

Infrared Structure of Spontaneously Broken Gauge Theories

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High Energy EW theory

The Problem: From EW Perturbation Theory → large double logs in high energy ($Q \gg M_W$) cross sections of IR origin

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

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

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

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High energy limit ($Q \rightarrow \infty$) \equiv *Infrared limit* ($M_W \rightarrow 0$)

Cancellation Theorems for **IR** divergences

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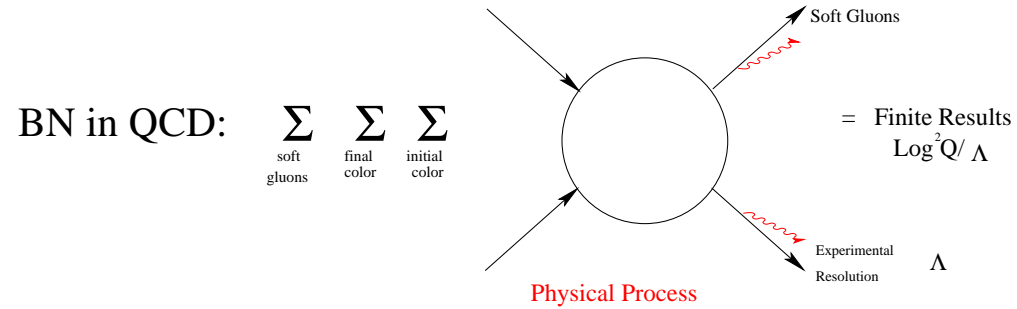
BN in QED: IR divergences cancel out after summation over all degenerate **final** soft photons compatible with experimental detection.

BN 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

EW violation of the Block-Nordsieck Theorem

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

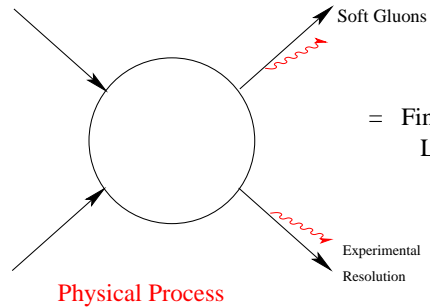


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BN in QCD:

$$\sum_{\text{soft gluons}} \sum_{\text{final color}} \sum_{\text{initial color}}$$



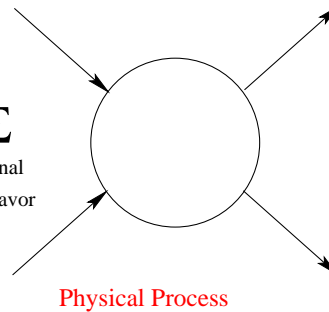
$$= \text{Finite Results} \log^2 Q / \Lambda$$

Λ

EW Sudakov

the Initial flavor
is dictated by the
accelerator

$$\cancel{\sum_{\text{soft } W}} \quad \cancel{\sum_{\text{initial flavor}}} \quad \sum_{\text{final flavor}}$$

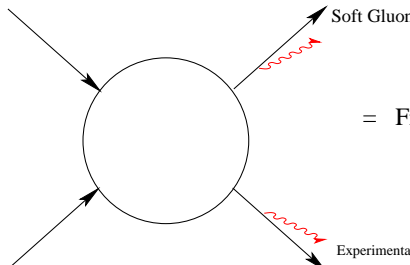


$$= \alpha_w \log^2 Q^2 / M_w^2$$

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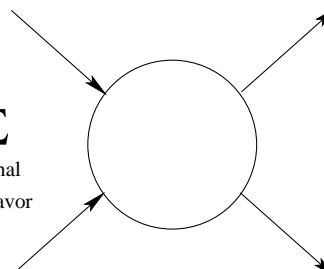
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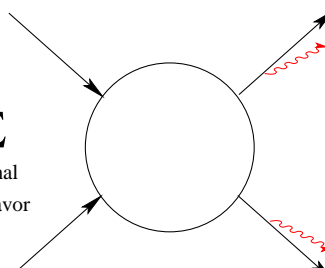


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BN violation

the Initial flavor is fixed by the accelerator

$\sum_{\text{soft } W} \sum_{\text{initial flavor}} \sum_{\text{final flavor}}$



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Leading Order Results for High Energy EW theory

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

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

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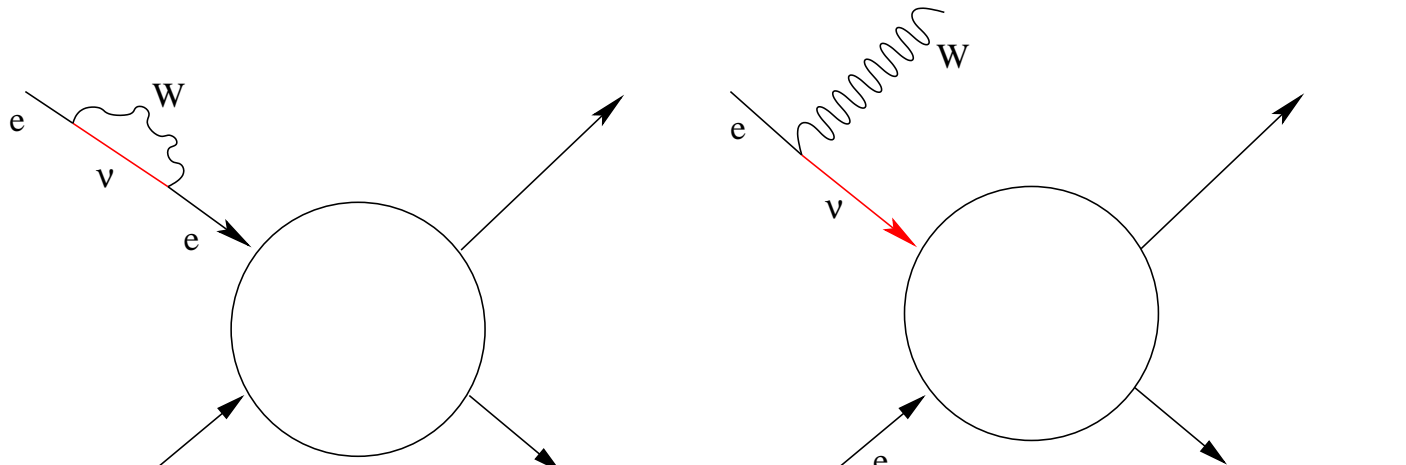
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Typical size at $Q \sim 1 \text{ TeV}$ (for $2 \rightarrow 2$ processes) present both at ILC and LHC (P.Ciafaloni,D.C.1999)

$$\begin{aligned} \left. \frac{\delta \sigma}{\sigma} \right|_{\text{one loop}}^{LL} &\sim -\frac{\alpha_W}{\pi} \text{Log}^2 \frac{Q^2}{M_W^2} \simeq -26\%, & \left. \frac{\delta \sigma}{\sigma} \right|_{\text{one loop}}^{NLL} &\sim \frac{3\alpha_W}{\pi} \text{Log} \frac{Q^2}{M_W^2} \simeq 16\% \\ \left. \frac{\delta \sigma}{\sigma} \right|_{\text{two loop}}^{LL} &\sim +\frac{\alpha_W^2}{2\pi^2} \text{Log}^4 \frac{Q^2}{M_W^2} \simeq +3.5\%, & \left. \frac{\delta \sigma}{\sigma} \right|_{\text{two loop}}^{NLL} &\sim -\frac{3\alpha_W^2}{2\pi^2} \text{Log}^3 \frac{Q^2}{M_W^2} \simeq -4.6\% \end{aligned}$$

EW violation of the Block-Nordsieck Theorem

One loop example of EW BN violation



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

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

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

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)

$$\sigma_{e\bar{e}}^{inclusive} = \frac{\sigma_{e\bar{e}}^H + \sigma_{\nu\bar{e}}^H}{2} + \frac{\sigma_{e\bar{e}}^H - \sigma_{\nu\bar{e}}^H}{2} e^{-\frac{\alpha_W}{2\pi} \text{Log}^2 \frac{Q^2}{M_W^2}} \xrightarrow{Q \gg M_W} \frac{\sigma_{e\bar{e}}^H + \sigma_{\nu\bar{e}}^H}{2}$$

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$$(ex : \sigma_{\nu\bar{e} \rightarrow q\bar{q}}^H = 2 \sigma_{e\bar{e} \rightarrow q\bar{q}}^H)$$

Effectively e_L becomes indistinguishable from ν_e !

Leading Order Results for High Energy EW theory

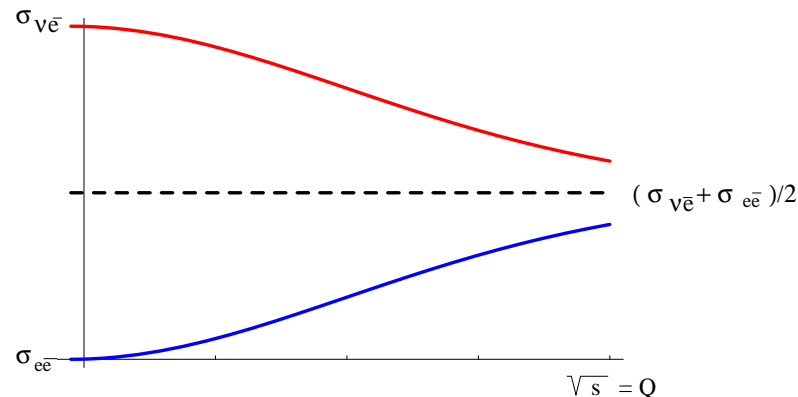
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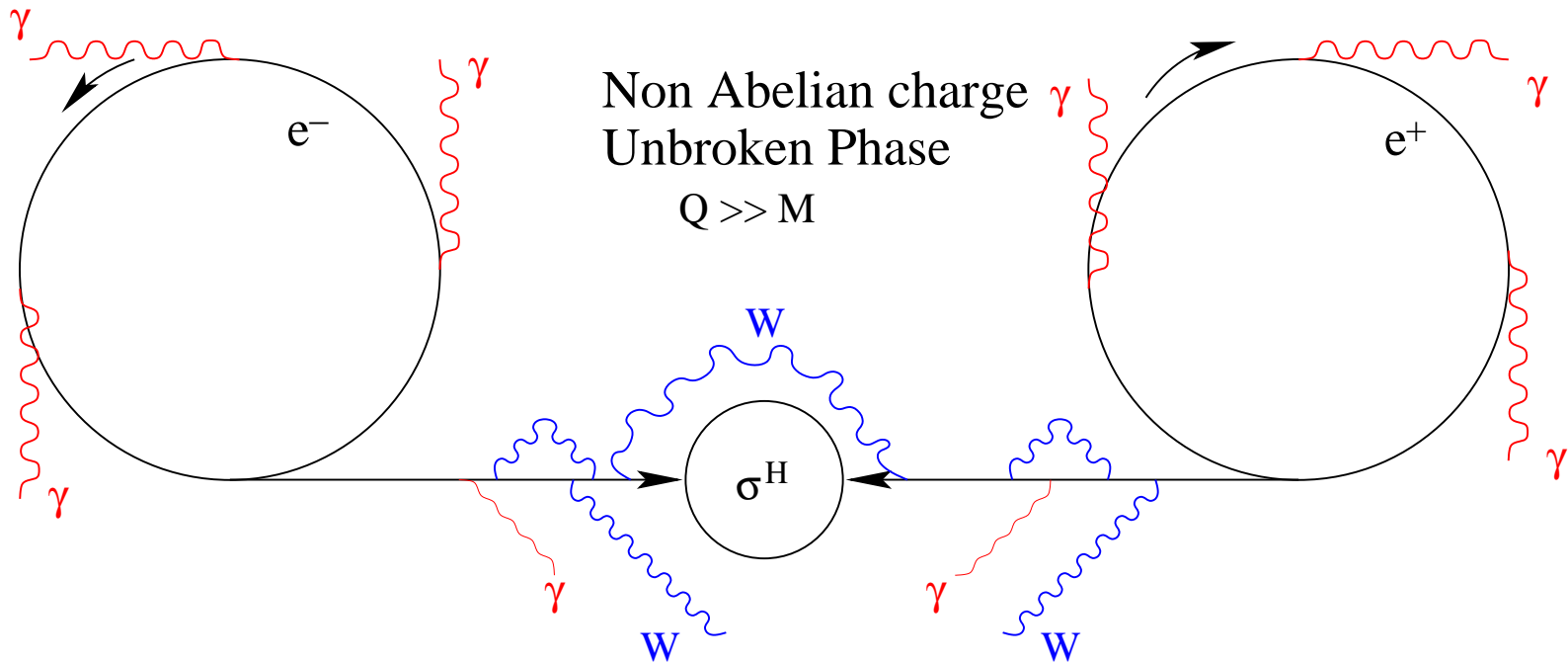
High Energy EW theory

Physical Pictorial idea: For low energies ($Q \leq M_W$) an e^- looks “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 losing his *identity* resembling more and more a ν .

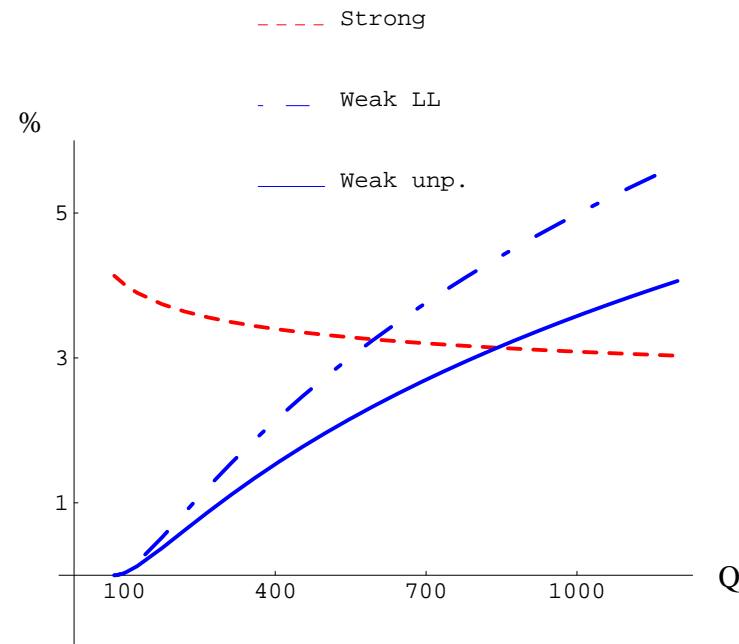
Broken Phase: Abelian charge

$$Q < M$$



EW corrections at ILC

Corrections to $\sigma(e^-e^+ \rightarrow 2 \text{ Jets} + X_{QCD} + \text{soft } W's)$
(M. & P.Ciafaloni,D.C.2000)



$$\frac{\delta\sigma}{\sigma} \simeq \frac{\alpha_S(Q)}{\pi} + \frac{\alpha_W}{4\pi} \text{Log}^2 \frac{Q^2}{M_W^2}$$

EW corrections at LHC

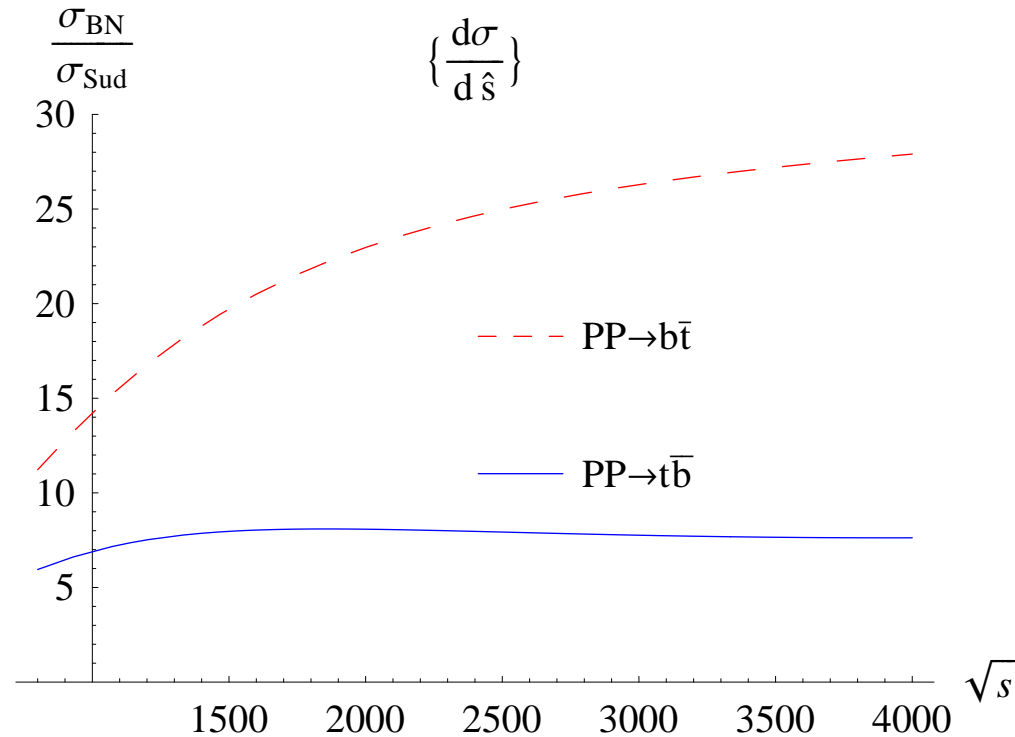
Heavy Quark Production at high energy $PP \rightarrow Q_i \bar{Q}_j + X$ where $Q_i = t, b$
(P.Ciafaloni,D.C.2006)

“Sudakov – like” : $(PP \rightarrow \text{tagged final states} + X)$ with $W, Z \notin X$

“BN – like” : $(PP \rightarrow \text{tagged final states} + X)$ with $W, Z \in X$

Cross sections	Isospin Structure	Tree Level σ^H ($X = 0$)	BN corrections
$pp \rightarrow Q_i \bar{Q}_j + X$	δ_{ij}	α_S^2	$\alpha_S^2 \alpha_W \text{Log}^2 \frac{Q^2}{M_W^2}$
	$i \neq j$	α_W^2	$\underbrace{\alpha_S^2}_{\sigma^H} \alpha_W \text{Log}^2 \frac{Q^2}{M_W^2}$

EW corrections at LHC



$Q = \sqrt{s}$ dependence of the ratio of BN and Sudakov cross sections for $p_{\perp} \geq 400$ GeV.

Dashed (red) line for $b\bar{t}$, continuous (blue) line for $t\bar{b}$.

BN violation in Spontaneously Broken Abelian Gauge Theories

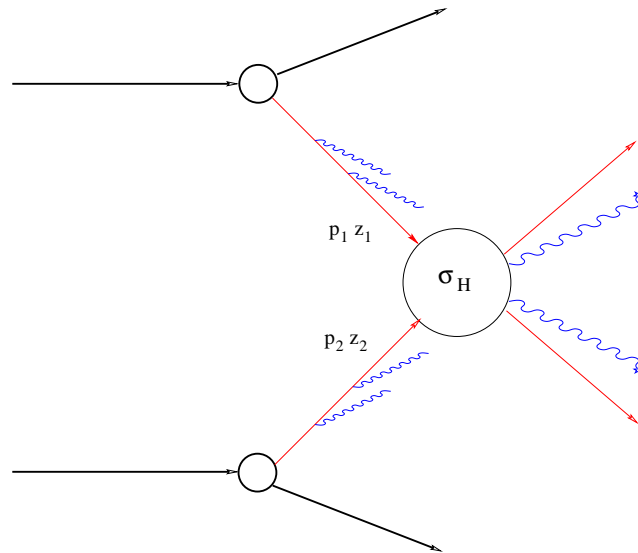
U(1) BN violation occur when are present asymptotic states that are a coherent **superposition of different U(1) gauge eigenstates**
(M. & P.Ciafaloni,D.C.2001)

In an unbroken $U(1)$ theory (see QED) mass eigenstates coincide with the gauge eigenstates.
while in a broken $U(1)$ theory (see $U_Y(1)$) mass eigenstates do not coincide necessary with the gauge eigenstates.

- transverse polarized fermions are a coherent superposition of left and right fermionic gauge charges.
- \underline{Z} and photon are a superposition of the B_μ and the W_μ^3 gauge fields.
- In the scalar sector the higgs and the longitudinal goldstone bosons are a superposition of the gauge doublets Φ and Φ^* (having opposite U(1) charges).

High Energy EW theory

Structure Function approach to EW Correction: Probability to find a parton inside



$$\sigma_{ij}(p_1, p_2, M_W) = \int \frac{dz_1}{z_1} \frac{dz_2}{z_2} \sum_{kl} F_i^k(z_1, Q, M_W) \sigma_{kl}^H(z_1 p_1, z_2 p_2) F_j^l(z_2, Q, M_W)$$

High Energy EW theory

EW structure functions evolution eqs

(M. & P.Ciafaloni,D.C.2002)

QCD: $f_{q_i}, f_{\bar{q}_i}, f_g$

EW: $f_{l_{Li}}, f_{l_{Ri}}, f_{\bar{l}_{Li}}, f_{\bar{l}_{Ri}}, f_{q_{Li}}, f_{q_{Ri}}, f_{\bar{q}_{Li}}, f_{\bar{q}_{Ri}}, f_h, f_{\phi^a}, f_{B_\mu}, f_{W_\mu^a}$

Due to mixing effects also mixed structure functions: f_{BW^3}, f_{LRi}

$$\begin{aligned} \frac{-d}{d \log \mu^2} \text{ (circle with two external lines } i, \alpha \text{ and } \beta) &= \text{ (circle with two external lines } i, \alpha \text{ and } \beta \text{, with a wavy line } f \text{ between } \alpha \text{ and } \beta) \\ &+ \text{ (circle with two external lines } i, \alpha \text{ and } \beta \text{, with a horizontal line } b \text{ between } \alpha \text{ and } \beta) \\ \frac{-d}{d \log \mu^2} \text{ (circle with two external lines } i, A \text{ and } B \text{, and two wavy lines } b) &= \text{ (circle with two external lines } i, A \text{ and } B \text{, and two wavy lines } b \text{, with a wavy line } f \text{ between } A \text{ and } B) \\ &+ \text{ (circle with two external lines } i, A \text{ and } B \text{, and two wavy lines } b \text{, with a horizontal line } f \text{ between } A \text{ and } B) \end{aligned}$$

$$\frac{\partial f_{QCD/EW}(x, \mu)}{\partial \text{Log} \mu} = \alpha_{S/W} \int_x^1 \frac{dz}{z} f_{QCD/EW} \left(\frac{x}{z}, \mu \right) P_0(z)$$

$$\frac{\partial f_{EW}(x, \mu)}{\partial \text{Log} \mu} = \alpha_W \int_x^1 \frac{dz}{z} f_{EW} \left(\frac{x}{z}, \mu \right) \left(P_1(z) + \text{Log} \frac{Q^2}{\mu^2} P_2(z) \right)$$

High Energy EW theory

Sudakov versus BN EW corrections:

- **Sudakov** EW corrections:

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

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

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

- 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.**

Do we have “*New IR Surprises*” inside the SM ?

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Where? Inside the higher twist operators

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

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$$\sigma \sim \frac{\alpha^2}{Q^2} \left(1 + \underbrace{\frac{m^2}{Q^2}} \right)$$

Is it always negligible for $Q \gg m$?

There are “New Physics” effect inside the SM ?

Probably Yes!

Where? Inside the higher twist operators

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

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

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$$\left(\frac{Q^2}{M^2} \right)^{-\alpha \text{Log} \frac{Q^2}{M^2}} \sim \left(\frac{Q^2}{M^2} \right)^{+\alpha \text{Log} \frac{Q^2}{M^2} - 1} \quad \text{for } M \sim m$$

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

There are “New Physics” effect inside the SM ?

An Explicit example: $Z' \rightarrow f \bar{f}$ (P.Ciafaloni, D.C. in preparation)

The model:

- Chiral Gauge group $U'_{Z'}(1) \otimes U_Z(1)$
- fermion $U'(1)$ charges: f_L, f_R
- fermion $U(1)$ charges: y_L, y_R
- with mass gap $M_{Z'} \gg M_Z \sim m_{\text{fermion}} \equiv m$

Effective $Z' \rightarrow f \bar{f}$ vertex for onshell particles:

$$Z'^\nu \bar{u}(p_1) \left(\gamma_\mu (F_L P_L + F_R P_R) + \frac{m}{Q^2} (p_{1\mu} - p_{2\mu}) F_m + \frac{m}{Q^2} (p_{1\mu} + p_{2\mu}) \gamma_5 F_e \right) v(p_2)$$

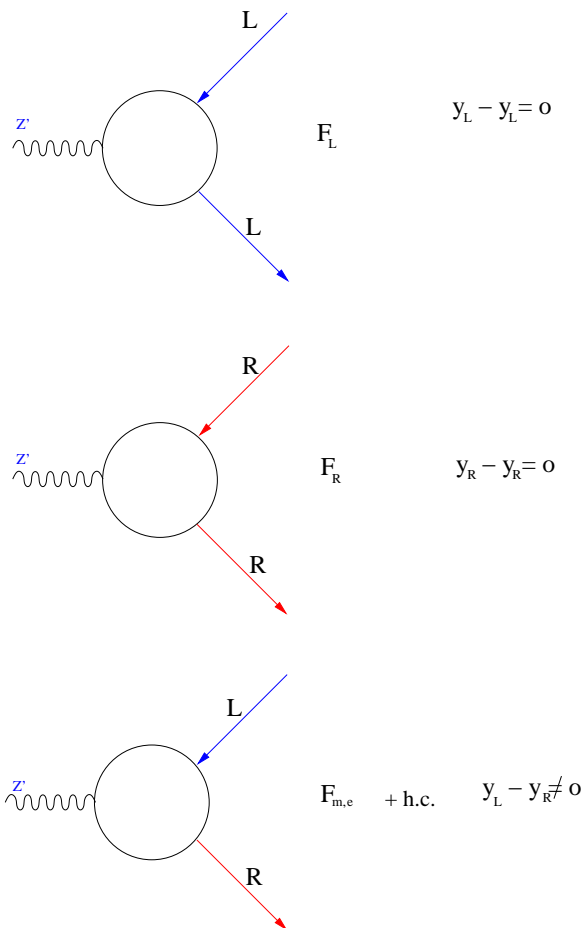
All F_i depend from $Q^2 = (p_1 + p_2)^2 = M_{Z'}^2$,

$F_{L,R}$ conserve chirality

$F_{m,e}$ violate chirality

There are “New Physics” effect inside the SM ?

Total External Legs U(1) Charge



Is it possible some “New Physics” effect inside the SM ?

All order results in $\bar{\alpha} \equiv \frac{\alpha_Z}{4\pi}$:

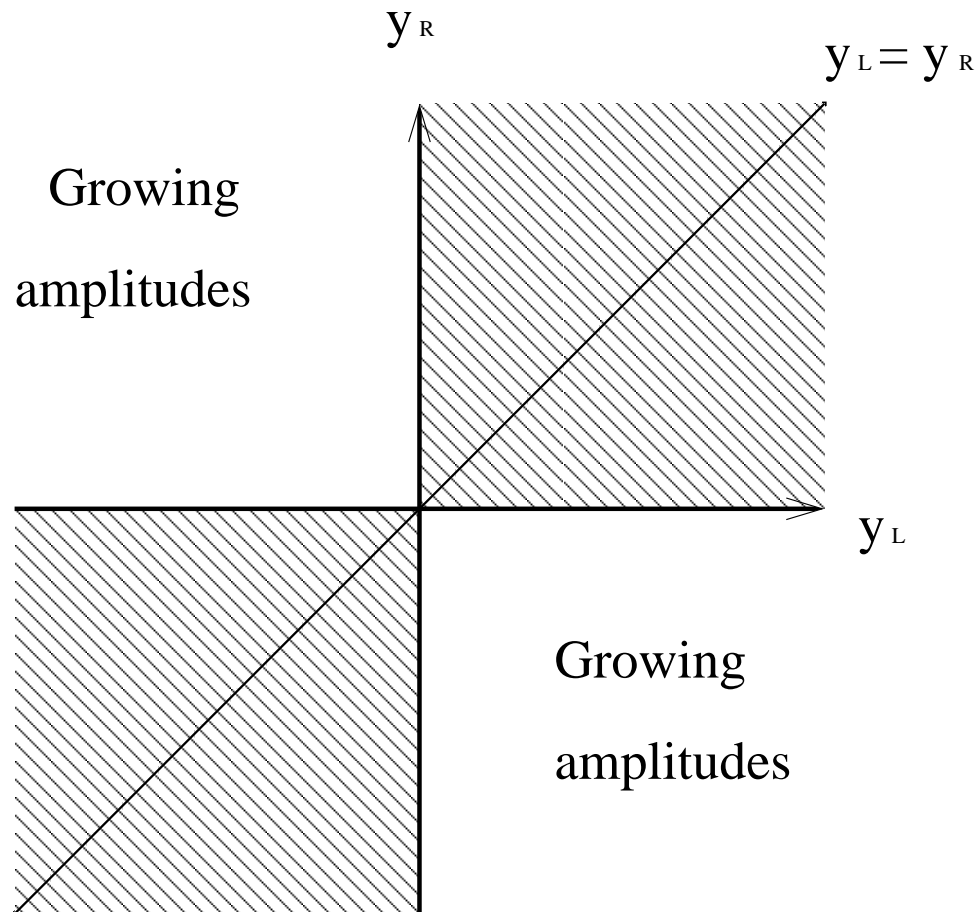
$$\begin{aligned}
 F_L &= f_L e^{-\bar{\alpha} y_L^2 \text{Log}^2 \frac{Q^2}{M_Z^2}} + \frac{m^2}{2Q^2} f_R (e^{-\bar{\alpha} y_L^2 \text{Log}^2 \frac{Q^2}{M_Z^2}} - e^{-\bar{\alpha} y_R^2 \text{Log}^2 \frac{Q^2}{M_Z^2}}) \\
 F_R &= f_R e^{-\bar{\alpha} y_R^2 \text{Log}^2 \frac{Q^2}{M_Z^2}} - \frac{m^2}{2Q^2} f_L (e^{-\bar{\alpha} y_L^2 \text{Log}^2 \frac{Q^2}{M_Z^2}} - e^{-\bar{\alpha} y_R^2 \text{Log}^2 \frac{Q^2}{M_Z^2}}) \\
 F_m &= \frac{1}{2} (f_L e^{-\bar{\alpha} y_L^2 \text{Log}^2 \frac{Q^2}{M_Z^2}} + f_R e^{-\bar{\alpha} y_R^2 \text{Log}^2 \frac{Q^2}{M_Z^2}}) - \frac{1}{2} (f_L + f_R) e^{-\bar{\alpha} y_L y_R \text{Log}^2 \frac{Q^2}{M_Z^2}} \\
 F_e &= \frac{1}{2} (f_L e^{-\bar{\alpha} y_L^2 \text{Log}^2 \frac{Q^2}{M_Z^2}} - f_R e^{-\bar{\alpha} y_R^2 \text{Log}^2 \frac{Q^2}{M_Z^2}}) - \frac{(f_L - f_R)}{2} e^{-\bar{\alpha} y_L y_R \text{Log}^2 \frac{Q^2}{M_Z^2}}
 \end{aligned}$$

Growing coefficients 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

$$y_{d_L} y_{d_R} = -\frac{1}{18} < 0!!!$$

There are “New Physics” effect inside the SM ?



Unitarity and KLN Theorem to be reanalyzed !

EW Corrections at high energies:

- Show the full **IR** structure of non abelian theories!
- In general affect **any** cross section (both exclusive than inclusive) with **at least** two external $SU(2)$ charged legs
- EW Sudakov: still relevant at 2 loop (for $Q \sim TeV$)
- EW BN violation (*"detector dependent"*):
At ILC leading also for supposed QCD dominated processes like $\sigma_{e\bar{e} \rightarrow \sum_q q\bar{q} + X_{g,w}}$
At LHC potentially relevant for many processes in particular for the *"flavor observables"*
(ex: $PP \rightarrow t\bar{t}; t\bar{t} Jet, W W$)
- SM **New Physics** effects in higher twist corrections

Publications on High Energy EW Corrections

● Exclusive observables: Theoretical analysis of **Virtual EW Corrections**

P. Ciafaloni , D. Comelli, *Sudakov Effects in Electroweak Corrections*, Phys. Lett. B (1999).

P. Ciafaloni, D. Comelli, *Electroweak Sudakov form factors and nonfactorizable soft QED effects at NLC energies*, Phys. Lett. B (2000).

● Inclusive observables: Theoretical analysis of **Virtual plus Real EW corrections**

M. Ciafaloni, P. Ciafaloni, D. Comelli , *Bloch-Nordsieck violating electroweak corrections to inclusive TeV scale hard processes*, Phys. Rev. Lett. (2000).

M. Ciafaloni, P. Ciafaloni, D. Comelli , *Bloch-Nordsieck Violation in Spontaneously Broken Abelian Theories*, Phys. Rev. Lett. (2001).

M. Ciafaloni, P. Ciafaloni, D. Comelli , *Towards Collinear Evolution Equations in Electroweak Theory* . Phys. Rev. Lett. 88 (2002).

Publications on this Subject

● Phenomenology : Potential impact at ILC and LHC :

M. Beccaria, P. Ciafaloni, D. Comelli, F. M. Renard, C. Verzegnassi, *Logarithmic expansion of electroweak corrections to four-fermion processes in the TeV region*, Phys. Rev. D 61 (2000)

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