FCC-ee:
Search for an heavy charged Higgs boson

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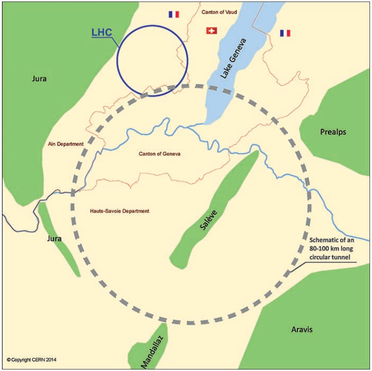
May 26, 2020

Outline

- Introduction to FCC-ee.
- Extensions of the Higgs sector.
- Description of the tools and procedure for Event generation.
- Status of the MC production.

- The ultimate goal for the next generation of circular colliders at CERN is a 100 TeV proton-proton collider.

- The FCC-ee (Previously named TLEP) is a e^+e^- circular collider foreseen in a new 80 km tunnel in Geneva.



Phase	Run Duration	CM Energy (GeV)	Integrated Luminosity (ab^{-1})	Event Statistics
FCC-ee-Z	4 years	88-95	150	3×10^{12} visible Z decays
FCC-ee-W	2 years	158-162	12	10^8 WW events
FCC-ee-H	3 years	240	5	10^6 ZH events
FCC-ee-tt	5 years	365	1.5	10^6 t events

Extension of the Higgs Sector

- We are interested in the Minimal SuperSymmetric Standard model (MSSM).
- The scalars and their complex conjugates belong to multiplets of opposite chiralities $\rightarrow$ Single Higgs doublet is not enough for mass generation $\rightarrow$ Additional doublet is added (Two Higgs Doublets Model (2HDM)).
- Extended Higgs Sector:
  $\rightarrow$ 2 doublets of complex scalar fields:

$$\phi_1 = \begin{pmatrix} \phi_1^+ \\ \phi_1^0 \end{pmatrix}, \phi_2 = \begin{pmatrix} \phi_2^0 \\ \phi_2^+ \end{pmatrix}$$

  $\rightarrow$ 2 × 2 × 2 = 8 d.o.f.

  $\rightarrow$ left with 5 physical d.o.f.: h^0, A^0, H^0, H^+, H^- .
- Type II 2HDM the $Q = 2/3$ RH quarks couple to ϕ_2 and the $Q = -1/3$ RH quarks couple to ϕ_1.

Georgi-Machacek (GM) Model

- Higgs bidoublet and two isospin-triplets in a bitriplet:

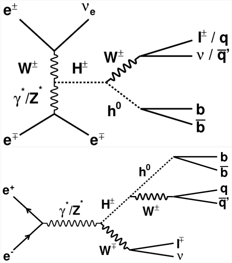
$$\phi = \begin{pmatrix} \phi^{0*} & \phi^{+} \\ -\phi^{+*} & \phi^{0} \end{pmatrix}$$

$$X = \begin{pmatrix} \chi^{0*} & \xi^{+} & \chi^{++} \\ -\chi^{+*} & \xi^{0} & \chi^{+} \\ \chi^{++*} & -\xi^{+*} & \chi^{0} \end{pmatrix}$$

- Physical spectrum: Custodial symmetry fixes almost everything !
  $SU(2)_L \times SU(2)_R \rightarrow SU(2)_{custodial}$:
  $\rightarrow$ Custodial singlets mix $\rightarrow h^0, H^0$
  $\rightarrow$ Custodial triplets mix $\rightarrow (H_3^+, H_3^0, H_3^-)$
  $\rightarrow$ Custodial fiveplet $(H_5^{++}, H_5^+, H_5^0, H_5^-, H_5^{--})$
- Custodial SU(2) symmetry allows the *WZH* coupling.

Search for a Heavy charged Higgs Boson in FCC-ee

- Simulation of a search for a Heavy Charged Higgs Boson at $\sqrt{s} = 240$ GeV and $\sqrt{s} = 365$ GeV, for different hypotheses of the charged Higgs masses at the FCC-ee.
- Evaluating the sensitivity of the FCC-ee to this signal in presence of all background processes.

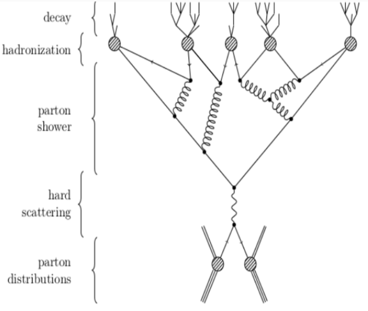


- Test of different MC generators e.g. (Madgraph5, Whizard) to generate events.
- Event generation and fast detector simulation using Delphes.
- The analysis code using Root to extract the signal.

Matching Parton Showers and Matrix Elements

Matching :

- ⋆ Matrix Elements describe correctly hard and at large angles emissions.
- ⋆ Soft emissions or with small angles lead the matrix elements to diverge $\rightarrow$ Cuts to eliminate them.
- ⋆ Parton showers account for the holes left in the phase space by these cuts $\rightarrow$ Redundancies.
- ⋆ We need to eliminate the double counting between the full matrix elements and the parton showers. $\rightarrow$ Matching procedures. (CKKW scheme, the Lonnblad scheme, and the MLM scheme, FxFx scheme...)



Accounting for spin correlation effects

Spin Correlation :

- ⋆ Computation of the matrix element → Summing over initial spin states and averaging over final spin states → Loss of non-trivial angular correlations among final-state particles.
- ⋆ Procedure that includes spin correlation effects at NLO accuracy → MadSpin.
- ⋆ For $t\bar{t}$ production, the observable that is most sensitive to spin correlation effects is cos(ϕ).
- ⋆ Including both spin correlation effects and QCD corrections → reduced uncertainties, while keeping the correlations between the top decay products.

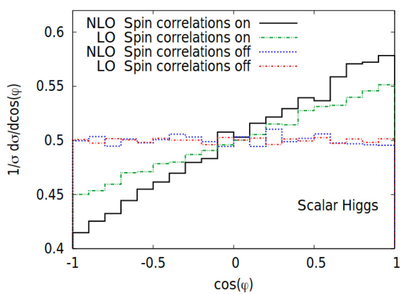


Figure: NLO cross sections differential in $cos(\phi)$ for $t\bar{t}H$ events, w/ ϕ the angle between the direction of flight of l^+ and the direction of flight of l^-.

Generated Events

- $e^+e^- collisionsat\sqrt{s} = 240$ GeV
- Integrated Luminosity: $L = \int \mathcal{L}dt = 5ab^{-1}$

SM Higgs processes	MG5 v2.7.2	Whizard v3
$e^+e^- \to HZ$	$\sigma_{LO} = 240.3 \pm 0.006$ $(Stat)$ $Ngen = 1.3(108.2\%)$ Spin Correl., No Matching	$\sigma_{LO} = 240.310 \pm 0.002$ $(Stat)$ fb $Ngen = 1.221(101.6\%)$ No Matching
$e^+e^- \to H\nu_e\bar{\nu_e}$	$\sigma_{LO} = 22.62 \pm 0.03$ $(Stat)$ $Ngen = 1.1(972.6\%)$ Spin Correl., No Matching	$\sigma_{LO} = 22.57 \pm 0.06$ $(Stat)$ fb $Ngen = 0.117250(103.9\%)$ No Matching
$e^+e^- \to e^+e^-H$	$\sigma_{LO} = 7.84 \pm 0.01$ $(Stat)$ $Ngen = 1.0(2551.0\%)$ Spin Correl., No Matching	$\sigma_{LO} = 8.53 \pm 0.02$ $(Stat)$ fb $Ngen = 0.0401(94.02\%)$ No Matching

Background processes (1/2)	MG5 v2.7.2	Whizard v3
$e^+e^- \to \tau^+\tau^-$	$\sigma_{LO} = \pm$ $(Stat)$ $Ngen = (\%)$ Spin Correl., No Matching	$\sigma_{LO} = 1.92 \pm 0.16$ $(Stat)$ pb $Ngen = 0.0401(94.02\%)$ No Matching
$e^+e^- \to W^+W^-$	$\sigma_{LO} = 17.167 \pm 0.020$ $(Stat)$ $Ngen = 1.0(1.2\%)$ Spin Correl., No Matching	$\sigma_{LO} = 17.173 \pm 0.005$ $(Stat)$ pb $Ngen = 0.0401(9.402\%)$ No Matching
$e^+e^- \to ZZ$	$\sigma_{LO} = 1.163 \pm 0.001$ $(Stat)$ $Ngen = 1.1(18.9\%)$ Spin Correl., No Matching	$\sigma_{LO} = 1.163 \pm 0.0003$ $(Stat)$ pb $Ngen = 0.5505(9.47\%)$ No Matching
$e^+e^- \to Ze^+e^-$	$\sigma_{LO} = 0.156 \pm 0.0001$ $(Stat)$ $Ngen = 1.7(217.9\%)$ Spin Correl., No Matching	$\sigma_{LO} = 2.13 \pm 0.09$ $(Stat)$ pb $Ngen = 0.077(0.723\%)$ No Matching
$e^+e^- \to W^\pm e^\mp \nu_e$	$\sigma_{LO} = 3.949 \pm 0.003$ $(Stat)$ $Ngen = 1.2(6.1\%)$ Spin Correl., No Matching	$\sigma_{LO} = 4.84 \pm 0.032$ $(Stat)$ pb $Ngen = 1.0(4.13\%)$ No Matching

Generated Events

- $e^+e^- collisionsat \sqrt{s} = 240$ GeV
- Integrated Luminosity: $L = \int \mathcal{L}dt = 5ab^{-1}$

Background processes (2/2)	MG5 v2.7.2	Whizard v3
$e^+e^- \rightarrow e^+e^- q\bar{q}$ (q = u/d/s/c)	LO MLM Matching	No Matching
$e^+e^- \rightarrow e^+e^- b\bar{b}$	LO MLM Matching	No Matching
$e^+e^- \rightarrow q\bar{q} + (0/1)lp$ (q = u/d/s/c)	Spin Correl., NLO FxFx Matching	$\sigma_{LO} = 10.49 \pm 0.001$ (*Stat*) *pb* $Ngen = 4.0(7.62\%)$ No Matching
$e^+e^- \rightarrow b\bar{b} + (0/1/2)lp$	$\sigma_{NLO} = 4272. \pm 48.$ (*Stat*) $\begin{pmatrix} +0.0\% \\ -2.4\% \end{pmatrix}$ (*scale*) *fb* Spin Correl., NLO FxFx Matching	$\sigma_{LO} = 1.95 \pm 0.0002$ (*Stat*) *pb* $Ngen = 4.0(41.03\%)$ No Matching

Table: MC Production for FCC-ee run at $\sqrt{s} = 240$ GeV

Generated Events

- $e^+e^- collisionsat\sqrt{s} = 365$ GeV
- Integrated Luminosity: $L = \int \mathcal{L}dt = 1.5ab^{-1}$

SM Higgs processes	MG5 v2.7.2	Whizard v3
$e^+e^- \rightarrow HZ$	$\sigma_{LO} = \pm$ (*Stat*) $Ngen = (\%)$ Spin Correl., No Matching	$\sigma_{LO} = 124.161 \pm 0.004$ (*Stat*) *fb* $Ngen = 0.176(94.50\%)$ No Matching
$e^+e^- \rightarrow H\nu_e\bar{\nu}_e$	$\sigma_{LO} = \pm$ (*Stat*) $Ngen = (\%)$ Spin Correl., No Matching	$\sigma_{LO} = 38.64 \pm 0.12$ (*Stat*) *fb* $Ngen = 0.061050(105.33\%)$ No Matching
$e^+e^- \rightarrow e^+e^-H$	$\sigma_{LO} = \pm$ (*Stat*) $Ngen = (\%)$ Spin Correl., No Matching	$\sigma_{LO} = 7.578 \pm 0.019$ (*Stat*) *fb* $Ngen = 0.011358(99.92\%)$ No Matching

Background processes (1/2)	MG5 v2.7.2	Whizard v3
$e^+e^- \rightarrow \tau^+\tau^-$	$\sigma_{LO} = \pm$ (*Stat*) $Ngen = (\%)$ Spin Correl., No Matching	- No Matching
$e^+e^- \rightarrow W^+W^-$	$\sigma_{LO} = \pm$ (*Stat*) $Ngen = (\%)$ Spin Correl., No Matching	- No Matching
$e^+e^- \rightarrow ZZ$	$\sigma_{LO} = \pm$ (*Stat*) $Ngen = (\%)$ Spin Correl., No Matching	- No Matching
$e^+e^- \rightarrow Ze^+e^-$	$\sigma_{LO} = \pm$ (*Stat*) $Ngen = (\%)$ Spin Correl., No Matching	- No Matching
$e^+e^- \rightarrow W^{\pm}e^{\mp}\nu_e$	$\sigma_{LO} = \pm$ (*Stat*) $Ngen = (\%)$ Spin Correl., No Matching	- No Matching

Generated Events

Background processes (2/2)	MG5 v2.7.2	Whizard v3
$e^+e^- \rightarrow e^+e^- q\bar{q}$ (q = u/d/s/c)	LO MLM Matching	No Matching
$e^+e^- \rightarrow e^+e^- b\bar{b}$	LO MLM Matching	No Matching
$e^+e^- \rightarrow q\bar{q} + (0/1)lp$ (q = u/d/s/c)	Spin Correl., NLO FxFx Matching	- No Matching
$e^+e^- \rightarrow b\bar{b} + (0/1/2)lp$	Spin Correl., NLO FxFx Matching	- No Matching
$e^+e^- \rightarrow t\bar{t} + (0/1/2)lp$	$\sigma_{NLO} = 727.7 \pm 1.1\ (Stat) \begin{pmatrix} +3.1\% \\ -2.6\% \end{pmatrix}\ (Scale)\ fb$ $Ngen = 2.0(183.2\%)$ Spin Correl., NLO FxFx Matching	- No Matching

Table: MC Production for FCC-ee run at $\sqrt{s} = 240$ GeV

- Successful generation of the $t\bar{t}$ background with good matching efficiency.
- Low matching efficiency ($\sim$30%) for $q\bar{q}$ and $b\bar{b}$.
- **Possible Sources of the issue** :
  $\rightarrow$ MadGraph doesn't take into account the "kT" clustering of the parton level event which is an important ingredient for the matching procedure.
  $\rightarrow$ Found improvement of the efficiency if photon irradiation in the initial state (ISR) is taken into account in the generation of events in MadGraph.

Signal Production

- 2HDM Type II Model with $M_H = 125$ *GeV* and $M_h = 50$ *GeV*.

  ⋆ Use of SUSY Les Houches Accord (SLHA) files that tell the MC generator how to simulate the simplified SUSY models.
  ⋆ **Difficulty** : Unable to Generate a Heavy Charged higgs in e^+e^- collision, in a precise SUSY scenario through both considered MC Generators (MadGraph and Whizard).

- Generation of Signal in the GM Model.

  ⋆ **Difficulty** : Model isn't implemented in any MC generator $\rightarrow$ Feynrules (a Feynman rules calculation tool) $\rightarrow$ Use of Universal FeynRules Output (UFO) files to simulate the processes of interest in MG5 or Whizard.

THANK YOU.

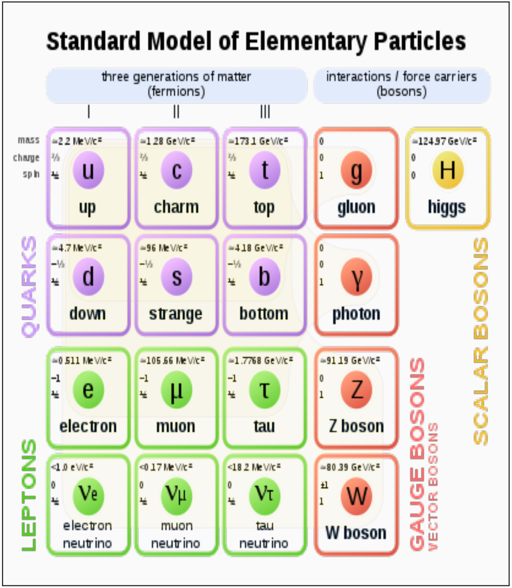
Backup

$H^{\pm}$ probed mass

$\sqrt{s}$ [GeV]	Channel	Mass range for the Charged Higgs [GeV]
240	t-channel	$206 \leq M_{H}^{\pm} \leq 240$
365	t-channel	$206 \leq M_{H}^{\pm} \leq 365$
365	s-channel	$206 \leq M_{H}^{\pm} \leq 285$

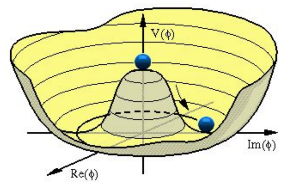
Table: Ranges of considered mass for the Charged Higgs boson w.r.t. the center-of-mass energy of the $e^{+}e^{-}$ collision.

- The Standard Model is a successful theory of particle interactions $\rightarrow$ Electro-weak and Strong interactions.
- All measurements at colliders and beyond are in agreement with Standard Model predictions (almost).
- No candidate for dark matter and it fails to explain the mass of neutrinos ...
  $\Longrightarrow$ the existence of physics beyond the SM (BSM).



The Brout-Englert-Higgs mechanism

- Brout-Englert-Higgs mechanism $\rightarrow$ Existence of a scalar field whose Lagrangian is invariant under local gauge symmetry $\rightarrow SU(2)$ doublet of complexe scalar fields: $\phi = \begin{pmatrix} \phi^+ \\ \phi^0 \end{pmatrix}$
- The most general Higgs field potential energy $V(\phi, \phi^\dagger)$ is given by: $V(\phi, \phi^\dagger) = \mu^2 \phi^\dagger \phi + \lambda(\phi^\dagger \phi)^2$



- Infinite number of degenerate states of minimum energy and choosing one particular solution for ϕ_{min} gives a fundamental state: $\langle 0|\phi(x)|0\rangle = \begin{pmatrix} 0 \\ \frac{v}{\sqrt{2}} \end{pmatrix}$
- $\mathcal{L}$ is invariant under $SU(2)_L \otimes U(1)_Y$ local gauge symmetry group but the fundamental state is invariant under $U(1)_{em}$ Local group. $\leftarrow$ Spontaneous Symmetry Breaking $SU(2)_L \otimes U(1)_Y \rightarrow U(1)_{em}$.
- Redefining the Higgs field as a fluctuation around its vev: $\phi(x) = \begin{pmatrix} 0 \\ \frac{v+H(x)}{\sqrt{2}} \end{pmatrix}$
- All massive elementary particles gain their mass by coupling with the Higgs field. Fermions through Yukawa coupling and Gauge Bosons through Gauge coupling.