Matching and Merging

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LAPTh Annecy

MC4BSM 2016, UCAS, Beijing, 20 July 2016

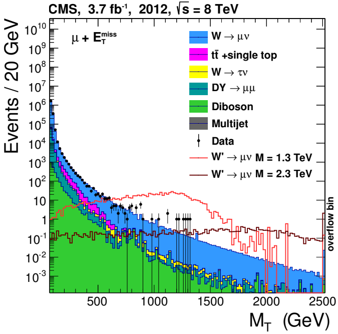
Introduction

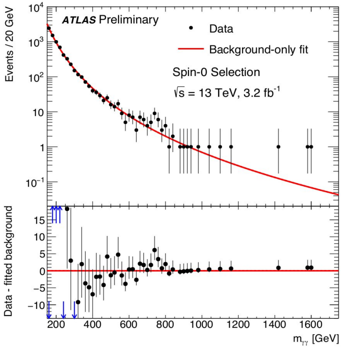
- this talk is about methods aiming at improving the accuracy of "LO" Monte Carlo event generators:
  - ★ when is this really important / needed?
- "matching" and "merging" are the keywords used to identify developments that took place in the last $\sim$ 10 years:
  - ★ overview, with some details, of (some of) these methods
  - not enough time to discuss all possible approaches. I've made a selection.
- event generators: simulate BSM signals and SM backgrounds:
  - so far "matching" and "merging" applied mostly to SM processes:
    - the theory uncertainty of SM predictions is (or will soon be) a limiting factor for "precision Physics", i.e. find a significant deviation from a very precise experimental measure.
  - (part of) current effort is to apply/automatise these methods also to BSM processes. I will show some examples. Some MC developers heavily involved in this task are at this workshop!

- I'm here till Friday evening: any question, don't hesitate!
- if you want to contact me by email: emanuele.re AT lapth.cnrs.fr
- Later today I'll add a slide with a list of references.

- matching and merging: when and why ?

Introduction: bump search



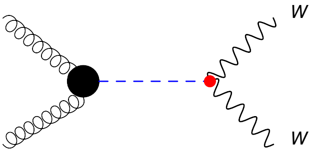


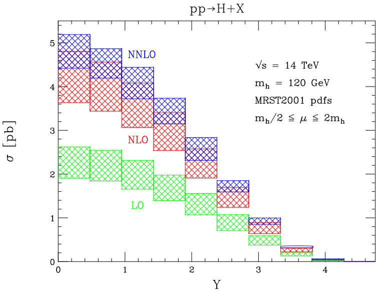
- s-channel resonance "easy" to discover:
  - Higgs discovery in $\gamma\gamma$ and ZZ
  - the "750 GeV diphoton bump"
- for discovery, one needs denough ata (possibly on both side of the bump) and (maybe) a fixed-order (N)LO prediction for the background.
- after discovery, characterization requires more theory input (rates, shapes, jet-binned x-sections), hence also more precise tools:

...let's see this with an example...

Introduction: Higgs characterization

- need to know expected signal events, precisely and with an associated theory uncertainty:
  - higher-order corrections





Introduction: Higgs characterization

- need to know expected signal events, precisely and with an associated theory uncertainty:
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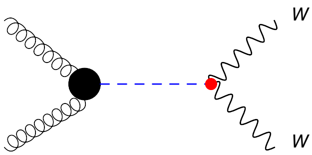
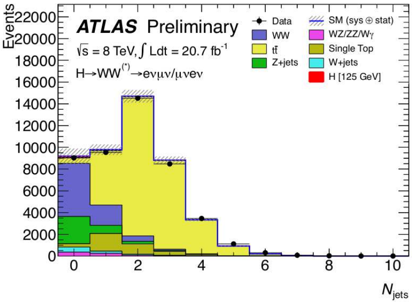
- S/B optimized using cuts/BDT: at times this implies probing phase space regions with widely separated scales:
  - large logs arise, need to resum them. PS do this in a fully differential way.





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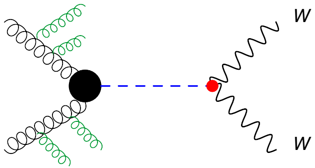

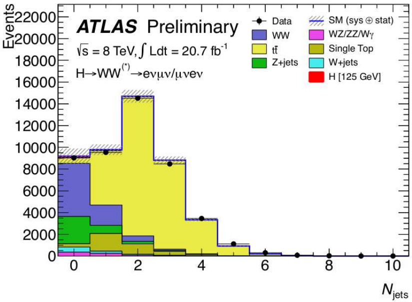

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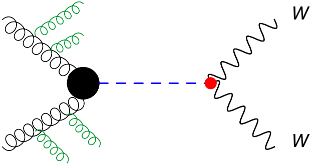

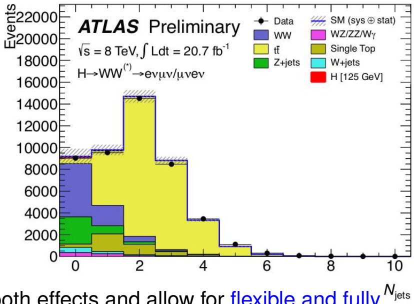

⇒ NLO+PS “matching” methods include both effects and allow for flexible and fully differential simulations.

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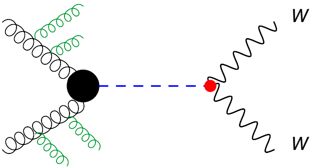
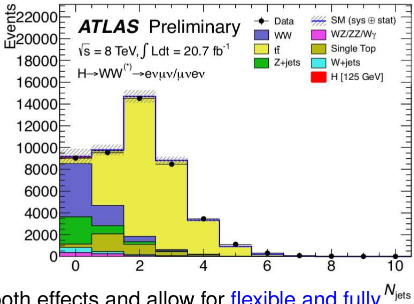




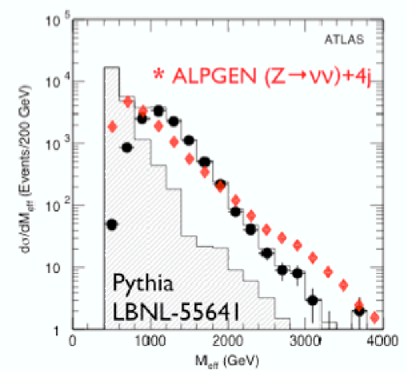
⇒ NLO+PS "matching" methods include both effects and allow for flexible and fully differential simulations.

⇒ for Higgs studies, NNLO+PS would be desirable, and it is available
...to this end merging NLO+PS computations for different multipicities is necessary...

Introduction: excess in p_T tail

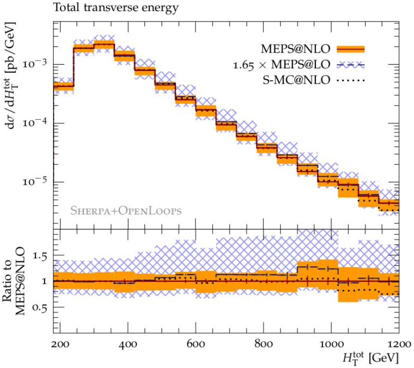
- ME+PS merging is particularly important to model "S+jets" processes, where:
  - S = hard system = $\{\ell, \nu, V, t\}$
  - jets are from QCD emissions (as opposed to jets from SUSY cascades)
- it becomes crucial to model kinematics regions characterized by variable number of jets:
  - cuts on $H_T = ... + \sum_{\text{all jets}} |\vec{p}_{T,j}|$ and/or tails of p_T distributions

LO+PS



plot from [Gianotti,Mangano 0504221]

NLO+PS merging

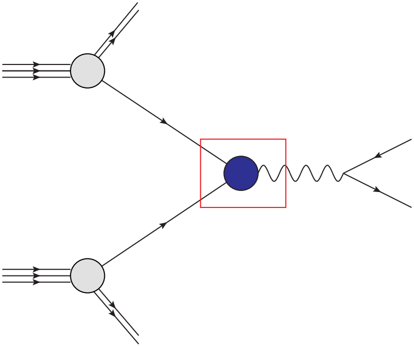


$t\bar{t}$+jets:Sherpa+OpenLoops [Hoeche,Krauss et al. 1402.6293]

- NLO+PS matching

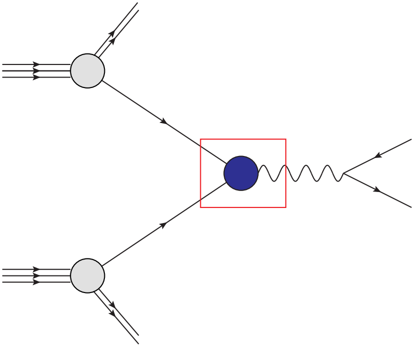
LO+PS in a nutshell

$$d\sigma_{\mathrm{SMC}} = \underbrace{B(\Phi_n)\, d\Phi_n}_{d\sigma_B} \Big\{ \qquad \Big\}$$



LO+PS in a nutshell

$$d\sigma_{\rm SMC} = \underbrace{B(\Phi_n)\, d\Phi_n}_{d\sigma_B} \Big\{ \Delta(t_{\max}, t_0) \qquad\qquad\qquad\qquad \Big\}$$

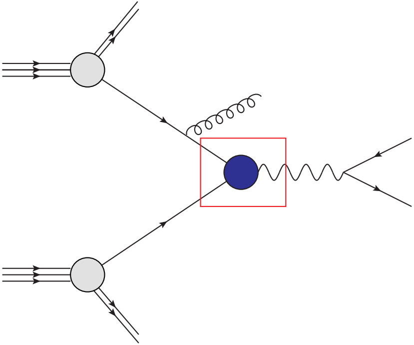


$$\Delta(t_{\max}, t) = \exp\left\{ -\int_t^{t_{\max}} d\Phi'_r \, \frac{\alpha_s}{2\pi} \frac{1}{t'} P(z') \right\}$$

SMC Sudakov form factor

LO+PS in a nutshell

$$d\sigma_{\text{SMC}} = \underbrace{B(\Phi_n)\, d\Phi_n}_{d\sigma_B} \left\{ \Delta(t_{\max}, t_0) + \Delta(t_{\max}, t) d\mathcal{P}_{\text{emis}}(t) \right\}$$



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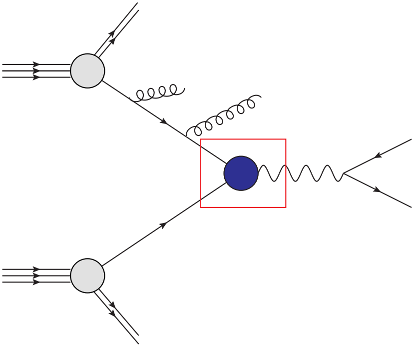

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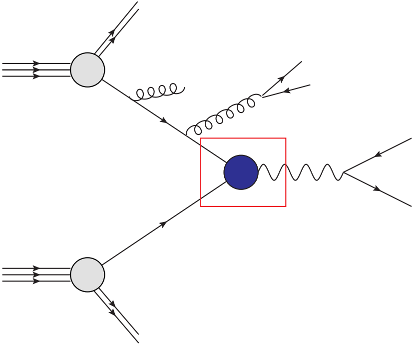

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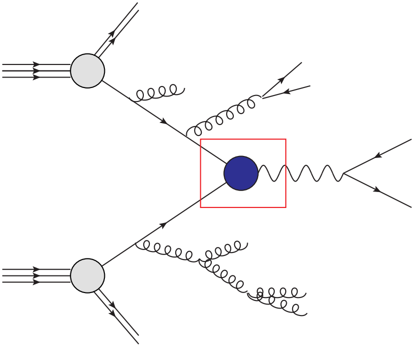

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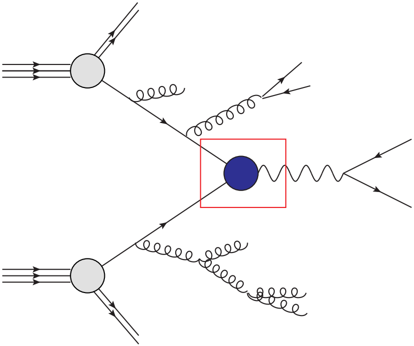

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This is “LOPS”

- shapes change (all-order effect!), but overall normalization fixed: it stays LO (*unitarity*)
- they are only LO+LL accurate (whereas we want (N)NLO QCD corrections)

Next-to-Leading Order in a nutshell

$\alpha_S \sim 0.1 \Rightarrow$ to improve the accuracy, use exact perturbative expansion

$$d\sigma = d\sigma_{\text{LO}} + \left(\frac{\alpha_S}{2\pi}\right) d\sigma_{\text{NLO}} + \left(\frac{\alpha_S}{2\pi}\right)^2 d\sigma_{\text{NNLO}} + \ldots$$

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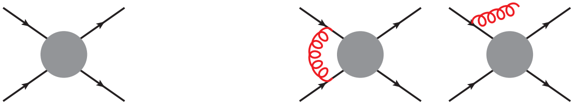

$$d\sigma = d\Phi_n \left\{ \underbrace{B(\Phi_n)}_{\text{LO}} + \frac{\alpha_s}{2\pi} \left[\underbrace{V(\Phi_n) + R(\Phi_{n+1})\, d\Phi_r}_{\text{NLO}} \right] \right\}$$

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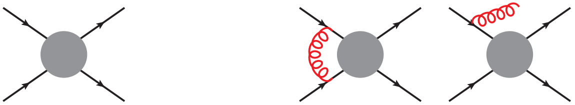

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- in reality, the above equation is implemented as follows:

$$\begin{aligned} d\sigma &= d\Phi_n \Big\{ B(\Phi_n) + \frac{\alpha_s}{2\pi}\Big[V(\Phi_n) + \int d\Phi_r C(\Phi_n, \Phi_r)\Big]\Big\} \\ &+ \frac{\alpha_s}{2\pi} d\Phi_{n+1}\Big[R(\Phi_{n+1}) - C(\Phi_n, \Phi_r)\Big] \end{aligned}$$

where $C(\Phi_n, \Phi_r)$ has the same soft/collinear singular behaviour of R, and it can be integrated explicitly over Φ_r.

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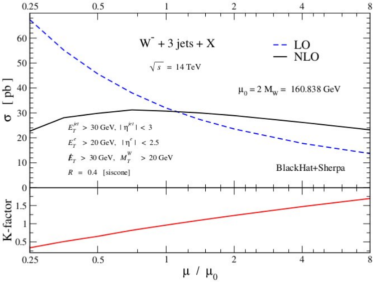
- first order where rates are reliable
- shapes are, in general, better described
- possible to attach sensible theoretical uncertainties [done typically by changing ren. and fac. scales]



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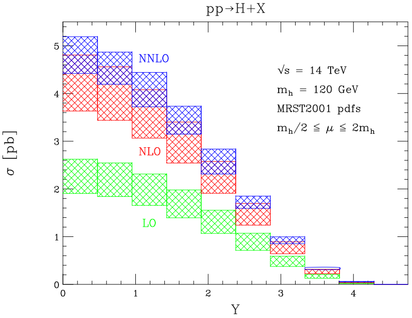
☞ When NNLO is needed?

- NLO corrections large
- very high-precision needed

$\Rightarrow$ Drell-Yan, Higgs, $t\bar{t}$ production



plot from [Anastasiou et al., '03]

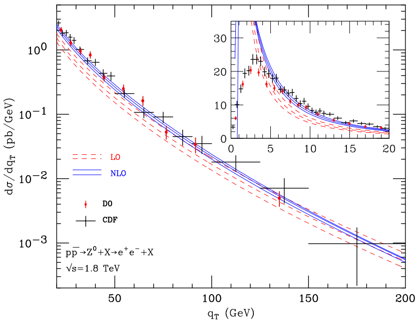
PS vs. NLO

NLO

- ✓ precision
- ✓ nowadays this is the standard
- ✗ limited multiplicity
- ✗ (fail when resummation needed)

parton showers

- ✓ realistic + flexible tools
- ✓ widely used by experimental coll's
- ✗ limited precision (LO)
- ✗ (fail when multiple hard jets)



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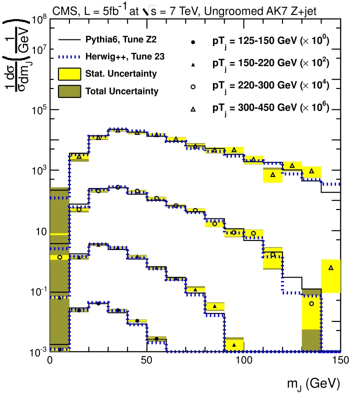

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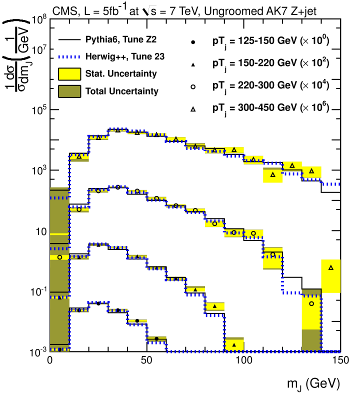

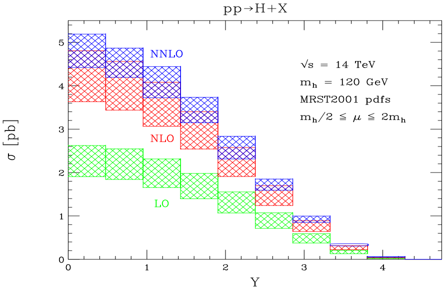

PS vs. NLO

☞ can we match them and build an NLOPS generator?

Problem:

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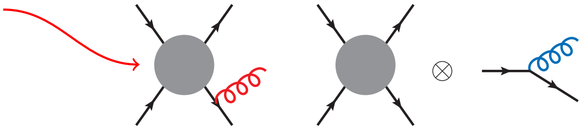
Problem: - overlapping regions!

NLO:



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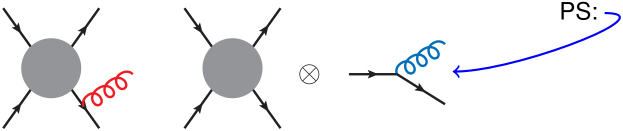

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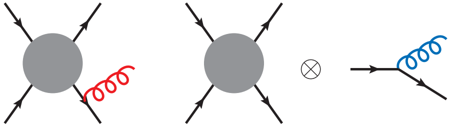

- double-counting also for virtual corrections: first order expansion of Sudakov FF for fully unresolved emission $\Delta(t, t_0)$

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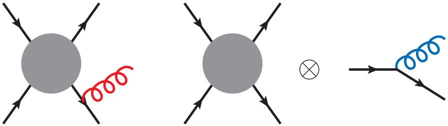

- double-counting also for virtual corrections: first order expansion of Sudakov FF for fully unresolved emission $\Delta(t, t_0)$

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

NLOPS: MC@NLO

$$d\sigma_{\rm LOPS} = d\Phi_n \quad B(\Phi_n) \quad \left\{ \Delta(t_{\rm max}, t_0) + \Delta(t_{\rm max}, t) \frac{\alpha_s}{2\pi} \; \frac{1}{t} P(z) \; d\Phi_r \right\}$$

NLOPS: MC@NLO

$$d\sigma_{\text{MC@NLO}} = d\sigma_{\mathbb{S},n}(\Phi_n) \otimes PS(\Phi_n) \quad + \quad d\sigma_{\mathbb{H},n}(\Phi_{n+1}) \otimes PS(\Phi_{n+1})$$

NLOPS: MC@NLO

$$d\sigma_{\mathbb{S},n} = d\Phi_n \Big\{ B(\Phi_n) + \frac{\alpha_s}{2\pi}\Big[V(\Phi_n) + \int R_{MC}(\Phi_{n+1})\, d\Phi_r \Big] \Big\}$$

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$$R_{MC}\; d\Phi_{n+1} \simeq B(\Phi_n)\frac{1}{t}P(z)\; d\Phi_n\; d\Phi_r$$

NLOPS: MC@NLO

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$$d\sigma_{\mathrm{MC@NLO}} = d\sigma_{\mathbb{S},n}(\Phi_n) \otimes PS(\Phi_n) \quad + \quad d\sigma_{\mathbb{H},n}(\Phi_{n+1}) \otimes PS(\Phi_{n+1})$$

$$d\sigma_{\mathbb{H},n} = d\Phi_{n+1} \frac{\alpha_s}{2\pi} \left[R(\Phi_{n+1}) - R_{MC}(\Phi_{n+1}) \right]$$

$$R_{MC}\, d\Phi_{n+1} \simeq B(\Phi_n) \frac{1}{t} P(z)\, d\Phi_n\, d\Phi_r$$

NLOPS: POWHEG

$$d\sigma_{\mathrm{LOPS}} = d\Phi_n \quad B(\Phi_n) \quad \left\{ \Delta(t_{\max}, t_0) + \Delta(t_{\max}, t) \frac{\alpha_s}{2\pi} \, \frac{1}{t} P(z) \, d\Phi_r \right\}$$

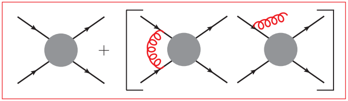
NLOPS: POWHEG

$$d\sigma_{\rm POW} = d\Phi_n \;\; \bar{B}(\Phi_n) \;\; \left\{ \Delta(\Phi_n; k_{\rm T}^{\rm min}) + \Delta(\Phi_n; k_{\rm T}) \frac{\alpha_s}{2\pi} \frac{R(\Phi_n, \Phi_r)}{B(\Phi_n)} \; d\Phi_r \otimes PS(\Phi_{n+1}) \right\}$$

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

NLOPS: POWHEG

$$B(\Phi_n) \Rightarrow \bar{B}(\Phi_n) = B(\Phi_n) + \frac{\alpha_s}{2\pi}\left[V(\Phi_n) + \int R(\Phi_{n+1})\, d\Phi_r\right]$$



$$d\sigma_{\mathrm{POW}} = d\Phi_n \;\; \bar{B}(\Phi_n) \;\; \left\{\Delta(\Phi_n; k_{\mathrm{T}}^{\min}) + \Delta(\Phi_n; k_{\mathrm{T}}) \frac{\alpha_s}{2\pi} \frac{R(\Phi_n, \Phi_r)}{B(\Phi_n)}\, d\Phi_r \otimes PS(\Phi_{n+1})\right\}$$

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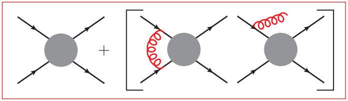

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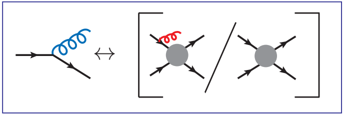
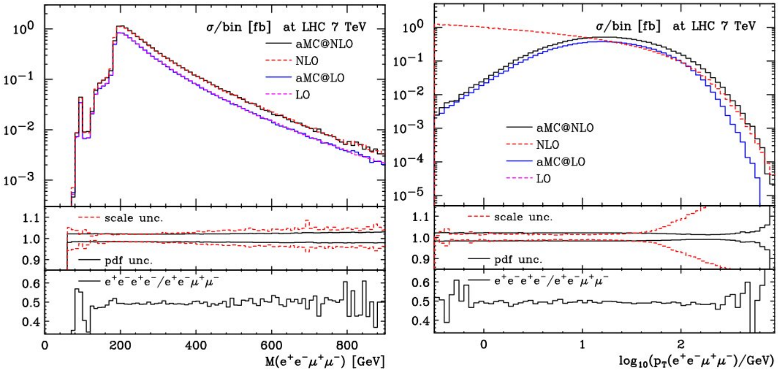


$$\Delta(t_{\mathrm{m}}, t) \Rightarrow \Delta(\Phi_n; k_{\mathrm{T}}) = \exp\left\{-\frac{\alpha_s}{2\pi}\int \frac{R(\Phi_n, \Phi'_r)}{B(\Phi_n)} \theta(k'_{\mathrm{T}} - k_{\mathrm{T}})\, d\Phi'_r\right\}$$

NLOPS: summary



- inclusive observables: @NLO
- first hard emission: full tree level ME
- (N)LL resummation of collinear/soft logs
- extra jets in the shower approximation (LL)

This is “NLOPS”

NLOPS: summary

By now NLO+PS tools are well established:

- POWHEG and MC@NLO usually agree well. When differences arise, they are usually understood, and they are typically due to terms beyond the nominal accuracy.
- NLO+PS is not yet a closed chapter; some important issues are still being addressed
  - $W^+W^-b\bar{b}$ @ NLOPS [Jezo,Nason, et al, this week!]
- in general, however, any process $pp \to X$ can be simulated at NLO+PS accuracy
  - X can contain jets. If it contains N jets, it's 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 methods: Geneva, KrK-NLO

NLOPS: summary

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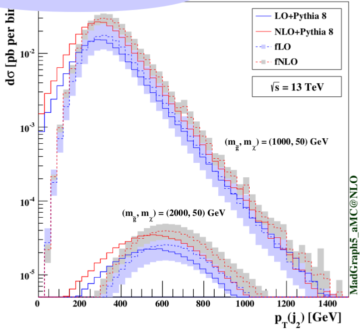
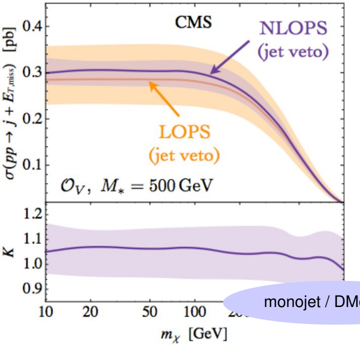
gluino pair production [Degrande,Fuks et al. '15]



[Haisch, Kahlhoefer & ER, 1310.4491]

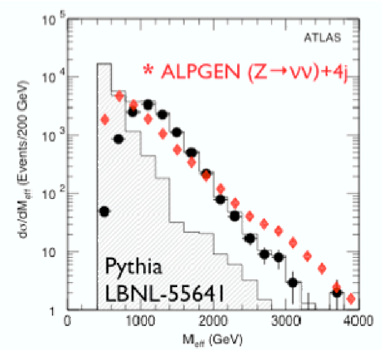


monojet / DM@LHC

- multijet merging [(N)LO+PS merging]

multijet merging

- 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

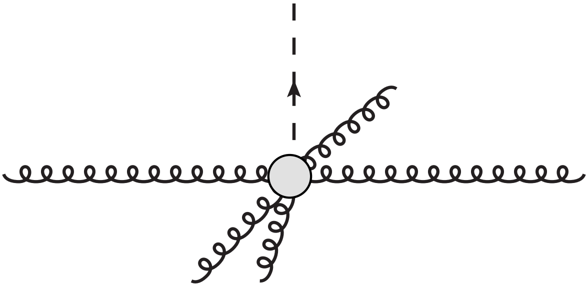
- ME generators: `Alpgen`, `MadGraph`, `Sherpa`
  - for at least one of them (typically both), interface/implementation available in general-purpose parton-shower program

---

- 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?
  - extending merging to NLO becomes important...

multijet merging at LO: CKKW in a nutshell

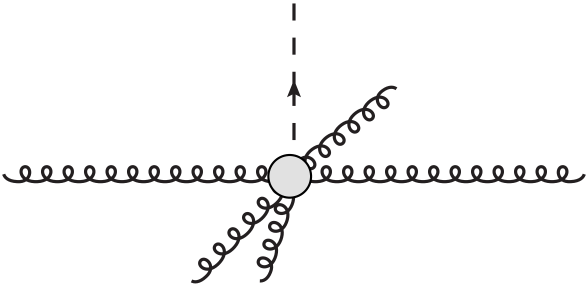
Fix a merging scale Q_{MS}, to separate ME and PS domains.



- start from ME weight $B(\mathbf{\Phi}_n)$, respecting Q_{MS} constraint

multijet merging at LO: CKKW in a nutshell

Fix a merging scale Q_{MS}, to separate ME and PS domains.



- find "most-likely" shower history (via k_T-algo)

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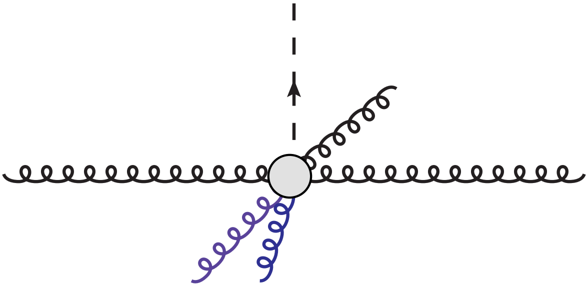

- find “most-likely” shower history (via k_T-algo)
- clustering scale $q_1 = k_T$

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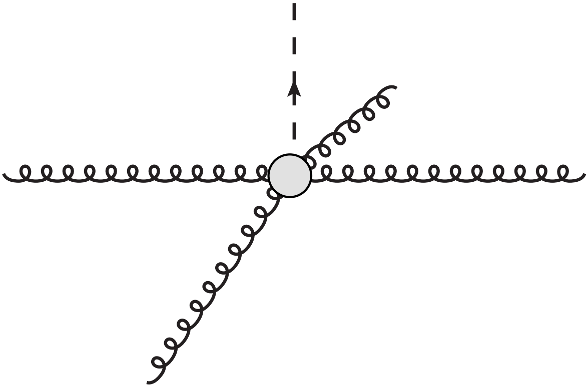

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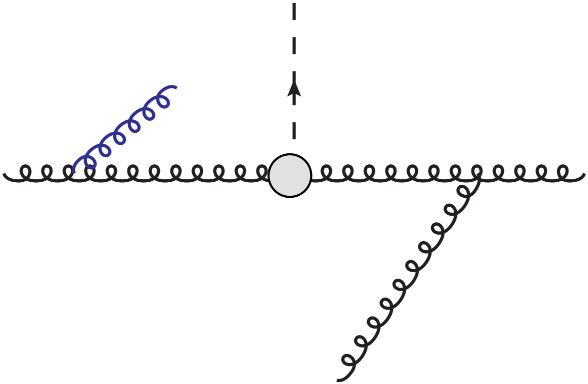
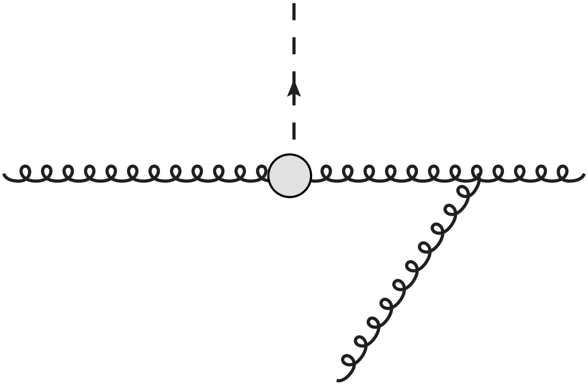


- find "most-likely" shower history (via k_T-algo)
- clustering scale $q_2 = k_T$

multijet merging at LO: CKKW in a nutshell

Fix a merging scale Q_{MS}, to separate ME and PS domains.



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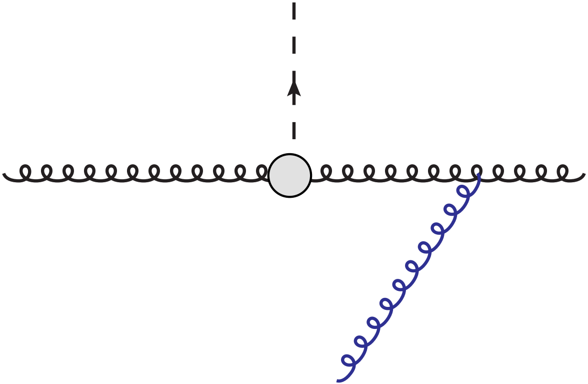
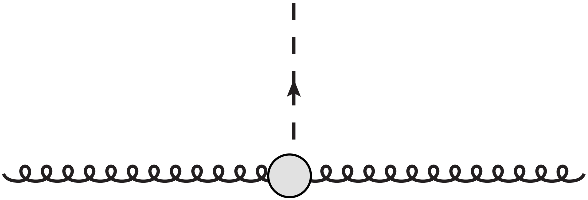


- find "most-likely" shower history (via k_T-algo)
- clustering scale $q_3 = k_T$

multijet merging at LO: CKKW in a nutshell

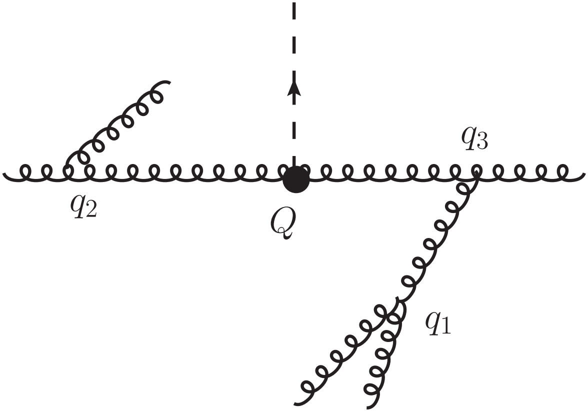
Fix a merging scale Q_{MS}, to separate ME and PS domains.



- Hard process scale Q

multijet merging at LO: CKKW in a nutshell

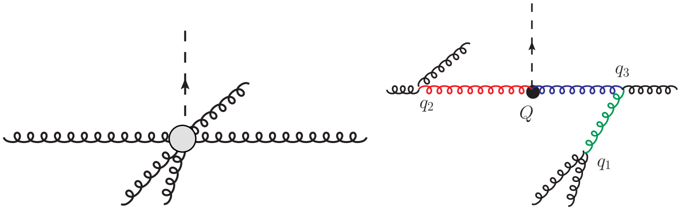
Fix a merging scale $Q_{\rm MS}$, to separate ME and PS domains.



- most-likely shower history

CKKW in a nutshell II

- original weight $B(\mathbf{\Phi}_n) \Rightarrow$ "most-likely" shower history (via k_T-algo): $Q > q_3 > q_2 > q_1$



- New weight:

$$\alpha_S^5(Q)B(\mathbf{\Phi}_3) \quad \rightarrow \quad \alpha_S^2(Q)B(\mathbf{\Phi}_3)\frac{\Delta_g(Q_0,Q)}{\Delta_g(Q_0,q_2)}\frac{\Delta_g(Q_0,Q)}{\Delta_g(Q_0,q_3)}\frac{\Delta_g(Q_0,q_3)}{\Delta_g(Q_0,q_1)}$$
$$\Delta_g(Q_0,q_2)\Delta_g(Q_0,q_2)\Delta_g(Q_0,q_3)\Delta_g(Q_0,q_1)\Delta_g(Q_0,q_1)$$
$$\alpha_S(q_1)\alpha_S(q_2)\alpha_S(q_3)$$

where $Q_0 \equiv Q_{\rm MS}$ and typically

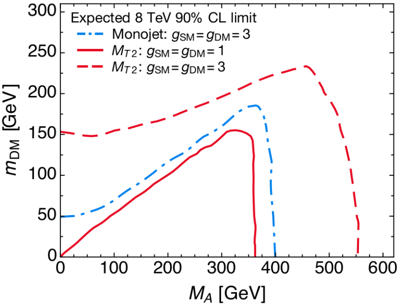
$$\log\Delta_{\rm f}(q_T,Q) = -\int_{q_T^2}^{Q^2}\frac{dq^2}{q^2}\frac{\alpha_S(q^2)}{2\pi}\left[A_{1,\rm f}\log\frac{Q^2}{q^2}+B_{1,\rm f}\right]$$

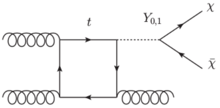
- Fill phase space below Q_0 with vetoed shower
(for highest multiplicity sample $Q_0 = q_1$; PS initial scale should be nodal scale at which parton was "created")

- This procedure guarantees that dependence upon $Q_{\rm MS}$ is beyond NLL (proved for e^+e^-)

LO+PS merging: a BSM example

- DM production at the LHC: scalar/pseudoscalar mediator. Usually: monojet search.
  ☞ these are "QCD" jets !
- analysis based on variable number of jets (H_T based) are potentially very powerful





[Buchmueller,Malik,McCabe,Penning '15]

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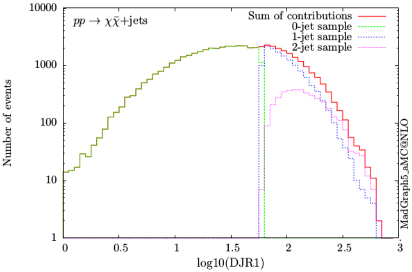

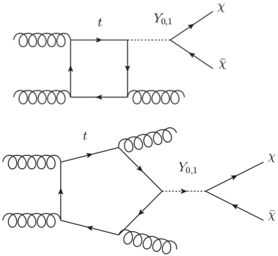

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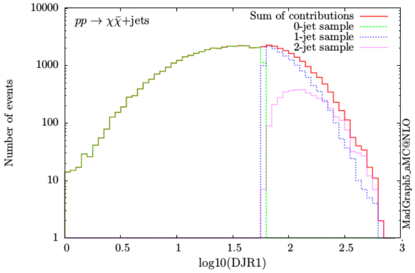

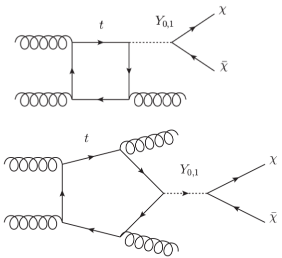

- for loop-induced processes: automation is now available

[Hirschi,Mattelaer '15, Mattelaer,Vryonidou '15 - also earlier studies with Sherpa]

  - the formal accuracy is leading-order
  - theoretical uncertainties will not be in general very small
  - however, shapes will be modelled properly!
- a-priori, dangerous to rely on a description mostly done by parton-shower

multijet merging at NLO

- 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`, `Vincia`

- 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

---

- for simple processes (color-singlet production), the development of these techniques lead to match PS with NNLO computations (NNLO+PS)

“FxFx” method

[Frixione,Frederix, ’12]

$$
\begin{aligned}
d\bar{\sigma}_{\mathbb{S},0} &= B_0 + V_0 + B_0\mathcal{K}_{\rm MC}\Theta(d_1 < Q_{\rm MS}) \\
d\bar{\sigma}_{\mathbb{H},0} &= \Big[B_1 - B_0\mathcal{K}_{\rm MC}\Big]\Theta(d_1 < Q_{\rm MS}) \\
d\bar{\sigma}_{\mathbb{S},1} &= \Big[B_1 + V_1 + B_1\mathcal{K}_{\rm MC}\Big]\Theta(Q_{\rm MS} < d_1) \\
d\bar{\sigma}_{\mathbb{H},1} &= \Big[B_2 - B_1\mathcal{K}_{\rm MC}\Big]\Theta(Q_{\rm MS} < d_1)
\end{aligned}
$$

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

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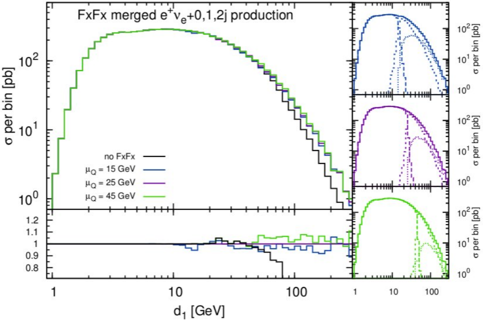

- fully inclusive result:

  - differences typically $\lesssim 1\%$ among different merging scales

  - quite good agreement with inclusive NLO+PS too

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\end{aligned}
$$

- 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

- when Sudakov reweighting applied:

$$
\begin{aligned}
d\hat{\sigma}_{\mathbb{S},1} &= \left(d\bar{\sigma}_{\mathbb{S},1} + d\sigma_1^{(\Delta)}\right)\Delta(\Phi_1 \to \Phi_0) \\
d\hat{\sigma}_{\mathbb{H},1} &= d\bar{\sigma}_{\mathbb{H},1}\,\Delta(\Phi_1 \to \Phi_0)
\end{aligned}
$$

where

$$
d\sigma_1^{(\Delta)} = -B_1\Delta^{(1)}(\Phi_1 \to \Phi_0),
$$

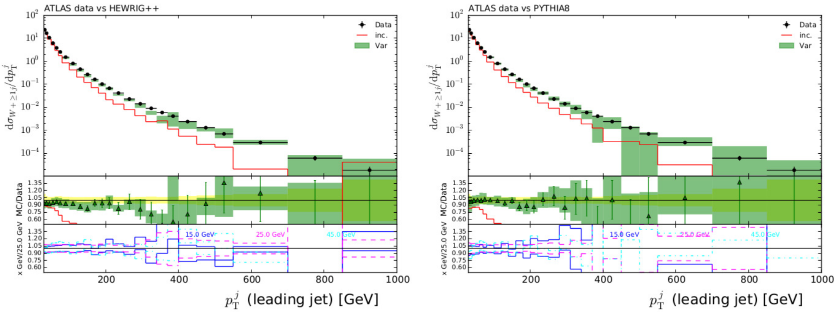
Δ are CKKW Sudakov factors, and $\Delta^{(1)}$ is the Sudakov expanded at 1st order.

- Above Q_{MS} the tail is NLO accurate. For not-too-small Q_{MS}, the integral is NLO accurate.
- merging NLO+PS for V production with $\texttt{MINLO}$ for $V+1$ jet, at “merging scale” Q_{MS}.

MadGrapg5_aMC@NLO: FxFx merging

★ V + 0,1,2,(3,4) jets: 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

MadGrapg5_aMC@NLO: FxFx merging

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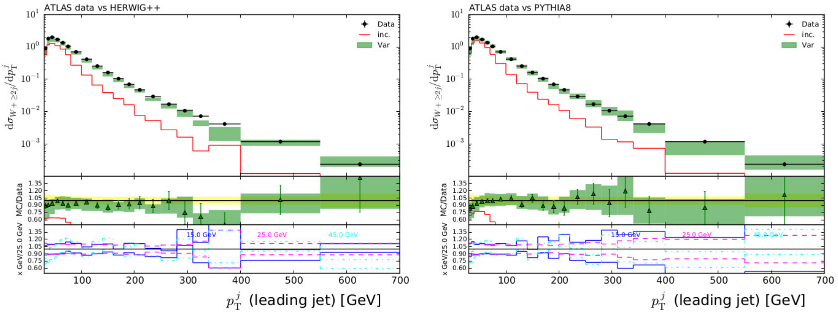

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Sherpa: MEPS@NLO

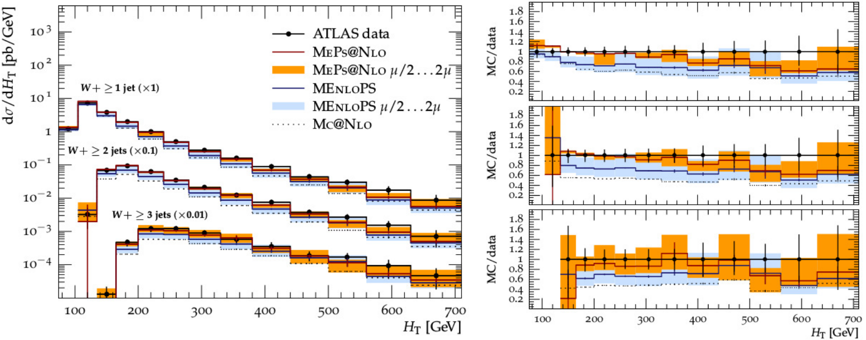
- similar to FxFx: generate MC@NLO samples, and separate their domain of validity using merging scale $Q_{\rm MS}$
- $d\Phi_{n+1}$ receives contribution from H_n-events below $Q_{\rm MS}$ and from S_{n+1} above $Q_{\rm MS}$
- procedure can be iterated

Uncertainties

- μ_R and μ_F scale variation
- shower (“resummation”) scale: upper limit of parton evolution
- merging scale

★ V + 0,1,2,(3,4) jets

[Hoeche,Krauss,Schoenherr,Siegert ’12]



MiNLO

Multiscale Improved NLO

[Hamilton,Nason,Zanderighi ’12]

- original goal: method to a-priori choose scales in multijet NLO computation
- non-trivial task, since phase space is by construction probed also in presence of widely separated energy scales

MiNLO

Multiscale Improved NLO

[Hamilton,Nason,Zanderighi '12]

- original goal: method to a-priori choose scales in multijet NLO computation
- how: correct weights of different NLO terms with CKKW-inspired approach (without spoiling formal NLO accuracy)
  - for each point sampled, build the "more-likely" shower history that would have produced that kinematics (can be done by clustering kinematics with k_T-algo, then, by undoing the clustering, build "skeleton")
  - "correct" original NLO à la CKKW:

    $\rightarrow$ α_S evaluated at nodal scales

    $\rightarrow$ Sudakov FFs

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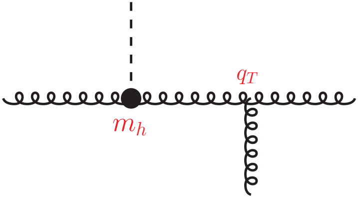
- how: correct weights of different NLO terms with CKKW-inspired approach (without spoiling formal NLO accuracy)

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



MiNLO

Multiscale Improved NLO

[Hamilton,Nason,Zanderighi '12]

- original goal: method to a-priori choose scales in multijet NLO computation
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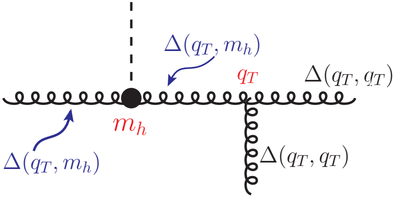

- $\bar{\mu}_R = (m_h^2 q_T)^{1/3}$
- $\log \Delta_{\mathrm{f}}(q_T, m_h) = -\int_{q_T^2}^{m_h^2} \frac{dq^2}{q^2} \frac{\alpha_{\mathrm{S}}(q^2)}{2\pi}\left[A_f \log \frac{m_h^2}{q^2} + B_f\right]$
- $\Delta_{\mathrm{f}}^{(1)}(q_T, m_h) = -\frac{\alpha_{\mathrm{S}}}{2\pi}\left[\frac{1}{2} A_{1,\mathrm{f}}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

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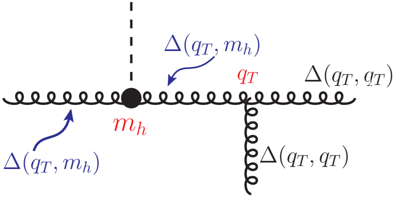

☞ Sudakov FF included on $H+j$ Born kinematics

- 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
- to reach genuine NLO when fully inclusive (NLO$^{(0)}$), “spurious” terms must be of relative order α_S^2, *i.e.*

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

- “Original `MiNLO`” contains ambiguous “$\mathcal{O}(\alpha_S^{2+1.5})$” terms

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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).

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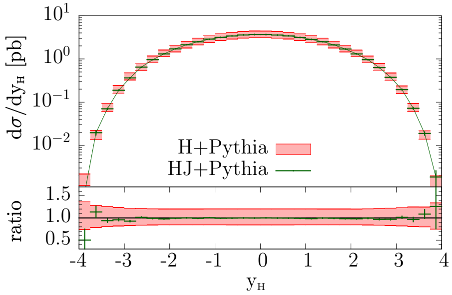
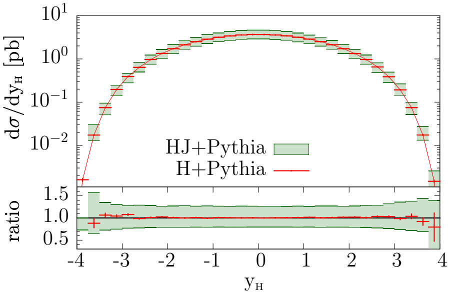
Effectively as if we merged NLO$^{(0)}$ and NLO$^{(1)}$ samples, without merging different samples (no merging scale used: there is just one sample).

- these terms are process dependent, and not known analytically for complex processes:
  for non-color-singlet production, possible to effectively extract them numerically [Frederix,Hamilton ’15]

MiNLO merging: results

[Hamilton et al., 1212.4504]





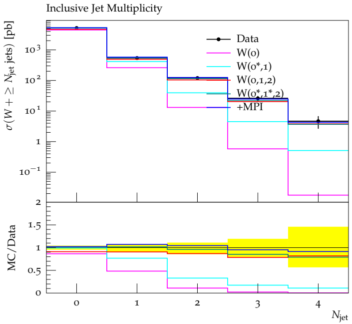
- "H+Pythia": standalone POWHEG ($gg \to H$) + PYTHIA (PS level) [7pts band, $\mu = m_H$]
- "HJ+Pythia": HJ–MiNLO* + PYTHIA (PS level) [7pts band, μ from MiNLO]

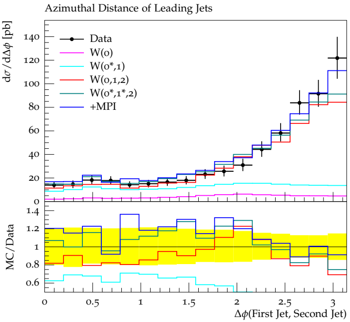
- very good agreement (both value and band) [✓]

☞ Notice: band is $\sim 20 - 30\%$...this is Higgs at NLO!

UNLOPS

- keyword: “unitarity” (preserve NLO inclusive cross section) [Lonnblad,Prestel ’12 , Platzer ’12]
- 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
    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
- full exploitation will also be the main focus in `Herwig 7` in the near future [Platzer et al.]





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")

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

where

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

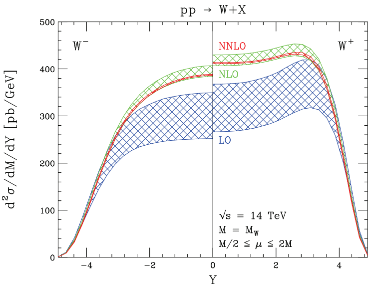
$$\frac{d\sigma}{d\Phi_{N+1}}(\mathcal{T}_N) = \frac{d\sigma^{\rm FO}}{d\Phi_{N+1}}(\mathcal{T}_N)\left[\frac{d\sigma^{\rm resum}}{d\Phi_N d\mathcal{T}_N} \Big/ \frac{d\sigma^{\rm resum}}{d\Phi_N\, d\mathcal{T}_N}\Big|_{\rm FO}\right],$$

- 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 $\sim$ unchanged
- can be extended to higher multiplicities

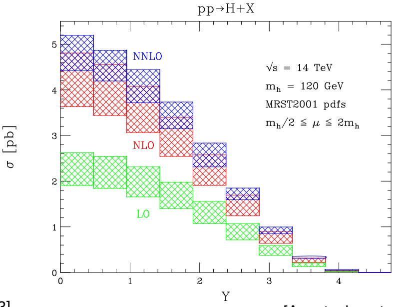
- implemented for e^+e^- and for Drell-Yan
- the method was also formulated to achieve NNLO+PS accuracy (results shown later)

NNLO+PS

- some of the above approaches allow(ed) to achieve NNLO+PS matching!
  - “just” NLO sometimes is not enough
  - NNLO is the frontier



[Anastasiou et al., ’03]

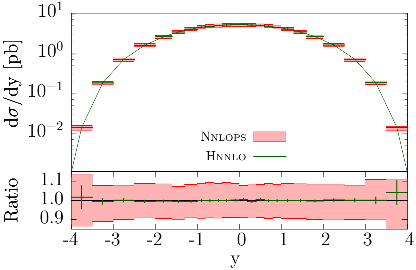


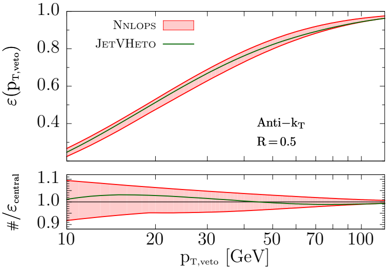
[Anastasiou et al., ’04-’05]

- these developments don’t have an immediate application for direct BSM searches
- however important for “indirect searches”, through precise measurements of SM and Higgs processes:
  - large NLO K-factors (Higgs production → Higgs characterization)
  - precision Physics (PDF extraction, W-mass measurement)

NNLO+PS Higgs production [POWHEG+MiNLO]

[Hamilton,Nason,ER,Zanderighi, 1309.0017]

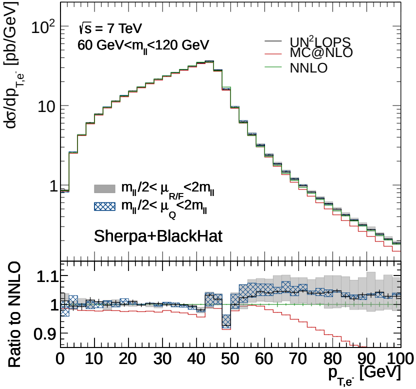


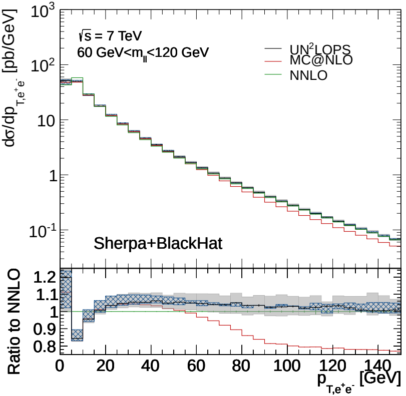


- uncertainty band is 10% (at NLO it was $\sim$ 20-30% !)
- nice agreement also with NNLL jet-veto resummed result, differences never more than 5-6%

NNLO+PS Drell-Yan [UNNLOPS]

- NNLOPS obtained also upgrading `UNLOPS` to `UNNLOPS` [Hoeche,Li,Prestel '14]





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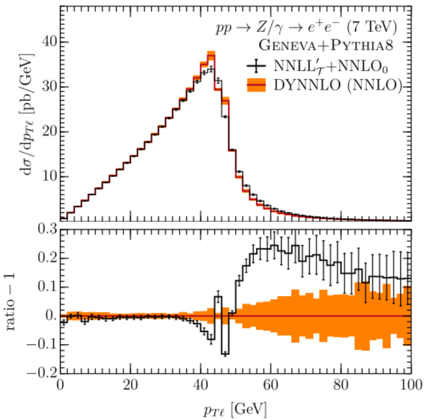
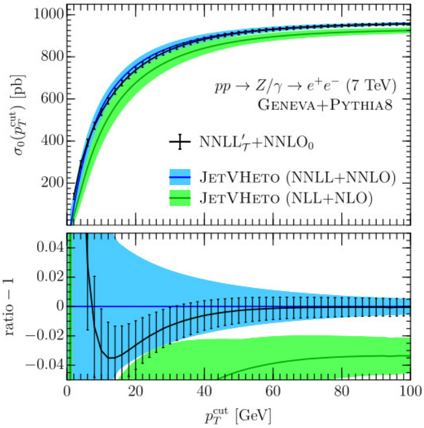
[Alioli,Bauer,Berggren,Tackmann,Walsh, ’15]





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

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

  - by now they are basically automated also for BSM processes

- major developments in last 3-4 years: NLOPS multijet merging

  - it might play a very important role in absence of smoking-gun BSM signal

- NNLO+PS is doable, at least for color-singlet production.

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Thank you for your attention!

Extra slides

“Improved” MiNLO & NLOPS merging: details

- Resummation formula

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

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

- If $C_{ij}^{(1)}$ included and R_f is LO$^{(1)}$, then upon integration we get NLO$^{(0)}$
- Take derivative, 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> $\mathcal{O}(\alpha_S^{3/2})$