

MARIA UBIALI
UNIVERSITY OF CAMBRIDGE

STATUS OF QCD

1966 - 2026: 60 YEARS OF RENCONTRES DE MORIOND

16-17 JANUARY 2026, PARIS

PBSP

European Research Council
Established by the European Commission

MORIOND QCD (1966 – 2026): HOW QCD BECAME REAL











QCD just passed its 50th year. For a fundamental theory, it's still young (Newtonian gravity is still going strong at 338.)

It is itself an astounding discovery, with its mysterious unbroken color symmetry.

More than that — QCD makes it possible for us to face the challenge of bridging "fundamental" and the "emergent" in the natural world.

G. Sterman's opening talk at QCD@LHC25

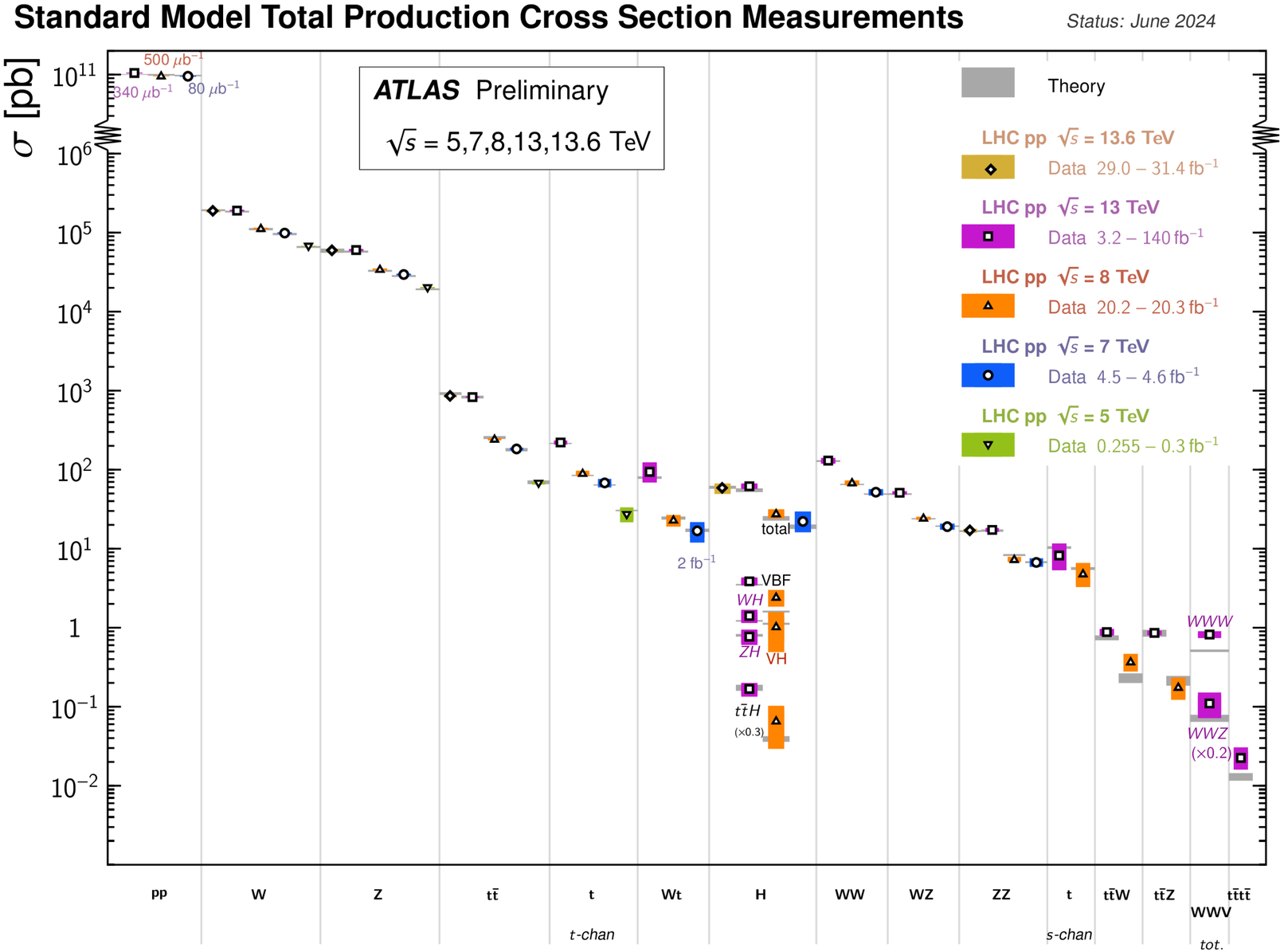
Moriond QCD didn't just report QCD, it was the privileged place of exchange between theorists and experimentalists that shaped how we understand QCD

From Moriond website and ATLAS website and from experimental summary talk 2025 by L. Shchutzska

A NEW PRECISION ERA

- Thanks to advances in experiments and theory, impressive range of precise cross section measurements matched by precise and increasingly accurate theory calculations

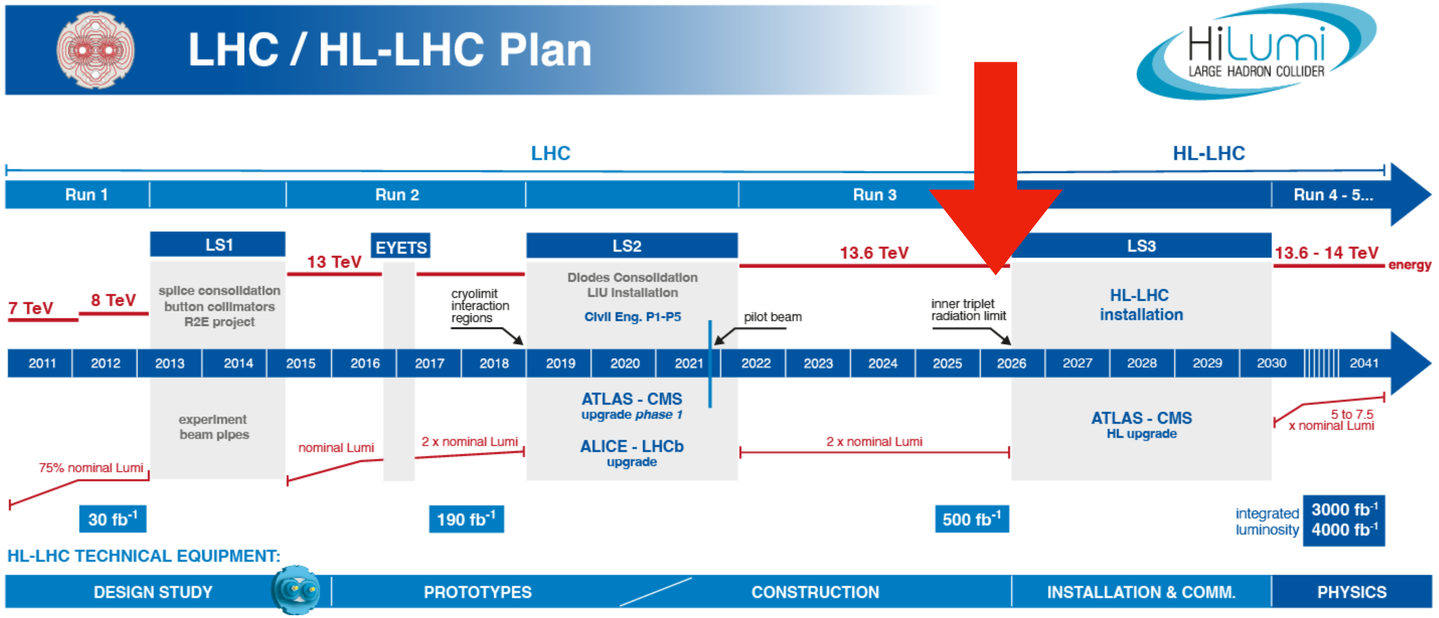
- Overall stunning agreement between data and SM predictions although we know that SM is necessarily incomplete

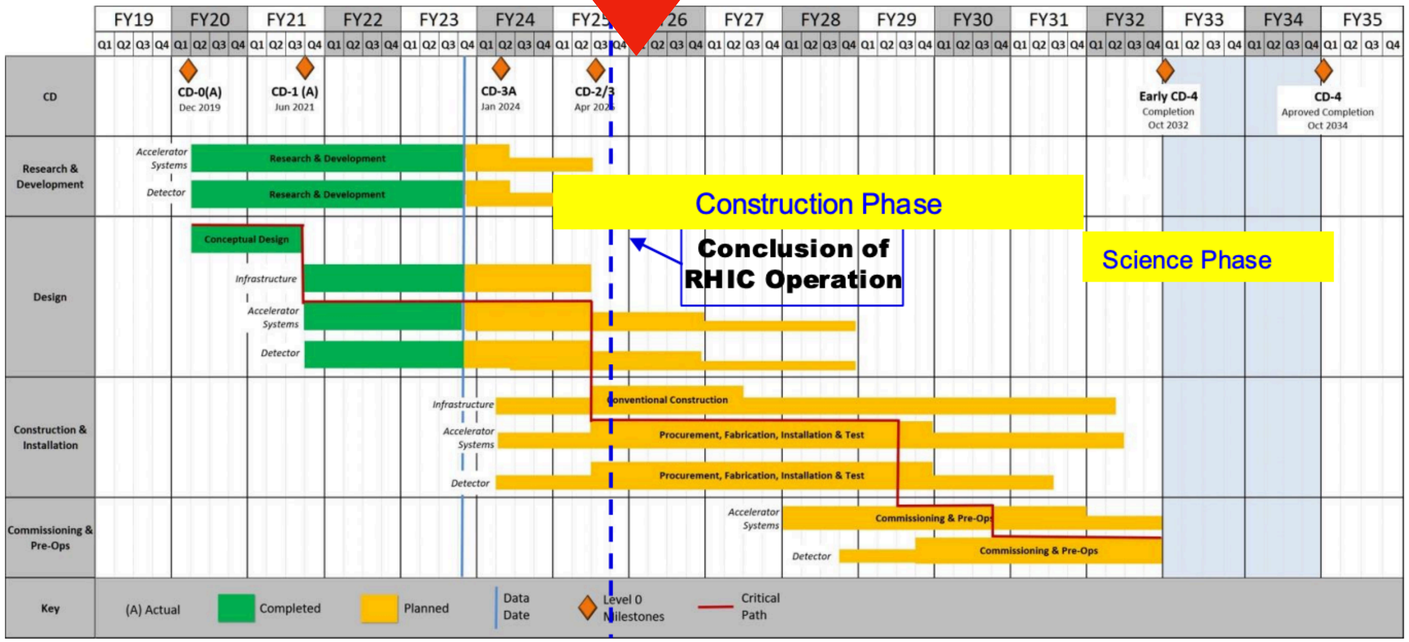


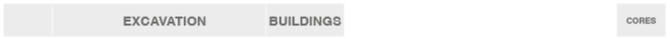
LHC the first precision hadron collider: discovery through precision & interpretation

MORE PRECISION AHEAD

- HL-LHC is about to start with an unprecedented luminosity yielding even more precise measurements
- EIC kicking in soon with many synergy opportunities

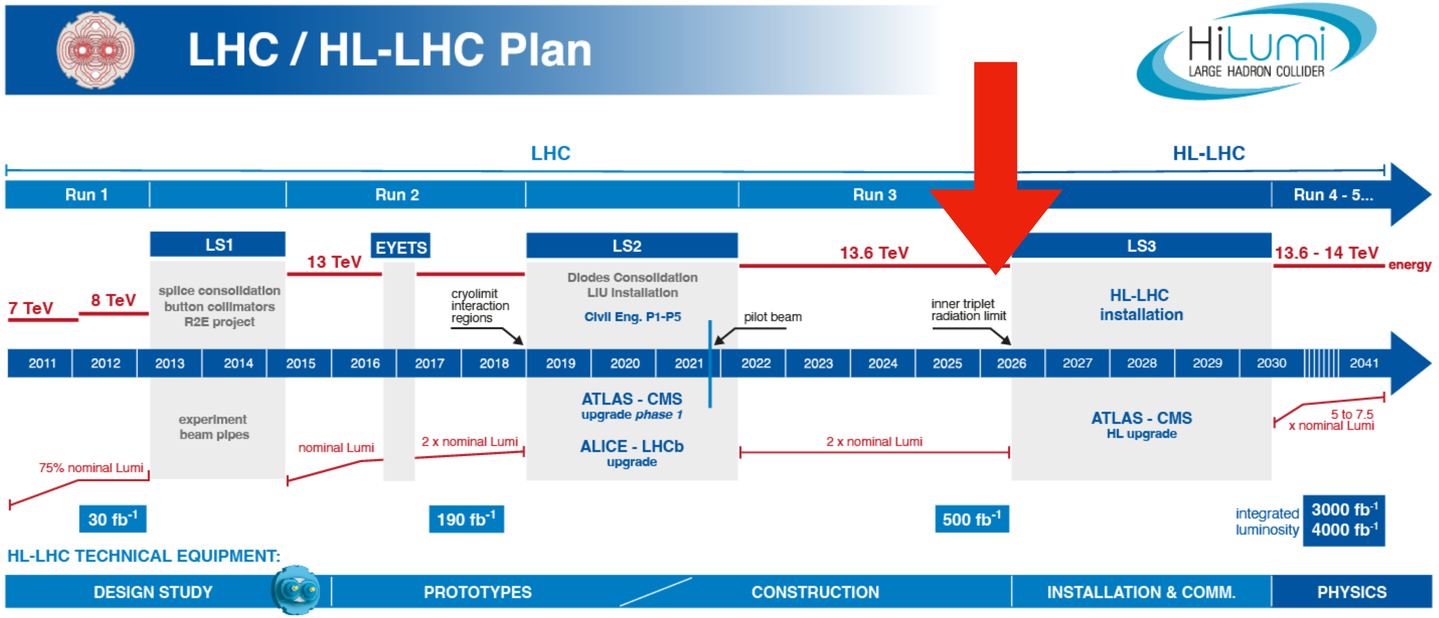


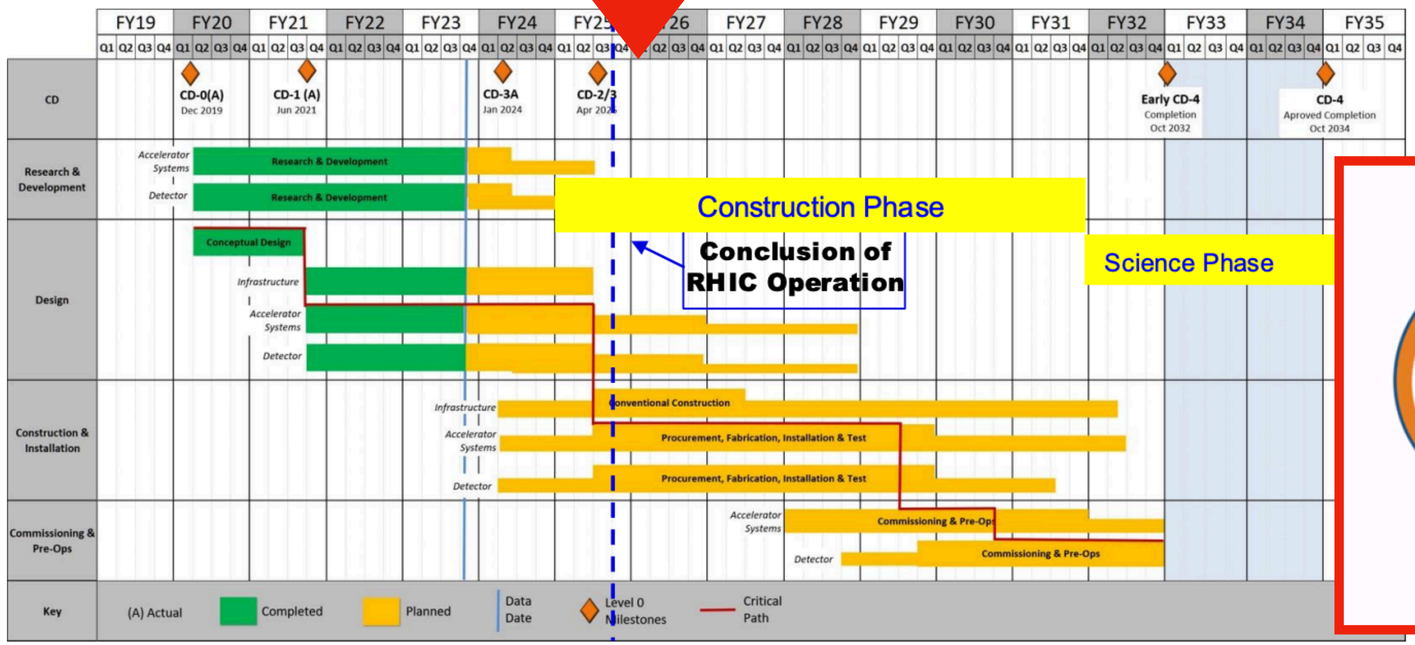


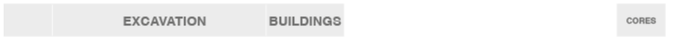


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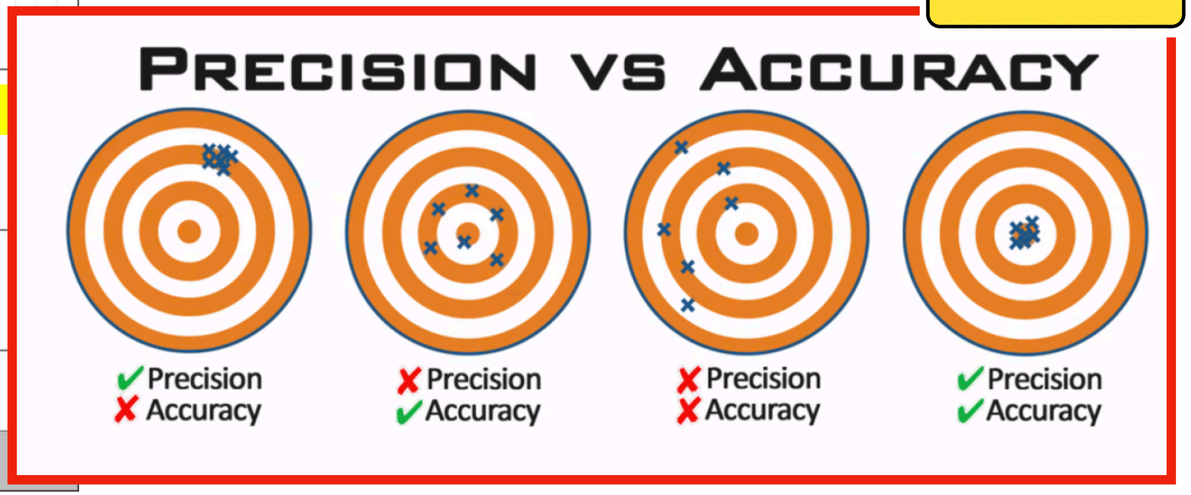
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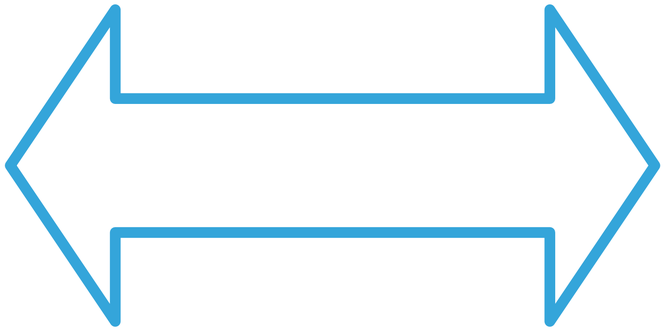


Warning:
1% accuracy target

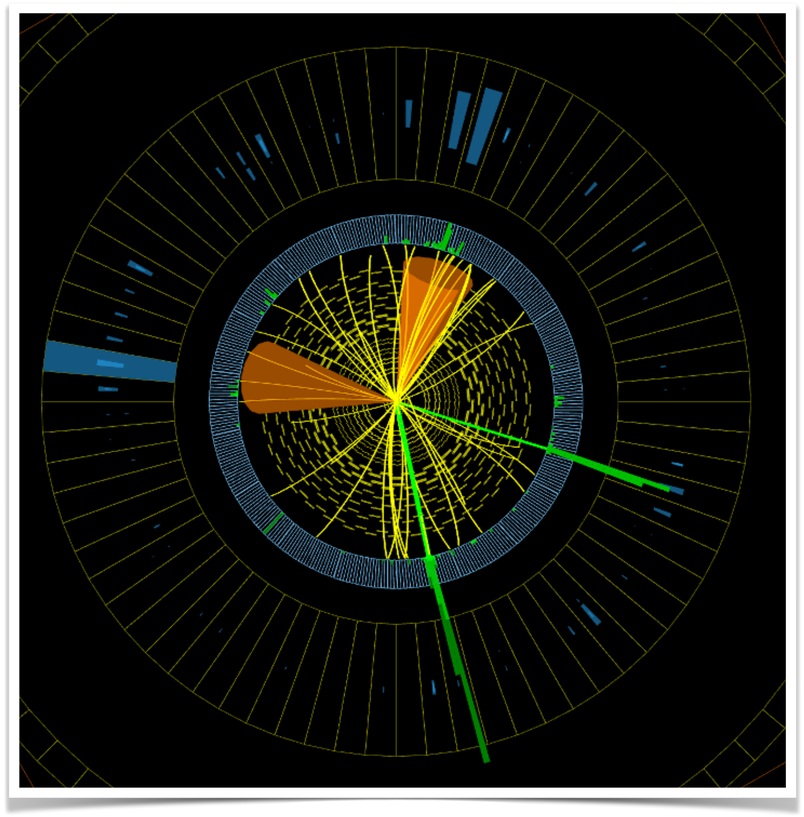


BRIDGE THE EMERGENT AND THE FUNDAMENTAL

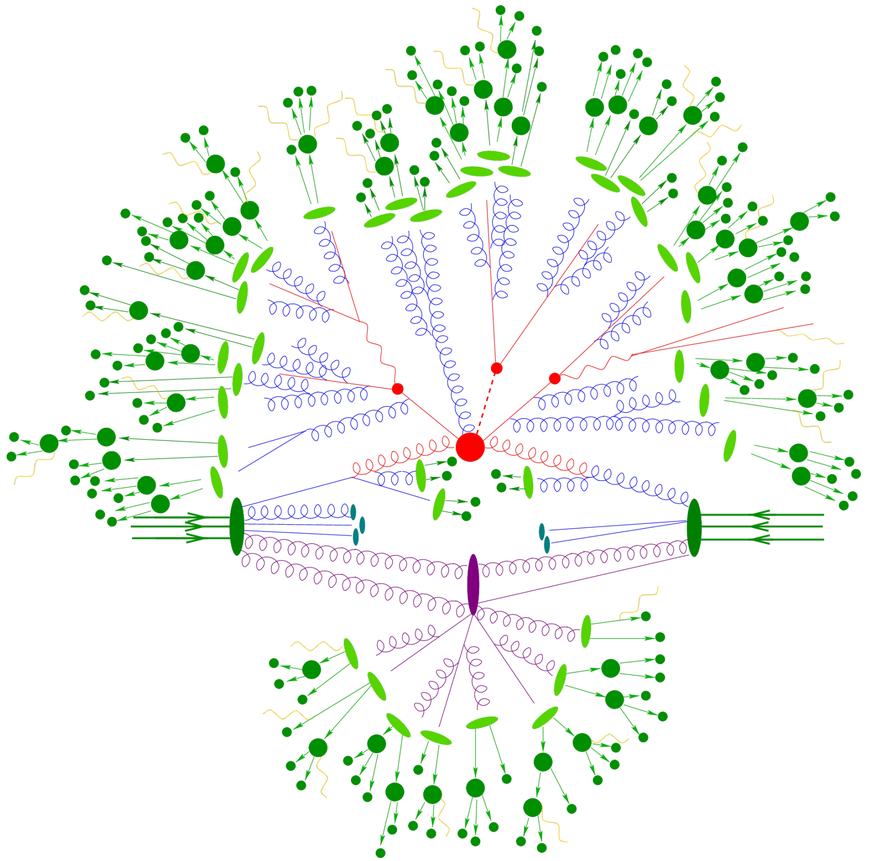
Experimental Data



Underlying Theory



CMS event, CERN website

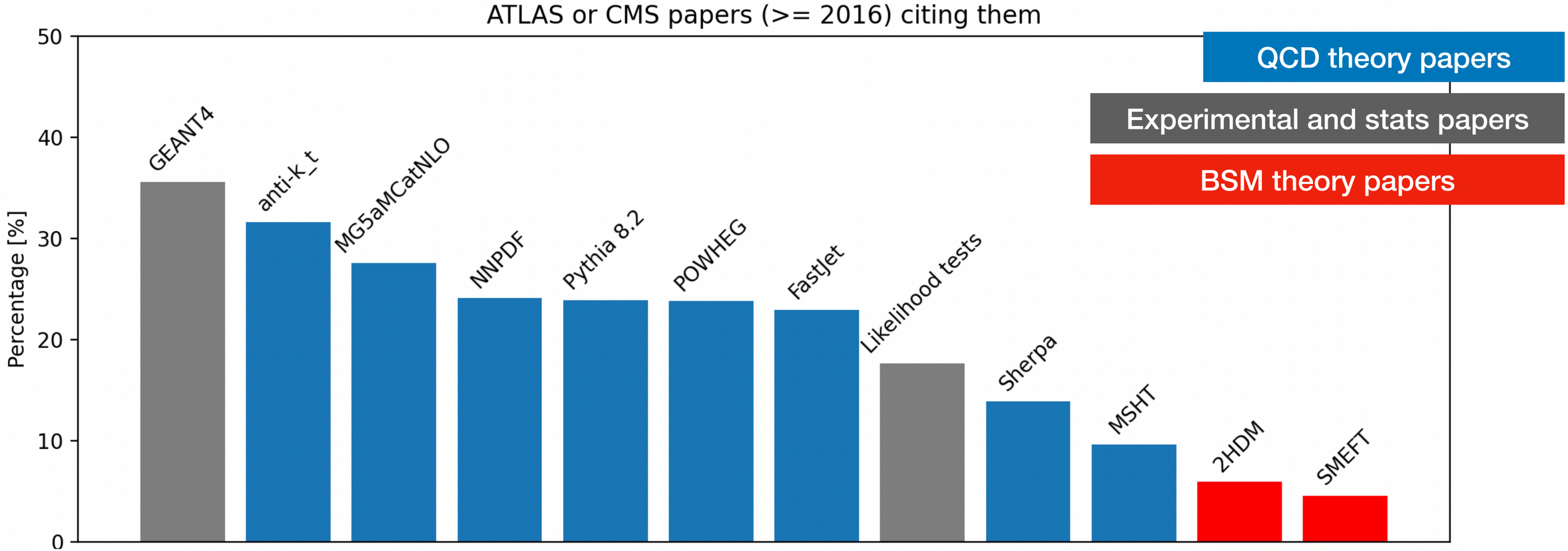


@SHERPA artist

BRIDGE THE EMERGENT AND THE FUNDAMENTAL

O(10^4) ATLAS and CMS papers since 2016

Papers they cite



Selection of papers cited ≥ 500 times *[inspired from G. Salam's talk colloquium at CERN (June 2025)]*

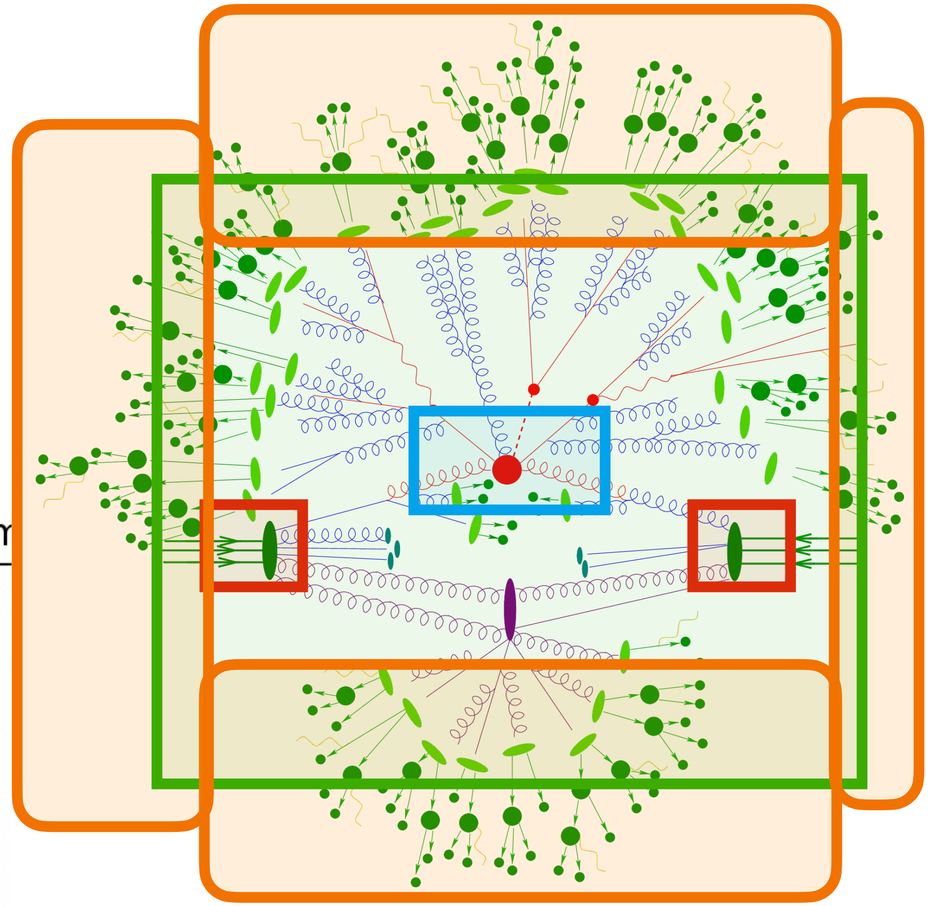
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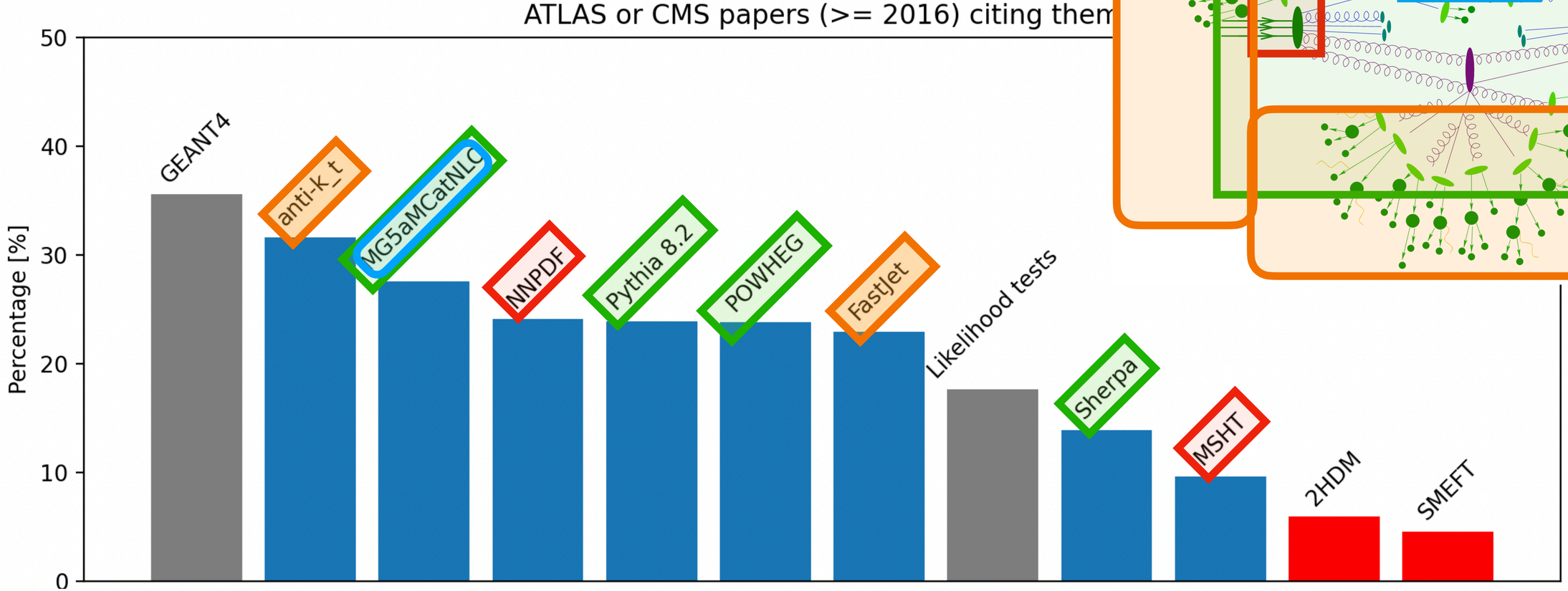
PDFs (proton structure)

Monte Carlo event generator

Hard scattering

Jet algorithm





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MORIOND QCD (2016)

Moriond QCD **2016** - some highlights from **T. Becher's** theory summary talk

- **BSM** searches: 750 GeV resonance
- **Higher order QCD**: the year of NNLO (2 → 2 processes)
- **PDFs**: PDF4LHC15 first combination of NNLO sets
- **NLO + PS** automation and first NNLO + PS
- **NNLL** resummation

We have entered the era of precision QCD, even in a hadron collider environment, as evidenced by the many new results presented at the conference.



50th anniversary cake *[courtesy of Stefano Forte]*

MORIOND QCD (2016 – 2026): HOW THE IMPOSSIBLE BECAME POSSIBLE

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2026

- **BSM** searches: ~~750 GeV resonance~~
  - Global and local SMEFT fits, NLO SMEFT, RGE…
  - New avenue explored: ALPs, dark photons…
- **Higher order QCD**: the year of NNLO (2 → 2 processes)
  - NNLO subtraction schemes refined, 2→3 processes appearing
  - N3LO computation of DY, ggH, VBF…, aN3LO splitting functions
- **PDFs**: PDF4LHC15 first combination of NNLO sets
  - Smaller ΔPDF , breakthrough in methodologies, accuracy, correlations
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  - EW and QCD joint resummation

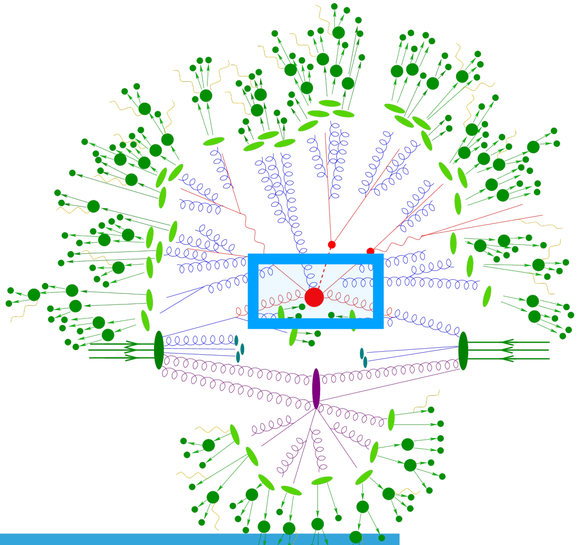
New

- The **Machine Learning** revolution

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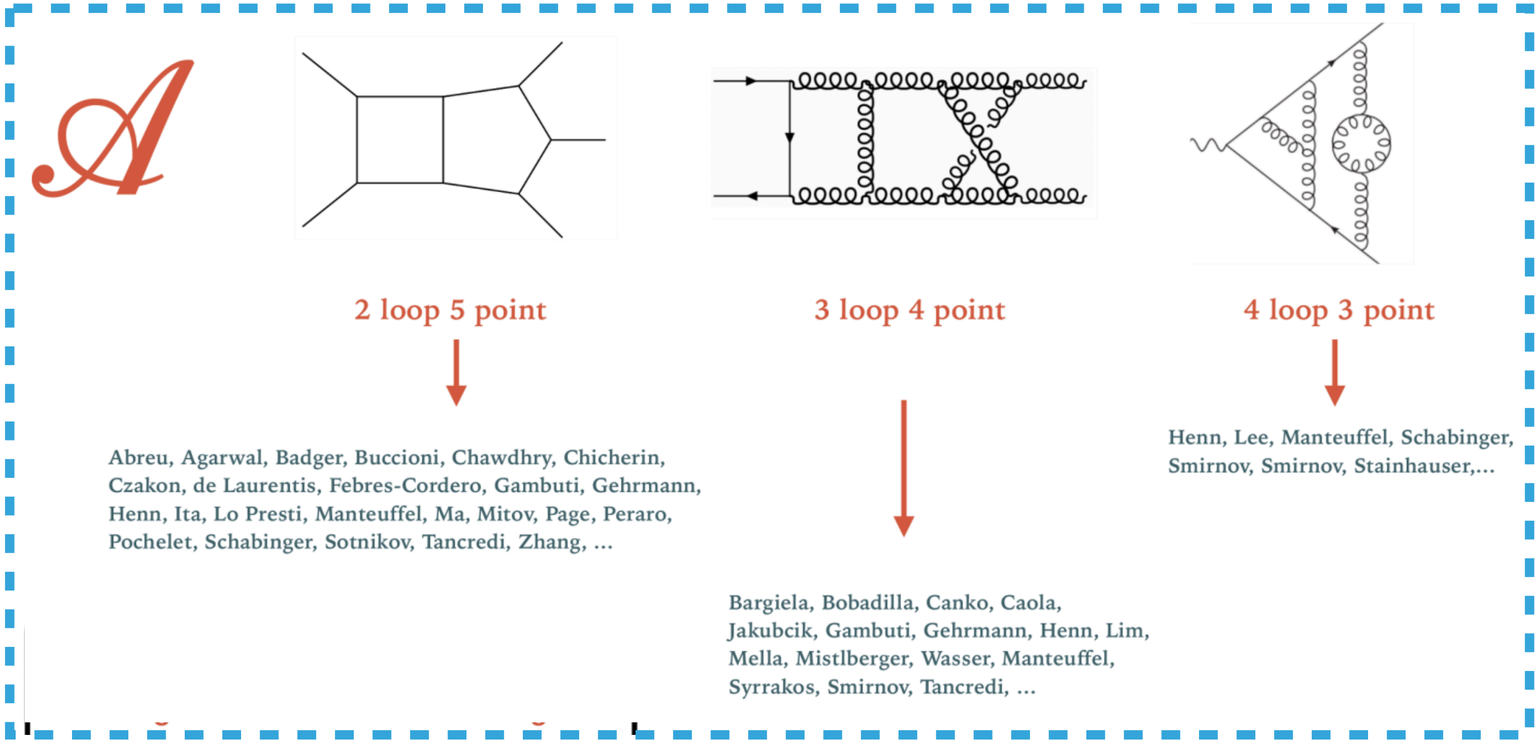
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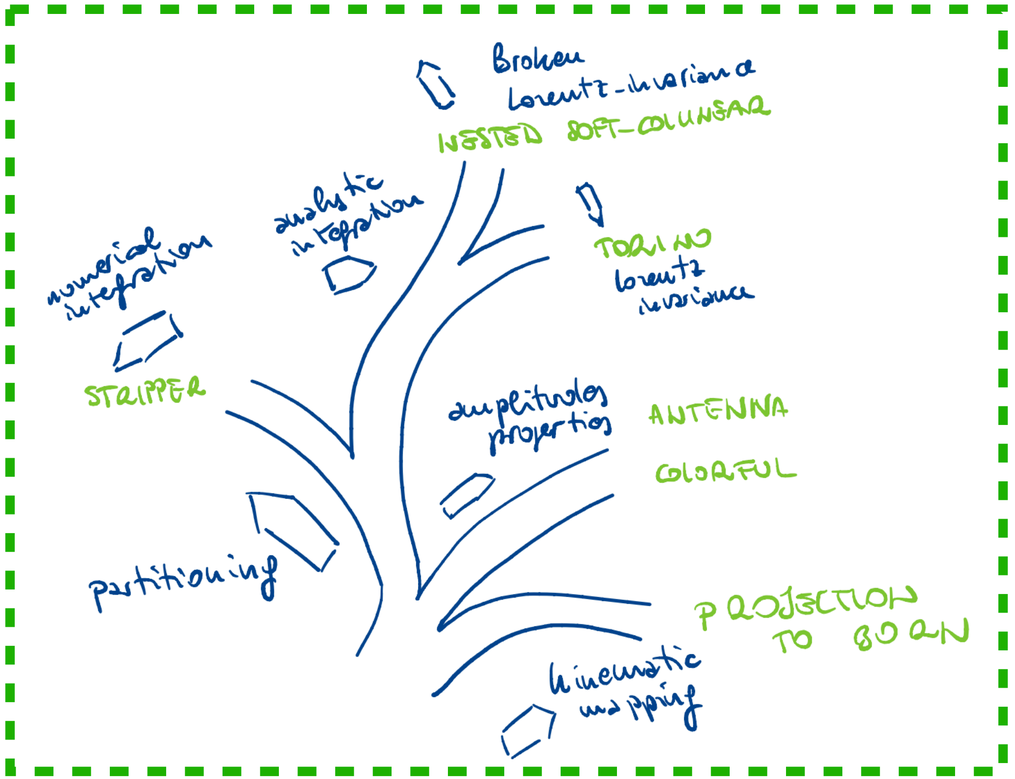


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HIGHER ORDER QCD: NNLO QCD CALCULATIONS



L. Tancredi, QCD@LHC2024



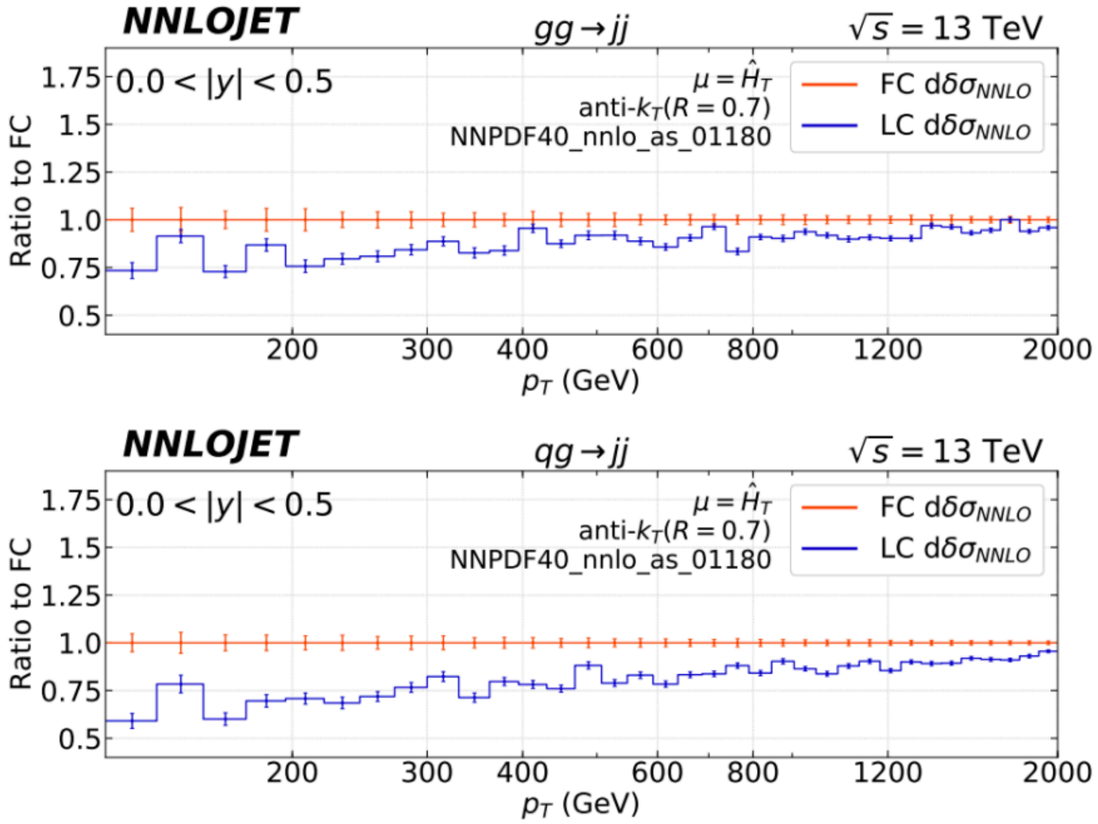
C. Signorile - Signorile MPI

- The amplitude revolution: all processes computed in full colour including planar and non-planar diagrams
- Flourishing of subtraction techniques at NNLO, benchmarking and constant improvements
- Many 2 → 3 processes appeared at NNLO QCD
- Combination of NNLO QCD and NLO EW corrections

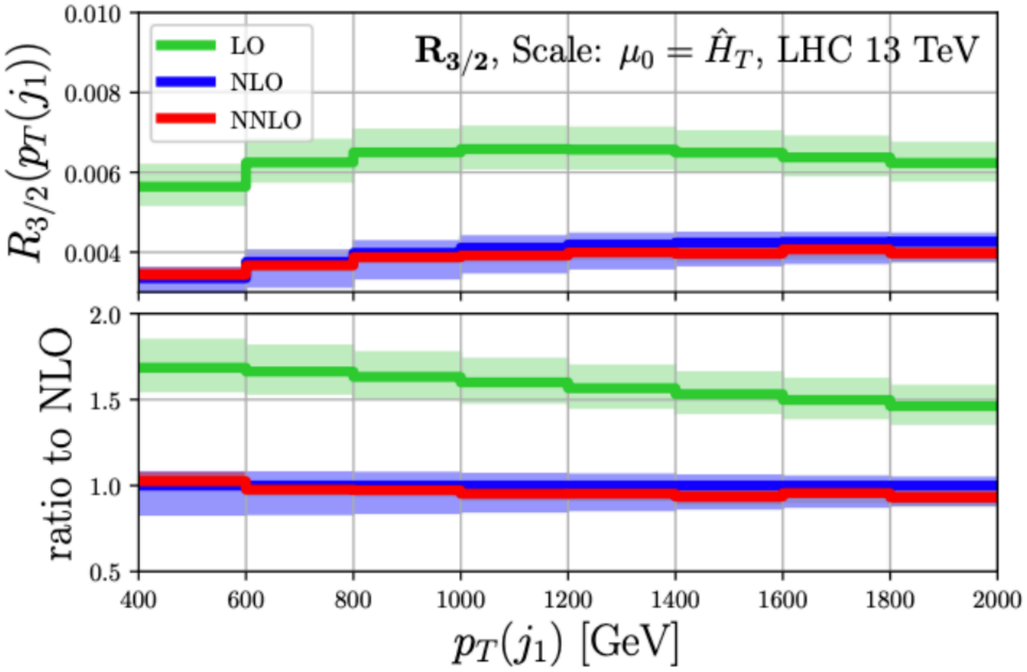
Antenna *[Gehrmann-De Ridder et al. '05]*
ColorfulNNLO *[Del Duca et al. '16]*
STRIPPER *[Czakon '10]*
Nested soft-collinear *[Caola et al. '17]*
Local analytic sector *[Magnea, CSS et al. '18]*
Geometric IR subtraction *[Herzog '18]*
Unsubtraction *[Sborlini et al. '16]*
FDR *[Pittau '12]*
Universal Factorisation *[Sterman et al. '20]*

HIGHER ORDER QCD: NNLO QCD CALCULATIONS

$$\frac{\mathrm{d}\sigma_3(\mu_R,\mu_F)/\mathrm{d}X}{\mathrm{d}\sigma_2(\mu_R,\mu_F)/\mathrm{d}X}$$



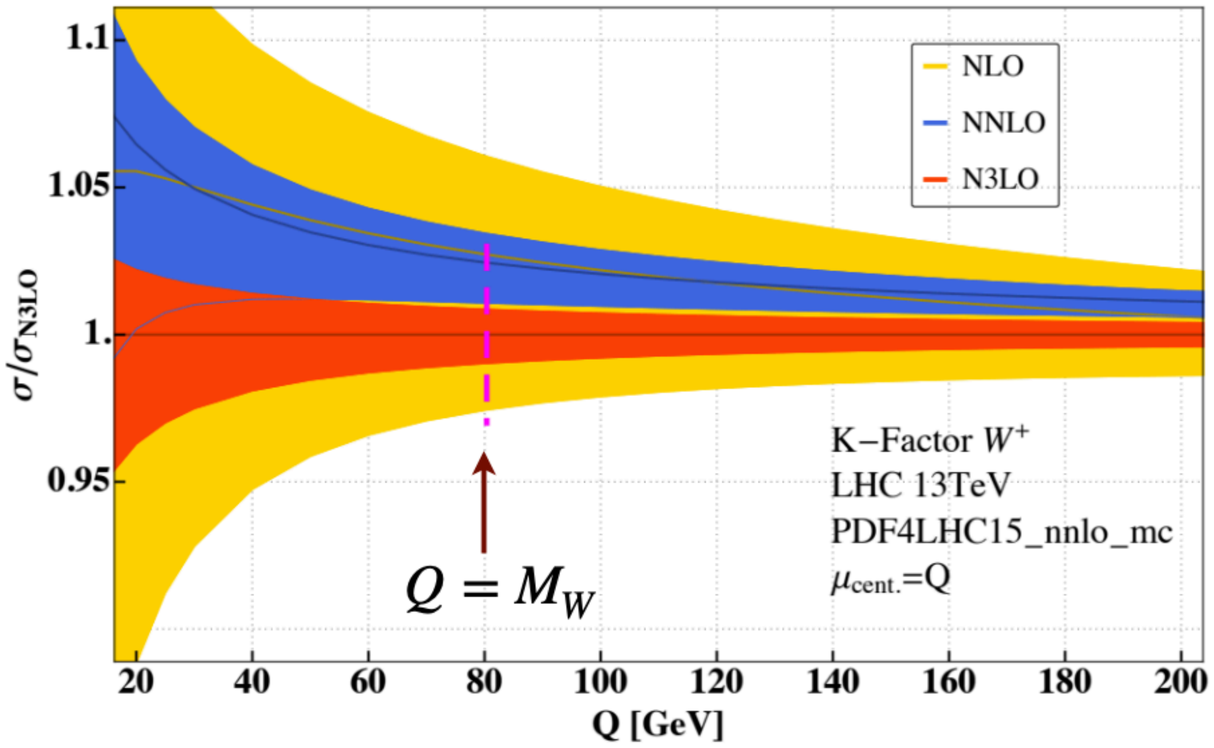
Chen et al 2204.10173



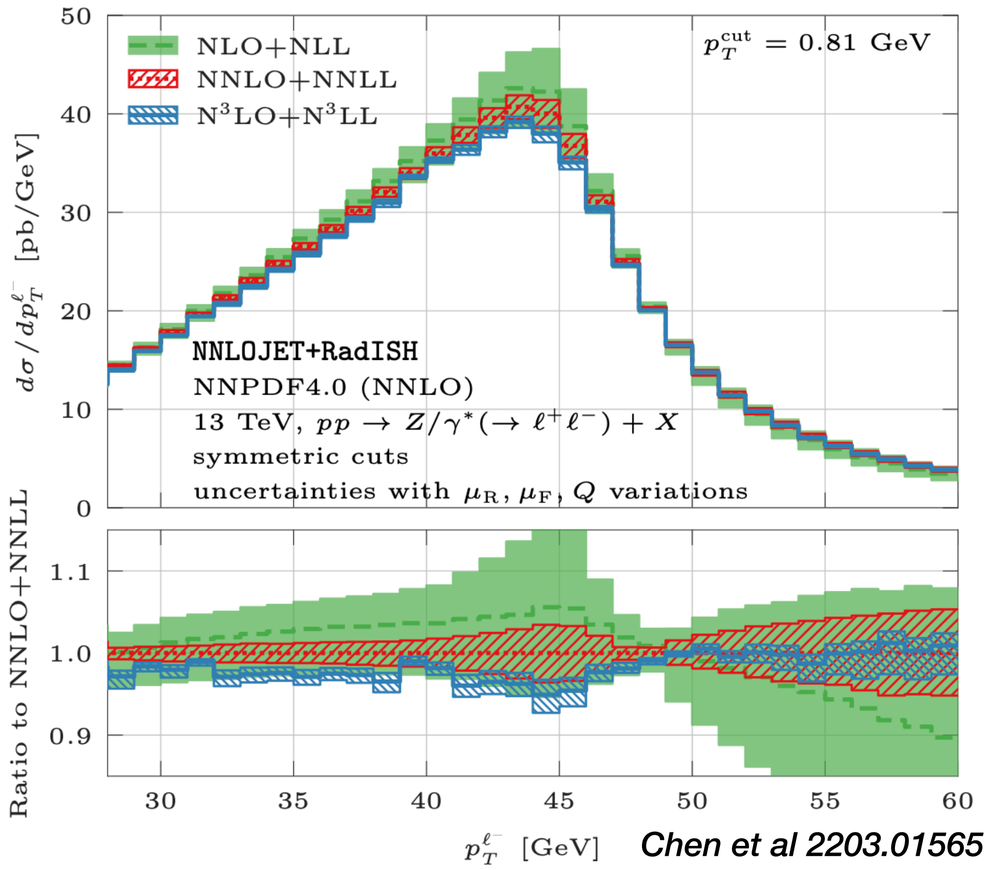
Czakon et al, 2106.05331

- Ex1: NNLO jet & dijet production at the LHC with full colour shows previously adopted leading colour approximation undershoots full result by ~ 20-30% [Chen et al, 2022…]
- Ex2: NNLO triple jet production at the LHC, precise predictions key for new physics backgrounds, extraction of strong coupling from ratio $R_{3/2}$ [Czakon et al, 2022…]
- Ex3: Full two loop QCD x EW corrections to neutral-current Drell-Yan including decay [Buccioni et al, 2022…] and exact two-loop virtual corrections to charged-current Drell Yan [Armadillo et al, 2024…]

HIGHER ORDER QCD: THE N3LO FRONTIER



Duhr et al, 2007.13313



Chen et al 2203.01565

- Several key LHC processes now available including N3LO QCD corrections:
  Higgs in gluon-gluon fusion (total 2016, diff 2021), VBF Higgs (2018), Higgs pair production (2020), …
- Drell Yan also available at N3LO at the fiducial level (2020 – 2022), realistic kinematic cuts can be applied
- More N3LO matrix elements on the way: H → bb~, H → gg parton level structure (2024)
- Huge phenomenological impact ahead: increased precision for key processes, exploration of perturbative convergence, perturbative stability optimised with tailored kinematic cuts

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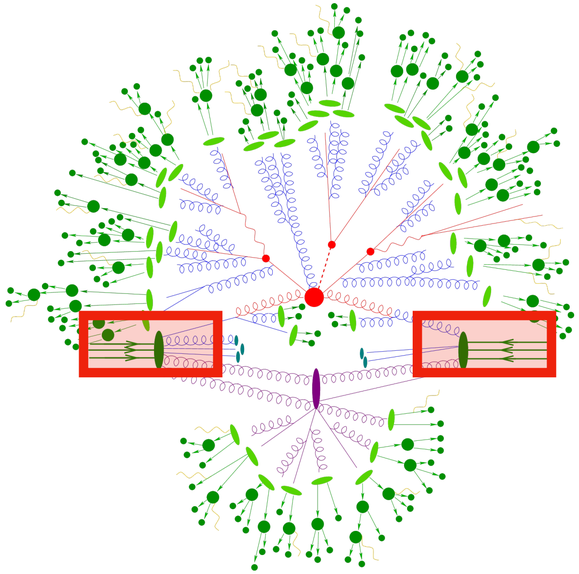
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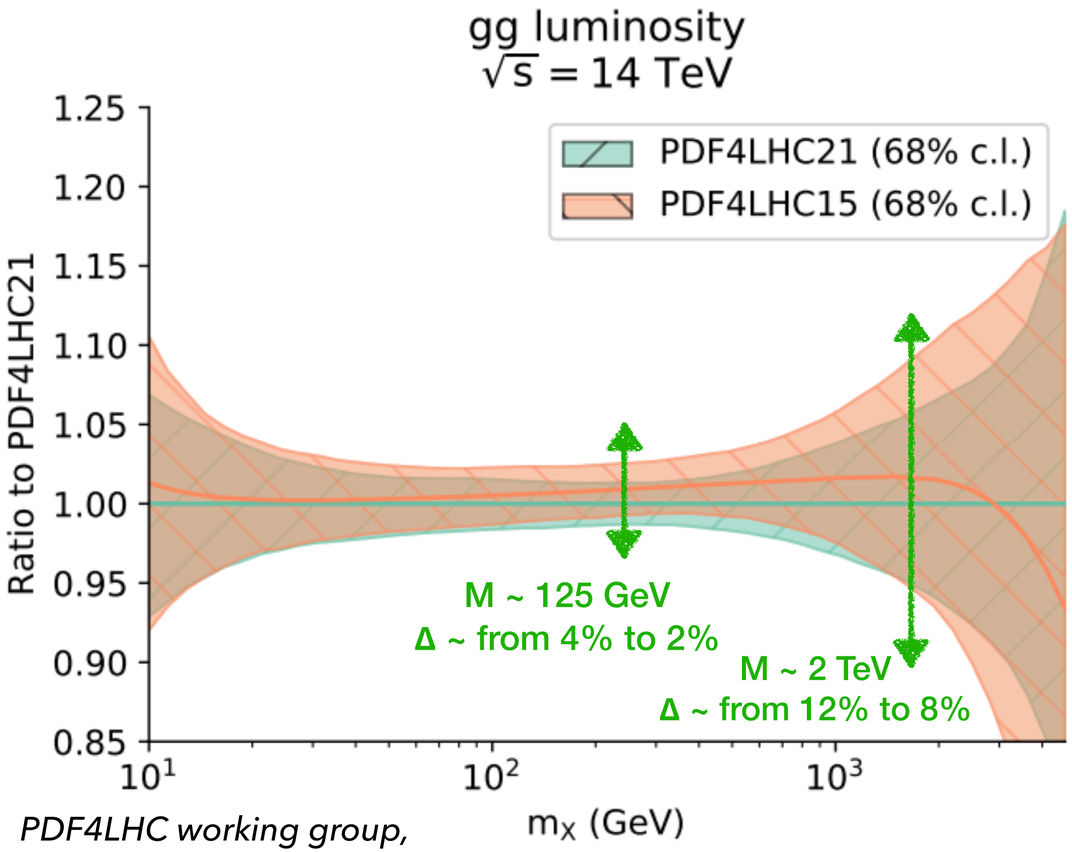
- **NNLL** resummation

2026



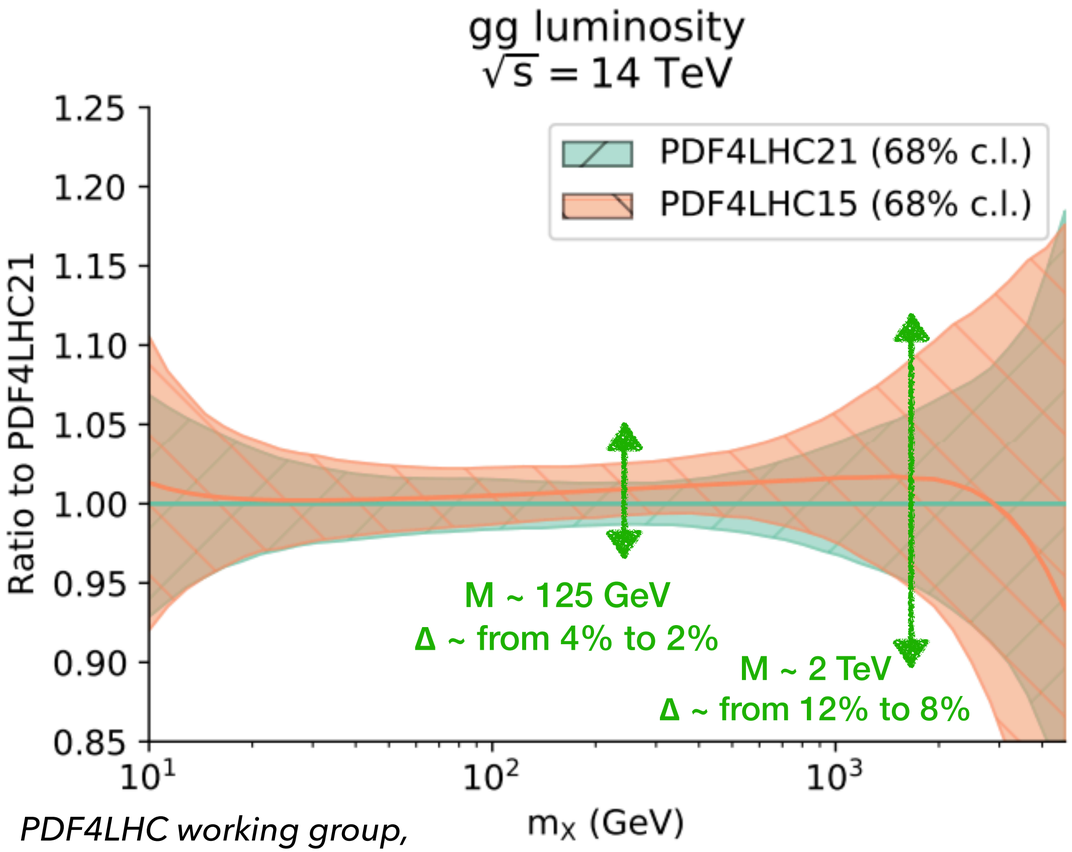
- Smaller ΔPDF , breakthrough in methodologies, accuracy, correlations
- ΔPDF including MHOUs, aN3LO PDFs, photons and QED

PARTON DISTRIBUTION FUNCTIONS



PDF4LHC working group, 2203.05506

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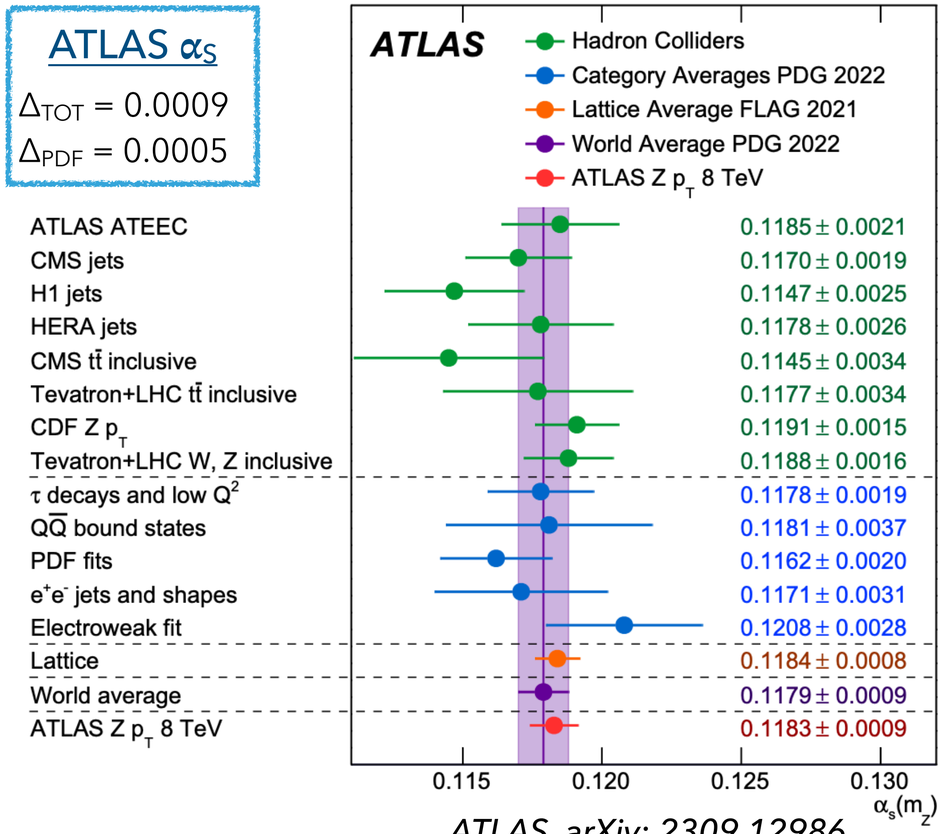


PDF4LHC working group, 2203.05506

ATLAS α_S

$\Delta_{TOT} = 0.0009$

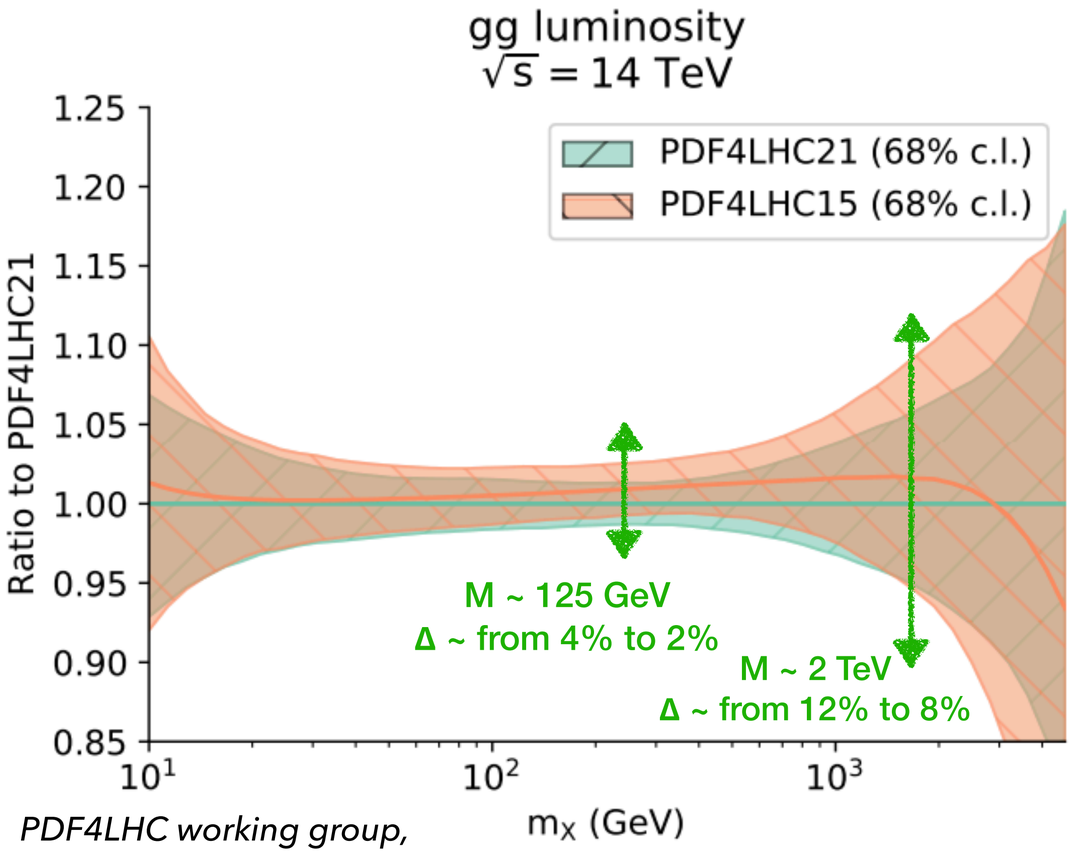
$\Delta_{PDF} = 0.0005$



ATLAS, arXiv: 2309.12986

- ATLAS determination of α_s from neutral-current Drell-Yan Z pT measurement most precise α_s determination ever performed from single experiment
- **But** significantly different results with different input PDFs
  $\Delta_{\alpha,TOT} = 0.0009$ with $\Delta_{\alpha,PDF} = 0.0005$ (MSHT20aN3LO)
  But
  $\delta_{\alpha,PDF} = 0.0020$ (shift CT18A versus NNPDF4.0)

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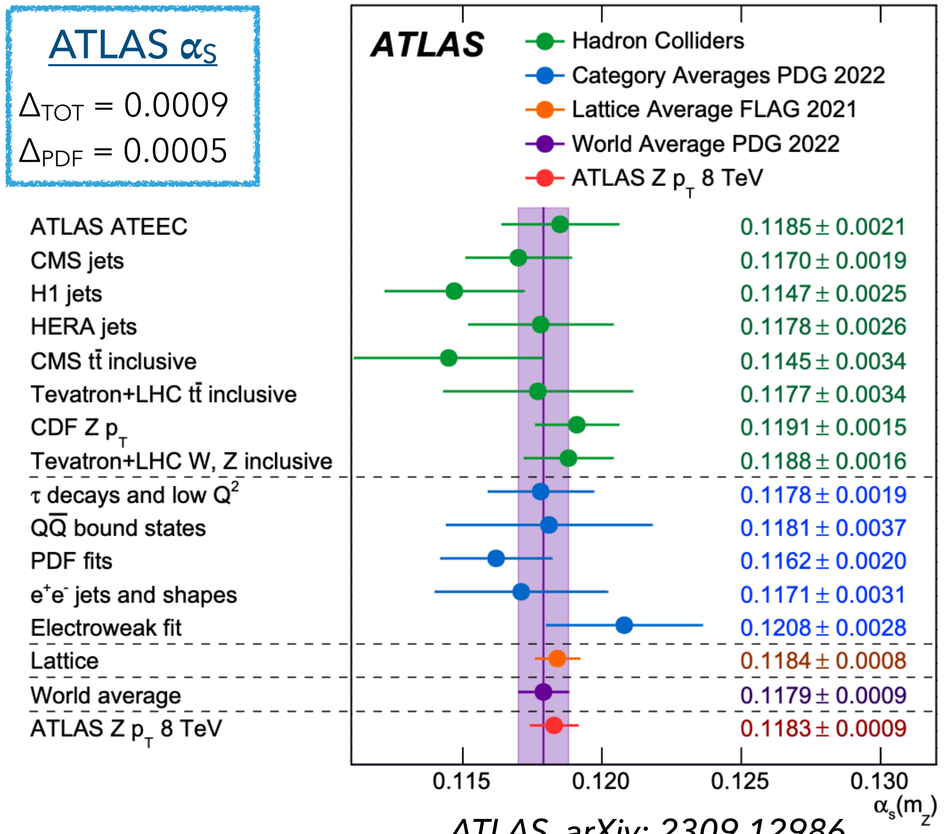
PDF4LHC working group, 2203.05506

For accurate PDFs many effects still to be kept into account
- ➡ Higher perturbative orders and MHOUs
- ➡ Electroweak corrections
- ➡ Methodologies and explicit effect of priors
- ➡ Correlations with SM parameters
- ➡ Interplay with BSM signals in the tails…

ATLAS α_S

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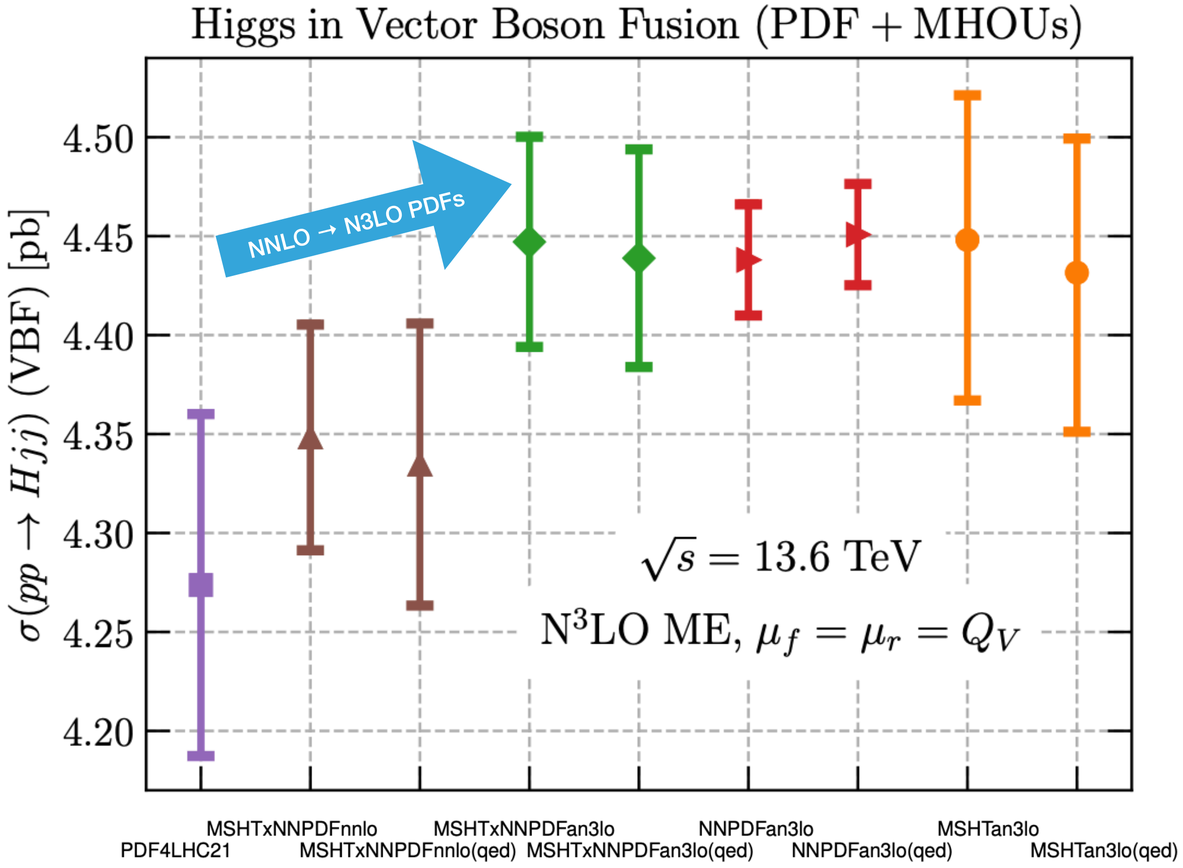
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PARTON DISTRIBUTION FUNCTIONS MEET HIGHER ORDER QCD

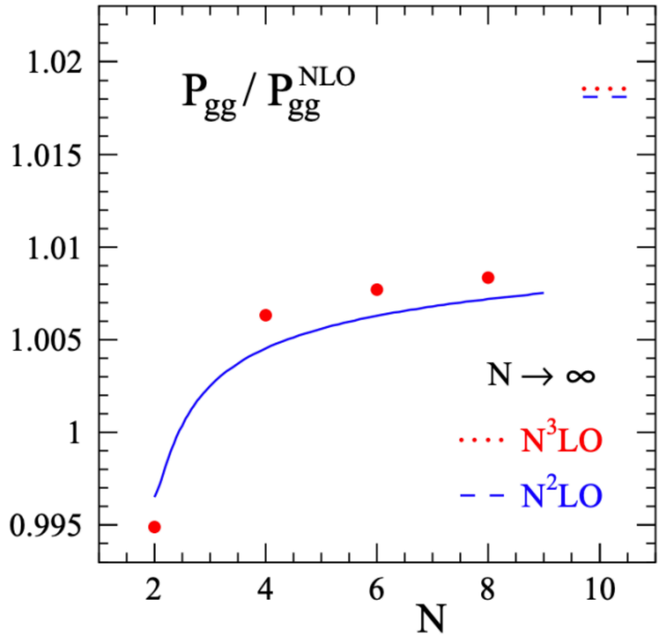
DGLAP splitting functions

$$P_{ij}(x,\alpha_s) = \alpha_s P_{ij}^{(0)}(x) + \alpha_s^2 P_{ij}^{(1)}(x) + \alpha_s^3 P_{ij}^{(2)}(x) + \alpha_s^4 P_{ij}^{(3)}(x) + \alpha_s^5 P_{ij}^{(4)}(x)$$

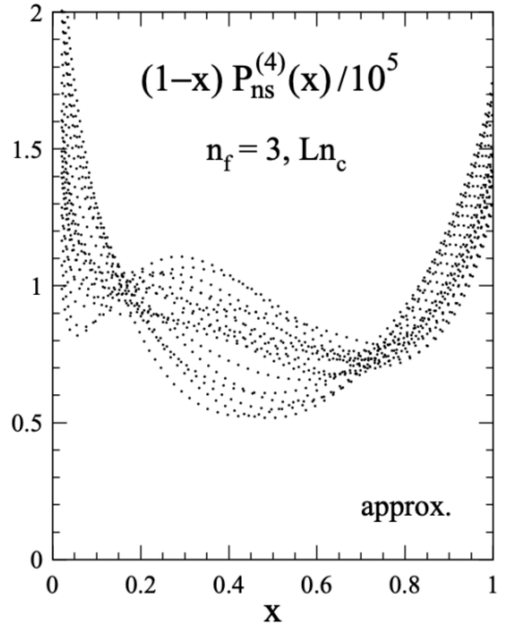
☑ LO (1973) ☑ NLO (1982) ☑ NNLO (2004) N³LO partial results N⁴LO partial results



MSHT+NNPDF 2411.05373



Moch et al, 2111.15561



Moch et al, 1812.11818

Previous estimates of the effect of NNLO/ N3LO mismatch between order of PDF fits and order of matrix elements were optimistic and **N3LO PDFs** needed for precision physics

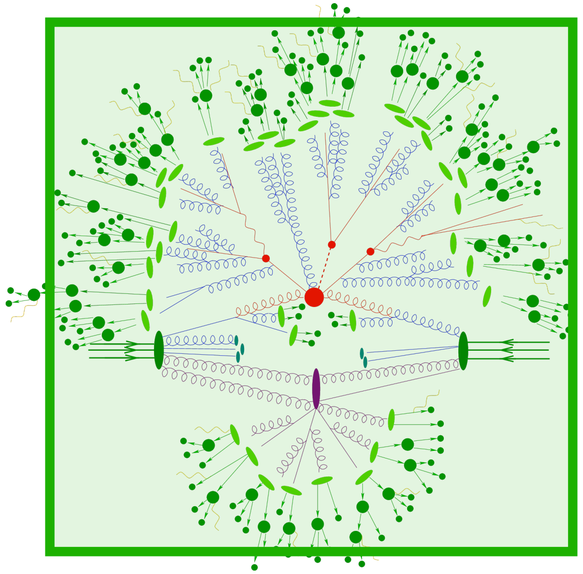
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- **BSM** searches: ~~750 GeV resonance~~

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2026



- **NLO + PS** automation and first NNLO + PS

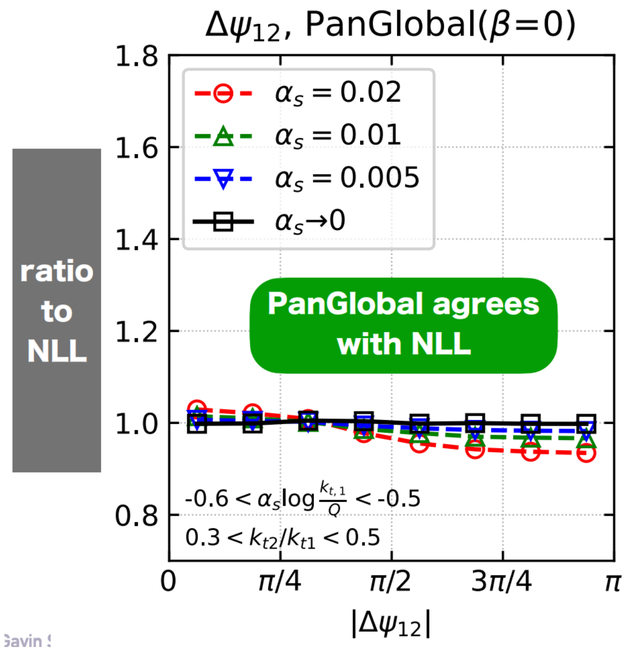
  - NLL parton showers, power corrections..
  - NNLO + PS consolidated

- **NNLL** resummation

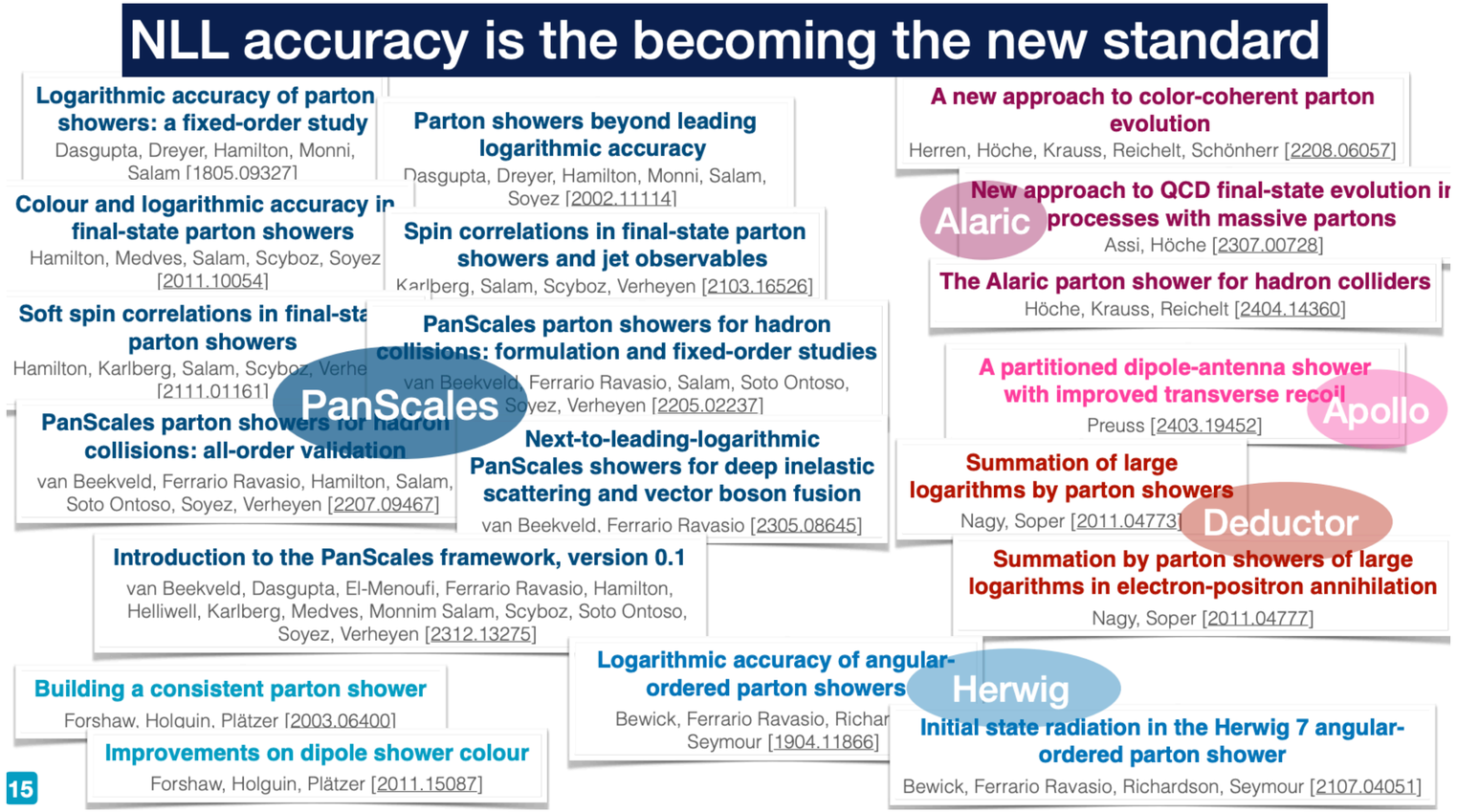
  - N^{k}LL and NLP resummations
  - EW and QCD joint resummation

NLL AND NNLL PARTON SHOWERS

- Standard parton showers are Leading Logarithmic (LL),
- Several groups work on new generation of showers aiming for NLL [Nagy&Soper, PanScales, HolguinForshaw-Platzer, Herren-Höche-KraussReichelt-Schönherr]
- Close to achieving full agreement with NLL analytic resummation!



G. Salam, 2025 CERN colloquium



M. Van Beekveld, DIS2025 plenary

- First steps towards NNLL-accurate parton showers announced at Moriond QCD 2024 for global event shape [M. Van Beekveld]

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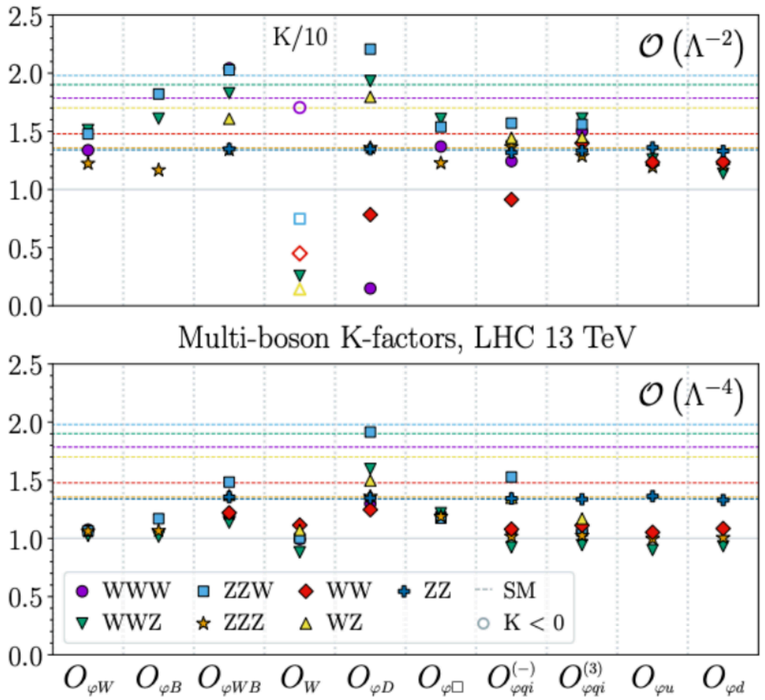
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- Global and local SMEFT fits, NLO SMEFT, RGE…
- New avenue explored: ALPs, dark photons…

SMEFT GLOBAL ANALYSES: BSM MEETS HIGHER ORDER QCD

$$\mathcal{L}_{\rm SMEFT} = \mathcal{L}_{\rm SM} + \sum_i^{N_{d6}} \frac{c_i}{\Lambda^2}\mathcal{O}_i^{(6)} + \sum_j^{N_{d8}} \frac{b_j}{\Lambda^4}\mathcal{O}_j^{(8)} + \dots$$

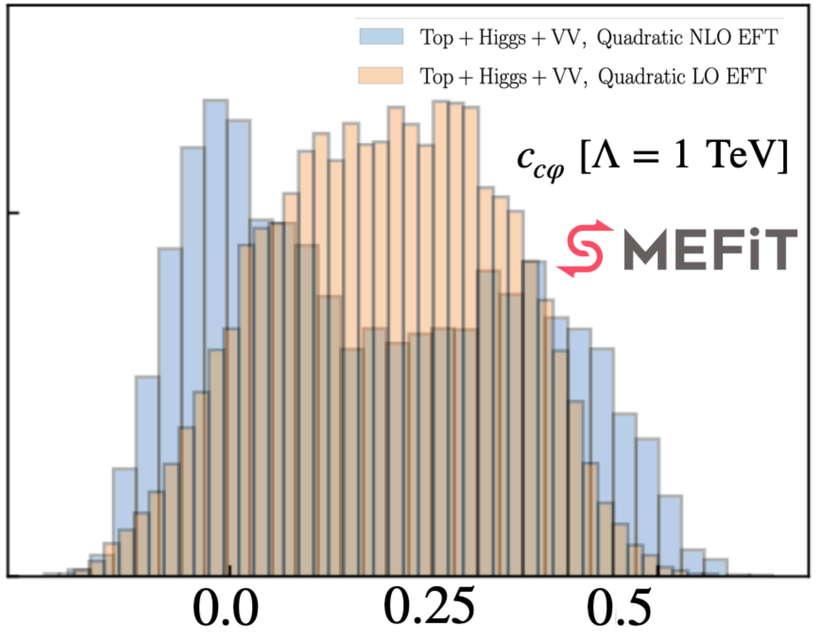


Multi-boson K-factors, LHC 13 TeV

Degrande et al, 2008.11743

Model semi-"agnostic" expansion assuming new physics states heavy

Charm Yukawa operator: $\left(\varphi^\dagger\varphi\right)\bar{q}_2\, c\,\tilde{\varphi} + \text{h.c.}$



SMEFiT collaboration, 2105.00006

Precise QCD and EQ calculations have shown to be crucial to accurately interpret collider data in BSM scenarios, for example the SMEFT and to derive bounds on the parameters of UV-complete theories

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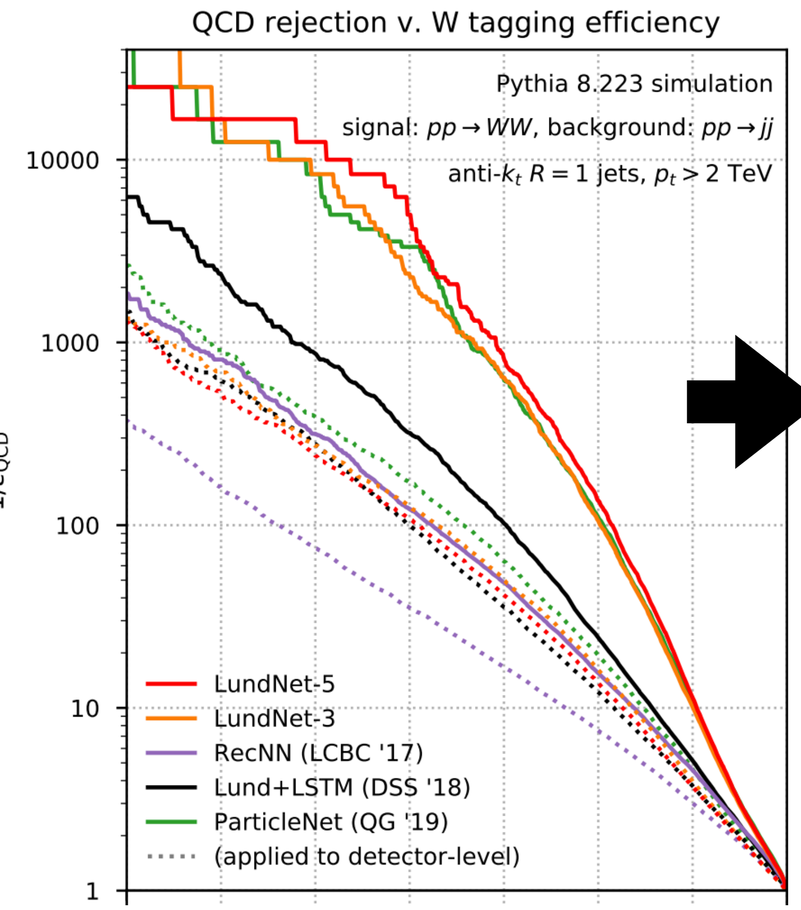
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- **NLO + PS** automation and first NNLO + PS

- **NNLL** resummation



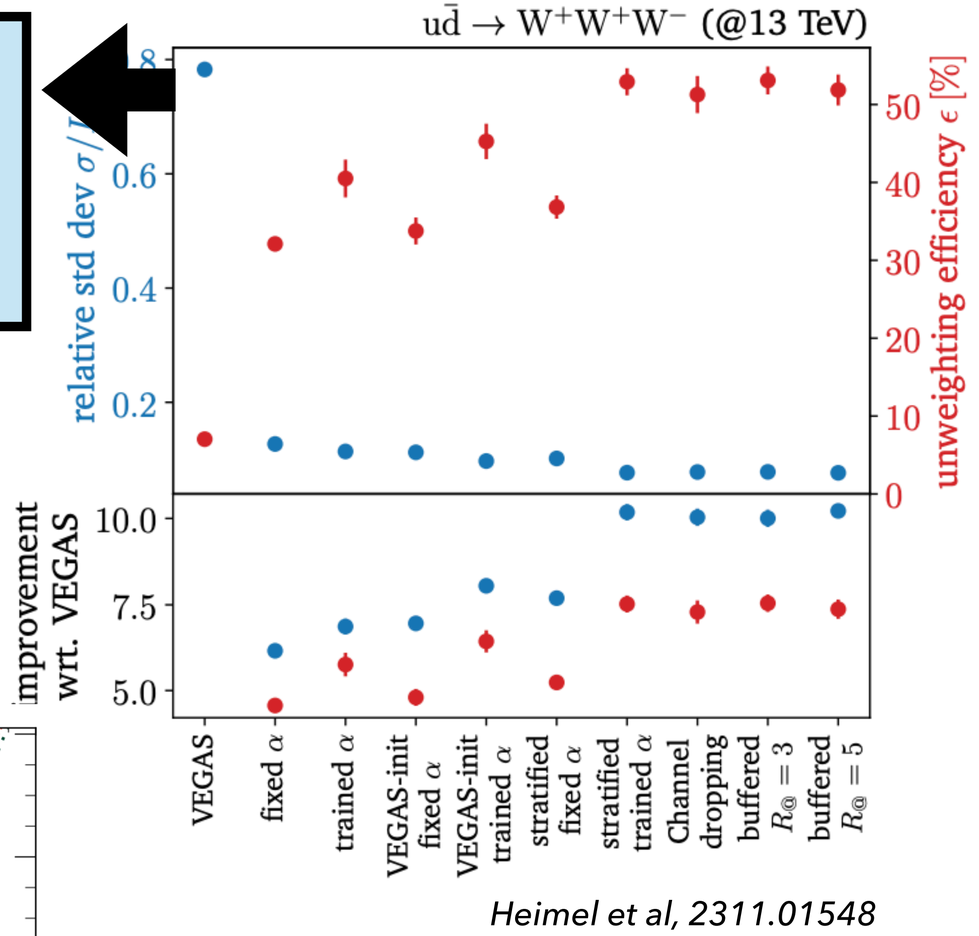
SELECTED ML-DRIVEN RESULTS



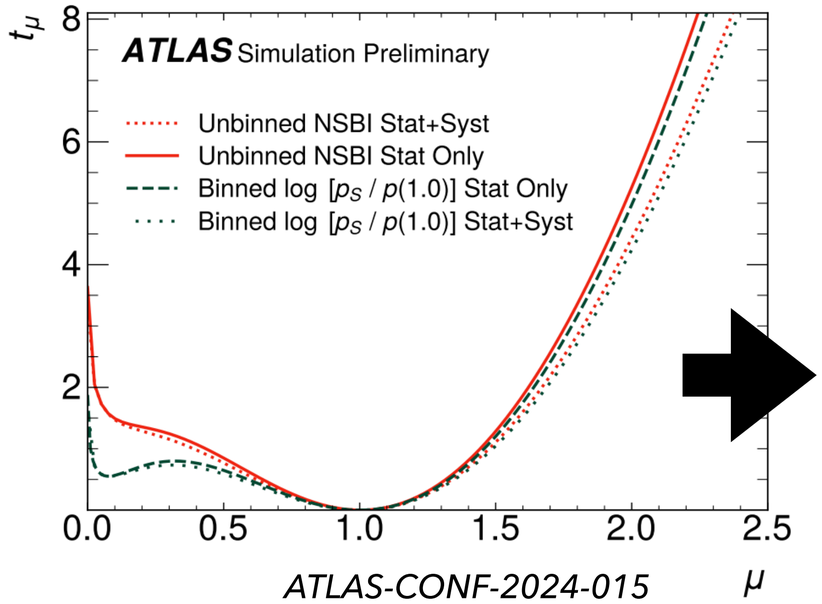
Dreyer,Qu 2012.08526

Using graph NNs improves over traditional top tagging by order of magnitudes!

Combining standard automated event generator MadGraph with ML tools ~10x improvements in accuracy and efficiency



Heimel et al, 2311.01548



ATLAS-CONF-2024-015

ML tool can make us "see" events in more dimensions: Neural Simulation Based Inference for unbinned distributions

CONCLUSIONS AND OUTLOOK

- Amazing progress in the past 10 years: what seemed unthinkable in terms of technical complexity has almost become the new standard [Disclaimer: in this talk only a small part was shown and many key developments could not be mentioned]
- New interplays emerged: BSM and higher order QCD, PDFs and SM/BSM parameters, EW and QCD, QM entanglement, machine learning, advanced statistics..
- Many new exciting frontiers ahead:
  - ★ Leveraging the HL-LHC and EIC synergy towards sub-percent accuracy and precision
  - ★ NNLL parton showers
  - ★ N3LO QCD matched to N(N)LO EW
  - ★ Next-to-leading power resummation
  - ★ Better constrain of PDFs
  - ★Exploit ML to its full to sharpen the tools
  - ★And much more (heavy quarks, heavy jets, fragmentation, lattice, TMDs, GPDFs…)



"We can only see a short distance ahead, but we can see plenty there that needs to be done."

– Alan Turing

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THANK YOU!

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