Correzioni elettrodeboli

ad alte energie

- Review -

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EW interactions at $E \gg M$ = week scale ~ 100 GeV

- EW rad. corr: $\frac{\Delta\sigma}{\sigma} \sim \underbrace{\alpha_w \log^2 \frac{E^2}{M^2}}_{\sim 7\% \text{ @ TeV}} + \cdots$

Kuroda et al '91
Degrassi et al '92
Beenakker et al '93

- Tied to IR structure of the theory: P. C., D. Comelli 98

$\overset{\text{coll}}{\log \frac{E}{M}} \quad \overset{\text{IR}}{\log \frac{E}{M}}$, divergent if $M \to 0$

$\Downarrow$

- Possible to address higher orders / resummation of leading L^{2n}, subleading L^{2n-1}, subsubleading L^{2n-2} ... terms

more than 50 works P.C., M.C., Comelli, Fadin, Melles, Lipatov, Kühn, Pozzorini, Denner, Vertegnassi, Beccaria .... 99 ÷ 03

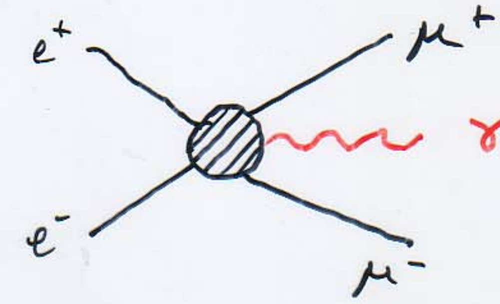
- In contrast with the QED, QCD cases, even fully inclusive (W, Z, γ radiation) quantities are affected by IR "divergences" $\log^2 \frac{E^2}{M^2}$:

Bloch - Nordsieck violation

P.C., M.C., D. Comelli 99 ÷ 02

Osservabili "esclusive"

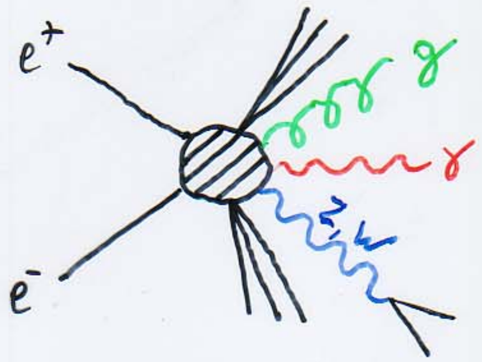
$e^+e^- \to \mu^+\mu^-\gamma$



soffice

Osservabili "inclusive"

$e^+e^- \to q\bar{q}\,X$



$M \ll E \ll \sqrt{s}$

$M = M_W \simeq M_Z$

- Large angle scattering

$$|s| \sim |t| \sim |u| \gg M$$

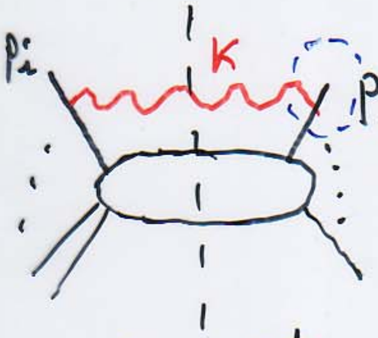
- Standard Model

- BN : virtuali e reali non si cancellano nelle quantità inclusive

Correzioni EW @ TeV - 1 loop

$$\left(\frac{\Delta\sigma}{\sigma}\right)^1 \xrightarrow[\sqrt{s} \gg M]{} \alpha \left\{ \underset{\uparrow \atop LL}{a \log^2 \frac{s}{M^2}} + \underset{\uparrow \atop NLL}{b \log \frac{s}{M^2}} + \underset{\uparrow \atop NNLL}{c} + \underset{\text{mass-suppressed}}{\cancel{O\left(\frac{M^2}{s}\right)}} \right\}$$

Es: DL (Sudakov) approx iconale



$$\cdots \bar{u}(p_J)\, \gamma_\mu \frac{1}{\not{p} - \not{K}} \underset{K \to 0}{\simeq} \frac{p_J^\mu}{K \cdot p_J}\, \bar{u}(p_J)$$

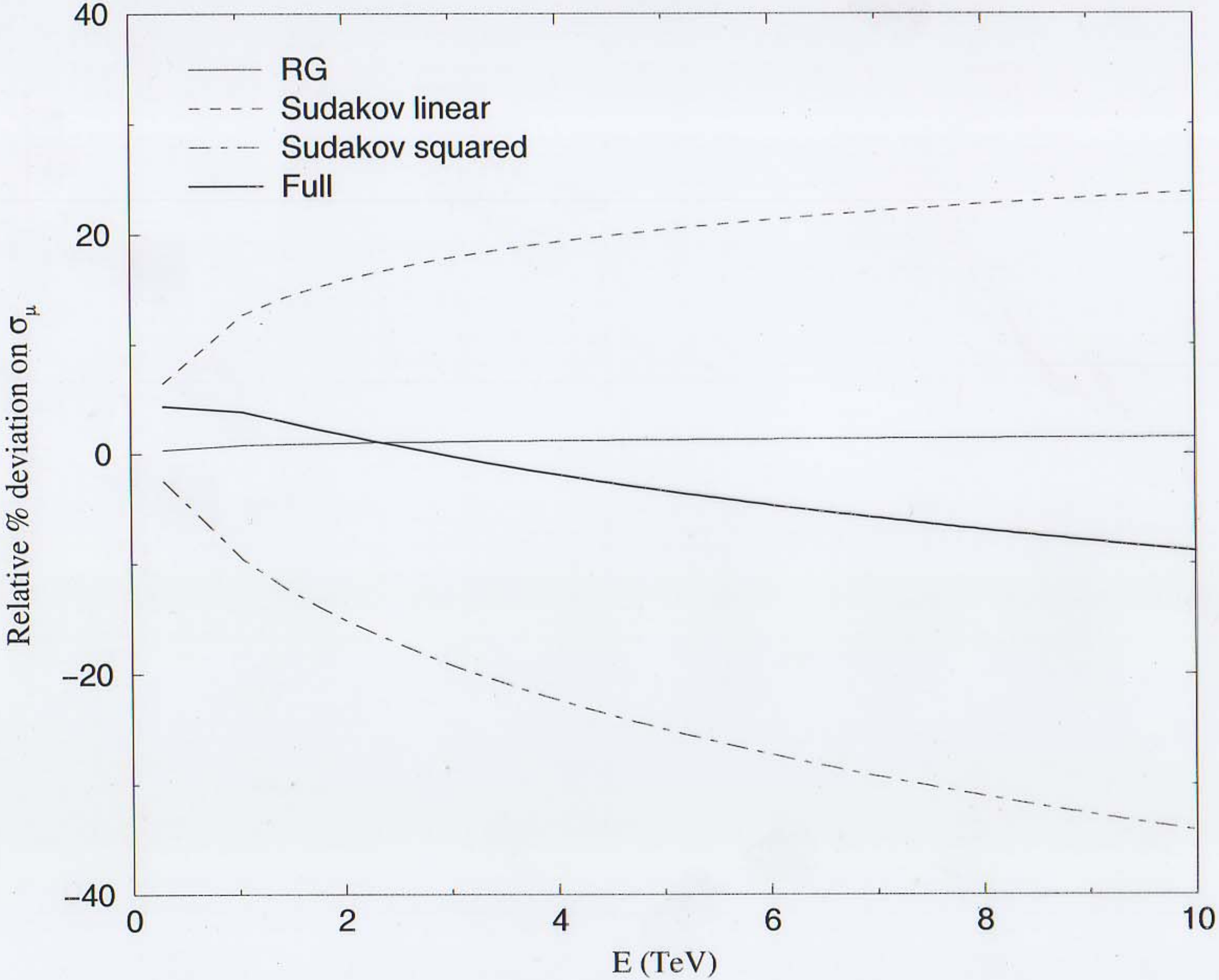
$S \quad S^+ \equiv O$

$$\Delta\sigma^1 \simeq \int \frac{d^3K}{\omega} \frac{p_i \cdot p_J}{(K \cdot p_i)(K \cdot p_J)}\, \sigma^0 \simeq \sigma^0 \underset{\omega\theta > M}{\int} \underset{IR}{\overset{\log \frac{E}{M}}{\frac{d\omega}{\omega}}} \int \underset{coll}{\overset{\log \frac{E}{M}}{\frac{d\theta^2}{\theta^2}}}$$

- inserzioni su gambe esterne (calcolo semplice)
- Fattorizzazione dei DL $\quad \sigma^1 \simeq \sigma^0 \left(1 + \alpha \log^2 \frac{s}{M^2}\right)$
- Struttura di isospin non banale: sorprese!

One Loop - NLC

Beccaria Ciafaloni Comelli Vertegnassi
Renard Layssac Gounaris



- Dominate da IR (non UV)
- Cancellazioni fra LL e NLL
- Precisione a NLC $\lesssim 1\%$ $\Rightarrow$ Necessità di higher order

One loop - LHC

Maina Moretti Ross '04

$$q\bar{q} \to g\,V \qquad V = \gamma, Z \qquad \left(\frac{\Delta\sigma}{\sigma}\right)^1 \sim 10 \div 20\,\%$$
$$q g \to q\,V$$

Accomando Denner Pozzorini '04

$pp \to l\nu_l l'\bar{l}'$				
$P_T^{cut}(l'\bar{l}')$ [GeV]	σ_{Born} [fb]	σ [fb]	Δ [%]	$1/\sqrt{2L\sigma_{Born}}$ [%]
250	1.716	1.595	−7.1	5.4
300	0.899	0.811	−9.8	7.5
350	0.503	0.441	−12.4	10
400	0.296	0.252	−14.9	13
450	0.181	0.150	−17.1	16.6
500	0.114	0.092	−19.3	20.9

Table 1: Cross section for $pp \to l\nu_l l'\bar{l}'$ for various values of $P_T^{cut}(l'\bar{l}')$

$$\bar{d} u \to WZ,\ W\gamma$$

$$\left(\frac{\Delta\sigma}{\sigma}\right)^1 \sim 5 \div 20\%$$

- Higher order probabilmente irrilevanti a LHC

Risommazione - tecniche di QCD ma differenze importanti

- <u>Fattorizzazione</u>

$$\sigma = \int dx \; f(x,\mu^2) \; \sigma_H(xs)$$

scala soffice   scala dura

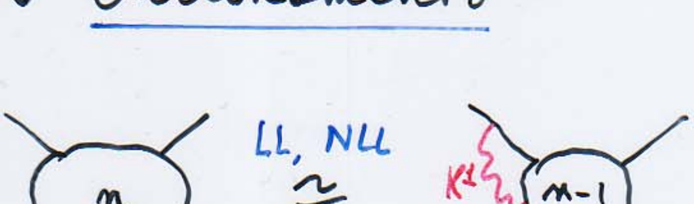
- fattorizzazione <-> C.W.I.   Amati Petronzio Veneziano '78

$$K_\mu \sim\!\!\sim \bigcirc = \begin{cases} 0 & \text{unbroken (QCD)} \\ M \text{- - - -} \bigcirc & \text{broken (EW)} \end{cases}$$

- accoppiamenti $\propto M$ trascurabili? (vedi avanti)

- Dimostrare a   LL all orders
  NLL 1 loop   Denner Pozzorini '01

- <u>Ordinamento</u>



$$\mu \ll K_\perp^1 \ll K_\perp^i \quad i \neq 1$$

$$\Downarrow$$

$$\mu^2 \frac{\partial}{\partial \mu^2} f(x,\mu^2) = \alpha \, [f \otimes P](x) \qquad f \otimes P = \int_x^1 P(x)\, f\!\left(\frac{x}{z}\right) \frac{dz}{z}$$

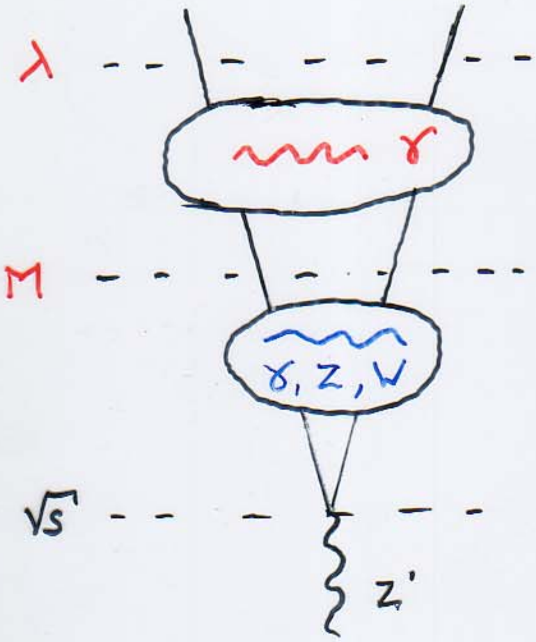
- Separazione di scale

$$\Delta \ll K_\perp^\gamma \ll M \qquad M \ll K_\perp^\gamma, K_\perp^W, K_\perp^Z \ll \sqrt{s}$$

Osservabili esclusive e LL $\alpha^n \ell^i L^j \quad i+j=2n$

3 scale $\sqrt{s}$, M, λ $\qquad \ell = \log \frac{M}{\lambda} \quad L = \log \frac{\sqrt{s}}{M}$

masse γ



pure QED

unbroken EW

Cosa vuol dire "soffice" ?

ordinamenti in ω Ciafaloni Comelli '00 danno

$K_\perp$ Fadin et al '00

risultati diversi. Calcoli a 2 loops con tecniche di approx

Hori et al '00

Beenakker et al '00

Denner et al '03

confermano i risultati di Fadin et al. (Perche'?)

Aglietti, Bonciani '03 '04

2 loop esatto !

$\Downarrow$

$\Rightarrow$

Feucht et al '03 '04

$L^4, L^3, L^2, L, 1, \ldots$

Osservabili esclusive e NLL

$\alpha^n \ell^i L^j \quad i+j \geq 2n-1$

Melles '00

Kühn Penin Smirnov '00

Tecniche mutuate da QCD

Assunzioni:

- fattorizzazione e NLL all orders
- separazione di scale e NLL QED ¦ unbroken EW

M

Recentemente confermate a 2 loops

Pozzorini hep-ph/0401087

Note:

- non direttamente confrontabili perché diversi cutoff IR per γ
- manca calcolo "vero": reali + virtuali

Osservebili esclusive e NLL

$$\alpha^n \ell^i L^j \qquad i+j \geq 2n-2$$

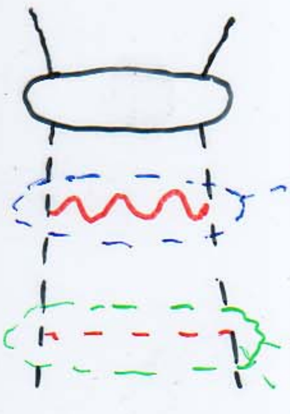
Kühn Moch Penin Smirnov '01

- four-fermion processes
- Grosse cancellezioni fre LL, NLL, NNLL

$$\Downarrow$$

$$\left(\frac{\Delta\sigma}{\sigma}\right)^{2\,\mathrm{loop}}_{\mathrm{NNL}} \sim 1 \div 2\ \%$$

Seperazione "unbroken EW" + "pure QED" dubbie per i longitudinali



$$\alpha \int \frac{dz}{1-z} \int \frac{dk_\perp^2}{k_\perp^2} \sim \alpha \log^2 \frac{s}{M^2}$$

$$\alpha M^2 \int \frac{dk_\perp^2}{k_\perp^4} \sim \alpha \qquad \text{FINITO}$$

$$\Downarrow$$

$\propto M$

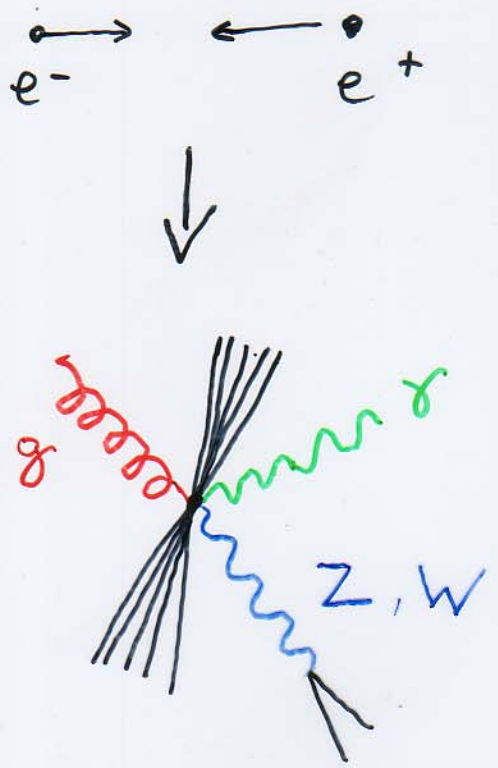
$$\alpha^2 \log^2 \frac{s}{M^2}$$ NNLL e 2 loops

Feucht Kühn Penin Smirnov

hep-ph/0404082

Fully inclusive observables

Ex : $e^+e^- \to$ hadrons $+ X$



~~BN~~

Large angle scattering:

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

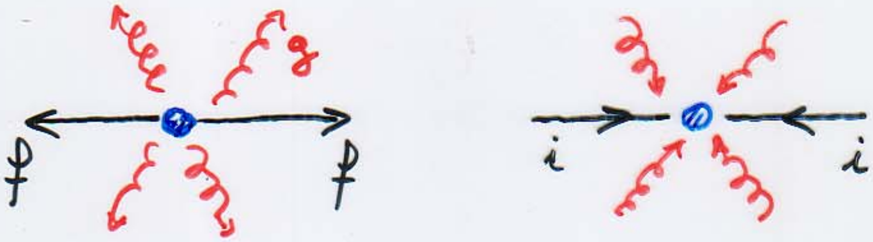
P. Ciafaloni, M. Ciafaloni, D. Comelli

'98 → '03

GENERAL IR THEOREMS

• KLN : f, i "hard", g "soft"

$$\sum_{i,f,g} \left|\langle f\, g(\Delta)|\, S\, |\, i\, g(\Delta)\rangle\right|^2 \quad \text{IR finite}$$

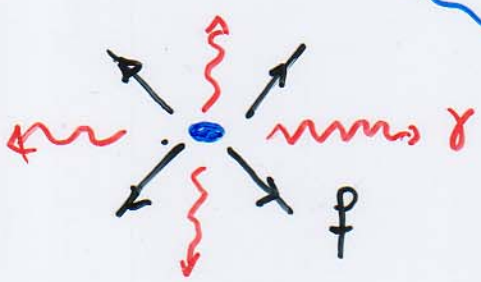


Unphysical ! NO general th. for phys. σ's

• QED : Bloch - Nordsieck

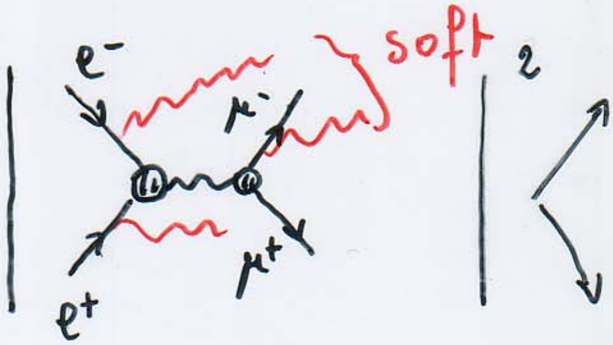
$$\sum_{\gamma} \left|\langle f, \gamma(\Delta)|\, S\, |\, i\rangle\right|^2 \quad \text{IR finite}$$

abelian



Physical : Δ = exp. res.

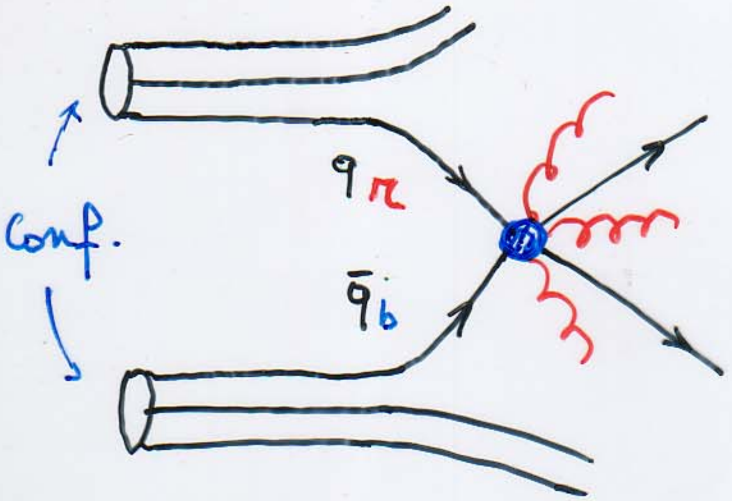
$\sum_{\text{soft } \gamma}$



finite Δ - dep.

1 if totally inclusive : no Δ - dep.

QCD: no BN, only KLN **BUT**



$\sum'_{r,b}$: color average over initial colors of the hard "i" states

Then, leading DL's cancel out

(subleading: Brodsky, Taylor, Bodwin, ⋮)

EW:

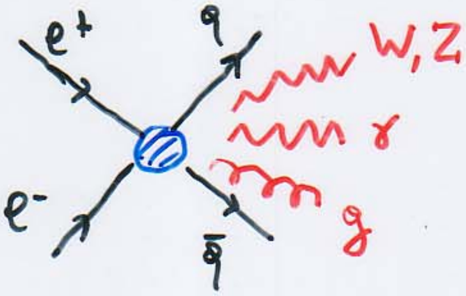
FIXED nonabelian initial charges

$\Downarrow$

full strenght DL's uncanceled:

} P.C., M.C., D.C.

Ex: $e^+e^- \to$ had., fully inclusive



$$\sum'_{q_i,\gamma,W,Z,g} \Rightarrow \Delta\sigma \sim \alpha_w \log^2\frac{s}{M_W^2}$$

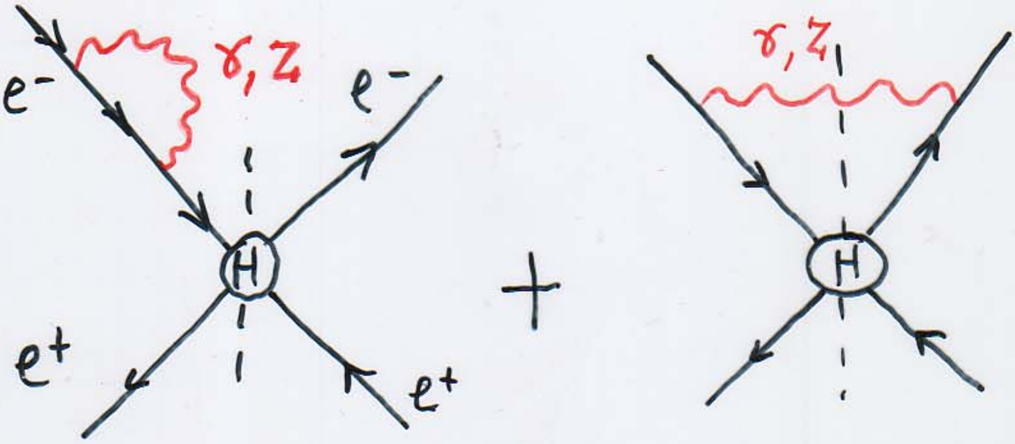
IR cutoff

BN theorem maximally violated

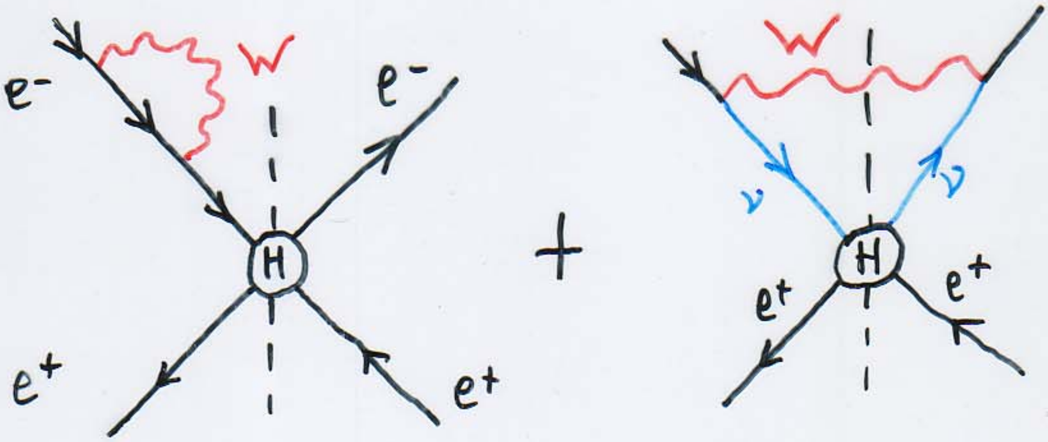
$e^+ e^- \to$ hadrons at 1 loop DL level

P. Ciafaloni M. Ciafaloni D. Comelli '00

Virtual Real



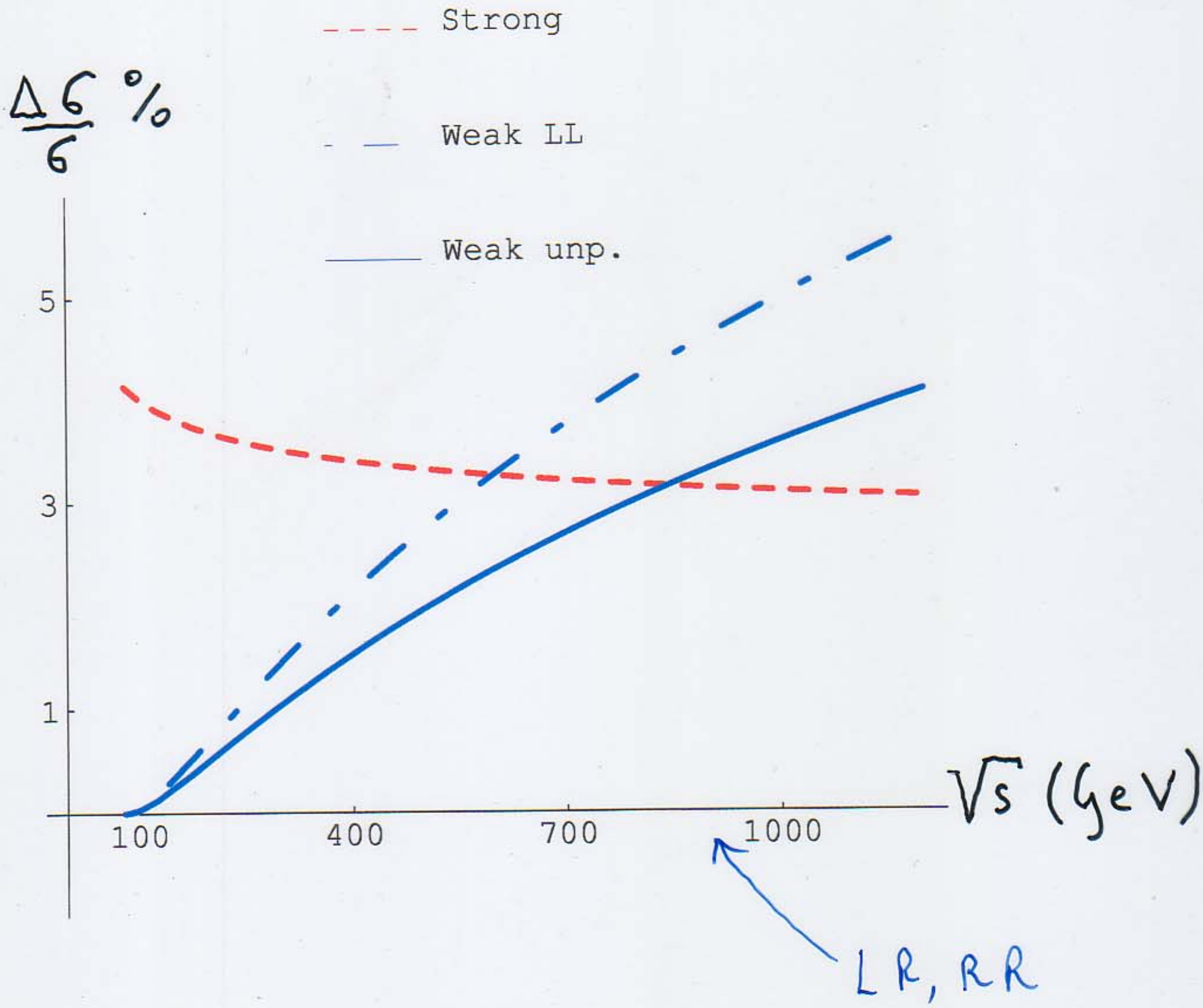
$$-\alpha \log^2 \frac{\sqrt{s}}{M}\, \sigma^{H}_{e^+e^-} + \alpha \log^2 \frac{\sqrt{s}}{M}\, \sigma^{H}_{e^+e^-} = 0$$



$$-\alpha \log^2 \frac{\sqrt{s}}{M}\, \sigma^{H}_{e^+e^-} + \alpha \log^2 \frac{\sqrt{s}}{M}\, \sigma^{H}_{e^+\nu} \neq 0 \ !$$

- BN violation : strong dependence on the IR cutoff M ! $\Delta\sigma \sim \log^2 \frac{\sqrt{s}}{M}$
- W exchange affects only L particles in a universal way

$e^+ e^- \to$ hadrons



- Strong EW effect !!

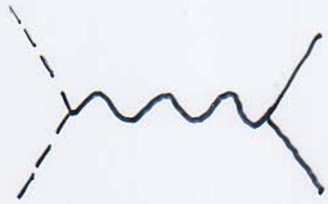
$$\sigma_{e^+e^-} = \sigma^H \left(1 + O\left(\frac{\alpha_s}{\pi}\right) + O\left(\frac{\alpha_W}{4\pi} \log^2 \frac{s}{M^2}\right)\right)$$

$\sim 3\,\%$ $\qquad \sim 5\,\%$

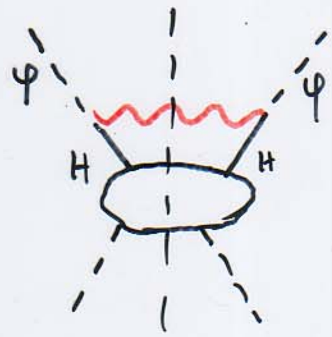
- Polarization dependence

"Nuove fisica"

• $W_L W_L \to f\bar{f}$



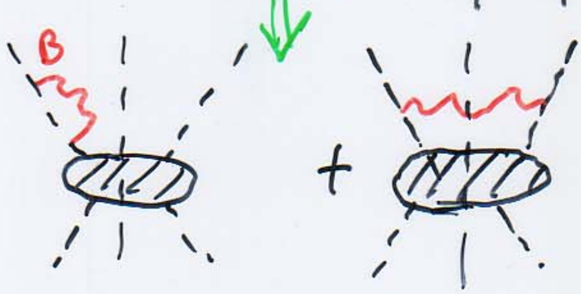
$\sigma^H \sim \frac{\alpha^2}{s}$ M_H - indep.



$\Delta\sigma\left(\alpha \log^2\frac{\sqrt{s}}{M}, \alpha \log^2\frac{M_H}{M_W}\right)$

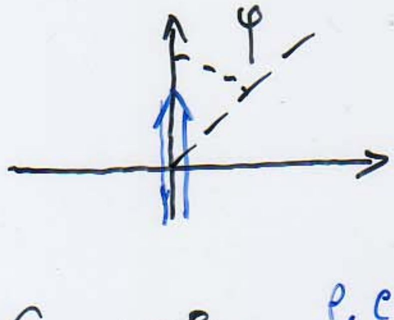
• ~~BN~~ in teorie abeliane $W_L W_L$ scatt.

$$\phi = H + i\chi \xrightarrow{SB} \begin{cases} H \sim \phi + \phi^* & m = v \\ \chi \sim \phi - \phi^* & m = 0 \end{cases}$$ mixing



$\neq 0$ $\cancel{BN}$

• BN in $e^\perp$ - effetti SU(2) e U(1)



$e^\perp = e^L + e^R$

$Y_L \neq Y_R$

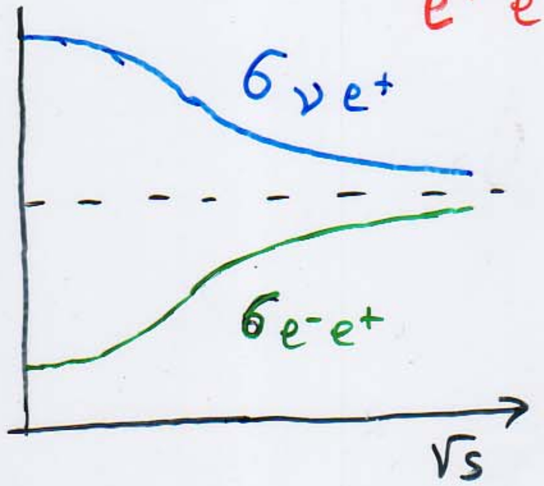
$\frac{\Delta\sigma}{\sigma} \sim 10\%$ P.C. Comelli '03

Resummation of leading IR double logs

- No ordering ambiguities! $\left(\alpha_W \log^2 \frac{s}{M^2}\right)^n$

- $s \sim t \sim u \gg M_W^2 \sim M_Z^2 = M^2$: recovered $SU(2) \otimes U(1)$

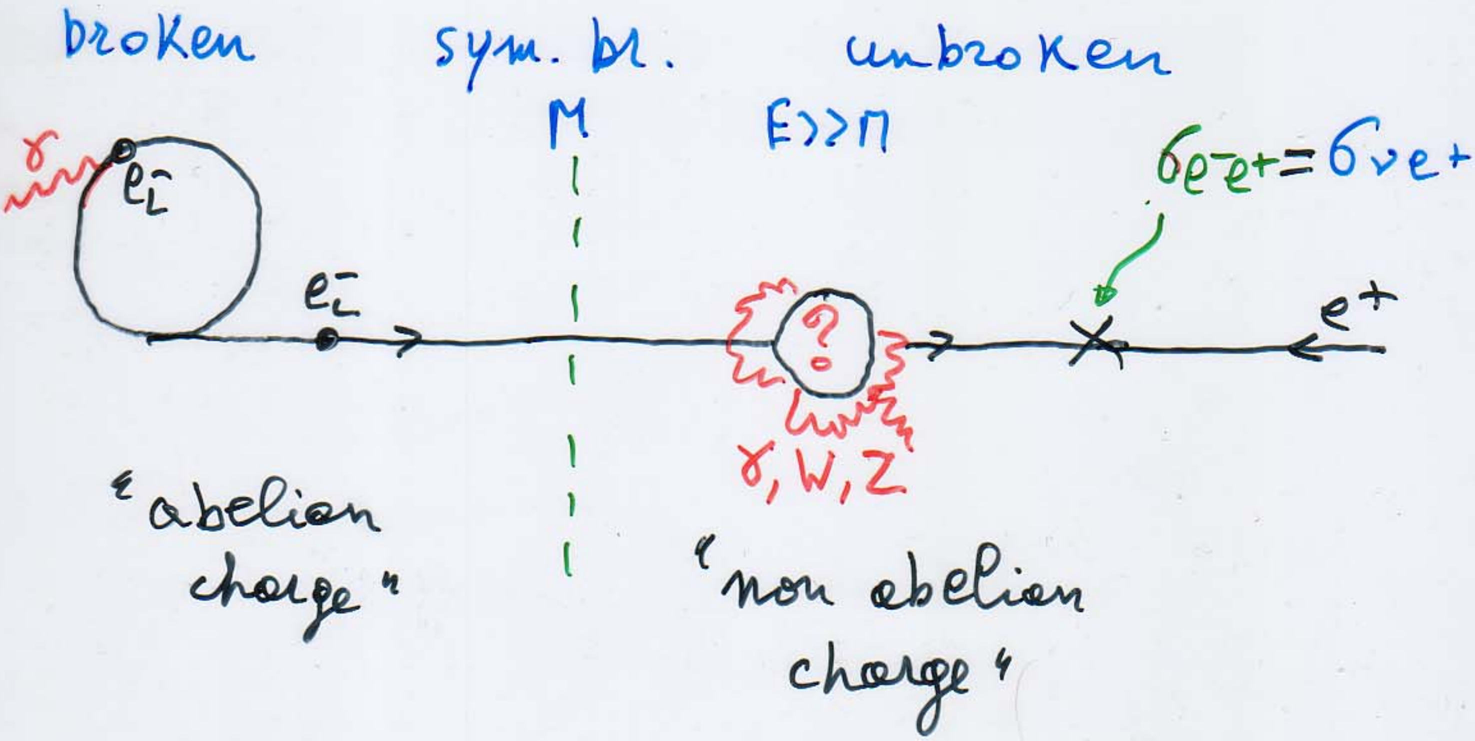
$e^+ e^- \to$ hadrons



$$\sigma_{\nu e^+} - \sigma_{e^- e^+} = e^{-\alpha_W L^2} (\sigma_\nu - \sigma_e)_H$$

$$\sigma_{\nu e^+} + \sigma_{e^- e^+} = (\sigma_\nu + \sigma_e)_H$$

Can you tell an electron from a neutrino?

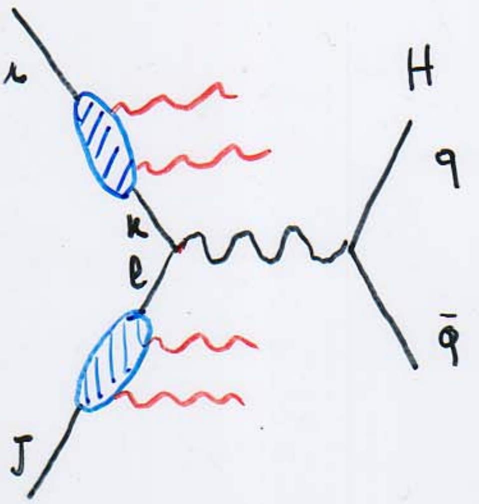


What about subleading logs? .....

EW evolution equations

M. Ciafaloni
P. C.
D. Comelli

I - factorization



probability of finding parton k inside parton i
i, k = fermion, transv. bos

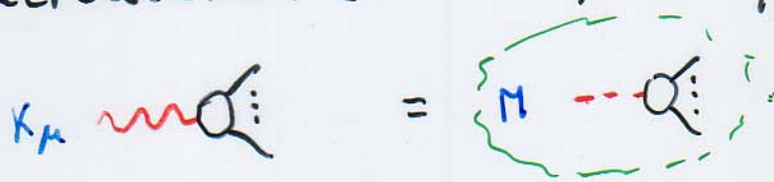
$$\sigma_{ij} = \int \frac{dx_1}{x_1} \frac{dx_2}{x_2} \, f_{ik}(x_1; s, M^2) \, \sigma^{H}_{kl}(x_1 p_1, x_2 p_2) \, f_{lj}(x_2; s, M^2)$$

describe all M-dep collinear/IR divergences

IR - free (M - indep.)

Differences with unbroken theories (QCD) :

- factorization $\leftrightarrow$ W.I., modified by G.B. insertion



not necessarily $\propto \frac{M^2}{s}$ (see later)

- Both collinear and infrared logs are taken into account:

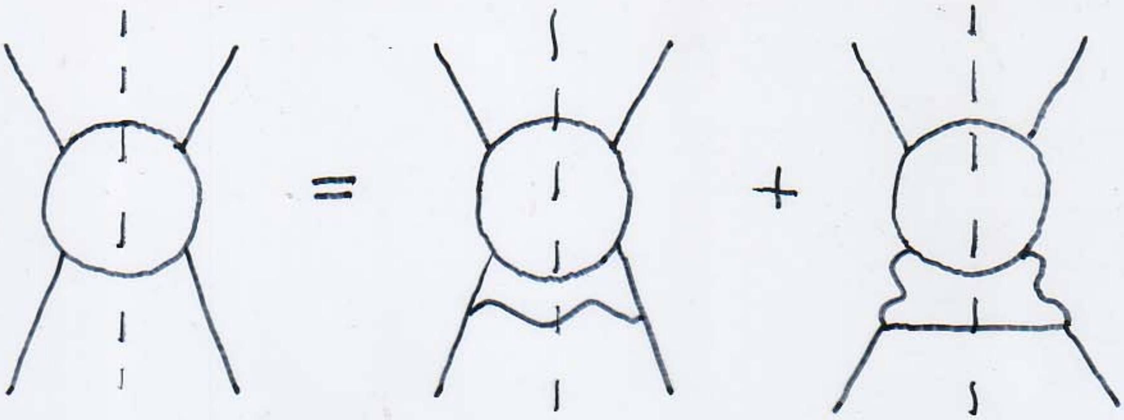
  "EW DGLAP" resum

  $(\alpha L^2)^n, \ldots, \alpha^n L^{n+1}, (\alpha L)^n$

  QCD DGLAP

- written for trans. g.b., fermions in SU(2)
- Soon available for full S.M.

$$-\frac{d}{d\log\mu^2}$$



$$\frac{-d}{d\log\mu^2} f_f^0(x,\mu^2) = \int_x^1 f_J^0\left(\frac{x}{z},\mu^2\right) P_{J,f}^0(z) \equiv f_J^0 \otimes P_{J,f}^0$$

← QCD-like

$$\frac{-d}{d\log\mu^2} f_f^1(x,\mu^2) = \left(a\log\frac{s}{\mu^2} + b\right) f_f^1(x,\mu^2) + f_J^1 \otimes P_{J,f}^1$$

↑ NEW IR-singular splitting function

$$f_f^0 = \frac{f^\nu + f^e}{2} \quad ; \quad f_f^1 = \frac{f^\nu - f^e}{2}$$

Redefinition:

$$f^1(x,\mu^2) = \exp\left[-\frac{\alpha_w}{4\pi}\log^2\frac{s}{\mu^2} - 3\log\frac{s}{\mu^2}\right]\tilde{f}^1(x,\mu^2)$$

$$-\frac{d}{d\log\mu^2}\tilde{f}^1(x,\mu^2) = \tilde{f}_J^1 \otimes P_{J,f}^1$$

Conclusioni

- Correzioni EW a $\sqrt{s} \gtrsim 1$ TeV dominate da dinamica IR $\Rightarrow$ effetti "grossi" $O\left(\alpha_w \log^2 \frac{s}{M^2}\right) \sim 10\%$; higher orders per NLC
- Osservabili "esclusive"
  - 3 scale di massa $\sqrt{s}, M_w, \Delta \gg m_f$
  - ambiguità di ordinamento
  - Disponibili LL, NLL, NNLL, 2 loops
- Osservabili "inclusive"
  - 2 scale $\sqrt{s}, M \Rightarrow$ ordinamento ok
  - BN $\Rightarrow \alpha \, \alpha \log^2 \frac{\sqrt{s}}{M} \leftarrow$ IR cutoff
- "Nuove fisica" : BN in SM, BN in teorie abeliane, $e_\perp$ ...
- Equazioni di evoluzione collineari coinvolgono nuove splitting functions. Presto disponibili in full SM
- Se non si costruiranno NLC e TeV

"Much ado about nothing"