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

Denis Comelli

INFN sezione di Ferrara Italy

(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):

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

Continuity of the massless limit for a SB gauge theory

Questions:

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

  ($\mathcal{O} \equiv$ observable)

  taking into account only Double Logs corrections and **no**: α running, Single Logs , anomalies, etc... ?

- Is it a smooth limit? we know that for explicitely broken gauge theory such a limit is not smooth, see for example the massive gravity case!

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:

$$\sum_n^{\infty} c_n \left(\alpha \log^2 \frac{Q^2}{m^2}\right)^n = f\left(\frac{Q^2}{m^2}\right)_{\frac{Q}{m}\to\infty} \to \begin{matrix}\infty\\ 0\end{matrix} \quad ?$$

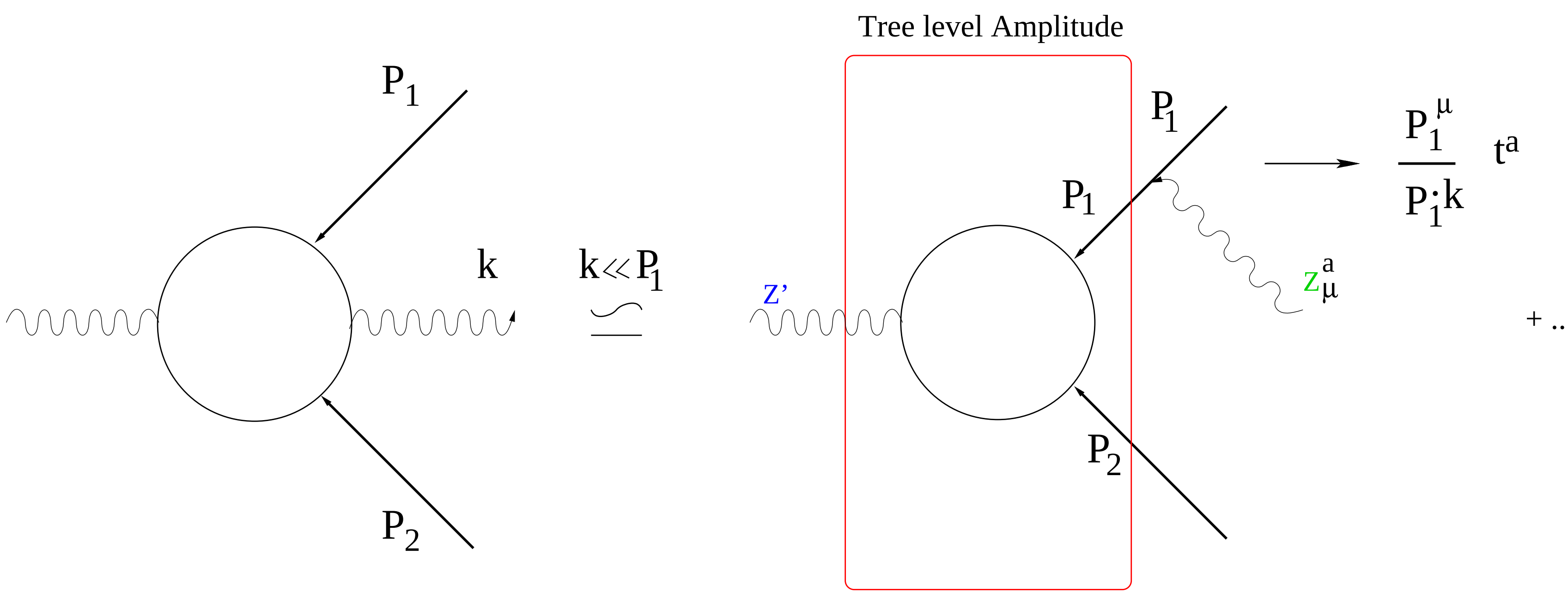
IR Resummation Techniques

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

The kinematical origin of the double Logs is Infrared

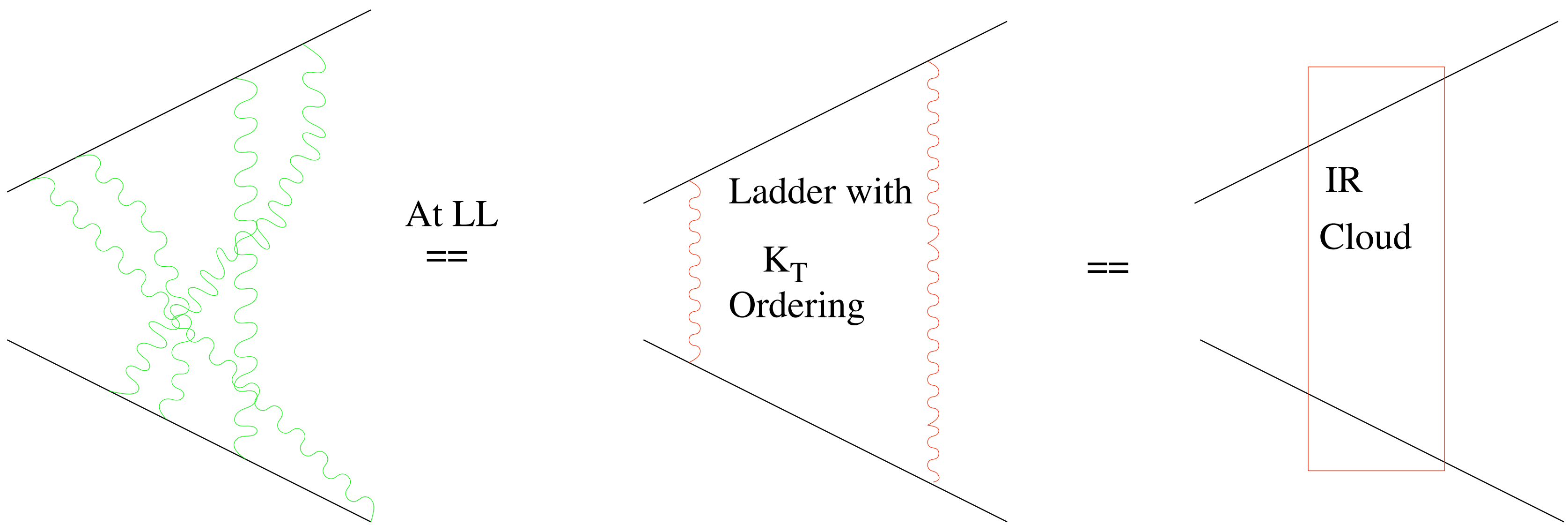
$$\alpha \int^{Q} \frac{dk_t^2}{k_t^2+m^2} \int_{k_t/Q} \frac{d\omega}{\omega} \sim \alpha \, \log^2 \frac{Q^2}{m^2}$$

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

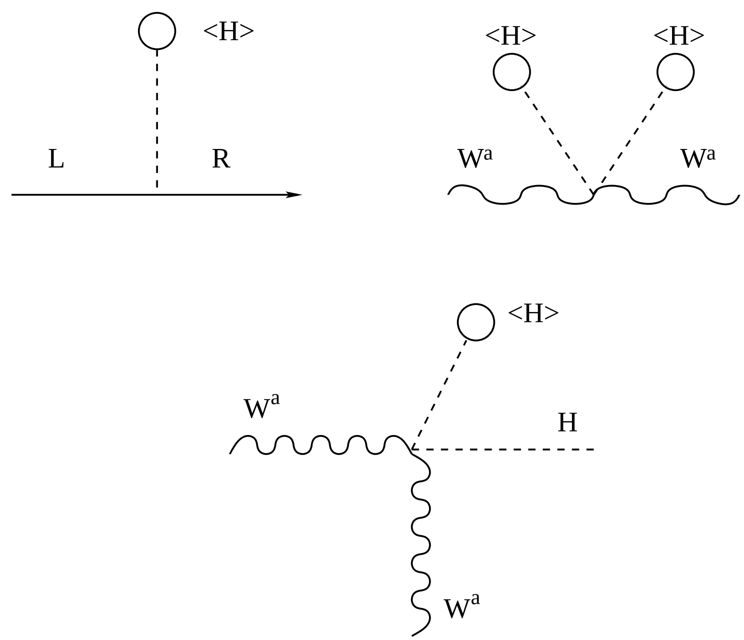
SB manifestation in gauge theories

Spectrum:

- Massive gauge bosons
- Asymptotic states consist of Free Non Abelian Charges

vev insertions:

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



SB manifestation in gauge theories at high energies $Q \gg M_W$

Spectrum effects:

- We consider Hard Gauge invariant amplitudes with fixed external flavor legs.
- The Hard processes are conserving the $SU_L(2) \otimes U_Y(1)$ quantum numbers!
- - exclusive observable $Z' \to \bar{e}_L \ + \ e_L$
  - Inclusive observable $\bar{e}_L \ + \ e_L \to \bar{q} + q + X$ with X=Soft W and Z emission

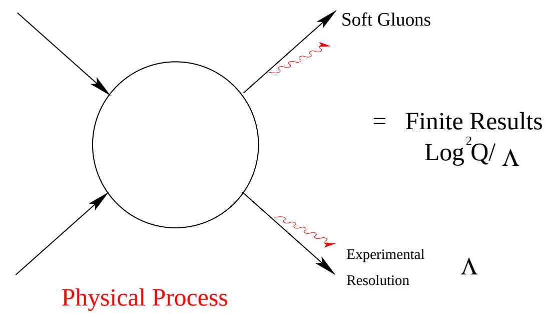
vev insertions effects:

- We consider Hard Gauge non invariant amplitudes with fixed external flavour legs.
- The hard processes are proportionals to the *vev* of the $SU_L(2) \otimes U_Y(1)$ gauge symmetry $\to$ higher twist processes $\propto \frac{v^2}{Q^2}$
- - exclusive observable $Z' \to \bar{e}_L \ + \ e_R$ with $U_Y(1)$ violation (Magnetic Dipole Moment of the Z')
  - exclusive observable $(Z' \to \bar{\nu}_L + \nu_L) - (Z' \to \bar{e}_L + e_L)$ induced by $\frac{m_\nu^2 - m_e^2}{Q^2} \neq 0$

Spectrum: EW Sudakov and EW violation of the Block-Nordsiek Theorem

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

BN in QCD: $\sum_{\text{soft gluons}} \sum_{\text{final color}} \sum_{\text{initial color}}$



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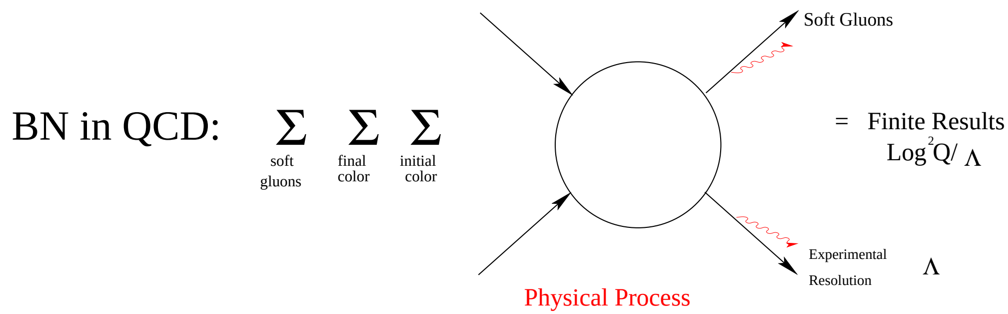

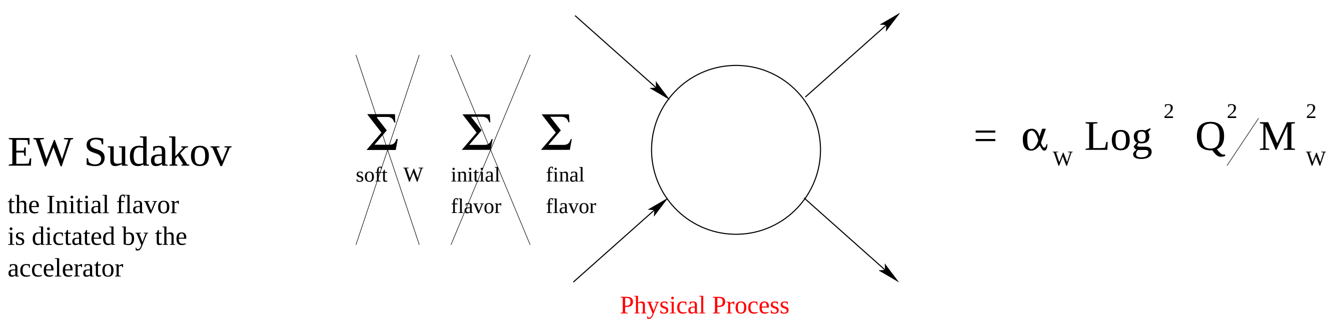

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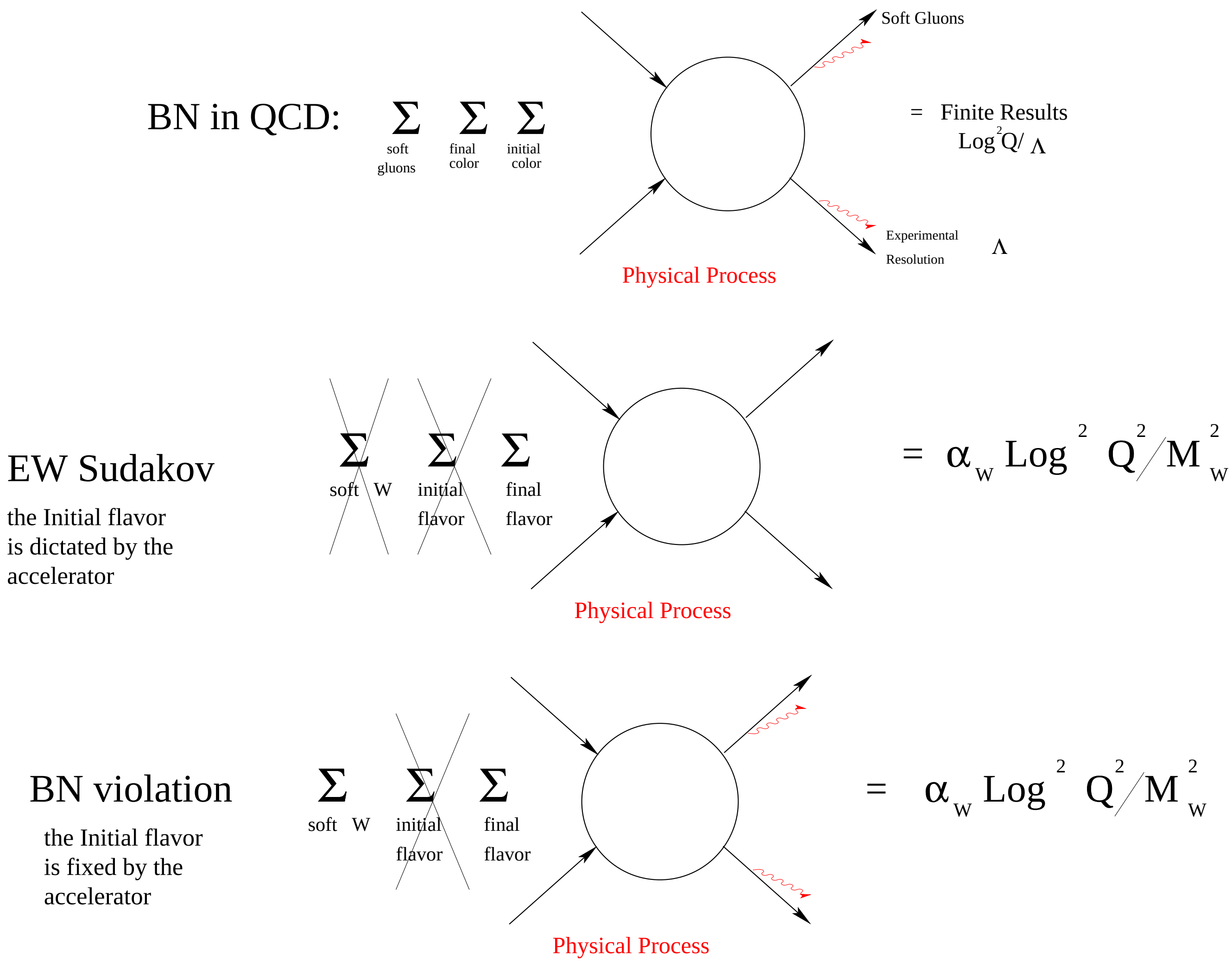


Structure of Sudakov and Block-Nordsiek violation in the EW theory

- Sudakov Form Factors EW corrections:

$$\sigma(s) = \sigma_H \; e^{-\frac{\alpha_W}{4\pi}\sum_i (t_i(t_i+1)+y_i^2\tan^2\theta_W) Log^2\frac{Q^2}{M_W^2}} \underbrace{\longrightarrow}_{\frac{Q}{M_W}\to\infty} 0$$

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

$$\sigma(s) = \sum_t e^{-\frac{1}{2}\frac{\alpha_W}{4\pi} t(t+1) Log^2\frac{Q^2}{M_W^2}} \; \sigma_t^H \underbrace{\longrightarrow}_{\frac{Q}{M_W}\to\infty} \sigma_{t=0}^H, \qquad \sigma_{t\neq 0}^H \lesseqgtr 0$$

- 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).
- while Sudakov corrections always depress the tree level cross section the BN violating ones can be negative or positive.

Sudakov Form Factors: Pure virtual corrections

$\mathcal{O}$ = **Exclusive observable** ex: $\mathcal{O} = \sigma_{Z' \to \bar{e}_L\, e_L}$

- In a SB theory:

$$\lim_{\substack{m \to 0 \\ Q \to \infty}} \mathcal{O}_{\frac{m}{Q}} = \lim_{\substack{m \to 0 \\ Q \to \infty}} \mathcal{O}^H \; e^{-\frac{\alpha_W}{4\pi} \sum_i C_i \; Log^2 \frac{Q^2}{m^2}} = 0$$

- In a massless gauge theory $\mathcal{O}_0 = \underline{\text{divergent}}$ but if we sum virtual plus a small real emission with restricted phase space ($\Delta \to 0$)

$$\lim_{\Delta \to 0} \mathcal{O}_\Delta = \lim_{\Delta \to 0} \mathcal{O}^H \; e^{-\frac{\alpha_W}{4\pi} \sum_i C_i \; Log^2 \Delta^2} = 0$$

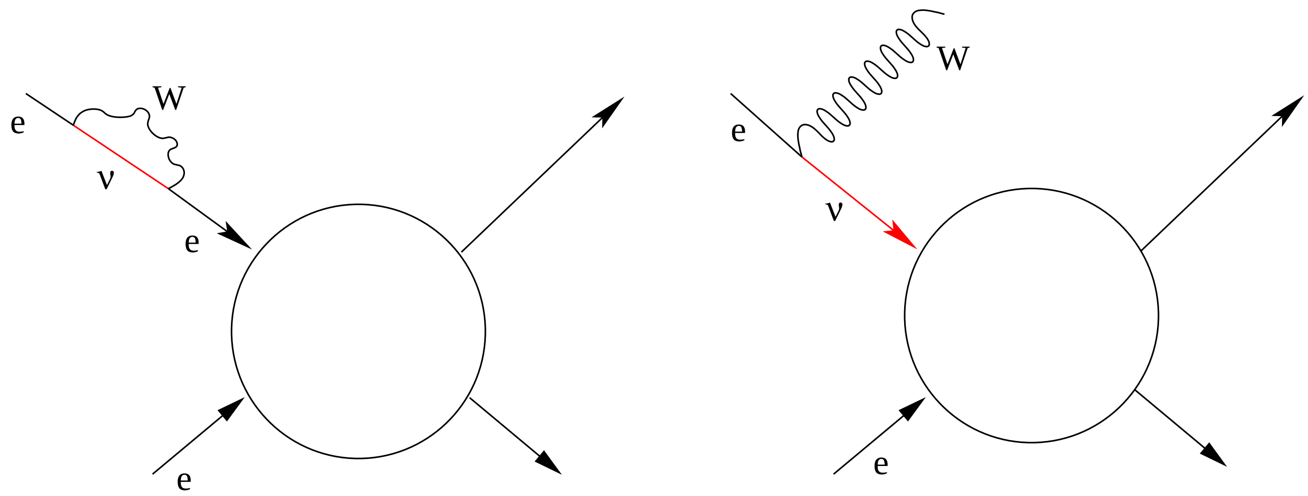
so we can write for exclusive observables

$$\boxed{\lim_{\substack{m \to 0 \\ Q \to \infty}} \mathcal{O}_{\frac{Q}{m}} = \lim_{\Delta \to 0} \mathcal{O}_\Delta = 0}$$

there is *continuity* in the Sudakov regime

EW violation of the Block-Nordsiek Theorem

One loop example of EW BN violation



$-\sigma_{ee}\ \alpha_w\ \text{Log}^2\ Q^2/M^2 \qquad + \sigma_{\nu e}\ \alpha_w\ \text{Log}^2\ Q^2/M^2 \qquad \neq \quad 0$

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: Resumation Leading EW Virtual plus Real radiative corrections (M. & P.Ciafaloni,D.C.2000)

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

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

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

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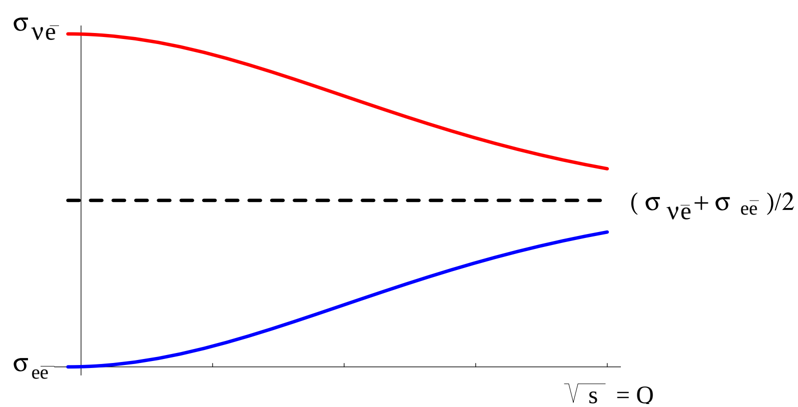

$\mathcal{O}$ = Inclusive observable

In a SB theory:

$$\lim_{\substack{m\to 0\\ Q\to\infty}} \mathcal{O}_{\frac{m}{Q}} = \lim_{\substack{m\to 0\\ Q\to\infty}} \sum_t \mathcal{O}_t^H \, e^{-\frac{\alpha_W}{8\pi}\, t\,(t+1)\, Log^2 \frac{Q^2}{m^2}} = \mathcal{O}_0^H = \frac{1}{N}\sum_i^N \sigma_i^H$$

In an exact theory

$$\mathcal{O}_0 = \frac{1}{N}\sum_i^N \sigma_i^H$$

because we cannot distinguish different flavors, in other words, physical cross sections are flavor blind!

$$\boxed{\lim_{\substack{m\to 0\\ Q\to\infty}} \mathcal{O}_{\frac{m}{Q}} = \mathcal{O}_0}$$

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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: $e^{+\alpha Log^2 \frac{Q^2}{M^2}}$

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

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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 Sudakov series

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

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

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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: $y_L^{(1,2)} \equiv y_L, \; y_{R_{1,2}}$
- with mass gap $M_{Z'} \gg M_W \sim M_Z \sim m_{\text{fermion}} \equiv m$

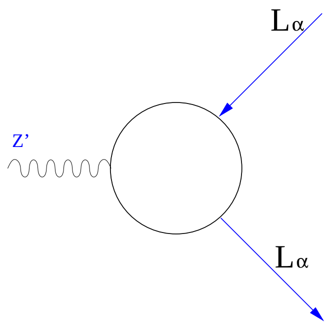
Effective $Z' \to f_i \bar{f}_i$ vertex for onshell particles ($i = 1, 2$):

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

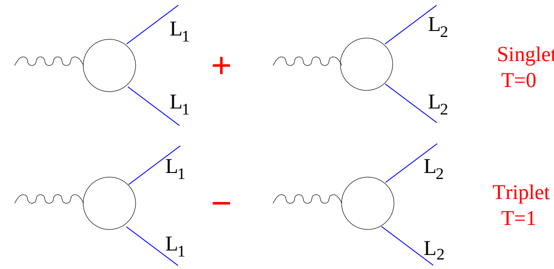
8 Form Factors: $F_{L,R}^{(i)}$ conserve chirality, $F_{M,P}^{(i)}$ violate chirality

vev insertions : News inside the SM ?

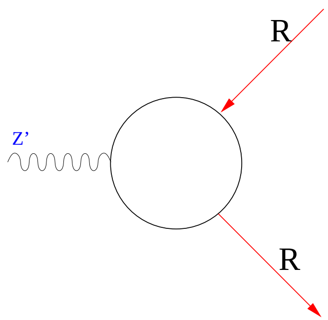
Total External Legs U(1) Charge | Total External Legs SU(2) Charge



F_L $y_L - y_L = o$

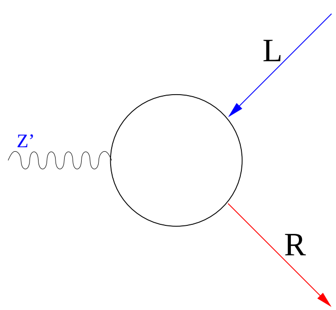


$\frac{1}{2} \otimes \frac{1}{2} = 1 \oplus 0$



F_R $y_R - y_R = o$

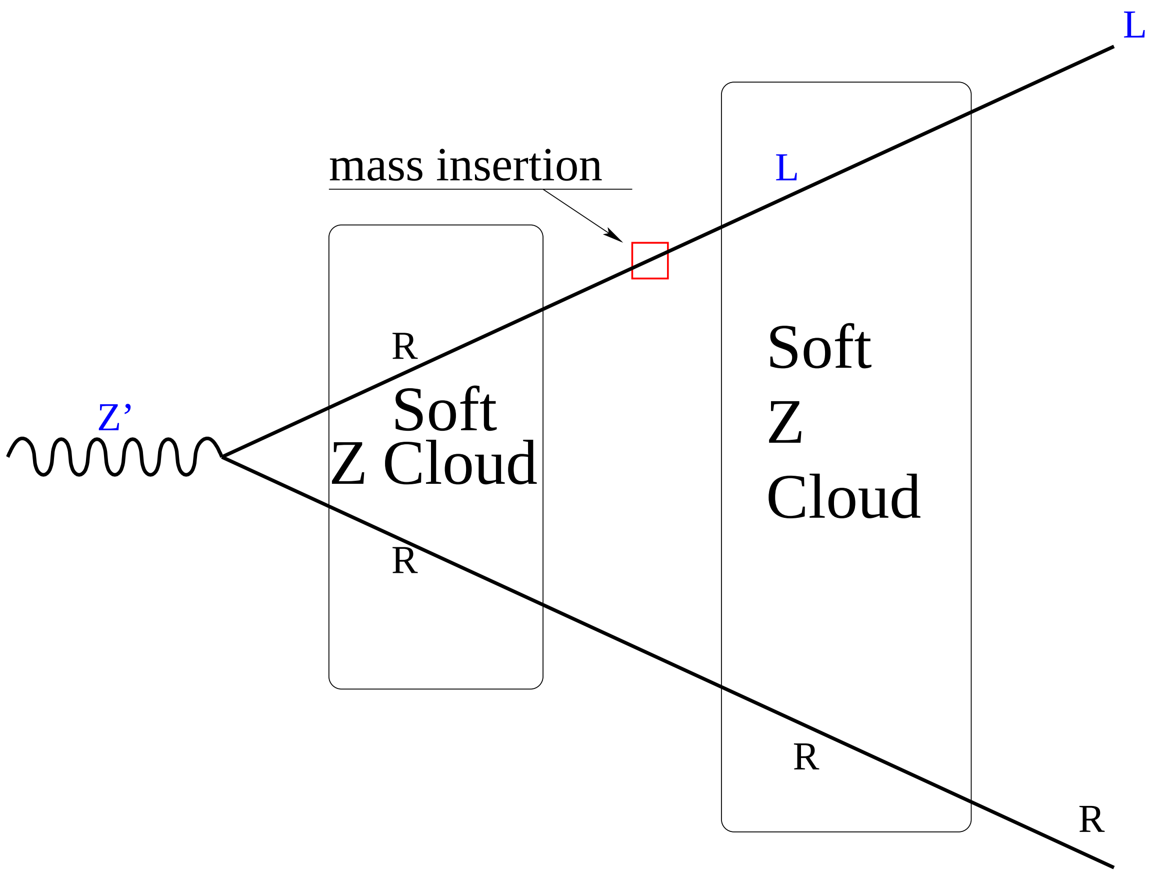
Singlet



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

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

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

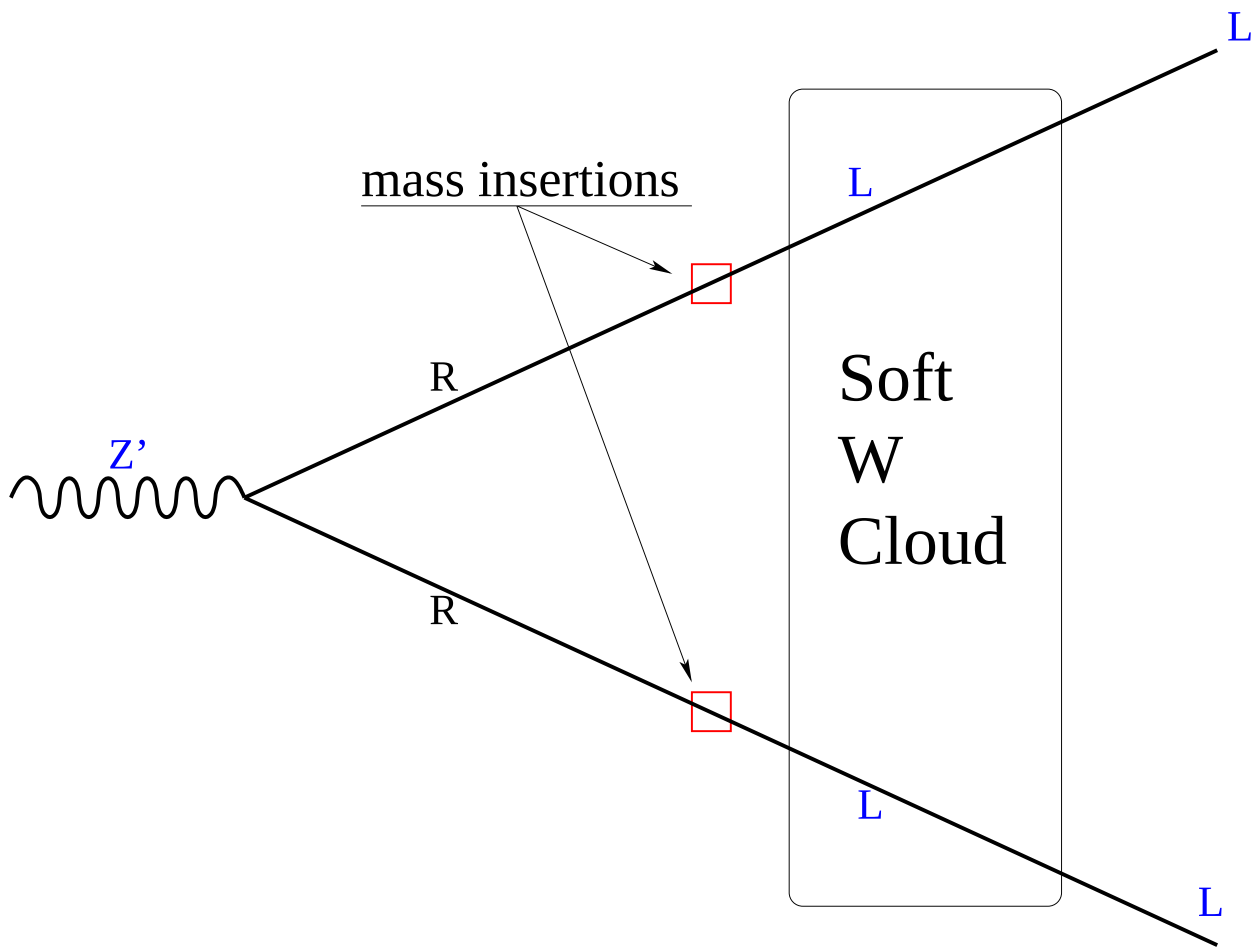
$$
\begin{aligned}
F_L^{(Z)} &= f \left(e^{-y_L^2 L^2} - \frac{\rho}{2} \left(e^{-y_R^2 L^2} - e^{-y_L^2 L^2}\right)\right) \\
F_R^{(Z)} &= f \left(e^{-y_R^2 L^2} - \frac{\rho}{2} \left(e^{-y_L^2 L^2} - e^{-y_R^2 L^2}\right)\right) \\
F_M^{(Z)} &= \frac{f}{2}\left(e^{-y_L^2 L^2} + e^{-y_R^2 L^2}\right)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

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

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

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



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

Growing exponentials for

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

Full Infrared $W - Z$ gauge boson exchange:

$SU_W(2) \otimes U_Y(1)$ (fermion quantum number: $y_{R_1},\ y_{R_2},\ \ y_{L_1} = y_{L_2},\ \ f_L = f_R$) $i = 1, 2$:

$$F_L^{(1)} = f\left(e^{-L^2 y_L^2 - \frac{3L^2}{4}} + \frac{1}{4}\left(\rho_1 - \rho_2\right) e^{\frac{L^2}{4} - L^2 y_L^2} + \frac{1}{4}\left(\rho_1 + \rho_2\right) e^{-L^2 y_L^2 - \frac{3L^2}{4}} - \frac{\rho_1}{2} e^{-L^2 y_{R_1}^2}\right)$$

$$F_L^{(2)} = f\left(e^{-L^2 y_L^2 - \frac{3L^2}{4}} - \frac{1}{4}\left(\rho_1 - \rho_2\right) e^{\frac{L^2}{4} - L^2 y_L^2} + \frac{1}{4}\left(\rho_1 + \rho_2\right) e^{-L^2 y_L^2 - \frac{3L^2}{4}} - \frac{\rho_2}{2} e^{-L^2 y_{R_2}^2}\right)$$

$$F_R^{(i)} = f\left(e^{-L^2 y_{R_i}^2} + \frac{\rho_i}{2}\left(e^{-L^2 y_{R_i}^2} - e^{-L^2 y_L^2 - \frac{3L^2}{4}}\right)\right)$$

$$F_M^{(i)} = \frac{f}{2}\left(-2\, e^{-L^2 y_L y_{R_i}} + e^{-L^2 y_L^2 - \frac{3L^2}{4}} + e^{-L^2 y_{R_i}^2}\right)$$

$$F_P^{(i)} = \frac{f}{2}\left(e^{-L^2 y_L^2 - \frac{3L^2}{4}} - e^{-L^2 y_{R_i}^2}\right)$$

the different limits $\alpha_{W,Y} \to 0$ are both compatibles with the previous results.

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 (?)*

$$\lim_{m\to 0}\mathcal{O}_m \neq \mathcal{O}_0$$

SB theories are dominated, for $Q \geq M e^{\frac{1}{\alpha}}$, by higher twist terms!

- Open Questions :
  - *Real emission*
  - *KLN Theorem (Reals + Virtuals)*
  - *Phenomenology: New observables with Anomalous Sudakov*

The Goran Future