Recent progress in QCD calculations

Fabrizio Caola
Rudolf Peierls Centre for Theoretical Physics & Wadham College

Ringberg 2024: 2nd Workshop on Tools for High Precision LHC Simulations

SOME

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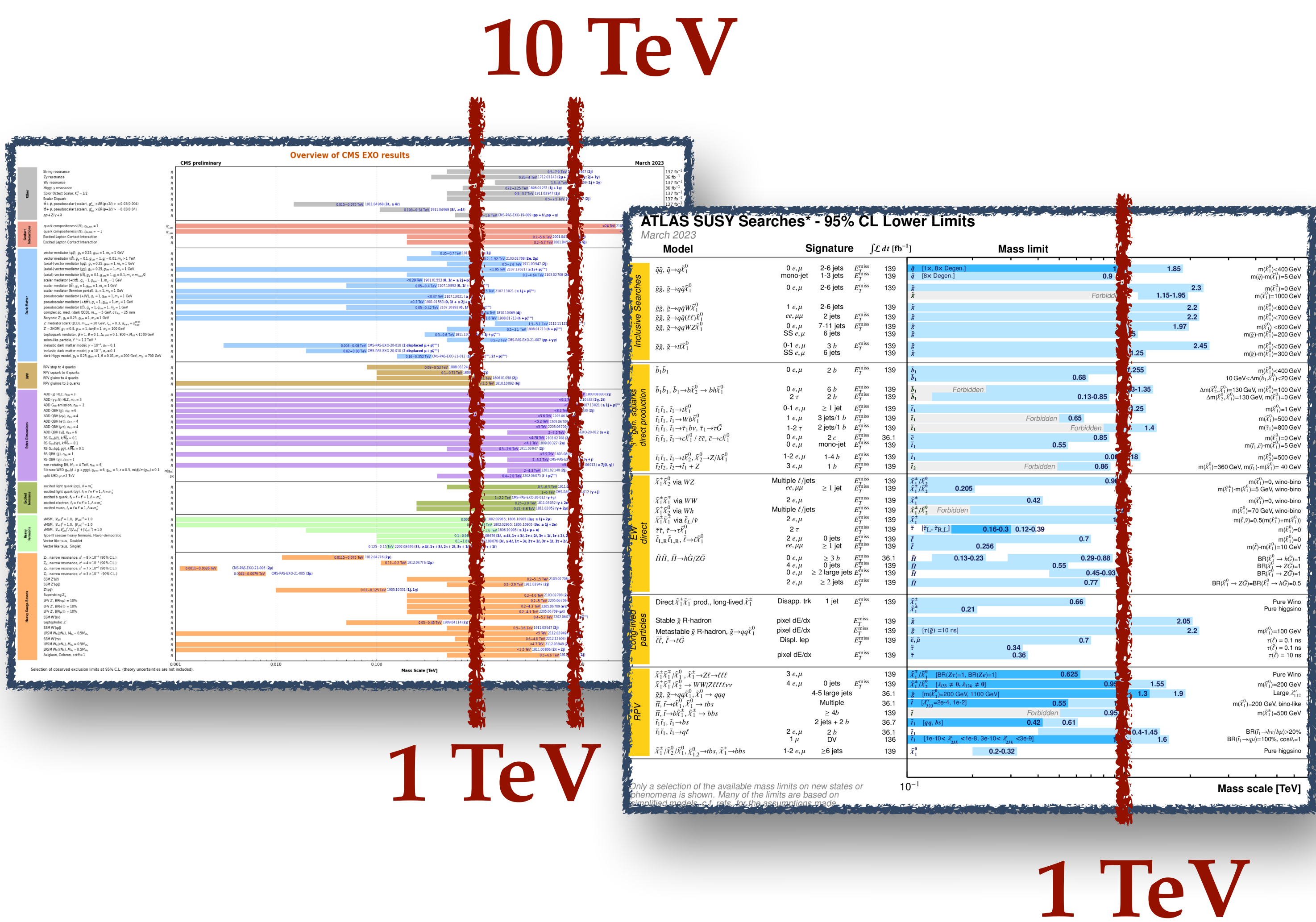
UNIVERSITY OF OXFORD

erc

* almost entirely fixed-order

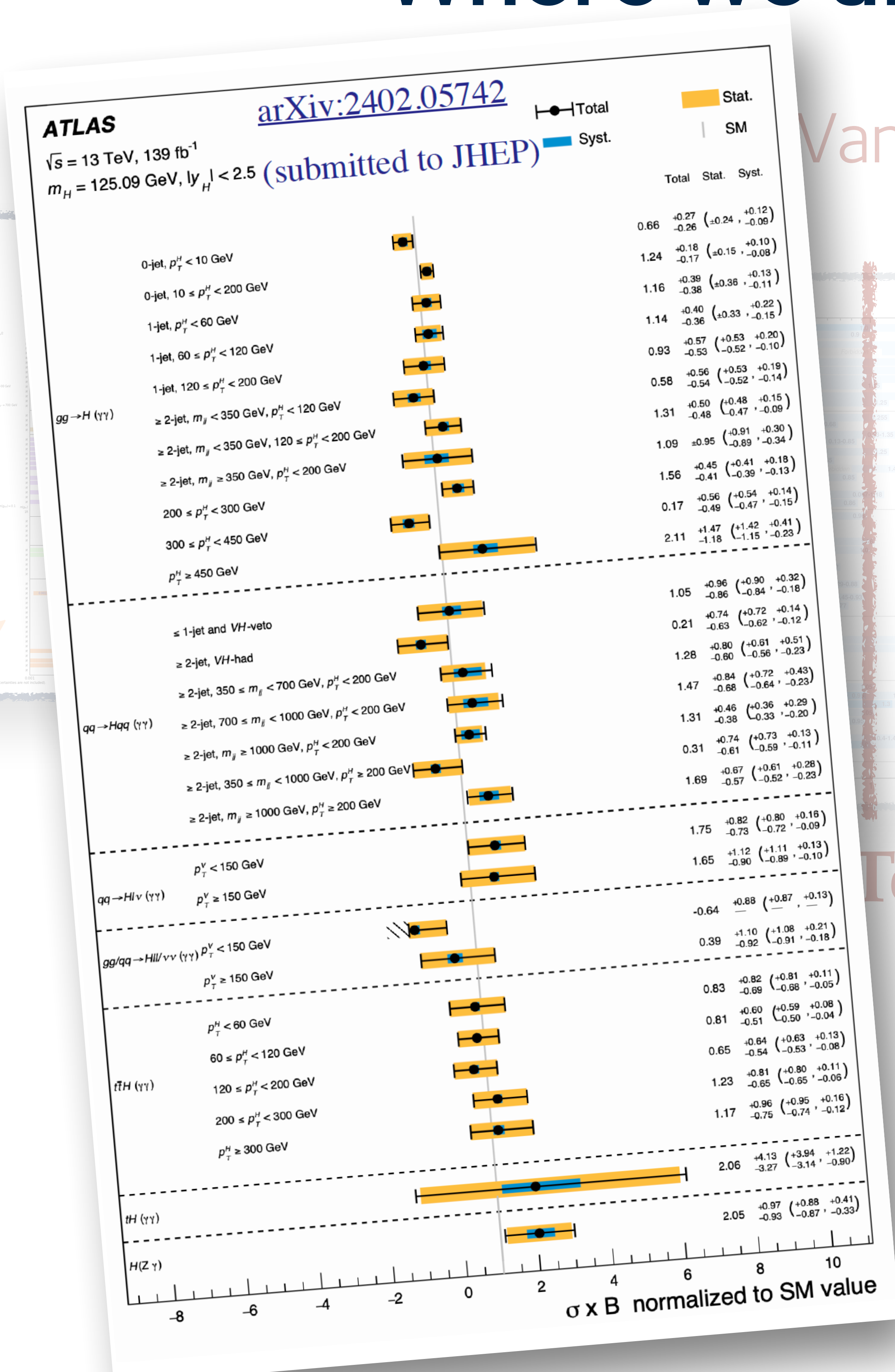
Where we are at a glance



"Vanilla" NP must be heavy

→ $\delta_{SM} \sim Q^2/\Lambda^2$ ~ percent or better

Where we are at a glance

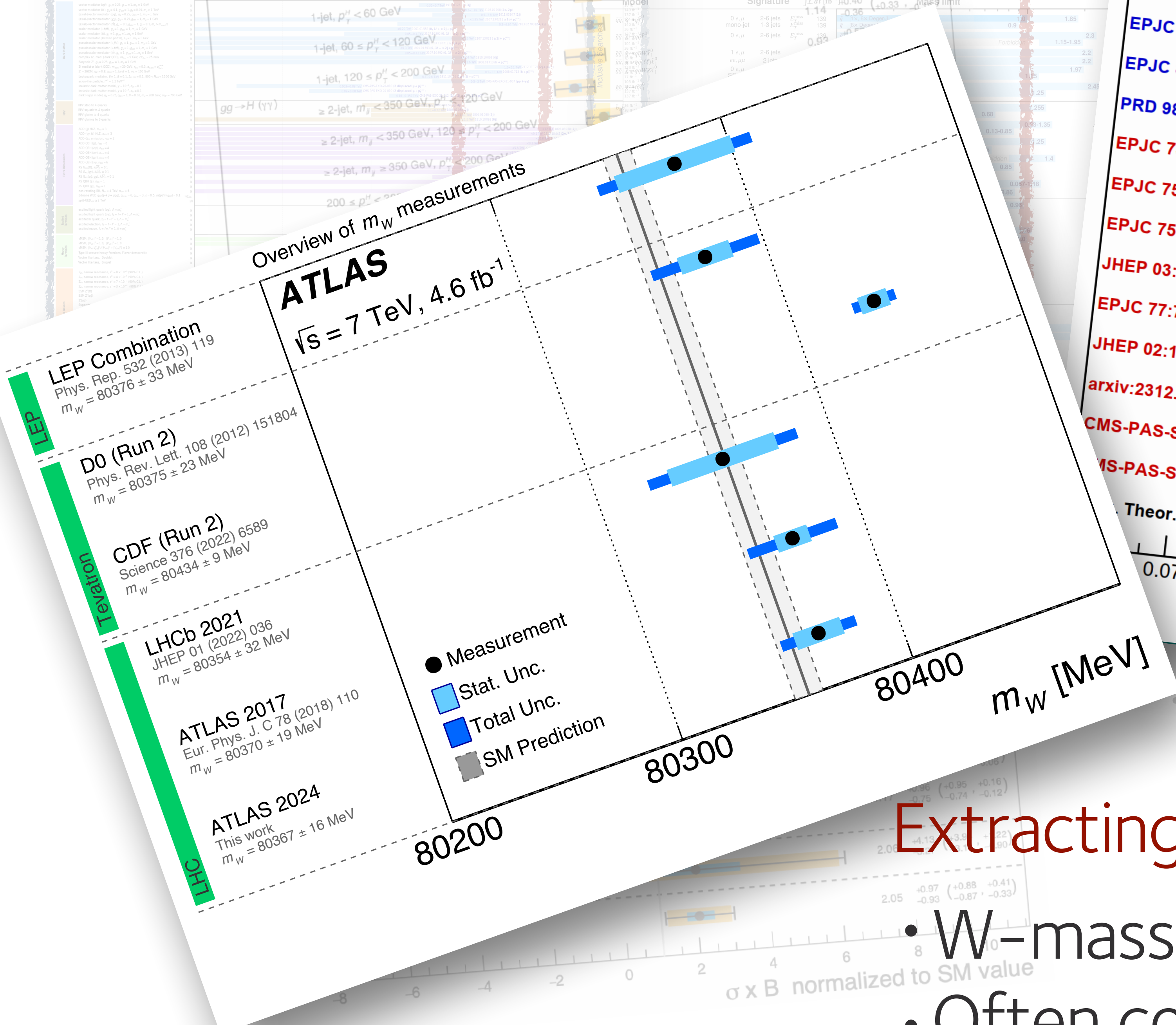


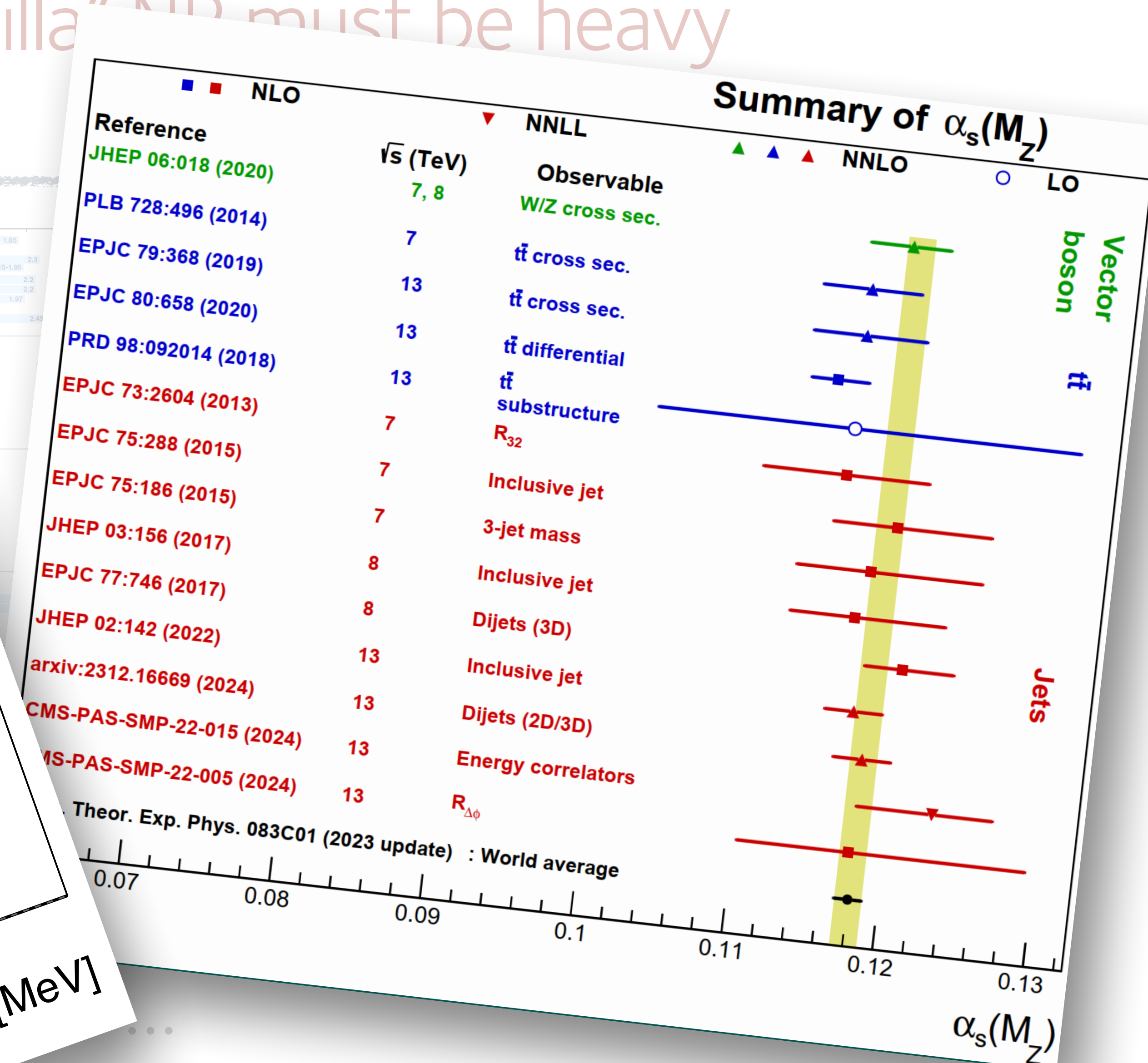
"Vanilla" NP must be heavy

Charting the Higgs sector

- ~5-10% accuracy in many channels/ observables
- Exploring Yukawa sector
- First steps towards Higgs potential
- …

Where we are at a glance

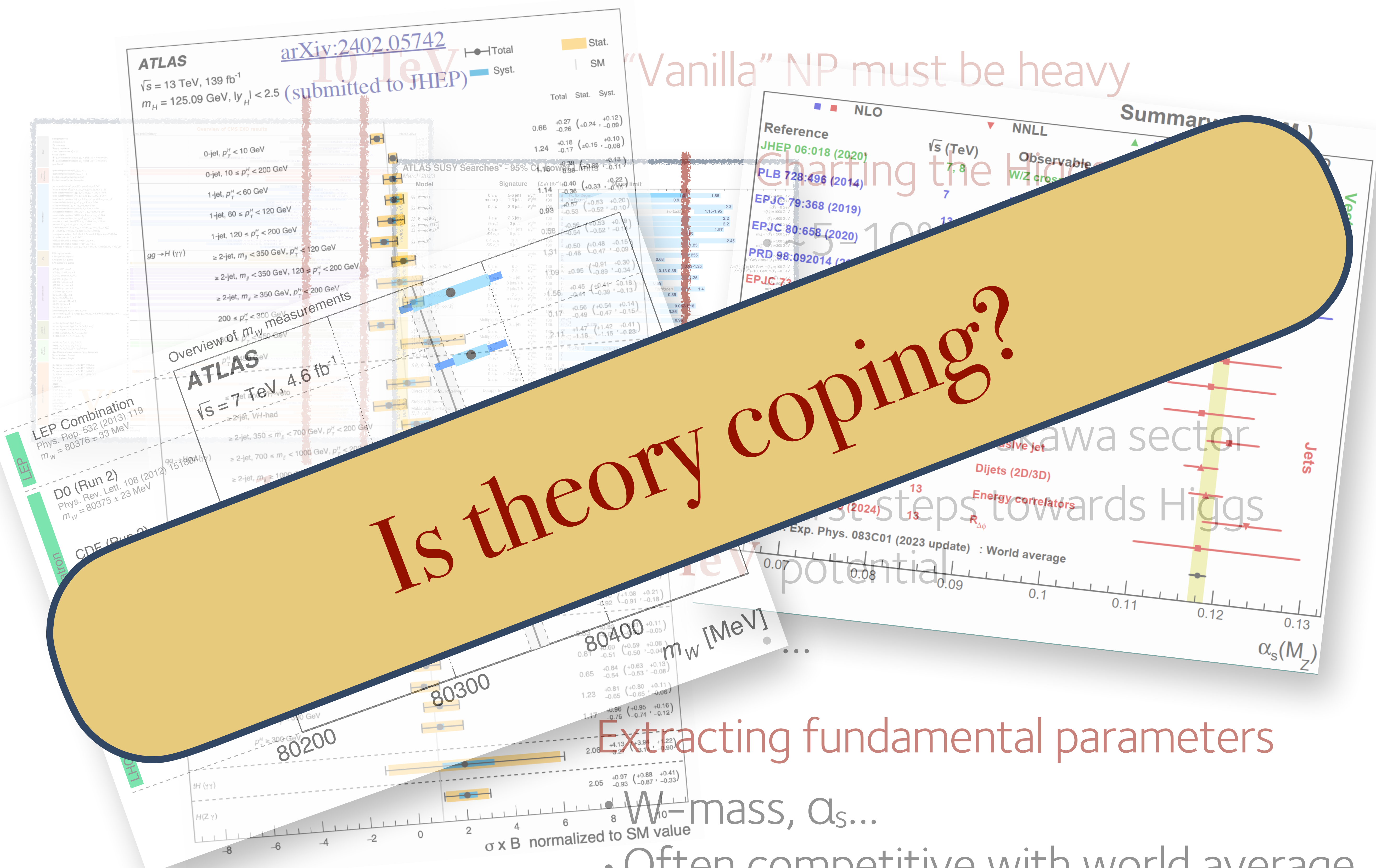




Extracting fundamental parameters

- W-mass, α_s…
- Often competitive with world average

Where we are at a glance



"Vanilla" NP must be heavy

Charting the Higgs

~5-10%

Yukawa sector

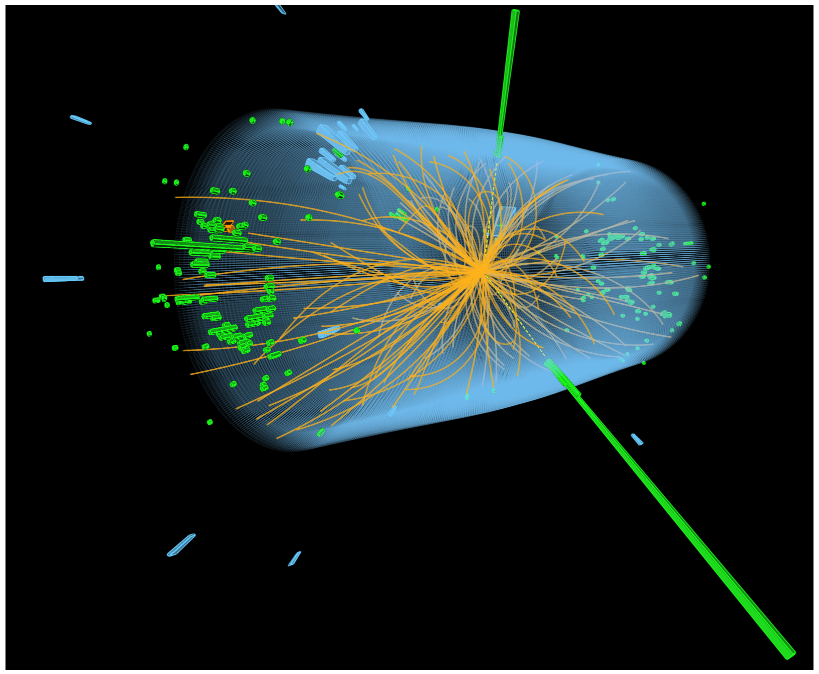
First steps towards Higgs potential

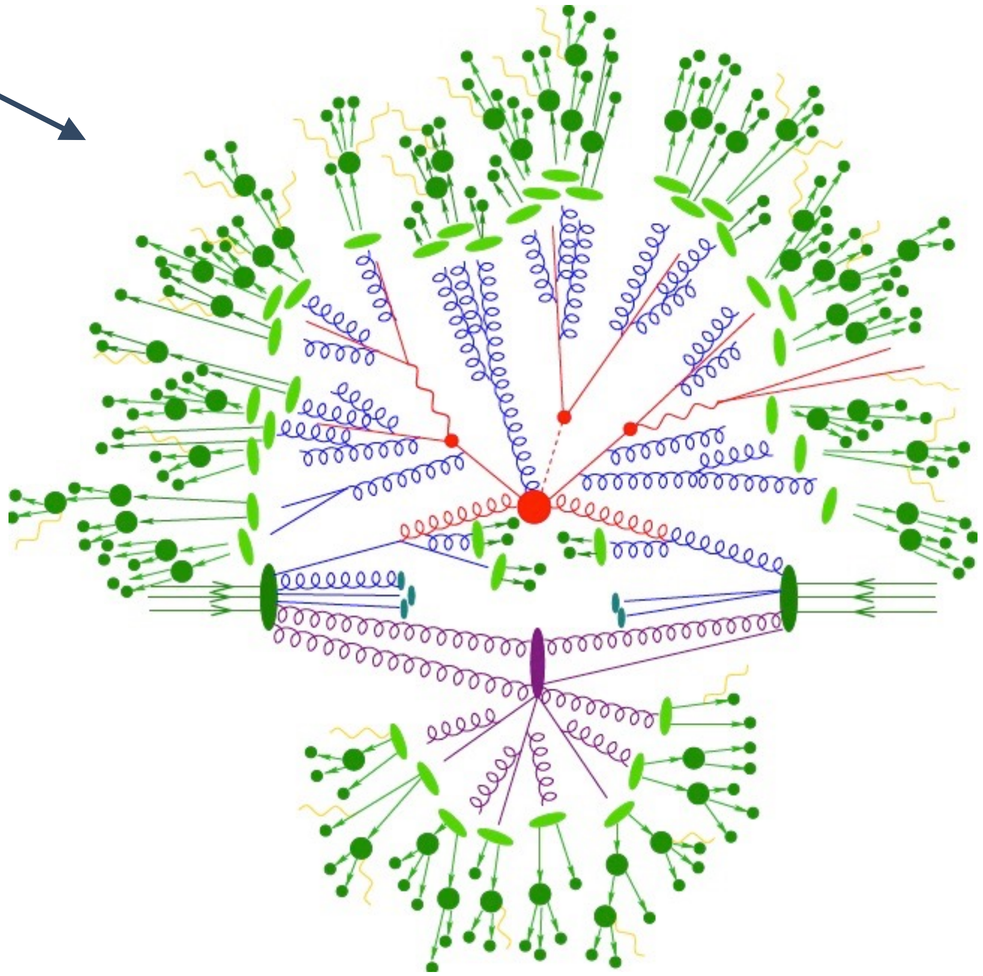
...

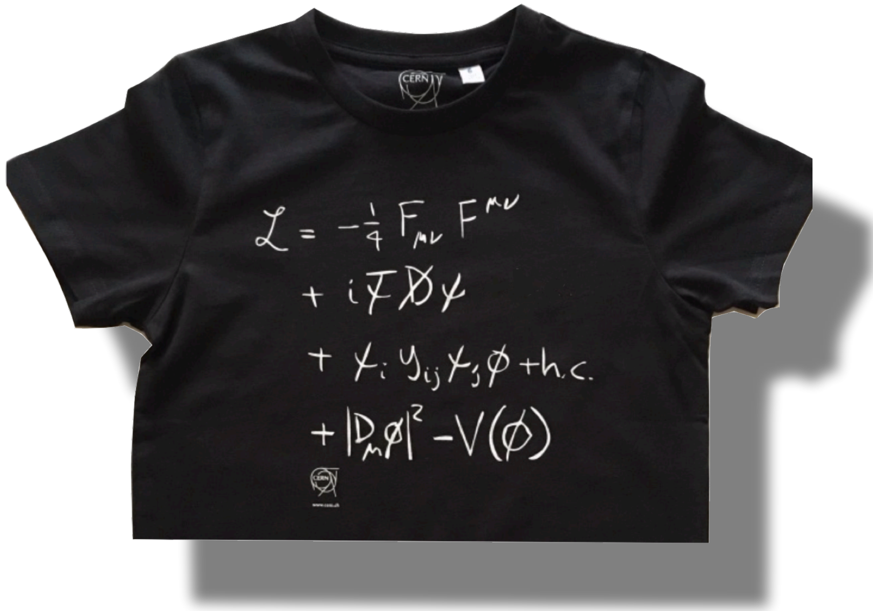
Extracting fundamental parameters

- W-mass, α_s…
- Often competitive with world average

The usual picture

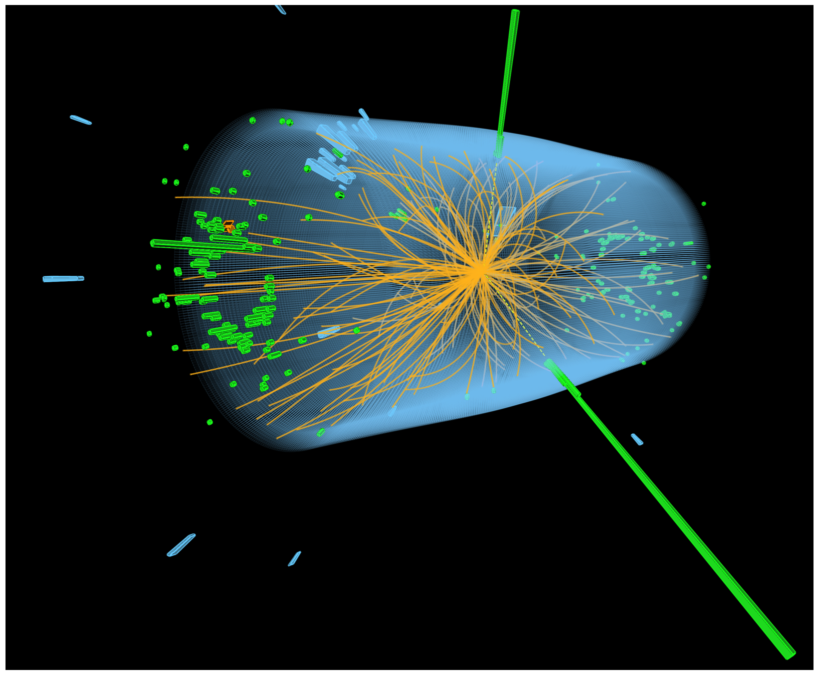


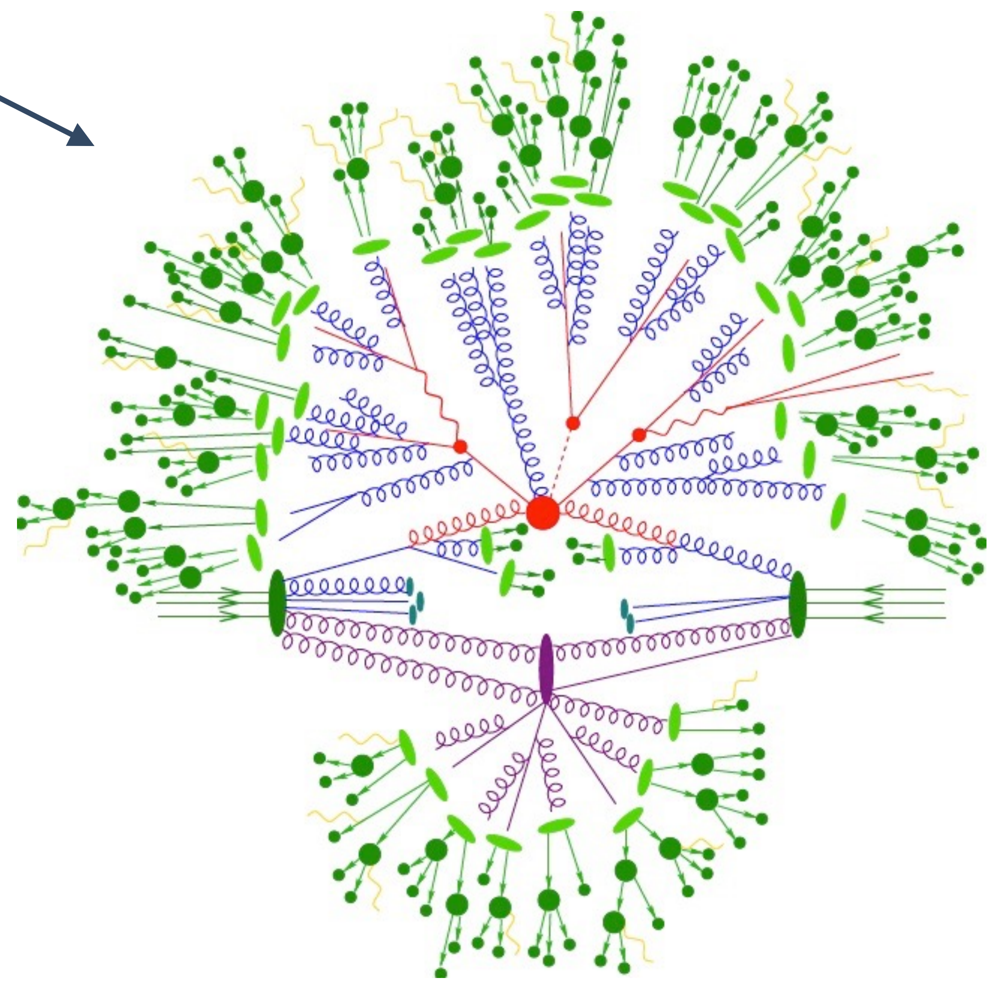


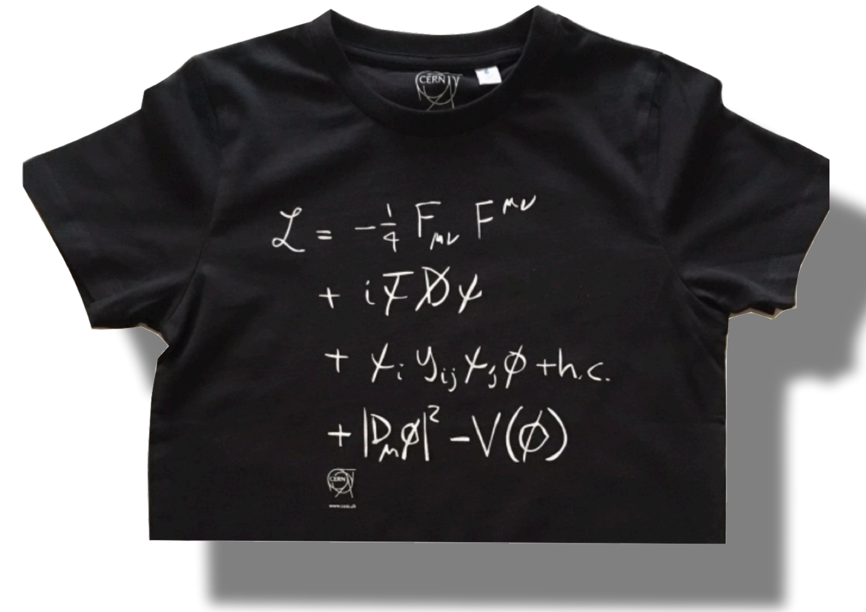


$$\mathrm{d}\sigma = \int \mathrm{d}x_1 \mathrm{d}x_2 f(x_1) f(x_2) \mathrm{d}\sigma_{\mathrm{part}}(x_1, x_2) F_J (1 + \mathcal{O}(\Lambda^n_{\mathrm{QCD}}/Q^n))$$

The usual picture







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Power corrections

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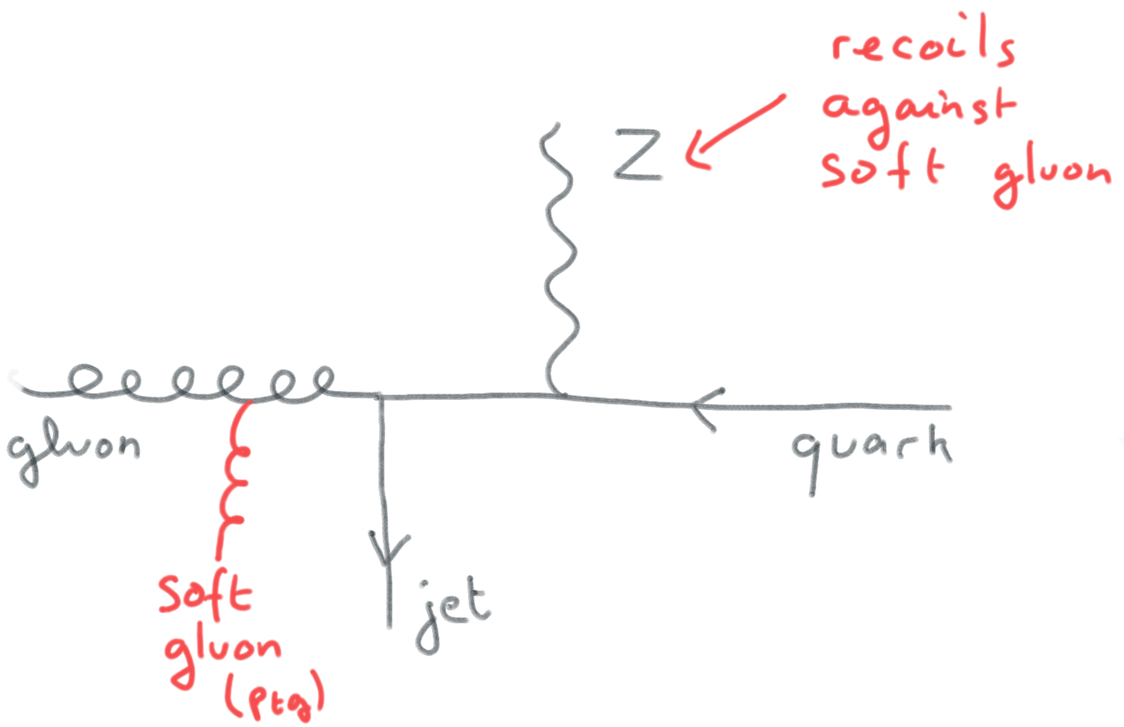
In principle, easy to imagine mechanisms for linear power corrections.

Disastrous for precision programme (1 GeV/30 GeV ~ 3%)

[G.P. Salam]



$$\sigma \sim \int \frac{dp_\perp}{p_\perp} \alpha_s(p_\perp)$$

Because of azimuthally asymmetric color flow: linear terms could be generated

Integrate over soft d.o.f. → NP

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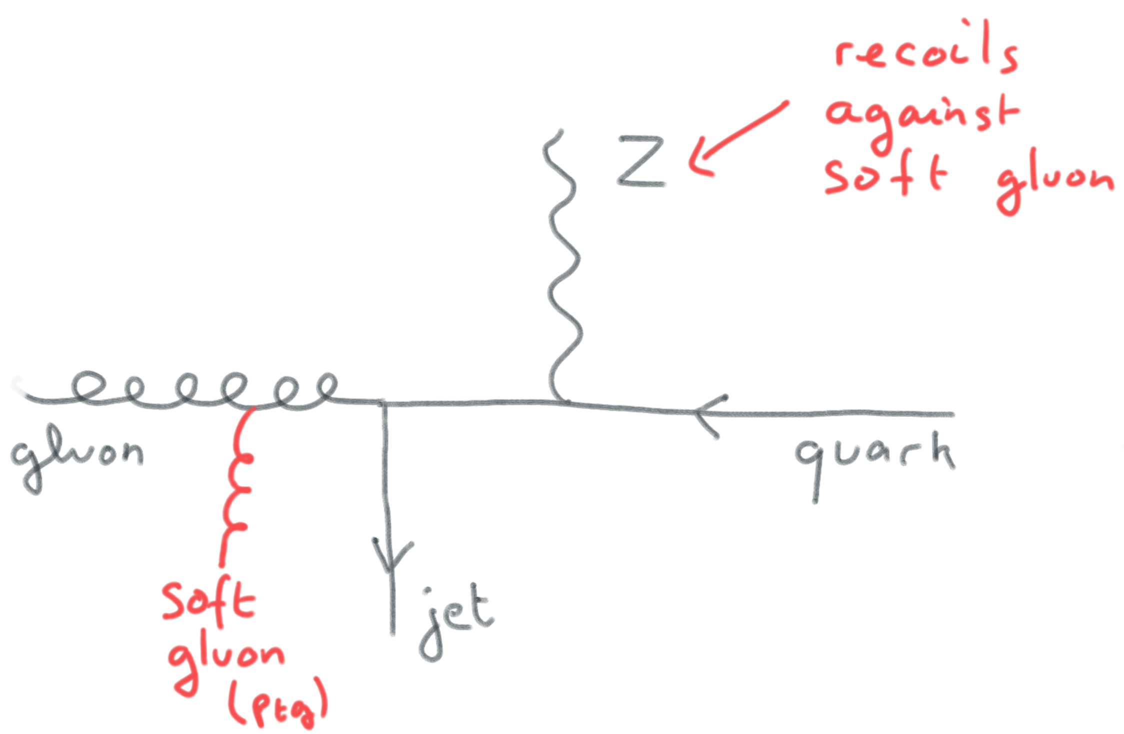

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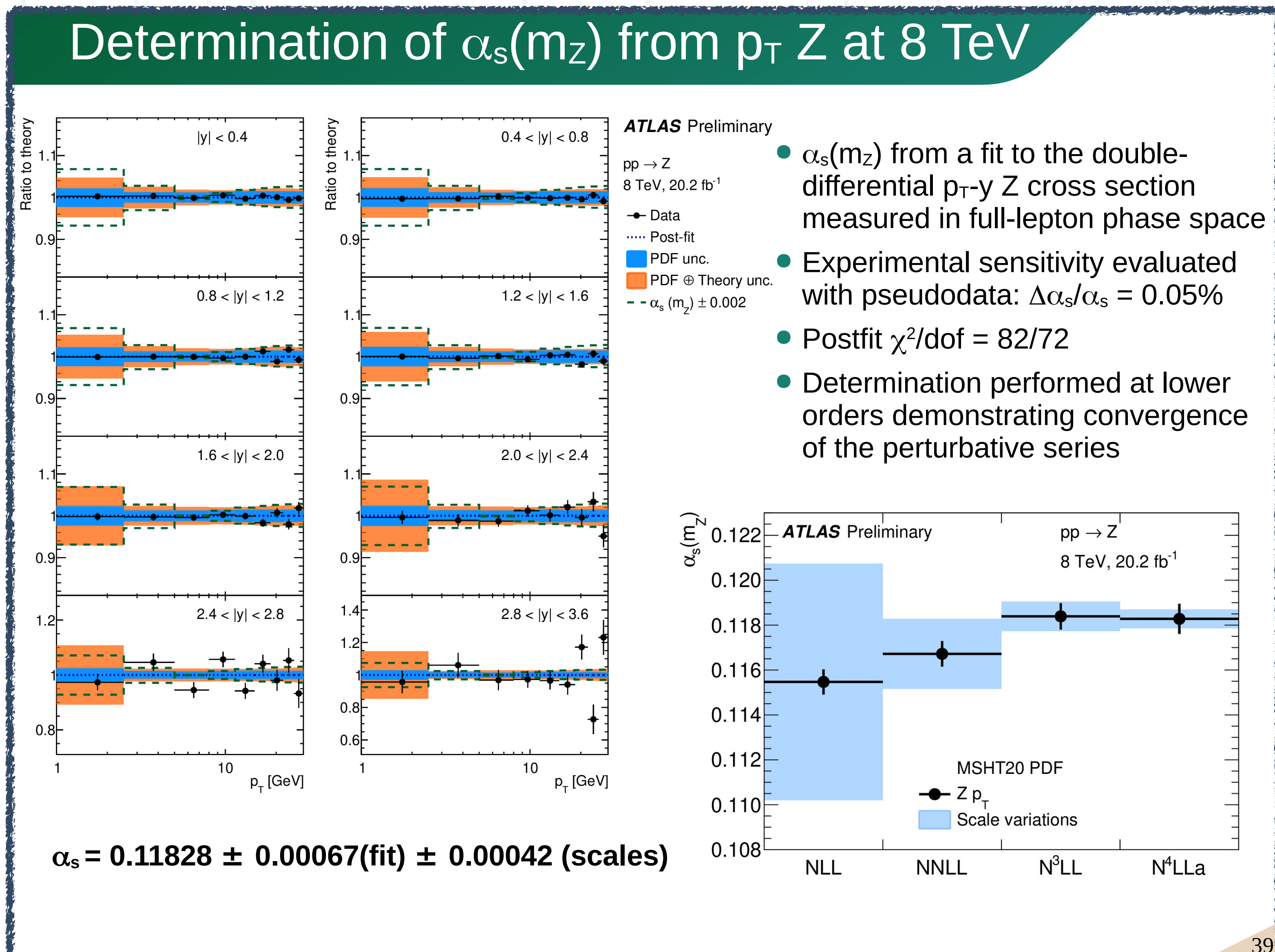
Because of azimuthally asymmetric color flow: linear terms could be generated

Integrate over soft d.o.f. → NP

For many interesting observables, this does not happen!
(→ see Paolo's talk)

Power corrections

What about $\Lambda^2 \ln^2 \Lambda \sim \%$ at 30 GeV…



[Camarda (LHC seminar 2023)]

Do we understand these effects well enough?

Impact on ultra-precise measurements?

PDFs and evolution: the rise of N^{3}LO (+th. unc.)

$$\mathrm{d}\sigma = \int \mathrm{d}x_1 \mathrm{d}x_2 f(x_1) f(x_2) \mathrm{d}\sigma_{\mathrm{part}}(x_1, x_2) F_J (1 + \mathcal{O}(\Lambda_{\mathrm{QCD}}^n / Q^n))$$

- A lot of effort in computing N^{3}LO evolution [Davies, Falcioni, Gehrmann, Herzog, von Manteuffel, Moch, Pelloni, Ruijl, Sotnikov, Ueda, Vermaseren, Vogt, Yang…]
- In many cases, enough moments + asymptotic for collider pheno

→ see Tommaso's talk

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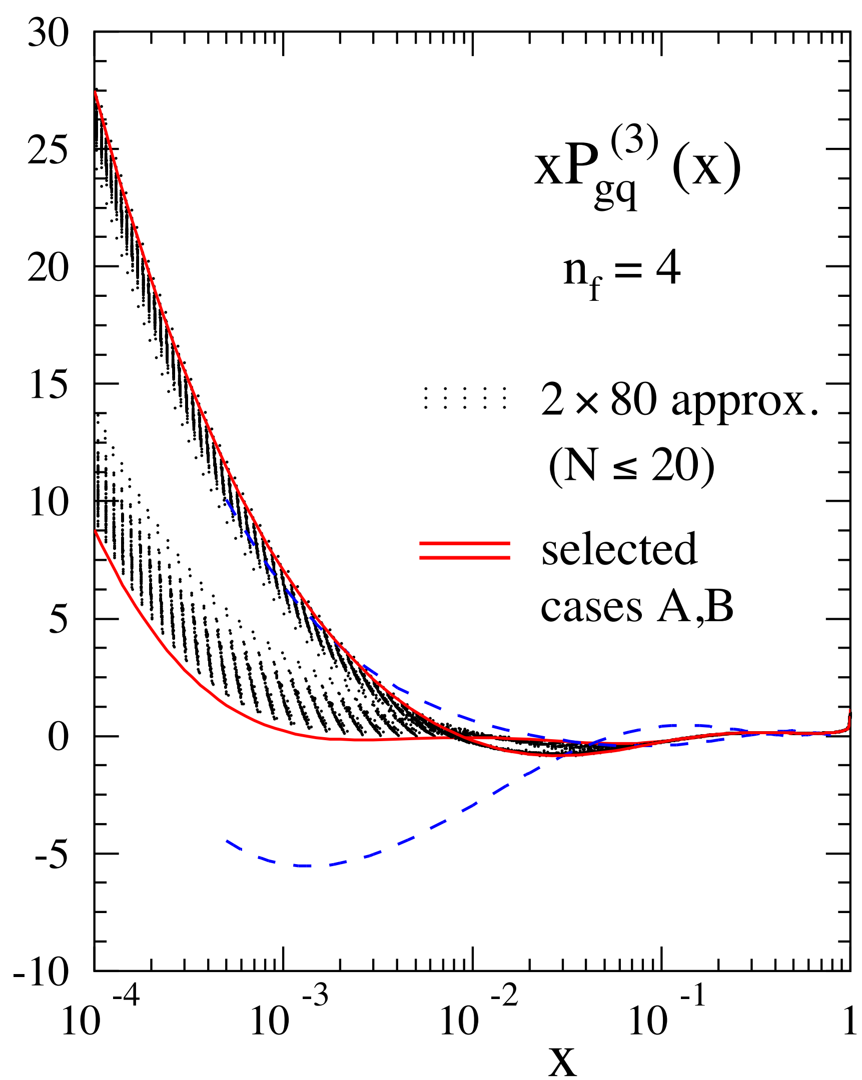
[Falcioni, Herzog, Moch, Pelloni, Vogt (2024)]



- Still to improve: small-x
  - Issue: DGLAP/BFKL duality problematic, because the latter ill-defined beyond (LC) NLL
  - Thanks to amplitudes development, better control on BFKL → interesting investigations ahead

→ see Tommaso's talk

N³LO: evolution and the problems of small-x

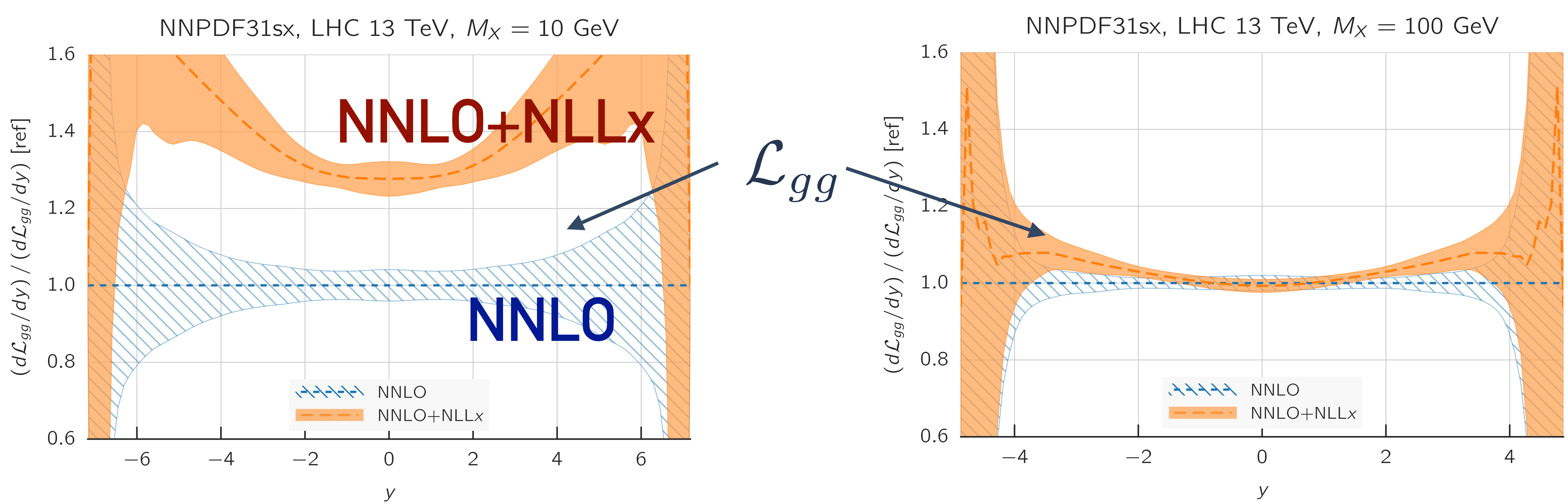
$$\gamma_{\text{pert}} = -2\bar{\alpha}_s + 0\,\bar{\alpha}_s^2 + 0\,\bar{\alpha}_s^3 - 4\zeta_3\,\bar{\alpha}_s^4 + \ldots,\ \bar{\alpha}_s = \alpha_s/(\pi N)$$

$$\gamma_{\text{res}} \sim N^{-0.3}$$

[Altarelli, Ball, Forte, Ciafaloni, Colferai, Salam, Stasto]

- N³LO: rapid small-x growth → perturbative instabilities@N³LO
- NLL resummation known, but large subleading effects [Bonvini, Marzani (2018)]

[Ball, Bertone, Bonvini, Marzani, Rojo, Rottoli (2018)]



NNLO: an issue at low-mass, not quite so at the EW scale

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$$\gamma_{\rm exact} \sim N^{-0.3}$$

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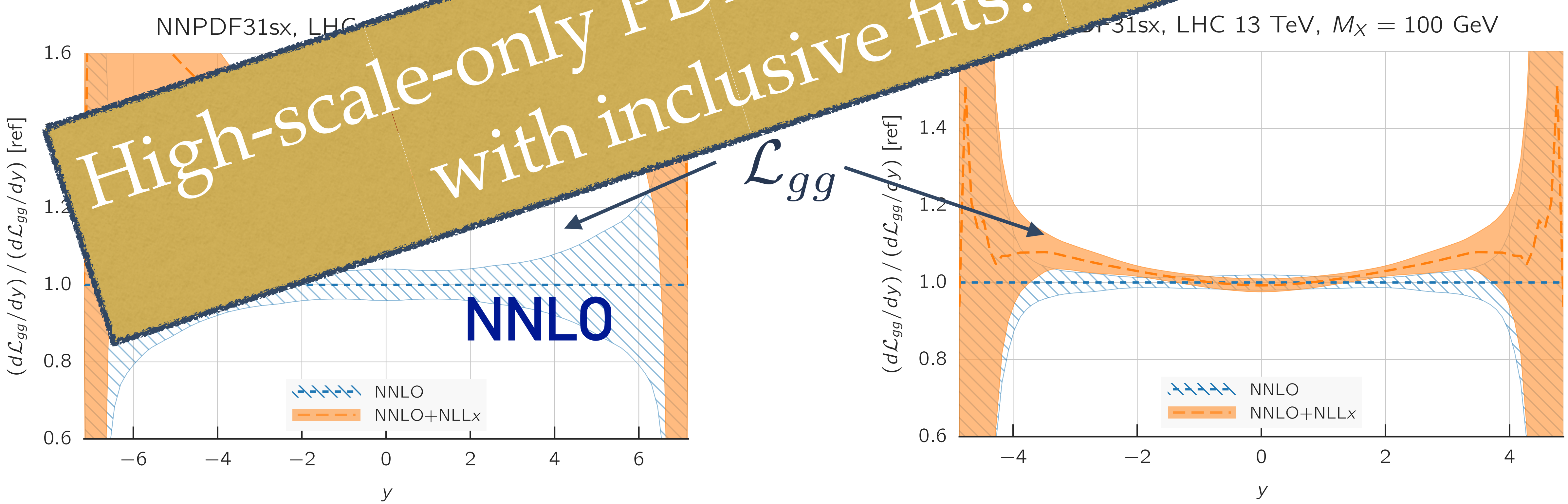
High-scale-only PDFs, to be compared with inclusive fits?

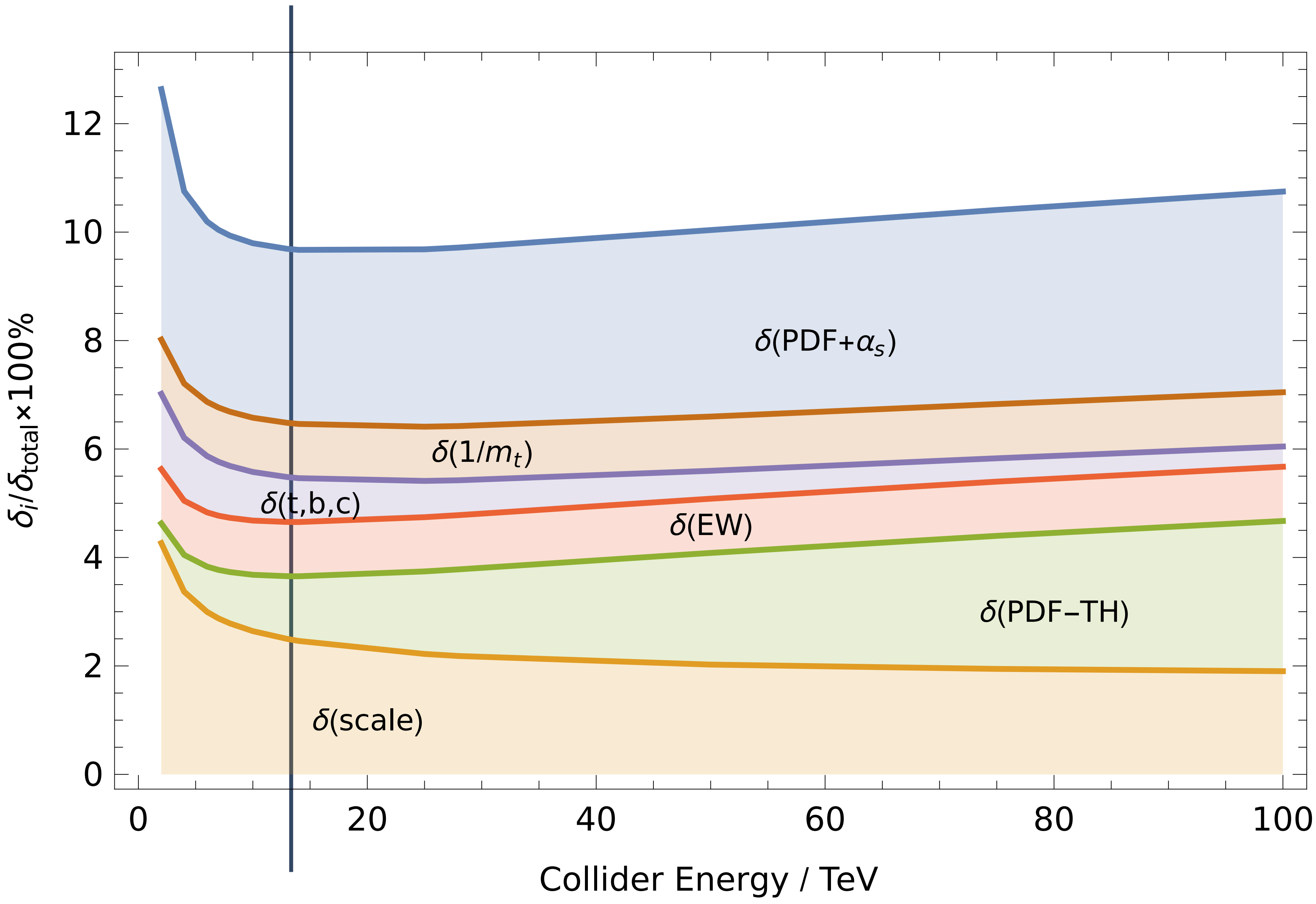
[Ball, Bertone, Bonvini, Marzani, Rojo, Rottoli (2018)]



NNLO: an issue at low-mass, not quite so at the EW scale

Hard scattering: Higgs, ggF

- ggF: N^{3}LO is not enough
- a lot of recent work (from many people in the audience!) to improve on it



[HE-HL LHC report, 2019]

Hard matrix element: Higgs, ggF

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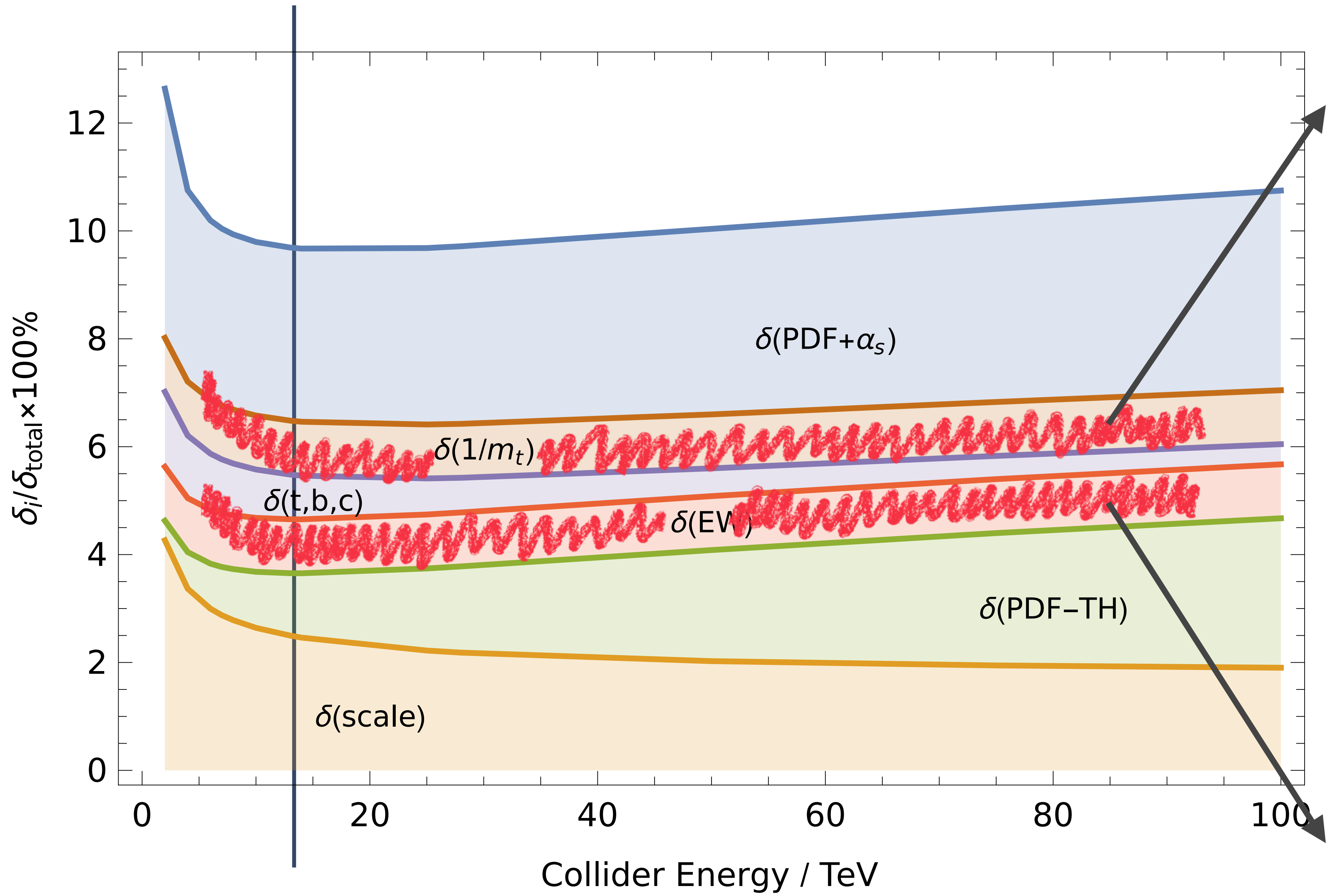

[Bonetti, Melnikov, Tancredi (2017); Bonetti, Panzer, Smirnov, Tancredi (2020); Bacchetti, Bonciani, del Duca, Hirschi, Moriello, Schweitzer (2020)]

[Czakon, Harlander, Klappert, Niggetiedt (2021); Higgs p_t: Bonciani, Del Duca, Frellesvig, Hidding, Hirschi, Moriello, Salvatori, Somogyi, Tramontano]

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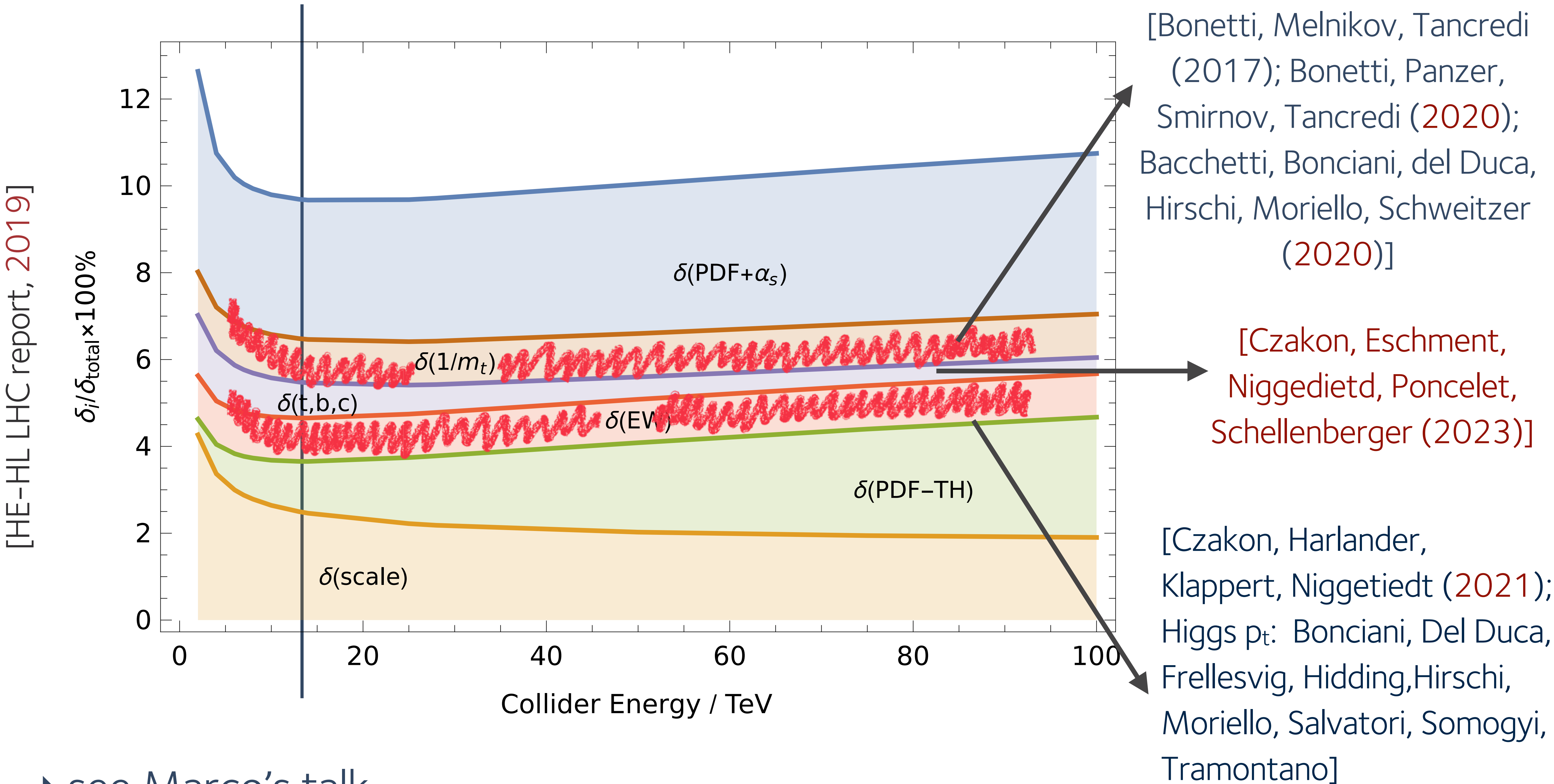

→ see Marco’s talk

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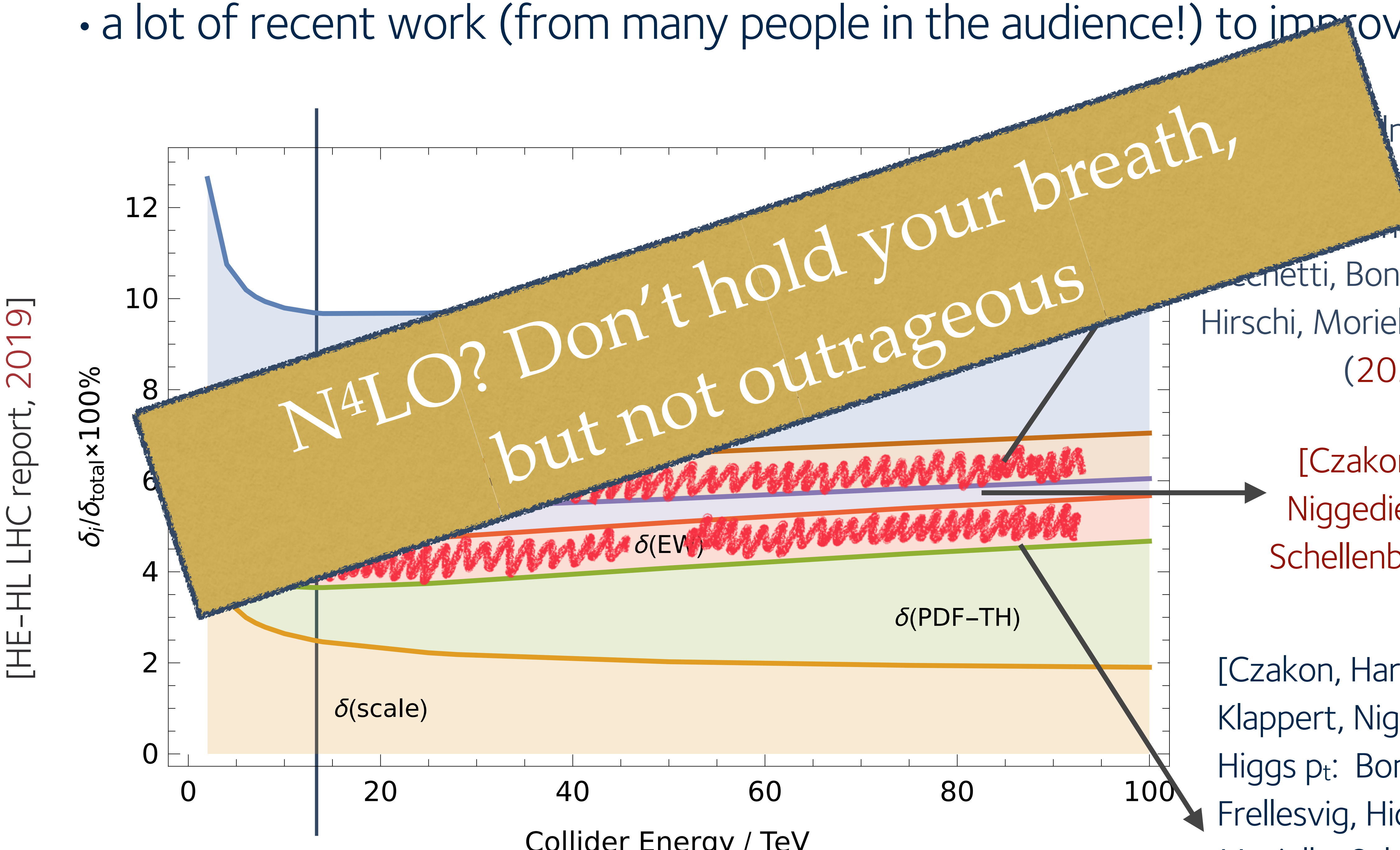

…nikov, Tancredi … etti, Panzer, … credi (2020); … chetti, Bonciani, del Duca, Hirschi, Moriello, Schweitzer (2020)]

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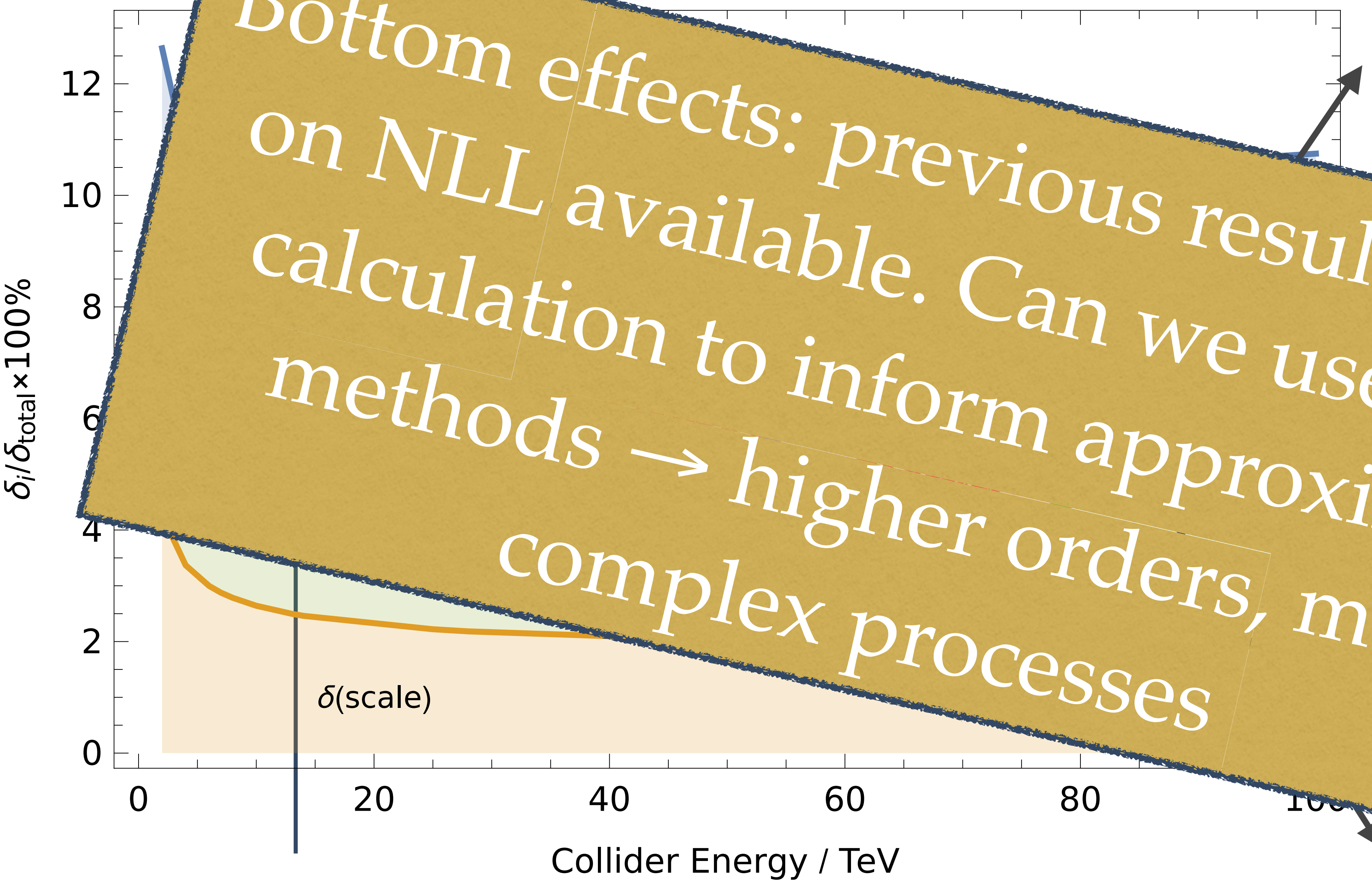

[HE-HL LHC report, 2019]

Bottom effects: previous results based on NLL available. Can we use exact calculation to inform approximate methods → higher orders, more complex processes

[Bonetti, Melnikov, Tancredi (2017); Bonetti, Panzer, Smirnov, Tancredi (2020); Bacchetti, Bonciani, del Duca, ... riello, Schweitzer

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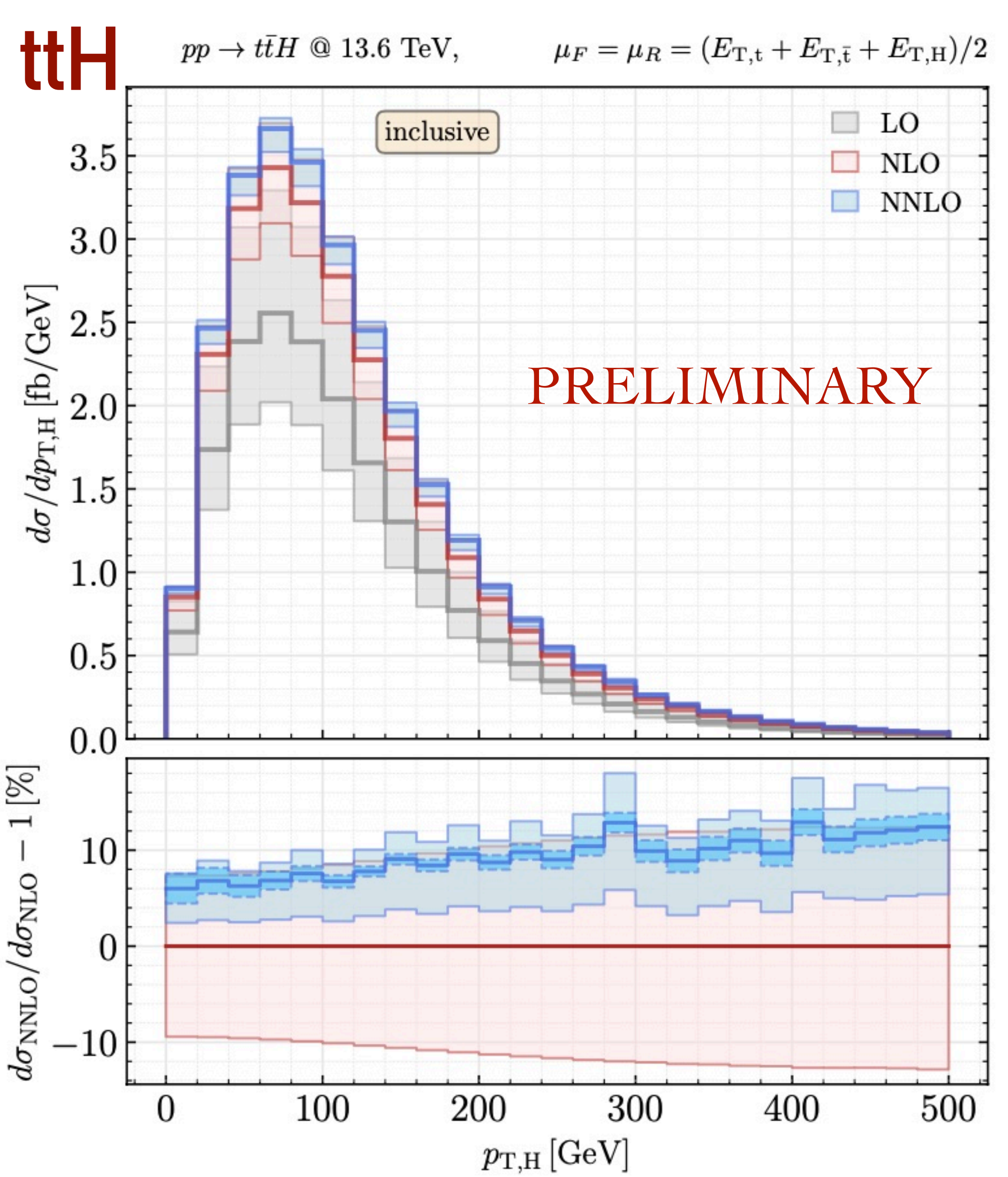
Tramontano]

→ see Marco's talk

ttH & ttV@NNLO

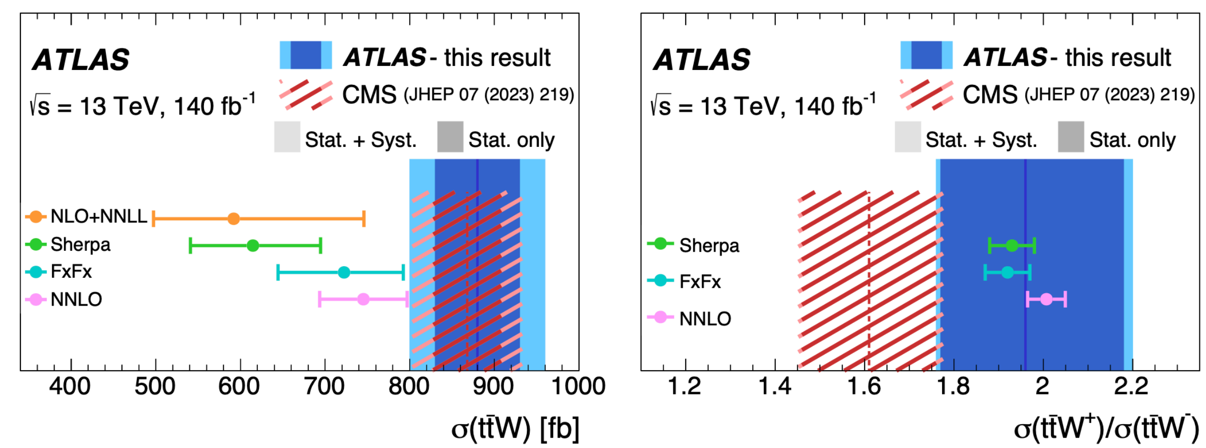
- Despite a lot of progress in scattering amplitudes (see Federico's, Vasily's & Andreas' talks), these amplitudes are still out of reach
- Idea: approximate them, and study impact on physical cross-section

ttH



[M. Grazzini, talk at Moriond 2023]

ttW



- the updated measurement is **compatible** with our prediction at the level of 1.4σ

$$\sigma_{\text{ATLAS}} = 880 \pm 50\,(\text{stat.}) \pm 70\,(\text{syst.}) = 880 \pm 80 \text{ fb}$$

$$\sigma_{\text{theory}} = 745 \pm 50\,(\text{scale}) \pm 13\,(\text{2loop approx.}) \pm 19\,(\text{PDF}, \alpha_s) \text{ fb}$$

[C. Savoini, talk at Moriond 2024]

→ see Simone's + Javier's talks

[Catani, Devoto, Grazzini, Kallweit, Mazzitelli, Savoini]

ttH & ttV@nNLO

- The problem: the approximations (soft Higgs/W, massless top) are non-parametric, and typically non-convergent

- The solution: it seems that the impact of the (properly defined) <u>finite remainder on the total cross section is small for the cross section</u>, as long as it is not outrageous, O(50%) control is enough

Do we understand this?

ttH & ttV@NNLO

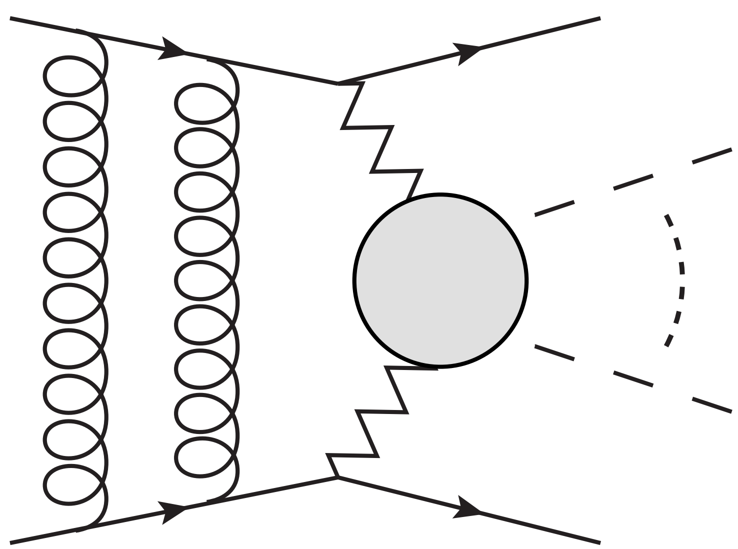
- This seems to be a feature of processes whose IR physics we control very well (basically p_t-like plus some soft stuff), with some caveat
- ttH, VV: finite remainder ~ 0.1% of the total NNLO cross-section
- This does not seem the case e.g. for jjj, but do we have a good IR control there?
- Validating these observation in more fiducial regions + wide class of processes is <u>paramount</u>. 2L amplitudes crucial
- But if this helps in elucidating what is going on, huge potential! The "ultimate" (f.o.) merging scheme, for processes for which N-loop is too difficult…

→ see Simone's + Javier's talks

ni, Kallweit, Mazzitelli, Savoini]

The revenge of amplitudes: VBF

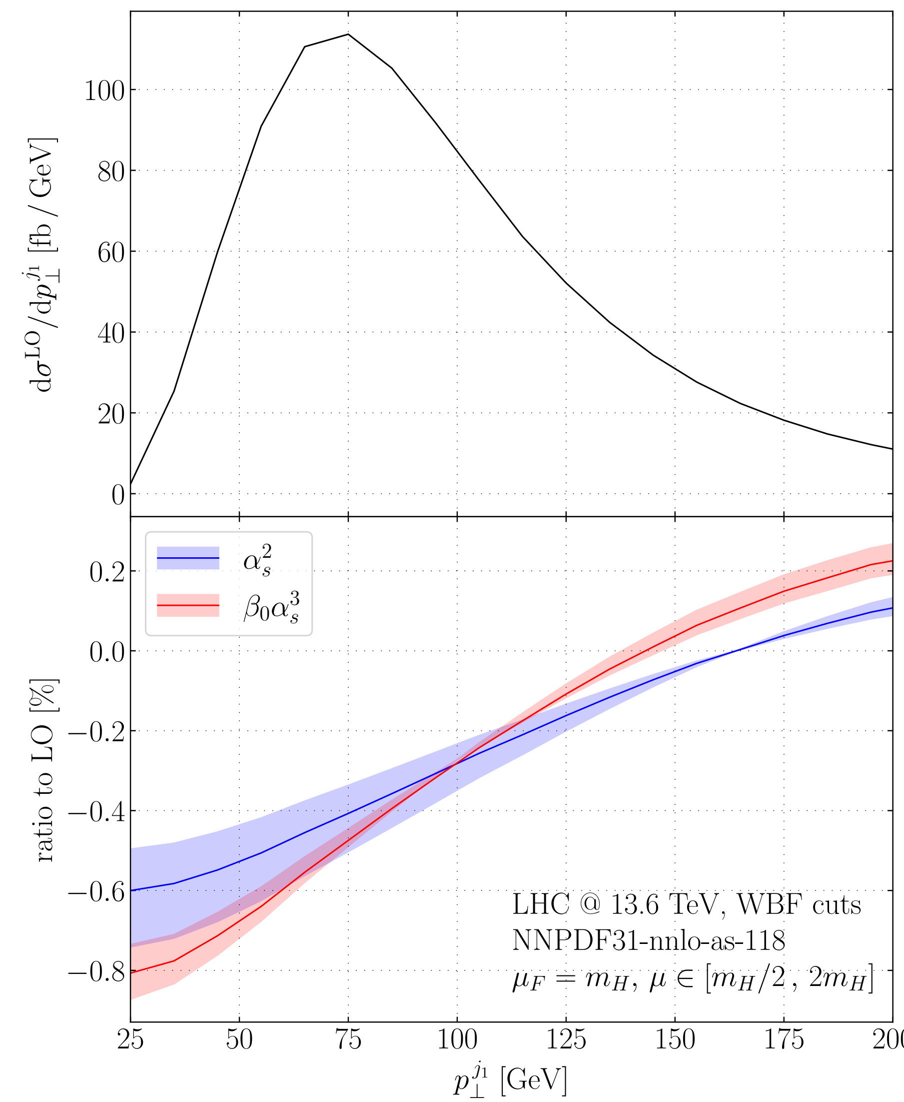
- Non-factorizable VBF: bulk of the effect comes from scattering amplitude



Starts at NNLO; kinematic suppressed in VBF region, color-suppressed (but π^2 enhanced)

Only recently leading contribution has been computed. Large residual scale uncertainty

[Liu, Melnikov, Penin (2019), Dreyer, Karlberg, Tancredi (2020)]



Recent progress: leading-n_f contribution, to fix this

[Brønnum-Hansen, Long, Melnikov (2023)]

Characterising the Higgs: Γ_H

- $\Gamma_H \sim 4$ MeV, detector resolution ~ GeV → need indirect constraints

$$\Gamma_H = 2.9^{+1.9}_{-1.4} \text{ MeV at 68\% CL}$$

→ latest CMS result

- Three main methods
  - global fits
  - Off-shell: ✓ very strong constraints, ✘ some model dependence
  - Mass shift in γγ: ✓ expected less model dependence, ✘ weaker constraints, difficult to compute exactly what experimentalists measure (detector simulation)

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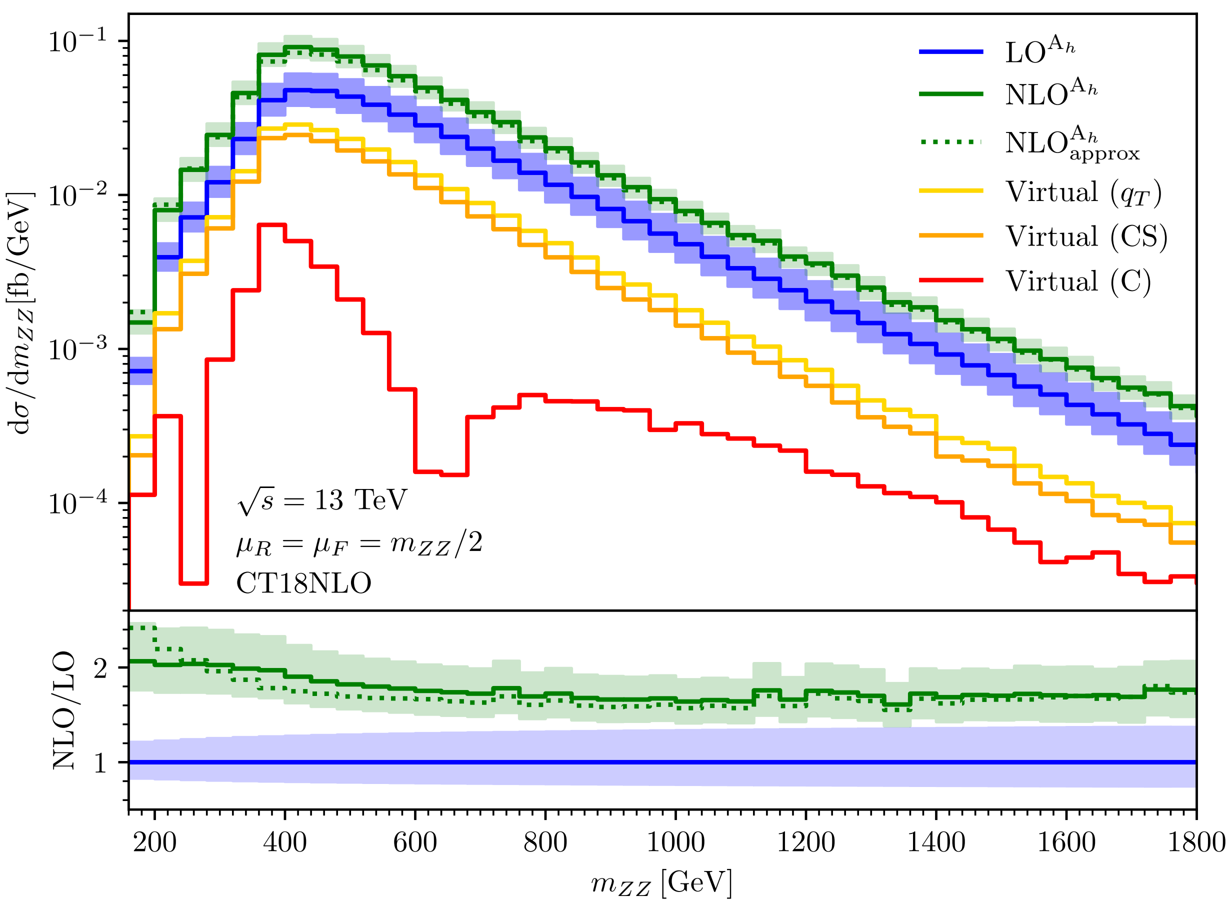
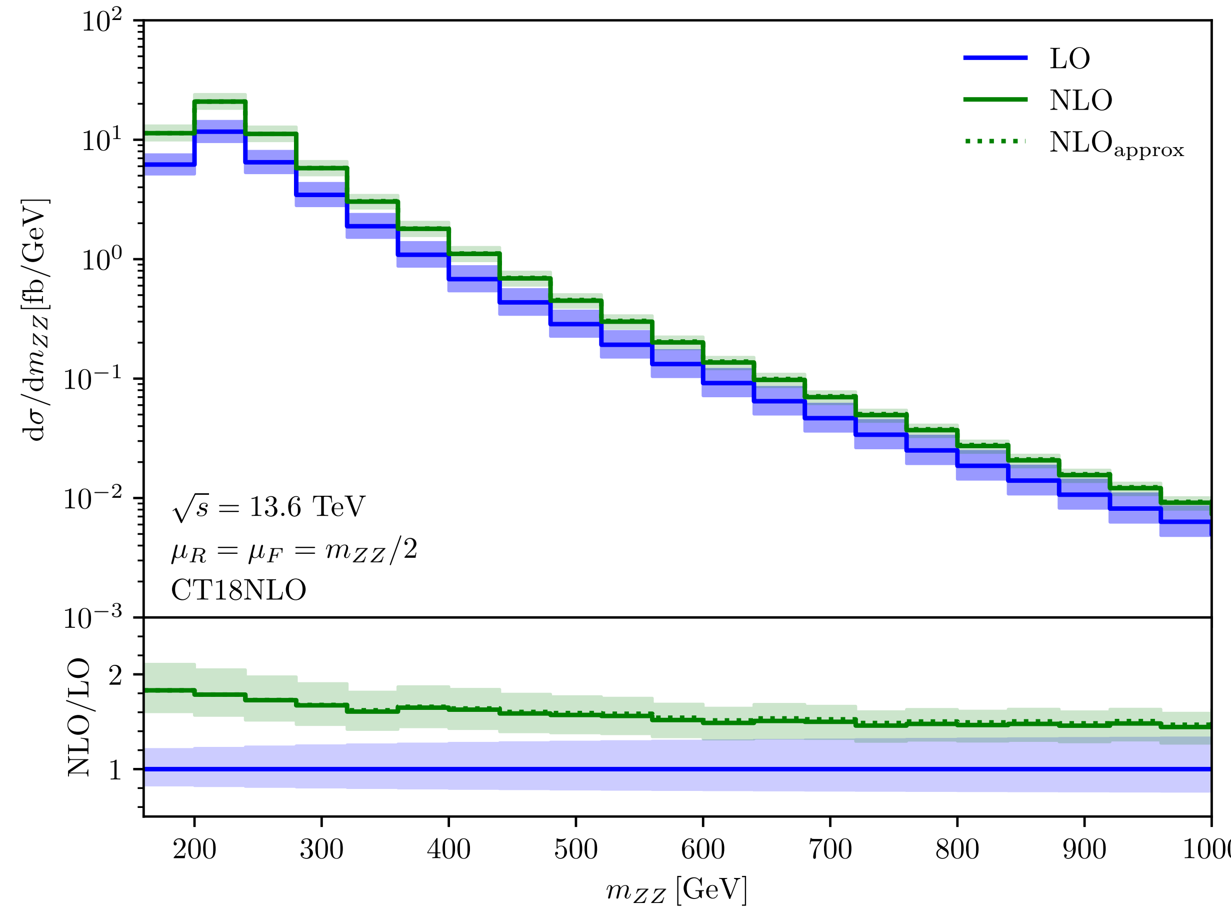
Important progress on both fronts

Off-shell: first full NLO result

[Agarwal, Jones, Kerner, von Manteuffel (2024)] → see Andreas' talk





- Mixed analytical/numerical approach
- Result provided much-needed validation for current estimates for the NLO K-factor (used by experiments...)
- Confirmed large destructive interference at NLO as well
- The usual issue: top-quark scheme uncertainties? Now we can study...

γγ interference: leading terms beyond NLO

[Bargiela, Buccioni, FC, Devoto, von Manteuffel, Tancredi]

[F. Devoto, talk at Moriond 2024]

$H \to \gamma\gamma$ NNLO SV calculation: results

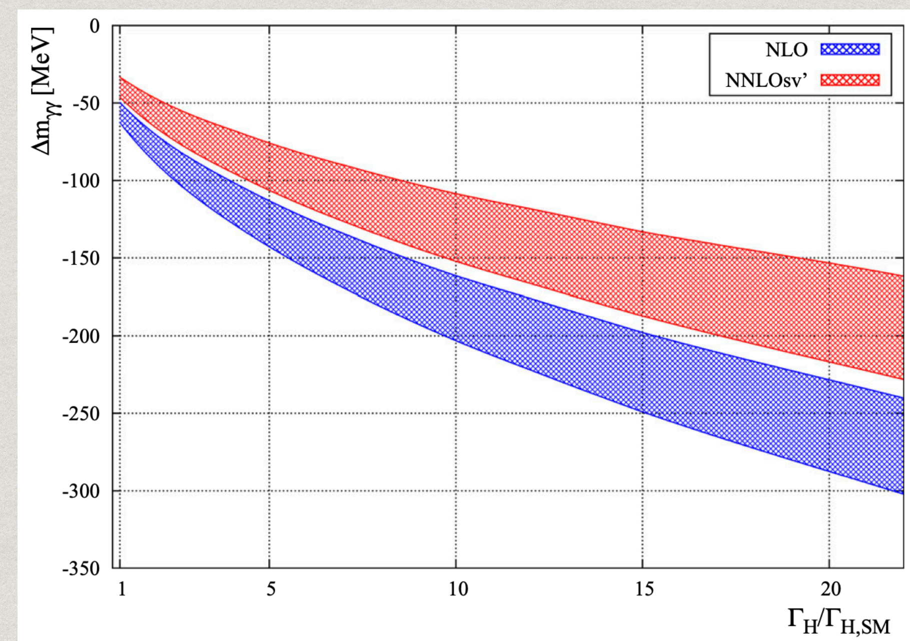
Table 3 Comparison of K-factors, measured w.r.t. the LO value, for the mass-shift at $\sqrt{s} = 13.6$ TeV calculated via a gaussian fit method and via a first-moment method

$\Delta m_{\gamma\gamma}/\Delta m_{\gamma\gamma}^{\mathrm{LO}}$	First moment	Gaussian Fit
K_{NLO}	0.665	0.664
K_{NNLOsv}	0.554	0.554
$K_{\mathrm{NNLOsv'}}$	0.475	0.474

$$\Delta M_{(N)NLO} = \Delta M_{\mathrm{LO}} K_{(N)NLO}$$

$\Delta M_{\gamma\gamma} \sim$ 150 MeV: Γ_H<(10-20)$\Gamma_{H,SM}$

$\Delta M_{\gamma\gamma} \sim$ 75 MeV: Γ_H<(3-5)$\Gamma_{H,SM}$



[similar approach applied to rare H→Zγ decay, Buccioni, Devoto, Djouadi, Ellis, Quevillon, Tancredi]

- Soft-virtual approx to NNLO (bulk of the effect: virtual + low-p_t physics)
- Unfortunately: looser bounds (but impressive experimental progress)
- Off-the-shelf "SV improvements" don't work for the background/interference → non-trivial NLP behaviour (→ see Michal's talk)

The devil is in the ~~details~~ backgrounds

Backgrounds playing an increasingly crucial role (e.g. ttH, VH)

Better handle on V+jets/V+HF needed

The good news: technology (=2L) is ~ready for Vjj → NNLO "around the corner"

All Two-Loop Feynman Integrals for Five-Point One-Mass Scattering

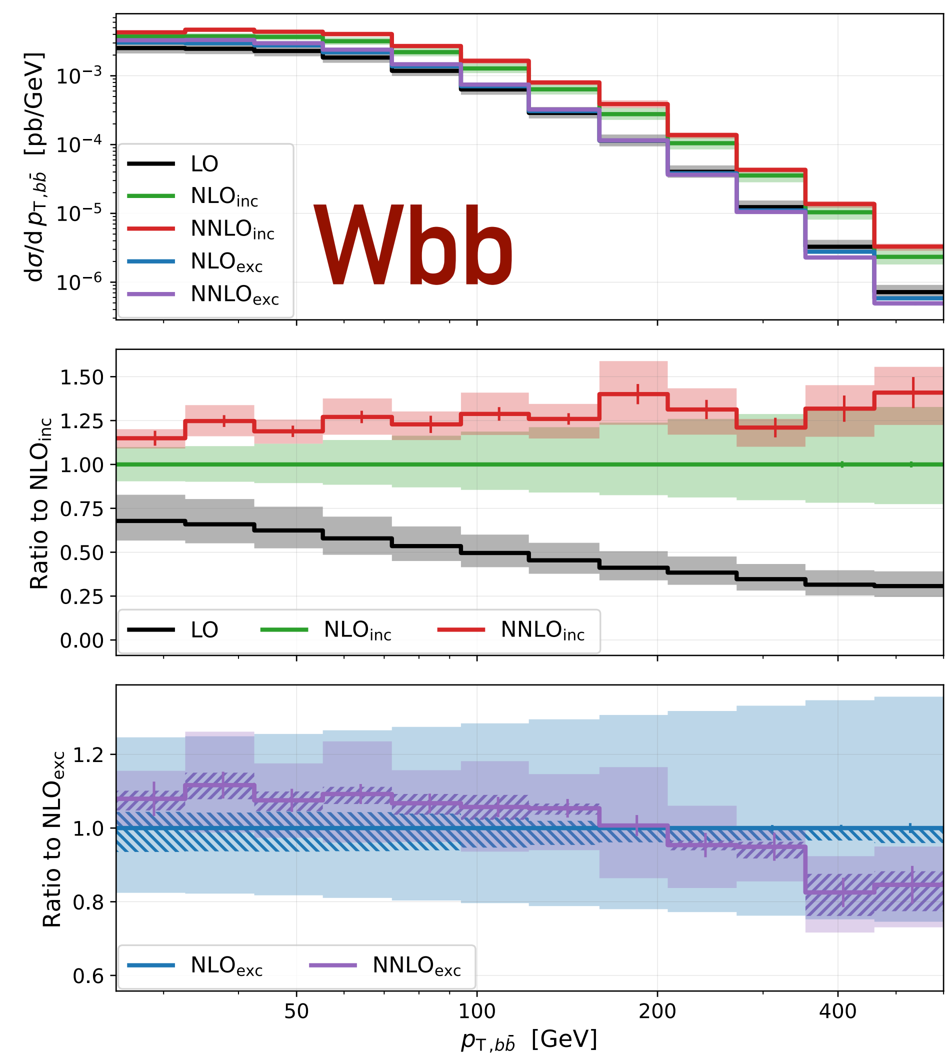
Samuel Abreu,[1,2] Dmitry Chicherin,[3] Harald Ita,[4,5] Ben Page,[1] Vasily Sotnikov,[6,7] Wladimir Tschernow,[8] and Simone Zoia[9]
[1]CERN, Theoretical Physics Department, CH-1211 Geneva 23, Switzerland
[2]Higgs Centre for Theoretical Physics, School of Physics and Astronomy, The University of Edinburgh, Edinburgh EH9 3FD, Scotland, United Kingdom
[3]LAPTh, Université Savoie Mont Blanc, CNRS, B.P. 110, F-74941 Annecy-le-Vieux, France
[4]Paul Scherrer Institut, Forschungsstrasse 111, 5232 Villigen, Switzerland
[5]ICS, University of Zurich, Winterthurerstrasse 190, Zurich, Switzerland
[6]Physik-Institut, University of Zurich, Winterthurerstrasse 190, 8057 Zurich, Switzerland
[7]Department of Physics and Astronomy, Michigan State University, 567 Wilson Road, East Lansing, Michigan 48824, USA
[8]Physikalisches Institut, Albert-Ludwigs-Universität Freiburg, D-79104 Freiburg, Germany
[9]Dipartimento di Fisica and Arnold-Regge Center, Università di Torino, and INFN, Sezione di Torino, Via P. Giuria 1, I-10125 Torino, Italy

Two-Loop Hexa-Box Integrals for Non-Planar Five-Point One-Mass Processes

Samuel Abreu,[1,2,3] Harald Ita,[4] Ben Page,[1] Wladimir Tschernow[4]

Leading-Color Two-Loop Amplitudes for Four Partons and a W Boson in QCD

S. Abreu,[a,b,c] F. Febres Cordero,[d] H. Ita,[e] M. Klinkert,[e] B. Page,[a] and V. Sotnikov[f]

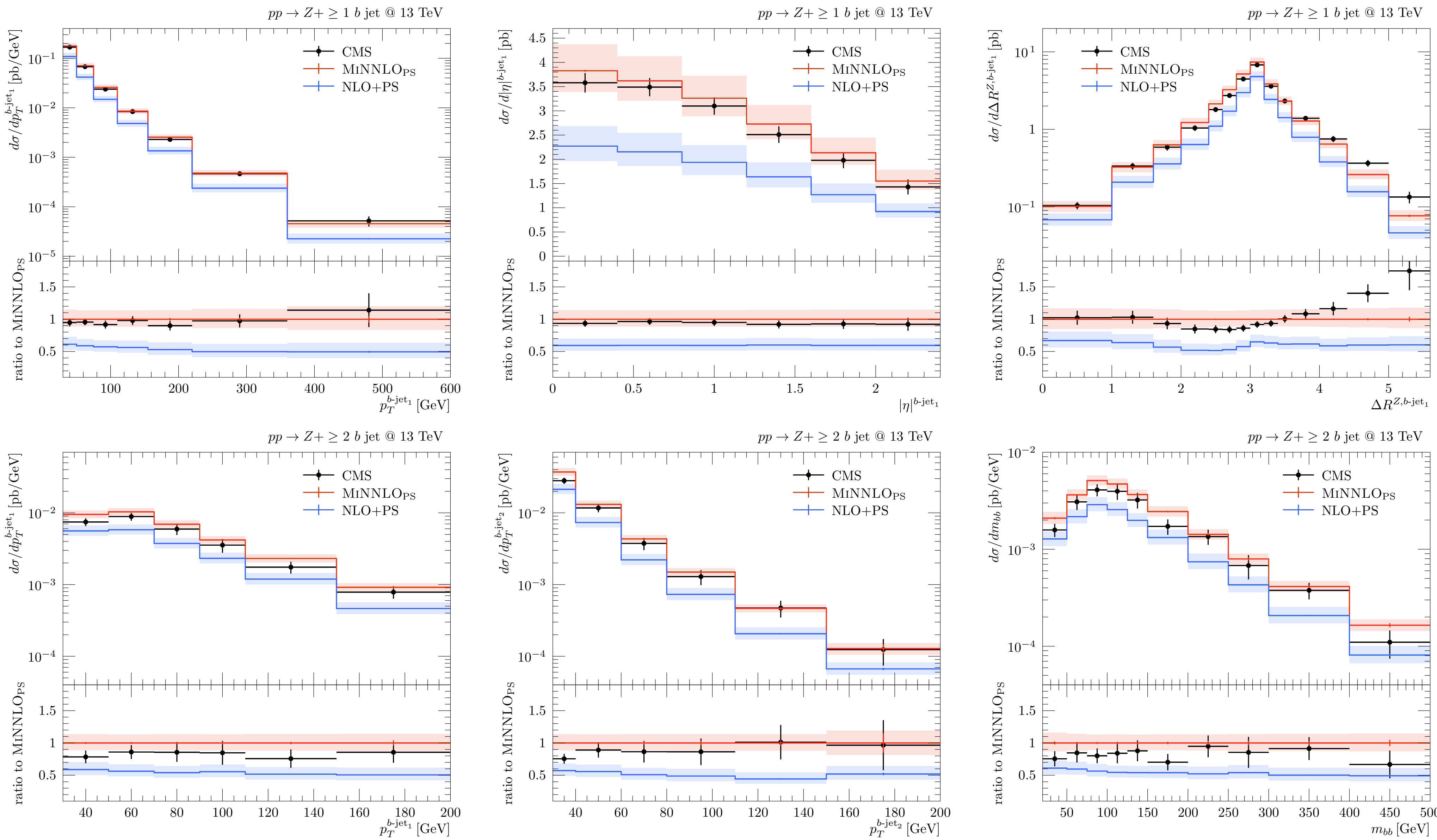


[Hartanto, Popescu, Poncelet, Zoia (2022)]

Fresh from the press: Zbb

[Mazzitelli, Sotnikov, Wiesemann]

→ see Javier's talk



- 4FNS, retain (dominant) kinematic mass effects, neglect (2L) dynamic effects, "massification". Matched with shower
- Large corrections, as expected from 4FS. Good agreement with data

Fresh from the press: Zbb

[Mazzitelli, Sotnikov, Wiesemann]

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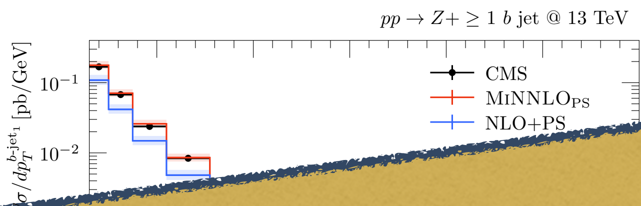
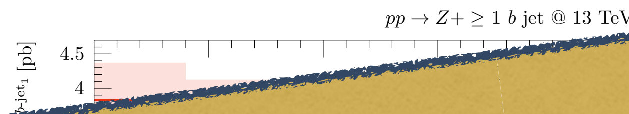


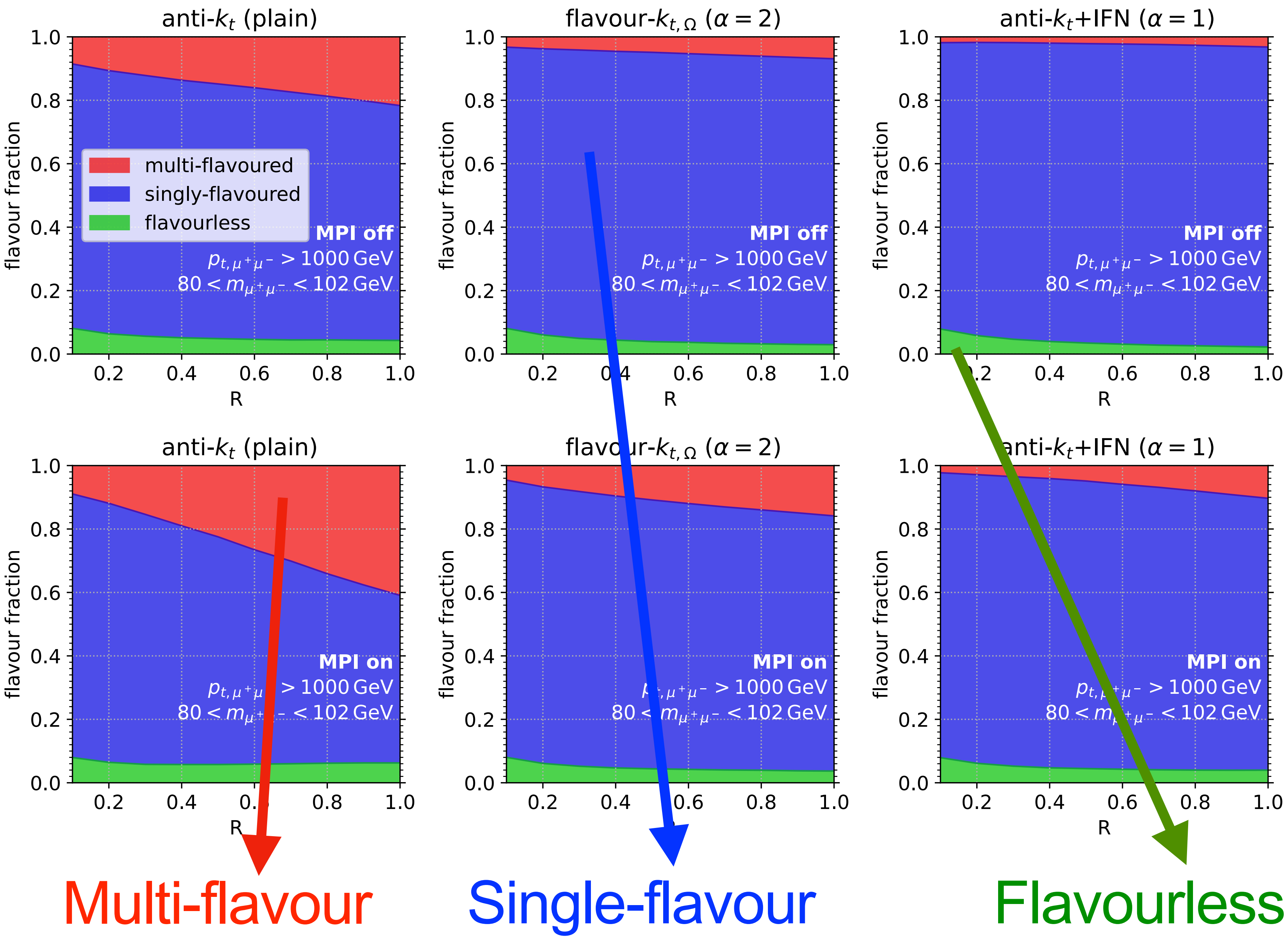


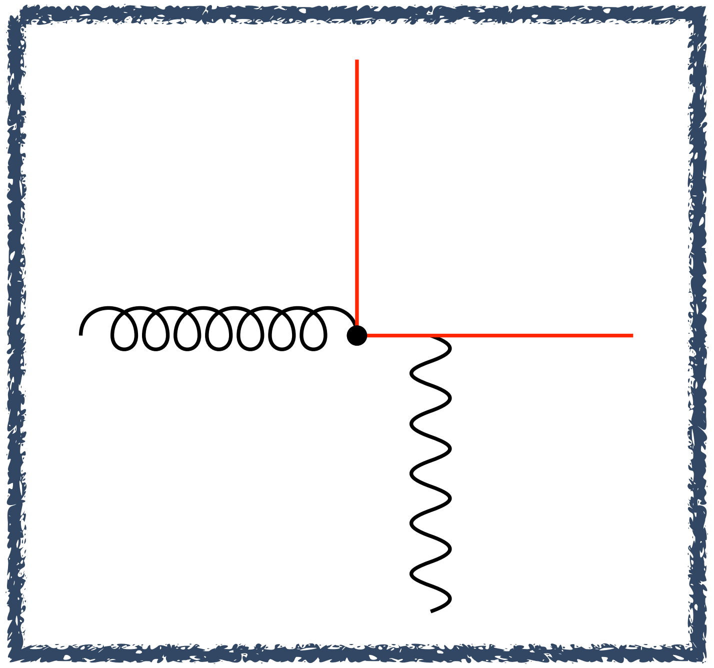
- Shower vs fixed-order effects?
- 5FNS (massification should still work, as an IR regulator)? Difference in the ΔR_{bZ} tail?
- Are there regions where dynamical mass effects are important? In general, how important mass effects are?
- Play with flavour algorithms…

- 4 …
  "r…
- La… …m 4FS. Good agreement with data

A word on jet flavour

[FC, Grabarczyk, Hutt, Salam, Scyboz, Thaler; Czakon, Mitov, Poncelet; Gauld, Huss Stagnitto]

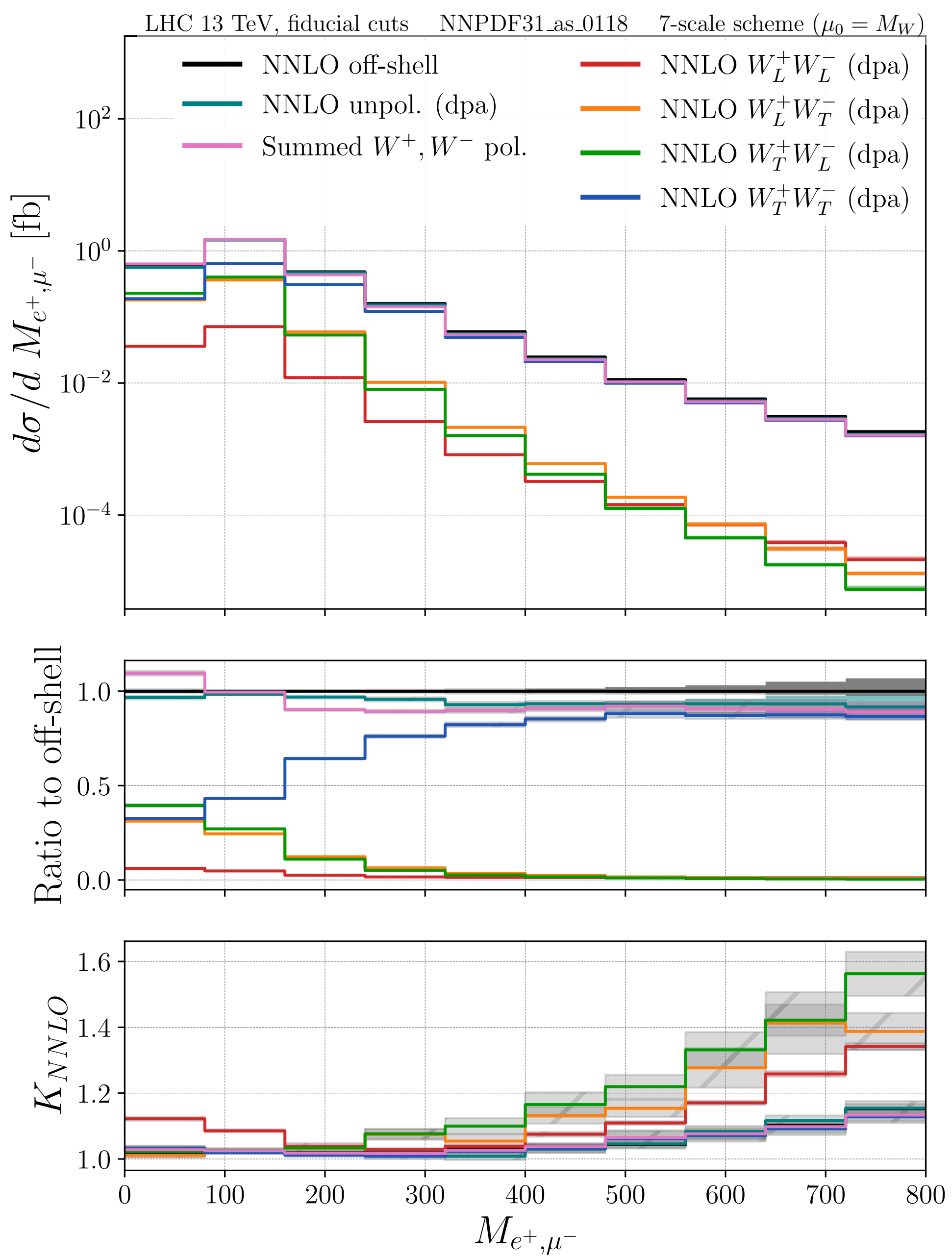




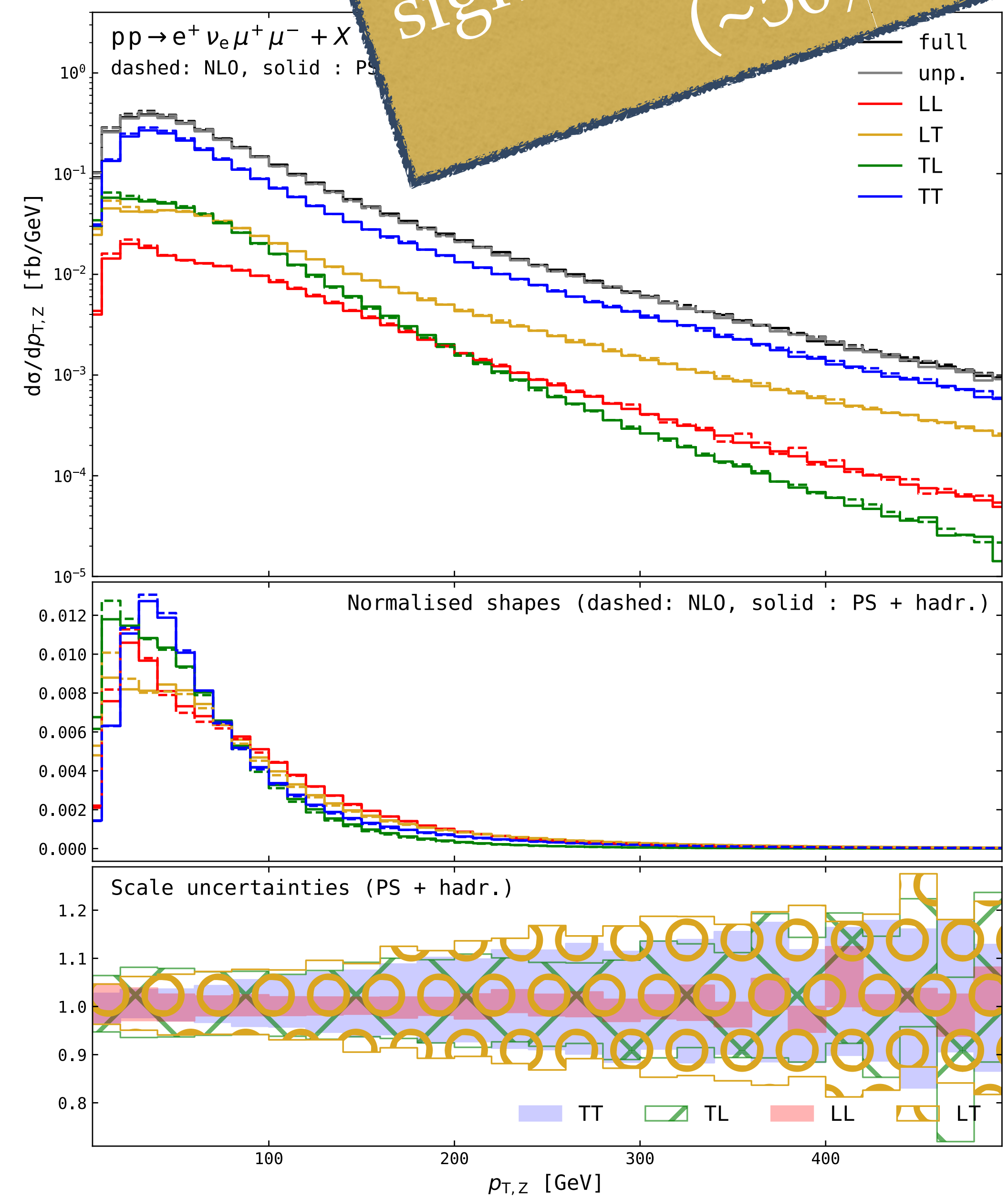
- anti-k_t does not do a good job in identifying "hard flavour"
- Many recent work, but any alternative must be experimentally feasible → non-trivial

Back to the Higgs, & beyond: EWSB

- More and more data to explore EWSB mechanism, beyond the Higgs → polarised cross sections



[Poncelet, Popescu (2021)]



Now also with PS, significant error budget (~50%)

[Pellicciol, Zanderighi (2023)]

→ see Giovanni's & Ansgar's talks

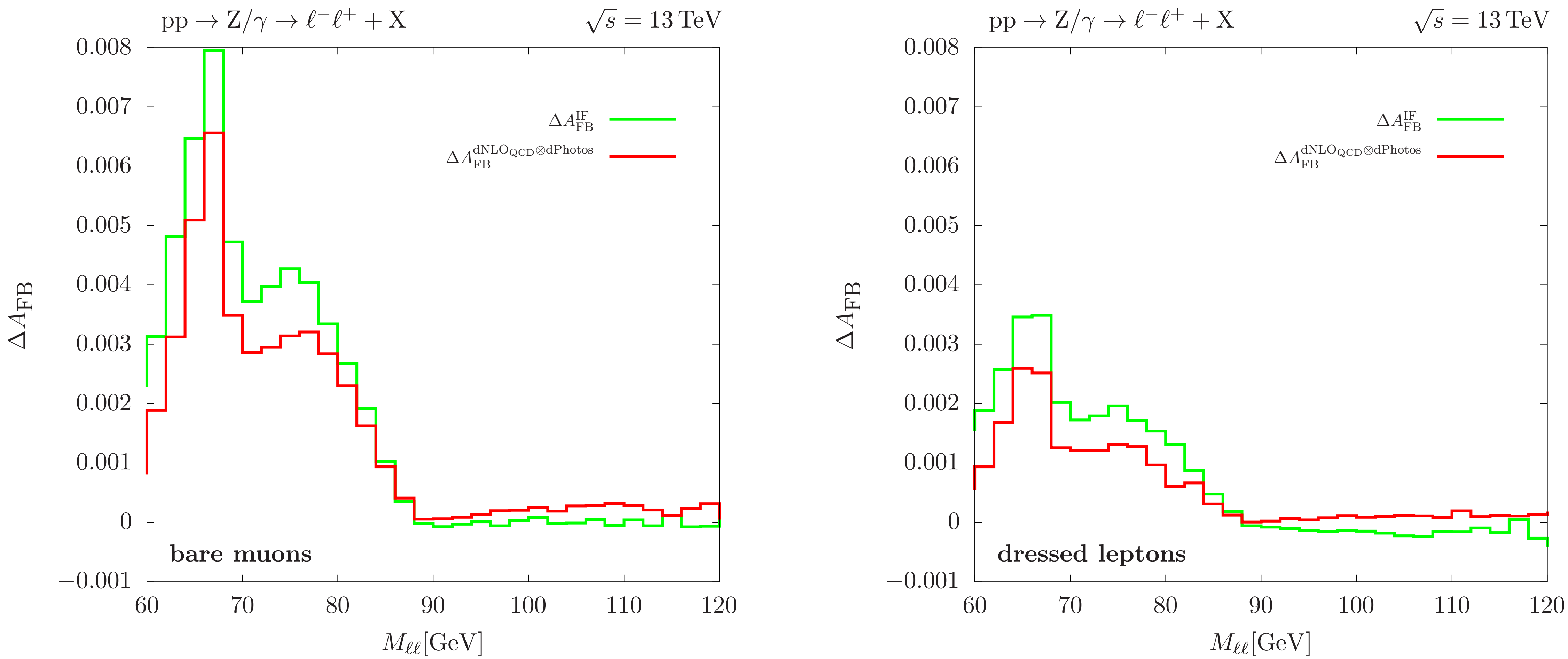
→ see Samuel's talk for WWj

… and to standard candles: DY

- N^3LO calculations and phenomenological explorations well underway (but see Arnd's & Chen-Yu's talks about going beyond colour singlet)
- Ultra-precise studies (e.g. M_W, $\sin\theta_W$), or large scale: mixed QCD-EWK

[Armadillo, Bonciani, Buccioni, Rana, Vicini, Devoto, Buonocore, Grazzini, Savoini, Kallweit, Dittmaier, Huss, Schwinn, Behring, FC, Delto, Devoto, Jaquier, von Manteuffel, Heller, Melnikov, Roentsch, Signorile-Signorile…]

[Dittmaier, Huss, Schwarz (2024)]



- Recent high-precision estimate of A_{FB} and its impact on parameter expansion
- In general, good agreement with expectations, but at this level of accuracy one has to be careful…

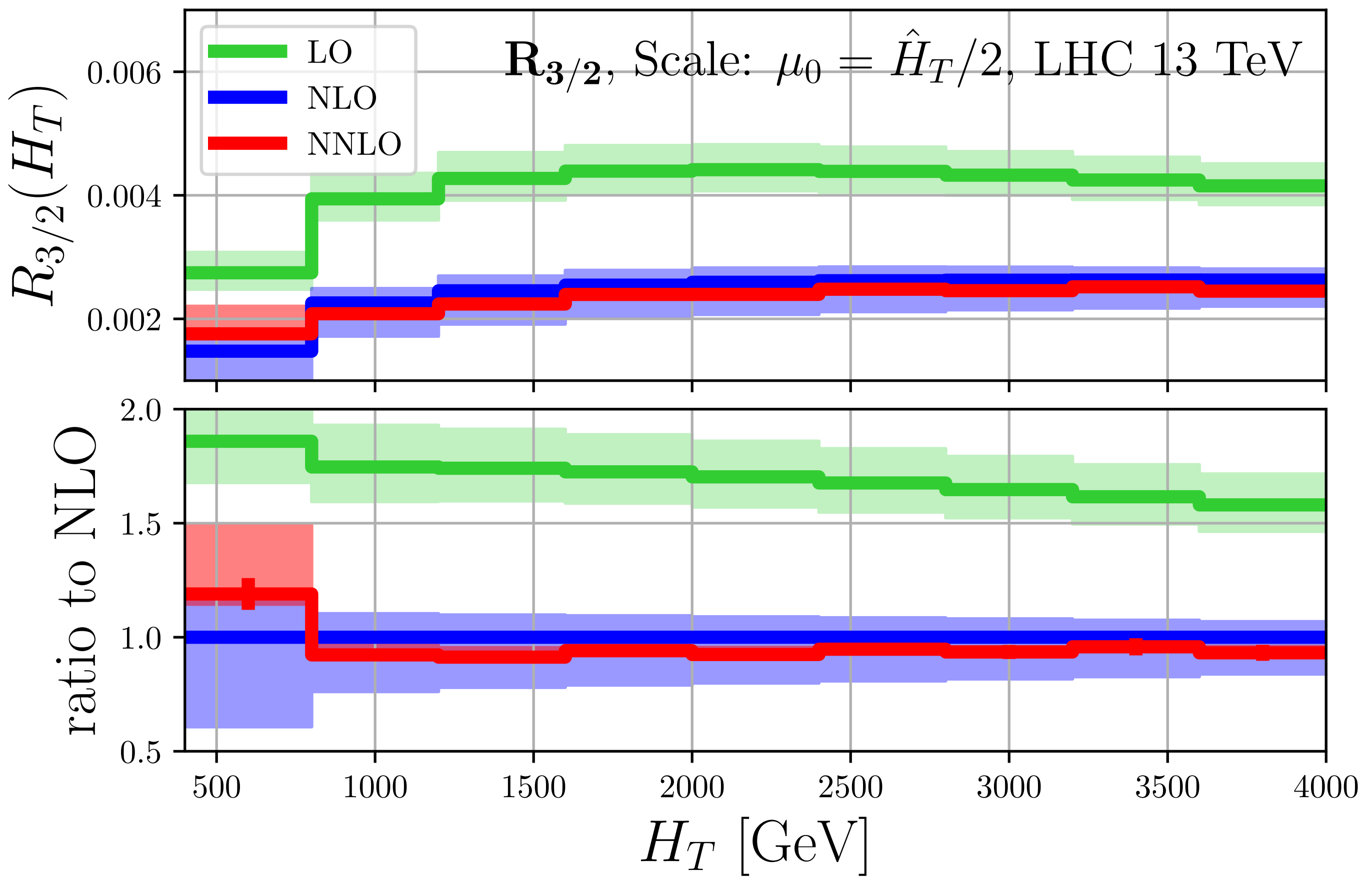
→ see also Luca's talk for resummation

Complex final states, event shapes

- Thanks to progress in scattering amplitudes (→ see Federico's, Vasily's & Andreas' talks) + efficient-enough subtraction formalisms: 2 → 3 processes are now a reality

[Badger, Czakon, Hartanto, Moodie, Peraro, Chawdhry, Mitov, Poncelet, Kallweit, Sotnikov, Wiesemann, Alvarez, Cantero, Llorente]

- A highlight: 3j production, $R_{3/2}$ and α_s in the TeV region



[Czakon, Mitov, Poncelet (2021)]

Can we use these results to "understand" / measure the proper scale of α_s in hard jet events?

also γγγ,γγj,γjj

Conclusions and outlook

A lot of technical progress in the last few years.
Now we are reaping the (phenomenological) fruits

- They may be cracks in our overall factorisation framework, but they are not (yet) hampering us
- A significant bottleneck has been removed with more 2→3 loop amplitudes becoming available
- With more complex final state, richer / more involved phenomenology. (Large K-factors etc should have a simple explanation…)
- A rich interplay of many different effects, QCD/EWK corrections
- An even richer interplay as you start showering down to the hadronic scale → plenty to discuss in the next few days…

Thank you very much for your attention!