LUND UNIVERSITY

CMS Generator Workshop
CERN
3 November 2004

Monte Carlos for LHC

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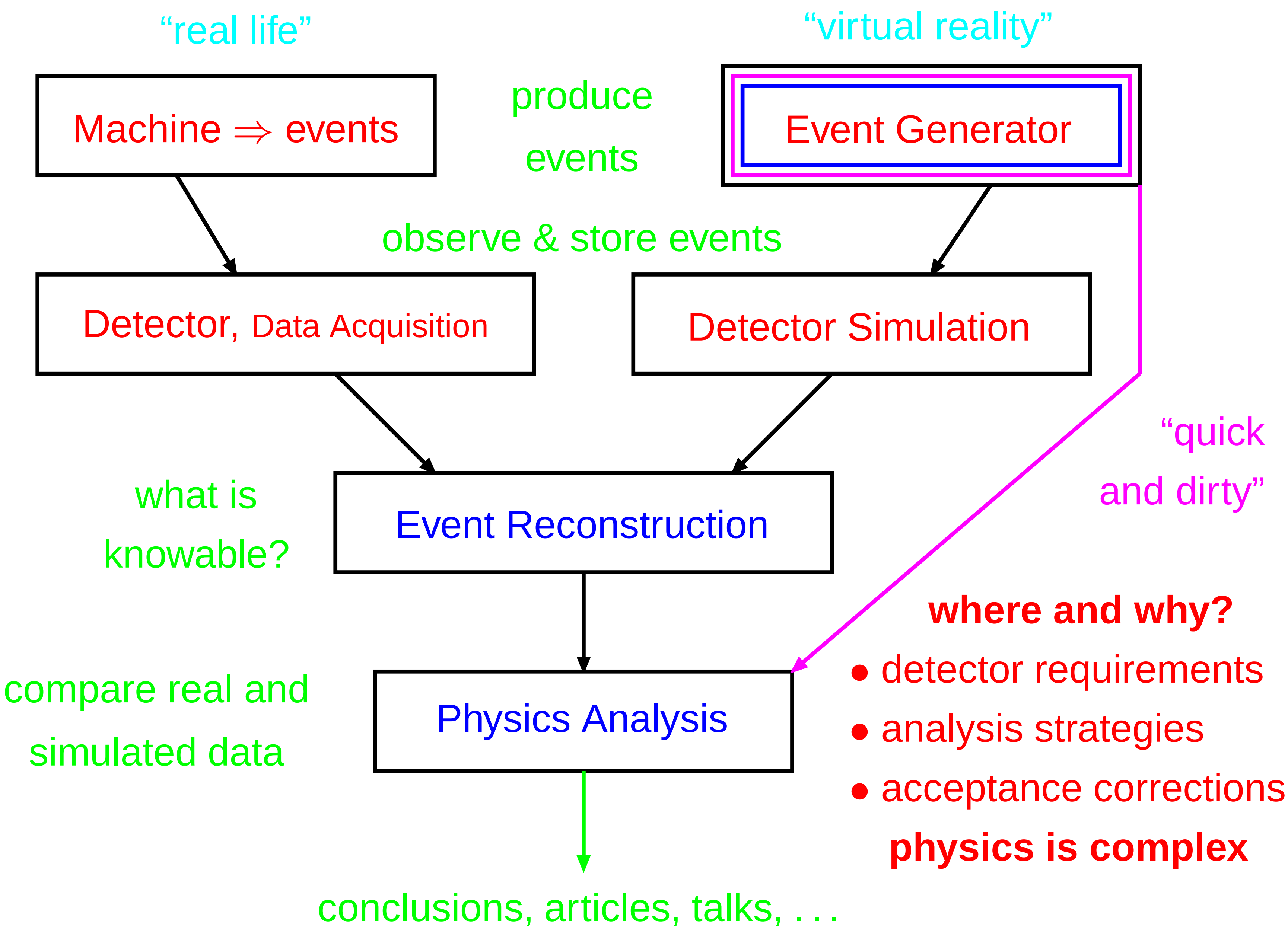
CERN and Lund University

Generator and Physics Overview
Matrix Elements vs. Parton Showers
Underlying Event and Hadronization
Outlook

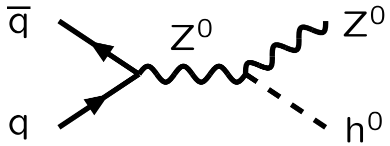
Event Generator Position



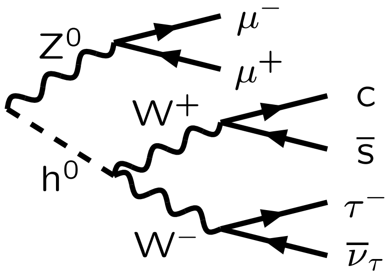
Event Physics Overview

Structure of the basic generation process:

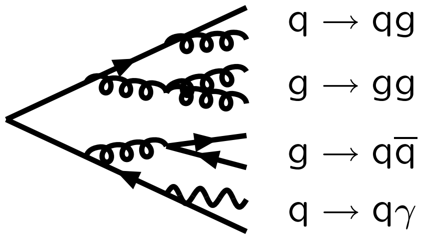
1) Hard subprocess:
$|\mathcal{M}|^2$, Breit-Wigners,
parton densities.



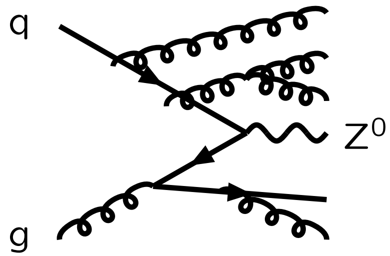
2) Resonance decays:
includes correlations.



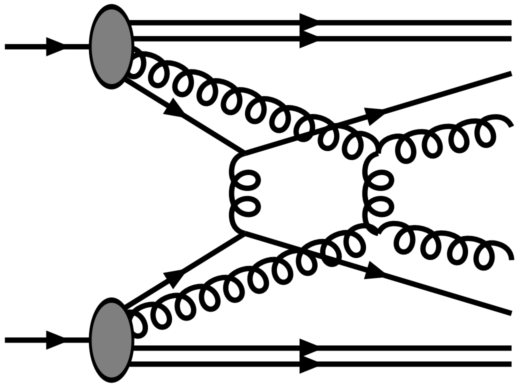
3) Final-state parton showers.



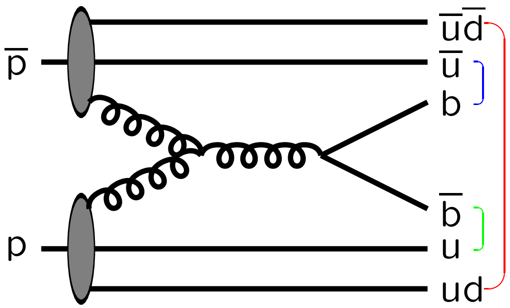
4) Initial-state parton showers.



5) Multiple parton–parton interactions.

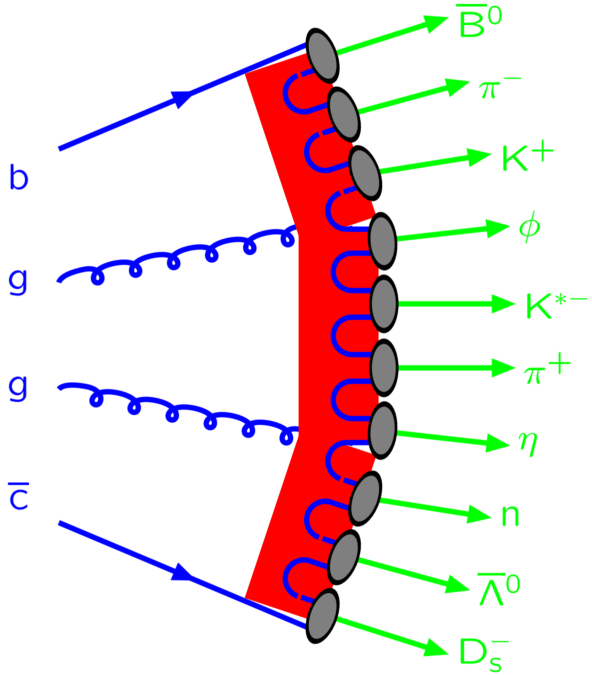


6) Beam remnants, with colour connections.

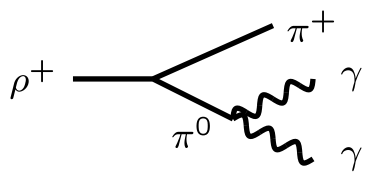


5) + 6) = Underlying Event

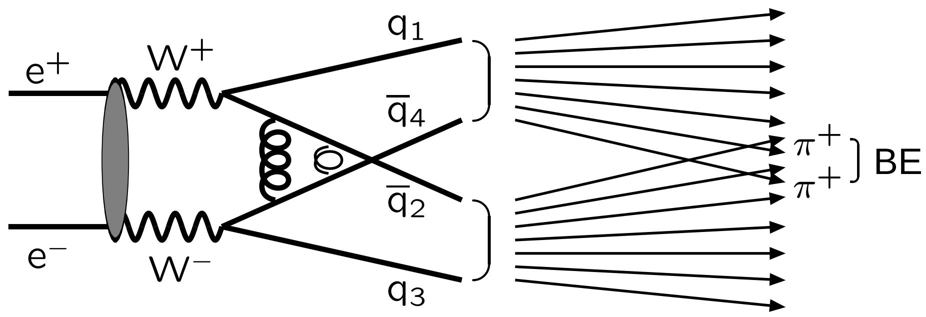
7) Hadronization



8) Ordinary decays: hadronic, τ, charm, . . .



9) QCD interconnection effects:



a) colour rearrangement
(⇒ rapidity gaps?);
b) Bose-Einstein.

10) The forgotten or unexpected: a chain is never stronger than its weakest link!

Many aspects still poorly understood,
but most good enough to work with

Generator Landscape

	General-Purpose	Specialized
Hard Processes	**HERWIG** **PYTHIA** ISAJET SHERPA	a lot
Resonance Decays		HDECAY, . . .
Parton Showers		Ariadne/LDC, NLLjet
Underlying Event		DPMJET
Hadronization		none (?)
Ordinary Decays		TAUOLA, EvtGen

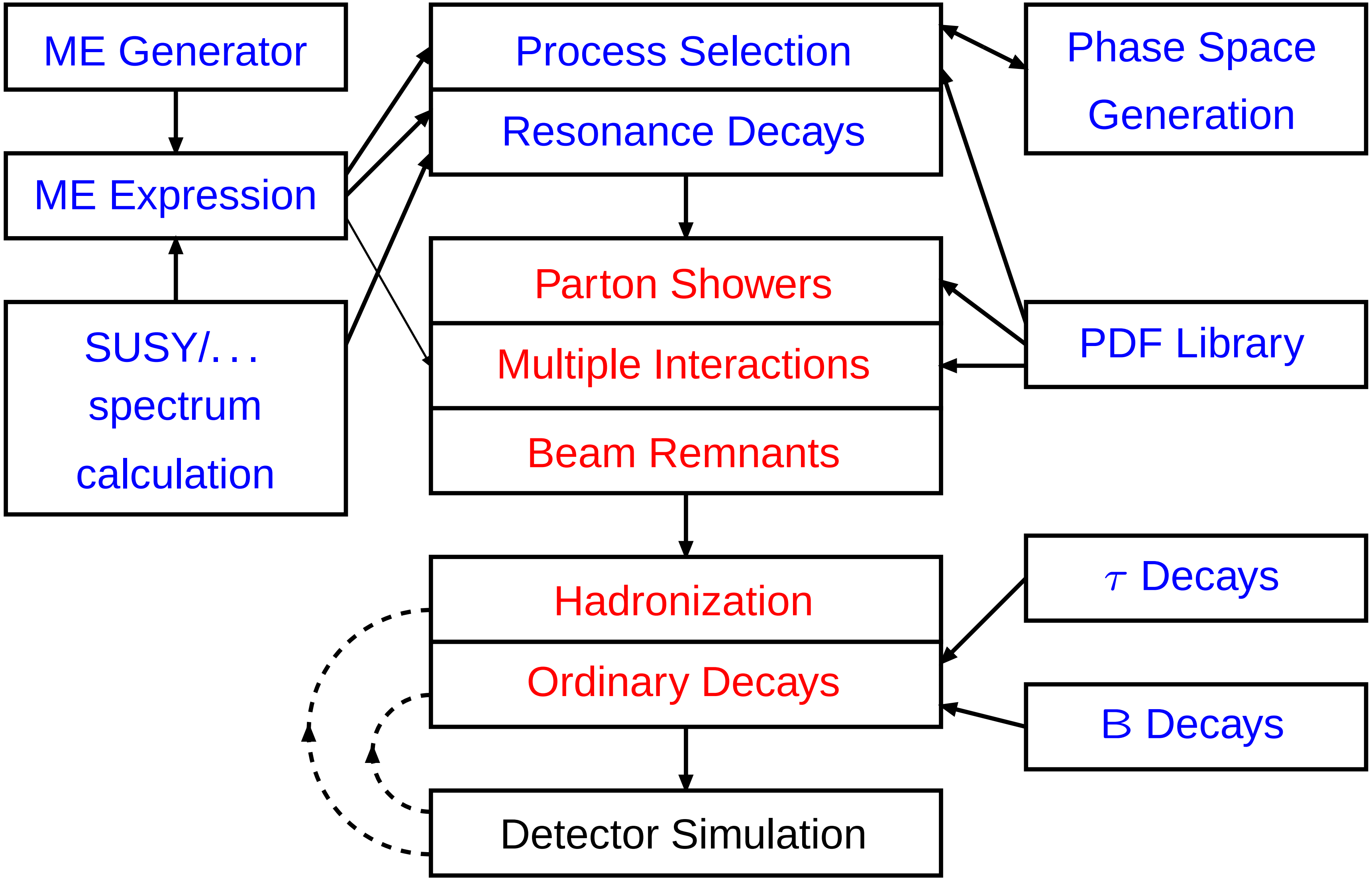
specialized often best at given task, but need General-Purpose core

The Smaller Picture: Subprocess Survey

Kind	Process	PYT	HER	ISA
QCD & related	Soft QCD	$\star$	$\star$	$\star$
	Hard QCD	$\star$	$\star$	$\star$
	Heavy flavour	$\star$	$\star$	$\star$
Electroweak SM	Single $\gamma^*/Z^0/W^\pm$	$\star$	$\star$	$\star$
	$(\gamma/\gamma^*/Z^0/W^\pm/f/g)^2$	$\star$	$\star$	$\star$
	Light SM Higgs	$\star$	$\star$	$\star$
	Heavy SM Higgs	$\star$	$\star$	$\star$
SUSY BSM	$h^0/H^0/A^0/H^\pm$	$\star$	$\star$	$\star$
	SUSY	$\star$	$\star$	$\star$
	$R\!\!\!/$ SUSY	$\star$	$\star$	—
Other BSM	Technicolor	$\star$	—	$(\star)$
	New gauge bosons	$\star$	—	—
	Compositeness	$\star$	—	—
	Leptoquarks	$\star$	—	—
	$H^{\pm\pm}$ (from LR-sym.)	$\star$	—	—
	Extra dimensions	$(\star)$	$(\star)$	$(\star)$

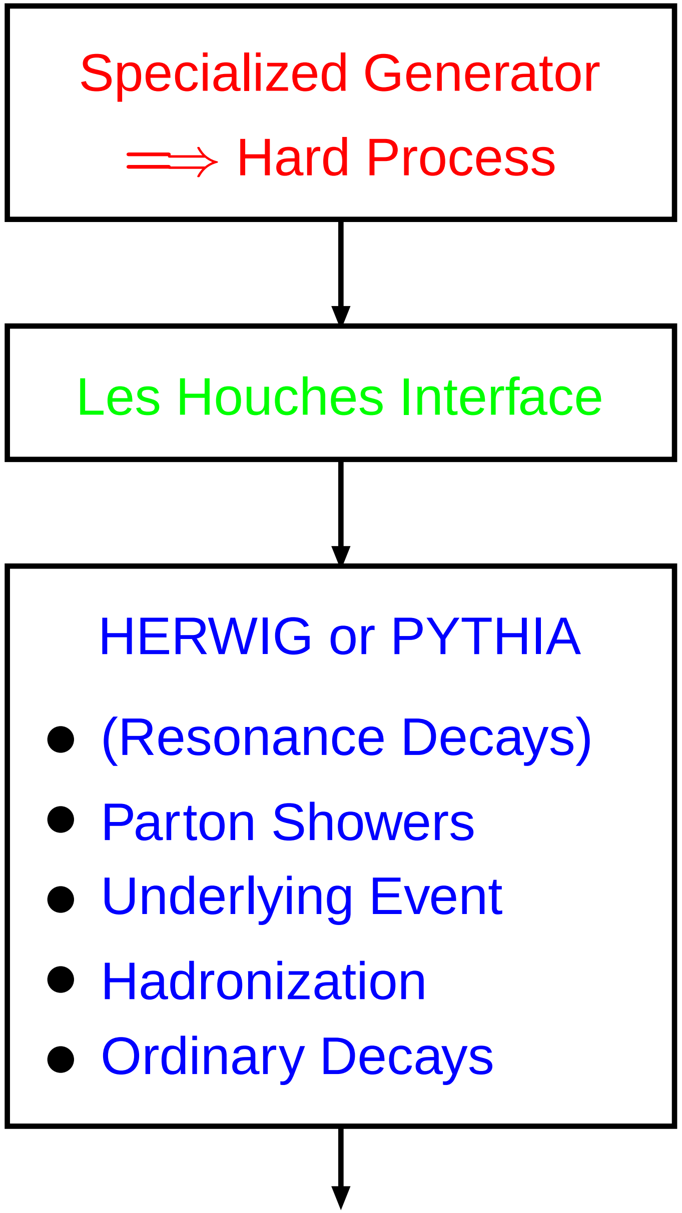
. . . but processes usually only in lowest nontrivial order

The Bigger Picture



$\Longrightarrow$ need standardized interfaces

The Les Houches Accord



Some Specialized Generators:

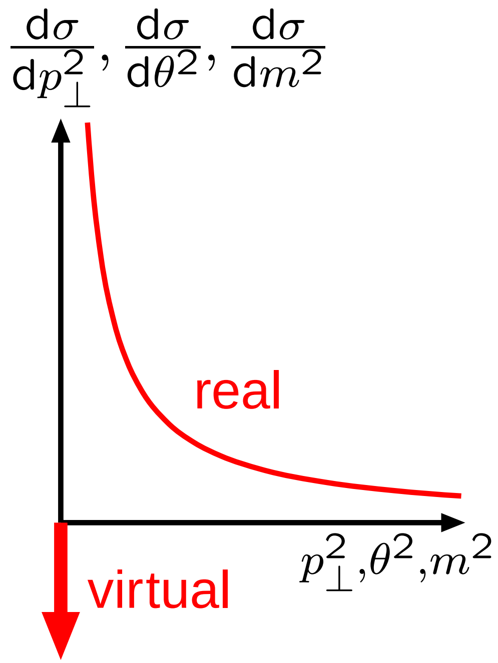
- AcerMC: $t\bar{t}b\bar{b}$, ...
- ALPGEN: $W/Z+ \leq 6j$, $nW + mZ + kH+ \leq 3j$, ...
- AMEGIC++: generic LO
- CompHEP: generic LO
- GRACE+Bases/Spring: generic LO+ some NLO loops
- GR@PPA: $b\bar{b}b\bar{b}$
- MadCUP: $W/Z+ \leq 3j, t\bar{t}b\bar{b}$
- MadGraph+HELAS: generic LO
- MCFM: NLO $W/Z+ \leq 2j$, WZ, WH, $H+ \leq 1j$
- O'Mega+WHIZARD: generic LO
- VECBOS: $W/Z+ \leq 4j$

Apologies for all unlisted programs

Matrix Elements vs. Parton Showers

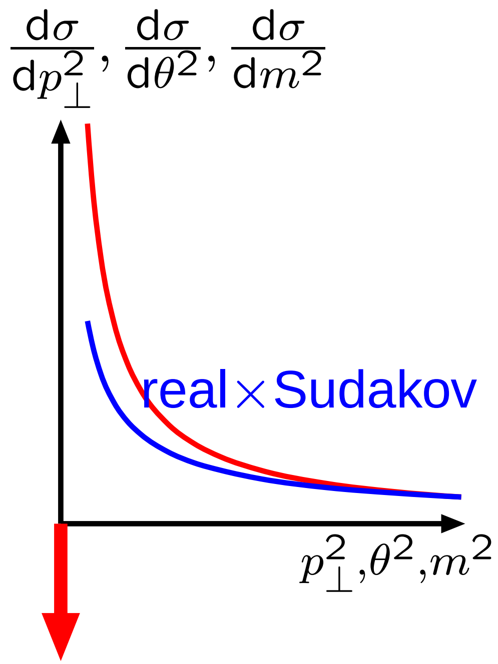
ME : Matrix Elements

+ systematic expansion in α_s ('*exact*')
+ powerful for multiparton Born level
+ flexible phase space cuts
− loop calculations very tough
− negative cross section in collinear regions
  $\Rightarrow$ unpredictive jet/event structure
− *no easy match to hadronization*



PS : Parton Showers

− approximate, to LL (or NLL)
− main topology not predetermined
  $\Rightarrow$ inefficient for exclusive states
+ process-generic $\Rightarrow$ simple multiparton
+ Sudakov form factors/resummation
  $\Rightarrow$ sensible jet/event structure
+ *easy to match to hadronization*



Parton Shower Approach

3 common algorithms:

HERWIG: θ-ordered emissions (ISR & FSR)

PYTHIA: M^2, Q^2-ordered emissions (ISR & FSR)

ARIADNE: $p_\perp$-ordered emissions (FSR primarily)

Steady evolution:

HERWIG: new angular evolution variable

$\Rightarrow$ improved phase space coverage,
better massive quark treatment

PYTHIA: $p_\perp$-ordered emissions (ISR & FSR)

$\Rightarrow$ improved coherence,
interleaved multiple interactions,
(to prove:) simplified vetoed parton showers

LDCMD, CASCADE: CCFM generators for ISR at small x

Matrix Elements and Parton Showers

Marriage desirable! But how?

Problems:
- gaps in coverage?
- doublecounting of radiation?
- Sudakov?
- NLO consistency?

Much work ongoing $\Longrightarrow$ no established orthodoxy

Three main areas, in ascending order of complication:

1) Match to lowest-order nontrivial process — merging

2) Combine leading-order multiparton process — vetoed parton showers (cf. talk by M. Mangano)

3) Match to next-to-leading order process — MC@NLO (covered in talk by S. Frixione)

Merging

= cover full phase space with smooth transition ME/PS

Want to reproduce $$W^{\mathrm{ME}} = \frac{1}{\sigma(\mathrm{LO})} \frac{\mathrm{d}\sigma(\mathrm{LO}+\mathrm{g})}{\mathrm{d(phasespace)}}$$

by shower generation + correction procedure

$$\overbrace{W^{\mathrm{ME}}}^{\text{wanted}} = \overbrace{W^{\mathrm{PS}}}^{\text{generated}} \; \frac{\overbrace{W^{\mathrm{ME}}}^{\text{correction}}}{W^{\mathrm{PS}}}$$

- Exponentiate ME correction by shower Sudakov form factor:

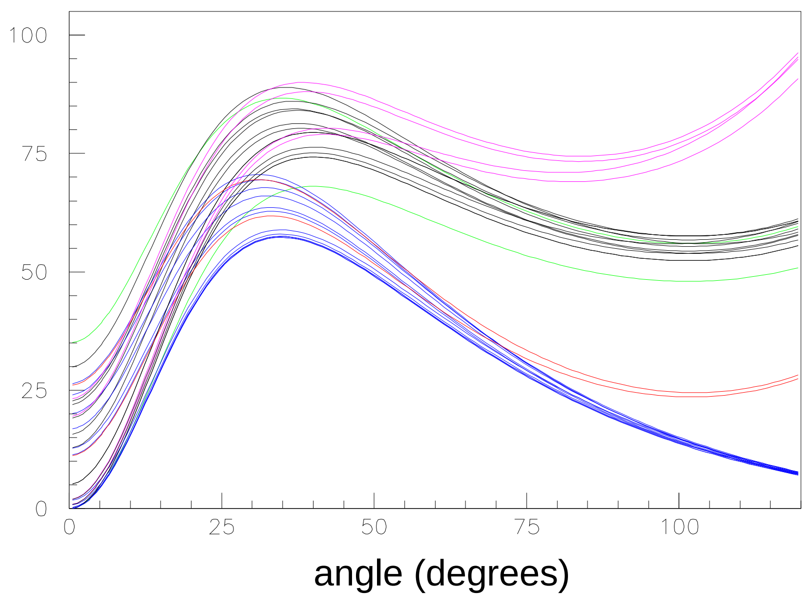
$$W^{\mathrm{PS}}_{\mathrm{actual}}(Q^2) = W^{\mathrm{ME}}(Q^2) \exp\left(-\int_{Q^2}^{Q^2_{\mathrm{max}}} W^{\mathrm{ME}}(Q'^2)\, \mathrm{d}Q'^2\right)$$

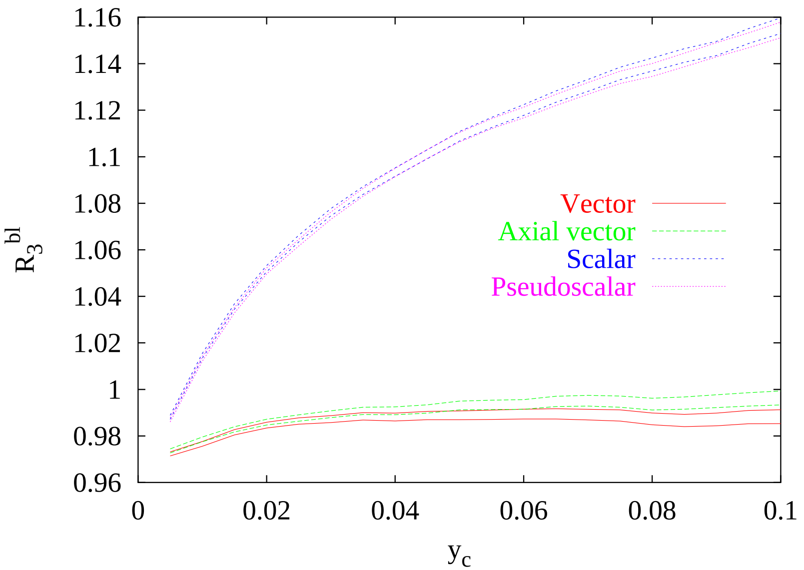
- Normally several shower histories $\Rightarrow$ $\sim$equivalent approaches
- Use $\mathrm{d}\sigma = K \;\sigma_0\; \mathrm{d}W^{\mathrm{PS}}$
  where $K = 1 + \mathcal{O}(\alpha_{\mathrm{s}})$ is set separately (ambiguity of $\mathcal{O}(\alpha_{\mathrm{s}}^2)$)

PYTHIA performs merging with generic FSR $a \to bc\mathrm{g}$ ME,
in SM: $\gamma^*/\mathrm{Z}^0/\mathrm{W}^\pm \to \mathrm{q\bar{q}}$, $\mathrm{t} \to \mathrm{bW}^+$, $\mathrm{H}^0 \to \mathrm{q\bar{q}}$,
and MSSM: $\mathrm{t} \to \mathrm{bH}^+$, $\mathrm{Z}^0 \to \tilde{\mathrm{q}}\bar{\tilde{\mathrm{q}}}$, $\tilde{\mathrm{q}} \to \tilde{\mathrm{q}}'\mathrm{W}^+$, $\mathrm{H}^0 \to \tilde{\mathrm{q}}\bar{\tilde{\mathrm{q}}}$, $\tilde{\mathrm{q}} \to \tilde{\mathrm{q}}'\mathrm{H}^+$,
$\chi \to \mathrm{q}\bar{\tilde{\mathrm{q}}}$, $\chi \to \mathrm{q}\bar{\tilde{\mathrm{q}}}$, $\tilde{\mathrm{q}} \to \mathrm{q}\chi$, $\mathrm{t} \to \tilde{\mathrm{t}}\chi$, $\tilde{\mathrm{g}} \to \mathrm{q}\bar{\tilde{\mathrm{q}}}$, $\tilde{\mathrm{q}} \to \mathrm{q}\tilde{\mathrm{g}}$, $\mathrm{t} \to \tilde{\mathrm{t}}\tilde{\mathrm{g}}$

g emission for different colour, spin and parity:

$R_3^{\mathrm{bl}}(y_c)$: mass effects in Higgs decay:





PYTHIA ISR: only $\mathrm{q\bar{q}} \to \gamma^*/\mathrm{Z}^0/\mathrm{W}^\pm$ and $\mathrm{gg} \to \mathrm{H}^0$ (for $m_\mathrm{t} \to \infty$)
(but K factor not implemented here)

HERWIG: fewer for FSR, comparable for ISR

Vetoed Parton Showers

S. Catani, F. Krauss, R. Kuhn, B.R. Webber, JHEP 0111 (2001) 063; L. Lönnblad, JHEP0205 (2002) 046;

F. Krauss, JHEP 0208 (2002) 015; S. Mrenna, P. Richardson, JHEP0405 (2004) 040;

M.L. Mangano, in preparation

Generic method to combine ME's of several different orders
to NLL accuracy; will be a 'standard tool' in the future

Basic idea:

- consider (differential) cross sections $\sigma_0, \sigma_1, \sigma_2, \sigma_3, \ldots$, corresponding to a lowest-order process (e.g. W or H production), with more jets added to describe more complicated topologies, in each case to the respective leading order
- σ_i, $i \geq 1$, are divergent in soft/collinear limits
- absent virtual corrections would have ensured "detailed balance", i.e. an emission that adds to σ_{i+1} subtracts from σ_i
- such virtual corrections correspond (approximately) to the Sudakov form factors of parton showers
- so use shower routines to provide missing virtual corrections
  $\Rightarrow$ rejection of events (especially) in soft/collinear regions

Veto scheme:

1) Pick hard process, mixing according to $\sigma_0 : \sigma_1 : \sigma_2 : \ldots$,
above some ME cutoff, with large fixed α_{s0}

2) Reconstruct imagined shower history (in different ways)

3) Weight $W_\alpha = \prod_{\mathrm{branchings}} (\alpha_s(k_{\perp i}^2)/\alpha_{s0}) \Rightarrow$ accept/reject

CKKW-L:

4) Sudakov factor for non-emission
on all lines above ME cutoff

$$W_{\mathrm{Sud}} = \prod_{\text{“propagators”}} \mathrm{Sudakov}(k_{\perp\mathrm{beg}}^2, k_{\perp\mathrm{end}}^2)$$

4a) CKKW : use NLL Sudakovs

4b) L: use trial showers

5) $W_{\mathrm{Sud}} \Rightarrow$ accept/reject

6) do shower,
vetoing emissions above cutoff

MLM:

4) do parton showers

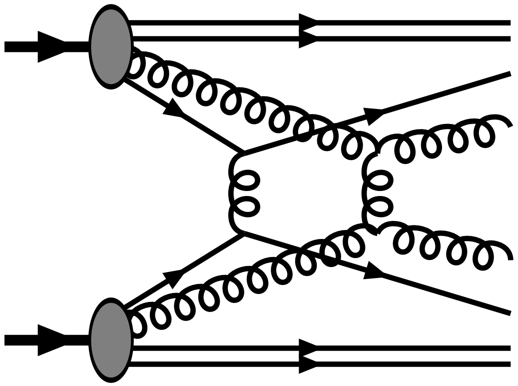
5) (cone-)cluster
showered event

6) match partons and jets

7) if all partons are matched,
and $n_{\mathrm{jet}} = n_{\mathrm{parton}}$,
keep the event,
else discard it

Multiple Interactions

Consequence of composite nature of hadrons!

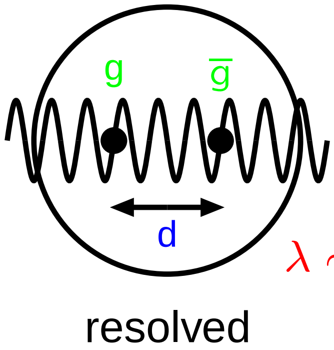


Evidence:

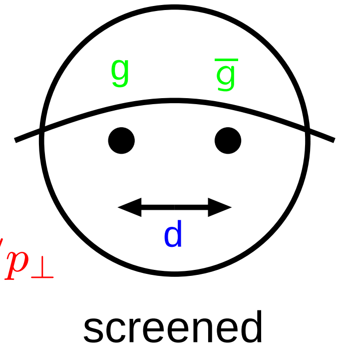
- direct observation: AFS, UA1, CDF
- implied by width of multiplicity distribution + jet universality: UA5
- forward–backward correlations: UA5
- pedestal effect: UA1, H1, CDF

One new free parameter: $p_{\perp\mathrm{min}}$

$$\frac{1}{2}\sigma_{\mathrm{jet}} = \int_{p^2_{\perp\mathrm{min}}}^{s/4} \frac{\mathrm{d}\sigma}{\mathrm{d}p_\perp^2}\,\mathrm{d}p_\perp^2 \quad \Longleftarrow \quad \int_0^{s/4} \frac{\mathrm{d}\sigma}{\mathrm{d}p_\perp^2}\,\frac{p_\perp^4}{(p^2_{\perp 0}+p_\perp^2)^2}\,\mathrm{d}p_\perp^2$$



$\lambda \sim 1/p_\perp$

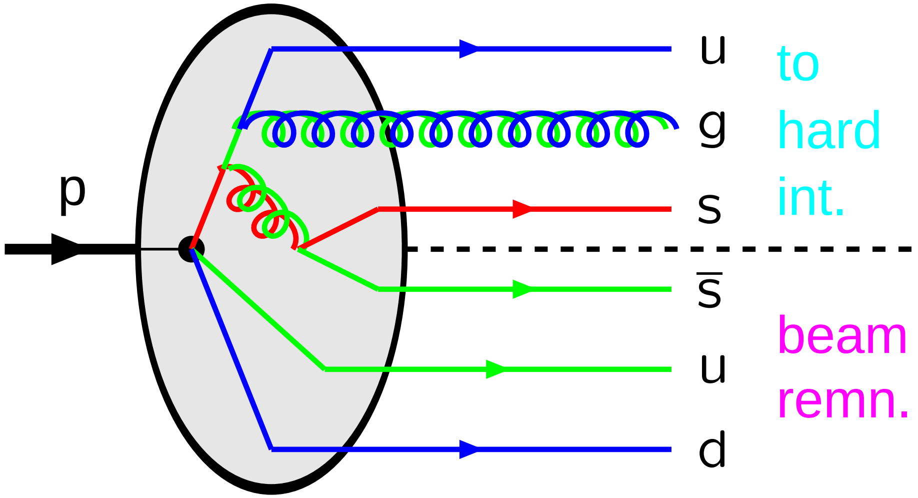


Measure of colour screening length d in hadron:

$p_{\perp\mathrm{min}}\,\langle d \rangle \approx 1 (= \hbar)$

Event Structure and Beam Remnants

(TS & P.Z. Skands, JHEP 03 (2004) 053)



Need to assign:

- correlated flavours
- correlated $x_i = p_{zi}/p_{z\text{tot}}$
- correlated primordial $k_{\perp i}$
- correlated colours

  for initiators and remnants

  + showers

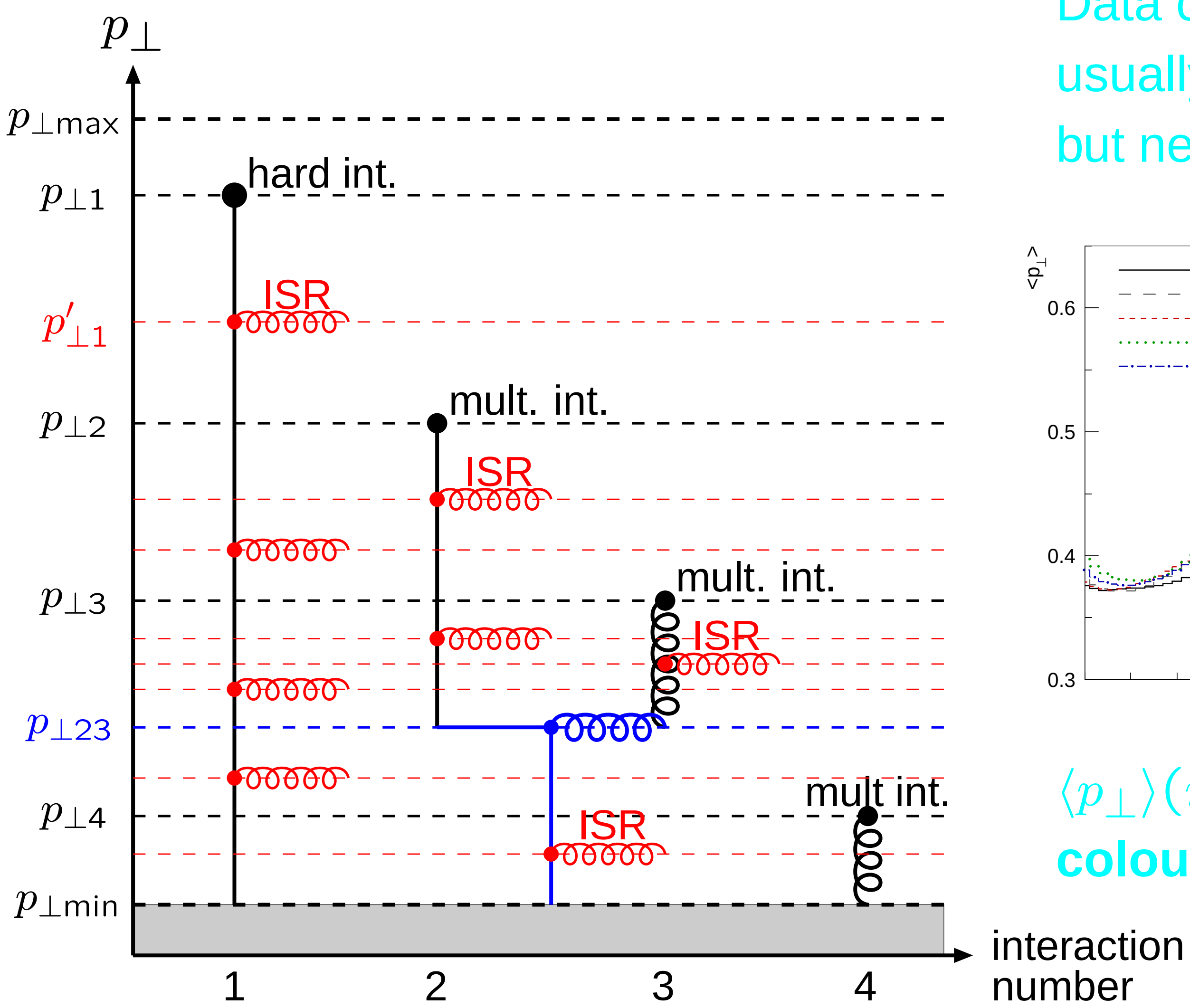
Example: parton densities after first interaction:

- valence: scale by #remaining/#original
- sea: bookkeep 'companion' by

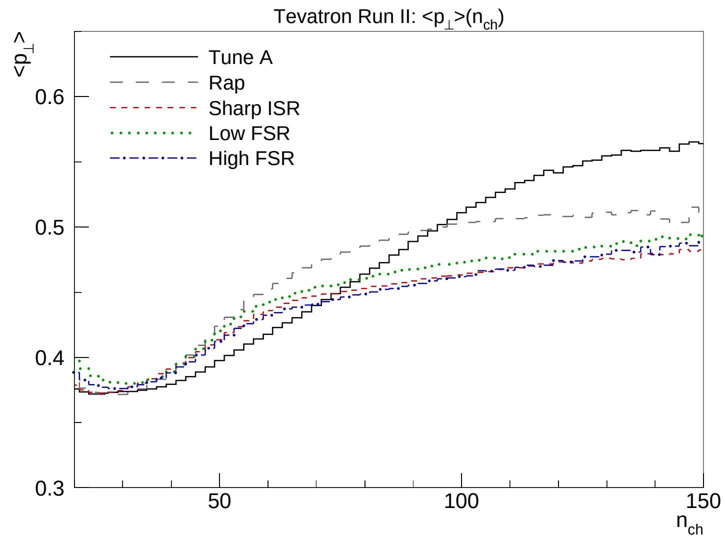
$$\overline{s}(x'; x) \quad \propto \quad \frac{g(x+x')}{x+x'} P_{\mathrm{g}\to\mathrm{s}\overline{\mathrm{s}}}\left(\frac{x}{x+x'}\right)$$

Interleaved Multiple Interactions

(TS & P.Z. Skands, hep-ph/0408302)



Data comparisons:
usually $\sim$ Tune A
but need good tuning



$\langle p_\perp \rangle (n_{\mathrm{ch}})$ problem:

colour correlations?

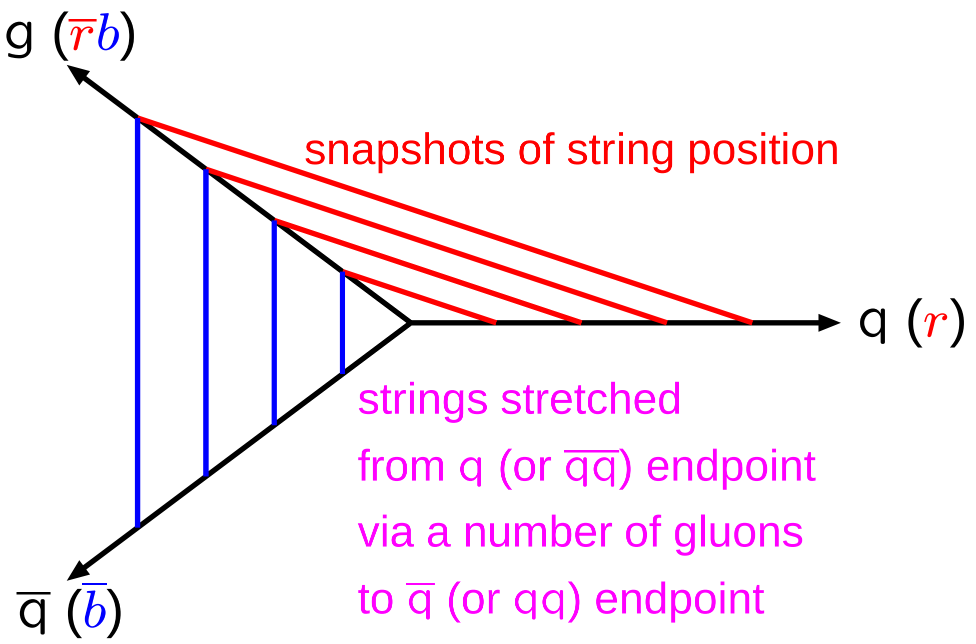
Hadronization: Lund String Model

In QCD, for large charge separation, field lines seem to be compressed to tubelike region(s) $\Rightarrow$ **string(s)**

String tension: $F(r) \approx \text{const} = \kappa \quad \Longleftrightarrow \quad V(r) \approx \kappa r$

Confirmed e.g. by quenched lattice QCD

Unquenched $\Longrightarrow$ nonperturbative string breakings

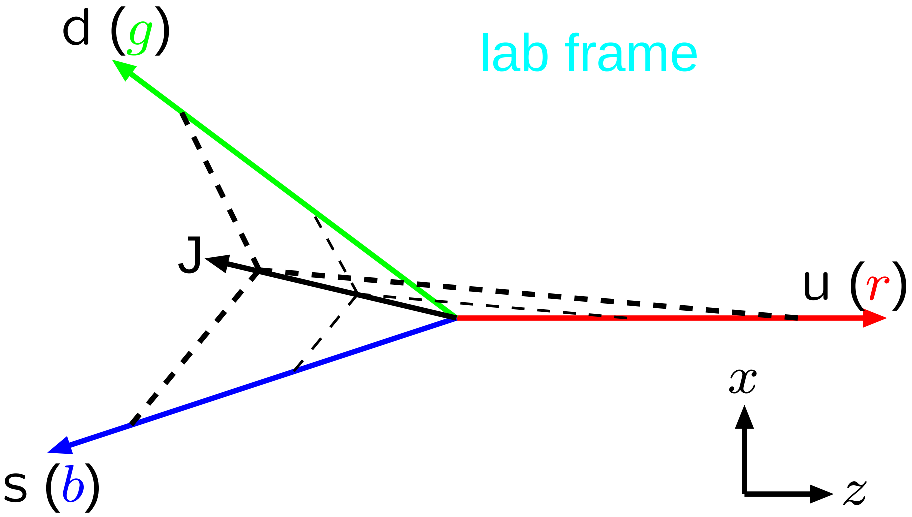


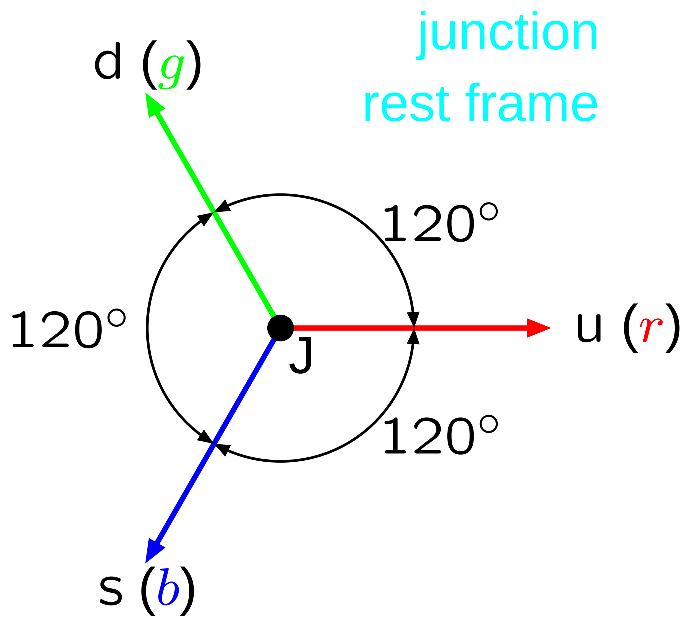
Gluon = kink on string, carrying energy and momentum. Force ratio gluon/ quark = 2, cf. QCD $N_C/C_F = 9/4$

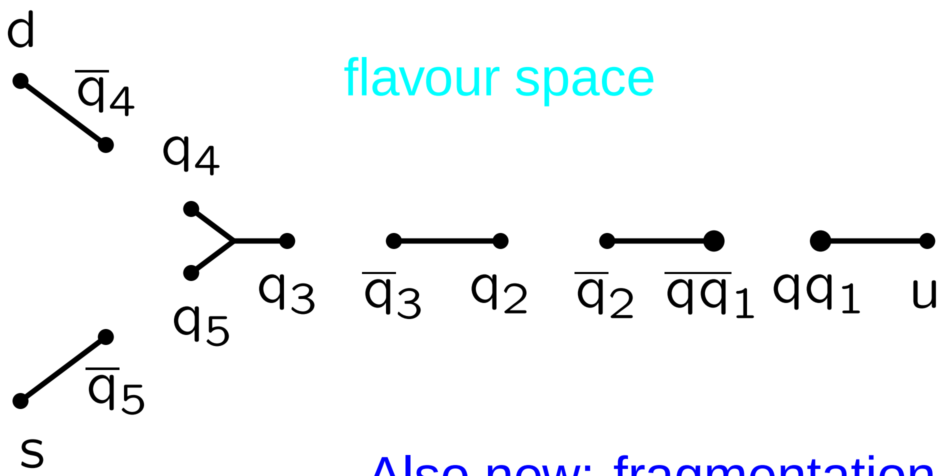
- Few parameters to describe energy–momentum structure!
  - Many parameters to describe flavour composition!

Lund hadronization news: fragmentation of junction topology,
in R-parity violating SUSY decays $\tilde{\chi}_1^0 \to$ uds,
or when 2 valence quarks kicked out of proton beam

(TS & P.Z. Skands, NPB659 (2003) 243)





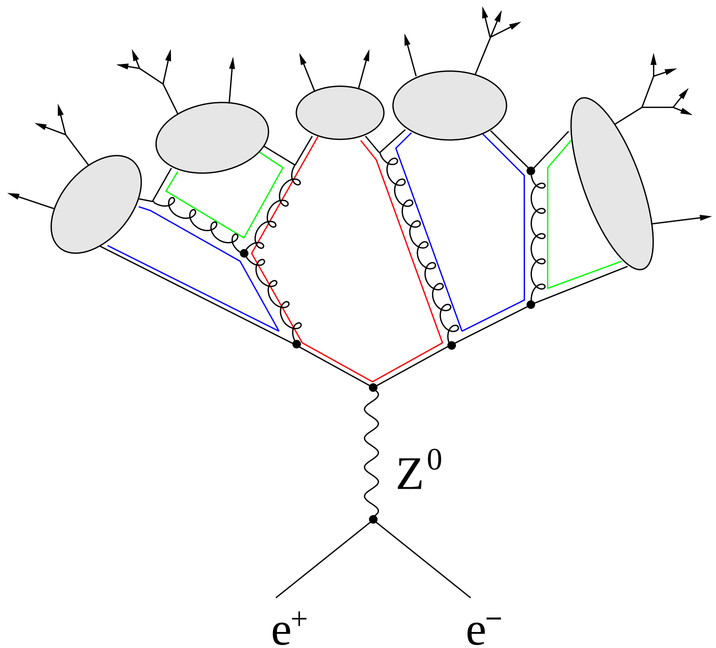


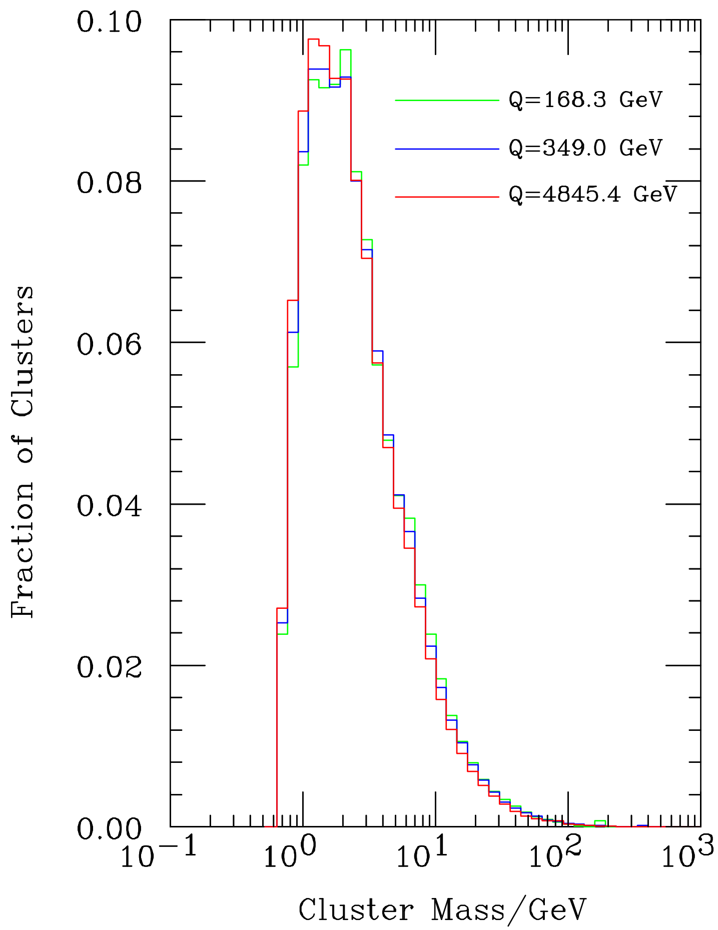
More complicated (but ≈solved) with gluon emission and massive quarks

Also new: fragmentation of stable gluino

Hadronization: HERWIG Cluster Model

Introduce forced
g $\longrightarrow q\bar{q}$ branchings:





Large-mass clusters require special attention

- Many parameters to describe energy–momentum structure!
  - Few parameters to describe flavour composition!

Standards and Interfaces

⋆ ⋆ ⋆ PDG particle codes

⋆ ⋆ ⋆ HEPEVT hadron-level Event Record

⋆ ⋆ ⋆ Les Houches Accord User Process Interface

⋆ ⋆ ⋆ LHAPDF: Les Houches Accord Parton Density Functions
(supersedes PDFLIB)

⋆ ⋆ ⋆ SLHA: SUSY mass/coupling spectrum calculator interface

⋆⋆ HepMC hadron-level Event Record in C++

⋆⋆ JetWeb/HZtools: automated data comparisons

⋆ StdHep, StdHepC++: converts non-standard particle codes

⋆ HepPDT particle data tables in C++

? For C++ era: (improved) Les Houches Interface for HO or NLO ME's,
standardized cuts, standard cone clustering algorithm, . . .

On To C++

PYTHIA7 project $\Longrightarrow$ **ThePEG**

Toolkit for High Energy Physics Event Generation:

general-purpose framework, kinematics, ME machinery, decays, . . .

(L. Lönnblad; S. Gieseke, A. Ribon, P. Richardson)

ARIADNE/LDC: to do ISR/FSR showers, multiple interactions

(L. Lönnblad; N. Lavesson)

PYTHIA7 leftover: old showers + incomplete string fragmentation

$\Rightarrow$ restart from scratch 2 months ago (TS)

HERWIG++: new final-state shower + improved cluster model

and decays $\Rightarrow$ e^+e^- complete, pp underway

(B.R. Webber; S. Gieseke, A. Ribon, P. Richardson, M. Seymour, P. Stephens)

SHERPA: does pp, but partly wrappers to PYTHIA Fortran; has CKKW

(F. Krauss; T. Gleisberg, S. Hoeche, A. Schaelicke, S. Schumann, J. Winter)

- Conversion effort: everything takes longer and costs more
  (as for LHC machine, detectors and software)
- The physics hurdle is as steep as the C++ learning curve

Outlook

Generators in state of continuous development:

• better & more user-friendly general-purpose matrix element calculators+integrators

• new libraries of physics processes, also to NLO

• more precise parton showers

• better matching matrix elements $\Leftrightarrow$ showers

• improved models for underlying events / minimum bias

• upgrades of hadronization and decays

• moving to C++

$\Rightarrow$ always better, but never enough

But what are the alternatives, when event structures are complicated and analytical methods inadequate?