QCD Radiative Effects in New Particle Searches

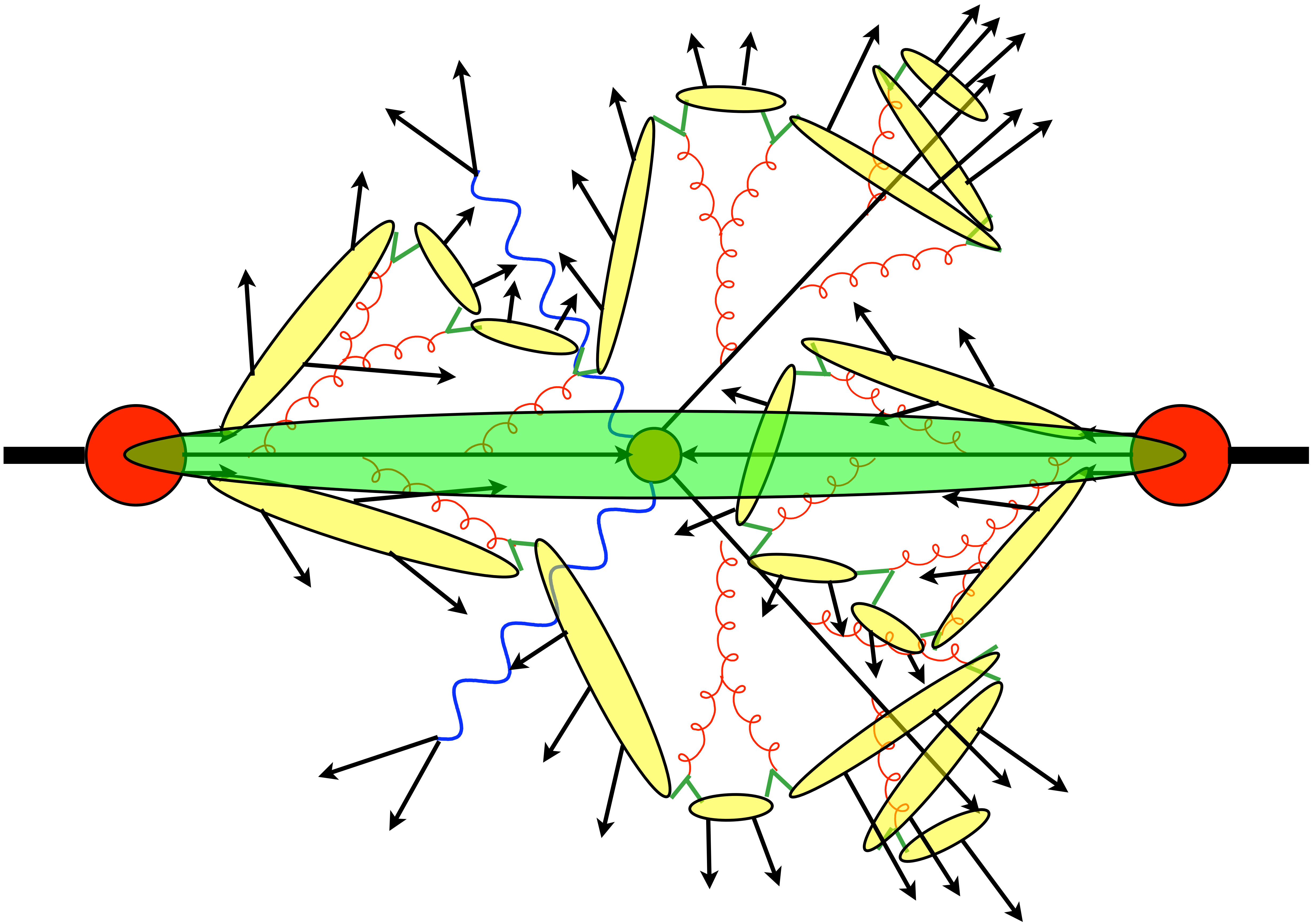
Bryan Webber

UNIVERSITY OF CAMBRIDGE 800 YEARS 1209 ~ 2009

Outline

- Calculating QCD radiative effects
  - Fixed order
  - Resummation
  - Parton shower Monte Carlo
  - Matching fixed orders to parton showers
- Dealing with QCD initial-state radiation
  - Global inclusive observables
  - Mass determination with M_{T2}
  - Mass determination with $M_{CT\perp}$
- Conclusions

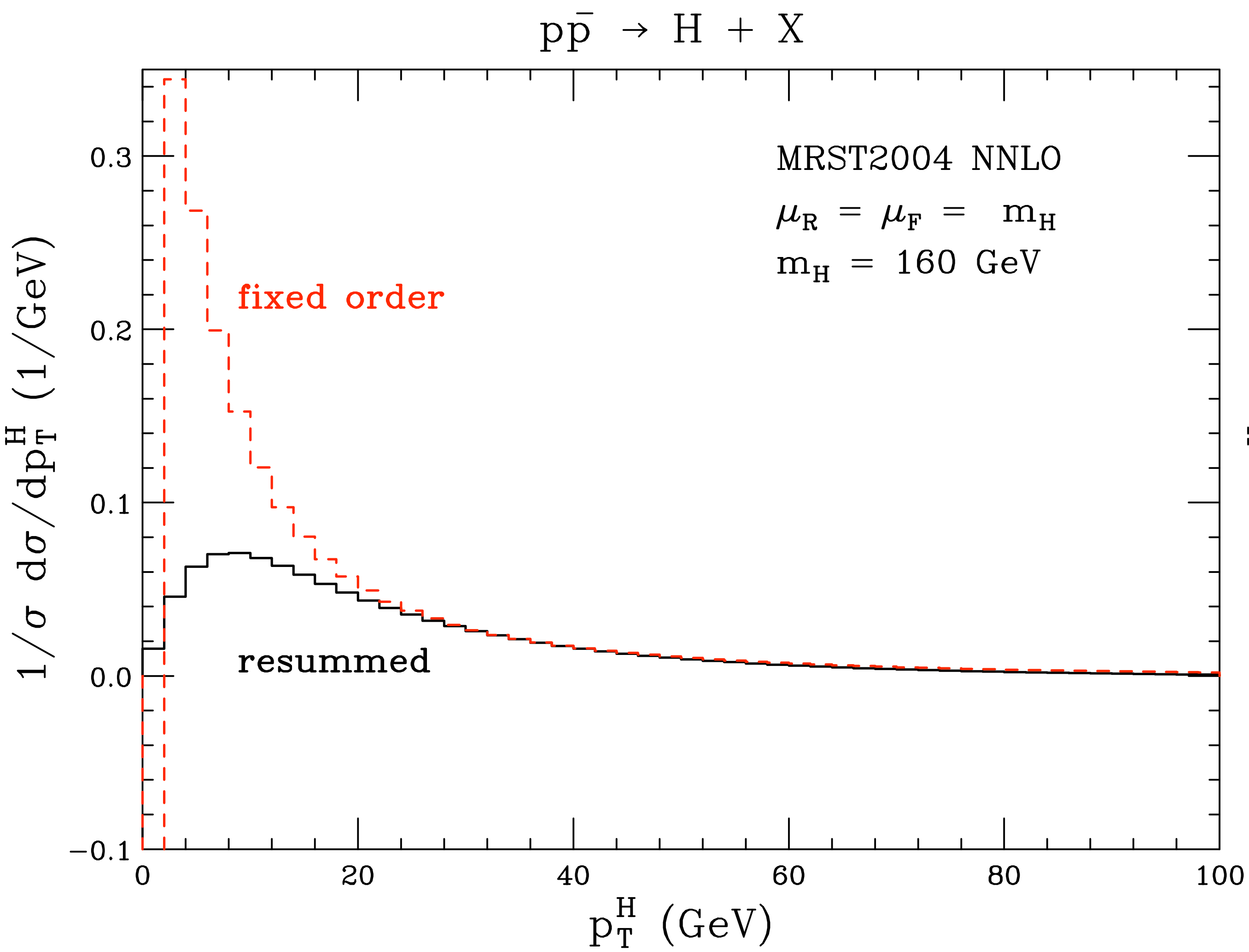
Collider Event Structure

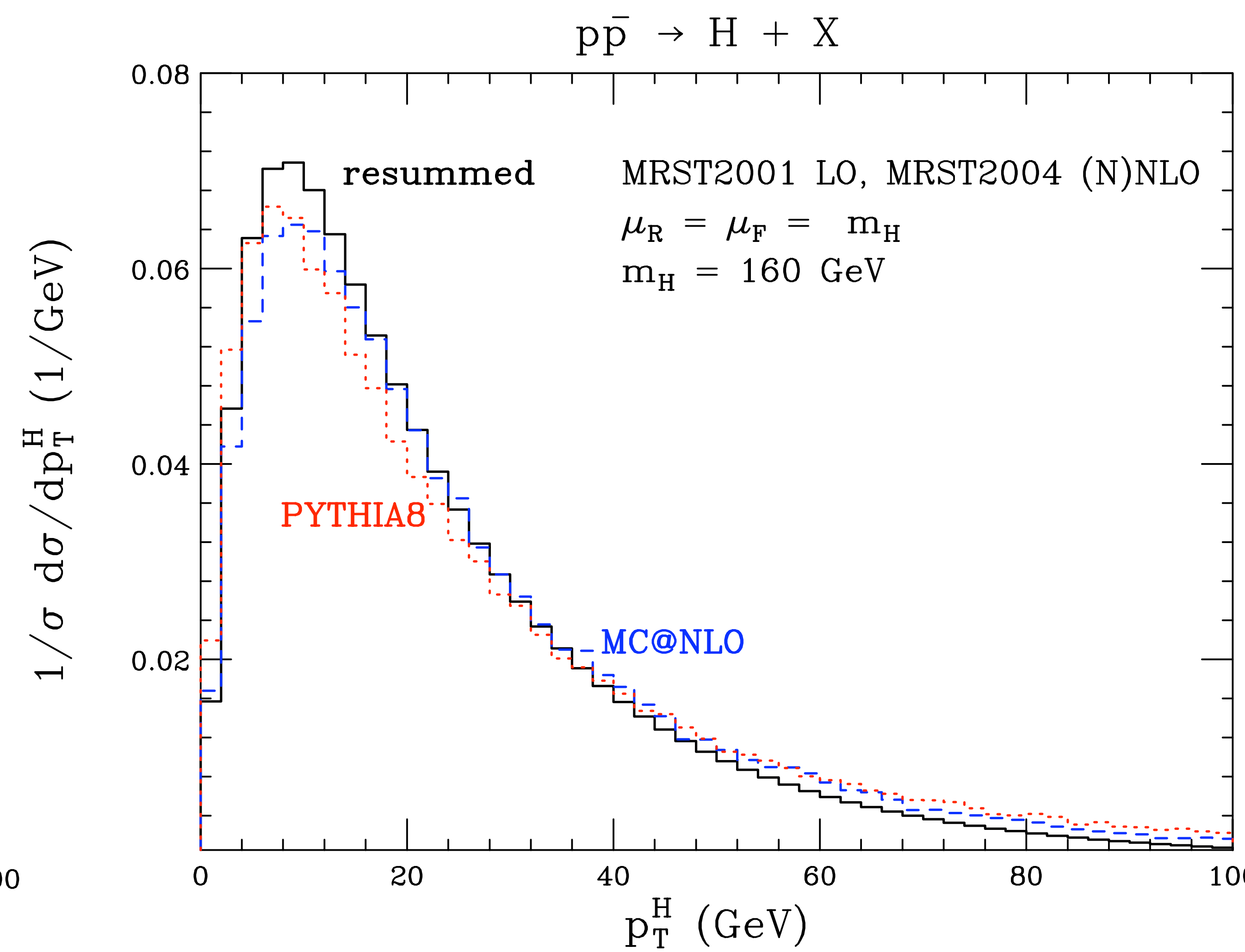


Calculating QCD Radiative Effects

- Fixed order (NLO, NNLO,...)
  - Well-controlled approximation
  - Laborious, numerical problems, divergences
- Resummation
  - Cures divergences, can be matched to fixed order
  - Only available for small number of observables
- Parton showers (Monte Carlo event generators)
  - Simple, fast approximation to all orders
  - Interfaces to hadronization models
  - Uncontrolled, bad approximation for hard emission

Example: Higgs p_T Distribution

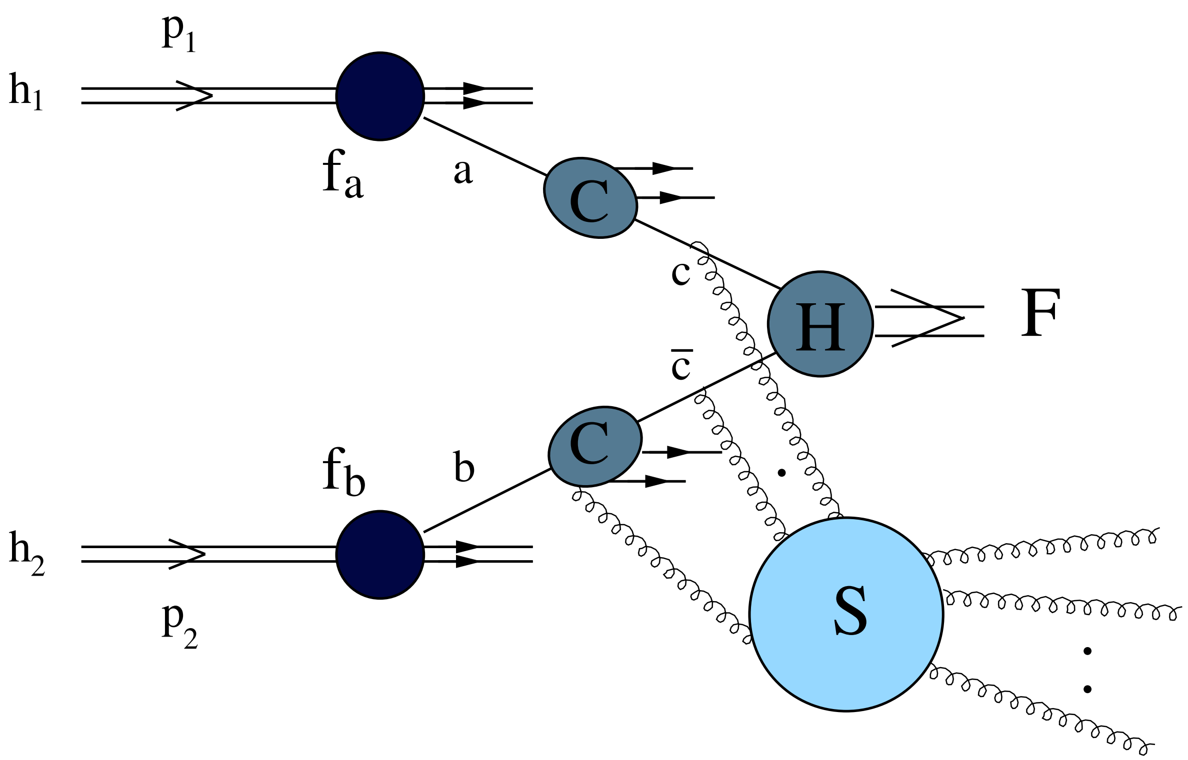




- MC@NLO matches fixed order and parton shower (more later)

C Anastasiou, G Dissertori, M Grazzini, F Stöckli & BW, JHEP08(2009)099 [arXiv:0905.3529]

Resummation of p_T in Higgs and Vector Boson Production



- $\delta(\mathbf{q}_\perp - \Sigma \mathbf{p}_T)$ → 2d Fourier (Bessel) transform

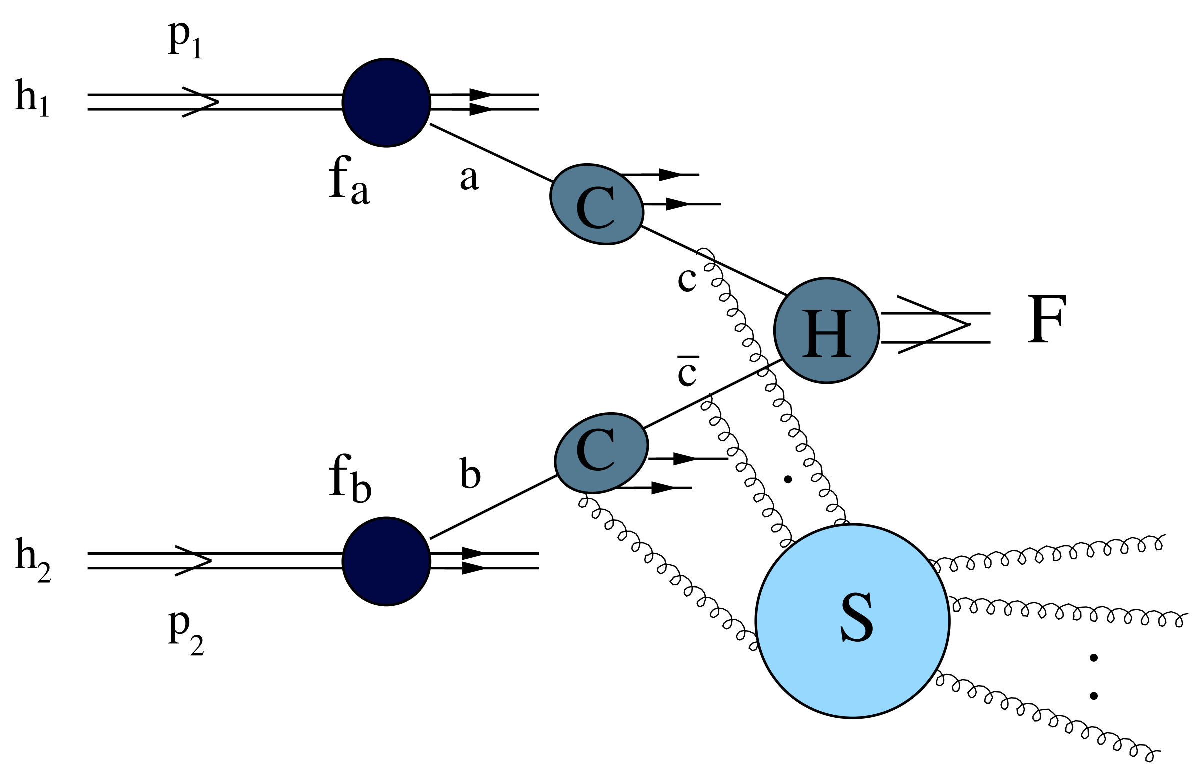
$$\left[\frac{d\sigma_F}{dQ^2\, dq_\perp^2}\right]_{\text{res.}} = \sum_{a,b} \int_0^1 dx_1 \int_0^1 dx_2 \int_0^\infty db\, \frac{b}{2}\, J_0(bq_\perp)\, f_{a/h_1}(x_1, b_0^2/b^2)\, f_{b/h_2}(x_2, b_0^2/b^2)\, W_{ab}^F(x_1 x_2 s; Q, b)$$

$$W_{ab}^F(s; Q, b) = \sum_c \int_0^1 dz_1 \int_0^1 dz_2\, C_{ca}(\alpha_S(b_0^2/b^2), z_1)\, C_{\bar{c}b}(\alpha_S(b_0^2/b^2), z_2)\, \delta(Q^2 - z_1 z_2 s)\, \sigma_{c\bar{c}}^F(Q^2, \alpha_S(Q^2))\, S_c(Q, b)$$

$$S_c(Q, b) = \exp\left\{ -\int_{b_0^2/b^2}^{Q^2} \frac{dq^2}{q^2} \left[A_c(\alpha_S(q^2))\, \ln \frac{Q^2}{q^2} + B_c(\alpha_S(q^2)) \right] \right\}$$

S Catani, D de Florian & M Grazzini, NP B596 (2001) 299

Resummation of E_T in Higgs and Vector Boson Production



- $\delta(E_T - \Sigma|\mathbf{p}_T|)$ → 1d Fourier transform

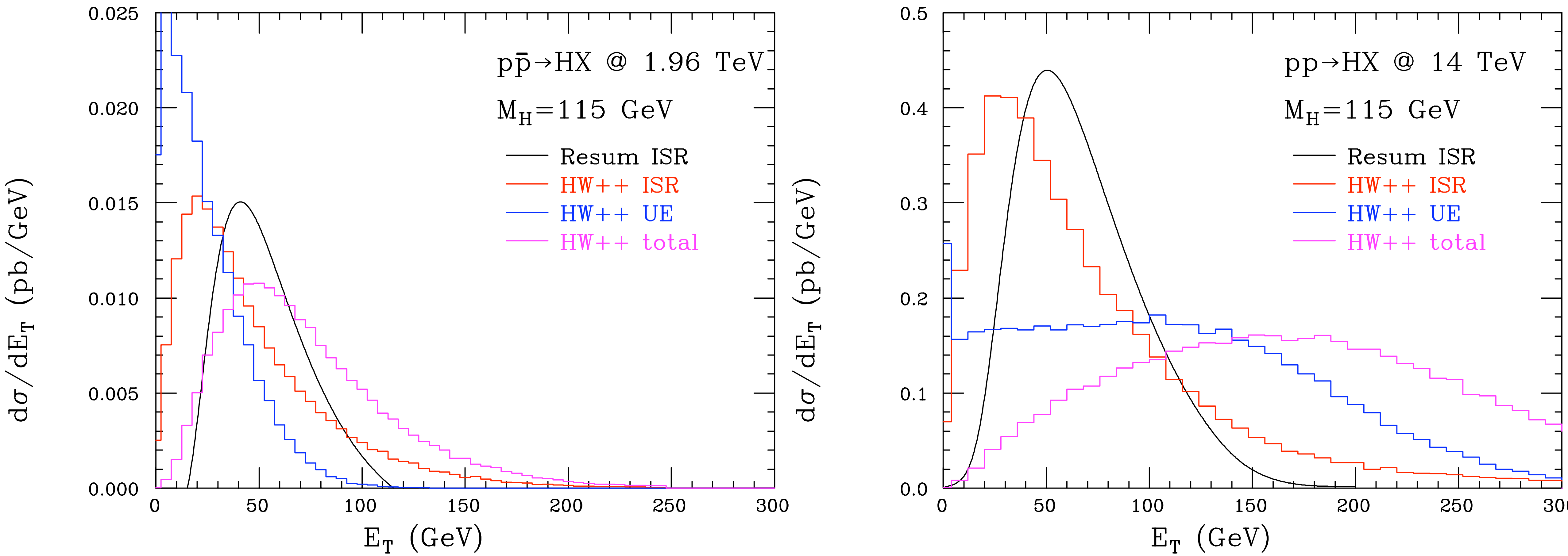
$$\left[\frac{d\sigma_F}{dQ^2\; dE_T}\right]_{\rm res.} = \frac{1}{2\pi}\sum_{a,b}\int_0^1 dx_1 \int_0^1 dx_2 \int_{-\infty}^{+\infty} d\tau\; {\rm e}^{-i\tau E_T}\; f_{a/h_1}(x_1,\mu)\; f_{b/h_2}(x_2,\mu)\, W_{ab}^F(x_1x_2s;Q,\tau,\mu)\;.$$

$$W_{ab}^F(s;Q,\tau) = \sum_c \int_0^1 dz_1 \int_0^1 dz_2\; \widetilde{C}_{ca}(\alpha_S(\tau_0/\tau),z_1)\; \widetilde{C}_{\bar{c}b}(\alpha_S(\tau_0/\tau),z_2)\; \delta(Q^2 - z_1z_2s)\; \sigma_{c\bar{c}}^F(Q,\alpha_S(Q))\; S_c(Q,\tau)$$

$$S_c(Q,\tau) = \exp\left\{-2\int_0^Q \frac{dq}{q}\left[2A_c(\alpha_S(q))\;\ln\frac{Q}{q} + B_c(\alpha_S(q))\right]\left(1 - {\rm e}^{iq\tau}\right)\right\}$$

C Davies & BW, Z Phys C24 (1984) 133
G Altarelli, G Martinelli & F Rapuano, Z Phys C32 (1986) 369
A Papaefstathiou, J Smillie & BW, in preparation

Resummation of E_T in Higgs Production



- Underlying event modelled by multiple parton interactions

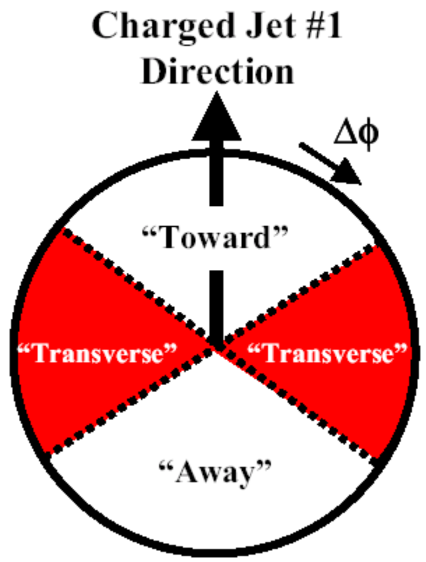
A Papaefstathiou, J Smillie & BW, in preparation

Parton Shower Event Generators

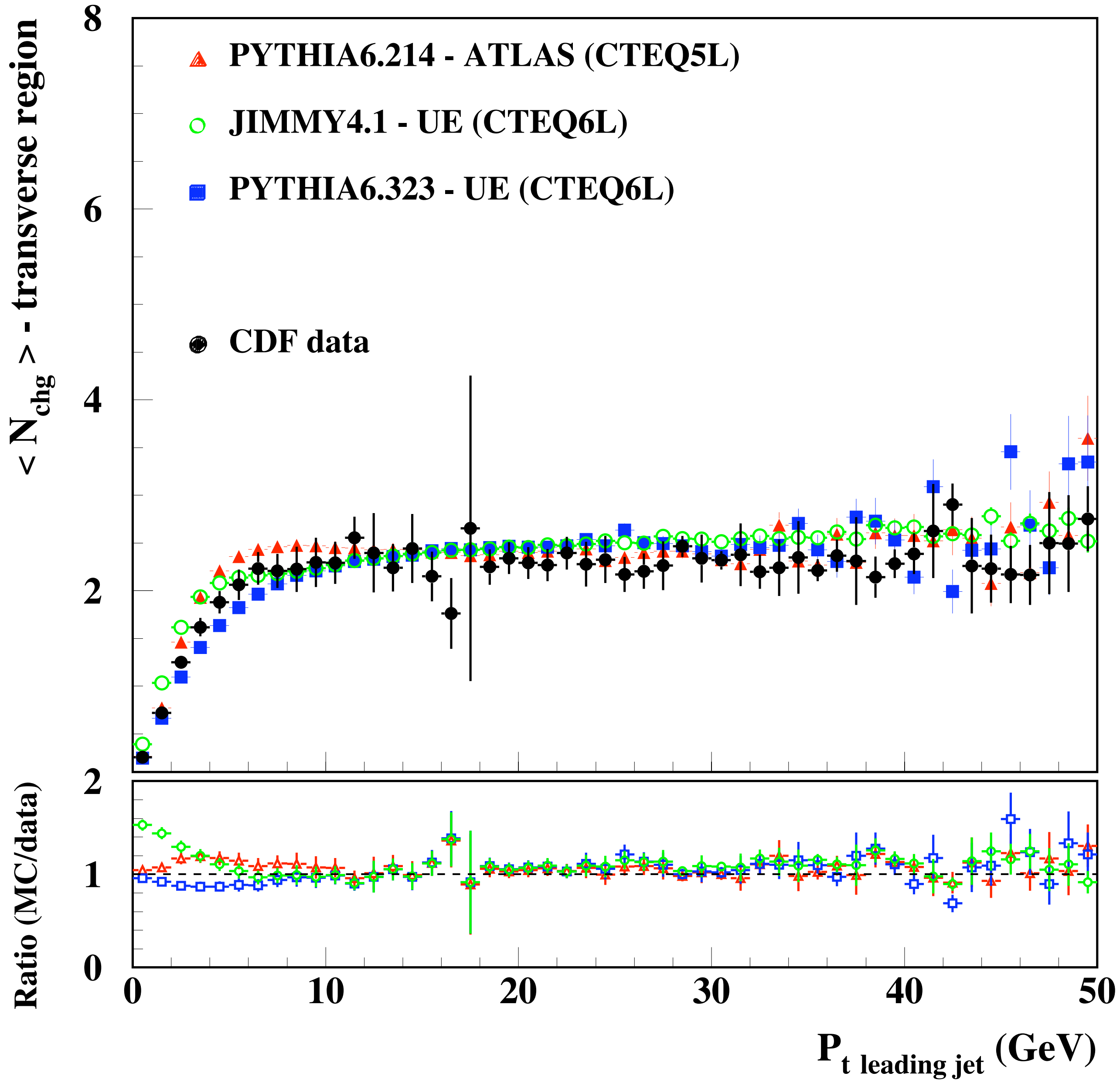
- HERWIG
  - Angular-ordered shower, cluster hadronization
  - v6 Fortran, now Herwig++
- PYTHIA
  - Virtuality/k_T-ordered shower, string hadronization
  - v6 Fortran, v8 C++
- SHERPA
  - Virtuality-ordered shower, string/cluster hadronization
  - C++

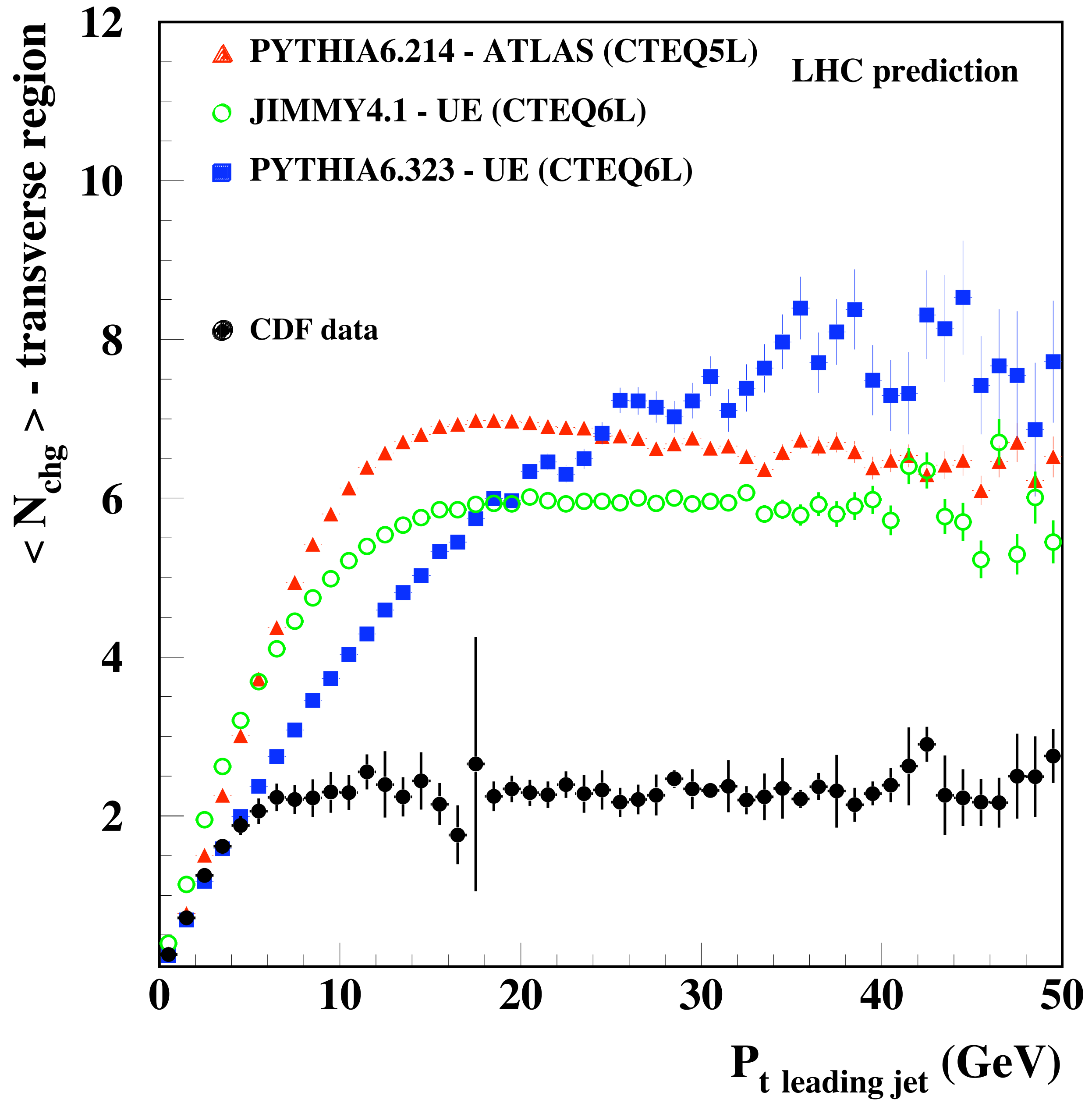
http://www.hepforge.org/projects

Underlying Event (MPI)

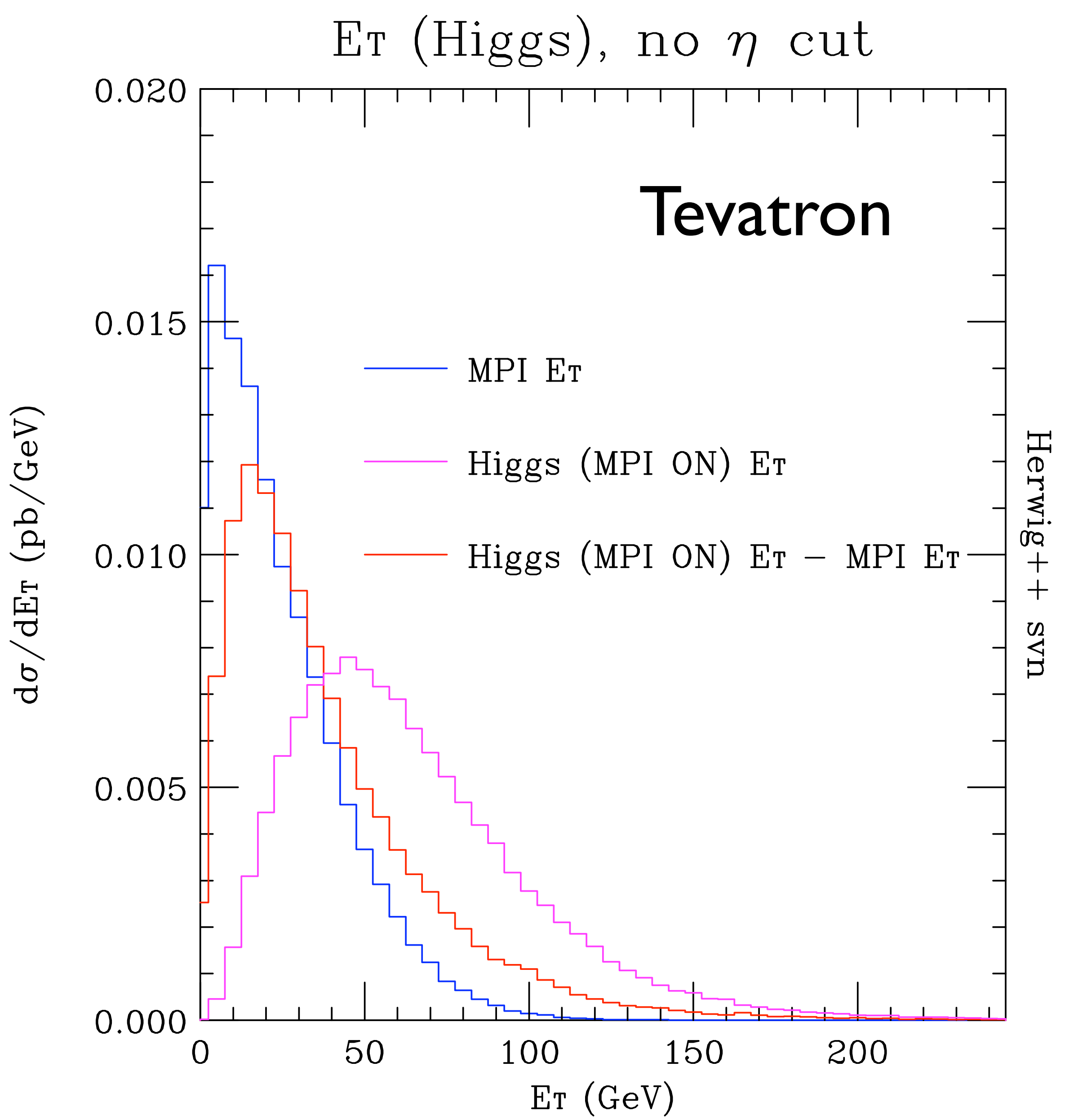


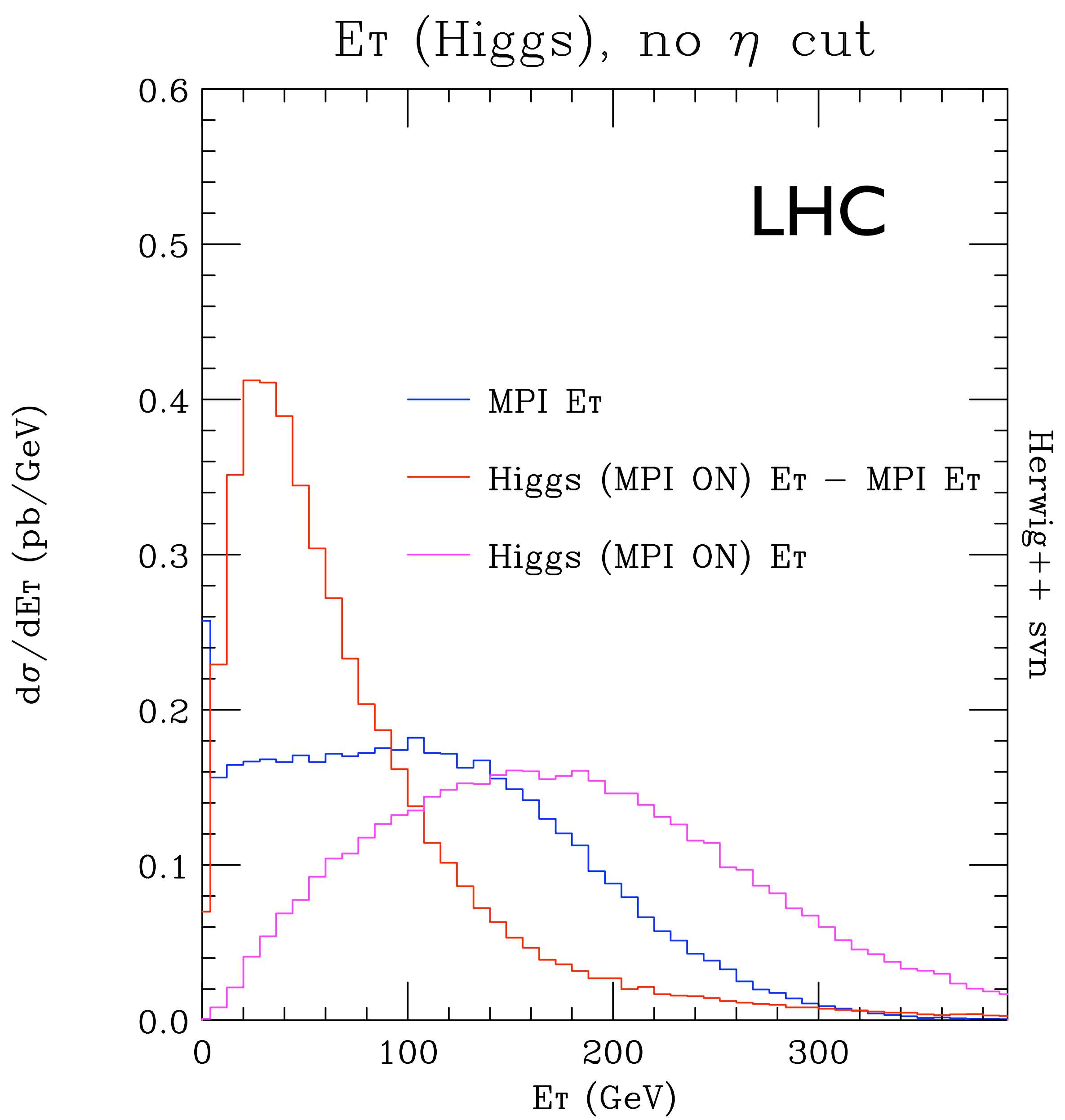
- Affects E_T and jet observables
- Extrapolation to LHC uncertain





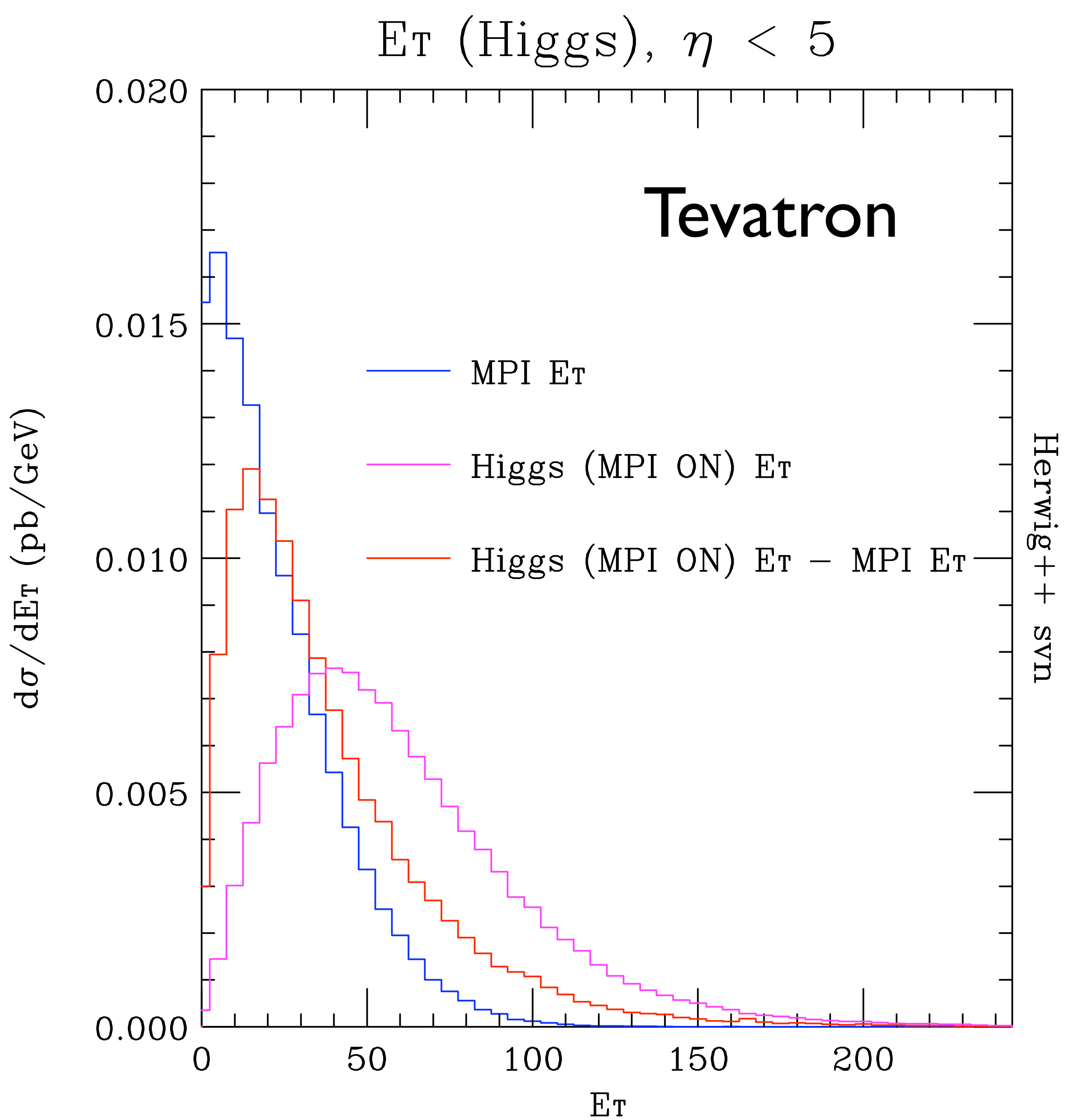
Monte Carlo E_T in Higgs Production

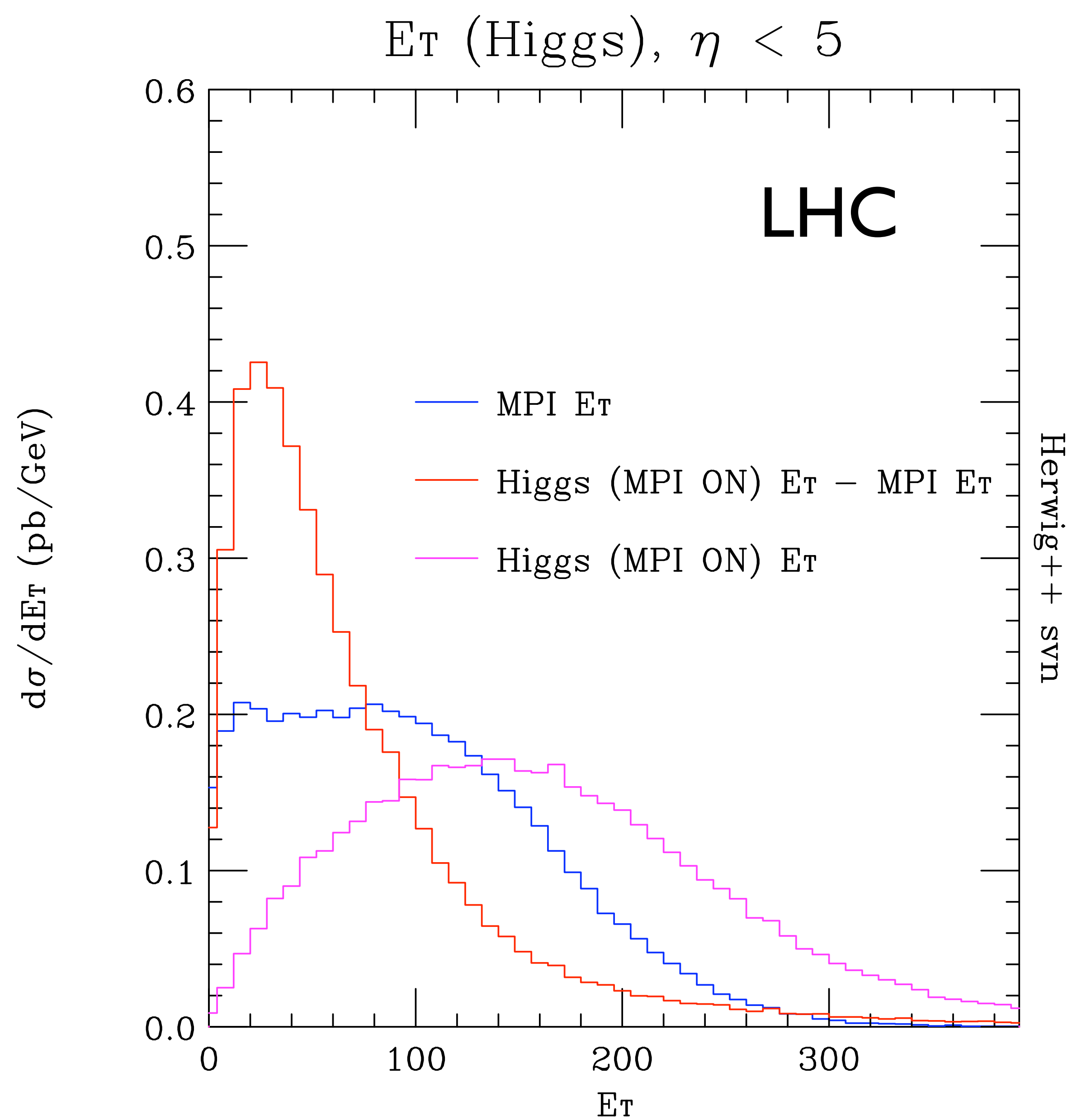




A Papaefstathiou, J Smillie & BW, in preparation

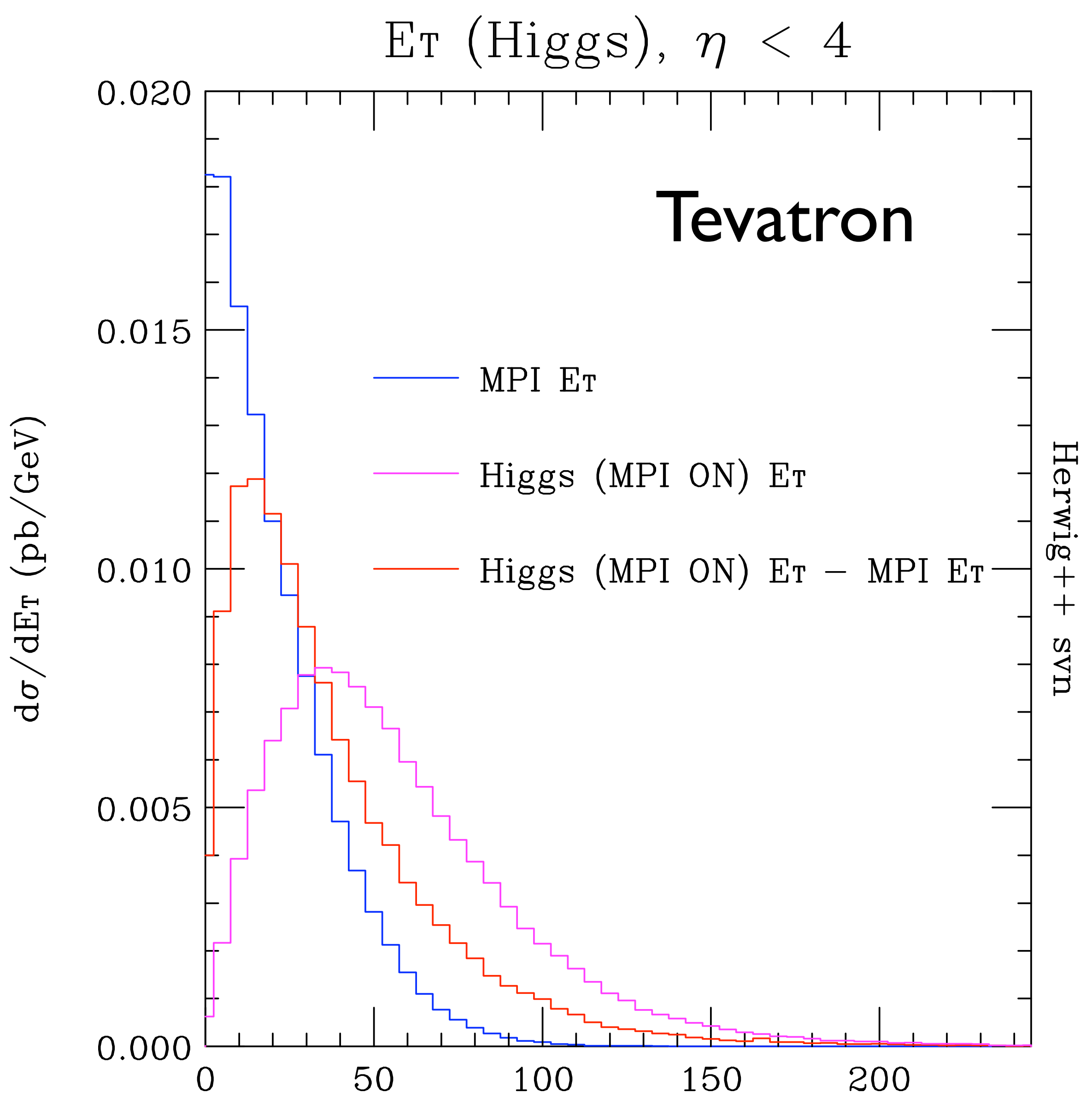
Monte Carlo E_T in Higgs Production

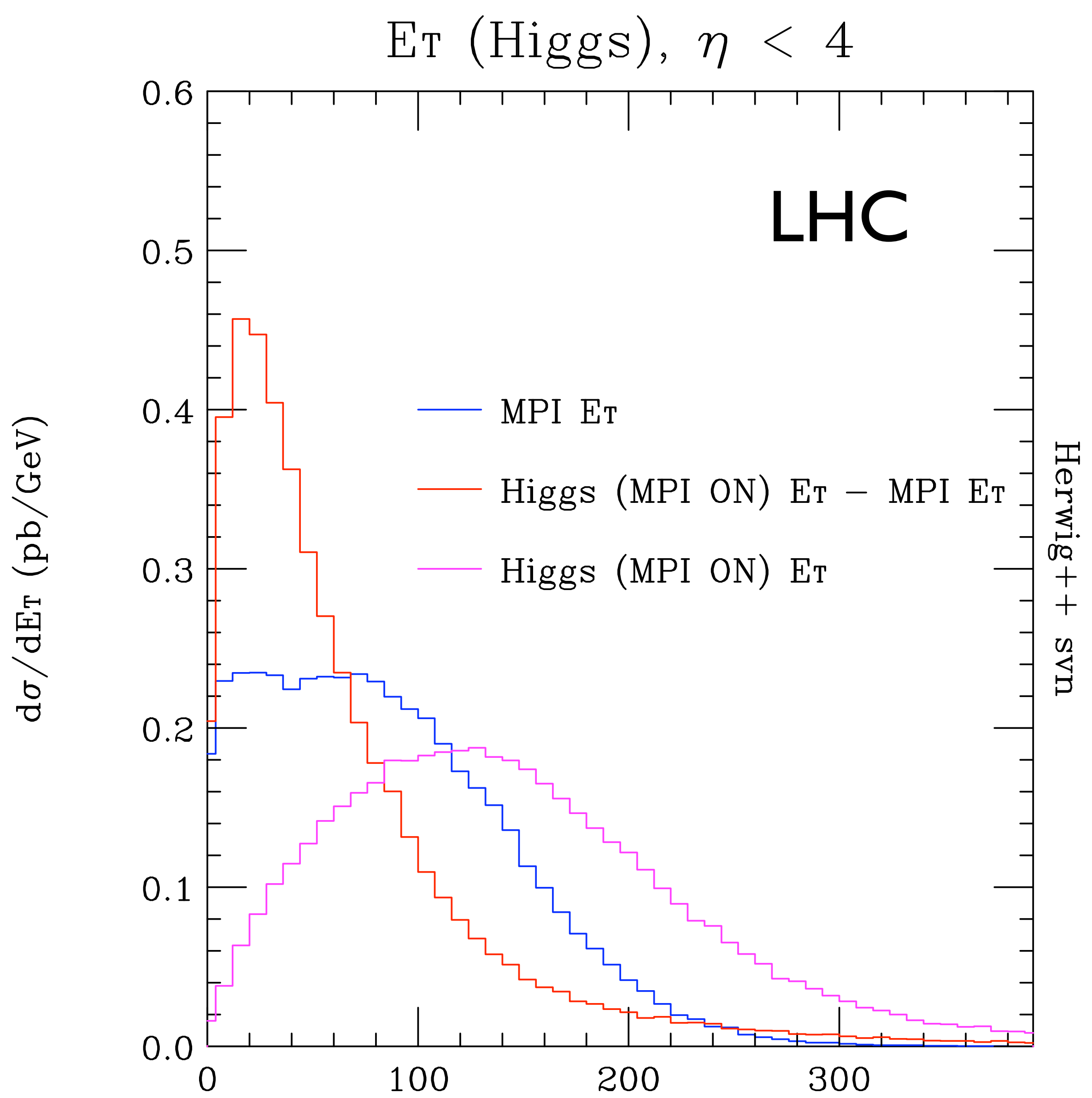




A Papaefstathiou, J Smillie & BW, in preparation

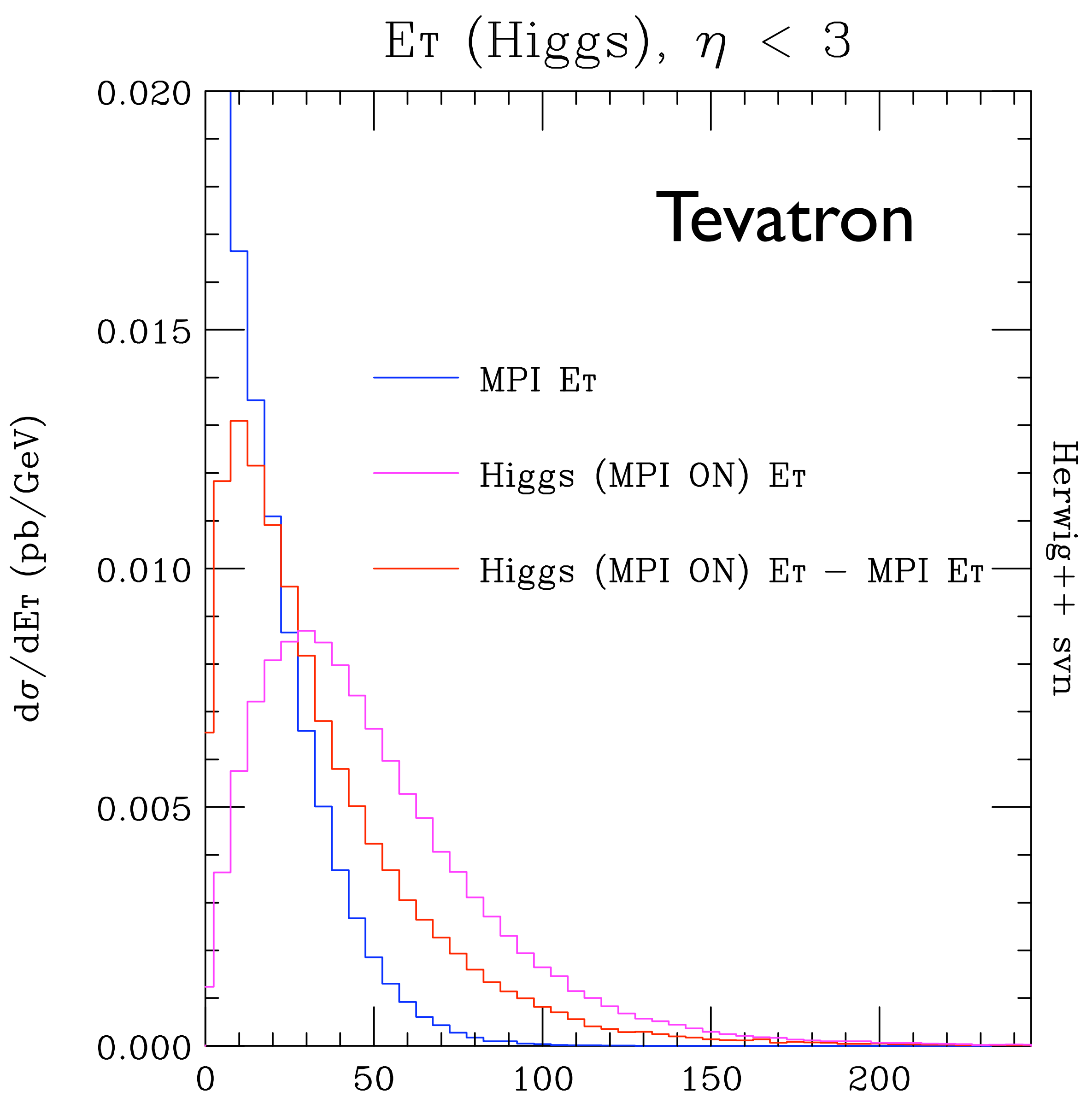
Monte Carlo E_T in Higgs Production

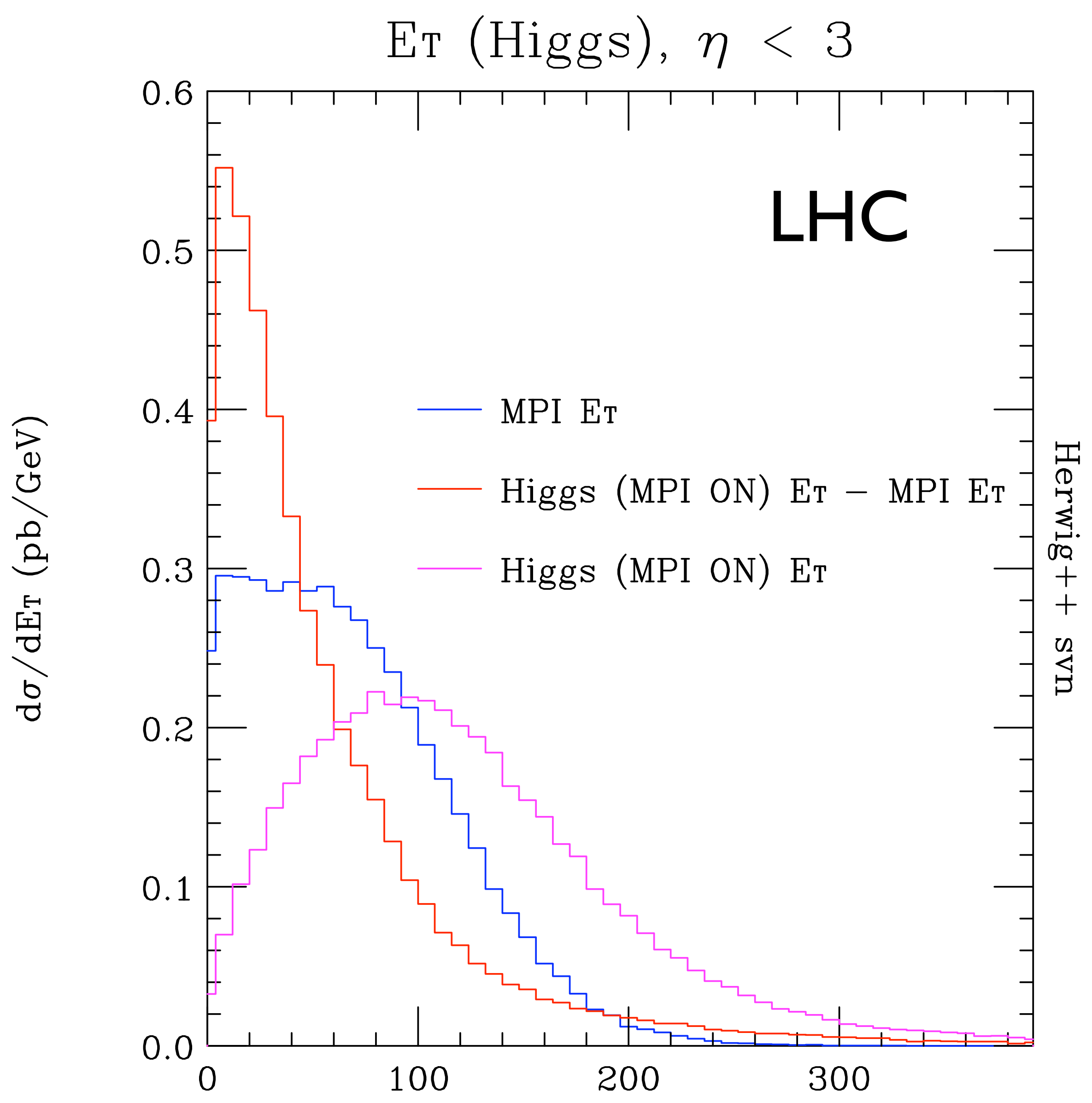




A Papaefstathiou, J Smillie & BW, in preparation

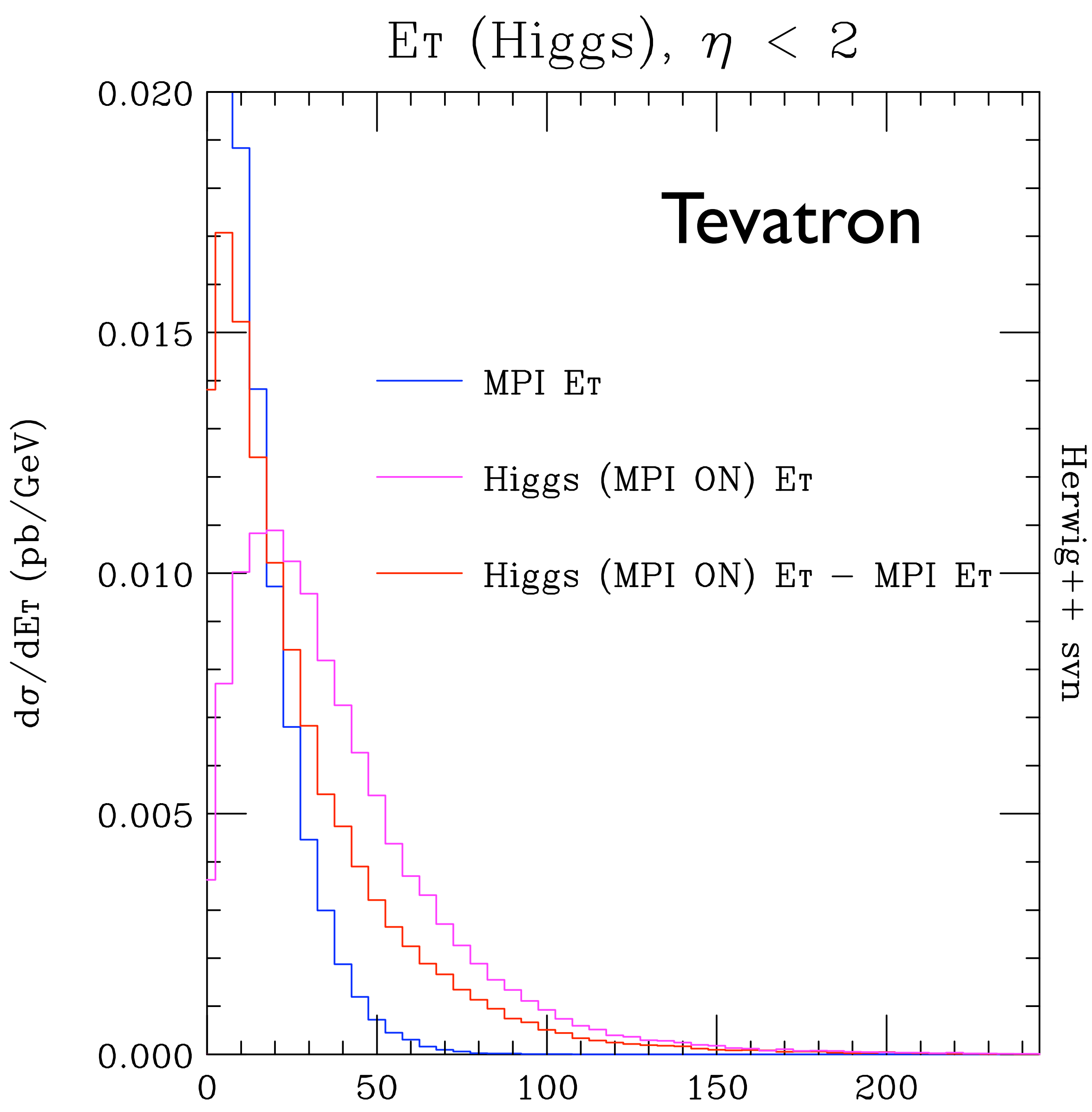
Monte Carlo E_T in Higgs Production

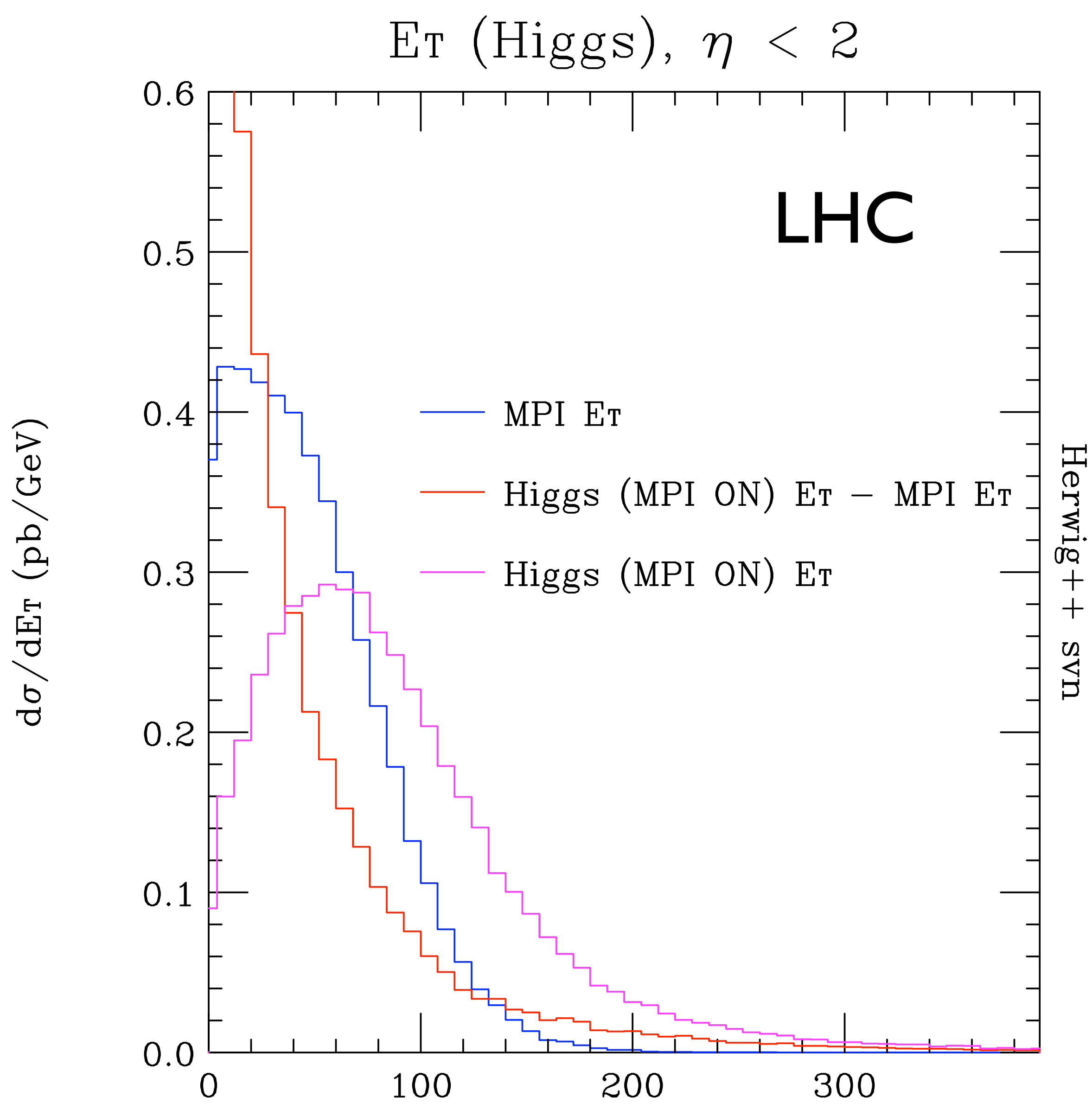




A Papaefstathiou, J Smillie & BW, in preparation

Monte Carlo E_T in Higgs Production





A Papaefstathiou, J Smillie & BW, in preparation

Matching fixed orders with parton showers

Fixed Order-Parton Shower Matching

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

MC@NLO

Illustrate with simple one-dim. example:

$$|\mathcal{M}_{m+1}|^2 \equiv \frac{1}{x}\mathcal{M}(x)$$

x = gluon energy or two-parton invariant mass.

Divergences regularized by $d = 4 - 2\epsilon$ dimensions.

$$|\mathcal{M}_m^{\text{one-loop}}|^2 \equiv \frac{1}{\epsilon}\mathcal{V}$$

Cross section in d dimensions is:

$$\sigma = \int_0^1 \frac{dx}{x^{1+\epsilon}}\,\mathcal{M}(x)\,F_1^J(x) + \frac{1}{\epsilon}\mathcal{V}\,F_0^J$$

Infrared safety: $F_1^J(0) = F_0^J$

KLN cancellation theorem: $\mathcal{M}(0) = \mathcal{V}$

Subtraction Method

Exact identity:

$$\sigma^J = \int_0^1 \frac{dx}{x^{1+\epsilon}} \mathcal{M}(x)\, F_1^J(x) - \int_0^1 \frac{dx}{x^{1+\epsilon}} \mathcal{V}\, F_0^J$$
$$+ \int_0^1 \frac{dx}{x^{1+\epsilon}} \mathcal{V}\, F_0^J + \frac{1}{\epsilon} \mathcal{V}\, F_0^J$$
$$= \int_0^1 \frac{dx}{x} \left(\mathcal{M}(x)\, F_1^J(x) - \mathcal{V}\, F_0^J \right) + \mathcal{O}(1)\, \mathcal{V}\, F_0^J .$$

➡ Two separate finite integrals.

Modified Subtraction

$$\sigma^J = \int_0^1 \frac{dx}{x} \left(\mathcal{M}(x)\, F_1^J(x) - \mathcal{V}\, F_0^J \right) + \mathcal{O}(1)\, \mathcal{V}\, F_0^J$$

Now add parton shower:

$F_{0,1}^J \;\Rightarrow$ result from showering after 0,1 emissions.

But shower adds $\mathcal{M}_{\rm MC}/x$ to 1 emission. Must subtract this, and add to 0 emission (so that $F_{0,1}^{\rm tot} = 1 \;\Rightarrow\; \sigma^{\rm tot}$ fixed)

$$\begin{aligned} \sigma^J \quad = \quad & \int_0^1 \frac{dx}{x} \Big(\{\mathcal{M}(x) - \mathcal{M}_{\rm MC}(x)\}\; F_1^J(x) \\ & - \{\mathcal{V} - \mathcal{M}_{\rm MC}(x)\}\; F_0^J \Big) + \mathcal{O}(1)\, \mathcal{V}\, F_0^J \end{aligned}$$

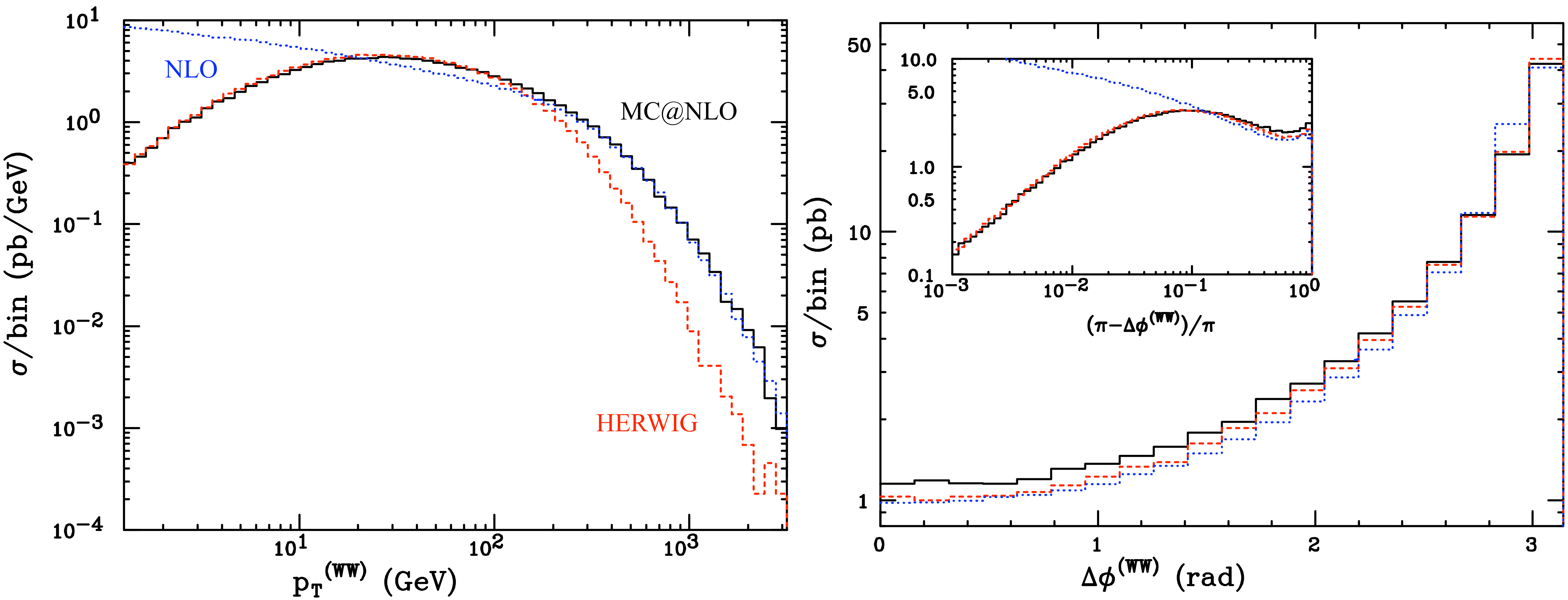
MC good for soft and/or collinear $\;\Rightarrow\; \mathcal{M}_{\rm MC}(0) = \mathcal{M}(0)$

➡ 0 & 1 emission contributions separately finite now!

(But some can be negative “counter-events”)

MC@NLO Results

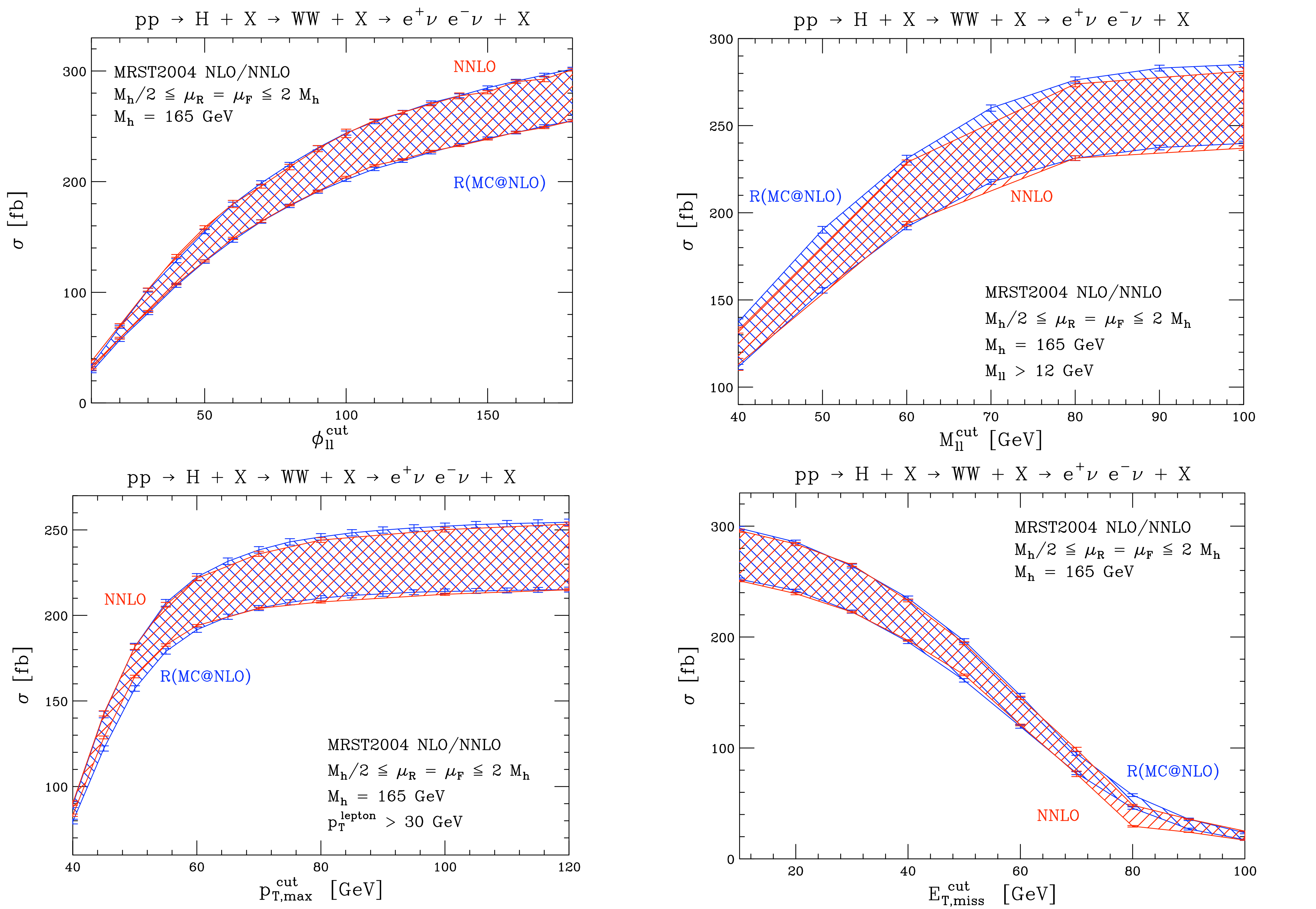
- WW production at LHC



- Interpolates between MC & NLO in $\mathrm{p}_{\mathrm{T}}^{(\mathrm{WW})}$
- Above both at $\Delta\phi^{(\mathrm{WW})} \simeq 0$

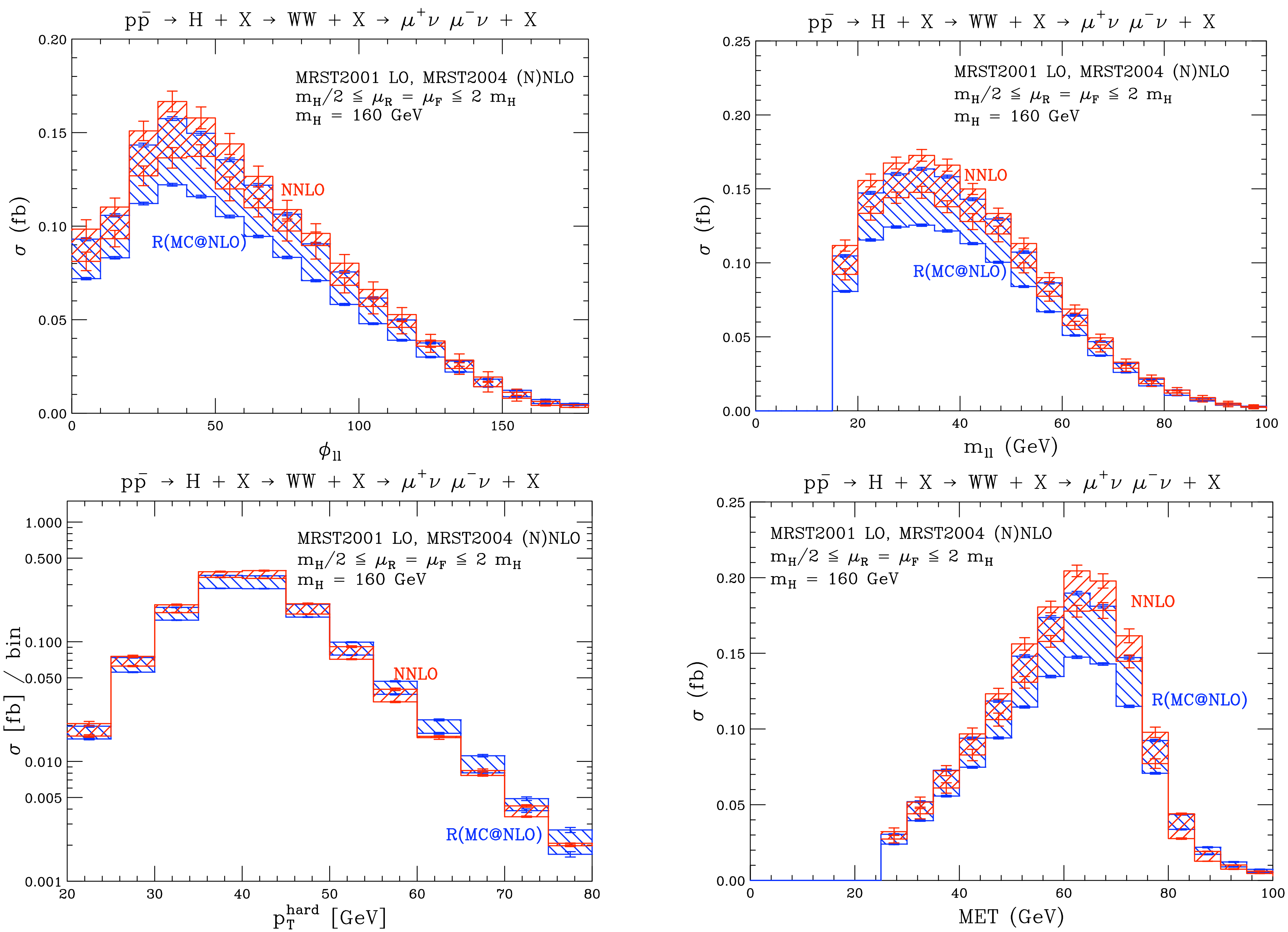
S Frixione & BW, JHEP 06(2002)029

H ⟶ WW: MC@NLO vs NNLO at LHC



C Anastasiou, G Dissertori, F Stöckli & BW, JHEP03(2008)017 [arXiv:0801.2682]

H→WW at Tevatron



C Anastasiou, G Dissertori, M Grazzini, F Stöckli & BW, JHEP08(2009)099 [arXiv:0905.3529]

Theoretical Uncertainties

- CDF separate events into jet samples:

0-jets | 1-jet | >1-jet

$$\frac{\Delta N_{\rm inc}(\rm scale)}{N_{\rm inc}} = 66.5\% \cdot \binom{+5\%}{-9\%} + 28.6\% \cdot \binom{+24\%}{-22\%} + 4.9\% \cdot \binom{+78\%}{-41\%} = \boxed{\binom{+14.0\%}{-14.3\%}}$$

- But selection cuts change jet fractions

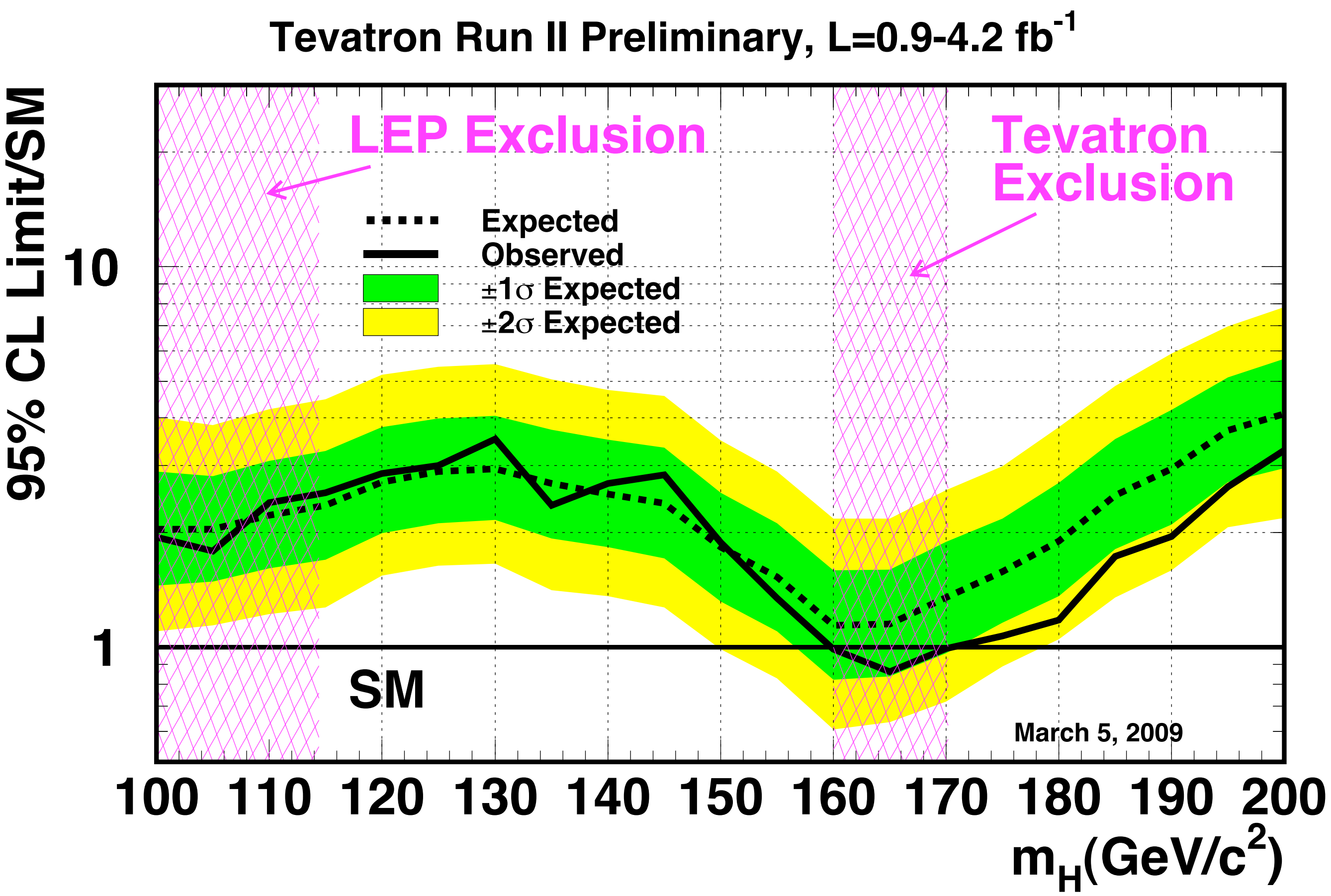
$$\frac{\Delta N_{\rm signal}(\rm scale)}{N_{\rm signal}} = 60\% \cdot \binom{+5\%}{-9\%} + 29\% \cdot \binom{+24\%}{-22\%} + 11\% \cdot \binom{+78\%}{-41\%} = \binom{+18.5\%}{-16.3\%}$$

- Also 1-jet is only NLO and >1-jet only LO

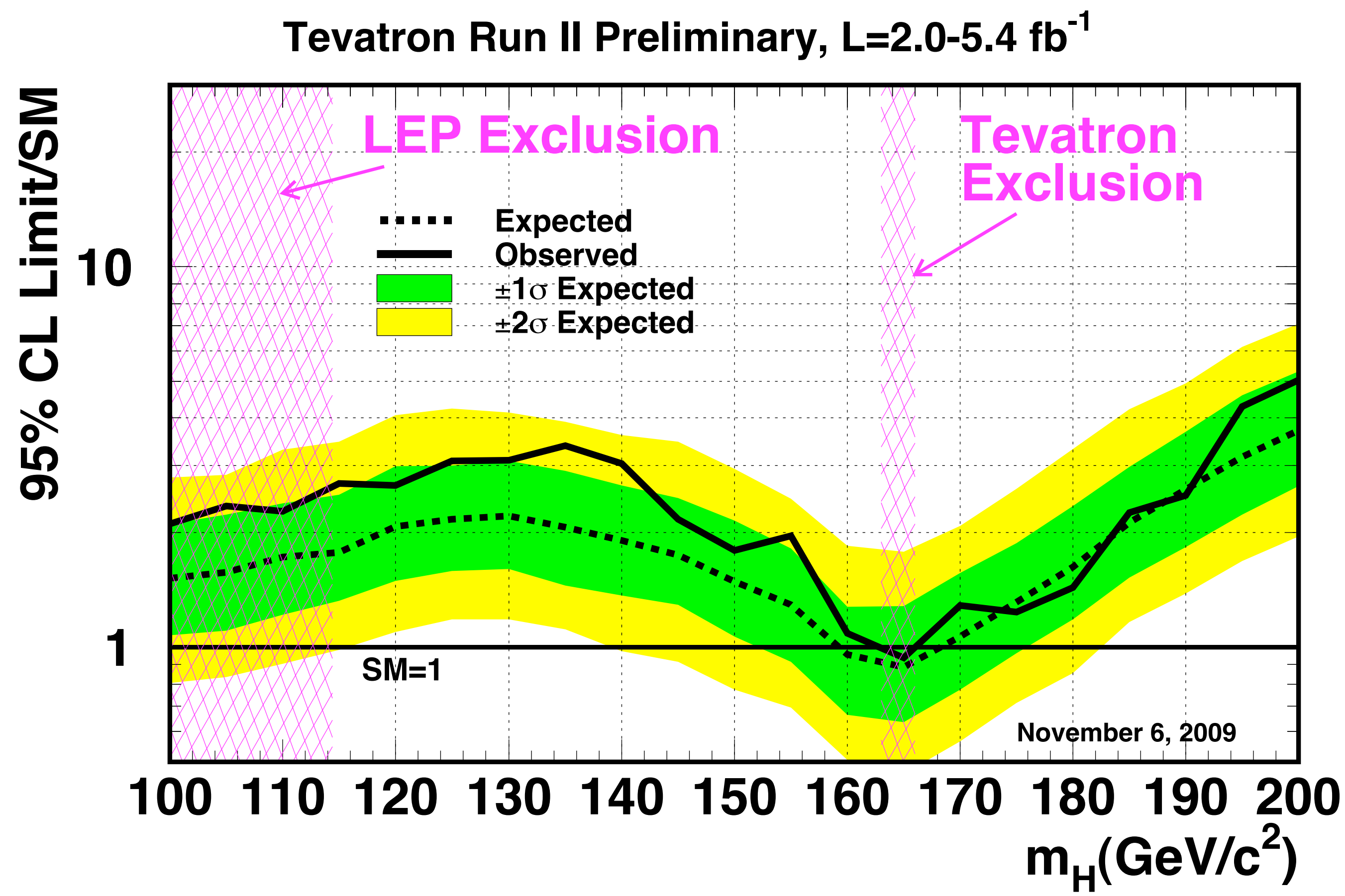
$$\frac{\Delta N_{\rm signal}(\rm scale)}{N_{\rm signal}} = 60\% \cdot \binom{+5\%}{-9\%} + 29\% \cdot \binom{+24\%}{-23\%} + 11\% \cdot \binom{+91\%}{-44\%} = \boxed{\binom{+20.0\%}{-16.9\%}}$$

Tevatron Higgs Exclusion

March 2009



November 2009

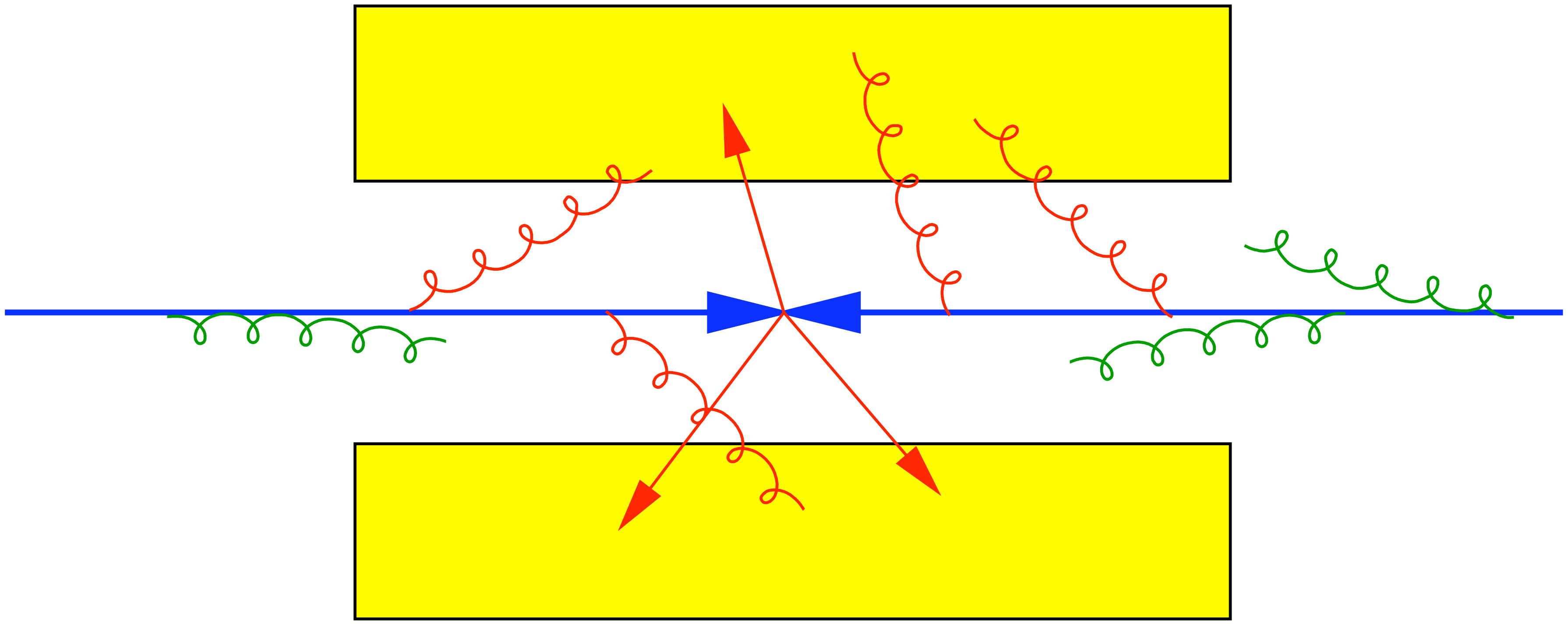


CDF & D0 combined

- Extra "signal-like" events
- Improved theoretical uncertainty

Dealing with QCD initial-state radiation

QCD Initial-State Radiation



- Modifies kinematics of hard process
- Irreducible source of “jet contamination”
  - ➔ Misidentification of processes
  - ➔ Combinatorial ambiguities

Global 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)

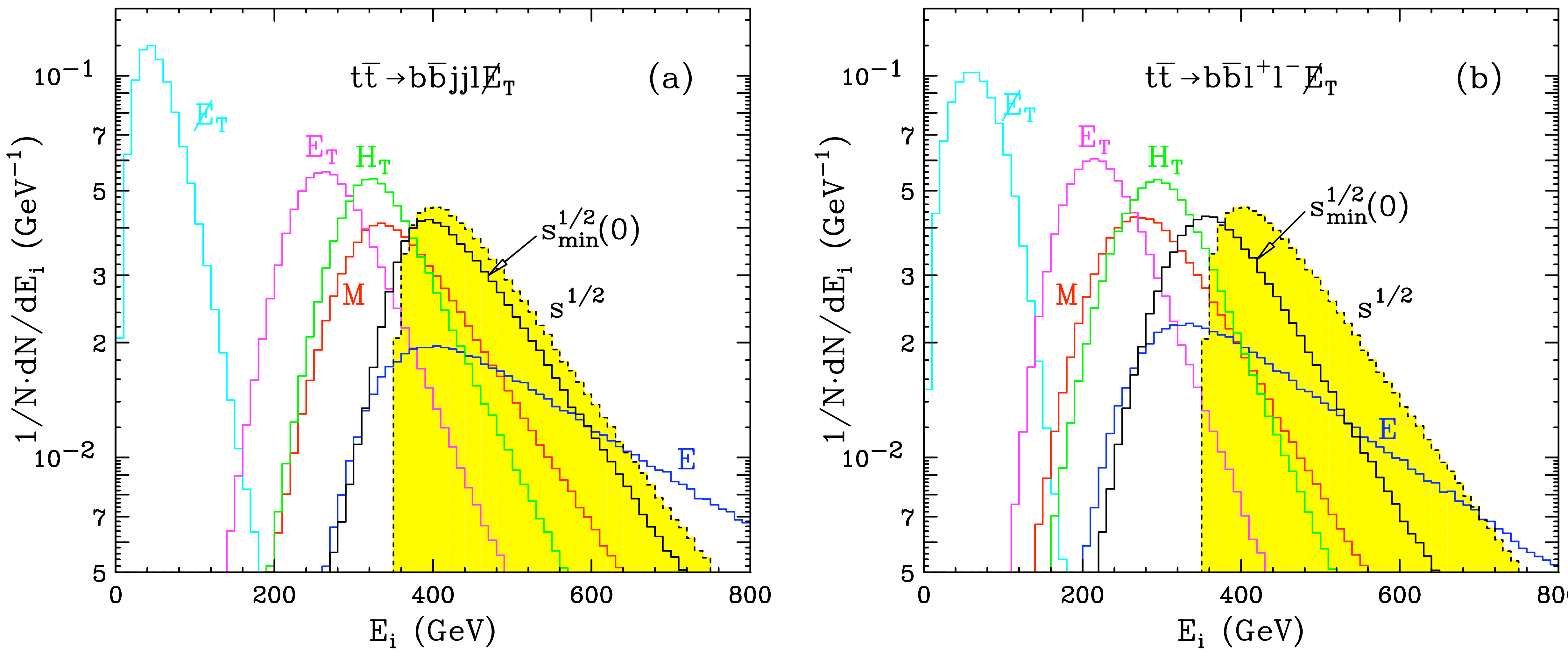
$$\hat{s}_{\min}^{1/2}(M_{\mathrm{inv}}) = \sqrt{M^2 + \not{E}_T^2} + \sqrt{M_{\mathrm{inv}}^2 + \not{E}_T^2}$$

Inclusive Observables: MC results

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

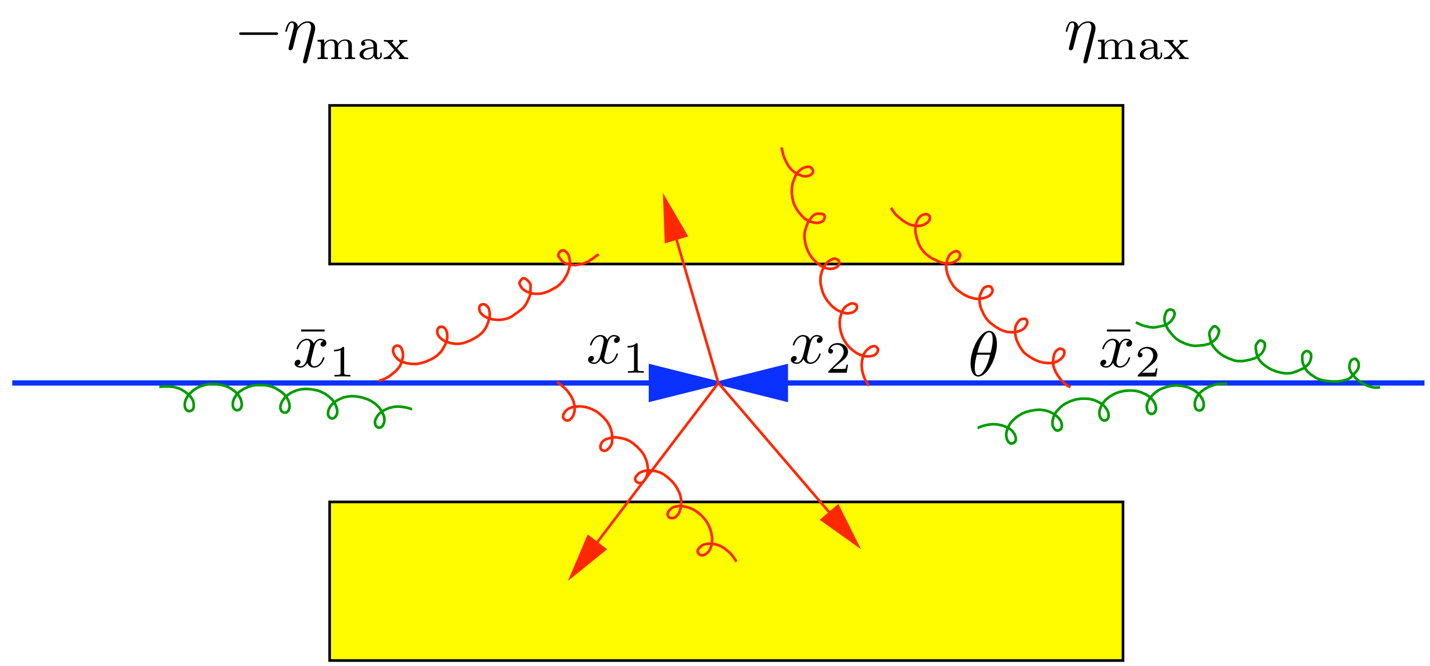
$$M = \sqrt{E^2 - P_z^2 - \not{E}_T^2} \qquad H_T = E_T + \not{E}_T$$

- PYTHIA top production: ISR off



Konar, Kong, Matchev, 0812.1042

ISR Effects on Inclusive Observables



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

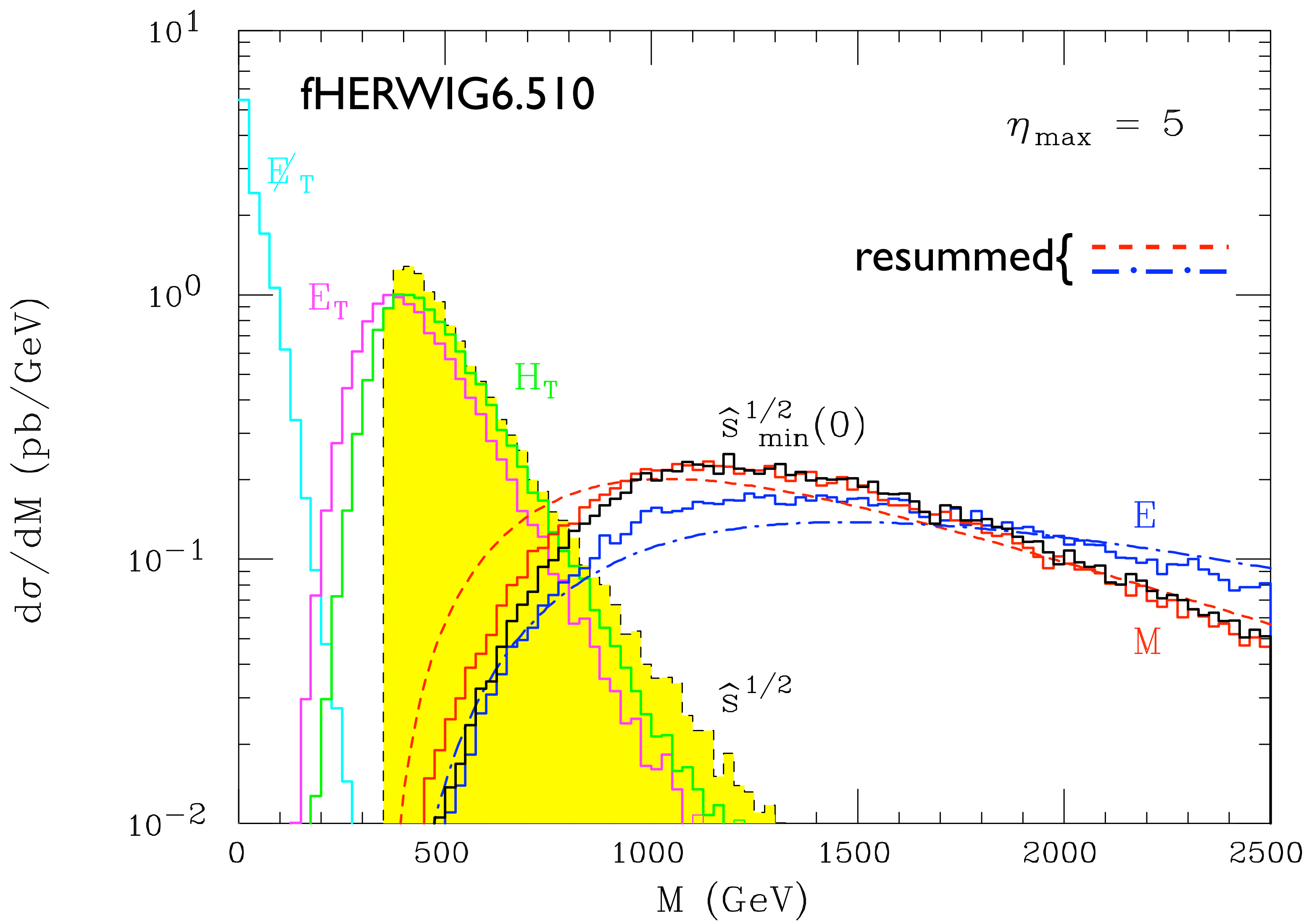
- ISR at $\theta > \theta_c \sim \exp(-\eta_{\max})$ enters detector
- Hard scale $Q^2 \sim \hat{s} = x_1 x_2 S$ but $M^2 = \bar{x}_1\bar{x}_2 S$
- PDFs sampled at $Q_c \sim \theta_c Q$

A Papaefstathiou & BW, 0903.2013

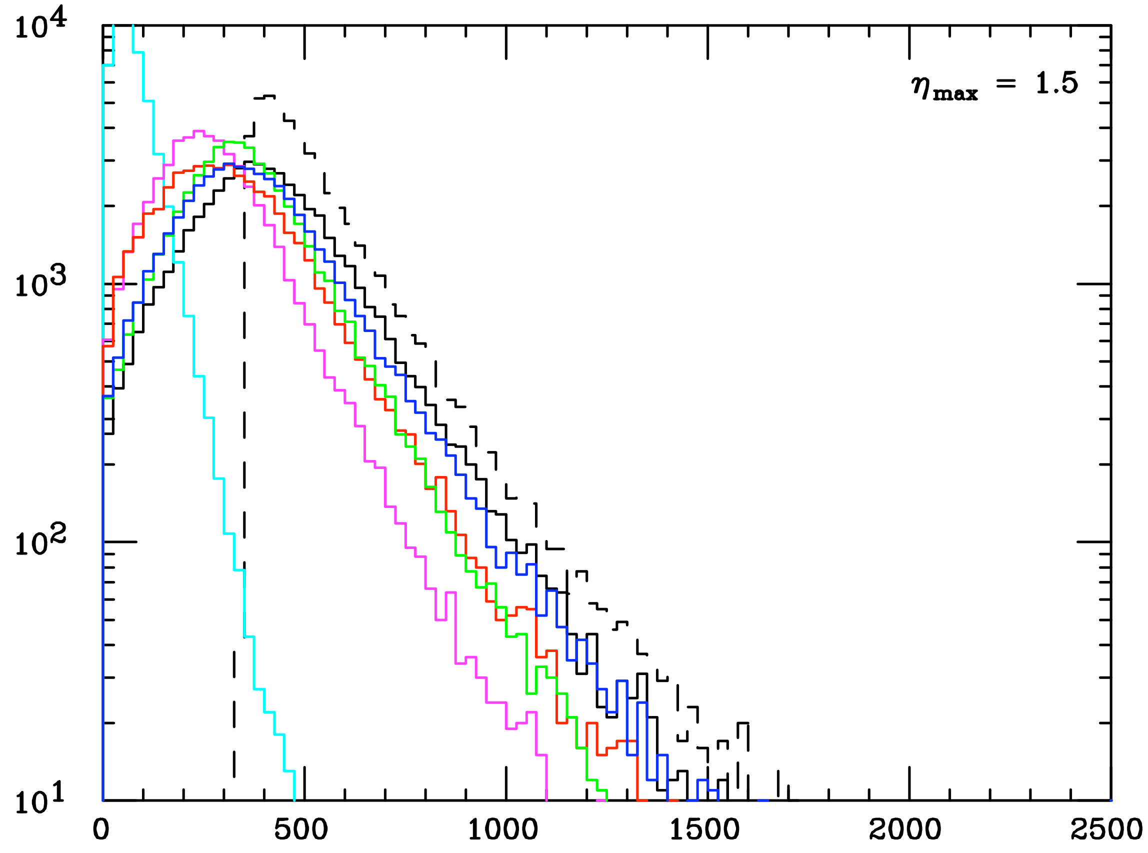
ISR Effects: MC & Resummed Results

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

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

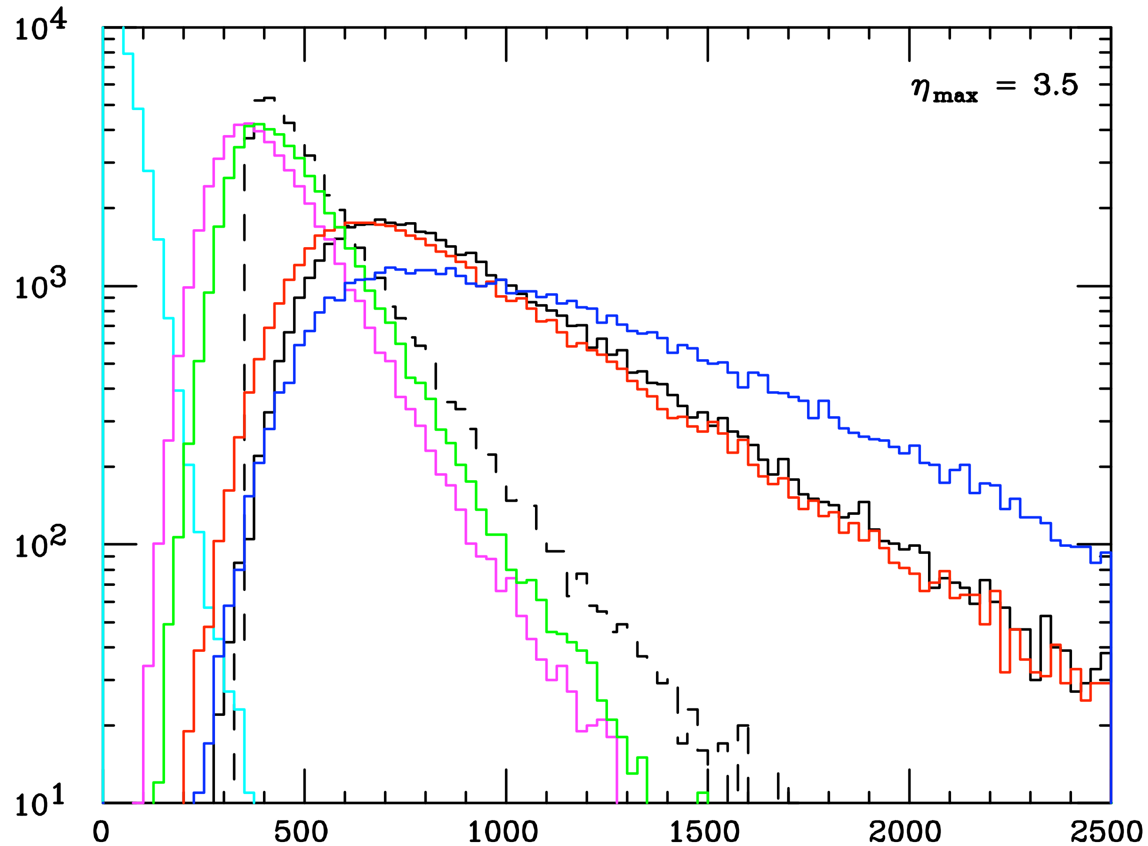


Dependence on $\eta_{\rm max}$



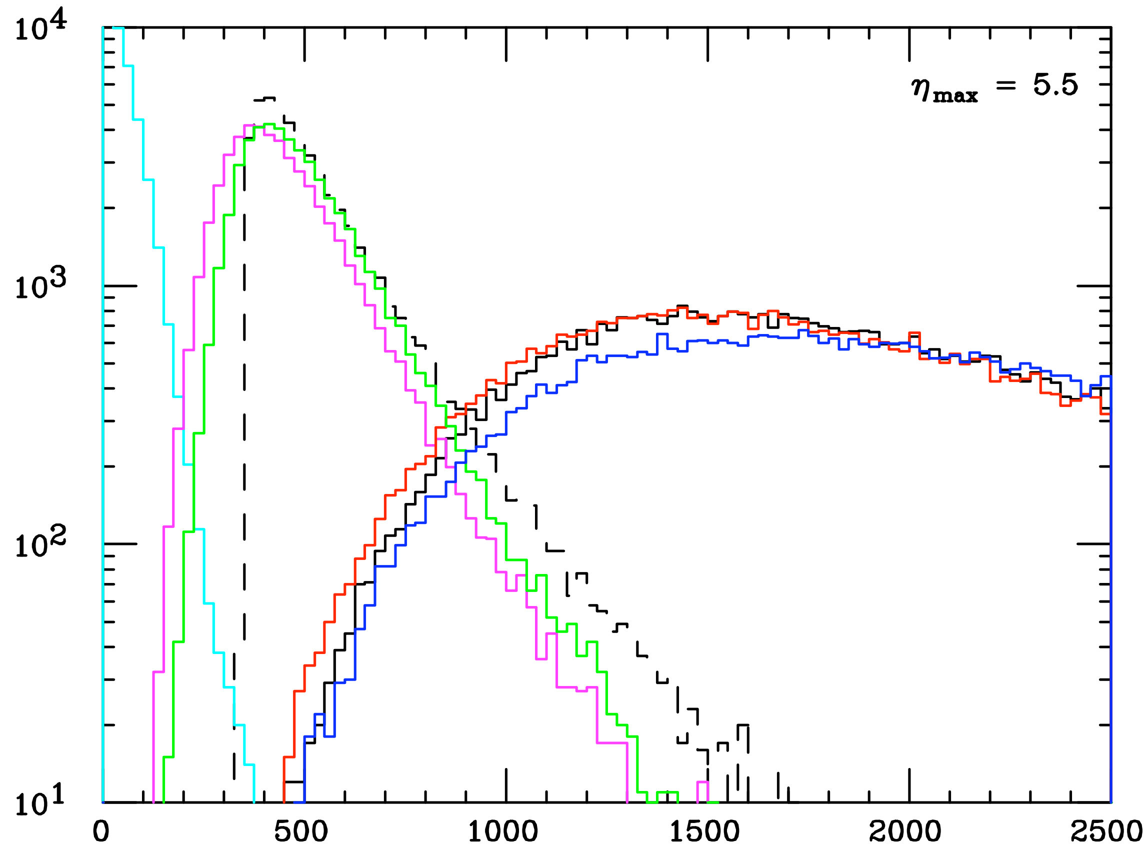
- E, M, $\hat{s}_{min}$ strongly dependent; $\not{E}_T$, E_T, H_T not

Dependence on $\eta_{\max}$



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

Dependence on $\eta_{\max}$

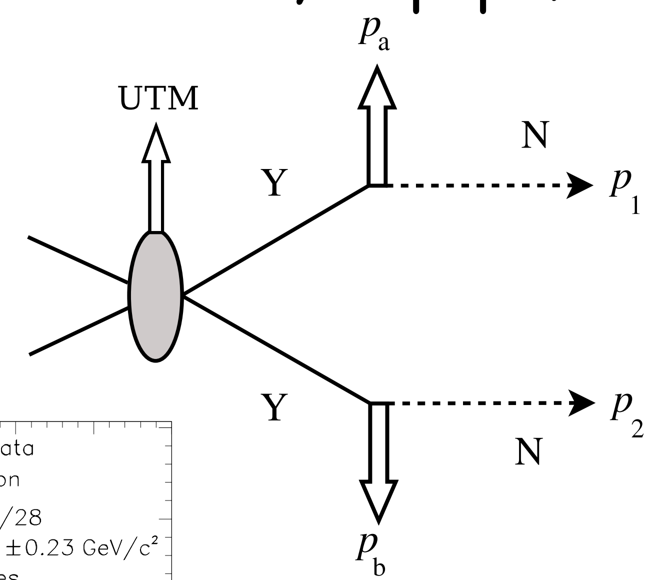


- E, M, $\hat{s}_{min}$ strongly dependent; $\not{E}_T$, E_T, H_T not

Mass determination with M_{T2} and $M_{CT\perp}$

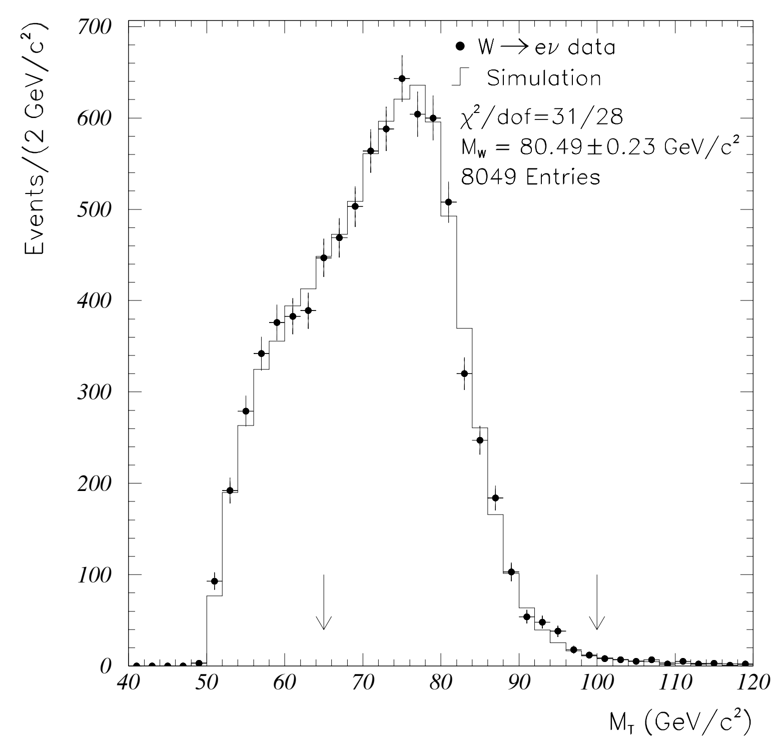
M_{T2} variable

Lester & Summers, hep-ph/9906349



- pp → YYX, Y → aN, Y → bN
- a,b visible, N invisible
- Transverse mass:

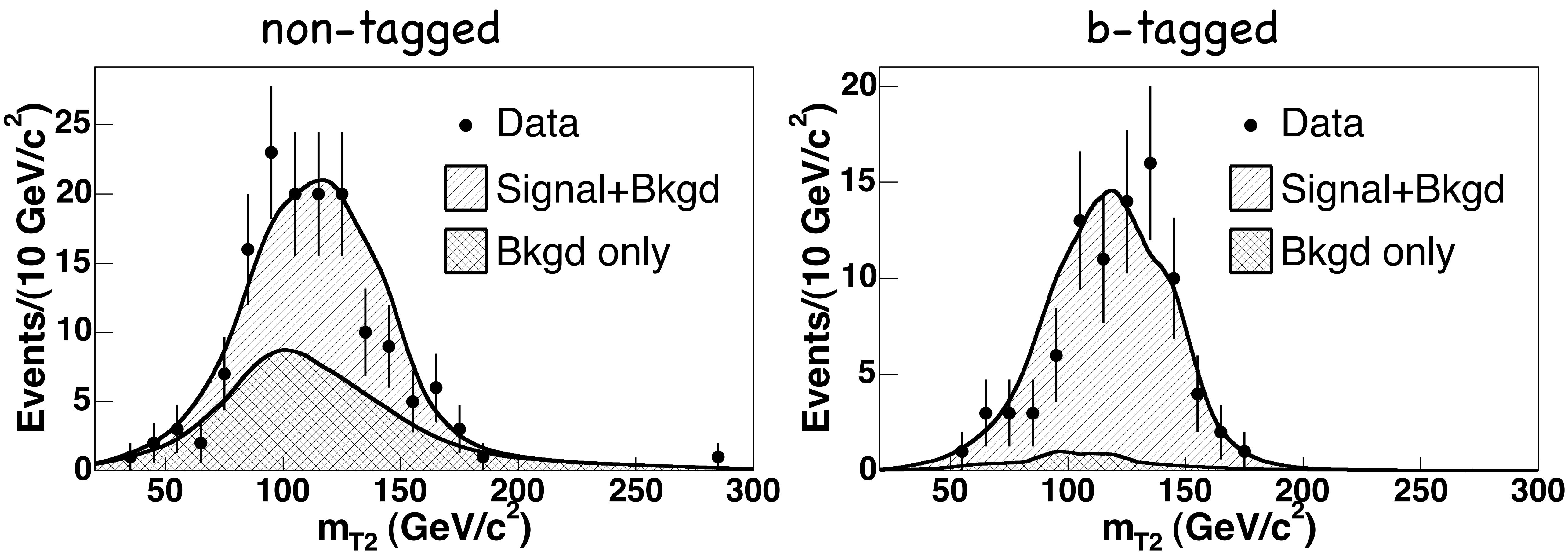
$$m_T^2(\mathbf{p}_T^1, \mathbf{p}_T^a; \mu_N) = \mu_N^2 + m_a^2 \\ +2\left(E_T^1 E_T^a - \mathbf{p}_T^1 \cdot \mathbf{p}_T^a\right)$$



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

$$\leq m_Y^2 \text{ when } \mu_N = m_N$$

CDF Top Mass from M_{T2}

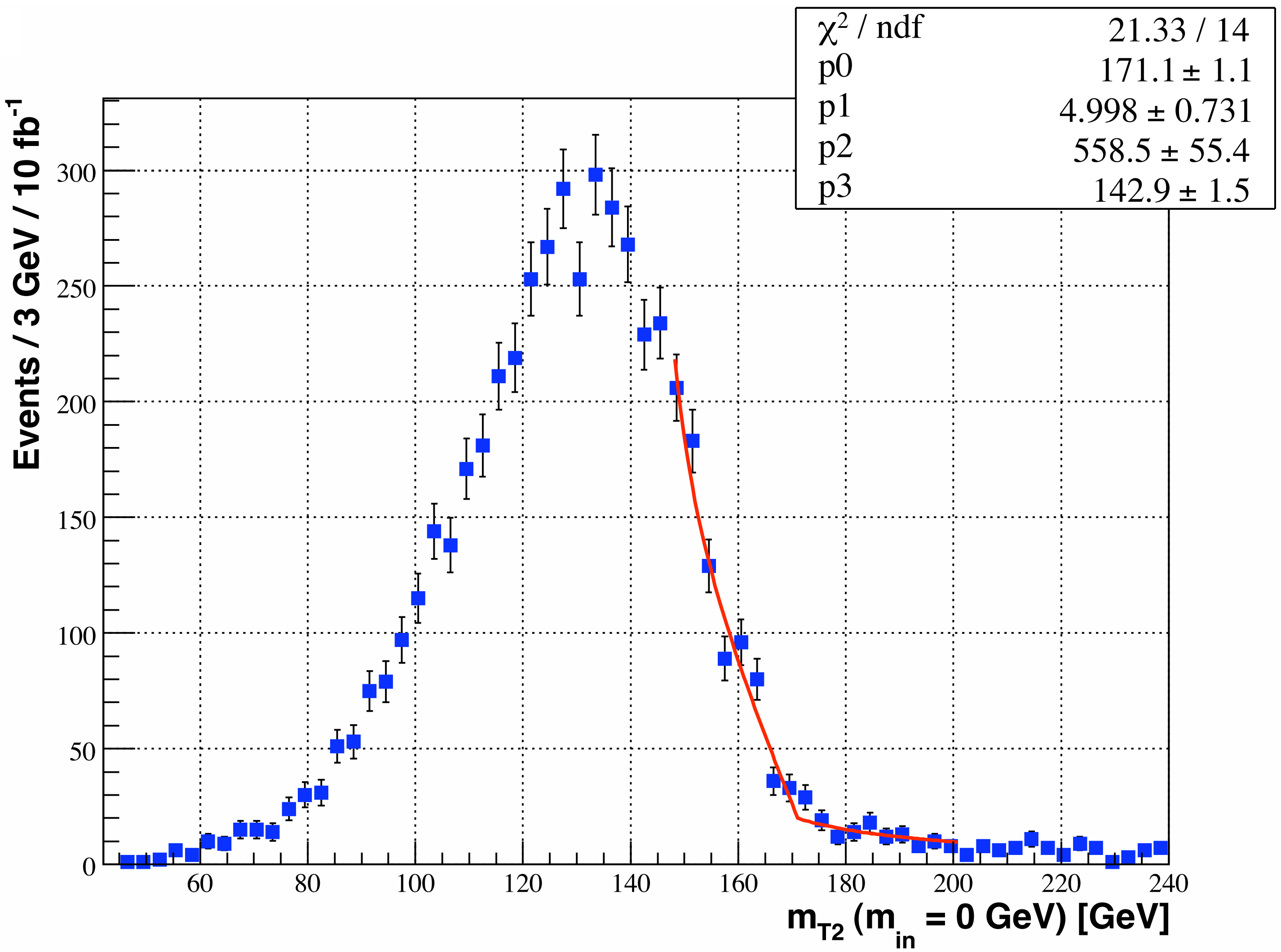


CDF, 0911.2956

- 3.4 fb^{-1} => m_t = 168.0 +5.6/-5.0 GeV (M_{T2} alone)

Top Mass from M_{T2} at LHC?

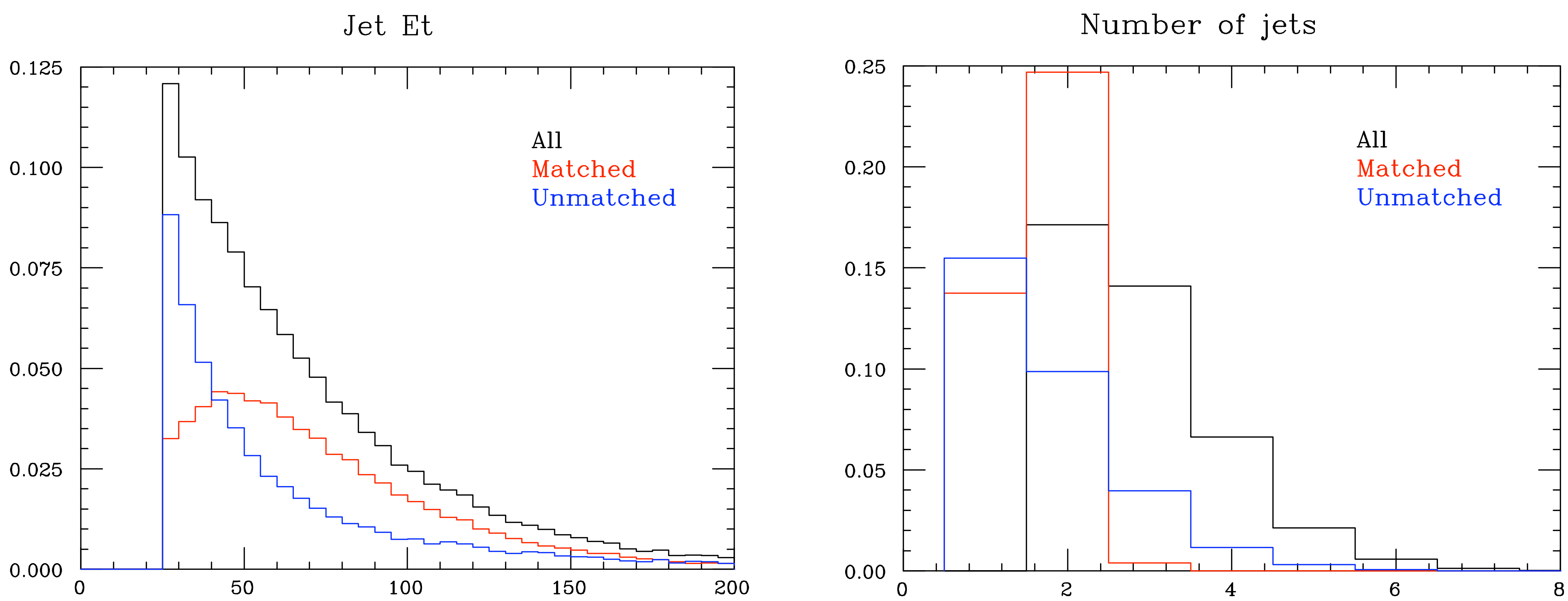
Cho, Choi, Kim & Park, 0804.2185



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

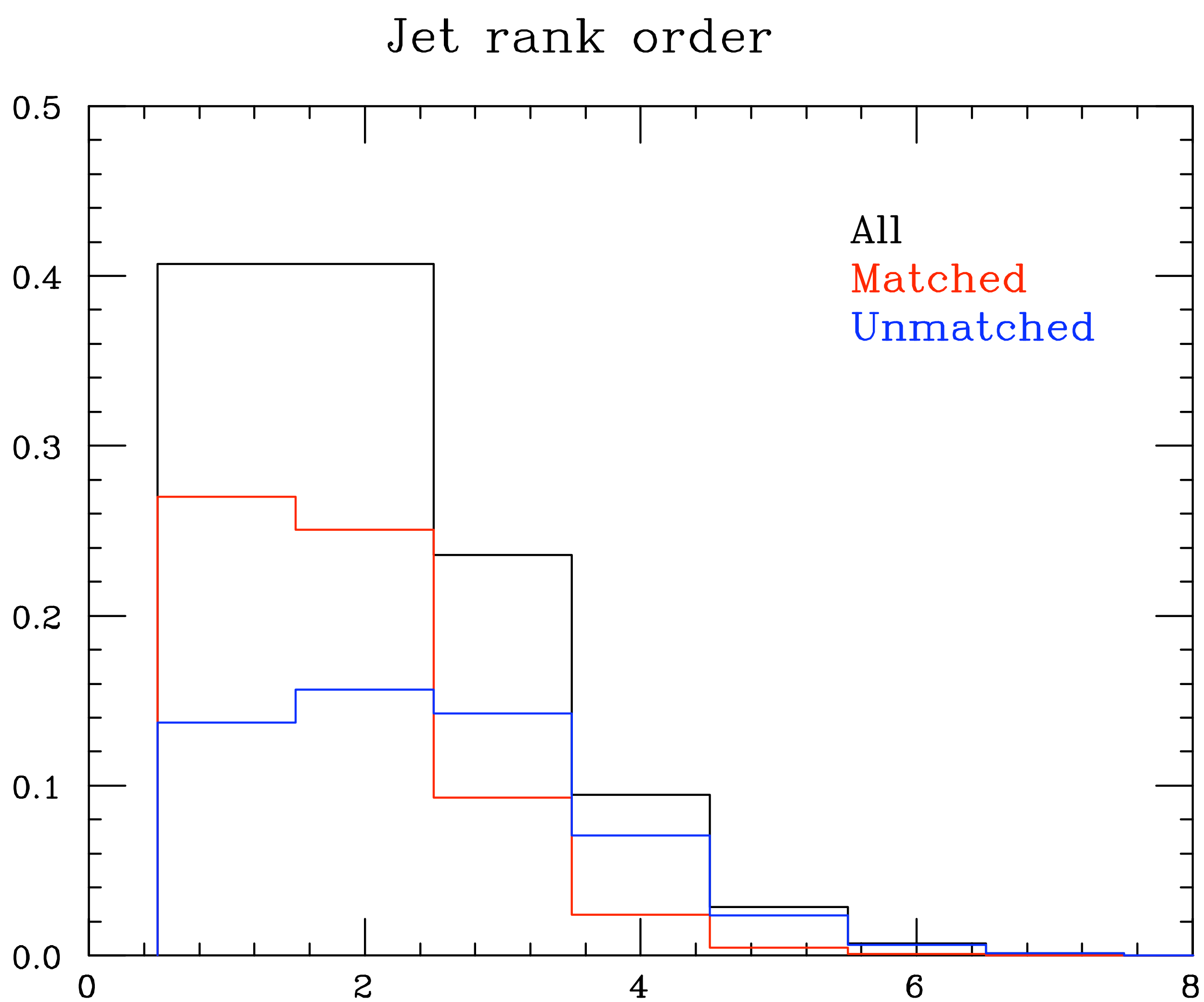
Jet contamination in $t\bar{t}$

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



➡ Half of events have an extra jet

E_T ordering of jets



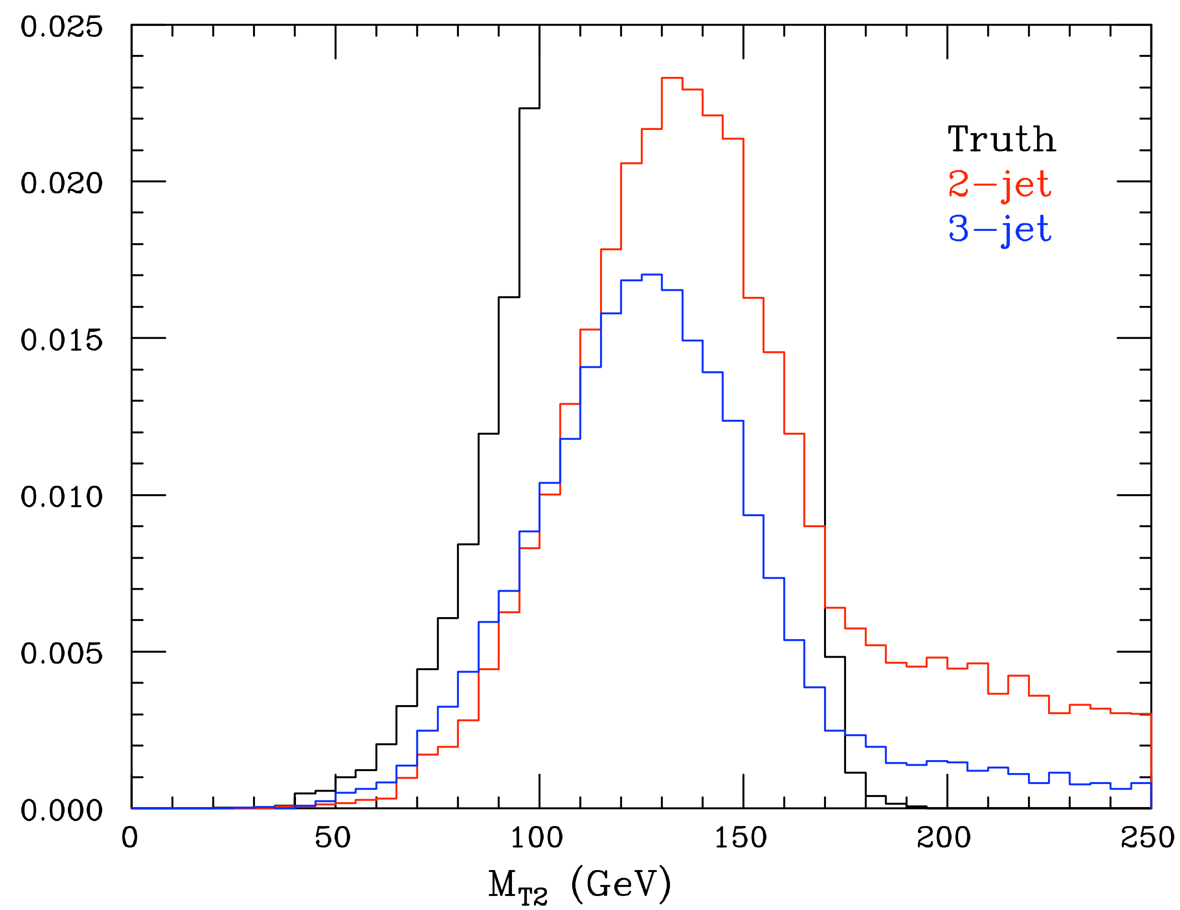
- P(1 or both leading jets unmatched) > 50%

Reducing jet contamination in $t\bar{t}$

- Idea: demand more jets, select lowest M_{T2}
  As long as one is correct, this cannot raise edge

Alwall, Hiramatsu, Nojiri & Shimizu, PRL103(2009)151802

- 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

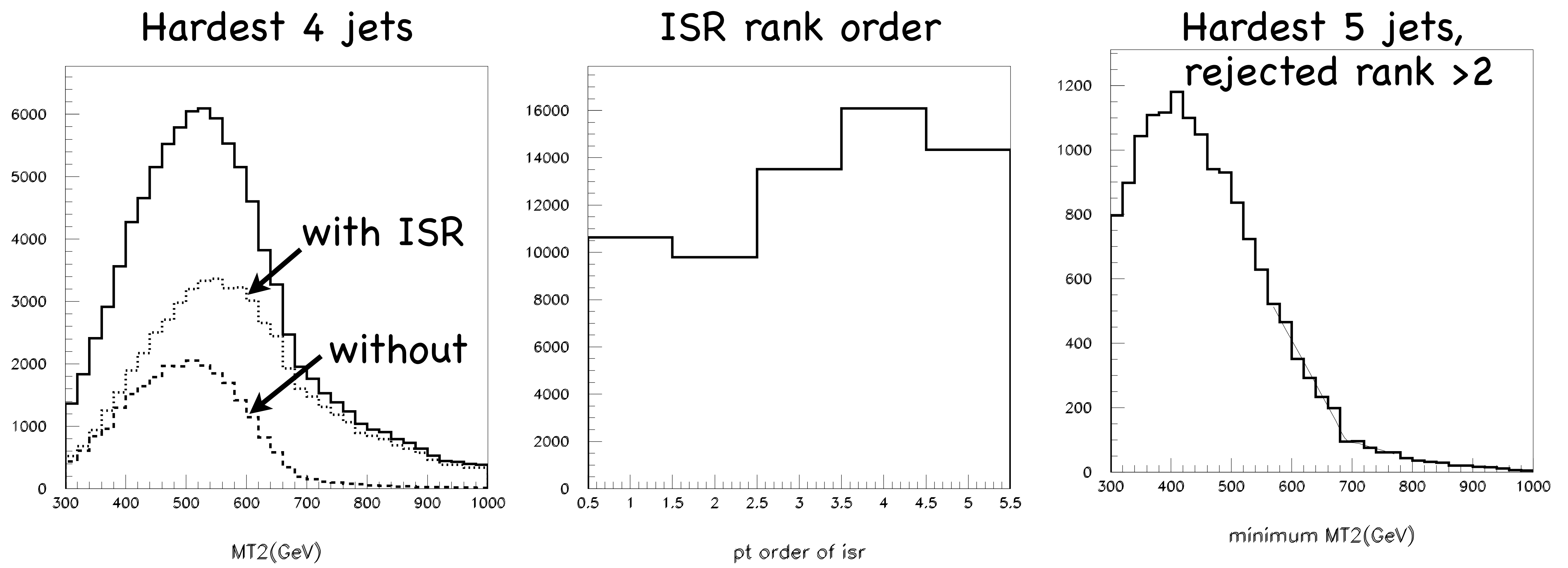


Reducing jet contamination in SUSY

Alwall, Hiramatsu, Nojiri & Shimizu, PRL103(2009)151802

- Consider $gg \to \tilde{g}\tilde{g}\,, \quad \tilde{g} \to q\bar{q}\tilde{\chi}_1^0$ at LHC (PYTHIA, 40 fb^{-1})

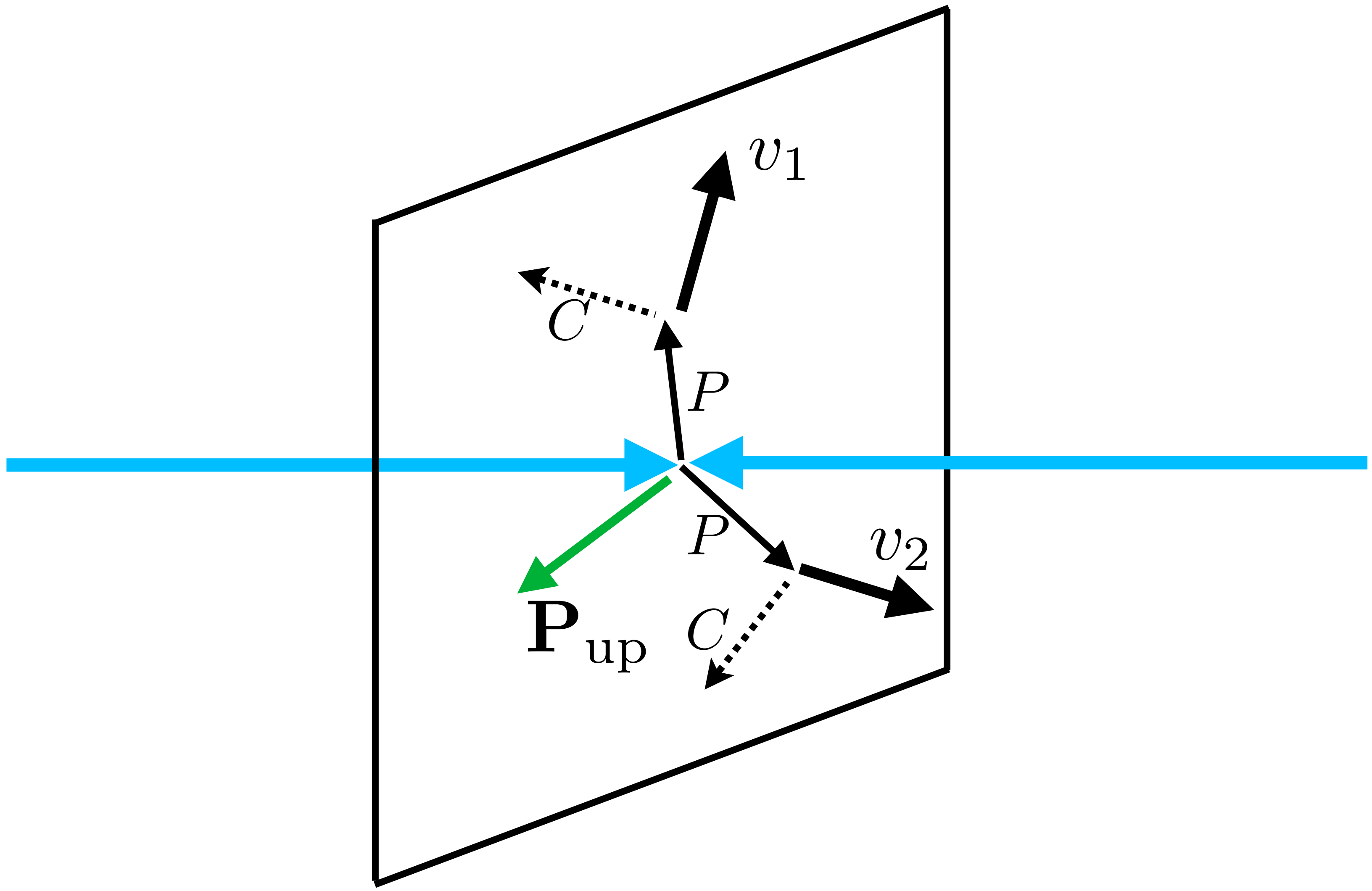
$$m_{\tilde{g}} = 685 \text{ GeV}\,,\ m_{\tilde{q}} = 1426 \text{ GeV}\,,\ m_{\tilde{\chi}_1^0} = 102 \text{ GeV}$$



- Again, endpoint is clearer for lowest M_{T2} with extra jet

$M_{CT\perp}$ Variable

Matchev & Park, 0910.1584

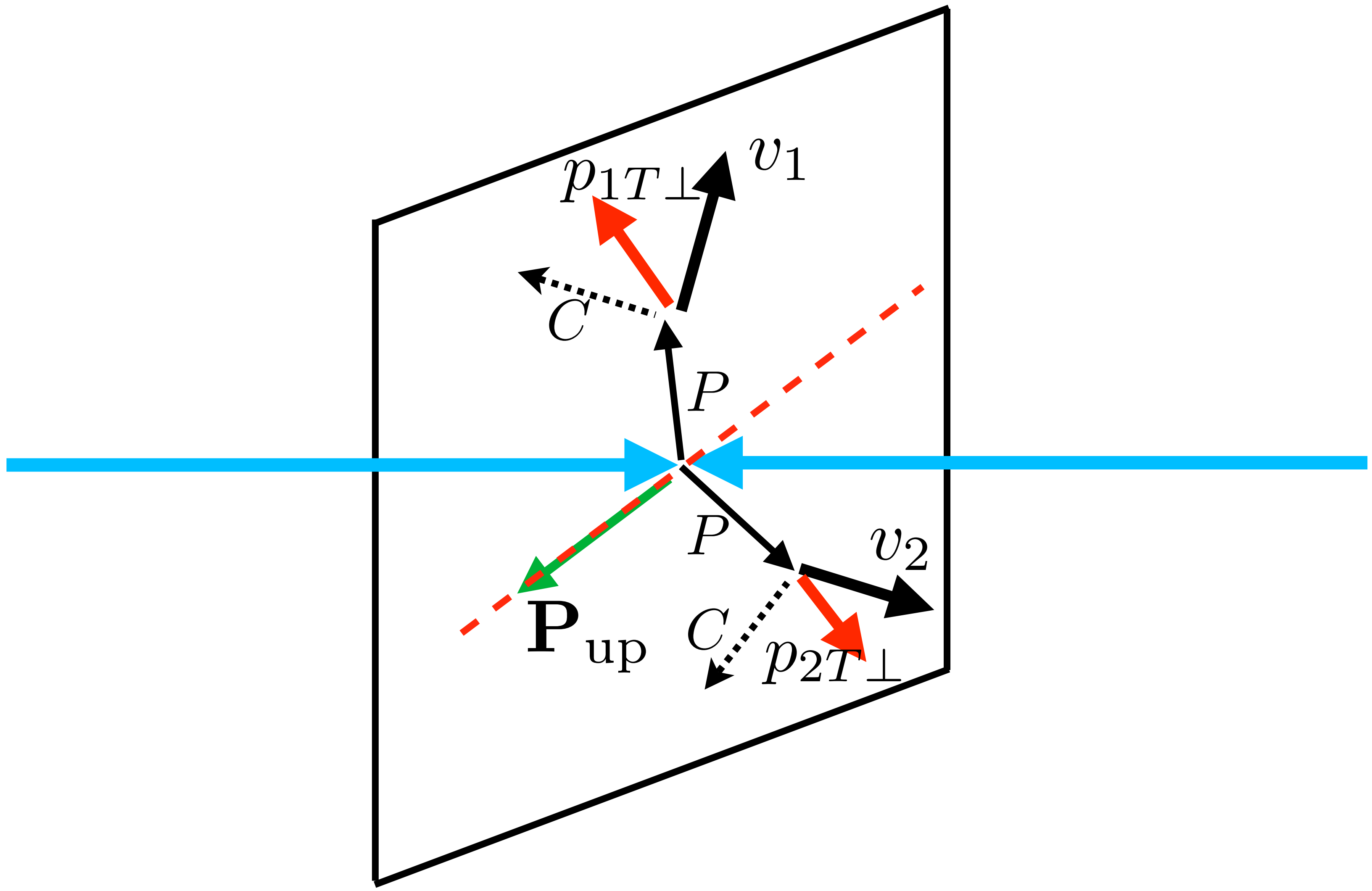


Upstream transverse momentum (ISR):

$$\mathbf{P}_{\rm up} = -(\mathbf{p}_{1T} + \mathbf{p}_{2T} + \mathbf{p}_{T\rm miss})$$

$M_{CT\perp}$ Variable

Matchev & Park, 0910.1584



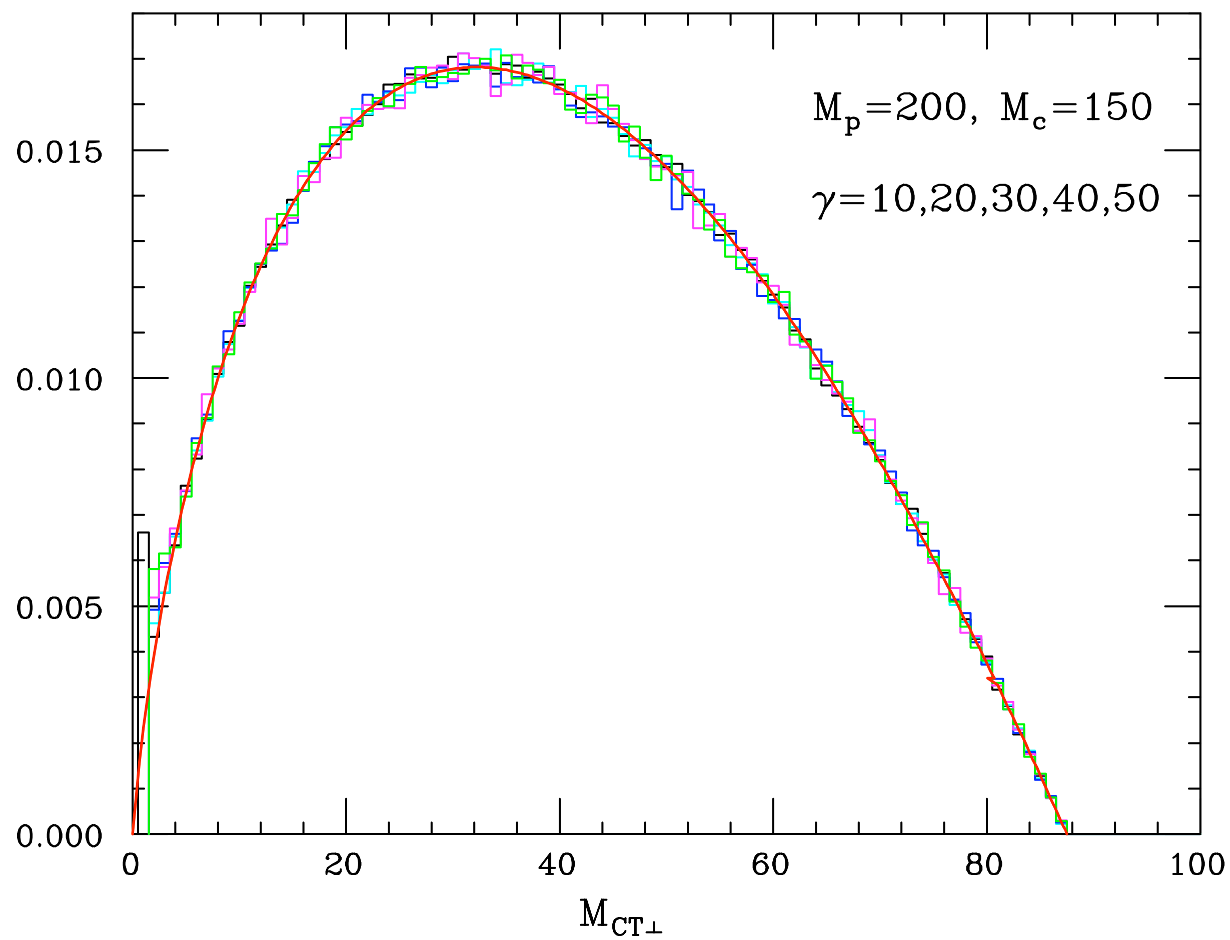
Neglecting visible masses:

$$M_{CT\perp} = 2\sqrt{p_{1T\perp}p_{2T\perp}\Theta(p_{1T\perp}p_{2T\perp})}$$

$$M_{CT\perp} = 2\sqrt{p_{1T\perp}p_{2T\perp}\Theta(p_{1T\perp}p_{2T\perp})}$$

- Phase-space distribution is universal:

$$\frac{dP}{dM_{CT\perp}} = 4\frac{M_{CT\perp}}{M_{\max}^2}\ln\frac{M_{CT\perp}}{M_{\max}} \qquad M_{\max} = \frac{M_P^2 - M_C^2}{M_P}$$

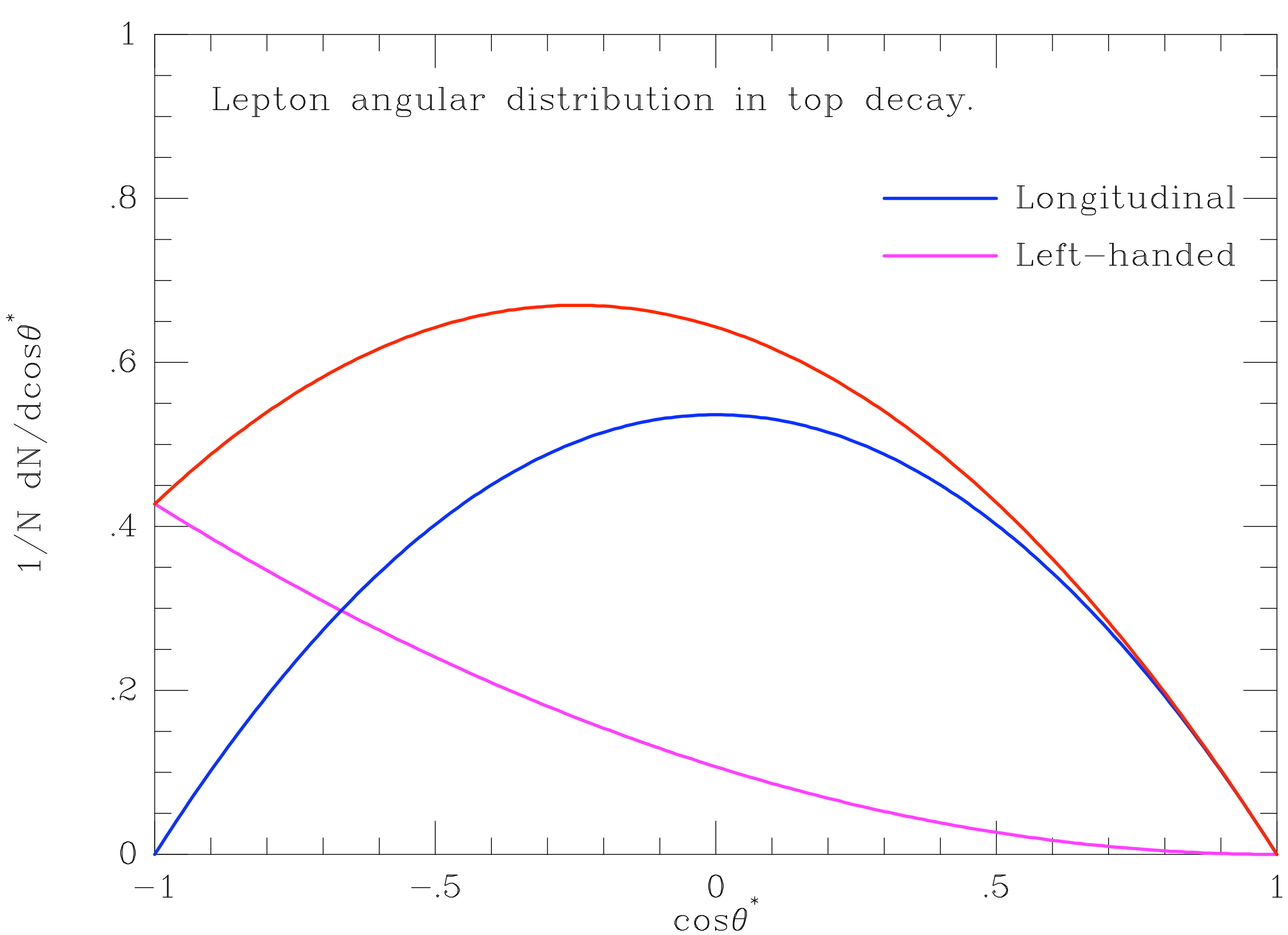


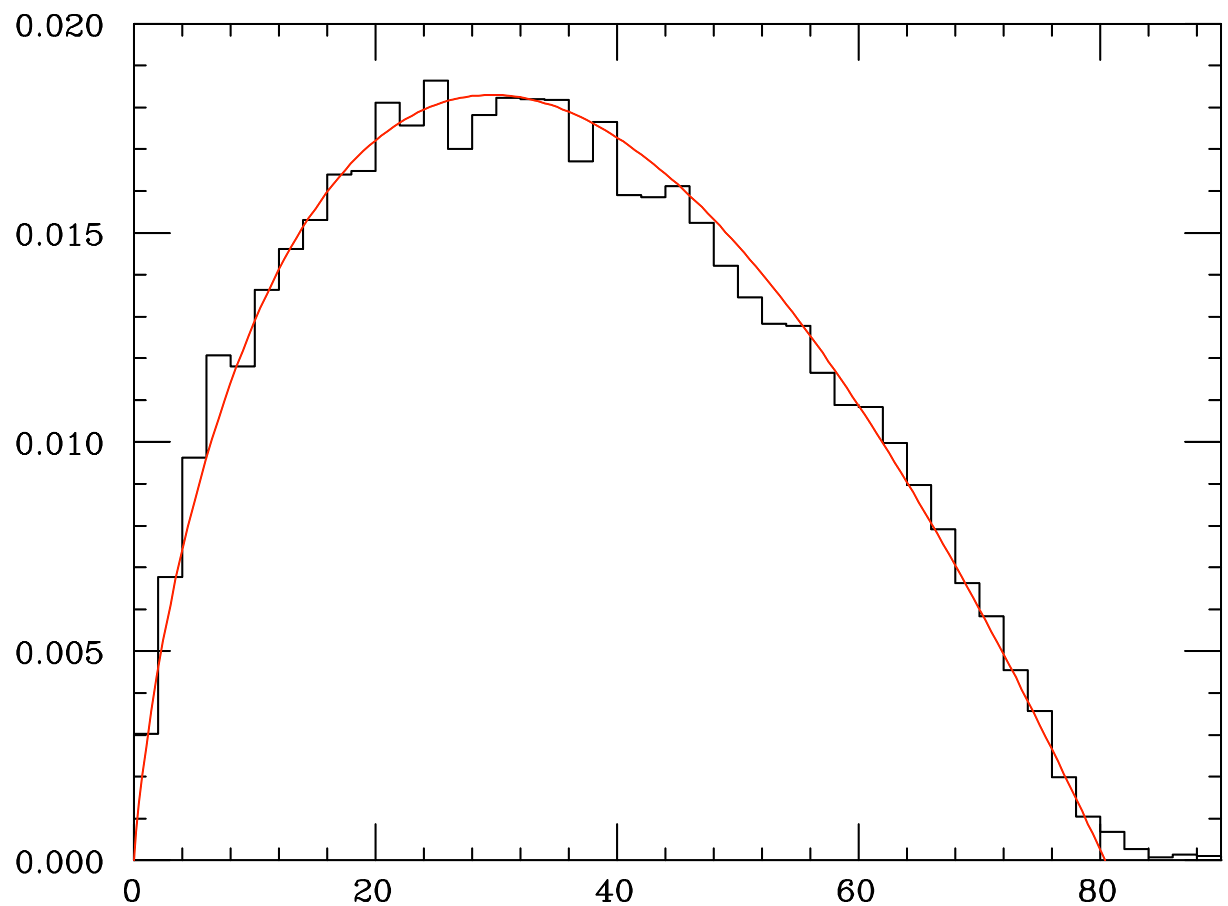
$$\gamma = \frac{\sqrt{\hat{s}}}{2M_P}$$

- Fraction of events with $p_{1T\perp}p_{2T\perp} > 0$ decreases $\sim 1/\gamma$

$M_{CT\perp}$ in Top Production (1)

- Dilepton endpoint gives W mass
- Not phase space, but still close in shape

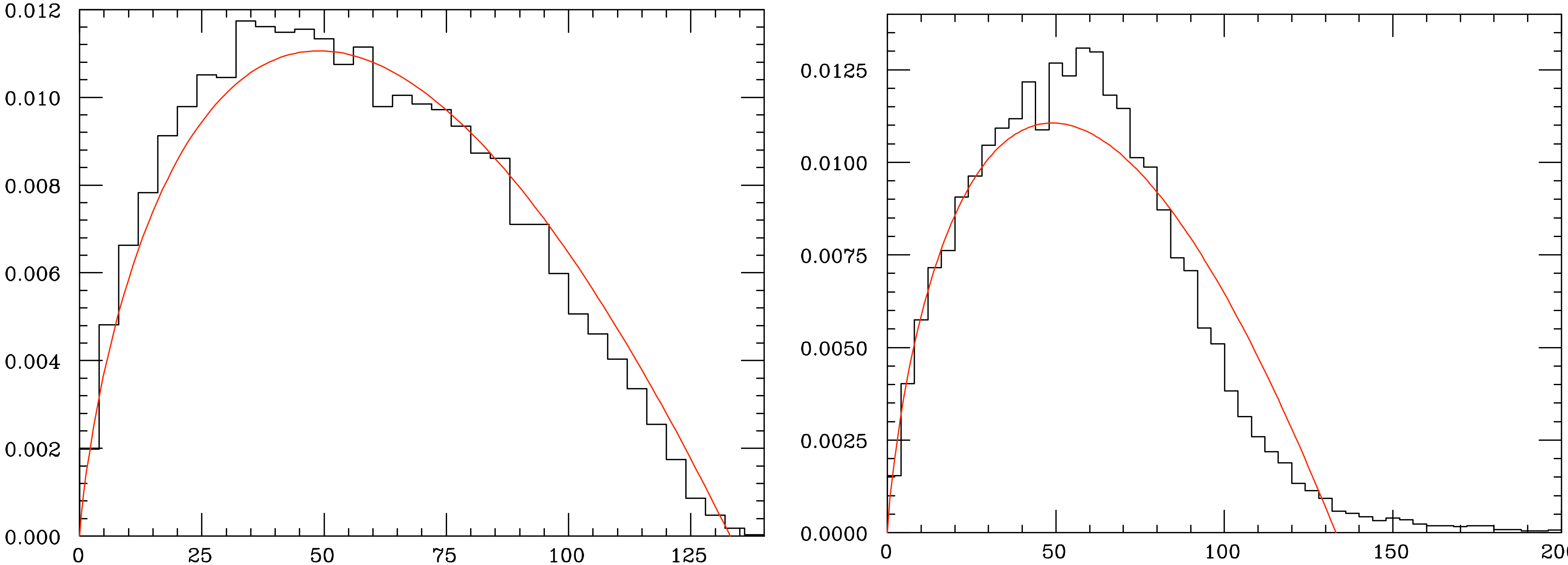




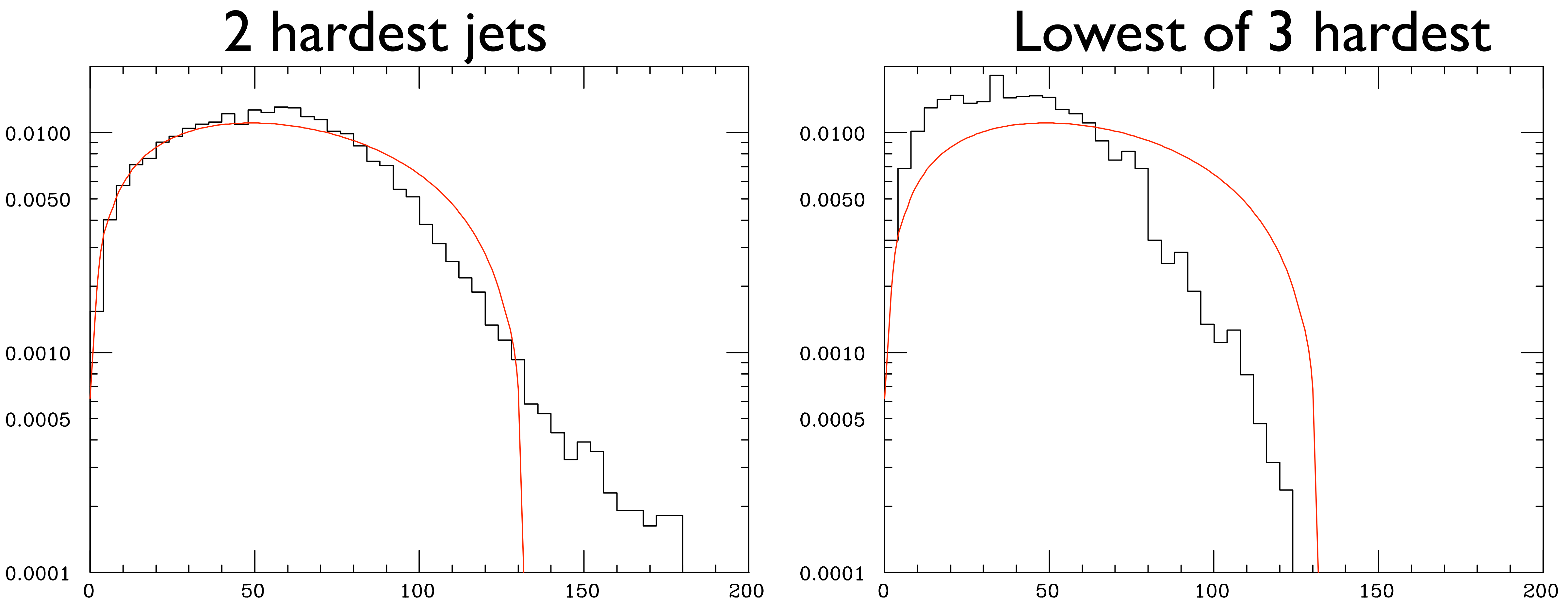
$M_{CT\perp}$ in Top Production (2)

- Quark jets endpoint $M_{\max} = \frac{M_t^2 - M_W^2}{M_t}$

Parton level | Two hardest jets



- Alwall et al. idea: demand more jets, select lowest $M_{CT\perp}$
  As long as one is correct, this cannot raise endpoint



- High-mass tail removed but shape deviates more
- Only a few percent of events have $p_{1T\perp}p_{2T\perp} > 0$
  for all 3 combinations

Conclusions

- QCD effects unavoidable at hadron colliders
  - Fixed-order, resummation & parton showers
- Matching fixed orders with parton showers
  - QCD effects in Higgs search
- Dealing with QCD initial-state radiation
  - Only transverse observables are robust
  - New ideas on reducing ISR jet contamination