Study of the Higgs self-coupling with the ATLAS detector at LHC

Océane PERRIN

University of Strasbourg

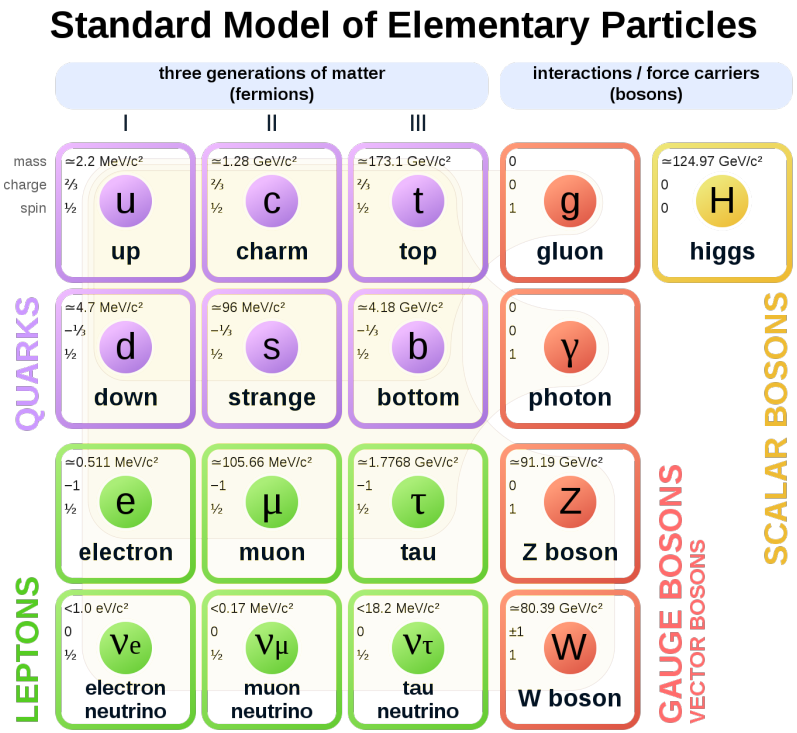
June 19, 2020

Supervised by Djamel Boumediene

Outline

Introduction

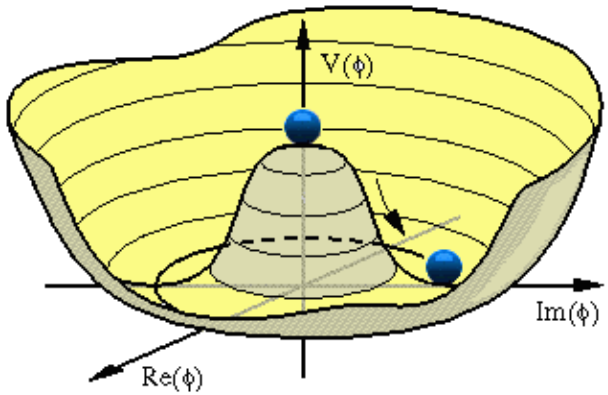
- Standard model: 12 elementary constituants + 4 gauge bosons
- Based on electroweak symmetry breaking
- 1964, physicists suggested BEH mechanism
- New particle called Higgs boson
- 2012: the particle has been observed by ATLAS and CMS experiments



Context - Higgs potential

Higgs field can be described by the Lagrangian:

$$L_H = (D_\mu \phi)^\dagger (D^\mu \phi) - \mu^2 \phi^\dagger \phi - \lambda (\phi^\dagger \phi)^2$$



Higgs potential after symmetry breaking

$$V = V_0 + \underbrace{\lambda \nu^2 h^2}_{\text{mass term}} + \underbrace{\lambda \nu h^3}_{\text{trilinear coupling}} + \underbrace{\frac{\lambda}{4} h^4}_{\text{quadrilinear term}} \quad \text{avec} \quad \frac{\mu}{\sqrt{\lambda}} \equiv \nu$$

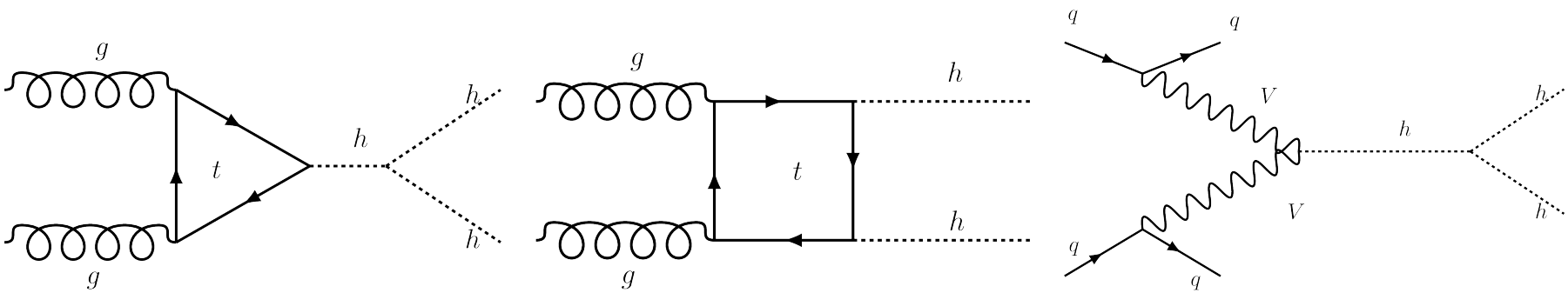
Aim of this study:

- Have a direct measurement of λ_{hhh}
- Probe the potential shape
- Find potential in vaccum v

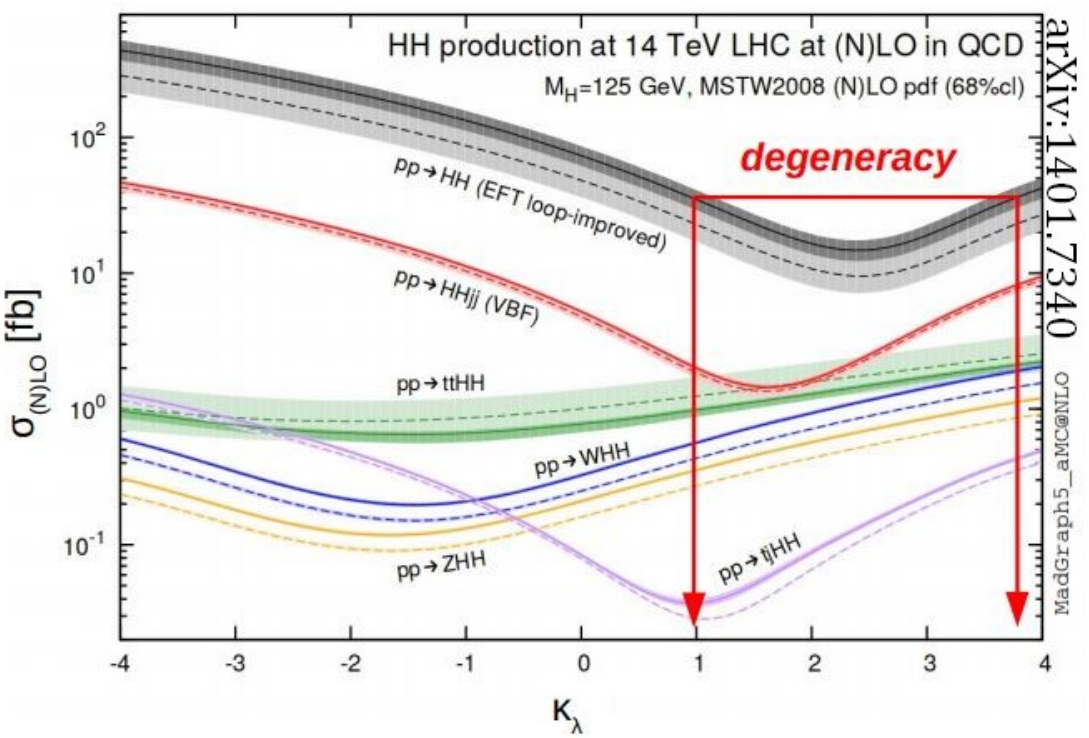
$$\lambda_{hhh}^{SM} = \frac{m_h^2}{2\nu^2}$$

Context - hh production mode at LHC

- Measure Higgs self coupling through hh production
- 2 main hh production modes at LHC ($\sqrt{s} = 13\ TeV$)
  - Gluon gluon fusion (ggF) $\sigma = 30\ fb$
  - Vector boson fusion (VBF) $\sigma = 2\ fb$
- The total Higgs boson production cross section: 57.0 pb
- ggF process: destructive interference between them



Context - Higgs self coupling

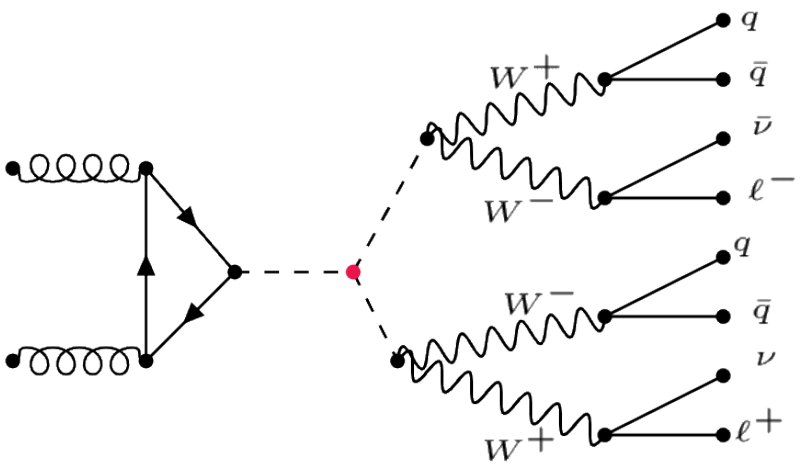


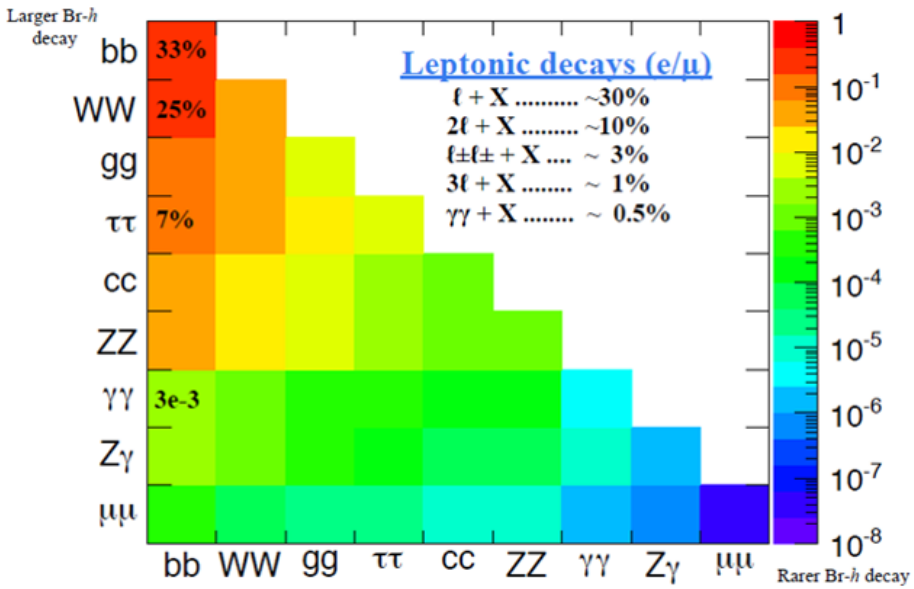
- Relation between cross section σ and λ
- $\kappa_\lambda = \frac{\lambda_{hhh}}{\lambda_{SM}}$
- Minimum at $\kappa_\lambda = 2.5\ SM$
- Degeneration for each process

Aim of this study:

- Highlight hh production $\equiv$ Distinguish it from other processes

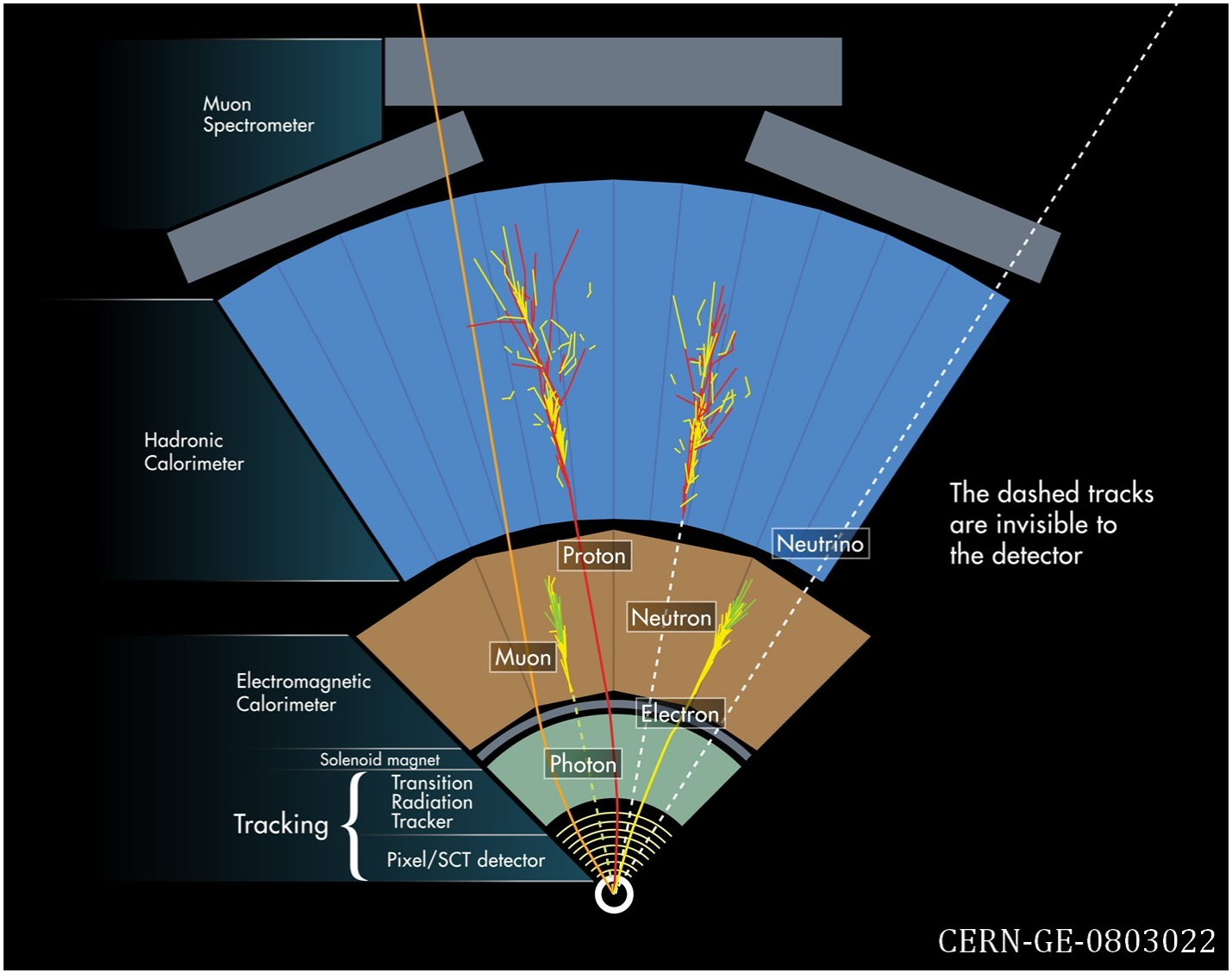
Context - Di-Higgs decays





- Signature $\ell^+\ell^-$ and $\ell^\pm\ell^\pm \rightarrow$ Reject background
- Main background : production of di-boson VV, boson Z, $t\bar{t}$
- Signature $\ell^+\ell^-$: physics background
- Signature $\ell^\pm\ell^\pm$: mainly instrumental backgrounds

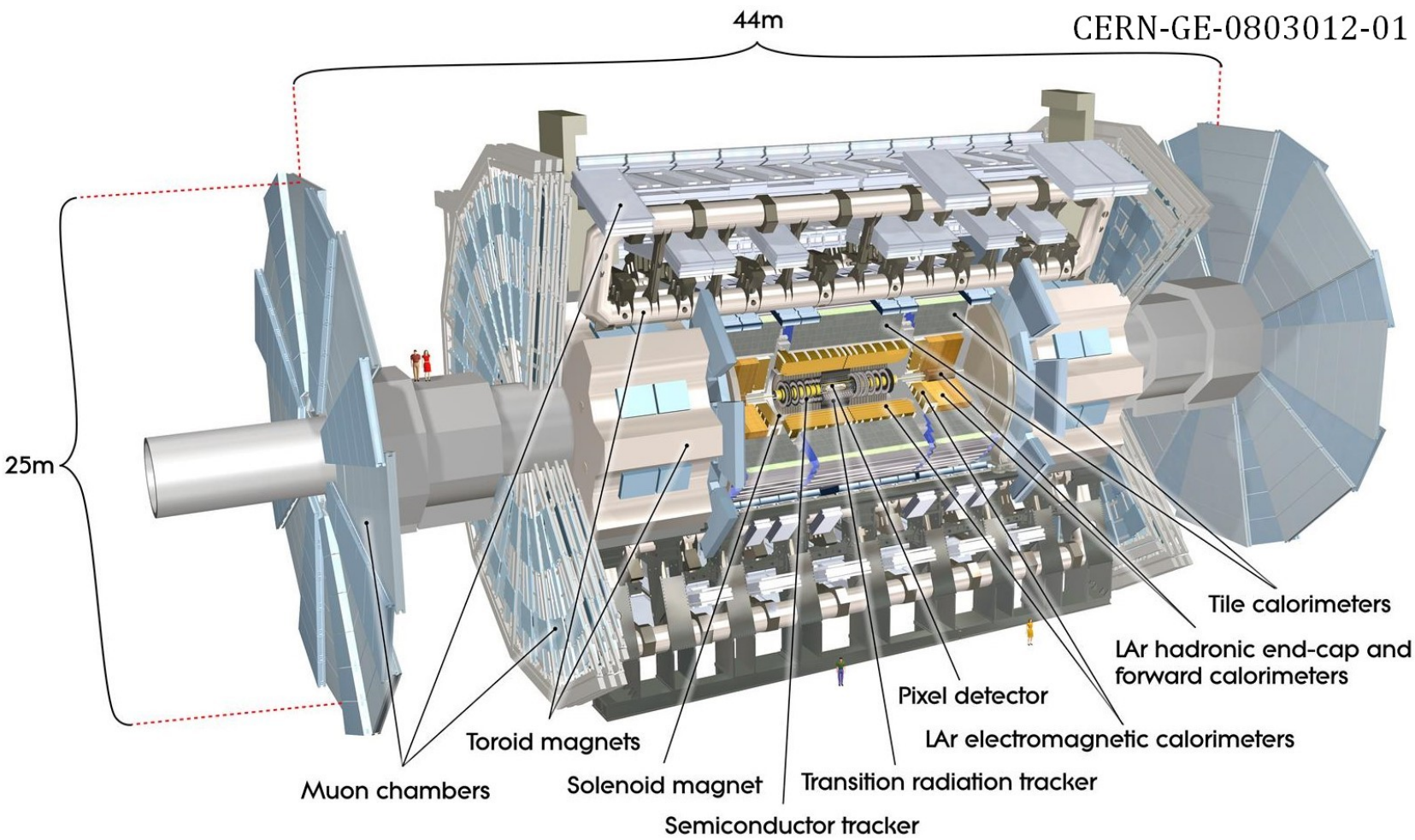
Context - Identification and reconstruction of objects at LHC



Objects:

- Électrons
- Muons
- Photons
- Jets

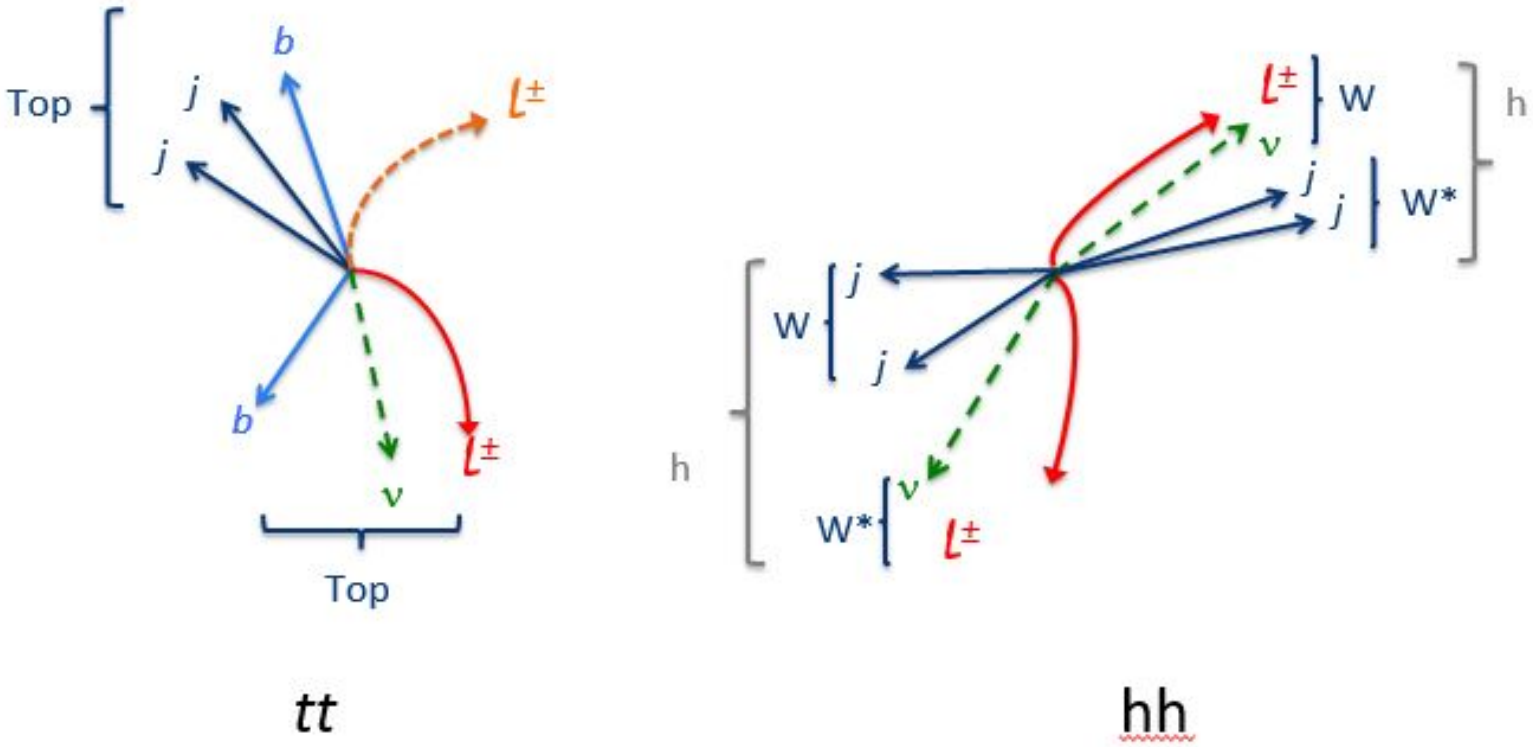
Context - ATLAS detector



Monte-Carlo simulations: Run II, 2015/2018, L= 139fb^{-1}, $\sqrt{s} = 13\ TeV$

Methods - Discriminating variables

- Preselections: at least 2 leptons with criterias + b-Veto



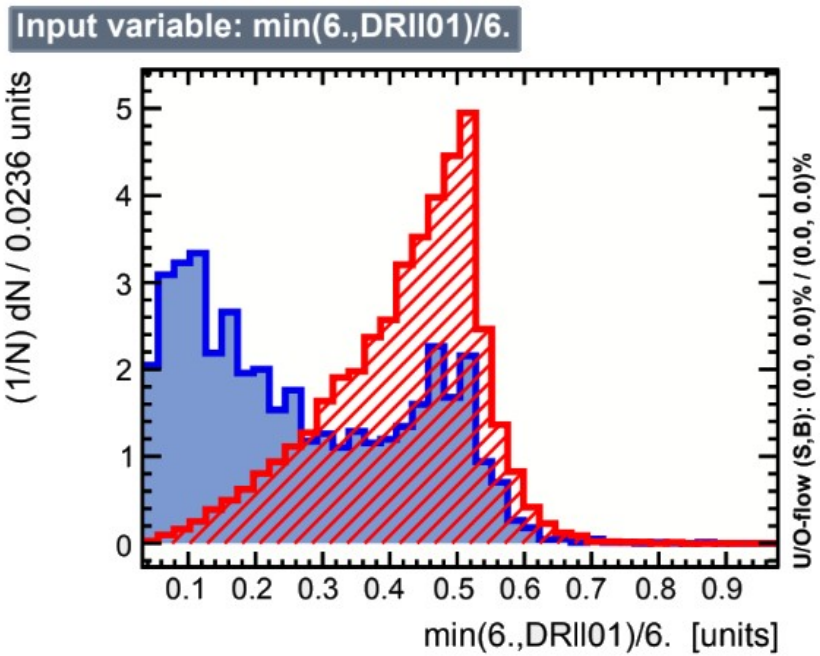
tt hh

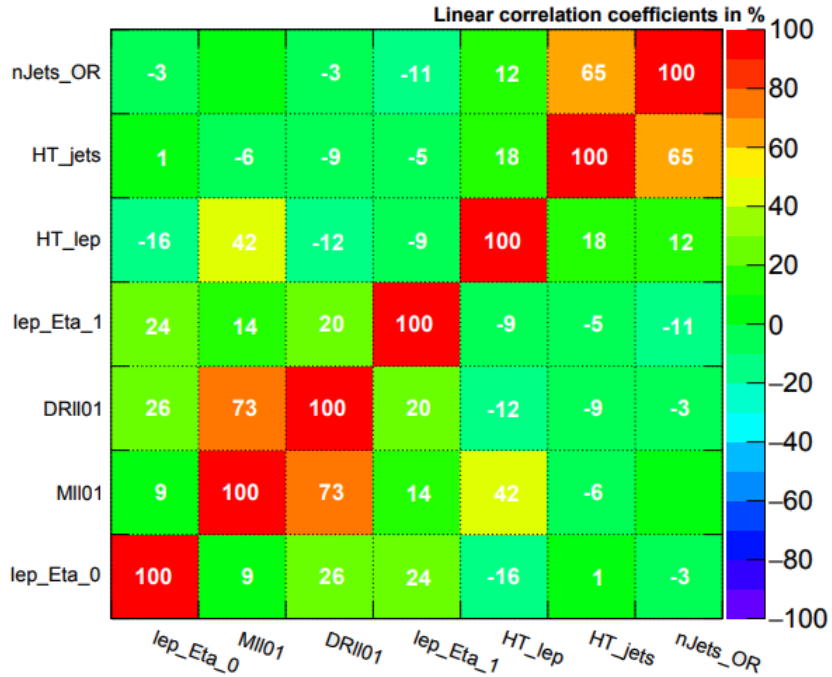
7 discriminating variables:

ΔR, M_{ll}, η_0, η_1, HT_{jets}, $HT_{leptons}$, n_{jets}

Methods - Cut based method

- Distinguish signal from background in order to maximize δ
- Quantified by significance $\delta = \sqrt{2((s+b)ln(1+\frac{s}{b})-s)}$
- Scan simultaneously all variable's space $\rightarrow$ optimal cuts
- Cross check with my own code
- Correlations influences are not fully considered

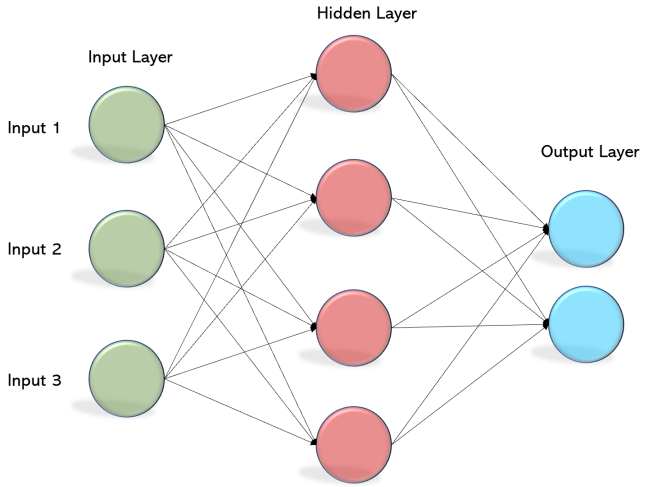




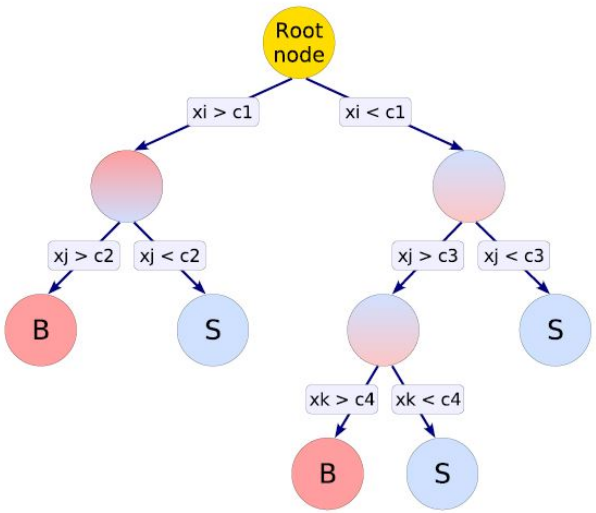
Methods - MLP and BDT methods

Multilayers Perceptron method (MLP BFGS)

- Solve no-linear problem using NN
- Create a no-linear function (mathematical)
- Training: define weights → maximize distance between s et b



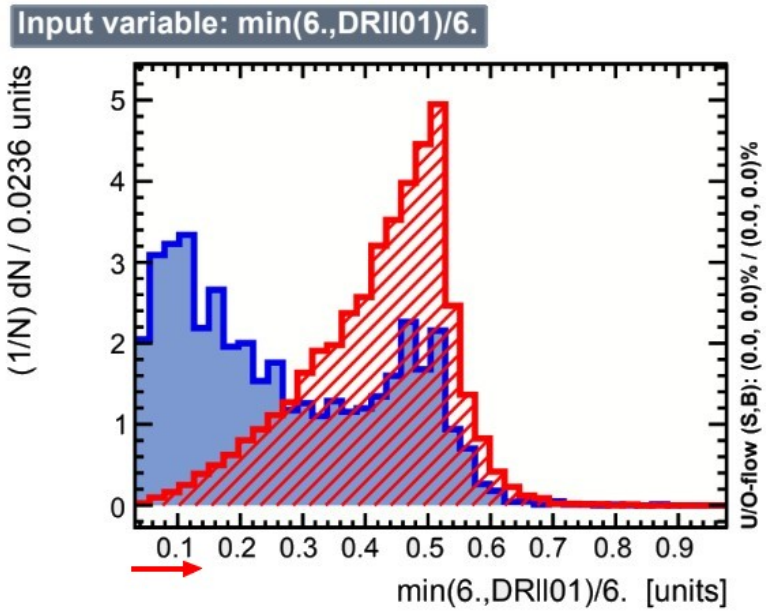
Boosted decision tree (BDT)



- 1 level = 1 binary criteria
- At node level: ordering variables and ordering respective optimal cut
- Training phase: ± 1 for s or b regions
- Iterate → validation of a stop criteria

Results - Cut based method

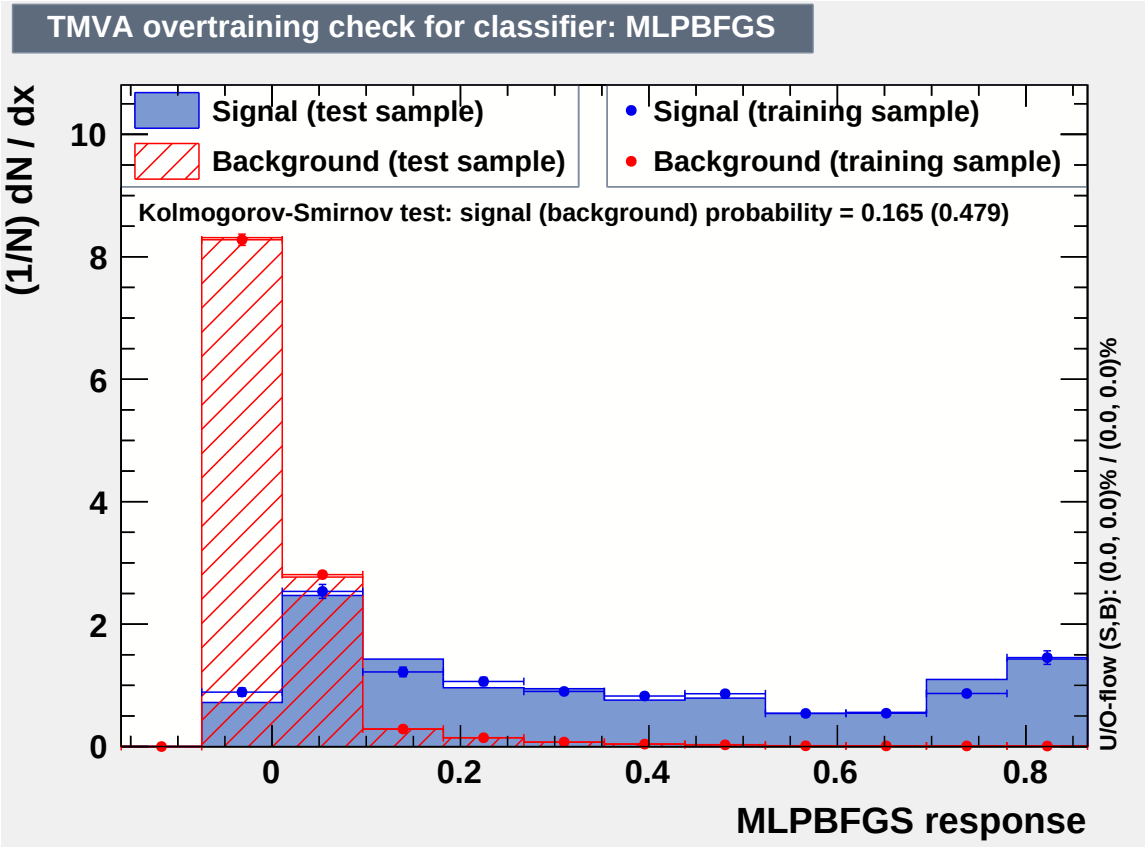
- Optimal cut applied on each discriminating variable
- Cut flow (example): signature e^+e^-
- $\delta_{preselections} < \delta_{cutbased}$



Cuts	hh	$t\bar{t}$	Zjets	VV	$\frac{s}{\sqrt{b}}$
Preselections	2.5	77600	1900000	29700	0.0018
abs(η_0) $<$ 2	2.5	73300	1760000	27500	0.0018
Mll$<$ 341 GeV	2.5	71400	1740000	26800	0.0018
$\Delta R <$ 0.77	0.74	4400	20300	1900	0.0045
abs(η_1) $<$ 2	0.72	4280	19300	1830	0.0045
$HT_{leptons} >$ 63 GeV	0.68	3570	16300	1400	0.0047
$HT_{jets} >$ 123 GeV	0.58	1960	13900	830	0.0048
$n_{jets} \geq 2$	0.56	1880	9880	660	0.0050

Results - Multilayer perceptron

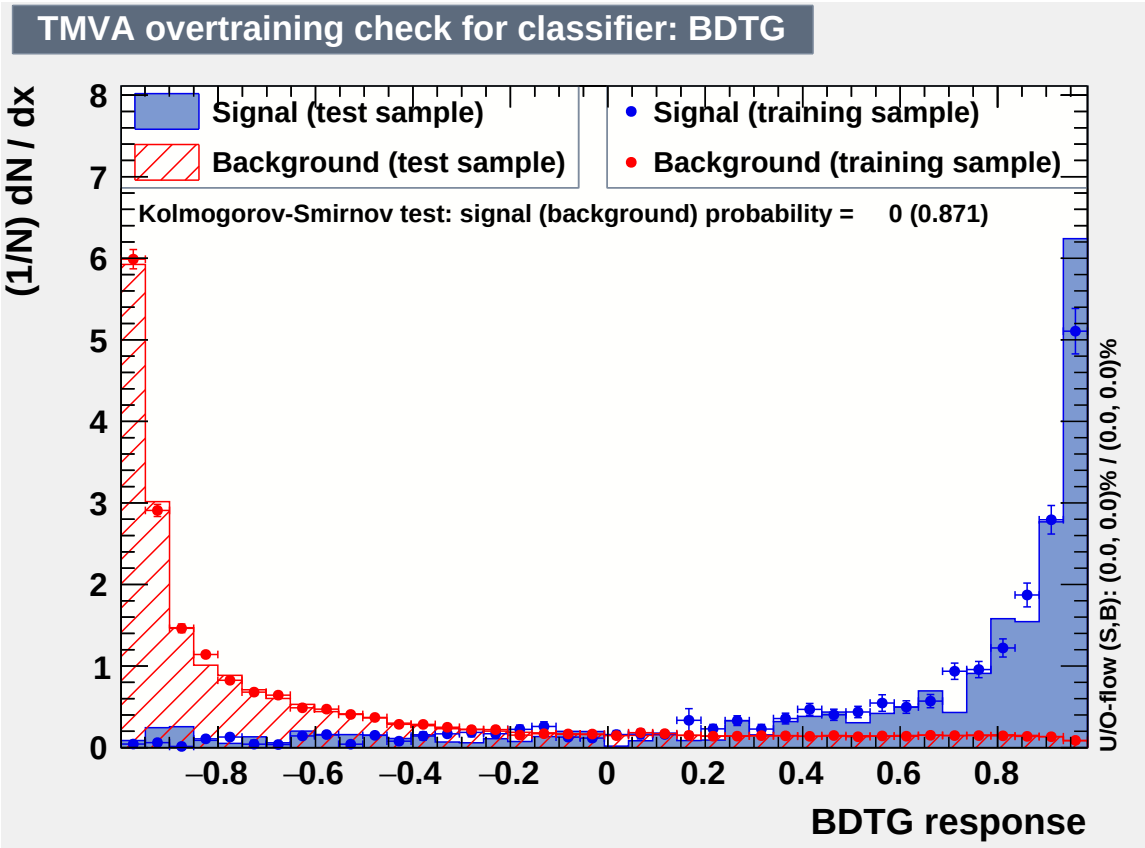
- Distinguish signal from background
- Problem: no-convergence + calculation time
- Optimal cut for signature e^+e^- at 0.56



e^+e^-	Preselections	Cut based	MLPBFGS>0.56
Significance $\frac{s}{\sqrt{b}}$	0.0018	0.0050	0.0063

Results - Boosted decision tree

- Distinguish signal from background
- Problem: no-convergence + calculation time
- Optimal cut for signature e^+e^- at 0.92



e^+e^-	Preselections	Cut based	MLPBFGS>0.56	BDT>0.92
Significance $\frac{s}{\sqrt{b}}$	0.0018	0.0050	0.0063	0.0078

Results - Final results

	Significance (x 10^{-3})				
Signatures	**Preselections**	**Cut based**	**MLP BFGS**	**BDT**	**Gain BDT**
e^+e^-	1.8	5.0	6.3	7.8	4.3
$e^\pm e^\pm$	5.3	6.3	16	20	3.8
$\mu^+\mu^-$	1.4	5.1	13	9.6	6.9
$\mu^\pm\mu^\pm$	30	33	45	59	2.0
μ^+e^- and $e^+\mu^-$	9.9	10.0	11	22	2.2
$e^\pm\mu^\pm$	31	32	33	55	1.8
Median significance	45	48	61	87	1.9

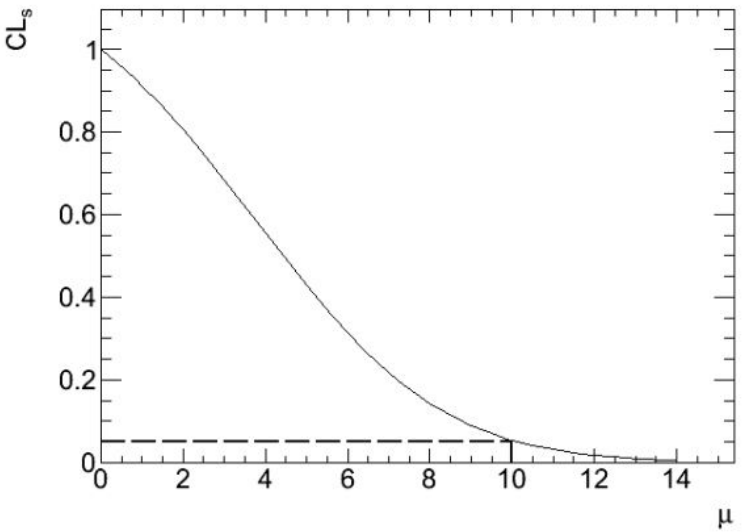
- Multivariate methods better performance than Cut based method
- Signature $\mu^+\mu^-$: $\delta_{MLP} > \delta_{BDT}$
- Other signatures: $\delta_{BDT} > \delta_{MLP}$

Statistical interpretation - CL_S method and signal strength

TRExFitter

- Define signal strength as $\mu = \frac{\sigma}{\sigma_{SM}}$, $\Delta\mu$
- Use CL_s method
- Some systematic uncertainties:

Charge mis ID, Cross section, Modelling e and μ, Luminosity

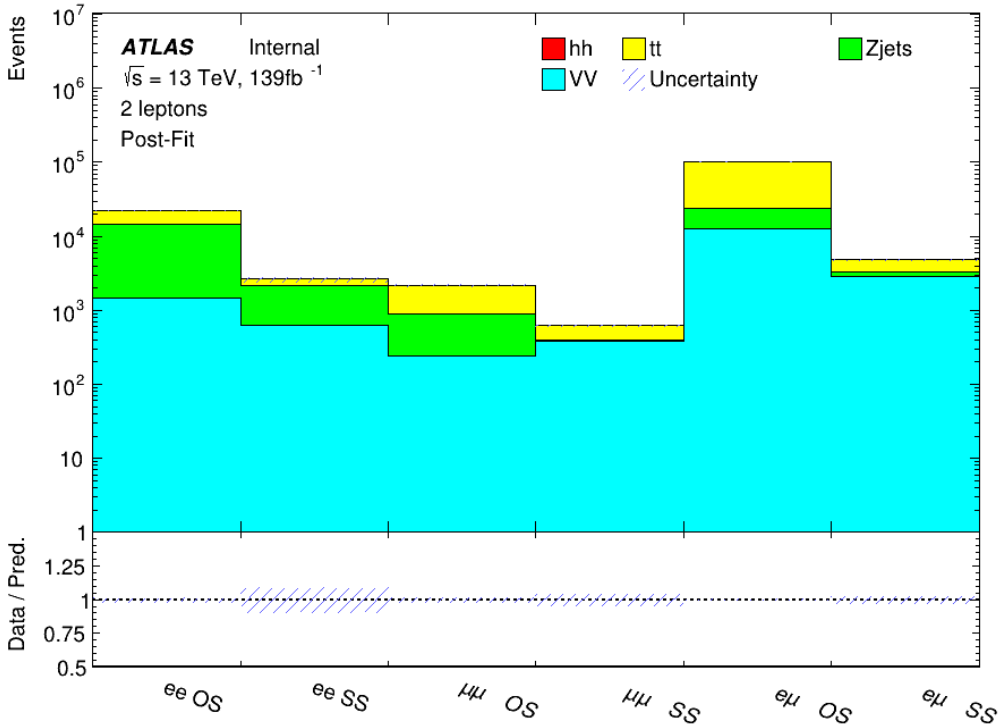


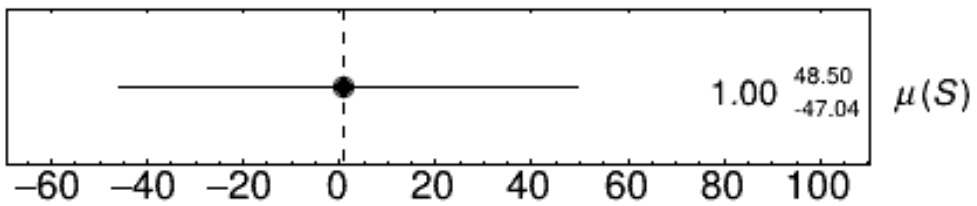
CL_s method:

- 2 hypotheses following Poisson distribution:
  - H1 b: Only background
  - H0 s+b: Background and signal
- Define confidence levels: CL_b and CL_{s+b} and $CL_s = \frac{CL_{s+b}}{CL_b}$
- Reject H1 at 95% with $CL_s = 0.05$

$\rightarrow$ $\mu_{95\%}$

Statistical interpretation - Results





- Apply on simulation (pseudo-data)
- 6 signal regions: 1 per signature
- BDT results used

Median significance : $2.4\ 10^{-2}$

$\mu_{95\%} = 90$

Conclusion

This internship :

- $\ell^+\ell^-$+X and $hh \rightarrow \ell^\pm\ell^\pm$+X $\rightarrow$ look for discriminating variables
- 3 methods: Cut based, MLP, BDT
- Statistical test

- λ: probe of Standard model or opening on a new physics
- Only direct measurement of Higgs potential
- Extrapolation to HL-LHC: L= 3000 fb^{-1} $\rightarrow$ $\mu_{95\%} = 18$

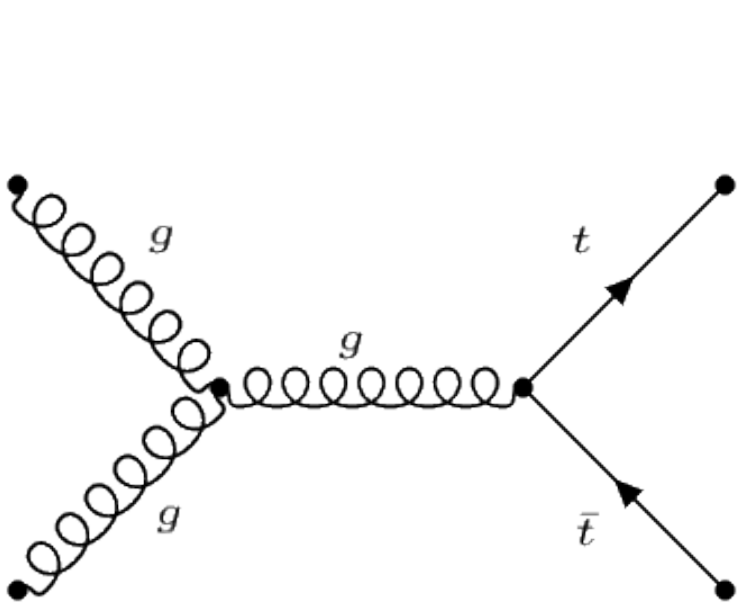
	Statistical-only		**Statistical + Systematic**	
	ATLAS	CMS	ATLAS	CMS
$HH \rightarrow b\bar{b}b\bar{b}$	1.4	1.2	0.61	0.95
$HH \rightarrow b\bar{b}\tau\tau$	2.5	1.6	2.1	1.4
$HH \rightarrow b\bar{b}\gamma\gamma$	2.1	1.8	2.0	1.8
$HH \rightarrow b\bar{b}VV(ll\nu\nu)$	-	0.59	-	0.56
$HH \rightarrow b\bar{b}ZZ(4l)$	-	0.37	-	0.37
combined	3.5	2.8	3.0	2.6
	Combined		Combined	
	4.5		4.0	

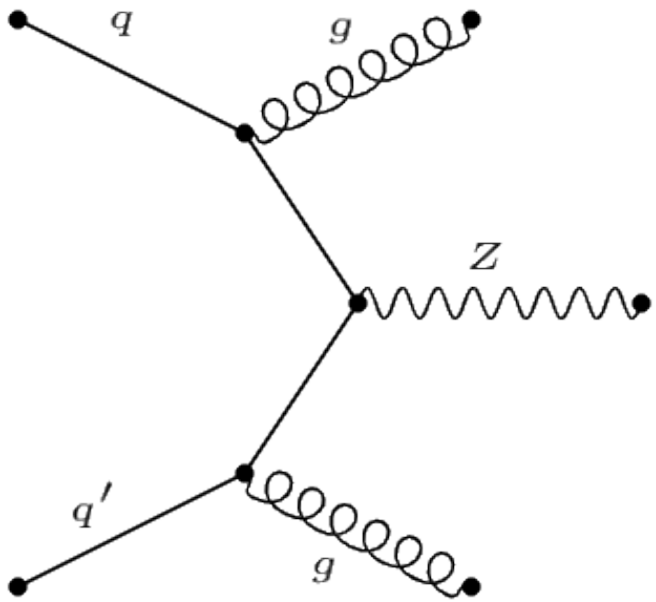
Backup

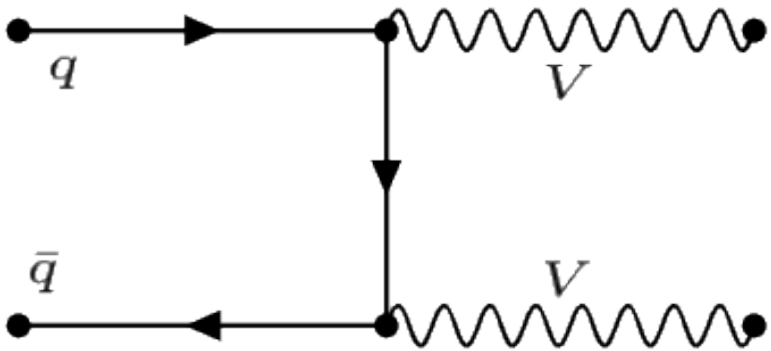
Backup - N train (no weight) - multivariate methods

Signatures	N train (Signal)	N train (BDF)
e^+e^-	6000	700000
$e^\pm e^\pm$	2500	80000
$\mu^+\mu^-$	15000	800000
$\mu^\pm\mu^\pm$	5000	80000
$e^+\mu^-$ et $e^-\mu^+$	13000	700000
$e^\pm\mu^\pm$	3000	70000

Backup - Background

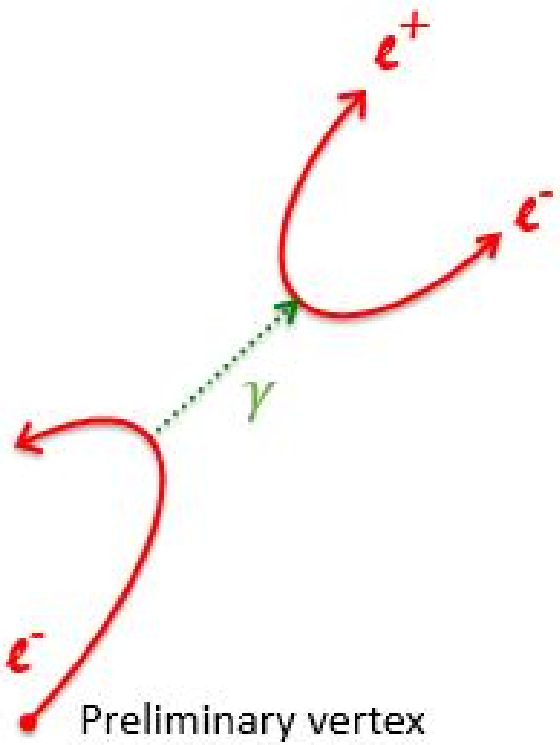




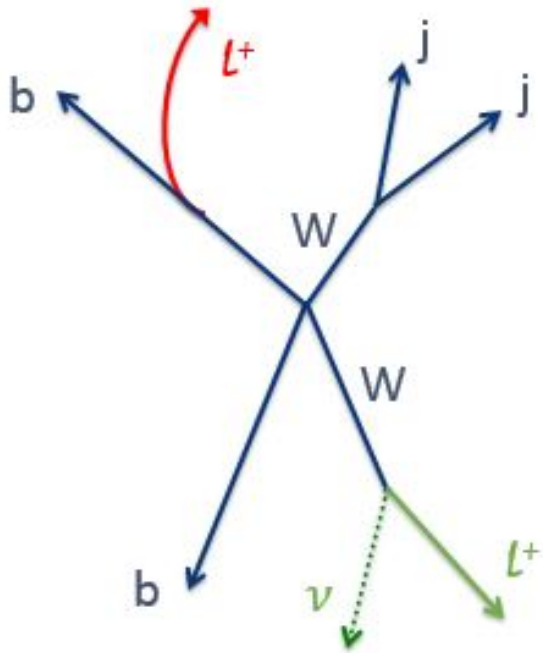


Backup - Fake leptons

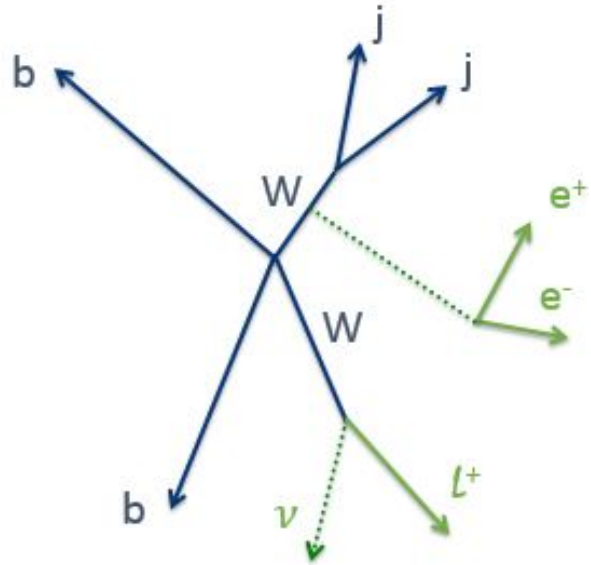
- Trident process



- Semileptonic b-decay



- Photon conversion

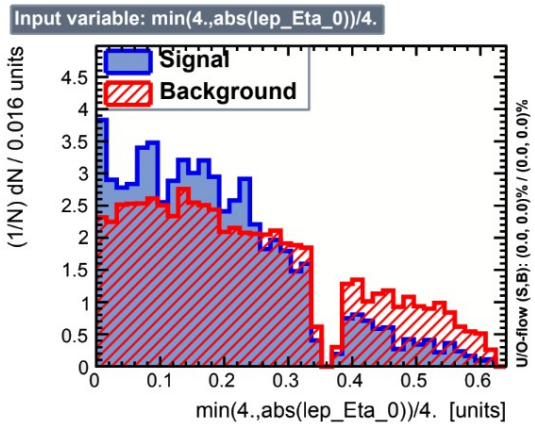


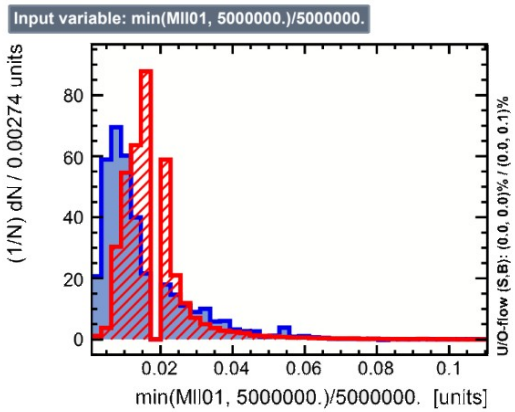
Backup - Systematic uncertainties and generators

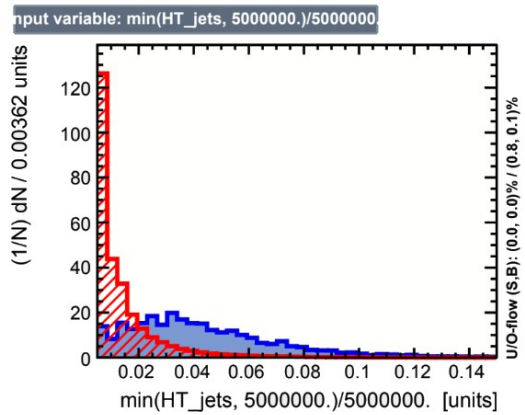
Systematic uncertainties	$t\bar{t}$	VV	Zjets	all
Cross section	5%	5%	5%	-
Luminosity	-	-	-	1%
QMisID ee SS	15%	-	25%	-
QMisID eμ SS	10%	-	-	-
noPrompt e ee SS	20%	-	5%	-
noPrompt e eμ SS	10%	-	20%	-
noPrompt μ $\mu\mu$ SS	20%	-	-	-
noPrompt μ eμ SS	10%	-	20%	-

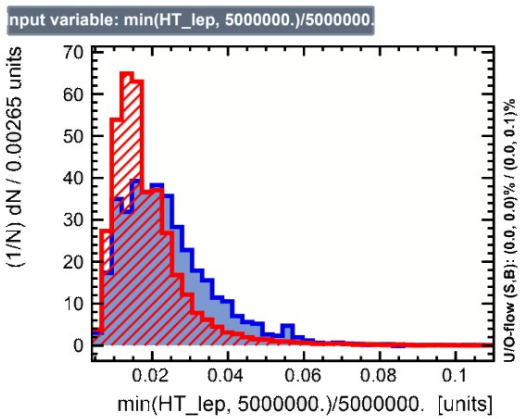
Process	Generator	ME order	Parton shower	PDF
hh	MadGraph	NLO	Herwig	CT10
t$\bar{t}$	Powheg-BOX	NLO	Pythia 8	NNPDF3.0 NLO
VV	Sherpa 2.2.1	NNLO	Sherpa	NNPDF3.0 NNLO
$Z \to \ell\ell$	Sherpa 2.2.1	NNLO	Sherpa	NNPDF3.0 NNLO

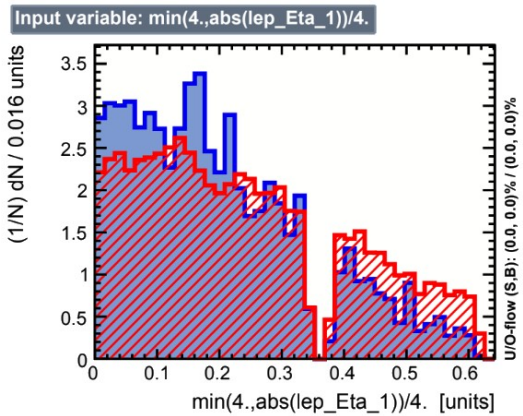
Backup - Discriminating variables

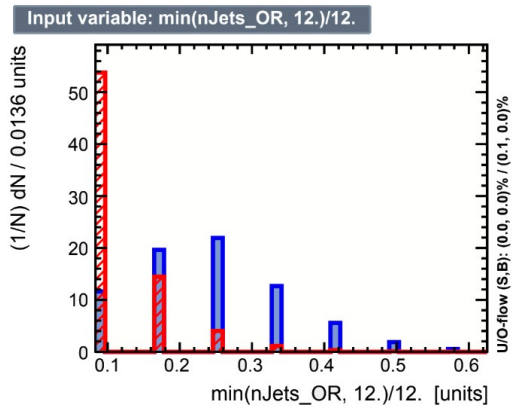












Backup - Discriminating variables - Choice

$\ell^+\ell^-$	Signal	Background	Variables
nb quarks	>0	0	n_{jets} HT_{jets}
nb b quark	0	>0 ($t\bar{t}$)	n_b
Angular correlation	no	π (Z boson)	ΔR
Inv. mass	no resonance	resonance(Zmass)	M_{ll}

$\ell^\pm\ell^\pm$	Signal	Background	Variables
nb quarks	4	0 (Z) 4($t\bar{t}$)	n_{jets} HT_{jets}
Charge miss ID	no	one electron with wrong charge	M_{ll} and $\eta_{leptons}$
nb b quark	0	2 ($t\bar{t}$)	n_b
Angular correlation	no	partially back-to-back	ΔR
Inv. mass	no resonance	resonance(Zmass)	M_{ll}

Backup - Control regions