Searching for new phenomena via the SMEFT approach at present and future colliders

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Context

New colliders to probe SM and go beyond

Two options :

- Giant hadron collider : highest energy
- Muon collider : higher energy than electron one, cleaner signals than with hadrons

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Effective theory

Key idea

Physics occurring at a certain energy or length scale can be described without the need of knowledge about physics occurring at a very different scale.

Example : motion of planets described with classical mechanics, approximation of special relativity when $v \ll c$

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Physics occurring at a certain energy or length scale can be described without the need of knowledge about physics occurring at a very different scale.

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Effective theory $\rightarrow$ full theory at a certain scale

Effective field theory $\leftrightarrow$ quantum field theory

Advantages of the EFT formalism :

- Effective theories formalism provides simpler expressions
- Both effective and full theory describe the same physics
  $\rightarrow$ they are not different theories
- Expressed as a series : by keeping more terms one can obtain results as close as needed from the full theory

Standard Model Effective Field Theory (SMEFT)

Effective theory applied to the whole Standard Model

SM :

- Fields implied in the theory
- Symmetries these fields must satisfy
- How these symmetries might be broken
- Renormalizability to provide physics predictions up to arbitrarily high energies

$\rightarrow$ Only relevant and marginal operators

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SMEFT :

- Fields implied in the theory
- Symmetries these fields must satisfy
- How these symmetries might be broken
- ~~Renormalizability to provide physics predictions up to arbitrarily high energies~~

$\rightarrow$ Can contain irrelevant operators

SMEFT Lagrangian

$$\mathcal{L} = \mathcal{L}_{\mathrm{SM}} + \frac{1}{\Lambda}\sum_{i=1}^{N_{d5}} c_i^{(5)}\mathcal{O}_i^{(5)} + \frac{1}{\Lambda^2}\sum_{i=1}^{N_{d6}} c_i^{(6)}\mathcal{O}_i^{(6)} + \frac{1}{\Lambda^3}\sum_{i=1}^{N_{d7}} c_i^{(7)}\mathcal{O}_i^{(7)} + \dots$$

$\mathcal{O}_i^{(d)}$: mass-dimension d operator
$c_i^{(d)}$: Wilson coefficient associated to the i-th mass-dimension d operator $\rightarrow$ coupling constant
Λ : cut-off scale $\rightarrow$ scale of new physics

SMEFT Lagrangian

Pure SM Pure SMEFT

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- Usually in the order of the TeV $\rightarrow$ terms quickly highly suppressed
- Mass-dimension 5 operators : few, do not respect baryon and lepton number conservation $\rightarrow$ usually not taken into account

$$\mathcal{L} = \mathcal{L}_{\mathrm{SM}} + \frac{1}{\Lambda^2} \sum_{i=1}^{N_{d6}} c_i^{(6)} \mathcal{O}_i^{(6)}$$

Z' model :

- Gauge group : $SU(3)_{SM} \times SU(2)_{SM} \times U(1)_{SM} \times U(1)_{B\text{-}L}$
- New Abelian gauge field couples via the $U(1)_{B\text{-}L}$ symmetry to all particles carrying a B-L charge $\rightarrow$ Z'

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W' model :

- Gauge group : $SU(3)_{SM} \times SU(2)_{SM} \times U(1)_{SM} \times SU(2)_{L}$
- Additional $SU(2)_L = SU(2)_{SM} \rightarrow$ W'

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Mathematica

Used for analytical cross section calculation in this work.

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- Create models, derive Feynman rules $\rightarrow$ *FeynRules*

MadGraph

Particle collisions simulator
Goal : obtain cross sections, but not only (Feynman diagrams, final state particles angular distribution, histograms)

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Particle collisions simulator
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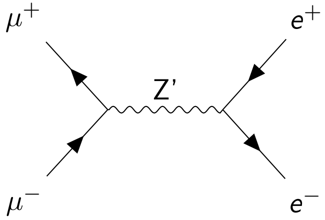
- Process generation : `generate mu+ mu- > z > e+ e-`
- `param_card.dat` : physics parameters (masses, decay widths)
- `run_card.dat` : run parameters (number of events, beam energies)
- Monte Carlo integral coupled to analytical computation

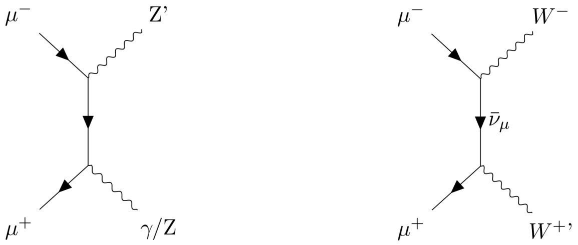
Direct probe

One way to find particles at colliders $\rightarrow$ produce them via a s-channel. The best way to do so is then to use an accelerator with an energy equal to the mass of the particle searched, to benefit from the high cross section of the resonance.



Radiative return

Second boson emitted from one of the inital state particles, balancing the total energy for the heavy vector boson to be still produced on shell, and thus with the highest cross section.



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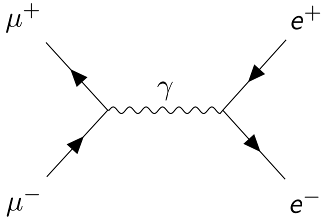
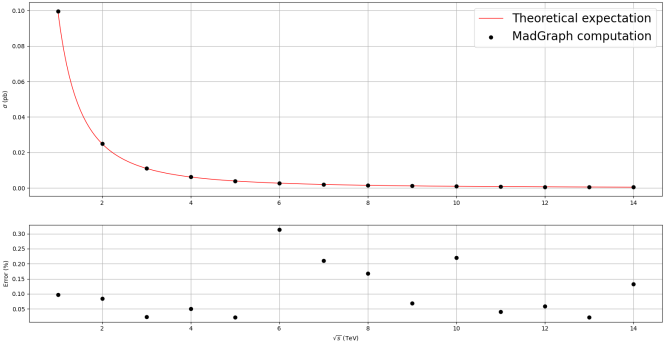
First goal : implement cross sections calculations with Mathematica and MadGraph for simple processes

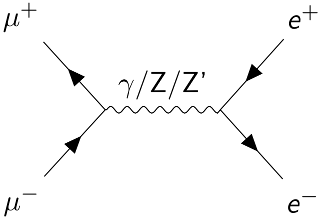


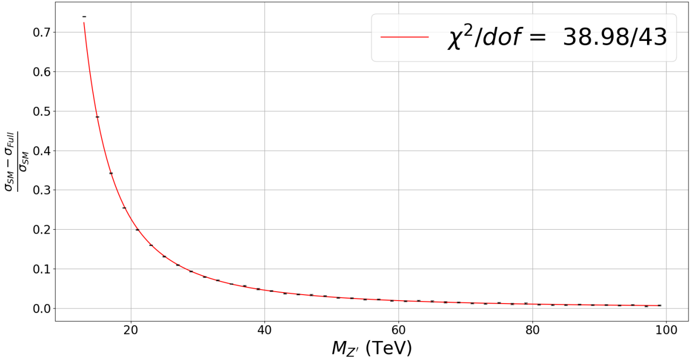
Very similar results with Z and Z'



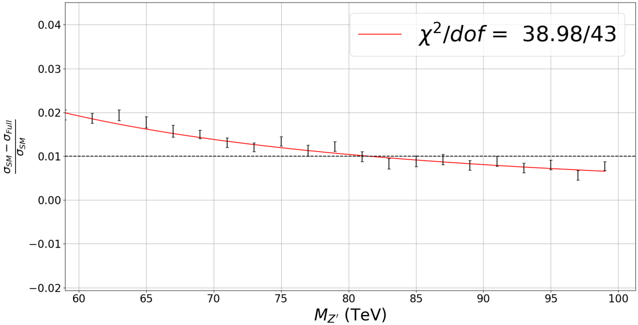
Consistent with MadGraph relative uncertainties : typically around 0.25%

Goal : compare SM cross section with Z' model one, for various Z' masses





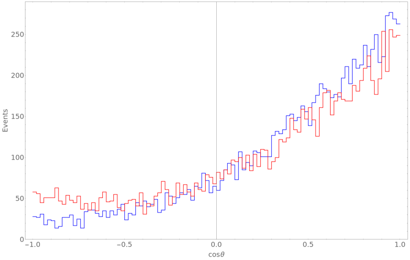
$$\text{Fit}: \frac{\sigma_{SM}-\sigma_{Full}}{\sigma_{SM}} = 10115\frac{1}{{M_{Z'}}^4} + 64.565\frac{1}{{M_{Z'}}^2} + 0.00093568$$



- Simple expression for the cross section behaviour
- Significant difference observed between SM and Z' model : more than 1% up to $m_{Z'} \sim 80$ TeV

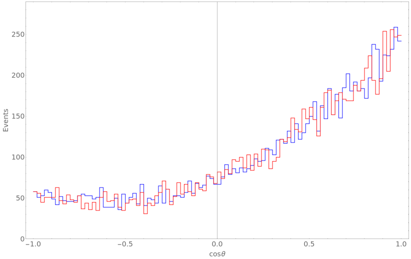
Final state particles angular distribution

Other observable that can be probed with MadGraph



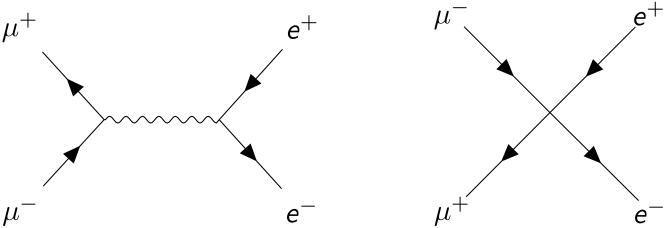
$m_{Z'} = 15$ TeV

Different shape : between 40 and 60% more events in SM case in the $cos(\theta) region \in [-1, -0.8]$

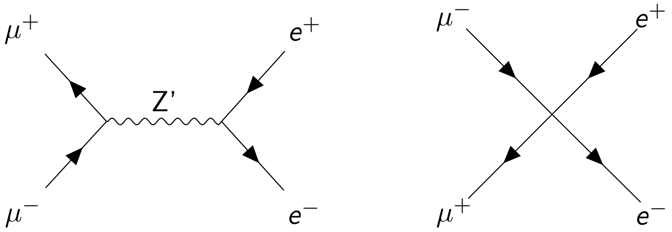


$m_{Z'} = 80$ TeV

No more difference than between two SM runs



$$\mathcal{L}_{SMEFT} = \frac{Q_{ll}}{\Lambda^2}(\overline{e_s}\, e_s)_L(\overline{\mu}\, \mu)_L + \frac{Q_{ee}}{\Lambda^2}(\overline{e_s}\, e_s)_R(\overline{\mu}\, \mu)_R + \frac{Q_{le}}{\Lambda^2}(\overline{e_s}\, e_s)_L(\overline{\mu}\, \mu)_R + \frac{Q_{le}}{\Lambda^2}(\overline{e_s}\, e_s)_R(\overline{\mu}\, \mu)_L$$



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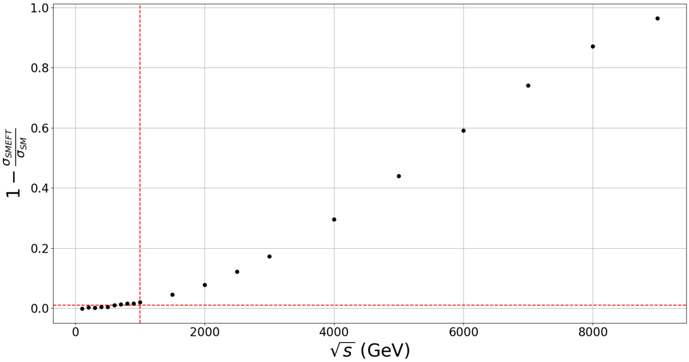
$$Q_{ll} = Q_{le} = Q_{ee} = (g_1')^2$$

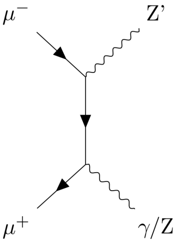
$$\Lambda = m_{Z'}$$

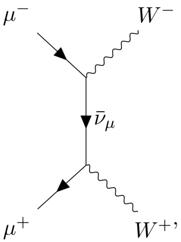
$$g_1{}' = 0.2,\ m_{Z'} = \Lambda = 10\ \text{TeV}$$



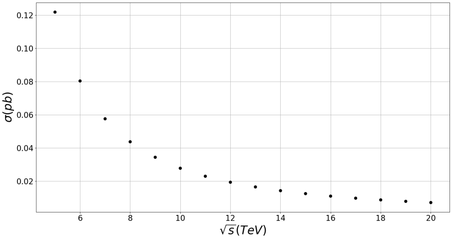
Work still in progress

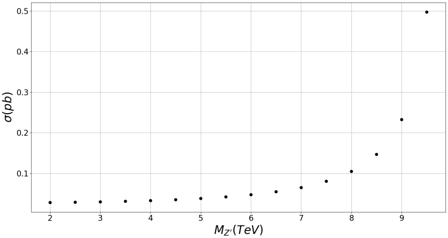
Goal : understand the behaviour of the cross section, obtain simple analytical expressions



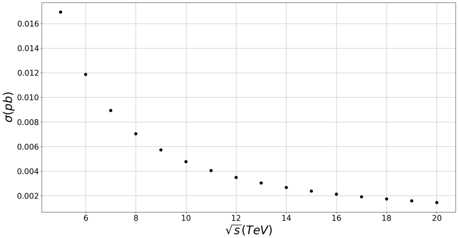


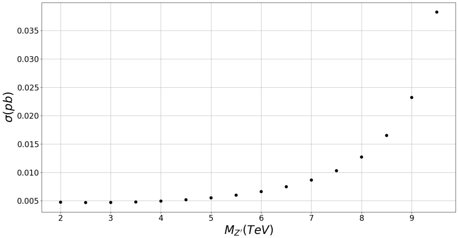
$\mu^+ \mu^- \to Z' \gamma$



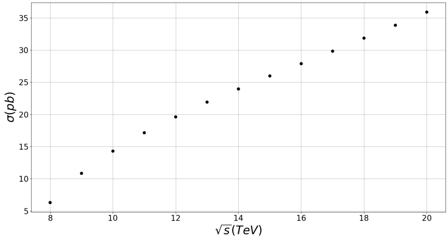


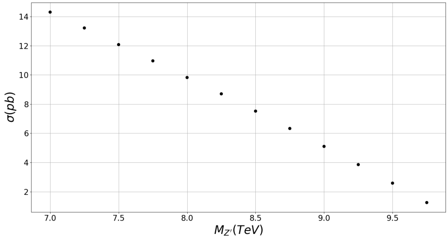
$\mu^+ \mu^- \to Z' Z$


0.016
0.014
0.012
0.010
0.008
0.006
0.004
0.002
σ(pb)
6
8
10
12
14
16
18
20
√s(TeV)

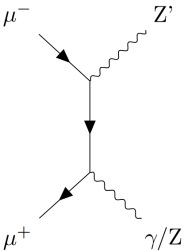

0.035
0.030
0.025
0.020
0.015
0.010
0.005
σ(pb)
2
3
4
5
6
7
8
9
M_{Z'}(TeV)

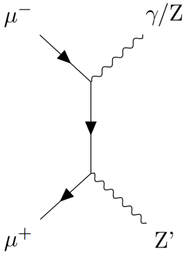
$\mu^+ \mu^- \to W^{-\prime}\ W^+$

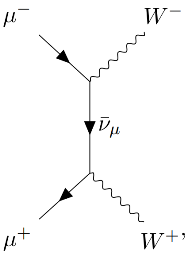




Very different behaviour between W' and Z' processes







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Obtained results

- Implementation : not a result in itself, but necessary (and long) $\rightarrow$ to get used to MadGraph and Mathematica, and be sure everything is properly set up
- Direct probe : two tools to probe Z' signatures : cross section and angular distribution $\rightarrow$ up to $\sim$80 TeV with cross sections, for lighter masses with angular distributions
  Indicates that a 10 TeV muon collider might be an appropriate tool to probe such a model
- SMEFT description of $\mu^+ \mu^- \rightarrow e^+ e^-$

Last month of work

Goals :

- Understand the behaviour of radiative return processes cross sections, obtain simple analytical expressions
- Fix unitarity violating behaviour of W' process : one idea would be to add a new fermion to the model to obtain another diagram, interfering with the current one
- Investigate heavy vector triplet model, in which both neutral and charged heavy particles are considered

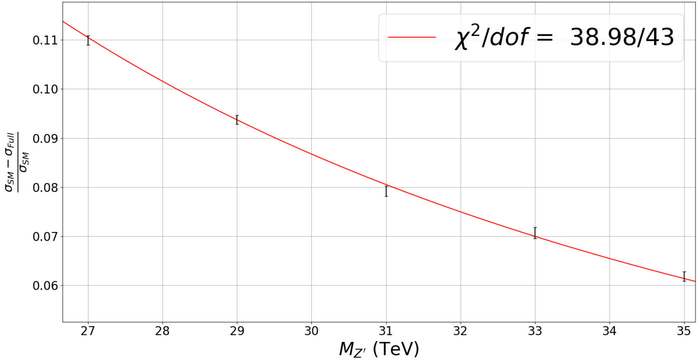
Perspectives

Long term study

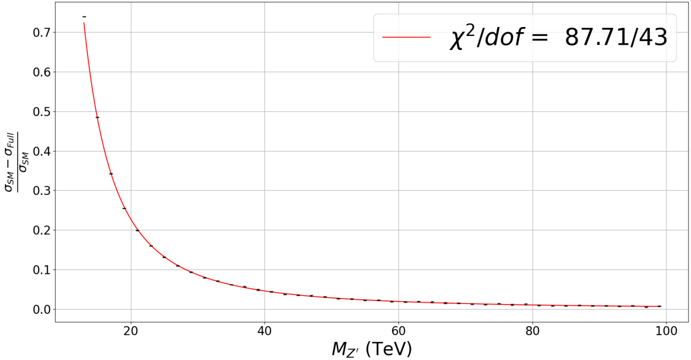
- Here, results at parton level $\rightarrow$ give a good idea but would be interesting to pursue the study with detector level simulation
- Same kind of study with proton collisions simulations (LHC, FCC-hh) $\rightarrow$ comparison to determine which collider would be more relevant

Thank you for your attention !

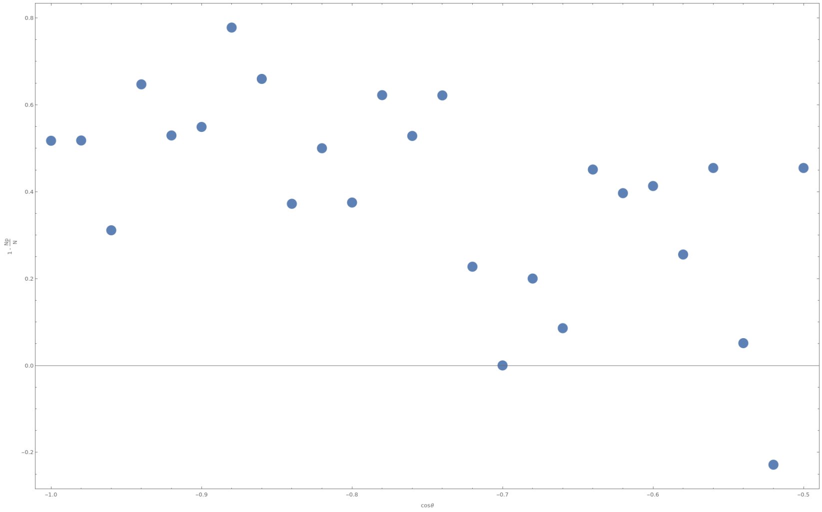
Appendix : Zoom on uncertainties



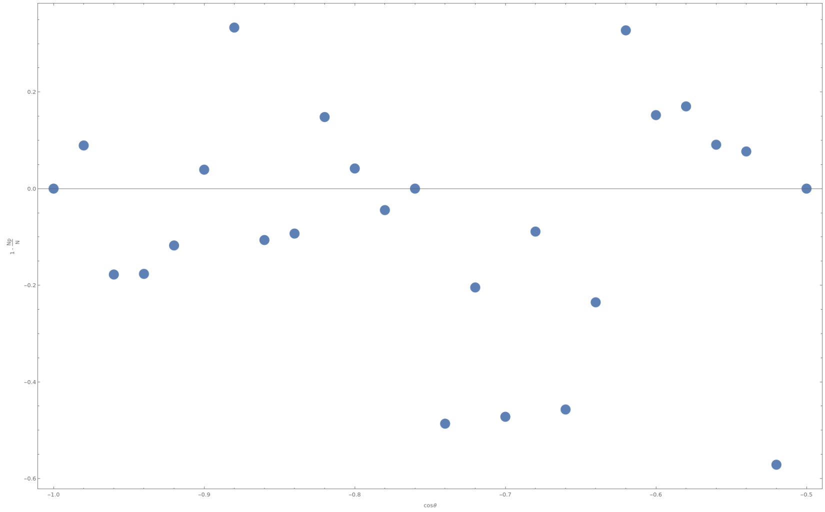
Appendix : Non corrected uncertainties



Appendix : Difference 15 TeV Z'



Appendix : Difference 80 TeV Z'

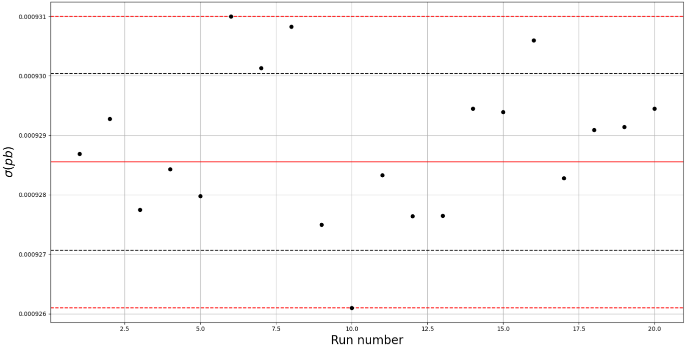


Appendix : MadGraph uncertainties

- Purely statistical (Monte Carlo)
- MadGraph provides uncertainties with results, known to be underestimated

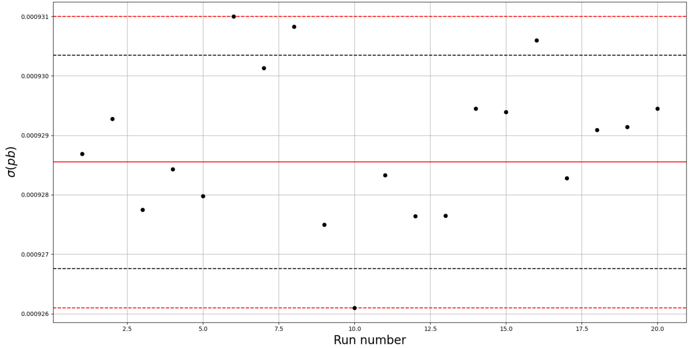
Appendix : MadGraph uncertainties

Mean provided uncertainties $\rightarrow$ factor $\simeq$1.65



Appendix : MadGraph uncertainties

Max provided uncertainties → factor ≃1.36



Appendix : MadGraph uncertainties

All studied processes were tested this way (using the mean provided uncertainty) $\rightarrow$ factor between $\simeq$1.3 and $\simeq$1.7
Consistent with what is known

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Consistent with what is known

Two ways of dealing with MadGraph uncertainties :

- Run each process several times and use the actual statistical fluctuation observed
- Use provided ones and correct them by an adequate factor

Appendix : EFT computation example

System : two charges of same magnitude and opposite signs, one located in x=0, the other in x=a

$$V_{full}(x) = Q\left(\frac{1}{|x|} - \frac{1}{|x-a|}\right)$$

$$x \gg a \rightarrow V_{full}(x) = \frac{Q}{x}\left(1 - \frac{1}{1-\frac{a}{x}}\right) = \frac{Q}{x}\sum_{n=1}^{\infty}\left(\frac{a}{x}\right)^n$$

$$V_{EFT}(x) = \frac{Qa}{x^2}$$

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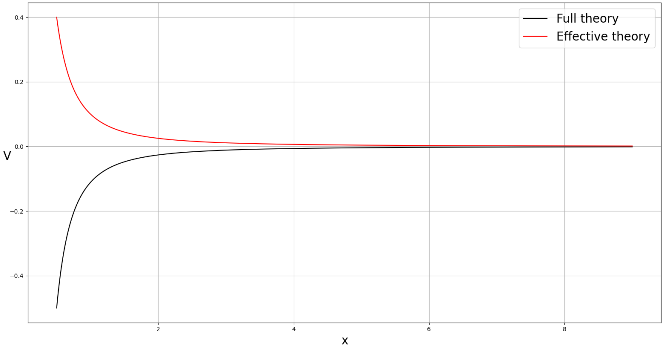

Appendix : Z' model

Gauge group : $SU(3)_{SM} \times SU(2)_{SM} \times U(1)_{SM} \times U(1)_{B\text{-}L}$

Additional content to SM :

- one Abelian gauge field
- one SM singlet scalar field
- Three right-handed neutrinos (necessary to cancel the appearing anomalies)

The Abelian gauge field couples via the $U(1)_{B\text{-}L}$ symmetry with a strength g'_1 to all particles carrying a B-L charge $\rightarrow$ Z'

Appendix : Z' model

Gauge group : $SU(3)_{SM} \times SU(2)_{SM} \times U(1)_{SM} \times U(1)_{B\text{-}L}$

Why this model is appealing :

- Anomaly-free gauge theory
- Few added parameters : $m_{Z'}$, g'_1, masses of the right-handed neutrinos

Appendix : W' model

Gauge group : two possibilities :
$SU(3)_{SM} \times SU(2)_{SM} \times U(1)_{SM} \times SU(2)_{L}$
$SU(3)_{SM} \times SU(2)_{SM} \times U(1)_{SM} \times SU(2)_{R}$

$$\mathcal{L} = \frac{g}{\sqrt{2}} \bar{f}_i \gamma_\mu \left(C^R_{f_i f_j} P_R + C^L_{f_i f_j} P_L \right) W' f_j + h.c.$$

Appendix : W' model

Gauge group :
$SU(3)_{SM} \times SU(2)_{SM} \times U(1)_{SM} \times SU(2)_{L}$

Why this model is appealing :

- Anomaly-free gauge theory
- Few added parameters : $m_{W'}$, couplings (LH, RH, quarks, leptons), mixing angle between W and W' $\rightarrow$ small and usually set to 0
- One Lagrangian, close to SM one, describing all possibilities of the model

Appendix : σ computation (FC)

Same structure as for hand-calculation. First step : draw Feynman diagram(s) and derive the matrix element.

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`InsertFields` : distribute fields over the topology
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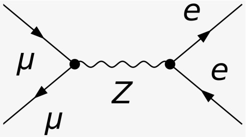


Appendix : σ computation (FC)

The next step is to obtain the matrix element squared.

`FCFAConvert` : obtain a matrix element expression compatible with FeynCalc
`SetMandelstam` : $s = (p_1 + p_2)^2$, $t = (p_1 - k_1)^2$, $u = (p_1 - k_2)^2$, $s + t + u = m_\mu^2 + m_\mu^2 + m_e^2 + m_e^2$
`ComplexConjugate` : to multiply the matrix element by its complex conjugate and obtain the matrix element squared
`FermionSpinSum` : perform Dirac trace technique

Appendix : σ computation (trace)

- Matrix element squared $\rightarrow$ sum over each polarity
- Separate each spinor / Dirac matrix in individual matrices
- $\sum_{s_1} [u_1]_j [\bar{u_1}]_k = [\not{p}_1 + m_1]_{jk}$
- $[\ldots]_{ii} \rightarrow Tr(\ldots)$

Result : matrix element squared expressed with gamma traces

Appendix : σ computation (trace)

$$\text{Tr}\left(\gamma^\mu\right) = 0$$
$$\text{Tr}\left(\gamma^\mu\gamma^\nu\right) = 4\eta^{\mu\nu}$$
$$\text{Tr}\left(\gamma^\mu\gamma^\nu\gamma^\rho\gamma^\sigma\right) = 4\left(\eta^{\mu\nu}\eta^{\rho\sigma} - \eta^{\mu\rho}\eta^{\nu\sigma} + \eta^{\mu\sigma}\eta^{\nu\rho}\right)$$
$$\text{Tr}\left(\gamma^5\right) = \text{Tr}\left(\gamma^\mu\gamma^\nu\gamma^5\right) = 0$$
$$\text{Tr}\left(\gamma^\mu\gamma^\nu\gamma^\rho\gamma^\sigma\gamma^5\right) = -4i\epsilon^{\mu\nu\rho\sigma}$$
$$\text{Tr}\left(\gamma^{\mu_1}\ldots\gamma^{\mu_n}\right) = \text{Tr}\left(\gamma^{\mu_n}\ldots\gamma^{\mu_1}\right)$$

Trace of any product of an odd number of γ^μ is zero
Trace of γ^5 times a product of an odd number of γ^μ is still zero

Appendix : σ computation (FC)

$2 \rightarrow 2$ process :

$$d\sigma = \frac{1}{64\pi^2 s}\frac{|\overrightarrow{p_f}|}{|\overrightarrow{p_i}|}|\overline{\mathcal{M}}|^2 dcos(\theta^*)d\varphi$$

$$t = \frac{-s}{2}(1 - cos(\theta^*)), u = \frac{-s}{2}(1 + cos(\theta^*))$$

Integration over $dcos(\theta^*)$ and $d\varphi$:

$$\sigma = \frac{\mathrm{e}^4 s \left(8\left(\sin\left(\theta_W\right)\right)^4 - 4\left(\sin\left(\theta_W\right)\right)^2 + 1\right)^2}{768\pi\left(\cos\left(\theta_W\right)\right)^4\left(s - m_Z^2\right)^2\left(\sin\left(\theta_W\right)\right)^4}$$

Appendix : σ computation (MG)

```
(> import model modelname)
 > generate mu+ mu- > z > e+ e-
 > launch
```

Appendix : σ computation (MG)

`param_card.dat` : physics parameters (masses, decay widths...)
`run_card.dat` : run parameters (number of events, beam energies...)

```
> set ebeam1 5000
> set ebeam2 5000
> set no_parton_cut
```

Result (10 000 events) : `0.0001245 +- 3.594e-08 pb`

Appendix : σ computation (comparison)

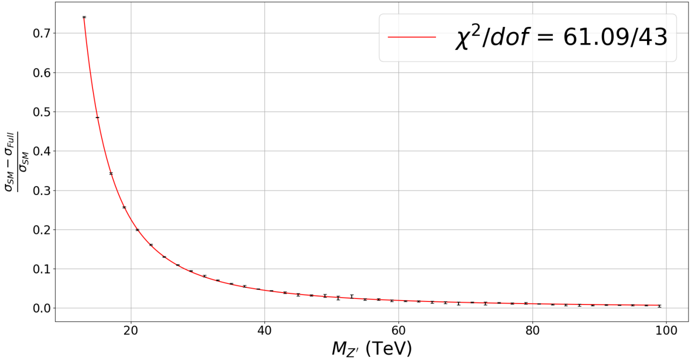
MadGraph result (10 000 events) : 0.0001245 +- 3.594e-08 pb
Mathematica result, using same parameter values : 0.000124359 pb

$$\frac{0.0001245 - 0.000124359}{0.000124359} \simeq 0.11\%$$

$\rightarrow$ consistent with MadGraph uncertainties (discussion about them in the results part)

Appendix : Several runs uncertainties

Uncertainties : 5 runs for each point, uncertainties taken as the gap between extremal values



Fit : $\frac{\sigma_{SM} - \sigma_{Full}}{\sigma_{SM}} = 10017 \frac{1}{{M_{Z'}}^4} + 65.329 \frac{1}{{M_{Z'}}^2} + 0.00044129$

Appendix : sigma error plot