New Monte Carlo* tools for hadronic collisions

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* event generators

MC event generators

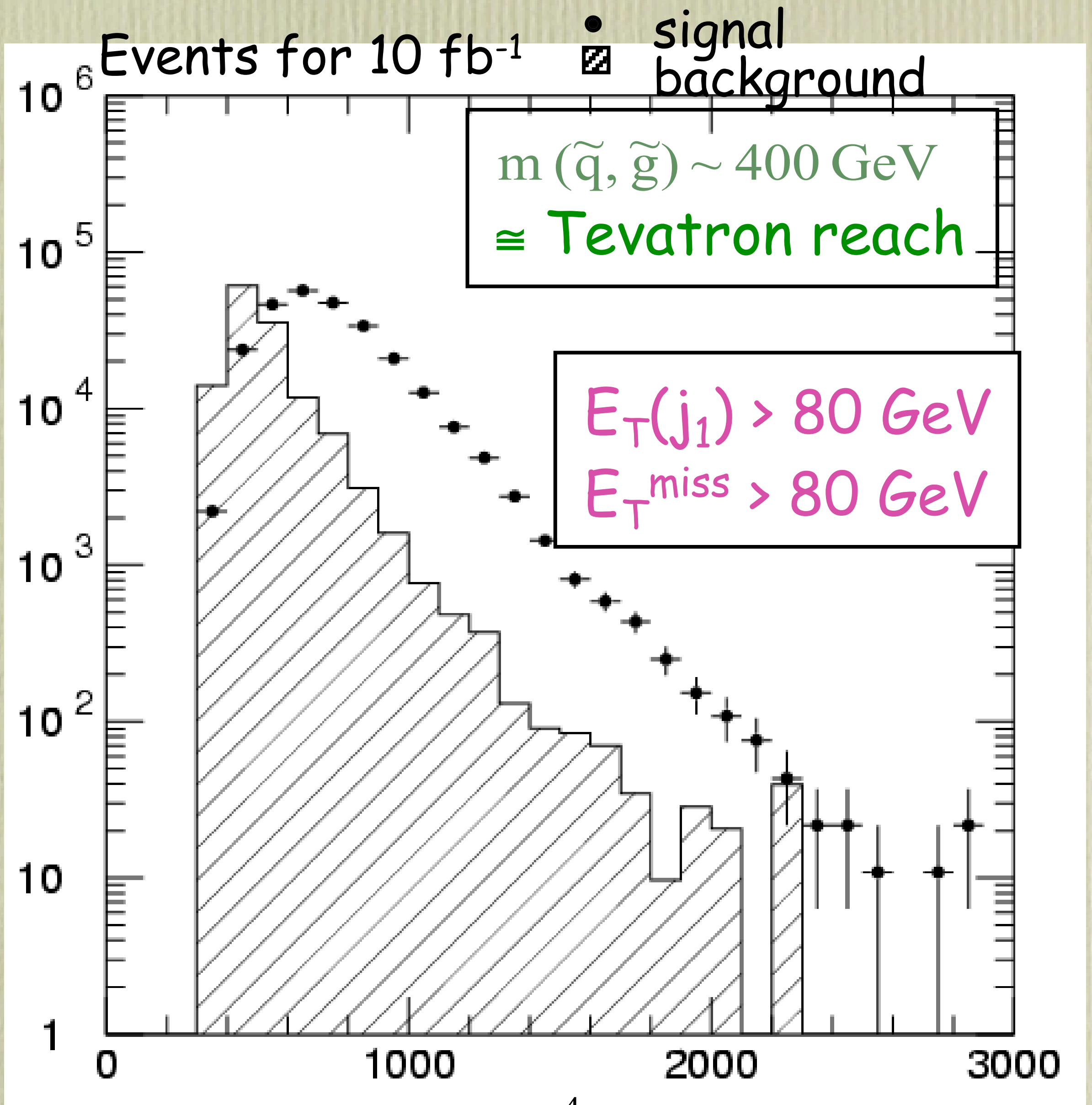
GOAL:

Complete description of the final state of pp collision, suitable for realistic detector simulation, including hard processes induced by new physics, as well as all possible SM backgrounds

It is often said (and written) that we need better MC's to allow the discovery of new physics in future experiments

To my knowledge, no discovery in HEP has ever been been obtained by comparing data to a MC: the data always spoke for themselves

This **might** (need to) change with the LHC.
Example, SUSY discovery via missET final states:



$$M_{eff} = E_T^{miss} + \sum_{i=1}^{4} p_T\,(jet_i) \quad (GeV)$$

While we can debate whether MCs will ever be discovery tools, one point is beyond doubt:

MC's are essential to measure the properties of the (possibly new) objects being studied:

masses and cross sections

This requires control over the complete behavior of both signals (typically easier) and backgrounds (typically harder)

A good MC should be able to describe the data, having enough knobs to be tuned allowing proper fits

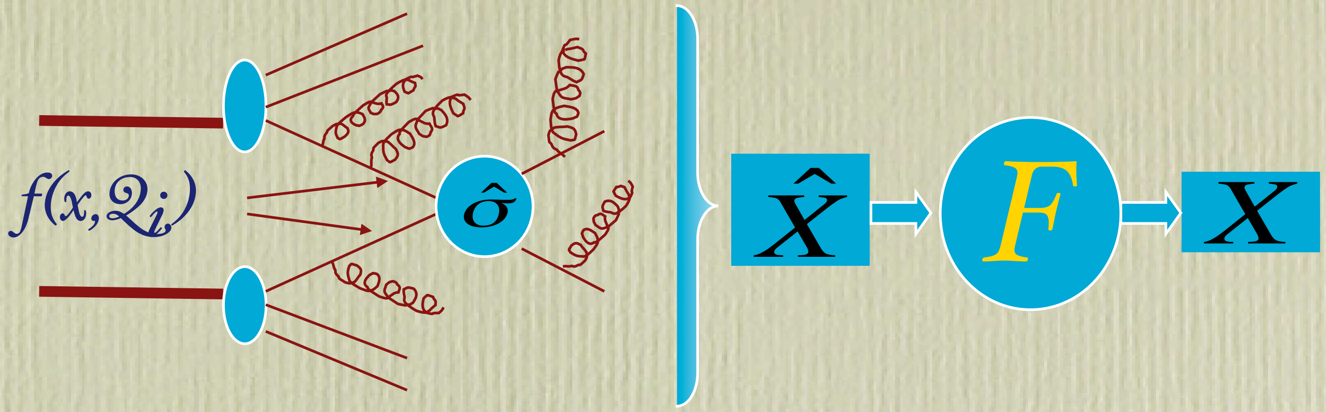
A better MC should do so by just using first principles, rather than ad hoc models, to provide a clear relation between input parameters (physical constants) and observables

A good experimentalist should identify the best observables to tune the MC and improve their quality

A better experimentalist, in addition to being good, will work as much as possible without a MC, using it only as an auxiliary tool to extrapolate the knowledge obtained from control samples to the observable being studied

Factorization Theorem

$$\frac{d\sigma}{dX} = \sum_{j,k} \int_{\hat{X}} f_j(x_1,Q_i)\, f_k(x_2,Q_i)\, \frac{d\hat{\sigma}_{jk}(Q_i,Q_f)}{d\hat{X}}\, F(\hat{X} \to X; Q_i,Q_f)$$



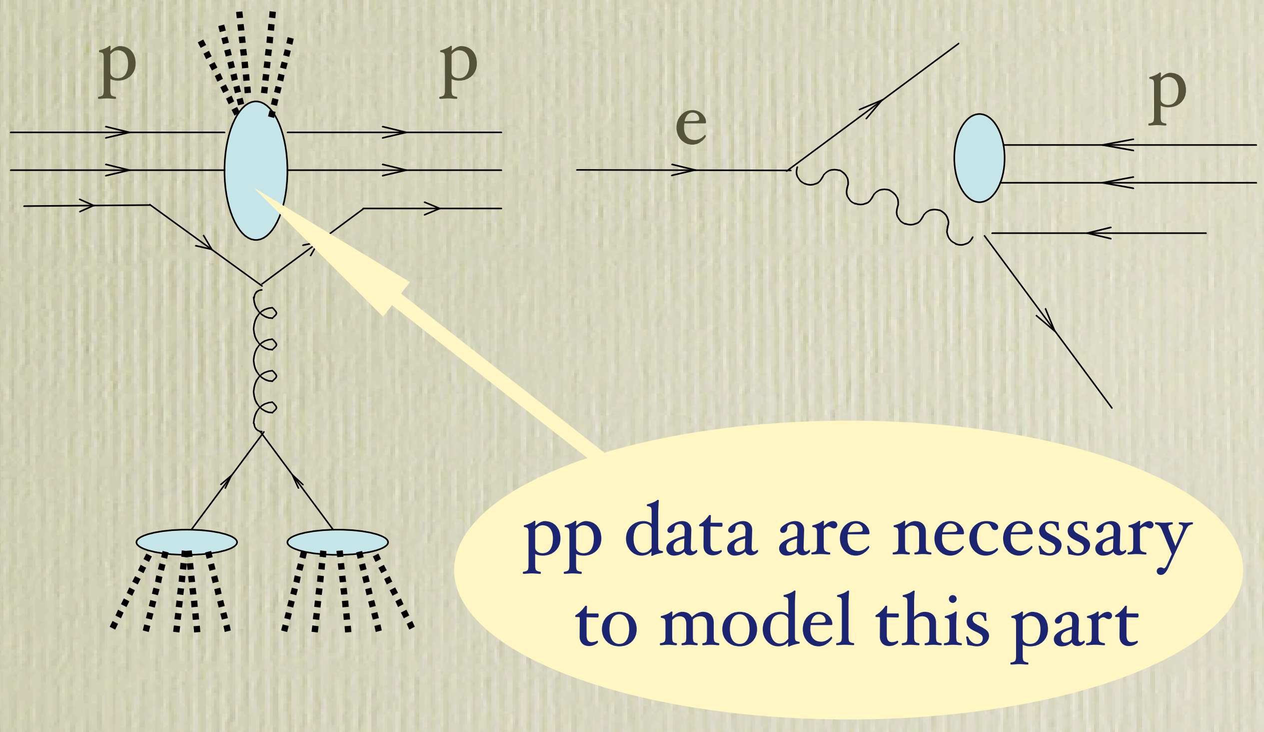
Ingredients:

- Matrix elements for the underlying parton-level hard process, evaluated within perturbation theory with accuracy as high as possible
- Parton distribution functions
- Inclusion of large logarithms appearing at all orders in perturbation theory via the development of a parton shower (emission of soft and collinear gluons)
- Reconstruction of the pp initial state from the backward evolution of the hard processes
- Description of the non-perturbative transition between soft partons (daughters of the perturbative shower evolution) and hadrons
- Description of the interactions of the fragments of the two protons

The factorization theorem provides the theoretical basis for the determination of the uncalculable non-perturbative elements of the description of hadronic collisions.

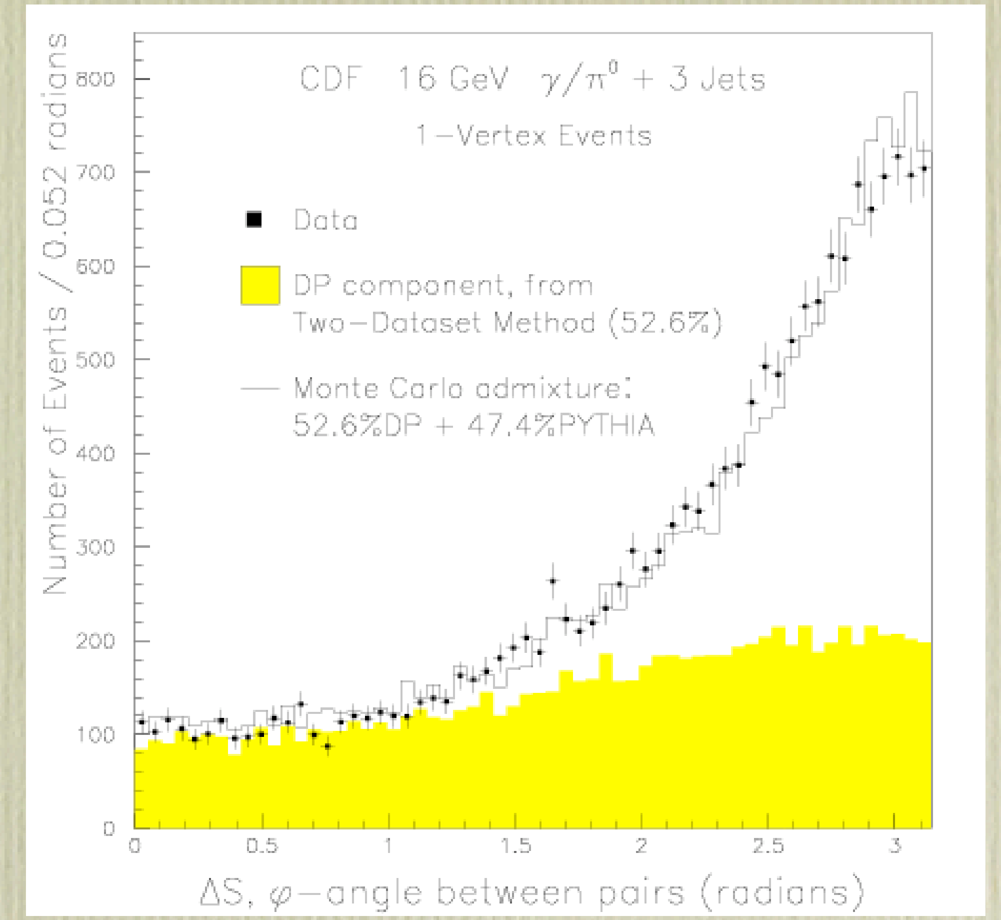
- the description of hadronization of final-state partons is modeled and tuned using high-precision data from **hadronic final states in Z^o decays**
- the description of initial-state parton densities and of the perturbative evolution of the partonic initial states is modeled using **DIS data**

Unfortunately e+e- and DIS data are not enough to provide a complete information on the non-PT input required to fully determine the final state of a pp collision: the fate of the fragments of the protons (the so-called underlying event) cannot be probed by either e+e-, nor DIS



Direct evidence for multiparton collisions

CDF, run I,
γ+3jet events



Since $\sigma_{tot}=\sigma_{jet}$(Et>few GeV), each individual collision at the LHC will lead to multiple hard scatterings

Need concrete models to describe correlations in multiparton density distributions. Recent developments include **momentum, flavour and colour correlations** among partons contributing to the multiple interactions (Skands&Sjöstrand, hep-ph/0310315)

Three complementary approaches

	ME MC's	X-sect evaluators	Shower MC's
Final state description	Hard partons → jets. Describes geometry, correlations, etc	Limited access to final state structure	Full information available at the hadron level
Higher order effects: loop corrections	Hard to implement, require introduction of negative probabilities	Straighforward to implement, when available	Included as vertex corrections (Sudakov FF's)

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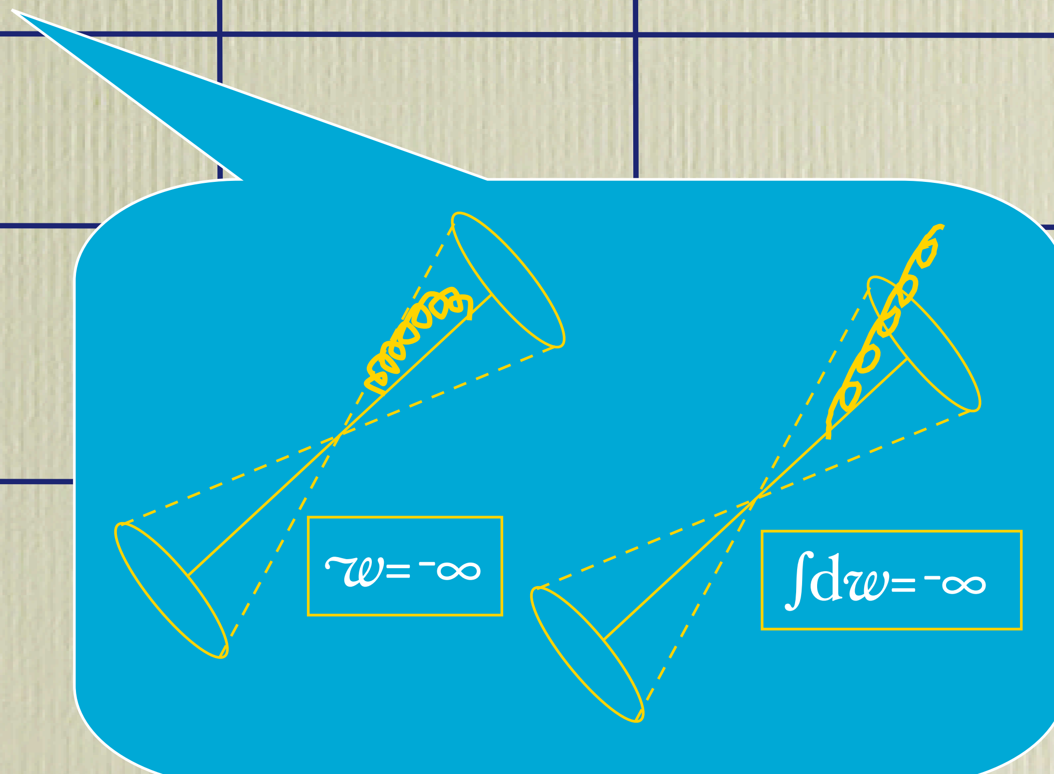

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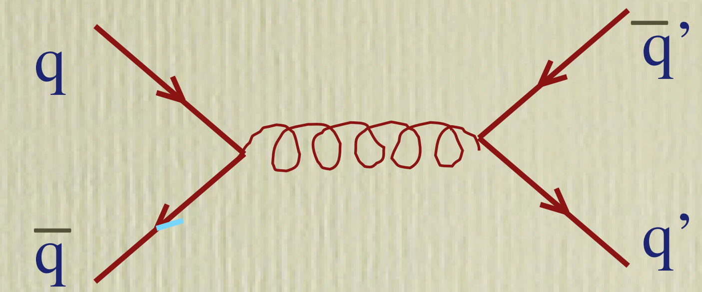
Higher order effects: hard emissions	Included, up to high orders (multijets)	Straighforward to implement, when available	Approximate, incomplete phase space at large angle
Resummation of large logs	??	Possible, when available	Unitary implementation (i.e. correct shapes, but not total rates)

2' guide to shower MC's

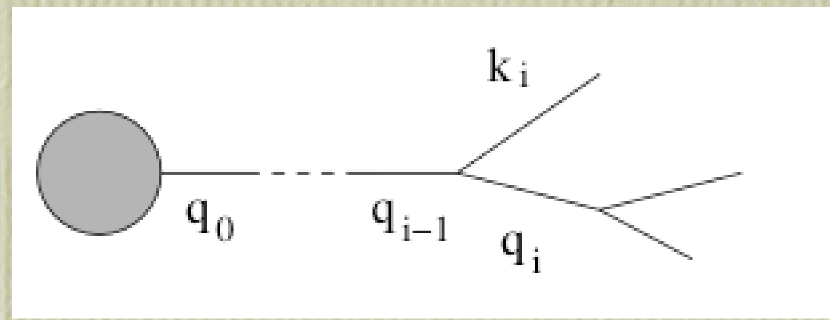


- After the generation of a given parton-level configuration (typically LO, 2→1 or 2→2) , each possible IS and FS parton-level evolution (***shower***) is generated, with probability defined by the shower algorithm (**unitary evolution**).

- ***Algorithm***: numerical, Markov-like evolution, implementing within a given appoximation scheme the QCD dynamics:
  - branching probabilities:
    - selection of evolution variables ⇒

Choice of shower-evolution variables

Q^2, z , $\alpha(\mu)$



$$Q^2 = \boxed{\begin{array}{l} q^2 \\ k_i \cdot q_i \\ q_T^{\;2} \\ \ldots \end{array}}$$

$$z \approx p_i / p_{i-1}\,, \quad p = \boxed{\begin{array}{l} E \\ q^{//} \\ q^{//}+E \\ \ldots \end{array}}$$

$$\mu^2 = \boxed{f(z,Q)}$$

While at LL all choices of evolution variables and of scale for αs are equivalent, more intelligent choices can lead to improved description of NLL effects and allow a more accurate and easy -to-implement inclusion of angular-ordering constraints and mass effects, as well as to a better merging of multijet ME's with the shower

New work appeared recently identifying new, improved, evolution variables. Catani, Dittmaier&Trocsany, Herwig++, Sherpa, Sjöstrand

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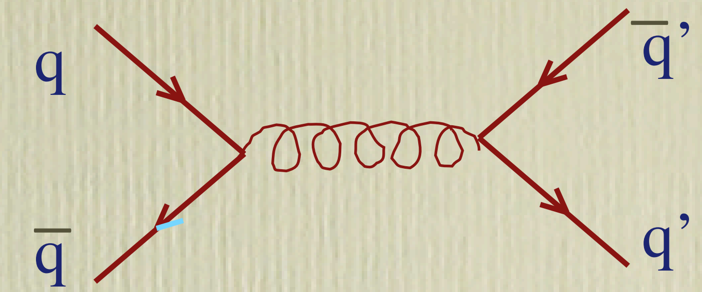

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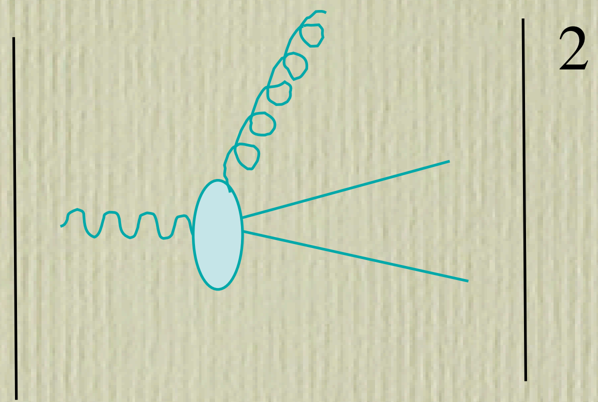
    - implementation of quantum coherence ⇒

Solution, to LL accuracy and $O(1/N_c)$

(a.k.a. angular ordering)



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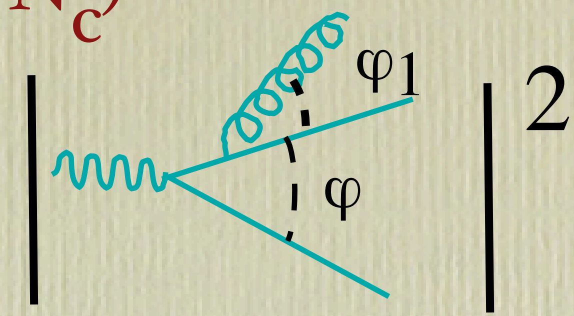
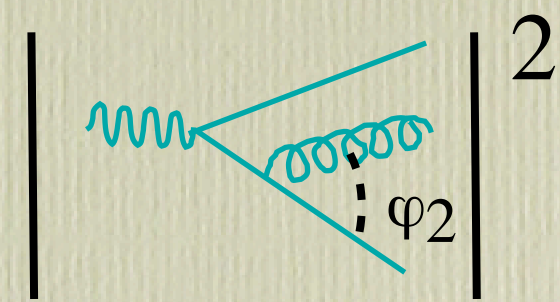


$\Theta(\varphi-\varphi_1)$

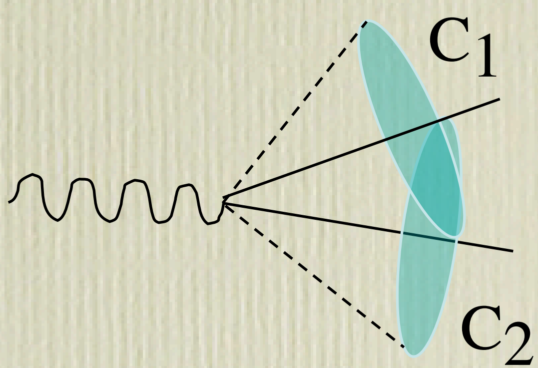
$+$



$\Theta(\varphi-\varphi_2)$

Limitations:

- no emission outside $C_1 \oplus C_2$:
  - lack of hard, large-angle emission
  - poor description of multijet events
- incoherent emission inside $C_1 \oplus C_2$:
  - loss of accuracy for intrajet radiation



Open issue: how (if at all possible) to maintain the Markov nature of shower evolution at the level of subleading logs and $1/N_c$?

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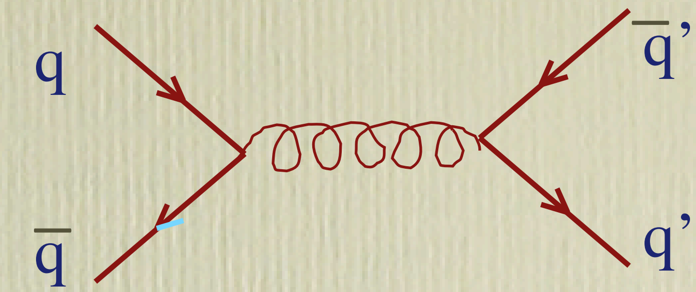

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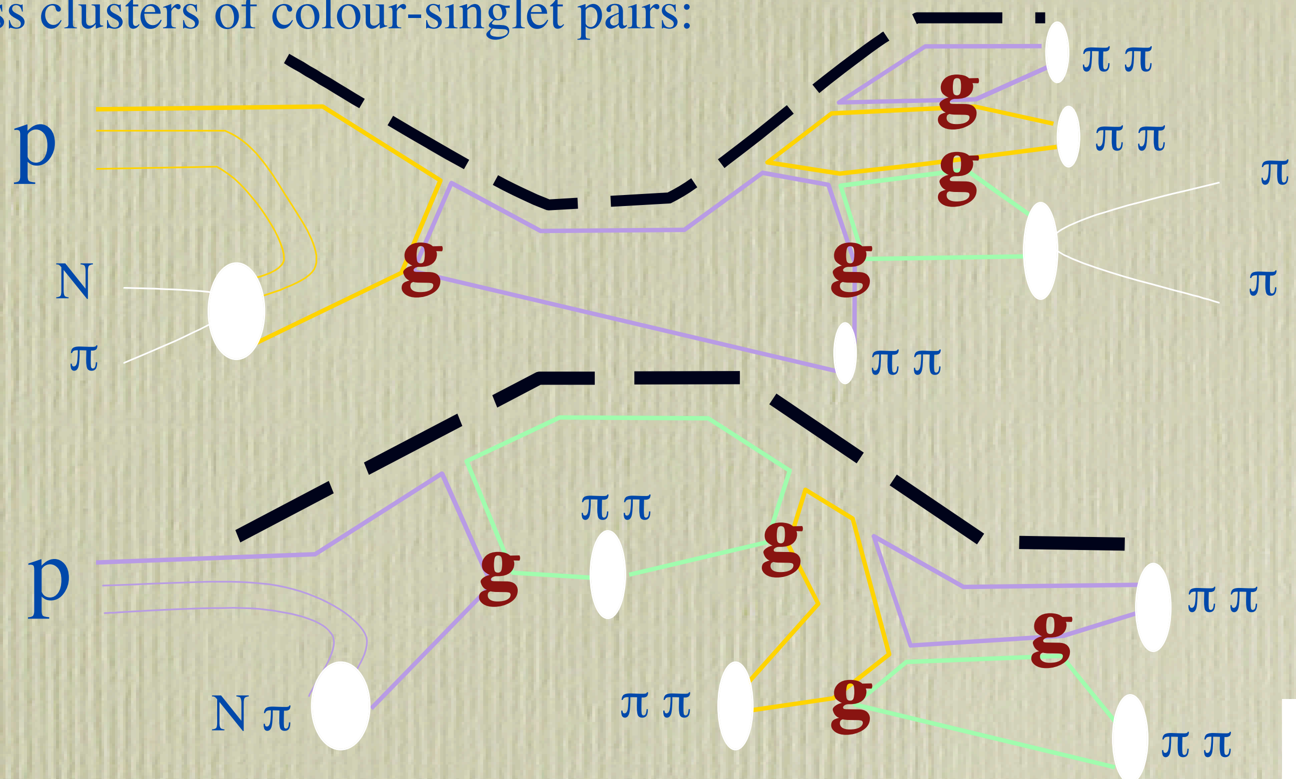
  - branching probabilities:
    - selection of evolution variables
    - implementaiton of quantum coherence
  - infrared cutoff scheme
  - hadronization model ⇒

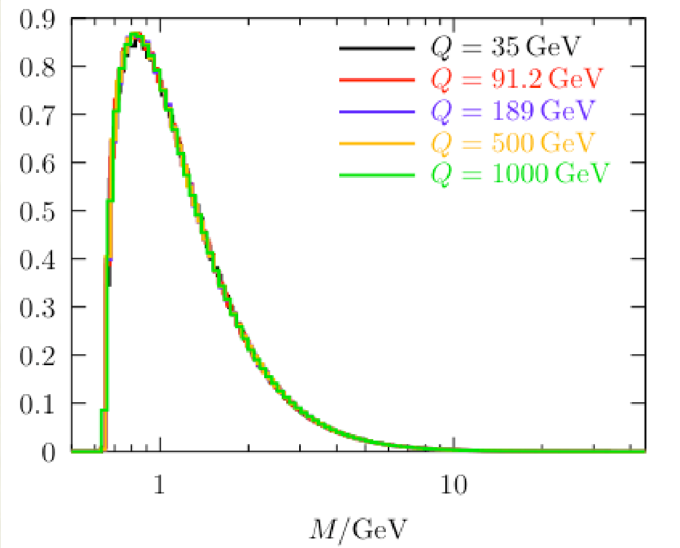
Hadronization

At the end of the perturbative evolution, the final state consists of quarks and gluons, forming, as a result of angular-ordering, low-mass clusters of colour-singlet pairs:



Thanks to the cluster pre-confinement, hadronization is local and independent of the nature of the primary hard process, as well as of the details of how hadronization acts on different clusters.

Models for hadronization can then be tuned on e+e- data at a given energy, and applied elsewhere

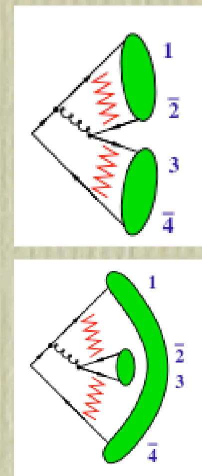


New cluster model

(Winter, Krauss, Soff,
hep-ph/0311085)

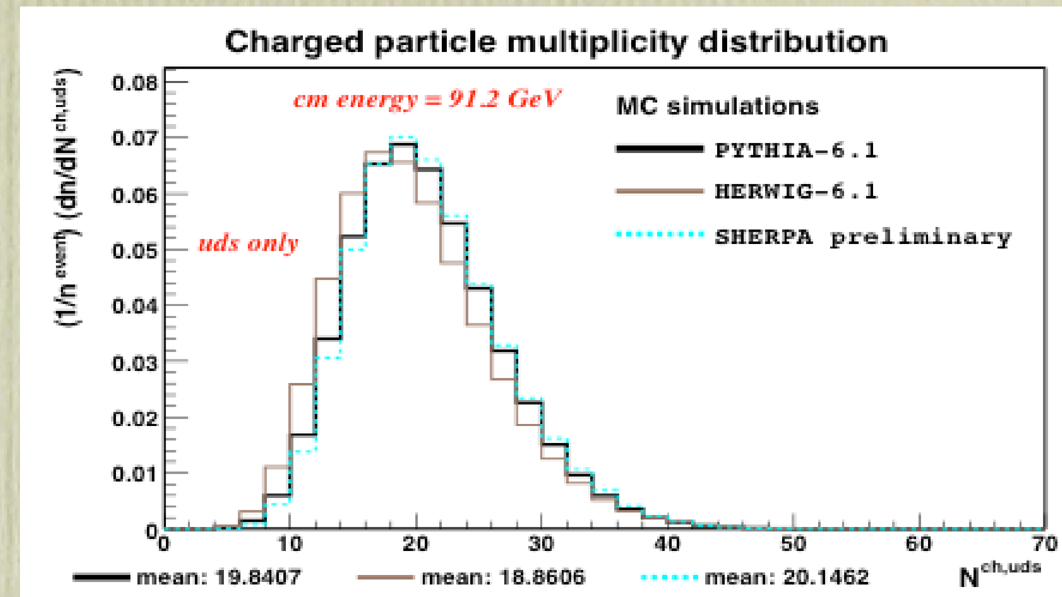
implementing:

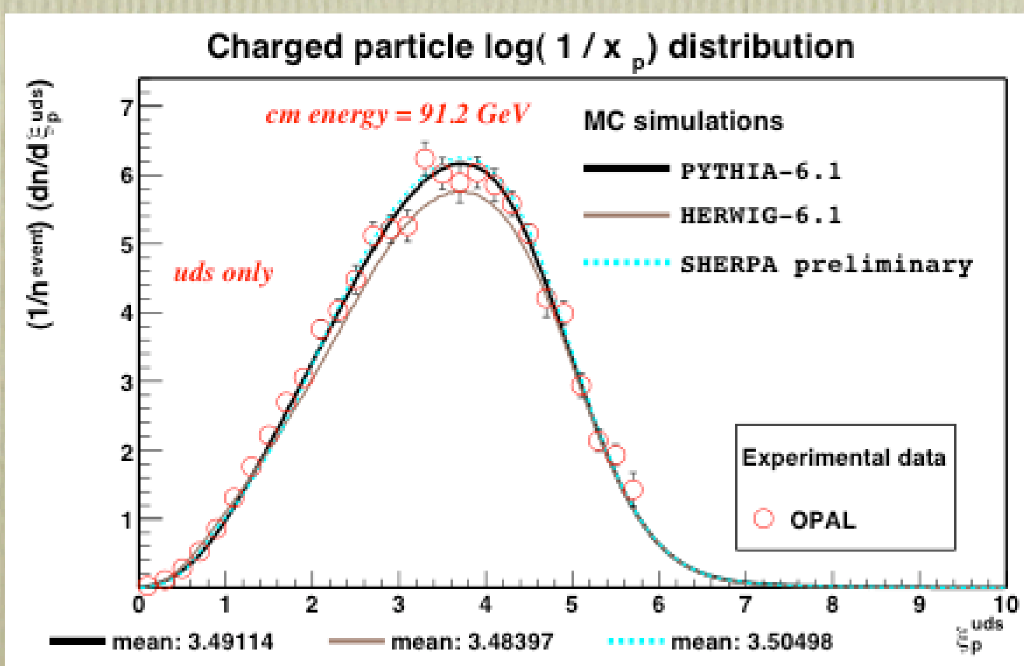
- colour reconnections ($1/N^2$ effects),
- flavour-dependent cluster evolution
- z-dependent non-perturbative gluon splitting

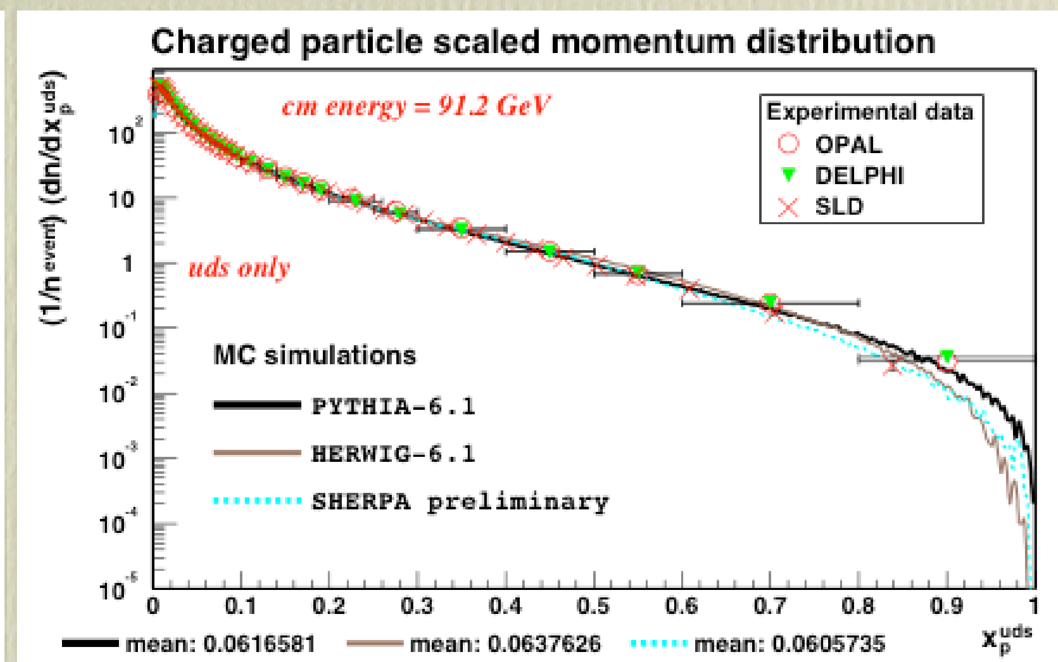


Leads to:

- lower cluster masses
- better description of $z \to 1$ region
- better description of <Nch>







Recent progress in MC-related tools

- New tools to calculate ME's for high multiplicity multijet final states (Alpgen, MacEvent, **2002**)

Codes available for:

- W/Z/gamma + N jets ($N \leq 6$)
- W/Z/gamma + Q Qbar + N jets ($N \leq 4$)
- Q Qbar + N jets ($N \leq 4$)
- Q Qbar Q' Q'bar + N jets ($N \leq 2$)
- Q Qbar H + N jets ($N \leq 3$)
- nW + mZ + kH + N jets ($n+m+k+N \leq 8$, $N \leq 2$)
- N jets ($N \leq 8$)

ALPGEN: MLM, Moretti, Piccinini, Pittau, Polosa
MADGRAPH: Maltoni, Stelzer
CompHEP: Boos etal
VECBOS: Giele et al
NJETS: Giele et al
Kleiss, Papadopoulos
......

Example of complexity of the calculations, for gg-> N gluons:

Njets	2	3	4	5	6	7	8
# diag's	4	25	220	2485	34300	5×10^5	10^7

For each process, flavour state and colour flow (leading 1/Nc) are calculated on an event-by-event basis, to allow QCD-coherent shower evolution

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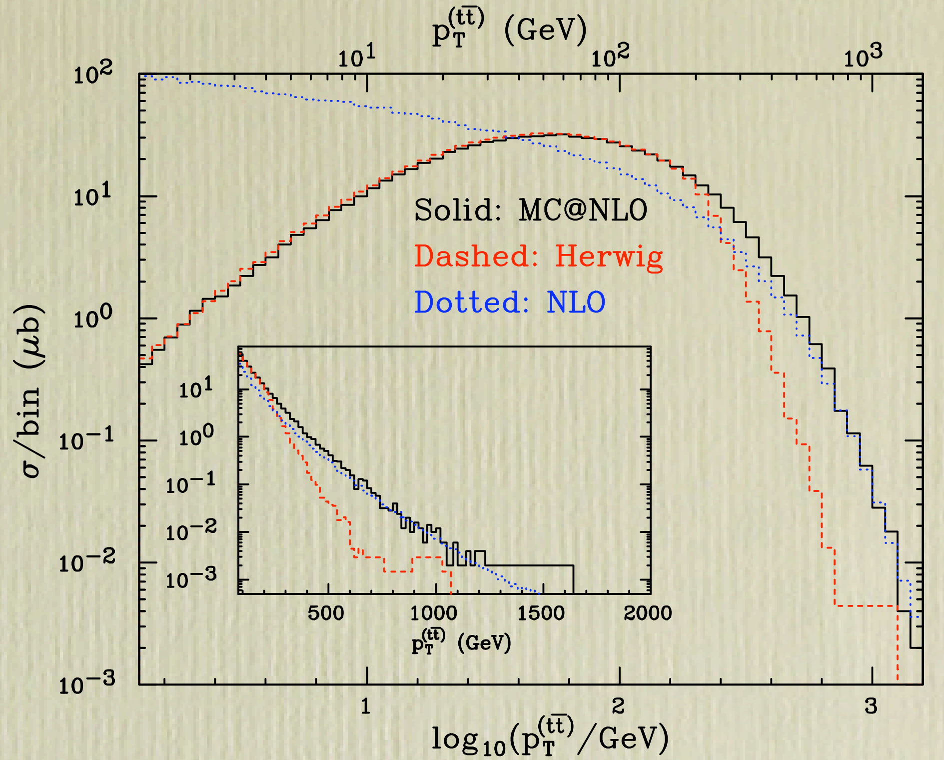
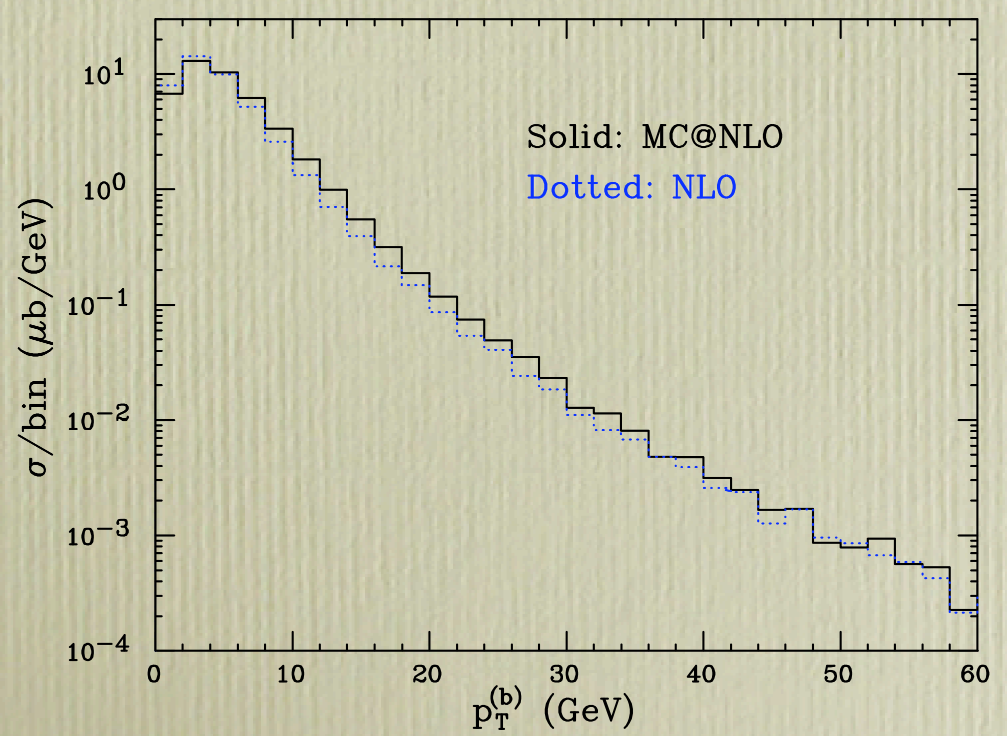
Recent development, MC@NLO

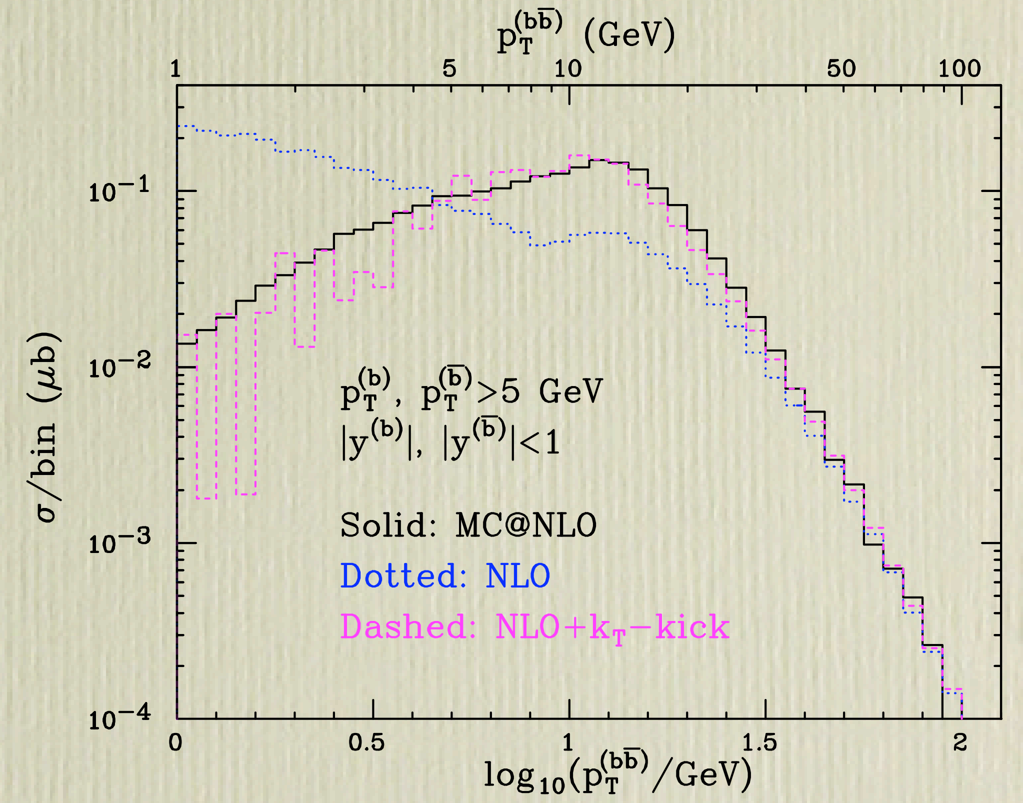
Frixione, Nason, Webber (WW, QQ)

The best balance available today between perturbative accuracy and realism in the description of the physical observables (e.g. in the description of the structure of an experimental jet)



Examples from heavy quark production





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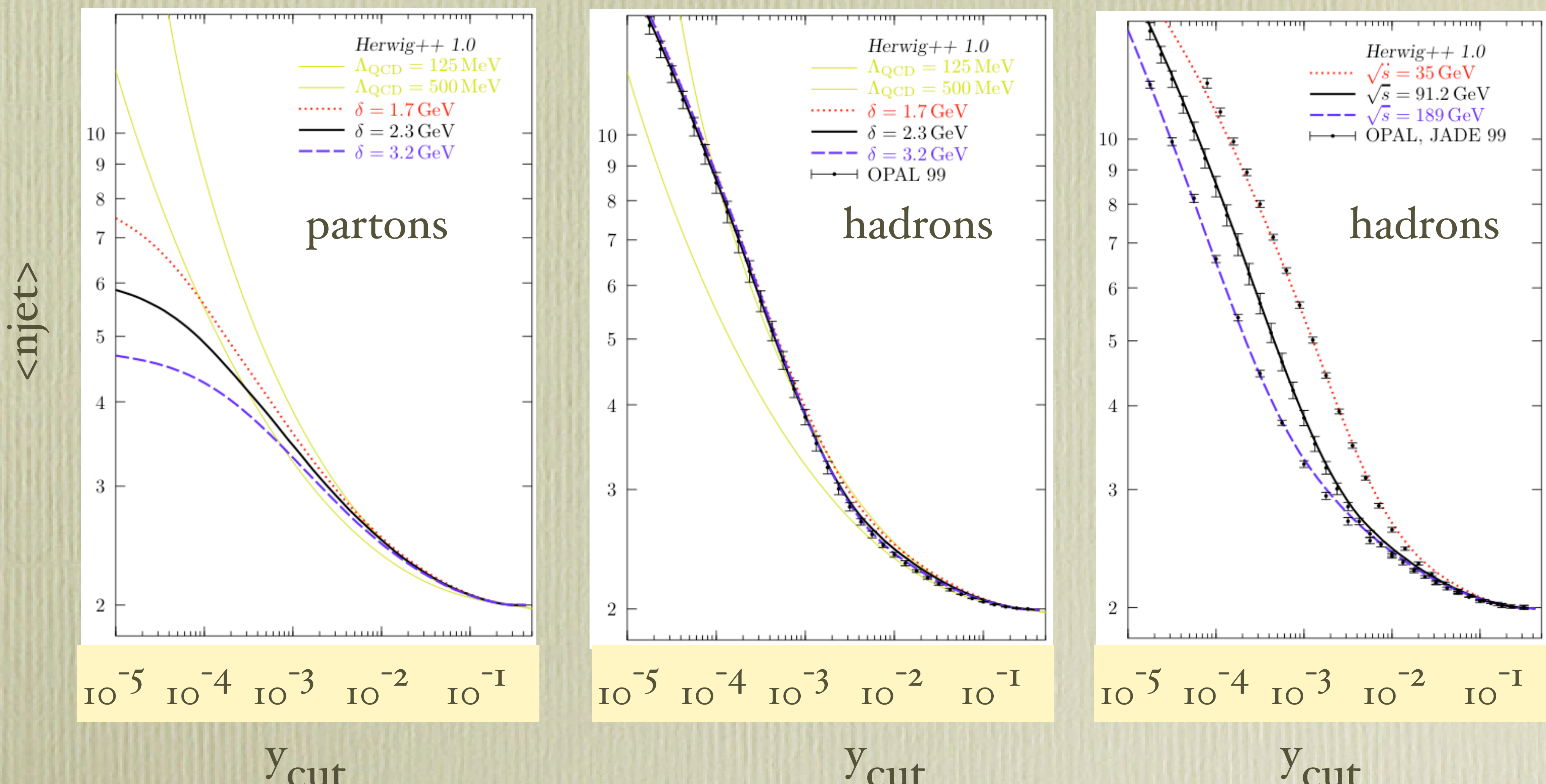
- New shower MC codes (**Sherpa**: Gleisber, Höche,Krauss, Schälicke, Schumann, Winter, **2003**), with new:
  - shower algorithms
  - hadronization schemes
- New incarnation of old MC codes. Pythia/Herwig=>C++ (**2003**) with
  - new features, better QCD, better hadronization

Examples of results from Herwig++ (e+e-)

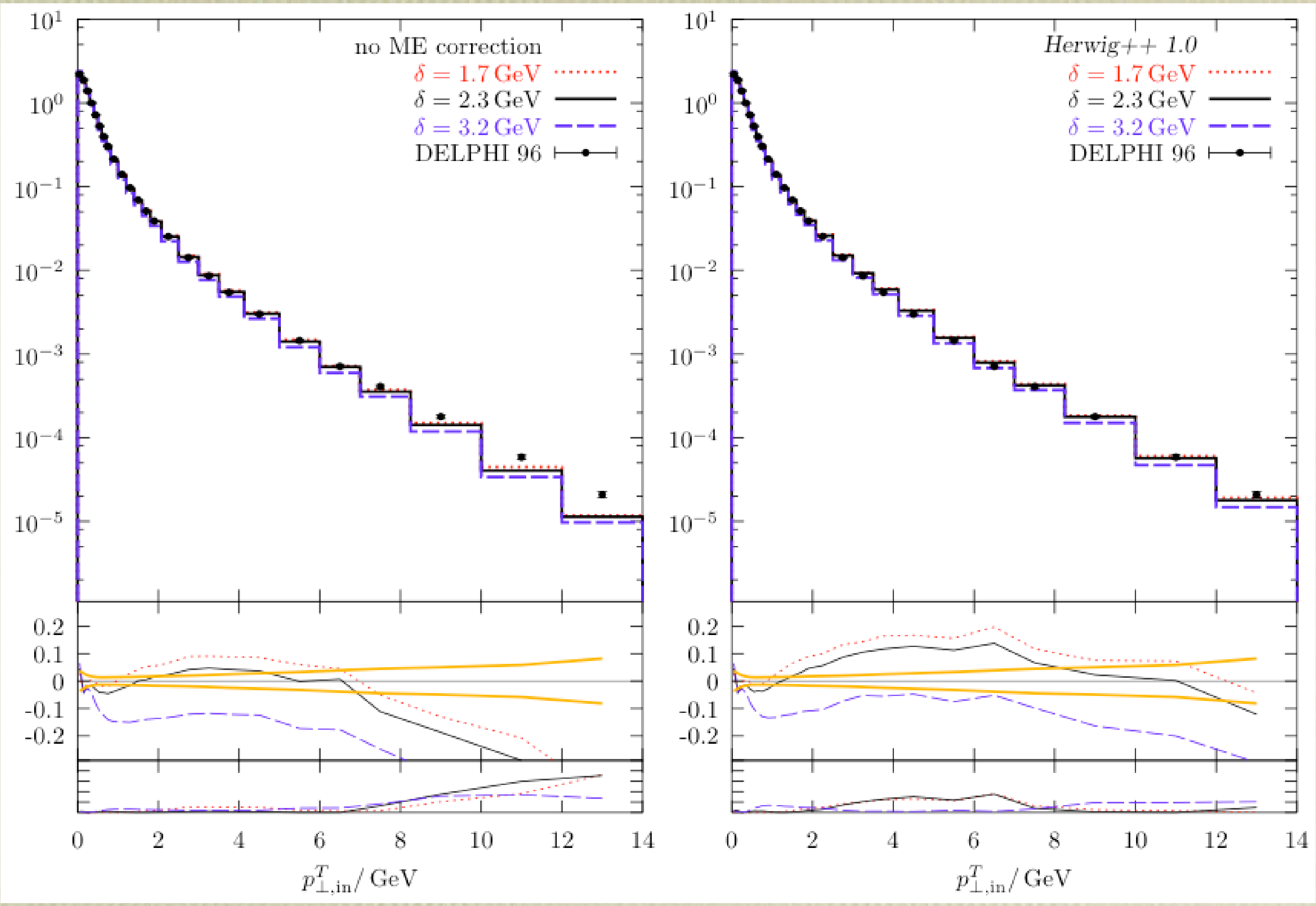
Gieseke, Ribon, Seymour, Stephens, Webber, hep-ph/0311208

Jet multiplicities:



Hadron-level results are rather independent of the IR cutoff (δ) ⇒ consistent merging of the PT↔nPT phases

Transverse momenta w.r.t. thrust axis:



Improvement in the shower algorithm reduces the impact of Matrix Element corrections:

=> expect improvement in the description of higher jet multiplicities

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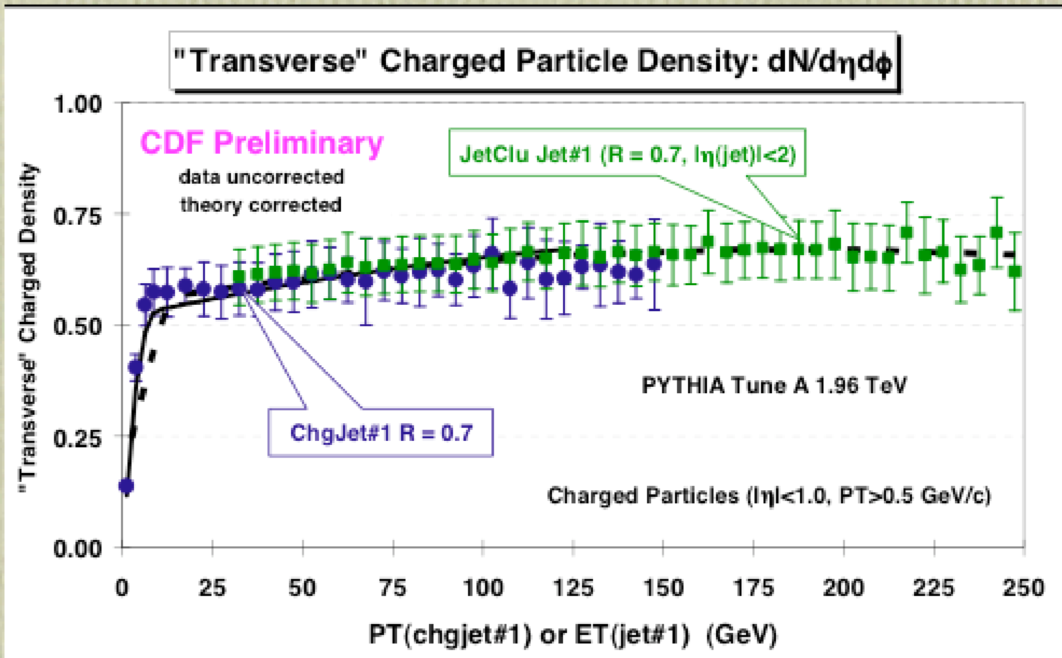
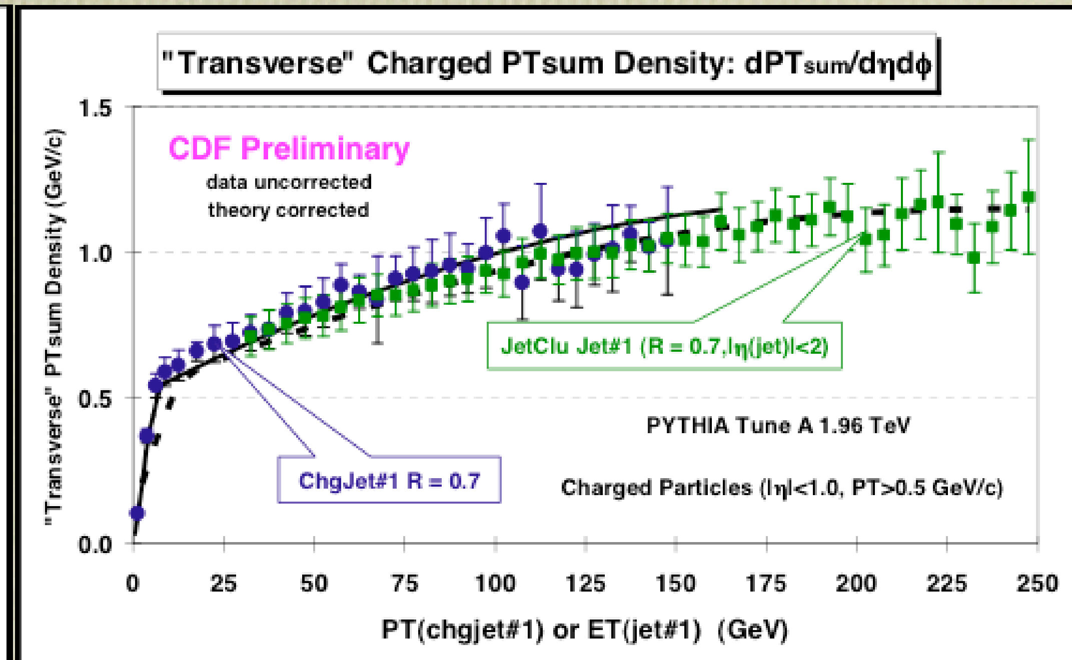
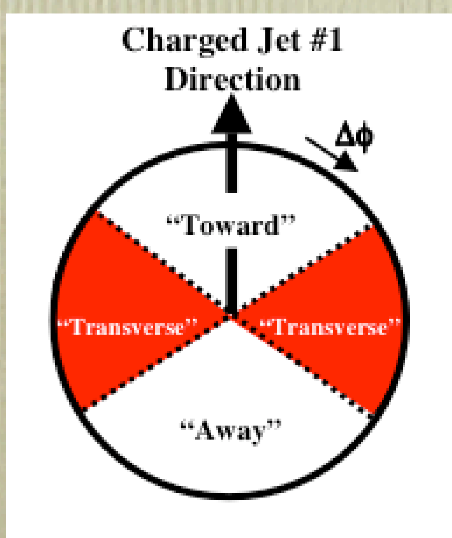
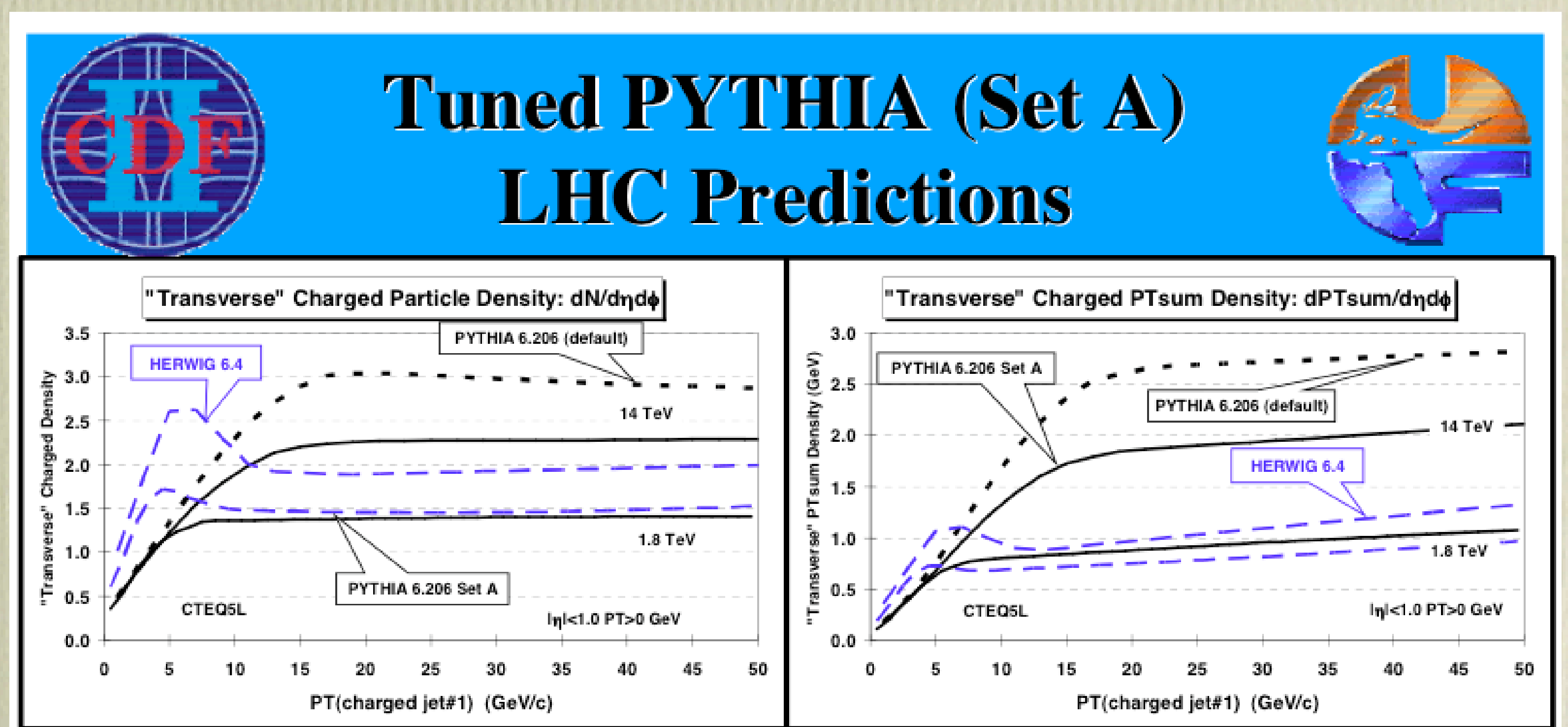
- Data from Tevatron to study and model the underlying event (R.Field-CDF, **2002**). New models (Skands & Sjöstrand, **2003**)

MC UE tuning with CDF data (R.Field, CDF)

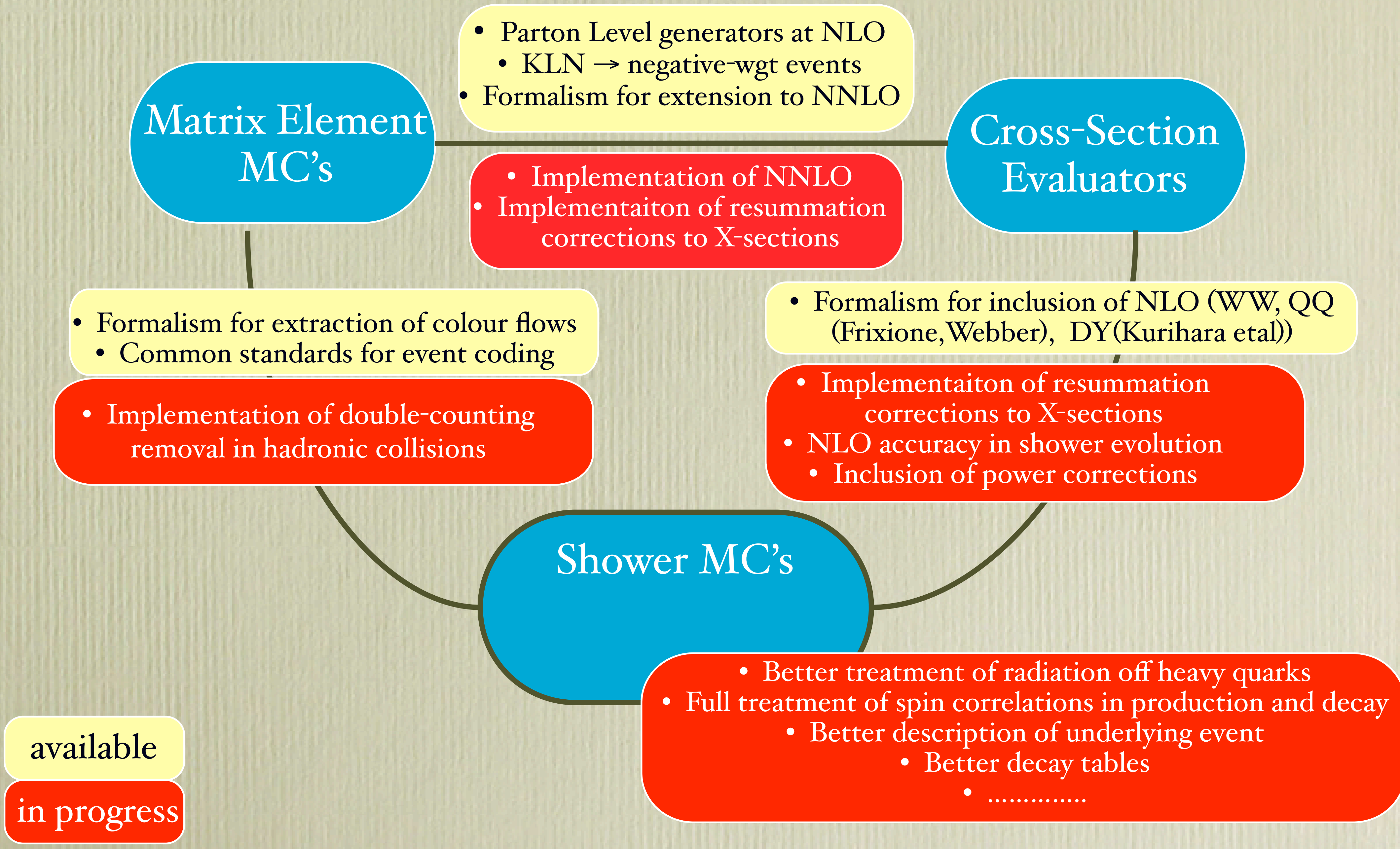








M(*ontecarlo*) o(*f*) E(*verything*)



Final remarks

- Our tools have significantly improved over the last 2-3 years:
  - inclusion of higher order matrix elements in shower MC's
  - inclusion of NLO corrections in shower MC's
  - better models for the underlying event, and for hadronization
- Proper use of these tools will require validation and tuning against data. The Tevatron experiments have not yet developed a culture of MC tuning, as has happened instead at LEP and HERA. As a result, I personally do not feel we have today a solid control over the theoretical systematic uncertainties in several crucial measurements at the Tevatron and at the LHC: $\Delta^{th}(m_W)$, $\Delta^{th}(m_{top})$, $\Delta^{th}(\sigma_W)$
- Improvement of our tools, via **theoretical developments** and via strategies for the **validation of the theoretical systematics** is a crucial duty of our community
- Future progress in the accuracy of MCs may be limited by some intrinsic theoretical difficulty (breaking of factorization, inadequacy of the Markovian evolution, etc)
- Very interesting and rewarding work ahead!