Abstract

While radiative corrections of infrared origin normally depress high energy amplitudes (Sudakov form factors), we find that in some cases resummation of leading effects produces exponentials with positive exponents, giving rise to amplitudes that grow indefinitely with energy. The effect happens in broken gauge theories like the electroweak sector of the Standard Model, and is related to the existence of amplitudes that do not respect the gauge symmetry. Contrary to expectations, these amplitudes, although mass suppressed, do not vanish in the very high energy limit, but rather become dominant.

References are at the end of the talk

Something New in the High Energy Limit of Spontaneously Broken Gauge Theories ?

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(Large energy limit $Q \to \infty$) $\equiv$ (IR limit $M_W \to 0$)

Computing loops in EW theory in the high energy limit ($Q \gg M_W$) we found the following series:

$$\frac{\Delta\sigma}{\sigma} = \alpha_W \left(\underbrace{Log^2 \frac{Q^2}{M_W^2} + Log \frac{Q^2}{M_W^2}}_{LHC+ILC} + \underbrace{1 + o(\frac{m^2}{Q^2})}_{LEP} \right)$$

IN QCD and QED only single logs ($\alpha \; Log \frac{Q^2}{m^2}$) for sufficient inclusive observables! Typical size of the one loop logs ($Q = 1$ TeV):

$$\frac{\alpha_W}{4\pi} Log^2 \frac{Q^2}{M_W^2} = 6.7\%, \qquad \frac{\alpha_{W/S}}{4\pi} Log \frac{Q^2}{M_W^2} = 1.4 \,/\, 3.6 \; \%$$

Massless/High Energy limit of a SB gauge theory

How to compute the limit $\boxed{\lim_{\substack{m\to 0\\ Q\to\infty}} \mathcal{O}_{\frac{m}{Q}} = \mathcal{O}_0}$?

($\mathcal{O} \equiv$ observable) from the IR point of view
(only DL corrections and **no**: α running, SL, anomalies etc)

The problems that we have to face:

- $\lim_{\substack{m\to 0\\ Q\to\infty}} \alpha \log^2 \frac{Q^2}{m^2} = \infty$
- A Resummation technique is needed:

$$\sum_n^\infty c_n \left(\alpha \log^2 \frac{Q^2}{m^2}\right)^n$$

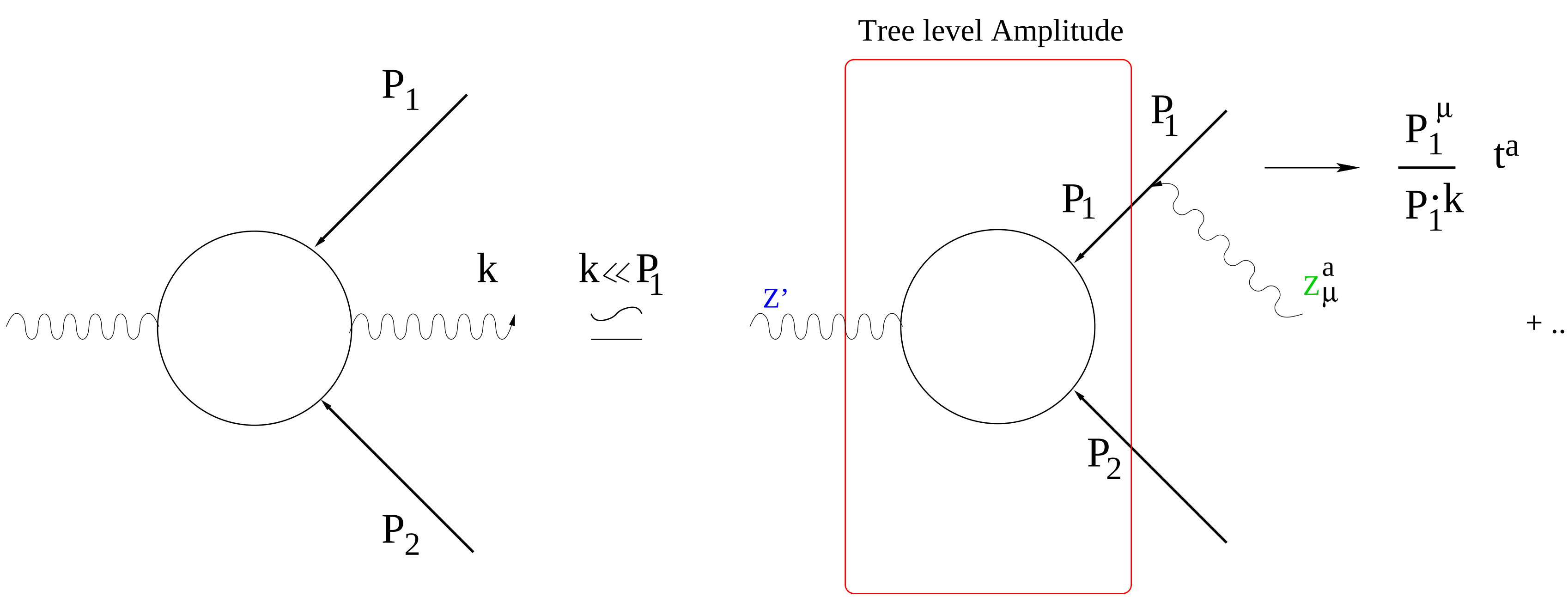
IR Resummation Techniques

How is it possible to sum up an infinite number of Feynman diagrams?

The kinematical origin of the double Logs is Infrared

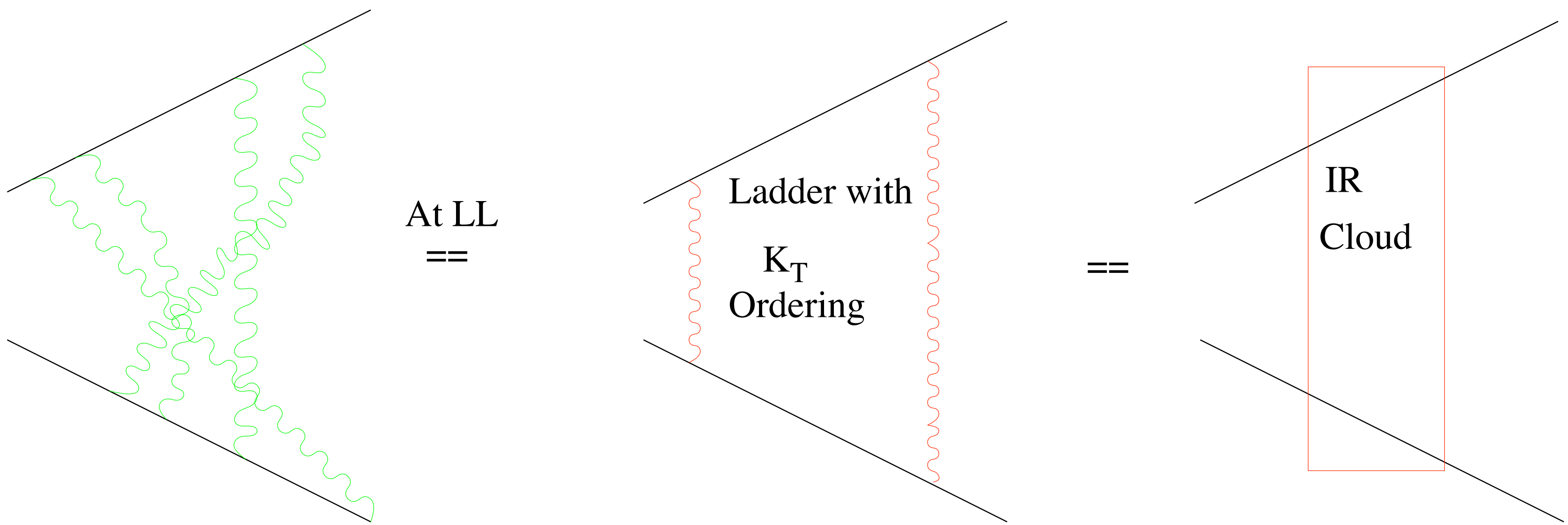
$$\alpha \int^{Q} \frac{dk_t^2}{k_t^2 + m^2} \int_{k_t/Q} \frac{d\omega}{\omega} \sim \alpha \, \log^2 \frac{Q^2}{m^2}$$

Eikonal Technique:



IR Resummation Techniques

Ladder diagrams:



$$\sum_n \alpha^n (t_1^{a_1} ... t_1^{a_n}) \otimes (t_2^{a_1} ... t_2^{a_n}) \int^Q \frac{dk_{t_1}^2}{k_{t_1}^2} \int_{k_{t_1}/Q} \frac{d\omega_1}{\omega_2} \quad ... \quad \int^{k_{t_{n-1}}} \frac{dk_{t_n}^2}{k_{t_n}^2} \int_{k_{t_n}/Q} \frac{d\omega_n}{\omega_n} =$$

$$P_{k_t} e^{\alpha \ t_1^a \otimes t_2^a \ \int \frac{dk_t^2}{k_t^2} \frac{d\omega}{\omega}}$$

Cancellation Theorems for IR divergencies

K.L.N. Theorem In a theory with massless fields, transition rates are free of IR divergences IF the summation over INITIAL and FINAL degenerate states is carried out.

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B.N. in QED: IR divergences cancel out after summation over all degenerate **final** soft photons compatible with experimental detection.

B.N. in QCD : Leading IR singularities cancel after:

- summation over **final soft gluons**
- average over **final color** and **initial color** or for **color singlet** initial states (like a proton)
- Violation of BN only at higher twist level

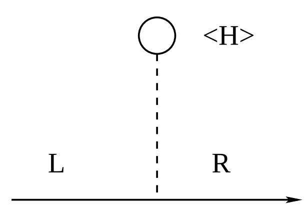
SB manifestation in gauge theories

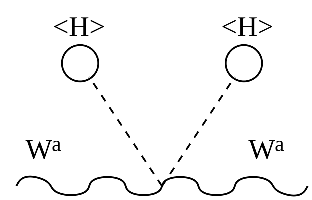
Spectrum:

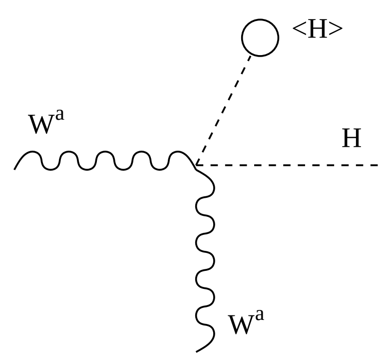
- Massive gauge bosons
- Asymptotic states contain Free non abelian charges

vev insertions:

- The vev insertions generate gauge non invariant amplitudes.
  At tree level we have masses and trilinear couplings:

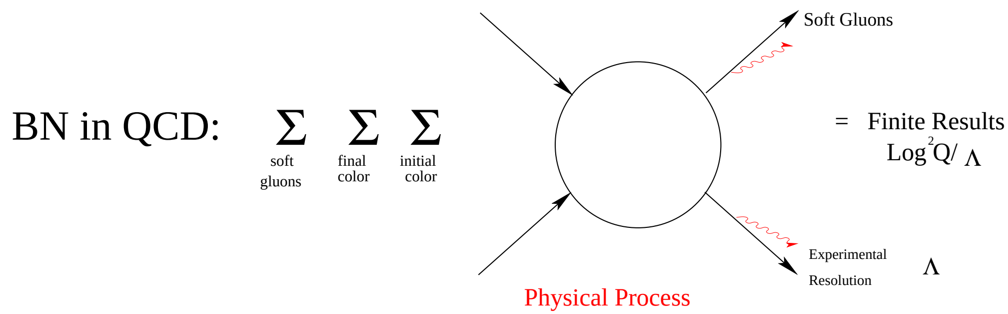






Spectrum: EW violation of the Block-Nordsiek Theorem

From QCD to EW: $SU(3) \rightarrow SU(2)$, (*Color* $\rightarrow$ *Flavor*), M_W <u>physical IR cutoff</u>



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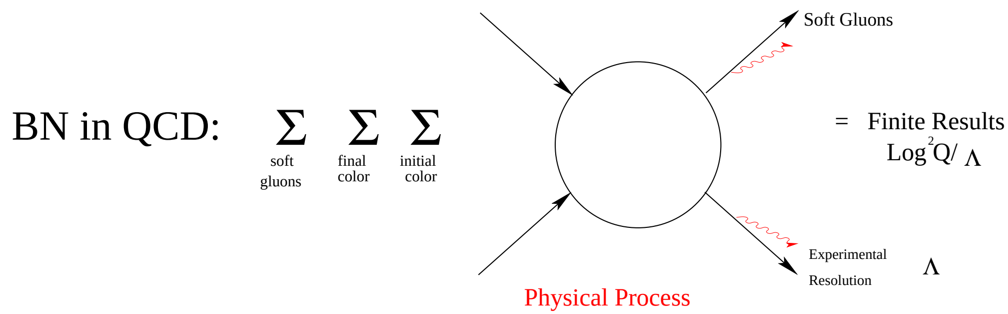

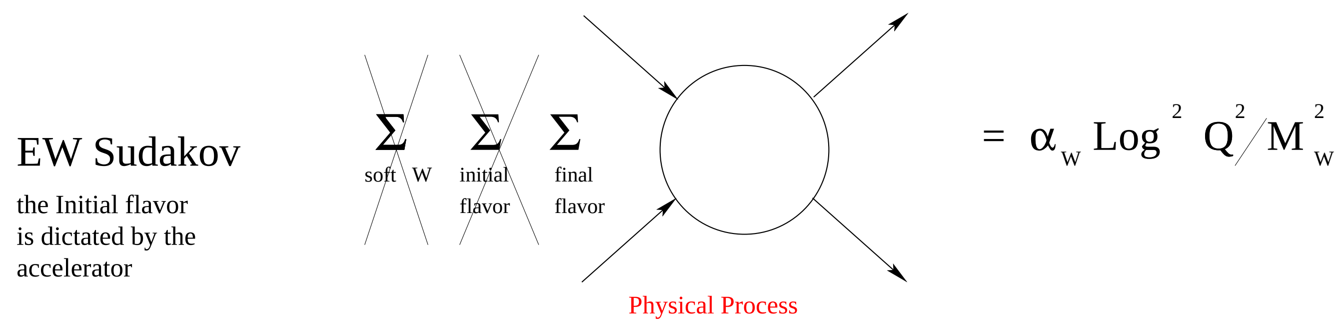

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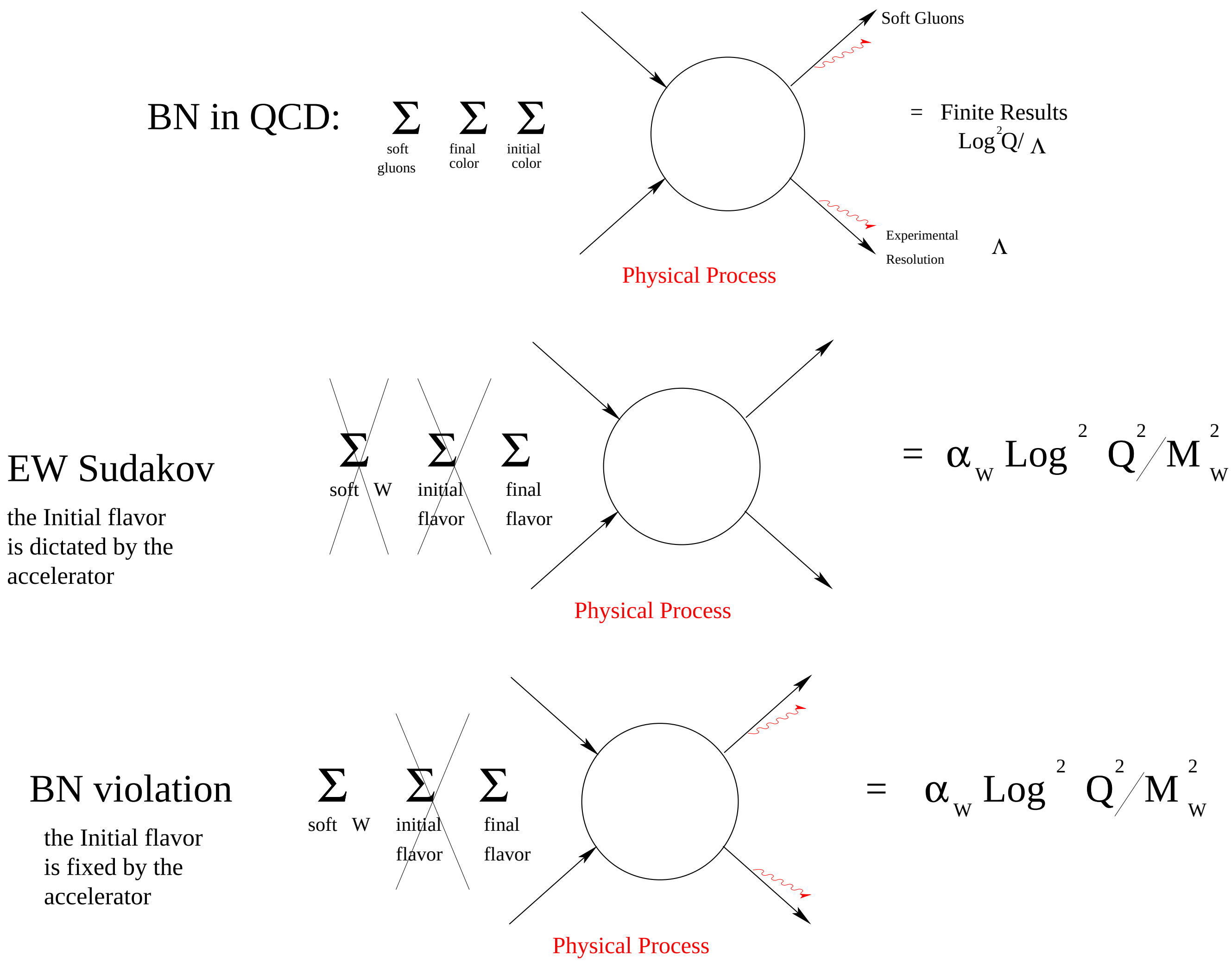

High Energy EW theory

Sudakov versus BN EW corrections:

- Sudakov Form Factors EW corrections:

$$\sigma(s) = \sigma_H \;\; e^{-\frac{\alpha_W}{4\pi}\sum_i (t_i(t_i+1)+y_i^2\tan^2\theta_W) Log^2 \frac{Q^2}{M_W^2}}$$

- BN EW corrections: The hard cross section is first decomposed in total t-channel isospin basis:

$$\sigma(s) = \sum_t e^{-\frac{1}{2}\frac{\alpha_W}{4\pi} t(t+1) Log^2 \frac{Q^2}{M_W^2}} \;\; \sigma_t^H \qquad \sigma_t^H \lessgtr 0$$

- For Sud t_i is the external leg isospin (e.g., $t_i = \frac{1}{2}$ for a fermion) while for BN t is obtained by composing two single-leg isospins (e.g., $\frac{1}{2} \otimes \frac{1}{2}$ =0 or 1 for a fermion).
- There is a factor 2 of difference in the argument of the exponentials.
- **while Sudakov corrections always depress the tree level cross section, BN ones can be negative or positive.**

Leading Order Results for High Energy EW theory

EW Sudakov structure: Resummation Leading EW Virtual radiative corrections (P.Ciafaloni,D.C.2000)

$$\sigma(Q) = \sigma_H(Q) \; \underbrace{e^{-\frac{\alpha_W}{4\pi}\sum_i C_i \; Log^2 \frac{Q^2}{M_W^2}}}_{\star \;\; \to 0 \quad \text{for}\, Q \gg M_W}$$

$C_i = SU(2)$ Casimir charge of the i-external leg

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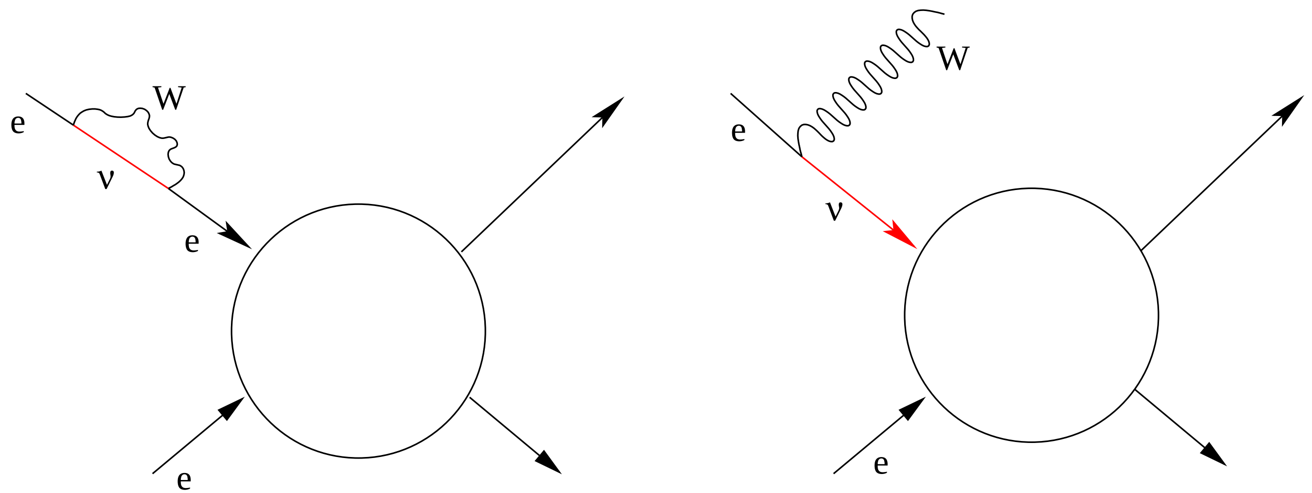
Typical size at $Q \sim 1\ TeV$ (for 2→ 2 processes) present both at ILC and LHC (P.Ciafaloni,D.C.1999)

$$\frac{\delta\,\sigma}{\sigma}\Big|_{\text{one loop}}^{LL} \sim -\frac{\alpha_W}{\pi}Log^2\frac{Q^2}{M_W^2} \simeq -26\%, \qquad \frac{\delta\,\sigma}{\sigma}\Big|_{\text{one loop}}^{NLL} \sim \frac{3\,\alpha_W}{\pi}Log\frac{Q^2}{M_W^2} \simeq 16\%$$

$$\frac{\delta\,\sigma}{\sigma}\Big|_{\text{two loop}}^{LL} \sim +\frac{\alpha_W^2}{2\pi^2}Log^4\frac{Q^2}{M_W^2} \simeq +3.5\%, \qquad \frac{\delta\,\sigma}{\sigma}\Big|_{\text{two loop}}^{NLL} \sim -\frac{3\,\alpha_W^2}{2\pi^2}Log^3\frac{Q^2}{M_W^2} \simeq -4.6\%$$

EW violation of the Block-Nordsiek Theorem

One loop example of EW BN violation



$$-\sigma_{ee}\ \alpha_{w}\ \mathrm{Log}^2\ Q^2/M^2 \qquad + \sigma_{\nu e}\ \alpha_{w}\ \mathrm{Log}^2\ Q^2/M^2 \qquad \neq \ 0$$

Different coefficients (the hard cross sections) for virtual ($\sigma_{e\bar{e}}$) and real ($\sigma_{\nu\bar{e}}$) corrections

($\sigma_{\nu\bar{e}\to\sum_q q\bar{q}} \simeq 2\ \sigma_{e\bar{e}\to\sum_q q\bar{q}}$ for $Q^2 \gg M_W^2$)

Leading Order Results for High Energy EW theory

EW BN violation structure: Resummation Leading EW Virtual plus Real radiative corrections (M. & P.Ciafaloni,D.C.2000)

$$\sigma^{inclusive}_{e\bar{e}} = \frac{\sigma^H_{e\bar{e}} + \sigma^H_{\nu\bar{e}}}{2} + \frac{\sigma^H_{e\bar{e}} - \sigma^H_{\nu\bar{e}}}{2} \, e^{-\frac{\alpha_W}{2\pi} Log^2 \frac{Q^2}{M^2_W}} \underbrace{\longrightarrow}_{Q \gg M_W} \frac{\sigma^H_{e\bar{e}} + \sigma^H_{\nu\bar{e}}}{2}$$

$$\sigma^{inclusive}_{\nu\bar{e}} = \frac{\sigma^H_{e\bar{e}} + \sigma^H_{\nu\bar{e}}}{2} - \frac{\sigma^H_{e\bar{e}} - \sigma^H_{\nu\bar{e}}}{2} \, e^{-\frac{\alpha_W}{2\pi} Log^2 \frac{Q^2}{M^2_W}} \underbrace{\longrightarrow}_{Q \gg M_W} \frac{\sigma^H_{e\bar{e}} + \sigma^H_{\nu\bar{e}}}{2}$$

$(ex : \sigma^H_{\nu\bar{e}\to q\bar{q}} = 2\,\sigma^H_{e\bar{e}\to q\bar{q}})$ Effectively e_L becomes indistinguishable from ν_e !

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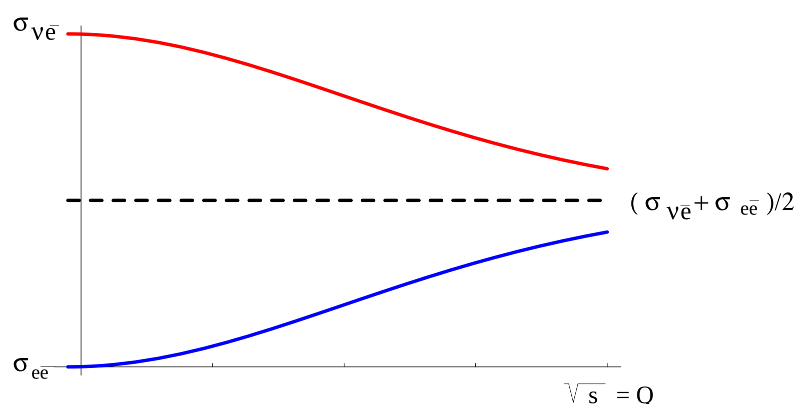
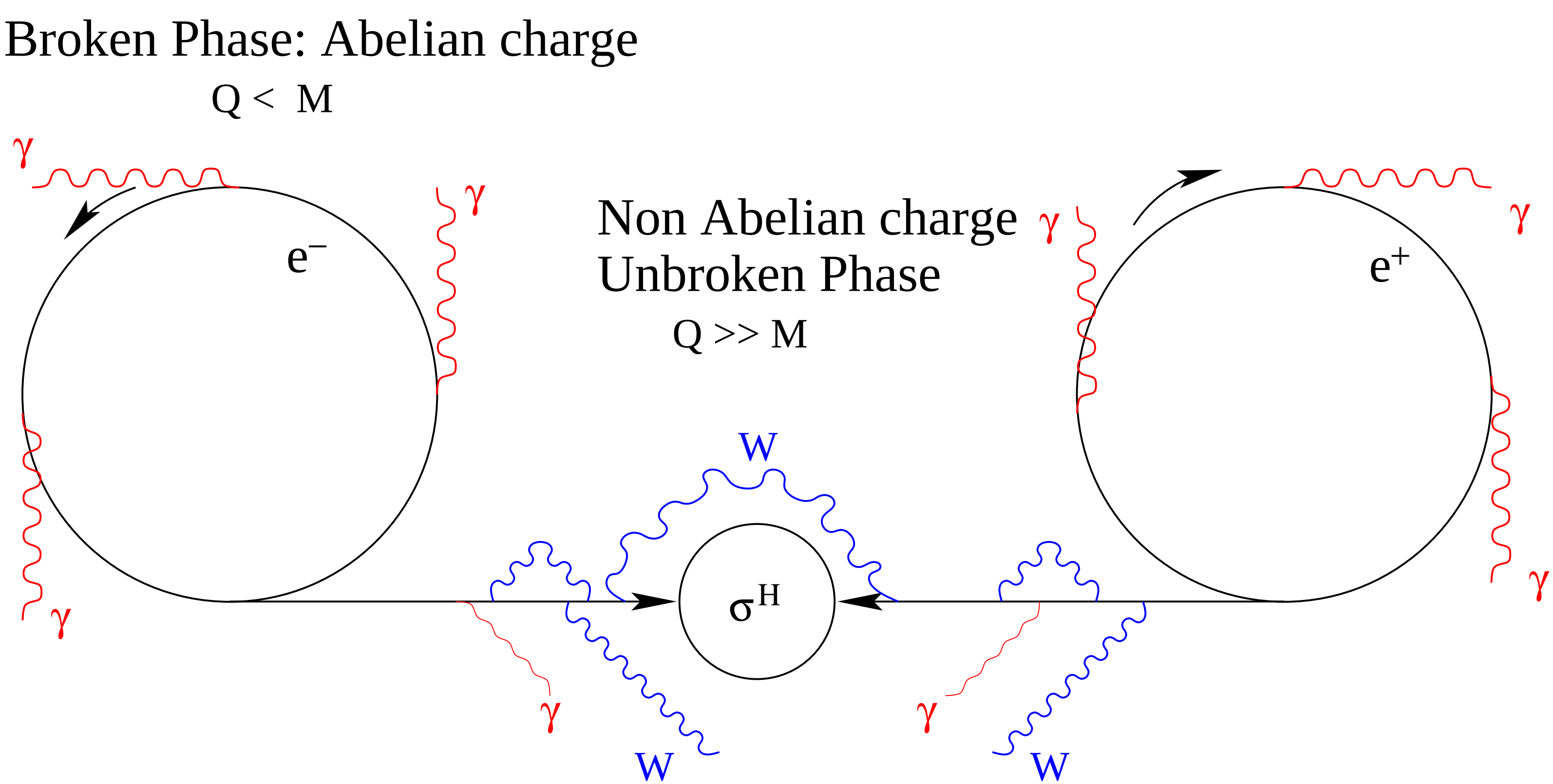


High Energy EW theory

Physical Pictorial idea: For low energies ($Q \leq M_W$) an e^- borns "effectively" as an abelian charge (clouds of photons), increasing the energy ($Q \gg M_W$) it becomes an "effective" non abelian charge (clouds of W's) .

The e when surrounded by the $W's$ is loosing his *identity* resembling more and more a ν.



Can we find something new in the High Energy limit of the SM ?

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Where? Inside the gauge non invariant amplitudes generated by vev insertions

Why? Growing Sudakov Form Factors: $e^{+\alpha Log^2 \frac{Q^2}{M^2}}$

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$$\sigma \sim \frac{\alpha^2}{Q^2} \left(\ 1 \quad + \quad \underbrace{\frac{m^2}{Q^2}}_{\text{Is it always negligible for } Q \gg m?} \quad \right)$$

Can we find something new in the High Energy limit of the SM ?

Probably Yes!

Where? Inside the higher twist operators

Why? Growing Sudakov Form Factors: $e^{+\alpha Log^2 \frac{Q^2}{M^2}}$

$$\sigma \sim \frac{\alpha^2}{Q^2}(1+\frac{m^2}{Q^2}) \underbrace{\longrightarrow}_{\text{IR Cloud}} \frac{\alpha^2}{Q^2}\left(e^{-\alpha Log^2 \frac{Q^2}{M^2}} + \frac{m^2}{Q^2} e^{+\alpha Log^2 \frac{Q^2}{M^2}}\right)$$

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$$e^{-\alpha Log^2 \frac{Q^2}{M^2}} \sim \frac{M^2}{Q^2}\, e^{+\alpha Log^2 \frac{Q^2}{M^2}} \qquad \text{for } M \sim m$$

$$Q \sim M\, e^{\frac{1}{2\alpha}}$$

Can we find something new in the High Energy limit of the SM ?

Structure of the Anomalous series

$$\frac{m^2}{Q^2}\ e^{+\alpha \log^2 \frac{Q^2}{m^2}} = \sum_n\ \alpha^n\,\frac{m^2}{Q^2}\ \log^{2\,n}\frac{Q^2}{m^2}$$

$$\lim_{m\to 0}\ \frac{m^2}{Q^2}\ \log^{2\,n}\frac{Q^2}{m^2}\overbrace{=}^{\forall\, n} 0; \quad \text{but} \quad \lim_{m\to 0}\frac{m^2}{Q^2}\ e^{\alpha \log^2 \frac{Q^2}{m^2}} = \infty$$

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Pole at $\frac{m^2}{Q^2}\to 0$ $\qquad \frac{m^2}{Q^2}\ e^{\alpha\log^2\frac{Q^2}{m^2}} = \left(\frac{m^2}{Q^2}\right)^{1+\alpha\log\frac{m^2}{Q^2}}$

vev insertions: News inside the SM ?

An Explicit example: $Z' \to f_i \bar{f}_i$, $\quad i = 1, 2$

The model:

- Chiral Gauge group $U'_{Z'}(1) \otimes SU_W(2) \otimes U_Z(1)$
- $(f_L^{(1)}, f_L^{(2)})$ doublet of $SU_W(2)$, $(f_R^{(1)}, f_R^{(2)})$ singlet of $SU(2)$
- fermion $U'(1)$ charges: $f_L^{(1,2)} = f_R^{(1,2)} \equiv f$
- fermion $U(1)$ charges: $y_L^{(1,2)} \equiv y_L$, $y_R^{(1,2)} \equiv y_R$
- with mass gap $M_{Z'} \gg M_W \sim M_Z \sim m_{\text{fermion}} \equiv m$

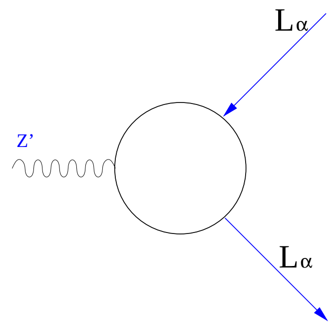
Effective $Z' \to f_i \bar{f}_i$ vertex for onshell particles ($i = 1, 2$):

$$Z'^{\nu} \; \bar{u}_i(p_1) \left(\gamma_\mu (F_L^{(i)} \, P_L + F_R^{(i)} \, P_R) + \frac{m}{Q^2} (p_{1\,\mu} - p_{2\,\mu}) F_M^{(i)} + \frac{m}{Q^2} (p_{1\,\mu} + p_{2\,\mu}) \gamma_5 \, F_P^{(i)} \right) v_i(p_2)$$

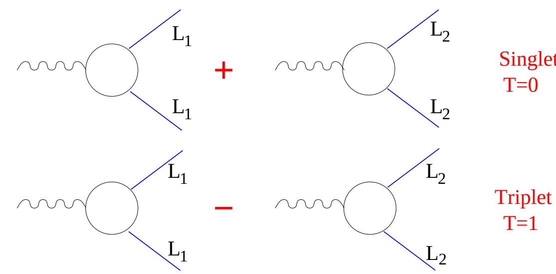
8 Form Factors: $F_{L,R}^{(i)}$ conserve chirality, $F_{M,P}^{(i)}$ violate chirality

vev insertions: News inside the SM ?

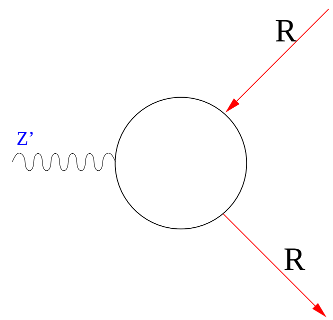
	Total External Legs U(1) Charge	Total External Legs SU(2) Charge



F_L $\quad y_L - y_L = 0$

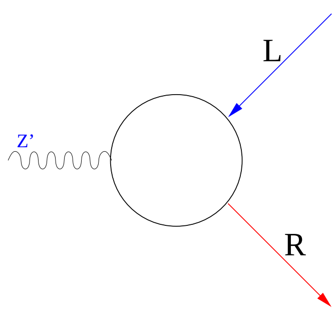


$$\frac{1}{2} \otimes \frac{1}{2} = 1 \oplus 0$$



F_R $\quad y_R - y_R = 0$

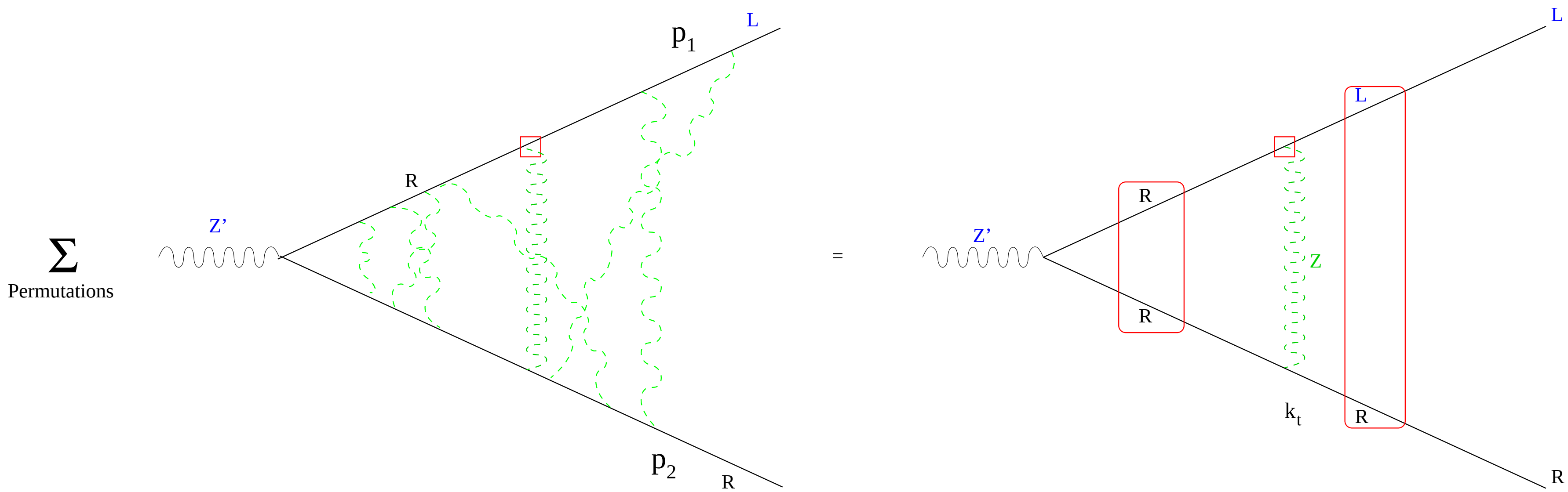
Singlet



$F_{m,e}$ + h.c. $\quad y_L - y_R \neq 0$

$$\frac{1}{2} \otimes 0 = \frac{1}{2}$$

vev insertions: $U(1)$ Z resummation.



The Boxes are Ladder clouds of IR Z gauge bosons ordered in transverse momentum variable.

vev insertions: $U(1)$ Z resummation. (M. and P. Ciafaloni, DC 2009)

All order results in $L^2 \equiv \frac{\alpha_Z}{4\pi}\ \log^2 \frac{Q^2}{M_Z^2}$:

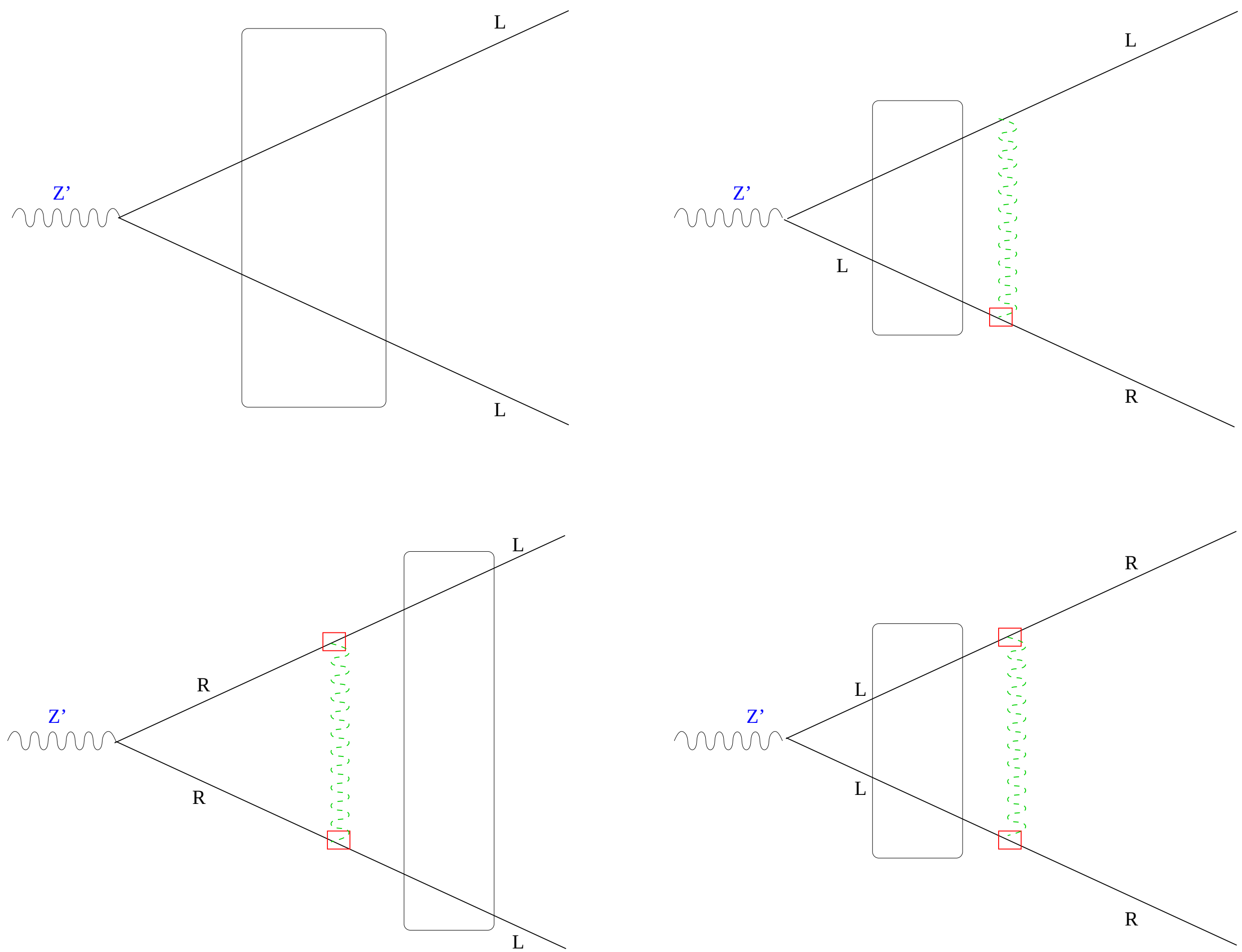
$$
\begin{aligned}
F_L^{(Z)} &= f\ \left(e^{-y_L^2 L^2} - \frac{\rho}{2}\ (e^{-y_R^2 L^2} - e^{-y_L^2 L^2}) \right) \\
F_R^{(Z)} &= f\ \left(e^{-y_R^2 L^2} - \frac{\rho}{2}\ (e^{-y_L^2 L^2} - e^{-y_R^2 L^2}) \right) \\
F_M^{(Z)} &= \frac{f}{2}(\ e^{-y_L^2 L^2} +\ e^{-y_R^2 L^2}) - f\ e^{-y_L\ y_R\ L^2} \\
F_P^{(Z)} &= \frac{f}{2}(\ e^{-y_L^2 L^2} - e^{-y_R^2 L^2})
\end{aligned}
$$

Growing exponentials when : $y_L\ y_R < 0\ \ \rightarrow\ \ y_L \neq y_R$

In SM we have $U_Y(1)$ with $y_{d_L} = \frac{1}{6}$ and $y_{d_R} = -\frac{1}{3}$ so

$$
\boxed{y_{d_L} y_{d_R} = -\frac{1}{18}}
$$

vev insertions: $SU(2)$ W resummation.



All order results in $L^2 \equiv \frac{\alpha_W}{4\pi} \; \log^2 \frac{Q^2}{M_W^2}$:

$$
\begin{aligned}
F_L^{(1)} &= f \left(e^{-\frac{3L^2}{4}} + \frac{1}{4} \left((\rho_1 - \rho_2)\, e^{\frac{L^2}{4}} + (\rho_1 + \rho_2)\, e^{-\frac{3L^2}{4}} - 2\rho_1 \right) \right) \\
F_L^{(2)} &= f \left(e^{-\frac{3L^2}{4}} + \frac{1}{4} \left((\rho_2 - \rho_1)\, e^{\frac{L^2}{4}} + (\rho_1 + \rho_2)\, e^{-\frac{3L^2}{4}} - 2\rho_2 \right) \right) \\
F_R^{(1)} &= f \left(1 + \frac{1}{2} \rho_1 \left(1 - e^{-\frac{3L^2}{4}} \right) \right) \\
F_R^{(2)} &= f \left(1 + \frac{1}{2} \rho_2 \left(1 - e^{-\frac{3L^2}{4}} \right) \right) \\
F_M^{(1)} &= F_M^{(2)} = F_P^{(1)} = F_P^{(2)} = \frac{f}{2} \left(e^{-\frac{3L^2}{4}} - 1 \right)
\end{aligned}
$$

Growing exponentials for

$$
F_L^{(1)} - F_L^{(2)} = \tfrac{f}{2} \, (\rho_1 - \rho_2) \; \left(e^{+\frac{L^2}{4}} - 1 \right)
$$

Anomalous Sudakov (AS) in physical cross sections.

We computed our observables at order ρ

$$\sigma \propto F_L^2 + F_R^2 + \rho \ \ (F_M^2 + F_M \ F_{L,R} + F_L F_R) + \mathcal{O}(\rho^2)...$$

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For SU(2) no AS is left at order ρ :

$$F_L \sim f \left(e^{-\frac{3}{4}L^2} + \rho \ e^{+\frac{1}{4}L^2} + \mathcal{O}(\rho)... \right) \rightarrow F_L^2 \sim f^2 \left(e^{-\frac{3}{2}L^2} + \rho \ e^{-\frac{1}{2}L^2} + \mathcal{O}(\rho^2)... \right)$$

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$$\sigma \propto F_L^2 + F_R^2 + \rho \ \left(F_M^2 + F_M \ F_{L,R} + F_L F_R\right) + \mathcal{O}(\rho^2)...$$

For SU(2) no AS is left at order ρ :

$$F_L \sim f \left(e^{-\frac{3}{4}L^2} + \rho \ e^{+\frac{1}{4}L^2} + \mathcal{O}(\rho)...\right) \rightarrow F_L^2 \sim f^2 \left(e^{-\frac{3}{2}L^2} + \rho \ e^{-\frac{1}{2}L^2} + \mathcal{O}(\rho^2)... \right)$$

For U(1) we have AS remnant at order ρ :

$$F_M \sim f \left(e^{-y_{L,R}^2 L^2} + e^{-y_L y_R \ L^2} + \mathcal{O}(\rho)...\right), \qquad F_{L,R} \sim f \ e^{-y_{L,R}^2 L^2} + \mathcal{O}(\rho)...$$

$$\rightarrow F_M^2 \sim f^2 \left(e^{-2 \, y_L y_R \ L^2} + \mathcal{O}(\rho)... \right), \quad F_M \ F_{L,R} \sim f^2 \left(e^{-(y_{L,R}^2 + y_L y_R) \ L^2} + \mathcal{O}(\rho)... \right)$$

So, for the $Z' \rightarrow \bar{f} f$ observables only the $U(1)$ AS appears at order ρ.

IR structure of SB gauge theories at high energies:

- "Normal"= e^{-L^2} and "Anomalous"= e^{+L^2} corrections
- SB is manifest in the spectrum and vev interactions
  - *Spectrum $\longrightarrow$ "Normal": in Virtual and Real emission*
  - *vev insertions $\longrightarrow$ "Anomalous": in Virtual, Real (?)*

  $\lim_{m\to 0} \mathcal{O}_m \neq \mathcal{O}_0$ dominated by higher twist terms!
- Open Questions :
  - *Real emission*
  - *KLN Theorem (Reals + Virtuals)*
  - *Phenomenology: New observables with AS*

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