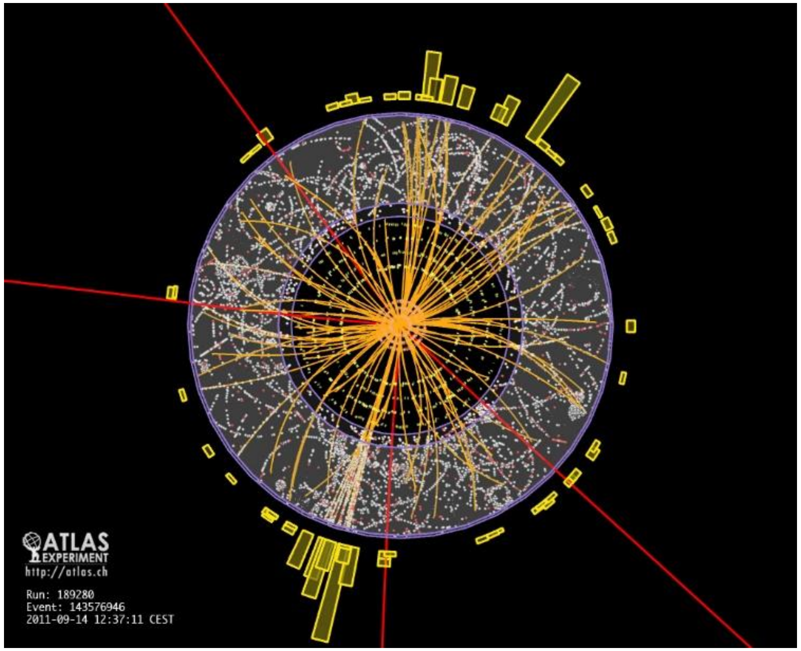
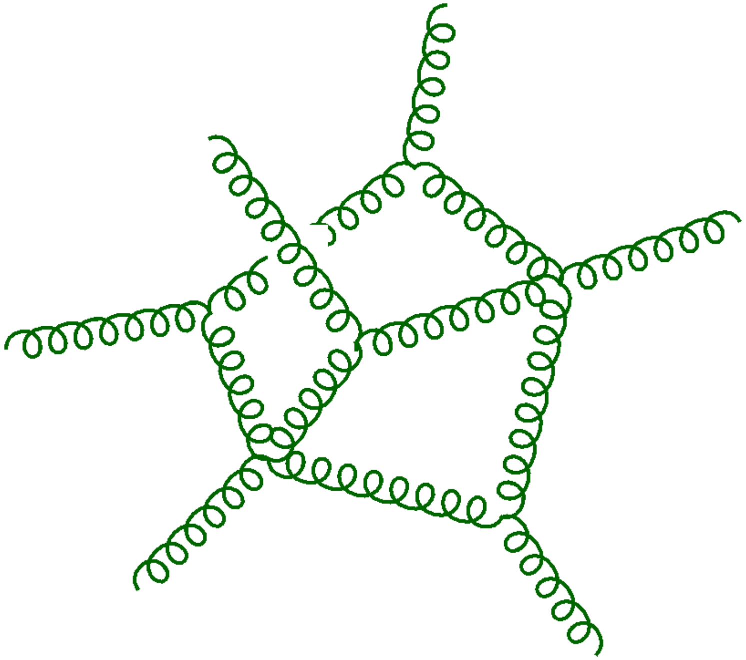
A Few Parting Thoughts



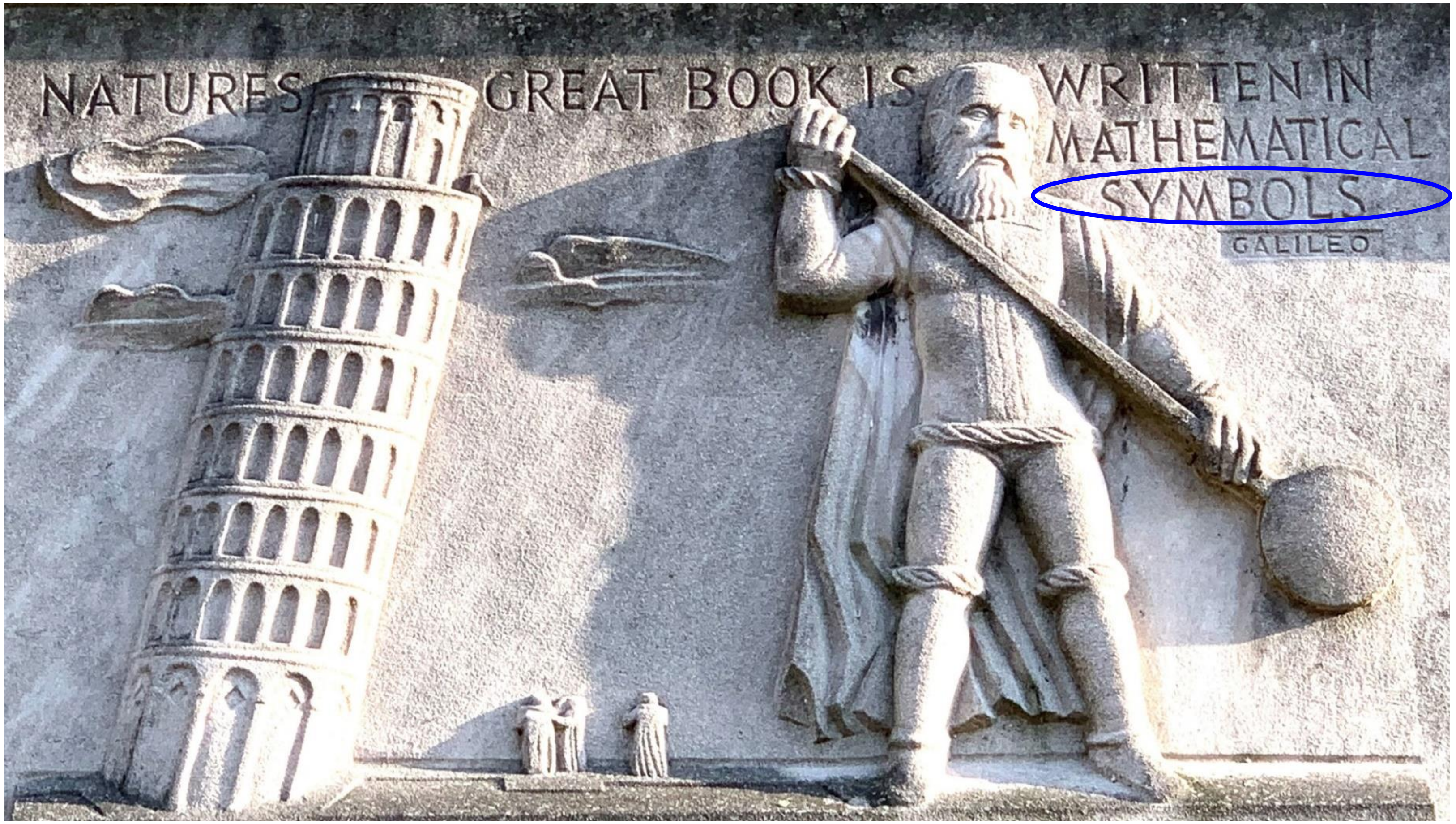


Lance Dixon
LoopFest, SLAC
June 28, 2023

Thank You!

- To all the speakers!
- To Glenna Paige, Faith Chow
- To Adi, Anthony, Shuo, Zhenjie
- To Bernhard Mistlberger

Entrance to Northwestern Physics Department

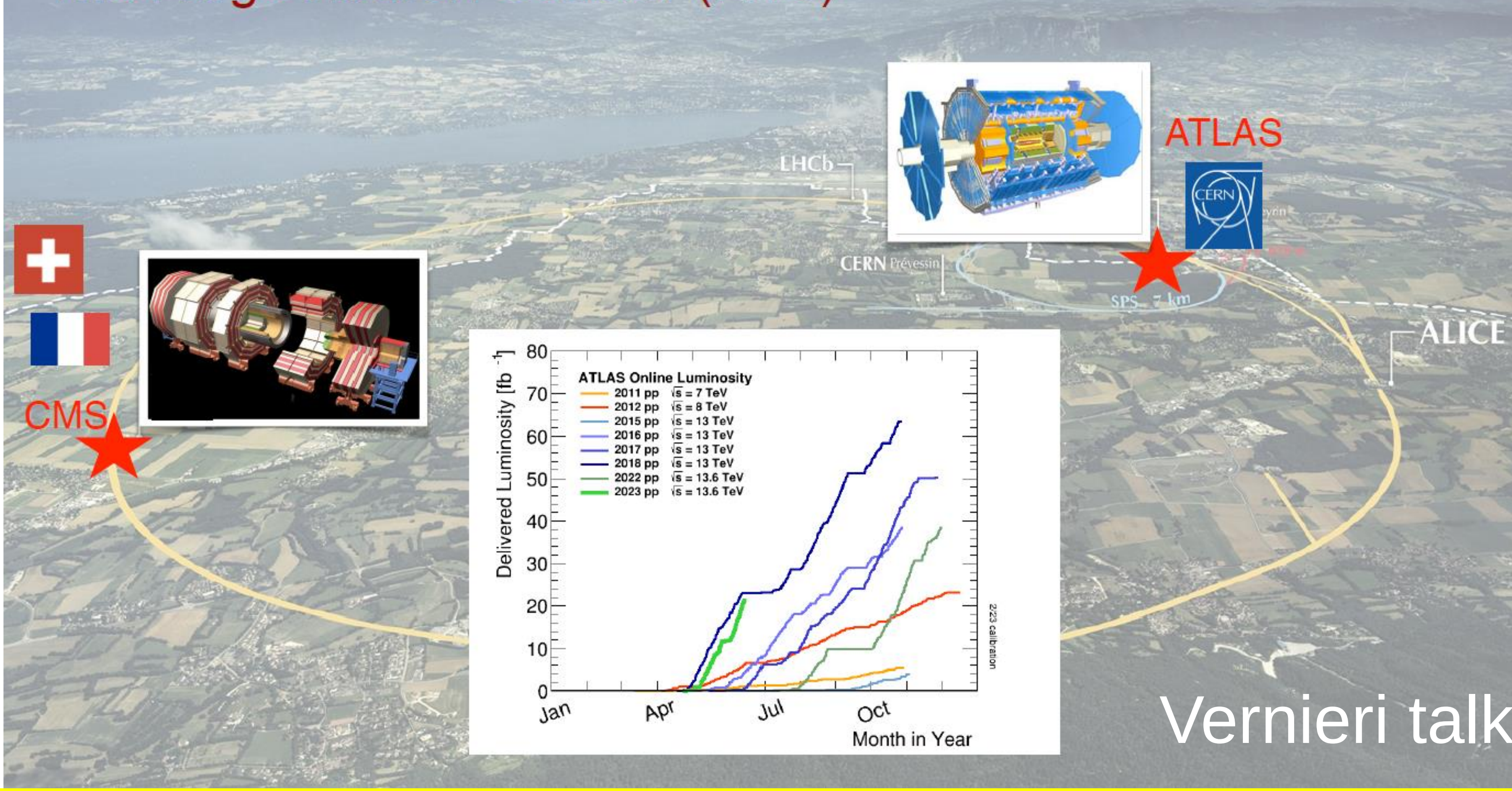


Longer Version

Philosophy [i.e. natural philosophy] is written in this grand book — I mean the Universe — which stands continually open to our gaze, but it cannot be understood unless one first learns to comprehend the language and interpret the characters in which it is written. It is written in the language of mathematics, and its characters are triangles, circles, and other geometrical figures, without which it is humanly impossible to understand a single word of it; without these, one is wandering around in a dark labyrinth.

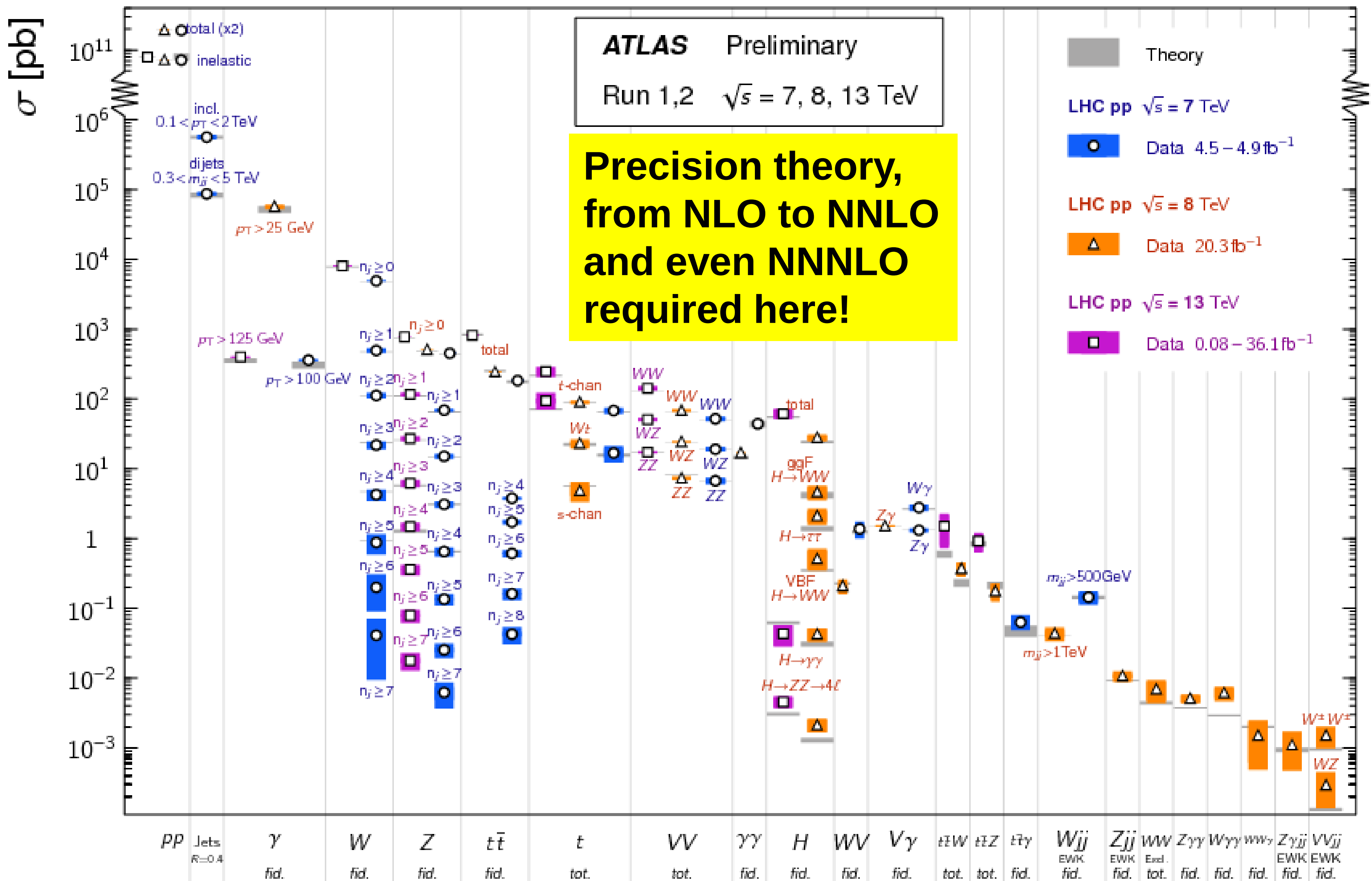
– G. Galilei, The Assayer

The Large Hadron Collider (LHC)



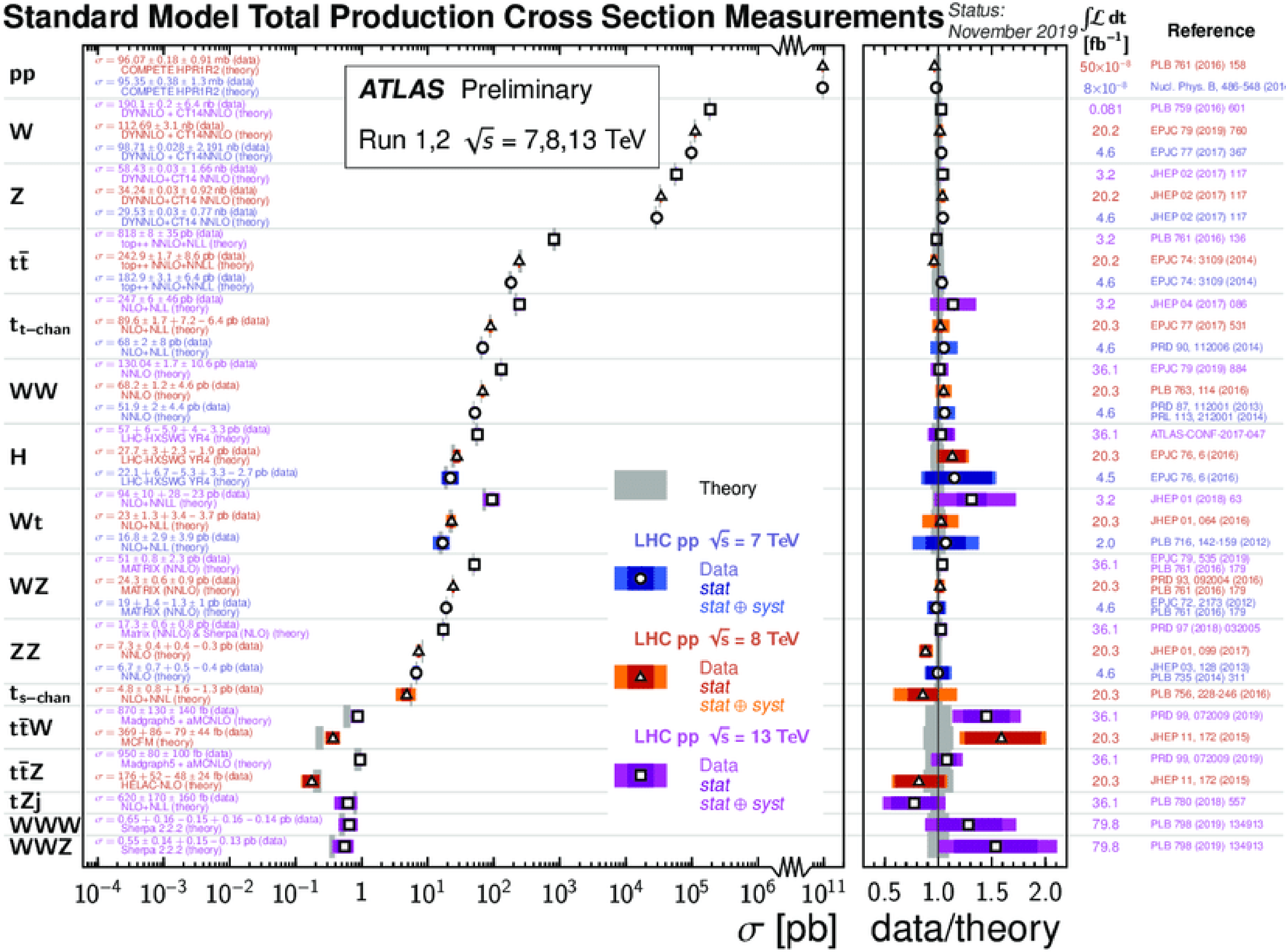
- **Our current labyrinth!**
- **The Energy Frontier for at least 20 years.**
- **Higgs discovered, now must study its properties (including its potential, via HH) and continue the search for new physics, largely by precision methods**

Standard Model Production Cross Section Measurements



Precision theory, from NLO to NNLO and even NNNLO required here!

Standard Model Total Production Cross Section Measurements



Short-Distance Cross Section in Perturbation Theory

$$\hat{\sigma}(\alpha_s) = {\alpha_s}^n [\, \hat{\sigma}^{(0)} + \alpha_s\, \hat{\sigma}^{(1)} + \alpha_s^2\, \hat{\sigma}^{(2)} + \alpha_s^3\, \hat{\sigma}^{(3)} + \cdots]$$

LO NLO NNLO NNNLO

- Leading-order (LO) predictions only qualitative

due to **poor convergence** of expansion in α_s

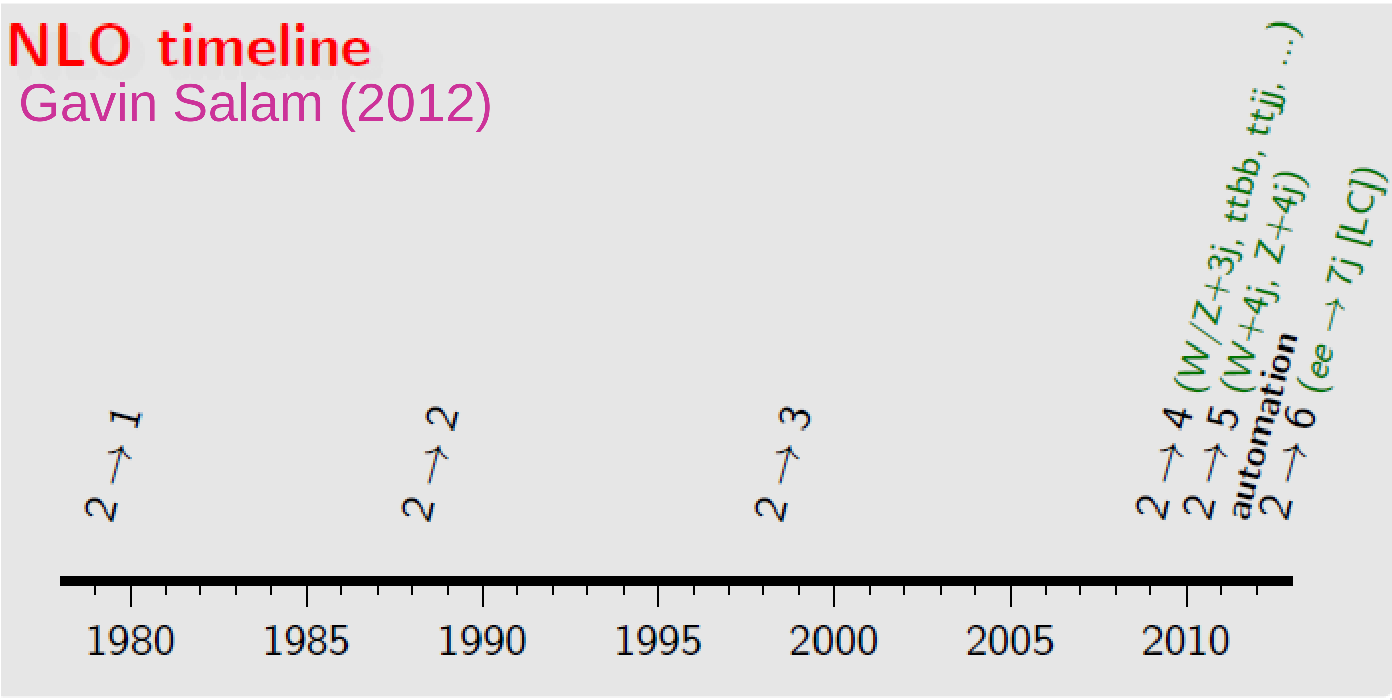
- Can easily get ~ 50-100% uncertainties in LO predictions

- Uncertainties brought under much better control with NLO corrections: ~ 15-20%

- NNLO ~ 3-8% uncertainties

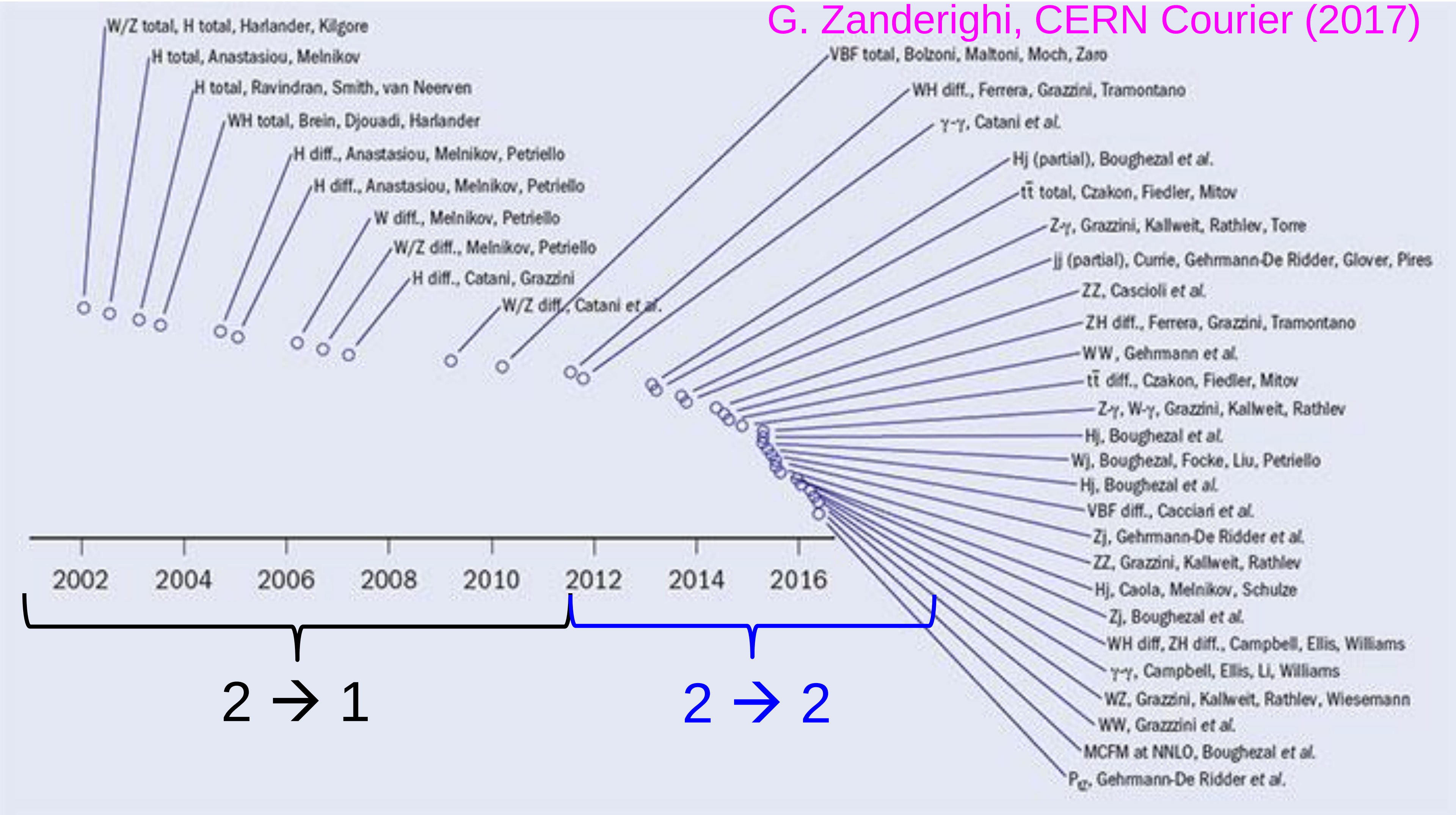
- N3LO, very few processes ~ 1-2% uncertainties

One revolution after another



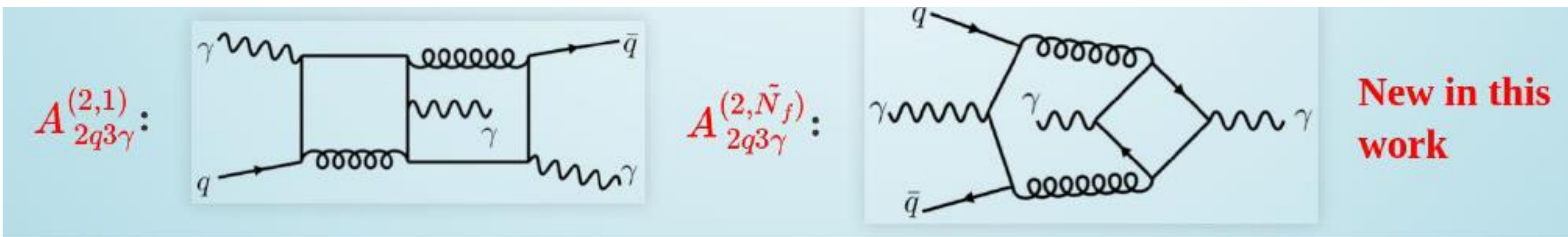
2010: NLO $W+4j$ [BlackHat+Sherpa: Berger et al] [unitarity]
2011: NLO $WWjj$ [Rocket: Melia et al] [unitarity]
2011: NLO $Z+4j$ [BlackHat+Sherpa: Ita et al] [unitarity]
2011: NLO $4j$ [BlackHat+Sherpa: Bern et al] [unitarity]
2011: first automation [MadNLO: Hirschi et al] [unitarity + feyn.diags]
2011: first automation [Helac NLO: Bevilacqua et al] [unitarity]
2011: first automation [GoSam: Cullen et al] [feyn.diags(+unitarity)]
2011: $e^+e^- \to 7j$ [Becker et al, leading colour] [numerical loops]

NNLO revolution (the beginning)

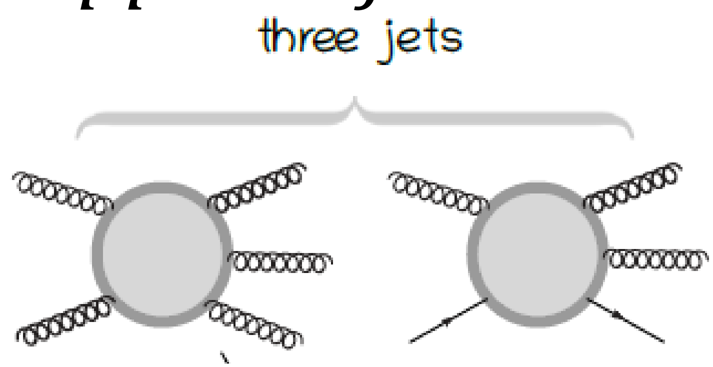


NNLO, 2→3 frontier now with full color or one mass

- DeLaurentis, $gg \rightarrow \gamma\gamma\gamma$, also

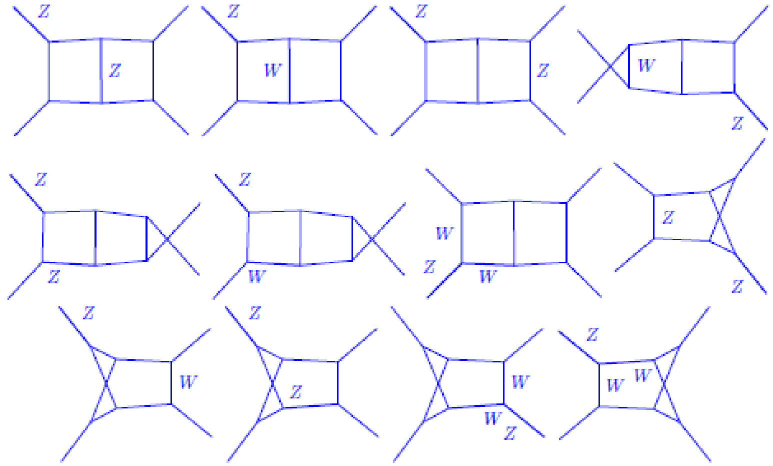


- Buccioni, for $pp \rightarrow 3\ jets$

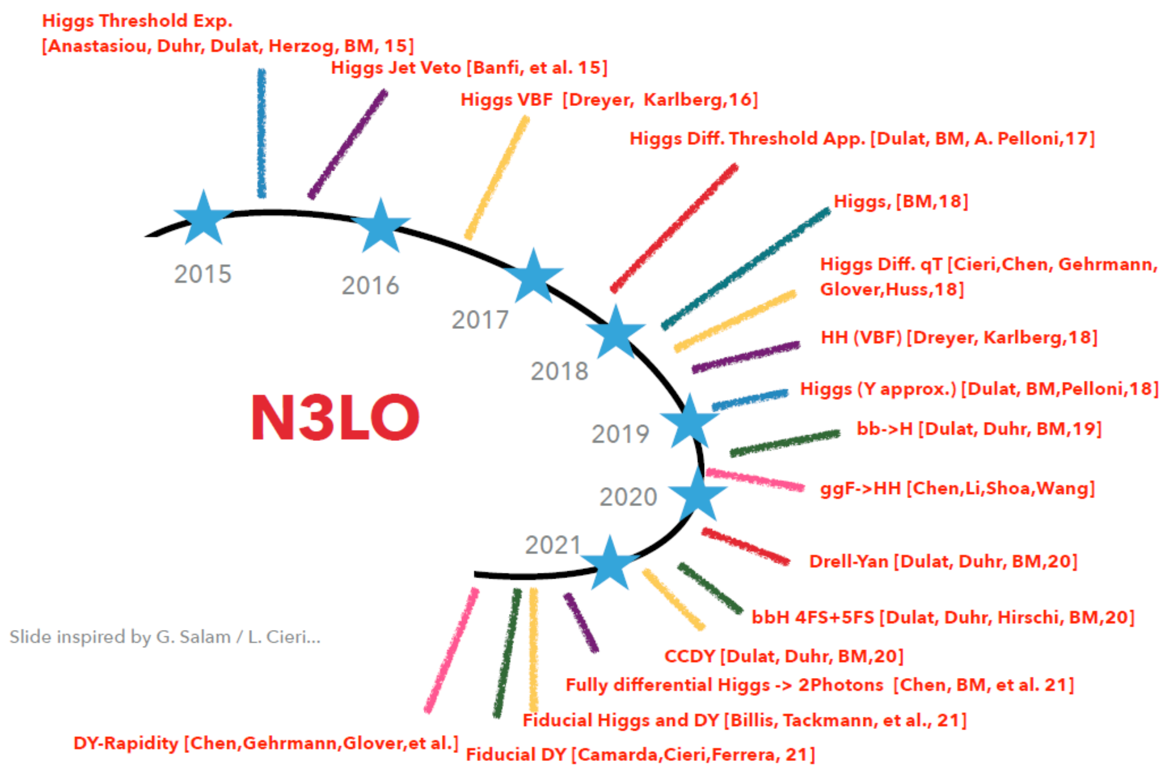


Also 2→2 EW or QCD+EW

- G. Fiore, $gg \to \gamma\gamma$
- Q. Song, $e^+e^- \to ZH$
- P. Bargiela, $q\bar{q} \to Zg$

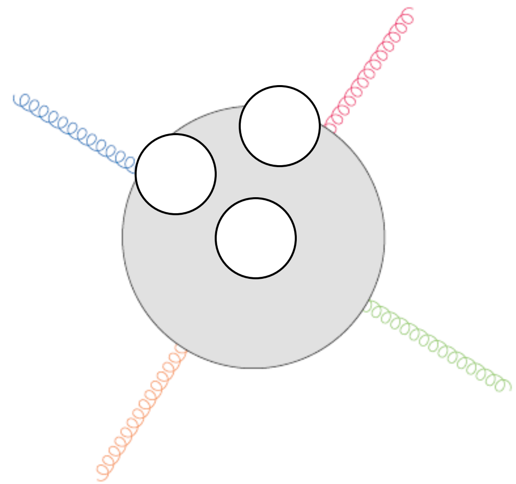


N3LO revolution too (circa 2021)!



- Work in progress to make N3LO more differential (i.e. implement actual experimental cuts)
- Enabling the next steps in the N3LO revolution

- Gambuti: 3 loop amplitudes for 2 → 2 partons [→ N3LO jets]



Feynman Rules

10^7 integrals

200 GB !!

Momentum Rerouting

10^6 integrals

30 GB

FinRed

IBPs

$$F_c^i = \sum_{masters}^{\sim 500} R_i \, M_i$$

1 GB

ε expansion

$$F_c^i = \sum \epsilon^{-n} \, r_i \, \mathbb{T}_i$$

Harmonic Polylogarithms

2 MB

- Now at 3 revolutions
- 2.5 more than in Russia recently…

The heart of many calculations:

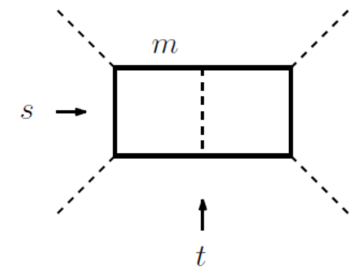
Evaluating Feynman integrals

- A classic problem, but also an active and expanding frontier.
  Applications in collider physics, gravitational waves, cosmology...
- Many methods available: Feynman parameter integration, Mellin Barnes representation, differential equations, difference equations, sector decomposition, Loop-tree duality and related representations, tropical geometry integration, bootstrap from symbols & boundary conditions, Yangian symmetry…
- Automated, widely applied ***numerical methods:*** sector decomposition [Binoth, Heinrich, '00], numerical series solution of differential equations, e.g. recent work of [Moriello, '19, Hidding, '20. Liu, Ma, '21. Hidding, Usovitsch, '22]
- Still challenging in practise. ***New explorations warranted***

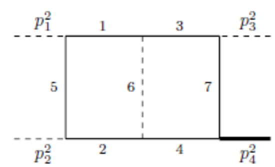
22 Feb 2023 Mao Zeng, University of Edinburgh 4

New integral methods

- Numerical via bounds with inequalities (M. Zeng)
- Analytic via Feynman Integral Bootstrap (H. Hannesdottir)



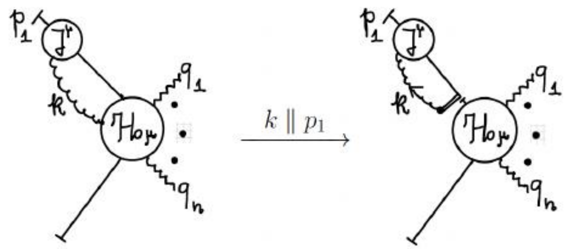
- Generalizing "canonical form" of differential equations beyond multiple polylogs using unipotency (L. Tancredi)



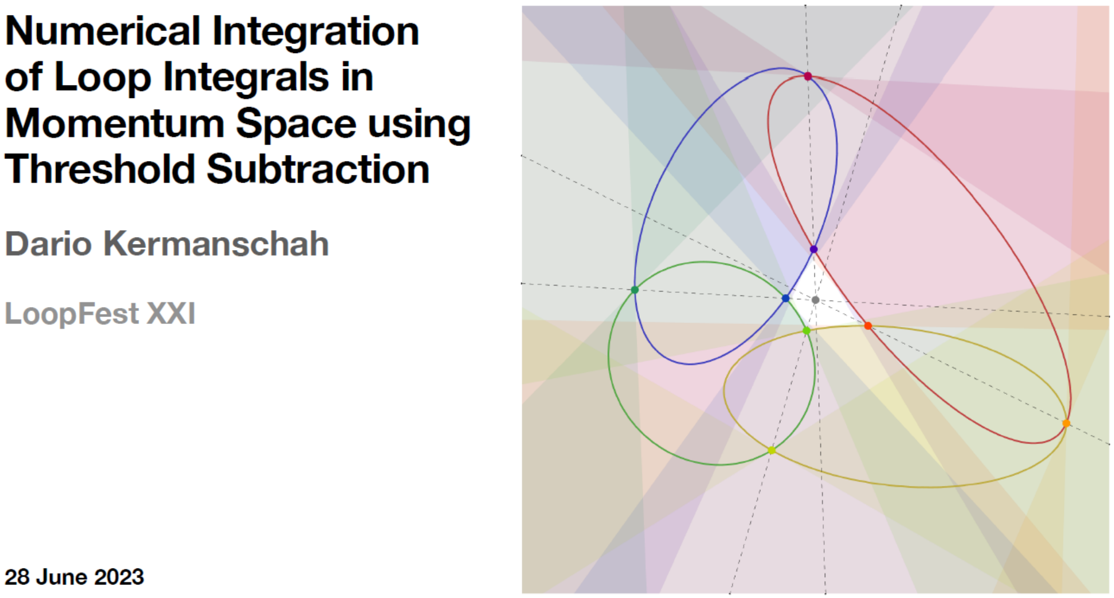
- Power series for NNLO $(m_t)\,\gamma\gamma$ (F. Coro)
- Dispersive approaches to 2-loop EW (Q. Song)

Sterman, local IR subtractions

- Things get a little complicated when we try to see how a "single-collinear" gluon separates from the hard subdiagram at the *integrand* level,



- Compared to one loop, we encounter two qualitative complications, associated with an extra loop, either in the jet or hard part:

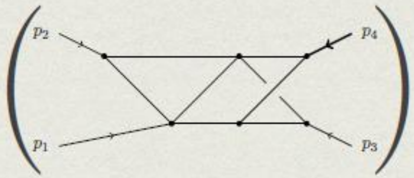


New letters in the alphabet

[Henn, Lim, WJT (2023)]

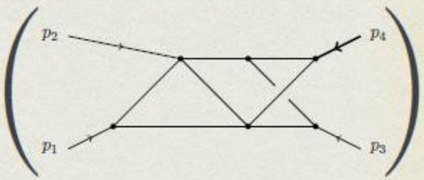
$$\vec{\alpha} = \{\alpha_0, \ldots, \alpha_8\} = \left\{p_4^2, s, t, -p_4^2+s+t, -p_4^2+s, -p_4^2+t, s+t, -\left(p_4^2-s\right)^2+p_4^2 t, s^2-p_4^2(s-t)\right\}.$$

$\epsilon^6\left(\left(p_4^2-s\right)^2-p_4^2 t\right)$



⟷

$\epsilon^6\left(\left(p_4^2-s\right)^2-p_4^2 u\right)$



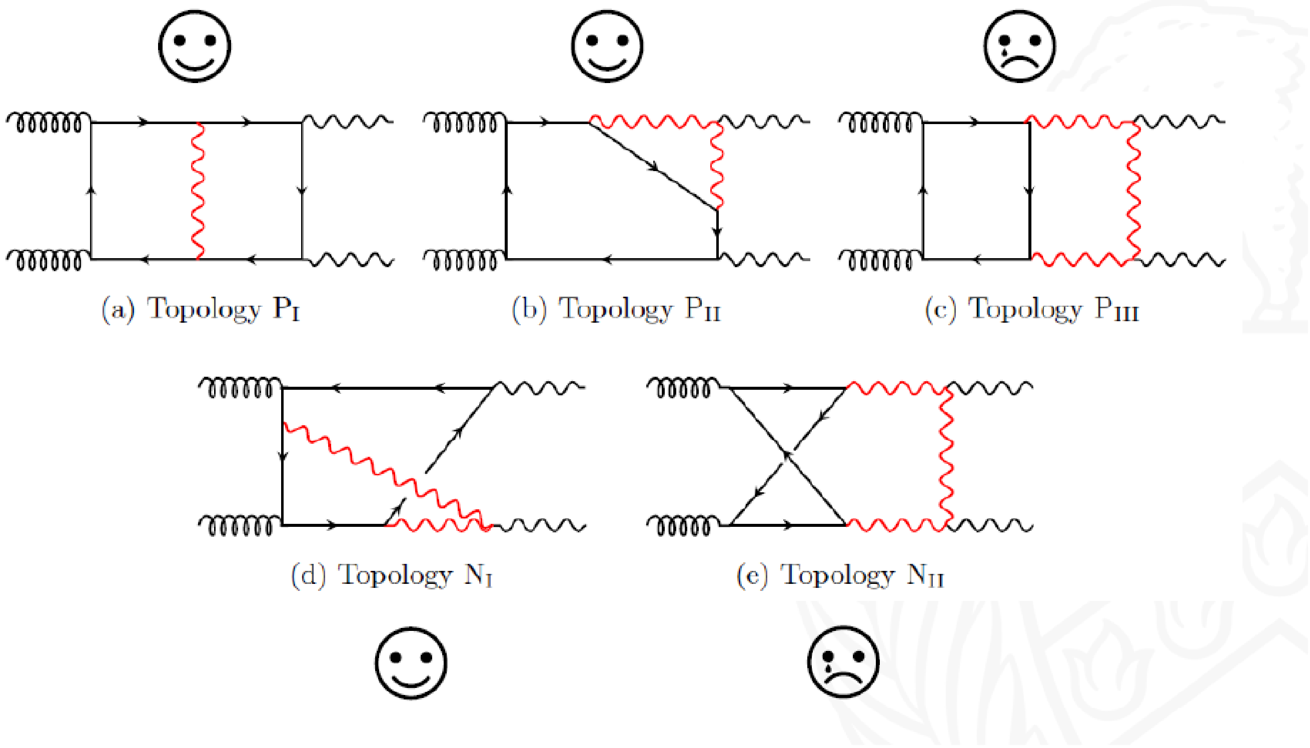
$p_1 \leftrightarrow p_2$ symmetry

Start appearing at weight 4

$$\mathcal{S}\left(f_{B1}^{41}\right)\Big|_{\epsilon^4} = 6\left[\alpha_1 \otimes \alpha_1 \otimes \frac{\alpha_2}{\alpha_4} \otimes \alpha_7 - \alpha_1 \otimes \alpha_1 \otimes \alpha_4 \otimes \alpha_7 + \alpha_1 \otimes \frac{\alpha_4}{\alpha_2} \otimes \frac{\alpha_3}{\alpha_1\alpha_4} \otimes \alpha_7 \right.$$
$$\left. + \alpha_2 \otimes \alpha_1 \otimes \frac{\alpha_1\alpha_4}{\alpha_3} \otimes \alpha_7 + \alpha_2 \otimes \alpha_5 \otimes \frac{\alpha_3}{\alpha_1} - \frac{1}{2}\alpha_2 \otimes \alpha_5 \otimes \alpha_2 \otimes \alpha_7 + \ldots\right]$$

William J. Torres Bobadilla 13

- G. Fiore, integrals for electroweak corrections to $gg \to \gamma\gamma$

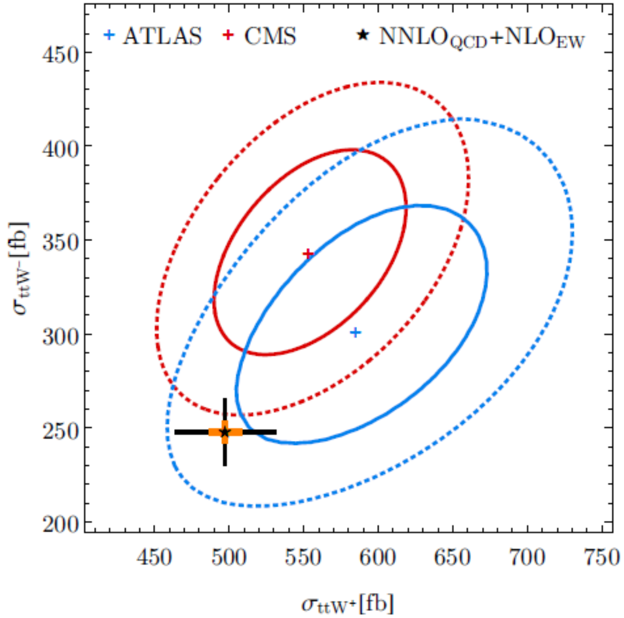


Savoini: approximate triple heavy NNLO using soft or small mass limits

$t\bar{t}W$

Results

setup: NNLO NNPDF31 luxqed, $\sqrt{s} = 13\,TeV$, $m_W = 80.385GeV$, $m_t = 173.2GeV$, $\mu_R = \mu_F = (2m_t + m_W)/2$

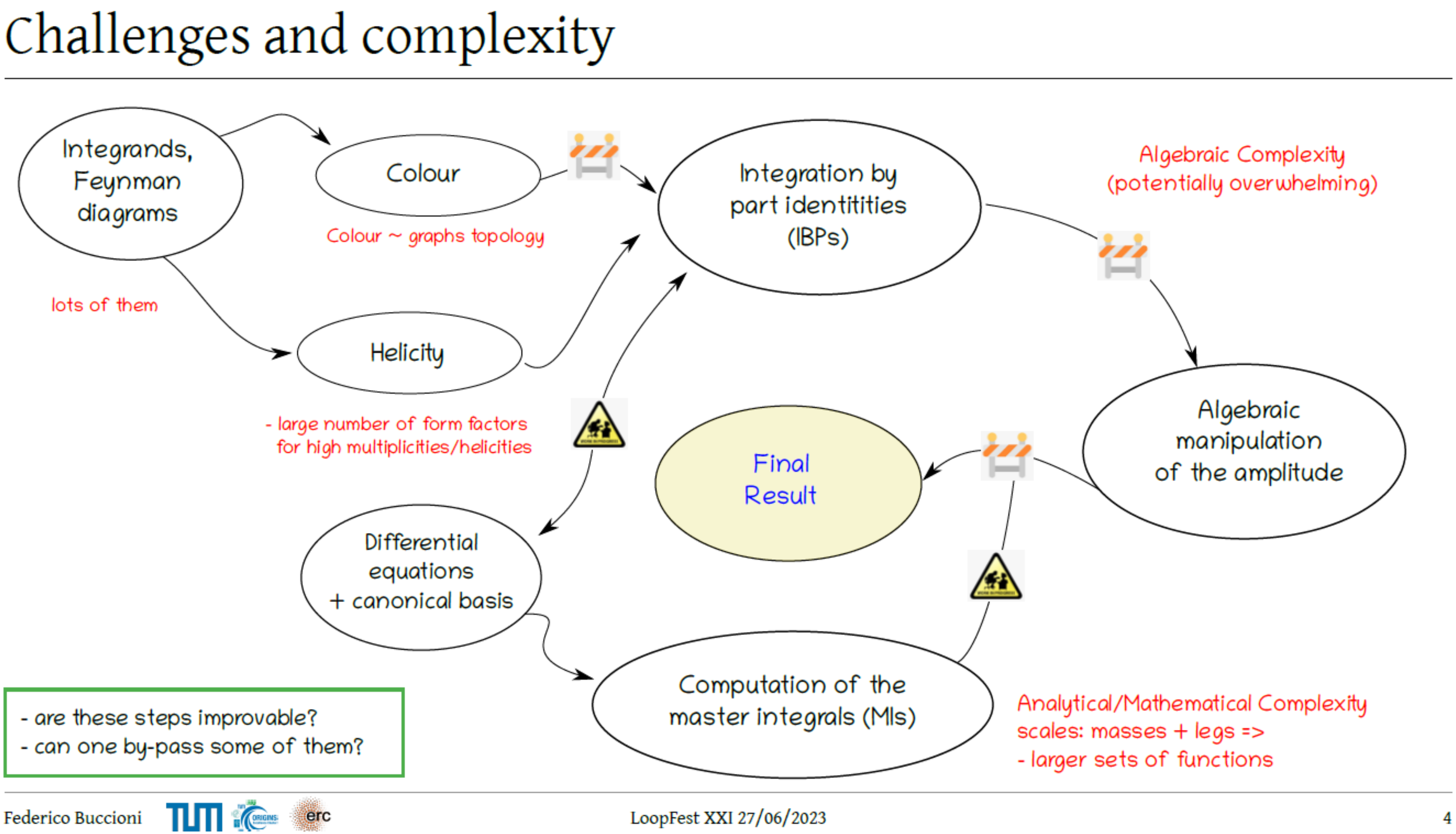


[ATLAS-CONF-2023-019]
[CMS: arXiv 2208.06485]

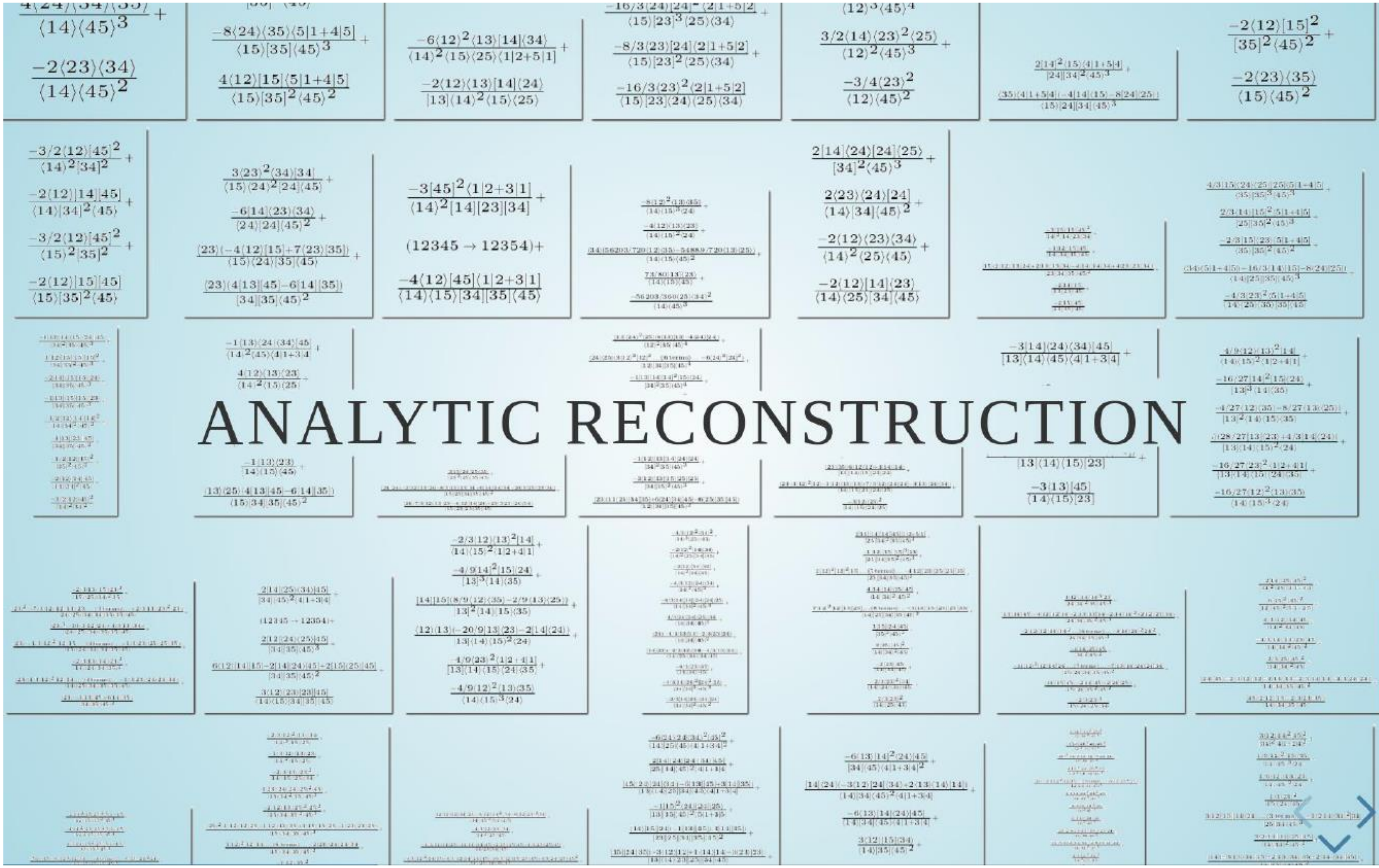
- comparison against the most recent ATLAS and CMS data:
  - the **agreement is at the** 1σ **and** 2σ **level** respectively
  - reduction of the perturbative scale uncertainties
  - systematic uncertainties due the two-loop approximation are under control and much smaller than the scale uncertainties

take-home message:
two completely different approximations lead to compatible results for the missing two-loop virtual contribution!!

Computational workflow and bottlenecks



DeLaurentis, 2-loop $\gamma\gamma\gamma$



Simplification strategy

1. Script to split up the expressions, and compile them ($\sim$ 20GB of C++) for evaluation over $\mathbb{F}_p$;

2. Recombine the 3 projections $p_V \parallel p_1, p_V \parallel p_2, p_V \parallel p_3$ and reintroduce the little group factors to build 6-point spinor-helicity amplitudes (subject to degree bounds on $|5\rangle, [5|, |6\rangle, [6|$);

3. Perform partial fraction decompositions* based on expected structures and fit the Ansatze.

Comparison of $q\bar{q} \to \gamma\gamma\gamma$ (in full color) to $pp \to Wjj$ (at leading color):

Kinematics	**# Poles (W)**	**LCD Ansatz**	**Partial-Fraction Ansatz**	**Rational Functions**
5-point massless	30	29k	4k	$\sim$300 KB
5-point 1-mass	>200	>5M	$\sim$40k	$\sim$25 MB

$$\{W_j\} = \bigcup_{\sigma \in \mathrm{Aut}(R_6)} \sigma \circ \{\langle 12\rangle, \langle 1|2+3|1], \langle 1|2+3|4], \Delta_{12|34|56}, \langle 3|2|5+6|4|3] - \langle 2|1|5+6|4|2]\}$$

- H. Chawdry: Bypass some intermediate steps with p-adic numbers

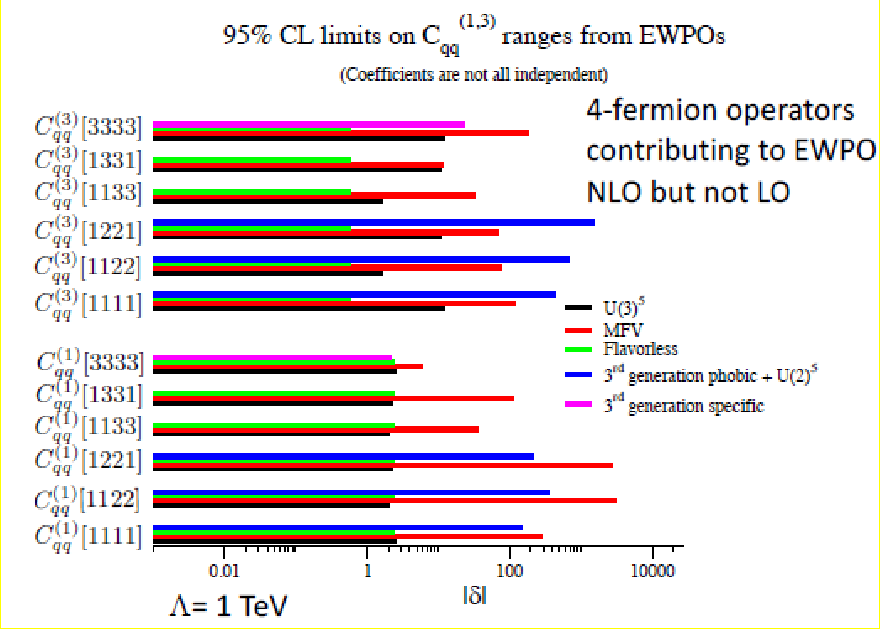
Precision beyond standard model – current focus SMEFT

Flavor matters

S. Dawson, SMEFT with flavor

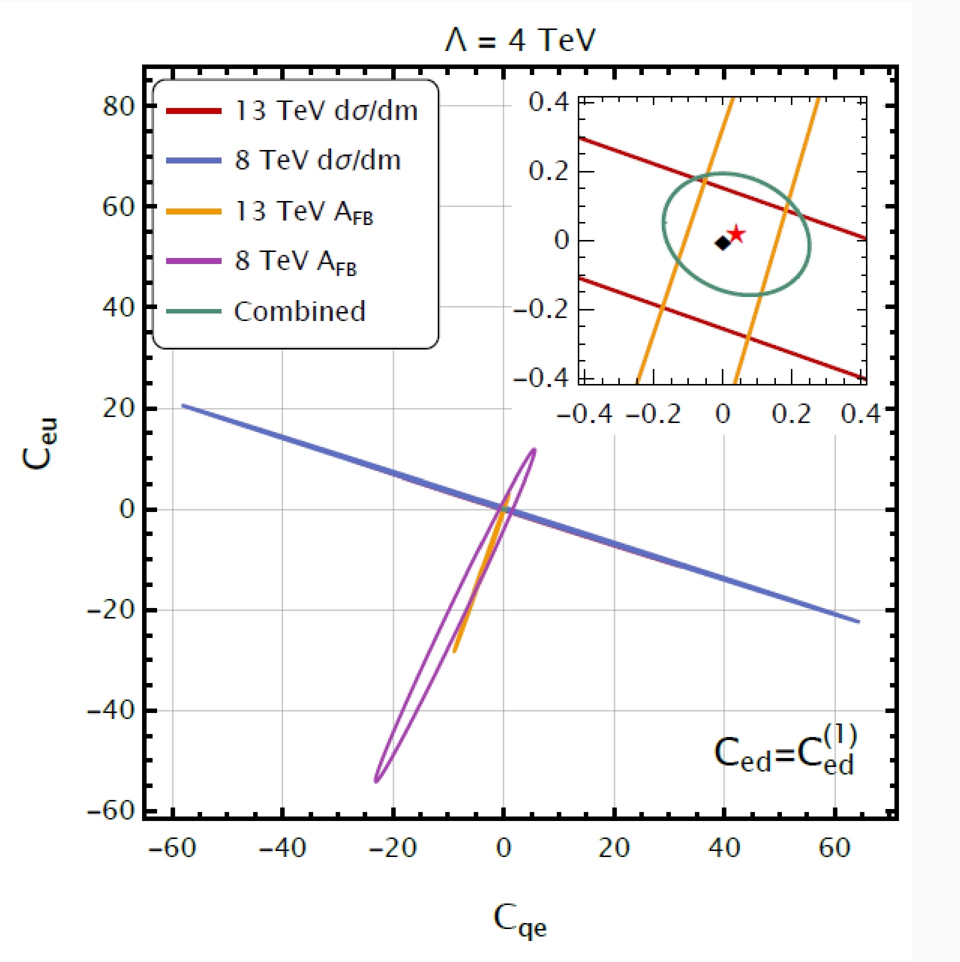
Flavorless assumption yields more stringent bounds than flavor scenarios

Can also limit these coefficients with fits to LHC dijets. More stringent limits for gens 1 and 2 from dijets (tree level process) [Bruggisser, Westhoff: 2212.02532]



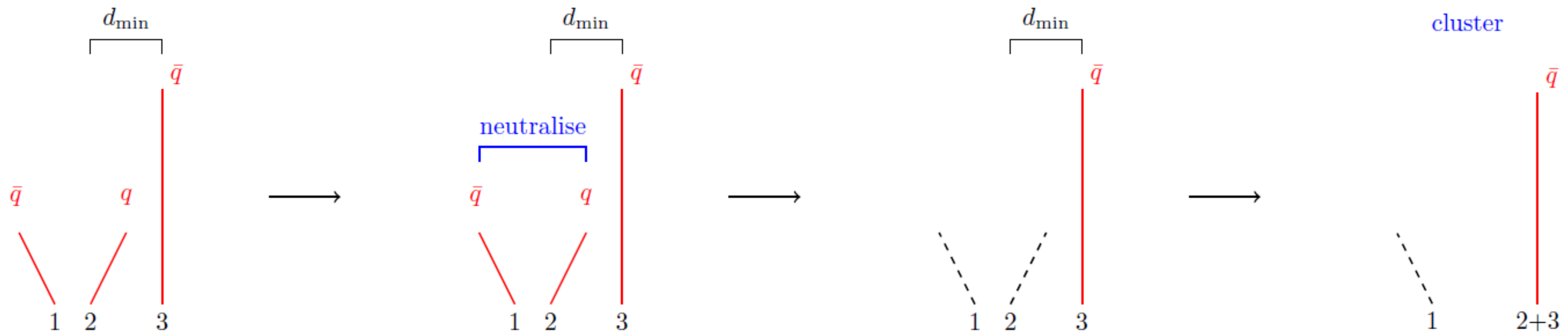
$U(3)^5$ results more constrained than MFV

Y. Huang
Using DY AFB to Lift SMEFT Flat Directions



Caola: Precision Flavored Jets

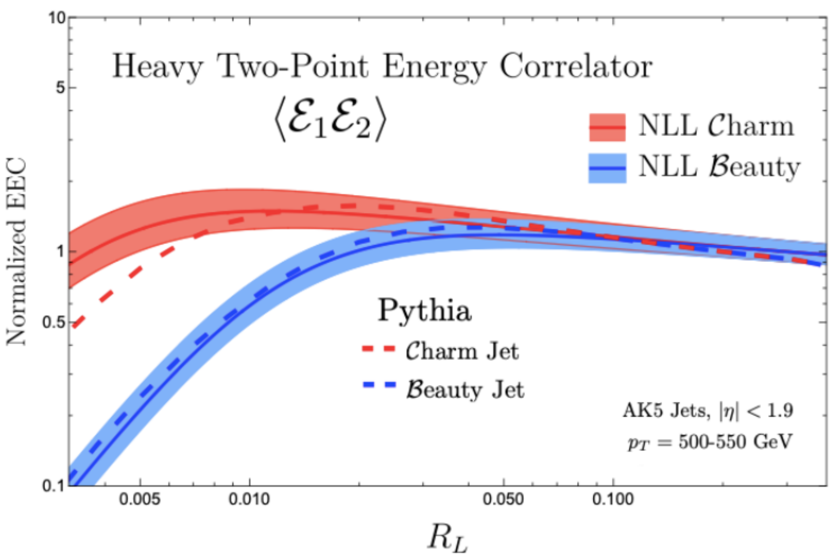
Integrated Flavour Neutralisation (IFN): a cartoon



Flavoured jets with anti-k_t/CA kinematics

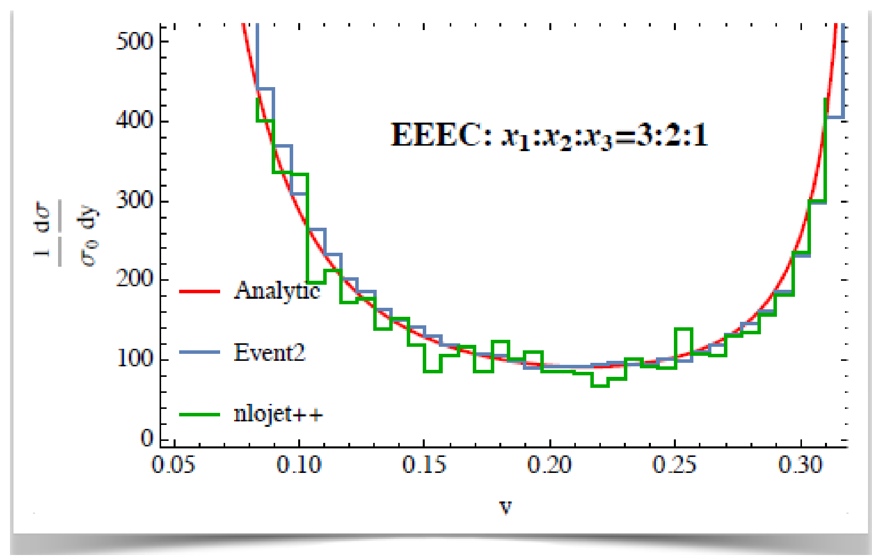
B. Mecaj and X. Zhang: Precision Energy Flow in [Flavored] Jets

B. Mecaj



[Craft, Lee, BM, Moult]

X. Zhang

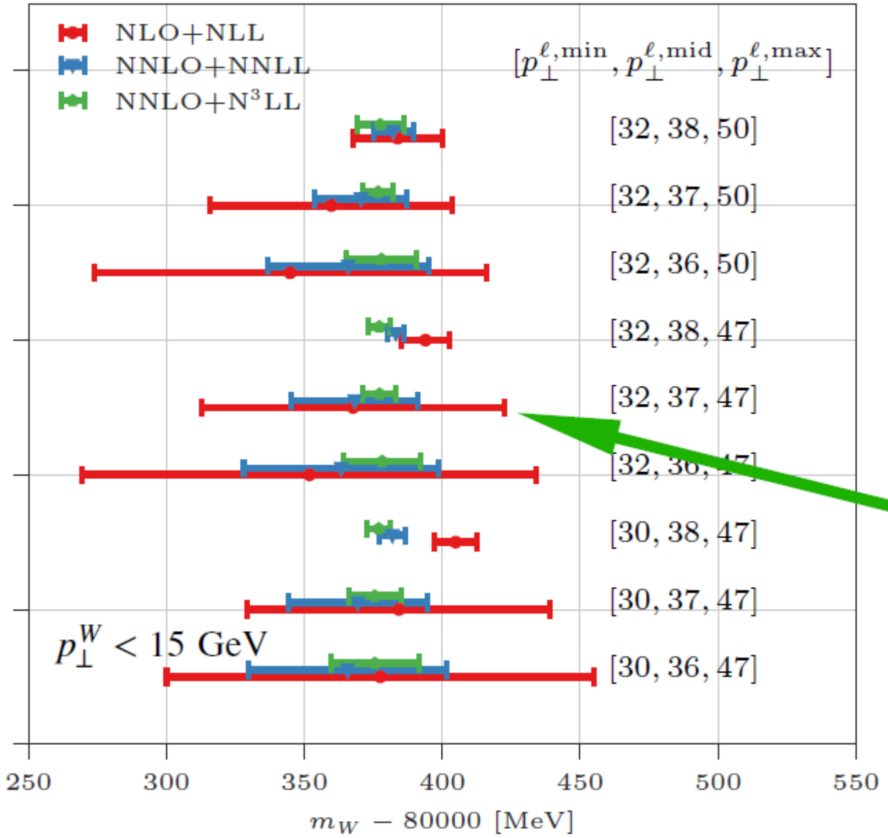


Vicini: Can get small pQCD uncertainty for MW via bin asymmetry

m_W determination at the LHC as a function of the $\mathscr{A}_{p_\perp^\ell}$ parameters (low pile-up setup)

as pseudo-experimental value we choose the NNLO+N3LL result with $m_W = 80.379$

L.Rottoli, P.Torrielli, AV; arXiv:2301.04059



Important role of the N3LL corrections

We first check the convergence order-by-order.
If we observe it, then we take the size of the m_W interval as estimator of the residual pQCD uncertainty

We do not trust the scale variations alone
→ cfr the choice with $p_\perp^{\ell,mid} = 38$ GeV

A pQCD uncertainty at the ± 5 MeV level is achievable based on CCDY data alone

The choice of the midpoint is important to identify two regions with excellent QCD convergence

Devoto: Higgs interference in $gg \to \mathrm{H} \to \gamma\gamma$ now @ NNLO

Results

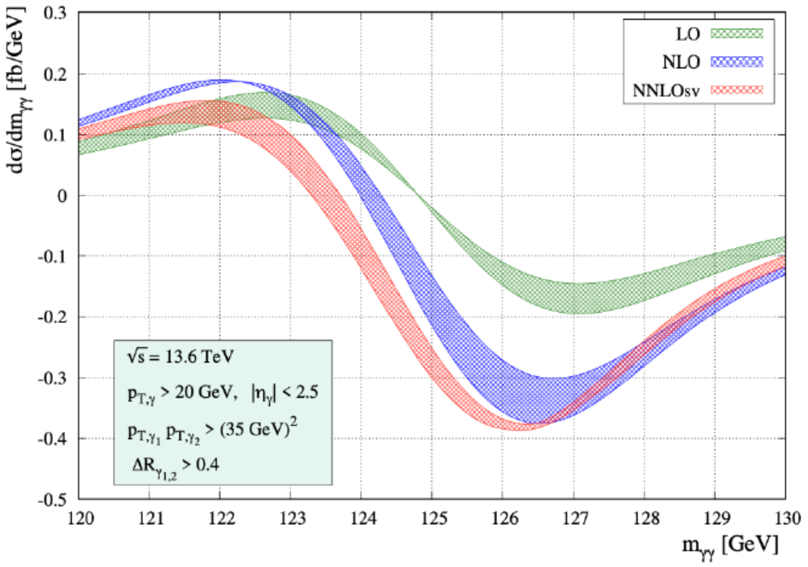


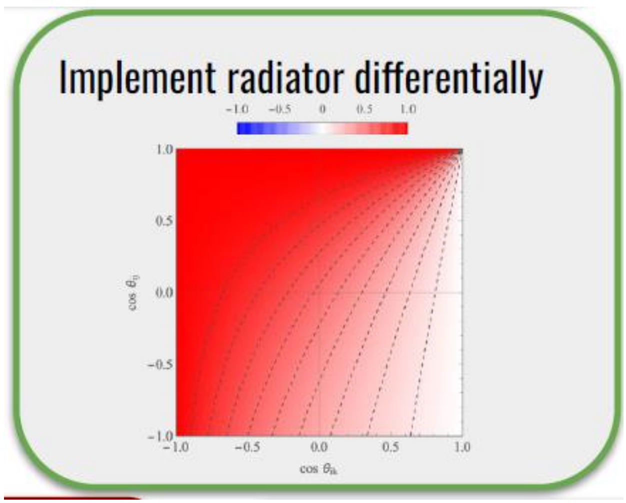
Fig. 4 Signal-background interference contribution to the diphoton invariant mass distribution after Gaussian smearing. Bands represent the envelope given by the scale variation.

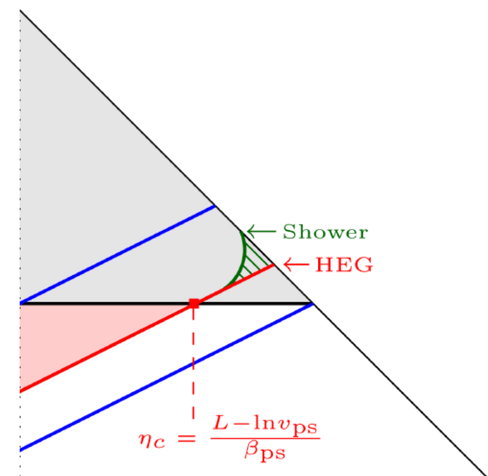
- NNLO correction not captured by the NLO scale variation bands…
- …but starting to converge
- Recall this is the sum of real and imaginary part of the interference
- Real part dictates the shape, imaginary part responsible for shift to the left

Federica Devoto LoopFest XXI, 27/06/2023 18

Parton showers

- No loops (Herren), or ∞ loops (Karlberg)??
- NLL and NNDL shower accuracy

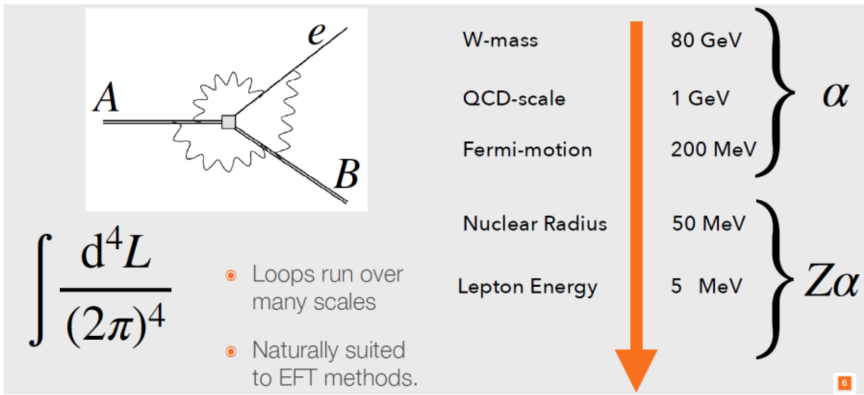




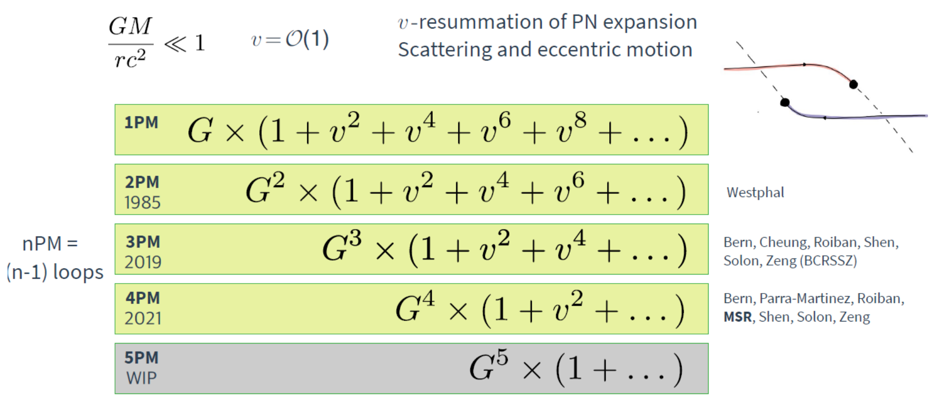
- "NLO showers" in future via interpolating gauges? (Soper)

Non-LHC applications

- From β decay (R. Plestid)

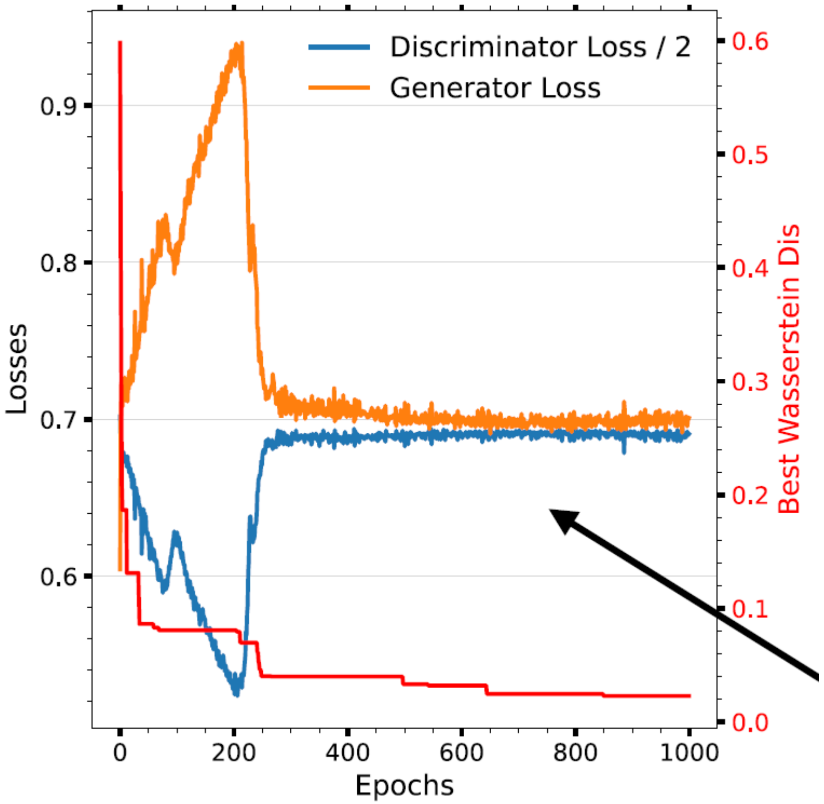


- to gravitational waves (M. Ruf)



B. Nachman:
ML for particle simulations

E.g. GANs learning hadronization



ML for conference summaries

ChatJesseT

Type your question below.

Ask

Question: *how should I summarize LoopFest 2023*

Ah, LoopFest 2023, a gathering of the finest minds in the world of theoretical physics! As Jesse Thaler, a theoretical physicist and Director of the NSF AI Institute for Artificial Intelligence and Fundamental Interactions (IAIFI), I must say that LoopFest is like a symphony of ideas, where physicists come together to harmonize their knowledge and explore the intricacies of quantum field theory. To summarize LoopFest 2023, imagine a cosmic dance of particles, where Feynman diagrams twirl and whirl, creating a mesmerizing spectacle of mathematical elegance. Physicists from around the globe gather to discuss the latest advancements in loop calculations, renormalization, and the ever-elusive quest for a unified theory. From the opening plenary session, where luminaries in the field share their groundbreaking research, to the parallel sessions where young and seasoned physicists alike present their work, LoopFest is a celebration of intellectual curiosity and collaboration. Throughout the conference, attendees engage in lively discussions, debating the merits of different approaches and exchanging insights that push the boundaries of our understanding. The coffee breaks become impromptu brainstorming sessions, where ideas percolate and collaborations are born. But LoopFest is not just about the science. It's also about the connections forged between physicists, the bonds that transcend borders and institutions. The late-night conversations over a pint of ale, the shared excitement of a breakthrough, and the camaraderie that comes from being part of a community

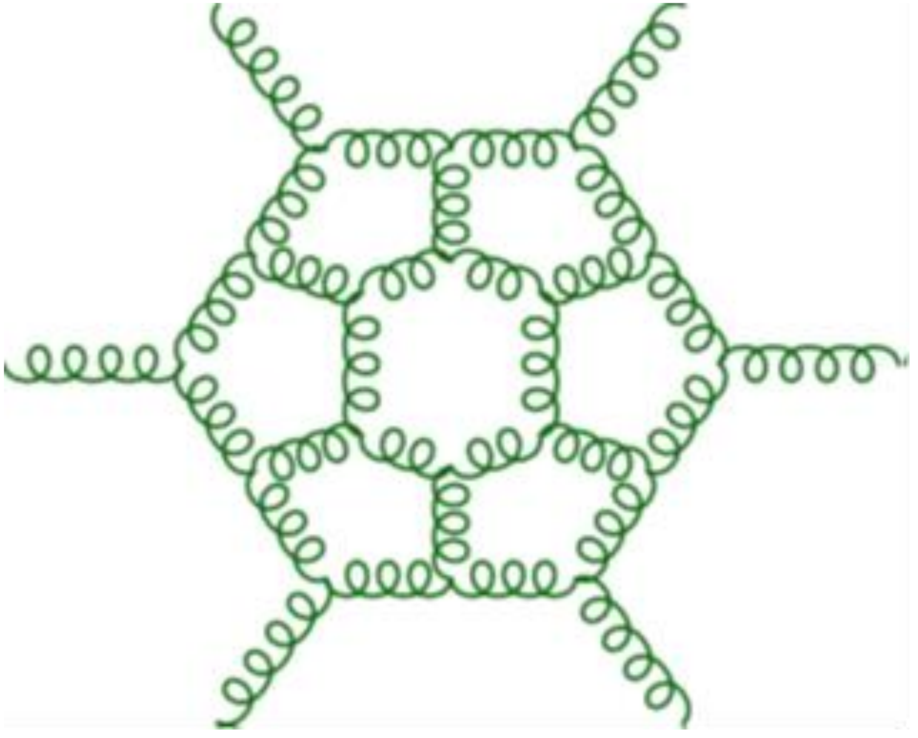
Those who explore an unknown world are travelers without a map: the map is the result of the exploration. The position of their destination is not known to them, and the direct path that leads to it is not yet made.

- Hideki Yukawa

LoopFest XXII

May 2024, SMU, Dallas, Texas, USA

Thank you for coming to [Multi]LoopFest!



And safe travels back, or onwards in California!!!