State-of-Art generators for top physics

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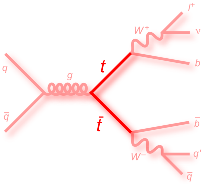
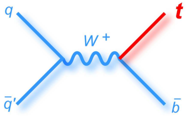
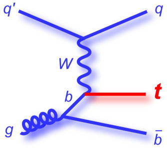
TOP 2011

Sant Feliu de Guixols, 26 September 2011

- Next-to-Leading Order predictions
  - (selected) results and recent progress
- Shower Monte Carlo event generators (and matching to matrix elements)
  - status
- Event generation with NLO accuracy
  - why ?
  - how ? (i.e. `POWHEG` and `MC@NLO` in a nutshell)
  - some results
- Conclusions and Outlook



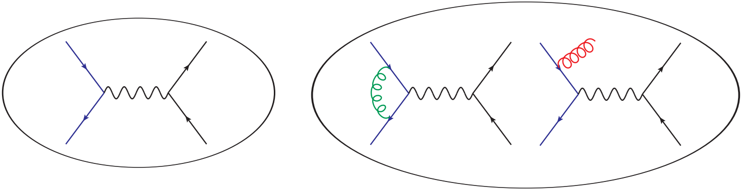




Next-to-Leading Order

Next-to-Leading-Order

- Cross sections are calculated using perturbative QCD.
- Typically, for differential distributions, we include *Leading Order* (LO) and *Next-to-Leading Order* (NLO) corrections:



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

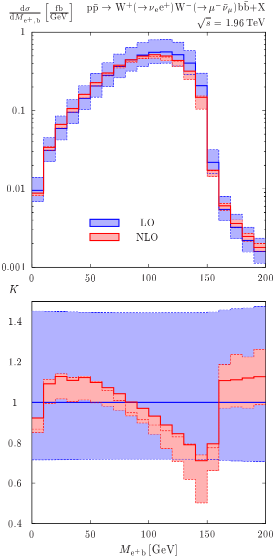
- Availability: $2 \rightarrow \leq 3/4$ for SM, $2 \rightarrow 2$ for BSM.
- Cutting-edge is $2 \rightarrow 5$ and automation.
- Recent progress for top physics: exact decays, offshellness effects, $t\bar{t}$+X.

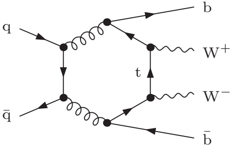
✓ Higher order because we want small theoretical uncertainty in the predictions.

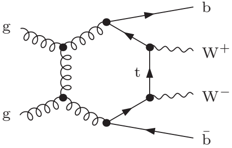
✗ Results are at the parton level: low multiplicity, quarks and gluons and not hadrons as final objects, not suitable to simulate fully realistic events.

Next-to-Leading-Order: top pair

[Denner & al., Bevilacqua & al., 2010]



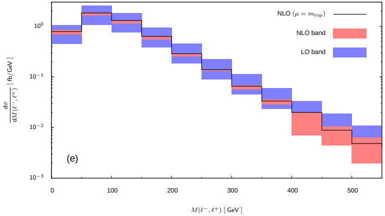


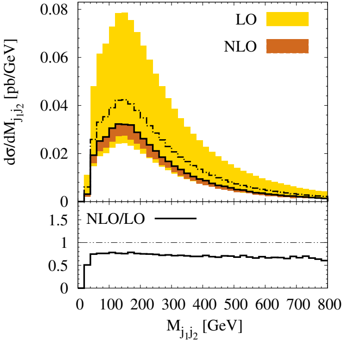


- at LO, and in the narrow-width approximation, $m^2_{e+,b} \leq m_t^2 - m_W^2$ (sharp)
- offshellness already has an impact at LO
- at NLO effects very sizeable (extra radiation can enter in b-jet)
- scale uncertainty is strongly reduced
- K-factor is not constant
- Complete $\ell\ \bar{\ell}\ \nu\ \bar{\nu}\ b\ \bar{b}$ final state with HELAC

Next-to-Leading-Order: top pair + X

- $t\bar{t} + X$ generically important as background for Higgs searches





[Dittmaier & al., Melnikov-Schulze, MadFKS/MadLoop]

- $t\bar{t}j$, $t\bar{t}\gamma$
- $t\bar{t}j$: particularly relevant at the LHC, since a top-pair is often produced with extra radiation.
- background to $H(\to WW)jj$

[Bredenstein & al., Bevilacqua & al.]

- $t\bar{t}H$: probe of top Yukawa couplings, but experimentally challenging
  $\hookrightarrow$ when H boosted, possible to be seen, with advanced analysis tecniques
- $t\bar{t}b\bar{b}$ is the main background
- $t\bar{t}jj$: background to $H(\to WW)jj$

Next-to-Leading-Order: summary

- Several state-of-the art tecniques used to compute 1-loop corrections:
  - unitarity, also for the massive case [Melnikov-Schulze, Badger &al]
  - OPP [Helac, MadLoop]
  - Feynman diagrams + sophisticated symbolic manipulation
- Automation: Helac-NLO, Madloop/MadFKS, Golem, Samurai, MadDipole

[Hirschi & al, 2011]

	Process	μ	n_{lf}	Cross section (pb) LO	NLO
a.1	$pp \to t\bar{t}$	m_{top}	5	123.76 ± 0.05	162.08 ± 0.12
a.2	$pp \to tj$	m_{top}	5	34.78 ± 0.03	41.03 ± 0.07
a.3	$pp \to tjj$	m_{top}	5	11.851 ± 0.006	13.71 ± 0.02
a.4	$pp \to t\bar{b}j$	$m_{top}/4$	4	25.62 ± 0.01	30.96 ± 0.06
a.5	$pp \to t\bar{b}jj$	$m_{top}/4$	4	8.195 ± 0.002	8.91 ± 0.01
c.2	$pp \to (W^+ \to)e^+\nu_e t\bar{t}$	$m_W + 2m_{top}$	5	0.009415 ± 0.000003	0.01159 ± 0.00001
c.4	$pp \to (\gamma^*/Z \to)e^+e^- t\bar{t}$	$m_Z + 2m_{top}$	5	0.0035131 ± 0.0000004	0.004876 ± 0.000002
c.5	$pp \to \gamma t\bar{t}$	$2m_{top}$	5	0.2906 ± 0.0001	0.4169 ± 0.0003
e.5	$pp \to Ht\bar{t}$	$m_{top} + m_H$	5	0.08896 ± 0.00001	0.09869 ± 0.00003

- All standard results already in public codes [MNR, ZTOP, MCFM (Campbell-Ellis & al)]
- Interesting improvements also for single-top [more in Motylinski talk]
- NNLO is not yet available, but almost.

Nowadays possible to have signals & backgrounds predicted with NLO accuracy.

Shower Monte Carlo Event Generators

SMC event generators

- Fully realistic simulation is not possible using a pure NLO computation
- Moreover, in some phase-space regions, NLO accuracy is not enough:
  $\hookrightarrow$ need to resum to all orders the dominant terms.
- A parton shower is an algorithm to resum (some classes of) collinear/soft logs.
  [similar ideas used in resummation for total cross sections; a PS is fully differential]
- SMC event generators are programs able to simulate events:
  $\hookrightarrow$ hard scattering $\longrightarrow$ parton shower $\longrightarrow$ (model for) hadronization.

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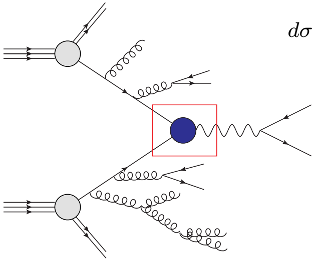


$$d\sigma = d\Phi_n\, B(\Phi_n) \left\{ \Delta(t_{\rm m}, t_0) + \Delta(t_{\rm m}, t) \underbrace{\frac{\alpha_s}{2\pi}\,\frac{1}{t}\,P(z)\, d\Phi_r}_{\rm coll.approximation} \right\}$$

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

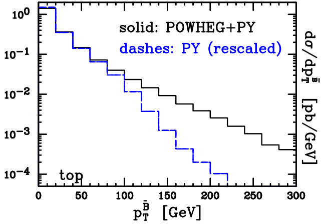
Traditional generators

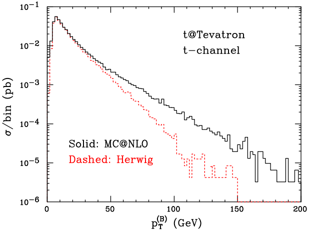
- 3 multipurpose, widely-used event generators: `PYTHIA`, `HERWIG` and `SHERPA`
- Main theoretical differences:
  - choice of the ordering variable
  - modelling of NP effects
- Big effort to rewrite `PYTHIA` and `HERWIG` in C++:
  now it's time for `HERWIG++` and `PYTHIA 8` to become the default, together with `SHERPA`

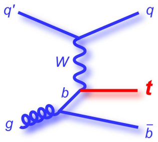
✓ High-multiplicity events simulated, at the hadron level: fully realistic analysis possible.

✗ Only LO accuracy in the high-scattering: unreliable normalization.

✗ Collinear approximation: bad description of high-p_{T} emissions.







$\hookrightarrow$ automated tools are available to generate high-multiplicity matrix-element...
$\hookrightarrow$ natural to use them to improve...

ME corrections

- Tools available to generate high-multiplicity matrix-element:
  - ALPGEN : α-algorithm [Mangano & al]
  - Comix (SHERPA), Helac : recursion [Gleisberg-Hoeche, Papadopoulos & al]
  - AMEGIC++, CompHEP, Madgraph : Feynman diagrams [Krauss, Maltoni-Stelzer & al]

σ [pb]	Number of jets						
$t\bar{t}$ + jets	0	1	2	3	4	5	6
ALPGEN	755.4(8)	748(2)	518(2)	310.9(8)	170.9(5)	87.6(3)	45.1(8)
AMEGIC	754.4(3)	747(1)	520(1)				
Comix	754.8(8)	745(1)	518(1)	309.8(8)	170.4(7)	89.2(4)	44.4(4)
CompHEP	757.8(8)	752(1)	519(1)				
HELAC	745(5)	711(7)	515(5)				
MadGraph	754(2)	749(2)	516(1)	306(1)			

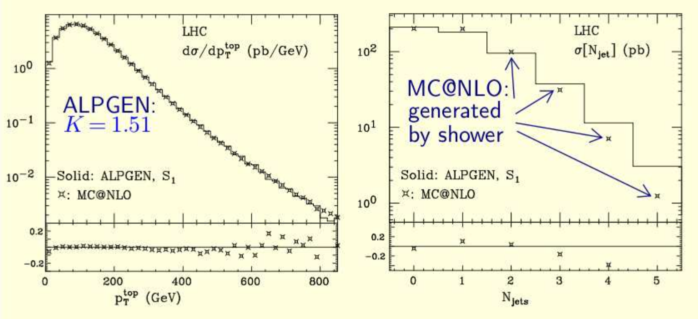
- Samples with different multiplicities can be merged consistently, and eventually matched to a PS
  $\hookrightarrow$ they overlap $\rightarrow$ prescription needed !
  - CKKW, automated in SHERPA
  - MLM, using ALPGEN and Madgraph together with HERWIG or PYTHIA
- Recent progress: Madgraph 5 [Alwall & al., 2011]

Process	Subproc. dirs.		Channels		Directory size		Event gen. time	
	MG 4	MG 5	MG 4	MG 5	MG 4	MG 5	MG 4	MG 5
$pp \rightarrow t\bar{t}$	3	2	5	3	49 MB	39 MB	2:39 min	1:55 min
$pp \rightarrow t\bar{t}j$	7	3	45	17	97 MB	56 MB	10:24 min	3:52 min
$pp \rightarrow t\bar{t}jj$	22	5	417	103	274 MB	98 MB	1:50 h	32:37 min
$pp \rightarrow t\bar{t}jjj$	34	6	3816	545	620 MB	209 MB	2:45 h*	23:15 min*

✓ Although at tree level only, high-p_{T} emissions and multijet region can be simulated properly.

✗ However, still only LO accuracy for rates.

SMC event generators/ME corrections: summary



- ✓ High-multiplicity events simulated, at the hadron level: well established tools, and allow fully realistic analysis.
- ✗ Only LO accuracy in the high-scattering: unreliable normalization.
- ✗ Collinear approximation: bad description of high-p_T emissions, but
- ✓ multijet region and high-p_T tails can be described properly, merging with ME (CKKW-MLM).
- ✓ Automation and speed are not really a problem anymore nowadays.

Event generation with NLO accuracy

NLO vs. SMC's (LO + Parton Shower)

- NLO

✓ NLO accuracy for inclusive observables (not only rates).

✓ reduced theoretical uncertainty (less sensitive to μ_{R} and μ_{F} choices).

✗ wrong shapes in small-p_{T} region (or generically where you want to resum logs).

✗ description only at the parton level.

- SMC's

✗ total normalization accurate only at LO (+ large scale dependence).

✗ poor description of high-p_{T} emissions, but can be improved using ME corrections and CKKW-MLM.

✓ Sudakov suppression of small p_{T} emissions (LL resummation, via parton showers).

✓ simulate high-multiplicity events at the hadron level, modelling also NP effects.

✓ largely used by experimental collaborations at various stages.

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natural to try to merge the 2 approaches, keeping the good features of both.

real emissions included in both approaches (and virtual corrections as well)

- NLO: exact $n+1$-body matrix element.
- PS's: multiple emissions in the collinear approximation.

main problem: avoid to double-count them !

many proposals, currently two fully tested solutions: `MC@NLO` [Frixione, Webber 2001] and `POWHEG` [Nason 2004]. Both already applied to a variety of processes with top quarks.

The MC@NLO method

$$
\begin{aligned}
d\sigma_{\mathrm{MC@NLO}} &= d\Phi_n\ \underbrace{\bar{B}(\Phi_n)_{\text{"SMC"}}}_{\mathcal{S}-\text{event}} \left\{ \Delta(t_{\mathrm{m}}, t_0) + \Delta(t_{\mathrm{m}}, t)\ \frac{\alpha_s}{2\pi}\ \frac{1}{t} P(z)\ d\Phi_r \right\} \\
&+ d\Phi_n\ d\Phi_r\ \underbrace{\left\{ R(\Phi_n, \Phi_r) - R_{\mathrm{SMC}}(\Phi_n, \Phi_r) \right\}}_{\mathcal{H}-\text{event}}
\end{aligned}
$$

where $\bar{B}(\Phi_n)_{\text{"SMC"}} = B(\Phi_n) + \frac{\alpha_s}{2\pi}\left[V(\Phi_n) + \int R_{\mathrm{SMC}}(\Phi_{n+1})\ d\Phi_r \right]$

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✓ $R - R_{\mathrm{SMC}}$: double-counting is avoided.

✓ Several processes implemented, no conceptual problems.

- the difference $R - R_{\mathrm{SMC}}$ can be negative $\rightarrow$ negative weighted events
- to perform the subtraction, use the kinematics inherited from the SMC
  $\hookrightarrow$ dependent on the specific PS used, but lot of progress has been done recently
  - matching with HERWIG and HERWIG++ possible [Frixione-Webber& al, 2001-2011]
  - general matching with PYTHIA, and automation (aMC@NLO) are getting closer: first applications already appeared.

The POWHEG method

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

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

POWHEG "master formula" for the hardest emission:

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

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

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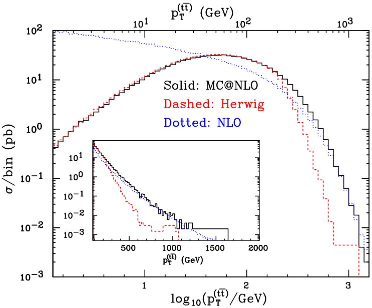
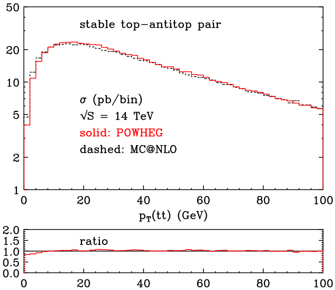
+ $p_{\rm T}$*-vetoing subsequent emissions*, to avoid double-counting.

- formally it has the same accuracy of MC@NLO:
  inclusive observables @NLO, first hard emission with full tree level ME, (N)LL resummation of collinear/soft logs, extra jets in the shower approximation.
- differences:
  - ✓ Events are positive weighted ⇒ POsitive Weight Hardest Emission Generator
  - ✓ does not depend on the parton-shower algorithm used.
  - truncated shower formally needed to restore soft wide-angle radiation effects, when using angular-ordered shower. Very small effects observed so far.
  - higher order terms in the expansion: origin is well understood, formalism can be easily adapted to ensure that at high-$p_{\rm T}$ the exact NLO is recovered (as MC@NLO).
  - (tree-level and) 1-loop amplitudes needed, all the rest automated

[POWHEG BOX, Alioli,Nason,Oleari,ER]
[SHERPA, Hoeche, Krauss, Shoenherr, Siegert]

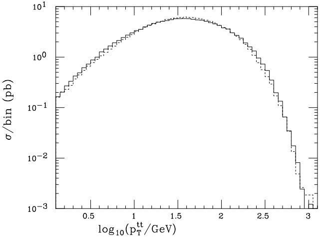
MC@NLO & POWHEG: top pair





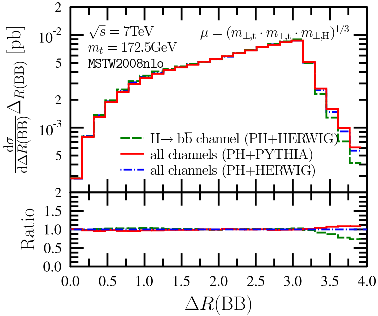
[Frixione-Nason-Webber 2003, Frixione-Nason-Ridolfi 2007]

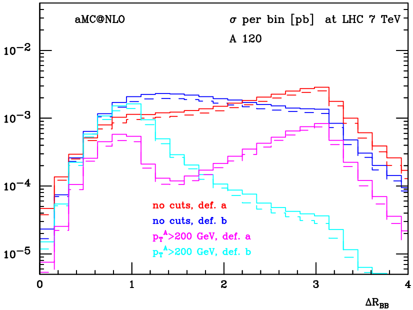
- Sudakov suppression of low p_{T} radiation, NLO divergent
- almost identical when `HERWIG++` is used instead of `HERWIG`

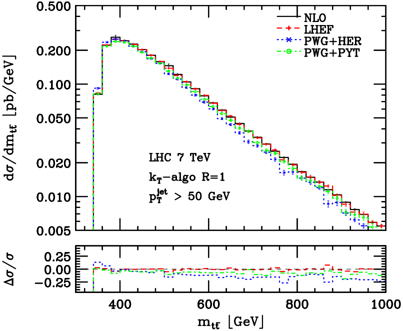


- important check that the 2 methods agree. Non trivial:
  - `MC@NLO`: low-p_{T} shape mainly due to the shower algorithm
  - `POWHEG`: “dominant” Sudakov suppression generated before the showering takes place.

MC@NLO & POWHEG: top pair + X







- $t\bar{t}H(A)$: first aMC@NLO result, also with POWHEG

  [Frederix & al. 2011, Garzelli & al. 2011]

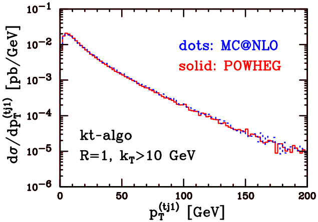
- here shown peak of $b\bar{b}$ distribution when Higgs is boosted ↔ jet substructure.

- $t\bar{t}j$: generation cut needed

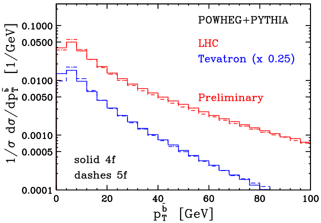
  [Kardos & al. 2011, Alioli & al.(to appear)]

MC@NLO & POWHEG: single top

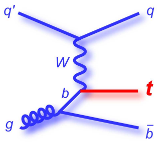
- The 3 traditional single-top production modes (s-, t-, Wt-channel) are available, both in MC@NLO and with the POWHEG BOX [Frixione & al. 2005-08, Alioli & al. 2009-10]
- $t + H^{\pm}$ in MC@NLO, work-in-progress in POWHEG



- Sudakov suppression of small p_{T} radiation (s-channel in the plot)



- 5-flavour scheme for t-channel
  $\Rightarrow$ spectator b-jet simulated only with LO accuracy
  $\Rightarrow$ mass effects missing at low-p_{T}
- in progress: 4-flavour scheme, to have a robust and NLO-accurate prediction.

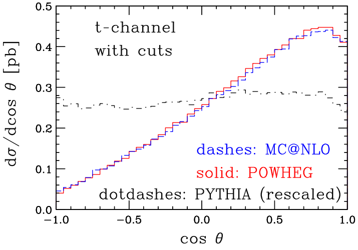


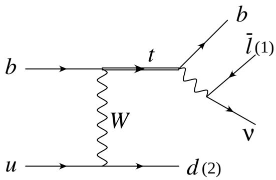
Spin correlations

- Although with tree-level accuracy, top decay products generated keeping spin correlation effects, both with POWHEG and MC@NLO.

method of [Frixione & al., 2007]

- Important for angular correlations, especially for single top:
  - used to isolate signal from backgrounds.
  - direct probe of V-A structure of weak interactions.





Conclusions

- Amazing progress in the last few years in NLO computations:
  - automation
  - high-multiplicity, e.g. $t\bar{t}+ \leq 2$ jets
- Standard MC generators are well established and invaluable tools, but, for precision studies, use them in association with ME generators (ME+PS), or matching with NLO (NLO+PS).
- with `POWHEG` and `MC@NLO` is already possible to study $t\bar{t}$ and single-top with NLO+PS accuracy
- in the last year, several processes relevant for top physics were also added
- and likely many more to come (both NLO codes and matching algorithm are now largely automated).
- possible improvements:
  - simulation of top decays (NLO corrections)
  - `ME+NLO+PS`: getting the best of NLO+PS and ME+PS

[Hamilton-Nason, Hoeche & al., 2010]

Apologies for topics not discussed, or that I forgot to mention.

Conclusions

- Amazing progress in the last few years in NLO computations:
  - automation
  - high-multiplicity, e.g. $t\bar{t}+\leq 2$ jets
- Standard MC generators are well established and invaluable tools, but, for precision studies, use them in association with ME generators (ME+PS), or matching with NLO (NLO+PS).
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Apologies for topics not discussed, or that I forgot to mention.

Thanks for your attention

Extra slides

Status and Availability of NLO+PS tools

`POWHEG BOX`

- automated, using the FKS subtraction scheme.
- all implementations included in a single and public framework
- it produces LHE files, ready to be showered through both `HERWIG` and `PYTHIA`.
- once needed ingredients are provided, it can be used as a "black-box" for theorists interested

`powhegbox.mib.infn.it`

- events available for processes where HELAC was used

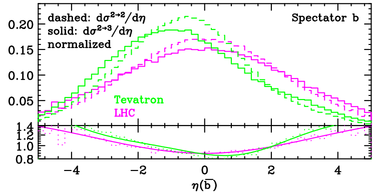
`(a)MC@NLO`

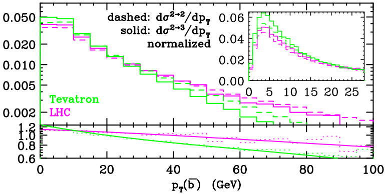
- automated, also for one-loop corrections, via `MadLoop` and `MadFKS`.
- so far, only with `HERWIG` and `HERWIG++` showers, but work is in progress to extend also to `PYTHIA`
- event samples available for new processes, public code for old ones; eventually all in the same framework.

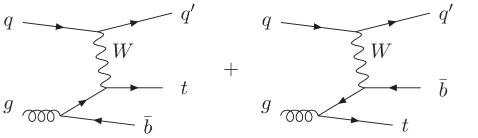
`www.hep.phy.cam.ac.uk/theory/webber/MCatNLO`
`amcatnlo.web.cern.ch/amcatnlo`

Next-to-Leading-Order: single-top

More details in talk by P. Motylinski

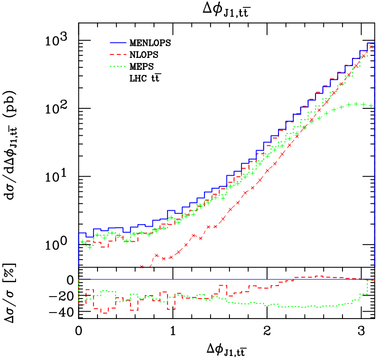






- traditionally computed using the 5 flavour scheme [Harris & al., 2002]
  $\hookrightarrow$ mass effects missing at low-p_T
- with the 4-flavour scheme, robust and accurate NLO prediction also for b-spectator jet [Campbell & al., 2009]
- Both included in MCFM, where spin-correlation effects at NLO, in the narrox-width approximation, are also available.
- Offshellness effects and non-factorizable production/decay effects studied using a SCET-inspired approach.
  Impact on total cross section is usually small, but some distributions are afffected sizeably. [Signer & al., 2010]

MENLOPS



$$d\sigma = d\sigma_{\mathrm{PW}}(0) + \frac{\sigma_{\mathrm{ME}}(1)}{\sigma_{\mathrm{ME}}(\geqslant 1)}\,\frac{\sigma_{\mathrm{PW}}(\geqslant 1)}{\sigma_{\mathrm{PW}}(1)}\,d\sigma_{\mathrm{PW}}(1) + \frac{\sigma_{\mathrm{PW}}(\geqslant 1)}{\sigma_{\mathrm{ME}}(\geqslant 1)}\,d\sigma_{\mathrm{ME}}(\geqslant 2)\,.$$