Recent developments in POWHEG

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LAPTh Annecy

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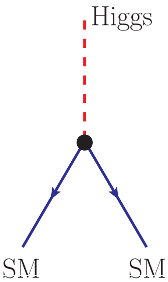
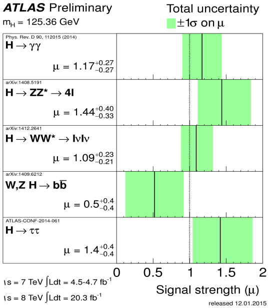
NLO computations + Parton Showers: why?

- in view of (current) absence of new Physics signatures at the LHC, BSM hints might be found in
  - small deviations from SM backgrounds
  - indirect searches





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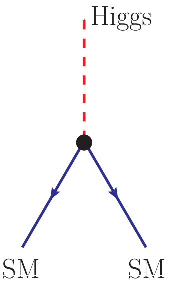
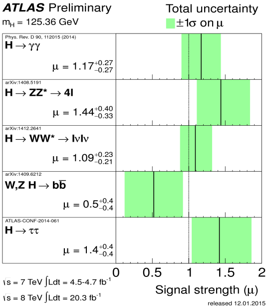
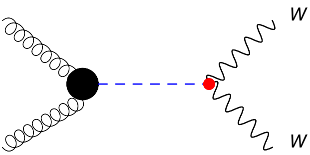


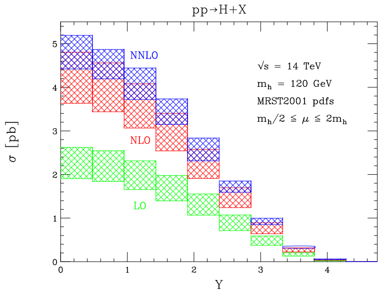


- precise Monte Carlo tools needed when looking for $\mathcal{O}(5-10\%)$ effects.
  - relevant to study Higgs couplings, but also to improve on measurement of W and top-quark masses

NLO+PS: why?

- higher-order corrections:
  - relevant when they are large or if experimental precision is extremely high.
  - relevant also to have reliable theoretical uncertainties.





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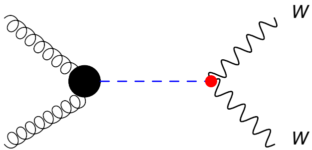

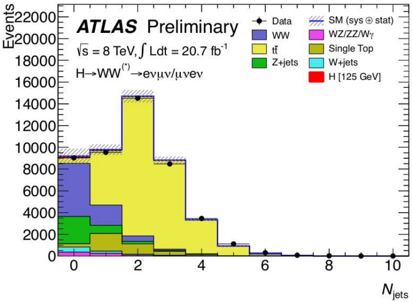

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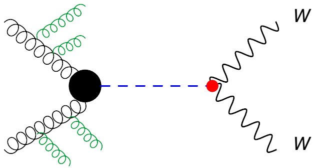

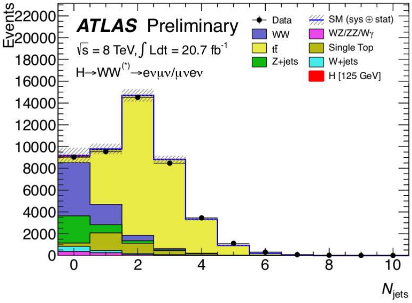

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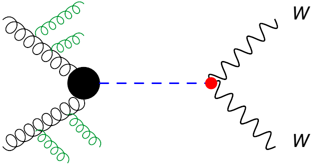
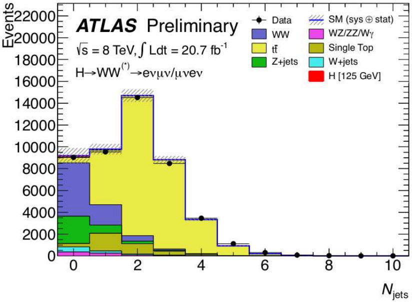
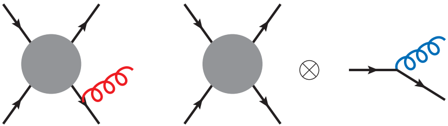




⇒ NLO+PS programs include both effects and allow for flexible and fully differential simulations.

NLO+PS: how-to

Problem: overlapping regions!



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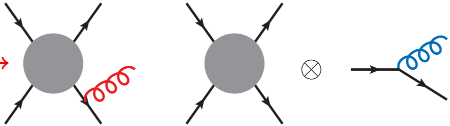

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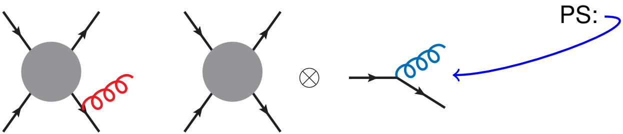

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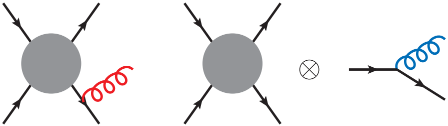

✓ 2 well-established methods available on the market to solve this problem: MC@NLO and POWHEG [Frixione-Webber '03, Nason '04]

- last decade has witnessed the success of these tools

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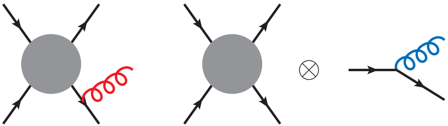

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rest of the talk: recent developments within the POWHEG BOX framework

- from merging different jet multiplicities to NNLO + PS
- handling processes with decaying intermediate resonances

NLO+PS: POWHEG how-to

$$d\sigma_{\mathrm{POW}} = d\Phi_n \quad \bar{B}(\Phi_n) \quad \left\{ \Delta(\Phi_n; k_{\mathrm{T}}^{\mathrm{min}}) + \Delta(\Phi_n; k_{\mathrm{T}}) \frac{\alpha_s}{2\pi} \frac{R(\Phi_n, \Phi_r)}{B(\Phi_n)} \, d\Phi_r \right\}$$

[+ p_{T}-*vetoing subsequent emissions*, to avoid double-counting]

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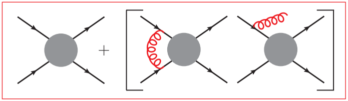

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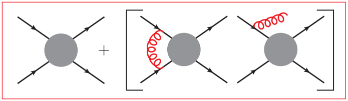

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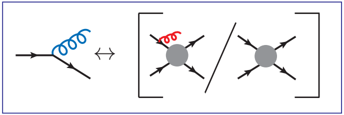


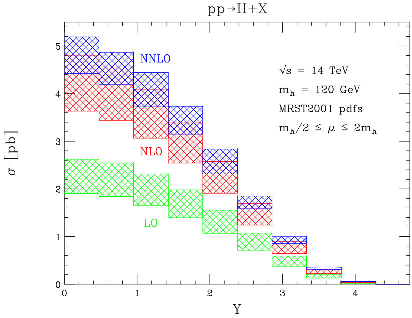
$$\Delta(t_{\mathrm{m}}, t) \Rightarrow \Delta(\Phi_n; k_{\mathrm{T}}) = \exp\left\{-\frac{\alpha_s}{2\pi}\int \frac{R(\Phi_n,\Phi_r')}{B(\Phi_n)}\theta(k_{\mathrm{T}}' - k_{\mathrm{T}})\, d\Phi_r'\right\}$$

NNLO+PS: why and where?

NLO+PS not always enough: NNLO required when

1. large NLO/LO "K-factor"
   [as in Higgs Physics]

2. very high precision needed
   [e.g. Drell-Yan, top pairs]



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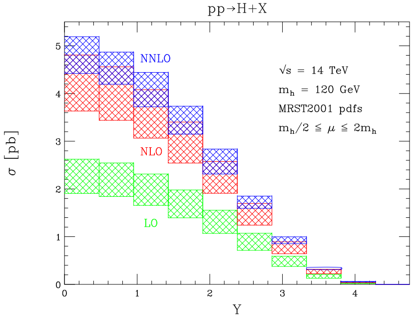

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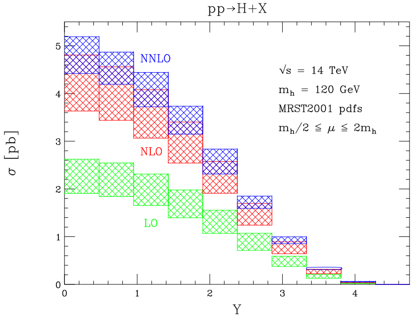


Q: can we match NNLO and PS?

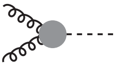
- In the POWHEG context this has been achieved (so far) for Higgs and Drell-Yan production
  [Hamilton,Nason,ER,Zanderighi, 1309.0017] [Karlberg,ER,Zanderighi, 1407.2940]

- The crucial point is to have a method to merge together two NLO+PS computations for different jet multiplicities:

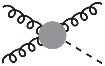
POWHEG + MiNLO [Multiscale Improved NLO] [Hamilton et al. '12]

POWHEG $\to$ MiNLO $\to$ NNLO+PS

Higgs at NNLO:



loops: 0 1 2



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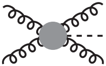

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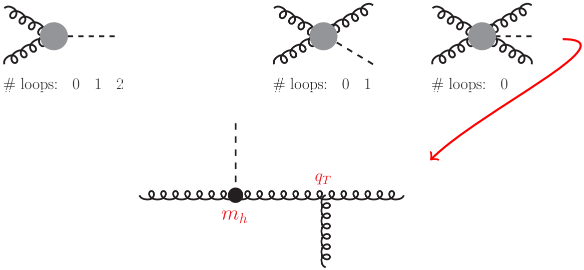

(a) 1 and 2 jets: POWHEG H+1j

POWHEG → MiNLO → NNLO+PS

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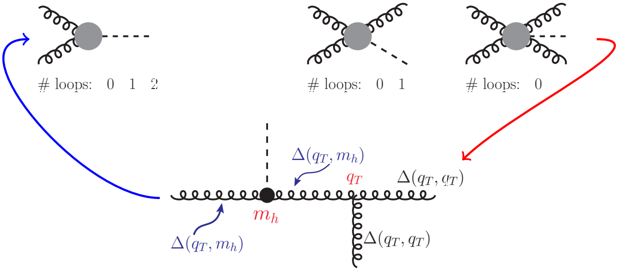

(b) - integrate down to $q_T = 0$ with MiNLO
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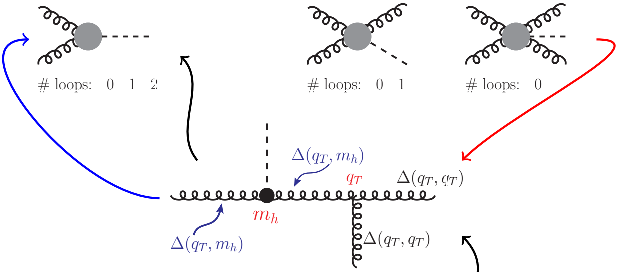

(c) 2 loops missing: from exact fixed-order NNLO

$$W(y) = \frac{d\sigma(y)_{\text{NNLO}}}{d\sigma(y)_{\text{MiNLO}}}$$

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Multiscale Improved NLO

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  - for each point sampled, build the “more-likely” shower history
  - “correct” original NLO à la CKKW:

    $\rightarrow \alpha_S$ evaluated at nodal scales

    $\rightarrow$ Sudakov FFs

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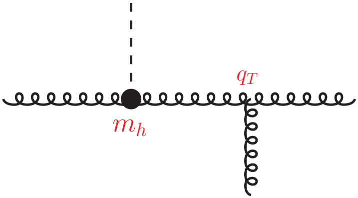
$$\bar{B}_{\rm NLO} = \alpha_{\rm S}^3(\mu_R)\Big[B + \alpha_{\rm S} V(\mu_R) + \alpha_{\rm S}\int d\Phi_{\rm r} R\Big]$$



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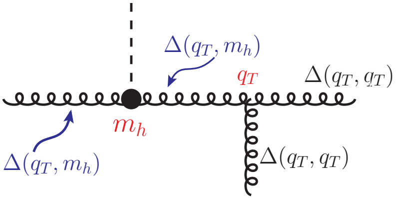
$$\bar{B}_{\mathrm{MiNLO}} = \alpha_{\mathrm{S}}^2(m_h)\alpha_{\mathrm{S}}(q_T)\Delta_g^2(q_T, m_h)\Big[B\left(1 - 2\Delta_g^{(1)}(q_T, m_h)\right) + \alpha_{\mathrm{S}}\, V(\bar{\mu}_R) + \alpha_{\mathrm{S}} \int d\Phi_{\mathrm{r}} R\Big]$$



- $\bar{\mu}_R = (m_h^2 q_T)^{1/3}$
- $\log \Delta_{\mathrm{f}}(q_T, m_h) = -\int_{q_T^2}^{m_h^2} \frac{dq^2}{q^2} \frac{\alpha_{\mathrm{S}}(q^2)}{2\pi}\left[A_f \log\frac{m_h^2}{q^2} + B_f\right]$
- $\Delta_{\mathrm{f}}^{(1)}(q_T, m_h) = -\frac{\alpha_{\mathrm{S}}}{2\pi}\left[\frac{1}{2}A_{1,\mathrm{f}} \log^2\frac{m_h^2}{q_T^2} + B_{1,\mathrm{f}} \log\frac{m_h^2}{q_T^2}\right]$
- $\mu_F = q_T$

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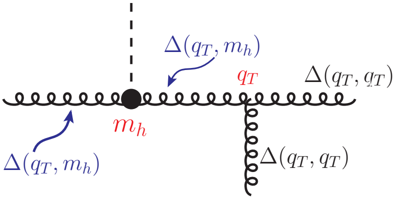

☞ Sudakov FF included on $H+j$ Born kinematics

- MiNLO-improved HJ yields finite results also when 1st jet is unresolved ($q_T \to 0$)
- $\bar{B}_{\mathrm{MiNLO}}$ ideal to extend validity of HJ−POWHEG [called "HJ−MiNLO" hereafter]

“Improved” MiNLO & NLOPS merging

- formal accuracy of `HJ-MiNLO` for inclusive observables carefully investigated
- `HJ-MiNLO` describes inclusive observables at order α_S, i.e. α_S^{2+1}
- to reach genuine NLO when fully inclusive, “spurious” terms must be of relative order α_S^2, *i.e.*

$$O_{\mathrm{HJ-MiNLO}} = O_{\mathrm{H@NLO}} + \mathcal{O}(\alpha_S^{2+2}) \qquad \text{if } O \text{ is inclusive}$$

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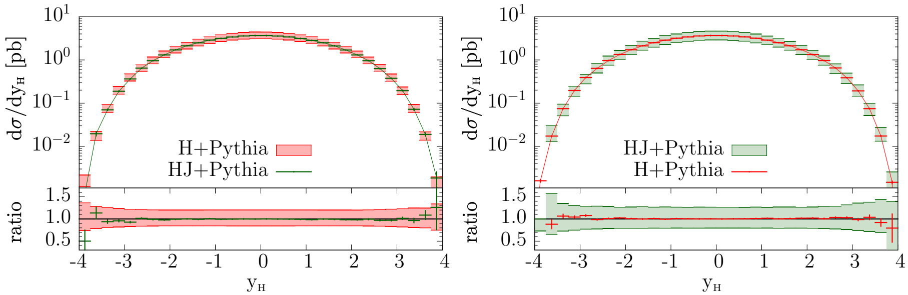
- Possible to improve `HJ-MiNLO` such that inclusive NLO is recovered (NLO$^{(0)}$), without spoiling NLO accuracy of $H+j$ (NLO$^{(1)}$).
- accurate control of subleading (NNLL) small-p_T logarithms is needed (scaling in low-p_T region is $\alpha_S L^2 \sim 1$, *i.e.* $L \sim 1/\sqrt{\alpha_S}$!)

Effectively as if we merged NLO$^{(0)}$ and NLO$^{(1)}$ samples, without merging different samples (no merging scale used: there is just one sample).

MiNLO merging: results

[Hamilton et al., 1212.4504]



- "H+Pythia": standalone POWHEG ($gg \to H$) + PYTHIA (PS level) [7pts band, $\mu = m_H$]
- "HJ+Pythia": HJ-MiNLO* + PYTHIA (PS level) [7pts band, μ from MiNLO]

- very good agreement (both value and band) [✓]

☞ Notice: band is $\sim 20 - 30\%$

Higgs at NNLO+PS: details

- `HJ−MiNLO+POWHEG` generator gives H-HJ @ NLOPS.
  This is almost what we want for NNLO+PS !

	H (inclusive)	H+j (inclusive)	H+2j (inclusive)
✓ H-HJ @ NLOPS	NLO	NLO	LO
H @ NNLOPS	NNLO	NLO	LO

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$$W(\Phi_B) = \frac{\left(\frac{d\sigma}{d\Phi_B}\right)_{\mathrm{NNLO}}}{\left(\frac{d\sigma}{d\Phi_B}\right)_{\mathrm{HJ-MiNLO}*}}$$

  - by construction NNLO accuracy on fully inclusive observables $(\sigma_{\mathrm{tot}}, y_H; m_{\ell\ell}, \ldots)$ [✓]
  - to reach NNLOPS accuracy, need to be sure that the reweighting doesn't spoil the NLO accuracy of HJ−MiNLO in 1-jet region [ ]

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✓ H @ NNLOPS	NNLO	NLO	LO

- reweighting (differential on Φ_B) of "MiNLO-generated" events:

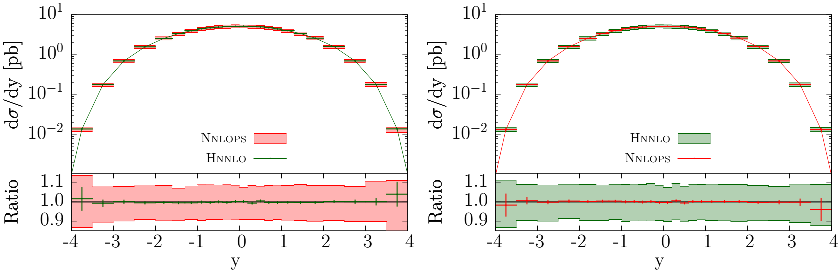
$$W(\Phi_B) = \frac{\left(\frac{d\sigma}{d\Phi_B}\right)_{\mathrm{NNLO}}}{\left(\frac{d\sigma}{d\Phi_B}\right)_{\mathrm{HJ-MiNLO*}}} = \frac{\alpha_S^2 c_0 + c_1 \alpha_S^3 + c_2 \alpha_S^4}{\alpha_S^2 c_0 + c_1 \alpha_S^3 + d_2 \alpha_S^4} \simeq 1 + \frac{c_2 - d_2}{c_0} \alpha_S^2 + \mathcal{O}(\alpha_S^3)$$

  - by construction NNLO accuracy on fully inclusive observables $(\sigma_{\mathrm{tot}}, y_H; m_{\ell\ell}, \ldots)$ [✓]
  - to reach NNLOPS accuracy, need to be sure that the reweighting doesn't spoil the NLO accuracy of HJ−MiNLO in 1-jet region [✓]
  - notice: formally works because no spurious $\mathcal{O}(\alpha_S^{2+1.5})$ terms in H-HJ @ NLOPS

H@NNLOPS (fully incl.)

To reweight, use y_H

- NNLO with $\mu = m_H/2$, `HJ-MiNLO` "core scale" m_H [NNLO from `HNNLO`, Catani,Grazzini]
- $(7_{\mathrm{Mi}} \times 3_{\mathrm{NN}})$ pts scale var. in `NNLOPS`, 7pts in NNLO

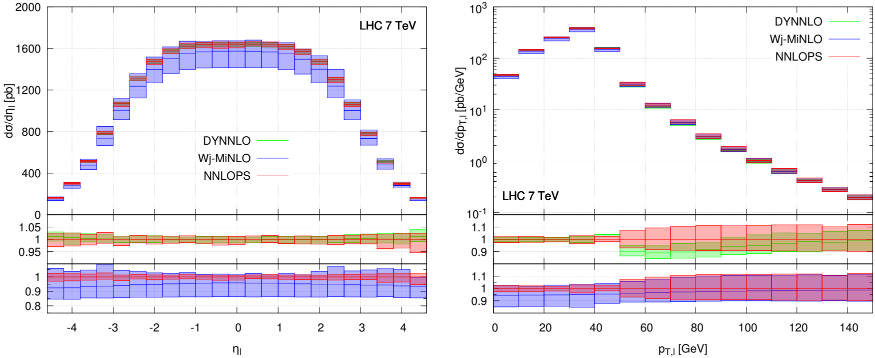


☞ Notice: band is 10% (at NLO would be $\sim$ 20-30%) [✓]

[Until and including $\mathcal{O}(\alpha_S^4)$, PS effects don't affect y_H (first 2 emissions controlled properly at $\mathcal{O}(\alpha_S^4)$ by MiNLO+POWHEG)]

W@NNLOPS

To reweight, use $(y_{\ell\ell}, m_{\ell\ell}, \cos\theta_\ell)$



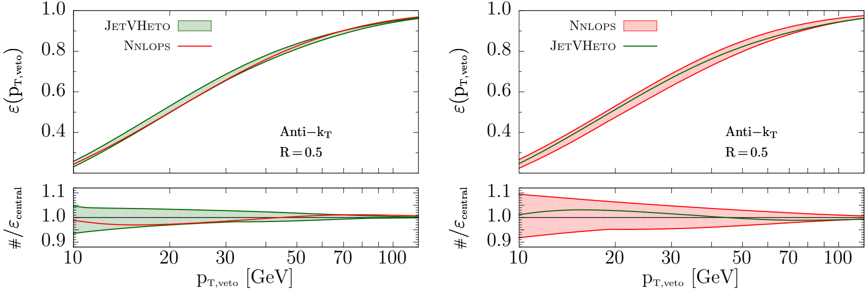
- left plot: all as expected
- right plot: not the observable used to construct the NNLO reweighting
  - observe exactly what we expect: $p_{T,\ell}$ has NNLO uncertainty if $p_T < M_W/2$, NLO if $p_T > M_W/2$
  - smooth behaviour when close to Jacobian peak (also with small bins) (due to resummation of logs at small $p_{T,V}$)

☞ important application: precise W mass measurement at the LHC

H@NNLOPS ($p_T^{j_1}$)

☞ Separation of $H \to WW$ from $t\bar{t}$ bkg: x-sec binned in $N_{\rm jet}$

0-jet bin ⇔ jet-veto accurate predictions needed !



$$\varepsilon\left(p_{\rm T,veto}\right) = \frac{\Sigma(p_{\rm T,veto})}{\sigma^{\rm tot}} = \frac{1}{\sigma^{\rm tot}} \int d\sigma\, \theta\left(p_{\rm T,veto} - p_{\rm T}^{\rm j_1}\right)$$

- `JetVHeto`: NNLL resum, $\mu_R = \mu_F = m_H/2$ [7pts], $Q_{\rm res} \equiv m_H/2$, (a)-scheme only

  [`JetVHeto`, Banfi et al.]

- nice agreement, differences never more than 5-6 %

$t\bar{t}$ and top-mass measurement

- Improvements on measurement of the top-mass at the LHC likely to be achieved from combination of different strategies: total x-section, $t\bar{t}$ + jet, leptonic spectra, $b\ell$ endpoint and distribution,... [see *e.g.* TOP LHC Working Group]

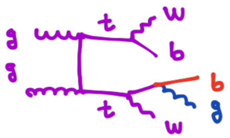


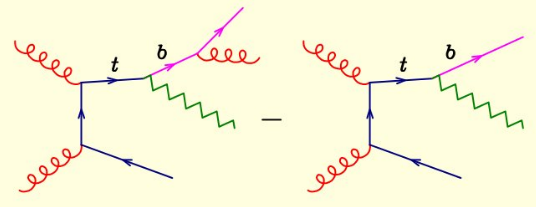
figure from R. Franceschini

- some techniques rely on looking into the kinematics of visible particles from top-decay
- important that simulations are as accurate as possible, and associated uncertainties are quantified

- instrumental to have a fully-consistent NLO+PS simulation of $WWbb$, with exact decays at NLO and offshellness effects.
- non trivial to obtain. In fact it hasn't been done yet, despite the fact that:
  - all ingredients are available
  - POWHEG and MC@NLO are well established
  - codes are fully (or almost fully) automated

towards $WWbb$ at NLO+PS

- issues already present at NLO (no shower): commonly-used subtraction schemes don't preserve top virtuality between real emission terms and their counterterms



  - when narrow-width limit approached, IR cancellation spoiled (when bgW is on-shell, the counterterm goes off-shell)

- at NLO+PS, further (more serious) problems:

$$d\sigma = d\Phi_{\rm rad} \bar{B}(\Phi_B) \frac{R(\Phi_B, \Phi_{\rm rad})}{B(\Phi_B)} \exp\left[- \int \frac{R(\Phi_B, \Phi_{\rm rad})}{B(\Phi_B)} d\Phi_{\rm rad} \right]$$

  $\Phi_B \to (\Phi_B, \Phi_{\rm rad})$ mapping doesn't preserve virtuality, therefore R/B can become large also far from collinear singularity, but it shouldn't

  - expect shape distorsions of b-jet distributions

towards $WWbb$ at NLO+PS

- end of last year: in POWHEG−BOX, general procedure to handle radiation in resonance decays in the zero-width limit. [Campbell,Ellis,Nason,ER '14]
  - if radiation comes from resonance, Φ_B constructed in the resonance frame $\Rightarrow$ top-virtuality preserved [✓]
  - finite-width effects included approximately, by rescaling with exact LO matrix elements (finite width, non-double-resonant diagrams,...)
  - "multiplicative POWHEG": keep multiple emissions before showering

towards $WWbb$ at NLO+PS

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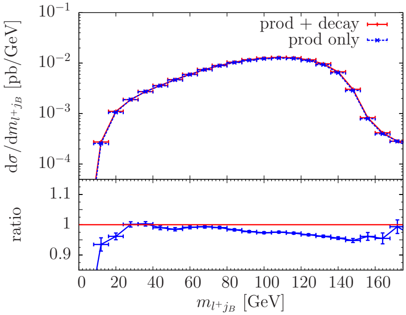

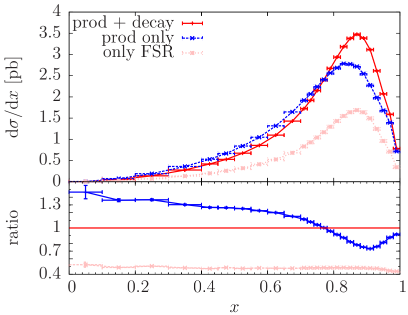

- left: 5% effects on $m_{\ell j_b}$ distribution.
- right: fragmentation function ($x = E_B/E_{B,max}$)

towards $WWbb$ at NLO+PS

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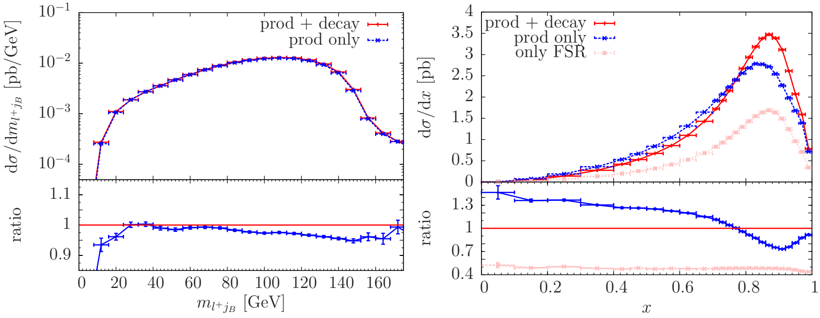

  - left: 5% effects on $m_{\ell j_b}$ distribution.
  - right: fragmentation function ($x = E_B/E_{B,max}$)

- above approach generalized further very recently: worked out procedure to consistently include all diagrams, with no approximations. Tested for single-top, work in progress for $WWbb$: stay tuned! [Jezo,Nason (et al) '15]

conclusions

- Especially in absence of very clear singals of new-physics, accurate tools are needed for LHC phenomenology
- POWHEG and MC@NLO are not new tools. Nevertheless, despite the level of automation (*e.g.* MadGraph5_aMC@NLO), a lot of progress is still taking place

⇒ shown results of merging NLOPS for different jet-multiplicities (without merging scale)

⇒ shown first working examples for NNLOPS

⇒ exact NLO+PS simulations for processes with intermediate resonances will soon be available

What next?

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Thank you for your attention!

Extra slides

“Improved” MiNLO & NLOPS merging: details

- Resummation formula can be written as

$$\frac{d\sigma}{dq_T^2 dy} = \sigma_0 \frac{d}{dq_T^2} \Big\{ [C_{ga} \otimes f_a](x_A, q_T) \times [C_{gb} \otimes f_b](x_B, q_T) \times \exp S(q_T, Q) \Big\} + R_f$$

$$S(q_T, Q) = -2 \int_{q_T^2}^{Q^2} \frac{dq^2}{q^2} \frac{\alpha_S(q^2)}{2\pi} \Big[A_f \log \frac{Q^2}{q^2} + B_f \Big]$$

- If $C_{ij}^{(1)}$ included and R_f is LO$^{(1)}$, then upon integration we get NLO$^{(0)}$
- `MiNLO` formula is not written as a total derivative: “expand” the above expression, then compare with `MiNLO` :

$$\sim \sigma_0 \frac{1}{q_T^2} [\alpha_S, \boxed{\alpha_S^2}, \alpha_S^3, \alpha_S^4, \alpha_S L, \alpha_S^2 L, \alpha_S^3 L, \alpha_S^4 L] \exp S(q_T, Q) + R_f \qquad L = \log(Q^2/q_T^2)$$

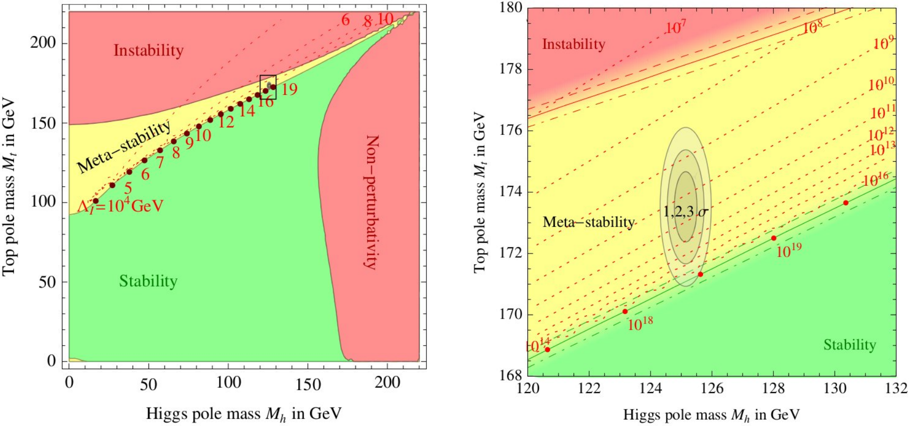
- highlighted terms are needed to reach NLO$^{(0)}$:

$$\int^{Q^2} \frac{dq_T^2}{q_T^2} L^m {\alpha_S}^n(q_T) \exp S \sim \big(\alpha_S(Q^2)\big)^{n-(m+1)/2}$$

(scaling in low-p_T region is $\alpha_S L^2 \sim 1$!)

- if I don’t include B_2 in `MiNLO` Δ_g, I miss a term $(1/q_T^2)\ \boxed{\alpha_S^2}\ B_2 \exp S$
- upon integration, violate NLO$^{(0)}$ by a term of <u>relative</u> $\mathcal{O}(\alpha_S^{3/2})$

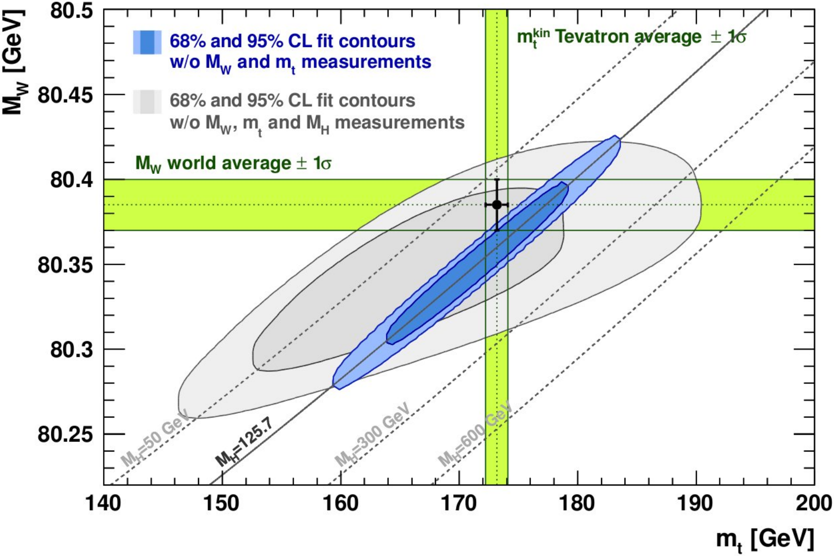
$t\bar{t}$ and top-mass measurement



plot from [Giudice et al. '13]

$$m_t \approx 173 \pm 1 \text{ GeV}$$

the W mass and consistency of SM



$$m_W = 80385 \pm 15 \ \text{MeV}$$