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New $p_\perp$-ordered showers

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Introduction and Objective
General strategy
The time-like shower (FSR)
The space-like shower (ISR)
Outlook

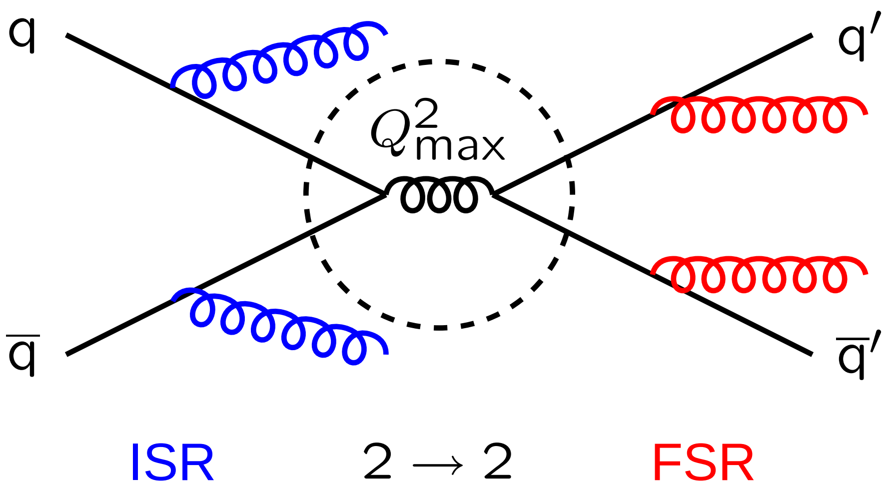
Parton Shower Approach

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

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

ISR = Initial-State Radiation: spacelike

FSR = Final-State Radiation: timelike

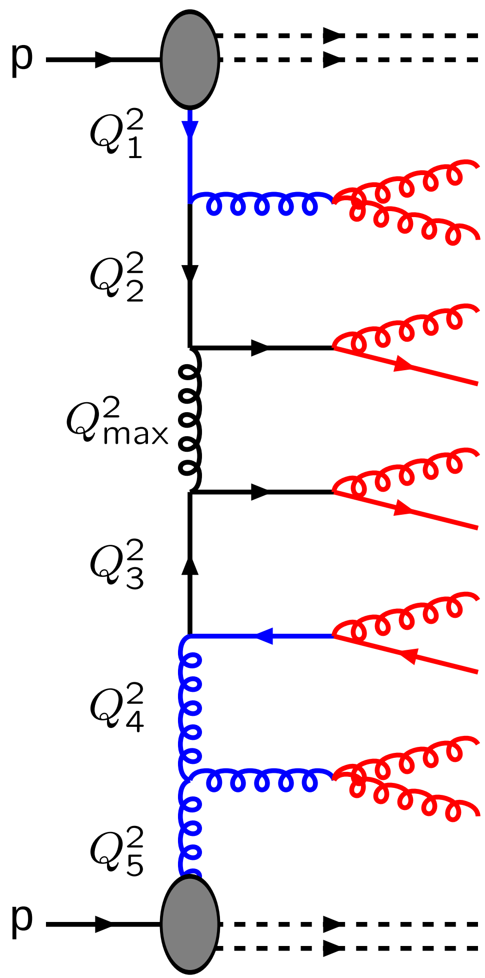


QCD processes: *Do not doublecount!*

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

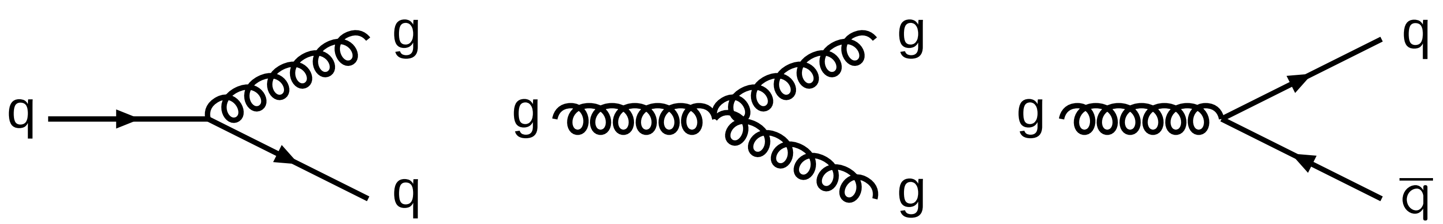
non-QCD (W/Z/H/SUSY/. . .): obvious

Ladder representation:



Existing Implementations (1)

3 main approaches to showering in common use:



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

$+$ angular ordering $\Rightarrow$ coherence inherent

$-$ emissions not ordered in hardness

$-$ emissions do not cover full phase space (messy kinematics)

$-$ kinematics constructed at the very end

PYTHIA: $Q^2 = m^2$ (timelike) or $= -m^2$ (spacelike)

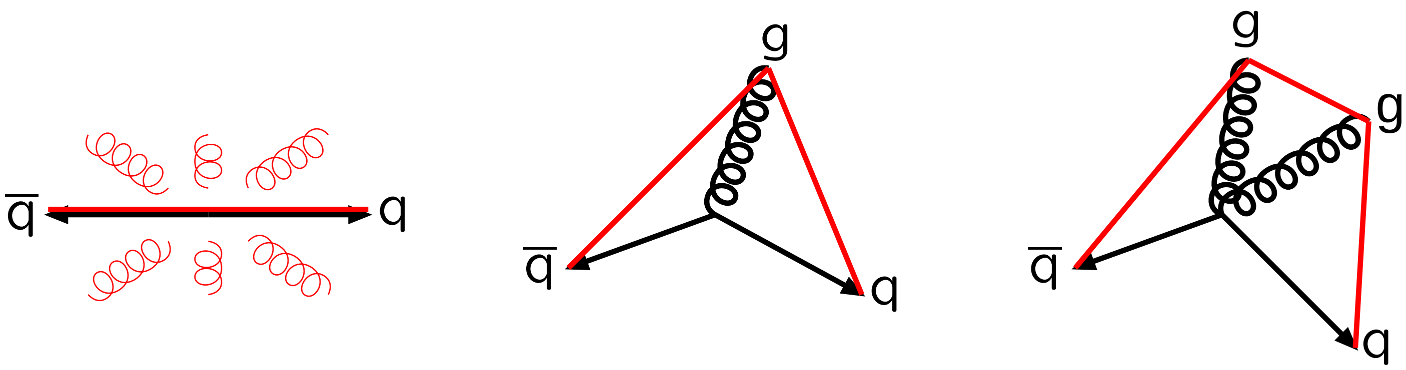
$+$ convenient merging with ME

$\pm$ emissions ordered in (some measure of) hardness

$-$ coherence by brute force $\Rightarrow$ approximate

$-$ kinematics constructed when daughter masses known

Existing Implementations (2)



ARIADNE: $Q^2 = p_\perp^2$, (final-state) dipole emission

$+$ $p_\perp$ ordering $\Rightarrow$ coherence inherent

$+$ Lorentz invariant

$+$ emissions ordered in hardness

$+$ kinematics constructed after each branching
(partons explicitly on-shell until they branch)

$+$ showers can be stopped and restarted at given $p_\perp$ scale
$\Rightarrow$ well suited for ME/PS matching (L-CKKW, real+fictitious showers)

$-$ $\mathrm{g} \to \mathrm{q}\overline{\mathrm{q}}$ artificial

$-$ not so suited for pp on its own: ISR is primitive in ARIADNE;
is sophisticated (CCFM) but complicated (forward evolution, unintegrated parton densities) in LDCMC

Objective

Incorporate several of the good points of the dipole formalism within the shower approach

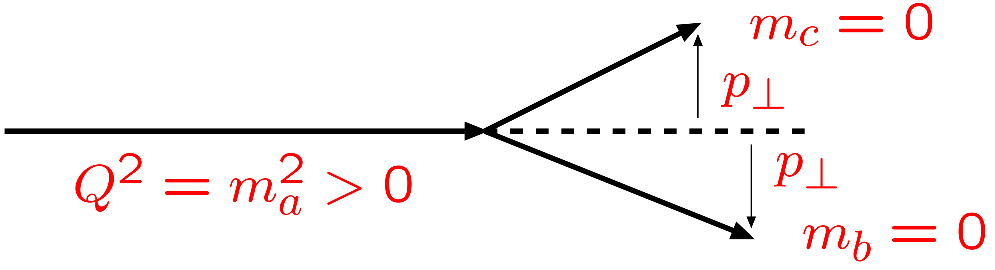
$\pm$ explore alternative $p_\perp$ definitions
$+$ $p_\perp$ ordering $\Rightarrow$ coherence inherent
$+$ ME merging works as before (unique $p_\perp^2 \leftrightarrow Q^2$ mapping; same z)
$+$ g $\rightarrow$ q$\overline{\text{q}}$ natural
$+$ kinematics constructed after each branching
(partons explicitly on-shell until they branch)
$+$ showers can be stopped and restarted at given $p_\perp$ scale
(not yet worked-out for ISR+FSR)
$+$ $\Rightarrow$ well suited for ME/PS matching (L-CKKW, real+fictitious showers)
$+$ $\Rightarrow$ well suited for simple match with $2 \rightarrow 2$ hard processes
$++$ well suited for *intertwined multiple interactions*

Simple kinematics

Consider branching $a \to bc$ in lightcone coordinates $p^{\pm} = E \pm p_z$

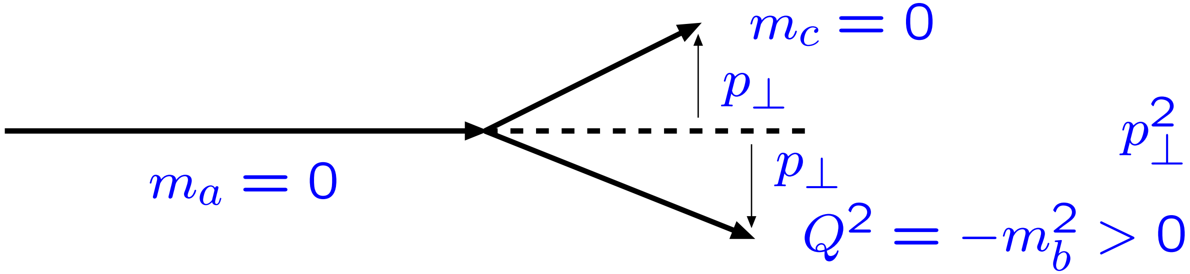
$$\left.\begin{array}{l} p_b^+ = z p_a^+ \\ p_c^+ = (1-z) p_a^+ \\ p^- \text{ conservation} \end{array}\right\} \implies m_a^2 = \frac{m_b^2 + p_\perp^2}{z} + \frac{m_c^2 + p_\perp^2}{1-z}$$

Timelike branching:



$$p_\perp^2 = z(1-z)Q^2$$

Spacelike branching:



$$p_\perp^2 = (1-z)Q^2$$

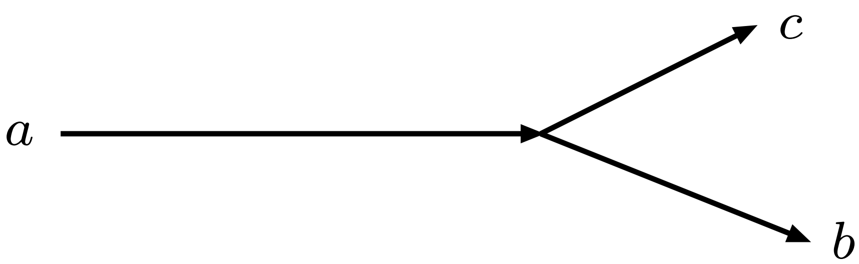
Guideline, not final $p_\perp$!

General Strategy (1)

1) *Define*
$$p^2_{\perp\mathrm{evol}} = z(1-z)Q^2 \text{ for FSR}$$
$$p^2_{\perp\mathrm{evol}} = (1-z)Q^2 \text{ for ISR}$$

2) Find list of *radiators* = partons that can radiate.
Evolve them all *downwards* in $p_{\perp\mathrm{evol}}$ from common $p_{\perp\mathrm{max}}$

$$\mathrm{d}\mathcal{P}_a = \frac{\mathrm{d}p^2_{\perp\mathrm{evol}}}{p^2_{\perp\mathrm{evol}}} \frac{\alpha_s(p^2_{\perp\mathrm{evol}})}{2\pi} P_{a\to bc}(z)\,\mathrm{d}z\, \exp\left(-\int_{p^2_{\perp\mathrm{evol}}}^{p^2_{\perp\mathrm{max}}} \cdots\right)$$



$$\mathrm{d}\mathcal{P}_b = \frac{\mathrm{d}p^2_{\perp\mathrm{evol}}}{p^2_{\perp\mathrm{evol}}} \frac{\alpha_s(p^2_{\perp\mathrm{evol}})}{2\pi} \frac{x' f_a(x', p^2_{\perp\mathrm{evol}})}{x f_b(x, p^2_{\perp\mathrm{evol}})} P_{a\to bc}(z)\,\mathrm{d}z\, \exp\left(-\cdots\right)$$

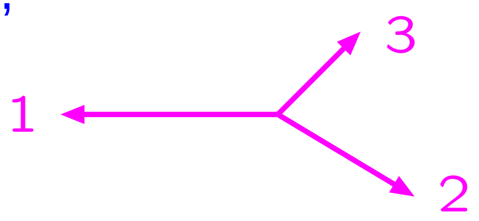
Pick the one with *largest* $p_{\perp\mathrm{evol}}$ to undergo branching; also gives z.

3) *Derive*
$$Q^2 = p^2_{\perp\mathrm{evol}}/z(1-z) \text{ for FSR}$$
$$Q^2 = p^2_{\perp\mathrm{evol}}/(1-z) \text{ for ISR}$$

General Strategy (2)

4) Find *recoiler* = parton to take recoil when radiator is pushed off-shell
usually nearest colour neighbour for FSR
incoming parton on other side of event for ISR

5) Interpret z as *energy fraction* (not lightcone)
in radiator+recoiler rest frame for FSR,
in mother-of-radiator+recoiler rest frame for ISR,
so that *Lorentz invariant*
$(2E_i/E_{\mathrm{cm}} = 1 - m_{jk}^2/E_{\mathrm{cm}}^2)$
and straightforward match to matrix elements

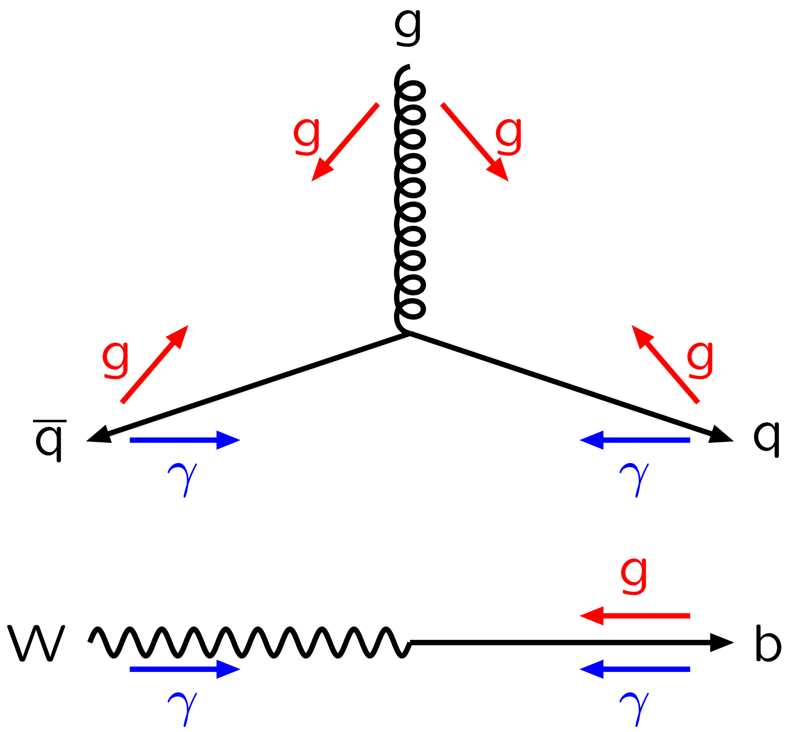


6) Do *kinematics* based on Q^2 and z,
a) assuming yet unbranched partons on-shell
b) shuffling energy–momentum from recoiler as required

7) Continue evolution of all radiators from recently picked $p_{\perp\mathrm{evol}}$.
Iterate until no branching above $p_{\perp\mathrm{min}}$.
$\Rightarrow$ One combined sequence $p_{\perp\mathrm{max}} > p_{\perp 1} > p_{\perp 2} > \ldots > p_{\perp\mathrm{min}}$.

The FSR algorithm — details (1)

- Radiators and recoilers:



g: counts twice,
half for each recoiler;
both g $\to$ gg and g $\to$ q$\overline{\text{q}}$

q: one recoiler for q $\to$ qg,
another recoiler for q $\to$ qγ

top decay (e.g.)
colour recoiler $\neq$ colour partner
(should not change top mass)

- Evolution:

a) Massive quarks: $\mathrm{p}^2_{\perp\mathrm{evol}} = z(1-z)(m^2 - m_0^2)$.

b) Matrix-element merging by veto for many SM+MSSM decays.

The FSR algorithm — details (2)

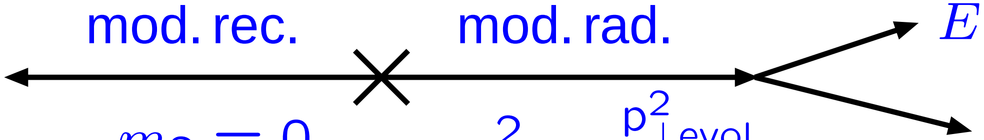
- Kinematics of a branching:

a) Boost radiator+recoiler to their rest frame; radiator along $+z$ axis

recoiler: $m = 0$, $E = \frac{\sqrt{\hat{s}}}{2}$

radiator: $m = 0$, $E = \frac{\sqrt{\hat{s}}}{2}$

b) Replace by



mod. rec.: $m_2 = 0$, $E_2 = \frac{\hat{s} - m_1^2}{2\sqrt{\hat{s}}}$

mod. rad.: $m_1^2 = \frac{\mathrm{p}_{\perp\mathrm{evol}}^2}{z(1-z)}$, $E_1 = \frac{\hat{s} + m_1^2}{2\sqrt{\hat{s}}}$

$E = (1 - z)E_1$

$E = zE_1$

Actual $p_\perp^2 = m^2 \frac{z(1-z)(\hat{s}+m_1^2)^2 - \hat{s}m_1^2}{(\hat{s}-m_1^2)^2} < \mathrm{p}_{\perp\mathrm{evol}}^2$

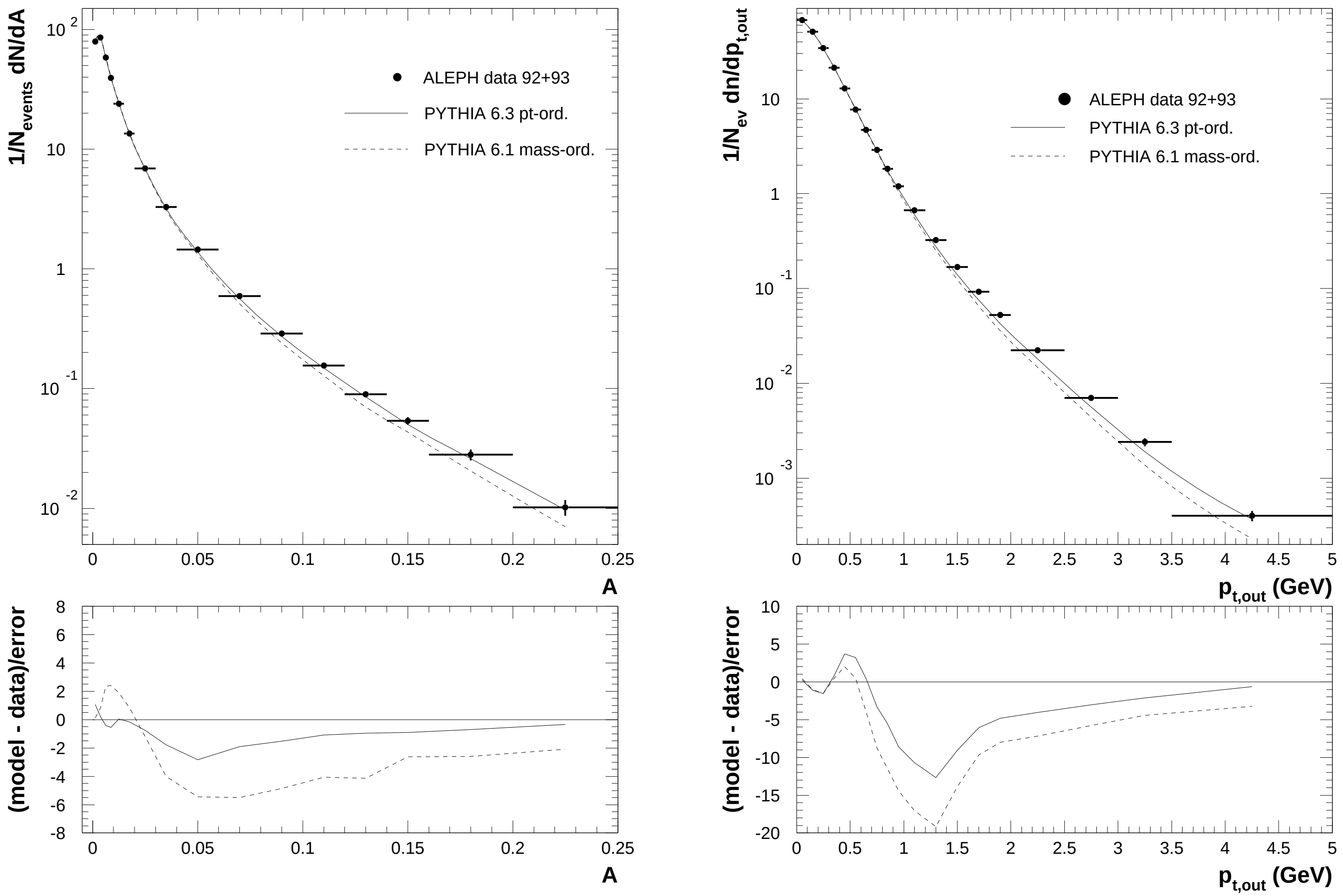
(since now z energy fraction, not lightcone)

c) φ angle nonisotropic by g polarization

d) Rotate and boost back

Testing the FSR algorithm

Tune performed by Gerald Rudolph (Innsbruck)
based on ALEPH 1992+93 data:



Quality of fit

Distribution of	nb.of interv.	$\sum \chi^2$ of model PY6.3 $p_\perp$-ord.	PY6.1 mass-ord.
Sphericity	23	25	16
Aplanarity	16	23	168
1$-$Thrust	21	60	8
Thrust$_{\text{minor}}$	18	26	139
jet res. y_3(D)	20	10	22
$x = 2p/E_{\text{cm}}$	46	207	151
$p_{\perp\text{in}}$	25	99	170
$p_{\perp\text{out}} < 0.7$ GeV	7	29	24
$p_{\perp\text{out}}$	(19)	(590)	(1560)
x(B)	19	20	68
sum $N_{\text{dof}} =$	190	497	765

Generator is not assumed to be perfect, so
add fraction p of value in quadrature to the definition of the error:

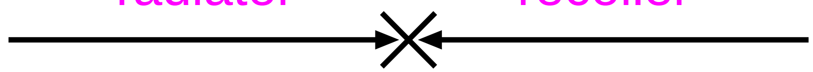
p	0%	0.5%	1%
$\sum \chi^2$	523	364	234

for $N_{\text{dof}} = 196 \Rightarrow$ generator is ‘correct’ to $\sim$1%
except $p_{\perp\text{out}} > 0.7$ GeV (10%–20% error)

The ISR algorithm — details

- Evolution: Matrix-element merging by veto for Z/W/H production.
- Kinematics of a branching:

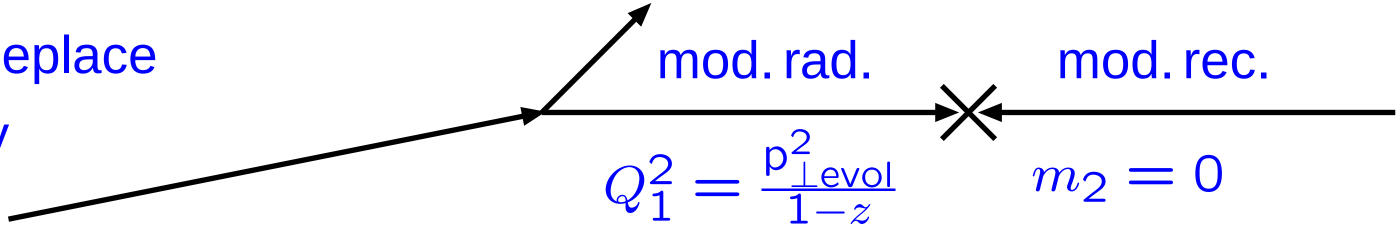
a) Boost radiator+recoiler to their rest frame; radiator along $\pm z$ axis



radiator: $m = 0$, $E_1 = \frac{\sqrt{\hat{s}}}{2}$

recoiler: $m = 0$, $E_2 = \frac{\sqrt{\hat{s}}}{2}$

b) Replace by



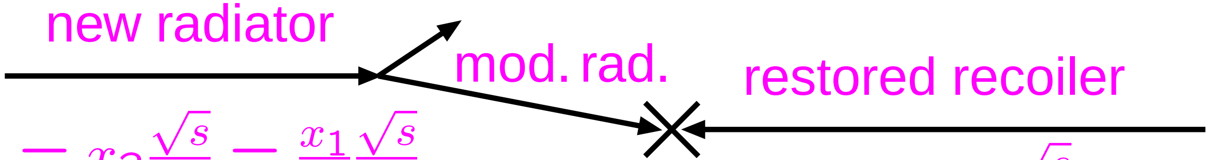
$m_{32}^2 = \frac{\hat{s}}{z} = x_3 x_2 s$

mod. rad.: $Q_1^2 = \frac{\mathrm{p}_{\perp\mathrm{evol}}^2}{1-z}$, $E_1 = \frac{\hat{s} - Q_1^2}{2\sqrt{\hat{s}}}$

mod. rec.: $m_2 = 0$, $E_2 = \frac{\hat{s} + Q_1^2}{2\sqrt{\hat{s}}}$

c) φ angle currently isotropic

d) Rotate and boost back



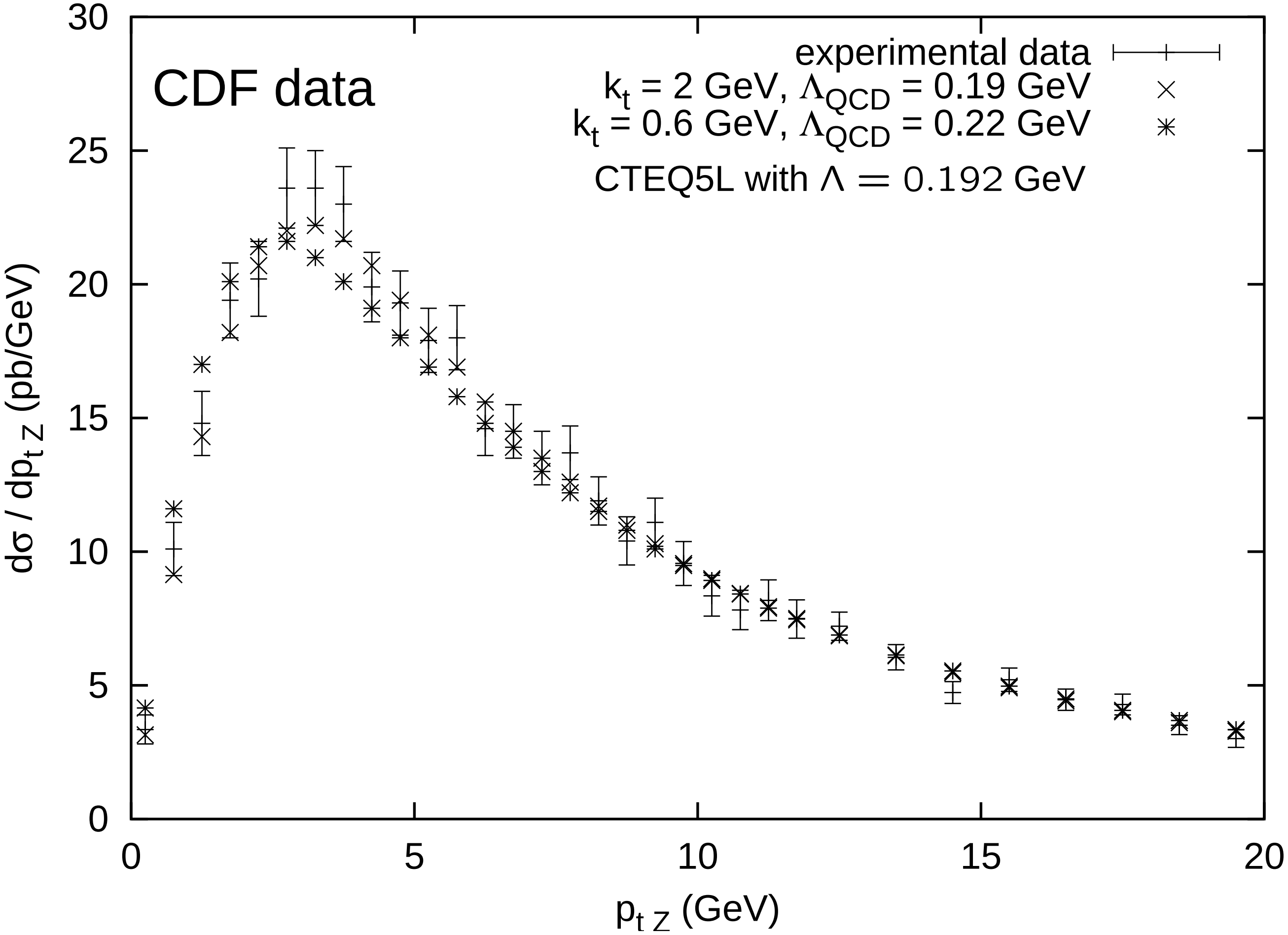
$E_3 = x_3 \frac{\sqrt{s}}{2} = \frac{x_1}{z} \frac{\sqrt{s}}{2}$

$E_2 = x_2 \frac{\sqrt{s}}{2}$

Actual $p_\perp^2 = (1-z) Q_1^2 - z \frac{Q_1^4}{\hat{s}} < \mathrm{p}_{\perp\mathrm{evol}}^2$

Testing the ISR algorithm

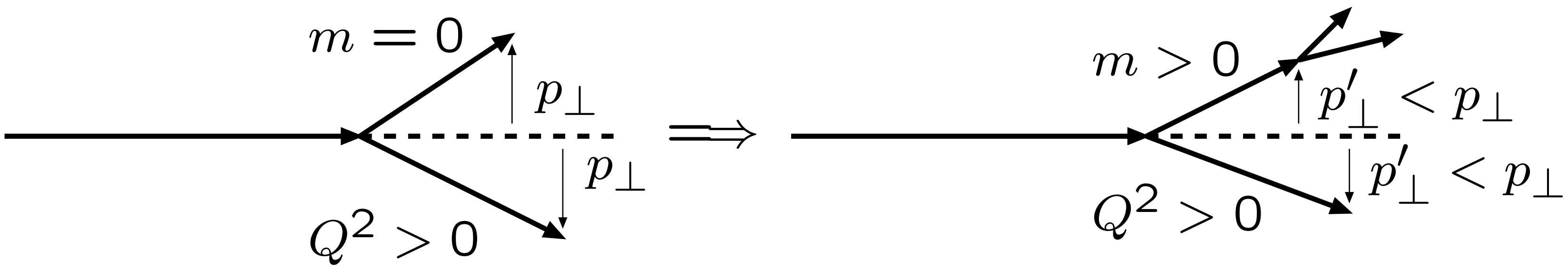
Still only begun. . .

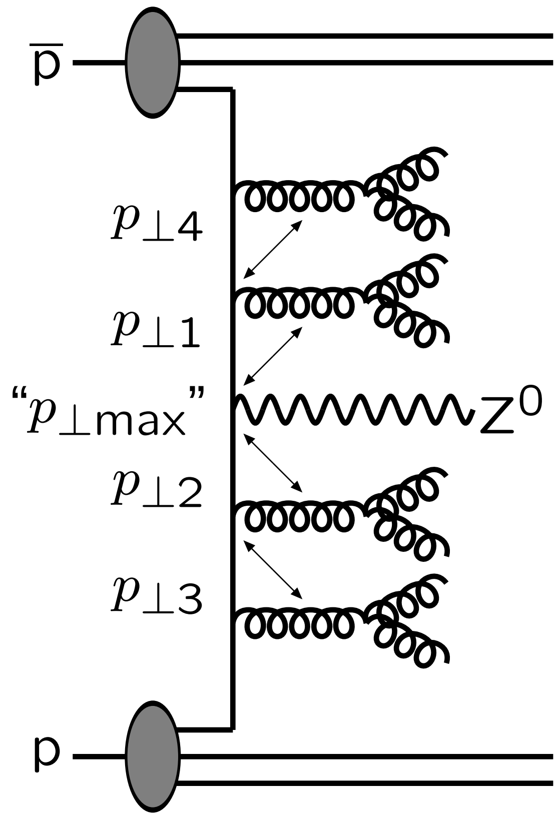


. . . but so far no showstoppers

Combining FSR with ISR

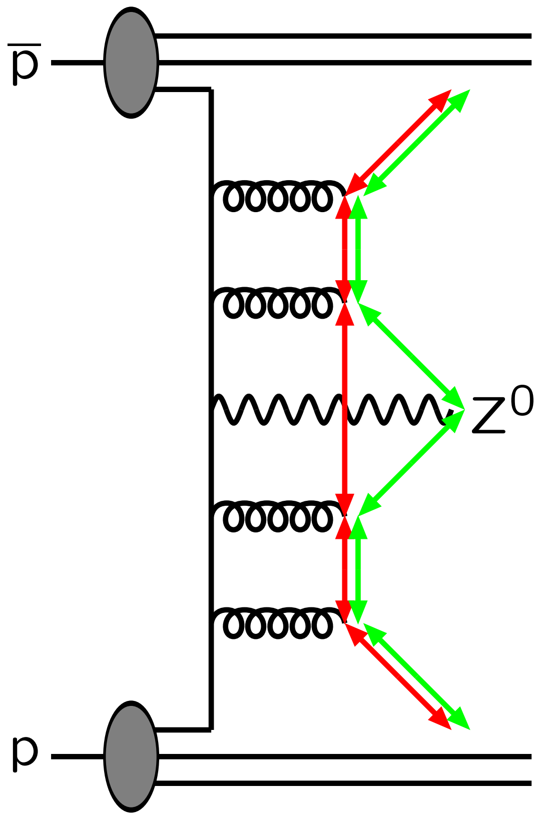
Evolution of timelike sidebranch cascades can reduce $p_\perp$:





Old:

Z^0 takes recoil



New:

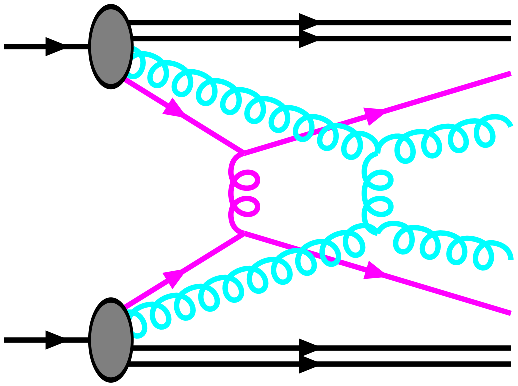
Z^0 takes recoil

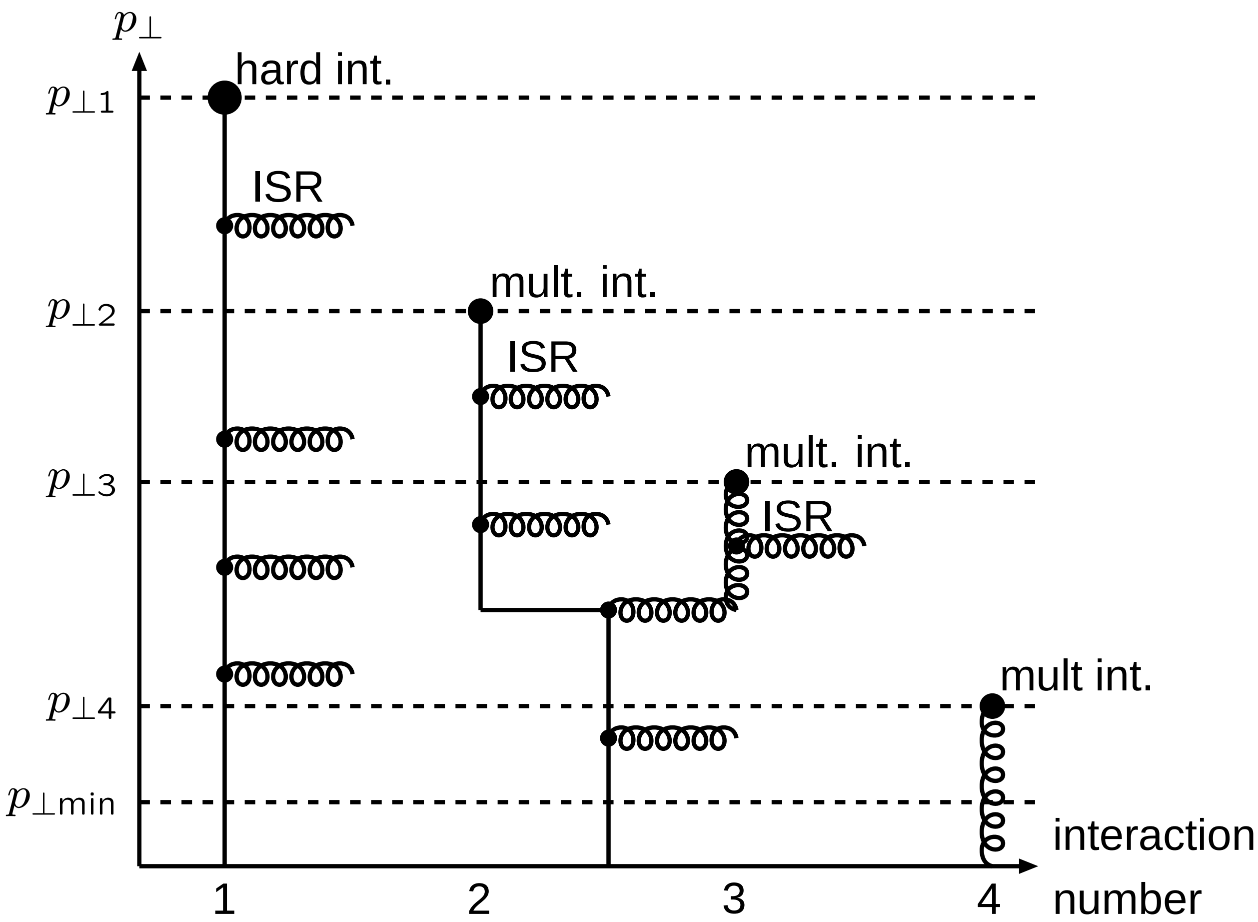
or

Z^0 unaffected by FSR (latter later)

Outlook: to do

- Complete ISR: heavy flavours
- Combine FSR with ISR
- Put in context of *intertwined multiple interactions*:





- Test for pp/p$\overline{\mathrm{p}}$
- Write it up (TS, Les Houches, LU TP 04–05 [hep-ph/0401061])