STATUS OF POWHEG

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MC4LHC readiness, CERN
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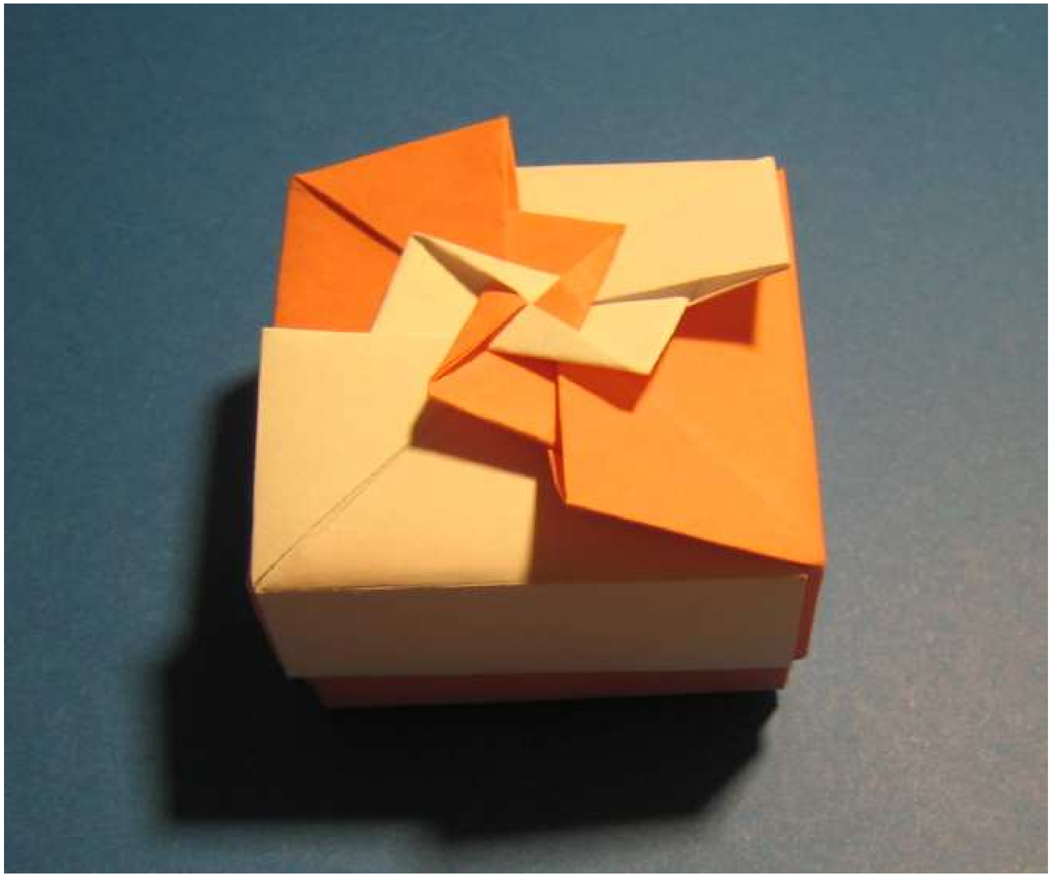
- Status of POWHEG
- The POWHEG BOX
- A few POWHEG results
- Conclusions



POsitive-Weight Hardest Emission Generator

- ✓ it is a method for interfacing NLO calculations with parton shower programs [Nason, `hep-ph/0409146`]
- ✓ it generates the hardest emission first, with NLO accuracy. The produced events have positive weights. The acronym comes from this feature
- ✓ it is independent from parton-shower programs. It can be interfaced with PYTHIA, HERWIG . . .
  It is then possible to compare the different outputs
- ✓ No need to implement new interfaces
  Two possible ways to interface to shower Monte Carlo programs
  1. Les Houches Event format. The event is written on a file that is subsequently showered by HERWIG, PYTHIA. . .
  2. on the fly. We provide UPINIT and UPEVNT directly running in HERWIG and PYTHIA

Existing implementations

Up to now, the following processes have been implemented using the POWHEG method:

- $pp \to ZZ$ [Nason and Ridolfi, `hep-ph/0606275`]
- $e^+e^- \to$ hadrons [Latunde-Dada, Gieseke and Webber, `hep-ph/0612281`]
  $e^+e^- \to t\bar{t}$ with top decay [Latunde-Dada, arXiv:0806.4560]
- $pp \to Q\overline{Q}$ ($c\bar{c}$, $b\bar{b}$, $t\bar{t}$) with spin correlations [Frixione, Nason and Ridolfi, arXiv:0707.3088]
- $pp \to W/Z$ with spin correlations [Alioli, Nason, Oleari and Re, arXiv:0805.4802; Hamilton, Richardson and Tully, arXiv:0806.0290]
- $pp \to H$ [Alioli, Nason, Oleari and Re, arXiv:0812.0578; Hamilton, Richardson and Tully, arXiv:0903.4345]
- $pp \to H + W/Z$ [Hamilton, Richardson and Tully, arXiv:0903.4345]

Existing implementations

- single-top production, in the s and t channel, with top decay [Alioli, Nason, Oleari and Re, arXiv:0907.4076]
- Higgs boson production in vector boson fusion [Nason and Oleari, arXiv:0911.5299] in the POWHEG BOX

All POWHEG implementations for hadronic colliders have been interfaced to both PYTHIA and HERWIG.

To appear very soon

- $pp \to Z + 1$ jet [Alioli, Nason, Oleari and Re] in the POWHEG BOX
- $pp \to VV$ [Hamilton]

The POWHEG BOX

The POWHEG BOX is a computer framework, presented in [Alioli, Nason, Oleari and Re, arXiv: 1002.2581], that implements in practice the theoretical construction of the POWHEG formalism, for generic NLO processes, according to the general formulation of POWHEG given in [Frixione, Nason and Oleari, arXiv:0709.2092]

More precisely, the user should only supply:

- ✓ the lists of the Born and real processes (i.e. $sc \to gud \Longleftrightarrow [3,4,0,2,1]$)
- ✓ the Born phase space
- ✓ the Born squared amplitudes, the color-correlated and spin-correlated amplitudes, for all partonic subprocesses
  All these amplitudes are common ingredients of a NLO calculation
- ✓ the real squared amplitude for all the relevant real-emission subprocesses
- ✓ the finite part of the virtual corrections, computed in conventional dimensional regularization or in dimensional reduction
- ✓ the Born color structures in the limit of large number of colors.

All the rest will be done **automatically**!

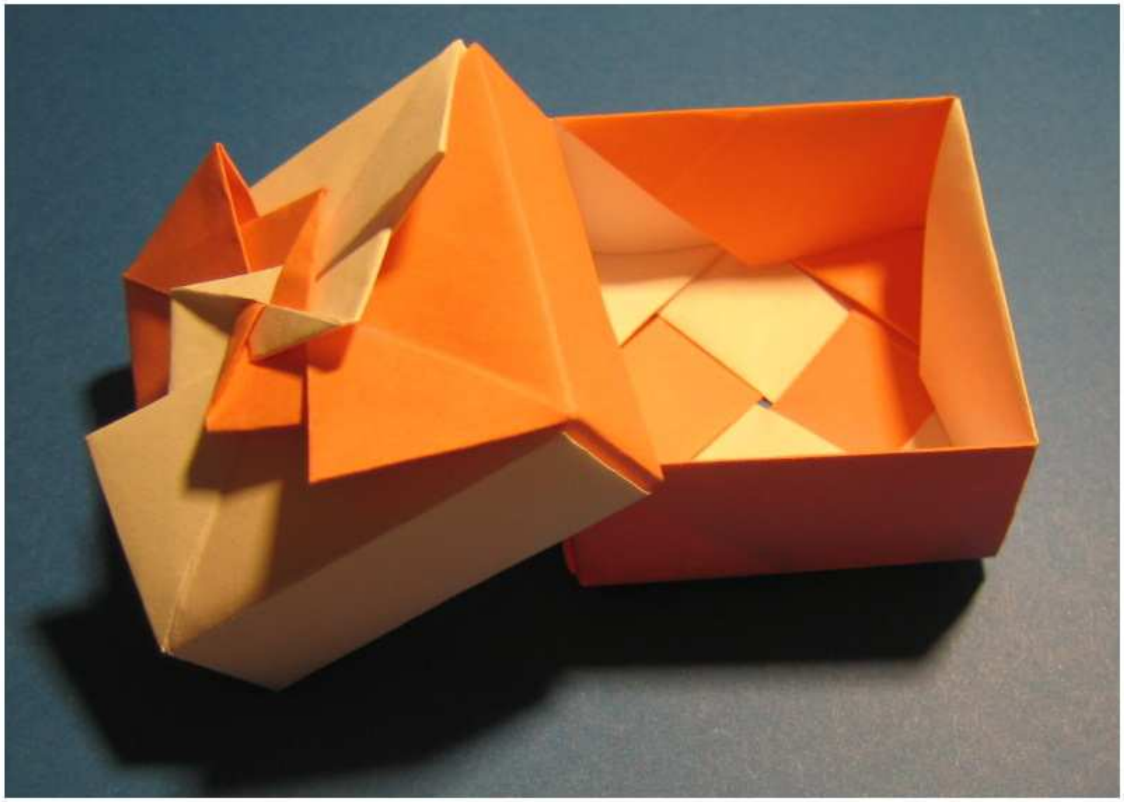
The POWHEG BOX

The user should not worry about

- ✓ the phase space for initial-state radiation and final-state radiation (i.e. the phase space for real emission)
- ✓ the combinatorics, the calculation of all singular regions in the real amplitude R, the soft and collinear limits, the calculation of all the counterterms
- ✓ the calculation of the differential NLO cross section (the $\bar{B}$ contribution). Spinoff: NLO results using the FKS subtraction scheme
- ✓ the calculation of the upper bounds for the generation of radiation
- ✓ the generation of radiation
- ✓ writing the event into the Les Houches interface

The user has only to know in which format to supply the ingredients listed before.

The POWHEG BOX



No need to open the BOX!

The POWHEG BOX How-To

- `parameter (nlegborn=5)` $[pp\to(Z\to e^+e^-)+j]$ in included file `pwhg_flst.h`
  `flst_nborn` and `flst_nreal`
- `flst_born(k=1..nlegborn,j=1..flst_nborn)`: flavour of the k-th leg of the j-th Born graph
  `flst_real(k=1..nlegreal,j=1..flst_nreal)`: flavour of the k-th leg of the j-th real graph.
  It is required that legs in the Born and real processes have to be ordered as follows:
  - leg 1, incoming parton with positive rapidity
  - leg 2, incoming parton with negative rapidity
  - from leg 3 onward, final state particles, in the order: colorless particles first, massive coloured particles, massless coloured particles.

  The flavour is taken incoming for the two incoming particles and outgoing for the outgoing particles. The flavour index is assigned according to PDG conventions, except for gluons, where 0 is used instead of 21.
  Example: $pp\to(Z\to e^+e^-)+2j$, the string `[1,0,-11,11,1,0]` labels the process $dg\to e^+e^-dg$
- `init_couplings`

- `born_phsp(xborn)` for Born phase space
  `xborn(1..ndim)` array of random numbers `ndim=(nlegborn-2)*3-4+2-1`
  - the Born Jacobian `kn_jacborn`, Born momenta in the laboratory frame `kn_pborn(0:3,1..nlegborn)`, Born momenta in the partonic CM frame `kn_cmpborn(0:3,1..nlegborn)` and Bjorken x (`kn_xb1` and `kn_xb2`).
- `set_ren_fac_scales(mur,muf)`
- `setborn(p,bflav,born,bornjk,bmunu)`
  - the momenta `p(0:3,1..nlegborn)`
  - the flavour string `bflav(1..nlegborn)`
  - `bornjk(1..nlegborn,1..nlegborn)`
  - the Born helicity-correlated squared amplitudes `bmunu(0:3,0:3,j=1..nlegborn)`
- `setvirtual(p,vflav,virtual)` returns finite part of the interference $2\,\mathrm{Re}\left(M_B \times M_V\right)$, after factorizing out ($d = 4 - 2\epsilon$)

$$\mathcal{N} = \frac{(4\pi)^\epsilon}{\Gamma(1-\epsilon)} \left(\frac{\mu^2}{Q^2}\right)^\epsilon \frac{\alpha_s}{2\pi}$$

- `setreal(p,rflav,amp2)`
  - the momenta `p(0:3,1..nlegreal)`
  - the flavour string `rflav(1...nlegreal)`
  - amp2: spin and color summed and averaged real squared amplitudes

The POWHEG BOX today

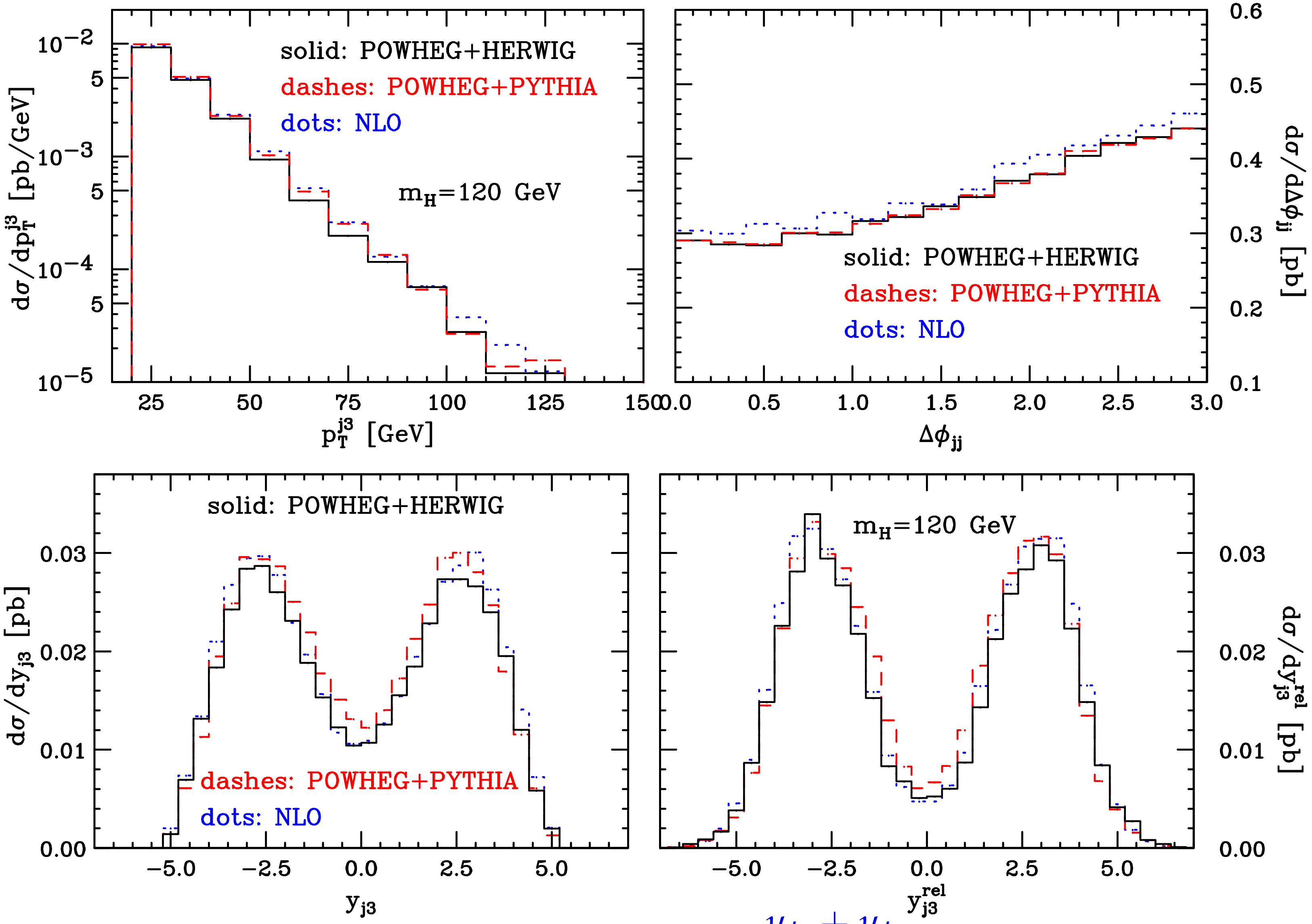
The POWHEG BOX is a package in evolution.

As new processes are implemented in the BOX, new problems will probably need to be solved and the code will change accordingly.

Right now, in the code, you can find

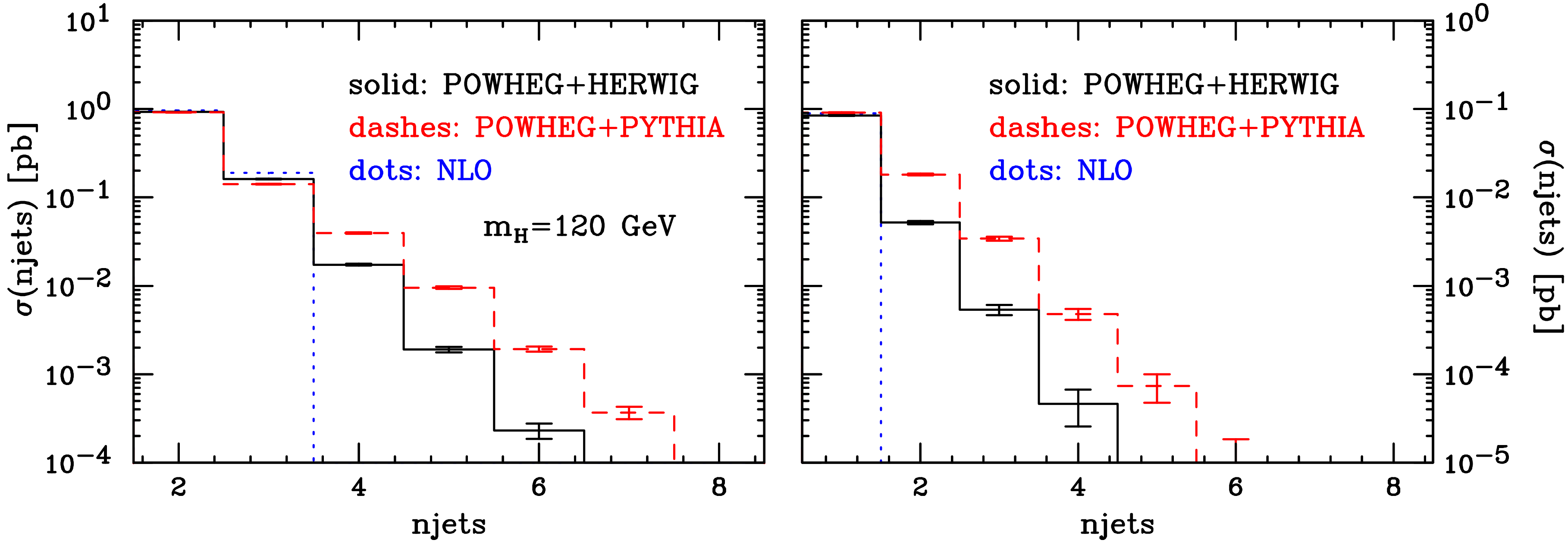
- W production: $pp(\bar{p}) \rightarrow W \rightarrow l\nu_l$ $\Longleftarrow$ Born zero diagrams
- Z production: $pp(\bar{p}) \rightarrow Z \rightarrow l^- l^+$
- Higgs production in gluon fusion $\Longleftarrow$ tuning of the real cross section
- Higgs production in VBF $\Longleftarrow$ tagging parton lines
- $Z+1$ jet: $pp(\bar{p}) \rightarrow Z + 1\ \text{jet} \rightarrow l^- l^+ + 1\ \text{jet}$ $\Longleftarrow$ divergent Born

Higgs boson in VBF



$$y_{j_3}^{\text{rel}} = y_{j_3} - \frac{y_{j_1} + y_{j_2}}{2}$$

Higgs boson in VBF

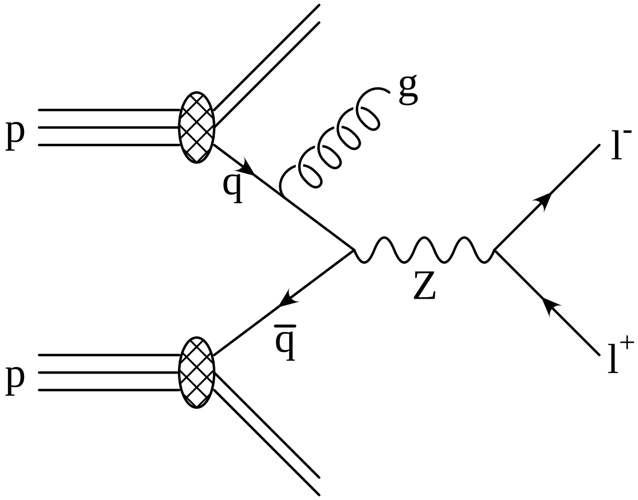


$$p_{Tj} > 20\,\text{GeV}, \qquad |y_j| < 5$$

$$p_T{}^{\text{tag}} > 30\,\text{GeV}, \qquad |y_{j_1} - y_{j_2}| > 4.2\,, \qquad y_{j_1} \cdot y_{j_2} < 0\,, \qquad m_{jj} > 600\,\text{GeV}$$

$$\text{veto jet}: \quad \min\left(y_{j_1}, y_{j_2}\right) < y_j < \max\left(y_{j_1}, y_{j_2}\right)$$

$Z + 1$ jet



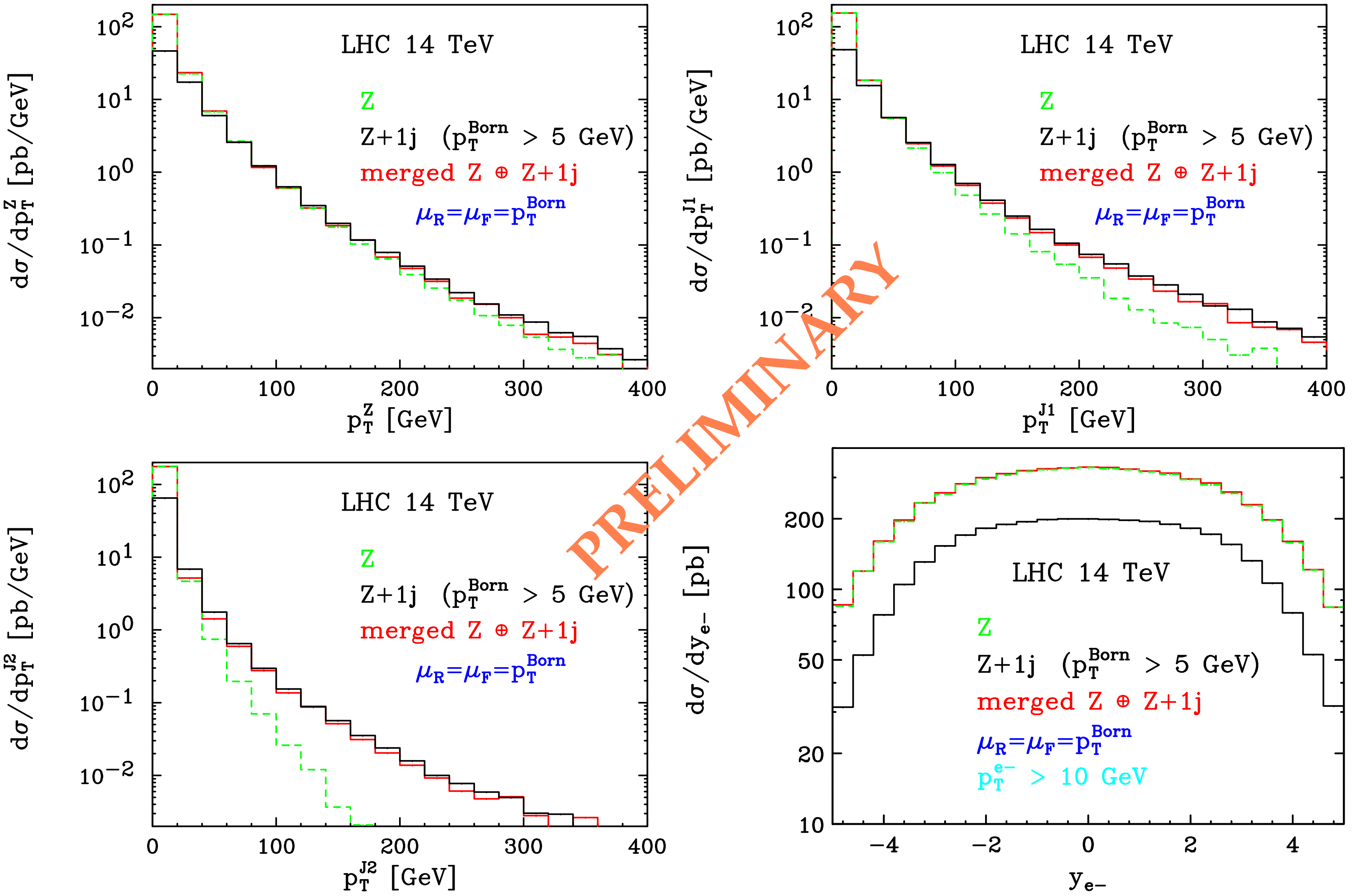
New problem to solve: the Born contributions are divergent.

POWHEG starts from a Born diagram and attaches radiation.

Simplest solution: introduce a cutoff. Generate events starting from partonic Born events with $p_T^{\text{Born}} > p_T^{\text{min}}$

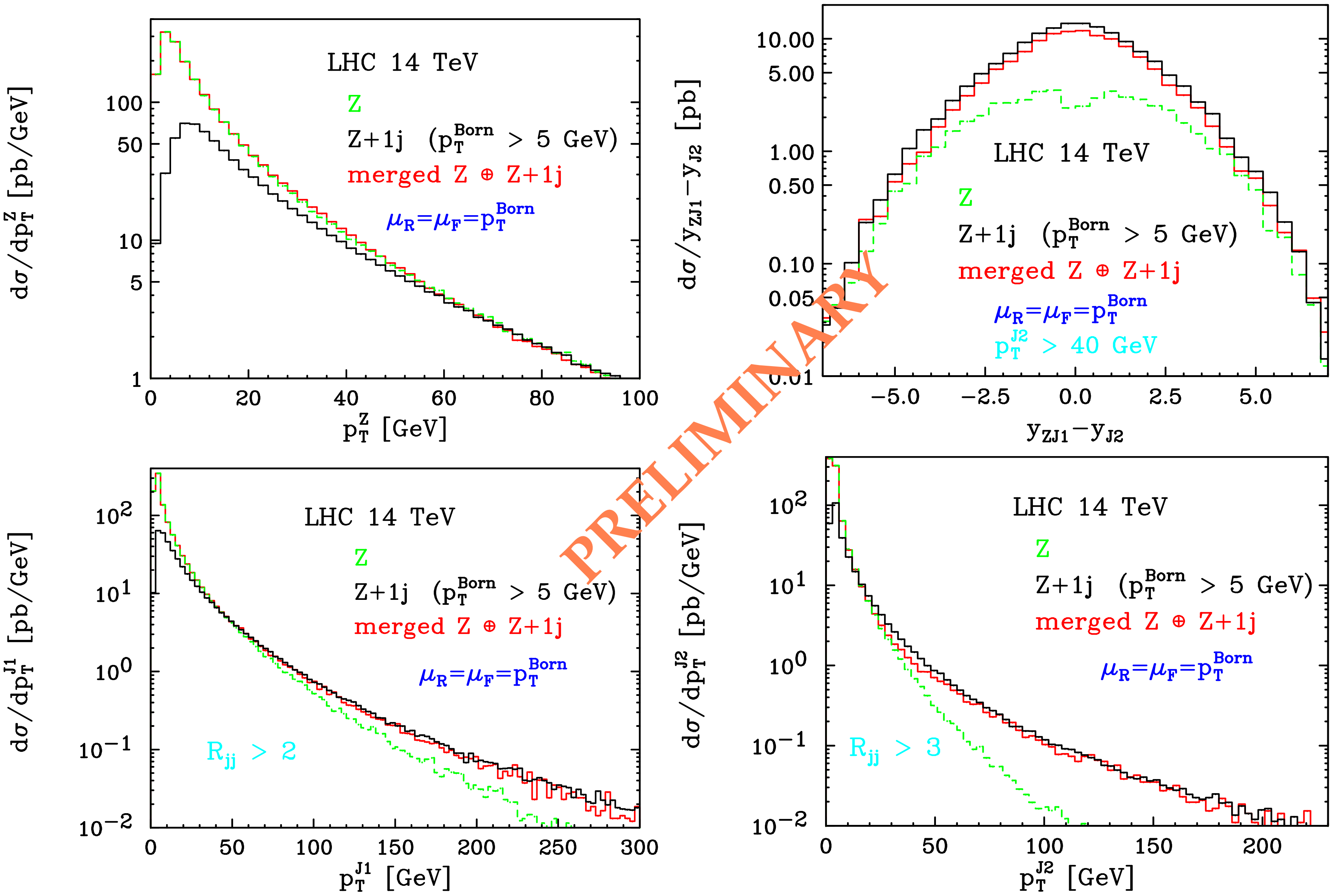
- Study the effect of the cutoff at the partonic Born level on showered events
- Find a way to merge consistently NLO Z and $Z + 1$ jet events.

Preliminary merged Z and $Z + 1$ jet events



All results showered by HERWIG

Preliminary merged Z and $Z + 1$ jet events



All results showered by HERWIG

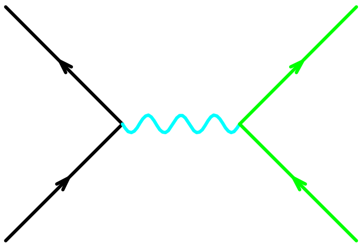
Conclusions

- ✓ It is relatively easy to add new processes in the POWHEG BOX.
- ✓ No need to know how it works but only how to “communicate” with it.
- ✓ Please, feel free to get in touch with us if you want to implement new NLO calculations into the POWHEG BOX.

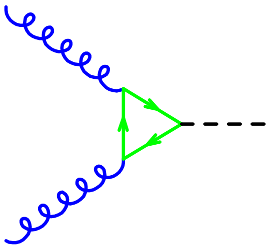
Backup slides

High energy collisions

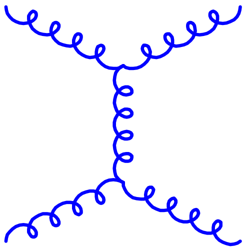
High-energy particle physics deals with the scattering and the production of elementary constituents



$e^+e^- \longrightarrow q\bar{q}$



$gg \longrightarrow H$

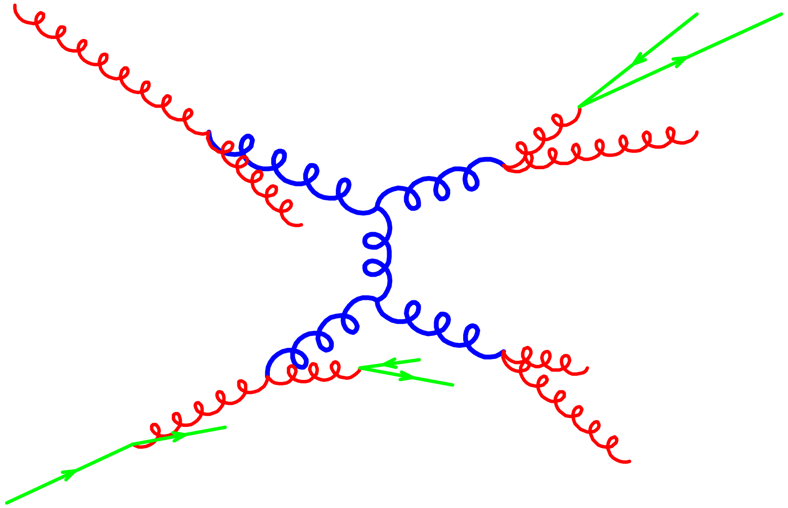


$gg \longrightarrow gg$

Ideally, one needs elementary constituents as projectiles and targets, (i.e. a collider for leptons, gluons and quarks) and a final-state detector of leptons, gluons and quarks. Not obvious for quarks and gluons:

- at short distance, due to asymptotic freedom, quarks and gluons behave as free particles
- at long distance, infrared slavery: very strong interactions hide the simplicity of the description of the constituents.

Dominant corrections



Collinear-splitting processes in the initial and final state (always with transverse momenta $> \Lambda_{\text{QCD}}$) are strongly enhanced. This is due to the fact that, in perturbation theory, the denominators in the propagators are small.

- The algorithms that evaluate all these enhanced contributions are called shower algorithms.
- Shower algorithms give a description of a hard collision up to distances of order $1/\Lambda_{\text{QCD}}$.
- At larger distances, perturbation theory breaks down and we need to resort to non-perturbative methods (i.e. lattice calculations). However, these methods can be applied only to simple systems. The only viable alternative is to use models of hadron formation.

Hadronic final states

```
IHEP    ID      IDPDG IST MO1 MO2 DA1 DA2   P-X     P-Y     P-Z  ENERGY    MASS     V-X       V-Y       V-Z       V-C*T
  30 NU_E          12   1  28  23   0   0   64.30   25.12-1194.4 1196.4    0.00 0.000E+00 0.000E+00 0.000E+00 0.000E+00
  31 E+           -11   1  29  23   0   0  -22.36    6.19 -234.2  235.4    0.00 0.000E+00 0.000E+00 0.000E+00 0.000E+00
 230 PI0          111   1 155  24   0   0    0.31    0.38    0.9    1.0    0.13 4.209E-11 6.148E-11-3.341E-11 5.192E-10
 231 RHO+         213 197 155  24 317 318   -0.06    0.07    0.1    0.8    0.77 4.183E-11 6.130E-11-3.365E-11 5.189E-10
 232 P           2212   1 156  24   0   0    0.40    0.78    1.0    1.6    0.94 4.156E-11 6.029E-11-4.205E-11 5.250E-10
 233 NBAR       -2112   1 156  24   0   0   -0.13   -0.35   -0.9    1.3    0.94 4.168E-11 6.021E-11-4.217E-11 5.249E-10
 234 PI-         -211   1 157   9   0   0    0.14    0.34  286.9  286.9    0.14 4.660E-13 8.237E-12 1.748E-09 1.749E-09
 235 PI+          211   1 157   9   0   0   -0.14   -0.34  624.5  624.5    0.14 4.056E-13 8.532E-12 2.462E-09 2.462E-09
 236 P           2212   1 158   9   0   0   -1.23   -0.26    0.9    1.8    0.94-4.815E-11 1.893E-11 7.520E-12 3.252E-10
 237 DLTABR--   -2224 197 158   9 319 320    0.94    0.35    1.6    2.2    1.23-4.817E-11 1.900E-11 7.482E-12 3.252E-10
 238 PI0          111   1 159   9   0   0    0.74   -0.31  -27.9   27.9    0.13-1.889E-10 9.893E-11-2.123E-09 2.157E-09
 239 RHO0         113 197 159   9 321 322    0.73   -0.88  -19.5   19.5    0.77-1.888E-10 9.859E-11-2.129E-09 2.163E-09
 240 K+           321   1 160   9   0   0    0.58    0.02  -11.0   11.0    0.49-1.890E-10 9.873E-11-2.135E-09 2.169E-09
 241 KL_1-     -10323 197 160   9 323 324    1.23   -1.50  -50.2   50.2    1.57-1.890E-10 9.879E-11-2.132E-09 2.166E-09
 242 K-          -321   1 161  24   0   0    0.01    0.22    1.3    1.4    0.49 4.250E-11 6.333E-11-2.746E-11 5.211E-10
 243 PI0          111   1 161  24   0   0    0.31    0.38    0.2    0.6    0.13 4.301E-11 6.282E-11-2.751E-11 5.210E-10
```

High-energy experimental physicists feed this kind of output through their detector-simulation software, and use it to determine efficiencies for signal detection, and perform background estimates.

Analysis strategies are set up using these simulated data.

A word of warning

> “The Monte Carlo simulation has become the major mean of visualization of not only detector performance but also of physics phenomena. So far so good. But it often happens that the physics simulations provided by the Monte Carlo generators carry the authority of data itself. They look like data and feel like data, and if one is not careful they are accepted as if they were data.”
>
> J.D. Bjorken

Talk given at the 75th anniversary celebration of the Max-Planck Institute of Physics, Munich, Germany, December 10th, 1992, as quoted in Beam Line, Winter 1992, Vol. 22, No. 4. Reference taken from Sjöstrand.

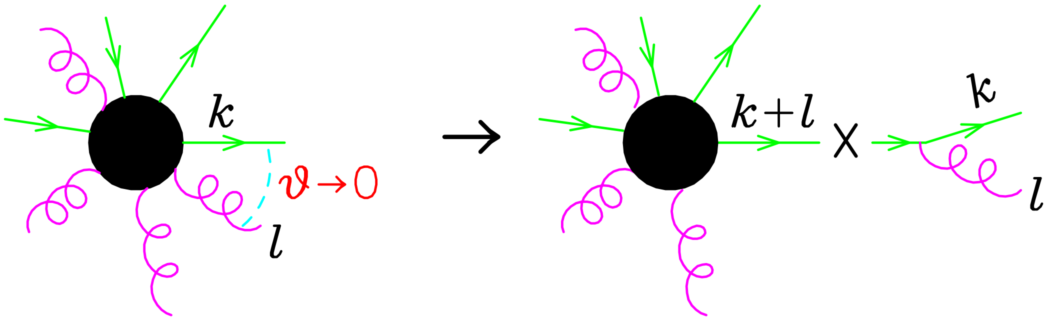
Summarizing

- In high-energy collider physics not many questions can be answered without a Shower Monte Carlo (SMC).
- The name shower comes from the fact that we dress a hard event with QCD radiation.
- After a latency period, many physicists are now looking at shower Monte Carlo models again, under different perspective: Catani, Krauss, Kühn & Webber; Mangano, Moretti, Piccinini, Pittau, Polosa & Treccani; Frixione & Webber; Kramer, Mrenna, Nagy & Soper; Giele, Kosower & Skands; Bauer & Schwartz; Schumann & Krauss; Dinsdale, Ternick & Weinzierl; . . .
- Shower algorithms summarize most of our knowledge in perturbative QCD: infrared cancellations, Altarelli-Parisi equations, soft coherence, Sudakov form factors. All have a simple interpretation in terms of shower algorithms.

Shower basics: collinear factorization

QCD emissions are enhanced near the collinear limit

Cross sections factorize near collinear limit



$$d\mathbf{\Phi}_{n+1} = d\mathbf{\Phi}_n \, d\Phi_r \qquad\qquad d\Phi_r \div dt\, dz\, d\varphi$$

$$|M_{n+1}|^2 d\mathbf{\Phi}_{n+1} \Longrightarrow |M_n|^2 \, d\mathbf{\Phi}_n \frac{\alpha_s}{2\pi} \frac{dt}{t} P_{q,qg}(z)\, dz\, \frac{d\varphi}{2\pi} \qquad \begin{cases} \dfrac{dt}{t} \approx \dfrac{d\theta}{\theta} & \text{collinear singularity} \\[2ex] \dfrac{dz}{1-z} \approx \dfrac{dE_g}{E_g} & \text{soft singularity} \end{cases}$$

t : $(k+l)^2,\ p_T^2,\ E^2\theta^2 \ldots$

$z = k^0/(k^0 + l^0)$: energy (or $p_{\parallel}$ or p^+) fraction of quark

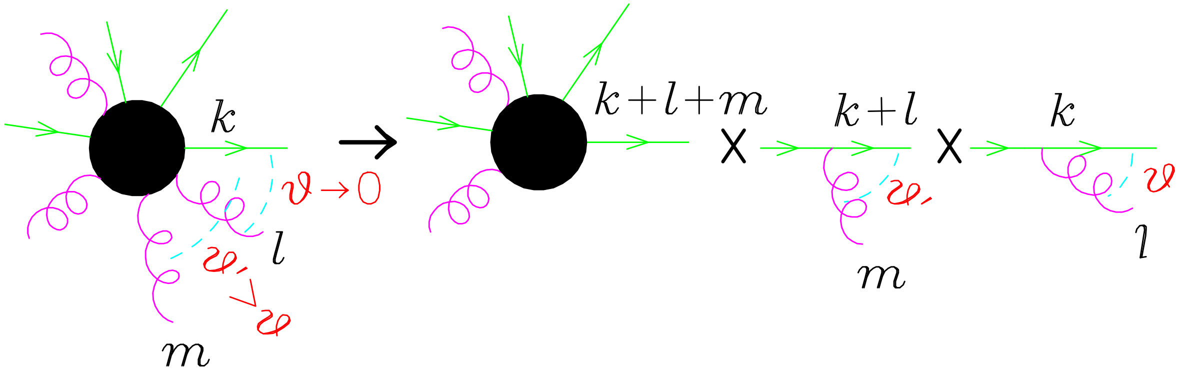
$P_{q,qg}(z) = C_F \dfrac{1+z^2}{1-z}$: Altarelli-Parisi splitting function

(ignore $z \to 1$ IR divergence for now)

Shower basics: collinear factorization

If another gluon becomes collinear, iterate the previous formula

$\theta', \theta \to 0$ with $\theta' > \theta$



$$|M_{n+1}|^2 d\mathbf{\Phi}_{n+1} \quad \Longrightarrow \quad |M_{n-1}|^2 d\mathbf{\Phi}_{n-1} \times \frac{\alpha_s}{2\pi}\frac{dt'}{t'} P_{q,qg}(z')\,dz'\,\frac{d\varphi'}{2\pi}$$
$$\times \frac{\alpha_s}{2\pi}\frac{dt}{t} P_{q,qg}(z)\,dz\,\frac{d\varphi}{2\pi}\,\theta(t'-t)$$

Collinear partons can be described by a factorized integral ordered in t.

Collinear factorization: multiple emissions

For n collinear emissions, the cross section goes as

$$\sigma \approx \sigma_0 \, \alpha_s^n \int_{t_0}^{Q^2} \frac{dt_1}{t_1} \frac{dt_2}{t_2} \ldots \frac{dt_n}{t_n} \, \theta\left(Q^2 > t_1 > t_2 > \ldots > t_n > t_0\right)$$

$$= \sigma_0 \, \alpha_s^n \int_{t_0}^{Q^2} \frac{dt_1}{t_1} \int_{t_0}^{t_1} \frac{dt_2}{t_2} \ldots \int_{t_0}^{t_{n-1}} \frac{dt_n}{t_n} \approx \sigma_0 \, \alpha_s^n \frac{1}{n!} \left(\log \frac{Q^2}{t_0}\right)^n$$

- Q^2 is an upper cutoff for the ordering variable t
- $t_0 \approx \Lambda^2 \approx \Lambda^2_{\rm QCD}$ is an infrared cutoff (quark mass, confinement scale)
- Due to the log dependence, we call it leading-log approximation.
- According to the Kinoshita-Lee-Nauenberg theorem, the virtual corrections, order by order, contribute with a comparable term, with opposite sign.
- The virtual leading-log contribution should be included in order to get sensible results!

Simple probabilistic interpretation of “not-resolved” corrections

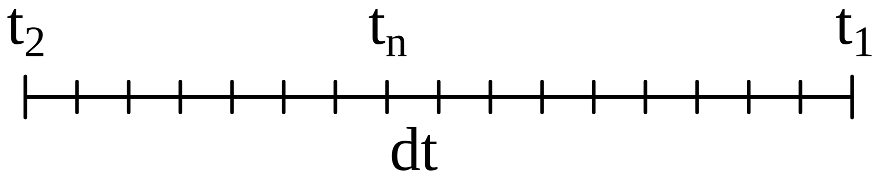
- probability of emission in the interval dt, at order α_s (multiple emissions are of higher orders in α_s)

$$dP_{\rm emis}(t+dt,t) = \frac{dt}{t}\,\frac{\alpha_s(t)}{2\pi}\int dz\, P_{i,jk}(z)$$

- probability of no emission in the interval dt

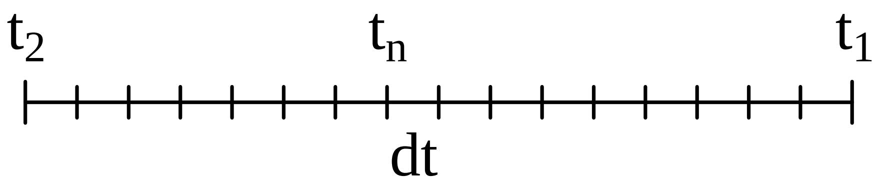
$$dP_{\text{no emis}}(t+dt,t) = 1 - dP_{\rm emis}(t+dt,t) = 1 - \frac{dt}{t}\,\frac{\alpha_s(t)}{2\pi}\int dz\, P_{i,jk}(z)$$

The “no emission” probability contains, through the 1, all the virtual corrections (in the collinear approximation, that is at the leading-log level).



Simple probabilistic interpretation of “not-resolved” corrections

- divide a finite interval $[t_2, t_1]$ in N small intervals $dt = (t_1 - t_2)/N$.



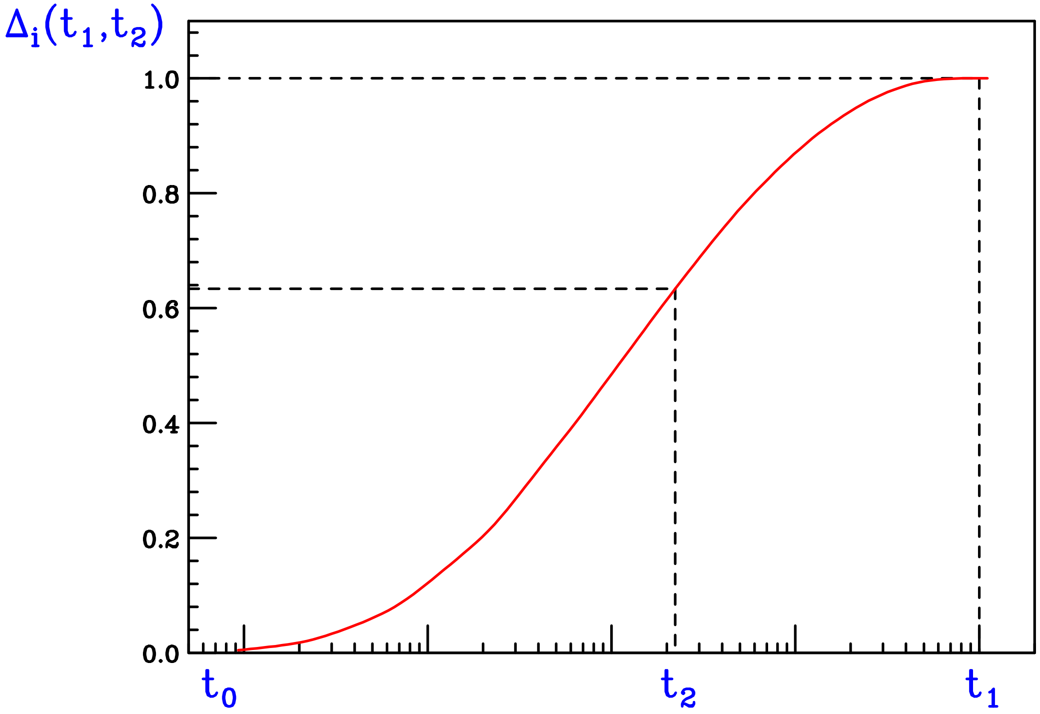
The probability of not emitting radiation between the two ordering scales t_1 and t_2 is given by the product

$$\begin{aligned} P_{\text{no emis}}(t_1, t_2) &= \lim_{N\to\infty} \prod_{n=1}^{N} \left[1 - \frac{dt}{t_n}\frac{\alpha_s(t_n)}{2\pi}\int dz\, P_{i,jk}(z)\right] \\ &= \exp\left\{-\int_{t_2}^{t_1}\frac{dt}{t}\frac{\alpha_s(t)}{2\pi}\int dz\, P_{i,jk}(z)\right\} \\ &\equiv \Delta(t_1, t_2) \end{aligned}$$

- The weight $\Delta(t_1, t_2)$ is called Sudakov form factor. It resums all the dominant virtual corrections to the tree graph (in the collinear approximation).

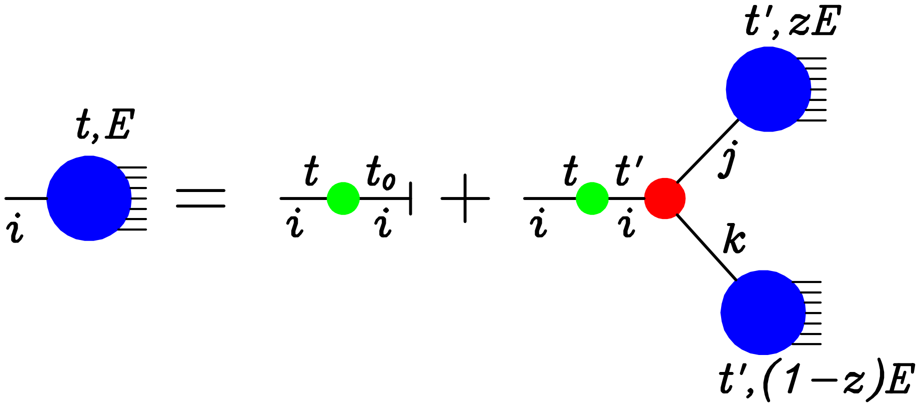
Sudakov form factors

$$\Delta_i(t_1,t_2) = \exp\left\{ -\sum_{jk} \int_{t_2}^{t_1} \frac{dt}{t} \frac{\alpha_s(t)}{2\pi} \int dz\, P_{i,jk}(z) \right\}$$



Notice that, when $t_2 \ll t_1$, $\Delta \to 0$, i.e. the probability that a hard parton turns into a narrow jet, or that it does not radiate at all, is small (it is Sudakov suppressed)

Final recipe



$$\mathcal{S}_i(t,E) = \Delta_i(t,t_0)\,\mathbb{1} + \sum_{(jk)} \int_{t_0}^{t} \frac{\alpha_S(t')}{2\pi}\,\frac{dt'}{t'} \int dz \int \frac{d\varphi}{2\pi}\,\Delta_i(t,t')\,P_{i,jk}(z)\,\mathcal{S}_j(t',zE)\;\mathcal{S}_k(t',(1-z)E)$$

- consider all tree graphs.
- assign values to the radiation variables Φ_r (t, z and φ) to each vertex.
- at each vertex, $i \longrightarrow jk$, include a factor

$$\frac{dt}{t}\,dz\,\frac{\alpha_s(t)}{2\pi}\,P_{i,jk}(z)\,\frac{d\varphi}{2\pi}$$

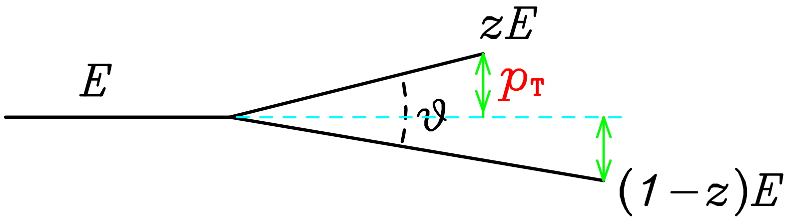
- include a factor $\Delta_i(t_1,t_2)$ to each internal parton i, from hardness t_1 to hardness t_2.
- include a factor $\Delta_i(t,t_0)$ on final lines (t_0 = IR cutoff)

Accuracy: soft divergences and double-log regions

$z \to 1$ ($z \to 0$) region problematic. In fact, for $z \to 1$, $P_{qq}, P_{gg} \div 1/(1-z)$

The choice of the ordering variable t makes a difference

$$
\begin{array}{llll}
\text{virtuality:} & t & \equiv & E^2 z(1-z) \overbrace{\theta^2}^{2(1-\cos\theta)} \\
p_T^2\text{:} & t & \equiv & E^2 z^2 (1-z)^2 \theta^2 \\
\text{angle:} & t & \equiv & E^2 \theta^2
\end{array}
$$



$$\text{virtuality}: \; z(1-z) > t/E^2 \quad \Longrightarrow \quad \int \frac{dt}{t} \int_{\sqrt{t}/E}^{1-\sqrt{t}/E} \frac{dz}{1-z} \approx \frac{1}{4} \log^2 \frac{t}{E^2}$$

$$p_T^2: \; z^2(1-z)^2 > t/E^2 \quad \Longrightarrow \quad \int \frac{dt}{t} \int_{t/E^2}^{1-t/E^2} \frac{dz}{1-z} \approx \frac{1}{2} \log^2 \frac{t}{E^2}$$

$$\text{angle}: \quad \Longrightarrow \quad \int \frac{dt}{t} \int_0^1 \frac{dz}{1-z} \approx \log t \, \log \Lambda$$

Sizable difference in double-log structure!

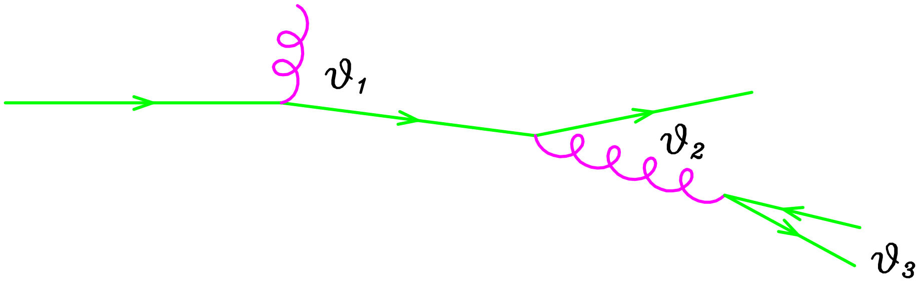
Angular ordering and color coherence

Mueller (1981) showed that angular ordering is the correct choice

$$\frac{d\theta}{\theta}\,\frac{\alpha_s\,(p_T^2)}{2\pi}\,P(z)\,dz$$

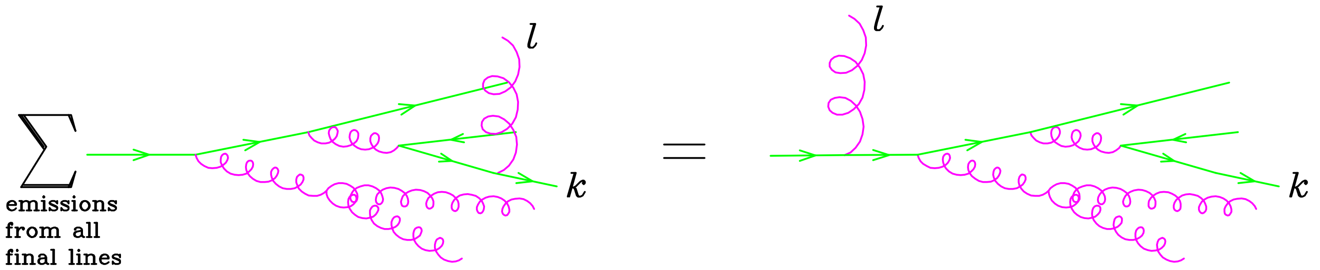
$$\theta_1 > \theta_2 > \theta_3 \ldots$$

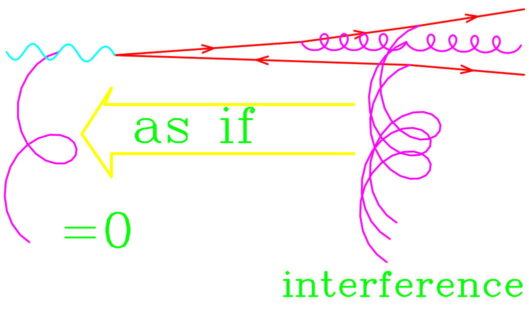
$$p_T^2 = E^2 z^2 (1-z)^2 \theta^2$$



$\alpha_s(p_T^2)$ for a correct treatment of charge renormalization in soft region

Soft gluons emitted at large angles from final-state partons add coherently





- angular ordering accounts for soft gluon interference.
- intensity for photon jets $= 0$
- intensity for gluon jets $= C_A$ instead of $2\,C_F + C_A$

New developments

- Interfacing Matrix Elements (ME) generators with Parton Showers
  - CKKW matching [Catani, Krauss, Küen, Webber]
  - MLM matching [Mangano]
- Interfacing NLO calculations with Parton Showers
  - MC@NLO [Frixione, Webber]
  - POWHEG [Nason]

Several other approaches have appeared

- $e^+e^- \rightarrow 3$ partons [Kramer, Mrenna, Soper]
- Shower by antenna factorization [Giele, Kosower, Skands]
- Shower by Catani-Seymour dipole factorization [Schumann, Krauss]
- Shower with quantum interference [Nagy, Soper]
- Shower by Soft Collinear Effective Theory [Bauer, Schwartz]
- Shower from the dipole formalism [Dinsdale, Ternick, Weinzierl]

Up to now, complete results for hadron colliders only from MC@NLO and POWHEG.

NLO + Parton Shower

LO-ME good for shapes. Uncertain absolute normalization

$$\alpha_s^n(2\mu) \approx \alpha_s^n(\mu)\left(1 - b_0 \alpha_s(\mu)\log(4)\right)^n \approx \alpha_s^n(\mu)\left(1 - n\alpha_s(\mu)\right)$$

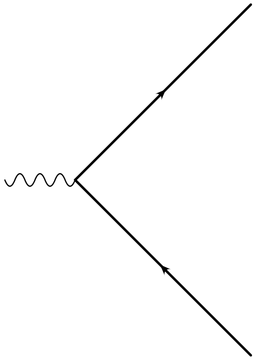
For $\mu = 100$ GeV, $\alpha_s = 0.12$, normalization uncertainty:

$W + 1J$	$W + 2J$	$W + 3J$
$\pm 12\%$	$\pm 24\%$	$\pm 36\%$

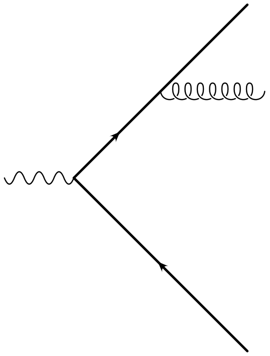
To improve on this, we need to go to NLO

The main problem in merging a NLO result and a Parton Shower is not to double-count radiation: the shower might produce some radiation already present at the NLO level (both at the virtual and at the real level).

LO:



NLO:



NLO vs Shower Monte Carlo

NLO

- ✓ accurate shapes at high p_T
- ✓ normalization accurate at NLO order
- ✓ reduced dependence on renormalization and factorization scales
- ✗ wrong shapes at small p_T
- ✗ description only at the parton level

SMC (LO + shower)

- ✗ bad description at high p_T
- ✗ normalization accurate only at LO
- ✓ correct Sudakov suppression at small p_T
- ✓ simulate events at the hadron level

It is natural to try to merge the two approaches, keeping the good features of both

MC@NLO [Frixione and Webber, 2001] and POWHEG [Nason, 2004] do this in a consistent way

POsitive-Weight Hardest Emission Generator

- ✓ it generates events with positive weights. NO negative weights to handle
- ✓ it is independent from parton-shower programs. Can be interfaced with PYTHIA, HERWIG, SHERPA…

  It is then possible to compare the different outputs
- ✓ No need to implement new interfaces

  Two possible ways to interface to shower Monte Carlo programs

  1. Les Houches Event format. The event is written on a file that is subsequently showered by HERWIG, PYTHIA…
  2. on the fly. We provide UPINIT and UPEVNT directly running in HERWIG and PYTHIA

Existing implementations

The POWHEG method has already been successfully used in

- $pp \to ZZ$ [Nason and Ridolfi, `hep-ph/0606275`]
- $e^+e^- \to$ hadrons [Latunde-Dada, Gieseke and Webber, `hep-ph/0612281`]
  $e^+e^- \to t\bar{t}$ with top decay [Latunde-Dada, arXiv:0806.4560]
- $pp \to Q\overline{Q}$ ($c\bar{c}$, $b\bar{b}$, $t\bar{t}$) with spin correlations [Frixione, Nason and Ridolfi, arXiv:0707.3088].
- $pp \to W/Z$ with spin correlations [Alioli, Nason, C.O. and Re, arXiv:0805.4802; Hamilton, Richardson and Tully, arXiv:0806.0290].
- $pp \to H$ [Alioli, Nason, C.O. and Re, arXiv:0812.0578; Hamilton, Richardson and Tully, arXiv:0903.4345]
- $pp \to H + W/Z$ [Hamilton, Richardson and Tully, arXiv:0903.4345]

All POWHEG implementations for hadronic colliders have been interfaced to both PYTHIA and HERWIG.

To appear very soon

- single-top production [Alioli, Nason, C.O. and Re]
- $pp \to W/Z + 1$ jet [Alioli, Nason, C.O. and Re]
- $pp \to VV$ [Hamilton and Nason]

We are working now on a general framework for the implementation of any NLO process into the POWHEG formalism.

Given the Born, real and virtual amplitudes, combine them automatically to produce POWHEG events.

Truncated shower

- in an approximate form, truncated shower has been studied in $e^+e^- \to$ hadrons [Latunde-Dada Gieseke and Webber, `hep-ph/0612281`]
- included in the HERWIG++ framework [Bähr, Gieseke, Gigg, Grellscheid, Hamilton, Plätzer, Richardson, Seymour and Tully, arXiv:0812.0529] and in all the HRT's papers

POWHEG

$$d\sigma_{\mathrm{NLO}} = d\mathbf{\Phi}_n \Big\{ B(\mathbf{\Phi}_n) + V(\mathbf{\Phi}_n) + \big[R(\mathbf{\Phi}_n, \Phi_r) - C(\mathbf{\Phi}_n, \Phi_r) \big] \, d\Phi_r \Big\}$$

$$d\mathbf{\Phi}_{n+1} = d\mathbf{\Phi}_n \, d\Phi_r \qquad\qquad d\Phi_r \div dt \, dz \, d\varphi$$

$$V(\mathbf{\Phi}_n) = V_b(\mathbf{\Phi}_n) + \int d\Phi_r \, C(\mathbf{\Phi}_n, \Phi_r) \qquad \Longleftarrow$$ finite

$$d\sigma_{\mathrm{SMC}} = B(\mathbf{\Phi}_n) \, d\mathbf{\Phi}_n \left\{ \Delta_{t_0} + \frac{\alpha_s}{2\pi} P(z) \, \frac{1}{t} \, \Delta_t \, d\Phi_r \right\}$$

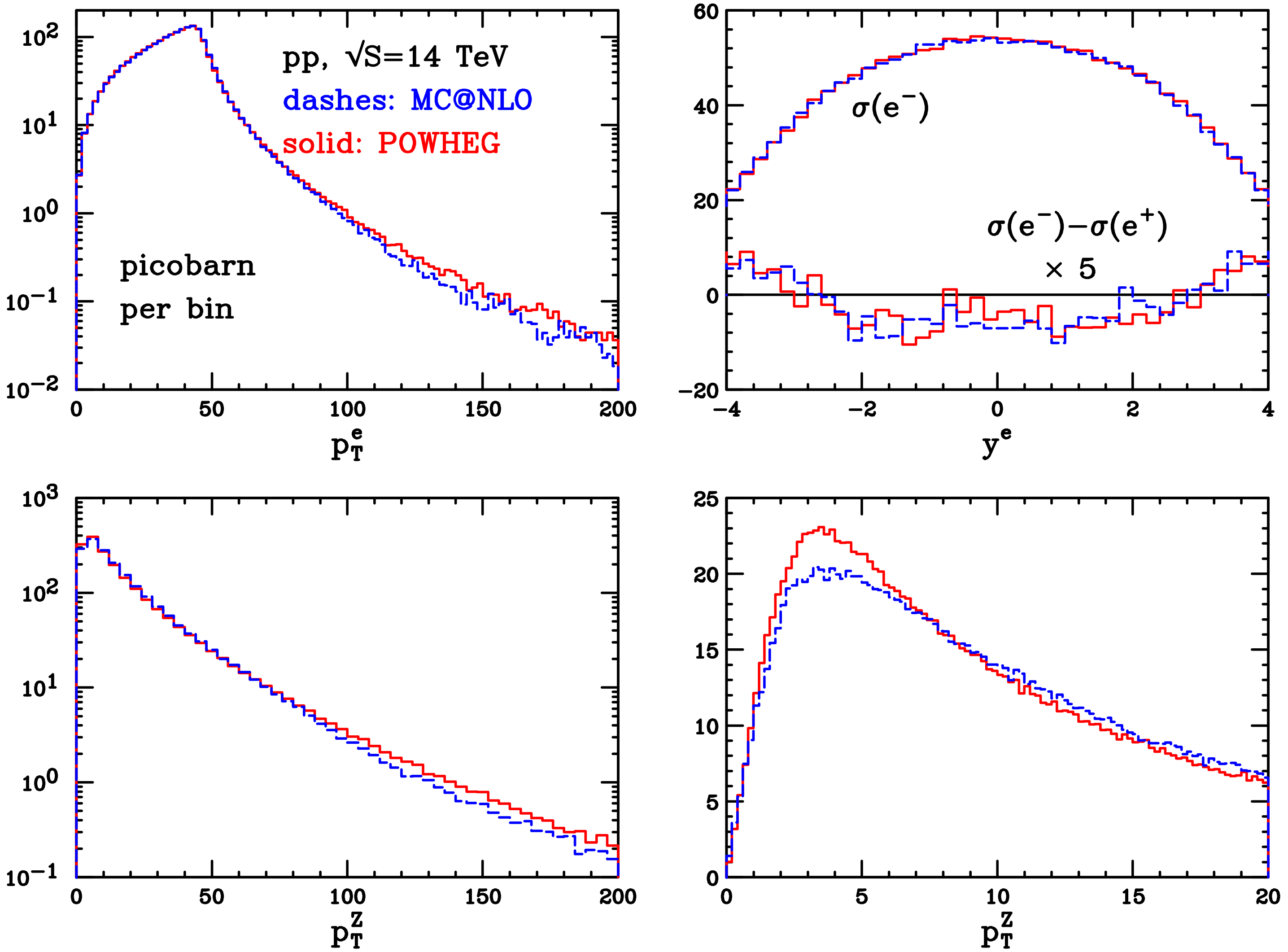
$$\Delta_t = \exp\left[- \int d\Phi_r' \, \frac{\alpha_s}{2\pi} P(z') \, \frac{1}{t'} \, \theta(t' - t) \right]$$ SMC Sudakov form factor

$$d\sigma_{\mathrm{POWHEG}} = \overline{B}(\mathbf{\Phi}_n) \, d\mathbf{\Phi}_n \left\{ \Delta\left(\mathbf{\Phi}_n, p_T^{min}\right) + \frac{R(\mathbf{\Phi}_n, \Phi_r)}{B(\mathbf{\Phi}_n)} \, \Delta(\mathbf{\Phi}_n, p_T) \, d\Phi_r \right\}$$

$$\overline{B}(\mathbf{\Phi}_n) = B(\mathbf{\Phi}_n) + V(\mathbf{\Phi}_n) + \int d\Phi_r \big[R(\mathbf{\Phi}_n, \Phi_r) - C(\mathbf{\Phi}_n, \Phi_r) \big]$$

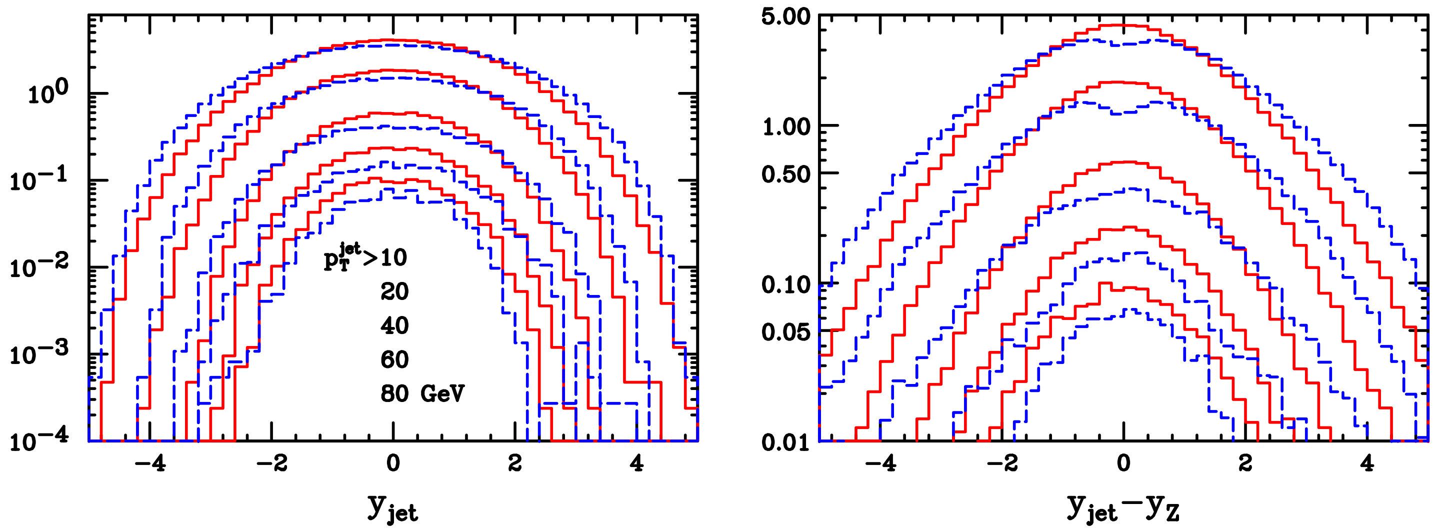
$$\Delta(\mathbf{\Phi}_n, p_T) = \exp\left[- \int d\Phi_r' \, \frac{R(\mathbf{\Phi}_n, \Phi_r')}{B(\mathbf{\Phi}_n)} \, \theta\left(k_T(\mathbf{\Phi}_n, \Phi_r') - p_T \right) \right]$$ POWHEG Sudakov

Z production: POWHEG + HERWIG vs MC@NLO



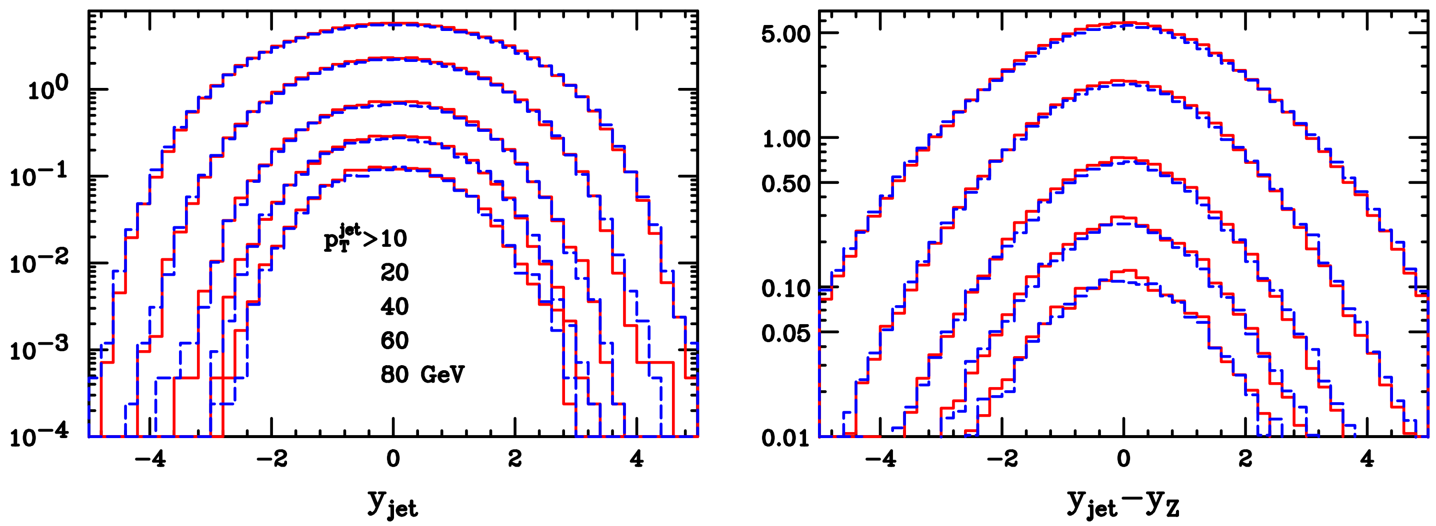
Small differences in the high- and low-p_T regions.

Rapidity distribution of hardest jet at Tevatron



POWHEG+HERWIG

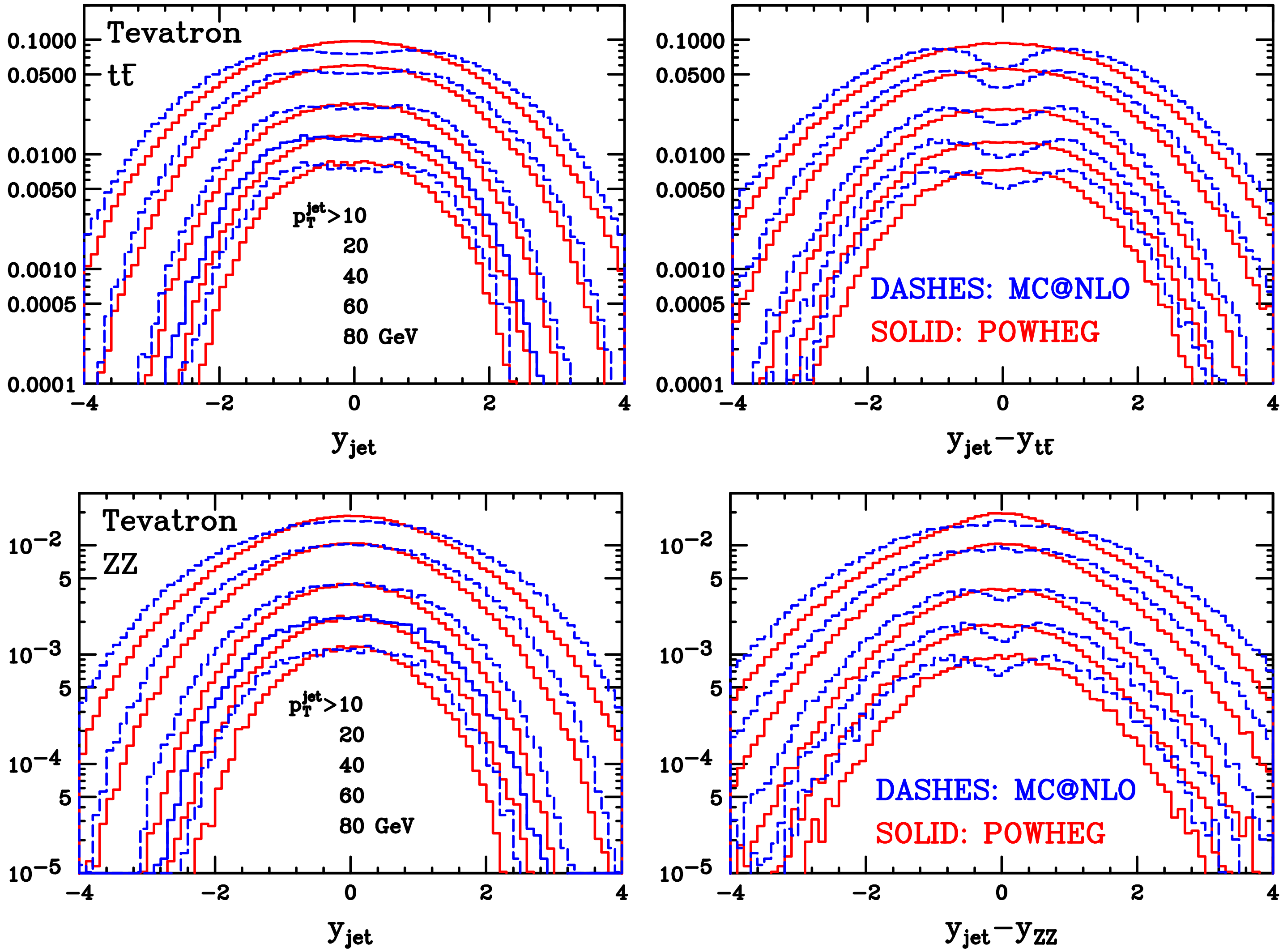
MC@NLO



POWHEG+PYTHIA

PYTHIA

Rapidity distribution of hardest jet at Tevatron



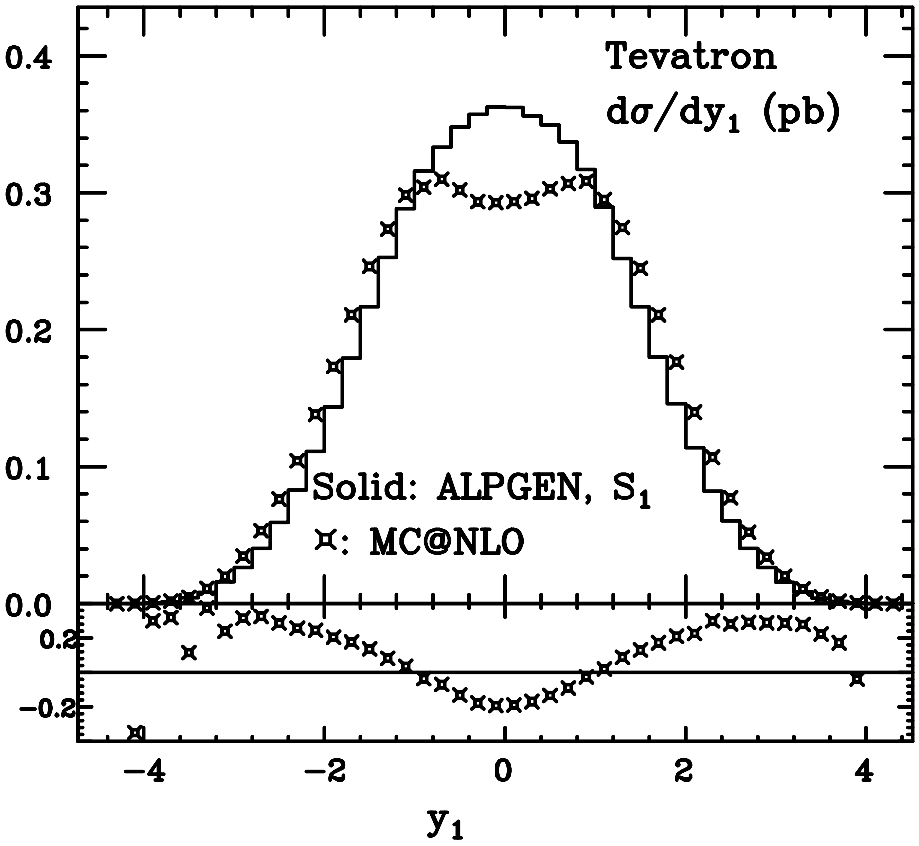
POWHEG+HERWIG

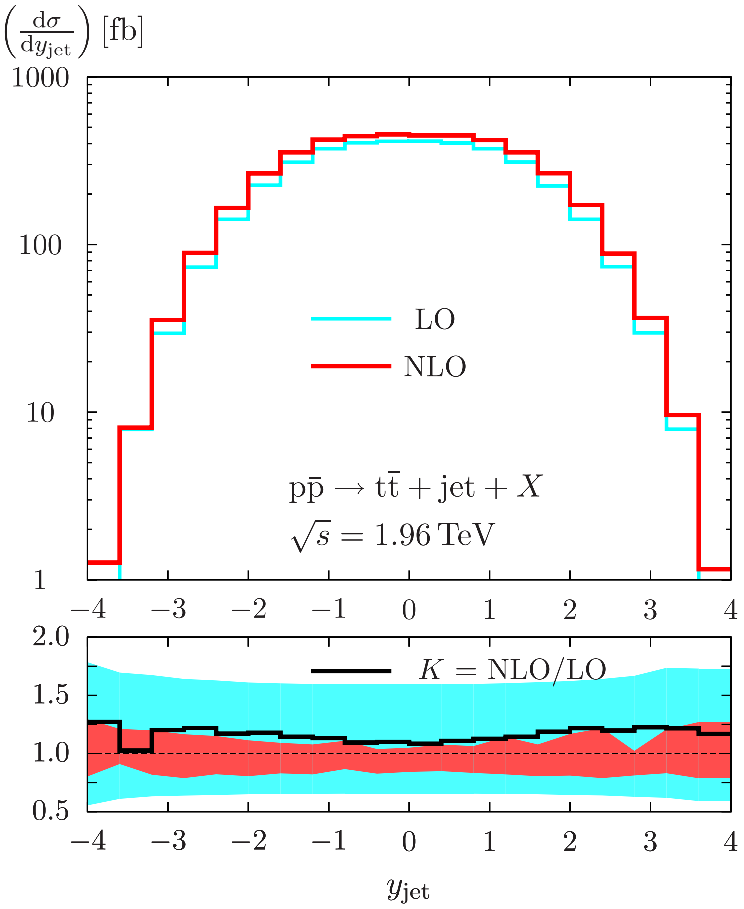
MC@NLO

POWHEG+HERWIG

MC@NLO

ALPGEN and NLO vs MC@NLO: $t\bar{t}$ + 1 jet



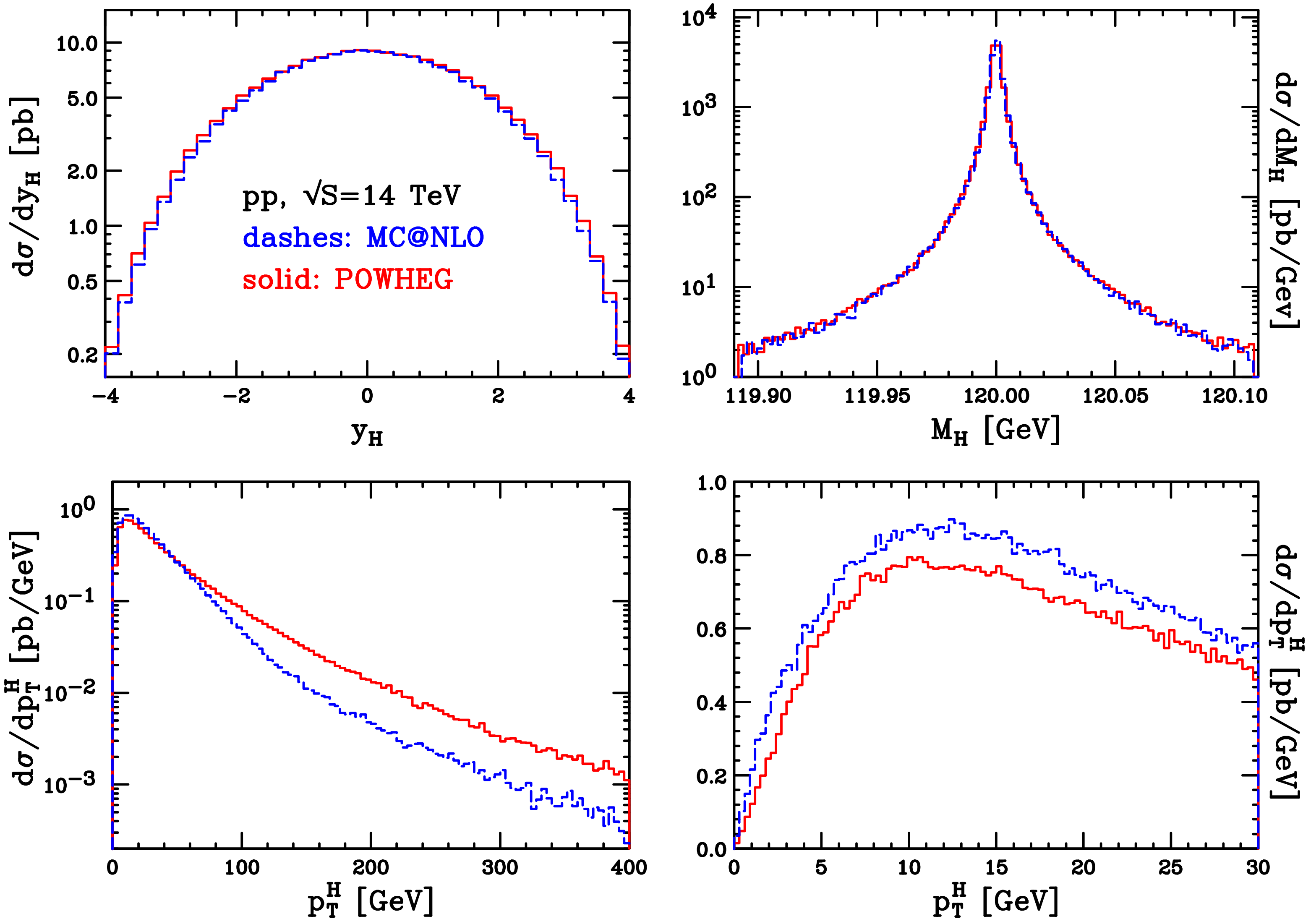


Rapidity y_1 of the leading jet (highest p_T).

POWHEG's distribution as in ALPGEN: no dip present. The size of discrepancy can be attributed to different treatment of higher-order terms.

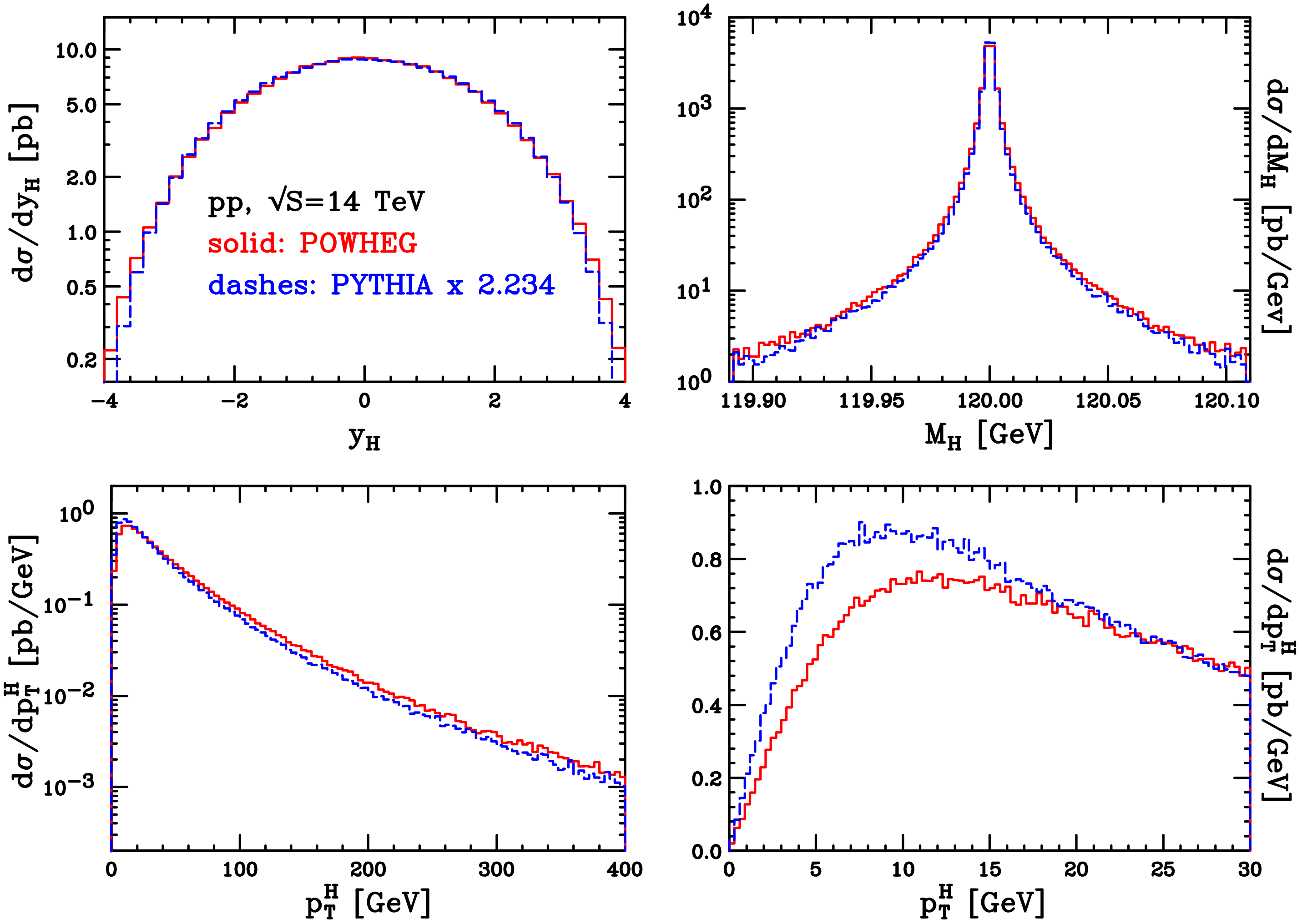
$pp \to t\bar{t}$ + jet at NLO [Dittmaier, Uwer and Weinzierl, arXiv:0810.0452] shows no dip too.

Higgs boson production: POWHEG + HERWIG vs MC@NLO



Differences in the high- and low-p_T regions. More in the next slides.

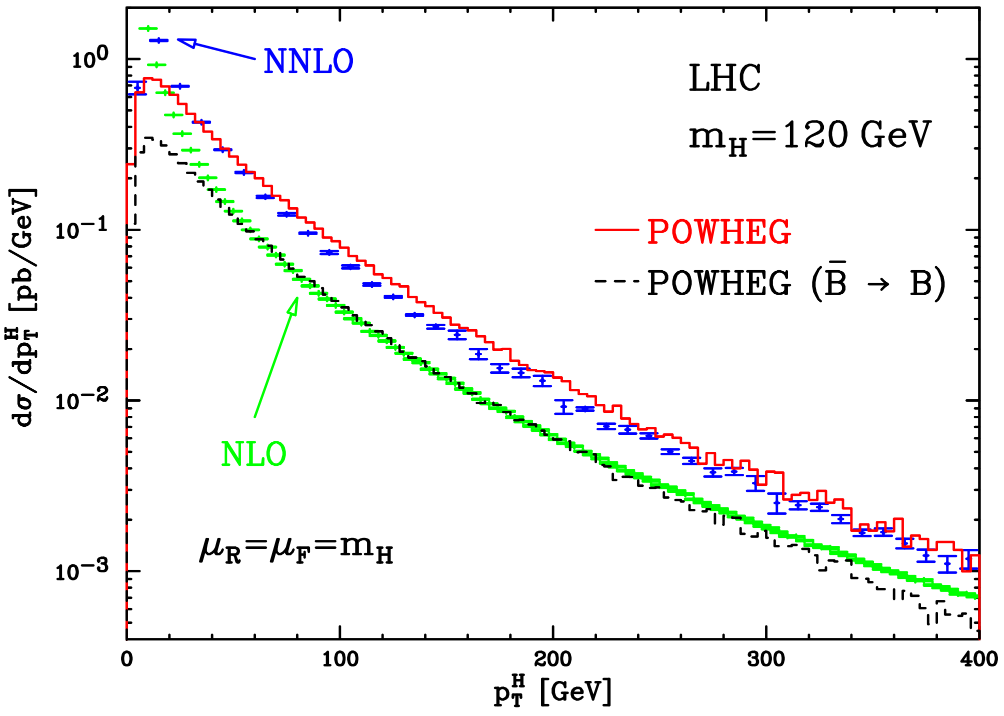
Higgs boson production: POWHEG + PYTHIA vs PYTHIA

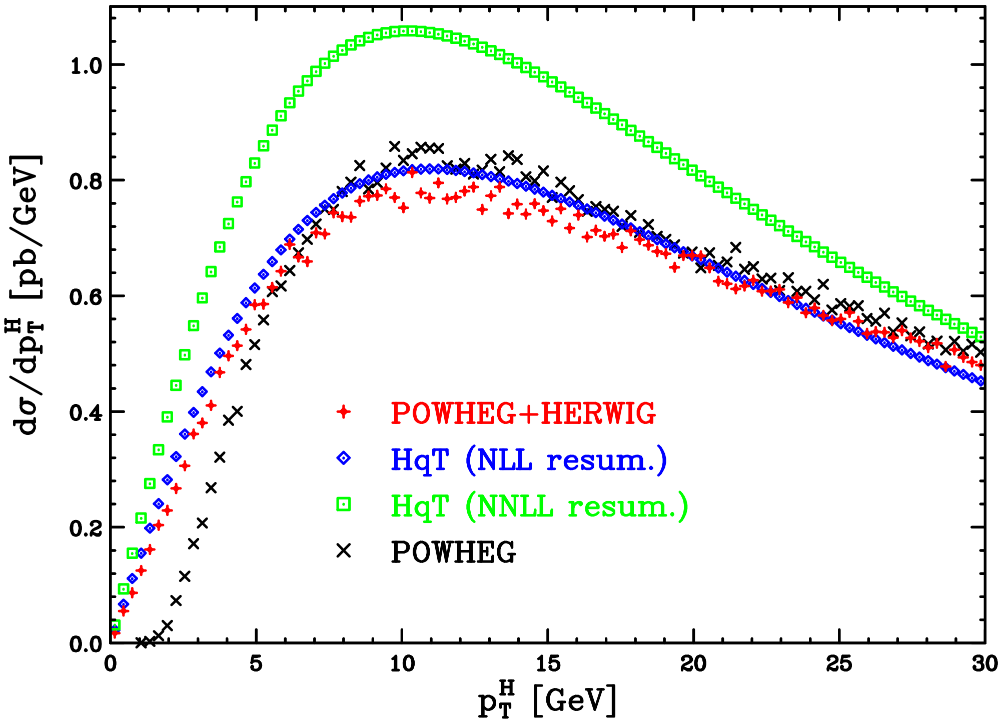


- A shower Monte Carlo is accurate in the radiation of the hardest jet only in the collinear regions.

- Only because the generation of radiation in vector-boson and Higgs boson production in PYTHIA is very similar to the POWHEG one, we can make comparisons of p_T^{jet} and p_T^H distributions.

Higgs boson production at the LHC





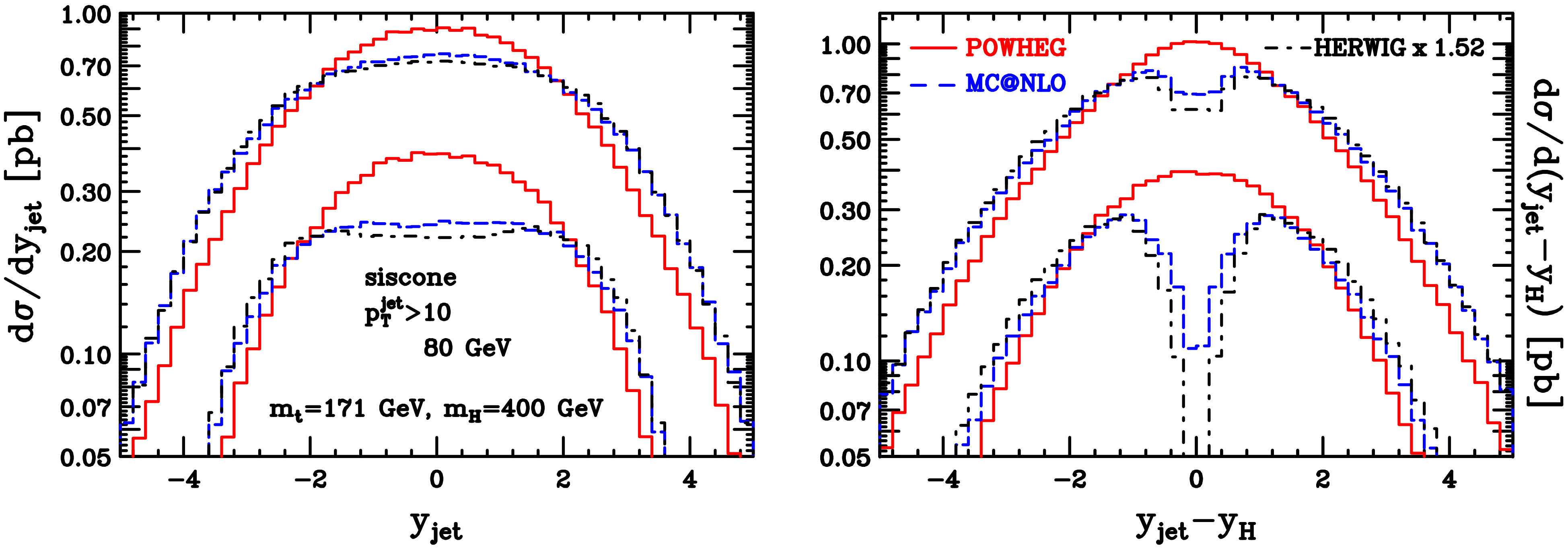
$$\overline{B}(\mathbf{\Phi}_n) = B(\mathbf{\Phi}_n) + V(\mathbf{\Phi}_n) + \int d\Phi_r \left[R(\mathbf{\Phi}_n, \Phi_r) - C(\mathbf{\Phi}_n, \Phi_r)\right]$$

$$d\sigma = \overline{B}(\mathbf{\Phi}_n)\, d\mathbf{\Phi}_n \left\{\Delta(\mathbf{\Phi}_n, p_T^{min}) + \Delta(\mathbf{\Phi}_n, p_T)\ \frac{R(\mathbf{\Phi}_n, \Phi_r)}{B(\mathbf{\Phi}_n)}\, d\Phi_r\right\}$$

$$d\sigma_{\mathrm{rad}} \approx \frac{\overline{B}(\mathbf{\Phi}_n)}{B(\mathbf{\Phi}_n)}\, R(\mathbf{\Phi}_{n+1})\, d\mathbf{\Phi}_{n+1} = \left\{1 + \mathcal{O}\left(\alpha_s\right)\right\} R(\mathbf{\Phi}_{n+1})\, d\mathbf{\Phi}_{n+1}$$

Better agreement with NNLO in this way

Higgs boson production at the LHC



- Dip inherited from the deeper dip of HERWIG. MC@NLO fills partially the dip.
- It gets worse for large p_T^{jet}
- Why MC@NLO has a dip in the hardest jet rapidity?
- Why POWHEG has no dip? Is that because of the hardest p_T spectrum?

Hard p_T spectrum in POWHEG

We have enough flexibility to get rid of higher cross section at high p_T, if we want. Go back to the POWHEG cross section

$$\begin{aligned} d\sigma &= \overline{B}(\mathbf{\Phi}_n)\left\{\Delta\left(p_T^{min}\right)+\Delta(p_T)\,\frac{R(\mathbf{\Phi}_{n+1})}{B(\mathbf{\Phi}_n)}\,d\Phi_r\right\}d\mathbf{\Phi}_n \\ \overline{B}(\mathbf{\Phi}_n) &= B(\mathbf{\Phi}_n)+V(\mathbf{\Phi}_n)+\int d\Phi_r\left[R(\mathbf{\Phi}_n,\Phi_r)-C(\mathbf{\Phi}_n,\Phi_r)\right] \\ \Delta(p_T) &= \exp\left[-\int d\Phi_r'\,\frac{R(\mathbf{\Phi}_n,\Phi_r')}{B(\mathbf{\Phi}_n)}\,\theta\left(p_T{}'-p_T\right)\right] \end{aligned}$$

Break $R = R_s + R_f$, with R_f finite in collinear and soft limit. Define

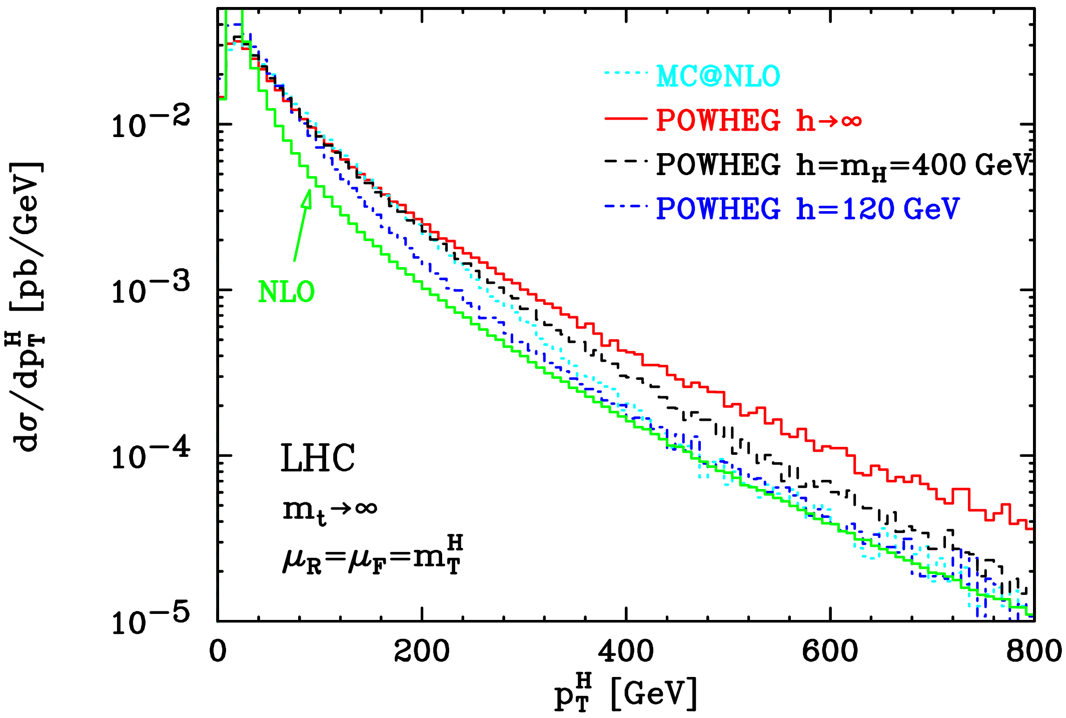
$$\begin{aligned} d\sigma' &= \overline{B}_s(\mathbf{\Phi}_n)\left\{\Delta_s\left(p_T^{min}\right)+\Delta_s(p_T)\,\frac{R_s(\mathbf{\Phi}_{n+1})}{B(\mathbf{\Phi}_n)}\,d\Phi_r\right\}d\mathbf{\Phi}_n + R_f(\mathbf{\Phi}_{n+1})\,d\mathbf{\Phi}_{n+1} \\ \overline{B}_s(\mathbf{\Phi}_n) &= B(\mathbf{\Phi}_n)+V(\mathbf{\Phi}_n)+\int d\Phi_r\left[R_s(\mathbf{\Phi}_n,\Phi_r)-C(\mathbf{\Phi}_n,\Phi_r)\right] \\ \Delta_s(p_T) &= \exp\left[-\int d\Phi_r'\,\frac{R_s(\mathbf{\Phi}_n,\Phi_r')}{B(\mathbf{\Phi}_n)}\,\theta\left(p_T{}'-p_T\right)\right] \end{aligned}$$

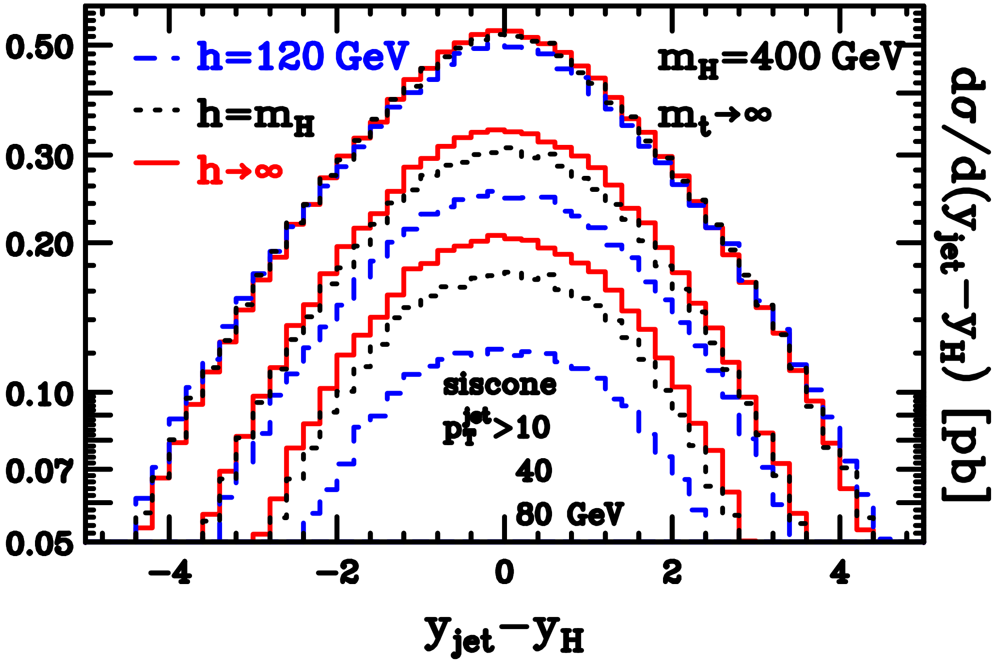
Easy to prove that $d\sigma'$ is equivalent to $d\sigma$. In other words, the part of the real cross section that is treated with the shower technique can be varied.

$$R_s = \frac{h^2}{p_T^2 + h^2} R$$

$$R_f = \frac{p_T^2}{p_T^2 + h^2} R$$

agrees with NLO at high p_T





No new features appear in all the other distributions

High p_T cross section and dips are unrelated issues

Why is there a dip in MC@NLO?

Write the MC@NLO hardest jet cross section in the POWHEG language. Hardest emission can be written as [Nason 2004]

$$d\sigma = \underbrace{\overline{B}_{\rm HW}\, d\mathbf{\Phi}_n}_{\mathbb{S}\text{ event}} \underbrace{\left[\Delta_{\rm HW}(p_T^{min}) + \Delta_{\rm HW}(p_T)\frac{R_{\rm HW}(\mathbf{\Phi}_{n+1})}{B(\mathbf{\Phi}_n)}\, d\Phi_r\right]}_{\text{HERWIG event}} + \underbrace{\left[R(\mathbf{\Phi}_{n+1}) - R_{\rm HW}(\mathbf{\Phi}_{n+1})\right] d\mathbf{\Phi}_{n+1}}_{\mathbb{H}\text{ event}}$$

$$\overline{B}_{\rm HW}(\mathbf{\Phi}_n) \quad = \quad B(\mathbf{\Phi}_n) + V(\mathbf{\Phi}_n) + \int \left[R_{\rm HW}(\mathbf{\Phi}_n, \Phi_r) - C(\mathbf{\Phi}_n, \Phi_r)\right] d\Phi_r$$

$$\Delta_{\rm HW}(p_T) \quad = \quad \exp\left[-\int d\Phi'_r \frac{R_{\rm HW}(\mathbf{\Phi}_n, \Phi'_r)}{B(\mathbf{\Phi}_n)}\theta({p_T}' - p_T)\right]$$

Like POWHEG with
$$\begin{cases} R_s = R_{\rm HW} & \\ R_f = R - R_{\rm HW} & \Longleftarrow \quad \text{can be negative} \end{cases}$$

This formula illustrates why MC@NLO and POWHEG are equivalent at NLO!
But differences can arise at NNLO…

At high p_T the cross section goes as

$$d\sigma \approx \left[\frac{\overline{B}_{\rm HW}(\mathbf{\Phi}_n)}{B(\mathbf{\Phi}_n)} R_{\rm HW}(\mathbf{\Phi}_{n+1}) + R(\mathbf{\Phi}_{n+1}) - R_{\rm HW}(\mathbf{\Phi}_{n+1})\right] d\mathbf{\Phi}_{n+1}$$

$$= \underbrace{R(\mathbf{\Phi}_{n+1})}_{\text{no dip}}\, d\mathbf{\Phi}_{n+1} + \underbrace{\left(\frac{\overline{B}_{\rm HW}(\mathbf{\Phi}_n)}{B(\mathbf{\Phi}_n)} - 1\right)}_{\mathcal{O}(\alpha_s)\text{ but large for Higgs}} \underbrace{R_{\rm HW}(\mathbf{\Phi}_{n+1})}_{\text{pure HERWIG dip}}\, d\mathbf{\Phi}_{n+1}$$

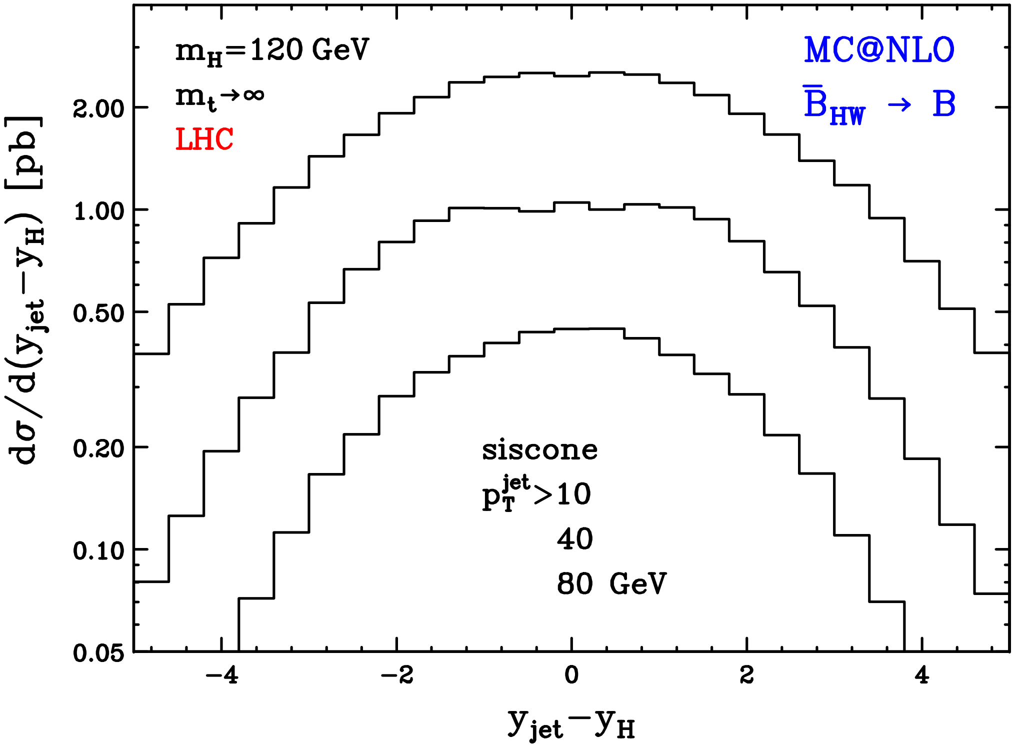
So: a contribution with a dip is added to the exact NLO result.

The contribution is $\mathcal{O}(\alpha_s R)$, i.e. NNLO

Can we test this hypothesis?

Replace $\overline{B}_{\rm HW} \to B$ in MC@NLO.

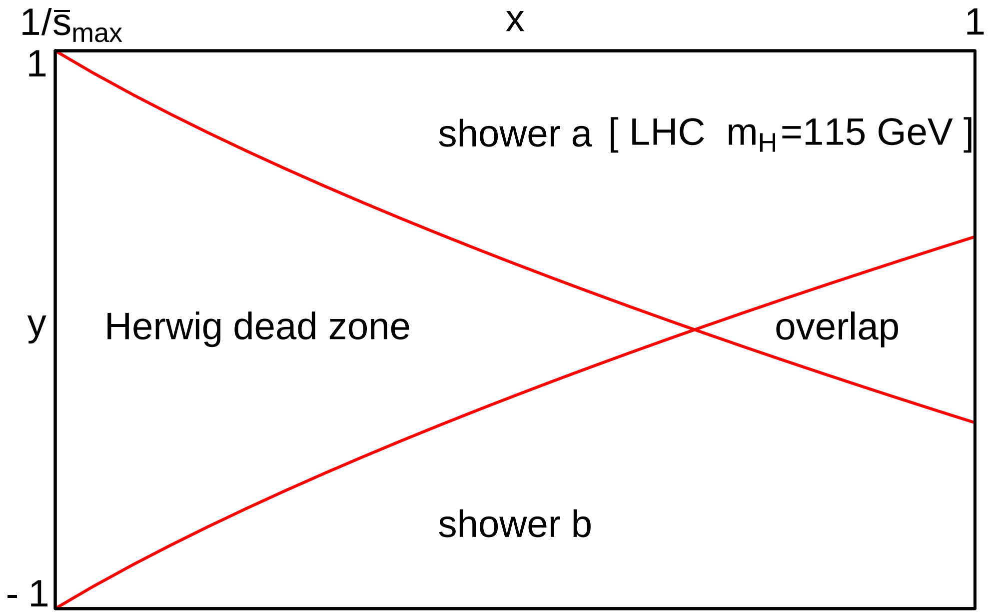
The dip should disappear…

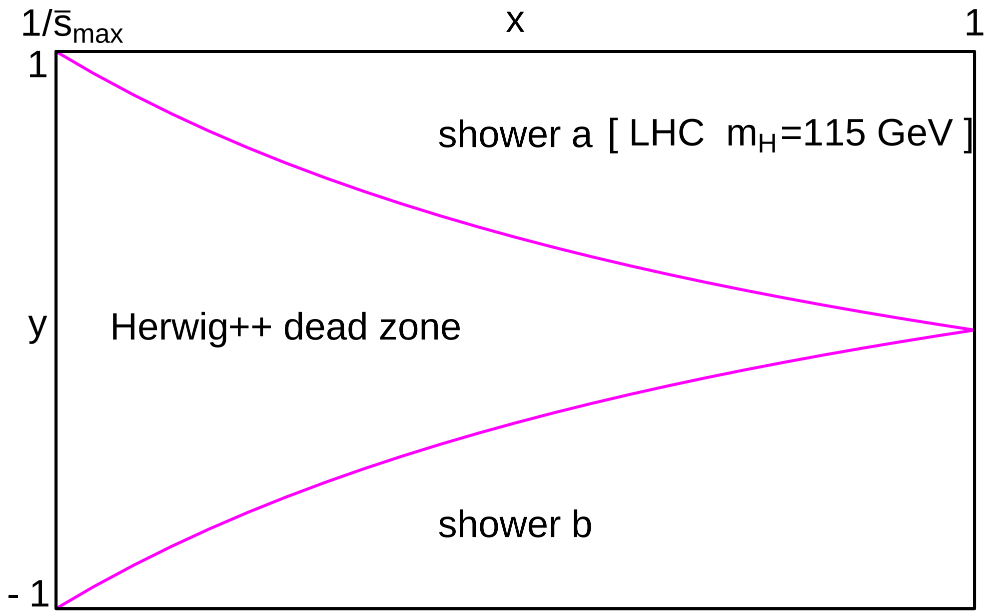


No visible dip is present.

HERWIG and HERWIG++ studies

[Hamilton, Richardson and Tully] arXiv:0903.4345

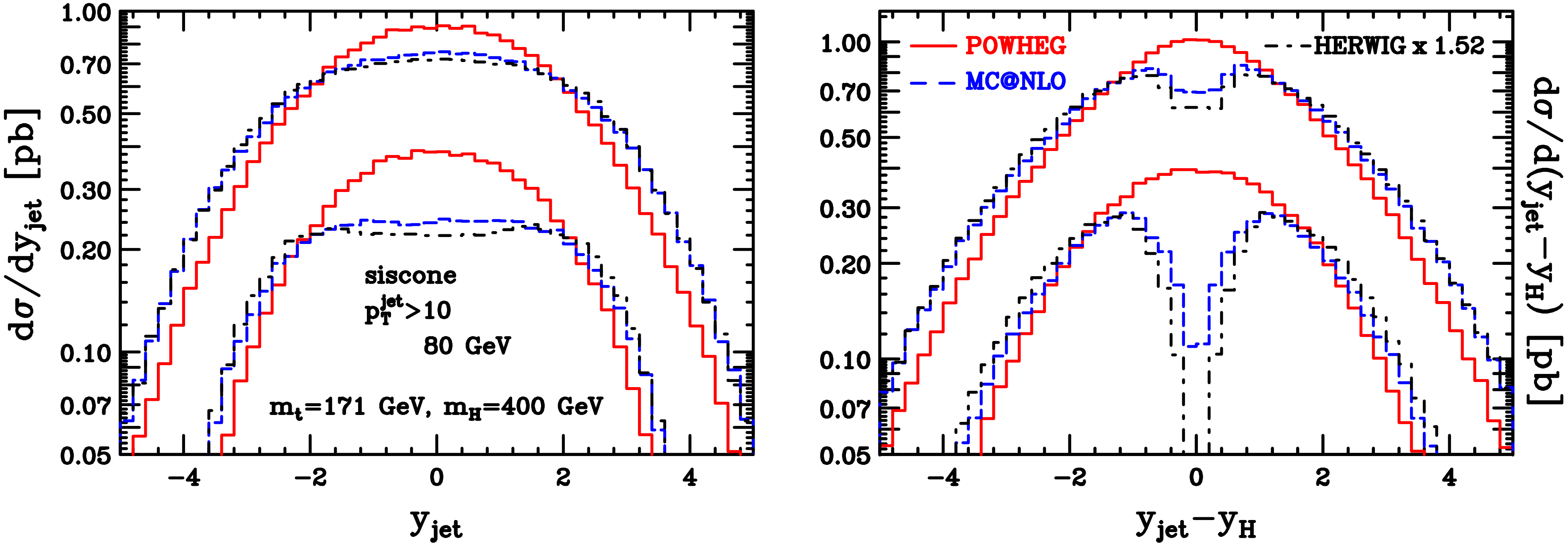




Both HERWIG and HERWIG++ have a dead radiation region corresponding to central rapidity and high energy.

Dip in central region in HERWIG can be attributed to the dead zone.

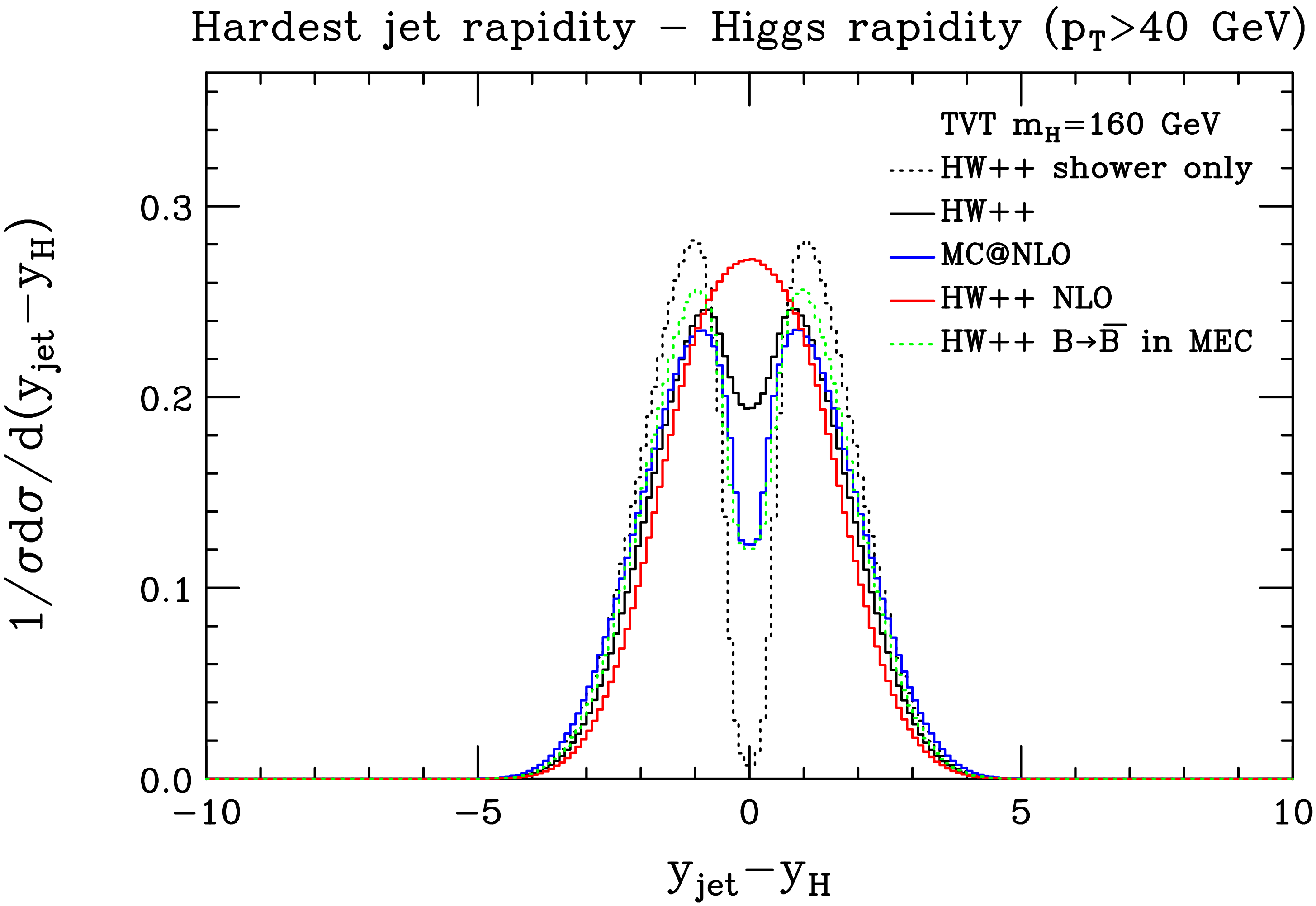
Higgs boson production at the LHC



- Why MC@NLO has a dip in the hardest jet rapidity?
  ANSWER: because it is very sensitive to the dead zone in the HERWIG phase space
- Why POWHEG has no dip? Is that because of the hardest p_T spectrum?
  ANSWER: NO, it does not depend on the hardest p_T spectrum. POWHEG generate by itself the hardest radiation.

HERWIG and HERWIG++ studies

[Hamilton, Richardson and Tully] arXiv:0903.4345

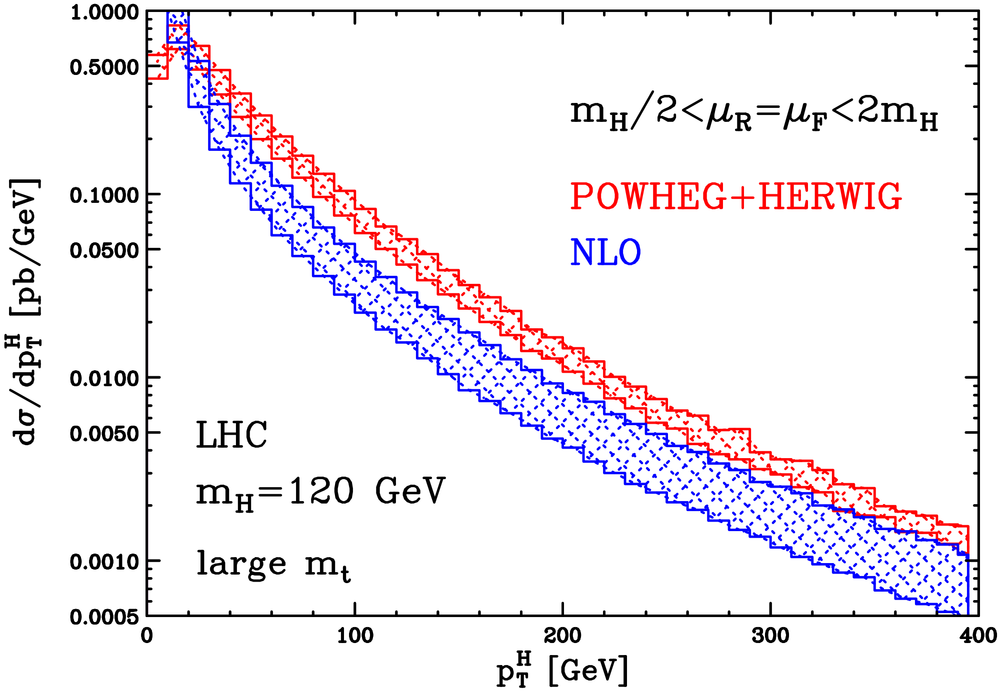


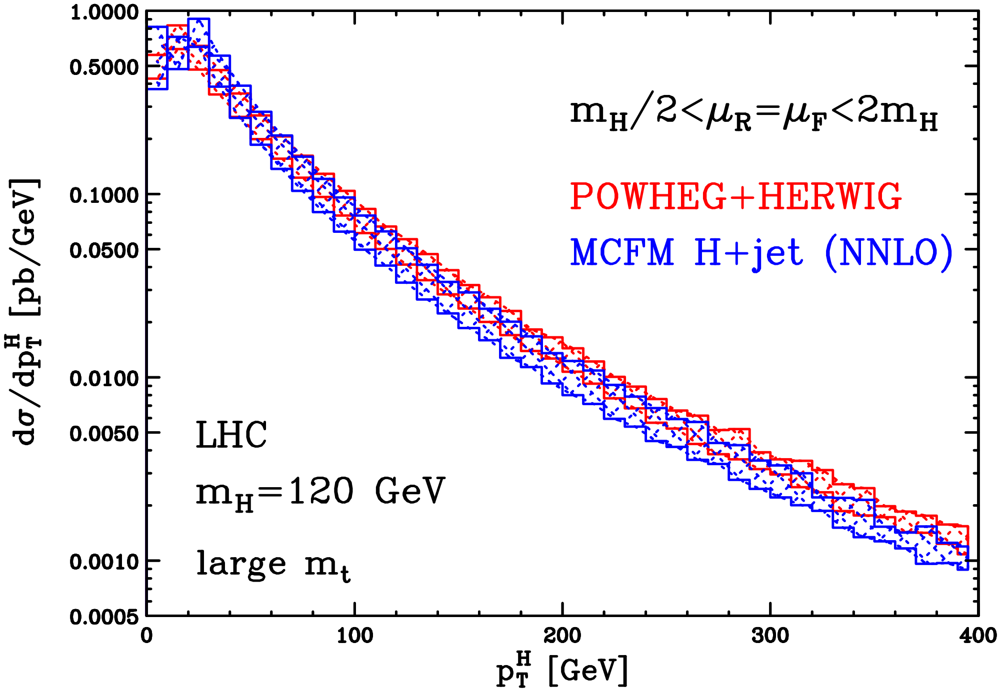
Summary of MC@NLO and POWHEG comparisons

- Fairly good agreement on most distributions
- Areas of disagreement can be tracked back to NNLO terms, arising mostly because of the use of an NLO inclusive cross section (the $\bar{B}$ function) to shower out the hardest radiation.
- In POWHEG, since the hardest radiation is generated by POWHEG itself, one has high flexibility in tuning the magnitude of these NNLO terms.
- For MC@NLO, these NNLO terms can generate unphysical behavior in physical distributions, reflecting the dead zones structure of the underlying shower Monte Carlo.

Since MC@NLO uses the underlying Monte Carlo to generate the hardest emission, to remedy to these problems one has to intervene on the Monte Carlo itself

Higgs boson production at the LHC





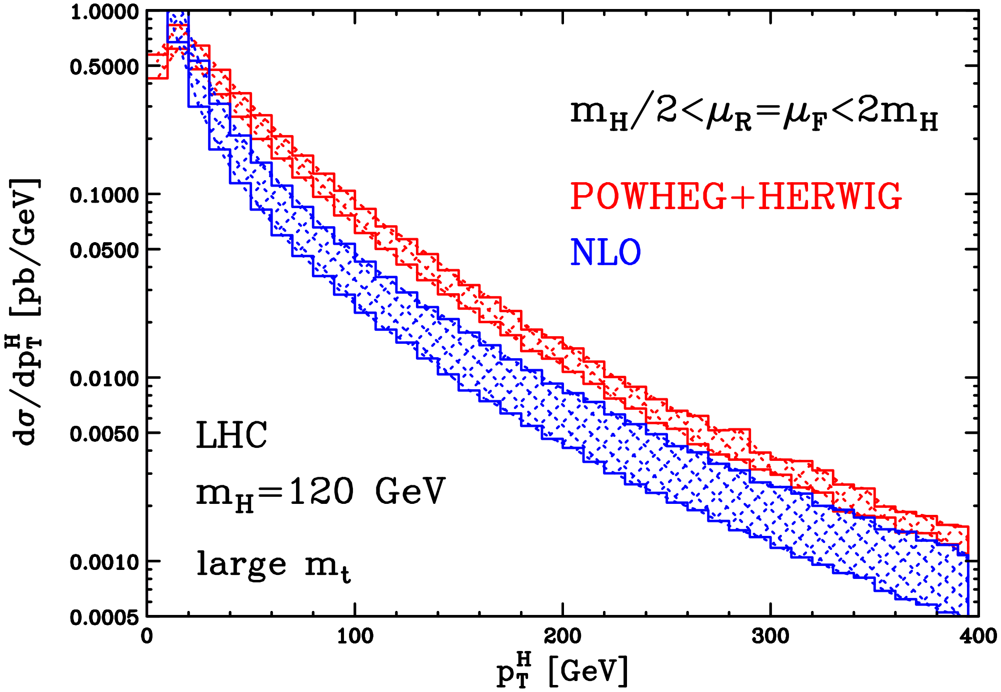
The NLO result is in reality a LO one $\Longrightarrow$ it depends upon $\alpha_s^3(\mu_R)$

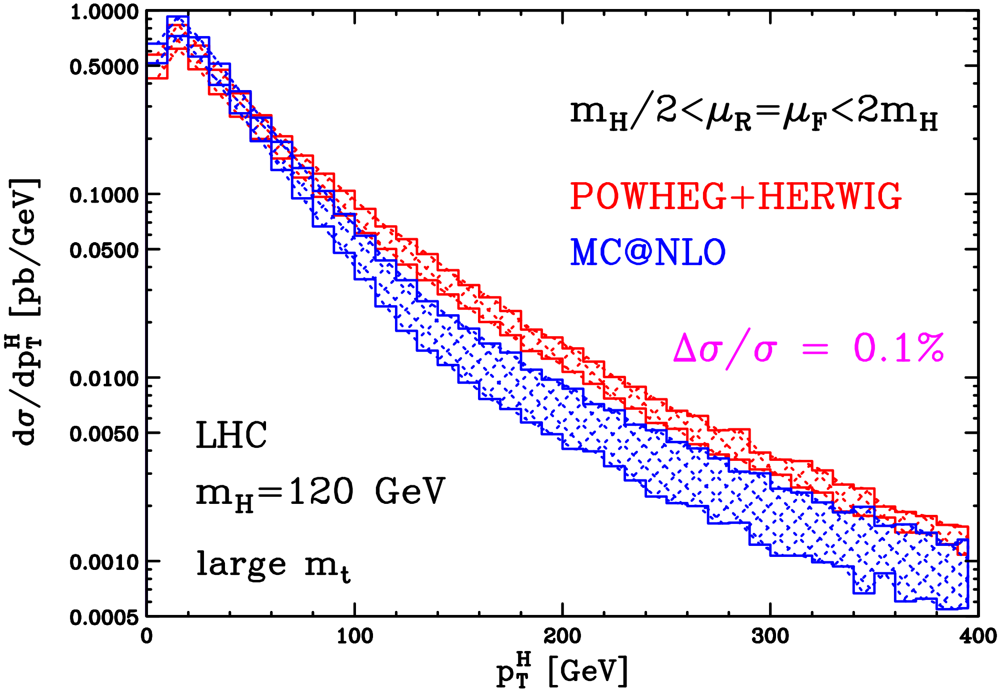
$$\overline{B}(\mathbf{\Phi}_n,\mu_R) = B(\mathbf{\Phi}_n) + V(\mathbf{\Phi}_n,\alpha_s(\mu_R)) + \int d\Phi_r\left[R(\mathbf{\Phi}_n,\Phi_r,\alpha_s(\mu_R)) - C(\mathbf{\Phi}_n,\Phi_r)\right]$$

$$d\sigma = \overline{B}(\mathbf{\Phi}_n,\mu_R)\,d\mathbf{\Phi}_n\left\{\Delta(\mathbf{\Phi}_n,p_T^{min}) + \Delta(\mathbf{\Phi}_n,p_T)\,\frac{R(\mathbf{\Phi}_n,\Phi_r)}{B(\mathbf{\Phi}_n)}\,d\Phi_r\right\}$$

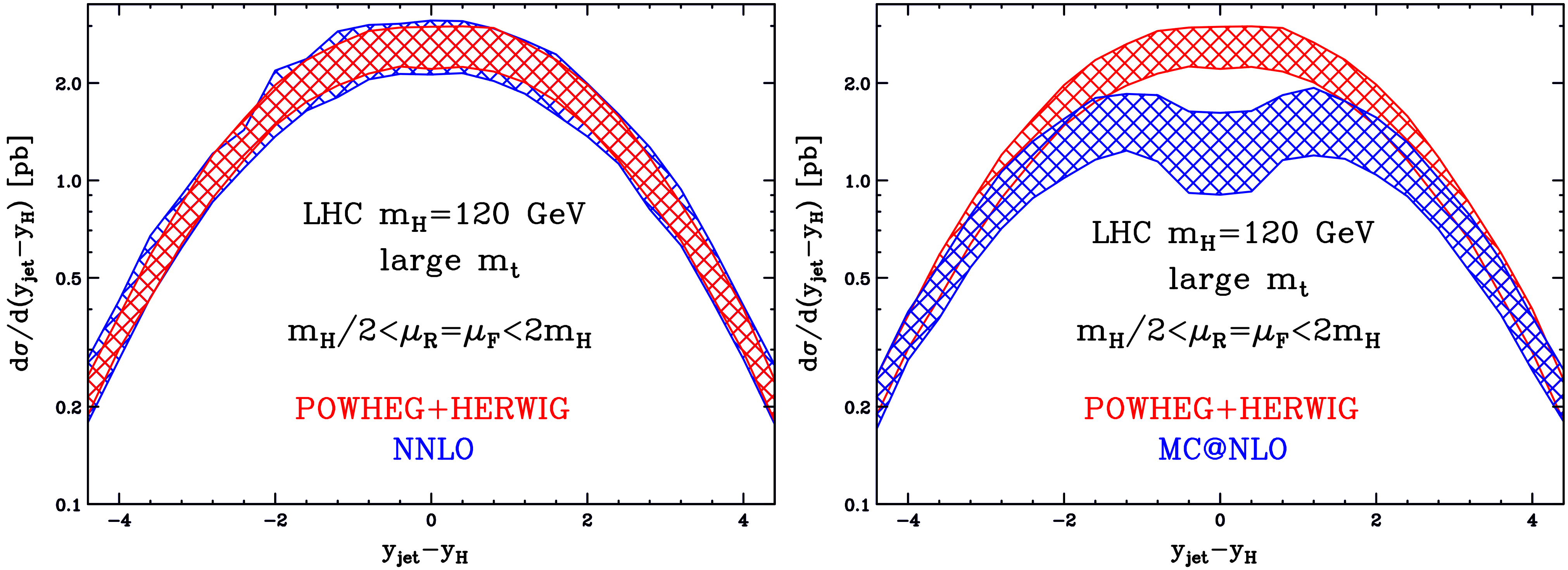
$$\Delta(\mathbf{\Phi}_n,p_T) = \exp\left[-\int d\Phi_r'\,\frac{R(\mathbf{\Phi}_n,\Phi_r',\alpha_s(k_T))}{B(\mathbf{\Phi}_n)}\,\theta(k_T(\mathbf{\Phi}_n,\Phi_r')-p_T)\right]$$

Higgs boson production at the LHC



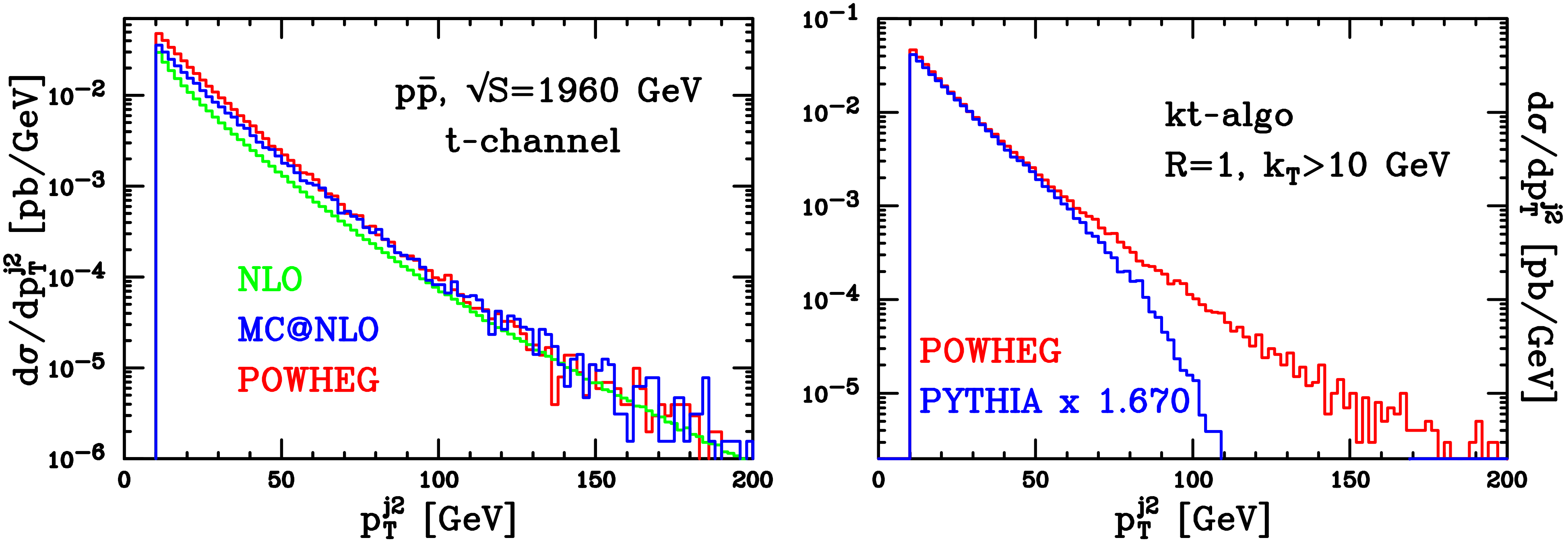


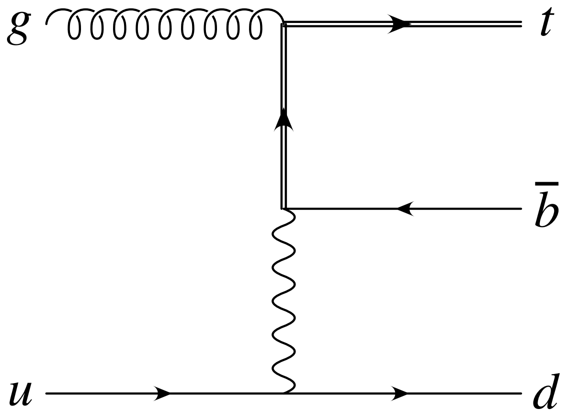
Higgs boson production at the LHC



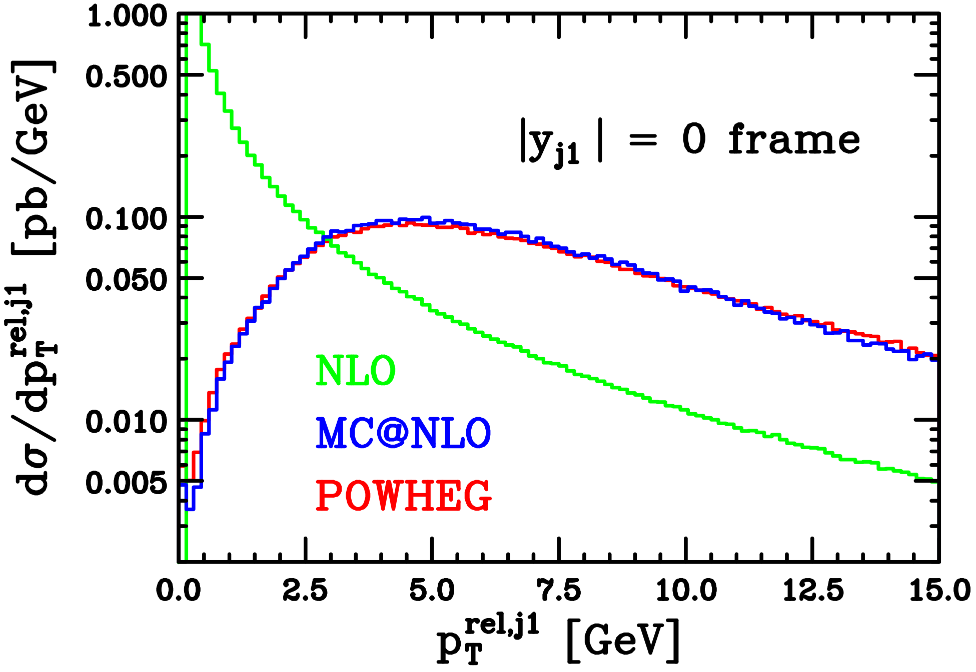
NNLO result obtained with `HNNLO` by Catani & Grazzini

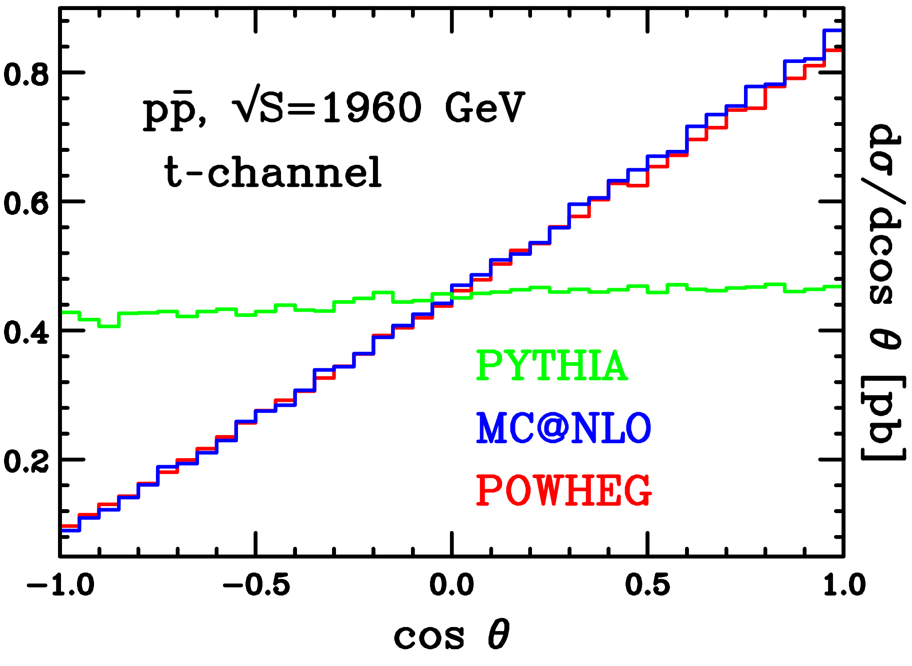
Single-top production + spin correlations



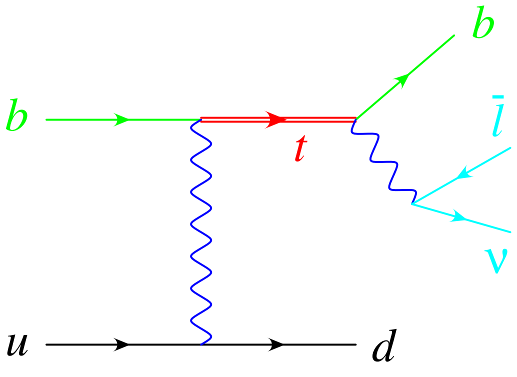


Single-top production + spin correlations



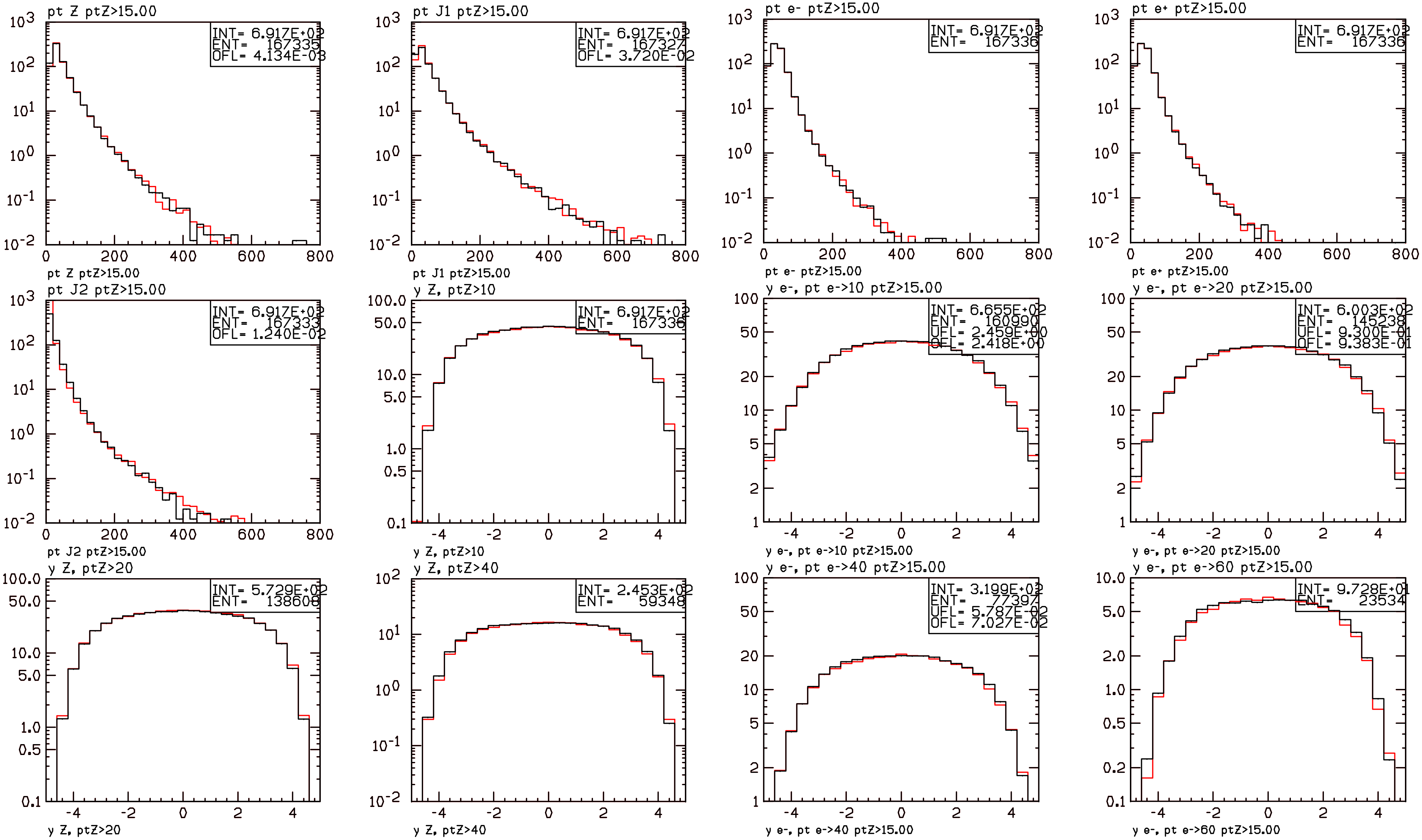


$$p_T^{\mathrm{rel},j_1} = \sum_{i \in j_1} \frac{|\vec{k}^i \times \vec{p}^{\,j_1}|}{|\vec{p}^{\,j_1}|}$$

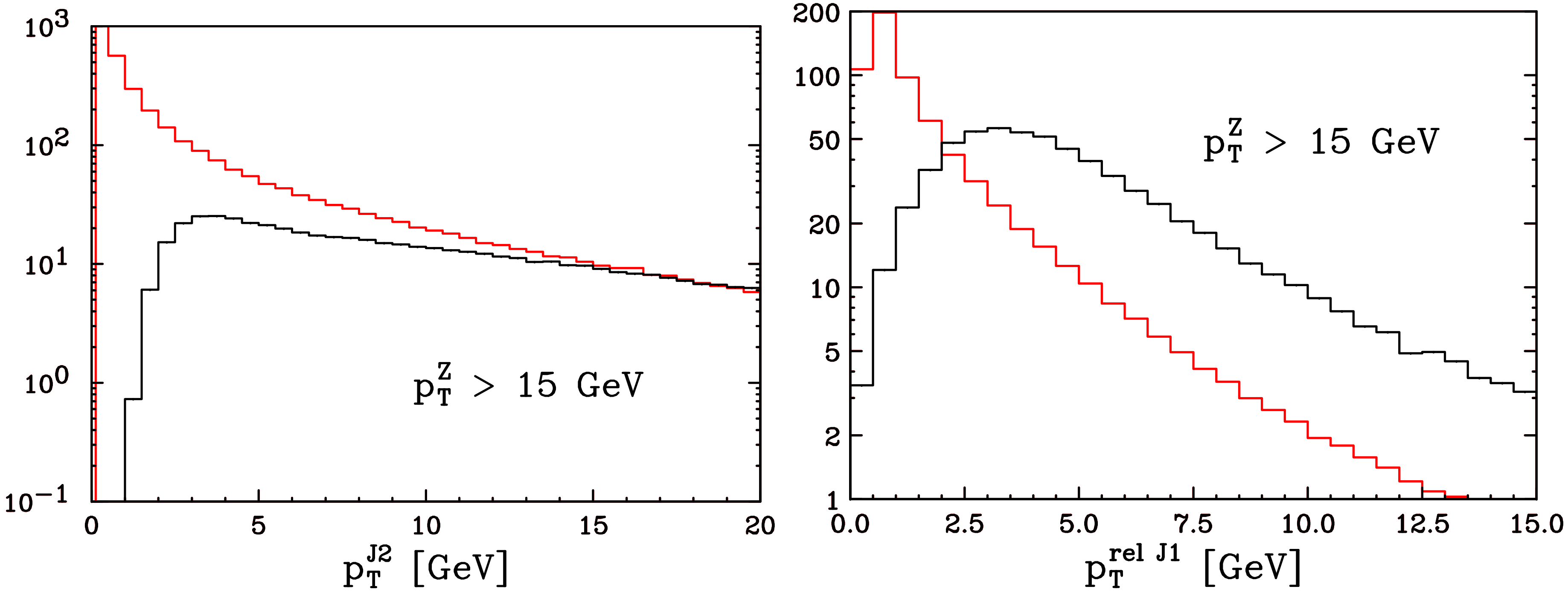


θ = angle between the charged lepton $\bar{l}$ and the hardest jet (d quark), in the top rest frame

Z + 1 jet: POWHEG+HERWIG with NLO



$Z + 1$ jet: POWHEG+HERWIG with NLO



Distributions sensitive to more than two jets show a noticeable difference

All others in agreement with NLO

First process not present in MC@NLO

The POWHEG BOX

Automatic implementation of POWHEG for generic NLO processes

More precisely, the user must supply

- ✓ the Born phase space
- ✓ the lists of Born and real processes (i.e. $u\bar{u} \to e^+e^-gg$)
- ✓ the Born squared amplitudes $\mathcal{B} = |\mathcal{M}|^2$, $\mathcal{B}_{ij}$ and $\mathcal{B}_{j,\mu\nu}$, for all relevant partonic processes. $\mathcal{B}_{ij}$ is the color-ordered Born amplitude squared, $\mathcal{B}_{j,\mu\nu}$ is the spin-correlated amplitude, where j runs over all external gluons in the amplitude. All these amplitudes are common ingredients of a NLO calculation.
- ✓ The real squared amplitude.
- ✓ The finite part of the virtual amplitude.

All the rest will be done automatically! The user should not worry about the subtraction scheme we use and all the other details.

The POWHEG BOX

Use the FKS (Frixione-Kunszt-Signer) subtraction scheme according to the general formulation of POWHEG given in [Frixione, Nason and C.O., 2007] (FNO), hiding all FKS implementation details.

In other words, the user needs not to know it!

It includes:

- ✓ the phase space for ISR and FSR, according to FNO.
- ✓ the combinatorics, the calculation of all singular regions in the real amplitude R, the soft and collinear limit
- ✓ the calculation of $\bar{B}$ (spinoff: NLO results using the FKS subtraction scheme)
- ✓ the calculation of the upper bounds for the generation of radiation
- ✓ the generation of radiation
- ✓ writing the event into the Les Houches interface

More testing needed. Further problems solved while we implement new processes.

The POWHEG BOX How-To

- `parameter (nlegborn=5)` $[pp\rightarrow(Z\rightarrow e^+e^-)+j]$ in included file `pwhg_flst.h`
  `flst_nborn` and `flst_nreal`
- `flst_born(k=1..nlegborn,j=1..flst_nborn)`: flavour of the k-th leg of the j-th Born graph
  `flst_real(k=1..nlegreal,j=1..flst_nreal)`: flavour of the k-th leg of the j-th real graph.
  It is required that legs in the Born and real processes have to be ordered as follows:
  - leg 1, incoming parton with positive rapidity
  - leg 2, incoming parton with negative rapidity
  - from leg 3 onward, final state particles, in the order: colorless particles first, massive coloured particles, massless coloured particles.

  The flavour is taken incoming for the two incoming particles and outgoing for the outgoing particles. The flavour index is assigned according to PDG conventions, except for gluons, where 0 is used instead of 21.
  Example: $pp\rightarrow(Z\rightarrow e^+e^-)+2j$, the string `[1,0,-11,11,1,0]` labels the process $dg\rightarrow e^+e^-dg$
- `init_couplings`

- `Born_phsp(xborn)` for Born phase space
  `xborn(1..ndim)` array of random numbers `ndim=(nlegborn-2)*3-4+2-1`
  - the Born Jacobian `kn_jacborn`, Born momenta in the laboratory frame `kn_pborn(0:3,1..nlegborn)`, Born momenta in the partonic CM frame `kn_cmpborn(0:3,1..nlegborn)` and Bjorken x (`kn_xb1` and `kn_xb2`).
- `set_ren_fac_scales(mur,muf)`
- `setborn(p,bflav,born,bornjk,bmunu)`
  - the momenta `p(0:3,1..nlegborn)`
  - the flavour string `bflav(1..nlegborn)`
  - `bornjk(1..nlegborn,1..nlegborn)`
  - the Born helicity-correlated squared amplitudes `bmunu(0:3,0:3,j=1..nlegborn)`
- `setvirtual(p,vflav,virtual)` returns finite part of the interference $2\,\mathrm{Re}\left(M_B \times M_V\right)$, after factorizing out ($d = 4 - 2\epsilon$)

$$\mathcal{N} = \frac{(4\pi)^\epsilon}{\Gamma(1-\epsilon)} \left(\frac{\mu^2}{Q^2}\right)^\epsilon \frac{\alpha_s}{2\pi}$$

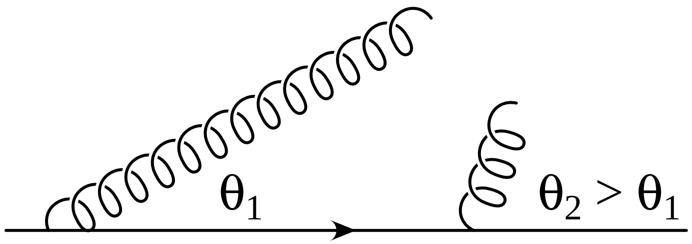
- `real_ampsq(p,rflav,amp2)`
  - the momenta `p(0:3,1..nlegreal)`
  - the flavour string `rflav(1...nlegreal)`
  - amp2: spin and color summed and averaged real squared amplitudes

Conclusions

- ✓ NLO accuracy with Shower Monte Carlo has become a reality in recent years.
- ✓ The POWHEG method is progressing, with new processes being included
- ✓ Progress in understanding agreement and differences between MC@NLO and POWHEG
- ✓ A path to full automation of POWHEG implementations of arbitrary NLO calculation is open: the POWHEG BOX
- ✓ Many interesting problems remain to be addressed, and the NLO+Shower community is steadily growing

Backup slides

POWHEG: truncated shower

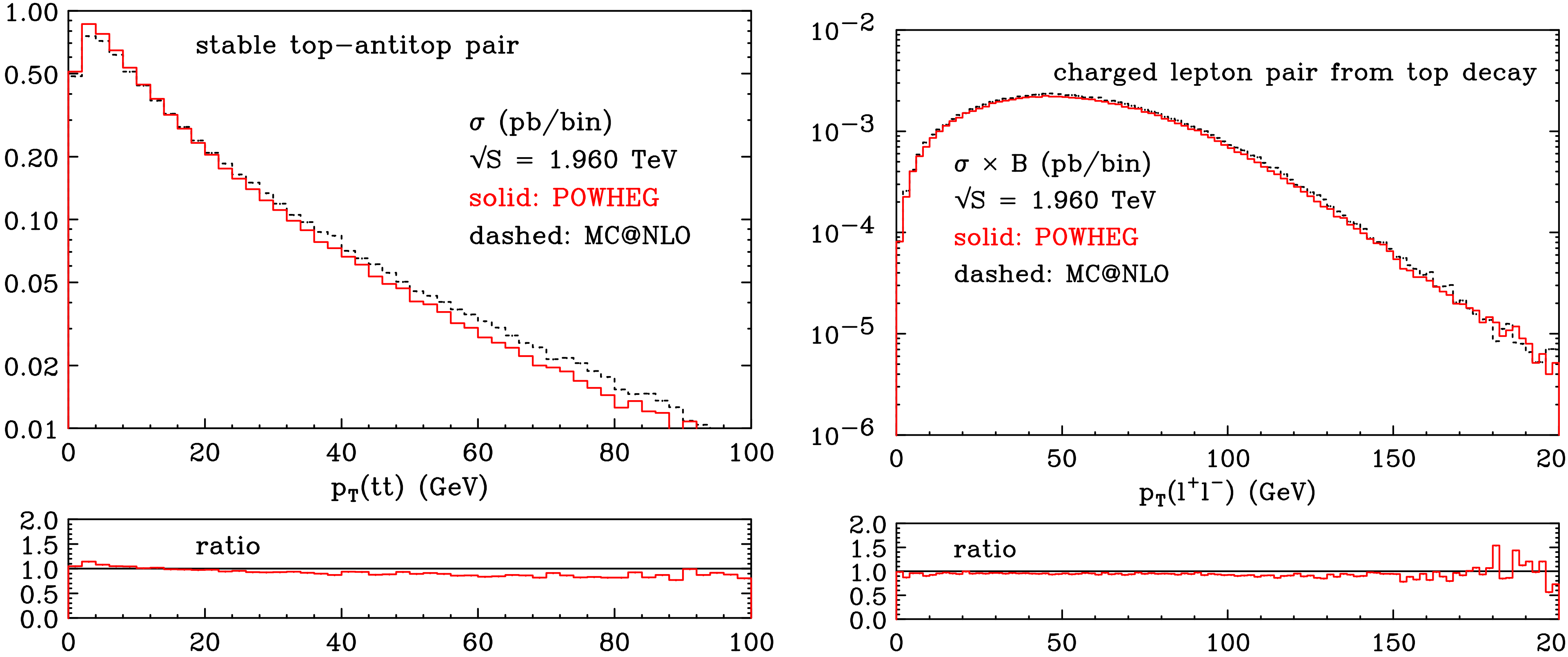


- if the shower is ordered in p_T (for example PYTHIA), nothing else needs to be done
- if the shower is ordered in angle (for example HERWIG), we need to generate correctly soft radiation at large angle.
  - pair up the partons that are nearest in p_T
  - generate an angular-ordered shower associated with the paired parton, stopping at the angle of the paired partons (truncated shower)
  - generate all subsequent vetoed showers

This is a problem that affects all the angular-ordered shower Monte Carlo programs when the shower is initiated by a relatively complex matrix element.

Truncated shower implemented only in HERWIG++

$t\bar{t}$ production



Good agreement for all observables considered. There are sizable differences that can be ascribed to different treatment of higher terms. But more investigation needed (different scale choices, no truncated shower, different hard/soft radiation emission,. . .).

ALPGEN vs MC@NLO: $t\bar{t}$ + 1 jet

ALPGEN can generate samples of $t\bar{t} + n$ jets. Can be compared to NLO + Parton Shower [Mangano, Moretti, Piccinini & Treccani, `hep-ph/0611129`]

✓ advantage: better high jet multiplicity (exact Matrix Element)

✗ disadvantage: worse normalization (no NLO)

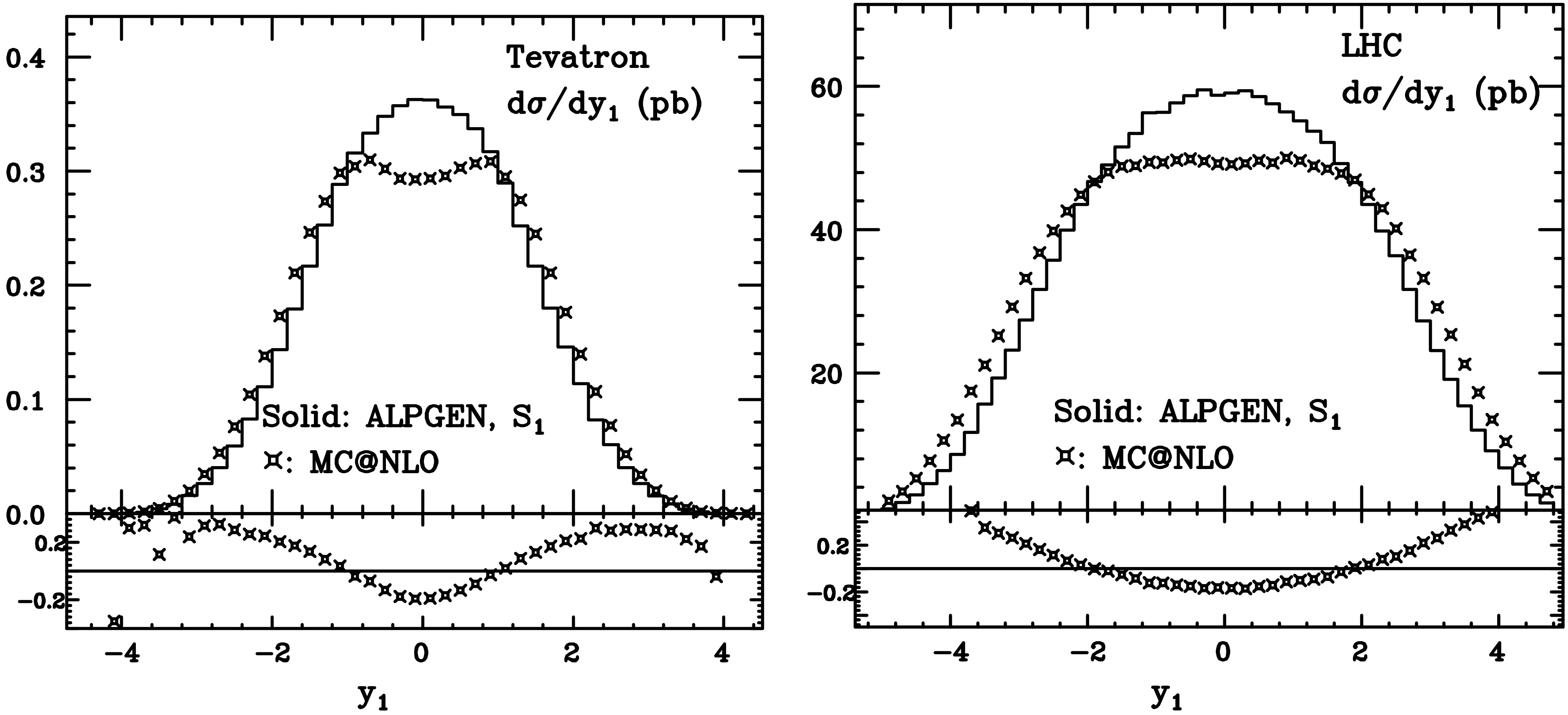
ALPGEN

- Generation: $P^T_{\rm min} = 30$ GeV, $\Delta R = 0.7$
- Matching: $E^T_{\rm min} = 30$ GeV, $\Delta R = 0.7$

Jet definitions

- Tevatron: $E^T_{\rm min} = 15$ GeV, $\Delta R = 0.4$, K factor = 1.45
- LHC: $E^T_{\rm min} = 20$ GeV, $\Delta R = 0.5$, K factor = 1.57

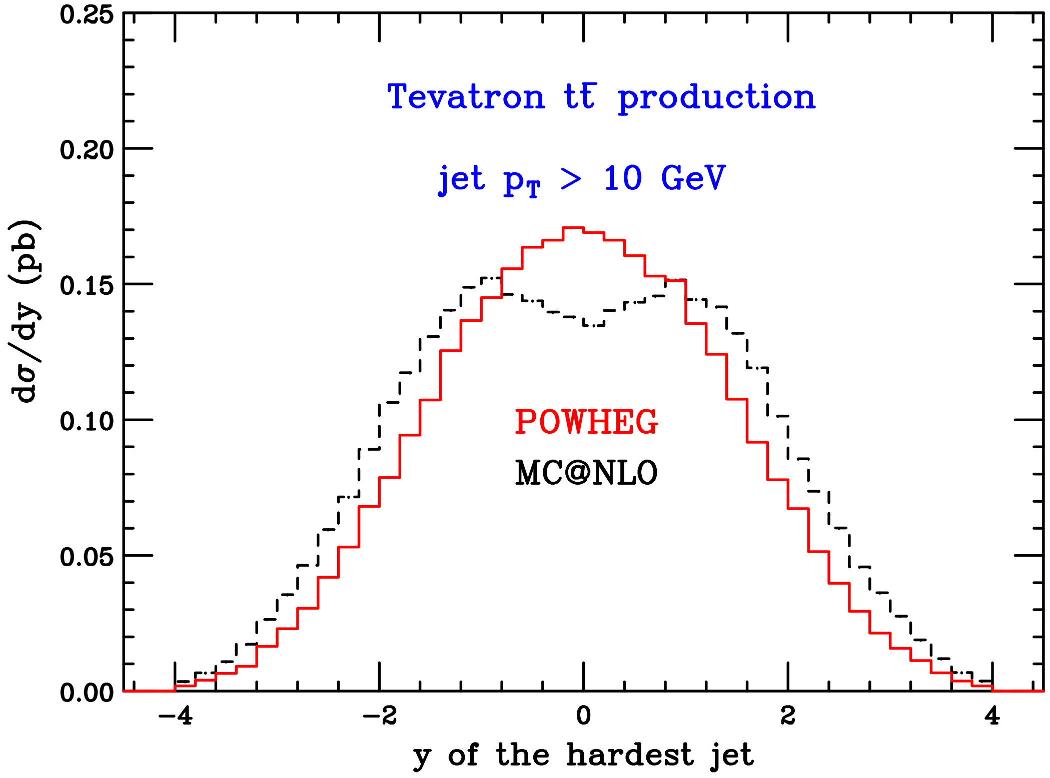
ALPGEN vs MC@NLO: $t\bar{t}$ + 1 jet

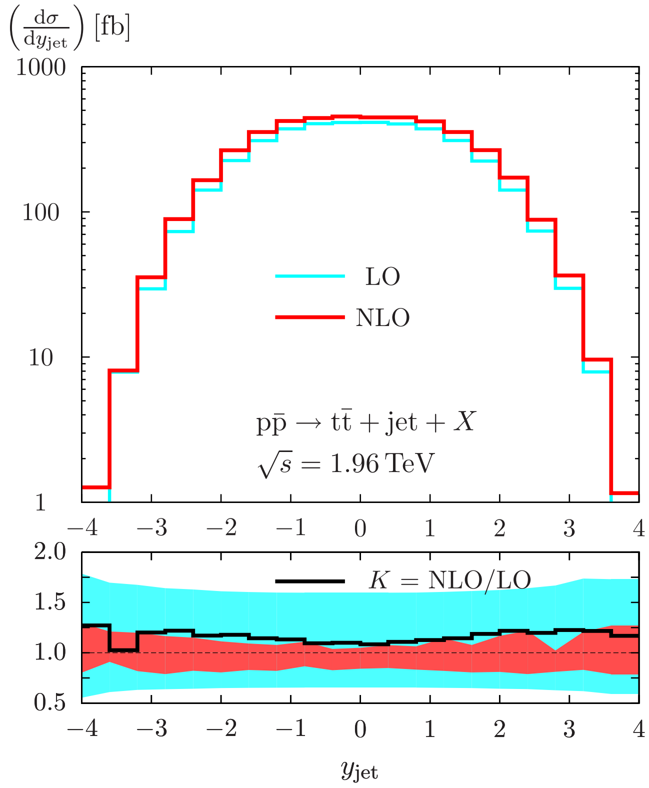


Rapidity y_1 of the leading jet (highest p_T).

Different shapes both at Tevatron and at the LHC

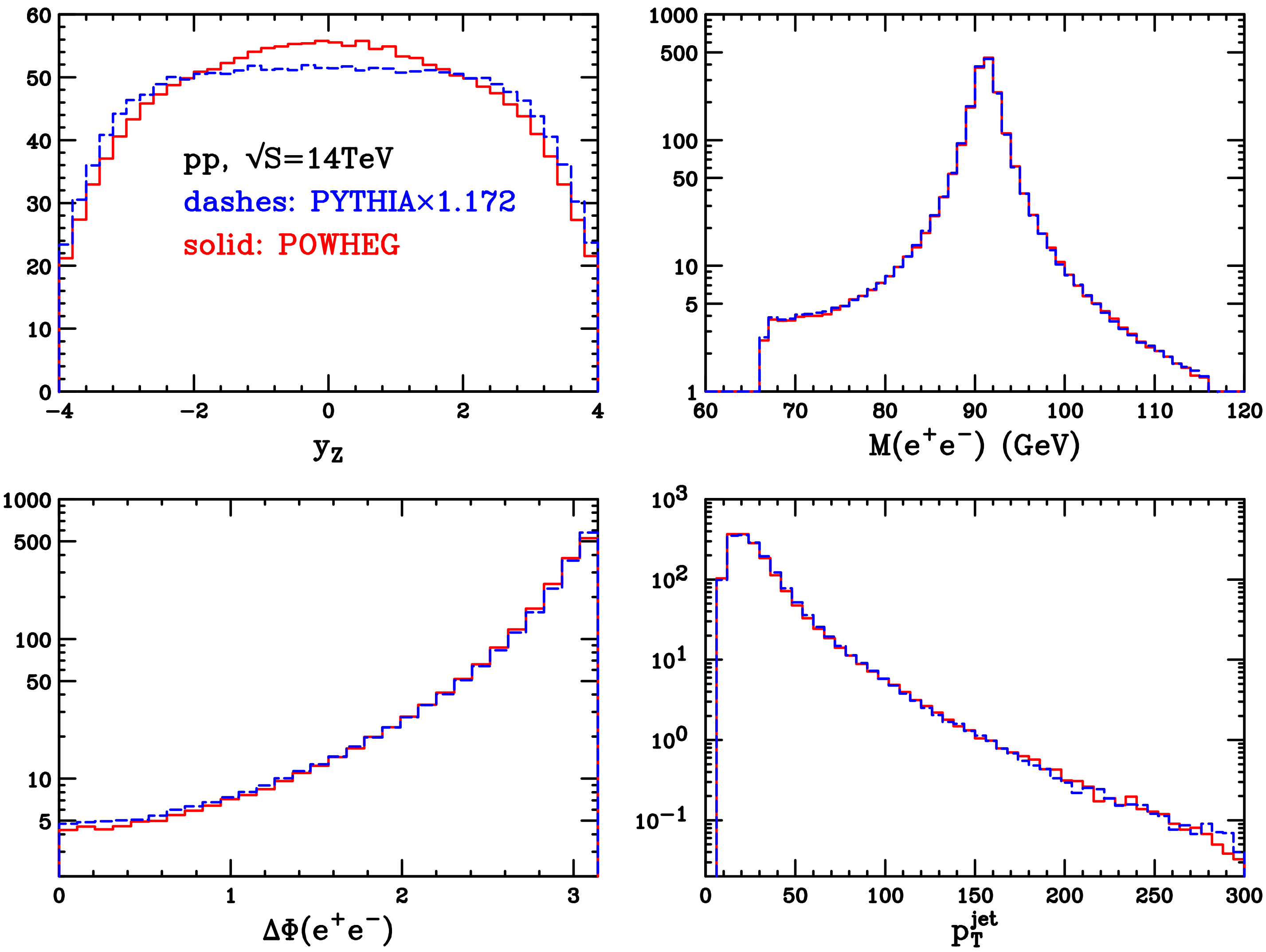
POWHEG: rapidity of the leading jet





POWHEG's distribution as in ALPGEN: no dip present. The size of discrepancy can be attributed to different treatment of higher-order terms. Is this "feature" really there? The new $pp \to t\bar{t}$ + jet at NLO [Dittmaier, Uwer, Weinzierl, `hep-ph/0703120`] shows no dip too.

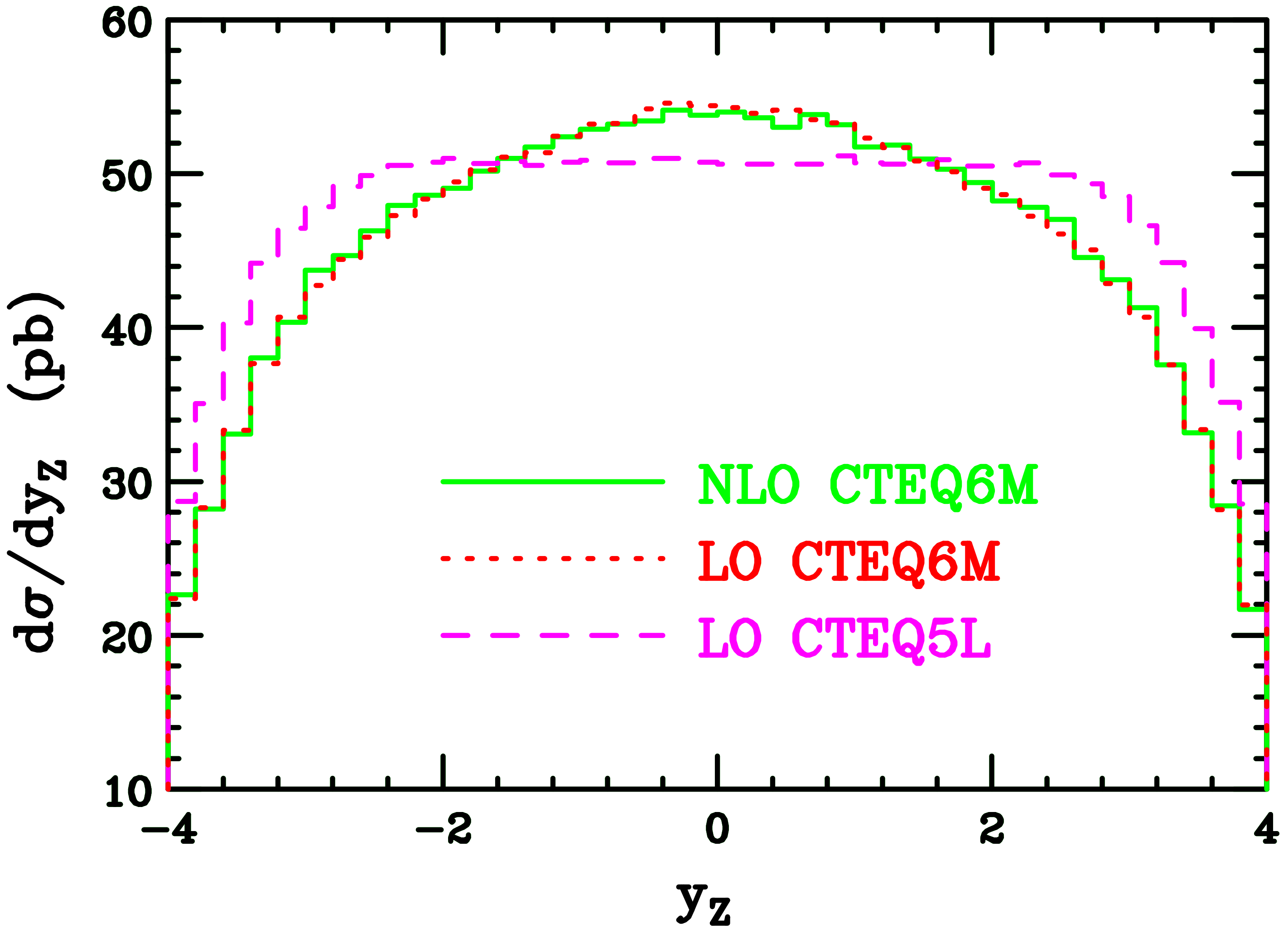
Z production: POWHEG + PYTHIA vs PYTHIA



For vector-boson production, PYTHIA generates radiation in a way similar to POWHEG.

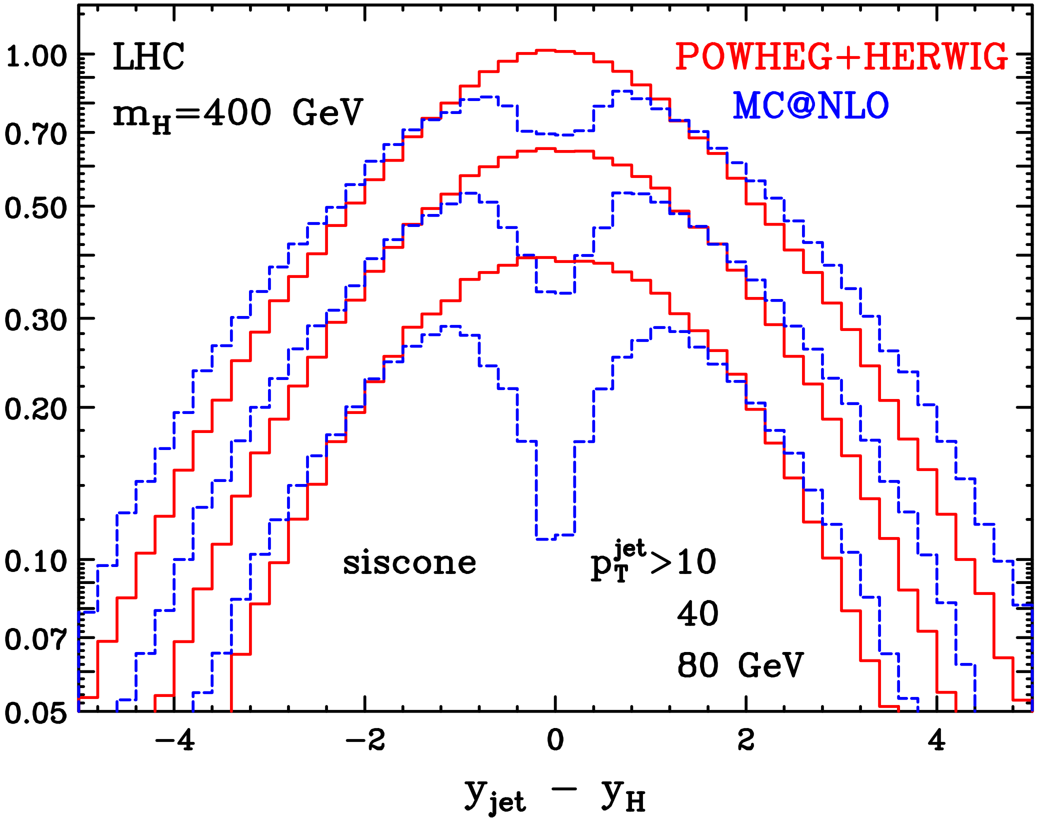
Differences ascribed to the use of LO parton densities.

Z production: POWHEG + PYTHIA vs PYTHIA



Plots normalized to the NLO total cross section.

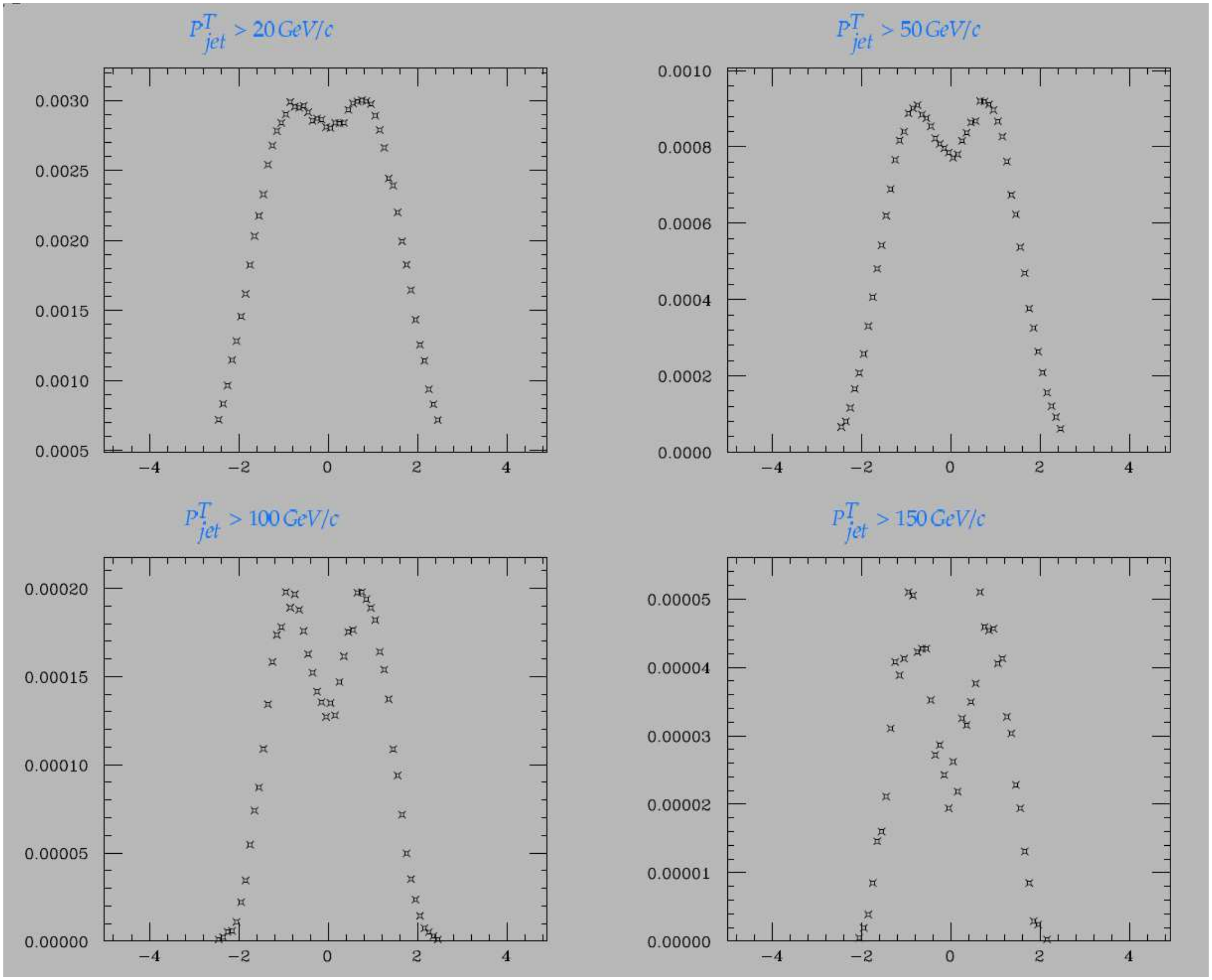
Higgs boson production at the LHC



POWHEG + HERWIG vs MC@NLO

$m_H = 400$ GeV

HERWIG: rapidity of the leading jet



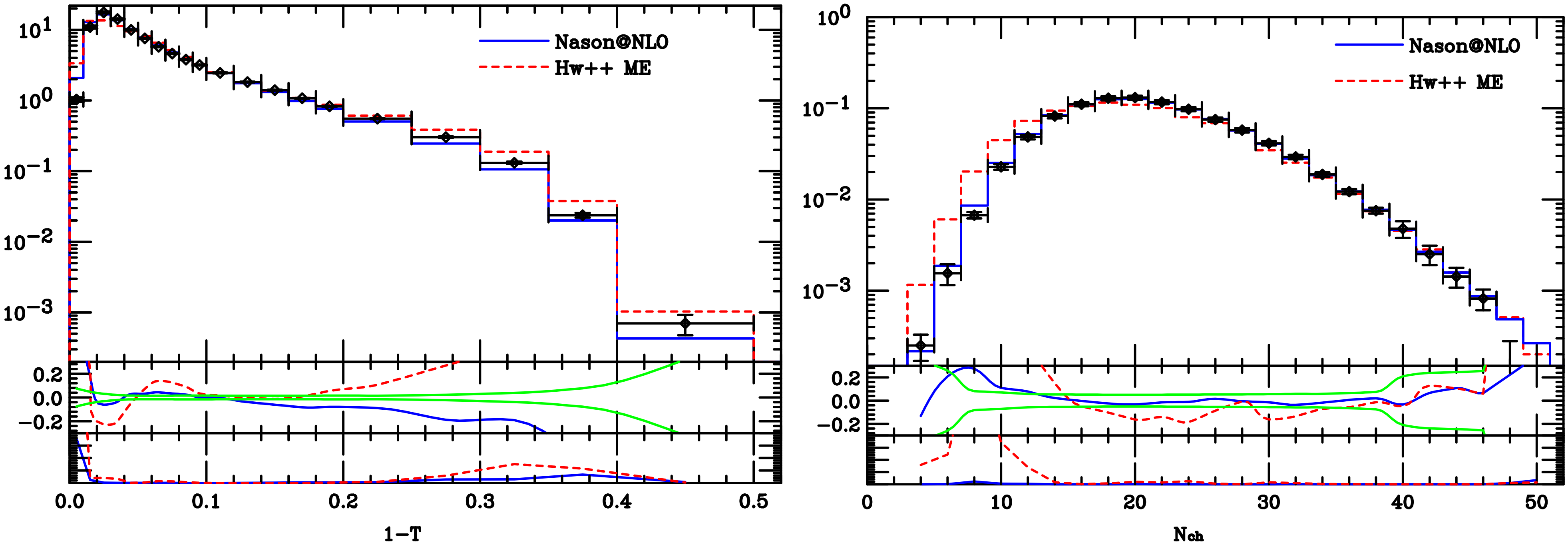
POsitive-Weight Hardest Emission Generator

[Nason, `hep-ph/0409146`]

is a **method**, NOT (only) a set of programs

- ✓ generates events with positive weights
- ✓ can be interfaced to any Parton Shower Monte Carlo, if the vetoed shower is implemented, according to the Les Houches Interface.
  It is independent from parton-shower programs. POWHEG can be interfaced with both PYTHIA and HERWIG, or with your favorite showering program,
- ✓ As far as the hardest emission is concerned, POWHEG guarantees:
  - ● NLO accuracy of (integrated) shape variables
  - ● Collinear, double-log, soft (large-N_c limit) accuracy of the Sudakov (in fact, corrections that exponentiates are obviously OK)
- ✓ As far as subsequent (less hard) emissions, the output has the accuracy of the SMC one is using.

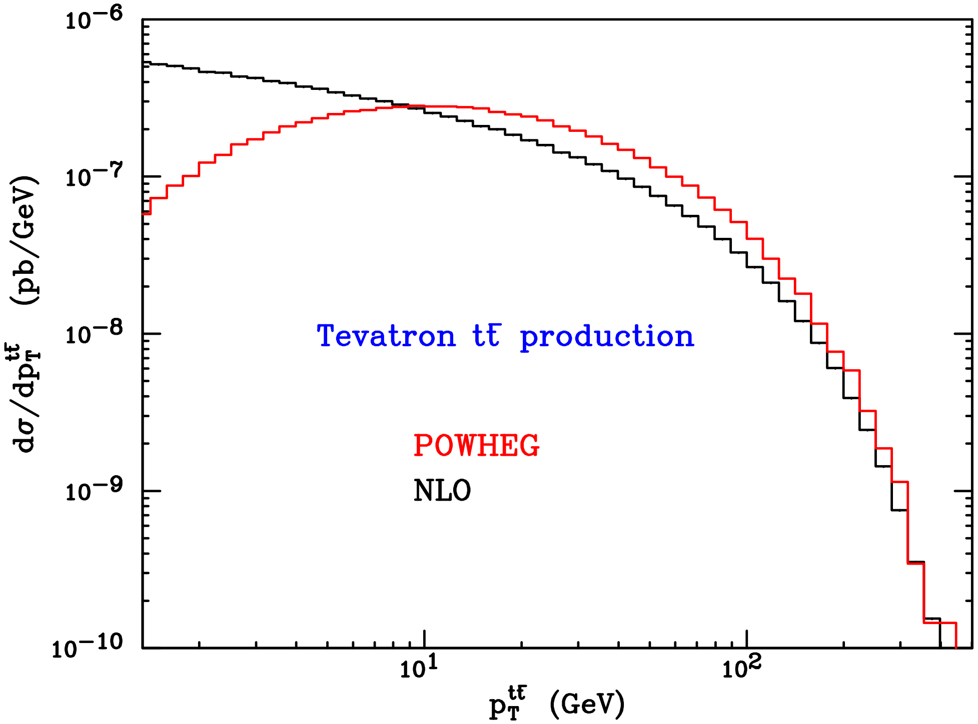
$e^+e^- \longrightarrow$ hadrons

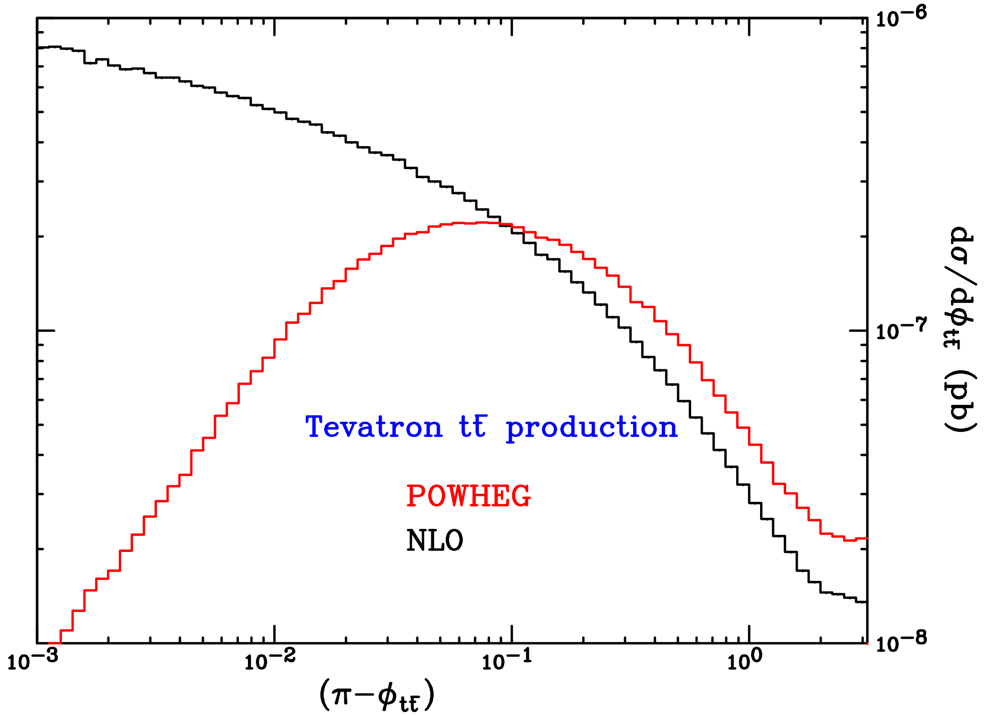


[Latunde-Dada, Gieseke and Webber, `hep-ph/0612281`]

Fit to e^+e^- data: better agreement than in the standard matrix-element correction approach.

$t\bar{t}$ production: POWHEG vs. NLO



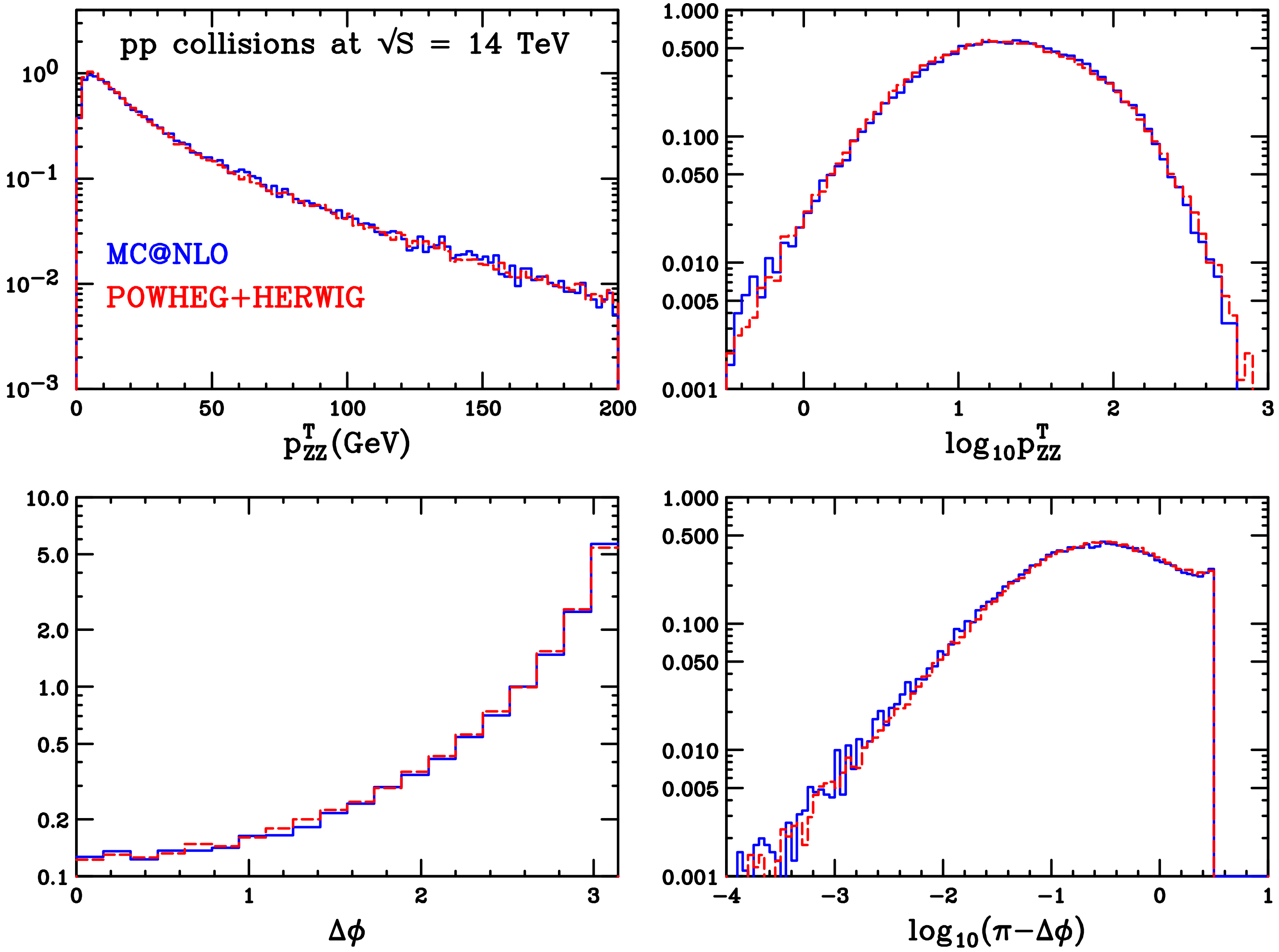


- when $p_T^{t\bar{t}} \to 0$, POWHEG treats correctly the resummation of soft/collinear radiation

\- when $p_T^{t\bar{t}}$ becomes large, POWHEG approaches the NLO result

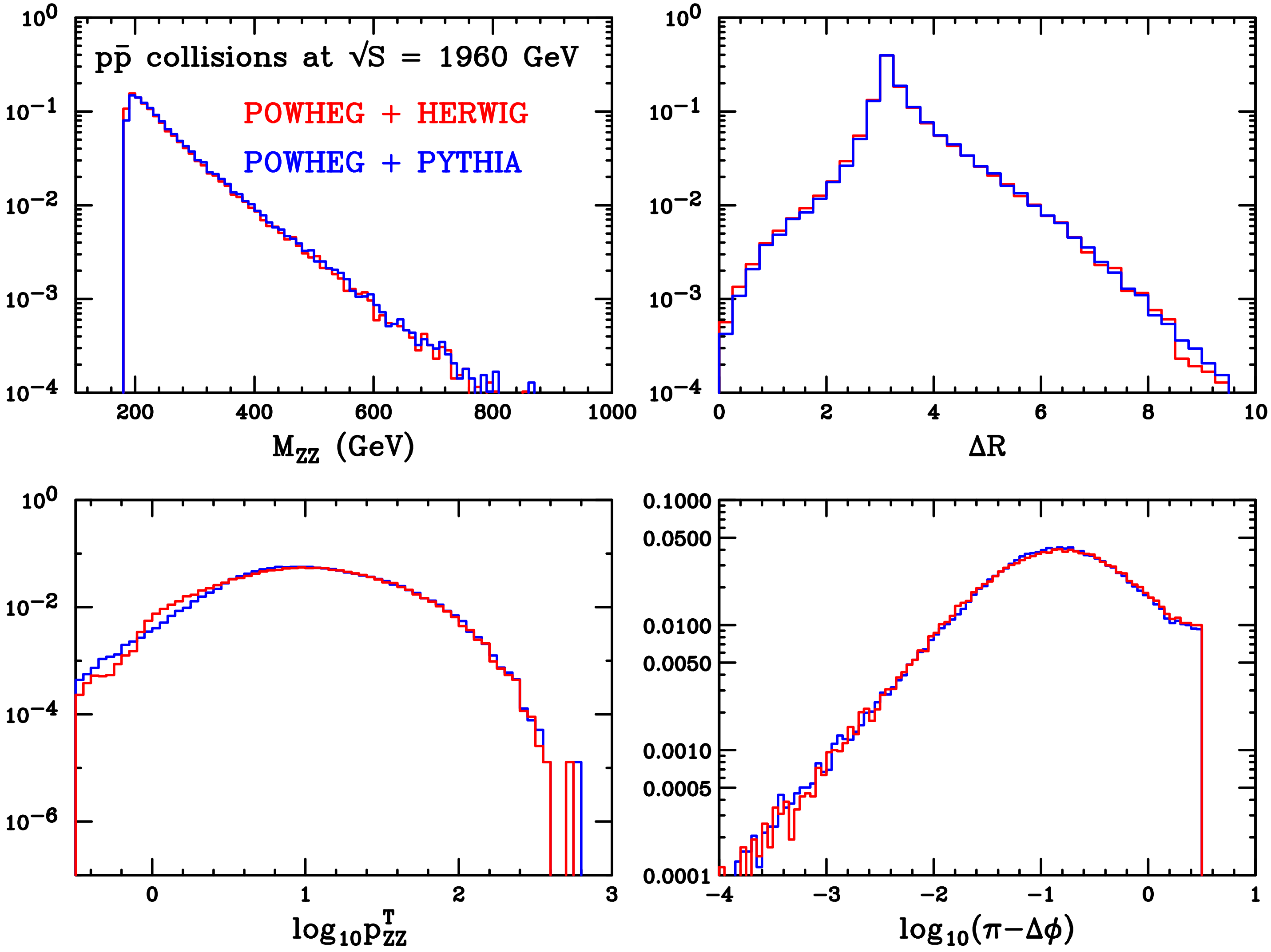
- when $\Phi_{t\bar{t}} \to 0$, the emitted radiation becomes hard and POWHEG goes to the NLO result.

ZZ production: POWHEG + HERWIG vs MC@NLO



No significant difference with MC@NLO [Nason and Ridolfi, hep-ph/0606275]

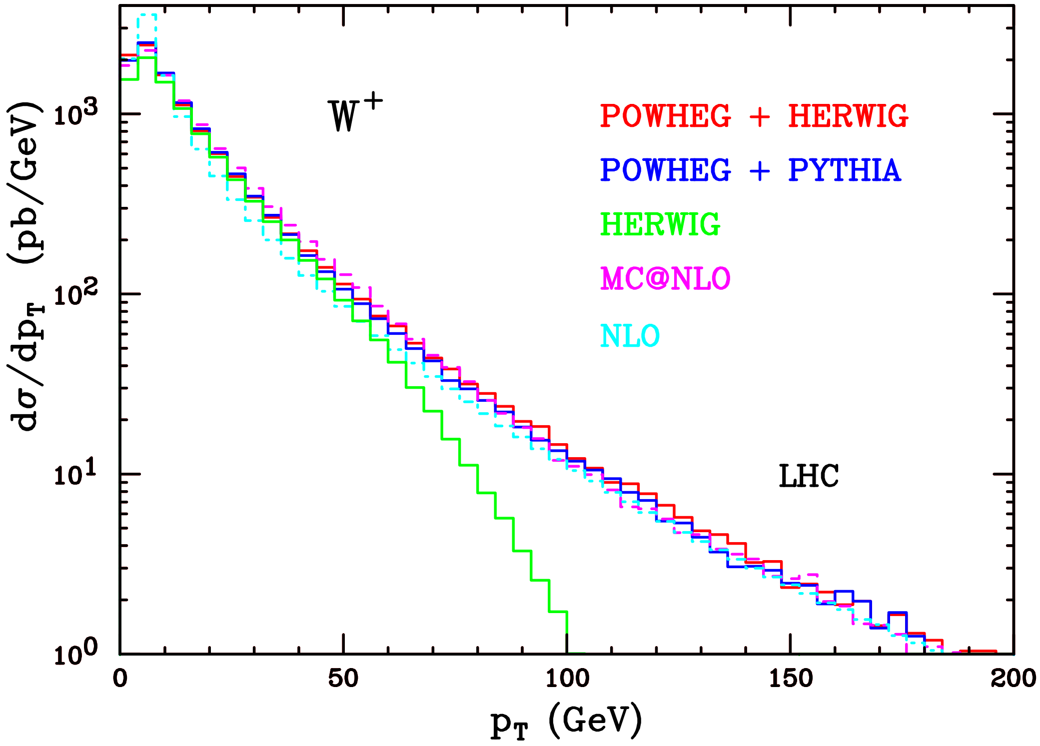
POWHEG + HERWIG vs POWHEG + PYTHIA

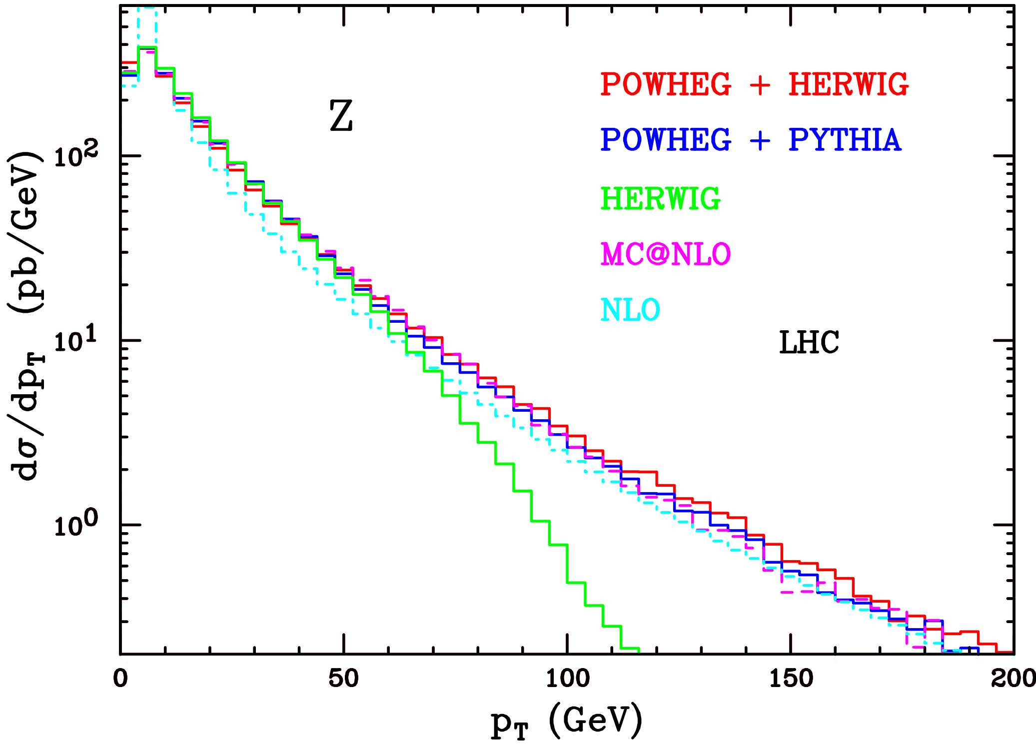


Agreement between POWHEG + HERWIG and POWHEG + PYTHIA

[Nason and Ridolfi, hep-ph/0606275]

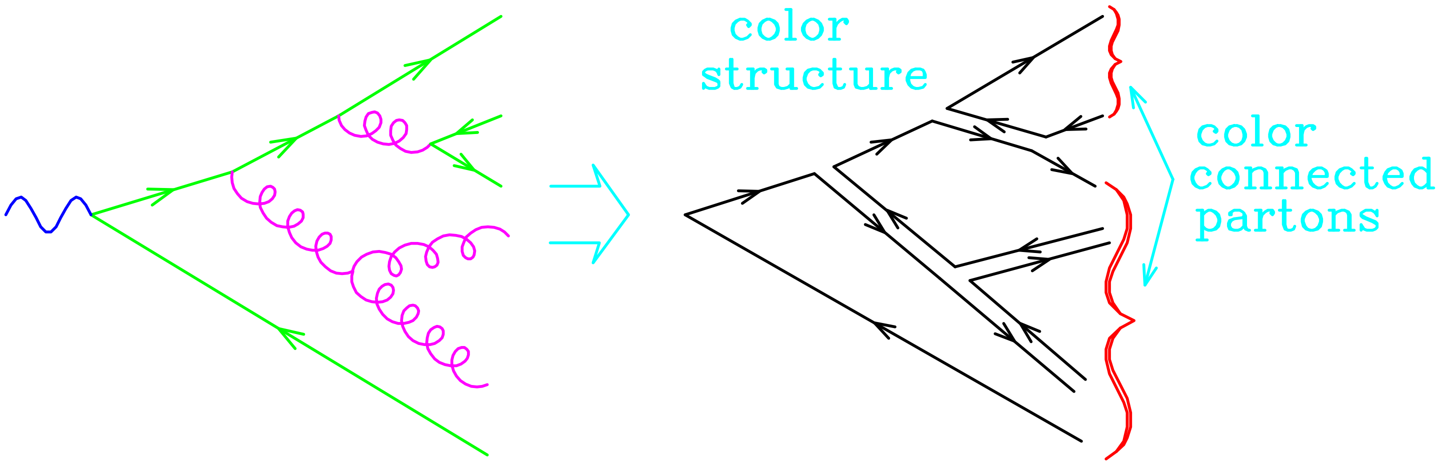
W/Z production





Color and hadronization

Shower Monte Carlo programs assign color labels to partons. Only color connections are recorded (in large N_c limit). The initial color is assigned according to hard cross section.



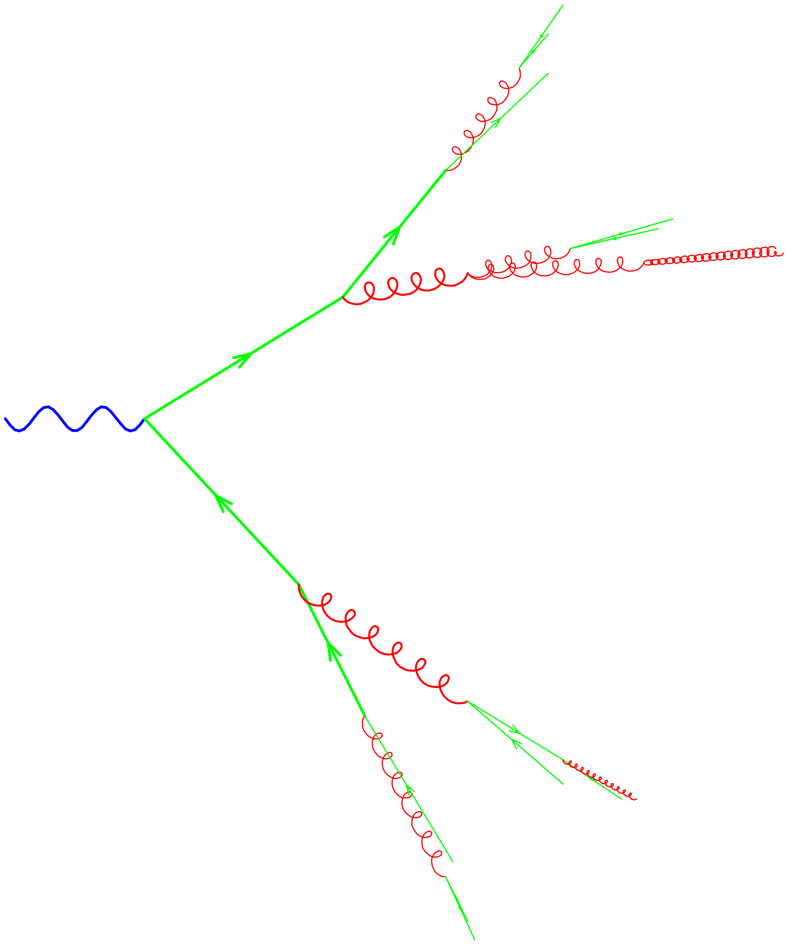
Color assignments are used in the hadronization model.

Most popular models: Lund string model, cluster model.

In all models, color singlet structures are formed out of color connected partons, and are decayed into hadrons, preserving energy and momentum.

Typical dominant configuration at very high Q^2

$\gamma^* \longrightarrow$ hadrons



- Besides $q \longrightarrow qg$, also $g \longrightarrow gg$, $g \longrightarrow q\bar{q}$ come into play.
- In the typical configurations, intermediate angles are of order of geometric average of upstream and downstream angles.
- Each angle is $\mathcal{O}(\alpha_s)$ smaller than its upstream angle, and $\mathcal{O}(\alpha_s)$ bigger than its downstream angle.
- As relative momenta become smaller, α_s becomes bigger, and this picture breaks down.

First branching

The probability of the first branching is independent of subsequent branchings because of Kinoshita-Lee-Nauenberg cancellation. It is given by

$$dP_{\text{first}} = \Delta_i(t,t') \, \frac{\alpha_S(t')}{2\pi} \, \frac{dt'}{t'} \, P_{i,jk}(z) \, dz \, \frac{d\varphi}{2\pi}$$

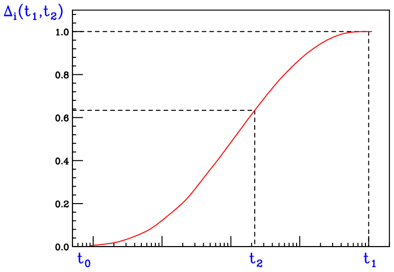
Upon integrating in z and φ, and summing over jk, we have

$$dP_{\text{first}} = \Delta_i(t,t') \, \frac{\alpha_S(t')}{2\pi} \, \frac{dt'}{t'} \int \sum_{(jk)} P_{i,jk}(z) \, dz \, \frac{d\varphi}{2\pi} = d\Delta_i(t,t')$$

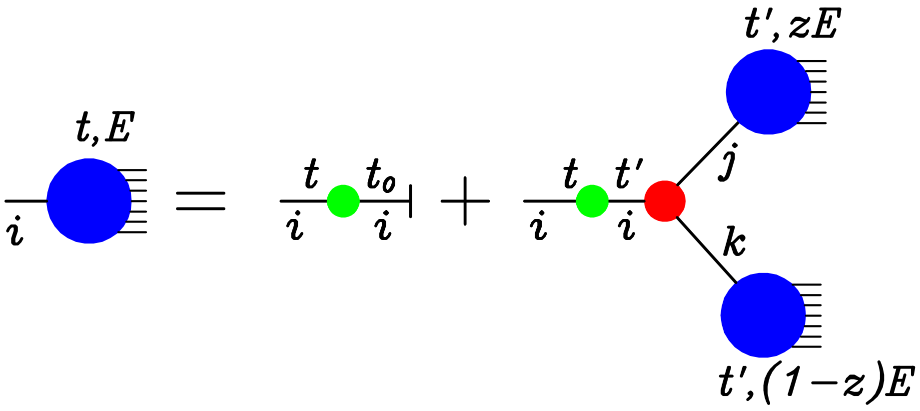
i.e. the distribution is uniform in the Sudakov form factor.
The integral over the whole t' range, from the minimum value t_0 (IR cutoff) up to t, is given by

$$\int_{t_0}^{t} dP_{\text{first}} = \int_{t_0}^{t} d\Delta_i(t,t') = \Delta_i(t,t) - \Delta_i(t,t_0) = 1 - 0 = 1$$

as it should be for a correct probabilistic interpretation.



Final recipe I

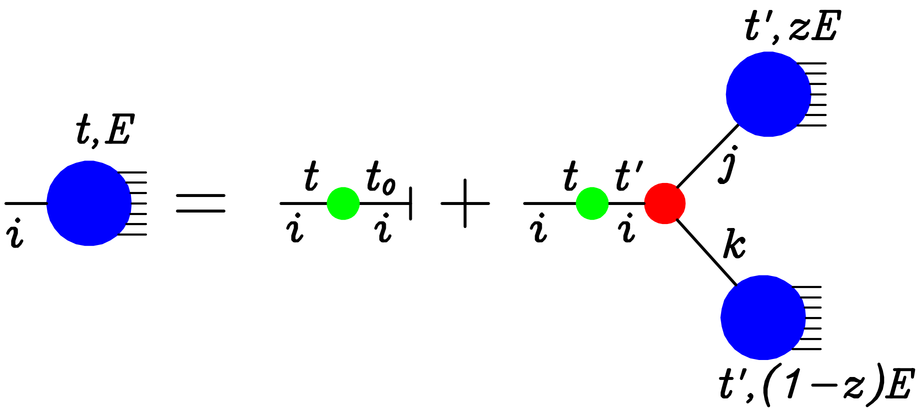


$$\mathcal{S}_i(t,E) = \Delta_i(t,t_0)\,\mathbb{1} + \sum_{(jk)} \int_{t_0}^{t} \frac{\alpha_S(t')}{2\pi}\,\frac{dt'}{t'} \int dz \int \frac{d\varphi}{2\pi}\,\Delta_i(t,t')\,P_{i,jk}(z)\,\mathcal{S}_j(t',zE)\;\mathcal{S}_k(t',(1-z)E)$$

- consider all tree graphs.
- assign values to the radiation variables Φ_r (t, z and φ) to each vertex.
- at each vertex, $i \longrightarrow jk$, include a factor

$$\frac{dt}{t}\,dz\,\frac{\alpha_S(t)}{2\pi}\,P_{i,jk}(z)\,\frac{d\varphi}{2\pi}$$

Final recipe II



- include a factor $\Delta_i(t_1,t_2)$ to each internal parton i, from hardness t_1 to hardness t_2.

$$\Delta_i(t_1,t_2) = \exp\left[-\sum_{(jk)}\int_{t_2}^{t_1}\frac{dt}{t}\,\frac{\alpha_S(t)}{2\pi}\int dz\,P_{i,jk}(z)\int\frac{d\varphi}{2\pi}\right]$$

The weights $\Delta_i(t_1,t_2)$ are called Sudakov form factors. They resum all the dominant virtual corrections to the tree graph (in the collinear approximation). Notice also that the inclusion of real and virtual corrections gives a net result of 1 (cancellation of collinear singularities in inclusive quantities).

- include a factor $\Delta_i(t,t_0)$ on final lines (t_0 = IR cutoff)

Actual implementation of the shower algorithm

We start from a given value of the ordering variable t. We want to generate the value t' for the next emission, according to the probability

$$dP_{\rm first} = \Delta_i(t,t')\,\frac{\alpha_S(t')}{2\pi}\,\frac{dt'}{t'}\int\sum_{(jk)} P_{i,jk}(z)\,dz\,\frac{d\varphi}{2\pi} = d\Delta_i(t,t')$$

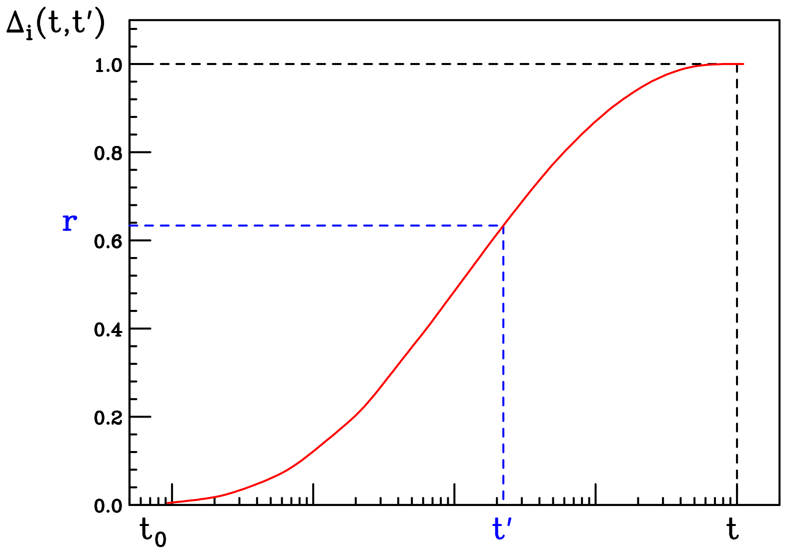
Since this is an exact differential form, we proceed as in the case we want to generate a random variable x according to a distribution function $f(x)$, whose indefinite integral is known, starting from a uniform random variable r

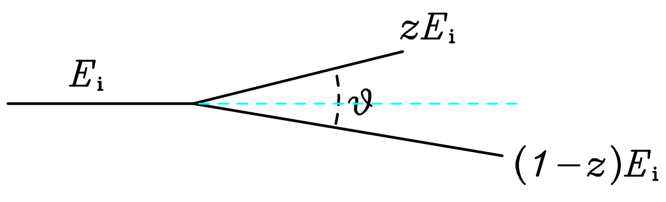
$$dP = f(X)\,dX = 1\,dR \qquad \text{where} \qquad f(X)\,dX = dF(X)$$

$$\int_{x_{\rm min}}^{x} f(X)\,dX = F(x) = \int_0^r 1\,dR = r \qquad \Longrightarrow \qquad x = F^{-1}(r)$$

Actual implementation of the shower algorithm

- ✓ generate a hard process configuration with a probability proportional to its parton-level cross section. Parton densities are evaluated at the typical “high” scale Q of the process
- ✓ for each final-state colored parton, generate a shower
  - set $t = Q^2$
  - generate a uniform random number $0 < r < 1$
  - solve the equation $\Delta_i(t, t') = r$ for t'
  - if $t' < t_0$ stop here (final state line). Begin hadronization
  - if $t' > t_0$, generate z, jk with probability $P_{i,jk}(z)$, and $0 < \varphi < 2\pi$ uniformly. Assign energies $E_j = zE_i$ and $E_k = (1-z)E_i$ to partons j and k. The angle θ between their momenta is fixed by t' and with φ their direction is completely specified
  - restart shower from each of the two branched parton j and k, setting the ordering parameter $t = t'$.





Shower algorithm

✓ for each initial-state colored parton, generate a shower in a similar way, but using a "trick": the backward evolution (Sjöstrand)

$$\frac{f_i^h(t',x)\,\Delta(t,t')}{f_i^h(t,x)} = r$$

where f_i^h is the parton density for the colliding hadron h, where parton i carries a momentum fraction $x = E_i/E_h$

Some momentum reshuffling is needed in order to preserve local (at each vertex) and global momentum conservation

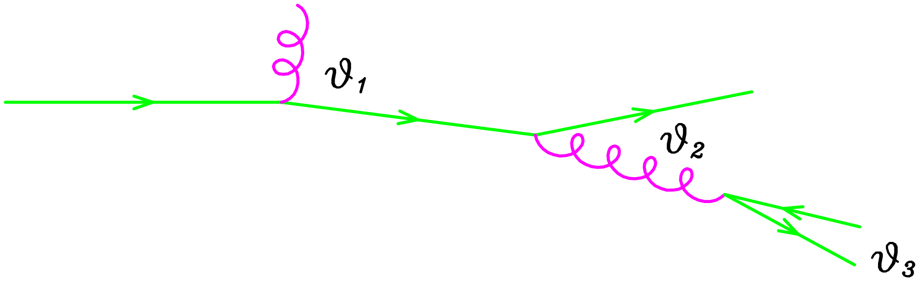
Angular ordering

Mueller (1981) showed that angular ordering is the correct choice

$$\frac{d\theta}{\theta}\,\frac{\alpha_s\left(p_T^2\right)}{2\pi}\,P(z)\,dz$$

$$\theta_1 > \theta_2 > \theta_3 \ldots$$

$$p_T^2 = E^2 z^2 (1-z)^2 \theta^2$$



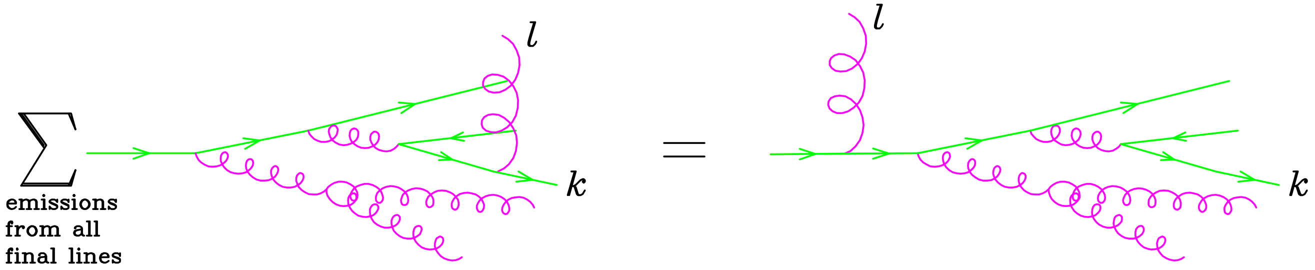
$\alpha_s(p_T^2)$ for a correct treatment of charge renormalization in soft region (p_T^2 equals to the maximum virtuality of the gluon line).

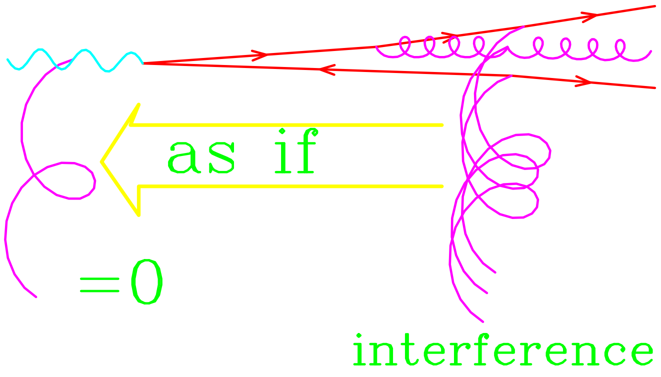
$$\begin{aligned}\Delta_i(t,t') &= \exp\left[-\int_{t'}^{t}\frac{dt}{t}\int_{\sqrt{\frac{t_0}{t}}}^{1-\sqrt{\frac{t_0}{t}}} dz\frac{\alpha_s(p_T^2)}{2\pi}\sum_{(jk)} P_{i,jk}(z)\right]\\ &\approx \exp\left\{-\frac{c_i}{4\pi b_0}\left[\log\frac{t}{\Lambda^2}\log\frac{\log\frac{t}{\Lambda^2}}{\log\frac{t_0}{\Lambda^2}}-\log\frac{t}{t_0}\right]_{t'}^{t}\right\}\qquad (c_q = C_F, c_g = 2C_A)\end{aligned}$$

Sudakov dumping stronger than any power of t.

Color coherence

Soft gluons emitted at large angles from final-state partons add coherently





- angular ordering accounts for soft gluon interference.
- intensity for photon jets $= 0$
- intensity for gluon jets $= C_A$ instead of $2\,C_F + C_A$

In angular-ordered shower Monte Carlo, large-angle soft emission is generated first.

Hardest emission, i.e. highest $p_T = E\,z(1-z)\,\theta$, in general, happens later.

Some available codes

- COJETS Odorico (1984)
- ISAJET Paige+Protopopescu (1986)
- FIELDAJET Field (1986)
- JETSET Sjöstrand (1986)
- PYTHIA Bengtsson+Sjöstrand (1987), Sjöstrand+Skands (2004)
- HERWIG Marchesini+Webber (1988), Marchesini+Webber+Abbiendi+Knowles+Seymour+Stanco (1992)
- ARIADNE Lönnblad (1992)
- SHERPA Gleisberg+Höche+Krauss+Schälicke+Schumann+Winter (2004)

Available accuracy

	collinear	soft-collinear	soft large-N_c	soft
PYTHIA	leading	partial	no	no
HERWIG	leading	leading	no	no
ARIADNE	partial	partial	leading	no
PYTHIA6.4	partial	partial	leading	no
SHERPA	leading	partial	no	no

One can realistically aim at

leading collinear, leading double log, leading soft in large-N_c limit

Soft effects for finite N_c require matrix exponentiation in the Sudakov form factor.

New developments

- Interfacing Matrix Elements (ME) generators with Parton Showers : CKKW matching [Catani, Krauss, Küen, Webber], MLM matching [Mangano]
- Interfacing NLO calculations with Parton Showers: MC@NLO [Frixione, Webber], POWHEG [Nason]

Several other approaches have appeared

- $e^+e^- \to 3$ partons [Kramer, Mrenna, Soper]
- Shower by antenna factorization [Giele, Kosower, Skands]
- Shower by Catani-Seymour dipole factorization [Schumann, Krauss]
- Shower with quantum interference [Nagy, Soper]
- Shower by Soft Collinear Effective Theory [Bauer, Schwartz]
- Shower from the dipole formalism [Dinsdale, Ternick, Weinzierl]

Up to now, complete results for hadron colliders only from MC@NLO and POWHEG.

NLO + Parton Shower

LO-ME good for shapes. Uncertain absolute normalization

$$\alpha_s^n(2\mu) \approx \alpha_s^n(\mu)\left(1 - b_0\alpha_s(\mu)\log(4)\right)^n \approx \alpha_s^n(\mu)\left(1 - n\alpha_s(\mu)\right)$$

For $\mu = 100$ GeV, $\alpha_s = 0.12$, normalization uncertainty:

$W + 1J$	$W + 2J$	$W + 3J$
$\pm 12\%$	$\pm 24\%$	$\pm 36\%$

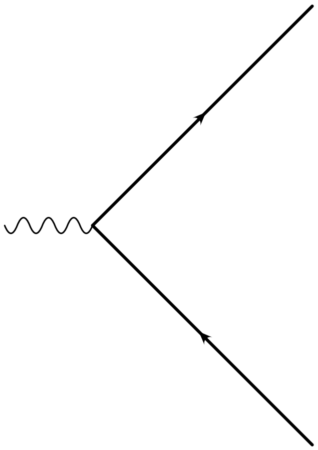
To improve on this, we need to go to NLO

- Positive experience with NLO calculations at LEP, HERA and Tevatron
- NLO results are cumbersome to compute: typically made up of an n-body (Born + virtual + soft and collinear remnants) and $(n+1)$-body (real emission) terms, both divergent (finite only when summed up).
- Merging NLO with shower is a natural extension of present approaches.

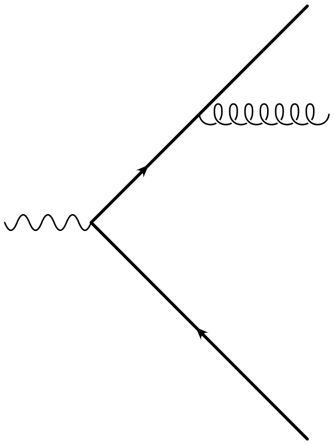
NLO + Parton Shower

The main problem in merging a NLO result and a Parton Shower is not to double-count radiation: the shower might produce some radiation already present at the NLO level.

LO:



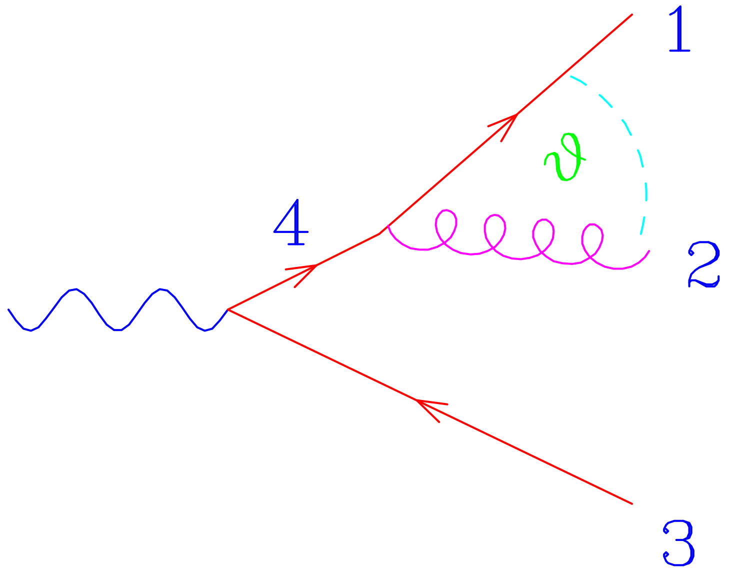
NLO:



POWHEG: how it works

1. POWHEG, POsitive Weight Hardest Emission Generator, [Nason, `hep-ph/0409146`], generates first a partonic event with just one single emission, at NLO level, and with the correct probability in order not to have double-counting coming from (subsequent) radiation. The p_T of the produced radiation works as an upper cutoff for the p_T's of the entire subsequent shower.
2. The event is written on a file using the standard Les Houches Interface and is processed by the Parton Shower program (HERWIG, PYTHIA…), that showers the event, but with a p_T less than the p_T generated by POWHEG (p_T veto).
   - if the shower is ordered in p_T (for example PYTHIA), nothing else needs to be done
   - if the shower is ordered in angle (for example HERWIG), we need to generate correctly soft radiation at large angle.
     - pair up the partons that are nearest in p_T
     - generate an angular-ordered shower associated with the paired parton, stopping at the angle of the paired partons (truncated shower)
     - generate all subsequent vetoed showers

Example of truncated shower: e^+e^-



- nearby partons: 1 and 2
- truncated shower: 1 and 2 pair, from θ up to a maximum angle. The truncated shower reintroduces coherent soft radiation from 1 and 2 at angles larger than θ (angular-ordered shower Monte Carlo programs generate those earlier).
- 1 and 2 shower from θ to cutoff
- 3 showers from maximum to cutoff

Truncated showers not yet implemented.

No evidence of effects from their absence in ZZ and e^+e^- production. Might be some effects in heavy-quark production.

NLO calculations

We can always parametrize the $(n+1)$-body phase space $\mathbf{\Phi}_{n+1}$ in terms of the Born phase space $\mathbf{\Phi}_n$ and three radiation variables Φ_r: $\mathbf{\Phi}_{n+1} = \{\mathbf{\Phi}_n, \Phi_r\}$

$$\langle O \rangle = \int O \, d\sigma = \int d\mathbf{\Phi}_n \, O(\mathbf{\Phi}_n) \, [B(\mathbf{\Phi}_n) + V_b(\mathbf{\Phi}_n)] + \int d\mathbf{\Phi}_n \, d\Phi_r \, O(\mathbf{\Phi}_n, \Phi_r) \, R(\mathbf{\Phi}_n, \Phi_r)$$

where V_b is the (divergent) virtual differential cross section. The virtual and real-radiation integrals are separate divergent. Their sum is finite (for any infra-red safe observable).
A typical subtraction method re-organize the integrals in the form

$$\begin{aligned} \langle O \rangle &= \int d\mathbf{\Phi}_n \, O(\mathbf{\Phi}_n) \left[B(\mathbf{\Phi}_n) + V_b(\mathbf{\Phi}_n) + \int d\Phi_r \, C(\mathbf{\Phi}_n, \Phi_r) \right] \\ &+ \int d\mathbf{\Phi}_n \, d\Phi_r \, \underbrace{[O(\mathbf{\Phi}_n, \Phi_r) \, R(\mathbf{\Phi}_n, \Phi_r) - O(\mathbf{\Phi}_n) \, C(\mathbf{\Phi}_n, \Phi_r)]}_{\text{finite}} \end{aligned}$$

Defining

$$V(\mathbf{\Phi}_n) = V_b(\mathbf{\Phi}_n) + \int d\Phi_r \, C(\mathbf{\Phi}_n, \Phi_r) \qquad \Longleftarrow \ \text{finite}$$

we have

$$\langle O \rangle = \int d\mathbf{\Phi}_n \, O(\mathbf{\Phi}_n) \, [B(\mathbf{\Phi}_n) + V(\mathbf{\Phi}_n)] + \int d\mathbf{\Phi}_n \, d\Phi_r \, [O(\mathbf{\Phi}_n, \Phi_r) \, R(\mathbf{\Phi}_n, \Phi_r) - O(\mathbf{\Phi}_n) \, C(\mathbf{\Phi}_n, \Phi_r)]$$

NLO in SMC

Shower Monte Carlo (SMC) cross section for first emission ($d\Phi_r = dt\, dz\, d\varphi$)

$$\langle O \rangle = \int d\mathbf{\Phi}_n\, B(\mathbf{\Phi}_n) \left\{ O(\mathbf{\Phi}_n)\Delta_{t_0} + \int_{t_0} \frac{dt}{t}\, dz\, d\varphi\, O(\mathbf{\Phi}_n, \Phi_r)\, \Delta_t\, \frac{\alpha_s}{2\pi}\, P(z) \right\}$$

with

$$\Delta_t = \exp\left[-\int_t \frac{dt'}{t'}\, dz'\, d\varphi'\, \frac{\alpha_s}{2\pi}\, P(z') \right]$$

The expansion at order α_s gives the $\mathrm{NLO}_{\mathrm{SMC}}$

$$\langle O \rangle = \int d\mathbf{\Phi}_n\, B(\mathbf{\Phi}_n) \left\{ O(\mathbf{\Phi}_n) + \int_{t_0} \frac{dt}{t}\, dz\, d\varphi\, [O(\mathbf{\Phi}_n, \Phi_r) - O(\mathbf{\Phi}_n)]\, \frac{\alpha_s}{2\pi}\, P(z) \right\}$$

This is the inexact NLO correction implemented by the SMC

How do we reach exact NLO accuracy?

Towards NLO accuracy

$$\begin{aligned}
\langle O\rangle &= \int d\mathbf{\Phi}_n\, O(\mathbf{\Phi}_n)\,[B(\mathbf{\Phi}_n)+V(\mathbf{\Phi}_n)] \\
&+ \int d\mathbf{\Phi}_n\, d\Phi_r\,[O(\mathbf{\Phi}_n,\Phi_r)\,R(\mathbf{\Phi}_n,\Phi_r)-O(\mathbf{\Phi}_n)\,C(\mathbf{\Phi}_n,\Phi_r)] \\
&= \int d\mathbf{\Phi}_n\, O(\mathbf{\Phi}_n)\left\{B(\mathbf{\Phi}_n)+V(\mathbf{\Phi}_n)+\int d\Phi_r\big[R(\mathbf{\Phi}_n,\Phi_r)-C(\mathbf{\Phi}_n,\Phi_r)\big]\right\} \\
&+ \int d\mathbf{\Phi}_n\, d\Phi_r\, R(\mathbf{\Phi}_n,\Phi_r)\,[O(\mathbf{\Phi}_n,\Phi_r)-O(\mathbf{\Phi}_n)]
\end{aligned}$$

Define

$$\overline{B}(\mathbf{\Phi}_n)=B(\mathbf{\Phi}_n)+V(\mathbf{\Phi}_n)+\int d\Phi_r\big[R(\mathbf{\Phi}_n,\Phi_r)-C(\mathbf{\Phi}_n,\Phi_r)\big]$$

$$\langle O\rangle=\int d\mathbf{\Phi}_n\, O(\mathbf{\Phi}_n)\,\overline{B}(\mathbf{\Phi}_n)+\int d\mathbf{\Phi}_n\, d\Phi_r\, R(\mathbf{\Phi}_n,\Phi_r)\big[O(\mathbf{\Phi}_n,\Phi_r)-O(\mathbf{\Phi}_n)\big]$$

In NLO_{SMC}, it was

$$\langle O\rangle=\int d\mathbf{\Phi}_n\, O(\mathbf{\Phi}_n)\, B(\mathbf{\Phi}_n)+\int d\mathbf{\Phi}_n\, d\Phi_r\, B(\mathbf{\Phi}_n)\,\frac{\alpha_s}{2\pi}\,P(z)\,\frac{1}{t}\big[O(\mathbf{\Phi}_n,\Phi_r)-O(\mathbf{\Phi}_n)\big]$$

POWHEG

$\mathrm{NLO_{SMC}} \leftrightarrow \mathrm{NLO}:$ $B(\mathbf{\Phi}_n) \leftrightarrow \overline{B}(\mathbf{\Phi}_n)$ $B(\mathbf{\Phi}_n)\frac{\alpha_s}{2\pi}P(z)\frac{1}{t} \leftrightarrow R(\mathbf{\Phi}_n, \Phi_r)$

All-order emission probability in SMC

$$\langle O \rangle = \int d\mathbf{\Phi}_n\, B(\mathbf{\Phi}_n) \left\{ O(\mathbf{\Phi}_n)\, \Delta_{t_0} + \int_{t_0} d\Phi_r\, O(\mathbf{\Phi}_n, \Phi_r)\, \Delta_t\, \frac{\alpha_s}{2\pi}\, P(z)\, \frac{1}{t} \right\}$$

with

$$\Delta_t = \exp\left[- \int d\Phi'_r\, \frac{\alpha_s}{2\pi}\, P(z')\, \frac{1}{t'}\, \theta(t' - t) \right]$$

All order emission probability in POWHEG

$$\langle O \rangle = \int d\mathbf{\Phi}_n\, \overline{B}(\mathbf{\Phi}_n) \left\{ O(\mathbf{\Phi}_n)\, \Delta_{t_0} + \int d\Phi_r\, O(\mathbf{\Phi}_n, \Phi_r)\, \Delta_t\, \frac{R(\mathbf{\Phi}_n, \Phi_r)}{B(\mathbf{\Phi}_n)} \right\}$$

$$\Delta_t = \exp\left[- \int d\Phi'_r\, \frac{R(\mathbf{\Phi}_n, \Phi'_r)}{B(\mathbf{\Phi}_n)}\, \theta(t' - t) \right]$$

with $t = k_T(\mathbf{\Phi}_n, \Phi_r)$ and $\overline{B}(\mathbf{\Phi}_n) = B(\mathbf{\Phi}_n) + V(\mathbf{\Phi}_n) + \int d\Phi_r \left[R(\mathbf{\Phi}_n, \Phi_r) - C(\mathbf{\Phi}_n, \Phi_r) \right]$

POSITIVE if $\overline{B}$ is positive (i.e. NLO < LO).

Accuracy of the Sudakov form factor

POWHEG's Sudakov form factor has the form (with $c \approx 1$)

$$\Delta_t = \exp\left[-\int_t^{Q^2} \frac{dk_T^2}{k_T^2} \frac{\alpha_s(c\,k_T^2)}{\pi} \left\{ A \log \frac{E^2}{k_T^2} + B \right\}\right]$$

The next-to-leading log (NLL) Sudakov form factor has the form

$$\Delta_t^{\rm NLL} = \exp\left[-\int_t^{Q^2} \frac{dk_T^2}{k_T^2} \frac{\alpha_s(k_T^2)}{\pi} \left\{ \left(A_1 + A_2 \frac{\alpha_s(k_T^2)}{\pi} \right) \log \frac{E^2}{k_T^2} + B \right\}\right]$$

provided the color structure of the process is sufficiently simple ($\leqslant$ 3 colored legs). Can use this to fix c in POWHEG's Sudakov form factor as suggested in Catani, Webber, Marchesini, (1991). HERWIG uses this.

For colored legs $\geqslant$ 4, exponentiation only holds at leading-log (LL) or LL + NLL in the large-N_c limit (i.e. planar color structure of Feynman diagrams)

POWHEG's Sudakov form factor is always LL accurate. NLL accurate for $\leqslant$ 3 colored legs, NLL accurate in leading N_c in all cases.

Mathematical tricks

- ✓ To generate the underlying Born variables ($\mathbf{\Phi}_n$), distributed according to $\overline{B}(\mathbf{\Phi}_n)$, one uses programs like BASES/SPRING or MINT, that, after a single integration, can generate points distributed according to the integrand function.

- ✓ Use the veto technique and the highest-p_T bid procedure, to generate the radiation variables, distributed according to $d\Delta_i(t, t')$.

These tricks are well known to Monte Carlo experts.

We have collected a few of them in the appendixes of our paper
[Frixione, Nason and C.O., arXiv:0709.2092 [hep-ph]].

POsitive-Weight Hardest Emission Generator

- ✓ it is independent from parton-shower programs. POWHEG can be interfaced with both PYTHIA and HERWIG, or with your favorite showering program, if the vetoed shower is implemented, according to the Les Houches Interface.
- ✓ it can use existing NLO results
- ✓ it generates events with positive weights
- ✓ As far as the hardest emission is concerned, POWHEG guarantees:
  - ● NLO accuracy on integrated quantities
  - ● collinear, double-log (soft-collinear), large-N_c-soft single-log of the Sudakov (in fact, corrections that exponentiates are obviously OK)
- ✓ As far as subsequent (less hard) emissions, the output has the accuracy of the SMC one is using.
- ✗ no truncated shower implemented up to now. But this is a problem that affects all the angular-ordered SMC when the shower is initiated by a relatively complex matrix element.

Existing implementations

The POWHEG method has already been successfully used in

- $pp \to ZZ$ [Nason and Ridolfi, `hep-ph/0606275`]
- $e^+e^- \to$ hadrons [Latunde-Dada, Gieseke and Webber, `hep-ph/0612281`]
  $e^+e^- \to t\bar{t}$ with top decay [Latunde-Dada, arXiv:0806.4560]
- $pp \to Q\overline{Q}$ ($c\bar{c}$, $b\bar{b}$, $t\bar{t}$) with spin correlations [Frixione, Nason and Ridolfi, arXiv:0707.3088].
- $pp \to W/Z$ with spin correlations [Alioli, Nason, C.O. and Re, arXiv:0805.4802; Hamilton, Richardson and Tully, arXiv:0806.0290].
- $pp \to H$ [Alioli, Nason, C.O. and Re, arXiv:0812.0578]

All POWHEG implementations for hadronic colliders have been interfaced to both PYTHIA and HERWIG.

To appear soon

- $pp \to H$ [Hamilton, Richardson and Tully, HERWIG++ group]
- single-top production [Alioli, Nason, C.O. and Re]
- $pp \to W/Z + 1$ jet [Alioli, Nason, C.O. and Re]

We are working now on a general framework for the implementation of any NLO process into the POWHEG formalism.

Given the Born, real and virtual amplitudes, combine them automatically to produce POWHEG events.

Truncated showers have been studied in $e^+e^- \to$ hadrons [Latunde-Dada, Gieseke and Webber] and are included in the HERWIG++ framework [Bähr, Gieseke, Gigg, Grellscheid, Hamilton, Plätzer, Richardson, Seymour and Tully, arXiv:0812.0529]

From NLO to POWHEG

POWHEG is a **method**, NOT (only) a set of programs!

POWHEG is fully general and can be applied to any NLO subtraction framework.

We have provided any user with all the formulae and ingredients to implement an existing NLO calculation in the POWHEG formalism [Frixione, Nason and C.O., arXiv:0709.2092 [hep-ph]].

We have looked in detail at POWHEG in two subtraction schemes:

- the Frixione, Kunszt and Signer scheme
- the Catani and Seymour scheme.

We have discussed, in a pedagogical way, two examples:

- $e^+e^- \longrightarrow q\bar{q}$
- $q\bar{q} \longrightarrow V$

The `fortran` implementation of the POWHEG code for these two processes (and all the others) can be found at

`http://moby.mib.infn.it/~nason/POWHEG`

Conclusions

- ✓ POWHEG is a viable method for interfacing NLO and Shower Monte Carlo programs
- ✓ It is easy to implement and does not require new NLO computations
- ✓ No commitment to a specific Shower Monte Carlo implementation is required
- ✓ It outputs positive, unweighted events, as in traditional Shower Monte Carlo programs
- ✓ Several processes already available. More to come
- ✓ Anybody can work on it!

POWHEG is a method, not (only) a set of programs!

- ✓ We have collected and published material to make it easy for others to implement POWHEG with their NLO calculations

`http://moby.mib.infn.it/~nason/POWHEG`

- ✓ A general framework for implementing arbitrary processes is work in progress