LUND UNIVERSITY

Linear Collider Workshop 2000
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QCD Radiation off Heavy Particles

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based on E. Norrbin and TS,
LU TP 00-42 (hep-ph/0010012)

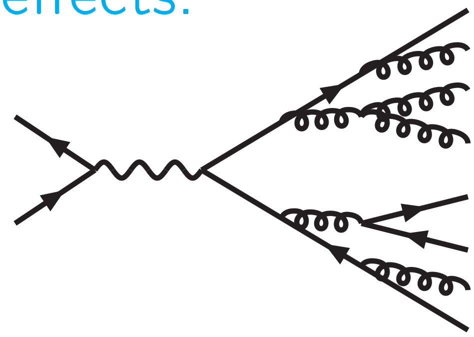
Objective:

- improved parton shower description,
- including mass effects ("dead cone"), and
- matched to process-specific $\mathcal{O}(\alpha_s)$ ME's

Why? (1) LEP data on b jets
(2) top at Tevatron/LHC/LC
(3) Higgs measurements
(4) SUSY studies

Where? PYTHIA 6.154 and onwards

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



Evolution variable Q^2:

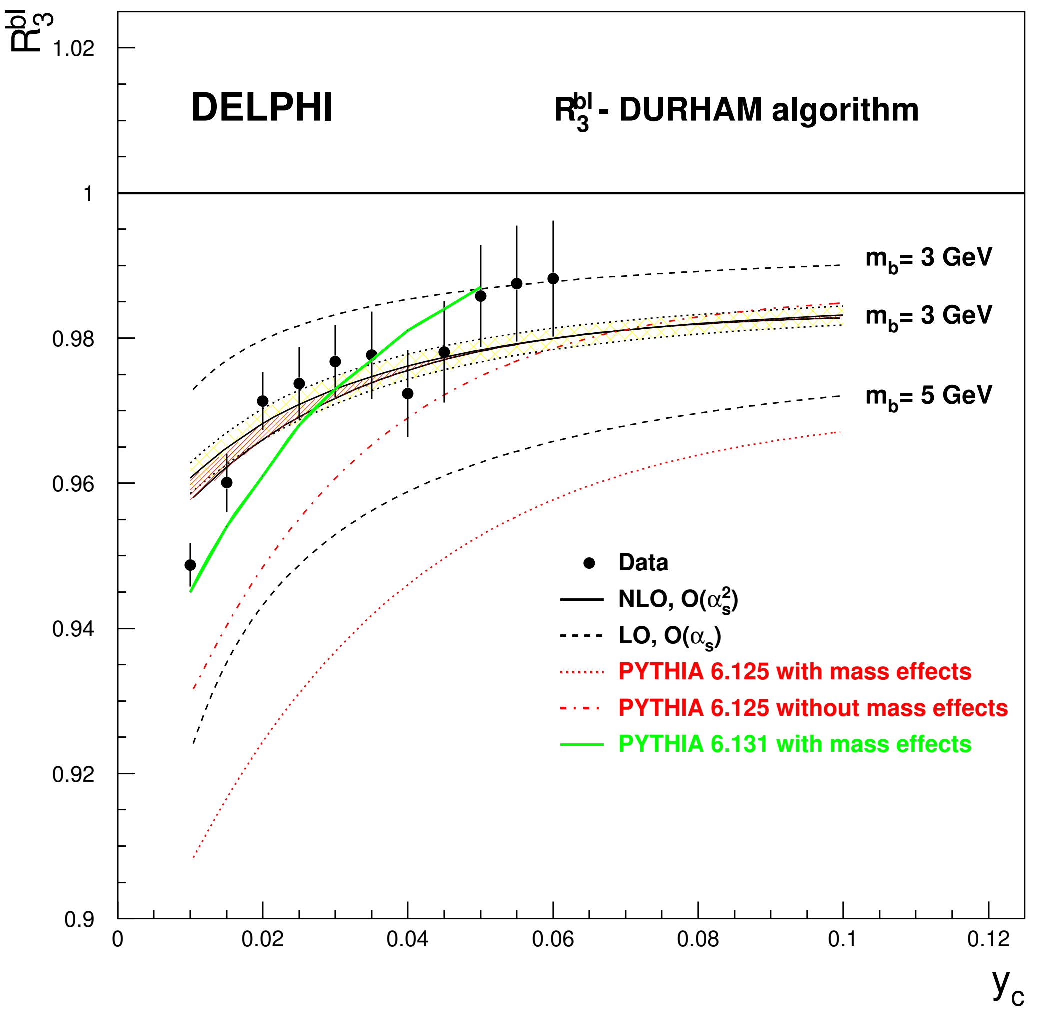
PYTHIA: m^2

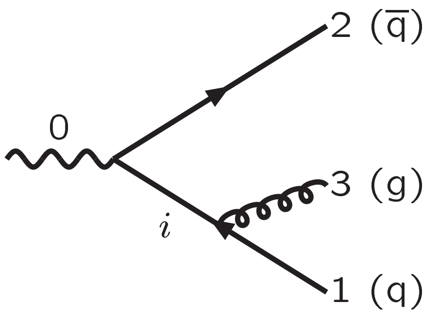
HERWIG: $E^2\theta^2$

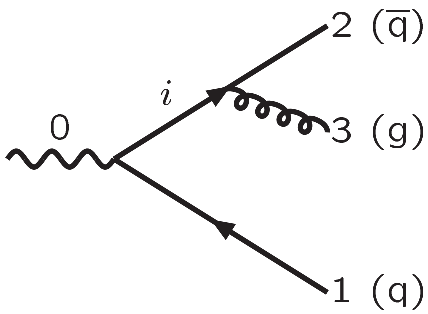
ARIADNE: $p_\perp^2$

z: energy/momentum sharing in branching

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







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

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

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

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

$$\begin{aligned} Q_1^2 &= m_i^2 = (p_0 - p_2)^2 = (1-x_2)E_{\mathrm{CM}}^2 \\ z_1 &= \frac{p_0 p_1}{p_0 p_i} = \frac{E_1}{E_i} = \frac{x_1}{x_1 + x_3} = \frac{x_1}{2 - x_2}\,, \\ &\Rightarrow \frac{\mathrm{d}Q_1^2}{Q_1^2}\frac{\mathrm{d}z_1}{1-z_1} = \frac{\mathrm{d}x_2}{1-x_2}\frac{\mathrm{d}x_1}{x_3} \end{aligned}$$

$$\begin{aligned} \Rightarrow \frac{1}{\sigma_0}\frac{\mathrm{d}\sigma_{\mathrm{PS}}}{\mathrm{d}x_1\,\mathrm{d}x_2} &\propto \frac{2}{(1-x_2)x_3} + \frac{2}{(1-x_1)x_3} \\ &= \frac{2}{(1-x_1)(1-x_2)} \end{aligned}$$

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

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

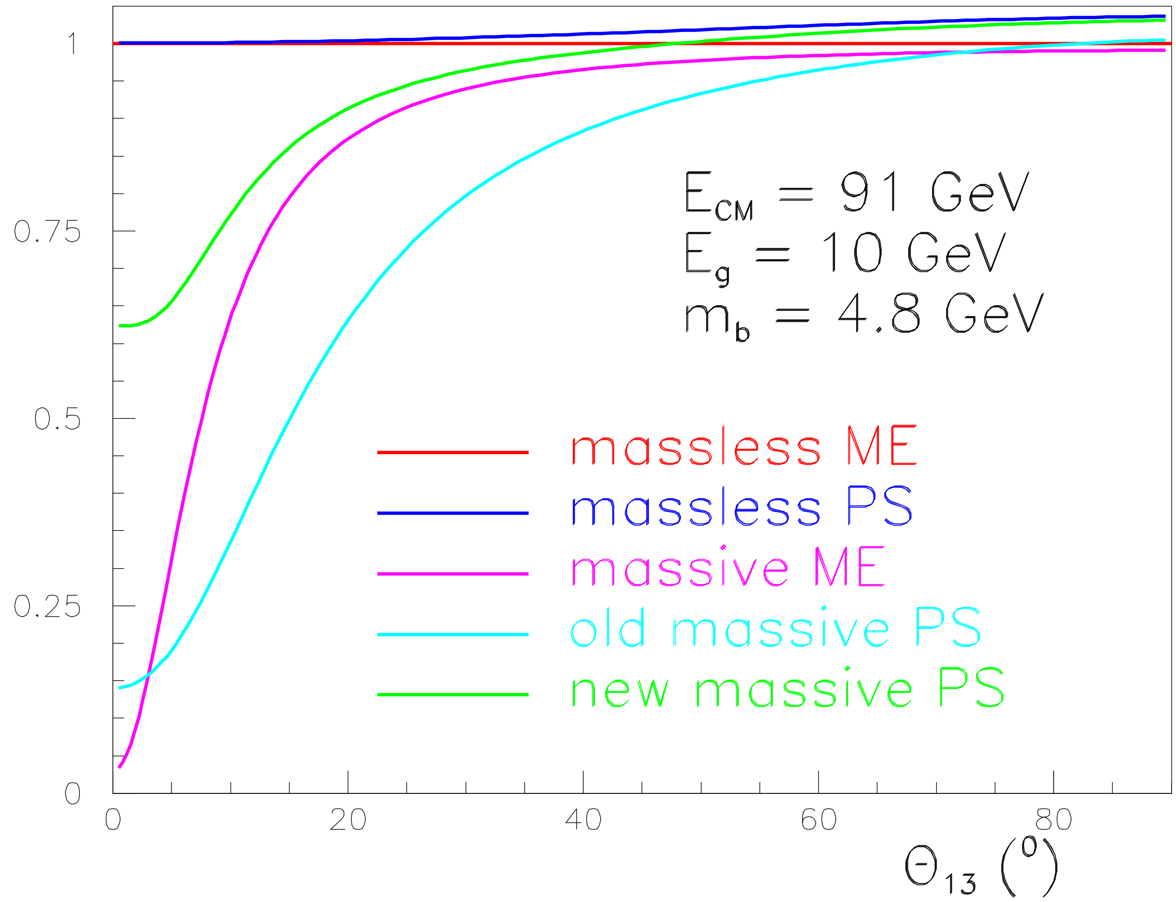
$r = m_\mathrm{q}/E_\mathrm{CM} > 0$:

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

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

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

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



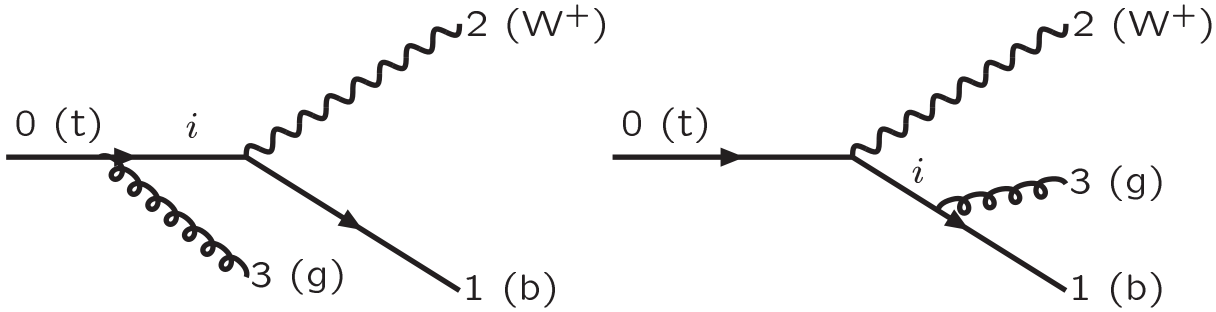
restore by

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

$Q_j^2 = m_j^2 - m_{j,\mathrm{onshell}}^2$ 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

$\boxed{\Rightarrow \text{ can match PS to generic } a \to bcg \text{ ME}}$

- 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:

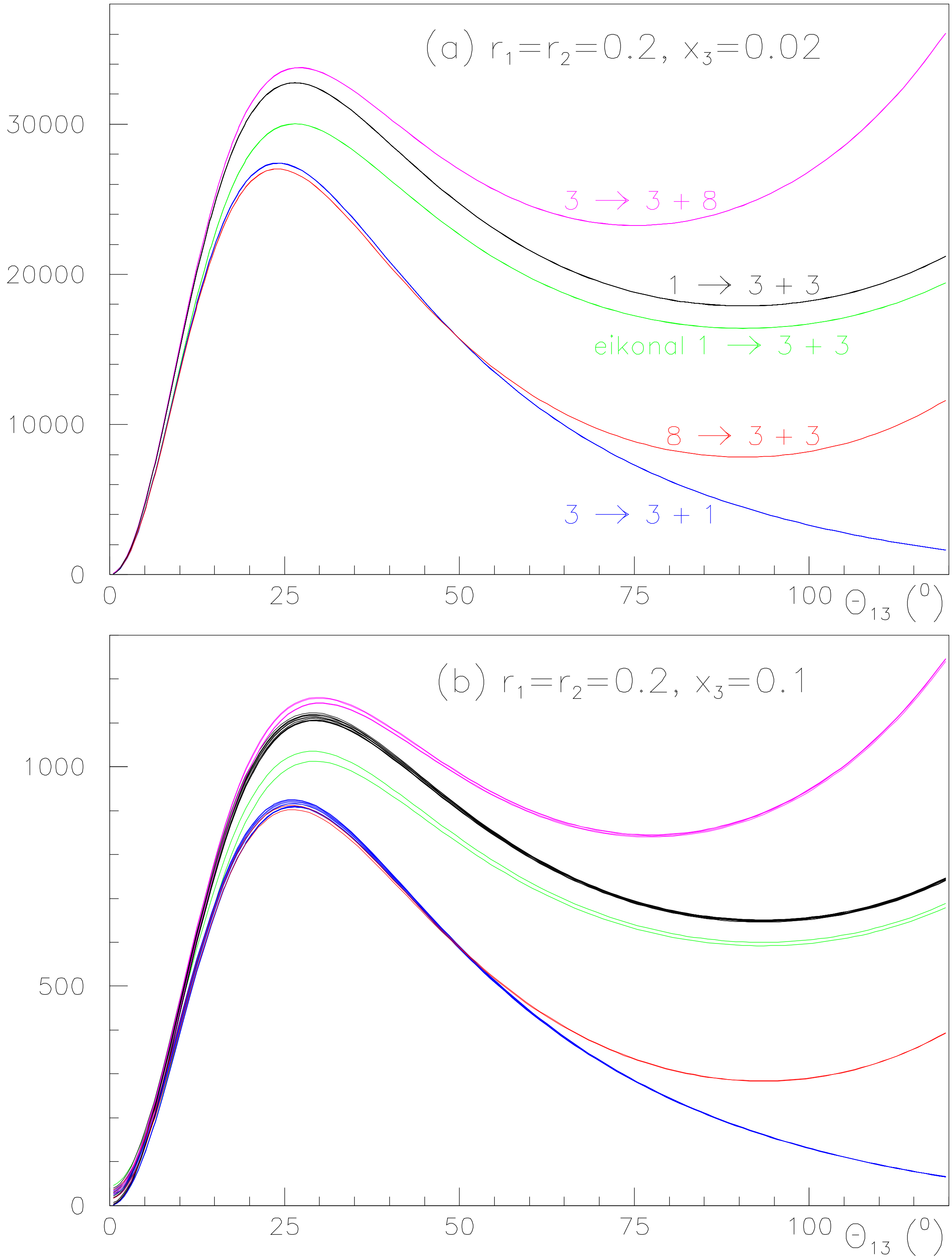
$$\frac{1}{\sigma(a \to bc)} \frac{\mathrm{d}\sigma(a \to bc\mathrm{g})}{\mathrm{d}x_1\,\mathrm{d}x_2}$$

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 $m_b, m_c \neq 0$

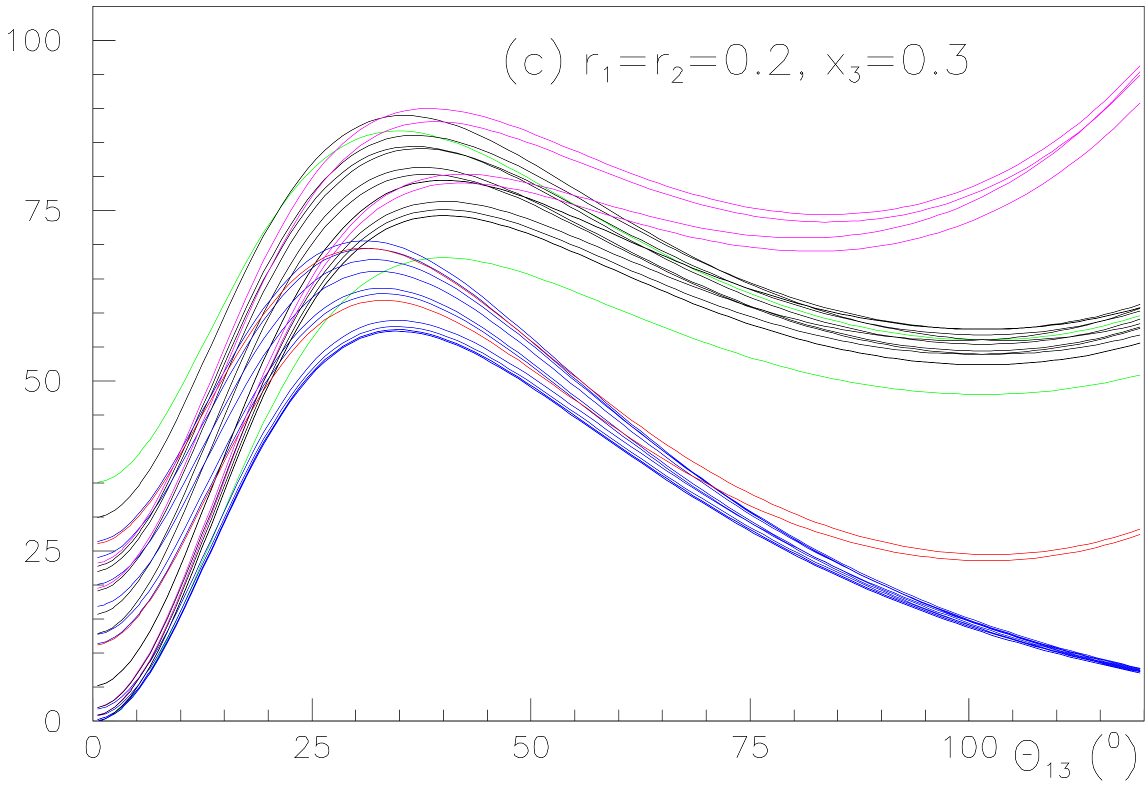
colour	spin	γ_5	example
$1 \to 3 + \overline{3}$	—	—	(eikonal)
$1 \to 3 + \overline{3}$	$1 \to \frac{1}{2} + \frac{1}{2}$	$1, \gamma_5, 1 \pm \gamma_5$	$\mathrm{Z}^0 \to \mathrm{q}\overline{\mathrm{q}}$
$3 \to 3 + 1$	$\frac{1}{2} \to \frac{1}{2} + 1$	$1, \gamma_5, 1 \pm \gamma_5$	$\mathrm{t} \to \mathrm{bW}^+$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

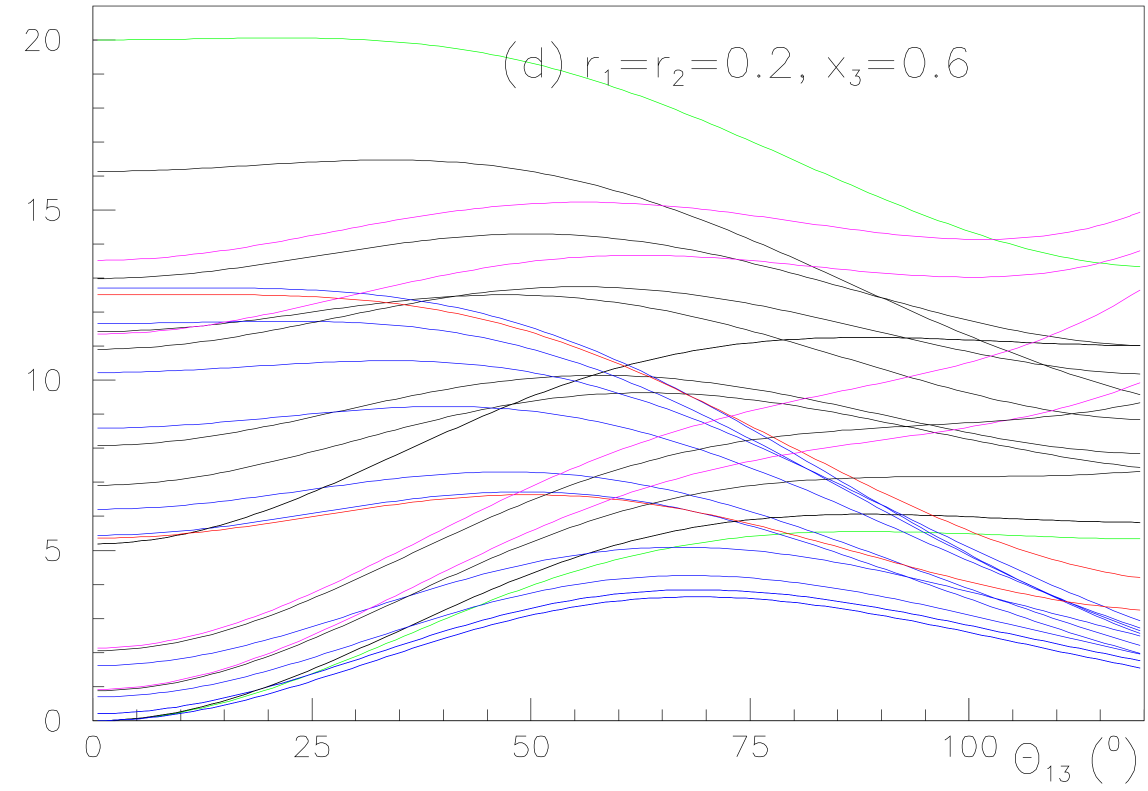
Universal gluon radiation patterns (= no spin dependence) for small gluon energies ...



(with textbook dead cone)

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

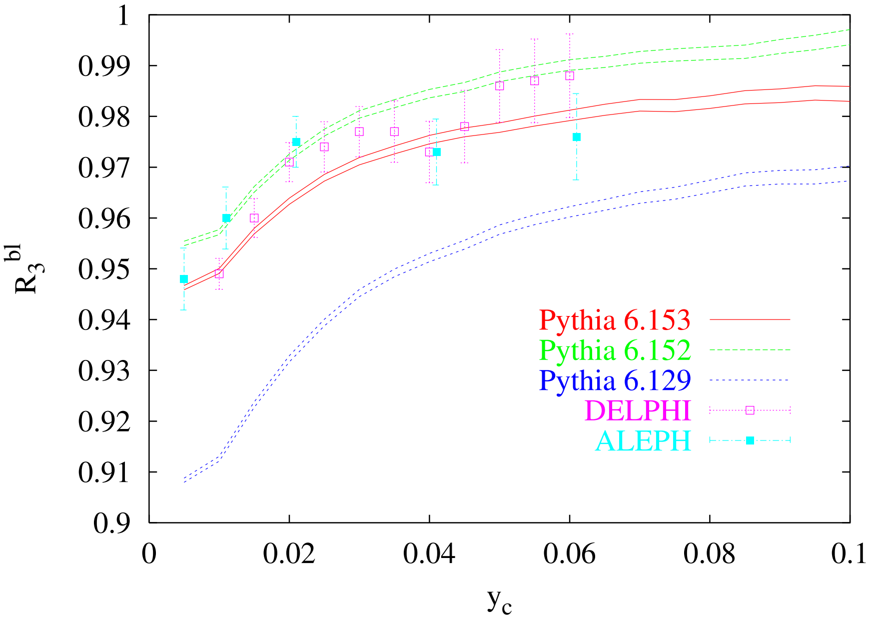




(and no dead cone except for spin $0 \to 0 + 0$)

... results in process-dependent jet rates

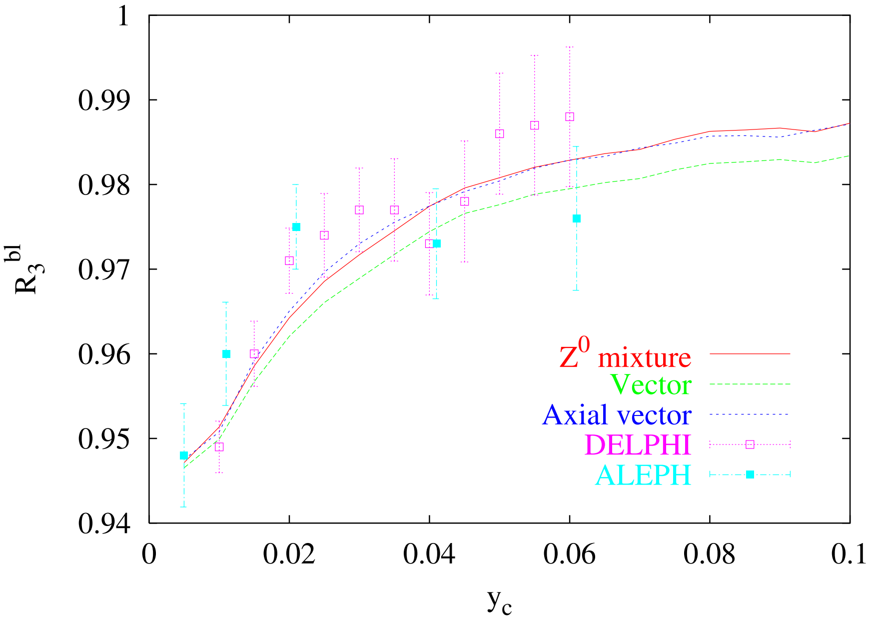
			$r_1 = r_2 = 0.2$		
colour	spin	γ_5	E_g	3 jet	3 jet'
$1 \to 3 + \overline{3}$	$1 \to \frac{1}{2} + \frac{1}{2}$	1	1.000	1.000	1.000
		γ_5	1.056	1.112	1.133
	$0 \to \frac{1}{2} + \frac{1}{2}$	1	1.134	1.293	1.376
		γ_5	1.093	1.207	1.271
	$1 \to 0 + 0$	1	1.073	1.205	1.310
	$0 \to 0 + 0$	1	0.875	0.758	0.720
	$\frac{1}{2} \to \frac{1}{2} + 0$	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



$R_3^{\mathsf{bl}}(y_c)$

$E_{\mathsf{CM}} = 91$ GeV

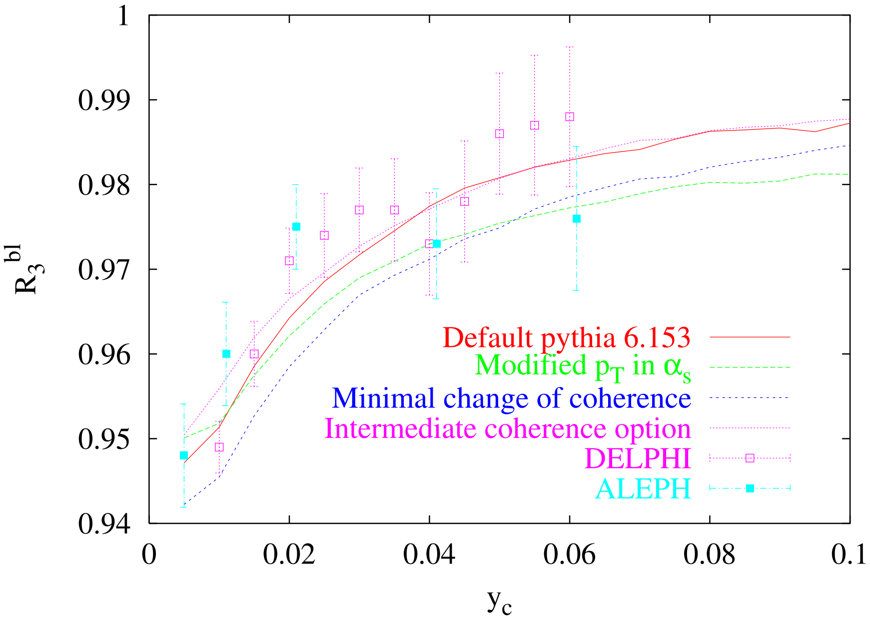
$m_{\mathsf{b}} = 4.8$ GeV

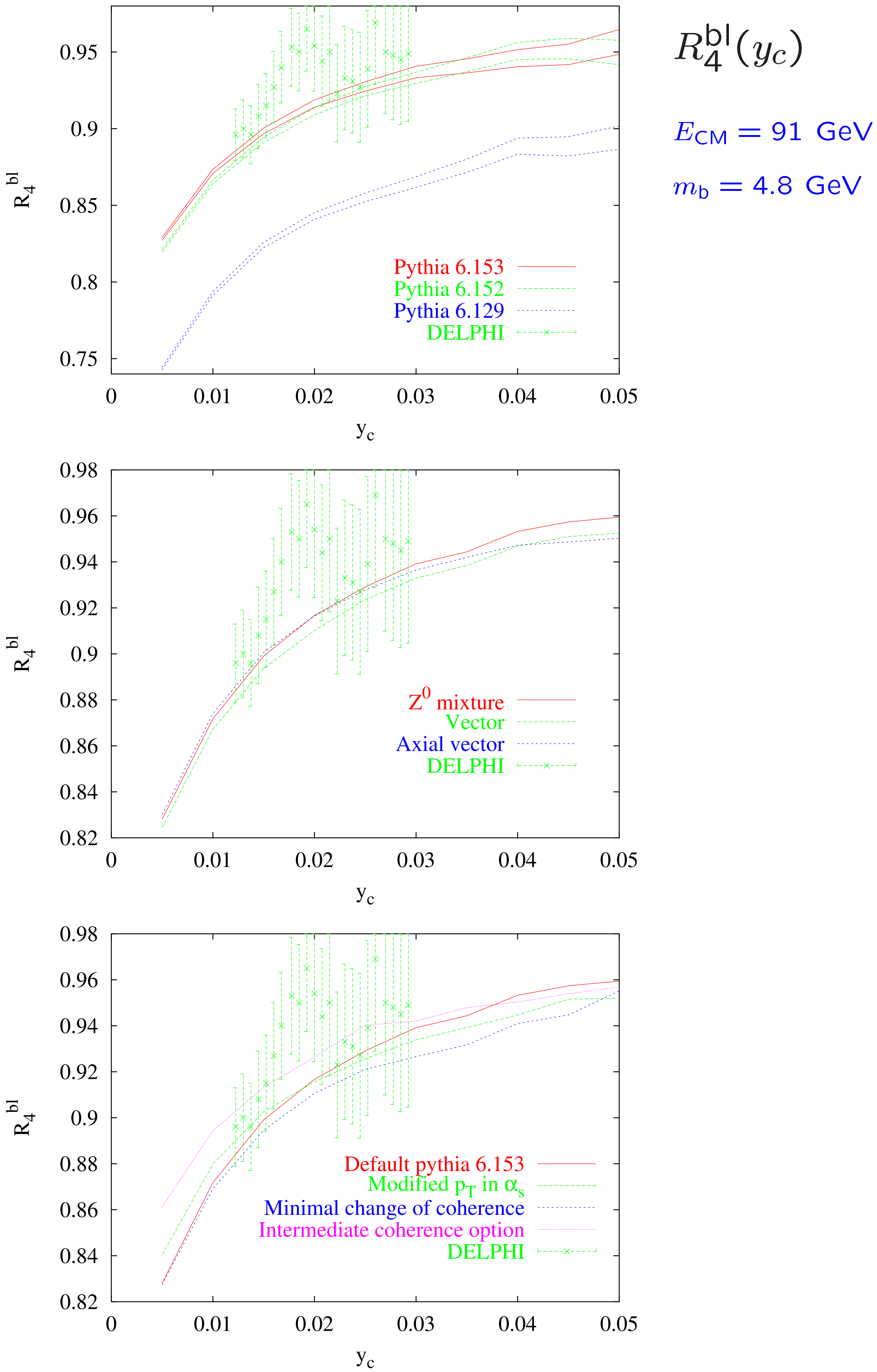


also e.g. m_{b}

dependence;

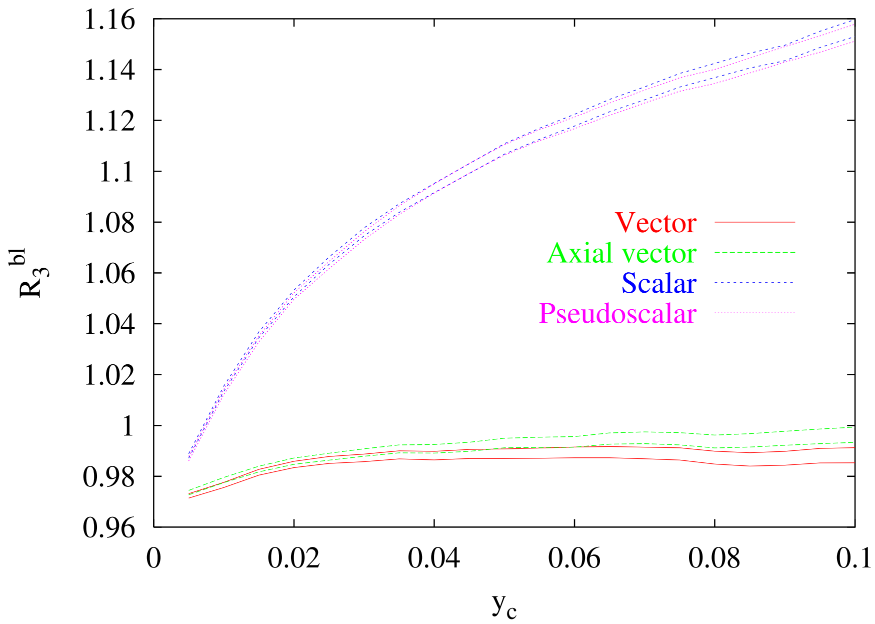
not shown





$R_4^{\mathrm{bl}}(y_c)$
$E_{\mathrm{CM}} = 91$ GeV
$m_{\mathrm{b}} = 4.8$ GeV
$\mathrm{R_4^{bl}}$
$\mathrm{y_c}$
Pythia 6.153
Pythia 6.152
Pythia 6.129
DELPHI
$\mathrm{Z^0}$ mixture
Vector
Axial vector
DELPHI
Default pythia 6.153
Modified p_T in α_s
Minimal change of coherence
Intermediate coherence option
DELPHI

Higgs physics: decay $h^0/H^0/A^0 \to b\bar{b}$



$R_3^{\mathrm{bl}}(y_c)$

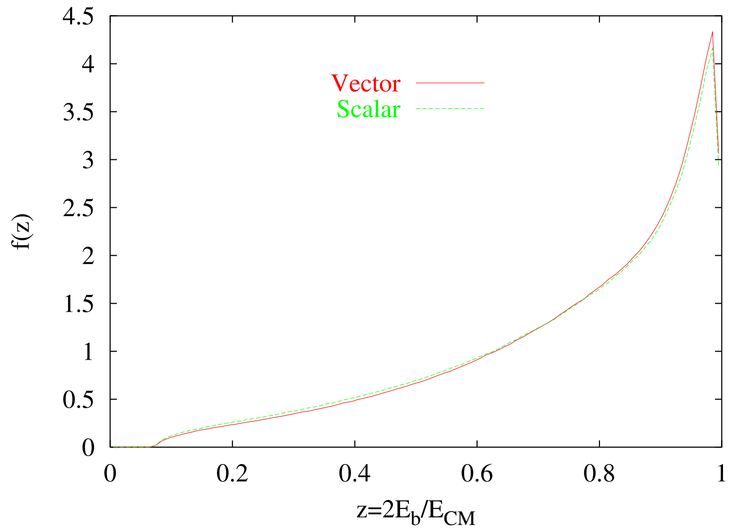
$E_{\mathrm{CM}} = m_{\mathrm{h/H/A}}$

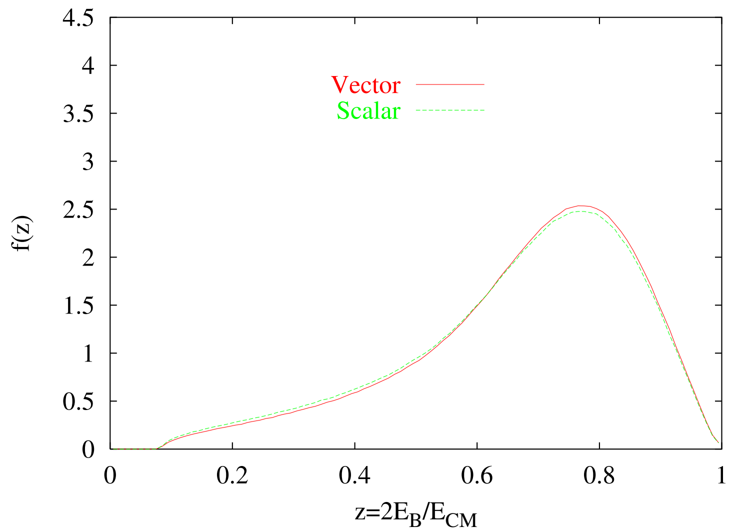
$= 120$ GeV

$m_{\mathrm{b}} = 4.8$ GeV

reference light q

from γ^*/Z^*





Worry:

larger gluon emission rate

$\Rightarrow$ softer fragmentation function

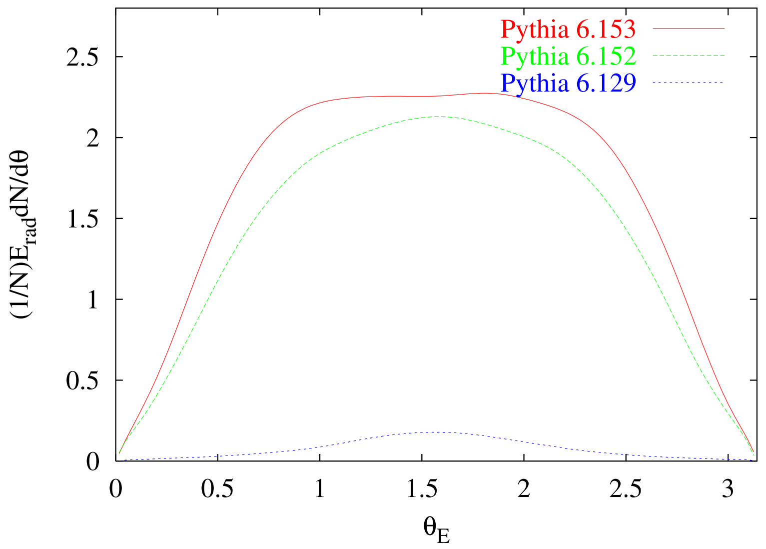
$\Rightarrow$ changed b tagging efficiency

$\Rightarrow$ error in $\mathrm{Br}(h^0/H^0/A^0 \to b\bar{b})$

but $\Delta\langle z\rangle \sim 1\%$

$\Rightarrow$ no worry!

Top physics: energy flow and jet rates



$\gamma^*/Z^* \to t\bar{t}$

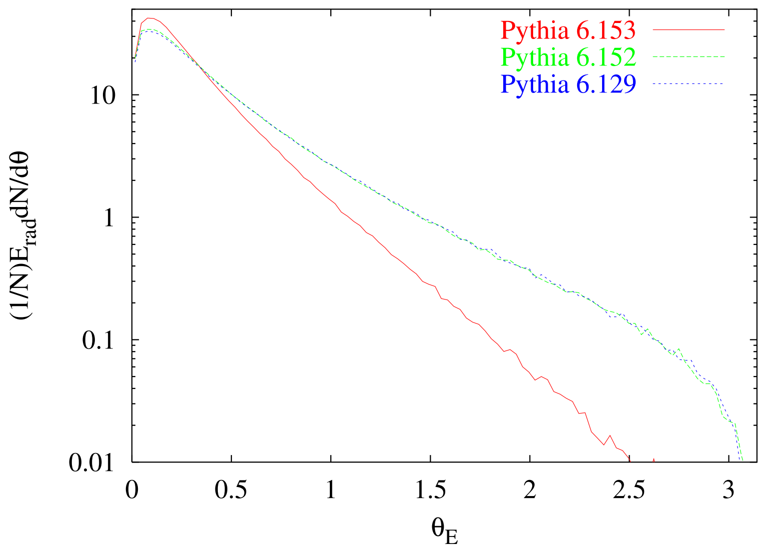
$E_{CM} = 500$ GeV

Increased gluon

emission off $t\bar{t}$ . . .

(θ_E w.r.t.

original $t\bar{t}$ axis)



. . . but decreased

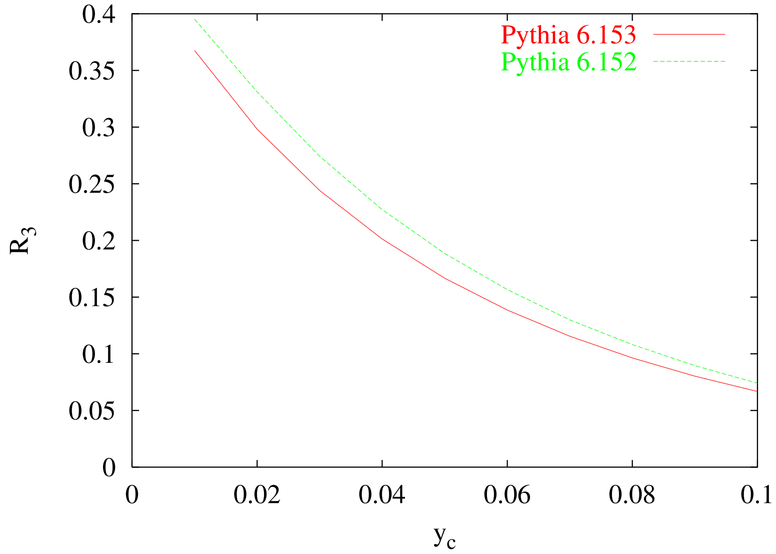
off b in t decay

(at large angles) . . .

(θ_E w.r.t.

original b axis

$\Rightarrow$ W at 180°)



. . . gives net decrease

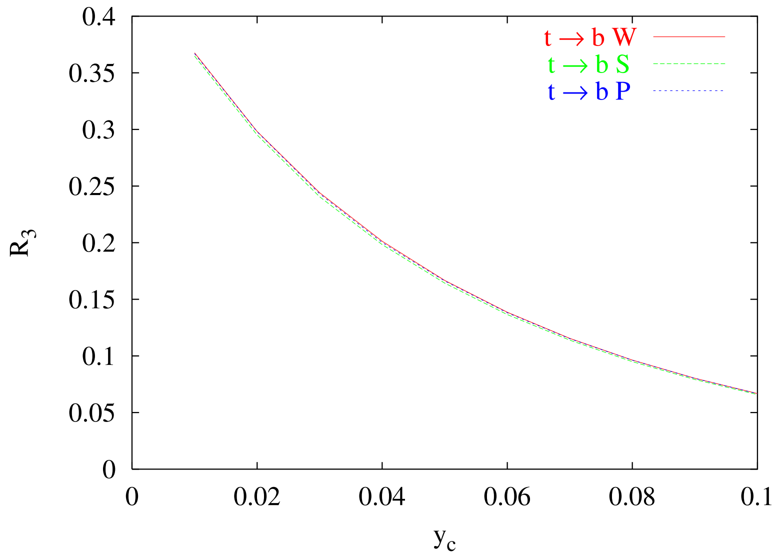
in 3-jet rate for

$t\bar{t} \to bW^+\bar{b}W^-$

(not counting W

decay products)

Top physics: the Higgs and SUSY connections

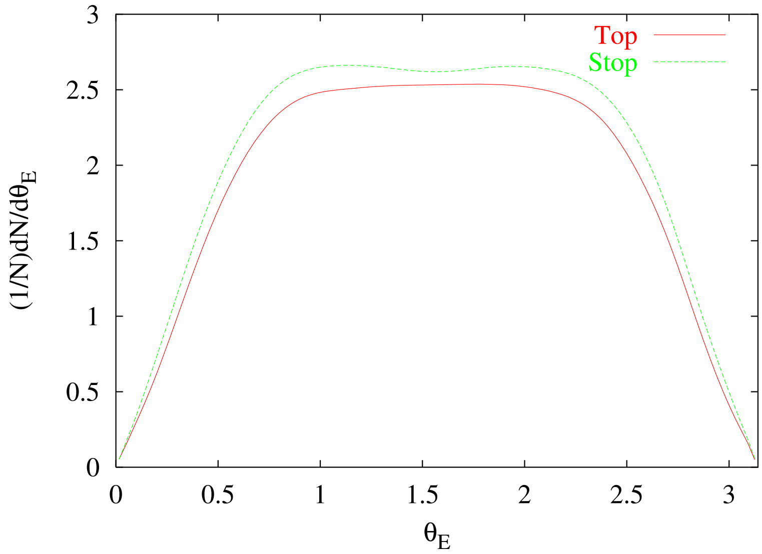


$t \to bH^+$

$\sim$ same radiation

as $t \to bW^+$

(for $m_H = m_W$)



$E_{CM} = 500$ GeV

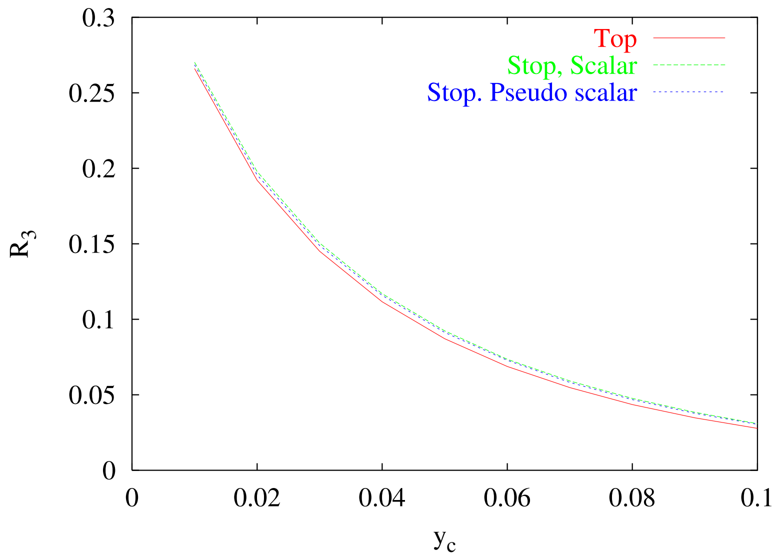
$m_{\tilde{t}} = m_t$

$\tilde{t}\bar{\tilde{t}}$ more radiation

than $t\bar{t}$ ...

(no ISR since

$t\bar{t}$ give more γ's)



$\tilde{t} \to b\tilde{\chi}^+ \sim t \to bW^+$

(for $m_{\tilde{\chi}} = m_W$;

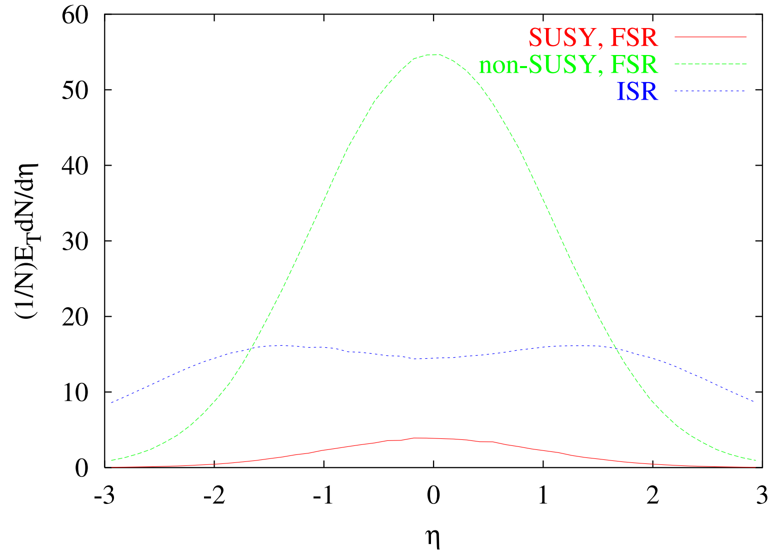
not shown)

$\Rightarrow$ $\tilde{t}\bar{\tilde{t}}$ still more jets

(not counting $W/\tilde{\chi}$

decay products)

SUSY cascades: gluino production at LHC



$E_{\mathrm{CM}} = 14$ TeV

$\mathrm{gg} \to \tilde{\mathrm{g}}\tilde{\mathrm{g}}$

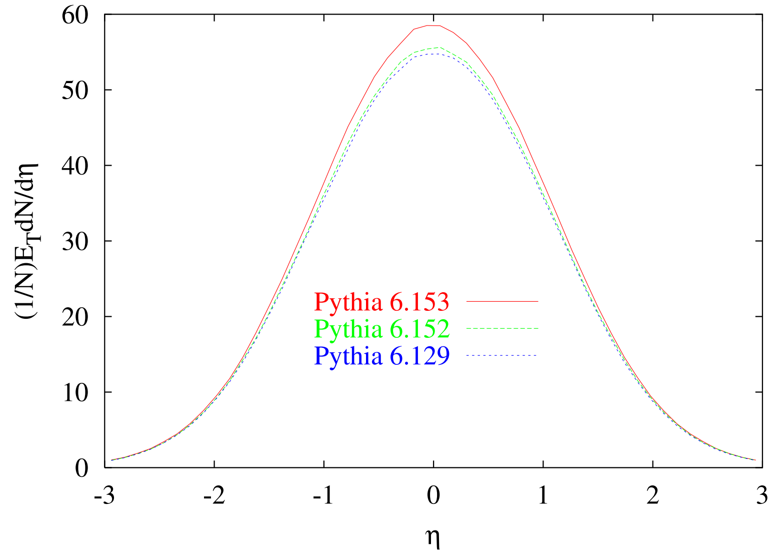
$\tilde{\mathrm{g}} \to \tilde{\mathrm{b}}_1\overline{\mathrm{b}} \,/\, \tilde{\mathrm{t}}_1\overline{\mathrm{t}}$

$\tilde{\mathrm{b}}_1 \,/\, \tilde{\mathrm{t}}_1 \to \mathrm{b}\tilde{\chi},\ \tilde{\chi} \to \ldots$

$m_{\tilde{\mathrm{g}}} = 450$ GeV, ...

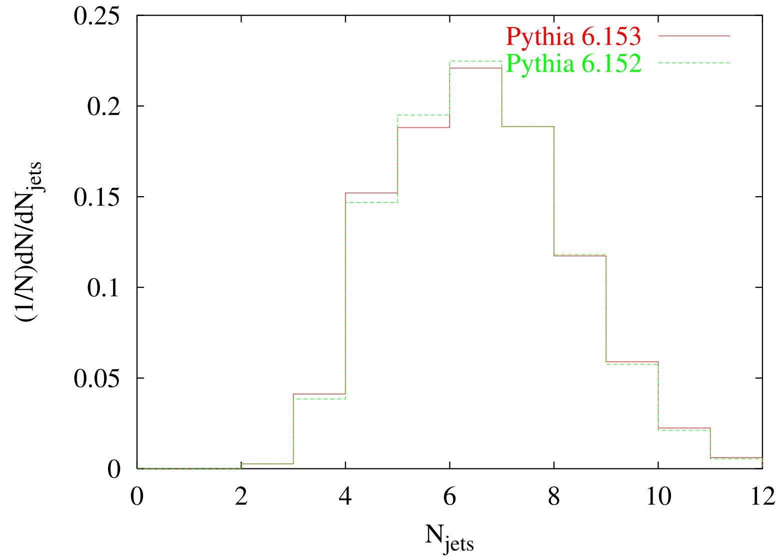
litte radiation

off SUSY particles



somewhat increased

total radiation ...



... but nontrivial

detection

($E_{\perp\mathrm{jet}} \geq 10$ GeV,

cone $R = 0.75$)