Recent improvements in QCD predictions

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Current status

- Only about 5% of data collected so far (compared to High-Lumi), yet no leap in energy in the coming years
- Hard to expect a striking signature in a signel process/observable
- Likely, if there will be a discovery, it will manifest itself first as a range of small deviations in various measurements
- Role of precision theory is clear: the more accurate the theory predictions are, the sooner, or the more sensitive, one can be to these small deviations

⇒ **Precise theory augments the discovery reach of the LHC and anticipates possible discoveries**

The master formula

Factorisation implies the following form of hadronic cross sections

$$d\sigma_{\mathrm{PP}\to\mathrm{final}} = \sum_{\mathrm{i,j,final}} \int dx_1 dx_2 d\Phi_{\mathrm{final}} f_i(x_1, \mu_F^2) f_j(x_2, \mu_F^2) \frac{d\hat{\sigma}_{\mathrm{ij}\to\mathrm{final}}}{d\Phi_{\mathrm{final}}} \Theta_{\mathrm{cuts}}$$

Parton Distributions Functions
Extracted from data at various experiments/energies. PDFs are universal and their evolution is perturbative (LO, NLO, NNLO...)

Partonic Cross Sections
Expansion in the coupling constants (LO, NLO, NNLO...), also including enhanced all-order terms (LL, NLL, NNLL…)

Precision theory is a multilateral challenge

- push frontier of the perturbative QCD expansion (NLO, NNLO, N^3LO)
- heavy-top and bottom/charm mass effects
- mixed QCD-electroweak corrections
- resummation of large logarithmically enhanced terms to all orders
- fully exclusive description of the final state through parton showers
  - improving the accuracy of parton showers
  - matching fixed-order calculations and parton showers
- modelling of non-perturbative effects (or ways to reduce them)
- issues with jet-flavour
- uncertainties due to input parameters: strong coupling, PDFs, masses… $\Rightarrow$ ways to reduce these uncertainties
- …

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- fully exclusive description of the final state through parton showers
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  - matching fixed-order calculations and parton showers
- modelling of non-perturbative effects (or ways to reduce them)
- issues with jet-flavour (strawberry plus banana)
- uncertainties due to input parameters: strong coupling, PDFs, masses…) ⇒ ways to reduce these uncertainties
- …

black: this talk

NLO QCD: the past

Example: single Higgs production processes (similar results available for all SM processes of similar complexity)

Alwall et al 1405.0301

	Process	Syntax	Cross section (pb)	
	Single Higgs production		LO 13 TeV	NLO 13 TeV
g.1	$pp \to H$ (HEFT)	`p p > h`	$1.593 \pm 0.003 \cdot 10^{1}$ $^{+34.8\%}_{-26.0\%}$ $^{+1.2\%}_{-1.7\%}$	$3.261 \pm 0.010 \cdot 10^{1}$ $^{+20.2\%}_{-17.9\%}$ $^{+1.1\%}_{-1.6\%}$
g.2	$pp \to Hj$ (HEFT)	`p p > h j`	$8.367 \pm 0.003 \cdot 10^{0}$ $^{+39.4\%}_{-26.4\%}$ $^{+1.2\%}_{-1.4\%}$	$1.422 \pm 0.006 \cdot 10^{1}$ $^{+18.5\%}_{-16.6\%}$ $^{+1.1\%}_{-1.4\%}$
g.3	$pp \to Hjj$ (HEFT)	`p p > h j j`	$3.020 \pm 0.002 \cdot 10^{0}$ $^{+59.1\%}_{-34.7\%}$ $^{+1.4\%}_{-1.7\%}$	$5.124 \pm 0.020 \cdot 10^{0}$ $^{+20.7\%}_{-21.0\%}$ $^{+1.3\%}_{-1.5\%}$
g.4	$pp \to Hjj$ (VBF)	`p p > h j j $$ w+ w- z`	$1.987 \pm 0.002 \cdot 10^{0}$ $^{+1.7\%}_{-2.0\%}$ $^{+1.9\%}_{-1.4\%}$	$1.900 \pm 0.006 \cdot 10^{0}$ $^{+0.8\%}_{-0.9\%}$ $^{+2.0\%}_{-1.5\%}$
g.5	$pp \to Hjjj$ (VBF)	`p p > h j j j $$ w+ w- z`	$2.824 \pm 0.005 \cdot 10^{-1}$ $^{+15.7\%}_{-12.7\%}$ $^{+1.5\%}_{-1.0\%}$	$3.085 \pm 0.010 \cdot 10^{-1}$ $^{+2.0\%}_{-3.0\%}$ $^{+1.5\%}_{-1.1\%}$
g.6	$pp \to HW^{\pm}$	`p p > h wpm`	$1.195 \pm 0.002 \cdot 10^{0}$ $^{+3.5\%}_{-4.5\%}$ $^{+1.9\%}_{-1.5\%}$	$1.419 \pm 0.005 \cdot 10^{0}$ $^{+2.1\%}_{-2.6\%}$ $^{+1.9\%}_{-1.4\%}$
g.7	$pp \to HW^{\pm}j$	`p p > h wpm j`	$4.018 \pm 0.003 \cdot 10^{-1}$ $^{+10.7\%}_{-9.3\%}$ $^{+1.2\%}_{-0.9\%}$	$4.842 \pm 0.017 \cdot 10^{-1}$ $^{+3.6\%}_{-3.7\%}$ $^{+1.2\%}_{-1.0\%}$
g.8*	$pp \to HW^{\pm}jj$	`p p > h wpm j j`	$1.198 \pm 0.016 \cdot 10^{-1}$ $^{+26.1\%}_{-19.4\%}$ $^{+0.8\%}_{-0.6\%}$	$1.574 \pm 0.014 \cdot 10^{-1}$ $^{+5.0\%}_{-6.5\%}$ $^{+0.9\%}_{-0.6\%}$
g.9	$pp \to HZ$	`p p > h z`	$6.468 \pm 0.008 \cdot 10^{-1}$ $^{+3.5\%}_{-4.5\%}$ $^{+1.9\%}_{-1.4\%}$	$7.674 \pm 0.027 \cdot 10^{-1}$ $^{+2.0\%}_{-2.5\%}$ $^{+1.9\%}_{-1.4\%}$
g.10	$pp \to HZj$	`p p > h z j`	$2.225 \pm 0.001 \cdot 10^{-1}$ $^{+10.6\%}_{-9.2\%}$ $^{+1.1\%}_{-0.8\%}$	$2.667 \pm 0.010 \cdot 10^{-1}$ $^{+3.5\%}_{-3.6\%}$ $^{+1.1\%}_{-0.9\%}$
g.11*	$pp \to HZjj$	`p p > h z j j`	$7.262 \pm 0.012 \cdot 10^{-2}$ $^{+26.2\%}_{-19.4\%}$ $^{+0.7\%}_{-0.6\%}$	$8.753 \pm 0.037 \cdot 10^{-2}$ $^{+4.8\%}_{-6.3\%}$ $^{+0.7\%}_{-0.6\%}$
g.12*	$pp \to HW^{+}W^{-}$ (4f)	`p p > h w+ w-`	$8.325 \pm 0.139 \cdot 10^{-3}$ $^{+0.0\%}_{-0.3\%}$ $^{+2.0\%}_{-1.6\%}$	$1.065 \pm 0.003 \cdot 10^{-2}$ $^{+2.5\%}_{-1.9\%}$ $^{+2.0\%}_{-1.5\%}$
g.13*	$pp \to HW^{\pm}\gamma$	`p p > h wpm a`	$2.518 \pm 0.006 \cdot 10^{-3}$ $^{+0.7\%}_{-1.4\%}$ $^{+1.9\%}_{-1.5\%}$	$3.309 \pm 0.011 \cdot 10^{-3}$ $^{+2.7\%}_{-2.0\%}$ $^{+1.7\%}_{-1.4\%}$
g.14*	$pp \to HZW^{\pm}$	`p p > h z wpm`	$3.763 \pm 0.007 \cdot 10^{-3}$ $^{+1.1\%}_{-1.5\%}$ $^{+2.0\%}_{-1.6\%}$	$5.292 \pm 0.015 \cdot 10^{-3}$ $^{+3.9\%}_{-3.1\%}$ $^{+1.8\%}_{-1.4\%}$
g.15*	$pp \to HZZ$	`p p > h z z`	$2.093 \pm 0.003 \cdot 10^{-3}$ $^{+0.1\%}_{-0.6\%}$ $^{+1.9\%}_{-1.5\%}$	$2.538 \pm 0.007 \cdot 10^{-3}$ $^{+1.9\%}_{-1.4\%}$ $^{+2.0\%}_{-1.5\%}$
g.16	$pp \to Ht\bar{t}$	`p p > h t t~`	$3.579 \pm 0.003 \cdot 10^{-1}$ $^{+30.0\%}_{-21.5\%}$ $^{+1.7\%}_{-2.0\%}$	$4.608 \pm 0.016 \cdot 10^{-1}$ $^{+5.7\%}_{-9.0\%}$ $^{+2.0\%}_{-2.3\%}$
g.17	$pp \to Htj$	`p p > h tt j`	$4.994 \pm 0.005 \cdot 10^{-2}$ $^{+2.4\%}_{-4.2\%}$ $^{+1.2\%}_{-1.3\%}$	$6.328 \pm 0.022 \cdot 10^{-2}$ $^{+2.9\%}_{-1.8\%}$ $^{+1.5\%}_{-1.6\%}$
g.18	$pp \to Hb\bar{b}$ (4f)	`p p > h b b~`	$4.983 \pm 0.002 \cdot 10^{-1}$ $^{+28.1\%}_{-21.0\%}$ $^{+1.5\%}_{-1.8\%}$	$6.085 \pm 0.026 \cdot 10^{-1}$ $^{+7.3\%}_{-9.6\%}$ $^{+1.6\%}_{-2.0\%}$
g.19	$pp \to Ht\bar{t}j$	`p p > h t t~ j`	$2.674 \pm 0.041 \cdot 10^{-1}$ $^{+45.6\%}_{-29.2\%}$ $^{+2.6\%}_{-2.9\%}$	$3.244 \pm 0.025 \cdot 10^{-1}$ $^{+3.5\%}_{-8.7\%}$ $^{+2.5\%}_{-2.9\%}$
g.20*	$pp \to Hb\bar{b}j$ (4f)	`p p > h b b~ j`	$7.367 \pm 0.002 \cdot 10^{-2}$ $^{+45.6\%}_{-29.1\%}$ $^{+1.8\%}_{-2.1\%}$	$9.034 \pm 0.032 \cdot 10^{-2}$ $^{+7.9\%}_{-11.0\%}$ $^{+1.8\%}_{-2.2\%}$

NLO QCD: the past

<u>Example:</u> single Higgs production processes (similar results available for all SM processes of similar complexity)

Alwall et al 1405.0301

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g.9	$pp \to$ [illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible] $^{+1.9\%}_{-1.4\%}$
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✓ A solved problem

NLO: the present

Today focus on

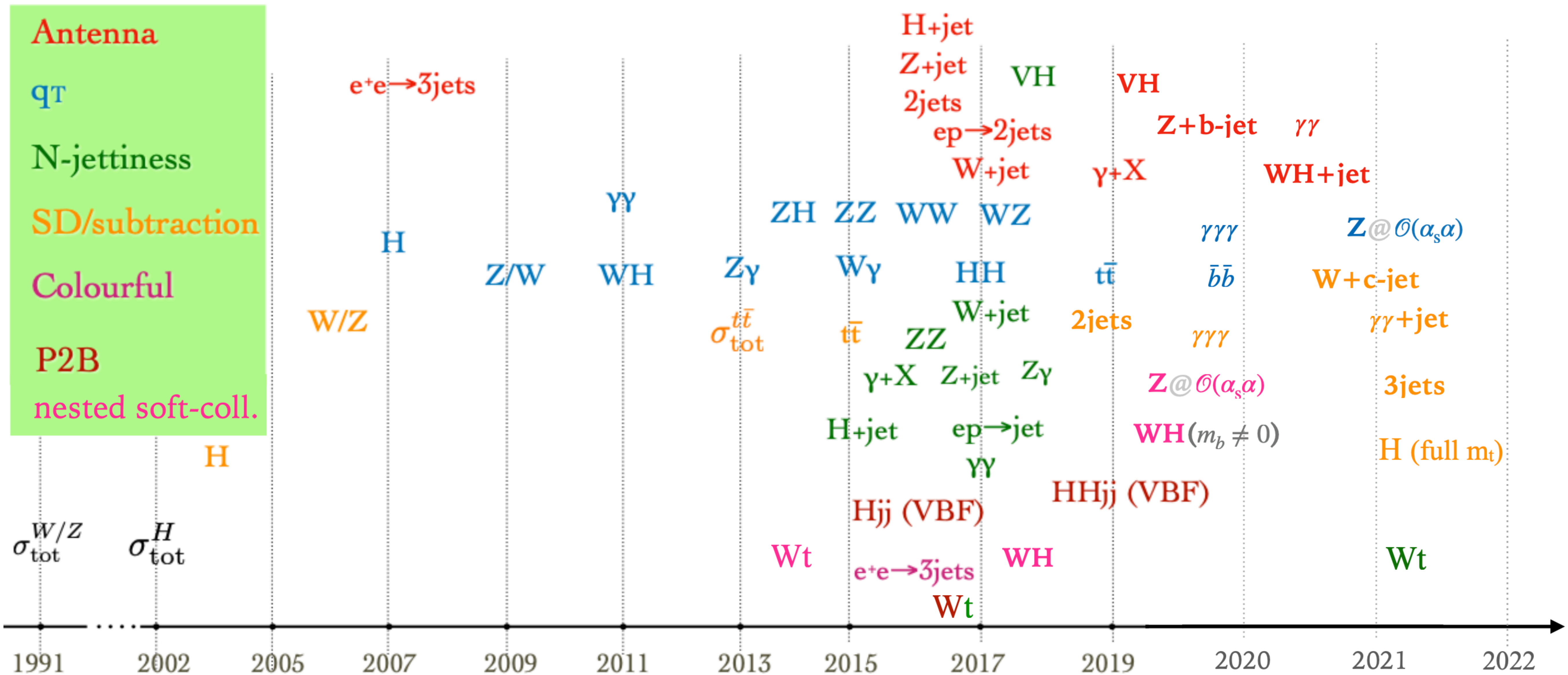
- automation of NLO for BSM signals
- loop-induced processes: higher-order, but enhanced by gluon PDF
- automation of NLO electroweak corrections (necessary to match accuracy of NNLO)
- automation of NLO in SMEFT

➡ Practical limitation: high-multiplicity difficult because of numerical instabilities, long run-time on clusters to obtain stable results (edge: about 6 particles in the final state, depending on the process)

Comparison to at least NLO is standard now in most LHC analyses

NNLO: status

adapted from A. Huss/G. Salam



Different colour: different way to handle intermediate divergences

See talk by F. Buccione

NNLO: status

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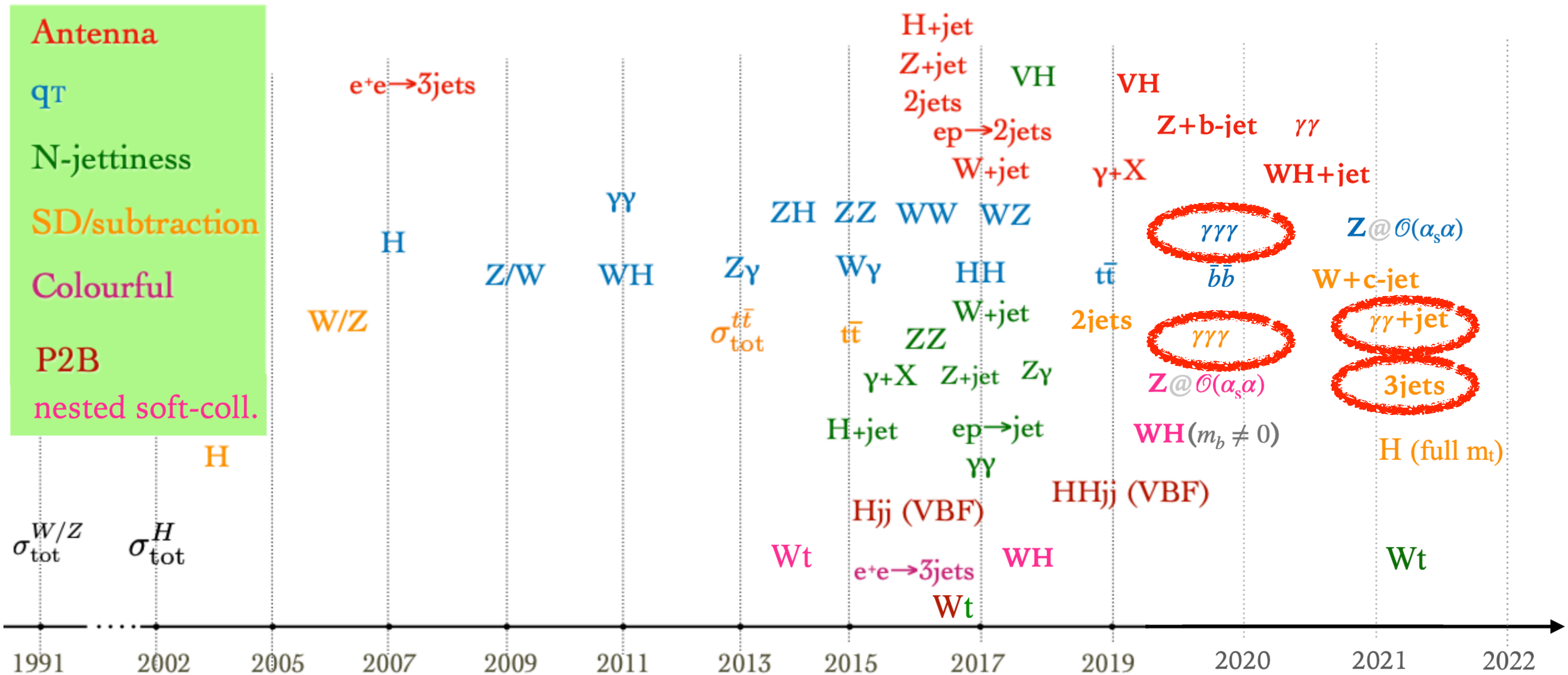

Different colour: different way to handle intermediate divergences

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NNLO: status

adapted from A. Huss/G. Salam

✓2 to 2 processes in the SM

➡ frontier is 2 to 3

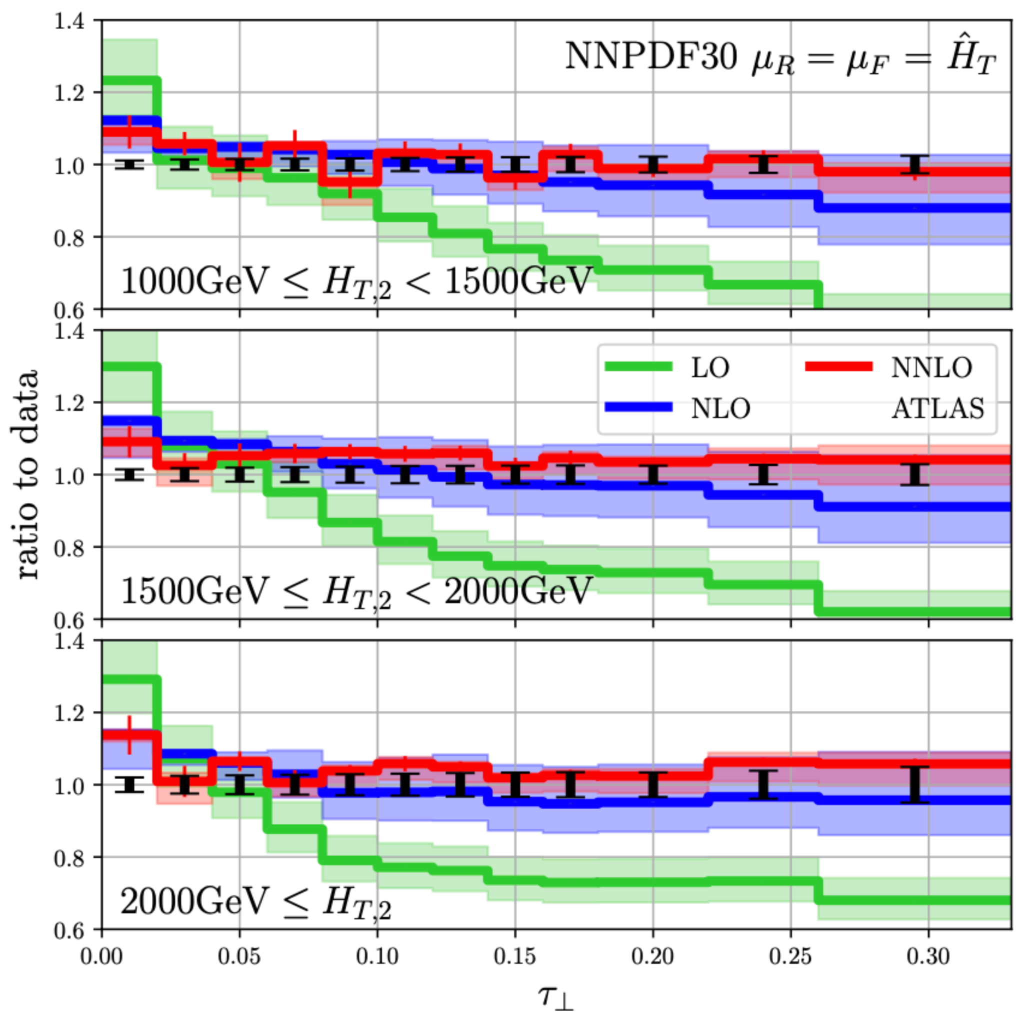
Different colour: c

NNLO: one highlight

<u>Recent milestone:</u> NNLO calculation of three jet production at the LHC

Recently applied to compute event shapes at the LHC, which might be used to fit the strong coupling

Alvarez et al *JHEP* 03 (2023) 129



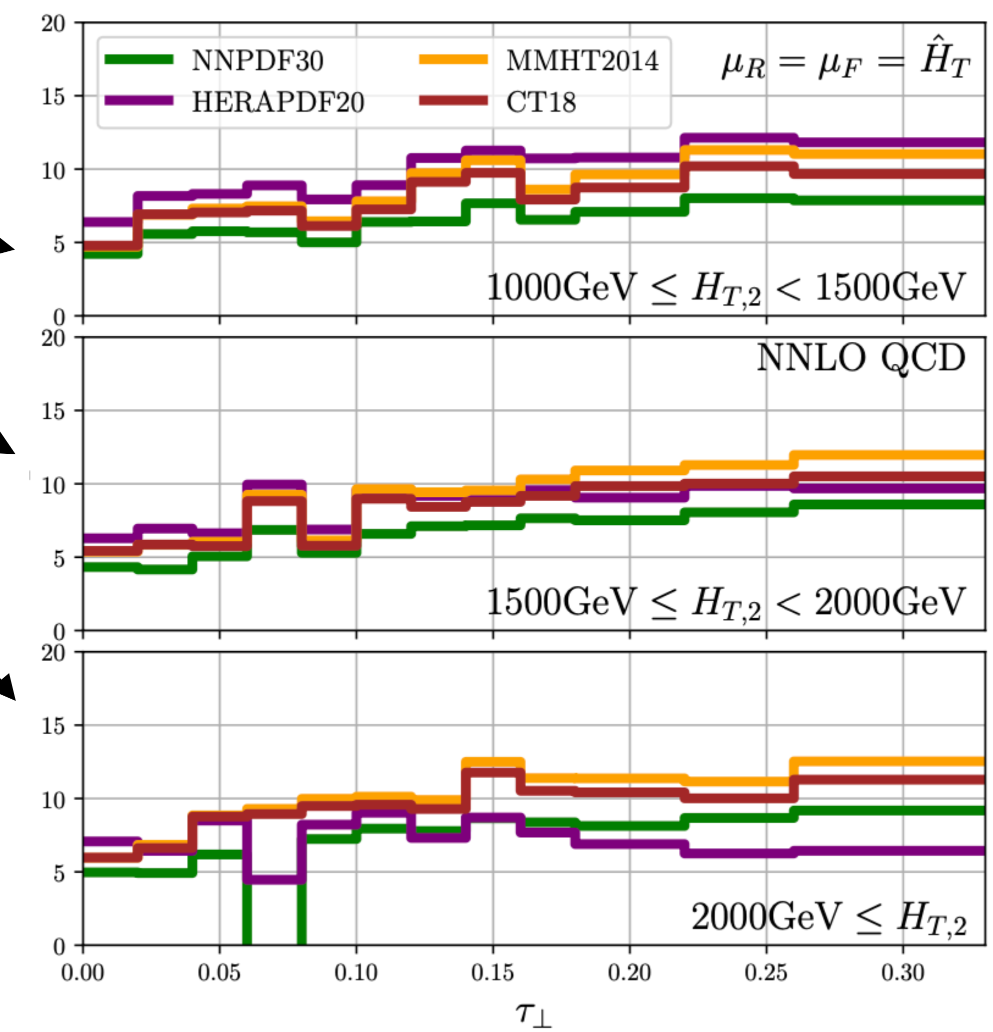
$$T_\perp = \frac{\sum_i |\vec{p}_{T,i} \cdot \hat{n}_\perp|}{\sum_i |\vec{p}_{T,i}|}$$

Shape dependent NNLO effects.
NNLO improves description of data

Application of 3jet@NNLO

$$R^{\text{NNLO}}(\alpha_s) = \frac{d\sigma_3(\alpha_s(\mu),\mu)}{d\sigma_2(\alpha_s(\mu),\mu)} = R^{\text{NNLO}}(\alpha_{s,0}) + R^{\text{NNLO}'}(\alpha_{s,0})\,(\alpha_s - \alpha_{s,0}) + \ldots$$

$$c = \frac{R^{\text{NNLO}'}(\alpha_{s,0})}{R^{\text{NNLO}}(\alpha_{s,0})}$$



Since $\alpha_s \approx 0.1$, c ≈ 10 implies that 1% shift in α_s leads to ≈ 1% shift in predictions

➠ good prospects for the precision determination of α_s and its running through TeV scales from LHC data

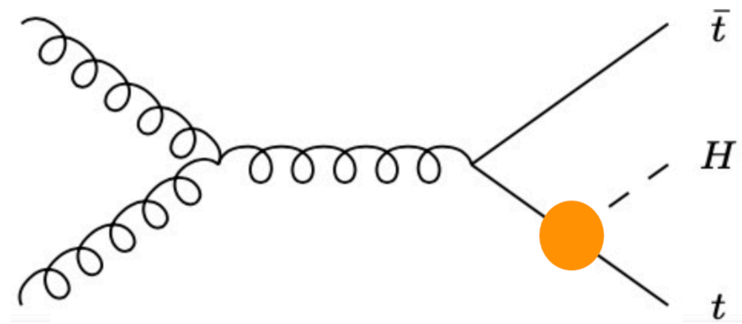
Alvarez et al *JHEP* 03 (2023) 129

Approximate ttH at NNLO

Catani et al 2210.04846

Two-loop pp → ttH amplitudes still missing.

Idea: approximate with amplitudes with a soft Higgs emitted off heavy quarks



See talk by J. Mazzitelli

	$\sqrt{s} = 13$ TeV		$\sqrt{s} = 100$ TeV	
σ [fb]	gg	$q\bar{q}$	gg	$q\bar{q}$
σ_{LO}	261.58	129.47	23055	2323.7
$\Delta\sigma_{\mathrm{NLO,H}}$	88.62	7.826	8205	217.0
$\Delta\sigma_{\mathrm{NLO,H}}\|_{\mathrm{soft}}$	61.98	7.413	5612	206.0
$\Delta\sigma_{\mathrm{NNLO,H}}\|_{\mathrm{soft}}$	−2.980(3)	2.622(0)	−239.4(4)	65.45(1)

Test the procedure at NLO

- approximation not that great! Works better for qq then gg channel

Approximate ttH at NNLO

Catani et al 2210.04846

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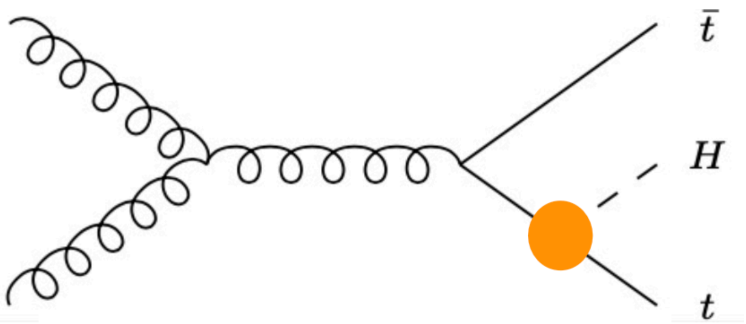

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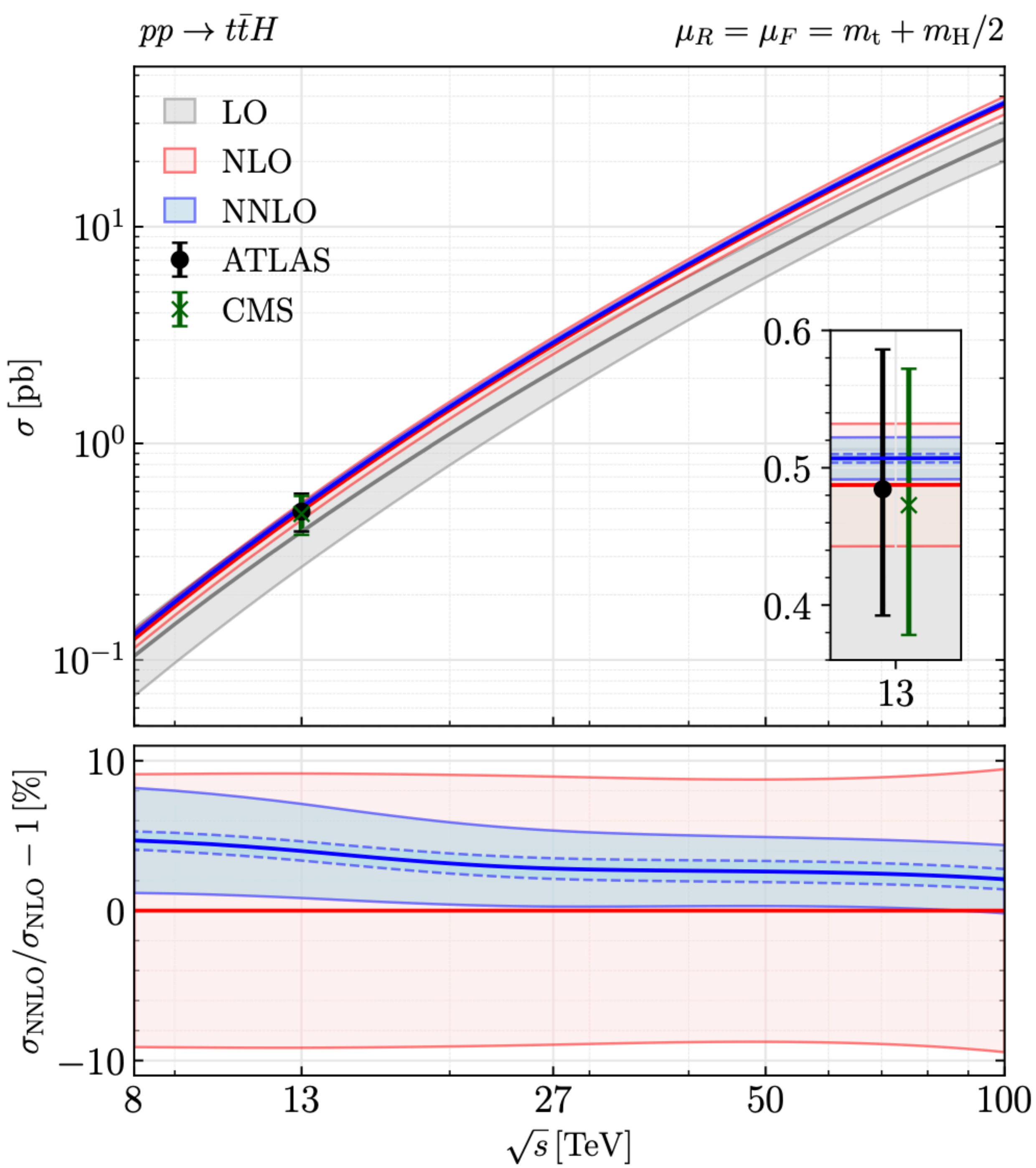
Size of approx. NNLO

- approximation works better for qq then gg channel
- but two-loop corrections are very small (below a %)

Approximate ttH at NNLO

Catani et al 2210.04846

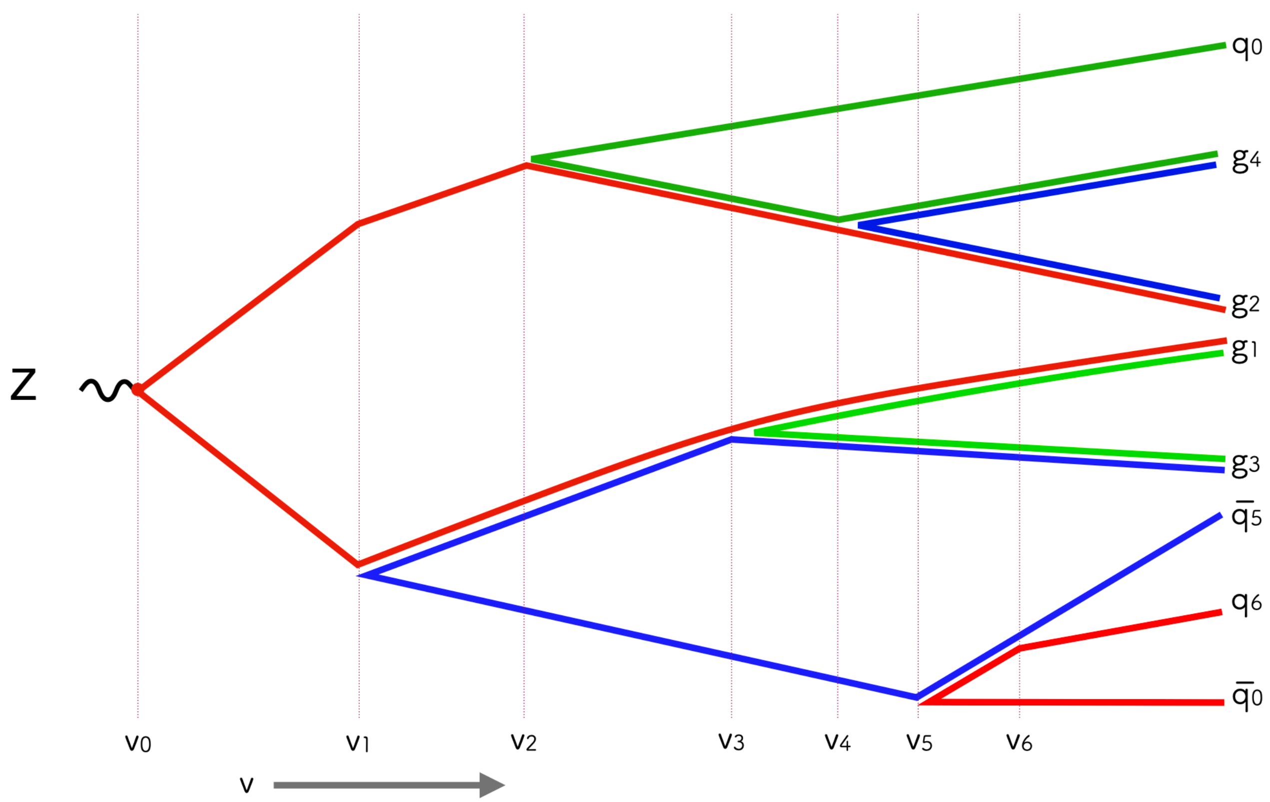


⇒ estimated uncertainty on the total cross section at the few percent level

Interesting to validate this once full is NNLO available

Parton showers

- Through multiple branchings, generated in an approximate and probabilistic way, parton showers describe complex final states
- Typically they describe data well, however discrepancies between data and shower predictions are hard to interpret (because it is hard to associate a theory uncertainty to showered predictions)



- Evolution variable?
- Recoil?
- Splitting kernels?
- Other choices?
- …

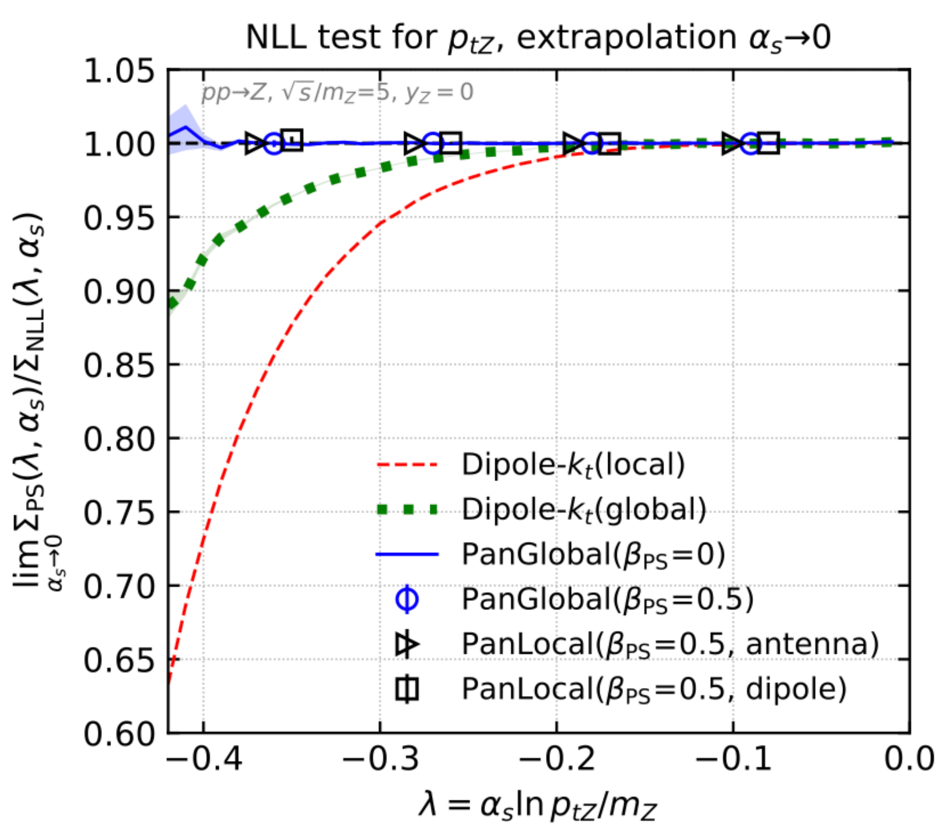
Parton showers

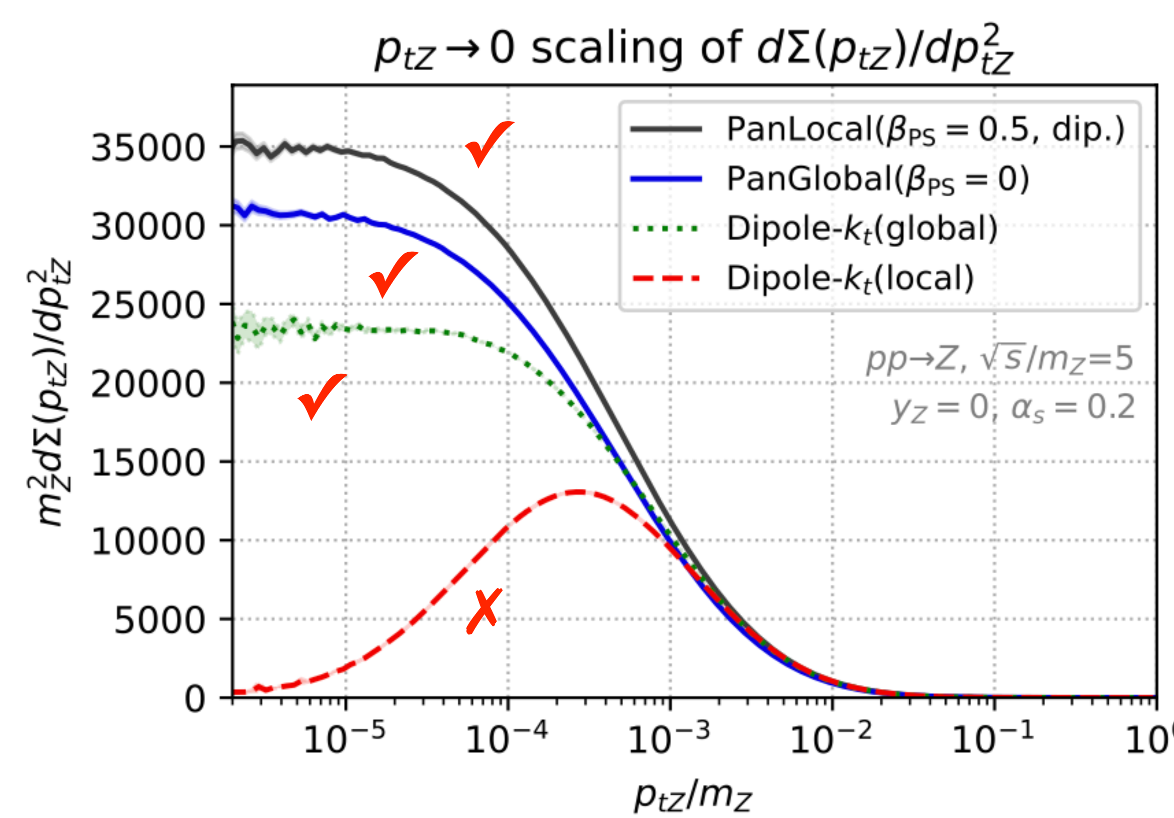
Andersson et al ’92; Nagy & Soper 2009; Dasgupta et al 2018

Recoil and other shower design should respect **absence of cross-talk between disparate scales**, i.e. QCD factorisation

Recent work in improving logarithmic accuracy of the shower and quantifying the associated uncertainty

Validation of accuracy using analytic resummations. e.g.

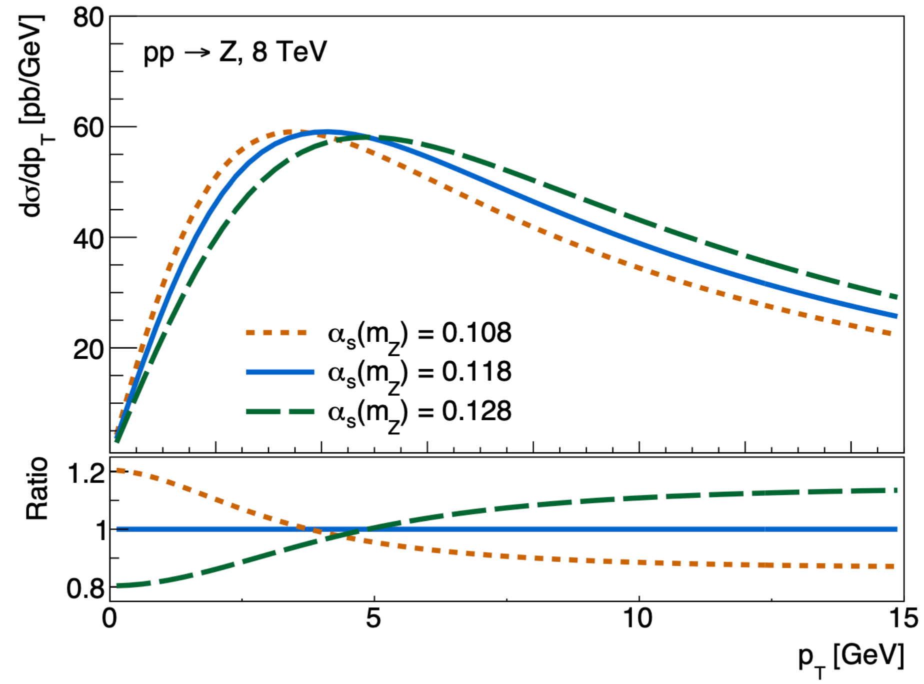




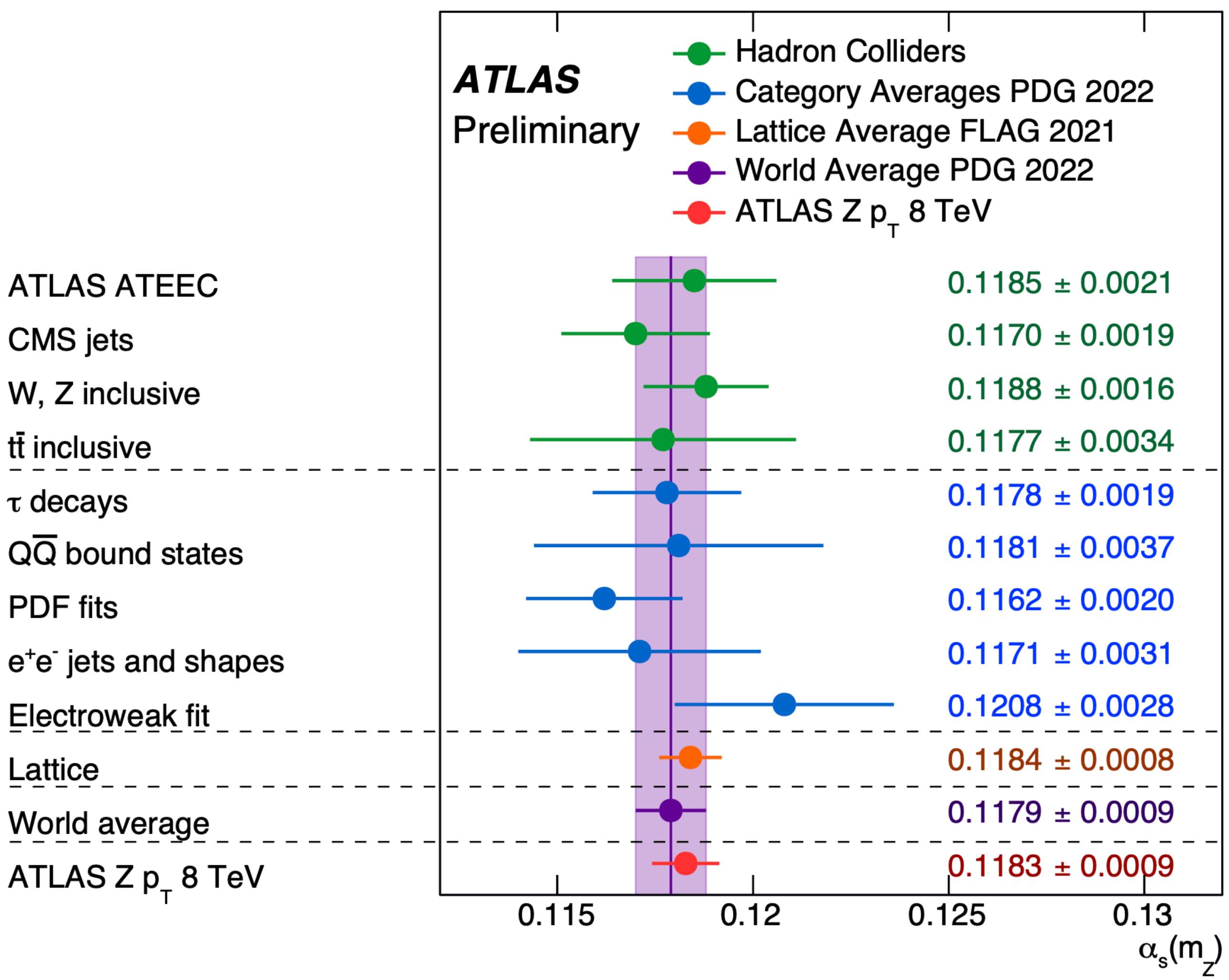
Van Beekveld et al. 2207.09467

α_s from $p_{t,Z}$

NB: $p_{t,Z}$ close to the Sudakov peak used recently by ATLAS to extract α_s with high precision



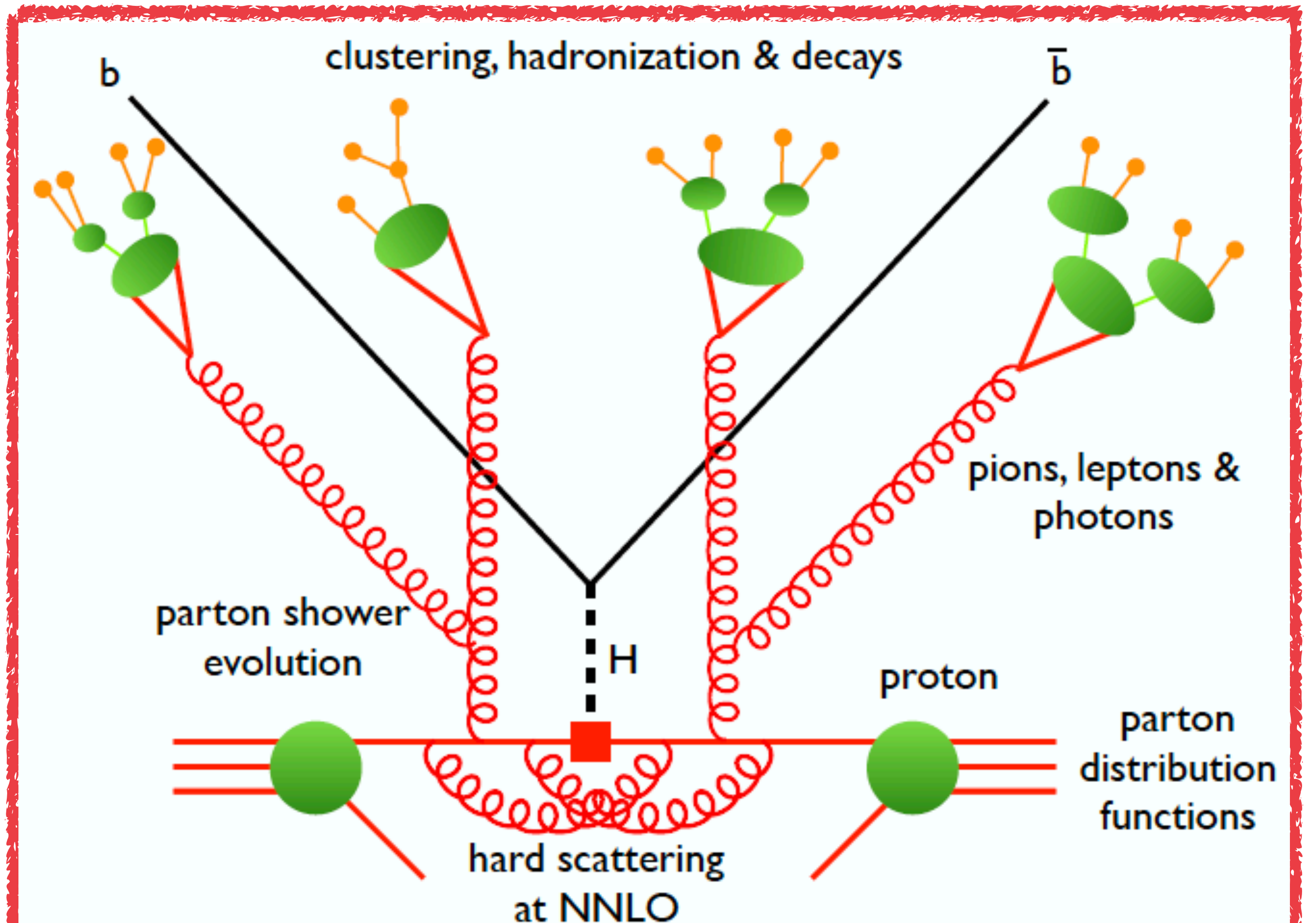
$$\alpha_s(m_Z) = 0.11828^{+0.00084}_{-0.00088}$$



Experimental uncertainty	+0.00044	-0.00044
PDF uncertainty	+0.00051	-0.00051
Scale variations uncertainties	+0.00042	-0.00042
Matching to fixed order	0	-0.00008
Non-perturbative model	+0.00012	-0.00020
Flavour model	+0.00021	-0.00029
QED ISR	+0.00014	-0.00014
N4LL approximation	+0.00004	-0.00004
Total	+0.00084	-0.00088

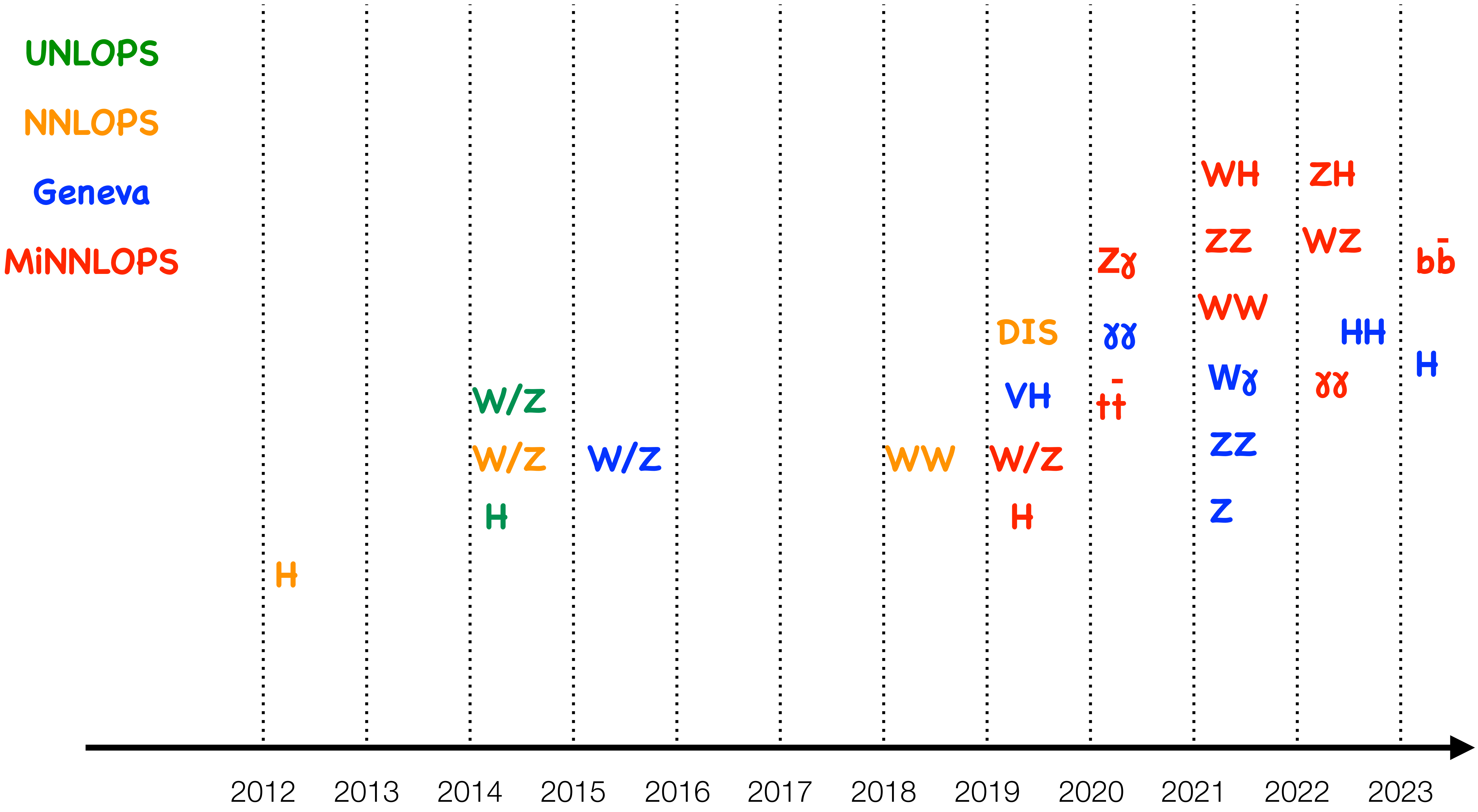
NNLO + parton shower

Merging NNLO and parton shower (NNLOPS) is a must to have the best perturbative accuracy with a realistic description of final state

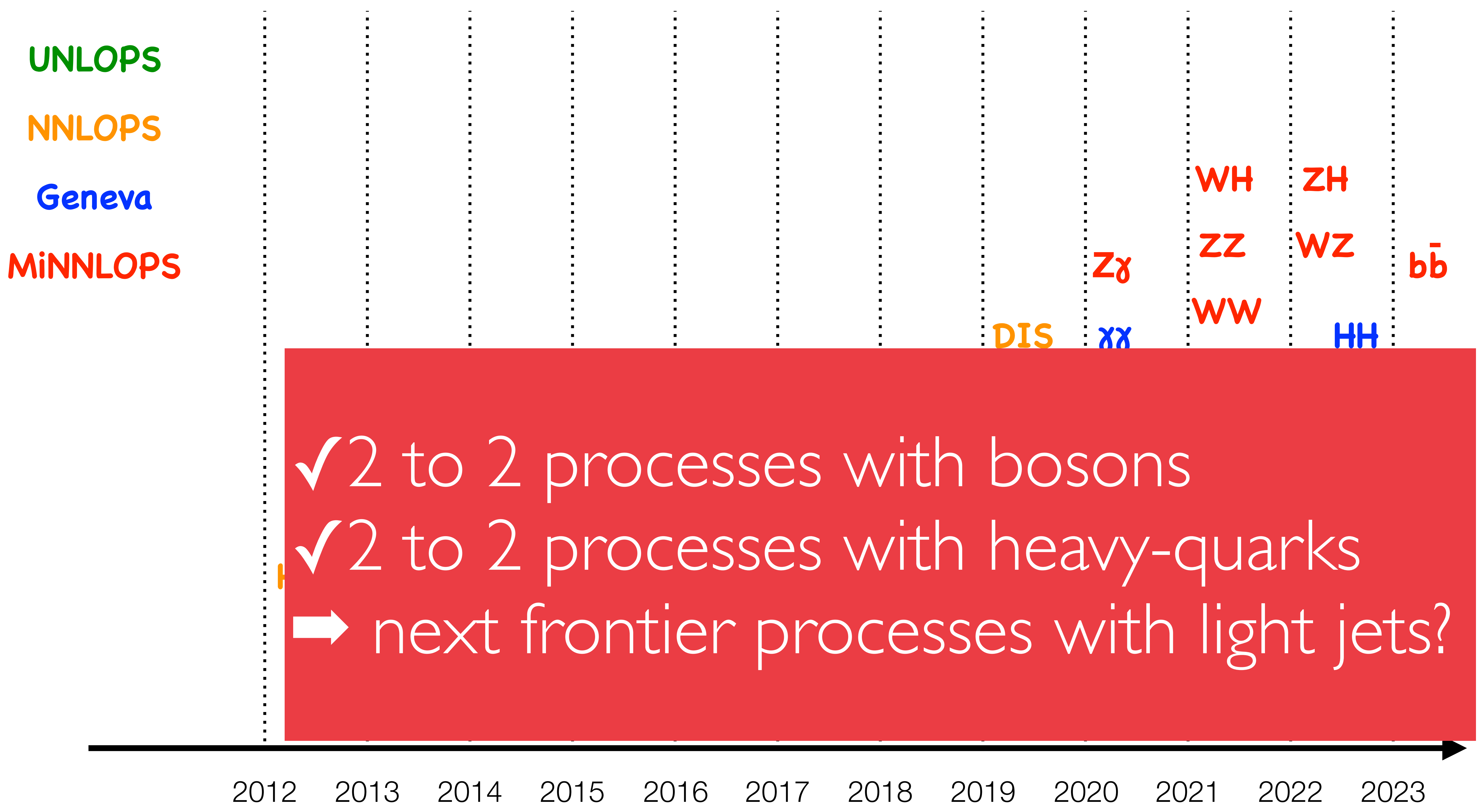


See talk by S. Zanoli

NNLO+PS timeline



NNLO+PS timeline

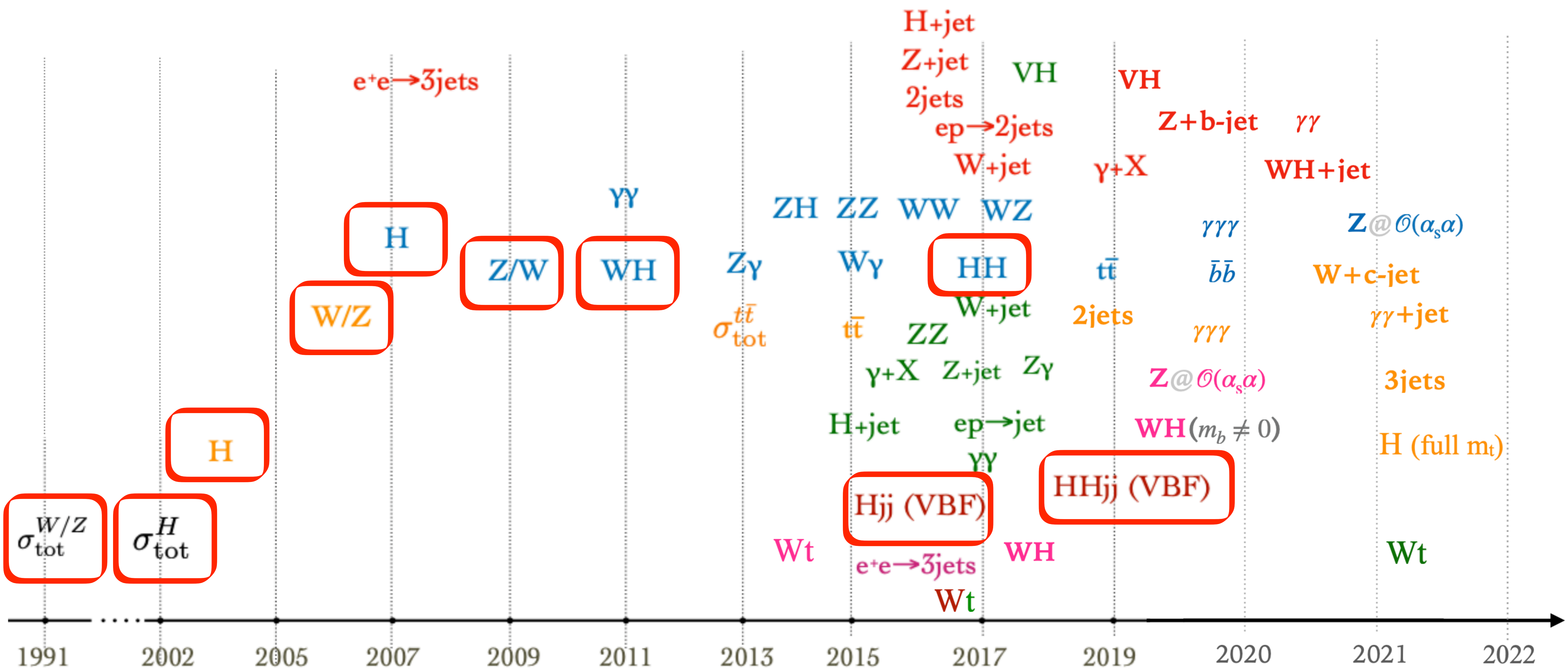


✓2 to 2 processes with bosons

✓2 to 2 processes with heavy-quarks

➡ next frontier processes with light jets?

NNLO → N3LO



2015 … **2023** **N3LO**

N^3LO status

Range of calculations and **public codes** allow comprehensive phenomenological studies at N^3LO:

- `iHixs2` H (gg) N^3LO+EW+threshold,HQ effects — Dulat et al. 1802.00827
- `ggHiggs` H (gg) N^3LO+N^3LL threshold — Bonvini et al. 1603.08000
- `SusHi` H (gg), also CP-odd — Harlander et al 1605.03190
- `ProVBFH` inclusive VBF Higgs and di-Higgs — Dreyer&Karlberg 1606.00840
- `n3loxs` inclusive H (gg or bb induced), Drell Yan and Higgsstrahlung (HV) — Baglio et al 2209.06138

See talk by F. Buccione

Sample N^{3}LO results

Baglio et al 2209.06138

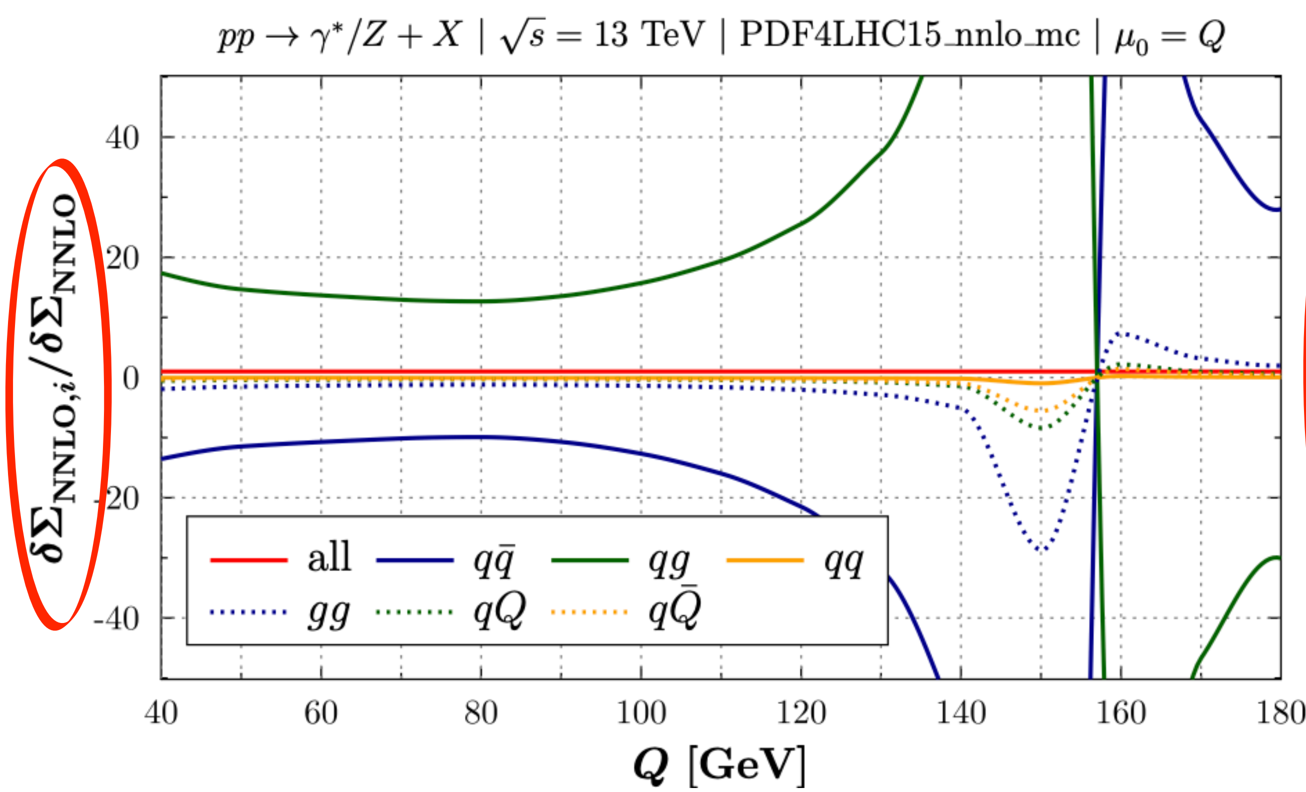
	Q [GeV]	$\delta\sigma^{\mathrm{N^3LO}}$	$\delta\sigma^{\mathrm{NNLO}}$	δ(scale)	$\delta(\mathrm{PDF}+\alpha_S)$	δ(PDF-TH)
$gg \to$ Higgs	m_H	3.5%	30%	$^{+0.21\%}_{-2.37\%}$	$\pm 3.2\%$	$\pm 1.2\%$
$b\bar{b} \to$ Higgs	m_H	-2.3%	2.1%	$^{+3.0\%}_{-4.8\%}$	$\pm 8.4\%$	$\pm 2.5\%$
NCDY	30	-4.8%	-0.34%	$^{+1.53\%}_{-2.54\%}$	$^{+3.7\%}_{-3.8\%}$	$\pm 2.8\%$
	100	-2.1%	-2.3%	$^{+0.66\%}_{-0.79\%}$	$^{+1.8\%}_{-1.9\%}$	$\pm 2.5\%$
CCDY(W^+)	30	-4.7%	-0.1%	$^{+2.5\%}_{-1.7\%}$	$\pm 3.95\%$	$\pm 3.2\%$
	150	-2.0%	-0.1%	$^{+0.5\%}_{-0.5\%}$	$\pm 1.9\%$	$\pm 2.1\%$
CCDY(W^-)	30	-5.0%	-0.1%	$^{+2.6\%}_{-1.6\%}$	$\pm 3.7\%$	$\pm 3.2\%$
	150	-2.1%	-0.6%	$^{+0.6\%}_{-0.5\%}$	$\pm 2\%$	$\pm 2.13\%$

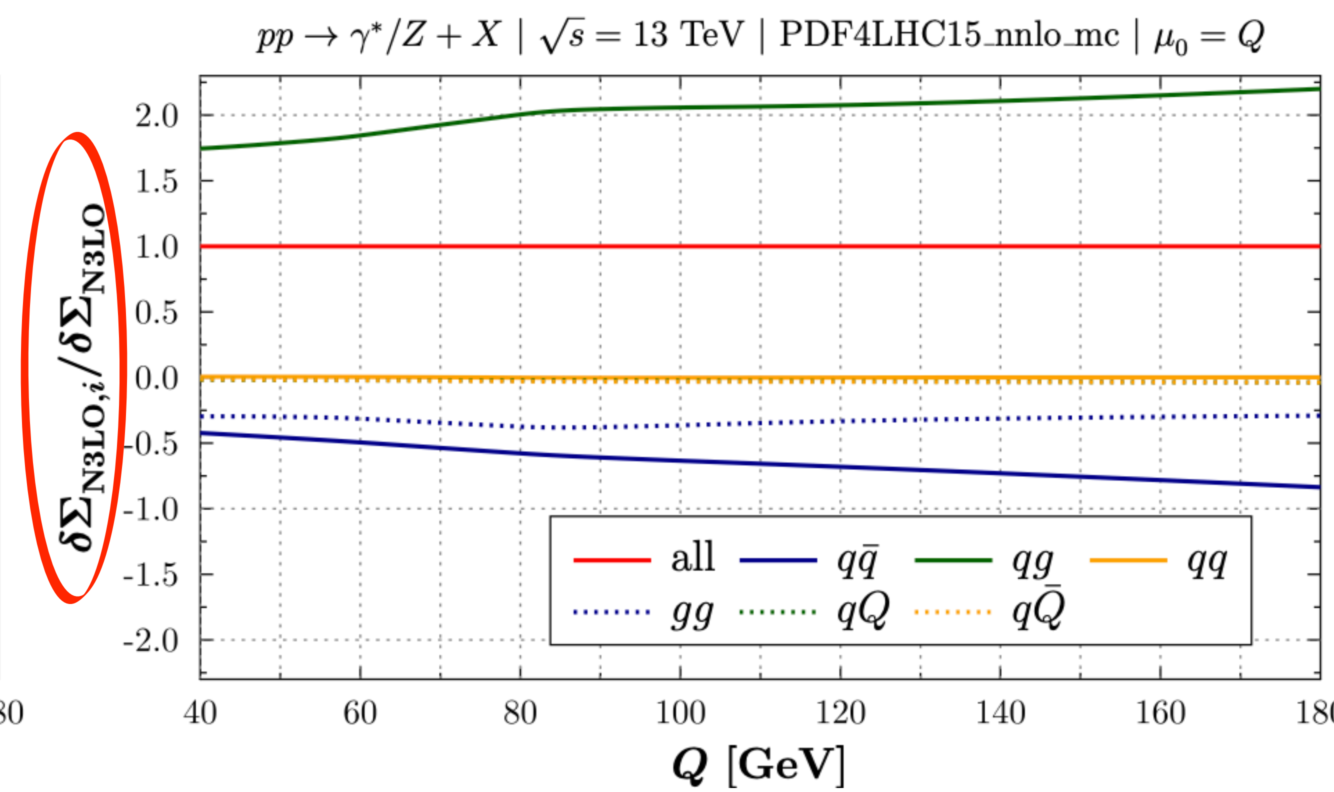
Process	σ^{LO} [pb]	σ^{NLO} [pb]	$\mathrm{K^{NLO}}$	σ^{NNLO} [pb]	$\mathrm{K^{NNLO}}$	$\sigma^{\mathrm{N^3LO}}$ [pb]	$\mathrm{K^{N^3LO}}$
W^+H	$0.758^{+2.43\%}_{-3.13\%}$	$0.883^{+1.38\%}_{-1.20\%}$	1.16	$0.891^{+0.28\%}_{-0.34\%}$	1.18	$0.884^{+0.27\%}_{-0.30\%}$	1.17
W^-H	$0.484^{+2.50\%}_{-3.26\%}$	$0.560^{+1.34\%}_{-1.23\%}$	1.16	$0.564^{+0.27\%}_{-0.34\%}$	1.17	$0.559^{+0.30\%}_{-0.33\%}$	1.16
ZH	$0.678^{+2.40\%}_{-3.11\%}$	$0.786^{+1.33\%}_{-1.16\%}$	1.16	$0.792^{+0.25\%}_{-0.32\%}$	1.17	$0.786^{+0.26\%}_{-0.29\%}$	1.16

$\Rightarrow$ N^{3}LO corrections sizeable (several %), often outside NNLO band

Sample N³LO results

Partonic channel contributions for e.g. neutral Drell Yan





- Caveat of N³LO predictions: PDFs are computed at NNLO
- Large cancelations between partonic channels can enhance PDF sensitivity ⇒ underlines the need for N³LO PDFs

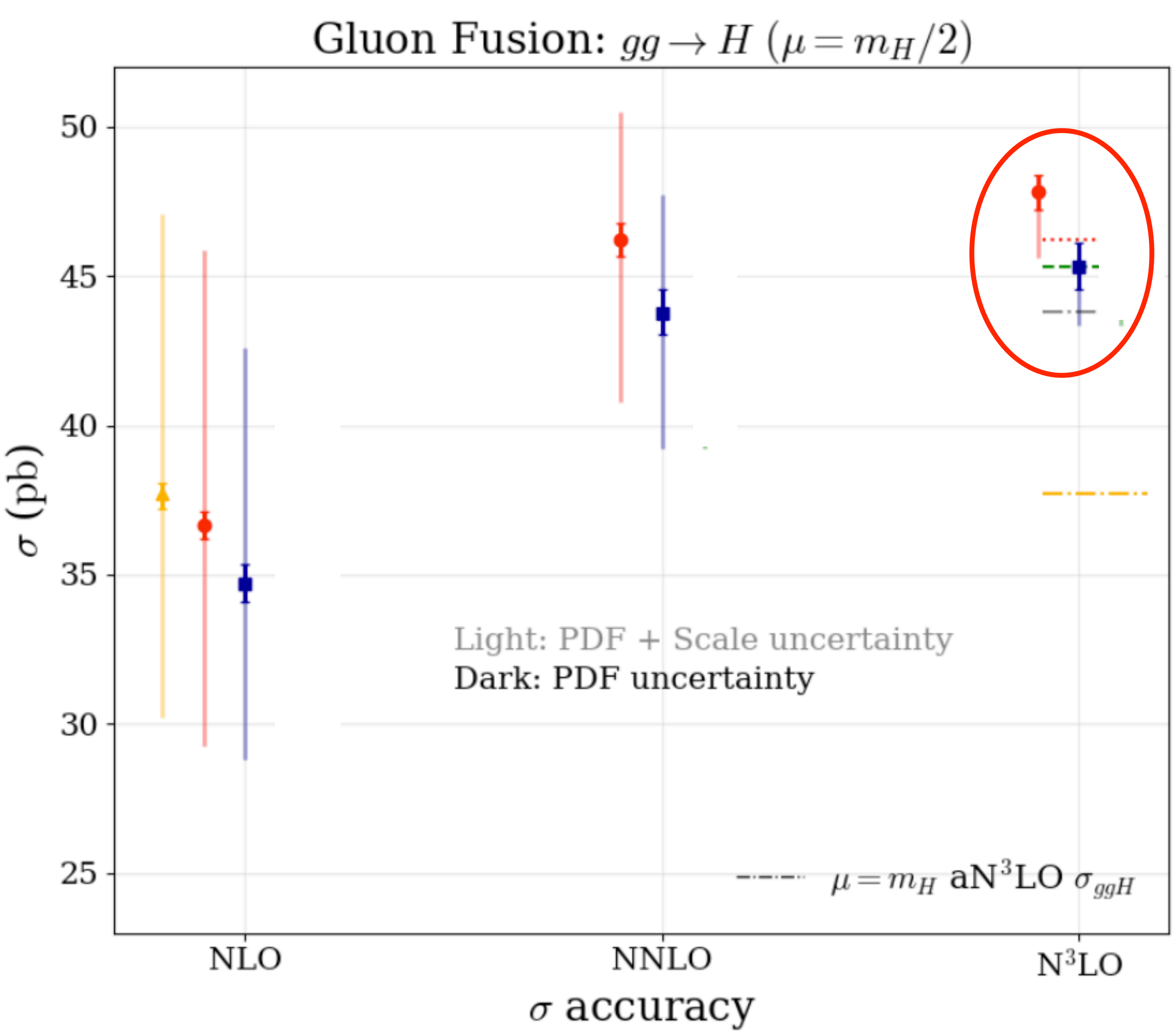
Baglio et al 2209.06138

Towards N^{3}LO PDFs

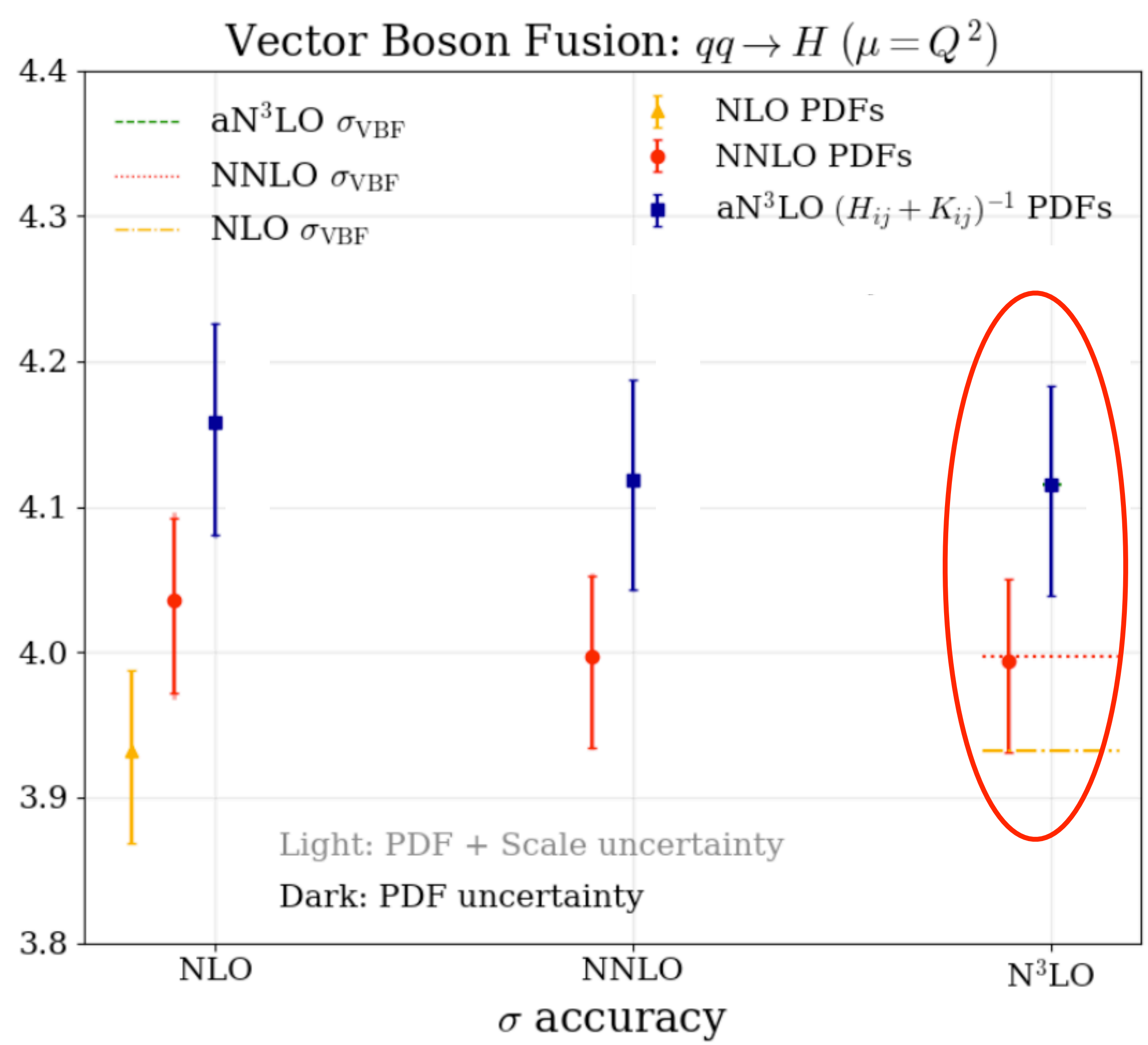
McGowan et al. 2207.04739

First approximate N^{3}LO PDF global fit (aN^{3}LO) in the MSHT framework

<u>ggH cross-section:</u>

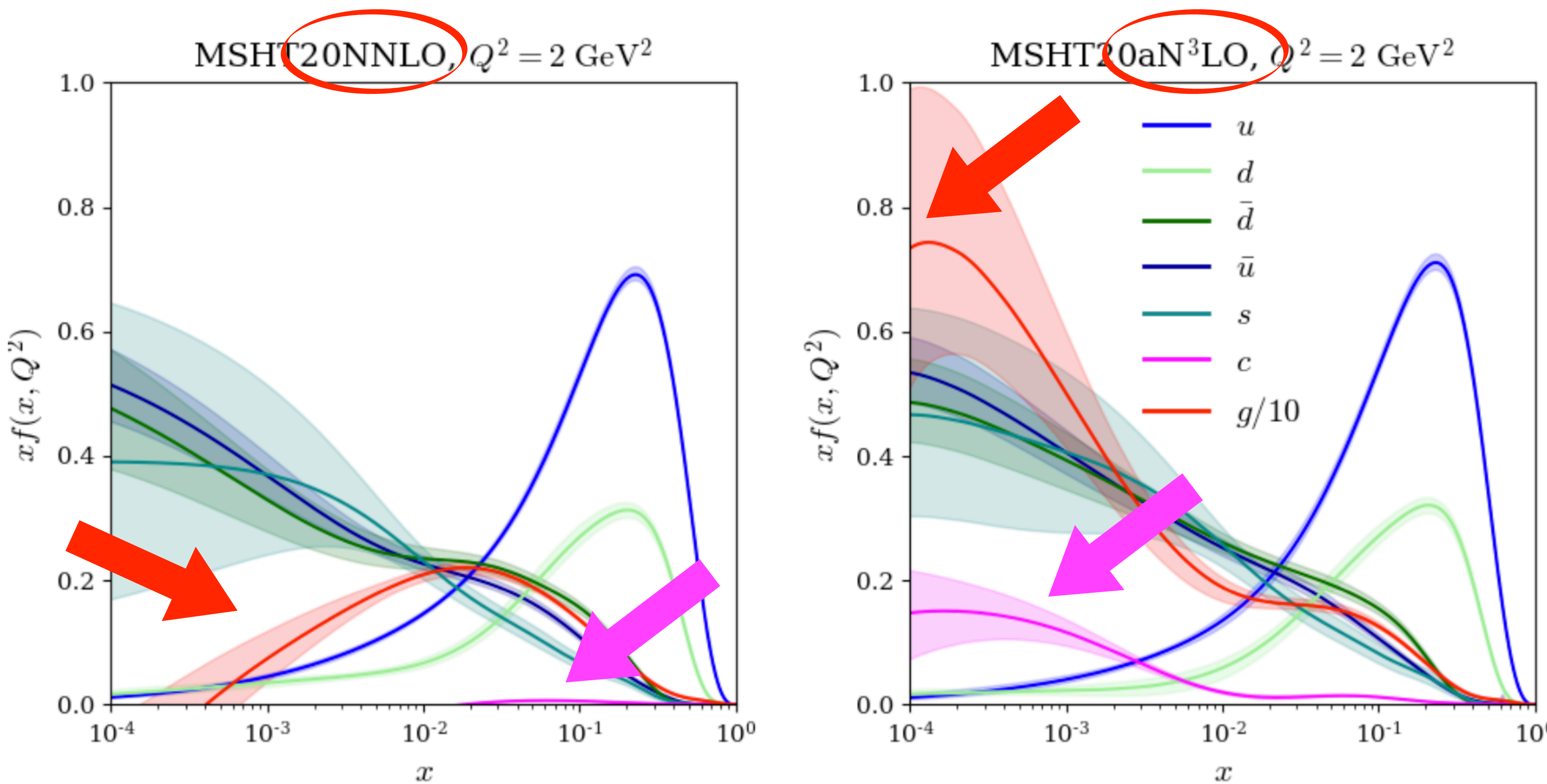


<u>VBF H:</u>



Towards N^{3}LO PDFs

McGowan et al. 2207.04739



Drastic change of gluon and heavy-quark PDF and low x and low Q^2.
aN^{3}LO completely outside NNLO band. Needs more investigation.

Infrared safe jet definitions

Infrared unsafe jet algorithms widely used at the Tevatron
[Infrared unsafe = the structure of the hard jets can be modified by very soft or collinear splittings in QCD]

Things changed at the LHC thanks seminal work which lead to the development of the fast-k_t, the SIScone and anti-kt algorithms

Cacciari & Salam hep-ph/0512210; Salam & Soyez 0704.0292; Cacciari, Salam, Soyez 0802.1189

This progress triggered considerable more work on jet-area, pileup subtraction and paved the way to the field of jet-substructure

Nobody, today, would use any old infrared unsafe jet-algorithm.
So, you will wonder, why I am talking about this at all here?

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Because jet-algorithms specifying the flavour of jets are still a notable exception!

Jet flavour

Where does jet flavour enter?

- Top reconstruction (top mass)
- Instrumental for QCD studies, e.g. inclusive b-jet ($\Rightarrow$ b-PDF)
- Z + charm-jet ($\Rightarrow$ charm PDF)
- W +charm-jet ($\Rightarrow$ strange PDF)
- Higgs to bottom ($\Rightarrow$ di-Higgs studies)
- Jet-substructure (mass reconstructions)
- …

Infrared safe jet definitions

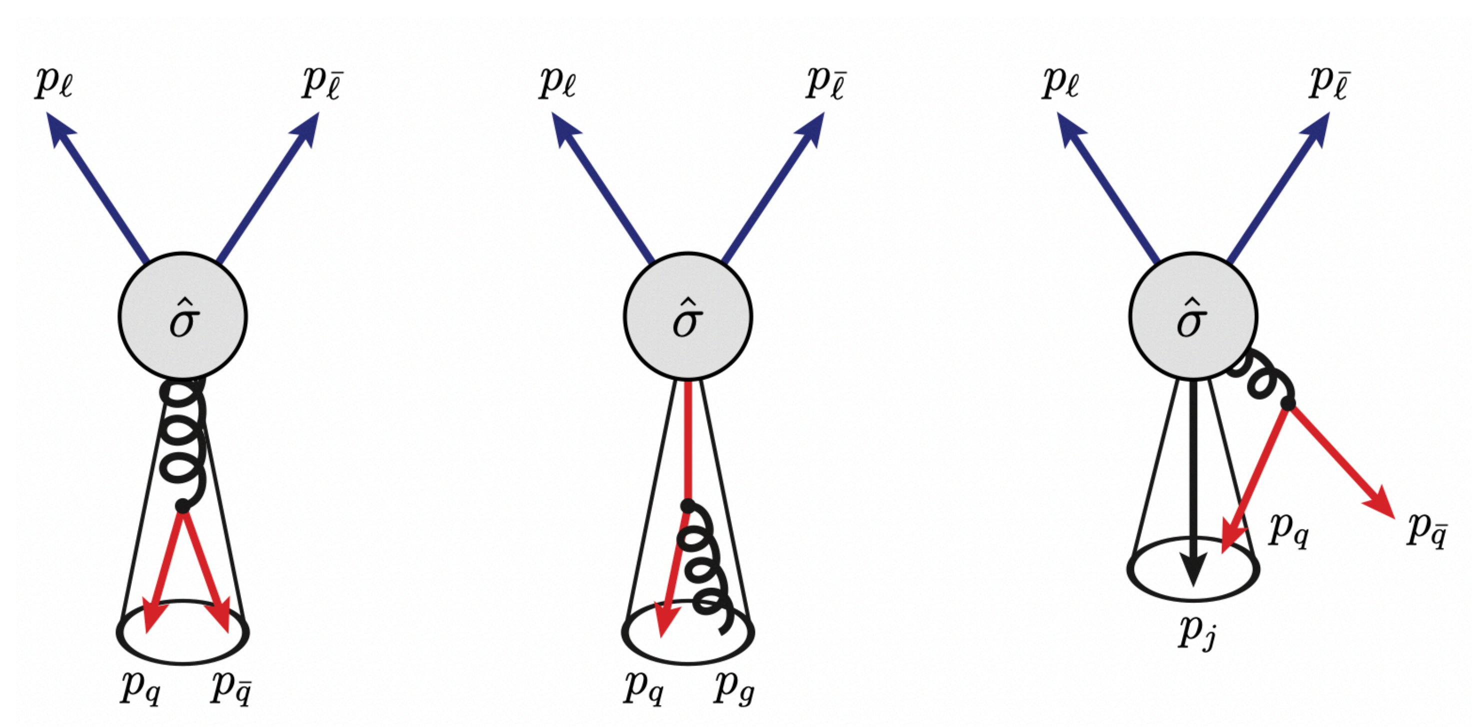
Example: LHCb charm-jet definition

LHCb 2109.08084

- reconstruct jets with anti-k_t algorithm
- require that the leading jet passes fiducial cuts
- the leading jet is considered a charm jet if there is at least one c-hadron satisfying $p_{t,\text{c-hadron}} > 5$ GeV and $\Delta R(\text{jet,c-hadron}) < 0.5$

See talk by G. Stagnitto

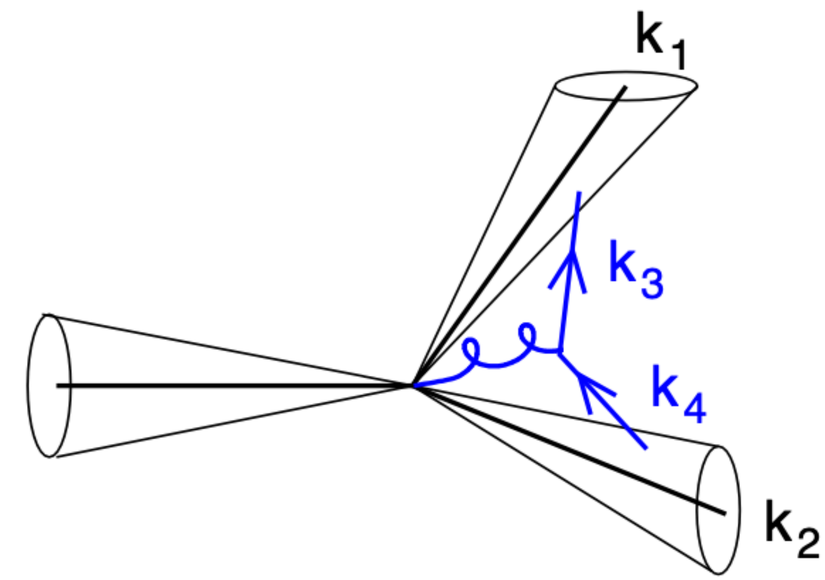
This definition is infrared and collinear unsafe



Gauld et al. 2302.12844

Jet flavour

The problem was addressed in 2006 (before the anti-k_t) and the proposed definition relies on a modification of the k_t-algorithm



Banfi, Salam, GZ hep-ph/0601139

<u>Two key elements:</u>

1) modification of the distance for flavoured particles

$$d_{ij}^{(F)} = (\Delta\eta_{ij}^2 + \Delta\phi_{ij}^2) \times \begin{cases} \max(k_{ti}^2, k_{tj}^2) & \text{if softer of } i,j \text{ is flavoured} \\ \min(k_{ti}^2, k_{tj}^2) & \text{if softer of } i,j \text{ is flavourless} \end{cases}$$

2) classify a jet containing flavour and anti-flavour as gluon jet

Because of the k_t-like distance and the fact that it requires tagging two nearby flavoured particles, the algorithm was not adopted in practice at the LHC

Jet flavour

Recent proposals:

- Practical jet flavour through NNLO — Caletti et al. 22
- Infrared-safe flavoured anti-k_t jets — Czakon et al. 22
- A dress of flavour to suit any jets — Gauld et al. 22
- Flavoured jets with exact anti-k_t kinematics — Caola et al

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Goals (in some cases not fully met yet…)

- anti-k_t like kinematics
- infrared-safe to all orders
- flavour information, e.g. for jet-substructure
- experimentally feasible

Whether or not these novel jet definitions will be used in realistic experimental analyses remains to be seen…

Conclusions

- ✓ Continuous fast progress in fixed-order calculations: NNLO 2 → 3, new N^3LO results. Progress driven by new ideas and methods.
- ✓ Steps towards N^3LO PDFs
- ✓ Progress in matching NNLO and parton shower (but not fully automated yet)
- ✓ Progress in parton showers ⇒ first NLL showers and ways to formally estimate accuracy
- ✓ Jet flavour: new ideas and algorithms. Theoretically interesting and useful ⇒ look forward to first experimental implementations

[Apologies for the personal selection of topics, and for the many interesting results not covered here]