MC @ NLO
a short introduction

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(based on a talk given by Bryan Webber at Les Houches)

S Frixione & BRW, JHEP 0206(2002)029 [hep-ph/0204244]; hep-ph/0207182

S Frixione, P Nason & BRW, *Matching NLO QCD and Parton Showers in Heavy Flavour Production*, CERN-TH/2003-102 [hep-ph/0305252].

Motivation

- Reliable prediction of cross sections and final-state distributions for QCD processes is important not only as a test of QCD but also for the design of collider experiments and new particle searches.
- All systematic approaches to this problem are based on perturbation theory, usually truncated at next-to-leading order (NLO).
- For the description of exclusive hadronic final states, perturbative calculations have to be combined with a model for the conversion of partonic final states int hadrons (hadronization). Existing hadronization models are in remarkably good agreement with a wide range of data, after tuning of model parameters.
- However, these models operate on partonic states with high multiplicity and low relative transverse momenta, which are obtained from a parton shower Monte Carlo (MC) approximation to QCD dynamics and not from fixed-order calculations.

Objectives

- Our aim is to develop a practical method for combining parton shower MC programs with NLO perturbative calculations (MC@NLO).
- We require MC@NLO to have the following characteristics:
  - The output is a set of events, which are fully exclusive.
  - Total rates are accurate to NLO.
  - NLO results for all observables are recovered upon expansion of MC@NLO results in α_s.
  - Hard emissions are treated as in NLO computations.
  - Soft/collinear emissions are treated as in MC.
  - The matching between hard- and soft-emission regions is smooth.
  - MC hadronization models are adopted.

Modified Subtraction

- Consider a hadron collider process which is $2 \to 2$ at LO, e.g. W^+W^- or $Q\bar{Q}$ pair production. Schematic expression for any observable O, evaluated by subtraction method, is

$$\langle O \rangle_{\text{sub}} = \sum_{ab} \int_0^1 dx_1\, dx_2\, d\phi_3\, f_a(x_1) f_b(x_2) \Big[O^{(2\to 3)} \mathcal{M}_{ab}^{(h)}(x_1, x_2, \phi_3)$$
$$+ \; O^{(2\to 2)} \left(\mathcal{M}_{ab}^{(b,v,c)}(x_1, x_2, \phi_2) - \mathcal{M}_{ab}^{(c.t.)}(x_1, x_2, \phi_3) \right) \Big]$$

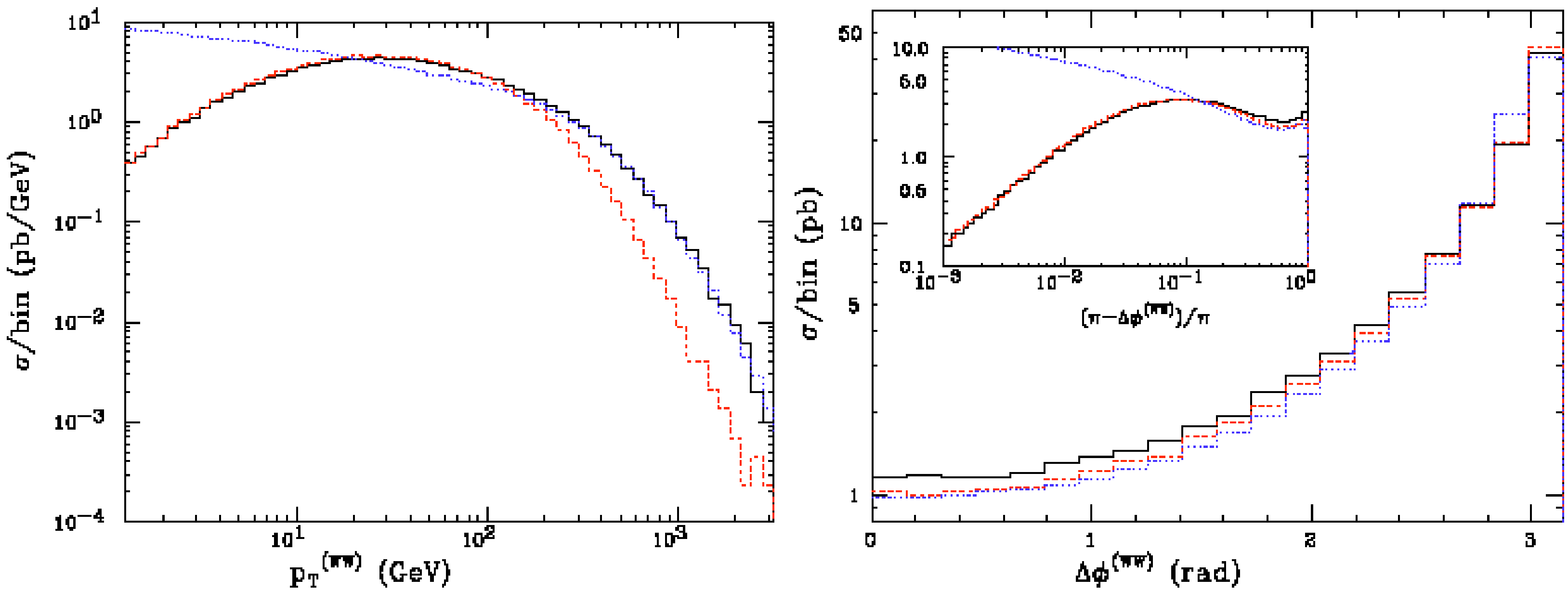
  - $\mathcal{M}_{ab}^{(h)}$ is NLO real-emission contribution;
  - $\mathcal{M}_{ab}^{(b,v,c)}$ are LO Born, NLO virtual and collinear (finite parts);
  - $\mathcal{M}_{ab}^{(c.t.)}$ are counter-terms which cancel divergences of $\mathcal{M}_{ab}^{(h)}$.

- Naively, for MC@NLO we would replace $O^{(2\to 2,3)}$ by $\mathcal{F}_{\text{MC}}^{(2\to 2,3)}$ (MC generating functionals starting from $2 \to 2, 3$ hard subprocesses), to obtain $\mathcal{F}_{\text{MC@NLO}}$.

- This would be WRONG because $\mathcal{F}_{\text{MC}}^{(2\to 2)}$ also generates $2 \to 3$ configurations, which must be subtracted from weight of $\mathcal{F}_{\text{MC}}^{(2\to 3)}$ (and added to that of $\mathcal{F}_{\text{MC}}^{(2\to 2)}$)

…so the tricky part of the whole business is to figure out what Herwig is doing at NLO

W^+W^- observables



These correlations are problematic: the soft and hard emissions are both relevant. MC@NLO does well, resumming large logarithms, and yet handling the large-scale physics correctly

Solid: MC@NLO

Dashed: HERWIG$\times\frac{\sigma_{NLO}}{\sigma_{LO}}$

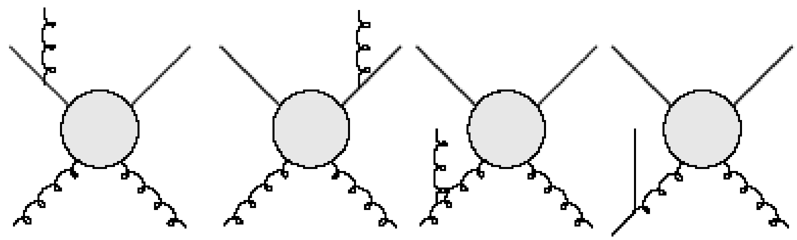
Dotted: NLO

Heavy Quark Production

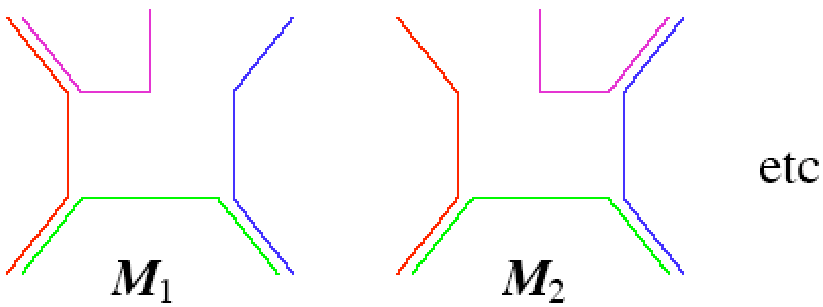
- Modified subtraction formula above can be used for any process.
  - Take standard subtraction formula;
  - Calculate analytically exactly what MC does at NLO;
  - Insert $\mathcal{M}_{ab}^{(\mathrm{MC})}(x_1, x_2, \phi_3)$ terms;
  - Generate $2 \to 2$ and $2 \to 3$ parton configurations and weights;
  - Feed into MC (using Les Houches interface, hep-ph/0109068).
- Most difficult part is calculating what MC does!
  - Details in hep-ph/0305252 (S Frixione, P Nason & BW)

MC Heavy Quark Production

- MC starts from $2 \to 2$ subprocess $\Rightarrow$ momentum reshuffling is done after real emission.

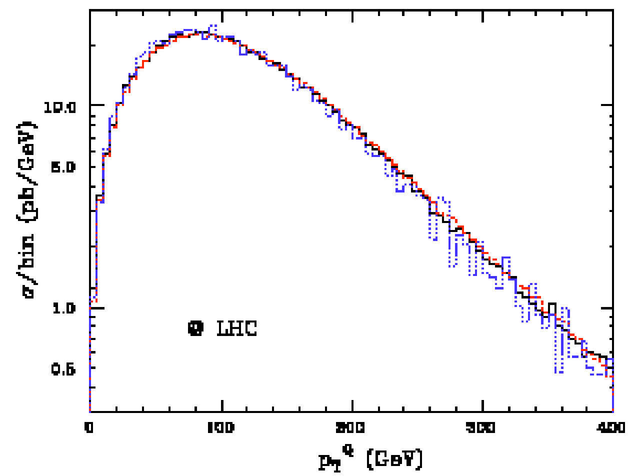


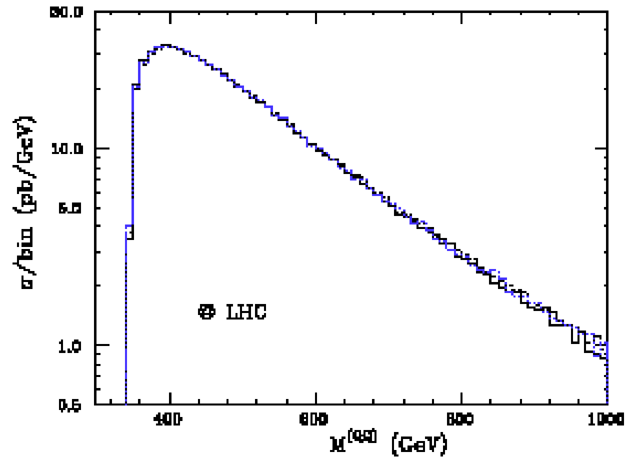
- Relation between invariants and shower variables depends on which leg emits!
- Colour structure assigned (for shower/hadronization) according to $N \to \infty$ limit

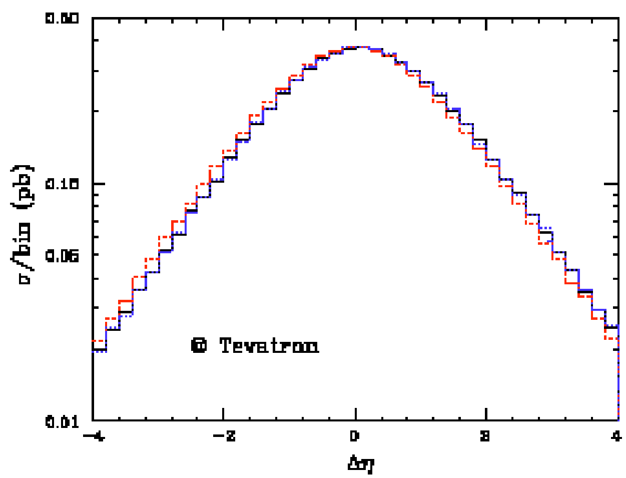


$$\text{Prob}_i = |\sum_j M_j^{(3)}|^2 \; |M_i^{(\infty)}|^2 / \sum_j |M_j^{(\infty)}|^2$$

t, $\bar{t}$ Observables at Colliders







Solid: MC@NLO

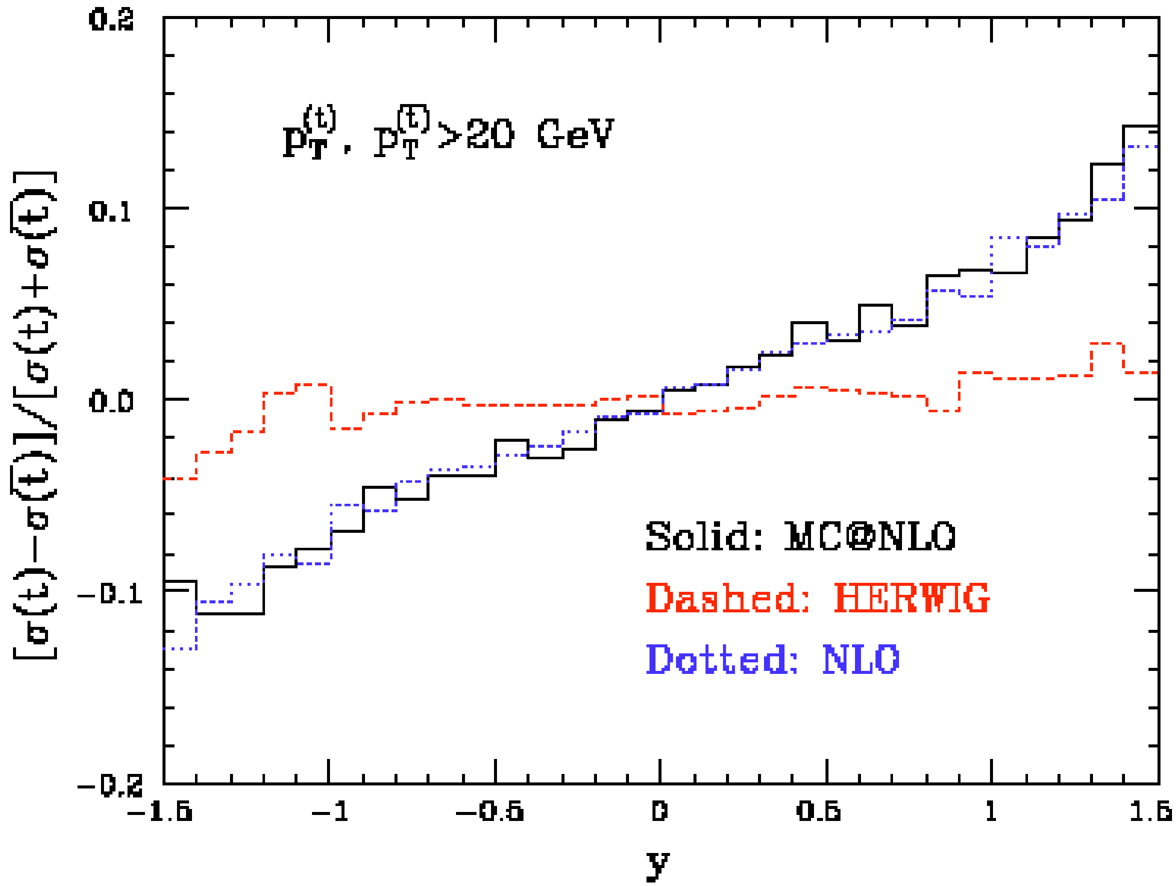
Dashed: HERWIG$\times\frac{\sigma_{NLO}}{\sigma_{LO}}$

Dotted: NLO

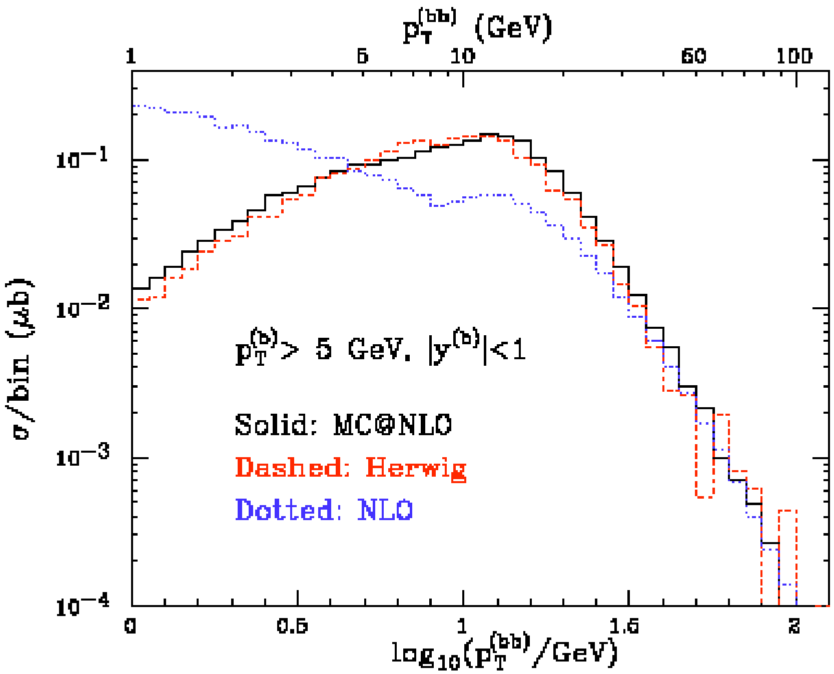
MC@NLO $\simeq$ NLO here.

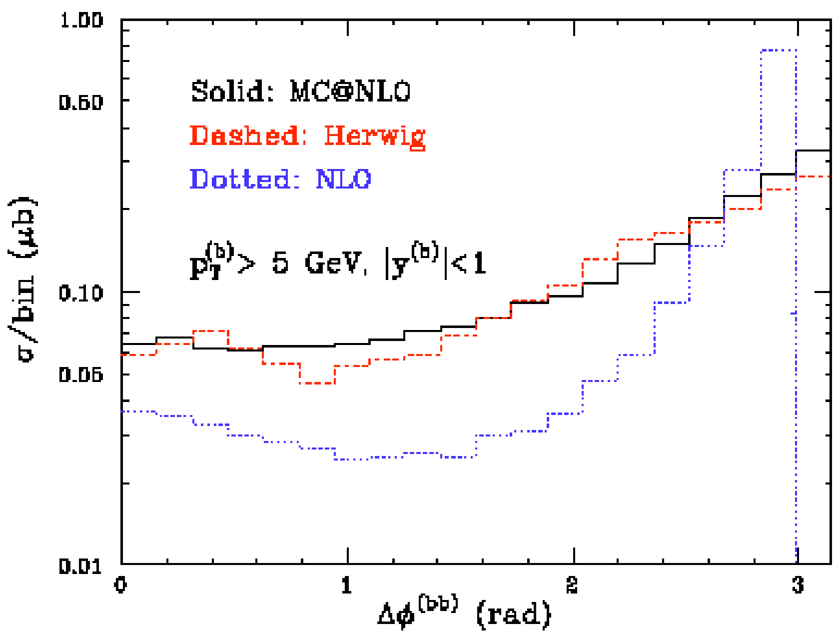
New feature in MC: $Q\overline{Q}$ asymmetry at Tevatron.

Top Rapidity Asymmetry at Tevatron



$b\bar{b}$ Correlations at Tevatron





HERWIG does surprisingly well (after cuts) but needs much more CPU: 14 million events vs 1 million for MC@NLO

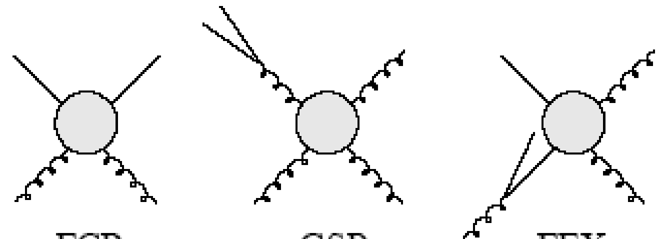
Solid: MC@NLO

Dashed: HERWIG (no K-factor)

Dotted: NLO

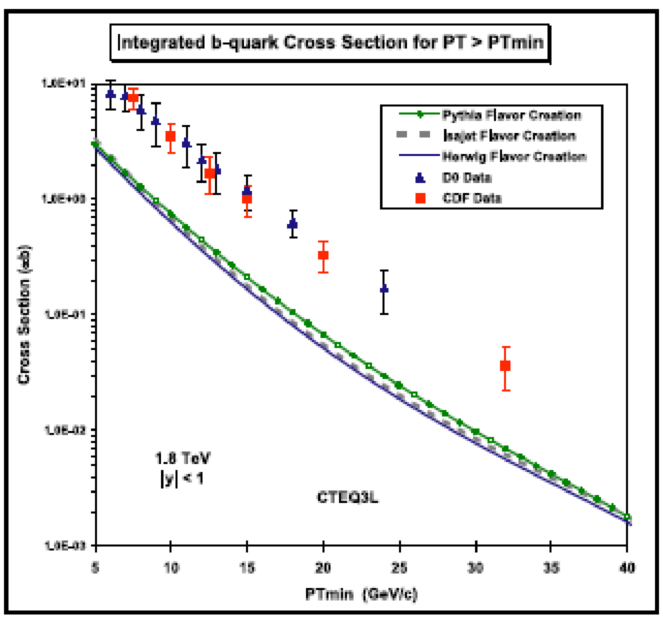
b Production with HERWIG

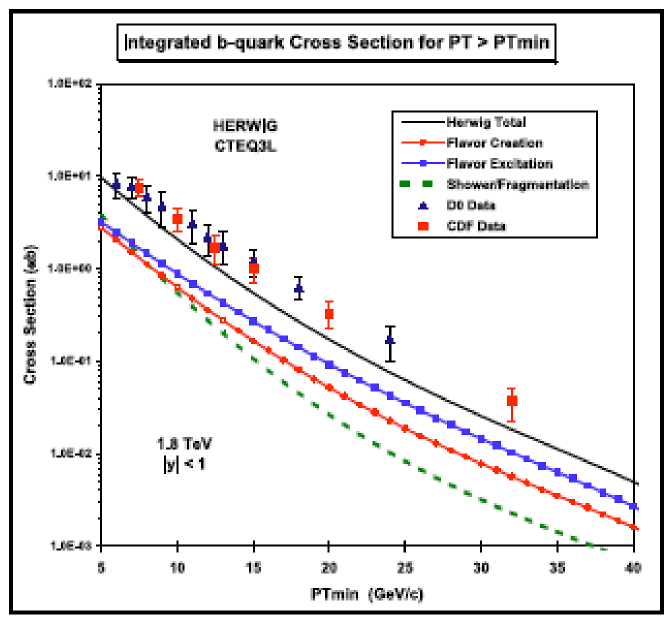
- In parton shower MC's, 3 classes of processes can contribute:



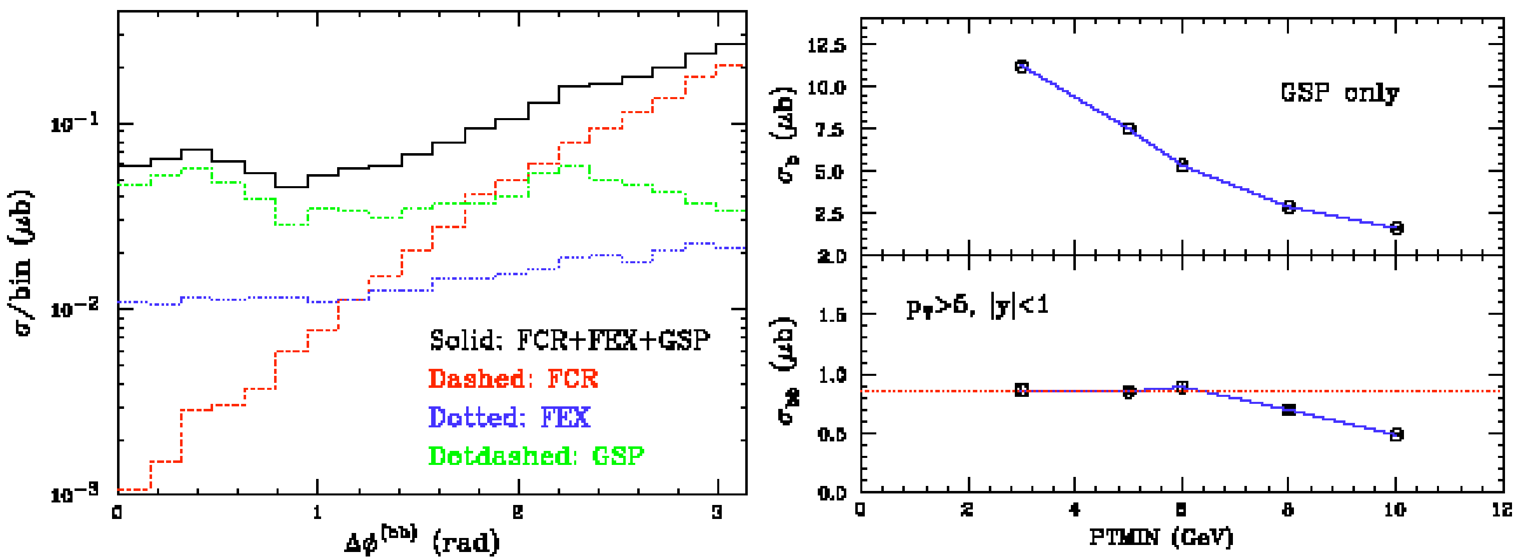
FCR GSP FEX

- All are needed to get close to data (RD Field, hep-ph/0201112):





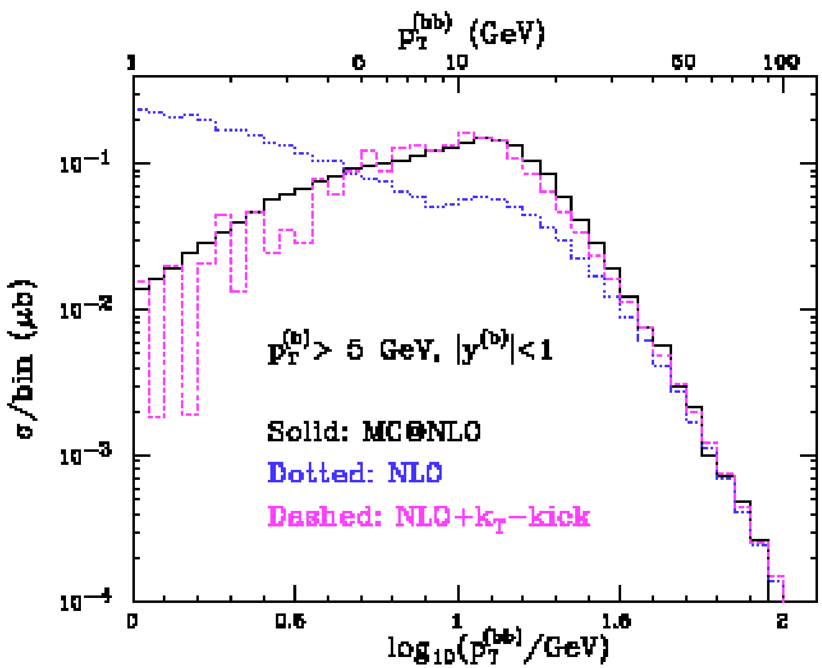
GSP and FEX contributions in HERWIG

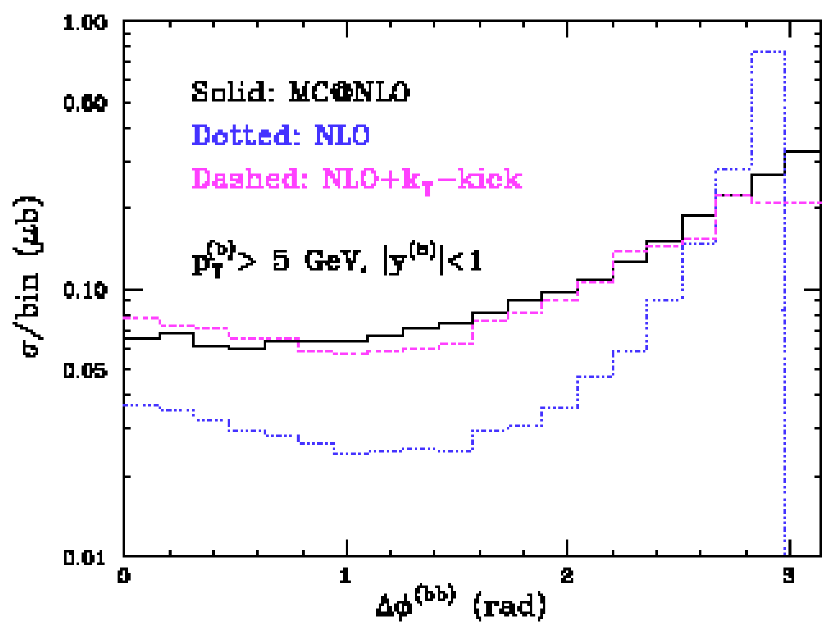


- GSP, FEX and FCR are complementary and all must be generated
  - GSP cutoff (PTMIN) sensitivity depends on cuts and observable
  - FEX sensitive to bottom PDF
  - GSP efficiency very poor, $\sim 10^{-4}$
- All these problems are avoided with MC@NLO!

NLO + k_T-kick vs MC@NLO

- (NLO + k_T-kick) with $\langle k_T \rangle = 4$ GeV $\simeq$ MC@NLO (at Tevatron)





- This does NOT mean that there is $\langle k_T \rangle = 4$ GeV inside proton: it simply emulates the effect of initial-state parton showers.

Conclusions

- If you can run Herwig, you can run MC@NLO
  - in fact, re-use the HWANAL files that you've used with Herwig
- Processes incorporated in 2.2
  - diboson
  - W/Z/Drell-Yan
  - heavy flavor
  - Higgs
- Next
  - inclusive jets
- See http://www.hep.phy.cam.ac.uk/theory/webber/MCatNLO
- Mary will now show the first comparisons (that I know of) of MC@NLO to collider data