

Pushing the boundaries of perturbative QCD (and more...) for LHC physics

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Outline

- **Motivation:** LHC measurements and future colliders
- **Theoretical calculations**
 - Preliminary considerations
 - The building blocks
 - The state of the art
 - Current bottlenecks and future improvements
- **Outlook**

GOAL of the TALK: Precision is the MVP of the GAME for decades to come.

LHC measurements

Reaching and breaking the 1% frontier

EUROPEAN ORGANISATION FOR NUCLEAR RESEARCH (CERN)



Submitted to: EPJC



CERN-EP-2023-171
19th September 2023

● **Differential in rapidity < 1% (integrated in pt)**

A precise measurement of the Z-boson double-differential transverse momentum and rapidity distributions in the full phase space of the decay leptons with the ATLAS experiment at $\sqrt{s} = 8$ TeV

The ATLAS Collaboration

Available on the CERN CDS information server

CMS PAS SMP-23-002

CMS Physics Analysis Summary

● **Uncertainty < 1%**

Contact: cms-pag-conveners-smp@cern.ch

2024/09/17

Measurement of the W boson mass in proton-proton collisions at $\sqrt{s} = 13$ TeV

The CMS Collaboration

EUROPEAN ORGANISATION FOR NUCLEAR RESEARCH (CERN)



Submitted to: Phys. Lett. B.



CERN-EP-2023-160
15th August 2023

● **Uncertainty of 1.1 per mille**
● **Most precise measurement in a single decay channel**

Measurement of the Higgs boson mass with $H \rightarrow \gamma\gamma$ decays in 140 fb^{-1} of $\sqrt{s} = 13$ TeV pp collisions with the ATLAS detector

The ATLAS Collaboration



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ACCEPTED: June 9, 2023
PUBLISHED: July 17, 2023

Inclusive and differential cross-sections for dilepton $t\bar{t}$ production measured in $\sqrt{s} = 13$ TeV pp collisions with the ATLAS detector



The ATLAS collaboration

● **Uncertainty < 2%**

E-mail: atlas.publications@cern.ch

EUROPEAN ORGANISATION FOR NUCLEAR RESEARCH (CERN)



Submitted to: Nature Phys.



CERN-EP-2023-200
22nd September 2023

● **Uncertainty < 1%**

A precise determination of the strong-coupling constant from the recoil of Z bosons with the ATLAS experiment at $\sqrt{s} = 8$ TeV

The ATLAS Collaboration **and L. Cieri**

EUROPEAN ORGANIZATION FOR NUCLEAR RESEARCH (CERN)



CMS-TOP-20-008



CERN-EP-2022-245
2023/02/07

● **Uncertainty < 1%**

Measurement of the top quark mass using a profile likelihood approach with the lepton+jets final states in proton-proton collisions at $\sqrt{s} = 13$ TeV

The CMS Collaboration

EUROPEAN ORGANIZATION FOR NUCLEAR RESEARCH (CERN)



CMS-LUM-21-001



CERN-EP-2023-163
2023/09/06

● **Uncertainty < 1%**

Luminosity determination using Z boson production at the CMS experiment

The CMS Collaboration*



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● **Uncertainty < 1%**

Measurement of the W boson mass



The LHCb collaboration

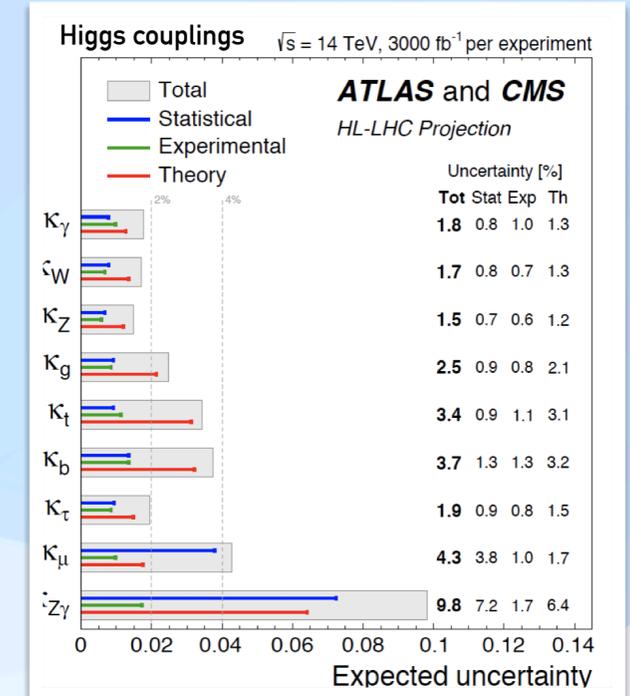
And the list goes on ...

Motivation

- Current CERN's LHC measurements reaching **1% precision** for several observables.
- In many cases → **total uncertainty** in precision measurements is **dominated by theory (TH) input** (e.g. extraction of Higgs couplings to the Standard Model (SM) bosons, top quark mass, the strong coupling, W boson mass, etc).
- **This limitation will worsen** in the LHC Run III (started in 2022), even more in the High Luminosity (HL) phase of the LHC and in the future colliders (FCC, CLIC, etc.).
- Most optimistic scenario establishes **1%-3%** theoretical accuracy as **mandatory** (at current Run III, HL-LHC and future colliders).
- *"The excessive success of the SM", emphasises the need for very accurate TH predictions.*



Ellis et al. Physics Briefing Book: Input for the European Strategy for Particle Physics Update 2020



TH uncertainties (in red) already reduced by a factor 2!
(respect to the current state of the art)



Guido Altarelli



Fabiola Gianotti
CERN director

"Monte Carlo (MC) developments and higher order (signal and background) calculations are fundamental for current and future projects"

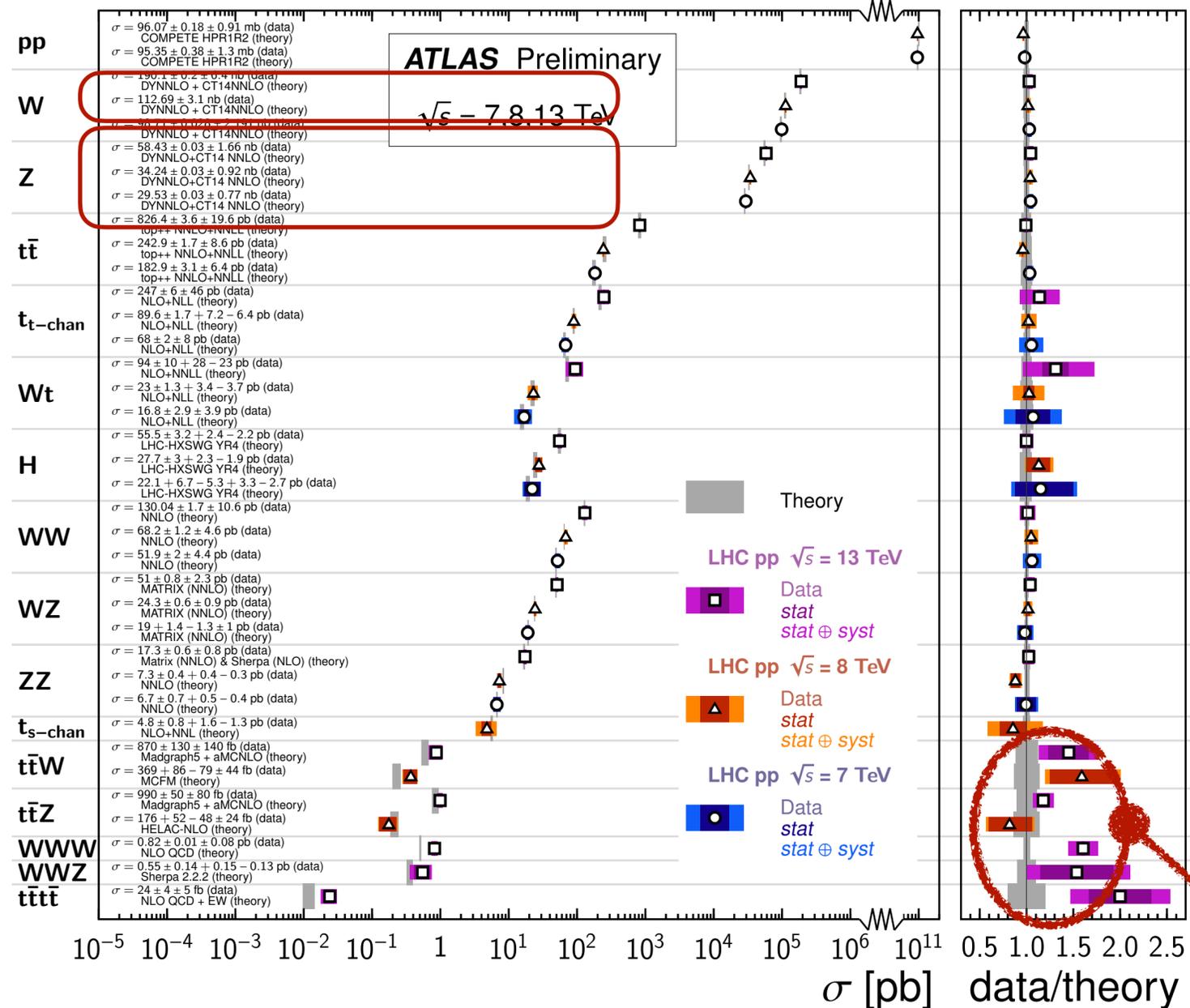
Extremely precise
LHC measurements



requires challenging precise
theoretical predictions

Everything looks SM-like at the LHC

Standard Model Total Production Cross Section Measurements



Standard Model Production Cross Section Measurements

ATLAS Preliminary

$\sqrt{s} = 5, 7, 8, 13, 13.6$ TeV

Status: June 2024

Model	E_{CM} [TeV]	$\int \mathcal{L} dt [fb^{-1}]$	Measurement	Theory	Reference
pp	13	34×10^8	$\sigma = 104.7 \pm 0.22 \pm 1.07$ mb	$\sigma = 100.3 \pm 0.12$ mb (COMPETE HPR1R2)	EPJ C 83 (2023) 441
pp	13	50×10^8	$\sigma = 96.07 \pm 0.18 \pm 0.91$ mb	$\sigma = 99.55 \pm 2.14$ mb (COMPETE HPR1R2)	PLB 761 (2016) 158
pp inelastic	13	8×10^8	$\sigma = 95.35 \pm 0.38 \pm 1.3$ mb	$\sigma = 97.26 \pm 2.12$ mb (COMPETE HPR1R2)	Nucl. Phys. B (2014) 486
pp inelastic	13	34×10^8	$\sigma = 77.41 \pm 1.08$ mb	$\sigma = 78.4 \pm 2$ mb (Schuler/Sjöstrand)	EPJ C 83 (2023) 441
pp inelastic	8	50×10^8	$\sigma = 71.73 \pm 0.15 \pm 0.69$ mb	$\sigma = 73 \pm 2$ mb (Schuler/Sjöstrand)	PLB 761 (2016) 158
pp inelastic	8	8×10^8	$\sigma = 71.34 \pm 0.36 \pm 0.83$ mb	$\sigma = 71.5 \pm 20 - 2$ mb (Schuler/Sjöstrand)	Nucl. Phys. B (2014) 486
Incl. jet R=0.4, $ \eta < 3.0$	13	3.2	$\sigma = 1845 \pm 4 \pm 119 - 120$ nb	$\sigma = 1997 \pm 152 - 208$ nb (NLOJet++, CT14)	JHEP 05 (2018) 195
Incl. jet R=0.4, $ \eta < 3.0$	8	20.2	$\sigma = 726.4 \pm 1.1 \pm 42.7 - 41.8$ nb	$\sigma = 800 \pm 59 - 100$ nb (NLOJet++, CT14)	JHEP 09 (2017) 020
Incl. jet R=0.4, $ \eta < 3.0$	7	4.5	$\sigma = 563.9 \pm 1.5 \pm 55.4 - 51.4$ nb	$\sigma = 569.8 \pm 29.5 - 46.3$ nb (NLOJet++, CT10)	JHEP 02 (2015) 153
Dijet R=0.4, $ \eta < 3.0, y' < 3.0$	13	3.2	$\sigma = 321 \pm 0.8 \pm 18.6 - 19$ nb	$\sigma = 340 \pm 17 - 54$ nb (NLOJet++, CT14)	JHEP 05 (2018) 195
Dijet R=0.4, $ \eta < 3.0, y' < 3.0$	7	4.5	$\sigma = 86.87 \pm 0.26 \pm 7.56 - 7.2$ nb	$\sigma = 86.9 \pm 4.7 - 12.4$ nb (NLOJet++, CT10)	JHEP 05 (2014) 059
γ	13	3.2	$\sigma = 399 \pm 0.4 \pm 16$ pb	$\sigma = 352 \pm 36 - 30$ pb (JETPHOX+MMHT2014 (NLO))	PLB 2017 04 072
γ	7	7	$\sigma = 56.8 \pm 0.1 \pm 5.8 - 5.6$ pb	$\sigma = 52.2 \pm 7$ pb (PETERR (NLO+NNLL))	JHEP 06 (2016) 005
γ [injet ν]	13	4.6	$\sigma = 359 \pm 3 \pm 22 - 16$ pb	$\sigma = 308 \pm 40$ pb (JETPHOX (NLO))	PRD 95 (2014) 052004
γ [injet ν]	8	3.2	$\sigma = 300 \pm 0.4 \pm 12$ pb	$\sigma = 319 \pm 55 - 46$ pb (SHERPA (NLO))	PLB 780 (2018) 578
γ [injet ν]	8	20.2	$\sigma = 134 \pm 0.1 \pm 4$ pb	$\sigma = 128 \pm 11 - 9$ pb (JETPHOX (NLO))	Nucl. Phys. B 918 (2017) 257
γ [injet ν]	8	20.2	$\sigma = 30.4 \pm 0.04 \pm 1.8$ pb	$\sigma = 29.2 \pm 2.8 - 2.7$ pb (NLOBlackhat+CT10)	Nucl. Phys. B 918 (2017) 257
γ [injet ν]	8	20.2	$\sigma = 8.7 \pm 0.02 \pm 0.8$ pb	$\sigma = 9.5 \pm 0.9 - 1.2$ pb (NLOBlackhat+CT10)	Nucl. Phys. B 918 (2017) 257
$\sigma_{had}(W \rightarrow e\nu, \mu\nu)$	13.6	29.0	$\sigma = 7560 \pm 0.76 \pm 265$ pb	$\sigma = 7757 \pm 154.59 - 247.31$ pb (DYTURBO+CT18 (NNLO+NNLL))	PLB 854 (2024) 138725
$\sigma_{had}(W \rightarrow e\nu, \mu\nu)$	13	0.3	$\sigma = 8057 \pm 6 \pm 87$ pb	$\sigma = 7870 \pm 161 - 235$ pb (DYTURBO+CT18 (NNLO+NNLL))	arXiv:2404.06204
$\sigma_{had}(W \rightarrow e\nu, \mu\nu)$	8	20.2	$\sigma = 5247 \pm 0.6 \pm 111$ pb	$\sigma = 5120 \pm 142$ pb (DYNNLO+CT14NNLO)	EPJ C 77 (2017) 387
$\sigma_{had}(W \rightarrow e\nu, \mu\nu)$	7	0.3	$\sigma = 4.777 \pm 0.12 - 0.14$ pb (DYNNLO+CT14NNLO)	$\sigma = 4.777 \pm 0.12 - 0.14$ pb (DYNNLO+CT14NNLO)	EPJ C 77 (2017) 387
$\sigma_{had}(W \rightarrow e\nu, \mu\nu)$	7	0.3	$\sigma = 3560 \pm 73 - 112$ pb (DYTURBO+CT18 (NNLO+NNLL))	$\sigma = 3560 \pm 73 - 112$ pb (DYTURBO+CT18 (NNLO+NNLL))	arXiv:2404.06204
W [injet ν]	8	20.2	$\sigma = 564.71 \pm 0.24 \pm 72.13$ pb	$\sigma = 584 \pm 8 - 37$ pb (Sherpa 2.2.1 NLO)	JHEP 05 (2018) 077
W [injet ν]	7	4.6	$\sigma = 493.8 \pm 0.5 \pm 45.1$ pb	$\sigma = 474.22 \pm 0.84$ pb (Blackhat)	JHEP 05 (2018) 077
W [injet ν]	8	20.2	$\sigma = 128.35 \pm 0.12 \pm 20.39$ pb	$\sigma = 126.5 \pm 2.1 - 14.4$ pb (Sherpa 2.2.1 NLO)	JHEP 05 (2018) 077
W [injet ν]	7	4.6	$\sigma = 111.98 \pm 0.44$ pb (Blackhat)	$\sigma = 111.98 \pm 0.44$ pb (Blackhat)	JHEP 05 (2018) 077
W [injet ν]	8	20.2	$\sigma = 26.38 \pm 0.06 \pm 5.34$ pb	$\sigma = 23.6 \pm 1.3 - 5$ pb (Sherpa 2.2.1 NLO)	JHEP 05 (2018) 077
W [injet ν]	7	4.6	$\sigma = 21.82 \pm 0.1 \pm 3.23$ pb	$\sigma = 23.47 \pm 0.22$ pb (Blackhat)	JHEP 05 (2018) 077
W [injet ν]	8	20.2	$\sigma = 5.47 \pm 0.03 \pm 1.47$ pb	$\sigma = 5 \pm 0.5 - 1.4$ pb (Sherpa 2.2.1 NLO)	JHEP 05 (2018) 077
W [injet ν]	7	4.6	$\sigma = 4.241 \pm 0.056 \pm 0.885$ pb	$\sigma = 4.67 \pm 0.06$ pb (Blackhat)	JHEP 05 (2018) 077
W [injet ν]	8	20.2	$\sigma = 1.107 \pm 0.013 \pm 0.423$ pb	$\sigma = 1.1 \pm 0.13 - 0.38$ pb (Sherpa 2.2.1 NLO)	JHEP 05 (2018) 077
W [injet ν]	7	4.6	$\sigma = 0.877 \pm 0.032 \pm 0.301$ pb	$\sigma = 0.933 \pm 0.027$ pb (Blackhat)	JHEP 05 (2018) 077
W [injet ν]	8	20.2	$\sigma = 0.22 \pm 0.006 \pm 0.121$ pb	$\sigma = 0.199 \pm 0.019 \pm 0.11$ pb	JHEP 05 (2018) 077
W [injet ν]	7	4.6	$\sigma = 0.199 \pm 0.019 \pm 0.11$ pb	$\sigma = 0.239 \pm 0.03 - 0.084$ pb (Sherpa 2.2.1 NLO)	JHEP 05 (2018) 077
W [injet ν]	8	20.2	$\sigma = 0.041 \pm 0.003 \pm 0.032$ pb	$\sigma = 0.052 \pm 0.007 - 0.02$ pb (Sherpa 2.2.1 NLO)	JHEP 05 (2018) 077
W [injet ν]	7	4.6	$\sigma = 0.041 \pm 0.0068 \pm 0.031$ pb	$\sigma = 0.052 \pm 0.007 - 0.02$ pb (Sherpa 2.2.1 NLO)	JHEP 05 (2018) 077
$\sigma_{had}(Z \rightarrow ee, \mu\mu)$	13.6	29.0	$\sigma = 744 \pm 0.15 \pm 20$ pb	$\sigma = 733 \pm 43 - 45$ pb (DYTURBO+CT18 (NNLO+NNLL))	PLB 854 (2024) 138725
$\sigma_{had}(Z \rightarrow ee, \mu\mu)$	13	0.3	$\sigma = 780 \pm 3 \pm 7$ pb	$\sigma = 748 \pm 19 - 25$ pb (DYTURBO+CT18 (NNLO+NNLL))	arXiv:2404.06204
$\sigma_{had}(Z \rightarrow ee, \mu\mu)$	8	20.2	$\sigma = 506 \pm 0.2 \pm 11$ pb	$\sigma = 486 \pm 13.6 - 6$ pb (DYNNLO+CT14 NNLO)	JHEP 02 (2017) 117
$\sigma_{had}(Z \rightarrow ee, \mu\mu)$	7	4.6	$\sigma = 451 \pm 0.4 \pm 8.8$ pb	$\sigma = 432 \pm 12.5 - 3.8$ pb (DYNNLO+CT14 NNLO)	JHEP 02 (2017) 117
$\sigma_{had}(Z \rightarrow ee, \mu\mu)$	5	0.3	$\sigma = 333 \pm 1.2 \pm 3.9$ pb	$\sigma = 320 \pm 5.1 - 9.1$ pb (DYTURBO+CT18 (NNLO+NNLL))	arXiv:2404.06204

Standard Model Production Cross Section Measurements

ATLAS Preliminary

$\sqrt{s} = 7, 8, 13, 13.6$ TeV

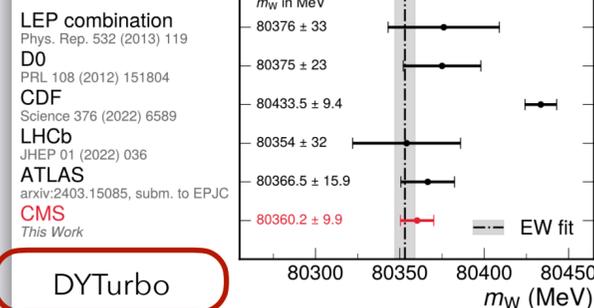
Status: June 2024

Model	E_{CM} [TeV]	$\int \mathcal{L} dt [fb^{-1}]$	Measurement	Theory	Reference
WWW	13	36.1	$\sigma = 130.04 \pm 1.7 \pm 10.6$ pb	$\sigma = 128.4 \pm 3.2 - 2.9$ pb (NNLO)	EPJ C 79 (2019) 884
WWW	8	20.3	$\sigma = 68.2 \pm 1.2 \pm 4.6$ pb	$\sigma = 65 \pm 1.2 - 1.1$ pb (NNLO)	PLB 763 (2016) 114
WWW	7	4.6	$\sigma = 51.9 \pm 2 \pm 4.4$ pb	$\sigma = 49.04 \pm 1.03 - 0.88$ pb (NNLO)	PRD 87 (2013) 112001, PRL 113 (2014) 212001
WZ	13	36.1	$\sigma = 51 \pm 0.8 \pm 2.3$ pb	$\sigma = 49.1 \pm 1.1 - 1$ pb (MATRIX (NNLO))	EPJ C 79 (2019) 535
WZ	8	20.3	$\sigma = 24.3 \pm 0.6 \pm 0.9$ pb	$\sigma = 23.92 \pm 0.4$ pb (MATRIX (NNLO))	PRD 93, 092004 (2016)
WZ	7	4.6	$\sigma = 19 \pm 1.4 - 1.3 \pm 1$ pb	$\sigma = 19.34 \pm 0.3 - 0.4$ pb (MATRIX (NNLO))	EPJ C 72 (2012) 2173
ZZ	13.6	29.0	$\sigma = 16.9 \pm 0.7 \pm 0.7$ pb	$\sigma = 16.7 \pm 0.4$ pb (Matrix (NNLO) & Sherpa (NLO))	PLB 855 (2024) 138764
ZZ	13	36.1	$\sigma = 17.3 \pm 0.6 \pm 0.8$ pb	$\sigma = 16.9 \pm 0.6 - 0.5$ pb (Matrix (NNLO) & Sherpa (NLO))	PRD 97 (2018) 032005
ZZ	8	20.3	$\sigma = 7.3 \pm 0.4 \pm 0.4 - 0.3$ pb	$\sigma = 8.284 \pm 0.249 - 0.191$ pb (NNLO)	JHEP 01 (2017) 099
ZZ	7	4.6	$\sigma = 6.7 \pm 0.7 \pm 0.5 - 0.4$ pb	$\sigma = 6.735 \pm 0.195 - 0.155$ pb (NNLO)	JHEP 03 (2013) 128, PLB 735 (2014) 311
$\sigma_{had}(\gamma\gamma) [\Delta R_{\gamma\gamma} > 0.4]$	13	139	$\sigma = 31.4 \pm 0.1 \pm 2.4$ pb	$\sigma = 29.7 \pm 2.4 - 2.2$ pb (MadGraph5+amcNLO)	JHEP 11 (2021) 169
$\sigma_{had}(\gamma\gamma) [\Delta R_{\gamma\gamma} > 0.4]$	8	20.2	$\sigma = 16.82 \pm 0.07 \pm 0.75 - 0.78$ pb	$\sigma = 14.2 \pm 1.25 - 2.2$ pb (MadGraph5+amcNLO)	PRD 95 (2017) 112005
$\sigma_{had}(W^+W^-) [\Delta R_{\gamma\gamma} > 0.4]$	13	140	$\sigma = 3.6 \pm 0.5 \pm 0.5$ fb	$\sigma = 3.5 \pm 0.2$ fb (MadGraph5+amcNLO)	PLB 846 (2023) 138222
$\sigma_{had}(W^+W^-) [\Delta R_{\gamma\gamma} > 0.4]$	8	20.3	$\sigma = 1.1 \pm 0.5 \pm 0.4$ fb	$\sigma = 0.94 \pm 0.09$ fb (VBFNNLO+Pythia8+Surv. Fact (0.82))	JHEP 07 (2017) 107
$\sigma_{had}(W^+W^-) [\Delta R_{\gamma\gamma} > 0.4]$	13	139	$\sigma = 3.13 \pm 0.31 \pm 0.28$ fb	$\sigma = 3.5 \pm 1$ fb (MG+amcNLO+Pythia8+Surv. Fact (0.82))	PLB 816 (2021) 136190
$\sigma_{had}(W^+W^-) [\Delta R_{\gamma\gamma} > 0.4]$	8	20.2	$\sigma = 6.9 \pm 2.2 \pm 1.4$ fb	$\sigma = 4.4 \pm 0.3$ fb (HERWIG++)	PRD 94 (2016) 032011
$\sigma_{had}(W^+W^-) [\Delta R_{\gamma\gamma} > 0.4]$	13	140	$\sigma = 2.7 \pm 0.34 - 0.32 \pm 0.39 - 0.36$ fb	$\sigma = 2.2 \pm 0.14 - 0.13$ fb (PowhegBox)	arXiv:2403.04869
$\sigma_{had}(W^+W^-) [\Delta R_{\gamma\gamma} > 0.4]$	13	139	$\sigma = 2.92 \pm 0.22 \pm 0.19$ fb	$\sigma = 2.53 \pm 0.22 - 0.19$ fb (MadGraph5+amcNLO)	JHEP 04 (2024) 026
$\sigma_{had}(W^+W^-) [\Delta R_{\gamma\gamma} > 0.4]$	8	20.3	$\sigma = 1.5 \pm 0.5 \pm 0.2$ fb	$\sigma = 0.95 \pm 0.06$ fb (PowhegBox)	PRD 96, 012007 (2017)
$\sigma_{had}(W^+W^-) [\Delta R_{\gamma\gamma} > 0.4]$	13	139	$\sigma = 0.82 \pm 0.18 \pm 0.11$ fb	$\sigma = 0.61 \pm 0.03$ fb (Sherpa 2.2.2)	Nature Phys. 19 (2023) 237
$\sigma_{had}(W^+W^-) [\Delta R_{\gamma\gamma} > 0.4]$	13	140	$\sigma = 0.368 \pm 0.037 \pm 0.059$ fb	$\sigma = 0.37 \pm 0.03$ fb (MadGraph+Pythia8)	arXiv:2403.15296
$\sigma_{had}(W^+W^-) [\Delta R_{\gamma\gamma} > 0.4]$	8	20.3	$\sigma = 0.29 \pm 0.14 - 0.12 \pm 0.09 - 0.1$ fb	$\sigma = 0.13 \pm 0.01$ fb (VBFNLO)	PRD 93 (2016) 092004

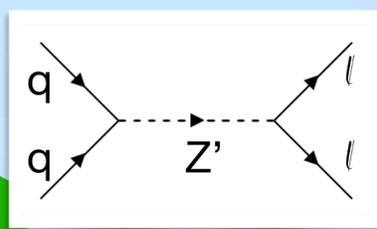
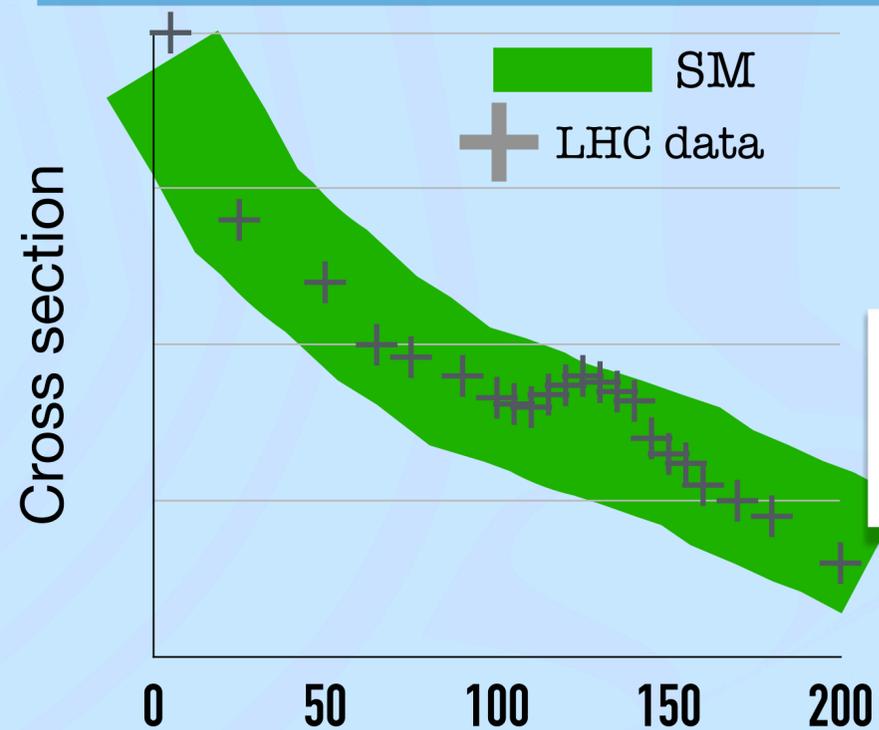
NLO QCD + EW at best

DYTurbo

CMS Preliminary

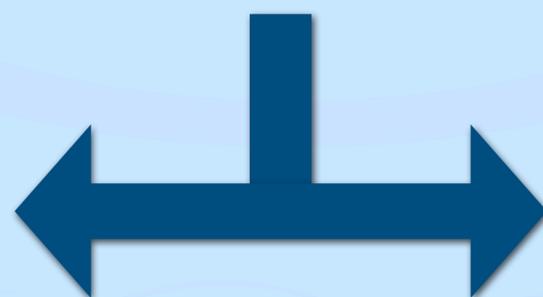


Motivation

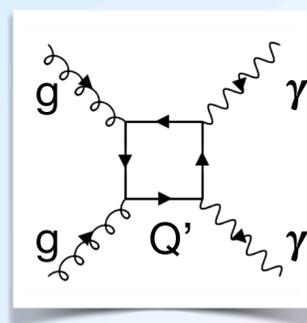
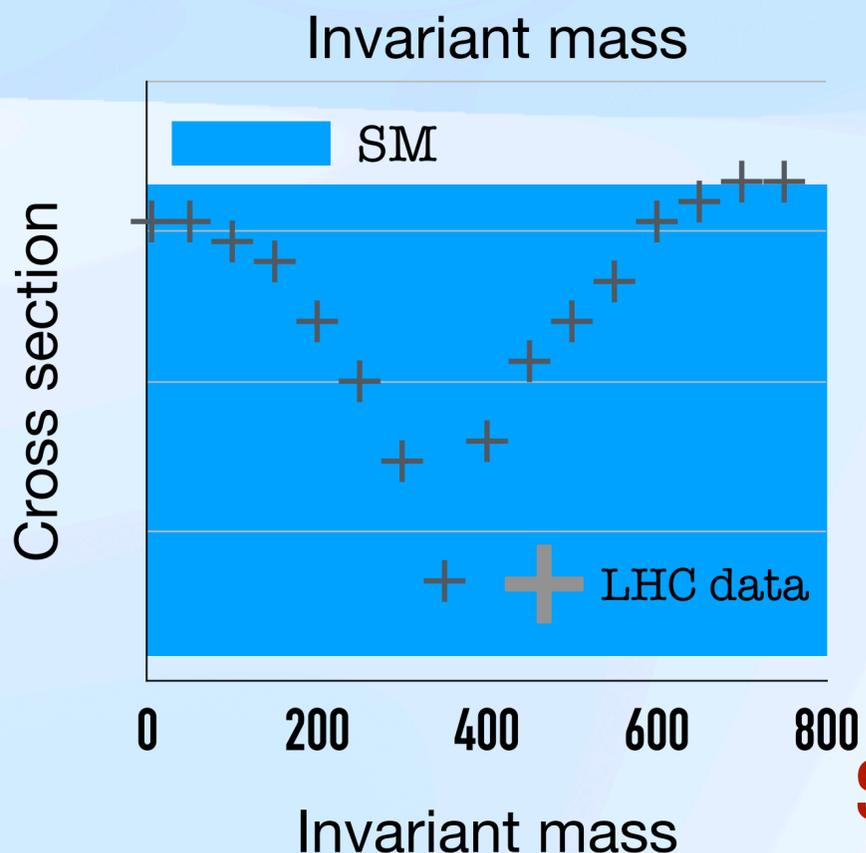
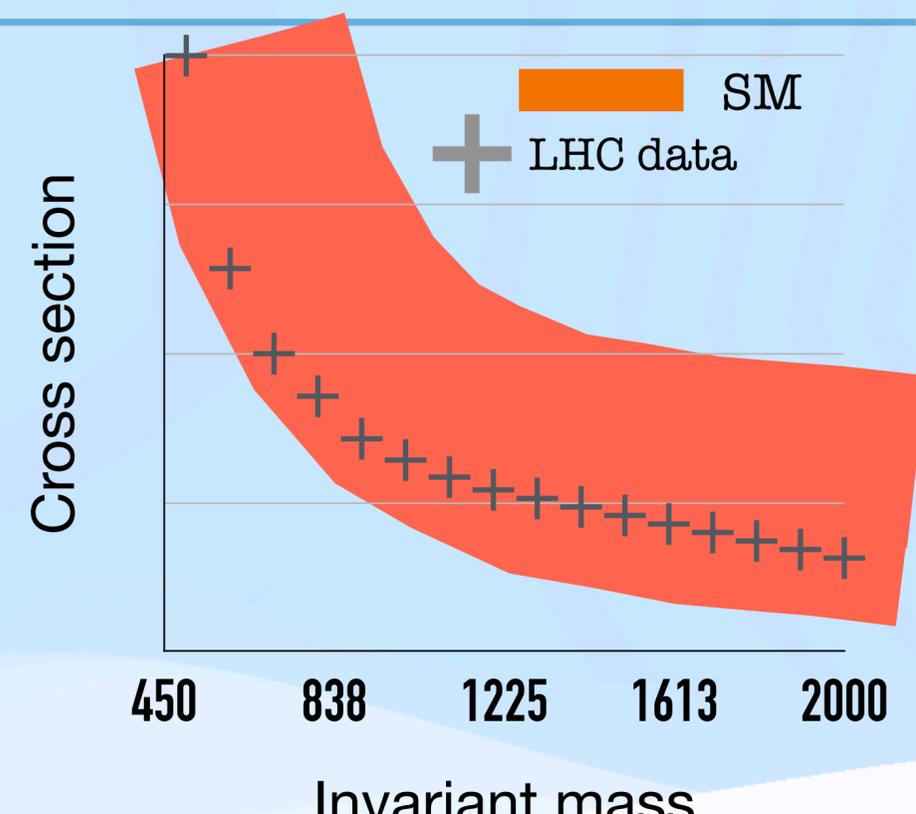


We are looking for new discoveries
Essentially, two possible scenarios

New resonances

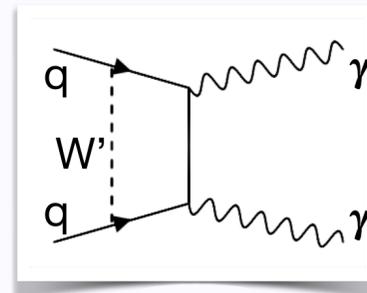


New interactions

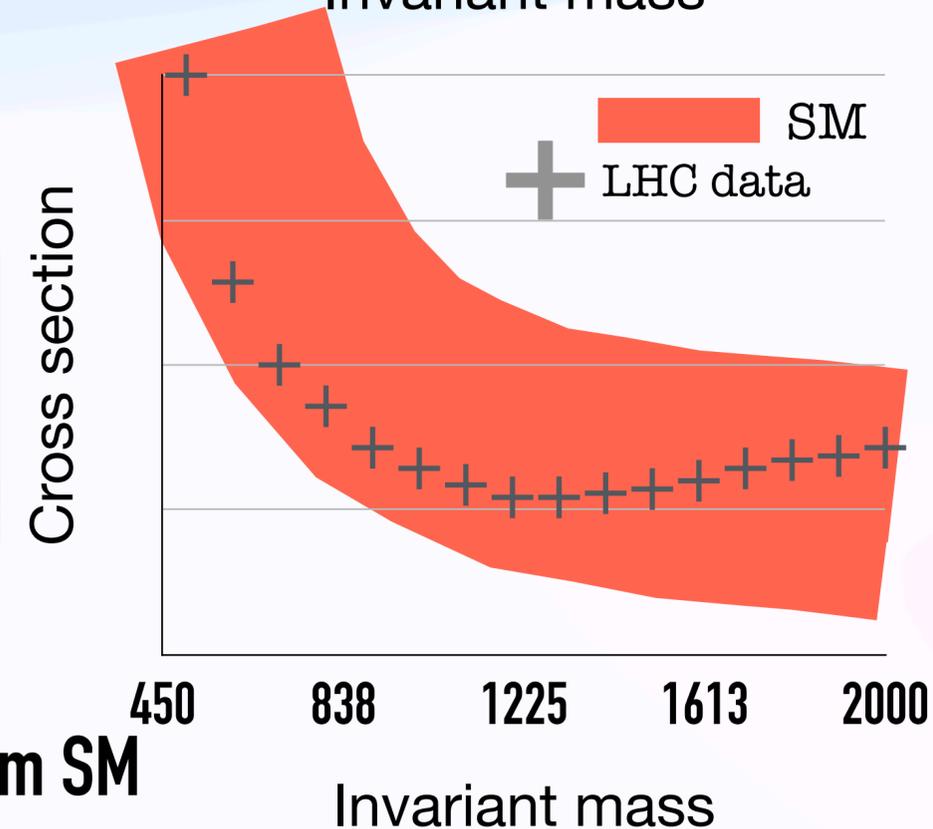


Small deviations from SM

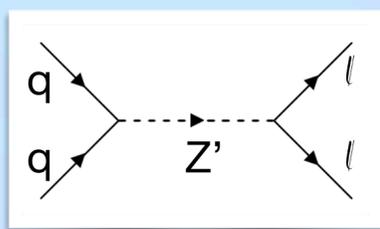
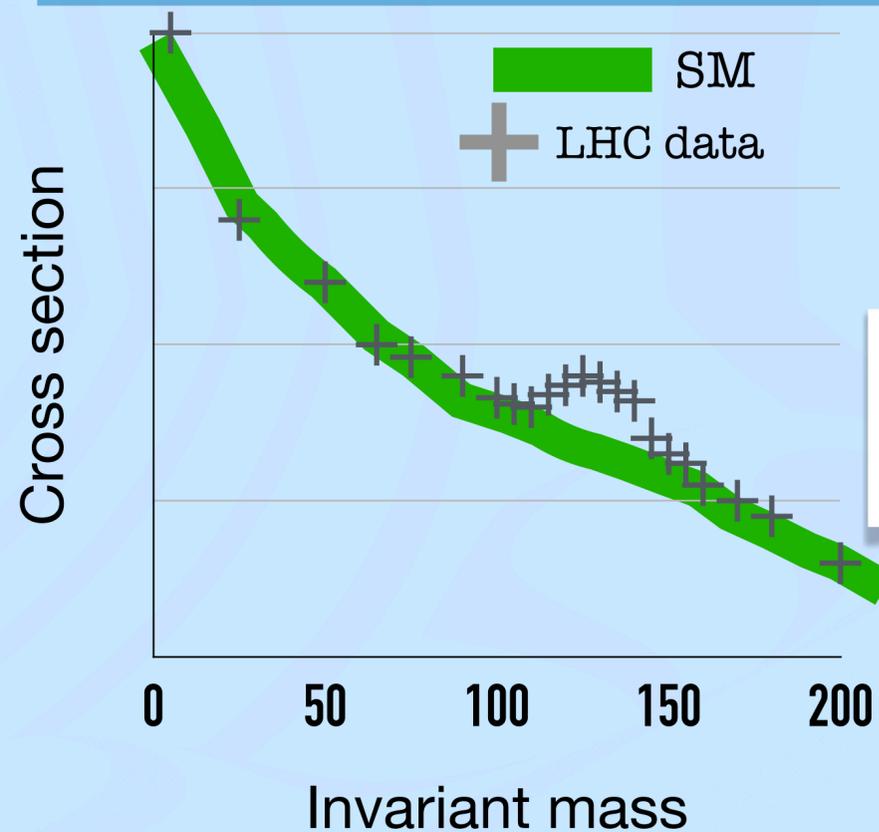
In both scenarios precision is a key ingredient



Small deviations from SM

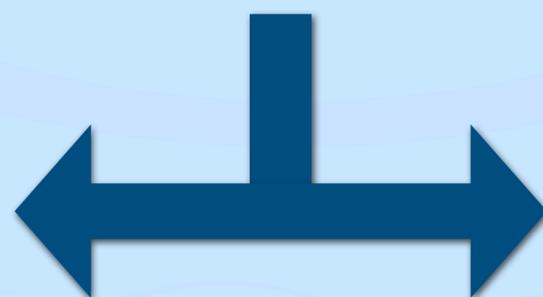


Motivation

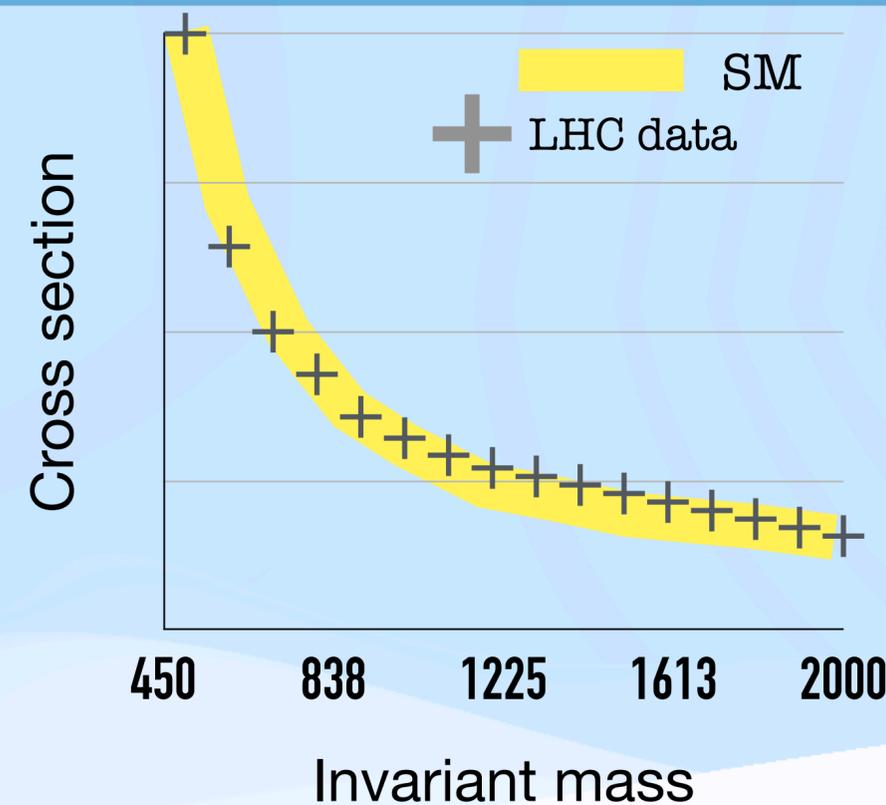


We are looking for new discoveries
Essentially, two possible scenarios

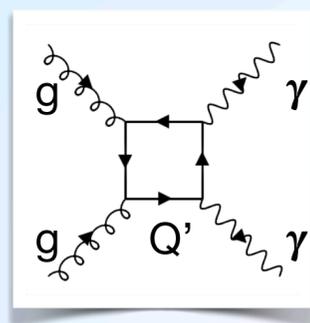
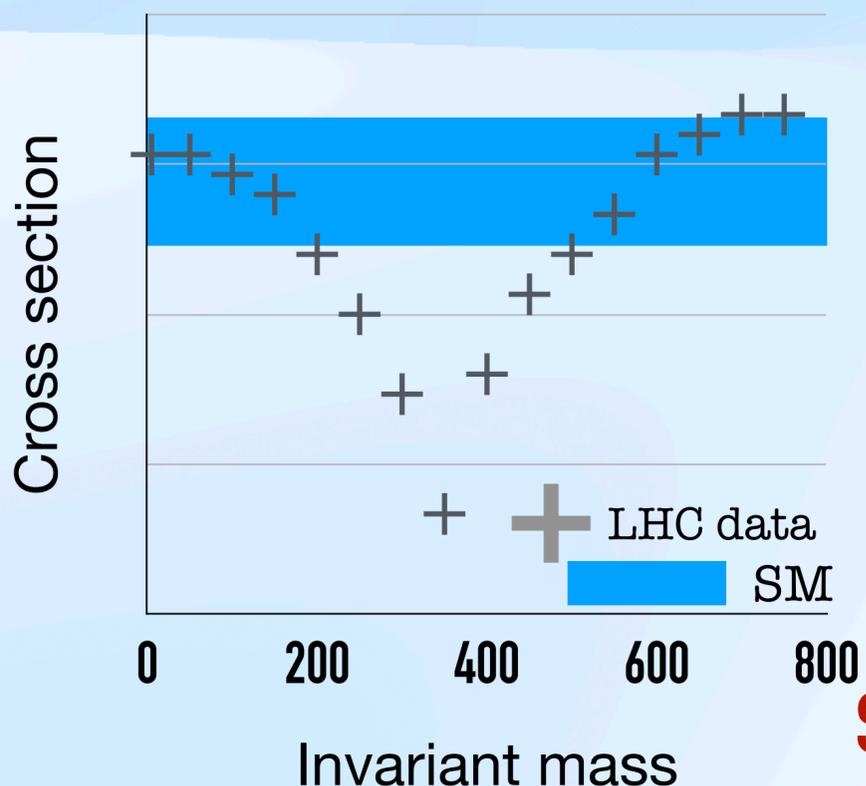
New resonances



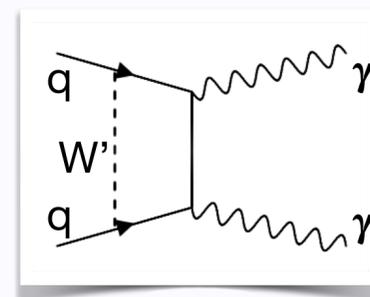
New interactions



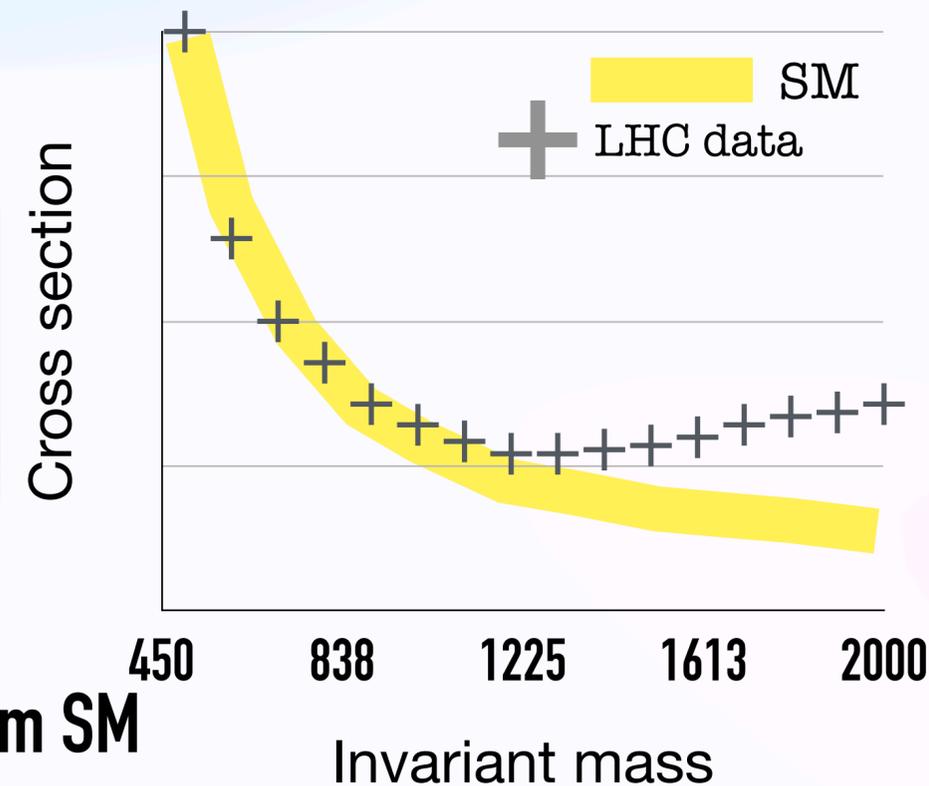
In both scenarios **precision** is a key ingredient



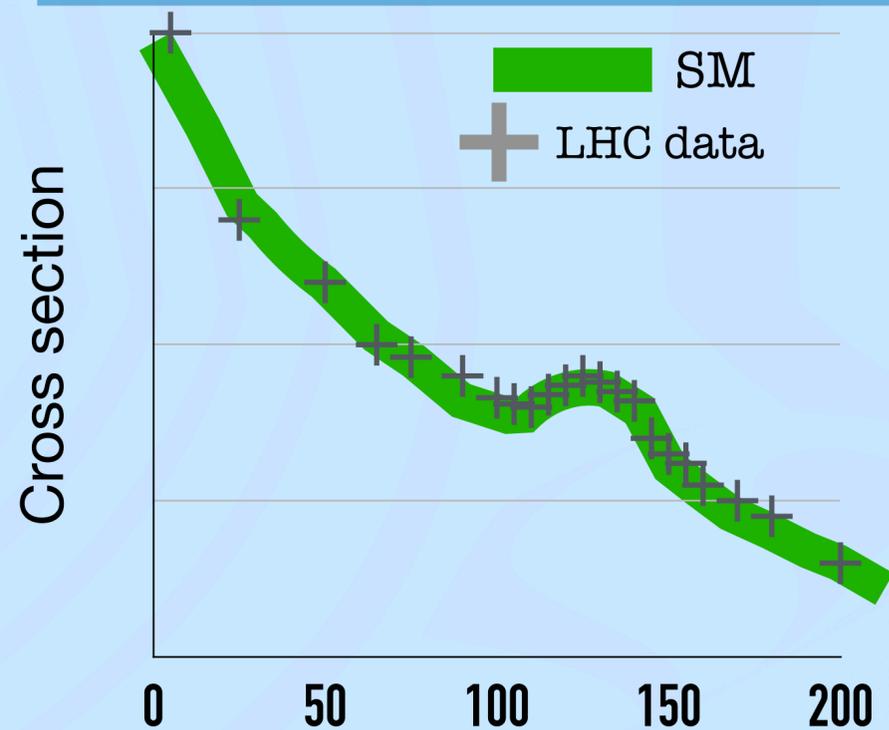
Small deviations from SM



Small deviations from SM

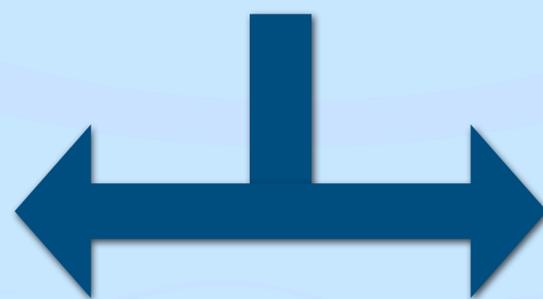


Motivation

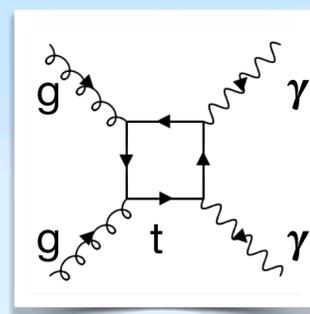
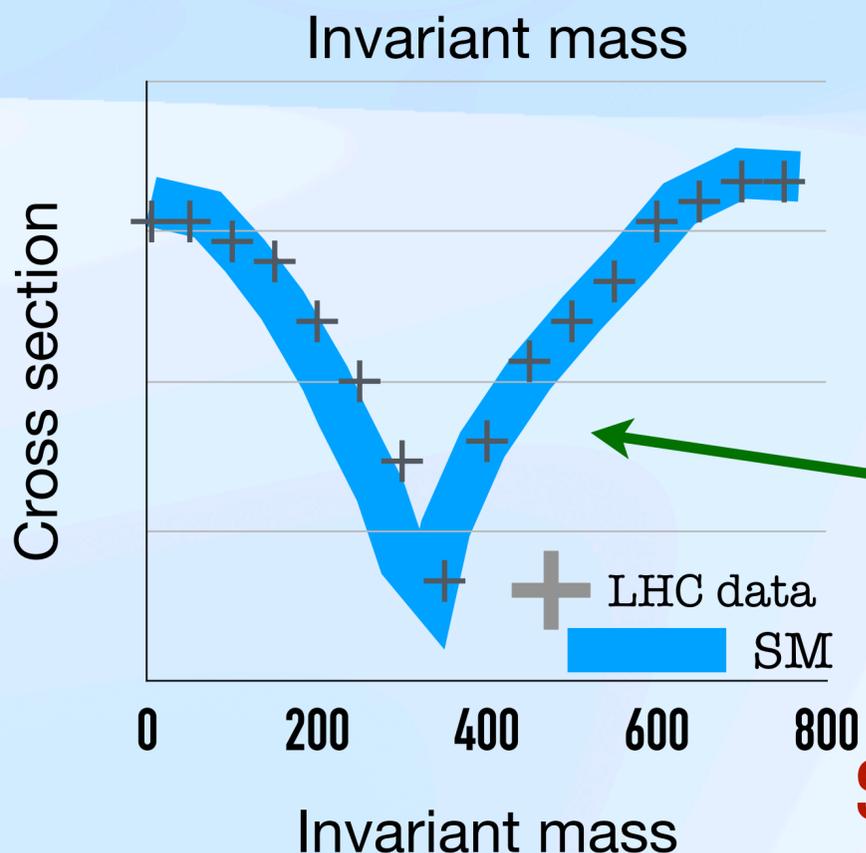
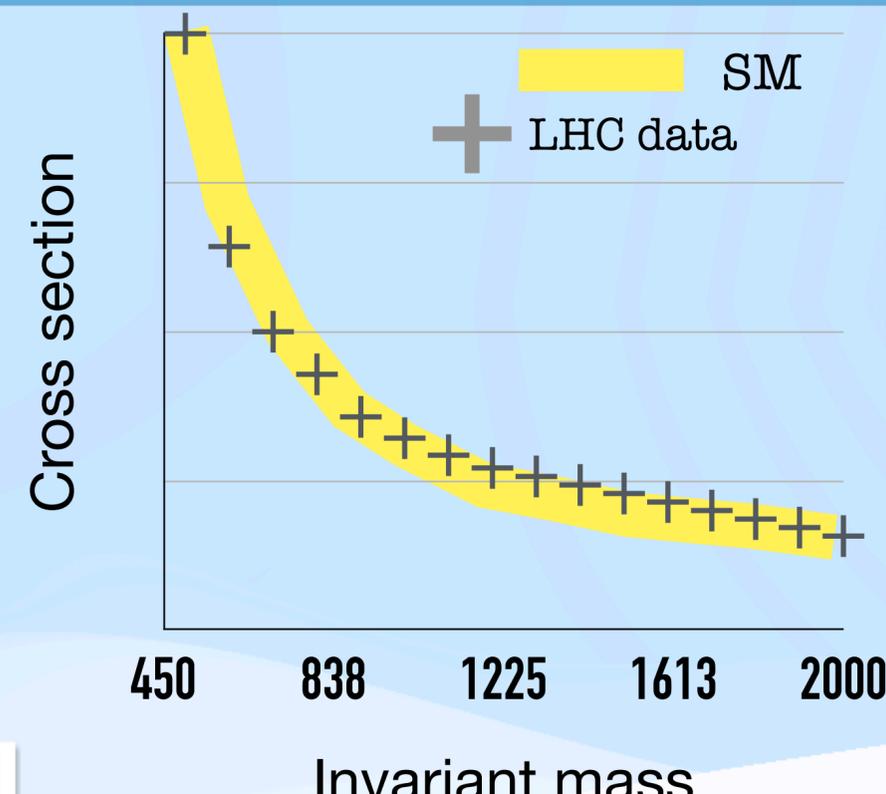


We are looking for new discoveries
Essentially, two possible scenarios

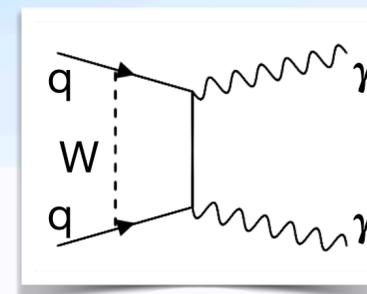
New resonances



New interactions

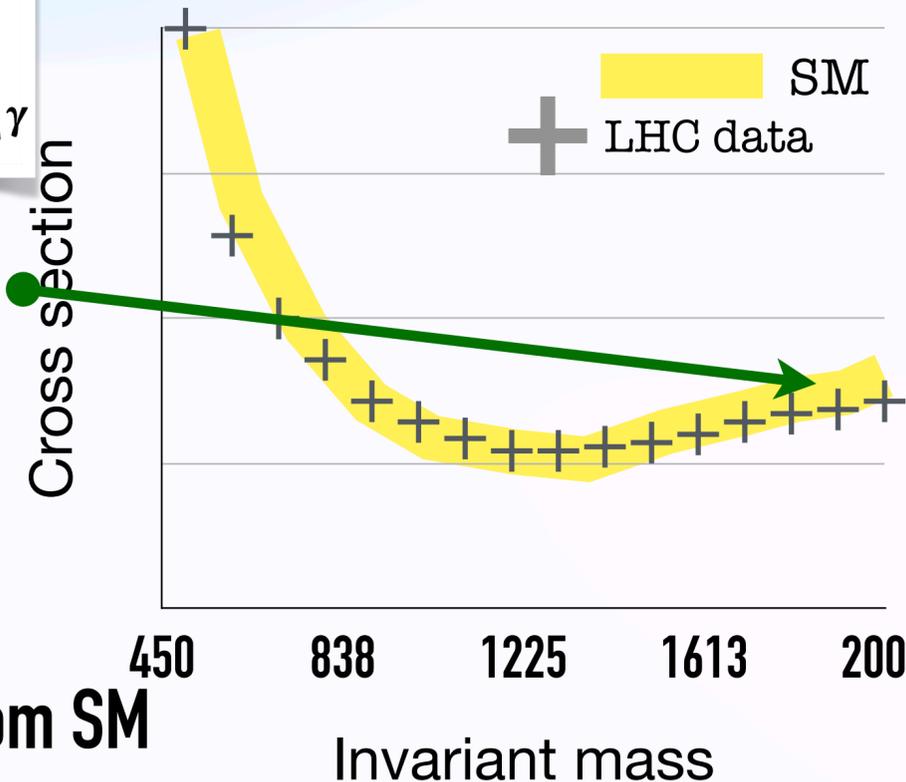


In both scenarios **precision** is a key ingredient



It is very likely that BSM will compete with EW effects

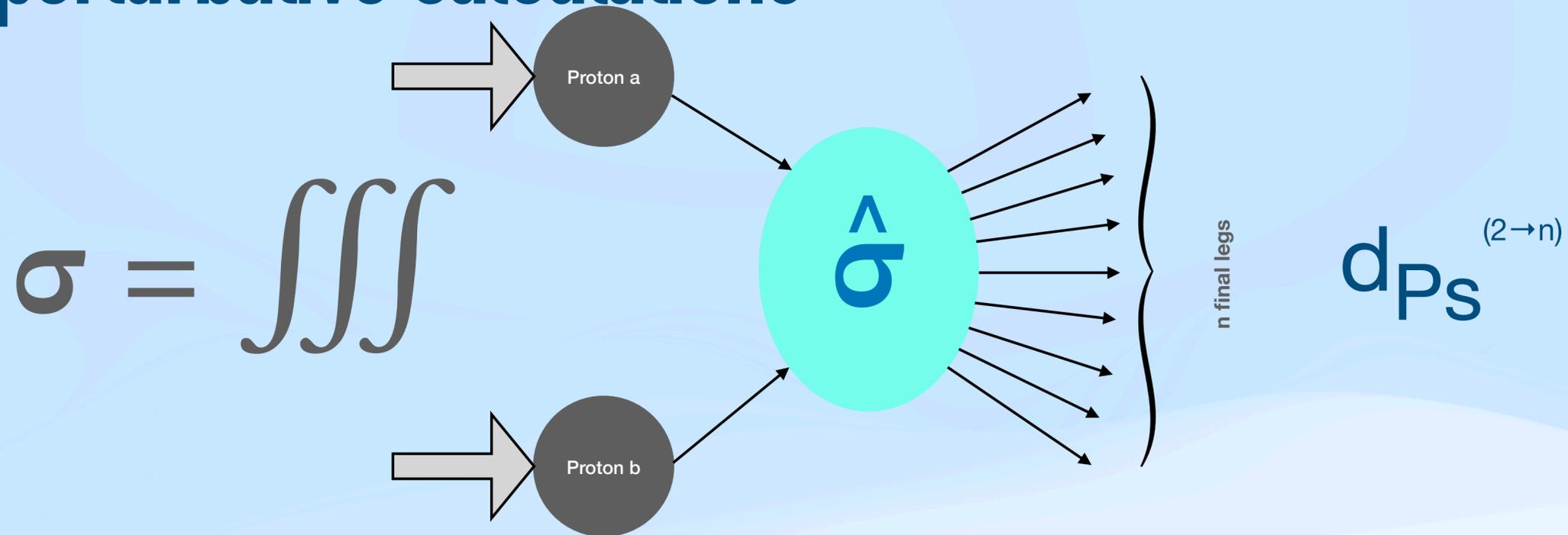
It is very likely that BSM will compete with SM threshold effects



Small deviations from SM

Small deviations from SM

Anatomy of perturbative calculations



$\hat{\sigma}$ stands for the total or differential cross section

Factorization theorem

$$\sigma = \int d_{Ps}^{(2 \rightarrow n)} \sum_{ab} \int dx_a \int dx_b f_a(x_a, \mu_F^2) f_b(x_b, \mu_F^2) \hat{\sigma}(x_a, x_b, \alpha_s(\mu_R^2), \alpha, M^2)$$

Perturbative expansion

$$\alpha_s \ll 1 ; \alpha \ll 1$$

$$\hat{\sigma} = \sigma^{(\hat{0})} + \underbrace{\alpha_s^1 \sigma^{(\hat{1})} + \alpha_s^2 \sigma^{(\hat{2})} + \dots}_{\text{QCD Plays a crucial role at the LHC}} + \alpha^1 \sigma^{(\hat{0};1)} + \alpha^2 \sigma^{(\hat{0};2)} + \dots + \alpha_s^1 \alpha^1 \sigma^{(\hat{1};1)} + \dots$$

LO
NLO
NNLO

NNLO: standard of theoretical frontier at the LHC

N3LO: represents a new quantum world that has only recently begun to be explored

NLO perturbative QCD TH predictions — Full automated calculations

2 → 6 (W+5jets) Bern, Dixon, Febres Cordero, Höche, Ita, Kosower, Maître, Ozeren [2013]

2 → 5 (W+4jets) Berger, Bern, Dixon, Febres Cordero, Forde, et al [2011]

(Z+4jets) Ita, Bern, Dixon, Febres Cordero, Kosower, et al [2012]

($\gamma\gamma$ +3jets) Badger, Guffanti, Yundin [2012]

2 → 4 (WW+2jets) Greiner, Heinrich, Mastrolia, Ossola, Reiter, Tramontano [2012]

(WZ+2jets) Campanario, Kerner, Ninh, Zeppenfeld [2013]

(4jets) Bern, Diana, Dixon, Febres Cordero, Hoeche, et al [2011]

Badger, Biedermann, Uwer, Yundin [2012]

(W $\gamma\gamma$ +jet) Campanario, Englert, Rauch, Zeppenfeld [2013]

The list is not exhaustive ...

Frontier: Very large multiplicities or correction to loop induced processes

5j available for LEP

Ivan's talk



HELAC-NLO, Rocket, BlackHat+SHERPA, GoSam+SHERPA/MADGRAPH, NJet+SHERPA, Madgraph5-aMC@NLO, RECOLA, OpenLoops+SHERPA, VBFNLO...

These codes offer add to the calculation: PS, EW corrections, fully automated scale variations, etc

Besides the limitations at the frontier, the automated structure fully understood

Theoretical calculations – State of the art – The standard of precision at the LHC

NNLO QCD HADRON-COLLIDER CALCULATIONS VS. TIME

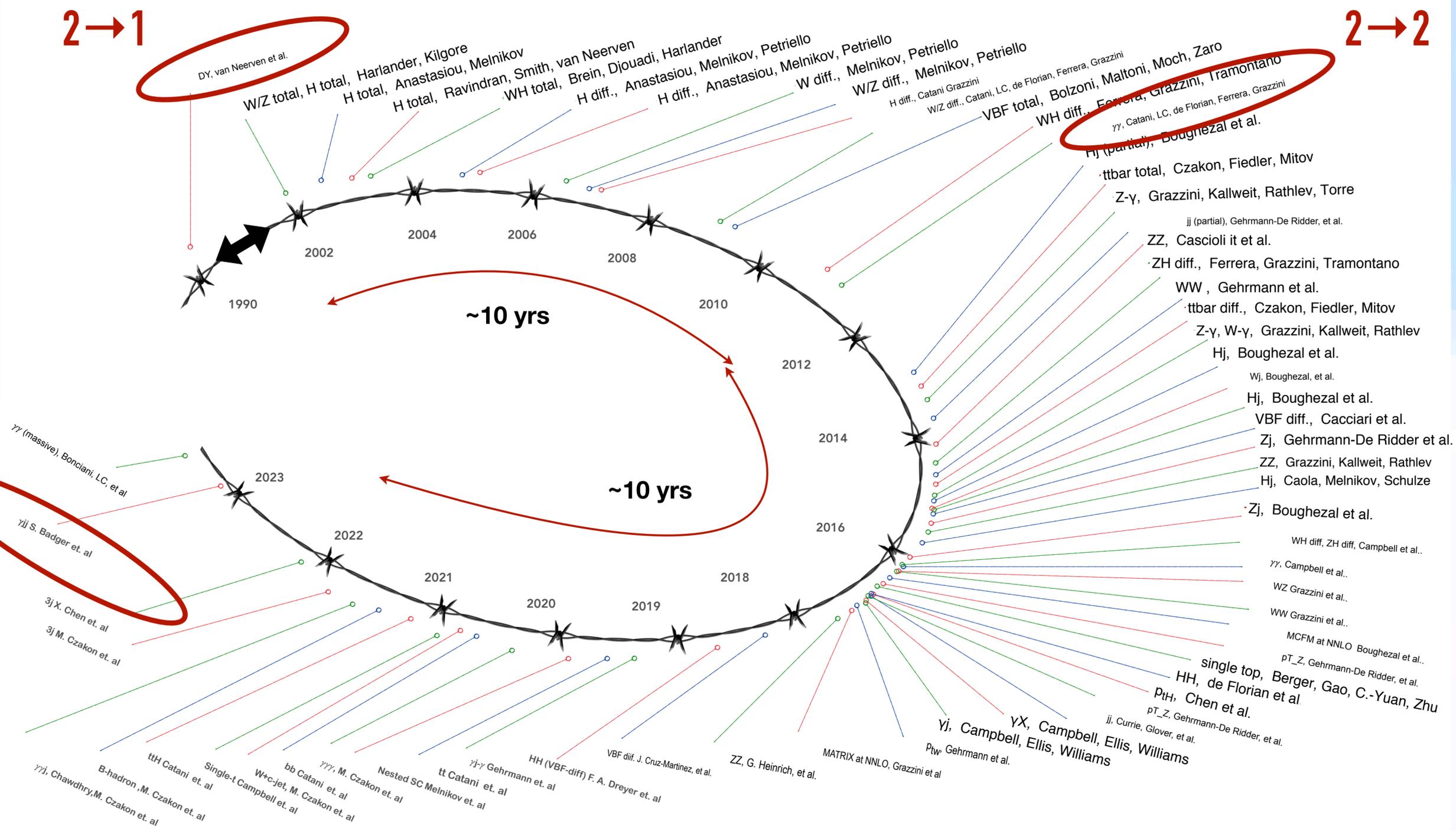
2 → 1

2 → 2

10yrs per leg
rule as in the
NLO case!

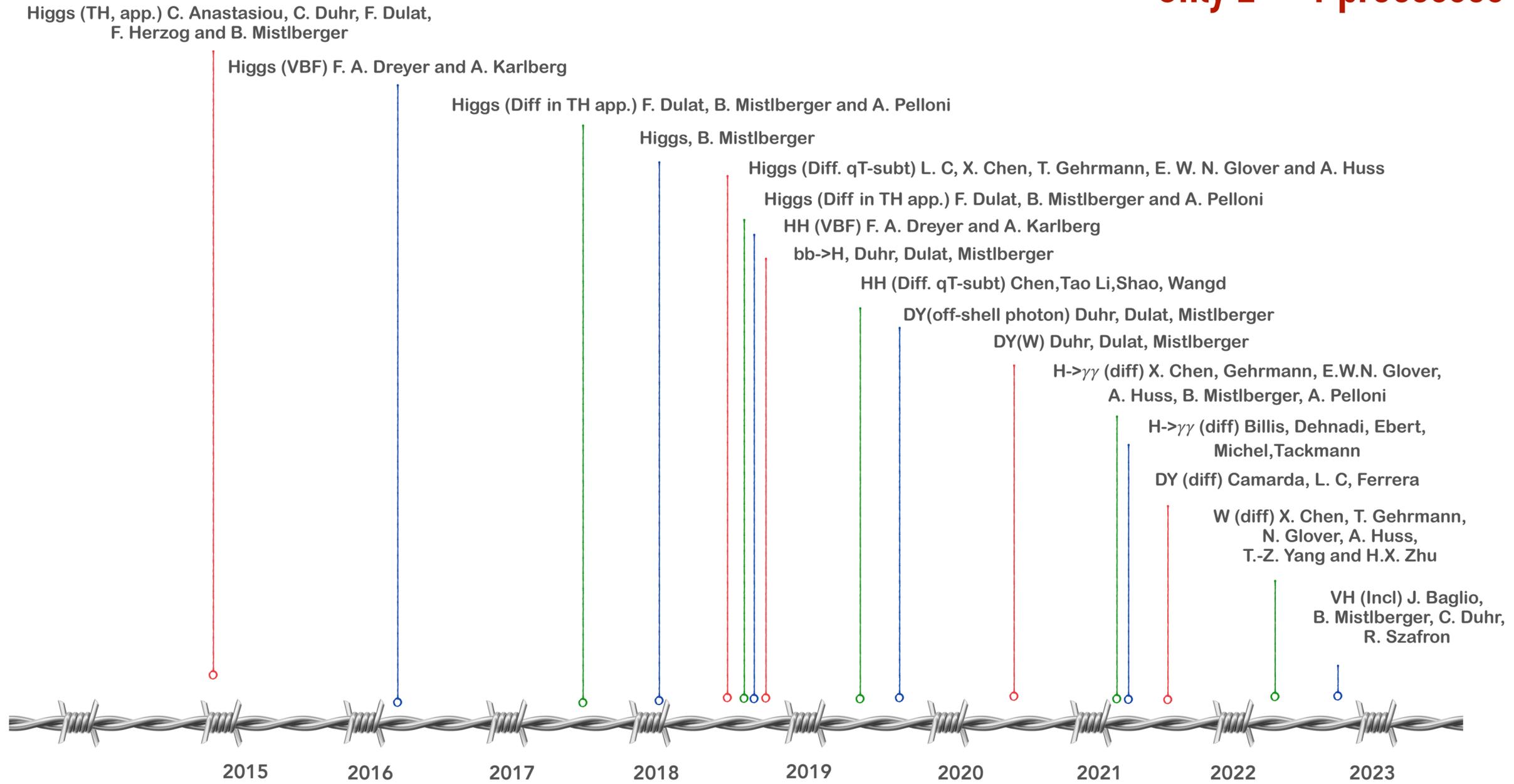
2 → 3

Without any
approximation
in the two-loop
part



N3LO QCD HADRON-COLLIDER CALCULATIONS VS. TIME

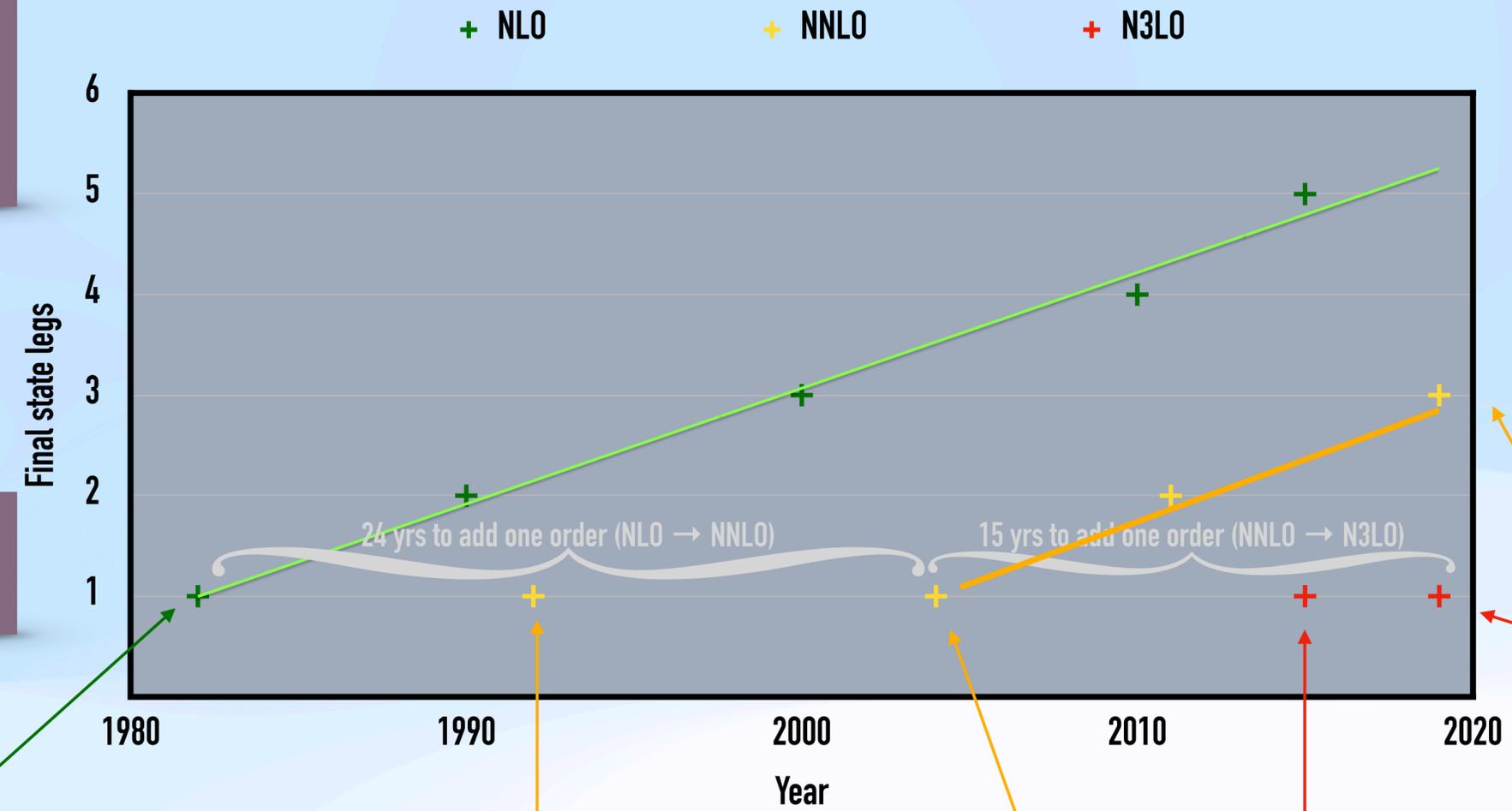
Only 2 → 1 processes



Why we are not breaking the 2 → 2 frontier? We are close to 10yrs per leg also here?

The multifaceted nature of collider perturbative calculations

Renders them exceptionally intricate and complex



Cost of add one extra leg in years

Slope ~ 1leg/10 yr ??

Differential X-sec
(required by LHC analyses)

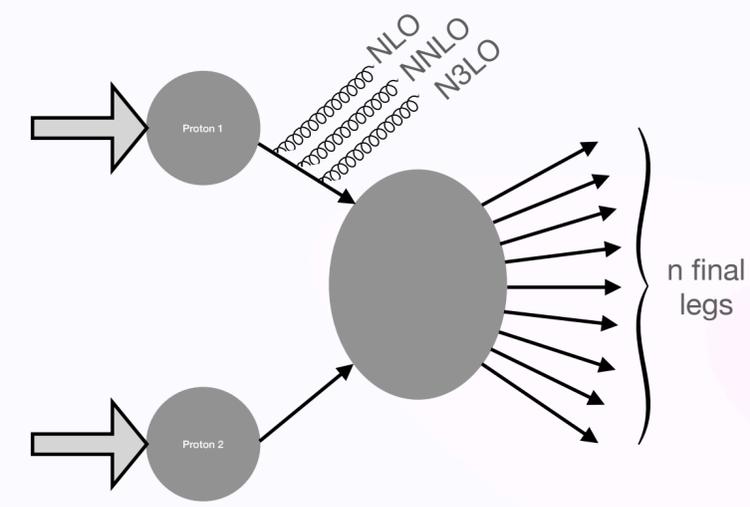
Slope ~ 1 leg/10 yr

Cost of add one extra leg measured in years

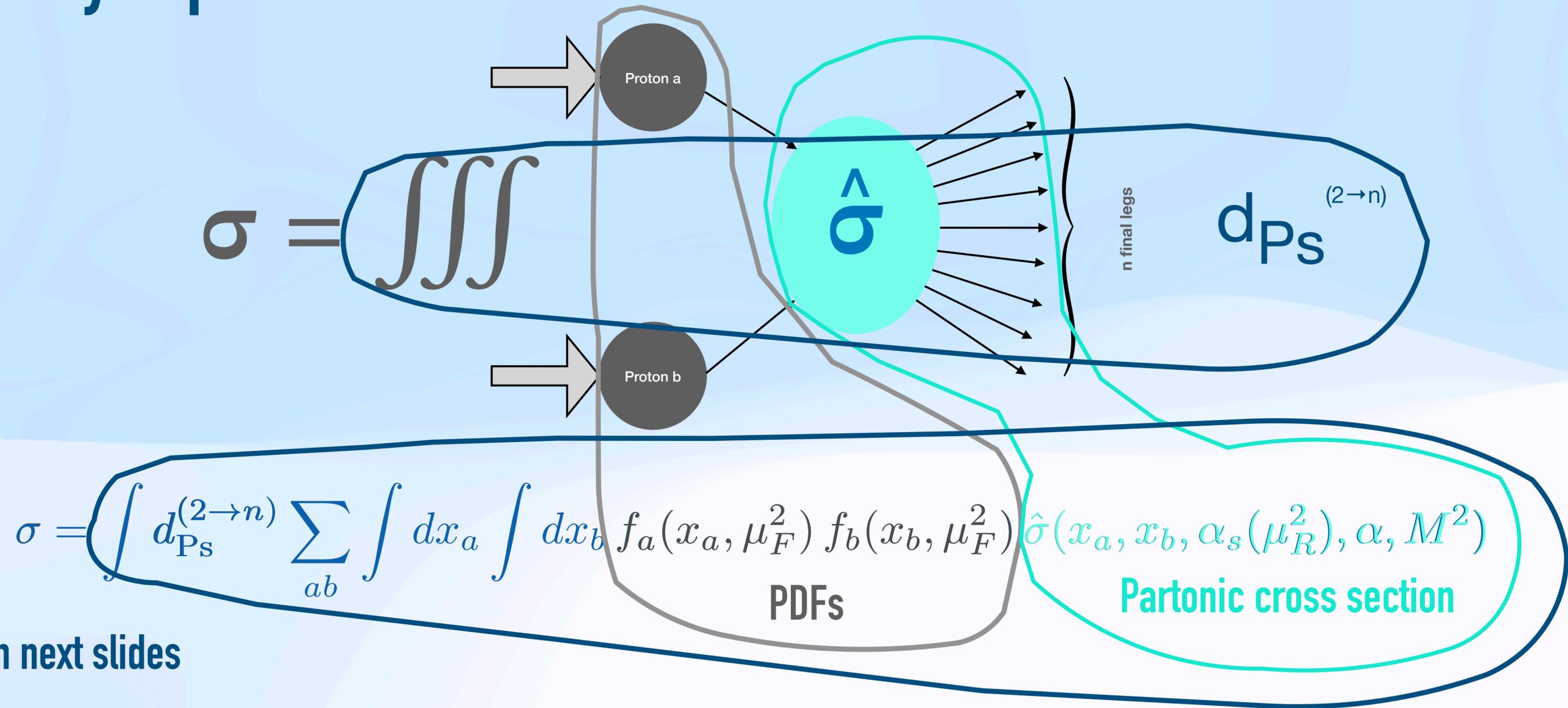
Total cross section (X-sec)
(a number)

Tot. X-sec
(a number)

Differential cross sections
(required by LHC analyses)



Anatomy of perturbative calculations



Organisation next slides

PDFs

Partonic cross section (scattering amplitudes)

Subtraction prescriptions and CPU cost

Subtraction prescriptions and CPU cost

State of the art PDFs (NNLO)

For sure there will be a lot of improvements in the next years regarding PDF uncertainties and accord between different groups

- CT18** LHC measurements in single-inclusive jet production with the full rapidity coverage, as well as production of Drell-Yan pairs, top-quark pairs, and high-pT Z bosons, are included to achieve the greatest sensitivity to the PDFs
- MSHT20** Determination controlled by LHC data: LHC 7 and 8 TeV data sets on vector boson production, inclusive jets and top quark distributions
Reduced uncertainties in predictions for processes such as Higgs, top quark pair and W, Z production at post LHC Run-II energies
- NNPDF4.0** Determination controlled by LHC data: unlike in the past, almost DIS-only
- ABMP16** The theory predictions include new improved approximations at NNLO for the production of heavy quarks in DIS and for the hadro-production of single-top quarks.
- ATLASpdf21** ATLAS sets of $W, Z\gamma^*$ data, tt^- data and $V+$ jets data considered in a single QCD fit (also other sets)
- PDF4LHC21** It is based on the Monte Carlo combination of the CT18, MSHT20, and NNPDF3.1 sets followed by either its Hessian reduction or its replica compression

In the extraction of many fundamental parameters, PDF uncertainties dominate

EUROPEAN ORGANISATION FOR NUCLEAR RESEARCH (CERN)



Submitted to: Nature Phys.



CERN-EP-2023-200
22nd September 2023

A precise determination of the strong-coupling constant from the recoil of Z bosons with the ATLAS experiment at $\sqrt{s} = 8$ TeV

The ATLAS Collaboration

Summary of the uncertainties in the determination of $\alpha_s(m_Z)$, in units of 10^{-3}

Experimental uncertainty	± 0.44	
PDF uncertainty	± 0.51	
Scale variation uncertainties	± 0.42	
Matching to fixed order	0	-0.08
Non-perturbative model	+0.12	-0.20
Flavour model	+0.40	-0.29
QED ISR	± 0.14	
N ⁴ LL approximation	± 0.04	
Total	+0.91	-0.88

State of the art PDFs (aN3LO)

NEW PDFs at approximate N3LO

MSHT20sN3LO McGowan, Cridge, Harland-Lang, Thorne [2022]
Cridge, Harland-Lang, Thorne [2023]

- Approximated splitting functions, transition matrix elements, coefficient functions and K-factors for multiple processes to N3LO → 20 nuisance parameters
- Improvement in data description from NNLO to N3LO
- aN3LO $\alpha_s(m_Z)$ value stated is in agreement with the MSHT20 NNLO result and the world average within uncertainties
- PDFs include an estimation for missing N3LO contributions (the leading theoretical uncertainty) and implicitly some MHOU beyond this within their PDF uncertainties. Due to this factorisation scale variations are no longer necessary in calculations involving aN3LO PDFs

In the extraction of many fundamental parameters, PDF uncertainties dominate

Summary of the uncertainties in the determination of $\alpha_s(m_Z)$, in units of 10^{-3}

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Total	+0.91 -0.88

EUROPEAN ORGANISATION FOR NUCLEAR RESEARCH (CERN)

ATLAS EXPERIMENT

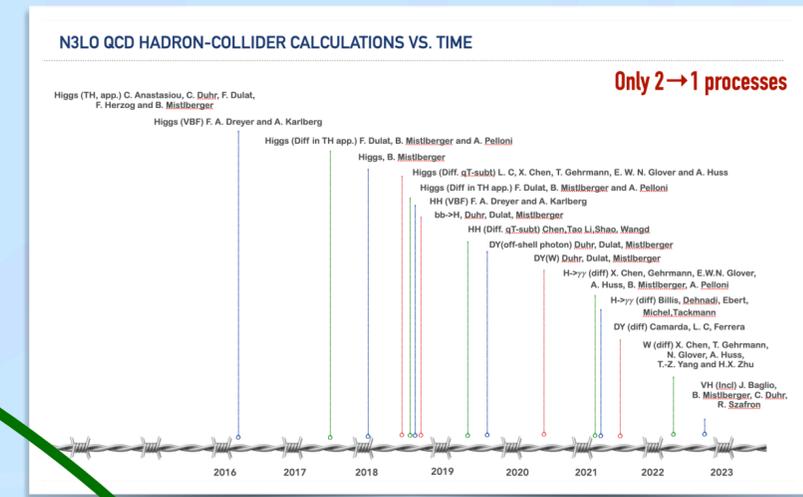
Submitted to: Nature Phys.

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The ATLAS Collaboration

We used NNLO PDFs in almost all our N3LO calculations!



NEW splitting functions at N3LO (P_{qg})

NEW splitting functions at N3LO (P_{qg})

Falcioni, Herzog, Moch, Vogt [2023]

NEW splitting functions at N3LO (P_{qg})

Falcioni, Herzog, Moch, Pelloni, Vogt [2024]

For sure there will be a lot of improvements in the next years reaching N3LO precision and controlling better the TH uncertainties (also including more data)

Theoretical calculations Scattering amplitudes – the frontier at NNLO and beyond

NEW All Two-Loop Feynman Integrals for Five-Point One-Mass Scattering

Abreu, Chicherin, Ita, Page, Sotnikov, Tschernow, Zoia [2023]

Relevant for H/Z/W production in association with two jets at NNLO, or in association with one jet at **N3LO** or H/Z/W at **N4LO**

Agarwal, Buccioni, von Manteuffel, Tancredi [2021]

Two-Loop Helicity Amplitudes for Diphoton Plus Jet Production in Full Color

Relevant for $\gamma\gamma$ production in association with one jet at NNLO, or $\gamma\gamma$ production at **N3LO**

NEW Planar three-loop QCD helicity amplitudes for V +jet production at hadron colliders

Gehrmann, Jakubcik, Mella, Syrrakos, Tancredi [2023]

Relevant for Z/W/ γ^* production in association with one jet at **N3LO** or Z/W/ γ^* at **N4LO**

Bargiela, Caola, von Manteuffel, Tancredi [2021]

Three-loop helicity amplitudes for diphoton production in gluon fusion

Relevant for $\gamma\gamma$ production at **N3LO**

Lee, von Manteuffel, Schabinger, Smirnov, Smirnov, Steinhauser [2022]

Quark and Gluon Form Factors in Four-Loop QCD

Relevant for H/Z/W/ γ^* at **N4LO**

Bargiela, Caola, Chawdhry, Liua [2023]

NEW Two-loop mixed QCD-electroweak amplitudes for Z+jet production at the LHC: bosonic corrections

Relevant for Z+j at **NNLO Mixed** or Z/W **N3LO Mixed**

Badger, Becchetti, Giraud, Zoia [2024]

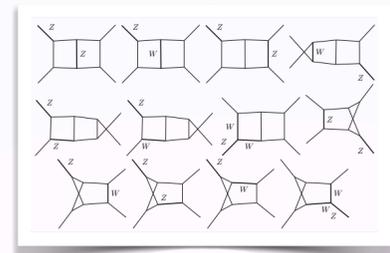
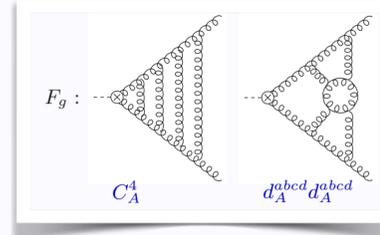
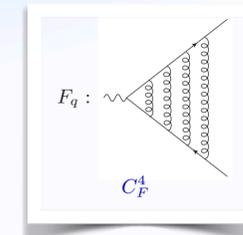
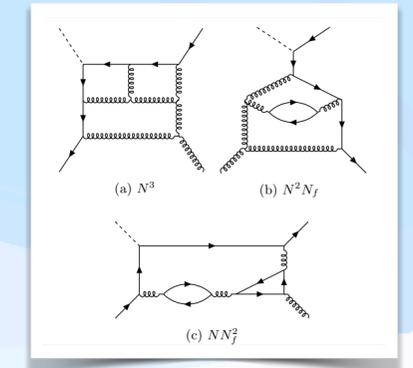
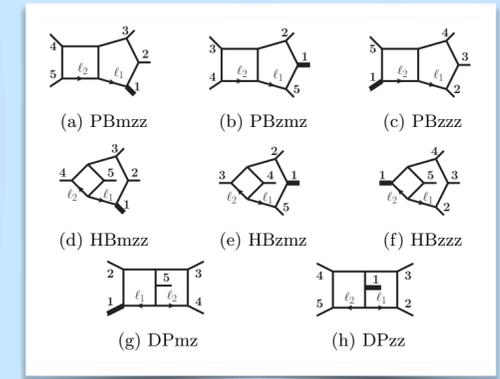
NEW Two-loop integrals for tt+jet production at hadron colliders in the leading colour approximation

Relevant for tt+j at **NNLO** or tt at **N3LO**

Badger, Hartanto, Wu, Zhang, Zoia [2024]

NEW Two-loop amplitudes for $W\gamma\gamma$ production at hadron colliders at NNLO

Relevant for $W\gamma\gamma$ at **NNLO**



Theoretical calculations Scattering amplitudes – the frontier at NNLO and beyond

NEW All Two-Loop Feynman Integrals for Five-Point One-Mass Scattering

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Quark and Gluon Form Factors in Four-Loop QCD

Relevant for H/Z/W/ γ^* at **N4LO**

Bargiela, Caola, Chawdhry, Liua [2023]

NEW Two-loop mixed QCD-electroweak amplitudes for Z+jet production at the LHC: bosonic corrections

Relevant for Z+jet at NNLO Mixed or Z/W+jet at N3LO Mixed

NEW Why did we not break the 2->1 barrier at N3LO?

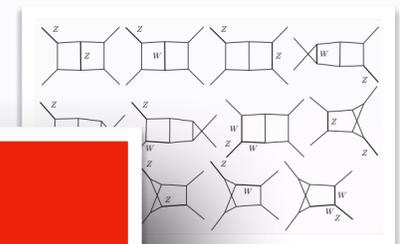
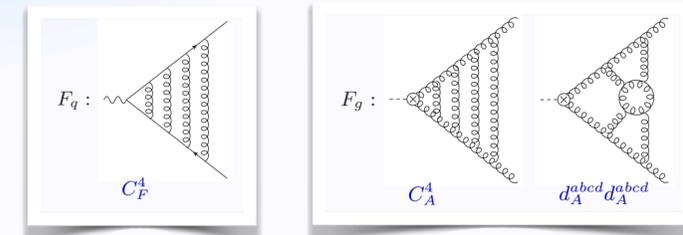
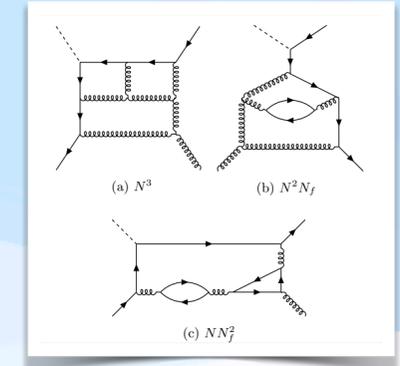
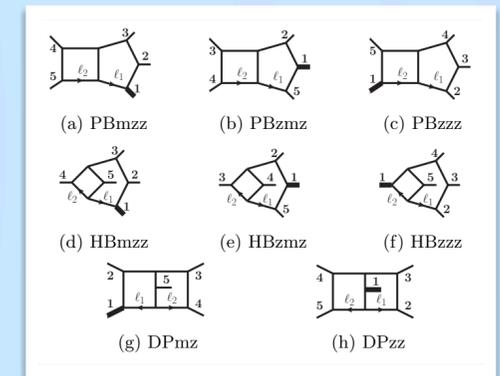
Two-loop integrals for tt+jet production at hadron colliders in the leading colour approximation

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Badger, Hartanto, Wu, Zhang, Zoia [2024]

NEW Two-loop amplitudes for $W\gamma\gamma$ production at hadron colliders at NNLO

Relevant for $W\gamma\gamma$ at NNLO

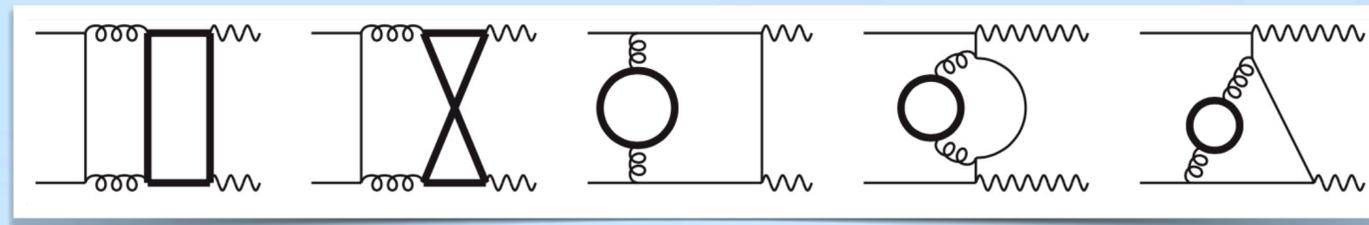


Scattering amplitudes – the frontier at NNLO full massive

NEW Becchetti, Bonciani, LC, Coro, Ripani [2023]
Two-loop form factors for diphoton production in quark annihilation channel with heavy quark mass dependence

Relevant for $\gamma\gamma$ production at NNLO with top and bottom quark mass dependence

2→2



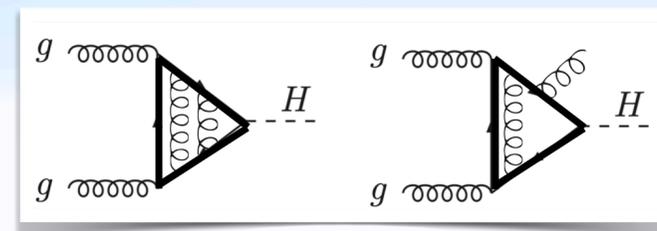
Czakon, Harlander, Klappert, Niggetiedt [2021]

Exact top-quark mass dependence in hadronic Higgs production

H production at NNLO with top and bottom quark mass dependence

Size: -0.16% at 8 TeV, and -0.32% at 13 TeV

2→1

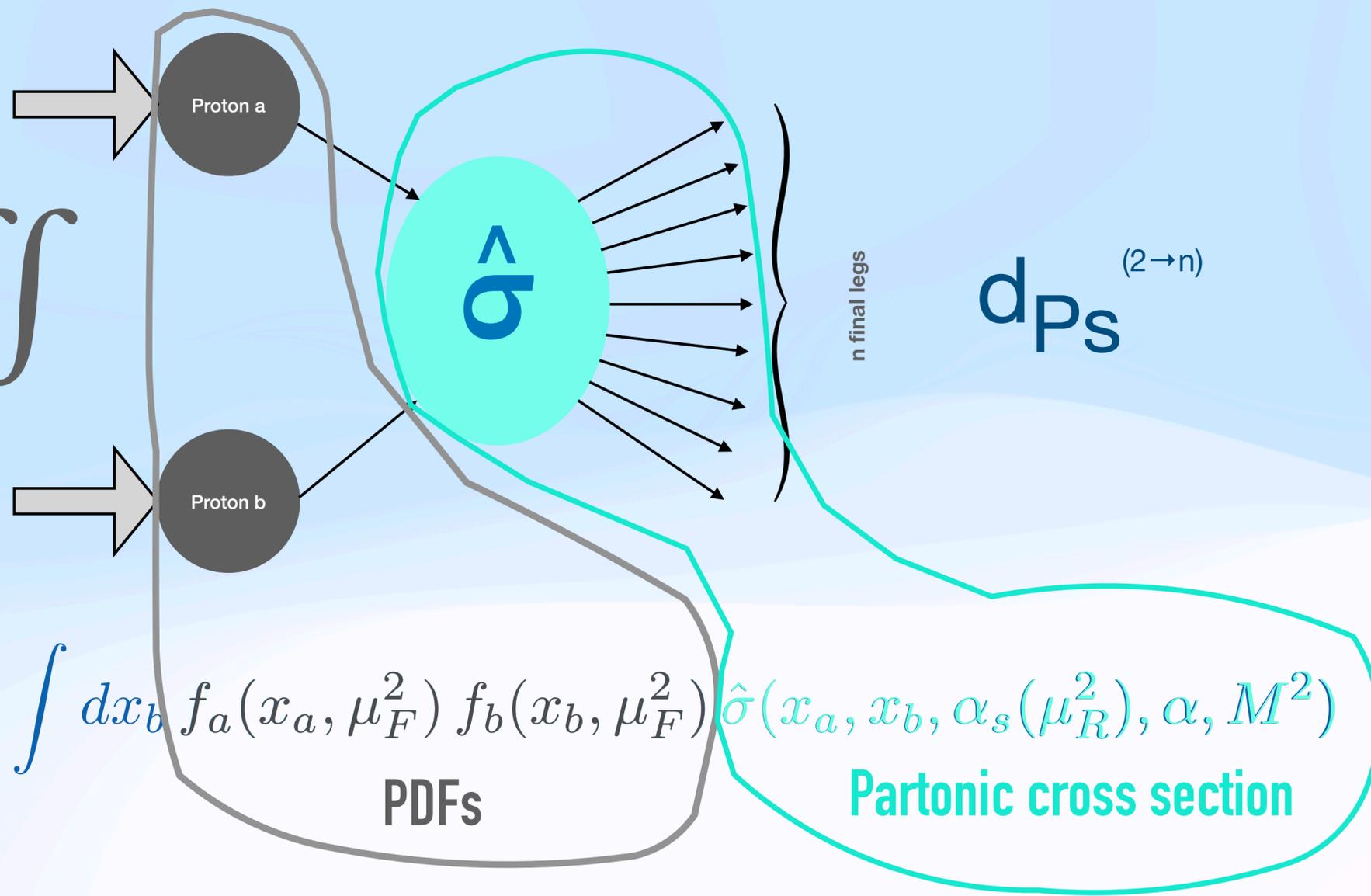


- ✓ Frontier at two-loop: 2→2
- ✓ Frontier at two-loop: 2→1

✓ Results using semi analytical methods

Anatomy of perturbative calculations

$$\sigma = \iiint$$



$$\sigma = \int d_{Ps}^{(2 \rightarrow n)} \sum_{ab} \int dx_a \int dx_b f_a(x_a, \mu_F^2) f_b(x_b, \mu_F^2) \hat{\sigma}(x_a, x_b, \alpha_s(\mu_R^2), \alpha, M^2)$$

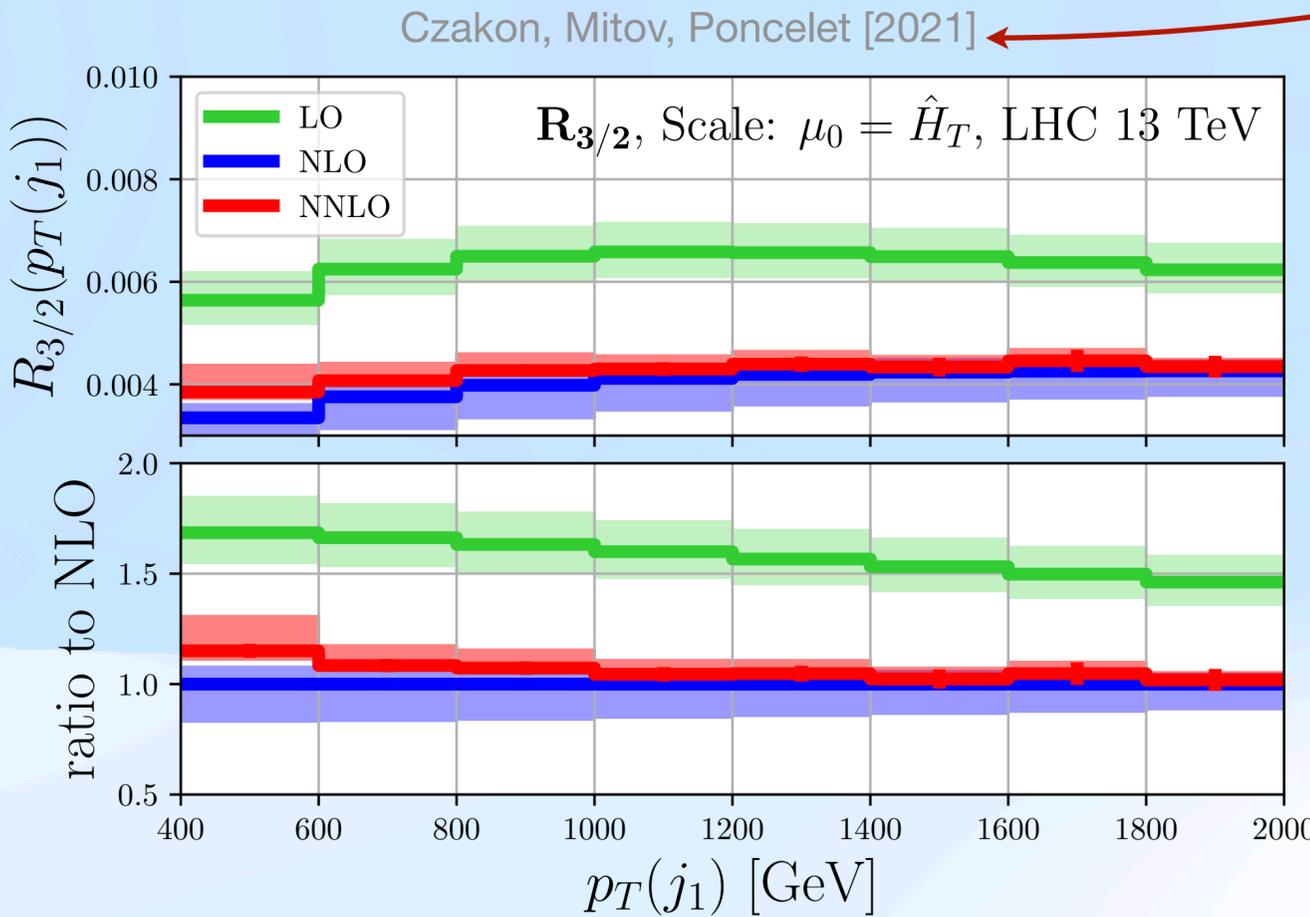
PDFs Partonic cross section

Organisation next slides

- PDFs
- Partonic cross section (scattering amplitudes)
- Pheno studies, subtraction prescriptions and CPU cost



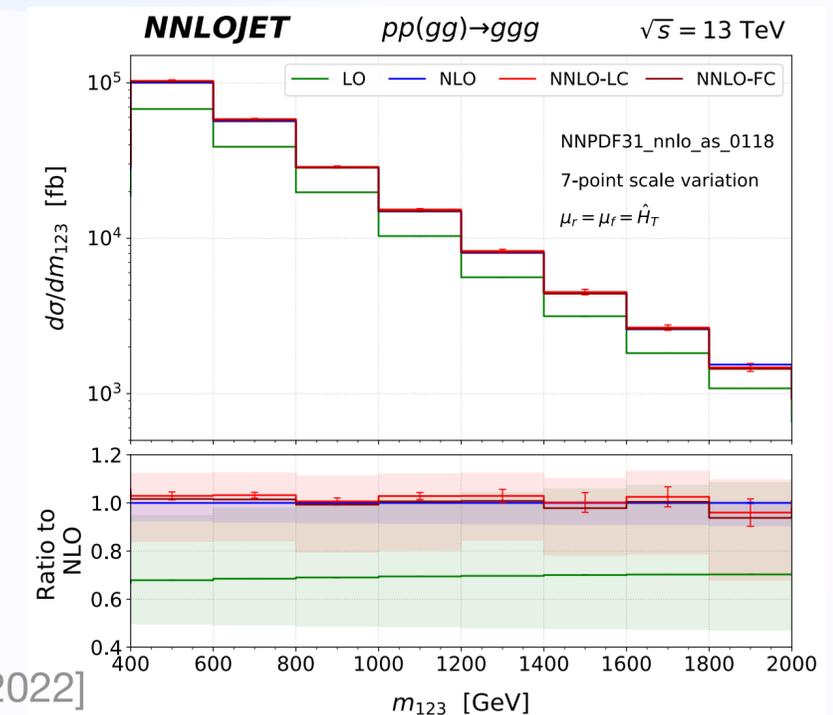
Three jet production at NNLO



Two orders of magnitude more what is claimed in their paper

Limitation in 2-loop Leading Color amplitudes and cancellation between double-real and subtraction terms (technical) \rightarrow 10^6 CPU hours

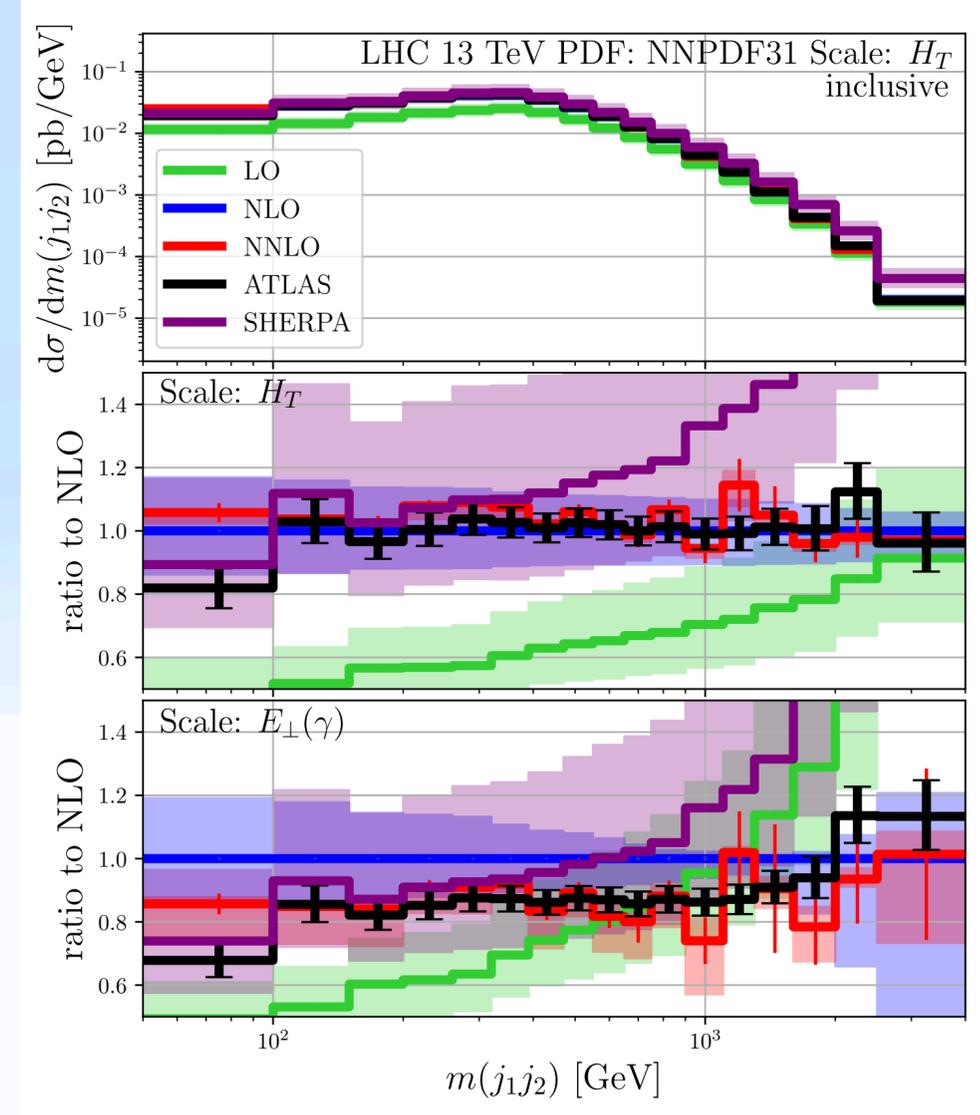
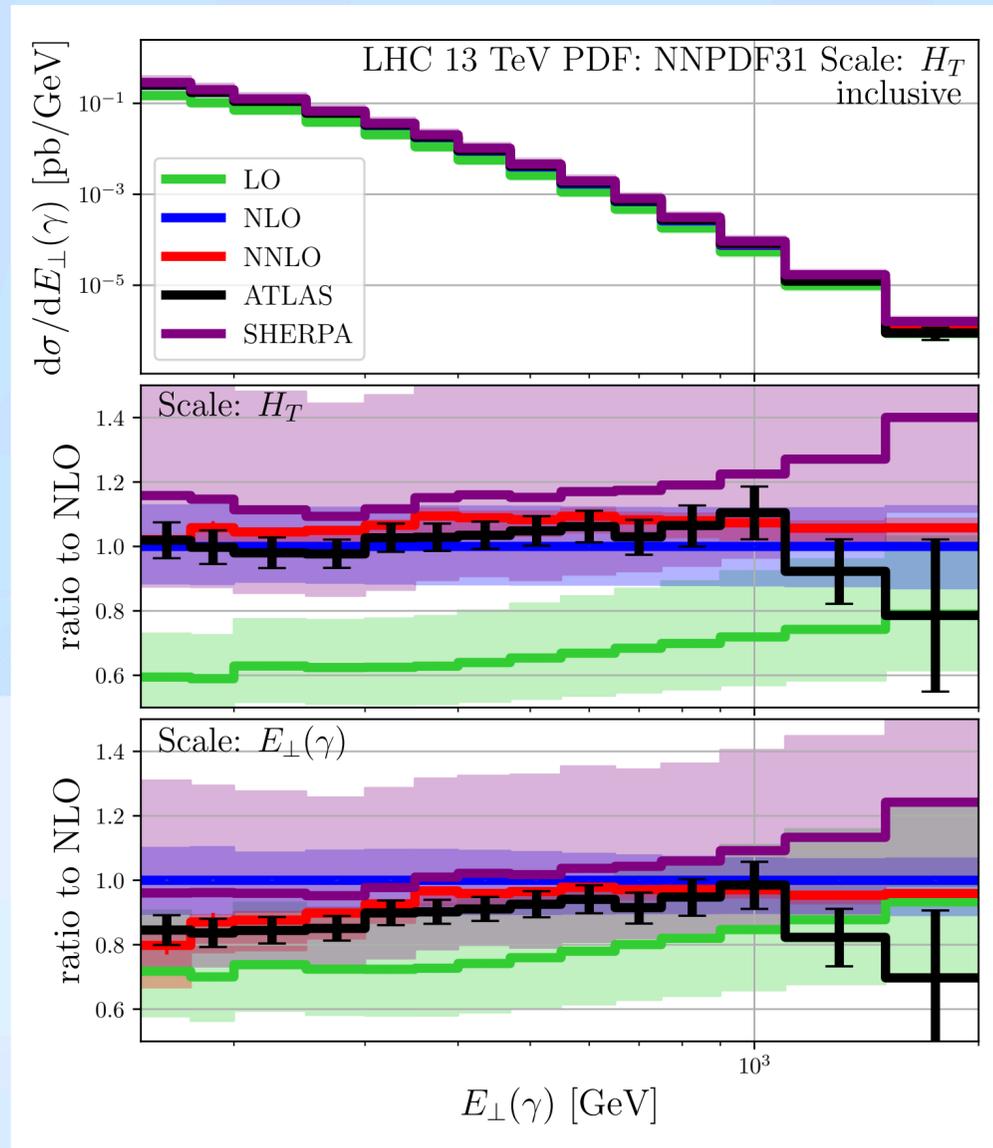
- Two different subtraction methods: sector-improve residue (left) vs antenna (right)
- NNLO corrections significantly reduces the dependence of those observables on the factorization and renormalization scales
- Leading colour two-loop scattering amplitudes or only gluons assumption



Chen, Gehrmann, Glover, Huss, Marcoli [2022]

NEW Photon plus two jet production at NNLO

Badger, Czakon, Hartanto, Moodie, Peraro, Poncelet, Zoia [2023]
 First exact 2 → 3

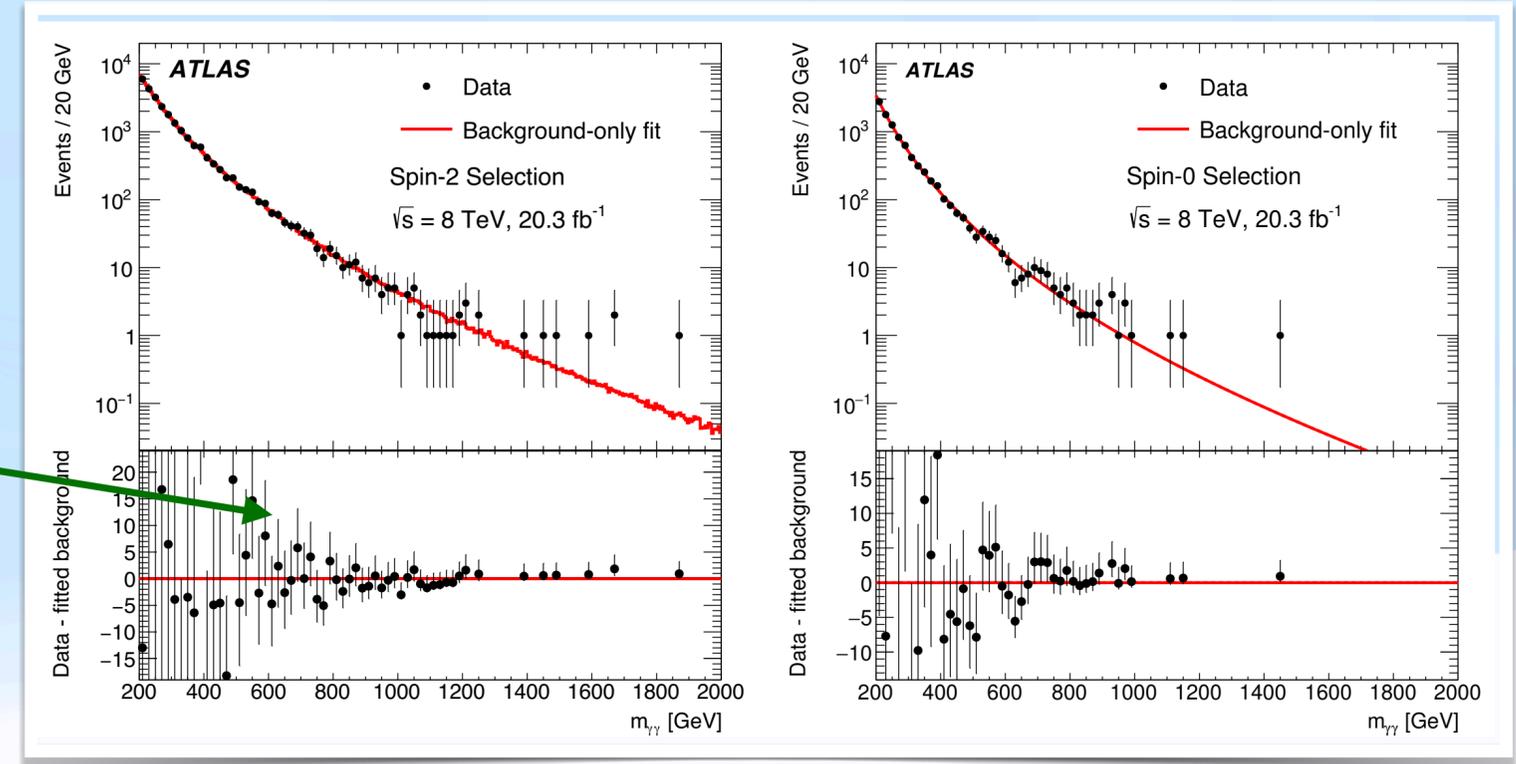
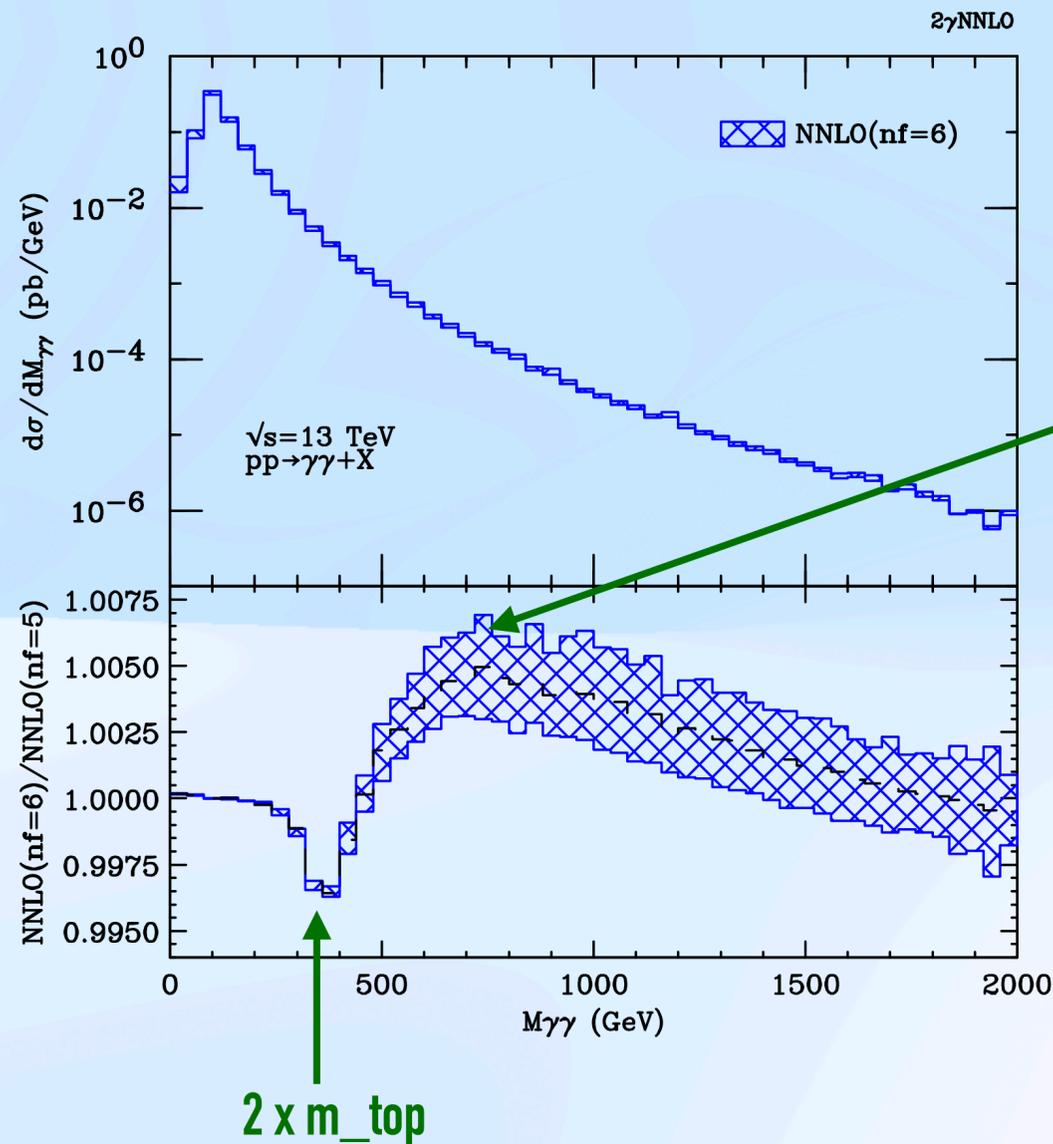


Discrepancy could be missing EW corrections (it has the correct sign)

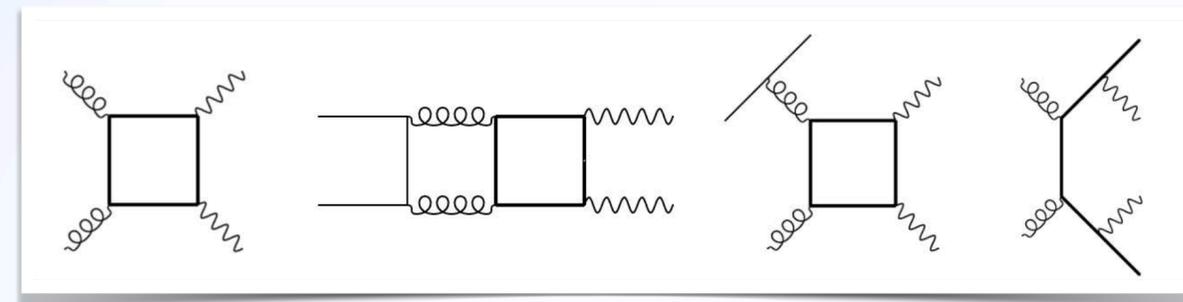
- NNLO results improve the description of the data in the case of the photon transverse energy, the jet transverse momentum, and the di-jet invariant mass
- Noticeable difference between theory and experiment in the case of the photon transverse energy starting around 1 TeV

NEW Diphoton production at NNLO with full top quark mass dependence

Becchetti, Bonciani, LC, Coro, Ripani [2023] Full massive $2 \rightarrow 2$



Example of the necessity of precise TH predictions



- All massive contributions taken into account: two-loop, loop induced, one-loop-real and double real ($pp \rightarrow \gamma\gamma tt$)
- Loop induced gg channel and two-loop ($q\bar{q}$) dominate the shape

JHEP

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PUBLISHED: September 1, 2016

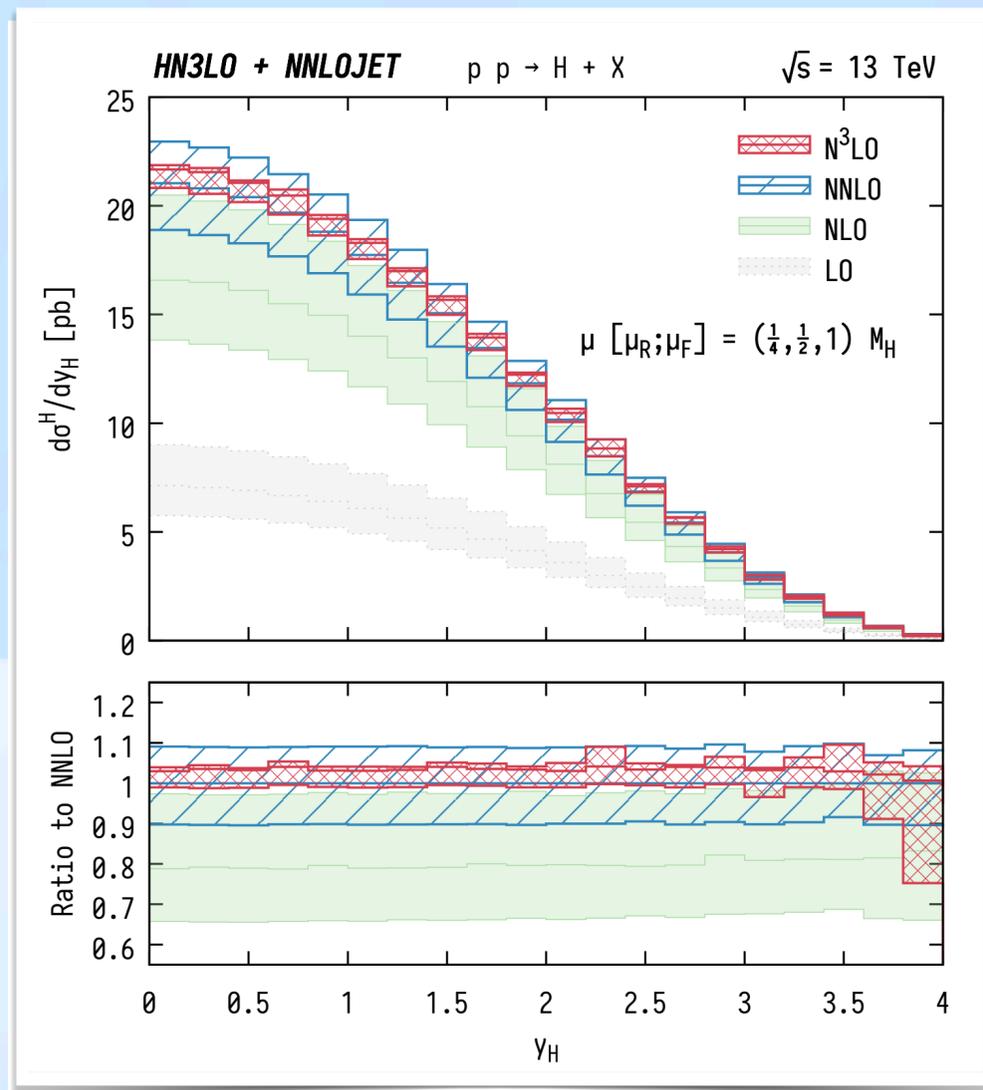
Search for resonances in diphoton events at
 $\sqrt{s} = 13$ TeV with the ATLAS detector

ATLAS EXPERIMENT

The ATLAS collaboration

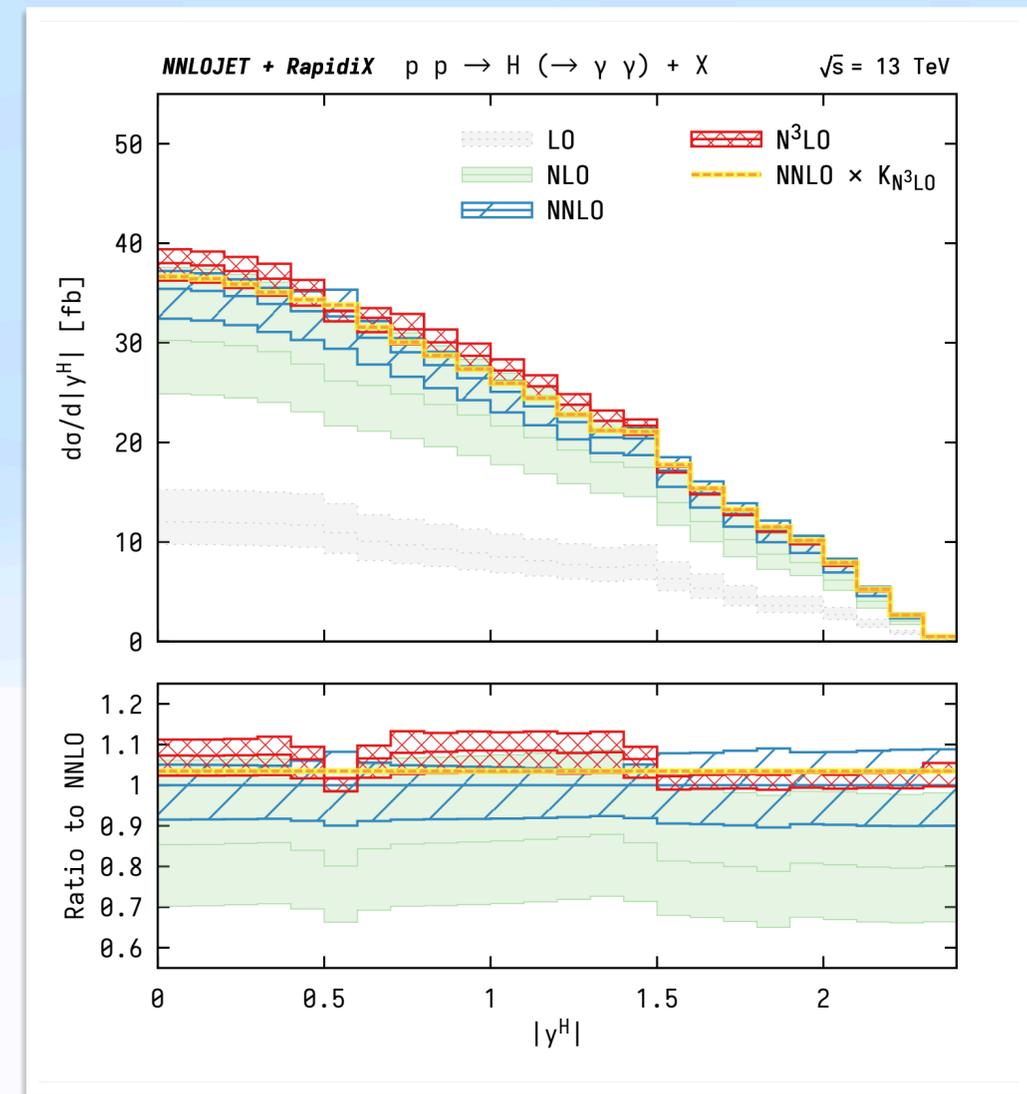
Higgs production a N3LO

LC, Chen, Gehrmann, Glover, Huss [2018]



Combination of H+jet at NNLO + qT-subtraction at N3LO

Chen, Gehrmann, Glover, Huss, Mistlberger, Pelloni [2021]

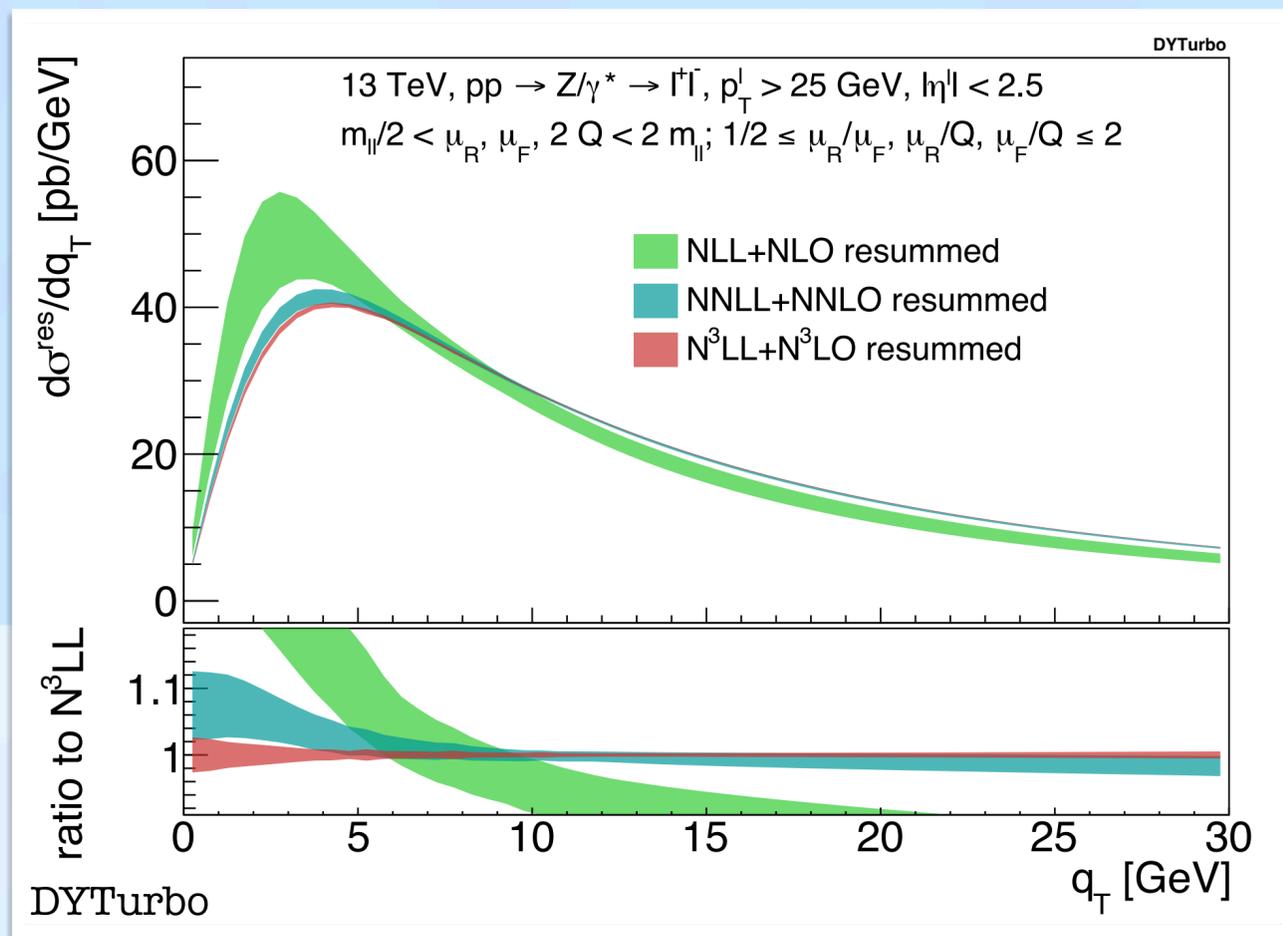


Combination of H+jet at NNLO + rapidity distribution at N3LO: P2B

- Flat K factor over the entire kinematical range
- Size of the N3LO corrections: 3.4% that can be further enhanced with fiducial cuts and certain kinematical regions
- Reduction of the 50% of the size of the NNLO scale variation band at N3LO (+-3% ; +-5%)

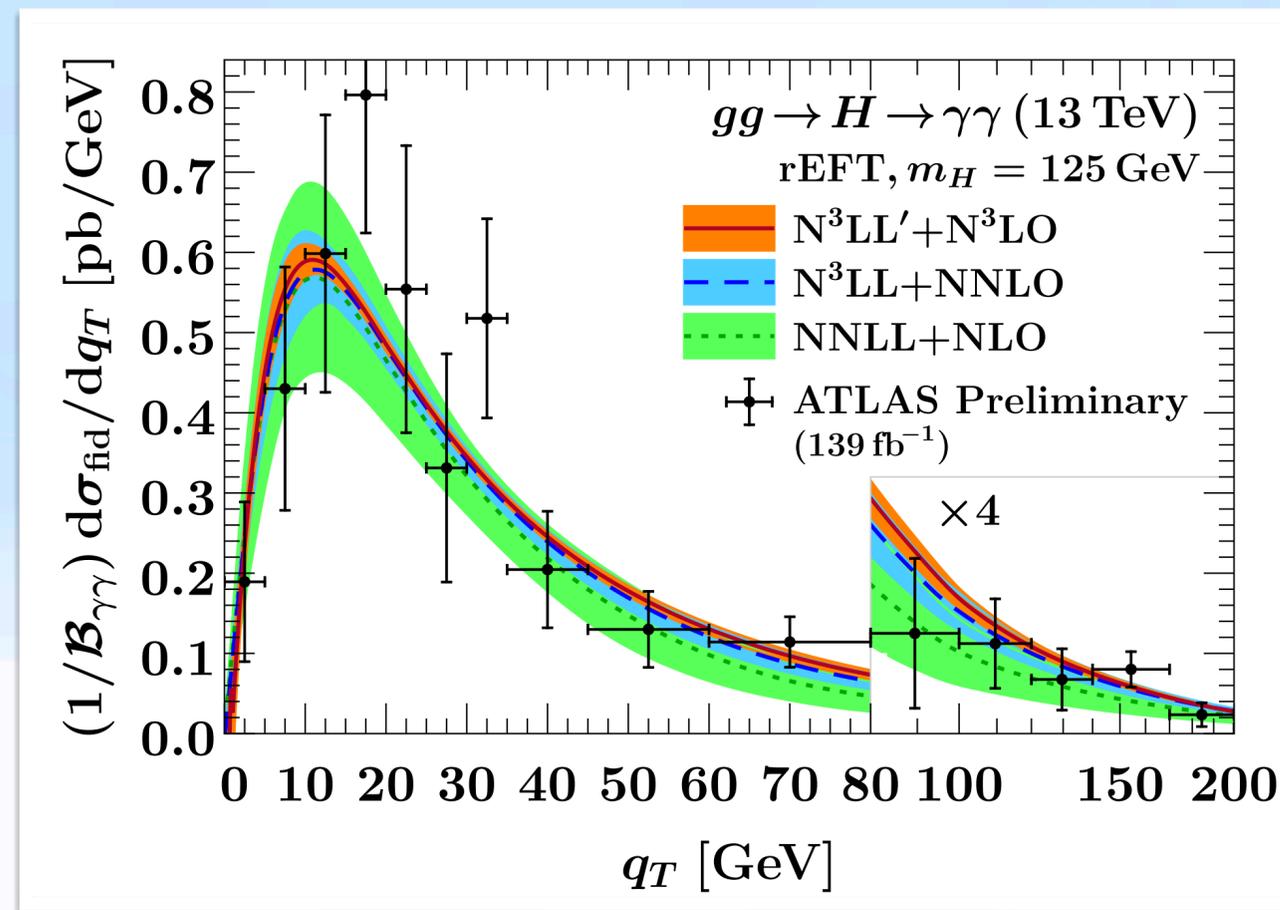
State of the art transverse momentum resummation at N3LO

Camarda, LC, Ferrera [2021]



Combination of Z+jet at NNLO + q_T -subtraction (QCD)

Billis, Dehnadi, Ebert, Michel, Tackmann [2021]

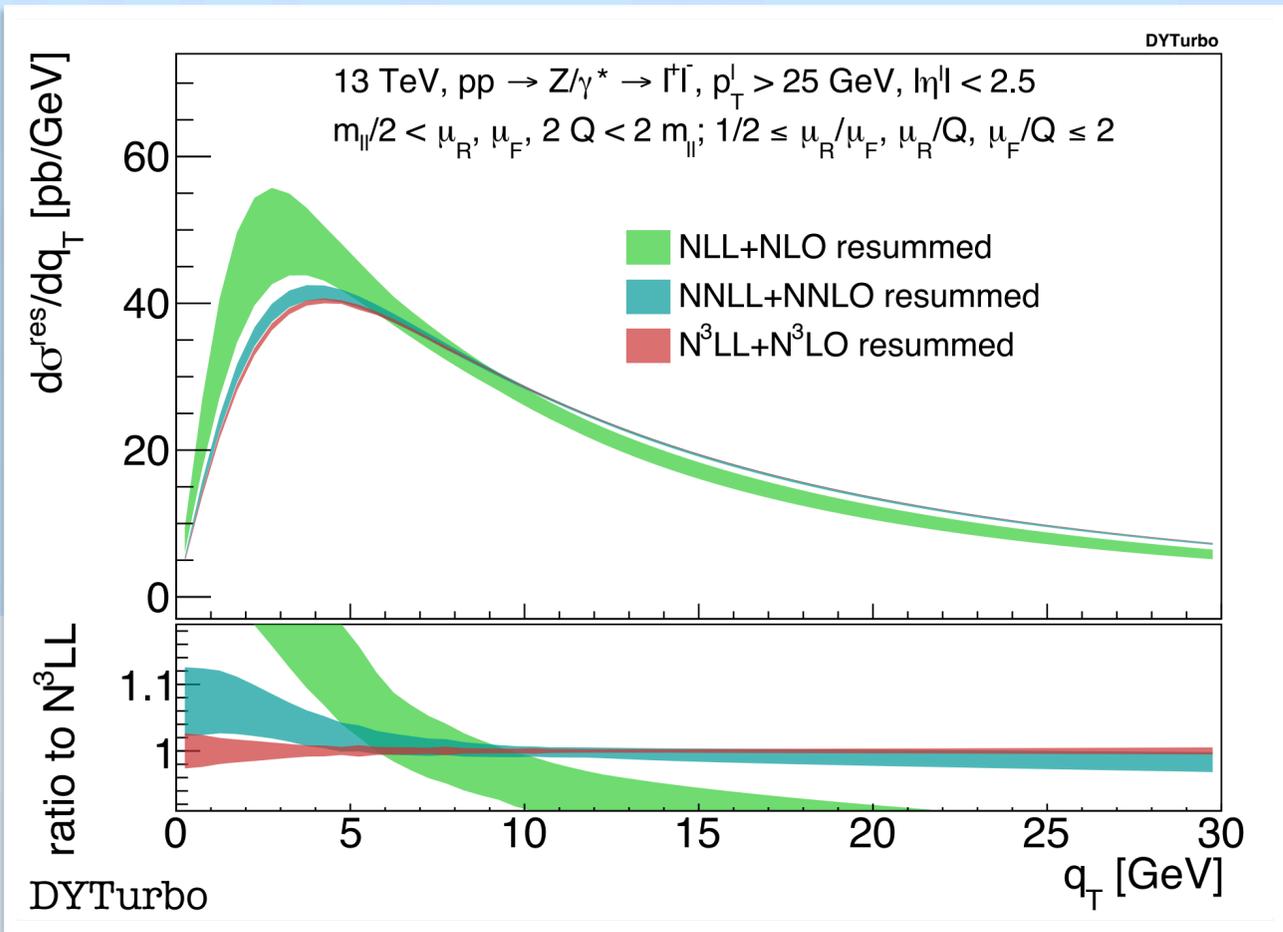


Combination of Z+jet at NNLO + SCET-subtraction

- In the small- q_T limit large logarithmic terms spoil the convergence of the perturbative series
- Transverse momentum resummation recover the reliability of the calculation in that kinematical region
- Differences between prime and unprimed version of resummation: exponentiate the finite part of the multi-loop scattering amplitudes, etc
- Size N3LO: percent corrections contained in the previous order variation of the scales

State of the art transverse momentum resummation at N3LO

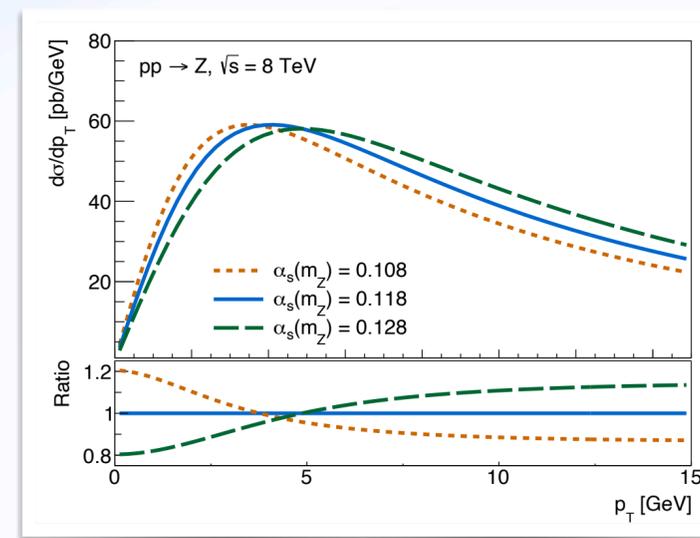
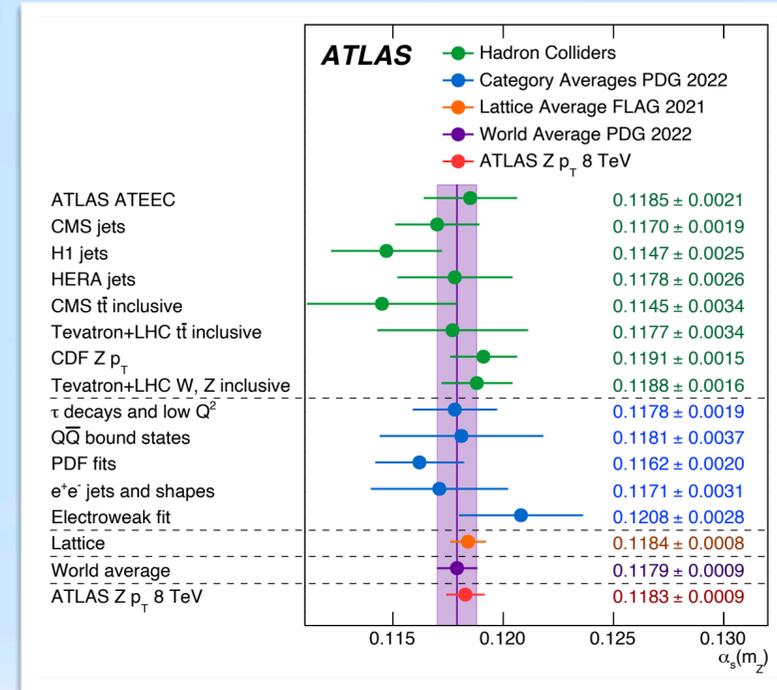
Camarda, LC, Ferrera [2021]



Combination of Z+jet at NNLO + qT-subtraction (QCD)

Another example of the necessity of precise TH predictions

NEW Most precise experimental determination of $\alpha_s(m_Z)$ achieved



EUROPEAN ORGANISATION FOR NUCLEAR RESEARCH (CERN)

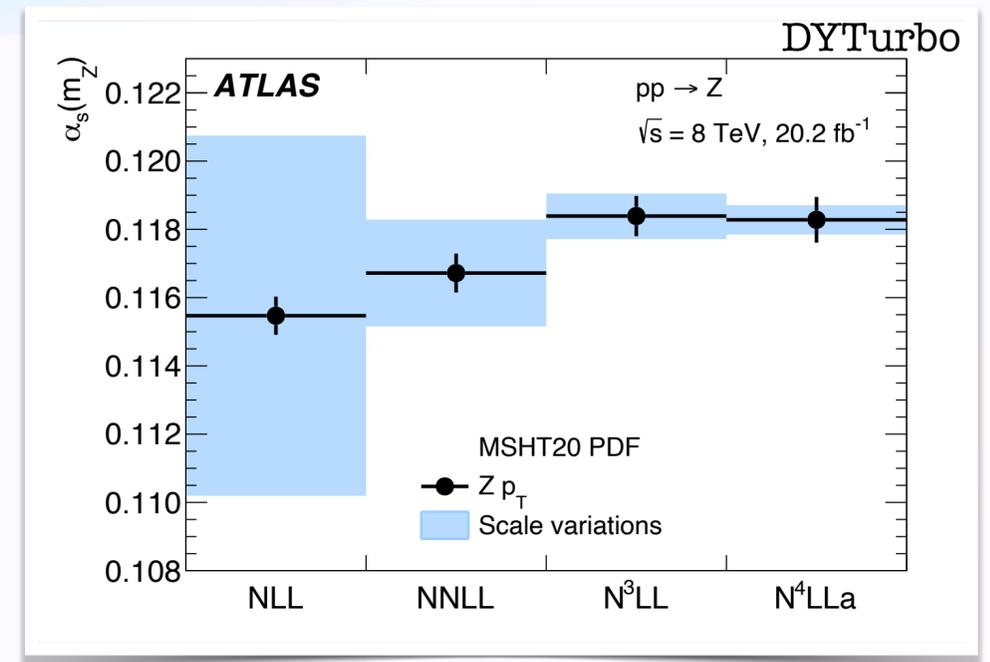
ATLAS EXPERIMENT

Submitted to: Nature Phys.

CERN-EP-2023-200
22nd September 2023

A precise determination of the strong-coupling constant from the recoil of Z bosons with the ATLAS experiment at $\sqrt{s} = 8 \text{ TeV}$

The ATLAS Collaboration + LC, Ferrera



State of the art Parton Showers

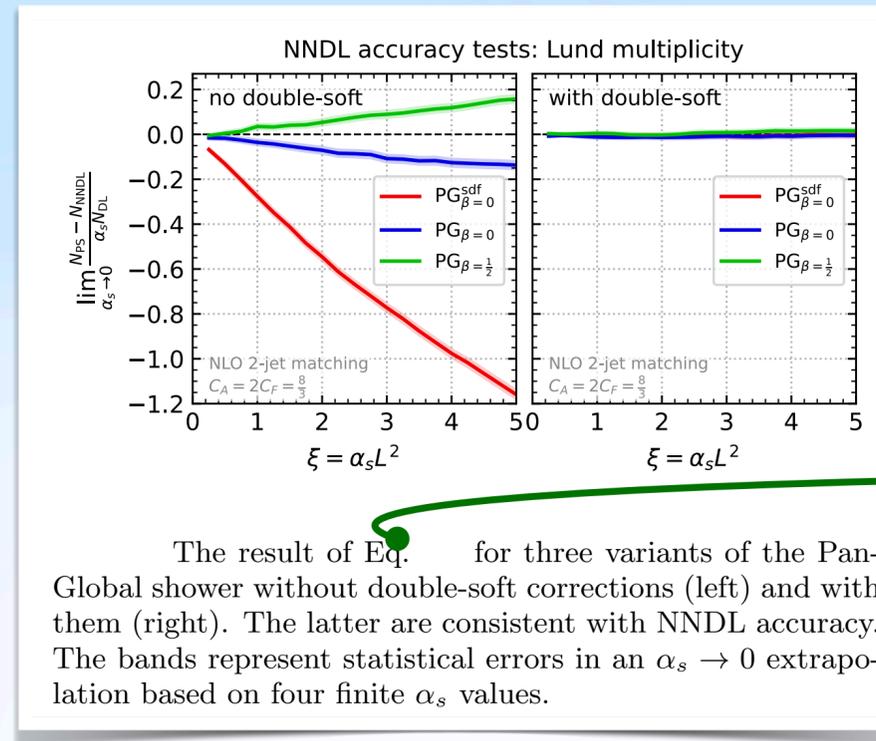
Alba's talk

- PS Monte Carlos constitute an essential tool for LHC analyses
- The majority of these tools are LL accurate → could introduce limitation in precision
- Several efforts trying to reach NLL for general observables and even higher accuracy
- PS Monte Carlos matched in general to 2 → 2 processes at NNLO **Very CPU demanding**
- PS Monte Carlo fully automated at NLO

Dasgupta, Dreyer, Hamilton, Monni, Salam [2018]
 Nagy-Soper, Holguin-Forshaw-Platzer, PanScales,
 Herren-Höche-Krauss-Reichelt-Schönherr + ...

PanScales: Ravasio, Hamilton, Karlberg, Salam, Scyboz, Soyez [2023]
 van Beekveld, Dasgupta, El-Menoufi, Ferrario Ravasio, Hamilton, Helliwell, Karlberg, Monni, Salam, Scyboz, Soto-Ontoso Soyez [2024]

NEW towards general NNLL precision



$$\lim_{\alpha_s \rightarrow 0} \frac{N_{PS} - N_{NNDL}}{\alpha_s N_{DL}} \Big|_{\text{fixed } \alpha_s L^2}$$

- The PanGlobal showers already reproduce terms up to NDL $\alpha_s^n L^{2n-1}$
- The addition of the double-soft corrections and matching is expected to bring NNDL accuracy $\alpha_s^n L^{2n-2}$

- State-of-the-art (SOTA) TH predictions (NNLO or N3LO precision) encoded *via* **Monte Carlo (MC) event generators** require multi core computers (generally clusters of thousand of CPUs).
- Such SOTA TH predictions typically require **weeks (or even several months/years)** in multi core clusters.
- TH Frontier at the fully differential level: at NNLO, up to three particles in the final state (recently); at N3LO just one particle.



The standard and current strategy in the literature to address this challenge is to **improve numerical integration.**



LHC phenomenological analyses per year ~ 400 (three main coll.)



10 Marenostrums needed continuously !!!!

Just for LHC TH analyses

Process	NLO (CPU years)	NNLO (CPU years)	N3LO (CPU years)
pp → W/Z	☞	0.6	160
pp → H	☞	0.6	160
pp → γγ	☞		
pp → tt	☞		
pp → γ+2jets	☞	2.4	Process not available
pp → 2 jets	☞	10	Process not available
pp → H+jet	☞	57	Process not available
pp → γγγ	☞	31	Process not available
pp → Z+jet	☞	57	Process not available
pp → 3 jets	☞	> 114	Process not available

📍 **57 CPU years** is equivalent to 1000 cores running the MC continuously for 21 days.



Why did we not break the 2->1 barrier at N3LO?

supercomputers. About 90k€/year in Switzerland → exclusive use of 2000 cores.

📍 **It is not a green way** to perform calculations.



→ **For LHC analyses 23k years!**

→ For LHC analyses x 10 factor at least

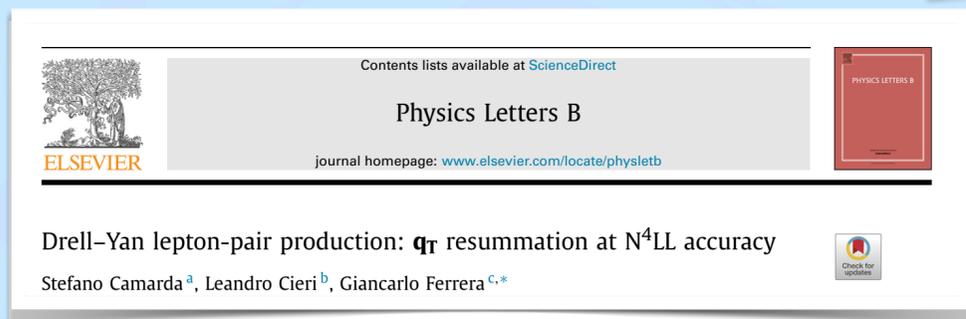
It is clear that we need something new

Table obtained from theoretical papers

Possible paths to the (immediate) Future

We are looking for

🔧 more precise TH tools → N3LO (or even N4LO)



Contents lists available at ScienceDirect
 Physics Letters B
 journal homepage: www.elsevier.com/locate/physletb

Drell-Yan lepton-pair production: $\mathbf{q_T}$ resummation at N⁴LL accuracy
 Stefano Camarda^a, Leandro Cieri^b, Giancarlo Ferrera^{c,*}

Single-soft emissions for amplitudes with two colored particles at three loops

Franz Herzog,^a Yao Ma,^b Bernhard Mistlberger,^c Adi Suresh^c

November 24, 2024

DESY 23-081
 MIT-CTP/5572
 Nikhef 2024-007

Drell-Yan Transverse-Momentum Spectra at N³LL' and Approximate N⁴LL with SCETlib

Georgios Billis,^a Johannes K. L. Michel,^{b,c,d} and Frank J. Tackmann^e

Extraction of unpolarized transverse momentum distributions from fit of Drell-Yan data at N⁴LL

Valentin Moos,^a Ignazio Scimemi,^b Alexey Vladimirov,^b Pia Zurita^{a,b}

Planar three-loop QCD helicity amplitudes for V+jet production at hadron colliders

Thomas Gehrmann,^{1,*} Petr Jakubčák,^{1,†} Cesare Carlo Mella,^{2,‡} Nikolaos Syrakos,^{2,§} and Lorenzo Tancredi^{2,¶}

¹Physik-Institut, Universität Zurich, Winterthurerstrasse 190, CH-8057 Zurich, Switzerland
²Technical University of Munich, TUM School of Natural Sciences, Physics Department, James-Frank-Straße 1, 85748 Garching, Germany

We compute the planar three-loop Quantum Chromodynamics (QCD) corrections to the helicity amplitudes involving a vector boson $V = Z, W^\pm, \gamma^*$, two quarks and a gluon. These amplitudes are relevant to vector-boson-plus-jet production at hadron colliders and other precision QCD observables. The planar corrections encompass the leading colour factors N^3 , $N^2 N_f$, NN_f^2 and N_f^3 . We provide the finite remainders of the independent helicity amplitudes in terms of multiple polylogarithms, continued to all kinematic regions and in a form which is compact and lends itself to efficient numerical evaluation.

Beware of strict collinear factorization violation at N3LO (and beyond)
 Catani, de Florian, Rodrigo [2012]

🔧 more precise PDFs → New fitting techniques, more data and N3LO PDFs

Approximate N³LO Parton Distribution Functions with Theoretical Uncertainties: MSHT20aN³LO PDFs

J. McGowan^a, T. Cridge^a, L. A. Harland-Lang^b, and R.S. Thorne^a

DESY-24-134
 TIF-UNIMI-2024-17
 Edinburgh 2024/9
 CERN-TH-2024-167

Combination of aN³LO PDFs and implications for Higgs production cross-sections at the LHC

The MSHT Collaboration:
 Thomas Cridge¹, Lucian A. Harland-Lang², Jamie McGowan², and Robert S. Thorne²

The NNPDF Collaboration:
 Richard D. Ball³, Alessandro Candido⁴, Stefano Carrazza⁵, Juan Cruz-Martinez⁴, Luigi Del Debbio³, Stefano Forte⁶, Felix Hekhorn^{6,7}, Giacomo Magni^{8,9}, Emanuele R. Nocera¹⁰, Tanjona R. Rabemananjara^{8,9}, Juan Rojo^{8,9}, Roy Stegeman³ and Maria Ubiali¹¹

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🔧 NNLO TH calculations at higher multiplicities → New loop integral techniques required (analytical or numerical)?

Slow evaluation of 2 → 3 two-loop contribution

Amplitude evaluation with pySecDec:
 A Higgs + three gluons example

C P Paranjape¹, G Heinrich² and S P Jones³

DiffExp, a Mathematica package for computing Feynman integrals in terms of one-dimensional series expansions

Martijn Hidding

Possible paths to the (immediate) Future

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- 🔧 more precise PDFs → New fitting techniques and more data and N3LO PDFs
- 🔧 NNLO TH calculations at higher multiplicities → New loop integral techniques required (analytical or numerical)?
- 🔧 more efficient MC for fixed order tools (CPU cost) → techniques with no distinction between real and virtual corrections?

A Tree–Loop Duality Relation at Two Loops and Beyond

Isabella Bierenbaum ^{(a)*}, Stefano Catani ^{(b)†}, Petros Draggiotis ^{(a)‡} and Germán Rodrigo ^{(a)§}

PHYSICAL REVIEW LETTERS **124**, 211602 (2020)

Open Loop Amplitudes and Causality to All Orders and Powers from the Loop-Tree Duality

J. Jesús Aguilera-Verdugo,^{1,*} Félix Driencourt-Mangin,^{1,†} Roger J. Hernández-Pinto,^{2,‡} Judith Plenter,^{1,§} Selomit Ramírez-Uribe,^{1,2,3,||} Andrés E. Rentería-Olivo,^{1,¶} Germán Rodrigo,^{1,**} Germán F. R. Sborlini,^{1,††} William J. Torres Bobadilla,^{1,‡‡} and Szymon Tracz^{1,§§}



PUBLISHED FOR SISSA BY SPRINGER

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REVISED: July 13, 2016
ACCEPTED: August 20, 2016
PUBLISHED: August 29, 2016

Four-dimensional unsubtraction from the loop-tree duality

Germán F. R. Sborlini,^{a,b} Félix Driencourt-Mangin,^a Roger J. Hernández-Pinto^{a,c} and Germán Rodrigo^a

^aInstituto de Física Corpuscular,

Vacuum amplitudes and time-like causal unitarity in the loop-tree duality

The LTD Collaboration, Selomit Ramírez-Uribe ^(a,b), Andrés E. Rentería-Olivo ^(a), David F. Rentería-Estrada ^(a), Jorge J. Martínez de Lejarza ^(a), Prasanna K. Dhani ^(a), Leandro Cieri ^(a), Roger J. Hernández-Pinto ^(b), German F. R. Sborlini ^(c), William J. Torres Bobadilla ^(d), and Germán Rodrigo ^{(a)*}

Eur. Phys. J. C (2014) 74:2864
DOI 10.1140/epjc/s10052-014-2864-9

THE EUROPEAN
PHYSICAL JOURNAL C

Regular Article - Theoretical Physics

FDR, an easier way to NNLO calculations: a two-loop case study

Alice Maria Donati^a, Roberto Pittau^b

PHYSICAL REVIEW LETTERS **133**, 211901 (2024)

Rewording Theoretical Predictions at Colliders with Vacuum Amplitudes

Selomit Ramírez-Uribe^{1,2,*} Prasanna K. Dhani^{1,†} German F. R. Sborlini^{3,‡} and Germán Rodrigo^{1,§}

¹Instituto de Física Corpuscular, Universitat de València—Consejo Superior de Investigaciones Científicas, Parc Científic, E-46980 Paterna, Valencia, Spain

²Facultad de Ciencias Físico-Matemáticas, Universidad Autónoma de Sinaloa, Ciudad Universitaria, CP 80000 Culiacán, Mexico

³Departamento de Física Fundamental e IUFFyM, Universidad de Salamanca, 37008 Salamanca, Spain

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- 📌 NNLO TH calculations at higher multiplicities → New loop integral techniques required (analytical or numerical)?
- 📌 more efficient MC for fixed order tools (CPU cost) → techniques with no distinction between real and virtual corrections?
- 📌 Quantum Computing → Quantum Algorithms


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 PUBLISHED: May 16, 2022

Quantum algorithm for Feynman loop integrals

Selomit Ramírez-Uribe^{a,b,c}, Andrés E. Rentería-Olivo^a, Germán Rodrigo^a, German F.R. Sborlini^{d,a} and Luiz Vale Silva^a

Quantum Fourier Iterative Amplitude Estimation

Jorge J. Martínez de Lejarza^a, Michele Grossi^b, Leandro Cieri^a and Germán Rodrigo^a

Quantum querying based on multicontrolled Toffoli gates for causal Feynman loop configurations and directed acyclic graphs

Selomit Ramírez-Uribe^b, Andrés E. Rentería-Olivo^a and Germán Rodrigo^a

PHYSICAL REVIEW D **108**, 096035 (2023)

Variational quantum eigensolver for causal loop Feynman diagrams and directed acyclic graphs

Giuseppe Clemente^{1,*}, Arianna Crippa^{1,†}, Karl Jansen^{1,‡}, Selomit Ramírez-Uribe^{2,3,4,§}, Andrés E. Rentería-Olivo^{2,‡}, Germán Rodrigo^{2,4}, German F.R. Sborlini^{5,6,**} and Luiz Vale Silva^{2,††}

PHYSICAL REVIEW D **106**, 036021 (2022)

Quantum clustering and jet reconstruction at the LHC

Jorge J. Martínez de Lejarza^{a,*}, Leandro Cieri^{b,†} and Germán Rodrigo^{c,‡}

PHYSICAL REVIEW LETTERS **133**, 211901 (2024)

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PHYSICAL REVIEW LETTERS **124**, 211602 (2020)

Open Loop Amplitudes and Causality to All Orders and Powers from the Loop-Tree Duality

J. Jesús Aguilera-Verdugo^{1,*}, Félix Driencourt-Mangin^{1,†}, Roger J. Hernández-Pinto^{2,‡}, Judith Plenter^{1,§}, Selomit Ramírez-Uribe^{1,2,3,||}, Andrés E. Rentería-Olivo^{1,4}, Germán Rodrigo^{1,**}, Germán F.R. Sborlini^{1,††}, William J. Torres Bobadilla^{1,‡‡} and Szymon Tracz^{1,§§}

THE EUROPEAN PHYSICAL JOURNAL C

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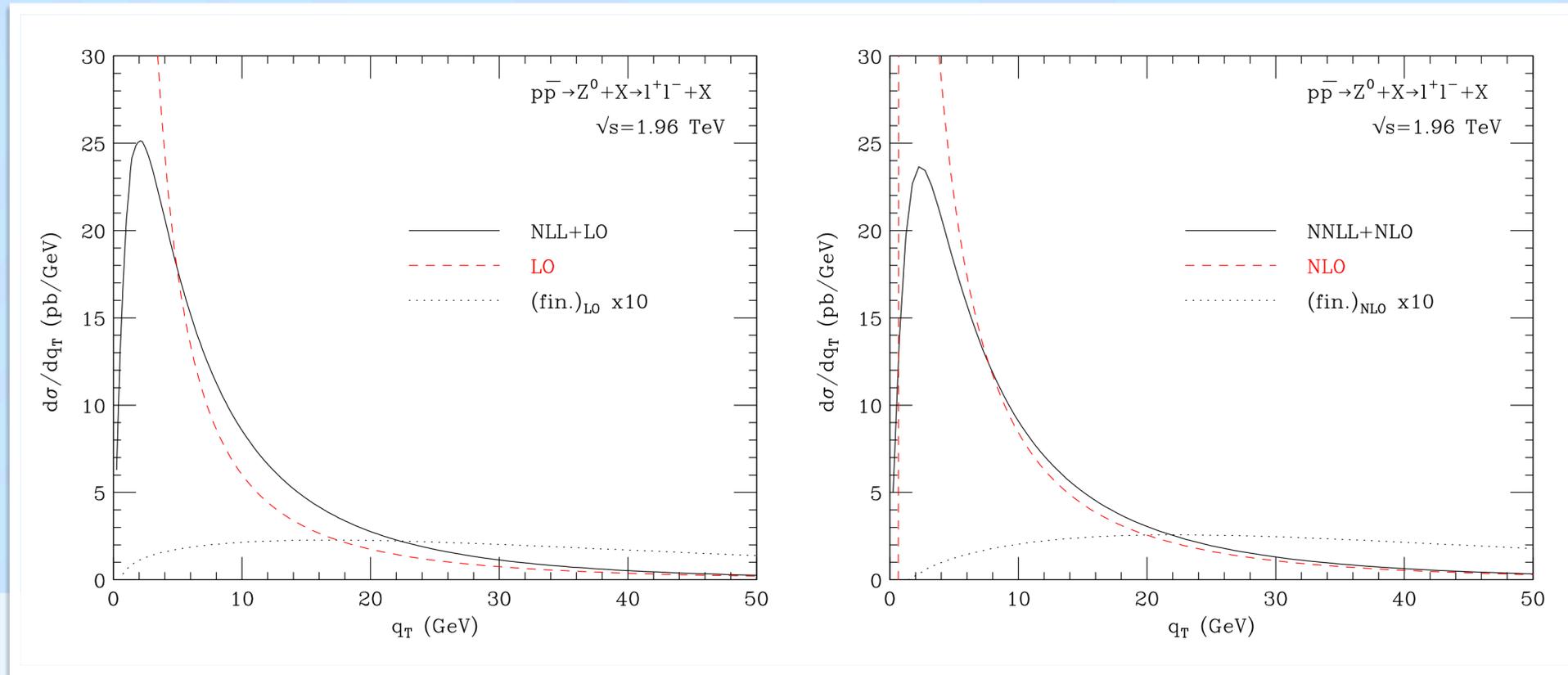
Alice Maria Donati^a, Roberto Pittau^b

Isabella Bierenbaum^{(a)*}, Stefano Catani^{(b)†}, Petros Draggiotis^{(a)‡} and Germán Rodrigo^{(a)§}

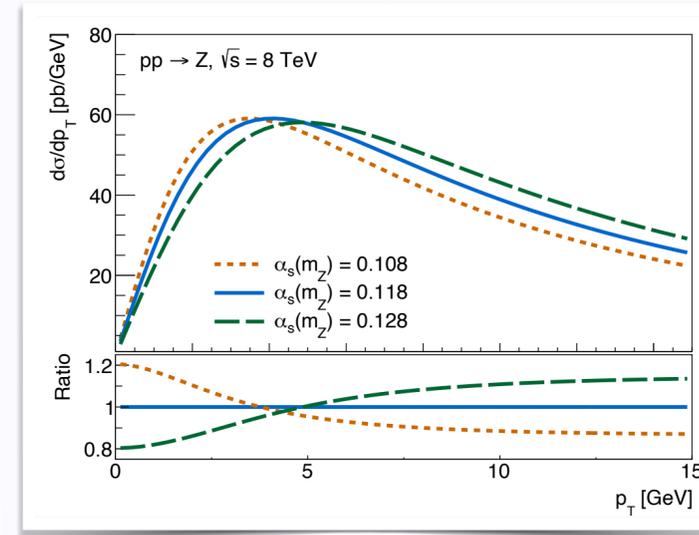
Quantum integration of decay rates at second order in perturbation theory

Jorge J. Martínez de Lejarza^{a,*}, David F. Rentería-Estrada^{a,†}, Michele Grossi^{b,‡} and Germán Rodrigo^{a,§}
^aInstituto de Física Corpuscular, Universitat de València - Consejo Superior de Investigaciones Científicas, Parc Científic, E-46980 Paterna, Valencia, Spain and
^bEuropean Organization for Nuclear Research (CERN), 1211 Geneva, Switzerland
 (Dated: September 20, 2024)

State of the art transverse momentum resummation at N3LO



The size of the finite: Real+CT



EUROPEAN ORGANISATION FOR NUCLEAR RESEARCH (CERN)

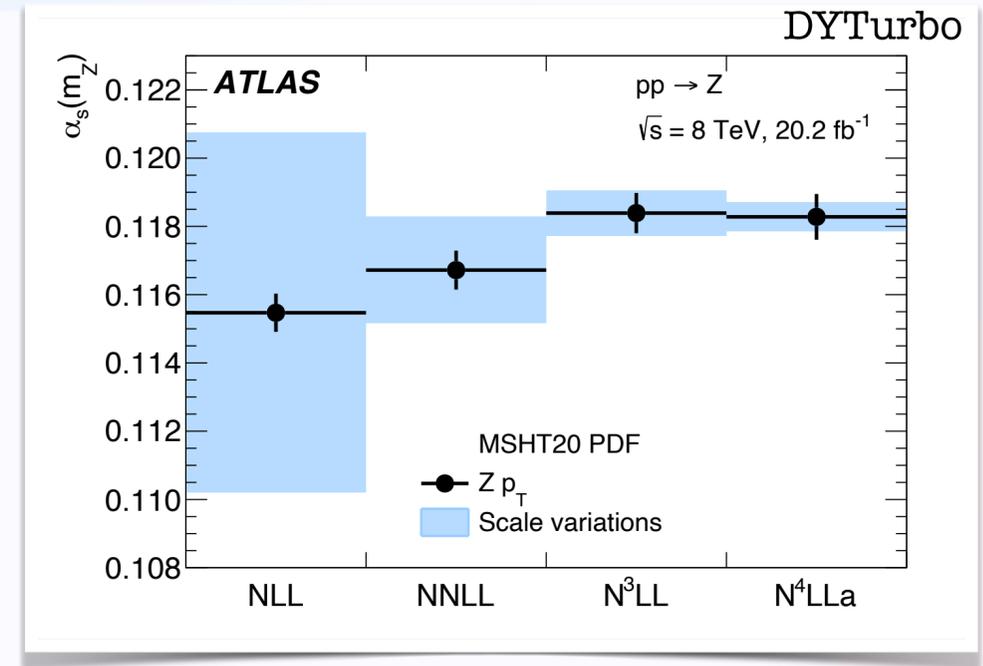
ATLAS
EXPERIMENT

Submitted to: Nature Phys.

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A precise determination of the strong-coupling constant from the recoil of Z bosons with the ATLAS experiment at $\sqrt{s} = 8$ TeV

The ATLAS Collaboration + **LC**, Ferrera

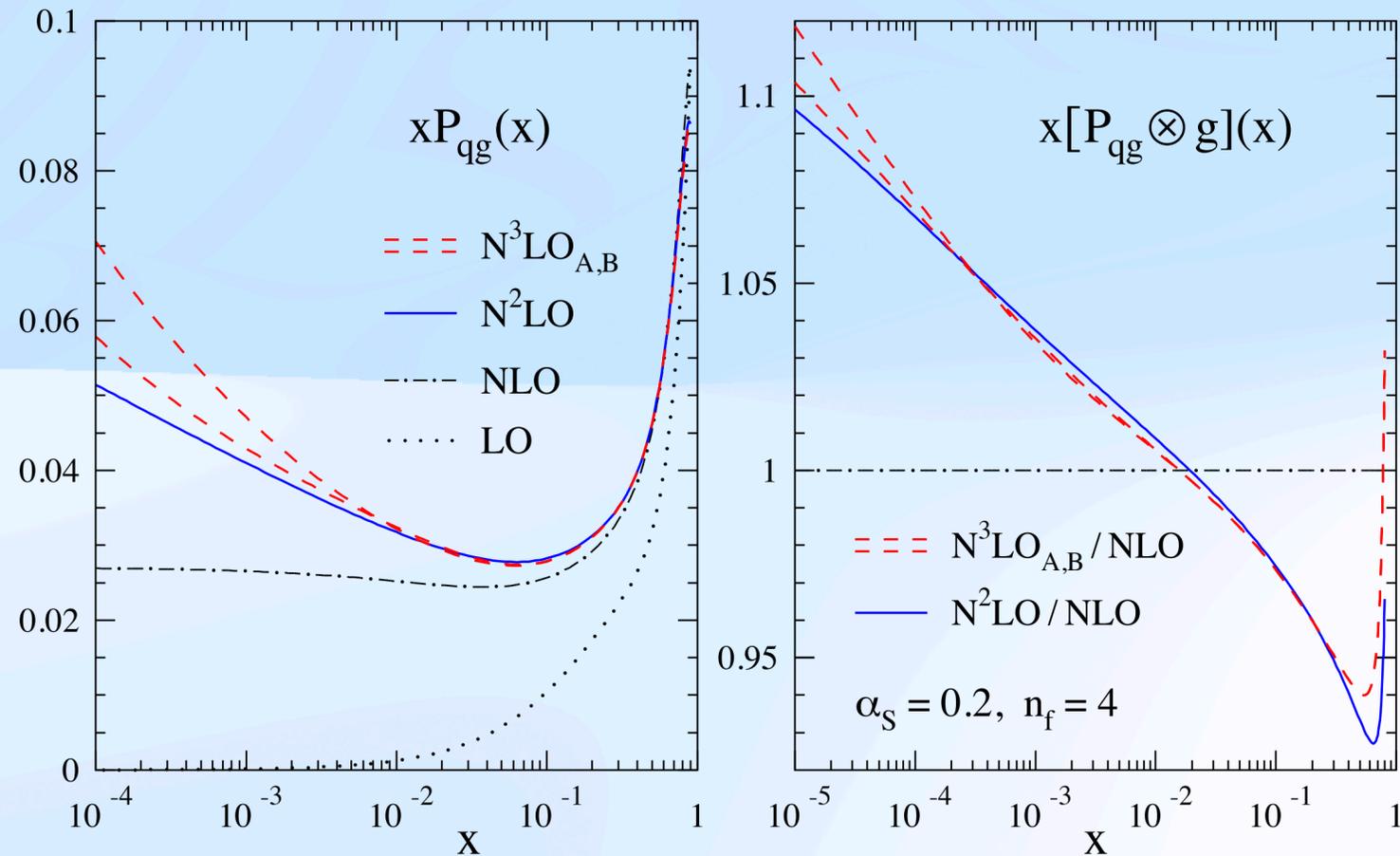


Most precise experimental determination of $\alpha_s(m_Z)$ achieved

New Splitting functions at N3LO (P_{qg} and contributions to P_{gq})

Falcioni, Herzog, Moch, Vogt [2023]

N(20) moments + available endpoint constraints → the four-loop P_{qg}(x) that should be sufficient for a wide range of collider-physics applications



2 Oct 2023

The double fermionic contribution to the four-loop quark-to-gluon splitting function

P_{gq}

G. Falcioni^{a,b}, F. Herzog^c, S. Moch^d, J. Vermaseren^e and A. Vogt^f

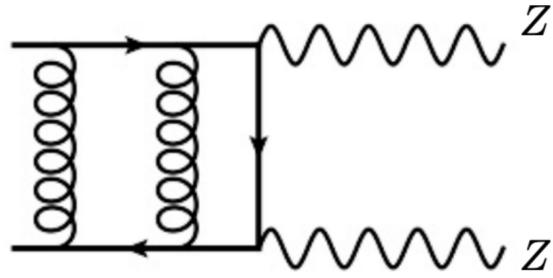
P_{gq} should be feasible soon

Perturbative QCD TH predictions & more

Theory	Highest perturbative order reached	Typical uncertainty	Final state multiplicity	Well under control at
QCD ⊕ EW	Next-to-next-to-leading order (NNLO)	8%-12% (inherited from QCD part)	$2 \rightarrow (n=)$ 3 legs	QCD NNLO ($2 \rightarrow 2$ processes)
QCD	Next-to-next-to-next-to-leading order (N3LO)	3%-5%	$2 \rightarrow (n=)$ 1 legs	Hard to obtain differential results in a short time (at least 2 months in 2000 CPUs)

Degree of complexity at NNLO

2 loop



loop integrals

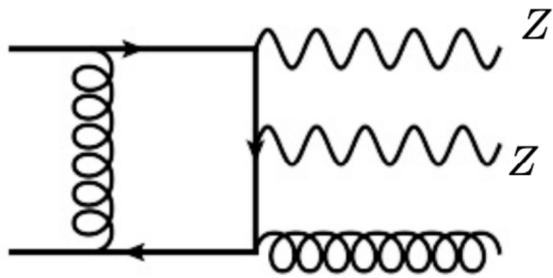


explicit infrared poles

$$\frac{1}{\epsilon^4}$$

- Bottleneck for larger multiplicities
- Many becoming available

1 loop + single emission



“NLO complexity” : loop

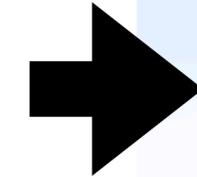


$$\frac{1}{\epsilon^2}$$

singular emission (extra)

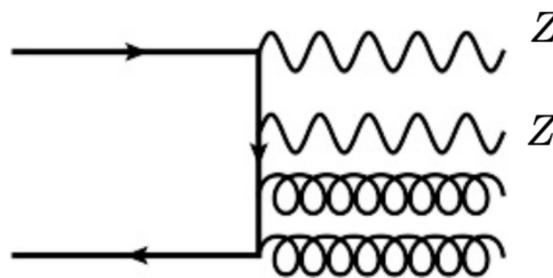


$$\frac{1}{\epsilon^2}$$



$$\log^2\left(\frac{q_{TZZ}^2}{M_{ZZ}^2}\right)$$

Double real emission



Tree level

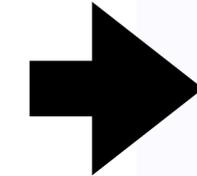
a Hell of infrared singularities

- Bottleneck for larger multiplicities: implementation

after integration over unresolved partons



$$\frac{1}{\epsilon^4} \text{ poles}$$



$$\log^4\left(\frac{q_{TZZ}^2}{M_{ZZ}^2}\right)$$

If you regularise in qT space



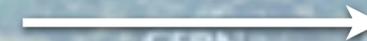
Organisation of the talk

Disclaimers

- Theoretical results for LHC phenomenology constitutes a **vast field**



&



~10 LHC hep-ph papers per day from 2020
→ 16000 papers

- The aim of this talk is to present results:

- LHC TH predictions → Precise TH predictions
- Newest
- Most interesting 
- Point to possible future directions in our field 

- There will be an inevitable degree of **subjectivism** 

- I am sorry if your favourite calculation or phenomenological study is not included in these slides. I will be happy to discuss it with you after the talk.

EPS-2023 - Future collider talks

<p>Status and prospects of the HL-LHC project <i>Markus Zerlauth</i></p>	<p>Physics Performance and Detector Requirements at an Asymmetric Higgs Factory <i>Antoine Laudrain</i></p>	<p>Precise predictions for the trilinear Higgs self-coupling in the Standard Model and beyond <i>Martin Gabelmann</i></p>	<p>Precision measurements of W and Z production in ATLAS and CMS <i>Prof. Ulrich Goerlach</i></p>	<p>J/ψ-pair production at NLL in TMD factorisation at LHC <i>Alice Colpani Serri</i></p>
<p>Impact of accelerator physics on van der Meer luminosity calibrations at the LHC <i>Witold Kozanecki</i></p>	<p>Prototype test beam results and design of the future Forward Calorimeter in ALICE <i>Ian Bearden</i></p>	<p>Two-loop Electroweak corrections to $gg \rightarrow HH$ <i>Hantian Zhang</i> Hörsaal B, Historic main building 08:50 - 09:10</p>	<p>Physics with W and Z bosons at the LHCb experiment <i>Nathan Allen Grieser</i> Hörsaal M, Historic main building 08:50 - 09:10</p>	<p>One-loop corrections to inclusive production of J/ψ and $\psi(2S)$ <i>Yelyzaveta Yedelkina</i></p>
<p>Beam-beam interaction-induced bias to precision luminosity measurement <i>Joanna Wanczyk</i></p>	<p>The CMS ECAL upgrade for the High-Luminosity LHC era <i>Ka Wa Ho</i> Audimax, Universität Hamburg 09:10 - 09:30</p>	<p>Higgs Pair Production and Triple Higgs Couplings at the LHC in the 2HDM framework <i>Kateryna Radchenko Serdula</i></p>	<p>Compatibility and combination of world W-boson mass measurements <i>William Barter</i></p>	<p>Production of exotic $X(3872)$ in proton-proton and e^+e^- <i>Antoni Szczurek</i></p>
<p>TWOCRIST: a proof-of-principle of a double-crystal setup <i>Stefano Redaelli</i></p>	<p>Development of the ATLAS Liquid Argon Calorimeter Readout Electronics for the HL-LHC <i>Maheyer Shrofi</i></p>	<p>Probing the nature of electroweak symmetry breaking with Higgs boson pairs in ATLAS <i>Viviana Cavaliere</i></p>	<p>Probing the weak mixing angle at high energies at the LHC and HL-LHC <i>Simone Amoroso</i></p>	<p>Heavy flavor production studies at CMS <i>Valentina Mariani</i></p>
<p>Status of the International Muon Collider Complex Study at 10 TeV <i>KYRIACOS SKOUFARIS</i></p>	<p>The Mu2e crystal calorimeter <i>Dr Stefano Di Falco</i> Audimax, Universität Hamburg 09:50 - 10:10</p>	<p>Higgs self coupling: status and projections at CMS <i>Saswati Nandan</i> Hörsaal B, Historic main building 09:50 - 10:10</p>	<p>Global fit of electroweak data in the Standard Model and beyond <i>Maurizio Pierini</i> Hörsaal M, Historic main building 09:50 - 10:10</p>	<p>Study of associated quarkonium production in pp collisions <i>Liupan An</i></p>
<p>Machine-Detector interface for multi-TeV Muon Collider <i>Donatella Lucchesi</i></p>	<p>Compact forward e.m. calorimeter based on oriented crystals <i>Marco Romagnoni</i></p>	<p>Constraints on the trilinear and quartic Higgs couplings from triple Higgs production at the LHC and beyond <i>Georg Weiglein</i></p>	<p>The global electroweak fit in the SM and SMEFT <i>Yannick Fischer</i></p>	<p>Latest ALICE results on charm and beauty hadronization <i>Biao Zhang</i></p>
<p>Green Accelerators? Lessons learned from ESS. <i>Dr Anders Sunesson</i></p>				<p>Measurement of the cross-section ratio $\sigma(\psi(2S))/\sigma(J/\psi)$ in pp collisions <i>Alessia Bruni</i></p>

EPS-2023 - Future collider talks

The image displays a collection of overlapping rectangular cards, each representing a talk at the EPS-2023 conference. The cards are arranged in a perspective view, creating a sense of depth. Each card contains the following information:

- Title:** The main topic of the talk, often including specific physics concepts or experiments.
- Speaker:** The name of the person presenting the talk.
- Location and Time:** The specific room (e.g., Hörsaal H, Audimax) and the scheduled time slot.

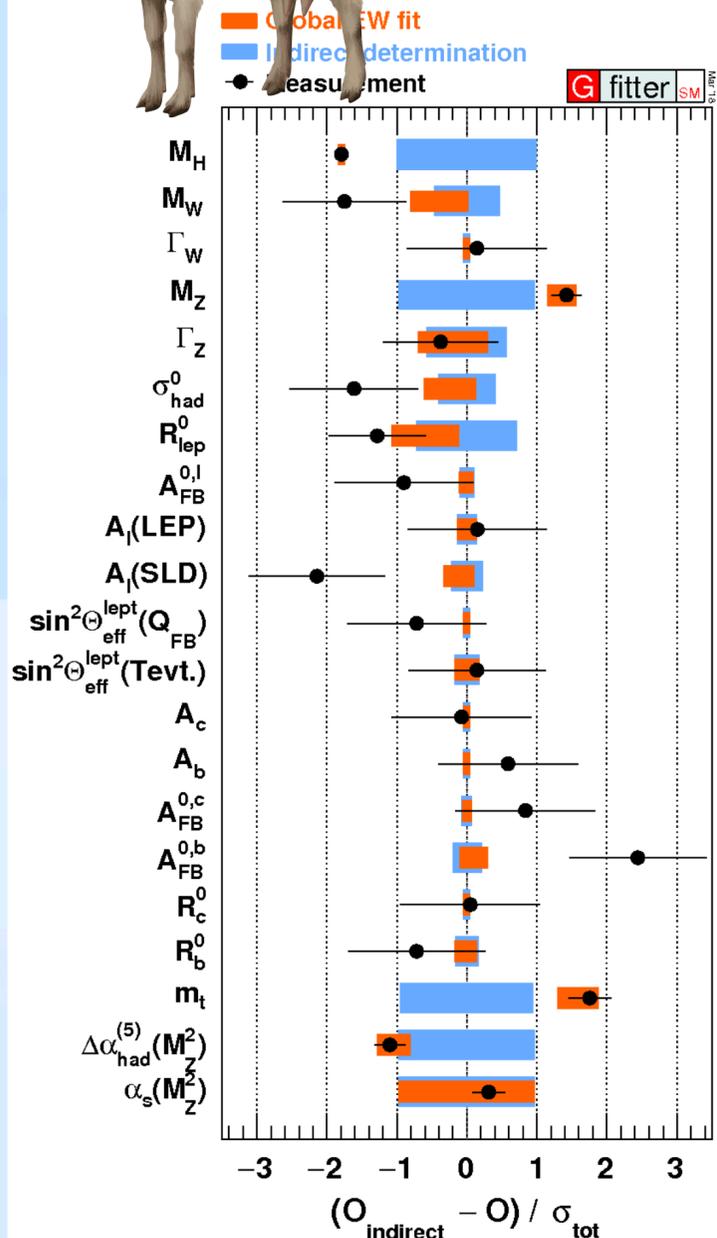
Some visible titles and speakers include:

- SuperKEKB Status** by Prof. Mika Masuzawa
- Experimental observation of polarization correl.** by Deepak Kumar
- New tests of short-distance dynamics in $b \rightarrow sll$ decays** by Arianna Tinari
- Higgs physics with II C** by Dr Guennadi Borissov
- Hadron physics results at KLOE-2** by Paolo Gauzzi
- The Mu2e experiment** by Stefano Di Falco
- Associated top pair and single top production in ATLAS and CMS (excluding ttW and tttt, but including heavy flavour)** by Dr Guennadi Borissov
- Observation of anti-** by Lovisa Rygaard
- The search of the X17 particle with the MEG-II detector** by Hicham Benmansour
- Flavor Hierar** by Dr Lorenzo Sestini
- Long-lived ALPs in top final states** by Carl Mikael Berggren
- The road to a time-resolved RICH at LHCb** by Federica Borgato
- New results on $S\bar{t}l\bar{b}(\bar{t})W$ and 4-top production with the ATLAS experime** by Rustem Ospanov
- "Here be SUSY" - Prospects for SUSY searches at future c** by Sourav Patra
- R&D towards the detector for the Muon Collider** by Matthew Wing
- Soft-QCD and forward proton measurements with ATLAS** by Gabriela Alejandra Navarro
- Search for charged lepton flavor violation at Belle** by Sven Teunissen
- Obtaining the ultimate calibration and performance of the CMS Electromagnetic Calorimeter in LHC Run 2** by Jin Wang
- Central exclusive production in CMS+TOTEM** by Ferenc Siklér
- Lepton and neutron EDM as probe of general 2HDM** by Sven Teunissen
- Scintillating sampling ECAL technology for the LHCb PicoCal** by Matteo Salomoni
- Asymmetric collisions in MadGraph5_aMC@NLO** by Ms LABONI MANNA
- Searching for top squarks from the landscape at HL-LHC** by Juhi Dutta
- An overview of the CMS detector** by Stefano Manzoni
- Latest Magnetic Monopole Search Results from NOVA** by Martin Frank
- Higgs boson mass and width measurement with the ATLAS detector** by Stefano Manzoni
- Asymmetric collisions in MadGraph5_aMC@NLO** by Ms LABONI MANNA
- Exclusive diffractive bremsstrahlung of one and two photons** by Antoni Szczurek
- Boosted Higgs boson properties (mass/width) at CMS** by Filippo Errico
- Production of charm and neutrinos in far-forward experim** by Prof. Antoni Szczurek
- Higgs boson CP property measurements at the ATLAS exper** by Christian Grefe
- Stray light noise simulations for the Einstein Telescope and Virgo and the use of instrumented baffles** by Marc Andrés-Carcasona
- Hadron Production at LHCb Experiment** by Saliha Bashir
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SM

Everything looks SM-like at LHC Greatest Of All Theories



Standard Model Total P

pp	$\sigma = 96.07 \pm 0.18 \pm 0.91$ mb (data) COMPETE HPR1R2 (theory)
W	$\sigma = 95.35 \pm 0.38 \pm 1.3$ mb (data) COMPETE HPR1R2 (theory)
Z	$\sigma = 190.1 \pm 0.2 \pm 6.4$ nb (data) DYNLO + CT14NNLO (theory)
t \bar{t}	$\sigma = 112.69 \pm 3.1$ nb (data) DYNLO + CT14NNLO (theory)
t \bar{t} -chan	$\sigma = 98.71 \pm 0.028 \pm 2.191$ nb (data) DYNLO + CT14NNLO (theory)
Wt	$\sigma = 56.43 \pm 0.03 \pm 1.66$ nb (data) DYNLO+CT14 NNLO (theory)
H	$\sigma = 34.24 \pm 0.03 \pm 0.92$ nb (data) DYNLO+CT14 NNLO (theory)
WW	$\sigma = 29.53 \pm 0.03 \pm 0.77$ nb (data) DYNLO+CT14 NNLO (theory)
WZ	$\sigma = 826.4 \pm 3.6 \pm 19.6$ pb (data) top++ NNLO+NNLL (theory)
ZZ	$\sigma = 242.9 \pm 1.7 \pm 8.6$ pb (data) top++ NNLO+NNLL (theory)
t \bar{t} W	$\sigma = 182.9 \pm 3.1 \pm 6.4$ pb (data) top++ NNLO+NNLL (theory)
t \bar{t} Z	$\sigma = 247 \pm 6 \pm 46$ pb (data) NLO+NNLL (theory)
WWZ	$\sigma = 89.6 \pm 1.7 \pm 7.2 \pm 6.4$ pb (data) NLO+NNLL (theory)
t \bar{t} t \bar{t}	$\sigma = 68 \pm 2 \pm 8$ pb (data) NLO+NNLL (theory)
WWWW	$\sigma = 94 \pm 10 \pm 28 \pm 23$ pb (data) NLO+NNLL (theory)
WWZZ	$\sigma = 23 \pm 1.3 \pm 3.4 \pm 3.7$ pb (data) NLO+NNLL (theory)
WWZZ	$\sigma = 16.8 \pm 2.9 \pm 3.9$ pb (data) NLO+NNLL (theory)
WWZZ	$\sigma = 55.5 \pm 3.2 \pm 2.4 \pm 2.2$ pb (data) LHC-HXSWG YR4 (theory)
WWZZ	$\sigma = 27.7 \pm 3 \pm 2.3 \pm 1.9$ pb (data) LHC-HXSWG YR4 (theory)
WWZZ	$\sigma = 22.1 \pm 6.7 \pm 5.3 \pm 3.5 \pm 2.7$ pb (data) LHC-HXSWG YR4 (theory)
WWZZ	$\sigma = 130.04 \pm 1.7 \pm 10.6$ pb (data) NNLO (theory)
WWZZ	$\sigma = 68.2 \pm 1.2 \pm 4.6$ pb (data) NNLO (theory)
WWZZ	$\sigma = 51.9 \pm 2 \pm 4.4$ pb (data) NNLO (theory)
WWZZ	$\sigma = 51 \pm 0.8 \pm 2.3$ pb (data) MATRIX (NNLO) (theory)
WWZZ	$\sigma = 24.3 \pm 0.6 \pm 0.9$ pb (data) MATRIX (NNLO) (theory)
WWZZ	$\sigma = 19 \pm 1.4 \pm 1.3 \pm 1$ pb (data) MATRIX (NNLO) (theory)
WWZZ	$\sigma = 17.3 \pm 0.6 \pm 0.8$ pb (data) Matrix (NNLO) & Sherpa (NLO) (theory)
WWZZ	$\sigma = 7.3 \pm 0.4 \pm 0.4 \pm 0.3$ pb (data) NNLO (theory)
WWZZ	$\sigma = 6.7 \pm 0.7 \pm 0.5 \pm 0.4$ pb (data) NNLO (theory)
WWZZ	$\sigma = 4.8 \pm 0.8 \pm 1.6 \pm 1.3$ pb (data) NLO+NNLL (theory)
WWZZ	$\sigma = 870 \pm 130 \pm 140$ fb (data) Madgraph5 + aMCNLO (theory)
WWZZ	$\sigma = 369 \pm 86 \pm 79 \pm 44$ fb (data) MCFM (theory)
WWZZ	$\sigma = 990 \pm 50 \pm 80$ fb (data) Madgraph5 + aMCNLO (theory)
WWZZ	$\sigma = 176 \pm 52 \pm 48 \pm 24$ fb (data) HELAC+NLO (theory)
WWZZ	$\sigma = 0.82 \pm 0.01 \pm 0.08$ pb (data) NLO QCD (theory)
WWZZ	$\sigma = 0.55 \pm 0.14 \pm 0.15 \pm 0.13$ pb (data) Sherpa 2.2.2 (theory)
WWZZ	$\sigma = 24 \pm 4 \pm 5$ fb (data) NLO QCD + EW (theory)

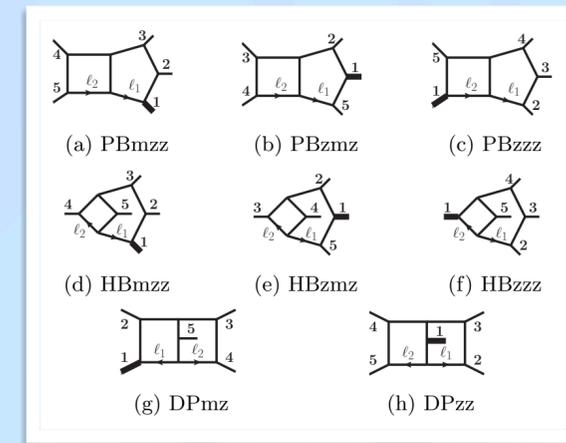


Scattering amplitudes – the frontier at NNLO and beyond

NEW All Two-Loop Feynman Integrals for Five-Point One-Mass Scattering

Abreu, Chicherin, Ita, Page, Sotnikov, Tschernow, Zoia [2023]

Relevant for H/Z/W production in association with two jets at NNLO, or in association with one jet at **N3LO** or H/Z/W at **N4LO**



Two-Loop Helicity Amplitudes for Diphoton Plus Jet Production in Full Color

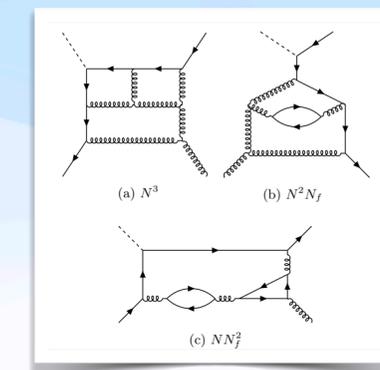
Agarwal, Buccioni, von Manteuffel, Tancredi [2021]

Relevant for $\gamma\gamma$ production in association with one jet at NNLO, or $\gamma\gamma$ production at **N3LO**

NEW Planar three-loop QCD helicity amplitudes for V +jet production at hadron colliders

Gehrmann, Jakubcik, Mella, Syrrakos, Tancredi [2023]

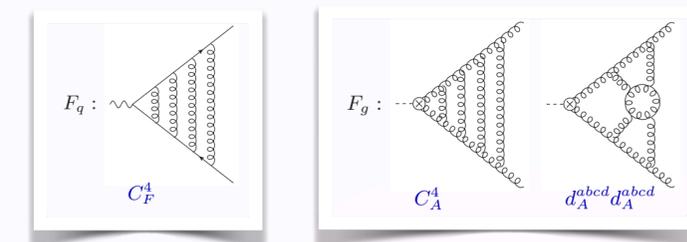
Relevant for Z/W/ γ^* production in association with one jet at **N3LO** or Z/W/ γ^* at **N4LO**



Three-loop helicity amplitudes for diphoton production in gluon fusion

Bargiela, Caola, von Manteuffel, Tancredi [2021]

Relevant for $\gamma\gamma$ production at **N3LO**



Quark and Gluon Form Factors in Four-Loop QCD

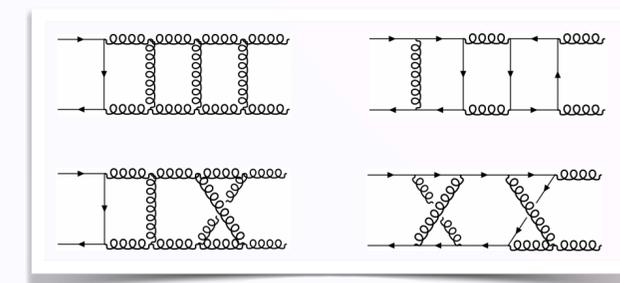
Lee, von Manteuffel, Schabinger, Smirnov, Smirnov, Steinhauser [2022]

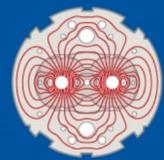
Relevant for H/Z/W/ γ^* at **N4LO**

Three-loop helicity amplitudes for quark-gluon scattering in QCD

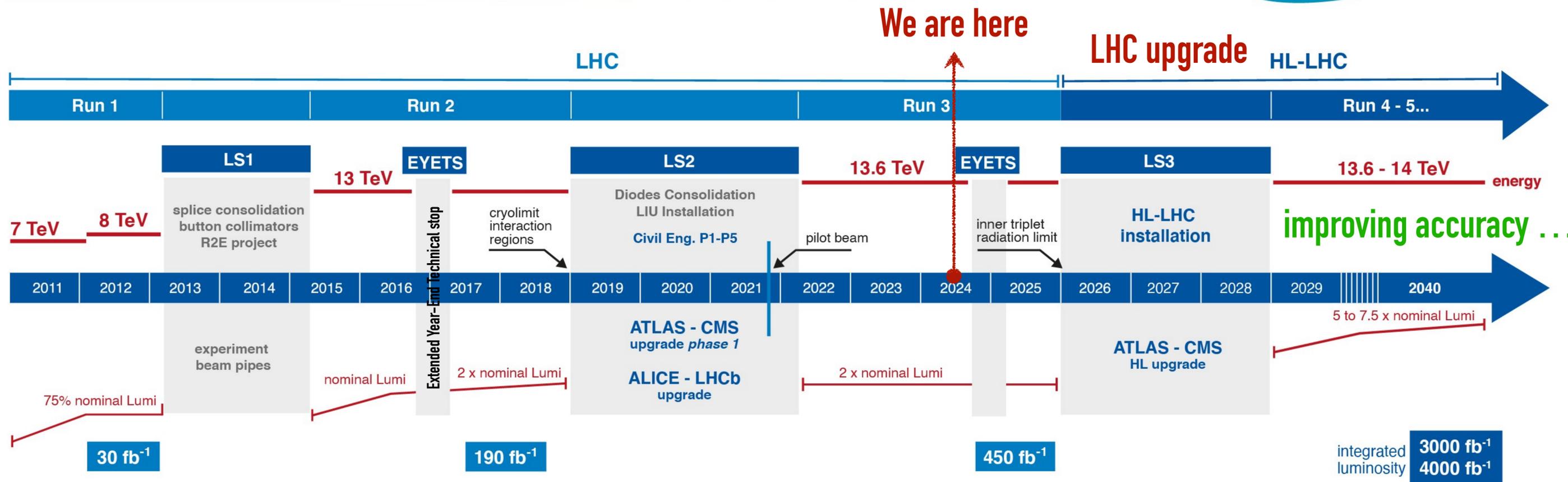
Caola, Chakraborty, Gambuti, von Manteuffel, Tancredi [2022]

Relevant for jj at **N3LO**





LHC / HL-LHC Plan



improving accuracy ...

HL-LHC TECHNICAL EQUIPMENT:



HL-LHC CIVIL ENGINEERING:



LHC operational in its 3rd and last running period
LHC exceed its design luminosity
but did not reach (almost) design energy

Motivation

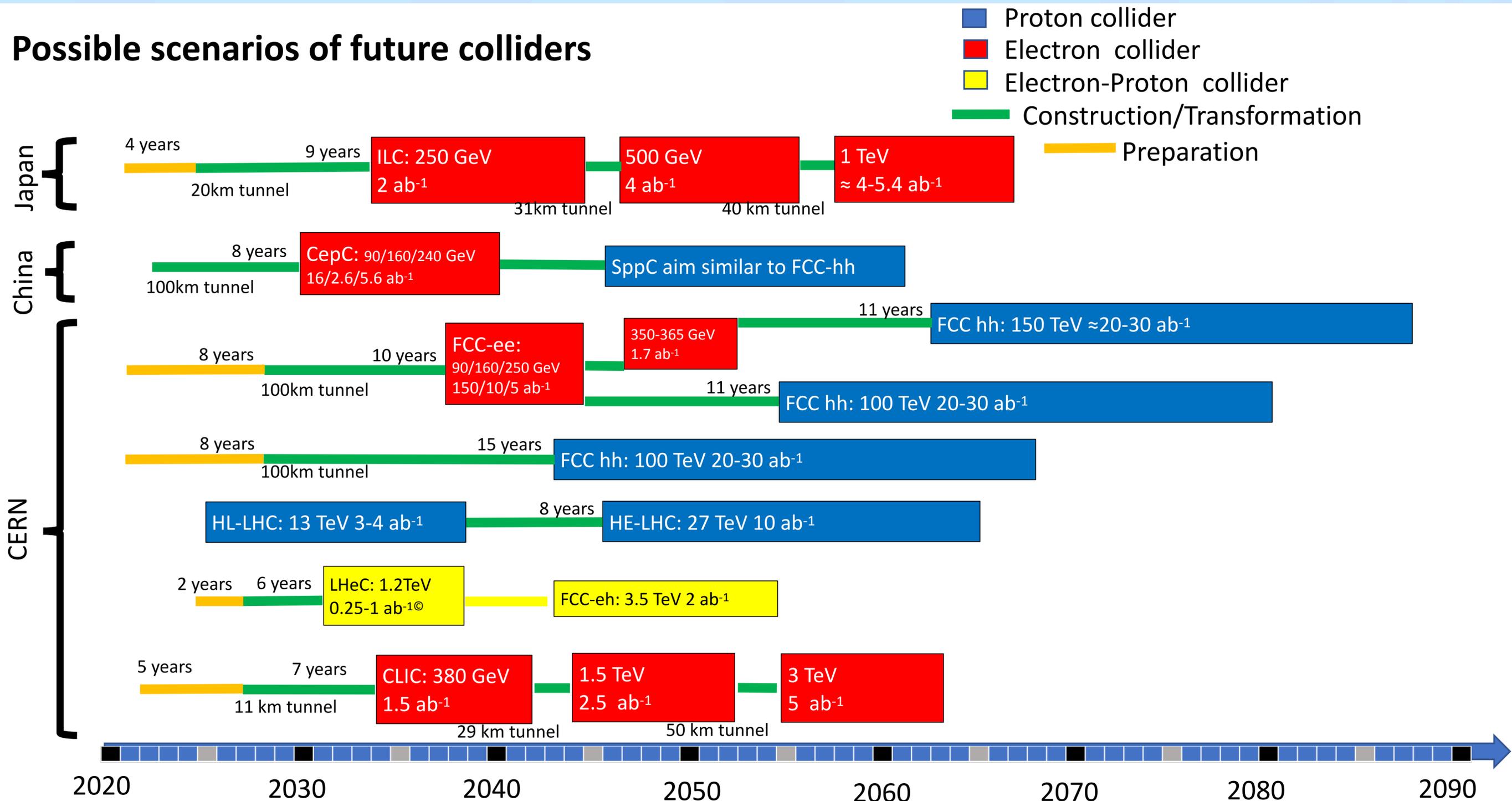
All options are aimed at attobarn⁻¹ physics

It requires going well beyond NNLO for theory

Even conservative estimates are not achievable with current techniques

Most optimistic scenario establishes 1% – 3% theoretical accuracy as mandatory at current Run III and at the HL-LHC

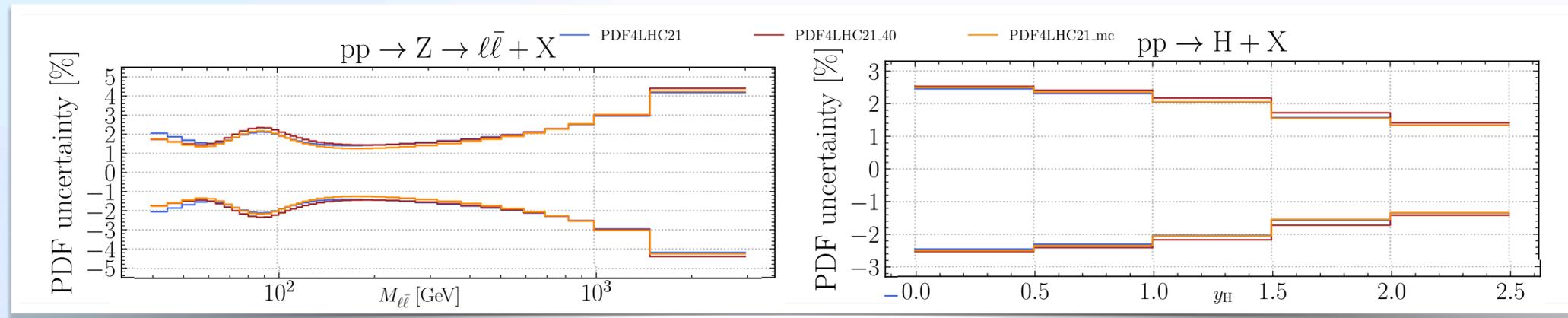
Possible scenarios of future colliders



The Path forward to N3LO. In 2022 Snowmass Summer Study, 3 2022

State of the art PDFs (NNLO)

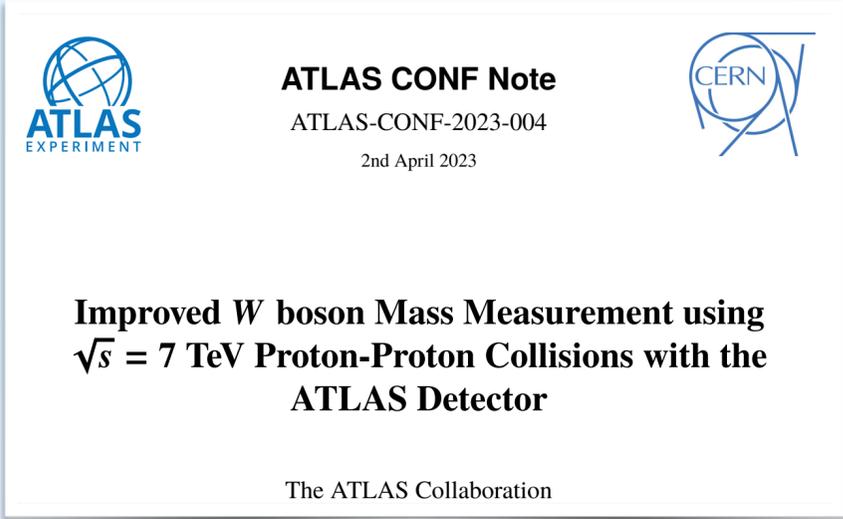
- CT18** LHC measurements in single-inclusive jet production with the full rapidity coverage, as well as production of Drell-Yan pairs, top-quark pairs, and high-pT Z bosons, are included to achieve the greatest sensitivity to the PDFs
- MSHT20** Determination controlled by LHC data: LHC 7 and 8 TeV data sets on vector boson production, inclusive jets and top quark distributions
Reduced uncertainties in predictions for processes such as Higgs, top quark pair and W, Z production at post LHC Run-II energies
- NNPDF4.0** Determination controlled by LHC data: unlike in the past, almost DIS-only
- ABMP16** The theory predictions include new improved approximations at NNLO for the production of heavy quarks in DIS and for the hadro-production of single-top quarks.
- ATLASpdf21** ATLAS sets of $W, Z/\gamma^*$ data, $tt^{\bar{}}$ data and $V+$ jets data considered in a single QCD fit (also other sets)
- PDF4LHC21** It is based on the Monte Carlo combination of the CT18, MSHT20, and NNPDF3.1 sets followed by either its Hessian reduction or its replica compression



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In the extraction of many fundamental parameters, PDF uncertainties dominate

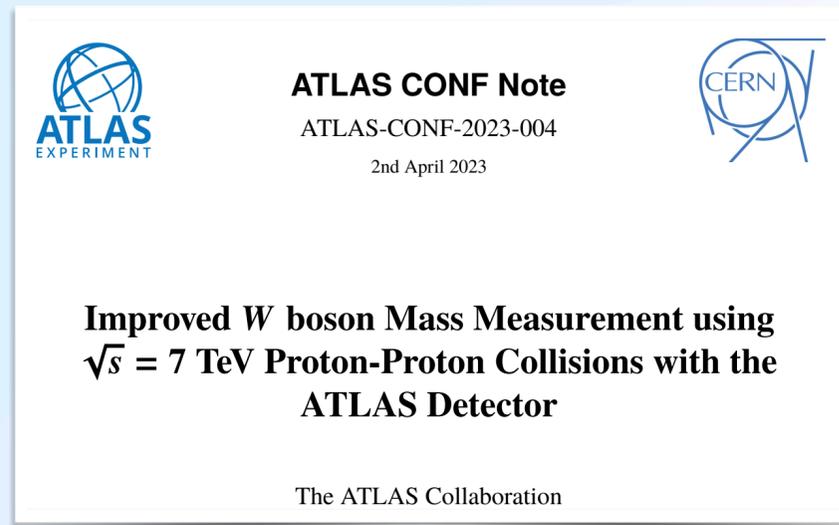


Obs.	Mean [MeV]	Elec. Unc.	PDF Unc.	Muon Unc.	EW Unc.	PS & A_i Unc.	Bkg. Unc.	Γ_W Unc.	MC stat. Unc.	Lumi Unc.	Recoil Unc.	Total sys.	Data stat.	Total Unc.
p_T^ℓ	80360.1	8.0	7.7	7.0	6.0	4.7	2.4	2.0	1.9	1.2	0.6	15.5	4.9	16.3
m_T	80382.2	9.2	14.6	9.8	5.9	10.3	6.0	7.0	2.4	1.8	11.7	24.4	6.7	25.3

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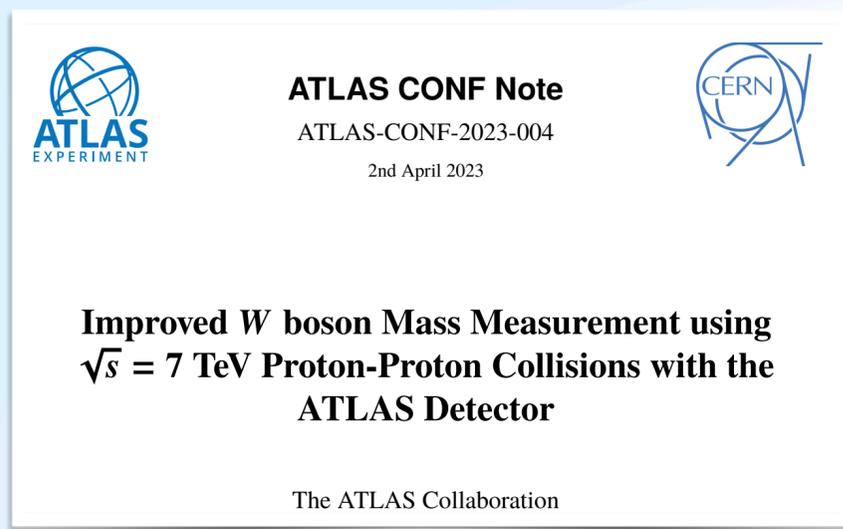
Discrepancies between NNPDF4.0 and the data are observed for the measured Z-boson rapidity distribution at 7 TeV

Obs.	Mean [MeV]	Elec. Unc.	PDF Unc.	Muon Unc.	EW Unc.	PS & A_i Unc.	Bkg. Unc.	Γ_W Unc.	MC stat. Unc.	Lumi Unc.	Recoil Unc.	Total sys.	Data stat.	Total Unc.
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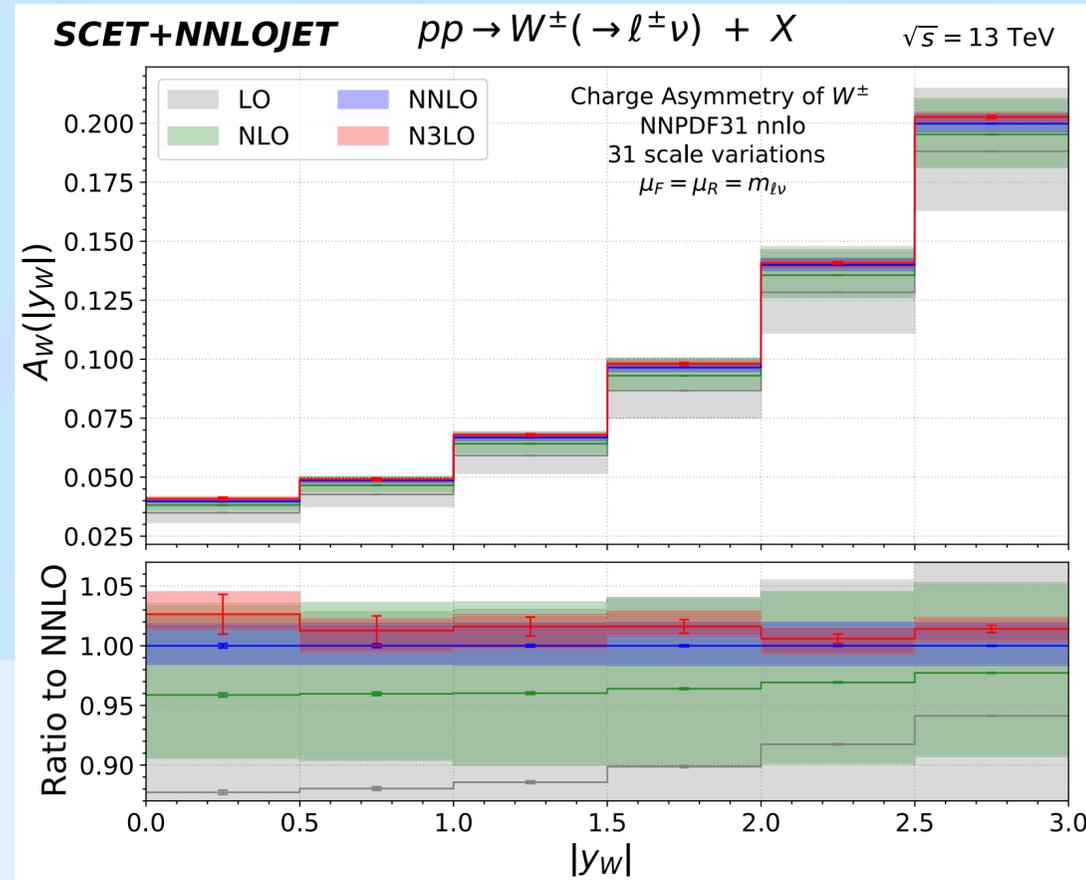
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For sure there will be a lot of improvements in the next years regarding PDF uncertainties and accord between different groups

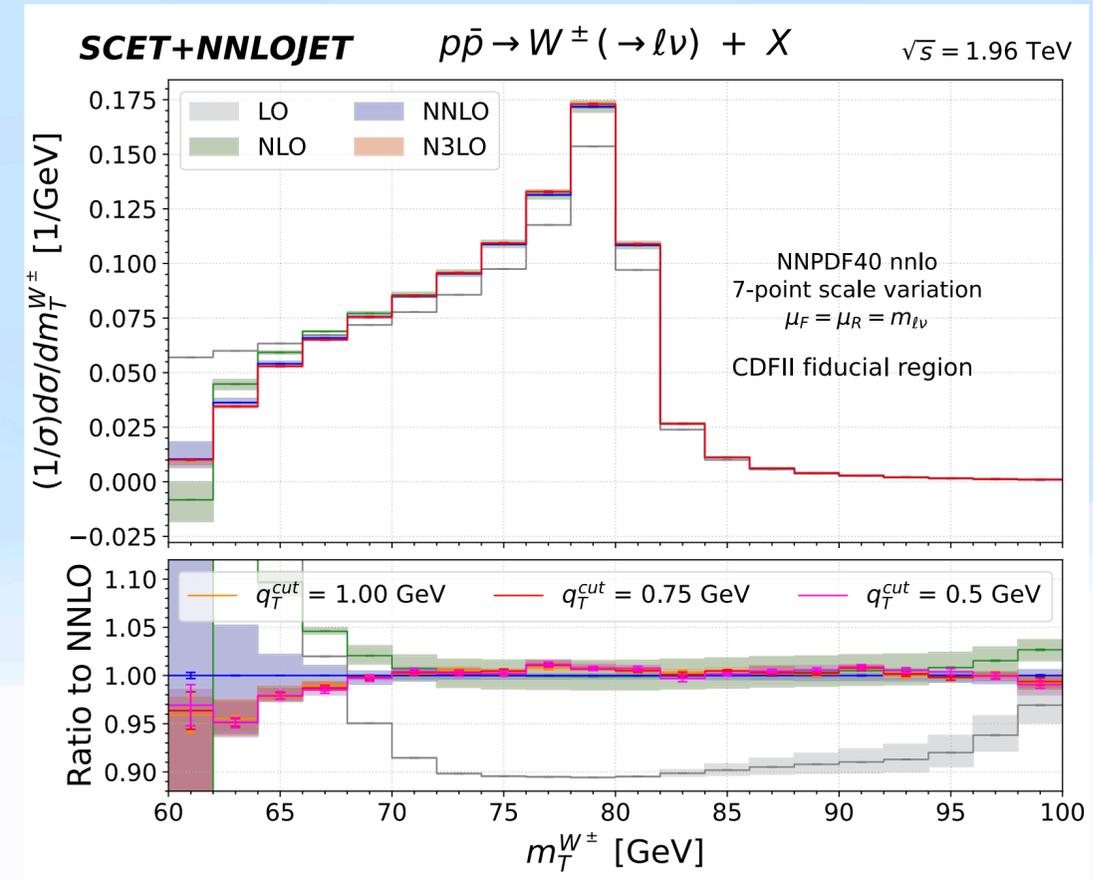
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NEW Transverse mass distribution and charge asymmetry in W boson production to third order in QCD

Chen, Gehrmann, Glover, Huss, Yang, Zhu [2023]



$$A_W(|y_W|) = \frac{d\sigma/d|y_{W^+}| - d\sigma/d|y_{W^-}|}{d\sigma/d|y_{W^+}| + d\sigma/d|y_{W^-}|}$$



$$m_T^{W^\pm} = \sqrt{2E_T^{\ell^\pm} E_T^\nu (1 - \cos\Delta\phi)},$$

- Charge asymmetry relevant for determination of PDFs
- Transverse mass relevant for M_W determination
- N3LO perturbative uncertainties estimated by scale variations are found to be about $\pm 1\%$ to $\pm 1.5\%$
- Distortions to the shape of the distributions are minimal at N3LO and only become visible outside the peak region of the m_{W^\pm} distribution

Claiming “true N3LO precision” → including mixed QCD+EW effects

$$\alpha_s^2 \sim \alpha$$

Including all the effects that could compete with the size of the NNLO or N3LO QCD corrections

Perturbative expansion
 $\alpha_s \ll 1 ; \alpha \ll 1$

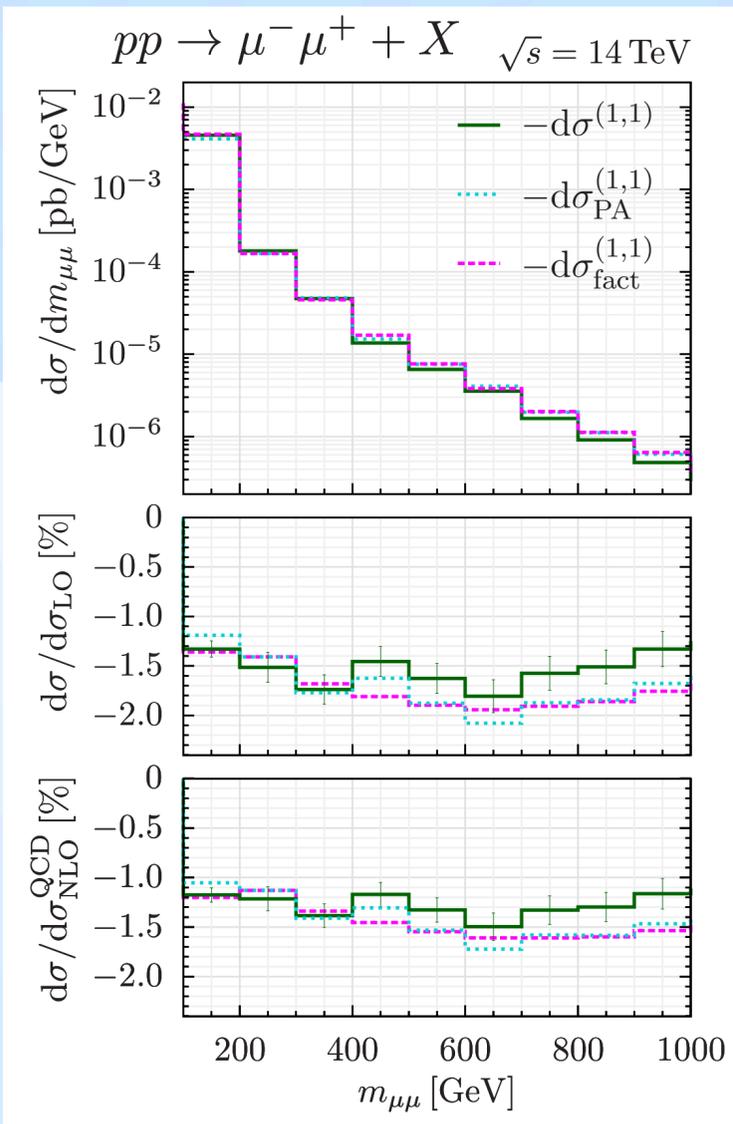
$$\hat{\sigma} = \underbrace{\sigma^{(\hat{0})}}_{\text{LO}} + \underbrace{\alpha_s^1 \sigma^{(\hat{1})}}_{\text{NLO}} + \underbrace{\alpha_s^2 \sigma^{(\hat{2})}}_{\text{NNLO}} + \dots + \underbrace{\alpha^1 \sigma^{(\hat{0};1)}}_{\text{NLO EW}} + \alpha^2 \sigma^{(\hat{0};2)} + \dots + \underbrace{\alpha_s^1 \alpha^1 \sigma^{(\hat{1};1)}}_{\text{NNLO QCD+EW}} + \dots$$

Claiming “true N3LO precision” → including mixed QCD+EW effects

$$\alpha_s^2 \sim \alpha$$

Including all the effects that could compete with the size of the NNLO or N3LO QCD corrections

Bonciani et al [2021]



- Effects typically at the level of the $\mathcal{O}(1\%)$
- EW could be enhanced in certain kinematical regions

A lot of recent activity computing this kind of corrections (not complete list)

Dittmaier, Huss, Schwinn [2015]
 LC, Ferrera, Sborlini [2018]
 Dittmaier, Schmidt, Schwarz [2020]
 Delto, Jaquier, Melnikov, Röntsch [2020]
 LC, de Florian, Der, Mazzitelli [2020]
 Buonocore, Grazzini, Kallweir, Savoini, Tramontano [2021]
 Behring, Buccioni, Caola, Delto, Jaquier, Melnikov, Röntsch [2020]
 Dittmaier, Schmidt, Schwarz [2020]
 Buccioni et al [2022]
 Autieri, LC, Ferrera, Sborlini [2023]

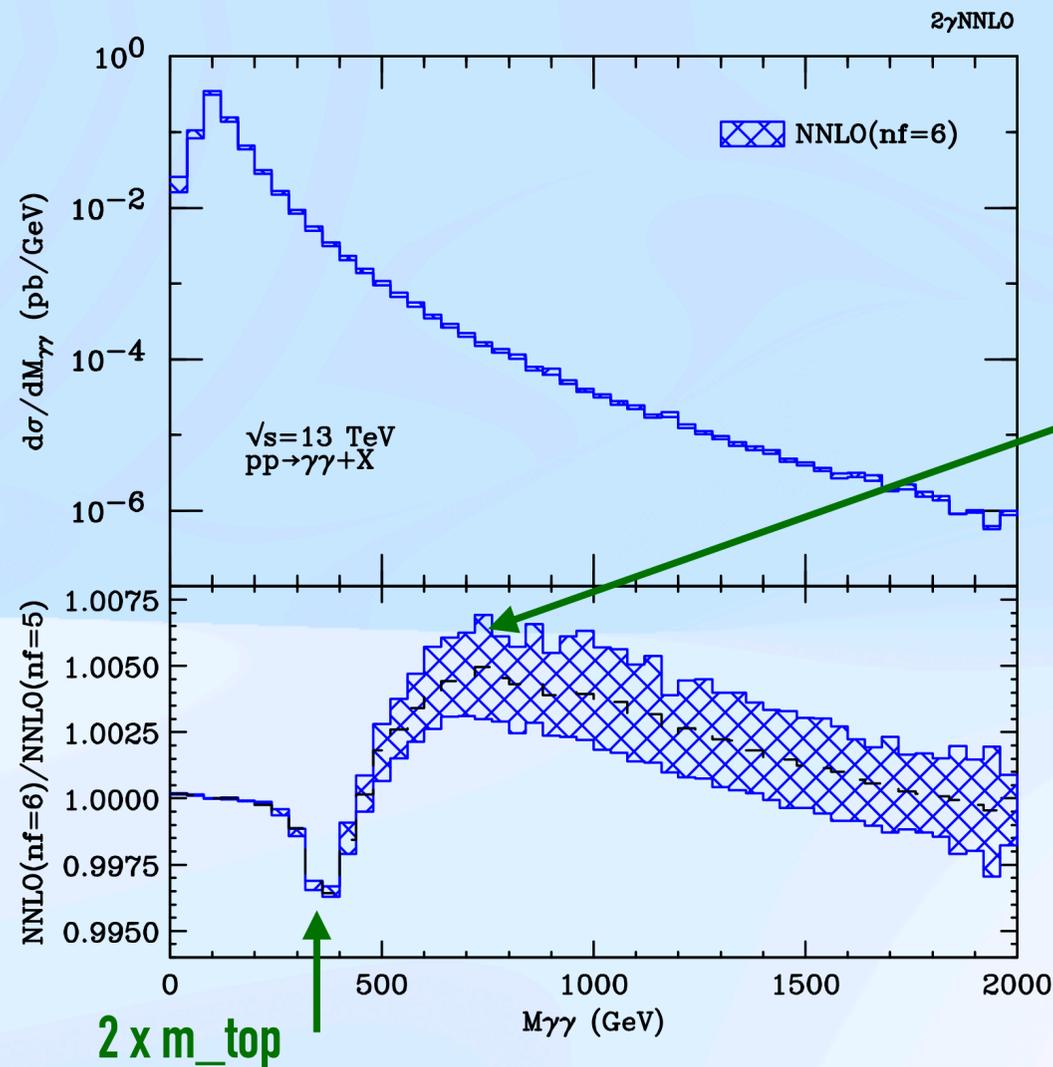
Mixed QCD+EW(QED) effects

Subtraction prescriptions requires splitting functions at the same level of accuracy

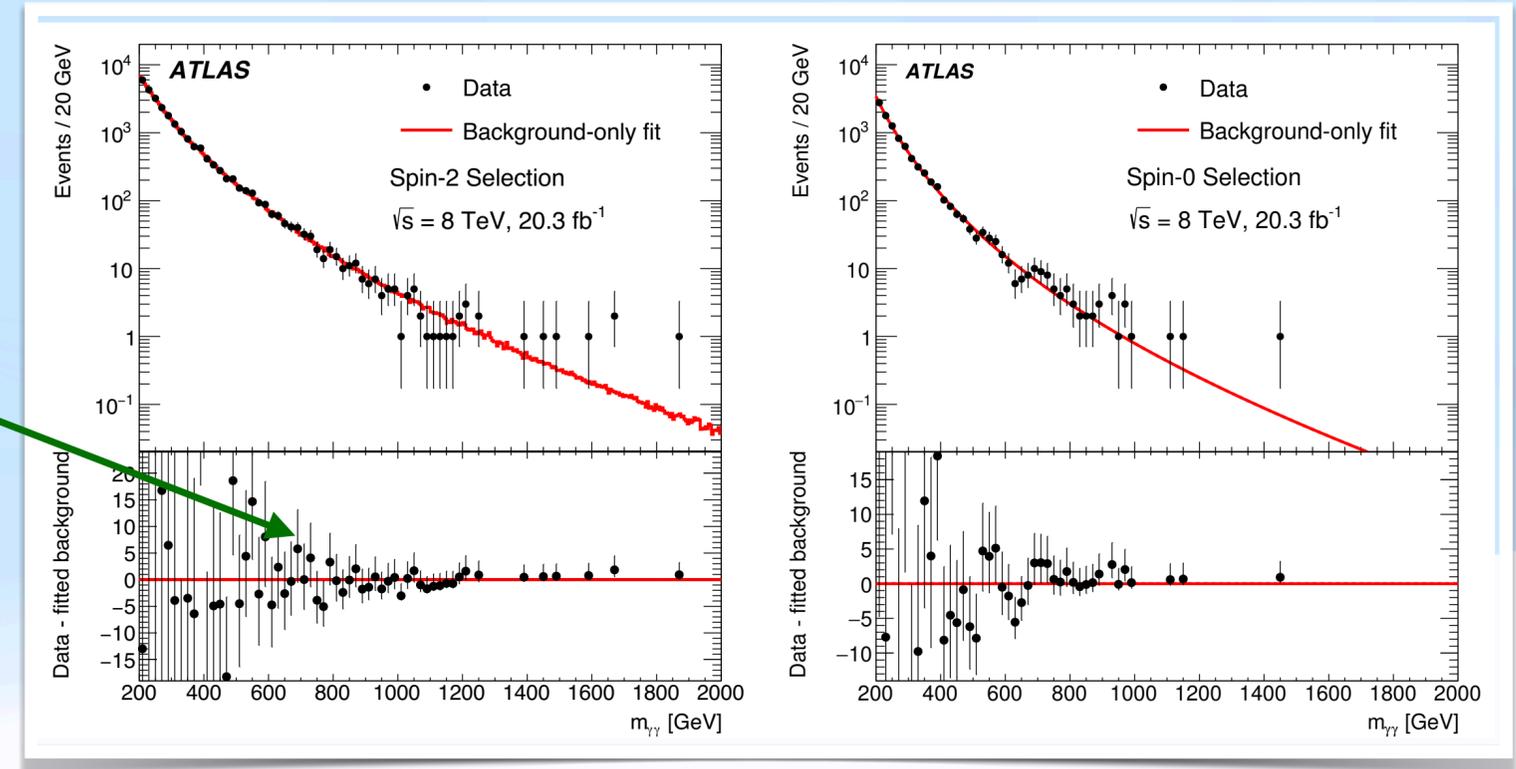
Mixed QCD+QED splitting functions known De Florian, Rodrigo, Sborlini [2016]

NEW Diphoton production at NNLO with full top quark mass dependence

Becchetti, Bonciani, LC, Coro, Ripani [2023] Full massive $2 \rightarrow 2$



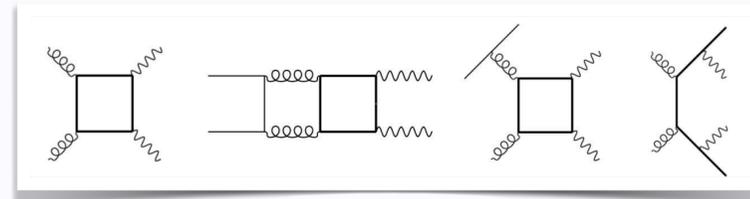
750 GeV not "very" affected by fiducial cuts



Example of the necessity of precise TH predictions

Example of comparison of "NEW" bumps or kinks inside the SM

- All massive contributions taken into account: two-loop, loop induced, one-loop-real and double real ($pp \rightarrow \gamma\gamma tt$)
- Loop induced gg channel and two-loop ($qqbar$) dominate the shape



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Search for resonances in diphoton events at $\sqrt{s} = 13$ TeV with the ATLAS detector

ATLAS EXPERIMENT
 The ATLAS collaboration

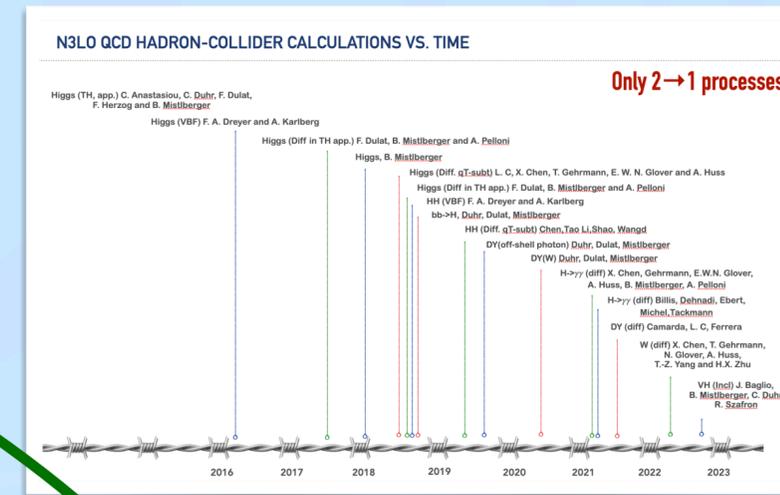
State of the art PDFs (aN3LO)

NEW PDFs at approximate N3LO

MSHT20sN3LO McGowan, Cridge, Harland-Lang, Thorne [2022]
Cridge, Harland-Lang, Thorne [2023]

- Approximated splitting functions, transition matrix elements, coefficient functions and K-factors for multiple processes to N3LO → 20 nuisance parameters
- Improvement in data description from NNLO to N3LO
- aN3LO $\alpha_s(m_Z)$ value stated is in agreement with the MSHT20 NNLO result and the world average within uncertainties
- PDFs include an estimation for missing N3LO contributions (the leading theoretical uncertainty) and implicitly some MHOU beyond this within their PDF uncertainties. Due to this factorisation scale variations are no longer necessary in calculations involving aN3LO PDFs

We used NNLO PDFs in almost all our N3LO calculations!



NEW splitting functions at N3LO (Pqq)

Falcioni, Herzog, Moch, Vogt [2023]

Notice that in fixed order calculations

σ order	PDF order	$\sigma + \Delta\sigma_+ - \Delta\sigma_-$ (pb)	σ (pb) + $\Delta\sigma_+ - \Delta\sigma_-$ (%)
PDF uncertainties			
N ³ LO	aN ³ LO (no theory unc.)	45.296 + 0.723 - 0.545	45.296 + 1.60% - 1.22%
	aN ³ LO ($H_{ij} + K_{ij}$)	45.296 + 0.832 - 0.755	45.296 + 1.84% - 1.67%
	aN ³ LO (H'_{ij})	45.296 + 0.821 - 0.761	45.296 + 1.81% - 1.68%
	NNLO	47.817 + 0.558 - 0.581	47.817 + 1.17% - 1.22%
NNLO	NNLO	46.206 + 0.541 - 0.564	46.206 + 1.17% - 1.22%
PDF + Scale uncertainties			
N ³ LO	aN ³ LO (no theory unc.)	45.296 + 0.723 - 1.851	45.296 + 1.60% - 4.09%
	aN ³ LO ($H_{ij} + K_{ij}$)	45.296 + 0.832 - 1.923	45.296 + 1.84% - 4.25%
	aN ³ LO (H'_{ij})	45.296 + 0.821 - 1.926	45.296 + 1.81% - 4.25%
	NNLO	47.817 + 0.577 - 2.210	47.817 + 1.21% - 4.62%
NNLO	NNLO	46.206 + 4.284 - 5.414	46.206 + 9.27% - 11.72%

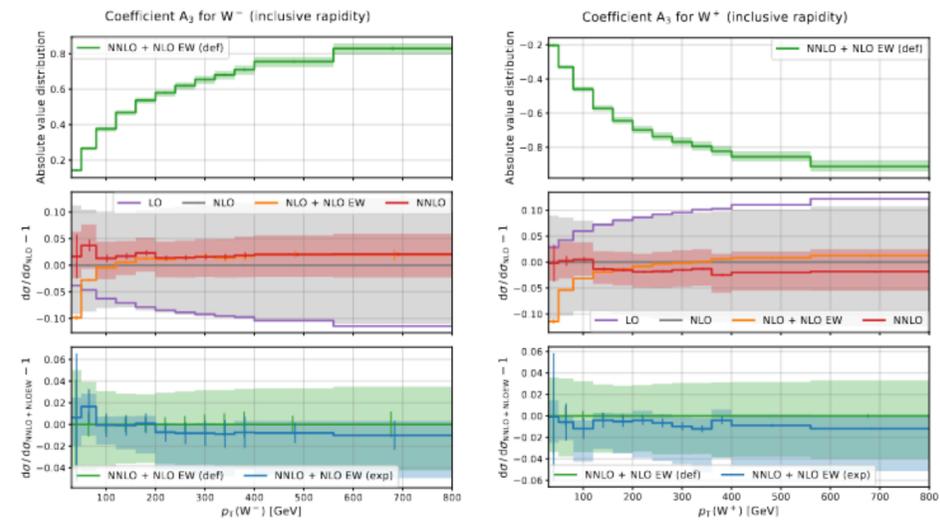
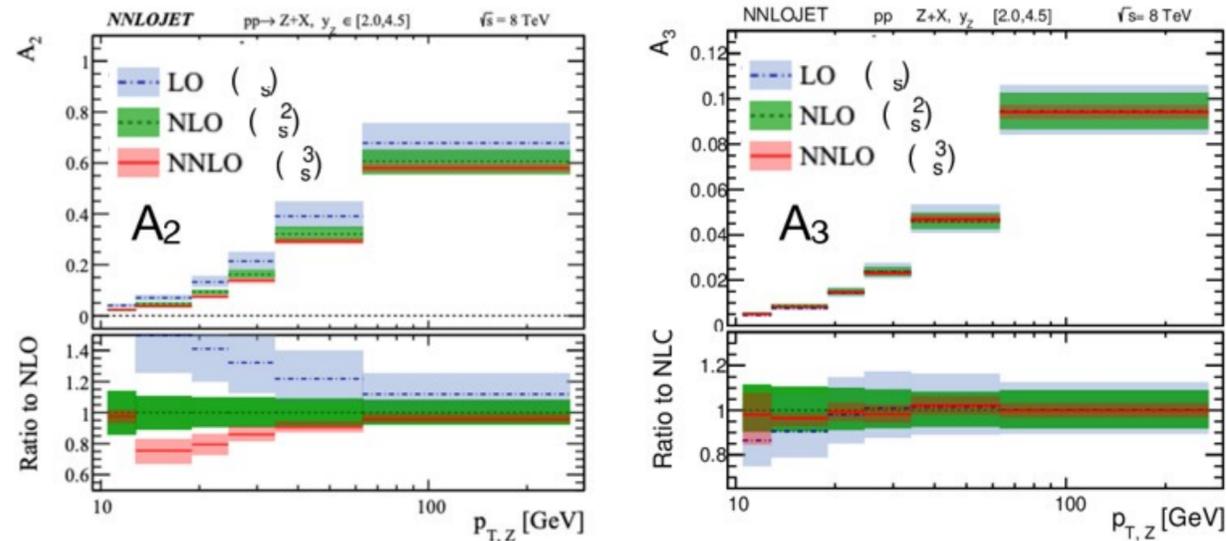
factorisation scale variation is contained within the PDF uncertainties.

The decreasing central value is not covered by the uncertainties >5%

The complexity is fourth order

Order fixed order	Order required Splitting
LO	-
NLO	LO
NNLO	NLO
N3LO	NNLO
N4LO	N3LO

Ai at $O(\alpha_s^3)$



- Accurate modelling of W Ai is very important for the W mass measurement
- Recently achieved α_s^3 accuracy with
 - ➔ NNLOJET
 - ➔ STRIPPER
 - ➔ MCFM/NJETTI
- However no public code yet available for W
- Computing Ai coefficients for the W mass is very expensive ATLAS measurement used $O(\alpha_s^2)$ predictions, and took about 500K CPU hours
- Is it possible to have these predictions available for the next round of W mass measurements?
- What is the preferred and more efficient way of providing these calculations to the experiments?
- Is [HighTea](#) an option?
- Analytic calculations a-la Mirkes [Nucl.Phys.B 387 (1992) 3-85], if feasible, would be extremely useful

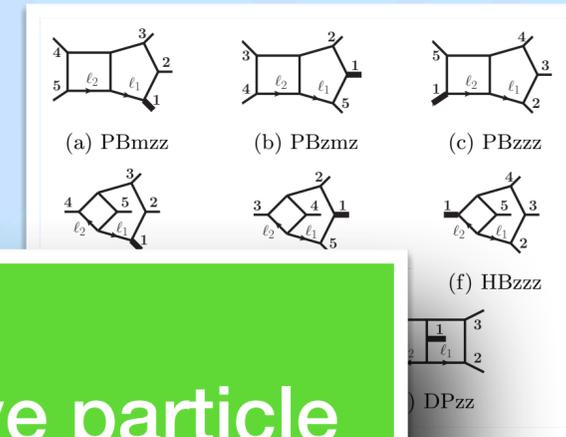
At NNLO!!

~ 60 years!!!!

Scattering amplitudes – the frontier at NNLO and beyond

Abreu, Chicherin, Ita, Page, Sotnikov, Tschernow, Zoia [2023]

NEW All Two-Loop Feynman Integrals for Five-Point One-Mass Scattering

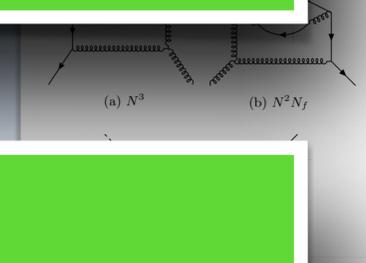


- Relev Frontier at two-loop: 2->3 with one external massive particle
- Two- Frontier at three-loop: 2->2, planar 2->2 with one external massive particle
- Relev Frontier at four-loop: 2->1

Gehrmann, Jakubcik, Mella, Syrrakos, Tancredi [2023]

NEW Planar three-loop QCD helicity amplitudes for V pair production at hadron colliders

- Relev All scattering amplitudes available for $\gamma\gamma$ at N3LO
- All scattering amplitudes available for jj at N3LO



Three-loop helicity amplitudes for diphoton production in gluon fusion

Relevant for $\gamma\gamma$ production at **N3LO**

Lee, von Manteuffel, Schabinger, Smirnov, Smirnov, Steinhauser [2022]

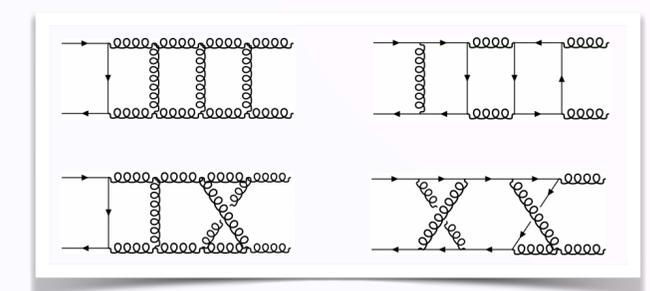
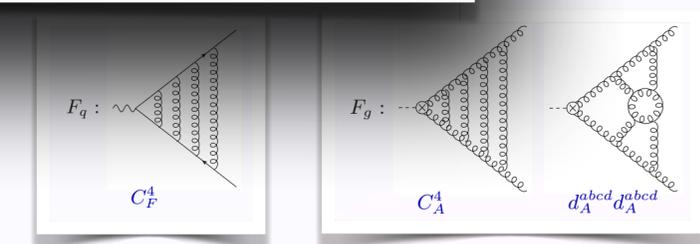
Quark and Gluon Form Factors in Four-Loop QCD

Relevant for $H/Z/W/\gamma^*$ at **N4LO**

Caola, Chakraborty, Gambuti, von Manteuffel, Tancredi [2022]

Three-loop helicity amplitudes for quark-gluon scattering in QCD

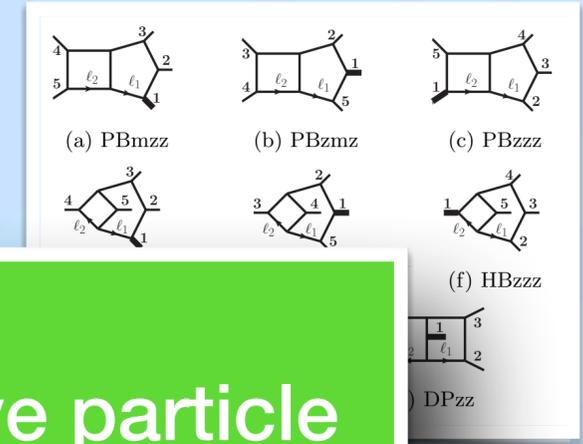
Relevant for jj at **N3LO**



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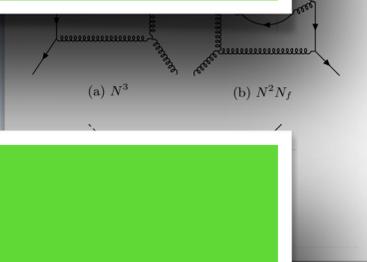


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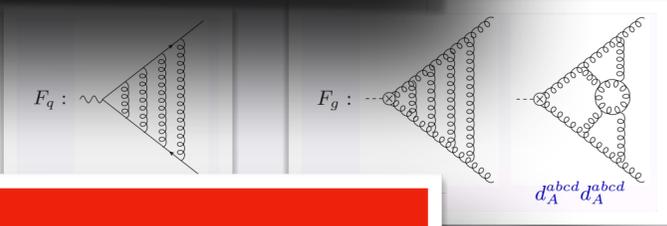
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Three-loop helicity amplitudes for diphoton production in gluon fusion

Relevant for $\gamma\gamma$ production at N3LO



Qual Why did we not break the 2->1 barrier at N3LO?

Relevant for H/Z/W/ γ^* at N4LO

Caola, Chakraborty, Gambuti, von Manteuffel, Tancredi [2022]

Three-loop helicity amplitudes for quark-gluon scattering in QCD

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