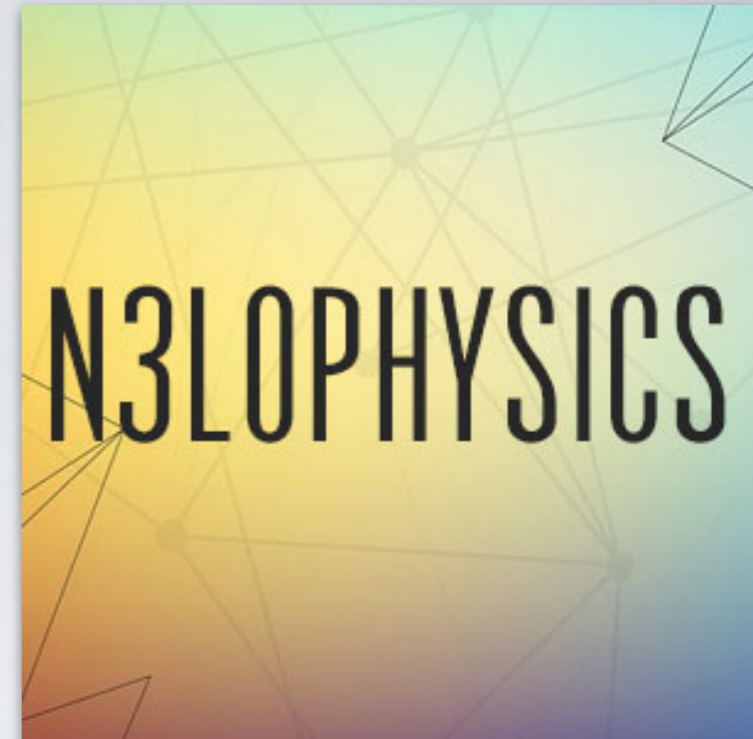# N3LOPHYSICS

Leandro Cieri
INFN Firenze
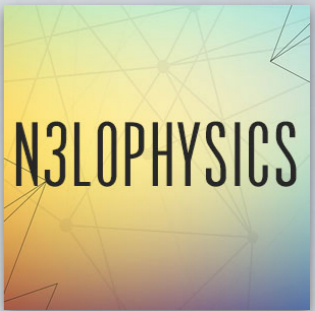
General remote meeting
Fellini Program
04.03.2021

OUTLINE

- **Introduction**
  - Motivation
  - Brief description (state of the art (QCD) computations for the LHC)
- **Fellini Project –** N3LO as the New Standard for Precision Physics at the LHC
  - The qT-subtraction/resummation formalism
  - The third order (N³LO)
- **Outlook**

MOTIVATION

N3LOPHYSICS

Why precision physics is important at the LHC?

Higgs Physics

The success in comparisons TH/Data wouldn't be possible with NLO precision

The 750 GeV excess

Precision Modeling and Model Building working together

Bottom Hadroproduction at the Tevatron

a 10 yrs discrepancy between theory (NLO QCD) and data (CDF and D0)

Photon PDFs   **LUX qed PDFs**

Vector boson measurements   **Data already at O(1%)**

Diphoton production   **Very large NNLO corrections**

Triphoton production   **Very large NNLO corrections**

etc, ...

S. Catani, L. C, D. de Florian, G. Ferrera and M. Grazzini (2011)

DYTurbo
Camarda, Bozzi, Catani, L. C, Ferrera, et. al (2019)
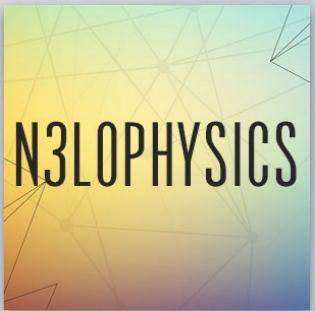
S. Catani, L. C, D. de Florian, G. Ferrera and M. Grazzini (2011)

S. Catani, L. C, D. de Florian, G. Ferrera and M. Grazzini (2018)

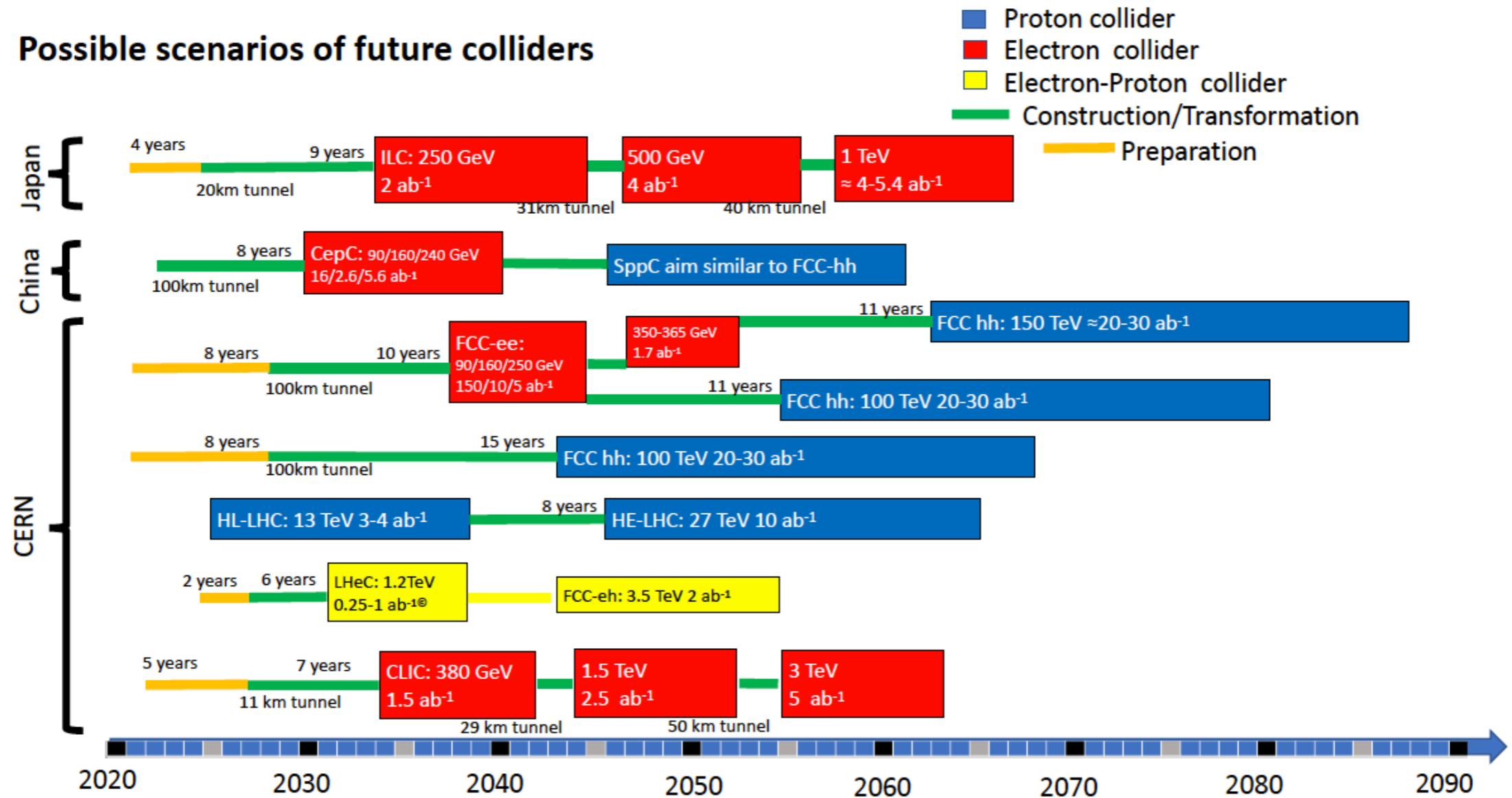## New interesting tasks are just recently initiated: Yukawas

Nello Bruscino's Talk

MOTIVATION

Why precision physics is important at the LHC?

Possible scenarios of future colliders

Legend:
- Proton collider (blue)
- Electron collider (red)
- Electron-Proton collider (yellow)
- Construction/Transformation (green)
- Preparation (orange)

Japan:
- 4 years — 20km tunnel — 9 years — ILC: 250 GeV 2 ab⁻¹ — 31km tunnel — 500 GeV 4 ab⁻¹ — 40 km tunnel — 1 TeV ≈ 4-5.4 ab⁻¹

China:
- 8 years — 100km tunnel — CepC: 90/160/240 GeV 16/2.6/5.6 ab⁻¹ — SppC aim similar to FCC-hh

CERN:
- 8 years — 100km tunnel — 10 years — FCC-ee: 90/160/250 GeV 150/10/5 ab⁻¹ — 350-365 GeV 1.7 ab⁻¹ — 11 years — FCC hh: 150 TeV ≈20-30 ab⁻¹
- 11 years — FCC hh: 100 TeV 20-30 ab⁻¹
- 8 years — 100km tunnel — 15 years — FCC hh: 100 TeV 20-30 ab⁻¹
- HL-LHC: 13 TeV 3-4 ab⁻¹ — 8 years — HE-LHC: 27 TeV 10 ab⁻¹
- 2 years — 6 years — LHeC: 1.2TeV 0.25-1 ab⁻¹⊕ — FCC-eh: 3.5 TeV 2 ab⁻¹
- 5 years — 11 km tunnel — 7 years — CLIC: 380 GeV 1.5 ab⁻¹ — 29 km tunnel — 1.5 TeV 2.5 ab⁻¹ — 50 km tunnel — 3 TeV 5 ab⁻¹

Timeline: 2020 · 2030 · 2040 · 2050 · 2060 · 2070 · 2080 · 2090

13/05/2019 UB

Summary of National Inputs   S. Bethke (MPP Munich)   ESPP Symposium, Granada, 15 May 2019   4

- all options aimed at **attobarn⁻¹ physics**
- requires to go **far beyond NNLO for theory**
- Even conservative estimates **not reachable with current techniques**
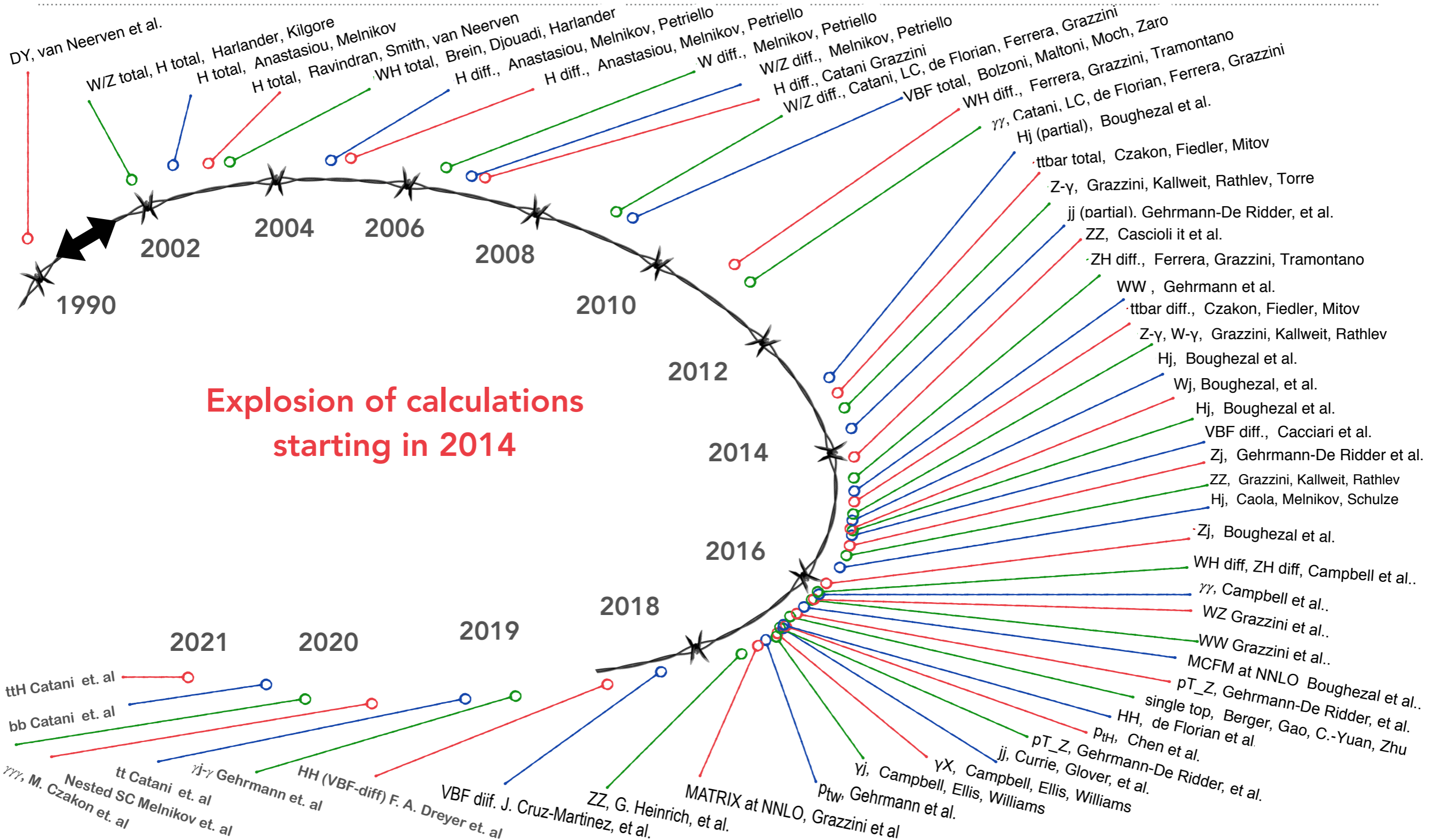
N3LOPHYSICS

- QCD perturbative corrections play a crucial role at modern colliders (LHC, Tevatron)
- Until a few years ago, the standard for such calculations was next-to-leading order (NLO) accuracy
- In the past recent years a number of growing next-to-next-to-leading order (NNLO) results were computed
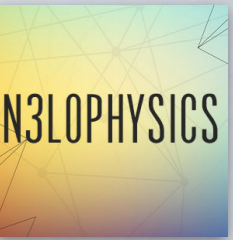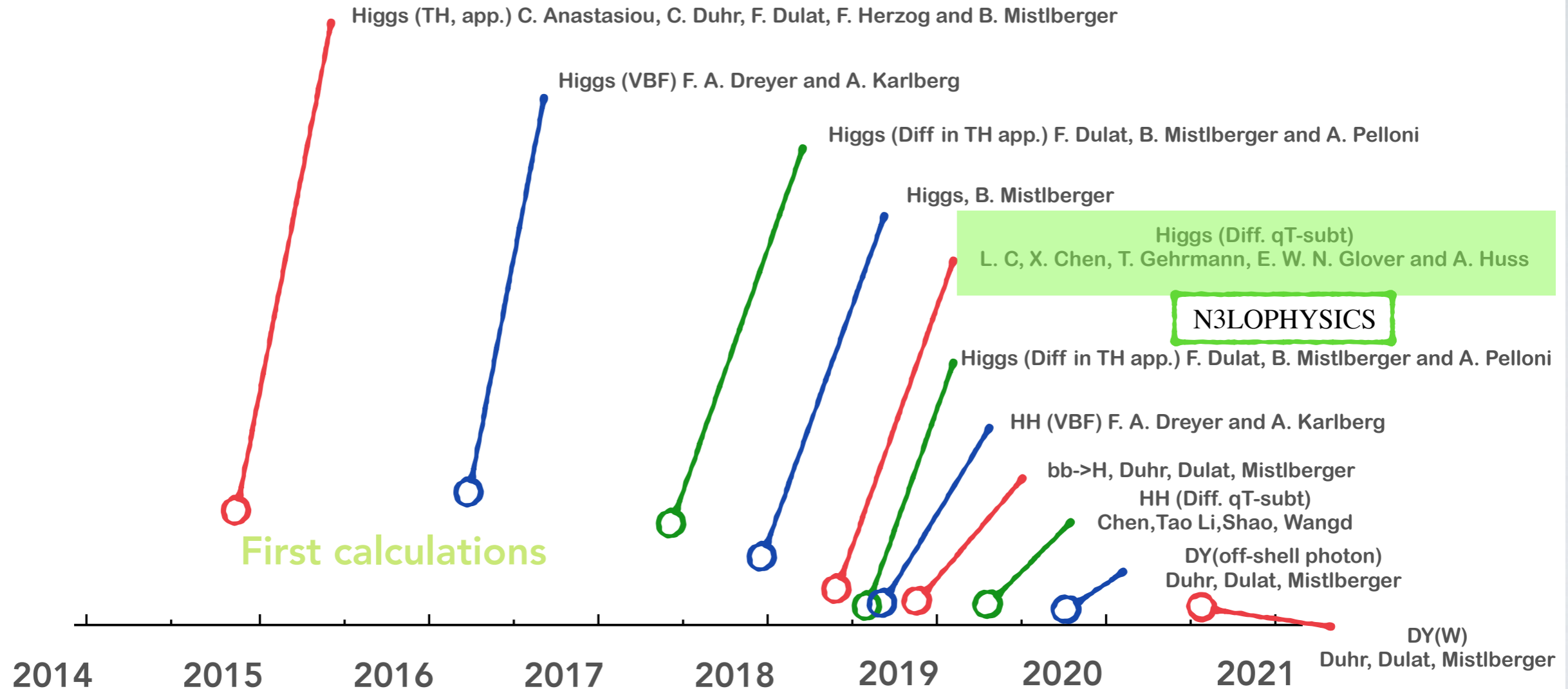
"The NNLO revolution"

THE NNLO STANDARD

N3LOPHYSICS

NNLO HADRON-COLLIDER CALCULATIONS VS. TIME

DY, van Neerven et al.

W/Z total, H total, Harlander, Kilgore

H total, Anastasiou, Melnikov

H total, Ravindran, Smith, van Neerven

WH total, Brein, Djouadi, Harlander

H diff., Anastasiou, Melnikov, Petriello

H diff., Anastasiou, Melnikov, Petriello

W diff., Melnikov, Petriello

W/Z diff., Melnikov, Petriello

H diff., Catani Grazzini

W/Z diff., Catani, LC, de Florian, Ferrera, Grazzini

VBF total, Bolzoni, Maltoni, Moch, Zaro

WH diff., Ferrera, Grazzini, Tramontano

γγ, Catani, LC, de Florian, Ferrera, Grazzini

Hj (partial), Boughezal et al.

ttbar total, Czakon, Fiedler, Mitov

Z-γ, Grazzini, Kallweit, Rathlev, Torre

jj (partial), Gehrmann-De Ridder, et al.

ZZ, Cascioli it et al.

ZH diff., Ferrera, Grazzini, Tramontano

WW, Gehrmann et al.

ttbar diff., Czakon, Fiedler, Mitov

Z-γ, W-γ, Grazzini, Kallweit, Rathlev

Hj, Boughezal et al.

Wj, Boughezal, et al.

Hj, Boughezal et al.

VBF diff., Cacciari et al.

Zj, Gehrmann-De Ridder et al.

ZZ, Grazzini, Kallweit, Rathlev

Hj, Caola, Melnikov, Schulze

Zj, Boughezal et al.

WH diff, ZH diff, Campbell et al..

γγ, Campbell et al..

WZ Grazzini et al..

WW Grazzini et al..

MCFM at NNLO Boughezal et al..

pT_Z, Gehrmann-De Ridder, et al..

single top, Berger, Gao, C.-Yuan, Zhu

HH, de Florian et al.

pT_Z, Gehrmann-De Ridder, et al..

p_tH, Chen et al.

jj, Currie, Glover, et al.

γX, Campbell, Ellis, Williams

γj, Campbell, Ellis, Williams

p_tw, Gehrmann et al.

MATRIX at NNLO, Grazzini et al

ZZ, G. Heinrich, et al.

VBF diff. J. Cruz-Martinez, et al.

HH (VBF-diff) F. A. Dreyer et. al

γj-γ Gehrmann et. al

tt Catani et. al

Nested SC Melnikov et. al

γγγ, M. Czakon et. al

bb Catani et. al

ttH Catani et. al

Explosion of calculations starting in 2014

1990
2002
2004
2006
2008
2010
2012
2014
2016
2018
2019
2020
2021

THE N³LO ERA

N³LO HADRON-COLLIDER CALCULATIONS VS. TIME

THE QT-SUBTRACTION/RESUMMATION FORMALISM

📌 NNLO+NNLL QCD

The method

Explicit form
qT-subt. Ingredients

Helicity-Flip
Contributions

Universal relation between
hard-virtual factors and
two-loop scattering amplitudes

Colourless final states

→ S. Catani and M. Grazzini (2007)

→ G. Bozzi, S. Catani, D. de Florian and M. Grazzini (2005)

→ S. Catani and M. Grazzini (2011)

→ S. Catani, L. C, D. de Florian, G. Ferrera and M. Grazzini (2013)

Heavy quark production → S. Catani, S. Devoto, M. Grazzini, S. Kallweit and J. Mazzitelli and H. Sargsyan (2019)
Bonciani, Catani, Grazzini, Sargsyan, Torre (2015)

Extension at NLO+NLL QED+QCD → L. C, G. Ferrera and G. F. R. Sborlini (2018)

Extension at NNLO QED+QCD → L. C, M. Der, de Florian and J. Mazzitelli (2020)   **New**

Extension at NLO QED FSR → Buonocore, Grazzini, Tramontano (2019)

Extension at NNLO QED FSR → Buonocore, Grazzini, Kallweit, Savoini, Tramontano (2021)

Sub leading power corrections NLO → L. C, Oleari, Rocco (2019)   **Leonardo Vernazza's Talk**

📌 N3LO+N3LL QCD

Soft virtual cross sections and threshold resummation → S. Catani, L. C, D. de Florian, G. Ferrera and M. Grazzini (2014)

N3LO QCD → L. C, X. Chen, T. Gehrmann, E. W. N. Glover, and A. Huss (2018)   **Manoj Kumar Mandal Talk**

8

RESEARCH PROJECT

- **Goals**
  - qT-subtraction formalism at N3LO in QCD (in a closed form)
  - qT-resummation formalism at N3LO+N3LL in QCD (in a closed form)
  - qT-subtraction formalism for mixed NNLO (QCD+QED)
    - Drell-Yan phenomenology at NNLO (QCD+QED)
  - Application of precedent formalisms to
    - Higgs boson phenomenology at N3LO+N3LL
    - Drell-Yan phenomenology at N3LO+N3LL
- **Research development**
  - qT-subtraction formalism for mixed NNLO (QCD+QED)
  - Drell-Yan phenomenology at NNLO (QCD+QED)
  - qT-subtraction formalism at N3LO in QCD (in a closed form)
  - qT-resummation formalism at N3LO+N3LL in QCD
  - Drell-Yan phenomenology at N3LO+N3LL
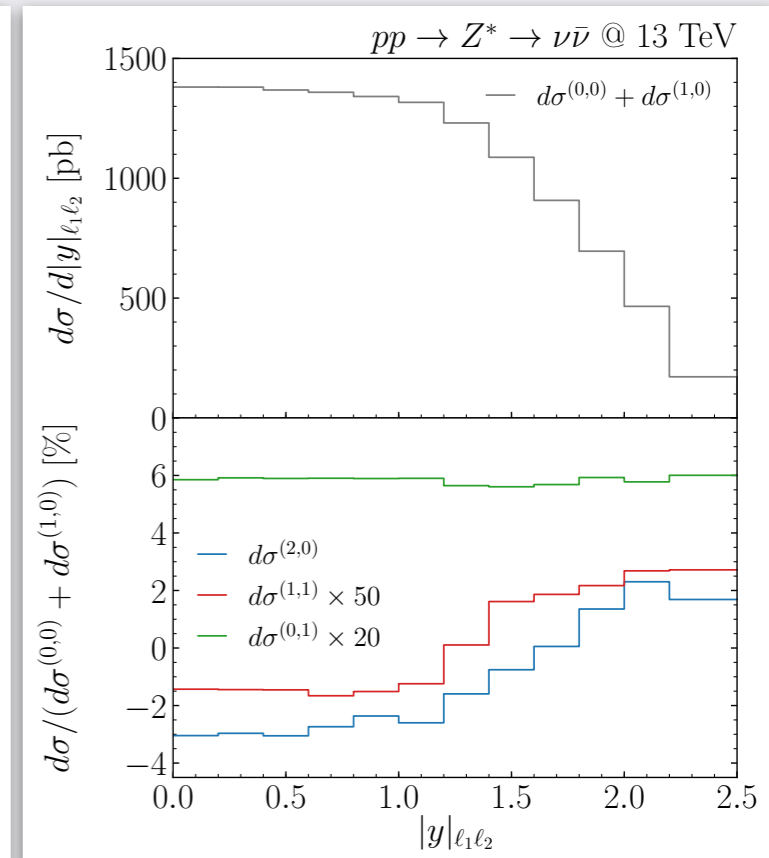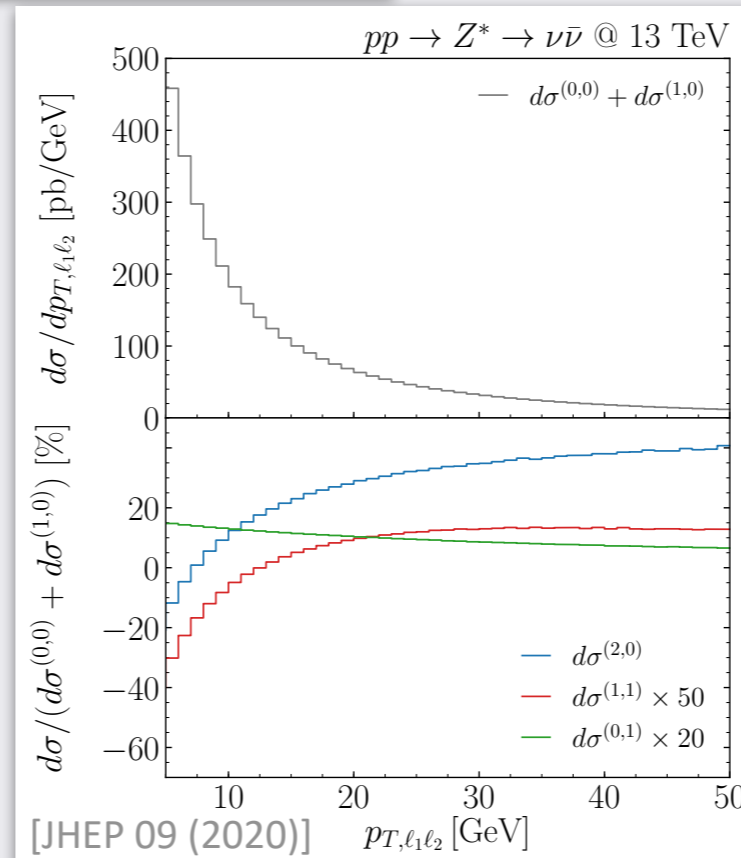 - Higgs boson phenomenology at N3LO+N3LL

✔ Published
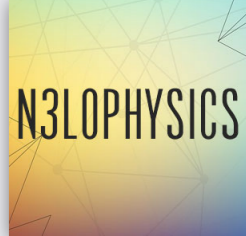
✔ Unpublished

L. C, D. De Florian, M. Der and J. Mazzitelli (2020)

$$p_{T,\ell_1} > 25\,\text{GeV}\,, \quad p_{T,\ell_2} > 20\,\text{GeV}\,, \quad |y|_{\ell_{1,2}} < 2.5\,, \quad m_{\ell_1\ell_2} > 50\,\text{GeV}\,,$$
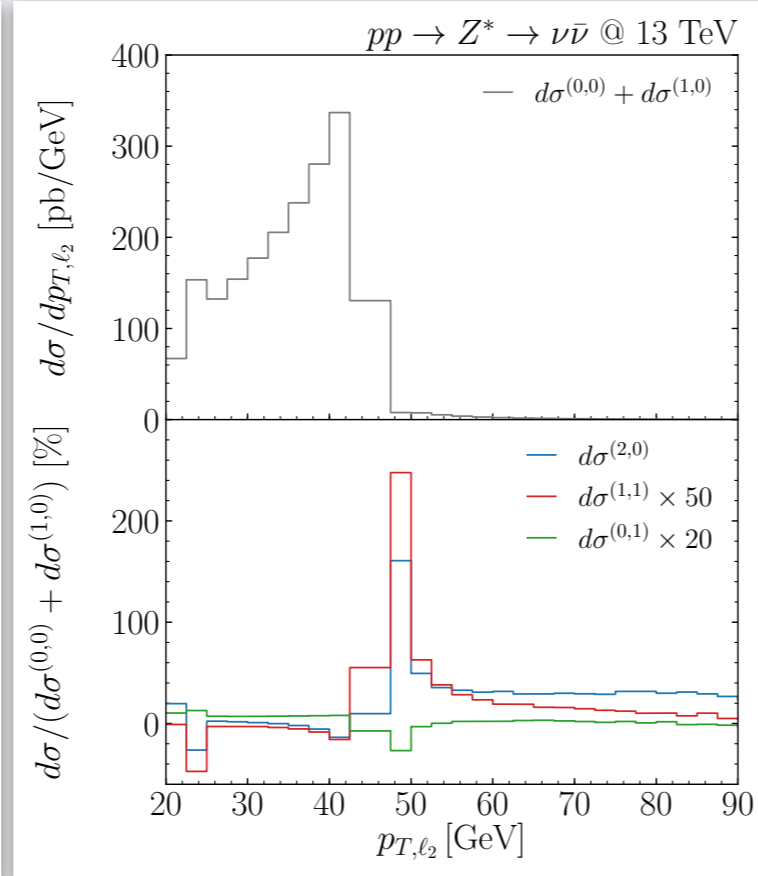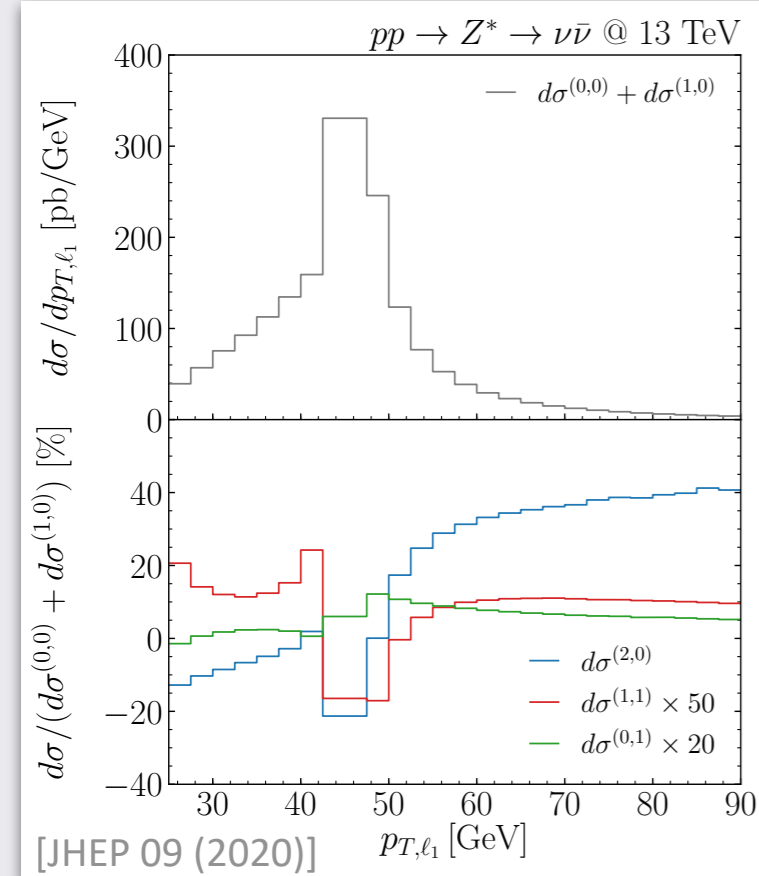
[JHEP 09 (2020)]

**The new version of DYTurbo, will be published
and it will be publicly available also for QED+QCD.
The first version of DYTurbo [Eur. Phys. J.C 80 (2020)]
can be found in**

https://dyturbo.hepforge.org

[JHEP 09 (2020)]

OUTLOOK

- **Fellini Program First Year**
  - 1 published paper [JHEP 09 (2020)]
  - 1 published Les Houches proceeding [2003.01700]
  - 1 published review [EPJC-20-12-127]
  - 1 co-supervised PhD Thesis [Marco Rocco — Milano Bicocca]
  - 1 workshop organized [GGI]
  - 5 invited talks [CERN, Workshop ThinkStart — GGI, ICAS, Florence University, REF Workshop]
  - 2 publicly available numerical tools (summer 2021) [DYTurbo]
- **Scientific equipment** [1. Desktop 20 threads computer. 1. Notebook 16 threads computer]
- **Course work** [several courses followed]
- **Scientific collaborations**
  - It is still uncertain the situation (COVID-19)
- **New sources of interaction and collaborations**
  - **Factorization**
  - **Sub-leading power corrections**
  - **Multi-loop scattering amplitudes**
- **Secondment [IFIC 2021 ?]**

> **Yiannis Makris Talk**

> **Leonardo Vernazza's Talk**

> **Manoj Kumar Mandal Talk**

THANK YOU!