LUND UNIVERSITY

Les Houches Workshop:
Physics at TeV Colliders
26 May - 6 June 2003

Monte Carlos for TeV Colliders

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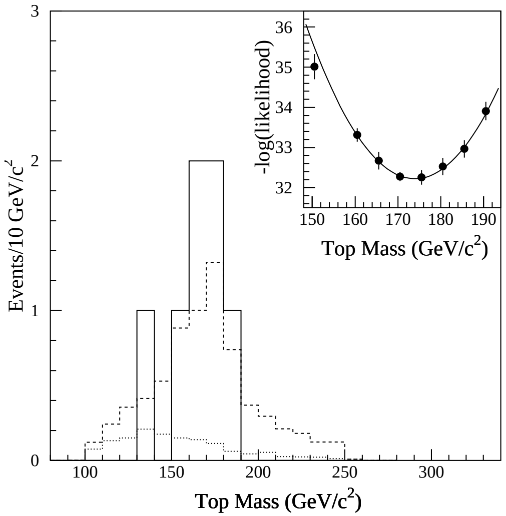
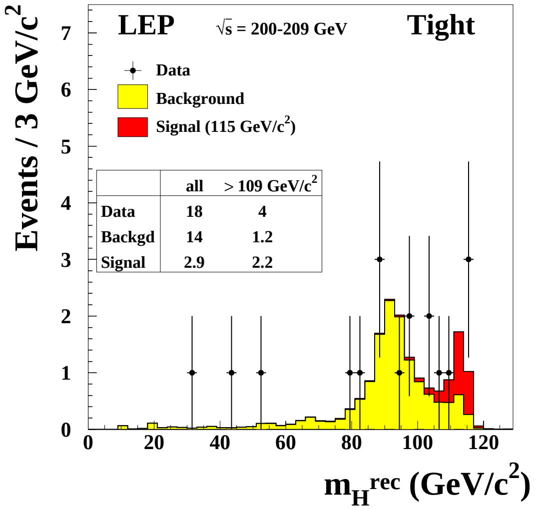
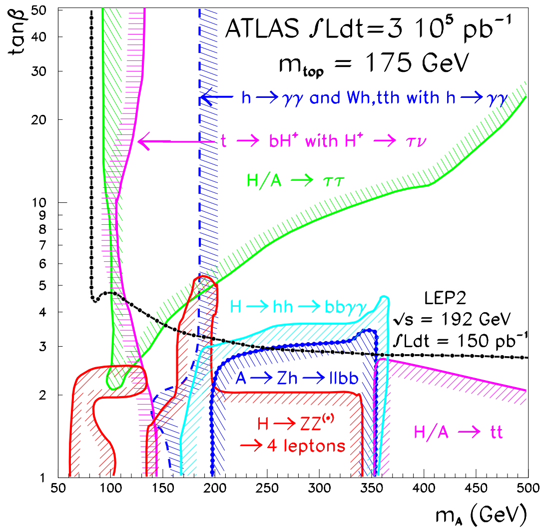
Generator and Physic Overview
Matrix Elements vs. Parton Showers
Hadronization and Underlying Event
Outlook

Why Generators? (I)





	all	> 109 GeV/c^2
Data	18	4
Backgd	14	1.2
Signal	2.9	2.2



top discovery and mass determination

Higgs (non) discovery

Higgs and supersymmetry exploration

not feasible without generators

Why Generators? (II)

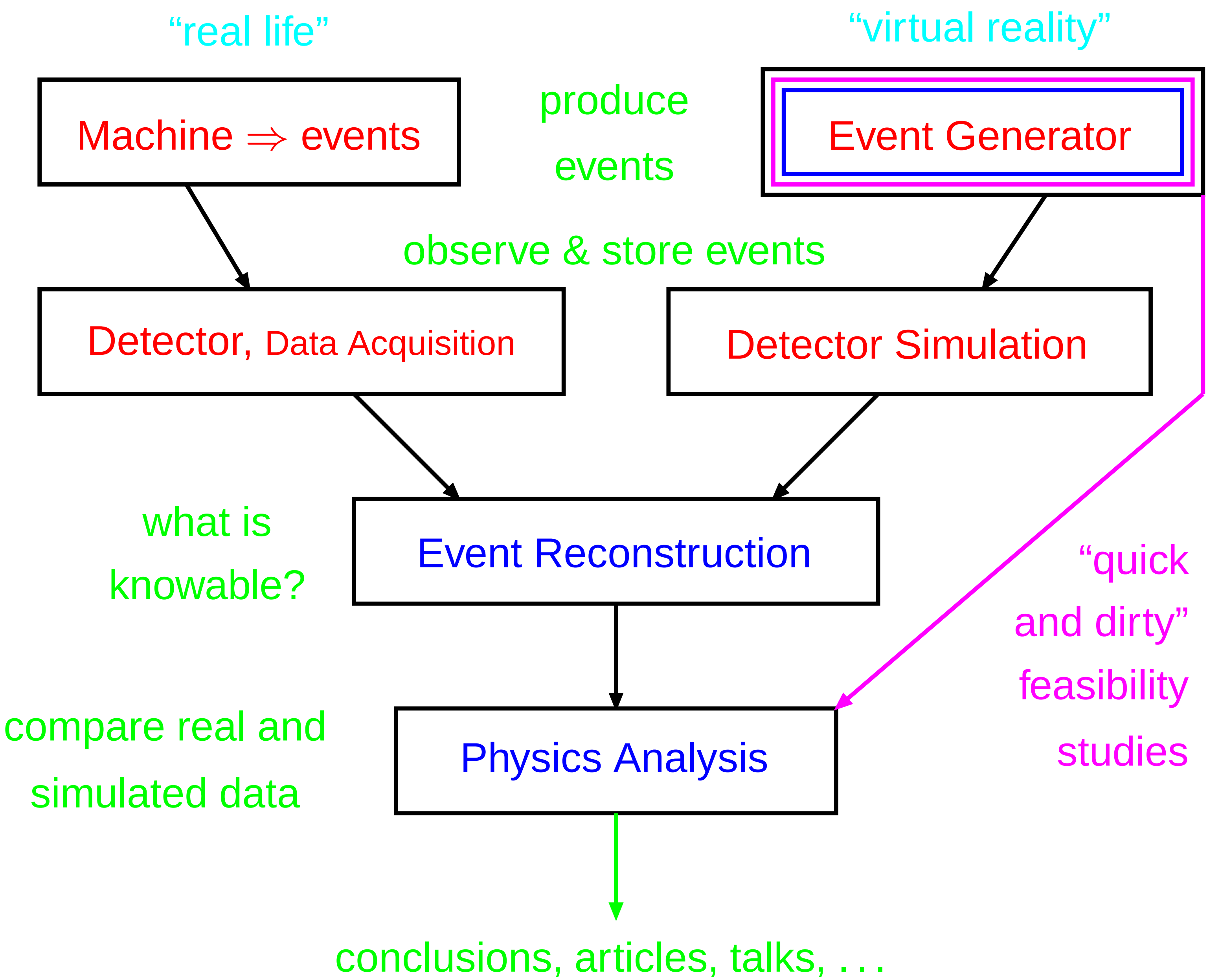
- Allow theoretical and experimental studies of *complex* multiparticle physics
- Large flexibility in physical quantities that can be addressed
- Vehicle of ideology to disseminate ideas from theorists to experimentalists

Can be used to

- predict event rates and topologies
  ⇒ can estimate feasibility
- simulate possible backgrounds
  ⇒ can devise analysis strategies
- study detector requirements
  ⇒ can optimize detector/trigger design
- study detector imperfections
  ⇒ can evaluate acceptance corrections

God does not throw dice . . . but Mother Nature does!

Event Generator Position



“real life”

“virtual reality”

Machine ⇒ events

produce

events

Event Generator

observe & store events

Detector, Data Acquisition

Detector Simulation

what is

knowable?

Event Reconstruction

“quick

and dirty”

feasibility

studies

compare real and

simulated data

Physics Analysis

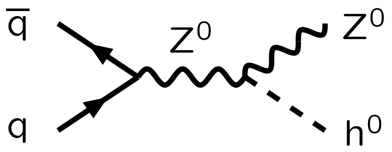
conclusions, articles, talks, . . .

Event Physics Overview

Structure of the basic generation process:

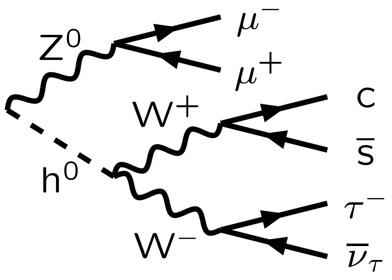
1) Hard subprocess:

$|\mathcal{M}|^2$, Breit-Wigners, parton densities.

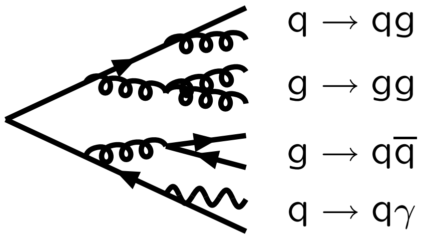


2) Resonance decays:

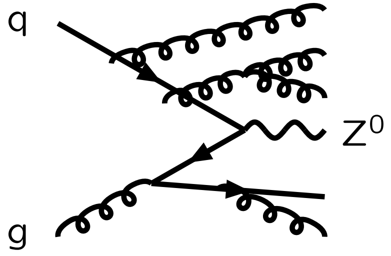
includes correlations.



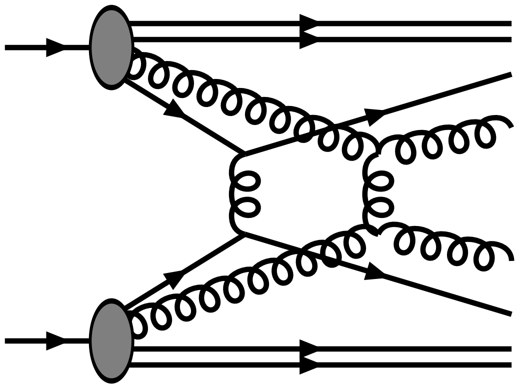
3) Final-state parton showers.



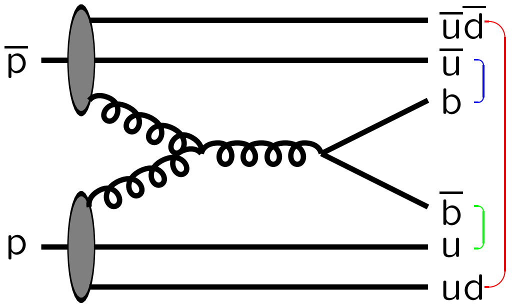
4) Initial-state parton showers.



5) Multiple parton–parton interactions.

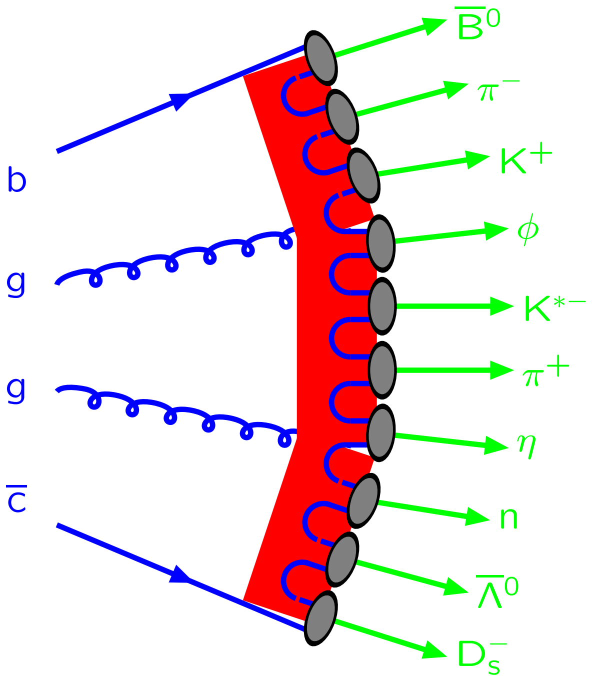


6) Beam remnants, with colour connections.

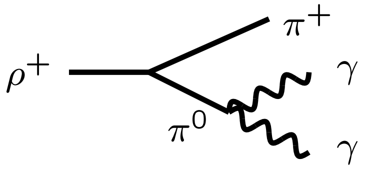


5) + 6) = Underlying Event

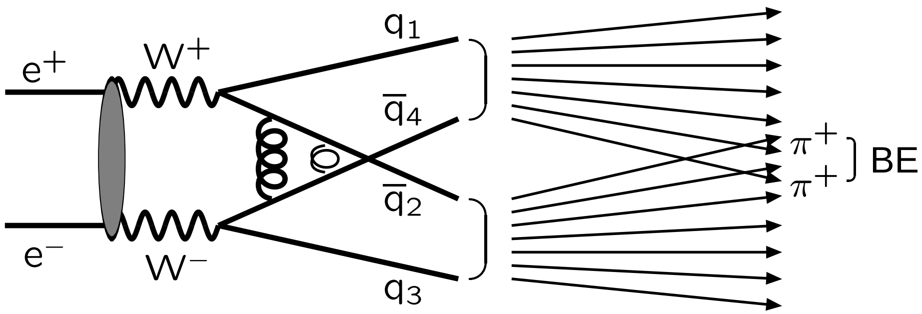
7) Hadronization



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 ISAJET PYTHIA	a lot
Resonance Decays		HDECAY
Parton Showers		Ariadne/LDC, NLLjet
Underlying Event		DPMJET
Hadronization		none (?)
Ordinary Decays		TAUOLA, EvtGen

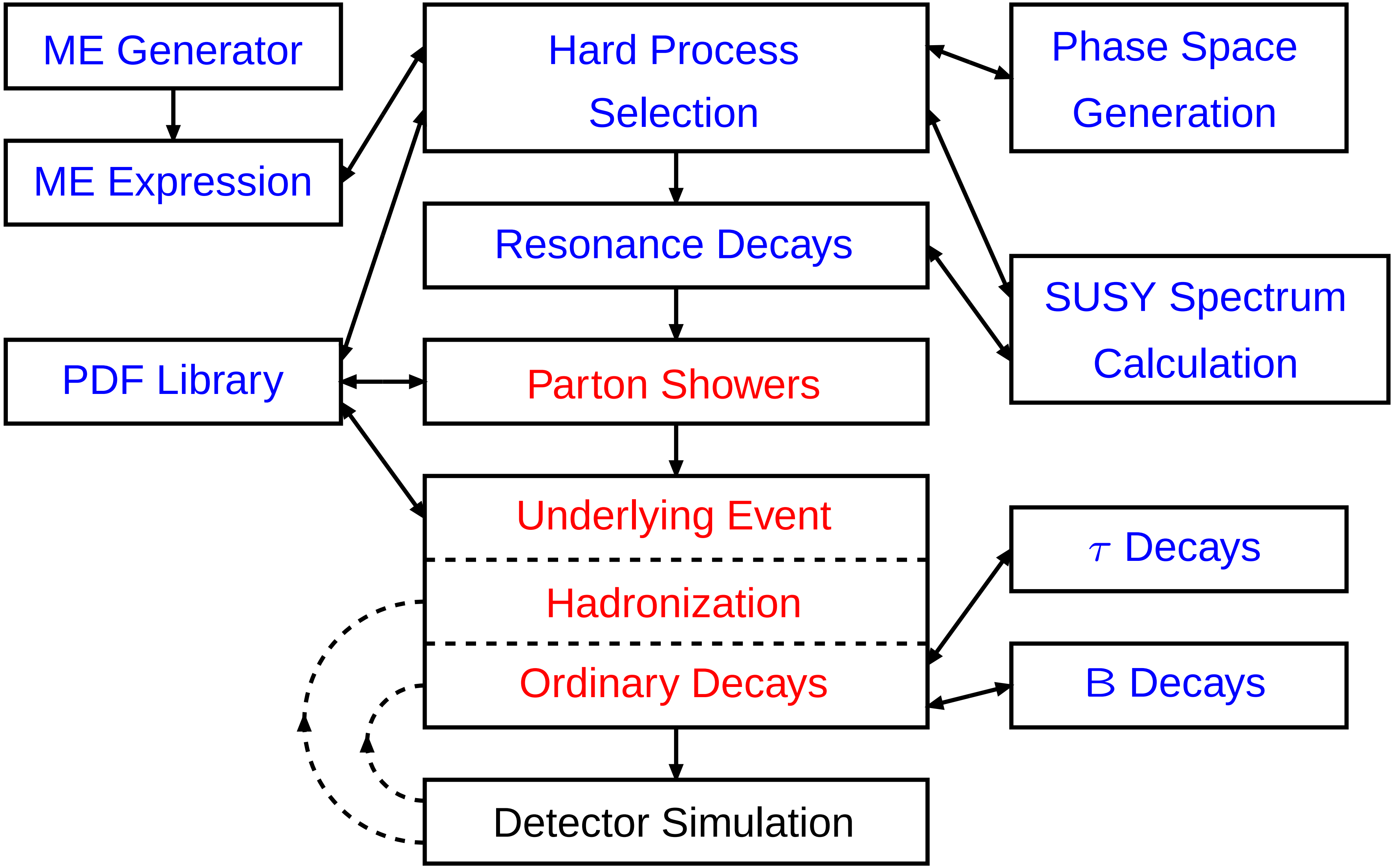
specialized often best at given task, but no way around Big Three

The Smaller Picture: Subprocess Survey

Kind	Process	PYT	HER	ISA
QCD & related	Soft QCD	⋆	⋆	⋆
	Hard QCD	⋆	⋆	⋆
	Heavy flavour	⋆	⋆	⋆
Electroweak SM	Single $\gamma^*/Z^0/W^\pm$	⋆	⋆	⋆
	$(\gamma/\gamma^*/Z^0/W^\pm/f/g)^2$	⋆	⋆	⋆
	Light SM Higgs	⋆	⋆	⋆
	Heavy SM Higgs	⋆	⋆	⋆
SUSY BSM	$h^0/H^0/A^0/H^\pm$	⋆	⋆	⋆
	SUSY	⋆	⋆	⋆
	$\not{R}$SUSY	⋆	⋆	—
Other BSM	Technicolor	⋆	—	(⋆)
	New gauge bosons	⋆	—	—
	Compositeness	⋆	—	—
	Leptoquarks	⋆	—	—
	$H^{\pm\pm}$ (from LR-sym.)	⋆	—	—
	Extra dimensions	(⋆)	(⋆)	(⋆)

. . . but processes usually only in lowest nontrivial order

The Bigger Picture



ME Generator

ME Expression

Hard Process Selection

Phase Space Generation

Resonance Decays

SUSY Spectrum Calculation

PDF Library

Parton Showers

Underlying Event

Hadronization

Ordinary Decays

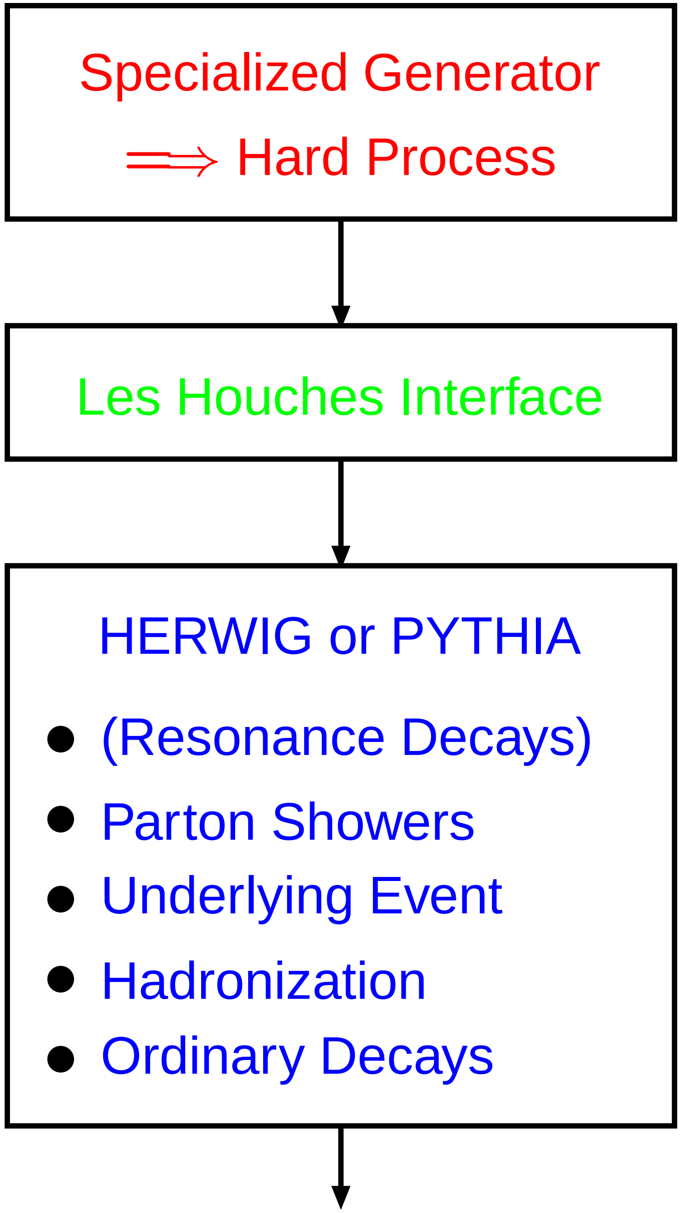
τ Decays

B Decays

Detector Simulation

$\Longrightarrow$ need standardized interfaces

The Les Houches Accord



Specialized Generator

$\Longrightarrow$ Hard Process

Les Houches Interface

HERWIG or PYTHIA

- (Resonance Decays)
- Parton Showers
- Underlying Event
- Hadronization
- Ordinary Decays

Some Specialized Generators:

- AcerMC: $t\bar{t}b\bar{b}, \ldots$
- 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

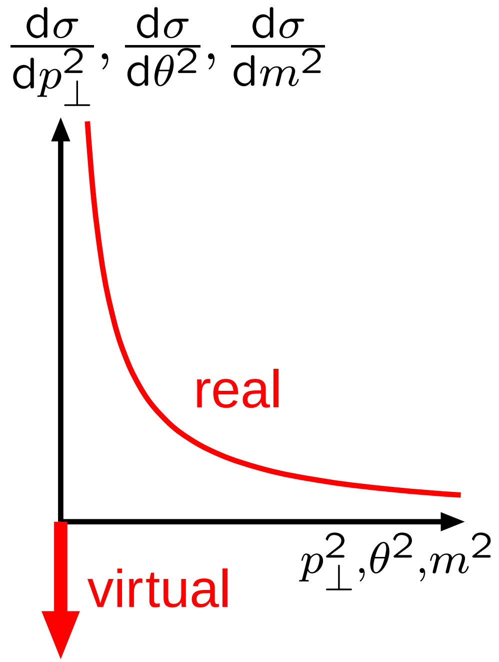
$+$ flexible phase space cuts

$-$ 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

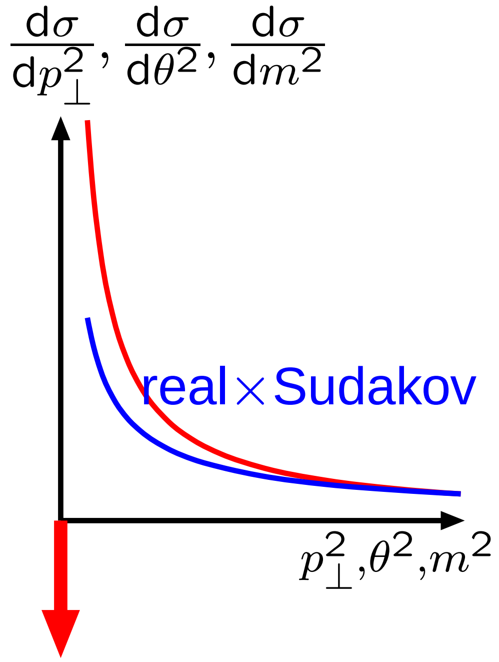
$\Rightarrow$ inefficient for exclusive states

$+$ process-generic $\Rightarrow$ simple multiparton

$+$ Sudakov form factors/resummation

$\Rightarrow$ sensible jet/event structure

$+$ *easy to match to hadronization*

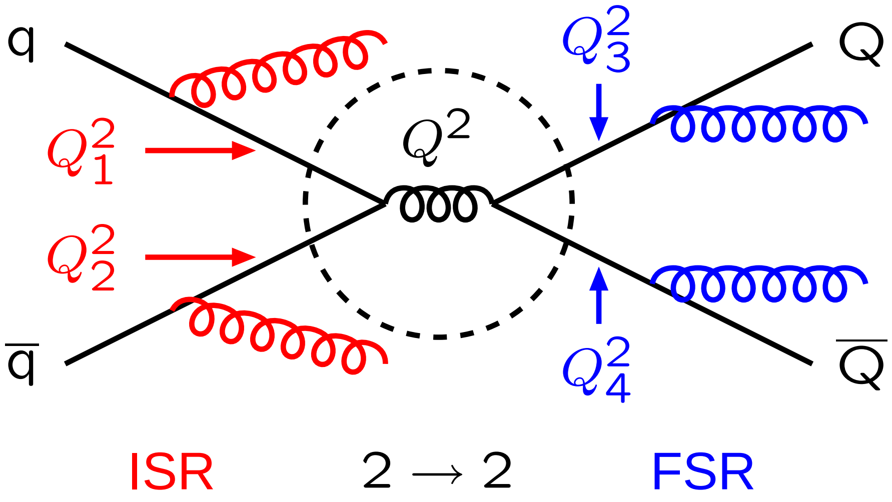


Parton Shower Approach

$$2 \to n \;=\; (2 \to 2) \oplus \text{ISR} \oplus \text{FSR}$$

$2 \to 2$ = hard scattering (on-shell):

$$\sigma = \iiint \mathrm{d}x_1\, \mathrm{d}x_2\, \mathrm{d}\hat{t}\; f_i(x_1, Q^2)\; f_j(x_2, Q^2)\; \frac{\mathrm{d}\hat{\sigma}_{ij}}{\mathrm{d}\hat{t}}$$



FSR = Final-State Rad.;
timelike shower
$Q_i^2 = m^2 > 0$ decreasing
+ coherence

ISR = Initial-State Rad.;
spacelike shower
$Q_i^2 = -m^2 > 0$ increasing
+ coherence

Do not doublecount! $\boxed{Q^2 > Q_1^2, Q_2^2, Q_3^2, Q_4^2}$

$2 \to 2$ = most virtual = shortest distance

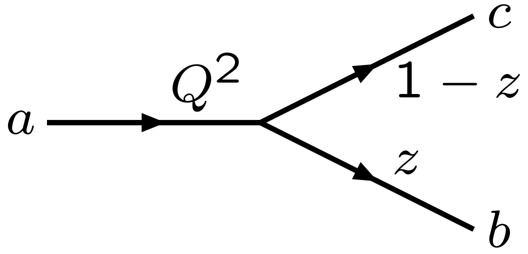
Final-State Shower Basics

$$\mathrm{d}\mathcal{P}_{a\to bc} = \frac{\alpha_{\mathrm{s}}}{2\pi}\,\frac{\mathrm{d}Q^2}{Q^2}\,P_{a\to bc}(z)\,\mathrm{d}z$$

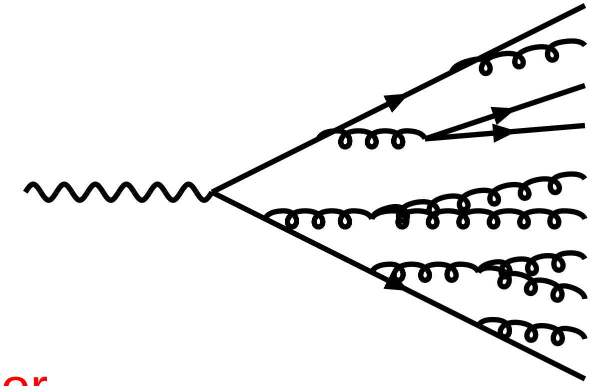
$$P_{\mathrm{q}\to\mathrm{qg}} = \frac{4}{3}\,\frac{1+z^2}{1-z}$$

$$P_{\mathrm{g}\to\mathrm{gg}} = 3\,\frac{(1-z(1-z))^2}{z(1-z)}$$

$$P_{\mathrm{g}\to\mathrm{q\overline{q}}} = \frac{n_f}{2}\,(z^2+(1-z)^2)$$



Iteration with decreasing Q^2 gives final-state shower:



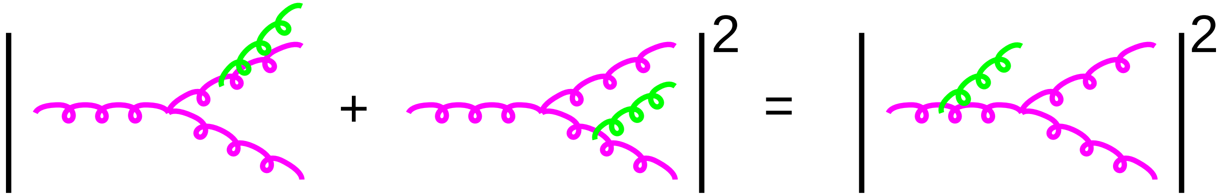
Sudakov form factor

$$\mathcal{P}^{\mathrm{corr}}(Q^2) = \frac{\mathrm{d}\mathcal{P}}{\mathrm{d}Q^2}\,\exp\left(-\int_{Q^2}^{Q^2_{\mathrm{max}}}\frac{\mathrm{d}\mathcal{P}}{\mathrm{d}Q^2}\,\mathrm{d}Q^2\right)$$

(cf. radioactive decay; ‘time’ ordering);
compensated by subsequent branchings

Final-State Shower Comparison

Avoid doublecounting: coherence $\Rightarrow$ angular ordering



Loop corrections $\Rightarrow \alpha_\mathrm{s}(p_\perp^2)$

Soft/collinear cut-off $m_0 = \mathrm{min}(m_{ij}) \approx 1$ GeV

at hadronic mass scales

HERWIG: $Q^2 \approx E^2(1 - \cos\theta) \approx E^2\theta^2/2$

$+$ angular ordering inherent $\Rightarrow$ coherence

$-$ emissions do not cover full phase space

PYTHIA: $Q^2 = m^2$

$+$ convenient match to ME

$-$ coherence by brute force

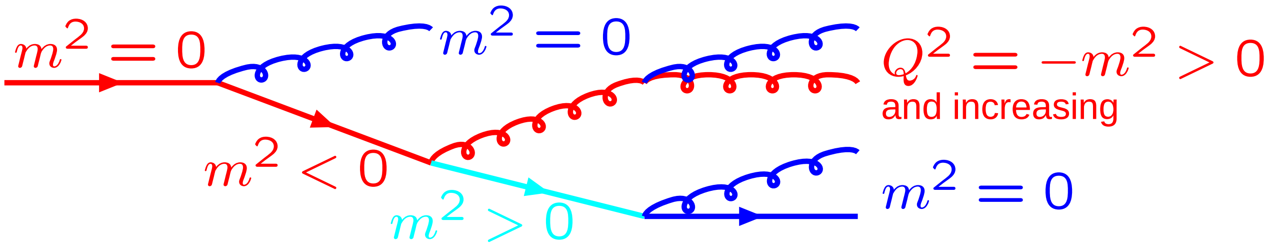
ARIADNE: $Q^2 = p_\perp^2$, dipole emission

$+$ coherence inherent; ordered in hardness $\approx$ time

$-$ $\mathrm{g} \to \mathrm{q}\overline{\mathrm{q}}$ artificial; not suited for pp on its own

Initial-State Shower Basics

- Parton cascades in p are continuously born and recombined.
- A hard scattering at Q^2 probes fluctuations up to that scale.
- A hard scattering inhibits full recombination of the cascade.
- Convenient reinterpretation:



Monte Carlo approach: recast

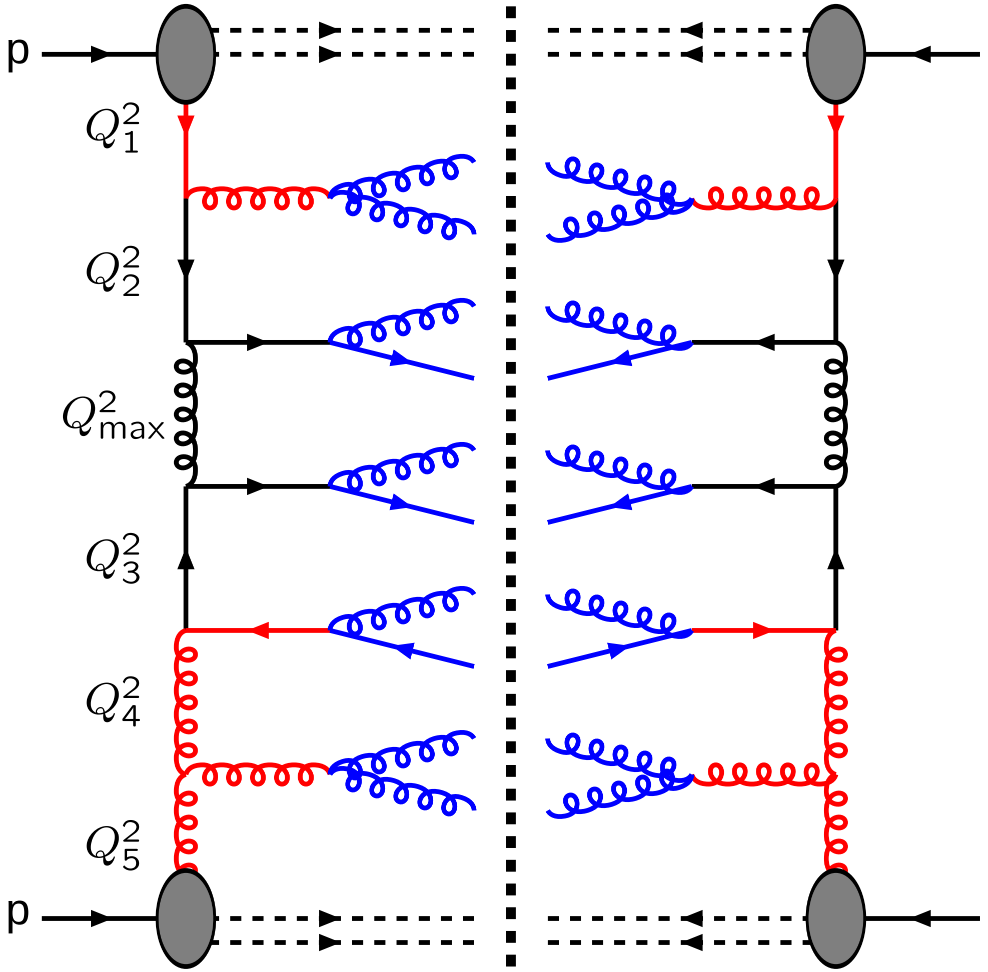
$$\frac{\mathrm{d}f_b(x,Q^2)}{\mathrm{d}t} = \sum_a \int_x^1 \frac{\mathrm{d}z}{z}\, f_a(x',Q^2)\, \frac{\alpha_s}{2\pi}\, P_{a\to bc}(z)$$

with $t = \ln(Q^2/\Lambda^2)$ and $z = x/x'$ to

$$\mathrm{d}\mathcal{P}_b = \frac{\mathrm{d}f_b}{f_b} = |\mathrm{d}t| \sum_a \int \mathrm{d}z\, \frac{x' f_a(x',t)}{x f_b(x,t)}\, \frac{\alpha_s}{2\pi}\, P_{a\to bc}(z)$$

then solve by *backwards evolution*, starting at high Q^2
and moving towards lower, with Sudakov form facter

Ladder representation combines whole event:



One possible

Monte Carlo order:

1) Hard scattering

2) Initial-state shower

from center outwards

3)Final-state showers

DGLAP: $Q_{\rm max}^2 > Q_1^2 > Q_2^2 \sim Q_0^2$

$Q_{\rm max}^2 > Q_3^2 > Q_4^2 > Q_5^2 \sim Q_0^2$

BFKL/CCFM: go beyond Q^2 ordering;

important at small x and Q^2

Initial-State Shower Comparison

Two(?) CCFM Generators:

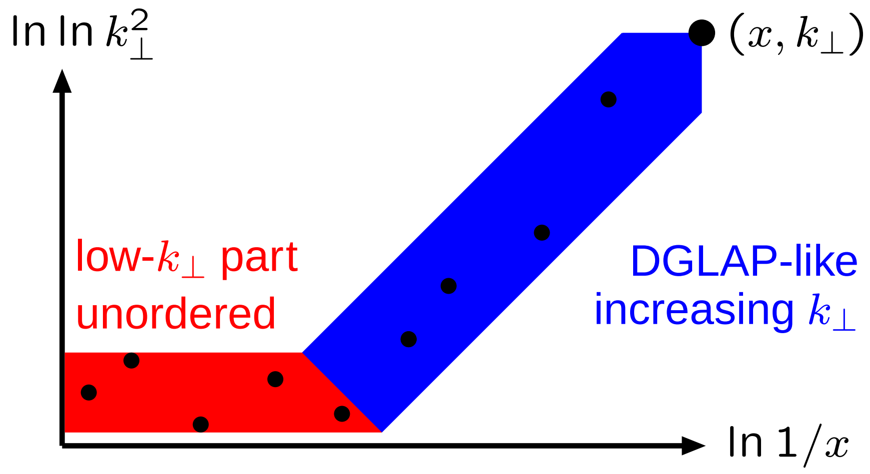
(SMALLX (Marchesini, Webber))

CASCADE (Jung, Salam)

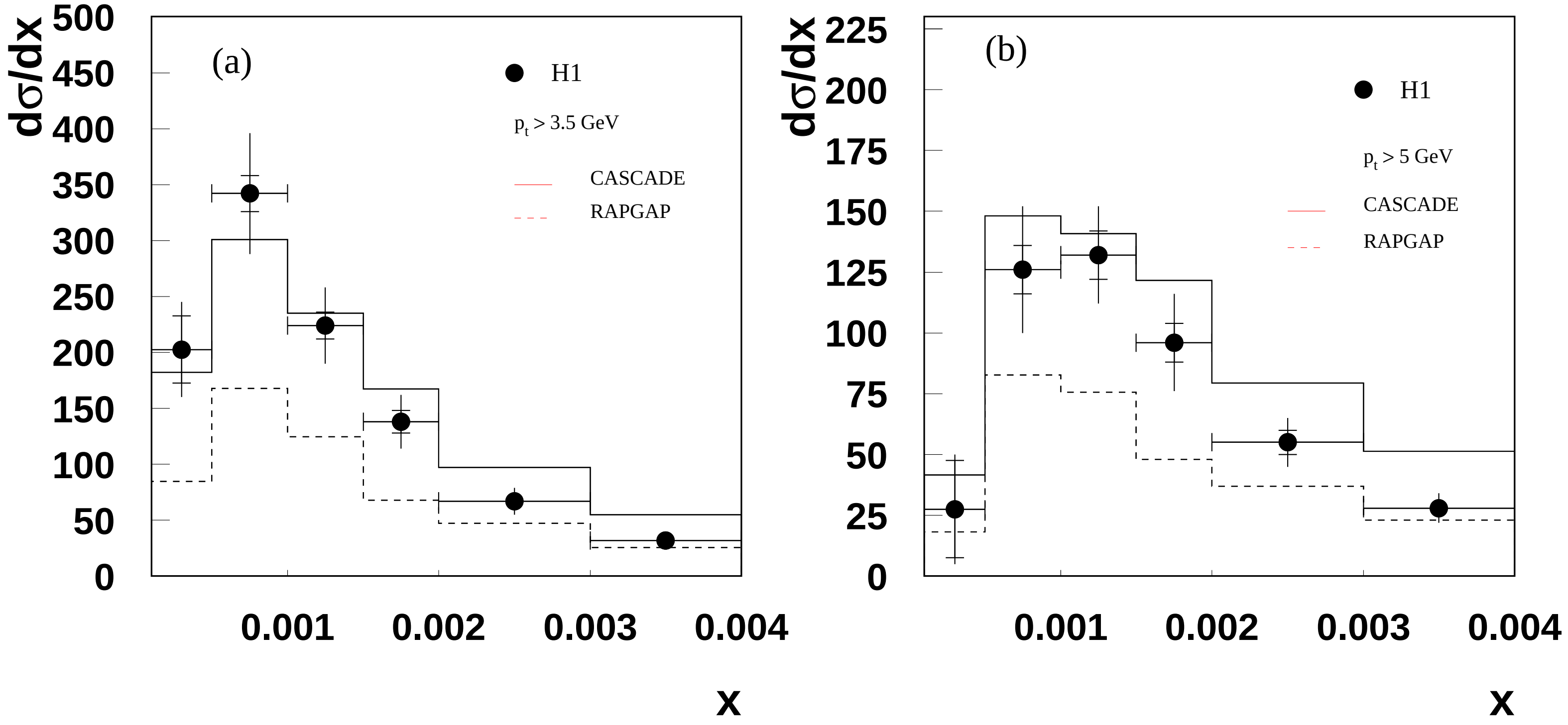
LDC (Gustafson, Lönnblad):

reformulated initial/final rad.

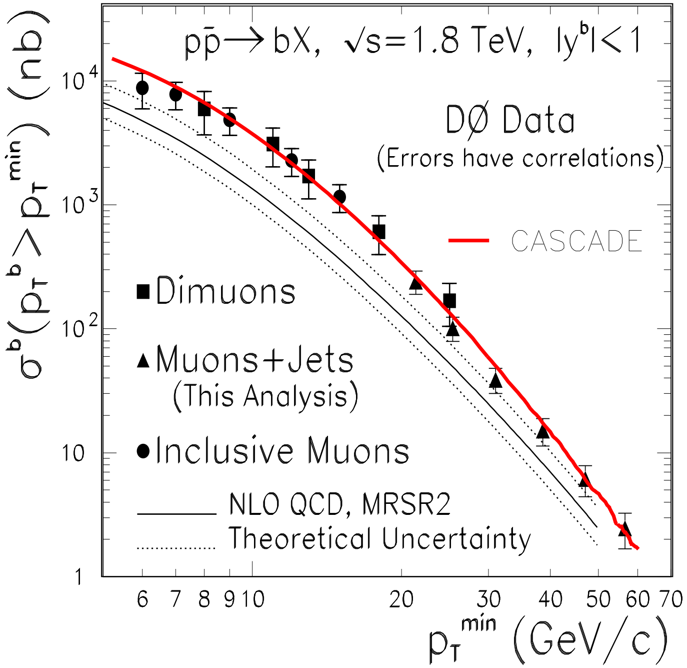
$\Longrightarrow$ eliminate non-Sudakov

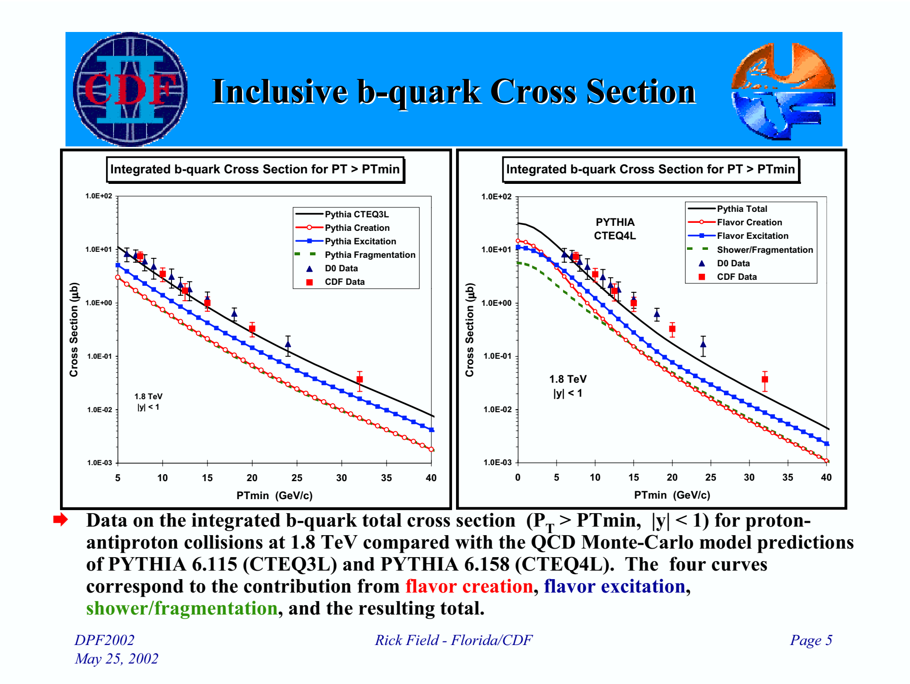


1) Forward jet activity 1′) Primordial $k_\perp$?



2) Heavy flavour production





Inclusive b-quark Cross Section

➡ **Data on the integrated b-quark total cross section (P_T > PTmin, $|y| < 1$) for proton-antiproton collisions at 1.8 TeV compared with the QCD Monte-Carlo model predictions of PYTHIA 6.115 (CTEQ3L) and PYTHIA 6.158 (CTEQ4L). The four curves correspond to the contribution from flavor creation, flavor excitation, shower/fragmentation, and the resulting total.**

DPF2002
May 25, 2002
Rick Field - Florida/CDF
Page 5

Requires off-shell ME’s + unintegrated parton densities

$$F(x,Q^2) = \int^{Q^2} \frac{\mathrm{d}k_\perp^2}{k_\perp^2} \mathcal{F}(x,k_\perp^2) + \text{suppressed with } k_\perp^2 > Q^2$$

so not ready for prime time in pp

also explained by DGLAP with
a) leading order pair creation
b) flavour excitation (≈ unordered chains)

c) gluon splitting (final-state radiation)

Matrix Elements and Parton Showers

Marriage desirable! But how?

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

Much work ongoing $\Longrightarrow$ a main theme of workshop

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 S. Frixione)

3) Match to next-to-leading order process — MC@NLO (covered in talk by S. Frixione)
S. Frixione, B.R. Webber, JHEP 0206 (2002) 029
but also S. Mrenna; M. Dobbs, M. Lefebvre; J.C. Collins, Y. Chen, N. Tkachuk, X. Zu; B. Pötter, T. Schörner; C. Friberg, TS; . . .

Merging

= cover full phase space with smooth transition ME/PS

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

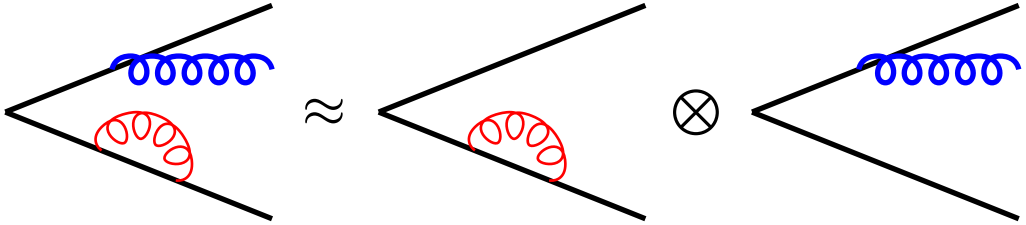
by shower generation + correction procedure

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

- Exponentiate ME correction by shower Sudakov form factor:

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

- Do not normalize W^{ME} to $\sigma(\mathrm{NLO})$ (error $\mathcal{O}(\alpha_{\mathrm{s}}^2)$ either way)



$$\boxed{\mathrm{d}\sigma \;=\; \overset{1+\mathcal{O}(\alpha_{\mathrm{s}})}{\overset{\downarrow}{K}} \;\; \sigma_0 \;\; \overset{\int = 1}{\overset{\downarrow}{\mathrm{d}W^{\mathrm{PS}}}}}$$

- Normally several shower histories ⇒ ~equivalent approaches

Final-State Shower Merging

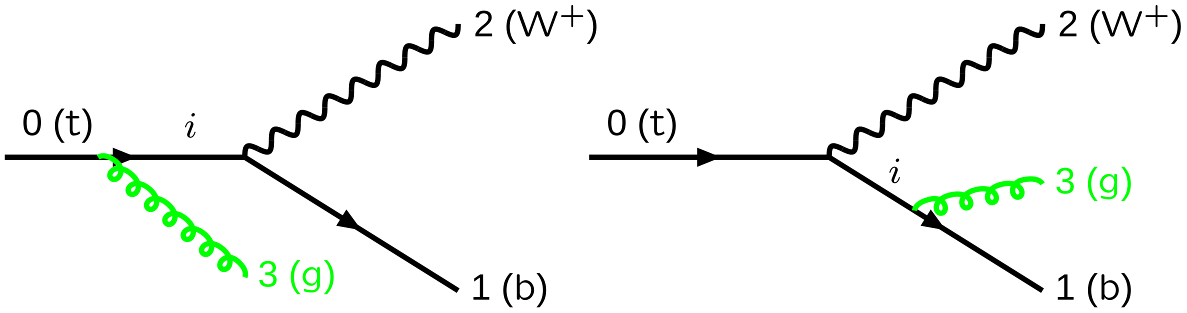
Merging with $\gamma^*/\mathrm{Z}^0 \to \mathrm{q\overline{q}g}$ for $m_\mathrm{q} = 0$ since long

(M. Bengtsson & TS, PLB185 (1987) 435, NPB289 (1987) 810)

For $m_\mathrm{q} > 0$ pick $Q_i^2 = m_i^2 - m_{i,\mathrm{onshell}}^2$ as evolution variable since

$$W^\mathrm{ME} = \frac{(\ldots)}{Q_1^2 Q_2^2} - \frac{(\ldots)}{Q_1^4} - \frac{(\ldots)}{Q_2^4}$$

Coloured decaying particle also radiates:



ME $\frac{1}{Q_0^2 Q_1^2}$

matches

PS $\mathrm{b} \to \mathrm{bg}$

$\Rightarrow$ can merge PS with generic $a \to bc\mathrm{g}$ ME

(E. Norrbin & TS, NPB603 (2001) 297)

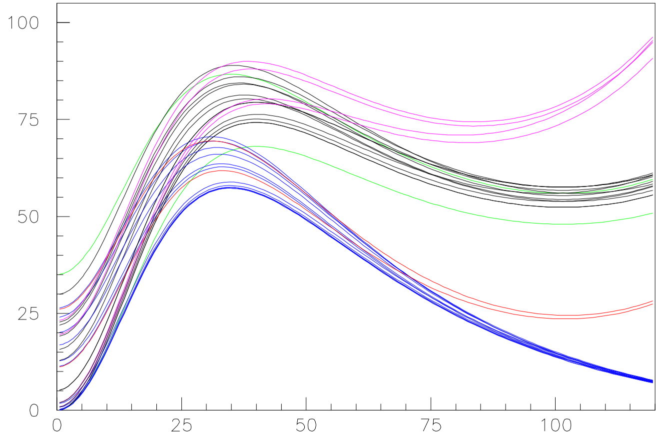
Subsequent branchings $\mathrm{q} \to \mathrm{qg}$: also matched to ME, with reduced energy of system

Means we have process-dependent “splitting kernels”

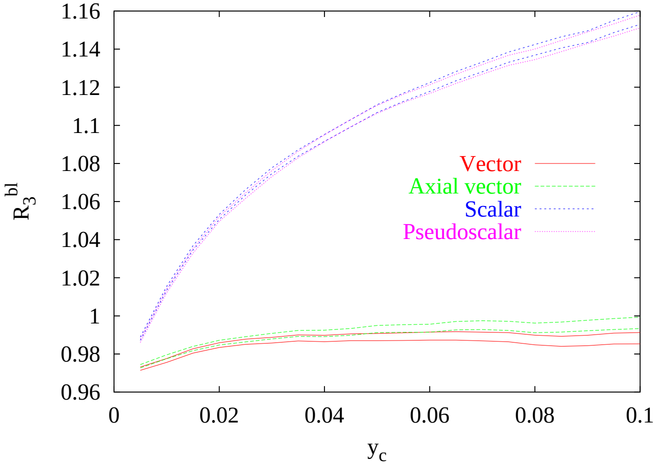
completely incorporating respective $\mathcal{O}(\alpha_s)$ ME for

colour	spin	γ_5	example
$1 \to 3 + \bar{3}$	—	—	(eikonal)
$1 \to 3 + \bar{3}$	$1 \to \frac{1}{2} + \frac{1}{2}$	$1, \gamma_5, 1 \pm \gamma_5$	$Z^0 \to q\bar{q}$
$3 \to 3 + 1$	$\frac{1}{2} \to \frac{1}{2} + 1$	$1, \gamma_5, 1 \pm \gamma_5$	$t \to bW^+$
$1 \to 3 + \bar{3}$	$0 \to \frac{1}{2} + \frac{1}{2}$	$1, \gamma_5, 1 \pm \gamma_5$	$H^0 \to q\bar{q}$
$3 \to 3 + 1$	$\frac{1}{2} \to \frac{1}{2} + 0$	$1, \gamma_5, 1 \pm \gamma_5$	$t \to bH^+$
$1 \to 3 + \bar{3}$	$1 \to 0 + 0$	1	$Z^0 \to \tilde{q}\bar{\tilde{q}}$
$3 \to 3 + 1$	$0 \to 0 + 1$	1	$\tilde{q} \to \tilde{q}'W^+$
$1 \to 3 + \bar{3}$	$0 \to 0 + 0$	1	$H^0 \to \tilde{q}\bar{\tilde{q}}$
$3 \to 3 + 1$	$0 \to 0 + 0$	1	$\tilde{q} \to \tilde{q}'H^+$
$1 \to 3 + \bar{3}$	$\frac{1}{2} \to \frac{1}{2} + 0$	$1, \gamma_5, 1 \pm \gamma_5$	$\chi \to q\bar{\tilde{q}}$
$3 \to 3 + 1$	$0 \to \frac{1}{2} + \frac{1}{2}$	$1, \gamma_5, 1 \pm \gamma_5$	$\tilde{q} \to q\chi$
$3 \to 3 + 1$	$\frac{1}{2} \to 0 + \frac{1}{2}$	$1, \gamma_5, 1 \pm \gamma_5$	$t \to \tilde{t}\chi$
$8 \to 3 + \bar{3}$	$\frac{1}{2} \to \frac{1}{2} + 0$	$1, \gamma_5, 1 \pm \gamma_5$	$\tilde{g} \to q\bar{\tilde{q}}$
$3 \to 3 + 8$	$0 \to \frac{1}{2} + \frac{1}{2}$	$1, \gamma_5, 1 \pm \gamma_5$	$\tilde{q} \to q\tilde{g}$
$3 \to 3 + 8$	$\frac{1}{2} \to 0 + \frac{1}{2}$	$1, \gamma_5, 1 \pm \gamma_5$	$t \to \tilde{t}\tilde{g}$

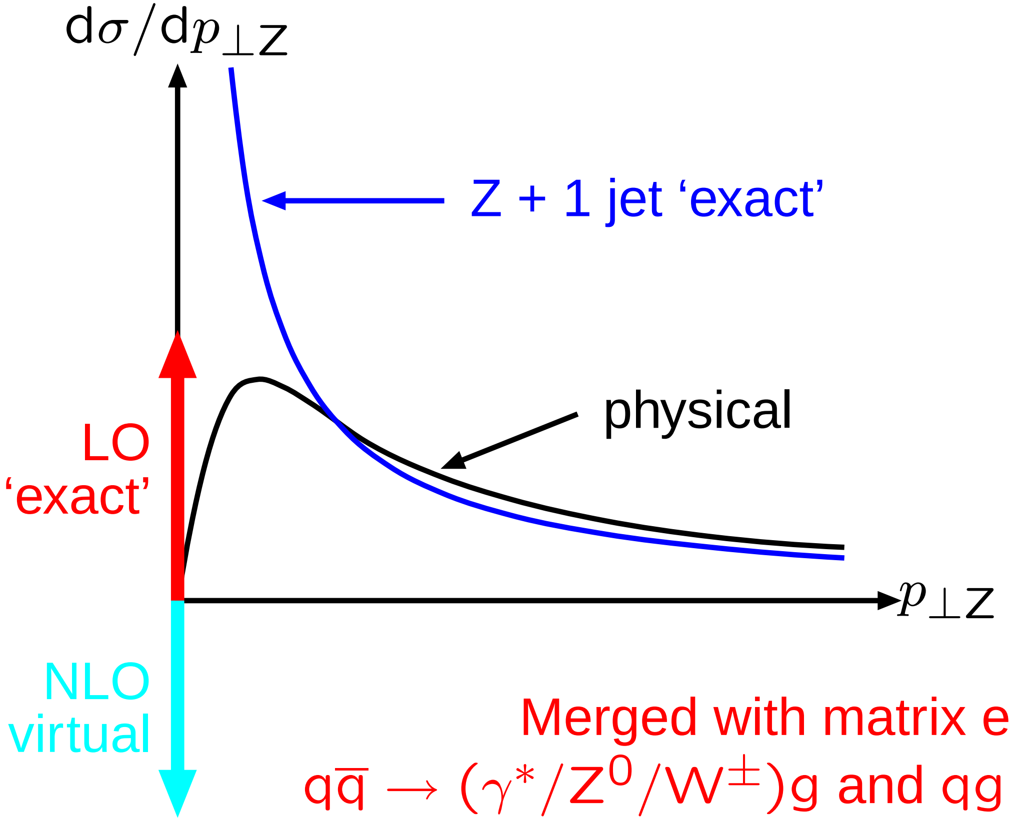
g emission for different colour,spin and parity:



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



Initial-State Shower Merging



resummation:
physical $p_{\perp\mathrm{Z}}$ spectrum

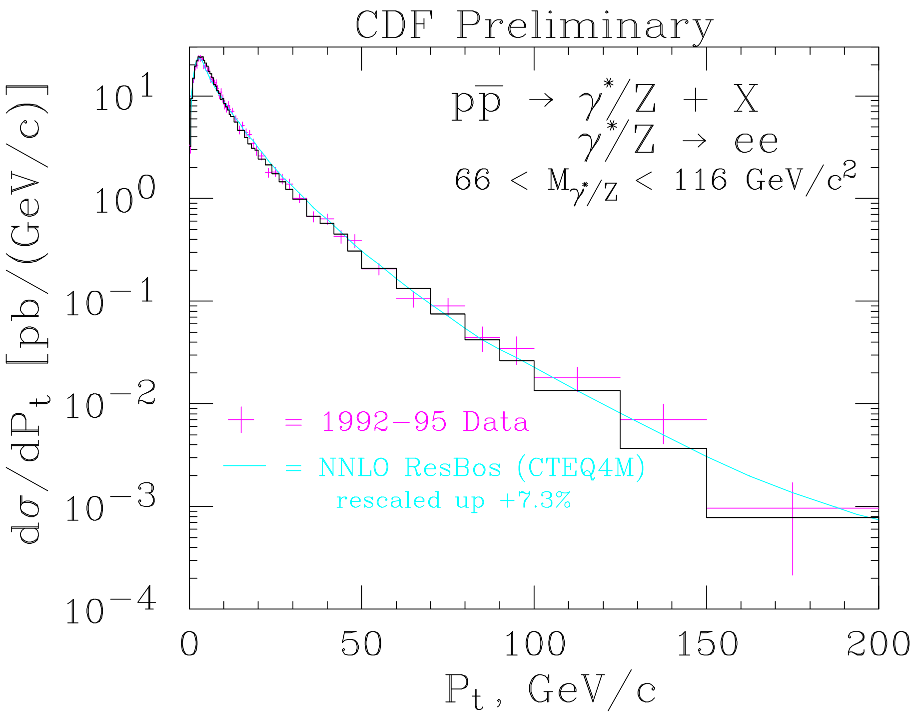
shower: ditto
+ accompanying
jets (exclusive)

Merged with matrix elements for
$\mathrm{q}\overline{\mathrm{q}} \to (\gamma^*/\mathrm{Z}^0/\mathrm{W}^\pm)\mathrm{g}$ and $\mathrm{qg} \to (\gamma^*/\mathrm{Z}^0/\mathrm{W}^\pm)\mathrm{q}'$:
(G. Miu & TS, PLB449 (1999) 313)

$$\left(\frac{W^{\mathrm{ME}}}{W^{\mathrm{PS}}}\right)_{\mathrm{q}\overline{\mathrm{q}}'\to\mathrm{gW}} = \frac{\hat{t}^2+\hat{u}^2+2m_{\mathrm{W}}^2\hat{s}}{\hat{s}^2+m_{\mathrm{W}}^4} \leq 1$$

$$\left(\frac{W^{\mathrm{ME}}}{W^{\mathrm{PS}}}\right)_{\mathrm{qg}\to\mathrm{q}'\mathrm{W}} = \frac{\hat{s}^2+\hat{u}^2+2m_{\mathrm{W}}^2\hat{t}}{(\hat{s}-m_{\mathrm{W}}^2)^2+m_{\mathrm{W}}^4} < 3$$

with $Q^2 = -m^2$
and $z = m_{\mathrm{W}}^2/\hat{s}$



curve=ResBos

black=PYTHIA

$K_{\text{PYTHIA}} = 1.4$

$\boxed{Q^2_{\text{max}} = s}$

C. Balázs, J. Huston and I. Puljak, PRD63 (2001) 014021

Modified algorithm also affects other processes

- prefer $Q^2_{\text{max}} = s$ where no doublecounting
  - $\Rightarrow$ more radiation at large $p_\perp$
- require $\hat{u} = Q^2 - \hat{s}(1 - z) < 0$ in branchings
  - $\Rightarrow$ fewer but harder emissions

Similarly for Higgs production in $m_t \to \infty$ limit:

- $gg \to gh^0$ and $qg \to qh^0$ simple
- $q\bar{q} \to gh^0$ nonsingular & small $\Rightarrow$ add

More processes possible, but none to report so far

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

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

Application to hadronic collisions under development; existing is simplest example: $\mathrm{e}^+\mathrm{e}^- \to 2, 3, 4$ jets

1) Calculate n-jet cross sections by respective LO ME inside phase space region given by Durham y_{ME}

$$\begin{aligned}
\sigma_2 &\propto |\mathcal{M}_{\mathrm{q\bar{q}}}|^2 \\
\sigma_3 &\propto \alpha_{\mathrm{s0}} \int_{y_{\mathrm{ME}}} |\mathcal{M}_{\mathrm{q\bar{q}g}}|^2 \\
\sigma_4 &\propto \alpha_{\mathrm{s0}}^2 \int_{y_{\mathrm{ME}}} \left(|\mathcal{M}_{\mathrm{q\bar{q}gg}}|^2 + |\mathcal{M}_{\mathrm{q\bar{q}q'\bar{q}'}}|^2\right)
\end{aligned}$$

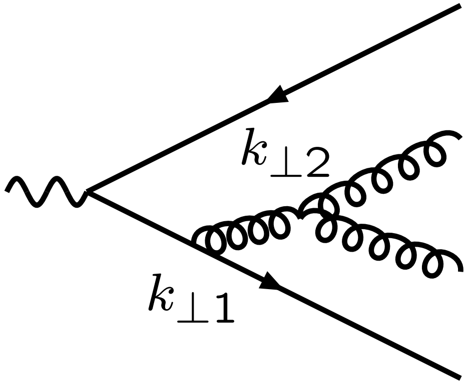
with $\alpha_{\mathrm{s0}} = \alpha_{\mathrm{s}}(y_{\mathrm{ME}} s)$

2) Pick n-jet according to $\sigma_2 : \sigma_3 : \sigma_4$
and kinematics according to relevant $|\mathcal{M}|^2$

3) Reconstruct showering history by Durham algorithm
(and criterion of sensible branchings, e.g. no $X \to$ qq)

4) Correction factor for running α_s

$$W_\alpha = \prod_{\text{branchings}} \frac{\alpha_\mathrm{s}(k_{\perp i}^2)}{\alpha_{\mathrm{s}0}}$$



5) Correction factor for intermediate
partons, expressing that these should not
populate the $n+1$-parton phase space

$$W_\mathrm{Sud} = \prod_{\text{propagators}} \text{Sudakov}(y_\mathrm{beg} s, y_\mathrm{end} s)$$

6) Accept event with $\mathcal{P} = W_\alpha W_\mathrm{Sud}$, else start over at 2).

7) Continue shower down to ‘normal’ y_cut,
but veto emissions above y_ME so as not to doublecount.

Hadronization: Lund string model

In QCD, for large charge separation, field lines seem to be compressed
to tubelike region by nonperturbative self-interactions

Analogy: vortex lines in type II superconductor

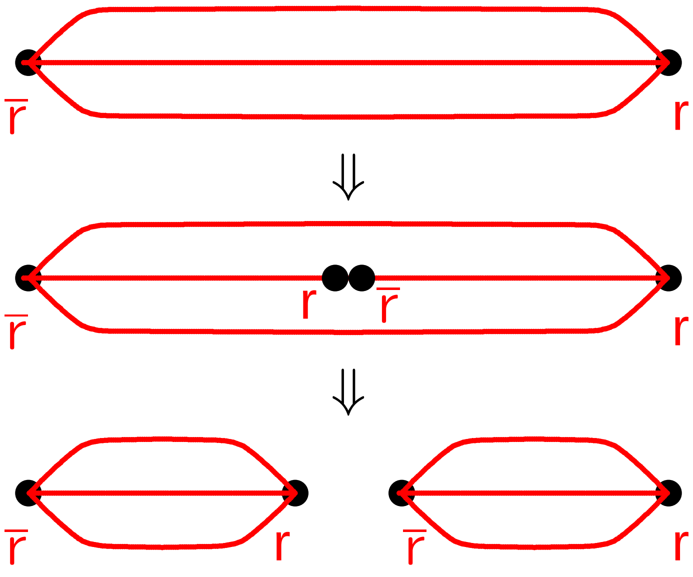
Quenched lattice QCD confirms large-distance behaviour

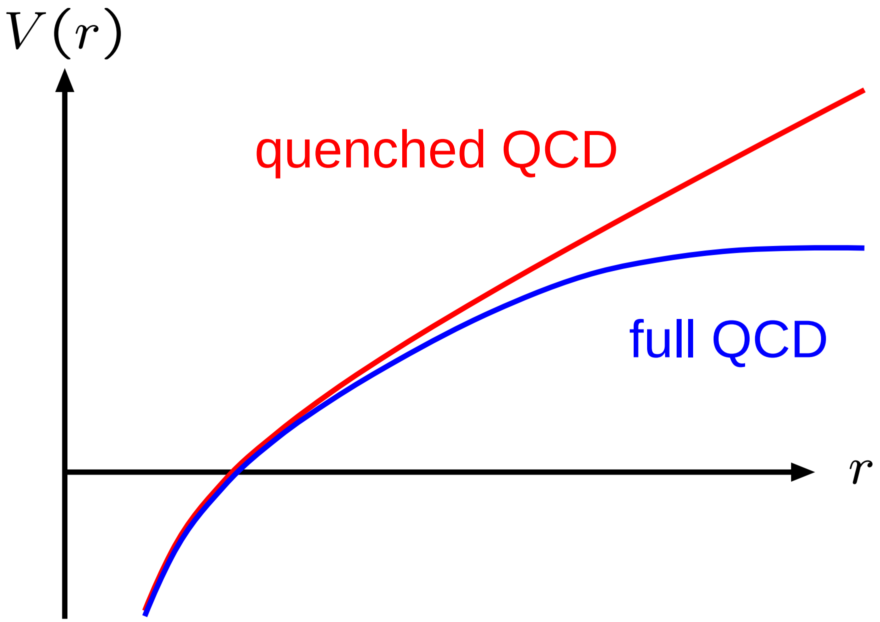
$$F(r) \approx \text{const} = \kappa \quad \Longleftrightarrow \quad V(r) \approx \kappa r$$

Input from hadronic spectroscopy gives string tension

$\kappa \approx$ 1 GeV/fm (= 160 kJ/m = 16 ton/m)

Extra: nonperturbative splittings g → $\mathrm{q}\overline{\mathrm{q}}$ can break string



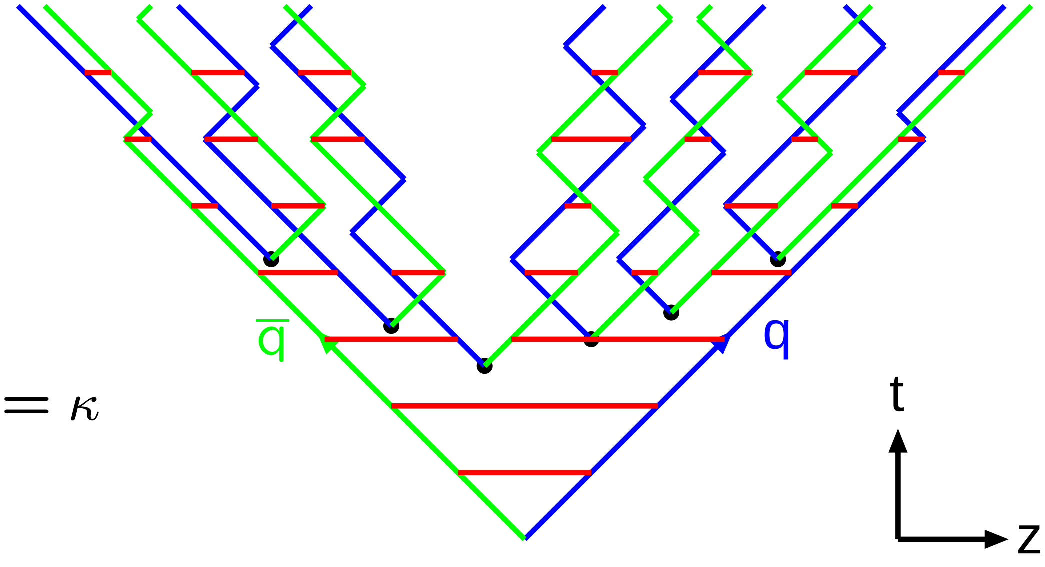


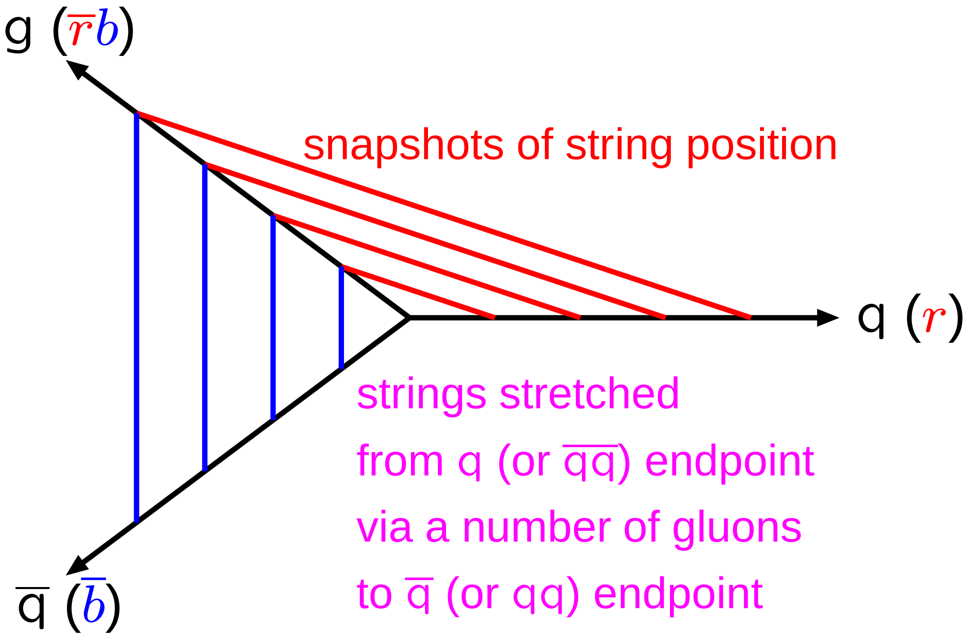
Lund model:

Repeated string breaks
for large system
with $V(r) = \kappa r$

$$\left|\frac{\mathrm{d}E}{\mathrm{d}x}\right| = \left|\frac{\mathrm{d}p}{\mathrm{d}x}\right| = \left|\frac{\mathrm{d}E}{\mathrm{d}t}\right| = \left|\frac{\mathrm{d}p}{\mathrm{d}t}\right| = \kappa$$

Motion of quarks and antiquarks:





snapshots of string position

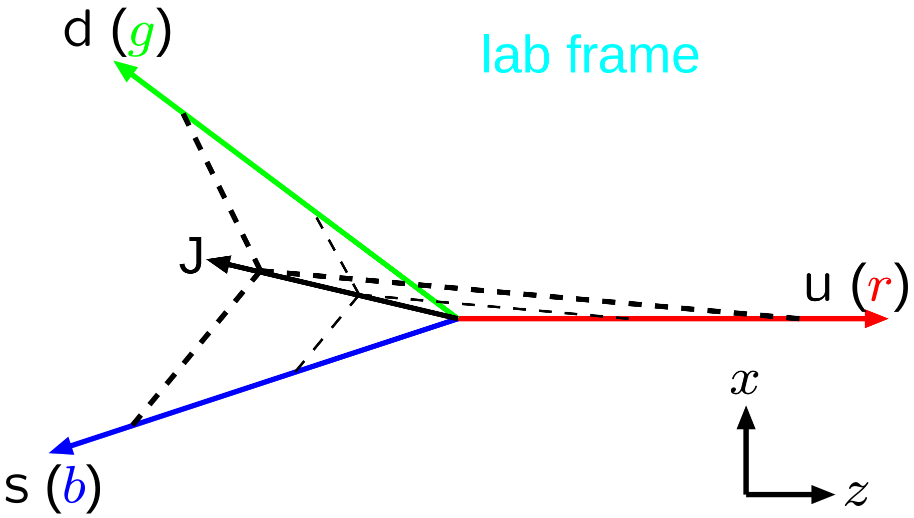
strings stretched
from q (or $\overline{\text{q}}\overline{\text{q}}$) endpoint
via a number of gluons
to $\overline{\text{q}}$ (or qq) endpoint

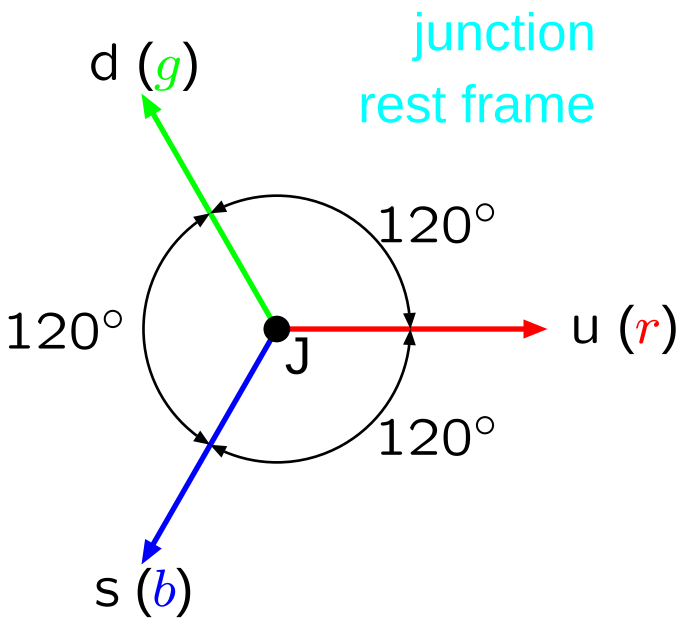
Gluon = kink on string,
carrying energy
and momentum.
Force ratio
gluon/ quark = 2,
cf. QCD $N_C/C_F = 9/4$

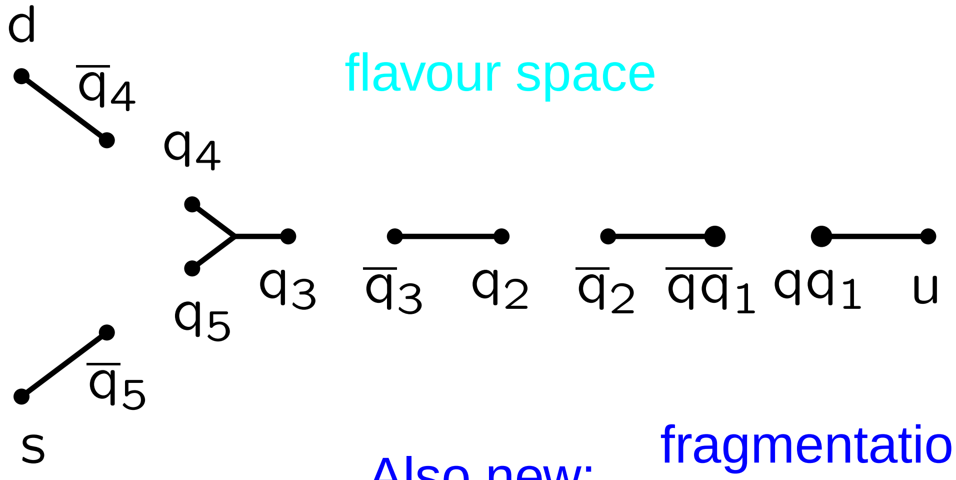
- Few parameters to describe energy–momentum structure!
  - Many parameters to describe flavour composition!

Lund hadronization news: fragmentation of junction topology, e.g. in R-parity violating SUSY decays $\tilde{\chi}_1^0 \to$ uds

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







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

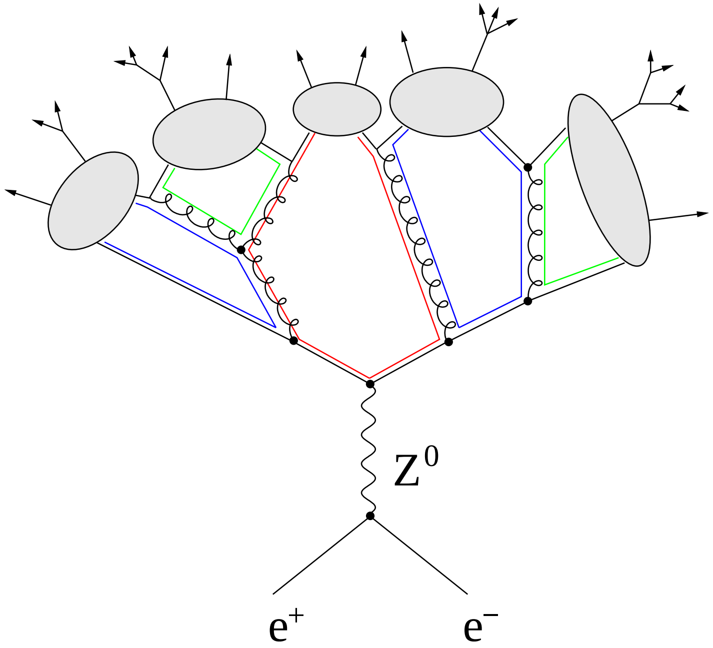
Also new:

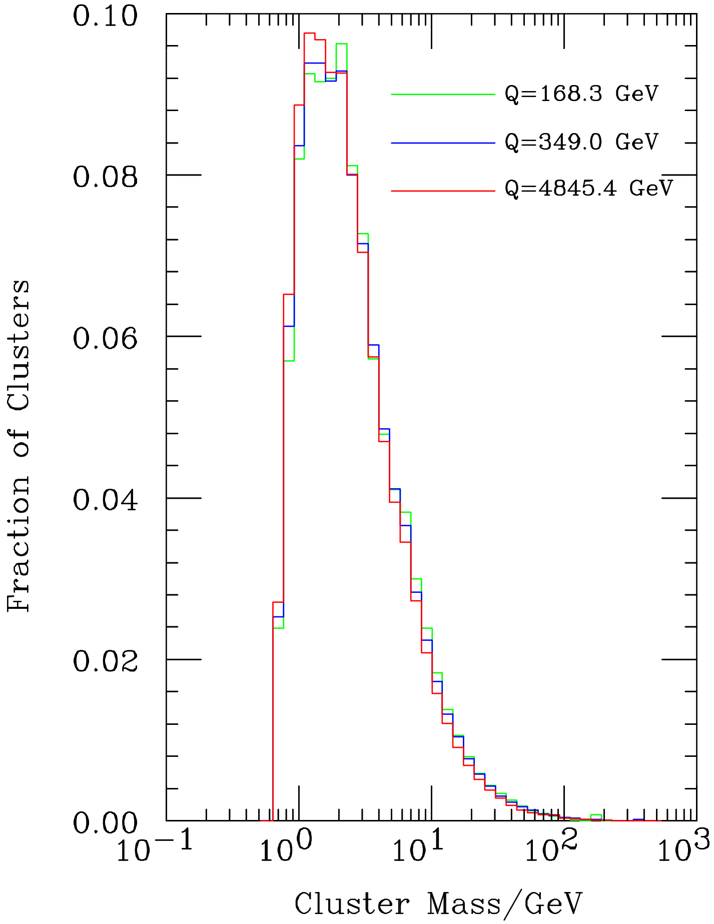
- fragmentation of stable gluino
- expanded Bose-Einstein

Hadronization: HERWIG Cluster Model

Introduce forced

g → $q\bar{q}$ branchings:





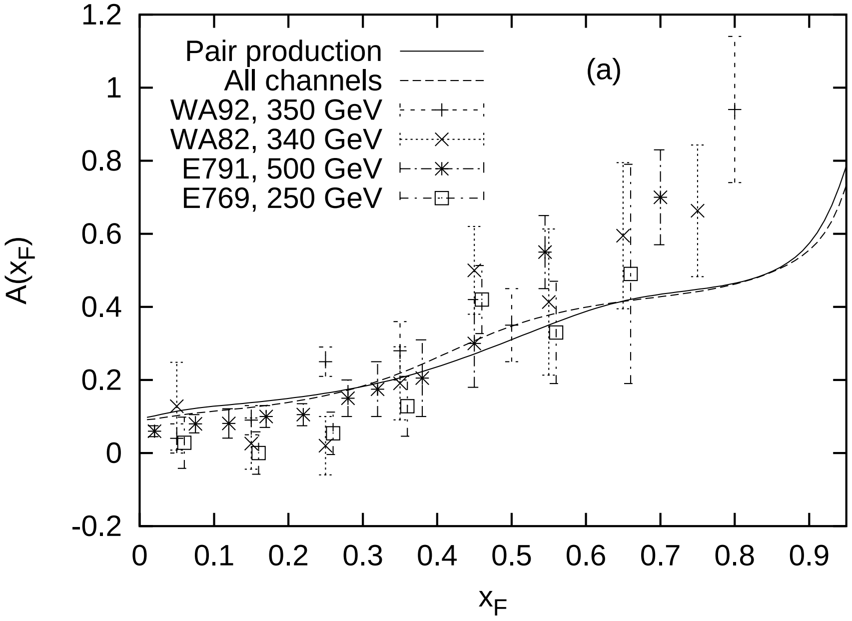
Large-mass clusters require special attention

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

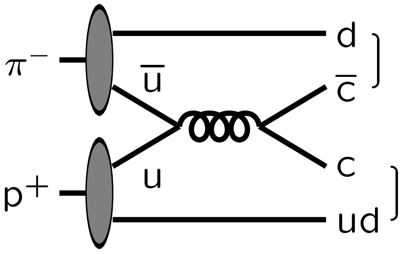
Beam remnant physics

Colour flow connects hard scattering to beam remnants. Can have consequences, e.g. in $\pi^- \mathrm{p}$

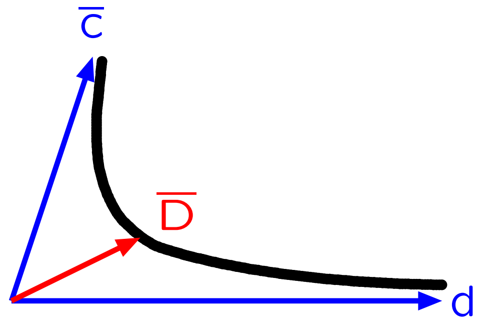
$$A(x_{\mathrm{F}}) = \frac{\#\mathrm{D}^- - \#\mathrm{D}^+}{\#\mathrm{D}^- + \#\mathrm{D}^+}$$



(E. Norrbin & TS, EPJC17 (2000) 137)



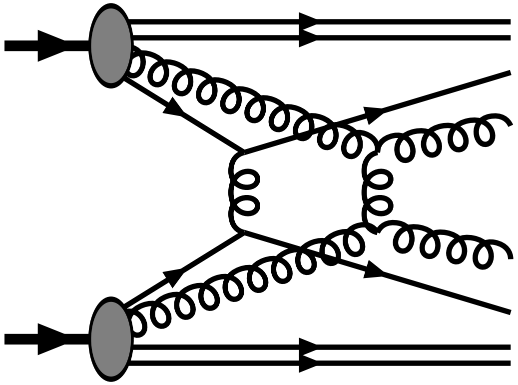
If low-mass string e.g.:
$\overline{\mathrm{c}}\mathrm{d}$: D^-, D^{*-}
cud: Λ_{c}^+, Σ_{c}^+, Σ_{c}^{*+}
⇒ flavour asymmetries



Can give D ‘drag’ to larger x_{F} than c quark for any string mass

Multiple Interactions

Consequence of composite nature of hadrons!

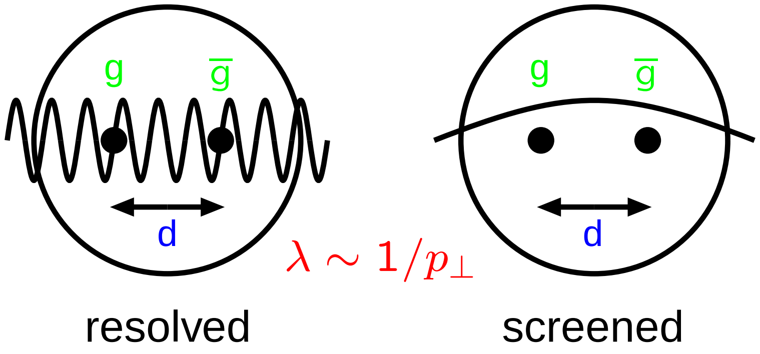


Evidence:

- 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: $p_{\perp\mathrm{min}}$

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



Measure of
colour screening length d
in hadron:

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

Small-x behaviour:

In olden days
$xg(x, Q_0^2) \to$ const.
but post-HERA
$xg(x, Q_0^2) \sim x^{-\epsilon}$,
with some $\epsilon \gtrsim 0.08$

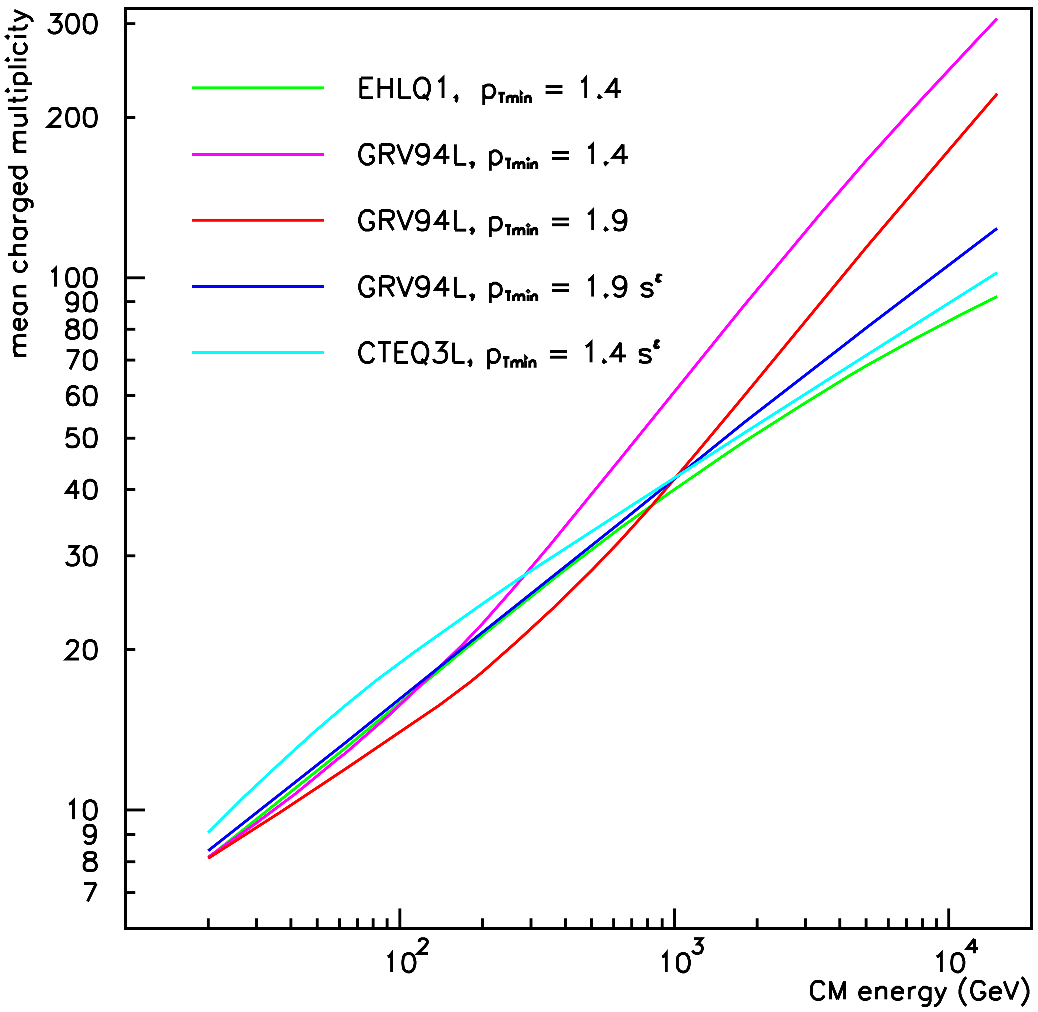
$\Rightarrow p_{\perp\mathrm{min}} \sim \frac{1}{\langle d \rangle}$
$\sim N_{\mathrm{partons}} \sim s^{\epsilon}$

so ‘new’ PYTHIA
default $p_{\perp\mathrm{min}} =$
$(1.9\ \mathrm{GeV}) \left(\frac{s}{1\ \mathrm{TeV}^2} \right)^{0.08}$

Importance:

- comparison of data at 630 GeV & 1.8 TeV
- LHC extrapolations

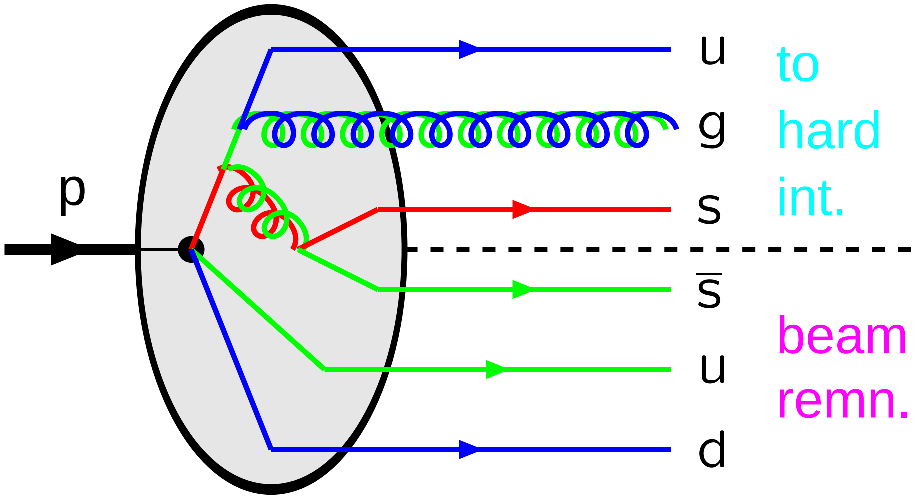
Mean charged multiplicity in inelastic non-diffractive ‘minimum bias’:



(TS & M. van Zijl, PRD36 (1987) 2019; J. Dischler & TS, EPJdir C2 (2001) 1)

Event structure in multiple interactions

(TS & P.Z. Skands, in preparation)



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 (intertwined?)

Example: parton densities after first interaction:

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

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

- gluon and normal sea: rescale for momentum conservation

Baryon number topology: junction fragmentation
(nontrivial when $\geq$ 2 valence quarks kicked out)

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)

+ HepMC hadron-level Event Record in C++

+ HepPDT particle data tables in C++

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

- JetWeb — automated data comparisons

? SUSY mass/coupling spectrum calculator interface
— to be discussed here

? Improved Les Houches Interface for HO or NLO ME's
— to be discussed here

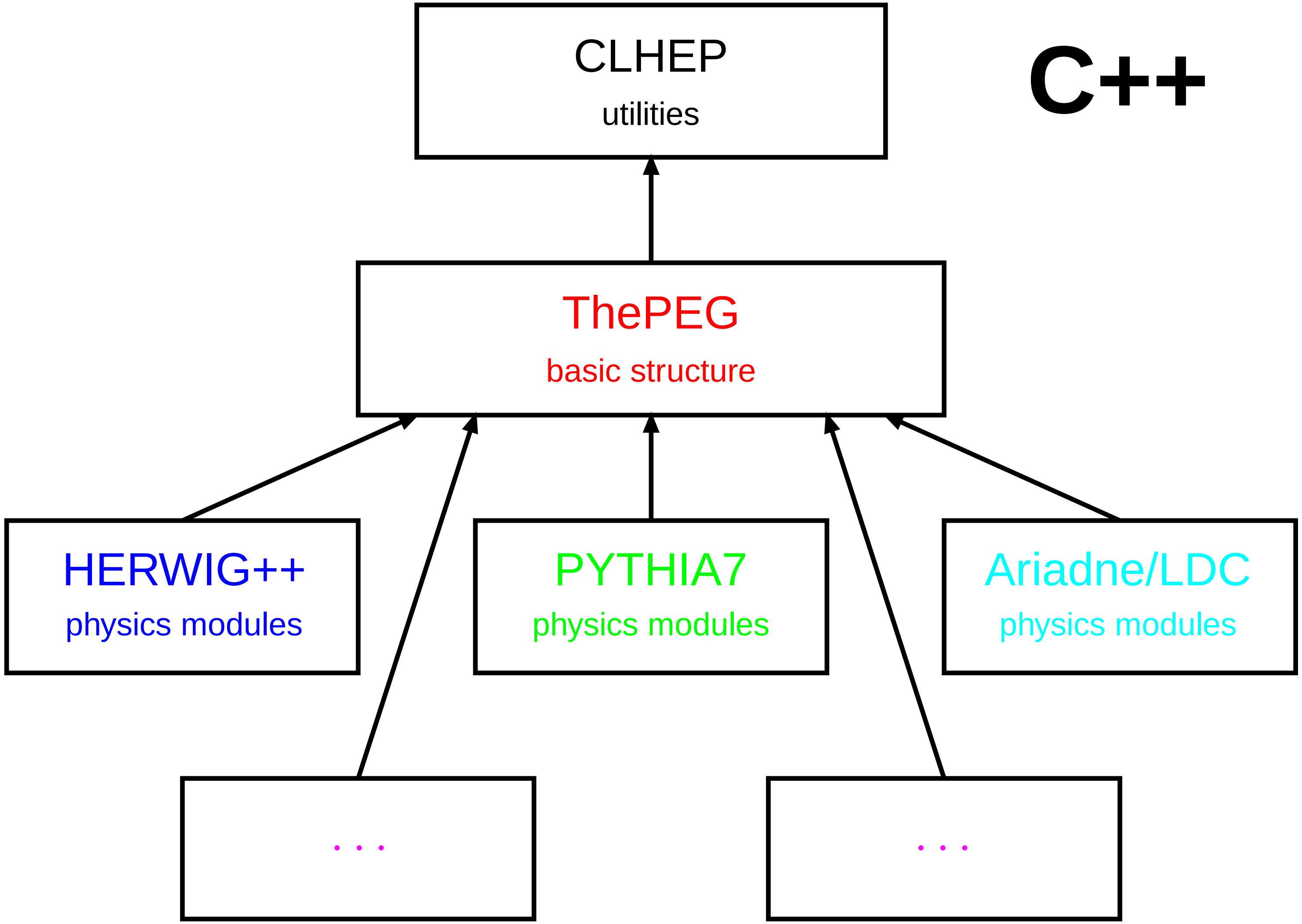
? For C++ era: (Les Houches) interfaces, CLHEP, . . .

What is ThePEG?

Toolkit for High Energy Physics Event Generation

recently separated out from PYTHIA7 (L. Lönnblad)

C++



CLHEP
utilities

ThePEG
basic structure

HERWIG++
physics modules

PYTHIA7
physics modules

Ariadne/LDC
physics modules

. . .

. . .

Handlers

ThePEG defines a set of abstract `Handler` classes for
hard partonic sub-processes, parton densities, QCD cascades, hadronization, …

These handler classes interacts with the underlying structure using a special `Event Record` and a pre-defined set of `virtual` function definitions.

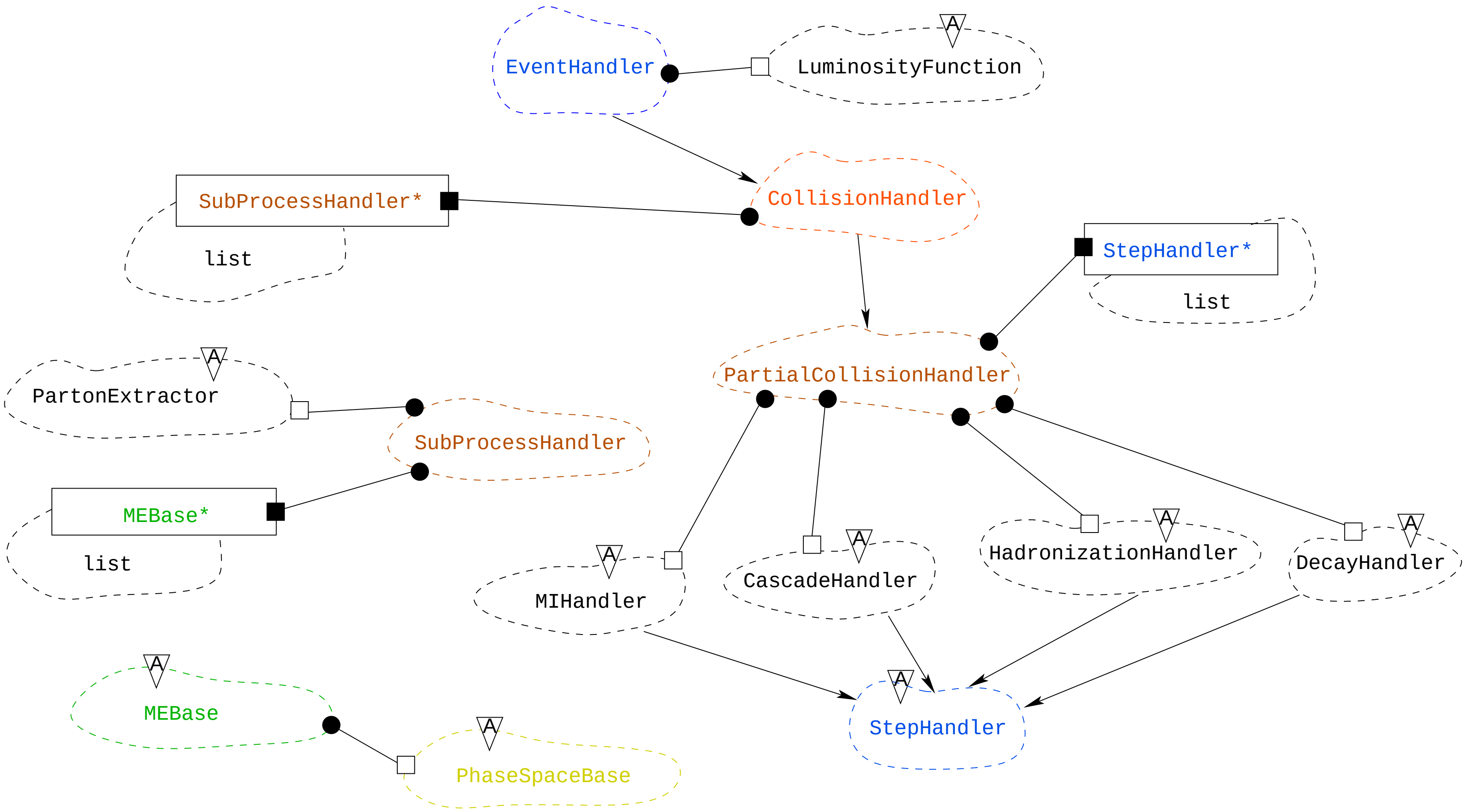
The procedure to implement e.g. a new hadronization model, is to write a new (C++) class *inheriting* from the abstract `HadronizationHandler` base class, implementing the relevant virtual functions.

The structure of the generation process is extremely dynamic:

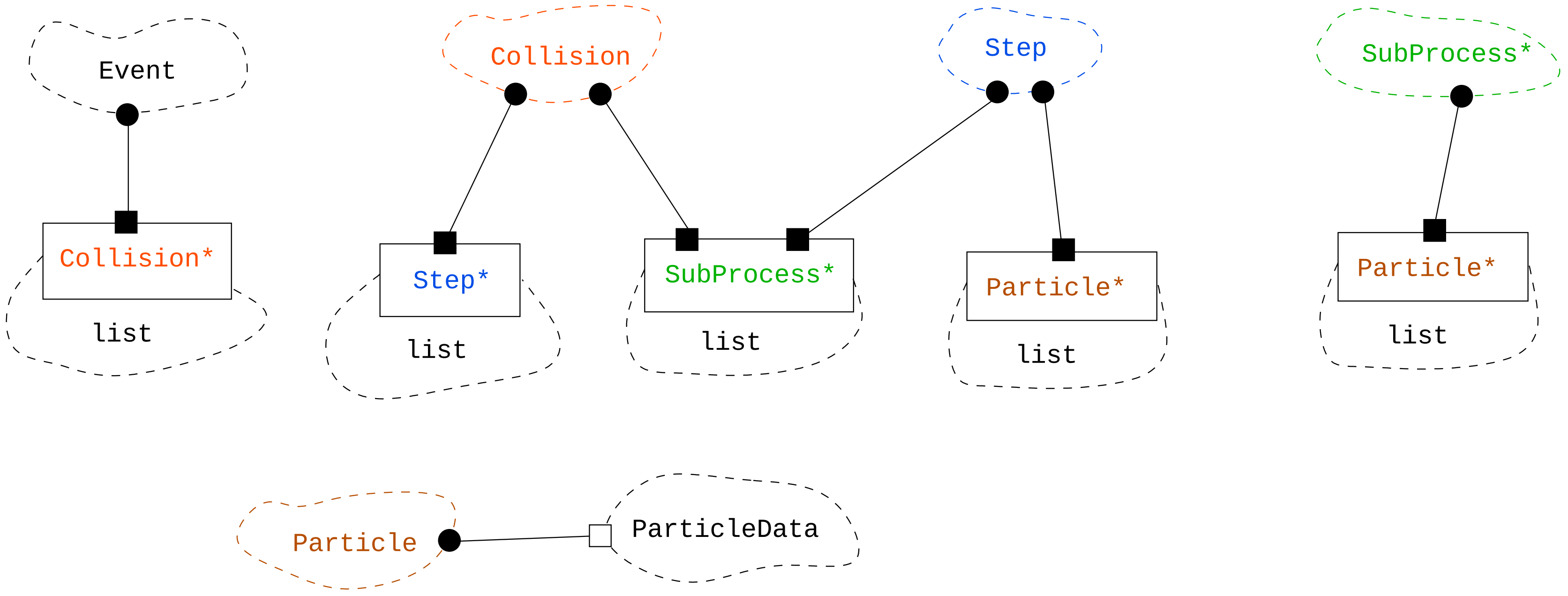
Besides the standard Handler classes, there is also a general `StepHandler` class which can do anything and can be inserted anywhere in the generation chain.

In addition, each handler can add steps in the generation chain or redo previous steps depending on the history of each event.

Class Structure of Handlers



Class Structure of an Event



The `Particle` class provides access to a lot of information. But it only has a pointer to a `ParticleData`, a `Lorentz5Momentum` and a pointer to another object carrying the rest of the information (colour, spin etc.) if needed.

Some of this information can be user-defined by creating classes inheriting from e.g. the `SpinBase` or the completely general `EventInfoBase` classes. This information can then be accessed through `dynamic_cast`ing.

Running ThePEG

The end-user will use a setup program to be able to pick objects corresponding to different physics models to build up an `EventGenerator` which then can be run interactively or off-line, or as a special slave program e.g. for Geant4.

The setup program is used to choose between a multitude of pre-defined generators, to modify parameters and options of the selected models and, optionally, to specify the analysis to be done on the generated events.

The `Repository` is the central part of the setup phase. It handles a structured list of all available objects and allows the user to manipulate them.

A flashy Graphical User Interface should be built on top of this `Repository`. Currently there is only a rudimentary command-line interpreter.

In the end of the run you will get a number of files with statistics and messages. And a LaTeX-file with references suitable for inclusion in an appendix of a paper.

ThePEG Status

ThePEG : operational; to be renamed from PYTHIA7
process generation machinery and event structure
http://www.thep.lu.se/Pythia7 Leif Lönnblad

HERWIG:
cluster fragmentation ready
showers on the way
+ ??
(Alberto Ribon)
Stefan Gieseke
Philip Stephens

Frank Krauss : SHERPA
(≈ 80 000 lines!)

PYTHIA:
QCD $2 \to 2$, $e^+e^- \to q\overline{q}$
GRV 94 series PDF
showers on the way
simple string fragmentation
+ low-mass corrections
Ariadne beam remnants
simple isotropic decay
Leif Lönnblad
(TS)

- Conversion effort: everything takes longer and costs more
- The physics hurdle is as steep as the C++ learning curve

Outlook

Generators in state of continuous development

- new physics processes
- more precise parton showers matched to ME’s
- improved models soft physics
- moving to C++

$\Rightarrow$ always better, but never enough

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

CMS full GEANT simulation of

H(150 GeV) --> ZZ*--> 4e