Monte Carlo generators for top physics at the LHC

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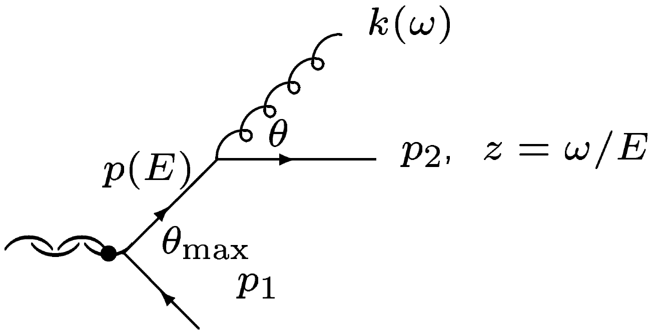
1. **Introduction**
2. **Parton-shower and matrix-element generators for top-quark signals and backgrounds**
3. **Results and comparisons at the LHC**
4. **Theoretical uncertainties on the top mass reconstruction**
5. **Conclusions**

Great improvement in the latest few years in Monte Carlo generators for $t\bar{t}$ and single-top production, top decay, and backgrounds

HERWIG and PYTHIA to simulate parton showers and hadronization

Multiple radiation in soft or collinear approximation



$$dP \sim \frac{\alpha_S}{2\pi}\, P(z) dz\, \frac{dQ^2}{Q^2}$$

Q^2: ordering variable

HERWIG: $Q^2 \simeq E^2\theta^2 \Rightarrow$ angular ordering in soft limit

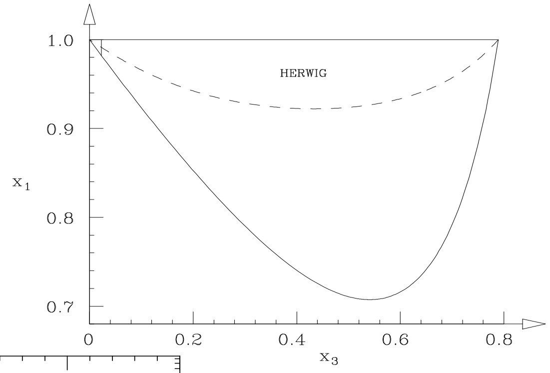
PYTHIA: $Q^2 = p^2$ or k_T^2, with an option to veto non-angular-ordered showers

Parton showers equivalent to a LL resummation, with some NLLs

PYTHIA and HERWIG simulate $t\bar{t}$ and single-top production

HERWIG and TopRex+PYTHIA account for spin correlations in top decays

Matrix-element corrections for hard/large-angle radiation: implemented for top decay $t \to bW$, but not for production

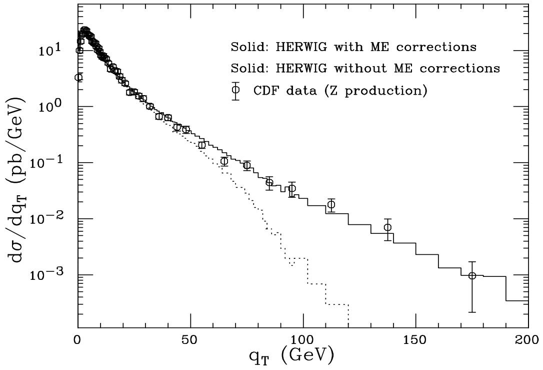


HW: exact amplitude in the dead zone (t rest frame)

PY: exact matrix element corrects first emission

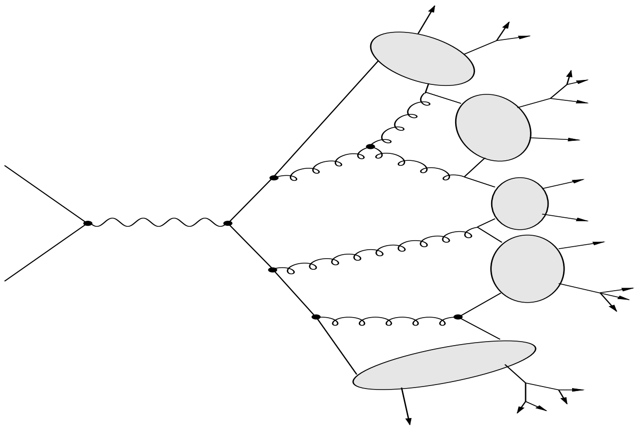
Still LO total cross section

Background: matching for W/Z+1 jet

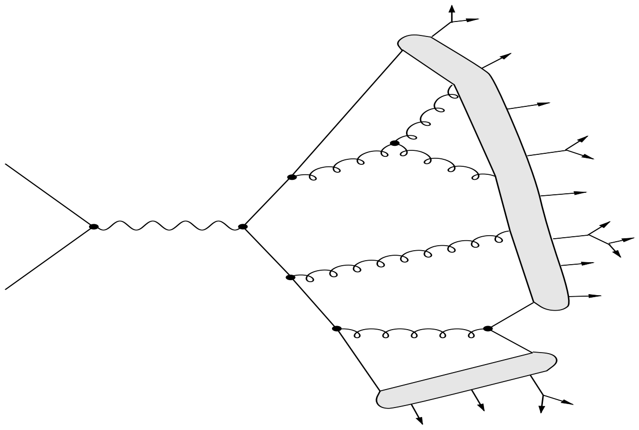


Hadronization:

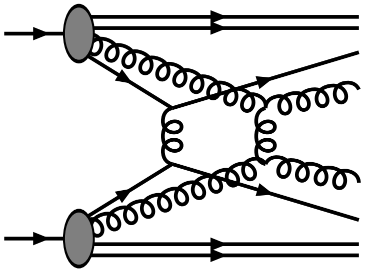
Cluster model (HERWIG)



String model (PYTHIA)



PYTHIA and HERWIG (interface with JIMMY) account for multiple interactions to model the underlying event



HERWIG++ and PYTHIA 8: new object-oriented versions in C++

PYTHIA 8: Transverse-momentum ordering, initial-, final-state radiation and multiple interactions interleaved in a common p_T ordering (fortran only initial-state radiation)

Multiple interactions for QCD $2 \to 2$ processes, prompt photons, charmonia and bottomonia, low-mass Drell–Yan pairs

Not yet tested for top-quark signals or backgrounds (Sjostrand)

HERWIG ++: $Q^2 \to Q'^2 = Q^2 + \frac{\max(m_g^2, p^2)}{z^2} + \frac{k^2}{z^2(1-z)^2}$ **(angular ordering)**

Mass-dependent term in the splitting function: $P_{qq}(z) = C_F \left[\frac{1+z^2}{1-z} - \frac{2z(1-z)m^2}{p_T^2+(1-z)^2 m^2}\right]$

Better treatment of radiation off heavy quarks, improved fragmentation, especially B-hadrons

ARIADNE and dipole cascade (L.Lönnblad) **:** $2 \to 3$ **splittings rather than** $1 \to 2$

Only parton showers: hard scattering and hadronization are taken from PYTHIA

qg $(\bar{q}g)$ **dipole:** $qg \to qgg$ **splitting**

Strong ordering in k_T**:** $k_{T,1}^2 \gg k_{T,2}^2 \gg \ldots$ **(no need for angular ordering)**

SHERPA

Multipurpose parton-level generator AMEGIC++ generates hard scattering

Clustering of jets using the k_T **algorithm**

Parton showers (APACIC++): ordering in virtuality, with possible enforcement of angular ordering (like PYTHIA)

Hadronization: Lund string model

Monte Carlo generators at NLO

MC@NLO (Frixione & Webber) : **NLO (real+virtual) hard scattering: parton showers and hadronization are taken from HERWIG**

Identical to HERWIG in soft or collinear regions, and to NLO computations for hard or large-angle radiation

Main improvements: cross sections are NLO, predicted observables are NLO

Drawbacks of MC@NLO: shower model specific (HERWIG), generates few events with negative weights

POWHEG (Nason, Frixione, Oleari and Ridolfi) : **NLO cross sections, interface to any parton shower model, no negative weights**

The hardest emission (p_T) is the first and is generated exactly at NLO

Veto in p_T for subsequent radiation

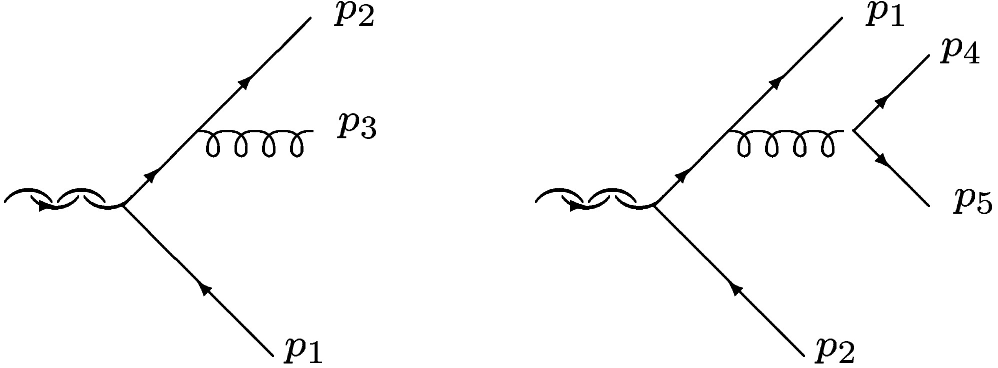
The procedure is independent of the MC program and works well for p_T-ordered showers; truncated showers for angular ordering

Matrix-element generators (ALPGEN, MadGraph, CalcHep, HELAC, etc.):
Higher-jet multiplicites, e.g. $W/Z + n$ jets **, at LO interfaced to HERWIG and/or PYTHIA for showering and hadronization (Les Houches accord)**

ALPGEN : $t\bar{t} + 6$ **jets,** $V + 6$ **jets,** $Wb\bar{b} + 4$ **jets,** $VV + 3$ **jets**

MadGraph: $t\bar{t} + 3$ **jets,** $V + 4$ **jets,** $V + b\bar{b} + 3$ **jets,** $VV + 2$ **jets, etc.**

Matching schemes (CKKW and MLM) to avoid double countings and prevent parton showers from generating radiation harder than matrix elements



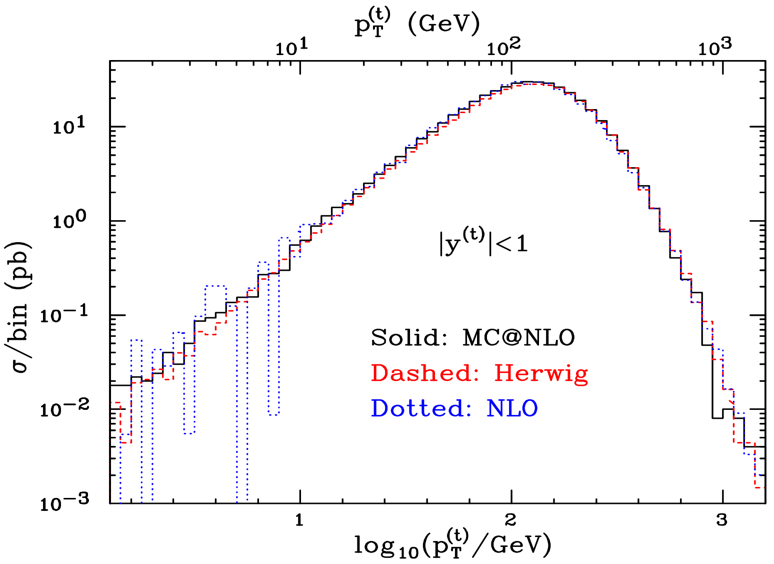
CKKW (SHERPA, ARIADNE): k_T algorithm, $y_{\rm cut}$, $y_{ij} = \frac{2\min\{E_i^2, E_j^2\}}{Q^2}[1 - \cos\theta_{ij}]$

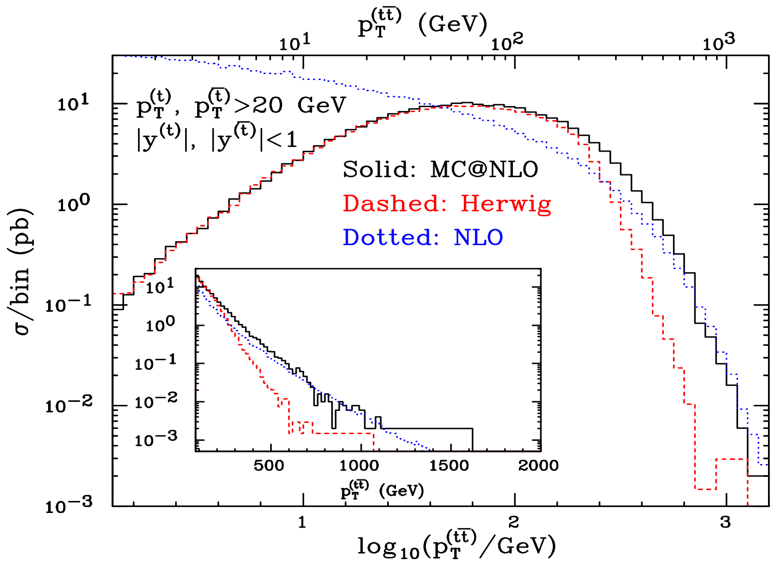
Ex. 3 jets $(y_{12,13,23} > y_{\rm cut})$ $y_{45} < y_{\rm cut} \Rightarrow$ accept parton showers; $y_{45} > y_{\rm cut} \Rightarrow$ reject

MLM matching (ALPGEN): define n **cone jets** $(\Delta R > R_0, p_T > p_{t,min}, |\eta| < \eta_{max})$ **shower and cluster the event into** k **jets**

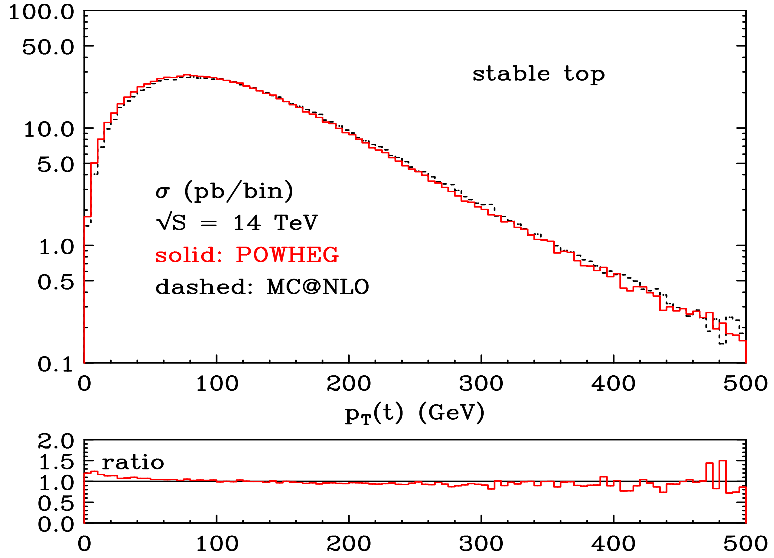
Accept the event if $k \geq n$ **and each of the** n **original partons in a different jet**

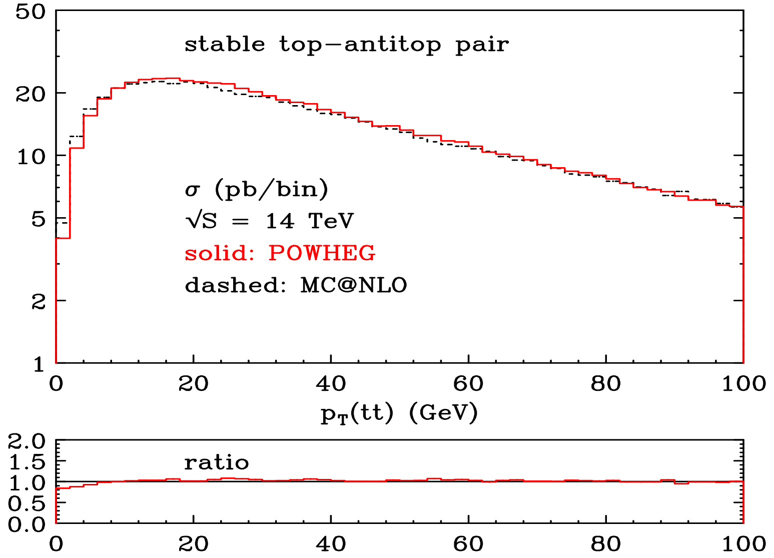
Comparing MC@NLO, HERWIG and NLO results





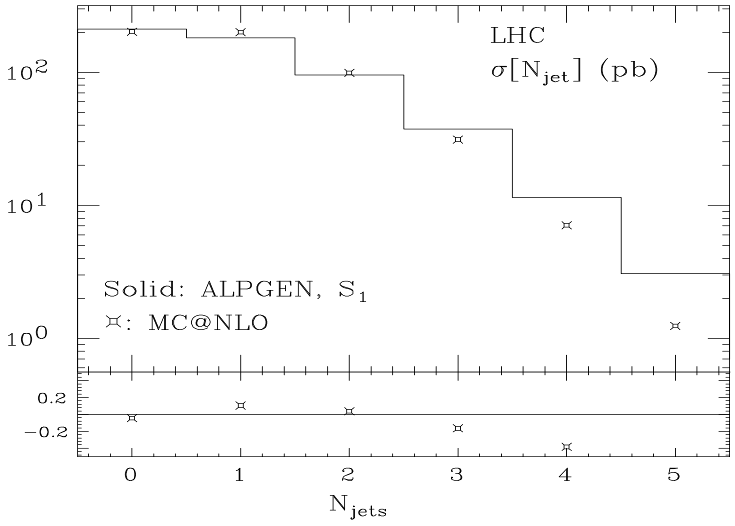
POWHEG vs. MC@NLO

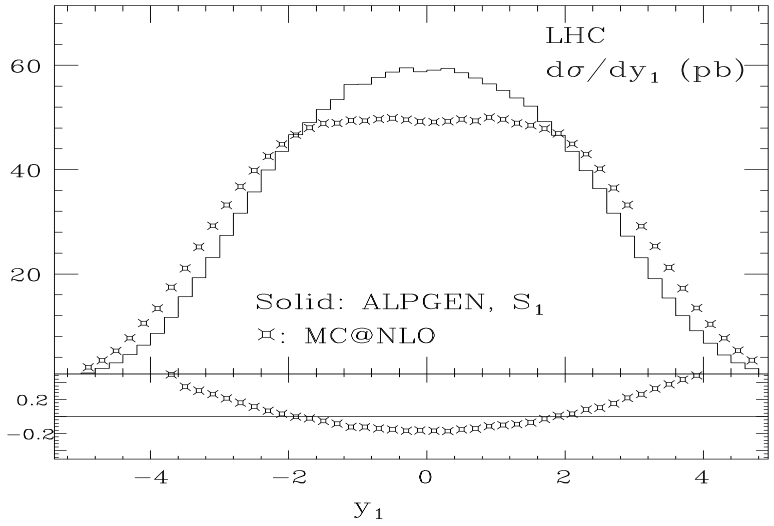




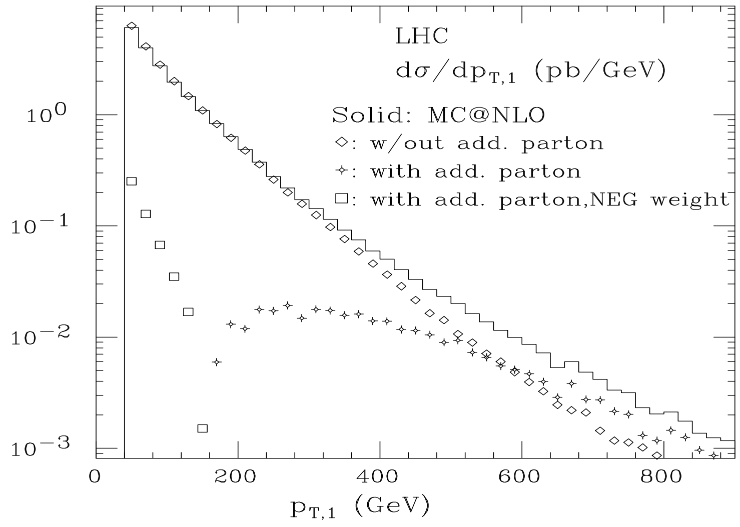
ALPGEN vs. MC@NLO for $t\bar{t}$ production (Mangano, Moretti, Piccinini, Treccani)

Cone algorithm ($R = 0.7$, $E_T > 20$ GeV, $|\eta| \leq 6$): general agreement, but discrepancy for y_1

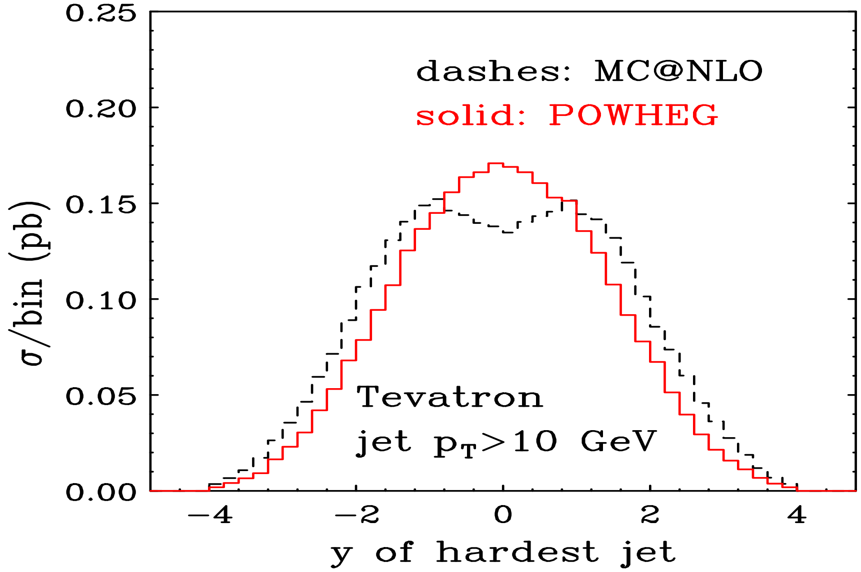




Very little contribution of $t\bar{t}g$ hard process in MC@NLO

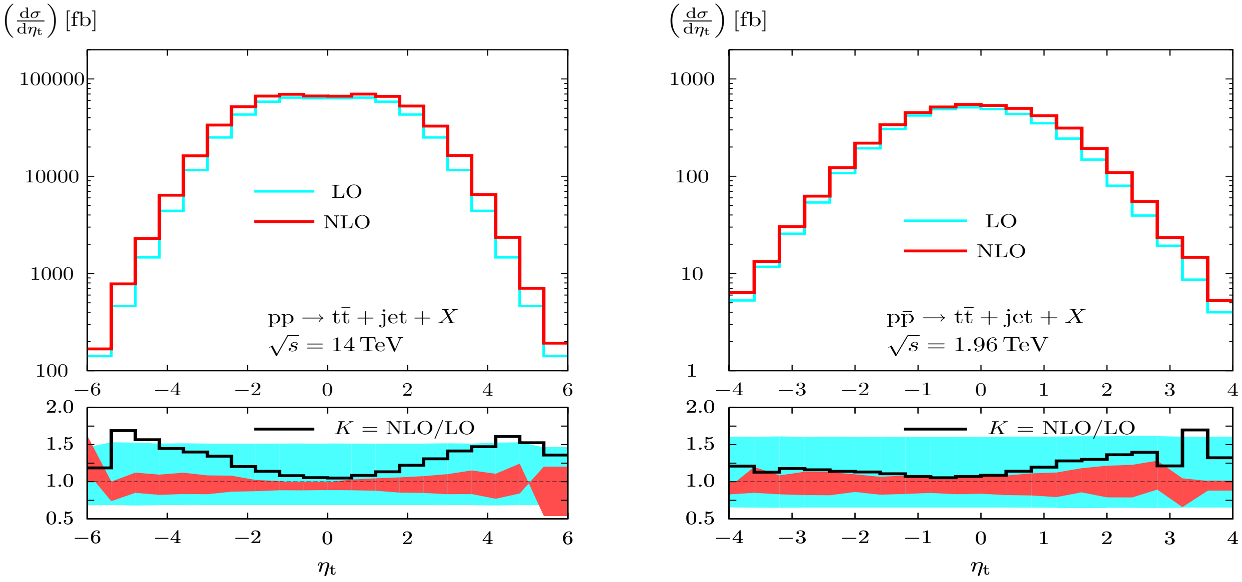


POWHEG seems to agree with ALPGEN with no dip at $y_1 = 0$



Preliminary result from $t\bar{t}+$ jet at NLO similar to ALPGEN and POWHEG

(Dittmaier, Uwer and Weinzierl, RADCOR’07)



Workshop MC4LHC: comparison of different matrix-element generators

Parton-level jet cross sections after cuts:

$p_{i,T} > 20$ GeV, $|\eta_i| < 2.5$, $\Delta R = \sqrt{\Delta\phi^2 + \Delta\eta^2} > 0.4$ (table by F. Piccinini)

Cross sections in pb for $(Z/\gamma^* \to e^+e^-) + n$ jets

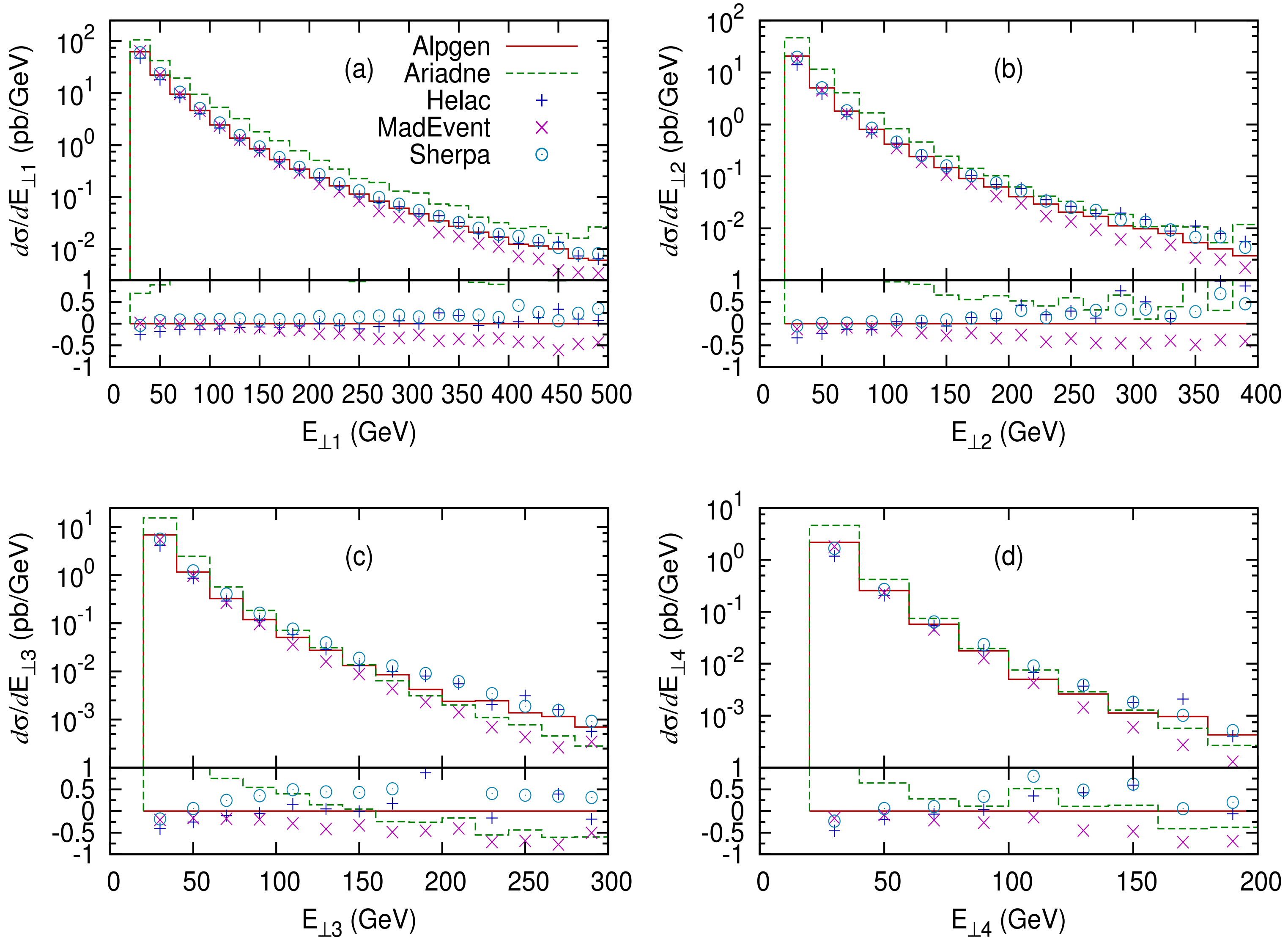
$e^+e^- + n$ QCD jets	0	1	2	3	4	5	6
ALPGEN	723.4(9)	188.3(3)	69.9(3)	27.2(1)	10.95(5)	4.6(1)	1.85(1)
SHERPA	723.9(7)	189.6(9)	71.4(4)	30(2)			
CompHEP	730.9(1)	190.20(7)	70.22(7)				
MadEvent	723(1)	188.6(3)	69.3(1)	27.1(2)	10.6(1)		
GR@APPA	744(7)	182.77(8)	67.70(3)				

Cross sections in pb for $(Z/\gamma^* \to e^+e^-) + b\bar{b} + n$ jets

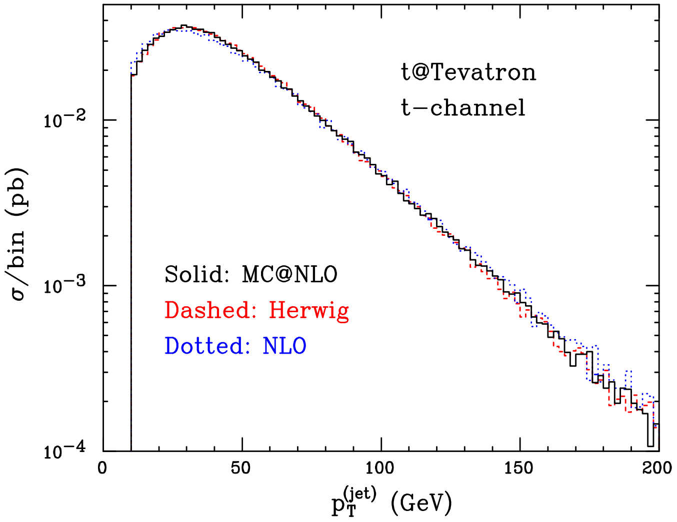
$e^+e^- + b\bar{b} + n$ QCD jets	0	1	2	3	4
ALPGEN	18.95(8)	6.80(3)	3.13(2)	1.58(1)	0.80(1)
SHERPA	18.8(2)				
CompHEP	19.45(2)				
MadEvent	18.7(1)	6.72(2)	2.96(1)		

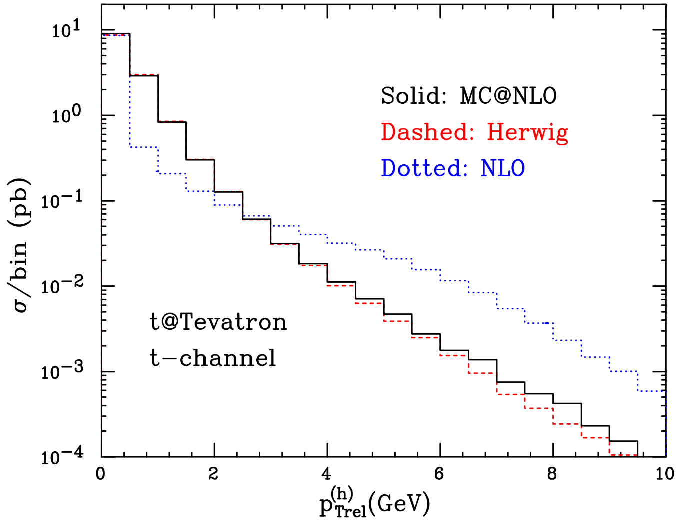
Whenever a given process is implemented, the four generators agree

More recent exclusive studies on W+jets (J.Alwall et al.)



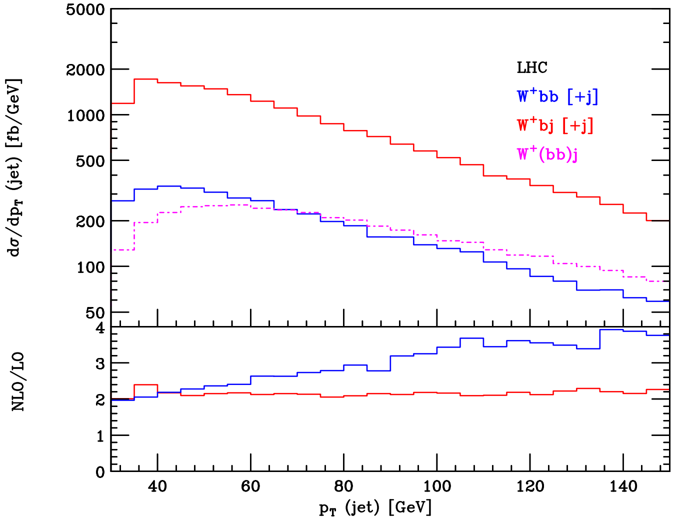
Single top production in MC@NLO (Frixione, Laenen, Motylinski, Webber)

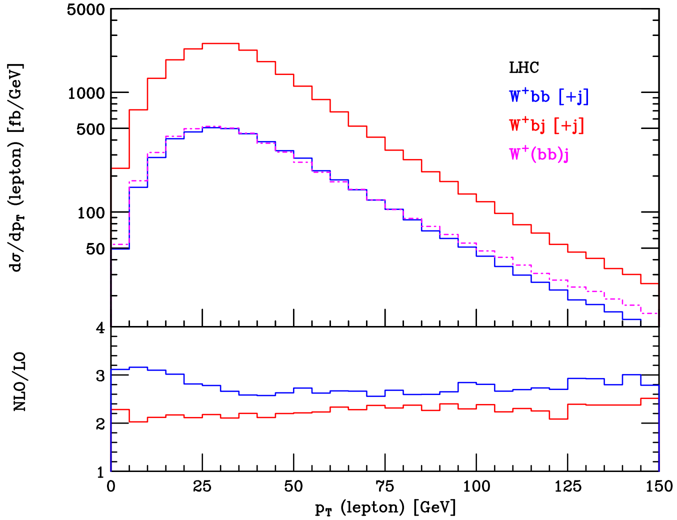




Background at NLO (MCFM): $pp \to Wjj$, with a tagged b-quark

(Campbell, Ellis, Maltoni, Willenbrock)



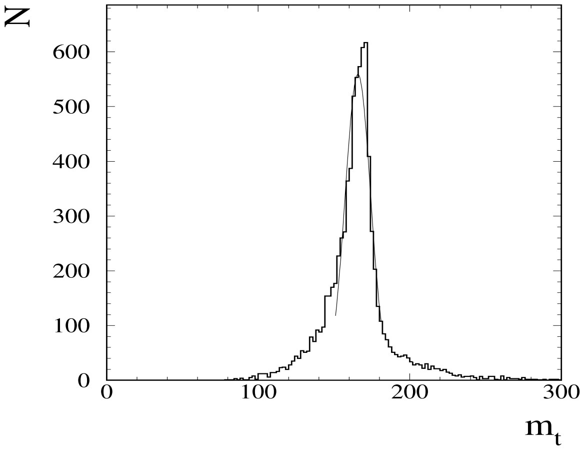


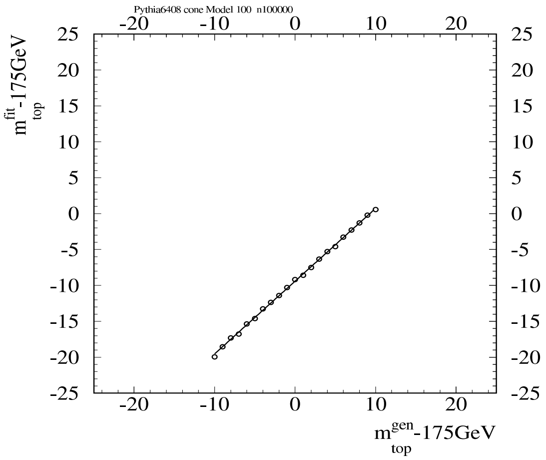
Non-perturbative physics and top mass reconstruction (P. Skands and D. Wicke)

Lepton+jets channel: $t\bar{t} \to b\bar{b}q\bar{q}'\ell\nu$;
Three jets in hadronic top decay, $p_T > 15$ **GeV and** $\Delta R = 0.5$

Run PYTHIA with $165\ \mathrm{GeV} < m_t^{\mathrm{gen}} < 185\ \mathrm{GeV}$ **and fit** m_t^{fit} **within** $15\ \mathrm{GeV}$

Rescale accounting for JES: $m_t^{\mathrm{scaled}} = s_{\mathrm{JES}} m_t^{\mathrm{fit}}$, $s_{\mathrm{JES}} = 80.4\ \mathrm{GeV}/m_W$

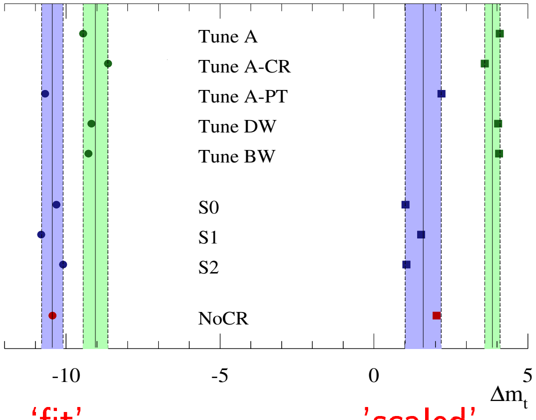




Green: virtuality-ordering; Blue: p_T-ordering

See talk by L.Fanò on underlying event

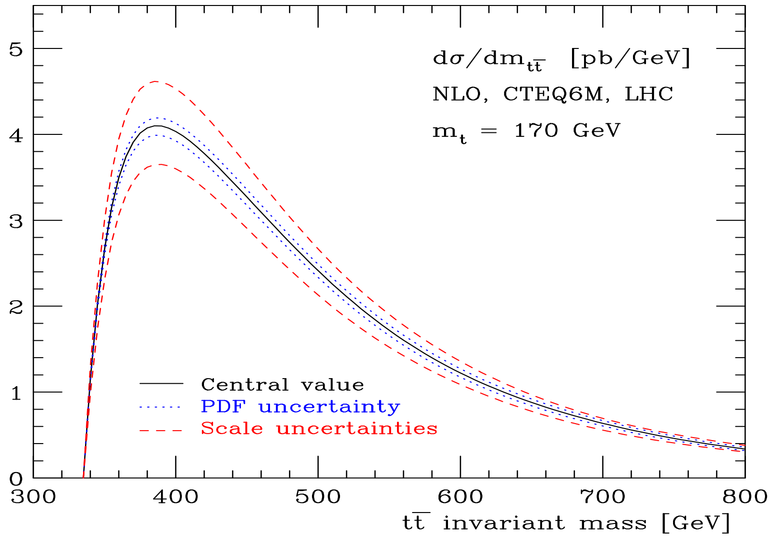
$\Delta m_t \simeq \pm 0.5$ GeV



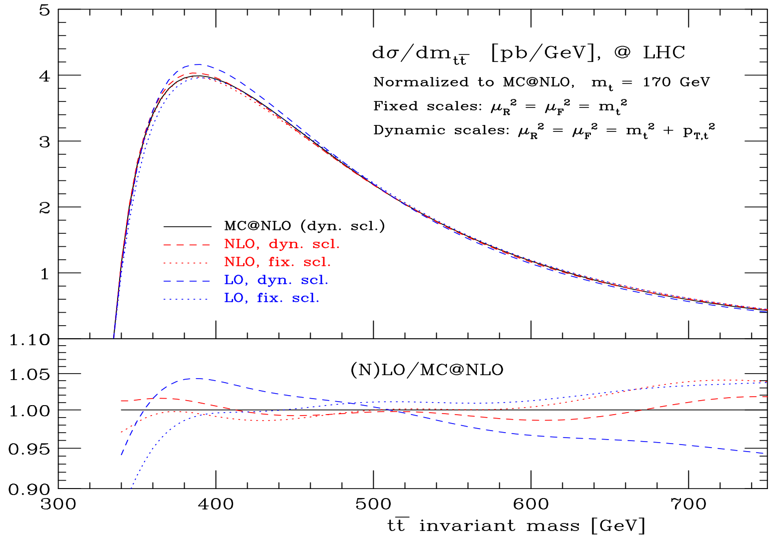
'fit' 'scaled'

Scale and parton distribution uncertainties (R. Frederix and F. Maltoni)

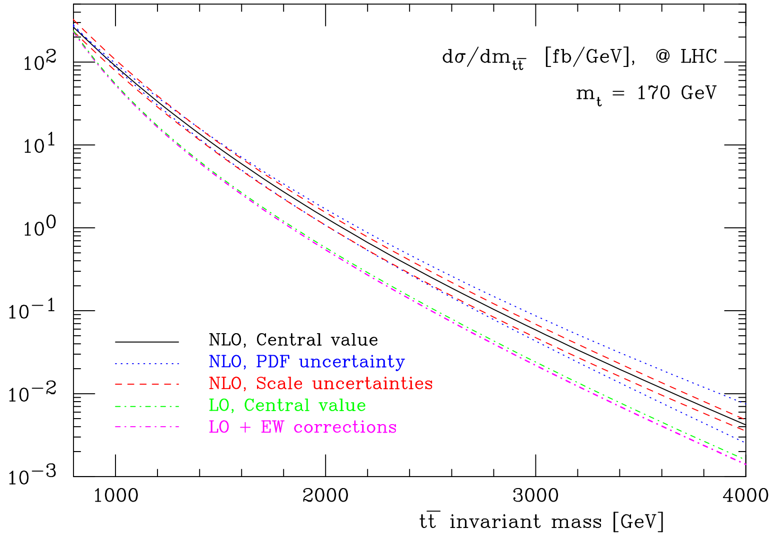
MCFM:



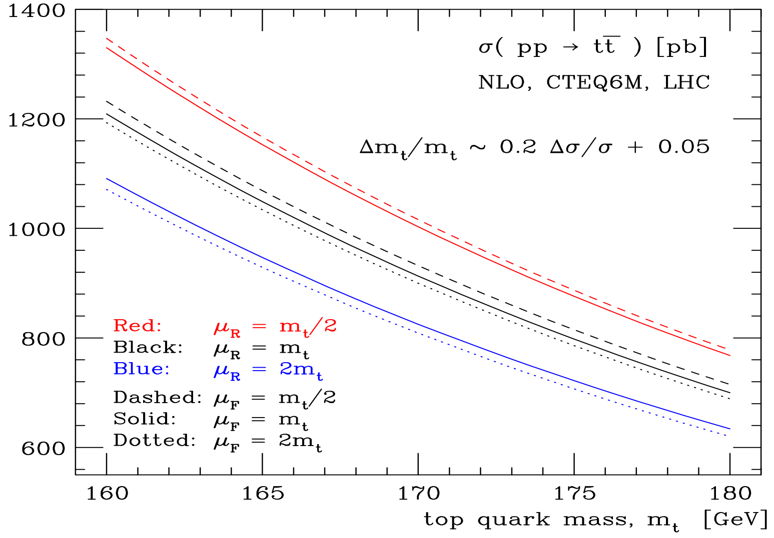
MC@NLO:



MCFM:

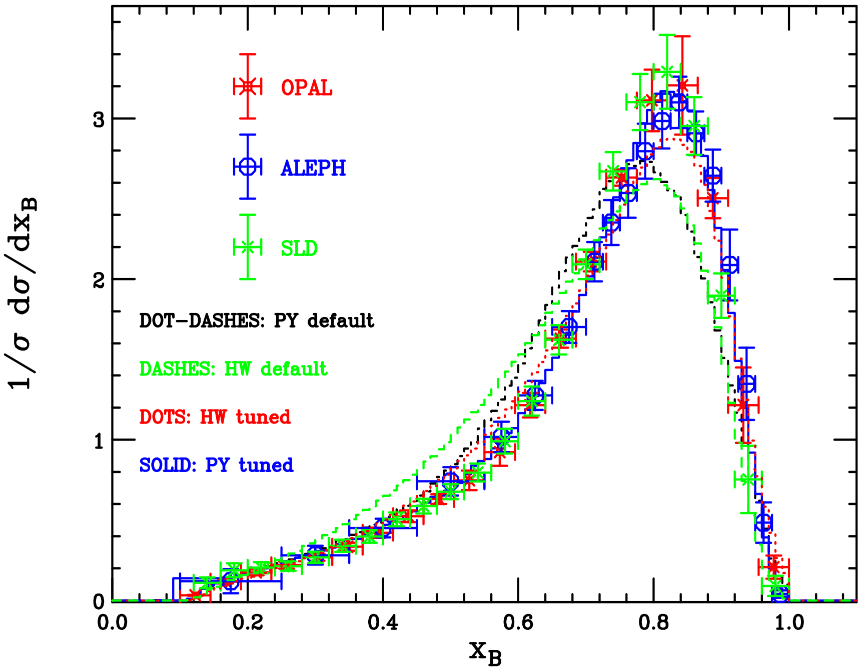


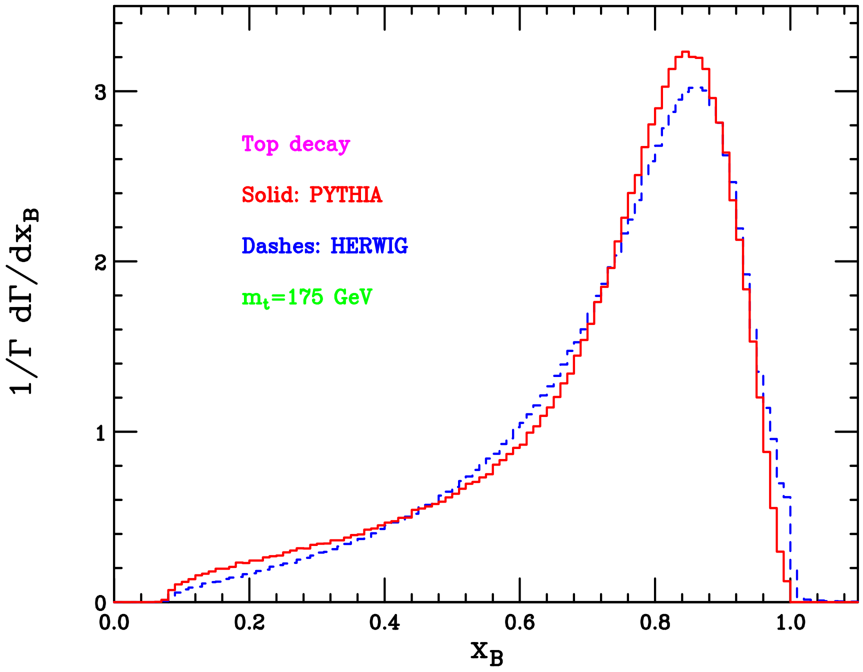
MCFM:



Bottom-quark fragmentation from e^+e^- to top decay (G.C. and V. Drollinger)

HERWIG 6.506	PYTHIA 6.202
CLSMR(1) = 0.4 (0.0)	
CLSMR(2) = 0.3 (0.0)	PARJ(41) = 0.85 (0.30)
DECWT = 0.7 (1.0)	PARJ(42) = 1.03 (0.58)
CLPOW = 2.1 (2.0)	PARJ(46) = 0.85 (1.00)
PSPLT(2) = 0.33 (1.00)	
χ^2/dof = 222.4/61 (739.4/61)	χ^2/dof = 45.7/61 (467.9/61)

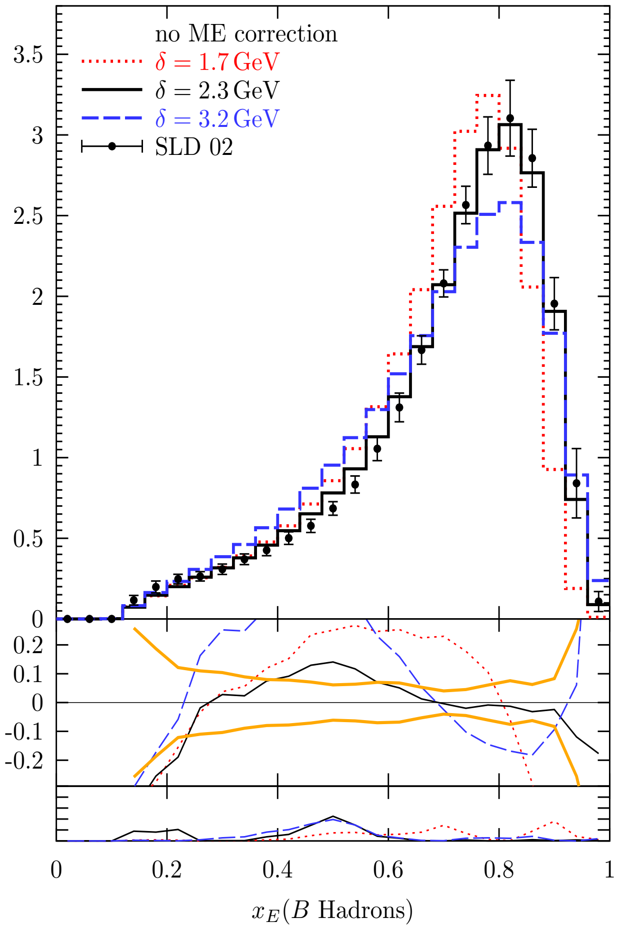




In progress: uncertainty on m_t due to b-quark fragmentation

HERWIG ++: improved treament of heavy quarks and better description of baryon formation, treated independently of mesons

$\chi^2/\mathrm{dof} \simeq \mathcal{O}(1)$ **vs. SLD B mesons/baryons, tuning only the shower cutoff δ**



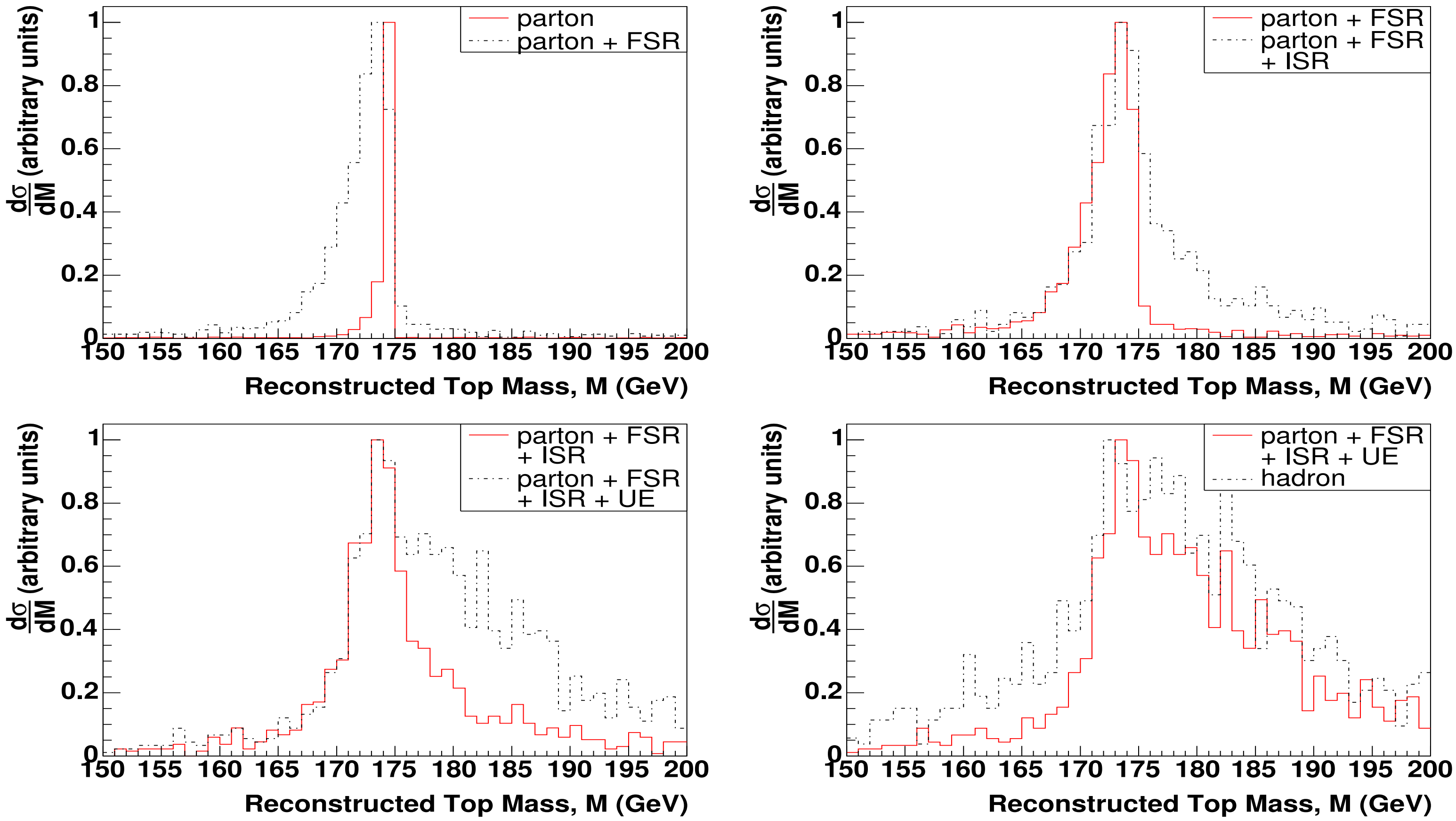
Plot by S. Gieseke

Systematic errors on the top mass reconstruction (M.H. Seymour and C. Tevlin)

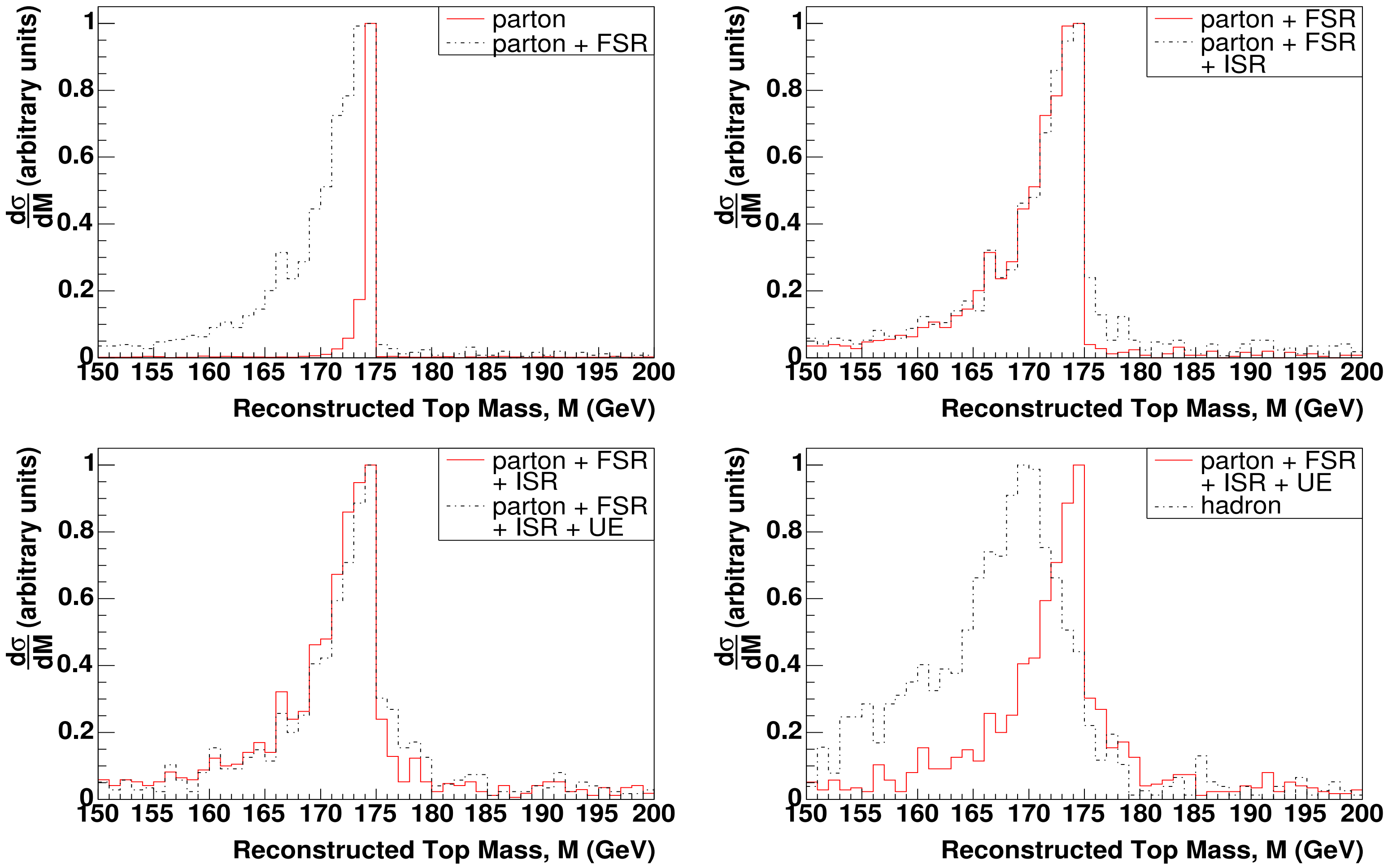
'Lepton + jets': top quark reconstruction as $W + b-$jet combination

Investigating FSR, ISR, underlying event and hadronization

k_T clustering algorithm (KtJet package)



Cone algorithm (PxCone, mid-point algorithm, infrared safe)



k_T algorithm mostly affected by ISR and UE; cone algorithm by FSR and hadronization

Useful employing both algorithms

Conclusions

Great improvement in Monte Carlo generators for top physics

Parton-shower generators HERWIG and PYTHIA, now rewritten in C++

MC@NLO and POWHEG: top production at NLO, plus showering

Matrix-element generators (ALPGEN, MadGraph, etc.) for multi-jet production

Available NLO calculations (MCFM, $t\bar{t}j$, etc.) not yet interfaced for parton showers and hadronization

Work devoted to estimate theoretical systematics: pdfs, underlying event, ISR, FSR, bottom-quark fragmentation

Several generators are now available to describe top quark signals and backgrounds

For any given analysis, using two codes and comparing is always advisable