Monte Carlo Tools for Top Physics

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Plan of the talk

- How events are simulated: PS (parton showers), ME+PS merging, NLO+PS merging.
- What is available now: $t\bar{t}$, single top, tW, tH
- Perspective for NLO+PS: automation
- Merging NLO+PS and ME+PS

How events are simulated

- Traditional PS (Parton Shower generators)
- ME+PS generators
- NLO+PS generators

Traditional generators

"Traditional" PS's: `PYTHIA`, `HERWIG`, `HERWIG++`; give a fair description of the bulk of the production process, where "fair" means LO

- They use LO matrix elements for the partonic production process ($\mathcal{O}(\alpha_s^2)$ for $t\bar{t}$)
- They generate QCD radiation using the collinear approximation, and, to a limited extent, the soft approximation.
  For example, in $t\bar{t}$ production, jets at small angle with respect to the collision axis, and to a minor extent soft jets, are well described. In short: low p_T jets.
- They may or may not include spin correlations in decay.
- They include more or less sofisticated models for hadron formation and for the underlying event, including multiparton collisions.

ME+PS

ME+PS can achieve LO accuracy for the prorduction of a fairly large number of associated jets.

In the $t\bar{t}$ example, they achieve the accuracy:
$t\bar{t}\colon \alpha_s^2$, $\quad t\bar{t} + \text{jet}\colon \alpha_s^3$, $\quad t\bar{t} + 2\,\text{jets}\colon \alpha_s^4$, $\quad$ etc.

Some of them are standalone ME generators that can be interfaced to traditional Monte Carlo programs (`ALPGEN`, `MadEvent`, `HELAC`).
Others are embedded in fully featured SMC programs (`SHERPA`).

Traditional generators include sometimes ME corrections. This, however, only for the hardest jet, and only for few processes (basically $2 \to 1$).

NLO+PS

NLO+PS generators are able to describe the emission of the hardest jet with LO accuracy (α_s^3 for $t\bar{t}$, same as ME+PS generator), but are also capable to achieve NLO accuracy (i.e. $\alpha_s^2 + \alpha_s^3$ for $t\bar{t}$ production) for inclusive observables.

Several proposed methods:

(Giele,Kosower,Skands 2007; Lavesson,Lonnblad,2008; Nagy,Soper, 2005, etc.)

Available generators at present:

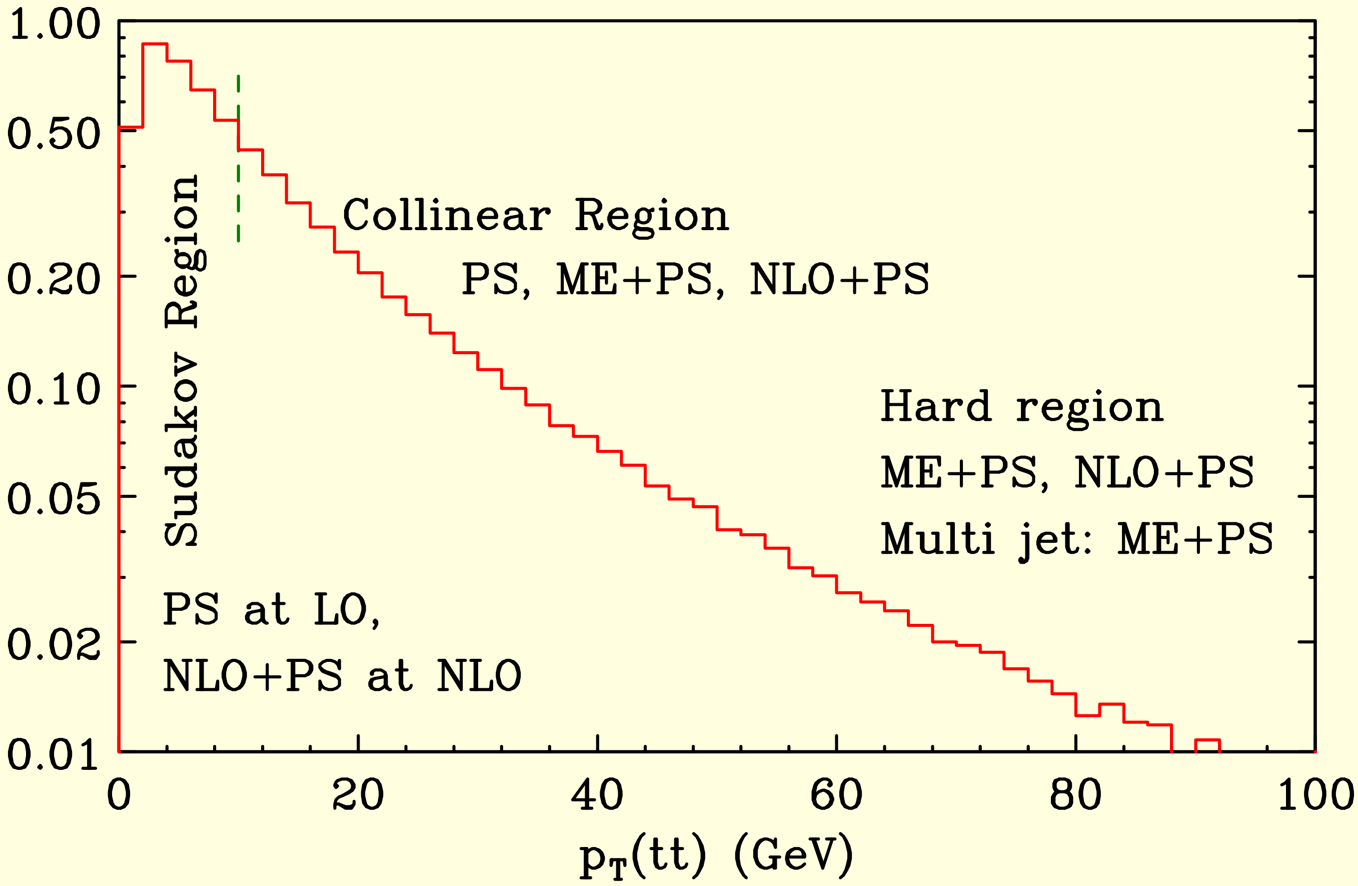
`MC@NLO` (Frixione, Webber 2002) `POWHEG` (P.N. 2004)

They use a traditional PS for radiation bejond the hardest jet, and for hadronization and event completion.

Thus, in the example of $t\bar{t}$, only the hardest jet is described with NLO accuracy. Further jets are generated by the shower in the collinear or soft approximation.

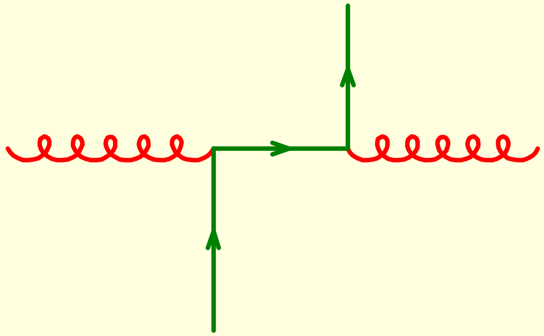
Domain of PS, ME+PS, NLO+PS

Sudakov region: $p_T \lesssim m_t \alpha_s$; collinear region: $p_T \ll m_T$; hard region: $p_T \gtrsim m_t$

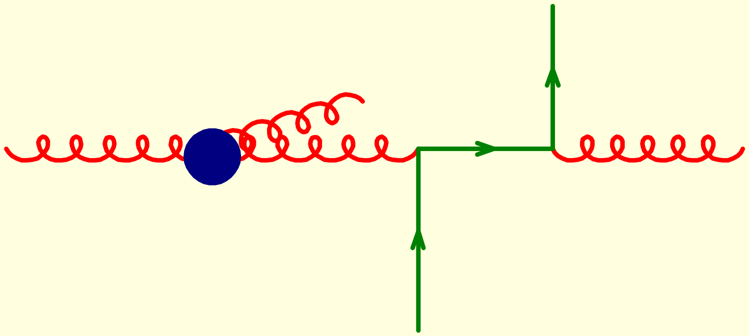


Parton Shower basic concepts

Born cross section: partonic cross section convoluted with parton density functions $B(\Phi_B)$, where Φ_B is the Born phase space.



The splitting algorithm is applied to each external coloured line, recursively, according to a splitting probability $P(\Phi_r)$ ($\Phi_r = \theta, z, \phi$, radiation variables)



So: from Φ_B, Φ_r we recover Φ, the full kinematics of the first radiation;

The other way around, $\Phi \Rightarrow (\Phi_r, \Phi_B)$, where Φ_B is the underlying Born of Φ.

- $P(\Phi_r)$ is such that, for $p_T \ll m_t$, (but $p_T \gg \alpha_s m_T$) we have

$$P(\Phi_r) \times B(\Phi_B) \approx R(\Phi)$$

- For $p_T \lesssim \alpha_s\, m_t$, $P(\Phi_r)$ is damped by a Sudakov Form Factor $\Delta(\Phi_r)$, arising from dominant virtual corrections.

- $P(\Phi_r)$ is such that (unitarity of the shower)

$$\int P(\Phi_r)\, d\Phi_r + P_0 = 1$$

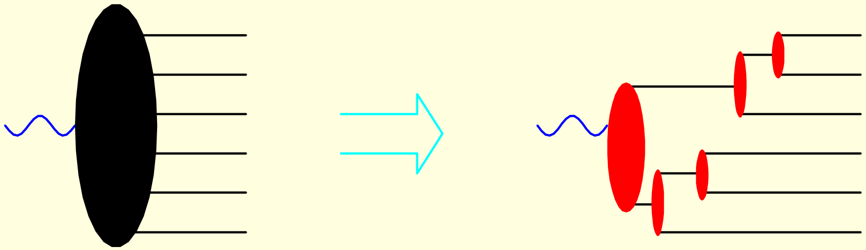
ME+PS

Historical approach: CKKW

Catani, Krauss, Küen, Webber (2001), (in e^+e^- annihilation).

In a nut-shell:

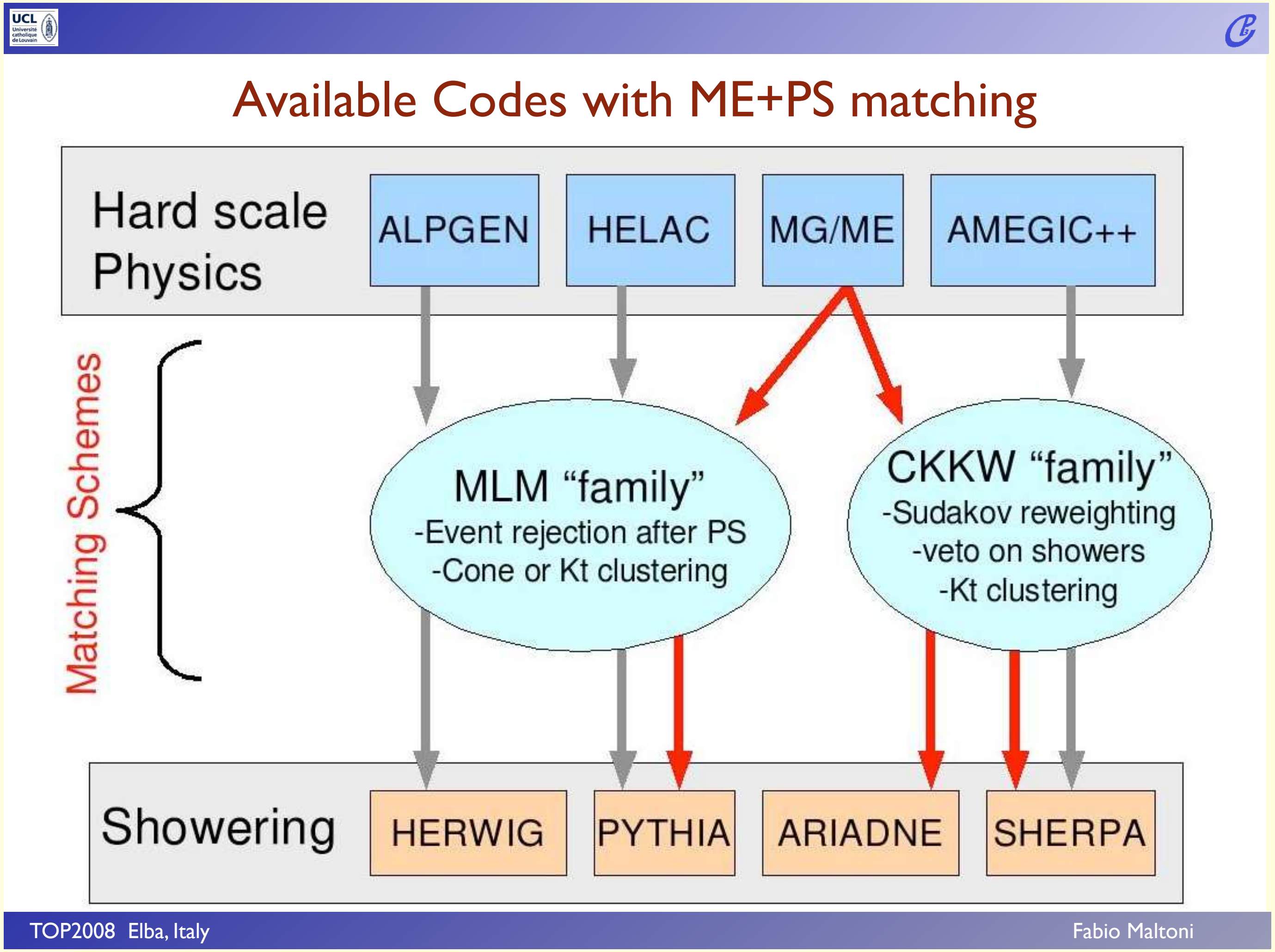
- Clusterize ME partons to reconstruct a shower skeleton (by pairing up particles that yield smallest t recursively)



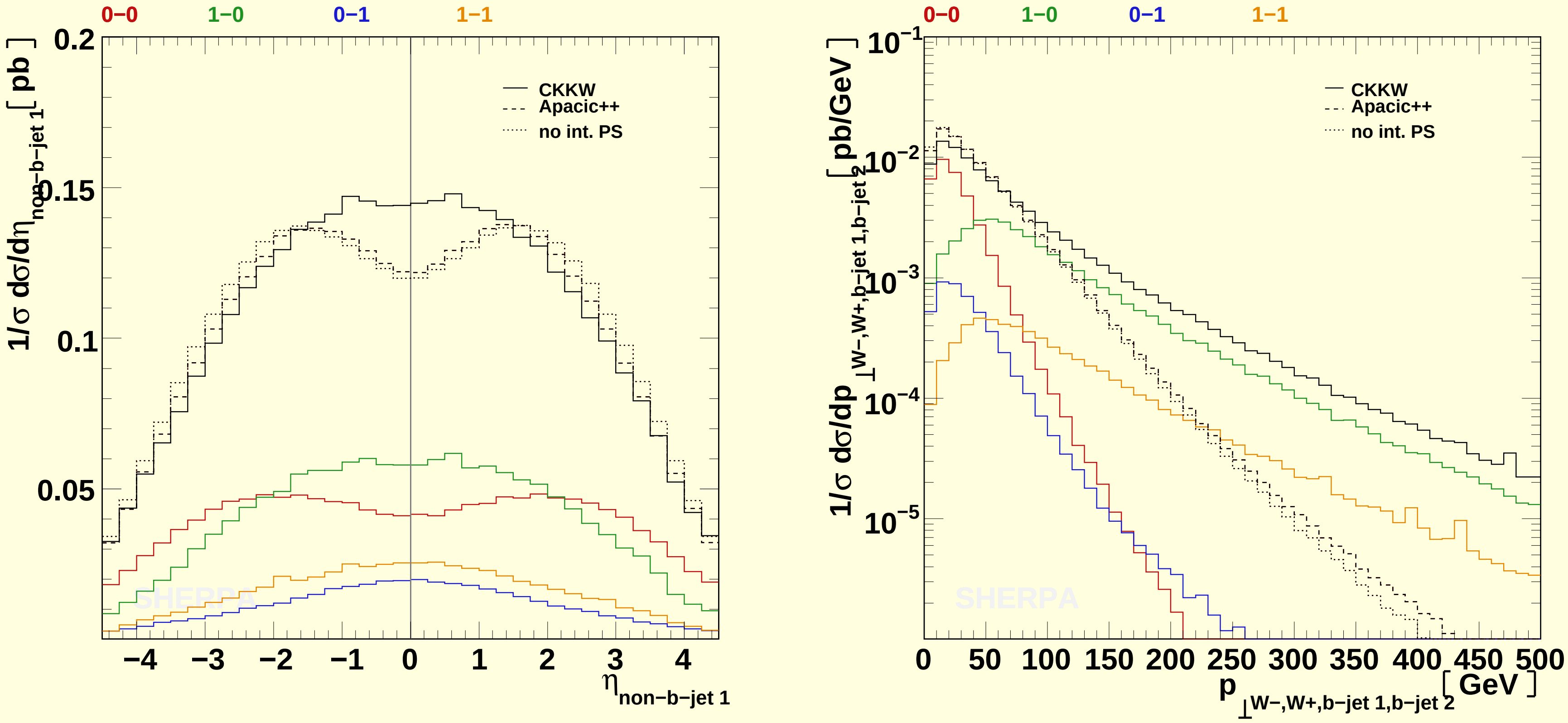
Red blobs have decreasing t values

- Correct exact tree level ME calculations with Sudakov form factor so that they reproduce the Shower results in the small k_T limit.
- Let the Shower take care of radiation with $k_T < M_{\rm cut}$, where $M_{\rm cut}$ is a cutoff on the jet separation

Alternative methods: MLM matching (no proofs, but it seems to work).
Others: CKKW-L (Lonnblad).



Inclusion of jet radiation in decays also possible (Sherpa , Gleisberg al, 2008)



$t\bar{t}$ sample formed by events with zero extra jets, and up to one jet in production and decay of top

NLO+PS

Hardest radiation:

$$d\sigma = \overbrace{\bar{B}^s(\Phi_B)}^{\text{NLO!}} d\Phi_B \left[\overbrace{\Delta^s_{t_0}}^{P_0} + \overbrace{\Delta^s_t \frac{R^s(\Phi)}{B(\Phi_B)} d\Phi_r}^{P(\Phi_r)} \right] + \overbrace{[R(\Phi) - R^s(\Phi)]}^{\text{ME correction}} d\Phi$$

where $R \Rightarrow R^s$ in the soft and collinear limit,

$$\bar{B}^s(\Phi_B) = B(\Phi_B) + \underbrace{\left[\underbrace{V(\Phi_B)}_{\text{infinite}} + \underbrace{\int R^s(\Phi)\, d\Phi_r}_{\text{infinite}} \right]}_{\text{finite}}$$

The Born cross section is replaced by the inclusive cross section at fixed underlying Born

and

$$\Delta^s_t = \exp\left[- \int_{t_l} \frac{R^s}{B} d\Phi_r \theta(t(\Phi) - t_l) \right]$$

so that

$$\Delta^s_{t_0} + \int \Delta^s_t \frac{R^s(\Phi)}{B(\Phi_B)} d\Phi_r = 1 \; (\text{Unitarity})$$

In MC@NLO: $R^s d\Phi_r = R^{\rm MC} d\Phi_r^{\rm MC}$

Furthermore:
in MC@NLO the phase space parametrization Φ_B, $\Phi_r \Rightarrow \Phi$ is the one of the Shower Monte Carlo. We have:

$$\underbrace{\bar{B}^s(\Phi_B) d\Phi_B}_{\substack{\text{provided by \texttt{MCatNLO}} \\ \mathcal{S}\text{ event}}} \left[\underbrace{\Delta^s_{t_0} + \Delta^s_t \frac{R^s(\Phi)}{B(\Phi_B)} d\Phi_r}_{\text{generated by \texttt{HERWIG}}} \right] + \underbrace{\left[R(\Phi) - R^s(\Phi) \right] d\Phi}_{\substack{\text{provided by \texttt{MCatNLO}} \\ \mathcal{H}\text{ event}}}$$

More synthetically

$$\texttt{MCatNLO}\ \mathcal{S} = \frac{\bar{B}^s(\Phi_B)}{B(\Phi_B)} \times \texttt{HERWIG}\ \text{basic process}$$

$$\texttt{MCatNLO}\ \mathcal{H} = R(\Phi) - R^s(\Phi)\ \text{fed through}\ \texttt{HERWIG}$$

Issues:

- Must use of the MC kinematic mapping $(\Phi_B, \Phi_r^{\mathrm{MC}}) \Rightarrow \Phi$.
- For $R - R^{\mathrm{MC}}$ to be non singular, the MC should reproduce exactly the soft and collinear singularities of the radiation matrix element.
  No existing PS can do that. For example, the azimuthal dependence of collinear singularities is neglected in the MC's.
  In `MC@NLO` this difference is essentially damped by an extra factor, that vanishes in the collinear and in the soft limit.
- $R - R^{\mathrm{MC}}$ can be negative: negative weights in the output.

In POWHEG: $R^s d\Phi_r = R F(\Phi)$

where $0 \leqslant F(\Phi) \leqslant 1$, and $F(\Phi) \Rightarrow 1$ in the soft or collinear limit.
$F(\Phi) = 1$ is also possible, and often adopted.
The parametrization $\Phi_B, \Phi_r \Rightarrow \Phi$ is within POWHEG, and there is complete freedom in its choice.

$$\underbrace{\bar{B}^s(\Phi_B) d\Phi_B}_{\texttt{POWHEG}} \left[\underbrace{\Delta^s_{t_0} + \Delta^s_t \frac{R^s(\Phi)}{B(\Phi_B)} d\Phi_r}_{\texttt{POWHEG}} \right] + \underbrace{[R(\Phi) - R^s(\Phi)]\, d\Phi}_{\texttt{POWHEG}}$$

All the elements of the hardest radiation are generated within POWHEG

Recipe

- POWHEG generates an event, with $t = t_{\texttt{powheg}}$
- The event is passed to a SMC, imposing no radiation with $t > t_{\texttt{powheg}}$.

Improvements over MC@NLO:

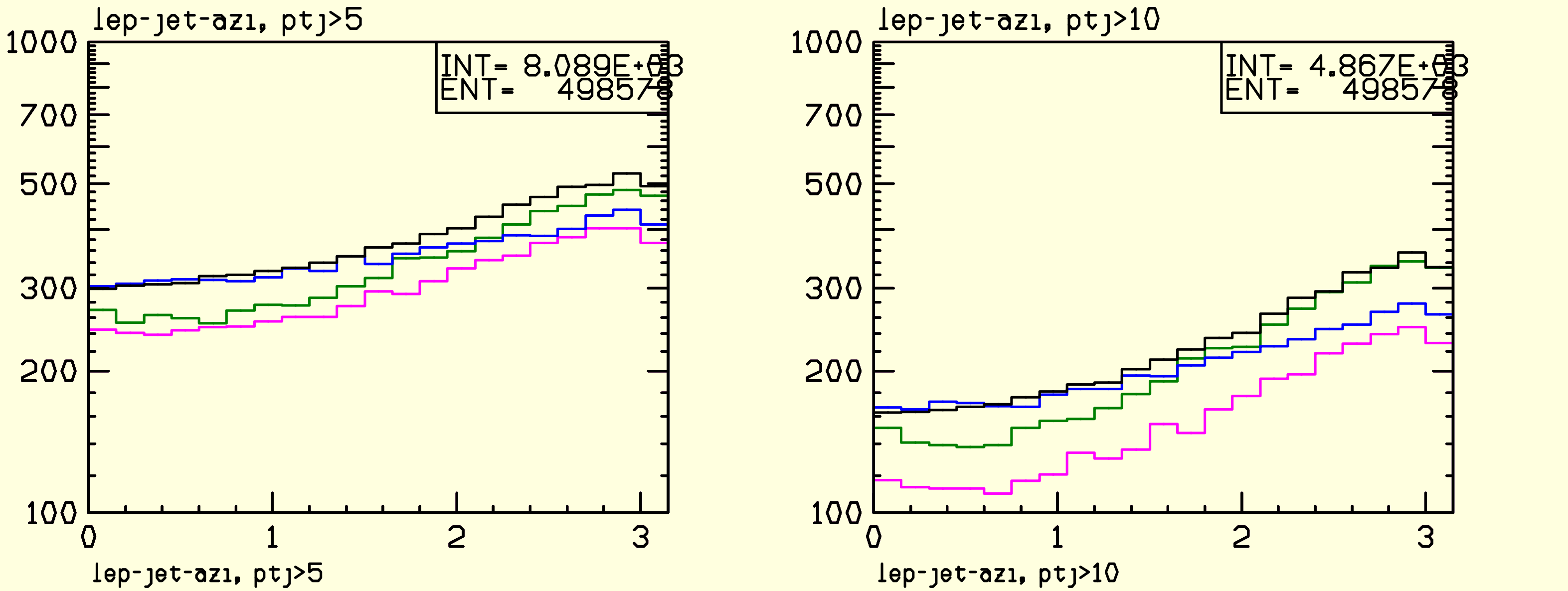
- Positive weighted events: $R - R_s = R(F-1) \geqslant 0$!
- Independence on the Shower MC: The hardest emission is generated by POWHEG; less hard emissions are generated by the shower.
- No issues with improper cancellation of PS singularities

Do we expect differences at NLO?

In `MC@NLO`: $R - R^{\mathrm{MC}}$ difference in $\mathcal{H}$ events is explicitly suppressed in the collinear and soft region. This may cause inaccuracies of NLO order when describing relatively soft jets.

Preliminary investigation in W production: look at the relative azimuth of the hardest jet and lepton. Expect flatter distributions in `MC@NLO` for small jet k_T.

Observed, but not (yet) fully understood:



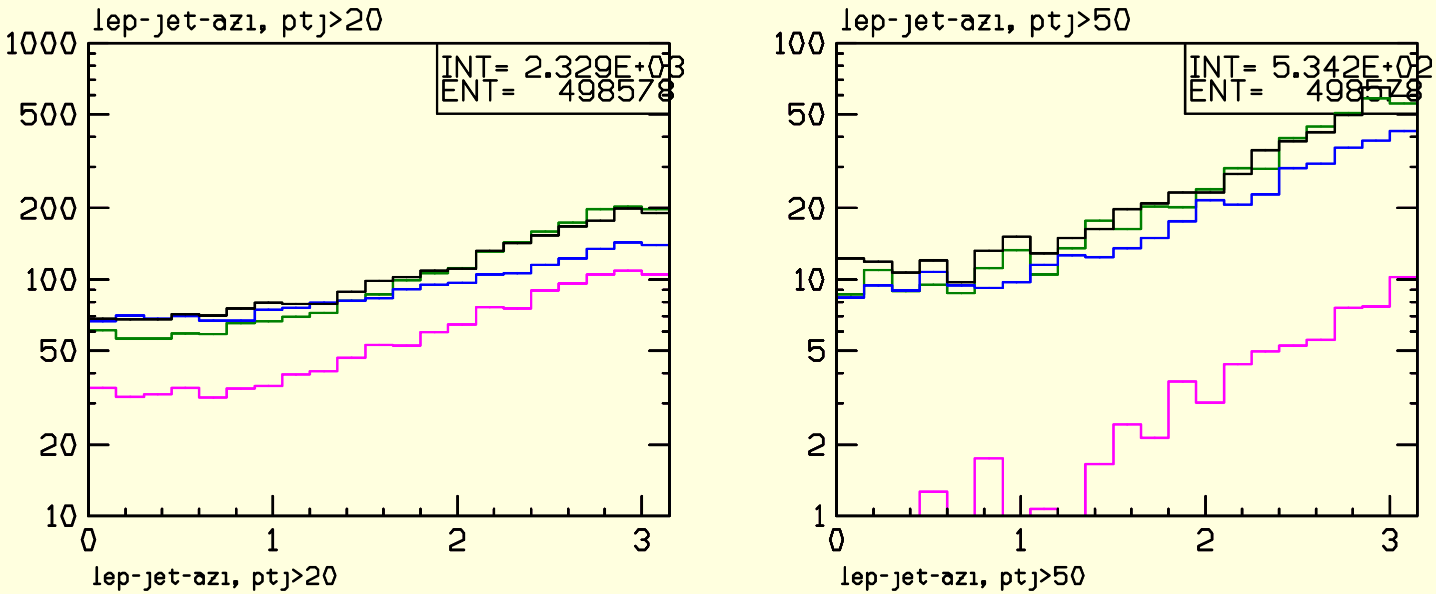
W production, LHC, 7 TeV; $\Delta\phi$ between the lepton and the hardest jet.

Black: POWHEG

Blue: MC@NLO

Green, HERWIG with soft and hard ME corrections

Magenta: HERWIG without soft and hard ME



MC@NLO is flatter (but HERWIG without ME is not flat). Needs more study.

POWHEG and MC@NLO in top production

The available processes are now:

Process	$t\bar{t}$	ST, s ch.	ST, t ch.	tW	tH
MC@NLO	$\checkmark$	$\checkmark$	$\checkmark$	$\checkmark$	$\checkmark$
POWHEG	$\checkmark$	$\checkmark$	$\checkmark$	in progress	in progress

Both include spin correlation effects in an approximate way

In essence, they are included at the ME+PS level (no NLO accuracy)

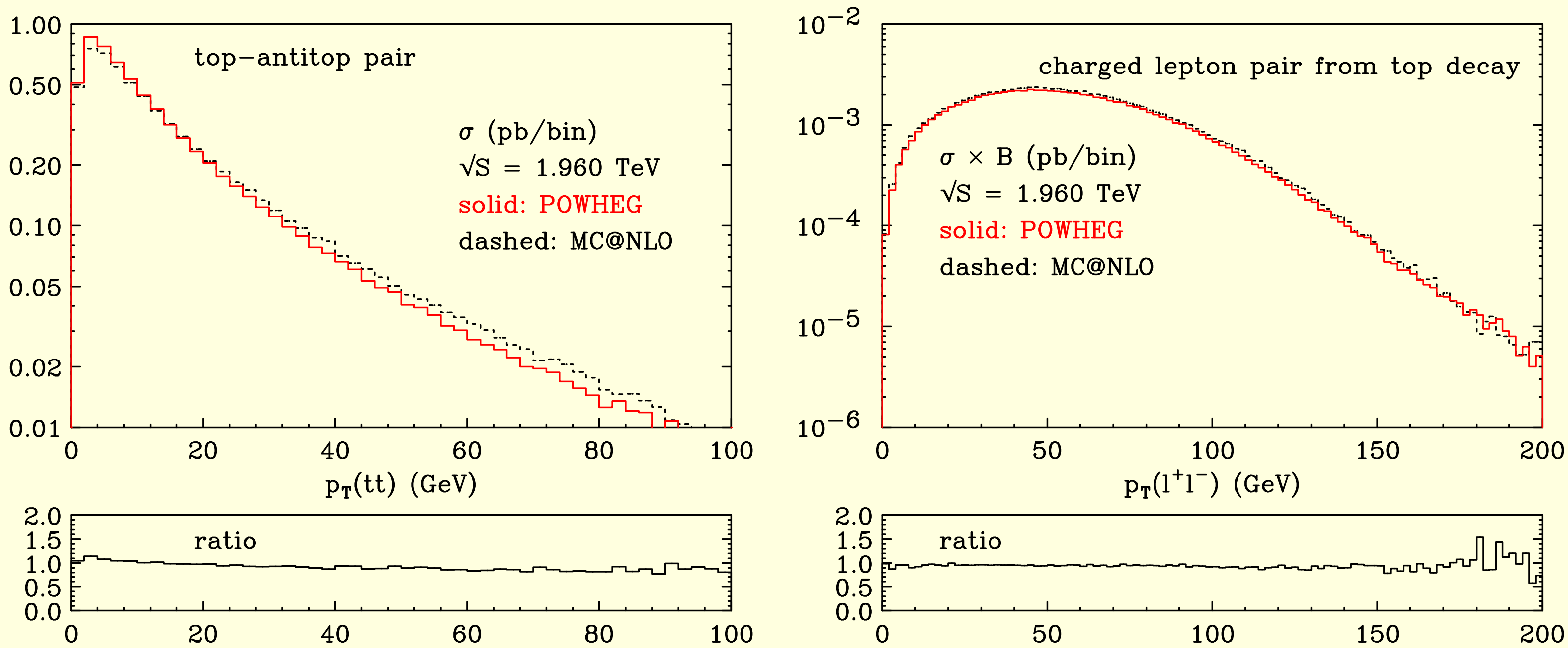
(method by Frixione, Laenen, Motylinski, Webber, 2007)

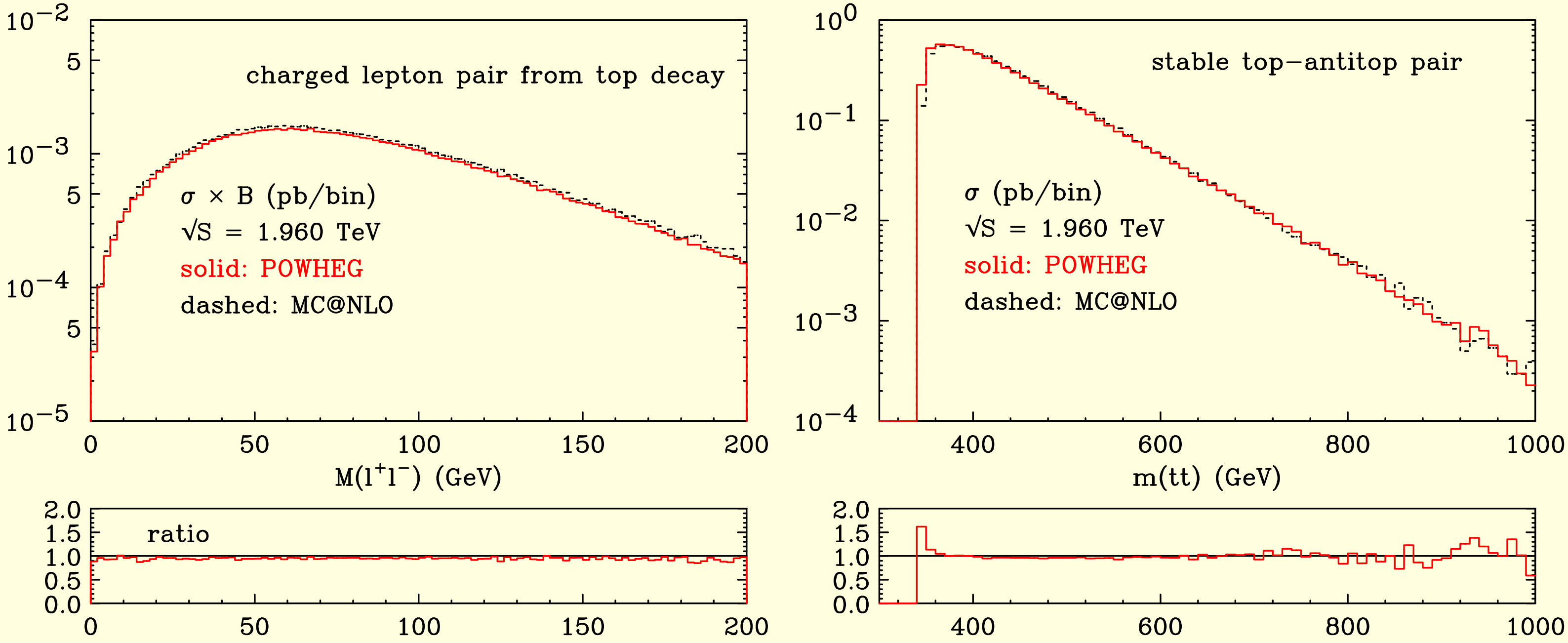
None includes NLO corrections to the top decay chain.

POWHEG and MC@NLO comparison: Top pair production

MC@NLO $t\bar{t}$: Frixione, Webber, P.N., 03

POWHEG $t\bar{t}$: Frixione, Ridolfi, P.N. 07





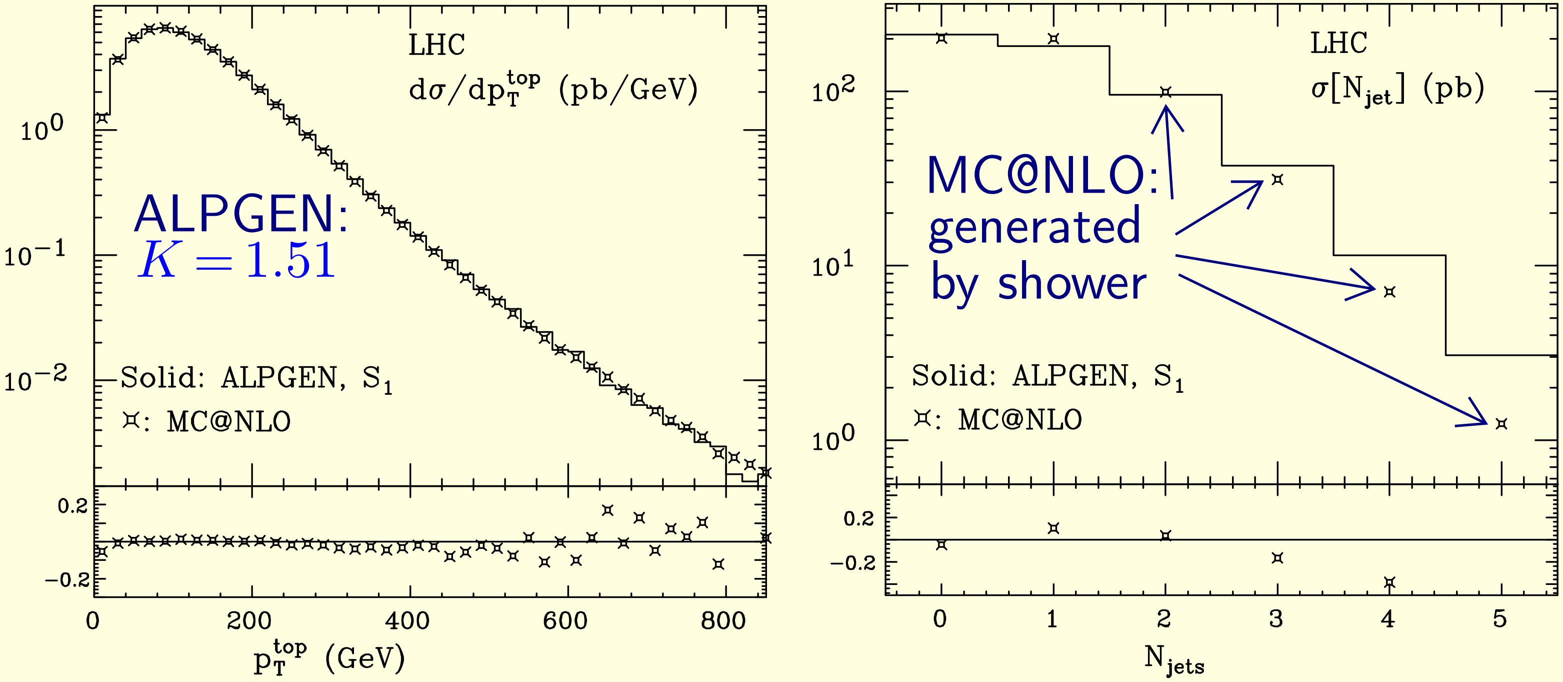
Good agreement for most observables considered
(differences can be ascribed to different treatment of higher order terms)

ME+PS can generate samples of $t\bar{t} + n\,\mathrm{jets}$; can be compared to NLO+PS;

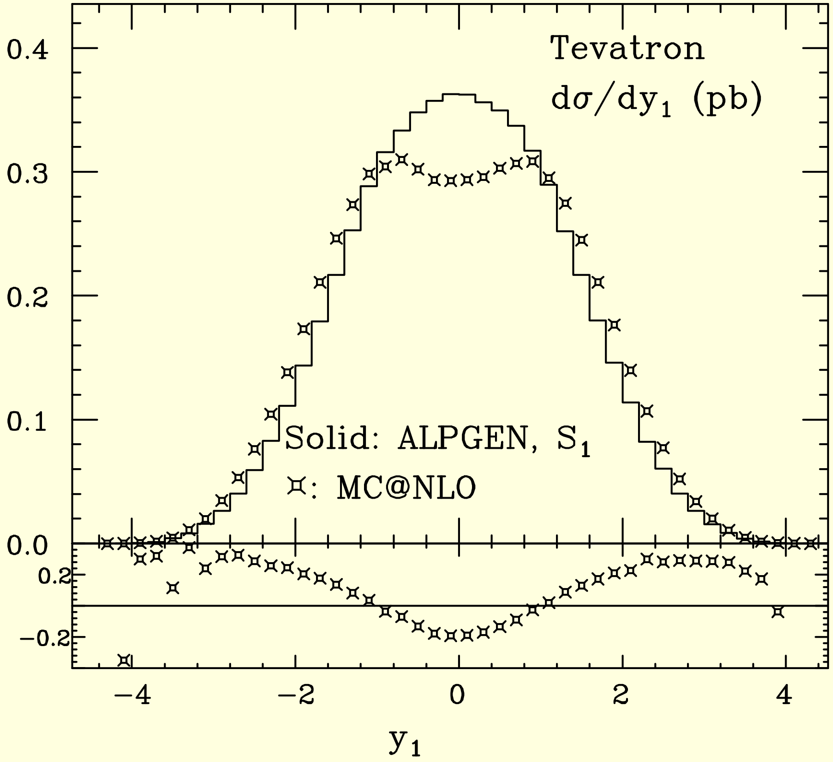
expect:

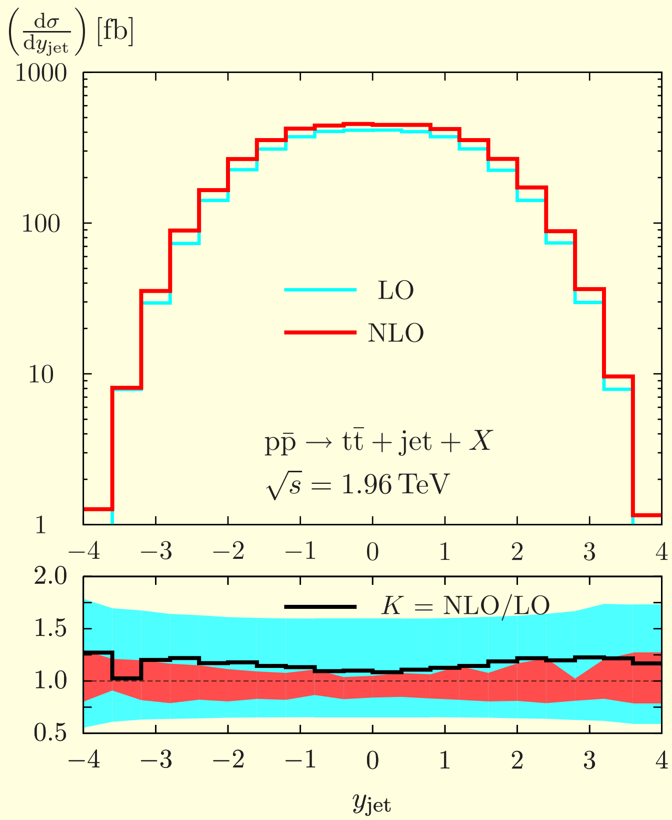
- Disadvantage: worse normalization (no NLO)
- Advantage: better high jet multiplicities (exact ME)

Comparison ALPGEN-MC@NLO carried out in detail
(Mangano, Moretti,Piccinini,Treccani, Nov.06)



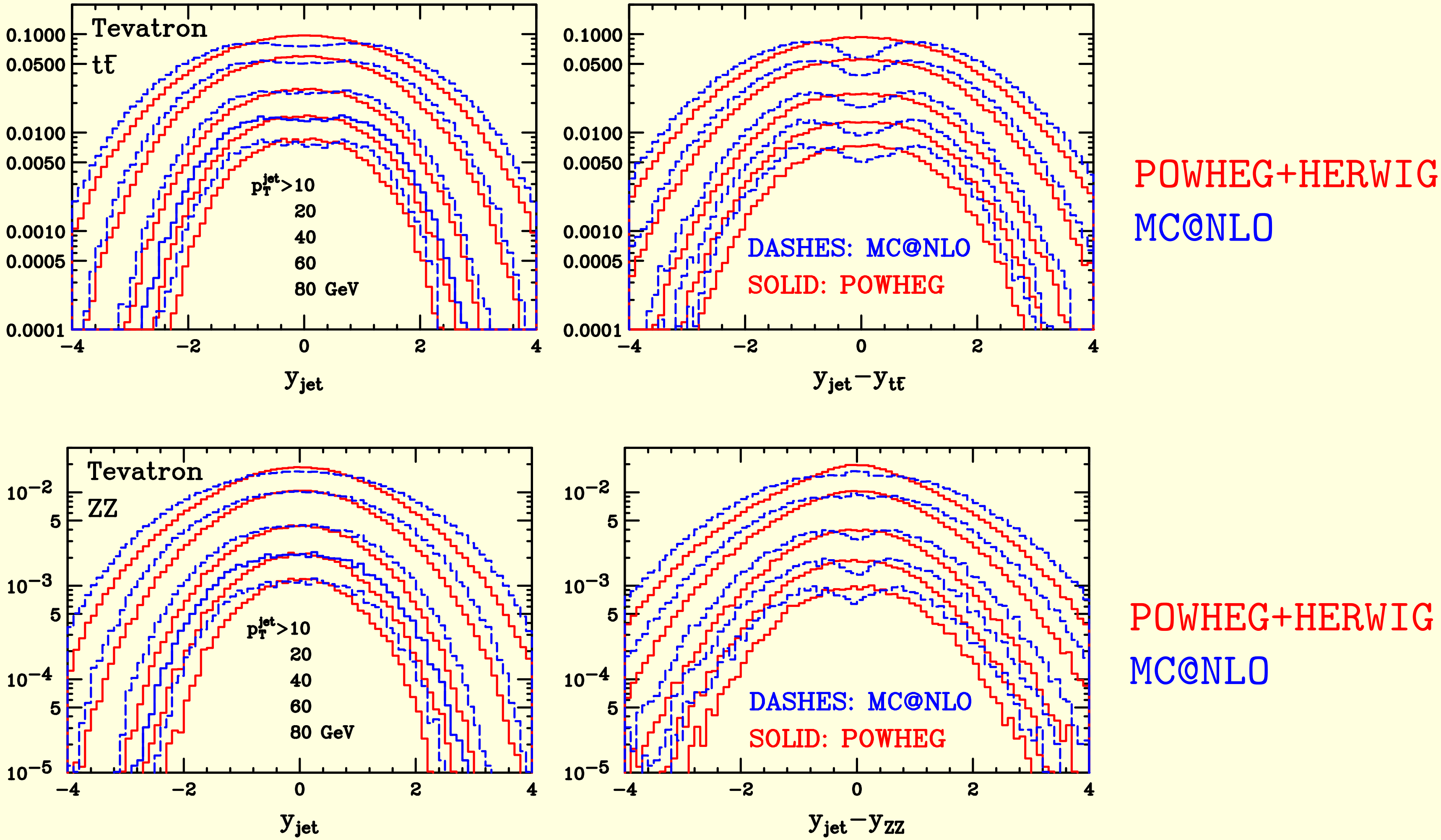
ALPGEN and $t\bar{t}+\mathrm{jet}$ at NLO vs. MC@NLO



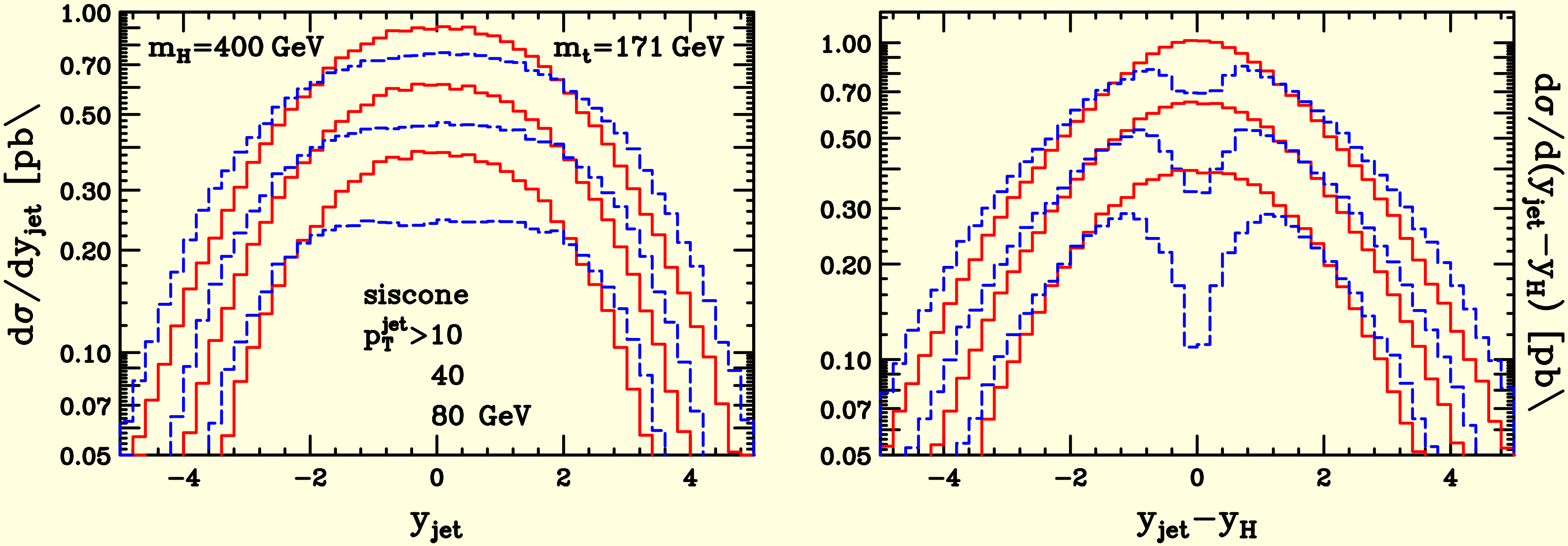


POWHEG distribution as in ALPGEN (Mangano,Moretti,Piccinini,Treccani,Nov.06) and in $t\bar{t}+\mathrm{jet}$ at NLO (Dittmaier, Uwer, Weinzierl) : no dip present.

POWHEG presents no dip; MC@NLO has the dip also in several other distributions



Very evident in Higgs production via gluon fusion:



Why is there a dip in MC@NLO?

The dip is already present in HERWIG alone.

How it propagates to MC@NLO has been clarified in recent publications:

(Hamilton,Richardson,Tully, 2009; Alioli, Oleari, Re, P.N. 2009; P.N. 2010)

In short: in MC@NLO $\mathcal{S}$-events carry a K factor; $\mathcal{H}$-events do not

$$d\sigma = K(\Phi_B) \times \texttt{HERWIG} + [R(\Phi) - R^s(\Phi)]\, d\Phi$$

$$K(\Phi_B) = \frac{\bar{B}(\Phi_B)}{B(\Phi_B)}$$

for large k_T:

$$\frac{d\sigma}{d\Phi} = \underbrace{K R^s(\Phi)}_{\mathcal{S}} + \underbrace{[R(\Phi) - R^s(\Phi)]}_{\mathcal{H}}$$

The $\mathcal{H}$ contribution should cancel the dip in R^s, but, if K is large, there is a leftover. Since $K = 1 + \mathcal{O}(\alpha_s)$, this is an NNLO effect.

Single top

MC@NLO: Frixione, Laenen, Motylinki, Webber, 2006, s and t channel
Frixione, Laenen, Motylinski, Webber, White, 2008, tW (talk by C.White)

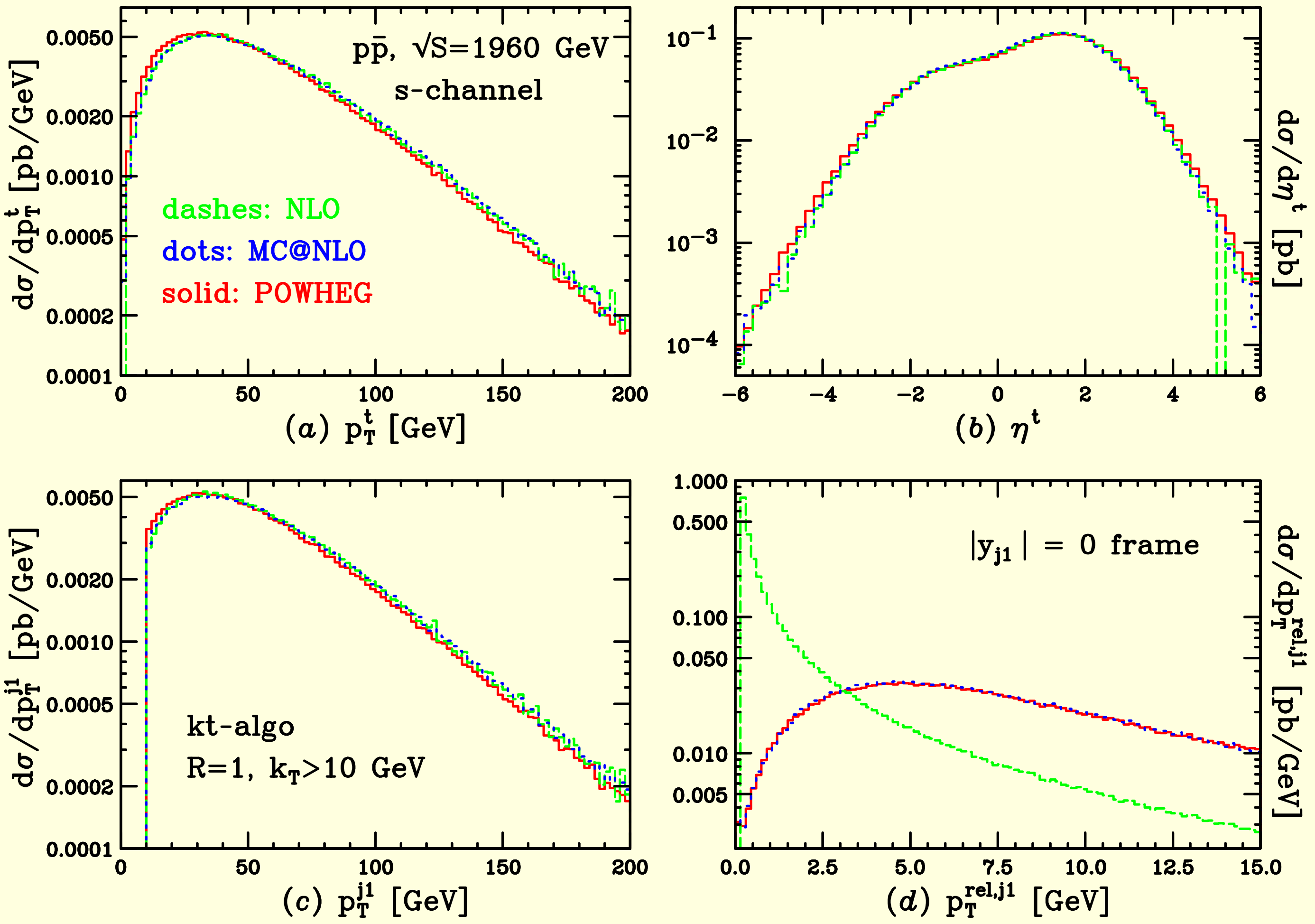
POWHEG: Alioli, Oleari, Re, P.N. 2009, s and t channel; Re, tW (in progress)

Both approaches use:

- Massless b's
- Approx. spin correlations (Frixione, Laenen, Motylinski, Webber, 2007)
- No NLO corrections to top decay

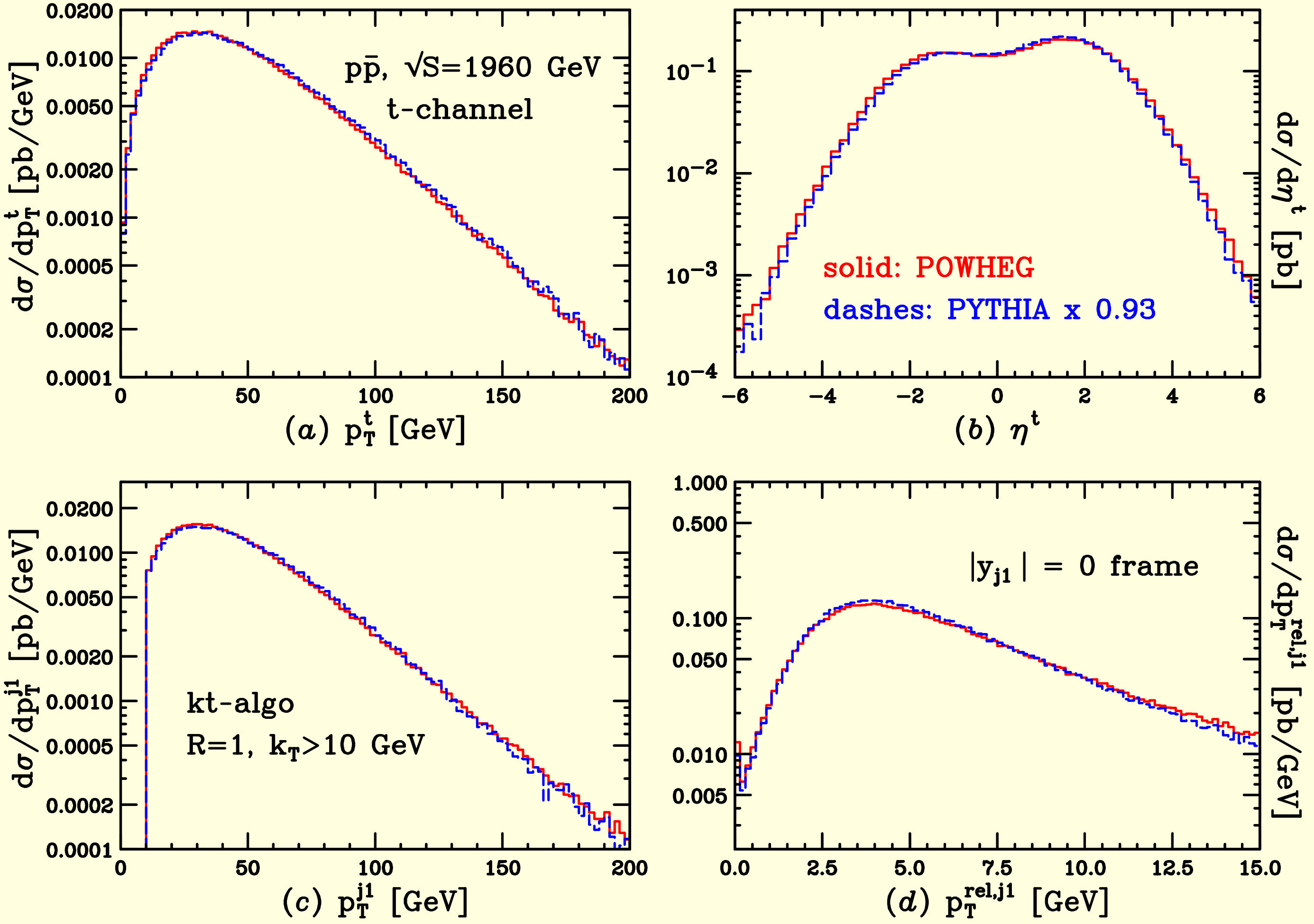
Notice that NLO results are available to remedy to all of these problems:
NLO spin correlations+NLO corrections for top decay:
Campbell, Ellis, Tramontano, 2004; Campbell, Tramontano, 2005;
Mass effects:
Campbell, Frederix, Maltoni, Tramontano, 2009 (see Frederix talk)

Single top POWHEG-MC@NLO comparisons

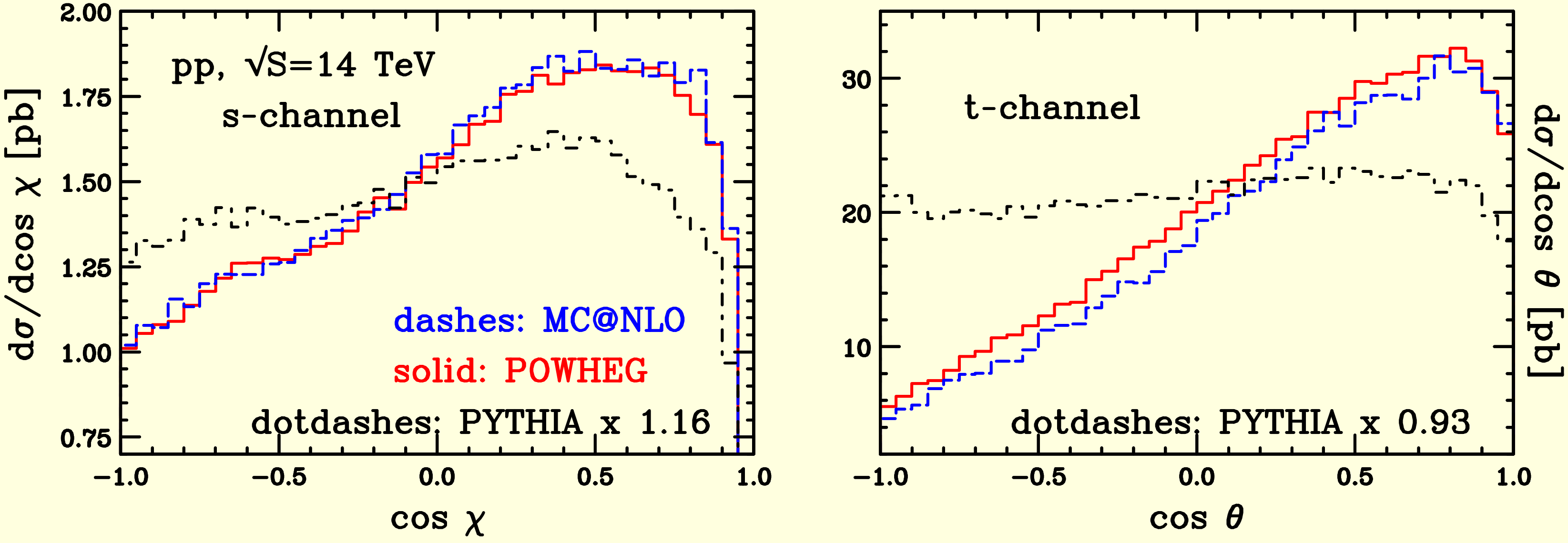


Very good agreement;

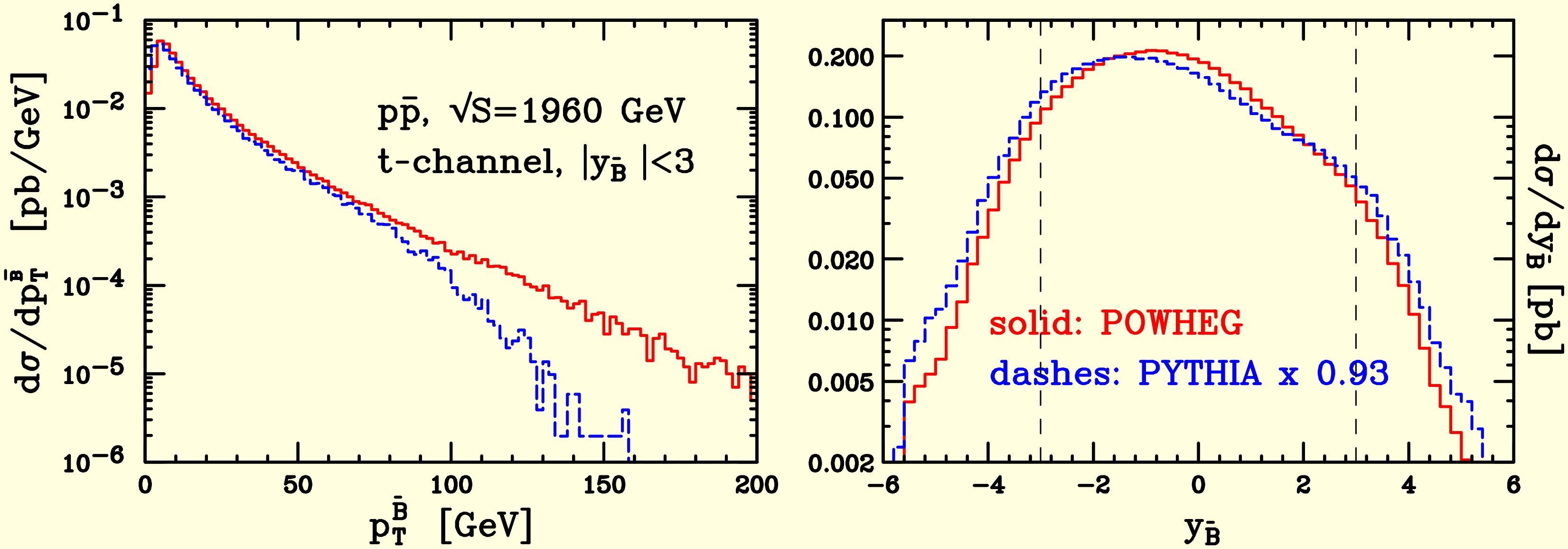
POWHEG-PYTHIA comparisons



PYTHIA with a K factor also good, except for

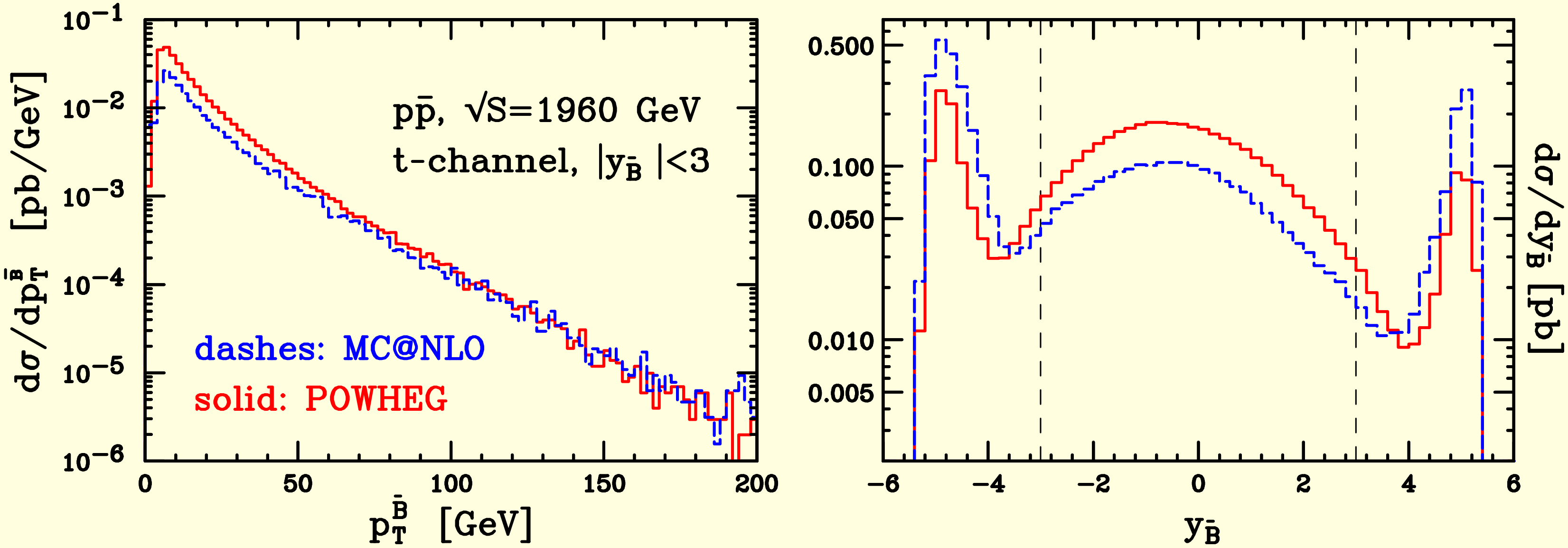


(PYTHIA has no spin correlations)



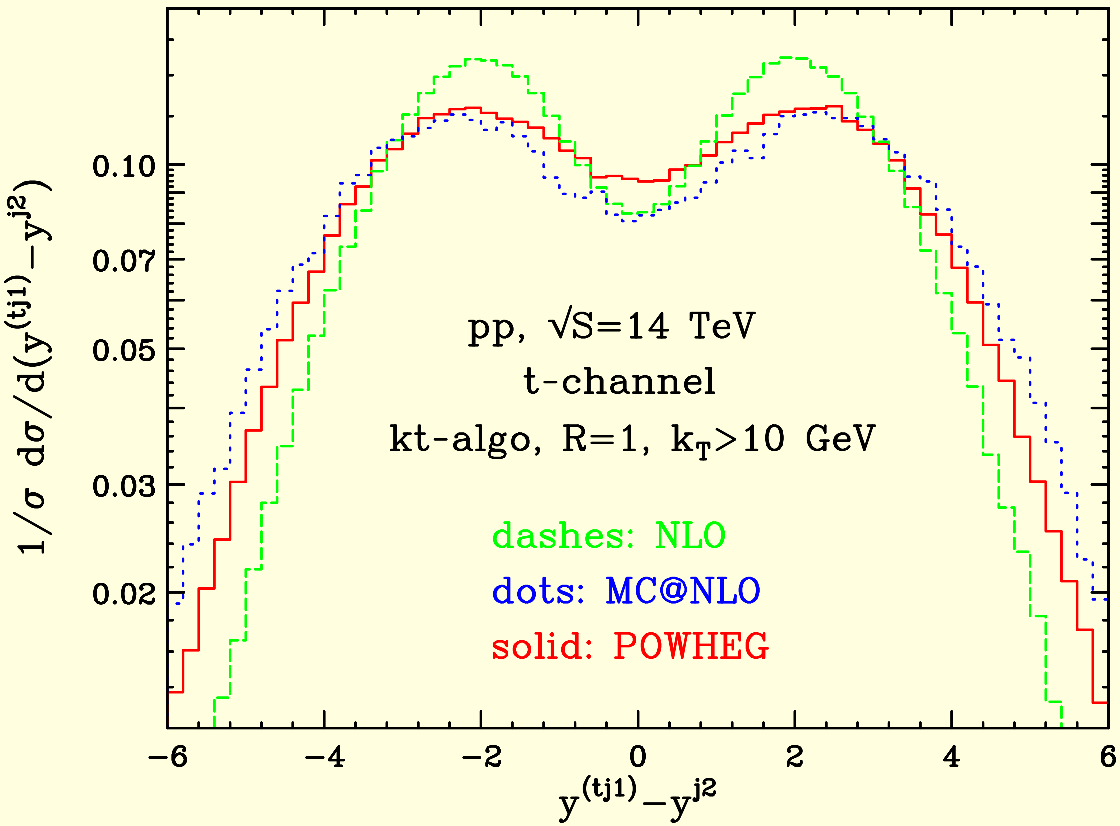
$\bar{B}$ in PYTHIA generated by the backward shower (only accurate at small p_T)

Same plot with `MC@NLO`:



Related to known problem in `HERWIG` in shower generated b quarks.

b's at small p_T not well described in POWHEG and MC@NLO: no b mass.



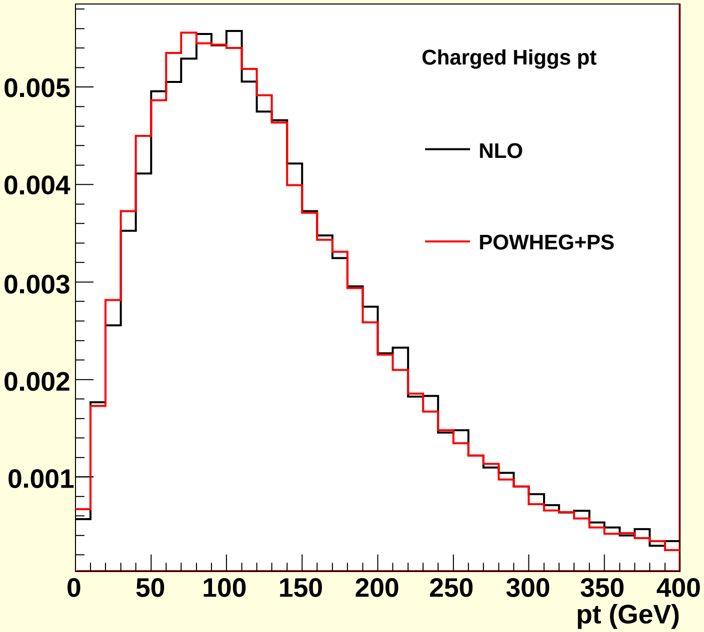
y distribution of radiated jet: a dip is already present at the NLO level, MC@NLO only slightly deeper than POWHEG (K factor near 1 here)

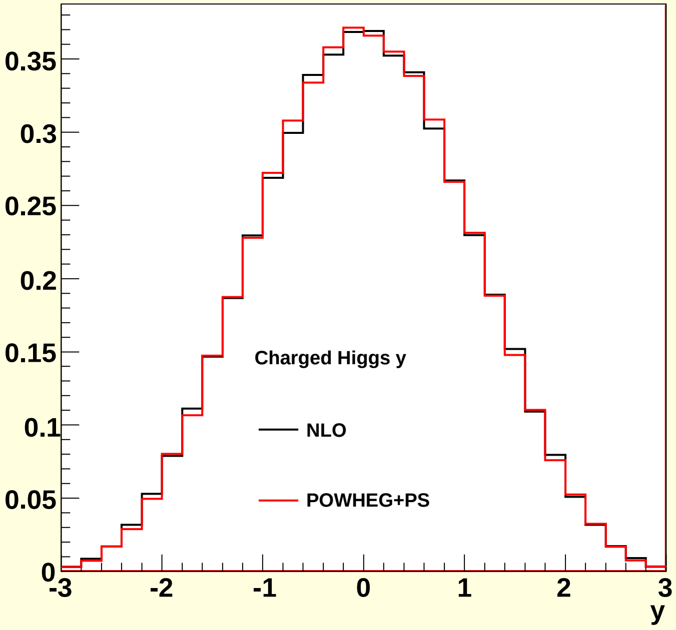
Wt, Ht production

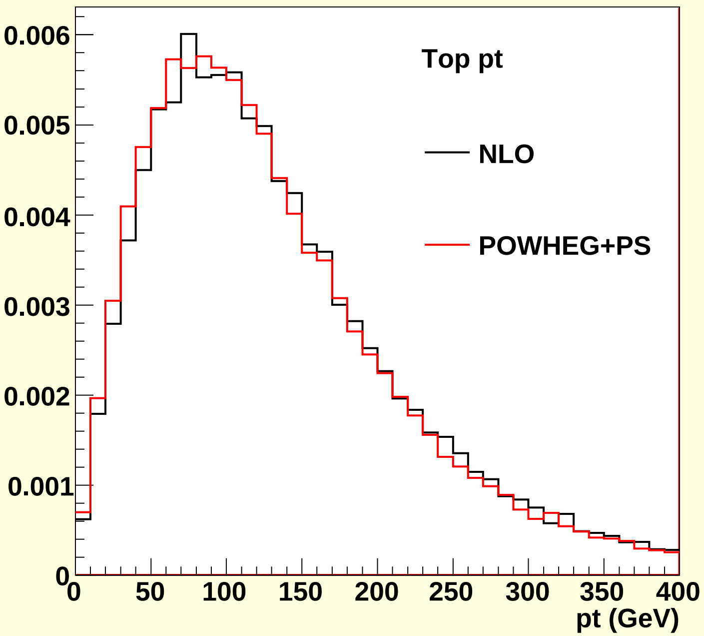
Talk by Chris White

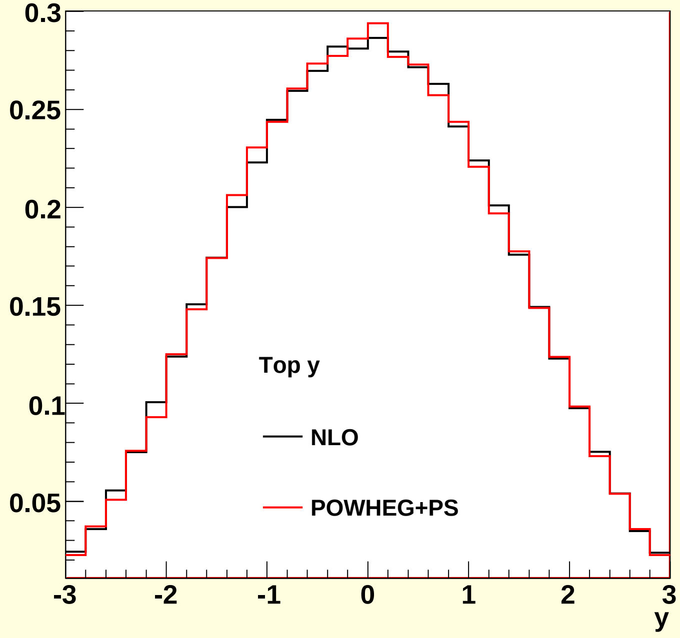
MC@NLO: Weydert,Frixione,Herquet,Klasen,Laenen,Plehn,Stavenga,White 2009

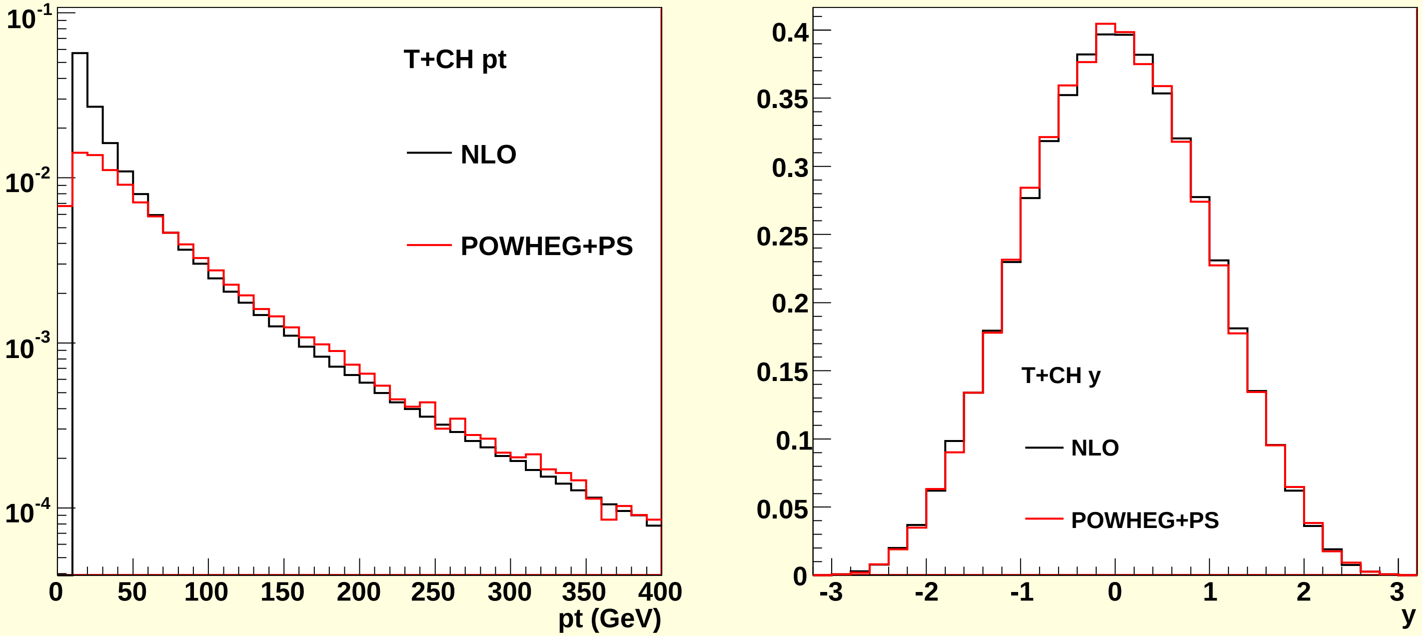
POWHEG: Weydert,Kovarik,Klasen,P.N., in progress (Weydert's poster session)






Top pt
NLO
POWHEG+PS
0.006
0.005
0.004
0.003
0.002
0.001
0
0
50
100
150
200
250
300
350
400
pt (GeV)


Top y
NLO
POWHEG+PS
0.3
0.25
0.2
0.15
0.1
0.05
-3
-2
-1
0
1
2
3
y



T+CH pt
NLO
POWHEG+PS
pt (GeV)
T+CH y
NLO
POWHEG+PS
y

Summary on NLO+PS

- NLO+PS available for several processes, including t production
- The two available methods, `MC@NLO` and `POWHEG` compare reasonably

Several improvements possible from already available NLO results:

$t\bar{t}$:	NLO decays and spin correlations, Melnikov, Shulze 2009
$t\bar{t}+\mathrm{jet}$:	Melnikov, Shulze 2010; Dittmayer, Uwer and Weinzierl, 2007
$t\bar{t}+2\mathrm{jets}$:	Bevilacqua, Czakon, Papadopoulos, Worek, 2010 (talk by Worek)
Single top:	NLO decays and spin correlations, Campbell, Ellis, Tramontano, 2004; Campbell, Tramontano, 2005; b mass effects: Campbell, Frederix, Maltoni, Tramontano, 2009

From Worek talk: several processes involving t quarks have been computed at NLO. NLO calculation are reaching automation.

Perspective

In `POWHEG`: the `POWHEG BOX`, (Alioli, Oleari, Re, P.N. 2009)

a framework for implementing generic NLO processes has been released,

based upon previous theoretical work (Frixione, Oleari, P.N. 2007).

It has been used to implement two fairly complex processes:

VBF Higgs production, (Oleari, P.N. 2009)

$Z + \mathrm{jet}$ production, (Alioli, Oleari, Re, P.N.)

It can be applied to the new NLO results in t production.

Study are under way to merge Z and $Z + \mathrm{jet}$ `POWHEG` samples, thus moving a first step towards including NLO corrections also to associated multijets.

It is conceivable that in the future the same merging may be carried out in $t\bar{t}$ production.

It is time to put together automatic NLO generators and NLO+PS ones!

Given the fact that NLO+PS and ME+PS cover complementary aspects of the production process, the natural question arises: can they be merged?

BIG problem; proposals:

Giele, Kosower, Skands, 2008, VINCIA proposal

Bauer, Tackmann, Thaler, 2009 GenEva (e^+e^-)

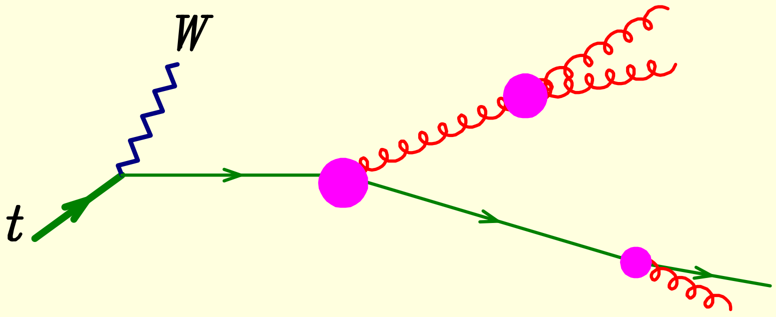
Lavesson, Lonnblad, 2009, (e^+e^-)

First attempt in hadronic collision processes: W and $t\bar{t}$ (Hamilton, P.N. 2010)

Look at ME+PS sample; what does it lack to be NLO accurate?

Simple example: t decay (just one jet!)

In the ME+PS, clusterising final state particles in order of increasing relative k_T, the configuration of hardest emission is the one just before the last clustering. From this configuration, one can also assign an underlying Born configuration to the event.



It can be demonstrated (Hamilton, P.N. 2010) that: in order to achieve NLO accuracy:

the ME+PS result should be reweighted with a $K(\Phi_B)$ factor.

$K(\Phi_B)$ hard to compute numerically (requires further studies).

merge POWHEG and ME+PS samples: MENLOPS

Alternative (approximate) method: build a sample according to the equation

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

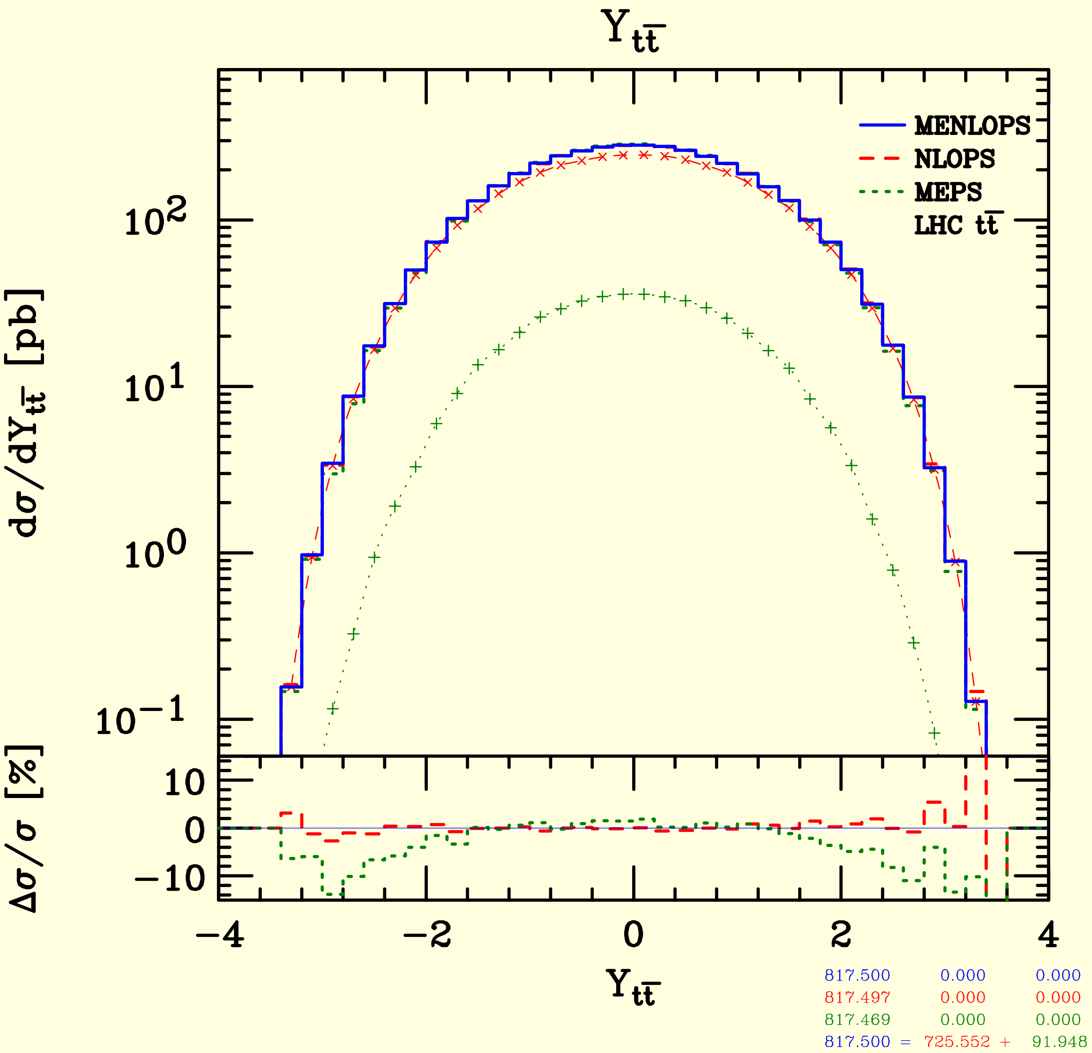
where $\sigma(j)$ is the cross section for j extra jets ($\sigma(\geqslant j)$: j or more). So:

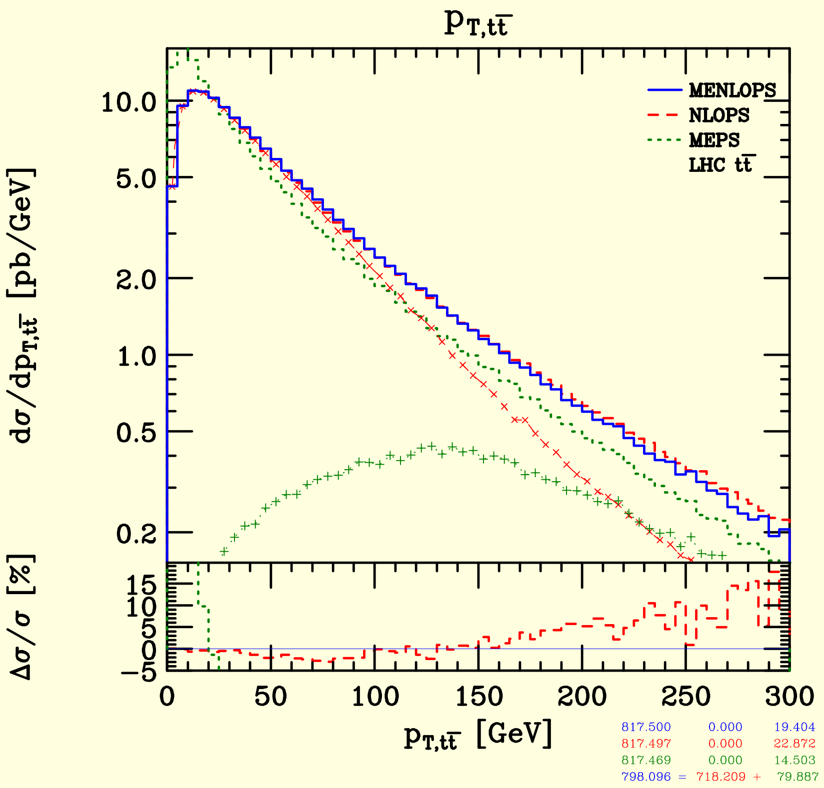
i. Events with no extra jet are always generated by POWHEG
ii. Events with one jet are also generated by POWHEG
iii. Events with more than one jet are generated by the ME+PS
iv. events ii and iii are reweighted, so that:
 the ii to iii ratio is as given by the ME+PS generator
 the total equals the POWHEG total

For our $t\bar{t}$ study:

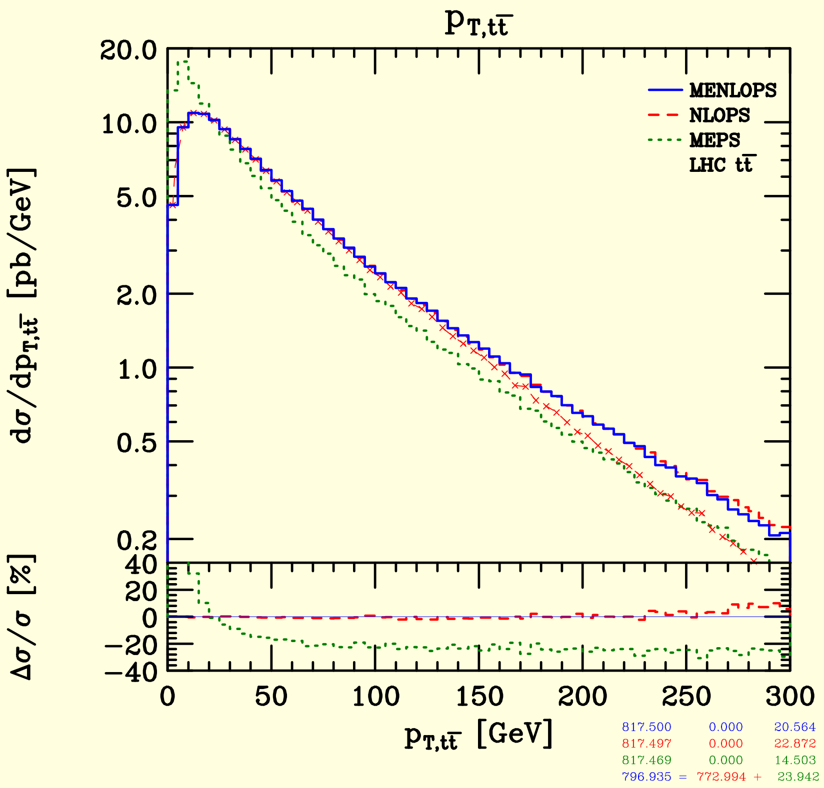
- NLO+PS sample generated using POWHEG
- ME+PS sample from Madgraph (using MLM matching, 20 GeV gen. cut, 30 GeV merging scale, virtuality ordered)
- The MENLOPS mergins scale was chosen equal to 60 GeV.

MEPS slightly too central.
NLOPS recovers NLO accuracy for this distribution.



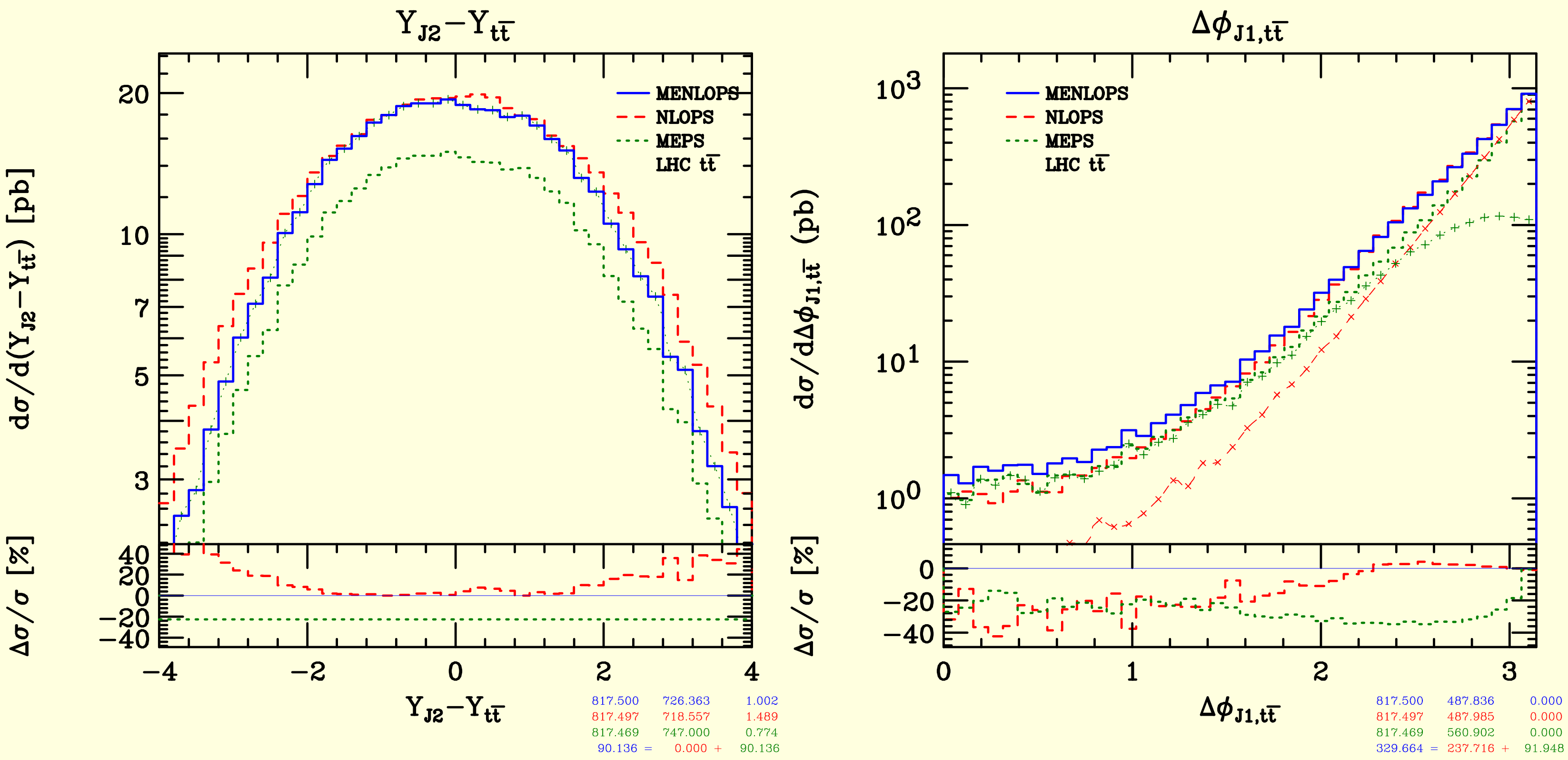


60 GeV MENLOPS scale



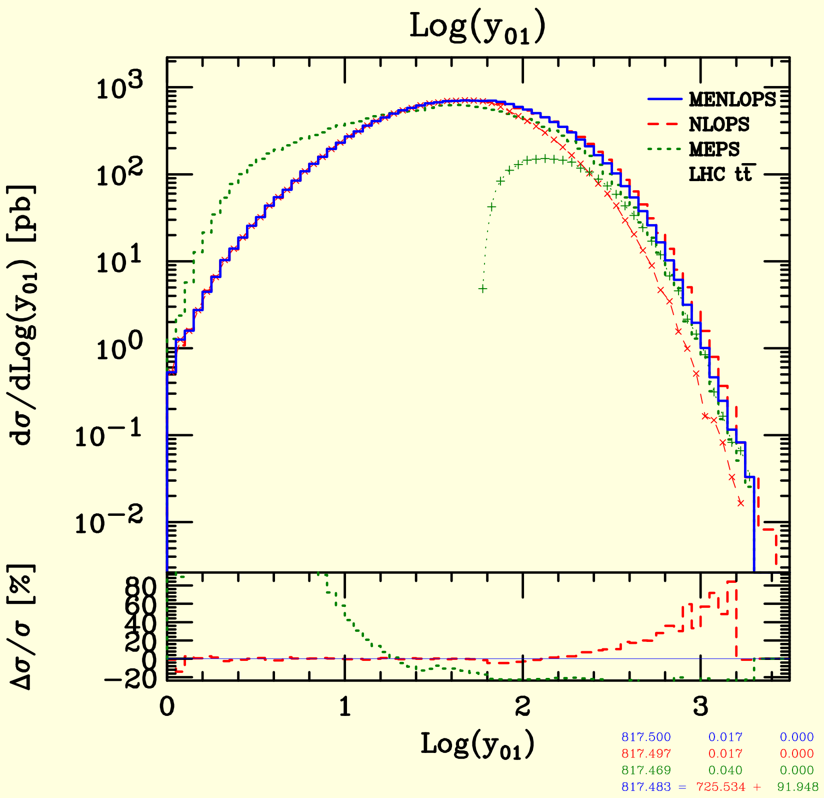
100 GeV MENLOPS scale

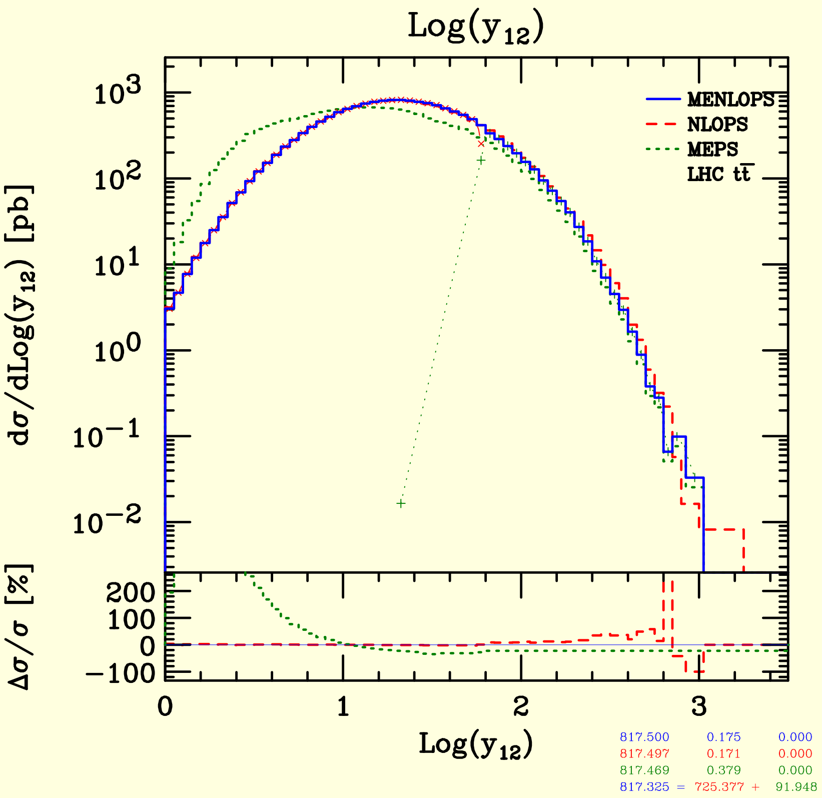
MENLOPS result stable with respect to variation of the merging scale

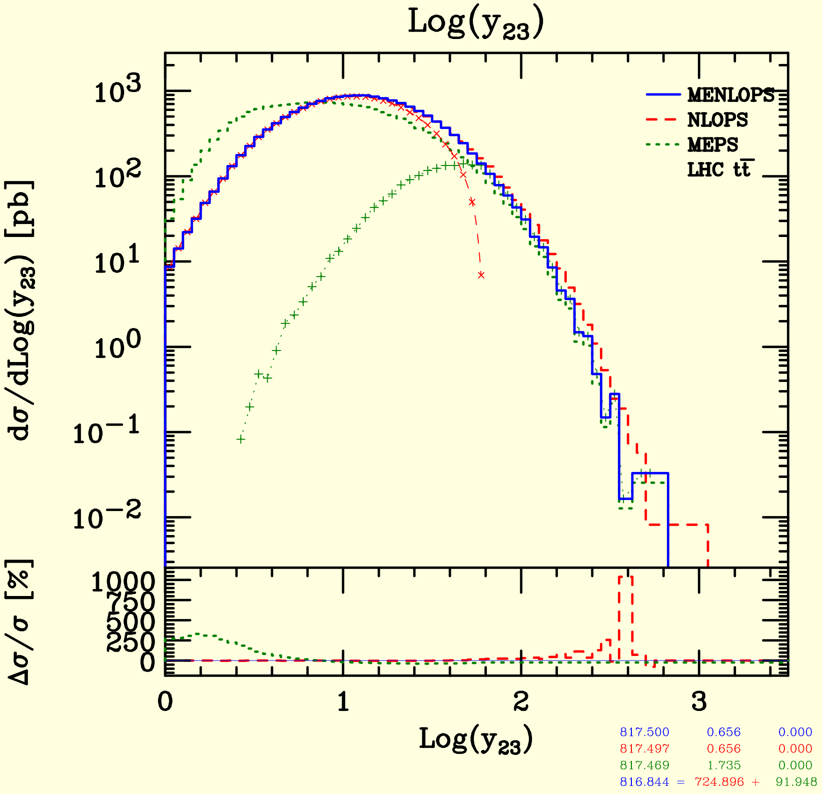


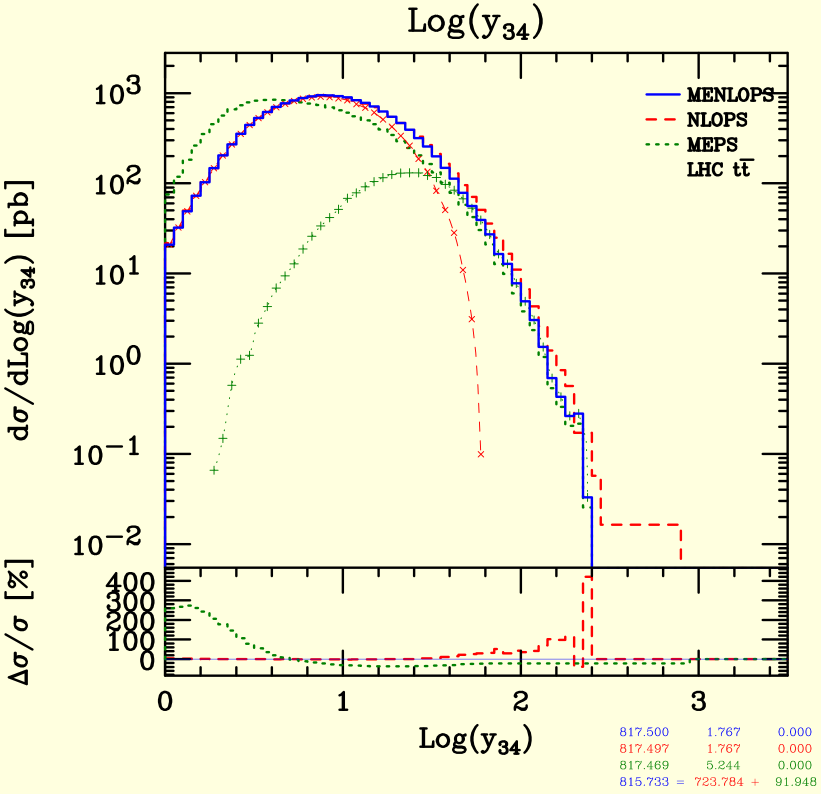
Rapidity of second jet corrected according to the MEPS result.

Azimuthal distance between $t\bar{t}$ system and hardest jet controlled by NLOPS in the back-to-back region, MEPS in the multijet region.


Log(y01)
MENLOPS
NLOPS
MEPS
LHC tt̄
dσ/dLog(y01) [pb]
Δσ/σ [%]
Log(y01)
817.500 0.017 0.000
817.497 0.017 0.000
817.469 0.040 0.000
817.483 = 725.534 + 91.948


Log(y12)
MENLOPS
NLOPS
MEPS
LHC tt̄
dσ/dLog(y12) [pb]
Δσ/σ [%]
Log(y12)
817.500 0.175 0.000
817.497 0.171 0.000
817.469 0.379 0.000
817.325 = 725.377 + 91.948





No kinks observed at the boundary of the merging parameters. So:

- Merging NLO+PS and ME+PS does not look easy
- However: even a very crude approach leads to sensible results

Conclusions

- New techniques for event generators, with higher accuracy, are becoming available: ME+PS and NLO+PS.
- Basic t production processes available.
- Room for improvements: NLO decays, spin correlations
- New avenues:
  - Automation
  - `MENLOPS`: getting the best of NLO+PS and ME+PS
  - NLO accuracy for multijet (i.e. CKKW at NLO)