EW corrections in the Sudakov limit at the LHC

Mauro Chiesa

Università di Pavia
and INFN Sezione di Pavia

September 19th 2013, LC13 Workshop

in collaboration with L. Barzè, G. Montagna, M. Moretti, O. Nicrosini, F. Piccinini and F. Tramontano

based on arXiv:1305.6837 and arXiv:1308.1430

Outline

Introduction:

- definition of Sudakov logs
- Sudakov logs and IR logs (QCD analogy)
- universality of Sudakov logs: Denner-Pozzoroni algorithm (and implementation in ALPGEN)

Results:

- $Z + n$jets as SM background for NP searches ($n$jets $+E_T^{miss}$)
- Sudakov EW corrections to $Z + 2/3$ jets at $\sqrt{s} = 7, 14$ TeV
- Results for pp collisions at 33/100 TeV
- Real W/Z radiation: partial cancellation of Sudakov logs

Sudakov logs: introduction

In virtual one loop EW corrections appear terms like [1] (EW Sudakov logs):

$$-L(s) = -\frac{\alpha}{4\pi s_W^2}\log^2\frac{s}{M_W^2} \qquad \mathrm{DL}$$

$$+l(s) = +\frac{\alpha}{4\pi s_W^2}\log\frac{s}{M_W^2} \qquad \mathrm{SL}$$

(for $\sqrt{s} = 1$ Tev $-L(s) \simeq -6.6$, $l(s) \simeq 1.3$)

[1] e.g. $e^+e^- \to f\bar{f}$ (M. Beccaria et al., Phys.Rev.**D58** (1998) 093014), P. Ciafaloni and D. Comelli Phys.Lett. **B446** (1999) 278-284

Sudakov logs: IR limit of EW corrections

Extensive literature on the origin of Sudakov logs [2]

- one loop explicit calculations:
- general analysis of 1 loop corrections (QCD analogy)
- general analysis of 2 loop corrections (QCD analogy)
- resummation techniques (QCD analogy)
- Bloch-Nordsieck violating effects

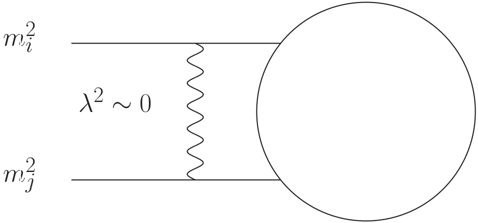
Sudakov logs are the IR limit of EW corrections

$s \gg M_W \Longrightarrow M_W \sim 0$

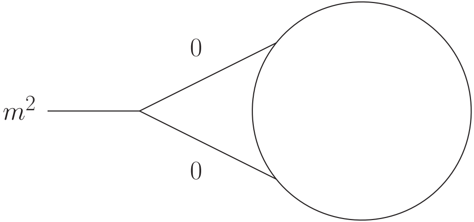
[2] comprehensive bibliography in A. Denner PoS HEP **2001**, 129 (2001)

IR logs in 1 loop diagrams [3]

- Soft singularities

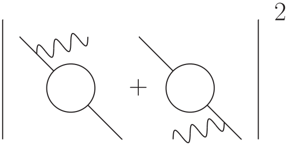


- Collinear singularities



[3] T. Kinoshita, J. Math. Phys. **3** (1962) 650

real IR logs in massless gauge theories



$$\propto \int \frac{d^3k}{2k_0} \frac{1}{p_i k} \frac{1}{p_j k} |M_0|^2$$

$$= \int_0^{\Delta E} \frac{dk_0}{2k_0} \int d\Omega_k \frac{1}{p_{i,0} p_{j,0} (1 - \beta_i \cos\vartheta_{ik})(1 - \beta_j \cos\vartheta_{jk})} |M_0|^2$$

- $k_0 \to 0$ (*soft singularity*):

$$\int_0^{\Delta E} \frac{dk_0}{2k_0} \longleftrightarrow \int_{\lambda^2}^{\Delta E} \frac{dk_0}{2k_0} \propto \log \frac{\lambda^2}{\Delta E}$$

- $\beta_i(\beta_j) \to 1$ (*collinear*):

$$\propto \log \frac{m_i^2}{s}$$

properties of IR corrections

- Real and Virtual IR logs factorize on a Born matrix element

- IR corrections are universal:
  the coefficients of the logs depend only on the flavour structure of the Born process

- IR logs depend on cutoffs: λ, m

KLN theorem

- KLN theorem: (abelian gauge theories $\rightarrow$ QED) IR logs of the cutoffs (λ, m) cancel in the sum of real and virtual corrections for observables inclusive w.r.t. degenerate final states

- cancellation also in QCD after color averaging

Sudakov logs as weak IR logs: differences w.r.t. QCD

- $\lambda \leftrightarrow M_W$ (no arbitrary cutoffs):
  it is possible to compute virtual corrections only

- weak bosons decay: additional real radiation in principle leads to final states different from the signal

- color $\leftrightarrow$ isospin charges

Sudakov logs as weak IR logs: universality and Denner-Pozzorini algorithm

In the Sudakov limit

$$\forall \quad l, k \quad 2p_k p_l \gg M_W^2$$

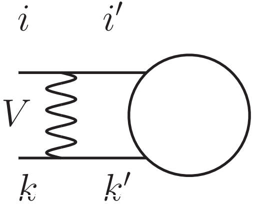
for virtual one loop EW corrections Denner and Pozzorini [4] proved that

$$\begin{aligned} M^{\mathrm{Virt}\ O(\alpha)} = & \ \mathrm{Double\ log.\ part} \\ & + \mathrm{Single\ log.\ part} \\ & + \delta\,(\mathrm{parameter\ renorm.})\, M^{\mathrm{Born}} \end{aligned}$$

[4] A. Denner and S. Pozzorini Eur.Phys.J. **C18** (2001) 461-480, Eur.Phys.J. **C21** (2001) 63-79

Denner-Pozzorini algorithm: double logs

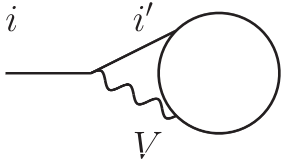
$$\sum_{i,k}\sum_{i',k'}\sum_{V}$$



$$= \sum_{i,k}\sum_{i',k'}\sum_{V} \delta^{DL}\left(V; i, i'; k, k'\right) M_{\mathrm{Born}}\left(i', k'\right)$$

- $\delta^{DL} \propto \log^2 \frac{2p_i p_k}{M_V^2}$
- i' and k' may be $SU2$ transformed of i and k

Denner-Pozzorini algorithm: single logs

$\sum_i \sum_{i'} \sum_V$ 

$$= \sum_i \sum_{i'} \sum_V \delta^{SL}\left(V; i, i'\right) M_{\rm Born}\left(i'\right)$$

- $\delta^{SL} \propto \log \frac{r}{M_V^2}$
- i' may be $SU2$ transformed of i

Denner-Pozzorini algorithm: implementation in ALPGEN

In the Sudakov limit EW corrections:

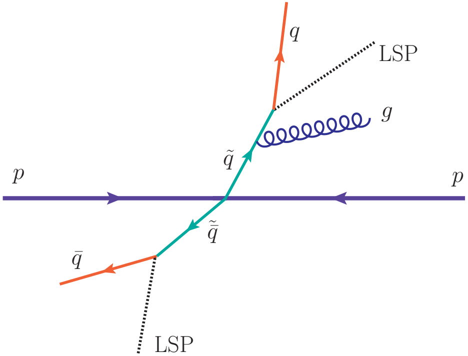
- depend only on the the kinematics and on the flavour of each external leg (and pairs of external legs)
- the expression for δ^{DL} and δ^{SL} in known (universality)
- factorize on the Born (and $SU2$-correlated) matrix element

$\Longrightarrow$ The algorithm can be implemented into a LO event generator (as ALPGEN [5])

[5] C. et al. arXiv:1305.6837v2

Results

Direct search of squark and gluinos at LHC



taken from Z. Bern et al. arXiv:1206.6064

ATLAS: Phys.Lett. **B710** 67 (2012)

- observable: $m_{\rm eff} = \sum_{jet_i} |p_{T\,jet_i}| + \not{E}_T$
- channels: 2, 3, 4 jets plus missing E_T
- basic experimental cuts:

$$m_{\rm eff} > 1 \text{ TeV} \qquad \not{E}_T / m_{\rm eff} > 0.3$$
$$p_T^{j_1} > 130 \text{ GeV} \qquad p_T^{j_2} > 40 \text{ GeV} \qquad |\eta_j| < 2.8$$
$$\Delta\phi(\vec{p}_T^{\,j}, \vec{\not{p}}_T) > 0.4 \qquad \Delta R_{(j_1,j_2)} > 0.4$$

CMS: Phys.Rev.Lett. **109** 171803 (2012)

- observables: $\vec{\not{H}}_T = -\sum_i \vec{p}_{t\,i}$ $\qquad H_T = \sum_i p_{T\,i}$
- channels: at least 3 jets plus missing E_T
- basic experimental cuts:

$$H_T > 500 \text{ GeV} \qquad |\vec{\not{H}}_T| > 200 \text{ GeV}$$

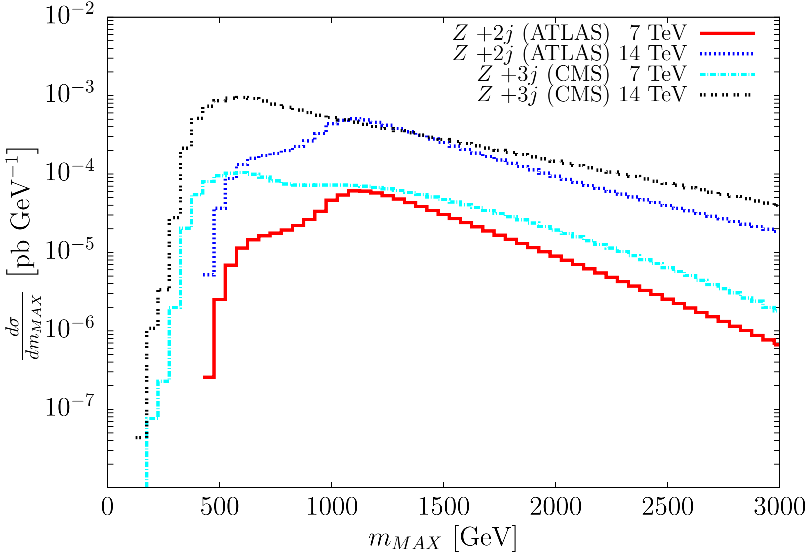
$$p_T^j > 50 \text{ GeV} \qquad |\eta_j| < 2.5 \quad \Delta R_{(j_i, j_k)} > 0.5$$

$$\Delta\phi(\vec{p}_T^{\,j_1, j_2}, \vec{\not{H}}_T) > 0.5 \qquad \Delta\phi(\vec{p}_T^{\,j_3}, \vec{\not{H}}_T) > 0.3$$

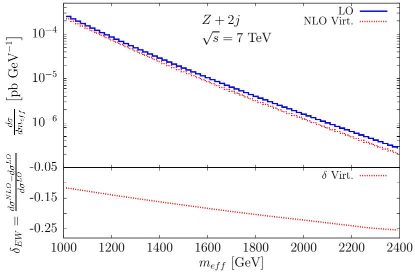
in both analysis:

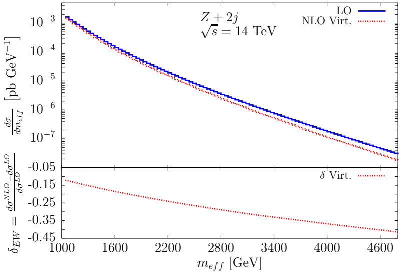
- large amount of missing E_T plus hard jets
- $Z(\nu\bar{\nu})$+jets irreducible SM background (the most relevant for 2 and 3 jets)
- Denner-Pozzorini algorithm provides a good estimate of the $\mathcal{O}(\alpha)$ corrections to the background processes $Z(\nu\bar{\nu}) + 2/3$jets

Experimental cuts and the Sudakov region

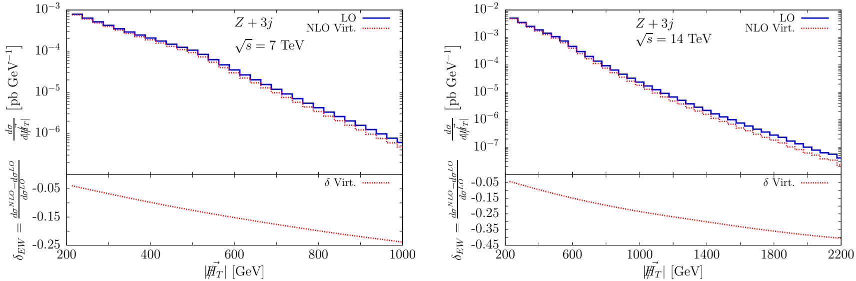


Results for $Z+2$jets, ATLAS setup

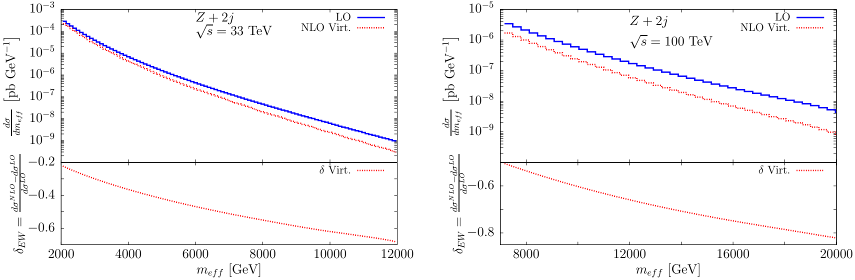




Results for $Z + 3$jets, CMS setup

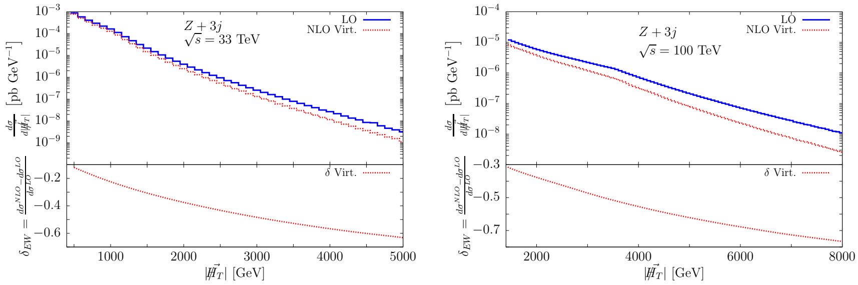


Results for $Z + 2$jets at 33/100 TeV, ATLAS-like setup



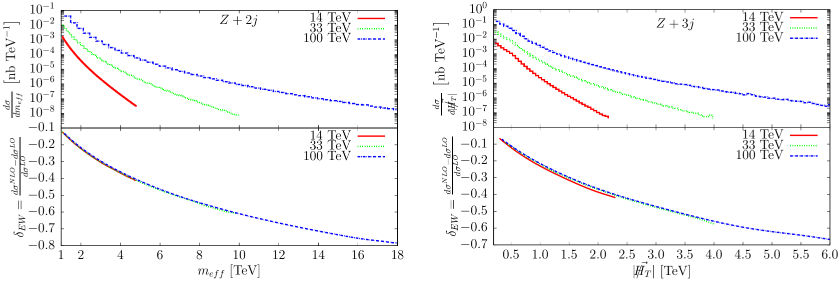
basic cuts rescaled by a factor of 2 for 33 TeV (7 at 100 TeV)

Results for $Z + 3$jets at 33/100 TeV, CMS-like setup



basic cuts rescaled by a factor of 2 for 33 TeV (7 at 100 TeV)

Results for LHC at 33/100 TeV: remark



- the increase of the corrections is a kinematical effect
- the same behaviour shown in arXiv:1308.1430 for several processes (dijet,diboson,Z/W+1jet) also from complete $\mathcal{O}(\alpha)$ calculations

Real weak corrections in the Sudakov limit

- Sudakov logs: IR limit of virtual one loop EW corrections
- $\lambda \leftrightarrow M_W \neq 0$
- finite corrections even without real contributions

... but virtual correction are *quite* large

Real weak corrections in the Sudakov limit (literature)

From a *theoretical* point of view

- on shell additional Z/W integrated everywhere

M. Ciafaloni, P. Ciafaloni and D. Comelli Phys.Rev.Lett. **84** (2000) 4810-4813, Nucl.Phys. **B589** (2000) 359-380, Phys.Rev.Lett.**87** (2001) 211802
G. Bell, J. Kuhn, and J. Rittinger, Eur.Phys.J. **C70**,659 (2010)
W. Stirling and E. Vryonidou, JHEP04, **155** (2013)

- only partial cancellation (incomplete isospin average)

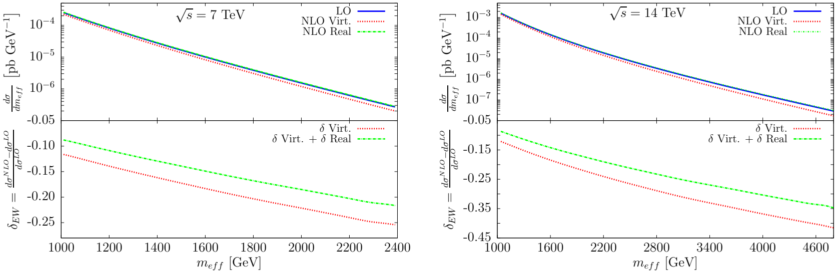
From a *phenomenological* point of view

- additional Z/W decay and are integrated only for final states degenerate with the signal

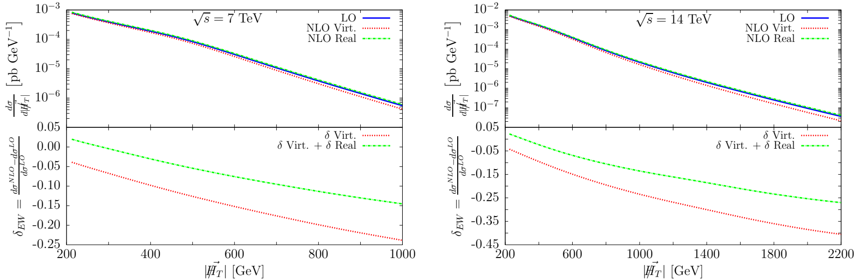
U. Baur, Phys. Rev. **D 75**, 013005 (2007)

- the size of real corrections depends strictly on the definition of observables

Real weak corrections to $Z + 2$jets, ATLAS setup



Real weak corrections to $Z + 3$jets, CMS setup

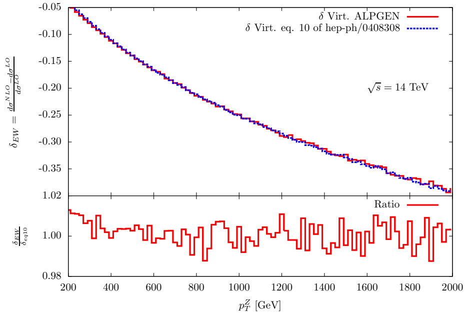


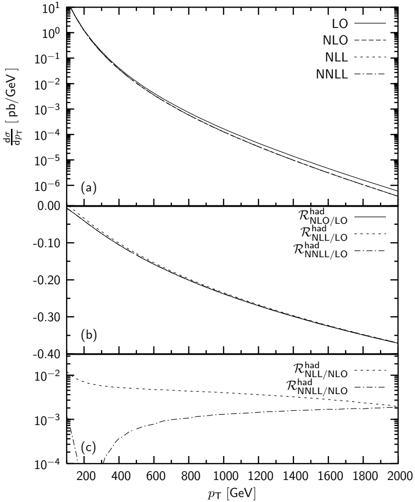
Conclusions

- at high energies weak corrections may become large
- in the Sudakov limit the leading part of virtual weak corrections can be computed in a process independent way (Denner-Pozzorini algorithm)
- the algorithm has been implemented in the LO event generator ALPGEN for the processes $Z/W+$ multijets
- also real radiation effects may not be negligible

Backup slides

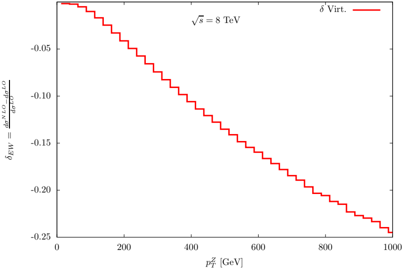
Cross-check and code validation (1): $Z + 1$jet

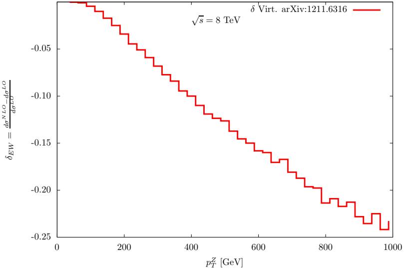




from J.H. Kuhn et al. hep-ph/0507178

Cross-check and code validation (2): $Z + 2$jet





with one fermionic current

List of real radiation processes

$ZW(\to \nu_l\bar{\nu}_l jj)+jj$	$ZZ(\to \nu_l\bar{\nu}_l jj)+jj$	$WW(\to \nu_l l jj)+jj$
$ZW(\to \nu_l\nu_l\nu_l l)+jj$	$ZW(\to \nu_l lll)+jj$	$ZZ(\to \nu_l\nu_l ll)+jj$
$ZZ(\to \nu_l\nu_l\nu_l\nu_l)+jj$	$WW(\to \nu_l\nu_l ll)+jj$	$ZW(\to \nu_l l jj)+jj$
$ZW(\to \nu_l\bar{\nu}_l jj)$	$ZW(\to \nu_l l jj)$	$ZZ(\to \nu_l\bar{\nu}_l jj)$
$WW(\to \nu_l l jj)$	$ZW(\to \nu_l l jj)+j$	$ZW(\to \nu_l\bar{\nu}_l jj)+j$
$ZZ(\to \nu_l\bar{\nu}_l jj)+j$	$WW(\to \nu_l l jj)+j$	

- ME jets required within acceptance cuts
- addition cuts on charged leptons imposed