LHC theoretical predictions

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Organisation of the talk

Disclaimers

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

iNSPIRE HEP & IArxiv beta → ~10 LHC hep-ph papers per day from 2020 → 14000 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.

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 the next decades

LHC measurements

Reaching and breaking the 1% frontier

EUROPEAN ORGANISATION FOR NUCLEAR RESEARCH (CERN)

Submitted to: EPJC

CERN-EP-2023-171
19th September 2023

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

- Integrated results at the 2% accuracy
- Differential in rapidity < 1% (integrated in pt)
- Double differential 0.5% < Uncert. < 7%

Available on the CERN CDS information server — **CMS PAS SMP-22-017**

CMS Physics Analysis Summary

- Uncertainty < 2.3% (due to lumi)

Contact: cms-pag-conveners-smp@cern.ch — 2023/08/20

Measurement of the inclusive cross section of Z boson production in pp collisions at $\sqrt{s} = 13.6$ TeV

The CMS Collaboration

EUROPEAN ORGANISATION FOR NUCLEAR RESEARCH (CERN)

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

Submitted to: Phys. Lett. B.

CERN-EP-2023-160
15th August 2023

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

The ATLAS Collaboration

JHEP — Published for SISSA by Springer

Received: March 28, 2023
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

- Uncertainty < 2%

The ATLAS collaboration

E-mail: atlas.publications@cern.ch

EUROPEAN ORGANISATION FOR NUCLEAR RESEARCH (CERN)

- Uncertainty < 1%

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

EUROPEAN ORGANISATION FOR NUCLEAR RESEARCH (CERN)

- Uncertainty < 1%

Submitted to: EPJC

CERN-EP-2022-281
20th December 2022

Luminosity determination in pp collisions at $\sqrt{s} = 13$ TeV using the ATLAS detector at the LHC

The ATLAS Collaboration

EUROPEAN ORGANIZATION FOR NUCLEAR RESEARCH (CERN)

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

- Uncertainty < 1%

CMS-LUM-21-001

Luminosity determination using Z boson production at the CMS experiment

The CMS Collaboration*

JHEP — Published for SISSA by Springer

Received: September 3, 2021
Revised: November 16, 2021
Accepted: December 17, 2021
Published: January 10, 2022

- Uncertainty < 1%

Measurement of the W boson mass

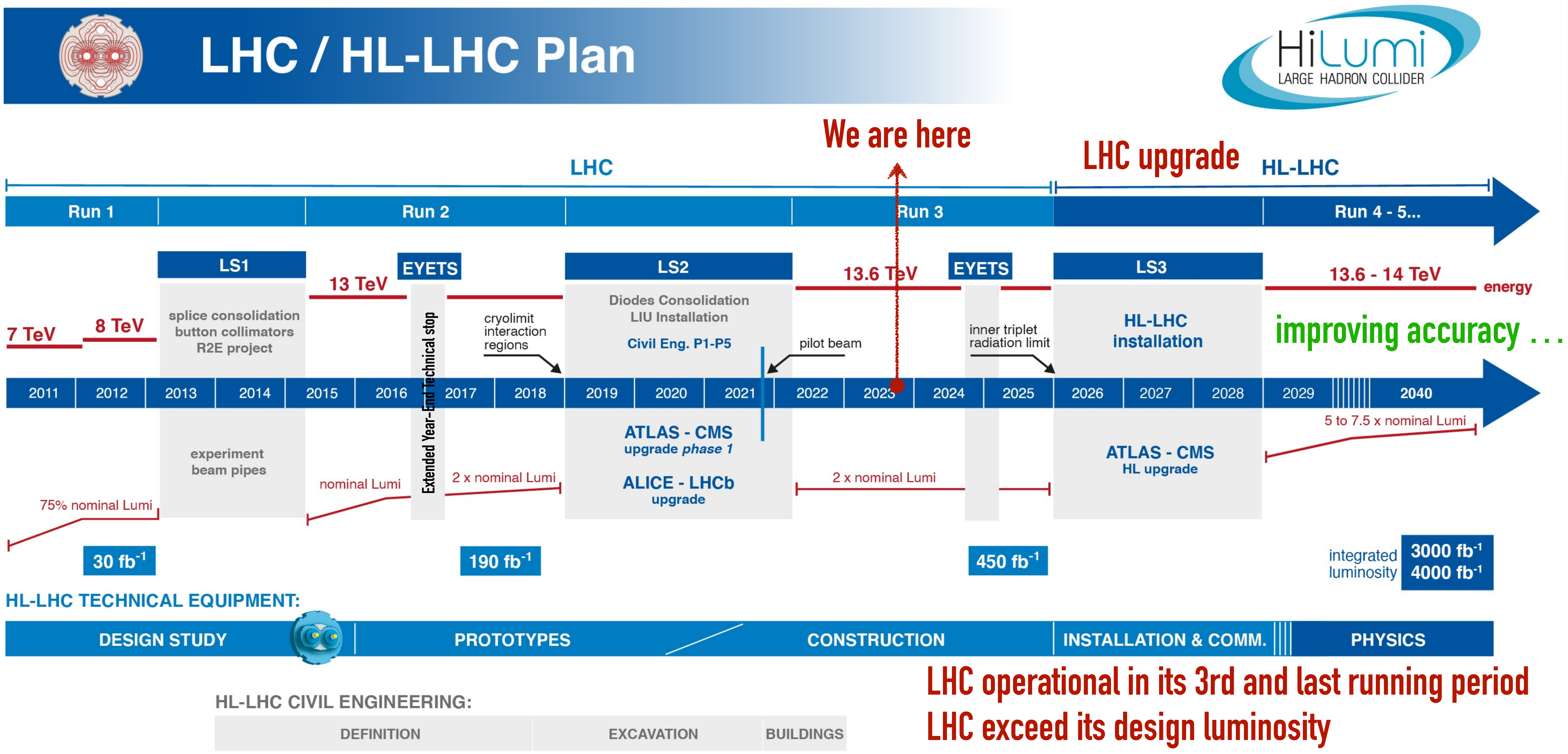
The LHCb collaboration

LHC measurements

Reaching and breaking the 1% frontier

We need equally precise TH predictions. Otherwise the TH uncertainties will dominate

Motivation

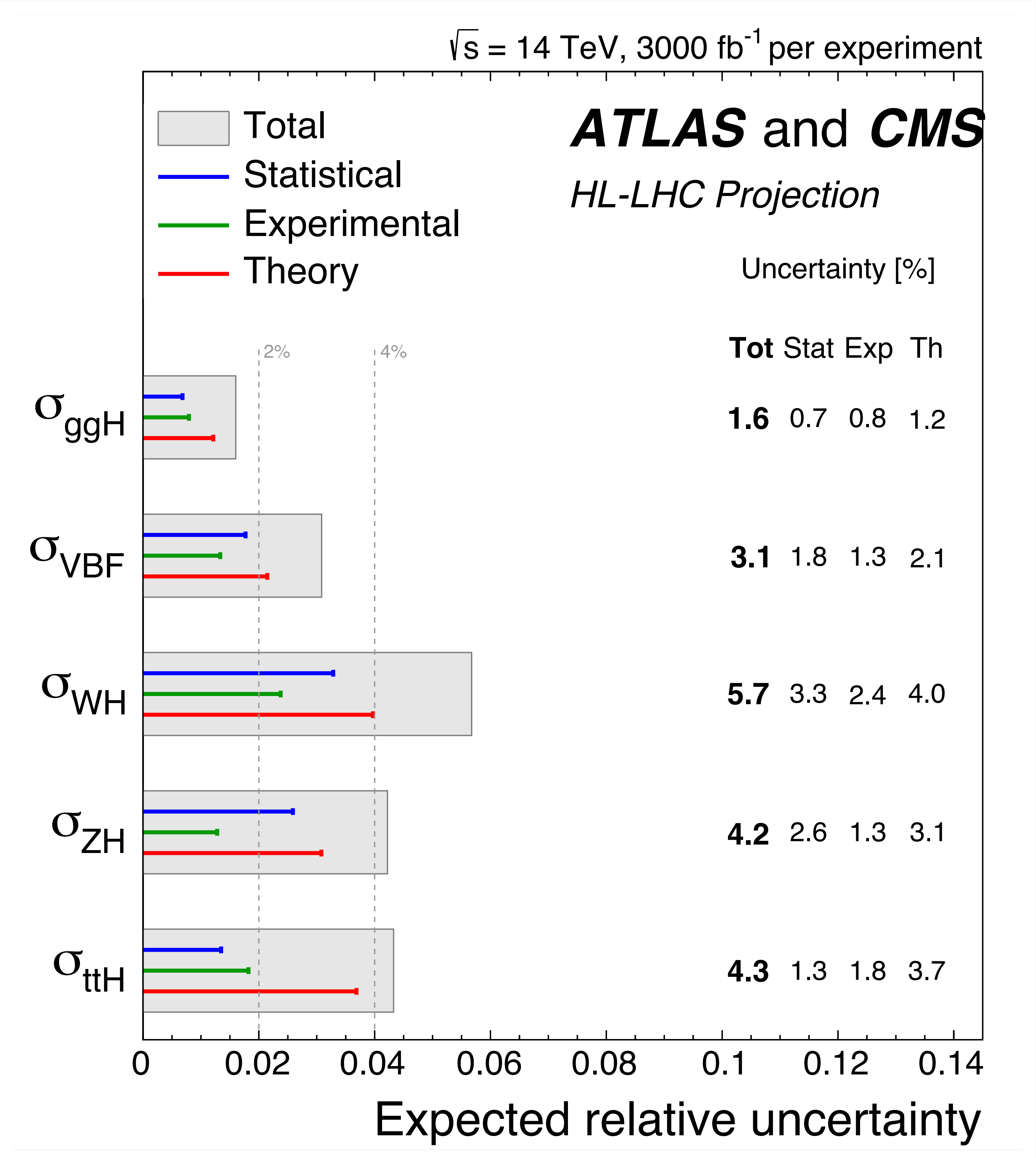


LHC operational in its 3rd and last running period

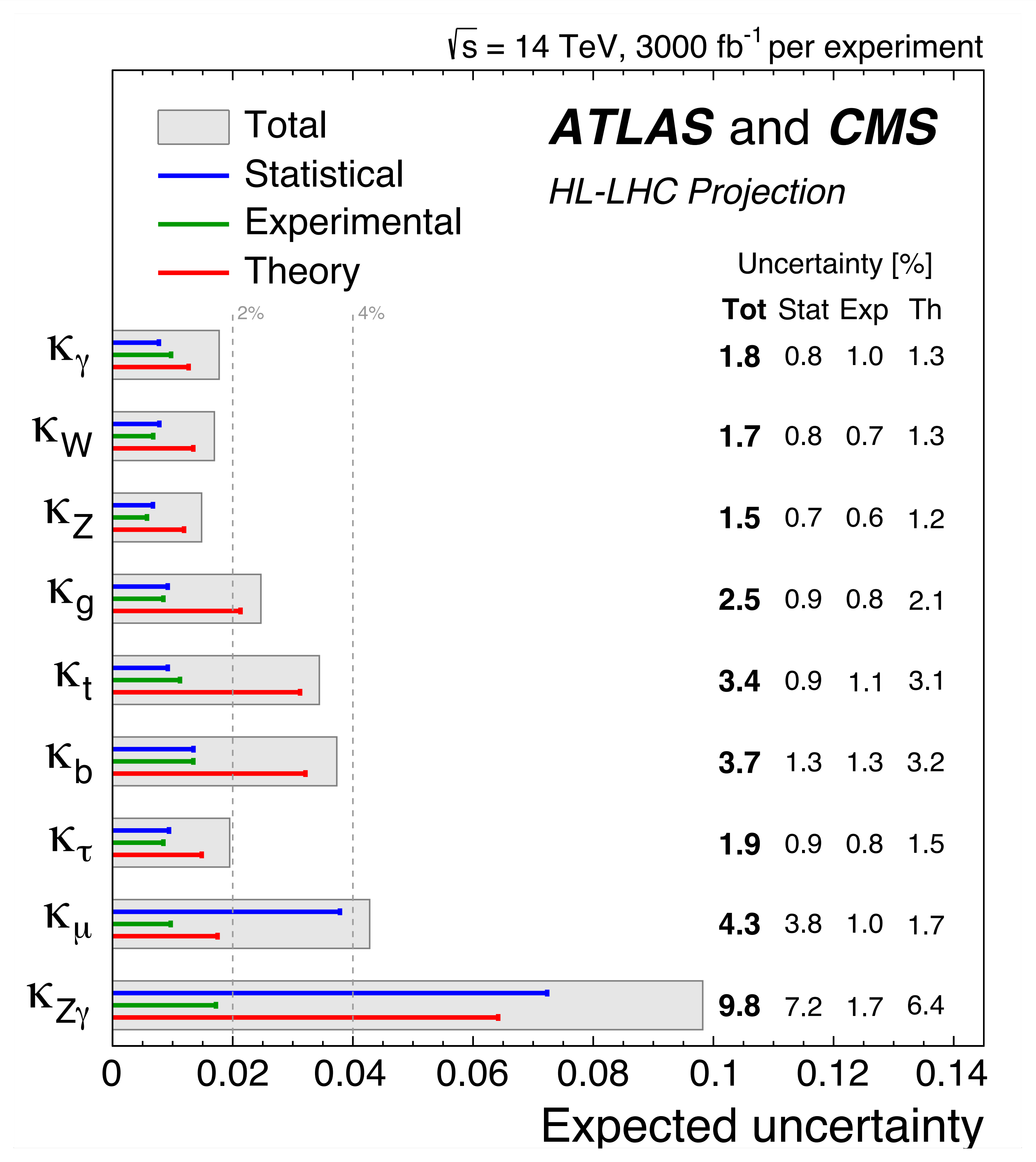
LHC exceed its design luminosity

but did not reach (almost) design energy

European Strategy for Particle Physics Update 2020



Higgs total cross sections



Higgs coupling parameters

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

- Theoretical uncertainties → already reduced by a factor 2 respect to the current state of the art
- If theoretical calculations cannot reach percent accuracy in the next five years, the interpretation of data will be severely affected and dominated by the TH accuracy

EPS-2023 - Future collider talks

Status and prospects of the HL-LHC project
Markus Zerlauth

Impact of accelerator physics on van der Meer luminosity calibrations at the LHC
Witold Kozanecki

Beam-beam interaction-induced bias to precision luminosi measurement
Joanna Wanczyk

TWOCRYST: a proof-of-principle of a double-crystal setup
Stefano Redaelli

Status of the International Muon Collider Complex Study a 10 TeV
KYRIACOS SKOUFARIS

Machine-Detector interface for multi-TeV Muon Collider
Donatella Lucchesi

Green Accelerators? Lessons learned from ESS.
Dr Anders Sunesson

Physics Performance and Detector Requirements at an Asymmetric Higgs Factory
Antoine Laudrain

Prototype test beam results and design of the future Forward Calorimeter in ALICE
Ian Bearden

The CMS ECAL upgrade for the High-Luminosity LHC era
Ka Wa Ho
Audimax, Universität Hamburg 09:10 - 09:30

Development of the ATLAS Liquid Argon Calorimeter Readout Electronics for the HL-LHC
Maheyer Shroff

The Mu2e crystal calorimeter *Dr Stefano Di Falco*
Audimax, Universität Hamburg 09:50 - 10:10

Compact forward e.m. calorimeter based on oriented crystals
Marco Romagnoni

Precise predictions for the trilinear Higgs self-coupling in the Standard Model and beyond
Martin Gabelmann

Two-loop Electroweak corrections to gg -> HH
Hantian Zhang
Hörsaal B, Historic main building 08:50 - 09:10

Higgs Pair Production and Triple Higgs Couplings at the LHC in the 2HDM framework
Kateryna Radchenko Serdula

Probing the nature of electroweak symmetry breaking with Higgs boson pairs in ATLAS
Viviana Cavaliere

Higgs self coupling: status and projections at CMS
Saswati Nandan
Hörsaal B, Historic main building 09:50 - 10:10

Constraints on the trilinear and quartic Higgs couplings from triple Higgs production at the LHC and beyond
Georg Weiglein

Precision measurements of W and Z production in ATLAS and CMS
Prof. Ulrich Goerlach

Physics with W and Z bosons at the LHCb experiment
Nathan Allen Grieser
Hörsaal M, Historic main building 08:50 - 09:10

Compatibility and combination of world W-boson mass measurements
William Barter

Probing the weak mixing angle at high energies at the LHC and HL-LHC
Simone Amoroso

Global fit of electroweak data in the Standard Model and beyond
Maurizio Pierini
Hörsaal M, Historic main building 09:50 - 10:10

The global electroweak fit in the SM and SMEFT
Yannick Fischer

J/ψ-pair production at NLL in TMD factorisation at LH
Alice Colpani Serri

One-loop corrections to inclusive production of J/psi and
Yelyzaveta Yedelkina

Production of exotic $X(3872)$ in proton-proton and $e^+
Antoni Szczurek

Heavy flavor production studies at CMS
Valentina Mariani

Study of associated quarkonium production in pp collisio
Liupan An

Latest ALICE results on charm and beauty hadronization .
Biao Zhang

Measurement of the cross-section ratio σψ(2S)/σJ/ψ(1S) i.
Alessia Bruni

EPS-2023 - Future collider talks

EPS-2023 - Future collider talks

We are looking to the future
We are looking for building new, more powerful and more precise colliders

We need theoretical calculations
The calculations that we have and even more precise theoretical tools
Precise theoretical calculations are essential partners for current and future colliders

Motivation

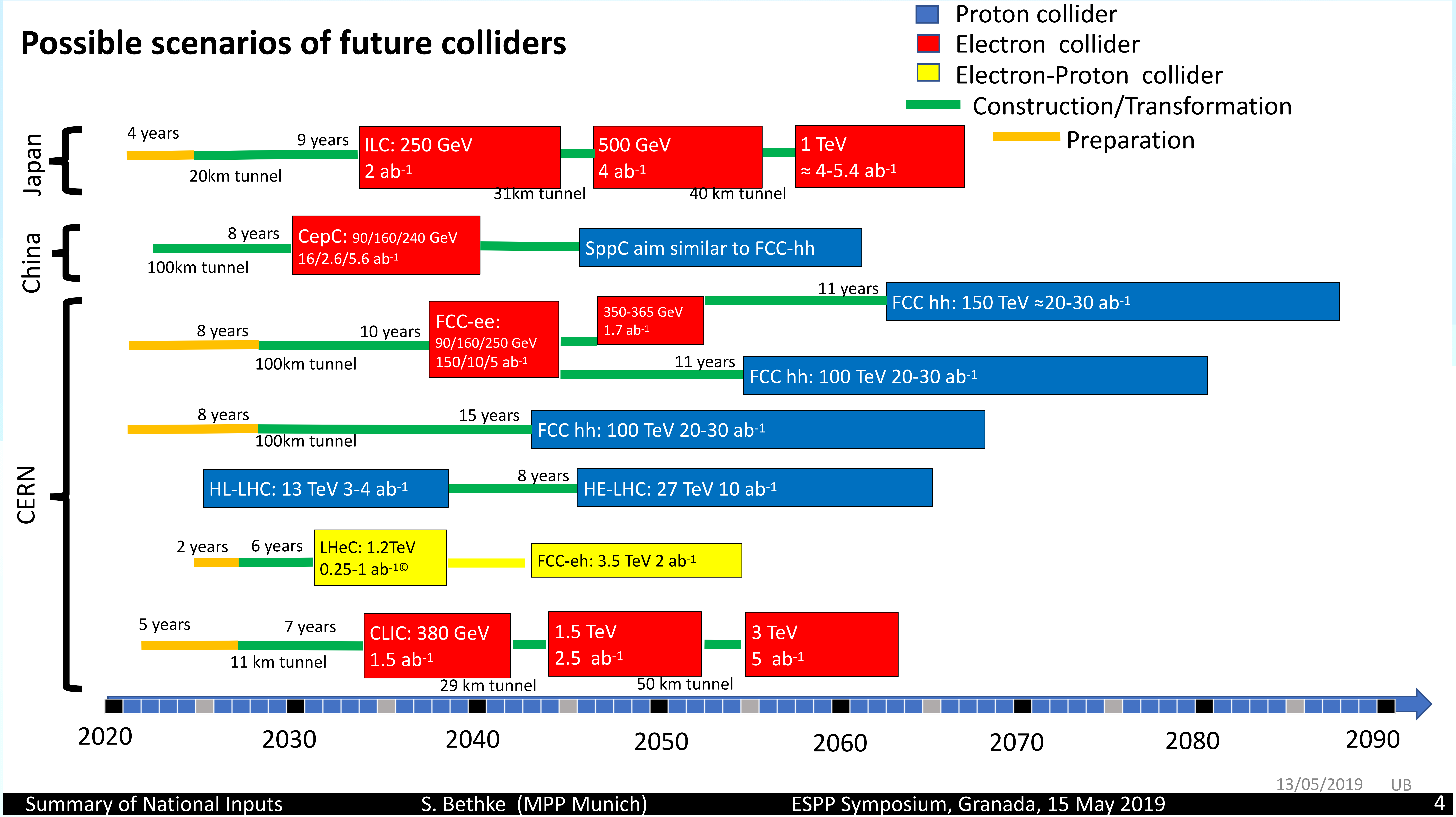
All options are aimed at attobarn^{-1} physics

It requires going well beyond NNLO for theory

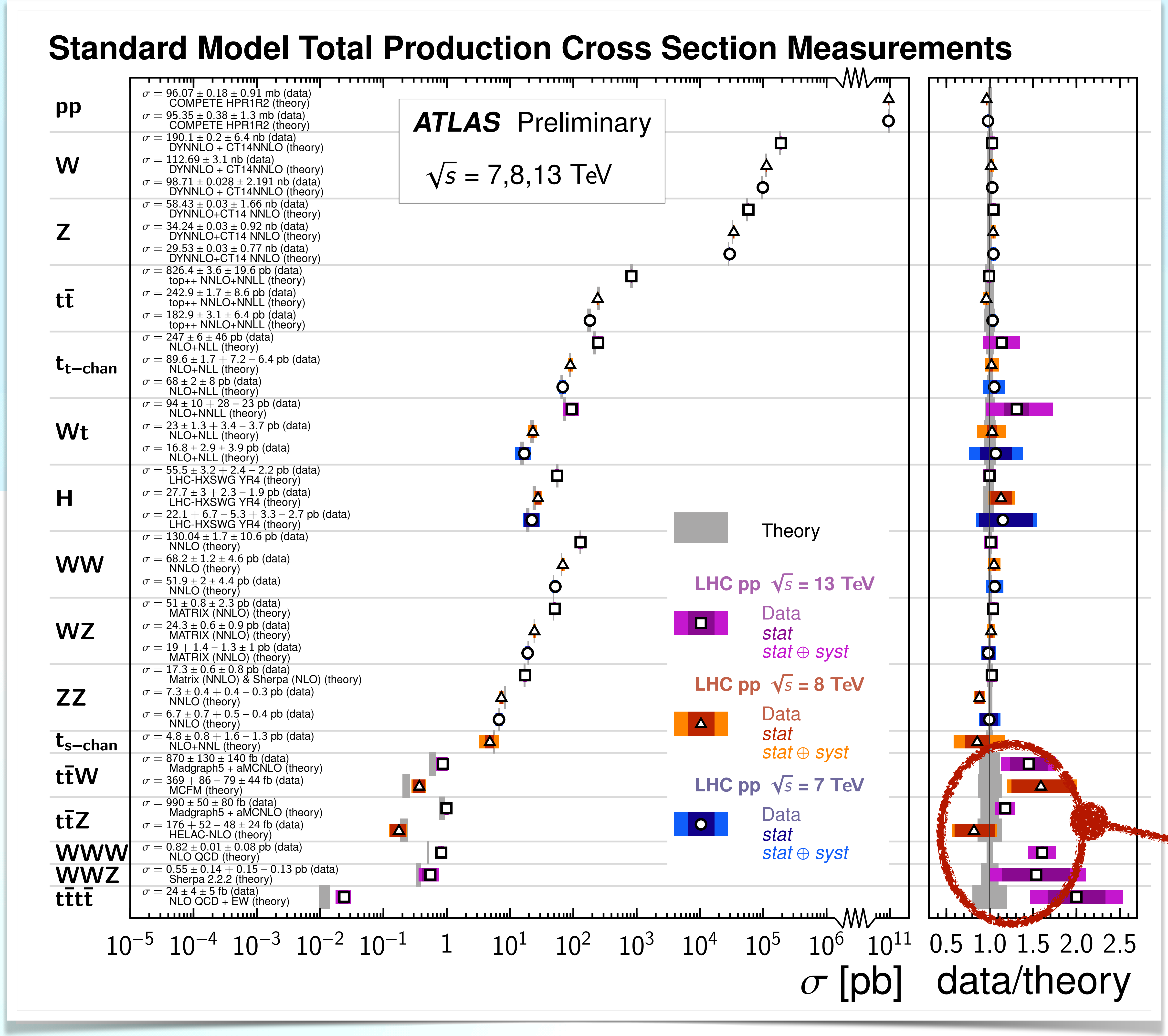
Even conservative estimates are not achievable with current techniques

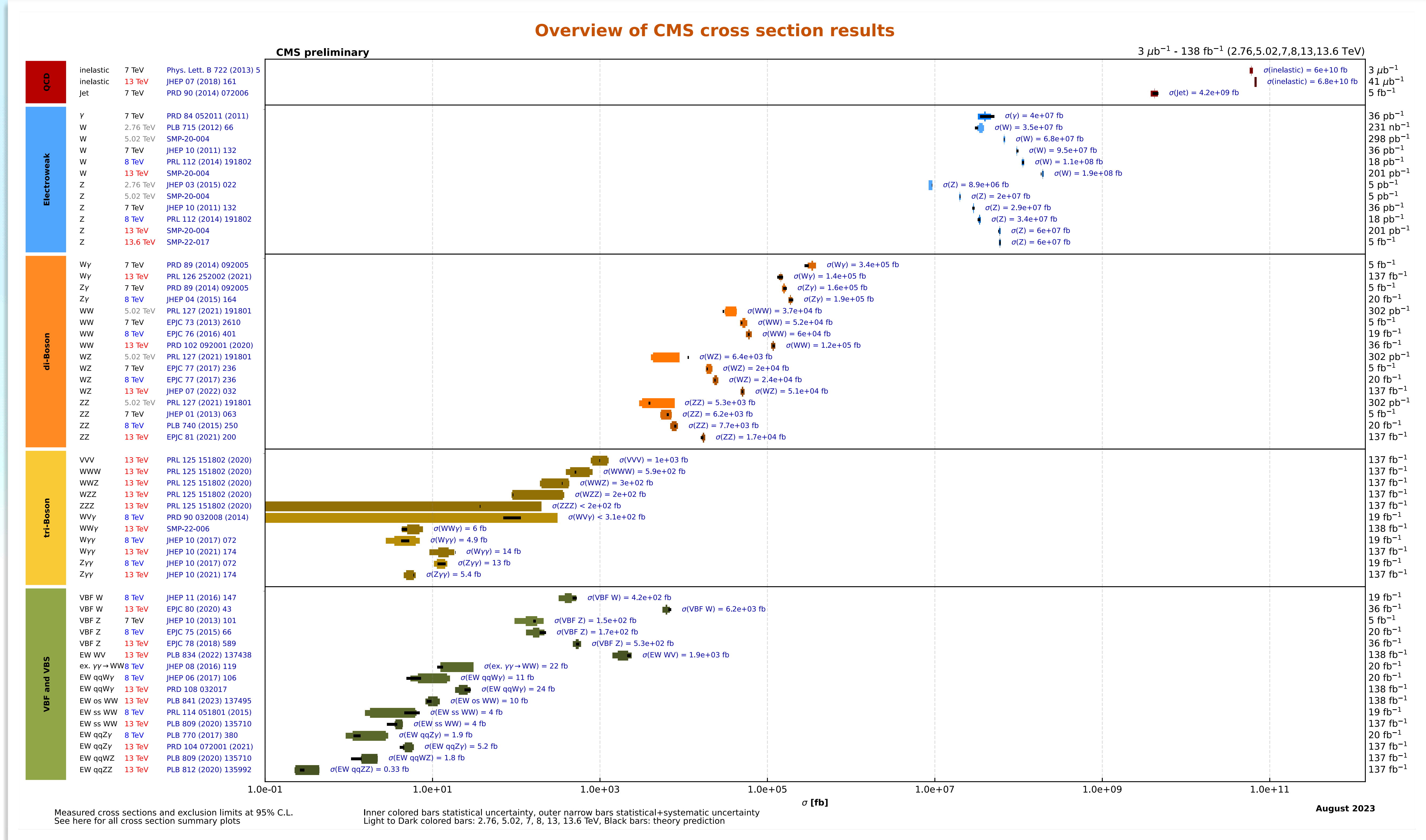
Most optimistic scenario establishes 1% – 3% theoretical accuracy as mandatory at current Run III and at the HL-LHC

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



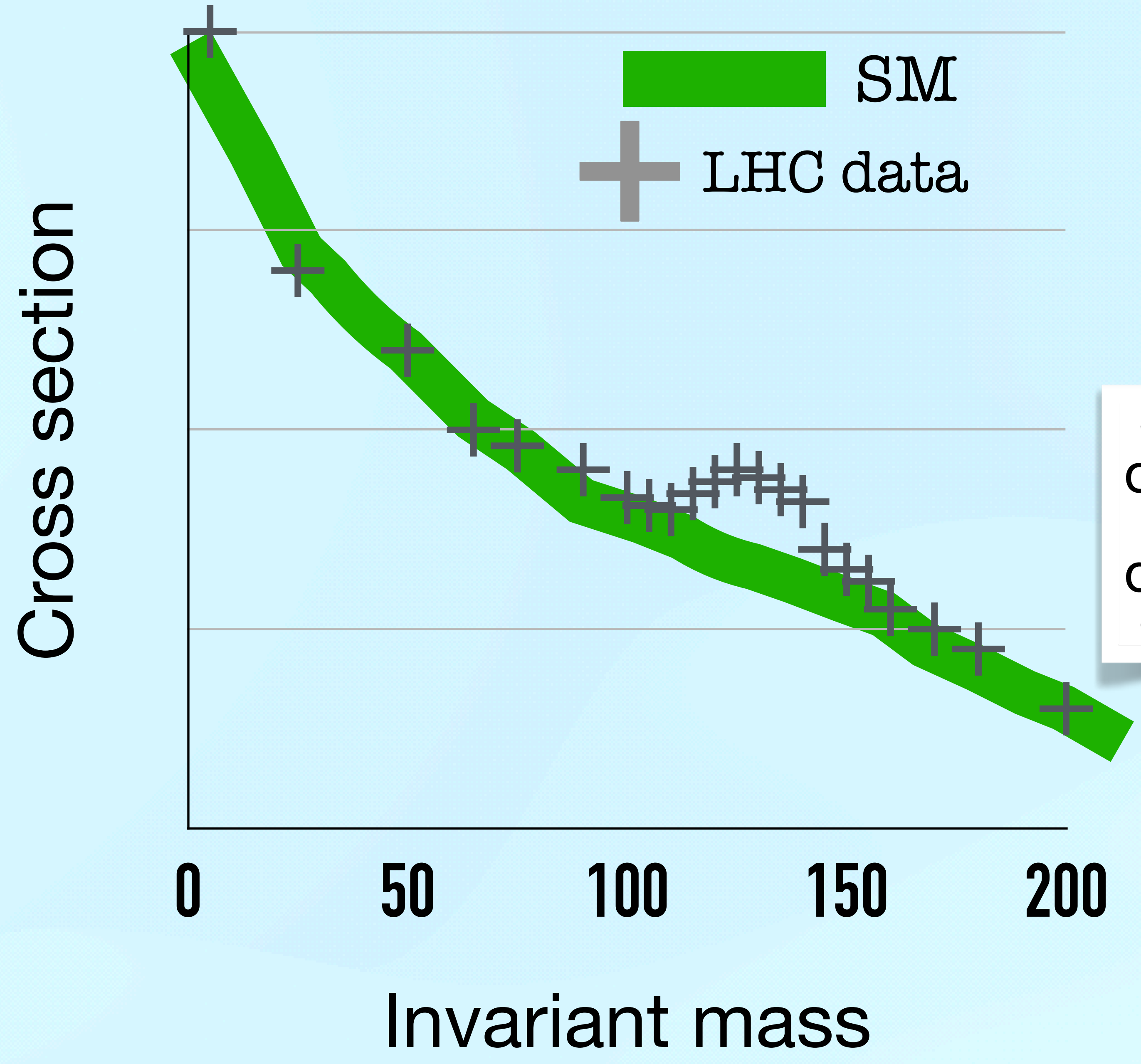
Everything looks SM-like at the LHC

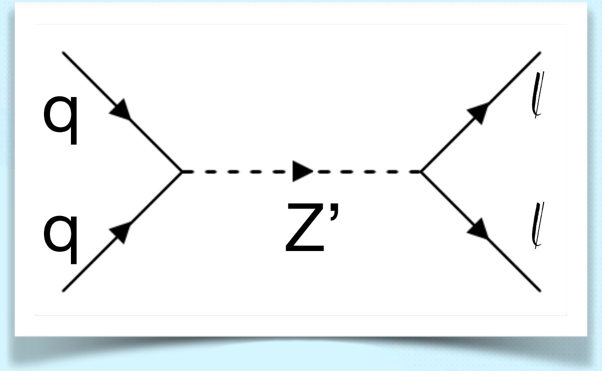




NLO QCD + EW at best

Motivation



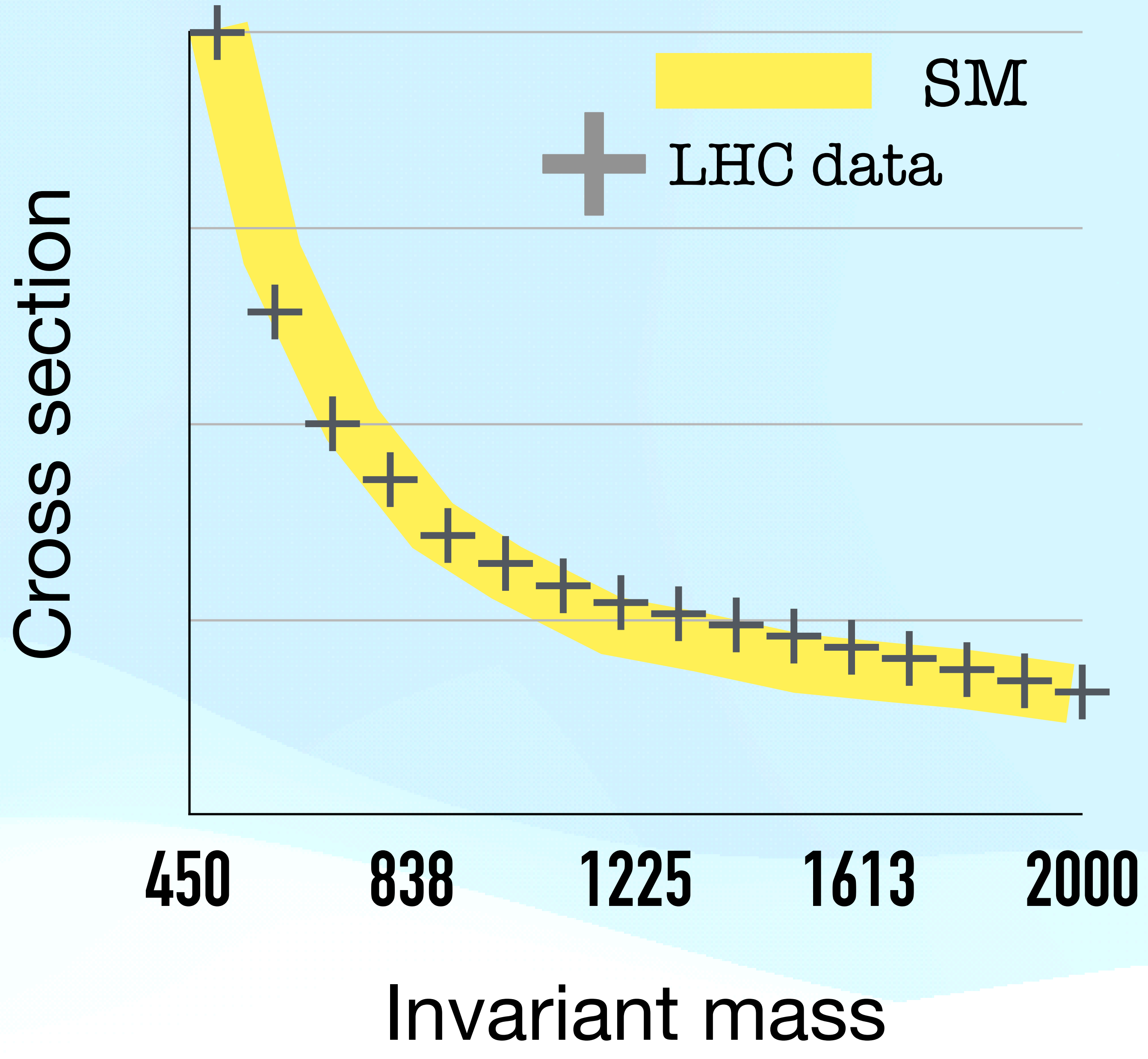


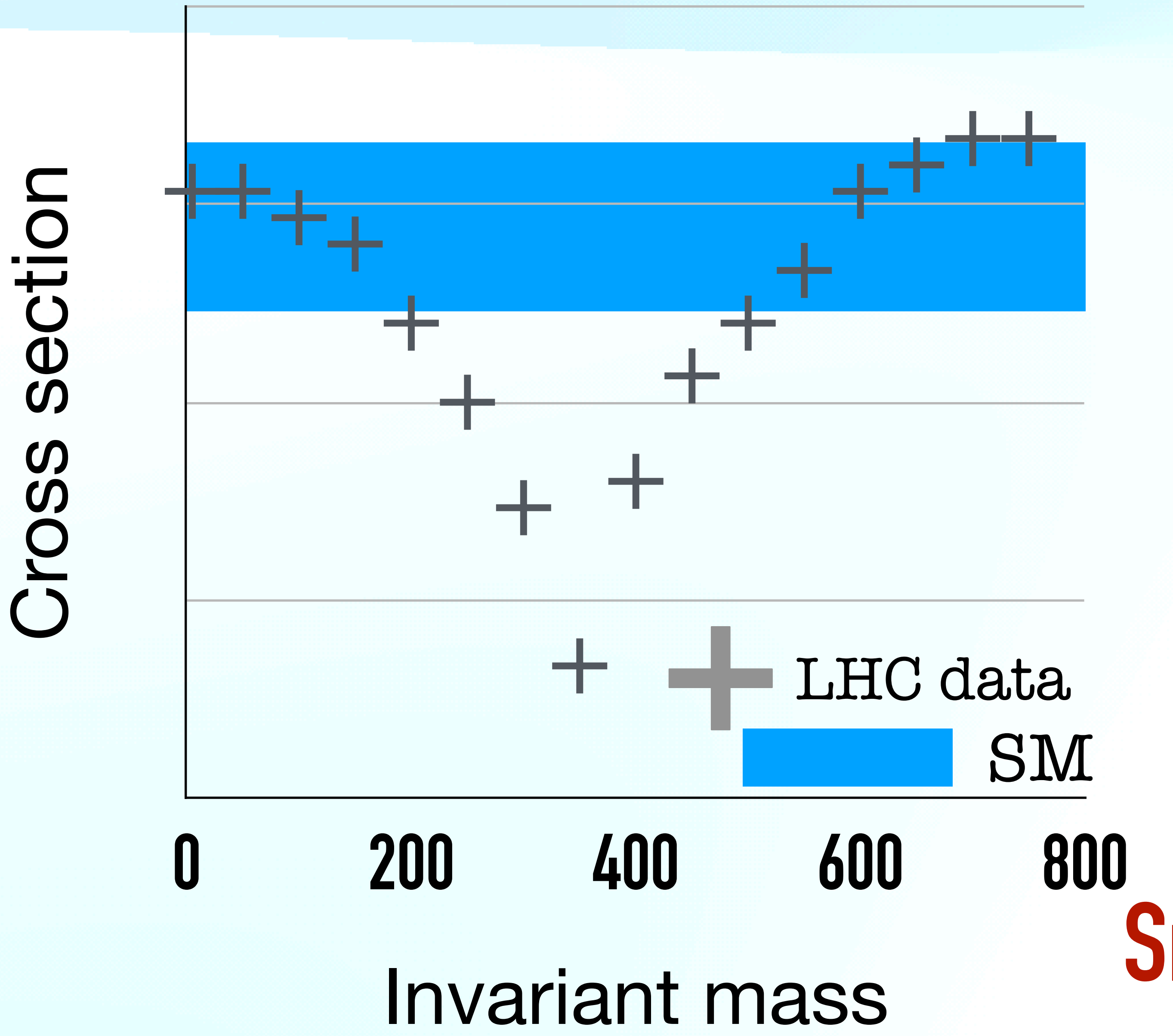
We are looking for new discoveries

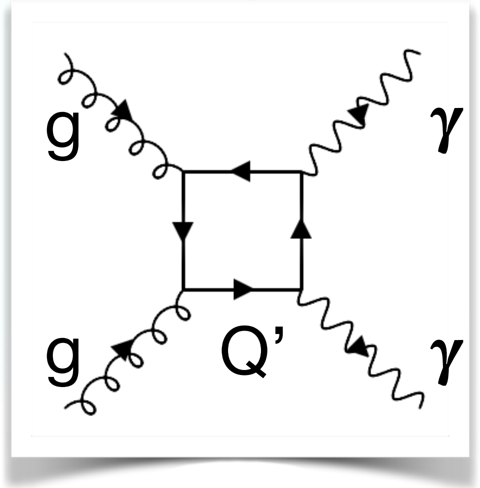
Essentially, two possible scenarios

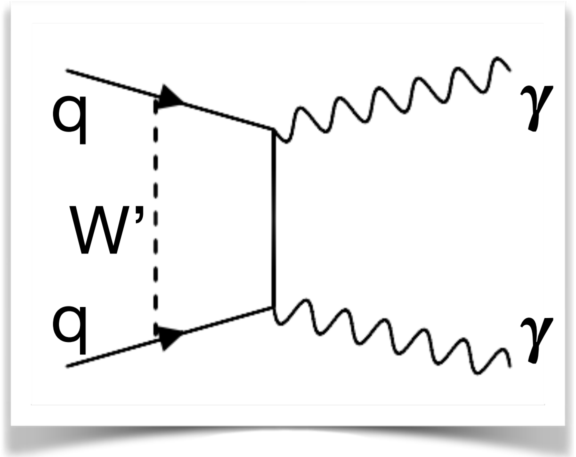
New resonances

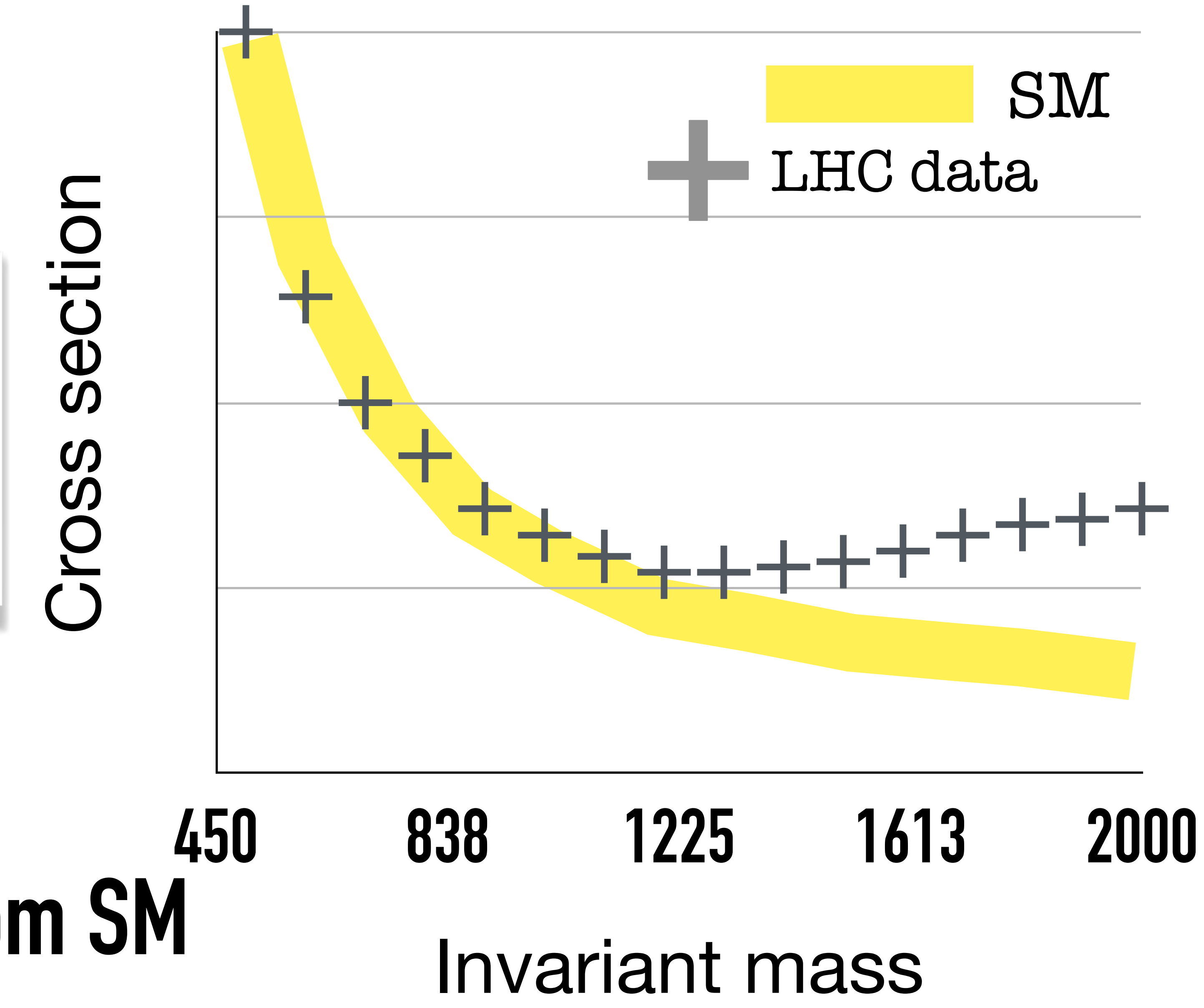
New interactions







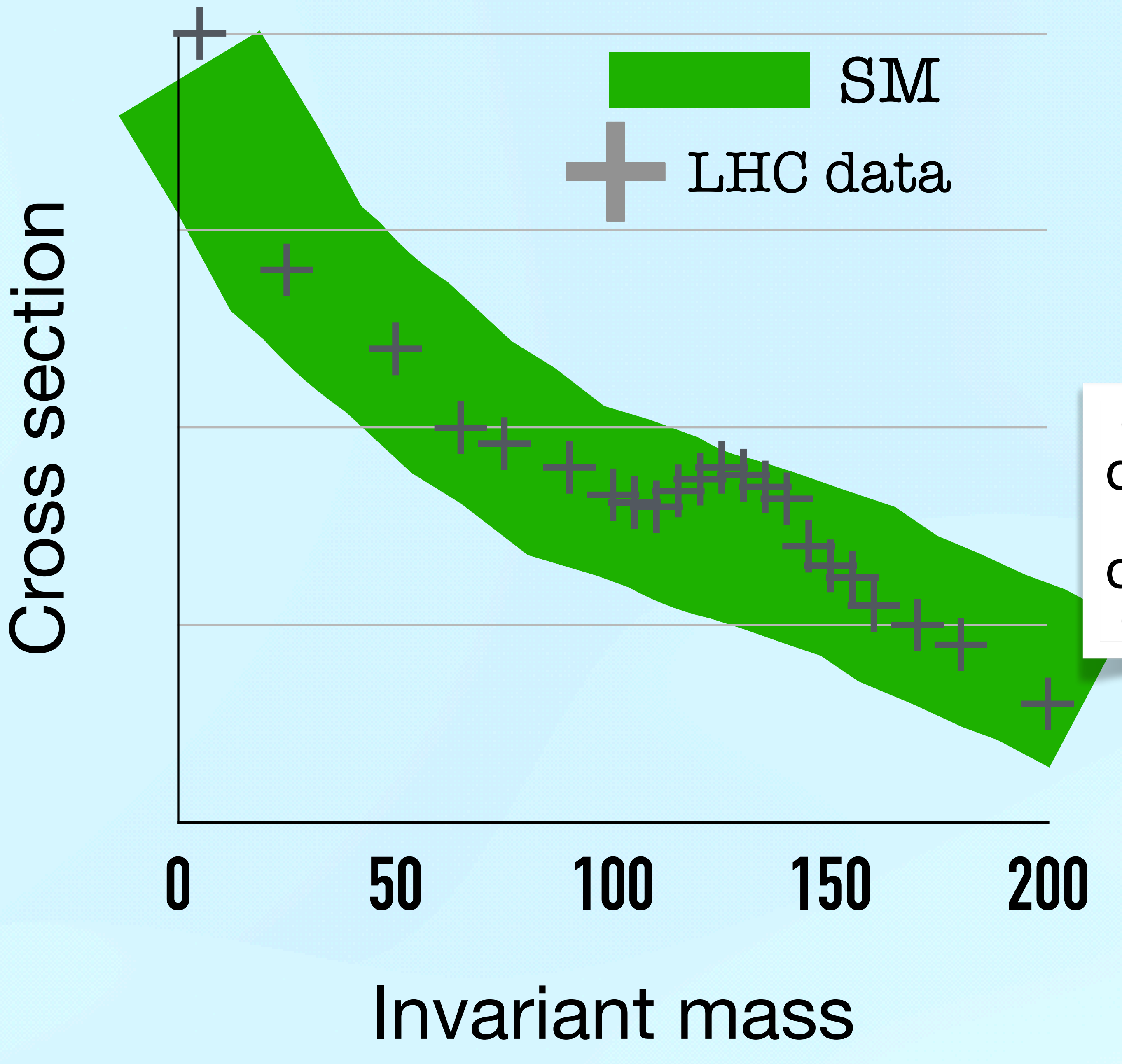




Small deviations from SM

Small deviations from SM

Motivation



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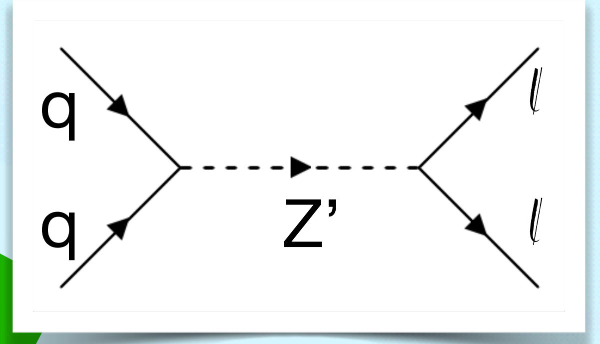

New resonances

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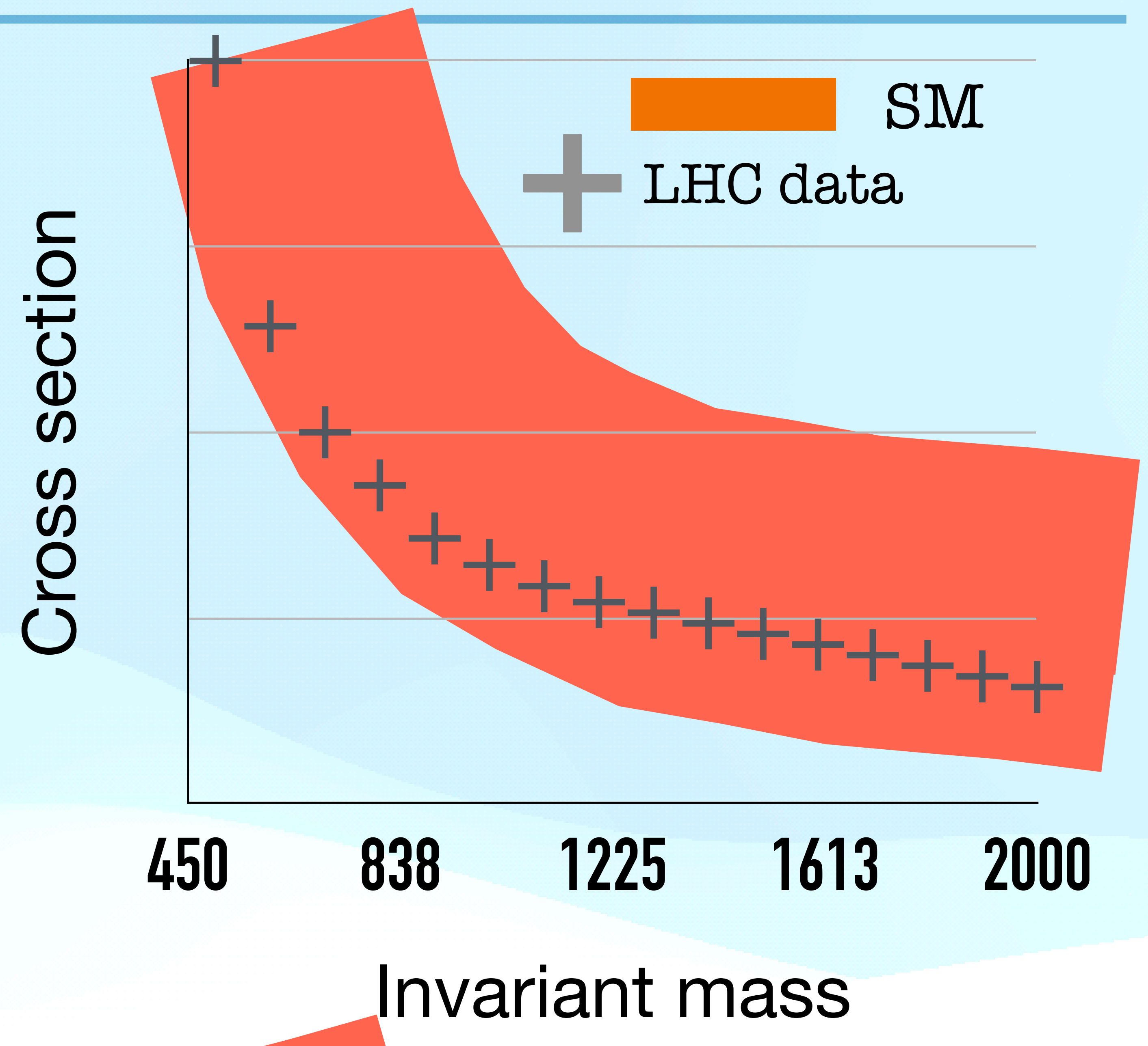
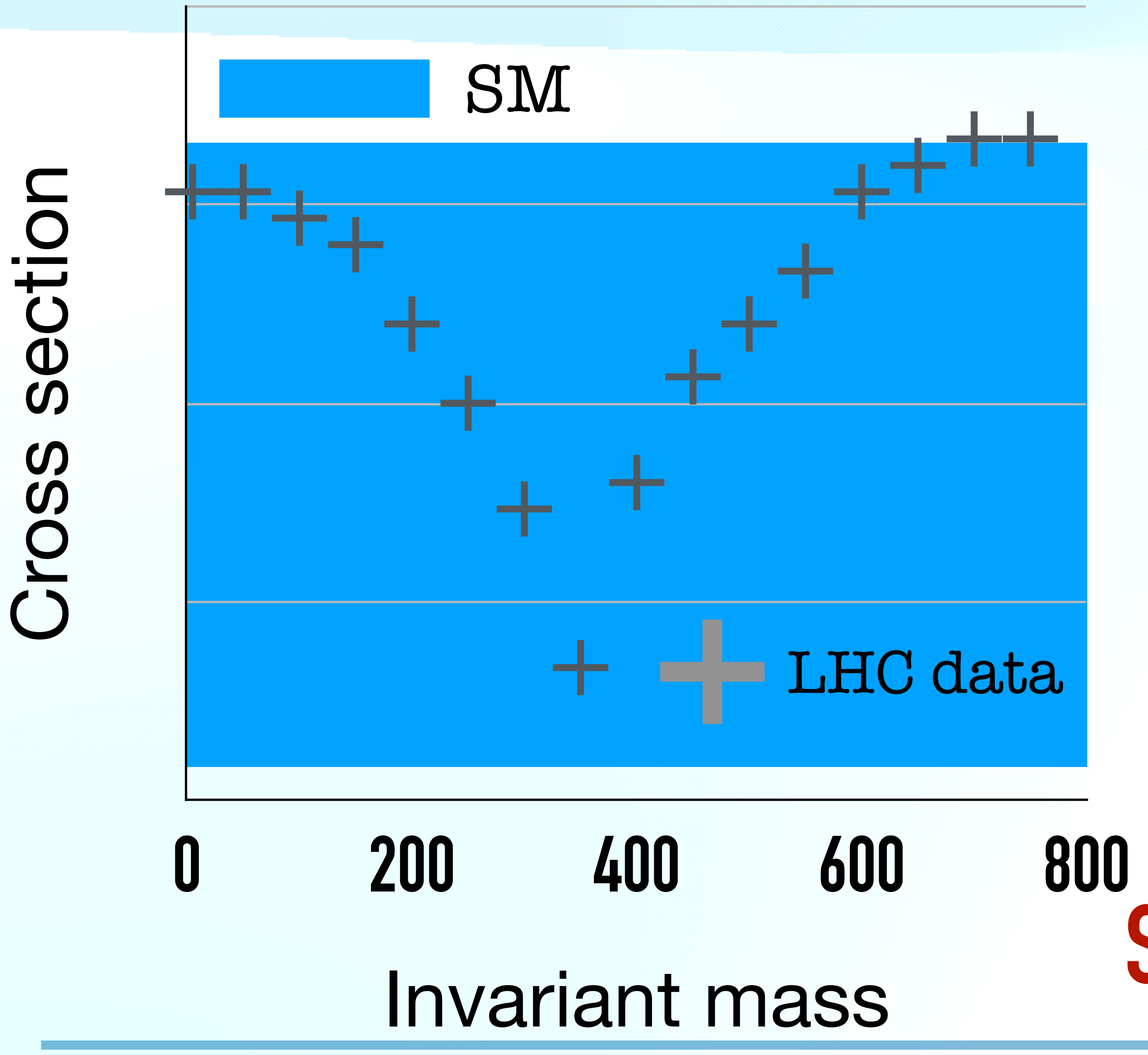
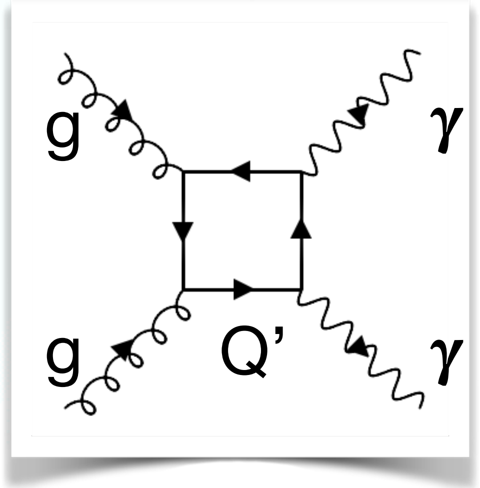
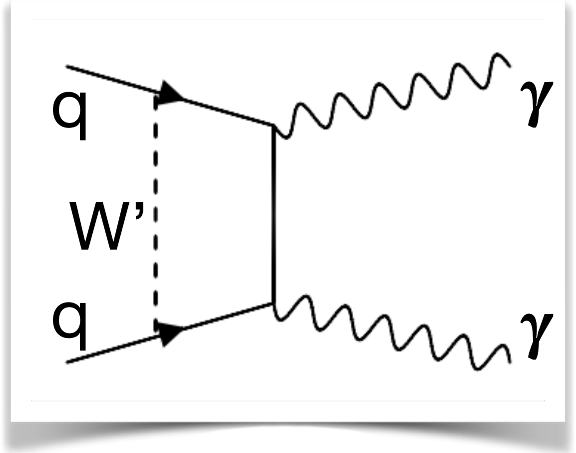
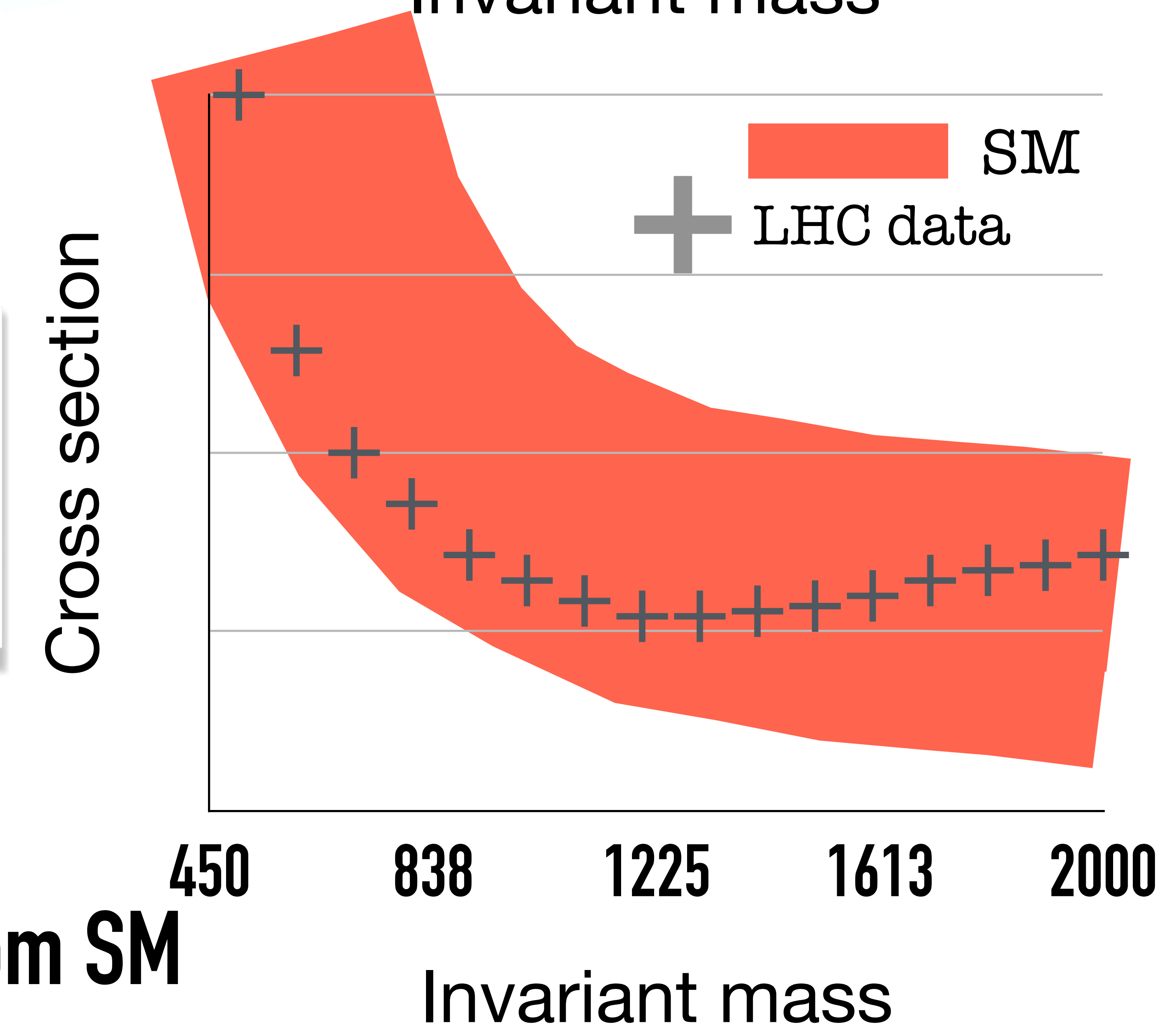


In both scenarios **precision** is a key ingredient









Small deviations from SM

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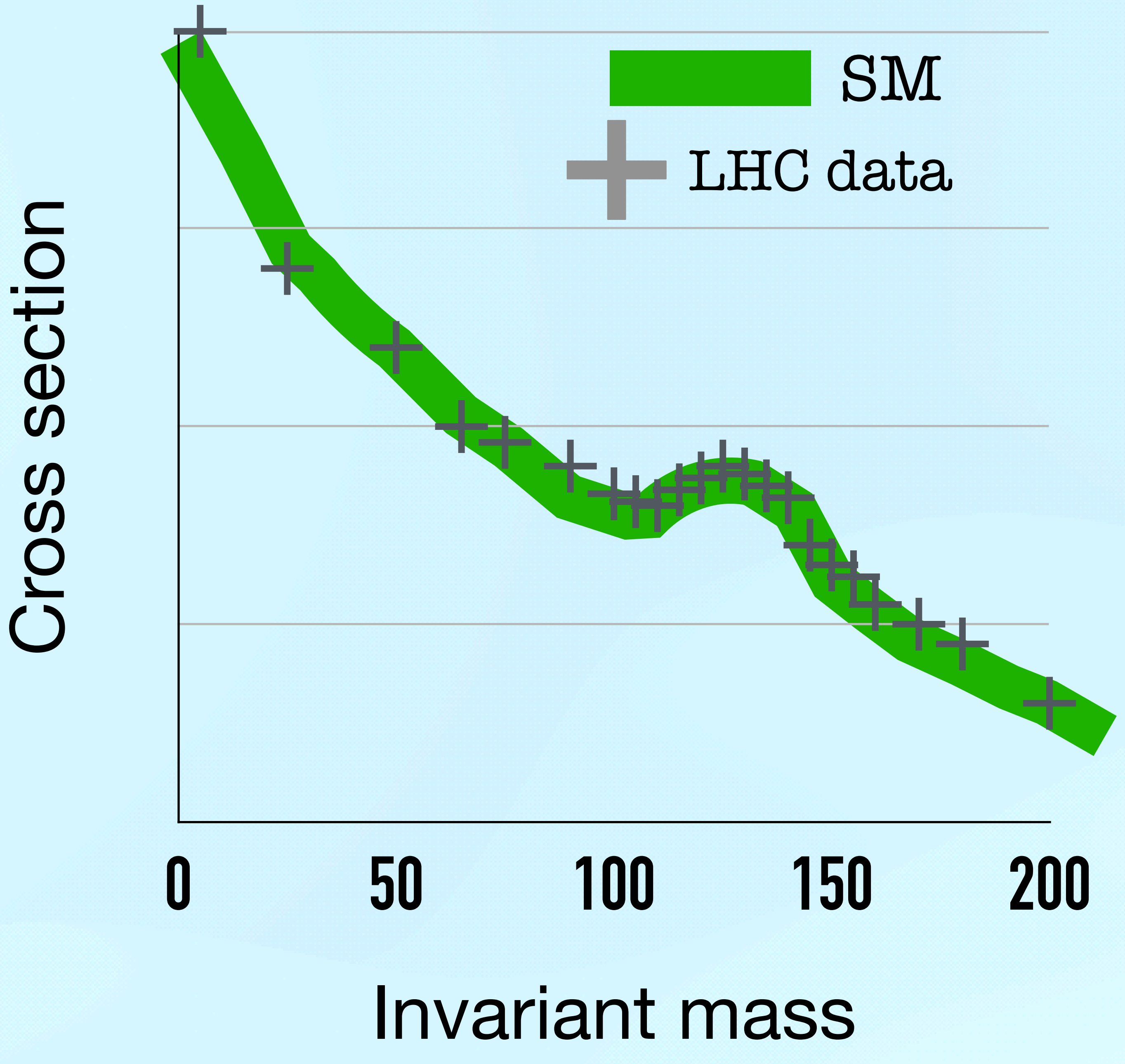
Motivation



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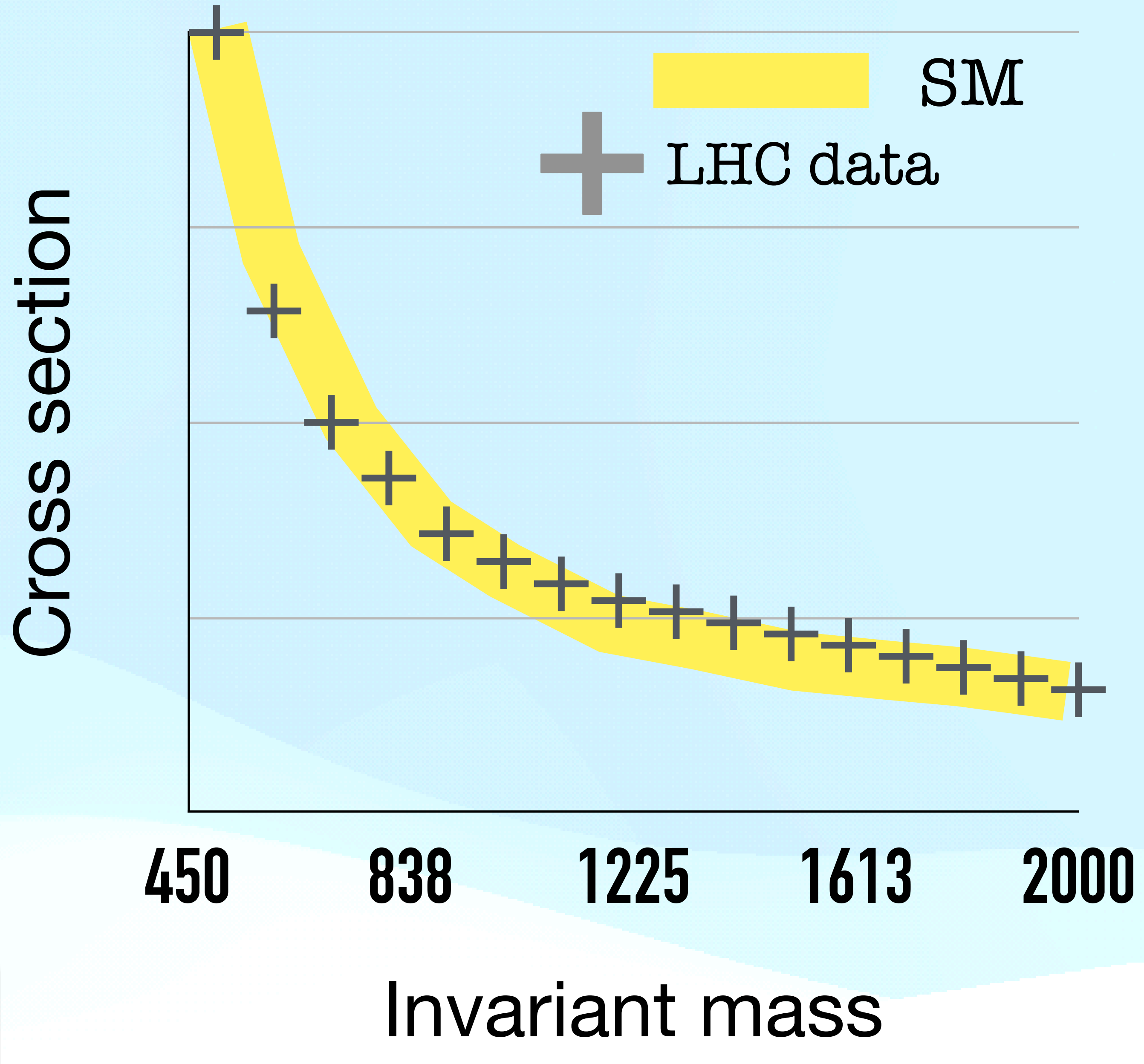
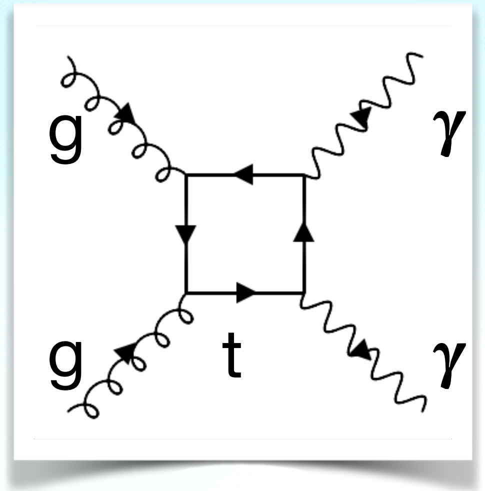
Essentially, two possible scenarios

New resonances

New interactions





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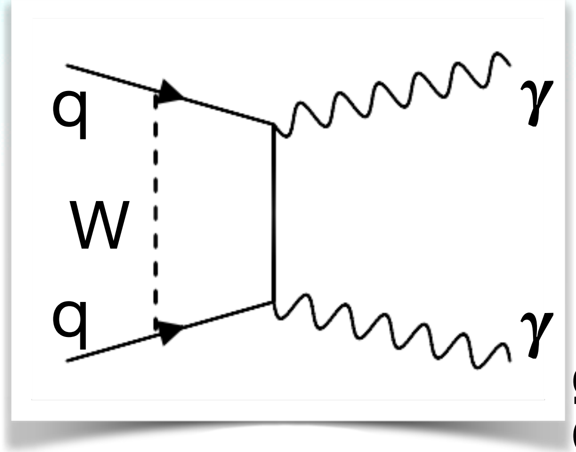
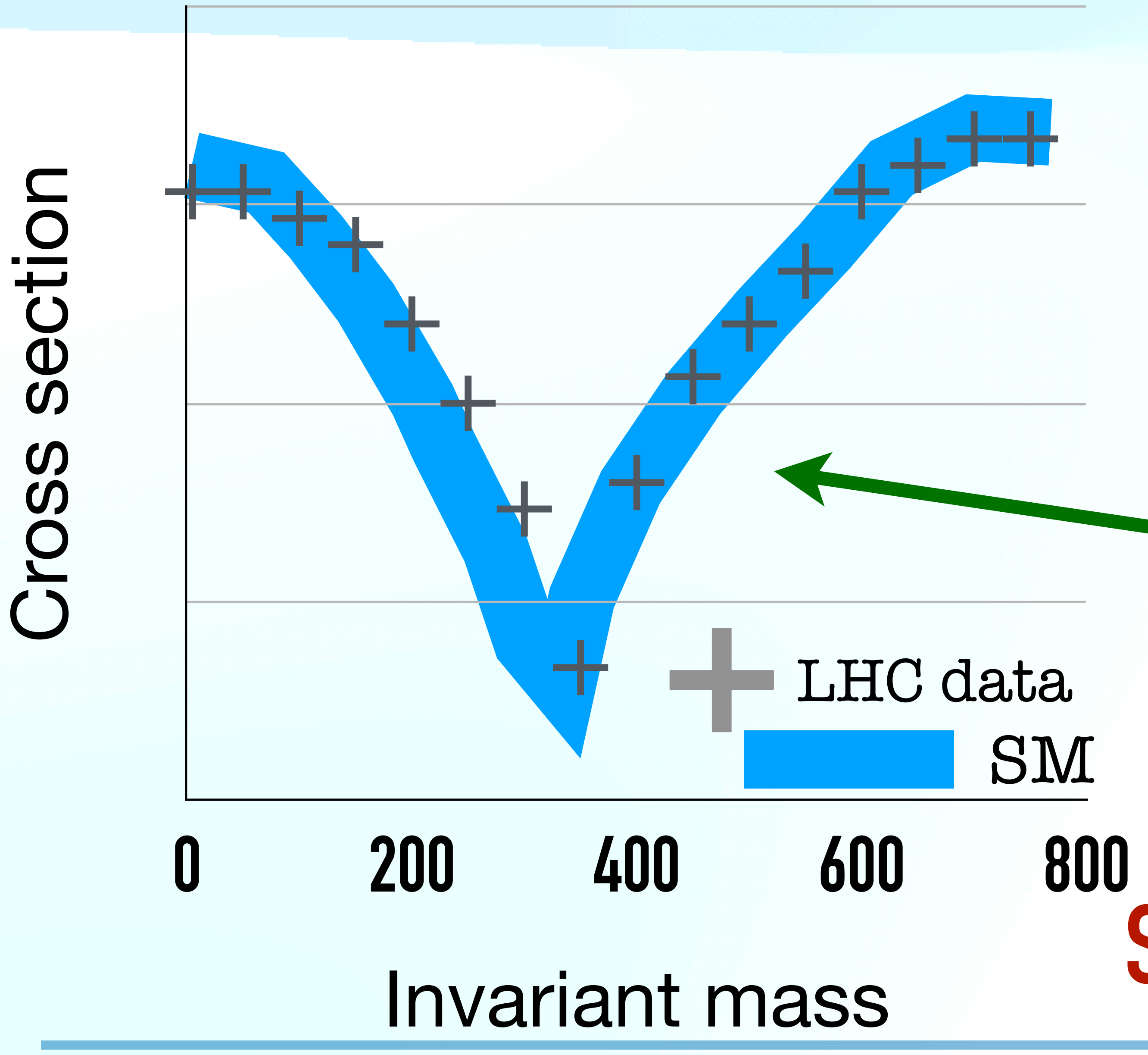
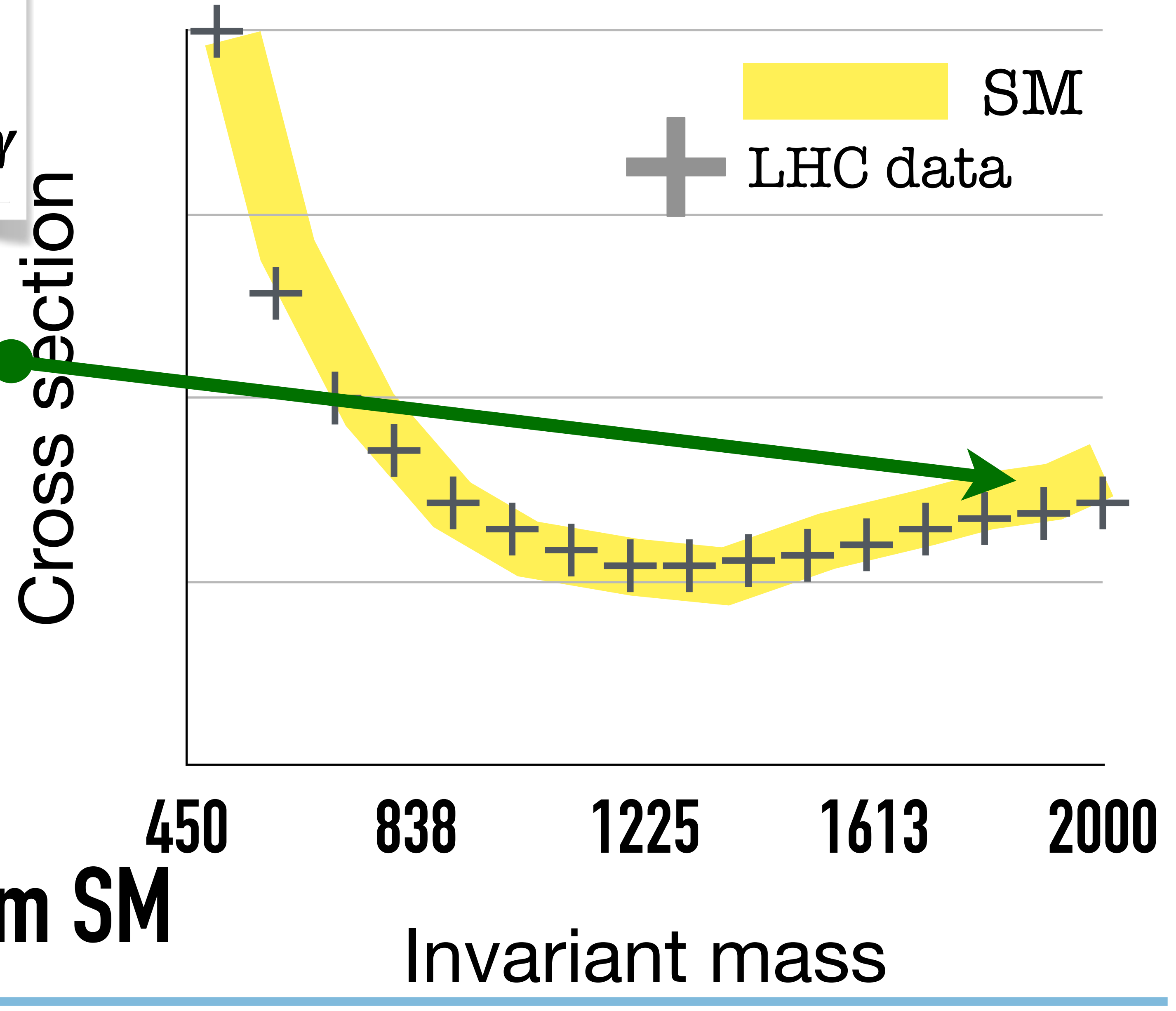


It is very likely that BSM will compete with EW effects



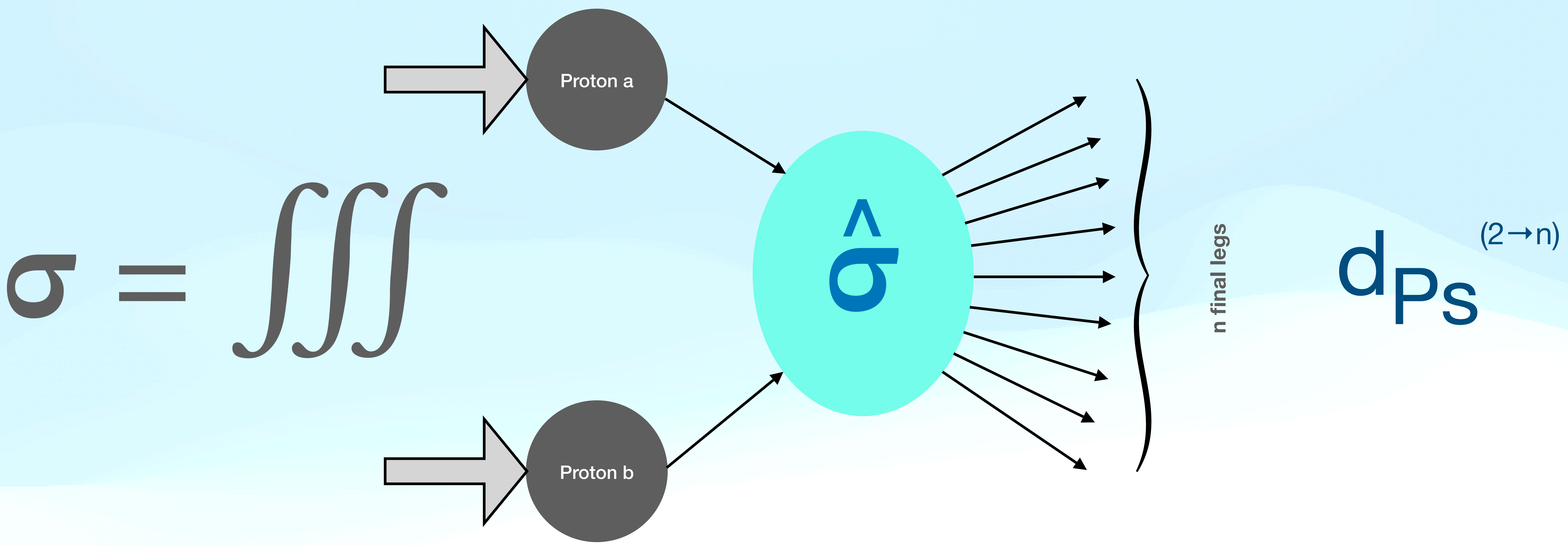
It is very likely that BSM will compete with SM threshold effects



Small deviations from SM

Small deviations from SM

Anatomy of perturbative calculations



Factorization theorem

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

Perturbative expansion

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

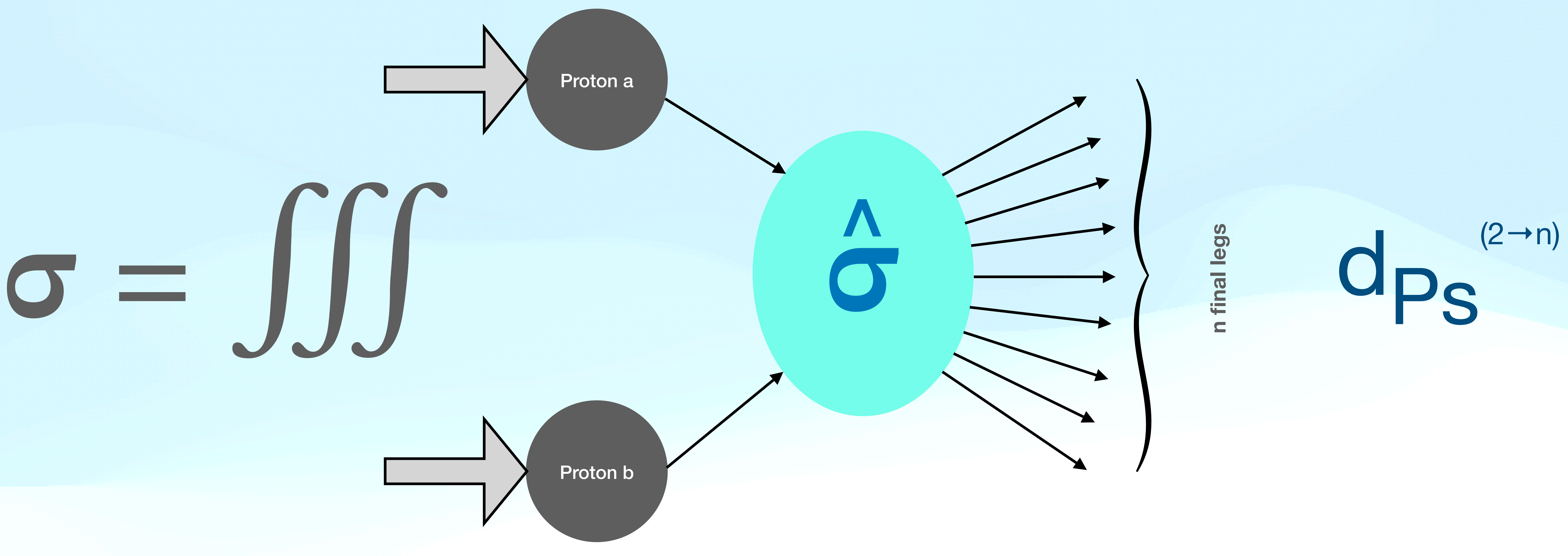
QCD — EW — MIXED

$$\hat{\sigma} = \sigma^{(\hat{0})} + \alpha_s^1 \sigma^{(\hat{1})} + \alpha_s^2 \sigma^{(\hat{2})} + \cdots + \alpha^1 \sigma^{(\hat{0};1)} + \alpha^2 \sigma^{(\hat{0};2)} + \cdots + \alpha_s^1 \alpha^1 \sigma^{(\hat{1};1)} + \cdots$$

LO NLO NNLO

σ stands for the total or differential cross section

Anatomy of perturbative calculations



Factorization theorem

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Perturbative expansion

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

QCD | EW | MIXED

$$\hat{\sigma} = \sigma^{(\hat{0})} + \alpha_s^1 \sigma^{(\hat{1})} + \alpha_s^2 \sigma^{(\hat{2})} + \cdots + \alpha^1 \sigma^{(\hat{0};1)} + \alpha^2 \sigma^{(\hat{0};2)} + \cdots + \alpha_s^1 \alpha^1 \sigma^{(\hat{1};1)} + \cdots$$

LO | NLO | NNLO

Play a crucial role

σ stands for the total or differential cross section

NLO perturbative QCD TH predictions —— Full automated calculations

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

$2 \to 5$ (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]

$2 \to 4$ (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

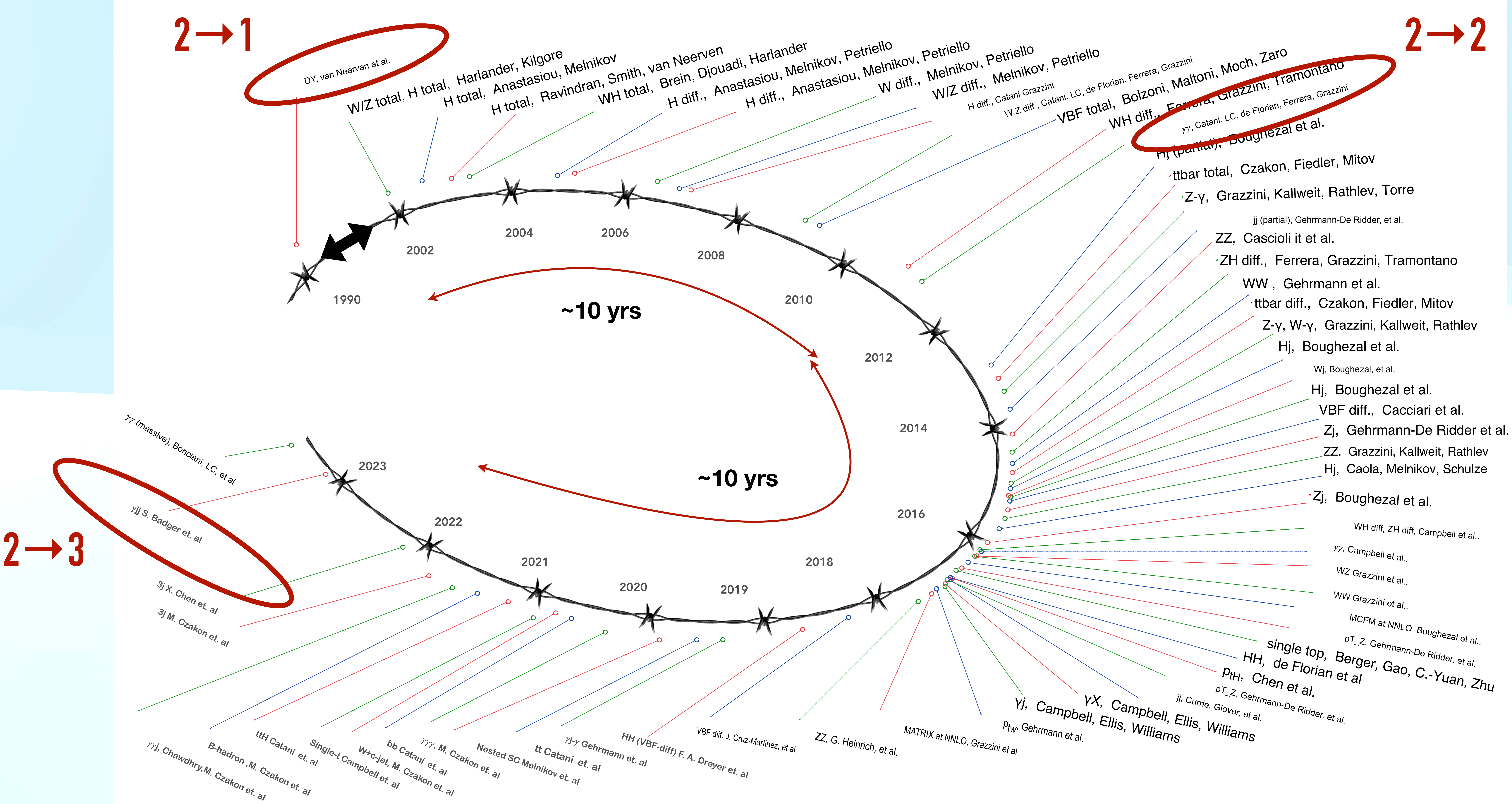
HELAC-NLO, Rocket, BlackHat+SHERPA, GoSam+SHERPA/MADGRAPH, NJet+SHERPA, Madgraph5-aMC@NLO, RECOLA, OpenLoops+SHERPA...

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

Besides the limitations at the frontier, automated structure fully understood

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

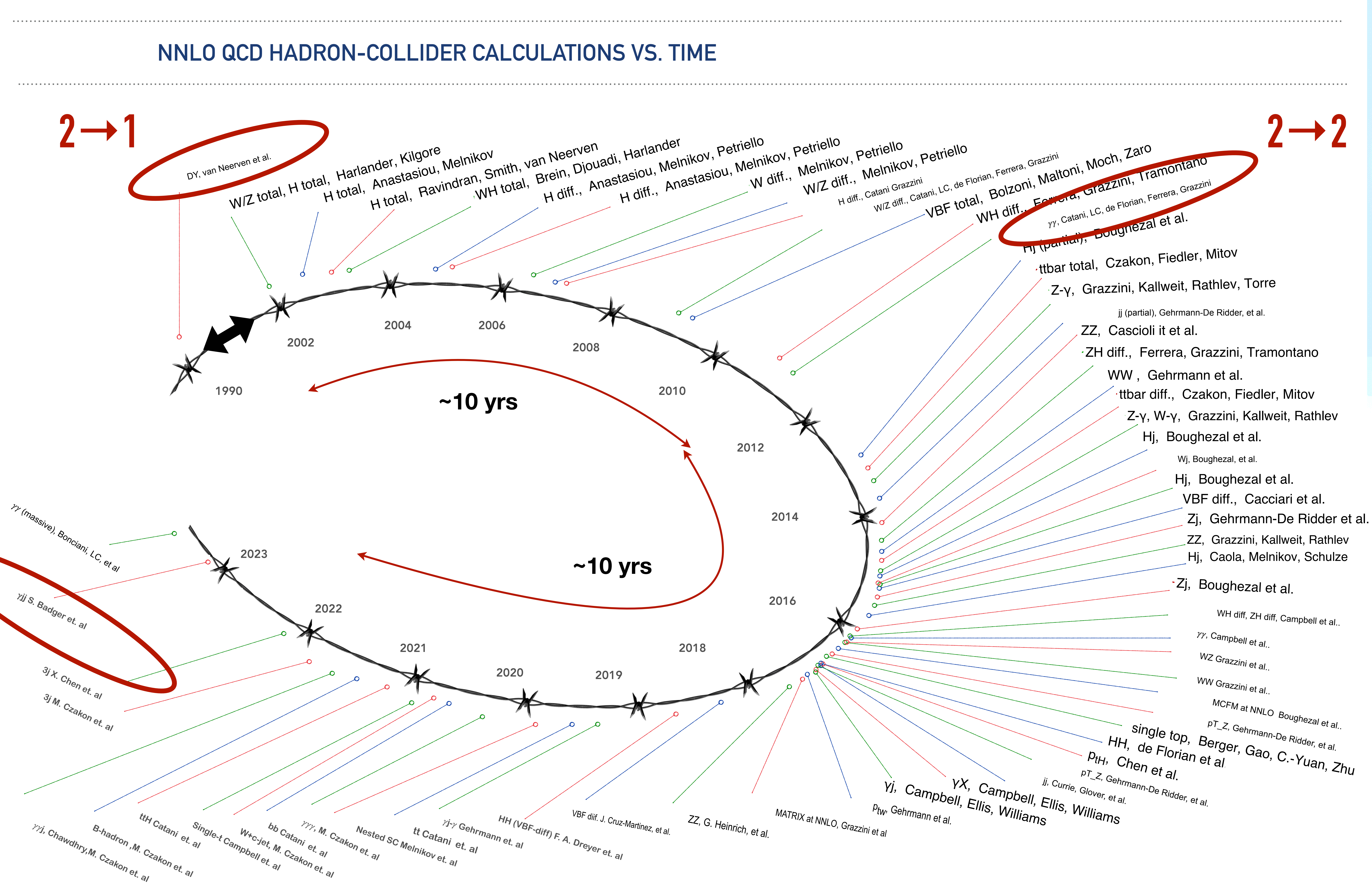
NNLO QCD HADRON-COLLIDER CALCULATIONS VS. TIME



Gavin Salam inspired slide

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

10yrs per leg rule as in the NLO case!



2→3

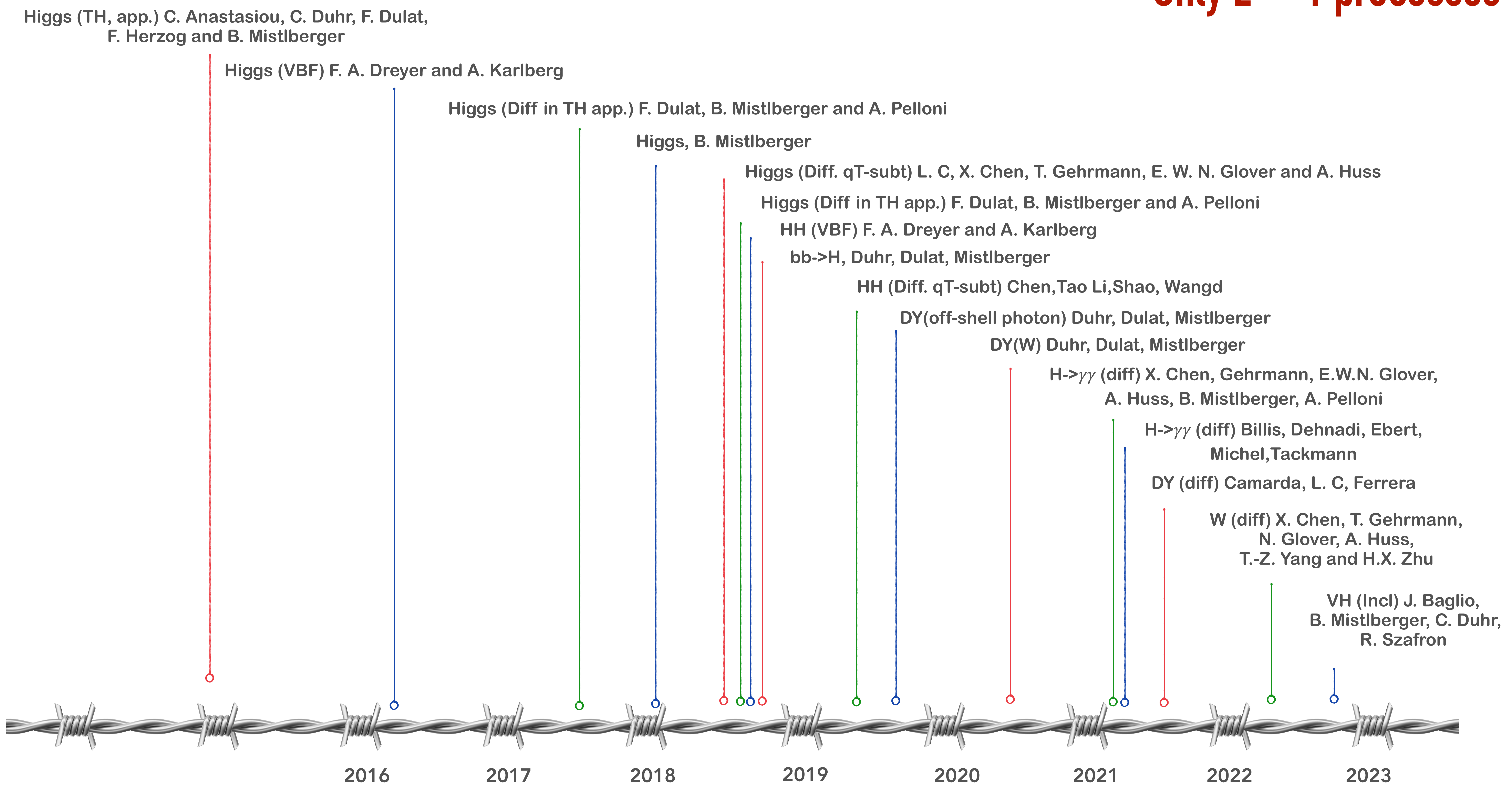
Without any approximation in the two-loop part

Gavin Salam inspired slide

Theoretical calculations – State of the art

N3LO QCD HADRON-COLLIDER CALCULATIONS VS. TIME

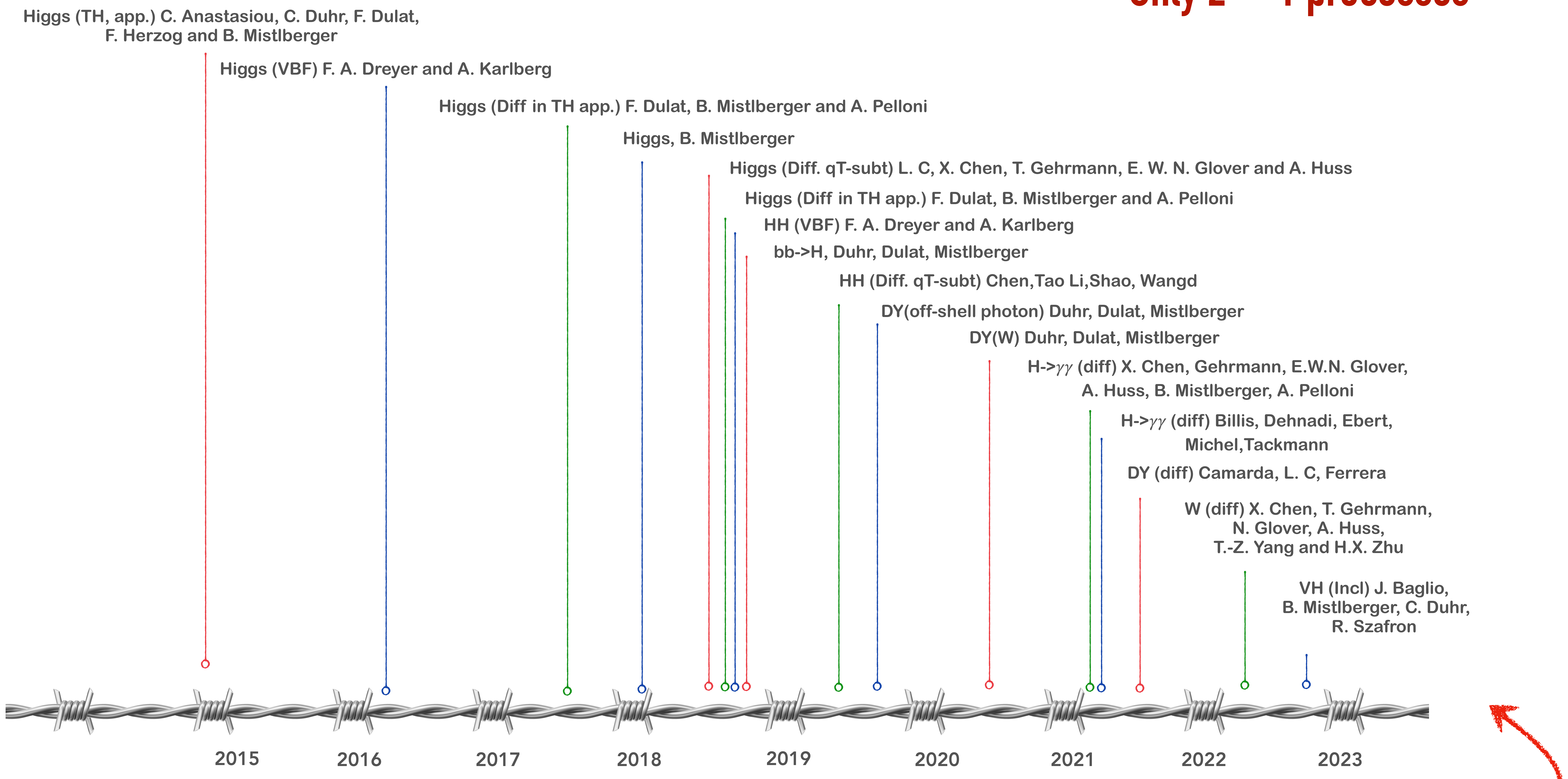
Only 2 → 1 processes



Theoretical calculations - State of the art

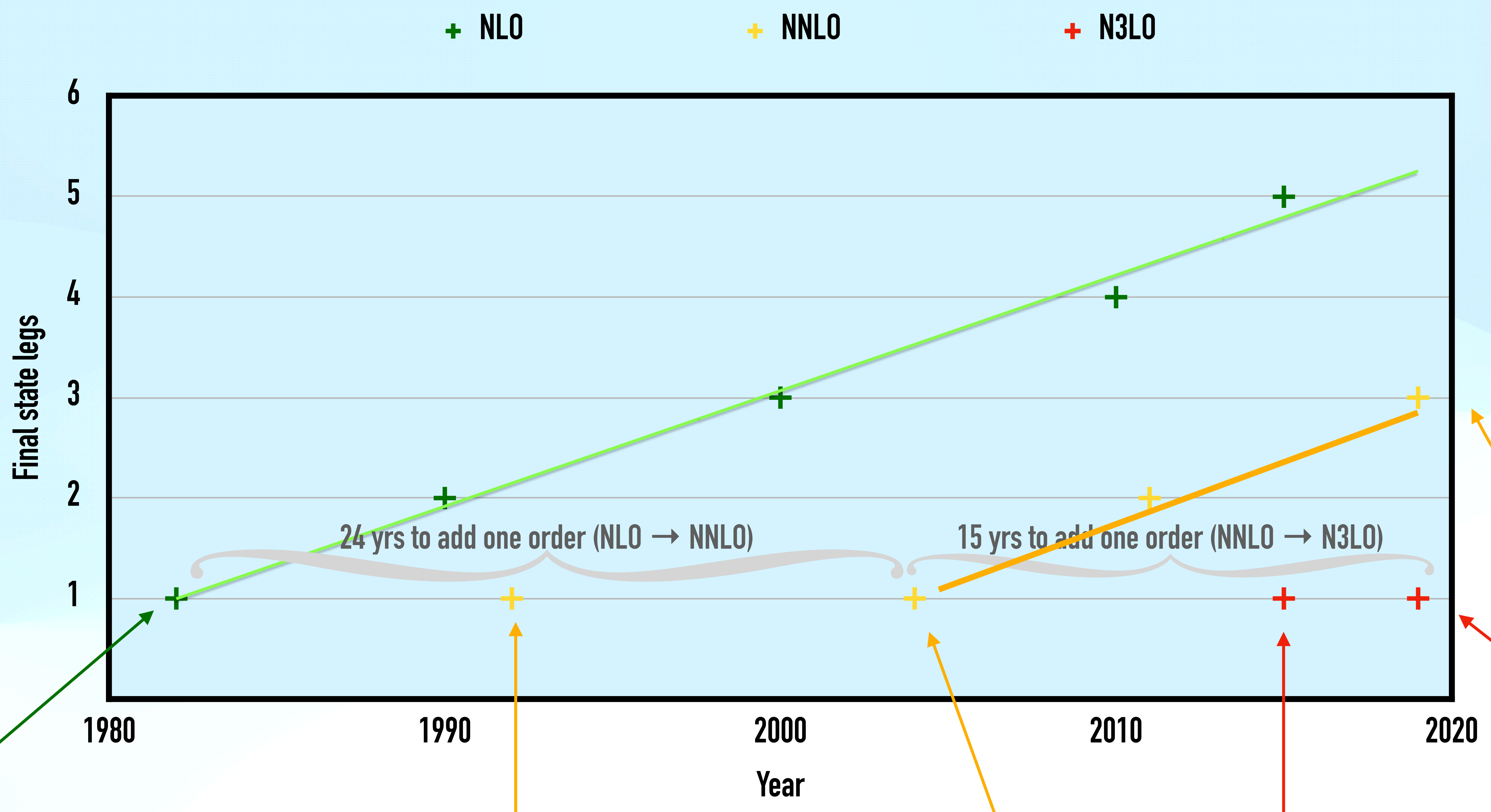
N3LO QCD HADRON-COLLIDER CALCULATIONS VS. TIME

Only 2→1 processes



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

Perturbative QCD TH predictions



Cost of add
one extra leg in years

Slope
~ 1leg/10 yr ??

Slope ~ 1 leg/10 yr

Cost of add
one extra leg measured in years

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

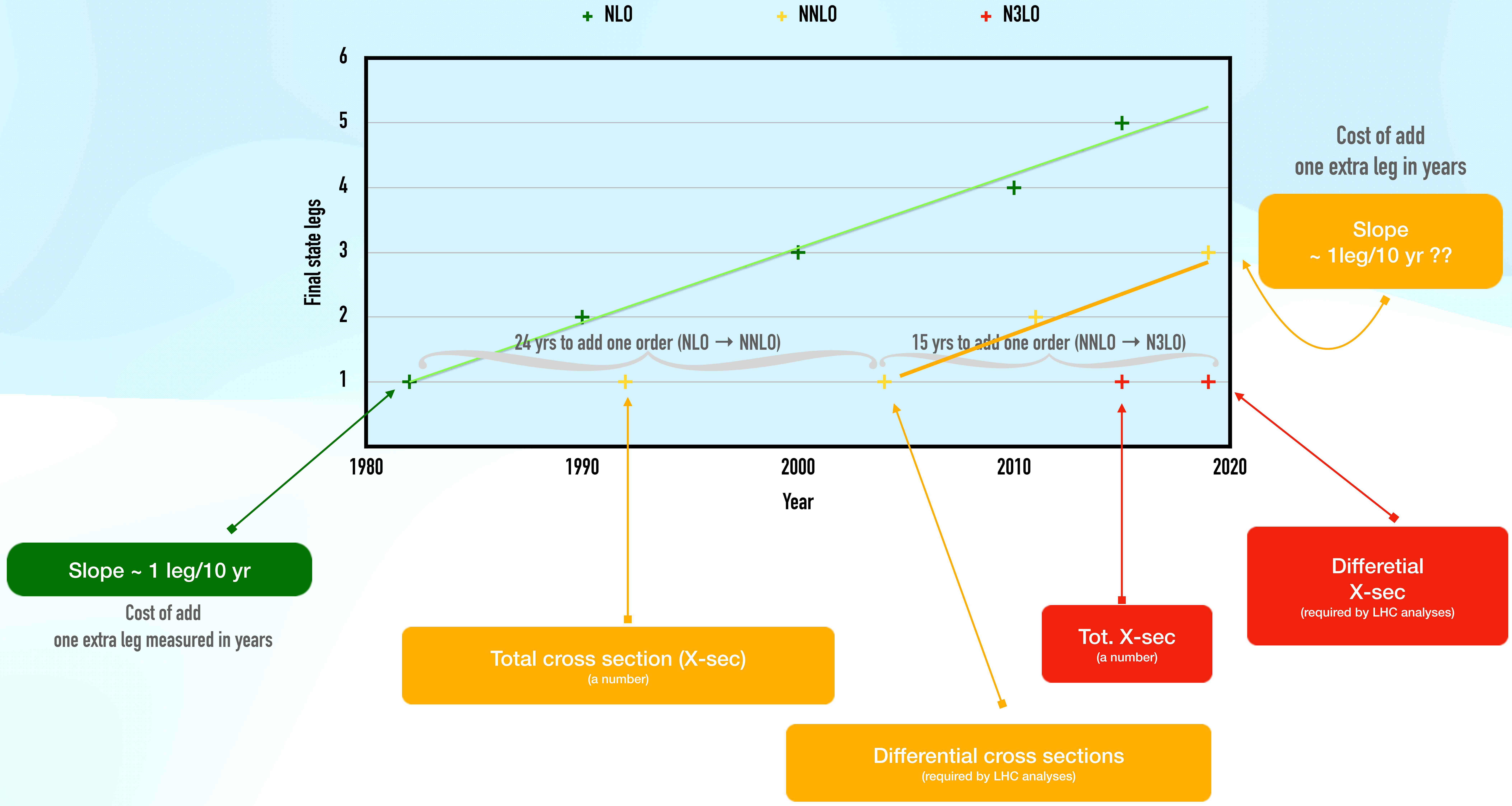
Differential cross sections
(required by LHC analyses)

Tot. X-sec
(a number)

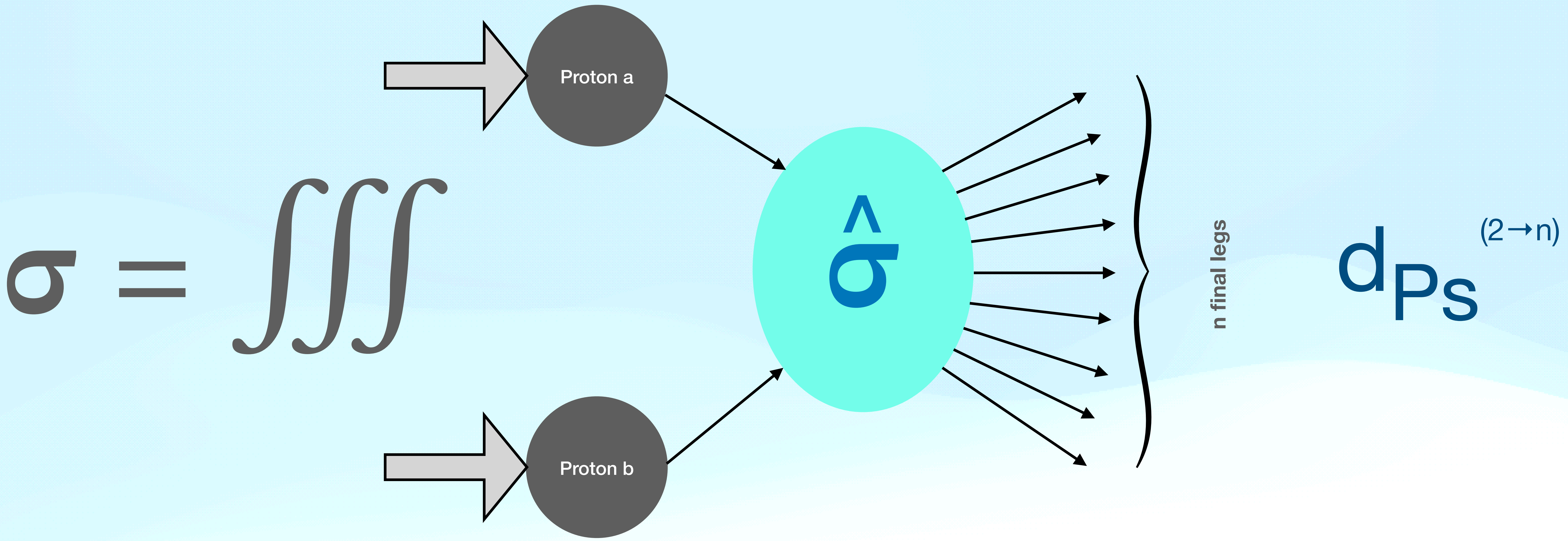
Differetial
X-sec
(required by LHC analyses)

Perturbative QCD TH predictions

How many years will it take to get an N4LO?



Anatomy of perturbative calculations



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PDFs

Partonic cross section

Organisation next slides

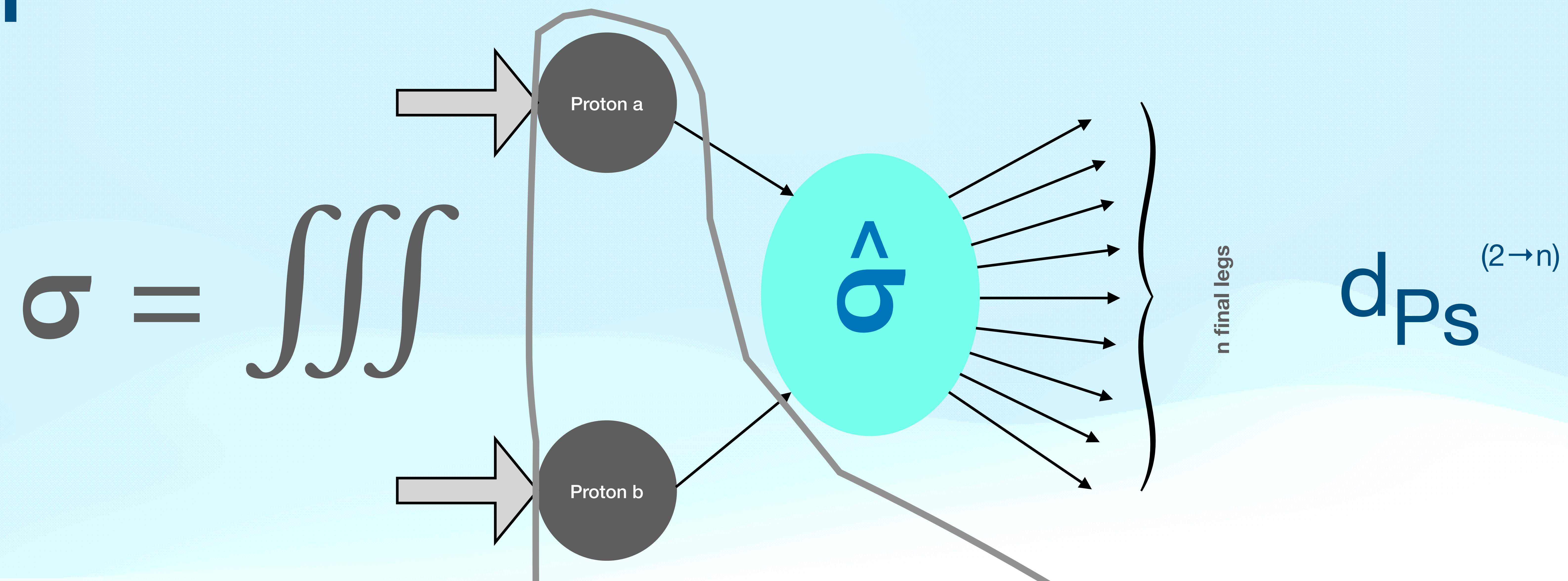
PDFs

Partonic cross section (scattering amplitudes)

Subtraction prescriptions and CPU cost

Subtraction prescriptions and CPU cost

Anatomy of perturbative calculations



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PDFs

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Organisation next slides

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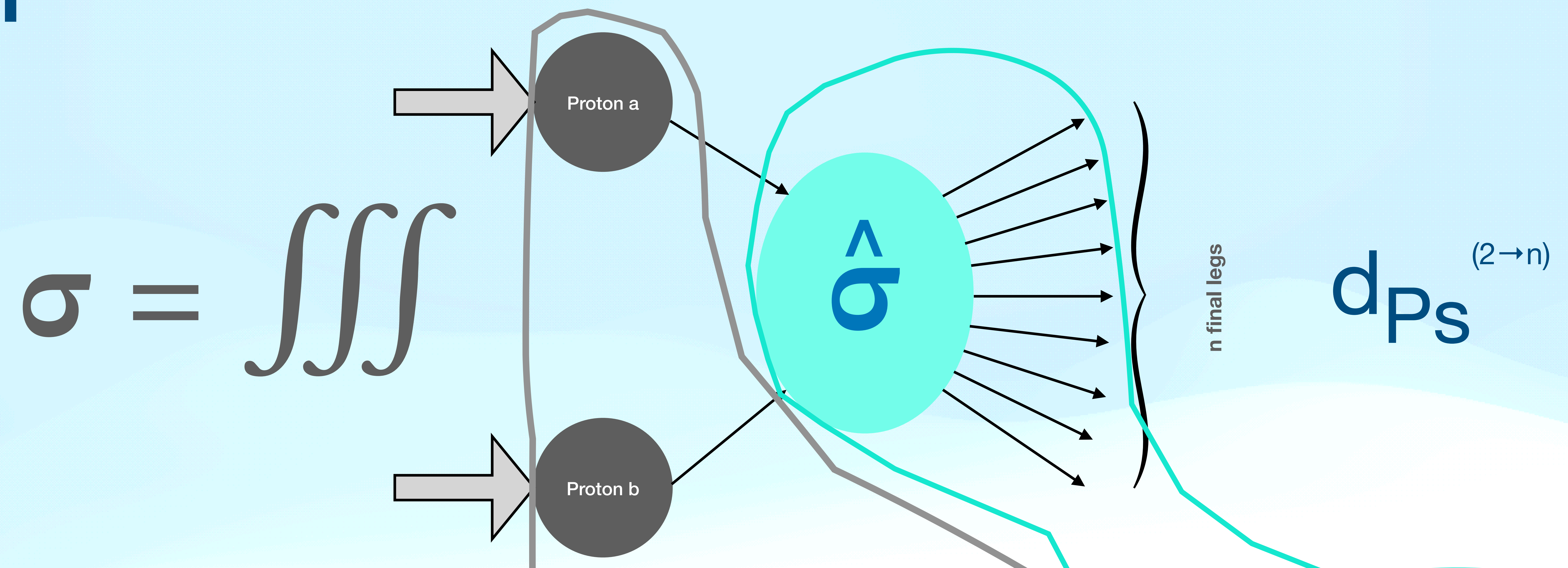
Anatomy of perturbative calculations



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PDFs

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Organisation next slides

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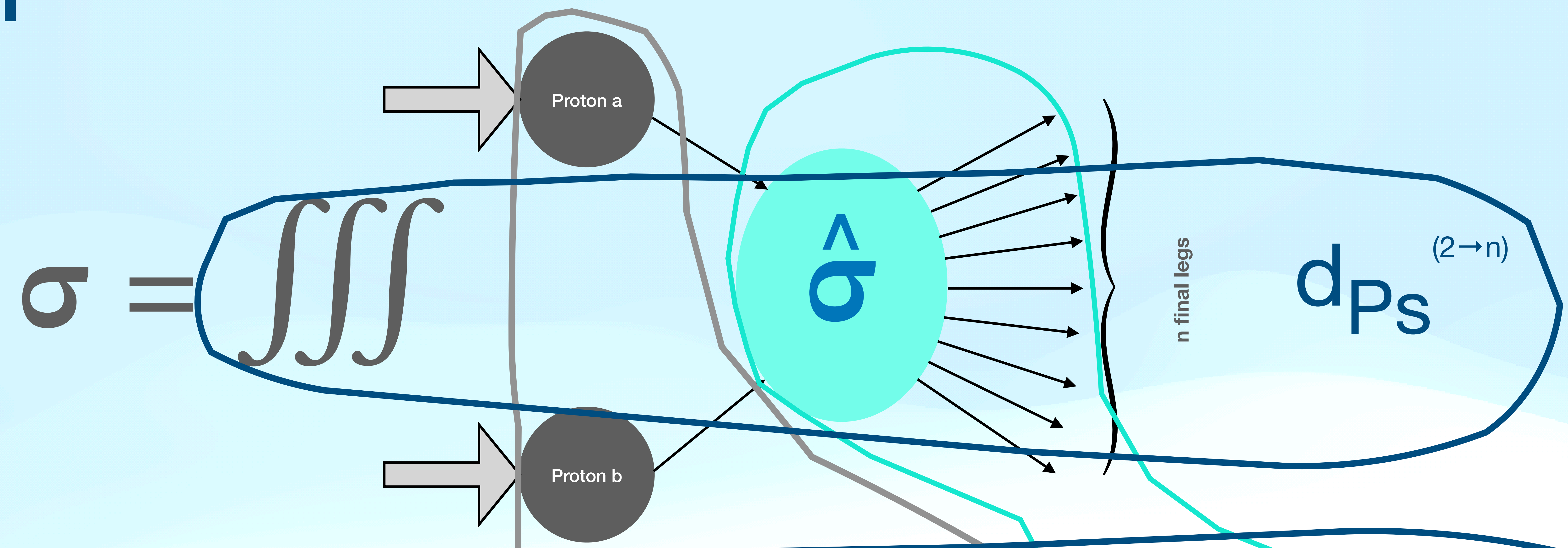
Subtraction prescriptions and CPU cost

Anatomy of perturbative calculations



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

PDFs

Partonic cross section

Organisation next slides

PDFs

Partonic cross section (scattering amplitudes)

Subtraction prescriptions and CPU cost

Subtraction prescriptions and CPU cost

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
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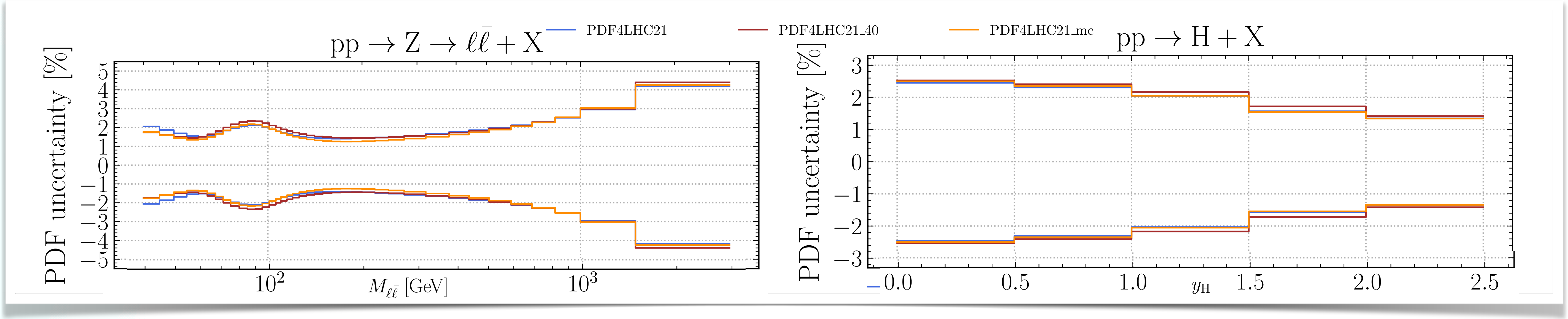

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In the extraction of many fundamental parameters, PDF uncertainties dominate

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 $\sqrt{s} = 8$ 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^4LL approximation	±0.04	
Total	+0.91	−0.88

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ATLAS CONF Note
ATLAS-CONF-2023-004
2nd April 2023

Improved W boson Mass Measurement using $\sqrt{s}$ = 7 TeV Proton-Proton Collisions with the ATLAS Detector

The ATLAS Collaboration

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

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In the extraction of many fundamental parameters, PDF uncertainties dominate

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

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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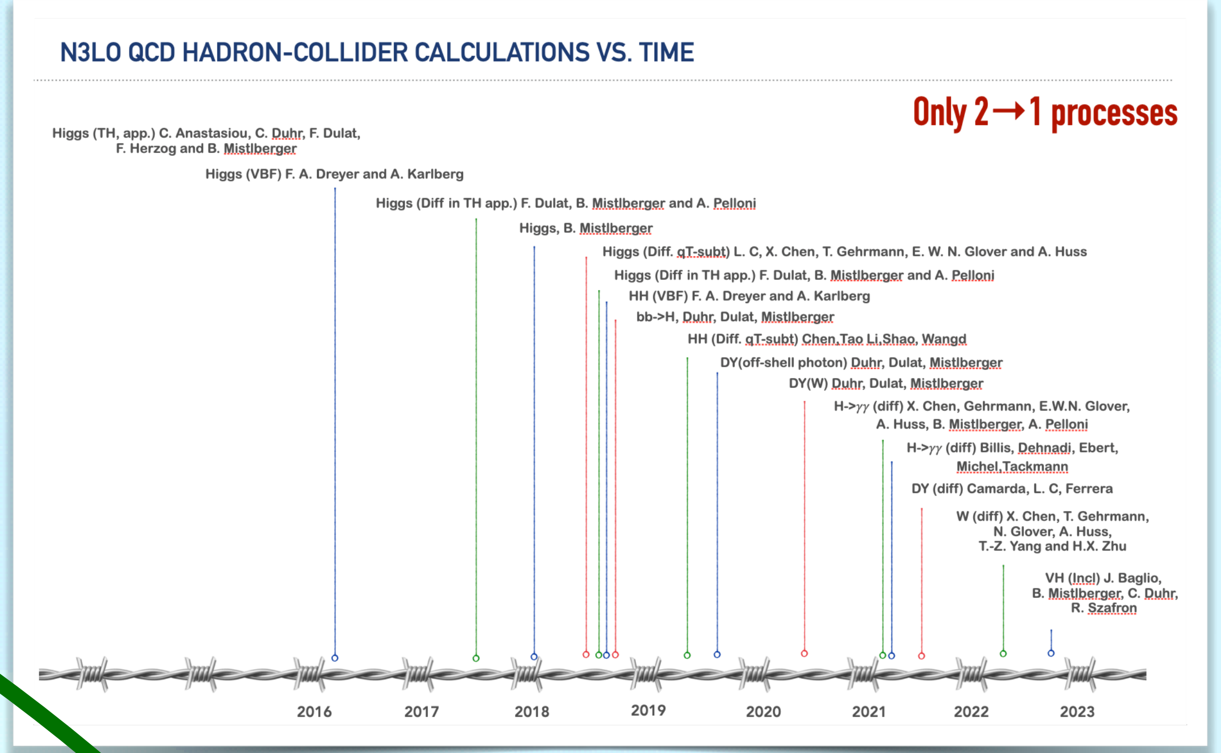
State of the art PDFs (N3LO)

We used NNLO PDFs in ~~almost~~ all our N3LO calculations!



NEW PDFs at approximate N3LO

MSHT20sN3LO

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

- 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 αs(mZ) 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

σ order	PDF order	$\sigma + \Delta\sigma_+ - \Delta\sigma_-$ (pb)	σ (pb) $+ \Delta\sigma_+ - \Delta\sigma_-$ (%)
		PDF uncertainties	
N^3LO	aN^3LO (no theory unc.)	$45.296 + 0.723 - 0.545$	$45.296 + 1.60\% - 1.22\%$
	aN^3LO $(H_{ij} + K_{ij})$	$45.296 + 0.832 - 0.755$	$45.296 + 1.84\% - 1.67\%$
	aN^3LO (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^3LO	aN^3LO (no theory unc.)	$45.296 + 0.723 - 1.851$	$45.296 + 1.60\% - 4.09\%$
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factorisation scale variation is contained within the PDF uncertainties.

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

NEW splitting functions at N3LO (Pqg)

Falcioni, Herzog, Moch, Vogt [2023]

Notice that in fixed order calculations

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

The complexity is fourth order

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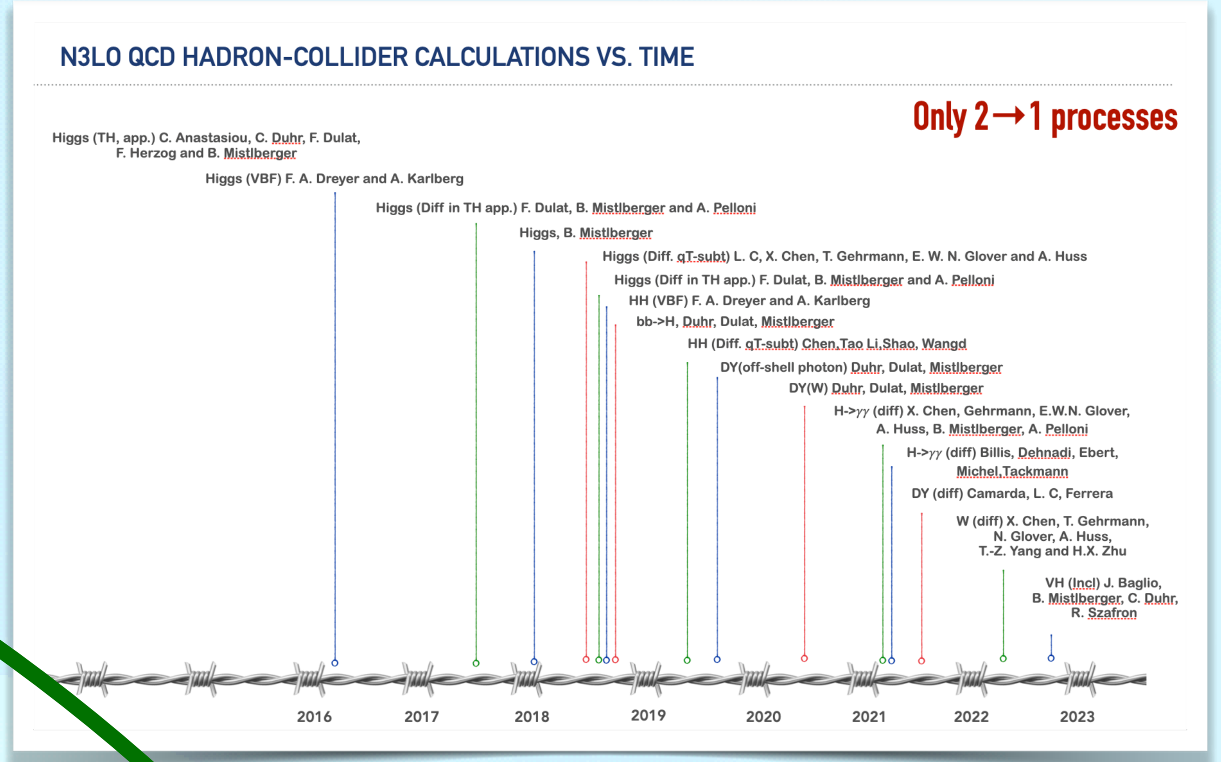

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From yesterday on the ArXiv

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factorisation scale variation is contained within the PDF uncertainties.

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

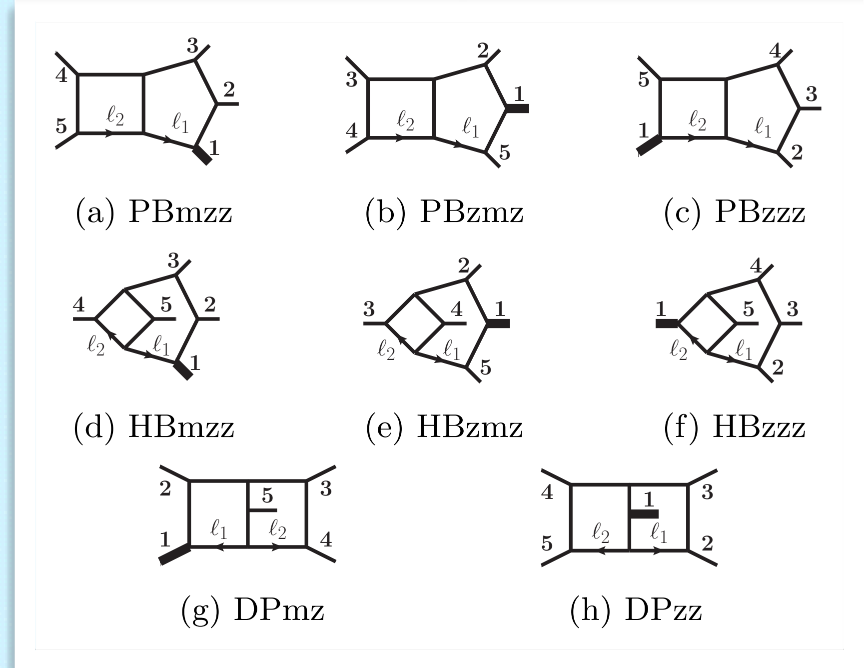
For sure there will be a lot of improvements in the next years reaching N3LO precision and controlling better the TH uncertainties (also including more data)

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

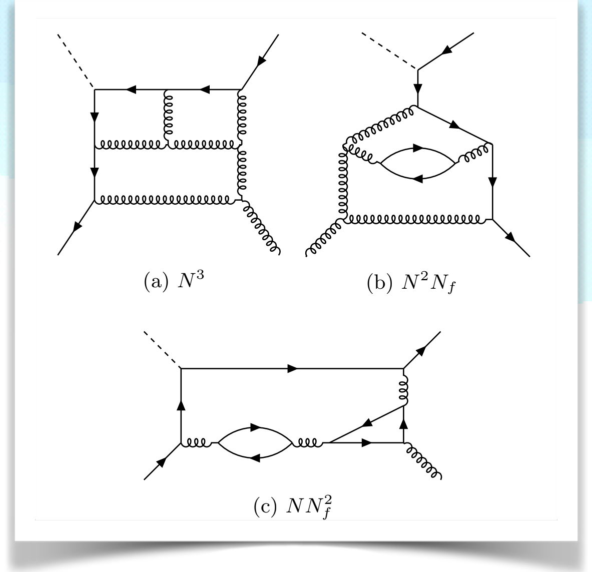
Relevant for H/Z/W production in association with two jets at NNLO, or in association with one jet at N3LO or H/Z/W at N4LO



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



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

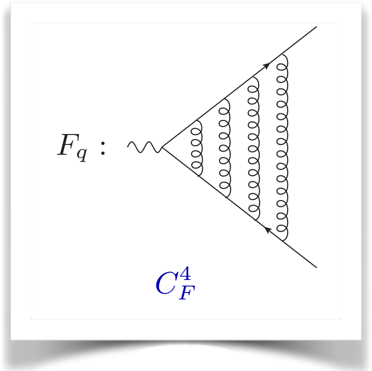
NEW Planar three-loop QCD helicity amplitudes for V +jet production at hadron colliders

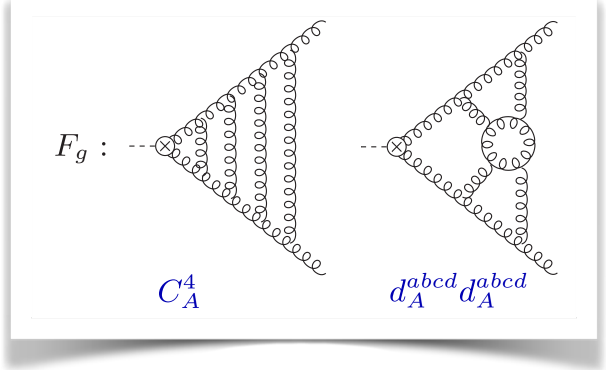
Relevant for Z/W/γ^* production in association with one jet at N3LO or Z/W/γ^* at N4LO

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]

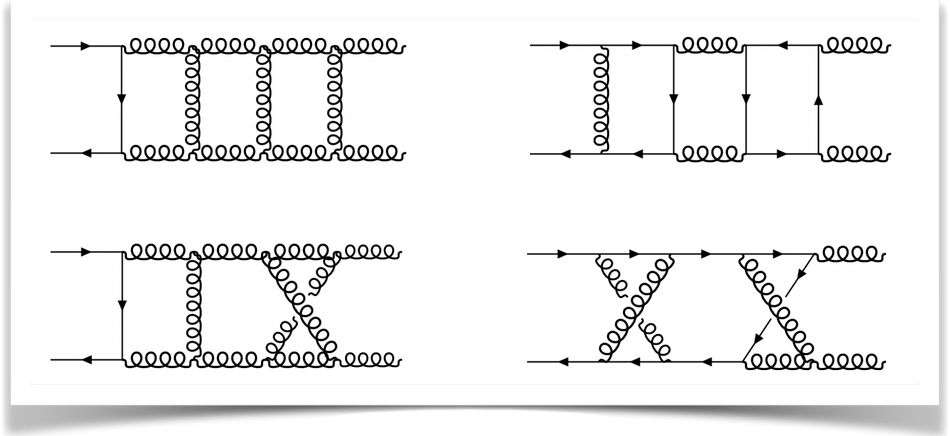
Quark and Gluon Form Factors in Four-Loop QCD

Relevant for H/Z/W/γ^* at N4LO

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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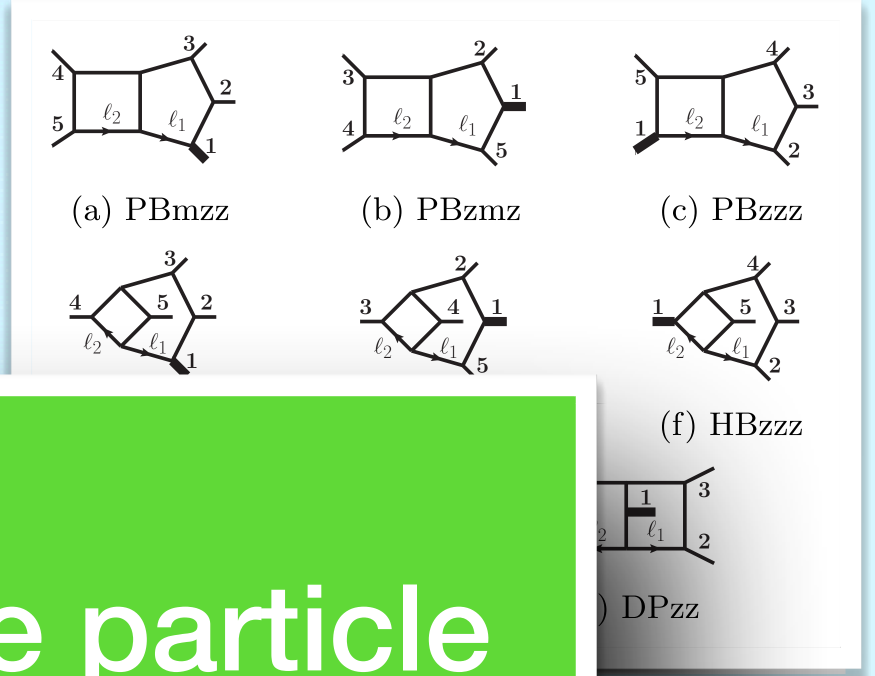
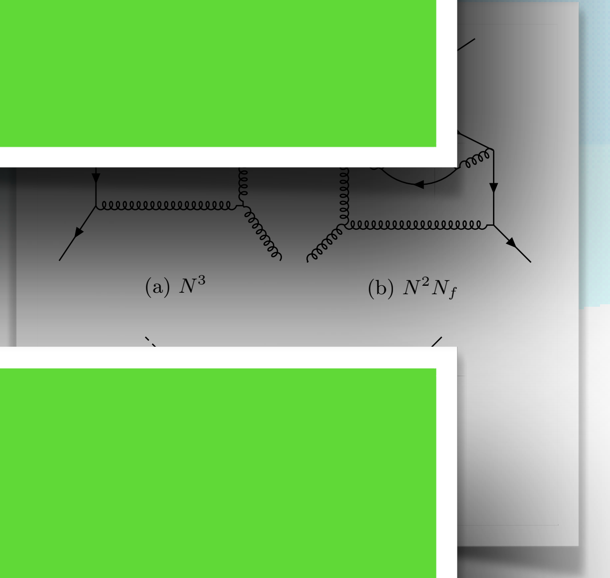


Relev

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

Two-

Relev



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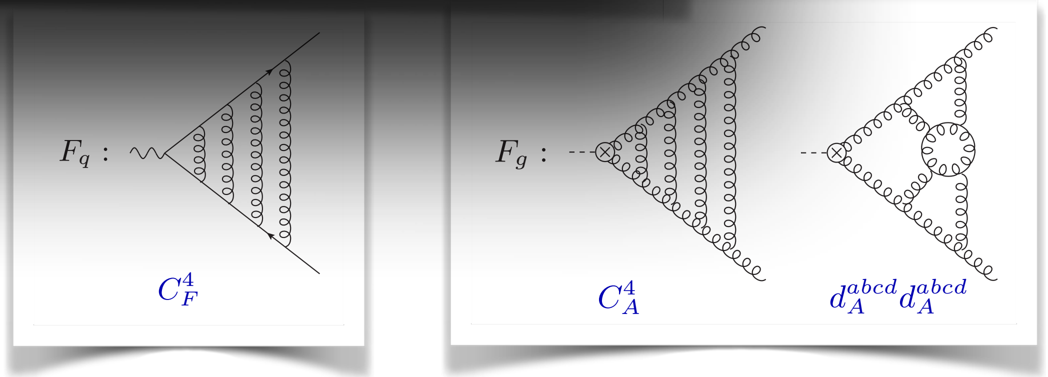

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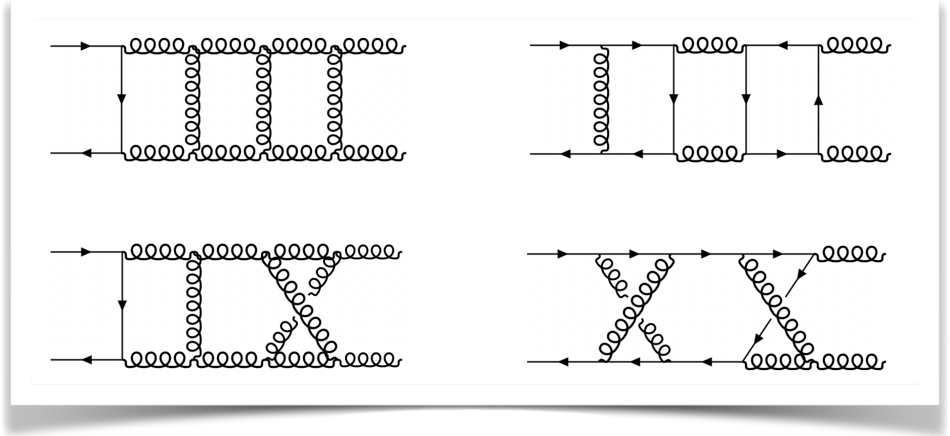

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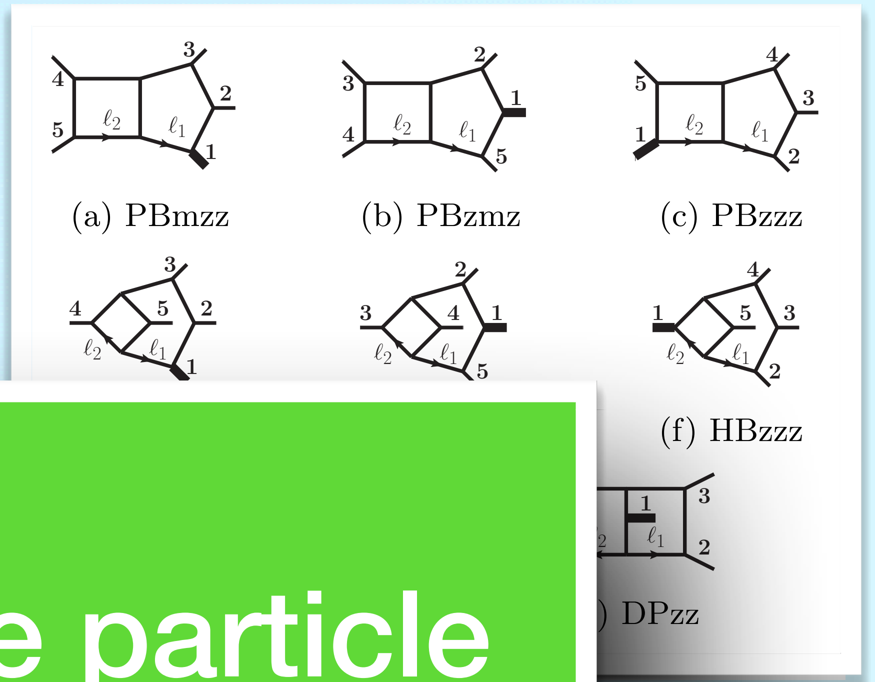

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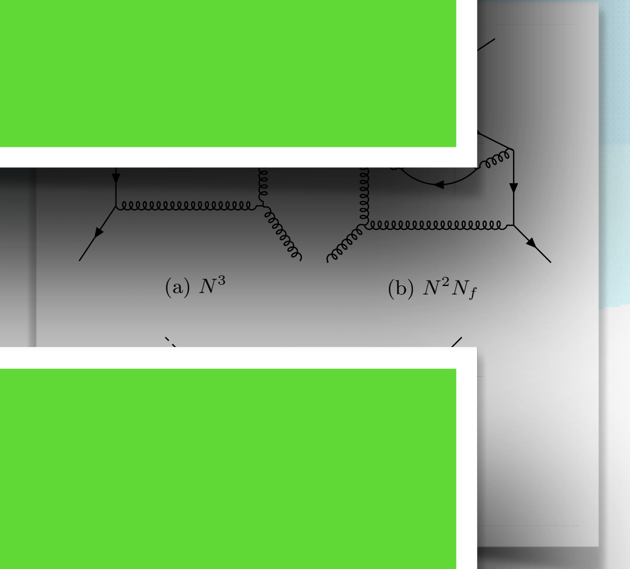

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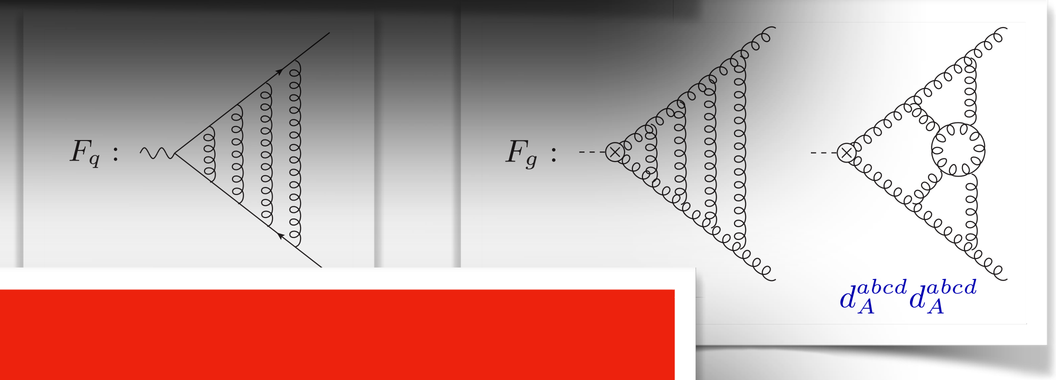
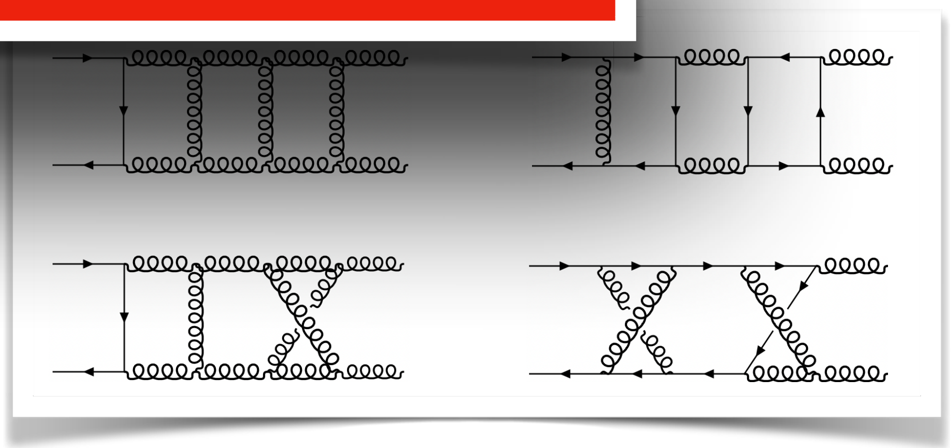


Lee, von Manteuffel, Schabinger, Smirnov, Smirnov, Steinhauser [2022]

Quar

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

Relevant for H/Z/W/γ^* at N4LO



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

Relevant for jj at N3LO

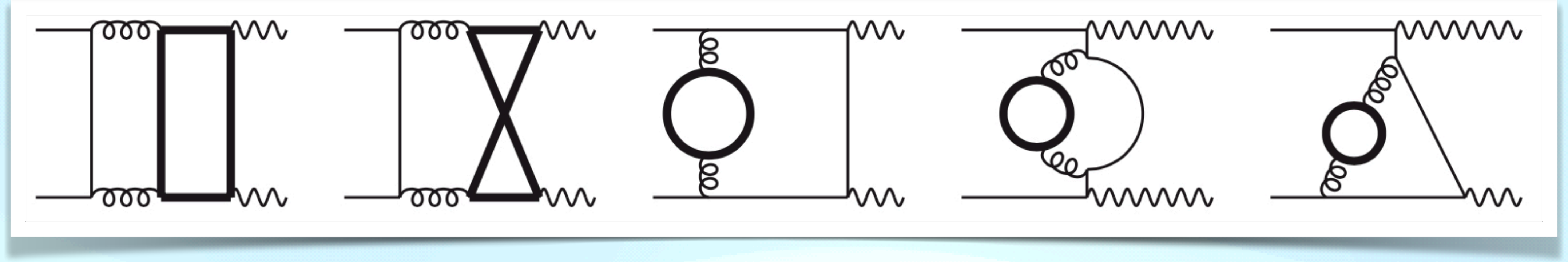
Scattering amplitudes – the frontier at NNLO full massive

Becchetti, Bonciani, **LC**, Coro, Ripani [2023]

NEW 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



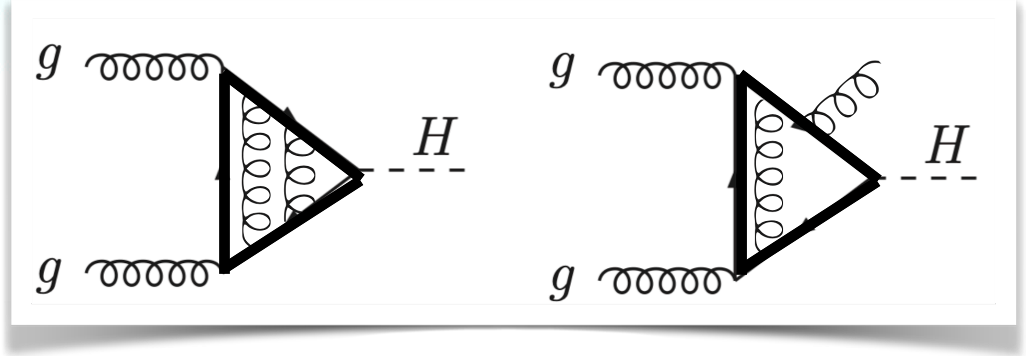
Czakon, Harlander, Klappert, Niggetiedt [2021]

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



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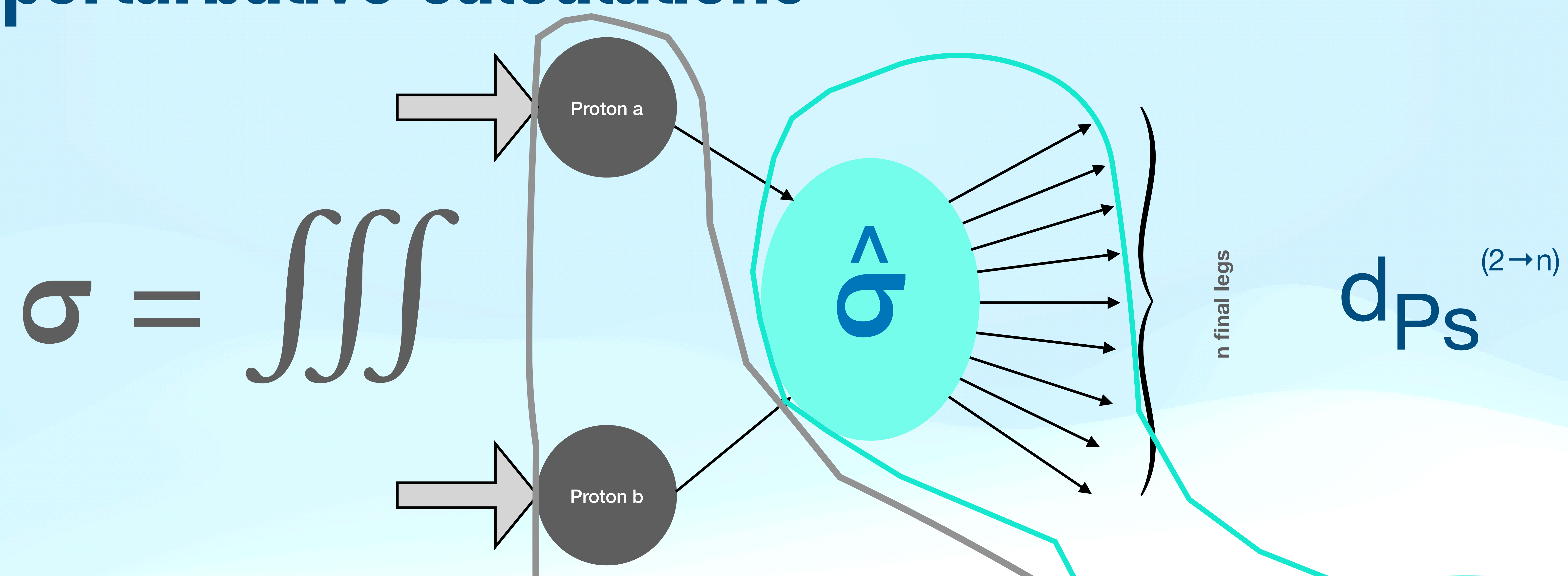
☑ Results using semi analytical methods

Anatomy of perturbative calculations



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PDFs

Partonic cross section

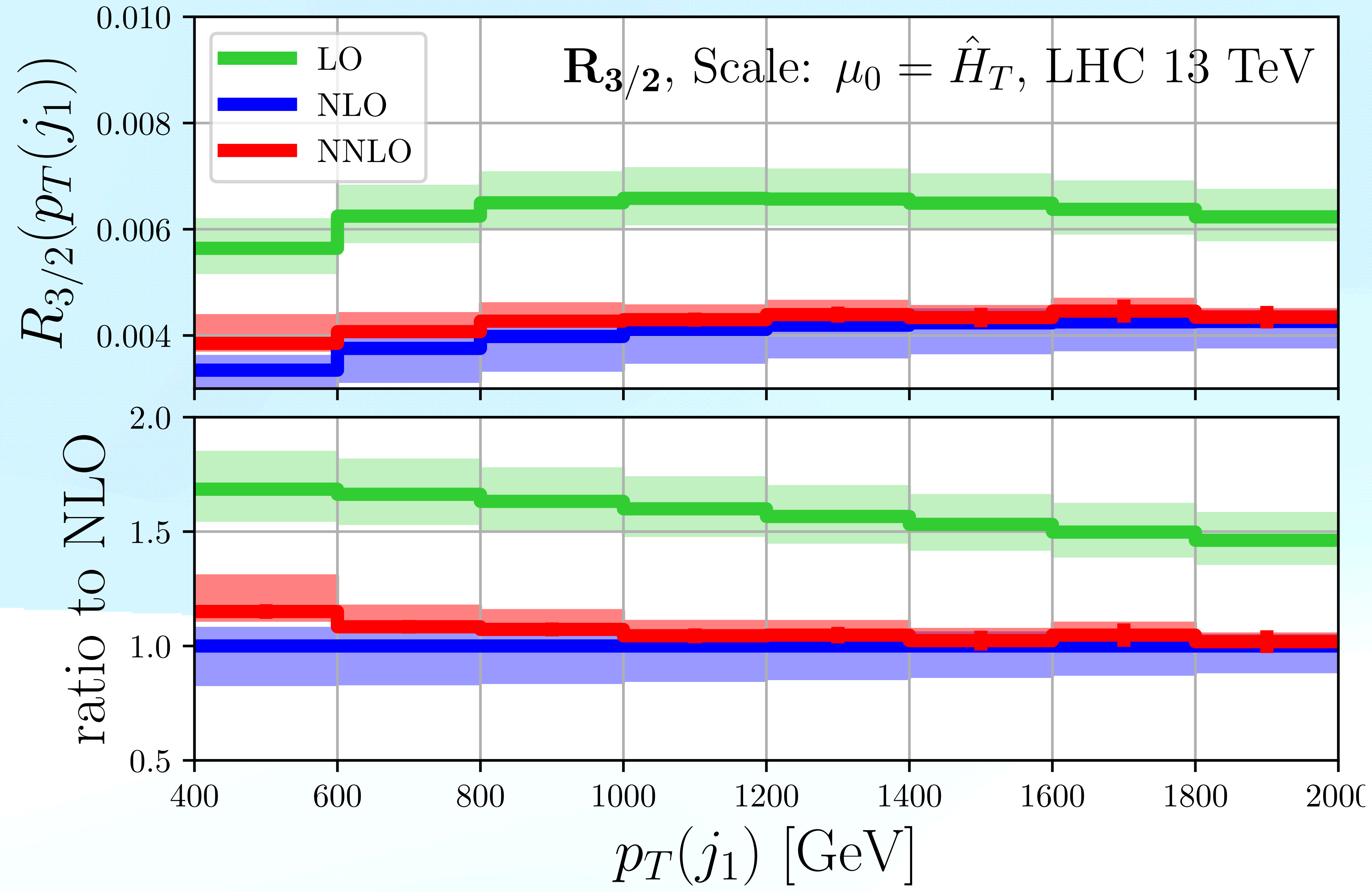
Organisation next slides

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

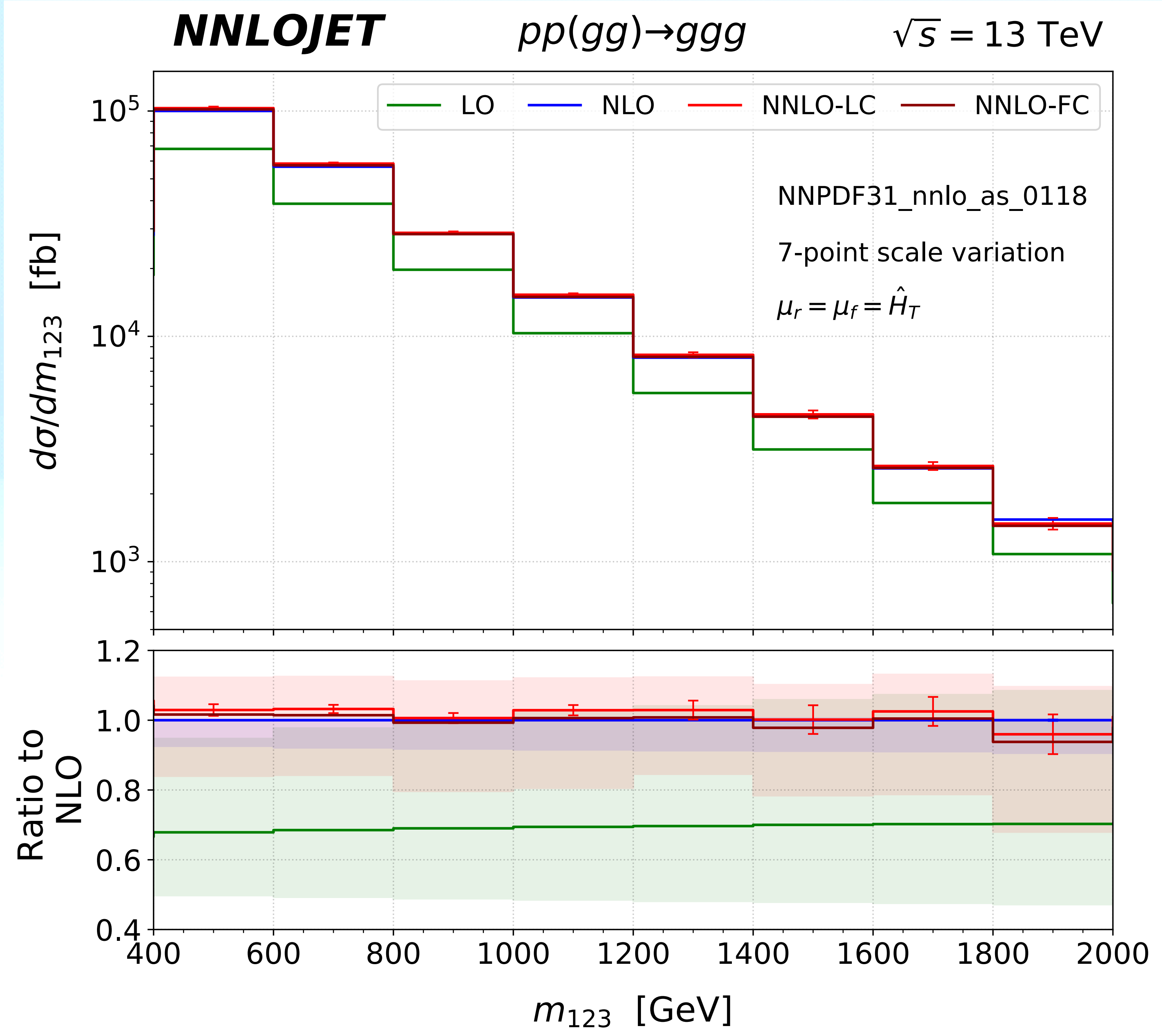
Next

Three jet production at NNLO

Czakon, Mitov, Poncelet [2021]



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

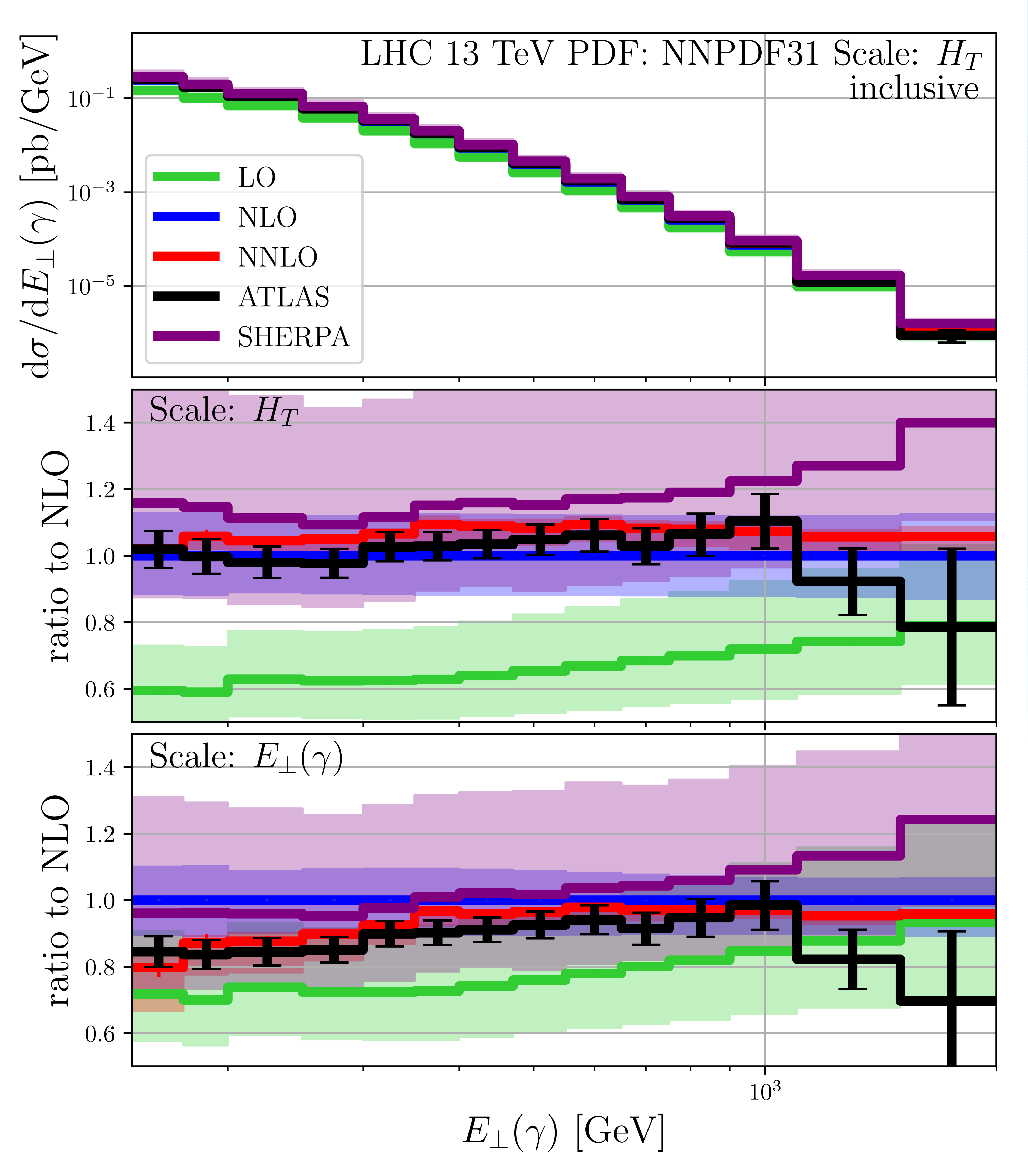


- Two different subtraction methods: sector-improve residue (left) vs antenna (right)
- NNLO corrections significantly reduces the dependence of those observables on the factorization and renormalization scales
- Leading colour two-loop scattering amplitudes or only gluons assumption
- Sizable reduction of the scale variation from NLO to NNLO (in the tail of pT from 10% to 3%)

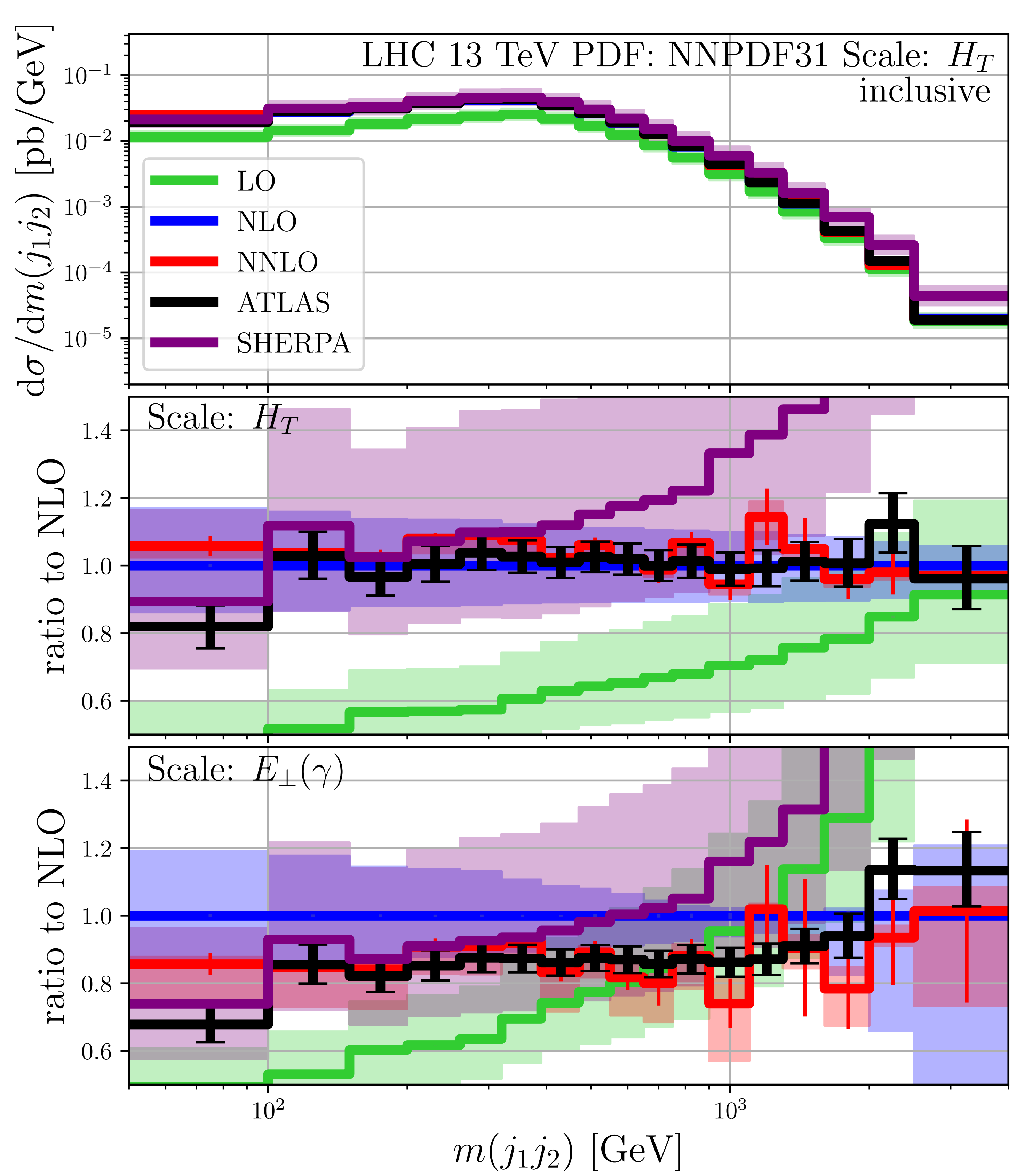
NEW Photon plus two jet production at NNLO

Badger, Czakon, Hartanto, Moodie, Peraro, Poncelet, Zoia [2023]

First exact 2 → 3



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

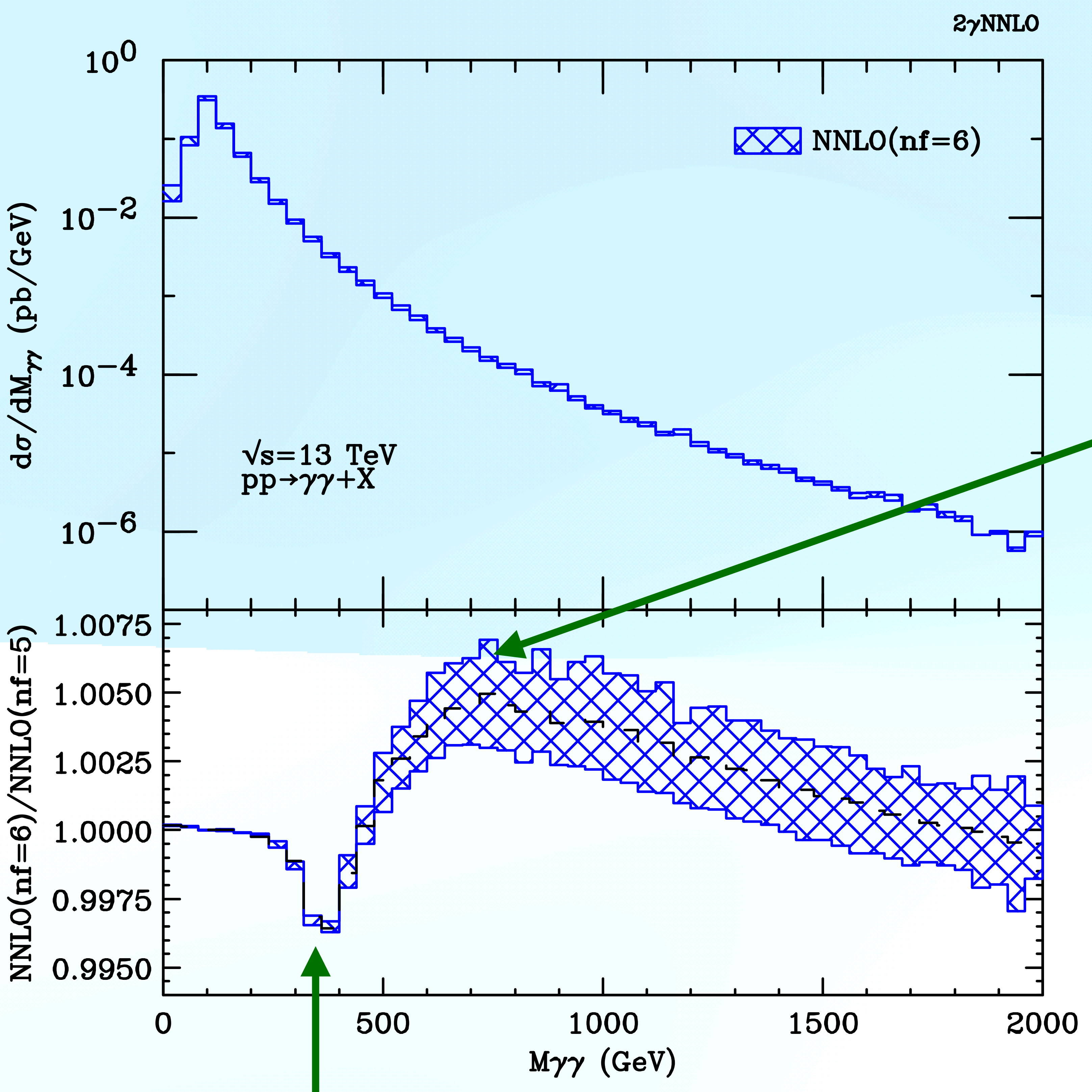


- NNLO results improve the description of the data in the case of the photon transverse energy, the jet transverse momentum, and the di-jet invariant mass
- Noticeable difference between theory and experiment in the case of the photon transverse energy starting around 1 TeV

NEW Diphoton production at NNLO with full top quark mass dependence

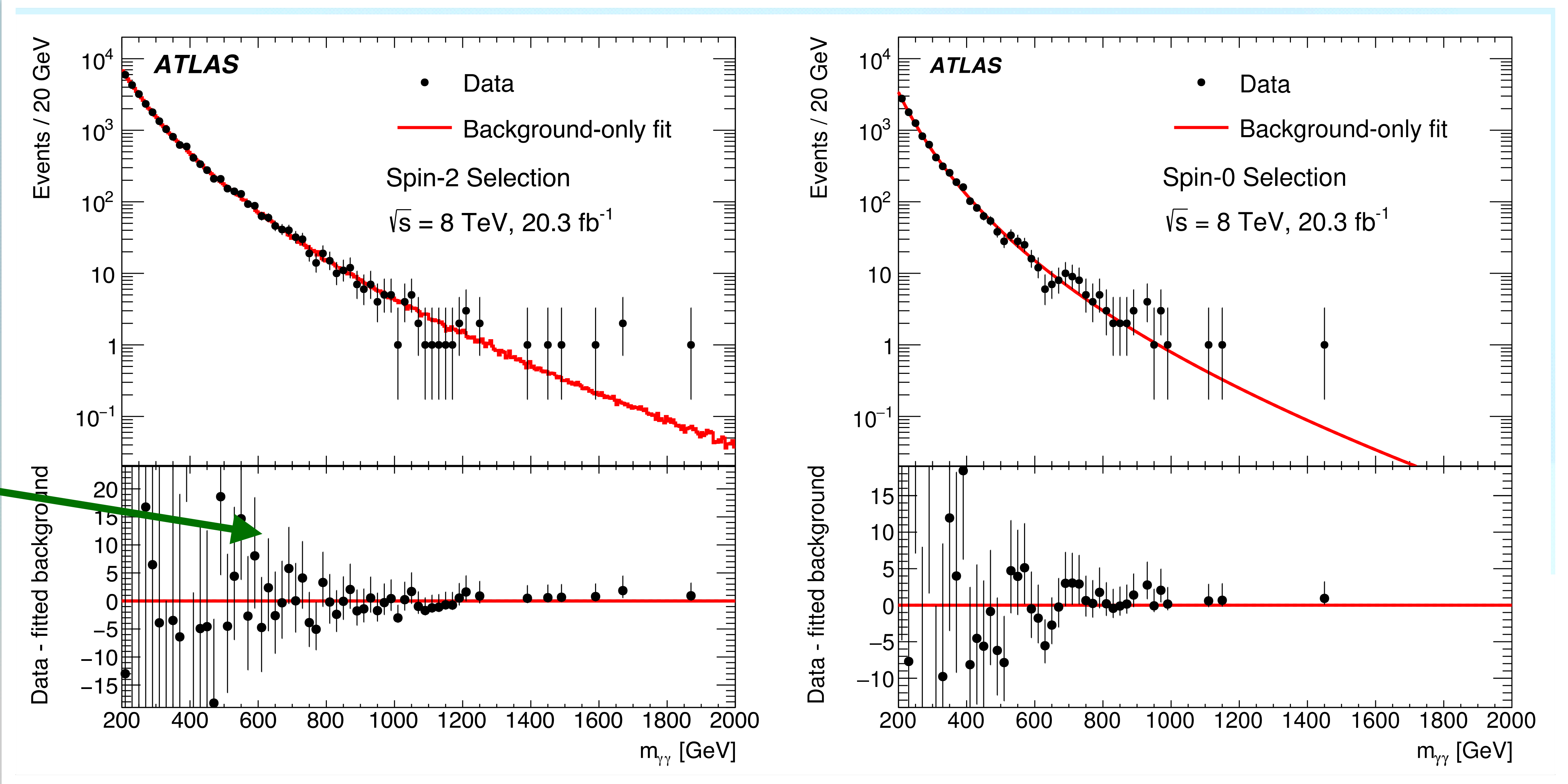
Becchetti, Bonciani, **LC**, Coro, Ripani [2023]

Full massive 2 → 2

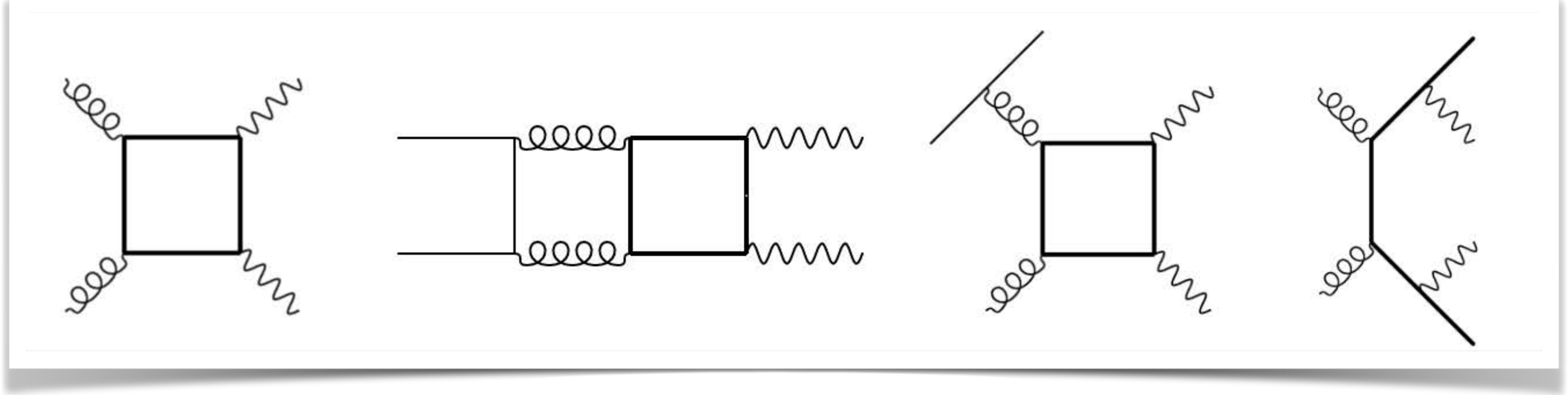


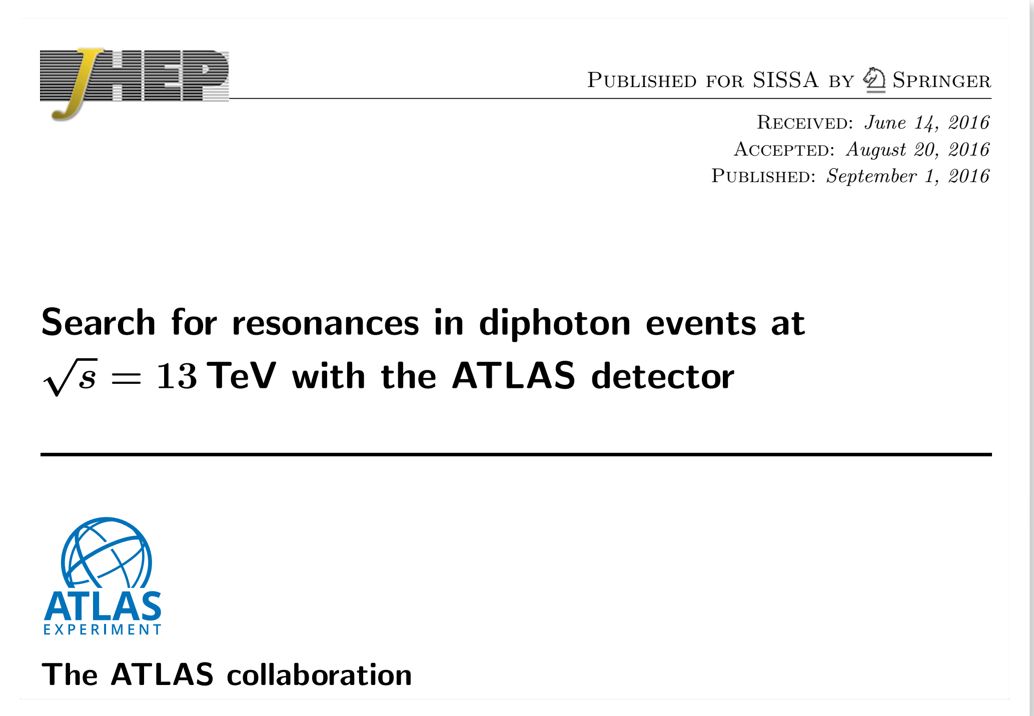
750 GeV

2 x m_top



Example of the necessity of precise TH predictions





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

NEW Diphoton production at NNLO with full top quark mass dependence

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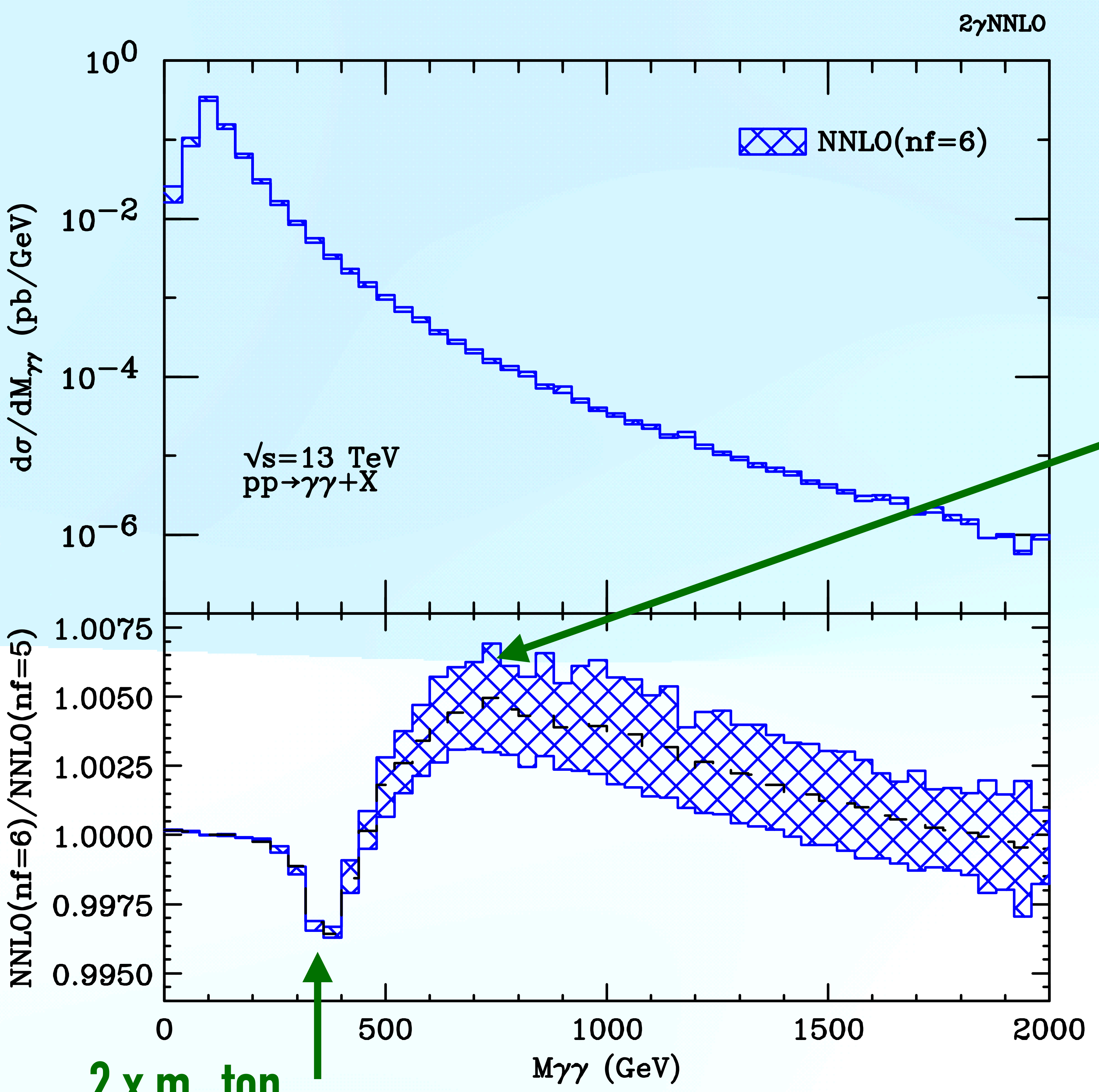
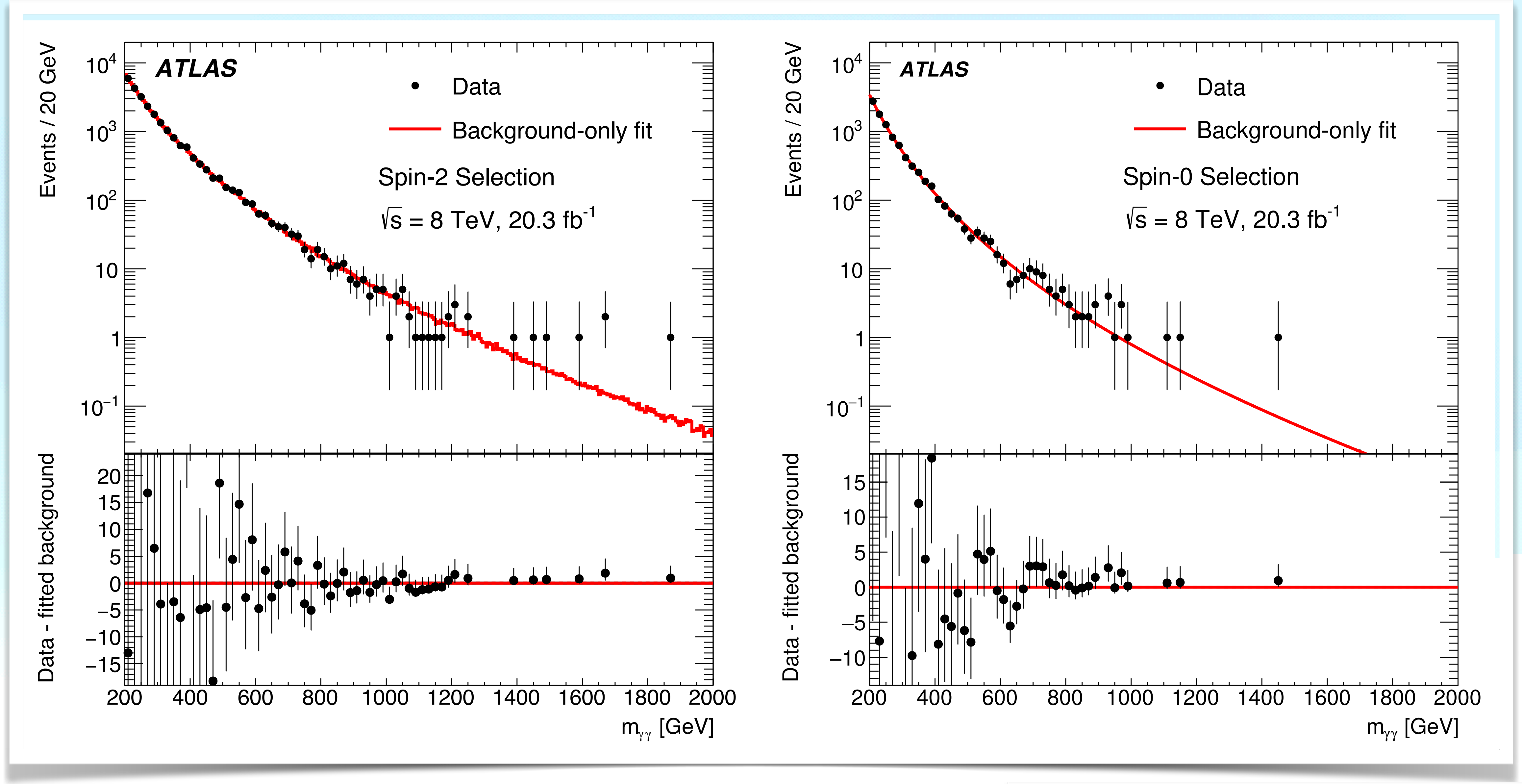
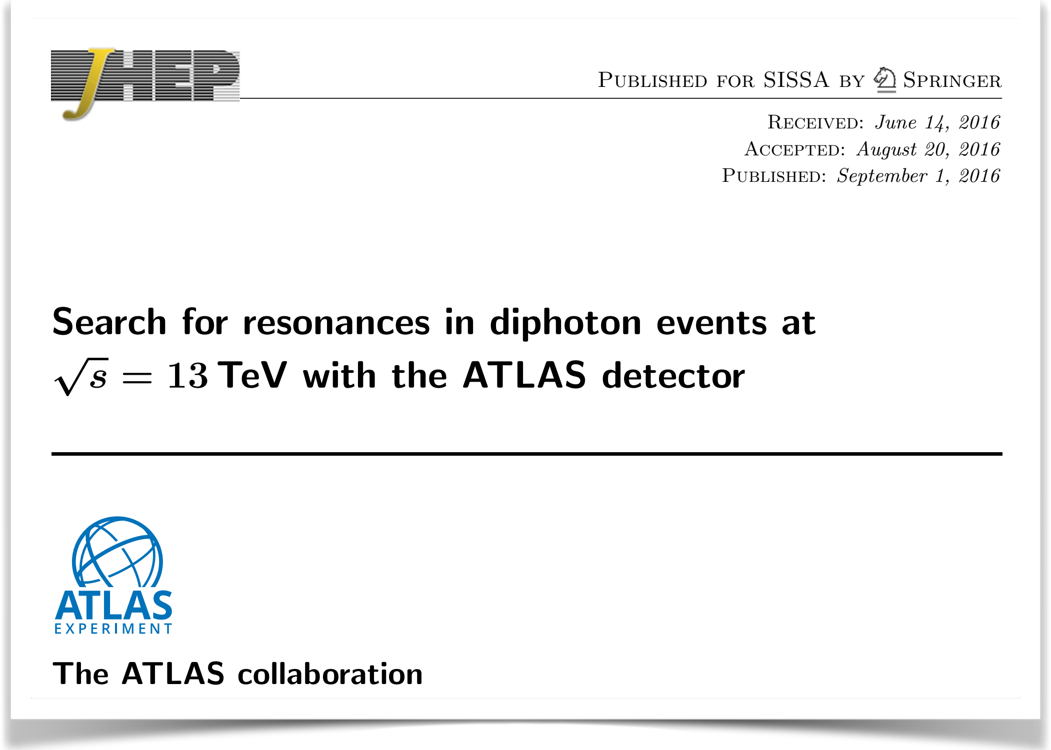


750 GeV not "very" affected by fiducial cuts

2 x m_top




JHEP
Published for SISSA by Springer
Received: June 14, 2016
Accepted: August 20, 2016
Published: September 1, 2016

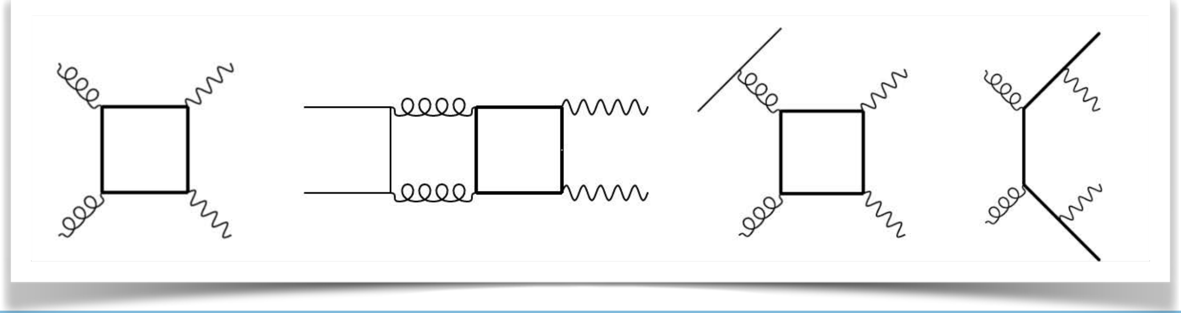
Search for resonances in diphoton events at $\sqrt{s} = 13$ TeV with the ATLAS detector

The ATLAS collaboration

Example of the necessity of precise TH predictions

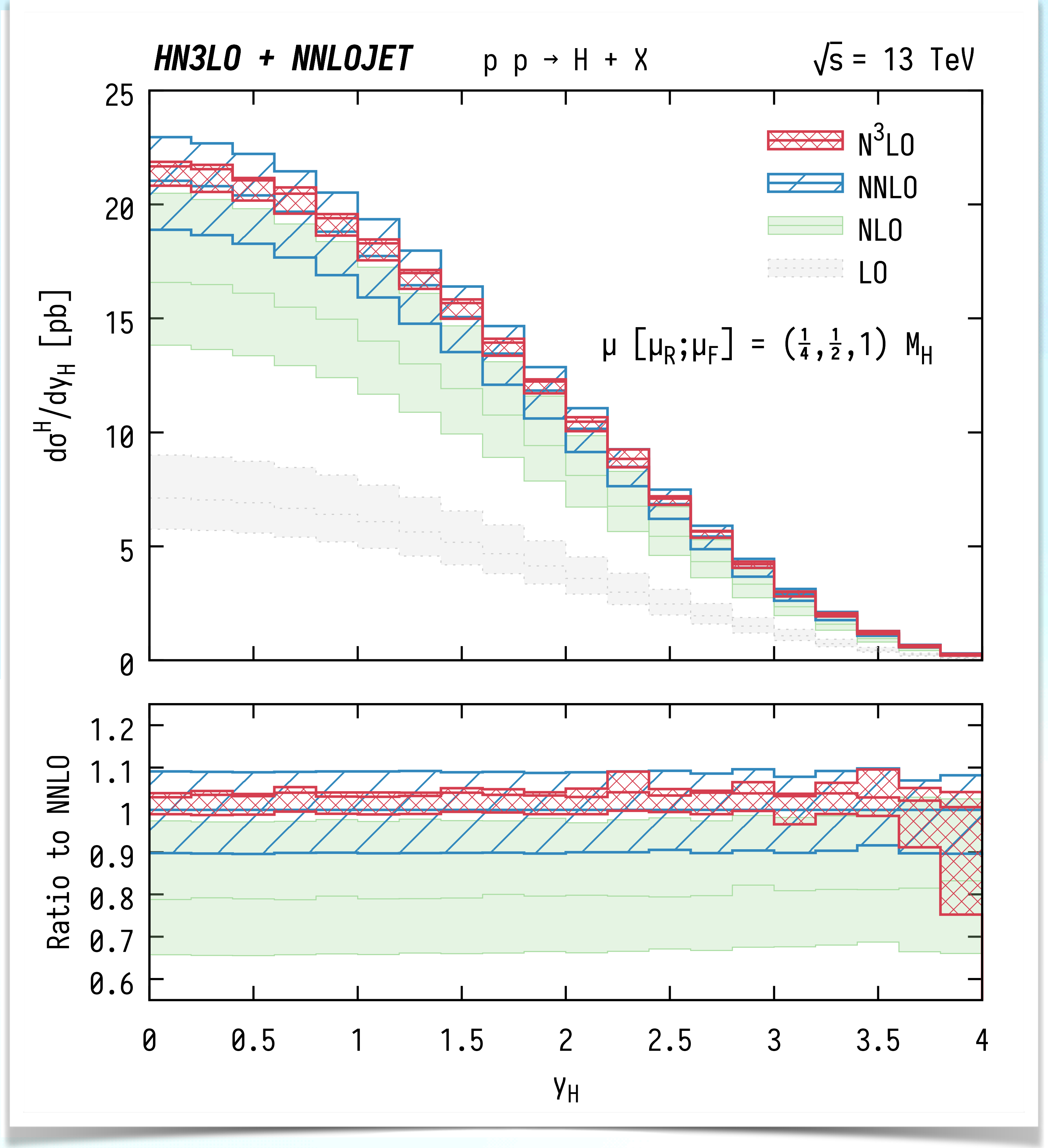
Example of comparison of "NEW" bumps or kinks inside the SM

- All massive contributions taken into account: two-loop, loop induced, one-loop-real and double real (pp→γγtt)
- Loop induced gg channel and two-loop (qqbar) dominate the shape



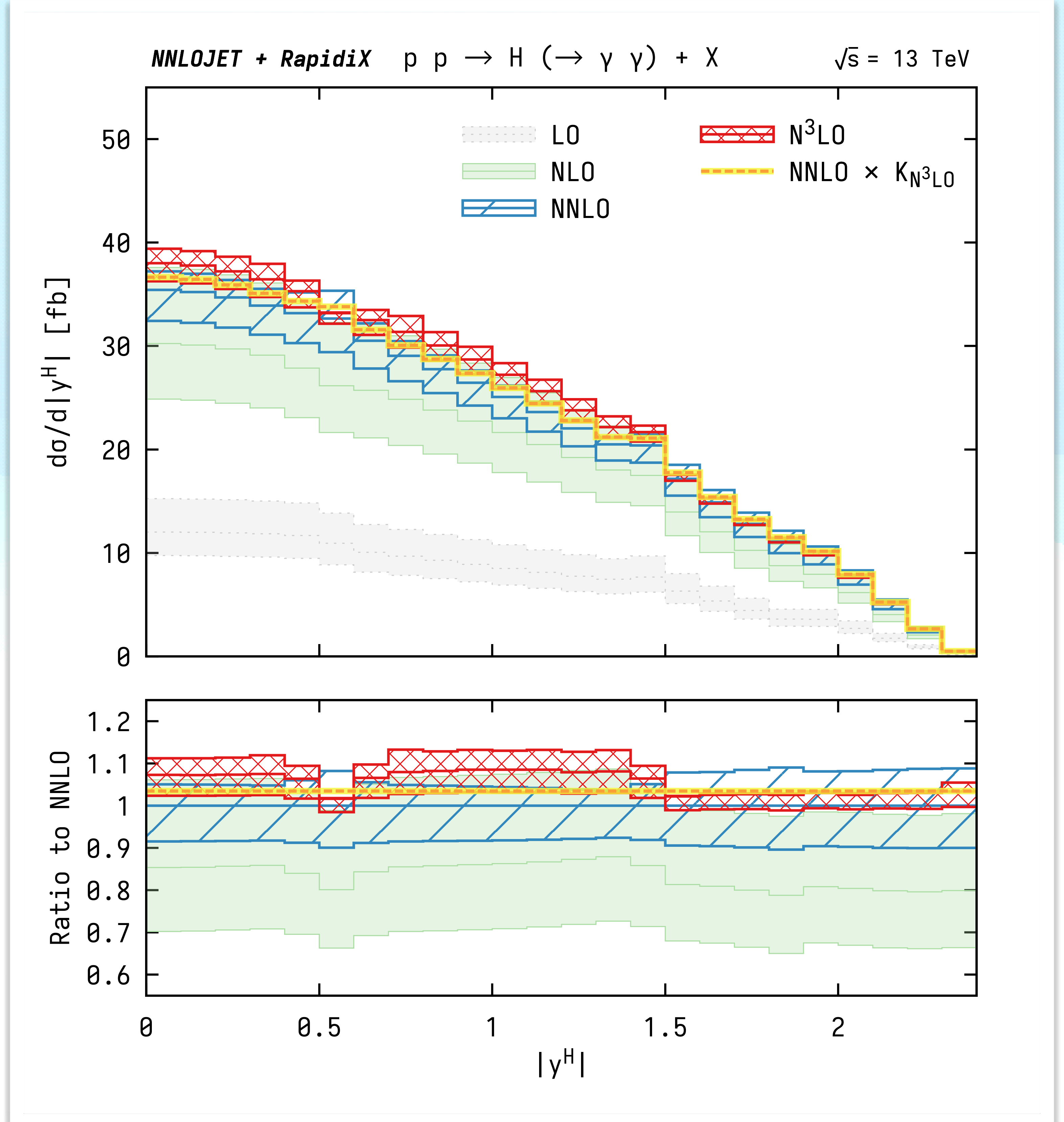
Higgs production a N3LO

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



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

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

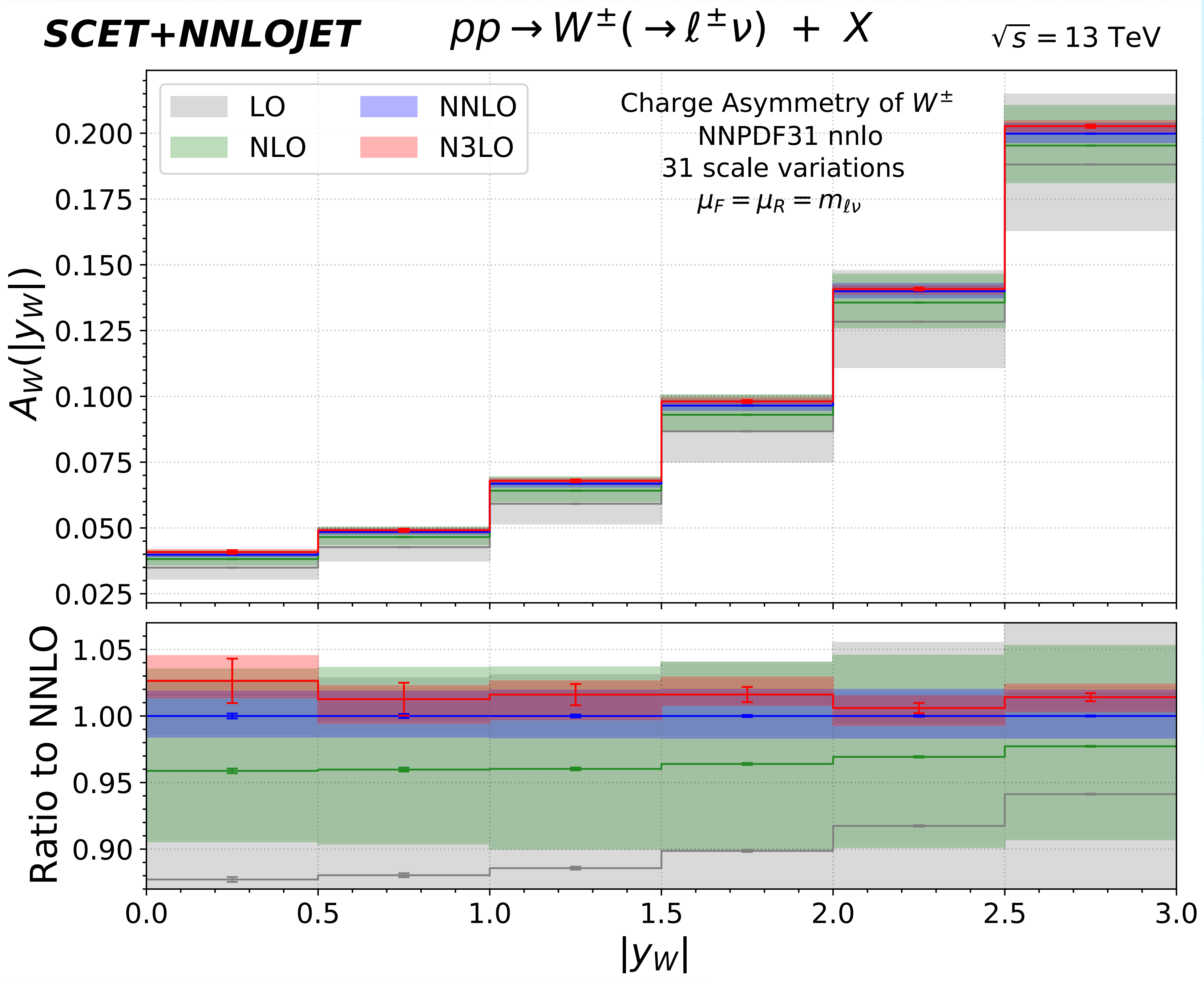


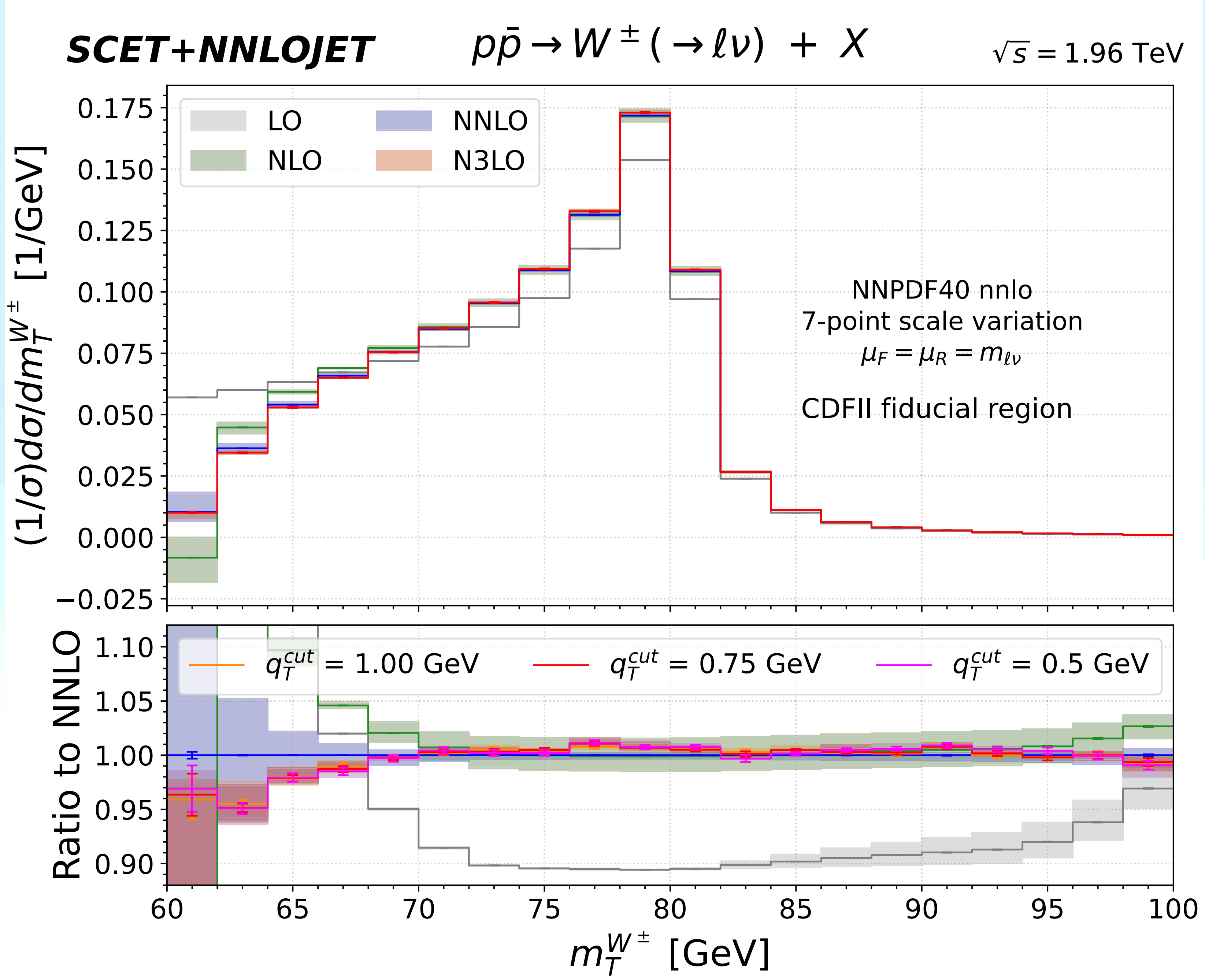
Combination of H+jet at NNLO + rapidity distribution at N3LO: P2B

- 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%)

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 MW determination
- N3LO perturbative uncertainties estimated by scale variations are found to be about ±1% to ±1.5%
- Distortions to the shape of the distributions are minimal at N3LO and only become visible outside the peak region of the mW± 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

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

QCD / EW / MIXED

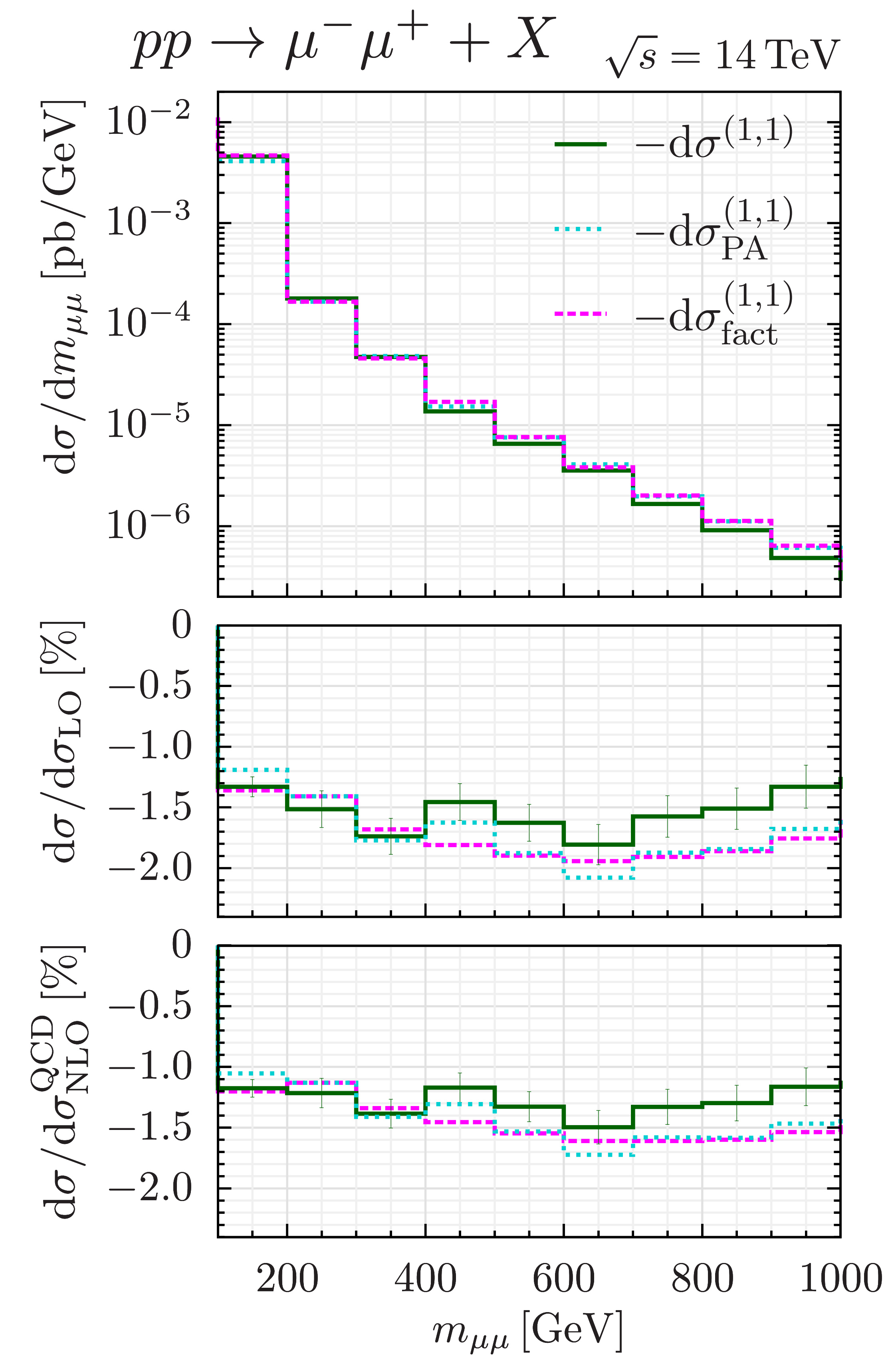
$$\hat{\sigma} = \sigma^{(\hat{0})} + \alpha_s^1 \sigma^{(\hat{1})} + \alpha_s^2 \sigma^{(\hat{2})} + \cdots + \alpha^1 \sigma^{(\hat{0};1)} + \alpha^2 \sigma^{(\hat{0};2)} + \cdots + \alpha_s^1 \alpha^1 \sigma^{(\hat{1};1)} + \cdots$$

LO NLO NNLO NLO EW NNLO QCD+EW

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]

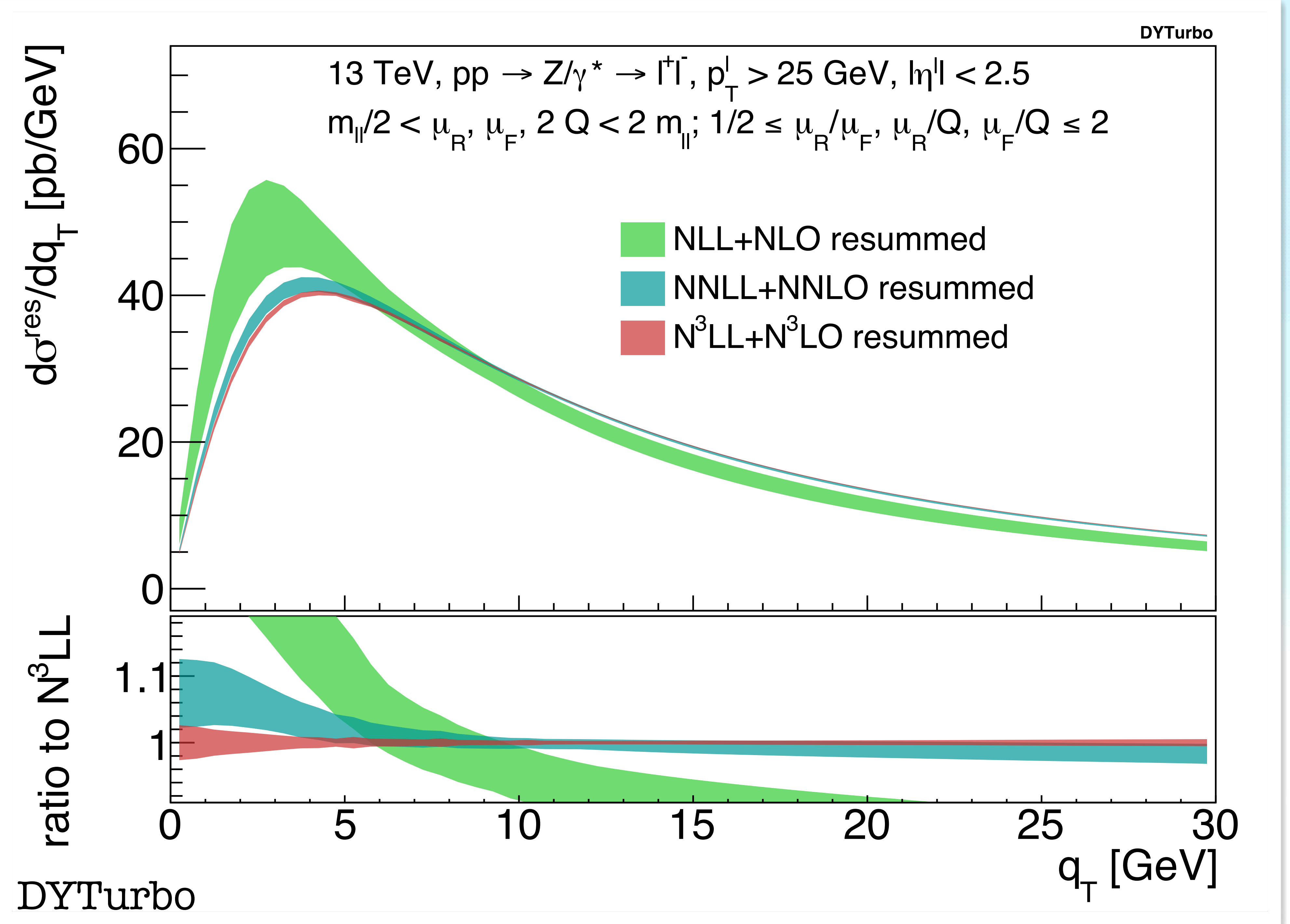
Mixed QCD+EW(QED) effects

Subtraction prescriptions requieres splitting functions at the same level of accuracy

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

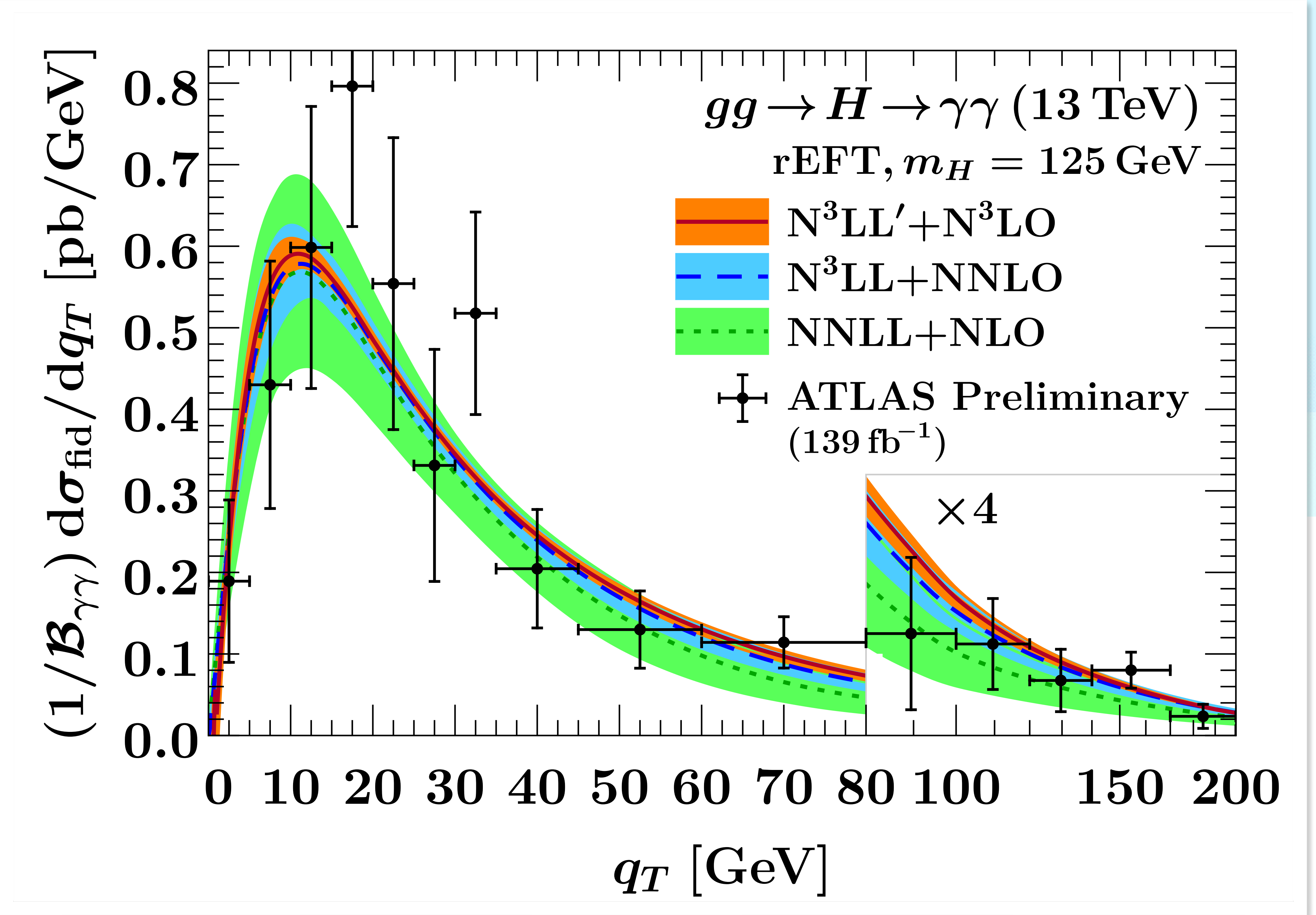
State of the art transverse momentum resummation at N3LO

Camarda, **LC**, Ferrera [2021]



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

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

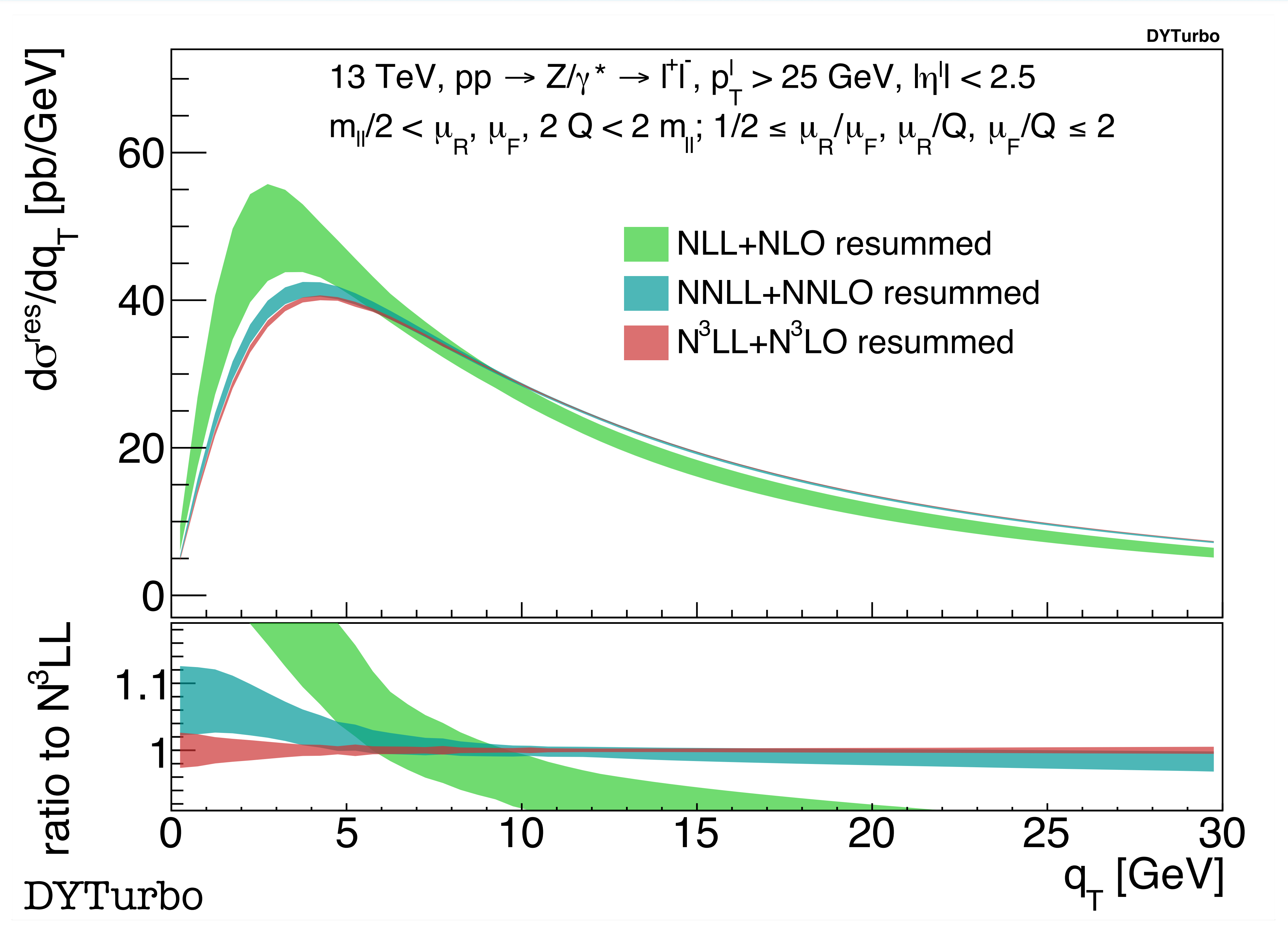


Combination of Z+jet at NNLO + SCET-subtraction

- In the small-qT 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

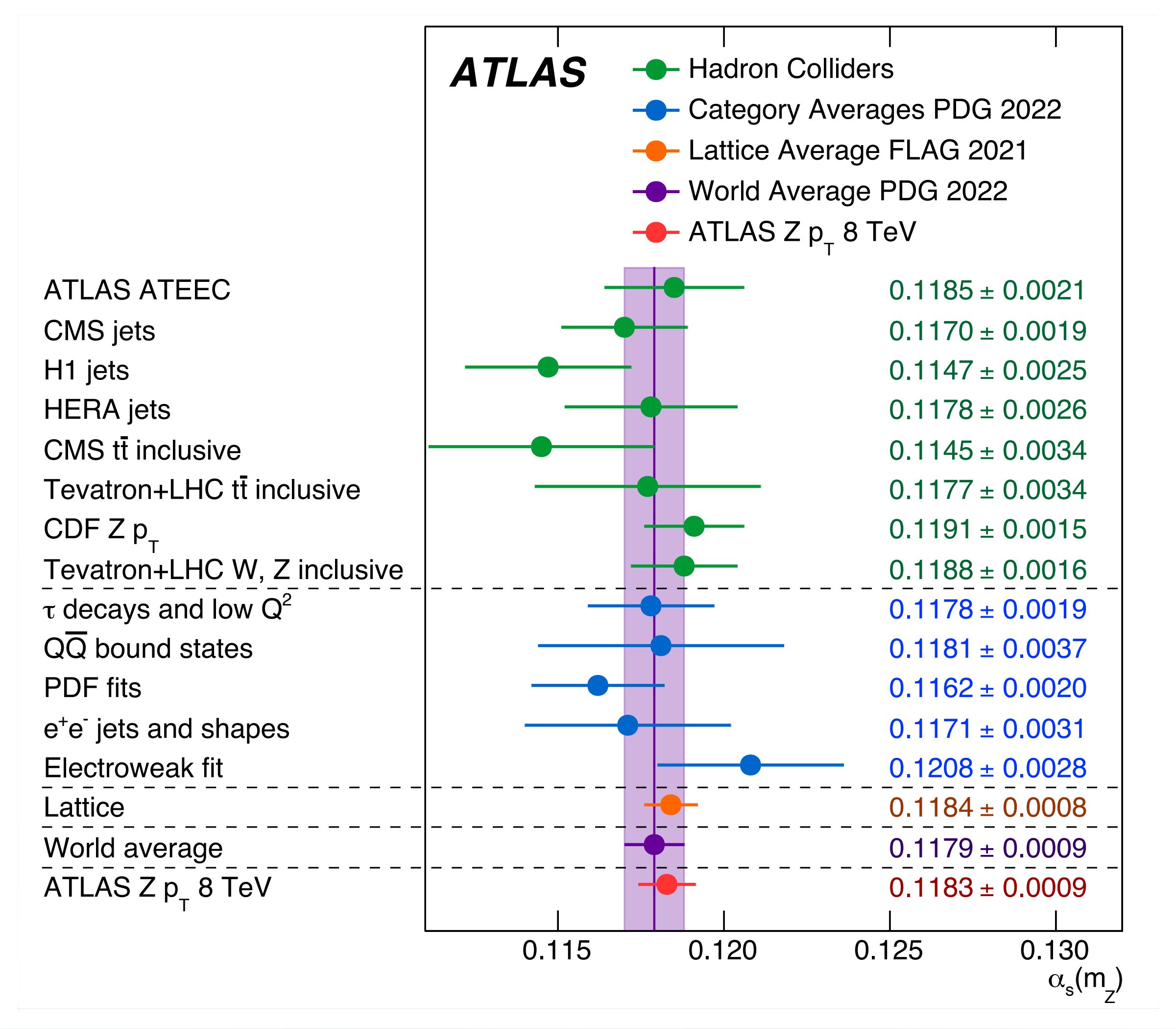
State of the art transverse momentum resummation at N3LO

Camarda, **LC**, Ferrera [2021]



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

Another example of the necessity of precise TH predictions



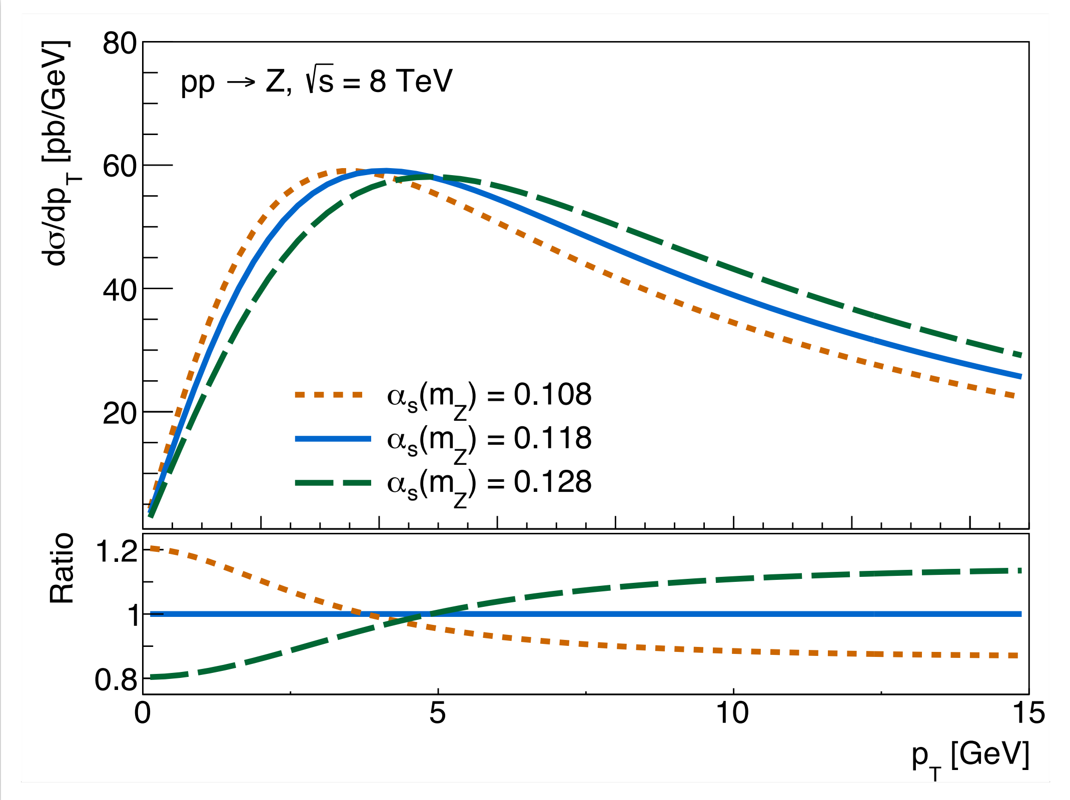
EUROPEAN ORGANISATION FOR NUCLEAR RESEARCH (CERN)

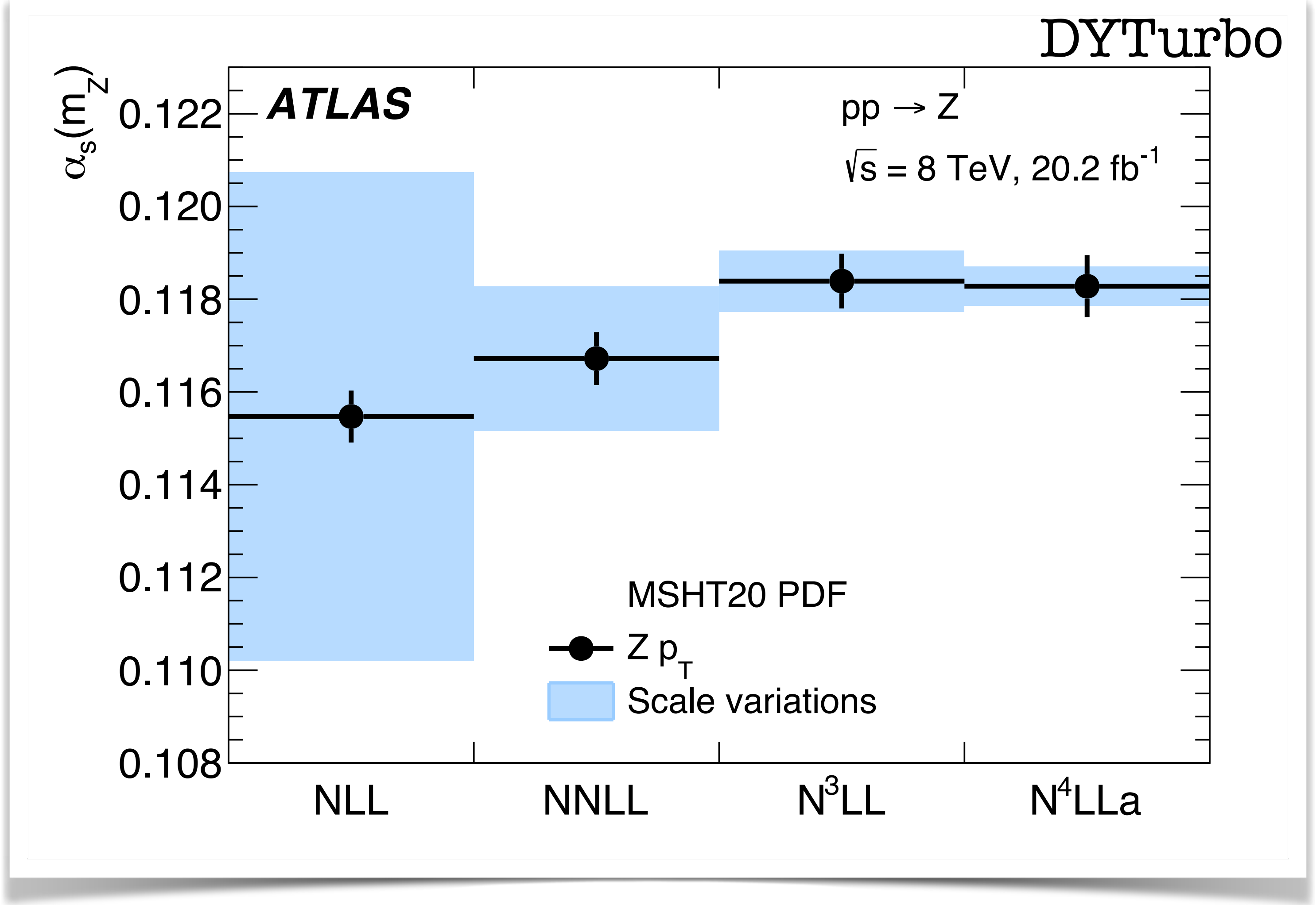
Submitted to: Nature Phys.

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 + **LC**, Ferrera





NEW Most precise experimental determination of $\alpha s\ (mZ)$ achieved

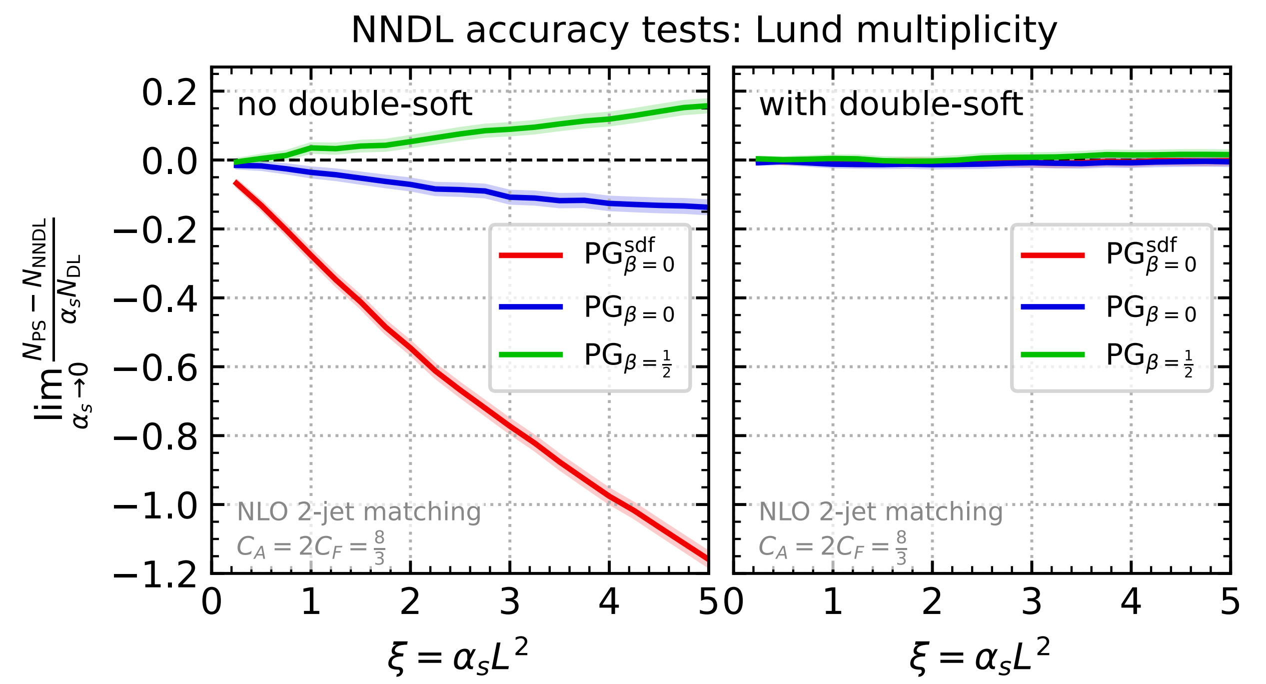
State of the art Parton Showers

- 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]

NEW towards general NNLL precision



The result of Eq. for three variants of the PanGlobal shower without double-soft corrections (left) and with them (right). The latter are consistent with NNDL accuracy. The bands represent statistical errors in an $\alpha_s \to 0$ extrapolation based on four finite α_s values.

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

- 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 $\alpha_s^n L^{2n-2}$

CPU cost at the frontier

Process	NLO (CPU years)	NNLO (CPU years)	N3LO (CPU years)
pp → W/Z		0.6	160
pp → H		0.6	160
pp → $\gamma\gamma$		4.6	Process not available
pp → tt		20	Process not available
pp → $\gamma\gamma$+2jets		2.4	Process not available
pp → 2 jets		10	Process not available
pp → H+jet		57	Process not available
pp → $\gamma\gamma\gamma$		31	Process not available
pp → Z+jet		57	Process not available
pp → 3 jets		> 114	Process not available

don't worry

Fixed order tools without resummation or PS, etc.

Valid for differential cross sections obtained with a numerical precision below 1% in the whole kinematical range

SUSTAINABLE DEVELOPMENT GOALS

- Table showing lowest CPU consumption. For some applications **(i.e. angular coefficients in pp → W/Z NNLO) CPU time ~ 60 years.**
- LHC and TH groups spend essentially almost all of their yearly generator CPU budgets.
- **57** CPU years is equivalent to run the code in **1000 cores continuously for 21 days.**
- **Not realistic scenario to perform phenomenological** analysis at the Run III of the LHC an in the HL-LHC and in future colliders.
- **Great inequality between theoretical groups** which have (or not) access to this super clusters. Roughly **50k€/year** (2017) in Switzerland → exclusive use of 2000 cores.
- **It is not a green way** to perform calculations.

It is clear that we need something new

CPU cost at the frontier

For $pT_{\gamma\gamma} \sim M_{\gamma\gamma}$

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

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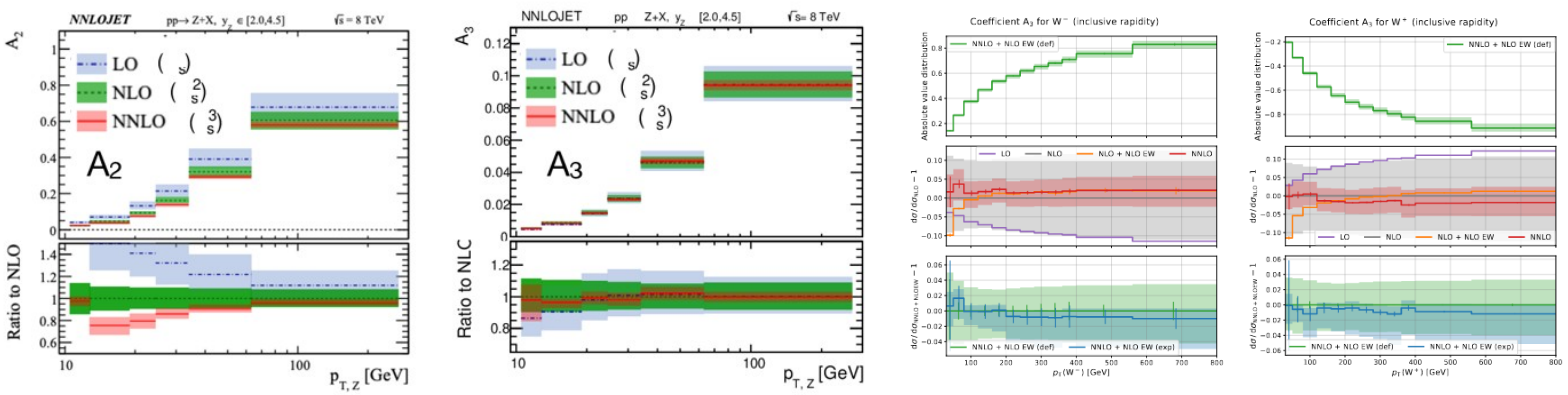
Ai at O(α_s^3)



- 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(α_s^2) predictions, and took about 500K CPU hours

At NNLO!! ~ 60 years!!!!

- 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

Possible paths to the (immediate) Future

We are looking for

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

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

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

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

Thomas Gehrmann,[1,*] Petr Jakubčík,[1,†] Cesare Carlo Mella,[2,‡] Nikolaos Syrrakos,[2,§] and Lorenzo Tancredi[2,¶]
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[2] Technical University of Munich, TUM School of Natural Sciences, Physics Department, James-Franck-Straße 1, 85748 Garching, Germany

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Stefano Camarda[a], Leandro Cieri[b], Giancarlo Ferrera[c,*]

Extraction of unpolarized transverse momentum distributions from fit of Drell-Yan data at N^{4}LL

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

These are only few 2023 papers (together with all the splitting papers) already working towards the N4LO

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- more precise PDFs → New fitting techniques and more data and N3LO PDFs

Approximate N^{3}LO Parton Distribution Functions with Theoretical Uncertainties: MSHT20aN^{3}LO PDFs

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

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

G. Falcioni[a,b], F. Herzog[c], S. Moch[d], J. Vermaseren[e] and A. Vogt[f]

2 Oct 2023

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Approximate N^{3}LO Parton Distribution Functions with Theoretical Uncertainties:
MSHT20aN^{3}LO PDFs

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

2 Oct 2023

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

G. Falcioni[a,b], F. Herzog[c], S. Moch[d], J. Vermaseren[e] and A. Vogt[f]

- 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 Paranjape[1], G Heinrich[2] and S P Jones[3]

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

Martijn Hidding

Possible paths to the (immediate) Future

We are looking for

- more precise TH tools → N3LO (or even N4LO) Catani, de Florian, Rodrigo [2012]
  Beware of strict collinear factorization violation at N3LO! (and beyond)
- 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?

Contents lists available at ScienceDirect

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

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

We provide the finite remainders of the independent helicity amplitudes in terms of multiple polylogrithms, continued to all kinematic regions and in a form which is compact and lends itself to efficient numerical evaluation.

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

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

Martijn Hidding

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

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, Félix Driencourt-Mangin, Roger J. Hernández-Pinto, Judith Plenter, Selomit Ramírez-Uribe, Andrés E. Rentería-Olivo, Germán Rodrigo, Germán F. R. Sborlini, William J. Torres Bobadilla and Szymon Tracz

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]

JHEP — Published for SISSA by Springer
Received: September 19, 2016
Accepted: October 18, 2016
Published: October 28, 2016

Four-dimensional unsubtraction with massive particles

Germán F.R. Sborlini, Félix Driencourt-Mangin and Germán Rodrigo
Instituto de Física Corpuscular, Universitat de València,

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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]
[a] Instituto de Física Corpuscular,

What about deterministic integration? Sparse Grids, etc?

Stay tuned for new and state of the art interesting theoretical calculations from our worldwide TH HEP community

But also stay tuned looking for new and interesting TH calculations from our TH HEP community based in Spain


Gracias
Ngiyabonga
Merci
Hvala
Xié
Barka
Moltes
Dankon
Maraba
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rhât
Paldies
Maketai
Grazzie
Ntyox
Grazias
Bedankt
Thanks
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Murakoze
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Kommol
Shokrán
Dannaba
Mwebare
Kaigai
Dekoju
Ka
Khawp
Arigato
Shukuriyyaa
Emitekati
Tesekkür
Matóndo
Tsin'aen
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Kulo
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Fa'afetai
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Trugarez
Ashoge
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Dyakooyu
Kili
Ngeyabonga
Xie
Evgaristó
Shterakravetsun
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Mahalo
Gunasakulila
Dziakuju
TashakkurBulgaro
Tapaidh
Webale
Rakhmat
Go
Khrap
Alla
Imela
Doh
Gmadlob
Obrigado
maith
suksama
Eskerrik
Fafetai
asko
Dêkuji
Ha'evete
Uzbezco
Rahmet
Danke
mamexes
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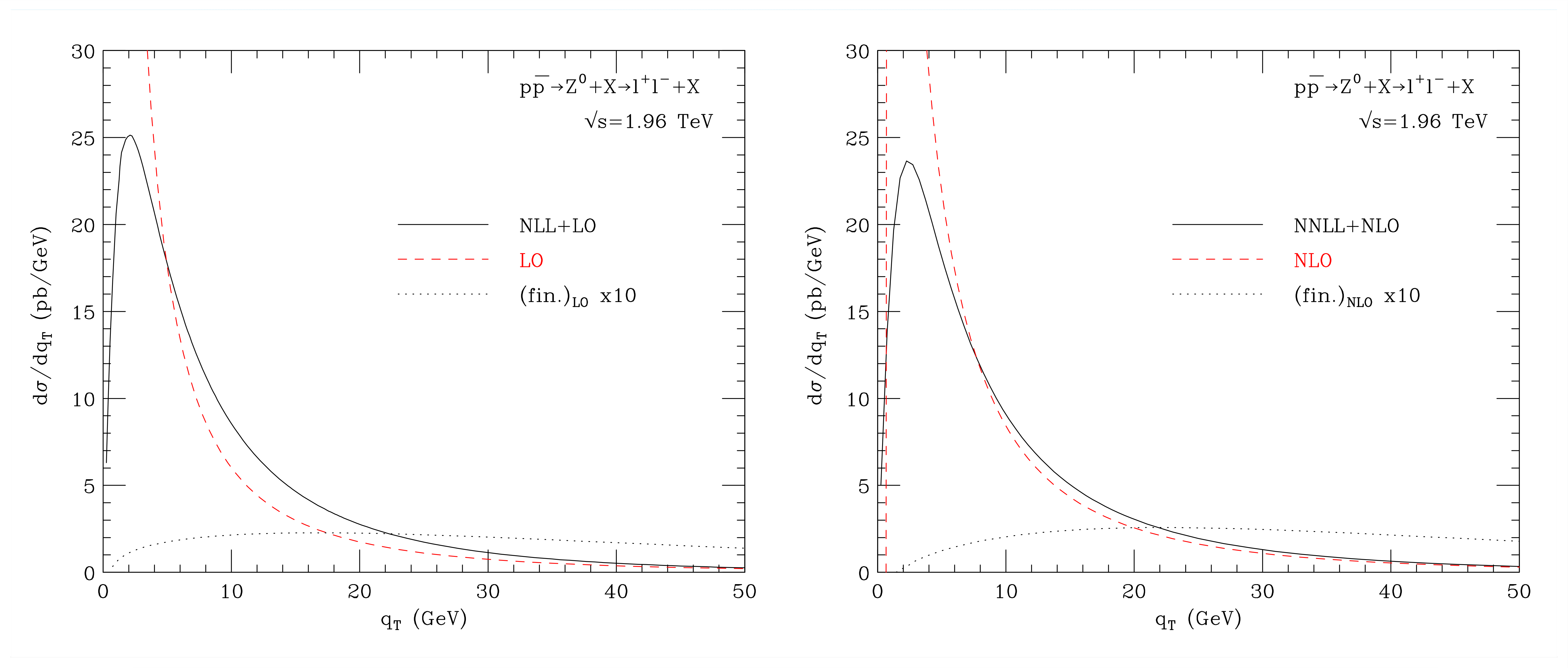
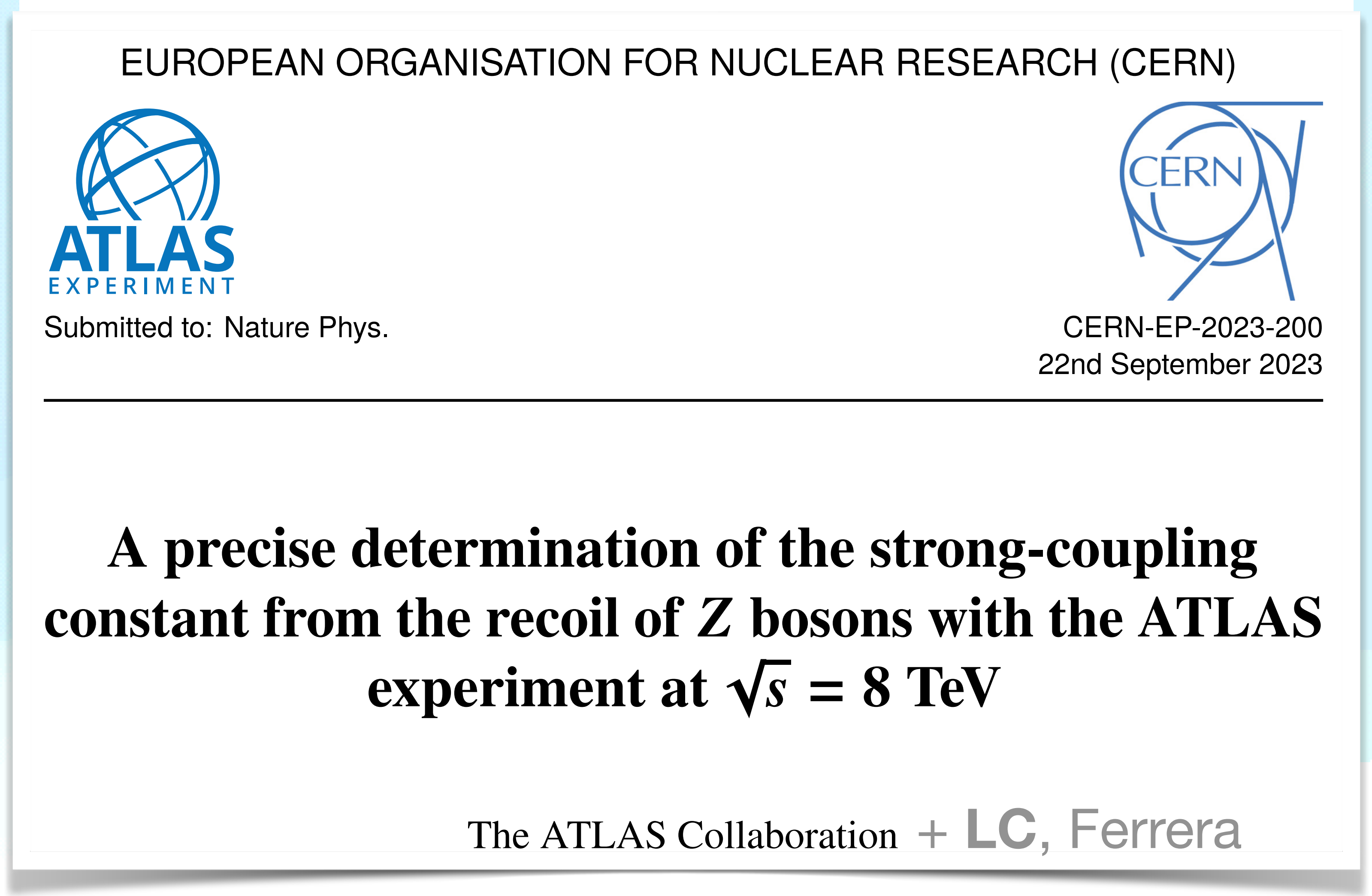
Ashi

State of the art transverse momentum resummation at N3LO



The size of the finite: Real+CT

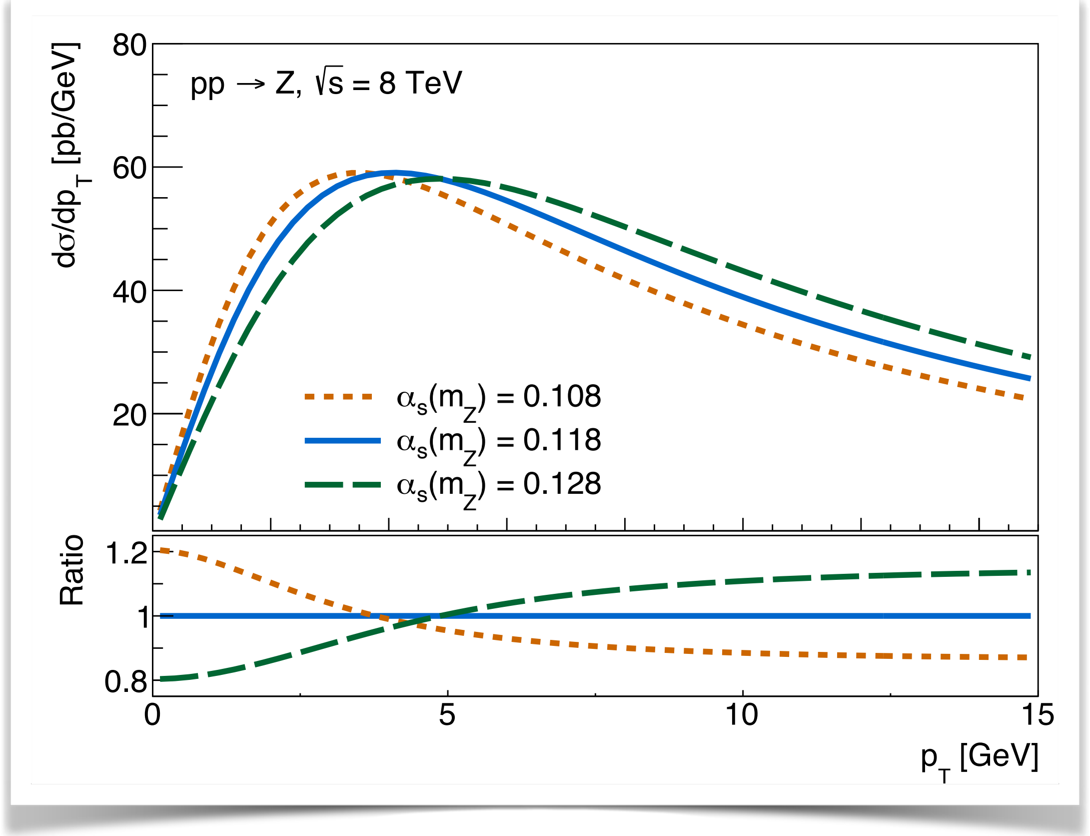

EUROPEAN ORGANISATION FOR NUCLEAR RESEARCH (CERN)

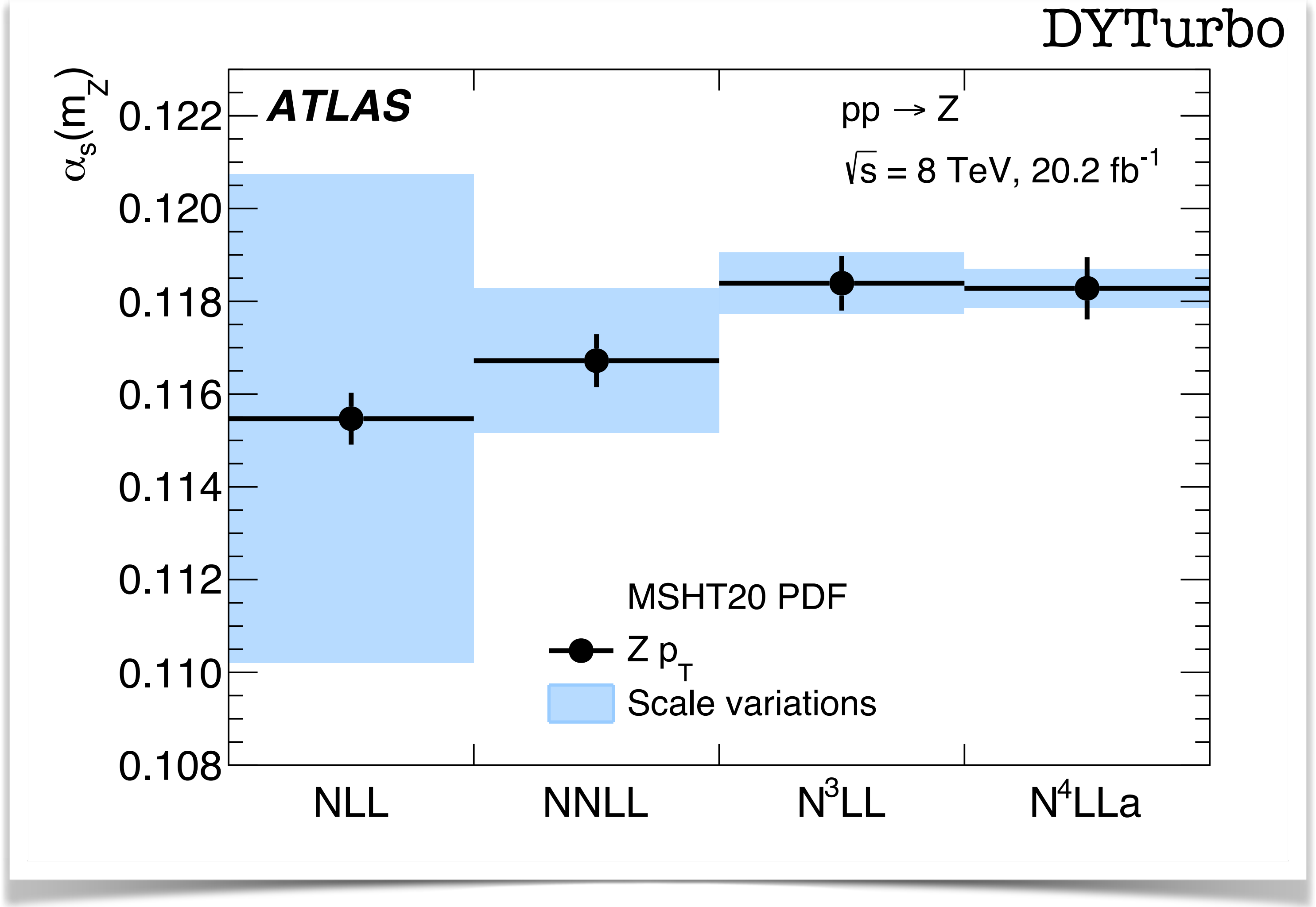
Submitted to: Nature Phys.

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 + LC, Ferrera



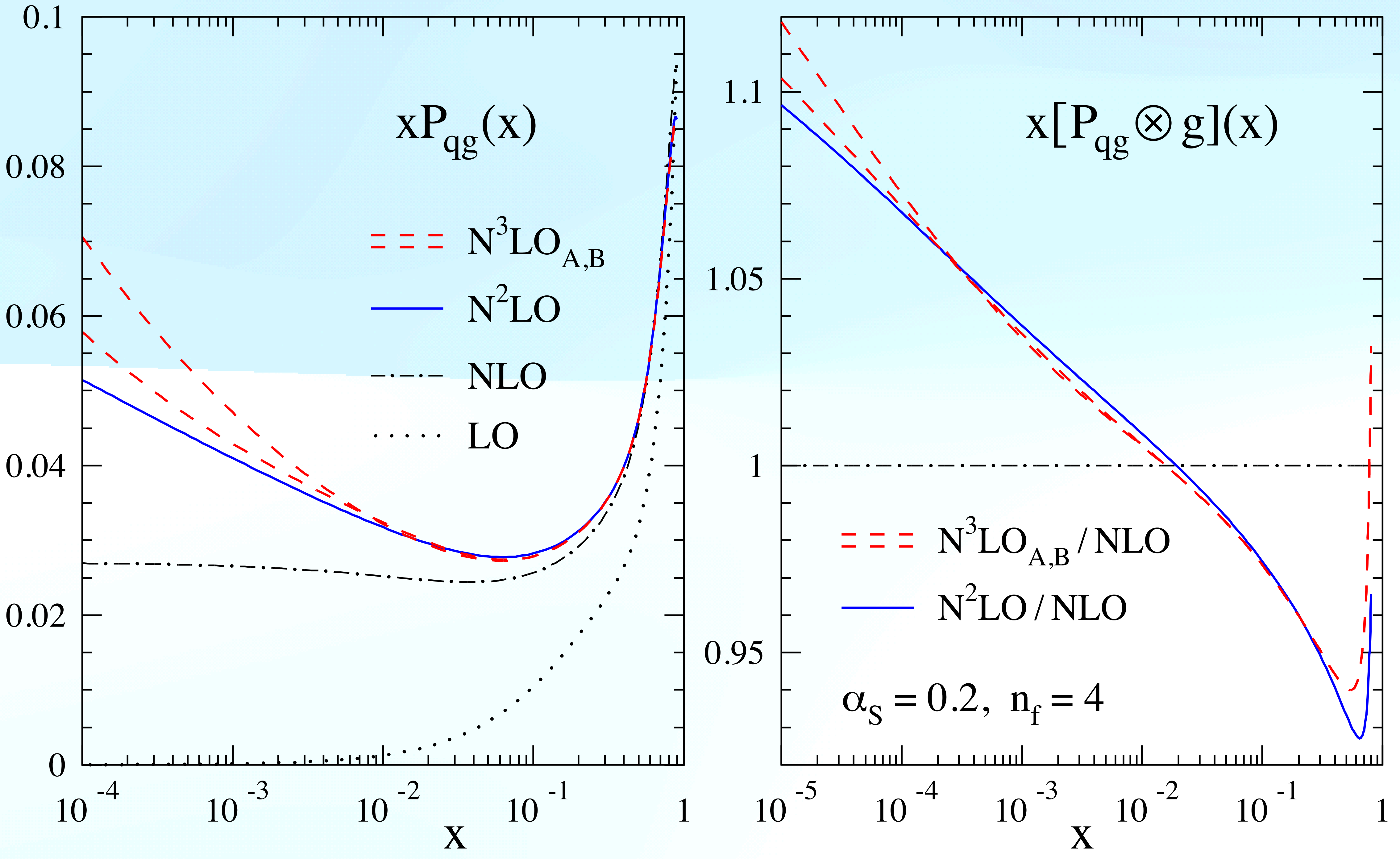


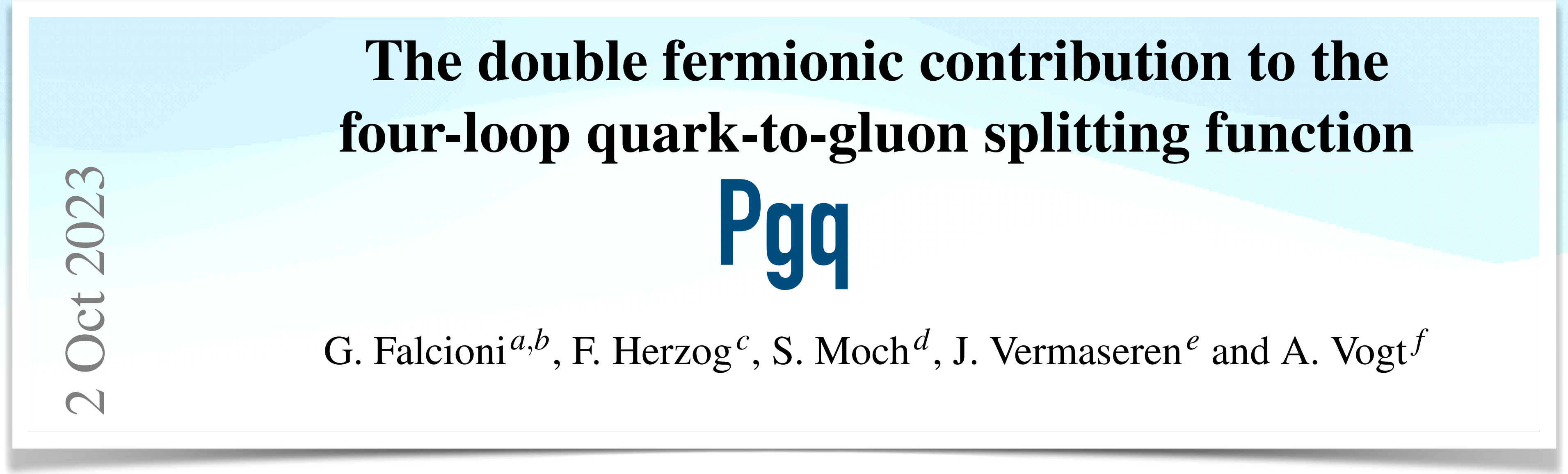
Most precise experimental determination of $\alpha s\ (mZ)$ achieved

New Splitting functions at N3LO (Pqg and contributions to Pgq)

Falcioni, Herzog, Moch, Vogt [2023]

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




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

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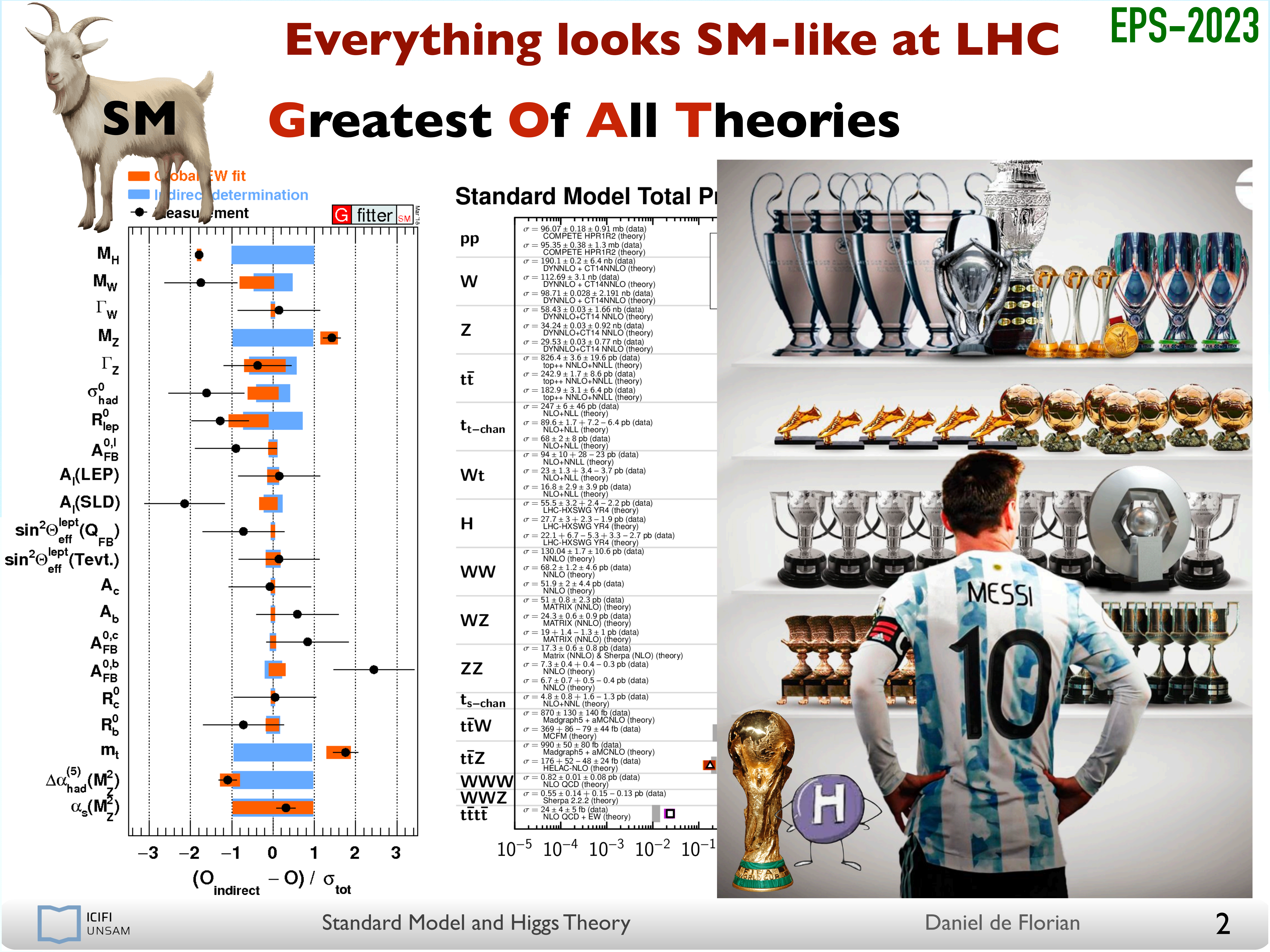
Pgq

Pgg should be feasible soon

Motivation



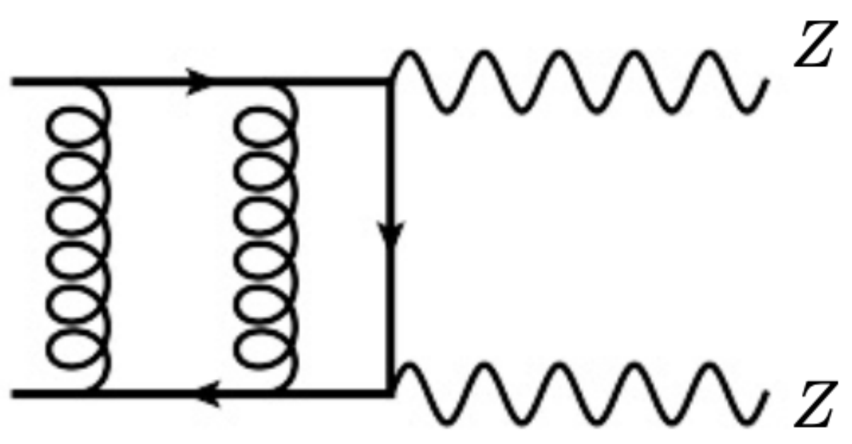
Everything looks SM-like at LHC
EPS-2023
SM
Greatest Of All Theories
Global EW fit
Indirect determination
Measurement
Standard Model Total Pr
pp
W
Z
tt̄
t_{t-chan}
Wt
H
WW
WZ
ZZ
t_{s-chan}
tt̄W
tt̄Z
WWW
WWZ
tt̄tt̄
MESSI
10
ICIFI
UNSAM
Standard Model and Higgs Theory
Daniel de Florian
2

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→(n=) 3 legs	QCD NNLO (2→2 processes)
QCD	Next-to-next-to-next-to-leading order (N3LO)	3%-5%	2→(n=) 1 legs	Hard to obtain differential results in a short time (at least 2 months in 2000 CPUs)

Degree of complexity at NNLO

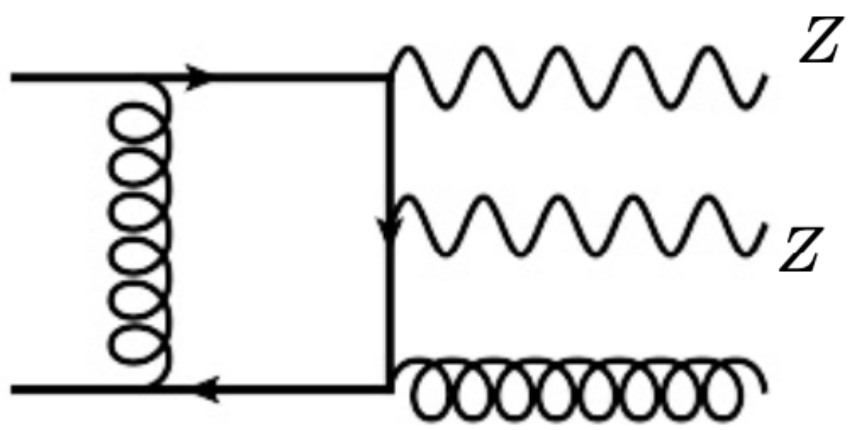
- 2 loop



loop integrals → explicit infrared poles $\frac{1}{\epsilon^4}$

- Bottleneck for larger multiplicities
- Many becoming available

- 1 loop + single emission

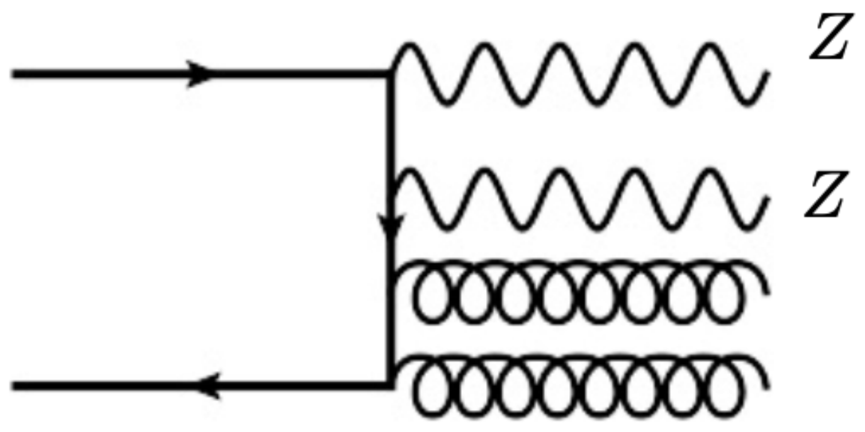


"NLO complexity" : loop → $\frac{1}{\epsilon^2}$

singular emission (extra) → $\frac{1}{\epsilon^2}$

- Double real emission

Tree level a Hell of infrared singularities



- Bottleneck for larger multiplicities: implementation

after integration over unresolved partons → $\frac{1}{\epsilon^4}$ poles