LUND UNIVERSITY
Faculty of Science

TH/LPCC Institute on SM at the LHC
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Inclusion of W/Z emission in showers

Torbjörn Sjöstrand
Dept. of Astronomy and Theoretical Physics, Lund University

based on ongoing work together with

Jesper Roy Christiansen

$\Rightarrow$ no definite conclusions

Motivation — Status — Prospects

Motivation 1

Why still try to improve showers? Did not matching solve it all?

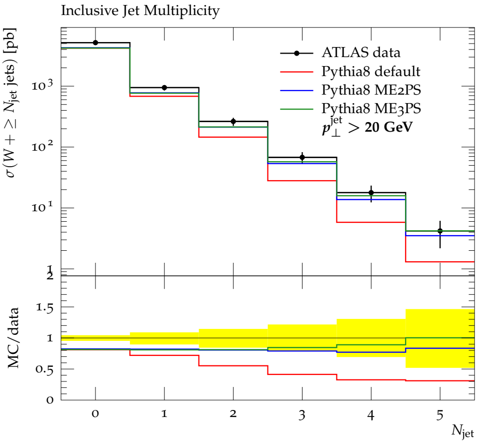
- curiosity: what are limits of shower approach?
- Sudakovs for CKKW-L merging
- showers below merging scale
- rapid implementation and studies of new processes
- ditto for showers in new sectors (gauge groups)

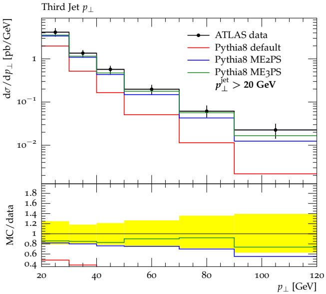
Past experience: showers often do better than expected

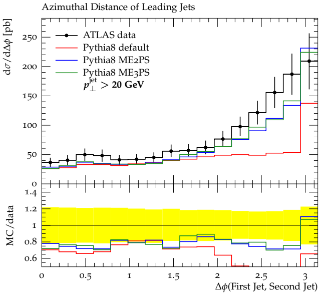
- FSR in $\mathrm{e}^+\mathrm{e}^- \to \gamma^*/\mathrm{Z}^0 \to \mathrm{q}\overline{\mathrm{q}}$ (1986), and other resonances
- ISR in $\mathrm{q}\overline{\mathrm{q}} \to \gamma^*/\mathrm{Z}^0/\mathrm{W}^{\pm}$ (1998), and other colour singlets
- ISR+FSR in QCD jets, with $p_{\perp\mathrm{shower}} < p_{\perp\mathrm{ME}}$
- ISR(+FSR) in other colour exchange processes (e.g. $\mathrm{t}\overline{\mathrm{t}}$), with $\mathrm{d}p_{\perp}^2/p_{\perp}^2 \to \mathrm{d}p_{\perp}^2/p_{\perp}^4$ at characteristic scale of process

Motivation 2

While showers work for $\mathrm{W/Z} + 1$ jet they fail for $\mathrm{W/Z} + \geq 2$ jets:





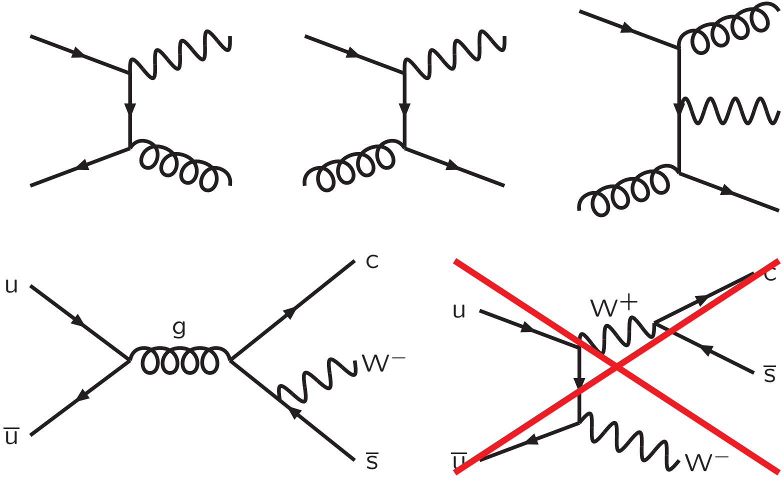


(CKKW-L merging by Stefan Prestel)

Histories for $\mathrm{W/Z}$ production

Q: So what is unique about $\mathrm{W/Z} + 2$ jets?

A: First order in which core “hard process” cannot be chosen as $\mathrm{W/Z}$ production!



$\mathrm{W/Z}$ production in showers

Need to start from QCD $2 \to 2$ and add shower emission of $\mathrm{W/Z}$:
- FSR: final-state radiation $\mathrm{q} \to \mathrm{q}' \, \mathrm{W}^{\pm}$, $\mathrm{q} \to \mathrm{q} \, \mathrm{Z}^0$.
- ISR: largely already covered by $\mathrm{W/Z}$ production processes.

Project at a primitive stage; for now only $\mathrm{e}^+\mathrm{e}^-$ annihilation.

Viewed as interleaved evolution:

$$\frac{\mathrm{d}\mathcal{P}}{\mathrm{d}p_\perp} = \left(\frac{\mathrm{d}\mathcal{P}_{\mathrm{QCD}}}{\mathrm{d}p_\perp} + \frac{\mathrm{d}\mathcal{P}_{\mathrm{QED}}}{\mathrm{d}p_\perp} + \frac{\mathrm{d}\mathcal{P}_{\mathrm{W/Z}}}{\mathrm{d}p_\perp} \right) \times \exp\left(- \int_{p_\perp}^{p_{\perp i-1}} \left(\frac{\mathrm{d}\mathcal{P}_{\mathrm{QCD}}}{\mathrm{d}p'_\perp} + \frac{\mathrm{d}\mathcal{P}_{\mathrm{QED}}}{\mathrm{d}p'_\perp} + \frac{\mathrm{d}\mathcal{P}_{\mathrm{W/Z}}}{\mathrm{d}p'_\perp} \right) \mathrm{d}p'_\perp \right)$$

Dipole formulation of shower, with each end radiating, e.g.

$$\mathrm{d}\mathcal{P}_{\mathrm{q}\to\mathrm{qg}} = \frac{\mathrm{d}p_\perp^2}{p_\perp^2} \, \frac{\alpha_{\mathrm{s}}}{2\pi} \, C_F \, \frac{1+z^2}{1-z} \, \mathrm{d}z$$

$+$ ME corrections where available/convenient ($\sim$POWHEG)

Matrix Elements merging

Consider $\mathrm{e^+e^-} \to \gamma^*/\mathrm{Z}^0 \to \mathrm{q\overline{q}} \to \mathrm{q\overline{q}Z}^0$:

$$\frac{1}{\sigma_0}\frac{\mathrm{d}\sigma}{\mathrm{d}x_1\,\mathrm{d}x_2} = \frac{\alpha_{\mathrm{em}}}{2\pi}\frac{v_{\mathrm{q}}^2 + a_{\mathrm{q}}^2}{16\sin^2\theta_W\cos^2\theta_W} \times \left(\frac{x_1^2 + x_2^2 + 2r(x_1+x_2) + 2r^2}{(1-x_1)(1-x_2)} - \frac{r}{(1-x_1)^2} - \frac{r}{(1-x_2)^2}\right)$$

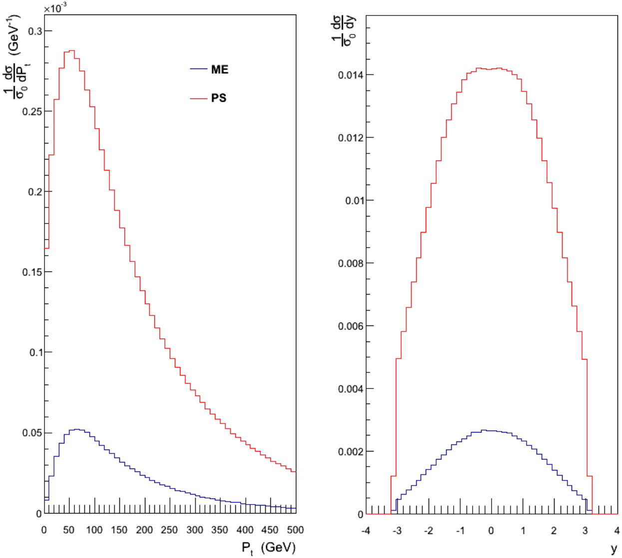
with $x_1 = 2E_{\mathrm{q}}/\sqrt{s}$, $x_2 = 2E_{\overline{\mathrm{q}}}/\sqrt{s}$, and $r = M_{\mathrm{Z}}^2/s$.

Split ME in "propagator" proportions $(1-x_1) : (1-x_2)$
for comparison with PS $\mathrm{q} \to \mathrm{qZ} : \overline{\mathrm{q}} \to \overline{\mathrm{q}}\mathrm{Z}$.

$$\mathrm{d}\mathcal{P}_{\mathrm{q}\to\mathrm{qZ}} = N\frac{\mathrm{dp}_{\perp\mathrm{evol}}^2}{\mathrm{p}_{\perp\mathrm{evol}}^2(+M_{\mathrm{Z}}^2)}\frac{1}{1-z'} = f_{\mathrm{Z}}(x_1,x_2)\,\mathrm{d}x_1\,\mathrm{d}x_2$$

Gives weight $\mathrm{ME}(x_1,x_2)/\mathrm{PS}(x_1,x_2) < 1$ + veto algorithm.

(Detailed kinematics: L. Carloni, J. Rathsman, T.S., JHEP 04(2011)091)

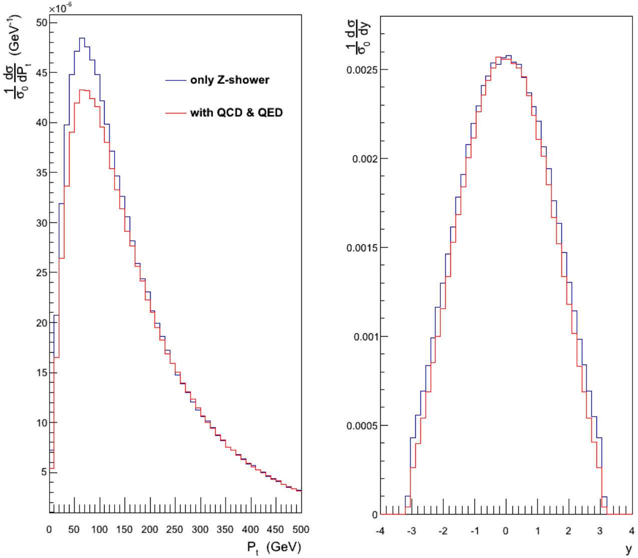


e^+e^-
$\to \gamma^*/Z^0$
$\to q\bar{q}$
$\to q\bar{q}Z^0$

$\sqrt{s} = 2$ TeV

$p_\perp$ and y w.r.t. original $q\bar{q}$ axis

Competition from interleaving



e^+e^-
$\rightarrow \gamma^*/Z^0$
$\rightarrow q\overline{q}$
$\rightarrow$ shower
$(g + \gamma + Z^0)$

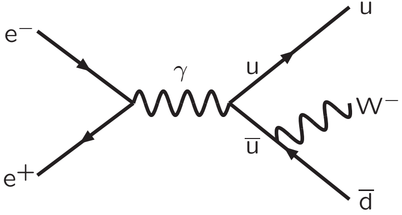
$\sqrt{s} = 2$ TeV

$p_\perp$ and y
w.r.t. original
$q\overline{q}$ axis

evolution
scale
ambiguity

Flavour interference in W emission

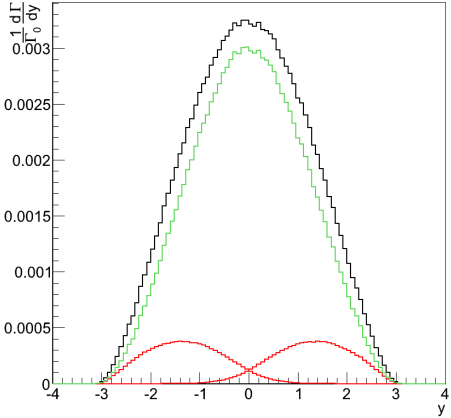
For W emission interference between two dipole ends is replaced by interference between two flavour topologies:



$$|M|^2(\gamma^* \to \mathrm{u\overline{d}W^-}) \quad = \quad e_\mathrm{u}^2 A(x_1, x_2) + e_\mathrm{d}^2 A(x_1, x_2) + 2 e_\mathrm{u} e_\mathrm{d} B(x_1, x_2)$$
$$+ \quad \text{diagrams with WW intermediate states}$$

- $\mathrm{Z \to u\overline{d}W^-}$: different couplings, same structure (& problem).
- $\mathrm{g \to u\overline{d}W^-}$: $e_\mathrm{u} \to 1, e_\mathrm{d} \to 1$.
- $\mathrm{H \to u\overline{d}W^-}$: $e_\mathrm{u} \to m_\mathrm{u}, e_\mathrm{d} \to m_\mathrm{d}$, and also $A \to A', B \to B'$.
- $\mathrm{Z^0}$ emission: common couplings, same A, B, no $\mathrm{Z^0 \to Z^0 Z^0}$.

Dipole radiation is it



$g \to q\bar{q}Z^0$

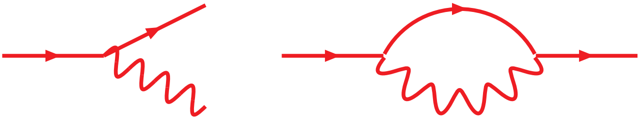
$\sqrt{s} = 2$ TeV

$$y = \frac{1}{2} \ln \frac{1 - x_1}{1 - x_2}$$

black = total emission
green = interference (B)
red = individual (A)

Non-unitary Sudakov factors (1)

Leading electroweak corrections of type $\alpha_{\mathrm{w}} \ln^2(Q^2/M_{\mathrm{W}}^2)$:



Bloch-Nordsieck violation: real/virtual non-cancellation

1. W/Z in final state is another class of events
   $\Rightarrow$ large negative correction to no-W/Z cross sections!
2. even if not separated, negative virtual win out (by how much?)

P. Ciafaloni and D. Comelli, Phys. Lett. B446 (1999) 278;
M. Beccaria, P. Ciafaloni, D. Comelli, F.M. Renard, C. Verzegnassi, Phys. Rev. D61 (2000) 073005;
M. Melles, Phys. Rep. 375 (2003) 219;
U. Baur, Phys. Rev. D75 (2007) 013005;
A. Banfi, G. Salam, G. Zanderighi, JHEP 0707 (2007) 026;
G. Bell, J.H. Kühn, J. Rittinger, Eur. Phys. J. C70 (2010) 659;
S. Dittmaier, A. Huss, C. Speckner, arXiv:1210.0438;

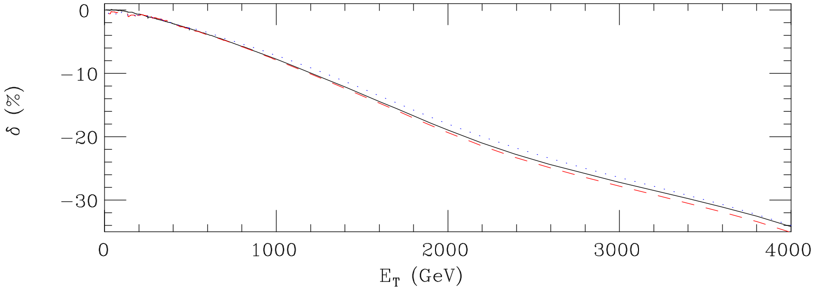
+ many more (apologies to anybody present who is forgotten)

Non-unitary Sudakov factors (2)

S. Moretti, M.R. Nolten and D.A. Ross, Nucl. Phys. B759 (2006) 50

Jet production $|\eta| < 2.5$, $\delta = (\mathrm{NLO} - \mathrm{LO})/\mathrm{LO}$,

$\mathrm{LO} = \mathcal{O}(\alpha_\mathrm{s}^2 + \alpha_\mathrm{s}\alpha_\mathrm{w} + \alpha_\mathrm{w}^2)$, $\mathrm{NLO} = \mathcal{O}(\alpha_\mathrm{s}^2\alpha_\mathrm{w})$



How much compensated by real emission? To come!

What to do with uncompensated part? Introduce by hand?

Outlook

Many issues remain to address before complete framework:

- step from e^+e^- to pp
- mass spectrum and complete interference for γ^*/Z^0
- flavour separation for W production
- polarized $\gamma^*/Z/W$ decays
- multiple emissions
- evolution scale ambiguity for competition
- **non-unitary Sudakovs**
- ...