Monte Carlo event generators for LHC physics

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CERN Academic Training Lectures

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http://seymour.home.cern.ch/seymour/slides/CERNlectures.html

Monte Carlo for the LHC

1. Basic principles
2. Parton showers
3. Hadronization
4. Monte Carlo programs in practice
5. Questions and answers

Frequently Asked Questions

- MC implementations of NLO calculations
  - Explain example better
  - Why did I say they were not event generators?
    - What is MC@NLO?
- String or elastic?
  - Quark—antiquark tunnelling
- "String model washes out too much perturbative information" – examples?
- "$\alpha_s(k_\perp)$ correct scale" – proof?
  - Possible to try other scales in HERWIG?
  - Possible to switch off radiation in HERWIG?
- Underlying event in HERWIG
  - Is independent of pdf set
  - Does not have a hard component
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Monte Carlo Calculations of NLO QCD

Two separate divergent integrals:

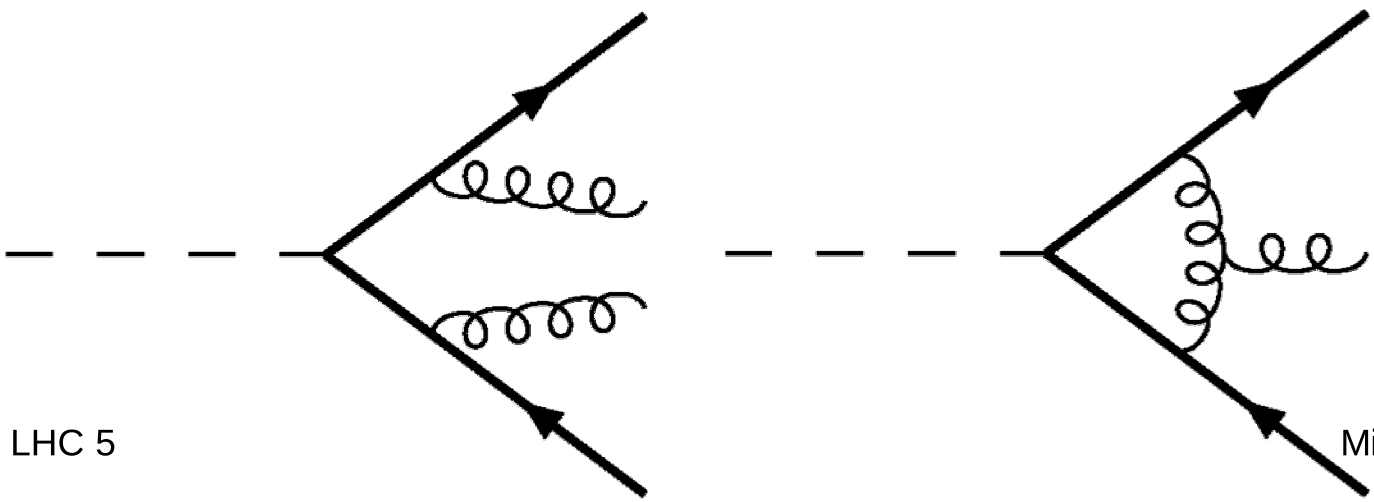
$$\sigma_{NLO} = \int_{m+1} d\sigma^R + \int_m d\sigma^V$$

Must combine before numerical integration.

Jet definition could be arbitrarily complicated.

$$d\sigma^R = d\Pi_{m+1}\,|\mathcal{M}_{m+1}|^2\,F^J_{m+1}(p_1,\ldots,p_{m+1})$$

How to combine without knowing F^J?



Subtraction Method

- Seek to define an approximate cross section that matches all the real singularities

$$\sigma^{NLO} = \int_{m+1} \left[d\sigma^R - d\sigma^A \right] + \int_{m+1} d\sigma^A + \int_m d\sigma^V$$

- but is feasible to integrate analytically

$$\sigma^{NLO} = \int_{m+1} \left[\left(d\sigma^R \right)_{\epsilon=0} - \left(d\sigma^A \right)_{\epsilon=0} \right] + \int_m \left[d\sigma^V + \int_1 d\sigma^A \right]_{\epsilon=0}$$

- To avoid dependence on unknown F^J, approximate cross section must project event kinematics onto an m-parton configuration and calculate F^J from that.

à m+ … erent kin … rbitrarily large weights

$$d\sigma^A = d\Pi_{m+1} \, |\mathcal{M}_{m+1}^{approx}|^2 \, F_m^J(\tilde{p}_1, \ldots, \tilde{p}_m).$$

$$\tilde{p}_i = \tilde{p}_i(p_1, \ldots, p_{m+1})$$

MC@NLO

- Basic idea: by showering lowest order contribution, have already taken account of soft/collinear divergent region with fully exclusive kinematics
- Subtraction method:

$$\sigma^{m+1} = \int_{m+1} d\Pi_{m+1}\Big[|\mathcal{M}_{m+1}|^2 \, F^J_{m+1}(p_1,\ldots,p_{m+1}) - |\mathcal{M}^{approx}_{m+1}|^2 \, F^J_m(\tilde{p}_1,\ldots,\tilde{p}_m)\Big]$$

- MC@NLO:

$$\sigma^{m+1} = \int_{m+1} d\Pi_{m+1}\Big[|\mathcal{M}_{m+1}|^2 - |\mathcal{M}^{approx}_{m+1}|^2\Big] F^J_{m+1}(p_1,\ldots,p_{m+1})$$

- Cancellation takes place before numerical integration
- Hard to guarantee positive definite

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The Lund String Model

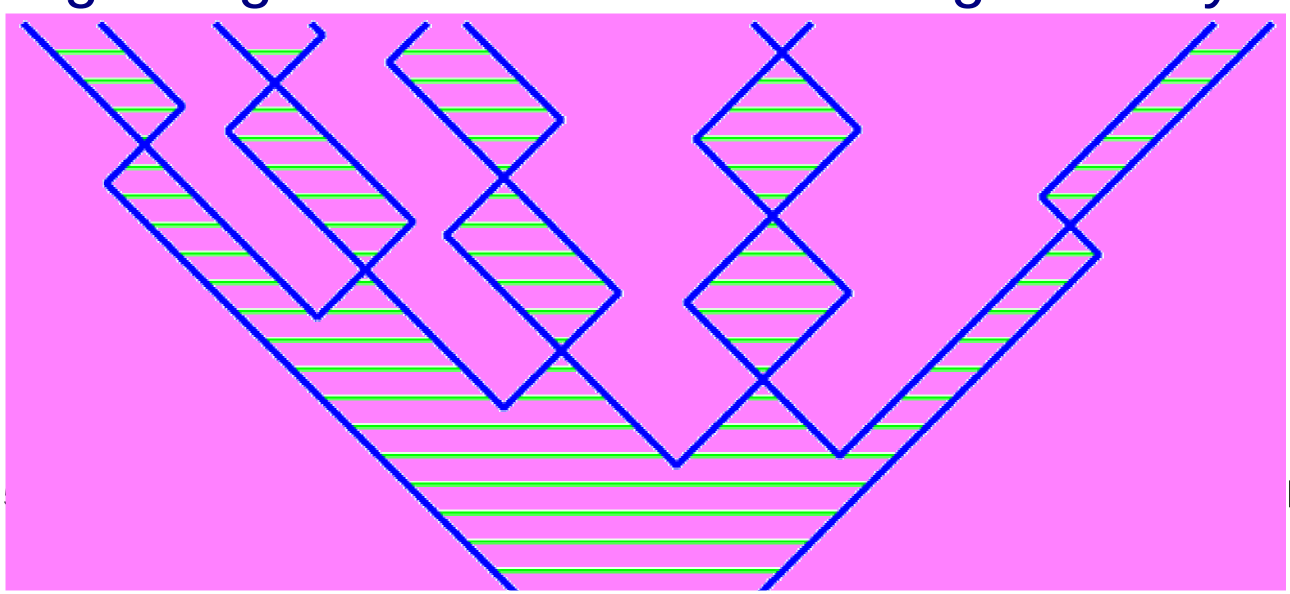
Start by ignoring gluon radiation:

e^+e^- annihilation = pointlike source of $q\bar{q}$ pairs

Intense chromomagnetic field within string à $q\bar{q}$ pairs created by tunnelling. Analogy with QED:

$$\frac{d(\text{Probability})}{dx\ dt} \propto \exp(-\pi m_q^2/\kappa)$$

Expanding string breaks into mesons long before yo-yo point.



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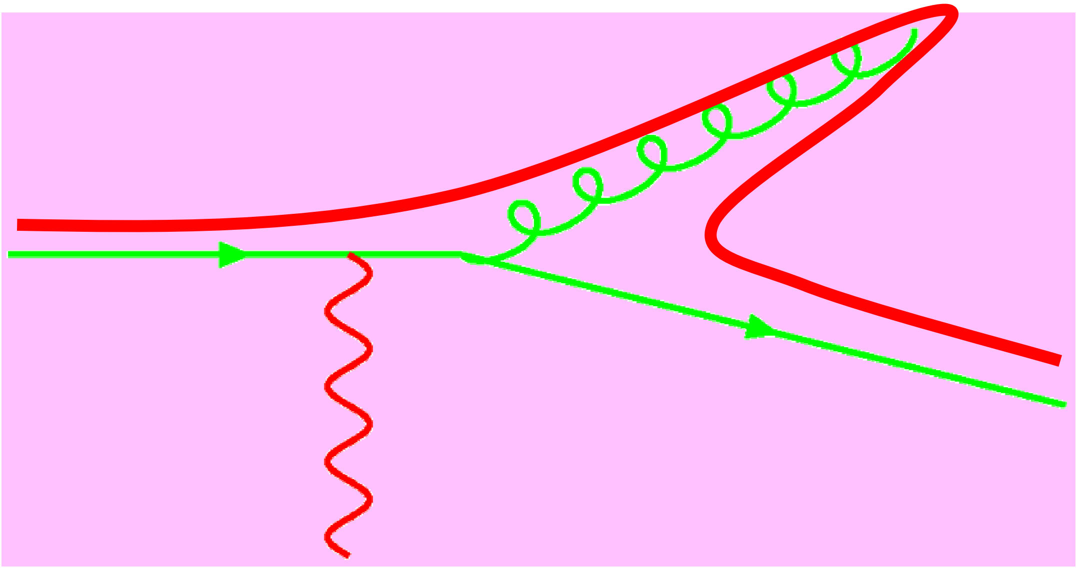
“String washes out too much perturbative information” ?

- e.g. soft wide angle gluons…



- PYTHIA vetoes non-order emission so produces no soft wide angle gluons
- but the string stretches across this region producing soft hadrons anyway

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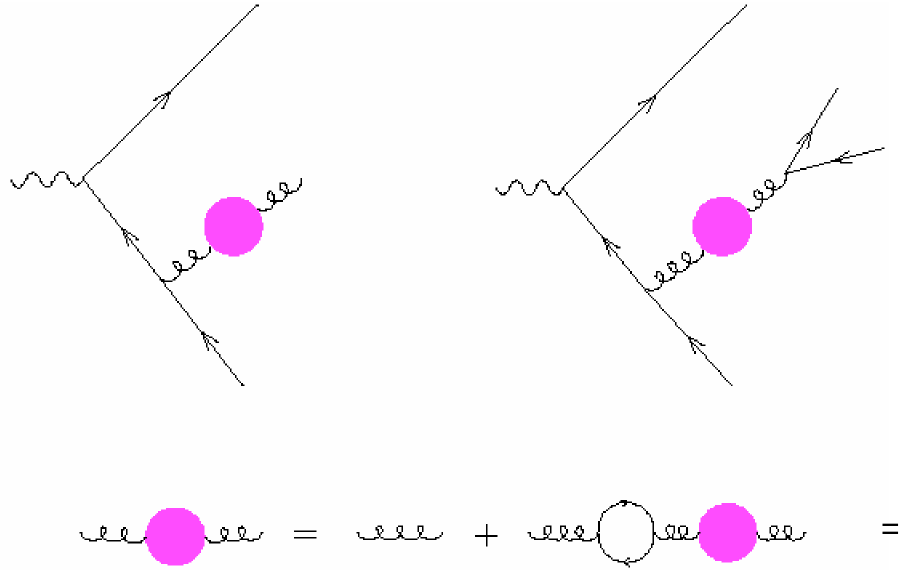
"$\alpha_s(k_\perp)$ correct scale" – proof?

- Start by considering fermion bubbles…



à $\alpha_s(k^2_{max}) = \alpha_s(k_\perp)$

$$= \frac{1}{1+\alpha_s b_0 \log(-k^2/\mu^2)} \qquad b_0 = -\frac{T_R}{3\pi}, \quad T_R = n_f/2.$$

see e.g. Nason and Seymour, Nucl. Phys. B454 (1995) 291.

- and rely on 'naïve non-Abelianization'
  (incomplete subset of higher order diagrams)

à a scale of order $k_\perp$

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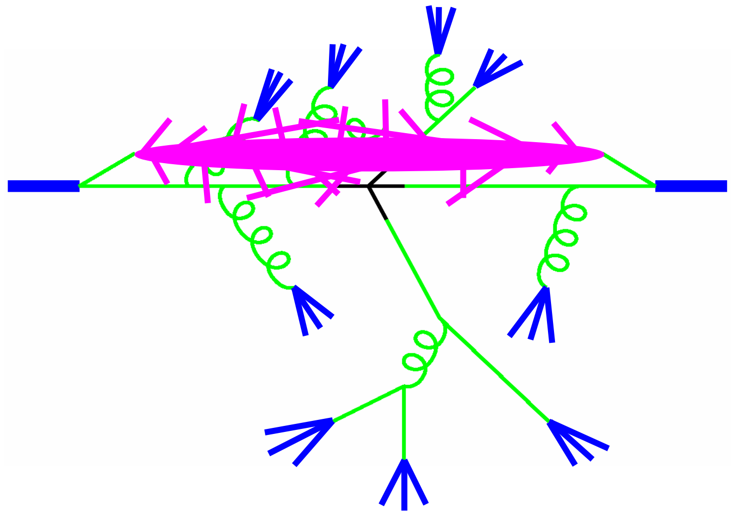
HERWIG’s underlying event has no hard component?

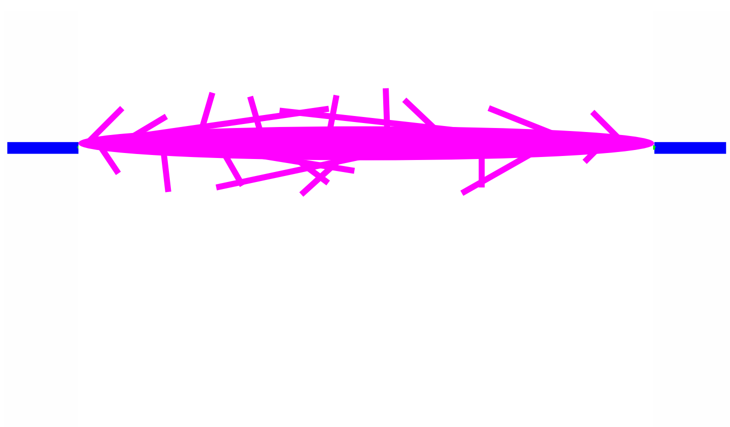
- Right!

Soft Underlying Event Model (HERWIG)

Compare underlying event with 'minimum bias' collision

('typical' inelastic proton—proton collision)



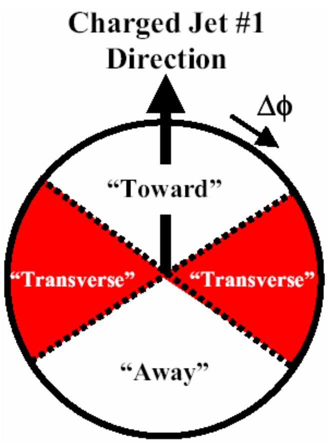


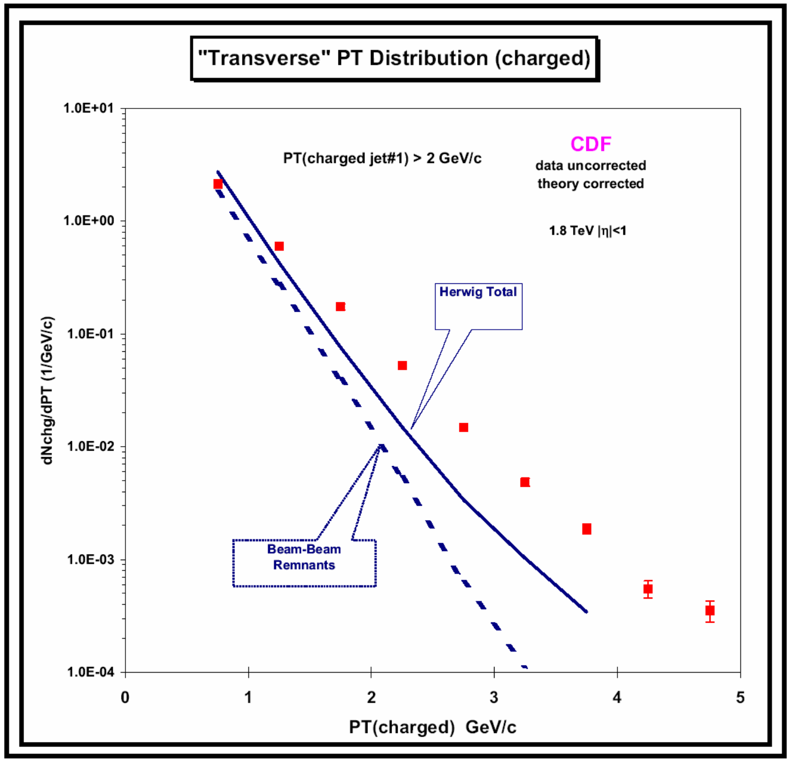
Parameterization of (UA5) data

+ model of energy-dependence

HERWIG's underlying event has no hard component?

- Right!
- Improve things somewhat by adding one hard collision (with pt>3GeV)…

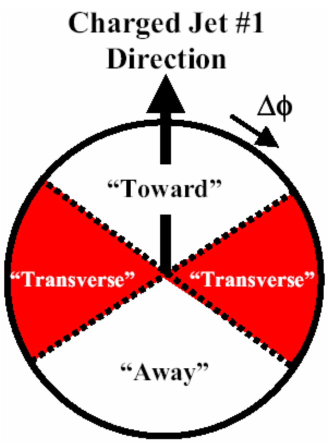


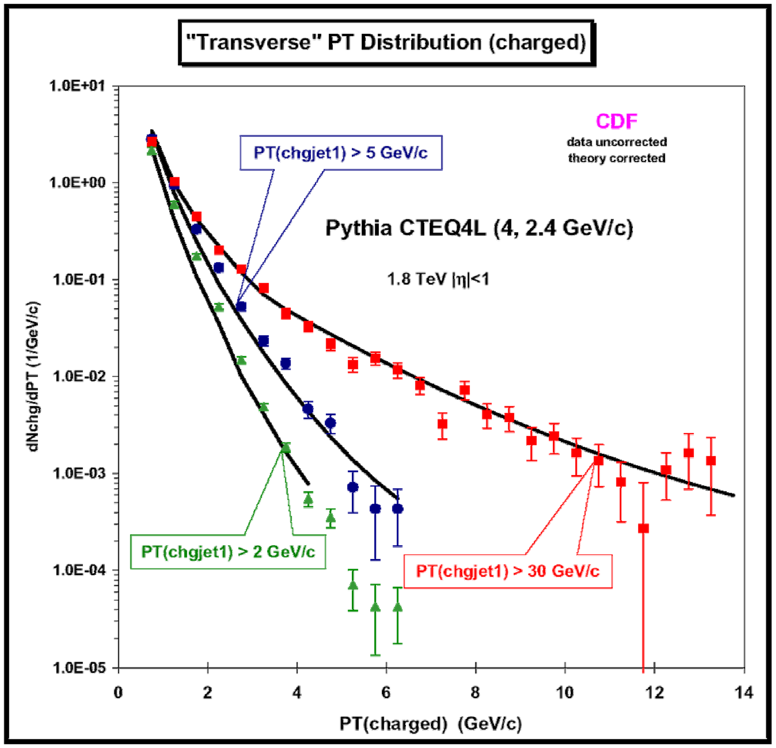


http://www.phys.ufl.edu/~rfield/cdf/chgjet/chgjet_intro.html

HERWIG's underlying event has no hard component?

- But need multiple interactions to really get it right…





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Secondary Decays and Decay Tables

- Often forgotten ingredient of event generators:
  - String and cluster decay to some stable hadrons but mainly unstable resonances
  - These decay further “according to PDG data tables”
    - Matrix elements for n-body decays
  - But…
    - Not all resonances in a given multiplet have been measured
    - Measured branching fractions rarely add up to 100% exactly
    - Measured branching fractions rarely respect isospin exactly
  - So need to make a lot of choices
  - Has a significant effect on hadron yields, transverse momentum release, hadronization corrections to event shapes, …
  - Should consider the decay table choice part of the tuned set

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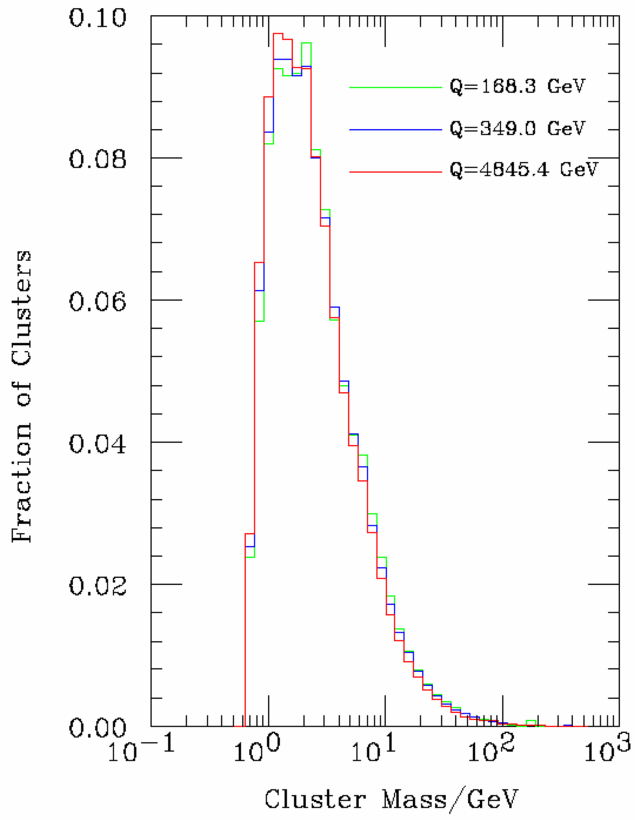
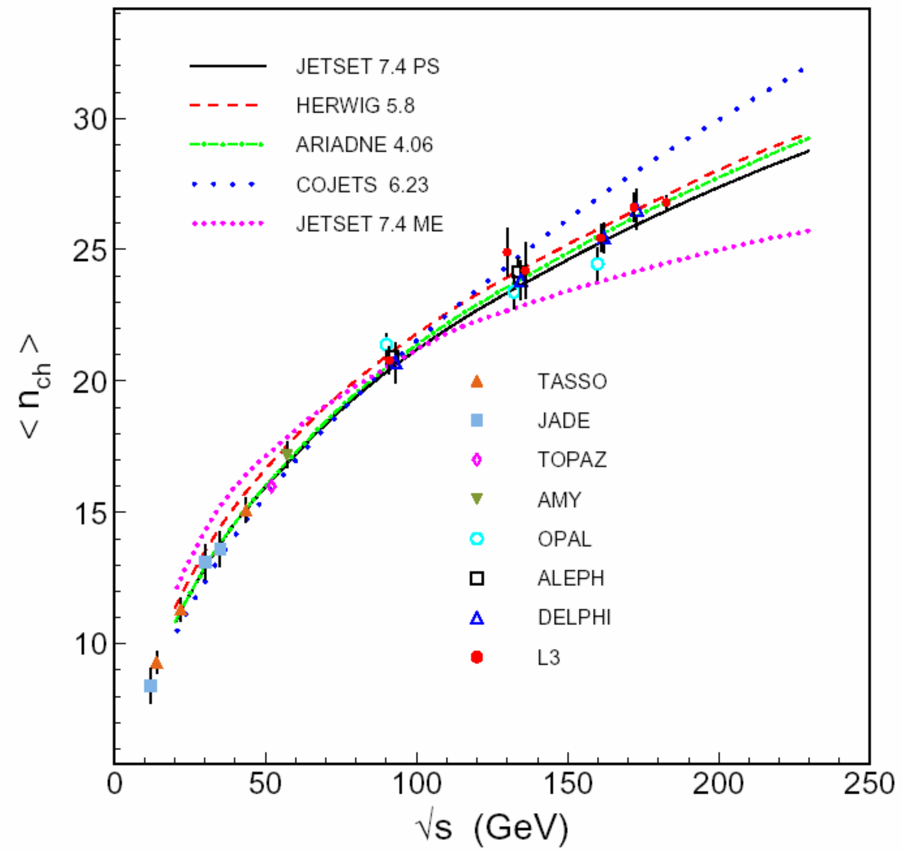
Universality of Hadronization Parameters

- Is guaranteed by preconfinement: do not need to retune at each energy





à Only tune what's new in hadron—hadron collisions

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Summary

- Event generators are central part of almost every collider physics analysis
- Very reliable implementations of QCD for some observables/phase space regions
- Complete guesses in others
- Get to know your generator:
  - where should it be reliable?
  - where can I tune it?
- Get ready for big steps forward:
  - Next generation of event generators
  - Matched to NLO and multijet matrix elements