Overview on Montecarlo event generators

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Outline

- brief overview
- recent results: non-perturbative regime
- recent results: perturbative regime
- conclusions and outlook

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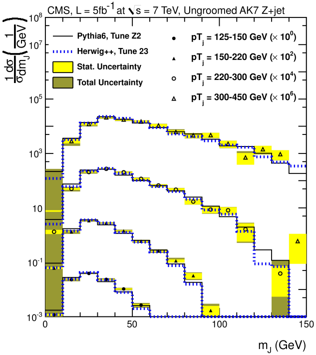
☞ any improvement is likely to play a role for LHC Physics in Run II and beyond
e.g.: think about the impact that `MC@NLO` and `POWHEG` had during LHC Run I

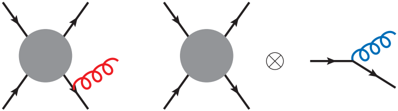
Event generators: generalities

- aim: fully differential and fully realistic description of high energy hadron collisions
  - fixed order & resummation: more accurate, but not fully differential
  - MC needed to estimate detector effects
  - MC needed to validate analysis
  - MC needed for analysis based on NN / BDT
  - MC very often required to compare with (extrapolate from) data with acceptance cuts
  - (so far) heavily used to study jet-substructure techniques
  - contamination of UE into purely perturbative jet predictions (or develop methods to reduce it!)
  - ...
- guiding principle: stages characterized by very different typical energy scales treated separately
  - clearly an approximation, although well motivated (and needed in practice)
  - I'll stick to the standard convention and separate "perturbative" from "non-perturbative"

perturbative regime [“hard scattering”, “parton shower”]

- allow to start from first-principles
- current progress: improve accuracy (thereby reducing theoretical uncertainties)
  - include higher order effects [from NLO & from resummation]
  - include subleading effects in PS (treating more precisely effects usually described (semi)-classically)
- key is consistency: the “less accurate” approach (that we want to improve) already includes an approximation of the terms we include exactly.
  - example: “double counting” in NLO+PS matching

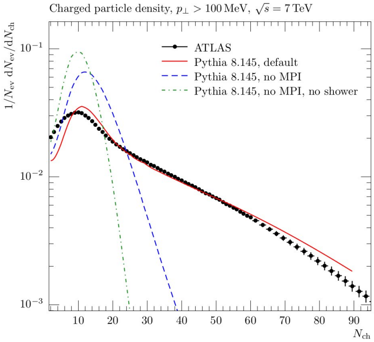




Event generators: generalities

non-perturbative regime [“hadronisation”, “UE/MPI”]

- “elementary” quantities, easily accesible, impossible to describe using just “factorisation” in pQCD
- need of models, built upon qualitative understanding of strong dynamics
- model ↔ parameters ↔ tune
- MPI modelling important for UE in Run II (e.g. additional “mini-jet” activity)
- interplay MPI-hadronisation, color reconnections (e.g. source of uncertainty to top-mass extraction)



Event generators: general purpose programs

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

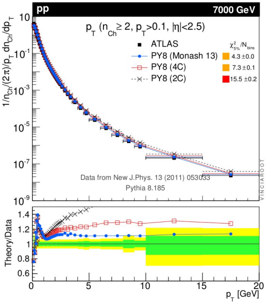
- "Workhorses" Monte Carlo programs currently used for LHC Physics: `Pythia8`, `Herwig++`, `Sherpa`
  - based on factorisation of QCD amplitudes
  - accuracy: LO, LL, leading colour (planar)
  - some NLL/subleading colour effects included
  - differences in PS details (in particular ordering), alhough all have same nominal accuracy
  - different models for hadronisation and MPI/UE

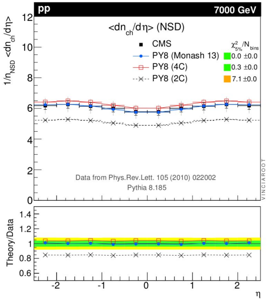
- will discuss selection of improvements upon this picture:
  - only LHC pp collisions, no MC's for heavy-ions
  - left out EW effects [Yost,Ward (HERWIRI)] [Christiansen,Sjöstrand '14] [Krauss,Petrov et al '14] [Gieseke,Kasprzik,Kühn, '14]
  - left out progress for BSM simulation (although `Madgraph5` is now incorporated into `MG5_aMC@NLO`)
  - apologise for other omissions !

hadronisation, MPI, UE

- UE: in a hard collisions, all activity not directly related to hard scattering
- UE is not just non-perturbative: MPI hard perturbative tail is simulated using QCD $2 \to 2$
- soft inclusive events (sometimes called “minimum bias”) also need MPI to be described (really NP here, model needed)

- Pythia: MPI model interleaved with p_T-ordered PS + min-bias via dampening
  new tune: “Monash 13” [Skands,Carrazza,Rojo ’14]
- Sherpa: MPI model independent from hard process + min-bias via dampening
  SHRiMPS: unique model for non-diffractive, single-diffractive and double-diffractive events
  [Hoeche;Hoeth,Khoze,Krauss, Martin,Ryskin,Zapp]
- Herwig++: MPI model independent from hard process + min-bias via “hot-spot” model
  [Baehr,Gieseke,Roehr,Seymour,Siodmok]



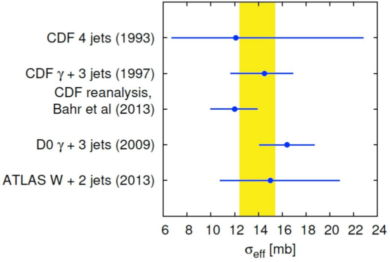


double parton scattering: MC predictions vs. direct measure

- effective x-section for double parton scattering:

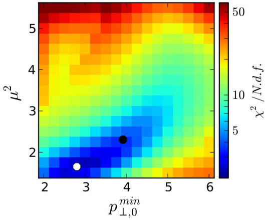
$$\sigma_{ab} = \frac{\sigma_a \sigma_b}{\sigma_{\text{eff}}}$$

- a tuned MPI model gives a prediction for σ_{eff}
  $\hookrightarrow$ all MC models give $20 - 30$ mb: disagreement with measured value 13.9 ± 1.5 mb
- possible to re-tune taking into account this constrain too?



- addressed carefully within `Herwig++` [Seymour,Siodmok '13]
- affect directly μ^2 parameter associated to "inverse proton radius": by describing σ_{eff}, break degeneracy among MPI parameters $(\mu^2, p_{T,0}^{\text{min}})$.

$$p_T^{\text{min}}(s) = p_{T,0}^{\text{min}} \left(\frac{\sqrt{s}}{E_0} \right)^b \qquad [E_0 = 7 \text{ TeV}]$$



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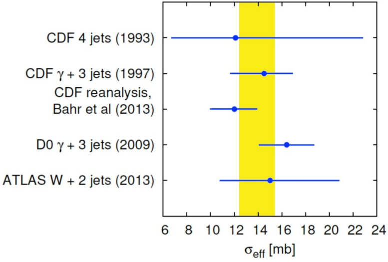

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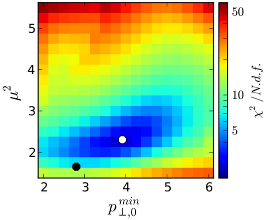

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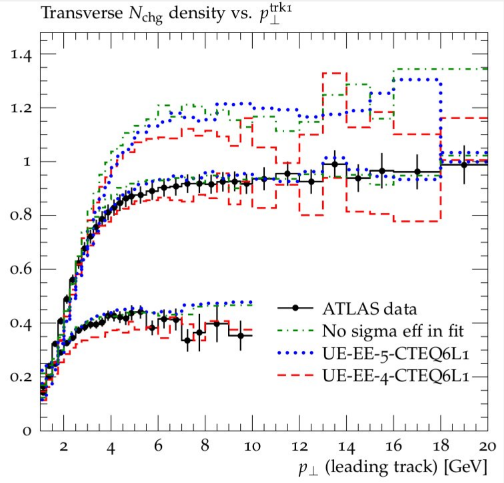
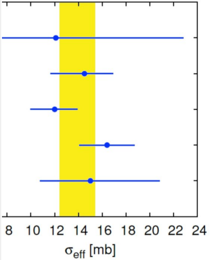
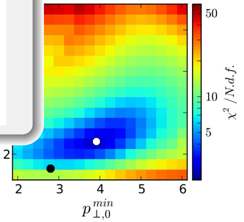




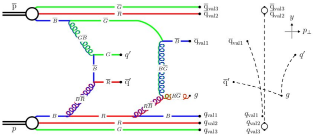


$$p_T^{min}(s) = p_{T,0}^{min}\left(\frac{\sqrt{s}}{E_0}\right) \qquad [E_0 = 7\ \text{TeV}]$$

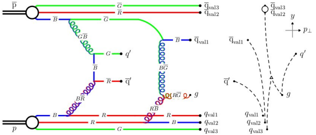
✓ kept good description of data

Color Reconnections

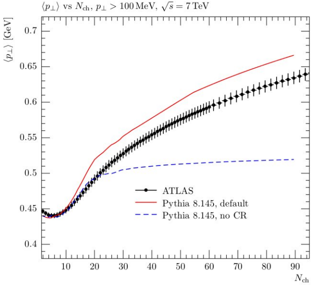
- models of hadronisation need to know color of partons: kept track of in planar approximation
- how is colour neutralized between different scatterings (and beam remnants)?
- even after dealing with ambiguities: color-connected systems typically lie at very different y:
  $\Rightarrow$ large invariant masses (with low p_T)
  $\Rightarrow$ too many (soft) particle are produced !



same color, same kinematics, different color flows !



- Need for "color reconnections" before hadronisation:
  - assume that hard jets from separate hard scatters have to be color connected if close in momentum space
  - generate clusters with smaller invariant mass (or shorter Lund strings) wrt strict color topology
- All MCs have one (or more) model for CR



Color reconnections and uncertainty on the top mass

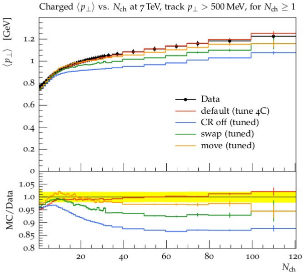
- precise extraction of top-mass is a hot-topic (and will possibly be more and more relevant in Run II)

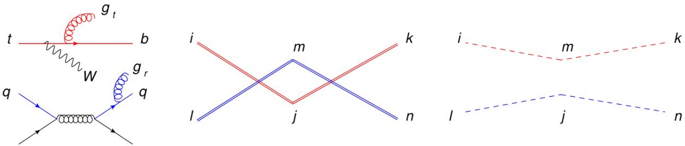
$$\mathcal{O}^{\text{exp}}(\{Q^2\}) = \mathcal{O}^{\text{th}}(m_t, \{Q^2\})$$

- when "traditional methods" are used, CR is among the dominant sources of uncertainty
- "uncertainty" typically estimated varying CR models

[Argyropoulos,Sjöstrand '14]

- PYTHIA8 current CR model doesn't directly affect top decay products
- $\delta_{m_t} \simeq m_{\text{top}}^{\text{CR}} - m_{\text{top}}^{\text{no-CR}}$ not realistic (CR needed to describe min-bias data!)
- dedicated study: $\delta_{m_t} \simeq \mathcal{O}(500 - 800)$ GeV
  - possible to gain precision by looking into "low-energy" stage
  - typical distributions in $t\bar{t}$ events can also be used to narrow down consistent CR model





Parton showers

PS: general overview & recent studies

- PS important: to resum soft/collinear logs, but also to perturbatively fragment partons (needed for hadronisation !)
- different choices ⇒ subleading effects

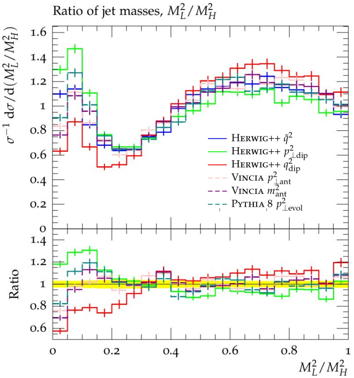
PS	construction	recoil
PYTHIA	DGLAP	local
HERWIG++ (angular)	DGLAP	global
HERWIG++ (dipole)	CS dipoles	local
Sherpa	CS dipoles	local
ARIADNE	antenna	local
VINCIA	antenna	local
Krk	DGLAP	global
DEDUCTOR ($n \to n+1$)	Nagy-Soper	local

- try to expose differences

- study radiation patterns in $e^+e^- \to 4$ jets

[Fischer,Gieseke,Plätzer,Skands, '14]

- several shower models, all tuned on same set of data, ME corrections switched off



- events where $y_{23} \sim y_{34}$
- ratio of jet masses (after recombining to 2-jets)
- strong ordering suppressed ↔ effective "$1 \to 3$" splittings exposed (when close to 0)

PS: beyond planar approximation

- PS are based on planar approximation (+ colour coherence), i.e. they potentially miss genuine effects formally $\mathcal{O}(10)\%$
- at first sight, this is not that small: to quantify, need to compare planar approximation against a more acurate (ideally complete) formulation

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- for quantities affected mostly by hard radiation, can expect that `MC@NLO` and `POWHEG` will capture some of these effects (via inclusion of exact full NLO)

- going beyond requires to include amplitudes into the PS machinery
- normal dipole shower

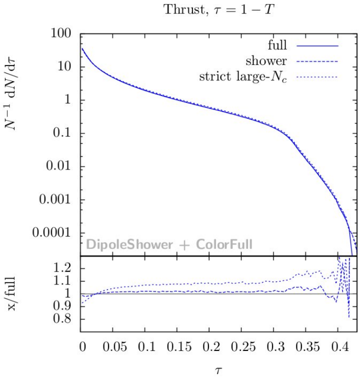
$$dP_{ij,k} \simeq \frac{\alpha_S}{2\pi}\frac{dp_T^2}{p_T^2}dz V_{ij,k}(p_T^2,z)$$

- generalize to [Platzer,Sjodahl, '12]

$$dP_{ij,k} \simeq \frac{\alpha_S}{2\pi}\frac{dp_T^2}{p_T^2}dz V_{ij,k}(p_T^2,z)\frac{-1}{\mathbf{T}_{\tilde{ij}}^2}\frac{\langle\mathcal{M}_n|\,\mathbf{T}_{\tilde{ij}}\cdot\mathbf{T}_k\,|\mathcal{M}_n\rangle}{|\mathcal{M}_n|^2}$$

where now, in step $n \to n+1$, allow any parton to radiate

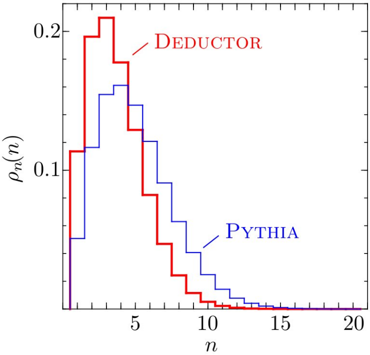
- iterate (so far tried up to 6 emissions)

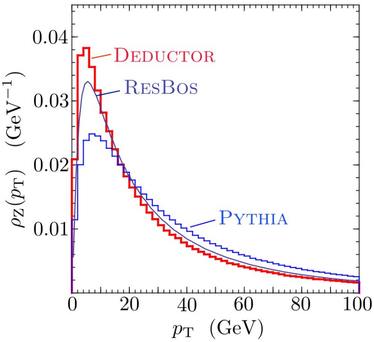


PS: towards quantum interference

[Nagy,Soper, '05 -]

- aim is to take into account quantum interference also in PS
- idea: use quantum density matrix in color and spin space, and evolve that
- DEDUCTOR: so far average over spins, but already allows off-diagonal color states
- can start shower using color-ordered amplitudes in hard scattering
- Begun extensive validation + comparisons with analytic resummation and other PS programs





[Nagy,Soper, '14]

Hard scattering

- NLO matching
- NLO merging

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], 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:
    - Vincia (also NLOPS merging, e^+e^-) [Skands,Giele,Hartgring,Kosower, et al, '08 -]
    - HEJ (so far only tree-level ME) [Andersen,Hapola,Smillie '11 -]
    - Geneva (also NLOPS merging) [Alioli,Bauer, et al '12 -]
    - KrkNLO [Jadach,Placzek,Sapeta,Siodmok,Skrzypek '14 -]

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)

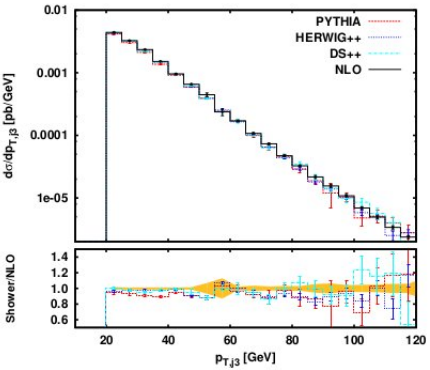
- top pairs: $t\bar{t}$, $t\bar{t}j$, $t\bar{t}H$, $t\bar{t}V$, $t\bar{t}b\bar{b}$, $W^+W^-b\bar{b}$

- 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 [Campbell,Ellis, Nason,ER, in progress]

NLO matching (POWHEG)

$pp \to Hjjj$ (VBF)

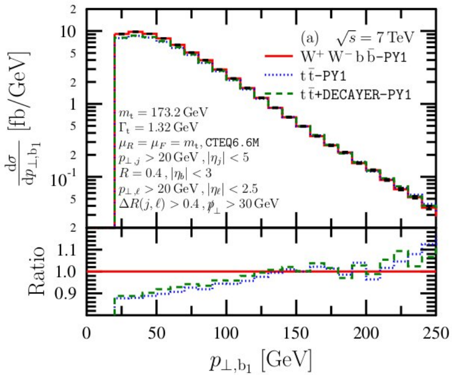
[Jäger,Schissler,Zeppenfeld '14]



- 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)

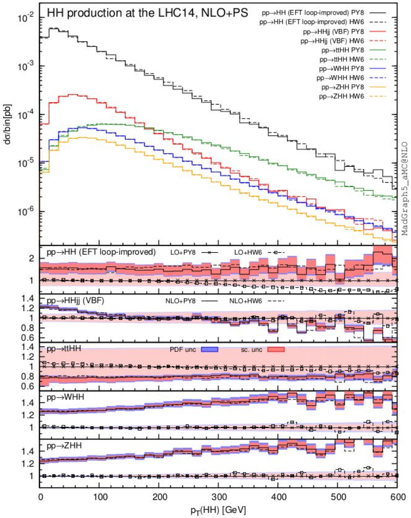
- MadGraph5_aMC@NLO [Alwall,Frederix,Frixione,Hirschi,Maltoni,Mattelaer,Shao,Stelzer,Torrielli,Zaro] (http://amcatnlo.web.cern.ch/amcatnlo/)
- milestone in 2014 for the QCD/MC community:
  - ☞ essentially all $2 \to 4$ processes you can think about (and also e^+e^-)
  - ☞ several of these processes were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

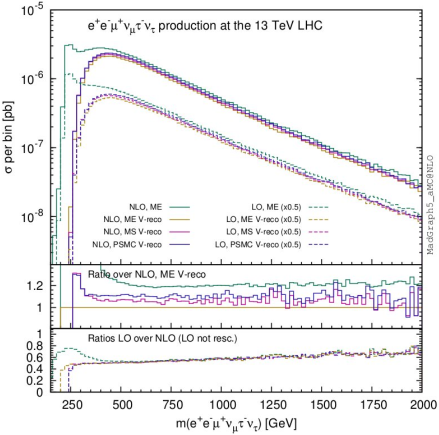
- embedded in Madgraph5
- fully automated (thanks to MadFKS and MadLoop)
- th. uncertainty: fast PDF and scale reweighting
- will soon allow also EW corrections and BSM models, thanks to interface to FeynRules [Alloul,Christensen,Degrande,Duhr,Fuks]

$pp \to HHX$

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

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





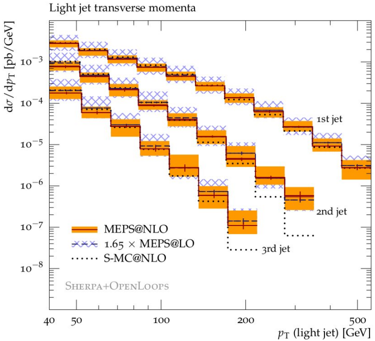
NLO matching (Sherpa-MC@NLO)

- `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]

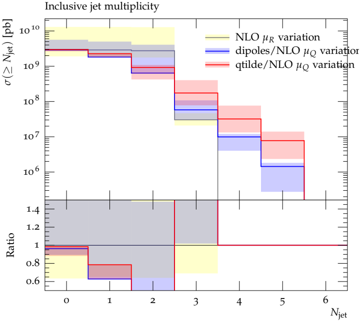


NLO matching in Herwig++

- 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
  - scheme for NLOPS merging [Plätzer '12]
- 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)
- rapid progress, stay tuned !

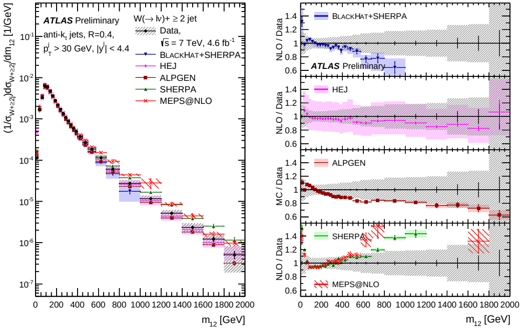


NLO+PS dijets [preliminary]

other approaches: HEJ

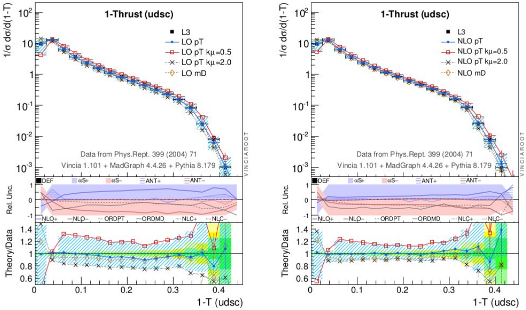
- High Energy Jets: (http://cern.ch/hej/)
  [Andersen,Hapola,Smillie]

- leading real and virtual corrections to hard scattering ME from wide-angle QCD (BFKL-inspired)
- merged with multileg tree-level ME's (but differently to shower merging); was matched also to PS (Ariadne)
- works well also when jets of similar transverse momentum (not based on collinear limit ⇒ no strong p_T-ordering required)
- should be the more reliable approach for "(X) + multijets" at large invariant mass or large rapidity intervals: very relevant for $H + jj$



- Vincia: (http://vincia.hepforge.org/)
[Skands,Giele,Hartgring,Kosower,Laenen,Larkoski,Lopez-Villarejo,Ritzmann]

- based upon antenna factorisation, substitute PYTHIA8 shower
- facility to evaluate uncertainties very comprehensively, and very efficiently
- systematically improve PS, order by order: during Sudakov veto algorithm, include also ratio of exact matrix elements (and compensate for mismatches)
- formalism for NLO+PS matching and merging worked out, and tested in e^+e^-

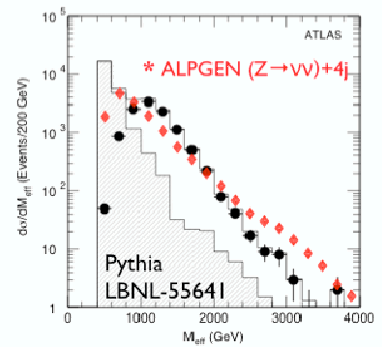


(a) $\mathrm{NLO}_2 + \mathrm{LO}_{2,3,4,5}$ + shower (b) $\mathrm{NLO}_{2,3} + \mathrm{LO}_{2,3,4,5}$ + shower

Hard scattering

- NLO matching
- NLO 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

- 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
    a) Born for "$pp \to S + n$ partons" @ NLO
    b) real contribution for "$pp \to S + (n-1)$ partons" @ NLO

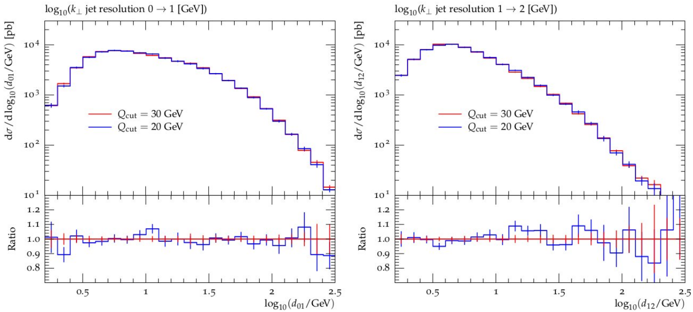
- as is at LO, many of these methods use a merging scale (Q_{MS})
  - a bad choice of merging scale can spoil formal accuracy one might want to claim
    - typically this can happen if $\alpha_{\mathrm{S}} \log^2 Q_{\mathrm{MS}} \simeq 1$ ($\to L \simeq 1/\sqrt{\alpha_{\mathrm{S}}}$)
  - in general,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

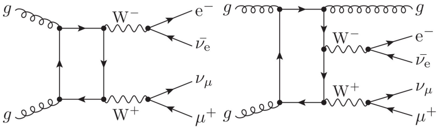
$$\begin{aligned} d\sigma &= d\Phi_0 \bar{\mathrm{B}}_0^{(\mathrm{A})} \otimes \tilde{\mathrm{PS}}_{t_{\min}} \Theta(d_1 < Q_{\mathrm{MS}}) \\ &+ d\Phi_1 H_0^{(\mathrm{A})} \Delta_{t_1} \Theta(d_1 < Q_{\mathrm{MS}}) \\ &+ d\Phi_1 \bar{\mathrm{B}}_1^{(\mathrm{A})} \otimes \tilde{\mathrm{PS}}_{t_{\min}}^{t_1}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

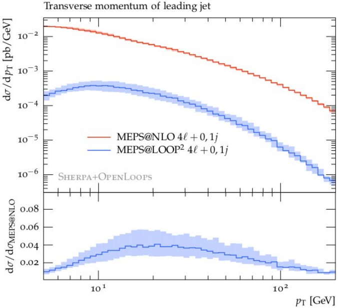
- possible to iterate to higher multiplicities
- residual dependence of total cross section on merging scale $\sim \alpha_S^2 L^3 / N_C^2$

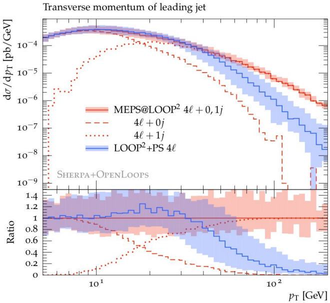


MEPS@NLO and loop-induced processes

- $gg \to VV$: finite subset of NNLO contribution
- numerically important, because of gluon flux
- first merging of 0-jet and 1-jet squared-loop contributions
- can use tree-level merging technique, since MEs are finite







FxFx method

[Frixione,Frederix, '12]

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

- 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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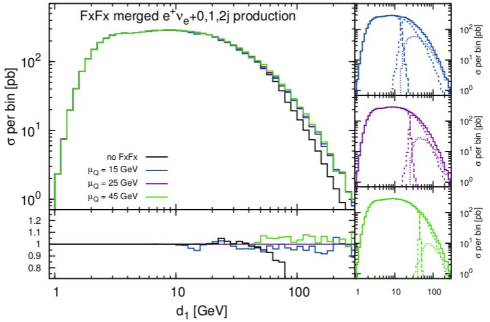

- fully inclusive result:
  - differences typically $\lesssim 1\%$ among different merging scales
  - quite good agreement with inclusive NLO+PS too

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

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

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

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

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

MiNLO

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

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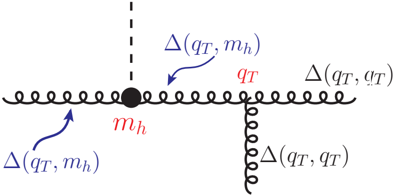

☞ Sudakov FF included on $H{+}j$ Born kinematics

☞ finite results if 1st jet unresolved

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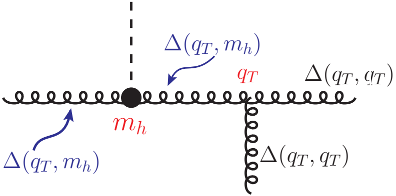


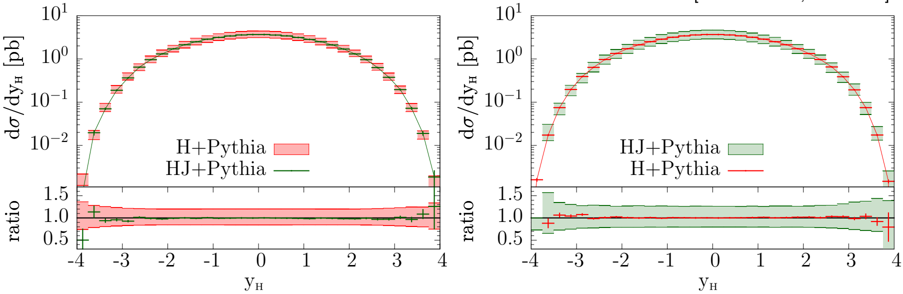
☞ Sudakov FF included on $H+j$ Born kinematics

☞ finite results if 1st jet unresolved

- $\bar{B}_{\mathrm{MiNLO}}$ 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

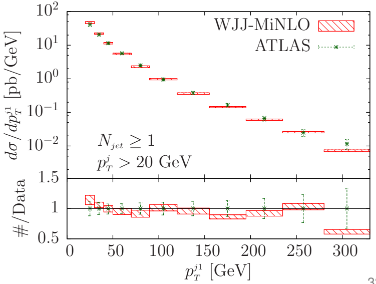
[Hamilton et al., 1212.4504]



- NLO merging available also for Drel-Yan, and VH [Luisoni,Nason,Oleari,Tramontano, 1212.4504]

VJJ−MiNLO [Campbell,Ellis,Nason,Zanderighi, 1303.5447]

- start from $W + 2$ jets @ NLO
- good agreement with data also when requiring $N_{\mathrm{jet}} \geq 1$!
- not possible in a standard NLO
- so far, no claim on formal accuracy here



- 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")

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

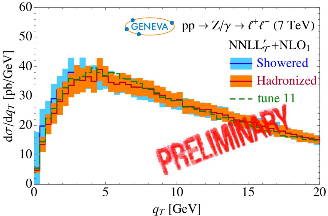
where

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

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

- 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 ~ 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]

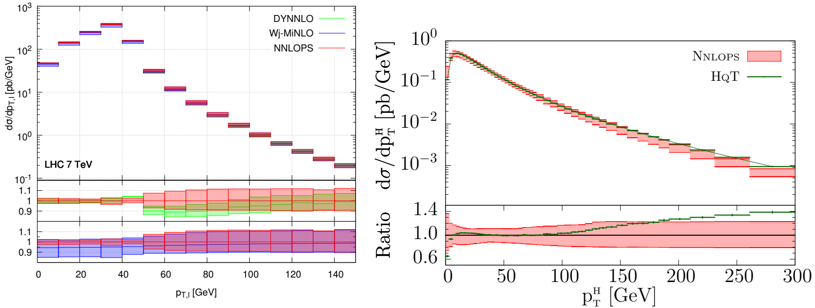


NNLO+PS

NNLO+PS results

Some of the methods described above allow to match NNLO with PS

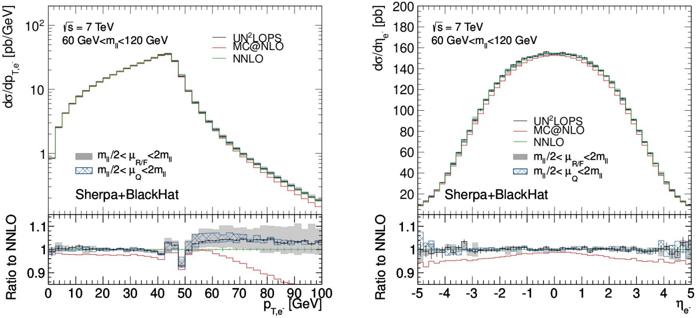
- Higgs [Hamilton,Nason,ER,Zanderighi '13] and Drell-Yan [Karlberg,ER,Zanderighi '14], using `MiNLO`-improved `POWHEG`



- 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.]

NNLO+PS results

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



- general framework and preliminary results for Drell-Yan also with `Geneva` [Alioli,Bauer, et al, '13]

Conclusions and Outlook

- 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
- summarised the huge amount of improvements over the last few years in the community

---

- continuous activity on improving “non-perturbative” stages. Could be relevant also for precision studies ?
- PS improvements: so far small effects, but clear picture not yet fully clear.
  - Effects observables with lots of data ?
  - If so, in the worst case scenario: we will have understood QCD better
- 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 (for simple processes) !