NNLO+PS MATCHING:
ASSOCIATED HIGGS PRODUCTION

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in collaboration with:
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LHC HXSWG – WG1 meeting (29/06/2017)

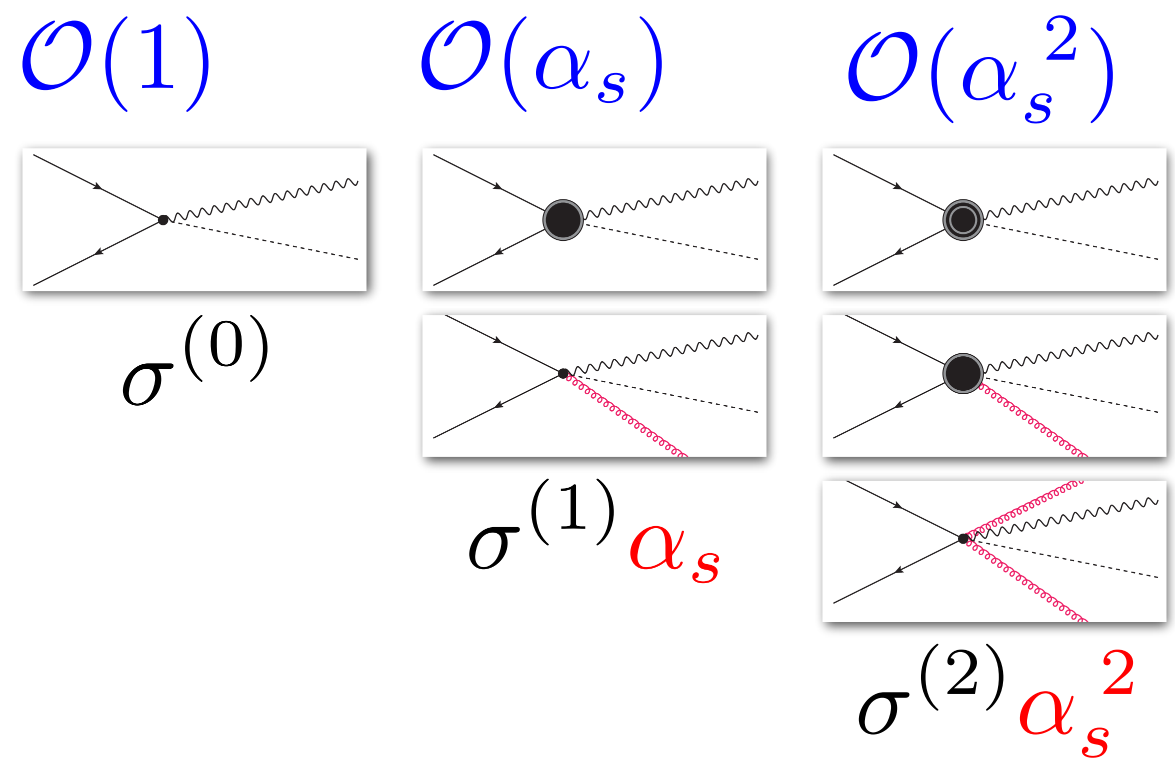
NNLO QCD

[1107.1164; G.Ferrera, M.Grazzini, F.Tramontano]
[1407.4747; G.Ferrera, M.Grazzini, F.Tramontano]
[1601.00658; J.Campbell, R.K.Ellis, C.Williams]

LO: $\sigma^{(0)}$

NLO: $\sigma^{(0)} + \sigma^{(1)}\alpha_s$

NNLO: $\sigma^{(0)} + \sigma^{(1)}\alpha_s + \sigma^{(2)}\alpha_s{}^2$



- At next-to-next-to-leading-order QCD scale uncertainty becomes much smaller.
- VH is in the same class of processes as ggH and DY (colour-singlet production) but the phase-space is significantly larger.
- Often we would like to move from fixed-order prediction (limited number of partons) to the physical situation observed in detector (O(100-1000) particles): parton shower

POWHEG + MINLO

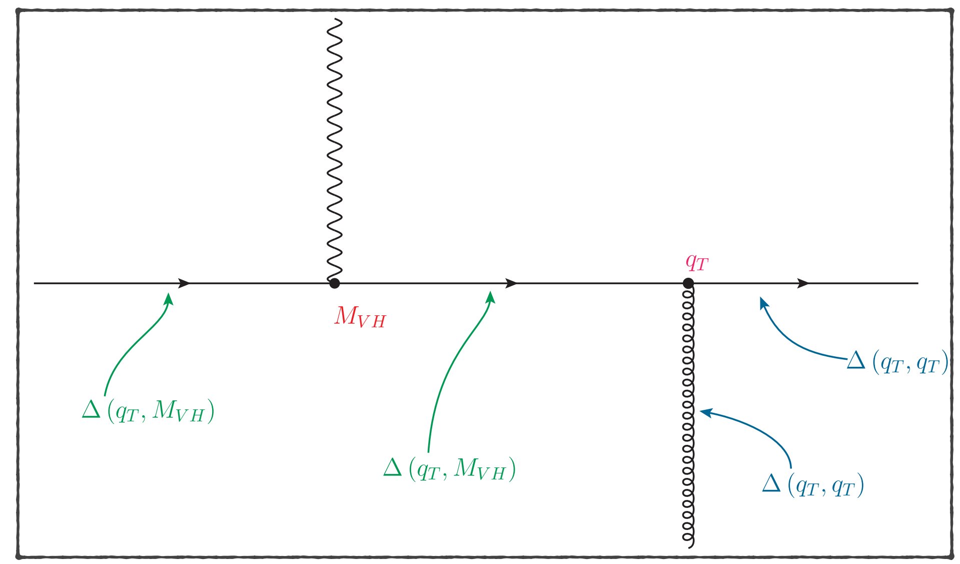
[1002.2581; Alioli, Nason, Oleari, Re]
[1206.3572; Hamilton, Nason, Zanderighi]

- POWHEG **VH+j** generator integrates the “B-tilde” function:

$$\tilde{B}_{\texttt{NLO}} = \alpha_s(\mu_R)\left[B + \alpha_s(\mu_R)\left(V(\mu_R) + \int d\Phi_r R\right)\right]$$

- Multiscale Improved NLO (MiNLO): change renormalisation scale in calculation

Recipe:
(a) Start with your old renormalisation scale (MVH).
(b) Change scale for each QCD vertex (CKKW-like clustering)
(c) attach Sudakov form factors for each coloured line
  i) emissions with very low qT are damped
  ii) finite results in $q_T \to 0$ limit (unresolved jet)



$$\Delta_i(q_T,\mu) \equiv \exp\left\{-\int_{q_T^2}^{\mu^2} \frac{dk_t^2}{k_t^2}\left(\frac{\alpha_s(k_t)}{2\pi}\right)\left[A_i \log\left(\frac{\mu^2}{k_t^2}\right) + B_i\right]\right\}$$

- Resulting function to integrate:

$$\tilde{B}_{\texttt{MiNLO}} = \alpha_s(q_T)\Delta^2(q_T,\bar{\mu}_R)\left[B\left(1 - 2\Delta^{(1)}(q_T,\bar{\mu}_R)\right) + \alpha_s(\bar{\mu}_R)\left(V(\bar{\mu}_R) + \int d\Phi_r R\right)\right]$$

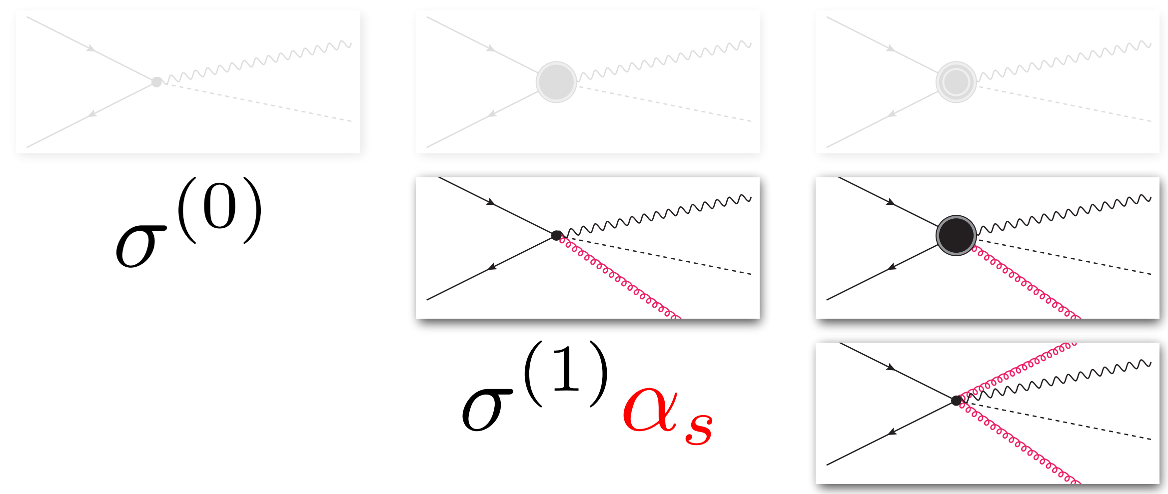
with: $\bar{\mu}_R = (q_{T,1}\cdot\ldots\cdot q_{T,N})^{(1/N)}$

- finite result when first jet unresolved $(q_T \to 0)$

- NLO accuracy retained after integrating out real radiation (no merging scale!)

NNLO REWEIGHTING (1)

$\mathcal{O}(1)$ $\mathcal{O}(\alpha_s)$ $\mathcal{O}({\alpha_s}^2)$



$\sigma^{(0)}$ $\sigma^{(1)}\alpha_s$ $\sigma^{(2)}{\alpha_s}^2$

- NLO (VH+j) computation:

  $\sigma_{\mathtt{PWHG}}(VH+j) = \tilde{\sigma}^{(1)}\alpha_s + \tilde{\sigma}^{(2)}{\alpha_s}^2$

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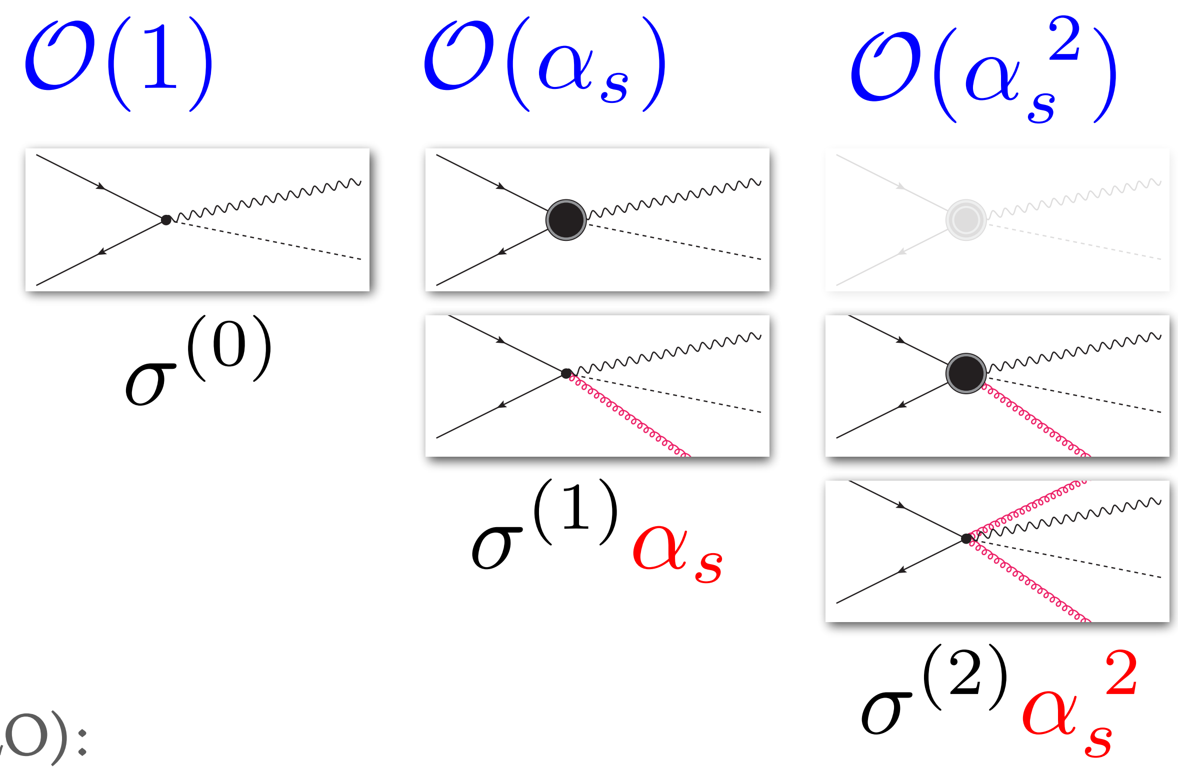

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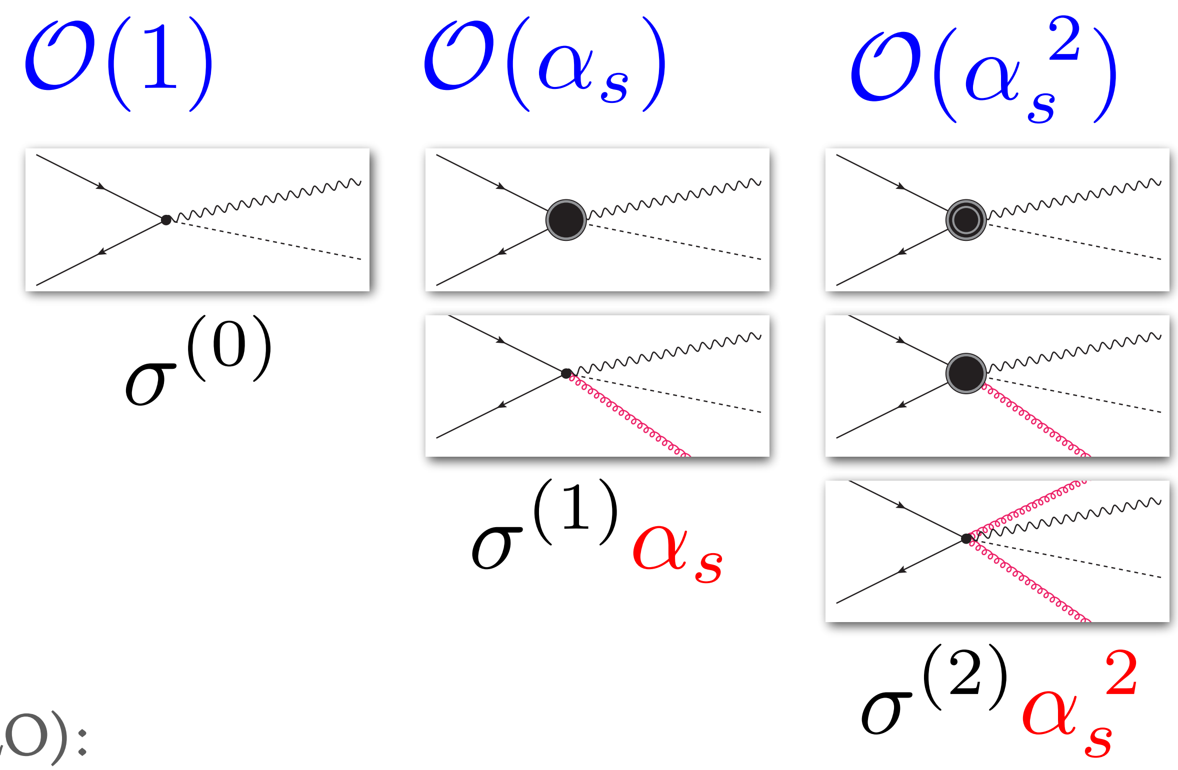

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- for full NNLO we need:

  $\sigma_{\mathtt{NNLO}}(VH) = \sigma^{(0)} + \sigma^{(1)}\alpha_s + \sigma^{(2)}\alpha_s{}^2$

NNLO REWEIGHTING (2)

- NLO accurate predictions from set of events produced by **VH+j** MiNLO generator:

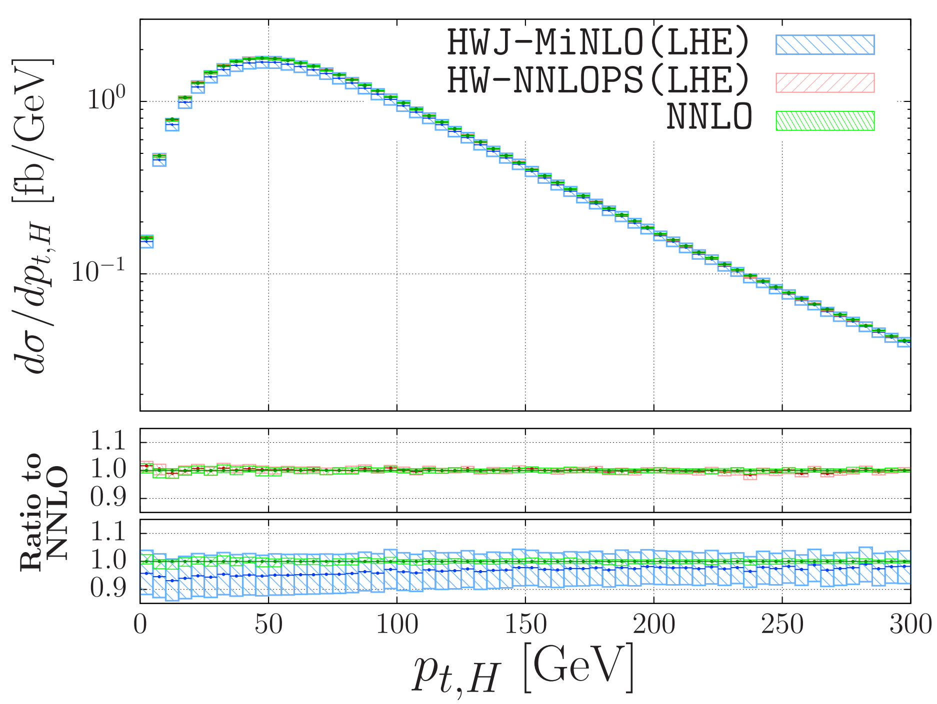
$$\texttt{MiNLO-events:} \quad \sum_i w_i \longrightarrow \sigma_{\texttt{MiNLO}} = \sigma^{(0)} + \sigma^{(1)}\alpha_s + \tilde{\sigma}^{(2)}\alpha_s^{\,2}$$

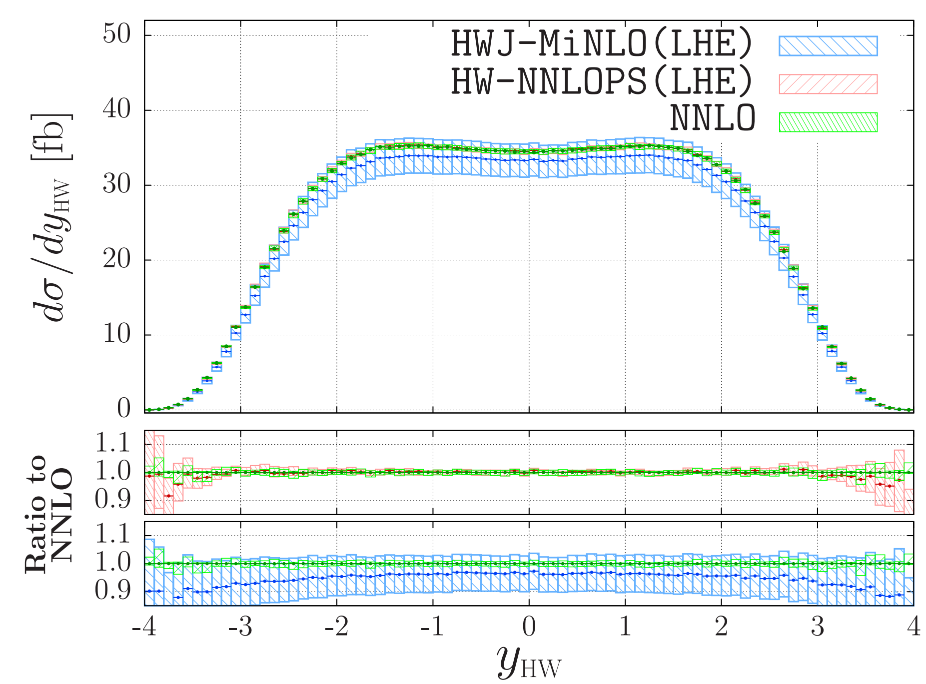
- Rescale all weights by a factor which is differential in Born kinematics:

$$W(\Phi_B) = \frac{\left(\frac{d\sigma}{d\Phi_B}\right)_{\texttt{NNLO}}}{\left(\frac{d\sigma}{d\Phi_B}\right)_{\texttt{MiNLO}}} = \frac{d\sigma^{(0)} + d\sigma^{(1)}\alpha_s + d\sigma^{(2)}\alpha_s^{\,2}}{d\sigma^{(0)} + d\sigma^{(1)}\alpha_s + d\tilde{\sigma}^{(2)}\alpha_s^{\,2}} = 1 + \frac{d\sigma^{(2)} - d\tilde{\sigma}^{(2)}}{d\sigma^{(0)}}\alpha_s^{\,2} + \mathcal{O}(\alpha_s^{\,3})$$

- Such a rescaling gives NNLO accurate set of events (by construction):

$$\texttt{NNLO-events:} \quad \sum_i w_i \times W(\Phi_B) \longrightarrow \sigma_{\texttt{NNLO}}$$





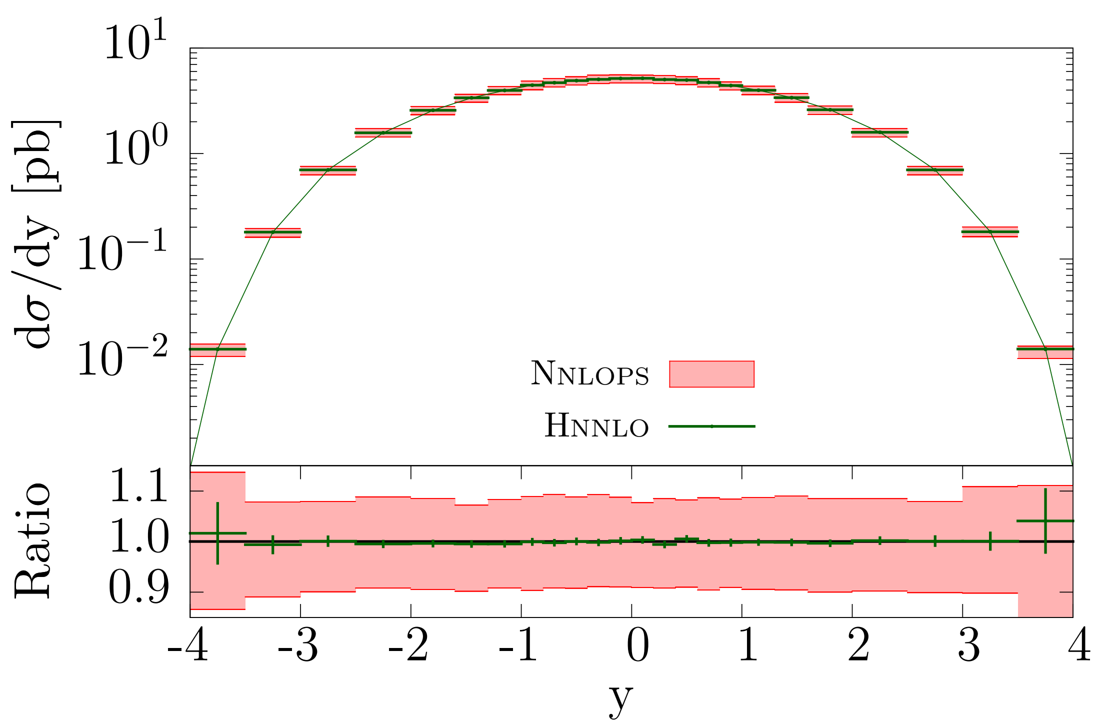
GROWING COMPLEXITY

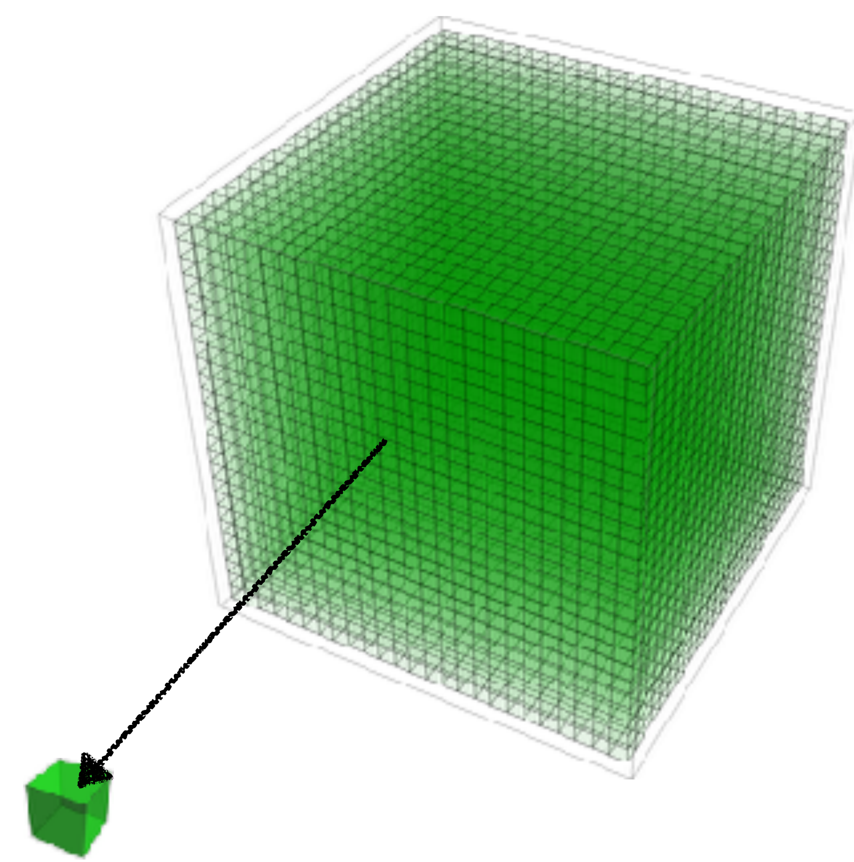
- Easy to imagine: with bigger phase-space (formally simple) procedure becomes computationally involving…

  (a) Higgs production (ggH): 1-dim 1 variable (1D histogram = 25 bins)

  (b) Drell-Yan production: 3-dim 3 variables (3D histogram = 15 625 bins)

  (c) VH production: 6-dim 6 variables (6D histogram = ??? [244M bins])



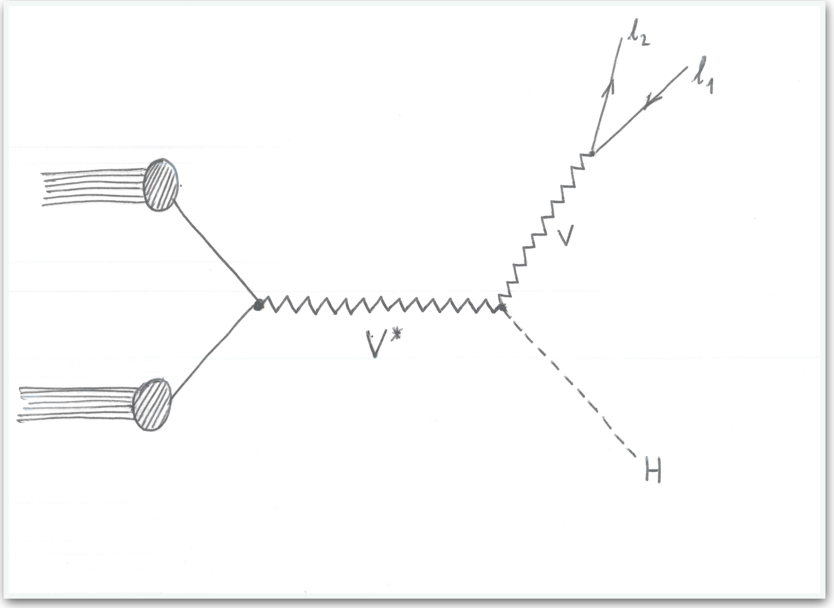


$$\frac{d^3\sigma}{dy_V\, d\theta_l\, dm_V} = \texttt{SINGLE-NUMBER}$$

ASSOCIATED HIGGS PRODUCTION

- phase-space parametrisation:

1	2	3	4	5	6
y_{VH}	$p_{t,H}$	Δy	θ^*	ϕ^*	$m_{\ell\bar{\ell}'}$



- cross-section in terms of Collins-Soper angles:

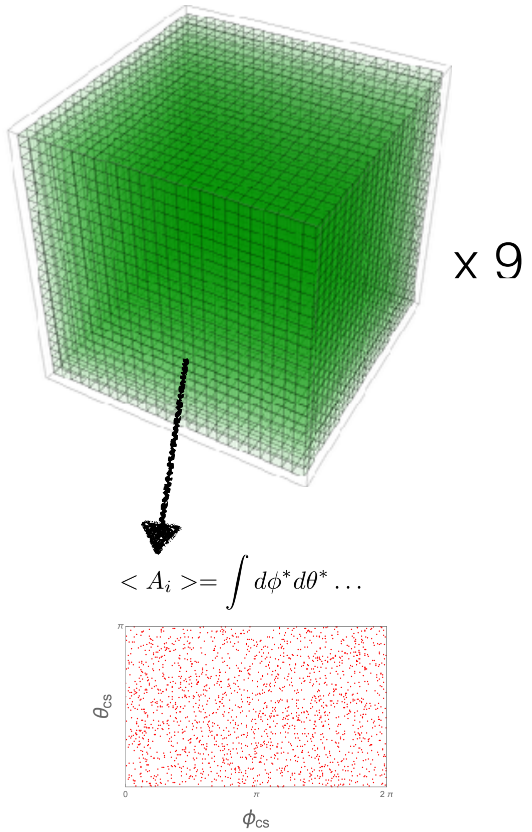
$$\frac{d\sigma}{d(\cos\theta^*)d\phi^*} = \frac{3}{16\pi}\frac{\sigma}{}\Big[(1+\cos^2\theta^*) + A_0\frac{1}{2}(1-3\cos^2\theta^*) + A_1\sin 2\theta^*\cos\phi^* + A_2\frac{1}{2}\sin^2\theta^*\cos 2\phi^* + A_3\sin\theta^*\cos\phi^* + A_4\cos\theta^* + A_5\sin\theta^*\sin\phi^* + A_6\sin 2\theta^*\sin\phi^* + A_7\sin^2\theta^*\sin 2\phi^*\Big]$$

- neglect dependence on $m_{\ell\bar{\ell}'}$ (validated)

FINALLY:

– one 3D histogram for each A-coefficient (8+1 tables)

– still numerically challenging as each bin is an integral over 2-dim phase-space



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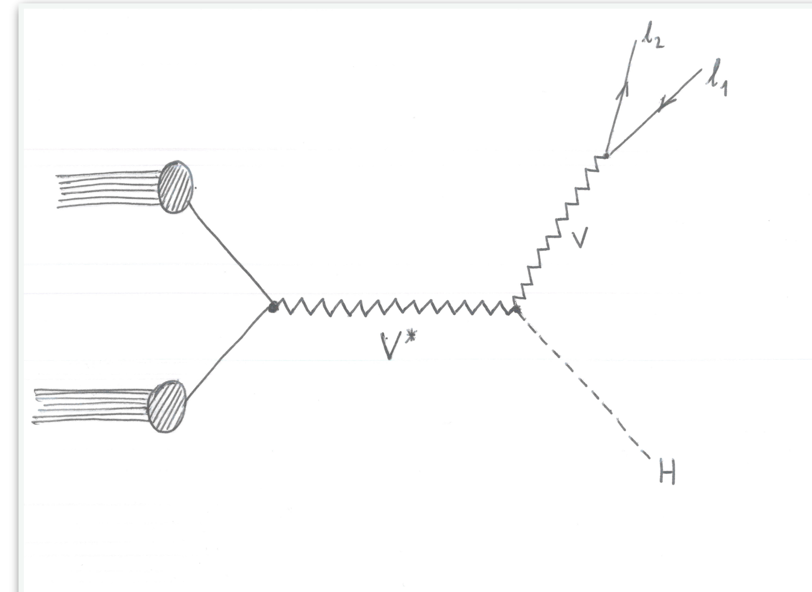

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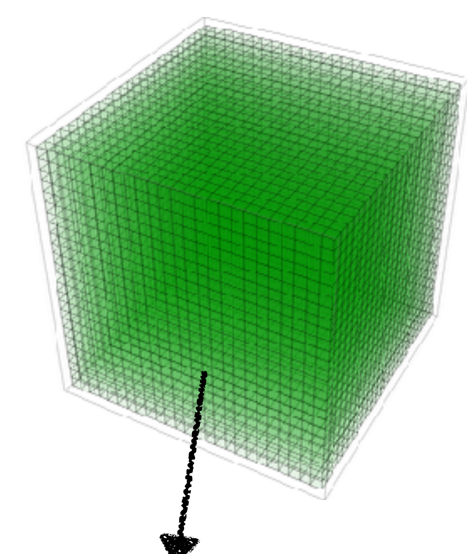
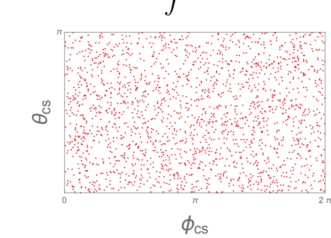
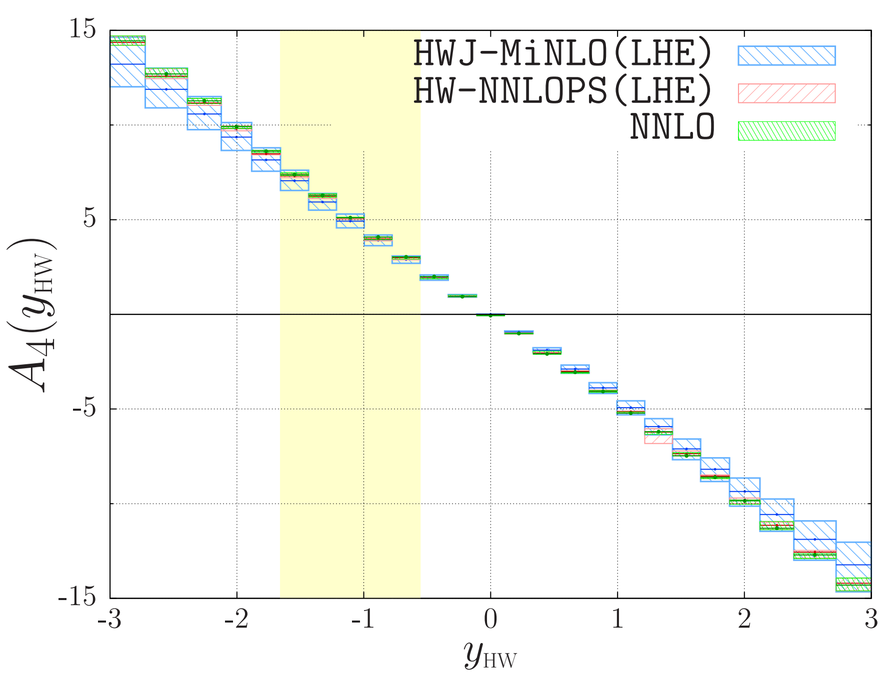


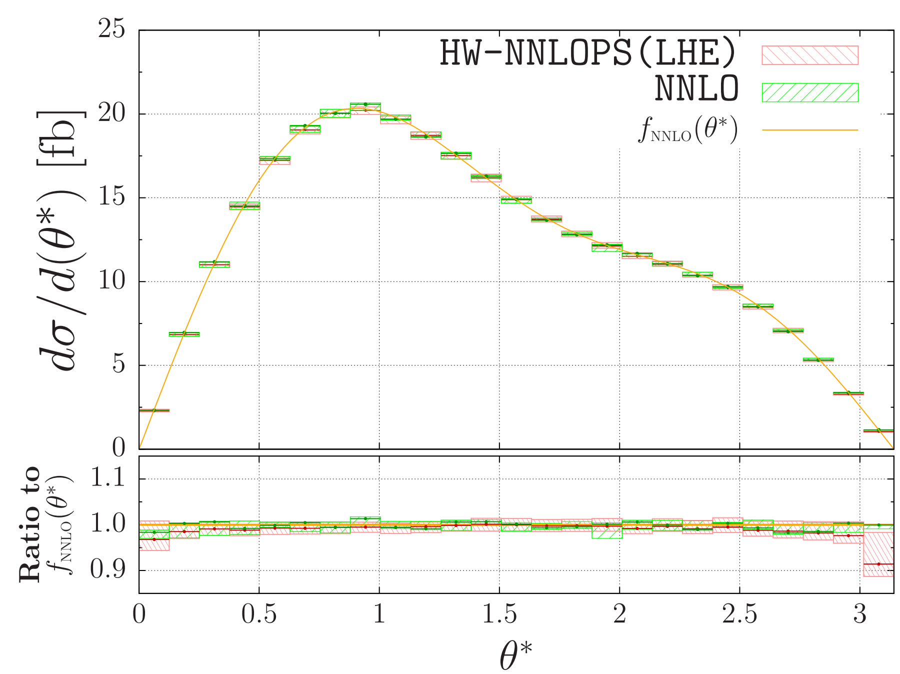
x 9

$< A_i >= \int d\phi^* d\theta^* \ldots$



RESULTS:





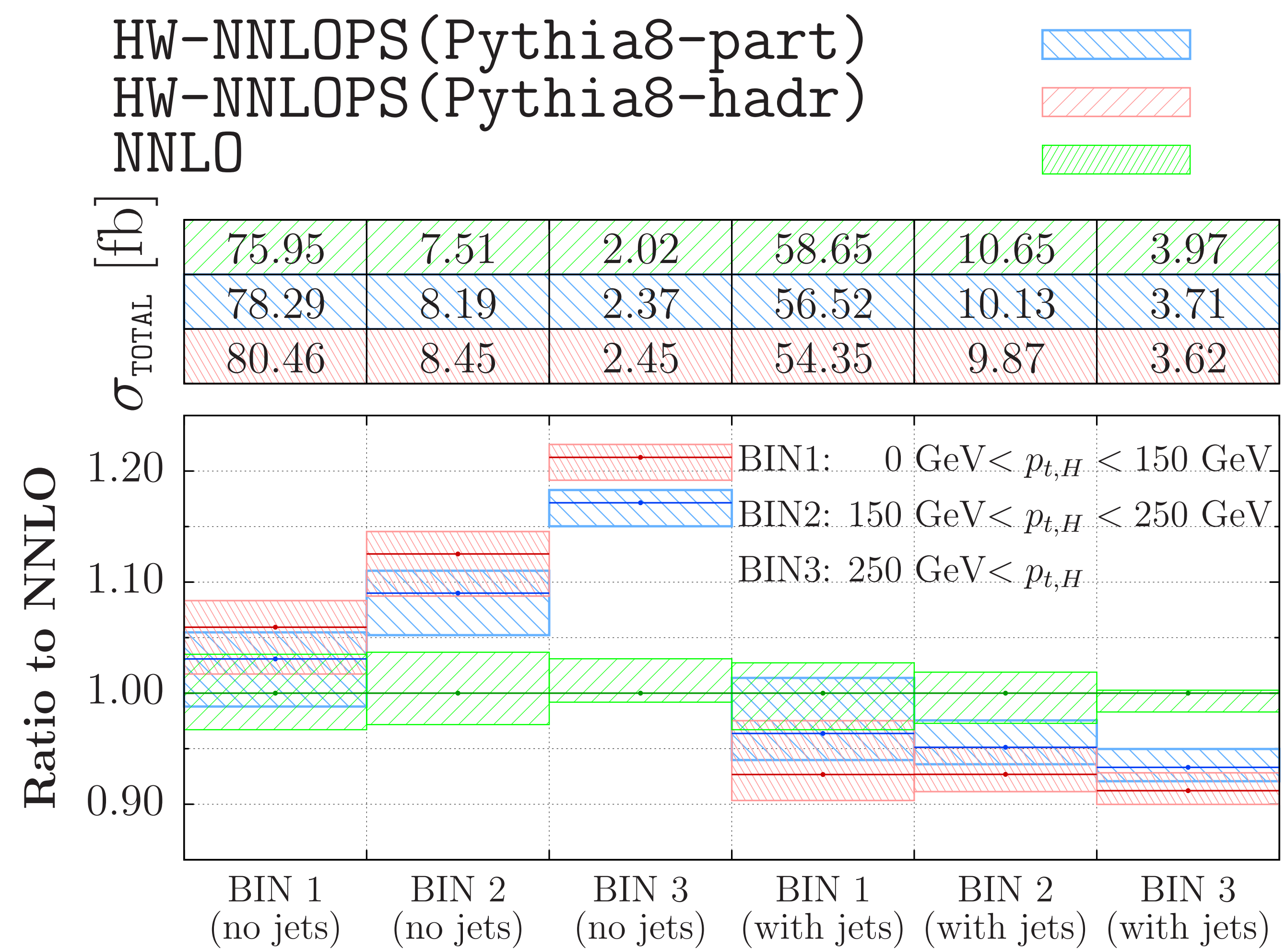
NNLO vs. NNLOPS (HW)

- Cross-section binned in 6 categories: according to transverse momentum of Higgs boson and presence of jets (YR4 recommendation):

(1) $0 < p_{t,H} < 150$ GeV

(2) $150 \text{ GeV} < p_{t,H} < 250$ GeV

(3) $250 \text{ GeV} < p_{t,H}$



- during parton shower evolution some of QCD radiation ends up outside the the cone (jets are softened, jet-vetoed cross-section larger)
- pt-jet cut was set to 20GeV which is close to the point where NNLO diverges
- further corrections due to hadronisation

Jet definition:

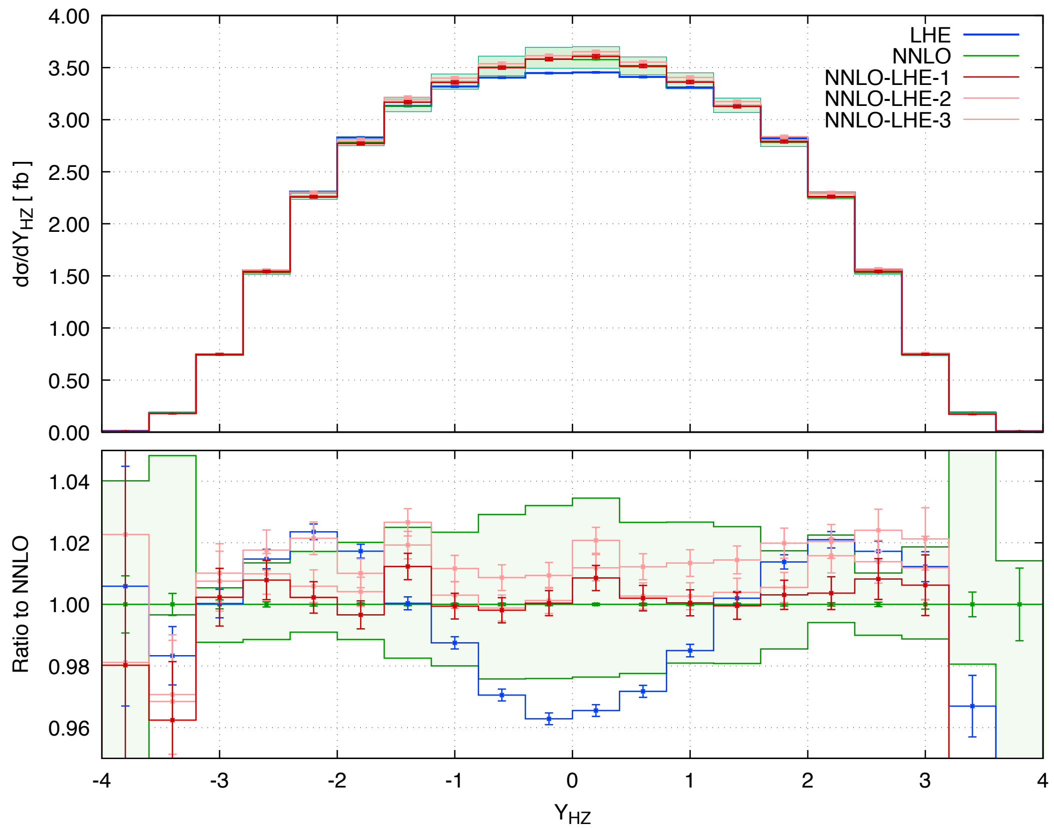
$\rightarrow$ anti-k_t algorithm

$\rightarrow R = 0.4$

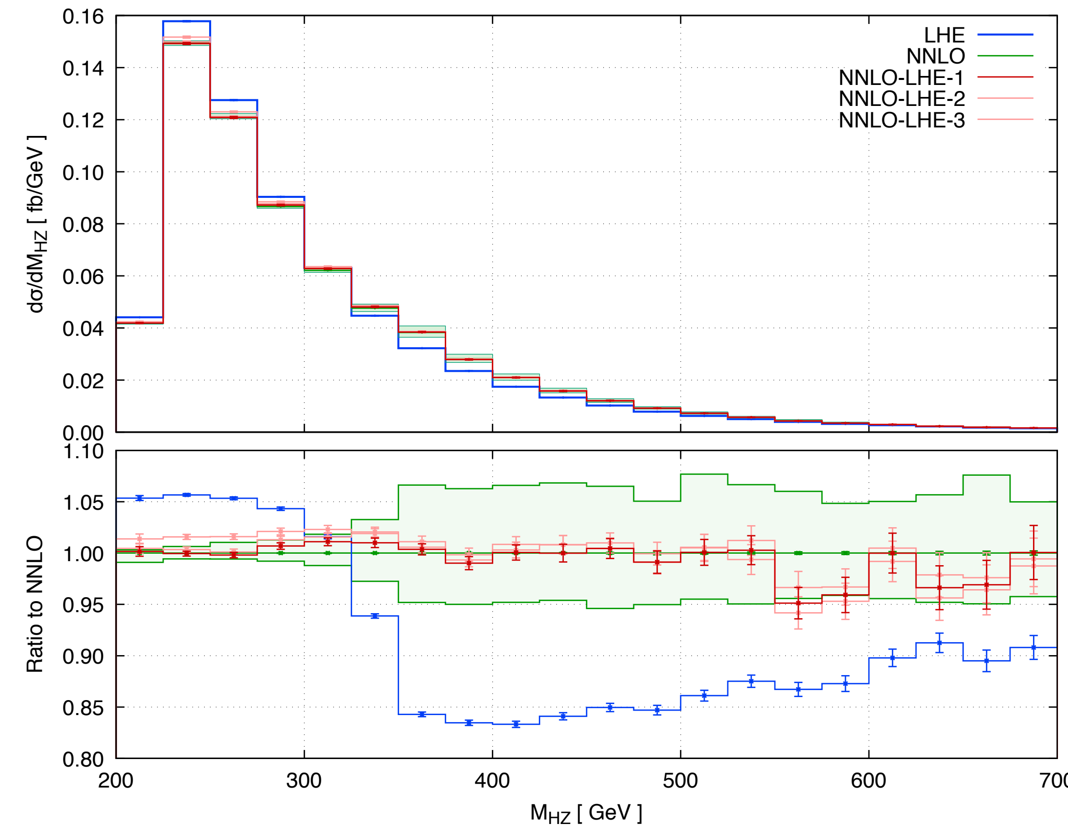
$\rightarrow p_{t,j} > 20$ GeV

REWEIGHTING UNCERTAINTY (HZ)

- large phase-space ==> computationally heavy task
- HW@NNLOPS: “smooth” enough distributions required very long runs (~1month x 300cores)
- Is it essential to have that long runs?
  - – results below (HZ) were prepared with NNLO runs (~2 days x 2000cores) and 12.5M HZJ events
  - – we have used various setups:
    - (a) reweight only with three basic variables (neglect Collins-Soper angles: A(i)=0)
    - (b) neglect A(i) coefficients with large uncertainties (stat.err > 200%, stat.err > 50%)
  - => use less precise histograms for reweighting but assign an error associated with this procedure



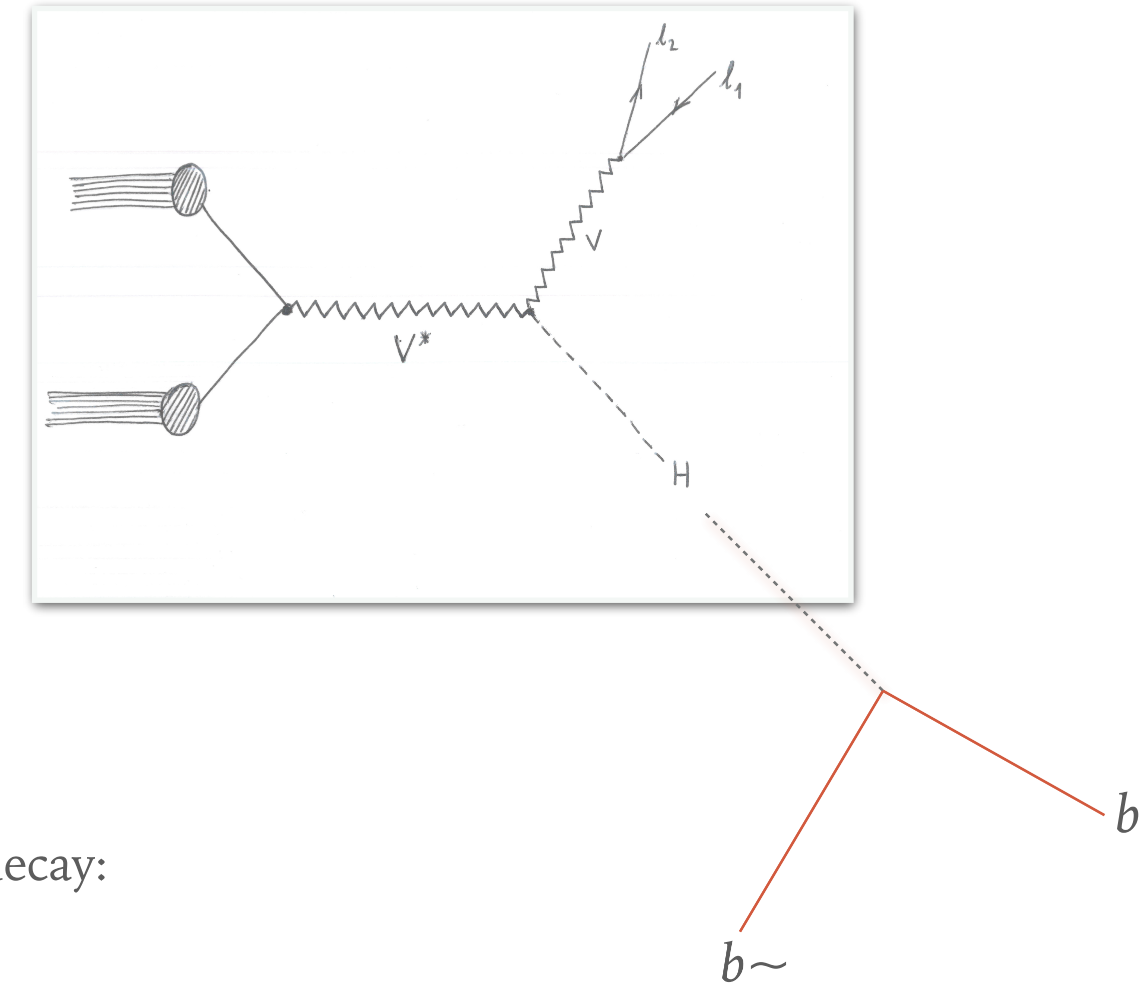
PRELIMINARY!



PRELIMINARY!

INCORPORATING HBB DECAY AT NLO

- **Hbb** – largest SM Branching Ratio (~60%)
- Allows for "precision" measurements in non-primary H-production channels



REWEIGHTING: TREATMENT OF THE DECAY

- in narrow width approximation phase-space split into production/decay:

$$d\Phi_{Vb\bar{b}} = d\Phi_{VH} \times d\Phi_{(H\to b\bar{b})}$$

- NNLO reweighting performed using Born kinematics hence we can use the same setup as without Higgs decay (we are actually changing setup but purely for practical purposes).
- This approach secures NNLO accuracy in production stage.
- NNLO-LHE: Hbb decay is treated at NLO within POWHEG (i.e. virtual corrections + some events contain real emission from bb-pair) which enables probing decay observables at NLO.

[170x.xxxxx; W.Astill, WB, E.Re, G.Zanderighi]

USING THE CODE

- VH Reweighting requires two sources of input

  (1) HWJ / HZJ @POWHEG+MiNLO

  (2) HW / HZ   @NNLO

- our code contains:

  – patches (analysis, identical physical parameters, …) to produce compatible results

  – `hv_minnlo`: program for reweighting event files using multidimensional histograms

- for HW(NNLOPS) we have used `HVNNLO` code:
  [1107.1164; G.Ferrera, M.Grazzini, F.Tramontano], [1407.4747; G.Ferrera, M.Grazzini, F.Tramontano]

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- for the time being, we are able to provide multidimensional HW distributions used in first paper [1603.01620], disadvantage: fixed settings

Should other NNLO codes become available in the meantime,

we can help interested users to interface it with our NNLO-reweighter!

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THANK YOU!