DELPHI week, Uppsala
15 September 2000

Recent QCD Generator Developments

(A Subjective Selection)

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Introduction
Improved parton showers
a) Final state showers
b) Initial state showers
Hadronization
$\gamma^*\gamma^*$ physics
Other topics

http://www.thep.lu.se/∼torbjorn/talks/uppsala00.ps

Goodbye LEP!

...and thanks for making life exciting

4 September 1979: my first LEP workshop

13 August 1989: first LEP events

1 November 2000 (?): closedown of LEP

LEP part of a High Energy Physics Landscape:

e^+e^-:	... $\rightarrow$ PETRA/PEP $\rightarrow$ TRISTAN
	$\rightarrow$ LEP 1 $\rightarrow$ LEP 2
	$\rightarrow$ LC (TESLA/NLC/CLIC)
ep:	fixed target $\rightarrow$ HERA $\rightarrow$ LEP+LHC?
pp:	... $\rightarrow$ $Sp\overline{p}S$ $\rightarrow$ Tevatron $\rightarrow$ LHC
$\mu^+\mu^-$:	?
AA:	fixed target $\rightarrow$ RHIC $\rightarrow$ LHC

+ fixed target, underground detectors, ...

Complexity:

$$e^+e^- \quad < \mathrm{ep} \quad < \mathrm{pp} \quad < \mathrm{AA}$$
$$< \gamma\mathrm{p} \quad < \gamma\gamma$$
$$= \mathrm{ep} \quad = e^+e^-$$

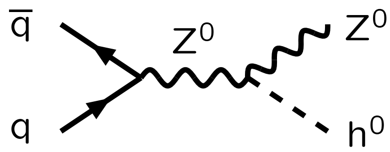
Building blocks of understanding

$\Rightarrow$ unity of observable particle physics

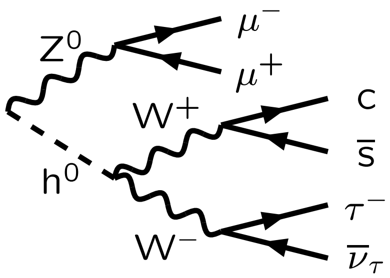
Event physics overview

Structure of the basic generation process:

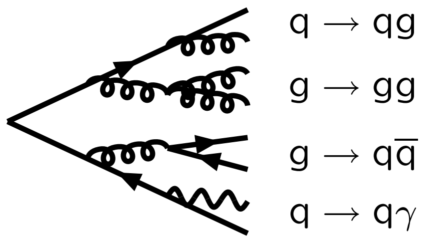
1) Hard subprocess:
$d\hat{\sigma}/d\hat{t}$, Breit-Wigners.



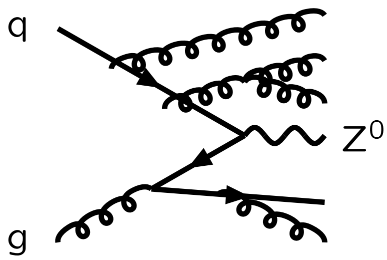
2) Resonance decays:
includes correlations.



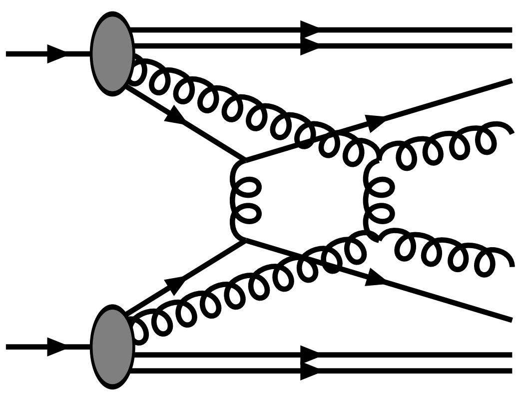
3) Final-state
parton showers:
(or matrix elements).



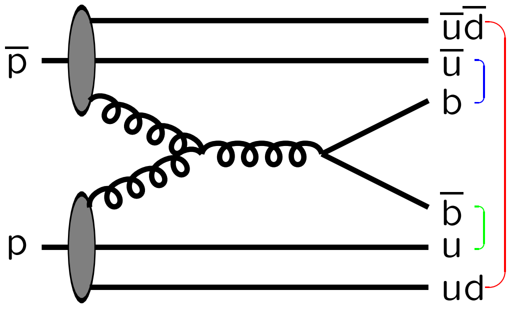
4) Initial-state
parton showers:
(or matrix elements).



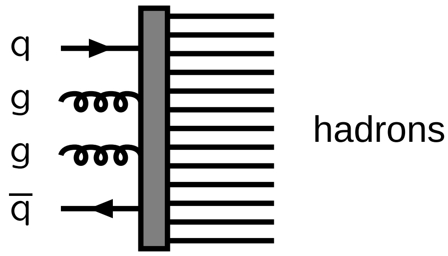
5) Multiple
parton–parton
interactions.



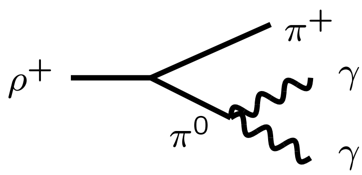
6) Beam remnants:
colour-connected
to rest of event



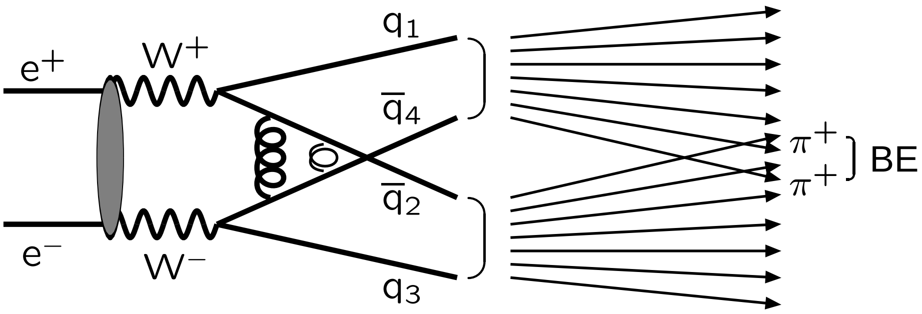
7) Hadronization
(PYTHIA: string;
HERWIG: cluster;
ISAJET: independent).



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



9) QCD interconnection effects:



a) colour rearrangement ($\Rightarrow$ rapidity gaps?);
b) Bose-Einstein.

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

The rôle of exploration, be it experimental, theoretical, or phenomenological:

- to predict: too late for LEP
  $\Rightarrow$ LHC/LC/...
- to explain/understand: never too late

LEP will provide the reference for

- final-state QCD showers
- hadronization
- $\gamma\gamma$ physics (?)
- some electroweak parameters: m_Z ...
- limits of non-observation (?)

cf. PETRA: QCD vs. top/SUSY limits

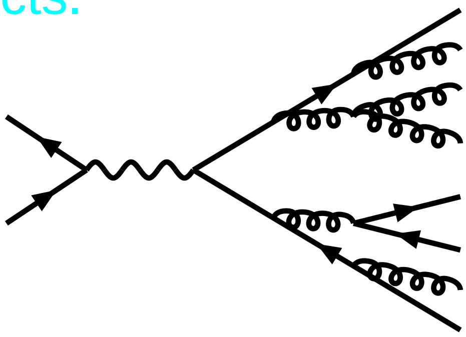
Improved models and new ideas coming along
$\Rightarrow$ important to preserve physics data in easily accessible form

HZTOOL: correct concept
wrong implementation
$\Rightarrow$ need clean, minimal interface

QCD Radiation off Heavy Particles

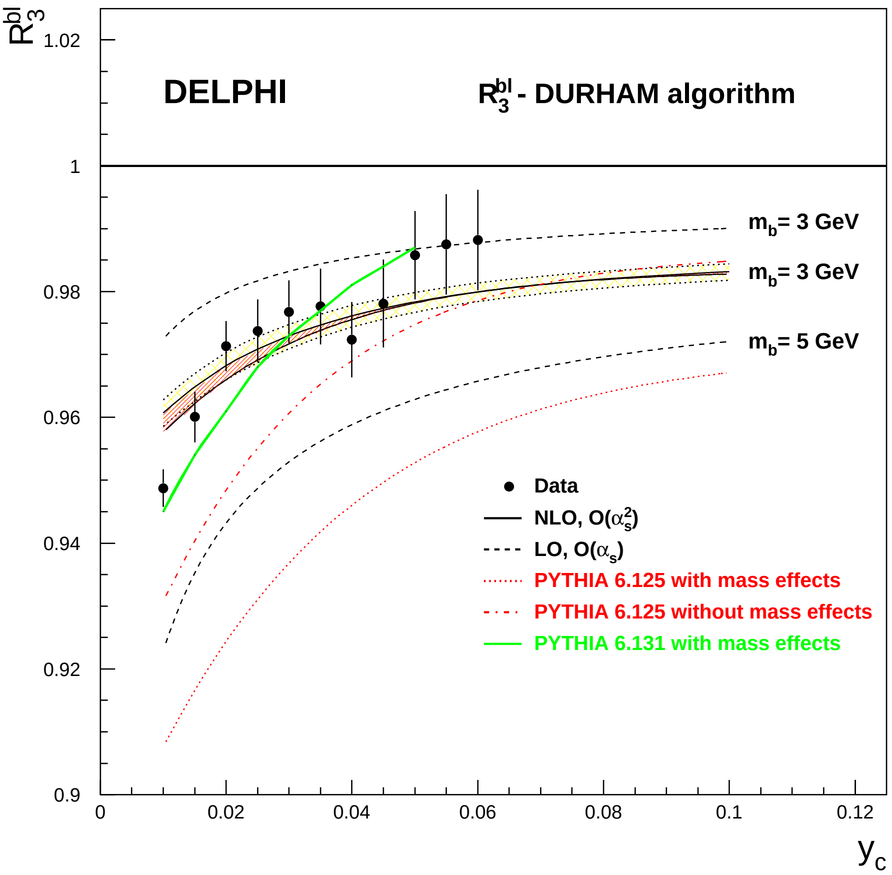
(E. Norrbin & TS, in preparation)

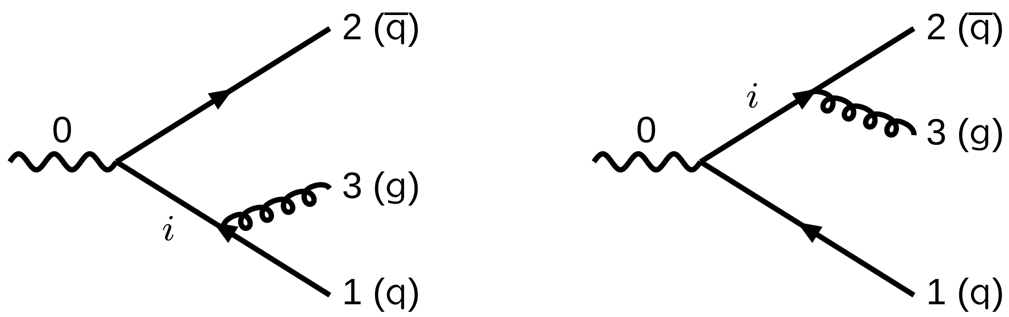
Shower: effective resummation of multiple-gluon-emission effects.



Evolution variable Q^2:
PYTHIA: m^2
HERWIG: $E^2\theta^2$
ARIADNE: $p_\perp^2$
z: energy/momentum sharing in branching

$$R_3^{\mathrm{bl}}(y_c) = \frac{R_3^{\mathrm{b}}(y_c)}{R_3^{\mathrm{u+d+s}}(y_c)} = \frac{\sigma(\mathrm{b\bar{b}} \to \mathrm{3jets})/\sigma(\mathrm{b\bar{b}})}{\sigma(\mathrm{q\bar{q}} \to \mathrm{3jets})/\sigma(\mathrm{q\bar{q}})}$$





$$x_j = 2E_j/E_{\text{CM}} \quad \Rightarrow \quad x_1 + x_2 + x_3 = 2$$

$m_{\text{q}} = 0$:

$$\frac{1}{\sigma_0}\frac{\text{d}\sigma_{\text{ME}}}{\text{d}x_1\,\text{d}x_2} = \frac{\alpha_{\text{s}}}{2\pi} C_F \frac{\overbrace{x_1^2 + x_2^2}^{\approx 2}}{(1-x_1)(1-x_2)}$$

$$\frac{1}{\sigma_0}\frac{\text{d}\sigma_{\text{PS}}}{\text{d}Q^2\,\text{d}z} = \frac{\alpha_{\text{s}}}{2\pi} C_F \frac{\text{d}Q^2}{Q^2}\frac{\overbrace{1+z^2}^{\approx 2}}{1-z}\text{d}z \cdot (\text{Sudakov})$$

$$Q_1^2 = m_i^2 = (p_0 - p_2)^2 = (1-x_2)E_{\text{CM}}^2$$

$$z_1 = \frac{p_0 p_1}{p_0 p_i} = \frac{E_1}{E_i} = \frac{x_1}{x_1 + x_3} = \frac{x_1}{2 - x_2},$$

$$\Rightarrow \frac{\text{d}Q_1^2}{Q_1^2}\frac{\text{d}z_1}{1-z_1} = \frac{\text{d}x_2}{1-x_2}\frac{\text{d}x_1}{x_3}$$

$$\Rightarrow \frac{1}{\sigma_0}\frac{\text{d}\sigma_{\text{PS}}}{\text{d}x_1\,\text{d}x_2} \propto \frac{2}{(1-x_2)x_3} + \frac{2}{(1-x_1)x_3} = \frac{2}{(1-x_1)(1-x_2)}$$

since $(1-x_1)+(1-x_2)=x_3$

$\Rightarrow$ ME/PS $<$ 1, i.e. good MC starting point

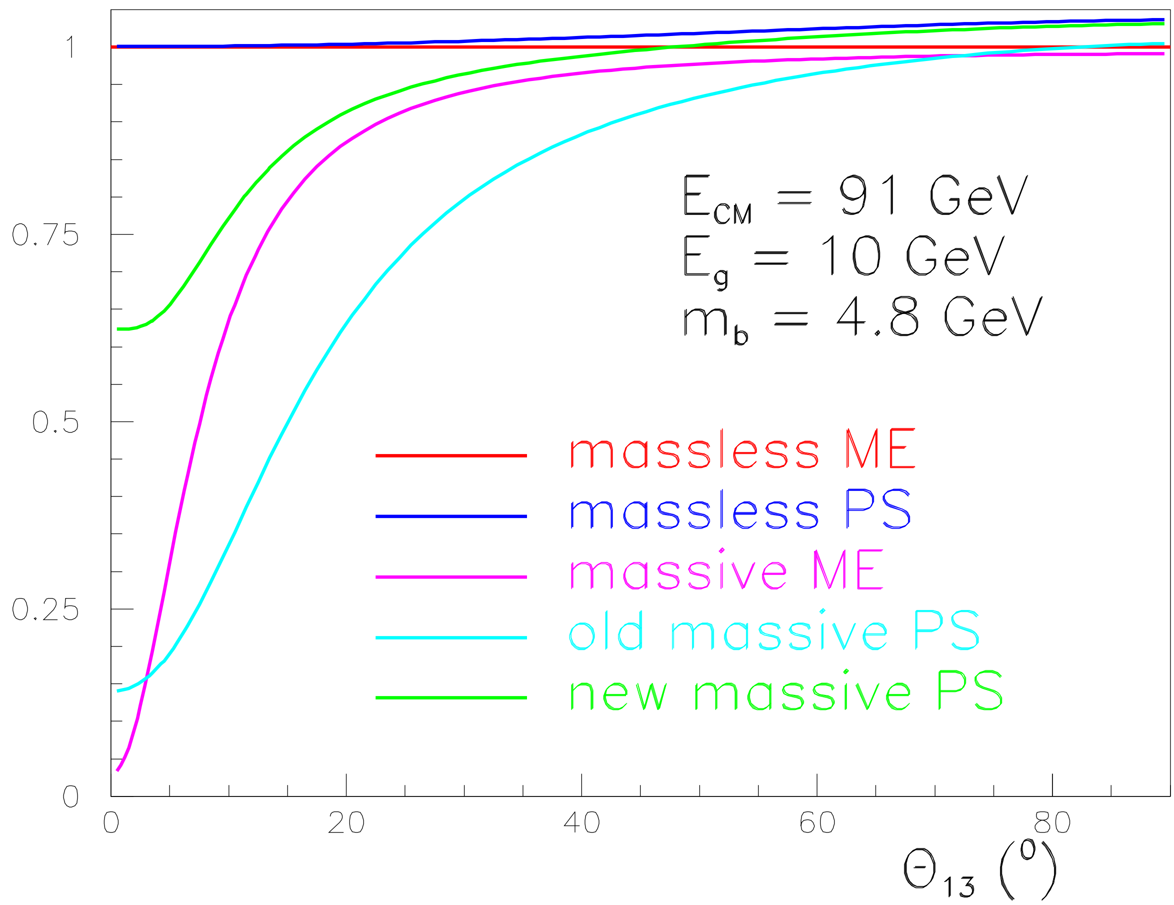
$r = m_{\mathrm{q}}/E_{\mathrm{CM}} > 0$:

$$\frac{1}{\sigma_0}\frac{\mathrm{d}\sigma_{\mathrm{ME}}}{\mathrm{d}x_1\,\mathrm{d}x_2} \propto \frac{x_1^2 + x_2^2 - r^2(\ldots)}{(1-x_1)(1-x_2)}$$

$$Q_1^2 = m_i^2 = (p_0 - p_2)^2 = (1 - x_2 + r^2)E_{\mathrm{CM}}^2$$

z more messy but $\mathrm{d}z/(1-z)$ unchanged

$$\Rightarrow \frac{1}{\sigma_0}\frac{\mathrm{d}\sigma_{\mathrm{PS}}}{\mathrm{d}x_1\,\mathrm{d}x_2} \propto \frac{2}{(1-x_1+r^2)x_3} + \frac{2}{(1-x_2+r^2)x_3}$$



restore by

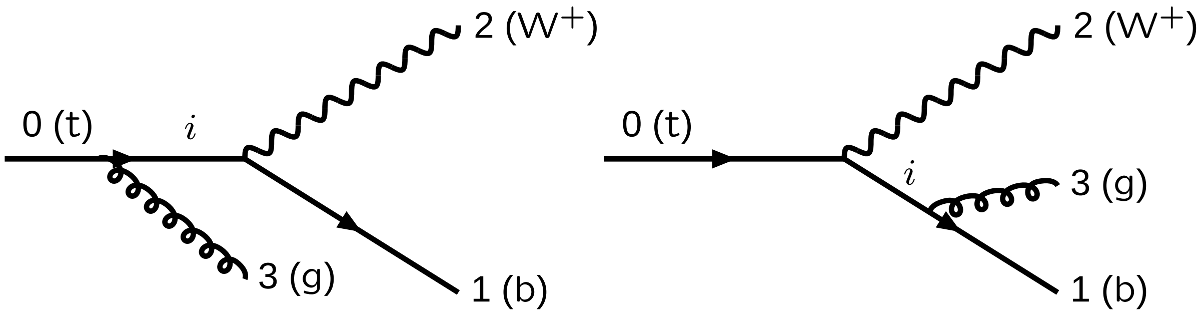
$$Q_1^2 = m_i^2 - m_{\mathrm{q}}^2 = (p_0 - p_2)^2 - p_1^2 = (1 - x_2)E_{\mathrm{CM}}^2$$

$Q_j^2 = m_j^2 - m_{j,\mathrm{onshell}}^2$ is relevant propagator;

generalized for $r_1 \neq r_2$, $r_j = m_j/E_{\mathrm{CM}}$:

$$
\begin{aligned}
Q_1^2 &= (1 + r_2^2 - r_1^2 - x_2)E_{\mathrm{CM}}^2 \\
Q_2^2 &= (1 + r_1^2 - r_2^2 - x_1)E_{\mathrm{CM}}^2 \\
\frac{1}{\sigma_0}\frac{\mathrm{d}\sigma_{\mathrm{ME}}}{\mathrm{d}x_1\,\mathrm{d}x_2} &= \frac{(\ldots)}{Q_1^2 Q_2^2} - \frac{(\ldots)}{Q_1^4} - \frac{(\ldots)}{Q_2^4}
\end{aligned}
$$

Also radiation from decaying particle:



$$Q_0^2 = |m_i^2 - m_0^2| = |(p_0 - p_3)^2 - m_0^2| = x_3 E_{\mathrm{CM}}^2$$

ME $\frac{1}{Q_0^2 Q_1^2}$ matches PS b $\to$ bg

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

- subsequent branchings: also matched to ME, with reduced energy of system
- angular ordering
- $\alpha_{\mathrm{s}}(p_\perp^2)$
- secondary heavy flavours by gluon splitting
- widths of unstable particles: for the future

Calculate for $1 \to 2$ processes in SM + MSSM:

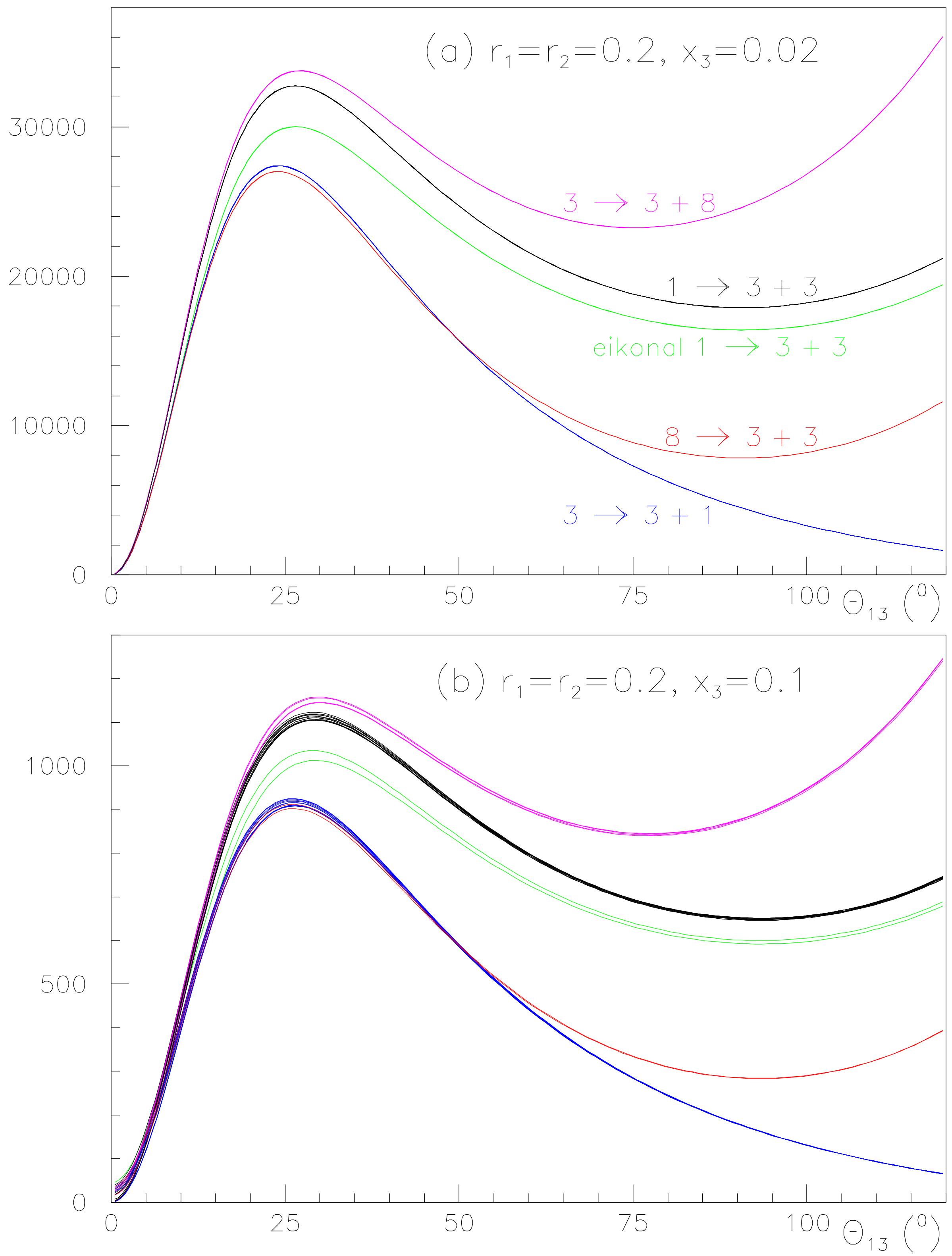
$$\frac{1}{\sigma(a \to bc)} \frac{\mathrm{d}\sigma(a \to bc\mathrm{g})}{\mathrm{d}x_1\,\mathrm{d}x_2}$$

Depends on

- mass ratios $r_1 = m_b/m_a$ and $r_2 = m_c/m_a$
- colour and spin structure
- vector vs. axial vector etc. (γ_5) when $m_b, m_c \neq 0$

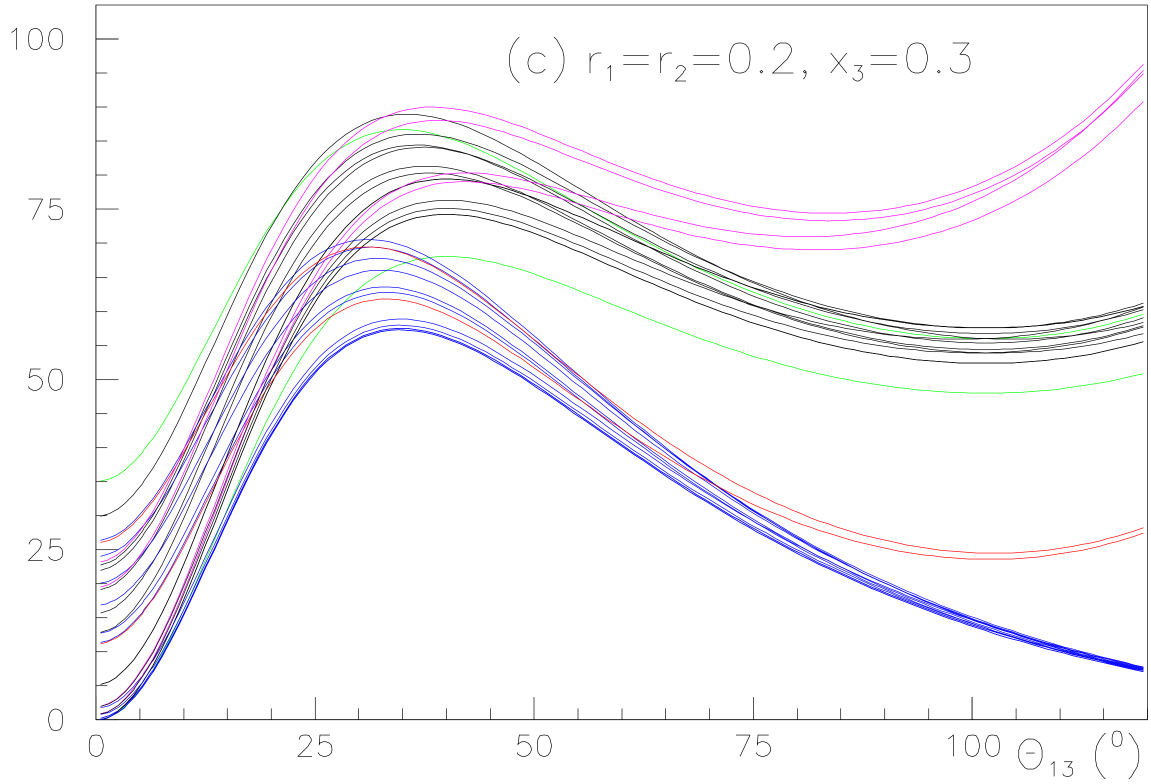
colour	spin	γ_5	example
$1 \to 3 + \overline{3}$	—	—	(eikonal)
$1 \to 3 + \overline{3}$	$1 \to \frac{1}{2} + \frac{1}{2}$	$1, \gamma_5, 1 \pm \gamma_5$	$Z^0 \to q\overline{q}$
$3 \to 3 + 1$	$\frac{1}{2} \to \frac{1}{2} + 1$	$1, \gamma_5, 1 \pm \gamma_5$	$t \to bW^+$
$1 \to 3 + \overline{3}$	$0 \to \frac{1}{2}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

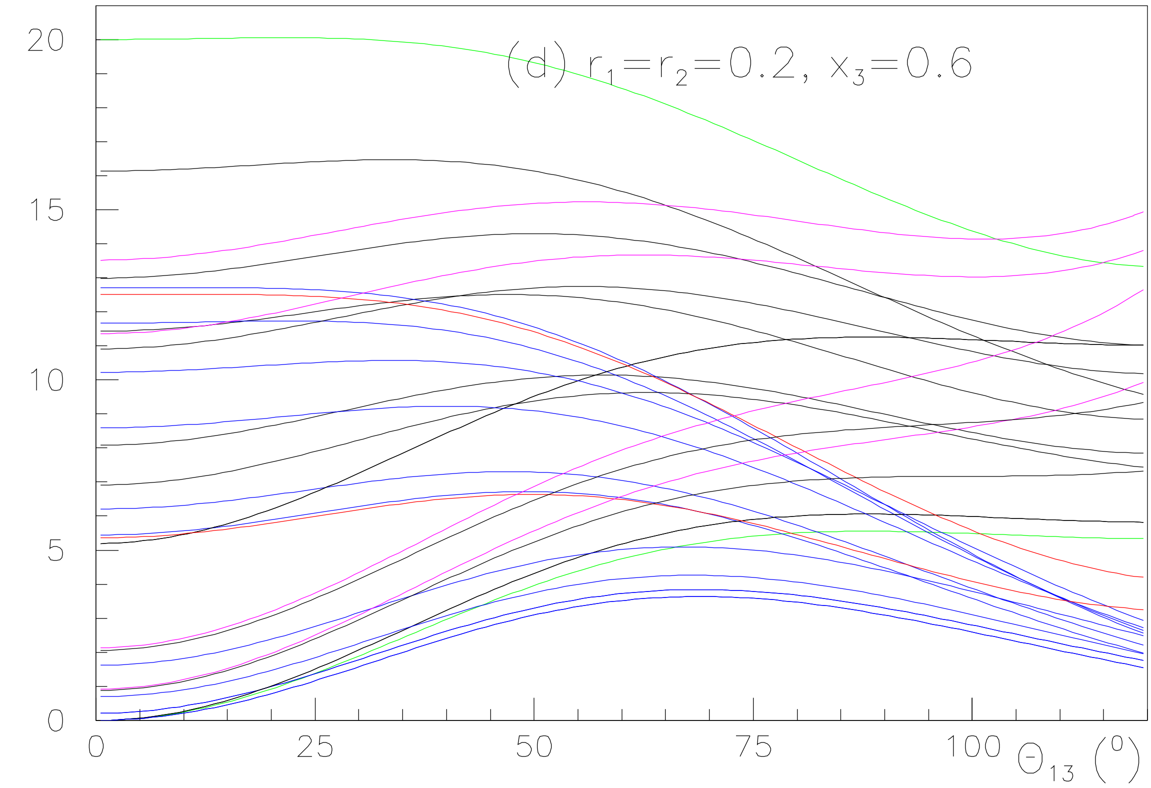
Universal gluon radiation patterns (= no spin dependence) for small gluon energies . . .



(with textbook dead cone)

...but very process-dependent for large gluon energies ...

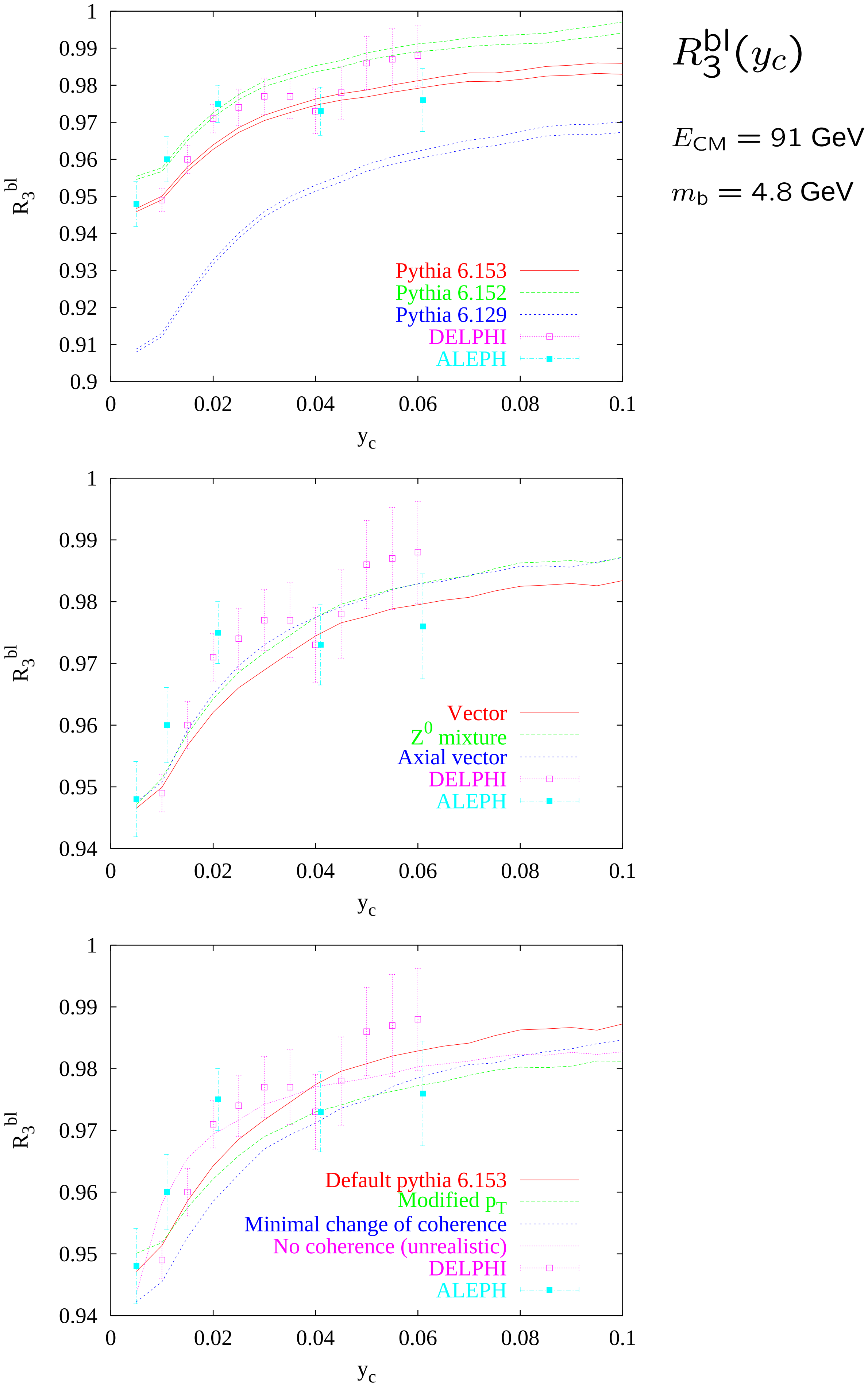




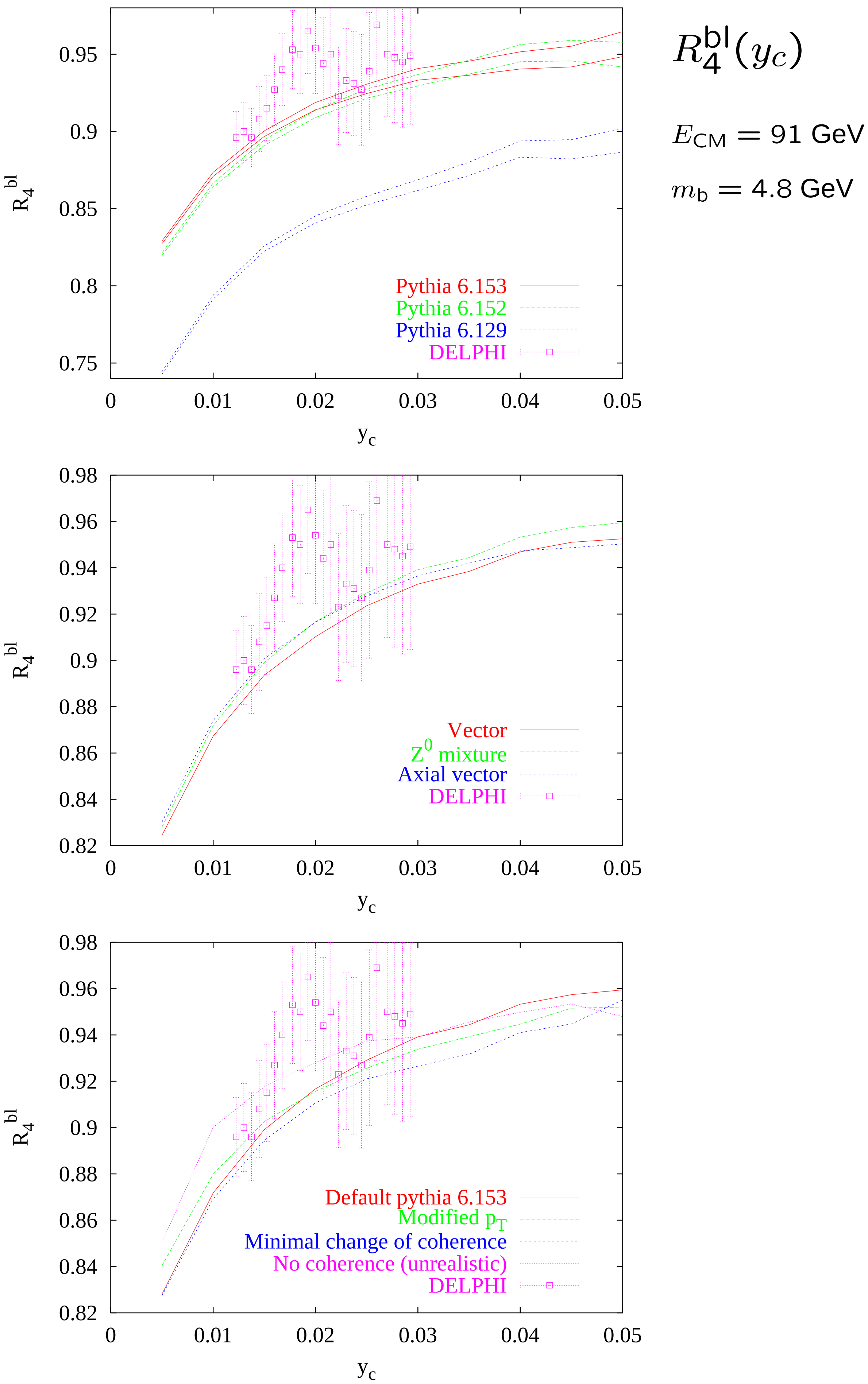
(and no dead cone except for spin $0 \to 0 + 0$)

...results in process-dependent jet rates

			$r_1 = r_2 = 0.2$		
colour	spin	γ_5	E_g	3 jet	3 jet'
$1 \to 3 + \overline{3}$	$1 \to \frac{1}{2} + \frac{1}{2}$	1	1.000	1.000	1.000
		γ_5	1.056	1.112	1.133
	$0 \to \frac{1}{2} + \frac{1}{2}$	1	1.134	1.293	1.376
		γ_5	1.093	1.207	1.271
	$1 \to 0 + 0$	1	1.073	1.205	1.310
	$0 \to 0 + 0$	1	0.875	0.758	0.720
	$\frac{1}{2} \to \frac{1}{2} + 0$	1	0.953	0.918	0.916
		γ_5	1.057	1.132	1.179
$1 \to 3 + \overline{3}$	eikonal	–	0.802	0.695	0.659
	eikonal $+x_3^2$	–	1.201	1.518	1.670
$3 \to 3 + 1$	$\frac{1}{2} \to \frac{1}{2} + 1$	1	0.323	0.306	0.287
		γ_5	0.356	0.365	0.349
	$\frac{1}{2} \to \frac{1}{2} + 0$	1	0.312	0.284	0.258
		γ_5	0.357	0.363	0.344
	$0 \to 0 + 1$	1	0.287	0.242	0.218
	$0 \to 0 + 0$	1	0.279	0.224	0.194
	$0 \to \frac{1}{2} + \frac{1}{2}$	1	0.359	0.379	0.375
		γ_5	0.347	0.354	0.346
	$\frac{1}{2} \to 0 + \frac{1}{2}$	1	0.294	0.257	0.239
		γ_5	0.314	0.302	0.298
$3 \to 3 + 8$	$0 \to \frac{1}{2} + \frac{1}{2}$	1	1.634	1.833	1.922
		γ_5	1.574	1.712	1.775
	$\frac{1}{2} \to 0 + \frac{1}{2}$	1	1.385	1.320	1.291
		γ_5	1.549	1.664	1.675
$8 \to 3 + \overline{3}$	$\frac{1}{2} \to \frac{1}{2} + 0$	1	0.561	0.493	0.445
		γ_5	0.621	0.607	0.574



R_3^bl(y_c)
E_CM = 91 GeV
m_b = 4.8 GeV
R_3^bl
y_c
Pythia 6.153
Pythia 6.152
Pythia 6.129
DELPHI
ALEPH
Vector
Z^0 mixture
Axial vector
Default pythia 6.153
Modified p_T
Minimal change of coherence
No coherence (unrealistic)



$R_4^{\rm bl}(y_c)$
$E_{\rm CM} = 91$ GeV
$m_{\rm b} = 4.8$ GeV
$R_4^{\rm bl}$
y_c
Pythia 6.153
Pythia 6.152
Pythia 6.129
DELPHI
Vector
Z^0 mixture
Axial vector
DELPHI
Default pythia 6.153
Modified p_T
Minimal change of coherence
No coherence (unrealistic)
DELPHI

HERWIG shower developments

(B. Webber, http://home.cern.ch/webber/)

Combine ME and PS for multijet production,
e.g. $e^+e^- \to$ 2 jet + 3 jet + 4 jet + ...

Define jet separation e.g. by Durham $p_\perp$
$y_{ij} = 2\min(E_i^2, E_j^2)(1 - \cos\theta_{ij})/E_{\mathrm{CM}}^2 \approx p_\perp^2/E_{\mathrm{CM}}^2$

For $y_{ij} > y_c$: exclusive multijet states by
ME · Sudakov
Sudakov: needs reconstructed shower history, by Durham clustering

For $y_{ij} < y_c$: further evolution by vetoed PS
Veto: Durham $p_\perp^2 \neq$ HERWIG Q^2
$\Rightarrow$ do evolution from $Q_{\mathrm{max}} \sim E_{\mathrm{CM}}$
but reject branchings that would give
extra jet by Durham $p_\perp$ definition

Correct to NLL = next-to-leading logarithm
but not to NLO = next-to-leading order
$\Rightarrow$ further development

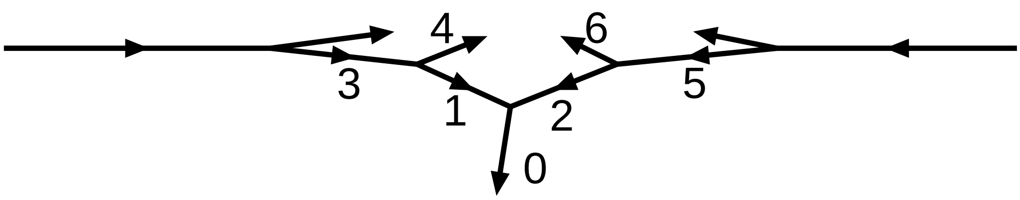
Photon ISR in Z^0 production

(G. Miu & TS, PLB449 (1999) 313)

By-product of a study on $W^{\pm}$ production in hadron colliders, attempting to combine matrix-element (ME) and parton-shower (PS) strengths.

Merging strategy: correct hardest emissions in showers so as to reproduce one order higher matrix elements.

$2 \to 1$ process $e^+(1) + e^-(2) \to Z^0(0)$ starting point for backwards shower evolution:



$2 \to 2$ process $e^+(3) + e^-(2) \to \gamma(4) + Z^0(0)$:

$$\hat{s} = (p_3 + p_2)^2 = \frac{(p_1 + p_2)^2}{z} = \frac{m_Z^2}{z}$$

$$\hat{t} = (p_3 - p_4)^2 = p_1^2 = -Q^2$$

$$\hat{u} = m_Z^2 - \hat{s} - \hat{t} = Q^2 - \frac{1-z}{z} m_Z^2$$

Relate ME and PS rates:

$$\left.\frac{d\hat{\sigma}}{d\hat{t}}\right|_{\mathrm{ME}} = \frac{\sigma_0}{\hat{s}} \frac{\alpha_{\mathrm{em}}}{2\pi} \frac{\hat{t}^2 + \hat{u}^2 + 2m_Z^2\hat{s}}{\hat{t}\hat{u}}$$

$$\stackrel{Q^2\to 0}{\longrightarrow} \sigma_0 \frac{\alpha_{\mathrm{em}}}{2\pi} \frac{1+z^2}{1-z} \frac{1}{Q^2} = \left.\frac{d\hat{\sigma}}{dQ^2}\right|_{\mathrm{PS1}}$$

$$\left.\frac{d\hat{\sigma}}{d\hat{t}}\right|_{\mathrm{PS1}} = \frac{\sigma_0}{\hat{s}} \frac{\alpha_{\mathrm{em}}}{2\pi} \frac{\hat{s}^2 + m_Z^4}{\hat{t}(\hat{t}+\hat{u})}$$

Add mirror $e^+(1) + e^-(5) \to \gamma(6) + Z^0(0)$:

$$\left.\frac{d\hat{\sigma}}{d\hat{t}}\right|_{\mathrm{PS}} = \left.\frac{d\hat{\sigma}}{d\hat{t}}\right|_{\mathrm{PS1}} + \left.\frac{d\hat{\sigma}}{d\hat{t}}\right|_{\mathrm{PS2}} = \frac{\sigma_0}{\hat{s}} \frac{\alpha_{\mathrm{em}}}{2\pi} \frac{\hat{s}^2 + m_Z^4}{\hat{t}\hat{u}}$$

$$R_{ee\to\gamma Z}(\hat{s},\hat{t}) = \frac{(d\hat{\sigma}/d\hat{t})_{\mathrm{ME}}}{(d\hat{\sigma}/d\hat{t})_{\mathrm{PS}}} = \frac{\hat{t}^2 + \hat{u}^2 + 2m_Z^2\hat{s}}{\hat{s}^2 + m_Z^4}$$

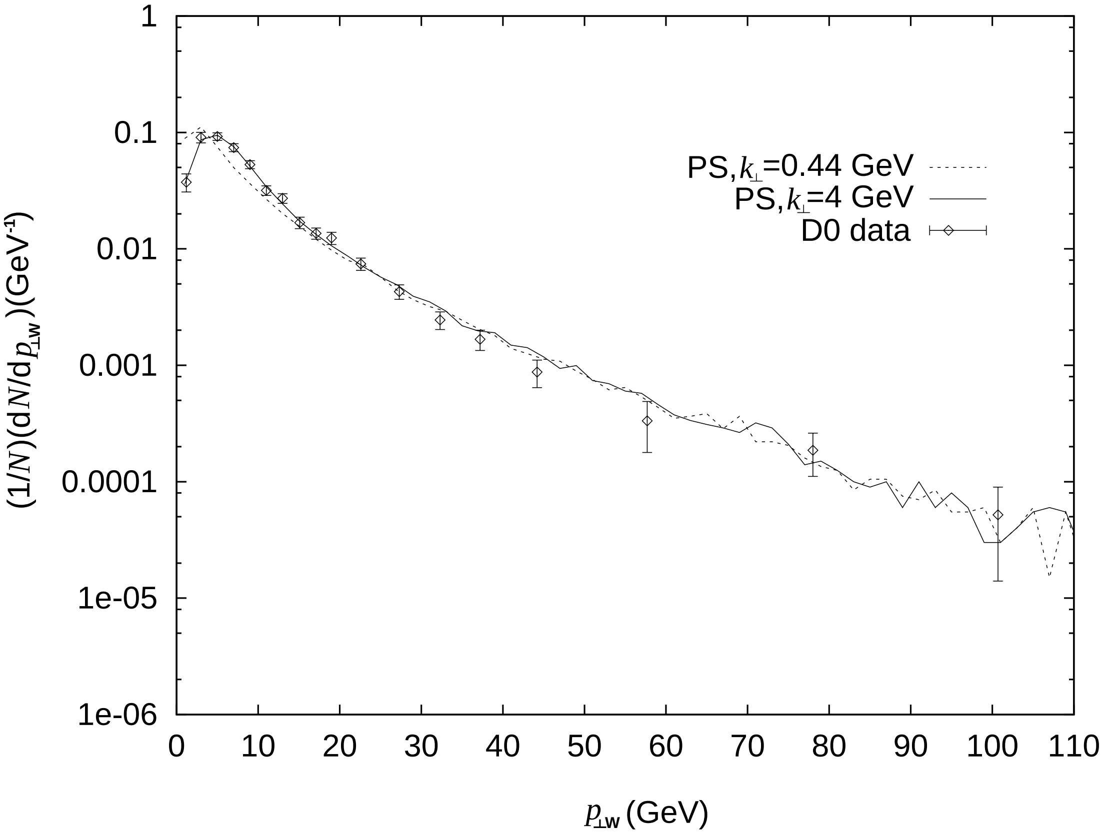
$$\frac{1}{2} < R_{ee\to\gamma Z}(\hat{s},\hat{t}) \leq 1$$

Improve PS:

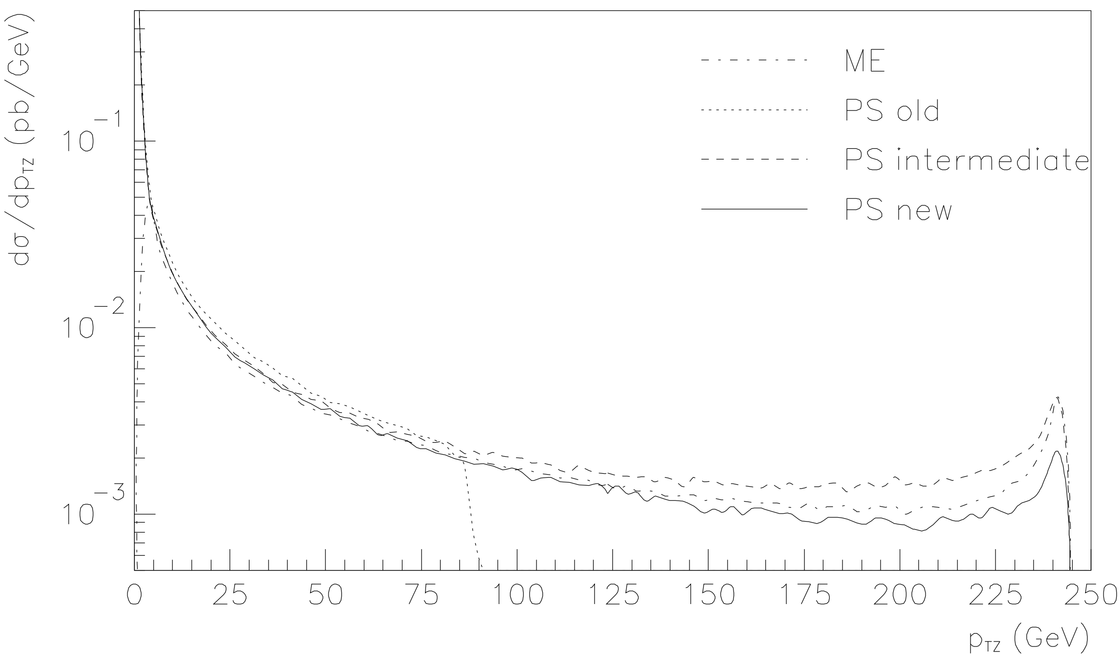
- $Q^2_{\mathrm{max}} = s$, not $Q^2_{\mathrm{max}} \approx m_Z^2$ (intermediate)
- MC correction by $R(\hat{s},\hat{t})$ for first ($\approx$ hardest) emission on each side (new)

Now default.

$p\overline{p} \to W^{\pm}$ at 1.8 TeV:



$e^+e^- \to Z^0$ at 500 GeV,
80 GeV $< \sqrt{\hat{s}} <$ 100 GeV:



Hadronization

Lund string successful . . .

even HERWIG adopts 'stringy' description:
• large-mass clusters split in two
• small-mass clusters decay anisotropically along 'string' direction

. . . but many murky issues

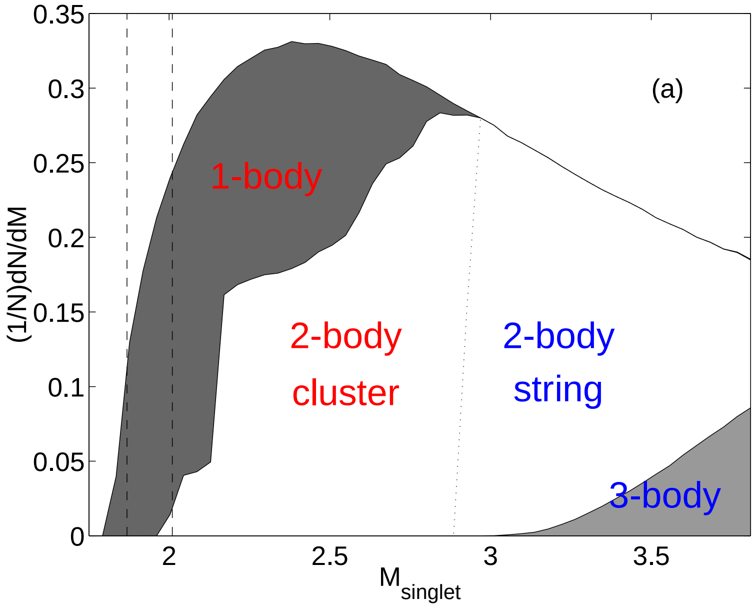
- perturbative ⇒ nonperturbative transition
- ambiguities of gluon structure
- origin of flavour composition
(hadron vs. quark masses, wave functions)
- baryon production mechanism
(diquark, popcorn, 'curtain' quark)
- rôle of higher resonances: tensor etc.
(poorly known, nonisotropic decays, duality with string description)
- spin/polarization phenomena
- interconnection
(colour rearrangement, Bose–Einstein)

Small-mass string ⇒ 'cluster',
by $\mathrm{g} \to \mathrm{q}\overline{\mathrm{q}}$ in shower

(E. Norrbin & TS, PLB442 (1998) 407,
LUTP 00-16 (hep-ph/0005110)

Improved description of when collapse occurs
(mass spectrum ⇐ constituent quark masses)

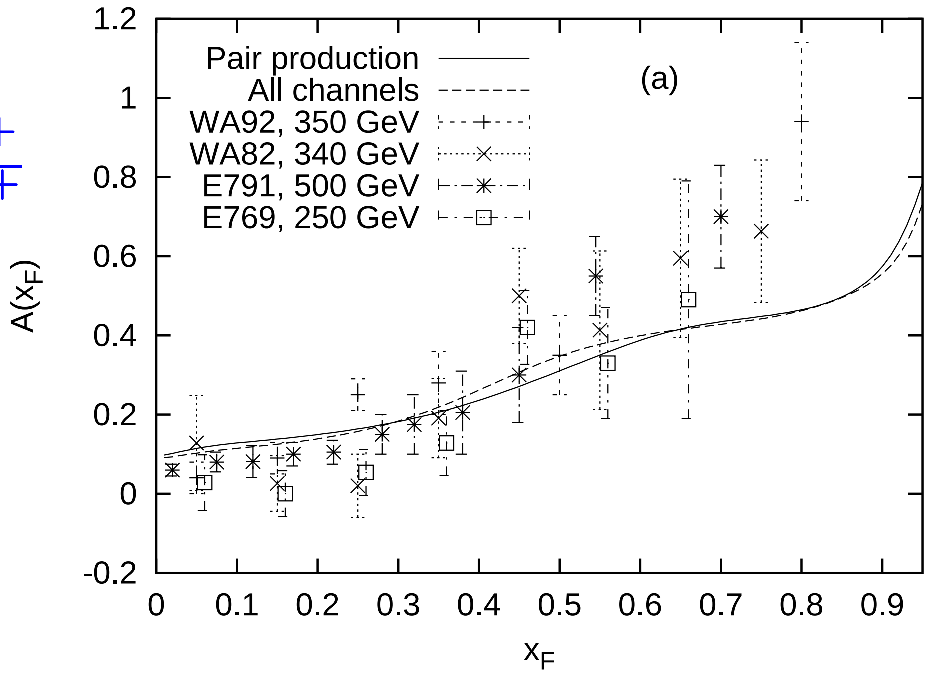
example:
charm
string
in πp
collision



and
1-body collapse: energy-momentum shuffling
2-body decay: smoother joining to string
picture (matched anisotropic decay)

$$A(x_F) = \frac{\#D^- - \#D^+}{\#D^- + \#D^+}$$

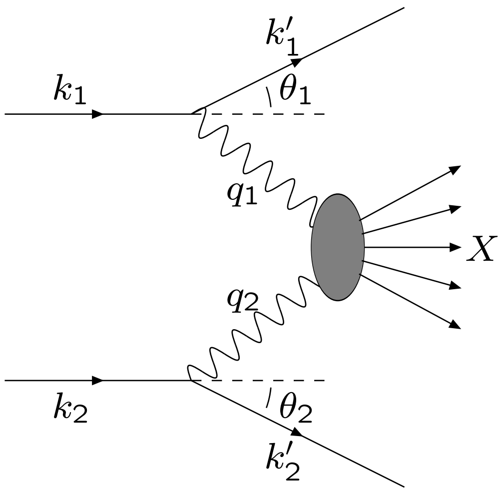
in π^-p



Virtual photon processes

(C. Friberg & TS, Eur. Phys. J. C13 (2000) 151,
LUTP 00-29 (hep-ph/0007314), LUTP 00-31 (hep-ph/0009003))

The photon flux



$$W^2 = (q_1 + q_2)^2$$
$$Q_i^2 = -q_i^2$$
$$y_i = \frac{q_i k_j}{k_i k_j} \quad j\!=\!2(1) \text{ for } i\!=\!1(2)$$
$$x_i = \frac{q_i(k_1 + k_2)}{k_i(k_1 + k_2)}$$
$$y_i \approx x_i + \frac{Q_i^2}{s}$$

$$Q_i^2 \approx \frac{x_i^2}{1 - x_i} m_i^2 + (1 - x_i) s \sin^2(\theta_i/2)$$

$$\mathrm{d}\sigma(\mathrm{ee} \to \mathrm{ee}X) = \sum_{\xi_1,\xi_2=\mathrm{T,L}} \int \mathrm{d}y_1\,\mathrm{d}Q_1^2\,\mathrm{d}y_2\,\mathrm{d}Q_2^2$$

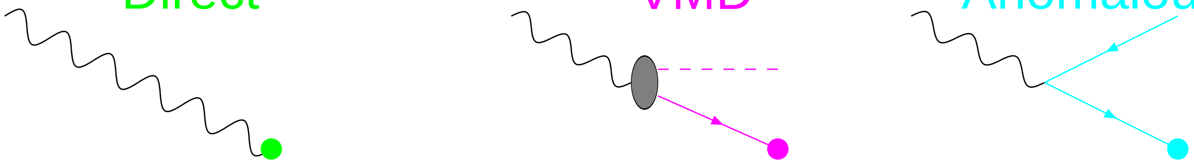
$$\times\; f_{\gamma/\mathrm{e}}^{\xi_1}(y_1, Q_1^2)\; f_{\gamma/\mathrm{e}}^{\xi_2}(y_2, Q_2^2)\; \mathrm{d}\sigma(\gamma^*_{\xi_1}\gamma^*_{\xi_2} \to X)$$

with

$$f_{\gamma/\mathrm{e}}^{\mathrm{T}}(y, Q^2) = \frac{\alpha_{\mathrm{em}}}{2\pi}\left(\frac{(1 + (1 - y)^2}{y}\frac{1}{Q^2} - \frac{2m_{\mathrm{e}}^2 y}{Q^4}\right)$$

$$f_{\gamma/\mathrm{e}}^{\mathrm{L}}(y, Q^2) = \frac{\alpha_{\mathrm{em}}}{2\pi}\frac{2(1 - y)}{y}\frac{1}{Q^2}$$

Photoproduction / $\gamma\gamma$



Direct: point-like Resolved: hadronic state

$\gamma\gamma$: $3 \times 3 = 9$ combinations (+ subdivisions)

Spectrum of fluctuations $\gamma \leftrightarrow \mathrm{q\bar{q}} \propto \mathrm{d}k_{\perp}^2/k_{\perp}^2$
alt. $m \simeq 2k_{\perp}$; $\mathrm{d}m^2/m^2$

$\star$ $k_{\perp} < k_0 \simeq 0.5$ GeV: nonperturbative $\gamma \to \mathrm{q\bar{q}}$
hadronic physics $\Rightarrow$ VMD
(Vector Meson Dominance)
parameterized couplings to ρ^0, ω, ϕ, J/ψ
$\sigma_{\mathrm{tot}}^{\gamma\to\rho} = \mathcal{P}(\gamma \to \rho) \cdot \sigma_{\mathrm{tot}}^{\rho}$
PDF $f_i^{\gamma\to\rho}(x, \mu^2)$, $\sigma_{\mathrm{jet}}^{\gamma\to\rho} = \ldots$
beam remnants, multiple interactions, ...

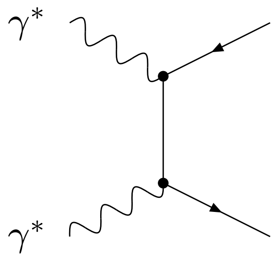
$\star$ $k_{\perp} > k_0$: perturbative $\gamma \to \mathrm{q\bar{q}}$
PDF calculable: anomalous part of γ
but $\sigma_{\mathrm{tot}}^{\mathrm{q\bar{q}}}$ not $\Rightarrow$ GVMD (Generalized VMD)
geometric scaling ansatz $\sigma_{\mathrm{tot}}^{\mathrm{q\bar{q}}} \propto k_V^2/k_{\perp}^2$,
$k_V \simeq m_{\rho}/2$ for light quarks
again hadronic character: beam remnants, ...

Photon 'high-$p_\perp$' processes

Three main 'high-$p_\perp$' jet process classes:

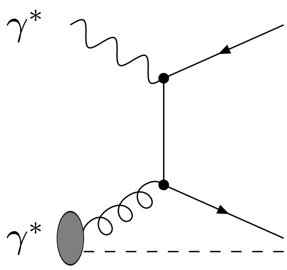
1. direct$\times$direct

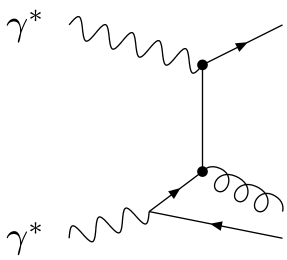
$\gamma^*_\mathrm{T}\gamma^*_\mathrm{T} \to \mathrm{q}\overline{\mathrm{q}}$
$\gamma^*_\mathrm{T}\gamma^*_\mathrm{L} \to \mathrm{q}\overline{\mathrm{q}}$
$\gamma^*_\mathrm{L}\gamma^*_\mathrm{L} \to \mathrm{q}\overline{\mathrm{q}}$



2. direct$\times$resolved , resolved = VMD or anomalous

$\gamma^*_\mathrm{T}\mathrm{g} \to \mathrm{q}\overline{\mathrm{q}}$
$\gamma^*_\mathrm{L}\mathrm{g} \to \mathrm{q}\overline{\mathrm{q}}$
$\gamma^*_\mathrm{T}\mathrm{q} \to \mathrm{qg}$
$\gamma^*_\mathrm{L}\mathrm{q} \to \mathrm{qg}$

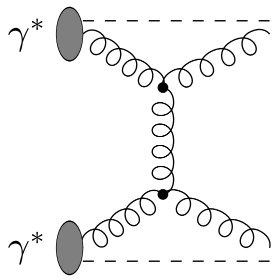


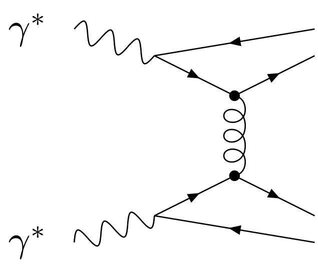


etc.

3. resolved$\times$resolved

$\mathrm{qq}' \to \mathrm{qq}'$
$\mathrm{q}\overline{\mathrm{q}} \to \mathrm{q}'\overline{\mathrm{q}}'$
$\mathrm{q}\overline{\mathrm{q}} \to \mathrm{gg}$
$\mathrm{qg} \to \mathrm{qg}$
$\mathrm{gg} \to \mathrm{gg}$
$\mathrm{gg} \to \mathrm{q}\overline{\mathrm{q}}$





etc.

$$\mathrm{d}\sigma(\gamma^*\gamma^* \to X) = \left(\int \mathrm{d}\widehat{x}_1 \, f_i^{\gamma^*}(\widehat{x}_1, \mu^2, Q_1^2) \right)$$

$$\times \left(\int \mathrm{d}\widehat{x}_2 \, f_j^{\gamma^*}(\widehat{x}_2, \mu^2, Q_2^2) \right) \int \mathrm{d}\widehat{t} \, \frac{\mathrm{d}\widehat{\sigma}}{\mathrm{d}\widehat{t}}(\widehat{s} = \widehat{x}_1 \widehat{x}_2 W^2)$$

Deeply Inelastic Scattering / $\gamma^*\gamma$

Virtual photon: $\gamma^*\mathrm{q} \to \mathrm{q}$, e.g. q in (VMD) ρ^0

$$\sigma_{\mathrm{tot}}^{\gamma^*\rho} \simeq \frac{4\pi^2\alpha_{\mathrm{em}}}{Q^2} F_2^{\rho}(x, Q^2) \simeq \frac{4\pi^2\alpha_{\mathrm{em}}}{Q^2} \sum_{\mathrm{q},\overline{\mathrm{q}}} e_{\mathrm{q}}^2 \, xq(x, Q^2)$$

but $F_2 \to 0$ for $Q^2 \to 0$ by gauge invariance,
+ limit doublecounting with photoproduction

$$\sigma_{\mathrm{DIS}}^{\gamma^*\rho} \simeq \left(\frac{Q^2}{Q^2 + m_\rho^2} \right)^2 \frac{4\pi^2\alpha_{\mathrm{em}}}{Q^2} \sum_{\mathrm{q},\overline{\mathrm{q}}} e_{\mathrm{q}}^2 \, xq(x, Q^2)$$

where $q(x, Q^2)$ frozen for $Q^2 < Q_0^2$;
and prefactor ensures $\sigma_{\mathrm{DIS}} \to 0$ for $Q^2 \to 0$

$$\mathcal{O}(\alpha_{\mathrm{s}}) \text{ DIS} = \left\{ \begin{array}{c} \text{QCDC } \gamma^*\mathrm{q} \to \mathrm{qg} \\ \text{BGF } \gamma^*\mathrm{g} \to \mathrm{q}\overline{\mathrm{q}} \end{array} \right\} = \text{dir} \times \text{res}$$

$$\sigma_{\text{LO DIS}}^{\gamma^*\rho} = \sigma_{\mathrm{DIS}}^{\gamma^*\rho} - \sigma_{\mathrm{dir}\times\mathrm{res}}^{\gamma^*\rho} \to \sigma_{\mathrm{DIS}}^{\gamma^*\rho} \exp\left(-\frac{\sigma_{\mathrm{dir}\times\mathrm{res}}^{\gamma^*\rho}}{\sigma_{\mathrm{DIS}}^{\gamma^*\rho}} \right)$$

corresponds to Sudakov form factor

$\gamma\gamma$:	9	combinations = (dir+VMD+GVMD)^2
$\gamma^*\gamma^*$:	+ 4	combinations = 2 sides$\times$(VMD+GVMD)
	13	!!

From Real to Virtual Photons

Direct photon: Q^2 in ME expression

Resolved photon:
total cross section $\sigma_{\mathrm{tot}}^{\gamma \to i}$ dampened by dipole

$$\left(\frac{m^2}{m^2 + Q^2} \right)^2 \quad \text{(fewer fluctuations, smaller size)}$$

VMD: $m = m_\rho, m_\omega, m_\phi, m_{\mathrm{J}/\psi}$
GVMD: $m \simeq 2k_\perp$; in total

$$\int_{k_0^2} \frac{\mathrm{d}k_\perp^2}{k_\perp^2} \frac{k_V^2}{k_\perp^2} \left(\frac{4k_\perp^2}{4k_\perp^2 + Q^2} \right)^2$$

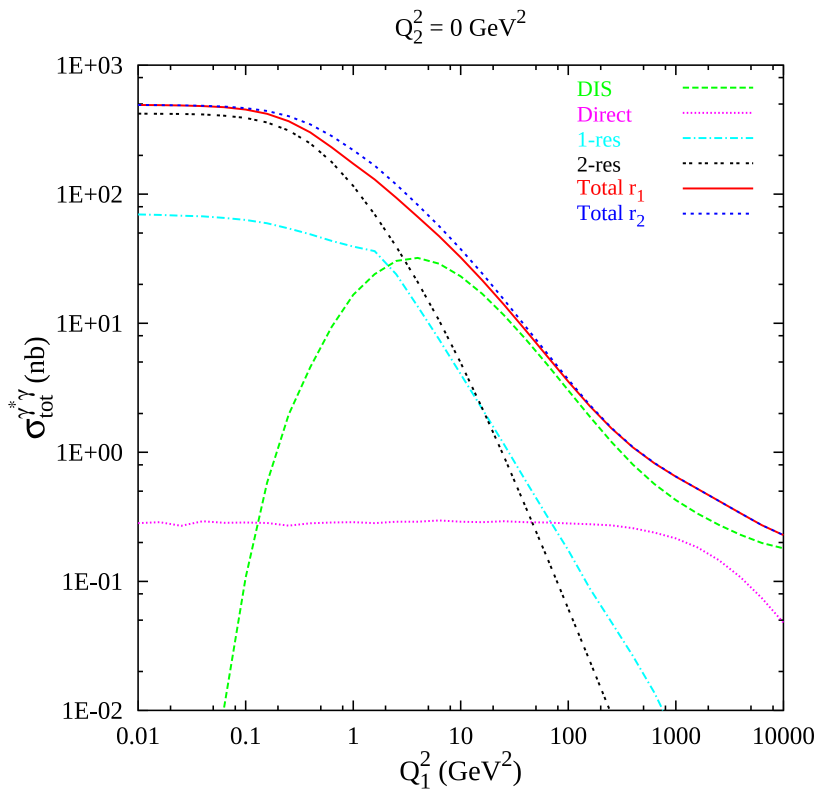
$f_i^{\gamma_\mathrm{T}^*}(x, \mu^2, Q^2)$: SaS 1D (also dipole-based)
$f_i^{\gamma_\mathrm{L}^*}(x, \mu^2, Q^2)$: simple multiplicative factor
or Chýla (hep-ph/0006232)

Putting it all together, res = VMD + GVMD:

$$\begin{aligned}
\sigma_{\mathrm{tot}}^{\gamma^*\gamma^*}(W^2, Q_1^2, Q_2^2) \quad = \quad & \sigma_{\mathrm{DIS}\times\mathrm{res}}^{\gamma^*\gamma^*} \exp\left(-\frac{\sigma_{\mathrm{dir}\times\mathrm{res}}^{\gamma^*\gamma^*}}{\sigma_{\mathrm{DIS}\times\mathrm{res}}^{\gamma^*\gamma^*}} \right) + \sigma_{\mathrm{dir}\times\mathrm{res}}^{\gamma^*\gamma^*} \\
+ \quad & \sigma_{\mathrm{res}\times\mathrm{DIS}}^{\gamma^*\gamma^*} \exp\left(-\frac{\sigma_{\mathrm{res}\times\mathrm{dir}}^{\gamma^*\gamma^*}}{\sigma_{\mathrm{res}\times\mathrm{DIS}}^{\gamma^*\gamma^*}} \right) + \sigma_{\mathrm{res}\times\mathrm{dir}}^{\gamma^*\gamma^*} \\
+ \quad & \sigma_{\mathrm{dir}\times\mathrm{dir}}^{\gamma^*\gamma^*} + \left(\frac{W^2}{Q_1^2 + Q_2^2 + W^2} \right)^3 \sigma_{\mathrm{res}\times\mathrm{res}}^{\gamma^*\gamma^*}
\end{aligned}$$

$(1 - x)^3$ reduces doublecounting at large x

Process composition



$W_{\gamma^*\gamma^*} = 100$ GeV

Direct = dir$\times$dir

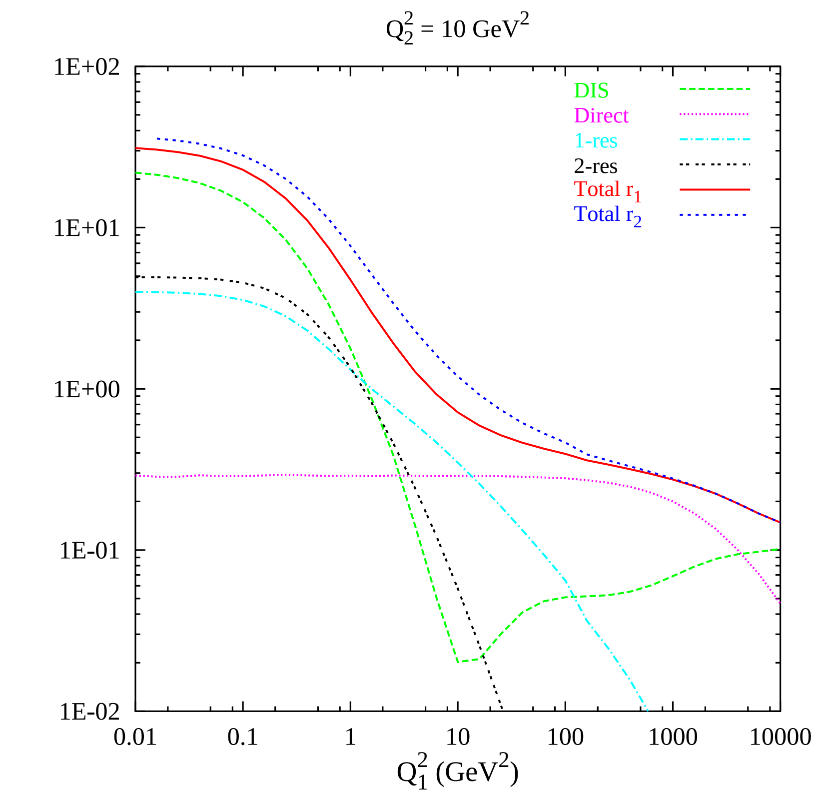
1-res = dir$\times$res

2-res= res$\times$res

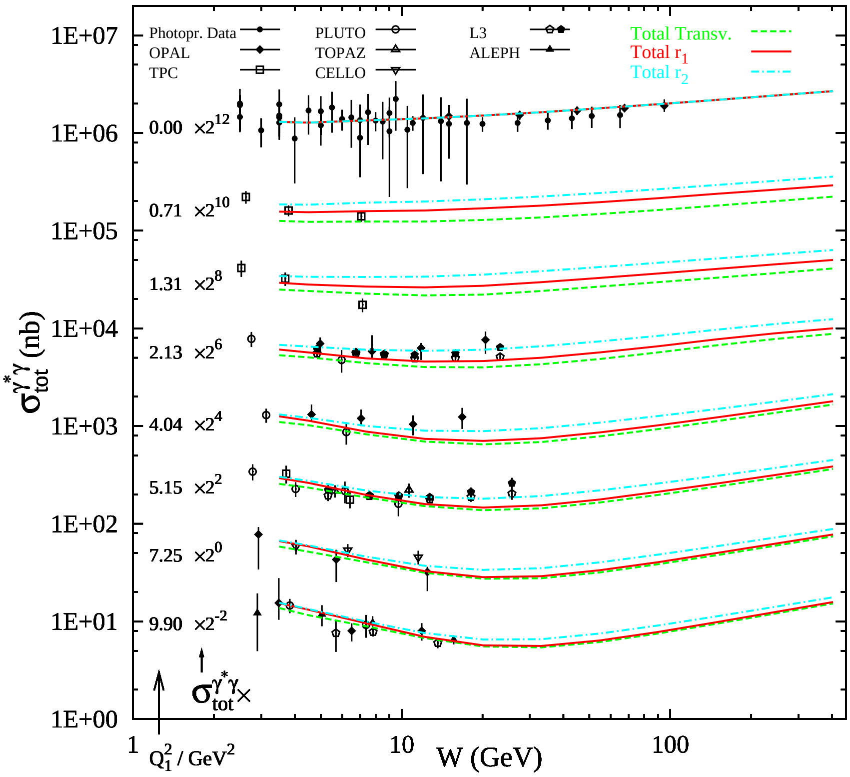
$f_i^{\gamma^*_L}/f_i^{\gamma^*_T}$:

$$r_1 = \frac{2m^2Q^2}{(m^2+Q^2)^2}$$

$$r_2 = \frac{2Q^2}{m^2+Q^2}$$



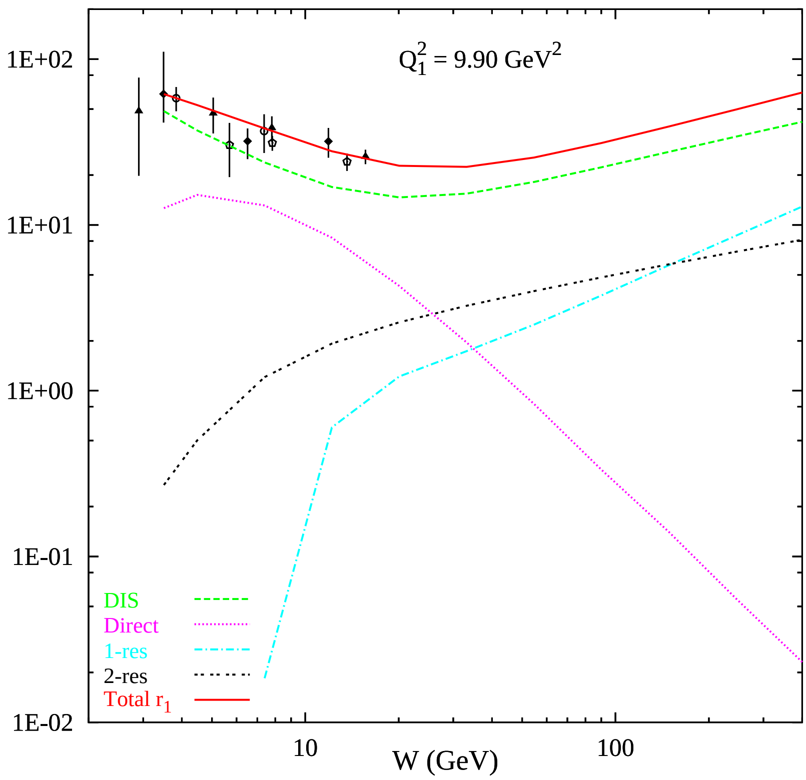
Energy dependence



$f_i^{\gamma^*_L}/f_i^{\gamma^*_T}$:

$$r_1 = \frac{2m^2Q^2}{(m^2+Q^2)^2}$$

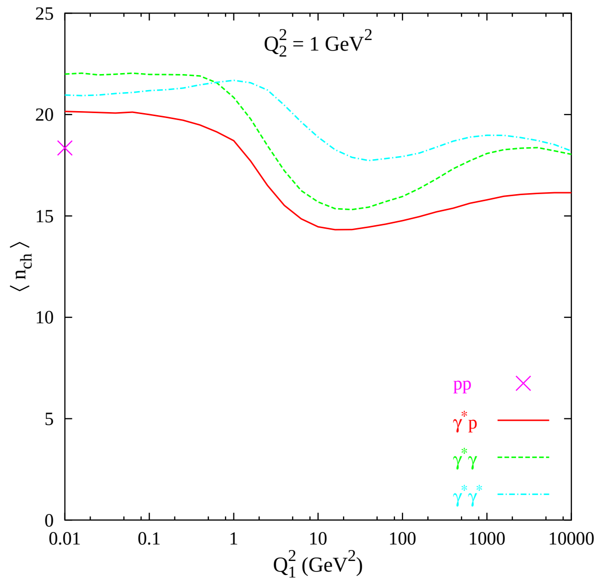
$$r_2 = \frac{2Q^2}{m^2+Q^2}$$

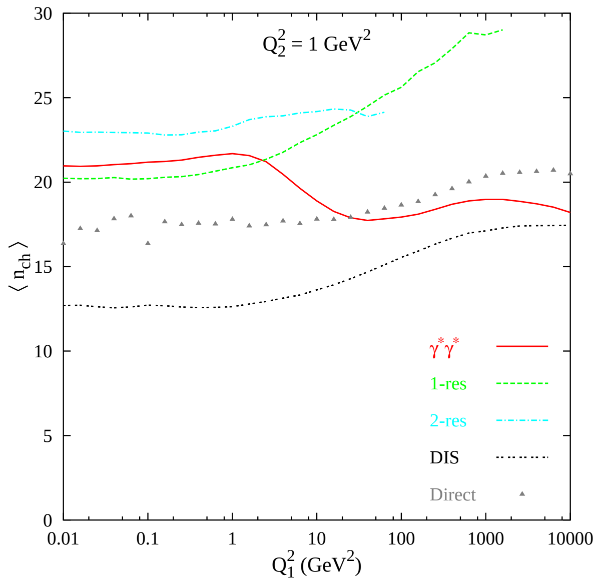


Event properties

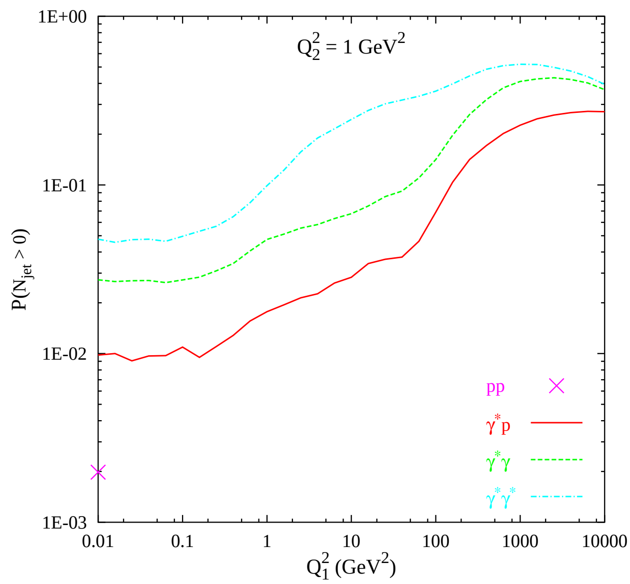
$W_{\gamma^*\gamma^*} = 100$ GeV

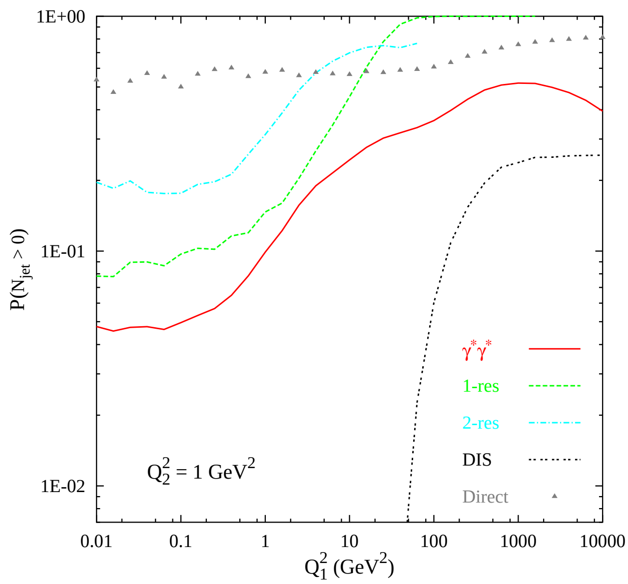
average charged multiplicity:



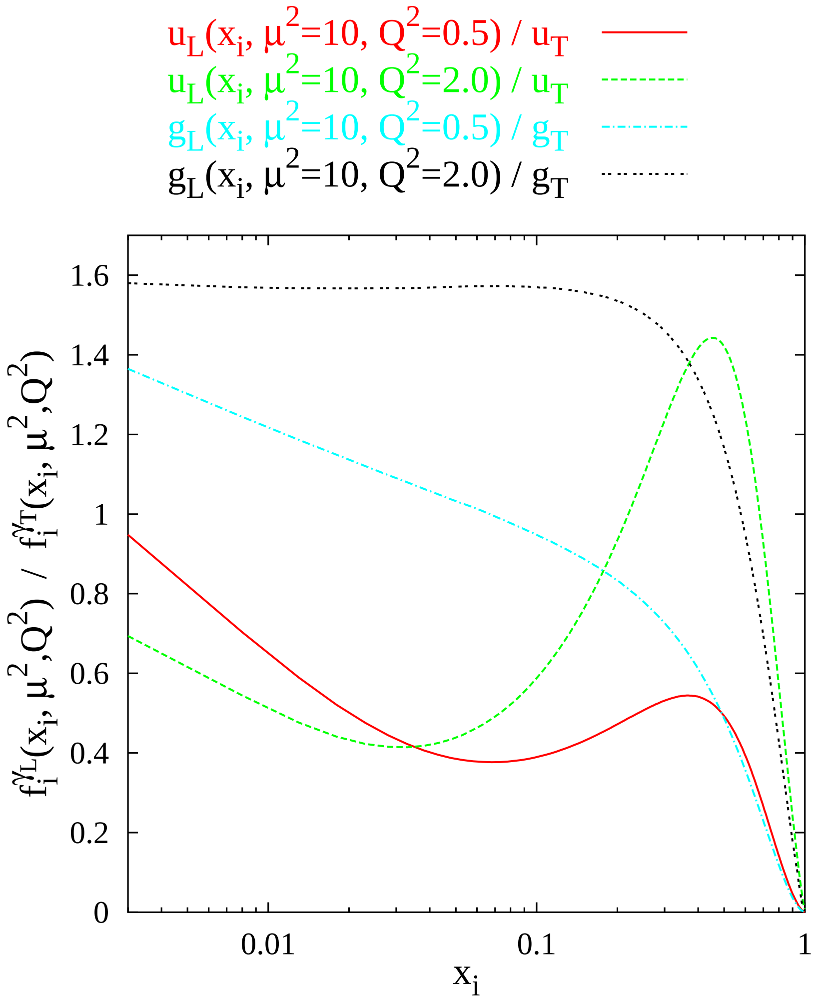


probability to have a jet with $E_\perp > 5$ GeV
inside a cone $R = \sqrt{(\Delta\eta)^2 + (\Delta\varphi)^2} < 1$:



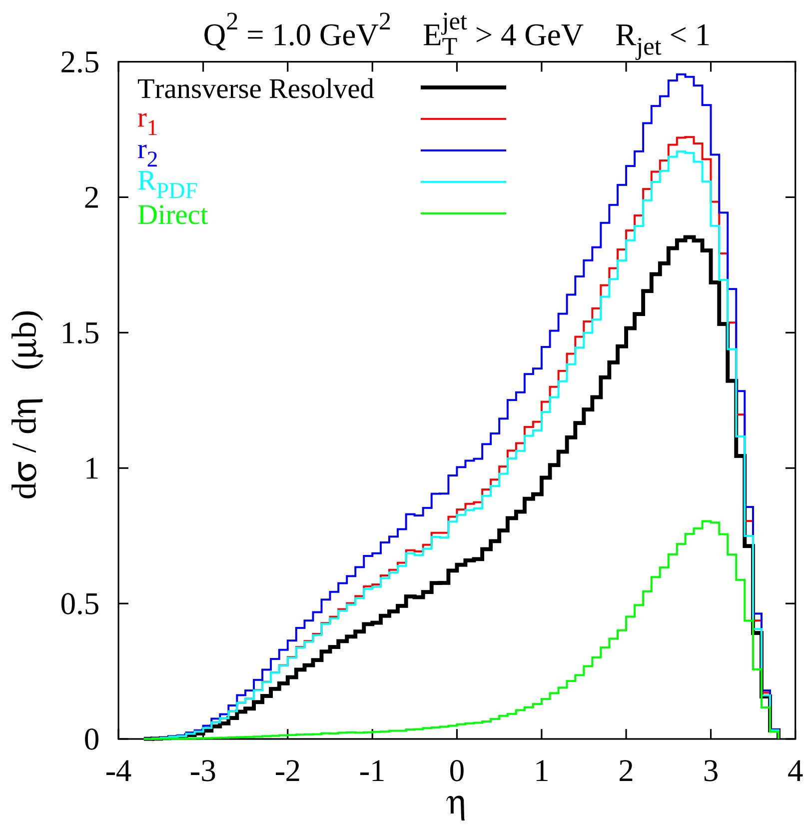


Effects of longitudinal photons



γ^*_{L}: Chýla

γ^*_{T}: SaS 1D



$$r_1 = \frac{2m^2Q^2}{(m^2+Q^2)^2}$$

$$r_2 = \frac{2Q^2}{m^2+Q^2}$$

$$R_{\mathrm{PDF}} = \frac{f_i^{\gamma^*_{\mathrm{L}}}(x,\mu^2,Q^2)}{f_i^{\gamma^*_{\mathrm{T}}}(x,\mu^2,Q^2)}$$

Program particulars

To access new γ^* flux convolution:
`CALL PYINIT('cms','gamma/e-','gamma/e+',200D0)`

Also possible to have $\gamma^*\gamma^*$ collisions directly:
`CALL PYINIT('five','gamma','gamma',100D0)`
with `P(1,J)` and `P(2,J)` defining momenta and virtualities (`P(I,5) < 0` for spacelike ones).

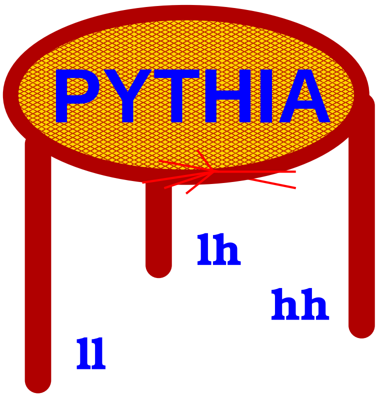
Photon character regulated by `MSTP(14)`:
= 10 : mix direct/VMD/anomalous for real photons; d$\times$V = V$\times$d etc. $\Rightarrow$ 6 classes.
= 30 : (new default) mix dir/VMD/GVMD and DIS for virtual photons; $\Rightarrow$ 13 classes.
= other numbers : individual classes.
Warning : $\gamma^*\gamma^* \to \ell^+\ell^-$ included in dir$\times$dir if not switched off (automatic when mixing).

`MSEL = 1, CKIN(3) > 2` : jets with $p_\perp >$`CKIN(3)`
`MSEL = 1, CKIN(3) = 0` : jet + low-$p_\perp$
`MSEL = 2, CKIN(3) = 0` : + diffractive + elastic

Possible to specify cuts on x_i, y_i, Q_i^2, θ_i, W^2 in `CKIN(61) - CKIN(78)`.
Phase space sampled according to

$$\prod_i (\mathrm{d}Q_i^2/Q_i^2)\,(\mathrm{d}x_i/x_i)\,\mathrm{d}\varphi_i$$

$\Rightarrow$ full efficiency for x_i and Q_i^2 cuts.



status

Authors: TS, P. Edén,
C. Friberg, L. Lönnblad,
G. Miu, S. Mrenna, E. Norrbin

JETSET 7.4
PYTHIA 5.7
SPYTHIA
} 4 March 1997 : → PYTHIA 6.1

Currently PYTHIA 6.152 of 17 August 2000
$\sim 51,900$ lines Fortran 77

Code, manuals, sample main programs:
`http://www.thep.lu.se/~torbjorn/Pythia.html`

PYTHIA 6.1 main news:

- JETSET routines renamed:
  `LUxxxx` $\longrightarrow$ `PYxxxx` + some more
- All real variables in `DOUBLE PRECISION`
- New SUSY processes and improved SUSY simulation; new PDG codes for sparticles
- New processes for Higgs, technicolour, ...
- Many improved resonance decays

- Several initial- and final-state showers matched to matrix elements
- New machinery to handle real and virtual photon fluxes and cross sections
- Newer parton distributions (but . . .)
- QED radiation off an incoming muon
- Energy-dependent $p_{\perp\mathrm{min}}$ in multiple interactions
- Colour rearrangement options for $\mathrm{W}^+\mathrm{W}^-$
- Expanded Bose-Einstein algorithm
- New baryon production scheme (optional)
- One-dimensional histograms (GBOOK)

2–, 4– and 6–fermion standard interfaces for showers and hadronization:

```
  CALL PY2FRM(IRAD,ITAU,ICOM)
  CALL PY4FRM(ATOTSQ,A1SQ,A2SQ,ISTRAT,
&IRAD,ITAU,ICOM)
  CALL PY6FRM(P12,P13,P21,P23,P31,P32,PTOP,
&IRAD,ITAU,ICOM)
```

$\mathrm{q\bar{q}gg}$ and $\mathrm{q\bar{q}q'\bar{q}'}$ QCD 4–jet standard interface for showers and hadronization:

```
  CALL PY4JET(PMAX,IRAD,ICOM)
```

HERWIG status

Authors: G. Marchesini, B.R. Webber,
G. Abbiendi, G. Corcella, I. Knowles,
S. Moretti, K. Odagiri, P. Richardson,
M. Seymour, L. Stanco.

Currently HERWIG 6.1 of 16 December 1999
$\sim 32,000$ lines Fortran 77

Code, manuals, related programs:
`http://hepwww.rl.ac.uk/theory/seymour/herwig/`
6.1 release notes: hep-ph/9912396

- SUSY production and decay (in hadron collisions) including R-parity violation
- matrix element corrections to top decay (and W/Z production in hadron collisions)
- $e^+e^- \to 4$ jets matrix element option
- new soft underlying event options
- new particles and updated particle data
- enhanced nonisotropic decay of clusters
- beamstrahlung (interface to CIRCE)

HERWIG 6.2 will follow soon, including e.g.
full simulation of MSSM Higgs physics.

Subprocess survey

Process	PYTH	HERW	ISAJ
QCD & related			
Soft QCD	$\star$	$\star$	$\star$
Hard QCD	$\star$	$\star$	$\star$
Heavy flavour	$\star$	$\star$	$\star$
Top threshold	—	—	—
$\gamma\gamma$ physics	$\star$	$\star$	—
DIS	$\star$	$\star$	—
$\gamma^*\gamma^*$ physics	$\star$	$(\star)$	—
Electroweak SM			
Single $\gamma^*/\mathrm{Z}^0/\mathrm{W}^\pm$	$\star$	$\star$	$\star$
$(\gamma/\gamma^*/\mathrm{Z}^0/\mathrm{W}^\pm/\mathrm{f}/\mathrm{g})^2$	$\star$	$\star$	$\star$
Light SM Higgs	$\star$	$\star$	$\star$
Heavy SM Higgs	$(\star)$	$\star$	$\star$
SUSY BSM			
$\mathrm{h}^0/\mathrm{H}^0/\mathrm{A}^0/\mathrm{H}^\pm$	$\star$	$\star$	$\star$
SUSY	$\star$	$\star$	$\star$
$\not{R}$SUSY	—	$\star$	—
Other BSM			
Technicolor	$\star$	—	$\star$
New gauge bosons	$\star$	—	—
Compositeness	$\star$	—	—
Leptoquarks	$\star$	—	—
$\mathrm{H}^{\pm\pm}$ (from LR-sym.)	$\star$	—	—
Extra dimensions	—	$(\star)$	$(\star)$

$\star$ = yes, $(\star)$ = partial/in progress, —= no

On to C++

(L. Lönnblad, CPC 118 (1999) 213;
M. Bertini, L. Lönnblad & TS, LUTP 00-23 (hep-ph/0006152);
input to `leif@thep.lu.se`)

Why Fortran $\to$ C++?

- SLAC $\to$, FNAL $\to$, CERN $\to$ LHC era.
- Industrial standard.
- Educational and professional continuity for students.
- Better to program – for experts.
- User-friendy interfaces – for the rest of us.

PYTHIA 7 milestones:

- January 1998: project formally started.
- June 2000: “proof of concept” version, with generic event generation machinery, some processes and string fragmentation.
- 2001–2002: useful version (?), but limited in scope.
- ??: more and better than current PYTHIA.

HERWIG++ progress:
PPARC funds 2 dedicated “postdocs”,
3-year work recently started.

Summary

$\star$ Renewed interest in shower evolution

- mass effects
- process dependence (spin, colour, . . .)
- multijet composition & topologies

Needed for future physics @ LHC/LC

$\Rightarrow$ LEP data needed for calibration

$\star$ Hadronization

- strings best first approximation
- slow but steady progress

$\Rightarrow$ LEP data needed as inspiration & reference

$\star$ $\gamma^*\gamma^*$ physics

- not for the weak of heart
- new 'complete' framework . . .
- . . . but still at level of 'strawman'

$\Rightarrow$ LEP will provide important tests

$\star$ Plea:

plan for easy comparison with final QCD data

$\Rightarrow$ will keep DELPHI alive in the LHC/LC era!