The Sherpa Monte Carlo

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The Sherpa project

brief history

- first version 1.0α released during MC4LHC workshop 2003
- largely independent approach to provide full C++ Monte Carlo
- since version 1.0.6 available in DØ production chain
- meanwhile integrated also in ATLAS, CMS and LHCb software
- versions available on Genser or from `http://www.sherpa-mc.de`

development team

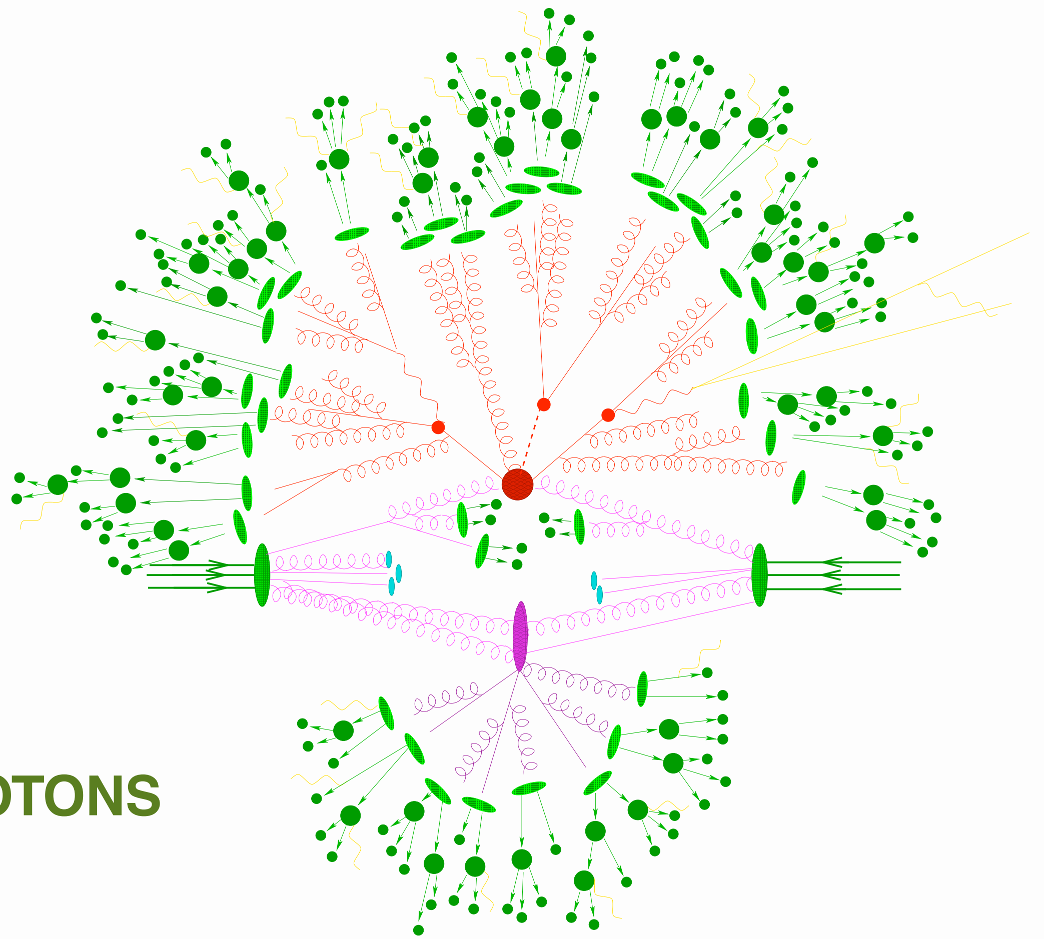
- Frank Krauss, Stefan Höche, Frank Siegert (Durham)
- Tanju Gleisberg (SLAC)
- Jan Winter (FNAL)
- Marek Schönherr (Dresden)
- Steffen Schumann (Dùn Èideann)

➔ **current version Sherpa-1.1.0 first complete physics version**

Physics of Sherpa

split simulation in phases

- **Hard interaction: AMEGIC**
  exact matrix elements $|\mathcal{M}|^2$
- **QCD bremsstrahlung: APACIC**
  parton showers in the initial and final state
- **Multiple Interactions: AMISIC**
  beyond factorisation: modelling
- **Hadronisation: AHADIC**
  non perturbative QCD: modelling
- **Hadron Decays: HADRONS/PHOTONS**
  matrix elements or phase space / YFS



➔ **Sherpa is the framework that steers the event generation**

Hard Process Simulation

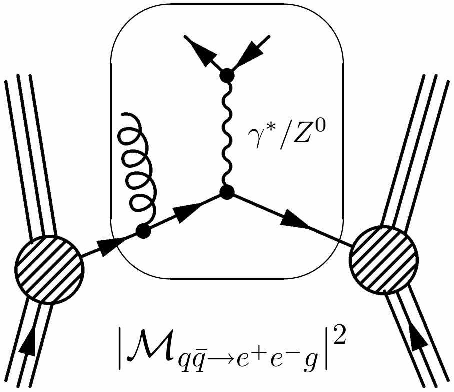
Hadronic Cross Section

- factorisation into hard and soft contribution (resummed in PDFs)

$$\sigma_{pp\to X}(Q^2) = \sum_{ab} \int \mathrm{d}x_a \mathrm{d}x_b \; f_a(x_a, Q^2) f_b(x_b, Q^2) \; \mathrm{d}\hat{\sigma}_{ab\to X}(Q^2)$$

- hard production process described through [Higgs, SUSY, ...]

$$\mathrm{d}\hat{\sigma}_{ab\to X} = |\mathcal{M}_{ab\to X}|^2 \; \mathrm{d}LIPS$$



➔ typical LHC signatures: several hard jets plus leptons

➔ best accounted for by multi-particle matrix elements

- calculation of the full matrix element
- integration over multi-dimensional peaked phase space

$\hookrightarrow$ **tree-level Matrix Element Generators**

Sherpa's Matrix Element Generator: AMEGIC

working principles

- specify initial and final states [intermediate resonances can be enforced]

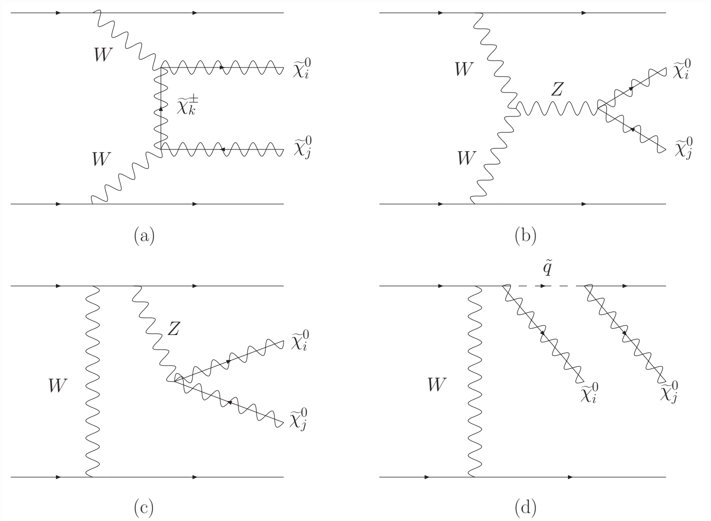
```
Process : 93 93 -> 25[a] 93 93
Order electroweak : 3
Decay : 25[a] -> -11 12 13 -14
End Process
```

- Feynman diagrams get constructed and translated into helicity amplitudes
- on the flight appropriate phase-space integrators are constructed
- amplitudes and phase-space mappings are stored as library files

implemented models

- SM + ggH + AGC + 4^{th} family
- MSSM (fully general)
- ADD model of extra dimensions
- additional scalar singlet

➔ generic interface soon [FeynRules]



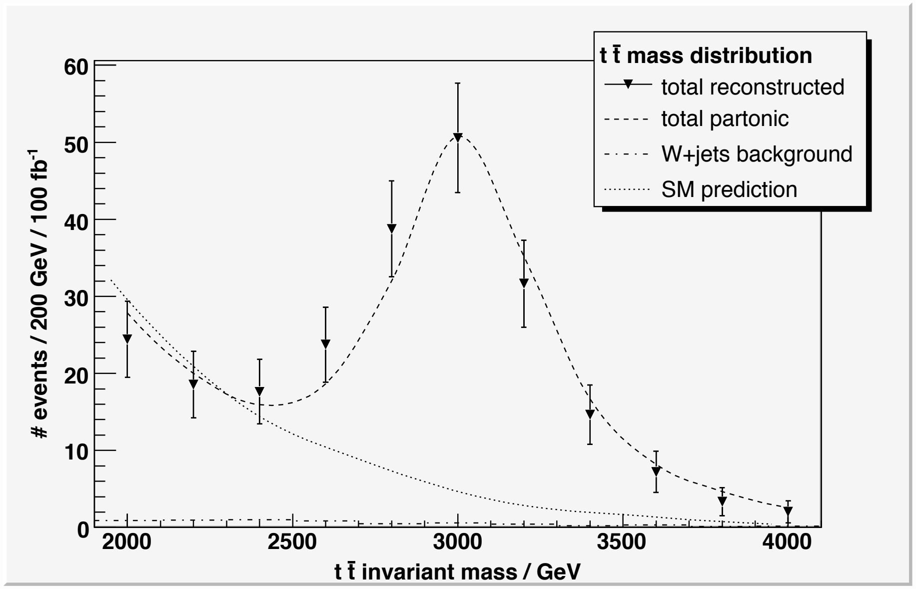
Sherpa's Matrix Element Generator: AMEGIC

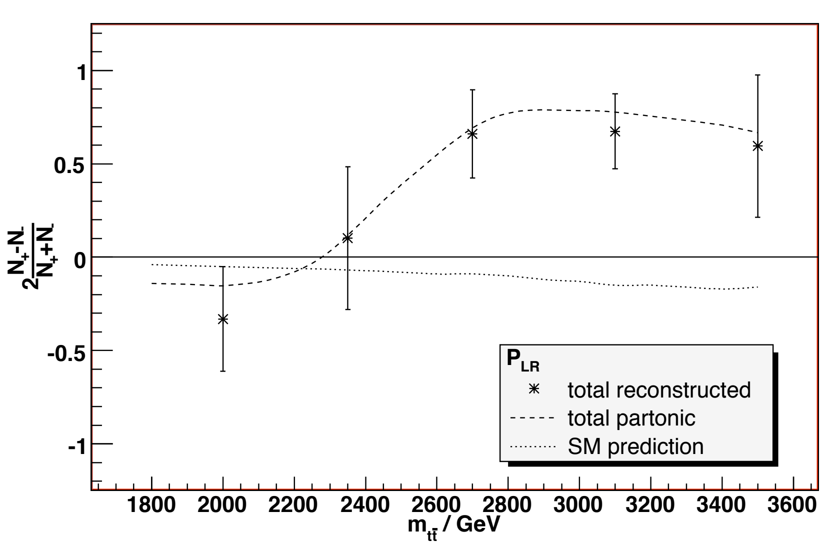
capabilities

- efficient generation of multi-parton amplitudes, e.g. $V + 4$j, $VV + 3$j, $t\bar{t} + 2$j
- include off-shell, interference and correlation effects in SM $\&$ BSM procs

example: Kaluza-Klein gluons at LHC [Agashe et al. 2006]

- specific RS scenario with proto- and lepto-phobic KK gauge bosons
- dominant decays to tops, look for $pp \to G^1 \to t\bar{t} \to b\bar{b}l\nu jj$
- search for peak in $m_{t\bar{t}}$, lepton asymmetry due to dominant coupling to t_R





Parton Shower Evolution: APACIC

initial and final-state parton shower simulation

- relying on collinear factorisation of real-emission matrix elements

$$|\mathcal{M}_{\mathrm{q\bar{q}g}}|^2 \mathrm{d}\Phi_{\mathrm{q\bar{q}g}} = |\mathcal{M}_{\mathrm{q\bar{q}}}|^2 \mathrm{d}\Phi_{\mathrm{q\bar{q}}} \left\{ \frac{\mathrm{d}t_{\mathrm{qg}}}{t_{\mathrm{qg}}} \frac{\alpha_S}{2\pi} P_{\mathrm{q,qg}}(z_{\mathrm{q}}) \mathrm{d}z_{\mathrm{q}} + \frac{\mathrm{d}t_{\mathrm{\bar{q}g}}}{t_{\mathrm{\bar{q}g}}} \frac{\alpha_S}{2\pi} P_{\mathrm{\bar{q},\bar{q}g}}(z_{\bar{q}}) \mathrm{d}z_{\bar{q}} \right\}$$

- $1 \to 2$ parton branchings given by spin averaged Altarelli-Parisi kernels
- shower sequence ordered in partons virtuality [backwards for initial state]
- angular ordering imposed by veto on rising opening angles only

➔ yields leading logarithmic approximation for real emission processes

merging of multi-jet matrix elements with parton showers

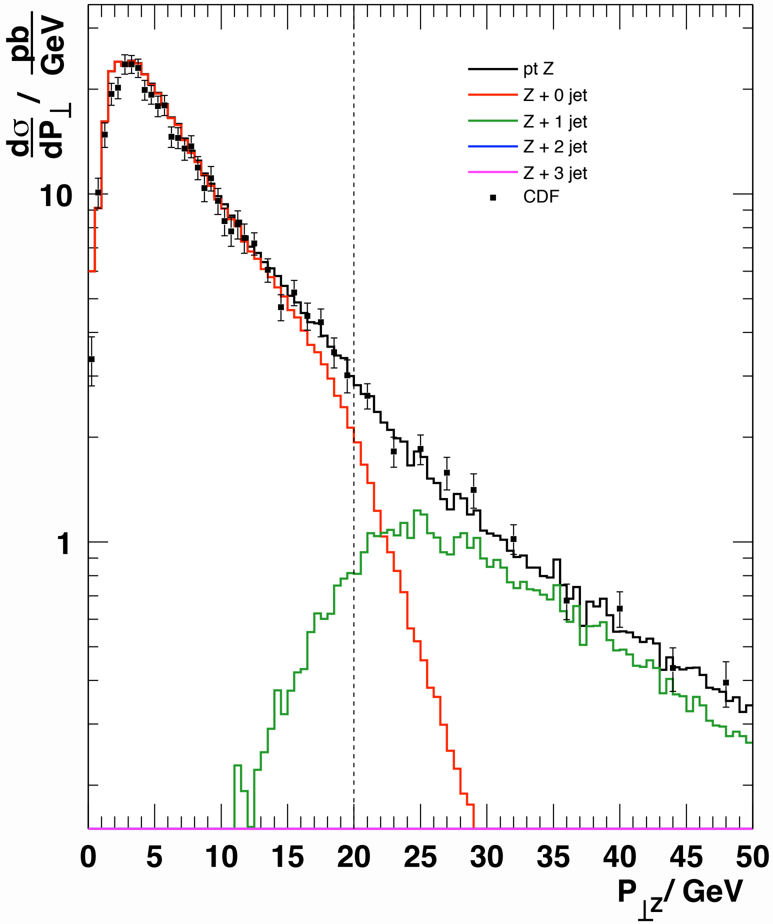
- first few hard emissions described through full matrix elements
- shower generates jet substructure and adds softer jets

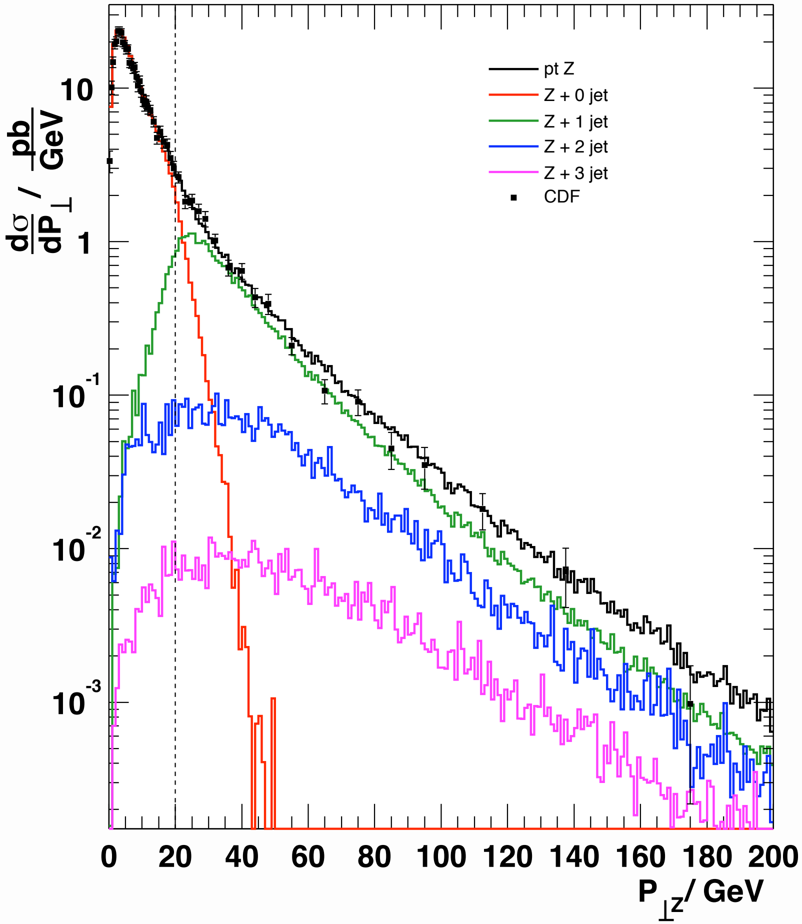
➔ must avoid double–counting of phase-space configurations

➔ reweighting of matrix elements + vetoed shower evolution (CKKW)

Combining Matrix Elements with Parton Showers

$Z\ p_\perp$ distribution measured by CDF [Affolder et al. 2000]



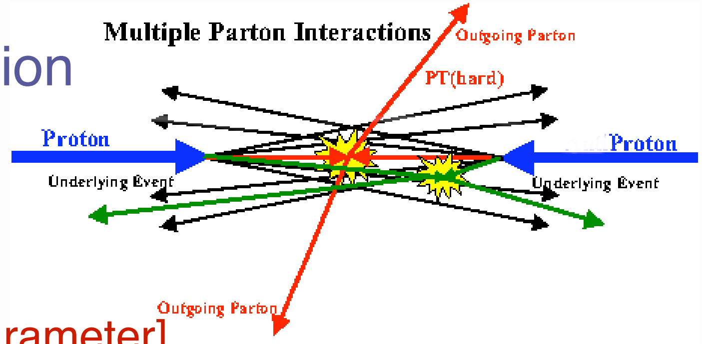


- **distribution multiplied by appropriate K-factor!**
- intrinsic transverse momentum smearing of $< k_T >= 0.8\,\mathrm{GeV}$ applied

Sherpa's Underlying Event Simulation: AMISIC

implementation of the Sjöstrand–Zijl model

➔ impact parameter dependent distribution of secondary interactions



- additional $2 \to 2$ QCD processes per pp interaction

$$\frac{d\sigma_{\rm hard}}{dp_\perp^2} \to \frac{d\sigma_{\rm hard}}{dp_\perp^2} \times \frac{p_\perp^4}{(p_\perp^2 + p_{\perp 0}^2)^2} \frac{\alpha_S^2(p_\perp^2 + p_{\perp 0}^2)}{\alpha_S^2(p_\perp^2)}$$

$\Rightarrow$ singularity regularised by cut-off $p_{\perp 0}^2$ [tuning parameter]

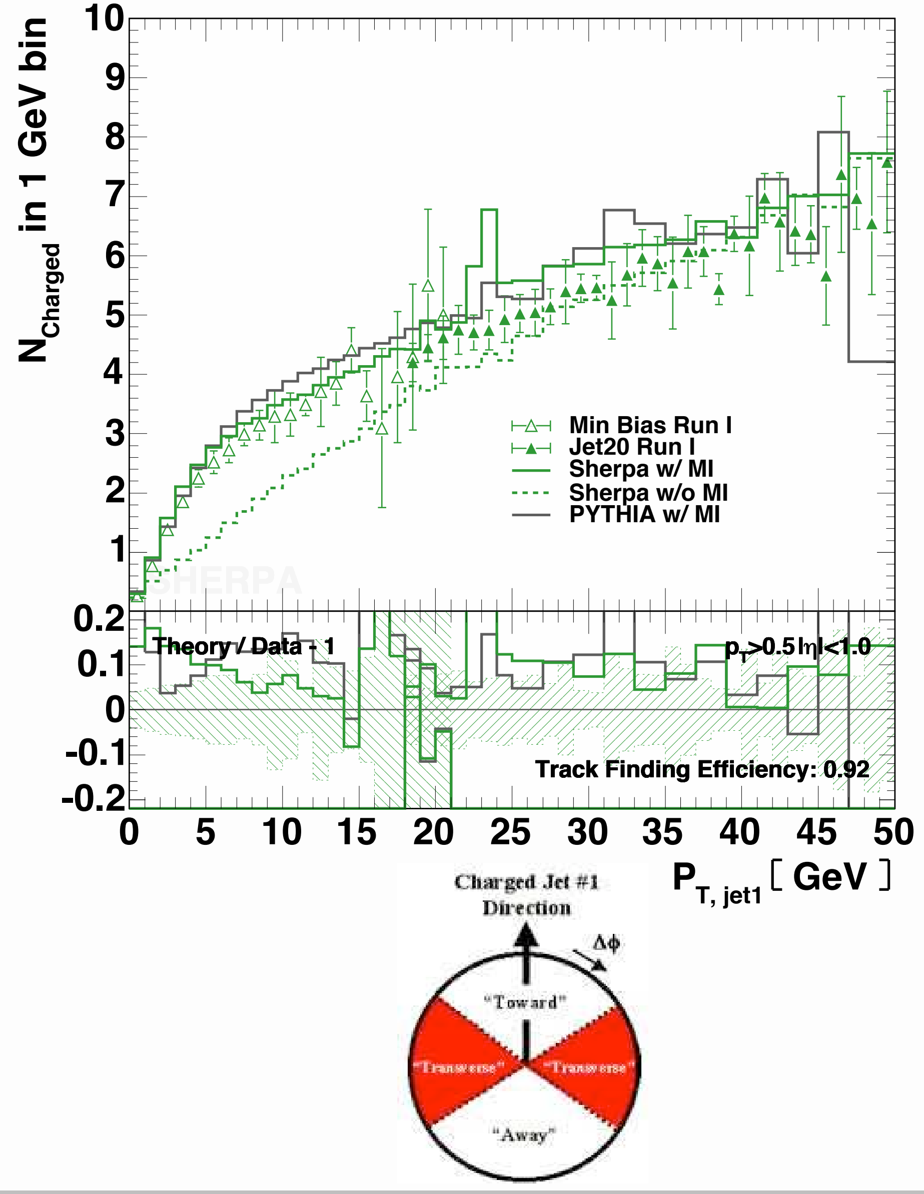
$\Rightarrow$ fixed at $E_{\rm REF}$ extrapolation to $E_{\rm CMS}$ according to

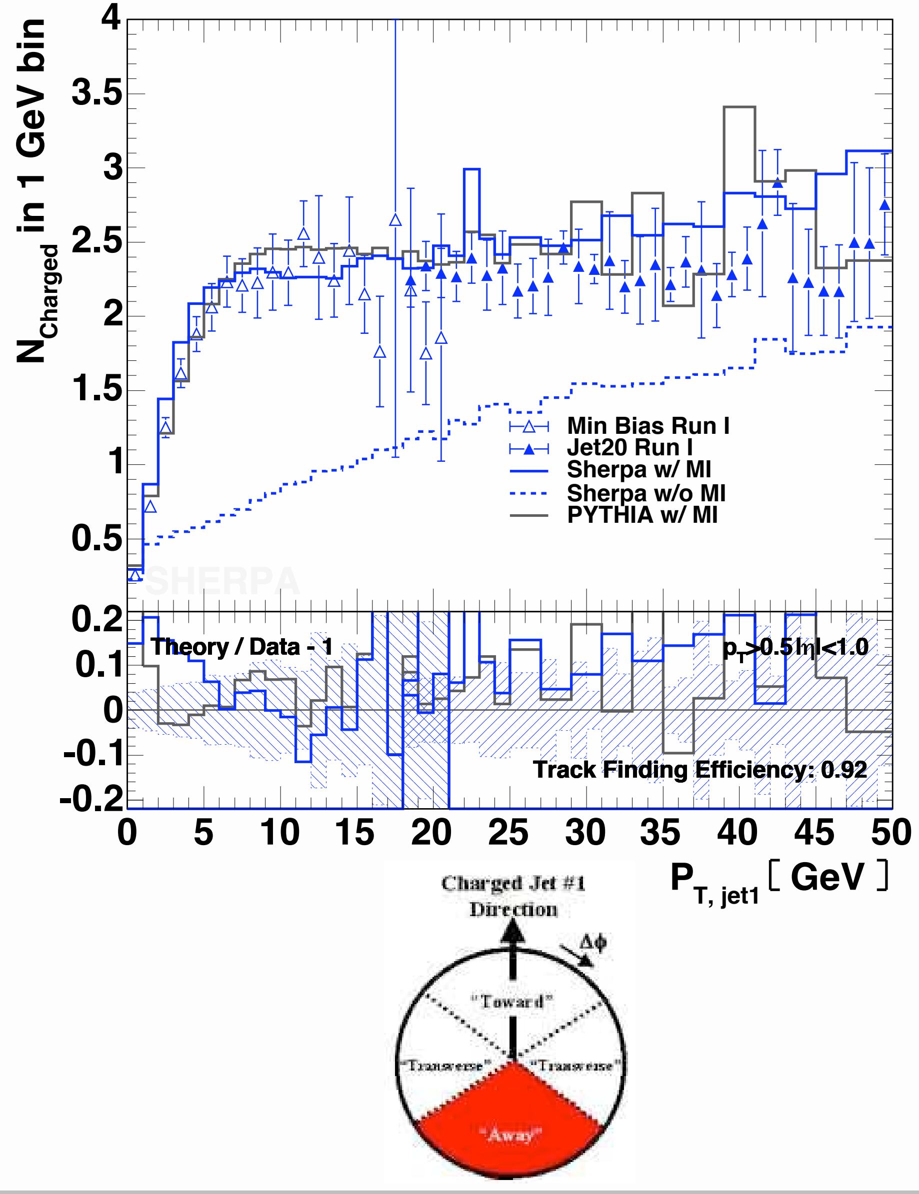
$$p_{\perp 0}(E_{\rm CMS}) = p_{\perp 0}(E_{\rm REF}) \times \left(\frac{E_{\rm CMS}}{E_{\rm REF}}\right)^\alpha$$ [default assumption $\alpha = 0.16$]

- secondary interactions dressed with parton showers
- start scale of UE linked to the hard process [adapted to ME+PS]
- (hand) tuned to Rick Fields CDF data (pre-1.1.0 versions)

$\hookrightarrow$ new tuning due to new hadronisation and hadron decays needed

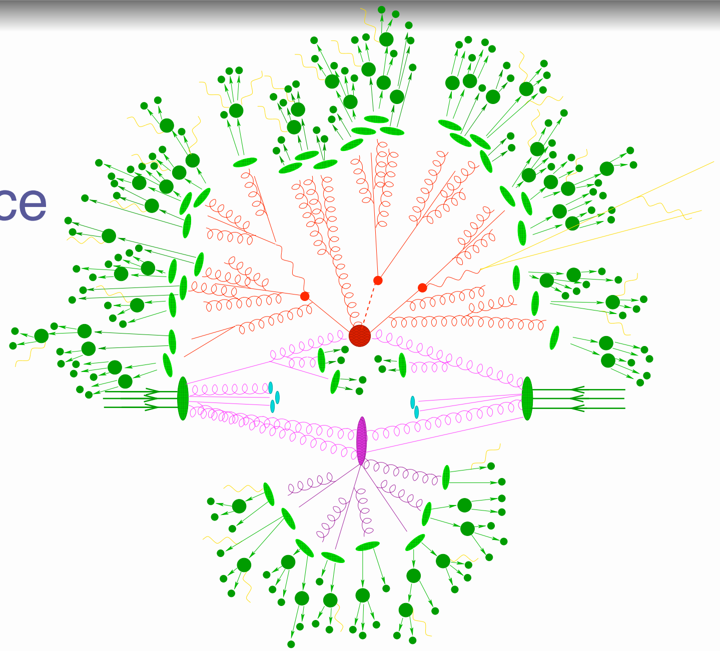
N_{charged} vs. $p_{\perp,\text{jet1}}$ in different $\Delta\phi$ regions w.r.t the leading jet





From Partons to Hadrons: AHADIC

Sherpa's new cluster hadronisation model



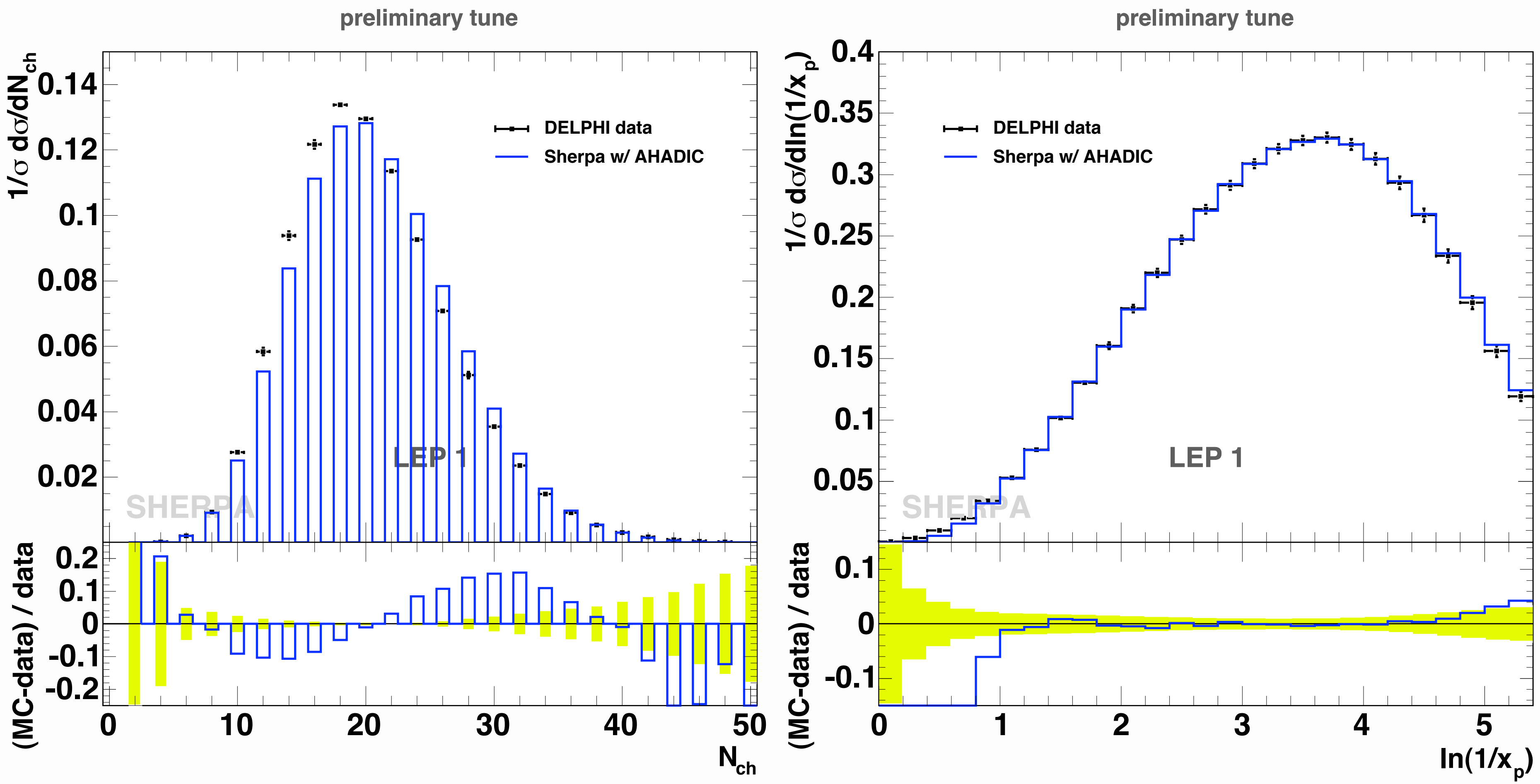
- after shower colour singlets close in phase space
- shift quarks to constituent masses
- split perturbative gluons into $q\bar{q}$
  - enforce dipole-like splittings $\sim \alpha_S/p_T^2$
  - parametrise of α_S at very low scales
  - gluons remain massless
- adjacent pairs colour connected, form colourless clusters
- clusters then decay, $C \to CC$, $C \to CH$, $C \to HH$, $C \to H$
- cluster–hadron transition determined by overlap w/ hadron wave functions

e.g. $u\bar{u}$ cluster vs. $\pi^0 = \frac{1}{\sqrt{2}}(u\bar{u} + d\bar{d})$ or $\eta = \frac{1}{\sqrt{6}}(u\bar{u} + d\bar{d} - 2s\bar{s})$ or $\eta' = \frac{1}{\sqrt{3}}(u\bar{u} + d\bar{d} + s\bar{s})$

$\hookrightarrow$ **existing interface to Lund string is still available**

From Partons to Hadrons: AHADIC

first AHADIC (hand) tune against LEP-data at Z-pole



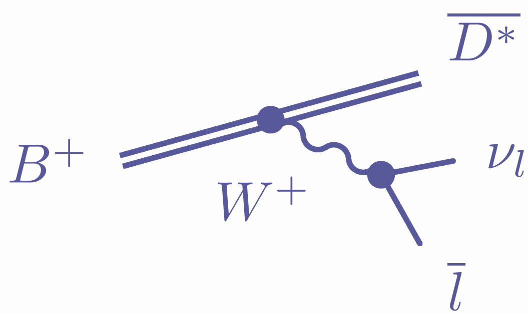
Sherpa's Hadron Decay Module: HADRONS

working principles

- for unstable hadrons choose decay channel according to branching ratio
  [large database of decay tables that specify corresponding decayers]
- decay kinematics according to differential decay rate

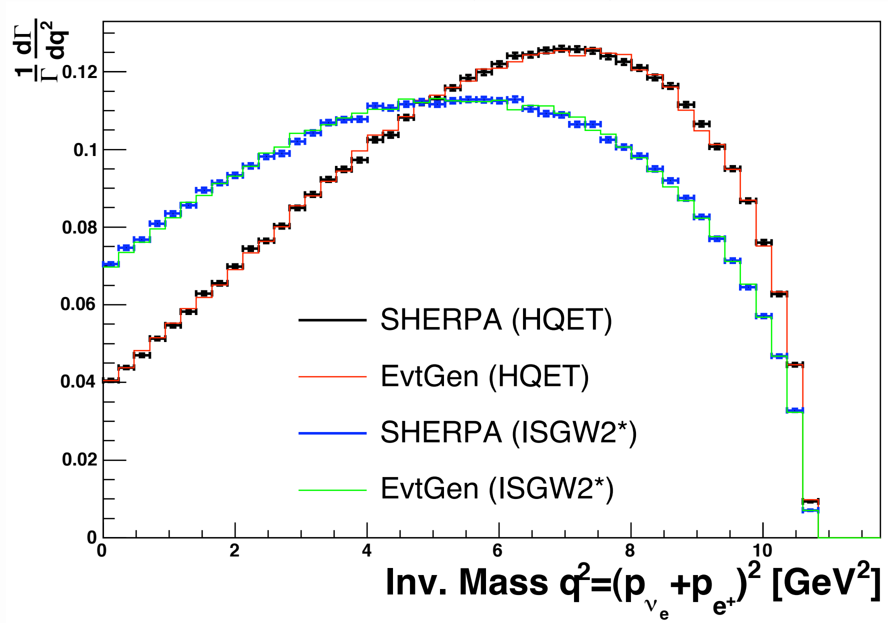
$$\mathrm{d}\Gamma(P \to p_1, \ldots, p_n) = \frac{1}{2M_{dec}} \cdot |\mathcal{M}|^2(P, p_1, \ldots, p_n) \cdot \mathrm{d}LIPS$$

- $|\mathcal{M}|^2$ for τ, B, D, light mesons



$$\hookrightarrow \mathcal{M} = -\mathrm{i}\frac{G_F}{\sqrt{2}} V_{cb}\, L_\mu\, H^\mu$$

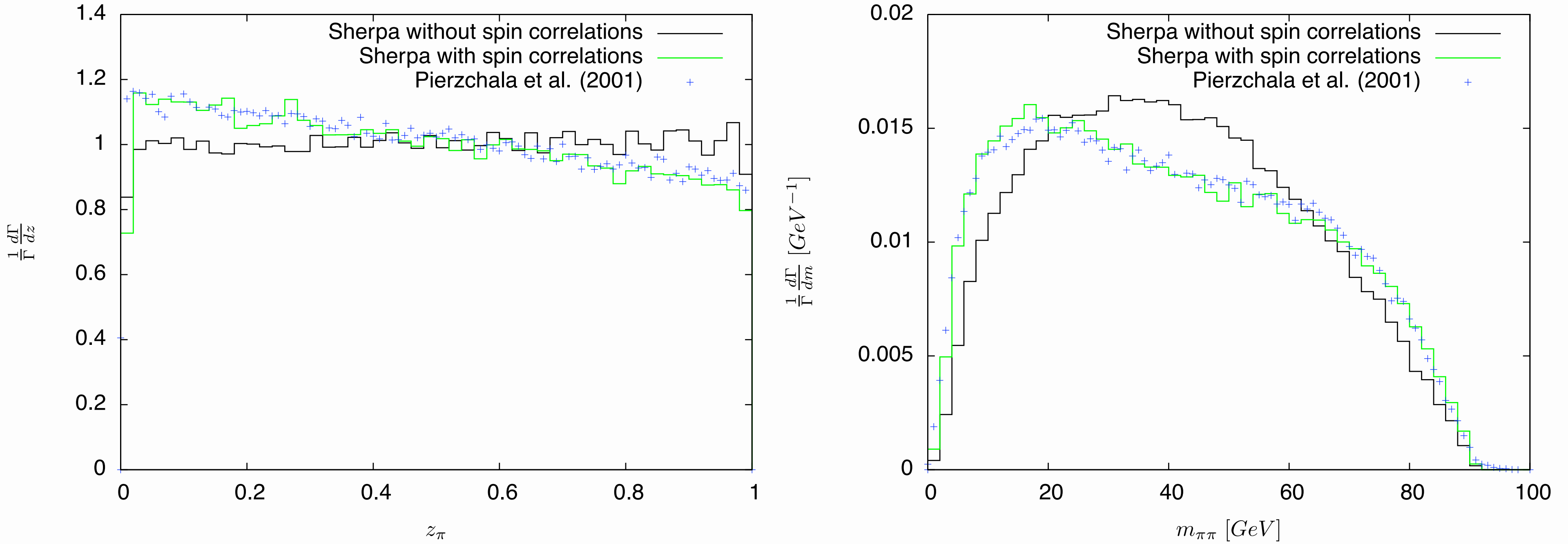
$B^+ \to \overline{D^*}(2007)^0 e^+ \nu_e$



- $B\bar{B}$ mixing & CP violation
- 2-body decays according to spins

Sherpa's Hadron Decay Module: HADRONS

example: spin correlations in $Z \to \tau^+\tau^- \to \pi^+\bar{\nu}_\tau\pi^-\nu_\tau$
comparison with Tauola



pion energy fraction in Z rest frame **pion-pion inv. mass**

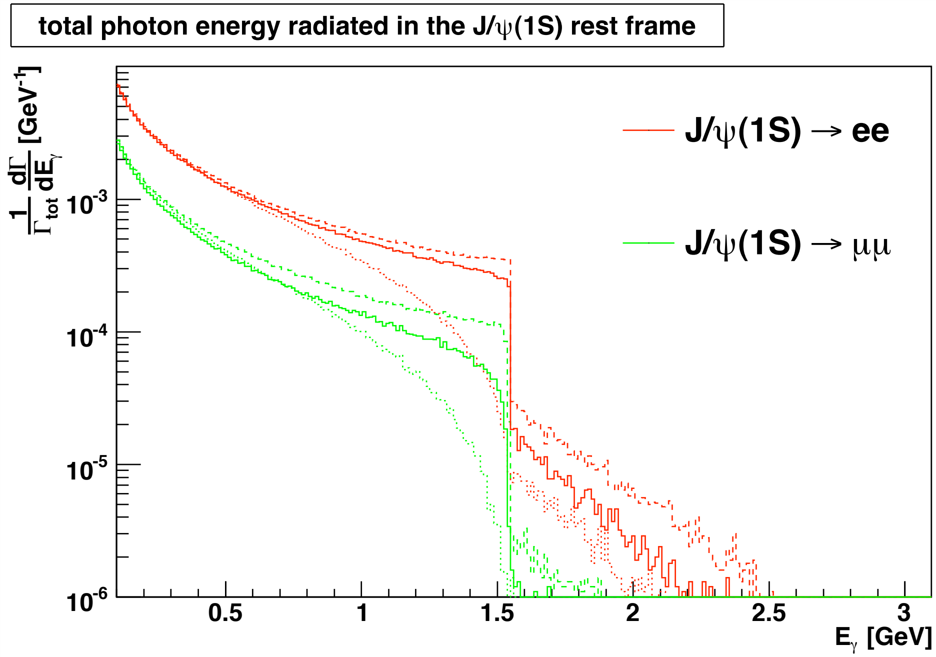
Dressing up with photons: PHOTONS

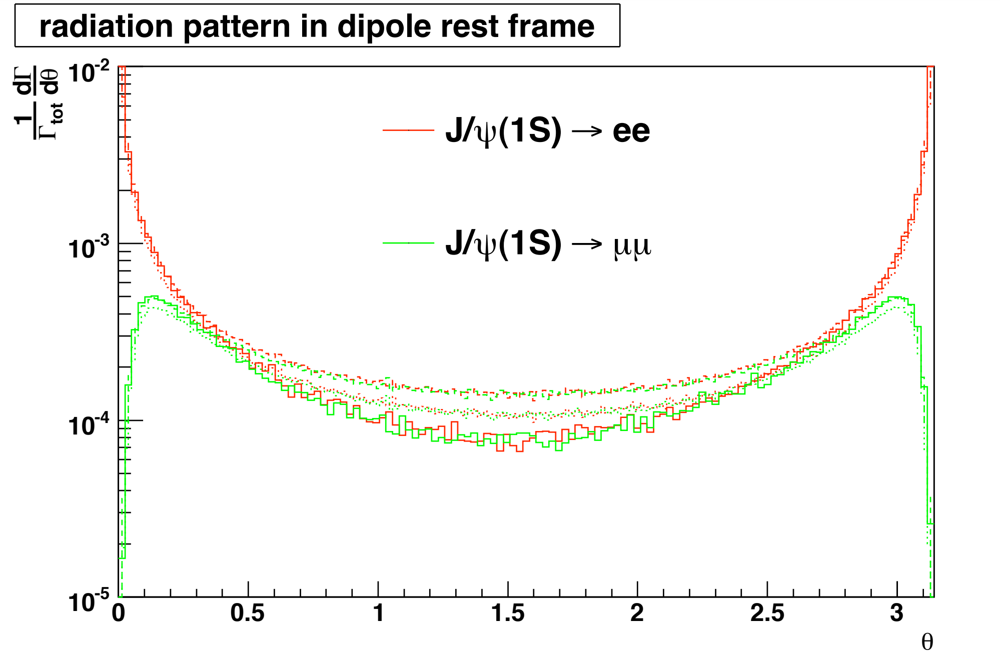
$U(1)_{\rm em}$ charged particles radiate off photons

➔ account for higher order QED effects: YFS approach [τ's & hadrons only]

- exponentiation of soft photon radiation (real and virtual)
- hard emissions at $\mathcal{O}(\alpha)$ through approx. matrix element

$\Rightarrow$ some cases through full $\mathcal{O}(\alpha)$ real/virtual matrix elements





soft only (dotted), coll. approx. ME (dashed), exact ME (solid)

Summary

Sherpa (hopefully) well equipped for the LHC challenge

- sophisticated description of perturbative physics
  - built-in matrix element generator for multi-leg processes [SM + BSM]
  - consistent merging of MEs with parton shower a la CKKW
- wide coverage of soft-physics aspects
  - new cluster hadronisation model
  - extensive τ and hadron decays package
  - multiple photon emission in YFS formalism

currently ongoing

- new parton showers [Catani-Seymour subtraction terms,Colour-Dipoles]
- new SM matrix element generator relying on Berends-Giele recursion

  $\Rightarrow$ faster and higher multiplicities
- new underlying event model [k_T-factorisation]
- going NLO for the matrix elements