLO

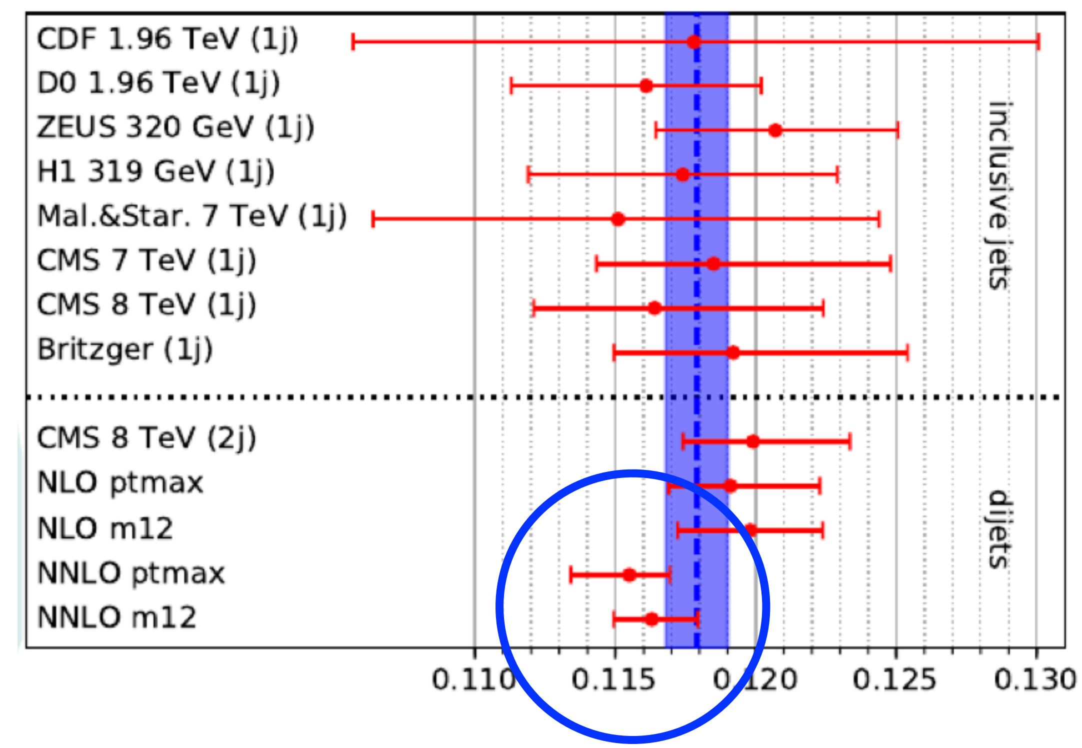
[Britzger, Gehrmann, Gehrmann-De Ridder, Glover, Gwenlan, Huss, JP, Rabbertz, Saviou, Sutton, Stark]

***[arXiv: 2207.13735] Eur.Phys.J.C* 82 (2022) 10, 930**

FITTED α_S VALUES

Fitted $\alpha_s(M_Z)$ values

NLO	$\mu = p_{T,1} e^{0.3y^*}$	$0.1191 \pm 0.0015(\text{exp})^{+0.0028}_{-0.0016}(\text{scale})$
	$\mu = m_{12}$	$0.1198 \pm 0.0015(\text{exp})^{+0.0021}_{-0.0021}(\text{scale})$
NNLO	$\mu = p_{T,1} e^{0.3y^*}$	$0.1155 \pm 0.0012(\text{exp})^{+0.0008}_{-0.0017}(\text{scale})$
	$\mu = m_{12}$	$0.1163 \pm 0.0013(\text{exp})^{+0.0010}_{-0.0004}(\text{scale})$



➤ Smaller α_S values at NNLO

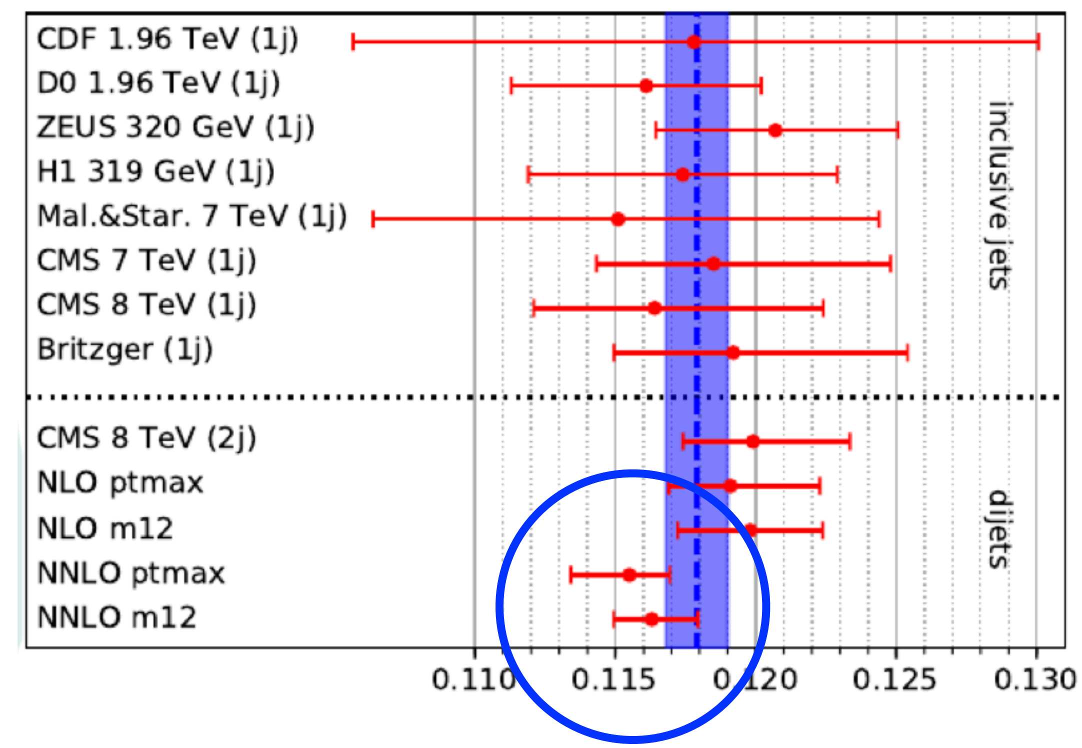
➤ Experimental and especially scale uncertainties reduced at NNLO

[Britzger, Gehrmann, Gehrmann-De Ridder, Glover, Gwenlan, Huss, JP, Rabbertz, Saviou, Sutton, Stark]

[arXiv: 2207.13735] Eur.Phys.J.C 82 (2022) 10, 930

FITTED α_S VALUES

Fitted $\alpha_s(M_Z)$ values		
NLO	$\mu = p_{T,1} e^{0.3y^*}$	$0.1191 \pm 0.0015(\text{exp})^{+0.0028}_{-0.0016}(\text{scale})$
	$\mu = m_{12}$	$0.1198 \pm 0.0015(\text{exp})^{+0.0021}_{-0.0021}(\text{scale})$
NNLO	$\mu = p_{T,1} e^{0.3y^*}$	$0.1155 \pm 0.0012(\text{exp})^{+0.0008}_{-0.0017}(\text{scale})$
	$\mu = m_{12}$	$0.1163 \pm 0.0013(\text{exp})^{+0.0010}_{-0.0004}(\text{scale})$



- ➤ Smaller α_S values at NNLO
- ➤ Experimental and especially scale uncertainties reduced at NNLO
- ➤ Results compatible with the world average α_S value (blue band)

[Britzger, Gehrmann, Gehrmann-De Ridder, Glover, Gwenlan, Huss, JP, Rabbertz, Saviou, Sutton, Stark]

[arXiv: 2207.13735] Eur.Phys.J.C 82 (2022) 10, 930

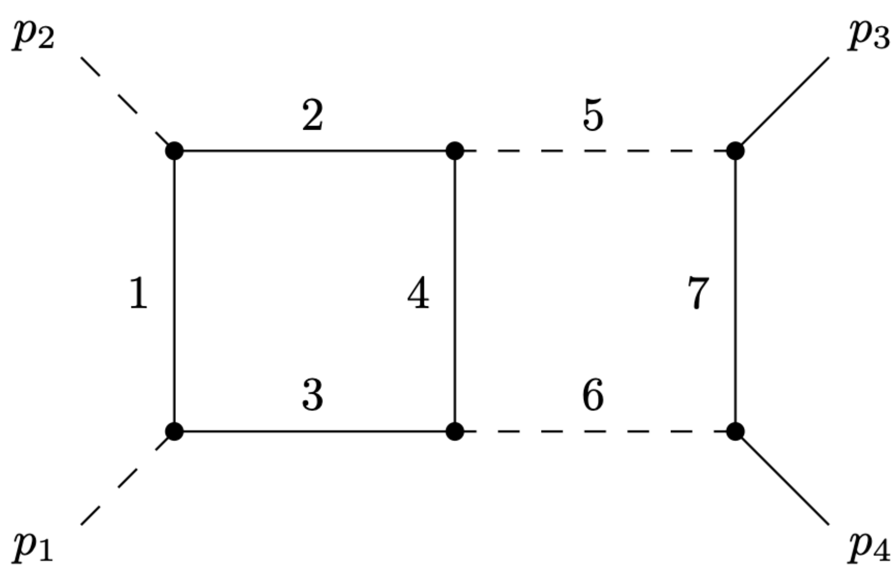
FUTURE STEPS: SCATTERING IN QCD AT TWO-LOOPS WITH MASSIVE FERMIONS

FUTURE STEPS: SCATTERING IN QCD AT TWO-LOOPS WITH MASSIVE FERMIONS

- Accessing the top-quark Higgs Yukawa coupling with higher precision requires significant extensions of the current methodologies

FUTURE STEPS: SCATTERING IN QCD AT TWO-LOOPS WITH MASSIVE FERMIONS

- Accessing the top-quark Higgs Yukawa coupling with higher precision requires significant extensions of the current methodologies

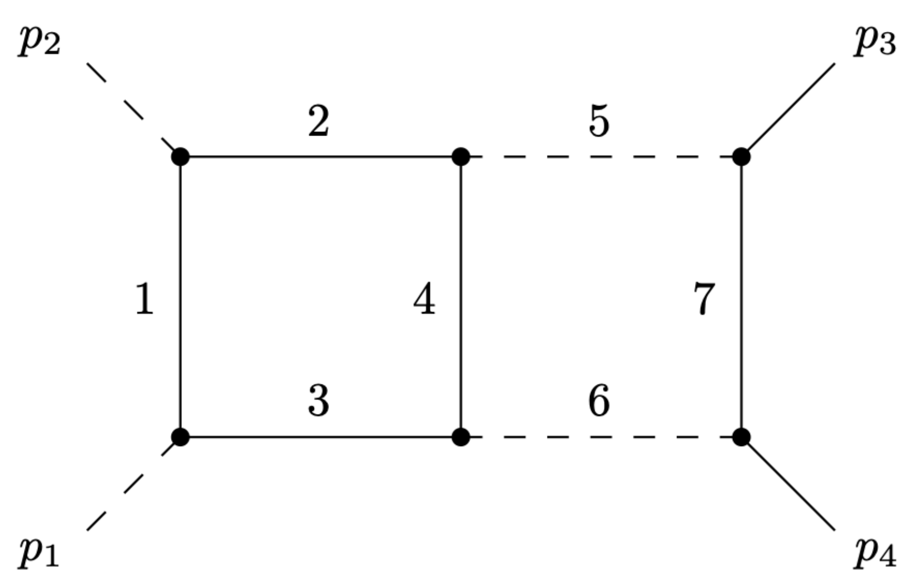


$$p_1^2 = p_2^2 = 0$$

$$p_3^2 = p_4^2 = m^2$$

FUTURE STEPS: SCATTERING IN QCD AT TWO-LOOPS WITH MASSIVE FERMIONS

➤ Accessing the top-quark Higgs Yukawa coupling with higher precision requires significant extensions of the current methodologies



$$p_1^2 = p_2^2 = 0$$

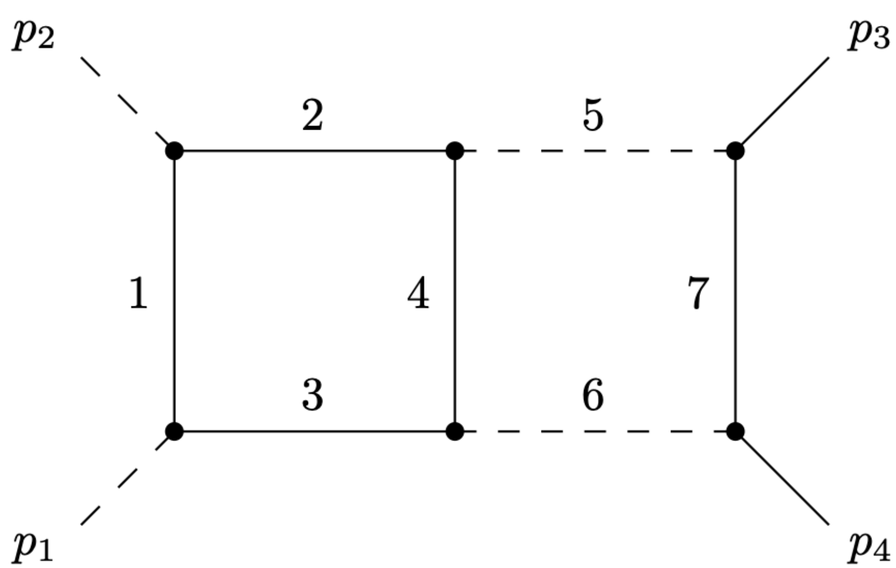
$$p_3^2 = p_4^2 = m^2$$

✔ New topologies involving massive internal propagators

✔ New explicit results in terms of PolyLogarithms and new Elliptic integrals

FUTURE STEPS: SCATTERING IN QCD AT TWO-LOOPS WITH MASSIVE FERMIONS

- Accessing the top-quark Higgs Yukawa coupling with higher precision requires significant extensions of the current methodologies



$$p_1^2 = p_2^2 = 0$$

$$p_3^2 = p_4^2 = m^2$$

✔ New topologies involving massive internal propagators

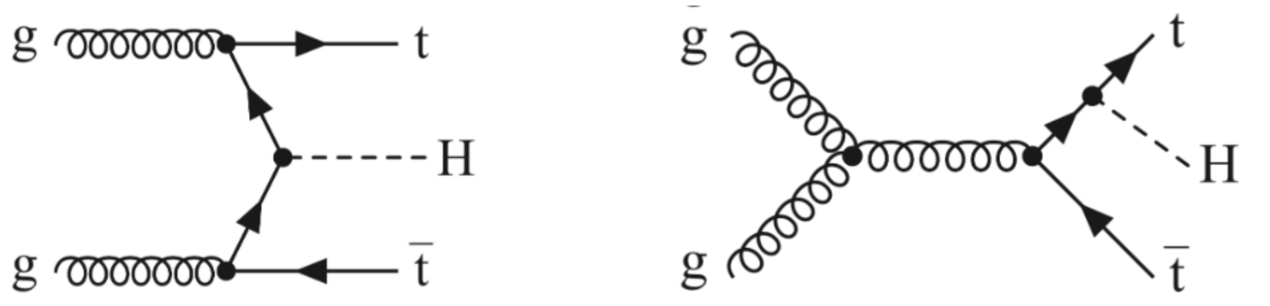
✔ New explicit results in terms of PolyLogarithms and new Elliptic integrals

✗ Not all integrals known analytically

✗ Subtraction of IR singularities within the massive antenna subtraction framework not fully established

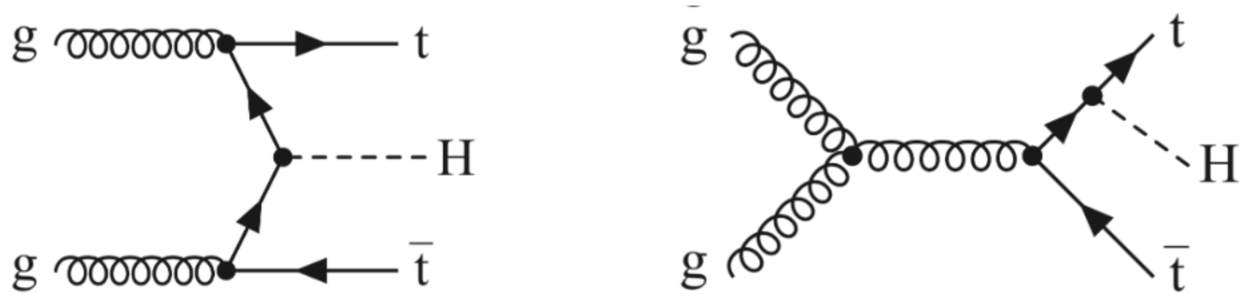
FUTURE STEPS: TTH PRODUCTION AT NNLO IN QCD

- Associated production of a Higgs boson and a top quark-antiquark pair (ttH production) is a direct probe of the top–Higgs coupling at tree-level

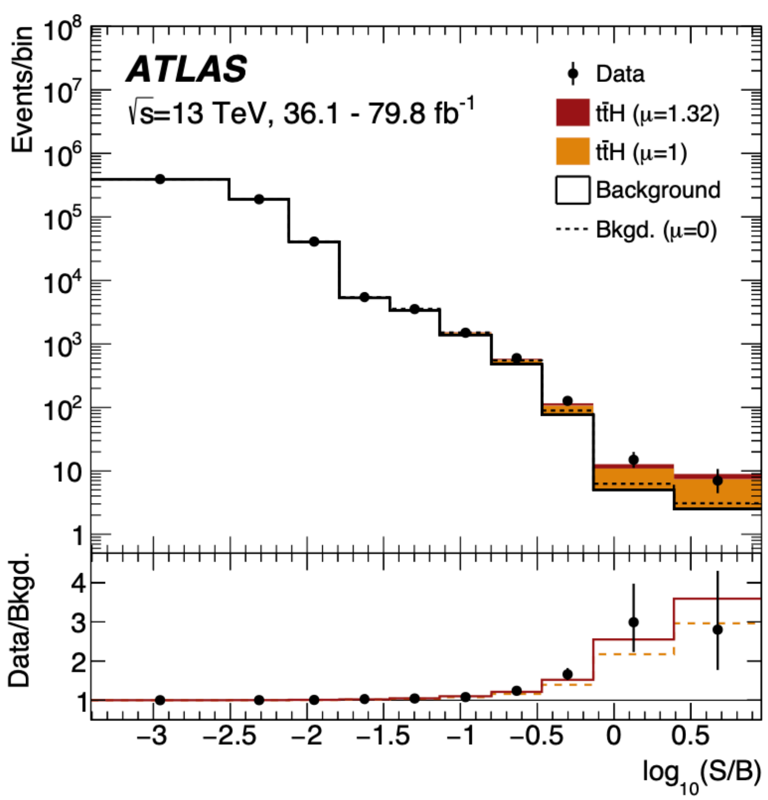


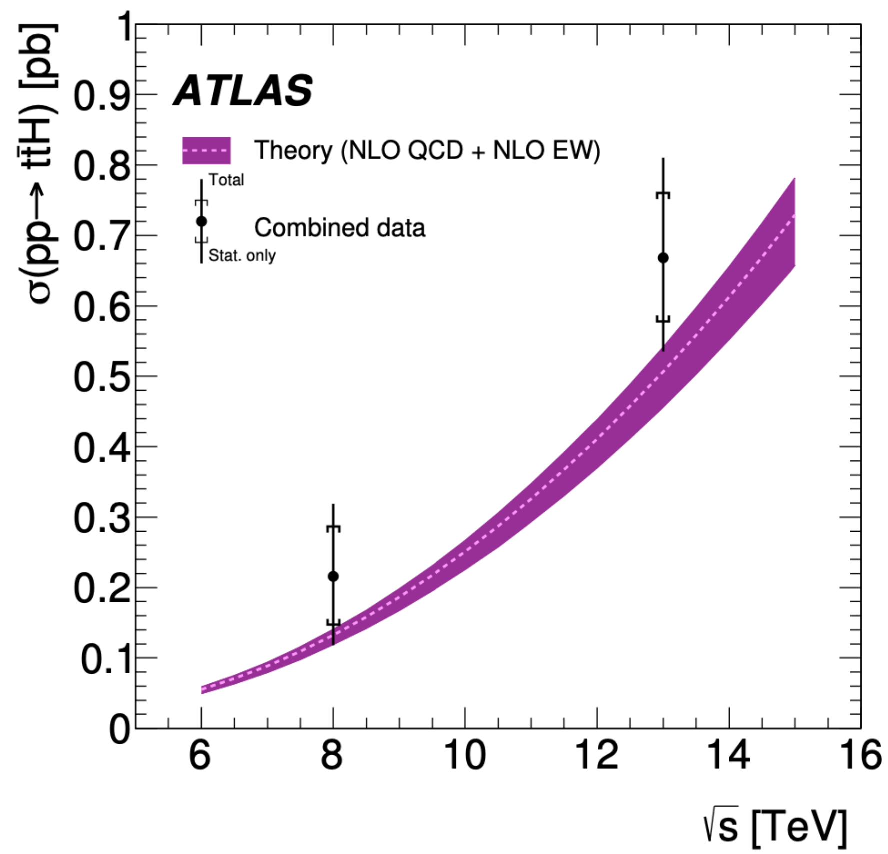
FUTURE STEPS: TTH PRODUCTION AT NNLO IN QCD

- Associated production of a Higgs boson and a top quark-antiquark pair (ttH production) is a direct probe of the top–Higgs coupling at tree-level



- 2018: First observation of this new Higgs boson production mechanism by CMS and ATLAS* (*with strong LIP involvement)

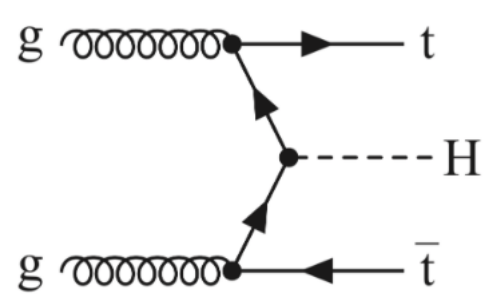


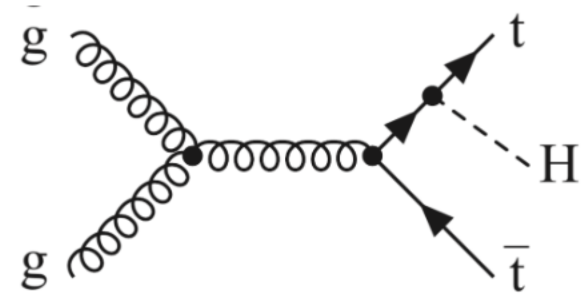


ATLAS Collaboration ***[arXiv: 1806.00425] Phys. Lett. B 784 (2018) 173***

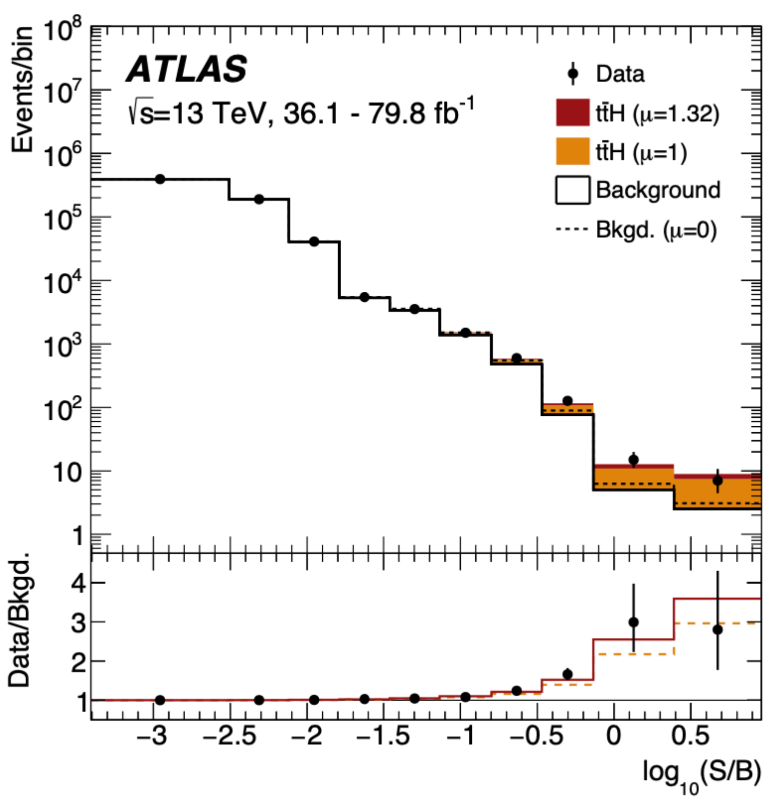
FUTURE STEPS: TTH PRODUCTION AT NNLO IN QCD

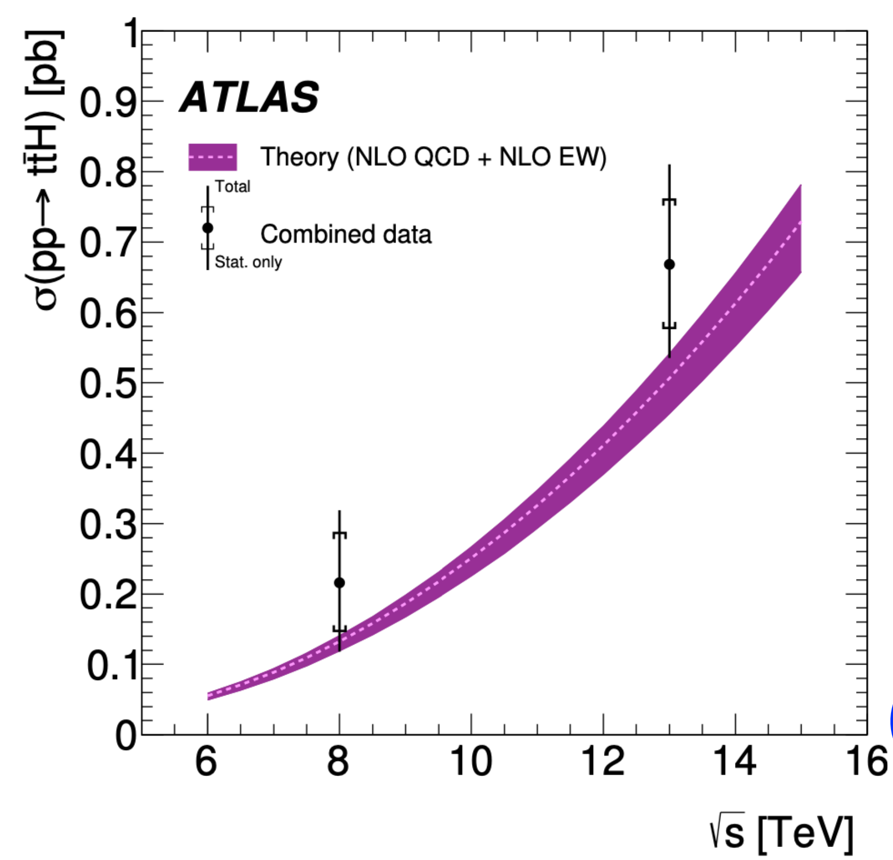
- Associated production of a Higgs boson and a top quark-antiquark pair (ttH production) is a direct probe of the top–Higgs coupling at tree-level

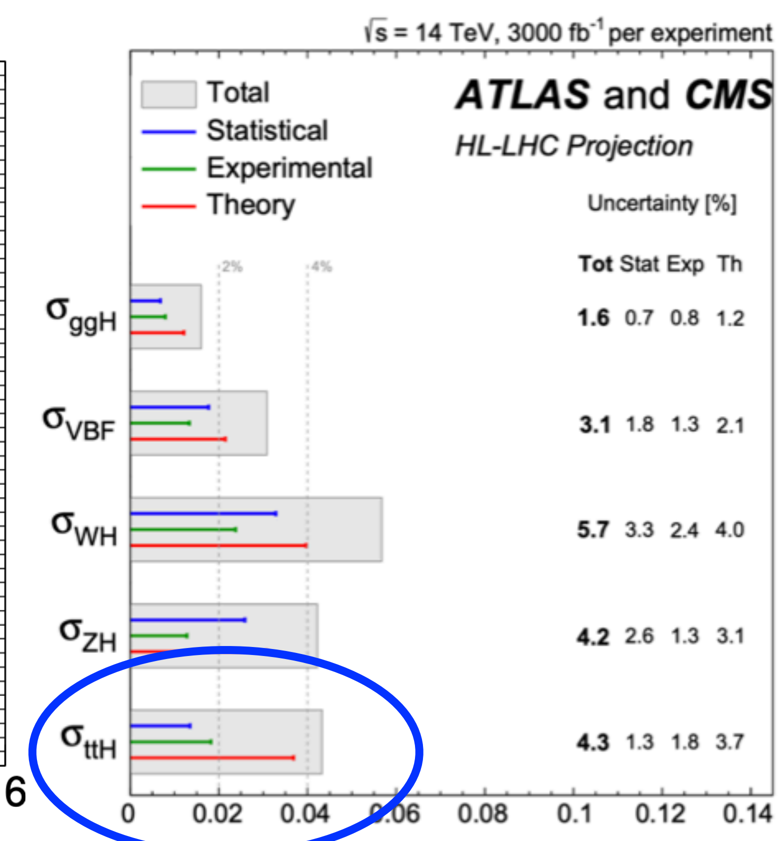




- Currently ATLAS+CMS measure ttH cross section to 20% accuracy → 2% level at the end of HL-LHC







ATLAS Collaboration ***[arXiv: 1806.00425] Phys. Lett. B 784 (2018) 173***

Thank You

For Your Attention