Monte Carlo Simulations for Top Physics

- Event generation issues
- Extra jets in top production
- Extra jets in top decay
- Spin correlations
- Mass measurement with M_{T2}
- `Global inclusive' observables
- Conclusions

General-purpose event generators

- HERWIG
  - Angular-ordered shower, cluster hadronization
  - v6 Fortran, now Herwig++
- PYTHIA
  - Virtuality/k_T-ordered shower, string hadronization
  - v6 Fortran, v8 C++
- SHERPA
  - Virtuality/dipole shower, cluster hadronization
  - C++ ab initio

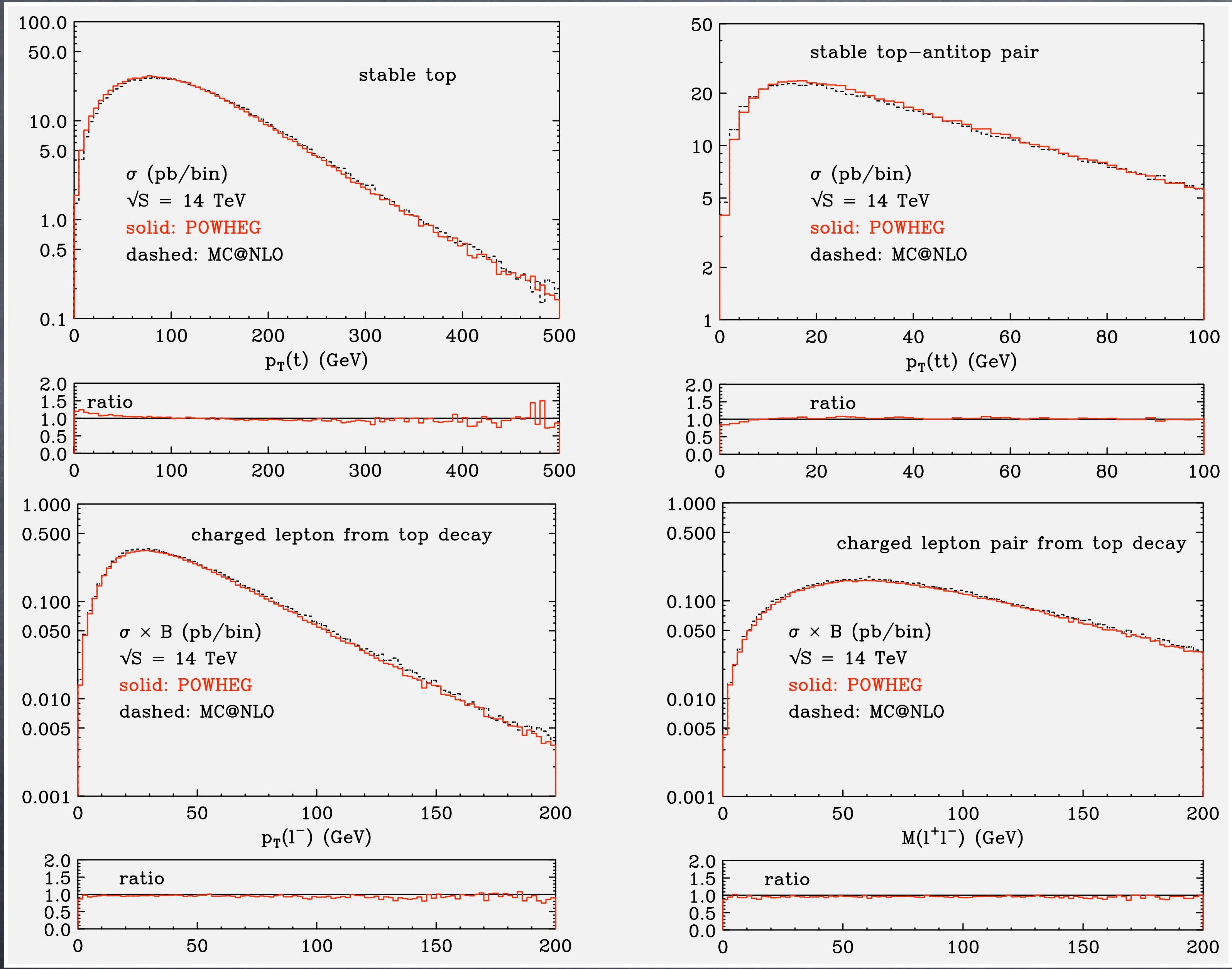
Issues for event generators

- Matrix elements
  - Internal/external generation
  - Spin, widths, off-shell effects
- Parton showers
  - Matching to NLO and/or LO n-jet MEs
  - Coherence, mass and spin effects, 1/N
  - NLO showering?
- Non-perturbative
  - Hadronization, decays
  - PDFs, underlying event, intrinsic p_T

ME-PS matching

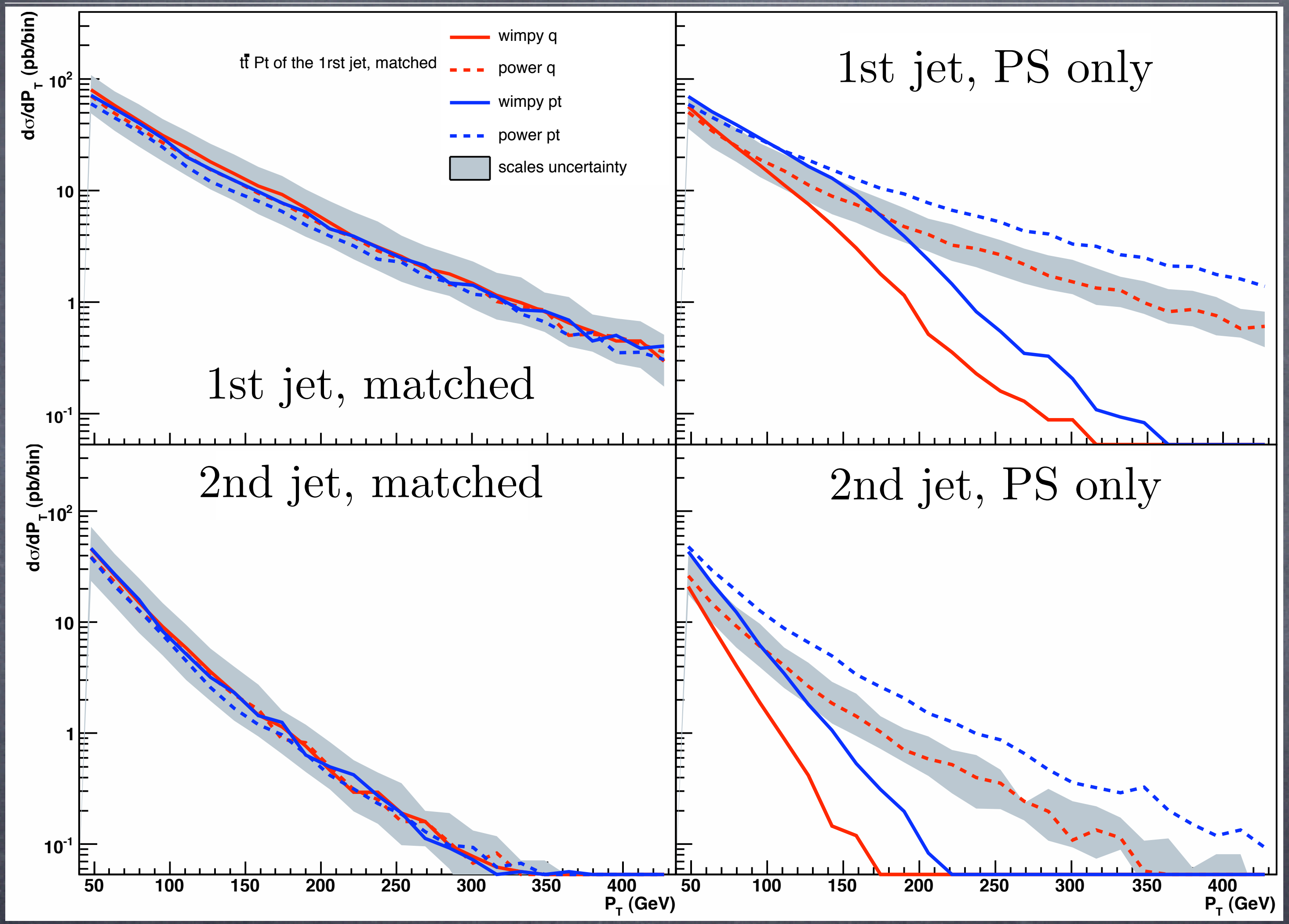
- Two rather different objectives:
- Matching to NLO MEs without double counting
  - MC@NLO
  - POWHEG
- Matching to LO n-jet MEs, minimizing jet resolution dependence
  - CKKW
  - Dipole
  - MLM matching

MC@NLO & POWHEG for $t\bar{t}X$



Frixione, Nason & Ridolfi, 0707.3088

MadEvent+Pythia matching



- Matching removes sensitivity to shower options

Alwall, de Visscher & Maltoni, 0810.5350

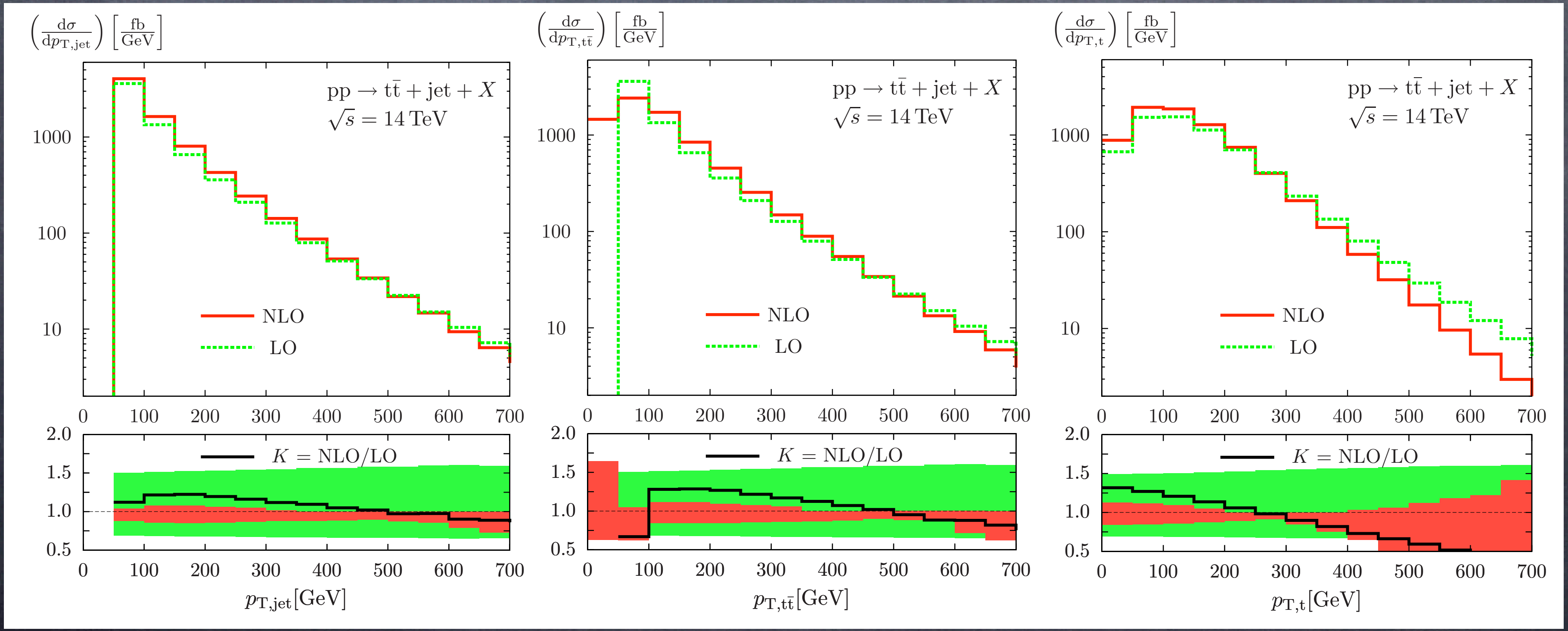
Extra jets in top production

NLO $t\bar{t}$ + jet

Dittmaier, Uwer & Weinzierl, 0810.0452

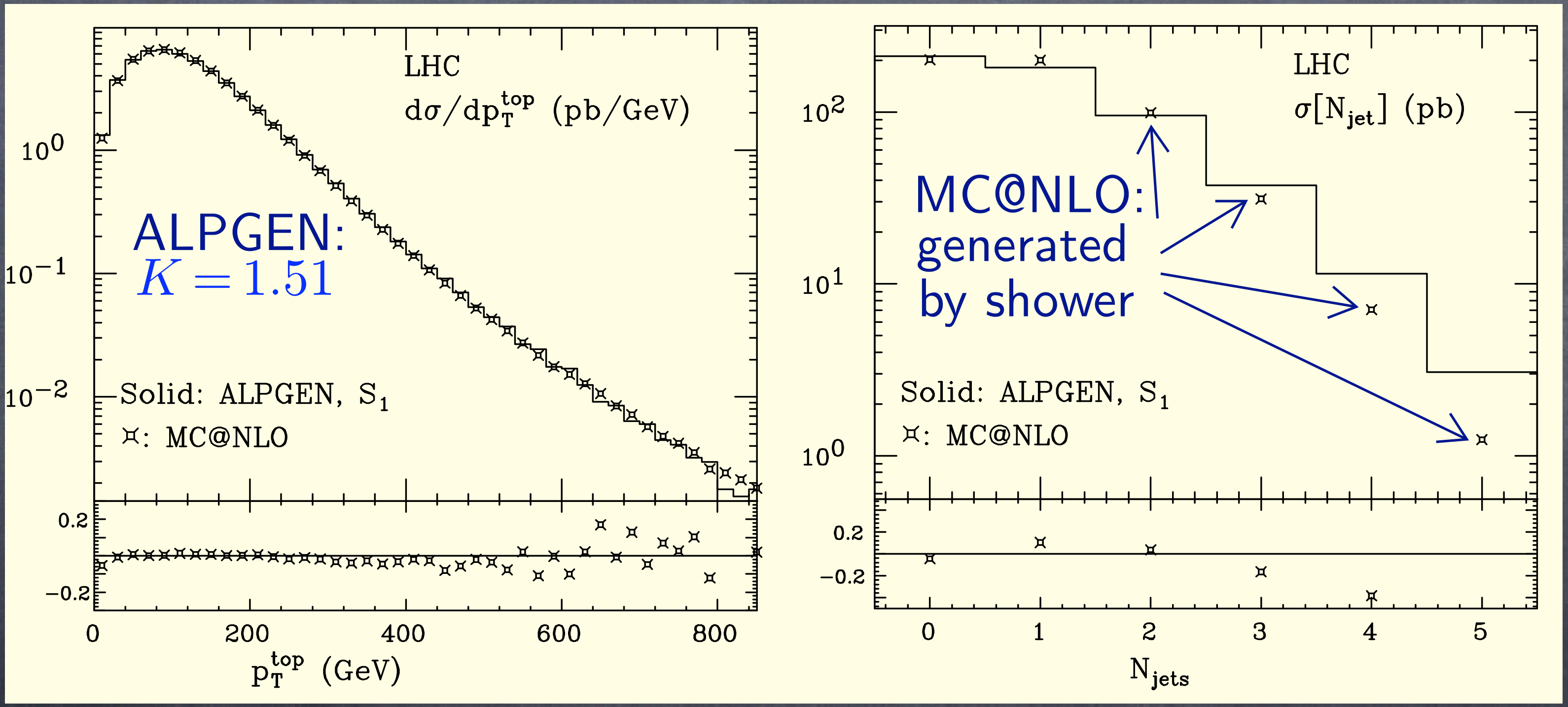
- Most events have jets with p_T > 30 GeV
- Top p_T degraded at NLO

$p_{T,\mathrm{jet,cut}}$ [GeV]	$\sigma_{t\bar{t}\mathrm{jet}}$[pb] LO	$\sigma_{t\bar{t}\mathrm{jet}}$[pb] NLO
20	$710.8(8)^{+358}_{-221}$	$692(3)3^{-40}_{-62}$
50	$326.6(4)^{+168}_{-103}$	$376.2(6)^{+17}_{-48}$
100	$146.7(2)^{+77}_{-47}$	$175.0(2)^{+10}_{-24}$
200	$46.67(6)^{+26}_{-15}$	$52.81(8)^{+0.8}_{-6.7}$



ALPGEN & MC@NLO

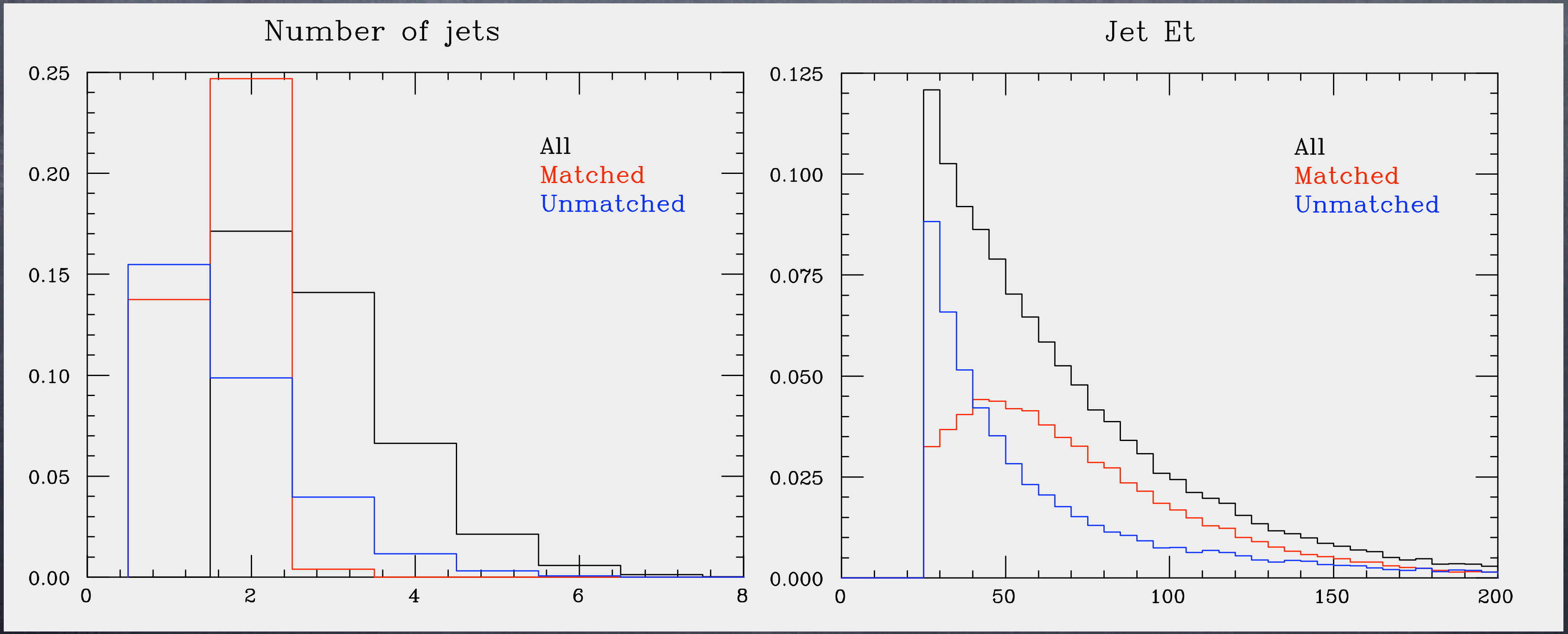
- ALPGEN x K-factor OK for top distributions
- MC@NLO deficit for (extra) N_{jets} > 2



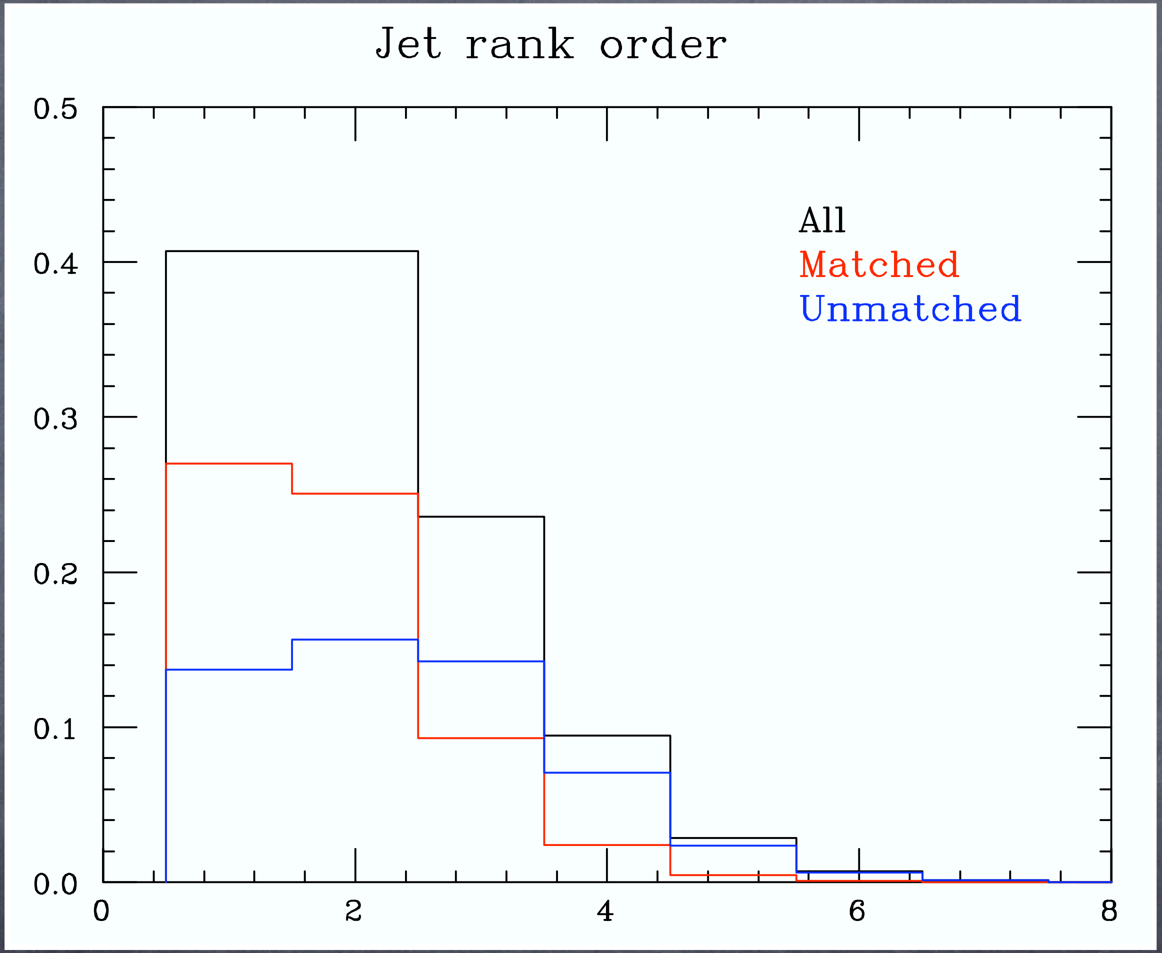
Mangano, Moretti, Piccinini & Treccani, hep-ph/06611129

Jet contamination

- Fully leptonic $t\bar{t}$: 2 jets (+2 leptons + MET)
- Matched = top decay parton within $\Delta R=0.5$ and $\Delta E/E=0.3$
- MC@NLO (no underlying event)



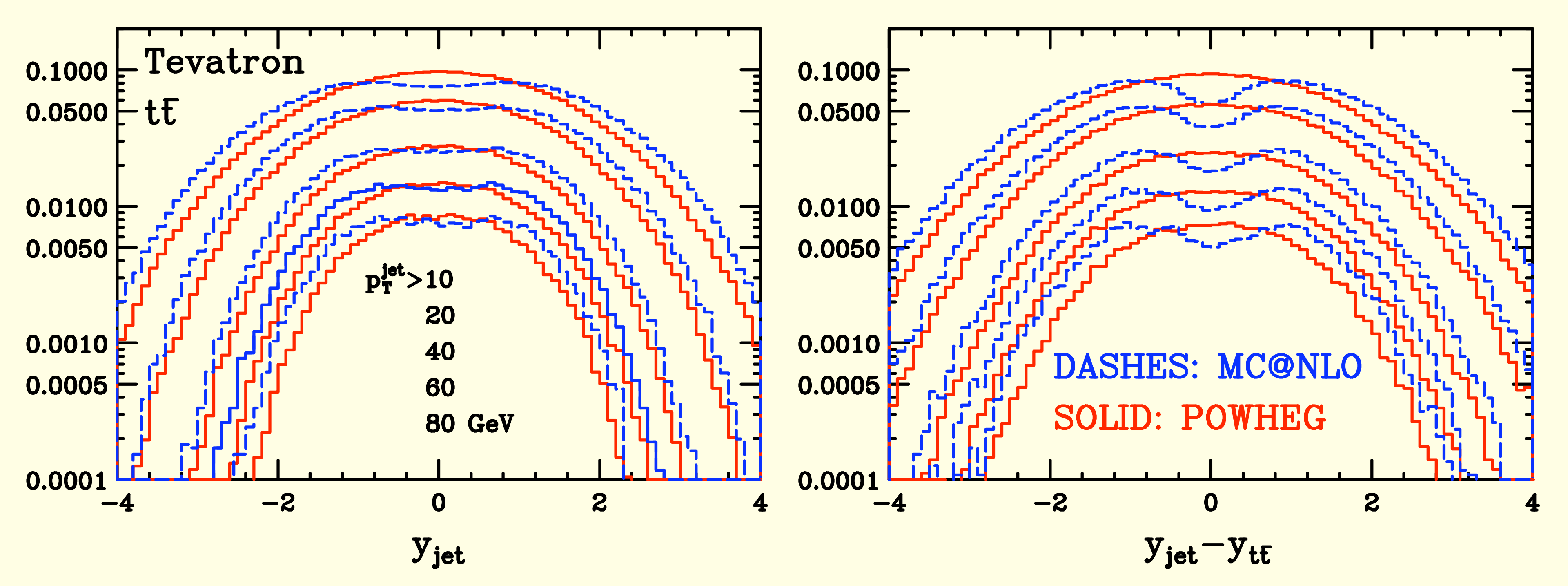
E_T ordering of jets



- P(1 or both leading jets unmatched) > 50%

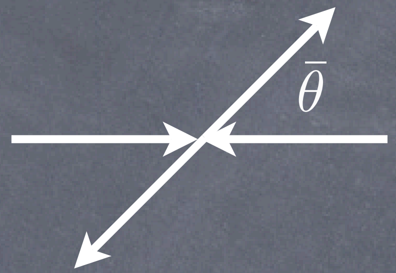
Rapidity of hardest extra jet

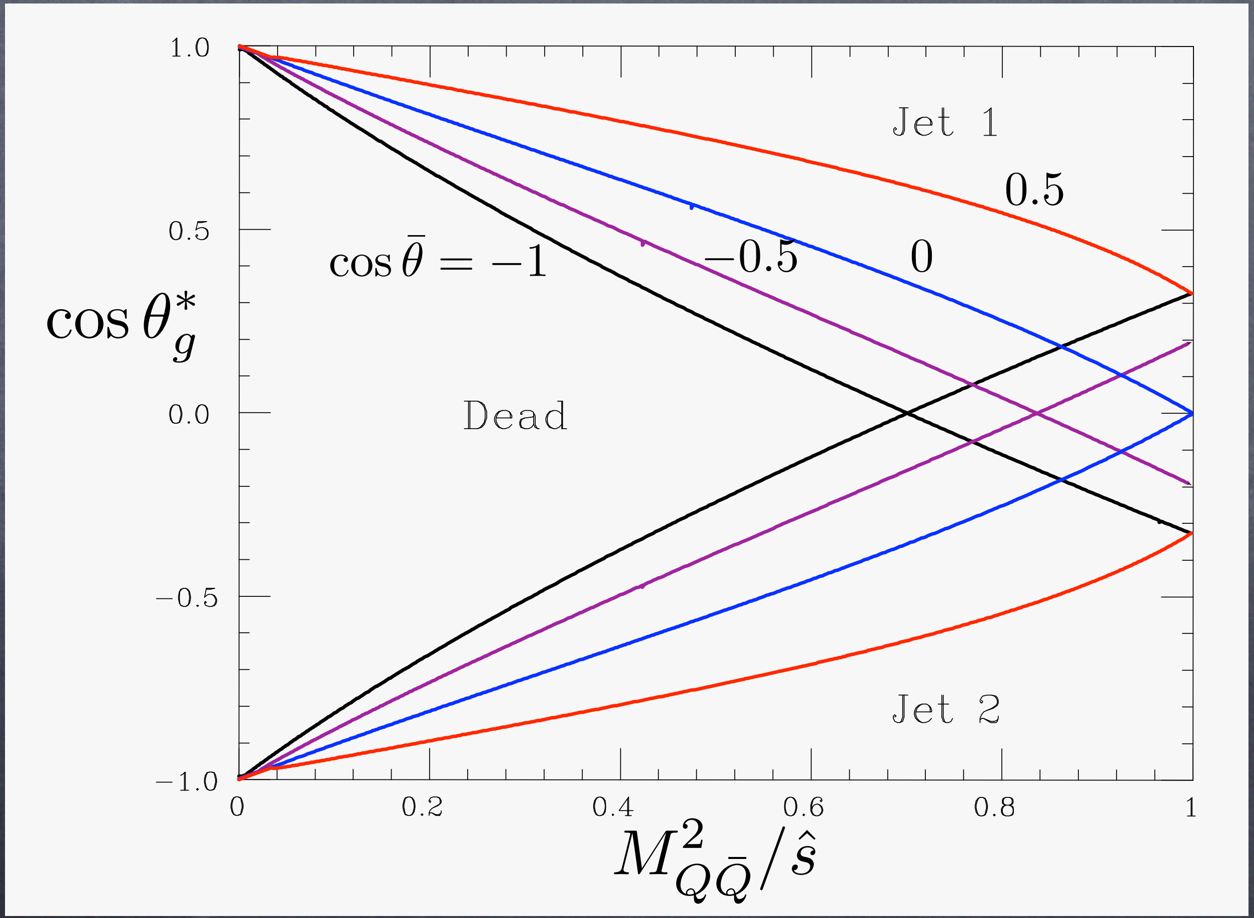
- Hardest non-top jet
- MC@NLO strictly LO in HERWIG 'dead region'



ISR jets in fHERWIG

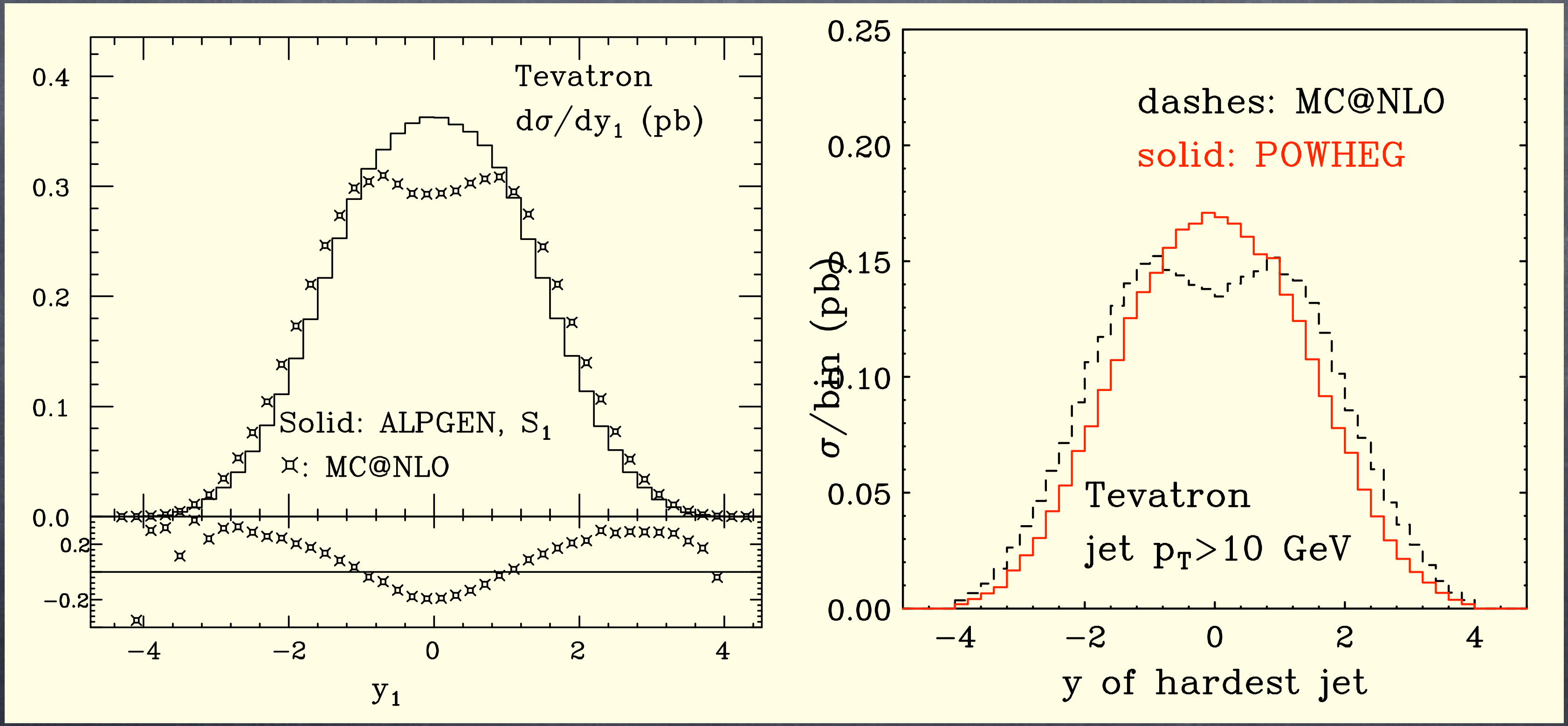
- Angular ordering gives ISR jet cones
- 'Dead' region filled by matrix element



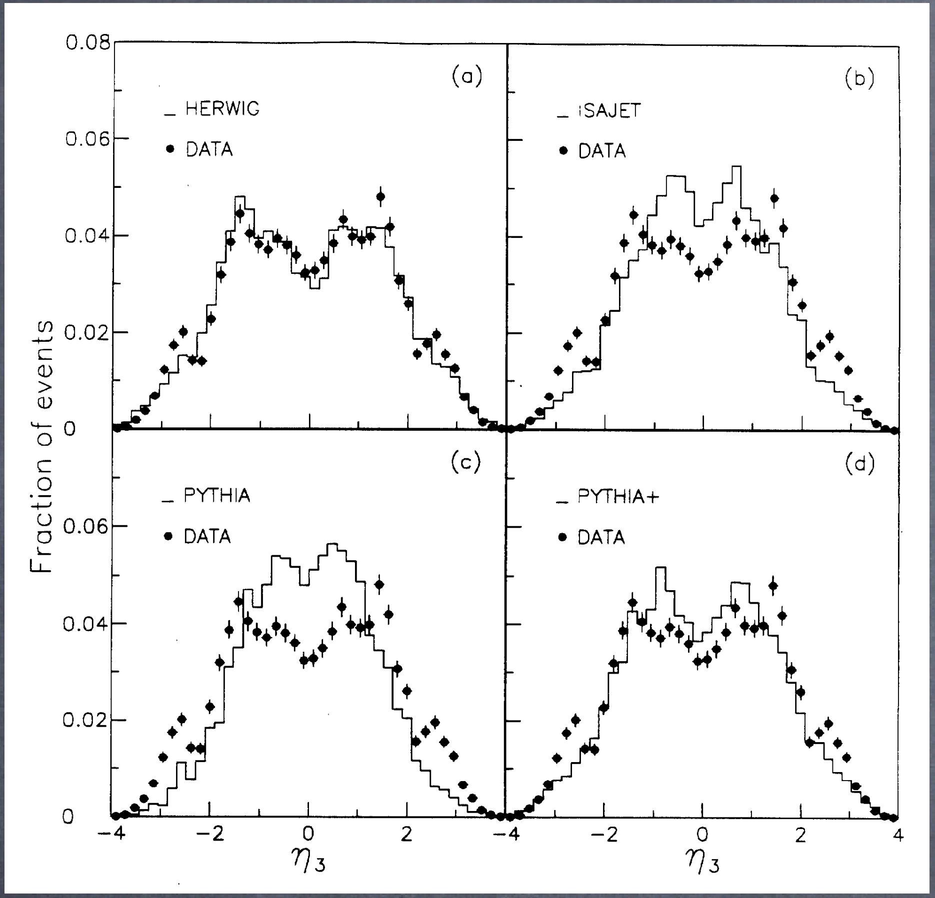


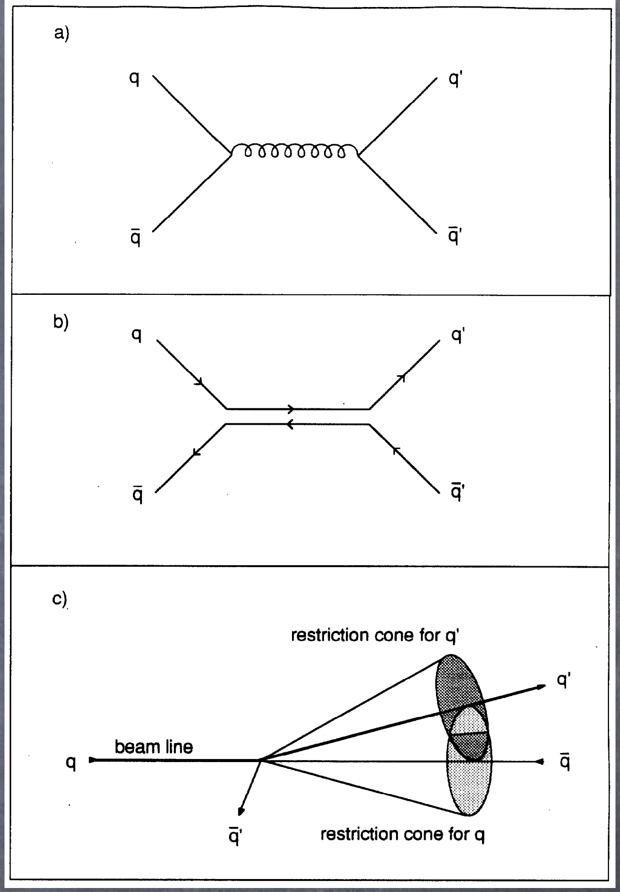
Discrepancies in y_{jet}

- ALPGEN and POWHEG agree
- Is MC@NLO within HO uncertainty?



Third jet rapidity in dijets

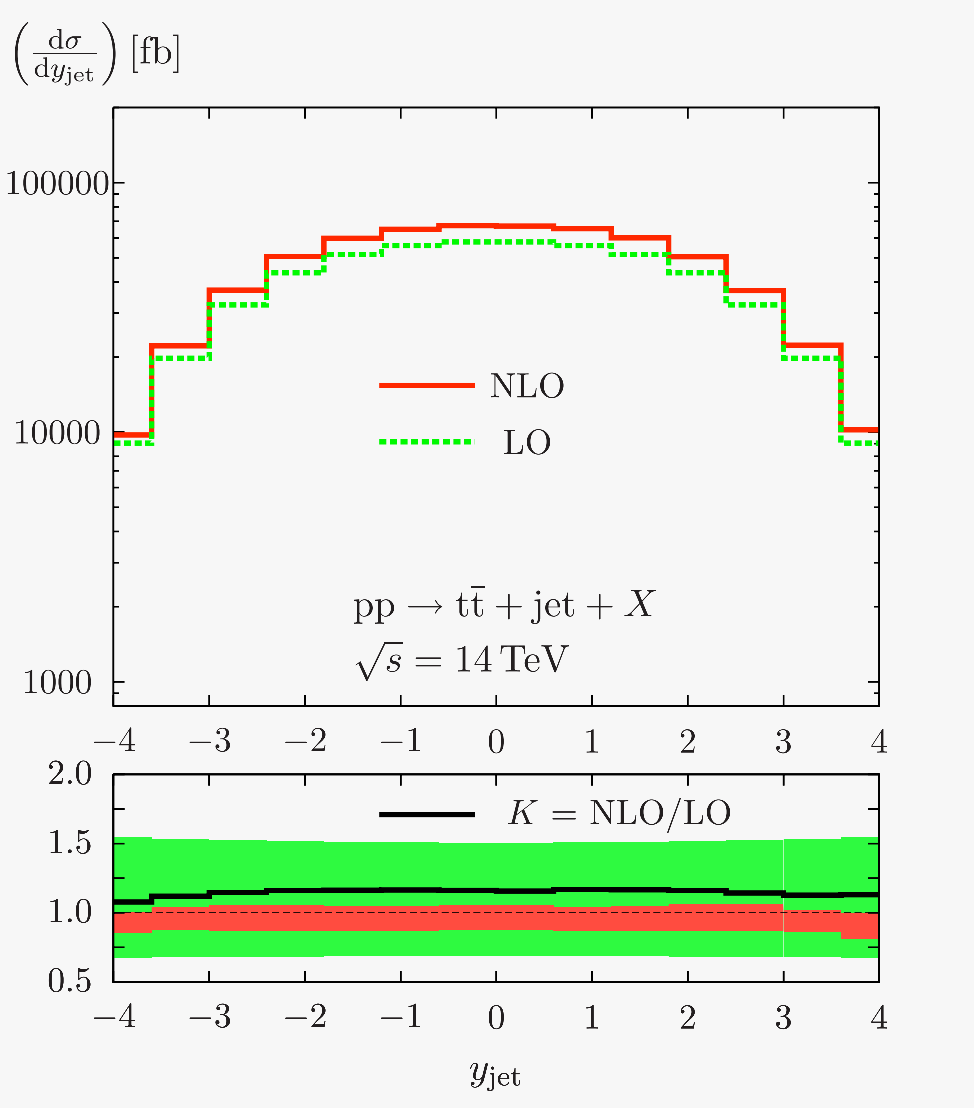




- $E_{T1} > 110$ GeV, $E_{T3} > 10$ GeV
- Colour coherence => central dip!

CDF: Abe et al., PRD 50 (94) 5562

NLO jet rapidity

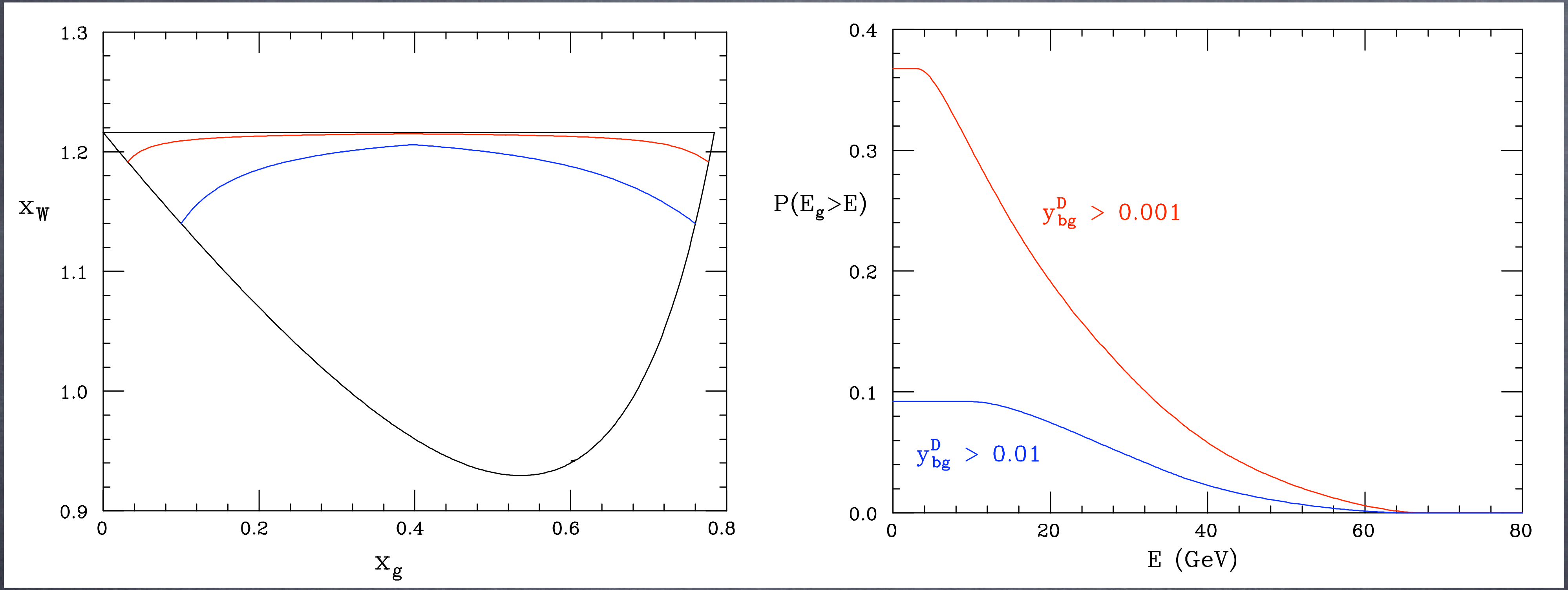


Dittmaier, Uwer & Weinzierl, 0810.0452

- No dip at small y_{jet}
- K = 1.2 at y_{jet} = 0
- MC@NLO lacks K-factor at small y

Extra jets in top decay

$t \to bWg$ matrix element

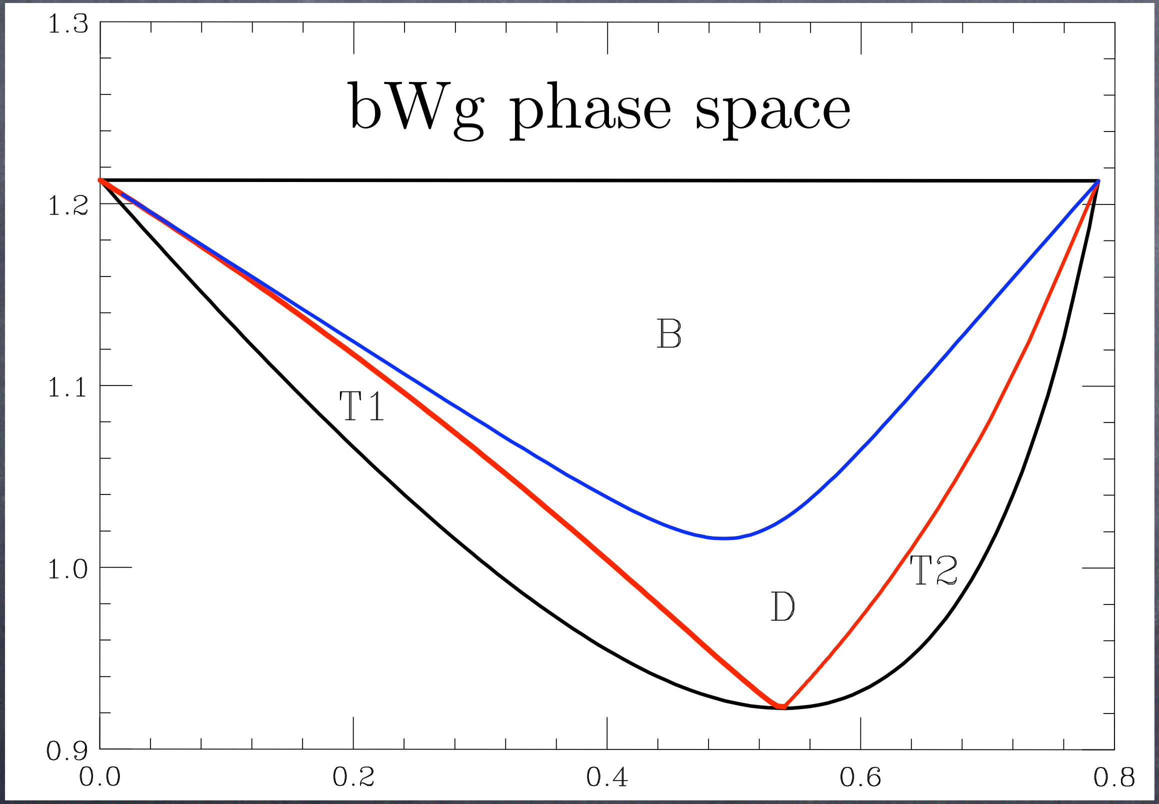


- Cut on Durham y_{bg} in top rest frame:

$$y^D_{bg} = 2\min\{E_b^2, E_g^2\}(1-\cos\theta_{bg})/m_t^2$$

ME+PS in top decay

- Narrow-width approximation ($\Gamma_t \sim 1.4\,\mathrm{GeV}$): production & decay treated separately



x_W

x_g

Herwig++:

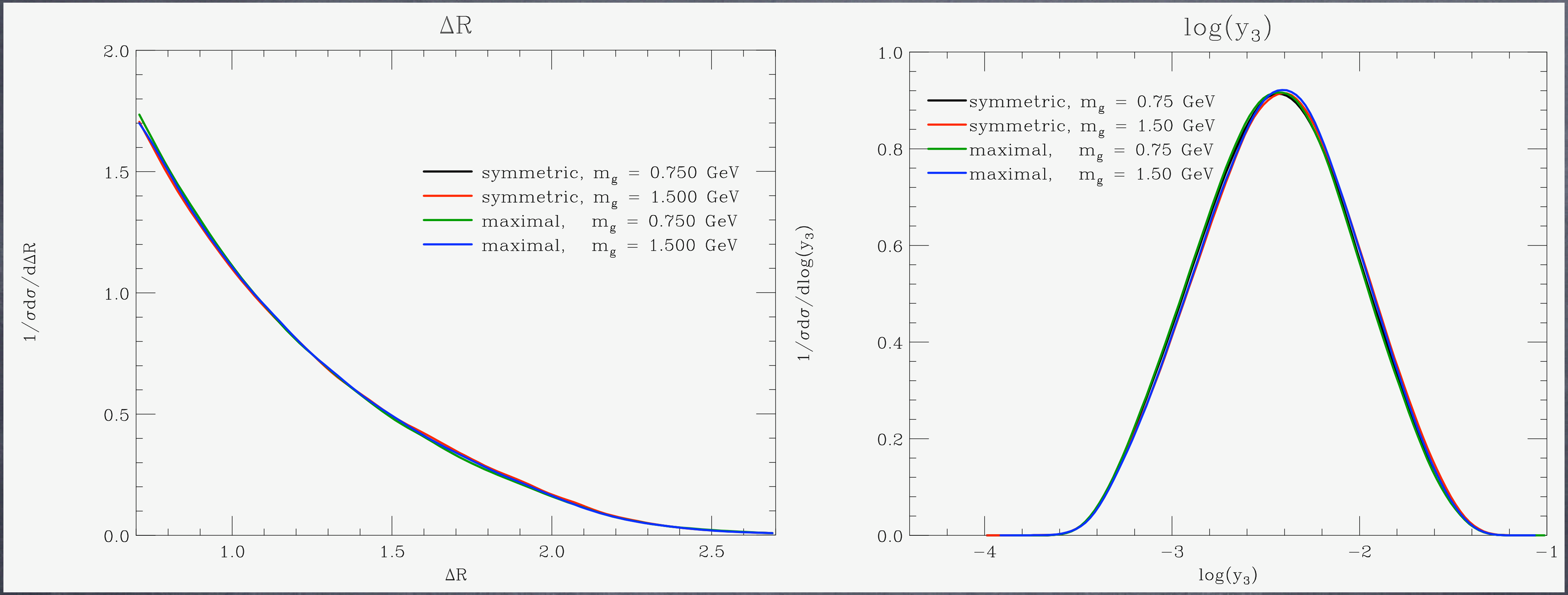
B = b shower

T1,2 = ‘t ISR’

D = ‘dead’ region (filled by M.E.)

Hamilton & Richardson, hep-ph/0612236

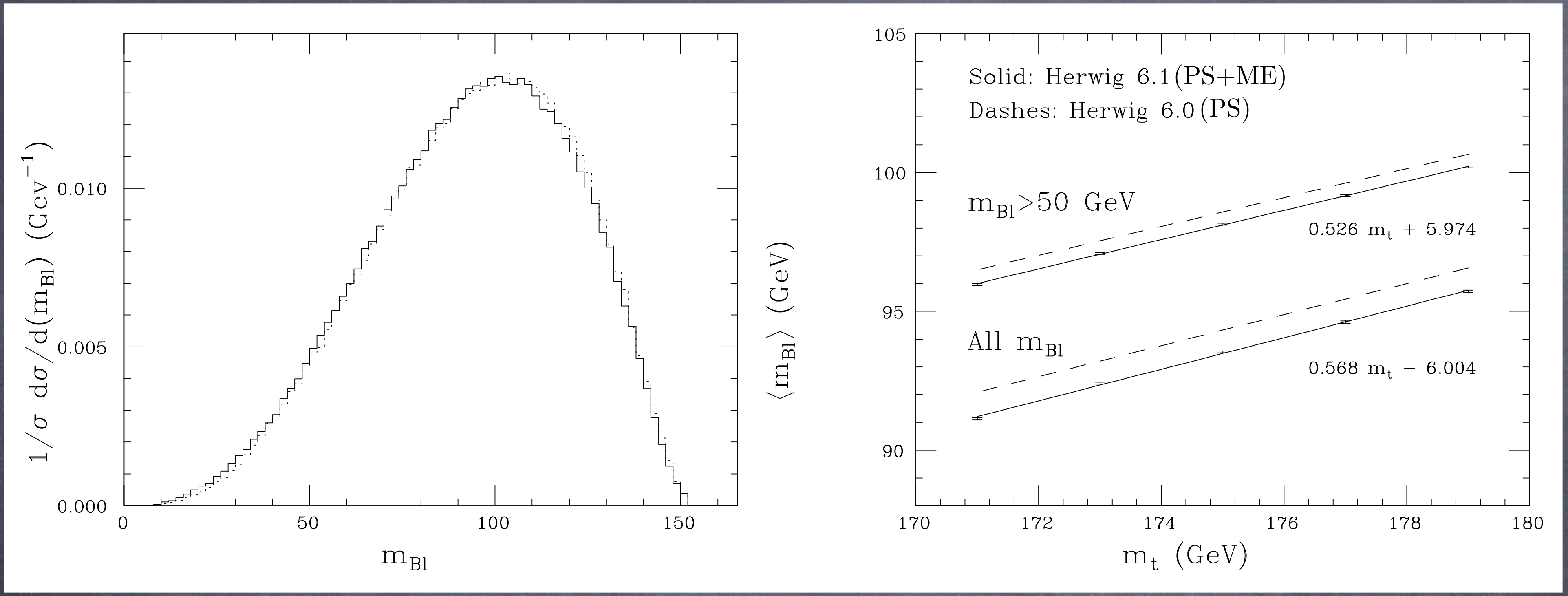
Resolving an extra decay jet



- Herwig++ $e^+e^- \to t\bar{t}$ at 360 GeV
- Stable w.r.t. shower rescaling

Hamilton & Richardson, hep-ph/0612236

m_t from $B(\to J/\psi)\ell$

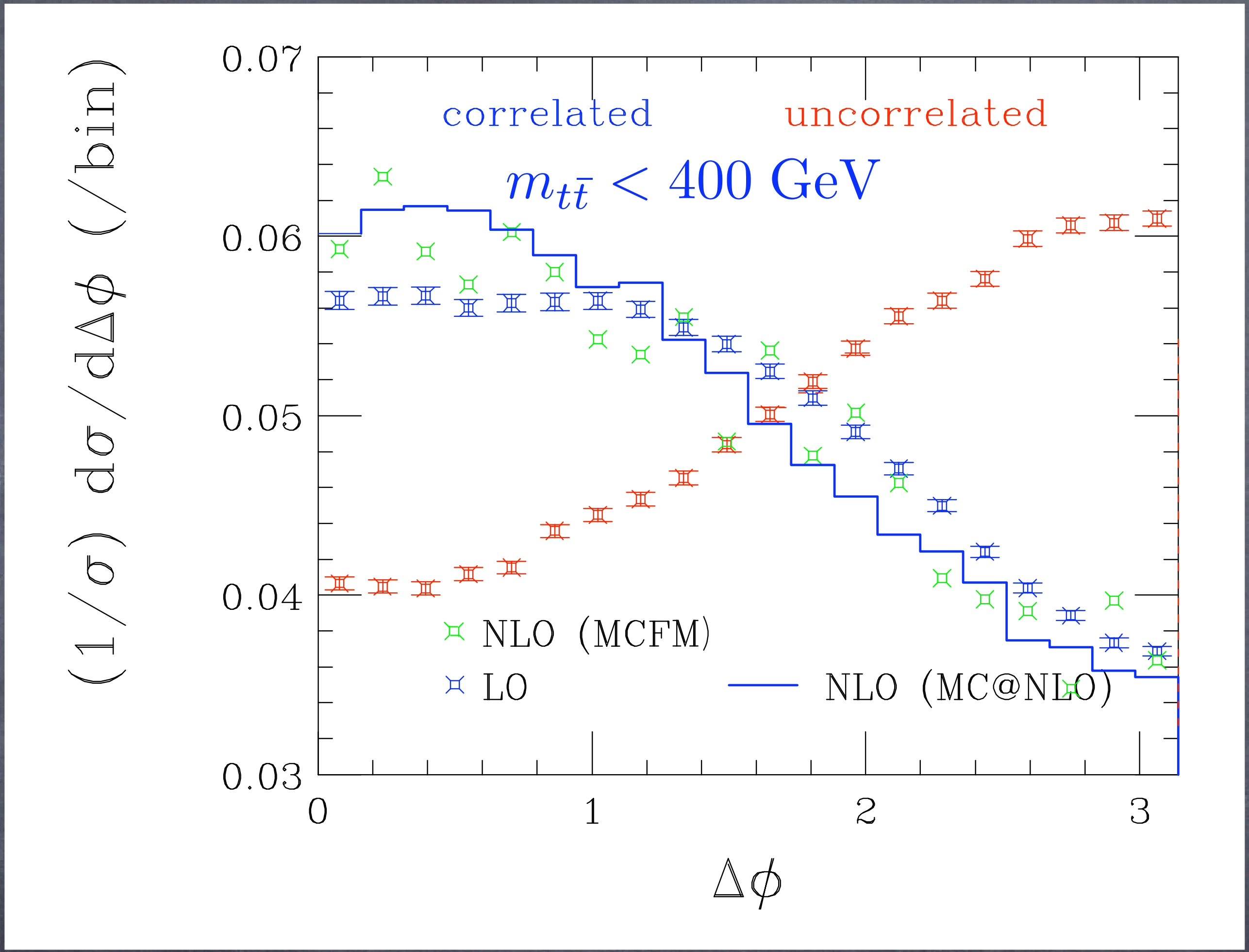


- Effect of hard radiation in decay:
  - $\Delta m_t \sim 1.5$ GeV for all $m_{B\ell}$
  - $\Delta m_t \sim 1$ GeV for $m_{B\ell} > 50$ GeV

Corcella, Mangano & Seymour, hep-ph/0004179

Spin correlations

Dilepton azimuthal correlation



- Strong correlation at low invariant mass!

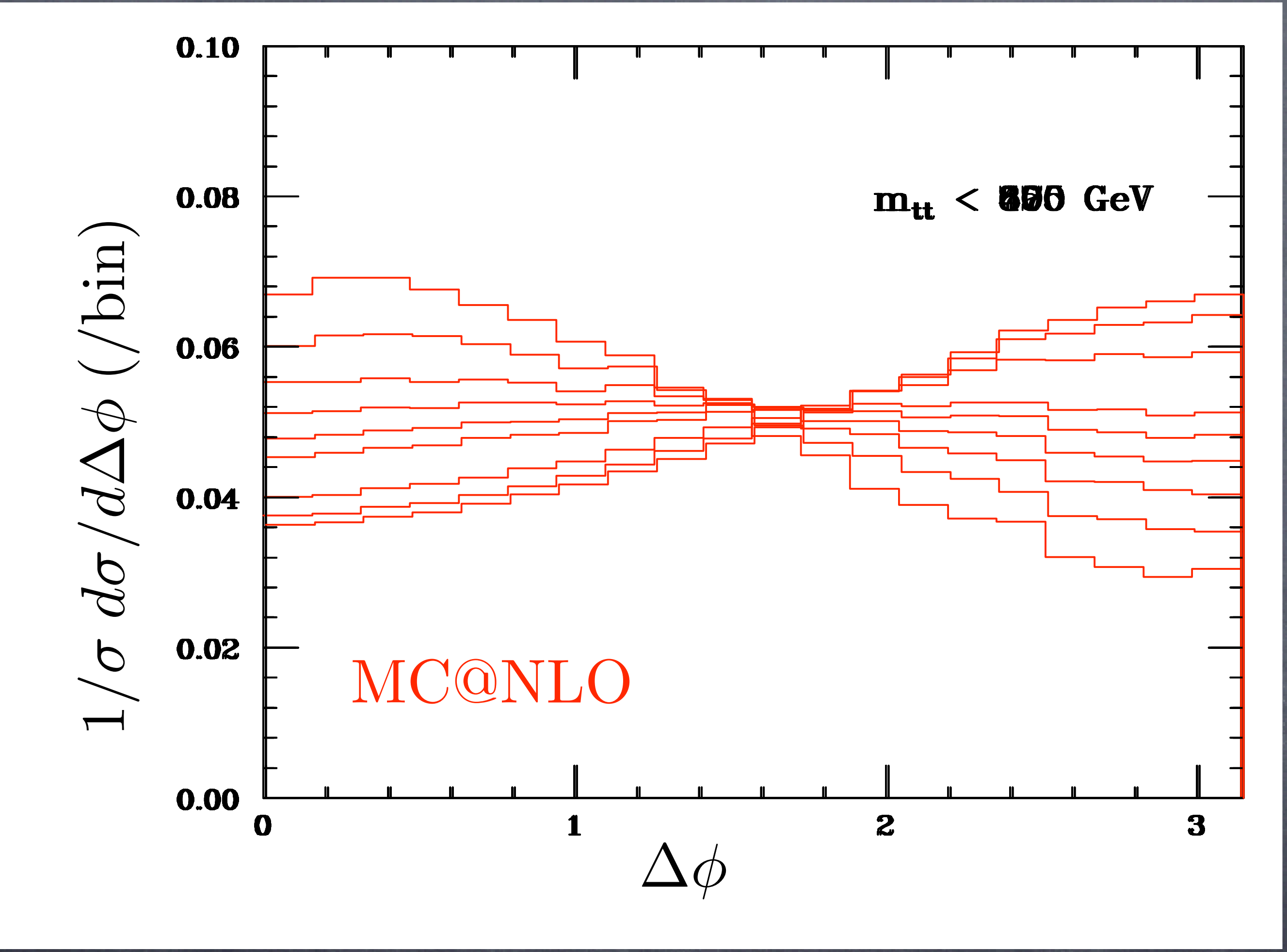
S Parke talk here, 25/05/09

Spin correlations in MC@NLO

- Narrow width approximation
- Exact NLO correlations in hard emission regions
- In soft/collinear regions:
  - NLO factorizable correlations
  - LO non-factorizable correlations
- Parton showers in production
- PS + ME corrections in decays
- High MC efficiency

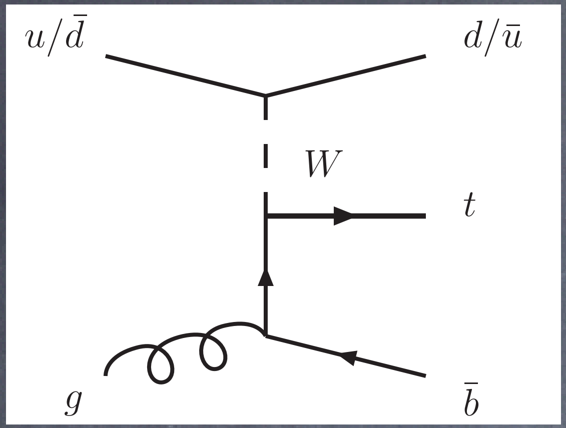
Frixione, Laenen, Motylinski & BW, hep-ph/0702198

Dilepton correlation: m_{tt} dependence

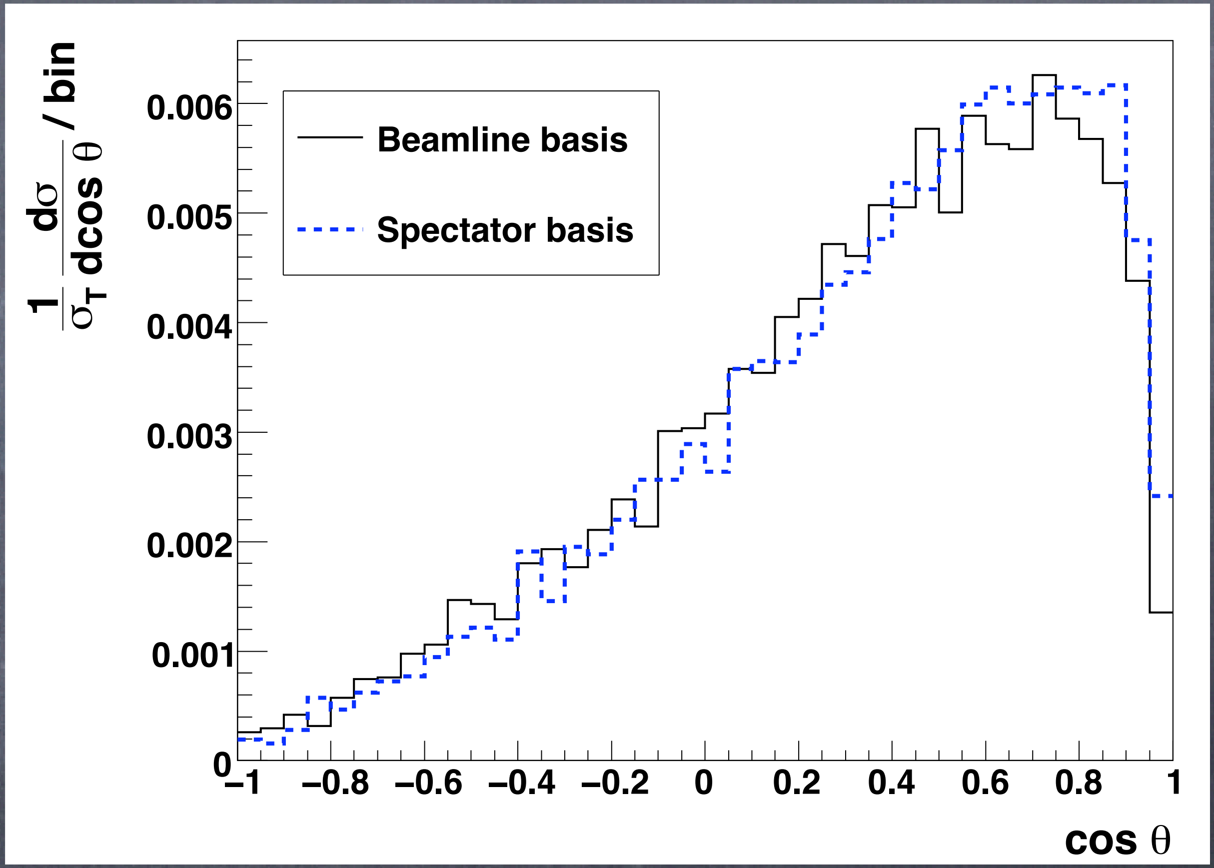


- Correlation lost by m_{tt} < 500 GeV (50% of data)

Correlations in single top



Motylinski, 0905.4754



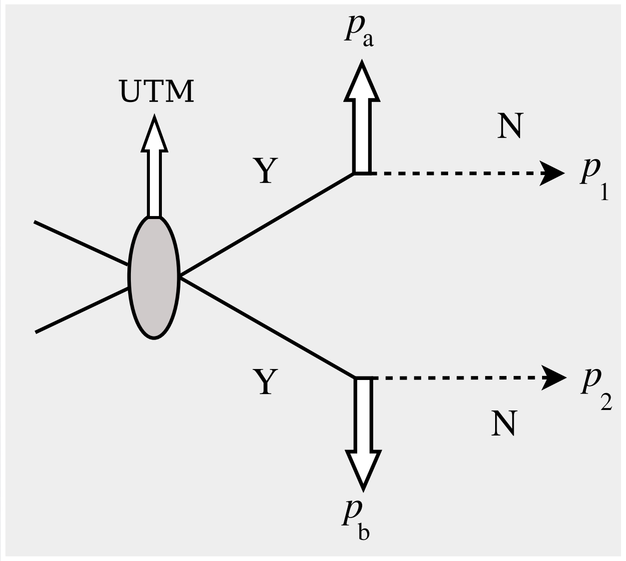
- MC@NLO at LHC
- t-channel process
- hadron-level cuts
- lepton angle in tRF

Mass measurement with M_{T2}

M_{T2} variable

Lester & Summers, hep-ph/9906349

- pp → YYX, Y → aN, Y → bN
- a,b visible, N invisible
- Here Y=t, a,b=(l+jet), N= ν
- Transverse mass:



$$m_T^2(\mathbf{p}_T^1,\, \mathbf{p}_T^a;\, \mu_N) = \mu_N^2 + m_a^2 + 2\left(E_T^1 E_T^a - \mathbf{p}_T^1 \cdot \mathbf{p}_T^a\right)$$

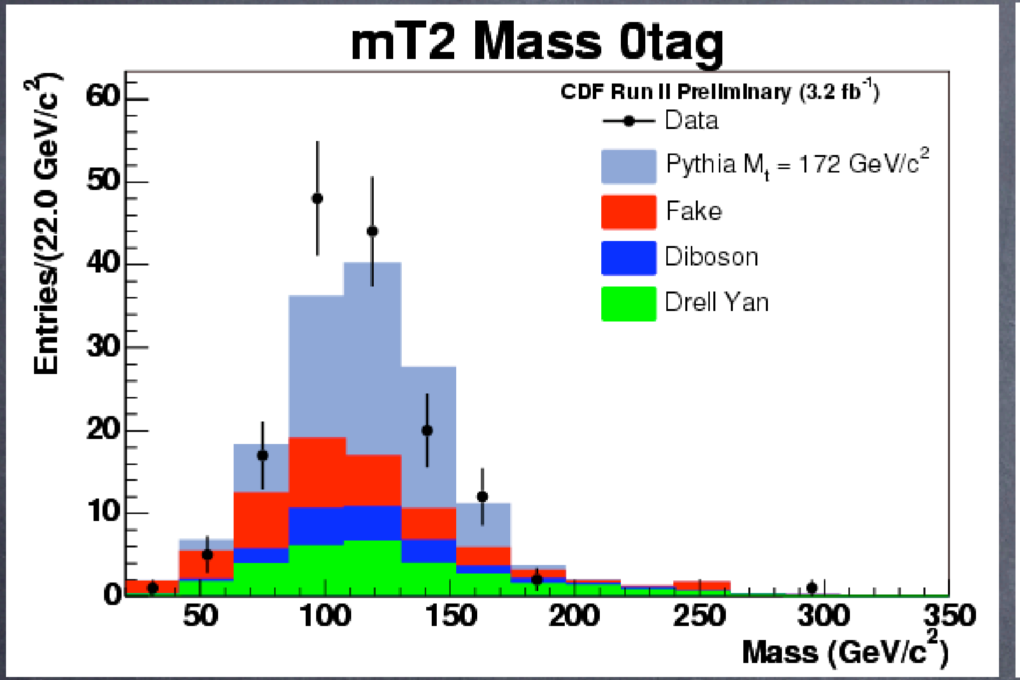
Then

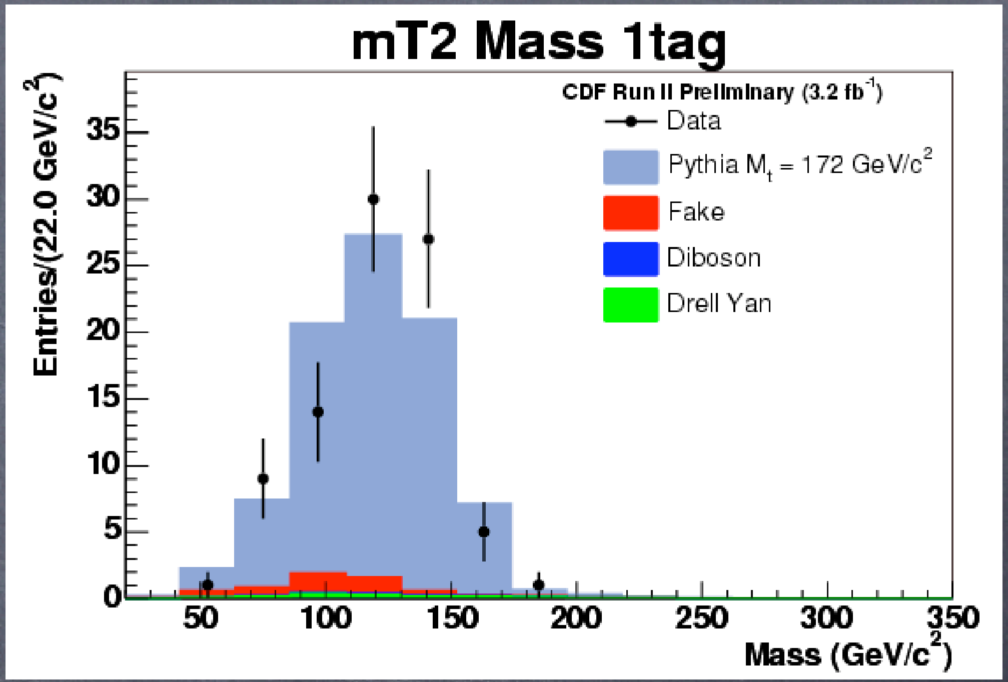
$$m_{T2}^2(\mu_N) \equiv \min_{\mathbf{p}_T^1 + \mathbf{p}_T^2 = \not{\mathbf{p}}_T} \left[\max\{m_T^2(\mathbf{p}_T^1,\, \mathbf{p}_T^a;\, \mu_N),\, m_T^2(\mathbf{p}_T^2,\, \mathbf{p}_T^b;\, \mu_N)\}\right]$$

$\leq m_Y^2$ when $\mu_N = m_N$

CDF top mass from M_{T2}

CDF note 9679

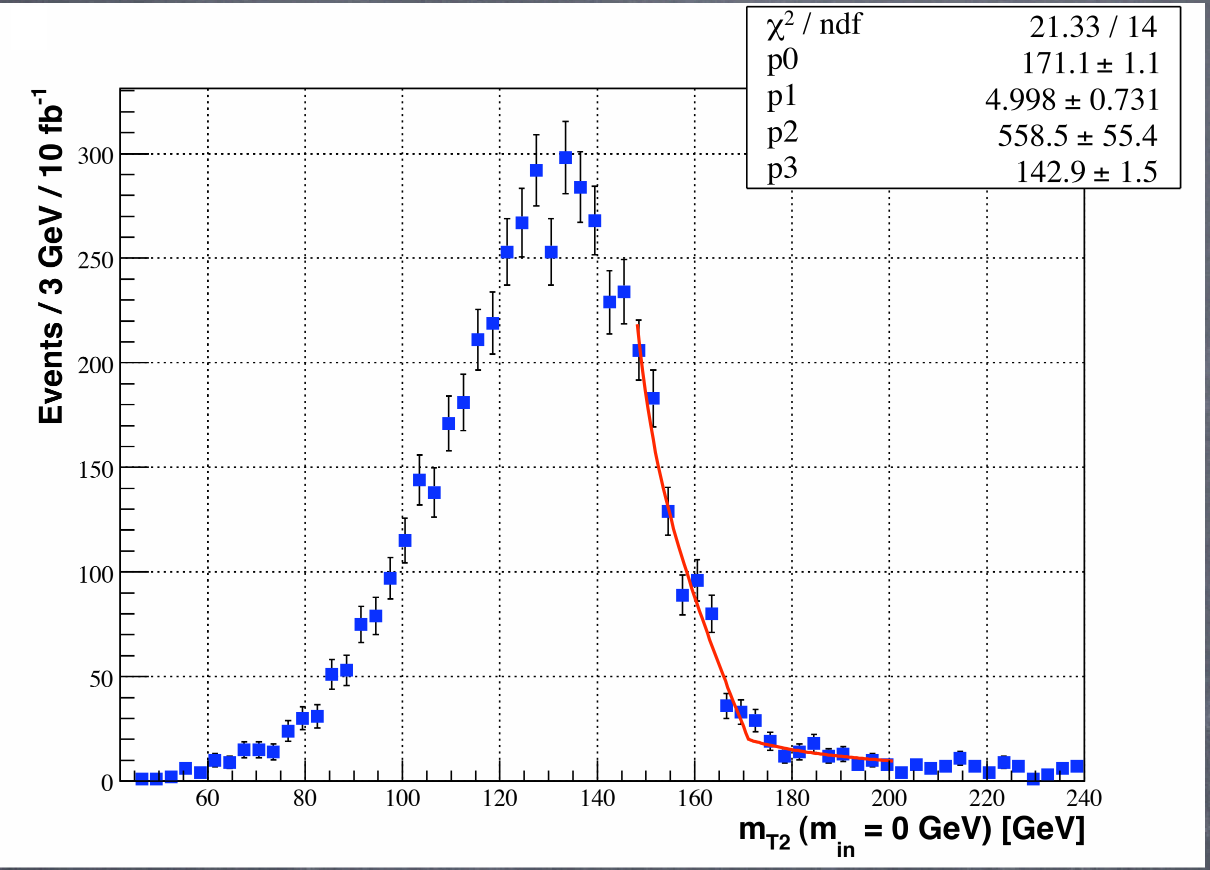




- 3.2 fb^{-1} => m_t = 168.0 +5.6/-5.0 GeV (prelim.)

Top mass from M_{T2} at LHC

Cho, Choi, Kim & Park, 0804.2185



- Input mass 170.9 GeV; PYTHIA+PGS; b-tagging ~50%
- 10 fb^{-1} @ LHC (14 TeV) => m_t = 171.1 +/- 1.1 GeV

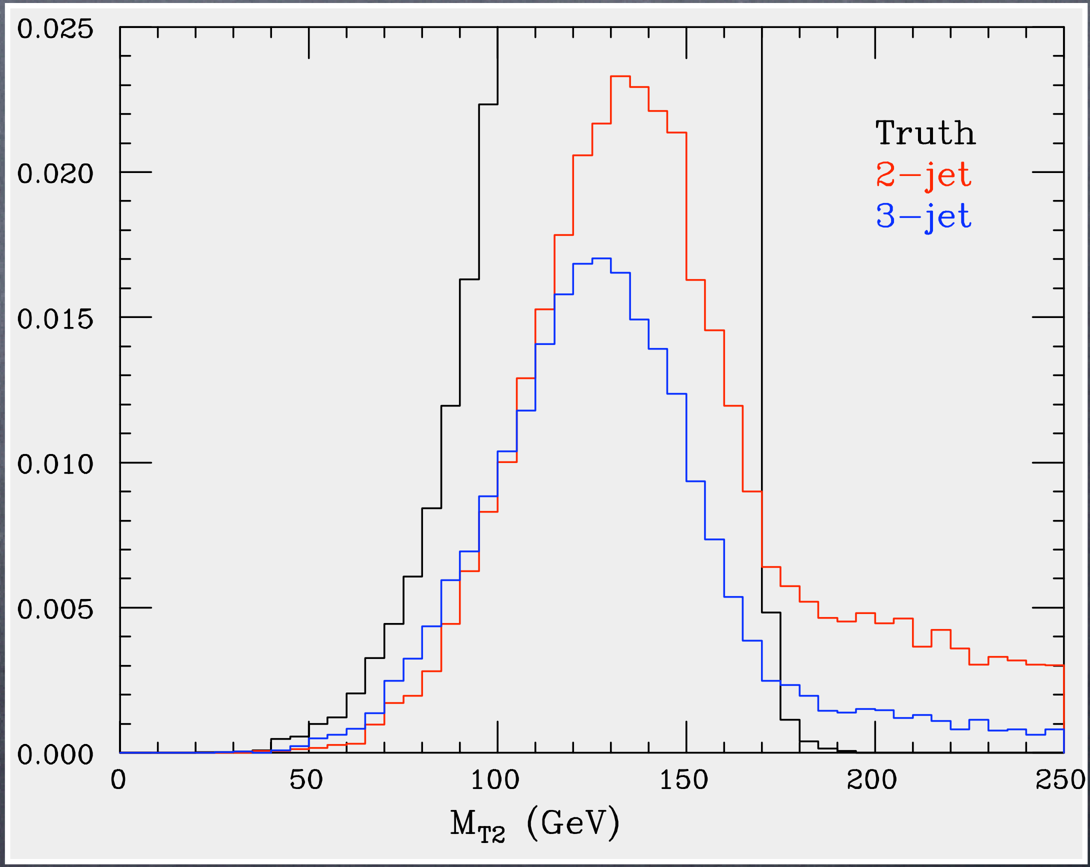
Reducing ISR contamination

Idea: demand more jets, select lowest M_{T2}

As long as one is correct, this cannot raise edge

Alwall, Hiramatsu, Nojiri & Shimizu, 0905.1201

- 7 fb^{-1} MC@NLO, no b-tagging
- > 50% events have extra jets
- Hardest 2 jets (red) => ISR contaminates edge
- Smallest M_{T2} from 3 hardest (blue) => less contamination



Global inclusive observables

Inclusive observables

- How can jets from hard subprocess be distinguished from ISR jets?
- In principle, there is no way! So let's look at "global inclusive" observables
- Consider e.g. the total invariant mass M visible in the detector:

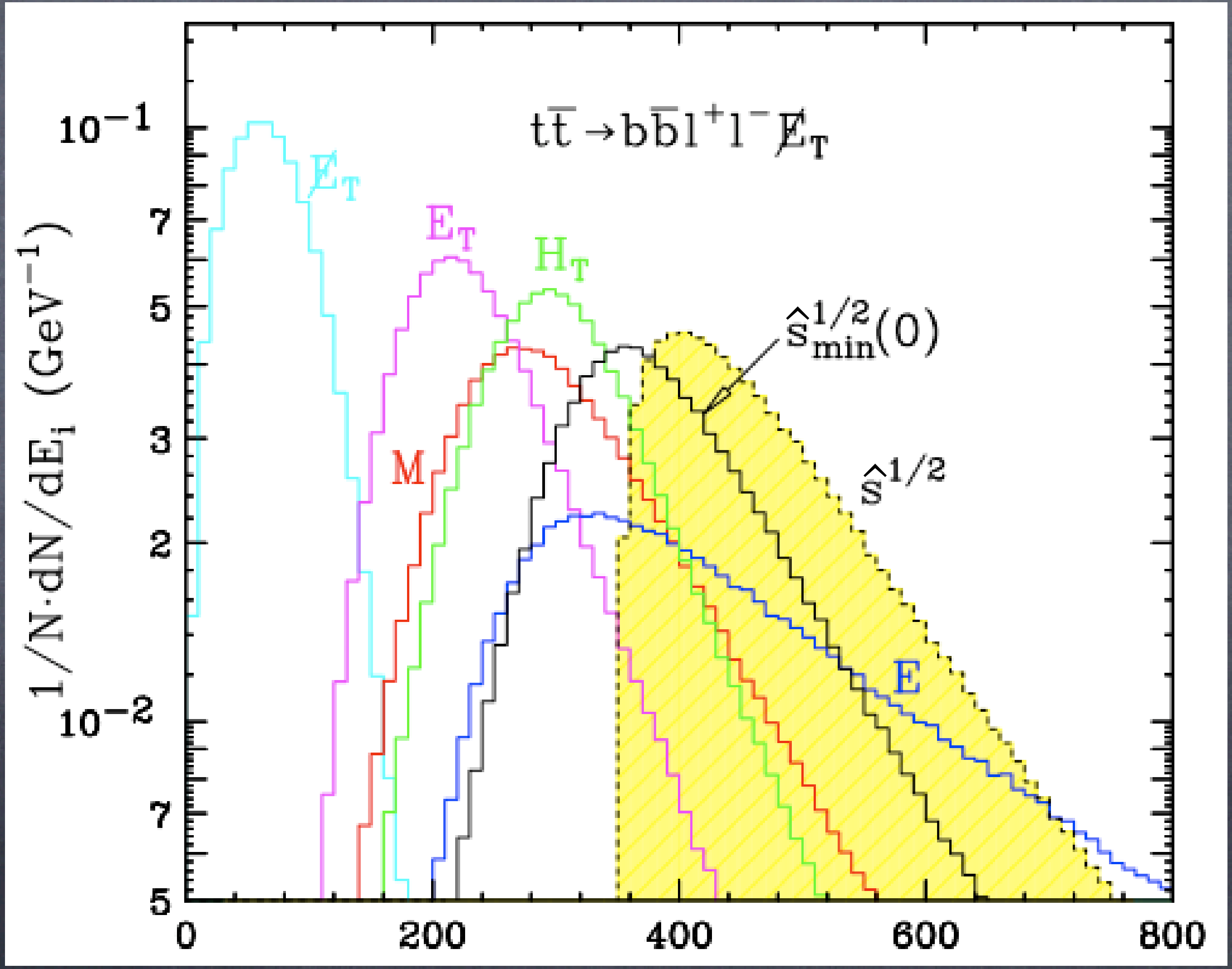
$$M = \sqrt{E^2 - P_z^2 - \not{E}_T^2}$$

or (Konar, Kong & Matchev, 0812.1042)

$$\hat{s}_{\min}^{1/2}(M_{\rm inv}) = \sqrt{M^2 + \not{E}_T^2} + \sqrt{M_{\rm inv}^2 + \not{E}_T^2}$$

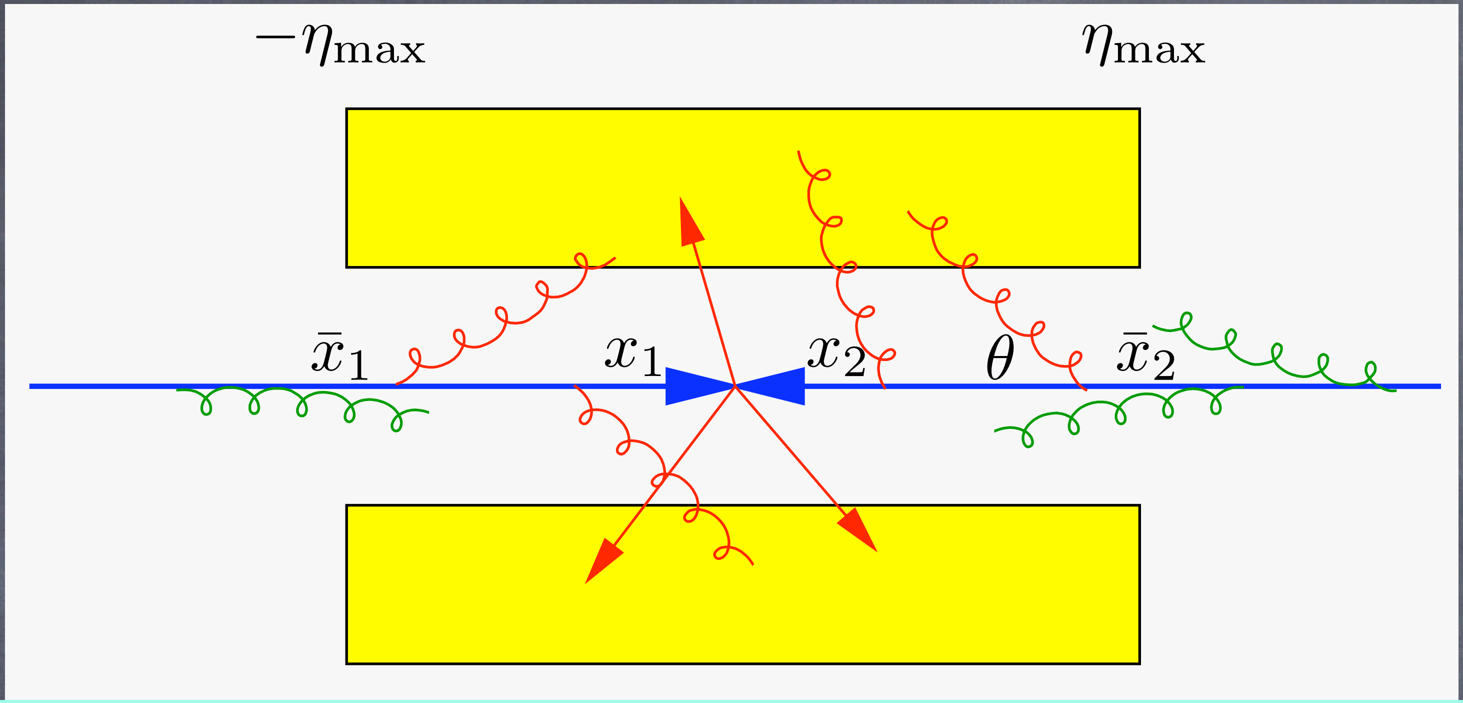
Inclusive observables for $t\bar{t}$

$$H_T = E_T + \not{E}_T \qquad \hat{s}^{1/2}_{\min}(0) = \sqrt{M^2 + \not{E}_T^2} + \not{E}_T$$



Konar, Kong & Matchev, 0812.1042

ISR effects on inclusive observables



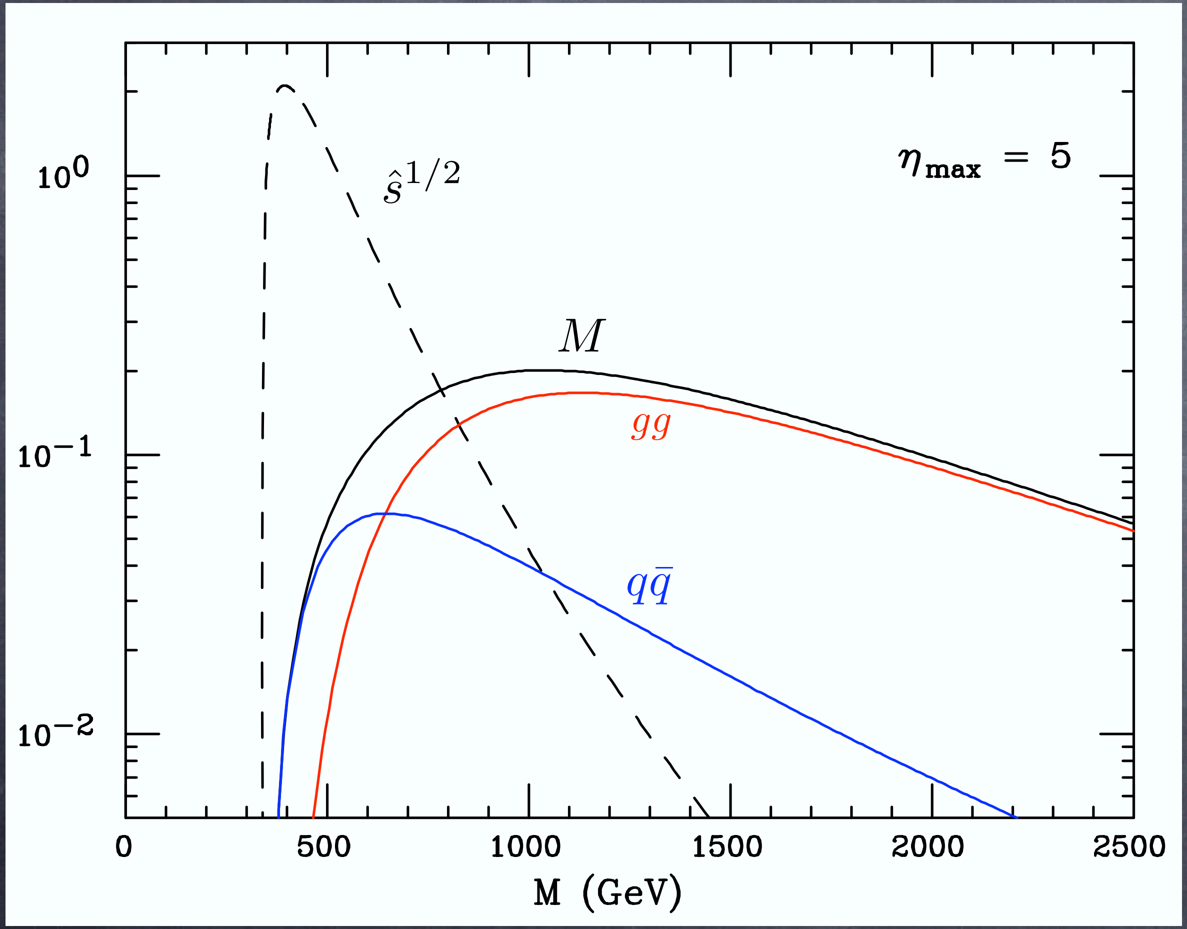
$$\frac{d\sigma}{dM^2} = \int \frac{d\bar{x}_1}{\bar{x}_1}\frac{d\bar{x}_2}{\bar{x}_2} dx_1\, dx_2 f(\bar{x}_1, Q_c) f(\bar{x}_2, Q_c) K\left(\frac{x_1}{\bar{x}_1}; Q_c, Q\right) K\left(\frac{x_2}{\bar{x}_2}; Q_c, Q\right) \hat{\sigma}(x_1 x_2 S)\delta(M^2 - \bar{x}_1\bar{x}_2 S)$$

- ISR at $\theta > \theta_c \sim \exp(-\eta_{\max})$ enters detector
- Hard scale $Q^2 \sim \hat{s} = x_1 x_2 S$ but $M^2 = \bar{x}_1 \bar{x}_2 S$
- PDFs sampled at $Q_c \sim \theta_c Q$

Papaefstathiou & BW, 0903.2013

ISR evolution kernel

$$K(x/\bar{x};Q_c,Q) = \int_{-i\infty}^{+i\infty} dN\,(\bar{x}/x)^N K_N(Q_c,Q)$$



$$K_N(Q_c,Q) = \left[\frac{\alpha_S(Q_c)}{\alpha_S(Q)}\right]^{\Gamma_N/\beta_0}$$

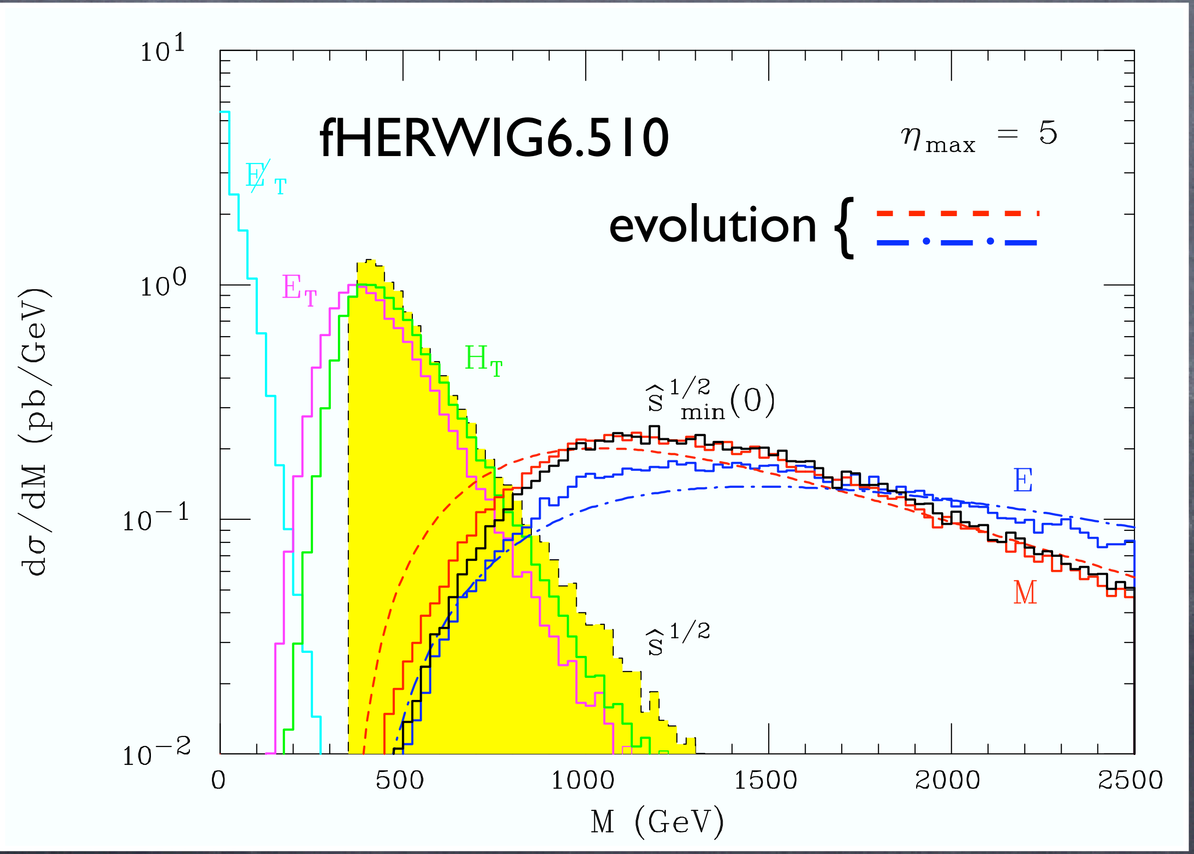
$$(\Gamma_N)_{ab} = \int_0^1 dz\, z^{N-1} P_{ab}(z)$$

- $pp \to t\bar{t}X$ @ LHC (14 TeV)
- gg dominant
- $q\bar{q}$ shifted less

ISR effects: MC results

$$\hat{s}^{1/2}_{\rm min}(M_{\rm inv}) = \sqrt{M^2 + \not{E}_T^2} + \sqrt{M^2_{\rm inv} + \not{E}_T^2}$$

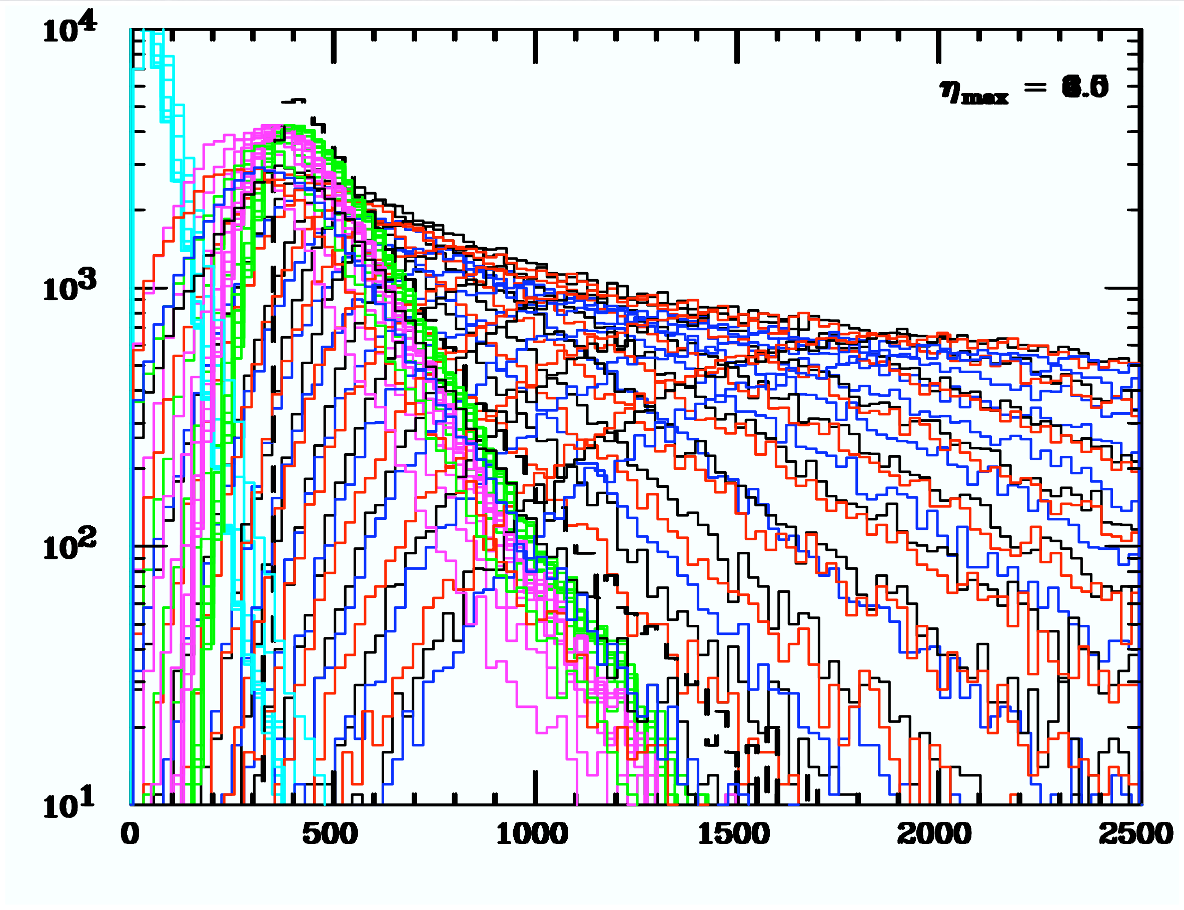
$$M = \sqrt{E^2 - P_z^2 - \not{E}_T^2} \qquad H_T = E_T + \not{E}_T$$



Papaefstathiou & BW, 0903.2013

Dependence on $\eta_{\max}$

E, M, $\hat{s}_{min}$ strongly dependent; $\not{E}_T$, E_T, H_T not



Conclusions

- Many sophisticated simulation tools available
  - ME, PS, matching, merging
- Important to take account of extra jets
  - ISR, decay, interference?
- Spin correlations are significant
  - Sensitive to new physics
- Testing ground for new physics searches
  - M_{T2}, global inclusive observables, ...