Search for doubly charged Higgs boson decaying to same-sign W boson

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On behalf of the analysis team

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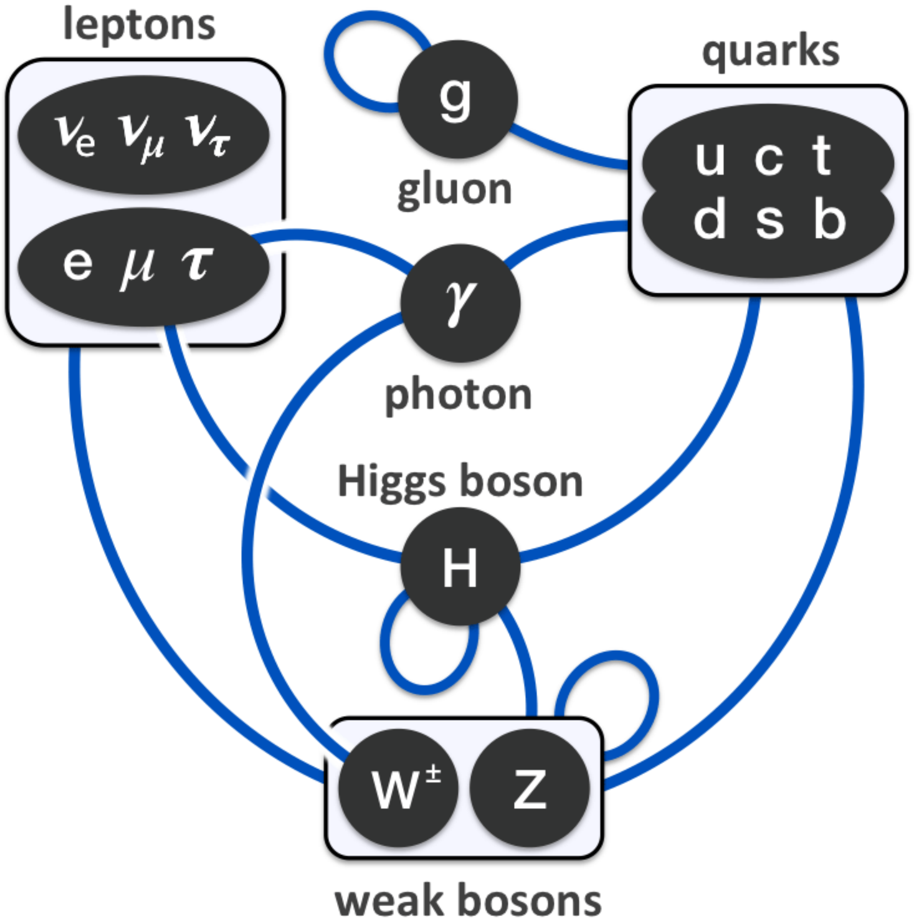
Outline

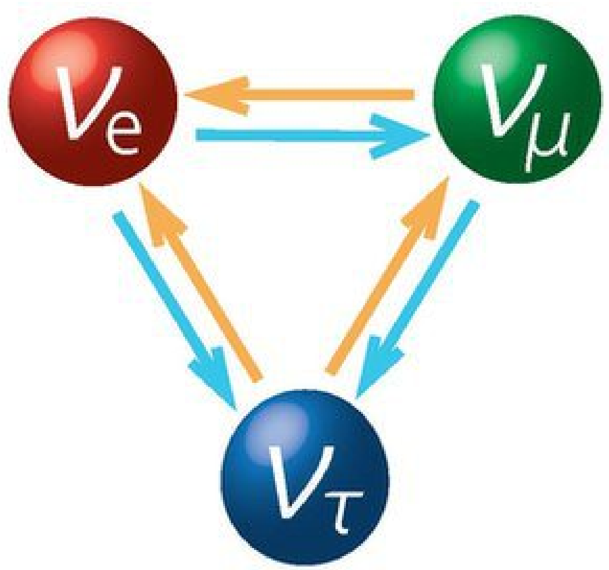
- Motivation
- Detector
- Background Estimation
- Discriminating Variables
- Result

The Standard Model(SM) of Particle Physics



- Describes 3 of the 4 fundamental forces in nature
- Matter particles (fermions) and their interactions (bosons)
- Include a mechanism to generate masses of these particles
- Demonstrated huge successes in providing experimental predictions

Neutrino Oscillations



- Neutrino oscillations observed by a multitude of experiments
- Flavor eigen states are a mixture of different mass eigen states
- Neutrinos are massive.

Give neutrino mass with mechanism in SM?

- Neutrino is the only fermion with no charge.
- Too light (< 0.120 eV/c^2)
- If follow the Yukawa form as other fermions, right-handed neutrino is needed.
- Only role is to allow for non-zero neutrino masses.
- But neutrino could be a Majorana fermion

Extensions of the Standard Model

Ultra-violet complete model

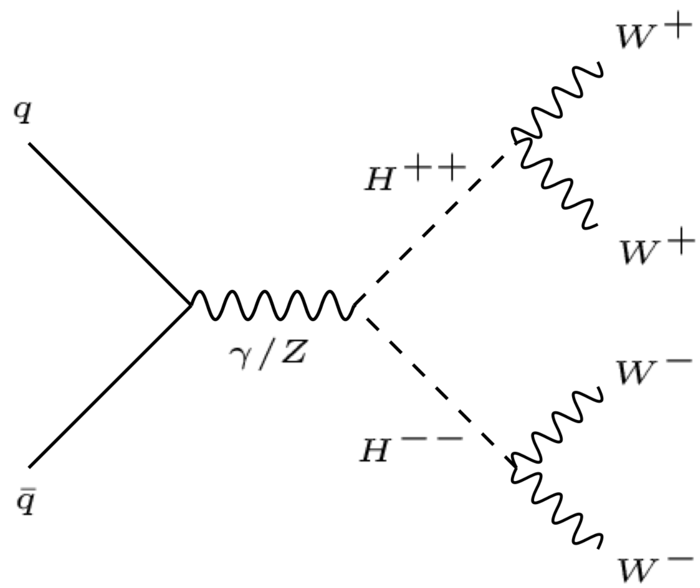
- Type-II Seesaw Model is an example (Phys. Rev. D84 (2011) 095005)
  - Extend the Higgs-Sector in SM by adding $SU(2)_L$ triplet Δ
  - $m_\nu \sim Y_\nu v_\Delta \sim \mu v_0^2/M_\Delta^2$ (v_0 is SM higgs v.e.v., v_Δ is v.e.v. of the triplet Δ, M_Δ is mass of th triplet)
- An explanation of the oscillations and finite mass of neutrinos.
- Predicting new scalars, some of which have mass in electroweak scale range.

Scalar Sector

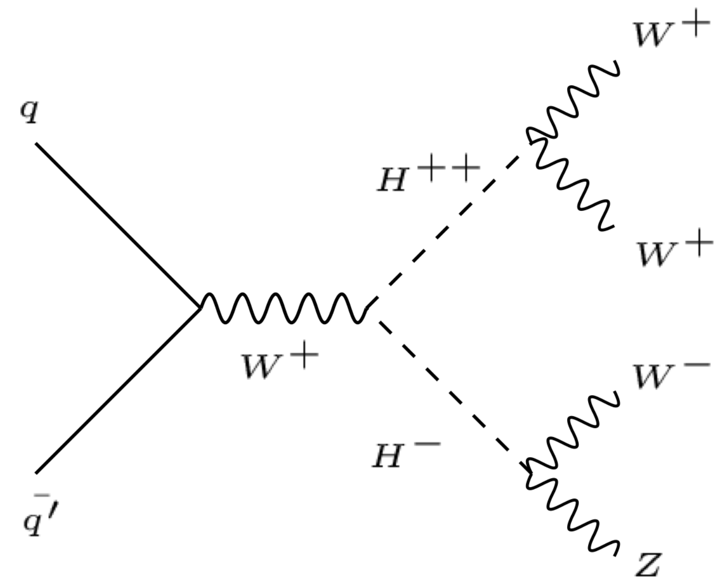
- $\mathcal{L} = (D_\mu H)^\dagger (D^\mu H) + Tr(D_\mu \Delta)^\dagger (D^\mu \Delta) - V(H,\Delta) + \mathcal{L}_{Yukawa}$
- $\mathcal{L}_{Yukawa} = \mathcal{L}_{Yukawa}^{SM} - Y_\nu L^T C \otimes i\sigma^2 \Delta L + h.c.$
  - Y_ν: neutrino Yukawa couplings
  - L: $SU(2)_L$ doublets of left-handed leptons
  - C: the charge conjugation operator

Production Mode

Pair Production

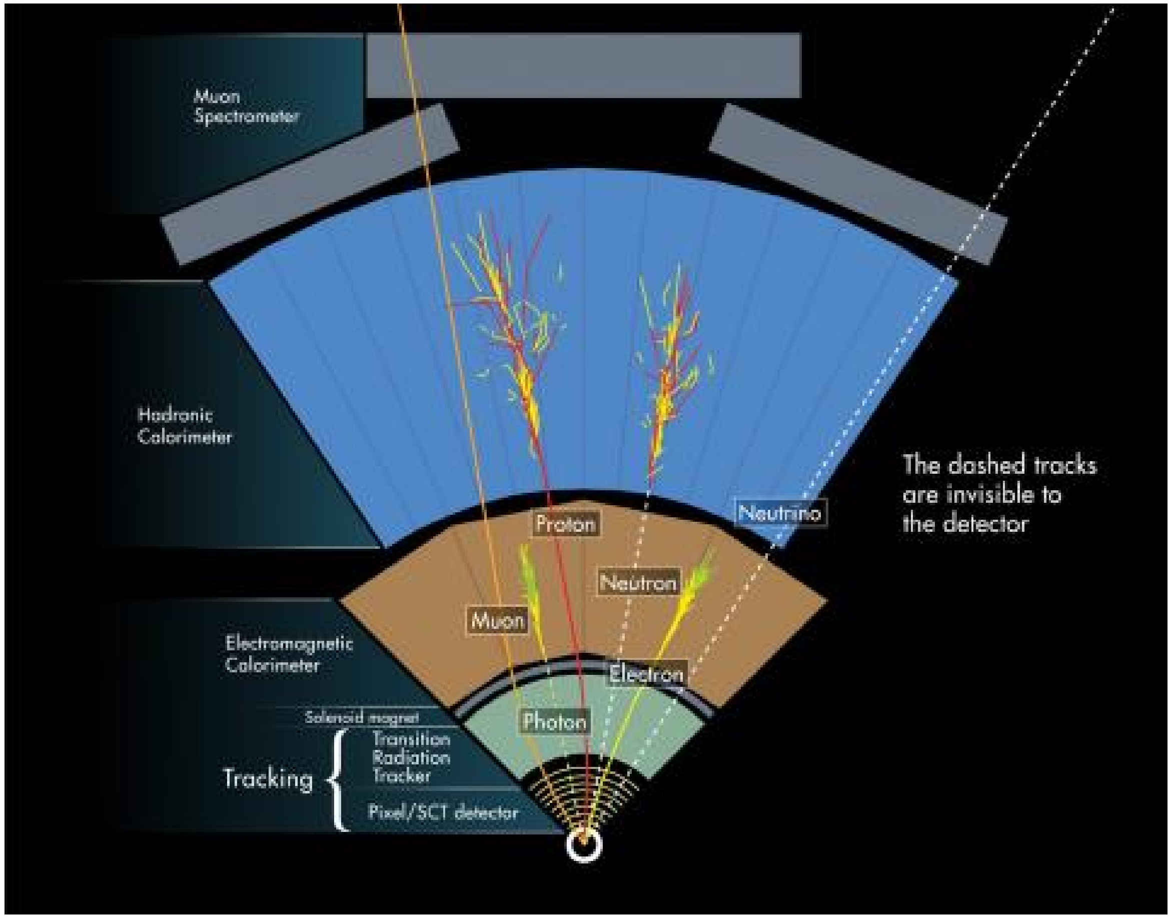


Associated Production



- Focus on the pair production mode: $pp \to \gamma^*, Z^* \to H^{\pm\pm}H^{\mp\mp}$
- Require $H^{\pm}$ heavier than the $H^{\pm\pm}$ by a few 100 GeV to suppress the associated production.
- Require higher ν_{Δ}(0.1 GeV) to suppress $H^{\pm\pm} \to \ell^{\pm}\ell^{\pm}$((arxiv: 1710.09748)) decay mode
  - Assuming BR($H^{\pm\pm} \to \ell^{\pm}\ell^{\pm}$) = 100%, model is excluded for $m_{H^{\pm\pm}} < 800$ [GeV]
- $H^{\pm\pm} \to W^{\pm}W^{\pm}$ (This analysis) as complements.

Atlas Detector

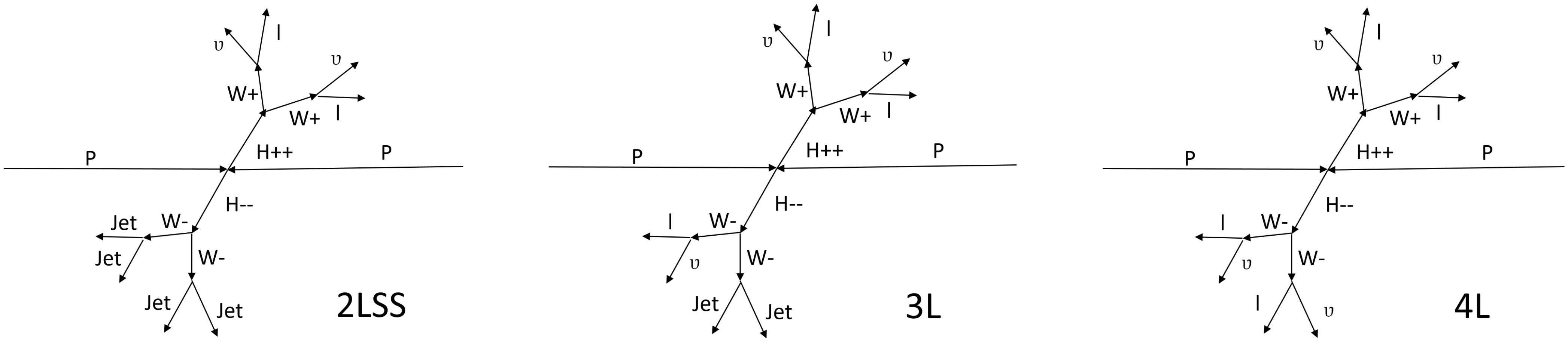


Object considered in this analysis

- Electron, Muon.
- Jets
  - Initiated by quarks and gluons that hadronise in jet of hadrons
- Missing Tranverse Energy(E_T^{miss})
  - Defined as the transverse momentum imbalance in the detector

Topology

Three channels with different final states.



- Two same sign leptons, E_T^{miss} and four jets.
- Three leptons, E_T^{miss} and two jets.
- Four leptons, and E_T^{miss} .
- Consider different masses of $H^{\pm\pm}$, from 200 GeV to 700 GeV. (100 GeV step)

Data and MC samples

Data

pp collision data at $\sqrt{s}$ = 13 TeV during 2015-2016, integrated luminosity = 36.1 fb^{-1}

Prompt background

- $t\bar{t}H$, $t\bar{t}V$
- VH
- $VV(V)$, $V\gamma$

(Note: V means vector bosons W, Z)

Signal Sample

- $H^{\pm\pm}H^{\mp\mp}$: 6 $m_{H^{\pm\pm}}$ points (200-700 GeV)
  CalcHEP generator, Pythia 8 parton shower

$m_{H^{\pm\pm}}$ [GeV]	200	300	400	500	600	700
cross-section (fb)	64.58	13.34	3.998	1.466	0.610	0.276

Overview of $2\ell ss$ channel

$2\ell ss$ channel

$H^{\pm\pm}H^{\mp\mp} \to 4W \to \ell^{\pm}\ell^{\pm} + E_T^{\text{miss}} + 4\text{jets}$

Three sub channels: $ee, e\mu, \mu\mu$

Background

- Background from prompt leptons:
  WZ, ZZ, same-sign WW, etc: Monte Carlo Simulation.
- Charge-MisID background:
  W^+W^- and Z+jets: Data-driven likelihood method.
- Background from fake leptons:
  Z+jets, W+jets and $t\bar{t}$: data-driven fake-factor method.

Background Estimation

Event Pre-Selection

- Trigger requirement (at least one lepton p_T > 24 GeV)
- Two tight leptons, p_T > 30, 20 GeV
  - Tight means several requirement about lepton performance in detector
  - p_T > 30 GeV to ensure efficient triggering
- M_{ll} <80 GeV or M_{ll} > 100 GeV for ee channel
  - Suppress the Z+jets Charge-MisID background.
- No b-jet (jet with b-hadron)
  - Suppress the $t\bar{t}$ Fake-Lepton backgrond.
- N_{jets} >= 3
- E_T^{miss} > 70 GeV

2015	2016
HLT_e26_lhmedium_L1EM20VH for data set	HLT_e26_lhtight_nod0_ivarloose
HLT_e60_lhmedium	HLT_e60_lhmedium_nod0
HLT_e120_lhloose	HLT_e140_lhloose_nod0
HLT_mu20_iloose_L1MU15	HLT_mu26_ivarmedium
HLT_mu50	HLT_mu50

Background Estimation: Charge-MisID

Likelihood Method

$$\ln \mathcal{L}(\varepsilon | N_{tot}, N_{ss}) = \sum_{i,j} \ln \left[N_{tot}^{i,j} (\varepsilon_i + \varepsilon_j) \right] N_{SS}^{i,j} - N_{tot}^{i,j} (\varepsilon_i + \varepsilon_j) \tag{1}$$

- Detector may measure wrong charge with an electron.
- Measured Charge-MisID rates in Z-enrich region (Which suppress Z-jets before) with likelihood method.
- Likelihood based on possion statistics of N_{ss}, of which the mean value is a function of Charge-MisID rate.
- Using opposite-sign event with Charge-MisID rates to calculate same-sign event in other region.
- Charge-MisID rates nominal results: $[0.021, 9.921]$ in percent for different kinematic bins
- Several systematic uncertainty taken due to background, kinematic difference and binning. (30%)

Background Estimation: Fake-Leptons

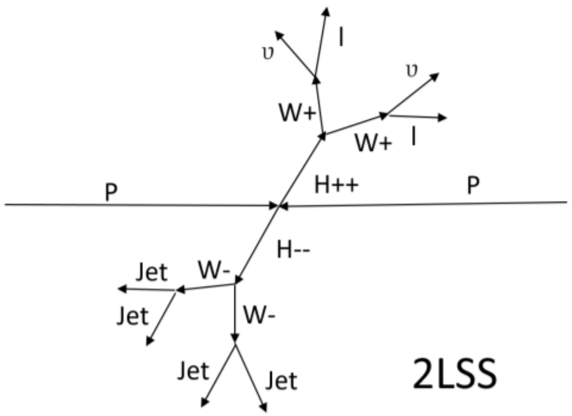
Definition for fake-factor measurement

- T(ℓ): lepton pass tight requirement.
- L($\not\ell$):lepton pass a requirement looser than tight, but failed passing tight.

Fake-factor measurement

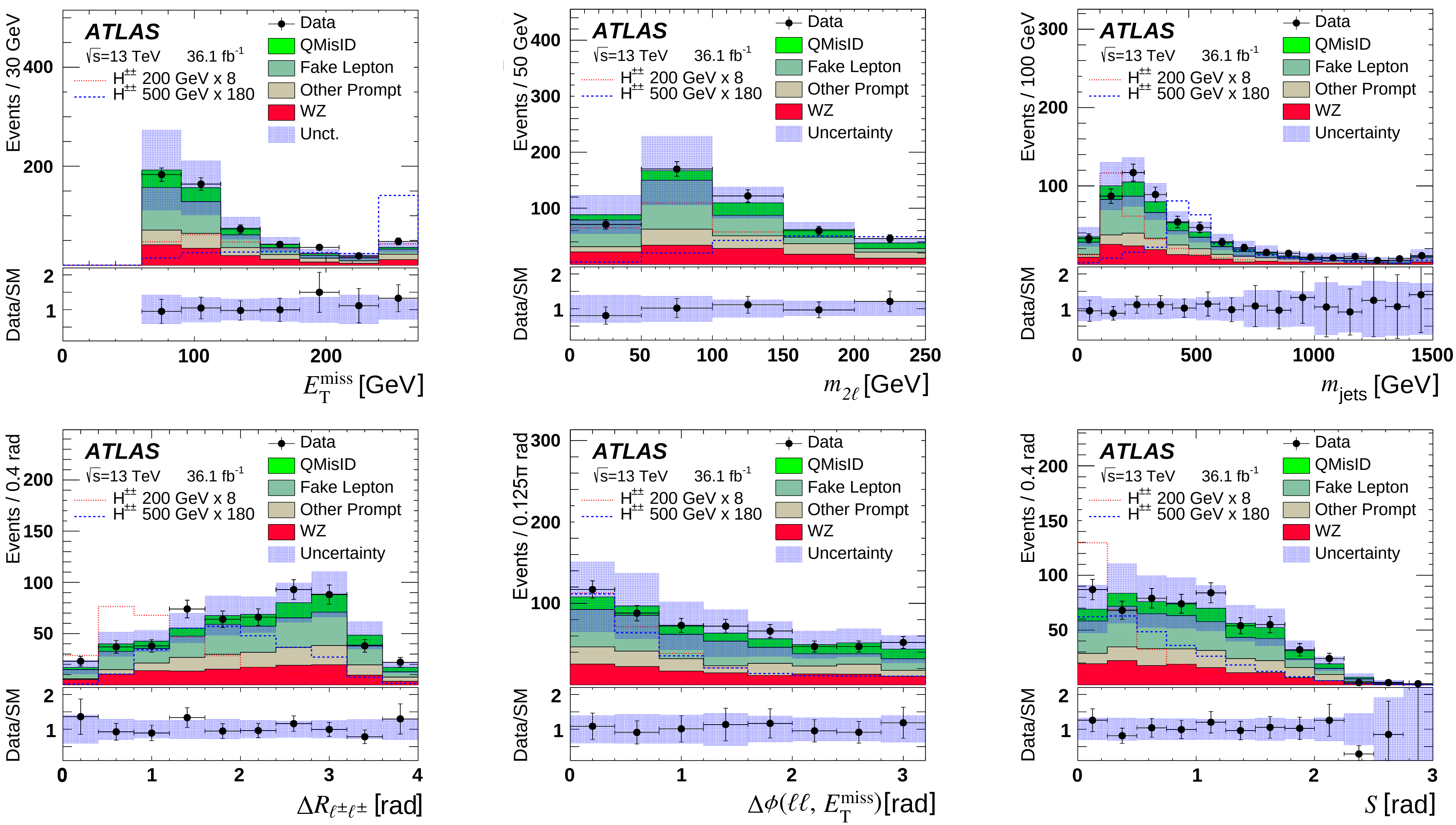
- Factor measured in $E_T^{miss} < 70$ GeV. extrapolated to $E_T^{miss} > 70$ GeV
- $\theta_\mu = \frac{N_{\mu\mu}}{N_{\mu\not\mu}}(E_T^{miss} < 70 \text{ GeV}) = \frac{N_{\mu\mu}^{Data} - N_{\mu\mu}^{\text{Prompt } SS}}{N_{\mu\not\mu}^{Data} - N_{\mu\not\mu}^{\text{Prompt } SS}}$ measured in $\mu\mu$ channel
- $\theta_e = \frac{N_{\mu e}}{N_{\mu\not e}}(E_T^{miss} < 70 \text{ GeV}) = \frac{N_{\mu e}^{Data} - N_{\mu e}^{\text{Prompt } SS} - N_{\mu e}^{\text{QMisId}} - N_{\mu e}^{\text{FakeMuon}}}{N_{\mu\not e}^{Data} - N_{\mu\not e}^{\text{Prompt } SS} - N_{\mu\not e}^{\text{QMisId}}}$ measured in $e\mu$ channel
- Fake-factor were using with TL($\ell\not\ell$) events in Event Pre-selection to estimate Fake-Leptons contribution to TT($\ell\ell$) events
- The measured muon fake factor is 0.14$\pm$0.08, and the measured electron fake factor is 0.48$\pm$0.25 (with Systematics uncertainty)

Discriminating Variables: Definition



- Three Mass-related Variables:
  - E_T^{miss}: Missing transverse energy
  - $M_{\ell\ell}$: Invariant mass of $\ell\ell$.
  - M_{jets}: Invariant mass of the system composed of all jets
- Three Angular Variables:
  - $\Delta R_{\ell^{\pm}\ell^{\pm}}$: the distance in $\eta - \phi$ between two same-sign leptons
  - $\Delta\Phi(\ell\ell, E_T^{miss})$: the difference in azimuth between the dilepton system and missing transverse energy
  - Variable S: $S = \frac{\mathcal{R}(\phi_{\ell_1},\phi_{\ell_2},\phi_{E_{\mathrm{T}}^{\mathrm{miss}}})*\mathcal{R}(\phi_{j1},\phi_{j2},\cdots)}{\mathcal{R}(\phi_{\ell_1},\phi_{\ell_2},\phi_{E_{\mathrm{T}}^{\mathrm{miss}}},\phi_{j1},\phi_{j2},\cdots)}$.: $\mathcal{R}$ is the root mean square that quantifies the spread, $\mathcal{R}(\phi_1,\ldots,\phi_n) = \sqrt{\frac{1}{n}\sum_{i=1}^{n}(\phi_i - \overline{\phi})^2}$

Discriminating Variables



Overview of 3ℓ channel

3ℓ channel

- $H^{\pm\pm}H^{\mp\mp} \to 4W \to \ell^{\pm}\ell^{\mp}\ell^{\mp} + E_T^{\text{miss}} + 2$jets
- Two subchannel: SFOS0, SFOS1,2
- SFOS0: no same flavor opposite sign leptons
- SFOS1,2: presence of same-flavor opposite sign leptons

Background

Background from prompt leptons:

- WZ, ZZ, etc: Monte Carlo

Background from fake leptons:

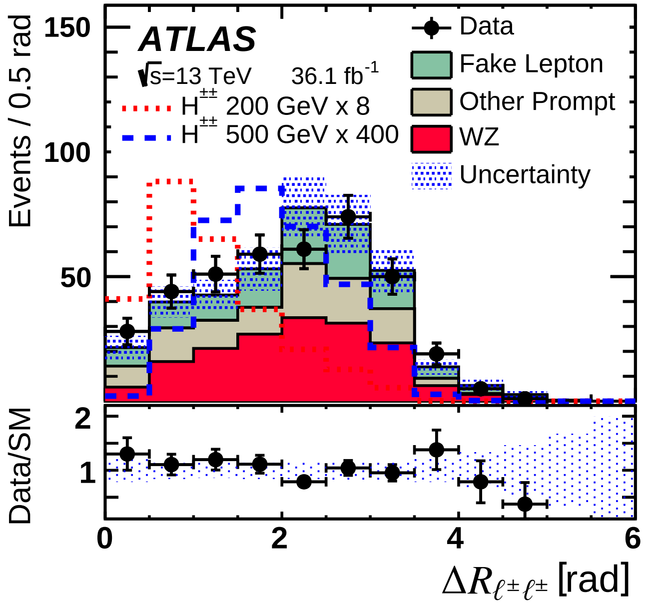
- $t\bar{t}$, Z+jets:
  data-driven fake-factor method.

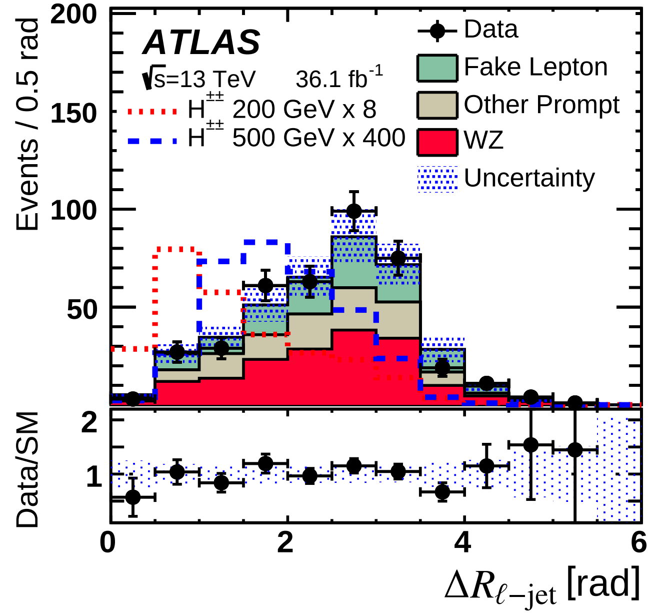
$$\theta_{e/\mu} = \frac{(Data - N_{prompt})_{\text{xee}/\text{x}\mu\mu}}{(Data - N_{prompt})_{\text{xe}\not{e}/\text{x}\mu\not{\mu}}} \quad (2)$$

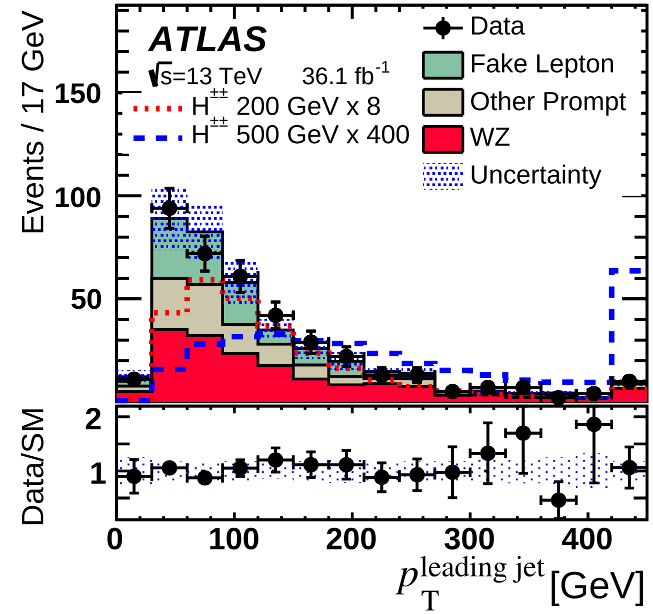
Pre-Selection(Red), Fake-enrich(Blue)

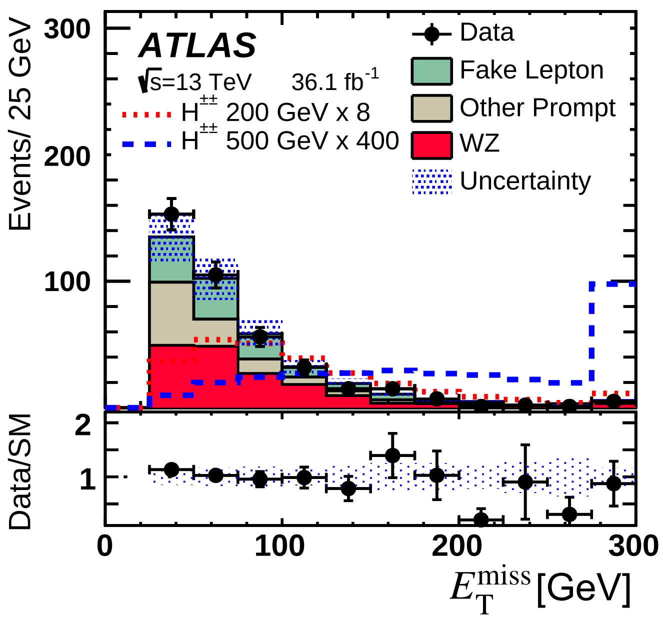
	Selection Criteria	Y	X	Z	T
A	Three leptons with $P_T^{0,1,2} > 10, 20, 20GeV$	√	√	√	√
B	$\lvert M_{01} - M_Z \rvert > 10$ GeV and $\lvert M_{02} - M_Z \rvert > 10$ GeV	√	√		√
*	$\lvert M_{01} - M_Z \rvert \leq 10$ GeV or $\lvert M_{02} - M_Z \rvert \leq 10$ GeV			√	
	$M_{01} > 15$ GeV and $M_{02} > 15$ GeV	√	√		√
	$MET > 30$ GeV		√		√
	$N_{\text{jet}} >= 2$		√		√
*	$N_{\text{jet}} = 1$	√			
*	$N_{\text{jet}} >= 1$			√	
C	$N_{\text{b-jet}} = 0$		√	√	
*	$N_{\text{b-jet}} >= 1$				√

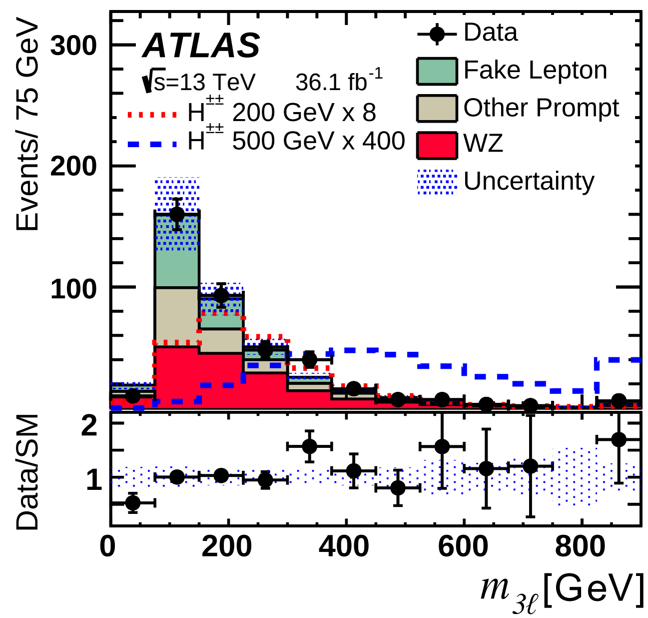
Discriminating Variables: Distribution after Pre-selection(3L)











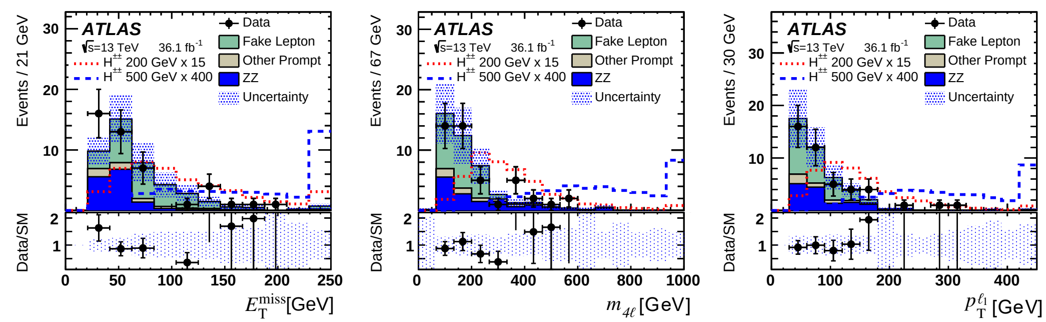
Overview of 4ℓ channel

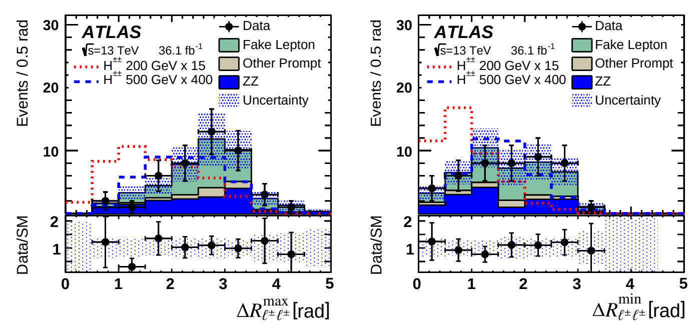
4ℓ channel

- $H^{\pm\pm}H^{\mp\mp} \to 4W \to \ell^{\pm}\ell^{\pm}\ell^{\mp}\ell^{\mp} + E_T^{\text{miss}}$

background

- Background from prompt leptons: Monte Carlo
- Background from fake leptons: Process-dependent scale factors to correct Monte Carlo





Selection Criteria
4 Leptons
$Q = 0$, trigger match
$\lvert M_{\ell^+\ell^-} - M_Z\rvert > 10$ GeV
$M_{\ell^+\ell^-} > 12$ GeV
$MET > 30$ GeV
$N_{b-jet} = 0$

Systematics

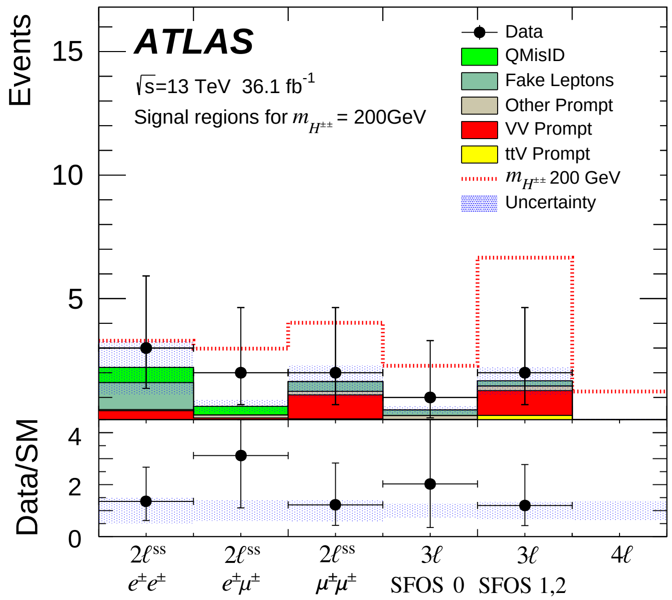
Systematics included	Relative error (%)
Theoretical uncertainties	$\sim$15%
Cross section measurements	20$\sim$30%
Luminosity measurements	$\sim$2.2%
Data-driven background estimation	30$\sim$80%
Detector simulation	5$\sim$40%

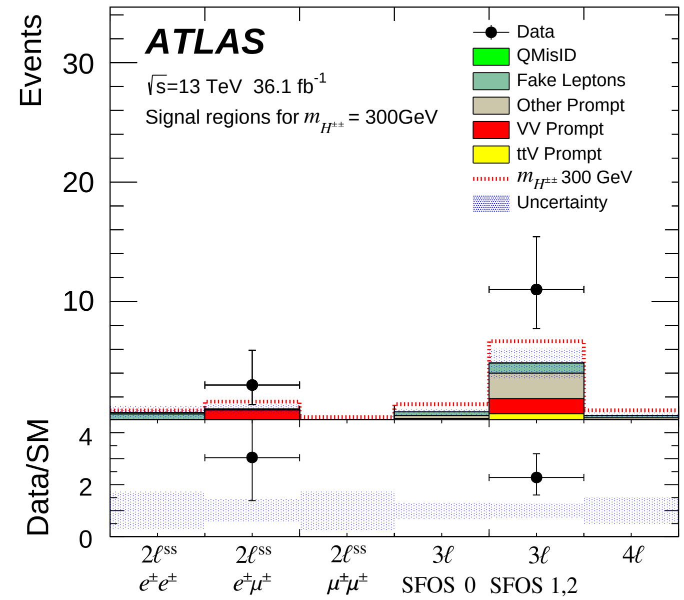
Signal Region

Strategy used to extract the signal

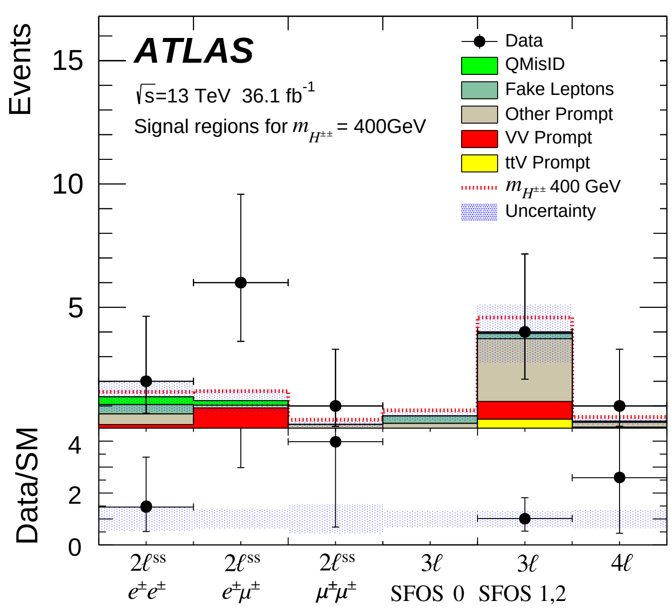
- based on rectangular cut optimisation from TMVA
- Six sub-channel (ee, $e\mu$, $\mu\mu$, $SFOS0$, $SFOS1,2$, 4ℓ) and six $m_{H^{\pm\pm}}$ optimized independently
- Choose the cut with highest expected significance as the baseline of the definition of the signal regions

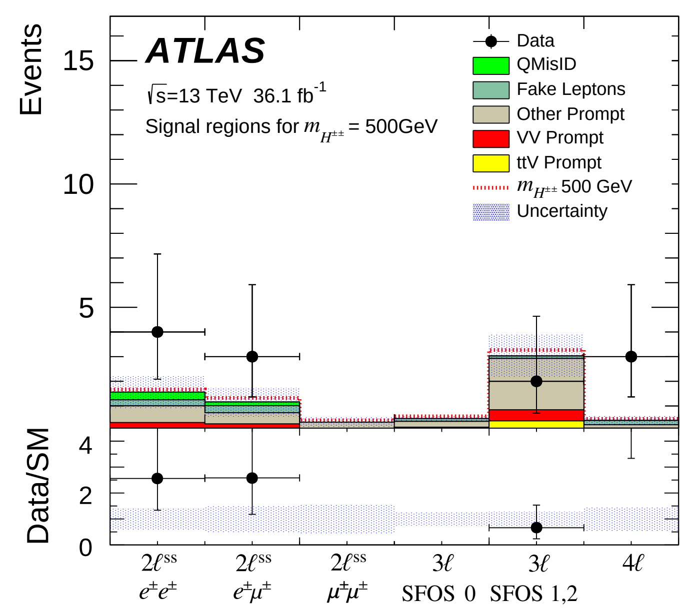
Signal Region



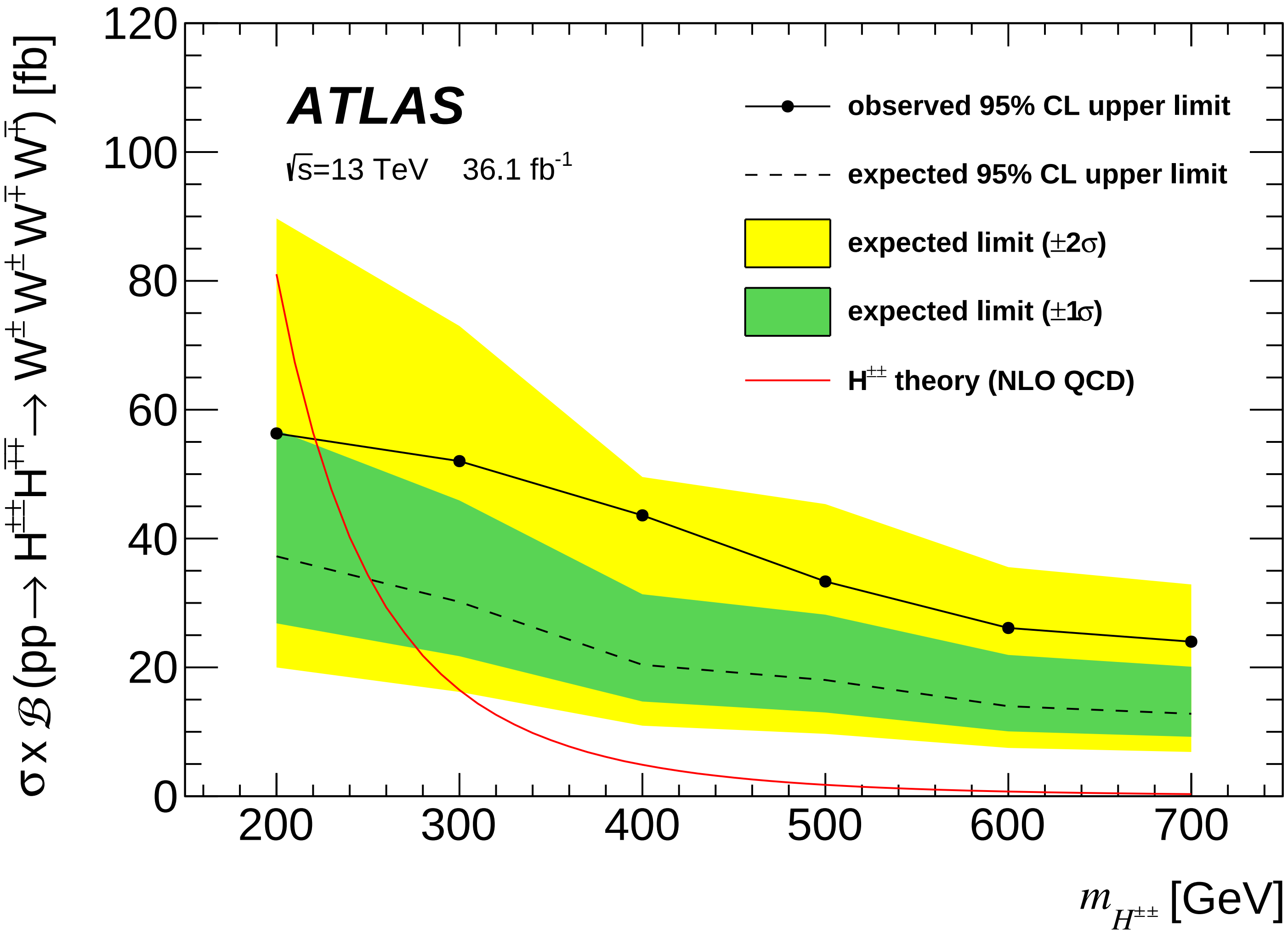


No significant signal observed, set limits.





Result (Upper Limit)



- Expected (observed) limits for the combination of $2\ell ss$, 3ℓ, 4ℓ channel.
- Limits are calculated based on likelihood ratio test. (95% CL)
- Mass range of 200 - 220 GeV excluded in the benchmarking model.

Conclusion

Status

- This is the first search for $H^{\pm\pm} \to W^{\pm}W^{\pm}$ at colliders
- No significant signal observed, limits are derived.
- Mass range of 200 - 220 GeV excluded in the benchmark model.
- Paper is accepted to EPJC.

Future: Next Run.

- Use full Run-2 data
- Associated production $pp \to W^{*+} \to H^{\pm\pm}H^{\mp}$

Back Up

Back Up

Back Up:Doublet-triplet-Higgs-Model

Higgs potential in Seesaw Model

$$V(H,\Delta) = -m_H^2 H^\dagger H + \frac{\lambda}{4}(H^\dagger H)^2 + m_\Delta^2 Tr(\Delta^\dagger\Delta)$$
$$+[\mu(H^\dagger i\sigma^2\Delta^\dagger H) + h.c.] + \lambda_1(H^\dagger H)Tr(\Delta^\dagger\Delta) + \lambda_2(Tr\Delta^\dagger\Delta)^2 + \lambda_3 Tr\left(\Delta^\dagger\Delta\right)^2$$
$$+\lambda_4 H^\dagger\Delta\Delta^\dagger H.$$

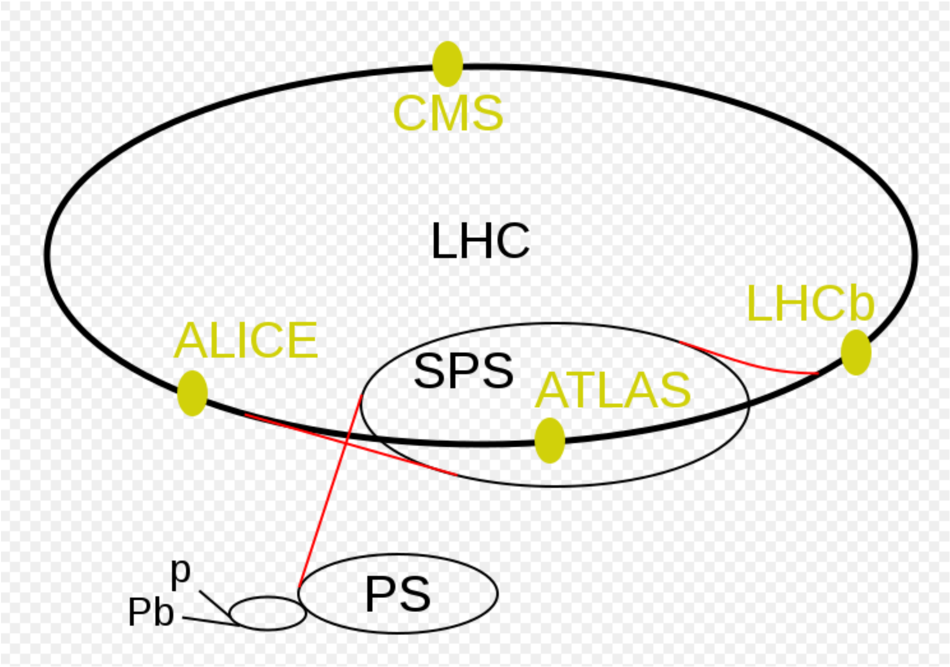
- Parameters: 5 independent couplings λ, 3 mass parameters $m_H^2,\ m_\Delta^2,\ \mu$
- SM-like Higgs naturally available. Can be either h^0 or H^0.
- Electro-Weak Symmetry Breaking results in 7 scalar bosons: $H^{\pm\pm},\ H^\pm,\ \Lambda^0(CP\ odd),\ H^0(CP\ even),\ h^0(CP\ even)$

Explanation and Prediction

- An explanation of the oscillations and finite mass of neutrinos.
- Predicting new scalars, some of which have mass in electroweak scale range.

Large Hadron Collider (LHC)

- Proton-Proton collision $@\sqrt{S} = 13TeV$
- $\mathrm{L} = 2 * 10^{34} cm^{-2} s^{-1}$
- 4 experiments: ATLAS, CMS, ALICE and LHCb
- Purpose:
  - Search for new physics
  - Precise measurement of parameters in EW and SM higgs



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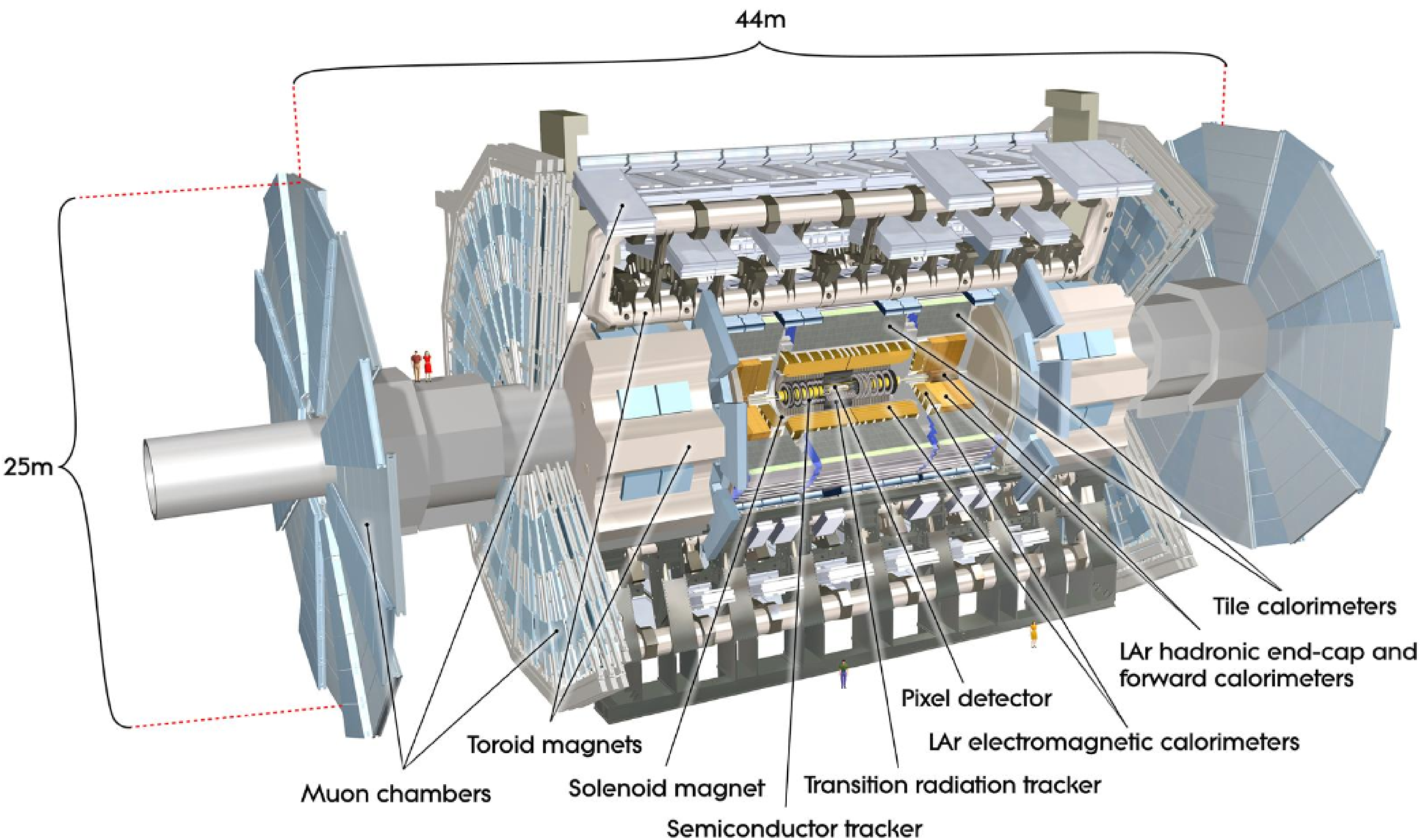

Background Estimation: Charge-MisID

Likelihood Method

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Background Estimation: Fake-Leptons

Definition for fake-factor measurement

- T(ℓ): lepton pass tight requirement.
- L($\not\ell$):lepton pass a requirement looser than tight, but failed passing tight.

Fake-factor measurement

- Factor measured in $E_T^{miss} < 70$ GeV. extrapolated to $E_T^{miss} > 70$ GeV
- $\theta_\mu = \frac{N_{\mu\mu}}{N_{\mu\not\mu}}(E_T^{miss} < 70 \text{ GeV}) = \frac{N_{\mu\mu}^{Data} - N_{\mu\mu}^{\text{Prompt } SS}}{N_{\mu\not\mu}^{Data} - N_{\mu\not\mu}^{\text{Prompt } SS}}$ measured in $\mu\mu$ channel
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Backup: Mass-related Variables

- Three Mass-related Variables:
  - E_T^{miss}: Missing transverse energy
  - $M_{\ell\ell}$: Invarient mass of $\ell\ell$.
  - M_{jets}: Invarient mass of the system composed of all jets
- Signal Characteristics:
  - All signal events are expected to feature significant E_T^{miss}
  - $M_{\ell\ell}$ and M_{jets} are closely related to $m_{H^{\pm\pm}}$

Backup: Angular Variables

- Three Angular Variables:
  - $\Delta R_{\ell^\pm\ell^\pm}$: the distance in $\eta-\phi$ between two same-sign leptons
  - $\Delta\Phi(\ell\ell, E_T^{miss})$: the difference in azimuth between the dilepton system and missing transverse energy
  - Variable S: $S = \frac{\mathcal{R}(\phi_{\ell_1},\phi_{\ell_2},\phi_{E_\mathrm{T}^\mathrm{miss}}) * \mathcal{R}(\phi_{j1},\phi_{j2},\cdots)}{\mathcal{R}(\phi_{\ell_1},,\phi_{\ell_2},\phi_{E_\mathrm{T}^\mathrm{miss}},\phi_{j1},\phi_{j2},\cdots)}$: $\mathcal{R}$ is the root mean square that quantifies the spread, $\mathcal{R}(\phi_1,\ldots,\phi_n) = \sqrt{\frac{1}{n}\sum_{i=1}^{n}(\phi_i-\overline{\phi})^2}$
- Signal Characteristics:
  - Due to spin correlations with low $m_{H^{\pm\pm}}$
  - $\ell^\pm\ell^\pm$ will emit in the closed direction as $H^{\pm\pm}$
  - $\ell^\pm\ell^\pm$ tend to be close in the $\eta-\phi$ plane
  - Small spread in both $\ell^\pm\ell^\pm - E_T^{miss}$ and $jets$ system
  - This correlations will break with high $m_{H^{\pm\pm}}$

Back Up: Preparation of the next round

- Reprocessing new version data/MC.
- ChargeFlip ScaleFactor with ChargeFlip Killer
  - ChargeFlip ScaleFactor: produced from performance group
  - ChargeFlip Killer: a tool reject ChargeFlip electrons
- PromptLepVeto: a tool reduce fake leptons
- Associate production
- Full Run-2 stat $150fb^{-1}$
- sinergy with $t\bar{t}H$ analysis (similar final states)

Back Up: Detector resolution

Detector component	**Required resolution**	**η coverage**	
		Measurement	Trigger
Tracking	$\sigma_{p_T}/p_T = 0.05\%\ p_T \oplus 1\%$	± 2.5	
EM calorimetry	$\sigma_E/E = 10\%/\sqrt{E} \oplus 0.7\%$	± 3.2	± 2.5
Hadronic calorimetry (jets)			
barrel and end-cap	$\sigma_E/E = 50\%/\sqrt{E} \oplus 3\%$	± 3.2	± 3.2
forward	$\sigma_E/E = 100\%/\sqrt{E} \oplus 10\%$	$3.1 < \lvert\eta\rvert < 4.9$	$3.1 < \lvert\eta\rvert < 4.9$
Muon spectrometer	σ_{p_T}/p_T=10% at p_T = 1 TeV	± 2.7	± 2.4

Back Up: Limit Setting

- CL: confidence level
  - $CL_{s+b} = P_{s+b}(X \leq X_{obs/exp}) = \frac{e^{-(s+b)} \sum_{n=0}^{n_{obs/exp}} (s+b)^n}{n!}$
  - $CL_b = \frac{e^{-(b)} \sum_{n=0}^{n_{obs/exp}} (b)^n}{n!}$
  - $CL_s = \frac{CL_{s+b}}{CL_b}$
- X: a test statistic or discriminant
- b: number of expected background events (estimated)
- n_{obs}: number of observed events in data (counted)
- s: estimated signal, when CLs reach 95%
- arXiv:hep-ex/9902006

Likelihood Ratio Test

CLs Method (Confidence level 95%)

- H_0: null hypothesis, signal plus background founded
- H_1: alternative hypothesis, background only.
- Parameter of interest: signal strength
  - $\sigma_{beyond\ SM} / \sigma_{benchmarkmodel}$
- Systematic uncertainties: nuisance parameters constraint with Gaussian PDF.