Anomalous Sudakov Form Factors

Denis Comelli

comelli@fe.infn.it

INFN sezione di Ferrara

High Energy EW theory

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

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

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):

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

High Energy EW theory

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

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

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

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

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

Cancellation Theorems for IR divergences

KLN 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.

IR divergences for exact Gauge Theories

Cancellation Theorems for IR divergences

KLN 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.

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

Cancellation Theorems for IR divergences

KLN 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.

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

IR divergences for Spontaneously Broken Gauge Theories

IR divergences for Spontaneously Broken Gauge Theories

- Asymptotic States
  - For Abelian Gauge theories (QED) $\longrightarrow$ Gauge Eigenstates$\equiv$ Mass Eigenstates
  - For SB Abelian Gauge theories ($U(1)_Y$) $\longrightarrow$ Gauge Eigenstates$\neq$ Mass Eigenstates
  - For non Abelian Gauge theories (QCD) $\longrightarrow$ Confinement (singlet composite states)
  - For SB Non Abelian theories ($SU(2)_W$) $\longrightarrow$ Free non abelian charges

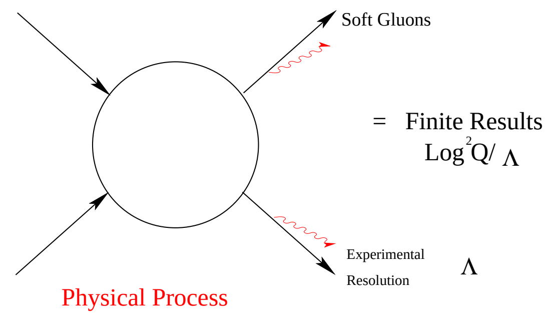
IR divergences for Spontaneously Broken Gauge Theories

- Asymptotic States
  - For Abelian Gauge theories (QED) $\rightarrow$ Gauge Eigenstates$\equiv$ Mass Eigenstates
  - For SB Abelian Gauge theories ($U(1)_Y$) $\rightarrow$ Gauge Eigenstates$\neq$ Mass Eigenstates
  - For non Abelian Gauge theories (QCD) $\rightarrow$ Confinement (singlet composite states)
  - For SB Non Abelian theories ($SU(2)_W$) $\rightarrow$ Free non abelian charges
- gauge properties for physical operators
  - In Exact Gauge theories all the Operators are GI
  - In SB Gauge theories there are operators (proportional to the vev) that are not necessarily gauge invariants (mass insertions, three gauge boson interactions).

Asymptotic state effect

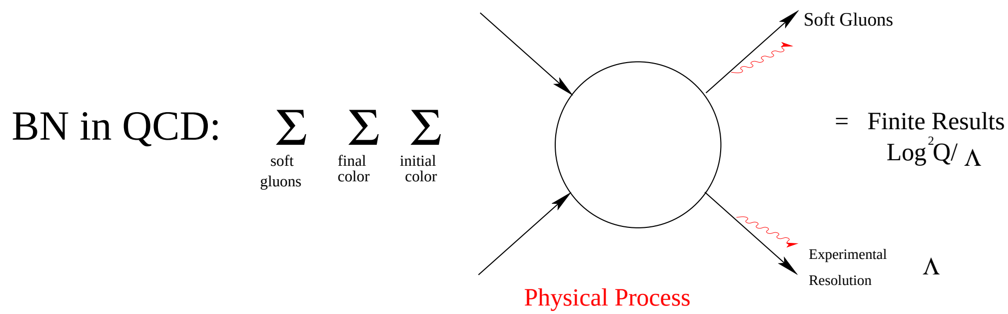
From QCD to EW: $SU(3) \to SU(2)$, (*Color* $\to$ *Flavor*), M_W physical IR cutoff

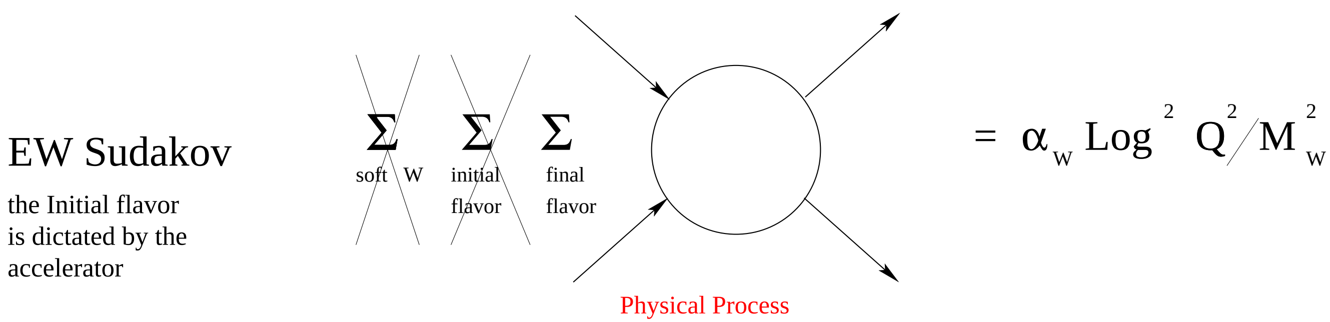
BN in QCD: $\sum_{\text{soft gluons}} \sum_{\text{final color}} \sum_{\text{initial color}}$



Asymptotic state effect

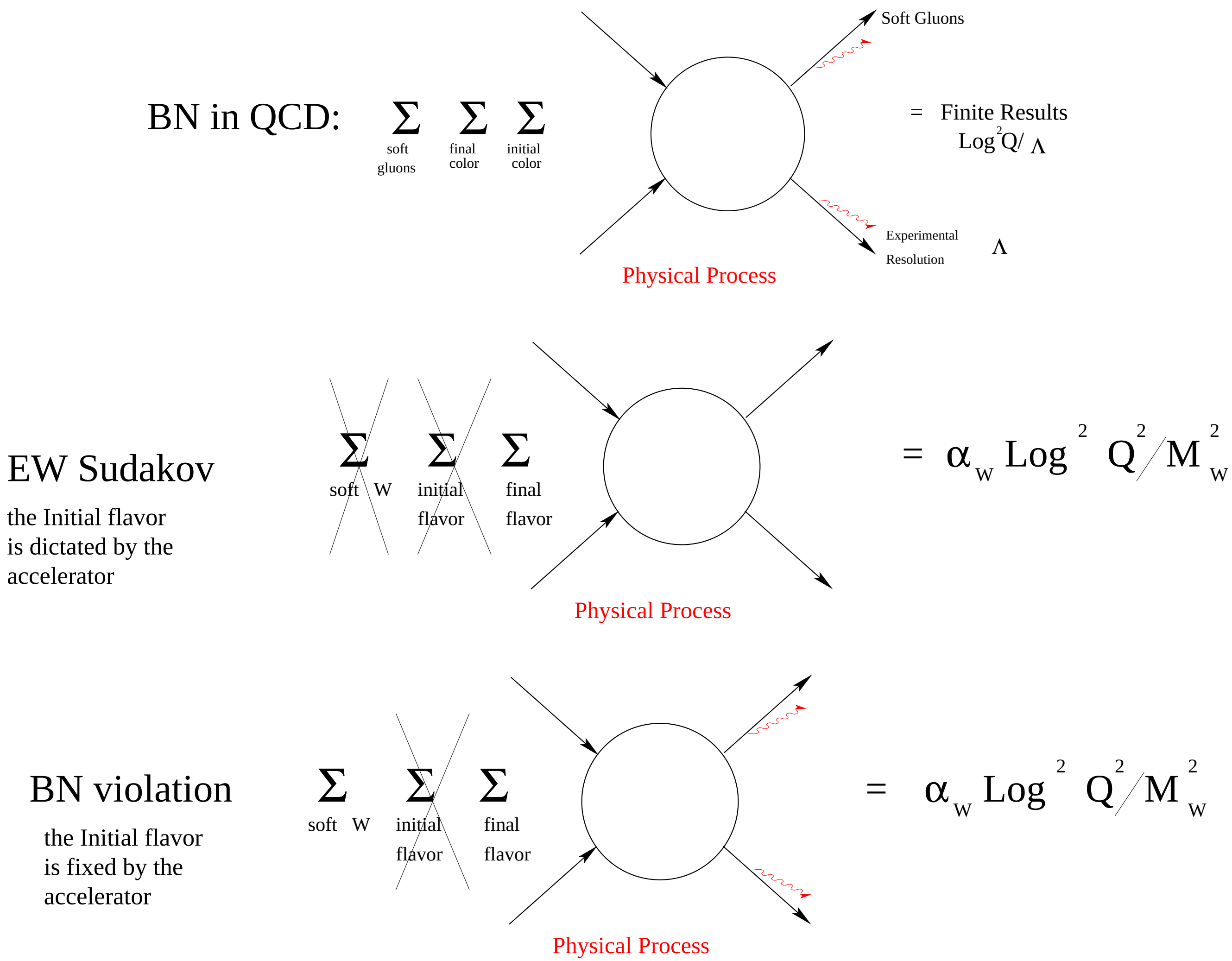
From QCD to EW: $SU(3) \rightarrow SU(2)$, (*Color* $\rightarrow$ *Flavor*), M_W physical IR cutoff





Asymptotic state effect

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



IR divergences for Spontaneously Broken Gauge Theories

Sudakov versus BN EW corrections:

- Sudakov EW corrections:

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

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

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

- 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).
- 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.**

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.
- *Z* and *photon* are a superposition of the B_μ and the W^3_μ 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).

Can we find an unexpected IR effects inside the SM ?

Can we find an unexpected IR effects inside the SM ?

Yes if we find Growing Sudakov Form Factors: $e^{+\alpha Log^2 \frac{Q^2}{M^2}}$

Can we find an unexpected IR effects inside the SM ?

Yes if we find Growing Sudakov Form Factors: $e^{+\alpha Log^2 \frac{Q^2}{M^2}}$
Where? Inside gauge non invariant Operators (higher twist)

Can we find an unexpected IR effects inside the SM ?

Yes if we find Growing Sudakov Form Factors: $e^{+\alpha Log^2 \frac{Q^2}{M^2}}$

Where? Inside gauge non invariant Operators (higher twist)

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

Can we find an unexpected IR effects inside the SM ?

Yes if we find Growing Sudakov Form Factors: $e^{+\alpha Log^2 \frac{Q^2}{M^2}}$

Where? Inside gauge non invariant Operators (higher twist)

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

Can we find an unexpected IR effects inside the SM ?

Yes if we find Growing Sudakov Form Factors: $e^{+\alpha Log^2 \frac{Q^2}{M^2}}$
Where? Inside gauge non invariant Operators (higher twist)

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

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

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

The simplest place where to find an unexpected IR effect !

An Explicit example: $Z' \longrightarrow f\bar{f}$ **(**M. e P. Ciafaloni, D.C. 2009**)**

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

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

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

$F_{L,R}$ conserve chirality

$F_{M,P}$ violate chirality

The simplest place where to find an unexpected IR effect !

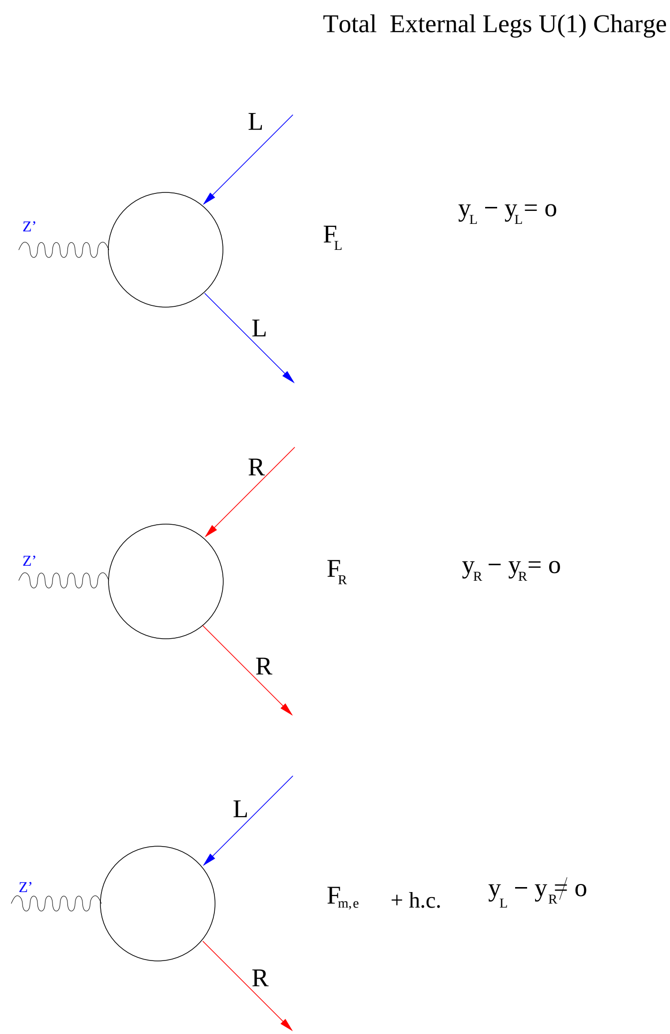
$F_V = \frac{1}{2}(F_R + F_L)$, $F_A = \frac{1}{2}(F_R - F_L)$, $\rho = \frac{m^2}{p_1 p_2}$

the amplitudes squared for the various positive (+) and negative (-) helicity states are given by:

$$\frac{|\mathcal{M}_{++}|^2}{4(p_1p_2)} = \left(F_V - F_A\sqrt{1-\rho}\right)^2 \qquad \frac{|\mathcal{M}_{--}|^2}{4(p_1p_2)} = \left(F_V + F_A\sqrt{1-\rho}\right)^2$$

$$\frac{|\mathcal{M}_{+-}|^2}{4(p_1p_2)} = \frac{|\mathcal{M}_{-+}|^2}{4(p_1p_2)} = \rho[F_A^2 + (F_V - F_M(1-\rho))^2]$$

The simplest place where to find an unexpected IR effect !



One Loop Anomalous Sudakov Form Factors

LL One Loop order results ($\bar{\alpha} \equiv \frac{\alpha_Z}{4\pi}$):

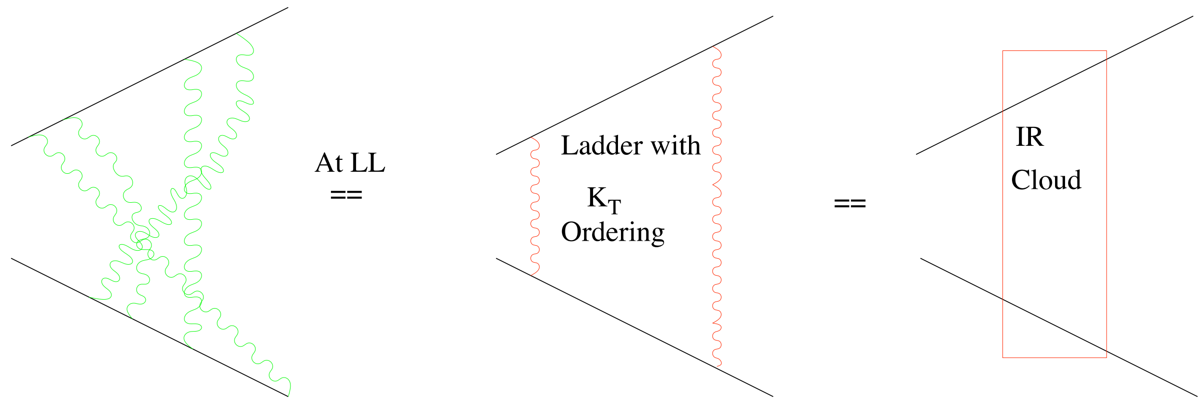
$$
\begin{aligned}
F_L^{(1)} &= f_L + \bar{\alpha} \left(-f_L \, y_L^2 + \frac{m^2}{2 \, Q^2} \, f_R \, (y_R^2 - y_L^2) \right) \, Log^2 \frac{Q^2}{m_Z^2} \\
F_R^{(1)} &= f_R + \bar{\alpha} \left(-f_R \, y_R^2 - \frac{m^2}{2 \, Q^2} \, f_L \, (y_L^2 - y_R^2) \right) \, Log^2 \frac{Q^2}{m_Z^2} \\
F_M^{(1)} &= \bar{\alpha} \, \frac{y_R - y_L}{2} \, (f_L \, y_L - f_R \, y_R) \, Log^2 \frac{Q^2}{m_Z^2} \\
F_P^{(1)} &= \bar{\alpha} \, \frac{y_R - y_L}{2} \, (f_L \, y_L + f_R \, y_R) \, Log^2 \frac{Q^2}{m_Z^2}
\end{aligned}
$$

remarks

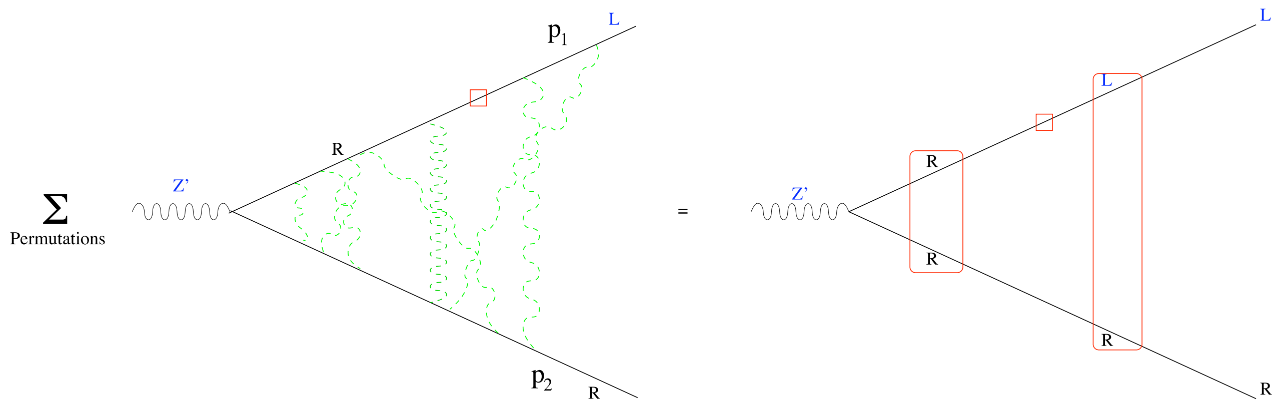
- $F_{M,P}$ born at one loop already IR ($\propto \; Log^2 \frac{Q^2}{m_Z^2}$)
- for vector like U(1) $\rightarrow y_L = y_R$ and $F_{M,P}^{(1)} = 0$
- for $m \rightarrow 0 \; F_{M,P}^{(1)}$ decouple

Anomalous Sudakov Form Factors

Cloud of soft gauge bosons



feynman diagrammatical picture of the sudakov



Anomalous Sudakov Form Factor

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

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

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

Anomalous Sudakov Form Factor

As a check we computed the Ward Identities

$$(p_1 + p_2)_\mu \, \Gamma^\mu_{Z'\bar{f}f} = M \, \Gamma_{\chi'\bar{f}f} \quad \rightarrow \quad F_A + (1+\rho)\, F_P = \, F_{\chi'}$$

that at tree level ($F_A^{(0)} = f_A, \;\; F_P^{(0)} = 0, \;\; F_{\chi'}^{(0)} = f_A$) is trivially satisfied, while at all order $L^{2\,n}$ requires the explicit evaluation of $F_{\chi'}$ at order $\mathcal{O}(\rho)$ in order to be consistent with the precision of the other form factors on the left.
the full result $\mathcal{O}(\rho)$ is

$$F_{\chi'} = (1-\rho) f_A \, e^{-\bar{\alpha} y_L \, y_R Log^2 \frac{Q^2}{M_Z^2}} + \frac{\rho}{2} \, f_A \, \left(e^{-\bar{\alpha} y_R^2 Log^2 \frac{Q^2}{M_Z^2}} + \, e^{-\bar{\alpha} y_L^2 \, Log^2 \frac{Q^2}{M_Z^2}} \right).$$

Anomalous Sudakov Form Factor

Structure of the expansion for small $x \equiv \frac{m^2}{Q^2}$

$$\frac{m^2}{Q^2}\ e^{\alpha\ log^2 \frac{Q^2}{m^2}} \underbrace{\rightarrow} x\ e^{\alpha\ Log^2 x}$$

The perturbative α expansion results

$$x\ e^{\alpha\ Log^2 x} \sim x\ (1 + \alpha\ Log^2 x + ... + \frac{\alpha^n}{n}\ Log^{2\,n} x + ...)$$

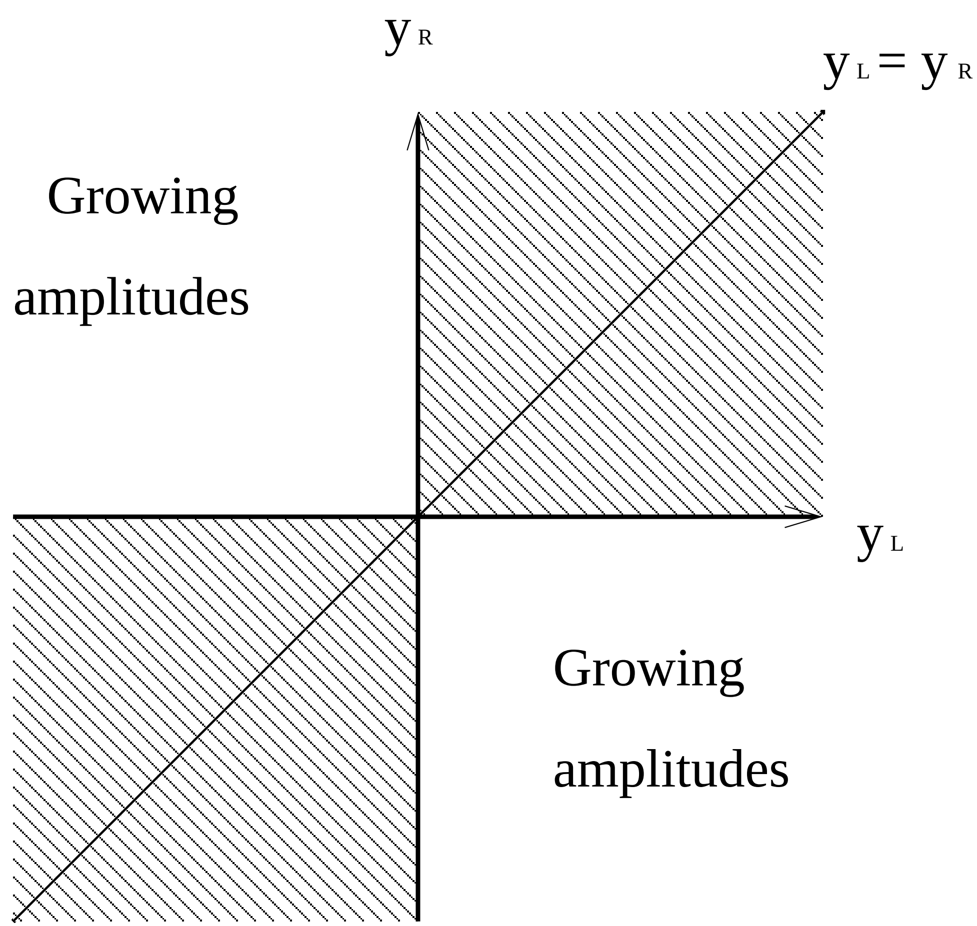
At each given order we have

$$\lim_{x \to 0}\ x\ \frac{\alpha^n}{n}\ Log^{2\,n} x = 0 \quad \vee\ n$$

while for the resumed series the results is different....

$$\lim_{x \to 0}\ x\ e^{\alpha\ Log^2 x}\ = \infty \qquad (= \sum^{\infty} 0)$$

There are “New Physics” effect inside the SM ?



Unitarity and KLN Theorem to be reanalyzed !

Conclusions

- SB Gauge theories show their IR properties at high energy (presence of $\alpha \; Log^2 Q^2/m^2$)
- Asymptotic state effects
  - In general Any cross section (both exclusive than inclusive) with at least two external charged legs is "IR" sensitive.
- Higher twist gauge non invariant operator
  - The presence of Growing Sudakov form factors is opening a *New Frontier* in the definition of the High energy asymptotic of the SB gauge theories

Revisitation Unitarity

EW Corrections at high energies:

$$\sigma \sim \frac{\alpha^2 \; \Gamma_i \; \Gamma_f}{Q^2 + \Pi(Q^2)}$$

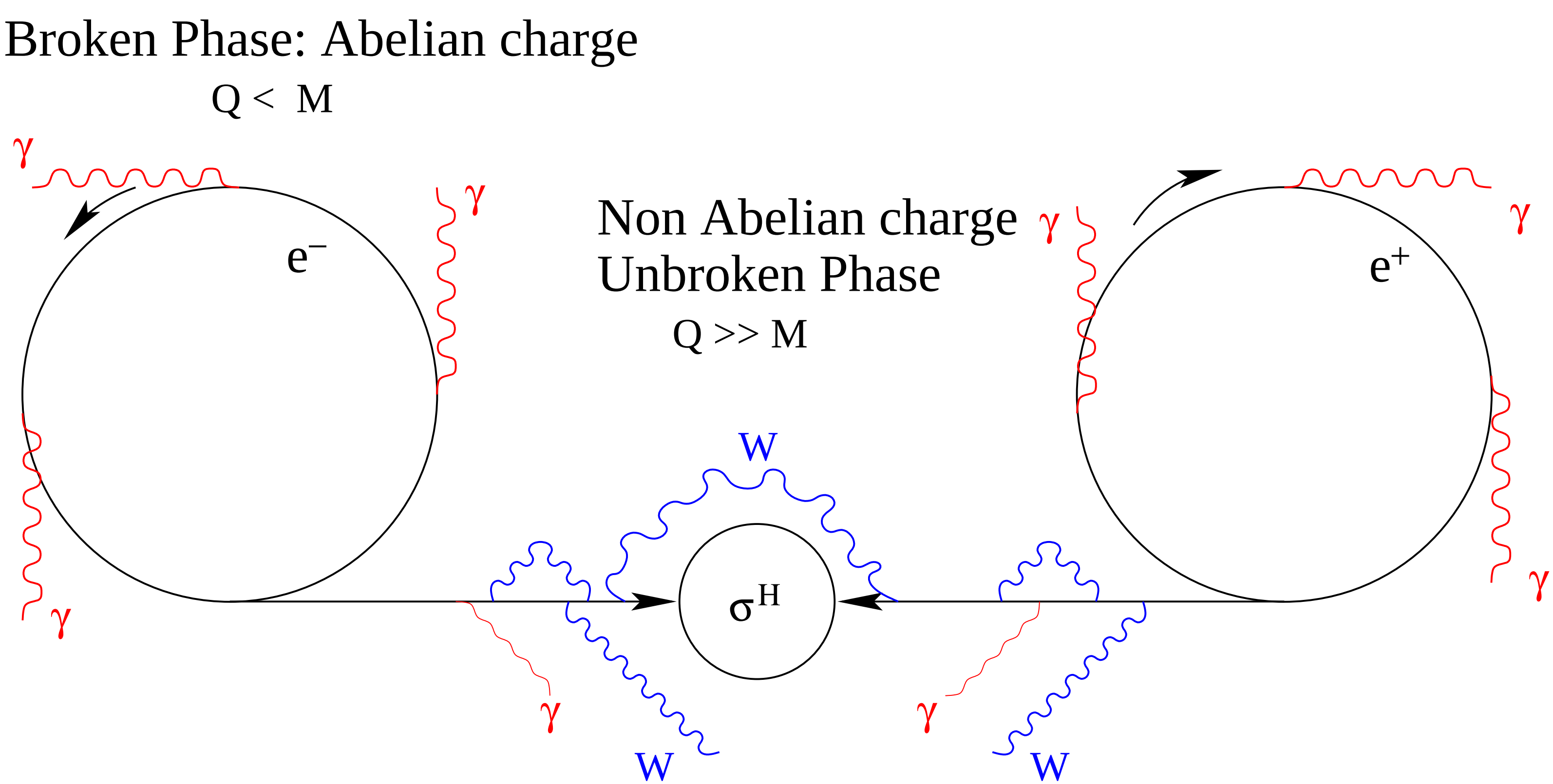
EW Corrections at high energies:

- Show the full IR structure of non abelian theories!
- In general affect any cross section (both exclusive than inclusive) with at least two externa l $SU(2)$ 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 $\sigma_{e\bar{e}\to\sum_q q\bar{q}+X_{g,W}}$
  At LHC potentially relevant for many processes in particular for the *"flavor observables"*
  (ex:$PP \to t\ b;\ t\ Jet,\ W\ W$)
- SM *New Physics* effects in higher twist corrections

High Energy EW theory

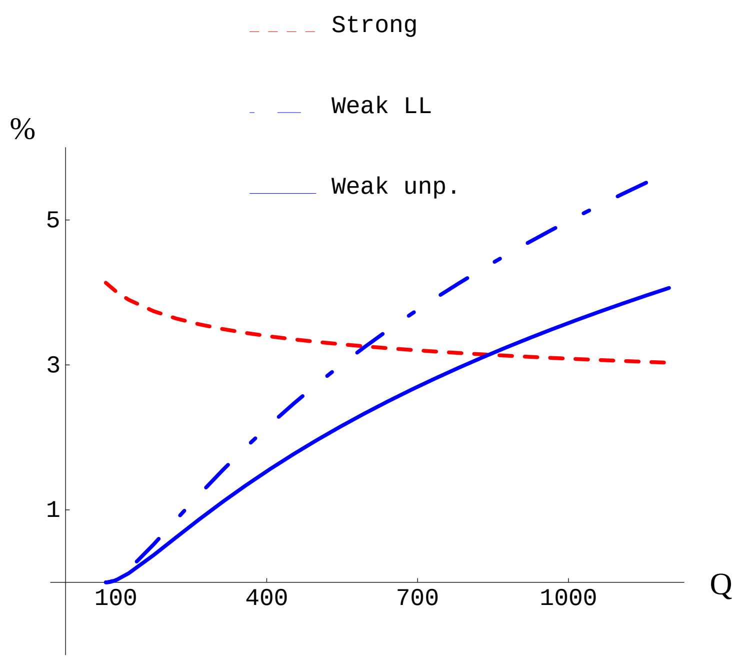
Physical Pictorial idea: For low energies ($Q \leq M_W$) an e^- borns "effectively" as an abelian charge (clouds of photons), increasing the energy ($Q \gg M_W$) it becomes an "effective" non abelian charge (clouds of W's) .

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



EW corrections at ILC

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



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

EW corrections at LHC

Heavy Quark Production at high energy $PP \to Q_i \bar{Q}_j + X$ where $Q_i = t, b$

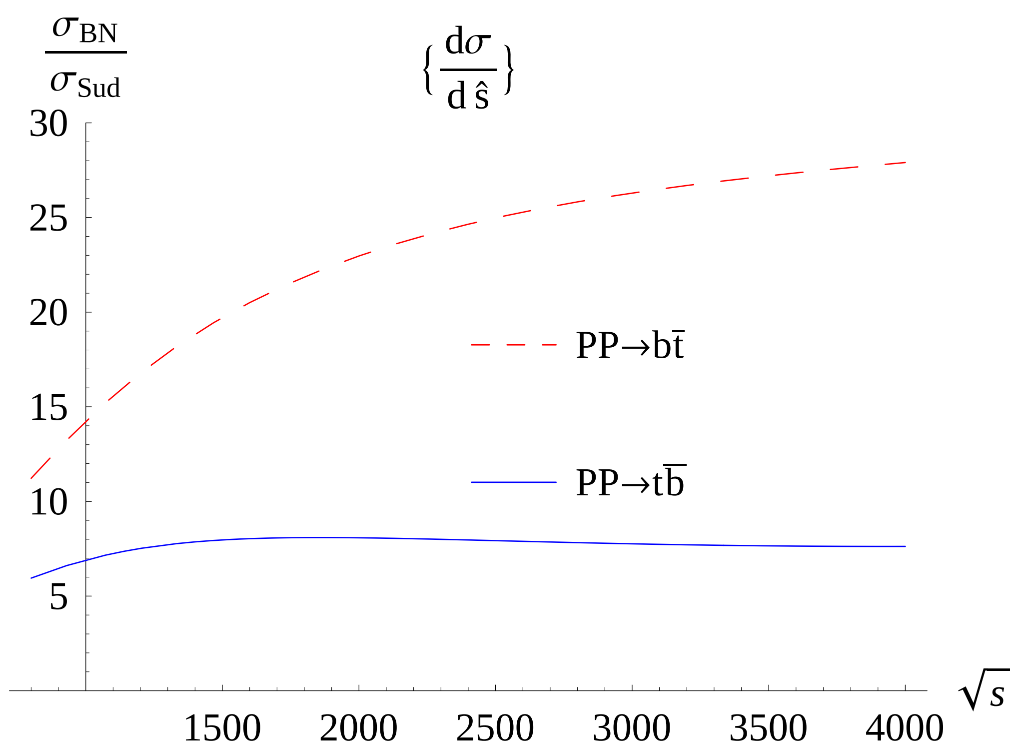
(P.Ciafaloni,D.C.2006)

$$\text{“}Sudakov - like'' \quad : (PP \to \text{tagged final states} + X) \text{ with } W, Z \notin X$$

$$\text{“}BN - like'' \quad : (PP \to \text{tagged final states} + X) \text{ with } W, Z \in X$$

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

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 $t\bar{b}$.

Leading Order Results for High Energy EW theory

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

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

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

Leading Order Results for High Energy EW theory

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

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

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

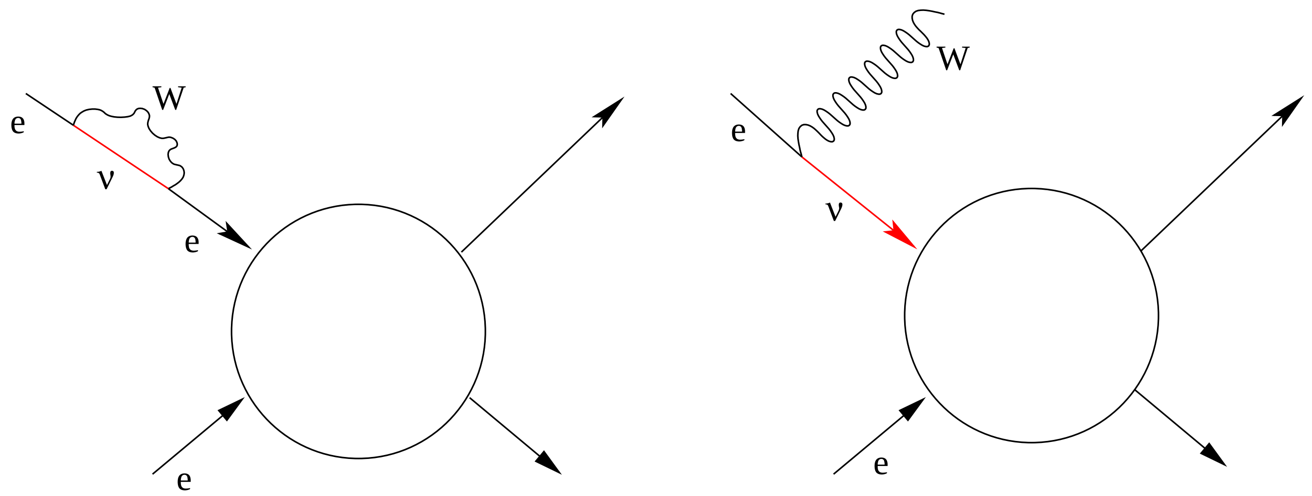
Typical size at $Q \sim 1\ TeV$ (for 2$\rightarrow$ 2 processes) present both at ILC and LHC (P.Ciafaloni,D.C.1999)

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

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

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)

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

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

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

Leading Order Results for High Energy EW theory

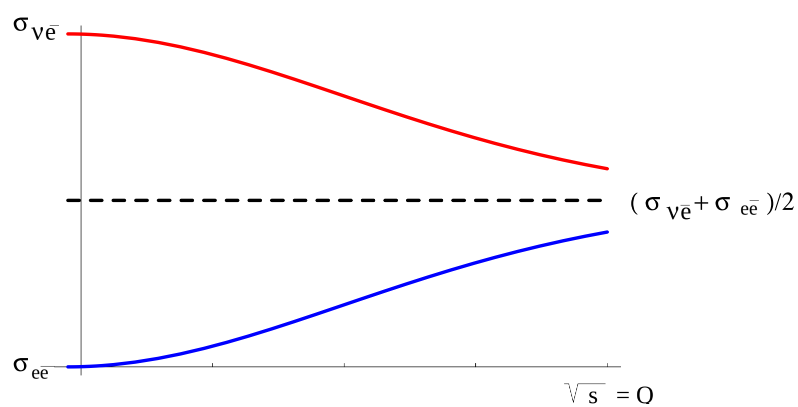
EW BN violation structure: Resummation Leading EW Virtual plus Real radiative corrections (M. & P.Ciafaloni,D.C.2000)

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

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

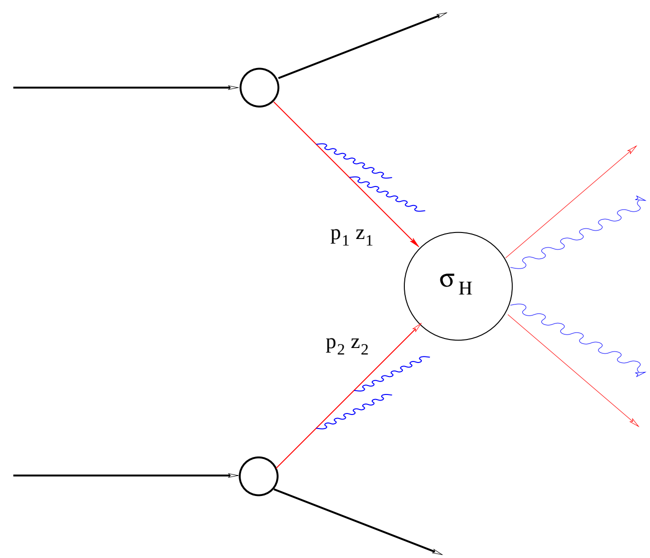
$(ex : \sigma^H_{\nu\bar{e}\to q\bar{q}} = 2\, \sigma^H_{e\bar{e}\to q\bar{q}})$

Effectively e_L becomes indistinguishable from ν_e !



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

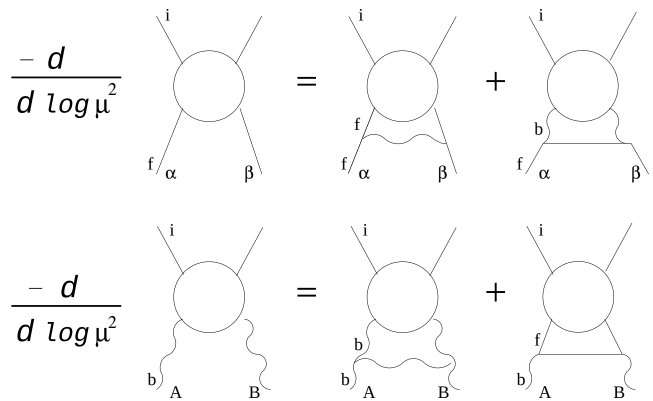
EW structure functions evolution eqs

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

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

EW: $f_{l_{L\,i}},\ f_{l_{R\,i}},\ f_{\bar{l}_{L\,i}},\ f_{\bar{l}_{R\,i}},\ f_{q_{L\,i}},\ f_{q_{R\,i}},\ f_{\bar{q}_{L\,i}},\ f_{\bar{q}_{R\,i}},\ f_h,\ f_{\phi^a},\ f_{B_\mu},\ f_{W^a_\mu}$

Due to mixing effects also mixed structure functions: $f_{BW^3},\ f_{LR\,i}$



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

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

Publications on High Energy EW Corrections

- <u>Exclusive observables</u>: 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).

- <u>Inclusive observables</u>: 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)

M. Ciafaloni, P. Ciafaloni, D. Comelli , *Electroweak Bloch-Nordsieck violation at the TeV Scale: "Strong" Weak Interactions?*, Nucl. Phys. B 589 (2000)

M. Ciafaloni, P. Ciafaloni, D. Comelli , *Electroweak Double Logarithms in Inclusive Observables for a Generic Initial State*,Phys. Lett. B 501 (2001)

M. Ciafaloni, P. Ciafaloni, D. Comelli , *Bloch-Nordsieck Violation in Spontaneously Broken Abelian Theories*, Phys. Rev. Lett. 87 (2001)

M. Ciafaloni, P. Ciafaloni, D. Comelli , *Enhanced Electroweak Corrections to Inclusive Boson Fusion Processes at the TeV Scale*, Nucl. Phys. B 613 (2001)

P. Ciafaloni, D. Comelli, A. Vergine, *Sudakov Electroweak effects in transversely polarized beams,* JHEP 0407, 039 (2004).

P. Ciafaloni and D. Comelli, *Electroweak evolution equations*, JHEP 0511 (2005)

P. Ciafaloni and D. Comelli, *The importance of weak bosons emission at LHC,* JHEP0609(2006)