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Electroweak corrections and BN violations at the LHC

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EW corrections for the LHC
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Outline

- Sudakov logs in EW corrections
- Double logs in real and virtual corrections
- Origin of BN violations
- Application to Photon/Z+jet
- Comments on other $2 \to 2$ processes
- Summary and Outlook

Sudakov double logs in EW corrections

- Real corrections:
  Double logs originate from soft gauge boson emission
- Interference of diagrams where the soft gauge boson emitted from external legs.
- Described by inserting the eikonal current:

$$J^{\mu}(k) = g_w \sum_{i=1}^{n} T_i \frac{p_i^{\mu}}{p_i k}$$

- Sum over all external legs-Squaring the eikonal current and integrating over the phase-space of the soft gauge boson leads to:

$$\int_M^E \frac{d^3k}{2\omega_k (2\pi)^3} \frac{2p_i p_j}{(kp_i)(kp_j)} = \frac{1}{8\pi^2} \log^2 \frac{2p_i p_j}{M^2}$$

With E the maximum energy allowed by $2\,p_i\,p_j$

Sudakov DL in virtual corrections

- Generalised formulae to obtain the leading logs in Denner and Pozzorini(2001). Correction to the matrix element:

$$\delta M^{i_1 \ldots i_n} = \frac{1}{2} \sum_{k=1}^{n} \sum_{l \neq k} \sum_{V_a = A,Z,W^{\pm}} I^{V_a}_{i'_k i_k}(k) I^{\bar{V}_a}_{i'_l i_l}(l) M_0^{i_1 \ldots i'_k \ldots i'_l \ldots i_n} \frac{\alpha}{4\pi} \log^2 \frac{2 p_k p_l}{M^2_{V_a}}$$

- Sum over external particles and includes exchange of Photon, W and Z.
- $ie I^{V_a}_{i'_k i_k}$ give the corresponding vertex-e.g. from the electron-photon coupling we have $I^{A}_{ee} = 1$
- Double Logarithms of Mandelstam variables s,t,u for the 2 ➔ 2 processes considered here.
- Higher order contribution is the interference between 1-loop diagram and the LO diagram.

Combination of real and virtual corrections

- Sudakov DL from real and virtual corrections take the same form: interference between the diagrams where V is emitted from i and j external legs and virtual V exchange between legs i and j.
- Difference is in matrix element i.e.

  Real ~ $M_0^{i_1 \ldots i'_k \ldots i_l \ldots i_n} M_0^{i_1 \ldots i_k \ldots i'_l \ldots i_n}$

  Virtual ~ $M_0^{i_1 \ldots i'_k \ldots i'_l \ldots i_n} M_0^{i_1 \ldots i_k \ldots i_l \ldots i_n}$
- Z,Photon emission does not change the particle type.
- W emission changes the particle type: $i'_k \neq i_k$
- Sum of the two not cancelling if the LO matrix elements differ → Block-Nordsieck violations

Block-Nordsieck violations

- When real and virtual EW corrections are added Sudakov double logs remain (Ciafaloni et al.).
- This is related to the non-Abelian nature of the EW theory and the fact that initial state partons have definite weak isospin.
- In practice BN violations are only relevant for W boson exchange, as this changes the parton type taking part in the hard scattering.
- BN violations in principle relevant for QCD corrections (non-Abelian theory).
- However summing over initial state colours means that violations are not present in QCD corrections (cancellation of divergences is exact).

Combination of real and virtual corrections

- Combining real and virtual EW corrections at the DL level, expect DL to remain from W exchange diagrams. Z,photon emissions never lead to BN violating logs.
- Therefore we only need to worry about W exchange terms and also only for initial state emission.
- Keep in mind that new processes open up at NLO-new parton combinations give non-zero contributions.
- Interesting to combine real and virtual corrections: Expect only partial compensation of the negative virtual DL-even when fully inclusive measurements are considered.
- Depends on how exclusive the measurements are-Effect of cuts considered in Bell et al.(2010) with cuts changing the real emission DL by restricting the phase space in the DL integrals.

Application to Photon plus jet

- Virtual corrections calculated in Kuhn et al. (2005)
- Analytical NLL expressions for the high energy limit

$$s, |t|, |u| \gg M_W^2$$

- No decays taken into account, photon produced on-shell.
- Only W,Z(weak) corrections are taken into account.
- Virtual corrections decrease the cross section by up to ~20% at high transverse momentum (~2TeV).

Parton processes in Photon+jet

- Processes to be considered, based on the initial state parton combination:

$$qg \to \gamma q$$
$$q\bar{q} \to \gamma g$$

- For the corrections, we need to consider:

Z emission
W emission

- Processes of the form:

$$qg \to \gamma q Z$$
$$q\bar{q} \to \gamma g Z$$
$$qg \to \gamma q' W$$
$$q\bar{q}' \to \gamma g W$$

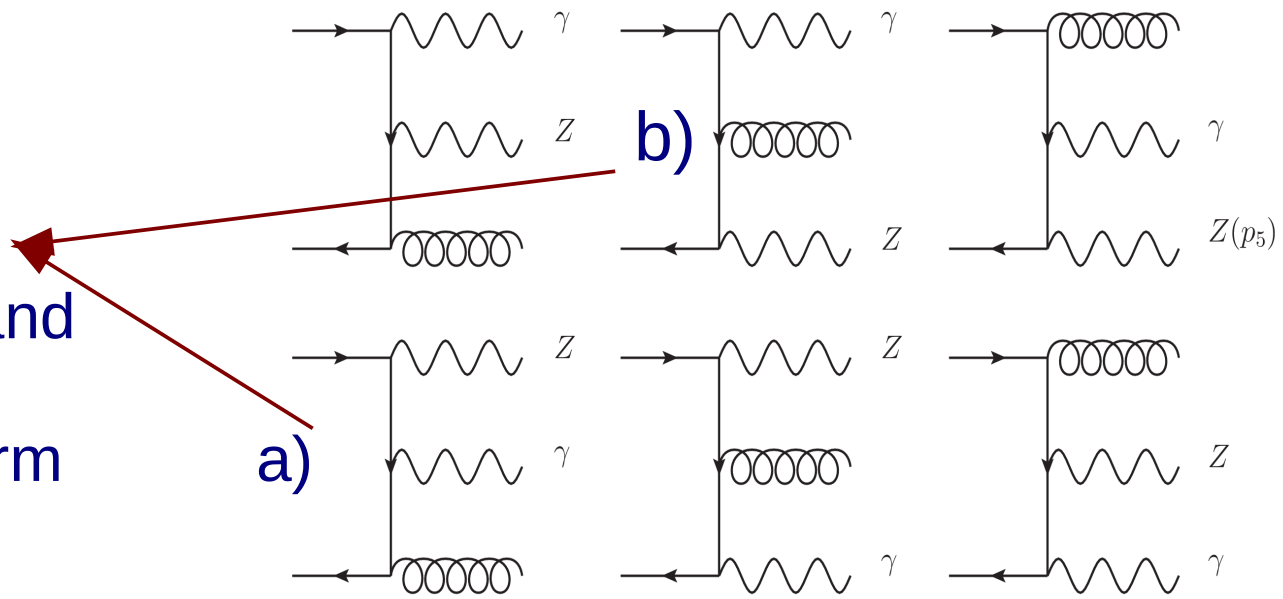
where q and q' are taken to be in the same generation (CKM diagonal)

- Note that new partonic combinations open up.

What form of DL do we expect?

- Feynman diagrams to be calculated in real corrections:

  Example:

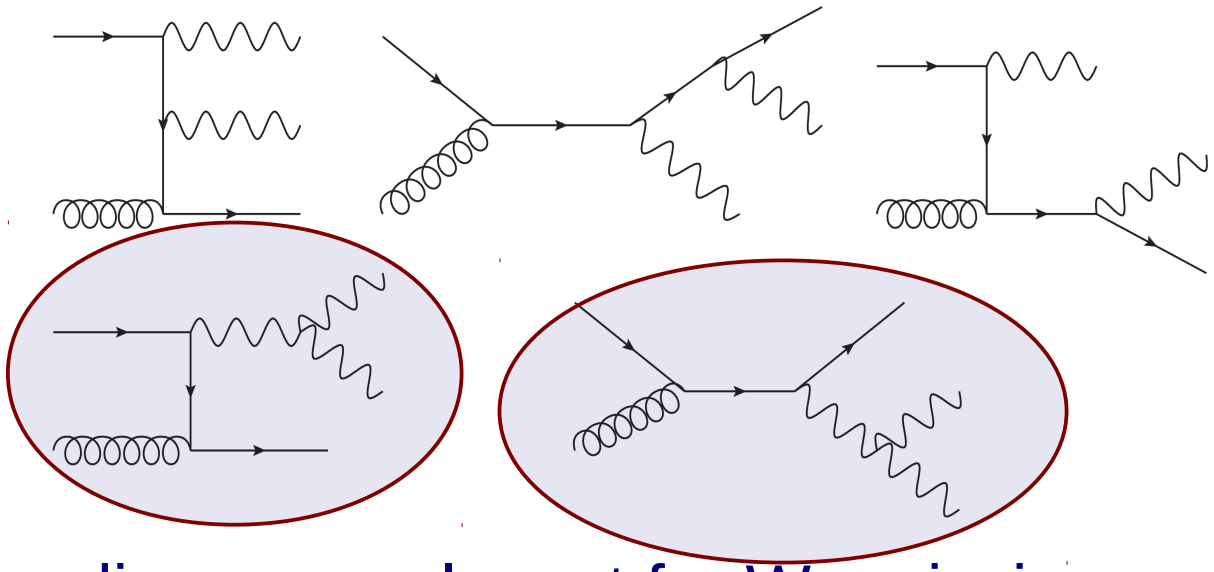


Interference between diagrams a) and b) leads to a $\log^2(s/M_V^2)$ term

- Expect Sudakov logs from the interference between diagrams where the soft Z is emitted from external legs.
- Take Z to be soft → eikonal current form, ignore Z mass terms.

Processes in real corrections

- In addition to Z emission, W emission is allowed for initial state qg.
- Sample of real emission Feynman diagrams:



- Last two diagrams relevant for W emission.
- We expect different logarithmic terms (s,t,u) coming from different combinations of diagrams.

Analytical partonic results

- Are the results what we expect?
- Real corrections results at the DL level for

$$u(p_1)g(p_2)\to u(p_3)\gamma(p_4)Z(p_5)$$

$c_v^2+c_a^2$

$$\sum\bar{}|M^{ug}|^2=\sum\bar{}|M^{ug}_{LO}|^2\frac{\alpha_w}{144\pi c_w^2 s_w^2}(9-24s_w^2+32s_w^4)\log^2\frac{2p_1p_3}{M_Z^2}$$

- While for $u(p_1)g(p_2)\to d(p_3)\gamma(p_4)W(p_5)$

$$\sum\bar{}|M^{ug}|^2=\sum\bar{}|M^{ug}_{LO}|^2\frac{a_w}{32s_w^2\pi}\left[3\mathrm{Log}^2\left(\frac{2p_1p_3}{M_W^2}\right)-2\mathrm{Log}^2\left(\frac{2p_1p_4}{M_W^2}\right)+6\mathrm{Log}^2\left(\frac{2p_3p_4}{M_W^2}\right)\right]$$

- In agreement with what we expect from the Feynman diagrams and the quark-gauge boson couplings.

Isospin averaging

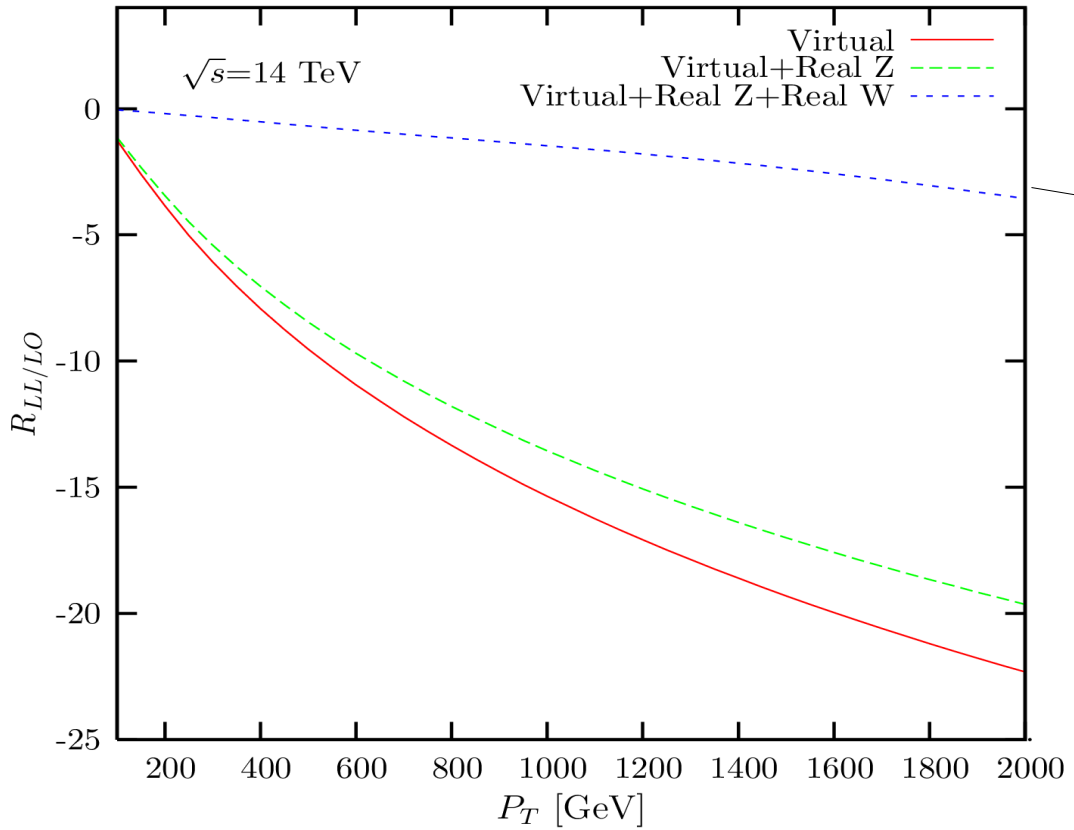
- Using the analytic expressions for the virtual and real corrections we can check that Sudakov logs exactly cancel when averaging over weak isospin states:

$$dg \to \gamma d \quad ug \to \gamma u$$

- We find that the s,t,u DL exactly cancel term by term.
- In practice the two processes are weighted by different PDFs and therefore BN violating logs remain when the proton-proton cross section is computed.

Results for the LHC

Results for the LHC at 14 TeV, using MSTW2008LO and the analytical virtual and real correction DL results.



Partial Compensation of the virtual DL by the real corrections

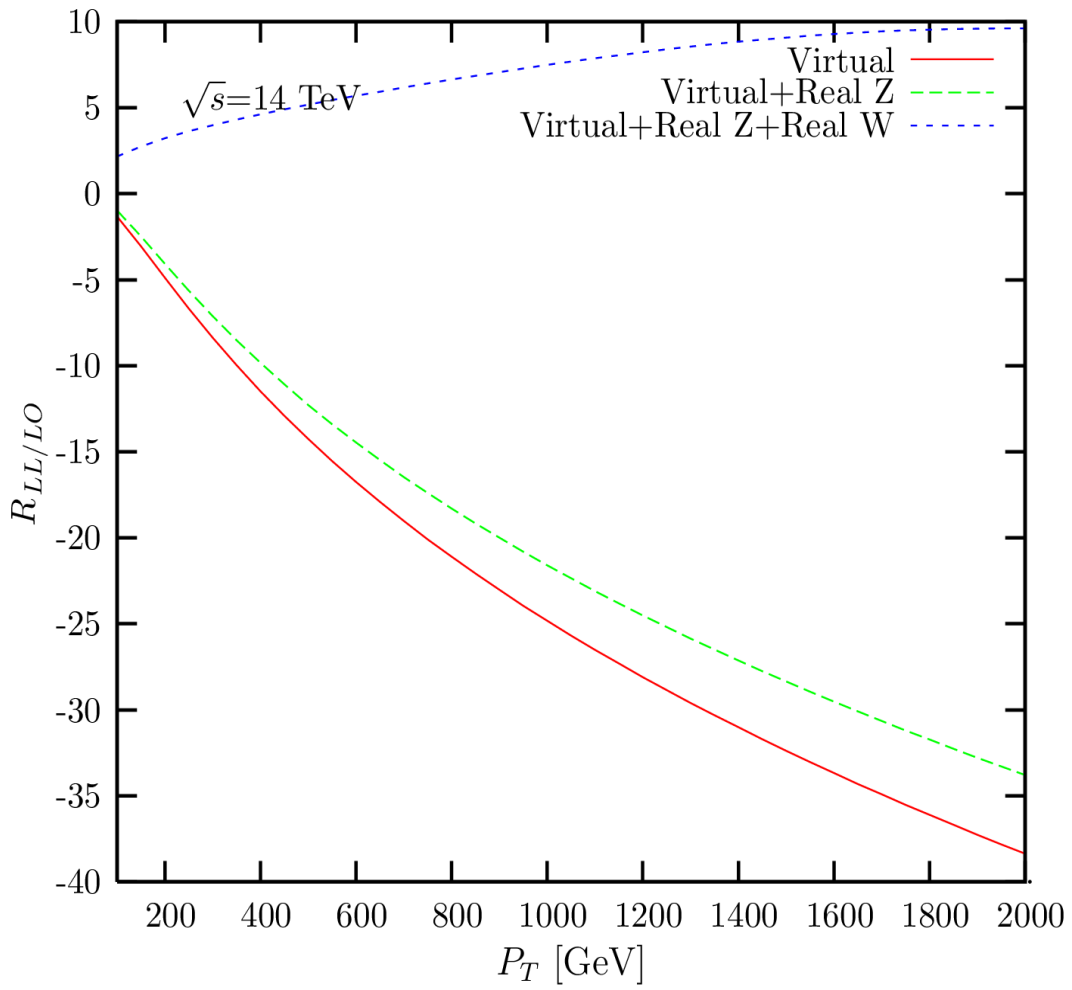
$$R_{LL/LO} = LL/LO - 1$$

We note that if all PDFs were the same for all quarks(as at low x) then the cancellation between real and virtual corrections is exact.

Z+jet

- Analysis similar to Photon+jet, with real Z and W emission.
- Virtual corrections available in the literature in the high energy limit in Kuhn et al.(2005)
- Analytical expressions for both real and virtual corrections more complex due to couplings.
- Again no Z decays are included.
- Only DL are taken into account. We don't keep the SL of the NLL virtual corrections for consistency. The SL contribution is subdominant at high transverse momentum (20% of the virtual NLL corrections at 2TeV).

Z+jet results at the LHC

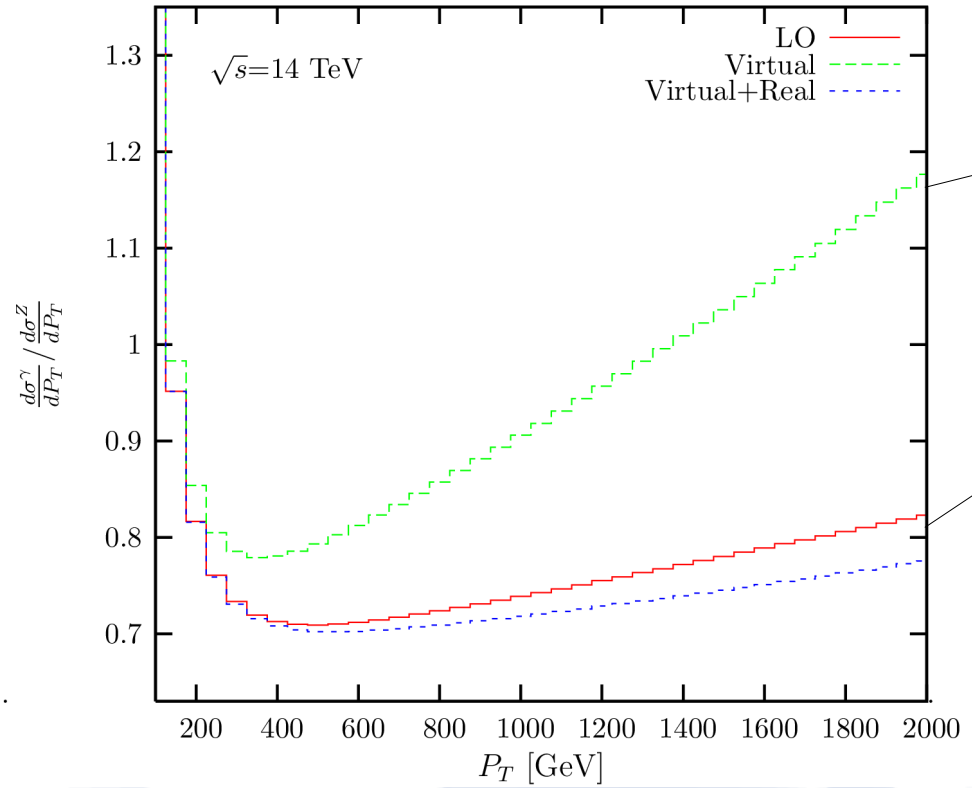


Compensation of the virtual DL by the real corrections

Largest contribution comes from W emission- determined by couplings

Ratio gamma to Z results

- Ratio gamma to Z studied in Ask et al. (2011)
- Ratio suffers less than cross sections from theoretical and experimental uncertainties, insensitive to QCD corrections. Simple dependence on the couplings at high p_T.
- Important in New Physics searches: Used to better calibrate the missing transverse energy + jets background to SUSY production coming from Z(→ neutrinos) + jets.



Virtual corrections increase ratio

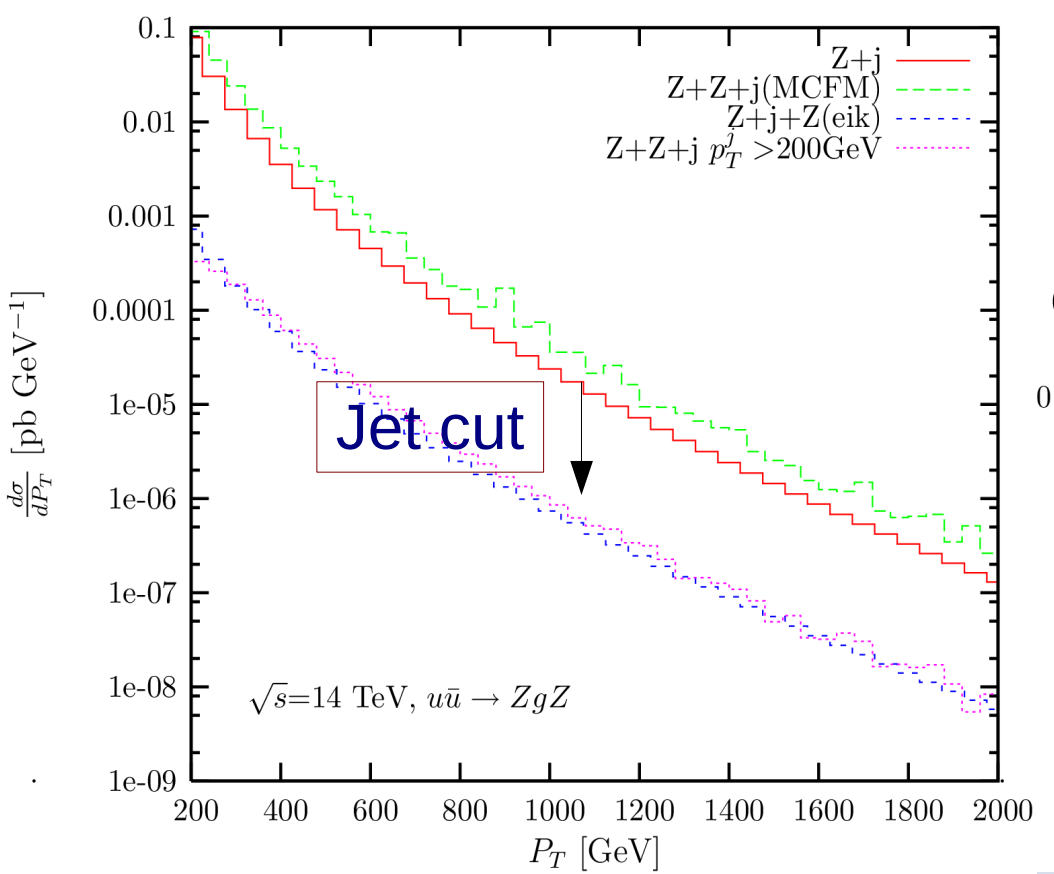
Real corrections push ratio close to the LO result

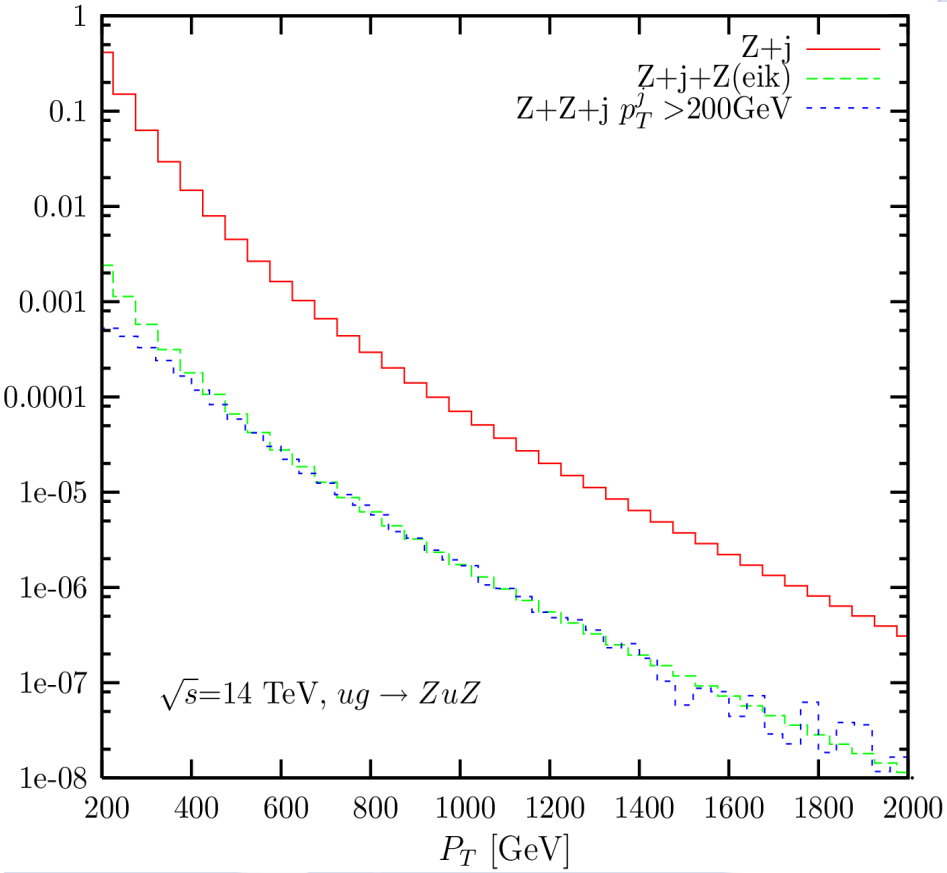
Z+jet comparison with MCFM

- Interesting to compare eikonal emission real correction results for Z+jet with full Z+Z+jet process.
- Use MCFM to compare with the eikonal approximation.
- Apply a cut on one Z transverse momentum.
- First attempt to combine real gauge boson radiation with virtual corrections in Baur (2006). Cuts and decays considered.
- Real corrections calculated in full, by considering $2 \rightarrow 3$ processes, using MCFM.
- Cut on jet transverse momentum needed to avoid large soft jet contribution.
- Compensation of real and virtual corrections depends strongly on the cuts, Bell et al.(2010).

Results comparison

- Pick individual subprocesses for clearer comparison.
- Set cut on the jet transverse momentum to be in the right kinematical region(hard jet balancing hard Z).
- Good agreement at high Z transverse momentum.





QCD dijets

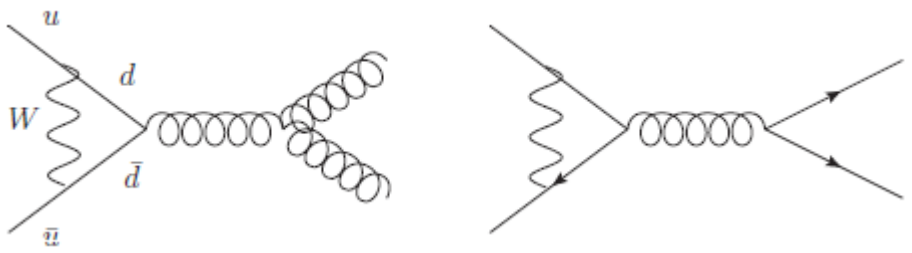
- Virtual corrections calculated in Moretti et al. (2006)
- A large number of diagrams needed when pure electroweak LO diagrams are taken into account. LO cross section: $\mathcal{O}(\alpha_s^2 + \alpha_s\alpha_w + \alpha_w^2)$
- Virtual corrections decrease cross sections up to ~35% at high energies (~4TeV).
- Only consider $\mathcal{O}(\alpha_s^2\alpha_w)$ EW corrections.
- Qualitative discussion-BN violating logs.
- Real EW corrections: W/Z+2 jets.

QCD dijets

- Examples of processes based on initial and final state parton combinations.
- No EW corrections: $g\,g \to g\,g$
- No BN violations e.g.: $g\,g \to q\,\bar{q}$
- BN violating DL e.g.:

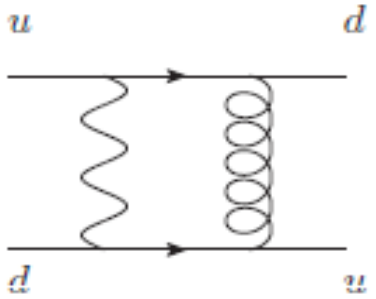
$$q\,\bar{q} \to g\,g, q\,\bar{q} \to Q\,\bar{Q}, q\,\bar{Q} \to q\,\bar{Q}, q\,Q \to q\,Q, q\,\bar{q} \to q\,\bar{q}$$

- Example of diagrams leading to BN violating logs:

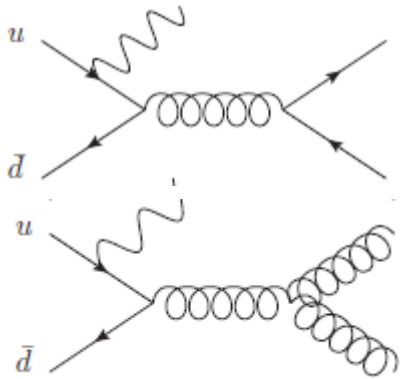


Virtual W exchange between initial state partons

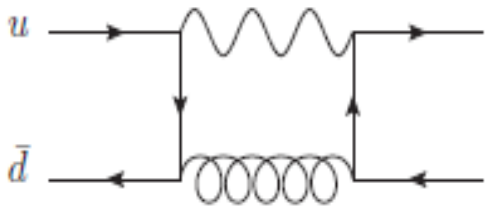
BN violating diagrams



Box diagram: Virtual W exchange between initial state partons.



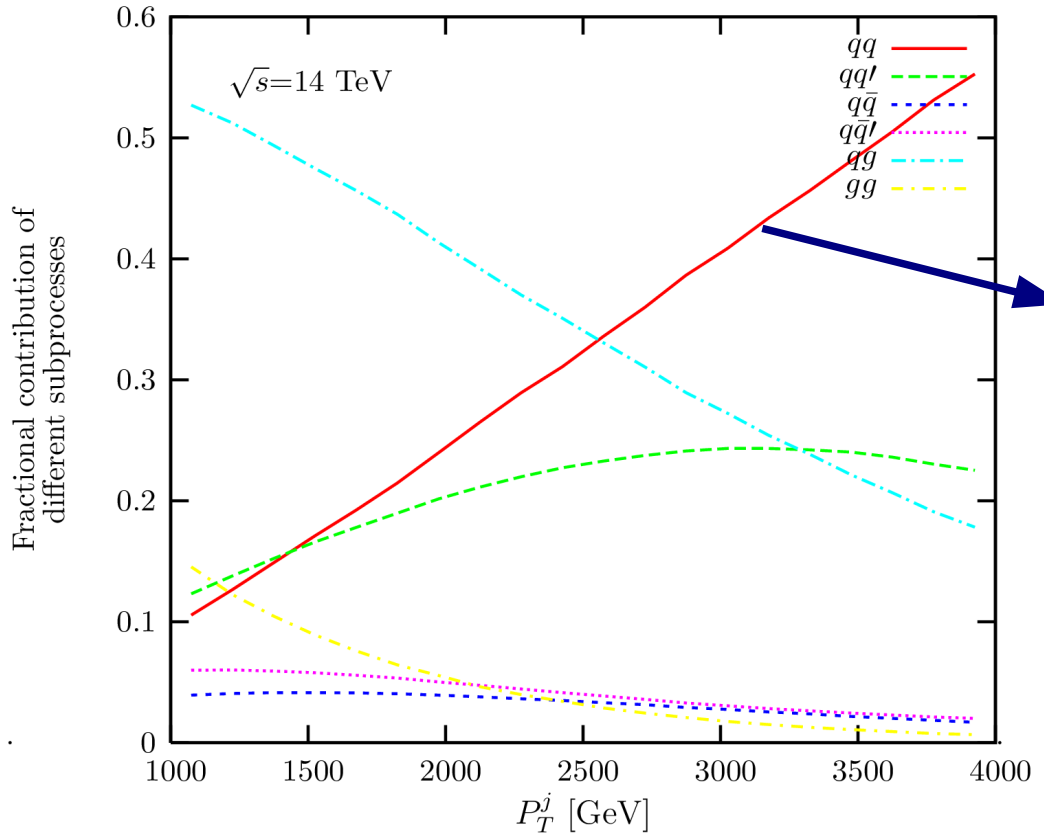
Real W emission from initial state partons.



Box diagram: Virtual W exchange between initial and final state partons.

QCD dijet results

- Parton combination decomposition as a function of the jet transverse momentum:



Valence quark dominance

- Expected effect: Partial compensation of negative virtual logs by real corrections. Overall importance of BN violations depend on which processes dominate at any p_T^j .

Electroweak processes: W+H, W+Z

- LO: $u\bar{d} \to W^+ H$
- NLO Real: $u\bar{d} \to W^+ H Z$

$q\bar{q} \to W^+ H W^-$

DL that cannot be cancelled by virtual corrections → BN violations

- Similarly for W+Z, new $q\bar{q}$ combination opens up in real corrections → BN violation
- Expect partial compensation of negative virtual corrections calculated in Accomando et al. and Ciccolini et al.

Summary-Outlook

- Overview of Sudakov DL in real and virtual electroweak corrections in $2 \to 2$ processes
- BN violations in EW corrections.
- Application to Z/Photon+jet-Analytical partonic results.
- Results for the LHC, real corrections only partially compensate the negative virtual corrections. In practice, to study experimentally decays and cuts need to be taken into account and compensation is expected to be even less efficient.
- Comments on other processes at the LHC.
- Plan to introduce cuts on emitted bosons and decay products (Bell et al.)
- More quantitative results for other processes.