Higgs Monte Carlo Simulation

Silvia Ferrario Ravasio

7th November 2024

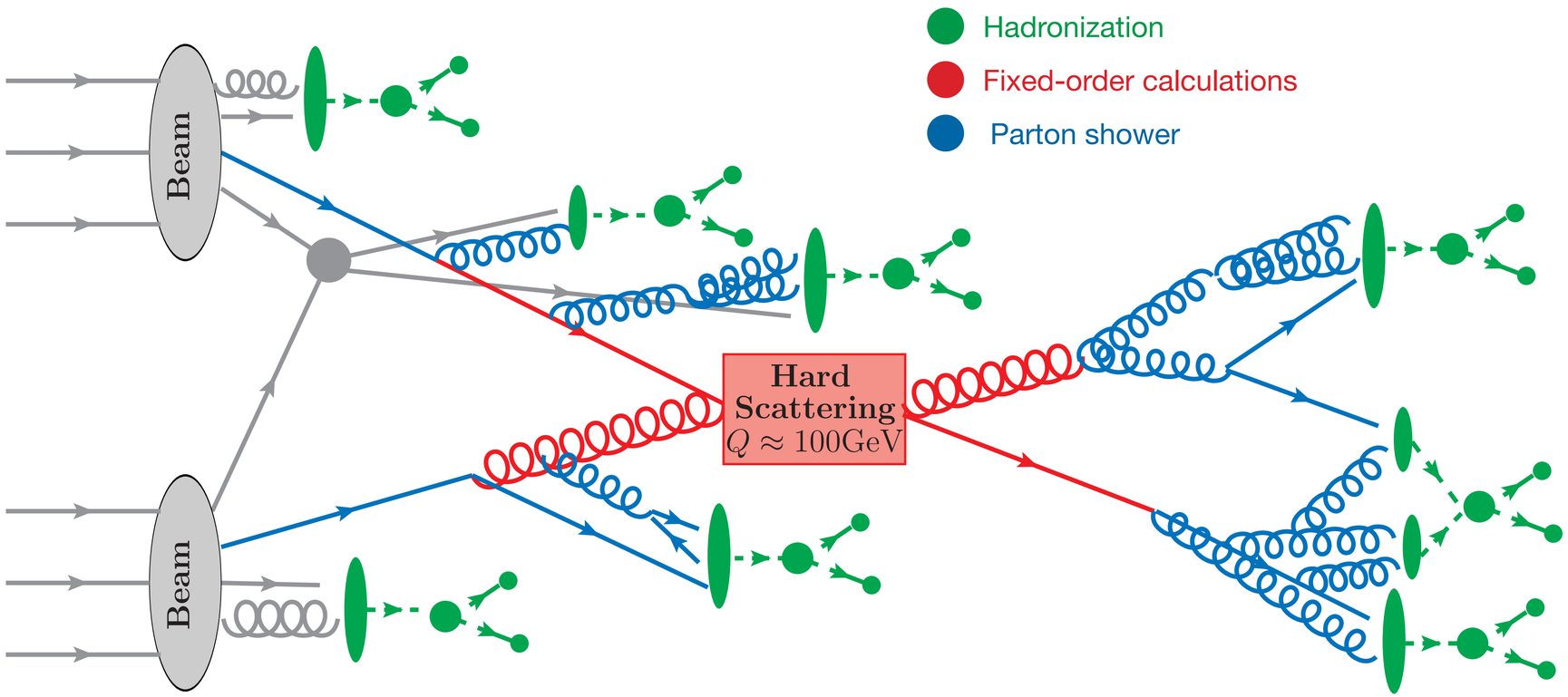
Monte Carlo event generators — why are they so important?

- **Shower Monte Carlo Event generator** are the **default theoretical** tool to interpret collider data

Pythia

Herwig

Sherpa



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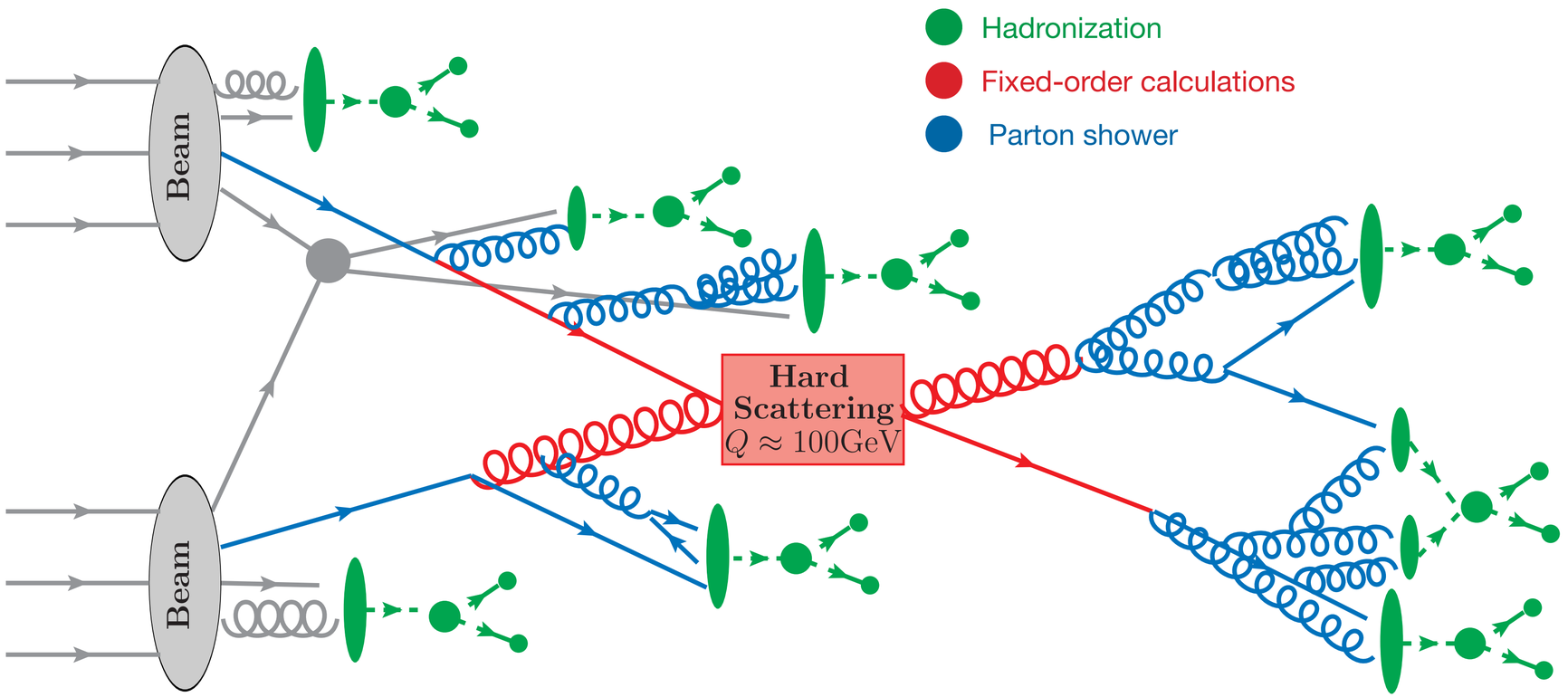
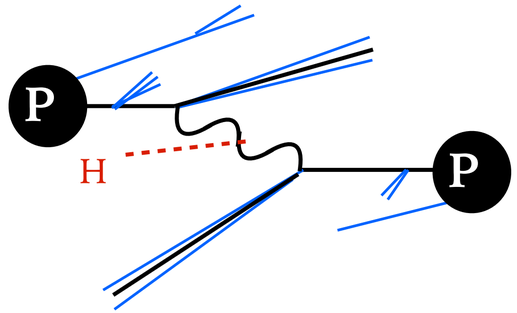


ARE CURRENT SMC GOOD ENOUGH (FOR HIGGS PHYSICS)?

A snapshot of theory uncertainties

➤ Example: theory uncertainties in typical **Vector Boson Fusion** measurements

	VBF H	ggH (in VBF-enriched region)
PDF	<1%	<3%
QCD scale	<1%	**2-20%**
UE	<1.5%	<2-3%
Parton shower	**5-15%**	**4-10%**



M. Pellen, HXWG meeting, 2023

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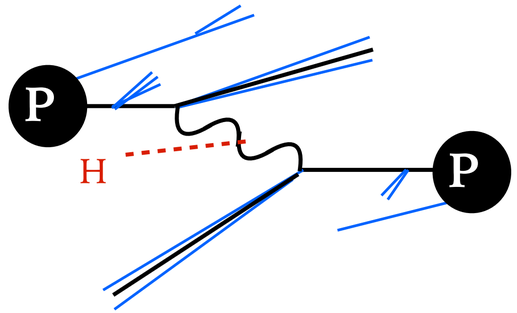
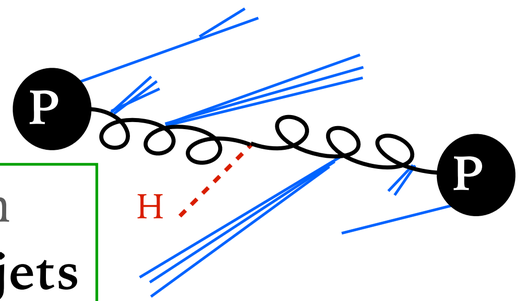


Primary theory uncertainties affecting experimental mesurements are:

Scale uncertainty in the **ggH** background



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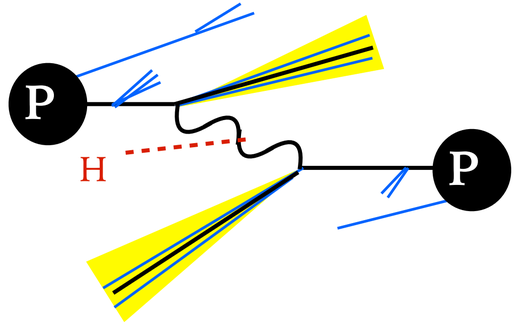
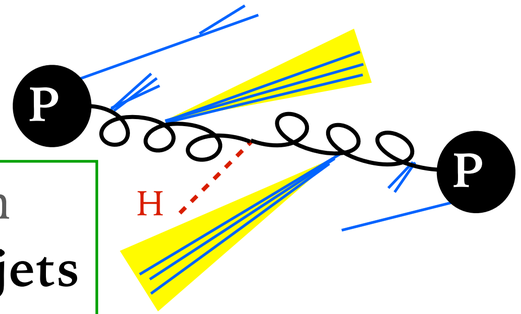


Better constraint the accuracy of **PS**

Primary theory uncertainties affecting experimental mesurements are:

➤ **Scale uncertainty** in the **ggH** background

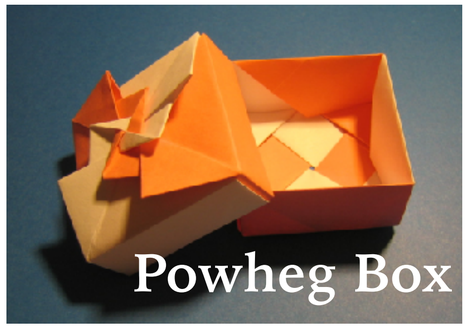
➤ Modelling of soft **radiation** inside the jets



We need to include an accurate **Higgs+2 hard jets** description in our SMC

Improving the **fixed order** accuracy of SMC

- For more then 2 decades the standard way to improve **showers** was to combine them with **fixed-order calculations** via a matching procedure that removes the double counting and preserves the fixed-order accuracy of the result



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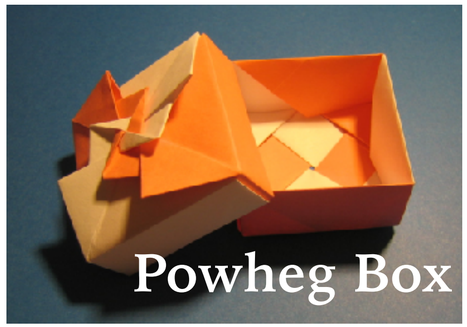
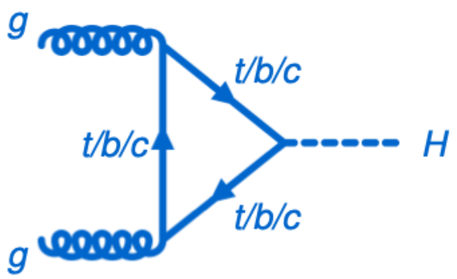
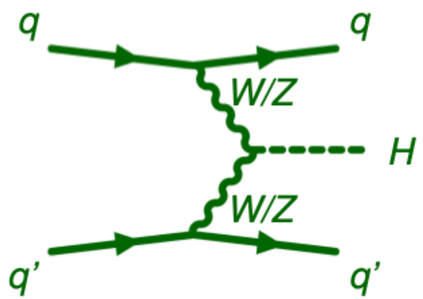


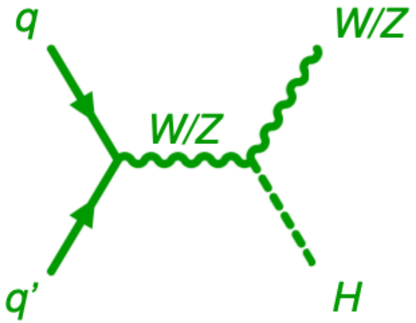
- What is the fixed-order accuracy we can reach for these processes?



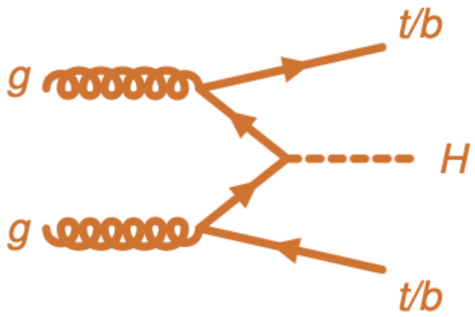
ggF (87%)



VBF (7%)



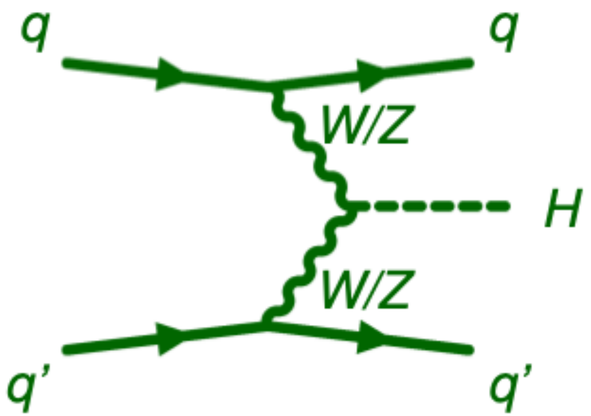
VH (4%)

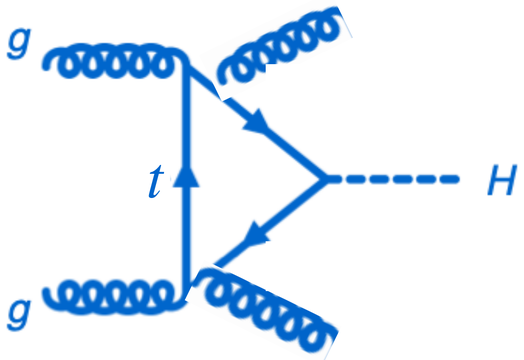


ttH/bbH (2%)

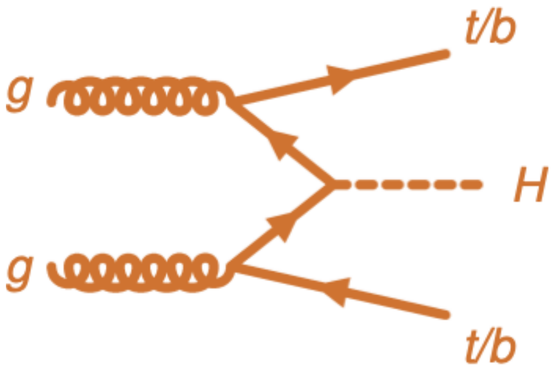
Higgs with jets

➤ For processes where the **Higgs** appears with **hard jets**, state of the art is **NLO+PS**





$m_t \to \infty$



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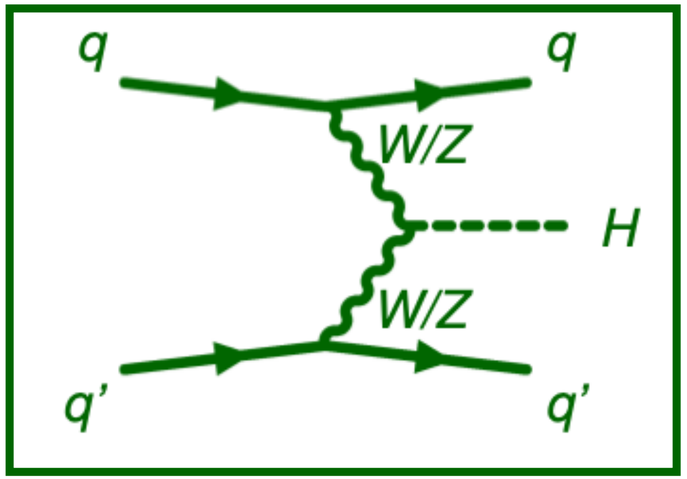
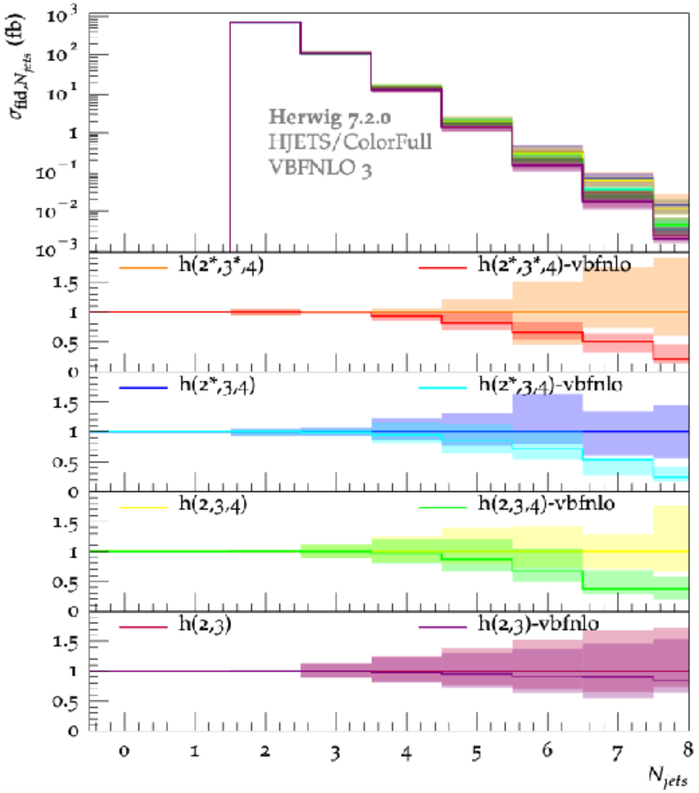


Can have **2 and 3 jets** at NLO via **multi-jet merging**

[Chen, Figy, Platzer, 2109.0373]



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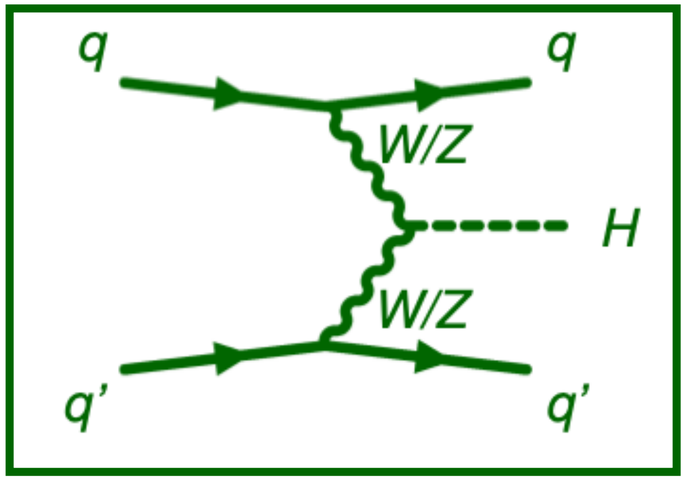

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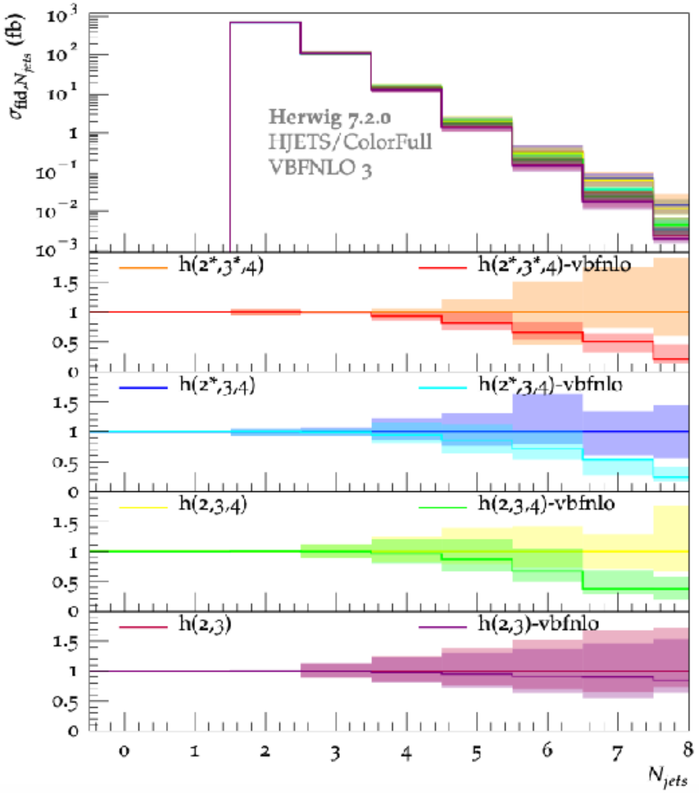
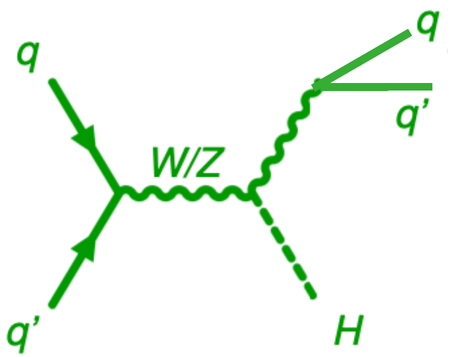
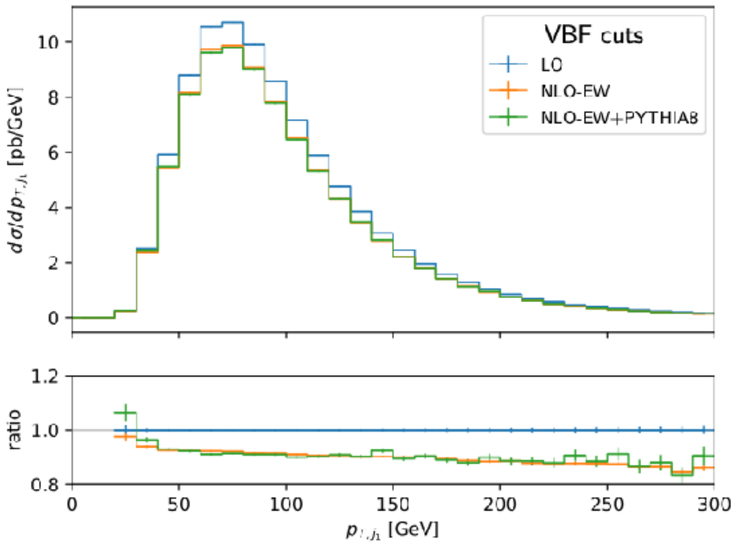


Interference effects with ***HV*** available in **Powheg, Mg5, Sherpa, Herwig**





EW corrections in Powheg (yet to be combined with QCD)

[Jager, Scheller, 2208.00013]

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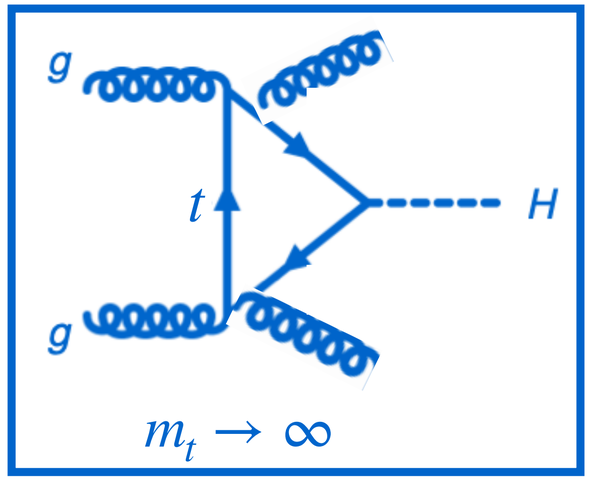
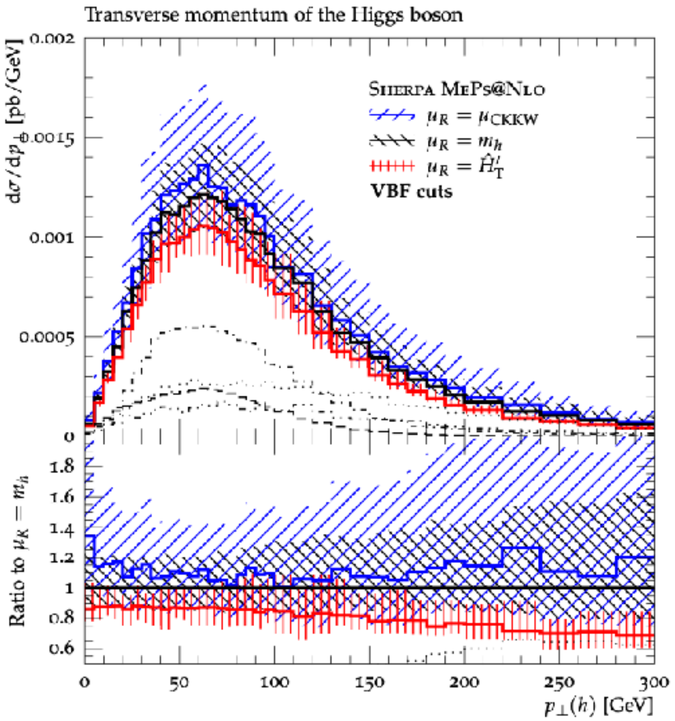


Can have **0,1,2** at NLO via **multi-jet merging**, in **Sherpa** [Hoche, Krauss, Schonherr, 1401.7971] and **Herwig** [Bellm, Gieseke, Platzer 1705.06700]



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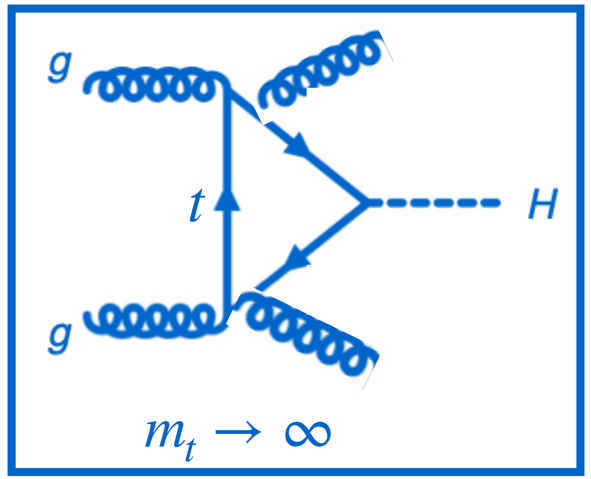

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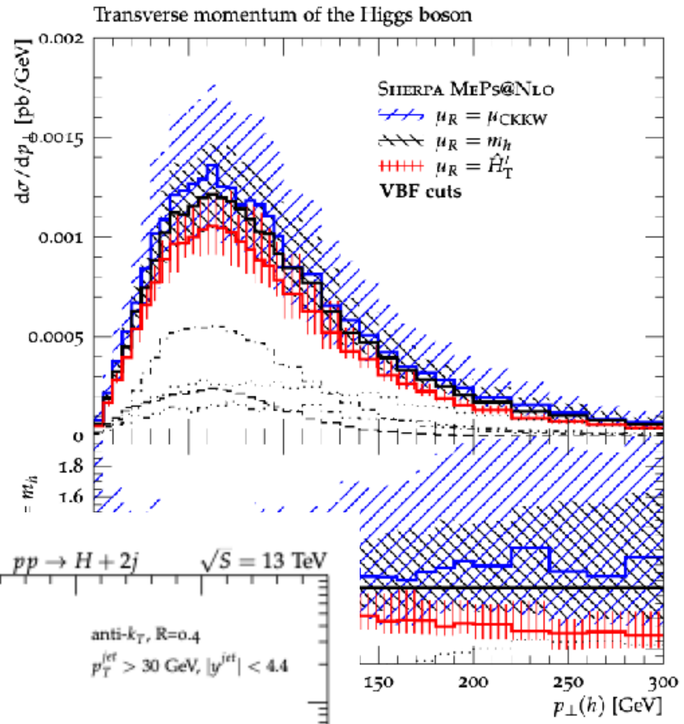
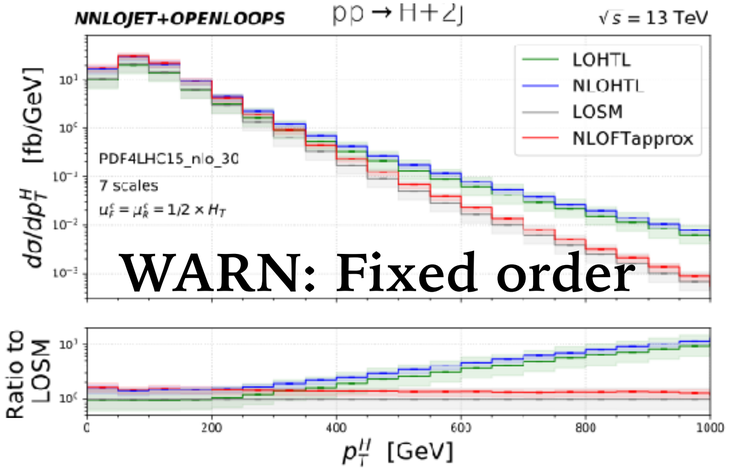
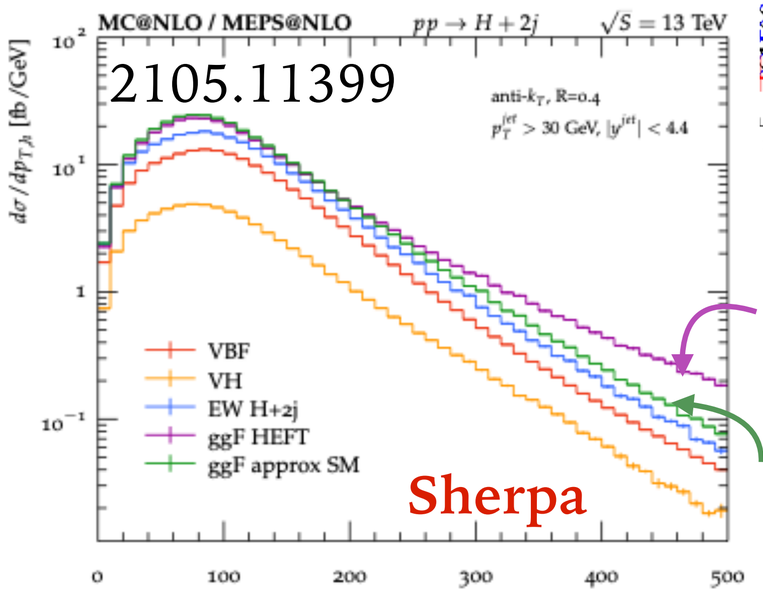




m_t effects are **important** but not known for the **2-loop amplitudes**: can be capured **LO reweighing** [Chen, Huss, Jones, Kerner, Lang, Lindert, Zhang; 2110.06953]

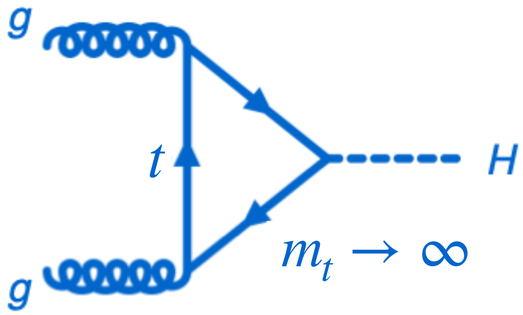


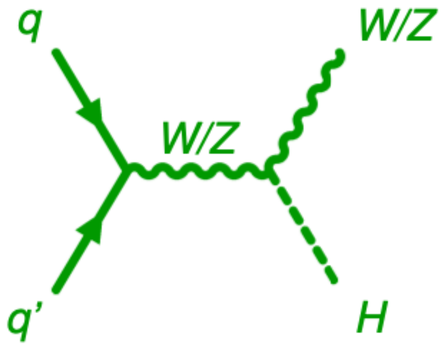
ggF+0,1,2 jets at NLO, $m_t \to \infty$

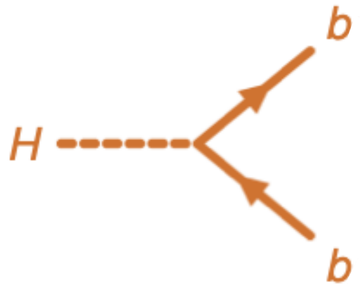
Including approx m_t effects

Higgs (without jets)

➤ **Higgs** production (plus **bosons**) and $H \to b\bar{b}$ decay is known at **NNLO+PS**





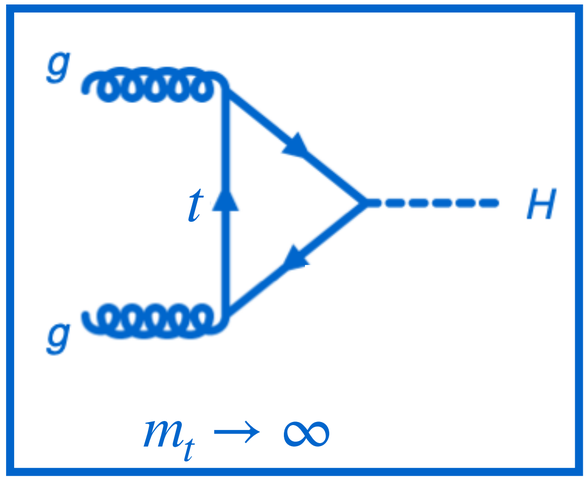


➤ NNLO event generators used in experiments:

GENEVA

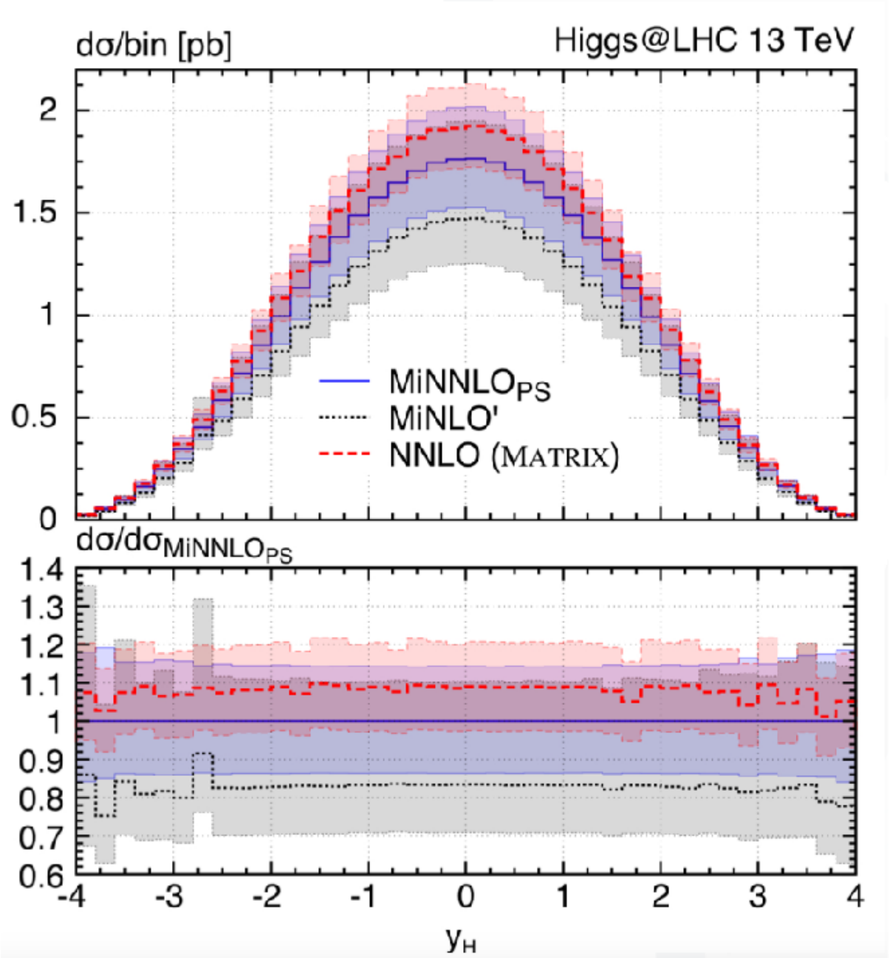
➤ Other NNLO+PS methods exist: **UNNLOPS** [Hoeche,Li,Prestel, 1405.3607], NNLOPS with sector showers [Cambell, Hoche, Li, Preuss, Skands, 2108.07133]

NNLO+PS with MiNNLO and Geneva



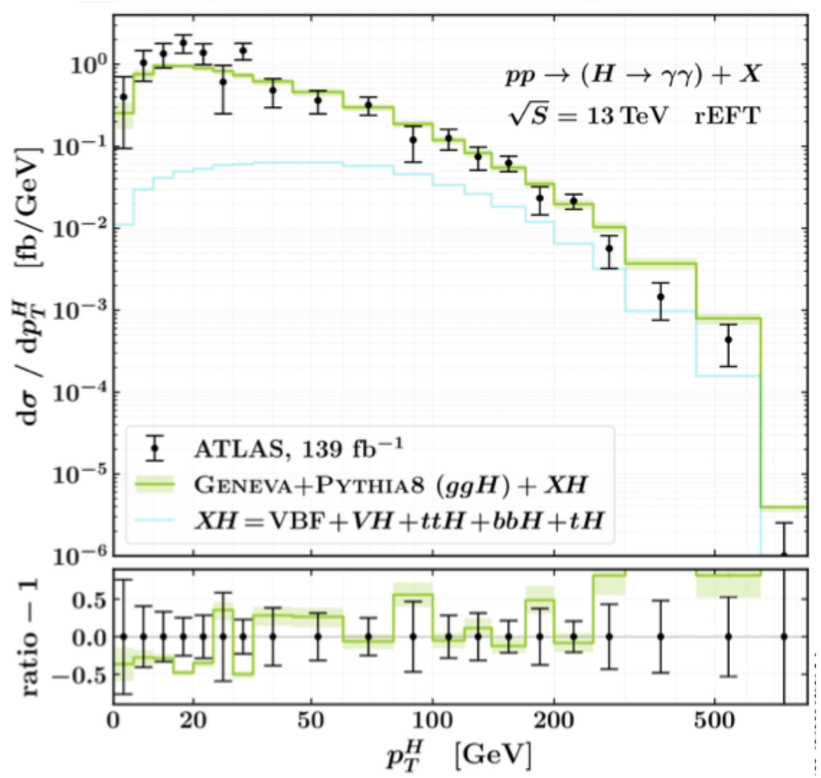
The idea behind both methods is to use ingredients from ***analytic resummation*** *at N^3LL for an observable such as 0-jettines or p_T^H to cast the FO calculation in a "parton-shower" like way before the matching*

MiNNLO [Monni, Nason et al., 1908.06987]

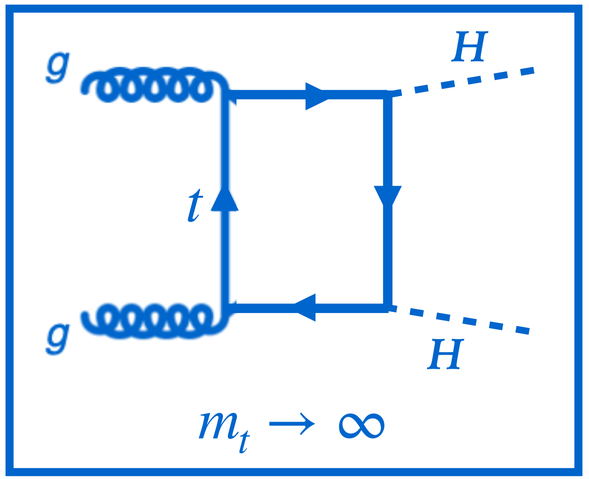


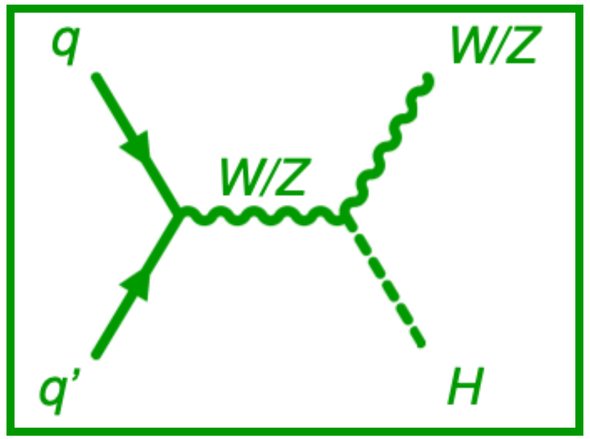
Both methods have **recently** been "refined" for ggF

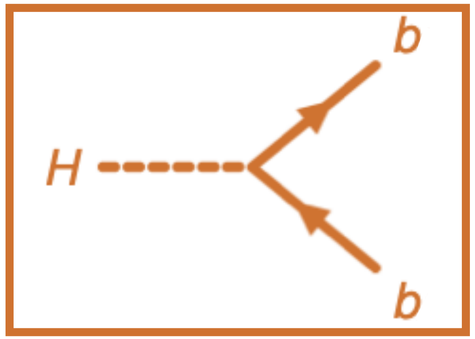
Geneva [Alioli, Billis et al., 2301.11875]

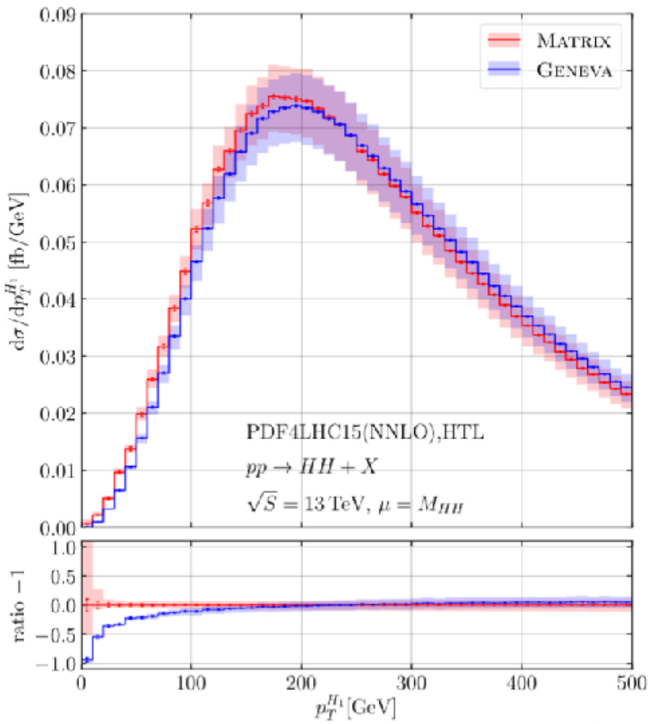


NNLO+PS with MiNNLO and Geneva

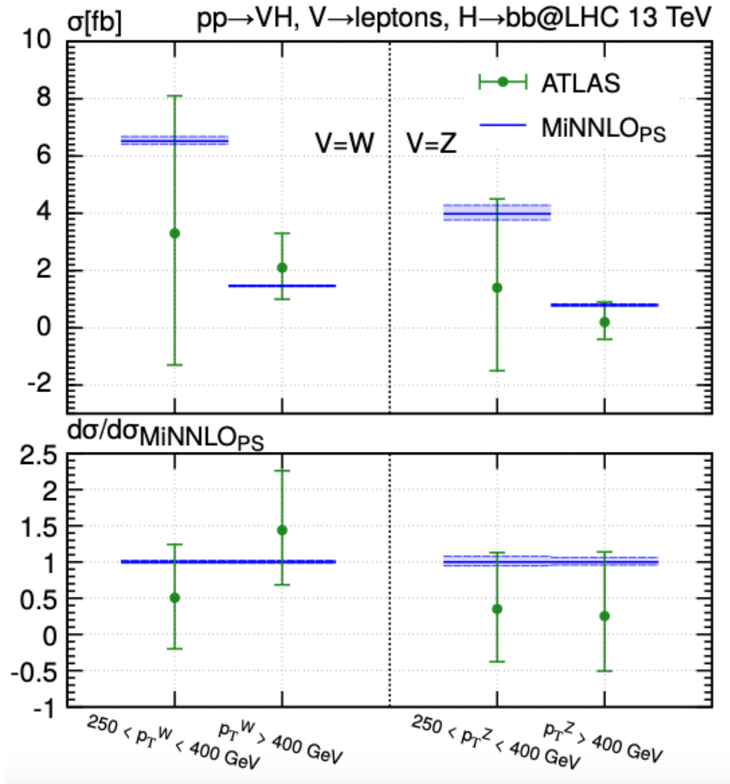








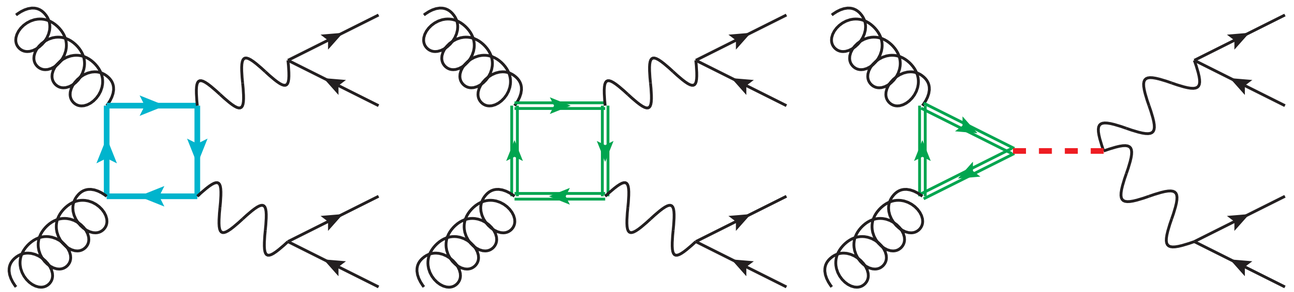
Geneva [Alioli et al., 2212.10489]



MiNNLO [Zanoli et al., 2112.04168]

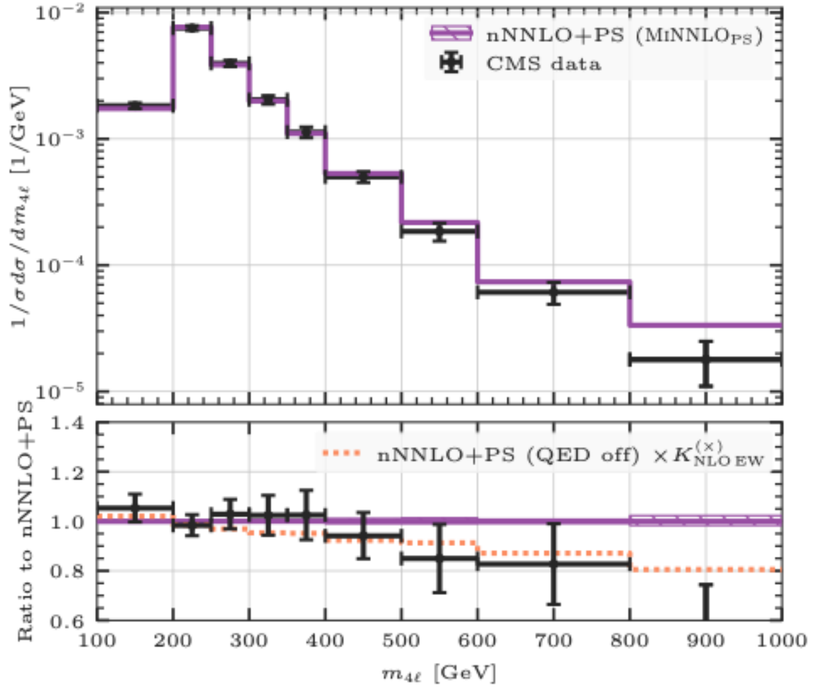
Loop-induced processes with an Higgs

- **Loop-induced** processes (**where $m_t \to \infty$ cannot be used**) obtained from gluon fusion are formally NNLO, but due to their size are being computed at **NLO+PS**



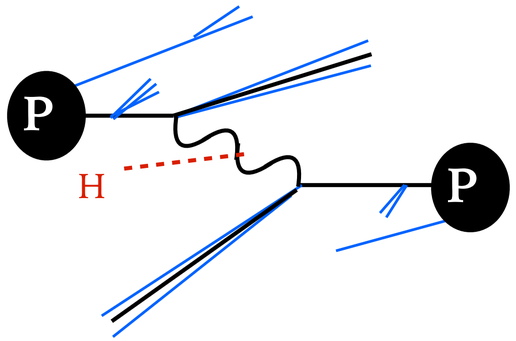
$gg \to 4\ell$ in the **Powheg Box**
[Alioli, SFR. et al., 2102.07783]

Combined with "standard"
MINNLO for $q\bar{q} \to ZZ \to 4\ell$
[Buonocore et al,
2108.05337]



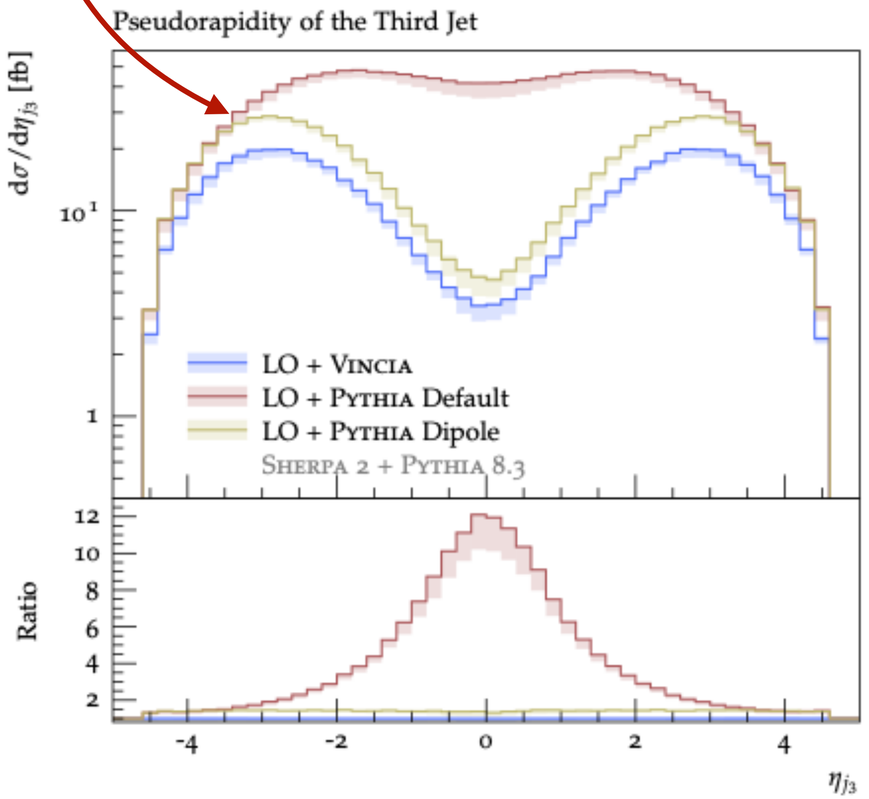
Is matching all we need?

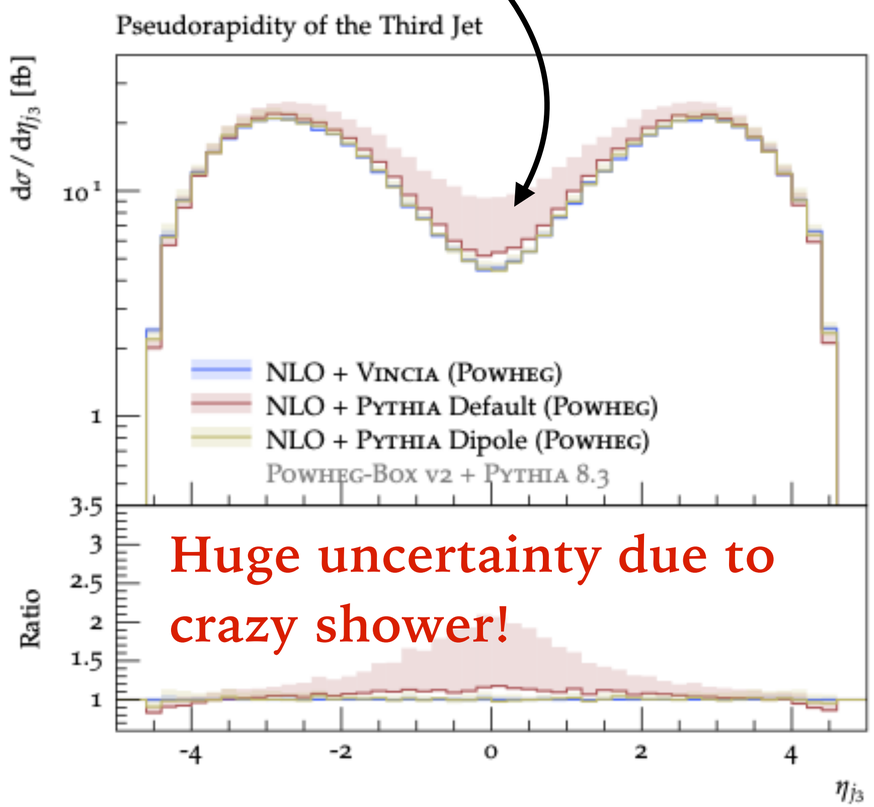
➤ If you have a **bad parton shower** (e.g. default Pythia8 shower), will **matching** save you? **NO!**



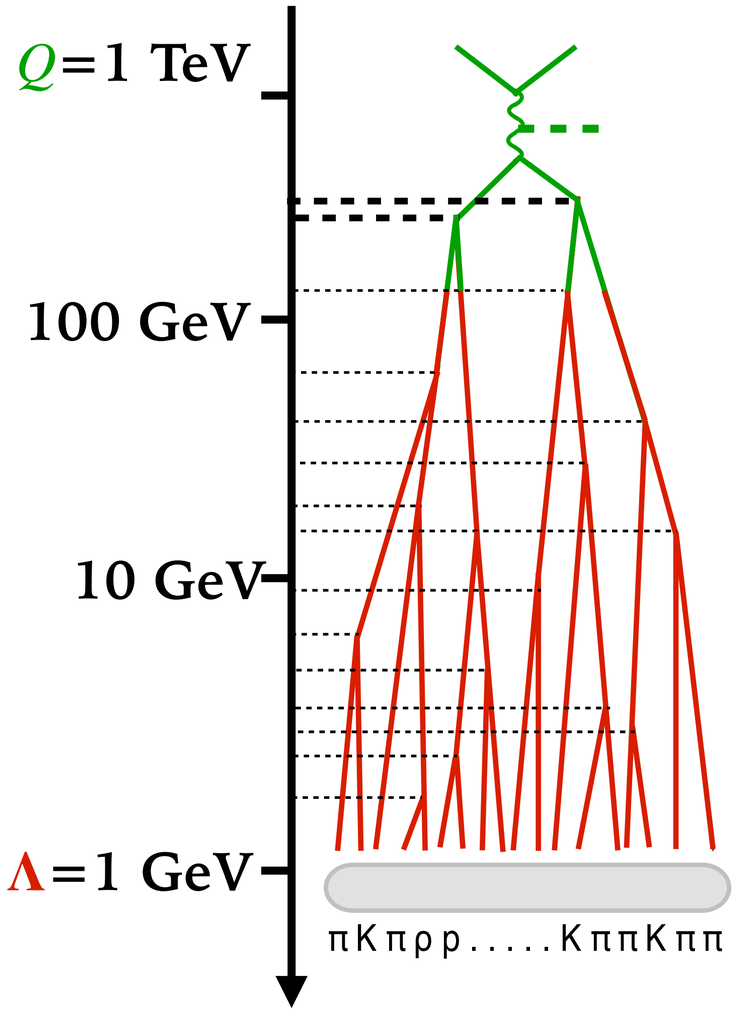
VBF: suppression of radiation at large angles

[Hoche, Mrenna, Payne, Preuss, Skands, 2106.10987]





What shall we aim for in a shower?



Parton shower: **logarithmically-enhanced** terms at all-orders in α_s; correct when $L = \ln \frac{Q}{\Lambda} \gg 1$

$$\Sigma_{\text{PS}} = \exp\left(L g_{\text{LL}}(\alpha_s L) + g_{\text{NLL}}(\alpha_s L) + \alpha_s g_{\text{NNLL}}(\alpha_s L) + \dots\right)$$

NLL $\approx 20 - 40\,\%$ correction and not entirely under control in standard GPMC :'(

NNLL necessary for %-level pheno!

NLL showers

- Recipe to get **NLL showers** known, at least in theory ([Catani, Webber, Marchesini '91; Dasgupta, Dreyer, Hamilton, Monni, Salam, Soyez '20])

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- This enabled the **PanScales** to devise the **first** showers with **general** NLL accuracy for

$e^+e^- \to j_1 j_2$	$pp \to$ *colour singlet*	**DIS & VBF**
Dasgupta, Dreyer, Hamilton, Monni, Salam, Soyez, 2002.11114	van Beekveld, **SFR**, Soto-Ontoso, Salam, Soyez, Verheyen, 2205.02237, + Hamilton 2207.09467	van Beekveld, **SFR**, 2305.08645

…with **subleading colour** (2011.10054) and **spin correlations** (2103.16526, 2111.01161)

NLL showers

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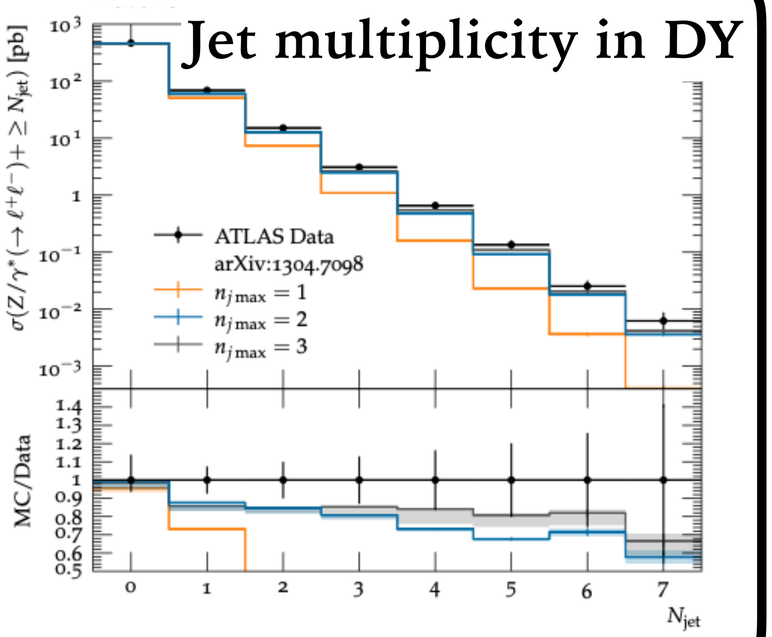
- **PanScales** devised the **first** showers with **general** NLL accuracy for processes with two coloured partons, including $H \to gg$ (2002.11114), **ggF** (2205.02237, 2207.09467) and **VBF** (2305.08645), with **subleading colour** (2011.10054) and **spin correlations** (2103.16526, 2111.01161)

- **Alaric** (Sherpa) NLL shower for $e^+e^- \to j_1 j_2$ [Hoche, Krauss, Reichelt, 2404.14360], with **mass effects** [Assi, Hoche, 2307.00728], recently extended to generic process in **hadron-hadron collisions** [Hoche, Krauss, Reichelt, 2404.14360]



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- **Apollo** (Pythia) NLL shower for $e^+e^- \to j_1 j_2$ [2403.19452, Preuss]
- **FHP** (soon in Herwig) NLL shower for $e^+e^- \to j_1 j_2$ [Forshaw, Holguin, Platzer, 2003.06400]
- **Deductor** NLL accuracy shown at least for $e^+e^- \to j_1 j_2$ [Nagy, Soper 2011.04777]

Matching with NLL showers

Status of **matching with NLL showers:**

- **PanScales** [Hamilton et al, 2301.09645] and **Apollo** [Preuss, 2403.19452] have **NLO** matching for **colour-singlet decay into 2 jets**

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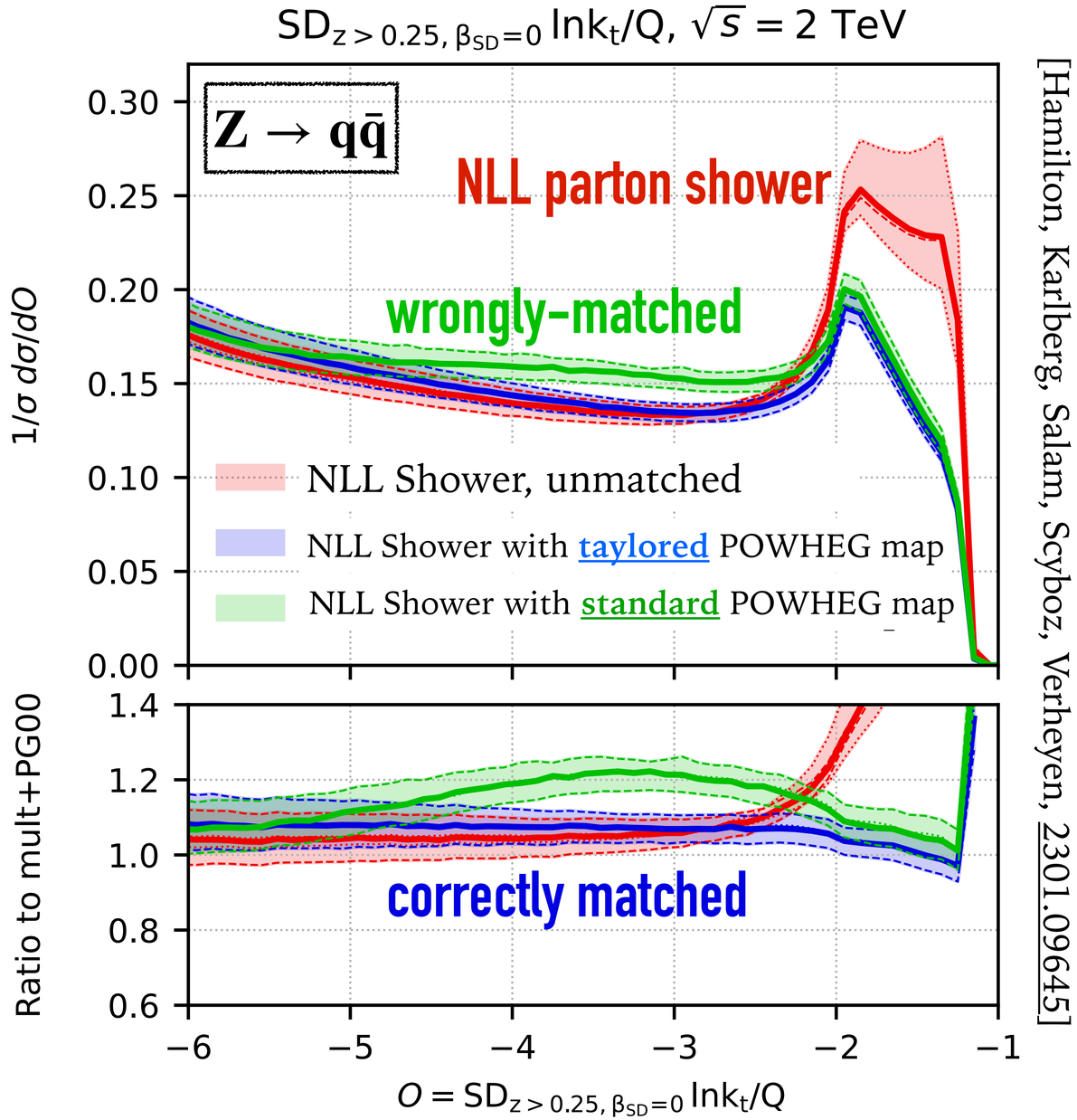
What is so difficult about getting NLO for generic process?

Find a nice NLO subtraction with kinematic mappings and counterterms compatible with the emission kernels of the shower!

Can we simply use an **existing external generator** not taylored to the shower, such as the **Powheg Box** (and **MiNNLO**) and **Geneva**?

Matching and Logarithmic Accuracy

- Take a **NLL shower**, match it using the **standard POWHEG BOX** mappings, then **taylor** them to match the shower, see any difference?



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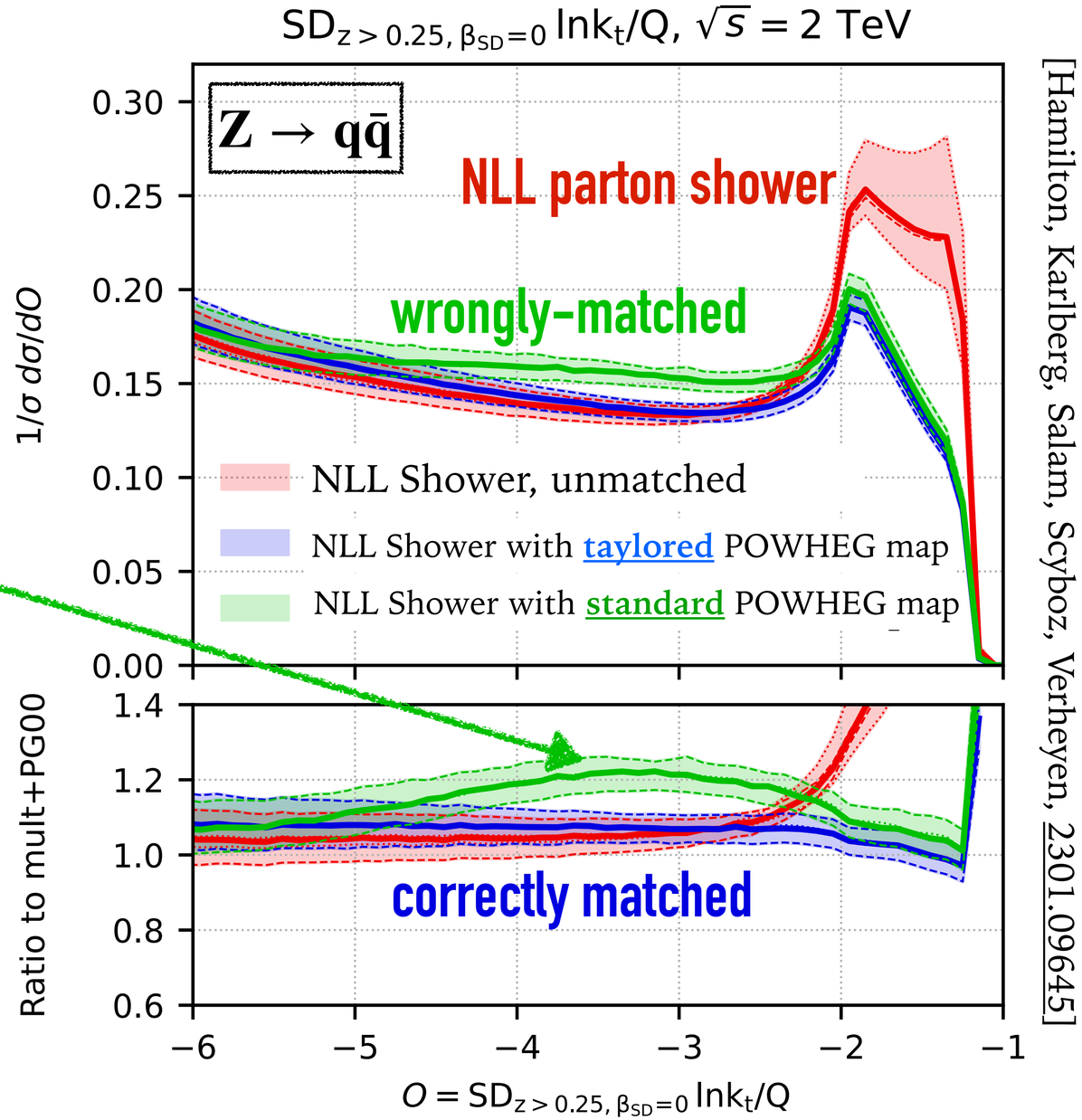

Matching and Logarithmic Accuracy

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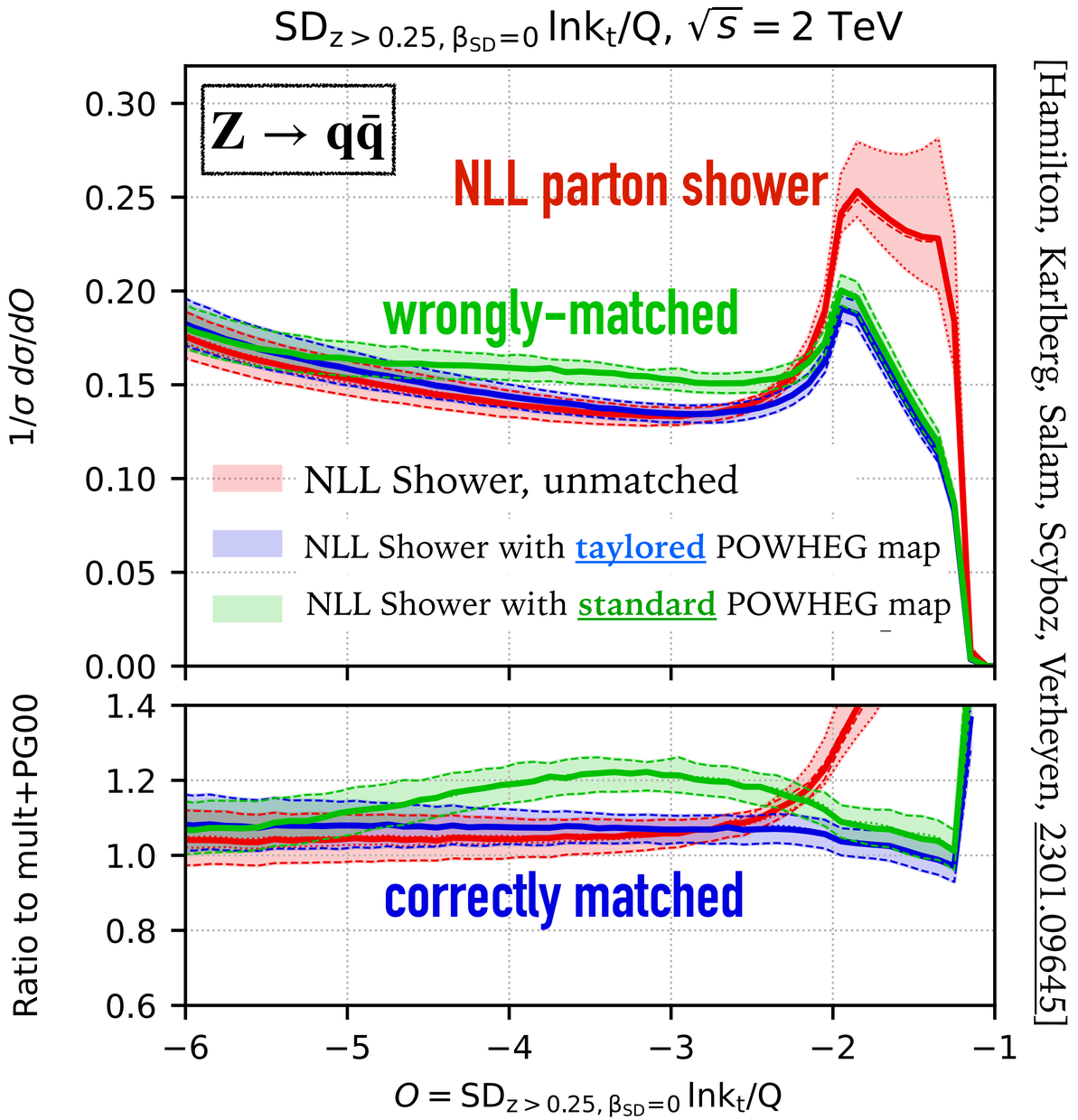
- While a **correct matching** will provide some **ingredients** necessary for **NNLL**!

$$\Sigma_{\mathrm{NNLL}} = (1 + \alpha_s C) \exp\left(L g_{\mathrm{LL}}(\alpha_s L) + g_{\mathrm{NLL}}(\alpha_s L) + \ldots\right)$$



Going Beyond NLL

The identification of the **relation** between critical **NNLL analytic resummation** ingredients and their **parton-shower counterparts** is the recipe to build a NNLL shower

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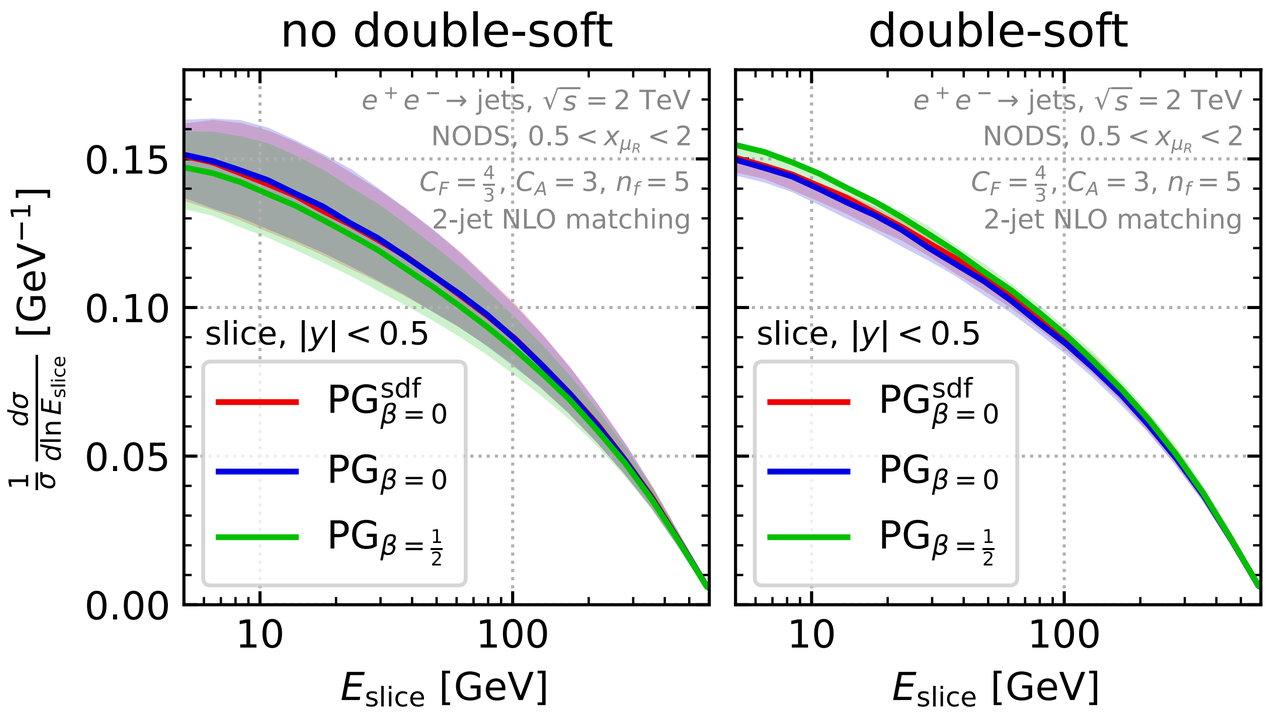
➤ **Soft-radiation** pattern at **NLO**

➥ NNLL accuracy for **non-global observables** such as central jet vetoes (important e.g. for ggF vs VBF discrimination); so far applied only to $e^+e^- \to j_1 j_2$ [S.F.R., Hamilton, Karlberg, Salam, Scyboz, Soyez 2307.11142]

➥ NNLL → NLL sizeable **reduction of the scale uncertainty**



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- **NLO matching**

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- **Collinear-radiation** pattern at **NLO**

- **Soft-collinear-radiation** pattern at **NNLO**

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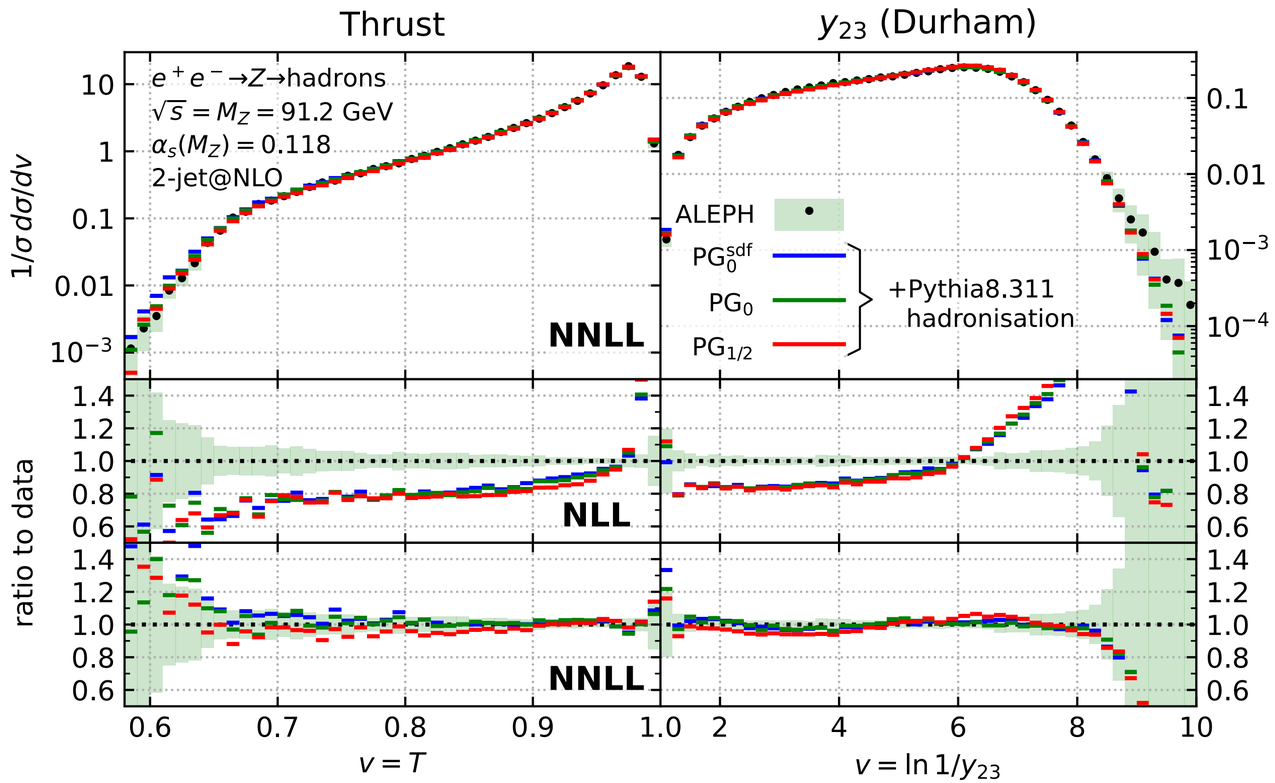
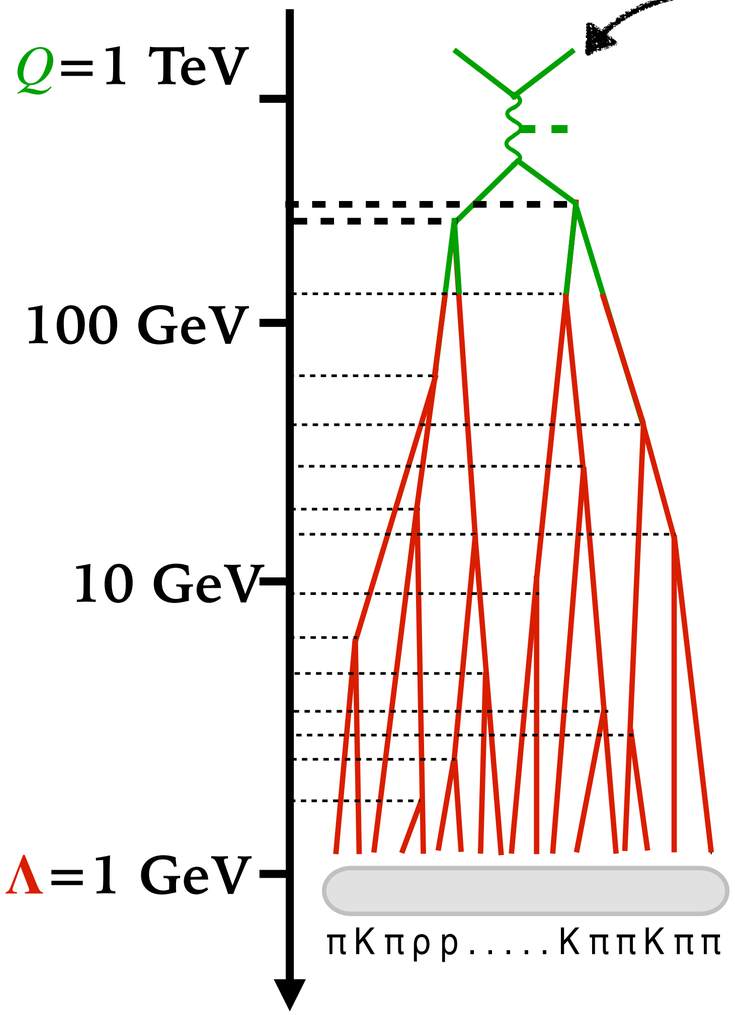


With this, we can build the **first** shower for $e^+e^- \to j_1 j_2$, and $H \to gg$, with **NNLL accuracy for global event shapes** [van Beekveld, Dasgupta, El-Menoufi, SFR et al, 2406.02661]

What to do

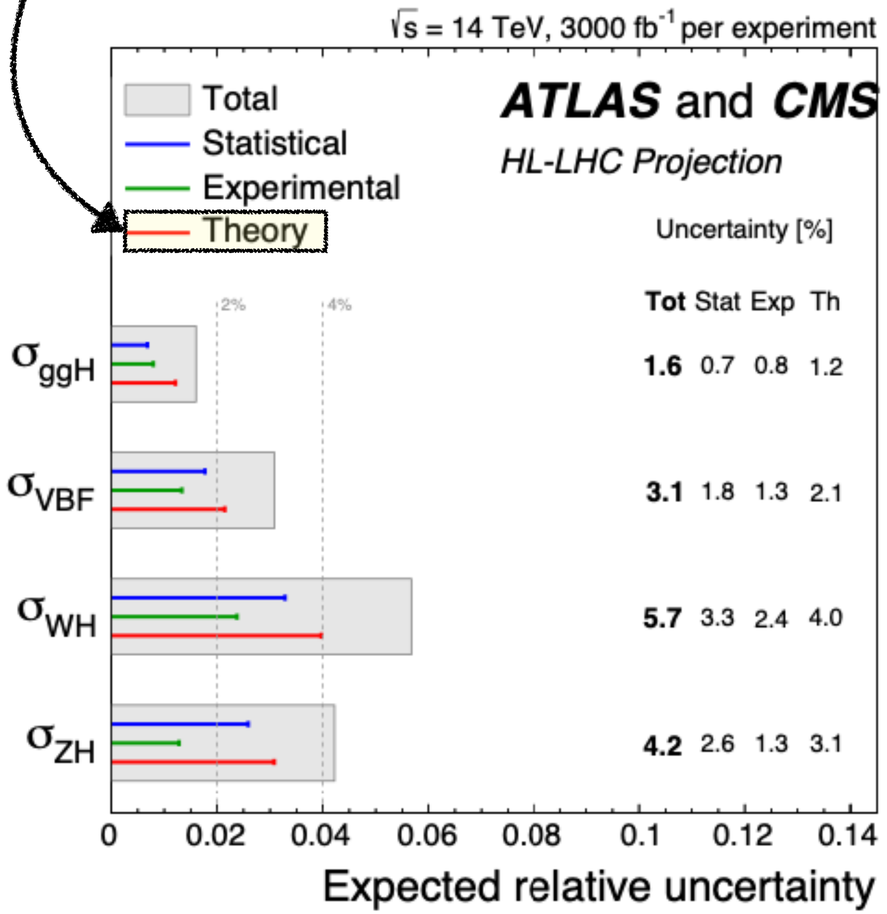
To exploit the physics potential of the LHC and future colliders, we need **theoretical predictions** spanning **several energy-regimes** with **percent-level precision**



Combine higer-order calculations with showers: NNLO current frontier

SIMULTANEOUSLY??

New showers with improved formal and practical accuracy: NNLL current frontier



[1902.00134]

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$e^+e^- \to j_1 j_2$	$pp \to$ *colour singlet*	**DIS & VBF**
Dasgupta, Dreyer, Hamilton, Monni, Salam, Soyez, 2002.11114	van Beekveld, **SFR**, Soto-Ontoso, Salam, Soyez, Verheyen, 2205.02237, + Hamilton 2207.09467	van Beekveld, **SFR**, 2305.08645

…with **subleading colour** (2011.10054) and **spin correlations** (2103.16526, 2111.01161)