NEW DEVELOPMENTS IN PERTURBATIVE QCD

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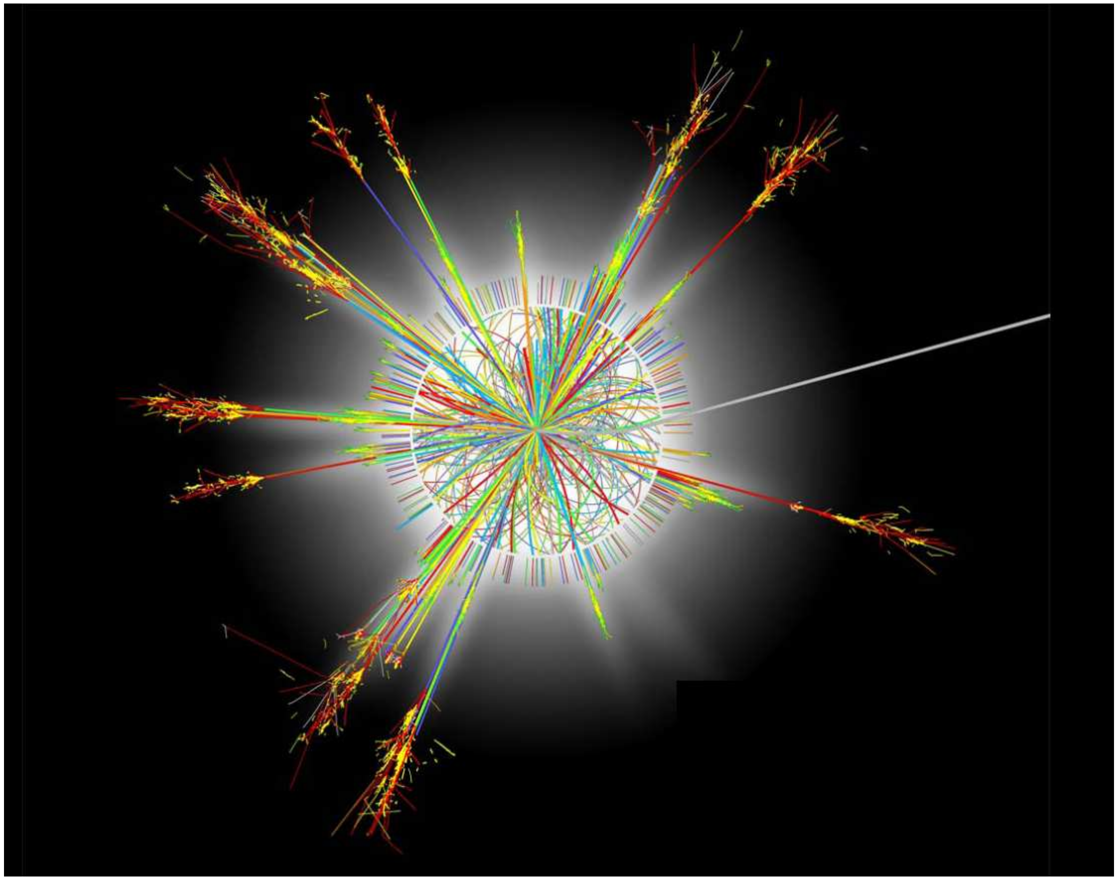
- Fixed-order calculations
  - Leading Order
  - Next-to-Leading Order
  - Next-to-Next-to-Leading Order
- Monte Carlo programs
- Jets
- Conclusions



QCD

Present status…

- Established theory of strong interactions
- Framework for computation of hard processes using asymptotic freedom
- Large body of tests of perturbative QCD predictions (very positive experience with LEP, HERA and TEVATRON results)
- No major areas of discrepancy with data

…and prospects

Focus is shifting from QCD tests to QCD applications for SM and BSM physics.
Problems:

- complexity: higher energy, more open thresholds, more particles, jets…
- unpredictability: it is fair to say that we do not know which physical scenario will open up when LHC starts

Complexity requires complex calculations of signal and backgrounds
Unpredictability requires the ability to perform them quickly and to make the results available in a flexible way.

State of the art

relative order	$2 \to 1$	$2 \to 2$	$2 \to 3$	$2 \to 4$	$2 \to 5$	$2 \to 6$
1	LO					
α_s	NLO	LO				
α_s^2	NNLO	NLO	LO			
α_s^3		NNLO	NLO	LO		
α_s^4			NNLO	NLO	LO	
α_s^5				NNLO	NLO	LO

LO Well-understood. Now more efficient than ever

NLO Many new $2 \to 3$ processes.

NLO Still waiting for a $2 \to 4$ process at the LHC

NNLO Recent breakthroughs for inclusive and exclusive $2 \to 1$.
Splitting functions (space-like and time-like evolution) known at this order too
[Moch, Vermaseren & Vogt]

NNLO Still waiting for $2 \to 2$

Tree level

- ✓ Many available programs for automatic generation of tree-level matrix elements
  - Feynman diagrams: MadGraph/MadEvent [Maltoni, Stelzer] using HELAS [Hagiwara et al], CompHEP/CalcHEP [Boos et al], SHERPA/AMEGIC++ [Krauss et al]
  - off-shell recursions relations: VecBos [Giele], ALPHA/ALPGEN [Caravaglios, Moretti; Mangano, Moretti, Piccinini, Pittau, Polosa], Helac [Kanaki, Papadopoulos]
  - on-shell recursions relations (twistor-inspired): CSW [Cachazo-Svrček-Witten; Dixon, Glover, Khoze, Badger, Bern, Forde, Kosower, Mastrolia]. BCFW [Britto, Cachazo, Feng, Witten] + masses [Badger, Glover, Khoze, Svrček; Schwinn, Weinzierl].

    No public tools yet.
- ✓ automatic/modular integration over phase space: HELAC/PHEGAS, MadGraph/MadEvent, Sherpa/AMEGIC++, ALPHA/ALPGEN…
- ✓ very good for estimating the importance of various processes in different models. They properly populate the phase space with multiple hard objects
- ✓ able to interface with Parton Showers: CKKW in SHERPA, MLM in ALPGEN, MLMKT in MadEvent…

Comparison of algorithms

10^4 phase space points. Time in seconds [Duhr, Höche, Maltoni]

Final State	BG		BCF		CSW	
	CO	CD	CO	CD	CO	CD
$2g$	0.24	0.28	0.28	0.33	0.31	0.26
$3g$	0.45	0.48	0.42	0.51	0.57	0.55
$4g$	1.20	1.04	0.84	1.32	1.63	1.75
$5g$	3.78	2.69	2.59	7.26	5.95	5.96
$6g$	14.20	7.19	11.90	59.10	27.80	30.60
$7g$	58.50	23.70	73.60	646.00	146.00	195.00
$8g$	276.00	82.10	597.00	8690.00	919.00	1890.00
$9g$	1450.00	270.00	5900.00	127000.00	6310.00	29700.00
$10g$	7960.00	864.00	64000.00		48900.00	

CO = color-ordered, CD = color-dressed (i.e. full amplitude)

BG = Berends-Giele (1988), BCF = Britto-Cachazo-Feng, CSW = Cachazo-Svrček-Witten

Although BCF and CSW yield more compact results, BG is faster

Same conclusions found by Dinsdale, Ternick, Weinzierl.

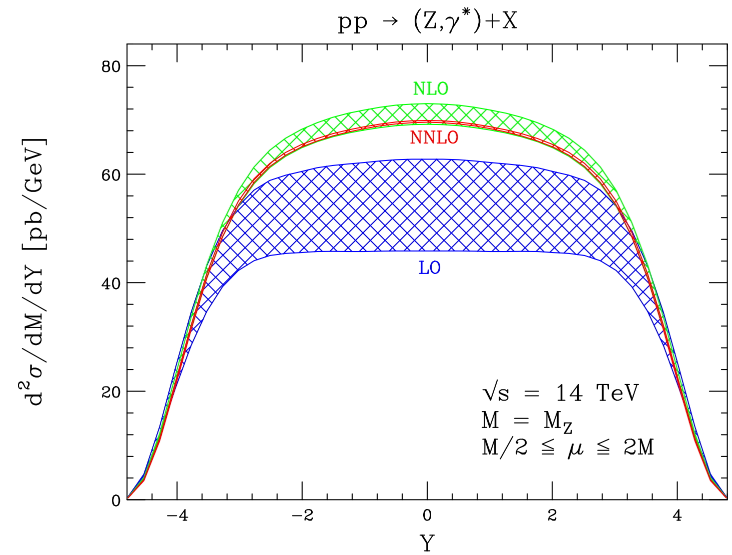
Limitations of LO calculations

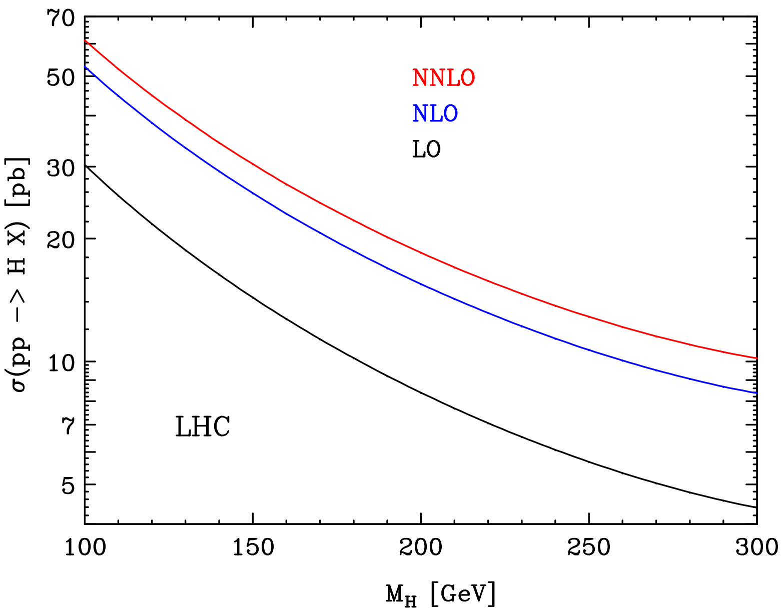
LO good for shapes. Uncertain absolute normalization

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

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

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

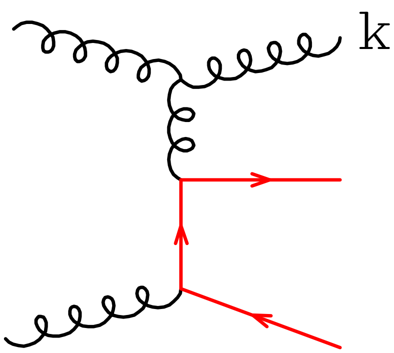




- ✗ new channels open up at higher orders + large gluon PDF
- ✗ large NLO corrections: 10% - 100%

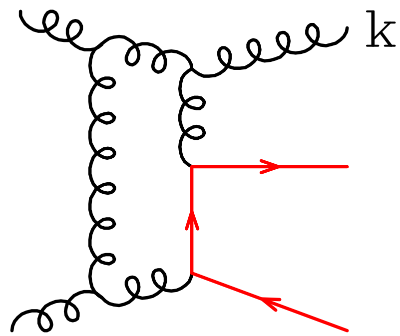
NLO ingredients

Born $q\bar{q}$ + jet



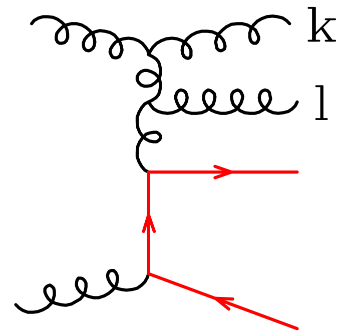
$k_T > p_T^{\rm cut}$

NLO virtual $q\bar{q}$ + jet



$k_T > p_T^{\rm cut}$

NLO real $q\bar{q}$ + jets



$k_T > p_T^{\rm cut}, \quad l_T$ unrestricted

- Born process may be of high order (with cuts on light-parton emission)
- NLO virtual: one-loop corrections
- NLO real emission: one more light parton, without cuts

Virtual and real contributions are infrared divergent. But their sum is finite.

The one-loop calculation is the **bottleneck** of the NLO calculation

NLO progresses

Process ($V \in \{Z, W, \gamma\}$)	background to/relevant for	status
$pp \to VVV$	SUSY tri-lepton	ZZZ: Lazopoulos, Melnikov, Petriello (07)
		Binoth, Ossola, Papadopoulos, Pittau (08)
$pp \to VVV \to$ 6 leptons (full spin corr.)		WWZ: Hankele, Zeppenfeld (07)
		ZZW and WWW to appear soon
$pp \to VV + 1$ jet	$t\bar{t}H$, new physics	$WW + 1$ jet: Dittmaier, Kallweit, Uwer (07)
		$WW + 1$ jet + decay: Campbell, Ellis, Zanderighi (07)
		Binoth, Karg, Kauer, Sanguinetti (in progress)
$pp \to VV + 2$ jets $\to$ 4 lept. + 2 jets via VBF	VBF $H \to VV$ & VV coupl.	(Bozzi), Jäger, Oleari, Zeppenfeld (07)
$pp \to V + 2$ jets (b)		Campbell, Ellis, Maltoni, Willenbrock (06)
$pp \to Vb\bar{b}$		Febres-Cordero, Reina, Wackeroth (07)
$pp \to H + 2$ jets via VBF	VVH couplings	QCD + EW: Ciccolini, Denner, Dittmaier (07)
$pp \to H + 2$ jets via gluon fusion	H via VBF	QCD: Campbell, Ellis, Zanderighi (06)
$pp \to H + 3$ jets via VBF (large N_c)		Figy, Hankele, Zeppenfeld (07)
$pp \to t\bar{t} + 1$ jet		Dittmaier, Uwer, Weinzierl (07)
		Ellis, Giele, Kunszt (in progress)
$pp \to t\bar{t}Z$	SUSY tri-lepton	Lazopoulos, McElmurry, Melnikov, Petriello (08)
$gg \to WW$		Binoth, Ciccolini, Kauer, Kramer (06)
$gg \to HH(H)$		Binoth, Karg, Kauer, Rückl (06)
$gg \to gggg$ (amplitude only)		. . . , Xiao, Yang, Zhu (06)
$\gamma\gamma \to \gamma\gamma\gamma\gamma$ (amplitude only)		Nagy, Soper (06); Binoth, Heinrich, Gehrmann, Mastrolia (07)
		Ossola, Papadopoulos, Pittau (07); Forde (07)

Wish list Les Houches 2007

Process	background to/relevant for
$pp \to t\bar{t}\, b\bar{b}$	$t\bar{t}H$, new physics
$pp \to t\bar{t}$ + 2 jets	$t\bar{t}H$, new physics
$pp \to VV\, b\bar{b}$,	relevant for VBF $\to H \to VV$, $t\bar{t}H$
$pp \to V$ + 3 jets	various new physics signatures
$pp \to b\bar{b}b\bar{b}$	Higgs and new physics signatures
Calculations beyond NLO added in 2007	
$gg \to W^*W^*\ \mathcal{O}(\alpha^2\alpha_s^3)$	backgrounds to Higgs
$pp \to t\bar{t}$	normalization of a benchmark process
VBF and Z/γ + jet	Higgs couplings and SM benchmark
Calculations including electroweak effects	
NNLO QCD + NLO EW for W/Z	precision calculation of a SM benchmark

Availability of NLO calculations

Parton-level generators

✓ $2 \to 2$ processes

- parton-level integrators available for SM and MSSM processes for some time
- extensively used at LEP, Tevatron and HERA
- DISPATCH, AYLEN/EMILIA, HVQMNR . . .

✓ $2 \to 3$ processes

- Many $2 \to 3$ processes are now available at NLO
- NLOJET++, PHOX FAMILY, MCFM, VBFNLO, HQQB . . .

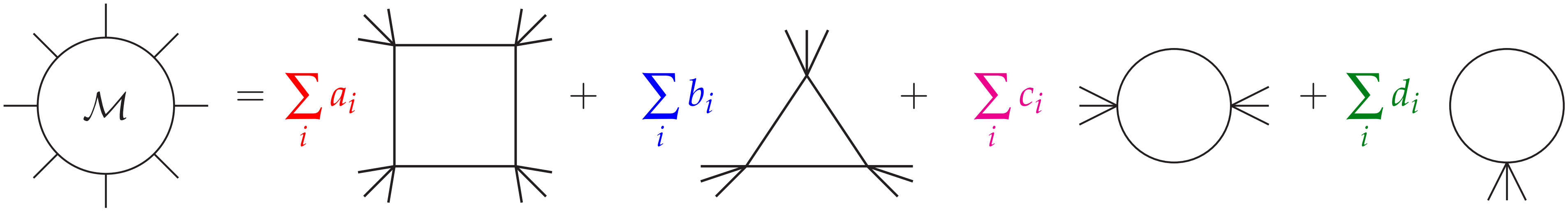
✗ $2 \to 4$ processes: no LHC cross sections computed yet

For a more complete list, and the corresponding web pages, see:

`http://www.cedar.ac.uk/hepcode`

The one-loop challenges

Any one-loop amplitude can be written as (Passarino-Veltman tensor reduction)



$$\mathcal{M} = \sum_i a_i(D)\,\mathrm{Boxes}_i + \sum_i b_i(D)\,\mathrm{Triangles}_i + \sum_i c_i(D)\,\mathrm{Bubbles}_i + \sum_i d_i(D)\,\mathrm{Tadpoles}_i$$

✓ all the scalar loop integrals are known [Ellis & Zanderighi, arXiv:0712.1851]
`http://qcdloop.fnal.gov; http://www.ippp.dur.ac.uk/LoopForge/index.php/Main_Page`

✗ only problem is to compute the D-dimensional coefficients: $a_i(D)$, $b_i(D)\ldots$: large number of terms (difficult to deal with even with computer algebra programs) with large cancellations $\Longrightarrow$ numerical instabilities: inverse Gram determinants, spurious phase-space singularities…

Sometimes it is better to compute

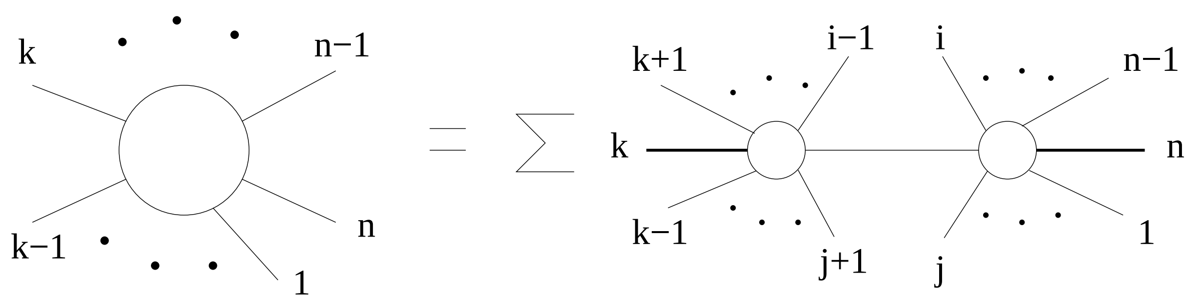
$$\mathcal{M} = \sum_i a_i(4)\,\mathrm{Boxes}_i + \sum_i b_i(4)\,\mathrm{Triangles}_i + \sum_i c_i(4)\,\mathrm{Bubbles}_i + \sum_i d_i(4)\,\mathrm{Tadpoles}_i + R$$

where R is a rational (non-logarithmic) function

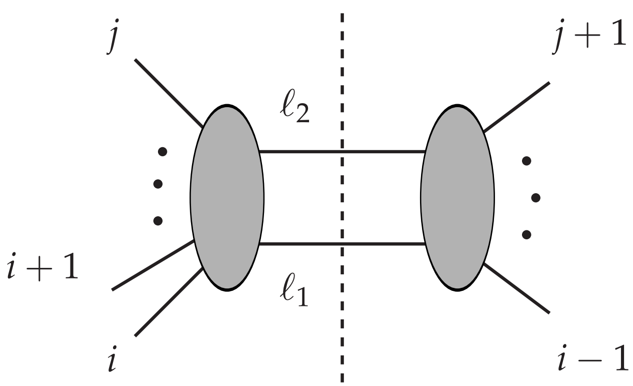
New one-loop ideas

Many ideas based on unitarity and analytic structure of the amplitude: construct a function from its poles and branch cuts

✓ poles: lower number of external lines. Cauchy residue theorem!



✓ branch cuts: lower number of loops

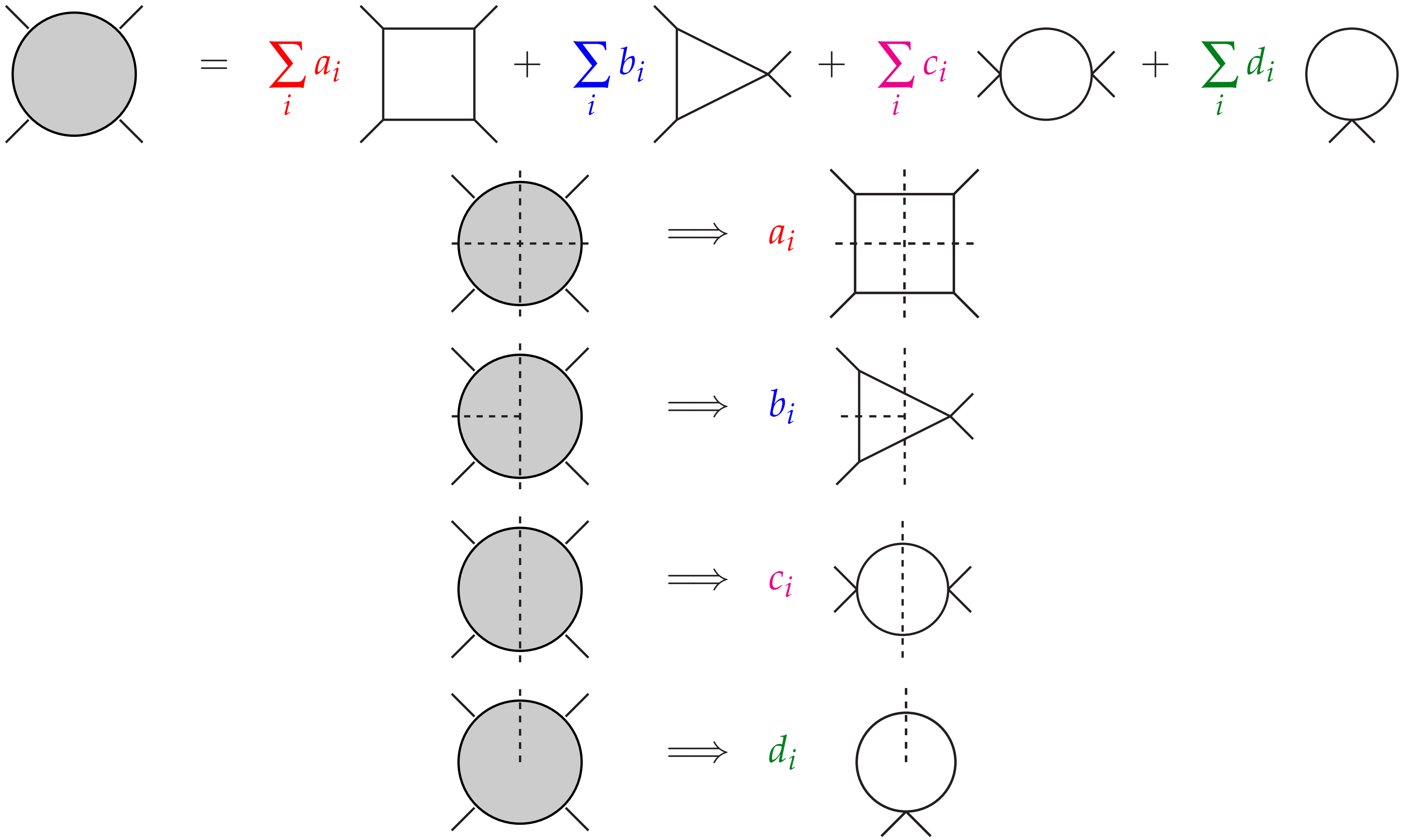


$$\text{Disc} = \int d^4\Phi \, A^{\text{tree}}(\ell_1, i, \ldots, j, \ell_2) \, A^{\text{tree}}(-\ell_2, j+1, \ldots, i-1, -\ell_1)$$

$$d^4\Phi = d^4\ell_1 \, d^4\ell_2 \, \delta^{(4)}(\ell_1 + \ell_2 - P_{ij}) \, \delta^{(+)}(\ell_1^2) \, \delta^{(+)}(\ell_2^2)$$

$$\delta^{(+)}(p^2) = \delta(p^2) \, \theta(p_0)$$ on-shell condition

Multiple (generalized) cuts



On-shell complex momenta satisfy all the cut constraints.

New one-loop ideas

Unitarity-based methods

Bern, Dixon, Dunbar & Kosower

Brandhuber, McNamara, Spence & Travaglini

Britto, Buchbinder, Cachazo, Feng, Mastrolia, Svrček & Witten

Anastasiou, Kunszt; Forde

Ossola, Papadopulos & Pittau

Ellis, Giele, Kunszt & Melnikov

Moretti, Piccinini & Polosa, arXiv:0802.4171

Catani, Gleisberg, Krauss, Rodrigo & Winter, arXiv:0804.3170

On-shell recurrence relations

Britto, Cachazo, Feng & Witten; Bern, Dixon & Kosower

Bjerrum-Bohr, Dunbar & Ita

Berger, Febres Cordero, Forde, Kosower & Maître

Glover, Mastrolia & Williams, arXiv:0804.4149

Improved tensor reduction

Binoth, Guillet, Pilon, Heinrich & Schubert

Denner & Dittmaier

Xiao, Yang & Zhu

The OPP method

Integrand-level reduction: it combines Passarino-Veltman and n-particle cuts

$$\int d^4\ell \, \frac{N(\ell)}{D_0 D_1 \cdots D_{m-1}} \qquad D_i = (\ell + p_i)^2 - m_i^2 \qquad \text{(simplified version!!)}$$

$$N(\ell) = \sum_{i_0<i_1<i_2<i_3}^{m-1} \left[a(i_0i_1i_2i_3) - \tilde{a}(\ell, i_0i_1i_2i_3)\right] \prod_{i\neq i_0,i_1,i_2,i_3}^{m-1} D_i + \sum_{i_0<i_1<i_2}^{m-1} \left[b(i_0i_1i_2) - \tilde{b}(\ell, i_0i_1i_2)\right] \prod_{i\neq i_0,i_1,i_2}^{m-1} D_i$$
$$+ \sum_{i_0<i_1}^{m-1} \left[c(i_0i_1) - \tilde{c}(\ell, i_0i_1)\right] \prod_{i\neq i_0,i_1}^{m-1} D_i + \sum_{i_0}^{m-1} \left[d(i_0) - \tilde{d}(\ell, i_0)\right] \prod_{i\neq i_0}^{m-1} D_i$$

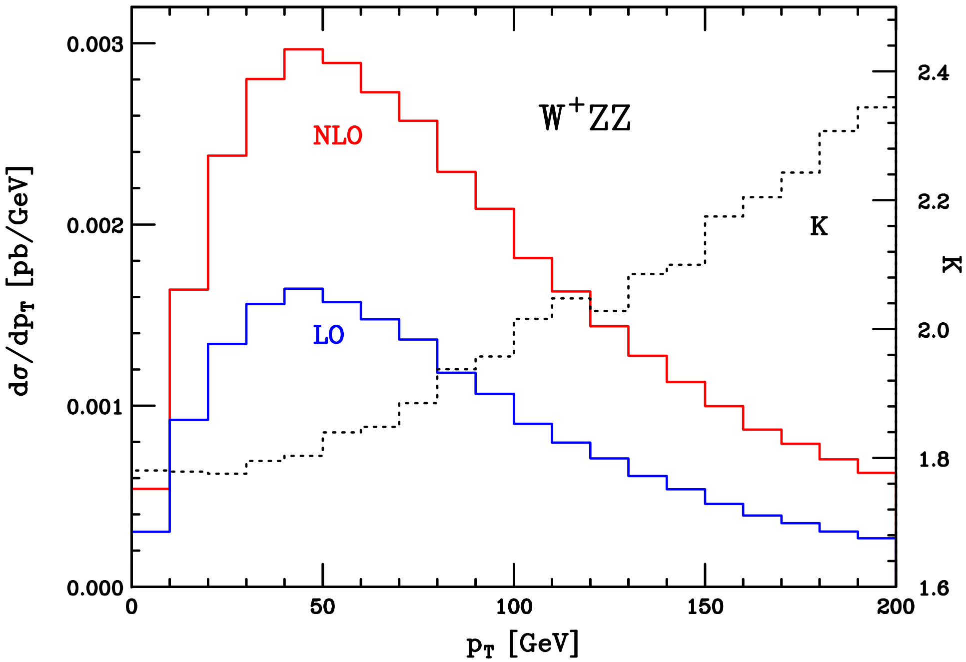
$a(..)$ are the coefficients of the boxes, $b(..)$ of the triangles, $c(..)$ of the bubbles and $d(..)$ of the tadpoles

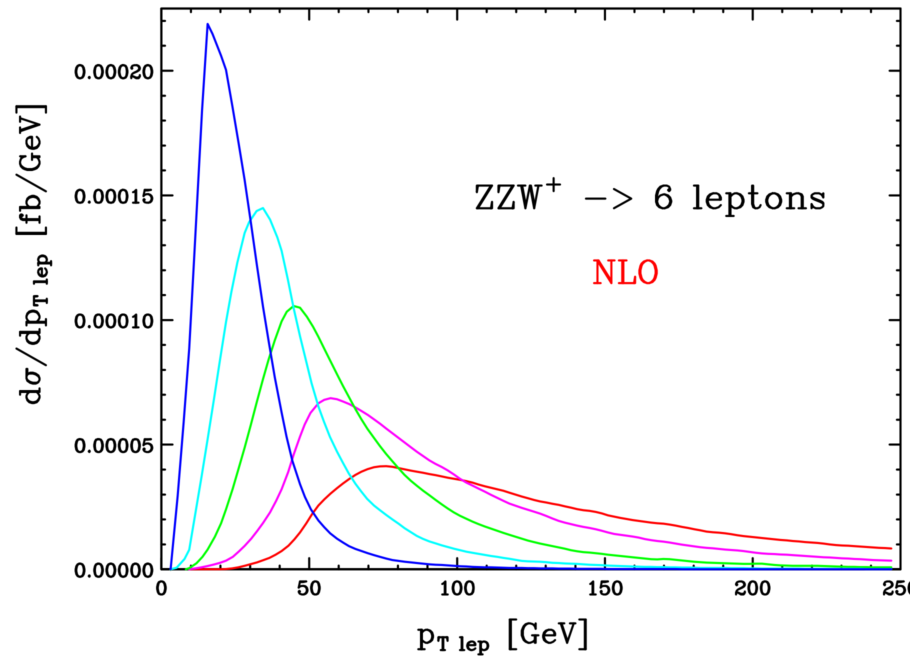
- Extract all the coefficients by evaluating numerically $N(\ell)$ for a set of values of the integration momentum ℓ at fixed external momenta and polarization vectors
- There is a very good set of such points: use values of ℓ for which a set of denominators D_i vanishes $\Longrightarrow$ The system becomes "triangular": solve first for 4-point functions, then 3-point functions and so on.
  Discrete Fourier transform to speed up calculation [MOPP, arXiv:0803.3964]

OPP implemented in `CutTools`

VVV

Background to various SUSY tri-lepton signatures, gauge-boson coupling measurements [Hankele & Zeppenfeld, arXiv:0712.3544; Binoth, Ossola, Papadopoulos & Pittau, arXiv:0804.0350]



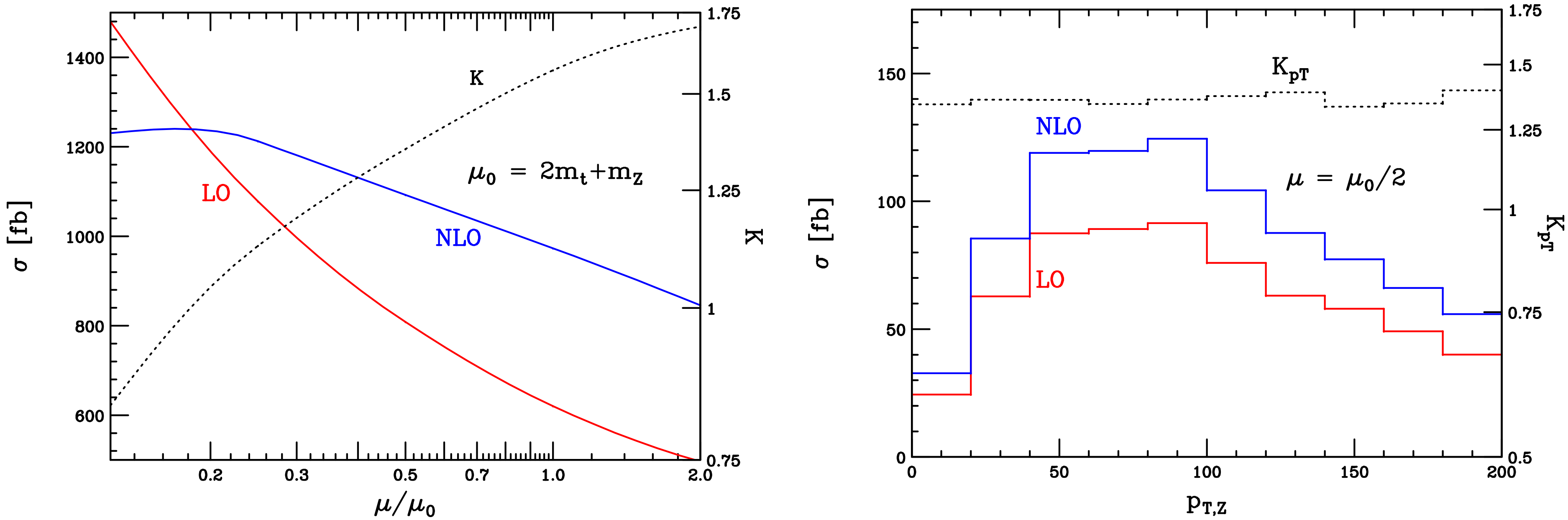


✗ Large NLO corrections

✓ Speed is an issue: HZ ∼ 20 msec, BOPP 200 msec!!

$t\bar{t}Z$

Background to various SUSY tri-lepton signatures, gauge-boson coupling measurements [Lazopoulos, McElmurry, Melnikov & Petriello, arXiv:0804.2220]

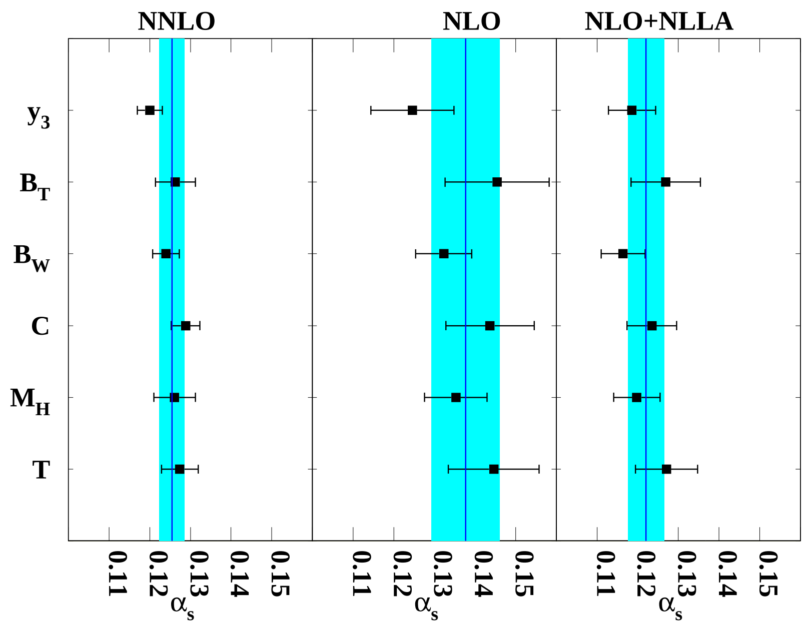


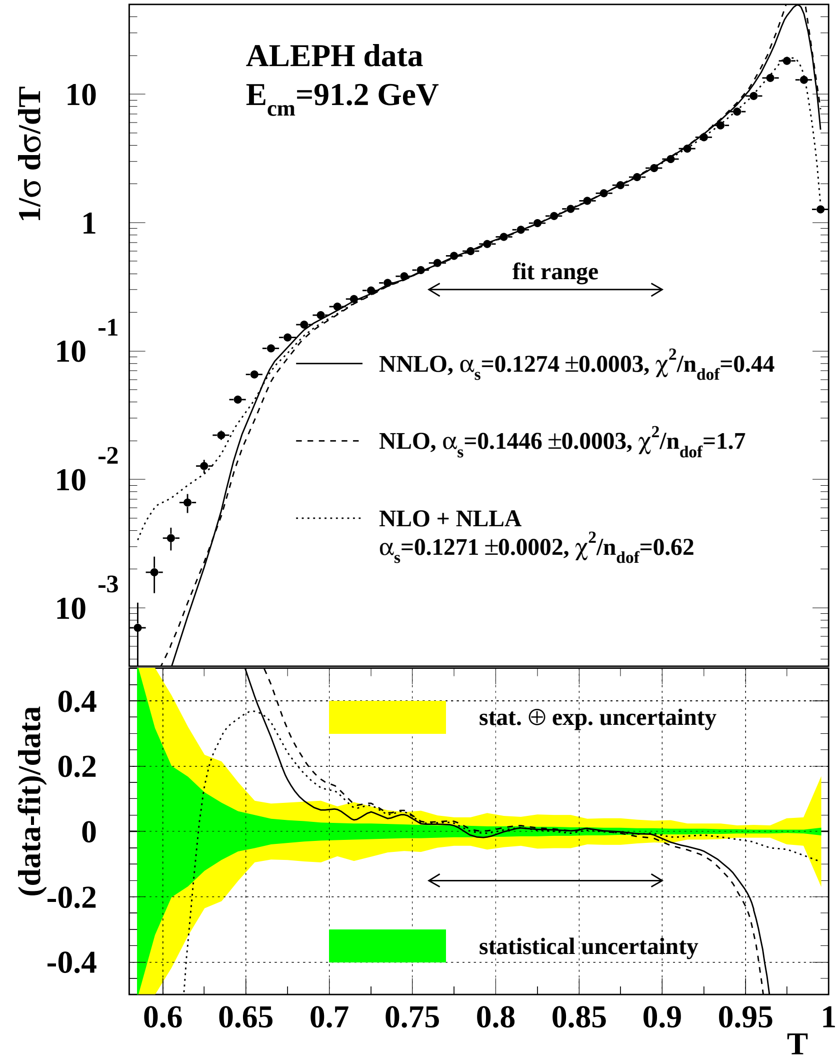
✓ Fully numerical calculation, using sector decomposition and contour deformation

✗ Large NLO corrections

NNLO

$e^+e^- \longrightarrow$ 3 jets completed! [Gehrmann–De Ridder, Gehrmann, Glover & Heinrich]

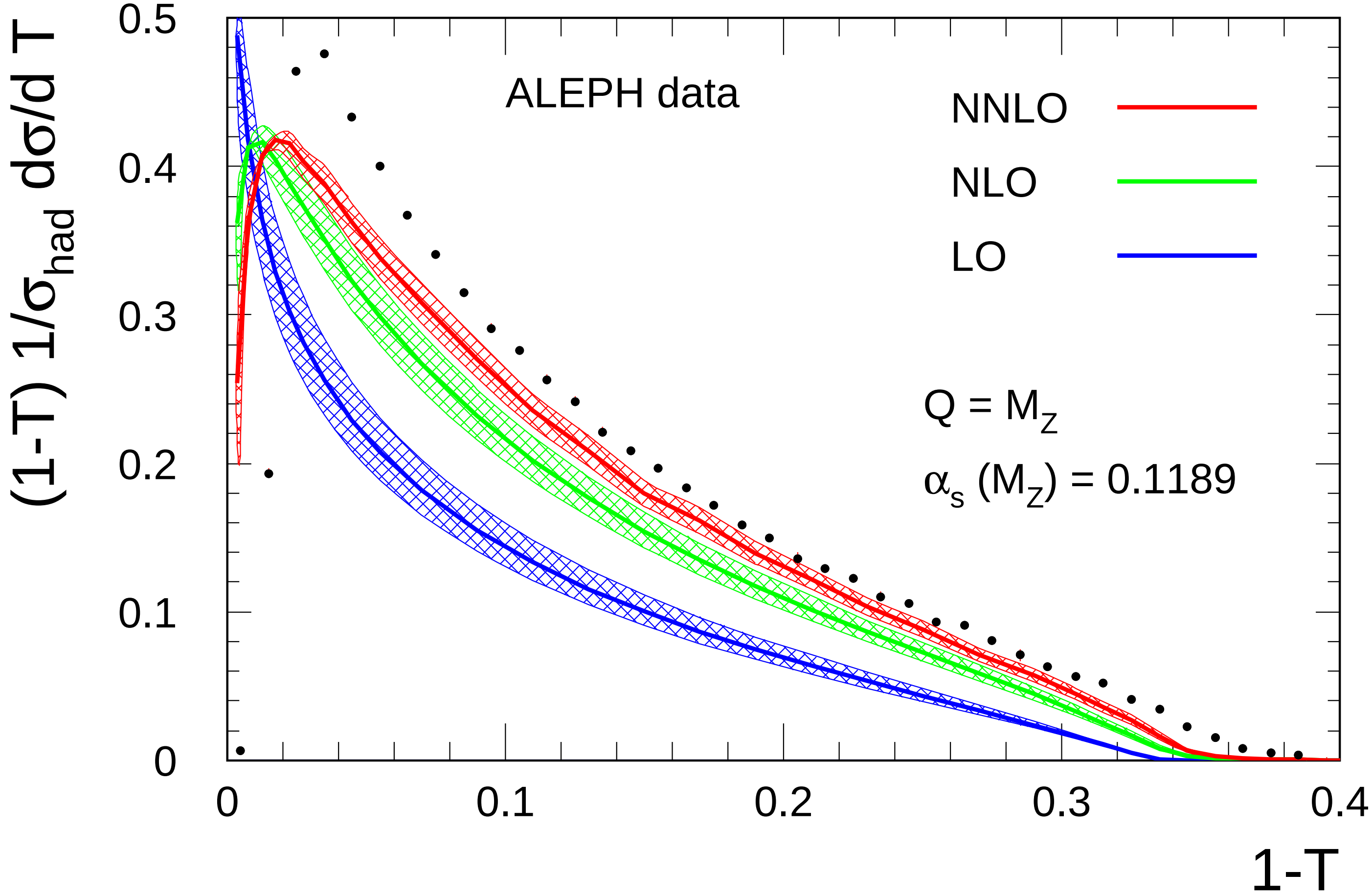




- ✓ lower central value
- ✓ more consistency
- ✓ matched to NLLA

$$\alpha_s(M_Z) = 0.1240 \pm 0.0008\,(\text{stat}) \pm 0.0010\,(\text{exp}) \pm 0.0011\,(\text{had}) \pm 0.0029\,(\text{theo})$$

NNLO



- NNLO corrections not negligible: $\sim 15\%$
- scale dependence reduced from LO to NLO to NNLO

Parton Shower Monte Carlo

Parton Shower (PS) Monte Carlo programs are tools to simulate full events

- Large library of hard-event cross sections (SM and BSM)
- Dress hard events with QCD radiation. From here the name of “shower”
- Models for hadron formation
- Models for underlying events, multi-parton collisions, minimum bias
- Library for decays of unstable particles

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.

Matching ME and PS

While PS programs resum correctly all the collinear-enhanced logs, they are not exact for large-angle radiation.
Can we use exact Matrix Element (ME) calculations instead of PS?

- ✗ We must limit them to large angles, since Sudakov form factors for small angles are not included
- ✗ We must interpret them as inclusive cross section. Final-state partons should be interpreted as jets with relatively small angular opening (a parton not turning into a jet is Sudakov suppressed)

In order to remedy to these problems one should:

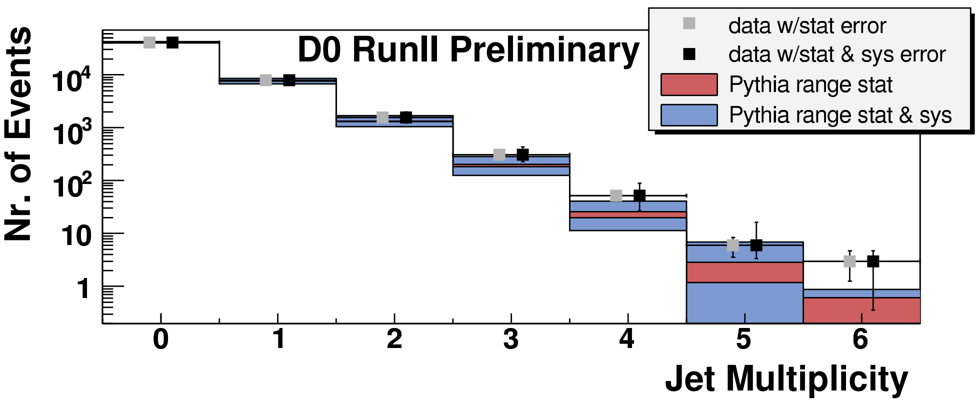
- ✓ Provide the dominant virtual corrections (i.e. the Sudakov form factors)
- ✓ Attach parton shower to final lines

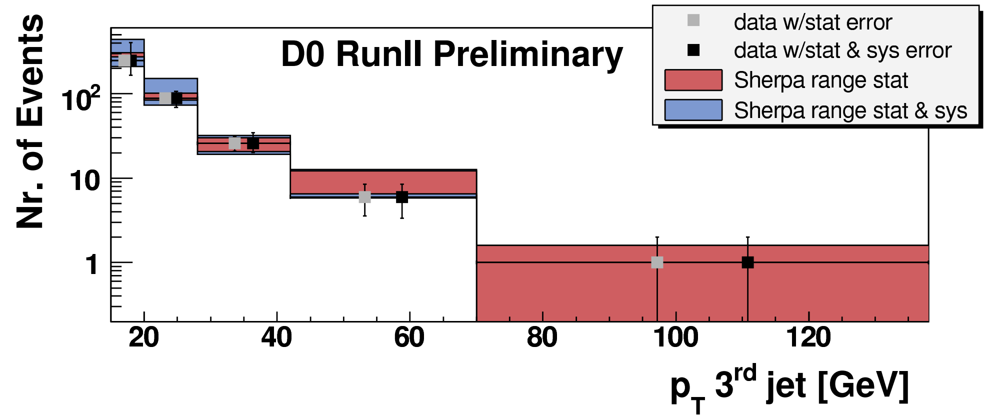
} This is: ME and PS matching

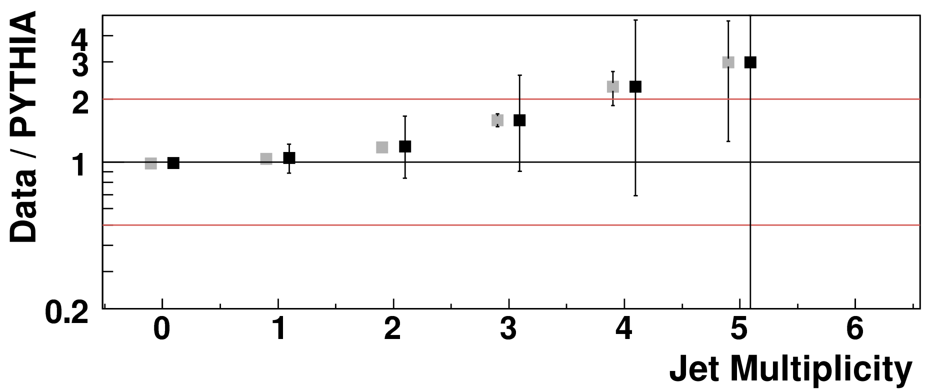
Problem: avoid overcounting

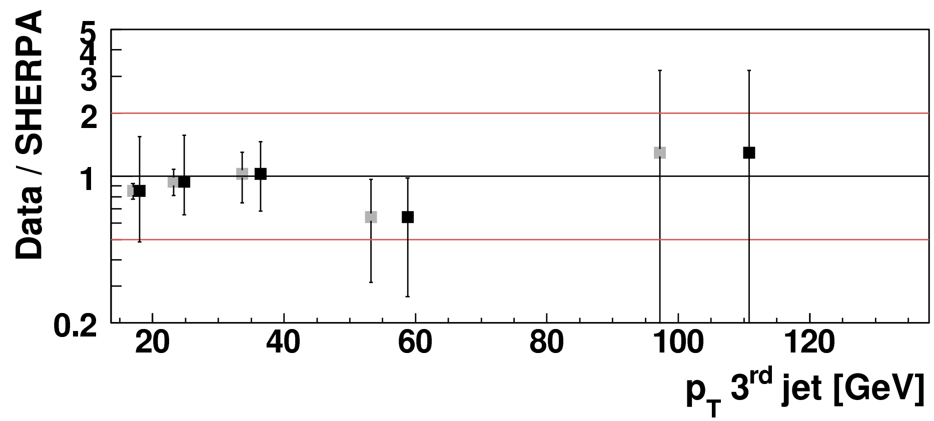
Solution: CKKW matching [Catani, Krauss, Küen, Webber]
MLM matching [Mangano]
and others (CKKW-L, pseudo-shower. . .)

Matching ME and PS









Jet multiplicity and p_T distributions of jets are better described by ME approach

The message: when detailed understanding of the jet structure of the event is needed ME approach performs much better than the simple PS.

Matching NLO and PS

Problem: double counting is more severe

- ✗ emissions from NLO and PS should be counted once
- ✗ virtual contributions in the NLO contribution and in the Sudakov should not overlap

Solution:

- ✓ MC@NLO [Frixione, Webber]
  - matches NLO to HERWIG angular-ordered PS
  - Some work to interface a NLO calculation to HERWIG. Uses only Frixione-Kunszt-Signer subtraction scheme
  - Some events with negative weight
- ✓ POWHEG [Nason]
  - all the formulae and ingredients ready to be used [Frixione, Nason & Oleari, arXiv:0709.2092].

POsitive-Weight Hardest Emission Generator

✓ it is independent from parton-shower programs. Can be interfaced with both PYTHIA and HERWIG, or with your favorite showering program

✓ it can use existing NLO results

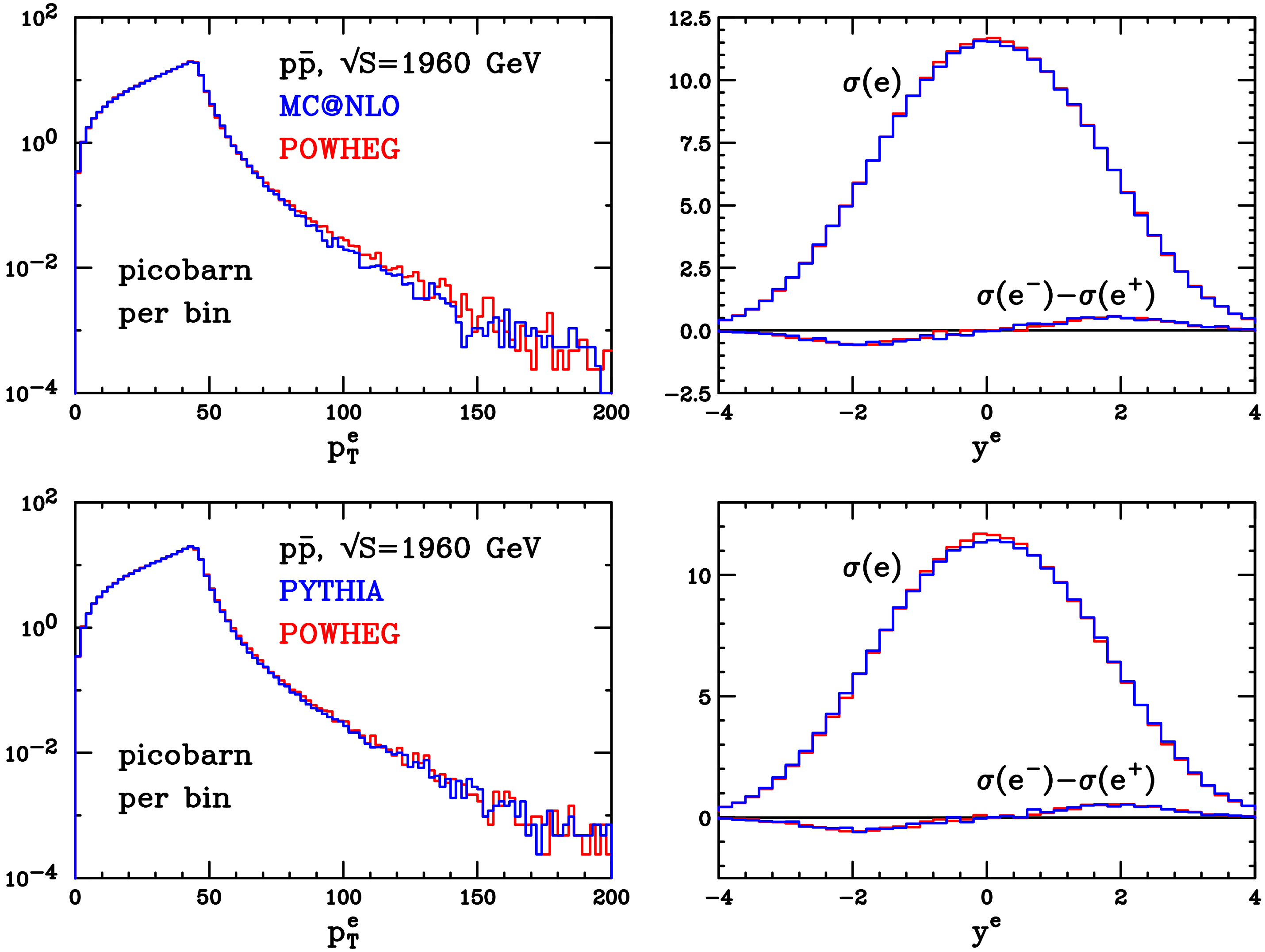
✓ it generates events with positive weights

✓ available implementations

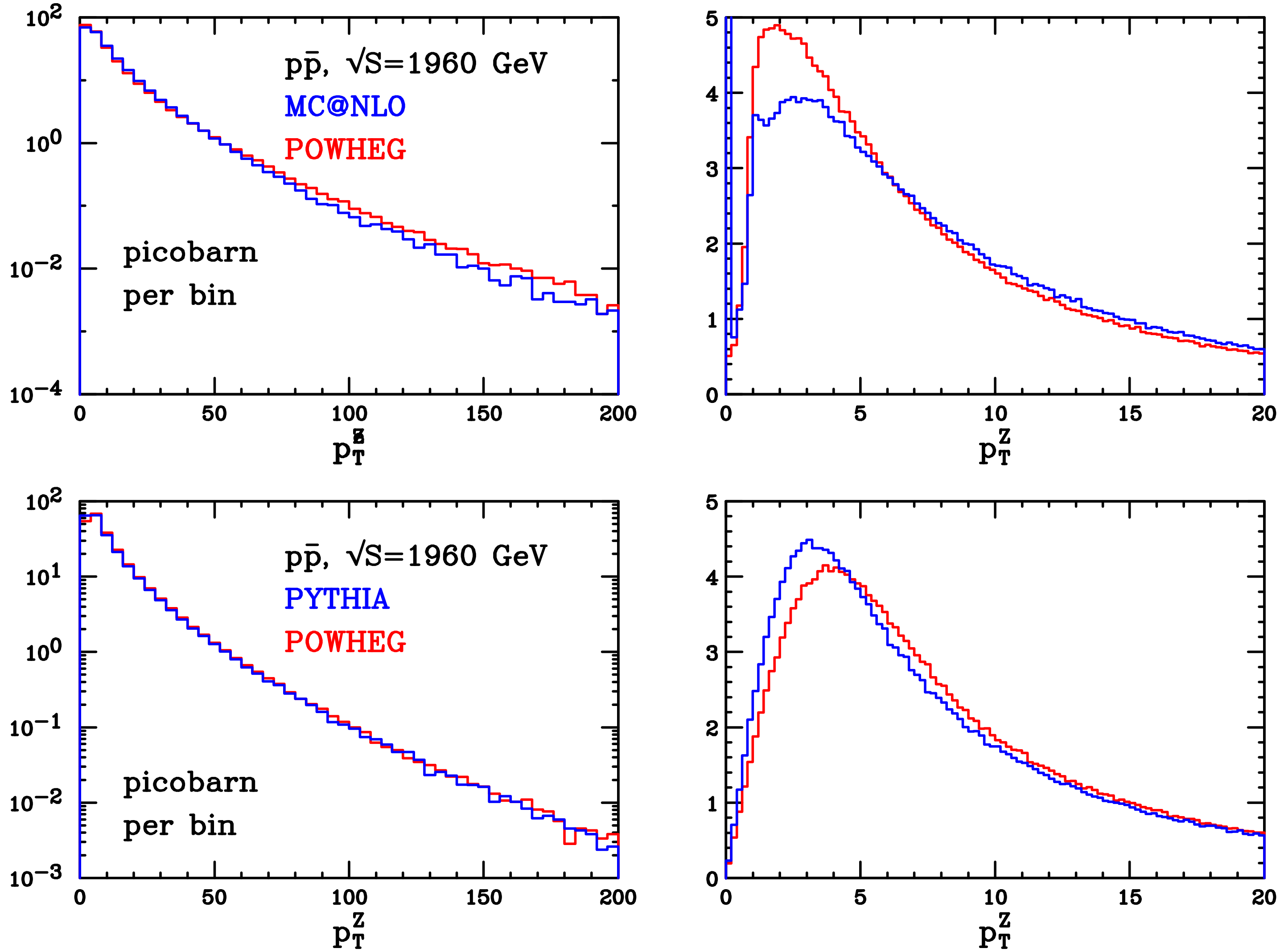
- ZZ production [Nason & Ridolfi, hep-ph/0606275]
- e^+e^- to hadrons [Latunde-Dada, Gieseke & Webber, hep-ph/0612281]
- heavy-quark $Q\overline{Q}$ production ($c\bar{c}$, $b\bar{b}$, $t\bar{t}$) with spin correlations [Frixione, Nason & Ridolfi, arXiv:0707.3088].
- single vector-boson production (with spin correlations) [Alioli, Nason, Oleari & Re]
- Higgs production, vector-boson production plus jet, single-top and Higgs boson production via vector-boson fusion are work in progress [Alioli, Nason, Oleari & Re]

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

POWHEG results



POWHEG results



Shower improvements

Several improvements in existing (popular) shower MCs:

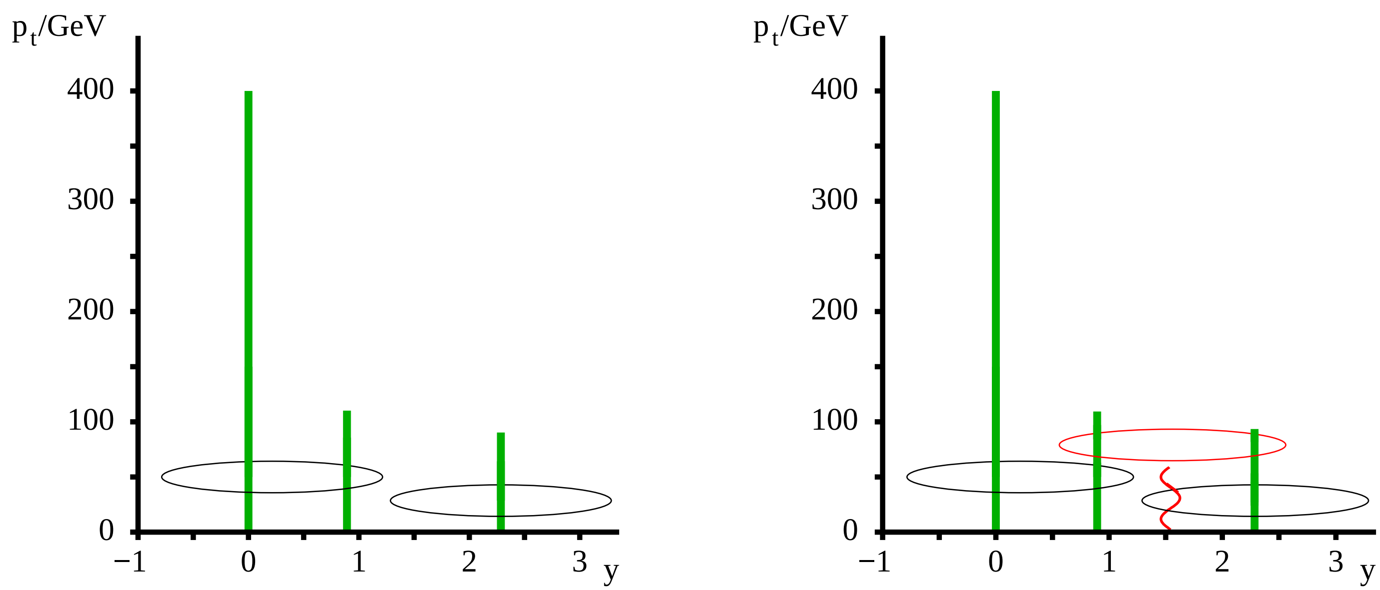
- PYTHIA has implemented a new, p_T ordered shower algorithm: easier to interface to ME generators
- HERWIG has introduced new shower variables, with improved Lorentz invariance properties, and better treatment of mass effects
- multiparton interactions in Underlying Event

Several proposals of new shower algorithms (not yet functional)

- $e^+e^- \to 3$ 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]

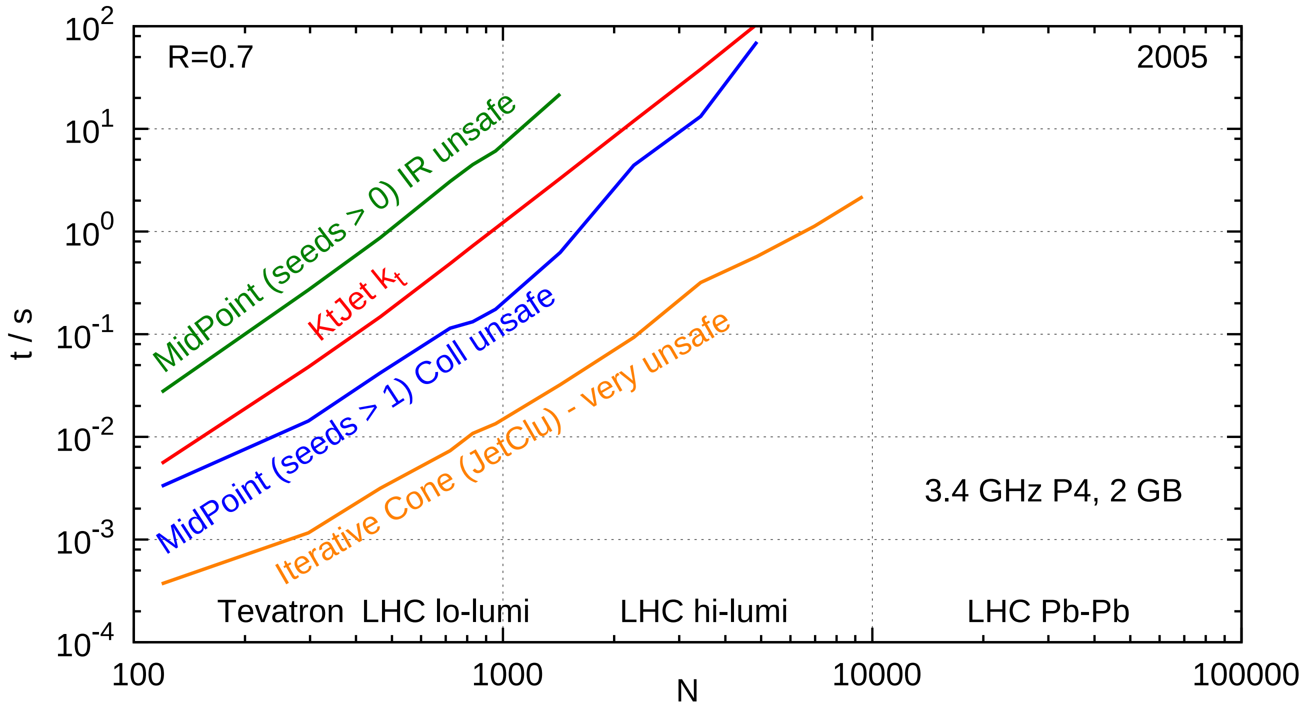
Jets: the past

- cone type: cluster particles according to their distance in coordinate space
  (UA1, JetClu, Midpoint, SISCone…)
  - ✓ IR safe
  - ✗ too slow $\mathcal{O}(N2^N)$ (10^{17} year to cluster 100 particles. 1 operation in 10^{-9} sec)
  - ✗ not IR safe approximations used by experimentalists: seed/midpoint cone
- sequential type: cluster particles according to their distance in momentum space
  (k_T, Jade, Cambridge/Aachen…)
  - ✓ IR safe
  - ✗ too slow $\mathcal{O}(N^3)$



Jets: the present

Both cone- and sequential-type jets can be properly defined and implemented in a fast and IR safe way [Cacciari, Salam & Soyez]



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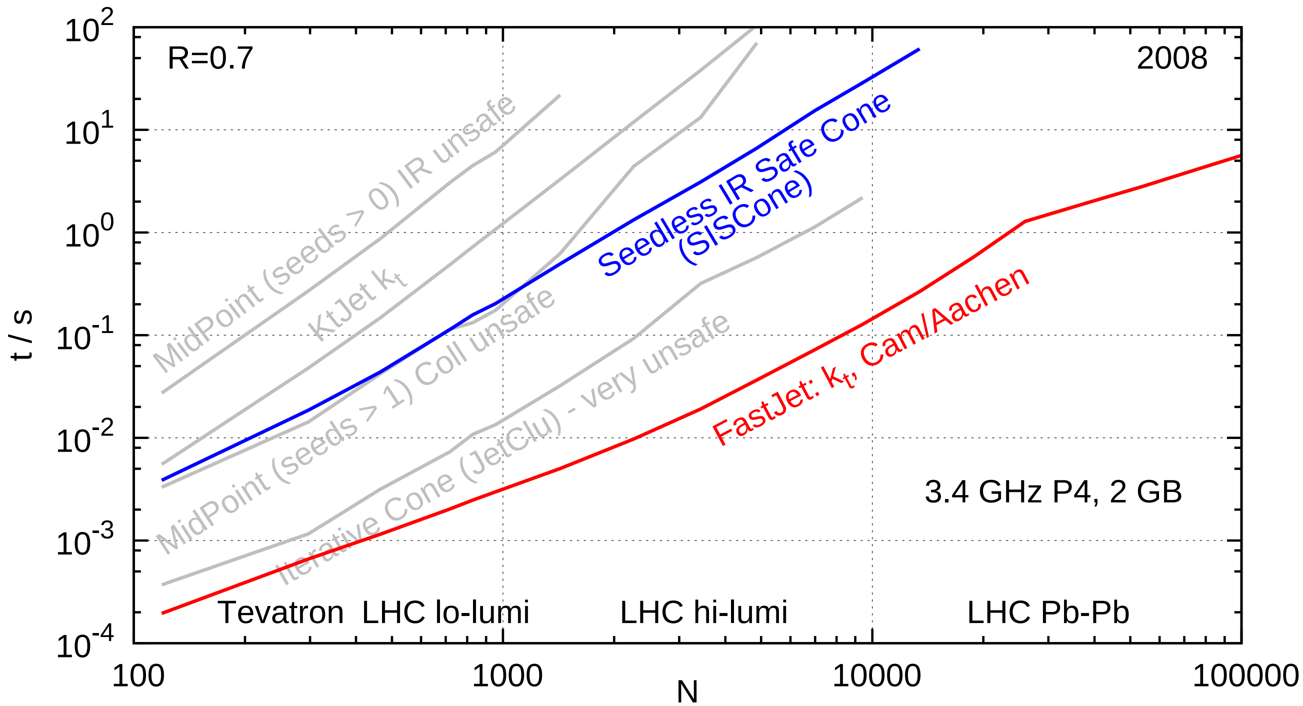


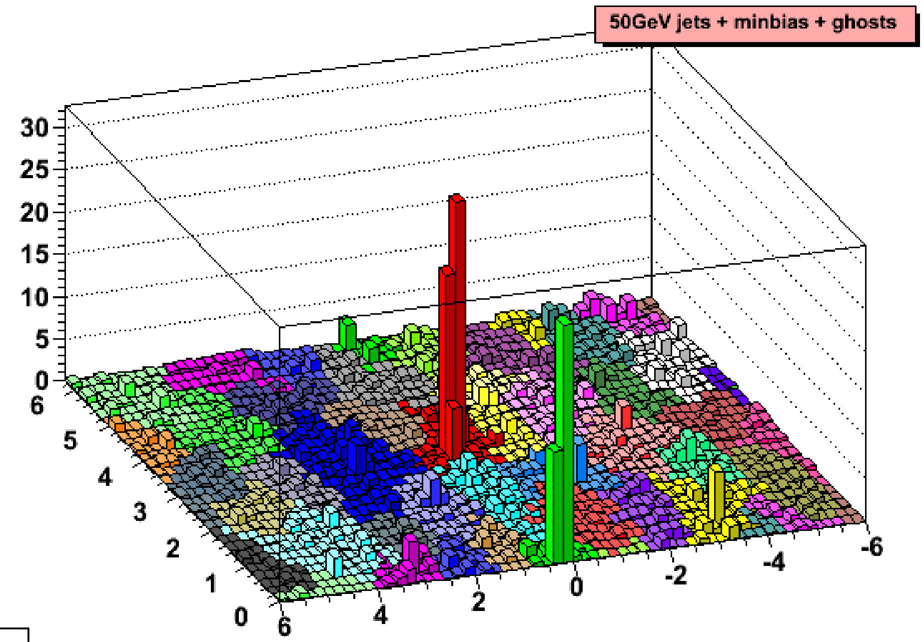
SISCone: $N^2 \log N$ and IR safe

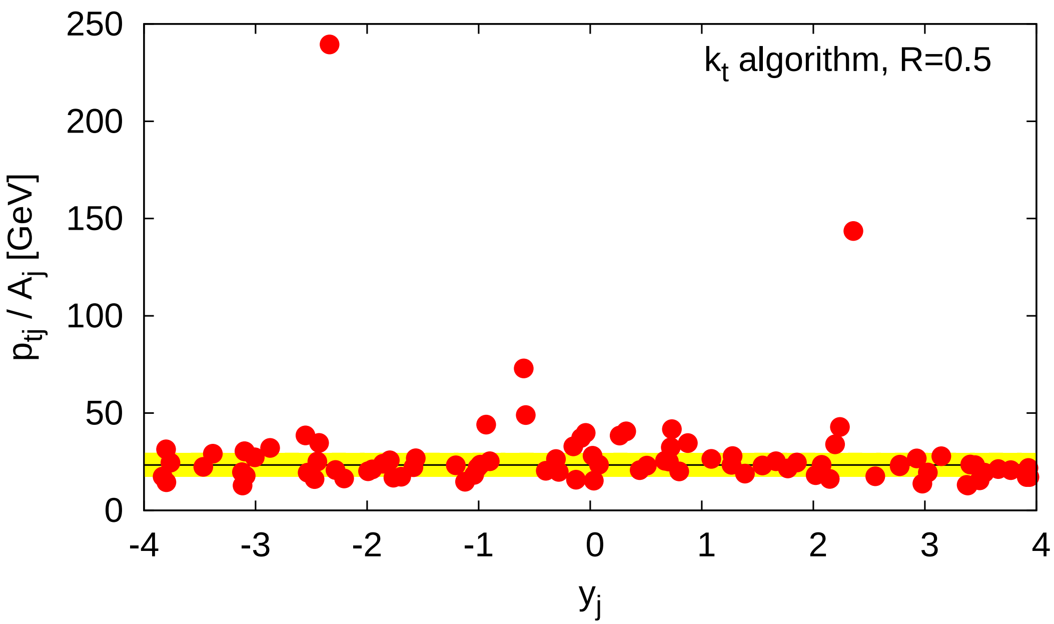
FastJet: $N \log N$

`http://www.lpthe.jussieu.fr/~salam/fastjet/`

Jet area

Define the jet area by clustering with many very soft ghosts and counting how many end up in a jet. They mimic the sensitivity of the jet clustering to a soft background



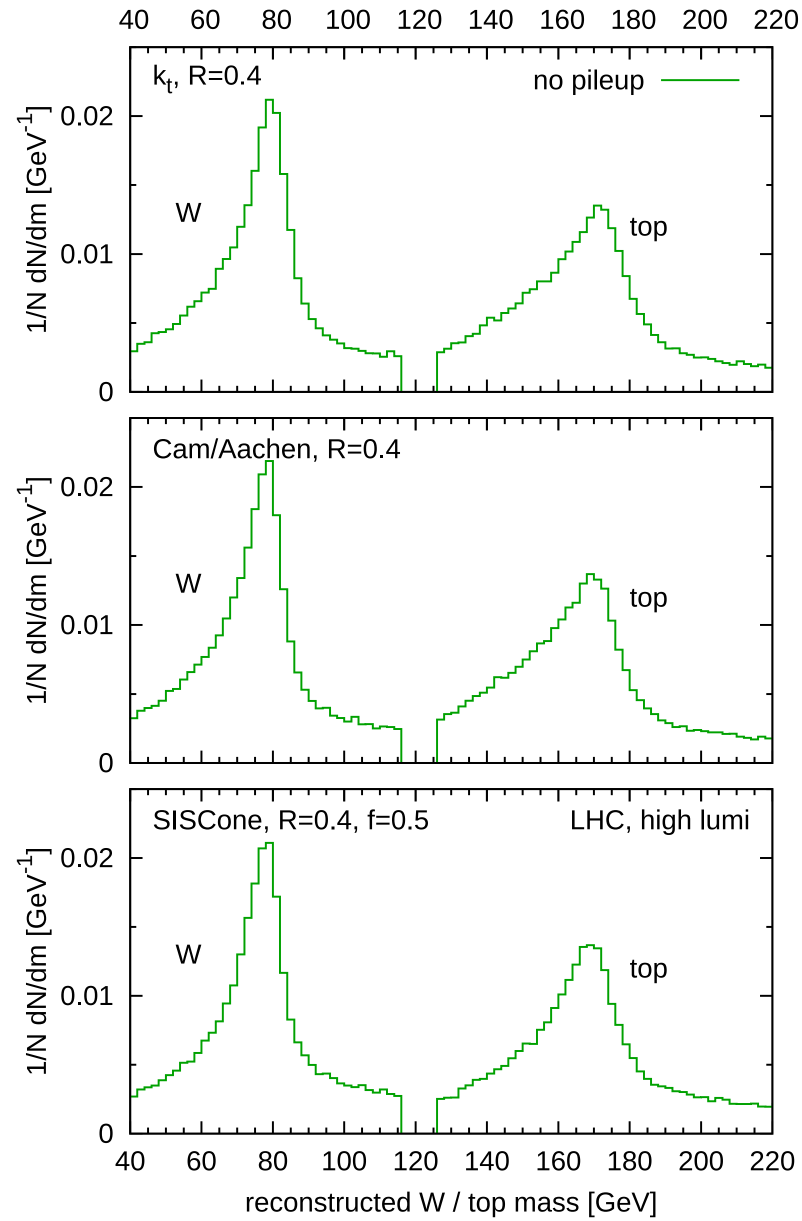


Notice that, **event-by-event**, p_{jT}/A_j is distributed uniformly for underlying events and pile up. Average value = ρ

Subtraction of pileup based on jet area

$$p_T^{\text{hard jet, corrected}} = p_T^{\text{hard jet, raw}} - \rho\, A^{\text{hard jet}}$$

Area-based subtraction



Illustration

- semi-leptonic $t\bar{t}$ production at LHC
- high-luminosity pileup (∼20 events/bunch-X)
- same simple procedure works for a range of algorithms

Area-based subtraction

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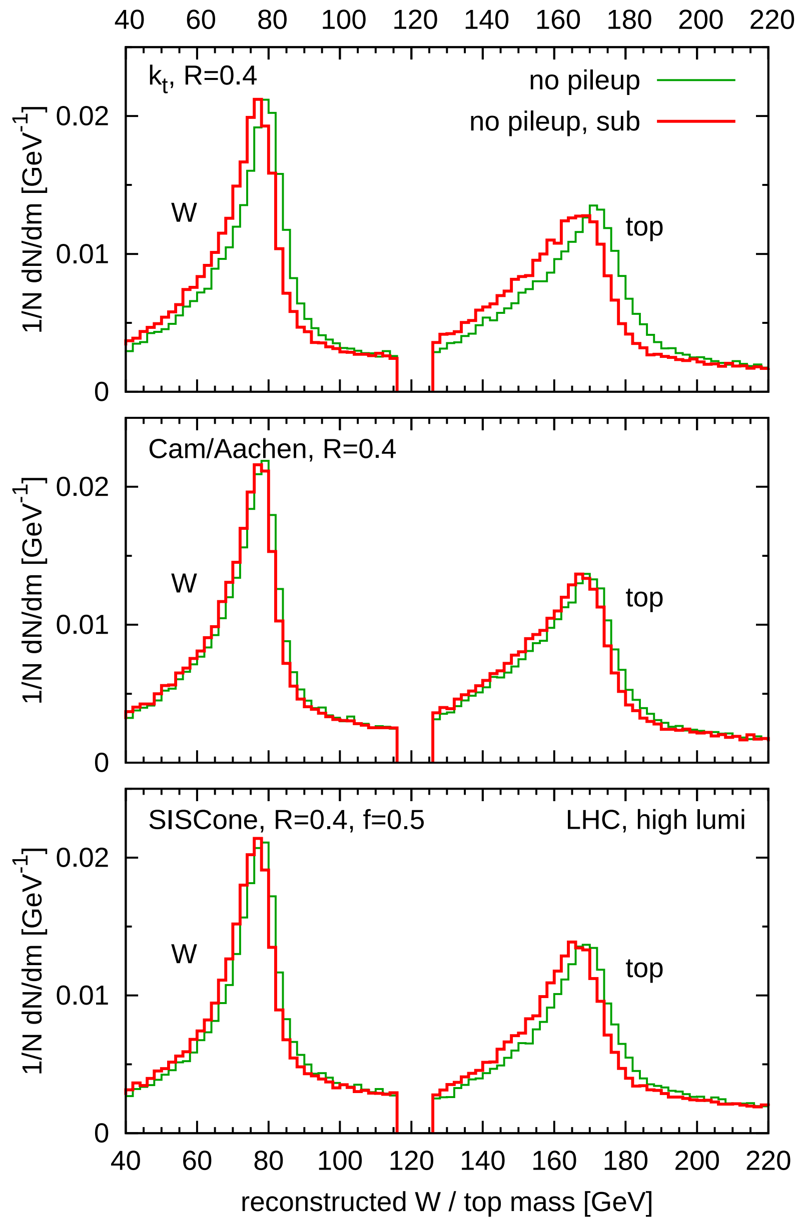
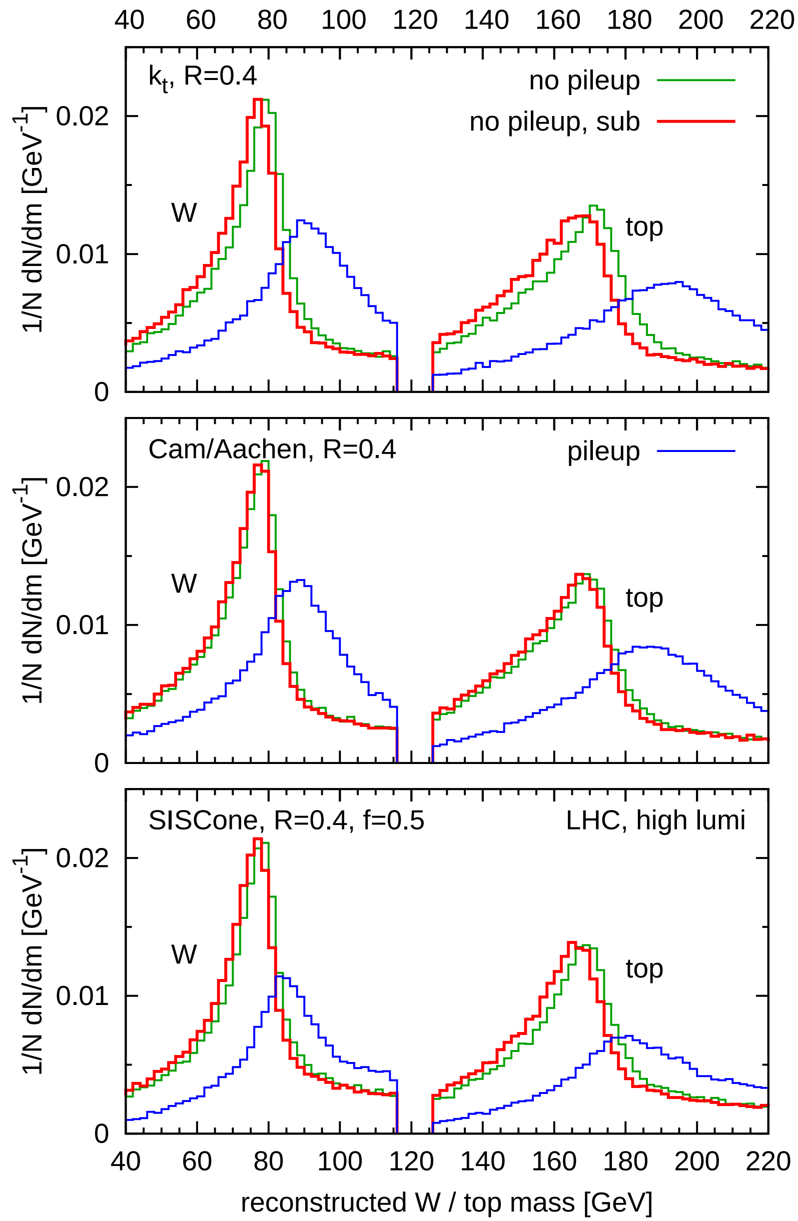


Area-based subtraction



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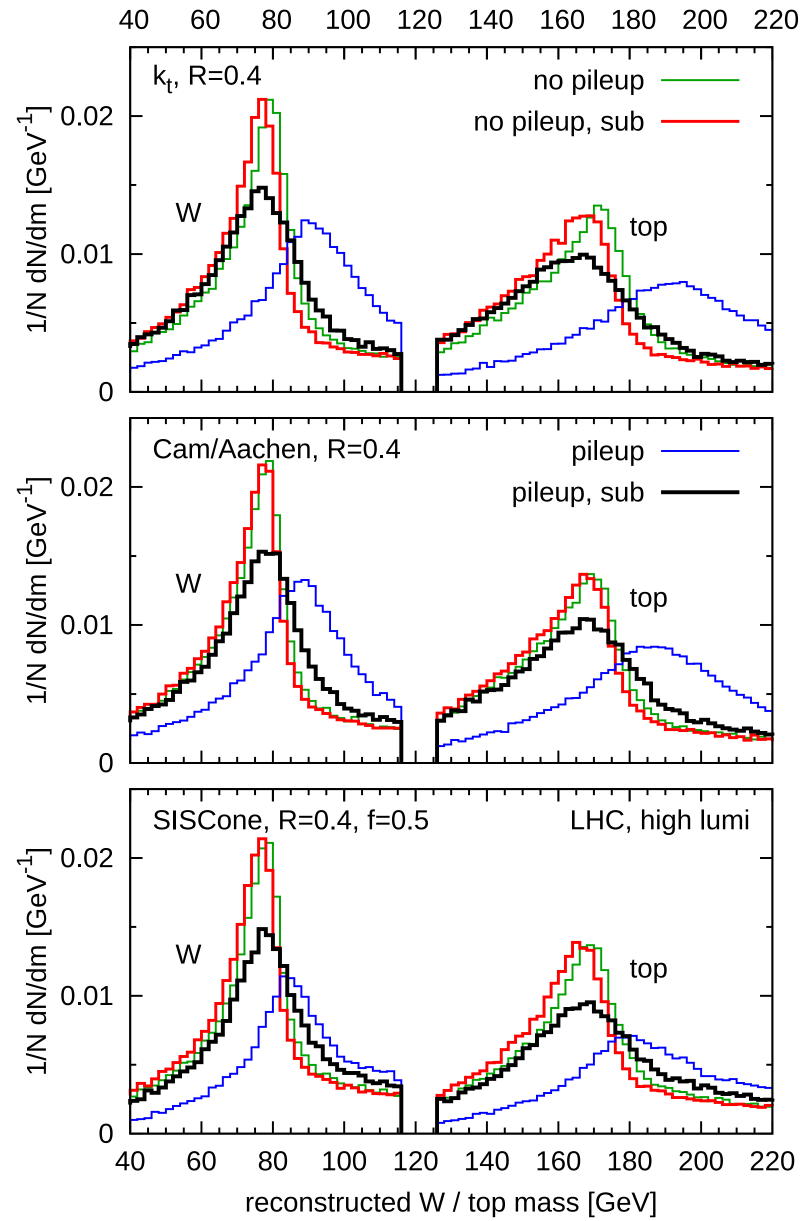


Illustration

- semi-leptonic $t\bar{t}$ production at LHC
- high-luminosity pileup (∼20 events/bunch-X)
- same simple procedure works for a range of algorithms

Conclusions

- Intense QCD theoretical activity in preparation for the LHC: new NLO results become available
- One remarkable result: $e^+e^- \to q\bar{q}g$ at NNLO
- Closer interaction between modeling (i.e. Shower Monte Carlo) and calculations (ME, NLO)
- The way events are simulated is changing in a fundamental way
- Lots of open problems and ideas for new developments

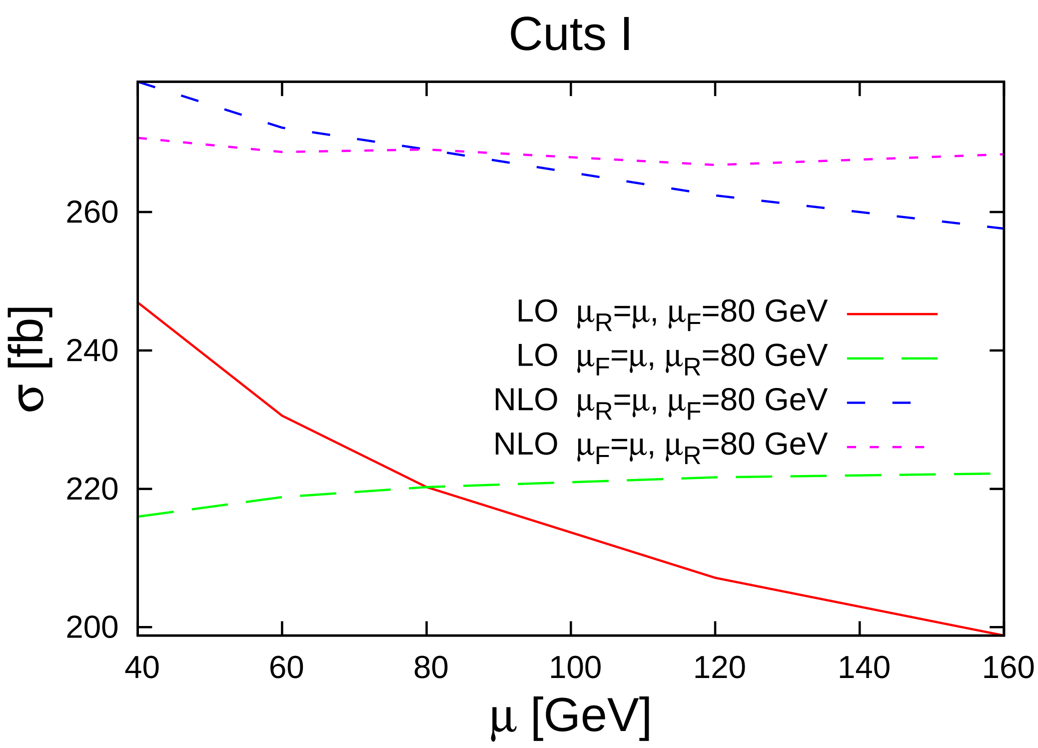
Apologies to those whose work I have not (sufficiently) discussed

Acknowledgments: Hankele, Glover, Laenen, Maltoni, Mastrolia, Nason, Ossola, Petriello, Pittau, Salam, Zeppenfeld.

Backup slides

W^+W^- + jet

Background to Higgs in both vector-boson and gluon fusion, $H \to W^+W^-$, with one jet missed or Higgs recoiling against jet [Dittmaier, Kallweit & Uwer, arXiv:0710.1577; Campbell, Ellis & Zanderighi, arXiv:0710.1832]

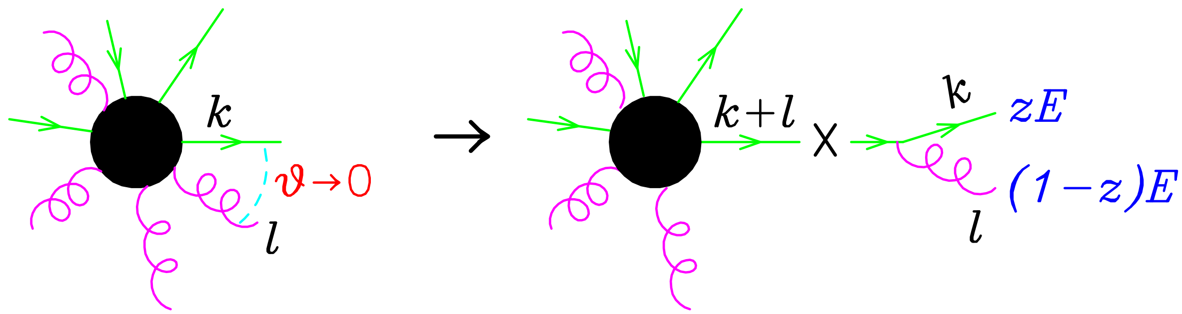


- ✓ For inclusive cuts, NLO increases cross section by about 25%
- ✓ Renormalization scale uncertainty reduced by $\sim$ 50%
- ✓ For VBF cuts, NLO increased by $\sim$ 70% with respect to the LO

Shower basics

QCD emissions are enhanced near the collinear limit

- The spin- and color-averaged, squared matrix elements factorize in the collinear limit



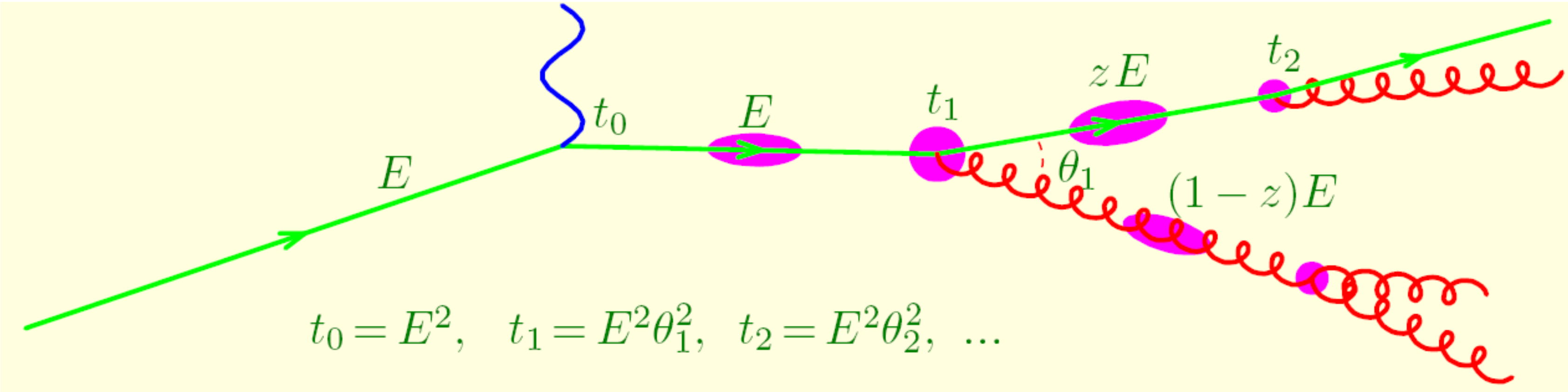
- The phase-space factorizes in terms of the "Born" variables and "radiation" variables

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

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

$t = E^2\theta^2$ $\qquad$ $z =$ energy fraction of quark $\qquad$ $P_{q,qg}(z) = C_F \dfrac{1+z^2}{1-z}$ AP splitting function

Shower basics



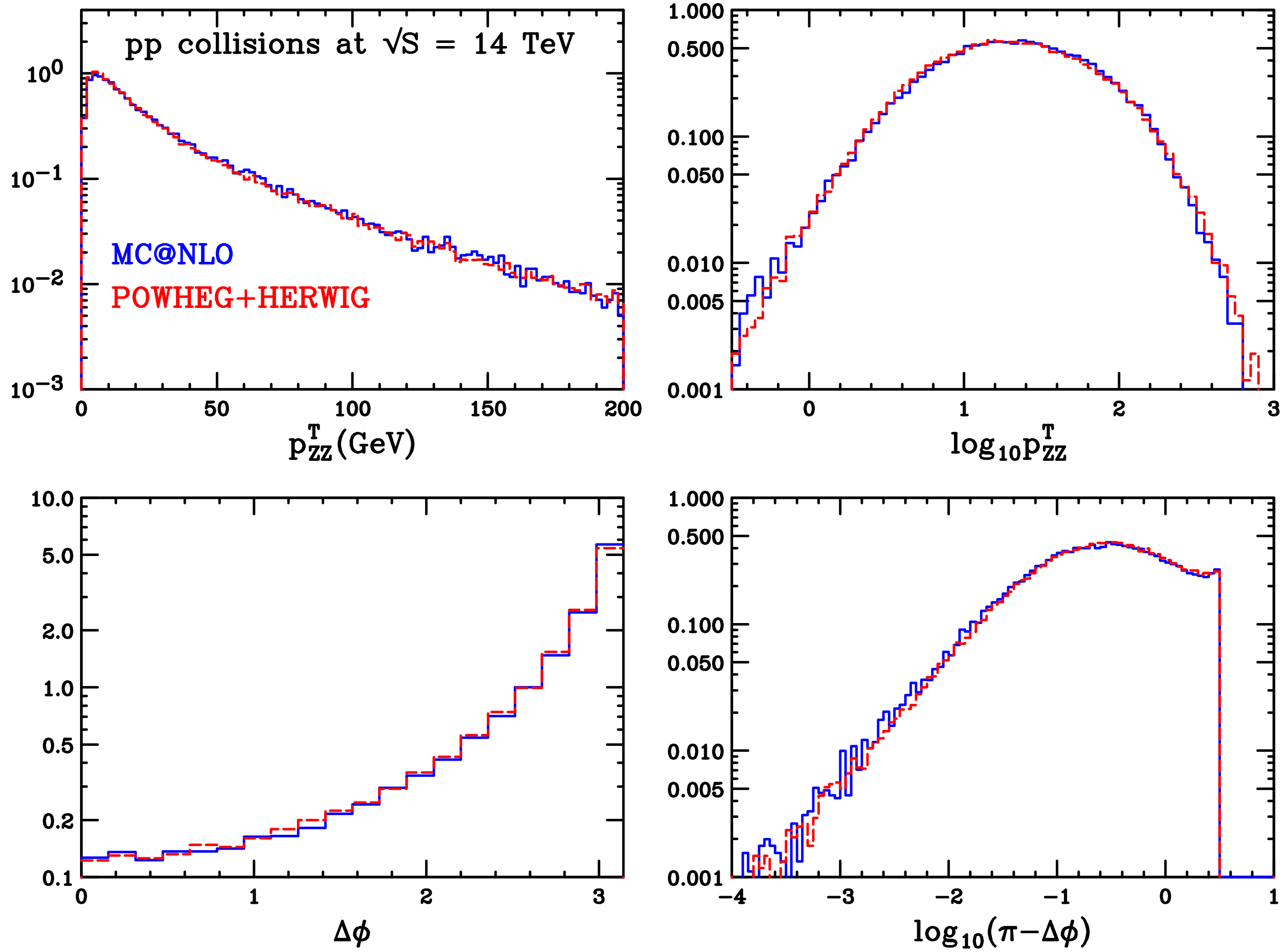
Approximate cross section for production of any number of partons including all dominant contributions for small angle splitting:

- dominant configurations: $t_0 \gg t_1 \gg t_2 \ldots$
- splitting vertexes approximated as: $\frac{\alpha_s}{2\pi}\frac{dt}{t}P(z)\,dz$
- all virtual corrections enhanced by $\log\frac{t_i}{t_{i+1}}$ included. Their effect
  - $\alpha_s \to \alpha_s(p_T)$ in splitting vertexes
  - Sudakov form factor, i.e. probability of no emission between the two scales

$$\Delta(t_i, t_{i+1}) = \exp\left[-\int_{t_{i+1}}^{t_i}\frac{dt}{t}\frac{\alpha_s(p_T)}{2\pi}\int dz\,P(z)\right]$$

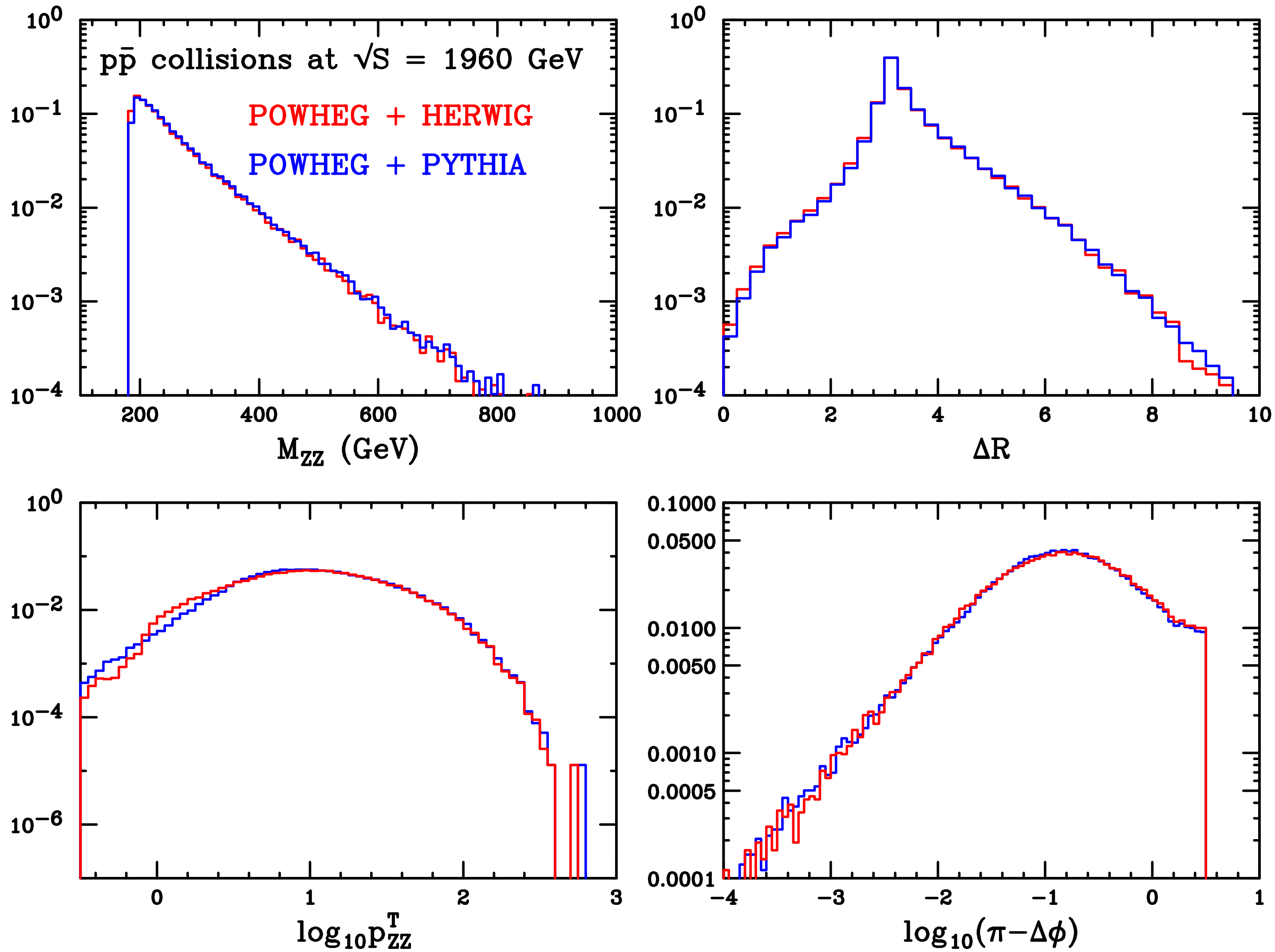
on intermediate lines

ZZ production: POWHEG + HERWIG vs MC@NLO



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

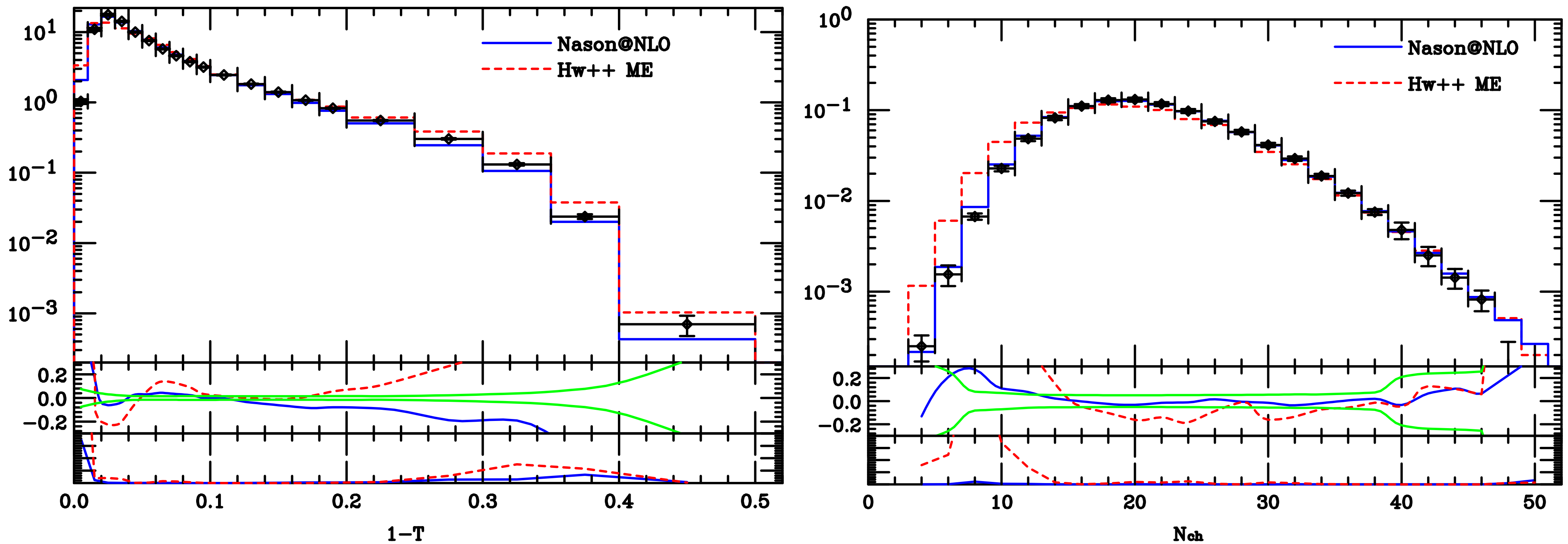
POWHEG + HERWIG vs POWHEG + PYTHIA



Agreement between POWHEG + HERWIG and POWHEG + PYTHIA

[Nason and Ridolfi, hep-ph/0606275]

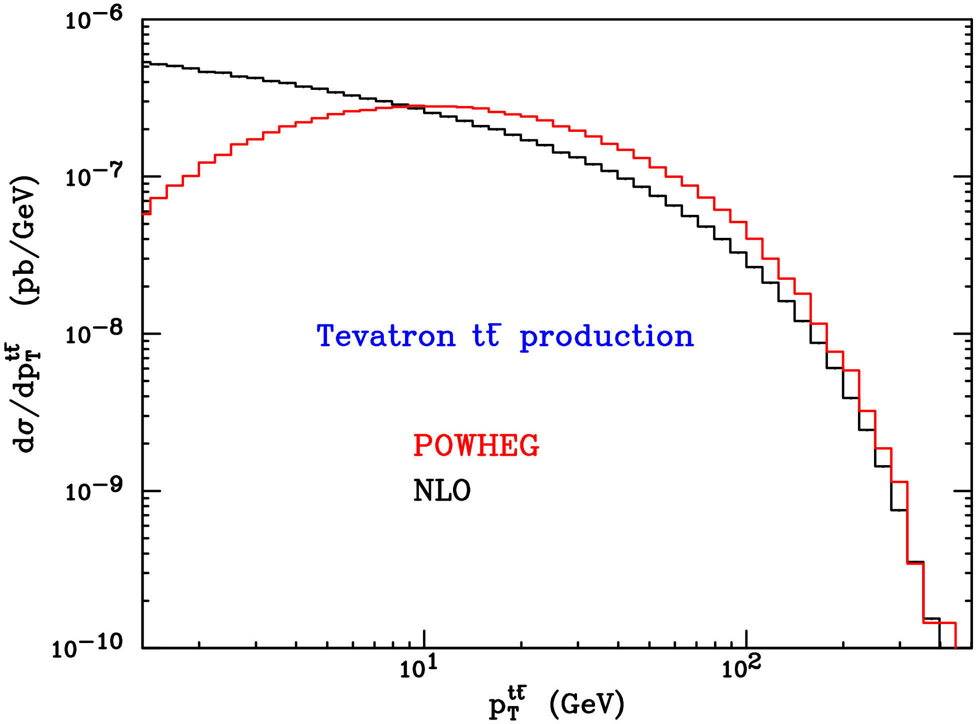
$e^+e^- \longrightarrow$ hadrons

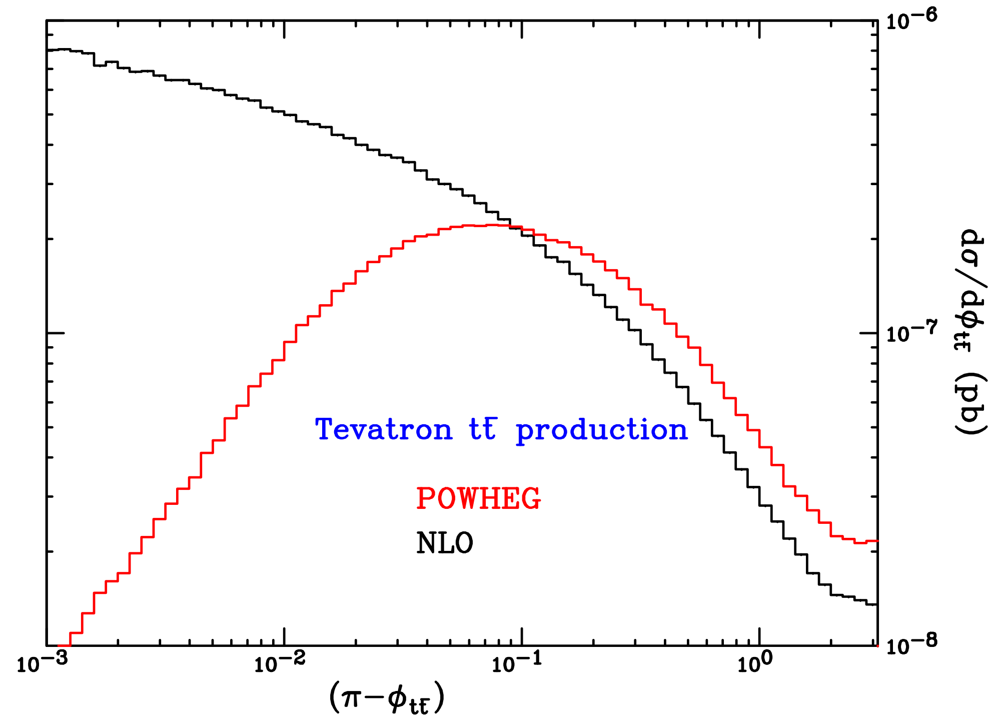


[Latunde-Dada, Gieseke and Webber, hep-ph/0612281]

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

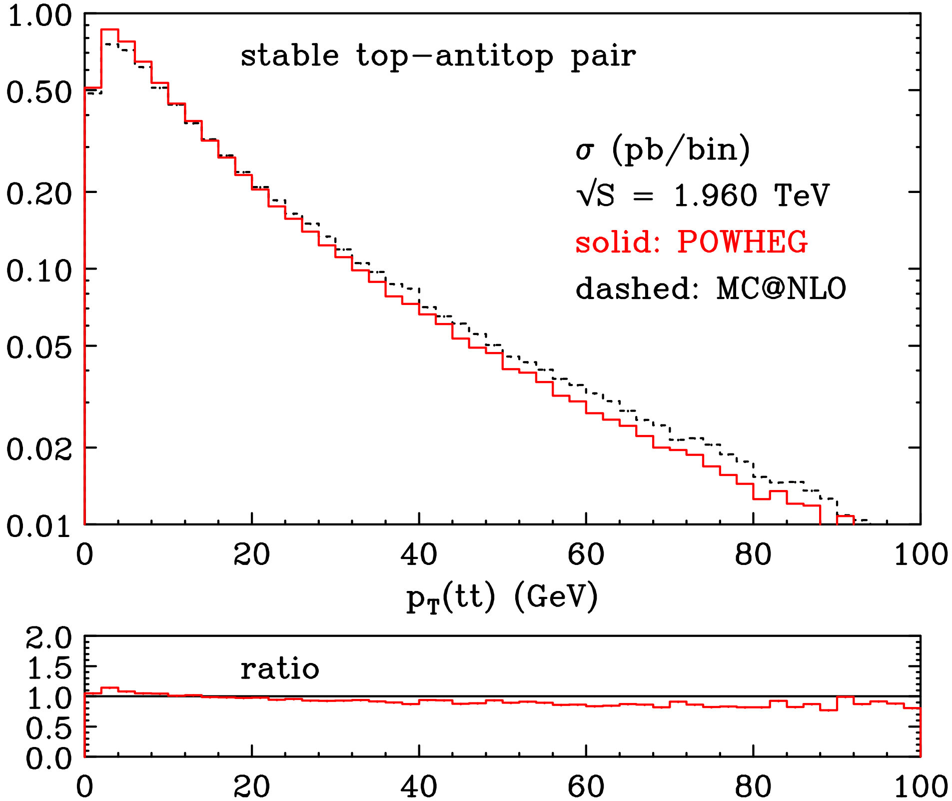
$t\bar{t}$ production: POWHEG vs. NLO

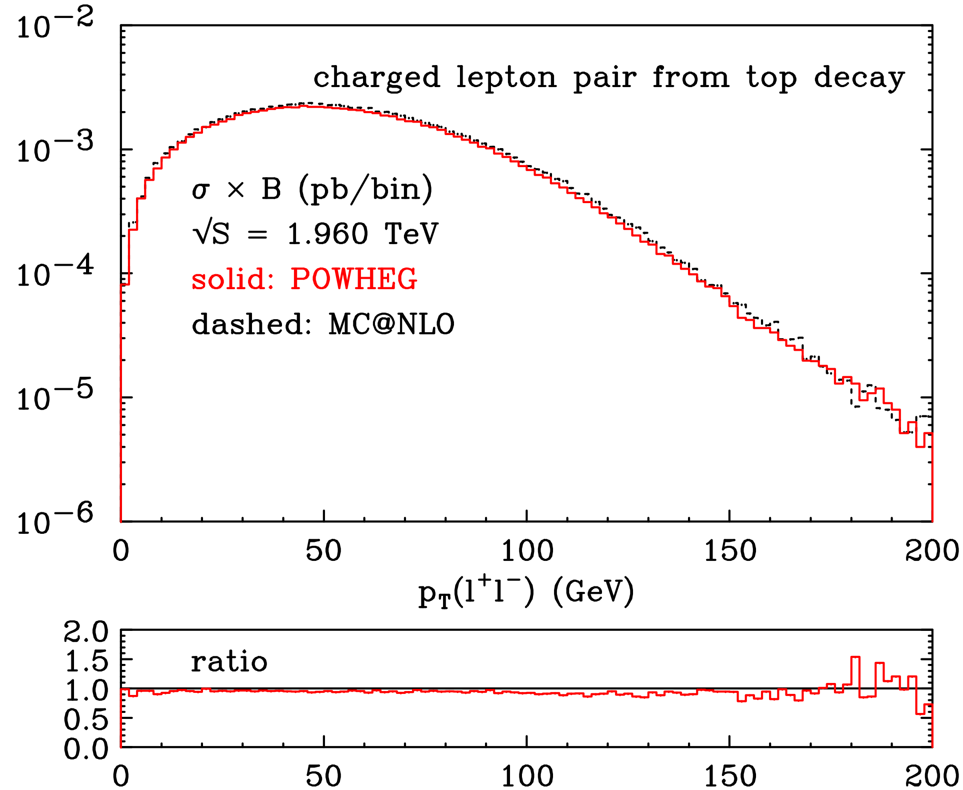




- when $p_T^{t\bar{t}} \to 0$, POWHEG treats correctly the resummation of soft/collinear radiation
- when $p_T^{t\bar{t}}$ becomes large, POWHEG approaches the NLO result
- when $\Phi_{t\bar{t}} \to 0$, the emitted radiation becomes hard and POWHEG goes to the NLO result.

$t\bar{t}$ 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)

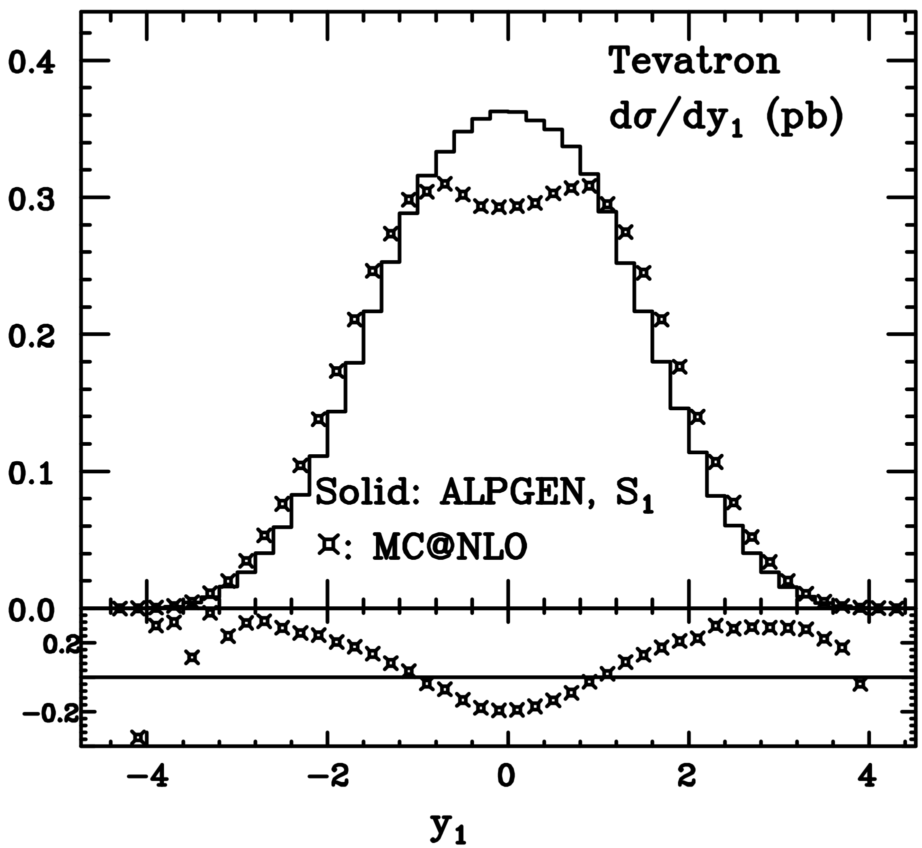
ALPGEN

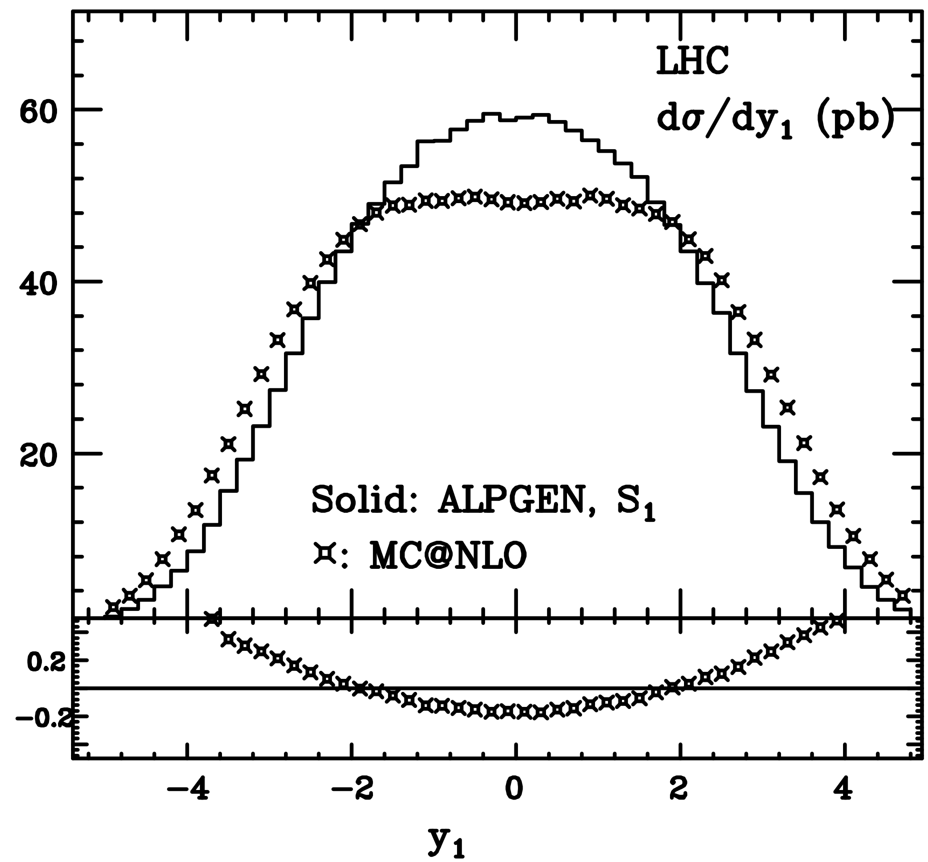
- Generation: $P^T_{\text{min}} = 30$ GeV, $\Delta R = 0.7$
- Matching: $E^T_{\text{min}} = 30$ GeV, $\Delta R = 0.7$

Jet definitions

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

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

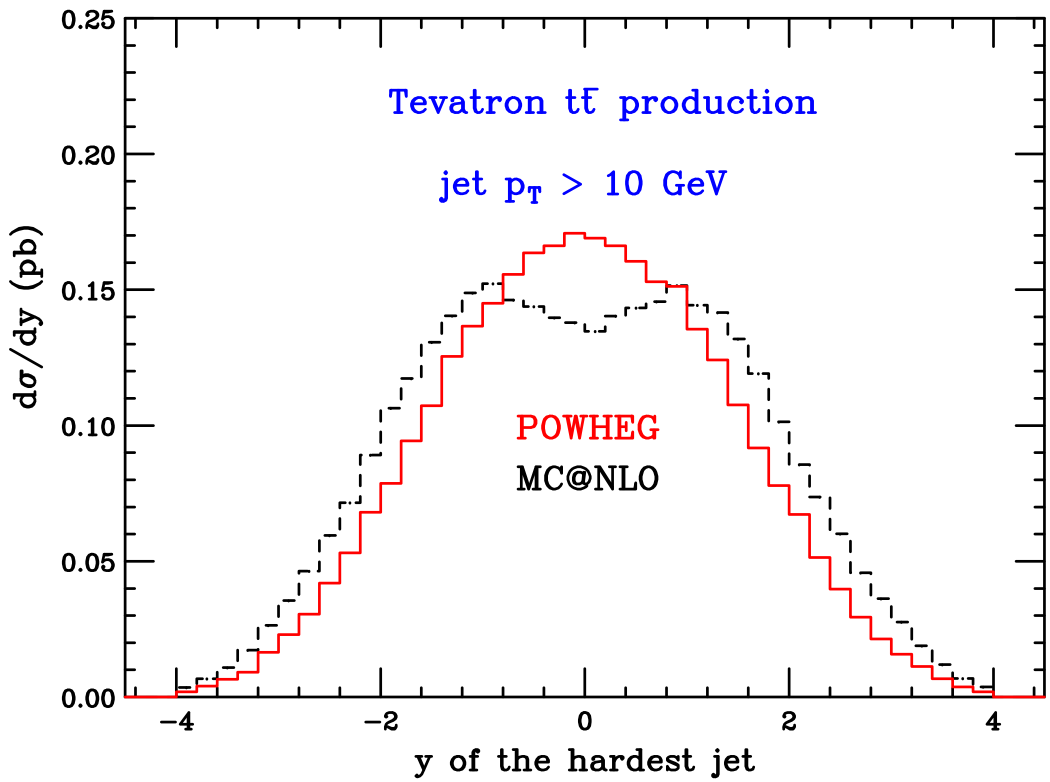


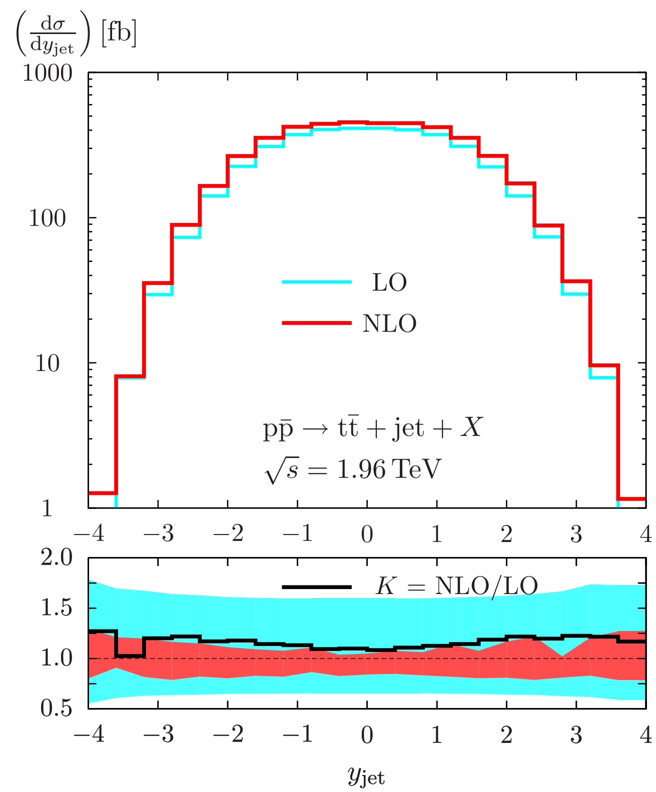


Rapidity y_1 of the leading jet (highest p_T).

Different shapes both at Tevatron and at the LHC

POWHEG: rapidity of the leading jet

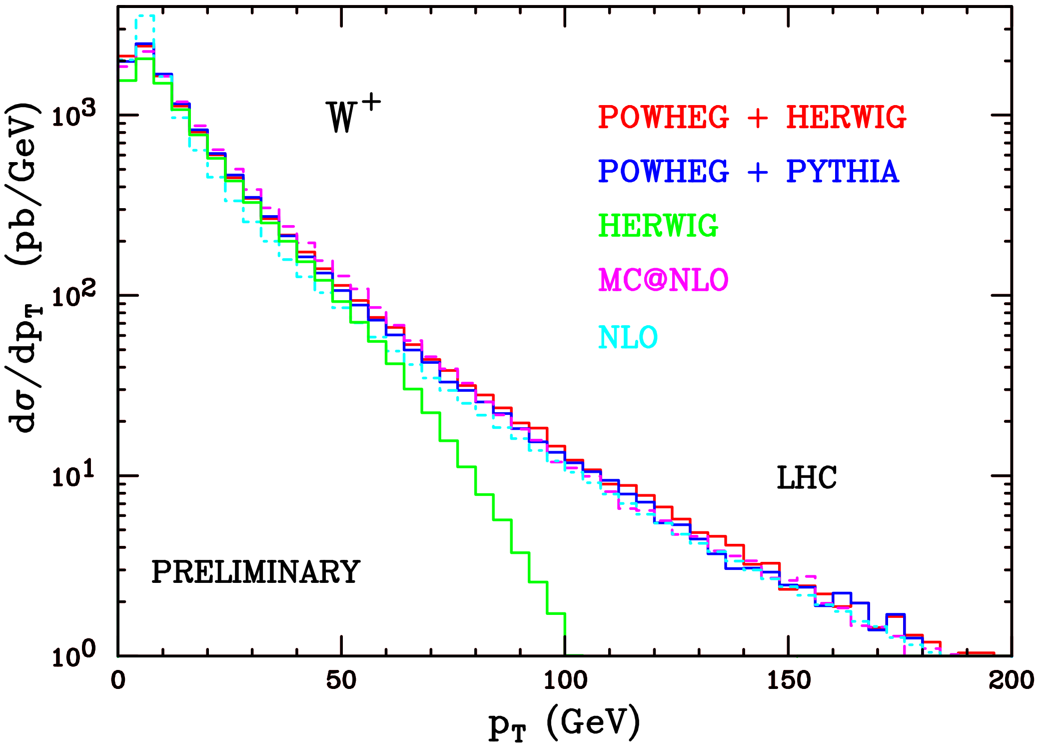


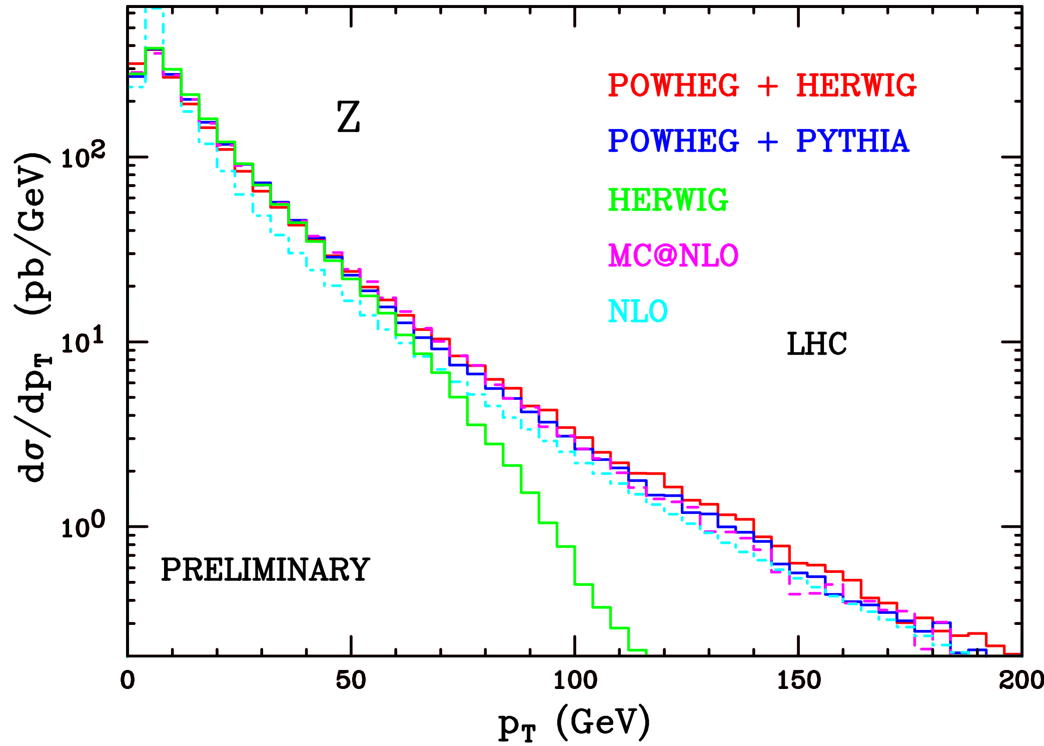


POWHEG's distribution as in ALPGEN: no dip present. The size of discrepancy can be attributed to different treatment of higher-order terms. Is this "feature" really there?

The new $pp \to t\bar{t}$ + jet at NLO [Dittmaier, Uwer, Weinzierl, hep-ph/0703120] shows no dip too (preliminary result).

W/Z production





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:

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

The `fortran` implementation of the POWHEG code for these two processes can be found at:

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

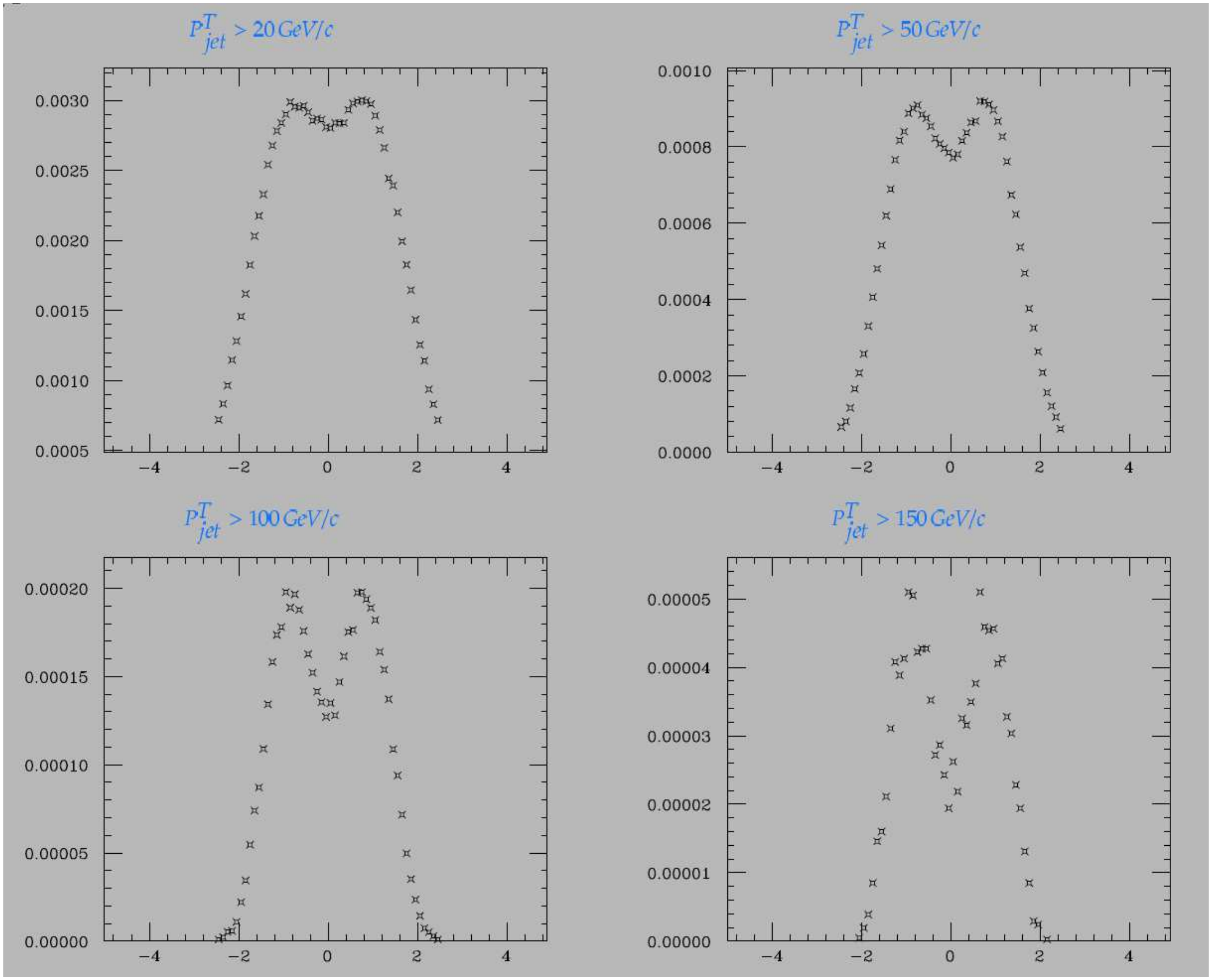
Strategy and conclusions

- ✓ Shower Monte Carlo programs to do the final shower already exist
- ✓ Most of them implement a p_T veto
- ✓ Most of them comply with a standard interface to hard processes, the so called Les Houches Interface (LHI)

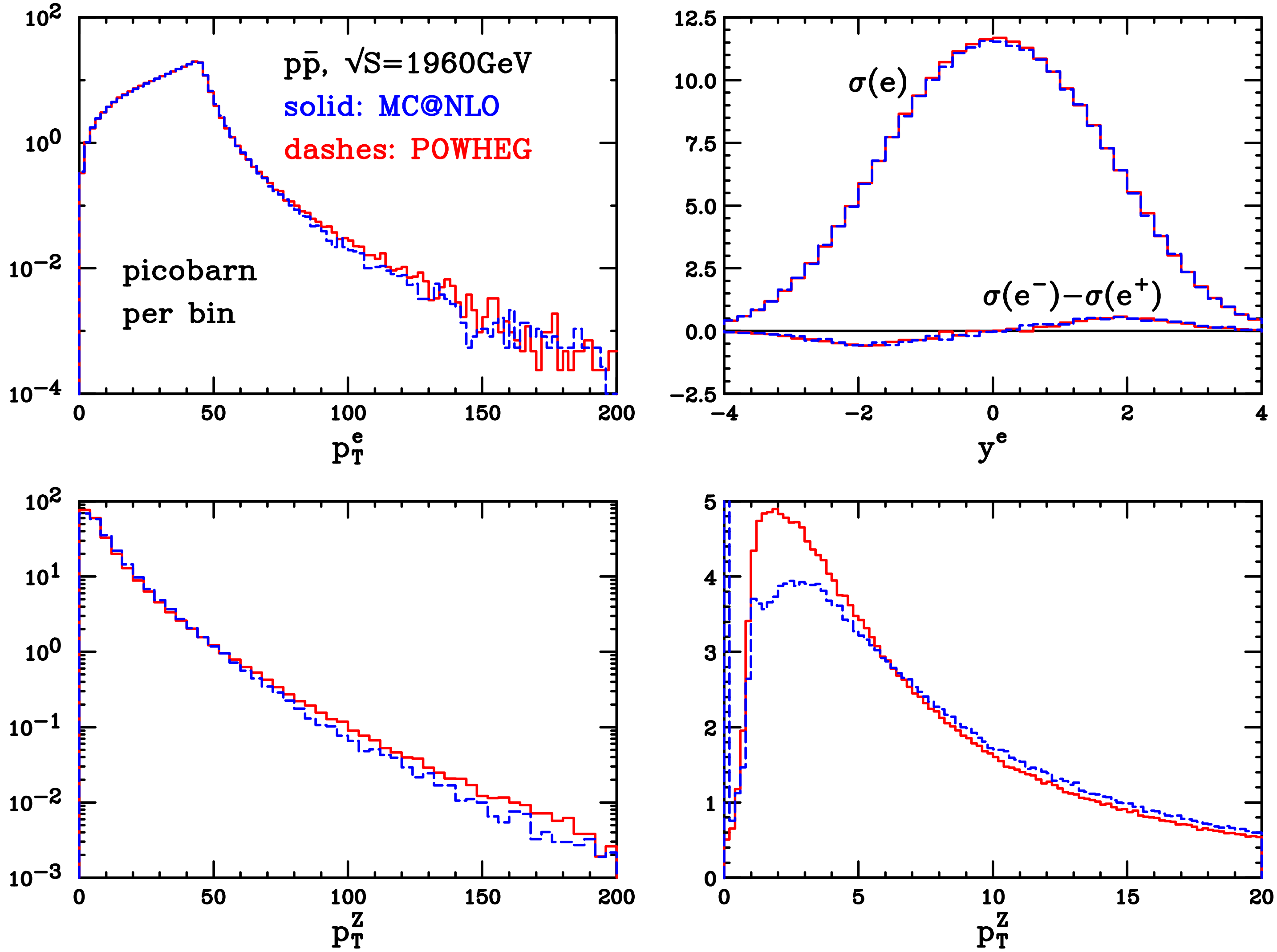
SO...

- construct a POWHEG for a NLO process. Output on LHI
- if needed, construct a generator capable to add truncated showers to events from the LHI. Output again on LHI
- use standard Shower Monte Carlo to perform the p_T-vetoed final shower from the event on LHI.

HERWIG: rapidity of the leading jet



POWHEG results



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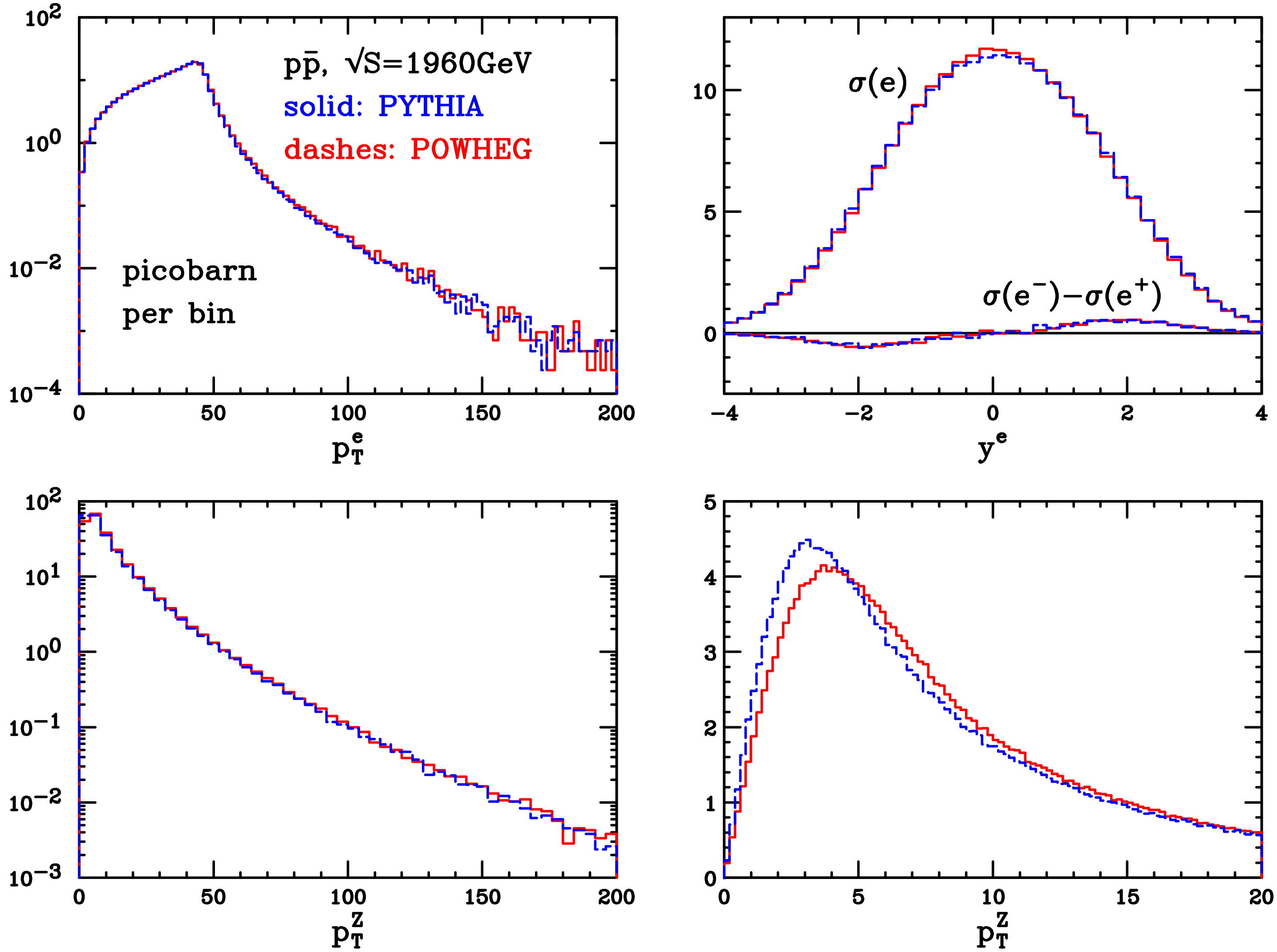

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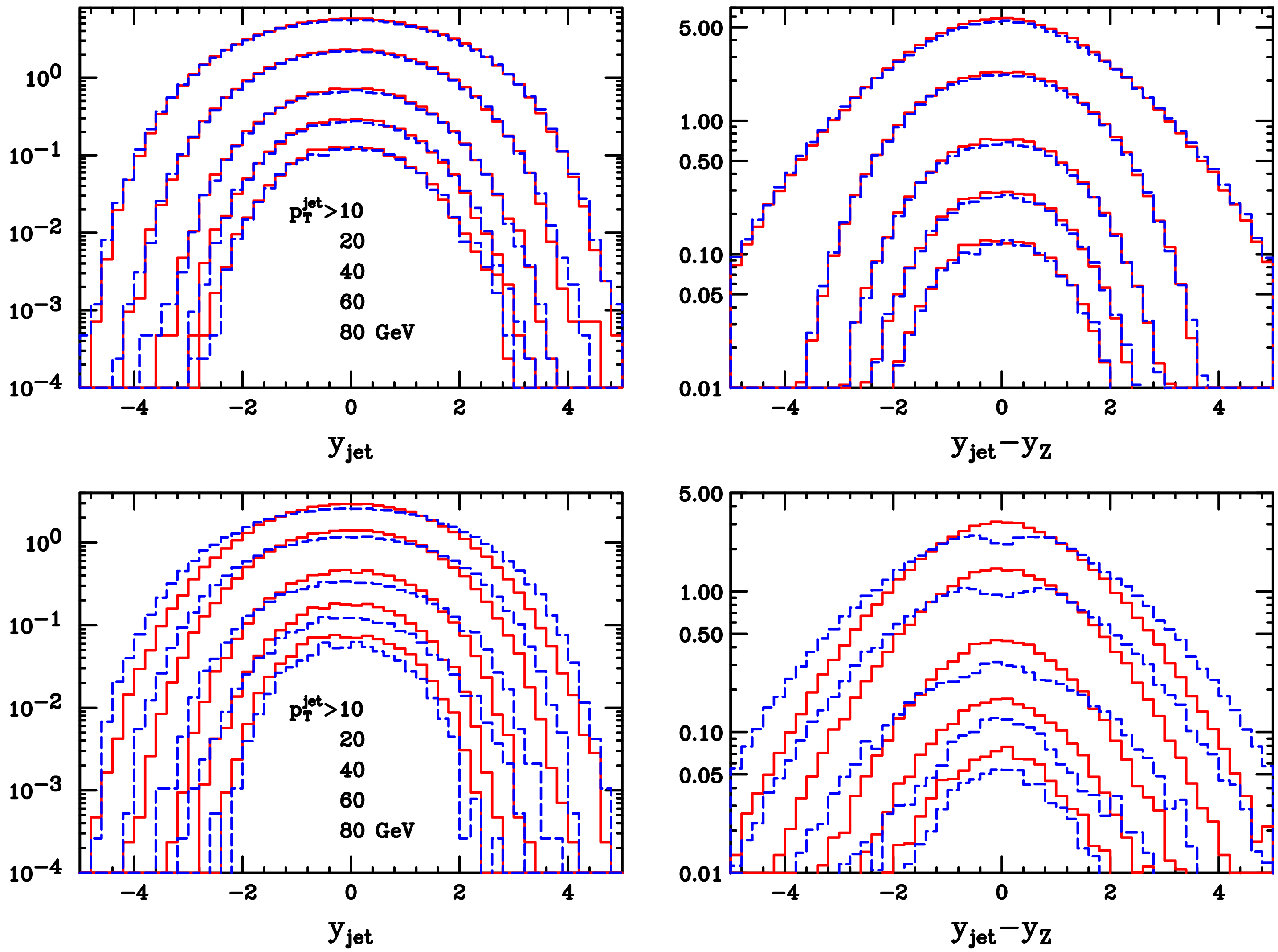

POWHEG results