NLO + Parton Showers merging: current status and future perspectives

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Introduction and outline

Key messages:

- This is a very rapidly evolving field, with many new methods being introduced or improved
- in 20' impossible to give a complete overview:
  certainly I forgot something: I apologise for this
- Monte Carlo tools are widely used:
  → impact of all these improvements likely important for LHC Physics
  (think about the impact that `MC@NLO` and `POWHEG` had during LHC Run I)

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Outline:

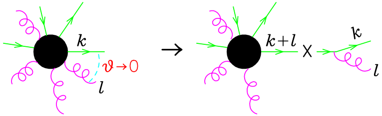
- status and improvements in parton showers
- NLO matching (NLO+PS)
- NLO multijet merging
- NNLO matching (NNLO+PS)
- conclusions and outlook

Parton Showers & LO+PS

LO+parton showers

parton-shower (PS) programs: backbones for all approaches that go beyond fixed-order accuracy, simulating fully exclusive events (including hadronisation, MPI,...)

- PS programs currently used for LHC Physics: Pythia8, Herwig++, Sherpa
  - based on factorisation of QCD amplitudes
  - accuracy: LL, leading colour (planar)
  - some NLL/subleading colour effects included



- differences in ordering variable, splitting kernels and recoiling scheme

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- other approaches exist (Ariadne, Vincia, KRK)
- ongoing activity also to improve PS algorithms
  - subleading-N effects [Plätzer,Sjödahl '13]
  - interference effects [Nagy,Soper '14]
  - EW showers [Christiansen,Sjöstrand / Krauss,Petrov et al '14]

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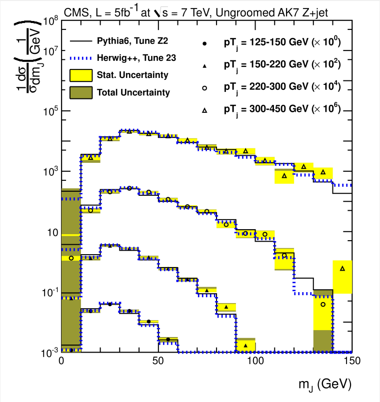

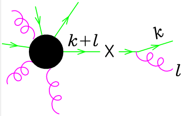

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beyond LO+PS

- standalone Monte Carlo are LO+(N)LL accurate (LO+PS)
- name of the game: improve the accuracy of Monte Carlo programs including as much information as possible from higher-order perturbative QCD (from fixed order, but also from resummation)

- this has to be done consistently: the "less accurate" approach we want to improve already includes some approximation of the terms we want to include exactly:

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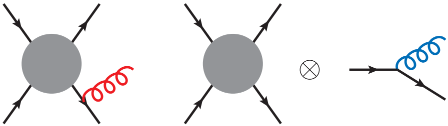

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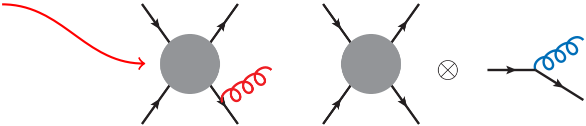

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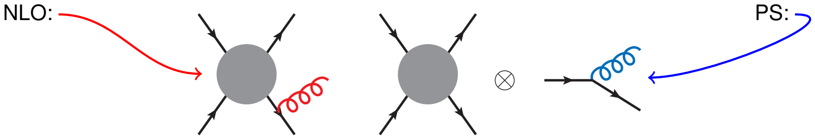

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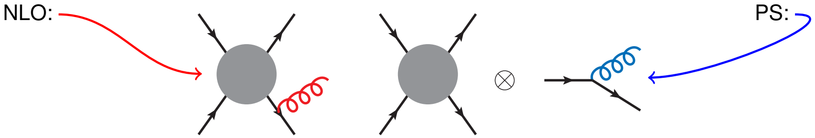


- will talk about recent progress in NLO+PS tools (POWHEG, MC@NLO,...) and improvements thereof ("NLOPS multijet merging", "NNLO+PS")

matching NLO and PS (NLO+PS)

NLO matching (NLO+PS)

- MC@NLO [Frixione,Webber '02] and POWHEG [Nason'04] are by now well established: method of choice when available
- if a QCD NLO computation for $pp \to X$ exists [by now it probably does, see S. Badger talk], it can be (was) matched to a PS
  - inclusive observables at NLO [much better than LO+PS ✓]
    ↪ normalisation starts to stabilise, meaningful assessment of theoretical uncertainties, K-factors included
  - (N)LL Sudakov resummation where relevant [much better than NLO ✓]
  - large-p_T hardest associated jet at LO [better than LO+PS ✓]
  - extra jets at LL [better than NLO ✓]
  - fully exclusive events
- X can contain jets
  (but if it contains N-jets, not possible to describe observables with $n < N$ jets)

- available tools:
  - POWHEG based: POWHEG-BOX, PowHel, Matchbox/Herwig++
  - MC@NLO based: MG5_aMC@NLO, Sherpa-MC@NLO, Matchbox/Herwig++
  - other approaches:
    - HEJ [Andersen,Hapola,Smillie]
    - Vincia [Giele,Kosower,Skands, et al]
    - Geneva [Alioli,Bauer, et al '12]
    - KRK see S. Sapeta talk this session

NLO matching (POWHEG)

- POWHEG-BOX [Alioli,Nason,Oleari,ER,Hamilton,Zanderighi + many others involved] (http://powhegbox.mib.infn.it/)

- pure QCD: jj, jjj
- EW: $V(+j,+jj)$, VV, $Wb\bar{b}$, W^+W^+jj (QCD)
- top: $t\bar{t}(+j)$, tj ("single top", also in 4f scheme), tW
- VBF: Vjj, $VVjj$
- Higgs: $H(+j,+jj)$, HV, HVj, Hjj (VBF), $Hjjj$ (VBF)
- BSM: tH^+, $\tilde{\ell}\tilde{\ell}$, $\tilde{q}\tilde{q}$, H/A in MSSM, DM+monojets
- QED/EW & QCD: Drell-Yan

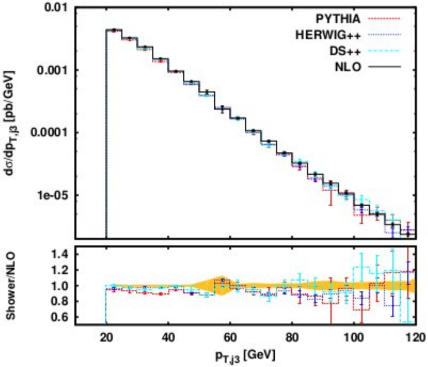
- PowHel [Garzelli,Kardos,Papadopoulos,Trócsányi] (http://grid.kfki.hu/twiki/bin/view/DbTheory/WebHome)

- top pairs: $t\bar{t}$, $t\bar{t}j$, $t\bar{t}H$, $t\bar{t}V$, $t\bar{t}b\bar{b}$, $W^+W^-b\bar{b}$

- POWHEG-BOX (V2):
  - th. uncertainty: fast PDF and scale reweighting
  - can use MadGraph4 for all tree-level terms
  - can be interfaced to 1-loop codes (HELAC, MCFM, GoSam, NLOJET++), supports BLHA
- possible to generate at NLO+PS also correction to decay of heavy resonances
  - validation and phenomenology for $t\bar{t}$ in progress [Nason,Campbell,Ellis,ER, in progress]

$pp \to Hjjj$ (VBF)

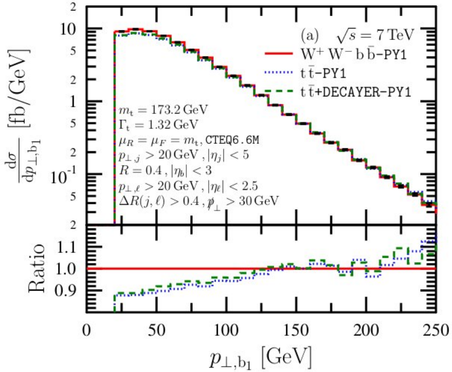
[Jäger,Schissler,Zeppenfeld '14]



- amplitudes from VBFNLO
- estimate uncertainties due to "Central Jet Veto" techniques

$pp \to W^+W^-b\bar{b}$ (5f-scheme)

[Garzelli,Kardos,Trócsányi '14]



- fully differential $t\bar{t}$ as signal and background
- exact handling of offshellenss effects by PS need be addressed in this context

NLO matching (aMC@NLO)

- MadGraph5_aMC@NLO [Alwall,Frederix,Frixione,Hirschi,Maltoni,Mattelaer,Shao,Stelzer,Torrielli,Zaro] (http://amcatnlo.web.cern.ch/amcatnlo/)
- milestone in 2014 for the QCD/MC community:
  - ☞ essentially all $2 \to 4$ processes you can think about (and also e^+e^-)
  - ☞ several of these processes were never computed before

- embedded in Madgraph5
- fully automated (thanks to MadFKS and MadLoop)
- th. uncertainty: fast PDF and scale reweighting
- will soon allow also EW corrections and BSM models, thanks to interface to FeynRules [Alloul,Christensen,Degrande,Duhr,Fuks]

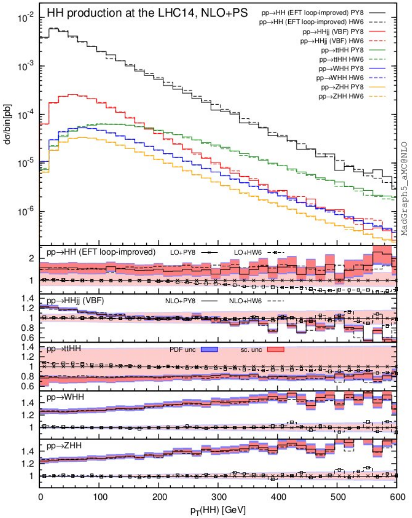
  - NLO EW & NLO QCD effects for $t\bar{t}H$ [Frixione,Hirschi,Pagani,Shao,Zaro, this week]

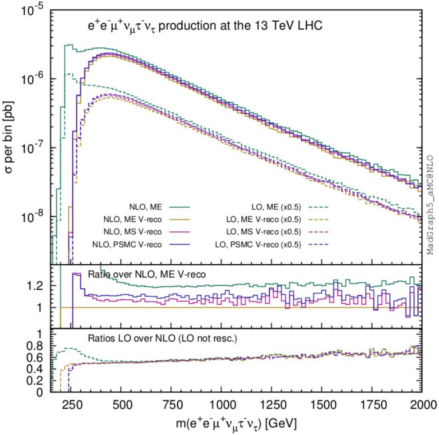
NLO matching (aMC@NLO)

$pp \to HHX$

[Frederix,Frixione,Hirschi,Maltoni,Mattelaer,Torrielli,Vryonidou,Zaro]

$pp \to e^+e^-\mu^+\nu_\mu\tau^+\nu_\tau$





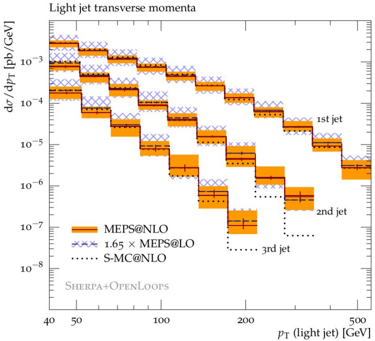
NLO matching (Sherpa-MC@NLO)

- `Sherpa-MC@NLO` [Hoeche,Krauss,Schoenherr,Siegert] (http://sherpa.hepforge.org)

- interfaced to 1 loop codes, typically with BLHA (`BlackHat`, `OpenLoops`, `GoSam`, `MCFM`)
- traditionally focussed on S + jets ($S = V, VV, H$)
- enormous progress over last 2 years; in particular:
  - NLO+PS multijet merging (`MEPS@NLO`)
  - thorough assessment of uncertainties

- $pp \to W+$ jets [NLO merging]
- $e^+e^- \to$ jets [NLO merging]
- $pp \to H+$ jets [NLO merging]
- $pp \to t\bar{t}+$ jets [NLO merging]
- $pp \to 4\ell+$ jets [NLO merging]
- $pp \to VH/VV/VVV+$ jets [NLO merging]
- $pp \to t\bar{t}b\bar{b}$ (4f) [NLO+PS]

[Cascioli,Gehrmann,Hoeche,Huang,Krauss,Luisoni,Maierhöfer, Pozzorini,Schoenherr,Siegert,Thompson,Winter,Zapp '13-'14]



NLO matching in Herwig++

- some processes available internally, in POWHEG approach

  [Richardson,Hamilton,d'Errico,Fridman-Rojas,Tully,Wilcock]

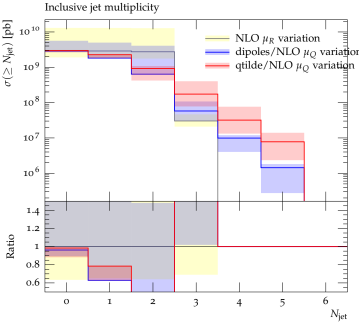
- Matchbox: new standard for NLO+PS within Herwig++ (https://herwig.hepforge.org/)

  [Gieseke,Plätzer;Bellm,Fischer,Rauch,Reuschle,Wilcock,Richardson]

- general and modular framework to do NLO+PS matching within Herwig++:
  - with POWHEG and MC@NLO schemes
  - using angular-ordered or dipole shower
  - focus also on assessment of uncertainties
- recently used to perform state-of-the art NLO computation: $Hjjj$ (VBF)

  [Campanario,Figy,Plätzer,Sjödahl '13]

- currently being interfaced to NLO codes, also via BLHA (GoSam, Njet, VBFNLO, OpenLoops)

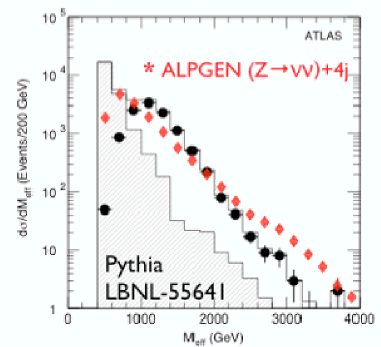


NLO+PS dijets [preliminary]

NLO multijet merging

beyond NLO+PS: multiplicity frontier

- typical background for many BSM signatures is “heavy object” + many jets



[Gianotti,Mangano hep-ph/0504221]

- relying on PS for tail of distributions is very dangerous, especially in a multijet environment

- CKKW(-L) and MLM methods address this issue at LO:

  - merge exact LO matrix elements for different multiplicities

  - very important for observables like H_T
    especially when not possible to use data-driven methods

- suppose LHC finds a small excess in H_T for some SUSY search (*e.g.* $\not{E}_T$ + jets)

  - what is the theoretical uncertainty of backgrounds?

NLO+PS multijet merging

- challenge: extend these methods to NLO ("NLOPS multijet merging"):
  - from one single event sample, have 1-, 2-,...,n-jet observables at NLO

- at NLO it is more complicated, and more subtle:
  - the matrix element $pp \to S + n$ partons enters in
    * Born for "$pp \to S + n$ partons" @ NLO
    * real contribution for "$pp \to S + (n-1)$ partons" @ NLO

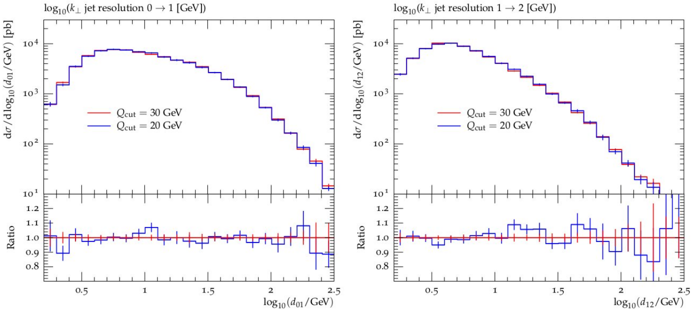
- as is at LO, many of these methods use a merging scale ($Q_{\rm MS}$)
  - a bad choice of merging scale can spoil formal accuracy one might want to claim
    * typically this can happen if $\alpha_{\rm S} \log^2 Q_{\rm MS} \simeq 1$ ($\to L \simeq 1/\sqrt{\alpha_{\rm S}}$)
  - in general, to avoid this problem, one needs not to have $Q_{\rm MS}$ at all, or have a very precise control on formal accuracy of underlying resummation (typically beyond PS), so that even if $\alpha_{\rm S} \log^2 Q_{\rm MS} \simeq 1$, the formal accuracy is not spoiled
  - to which extent this is a serious problem is still an open issue

[Hoeche,Krauss,Schoenherr,Siegert '12]

- proof of concept in e^+e^- and $W+$ jets, applied in several other processes
- share some similarities with "FxFx"

$$
\begin{aligned}
d\sigma &= d\Phi_0 \bar{\mathrm{B}}_0^{(\mathrm{A})} \otimes \tilde{\mathrm{PS}}_{t_{\min}} \Theta(d_1 < Q_{\mathrm{MS}}) \\
&+ d\Phi_1 H_0^{(\mathrm{A})} \Delta_{t_1} \Theta(d_1 < Q_{\mathrm{MS}}) \\
&+ d\Phi_1 \bar{\mathrm{B}}_1^{(\mathrm{A})} \otimes \tilde{\mathrm{PS}}_{t_{\min}}^{t_1} \cdot \text{[corr. factor]} \cdot \Theta(d_1 > Q_{\mathrm{MS}}) \\
&+ d\Phi_2 H_1^{(\mathrm{A})} \Delta_{t_1}^{t_2} \Delta_{t_{\min}}^{t_1} \Theta(d_1 > Q_{\mathrm{MS}})
\end{aligned}
$$

- possible to iterate to higher multiplicities
- residual dependence of total cross section on merging scale $\sim \alpha_S^2 L^3 / N_C^2$



FxFx method

[Frixione,Frederix, '12]

$$
\begin{aligned}
d\bar{\sigma}_{\mathbb{S},0} &= T_0 + V_0 - T_0\mathcal{K} + T_0\mathcal{K}_{\mathrm{MC}}\Theta(d_1 < Q_{\mathrm{MS}}) \\
d\bar{\sigma}_{\mathbb{H},0} &= \Big[T_1 - T_0\mathcal{K}_{\mathrm{MC}}\Big]\Theta(d_1 < Q_{\mathrm{MS}}) \\
d\bar{\sigma}_{\mathbb{S},1} &= \Big[T_1 + V_1 - T_1\mathcal{K} + T_1\mathcal{K}_{\mathrm{MC}}\Big]\Theta(Q_{\mathrm{MS}} < d_1) \\
d\bar{\sigma}_{\mathbb{H},1} &= \Big[T_2 - T_1\mathcal{K}_{\mathrm{MC}}\Big]\Theta(Q_{\mathrm{MS}} < d_1)
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$$

- limit contribution of $(\mathbb{H}, 0)$ events to region below Q_{MS}
- prescriptions for shower starting scale
- possible to include Sudakov reweighting á la CKKW
- “unitarity” not imposed
- possible to iterate

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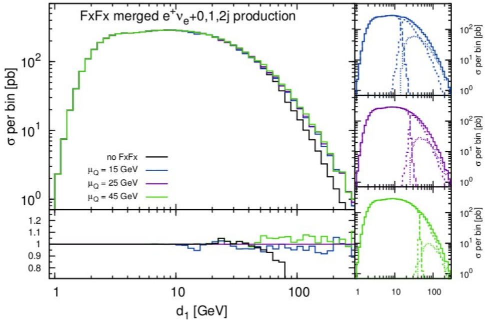

- fully inclusive result:
  - differences typically $\lesssim 1\%$ among different merging scales
  - quite good agreement with inclusive NLO+PS too

UNLOPS

[Lonnblad,Prestel '12 / (very similar approach by Plätzer '12)]

- keyword: "unitarity" (preserve NLO inclusive cross section)
- method: promote to NLO accuracy an "unitarised" CKKW approach, by carefully adding higher order contributions, and removing the pre-existing approximate α_S terms:
  1. start from UMEPS merging at LO

$$\langle \mathcal{O} \rangle = \int d\phi_0 \Big\{ \mathcal{O}(S_{+0j}) \Big(\mathrm{B}_0 + \quad - \int \widehat{\mathrm{B}}_{1\to 0} \quad - \int \widehat{\mathrm{B}}_{2\to 0} \Big) + \int \mathcal{O}(S_{+1j}) \Big(\widehat{\mathrm{B}}_1 \quad - \int \widehat{\mathrm{B}}_{2\to 1} \Big) + \int\!\!\int \mathcal{O}(S_{+2j}) \widehat{\mathrm{B}}_2 \Big\}$$

  2. remove terms that will be included exactly, and add NLO (exclusive) computations
  3. unitarise

$$\langle \mathcal{O} \rangle = \int d\phi_0 \Big\{ \mathcal{O}(S_{+0j}) \Big(\widetilde{\mathrm{B}}_0 - \int_s \widetilde{\mathrm{B}}_{1\to 0} + \int_s \mathrm{B}_{1\to 0} - \Big[\int \widehat{\mathrm{B}}_{1\to 0} \Big]_{-1,2} - \int_s \mathrm{B}^{\uparrow}_{2\to 0} - \int \widehat{\mathrm{B}}_{2\to 0} \Big) + \int \mathcal{O}(S_{+1j}) \Big(\widetilde{\mathrm{B}}_1 + \Big[\widehat{\mathrm{B}}_1 \Big]_{-1,2} - \Big[\int \widehat{\mathrm{B}}_{2\to 1} \Big]_{-2} \Big) + \int\!\!\int \mathcal{O}(S_{+2j}) \widehat{\mathrm{B}}_2 \Big\}$$

- can be iterated to higher multiplicities
- essentially no dependence on merging scale

"Multiscale Improved NLO" [Hamilton,Nason,Oleari,Zanderighi '12]

- original goal: method to a-priori choose scales in multijet NLO computation
  (in a multiscale process, this is not straightforward, in regions with widely-separated scales)
- idea: correct weights of different NLO terms with CKKW-inspired approach
  (without spoiling formal NLO accuracy)

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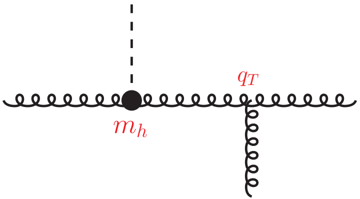
$$\bar{B}_{\rm NLO} = \alpha_{\rm S}^3(\mu_R)\Big[B + \alpha_{\rm S}^{(\rm NLO)} V(\mu_R) + \alpha_{\rm S}^{(\rm NLO)} \int d\Phi_{\rm rad} R\Big]$$



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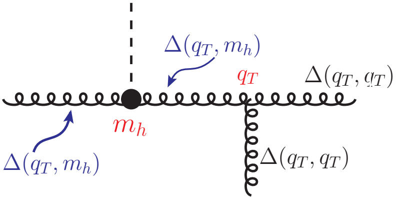
$$\bar{B}_{\rm MiNLO} = \alpha_{\rm S}^2(m_h)\alpha_{\rm S}(q_T)\Delta_g^2(q_T, m_h)\Big[B\left(1 - 2\Delta_g^{(1)}(q_T, m_h)\right) + \alpha_{\rm S}^{\rm (NLO)} V(\bar{\mu}_R) + \alpha_{\rm S}^{\rm (NLO)} \int d\Phi_{\rm rad} R$$



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

☞ finite results if 1st jet unresolved

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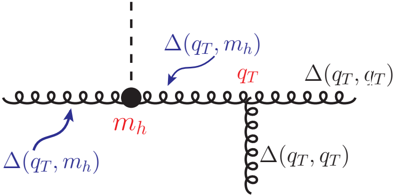
  (without spoiling formal NLO accuracy)

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

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



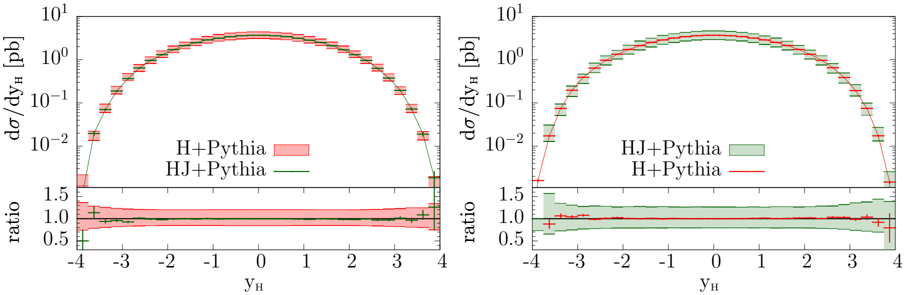
☞ Sudakov FF included on $H{+}j$ Born kinematics

☞ finite results if 1st jet unresolved

- $\bar{B}_{\rm MiNLO}$ ideal to extend validity of $H{+}j$ POWHEG
- including terms from NNLL resummation, NLO+PS merging for 0 and 1-jet, without a merging scale. However: for now not clear how to extend to higher multiplicity

MiNLO merging: results

[Hamilton et al., 1212.4504]



☞ Notice: band is ~ $20 - 30\%$ (typical uncertainty for Higgs production at NLO)

- 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")

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

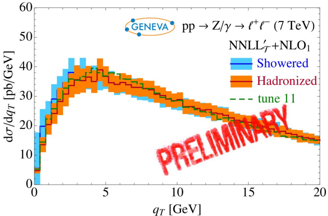
where

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

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

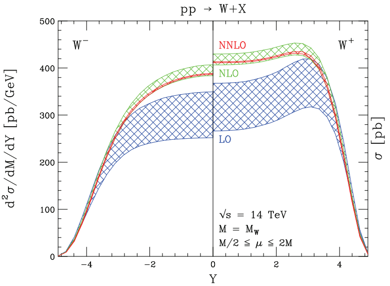
- no "dangerous" merging scale dependence, thanks to higher-order resummation for τ_N
- to retain formal accuracy, PS evolution very constrained: τ_N has to stay ~ unchanged

- can be extended to higher multeplicities
- implemented for e^+e^-, for LHC will be finished soon
  - talks by Alioli and Bauer at "PSR2014" [→link]

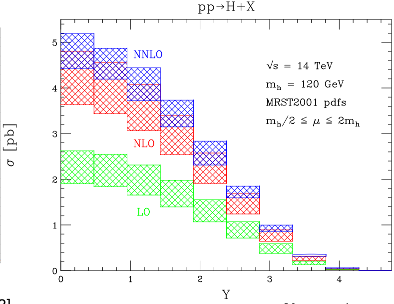


NNLO+PS

- some of the above approaches allow(ed) to achieve NNLO+PS matching!
  - “just” NLO sometimes is not enough
  - NNLO is the frontier [see C. Duhr talk]



[Anastasiou et al., ’03]

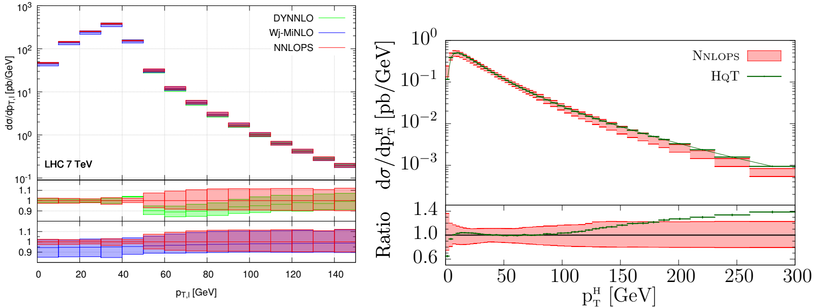


[Anastasiou et al., ’04-’05]

- already relevant: large NLO K-factor (Higgs production), precision Physics (PDF extraction, W-mass measurement), ...
- more and more relevant for Run II and high-luminosity phase

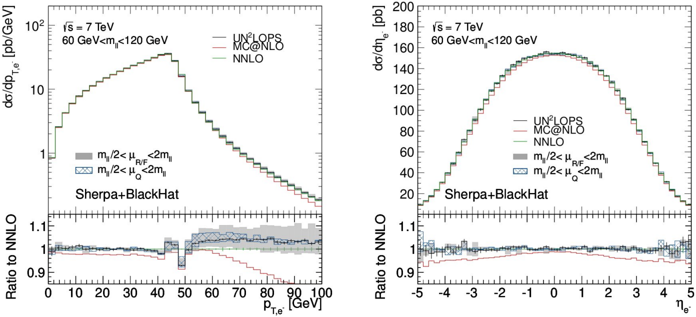
NNLO+PS results

- Higgs [Hamilton,Nason,ER,Zanderighi '13] and Drell-Yan [Karlberg,ER,Zanderighi (soon public)], using MiNLO-improved POWHEG



- charged DY (left): find exactly what we expect: $p_{T,\ell}$ has NNLO uncertainty if $p_T < M_W/2$, NLO if $p_T > M_W/2$
- Higgs p_T (right): good agreement with NNLL+NNLO analytic resummation [HqT, Bozzi et al.]

- Drell-Yan, using UNNLOPS [Hoeche,Li,Prestel '14]



- general framework and preliminary results for Drell-Yan also with Geneva [Alioli,Bauer, et al]

conclusions

- Monte Carlo tools play a major role for LHC searches
- especially if no “smoking gun” new-Physics around the corner, precision will be the key to maximise impact of LHC results
- huge amount of improvements over the last few years in the community
- part of this was possible due to impressive progress in NLO tools (automation), and development of standard interfaces (BLHA) between different codes

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- NLO+PS tools are by now well established and very mature

  - important work still ongoing to tackle subtleties
- major developments in last 2 years: NLOPS multijet merging

  - accurate comparisons will take place, as it was for NLO+PS programs
- NNLO+PS is doable !

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Thank you for your attention!