# *Monte Carlo generators for final states including vector bosons*

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# outline

- quick overview: tools on the market & their accuracy
- "Vector boson(s) + light jets" at NLO+PS (NLO merging)
- Drell-Yan production at NNLO+PS
- V + heavy flavour

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Not discussed:

- EW effects
  - in parton showers [Christiansen,Sjostrand '14 - Christiansen,Prestel '15]
  - reweighing to $VV$ production [Gieseke,Kasprzik,Kuhn '14]
- new parton-shower algorithms (within `Pythia` and `Sherpa`) [Hoeche,Prestel '15]
- new methods:
  - `KrkNLO` (only Drell-Yan at NLO+PS) [Jadach,Placzek,Sapeta et al. '15]
  - `Vincia` (so far $e^+e^-$, $hh$ is in progress) [Giele,Kosower,Skands, et al. '07-]
  - `Deductor` / "Nagy-Soper" (proof-of-concept for $t\bar{t}+j$) [Nagy,Soper '14, Czakon et al. '15]

# NLO+PS matching / LO+PS merging

- $pp \to X + 0, 1, 2, \ldots$ jets, valid if jets are close or widely separated: LO+PS merging
- ME generators: `Alpgen`, `MadGraph`, `Sherpa`
- methods: `CKKW-L`, `MLM`
  - for at least one of them (typically both), interface/implementation available in general-purpose parton-shower program

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- $pp \to X + k$ jets ($k$ fixed): NLO+PS matching
  - inclusive observables at NLO
  - (N)LL Sudakov resummation where relevant
  - large-$p_T$ hardest associated jet at LO
  - extra jets at LL
- available tools:
  - `POWHEG` based: `POWHEG-BOX`, `PowHel`, `Matchbox/Herwig++`
  - `MC@NLO` based: `MG5_aMC@NLO`, `Sherpa-MC@NLO`, `Matchbox/Herwig++`
  - other methods: `Geneva`, `KrK-NLO`

# NLO+PS merging / NNLO+PS

- multijet merging at NLO is more complicated than at LO, and more subtle:
  the matrix element "$pp \to S + (n+1)$ partons" enters in
  - real emission for "$pp \to S + n$ partons" @ NLO
  - Born contribution for "$pp \to S + (n+1)$ partons" @ NLO
- methods: `MEPS@NLO`, `FxFx`, `UNLOPS`, `Geneva`, `POWHEG+MiNLO` (and `Vincia` for $e^+e^-$)
- similarly to LO, many of these methods use a merging scale ($Q_{\rm MS}$):
  a bad choice of merging scale can spoil the formal accuracy
  - typically this can happen if $\alpha_{\rm S} \log^2 (Q_{\rm MS}/Q) \simeq 1$:
    when $L \simeq 1/\sqrt{\alpha_{\rm S}}$, uncontrolled NNLL logs $\alpha_{\rm S}^2 L$ scale as $\alpha_{\rm S}^{1.5}$ (and not as $\alpha_{\rm S}^2$).
  - to avoid any formal issue, one needs either to not have $Q_{\rm MS}$ at all, or have a very precise control of logarithmic structure (beyond the PS accuracy)
  - not having $Q_{\rm MS}$ requires control of NNLL terms (or at least part thereof)
  - if $Q_{\rm MS}$ is present, include the uncertainty due to its choice

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- for simple processes like Drell-Yan, the development of these techniques lead to match PS with NNLO computations (NNLO+PS)

# Sherpa: MEPS@NLO

- generate MC@NLO samples, and separate their domain of validity using merging scale $Q_{\mathrm{MS}}$
- $d\Phi_{n+1}$ receives contribution from $H_n$-events below $Q_{\mathrm{MS}}$ and from $S_{n+1}$ above $Q_{\mathrm{MS}}$
- procedure can be iterated

Uncertainties

- $\mu_R$ and $\mu_F$ scale variation
- shower ("resummation") scale: upper limit of parton evolution
- merging scale

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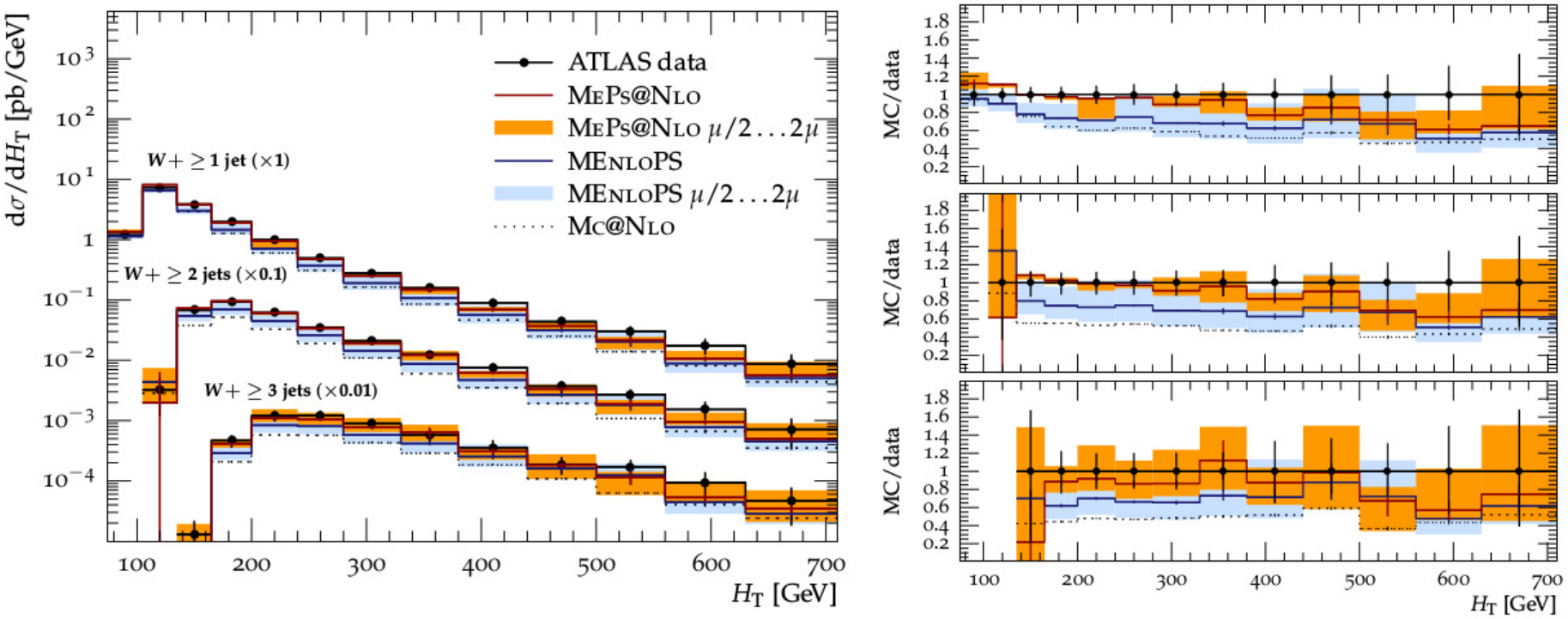
★ V + 0,1,2,(3,4) jets

[Hoeche,Krauss,Schoenherr,Siegert '12]



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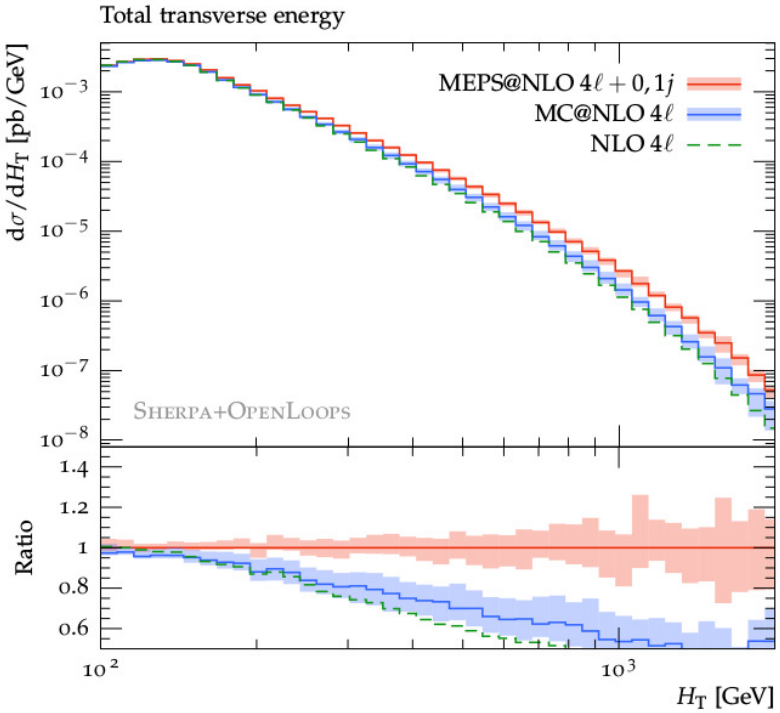
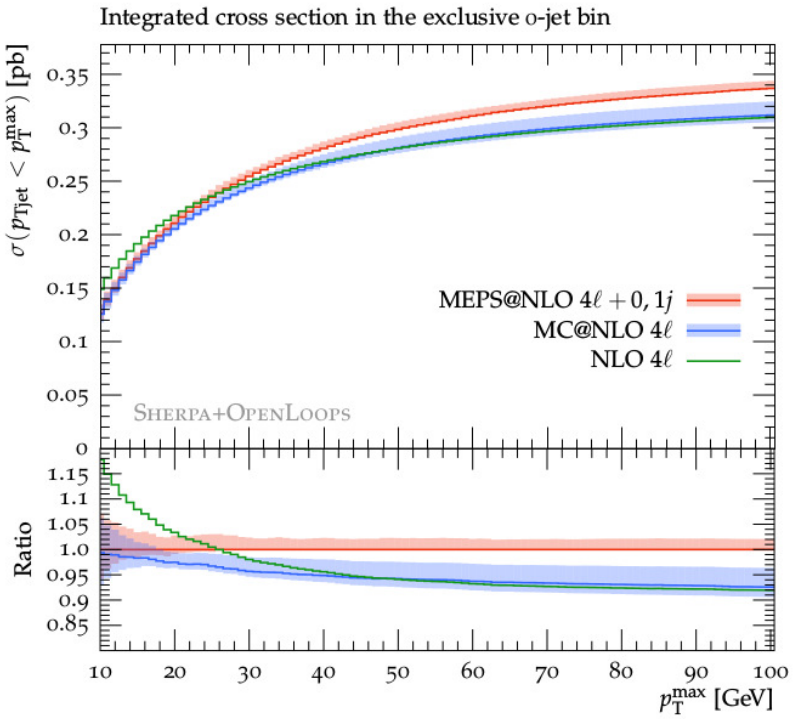
★ 4 leptons + 0,1 jets [Cascioli,Hoeche,Krauss,Maierhöfer,Pozzorini,Siegert '14]

- important background in $H \to WW$, typically suppressed by jet-vetoing



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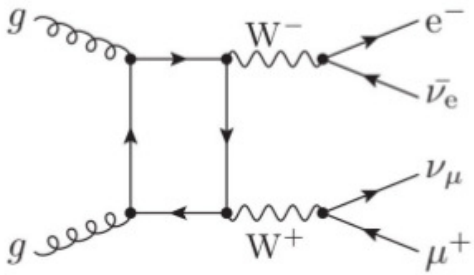
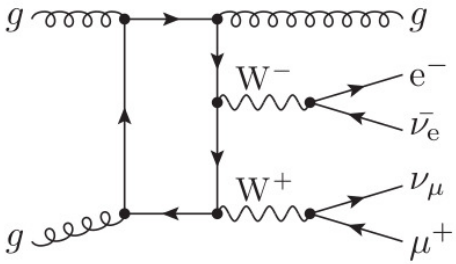
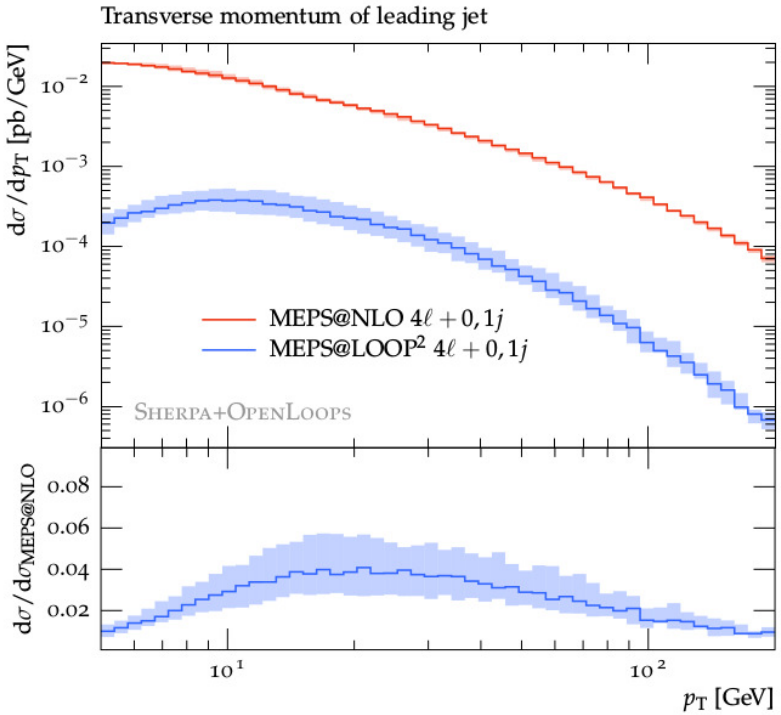
- $gg \to VV$: finite subset of NNLO contribution
  - first merging of 0-jet and 1-jet squared-loop contributions



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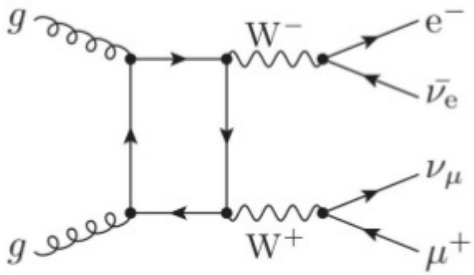


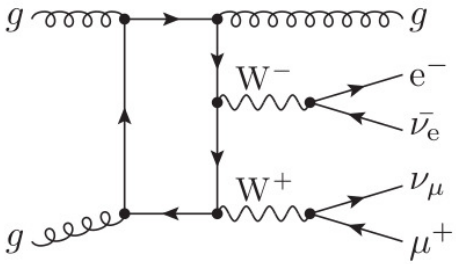


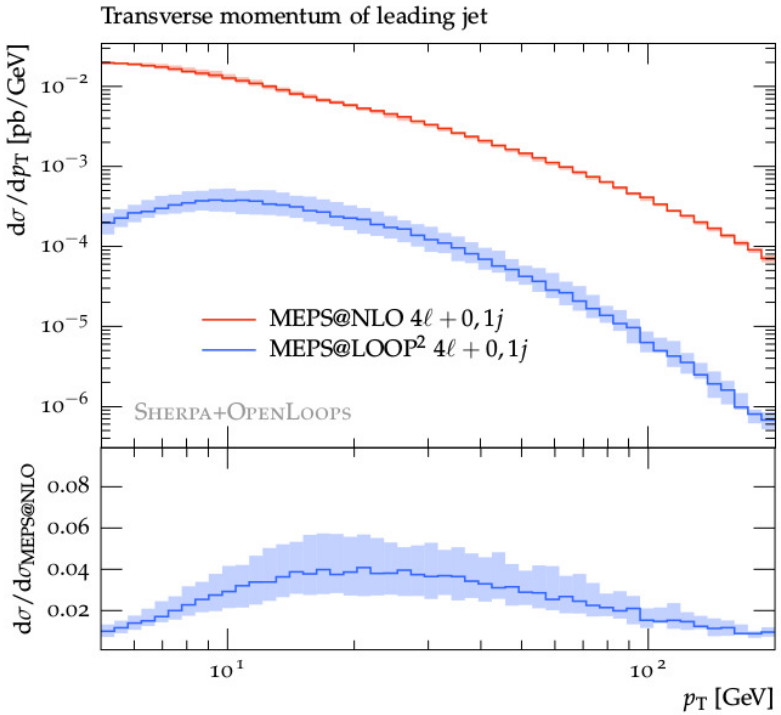


★ pheno study also for VV/VVV + 0,1 jets [Hoeche,Krauss,Pozzorini, et al. '14]

# MadGrapg5_aMC@NLO

[Alwall,Frederix,Frixione,Hirschi,Maltoni,Mattelaer,Shao,Stelzer,Torrielli,Zaro '14]

- NLO+PS matching for any process, fully automated in the strictest sense
- matching to `Herwig++` and `Pythia8` fully worked out
- Uncertainties: information to compute $\mu_R$ and $\mu_F$ scale variation "on-the-fly"

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- FxFx merging

[Frederix,Frixione '12]

$$
\begin{aligned}
d\bar{\sigma}_{\mathbb{S},0} &= T_0 + V_0 - T_0\mathcal{K} + T_0\mathcal{K}_{\mathrm{MC}}\Theta(d_1 < Q_{\mathrm{MS}}) \\
d\bar{\sigma}_{\mathbb{H},0} &= \Big[T_1 - T_0\mathcal{K}_{\mathrm{MC}}\Big]\Theta(d_1 < Q_{\mathrm{MS}}) \\
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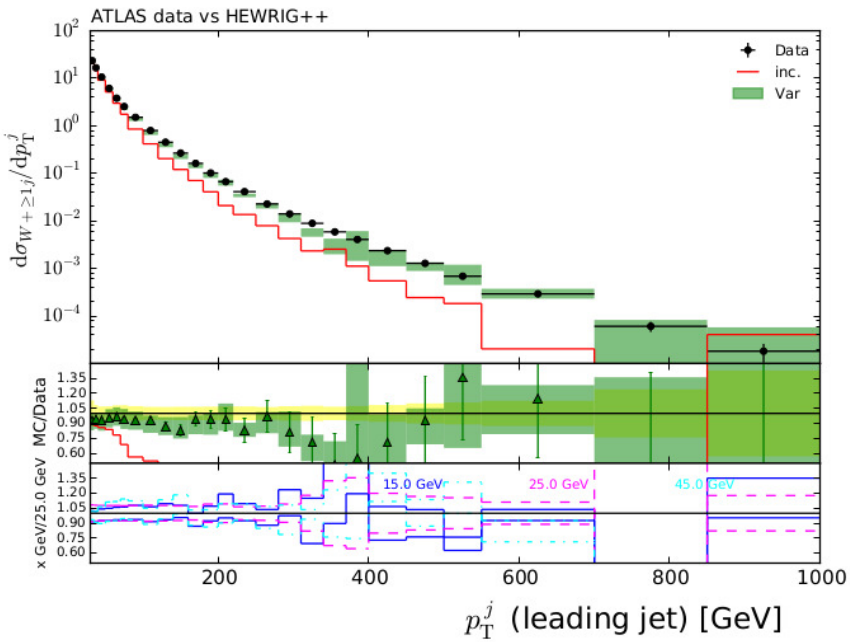
\end{aligned}
$$

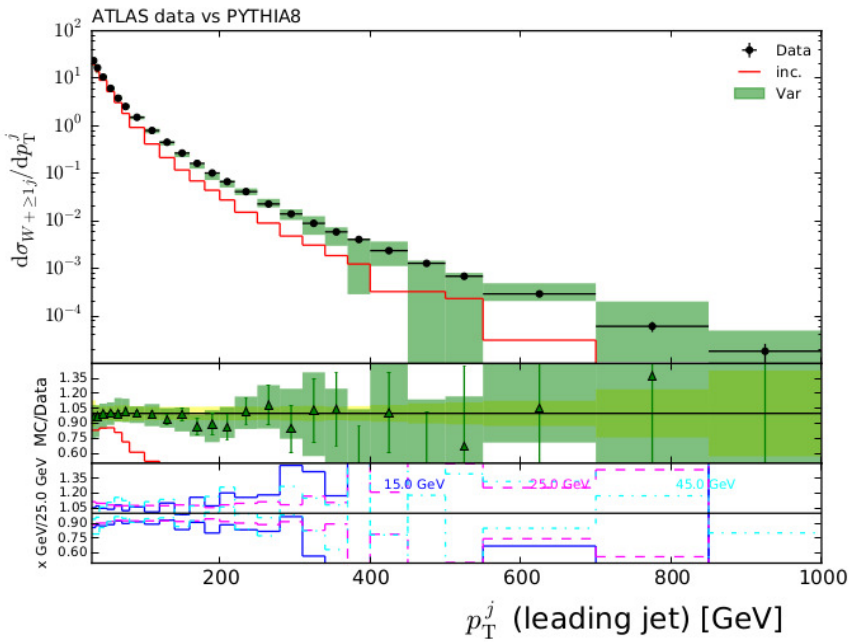
- limit contribution of $(\mathbb{H}, 0)$ events to region below $Q_{\mathrm{MS}}$
- prescriptions for shower starting scale
- include also Sudakov reweighting á la CKKW
- "unitarity" not imposed
- possible to iterate to higher multiplicities
- now fully automated

# MadGrapg5_aMC@NLO: FxFx merging

- extensive phenomenological study published recently

[Frederix,Frixione,Papaefstathiou,Prestel,Torrielli '15]




- estimation of perturbative uncertainty + shower "uncertainty"

1. $Q_{\rm MS}$ dependence is at most 1.5%. FxFx total typically 3-6% larger than exact inclusive NLO+PS
2. once $V+2$ jets at NLO+PS is included, also higher jet multiplicities are described reasonably well
3. the inclusive NLO+PS result depends much more on the PS used

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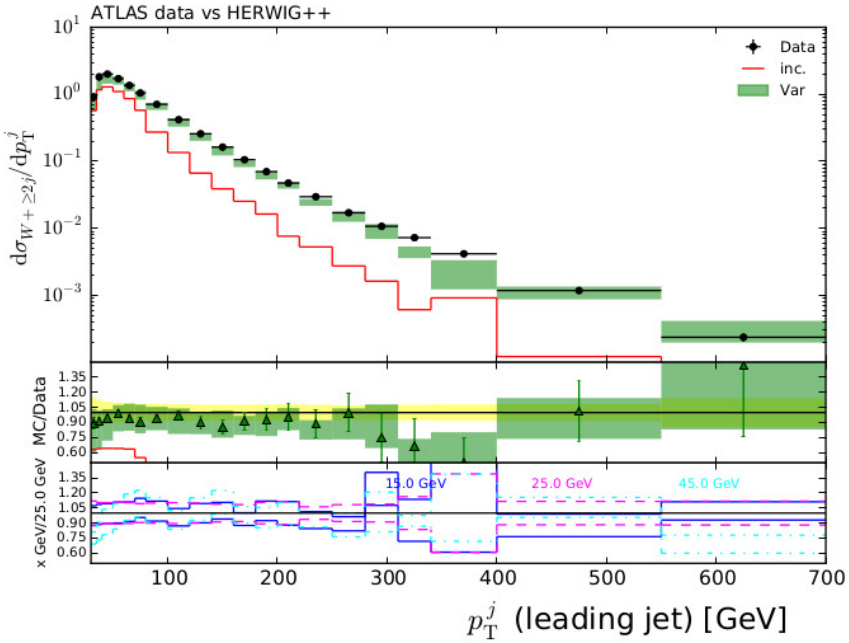


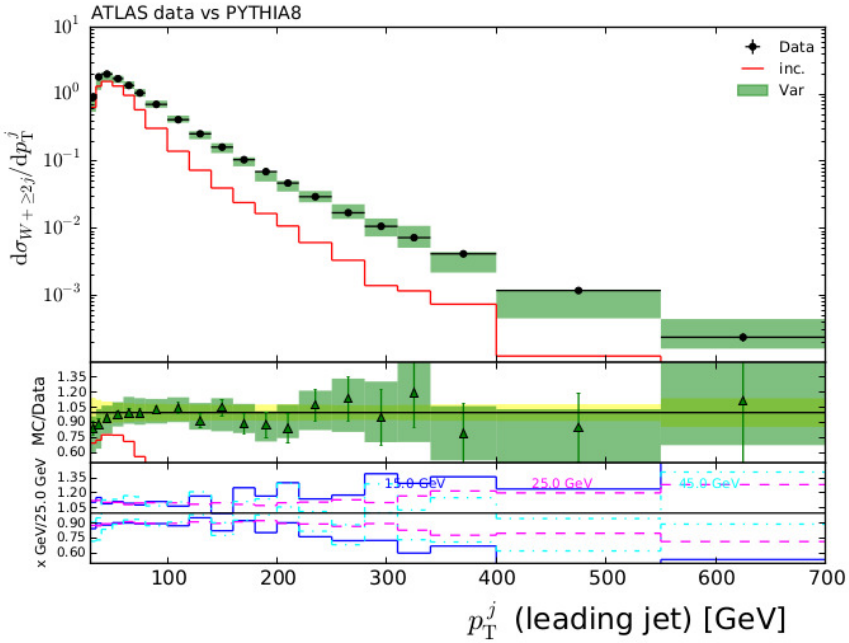


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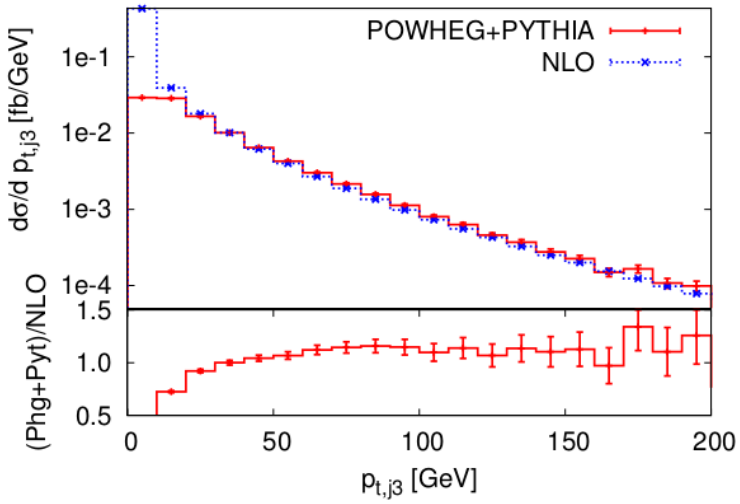
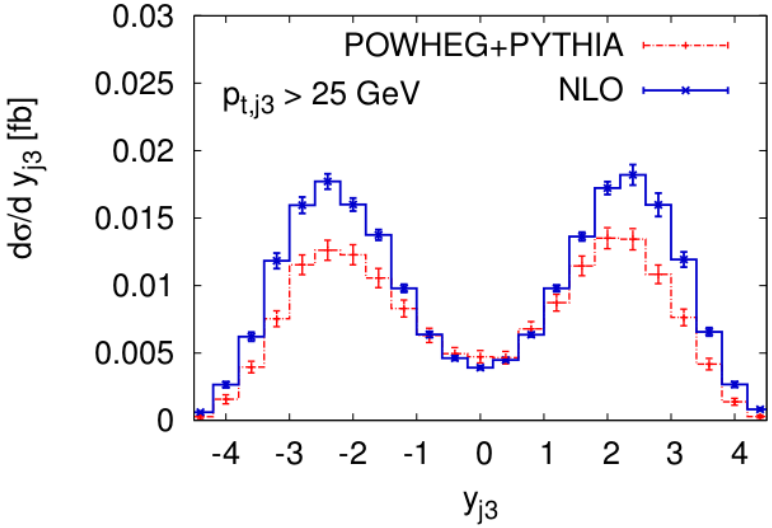
# POWHEG NLO+PS

- several processs @ NLOPS with 1 or 2 vector bosons and up to 2 jets are available




★ $W^+W^+$ + 2 jets

- computationally heavy, required several technical improvements in the code
- background for double-parton / BSM with 2 same-sign leptons




★ EW induced process

- several applications [Jaeger,Zanderighi + al.]
- anomalous $VVV$ couplings available for BSM studies e.g. [Jaeger,Karlberg,Zanderighi '13]
- plot: EW $W^+W^-jj$, with VBF cuts

...multijet merging with `MiNLO`...

# POWHEG+MiNLO merging

## Multiscale Improved NLO

[Hamilton,Nason,Oleari,Zanderighi, '12, '12]

- a-priori scale choice in multijet NLO computation
- correct weights of different NLO terms with CKKW-inspired approach (keeping NLO)
- from $X + n$ jets at NLO+PS, can get finite results also for $X + (n-1)$, $X + (n-2)$,... jets
  - $\Rightarrow$ it is a merging, without an external merging scale (just 1 event sample)
- formal accuracy of lower multiplicity fully understood for $V/V + 1$ jet merging (result shown later), not yet for higher multiplicities

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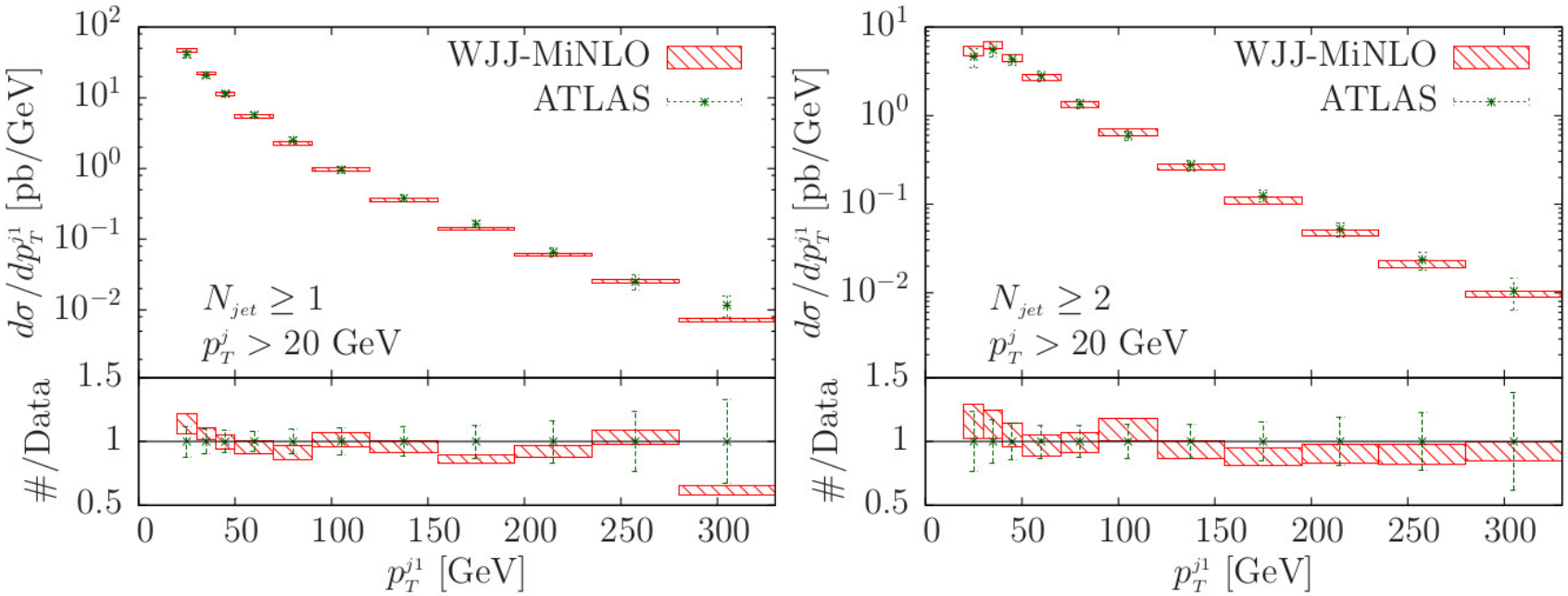
★ V + 0,1,2 jets

[Campbell,Ellis,Nason,Zanderighi, '13]




- works clearly well also for 0- and 1-jet region

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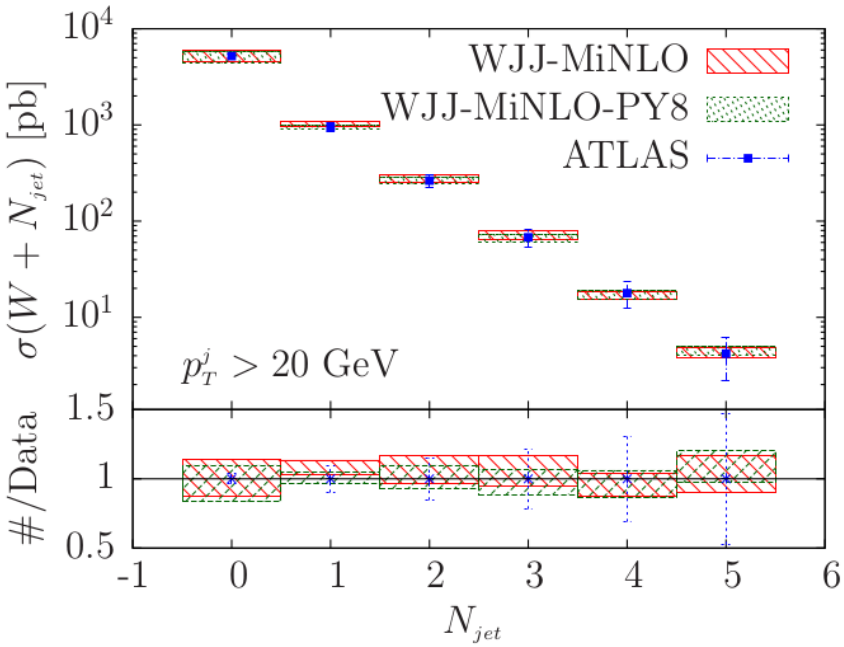


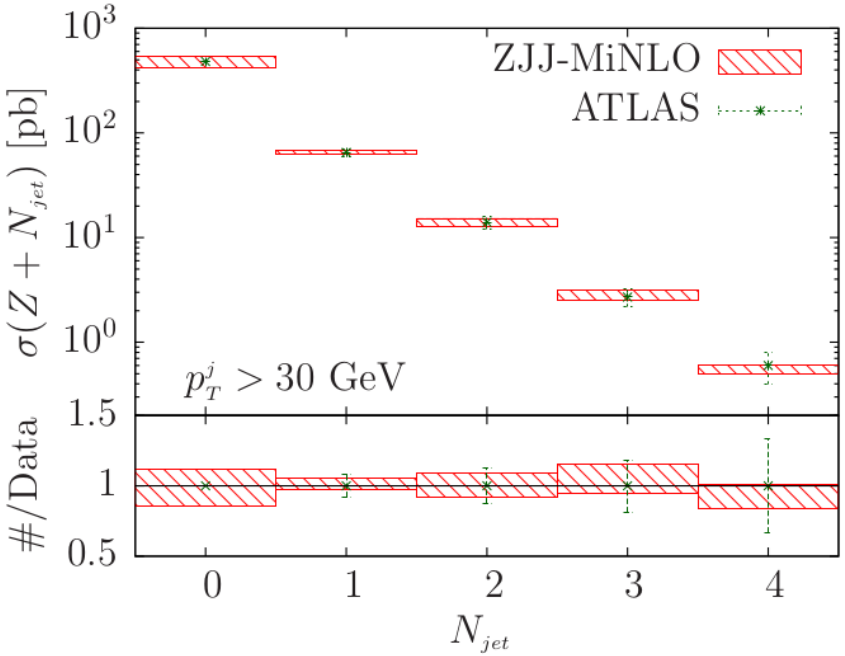


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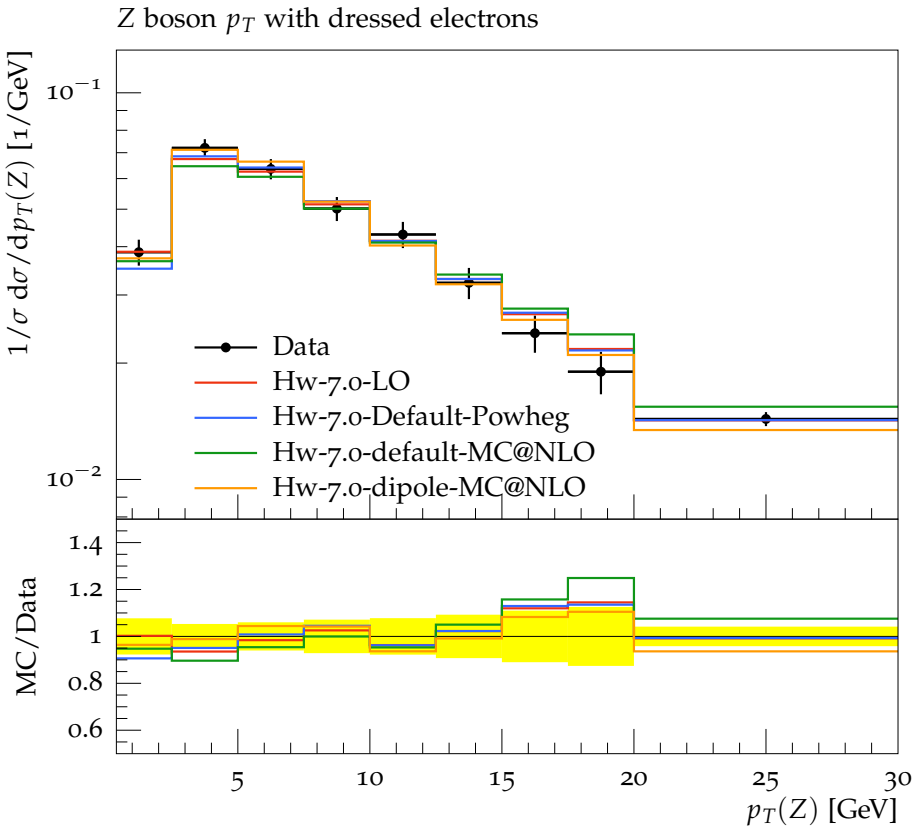
# Herwig 7: NLO+PS matching

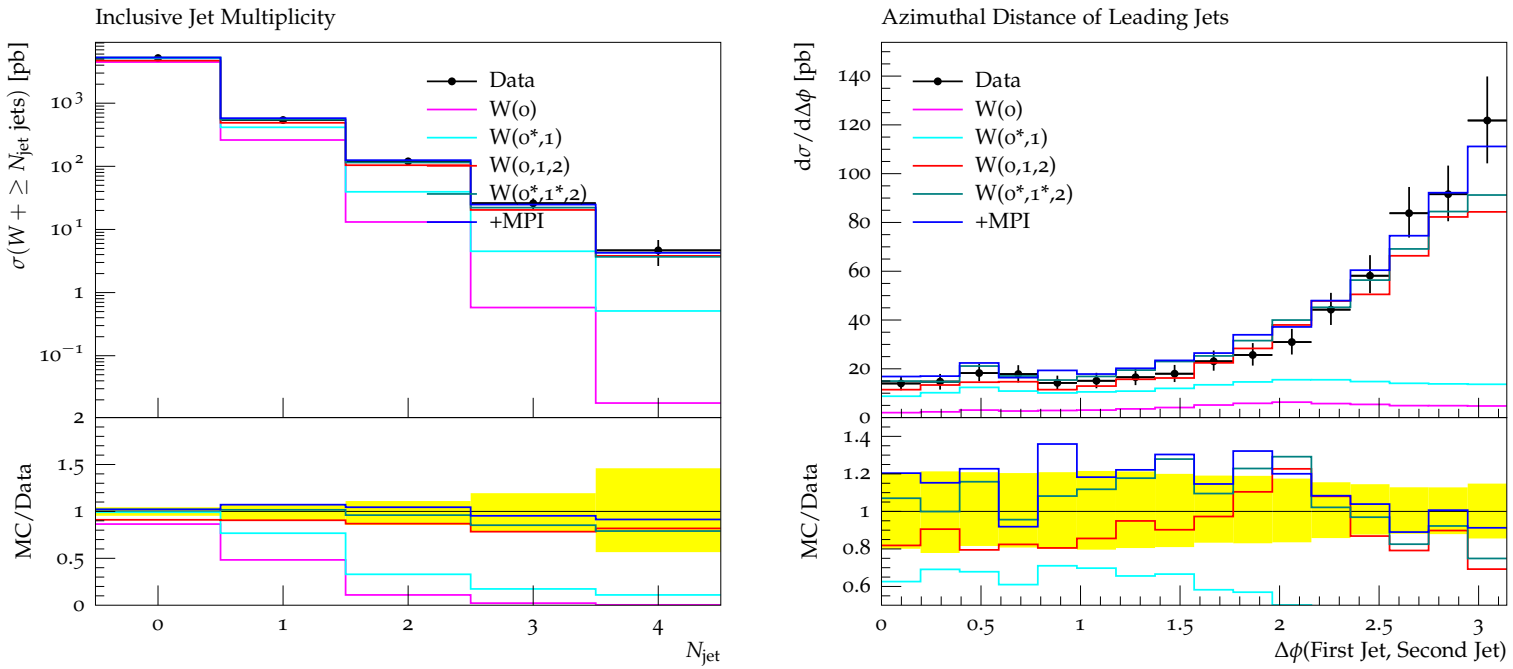
- `Herwig 7` now available, release note: arXiv:1512.01178




- New default: NLO matrix elements matched to the parton shower
  [Plätzer,Bellm,Wilcock,Rauch,Reuschle]
- NLOPS automated thanks to `Matchbox`: ME from external provider via BLHA [`GoSam`, `MadGraph`, `NJet`, `OpenLoops`, `VBFNLO`]
- internal `POWHEG` and `MC@NLO` NLOPS matching
- two different parton showers: angular-ordered, dipole
- comprehensive perturbative uncertainties estimation, within a single framework

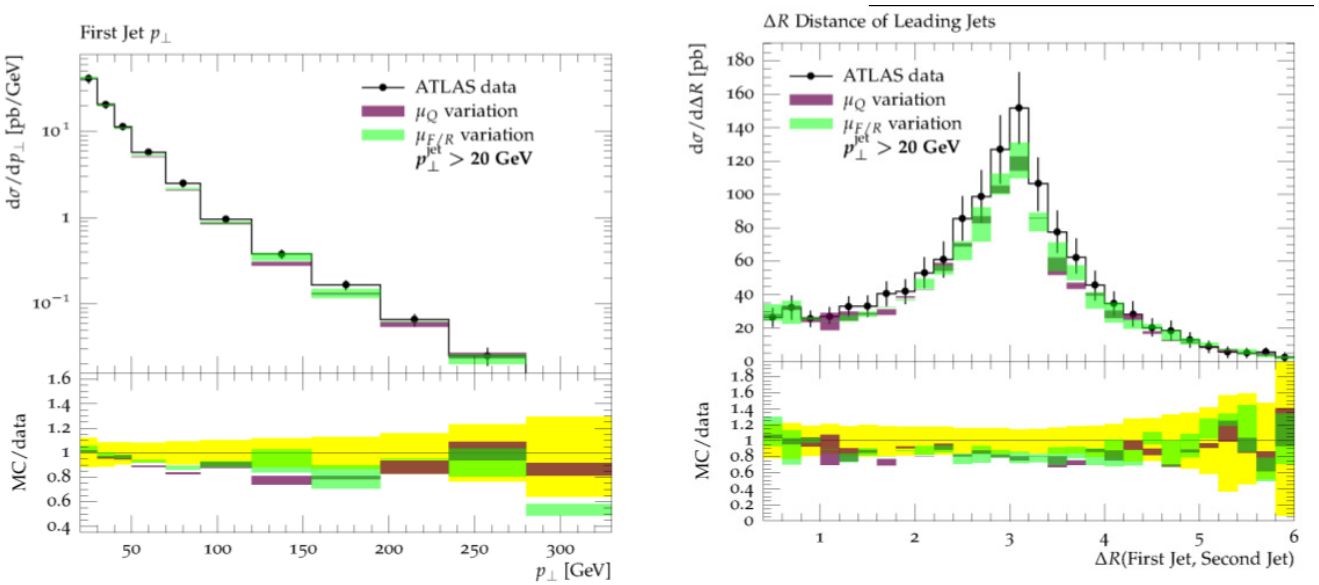
# Herwig 7: NLO+PS merging

- NLO+PS multijet merging [Plätzer '12 + Bellm,Gieseke]
- method very similar to UNLOPS
- its full exploitation will be the main focus in `Herwig 7` in the near future



# UNLOPS

- keyword: "unitarity" (preserve NLO inclusive cross section) [Lonnblad,Prestel '12]
- method: promote to NLO accuracy an "unitarised" CKKW approach, by carefully adding higher order contributions, and removing the pre-existing approximate $\alpha_S$ terms
  1. start from UMEPS merging at LO
  2. remove terms that will be included exactly, and add NLO (exclusive) computations
  3. unitarise
- can be iterated to higher multiplicities
- by construction, essentially no dependence on merging scale on inclusive cross section




- can now also use as input events from MC@NLO (so far mostly tested with `POWHEG-BOX`)

# Geneva

- new approach, SCET inspired [Alioli,Bauer,Berggren,Hornig,Tackmann,Vermilion,Walsh,Zuberi '12]
- idea: separate exclusive $N$-jet and inclusive $(N+1)$-jet regions using variable whose resummation is known at high order ("n-jettiness")

$$\sigma_{\geq N} = \int \mathrm{d}\Phi_N \, \frac{\mathrm{d}\sigma}{\mathrm{d}\Phi_N}(\mathcal{T}_N^{\mathrm{cut}}) + \int \mathrm{d}\Phi_{N+1} \, \frac{\mathrm{d}\sigma}{\mathrm{d}\Phi_{N+1}}(\mathcal{T}_N) \, \theta(\mathcal{T}_N > \mathcal{T}_N^{\mathrm{cut}})$$

where

$$\frac{\mathrm{d}\sigma}{\mathrm{d}\Phi_N}(\mathcal{T}_N^{\mathrm{cut}}) = \frac{\mathrm{d}\sigma^{\mathrm{resum}}}{\mathrm{d}\Phi_N}(\mathcal{T}_N^{\mathrm{cut}}) + \left[\frac{\mathrm{d}\sigma^{\mathrm{FO}}}{\mathrm{d}\Phi_N}(\mathcal{T}_N^{\mathrm{cut}}) - \frac{\mathrm{d}\sigma^{\mathrm{resum}}}{\mathrm{d}\Phi_N}(\mathcal{T}_N^{\mathrm{cut}})\bigg|_{\mathrm{FO}}\right],$$

$$\frac{\mathrm{d}\sigma}{\mathrm{d}\Phi_{N+1}}(\mathcal{T}_N) = \frac{\mathrm{d}\sigma^{\mathrm{FO}}}{\mathrm{d}\Phi_{N+1}}(\mathcal{T}_N) \left[\frac{\mathrm{d}\sigma^{\mathrm{resum}}}{\mathrm{d}\Phi_N \mathrm{d}\mathcal{T}_N} \bigg/ \frac{\mathrm{d}\sigma^{\mathrm{resum}}}{\mathrm{d}\Phi_N \, \mathrm{d}\mathcal{T}_N}\bigg|_{\mathrm{FO}}\right],$$

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- no "dangerous" merging scale dependence, thanks to higher-order resummation for $\tau_N$
- to retain formal accuracy, PS evolution very constrained: $\tau_N$ has to stay $\sim$ unchanged
- can be extended to higher multiplicities

- implemented for $e^+e^-$ and for Drell-Yan
- the method was also formulated to achieve NNLO+PS accuracy (results shown later)
- code not yet public, but events for 13 TeV Drell-Yan at NNLO+PS ready to be shared publicly

# NNLO+PS matching from MiNLO

- start from POWHEG V+j at NLO+PS

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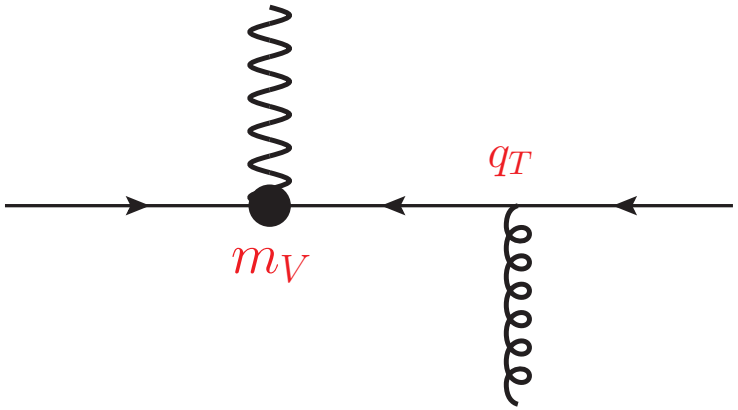
$$\bar{B}_{\mathrm{NLO}} = \alpha_{\mathrm{S}}(\mu_R)\Big[B + \alpha_{\mathrm{S}}^{(\mathrm{NLO})} V(\mu_R) + \alpha_{\mathrm{S}}^{(\mathrm{NLO})} \int d\Phi_{\mathrm{r}} R\Big]$$



# NNLO+PS matching from MiNLO

- start from POWHEG V+j at NLO+PS
- apply MiNLO, in its stronger formulation (MiNLO*) ⇒ V and V+1 jet at NLOPS

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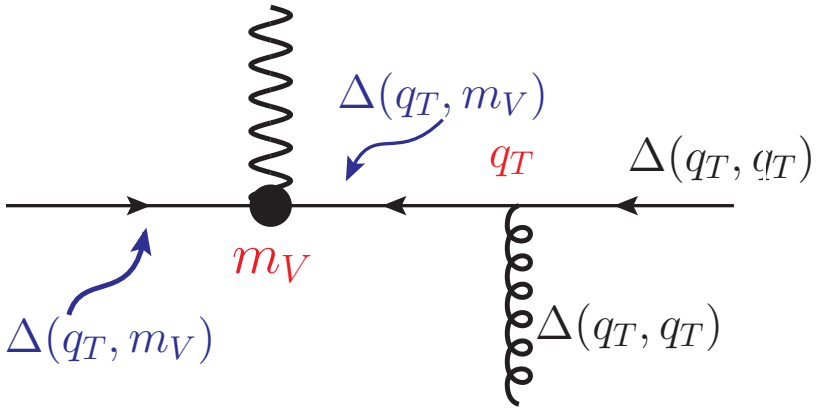
$$\bar{B}_{\rm MiNLO} = \alpha_{\rm S}(q_T)\Delta_q^2(q_T, m_V)\Big[B\left(1 - 2\Delta_q^{(1)}(q_T, m_V)\right) + \alpha_{\rm S}^{(\rm NLO)} V(\bar{\mu}_R) + \alpha_{\rm S}^{(\rm NLO)} \int d\Phi_{\rm r} R\Big]$$



# NNLO+PS matching from MiNLO

- start from POWHEG V+j at NLO+PS
- apply MiNLO, in its stronger formulation (MiNLO*) ⇒ V and V+1 jet at NLOPS
- reach NNLOPS accuracy by reweigting (differential on $\Phi_B$) of "MiNLO-generated" events [input from DYNNLO]

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

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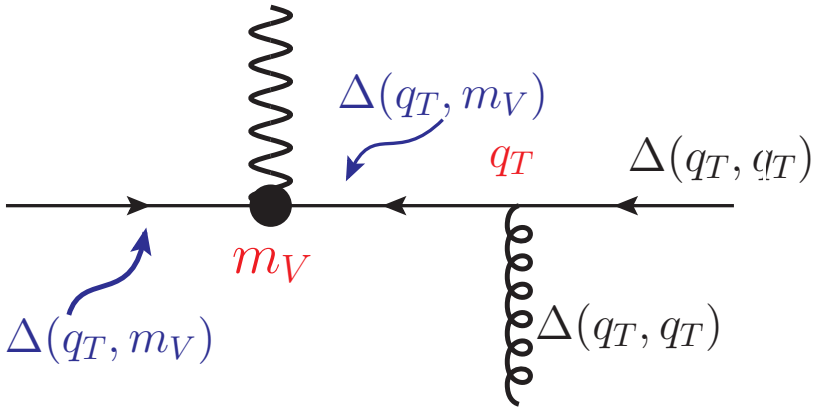
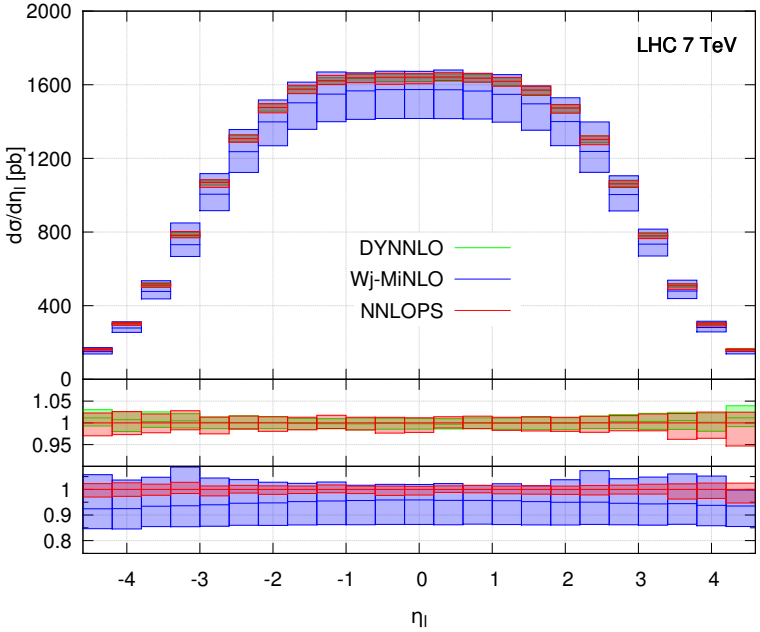


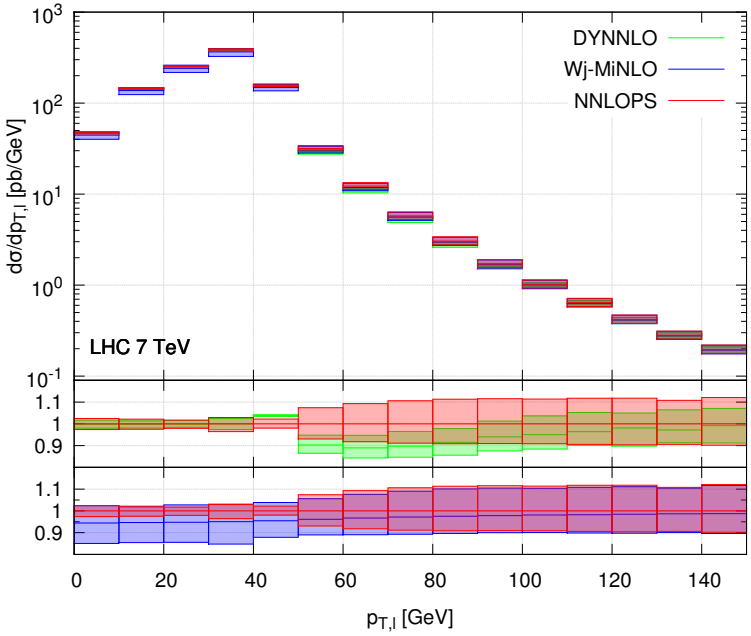

$$W(\Phi_B) = \frac{\left(\frac{d\sigma}{d\Phi_B}\right)_{\rm NNLO}}{\left(\frac{d\sigma}{d\Phi_B}\right)_{\rm MiNLO^*}} \simeq 1 + \mathcal{O}(\alpha_{\rm S}^2)$$

Reweighting function ($W(\Phi_B, ...)$) not unique, some choices possible

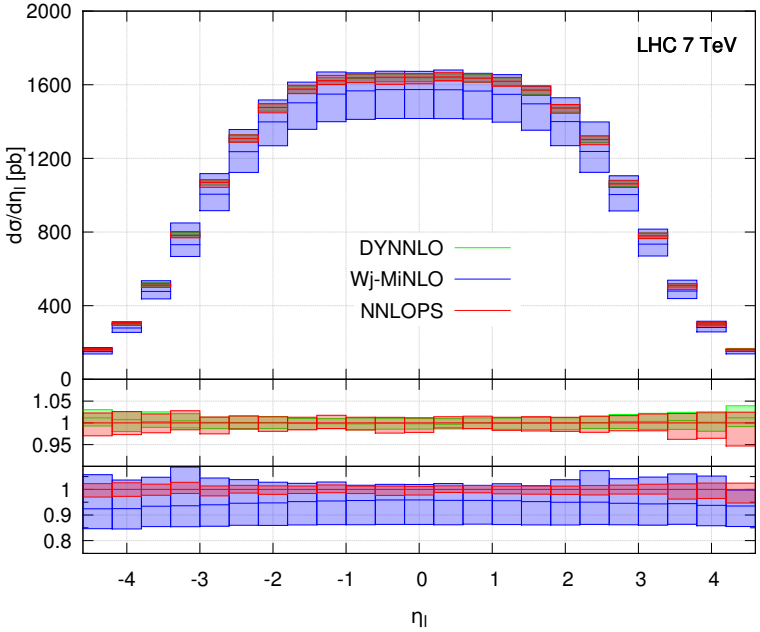
- partially explored in Higgs paper
- for DY, just one choice (but studying others not too demanding)

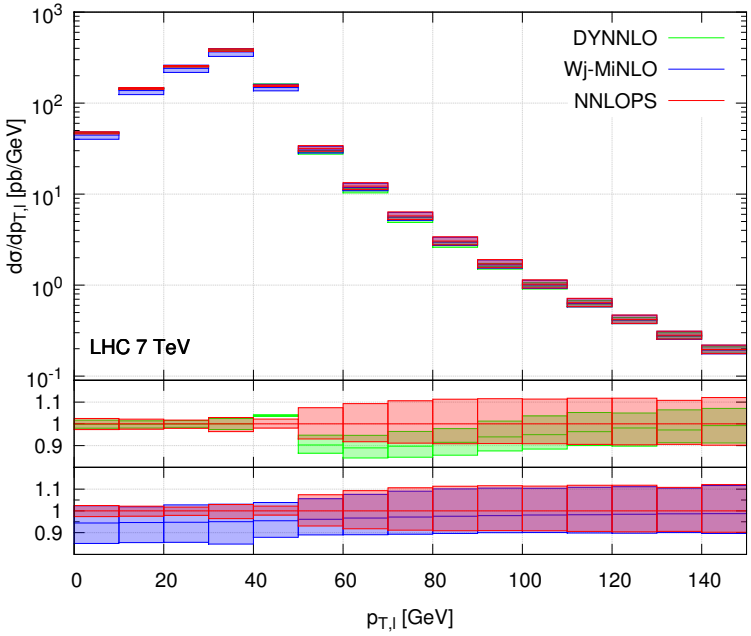
# DY@NNLOPS [POWHEG+MiNLO]

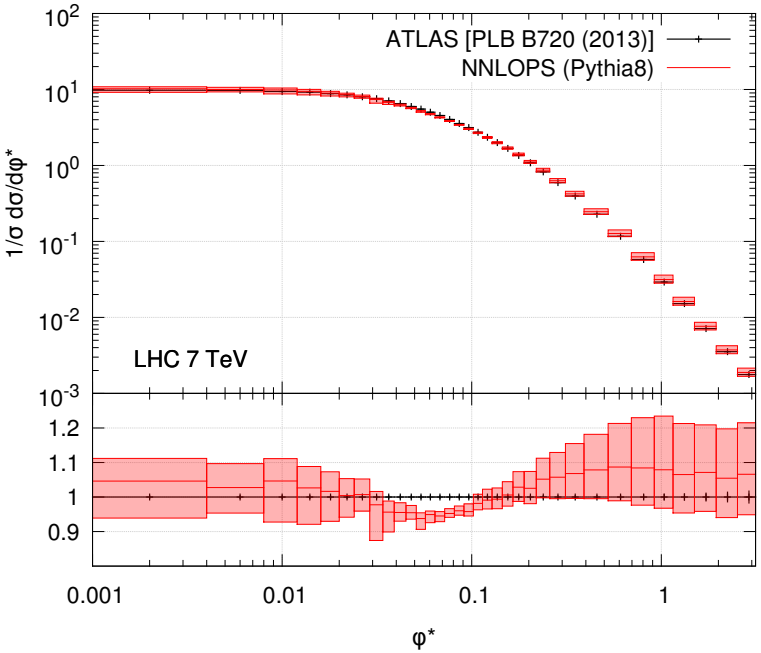


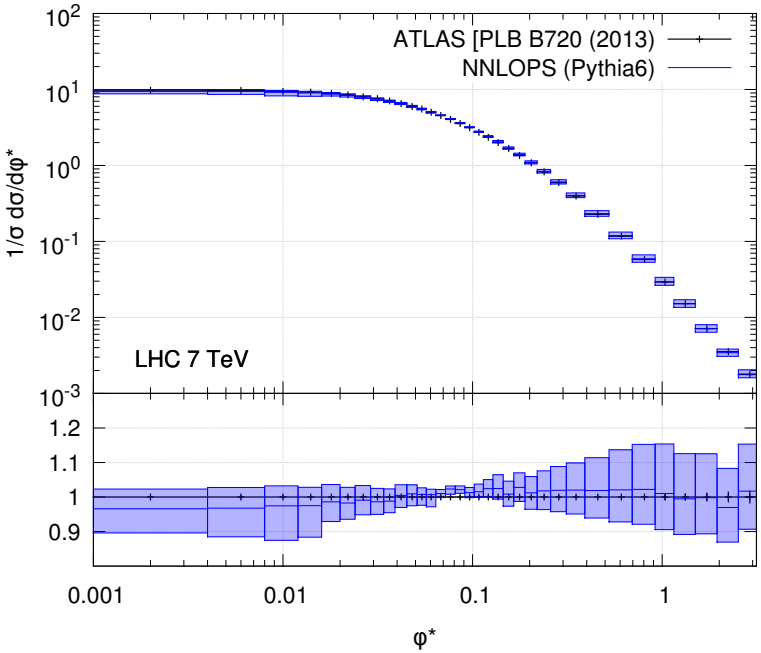



# DY@NNLOPS [POWHEG+MiNLO]



# NNLOPS Drell-Yan with UNNLOPS

- NNLOPS obtained also upgrading `UNLOPS` to `UNNLOPS` [Hoeche,Li,Prestel '14]
- code and more results in
  `http://www.slac.stanford.edu/~shoeche/pub/nnlo/`

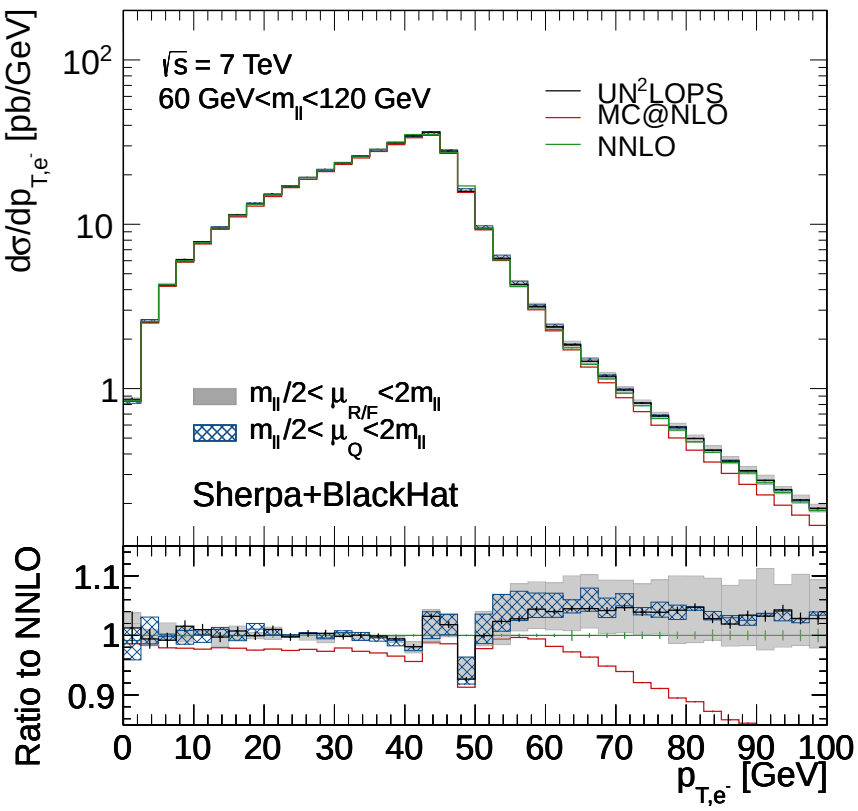
$$\langle \mathcal{O} \rangle \to \int d\Phi_0 \bar{B}_0^{t_c} \mathcal{O}(\Phi_0) + \int_{t_c} d\Phi_1 B_1 (1 - \omega_1 \Pi_0(t, \mu_Q^2)) \mathcal{O}(\Phi_0)$$
$$+ \int_{t_c} d\Phi_1 \omega_1 B_1 \Pi_0(t, \mu_Q^2) \mathcal{F}_1(t, \mathcal{O})$$

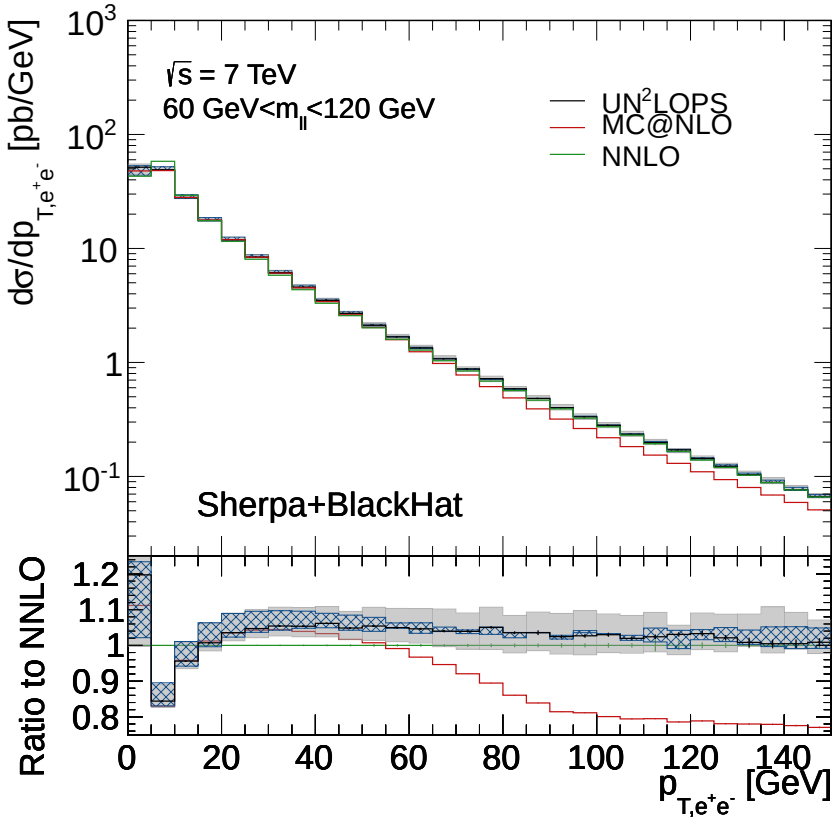
zero jet bin

$$\bar{B}_0^{t_c}(\Phi_0) = B_0(\Phi_0) + V_0(\Phi_0) + \int^{t_c} B_1 d\Phi_1$$

- inclusive NLO recovered from UNLOPS
- scheme pushed to NNLO
- notice: contributions in "zero-jet" bin are not showered:
  - in `POWHEG`(+`MiNLO`) , all "no-radiation" bin is Sudakov-suppressed
  - this issue triggered the development of the `DIRE` shower [Hoeche,Prestel '15]
  - for DY, however, this is unlikely to play a big role

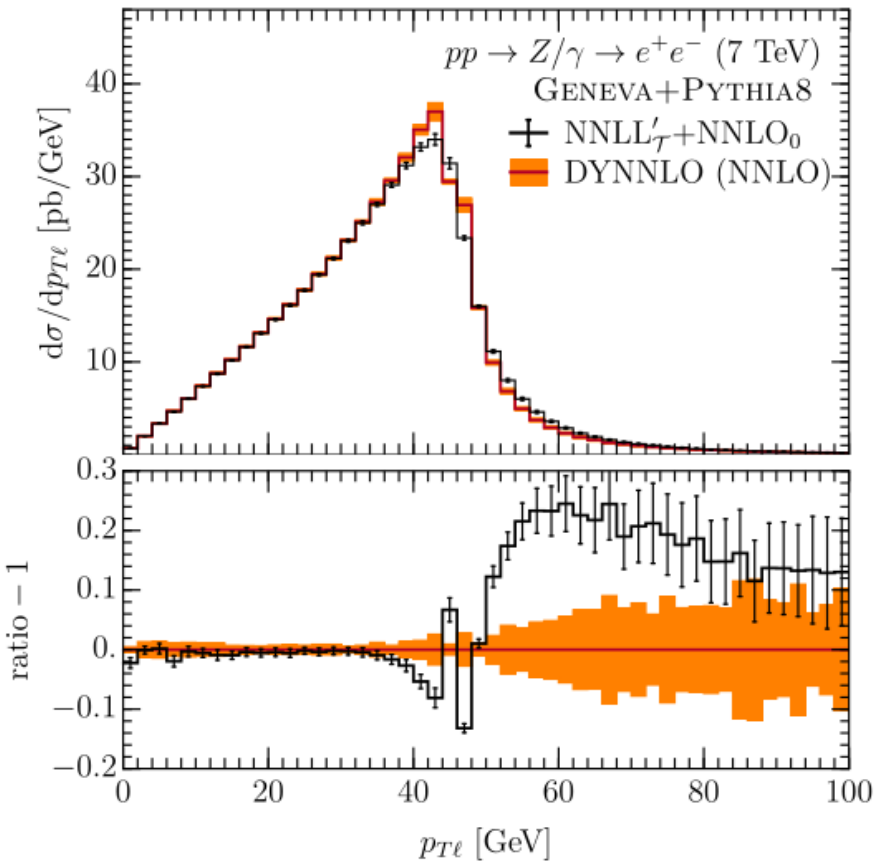
# NNLOPS Drell-Yan with UNNLOPS

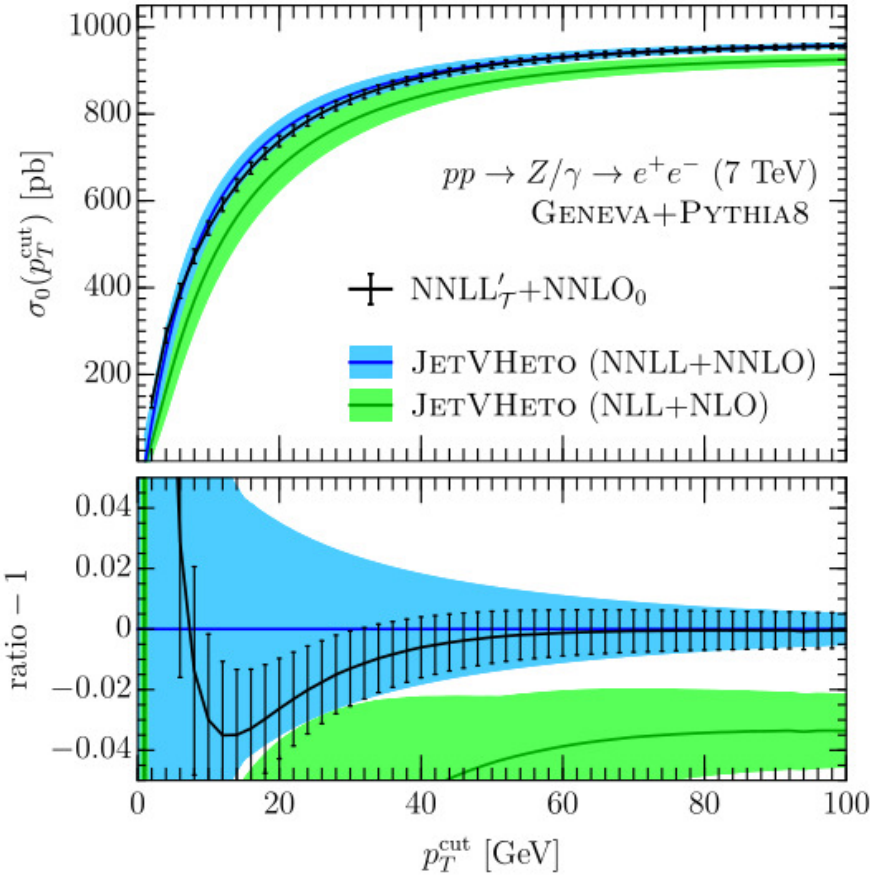


# NNLO+PS with Geneva

[Alioli,Bauer,Berggren,Tackmann,Walsh, '15]

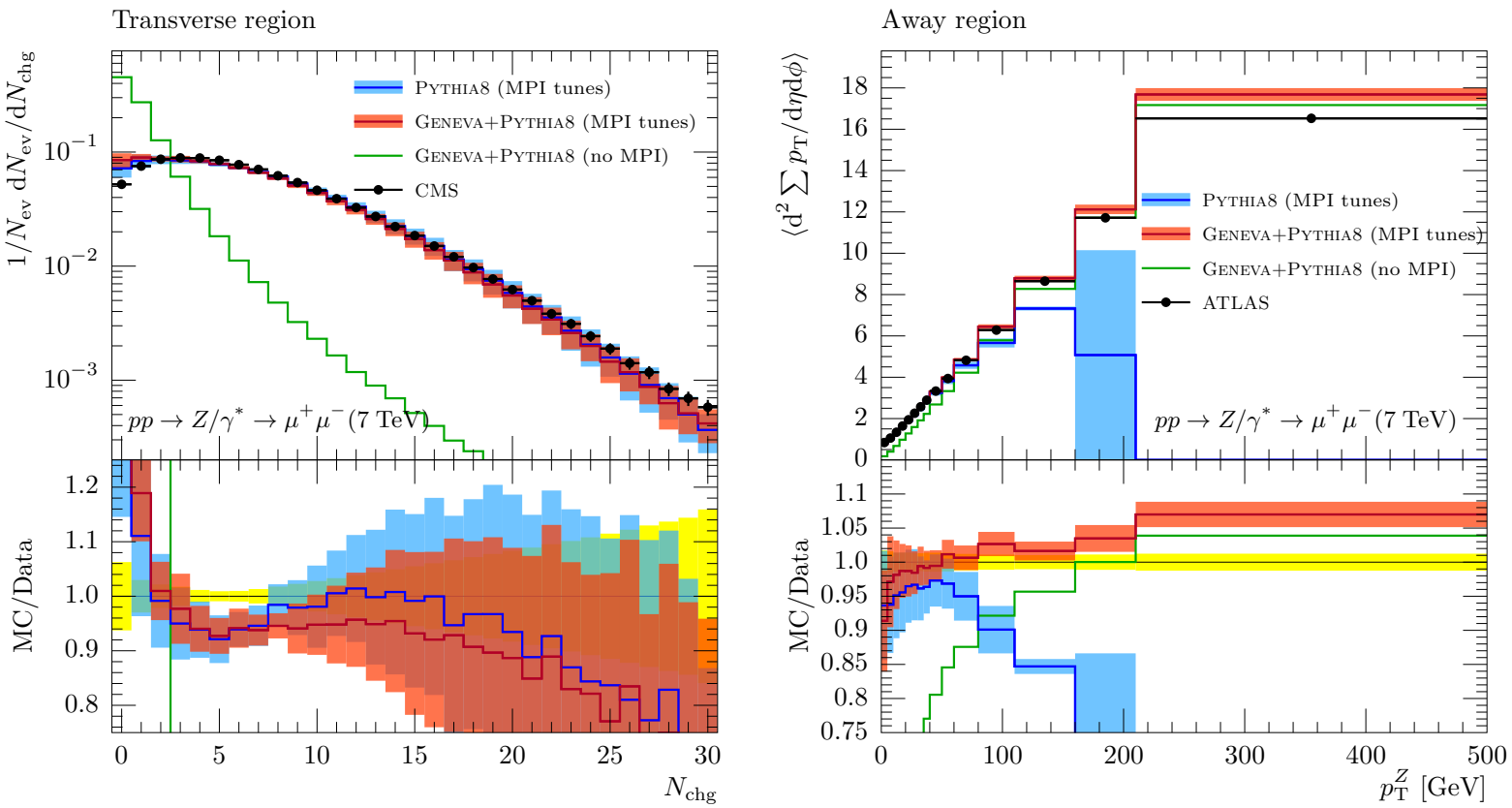



Events for 13 TeV studies are available

# NNLO+PS with Geneva

- first studies switching on MPI: results look promising



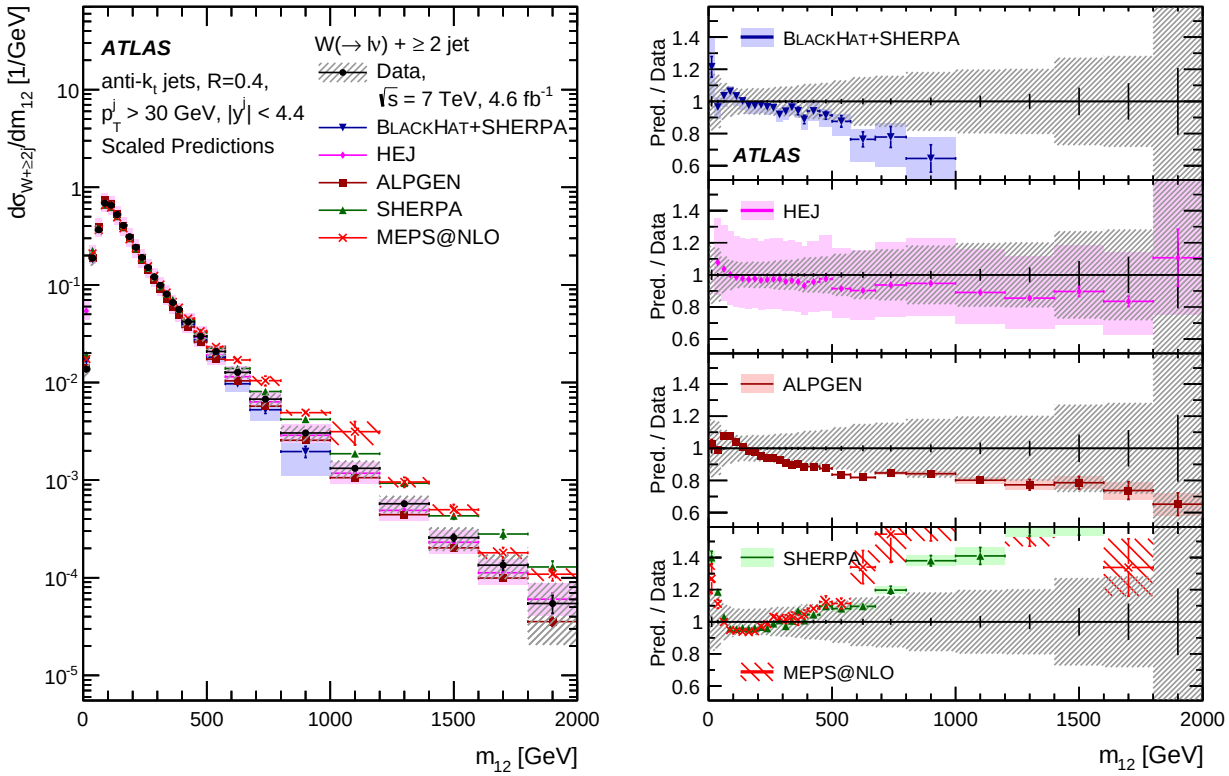
# High Energy Jets

[Andersen,Smillie]

- HEJ is a flexible event generator which contains the dominant logarithms in the high-energy limit at all orders. It uses "factorised" property of amplitudes in this limit.
- Publicly available for
  di-jets , $H + jj$ , $W + jj$ ($Z + jj$ on request)

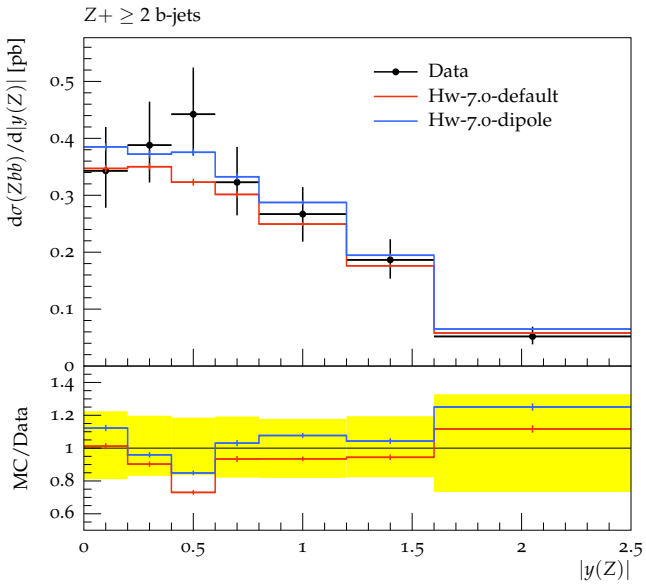
  http://hej.web.cern.ch
- The logs resummed by HEJ become large in regions of large invariant mass between jets (with fixed $p_T$), or at large rapidity separation ($> 3$).
- It is the only dedicated tool designed to model precisely the above kinematics region (which is important for instance in VBF searches)
  - not expected to give as good a description when large hierarchy in momentum scales is dominant, as this evolution not included.

# High Energy Jets




- The logarithms uniquely described in the HEJ event generator become increasingly important as $m_{12}$ increases. Their importance can be seen here! HEJ prediction remains flat, while others deviate.
- Some distributions show worse agreement with HEJ; they improve by including sub-leading corrections (ongoing work).

# V+$b\bar{b}$

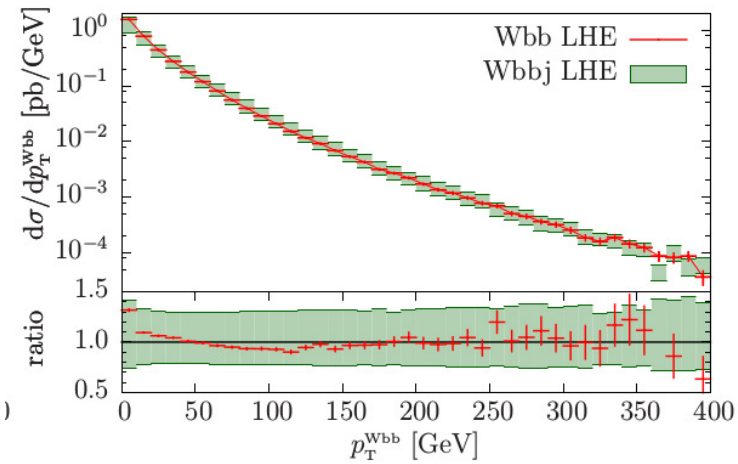


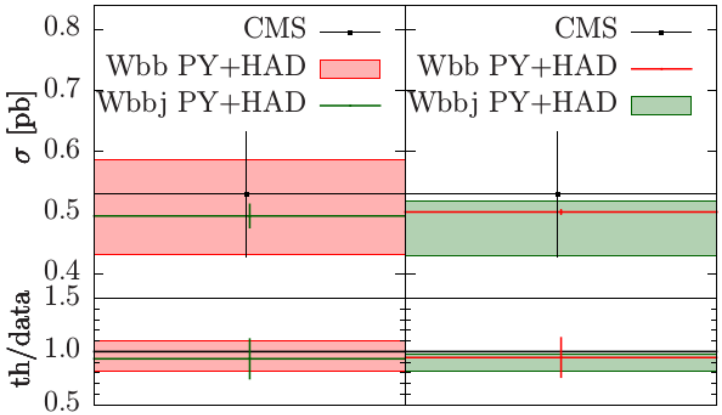

★ V + heavy (b)-flavour

- studied in `aMC@NLO` and `POWHEG` years ago.
- I assume it is available also in `Sherpa`
- this plot: preliminary result in `Herwig 7`

★ $V + b\bar{b}$ + 0,1 jet, with MiNLO

[Luisoni,Oleari,Tramontano, '15]




- good result for inclusive cross sections, uncertainty reduced in spectrum when using `MiNLO`
- agreement with jet-binned x-section from ATLAS not very satisfactory

# conclusions

- questions ?

# conclusions

- questions ?

*Thank you for your attention!*