

LHC Simulations

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From Strings to LHC II Advanced School

Fireflies Ashram, Bangalore, 11-18 December 2007

See also

ESW: “QCD and Collider Physics”, C.U.P. 1996

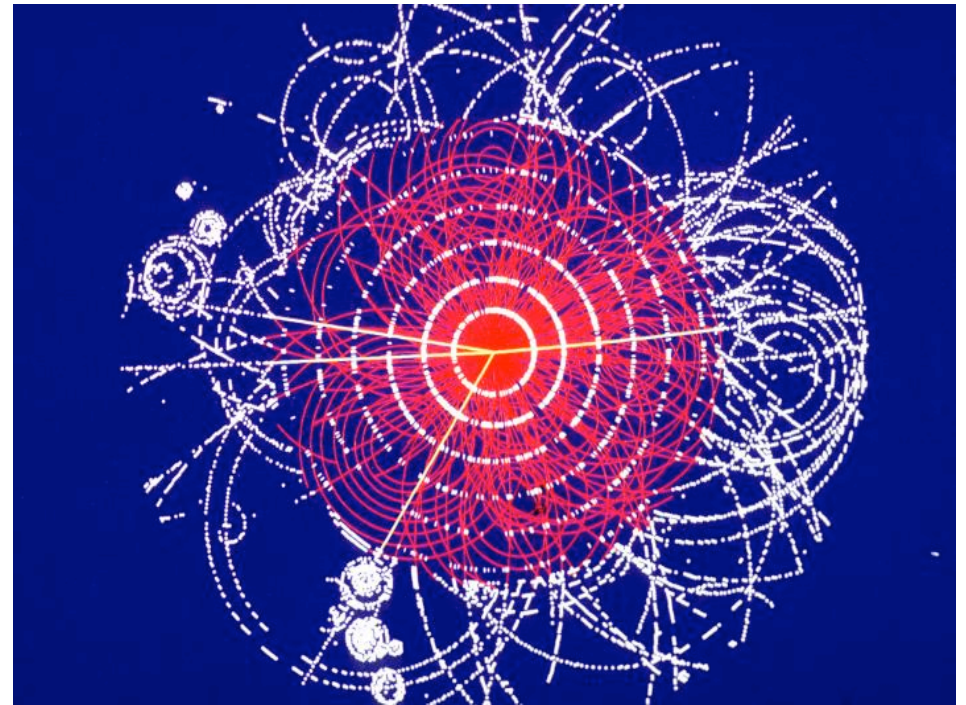
<http://www.hep.phy.cam.ac.uk/theory/webber/QCDupdates.html>

http://www.hep.phy.cam.ac.uk/theory/webber/QCD_03/

Thanks to Mike Seymour, Torbjörn Sjöstrand, Frank Krauss, Peter Richardson,...

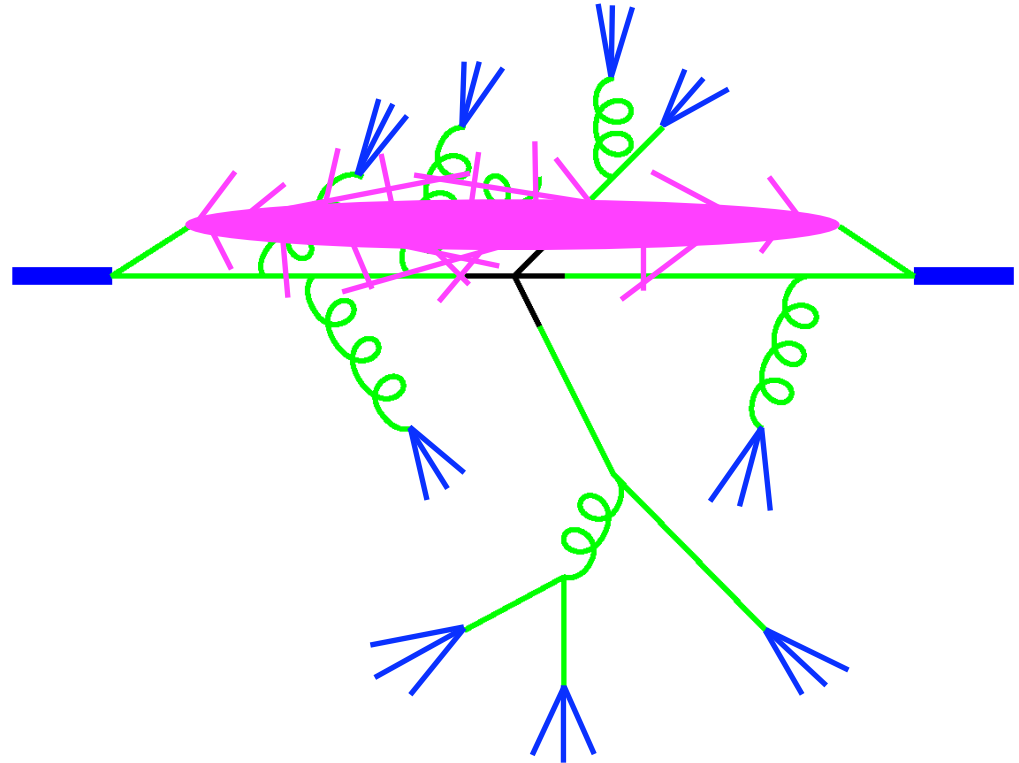
LHC Simulations

- Basic Principles
- Event Generation
- Parton Showers
- Hadronization
- Underlying Event
- Event Generator Survey
- Matching to Fixed Order



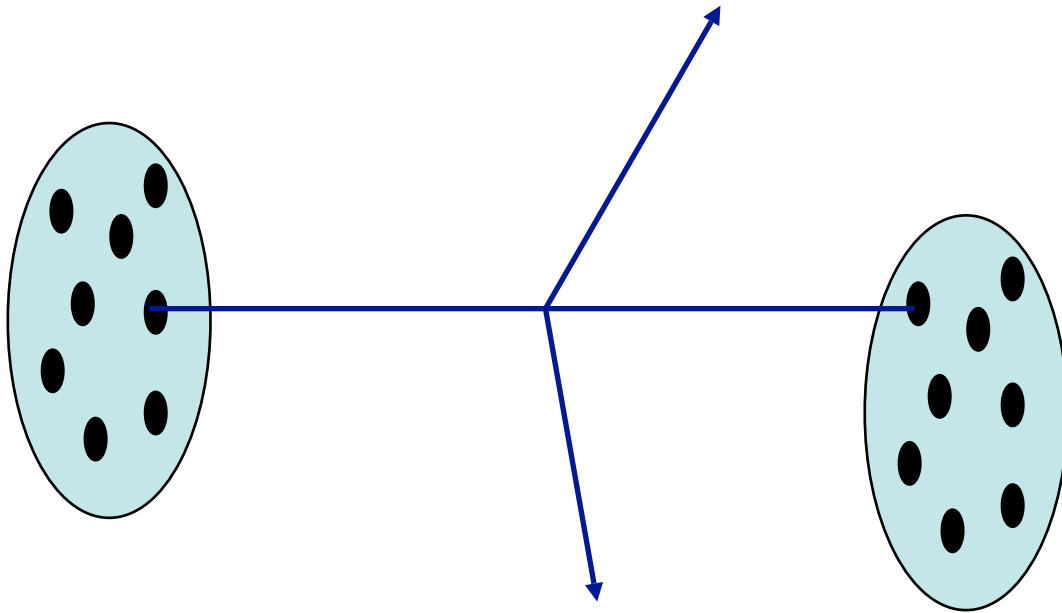
Structure of LHC Events

1. Hard process
2. Parton shower
3. Hadronization
4. Underlying event



The Underlying Event

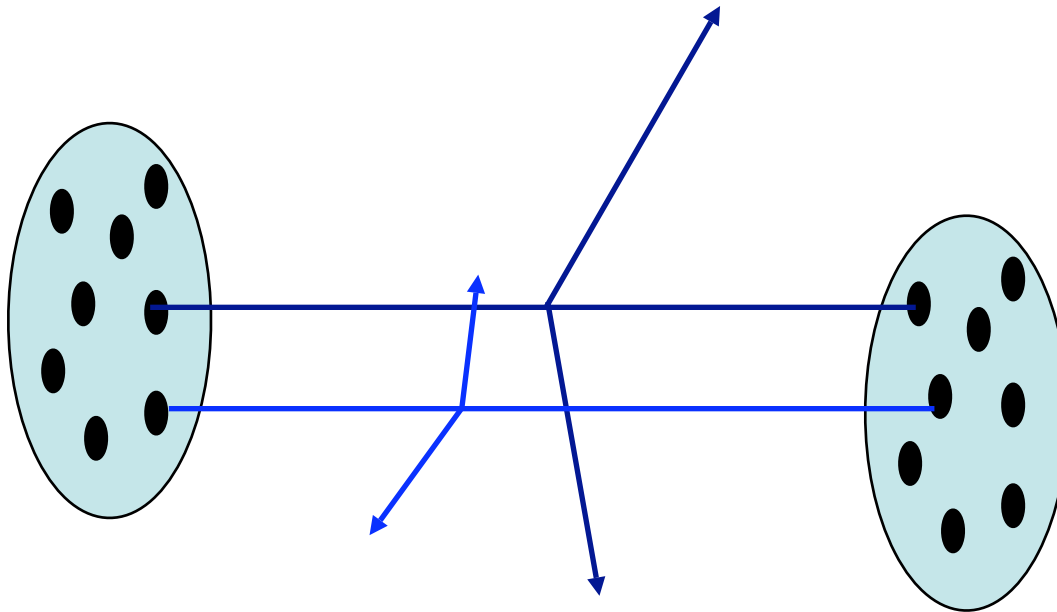
- Protons are extended objects
- After a parton has been scattered out of each, what happens to the remnants?



Multiparton Interaction Model (PYTHIA/JIMMY)

For small $p_{t \min}$ and high energy inclusive parton—parton cross section is larger than total proton—proton cross section.

→ More than one parton—parton scatter per proton—proton



Need a model of spatial distribution within proton

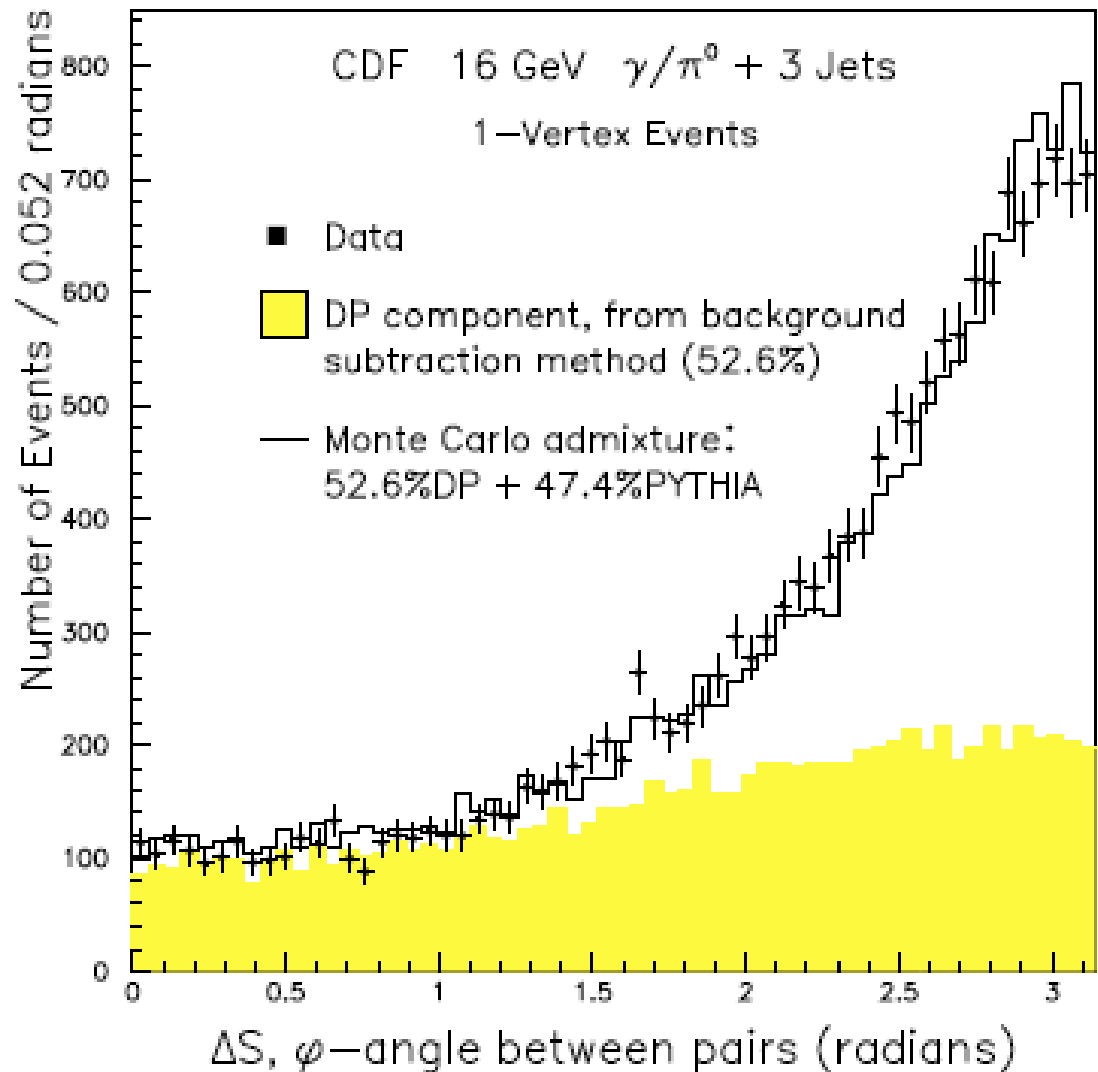
→ Perturbation theory gives n-scatter distributions

Double Parton Scattering

- CDF Collaboration,
PR D56 (1997) 3811

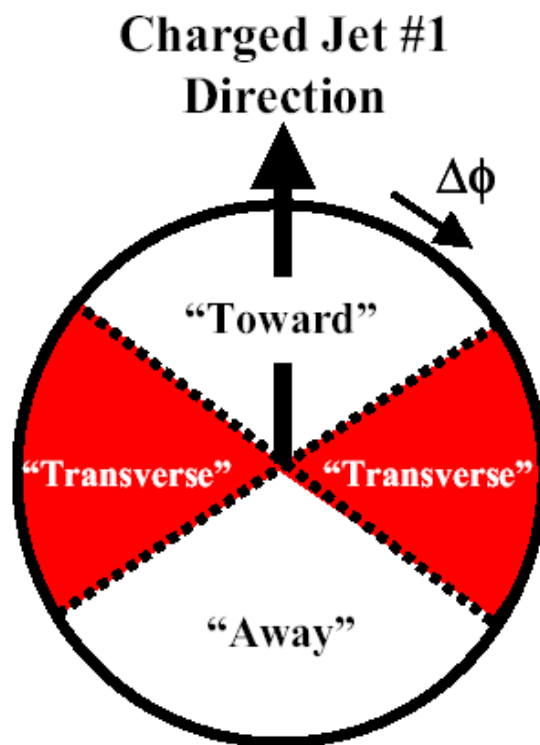
$$\sigma_{\text{DPS}} = \frac{\sigma_{\gamma j} \sigma_{jj}}{\sigma_{\text{eff}}}$$

$$\sigma_{\text{eff}} = 14 \pm 1.7^{+1.7}_{-2.3} \text{ mb}$$



Tevatron Comparisons

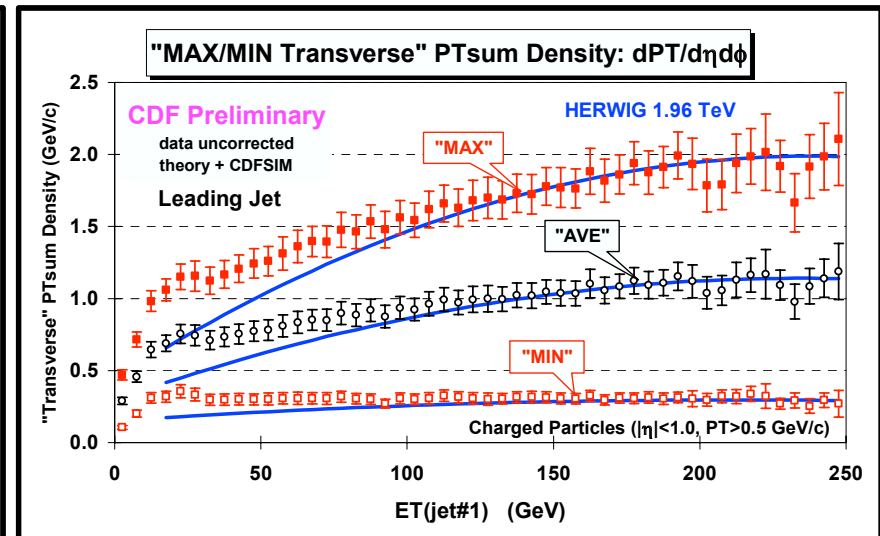
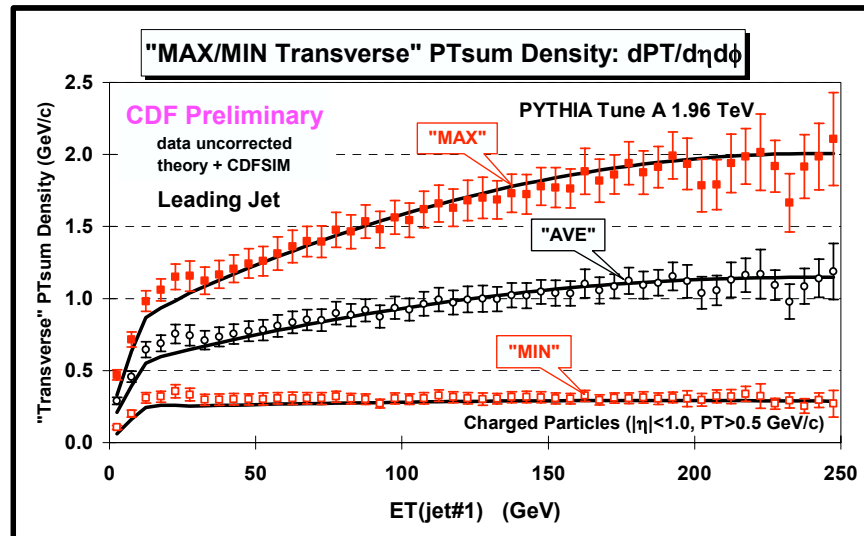
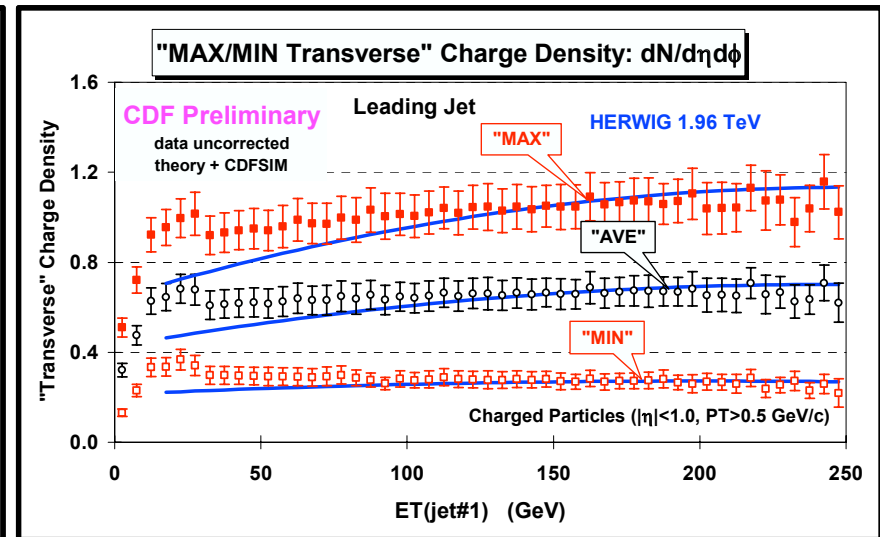
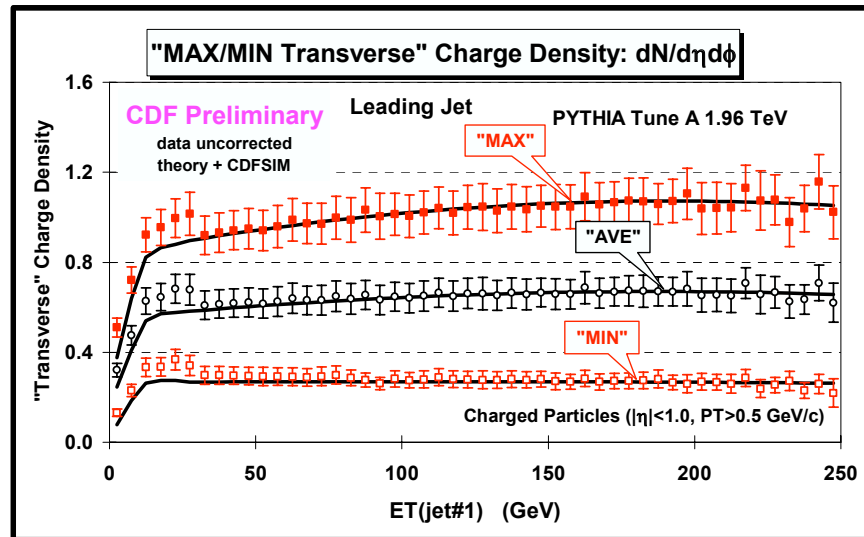
- N.B. not everyone means same thing by “underlying event”
 - Remnant—remnant interaction
 - Everything except hard process final state
- Separation into components is model dependent
 - Operational definition (R Field): “transverse” regions



Leading Jet: "MAX & MIN Transverse" Densities

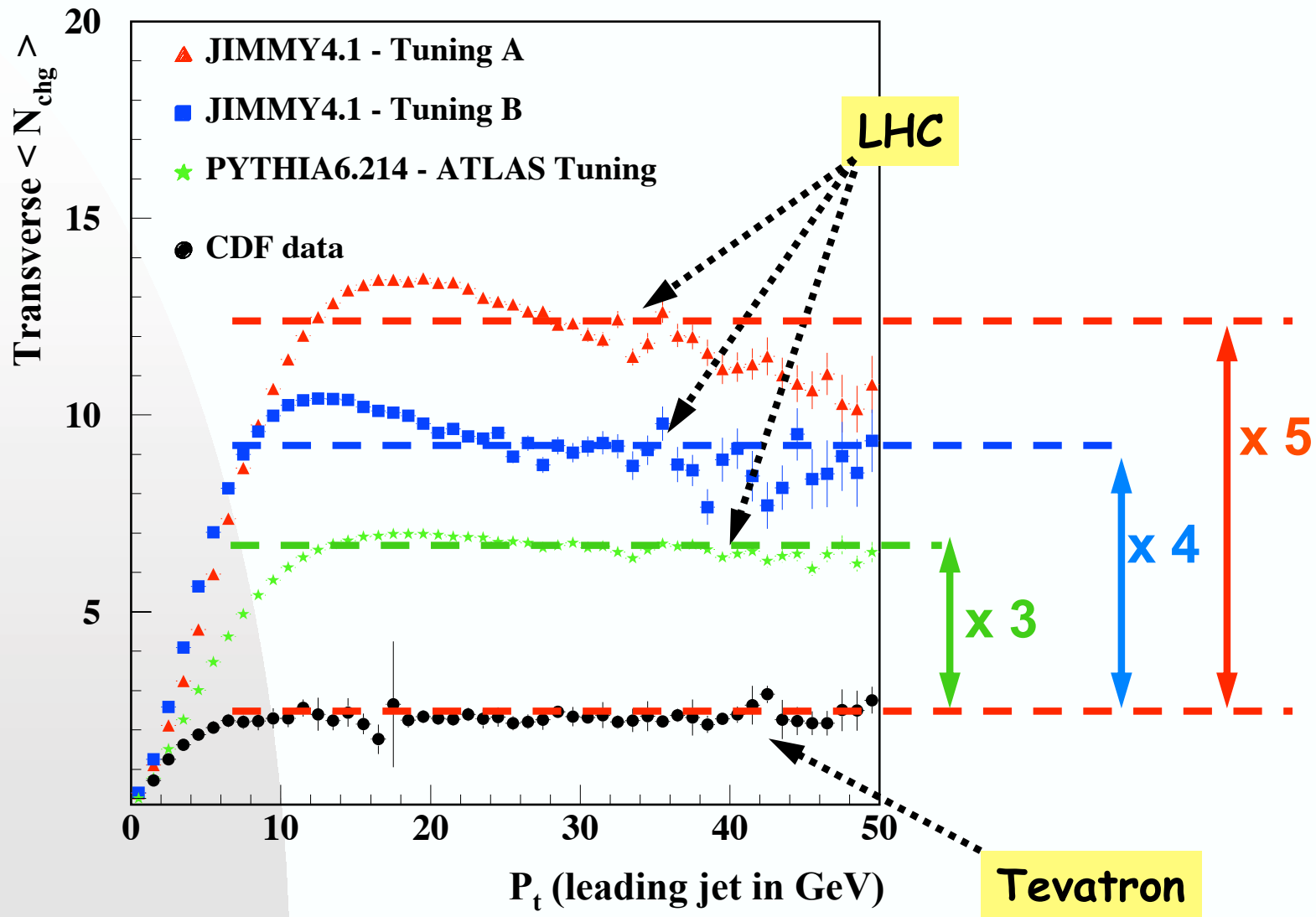
PYTHIA Tune A

HERWIG



Charged particle density and PTsum density for "leading jet" events versus $E_T(\text{jet}\#1)$ for PYTHIA Tune A and HERWIG.

Extrapolation to LHC



A. M. Moraes

Minimum-bias and the Underlying Event at the LHC

5th November 2004

Event Structure Summary

- Hard Process is very well understood: firm perturbative basis
- Parton Shower is fairly well understood: perturbative basis, with various approximations
- Hadronization is less well understood: modelled, but well constrained by data. Extrapolation to LHC fairly reliable.
- Underlying event least understood: modelled and only weakly constrained by existing data. Extrapolation?
- Always ask “What physics is dominating this effect?”

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++

Object Oriented Event Generators

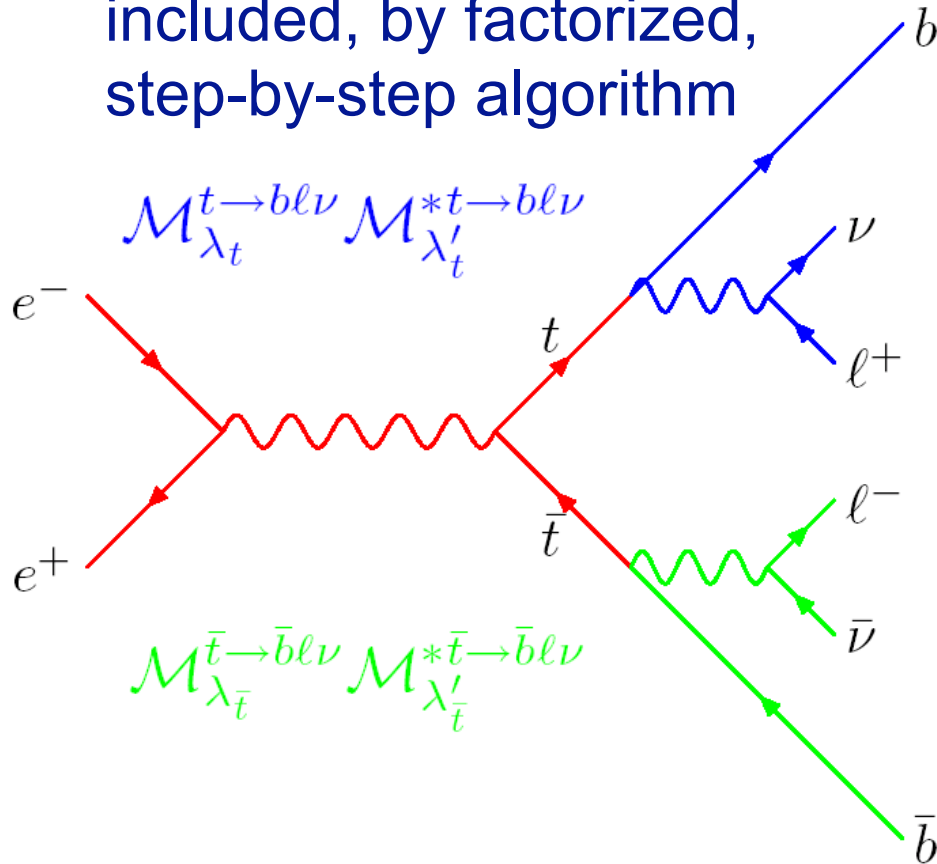
- ThePEG: Toolkit for High Energy Physics Event Generation, used by Herwig++ (and ARIADNE++?)
- Herwig++: Physics improvements from HERWIG 6
- PYTHIA 8: Implementation of physics of PYTHIA 6 plus some improvements: see <http://www.thep.lu.se/~torbjorn>
- SHERPA: Completely new event generator

<http://projects.hepforge.org/>

Herwig++ Spin Correlations

- Example: top quark pairs in e^+e^- annihilation:

Full spin correlations included, by factorized, step-by-step algorithm



$$\rho_{\text{prod}}^{\lambda_c \lambda'_c \lambda_d \lambda'_d} = \mathcal{M}_{ab \rightarrow cd}^{\lambda_c \lambda_d} \mathcal{M}_{ab \rightarrow cd}^{* \lambda'_c \lambda'_d},$$

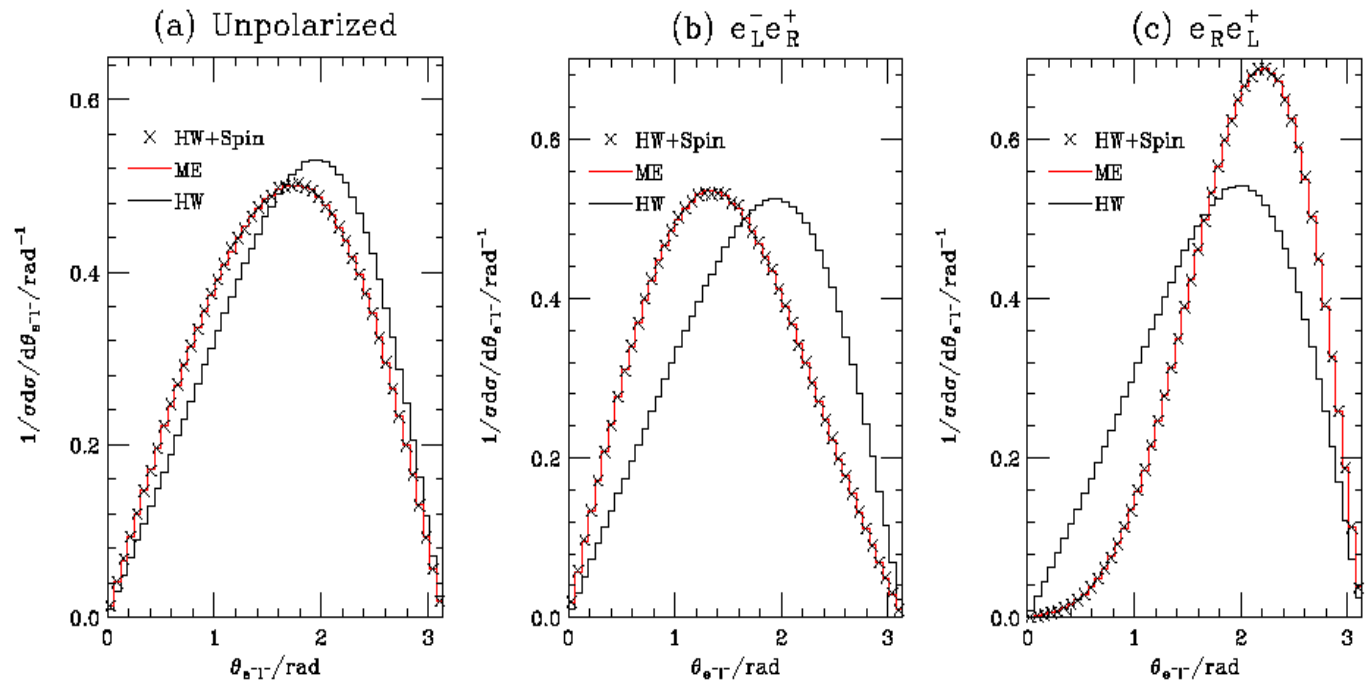
$$D_c^{\lambda_c \lambda'_c} = \mathcal{M}_{c \text{ decay}}^{\lambda_c} \mathcal{M}_{c \text{ decay}}^{* \lambda'_c},$$

$$|\mathcal{M}|^2 = \rho_{\text{prod}}^{\lambda_c \lambda'_c \lambda_d \lambda'_d} D_c^{\lambda_c \lambda'_c} D_d^{\lambda_d \lambda'_d}$$

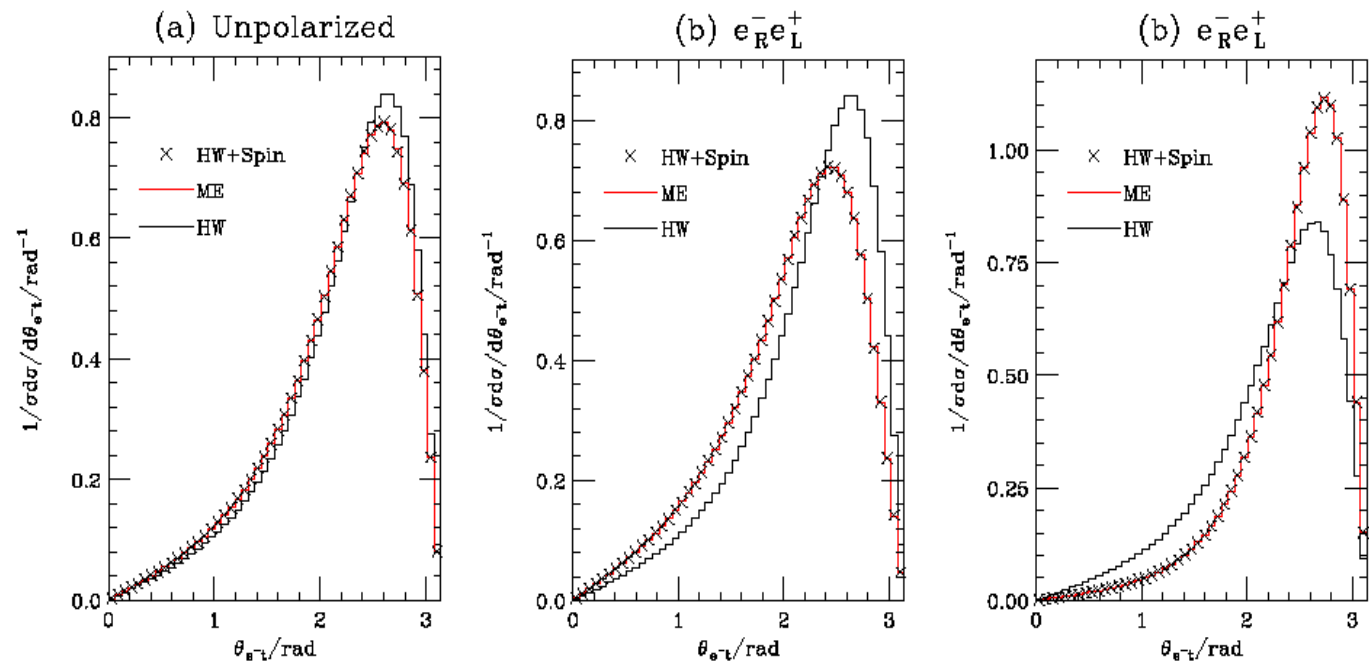
$$= \rho_{\text{prod}}^{\lambda_c \lambda_c \lambda_d \lambda_d} \left(\frac{\rho_{\text{prod}}^{\lambda_c \lambda'_c \lambda_d \lambda_d} D_c^{\lambda_c \lambda'_c}}{\rho_{\text{prod}}^{\lambda_c \lambda_c \lambda_d \lambda_d}} \right)$$

$$\times \left(\frac{\rho_{\text{prod}}^{\lambda_c \lambda'_c \lambda_d \lambda'_d} D_c^{\lambda_c \lambda'_c} D_d^{\lambda_d \lambda'_d}}{\rho_{\text{prod}}^{\lambda_c \lambda'_c \lambda_d \lambda_d} D_c^{\lambda_c \lambda'_c}} \right)$$

Correlation between lepton and beam

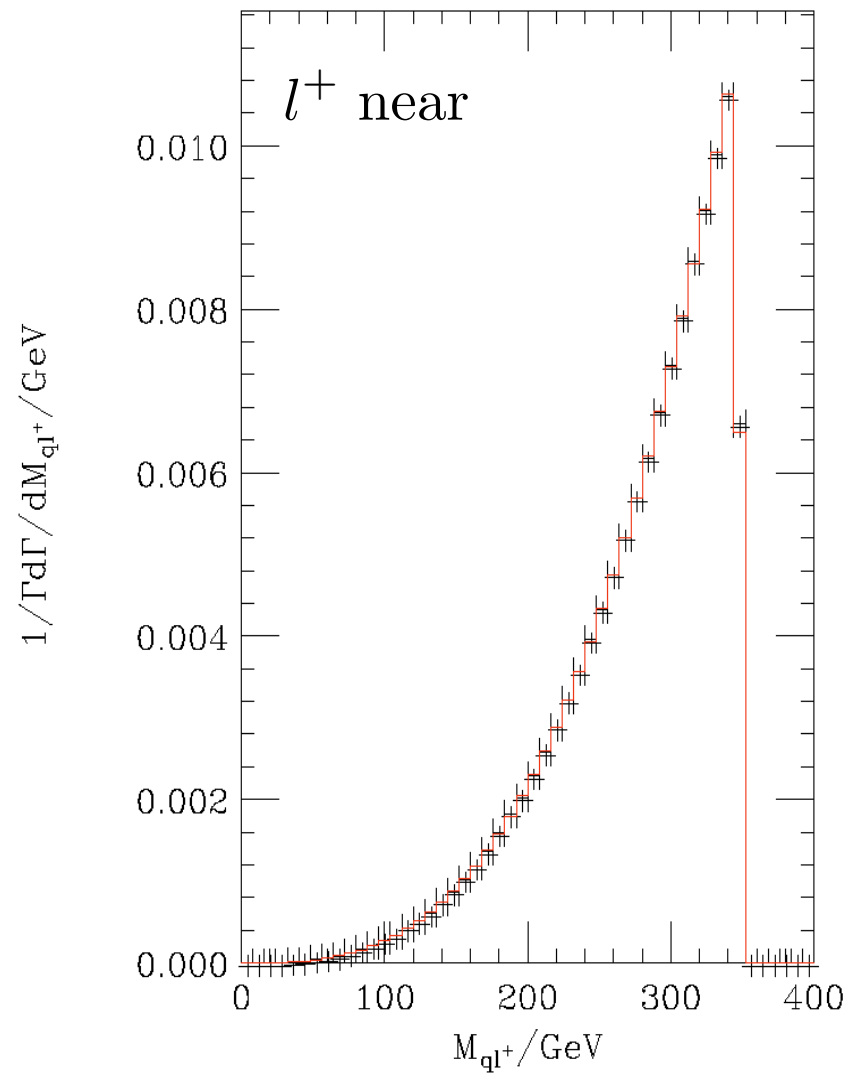
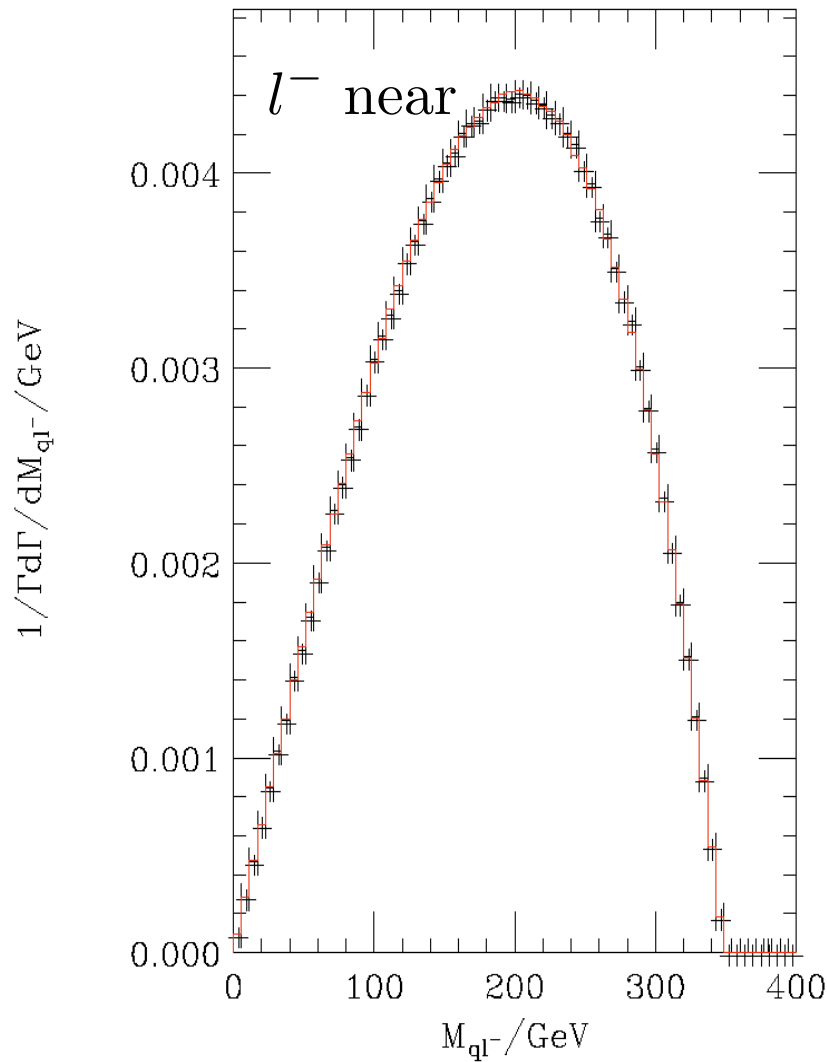


Correlation between lepton and top



Herwig++ New Physics: MSSM

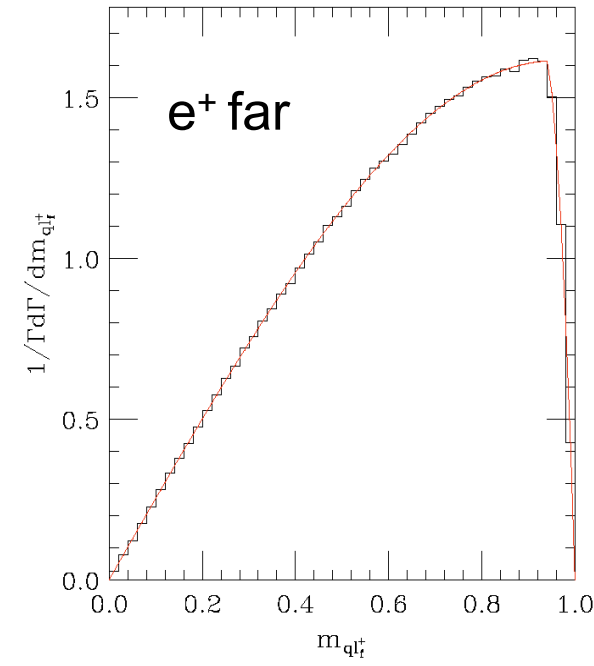
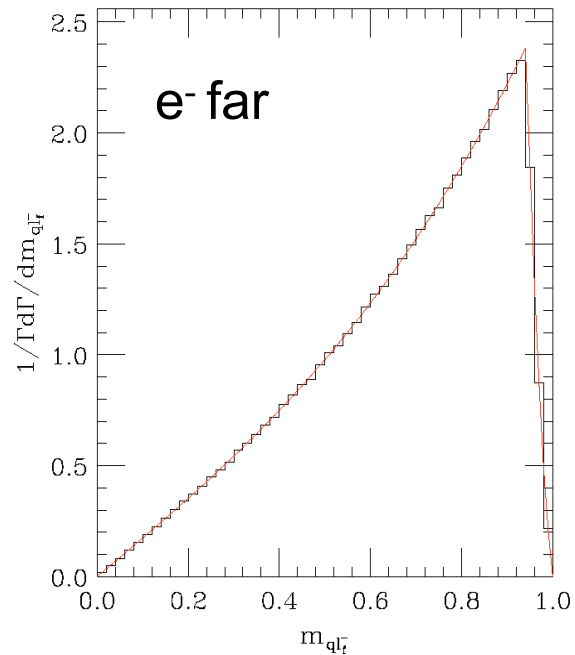
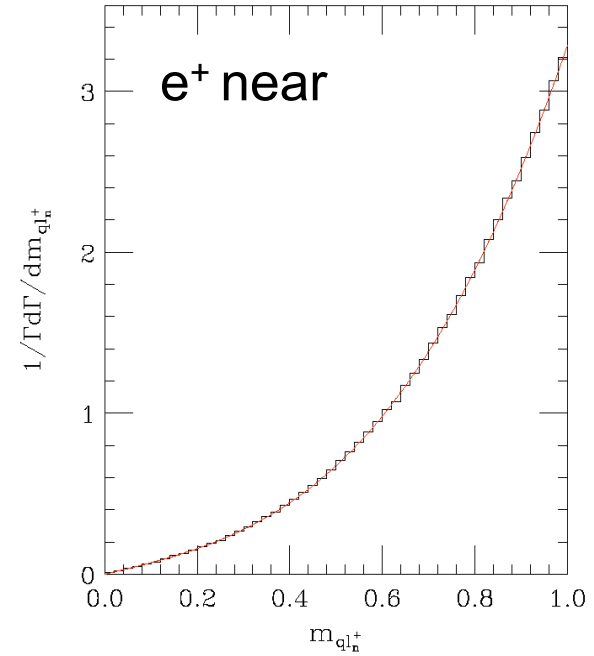
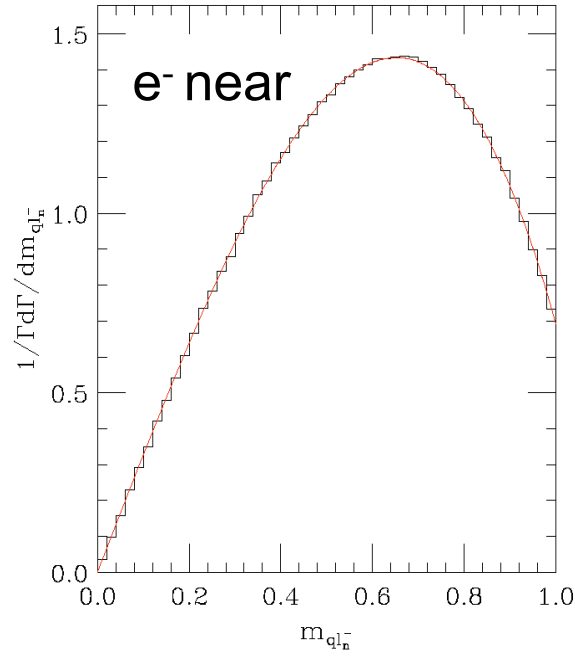
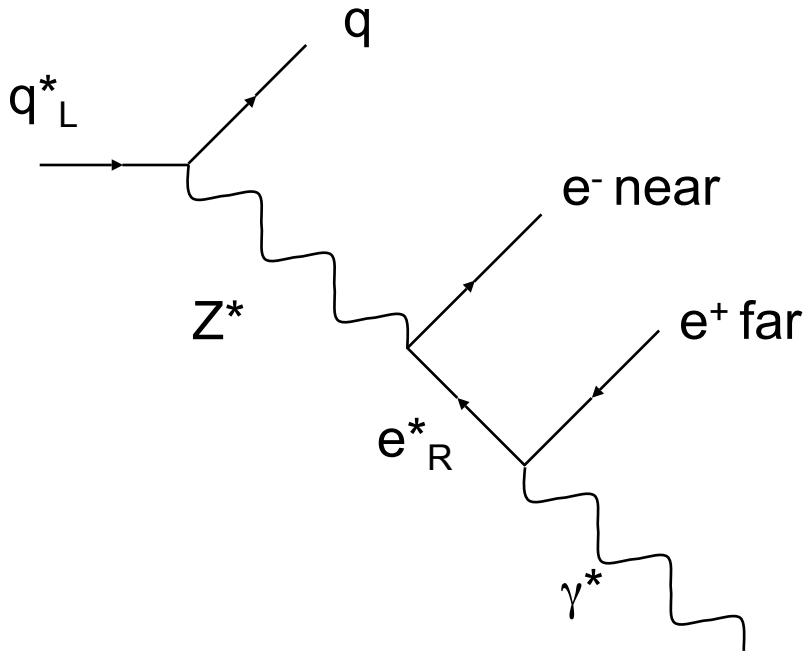
$$\tilde{q}_L \rightarrow q\tilde{\chi}_2^0 \rightarrow ql^\pm\tilde{l}^\mp \rightarrow ql^\pm l^\mp\tilde{\chi}_1^0$$



M Gigg and P Richardson hep-ph/0703199

Herwig++ New Physics: UED

Analogous decay:



Summary on Event Generators

- Get to know the event generators!
- Remember what is fixed by LEP and HERA data
- Question what isn't
- Tevatron data crucial testing ground

- The next generation is here...
 - Software improvements
 - Physics improvements

Monte Carlo Calculations of NLO QCD

Two separate divergent integrals:

$$\sigma_{NLO} = \int_{m+1} d\sigma^R + \int_m d\sigma^V$$

Must combine before numerical integration.

Jet definition could be arbitrarily complicated.

$$d\sigma^R = d\Pi_{m+1} |\mathcal{M}_{m+1}|^2 F_{m+1}^J(p_1, \dots, p_{m+1})$$

How to combine without knowing F^J ?

Exact solution: subtraction method.

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:

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

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

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

Subtraction method

Exact identity:

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



Two separate finite integrals.

Programs: EVENT2, DISENT, NLOJET++, MCFM, ...

MC@NLO

Simple one-dim. example again:

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

x = gluon energy or two-parton invariant mass.

MC@NLO is based on subtraction method:

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

Modified subtraction takes account of parton showers.

Modified Subtraction

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

Now add parton shower:

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

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

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

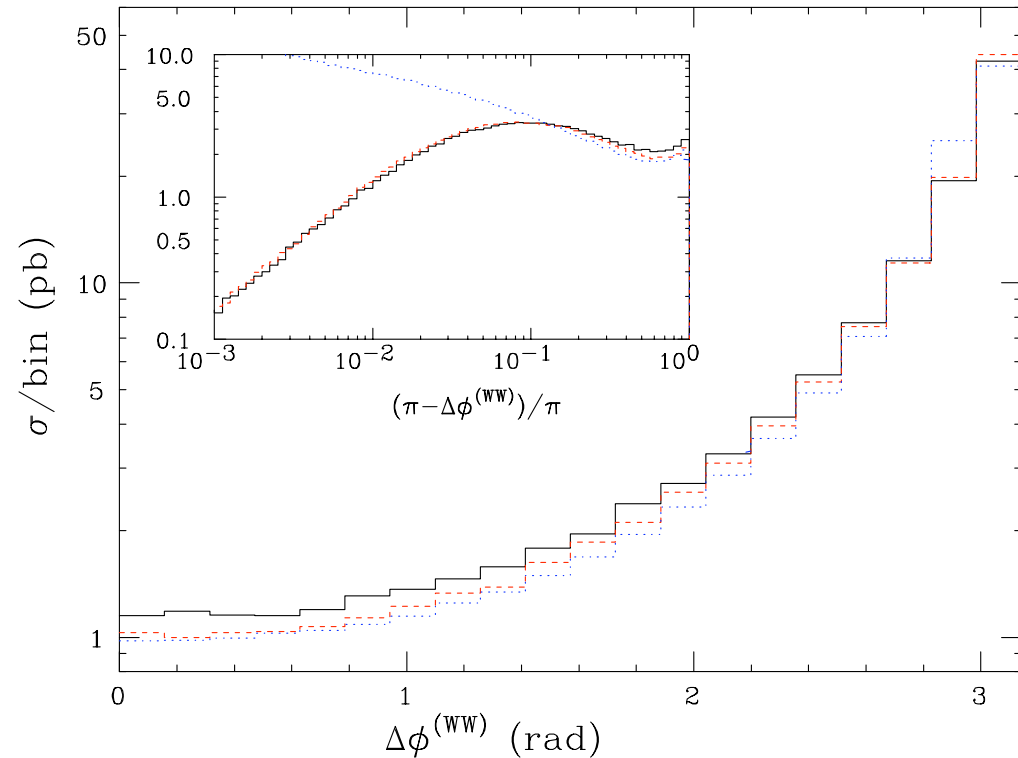
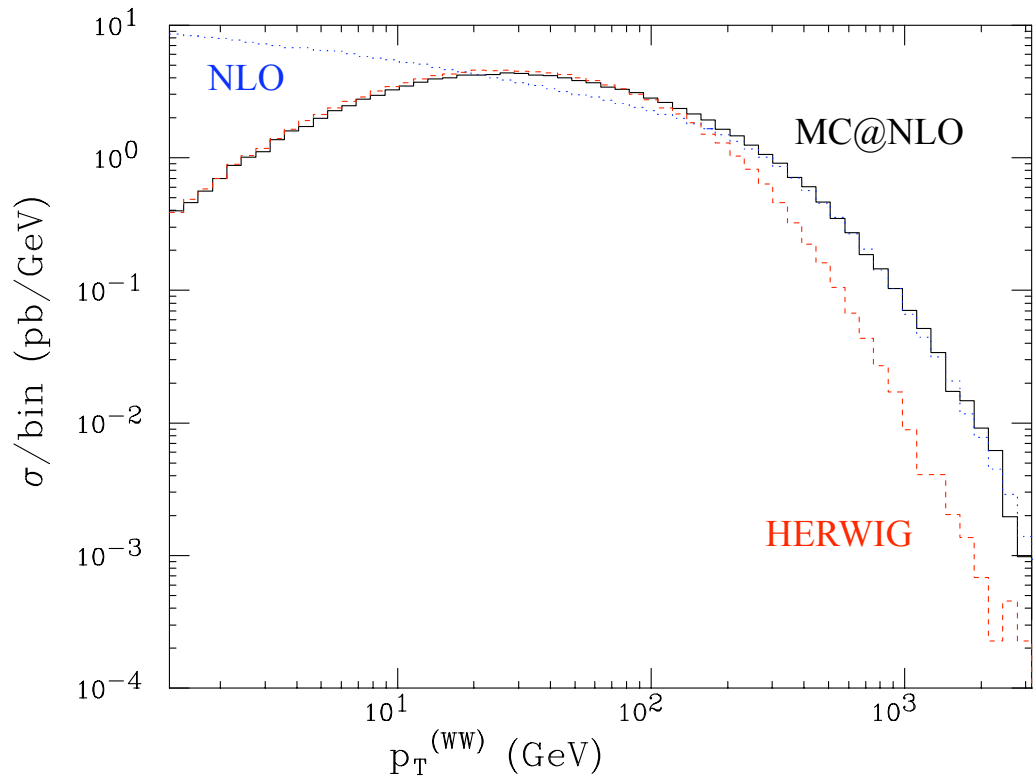
MC good for soft and/or collinear $\Rightarrow \mathcal{M}_{\text{MC}}(0) = \mathcal{M}(0)$

 0 & 1 emission contributions separately finite now!

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

MC@NLO Results

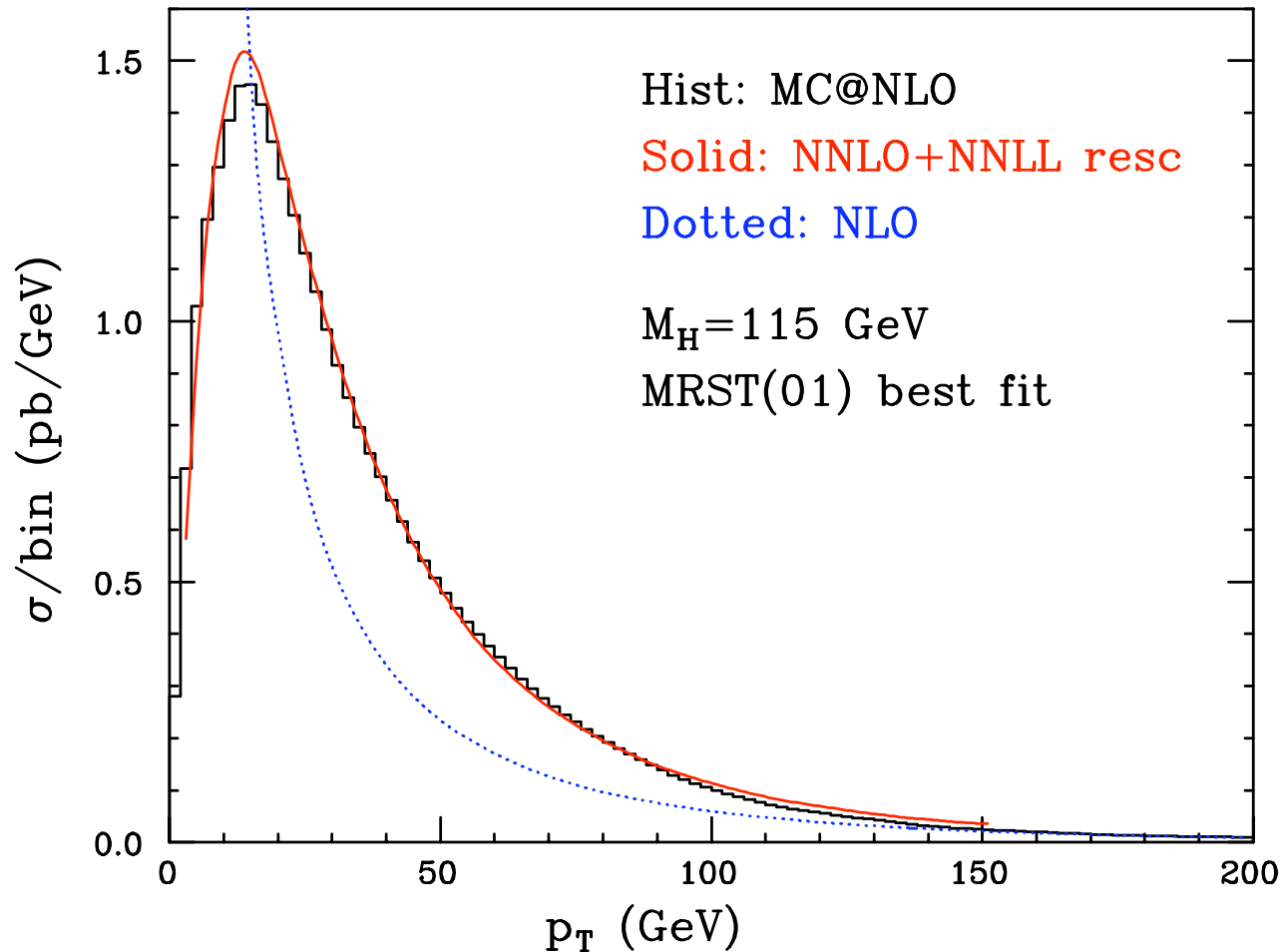
- WW production at LHC



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

S Frixione & BW, JHEP 06(2002)029

MC@NLO: Higgs Production at LHC



V Del Duca, S Frixione, C Oleari & BW, in prep.

➔ Good agreement with state-of-the-art resummation

LHC Simulations Summary

- Four components
 - Hard process (LO, some NLO)^{***}
 - Parton showers (NLL)^{**}
 - Hadronization (strings or clusters)^{*}
 - Underlying event (multiple interactions)
- Several generators
 - Herwig, Pythia, Sherpa
- Agreement with existing data
 - LEP^{**}, HERA^{*}, Tevatron^{*}
- Extrapolation to LHC?
 - Remember the *s!