PRECISION PHYSICS AT THE LHC

Leandro Cieri
INFN Firenze

First Fellini Meeting
Roma
24.02.2020

OUTLINE

- Past research activity
  - Motivation
  - Brief description (state of the art (QCD) computations for LHC)
- Fellini Project - N3LO as the New Standard for Precision Physics at the LHC
  - The qT-subtraction/resummation formalism
  - The third order (N^3LO)
  - Higgs Phenomenology at N^3LO
- Outlook

MOTIVATION

Why precision physics is important at the LHC?

- Higgs Physics

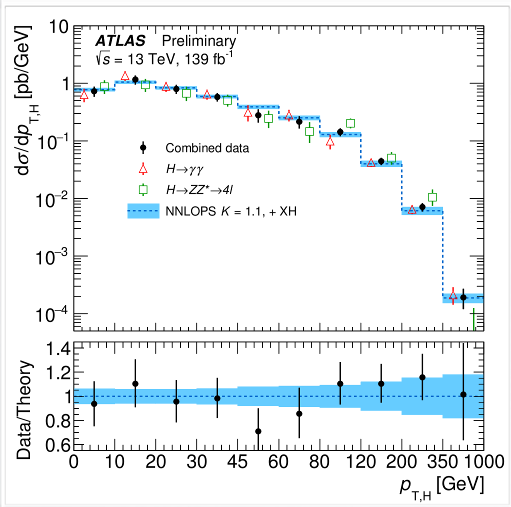
MOTIVATION

Why precision physics is important at the LHC?

Higgs Physics

15 yrs ago

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



Combined results for H→$\gamma\gamma$ and H→4l

ATLAS-CONF-2019-032

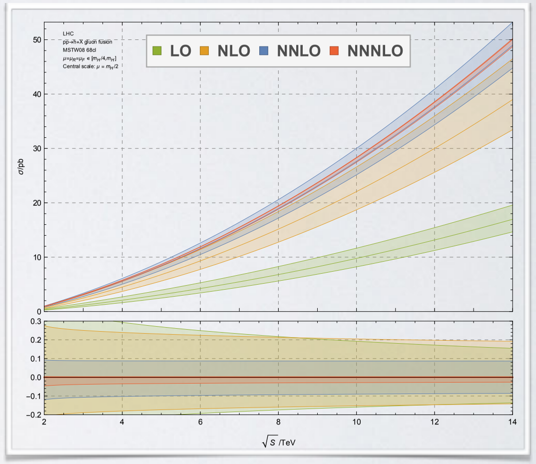
$$55.4^{+4.3}_{-4.2}\ \text{pb}\ (\ \pm 3.1(\text{stat.})\ ^{+3.0}_{-2.8}(\text{sys.})\ )$$

ATLAS

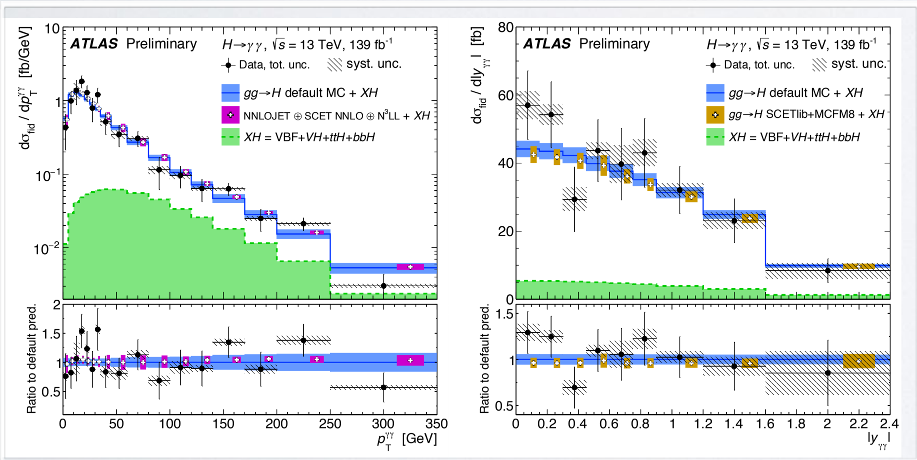
$$55.6 \pm 2.5\ \text{pb}$$

TH

Process	Accuracy	Fraction [%]
ggF	N^{3}LO in QCD, NLO in EW	87.2
VBF	(approximate) NNLO in QCD, NLO in EW	6.8
VH	qq/qg: NNLO in QCD, NLO in EW; gg: NLO+NLL in QCD	4.0
$t\bar{t}H + tH$	$t\bar{t}H$: NLO in QCD, NLO in EW, tH: NLO in QCD	1.1
$b\bar{b}H$	NNLO (NLO) in QCD for 5FS (4FS)	0.9



Anastasiou, Duhr, Dulat, Herzog, Mistlberger (2015)



$$\sigma_{\text{fid}} = 65.2 \pm 4.5\,(\text{stat.}) \pm 5.6\,(\text{syst.}) \pm 0.3\,(\text{theo.})\ \text{fb}$$

ATLAS

$$63.6 \pm 3.3\ \text{fb}$$

TH

ATLAS-CONF-2019-029

Results for H→$\gamma\gamma$

MOTIVATION

Why precision physics is important at the LHC?

- Higgs Physics
- The 750 GeV excess

MOTIVATION

Why precision physics is important at the LHC?

The 750 GeV excess

Precision Modeling and Model Building working together

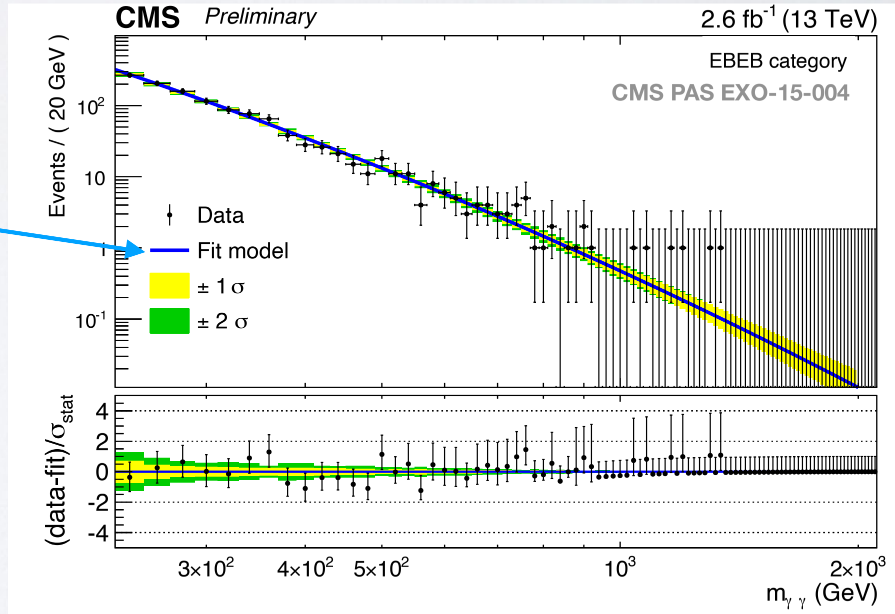
- Many interpretations in function of New Physics **More than 300 papers**
- The excess was detected by the ATLAS and CMS collaborations and published in December of 2015. It disappeared in July 2016

CMS PAS EXO-15-004

ATLAS-CONF-2015-081

More than 500 citations (each one)

Fit model tested with 2γNNLO



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)
L. C (2013)
L. C (2012)
L. C et. al - Les Houches proceedings (2015)
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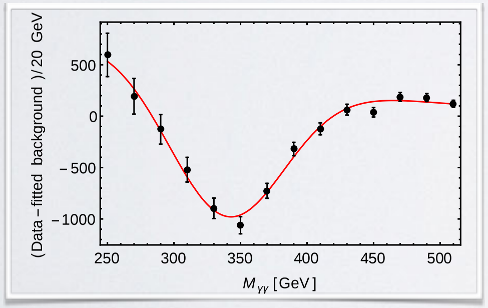
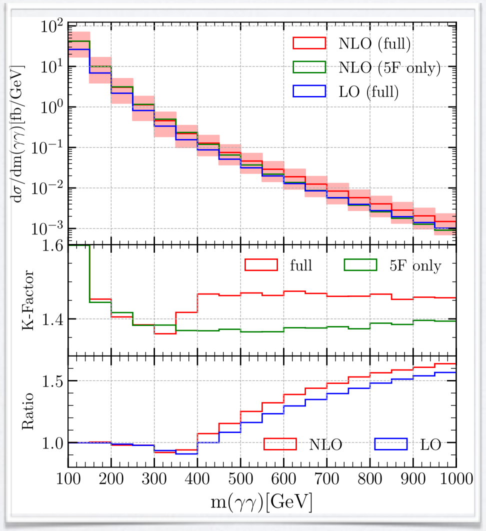
ATLAS-CONF-2015-081

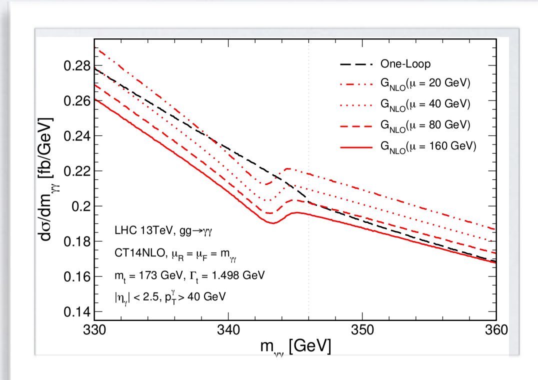
A fitting function is OK, but we have to be aware that backgrounds are not always completely flat



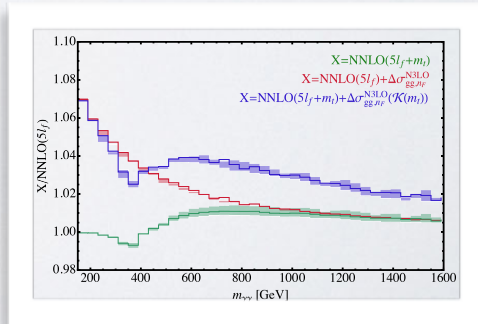
Dugad, Jain, Mitra, Sanyal, Verma (2016)

Maltoni, Mandal, Zhao (2019)





Kawabata, Yokoya (2016)



Campbell, Ellis, Li, Williams (2016)

MOTIVATION

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- Bottom Hadroproduction at the Tevatron

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Why precision physics is important at the LHC?

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- Photon PDFs
- Vector boson measurements
- Diphoton production
- Triphoton production
- etc, ...

MOTIVATION

Why precision physics is important at the LHC?

- Higgs Physics
- The 750 GeV excess
- Bottom Hadroproduction at the Tevatron

- 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)

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- etc, ...

- New interesting tasks are just recently initiated: Yukawas

Nello Bruscino’s Talk

MOTIVATION

Why precision physics is important at the LHC?

ESPPU 2013

g) Europe should support a diverse, vibrant theoretical physics programme, ranging from abstract to applied topics, in close collaboration with experiments and extending to neighbouring fields such as astroparticle physics and cosmology. Such support should extend also to high-performance computing and software development.

- Great progress since last ESPP in development of (NLO) MC generators and higher-order calculations (e.g. Higgs production at N3LO, NNLO for 2→2 QCD processes) to match precision of LHC (and other) data. Vibrant community in Europe, which also contributed significantly to the study of future facilities. Crucial funding from H2020 (e.g. MCnet).
  Note: strong support for theory is crucial for the future of the field: theoretical ideas have led to ground breaking developments in the understanding of nature and have inspired many experimental searches; MC developments and higher-order (signal and background) calculations are fundamental for current and future projects → HEP theory should be supported in Universities and labs and should be an integral part of planning for and funding of future colliders and other projects.

Fabiola Gianotti (Granada 2019)

physicsworld

PARTICLE AND NUCLEAR | INTERVIEW

Preparing for a post-LHC future

22 Feb 2019

Richard Blaustein talks to CERN director-general **Fabiola Gianotti** about how the lab is planning the next big experiment in particle physics beyond the Large Hadron Collider

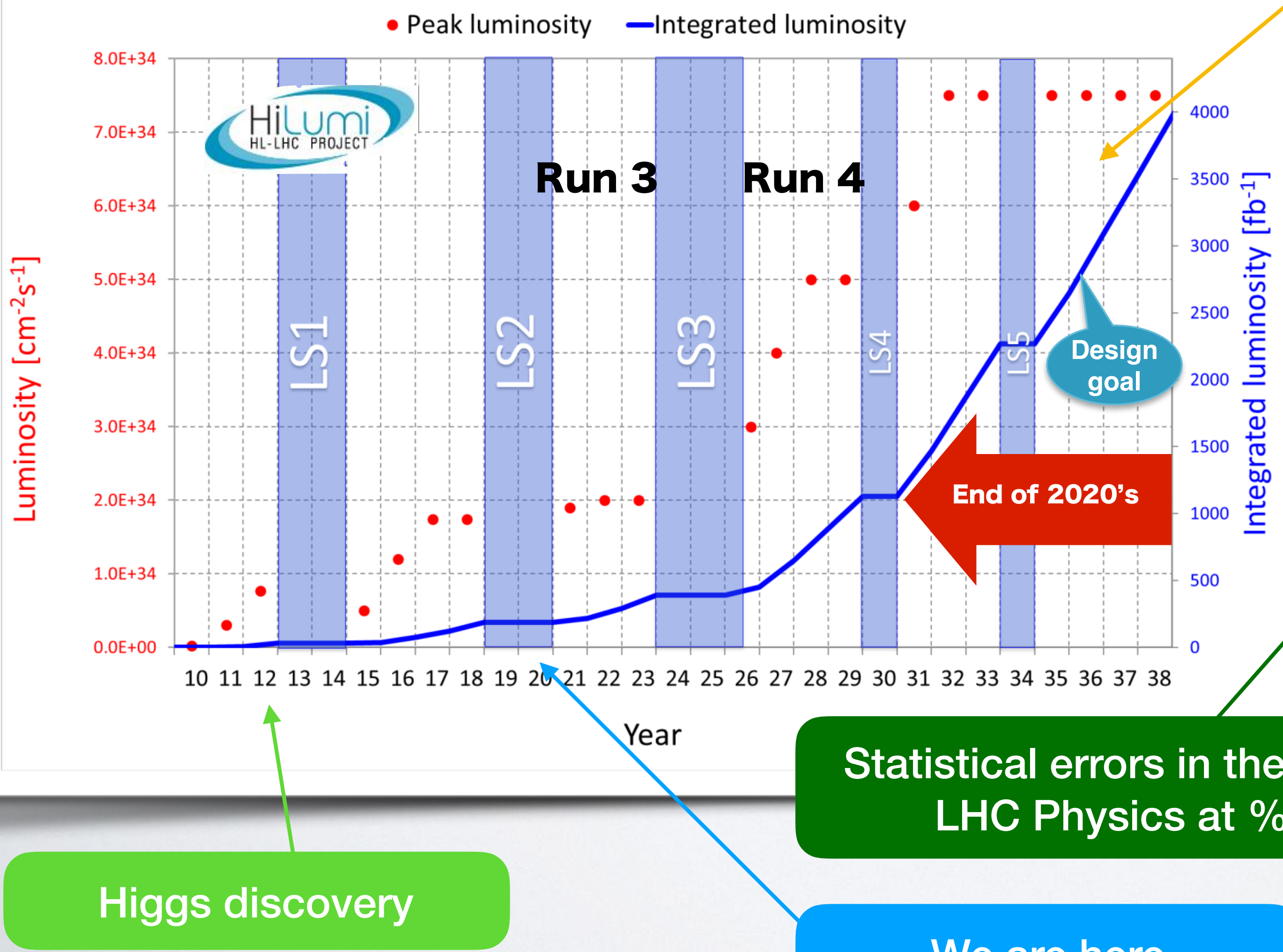
CERN director-general Fabiola Gianotti speaking at the 2019 AAAS meeting in Washington, DC. (Courtesy: Robb Cohen Photography & Video)

> “ Precise measurements of known particles and interactions are just as important as finding new particles

MOTIVATION

Why precision physics is important at the LHC?

HL-LHC lumi: 5-7x today's int.lumi by 2030, 20-30x by 2036



More than 30 yrs of LHC

ATLAS and CMS

Run 3	Run4	HL-LHC total
300 fb^{-1}	1 ab^{-1}	3 – 4 ab^{-1}

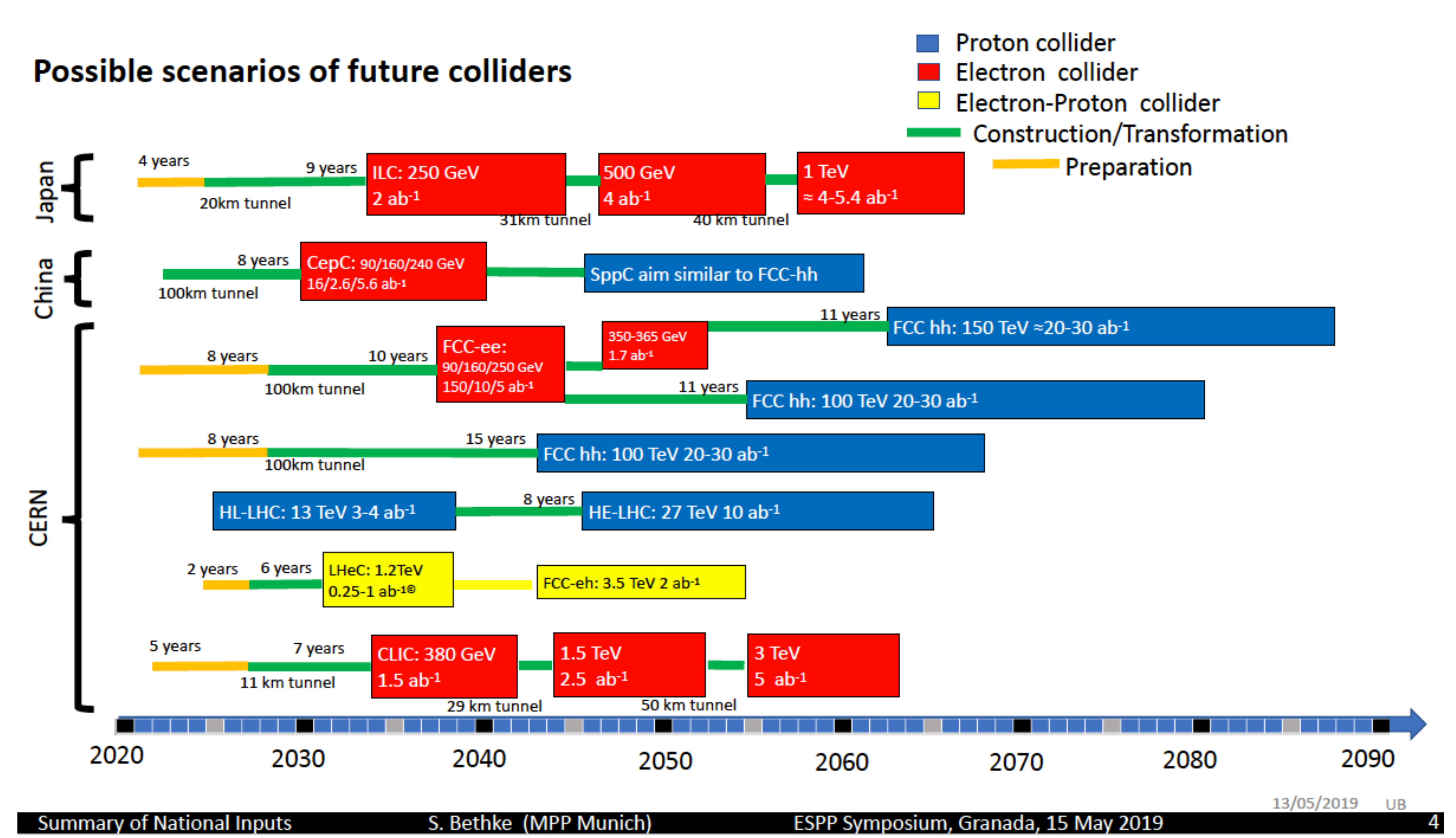
LHCb

Run 3	Run4	HL-LHC total
23 fb^{-1}	50 fb^{-1}	300 fb^{-1}

Statistical errors in the range 1% - 2%
LHC Physics at % precision?

MOTIVATION

Why precision physics is important at the LHC?



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

STATE OF THE ART OF PRECISION PHYSICS AT THE LHC

- 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

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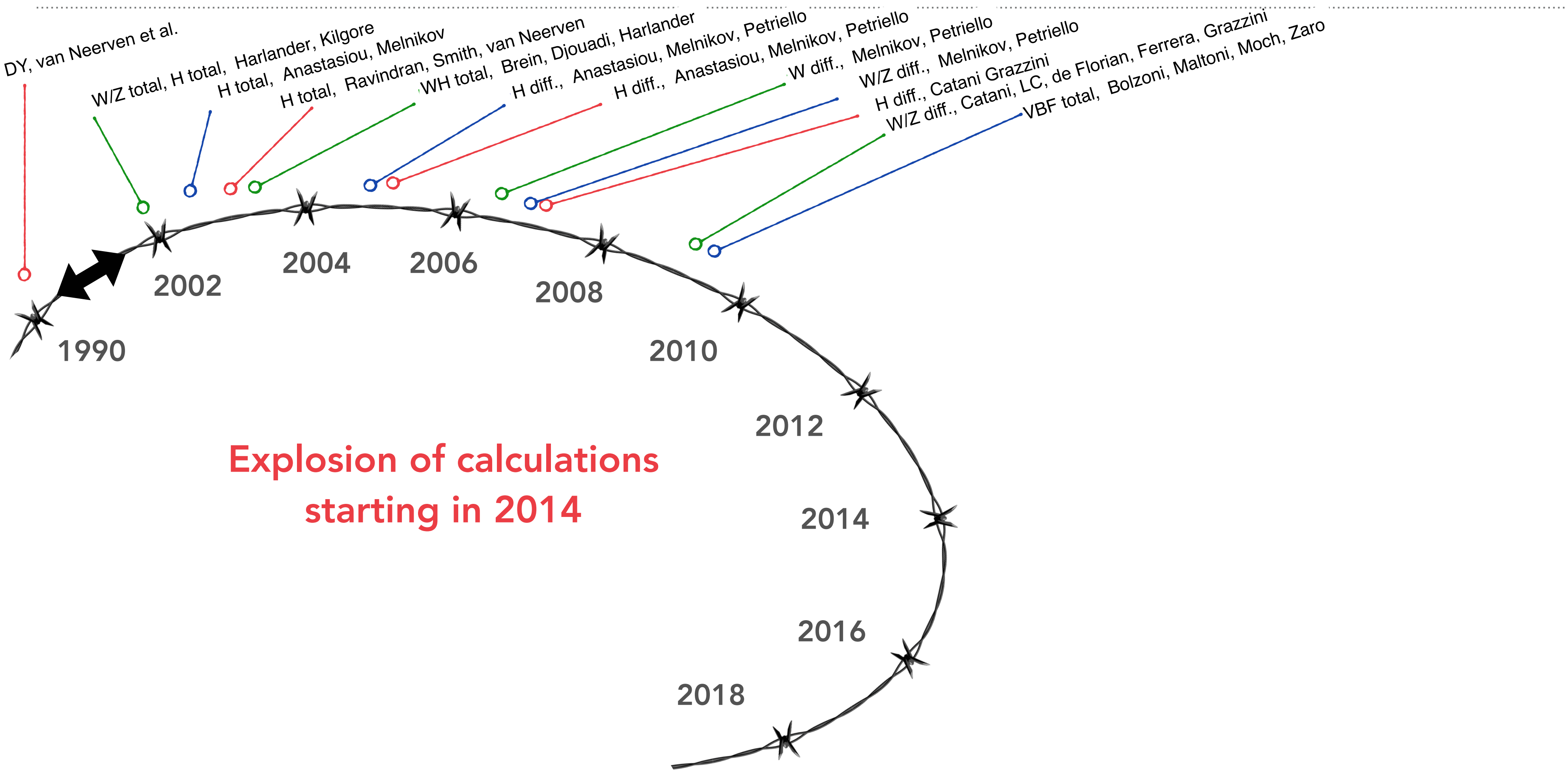
→ "The NNLO revolution"

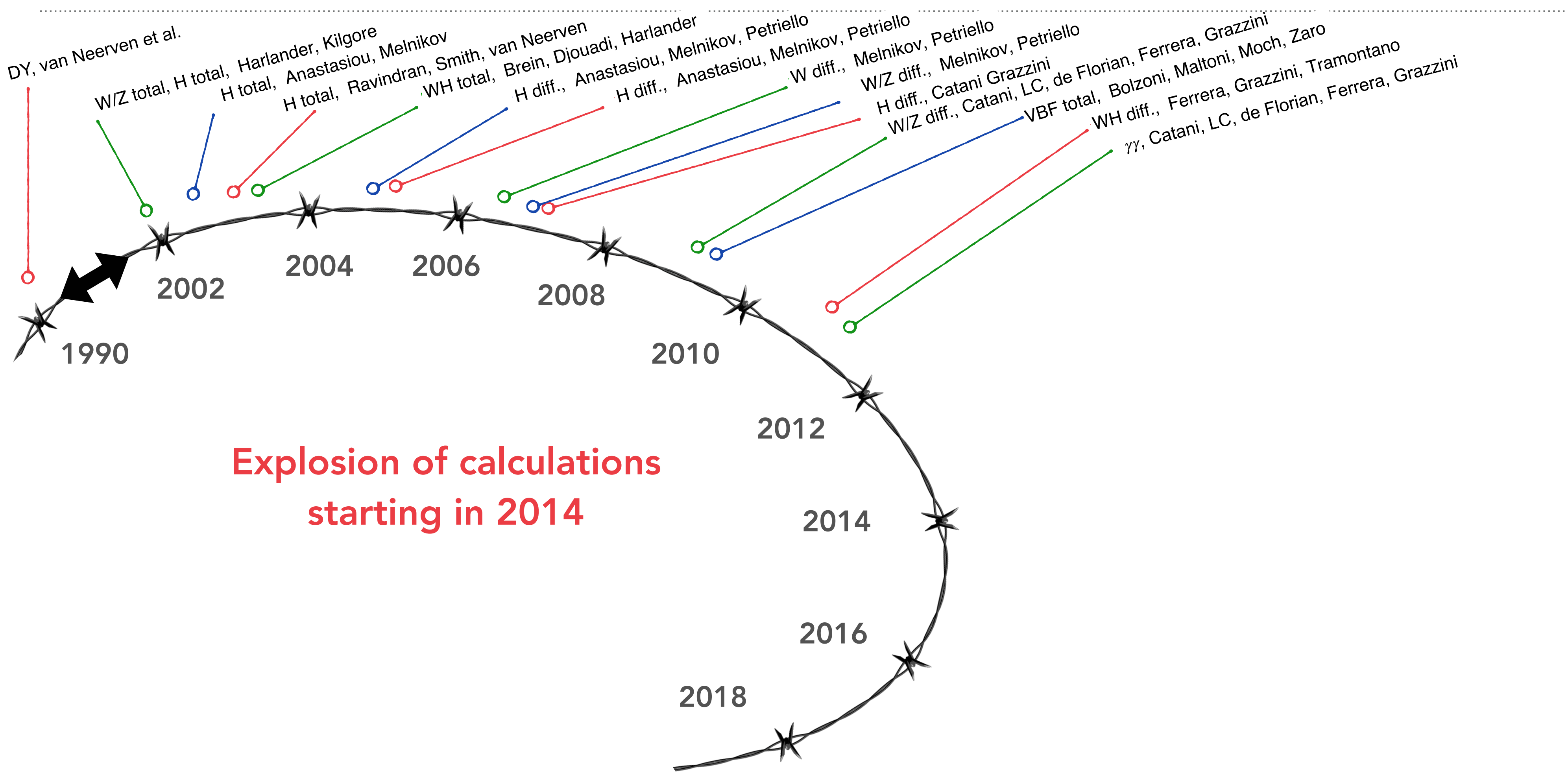
THE NNLO STANDARD

NNLO HADRON-COLLIDER CALCULATIONS VS. TIME



THE NNLO STANDARD

NNLO HADRON-COLLIDER CALCULATIONS VS. TIME



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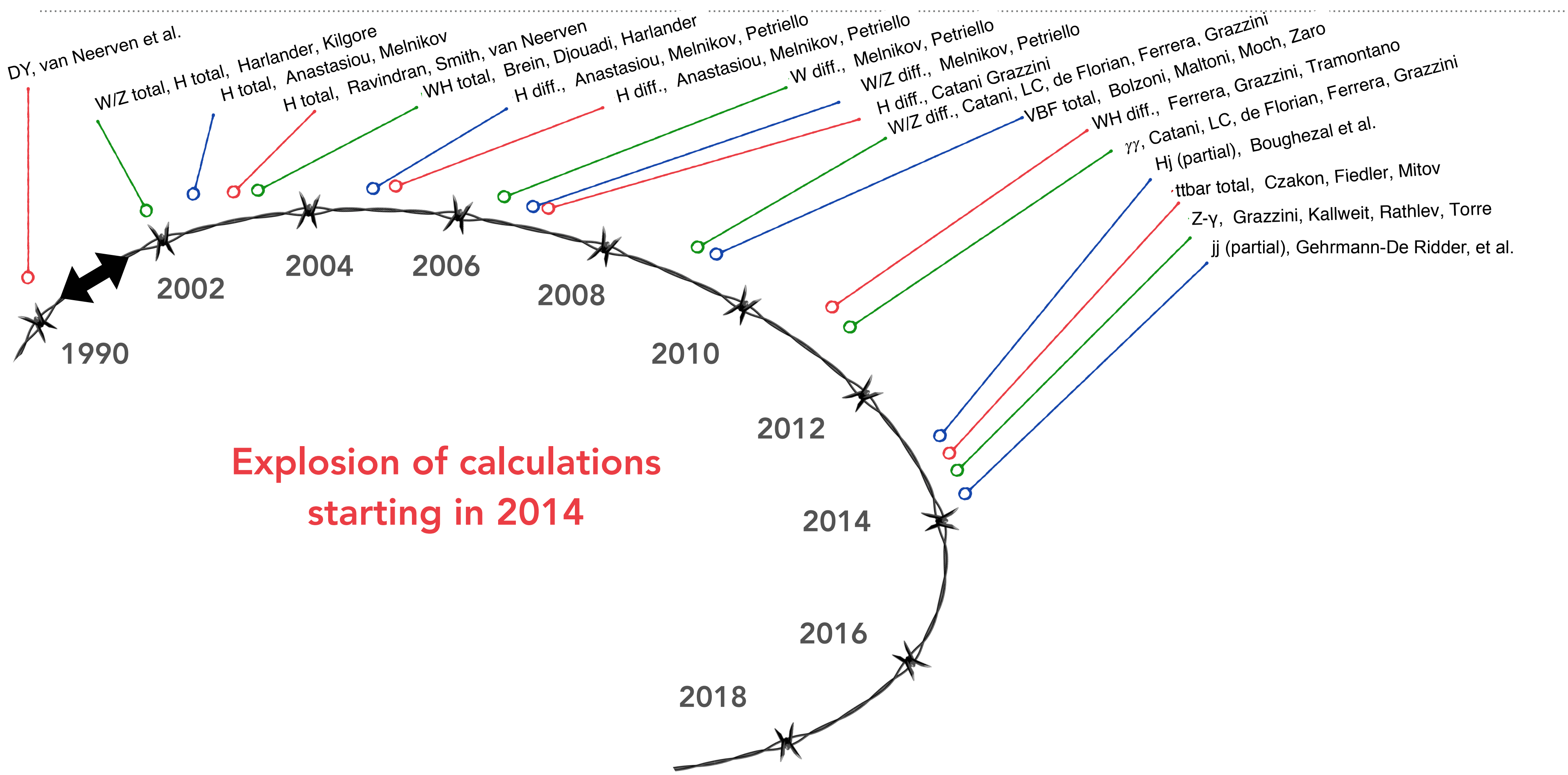

Slide inspired in Gavin Salam's talk

THE NNLO STANDARD

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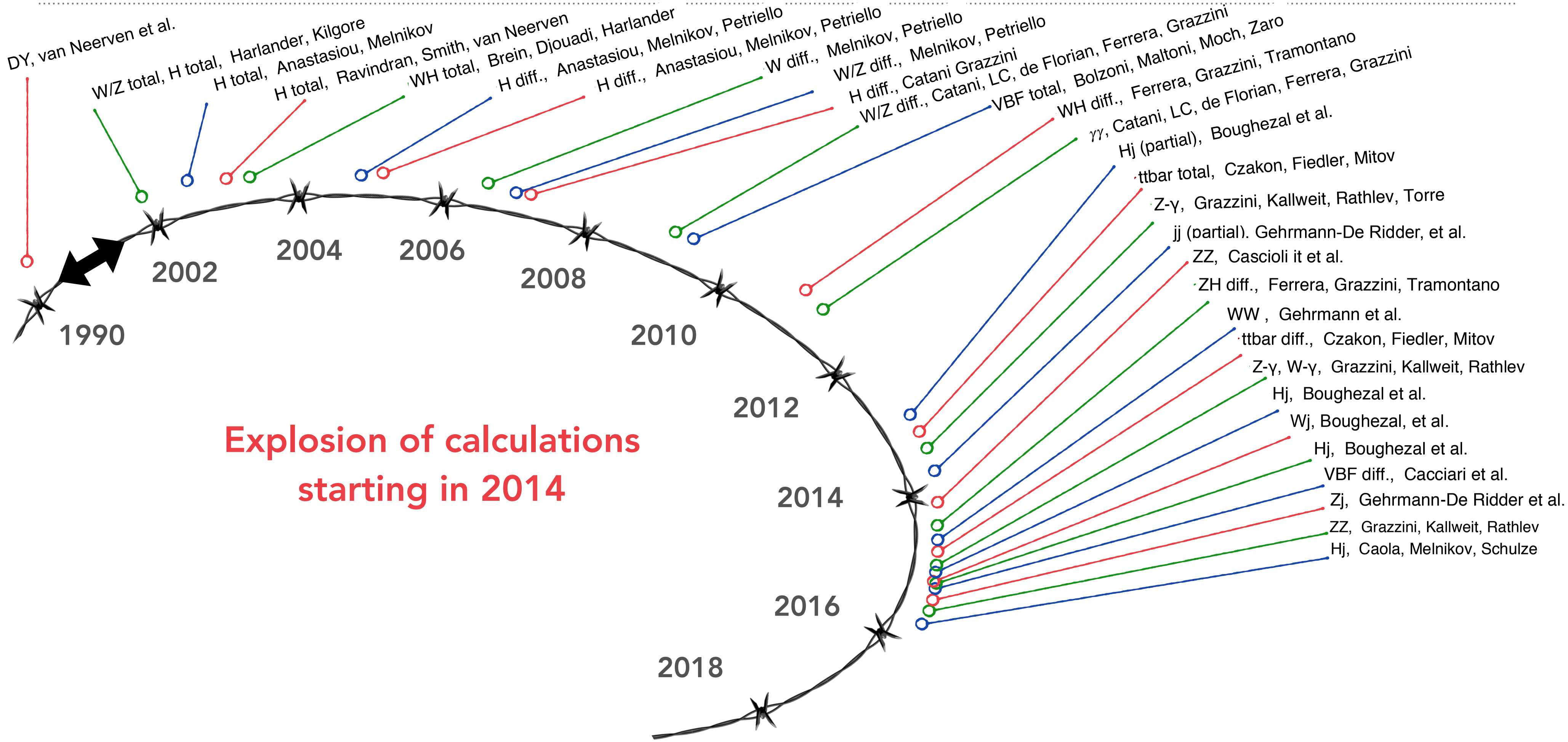

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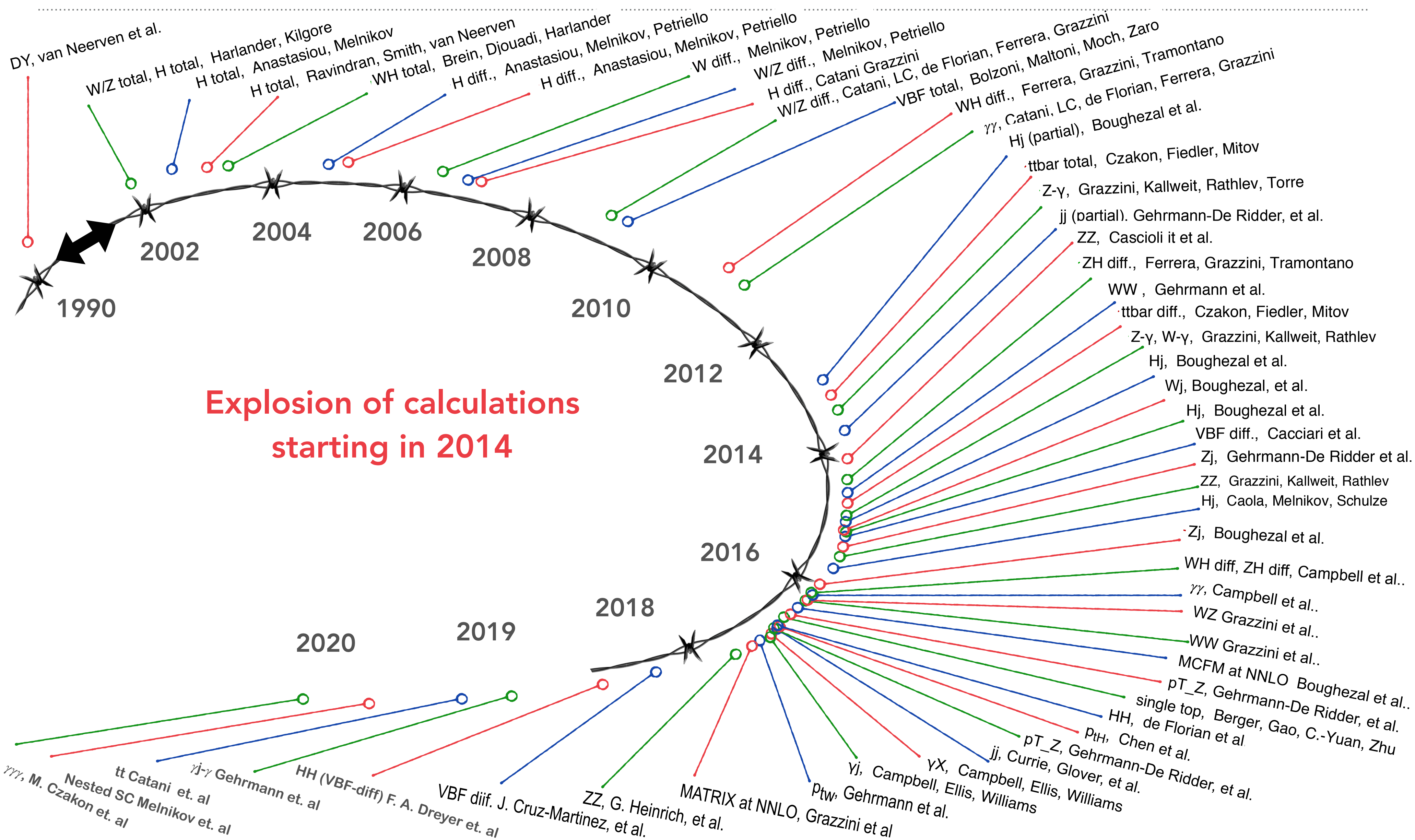

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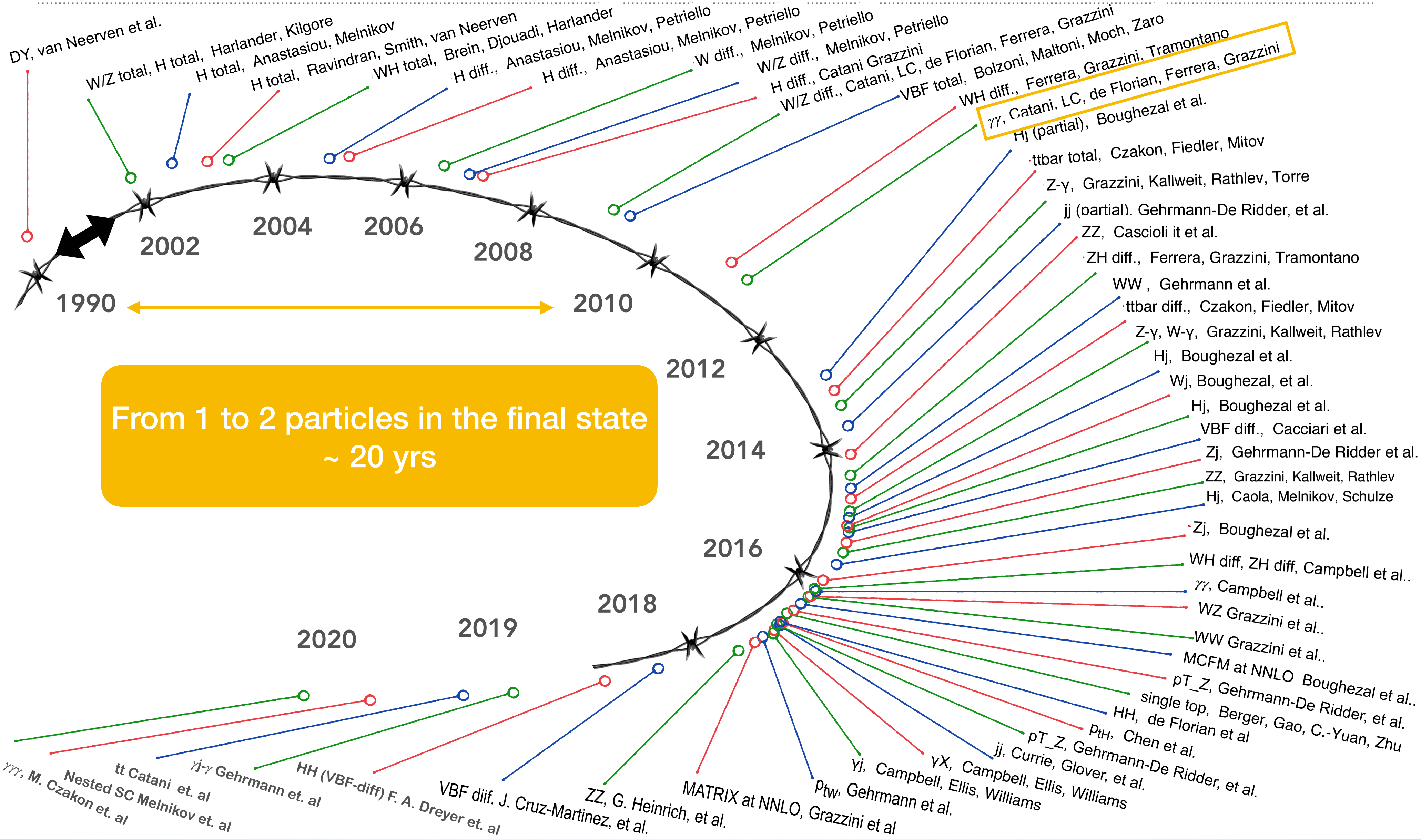

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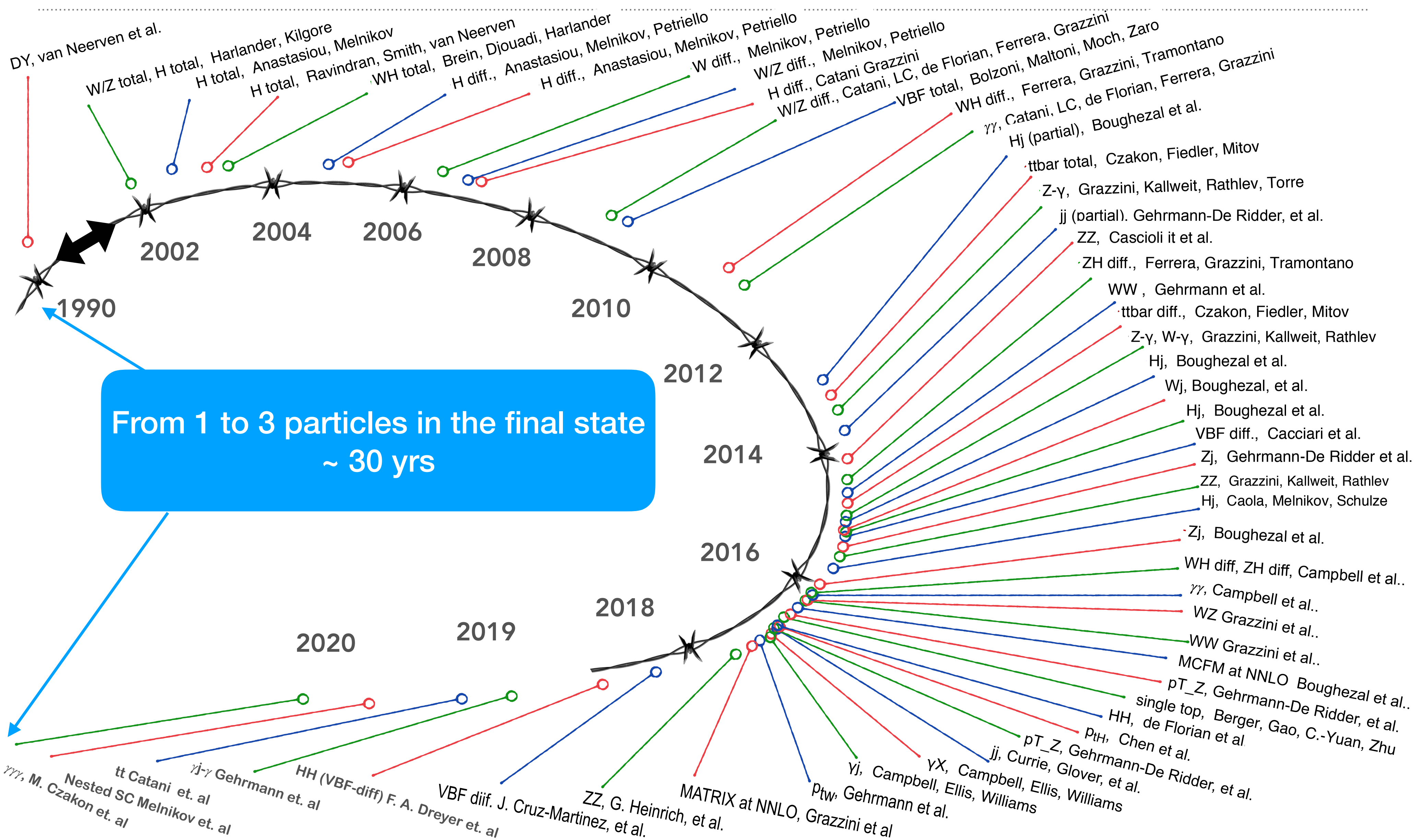

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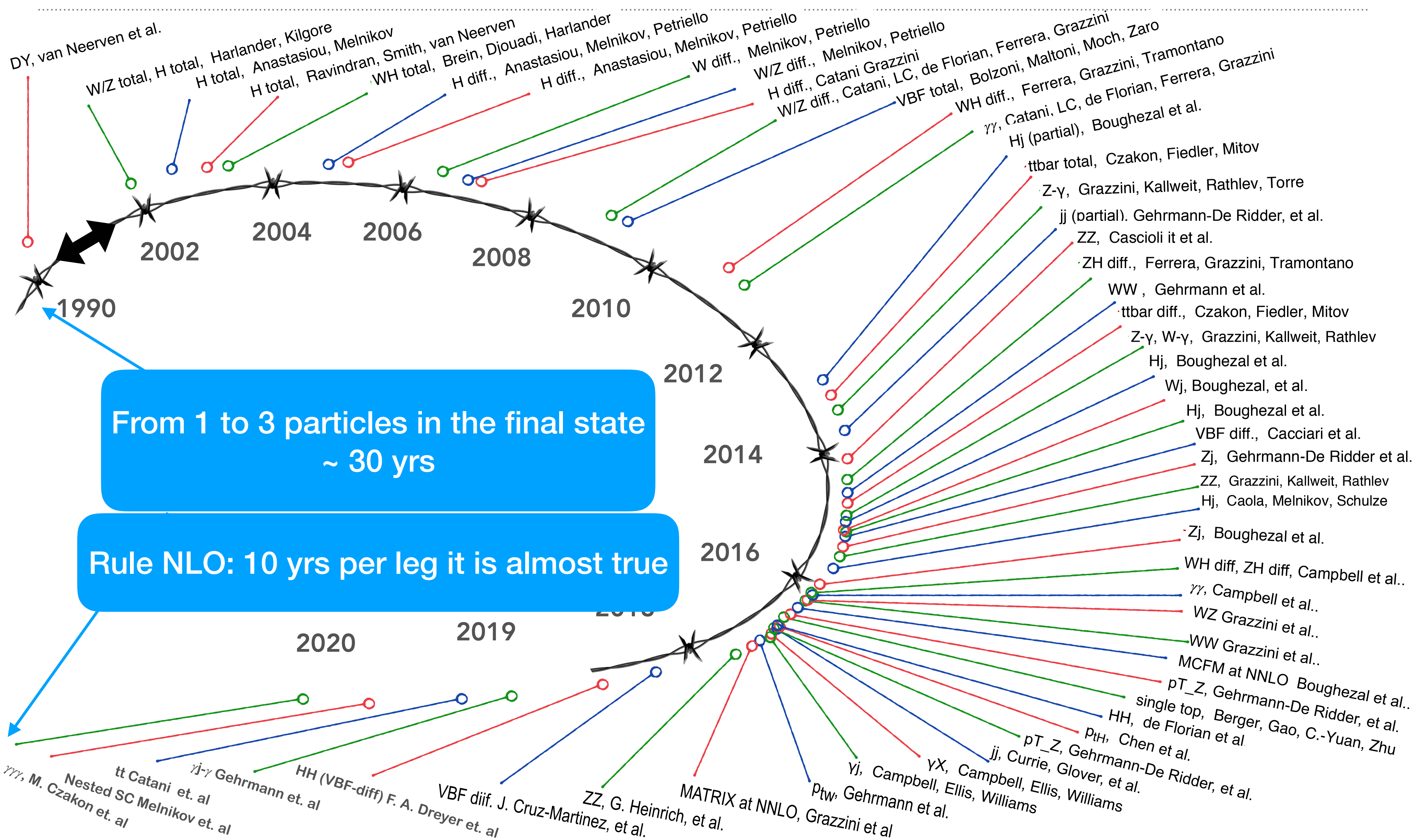

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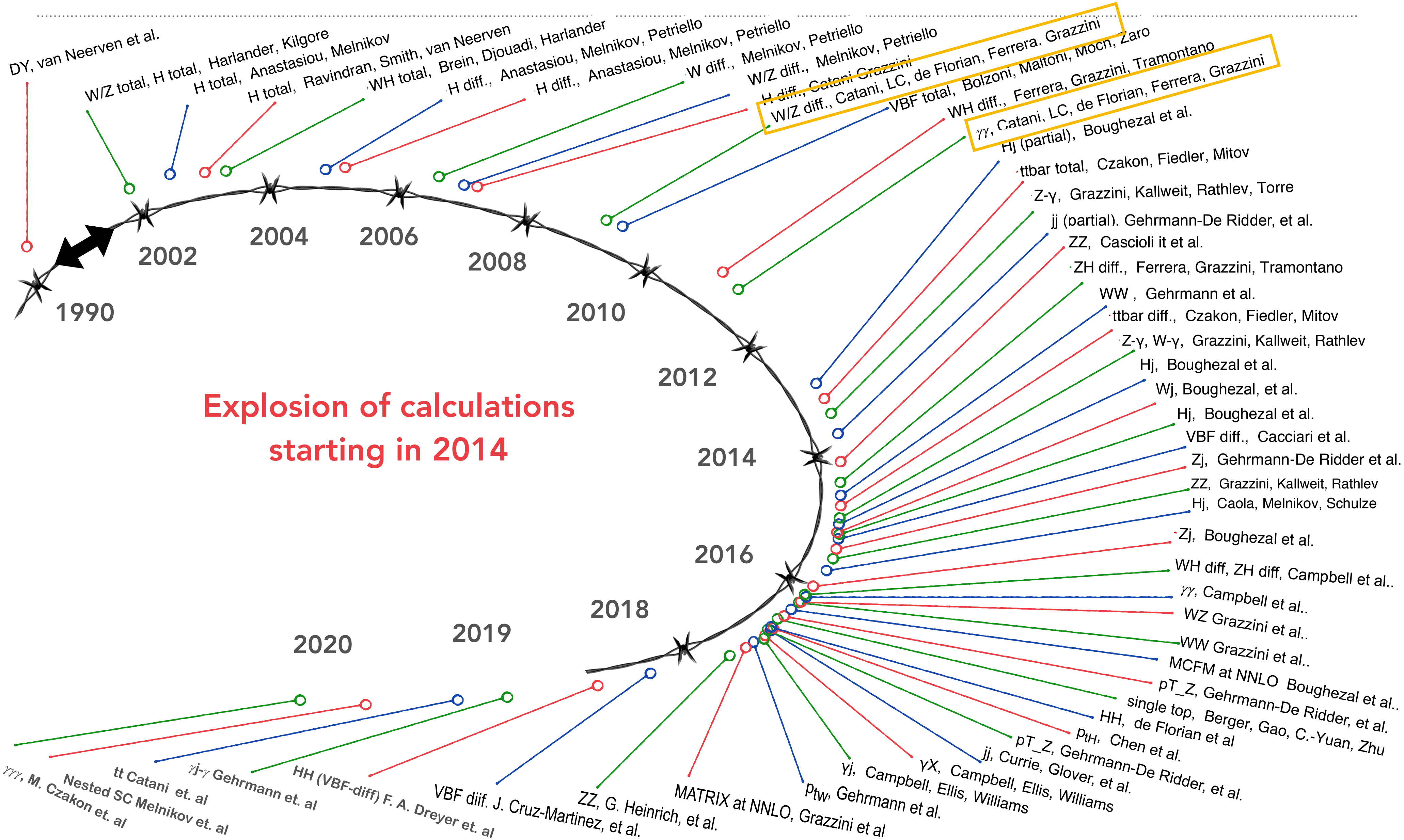
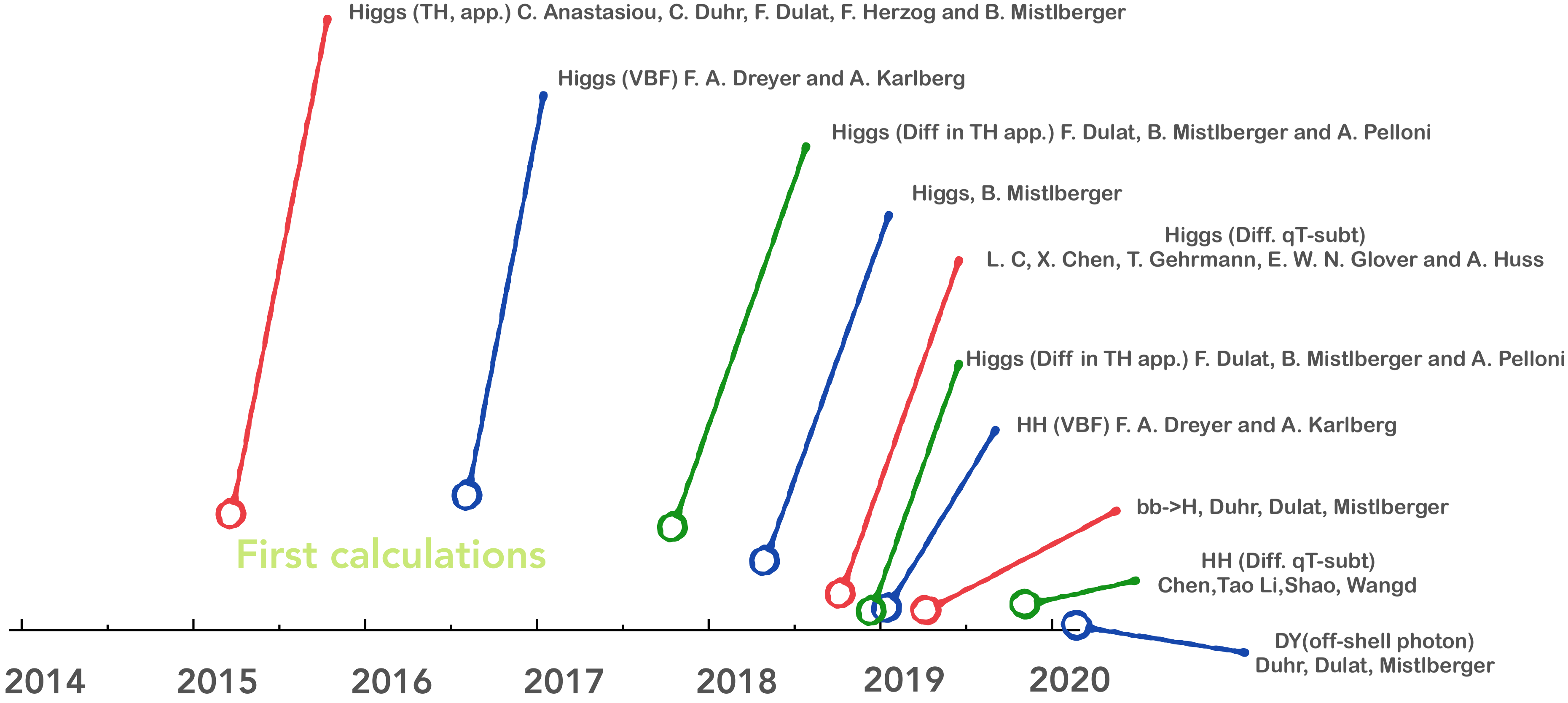


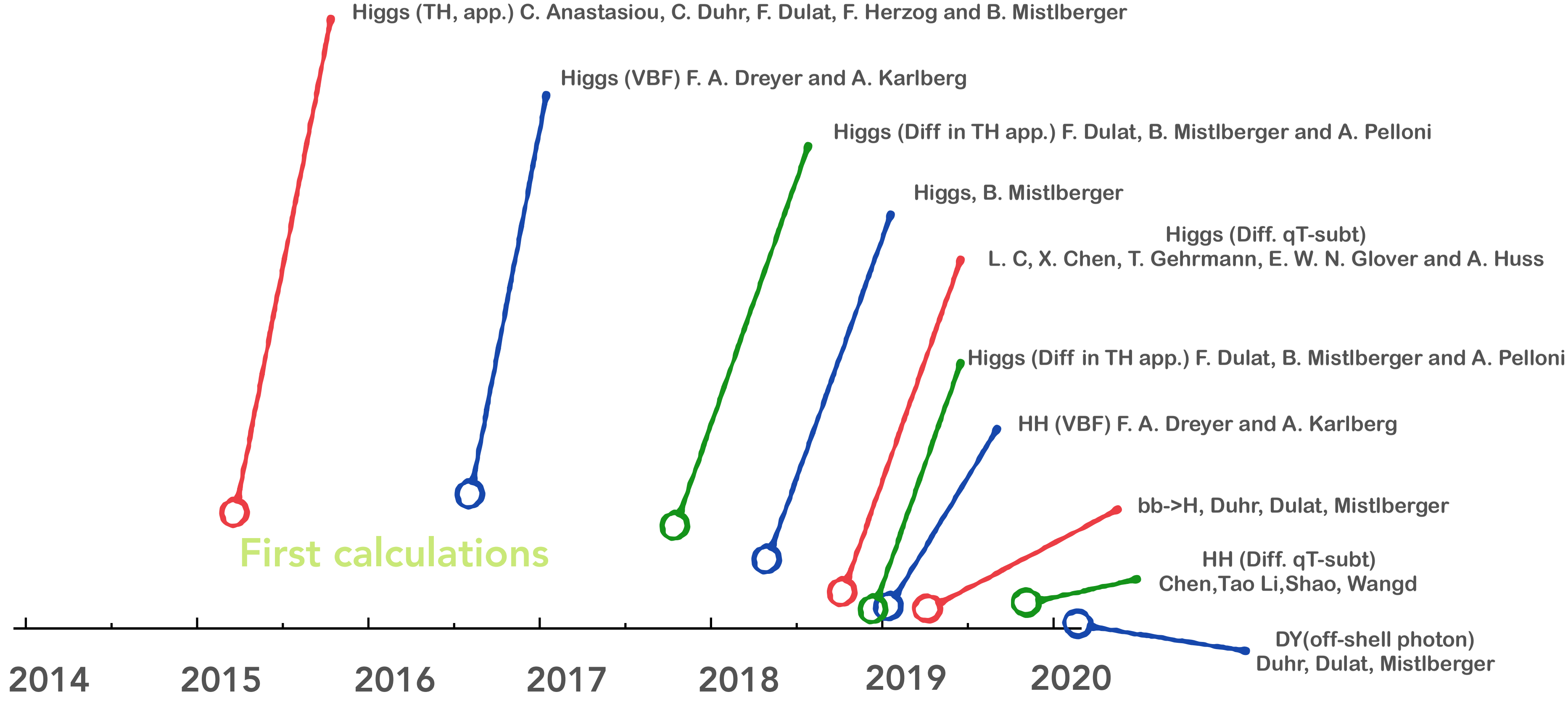
THE N^3LO ERA

N^3LO HADRON-COLLIDER CALCULATIONS VS. TIME



THE N^{3}LO ERA

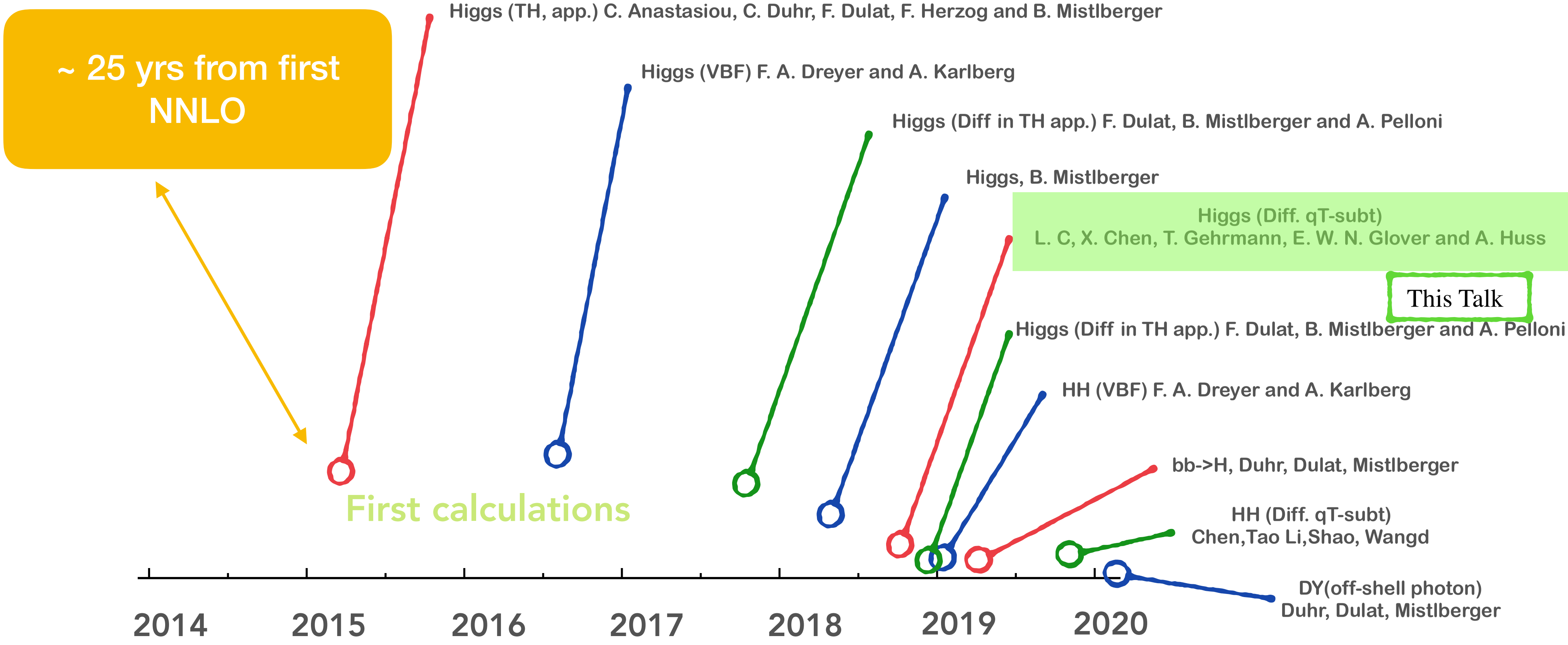
N^{3}LO HADRON-COLLIDER CALCULATIONS VS. TIME



This line starts to filling quickly

THE N^3LO ERA

N^3LO HADRON-COLLIDER CALCULATIONS VS. TIME



THE QT-SUBTRACTION/RESUMMATION FORMALISM

The method

Explicit form
qT-subt. Ingredients

Helicity-Flip
Contributions

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

NNLO+NNLL QCD

- 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 NLO QED FSR → Buonocore, Grazzini, Tramontano (2019)
- 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)

QT-SUBTRACTION AT N3LO

L. C, X. Chen, T. Gehrmann, E. W. N. Glover, and A. Huss (2018)

N^3LO DIFFERENTIAL DISTRIBUTIONS

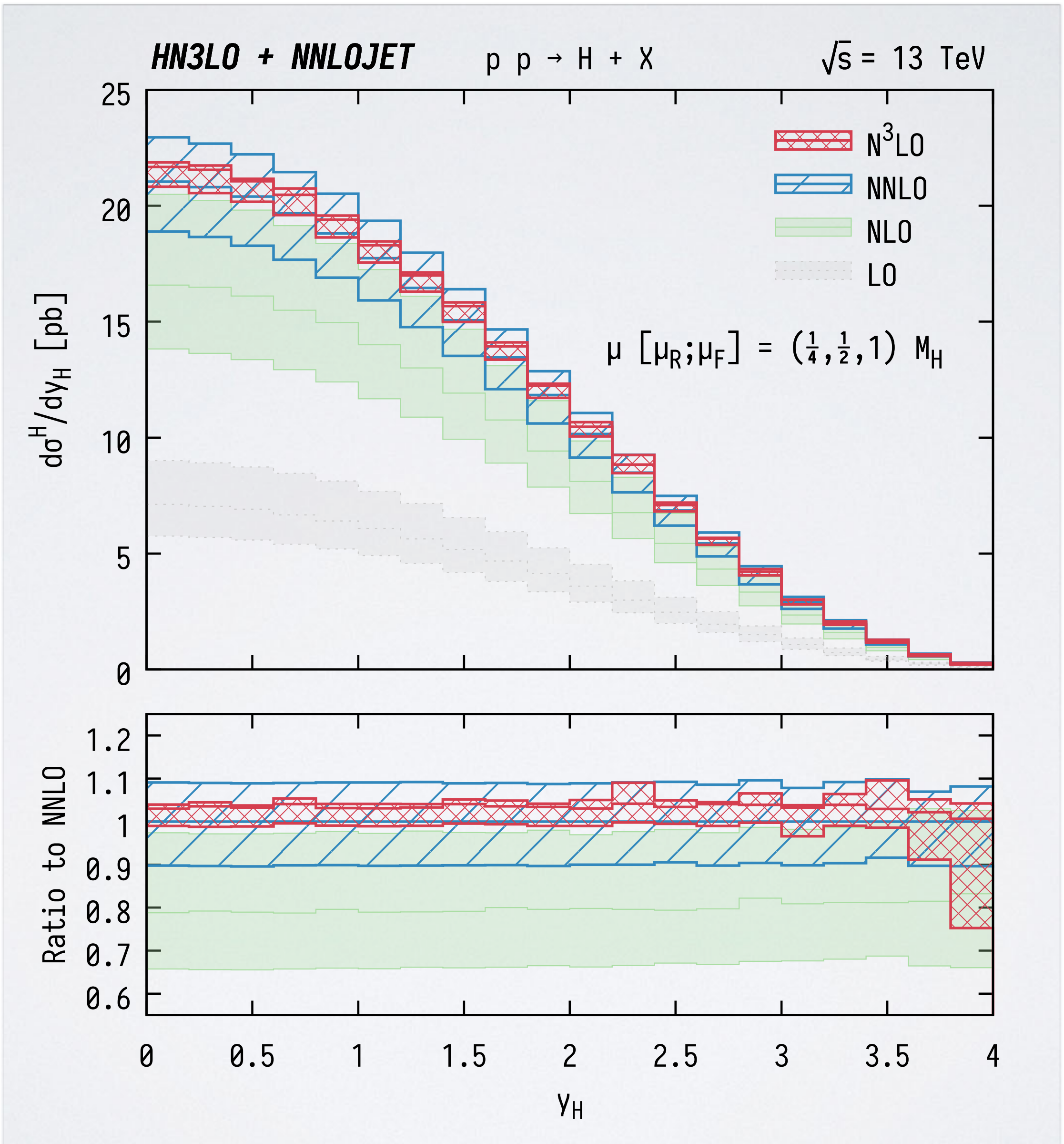
L. C, X. Chen, T. Gehrmann, E. W. N. Glover, and A. Huss (2018)

Rapidity distribution

We calculate the yH distribution at N3LO employing a seven-point scale variation and carefully assess systematic errors arising form different qTcut and CN3 values.

The combined theoretical uncertainty at N3LO is at most of ±5% level with respect to the central scale choice

N3LO prediction at qTcut=2GeV + qTcut uncertainties + systematic uncertainties



Compared to the NNLO yH distributions, we observe a large reduction of theory uncertainties by more than 50% at N3LO. The scale variation band at N3LO stays within the NNLO band with a flat K-factor of about 1.034 in the central rapidity region (|yH| ≤ 3.6).

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L. C, X. Chen, T. Gehrmann, E. W. N. Glover, and A. Huss (2018)

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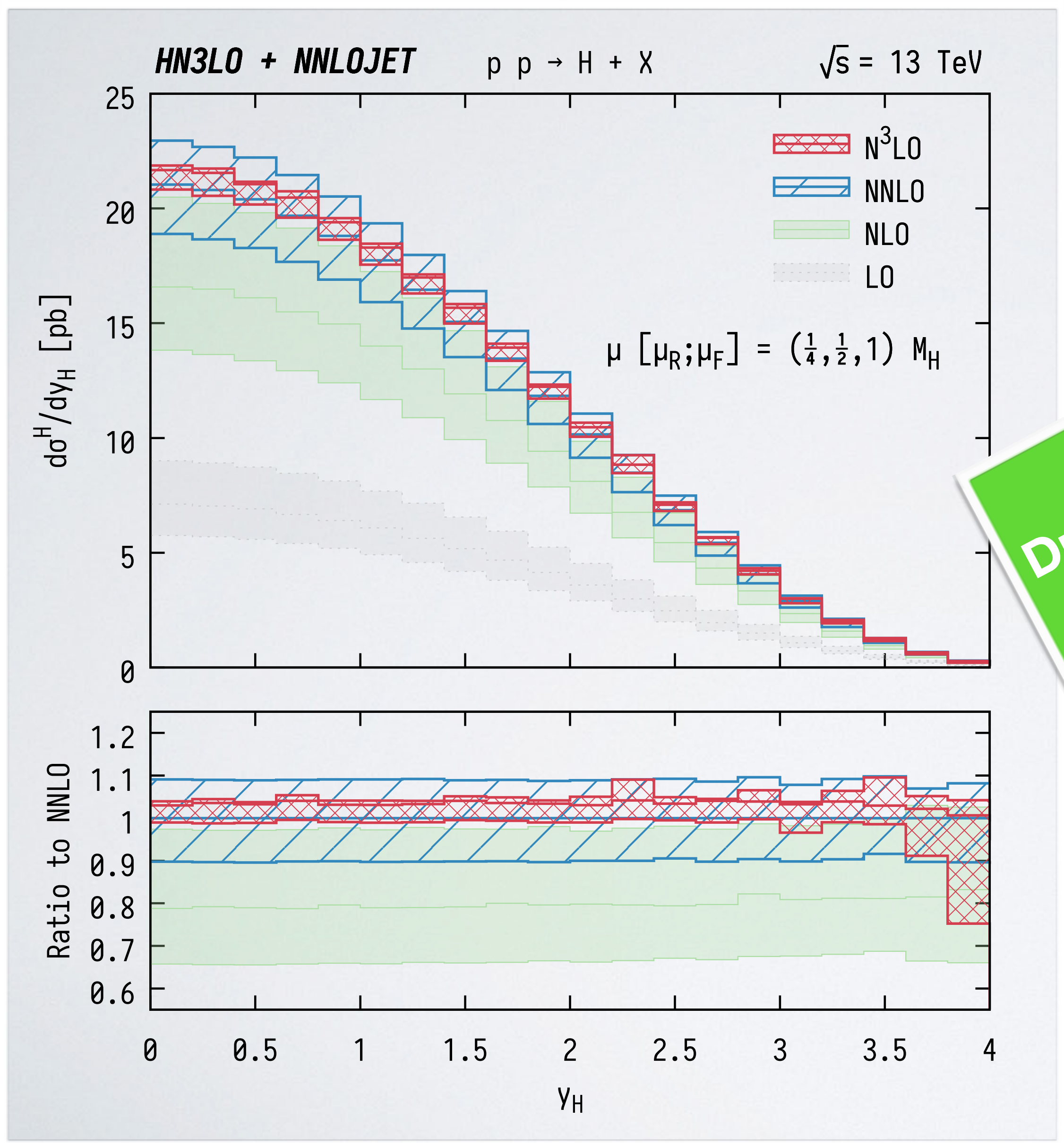


In agreement with Dulat, Mistlberger and Pelloni (2018) [Higgs production in TH expansion approximation]

Which is far from a trivial test!!

N^3LO DIFFERENTIAL DISTRIBUTIONS

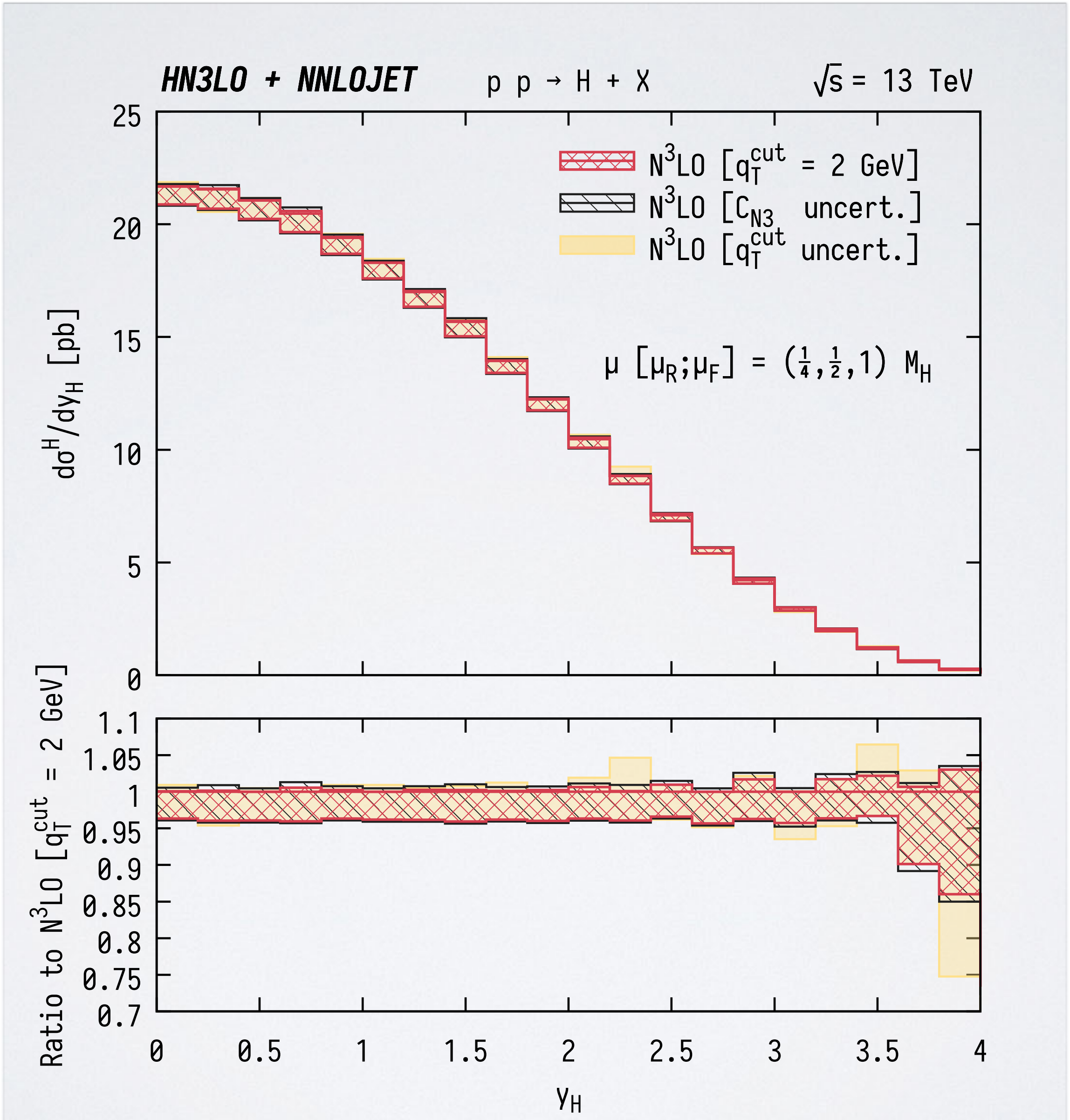
L. C, X. Chen, T. Gehrmann, E. W. N. Glover, and A. Huss (2018)

Uncertainties at N^3LO

N3LO prediction at qTcut=2GeV + qTcut uncertainties + systematic uncertainties

qTcut uncertainties Calculated taking three different predictions for qTcut = (2 ± 1) GeV

The black band is obtained as the envelope of the seven-point scale variation at qTcut = 2 GeV considering for each scale the two extremal CN3 coefficients corresponding to its maximum and minimum statistical deviations CN3 = {−1165,−721}



In order to produce smooth histograms the code has to run for a couple of months in 2000 cores approx.

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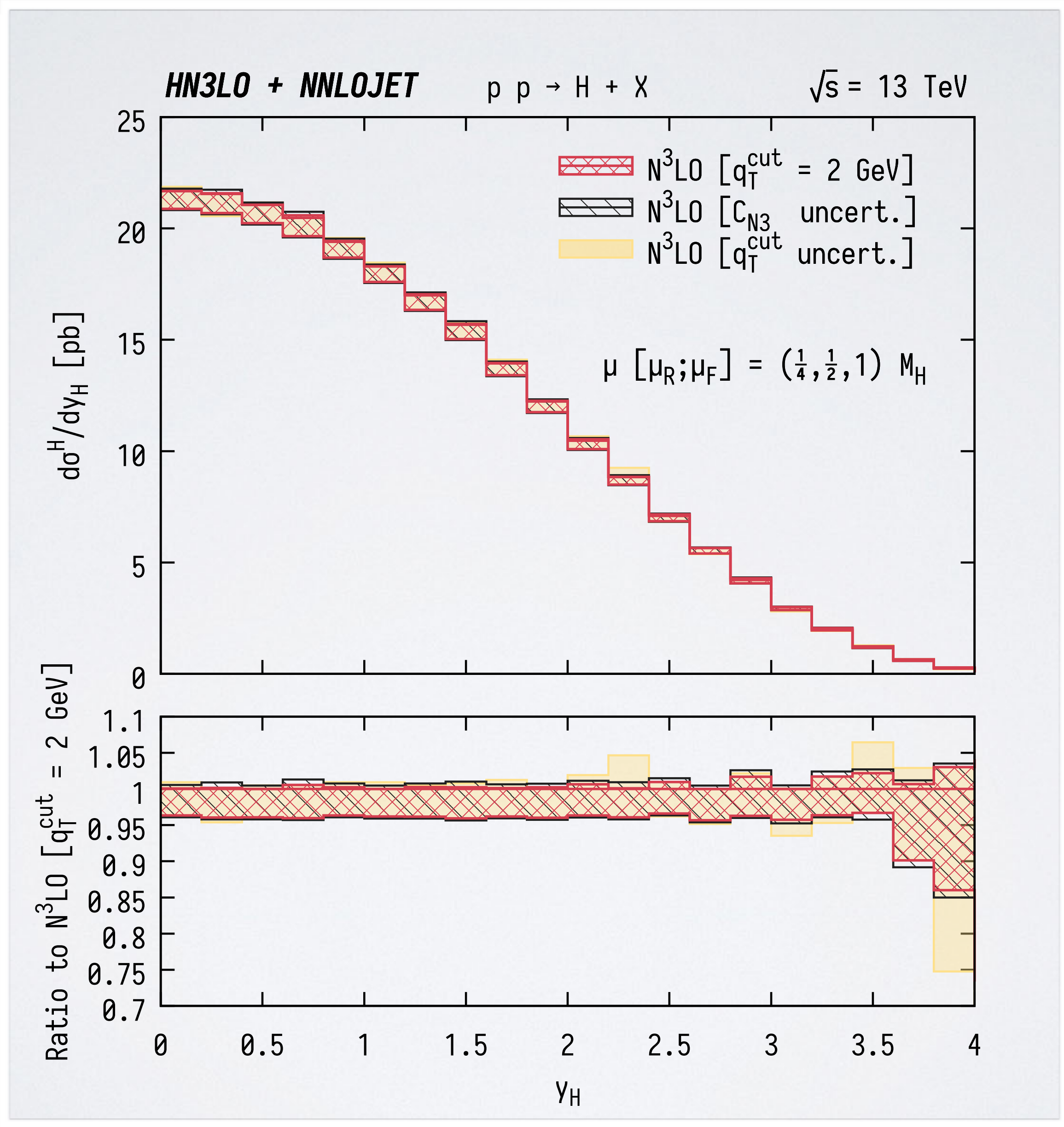

For the inclusive: ~2 min in one core!

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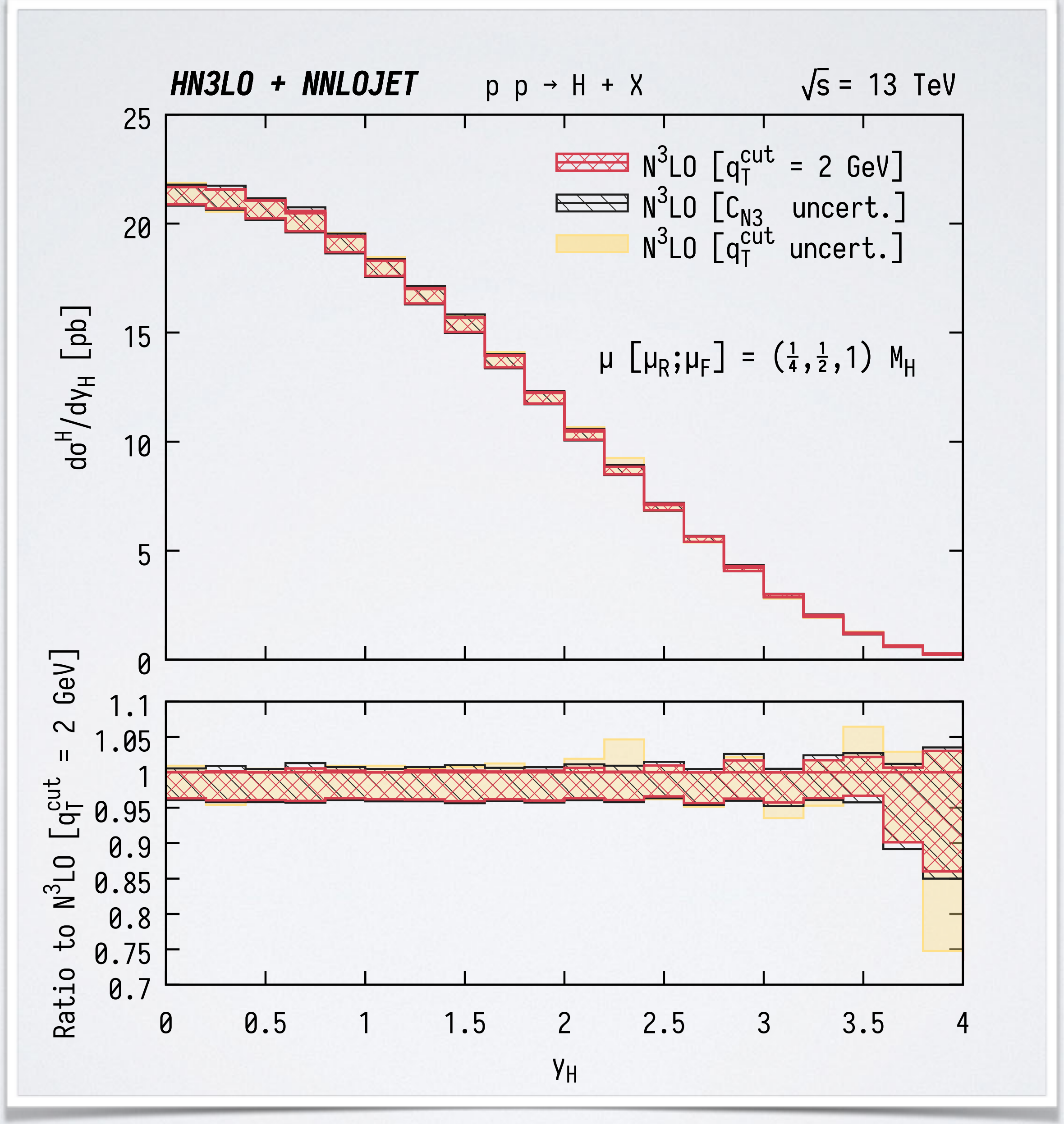

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In order to produce smooth histograms the code has to run for a couple of months in 2000 cores approx.

~ 100 yrs in a desktop computer

We need new techniques, new approaches

N3LO AS THE NEW STANDARD FOR PRECISION PHYSICS AT THE LHC

Next steps following the research plan

Drell-Yan at N3LO differential

All the qT-subtraction ingredients are known for qqbar

M. Luo, T. Yang, H. Xing Zhu, Y. Jiao Zhu (2019)

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Total cross section not known yet

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qT-resummation at the same order N3LL

DYTurbo

Camarda, Bozzi, Catani, L. C, Ferrera, et. al (2019)

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Sub-leading power corrections

L. C, Oleari, Rocco (2019)

Leonardo Vernazza's Talk

They are not known even at NNLO

Hints on local subtraction

Setup general framework (analytical/numerical) to apply to any colourless final state

CONCLUSIONS AND OUTLOOK

- We presented results at N^3LO for completely differential distributions for observables measured at the LHC **(in particular for Higgs boson production in gluon fusion)**
- The qT-subtraction method at N^3LO, presented here, can be applied to other processes initiated by gluon fusion (if the three-loop scattering amplitudes are known)
- In the future, two elements are necessary in order to complete analytically the qT-subtraction method at N^3LO
  - The universal relation between the three-loop virtual scattering amplitudes and the hard virtual factor
  - The third order collinear functions (gluon-gluon channel)
- Our results can be applied to perform qT-resummation at the corresponding level of logarithmic accuracy. **i.e without reweighing by the total cross section**
- We have all the elements in the case of the qqbar channel

CONCLUSIONS AND OUTLOOK

- The completion of this research project will produce
  - new complementary use of different techniques, analytic and semi-analytic techniques; new ideas related to the introduction of more complex mathematical structures related to the calculation of Feynman diagrams
  - new subtraction scheme developed
  - new developed Monte Carlo code at N^3LO **(one of the few existing)**
  - innovative studies of processes that test the SM with very high precision. Such high-precision can eventually give hints about NP contributions

CONCLUSIONS AND OUTLOOK

- I expect that our fellowship serve us to produce “state of the art computations" that can be used to compare with the most precise LHC data

- I particularly expect that our fellowship, and the work that we will perform along our research plans, will benefit us at the time of application to other prestigious fellowships and fixed positions

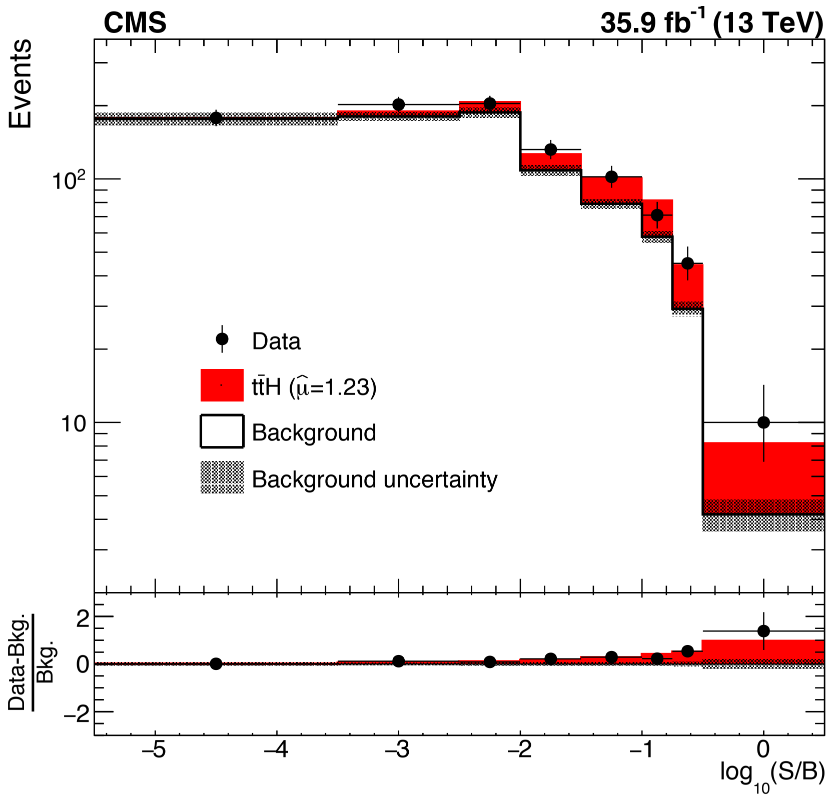
THANK YOU!

BACKUP SLIDES

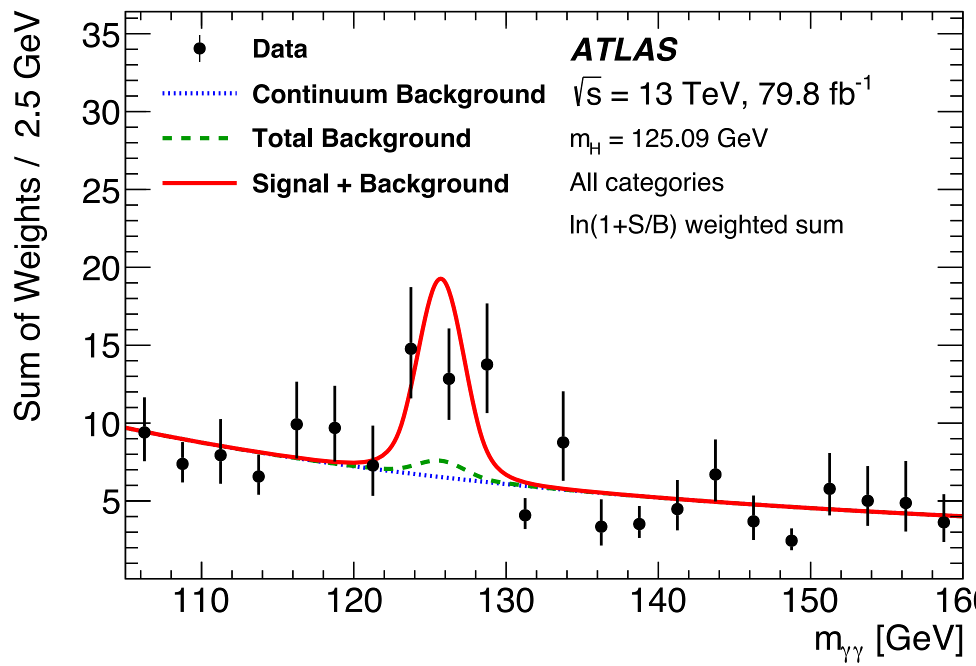
New interesting tasks are just recently initiated: Yukawas

the news of the past 12 months

A few weeks ago:
CMS >5-sigma ttH

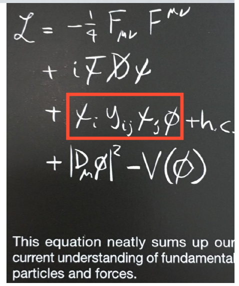


This week:
ATLAS >5-sigma ttH



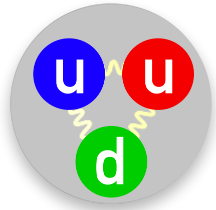
Why do Yukawa couplings matter?

(2) Because, within SM **conjecture**, they're what give masses to all **quarks**



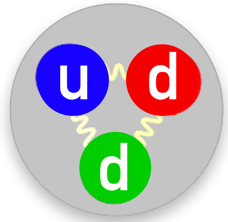
Up quarks (mass ~ 2.2 MeV) are lighter than
down quarks (mass ~ 4.7 MeV)

proton
mass = 938.3MeV



proton (up+up+down): 2.2 + **2.2** + 4.7 + ... = **938.3** MeV
neutron (up+down+down): 2.2 + **4.7** + 4.7 + ... = **939.6** MeV

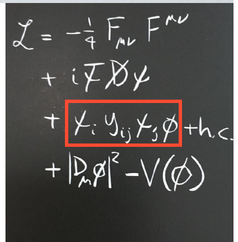
neutron
mass = 939.6MeV



So protons are **lighter** than neutrons,
→ protons are stable.

Which gives us the hydrogen atom,
& chemistry and biology as we know it

Why do Yukawa couplings matter?
(3) Because, within SM **conjecture**, they're what give masses to all **leptons**


This equation neatly sums up our current understanding of fundamental particles and forces.

Bohr radius

$$a_0 = \frac{4\pi\varepsilon_0 \hbar^2}{m_e e^2} = \frac{\hbar}{m_e\, c\, \alpha}$$

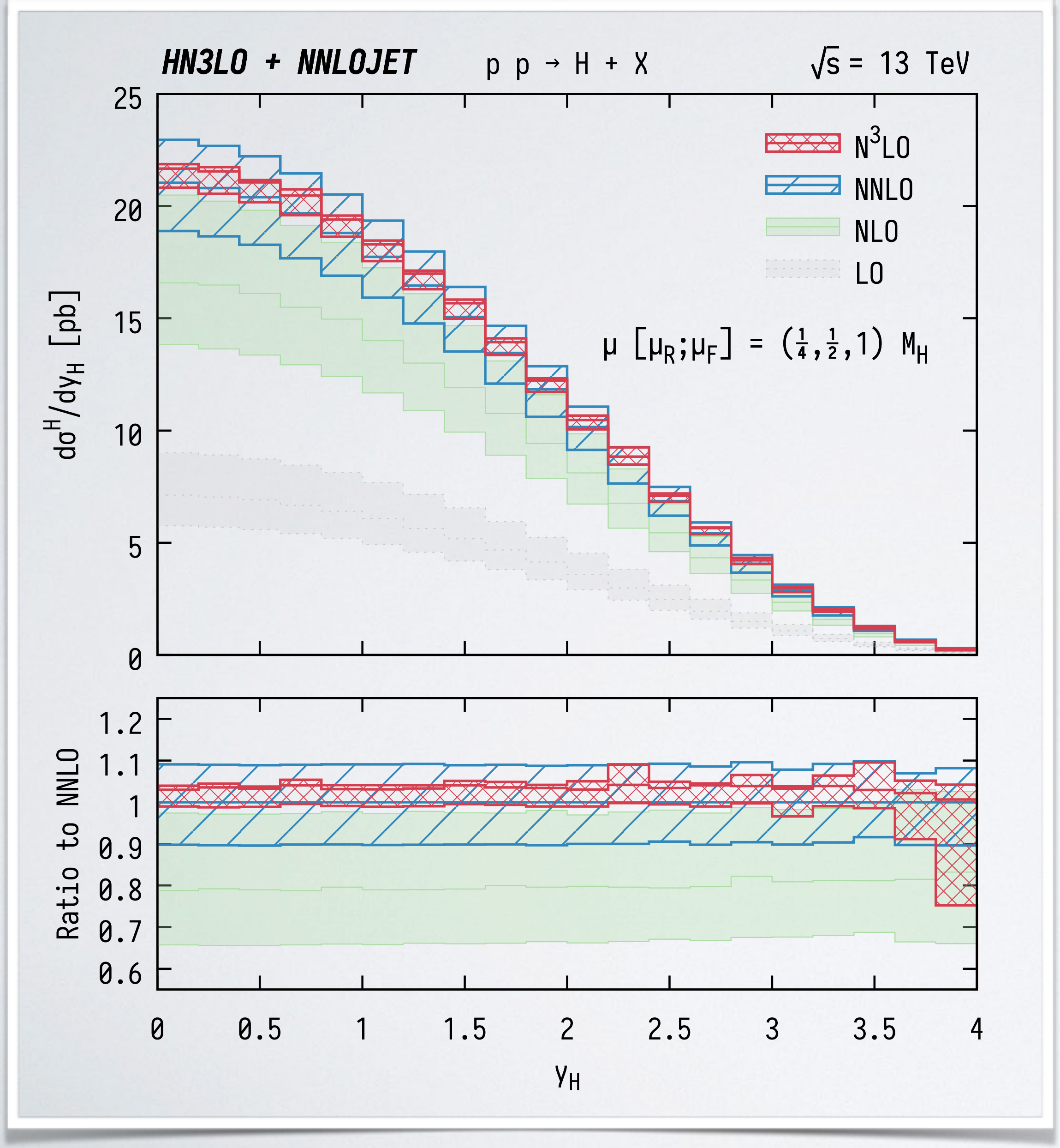
electron mass determines size of all atoms

it sets energy levels of all chemical reactions

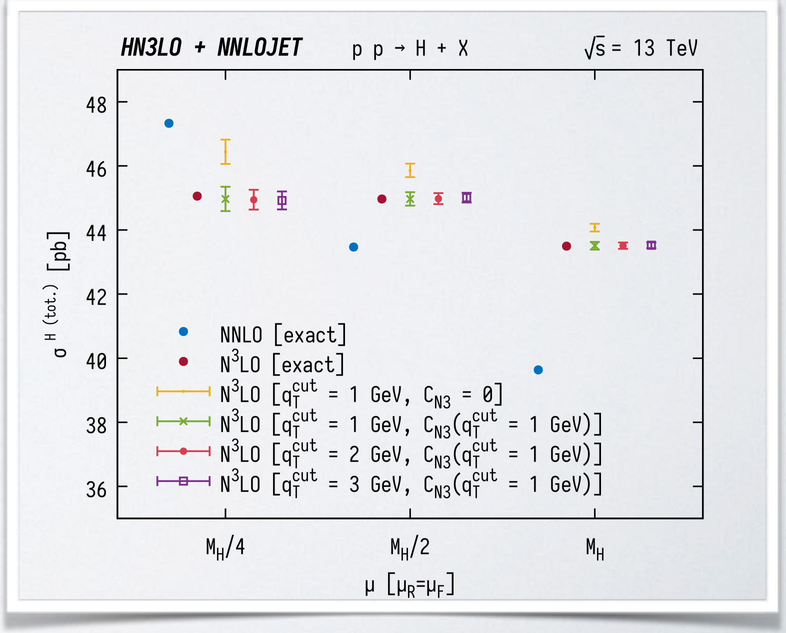
N^3LO DIFFERENTIAL DISTRIBUTIONS

L. C, X. Chen, T. Gehrmann, E. W. N. Glover, and A. Huss (2018)

Rapidity distribution



The central prediction at N^3LO, almost coincides with the upper edge of the band, as was already observed for the total cross section



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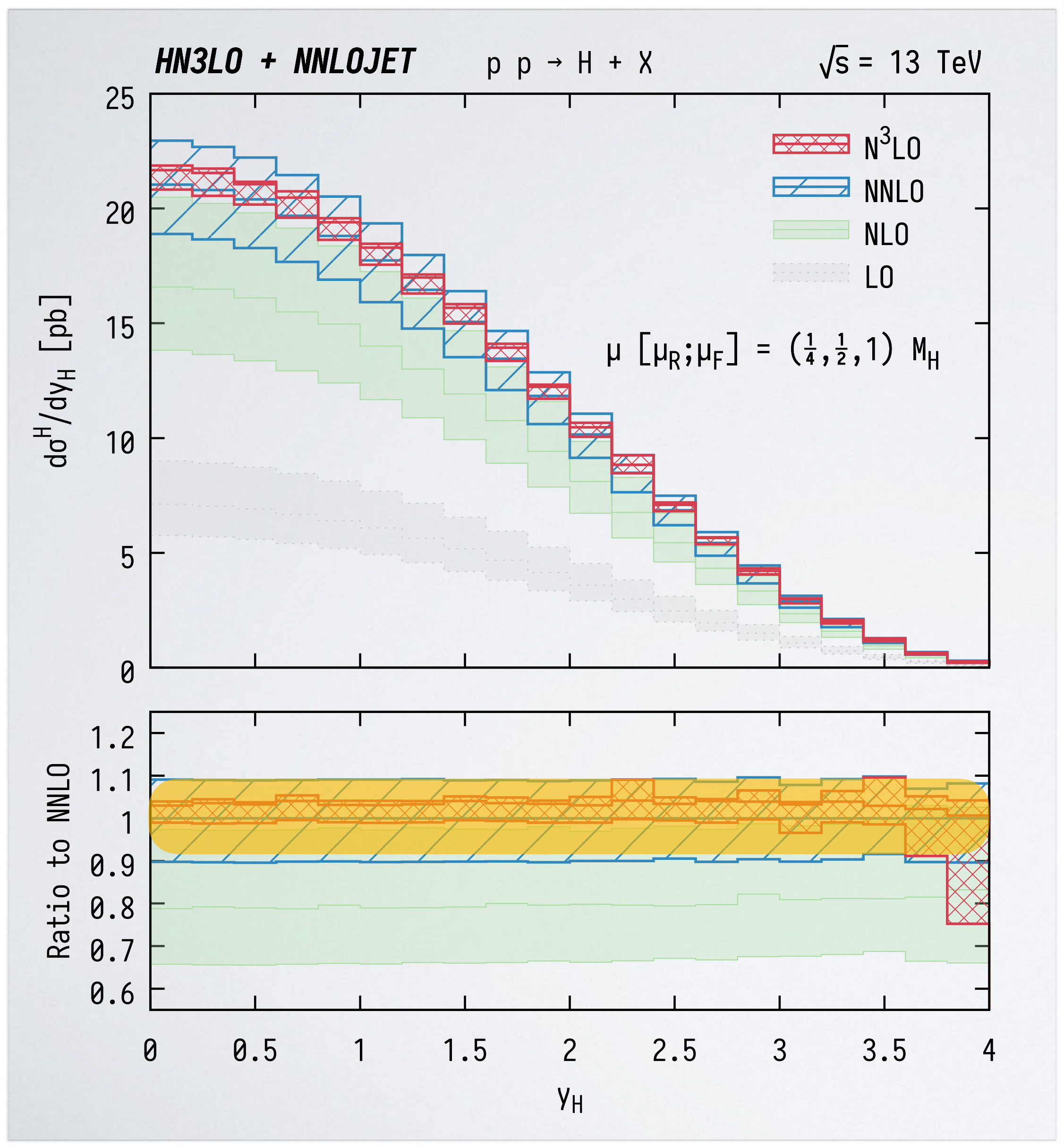

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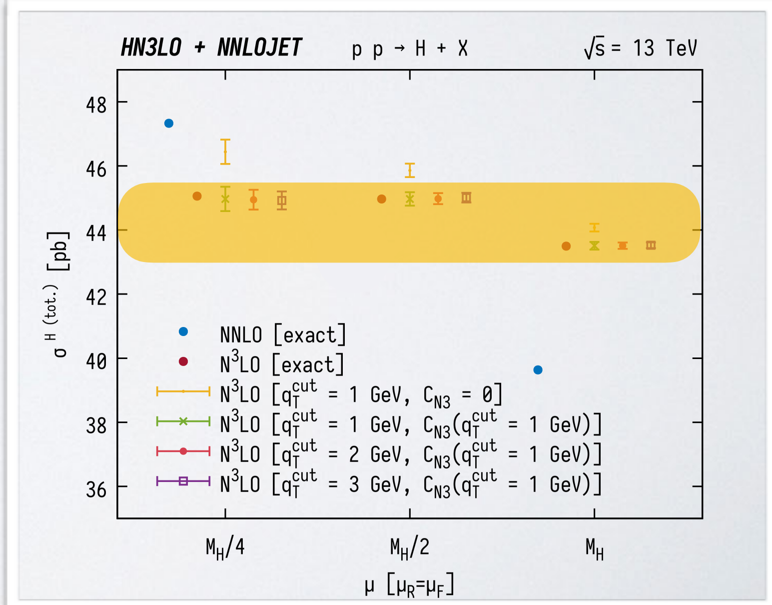
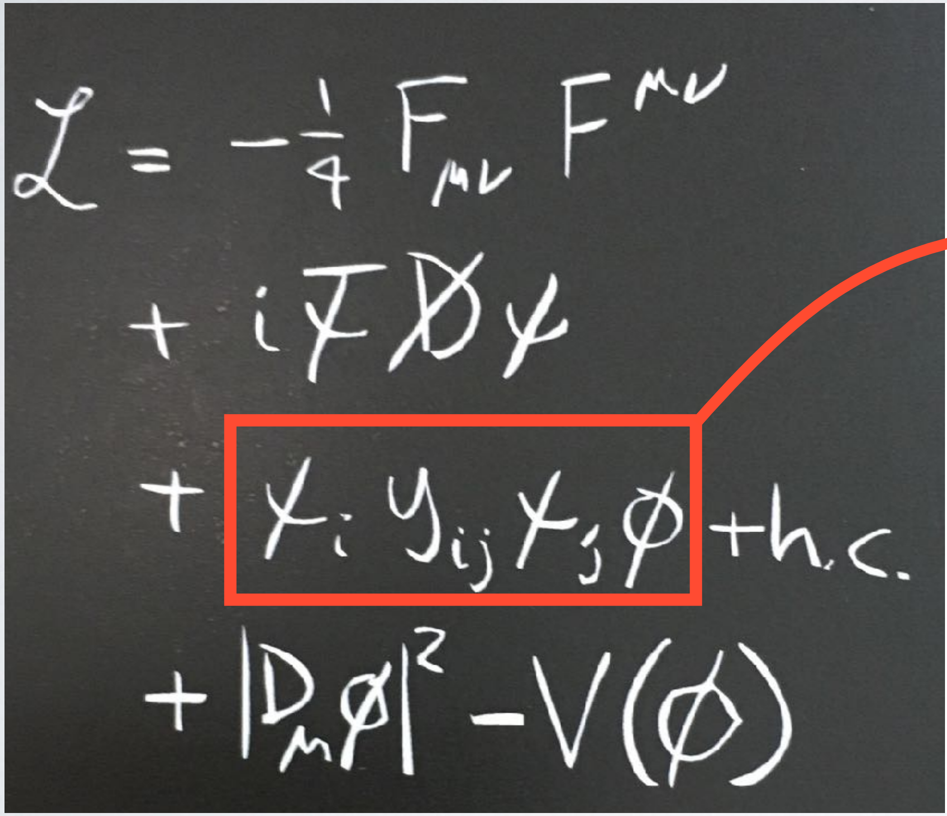


MOTIVATION

Why precision physics is important at the LHC?



Yukawa couplings

until 6 years ago this was essentially conjecture

no such term had ever been seen in nature

hadn't even been probed in electroweak precision tests

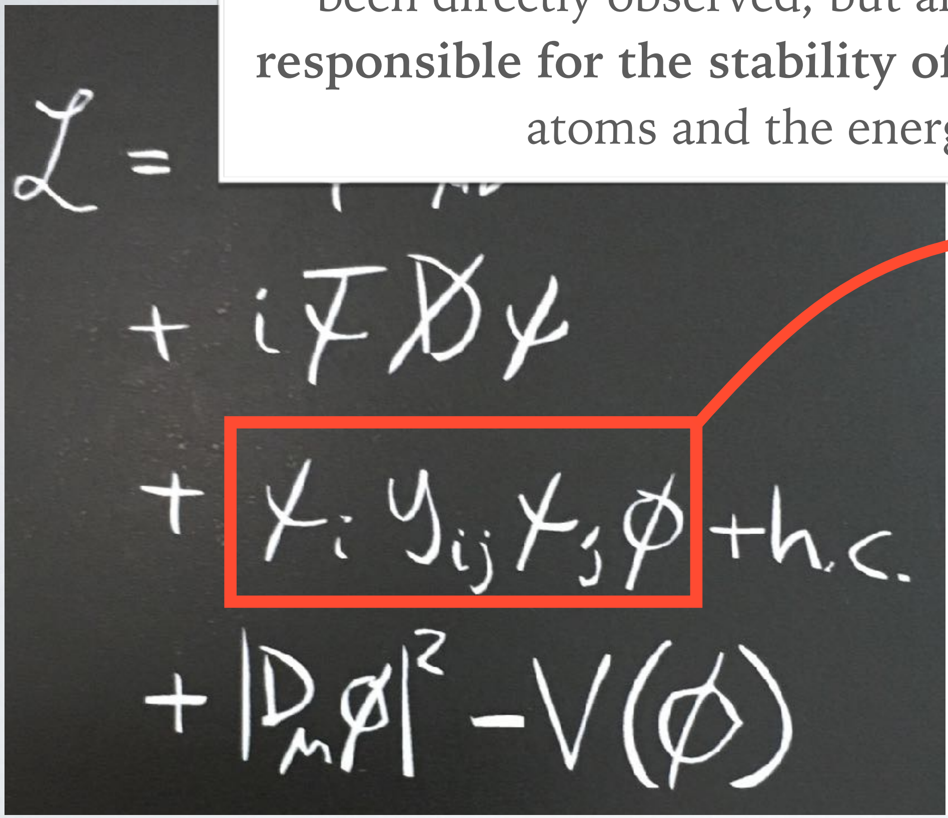
Gavin Salam's talk LHCP (2018)

- New interesting tasks are just recently initiated: Yukawas

MOTIVATION

Why precision physics is important at the LHC?

Yukawa interactions are important not merely because they had never before been directly observed, but also because they are **hypothesized to be responsible for the stability of hydrogen,** and for determining the size of atoms and the energy scales of chemical reactions.



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