# Theoretical progress in QCD

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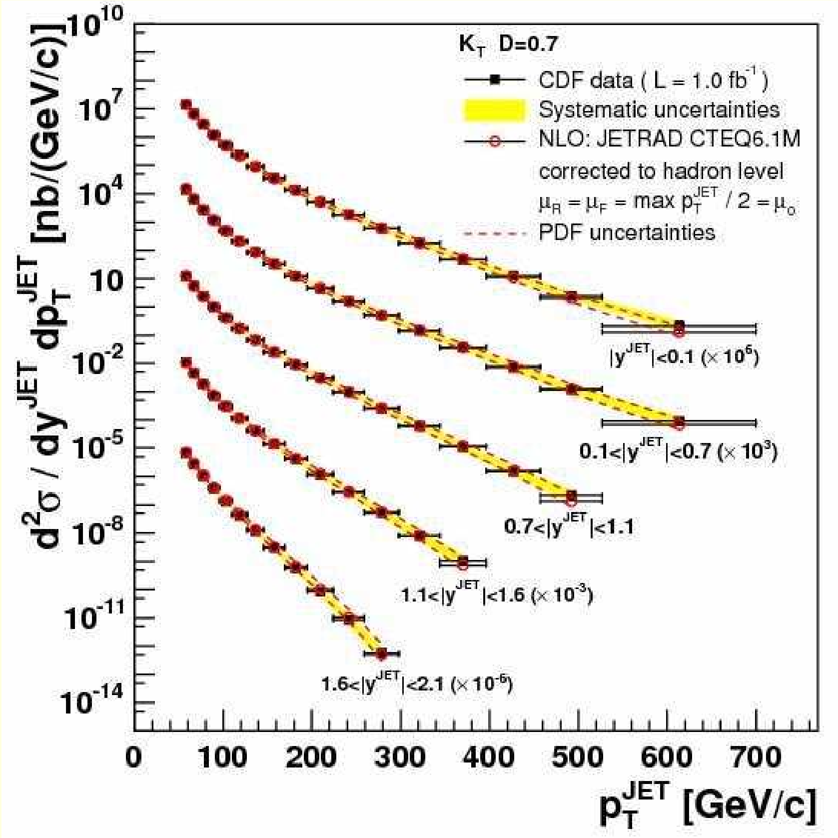
# Present Status of QCD

- Established theory of strong interactions
- Framework for computation of hard processes using asymptotic freedom
- Large body of tests of PQCD predictions
- No major areas of discrepancies with data

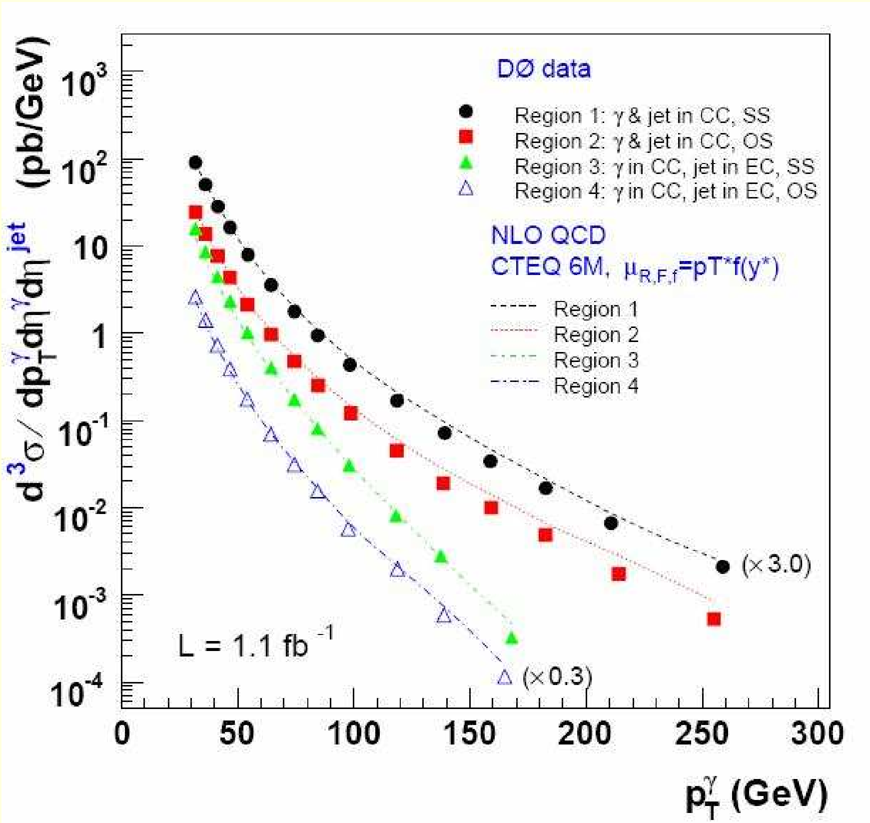
PQCD is based upon some assumptions, since we cannot fully solve the theory (Confidence in QCD prediction is also based upon validation with data)

- With LEP we have gained confidence in the correctness of PQCD
- Very positive experience with HERA and TEVATRON in dealing with processes with hadrons in the initial state

Inclusive jet cross section, CDF




Jet + isolated photon, D0




Two examples from Tevatron studies (R.Lefèvre,A.Kumar,this conf.)

Comparison with theoretical predictions often carried out at NLO level.

Good agreement in several areas: jets, photons, heavy flavours, $W/Z$, ...

# Prospects for the LHC

Focus is shifting from QCD tests to QCD applications for SM and BSM physics studies at colliders. Problems:

- Complexity: higher energy, more open thresholds, more particles, jets, ...
- Unpredictability: it is fair to say that we do not know which physical scenario will open up when LHC starts

Complexity requires complex calculations of signal and backgrounds; Unpredictability requires the ability to perform them quickly, and to make the results available in a flexible way.

## Covered in this talk

- Highlights in calculation of complex processes (LO, NLO, NNLO)
- Merging ME and Shower Monte Carlo
  - LO and Shower
  - NLO and Shower
- Shower Monte Carlo prospects

## Not covered in this talk

Left out many important topics: soft gluon resummation, small $x$ issues etc. and in particular theoretical studies on jet definitions

- Fast $k_T$ (Cacciari, Salam)
- Underlying event subtraction in $k_T$ algorithms (Cacciari, Salam)
- IR safe cone algorithms (Salam)
- IR safe definition of jet flavour (Banfi, Salam, Zanderighi)

# Calculation of Complex Processes: LO (tree Level) Matrix Elements

Many available programs can do automatic evaluation of LO cross sections.

1. Helicity amplitudes (HELAS, Hagiwara, Kanzaki, Murayama, Watanabe; MadGraph, Maltoni, Stelzer)
2. Behrends-Giele recursion relations (VecBos)
3. other recursive methods, (ALPHA, Caravaglios, M.Moretti)
   - ALPGEN, Mangano, Moretti, Piccinini, Pittau, Polosa
   - HELAC, Kanaki, Papadopoulos
4. CSW recursion (from twistors), Cachazo, Svrček, Witten,2004, Dixon, Glover, Khoze, Badger, Bern, Forde, Kosower, Mastrolia
5. BCFW recursion, Britto, Cachazo, Feng, Witten,2004 +masses: Badger, Glover, Khoze, Svrček; Schwinn, Weinzierl

# Comparison of algorithms

CSW and BCF yield more compact expressions.
Comparison of automated algorithms by
Duhr, Hoche, F.Maltoni, Jun.06; also Dinsdale, Ternick, Weinzierl, Feb.06;

BG=Berends-Giele, CSW=Cachazo-Svrček-Witten, BCF=Britto-Cachazo-Feng
CO=Colour ordered, CD=Colour dressed (i.e. full amplitude)

| Final state | BG | | BCF | | CSW | |
|---|---|---|---|---|---|---|
| | CO | CD | CO | CD | CO | CD |
| $2g$ | 0.24 | 0.28 | 0.28 | 0.33 | 0.31 | 0.26 |
| $3g$ | 0.45 | 0.48 | 0.42 | 0.51 | 0.57 | 0.55 |
| $4g$ | 1.20 | 1.04 | 0.84 | 1.32 | 1.63 | 1.75 |
| $5g$ | 3.78 | 2.69 | 2.59 | 7.26 | 5.95 | 5.96 |
| $6g$ | 14.20 | 7.19 | 11.9 | 59.10 | 27.80 | 30.60 |
| $7g$ | 58.50 | 23.70 | 73.6 | 646.00 | 146.00 | 195.00 |
| $8g$ | 276.00 | 82.10 | 597 | 8690.00 | 919.00 | 1890.00 |
| $9g$ | 1450.00 | 270.00 | 5900 | 127000.00 | 6310.00 | 29700.00 |
| $10g$ | 7960.00 | 864.00 | 64000 | | 48900.00 | |

Berends-Giele (comparable to ALPGEN, HELAC) still faster ...
See how new methods develop ... (CSW in Sherpa, Gleisberg etal, May 07)

## summarizing (LO):

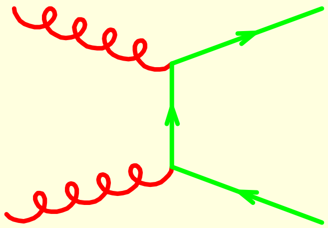
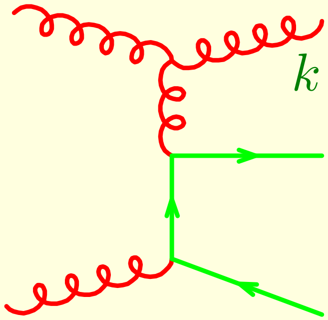
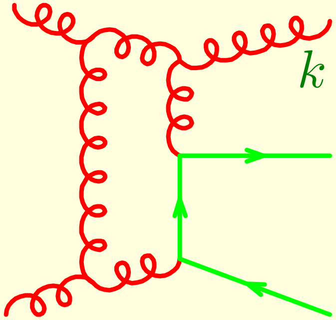
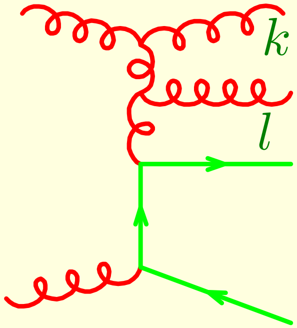
- General purpose ME generators for SM and MSSM tree level processes are available (example: Madgraph, any process, not very fast)
- Very fast generators, capable to add several gluons in the final state already available. Example: ALPGEN, processes added by authors

| | |
|---|---|
| $WQ\bar{Q}$ + up to 4 jets | $Q\bar{Q}\,H$ + up to 4 jets |
| $Z/\gamma + Q\bar{Q}$ + up to 4 jets | Inclusive $N$ jets, with $N$ up to 6 |
| $W$ + up to 6 jets | $N\gamma$ + $M$ jets |
| $W + c$ + up to 5 jets | Single top |
| $Z$ + up to 6 jets | $W$ + photons + jets |
| $nW + m\,Z + k\,H + l\gamma$ + up to 3 jets | $WQ\bar{Q}$ + photons + jet |
| $Q\bar{Q}$ + up to 6 jets | $Q\bar{Q}$ + $M$-photons + $N$-jets |
| $Q\bar{Q} + Q'\bar{Q}'$ + up to 4 jets | |

Total automation of fast techniques desirable (not far)

# Calculation of Complex Processes: NLO

## Reminder: what NLO means

| Born $Q\bar{Q}$ | Born $Q\bar{Q} + \mathrm{Jet}$ | NLO virtual $Q\bar{Q} + \mathrm{Jet}$ | NLO real $Q\bar{Q} + \mathrm{Jet}$ |
|---|---|---|---|
|  |   |   |   |
| | $k_T > p_T^{\mathrm{cut}}$ | $k_T > p_T^{\mathrm{cut}}$ | $k_T > p_T^{\mathrm{cut}}, l_T\,\mathrm{unrestr.}$ |

- Born process may be of high order (with cuts on light parton emission)
- NLO: real + virtual corrections to Born process
- real corrections: one more light parton emitted (without cuts)

In QCD virtual and real are infrared divergent, their sum is finite

Experience with hadron colliders has shown that NLO corrections are often large, ranging from 10% to 100%. There is a considerable ongoing effort to compute NLO corrections to interesting LHC processes, as well as an effort aimed at the automatic calculation of NLO corrections.
Recent results:

$pp \to H + 2\mathrm{Jets}$, gluon fusion, Campbell, R.K. Ellis, Zanderighi, Aug.06
"background" to higgs production by $W$ fusion

$pp \to VV + 2\mathrm{Jets}$, Bozzi, Jager, Oleari, Zeppenfeld, $V \in W, Z$, Mar.07.
(except $S$ channel)

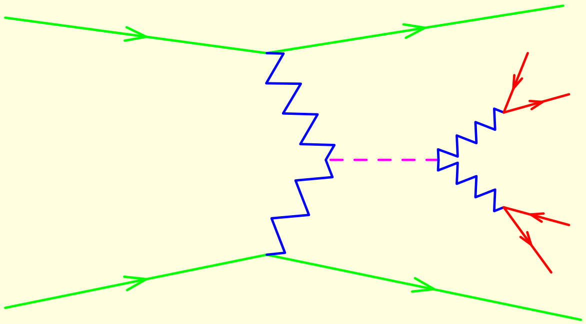
$pp \to t\bar{t} + \mathrm{Jet}$, Dittmaier, Uwer, Weinzierl, (Mar.07)

$pp \to ZZZ$, Melnikov, Lazopoulos, Petriello, (Mar.07)

$pp \to H + 2\mathrm{Jets}$, VBF, EW+Strong NL, Ciccolini,Denner,Dittmaier, Jul.07

# More about $pp \to H + 2\mathrm{Jets}$, $pp \to VV + 2\mathrm{Jets}$ and Vector Boson Fusion

$H$ production via VBF:
$H$ coupled directly to $W, Z$
Typical VBF cuts:
$|\eta_1 - \eta_2| > 4.2$, $\eta_1 \cdot \eta_2 < 0$, $m_{12} > 600\,\mathrm{GeV}$
central jet veto



Several processes can mimic VBF higgs production:

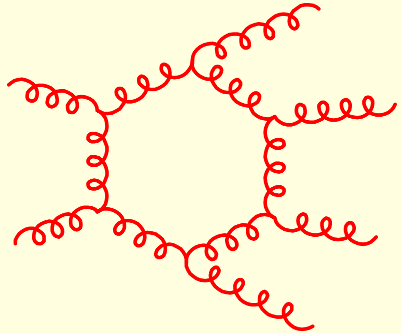
$pp \to H + 2\mathrm{Jets}$ (gluon fusion), Campbell, R.K. Ellis, Zanderighi:
with VBF cut is roughly a factor of two below VBF signal
(need NLO for safe subtraction)

$pp \to VV + 2\mathrm{Jets}$, Bozzi, Jager, Oleari, Zeppenfeld:
background to VBF signal with $H \to VV$.
All relevant contributions after VBF cuts included
if central jet veto is effective, i.e. $\alpha_{\mathrm{weak}}^6 \alpha_s$, no $\alpha_{\mathrm{weak}}^4 \alpha_s^3$ yet
Also: background (and signal) to $VV$ scattering;

## LHC priority wish list, Les Houches 2005 (hep-ph/0604120)

| process, $V \in \gamma, W^{\pm}, Z$ | background to | As of now |
|---|---|---|
| $pp \to VV + 1\mathrm{Jet}$ | $t\bar{t}H$, new physics | |
| $pp \to t\bar{t} + b\bar{b}$ | $t\bar{t}H$ | |
| $pp \to t\bar{t} + 2\mathrm{Jets}$ | $t\bar{t}H$ | $t\bar{t} + 1\mathrm{Jet}$ |
| $pp \to VV + b\bar{b}$ | $\mathrm{VBF} \to VV$, $t\bar{t}H$, new physics | |
| $pp \to VV + 2\mathrm{Jets}$ | $\mathrm{VBF} \to VV$ | ( $\alpha_{\mathrm{weak}}^6 \alpha_s$, no S channel) |
| $pp \to V + 3\mathrm{Jets}$ | new physics signatures | |
| $pp \to VVV$ | SUSY trilepton | $ZZZ$ |

Many of these processes
involve $2 \to 4$ particles:
hexagon virtual graphs.
Benchmark process:
6 gluon amplitude



Notice: All one loop integrals can be expressed in terms of known basic scalar integrals by tensor reduction (Passarino-Veltman, Denner-Dittmaier).
The only problem is complexity; the number of terms generated is too large to deal with, even with computer algebra systems.
Strategies:

- Find a way to evaluate the complex result; first evaluation of 6 gluon amplitude, R.K. Ellis, Giele, Zanderighi, Feb.06
  (So called semi-numerical method: does not yield a printable formula)

- Do them by numerical integration: accuracy of the virtual contribution has only to match that of the real emission contribution, i.e. the accuracy of a phase space integration
  Nagy and Soper, 6 photon amplitude with a massless fermion, Oct.06
  Anastasiou, Daleo: automated method, Nov.06:
    Sector decomposition (Binoth,Heinrich)+(N.S.) technique
    Reproduce analytic result on $gg \to h$ at 2 loops by
      C.Anastasiou, S.Beerli, S. Bucherer, A. Daleo, Z. Kunszt
    (same technique: Melnikov, Lazopoulos, Petriello, $pp \to ZZZ$)

- Complexity is often only in the intermediate results:
  find clever techniques to bypass it. Example:
  6 photon amplitude, Binoth, Heinrich, Gehrmann, Mastrolia, Mar.07

By now, compact formulae for the 6 gluon amplitudes have been obtained. Several authors have contributed to compute parts (i.e. different helicity contributions) to the amplitude:
Bedford, Berger, Bern, Bidder, Bjerrum-Bohr, Brandhuber, Britto, Buchbinder, Cachazo, Dixon, Dunbar, Feng, Forde, Kosower, Mastrolia, Perkins, Spence, Travaglini, Xiao, Yang, Zhu

One fruitful strategy: on shell methods (Bern, Dixon, Dunbar, Kosower)
On shell amplitudes are simpler than off-shell ones in gauge theories: construct on shell amplitudes from simpler ones using analyticity and unitarity.
Loops constructed from trees, trees from twistor inspired techniques (Kunszt,Glover, this conf.)
Several alternative approaches:
Amplitude reduction at the integrand level, (Ossola, Papadopoulos, Pittau)
6 photon amplitude with massive fermion loop, Apr.07.

## Summarizing (NLO):

- Lively community effort on NLO calculations
- Les Houches wish list under attack
- Several competing strategies for virtual corrections
- Promising developments towards full automation (but not yet on sight)

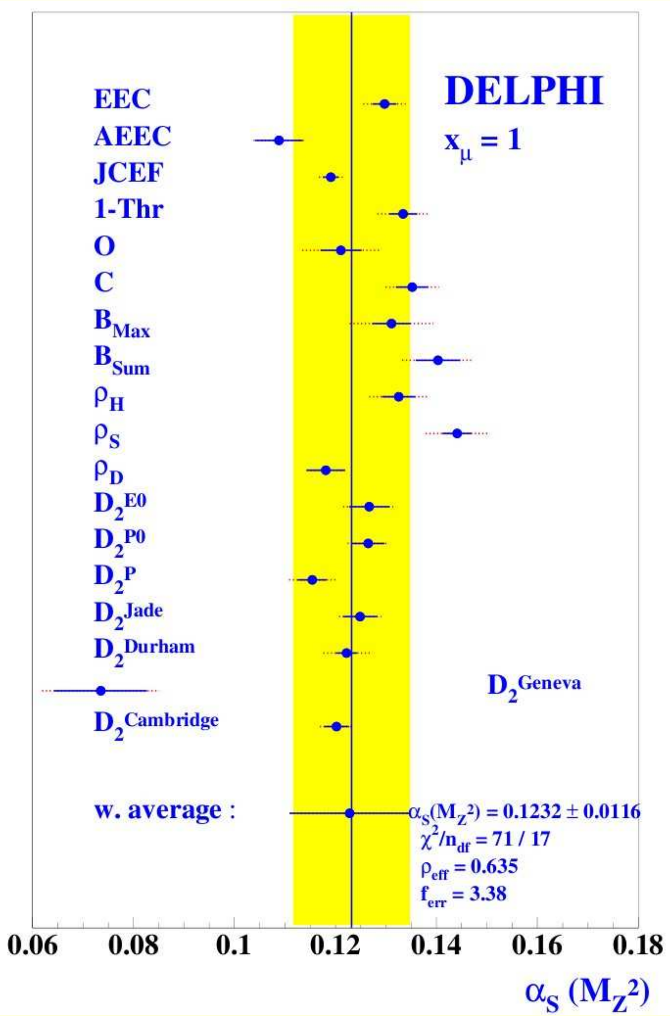
# NNLO: $e^+e^- \to 3\,\mathrm{jets}$ completed! (Glover, this conf.)

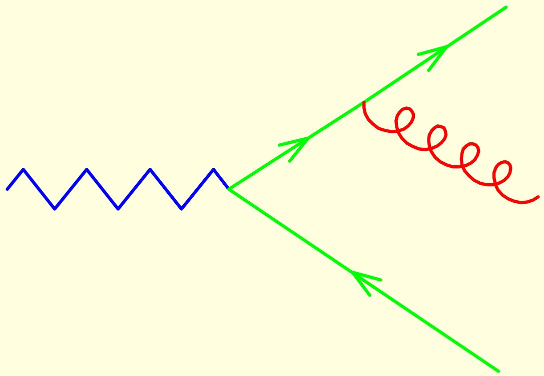
(A.Ghermann-De Ridder,T.Gehrmann,Glover,Heinrich, Jul.07)

Result of an effort that spans several years of work; many contributors:

- 2 loop $\gamma^\star \to q\bar{q}g$, Garland,Gehrman,Glover,Koukoutsakis,Remiddi,02
  - Methods of Tkachov,Chetyrkin,81;Gehrman,Remiddi,00;Laporta,02;
  - Master integrals for double boxes with 1 leg off-shell: Smirnov
  - $2 \to 2$ (on shell) at 2 loops ("warm up exercise", so to speak...):
    - full calculation: Anastasiou,Glover,Oleari,Tejeda-Yeomans,01
    - Master integrals for double boxes: Smirnov,99;Tausk,99;
- Sing. part of 4 and 5 parton ME: Catani,98; Sterman,Tejeda-Yeomans,03
- NLO corrections to 4 parton ME: Dixon,Signer;Nagy,Trocsanyi;Weinzierl,Kosower;
- All the rest: A.Ghermann-De Ridder,T.Gehrmann,Glover,Heinrich

In $e^+e^- \to \mathrm{hadrons}$: most events are 2 jets, a fraction $\mathcal{O}(\alpha_s)$ is 3 jets, etc.
3 jet events, (and corresponding shape variables) used to measure $\alpha_s$



Several shape variables sensitive to single gluon emission have been studied at LEP. Analysis carried out at NLO.

DELPHI example: $\alpha_s = 0.123 \pm 0.12$, bad $\chi^2$ (no theoretical error included ...)

A hint that NNLO corrections are large ...

## Now shape variables can now be computed at NNLO

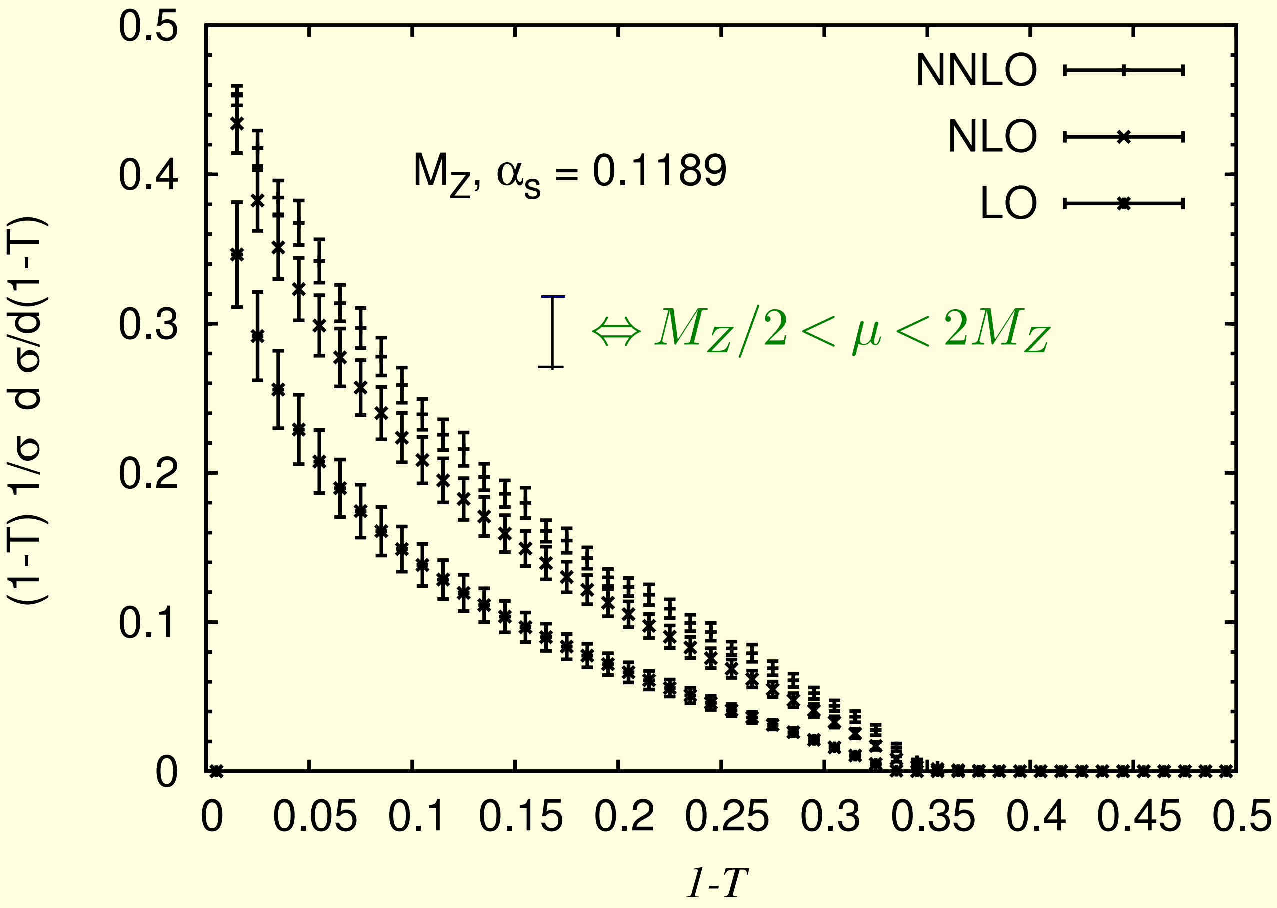
$$(1-t)\frac{1}{\sigma}\frac{d\sigma}{dt} = \left(\frac{\alpha_s}{2\pi}\right)A(t) + \underbrace{\left(\frac{\alpha_s}{2\pi}\right)^2 B(t)}_{\text{Ellis, Ross, Terrano (80)}} + \underbrace{\left(\frac{\alpha_s}{2\pi}\right)^3 C(t)}_{\text{NEW}}$$

LEP analysis of shape variables can be repeated with improved accuracy:

## First chance to extensively test QCD at NNLO level!

(new $\alpha_s$ from shape variables at next summer conferences ...)

# Thrust distribution




- NNLO corrections not negligible: $\sim 15\%$
- Scale dependence reduced from LO to NLO to NNLO

# Shower Monte Carlo

Tools to simulate the full event, using:

- Large library of hard events cross sections (SM and BSM)
- Dress hard events with QCD radiation (The name SHOWER from here)
- Models for hadron formation
- Models for underlying event, multi-parton collisions, minimum bias
- Library for (space-time) decays of unstable particles

# Implementation

- COJETS, Odorico (1984)
- ISAJET, Page+Protopopescu (1986)
- FIELDAJET, Field (1986)
- JETSET, Sjöstrand (1986)
- PYTHIA, Bengtsson,Sjöstrand (1987); Mrenna,Skands,Sjöstrand
- Ariadne, Lönnblad (1991)
- HERWIG, Marchesini,Webber (1988)
  Marchesini,Webber,Abbiendi,Knowles,Seymour,Stanco (1992)
- SHERPA, Gleisberg,Hoche,Krauss,Schälicke,Schumann,Winter (04)

Benchmarks in the theory of Showers:

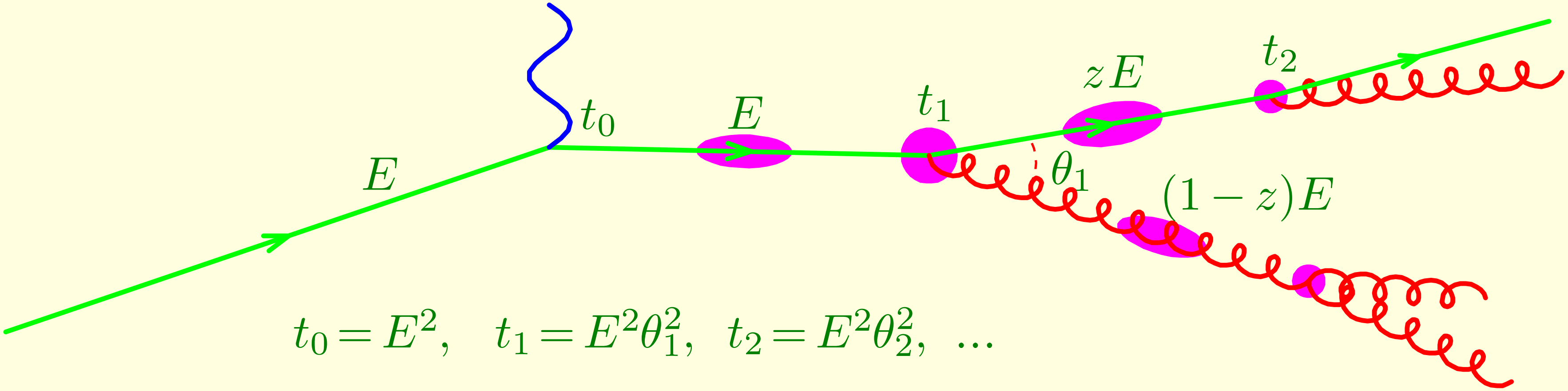
- Collinear Shower (Fox and Wolfram, 79)
- Soft radiation: angular ordering (Marchesini and Webber, 83)
- Soft radiation: dipole formulation (Gustafson,Pettersson, 88)
- Backward evolution (Sjöstrand, 85)

Not many new developments until very recent times;
New developments:

- CKKW matrix element and Parton Shower matching
  Catani, Krauss,Kühn, Webber, 01
- NLO improvement
  Frixione,Webber,02; Kramer,Soper,03; P.N.,04;

Furthermore, there are proposals for new shower algorithms:
Bauer,Schwartz; Frederix,Giele,Kosower,Skands; Schumann; Nagy,Soper;

# BASICS OF SHOWERING



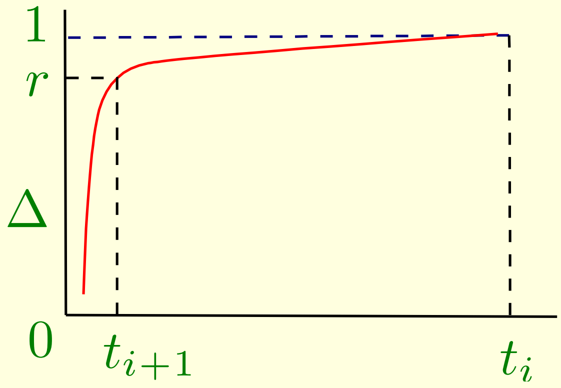

$$t_0 = E^2, \quad t_1 = E^2\theta_1^2, \quad t_2 = E^2\theta_2^2, \quad \ldots$$

Approximate cross section for production of any number of partons including all dominant contributions. Cross section simplifies:

- Dominant configurations: $t_0 \gg t_1 \gg t_2 \ldots$
- Splitting vertices approximated as $\frac{\alpha_S}{2\pi}\frac{dt}{t}dz P(z)$
- All virtual corrections enhanced as $\log\frac{t_i}{t_{i+1}}$ included. Their effect
  - $\alpha_s \rightarrow \alpha_s(t)$ in splitting vertices
  - Sudakov form factor $\Delta(t_i, t_{i+1}) = \exp\left[-\int_{t_{i+1}}^{t_i} \frac{\alpha_s(t)}{2\pi}\frac{dt}{t} dz P(z)\right]$ in intermediate lines

# Simple probabilistic interpretation of virtual corrections:

- $\frac{\alpha_s}{2\pi}\frac{dt}{t}\, dz\, P(z)$ is the splitting probability in the interval $dt\, dz$
- $\Delta(t_i, t_{i+1})$: probability that no splitting occours between $t_{i+1}$ and $t_i$; (equals product of non-emission probability in $dt$ subintervals in $t_{i+1}, t_i$)
  $\exp\Big[-\int_{t_{i+1}}^{t_i} \frac{\alpha_s(t)}{2\pi}\frac{dt}{t}\, dz\, P(z)\Big] = \prod \Big[1 - \frac{dt}{t}\int dz \frac{\alpha_s(t)}{2\pi} P(z)\Big]$




Notice:

– $\Delta(t_i, t_{i+1}) = 1$ for $t_{i+1} = t_i$

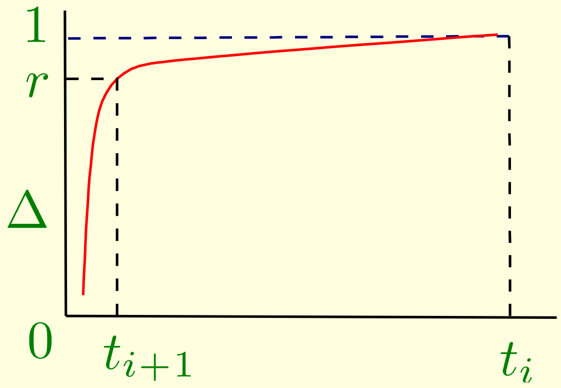
– $1 - \Delta(t_i, t_{i+1}) = \mathcal{O}(\alpha_s(t_i))$ for $t_{i+1} \lesssim t_i$

– $\Delta(t_i, t_{i+1})$ very small for $t_{i+1} \ll t_i$

So: the probability that a hard parton turns into a narrow jet, or that it does not radiate at all is small (i.e. is Sudakov suppressed).

How shower MC's work:

on each vertex at a given $t_i$ generate $t_{i+1}$ with probability $d\Delta(t_i, t_{i+1})$, then $z$ with probability $dzP(z)$. Continue recursively.




$t_{i+1}$ is generated by throwing a uniform random number $0 < r < 1$, and solving $r = \Delta(t_i, t_{i+1})$
We must stop at some scale $t_{\rm min} \approx \Lambda_{\rm QCD}$, ($\alpha_s$ becomes undefined). Below $t_{\rm min}$, we apply a model of hadronization.

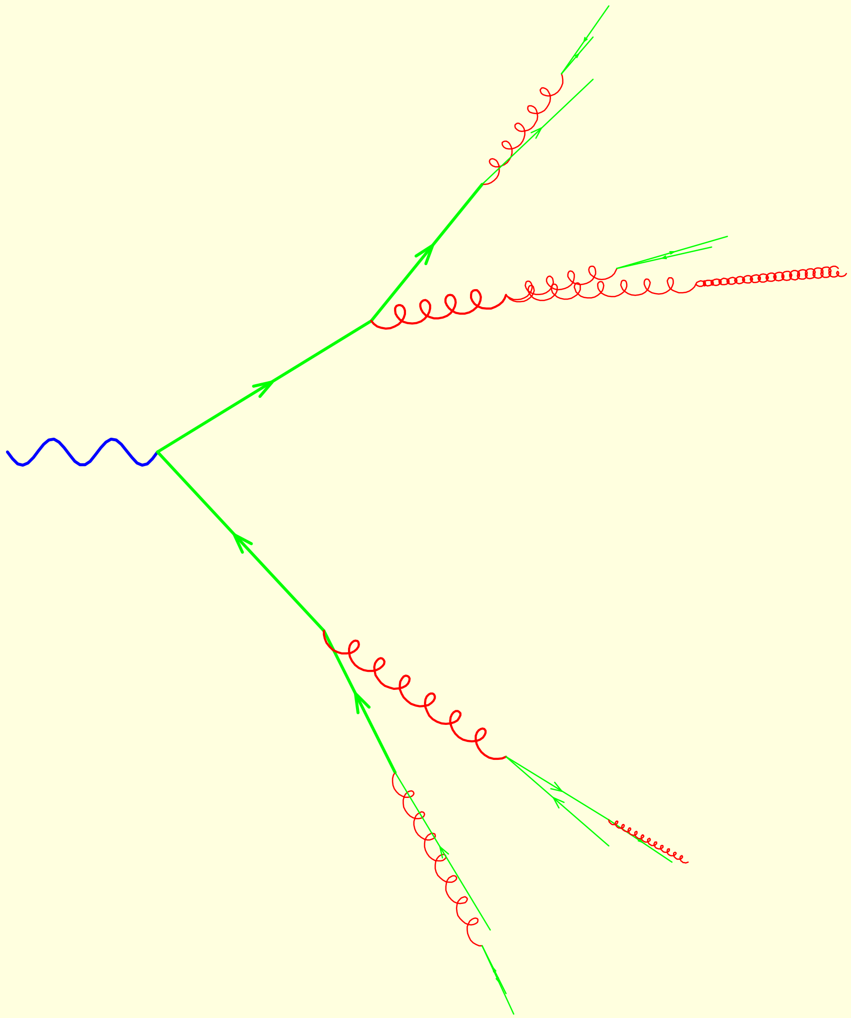
# Typical dominant configuration at very high $Q^2$

(Example: $\gamma^\star \to \mathrm{hadrons}$)
Besides $q \to qg$, also $g \to gg$, $g \to q\bar{q}$ come into play.

Typical configurations: intermediate angles of order of geometric average of upstream and downstream angles.

Each angle is $\mathcal{O}(\alpha_s)$ smaller than its upstream angle, and $\mathcal{O}(\alpha_s)$ bigger than its downstream angle.

As relative momenta become smaller $\alpha_s$ becomes bigger, and this picture breaks down (hadronization model).



# Use of exact LO (tree level) Matrix Element

SMC's are not exact for large angle radiation.
Can we use exact Matrix Element calculations instead of SMC?

- We must limit them to large angles, since Sudakov form factors for small angles are not included
- We must interpret them as inclusive cross sections; final state partons should be interpreted as jets with finite angular aperture
  (a parton turning into a narrow jet is Sudakov suppressed)

In order to remedy to these problems one should:

- Provide the dominant virtual corrections (i.e. the Sudakov form factors)
- Attach parton showers to final lines

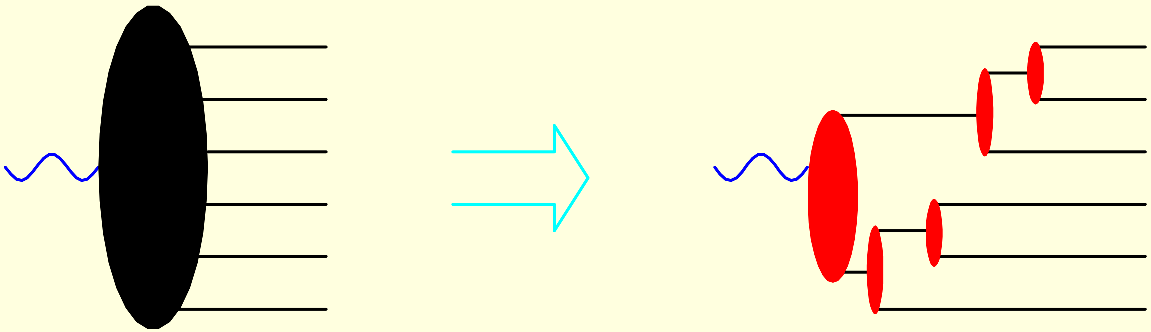
This is: ME and PS matching
Problem: avoid overcounting

Solution: Catani, Krauss, Küen, Webber (2001), (in $e^+e^-$ annihilation).
Krauss (2002) (Extension to hadron collisions)

# Rough description of CKKW ME and PS matching

Clusterize ME partons to reconstruct a shower skeleton
(by pairing up particles that yield smallest $t$ recursively)

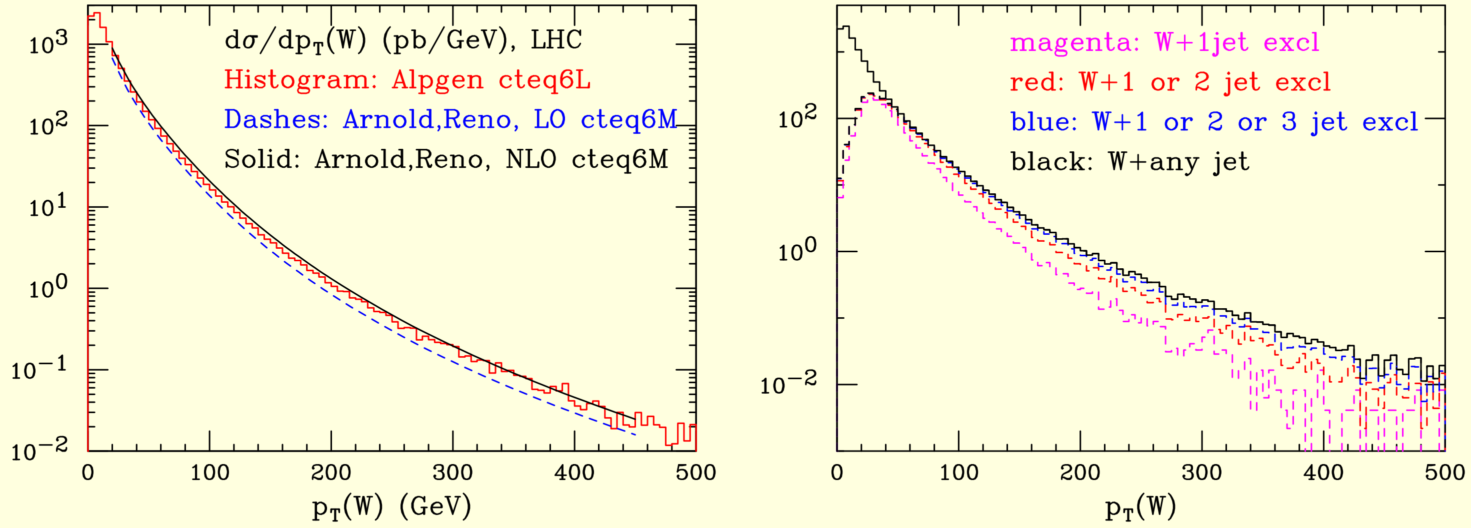
Red blobs have decreasing $t$



- Do not allow $t$ below a given cut $t_{\text{cut}}$.
- Re-evaluate ME couplings at scales $t$ of vertices in shower skeleton
- Assign Sudakov form factors to the skeleton (as in Shower MC)
- Continue the shower for $t < t_{\text{cut}}$ with the Shower MC

MLM matching: alternative procedure by M.L. Mangano
(used in ALPGEN, HELAC and Madevent)

# Example: $W + n$ jets




$p_T$ spectrum of $W$ from ALPGEN in agreement with $W + 1\text{jet}$ at NLO (plots by Mangano)

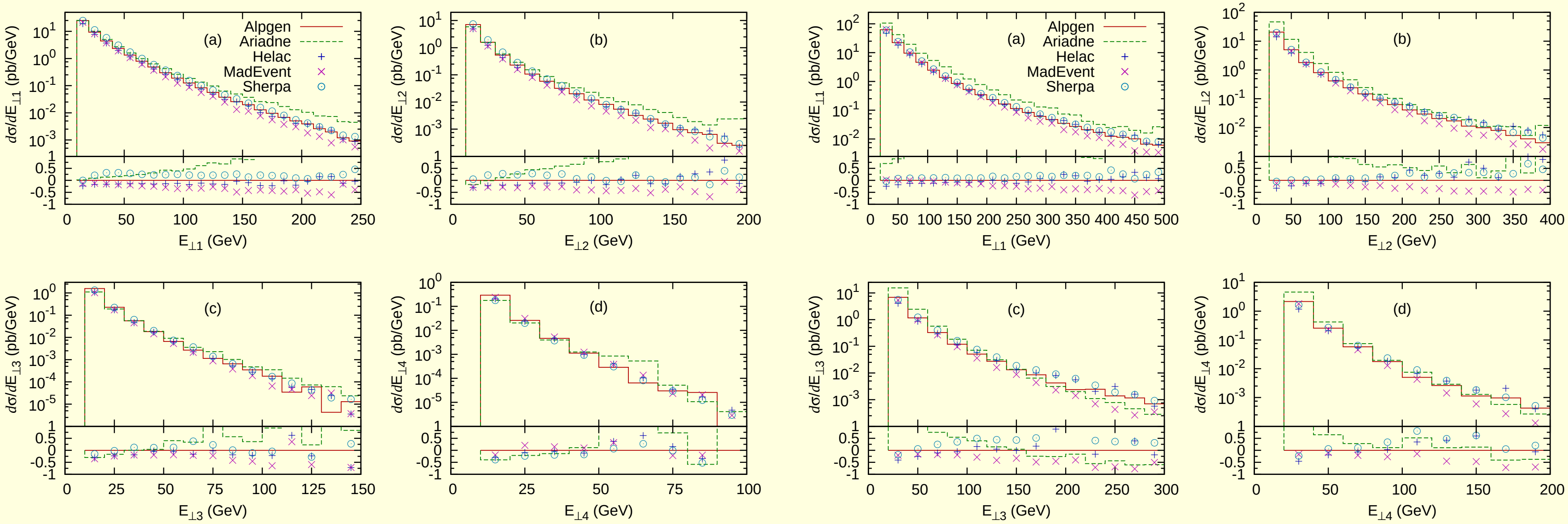
- NLO calculation inclusive (at most 2 light partons in final state)
- ME matched calculation can be broken into exclusive contributions: $W + 1\,\text{jet}$ (Sudakov suppressed), $W + n\,\text{jet}$ with $n < 2$, $W + n\,\text{jet}$ with $n < 3$, $W + n\,\text{jet}$ with any $n$.
  The sum of exclusive contributions builds up the inclusive cross section

# Comparison among different ME generators

(Alwall etal, Jul.07): compare Alpgen,Ariadne,Helac,MadEvent,Sherpa

## $W + n\,\mathrm{jets}$, jet $E_T$ spectra

TEVATRON LHC




THE MESSAGE:

good agreement among different ME implementation, in spite of different matching prescriptions (CKKW, MLM, and others)

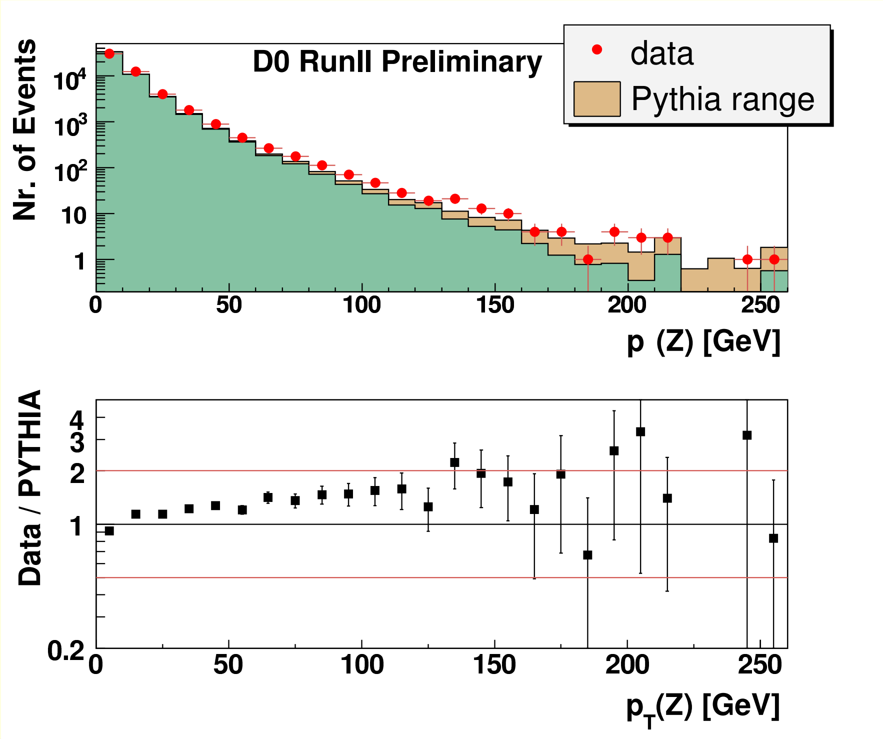
# Matched-ME (M-ME)

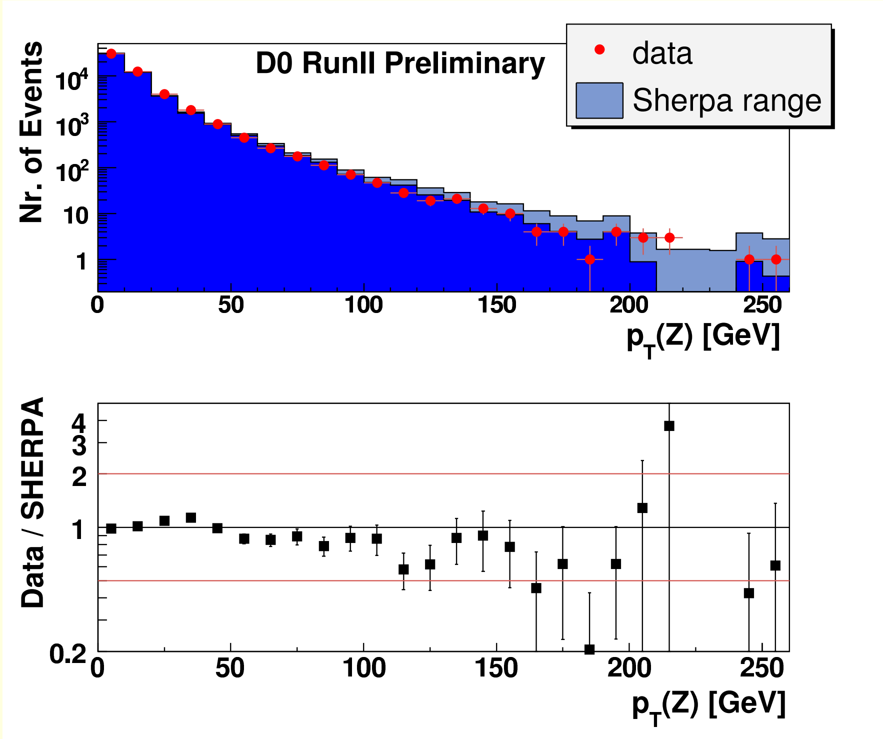
Put together the advantages of two approaches:

1. Improve shower to give exact LO large angle behaviour of jet cross section
2. Improve ME by giving correct Sudakov dumping at small angles, and allow interfacing with Shower algorithms

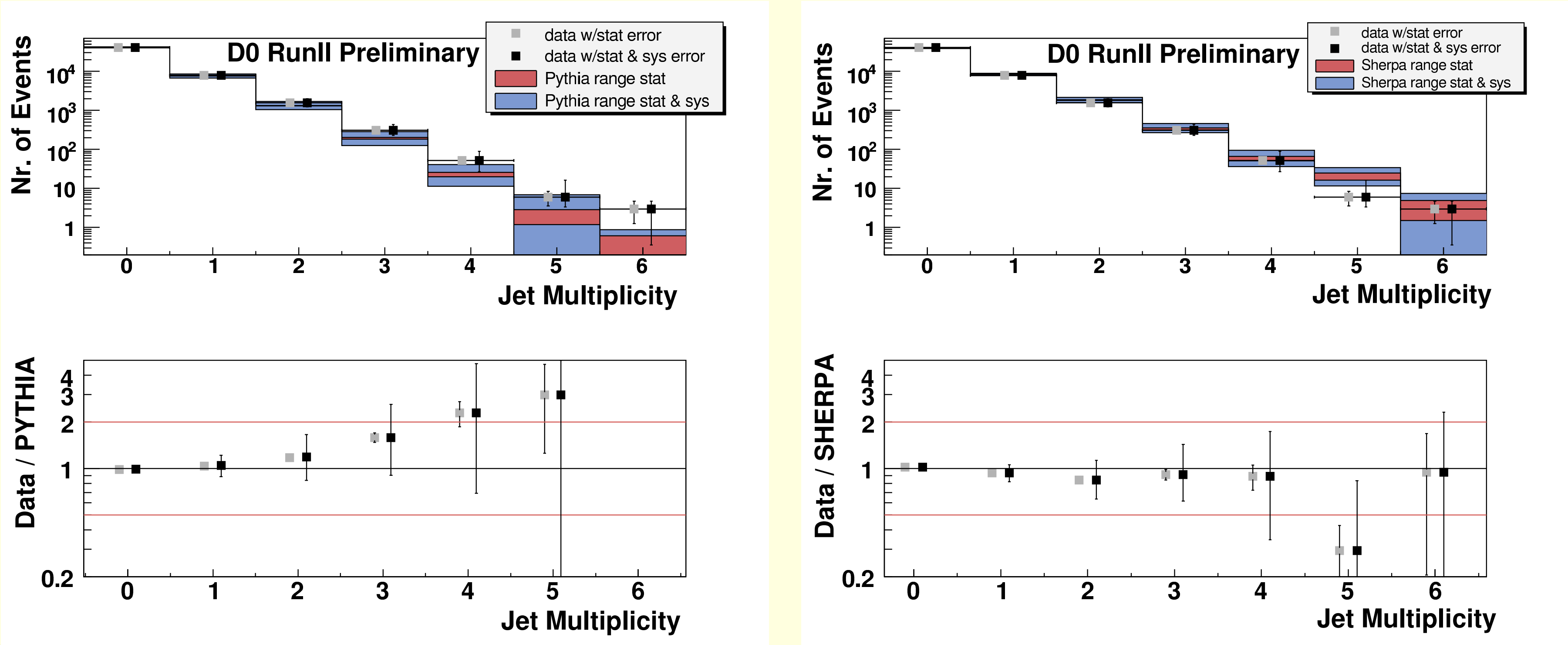
# Point (1): improve PS at large angles

## Validation study: D0 and SHERPA, $Z/\gamma^\star \rightarrow e^+e^- + \mathrm{jets}$

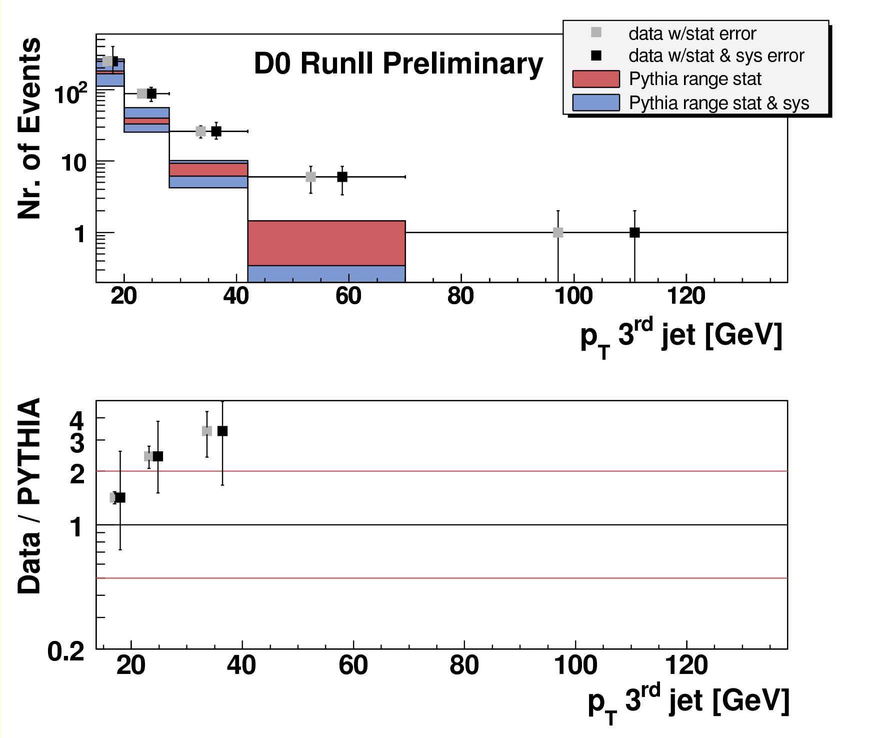


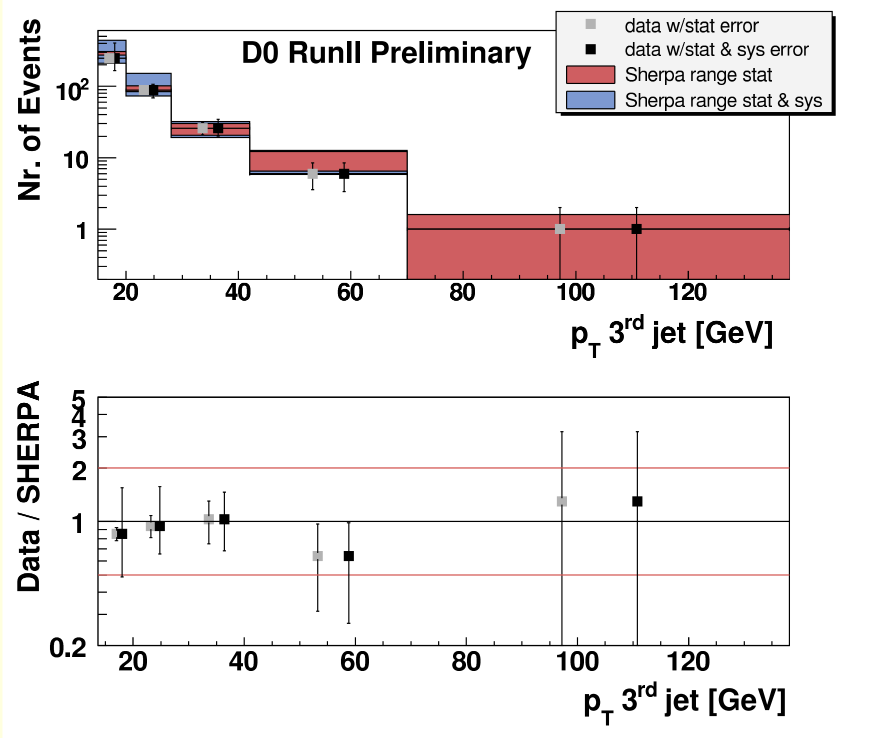




Transverse momentum of $Z$ well described by both SHERPA and PYTHIA




Jet multiplicity better described by ME approach;



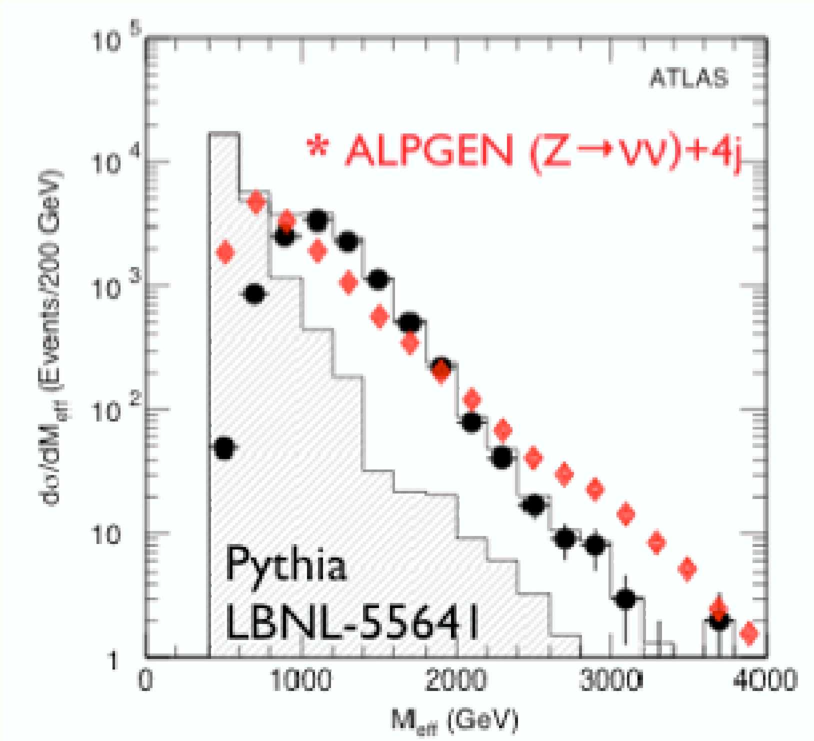




$p_T$ distribution of jets better described by ME approach

Thus: when detailed understanding of the jet structure of the event is needed ME approach performs much better.

The message: when estimating background for complex signals the use of ME is mandatory (Gianotti, Mangano, 05)

$M_{\rm eff}$ distribution for a potential multijet+$E_T^{\rm miss}$ SUSY signal
dark circles: signal
Shaded area: MC background



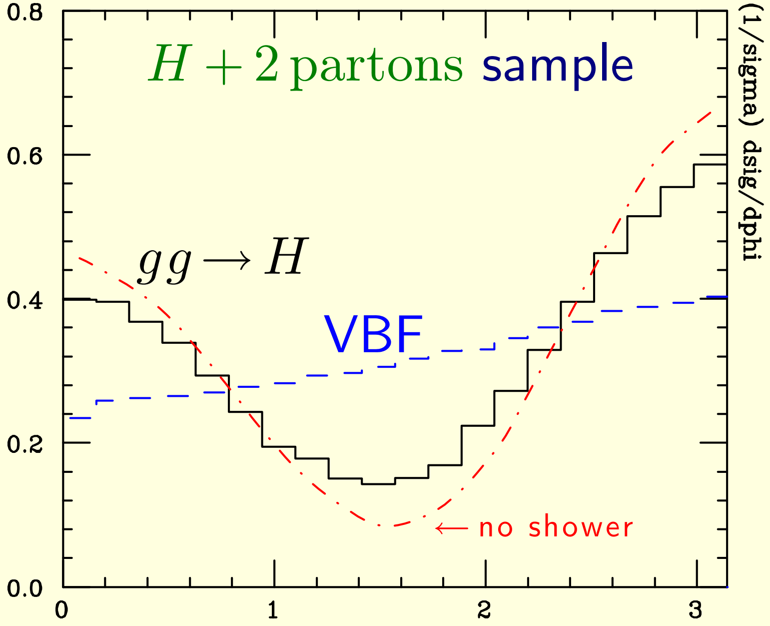
# Point (2): improve ME with Sudakov FF and showers

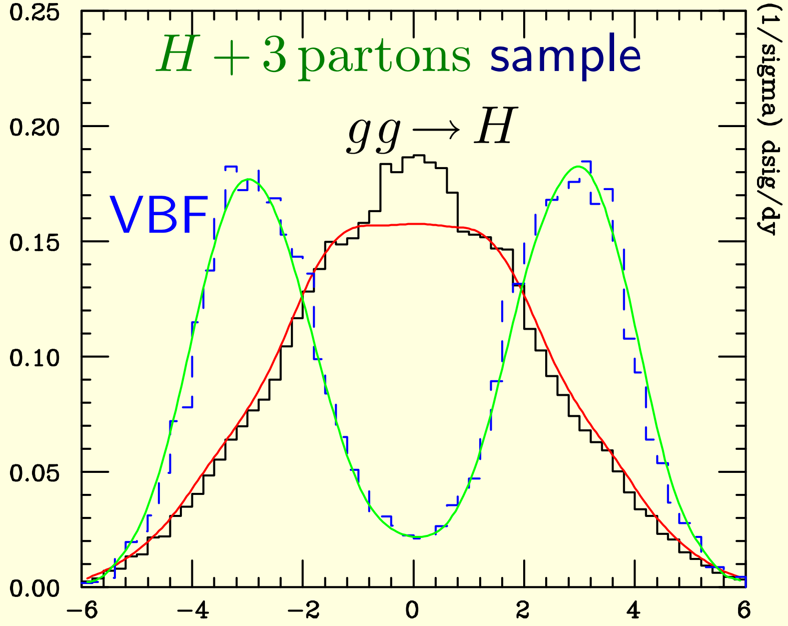
## $H + 2\mathrm{Jets}$, (Del Duca etal, Jul.06)

$H + 2\,\mathrm{Jets}$ can give information on $H$ couplings, in both $gg$ fusion and VBF.

Angular correlation of tagging jets is an important observable;
shower may wash out angular correlation

Central jet veto can be used to enhance VBF signal;
veto is sensitive to Sudakov dumpings




Evidence that angular correlation persists after shower
(using plain Shower Monte Carlo's yields in this case erroneous results)
Evidence that central jet veto can be used to reduce $gg \to H$ contamination of VBF signal

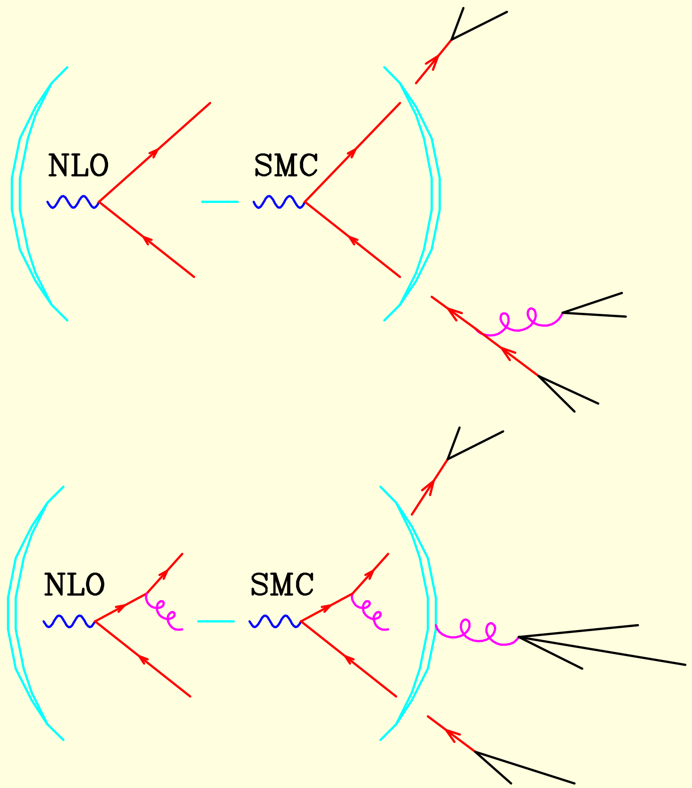
# NLO+Shower

Include shower in NLO calculation: makes their use more flexible;
The problem: overcounting (as in M-ME, but more severe)

Solutions:

- MC@NLO (Frixione,Webber 02; $pp \to Q\bar{Q}$, Frixione,Webber,P.N. 03; $pp \to t\bar{b}$, Frixione,Laenen,Motylinski,Webber, Dec.05)
- Kramer, Mrenna, Soper ($e^+e^- \to 3\,\mathrm{partons}$)
- POWHEG (P.N. 04; $pp \to ZZ$, Ridolfi,P.N., Jun.06; $e^+e^- \to 2\,\mathrm{partons}$, Latunde-Dada,Gieseke,Webber, Dec.06; $pp \to Q\bar{Q}$, Frixione,Ridolfi,PN, Jul.07)

# MC@NLO (2002, Frixione+Webber)




Add difference between exact NLO and approximate (MC) NLO.

- Must use MC kinematics
- Difference should be regular (if the MC is OK)
- Difference may be negative

Several collider processes already there: Vector Bosons, Vector Bosons pairs, Higgs, Heavy Quarks, Single Top.

# POWHEG

Positive Weight Hardest Emission Generator

Method to generate the hardest emission first, with NLO accuracy, and independently of the SMC (P.N. 2004).

- SMC independent; no need of SMC expert; same calculation can be interfaced to several SMC programs with no extra effort ($ZZ$ and $Q\bar{Q}$ calculation interfaced to both PYTHIA and HERWIG)
- SMC inaccuracies only affect next-to-hardest emissions;
- As the name says, it generates events with positive weight

# How it works (roughly)

In words: works like a standard Shower MC for the hardest radiation, with care to maintain higher accuracy.

Inclusive cross section $\Longrightarrow$ NLO inclusive cross section. Positive if $\mathrm{NL} < \mathrm{LO}$

$\Phi_n = \text{Born variables}$
$\Phi_r = \text{radiation vars.}$

$$\bar{B}(\Phi_n) = B(\Phi_n) + \underbrace{\left[ \overbrace{V(\Phi_n)}^{\text{INFINITE}} + \overbrace{\int R(\bar{\Phi}_n, \Phi_r)\, d\Phi_r}^{\text{INFINITE}} \right]}_{\text{FINITE!}}$$

Sudakov form factor for hardest emission built from exact NLO real emission

$$\Delta_t = \exp\left[ \underbrace{-\int \theta(t_r - t) \frac{R(\Phi_n, \Phi_r)}{B(\Phi_n)} d\Phi_r}_{\text{FINITE because of } \theta \text{ function}} \right]$$

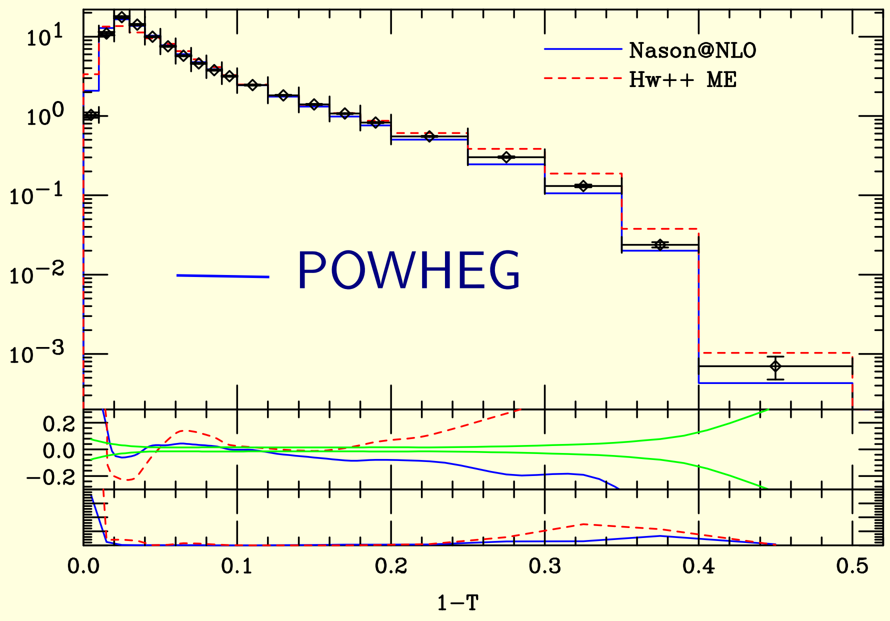
with $t_r = k_T(\Phi_n, \Phi_r)$, the transverse momentum for the radiation.

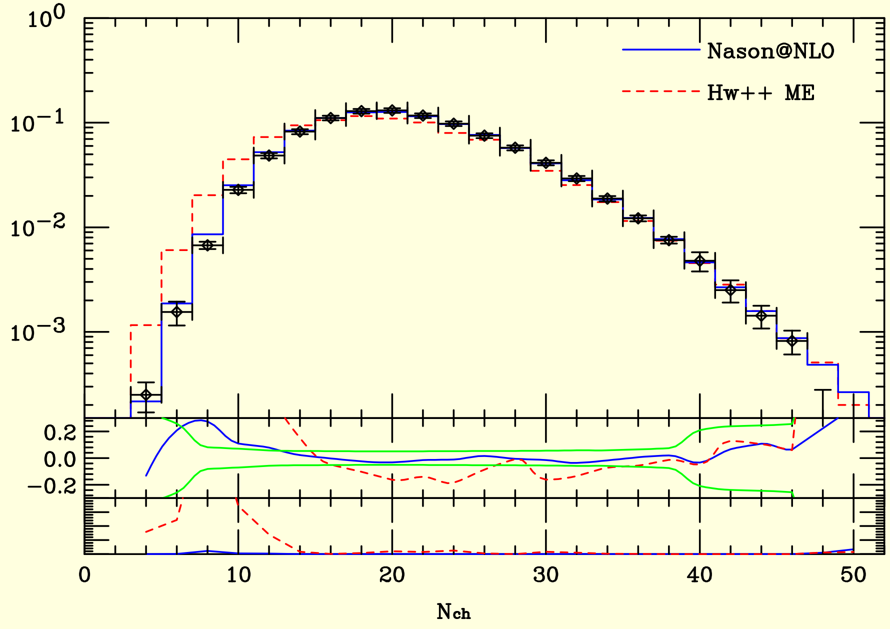
# Implementations

- $pp \to ZZ$, (Ridolfi,P.N. Jun.06), Proof of concept for collider process of intermediate complexity
- $e^+e^- \to \mathrm{hadrons}$, (Latunde-Dada,Gieseke,Webber, Dec.06), fit to $e^+e^-$ data: better than standard ME correction approach
- $pp \to Q\bar{Q}$, (Frixione,Ridolfi,P.N. Jul.07), $c\bar{c}$, $b\bar{b}$ and $t\bar{t}$ (with spin correlations)
- General formulation of the method (Frixione,Oleari,P.N., in preparation)

The POWHEG programs for $ZZ$ and $t\bar{t}$ production have been interfaced to both PYTHIA and HERWIG. Interfacing to other showering programs should be straightforward.

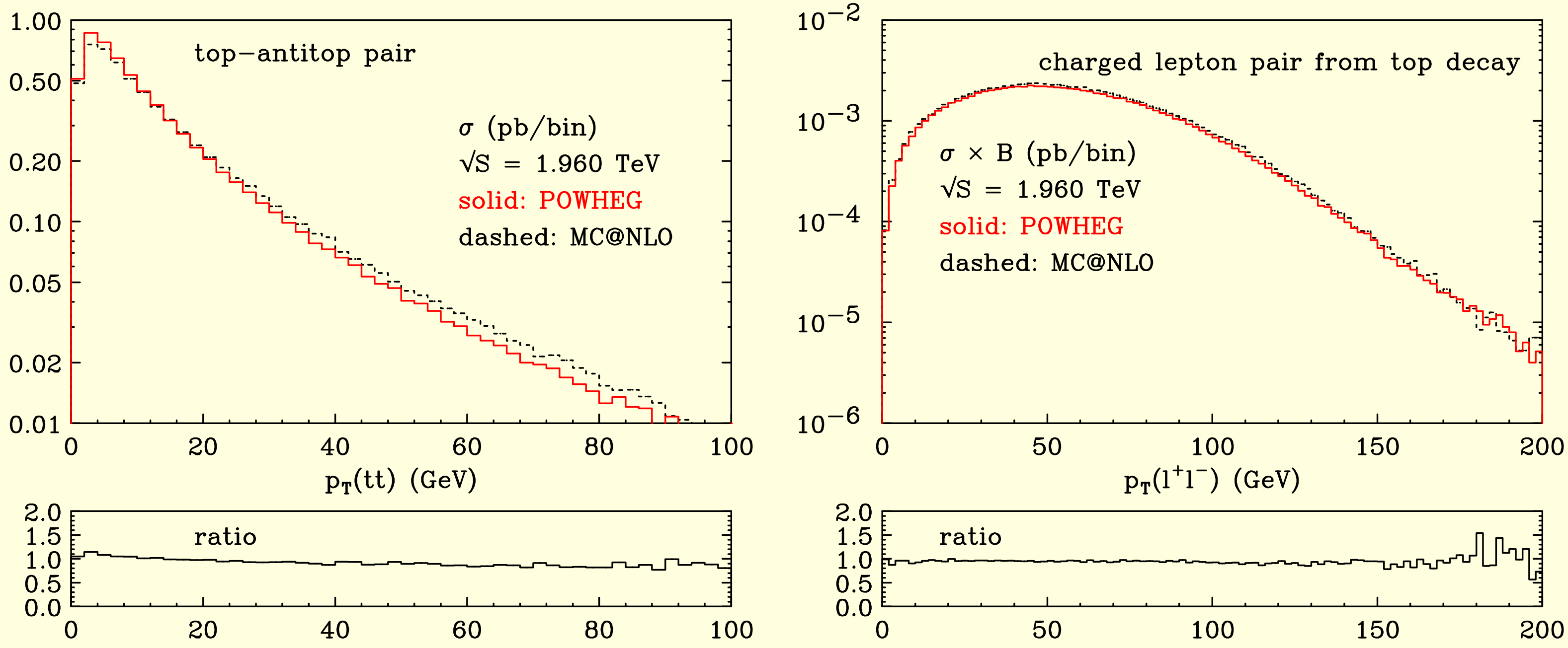
# $e^+e^- \to$ Hadrons



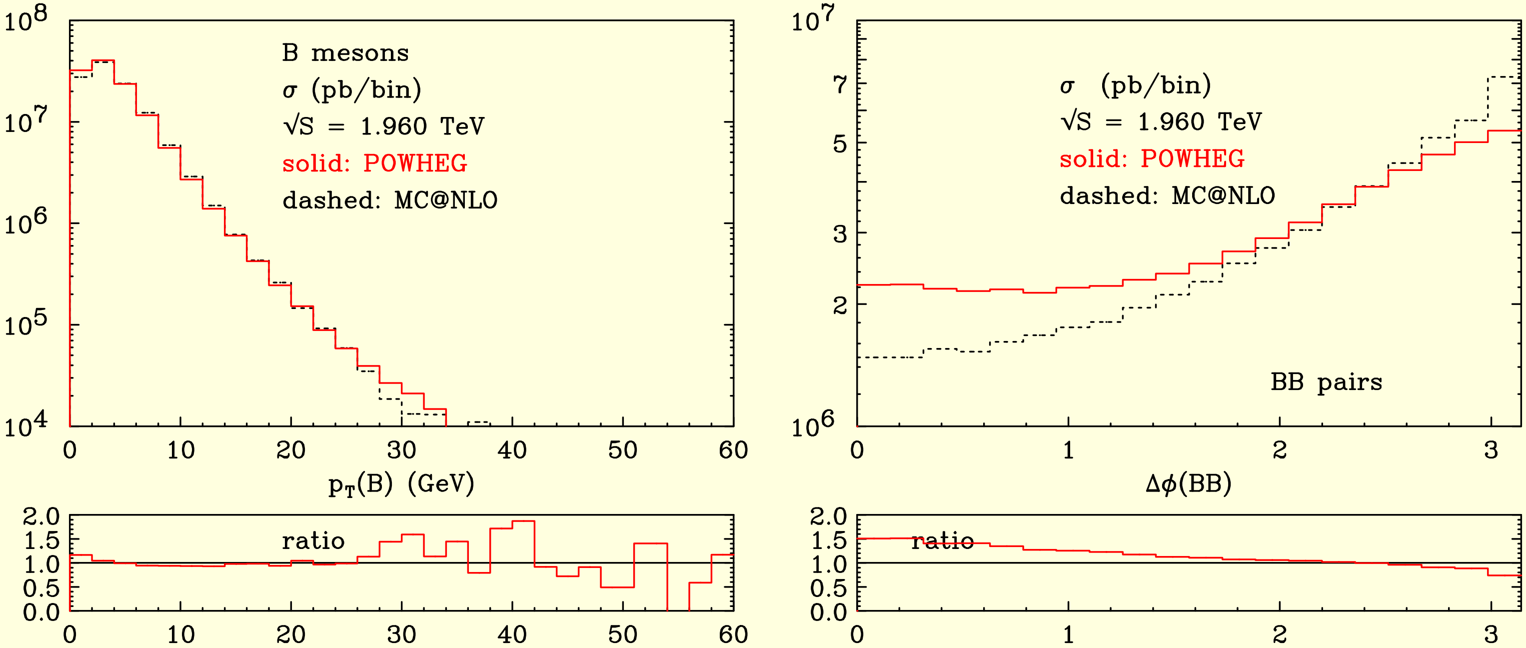

(Latunde-Dada,Gieseke,Webber, Dec.06),
fit to $e^+e^-$ data: better than standard ME correction approach,
shown for the Thrust distribution and the charged multiplicity.

# POWHEG and MC@NLO comparison:
# Top pair production




Good agreement for all observable considered
(differences can be ascribed to different treatment of higher order terms)

# Bottom pair production



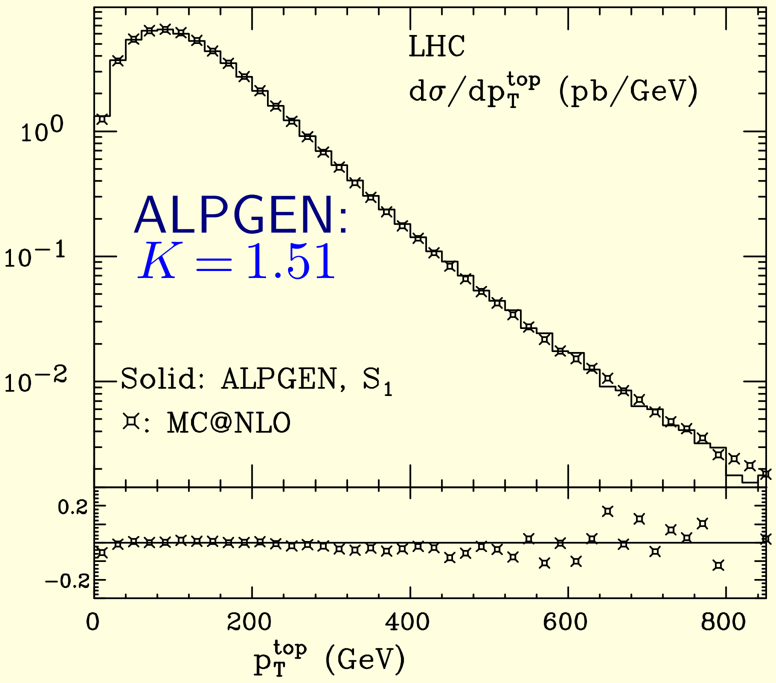

- Very good agreement For large scales ($ZZ$, $t\bar{t}$ production)
- Differences at small scales ($b\bar{b}$ at the Tevatron)
- POWHEG more reliable in extreme cases like $b\bar{b}, c\bar{c}$ at LHC (yields positive results, MC@NLO has problems with negative weights)

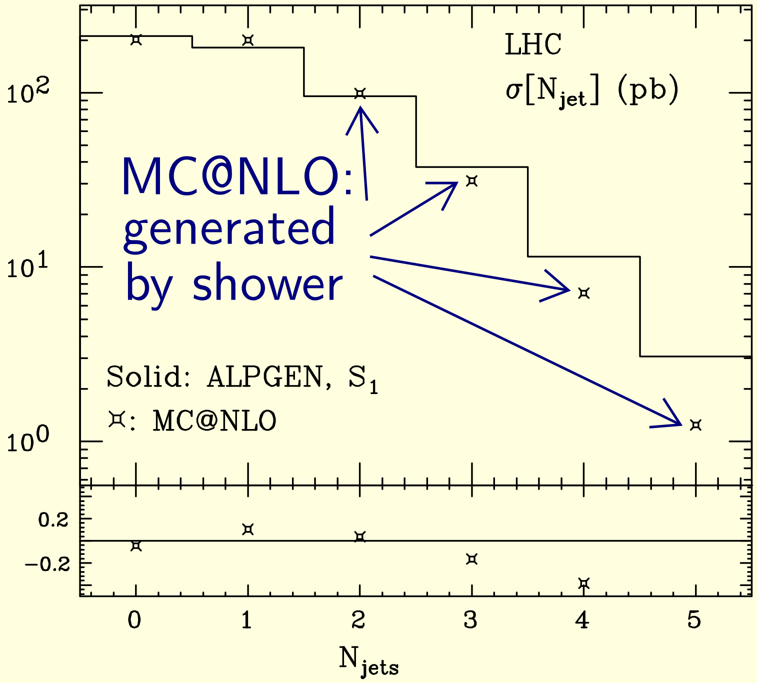
ALPGEN can generate samples of $t\bar{t} + n\,\mathrm{jets}$; can be compared to NLO+PS;

expect:

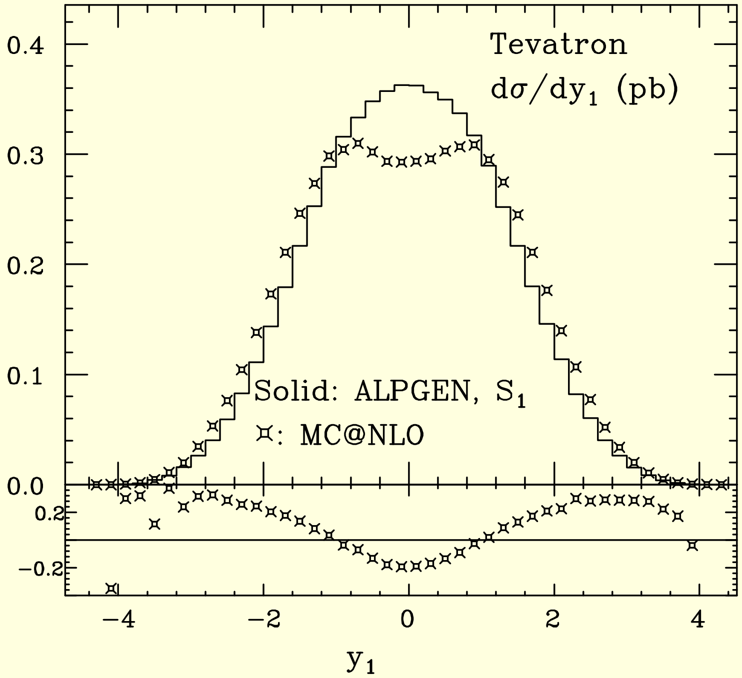
- Disadvantage: worse normalization (no NLO)
- Advantage: better high jet multiplicities (exact ME)

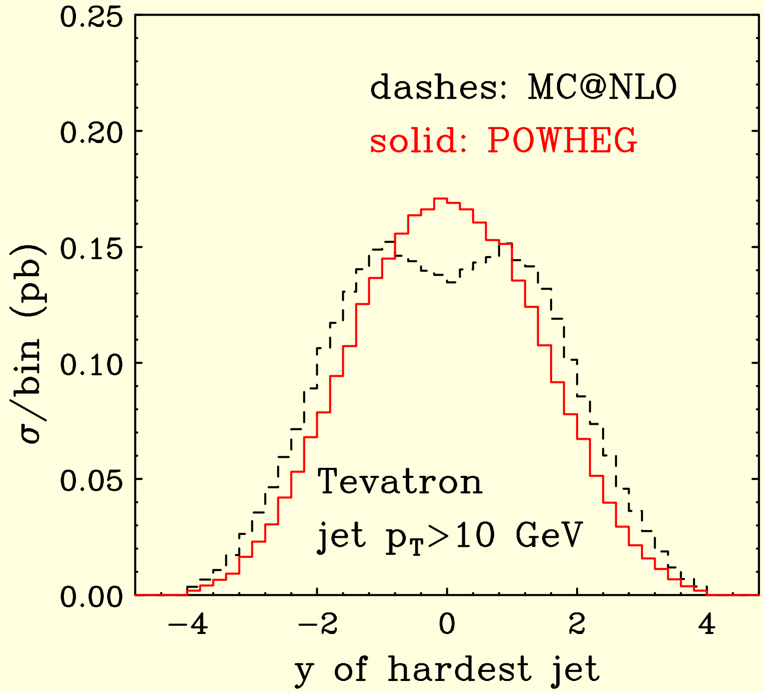
Comparison ALPGEN-MC@NLO carried out in detail (Mangano, Moretti,Piccinini,Treccani, Nov.06)



# Results as expected but for 1 observable




POWHEG's distribution as in ALPGEN (i.e., no dip);
Notice: size of discrepancy can be attributed to different treatment of higher order terms. Is this "feature" really there?
New $pp \rightarrow t\bar{t} + \mathrm{Jet}$ at NLO (Dittmaier, Uwer, Weinzierl)
can help to solve this issue: further study needed!

# Shower improvements

Several improvements in existing (popular) shower MC:

- PYTHIA has implemented a new, $p_T$ ordered shower algorithm: easier to interface to Matrix-Elements generators
- HERWIG has introduced new shower variables, with improved Lorentz invariance properties, and better treatment of mass effects
- Multiparton interactions in Underlying Event

Several proposals of new shower algorithms (not yet functional):

- Shower by antenna factorization (Frederix,Giele,Kosower,Skands) (toy implementation for $H \to gg$ )
- Shower by Catani-Seymour dipole factorization (Schumann)
- Shower with quantum interference (Nagy,Soper)
- Shower by Soft Collinear Effective Theory (Bauer,Schwartz)

# ISSUES on Shower Algorithms

- Collinear approximation neglects azimuthal dependent effects
- Colour flow is only treated in the large $N_c$ limit
- Soft effects treated only in the soft-collinear limit (angular ordering) or in the large $N_c$ limit (dipole showers, antenna showers)

Plenty of areas where to seek improvements.

Notice: ME+PS already improve upon many of these issues,
at least as far as the hardest jets are concerned. Since we can
generate many jets, to some extent they replace the shower Monte Carlo
Furthermore: they yield the correct behaviour for large angle jet emission
(perhaps this is the way to go ...)

# CONCLUSIONS

- Intense QCD theoretical activity in preparation for the LHC: new NLO results become available
- One remarkable result: $e^+e^- \to q\bar{q}g$ at NNLO
- Closer interaction between modeling (i.e. Shower Monte Carlo) and calculations (ME, NLO)
- The way events are simulated is changing in a fundamental way
- Lots of open problem, and ideas for new developments

Acknowledgments: S. Catani, F. Maltoni, M.L. Mangano, M. Moretti, C. Oleari, F. Piccinini, G. Zanderighi