KITP Santa Barbara
Collider Physics Workshop
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LUND UNIVERSITY

New $p_\perp$-ordered showers

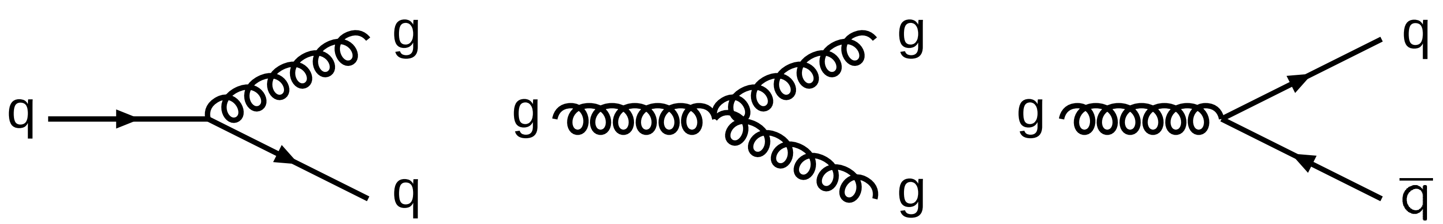
Torbjörn Sjöstrand

Department of Theoretical Physics
Lund University

Motivation
The time-like shower (FSR)
The space-like shower (ISR)
Outlook

Background (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)

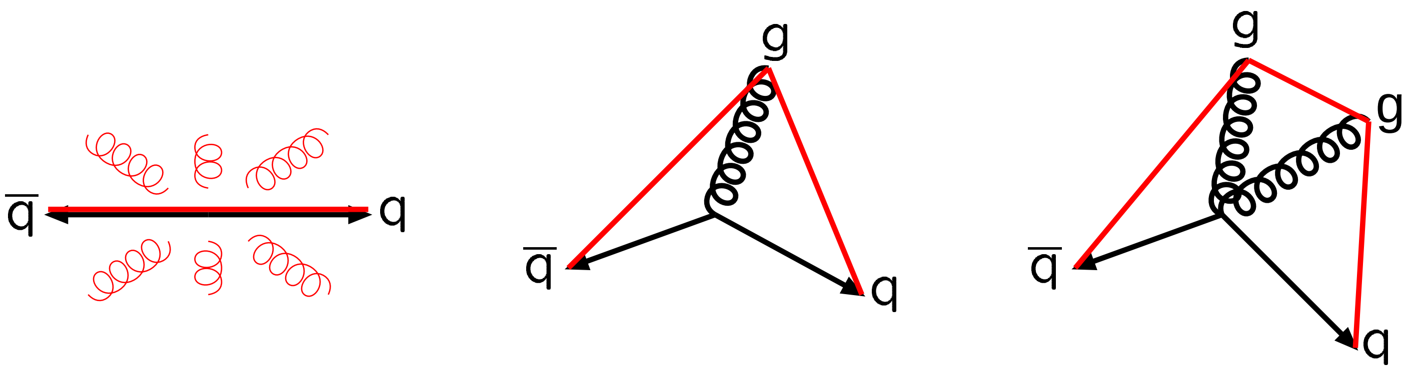
$+$ convenient merging with ME

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

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

$-$ kinematics constructed when daughter masses known

Background (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 L-CKKW (real and fictitious showers)

– g $\rightarrow$ q$\overline{\text{q}}$ artificial

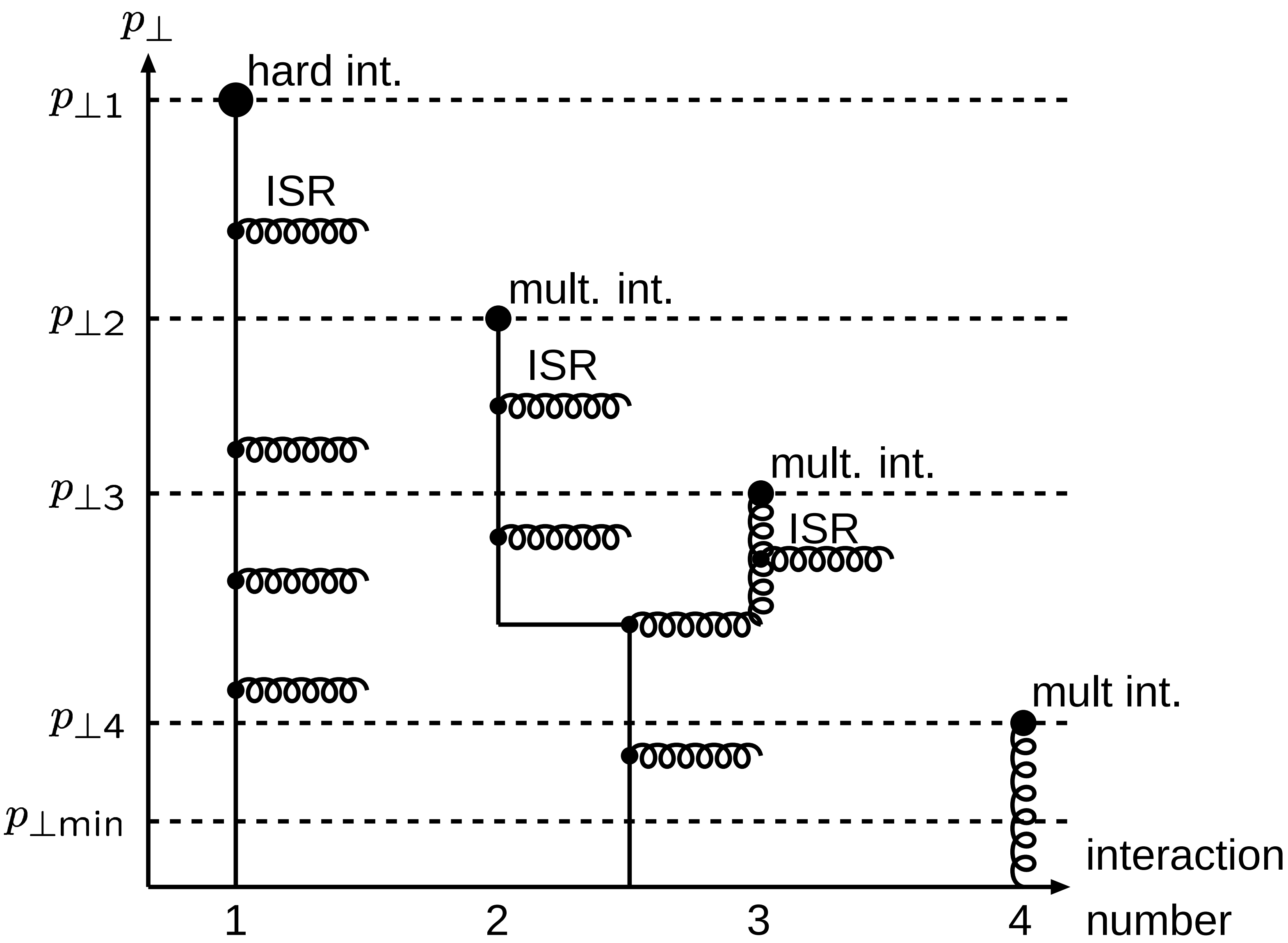
– not suited for pp on its own: ISR is primitive in ARIADNE;
  is sophisticated (CCFM) but complicated (forward evolution, unintegrated parton densities) in LDCMC

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 $\to$ 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 L-CKKW (real and fictitious showers)
$+$ $\Rightarrow$ well suited for simple match with $2 \to 2$ hard processes

$+ \Rightarrow$ well (?) suited for intertwined multiple interactions

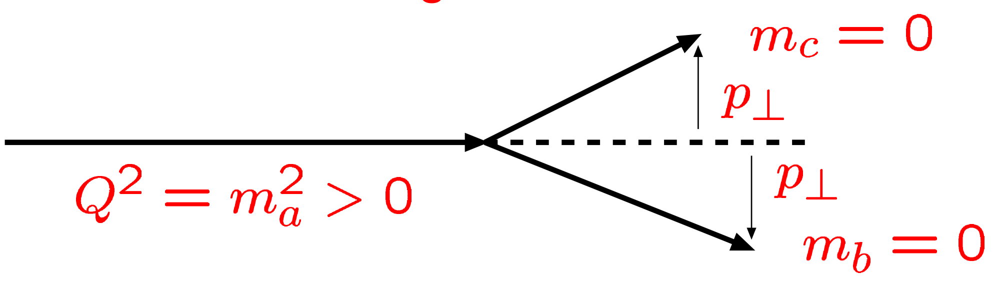


Simple kinematics

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

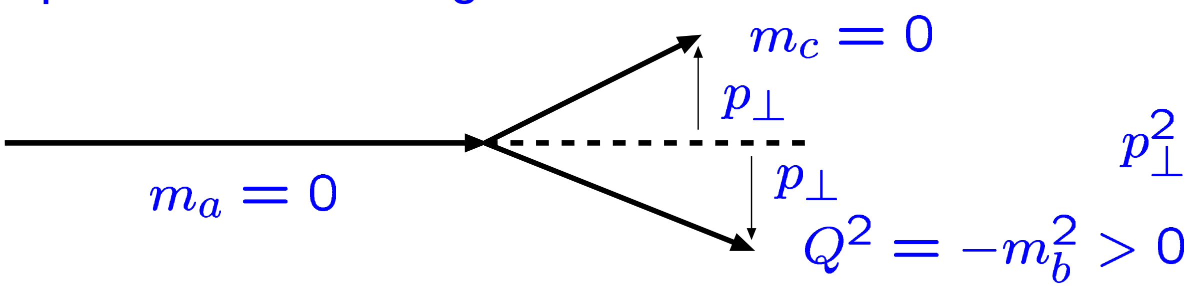
$$\left.\begin{array}{l} p_b^+ = z p_a^+ \\ p_c^+ = (1-z) p_a^+ \\ p^- \text{ conservation} \end{array}\right\} \Longrightarrow m_a^2 = \frac{m_b^2 + p_\perp^2}{z} + \frac{m_c^2 + p_\perp^2}{1-z}$$

Timelike branching:



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

Spacelike branching:



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

cf. LUCLUS/PYCLUS $p_\perp$ vs. Durham $k_\perp$

Strategy

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

2) *Evolve downwards* in $p_{\perp\mathrm{evol}}^2$

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

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

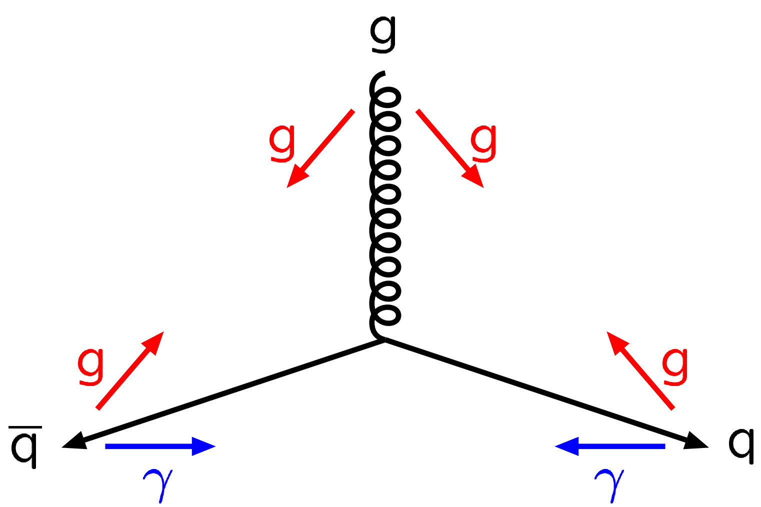
4) Do *kinematics* based on Q^2 and z,

a) assuming yet unbranched partons on-shell,

b) shuffling energy–momentum from recoil partner as required

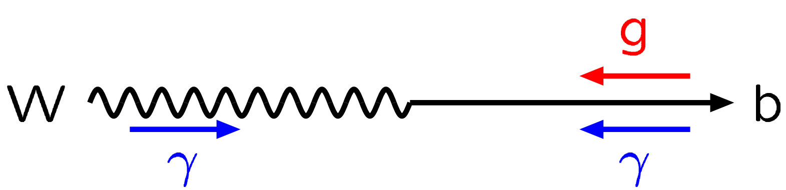
The FSR algorithm

1) Find radiators and recoilers from initial list of on-shell partons



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

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



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

2) Evolve all radiators downwards from common $p_{\perp\mathrm{max}}$.
Pick the one that branches at the largest actual $p_{\perp\mathrm{evol}}$.

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

b) $z_{\mathrm{min}}(p^2_{\perp\mathrm{evol}}, \hat{s}) < z < z_{\mathrm{max}}(p^2_{\perp\mathrm{evol}}, \hat{s})$ with $\hat{s} = (p_{\mathrm{rad}} + p_{\mathrm{rec}})^2$.

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

3) Construct kinematics of 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.: $m_1^2 = \frac{p_{\perp \mathrm{evol}}^2}{z(1-z)}$, $E_1 = \frac{\hat{s}+m_1^2}{2\sqrt{\hat{s}}}$

$E = (1-z)E_1$

$E = zE_1$

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

since now z energy fraction, not lightcone

(so that simpler merging matrix elements).

c) φ angle nonisotropic by g polarization.

d) Rotate and boost back.

4) 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 $p_{\perp \mathrm{max}} > p_{\perp 1} > p_{\perp 2} > \ldots > p_{\perp \mathrm{min}}$.

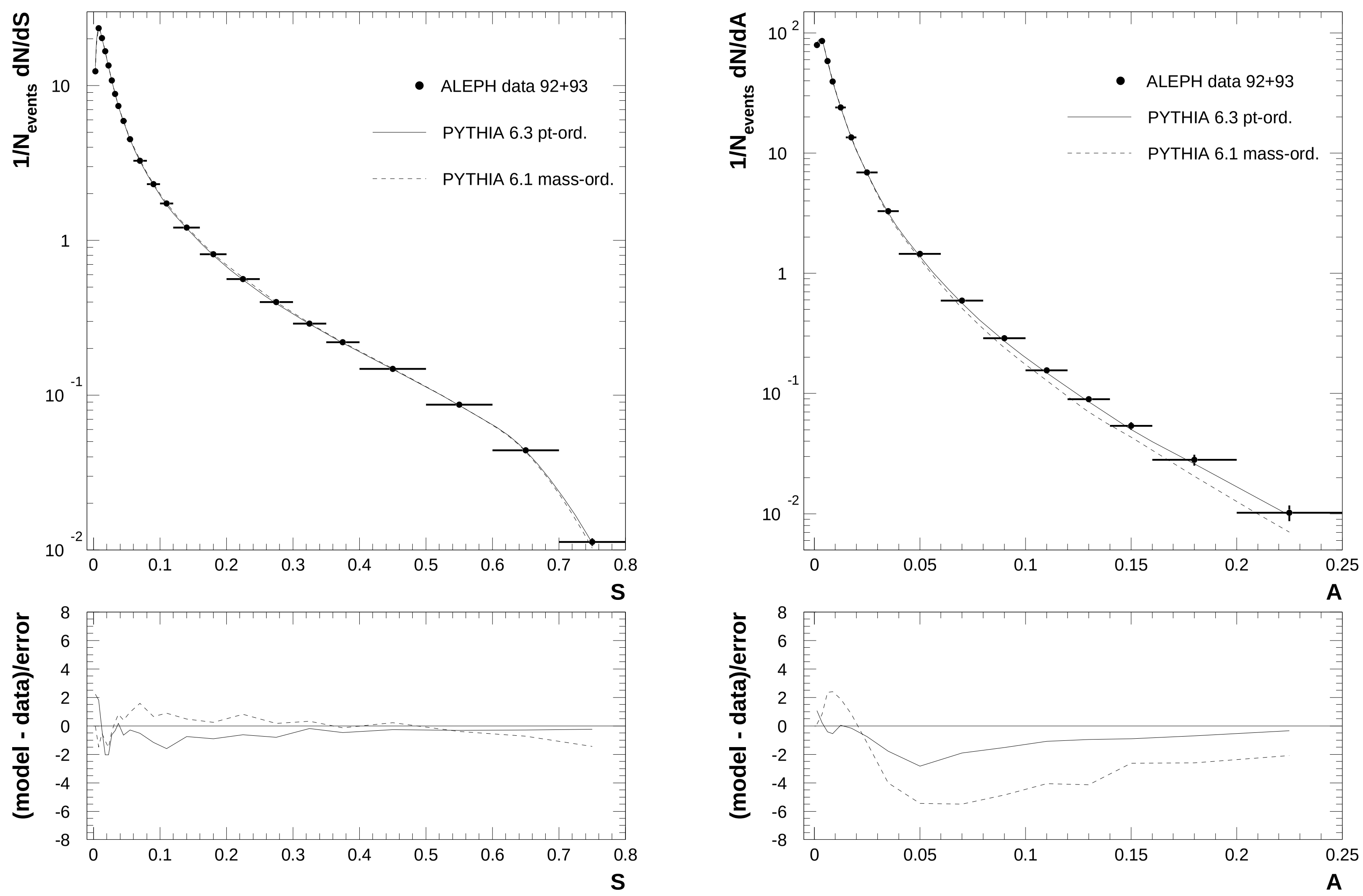
Testing the FSR algorithm

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

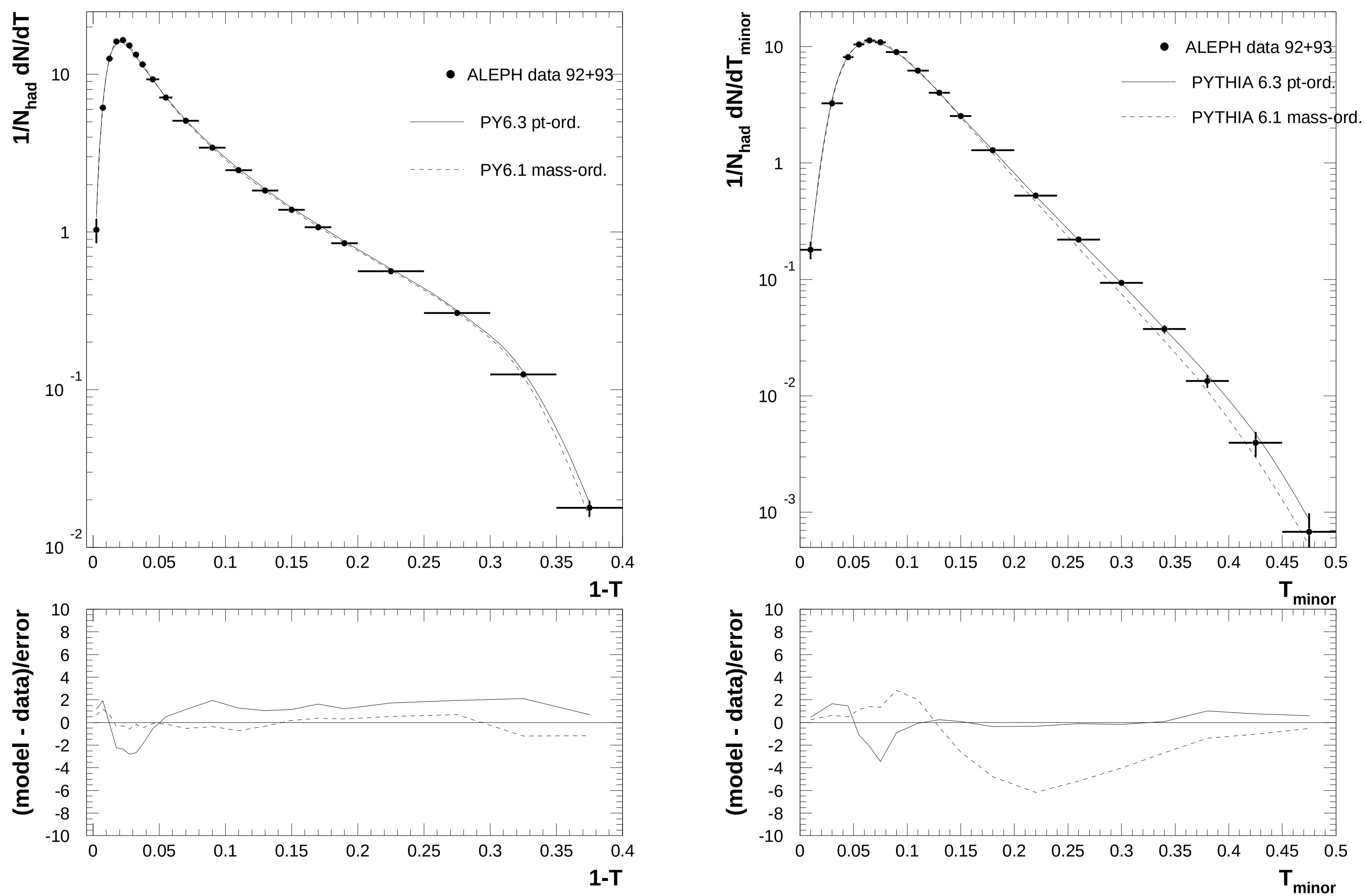
Best fit values of parameters:

parameter	name	value	comment
Λ_{QCD}	PARJ(81)	$0.141 \pm .001$	~half of old
$2p_{\perp\mathrm{min}}$	PARJ(82)	0.62 ± 0.04	rather low
σ	PARJ(21)	0.360 ± 0.002	
a	PARJ(41)	0.400 fixed	
b	PARJ(42)	$1.044 \pm .025$	
ϵ_{c}	-PARJ(54)	.040 fixed	
ϵ_{b}	-PARJ(55)	0.0012 ± 0.0001	
qq/q	PARJ(1)	0.115 ± 0.002	up
s/u	PARJ(2)	0.270 ± 0.004	down

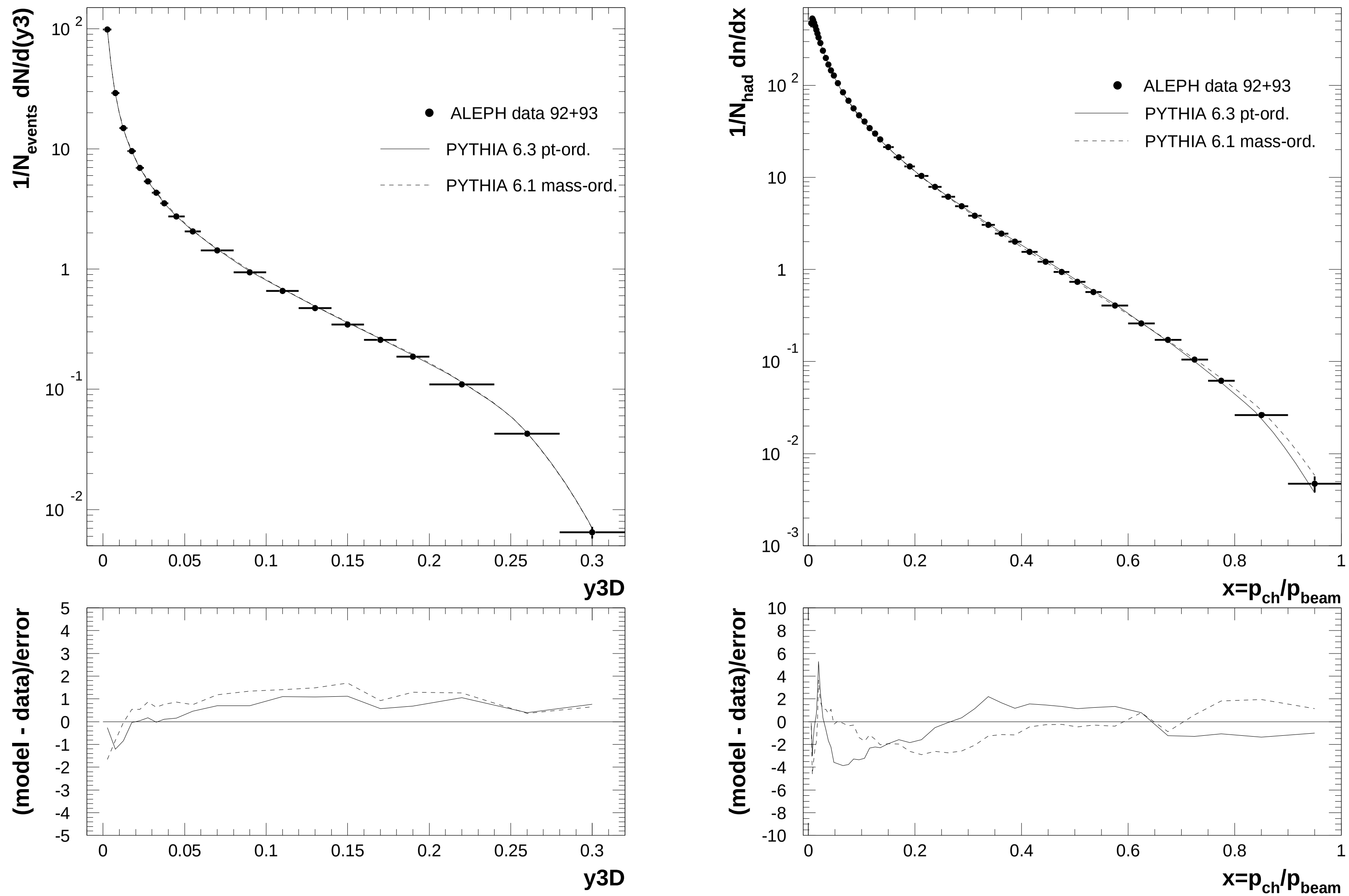
+ a few more flavour parameters



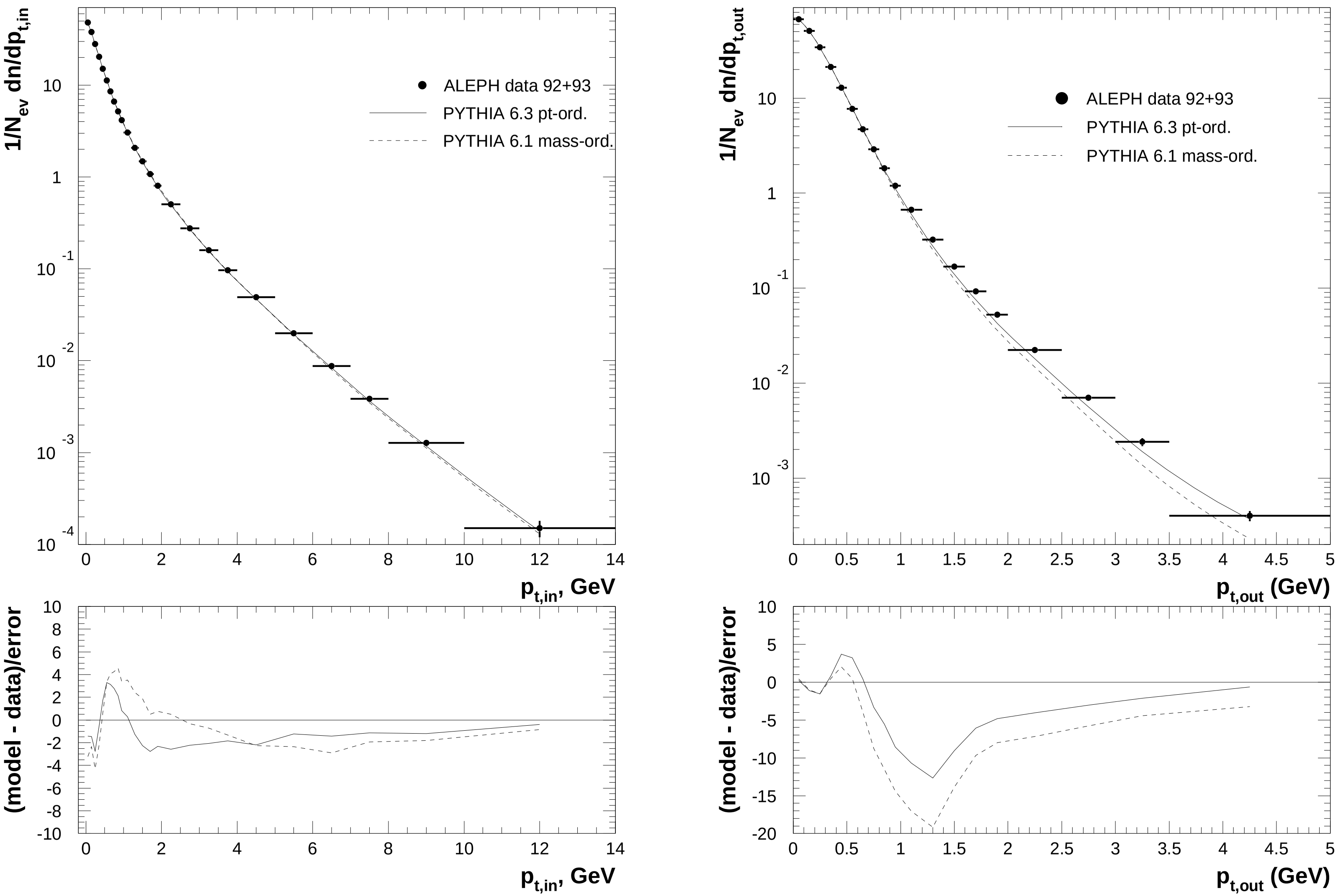
1/N_events dN/dS
ALEPH data 92+93
PYTHIA 6.3 pt-ord.
PYTHIA 6.1 mass-ord.
S
(model - data)/error
S
1/N_events dN/dA
ALEPH data 92+93
PYTHIA 6.3 pt-ord.
PYTHIA 6.1 mass-ord.
A
(model - data)/error
A



1/N_had dN/dT
ALEPH data 92+93
PY6.3 pt-ord.
PY6.1 mass-ord.
1-T
(model - data)/error
1-T
1/N_had dN/dT_minor
ALEPH data 92+93
PYTHIA 6.3 pt-ord.
PYTHIA 6.1 mass-ord.
T_minor
(model - data)/error
T_minor



1/N_events dN/d(y3)
ALEPH data 92+93
PYTHIA 6.3 pt-ord.
PYTHIA 6.1 mass-ord.
y3D
(model - data)/error
y3D
1/N_had dn/dx
ALEPH data 92+93
PYTHIA 6.3 pt-ord.
PYTHIA 6.1 mass-ord.
x=p_ch/p_beam
(model - data)/error
x=p_ch/p_beam


1/N_ev dn/dp_t,in
ALEPH data 92+93
PYTHIA 6.3 pt-ord.
PYTHIA 6.1 mass-ord.
p_t,in, GeV
(model - data)/error
p_t,in, GeV
1/N_ev dn/dp_t,out
ALEPH data 92+93
PYTHIA 6.3 pt-ord.
PYTHIA 6.1 mass-ord.
p_t,out (GeV)
(model - data)/error
p_t,out (GeV)

Quality of fit (1)

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
$\text{Thrust}_{\text{minor}}$	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

Quality of fit (2)

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
Λ_{QCD}	0.141	0.141	0.140
$2p_{\perp\mathrm{min}}$	0.62	0.66	0.69
σ	0.360	0.361	0.364
b	1.044	1.009	0.980
ϵ_{b}	0.012	0.0012	0.013

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

Increasing $p_{\perp\mathrm{min}}$ desirable since

$\langle n_{\mathrm{gluons}} \rangle =$ 4.5 in PY6.1 with $m_{\mathrm{min}} \approx 1.6$ GeV
13.0 in PY6.3 with $2p_{\perp\mathrm{min}} = 0.6$ GeV

and also higher $\mathrm{g} \to \mathrm{q}\overline{\mathrm{q}}$ rates

The ISR algorithm

1) Start with two incoming partons at hard interaction.

2) Evolve both radiators downwards from common $p_{\perp\mathrm{max}}$.
Pick the one that branches at the largest actual $\mathrm{p}_{\perp\mathrm{evol}}$.

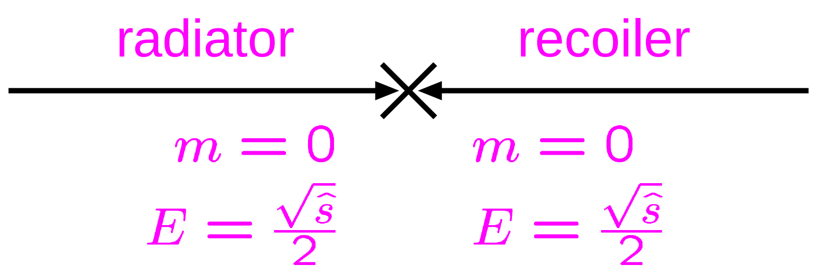
a) Massive quarks: not yet considered.

b) $z_{\mathrm{min}}(\mathrm{p}^2_{\perp\mathrm{evol}}, \hat{s}, x) < z < z_{\mathrm{max}}(\mathrm{p}^2_{\perp\mathrm{evol}}, \hat{s})$
with $\hat{s} = m^2_{12} = (p_1 + p_2)^2 = x_1 x_2 s$.

c) Matrix-element merging by veto for Z/W/H production.

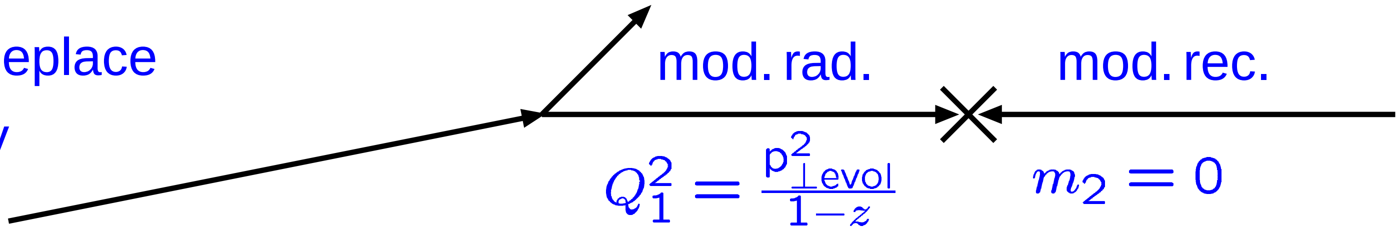
3) Construct kinematics of branching:

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



b) Replace

by



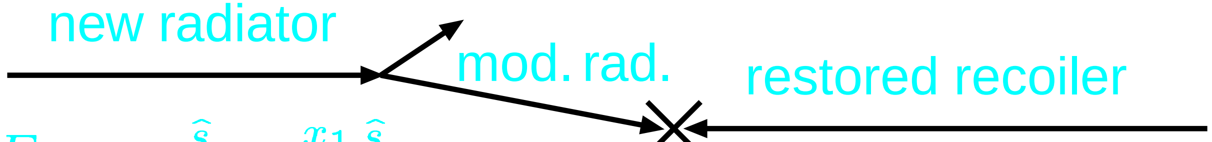
$m_{32}^2 = \frac{\hat{s}}{z} = x_3 x_2 s$ $\quad Q_1^2 = \frac{\mathrm{p}_{\perp\mathrm{evol}}^2}{1-z}$ $\quad m_2 = 0$

$E_1 = \frac{\hat{s}-Q_1^2}{2\sqrt{\hat{s}}}$ $\quad E_2 = \frac{\hat{s}+Q_1^2}{2\sqrt{\hat{s}}}$

c) φ angle currently isotropic

d) Rotate and

boost back



$E = x_3 \frac{\hat{s}}{2} = \frac{x_1}{z} \frac{\hat{s}}{2}$ $\quad E = x_2 \frac{\hat{s}}{2}$

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

since now z invariant-mass^2 fraction, not lightcone

(so that simpler merging with matrix elements, e.g. resonance mass).

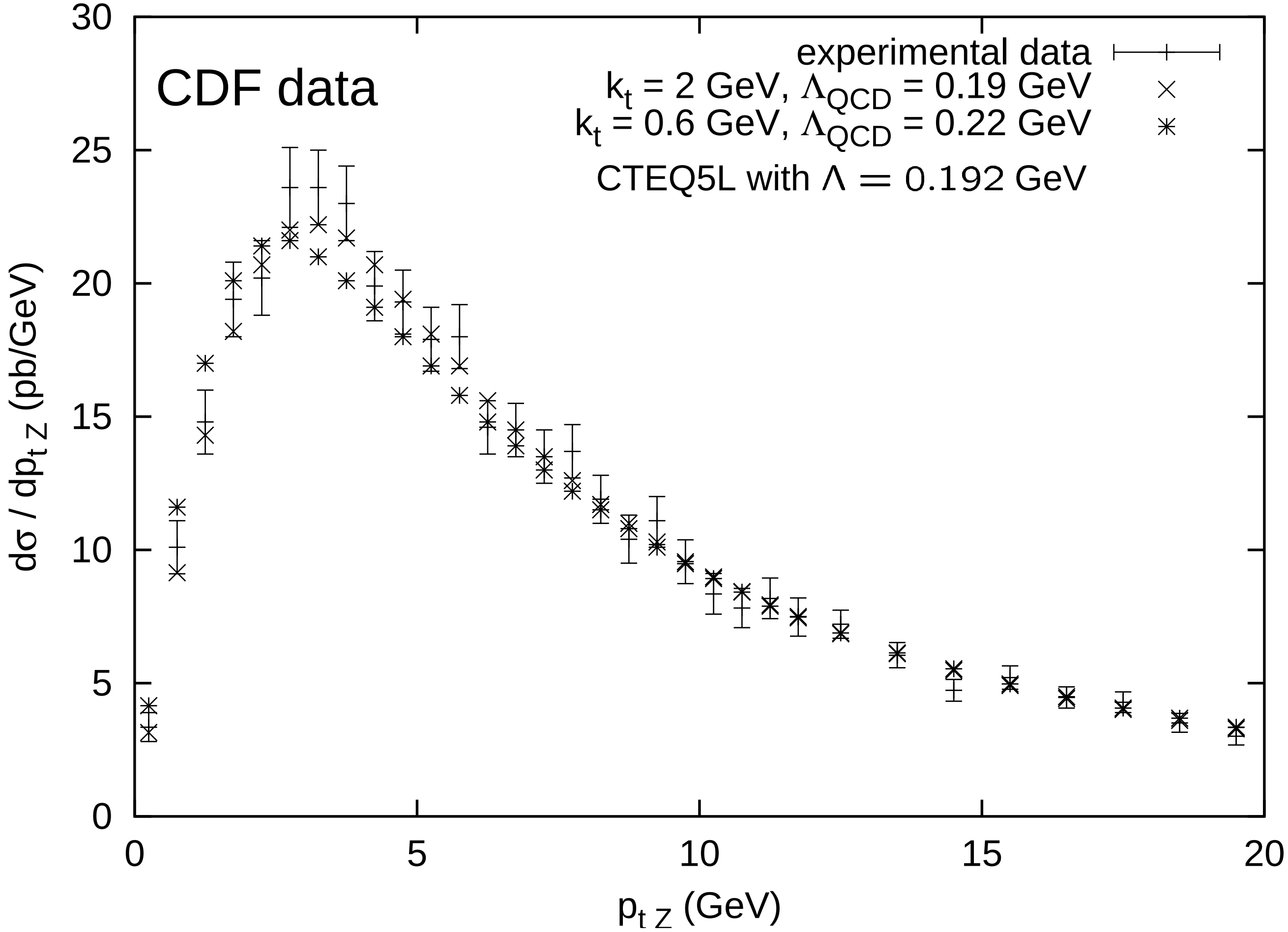
4) Continue evolution on both sides from recently picked $\mathrm{p}_{\perp\mathrm{evol}}$.

Iterate until no branching above $p_{\perp\mathrm{min}}$.

$\Rightarrow$ One combined sequence $p_{\perp\mathrm{max}} > p_{\perp 1} > p_{\perp 2} > \ldots > p_{\perp\mathrm{min}}$.

Testing the ISR algorithm

Still only begun. . .



. . . but so far no showstoppers

Why variable Λ_{QCD}?

E. Thomé, master's thesis, LU TP 04–01 [hep-ph/0401121]
J. Huston et al., Les Houches, LU TP 04–07 [hep-ph/0401145]

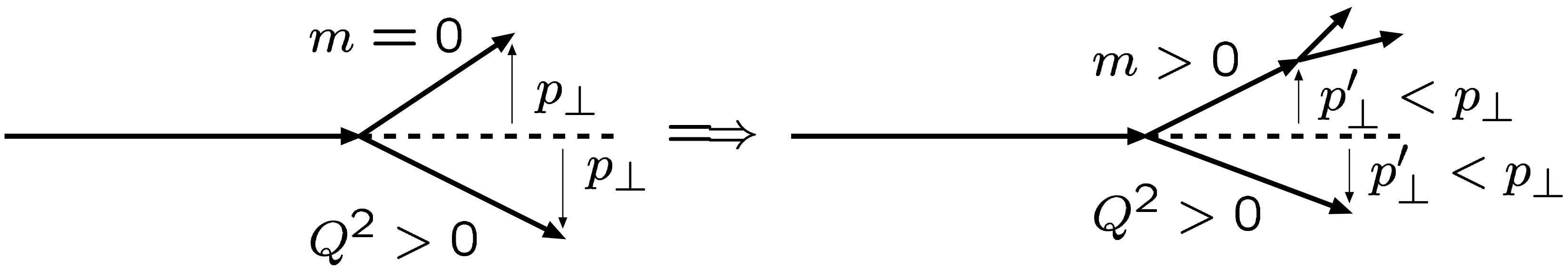
Old evolution in Q^2 is not equivalent to PDF LO evolution:
(i) angular ordering
(ii) $\hat{u} = Q^2 - \hat{s}(1-z) < 0$
(iii) $\alpha_s((1-z)Q^2)$ rather than $\alpha_s(Q^2)$ and thus cut $(1-z)Q^2 > Q_0^2$
(iv) further minor issues
$\Longrightarrow$ slower evolution; can be compensated by raised Λ_{QCD}

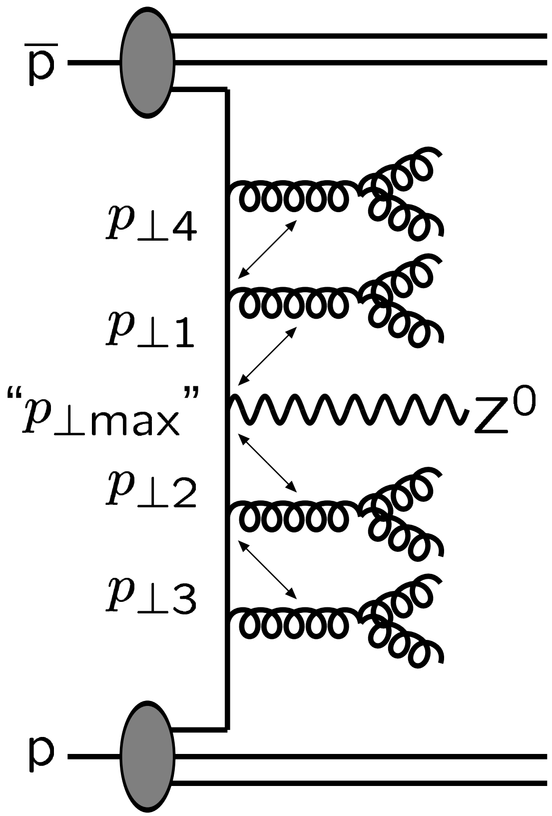
For instance, with CTEQ5L, $\Lambda = 0.192$ GeV, need
$\Lambda \approx 0.30$ GeV for $q\overline{q} \to Z^0$
$\Lambda \approx 0.48$ GeV for $gg \to H^0$
in shower to match PDF evolution rate.

Unfortunately, main effect of changed Λ is to reduce peak height and increase jet activity, not shift peak position.

Combining FSR with ISR

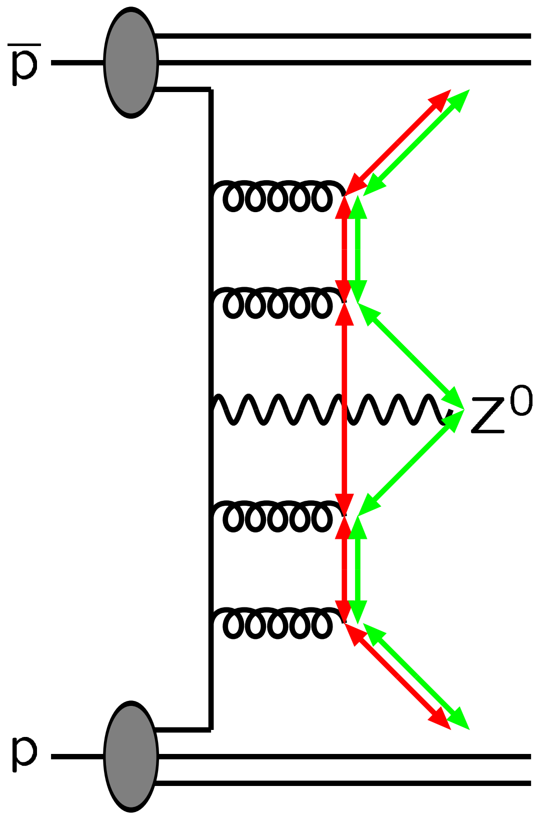
Evolution of timelike sidebranch cascades can reduce $p_\perp$:





Old:

Z^0 takes recoil



New:

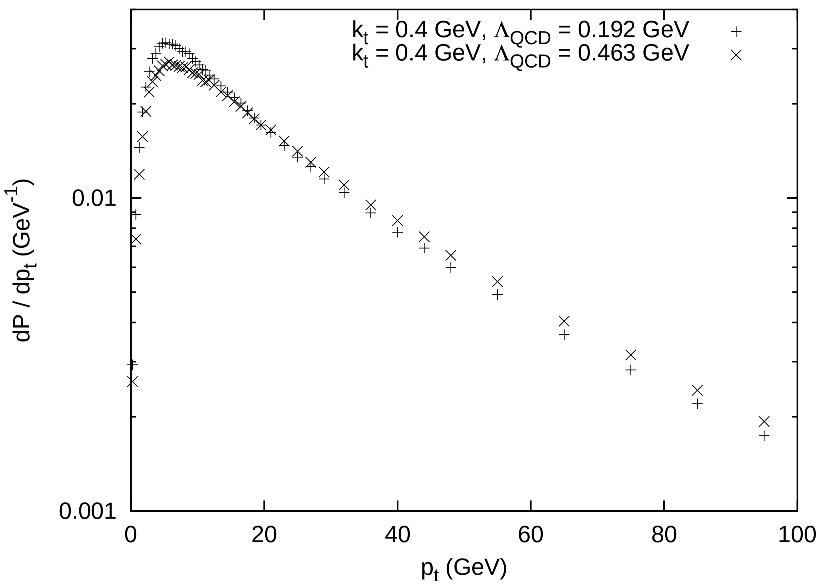
Z^0 takes recoil

or

Z^0 unaffected by FSR (latter later)

Examples with old shower

$gg \to H^0$ at the LHC:



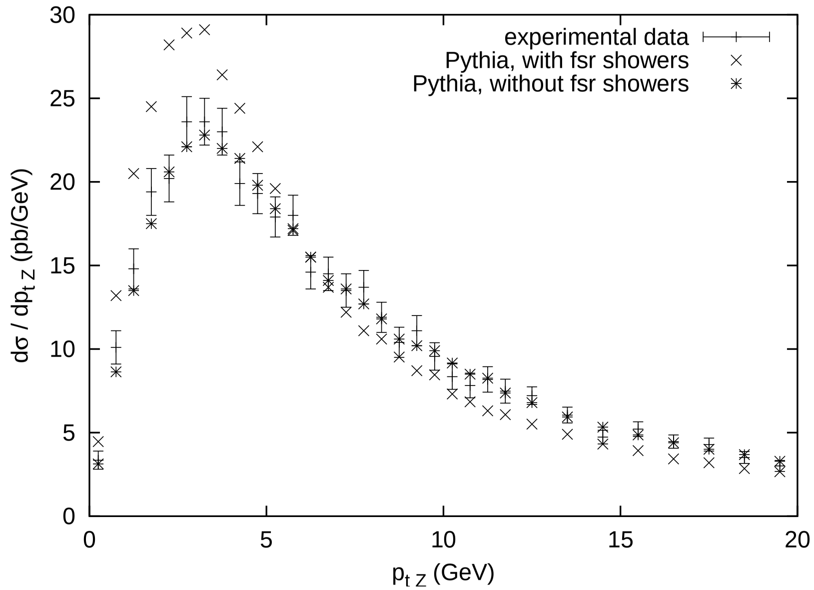
$\Lambda = 0.192 \to 0.463$ GeV with CTEQ5L.

$m_H = 120$ GeV.

Primordial $k_\perp = 0.4$ GeV (r.m.s. for Gaussian).

Including FSR effects.

$q\bar{q} \to Z^0$ at the Tevatron



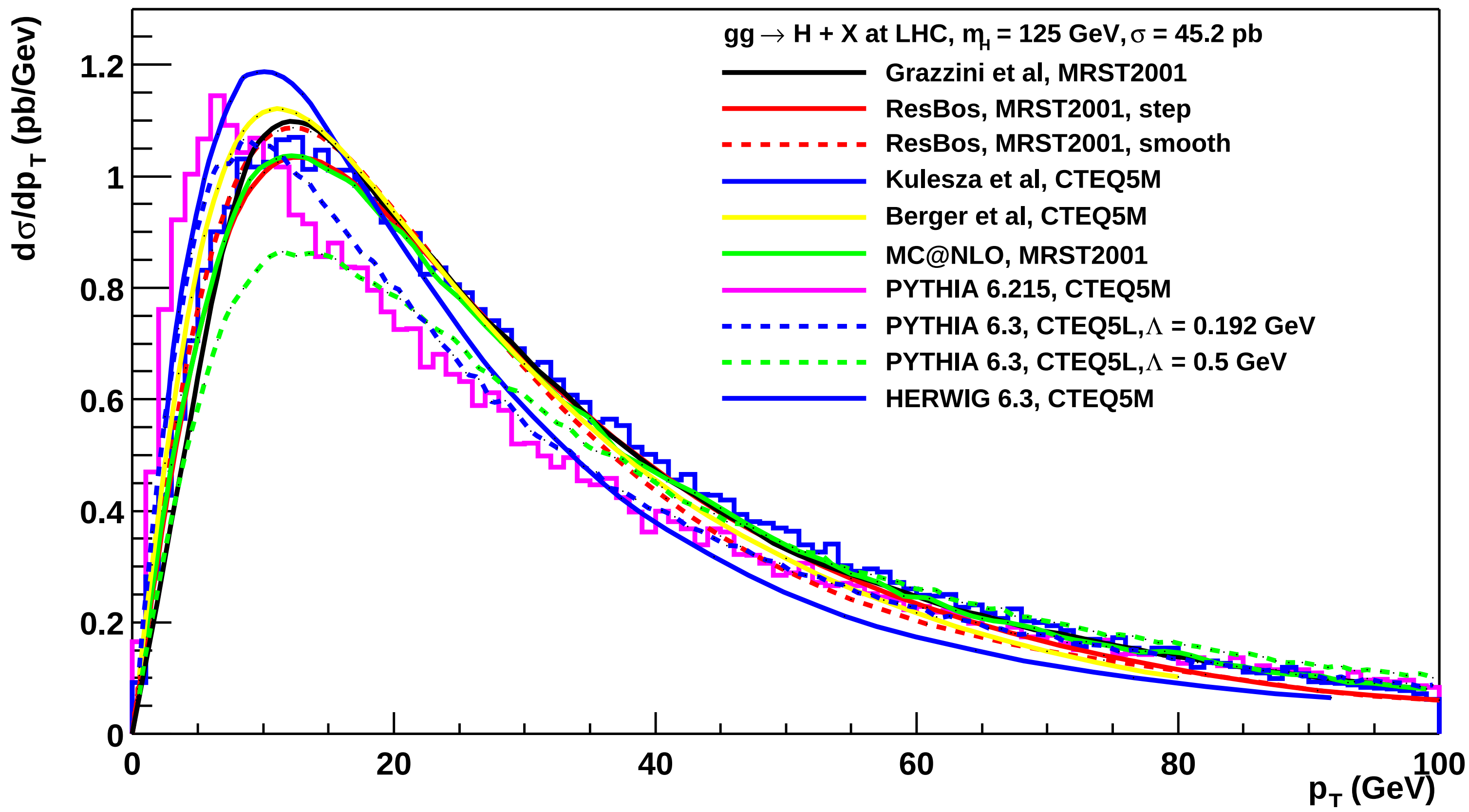
Including or not final-state showers.

CTEQ5L with $\Lambda = 0.192$ GeV.

Primordial $k_\perp = 2$ GeV.

Example with new shower

$gg \to H^0$ at the LHC:



To do

- Complete ISR: heavy flavours
- Combine FSR with ISR
- Test for pp
- Write it up

  TS, Les Houches, LU TP 04–05 [hep-ph/0401061]
- Combine with multiple interactions
- Rewrite in C++