Electroweak Sudakov Logs at the LHC

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- Introduction
- Source and origin of the EW logarithms
- EW correction effects at colliders
- Vector boson pair production at the LHC
- Single top production at the LHC
- Summary and discussion hints

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Introduction

In the energy range of future colliders $\sqrt{s} \gg M_W$, the electroweak corrections are enhanced by

large logarithmic contributions

In the past few years, the analysis of the high energy behaviour of the EW corrections has gathered a lot of interest

- on a general basis

  DL origin and 1-loop structure are now well established

  Resummation methods have been derived

- and for specific processes

  $e^+e^- \to f\bar{f}, \quad \gamma\gamma \to f\bar{f}, \quad pp \to f\bar{f},$

  $pp \to VV \to 4f$, $pp \to tq$

$\to$

sizeable effects not only at e^+e^- and $\gamma\gamma$ LC

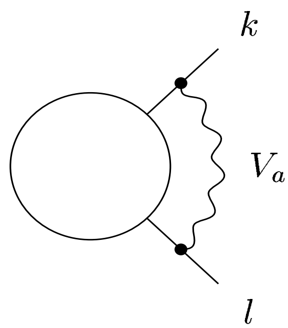
but also at Tevatron and LHC

Structure and origin of Log corrections

Sudakov Logs are related to the infrared structure of the theory

EW Leading Logs result as mass singularities from soft/collinear gauge bosons exchanged between external particles

$$\sum_{k=1}^{n} \sum_{l<k} \sum_{V_a = \mathrm{A,Z,W^{\pm}}}$$



$$\propto \alpha \log^2 \left(\frac{|r_{kl}|^2}{M_W^2} \right)$$

Next-to-Leading Logs from RGE have UV origin

Unlike QED and QCD

the large EW Logs from virtual corrections are physically significant

being M_W and M_Z a natural infrared cutoff

Structure and size of $O(\alpha)$ EW Logs

- Leading Logs (Sudakov)=$\alpha \log^2 (s/M_W^2)$
- Subleading Logs =$\alpha \log(s/M_W^2) \log(|t|/s)$

  i.e. angular-dependent Logs $\simeq \alpha \log(s/M_W^2) \log(|1 \pm cos\theta|)$
- Next-to-Leading Logs =$\alpha \log(s/M_W^2)$
- $+ \ \log(M_W/m_f) \ + \ \log(M_W/\lambda)$

What is their size at a typical energy of 1 TeV?

for $f\bar{f}' \to f\bar{f}'$**:**

$$\frac{\delta\sigma_{LL}}{\sigma_{Born}} \simeq -\frac{\alpha}{\pi s_w^2} \log^2\left(\frac{s}{M_W^2}\right) \simeq -26\%$$

$$\frac{\delta\sigma_{NLL}}{\sigma_{Born}} \simeq \frac{3\alpha}{\pi s_w^2} \log\left(\frac{s}{M_W^2}\right) \simeq 16\%$$

$\to$ Large cancellations!

Extracting the Logs

- 1-loop structure and DL origin
  [Ciafaloni and Comelli, Kühn and Penin]

- explicit calculation of DL corrections for
  $e^+e^- \to f\bar{f}$
  [Melles, Beenakker and Werthenbach, Hori, Kawamura and Kodaira]

- SL 1-loop corrections for
  $e^+e^- \to WW$ and $e^+e^- \to f\bar{f}$
  [Beenakker, Kühn, Moch, Penin and Smirnov, Beccaria, Ciafaloni, Comelli, Renard, Verzegnassi]

- A powerful method for EW 1-loop corrections to
  any exclusive process with N final state particles
  [Denner and Pozzorini]

  LL and NLL have been proven to factorize at HE

  $M(p_1, ...p_n) = M_{Born}(p_1, ...p_n)(1 + \delta_{EW})$

  compact formulas

  easy to automatize in a general Monte Carlo

Full agreement

Resummation

- Prescriptions for the resummation of the DL [Kühn, Penin, and Smirnov, Ciafaloni and Comelli, Fadin, Lipatov, Martin and Melles]

- general recipe for the resummation of the SL corrections to all orders for arbitrary processes [Melles]

- 2-loop agreement on DL and SL [Denner, Melles and Pozzorini]

Resummation amounts to Logs exponentiation

typical size of 2-loop DL and SL

for $f\bar{f}' \to f\bar{f}'$ at $\sqrt{s}$=1 TeV

$$\frac{\delta\sigma^{(2)}_{LL}}{\sigma_{Born}} \simeq +\frac{\alpha^2}{2\pi^2 s_w^4}\log^4\left(\frac{s}{M_W^2}\right) \simeq 3.5\%$$

$$\frac{\delta\sigma^{(2)}_{NLL}}{\sigma_{Born}} \simeq -\frac{3\alpha^2}{\pi^2 s_w^4}\log^3\left(\frac{s}{M_W^2}\right) \simeq -4.2\%$$

What the impact at hadron colliders?

- **Drell-Yan processes**
  [Baur, Brein, Hollik, Keller, Schappacher, Wacheroth, Dittmaier, Krämer]

$$pp \to \gamma, Z \to l^- l^+ \qquad pp \to W \to l\nu_l$$

Low energy: M_Z, Γ_Z, $A_{FB} \to sen^2\theta_{eff}^{lep}$ M_W, Γ_W

High energy: New Physics (Z', W', extra-dimensions..)

NP effects could show up

at high invariant masses $M(l\nu_l)$ e $M(ll)$

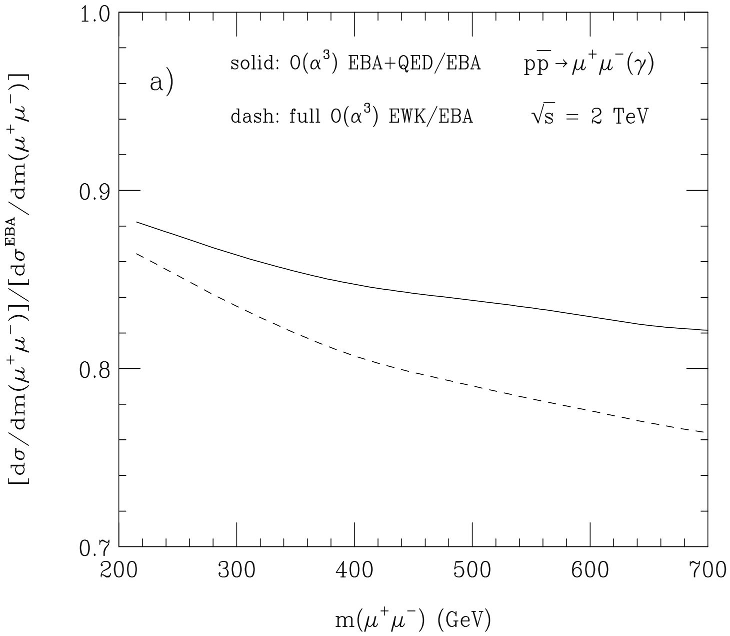
Optimizing the sensitivity to new signals requires a precise control of the background

QCD + EW corrections

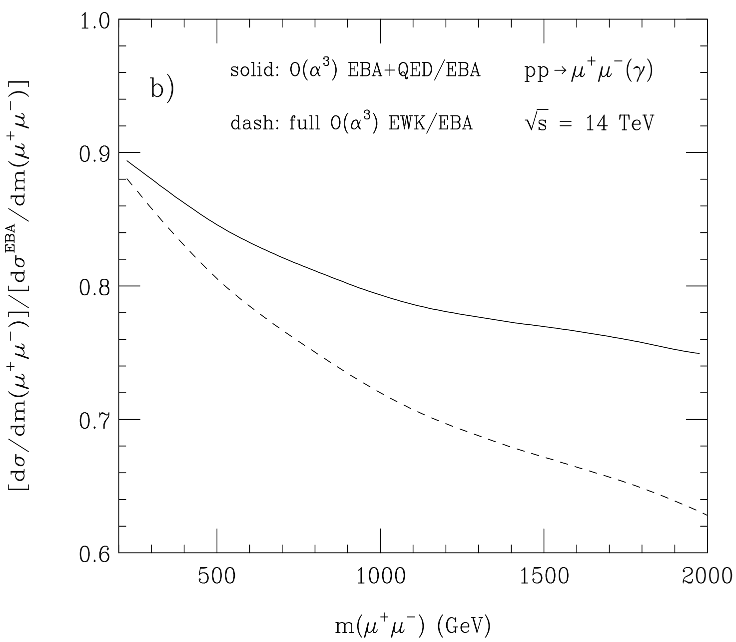
- $pp \to b\bar{b}$ [Maina, Moretti, Nolten, Ross]

EW radiative effects on QCD processes
sizeable corrections to b-quark asymmetries

[Baur, Brein, Hollik, Schappacher,Wackeroth '01]



Tevatron



LHC

Gauge boson pair production at high energy

- Gauge structure of the Standard Model
  first limits on anomalous couplings at Lep2 and Tevatron
  from angular distributions
  RunII and LHC will allow to extend the sensitivity to gauge couplings and possible anomalies
  observing the high-energy behaviour of σ_{VV}
- Background to SUSY signals

QCD effects have been widely analyzed for

$$WW,\ ZZ,\ WZ,\ W\gamma \text{ e } Z\gamma$$

and implemented in `different Monte Carlo's`

sizeable contributions in the high $M(VV)$ and $P_T(V)$ regions
proper for Anomalous Couplings analyses

`imposing a ''jet-veto'' is essential`

Recent computations at `NNLO` [Adamson, De Florian, Signer...]

Electroweak corrections ?

Tevatron: energy and statistics are too low

LHC: EW effects $\simeq$ QCD effects (jet veto)

Gauge boson pair production at high energy

ATLAS and CMS simulations have pointed out that

$$M(VV),\ P_T(V) \text{ and } \Delta y(V,l)$$

are some of the most sensitive variables to gauge couplings

In particular

$$P_T(V) \quad \rightarrow \quad \text{angular information + energy scale}$$

EW corrections increase with energy

$$log^2\left(\frac{M(VV)}{M_V}\right) \quad \text{and} \quad log\left(\frac{M(VV)}{M_V}\right)$$

but they contain also an angular dependence

$$log\left(\frac{M(VV)}{M_V}\right) \cdot log(1 \pm cos\theta_V)$$

EW radiative effects are important in the very same region where new-physics effects could show up

`the EBA` is not enough for any decent data analysis

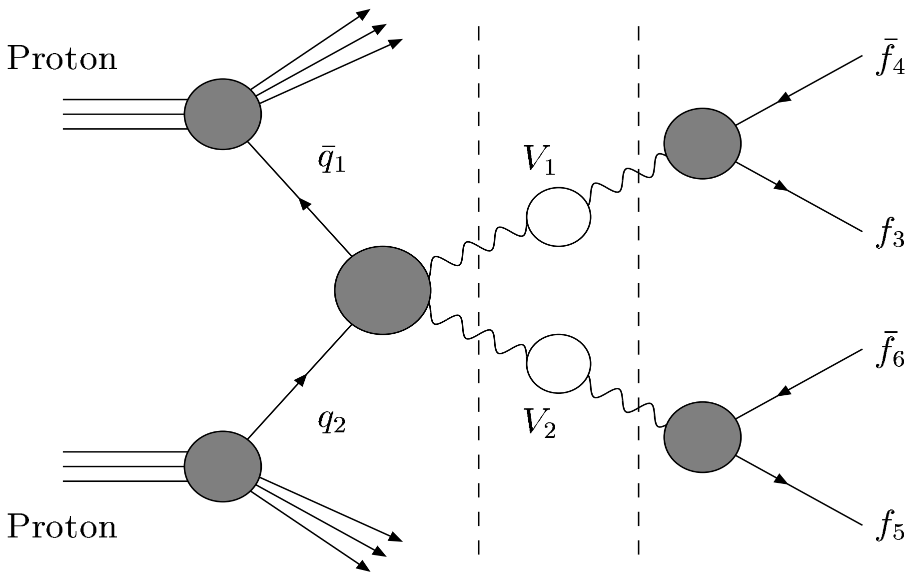
WZ, WW, and ZZ production at the LHC

structure and size of the $O(\alpha)$ EW corrections in

- $pp \to WZ + X \to l\nu_l l'\bar{l}'$
- $pp \to WW + X \to l\bar{\nu}_l \nu_{l'}\bar{l}'$
- $pp \to ZZ + X \to l\bar{l}l'\bar{l}'$

[E.A., Denner, Kaiser, Pozzorini]

as at Lep2 one can make use of the LPA

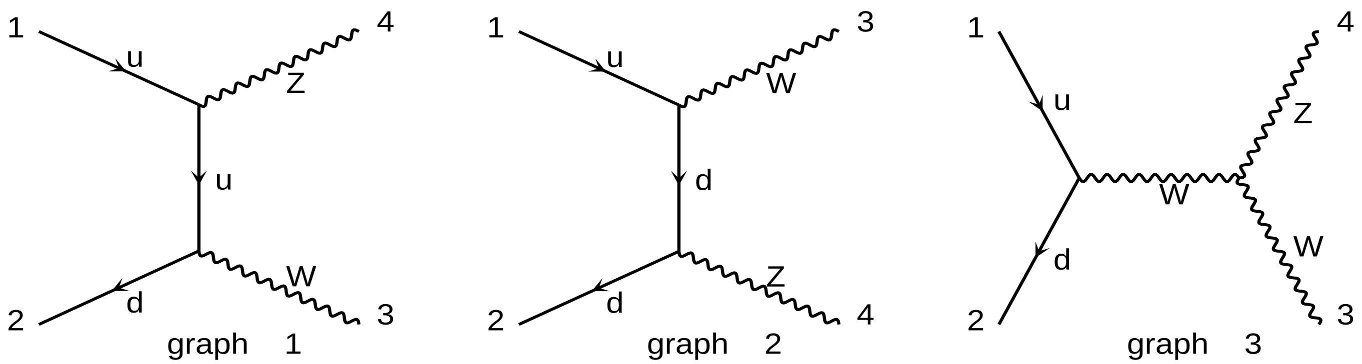


$\to$ `multi-scale processes`

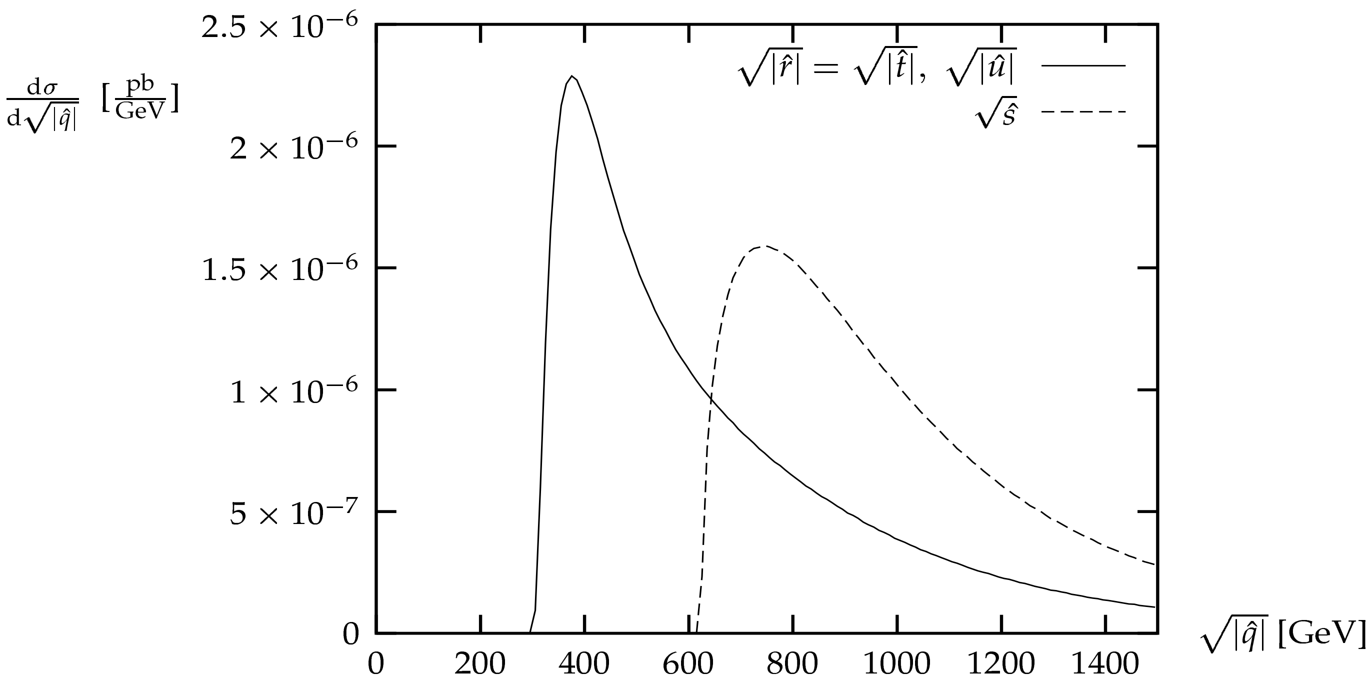
in the HE limit factorizable corrections associated to the decay $V \to f\bar{f}$ can be neglected at logarithmic level

the bulk is from $O(\alpha)$ corrections to the production process

The production processes are characterized by 2 scales

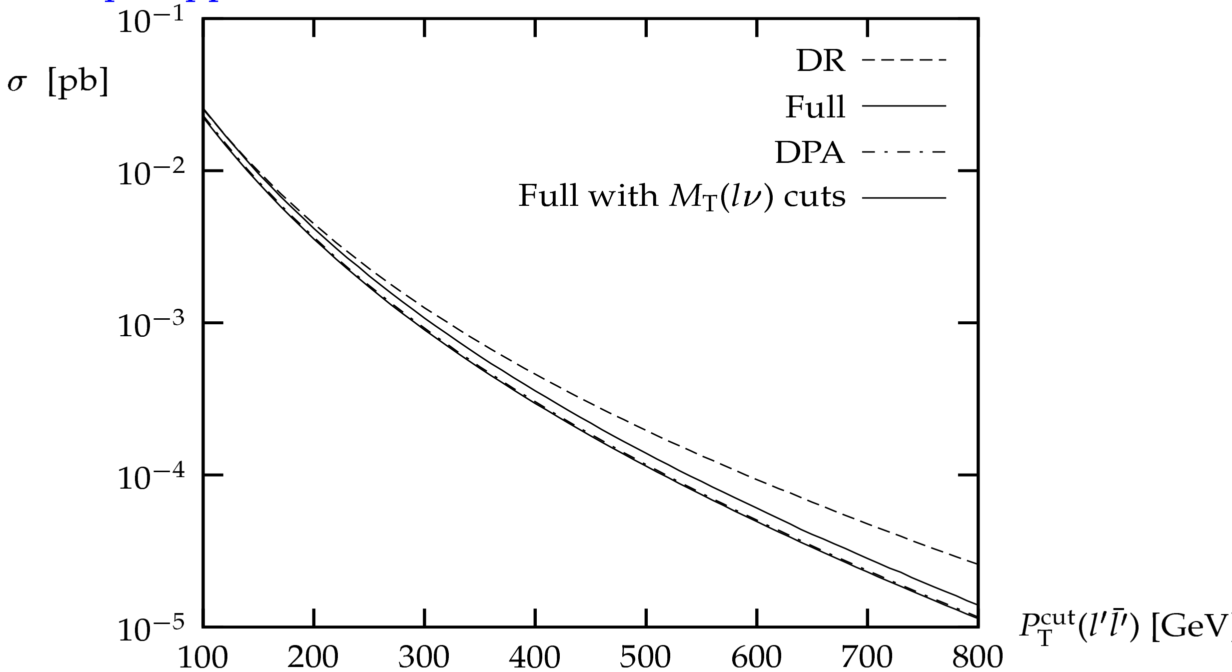


the high-energy limit $s, t, u \gg M_W^2$ must be ensured



LPA and $O(\alpha)$ result uncertainty

an example: $pp \to l\nu_l l'\bar{l}'$



heavy gauge cancellations at high $P_T^{cut}(l'\bar{l}')$

the pair-production signal definition on a diagramatic basis is not adequate anymore

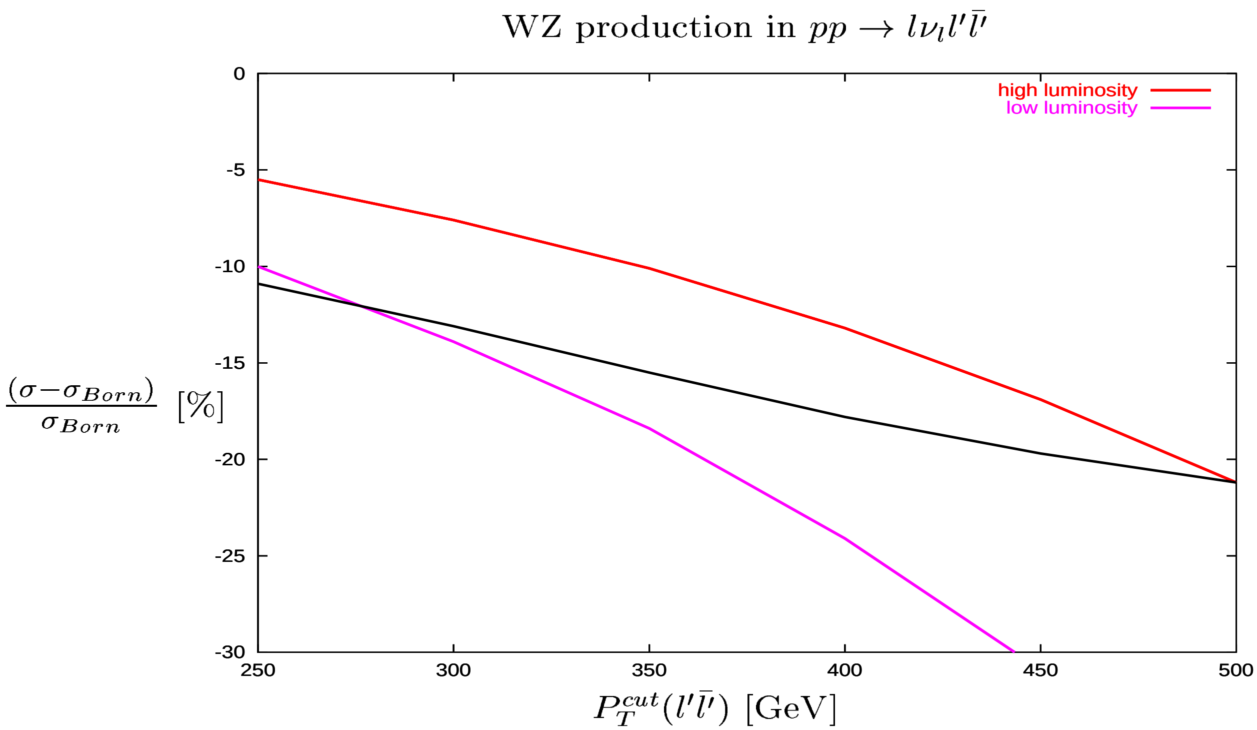
the G.I. total σ or DPA are the only observables

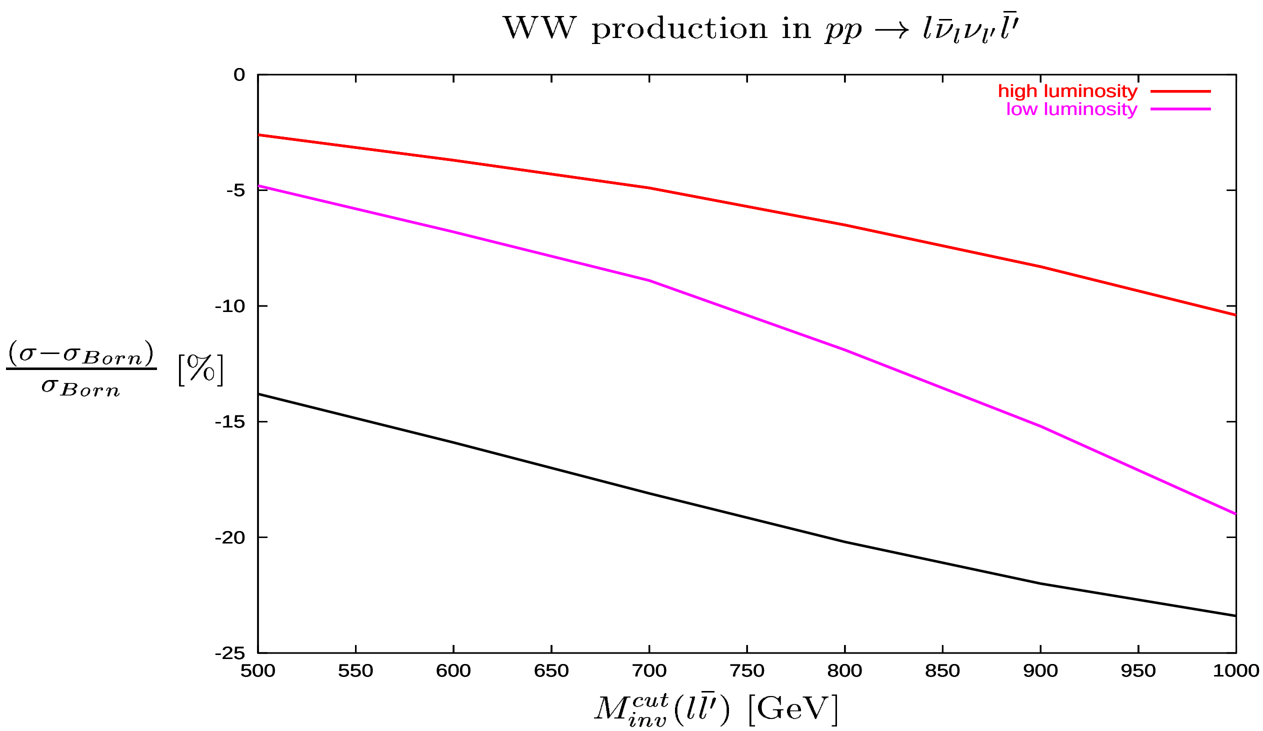
The typical difference DPA/Full $\simeq$ 15% goes down to DPA/Full $\simeq$ 1% with selection cuts

the $O(\alpha)$ result can be written as:

$$|M|^2 = |M_{Born}|^2 + 2Re\left[M_{Born,LPA}\delta M^{\dagger}_{virt,LPA}\right]$$

Statistical significance of the $O(\alpha)$ EW corrections

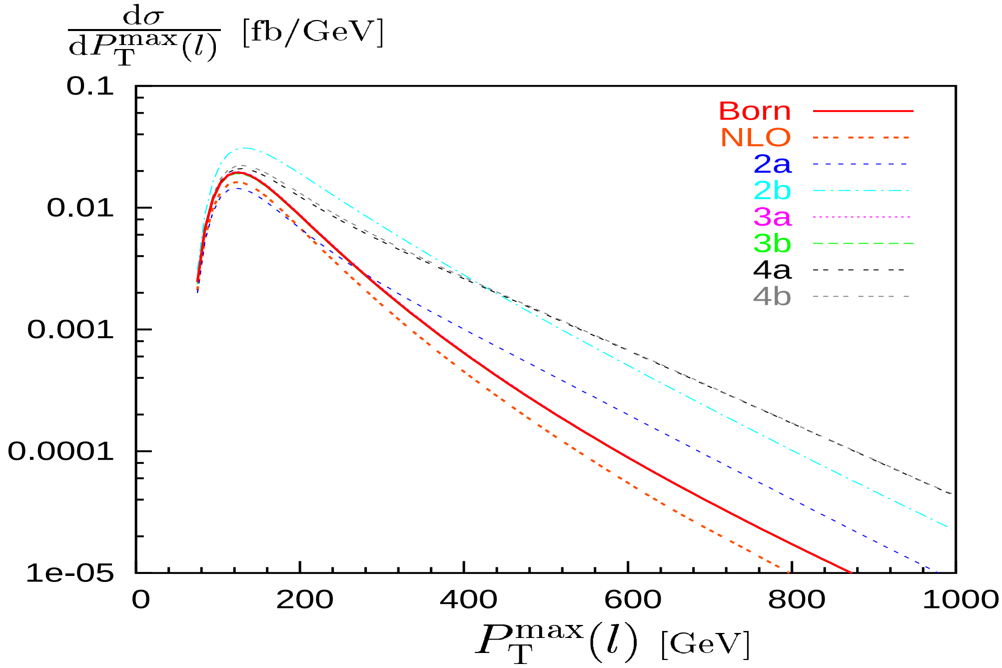


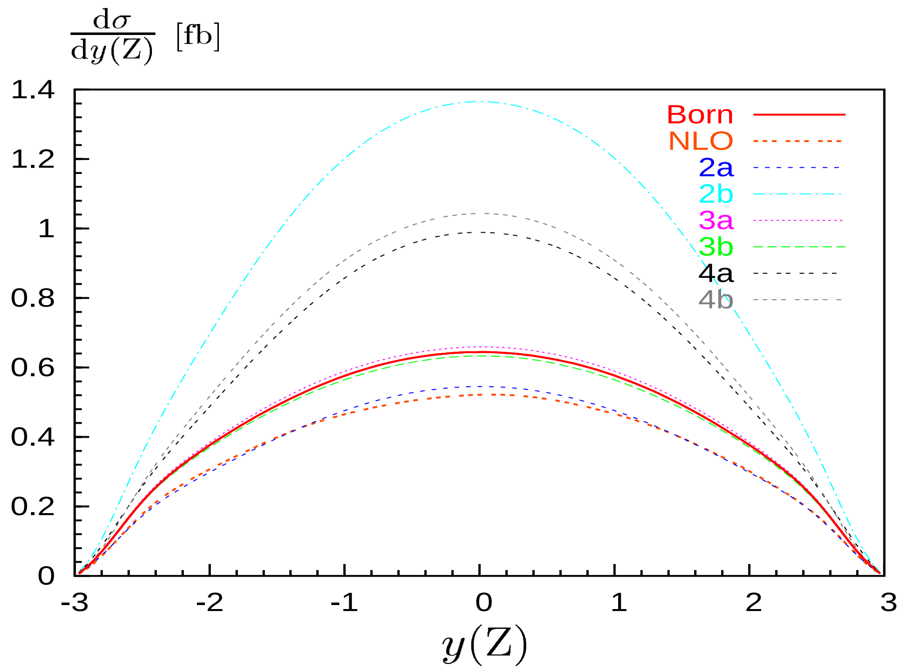


$O(\alpha)$ effects already in the first year of LHC

Impact of EW corrections

WZ production: $O(\alpha)$ effects vs anomalous TGC's

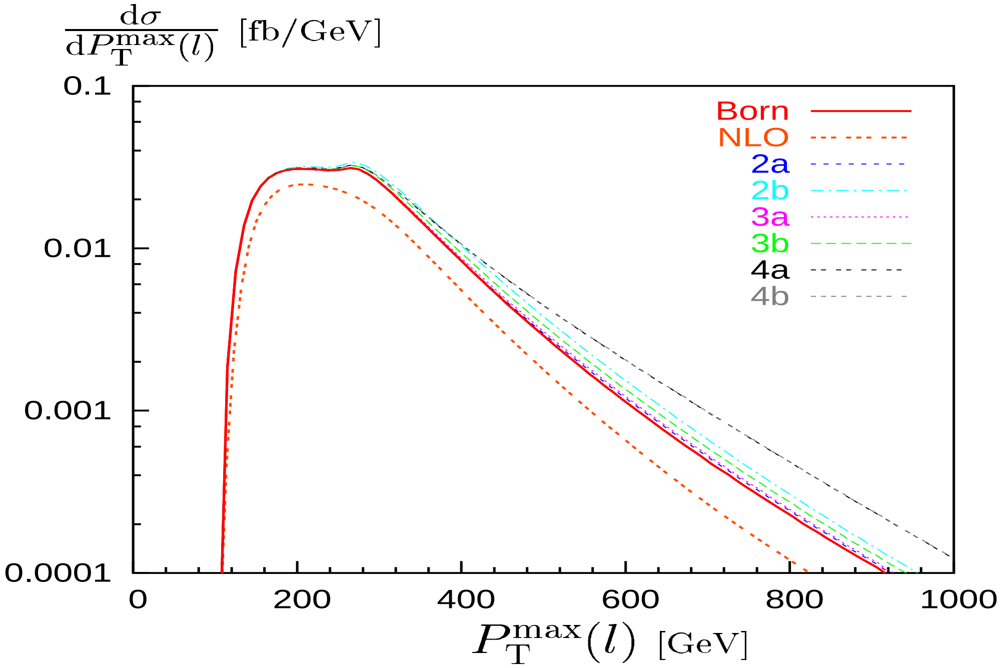


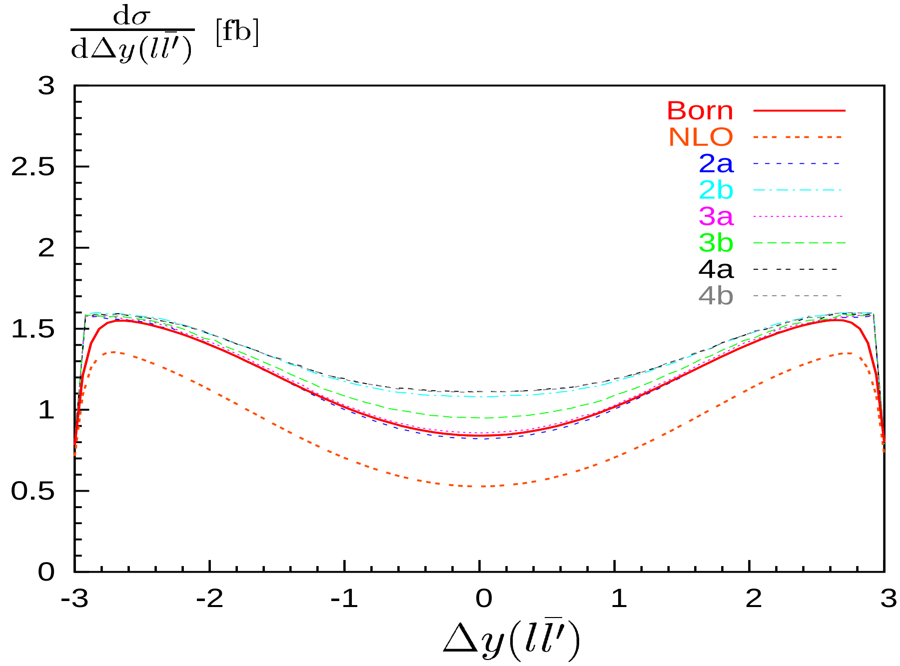


EW $O(\alpha)$ effects can fake new-physics signals

Impact of EW corrections

WW production: $O(\alpha)$ effects vs anomalous TGC's



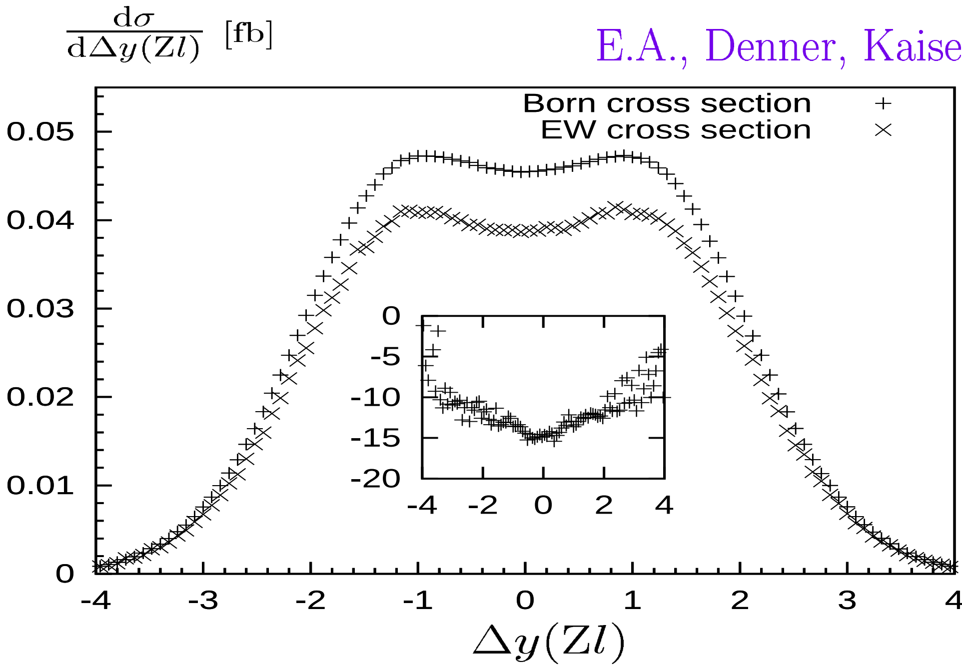


EW $O(\alpha)$ effects $\gg$ than NP signals

EW and QCD correction interplay

radiation zero: a peculiar SM prediction in $pp \to l\nu_l l'\bar{l}'$

E.A., Denner, Kaiser



Baur, Han, Ohnemus

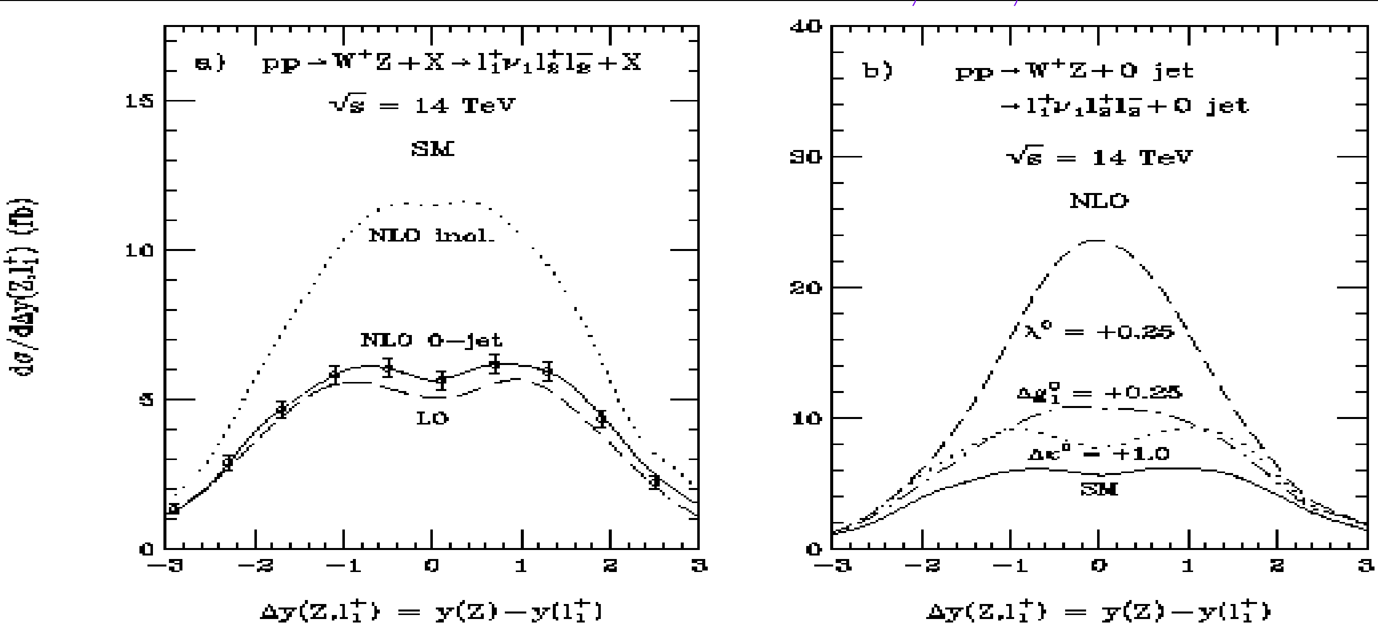


Figure 19

Strong interplay: EW corrections $\simeq$ QCD + jet veto

$W\gamma$ and $Z\gamma$ production

they have been analysed at 1-loop in

- $pp \to l\nu_l\gamma$ **[E.A., Denner, Meier]**
- $pp \to \nu\bar{\nu}\gamma$ **[Hollik, Meier, E.A., Denner]**
- $pp \to l\bar{l}\gamma$ **[Hollik, Meier, E.A., Denner]**

Total Hadronic Cross-Sections			
Process	$O(\alpha)$	High-Lum	EW effect
$\nu_l\bar{\nu}_l\gamma$	-4.5%	0.5%	$\mathbf{9}\sigma$
$l\bar{l}\gamma$	-6.7%	1.1%	$\mathbf{6}\sigma$
$\nu_l\bar{l}\gamma$	-1.9%	0.6%	$\mathbf{3}\sigma$

large impact already at low energy scales

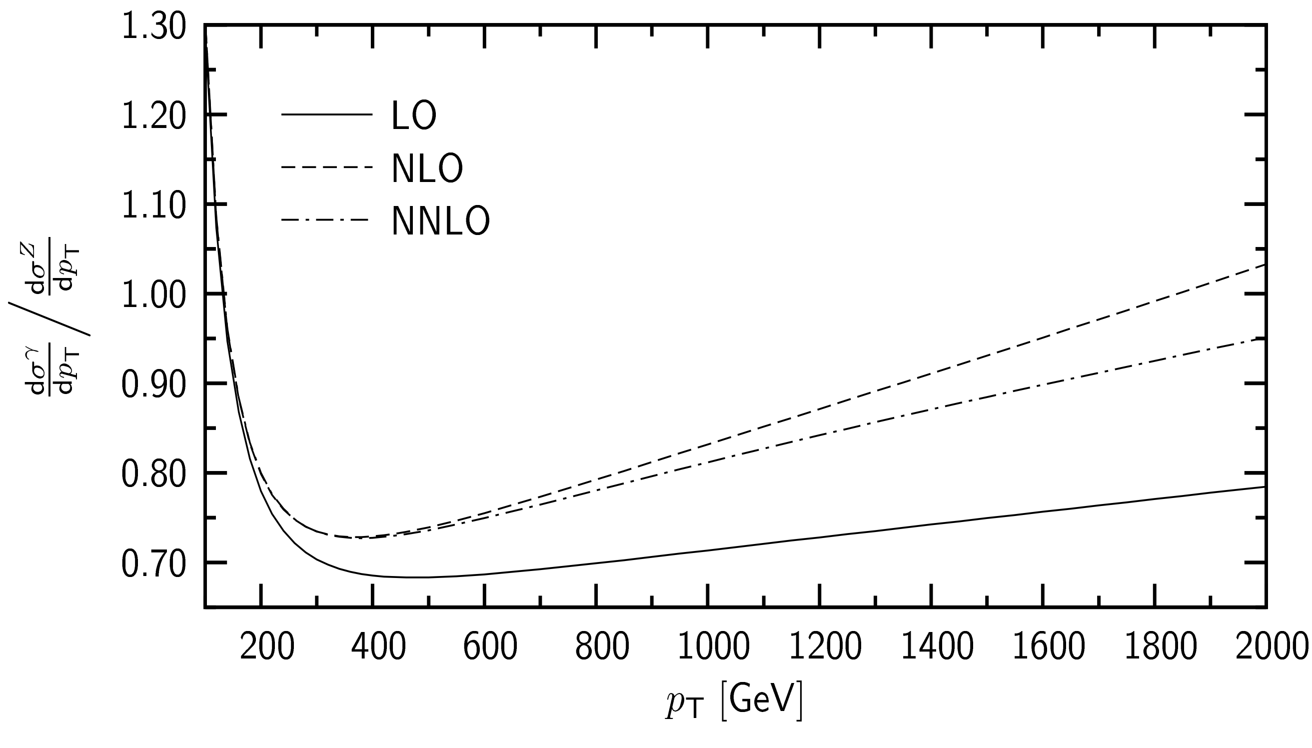
although statistically relevant, the EW $O(\alpha)$ effect

on TGC measurements has not been analysed yet!

$\gamma + j$ and $Z + j$ production

they have been analysed at 1-loop in

- $pp \to \gamma + j$ **[Kuhn, Kulesza, Pozzorini, Schulze]**
- $pp \to Z + j$ **[Maina, Moretti, Nolten, Ross]**

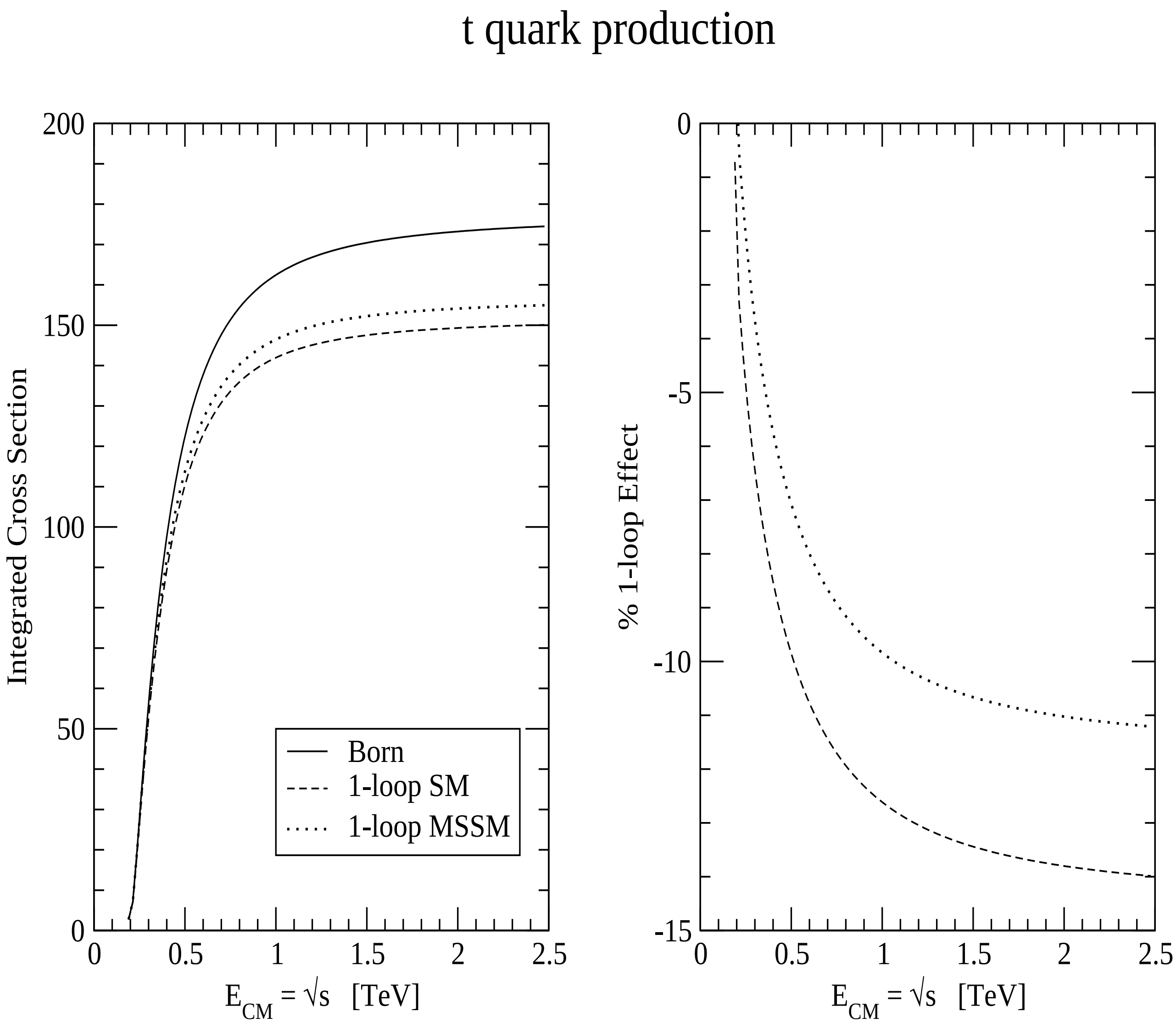


sizeable impact on hadronic observables

EW effects and Single-top production

towards a precise determination of V_{tb}

- $pp \to tq$ [Beccaria, Macorini, Renard, Verzegnassi]



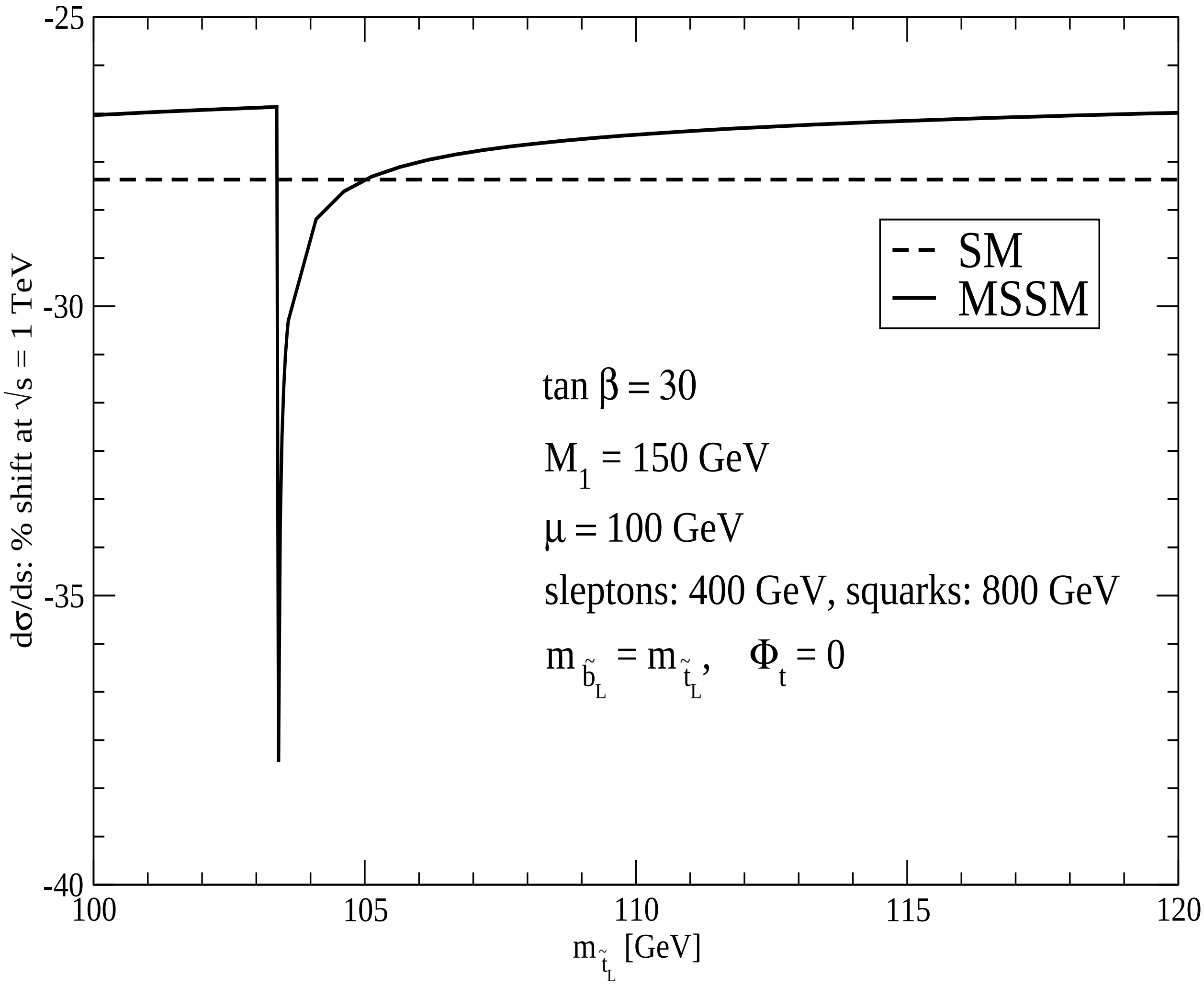
EW corrections are competitive with NLO QCD

SUSY EW effects and top production

$pp \to t\bar{t}$ [Hollik, Mosle, Kao, Wackeroth]

$pp \to tq$ [Beccaria, Macorini, Renard, Verzegnassi]

$pp \to tW$



a window to new physics

Summary and discussion hints

for theorists:

- Sudakov Logs origin and structure are well established
- also Resummation Methods have been derived

and phenomenologists:

- EW $O(\alpha)$ effects will be measurable at the LHC
- they are important for new-physics searches and precision measurements in Drell-Yang, di-boson and top processes
- their size $O(5-40\%)$ is competitive with NLO QCD

a good point [Ciafaloni and Comelli]:

- soft W/Z real emission could give a terrific enhancement to $O(\alpha)$ effects
- how much the experimental setup will cut it down?

EW radiative effects should be included for any decent data analysis

More on the method

- symmetric splitting of the virtual EW Log corrections

$$\delta_{EW} = \delta_{EW}|_{\lambda=M_W} + \left(\delta_{EW} - \delta_{EW}|_{\lambda=M_W}\right)$$

fictitious heavy γ, Z with $M = M_W$ above the weak scale
plus a 'subtracted electromagnetic' term due to $\lambda \ll M_W$

- $\mu_R^2 = s \rightarrow$ only mass-singular Logs are large

- Not mass-suppressed matrix elements

- works with physical fields

  mixing and mass gap between γ and Z

- fermions, γ, W_T, W_L, Z_T, Z_L and H

  as external particles

- Equivalence theorem

  for longitudinal gauge bosons

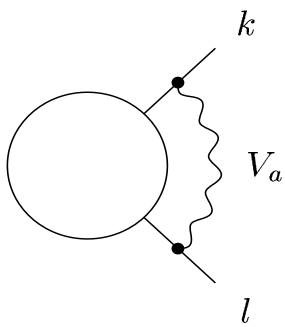
In this framework

$$M = (1 + \delta^{LSC} + \delta^{SSC} + \delta^{C} + \delta^{PR}) M_{Born}$$

- LSC contributions

when soft-collinear gauge bosons are exchanged between external pairs

$$\sum_{k=1}^{n} \sum_{l<k} \sum_{V_a = \mathrm{A,Z,W^{\pm}}}$$



$$\delta M \propto \sum_{k,l} \sum_{V_a=A,Z,W^{\pm}} I^{V_a} I^{\bar{V}_a} [log^2(\frac{|r_{kl}|}{M_W^2}) - \delta_{V_a \gamma} log^2(\frac{m_k^2}{\lambda^2})] M_{Born}$$

isolating the angular dependence

$$log^2(\frac{|r_{kl}|}{M_W^2}) = log^2(\frac{s}{M_W^2}) + 2log(\frac{s}{M_W^2}) log(\frac{|r_{kl}|}{s}) + log^2(\frac{|r_{kl}|}{s})$$

$$\delta^{LSC} = -\frac{\alpha}{8\pi} \left[C^{ew} log^2(\frac{s}{M_W^2}) + Q^2 L^{em}(s, \lambda^2, m^2) \right]$$

$$L^{em}(s, \lambda^2, m^2) \propto 2log(\frac{s}{M_W^2}) log(\frac{M_W^2}{\lambda^2}) + log^2(\frac{M_W^2}{\lambda^2}) - log^2(\frac{m^2}{\lambda^2})$$

- Subleading Soft-Collinear contributions

The angular-dependent contribution to δM

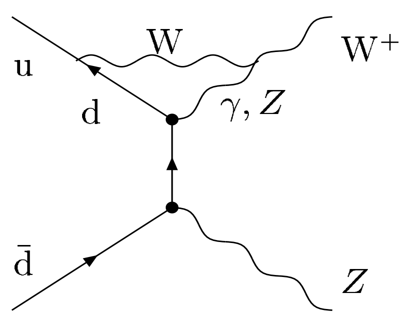
$$2log(\frac{s}{M_W^2})log(\frac{|r_{kl}|}{s}) = 2log(\frac{s}{M_W^2})log(|1 \pm cos\theta|)$$

is slightly more complicated

For neutral gauge boson exchange

$$\delta^{SSC} M \propto \sum_{V_a=A,Z} 2I^V I^{\bar{V}} \left[log(\frac{s}{M_W^2}) + log(\frac{M_W^2}{M_{V_a}^2})\right] log(\frac{|r_{kl}|}{s}) M_{Born}$$

For charged gauge boson exchange



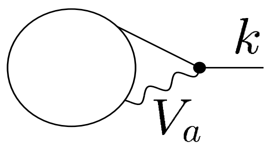
$$\delta_W^{SSC} M \propto$$

$$\left[I_\gamma^+ M_{Born}^{\bar{d}d\to\gamma Z} + I_Z^+ M_{Born}^{\bar{d}d\to ZZ} + I_Z^+ M_{Born}^{\bar{u}u\to W^+W^-}\right] log\left(\frac{s}{M_W^2}\right) log\left(\frac{|t|}{s}\right)$$

- Collinear and Soft SL contributions

from field renormalization and mass-singular loop diagrams with collinear virtual gauge bosons emitted by an external leg

$$\sum_{V_a=\mathrm{A,Z,W^{\pm}}}$$



$\rightarrow$ coll. limit $\rightarrow$ $\delta^{coll} M_{Born}$

factorization has been proven [Denner and Pozzorini]

$$\delta^C M = \sum_k [\delta^{coll} + FRC] M_{Born}$$

very compact expressions for fermions, W's, Z's, γ and H

$$\delta^C \propto \alpha \left[\{C^{ew}, b^{ew}\}\, log(\tfrac{s}{M_W^2}) + Q^2 l^{em} \right]$$

$$l^{em} \propto log(\tfrac{M_W^2}{m^2}) + log(\tfrac{M_W^2}{\lambda^2})$$

- SL connected to parameter renormalization

related to UV divergences

$$\delta^{PR} M = \frac{\delta M}{\delta e}\delta e + \frac{\delta M}{\delta c_w}\delta c_w + \frac{\delta M}{\delta h_t}\delta h_t + \frac{\delta M}{\delta h_H}\delta h_H |_{\mu^2=s}$$

$h_t = m_t/M_W$ and $h_H = M_H^2/M_W^2$