Search for doubly and singly charged Higgs bosons decaying into vector bosons in multi-lepton final states with the ATLAS detector using proton--proton collisions at $\sqrt{s}$ = 13 TeV

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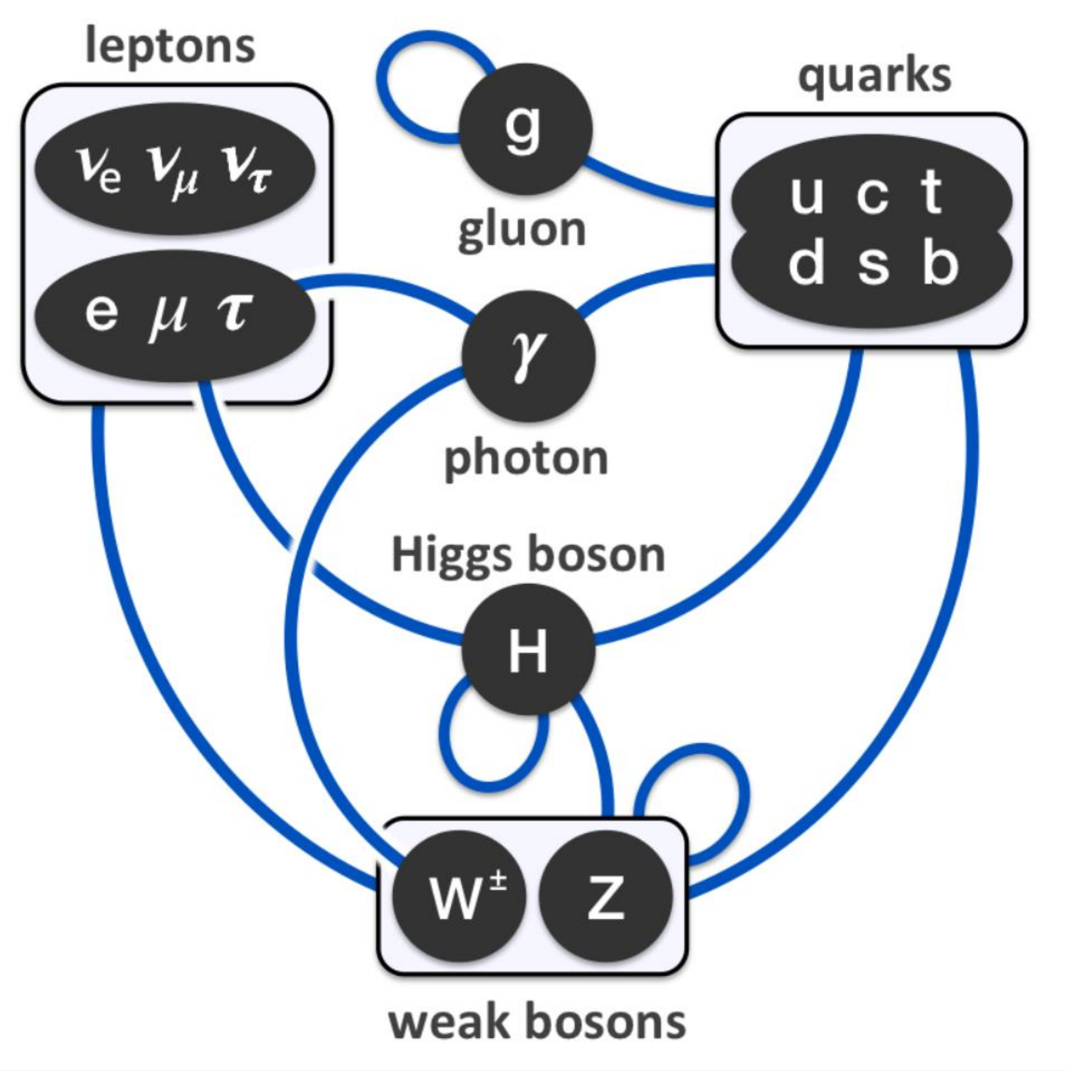
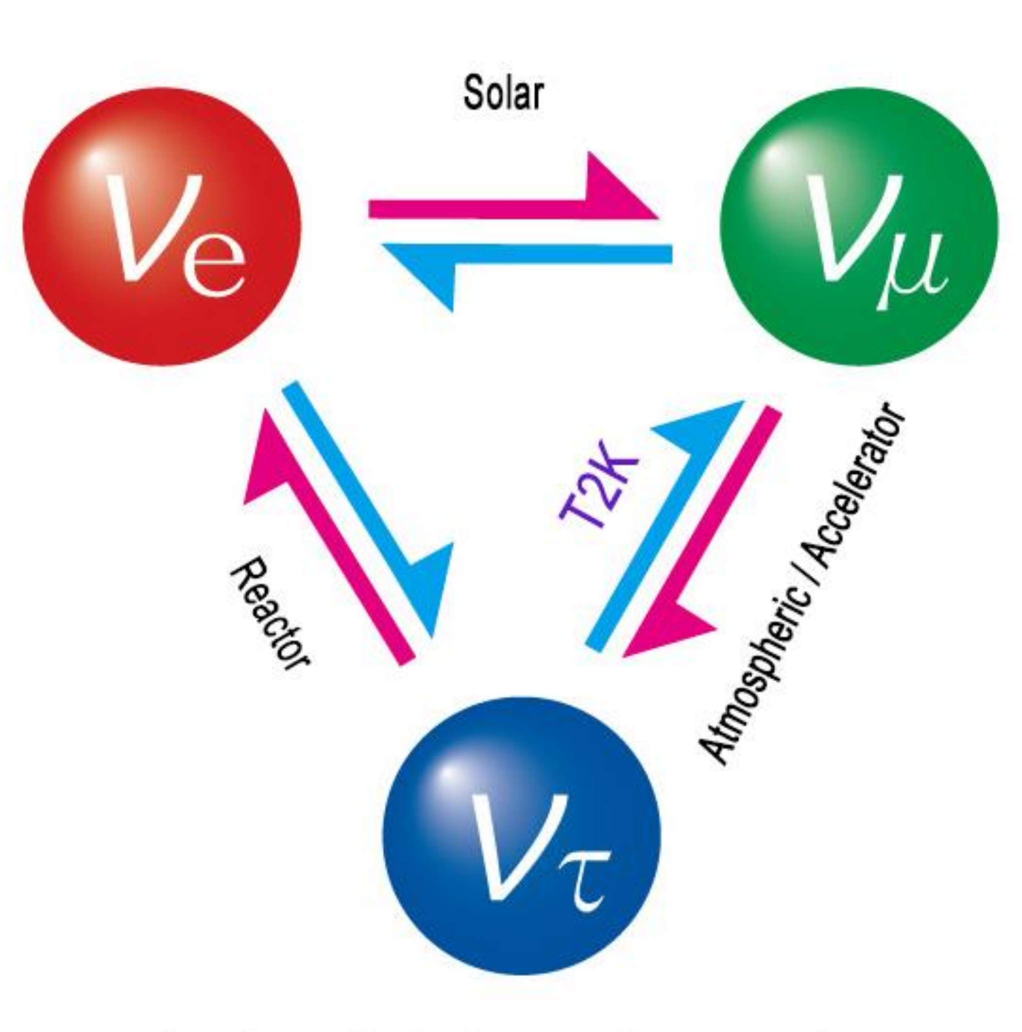
The Standard Model (SM)



- Matter particles (fermions).
  - Leptons and quarks.
- Interactions (bosons).
  - W/Z, photons (γ), gluons (g)
- Higgs mechanism:
  - To generate masses of these particles.
- Demonstrated huge successes in describing experimental measurements.
  - W/Z mass.



Neutrino oscillation between three generations

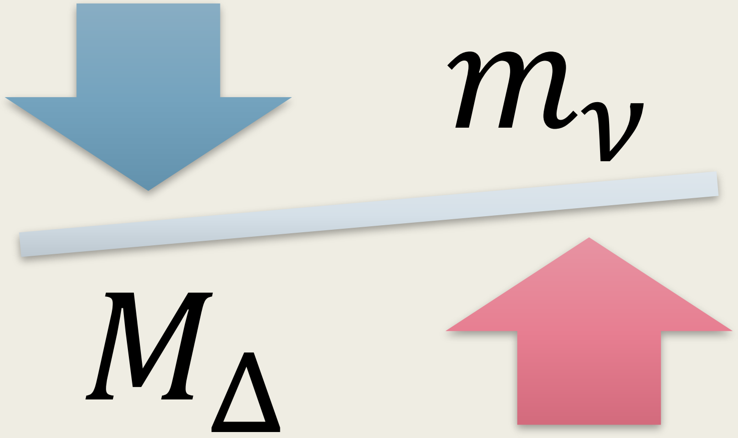
Neutrino Oscillations

- In the SM, neutrinos are massless.
- Neutrino oscillations observed.
  - Flavor eigen states ≠ mass eigen states.
  - Neutrinos are massive.
- How to give neutrinos masses?
  - No charge, and very light.
  - Yukawa form: right-handed neutrino.
  - Majorana fermion.

Extensions of the Standard Model

Doublet Triplet Higgs Model (DTHM)
[Phys.Rev.D 84 (2011) 095005]

- Add $SU(2)_L$ triplet Δ.
- Neutrino masses:
  - $m_\nu \sim \mu \mathbf{v}^2 / M_\Delta^2$. ($M_\Delta$: mass of Δ).
  - Seesaw mechanism.



Electro-Weak Symmetry Breaking

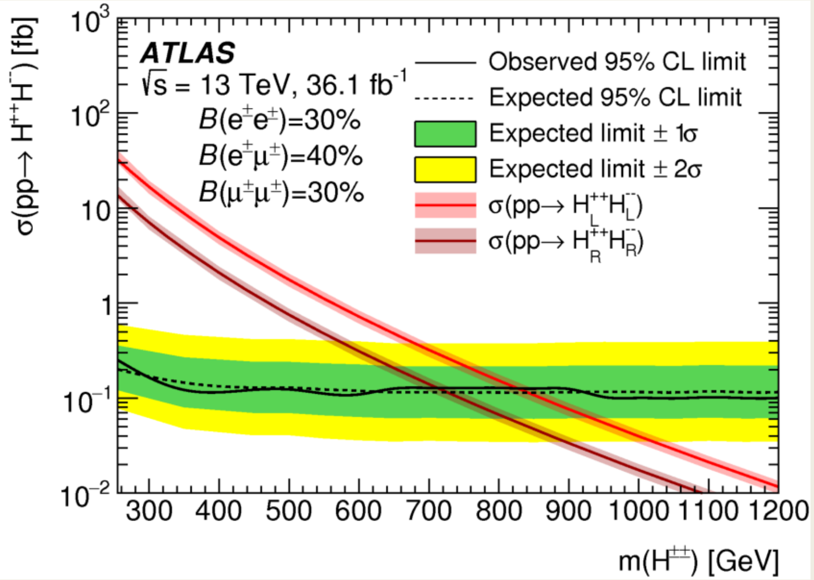
- Happens at $\mathbf{v}_{\mathrm{d(oublet)}}$, $\mathbf{v}_{\mathrm{t(riplet)}}$.
- $\mathbf{v}$: v.e.v of Higgs field.
- 7 scalar bosons: $H^{\pm\pm}$, $H^{\pm}$, A^0, H^0, and the SM h(125).

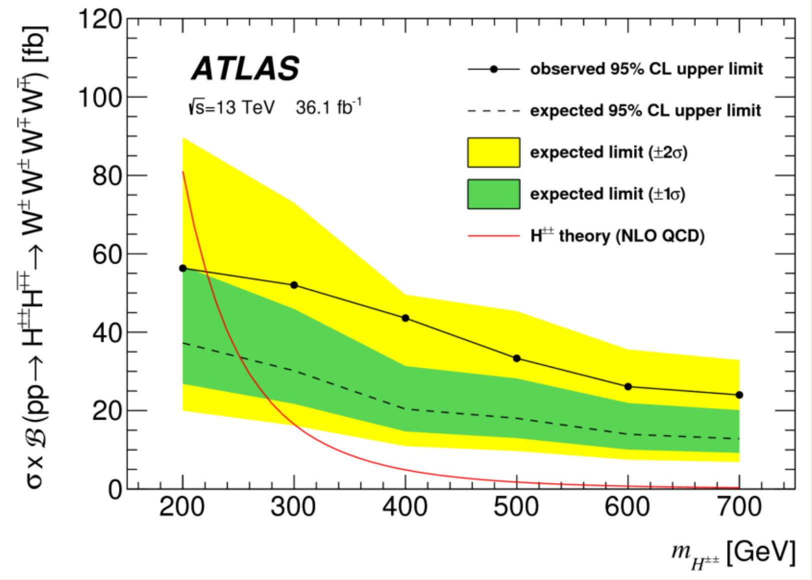
Param. In the Higgs Potential

- Original: λ, λ_{1-4}, M_h, M_Δ, μ.
- Instead: details
  - $m_{BSM-Higgs}$, $\sin\alpha$, $\mathbf{v}_{\mathrm{d}}$, $\mathbf{v}_{\mathrm{t}}$
  - $\sin\alpha$: mixing between H^0, h.

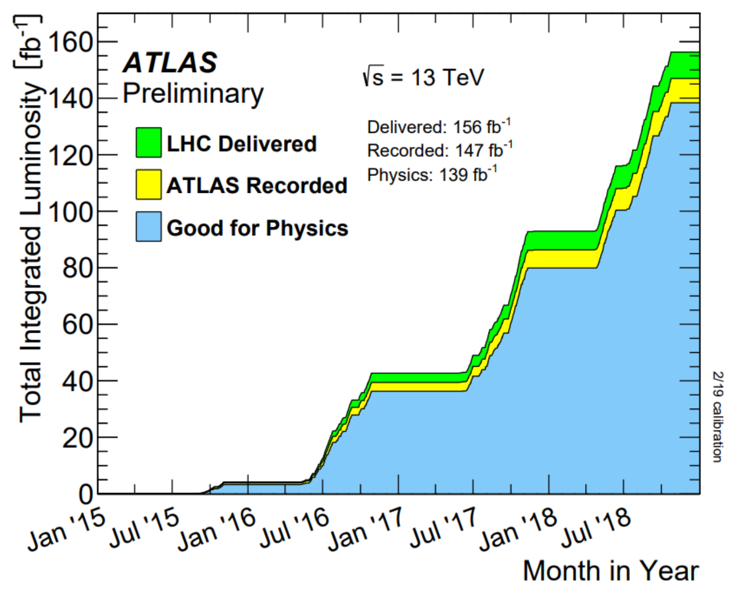
Previous Analysis

- Leptonic: [Eur.Phys.J.C 78 (2018) 3, 199]
  - LRS Model: $H_L^{\pm\pm}$ is similar as $H^{\pm\pm}$ in DTHM.
  - v_t = 0.001 GeV.
  - Excluded at $m_{H^{\pm\pm}} < 770$ GeV
  - Only $pp \rightarrow H^{++}H^{--}$.
- Bosonic: [Eur.Phys.J.C 79 (2019) 1, 58]
  - v_t = 0.1 GeV.
  - With ¼ dataset.
  - Excluded at $m_{H^{\pm\pm}} < 220$ GeV.
  - Only $pp \rightarrow H^{++}H^{--}$.





Data Samples



Years	2015	2016	2017	2018
Lumi [fb^{-1}]	3.2	32.6	44.4	58.5

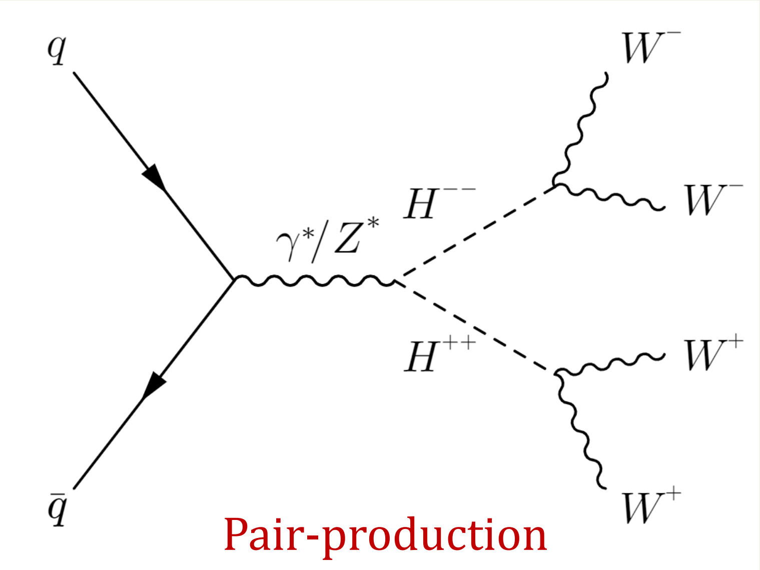
Previous Analysis

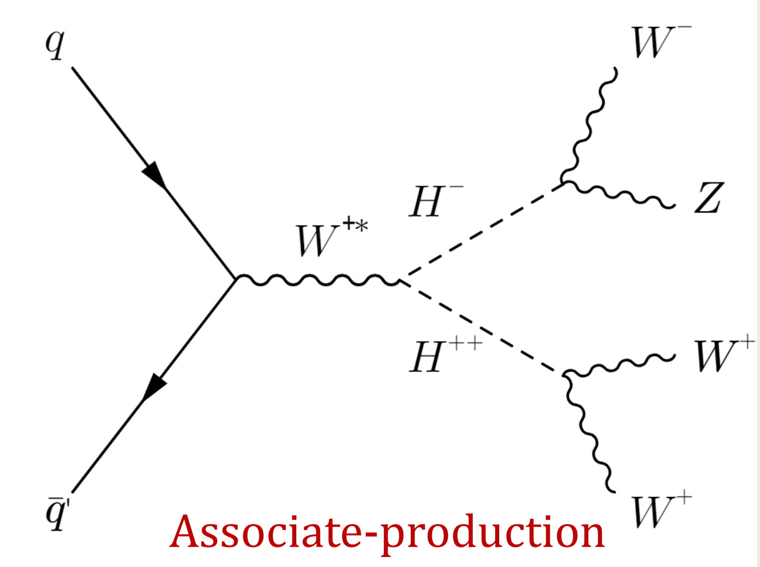
Smaller dataset (36.1 fb^{-1})

$m_{H^{\pm\pm}} < 220$ GeV excluded.

Present Analysis

Full Run-2 dataset (139 fb^{-1})





Signal Production

Production Information:

- ME LO + PDF LO with MG5_AMC.
- k-factor = 1.25 is applied for NLO.
- $m_{H^{\pm\pm}}$ = 200, 300, 400, 500, 600 GeV.

Production modes:

- Pair. prod: $m_{H^{\pm}} > m_{H^{\pm\pm}}$ (> 100 GeV).
- Asso. prod: $m_{H^{\pm}} \sim m_{H^{\pm\pm}}$ (< 5 GeV diff.).

Three channels:

- $2\ell^{sc}$: Two same-charge leptons.
- 3ℓ : Three leptons.
- 4ℓ : Four leptons.

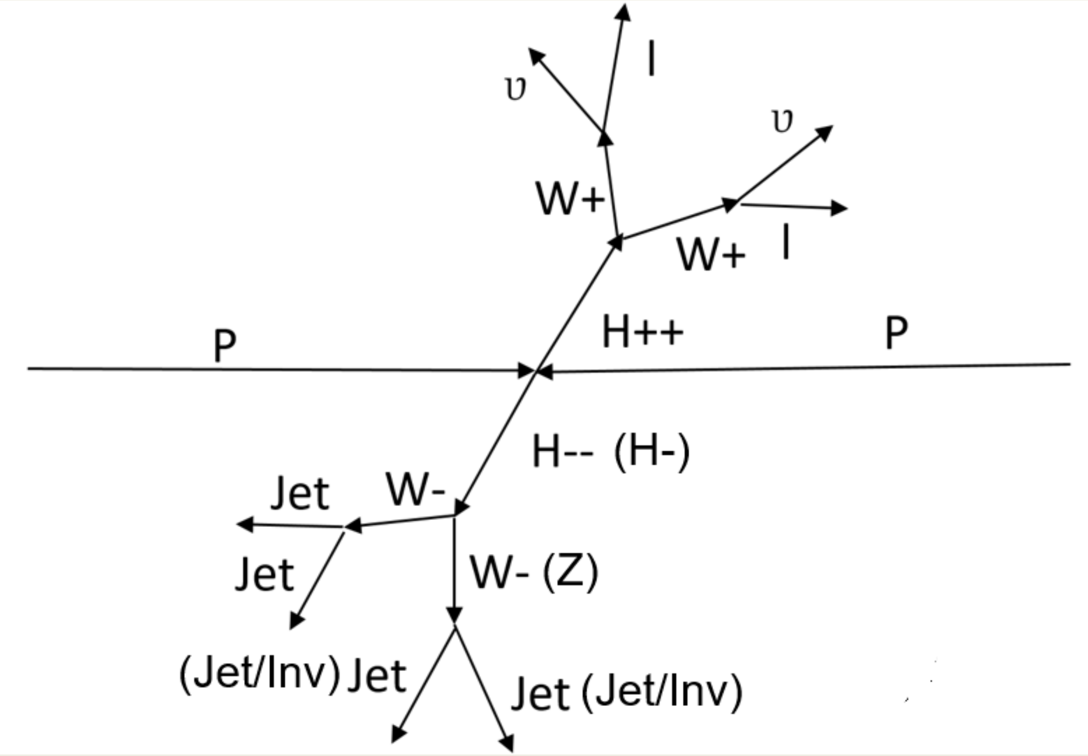
Pair-production

$m_{H^{\pm\pm}}$ (GeV)	200	300	400
xsec (fb)	81.04	16.48	4.883

Associate-production

$m_{H^{\pm\pm}}$ (GeV)	200	300
$m_{H^{\pm}}$ (GeV)	196	295
xsec (fb)	88.66	9.463

Signal Topology



- $H^{\pm\pm} \to W^{\pm}W^{\pm} \to \ell\nu\ell\nu$
- The other W bosons decay to:
  - Jets: $2\ell^{sc}$.
  - Lepton + ν + jets : 3ℓ.
  - Leptons + ν: 4ℓ.
  - Special cases for associate-production: back up.
- Main background:
  - Prompt Leptons (Diboson).
  - Electron charge flip (Z+jets).
  - Non-prompt leptons ($t\bar{t}$).

Event Selection

Trigger

- Single lepton triggers.

Leptons

- $2\ell^{sc}$, 3ℓ, 4ℓ.

E_T^{miss}, to suppress Z+jets(γ)

- $>$ 70 GeV ($2\ell^{sc}$), $>$ 30 GeV (3ℓ, 4ℓ).

Z-veto

- $|m_{ee} - m_Z| >$ 10 GeV ($2\ell^{sc}$, charge flip).
- $|m_{OC} - m_Z| >$ 10 GeV, $m_{OC} >$ 15 GeV (3ℓ, 4ℓ).
- $m_{4l} >$ 100 GeV (4ℓ, ZZ).

Jets

- $N_{bjets} = 0$ ($t\bar{t}$).
- N_{jets} >=3 ($2\ell^{sc}$), >=2 (3ℓ), =0 (4ℓ).

•3ℓ: •Has SFOC pairs? (Same flavor opposite charge) •Yes: SFOC12 / No: SFOC0	•$2\ell^{sc}$ •$ee, e\mu, \mu\mu$ •4ℓ

Background Categories

Prompt Background

- W/Z -> ℓ + X.
- MC simulation.
- WZ normalization
  - Control region.
  - Norm Factor
  - NF = $\frac{N_{data} - N_{noWZ}}{N_{(MC)WZ}}$

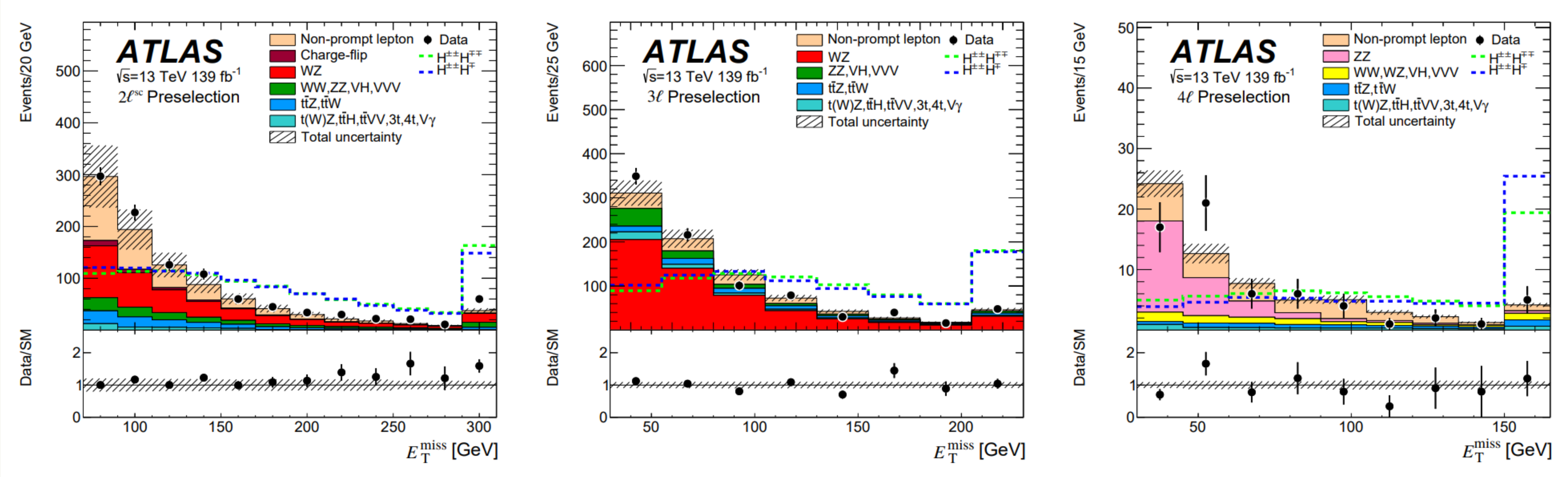
Electron charge-flip

- Mis-identify the electron charge.
- Data-based likelihood method. ($2\ell^{sc}$).

Non-prompt leptons

- Hadrons -> leptons
- Data-based fake factor method. ($2\ell^{sc}$, 3ℓ).
- Semi-data-based fake scale factor method. (4ℓ).

BACKGROUND SUMMARY



Generally good agreement.

Signal Optimization

Cut Optimization Provided by TMVA.

- Rectangular cuts optimization (cut-flow).
- Maximizes the background rejection ($1/eff_{bkg}$) at given signal efficiency.
- Simulate Anneal algorithm.

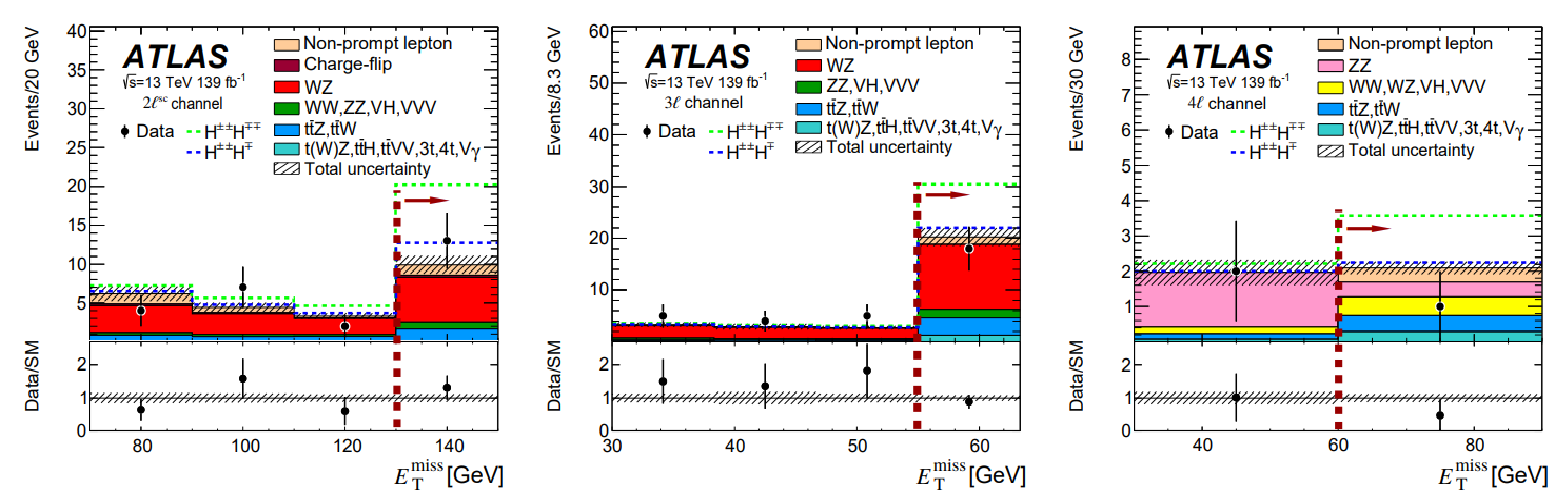
100 cut sets will be proposed.

Additional selection.

- Use signal significance (Cowan).
- All cuts are rounded.
- Stability checks were performed.

Optimization were done per mass point, per sub-channel.
(500 GeV results will be applied to 600 GeV signal.)

Signal Regions ($m_{H^{\pm\pm}}$ = 300 GeV)

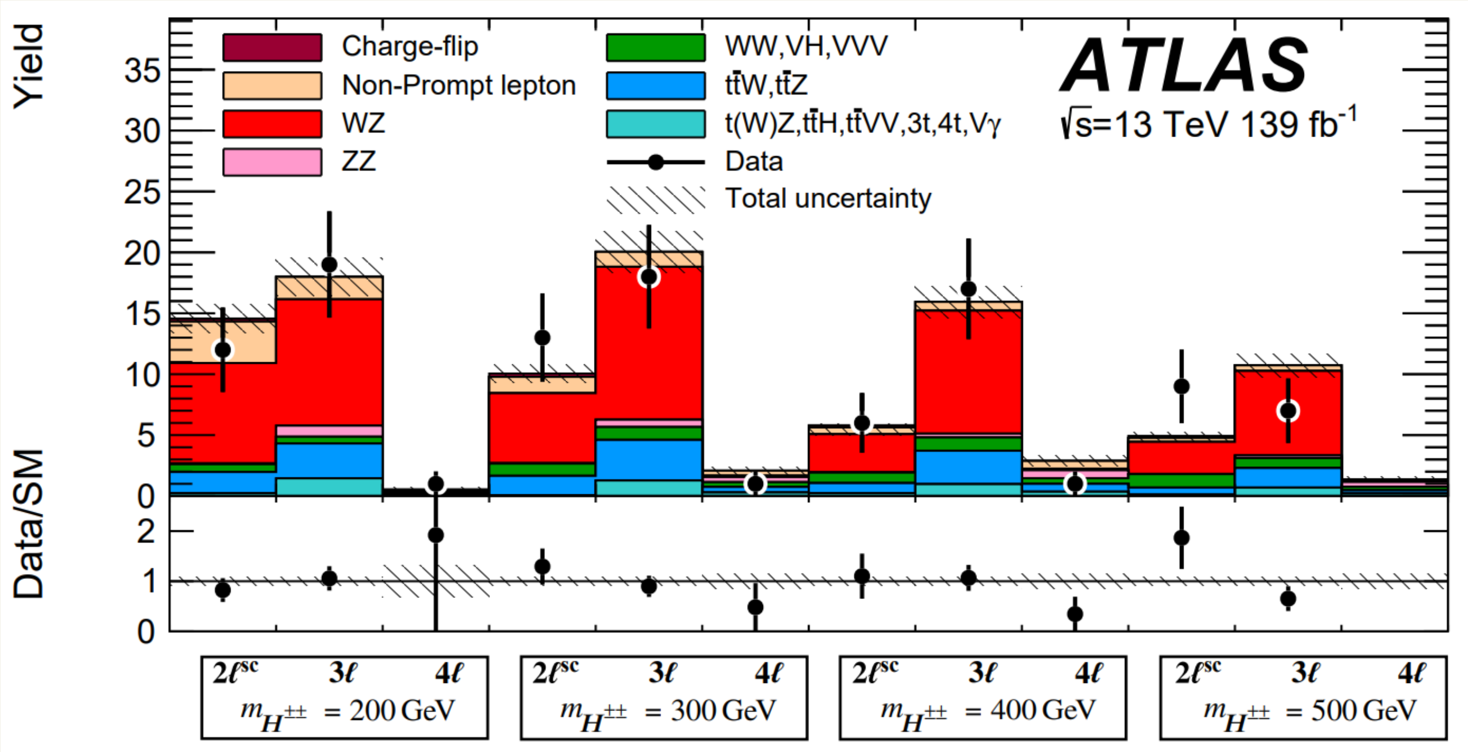


E_T^{miss} cuts relaxed E_T^{miss} distribution.

Vertical red dashed line indicates the E_T^{miss} cut.

Signal Regions

- No significant excess in any of the signal regions.
- Data is used to constrain the signal model.



Systematic Uncertainties

Theoretical. (Background Norm.)

- PDF, QCD scale and showering for signal. (~11% for signal)
- PDF, QCD scale for background. (~ 1.8% to 50% for processes)
- WZ data-driven in N_{jets}>1 regions. (9.0% for WZ)

Experimental. (For all MC processes.)

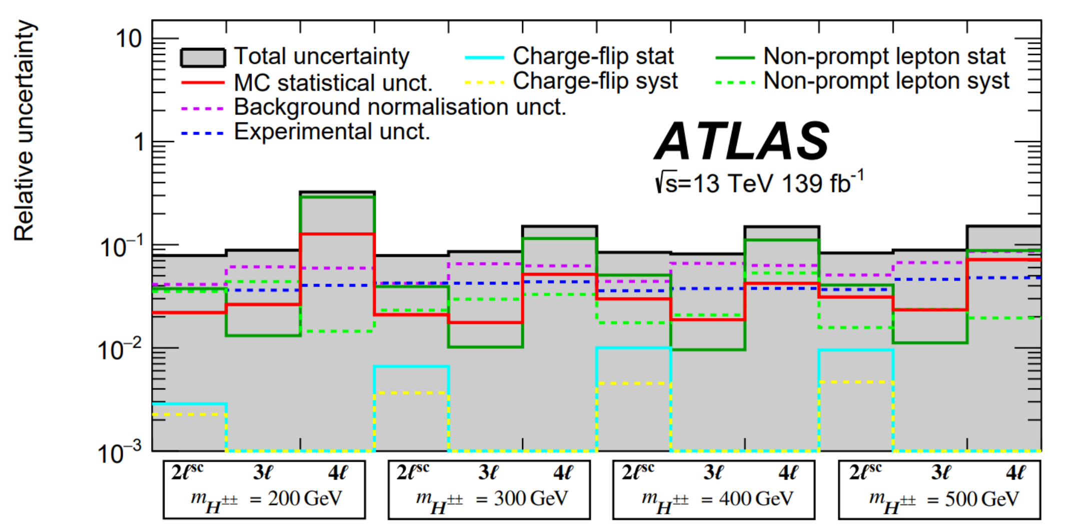
- Luminosity (1.7%)
- Electron/muon (~5%)
- pile-up modelling (~2%)
- Jet energy, E_T^{miss} (~10%)

Charge-flip.

- 20–30% for charge flip component.

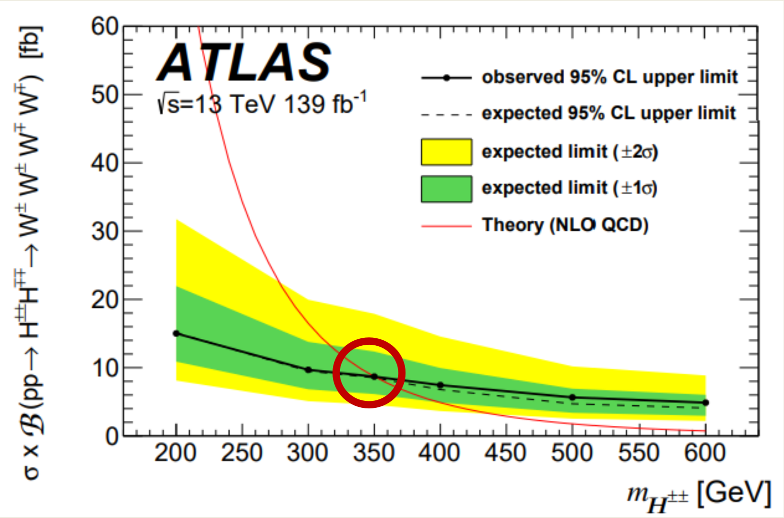
Non-prompt leptons.

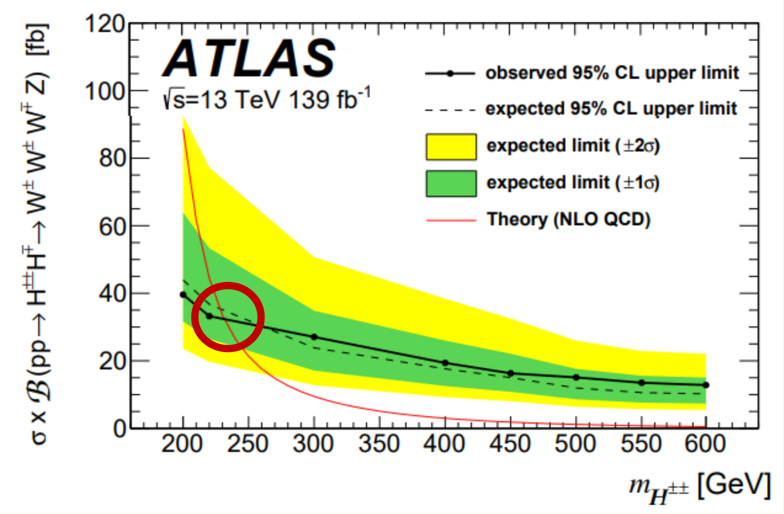
- 25–90% for non-prompt lepton component.



Charge-flip Unct. are small.

Non-prompt leptons statistical Unct. and background normalization Unct. are large.





Limits On Cross-sections

- Profiling likelihood ratio test.
  - Each channel as an individual bin of a histogram.
  - Parameter of interest (POI) is the signal strength (μ).
  - Systematics uncertainties were treated as nuisance parameters (θ).
- Cross-section times branching fraction.
- For the pair-production:
  - $m_{H^{++}} < 350$ GeV is excluded.
- For the associate-production:
  - $m_{H^{++}} < 230$ GeV is excluded.

Summary

- Run-2 139 fb^{-1} version of the analysis is finalized.
- The pair-production scenario:
  - Excluded for $m_{H^{\pm\pm}}$ < 350 GeV with 95% CL.
  - Increase from the previous analysis by approximately 130 GeV.
- The associate-production scenario:
  - Excluded for $m_{H^{\pm\pm}}$ <230 GeV with 95% CL.
  - The $m_{H^{\pm\pm}}$ exclusion applies also to $m_{H^{\pm}}$.
  - The associated production of $H^{\pm\pm}$ and $H^{\pm}$ bosons is explored.

Back Up

Pair. (36.1 fb^{-1})	200	300	400
All combined	0.89 (0.69)	3.09 (3.34)	11.32 (8.05)

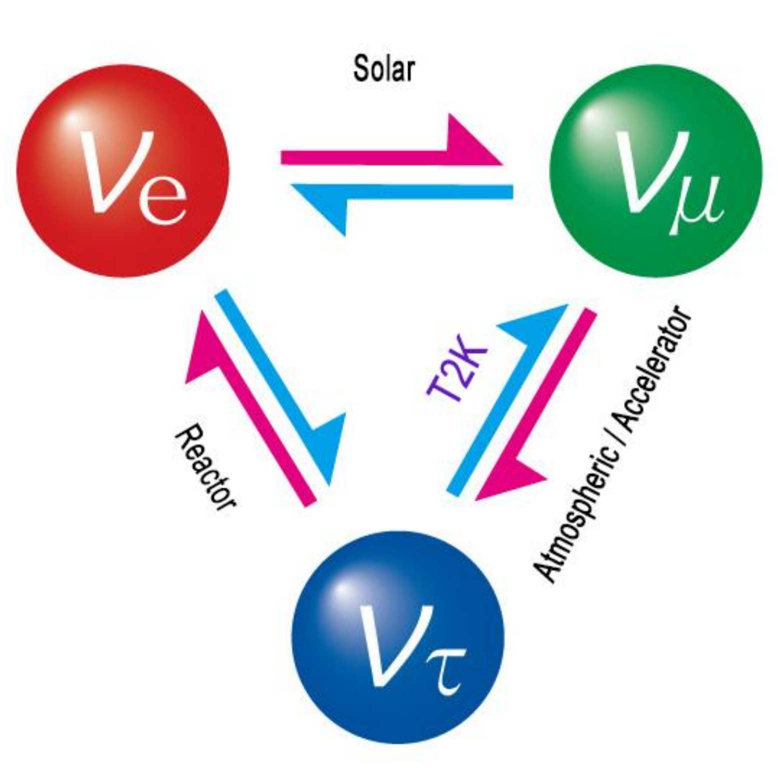
Pair. (139.0 fb^{-1})	200	300	400
All combined	0.19 (0.19)	0.59 (0.58)	1.52 (1.39)
ee	0.80 (0.81)	3.38 (2.23)	9.48 (5.42)
$e\mu$	0.33 (0.49)	1.07 (1.57)	2.48 (3.95)
$\mu\mu$	0.35 (0.37)	1.72 (1.13)	2.91 (2.82)
SFOC0	0.65 (0.52)	1.24 (1.62)	6.30 (4.41)
SFOC12	0.42 (0.42)	1.25 (1.36)	3.42 (3.51)
4ℓ	1.12 (0.90)	2.20 (2.94)	5.29 (8.04)

Asso. (139.0 fb^{-1})	200	300	400
All combined	0.45 (0.49)	2.86 (2.51)	6.44 (5.83)
ee	1.83 (1.85)	11.96 (7.85)	34.56 (19.50)
$e\mu$	0.74 (1.07)	4.00 (5.88)	9.26 (14.76)
$\mu\mu$	0.74 (0.78)	6.49 (4.24)	10.65 (10.32)
SFOC0	2.35 (1.86)	7.72 (10.06)	37.24 (26.01)
SFOC12	1.49 (1.49)	7.09 (7.71)	18.95 (19.46)
4ℓ	10.82 (8.53)	21.84 (29.27)	31.62 (48.17)

Limits on signal strength (μ)

- Separated channels.
- Observed (Expected).
- Improvement:
  - Pure statistical ~ 2
  - Analytical ~2-3
- Improved object selections.
- Finer background estimation.
- More stable and harmonized signal regions.
- Constraint of WZ.

Neutrino Experiments



Neutrino oscillation between three generations

- Atmospheric:
  - Super-Kamiokande Observatory
- Accelerator:
  - K2K and MINOS
  - T2K
- Solar:
  - Super Kamioka
  - Sudbury Neutrino Observatories
- Reactor:
  - Double Chooz
  - Daya Bay
  - RENO

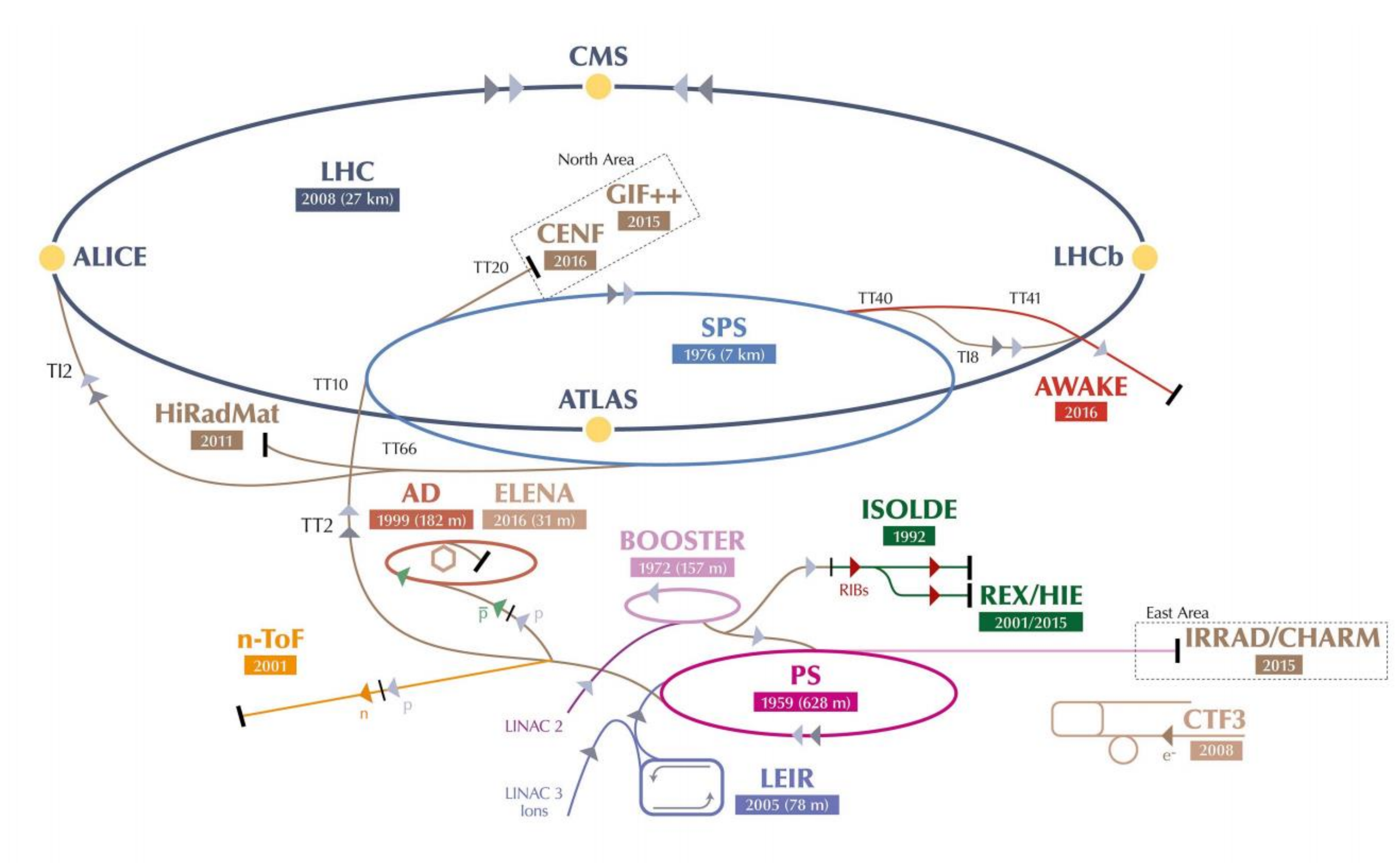
Large Hadron Collider (LHC)

Proton-Proton collision

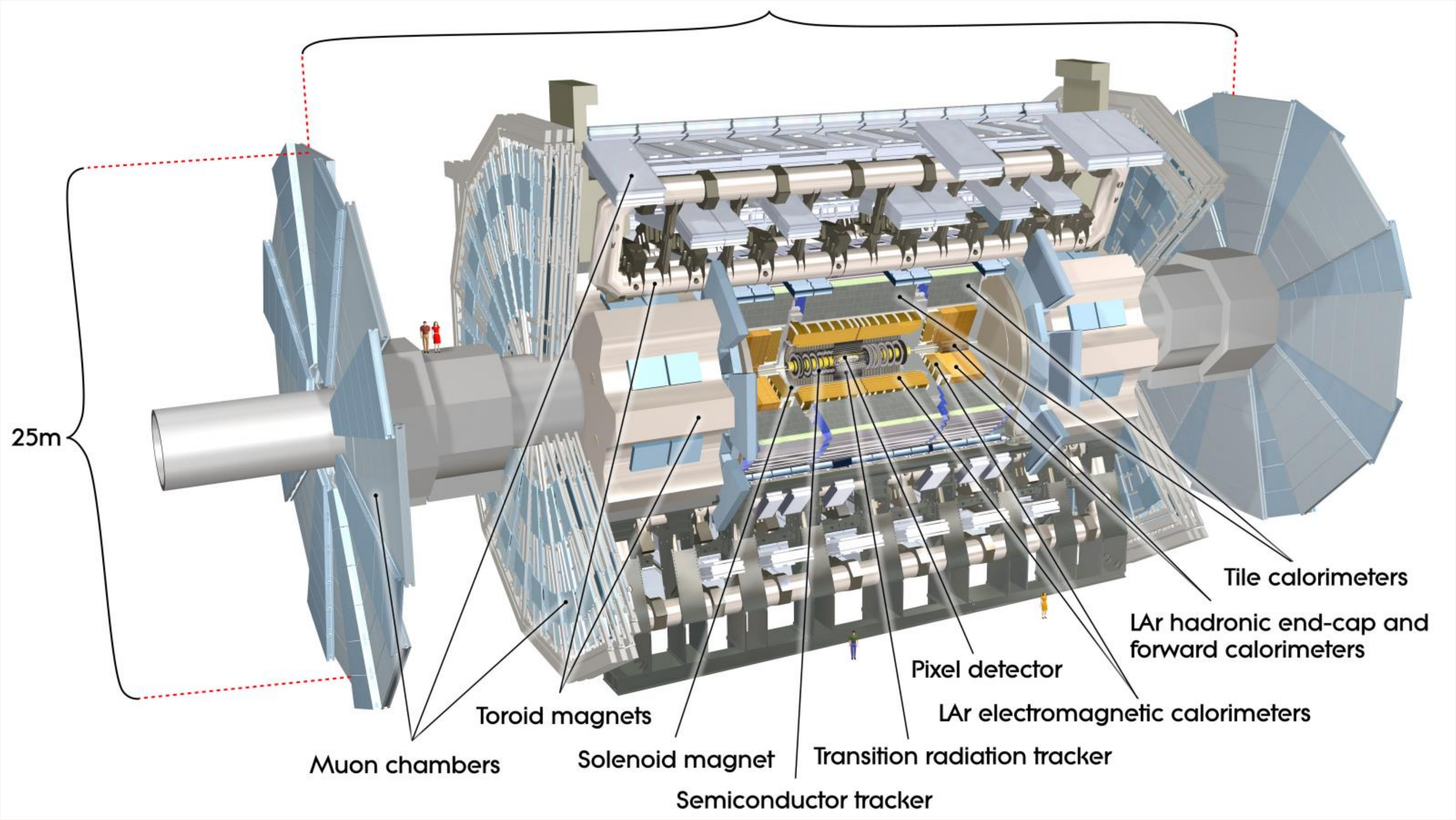
- $\sqrt{s}$ = 13 TeV.
- Lumi. = 2*10^{34} cm^{-2} s^{-1}

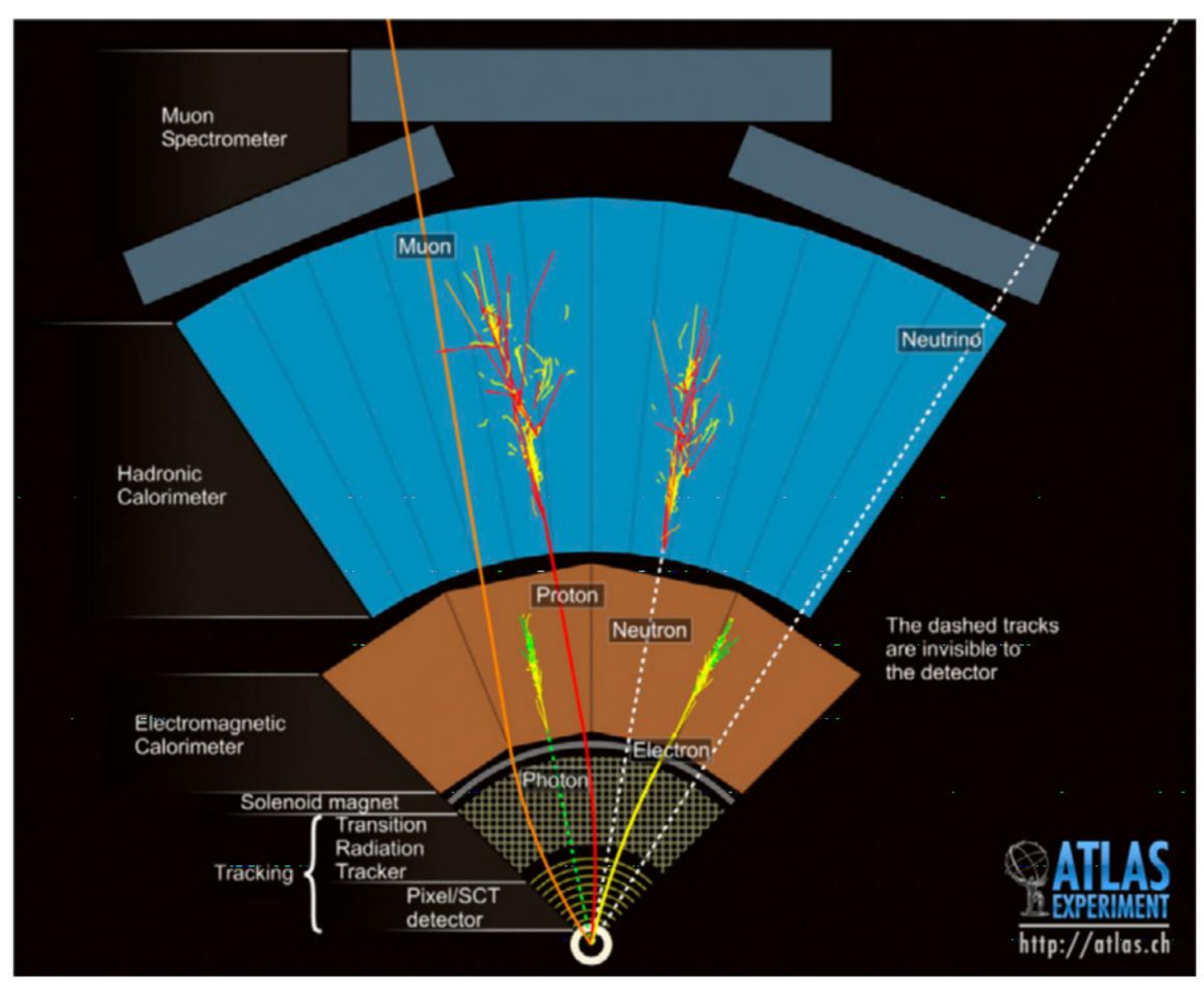
Four main experiments

- ATLAS, CMS.
- ALICE, LHCb.
- Search for new physics.
- Precise measurement.



ATLAS Detector





Atlas Detector: Objects

Leptons

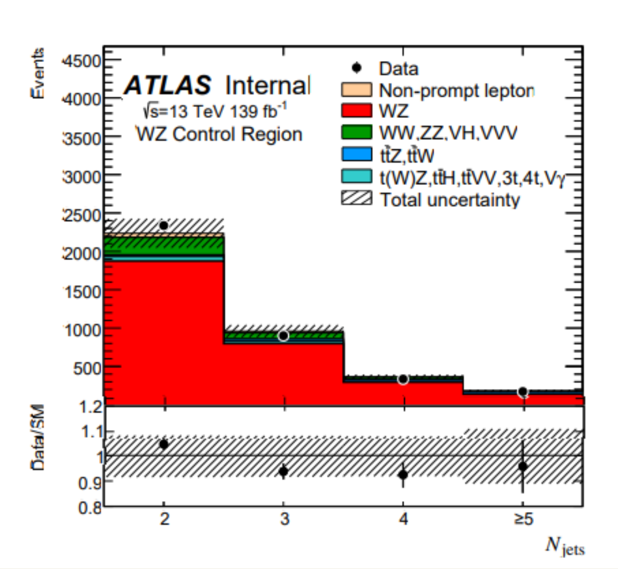
- Electrons and muons.
- Different criteria for analysis.

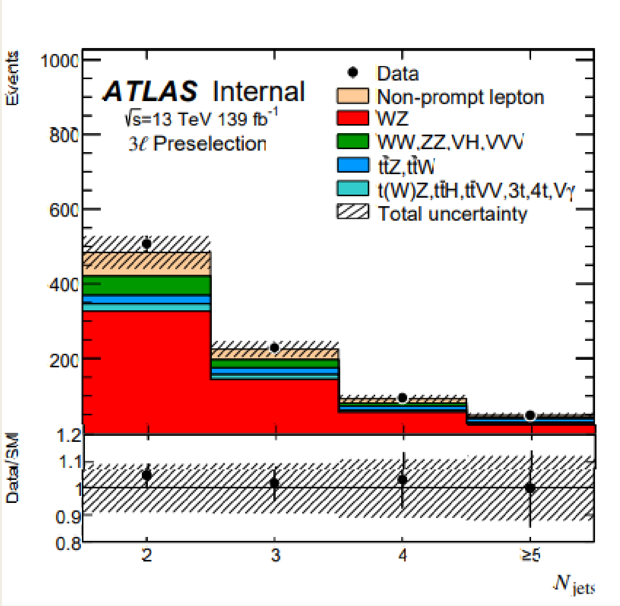
Jets

- Initiated by quarks and gluons.

E_T^{miss}

- Missing Transverse Energy.
- Transverse momentum imbalance.





WZ Norm. Results

NF = 0.83 ± 0.07 (stat. + syst.)

Measurement	Application
WZ Control Region	3ℓ selection
Z-selection	Z-veto
Normalized WZ in $N_{jets} > 1$	Good estimation

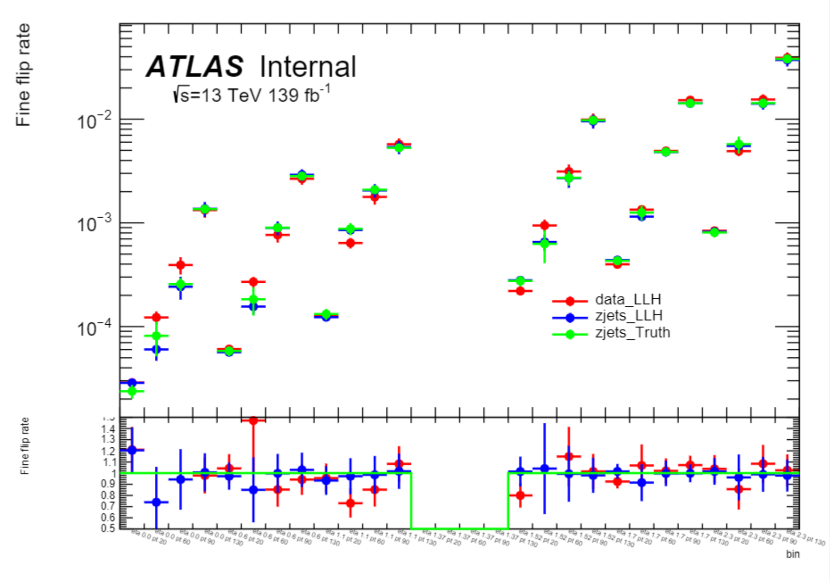
Systematic uncertainties include:

- Fit statistics uncertainty: 8.4%.
- Shape uncertainty from the QCD scale variations: 5%.

Selection criteria	$2\ell^{sc}$	3ℓ	4ℓ
Trigger	At least one *signal* lepton with $p_{\mathrm{T}}^{\ell} > 30$ GeV that triggered the event		
N_ℓ (*Candidate*)	=2	=3	=4
N_ℓ (*Candidate**)	–	–	=4
N_ℓ (*Signal*)	=2	≥ 2 $(\ell_{1,2})$	≥ 1
$\lvert \sum Q_\ell \rvert$	=2	=1	$\neq 4$
Lepton p_{T}	$p_{\mathrm{T}}^{\ell_1,\ell_2} > 30, 20$ GeV	$p_{\mathrm{T}}^{\ell_0,\ell_1,\ell_2} > 10, 20, 20$ GeV	$p_{\mathrm{T}}^{\ell_1,\ell_2,\ell_3,\ell_4} > 10$ GeV
E_T^{miss}	> 70 GeV	> 30 GeV	> 30 GeV
N_{jets}	≥ 3	≥ 2	–
$N_{b\text{-jets}}$	=0		
Low SFOC $m_{\ell\ell}$ veto	–	$m_{\ell\ell}^{\mathrm{oc}} > 15$ GeV	
Z boson decays veto	$\lvert m_{ee}^{\mathrm{sc}} - m_Z \rvert > 10$ GeV	$\lvert m_{\ell\ell}^{\mathrm{oc}} - m_Z \rvert > 10$ GeV	$m_{4\ell} > 100$ GeV

- Events are collected by lowest un-prescaled **single** lepton triggers.
- $2\ell^{sc} \rightarrow$ ee, $e\mu$, $\mu\mu$ sub-channels.
- $3\ell \rightarrow$ SFOC0, SFOC12 sub-channels (same-flavor opposite charge).
- In 3ℓ channel, two same charge lepton were named ℓ_1 and ℓ_2.

Electron Charge-flip



X-axis
- (p_T, η) bin index.

p_T bins
- [20, 60, 90, 130, inf) [GeV]

η bins
- [0.0, 0.6, 1.1, 1.37, 1.52, 1.7, 2.3, 2.47]

Use opposite charged events with flip rates (ϵ)

- $N_{sc} = N_{oc} * \frac{\epsilon^{\ell 1}+\epsilon^{\ell 2}}{1-\epsilon^{\ell 1}-\epsilon^{\ell 2}}$, $N_{tot} = N_{oc} + N_{sc}$

Flip rates measured from $Z \rightarrow ee$ events.

- Data-driven likelihood method.

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

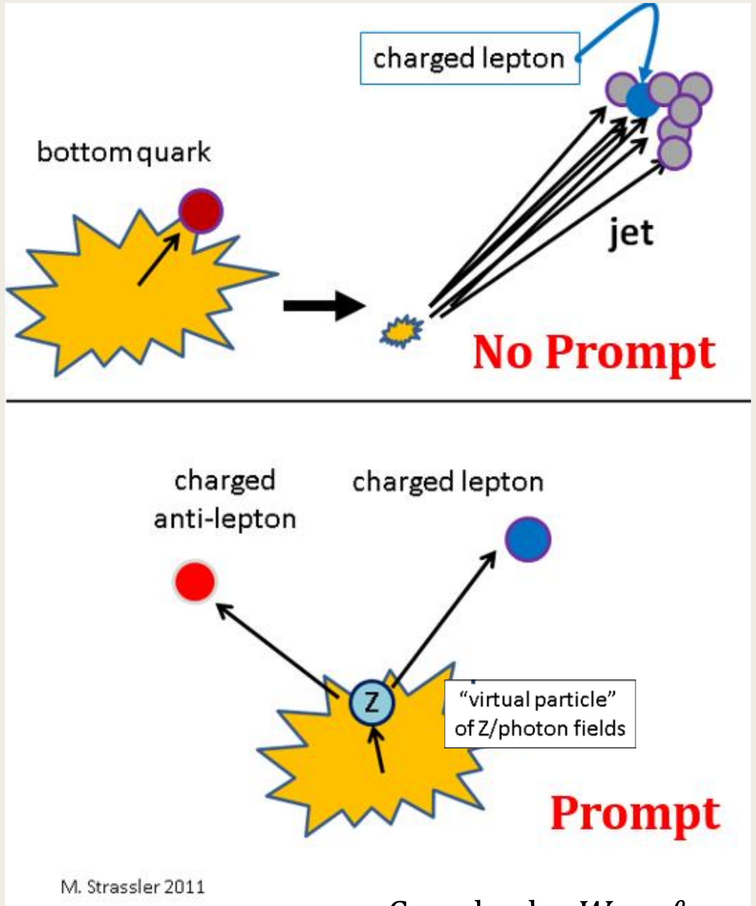
- flip rates (ϵ) results: 0.002%~3.14%

~30% Statistical and systematics uncertainties.

- Kinematics differences among processes.
- Background contamination.

Lepton Definition

Details.



Can also be $W \to \ell \nu$.

Baseline

- Minimum requirement.
- For E_T^{miss} calculation.

Candidate

- No isolation requirement.
- For background estimation.

Candidate*

- With loose isolation requirement.
- For low statistics channel (4ℓ).

Signal

- Most strong, with a GBDT isolation tool.
- For main analysis, to remove no prompt ℓ.

Non-prompt leptons ($2\ell^{sc}$ and 3ℓ)

A: Fake enriched region.

- Two *signal* leptons: $N_{\ell\ell}$.
- $\boldsymbol{N}$: $N_{non-prompt}$
  - $N_{data} - N_{Prompt}$ $(-N_{charge\ flip})$.
- Rare signal($H^{\pm\pm}$) MC.

B: Event selection region.

- Two *signal* leptons: $N_{\ell\ell}$.
- B = $\theta * $ D.
- More signal($H^{\pm\pm}$) MC.

$2\ell^{sc}$: $E_T^{miss} < 70$ GeV
3ℓ : $N_{jets} = 0$

$\frac{\boldsymbol{N_A}}{\boldsymbol{N_C}} \rightarrow$ **Fake Factor ($\boldsymbol{\theta}$)** $\rightarrow \frac{\boldsymbol{N_B}}{\boldsymbol{N_D}}$

$2\ell^{sc}$: $E_T^{miss} > 70$ GeV
3ℓ : $N_{jets} > 1$

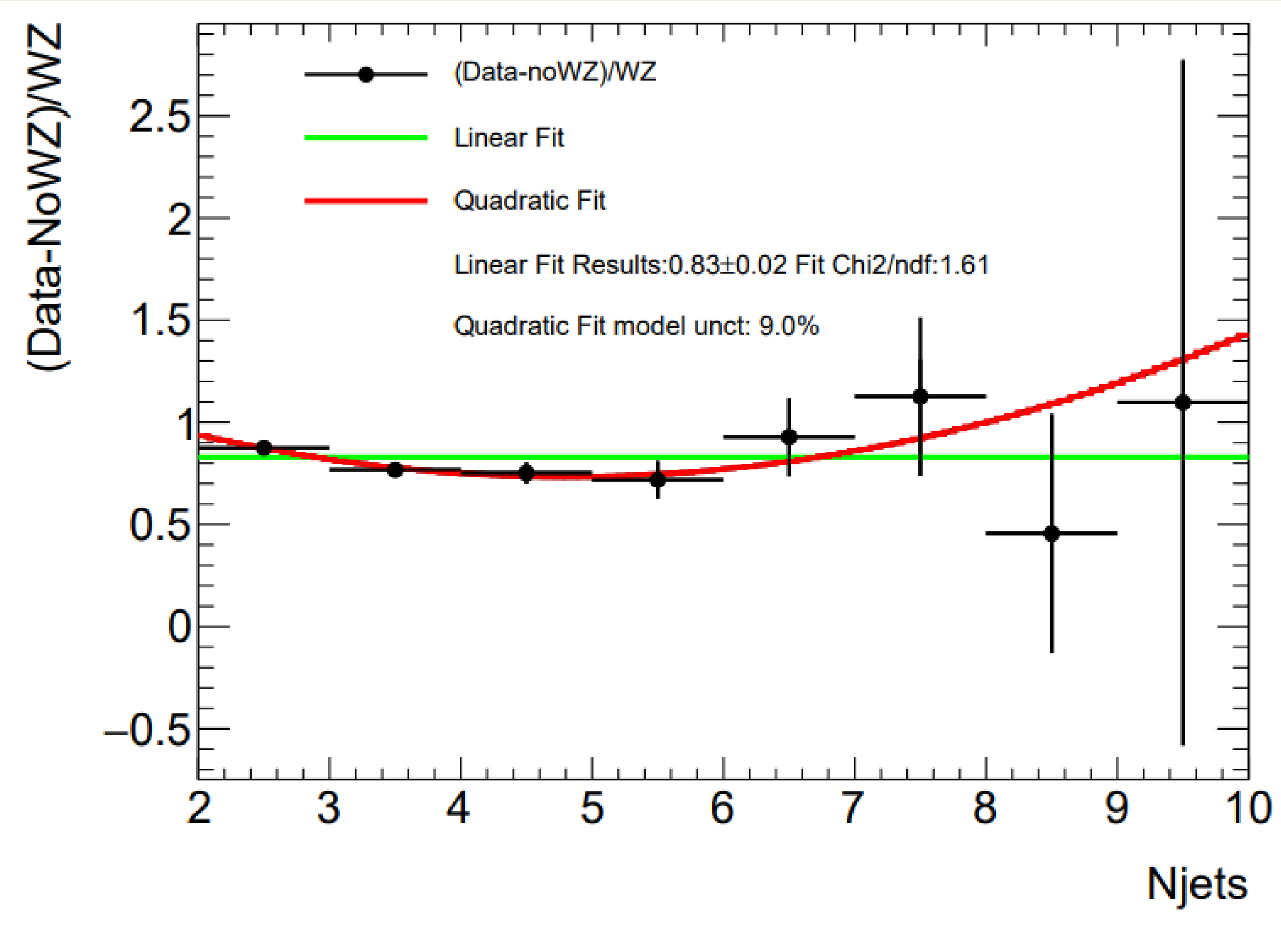
C: Fake enriched region.

- *Signal + CanNotSig:* $N_{\ell\not\ell}$.
- *CanNotSig*($\not\ell$): Pass *signal* fail *candidate.*

D: Event selection region.

- *Signal + CanNotSig:* $N_{\ell\not\ell}$.

WZ NORMALIZATION

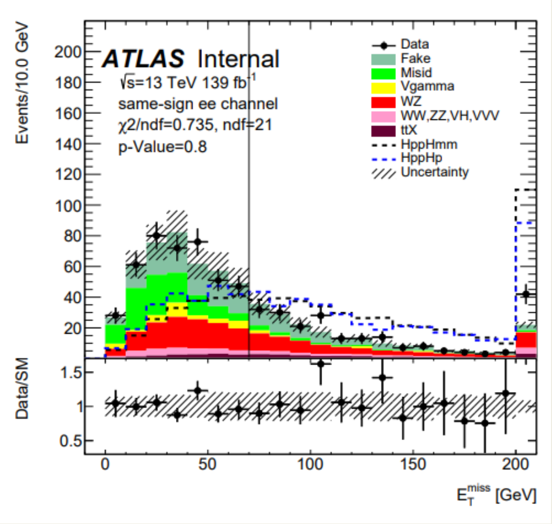


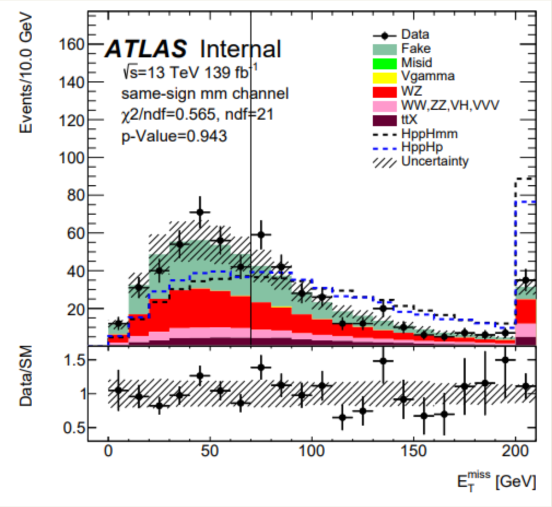
Selections

- Trigger — Single lepton trigger
- Leptons — $\ell_0^{\mp}\ell_1^{\pm}\ell_2^{\pm}$
- **Z-selection** — $|m_{OC} - m_Z| < 10$ GeV
- Jets — $N_{jets} \geq 2, N_{bjets} = 0$

$$\text{NF} = \frac{N_{data} - N_{noWZ}}{N_{(MC)WZ}}$$

Electron	Fake factor
20-40 GeV	$0.028 \pm 0.006_{stat} \pm 0.009_{glob\ syst} \pm 0.003_{method\ syst}$
40-60 GeV	$0.056 \pm 0.024_{stat} \pm 0.018_{glob\ syst} \pm 0.003_{method\ syst}$
60-inf GeV	$0.160 \pm 0.051_{stat} \pm 0.053_{glob\ syst} \pm 0.073_{method\ syst}$
Muon	Fake factor
20-40 GeV	$0.027 \pm 0.004_{stat} \pm 0.005_{glob\ syst} \pm 0.002_{method\ syst}$
40-60 GeV	$0.049 \pm 0.013_{stat} \pm 0.010_{glob\ syst} \pm 0.005_{method\ syst}$
60-inf GeV	$0.085 \pm 0.024_{stat} \pm 0.017_{glob\ syst} \pm 0.069_{method\ syst}$

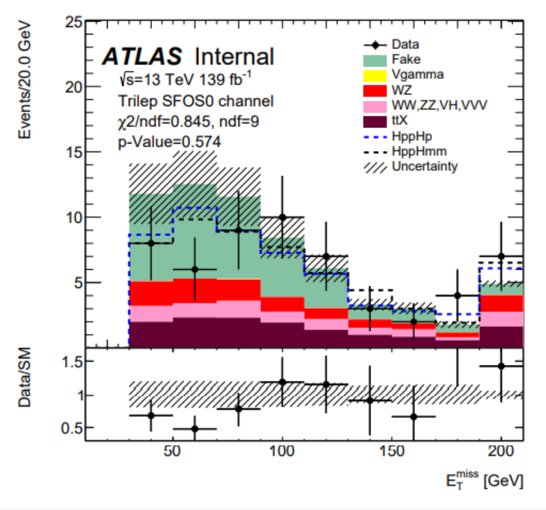


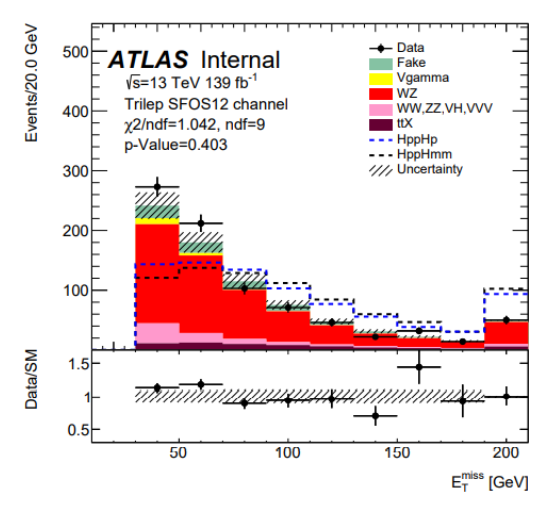


Non-prompt leptons in $2\ell^{sc}$

- p_T bins: [20, 40, 60, inf) [GeV]
- $\theta = N_{\ell\ell} / N_{\not\ell\ell}$.
  - ℓ: lower p_T, assumed to be non-prompt.
- Uncertainties from $N_{Prompt}/N_{charge\ flip}$ will be extrapolated.
- Method syst:
  - MC-based uncertainty for misclassification (6~82%).
  - For basic assumption (19% for e, 7% for μ).
    - Test between low E_T^{miss} and high E_T^{miss}

Flavor	Fake factor
Electron	$0.021 \pm 0.009_{\text{stat}} \pm 0.012_{\text{syst}}$
Muon	$0.032 \pm 0.009_{\text{stat}} \pm 0.016_{\text{syst}}$





Non-prompt leptons in 3ℓ

- Same charged pairs ($\ell\ell$) are used.
- For 3ℓ channel, the ℓ^0 only needs to pass *candidate.*
- $\theta = N_{(\ell)\ell\ell} \;/\; N_{(\ell)\not\ell\ell}$
- Method syst:
  - MC-based uncertainty for prompt OC ℓ assumption (20%).
  - MC-based uncertainty for basic assumption (15%)
    - Test between N_{jets} = 1 and N_{jets} > 1.
- SFOC0 and SFOC12 are merged in measurement.

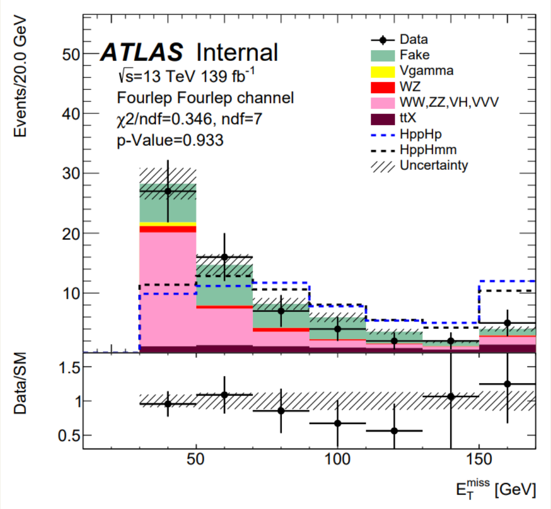
Trigger, $\ell_0^{\mp}\ell_1^{\pm}\ell_2^{\pm}$, 1 or 2 jets

$t\bar{t}$ enriched	Z+jets enriched
NO SFOC	$\lvert m_{OC} - m_Z \rvert$ < 10 GeV
	To suppress WZ
	E_T^{miss} , m_T < 50 GeV

$\lambda^{e}_{\mathrm{HF}} = 0.98 \pm 0.18\ (\mathrm{stat}) \pm 0.06\ (\mathrm{syst})$

$\lambda^{e}_{\mathrm{LF}} = 1.34 \pm 0.17\ (\mathrm{stat}) \pm 0.20\ (\mathrm{syst})$

$\lambda^{\mu}_{\mathrm{HF}} = 0.94 \pm 0.04\ (\mathrm{stat}) \pm 0.04\ (\mathrm{syst})$



Non-prompt leptons in 4ℓ

- Not enough statistics.
- MC yields corrected with scale factors (SFs).
- $N = \lambda_{HF} N_{HF} + \lambda_{LF} N_{LF}$
  - HF: Heavy flavor non-prompt.
  - LF: Light Flavor.
- Two factors, two regions.
  - $t\bar{t}$ enriched by HF.
  - Z+jets enriched by LF. (Found negligible for μ.)
- Component ratios depend on selections.
- Uncertainties include:
  - Jet and p_T selection impact.
  - Statistics and Prompt MC subtraction.

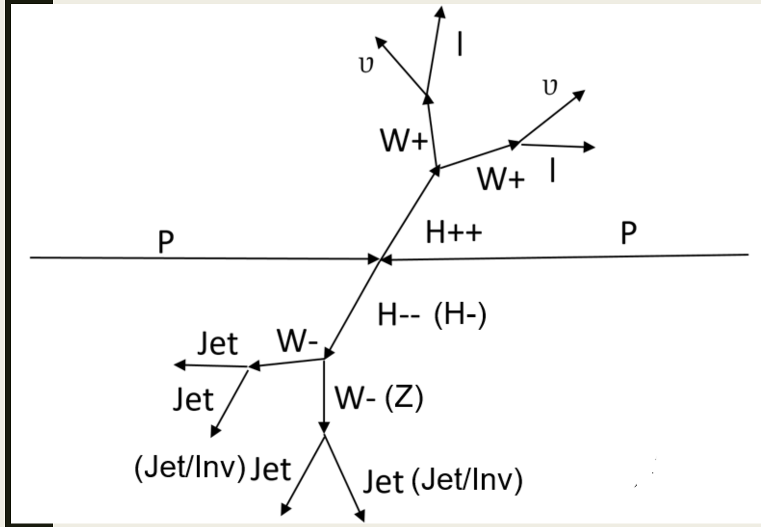
$N = N_{data} - N_{Prompt}$

$N^Z = \lambda_{HF} N^Z_{HF} + \lambda_{LF} N^Z_{LF}$

$N^T = \lambda_{HF} N^T_{HF} + \lambda_{LF} N^T_{LF}$

Signal Topology

$2\ell^{sc}$



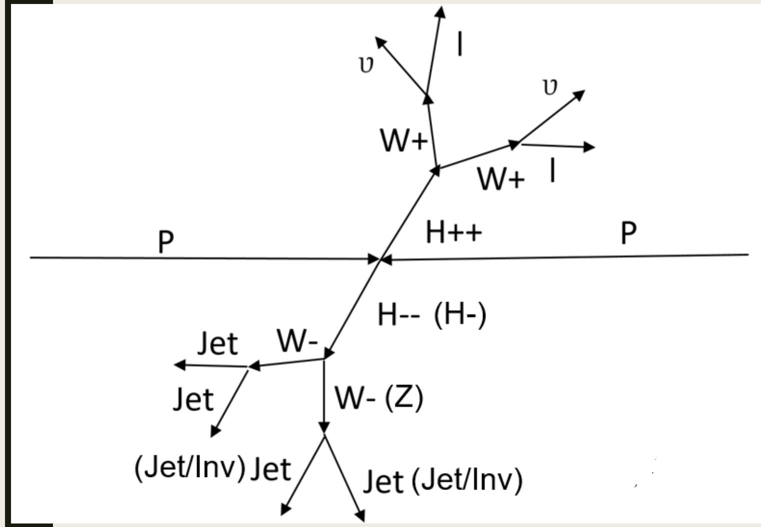
Backgrounds

- Prompt Leptons — $scWW, WZ, t\bar{t}V$
- Electron Charge Flip — $ocWW, Z$+jets(γ), $t\bar{t}$
- Non-prompt leptons — V+jets(γ), $t\bar{t}$

Selection

- Trigger — Single lepton trigger
- Leptons — 2 same charge leptons
- E_T^{miss} — > 70 GeV — Z+jets(γ)
- Z-veto — $|m_{ee} - m_Z| > 10$ GeV — Charge Flip
- Jets — $N_{jets} \geq 3, N_{bjets} = 0$ — $t\bar{t}, t\bar{t}V$
- Sub channels — $ee, e\mu, \mu\mu$

Signal Topology
$2\ell^{sc}$



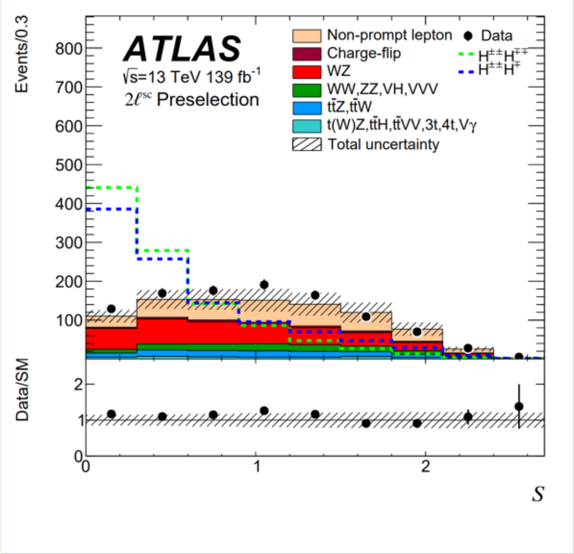
$$S = \frac{\text{R.M.S.}(\phi_{\ell_1}, \phi_{\ell_2}, \phi_{E_T^{\text{miss}}}) * \text{R.M.S.}(\phi_{j1}, \phi_{j2}, \cdots)}{\text{R.M.S.}(\phi_{\ell_1}, \phi_{\ell_2}, \phi_{E_T^{\text{miss}}}, \phi_{j1}, \phi_{j2}, \cdots)}.$$

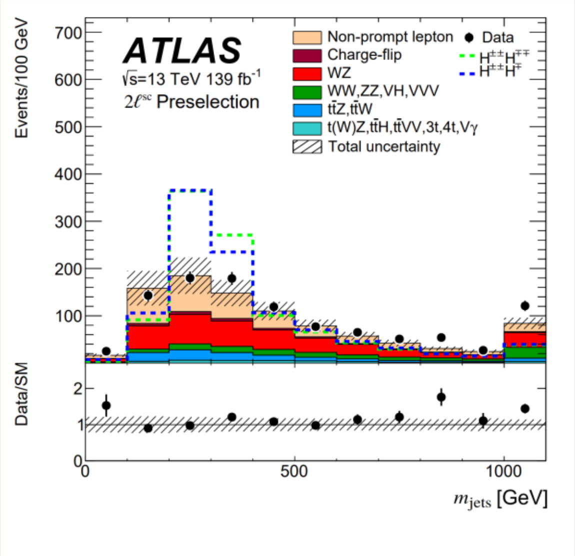
R.M.S: Root Mean Square

Features

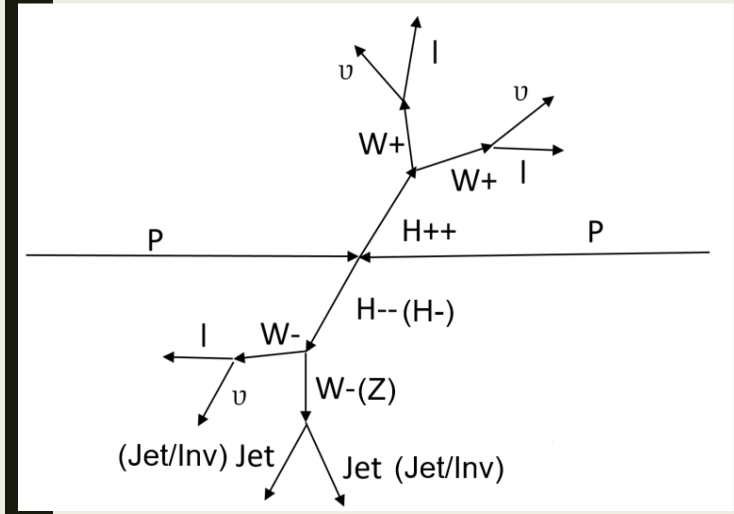
- $H^{\pm\pm} \to W^{\pm}W^{\pm}$
  - $\ell\nu$/Jets Φ plane distance: S
  - $\ell\nu$ Φ plane distance: $\Delta\phi(\ell\ell, E_T^{miss})$
  - $\ell\ell$ radius distance: $\Delta R_{\ell\ell}$
- Neutrinos
  - E_T^{miss}
- $H^{\pm\pm}$ mass
  - Mass of 4 jets: M_{4j}
  - Mass of $\ell\ell$: $M_{\ell\ell}$

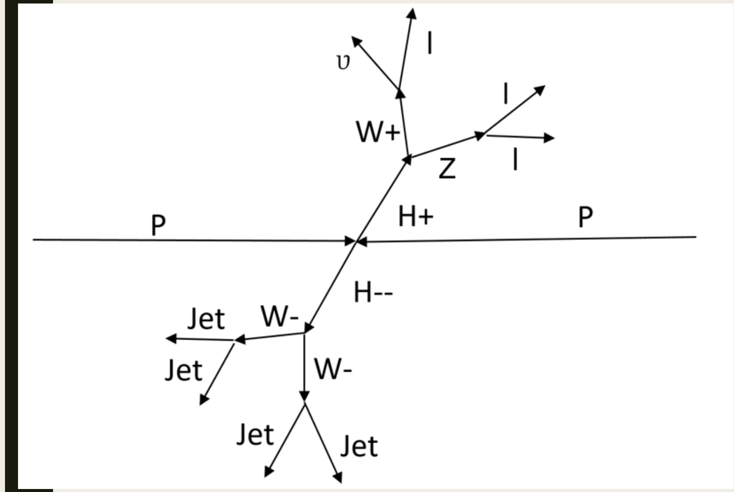
$$\Delta R = \sqrt{\Delta\phi^2 + \Delta\eta^2}$$





Signal Topology
3ℓ





Backgrounds

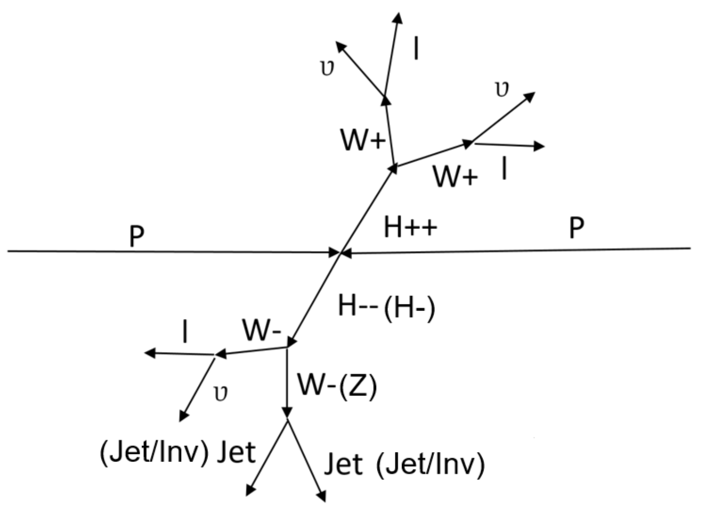
- Prompt Leptons — $WZ, ZZ, t\bar{t}V$
- Non-prompt leptons — V+jets(γ), $t\bar{t}$

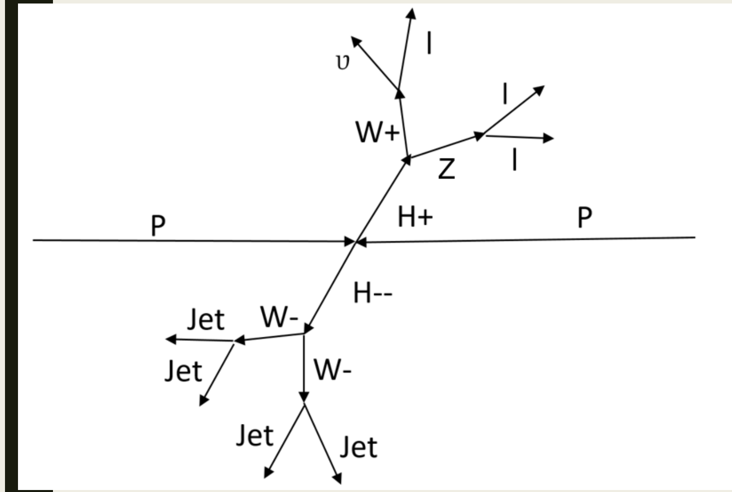
Selections:

- Trigger — Single lepton trigger
- Leptons — $\ell_0^{\mp}\ell_1^{\pm}\ell_2^{\pm}$
  - $\ell^1\ell^2$: Same charged.
  - ℓ^0: the opposite charged.
- E_T^{miss} — > 30 GeV
- Z-veto
  - $|m_{OC} - m_Z| > 10$ GeV
  - $m_{OC} > 15$ GeV — Low mass Z
- Jets — $N_{jets} \geq 2, N_{bjets} = 0$
- Sub channels — Has SFOC pairs?
  - No — SFOC0
  - Yes — SFOC12

SFOC
- Same flavor opposite charge.

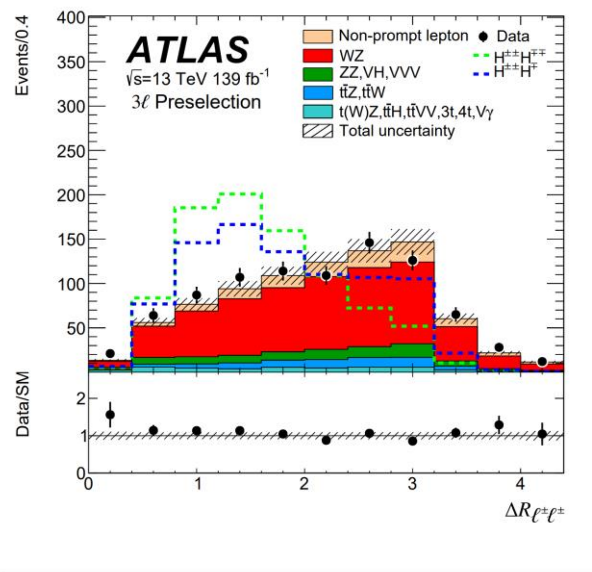
Signal Topology 3ℓ

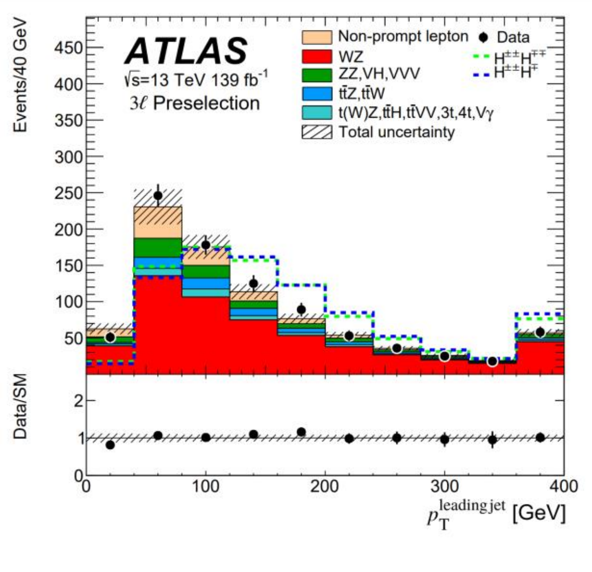




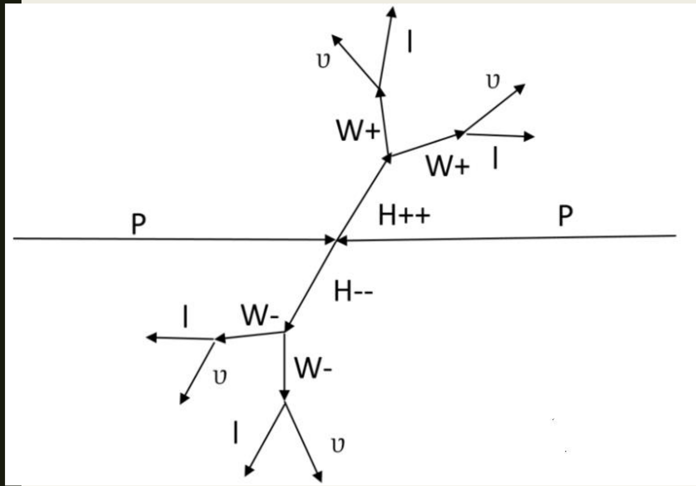
Features

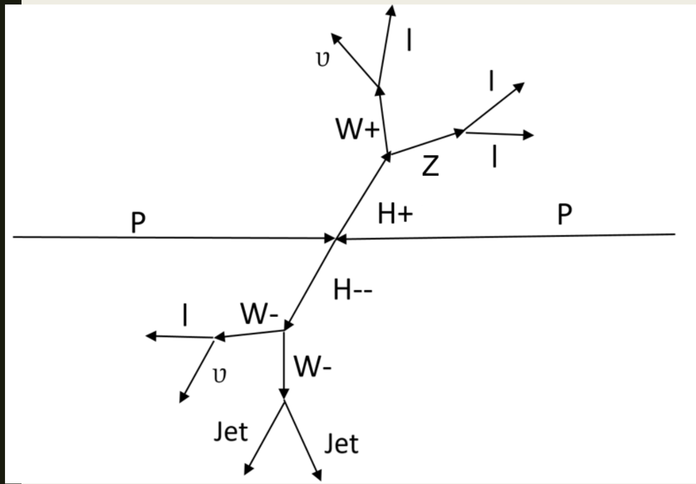
- $H^{\pm\pm} \rightarrow W^{\pm}W^{\pm}$
  - Same charged $\ell^{\pm}\ell^{\pm}$: $\Delta R_{\ell^{\pm}\ell^{\pm}}$
  - The opposite ℓ and jet: $\Delta R_{\ell-jet}$
- Neutrinos
  - E_T^{miss}
- $H^{\pm\pm}$ mass
  - Mass of 3ℓ: $M_{3\ell}$
  - Leading jet momentum: $p_T^{lead-jet}$

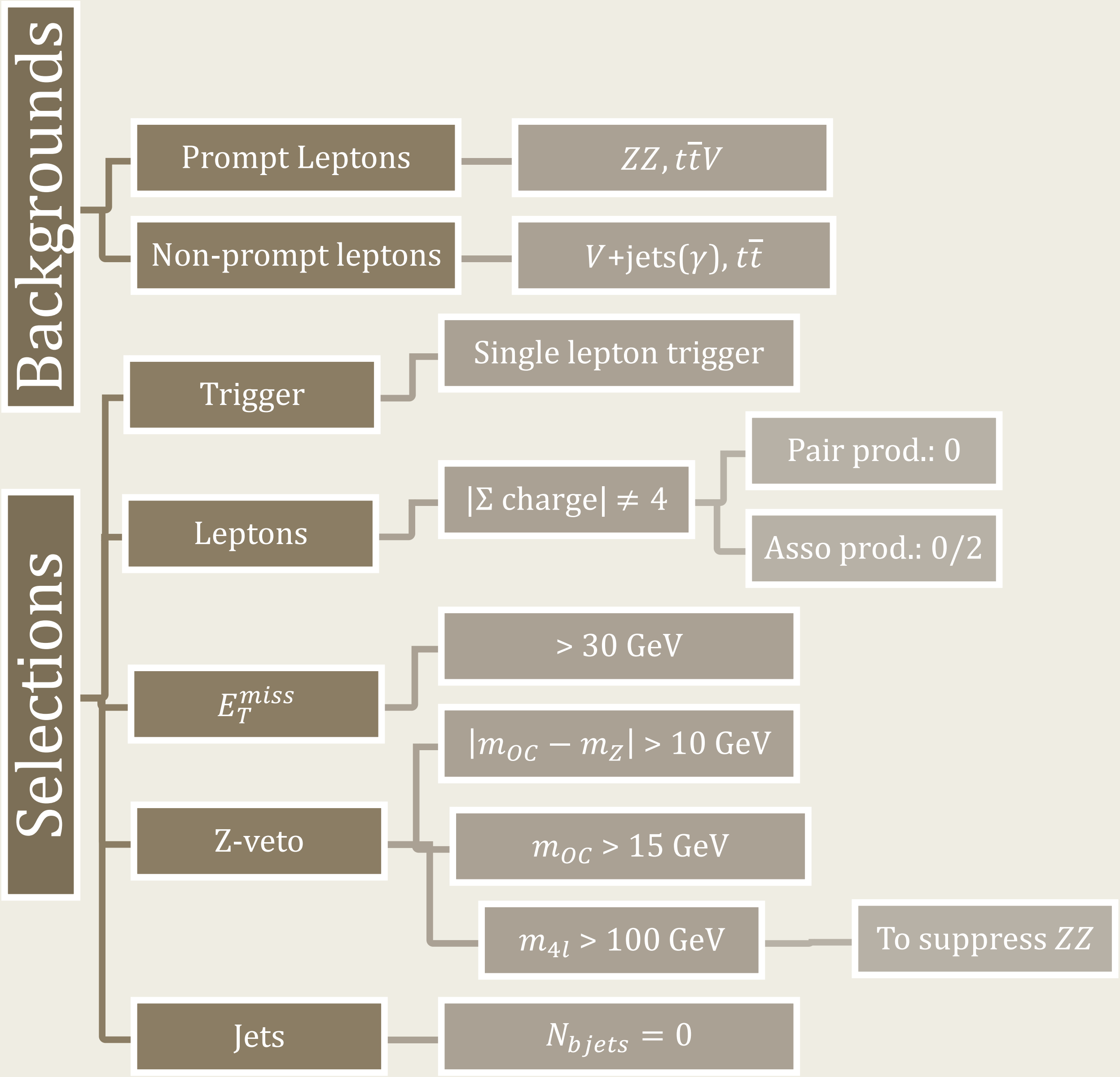




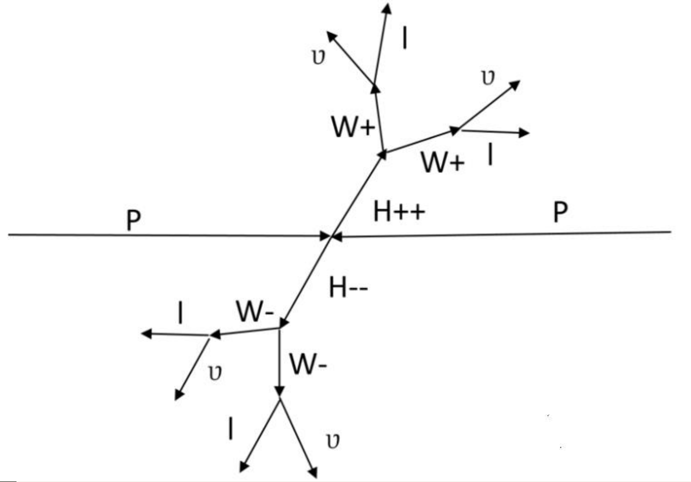
Signal Topology
4ℓ

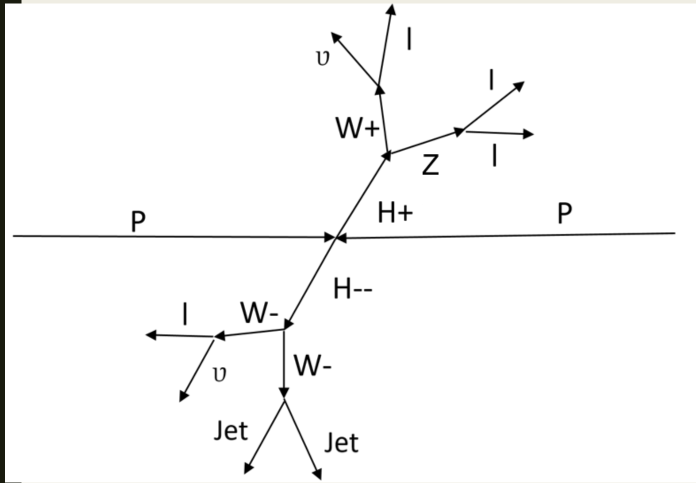






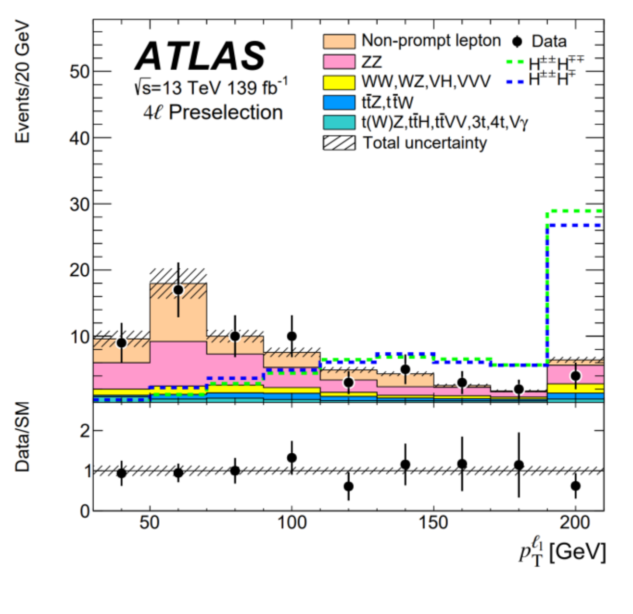
Signal Topology
4ℓ

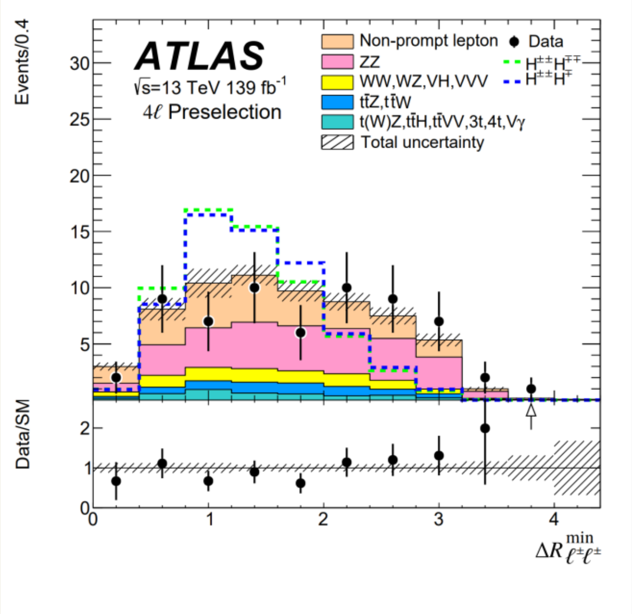




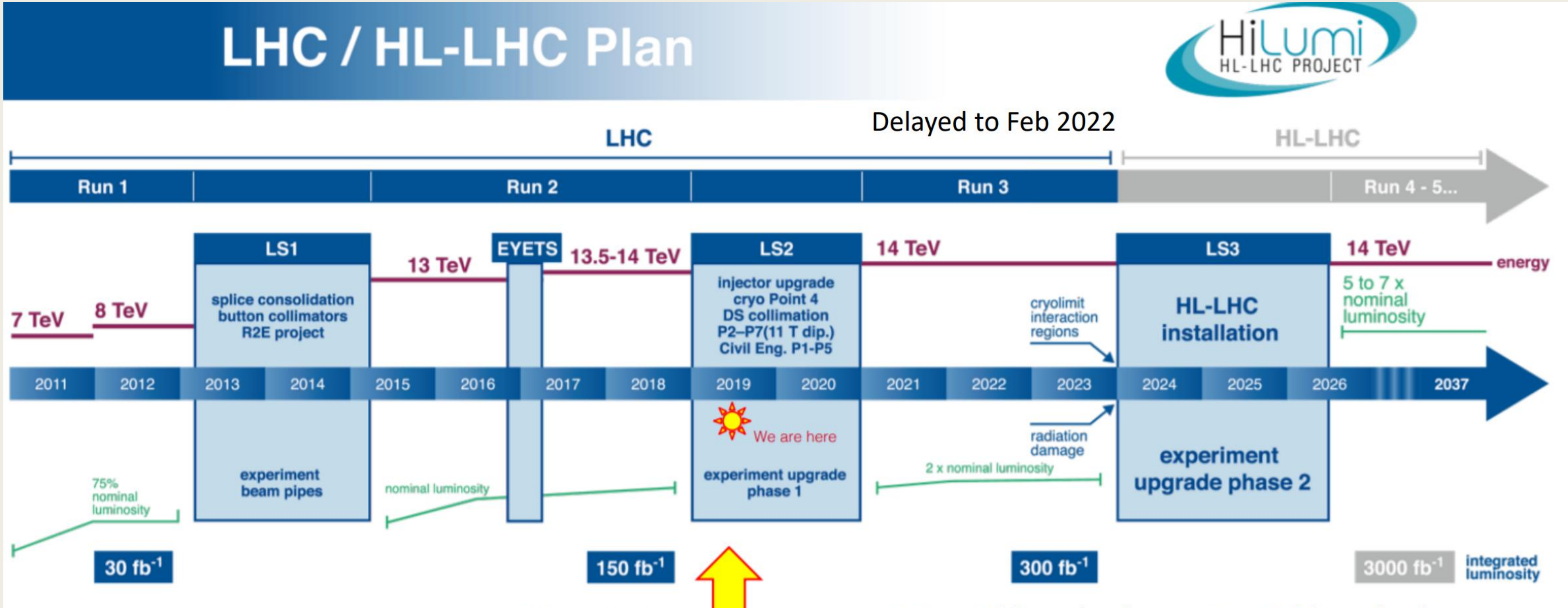
Features

- $H^{\pm\pm} \rightarrow W^{\pm}W^{\pm}$ — Same charged $\ell\ell$: $\Delta R_{\ell\ell}^{max}, \Delta R_{\ell\ell}^{min}$
- Neutrinos — E_T^{miss}
- $H^{\pm\pm}$ mass
  - Mass of 4ℓ: $M_{4\ell}$
  - Leading ℓ momentum: p_T^1





LHC RUN-3



$1.5 \times 10^{34} cm^{-2} s^{-1}$
Pile-up~40

$2.2 \times 10^{34} cm^{-2} s^{-1}$
Pile-up~60

$5 \times 10^{34} cm^{-2} s^{-1}$
Pile-up~140-200

DTHM Masses

$$\mathcal{L} = (D_\mu H)^\dagger (D^\mu H) + Tr(D_\mu \Delta)^\dagger (D^\mu \Delta) - V(H,\Delta) + \mathcal{L}_{Yukawa}$$

$$\mathcal{L}_{Yukawa} \supset -Y_\nu L^T C \otimes i\sigma^2 \Delta L$$

$$V(H,\Delta) = -m_H^2 H^\dagger H + \frac{\lambda}{4}(H^\dagger H)^2 + m_\Delta^2 Tr(\Delta^\dagger \Delta) \quad (2.35)$$

$$+ [\mu(H^T i\sigma^2 \Delta^\dagger H) + h.c.] + \lambda_1 (H^\dagger H) Tr(\Delta^\dagger \Delta) + \lambda_2 (Tr\Delta^\dagger \Delta)^2 + \lambda_3 Tr\left(\Delta^\dagger \Delta\right)^2 \quad (2.36)$$

$$+ \lambda_4 H^\dagger \Delta \Delta^\dagger H. \quad (2.37)$$

$$m_{H^{\pm\pm}} = \frac{\sqrt{2}\mu {v_d}^2 - \lambda_4 {v_d}^2 v_t - 2\lambda_3 {v_t}^3}{2v_t} \quad (2.41)$$

$$m_{H^\pm} = \frac{({v_d}^2 + {v_t}^2)[2\sqrt{2}\mu - \lambda_4 v_t]}{4v_t} \quad (2.42)$$

$$m_H = \frac{\lambda {v_d}^2}{4} - \sqrt{2}\mu v_t + \frac{\lambda_1 + \lambda_4}{2} v_t^2 \quad (2.39)$$

$$M_\Delta = \frac{2\mu {v_d}^2 - \sqrt{2}(\lambda_1 + \lambda_4){v_d}^2 v_t - 2\sqrt{2}(\lambda_2 + \lambda_3) v_t^3}{2\sqrt{2} v_t} \quad (2.40)$$

$$\mathcal{M}^2_{\mathrm{CP_{even}}} = \begin{pmatrix} \frac{\lambda {v_d}^2}{2} & v_d(-\sqrt{2}\mu + (\lambda_1 + \lambda_4) v_t) \\ v_d(-\sqrt{2}\mu + (\lambda_1 + \lambda_4) v_t & \frac{\sqrt{2}\mu {v_d}^2 + 4(\lambda_2 + \lambda_3){v_t}^3)}{2v_t} \end{pmatrix} \quad (2.43)$$

$$\mathcal{M}^2_{\mathrm{CP_{odd}}} = \begin{pmatrix} 2v_t & -v_d \\ -v_d & {v_d}^2/2v_t \end{pmatrix} \quad (2.44)$$

Diagonalizing these matrices gives the mass eigenstates. The mass eigenstates for the $\mathrm{CP_{even}}$ mass states is found to be,

$$\begin{pmatrix} h^0 \\ H^0 \end{pmatrix} = \begin{pmatrix} \cos\alpha & \sin\alpha \\ -\sin\alpha & \cos\alpha \end{pmatrix} \begin{pmatrix} h \\ \xi^0 \end{pmatrix}; \quad \begin{pmatrix} A^0 \\ G^0 \end{pmatrix} = \begin{pmatrix} -\sin\beta & \cos\beta \\ \cos\beta & \sin\beta \end{pmatrix} \begin{pmatrix} Z_1 \\ Z_2 \end{pmatrix}; \quad (2.45)$$

Parameters represented by experimental measurable

$$v_d^2 = \frac{\sin^2\theta_W}{\pi\alpha_{QED}}(2M_W^2 - \cos^2\theta_W M_Z^2)\ , \qquad v_t^2 = \frac{\sin^2\theta_W}{2\pi\alpha_{QED}}(\cos^2\theta_W M_Z^2 - M_W^2)$$

$$\lambda_1 = -\frac{2}{v_d^2+4v_t^2}.m_A^2 + \frac{4}{v_d^2+2v_t^2}.m_{H^\pm}^2 + \frac{\sin 2\alpha}{2v_d v_t}.(m_{h^0}^2 - m_{H^0}^2) \tag{2.44}$$

$$\lambda_2 = \frac{1}{v_t^2}\{\frac{s_\alpha^2 m_{h^0}^2 + c_\alpha^2 m_{H^0}^2}{2} + \frac{1}{2}.\frac{v_d^2}{v_d^2+4v_t^2}.m_A^2 - \frac{2v_d^2}{v_d^2+2v_t^2}.m_{H^\pm}^2 + m_{H^{\pm\pm}}^2\} \tag{2.45}$$

$$\lambda_3 = \frac{1}{v_t^2}\{\frac{-v_d^2}{v_d^2+4v_t^2}.m_A^2 + \frac{2v_d^2}{v_d^2+2v_t^2}.m_{H^\pm}^2 - m_{H^{\pm\pm}}^2\} \tag{2.46}$$

$$\lambda_4 = \frac{4}{v_d^2+4v_t^2}.m_A^2 - \frac{4}{v_d^2+2v_t^2}.m_{H^\pm}^2 \tag{2.47}$$

$$\lambda = \frac{2}{v_d^2}\{c_\alpha^2 m_{h^0}^2 + s_\alpha^2 m_{H^0}^2\} \tag{2.48}$$

$$\mu = \frac{\sqrt{2}v_t}{v_d^2+4v_t^2}.m_A^2 \tag{2.49}$$

Constraints

$$\rho \equiv \frac{M_W^2}{M_Z^2 \cos^2\theta_W}$$

$$M_Z^2 = \frac{(g^2+g'^2)(v_d^2+4v_t^2)}{4} = \frac{g^2(v_d^2+4v_t^2)}{4\cos^2\theta_W} \quad (3.53)$$

$$M_W^2 = \frac{g^2(v_d^2+2v_t^2)}{4} \quad (3.54)$$

whence the modified form of the ρ parameter:

$$\rho = \frac{v_d^2+2v_t^2}{v_d^2+4v_t^2} \neq 1 \quad (3.55)$$

From Eq. (2.31), the requirement that m_A^2 should be positive implies $\mu v_t > 0$. The same positivity requirement in the singly charged and doubly charged sectors, Eqs. (2.13, 2.11), together with our phase convention $v_t > 0$ discussed in section 2, lead to the following bounds on μ:

$$\mu > 0 \quad (3.57)$$

$$\mu > \frac{\lambda_4 v_t}{2\sqrt{2}} \quad (3.58)$$

$$\mu > \frac{\lambda_4 v_t}{\sqrt{2}} + \sqrt{2}\frac{\lambda_3 v_t^3}{v_d^2} \quad (3.59)$$

BFB: potential stability constraints

$$\lambda \geq 0 \ \ \& \ \ \lambda_2+\lambda_3 \geq 0 \ \ \& \ \ \lambda_2 + \frac{\lambda_3}{2} \geq 0 \quad (6.1)$$

$$\& \ \ \lambda_1 + \sqrt{\lambda(\lambda_2+\lambda_3)} \geq 0 \ \ \& \ \ \lambda_1 + \sqrt{\lambda(\lambda_2+\frac{\lambda_3}{2})} \geq 0 \quad (6.2)$$

$$\& \ \ \lambda_1 + \lambda_4 + \sqrt{\lambda(\lambda_2+\lambda_3)} \geq 0 \ \ \& \ \ \lambda_1 + \lambda_4 + \sqrt{\lambda(\lambda_2+\frac{\lambda_3}{2})} \geq 0 \quad (6.3)$$

unitarity:

$$|\lambda_1+\lambda_4| \leq \kappa\pi \quad (6.4)$$
$$|\lambda_1| \leq \kappa\pi \quad (6.5)$$
$$|2\lambda_1+3\lambda_4| \leq 2\kappa\pi \quad (6.6)$$
$$|\lambda| \leq 2\kappa\pi \quad (6.7)$$
$$|\lambda_2| \leq \frac{\kappa}{2}\pi \quad (6.8)$$
$$|\lambda_2+\lambda_3| \leq \frac{\kappa}{2}\pi \quad (6.9)$$
$$|\lambda+4\lambda_2+8\lambda_3 \pm \sqrt{(\lambda-4\lambda_2-8\lambda_3)^2+16\lambda_4^2}\,| \leq 4\kappa\pi \quad (6.10)$$
$$|3\lambda+16\lambda_2+12\lambda_3 \pm \sqrt{(3\lambda-16\lambda_2-12\lambda_3)^2+24(2\lambda_1+\lambda_4)^2}\,| \leq 4\kappa\pi \quad (6.11)$$
$$|2\lambda_1-\lambda_4| \leq 2\kappa\pi \quad (6.12)$$
$$|2\lambda_2-\lambda_3| \leq \kappa\pi \quad (6.13)$$

Masses were chosen to satisfy not-EWscale constraint.

The Atlas experiment parameters

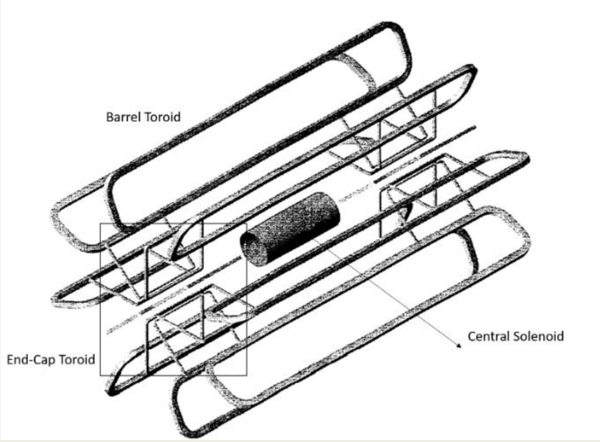
Parameters	2015 - 2018	Design
Beam Energy [TeV]	6.5	7
Integrated Luminosity [fb^{-1}]	156	
Max Peak Luminosity [$10^{34} cm^{-2} s^{-1}$]	2.14	1
Bunch Spacing [ns]	25/50	25

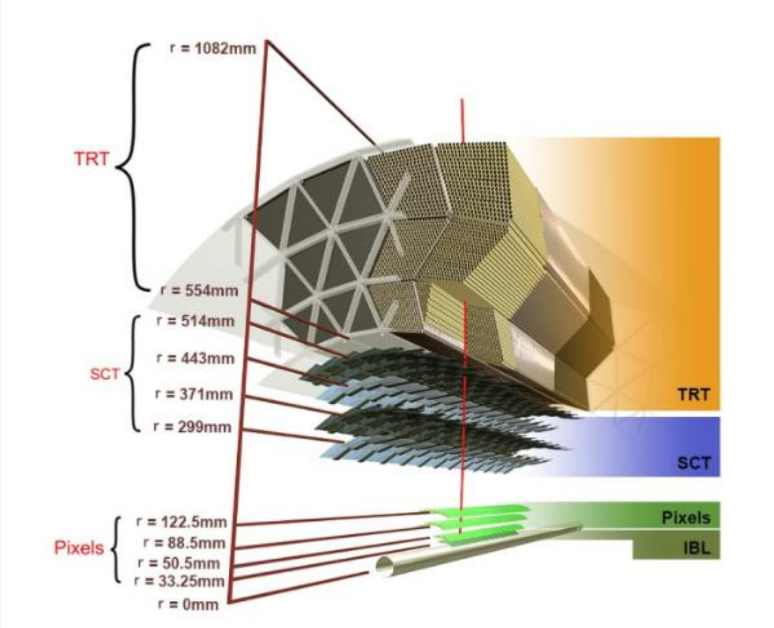
Table 3.1: Status of the LHC as of 2019 and its running parameters. Taken from Ref. [92]. In early 2015 the bunch spacing was set as 50 ns to re-establish operation at high stored energies [93].

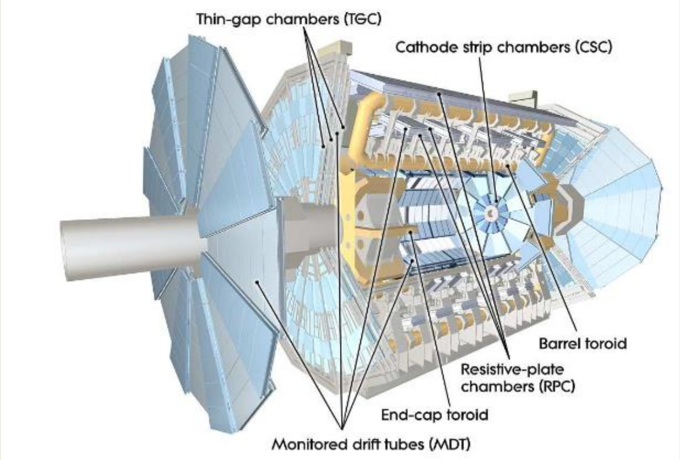
Table 3.2: Resolution goals and pseudorapidity coverage of the sub-systems of the ATLAS detector. Numbers for energy and transverse momentum are in units of GeV. Taken from Table 1.1 in Ref. [40].

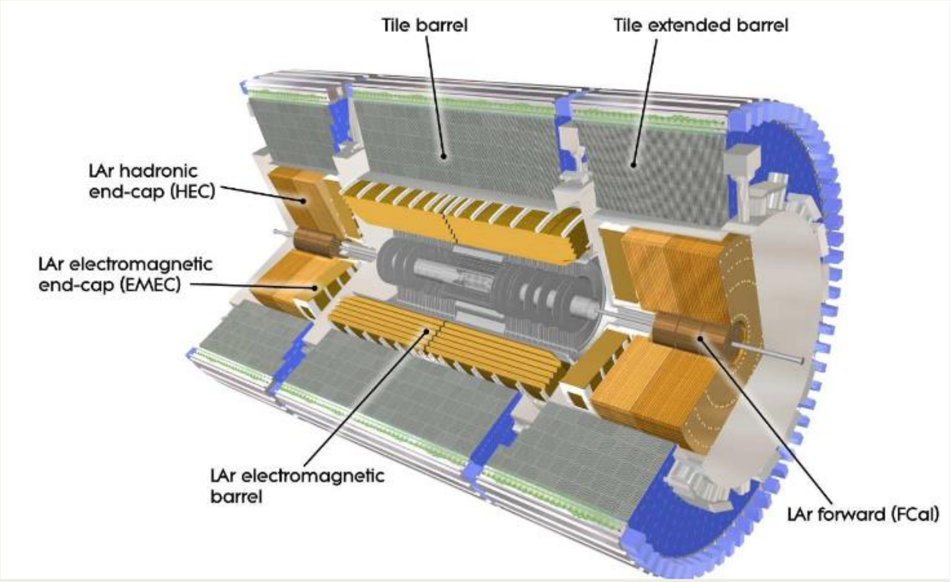
Sub-detector	required resolution	η-coverage measurement	η-coverage trigger
Inner Detector	$\sigma_{p_T}/p_T = 0.05\%\ p_T \oplus 1\%$	$\|\eta\| < 2.5$	
Electromagnetic LAr calorimeter	$\sigma_E/E = 10\%/\sqrt{E} \oplus 0.7\%$	$\|\eta\| < 3.2$	$\|\eta\| < 2.5$
Hadronic calorimeter			
Barrel and end-cap	$\sigma_E/E = 50\%/\sqrt{E} \oplus 3\%$	$\|\eta\| < 3.2$	$\|\eta\| < 3.2$
Forward	$\sigma_E/E = 100\%/\sqrt{E} \oplus 10\%$	$3.1 < \|\eta\| < 4.9$	$3.1 < \|\eta\| < 4.9$
Muon Spectrometer	$\sigma_{p_T}/p_T = 10\%$ at $p_T = 1$ TeV	$\|\eta\| < 2.7$	$\|\eta\| < 2.4$

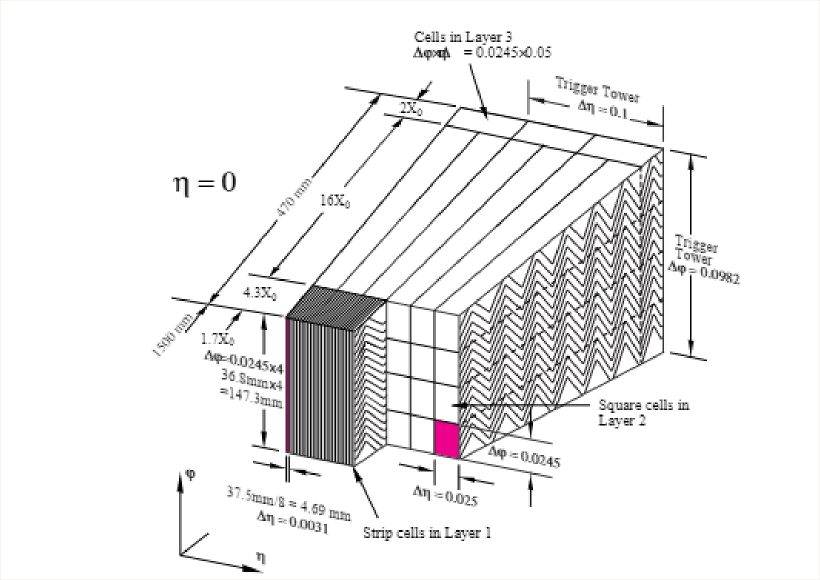
Detectors


Barrel Toroid
End-Cap Toroid
Central Solenoid

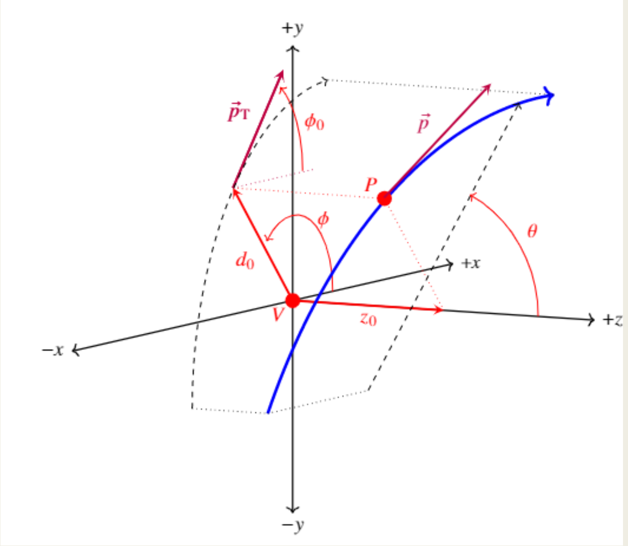

r = 1082mm
TRT
r = 554mm
r = 514mm
SCT
r = 443mm
r = 371mm
r = 299mm
Pixels
r = 122.5mm
r = 88.5mm
r = 50.5mm
r = 33.25mm
r = 0mm
TRT
SCT
Pixels
IBL

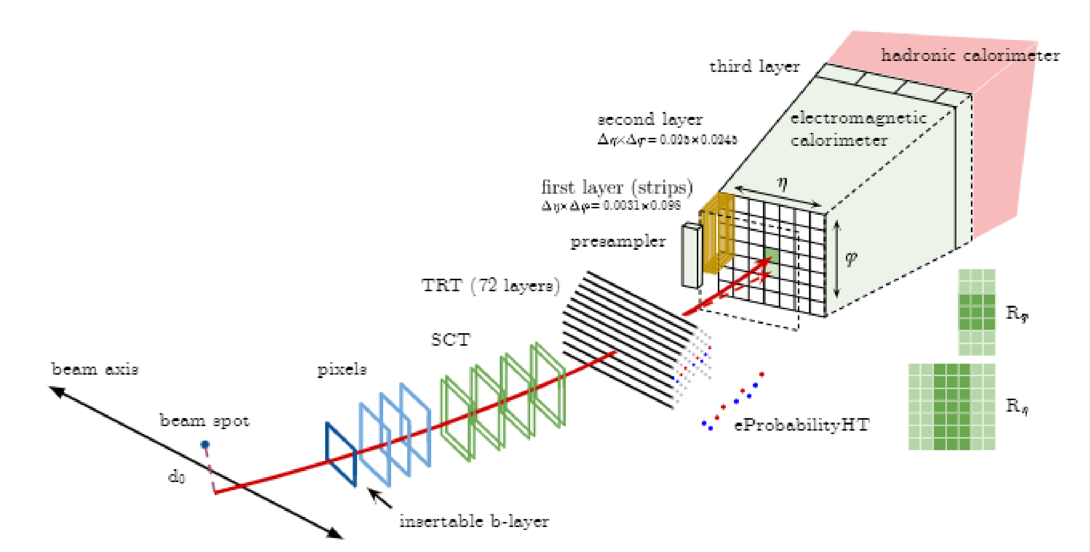

Thin-gap chambers (TGC)
Cathode strip chambers (CSC)
Barrel toroid
Resistive-plate chambers (RPC)
End-cap toroid
Monitored drift tubes (MDT)

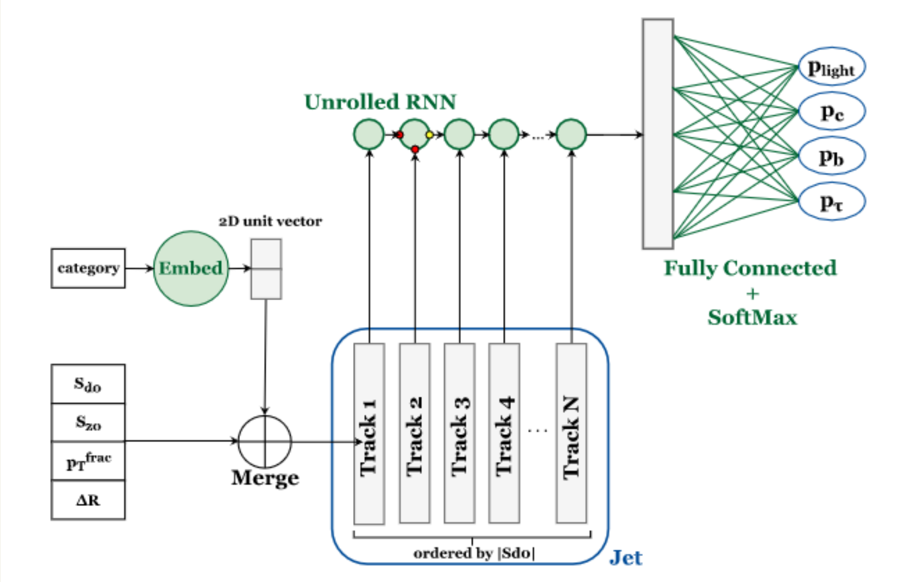

Tile barrel
Tile extended barrel
LAr hadronic end-cap (HEC)
LAr electromagnetic end-cap (EMEC)
LAr electromagnetic barrel
LAr forward (FCal)

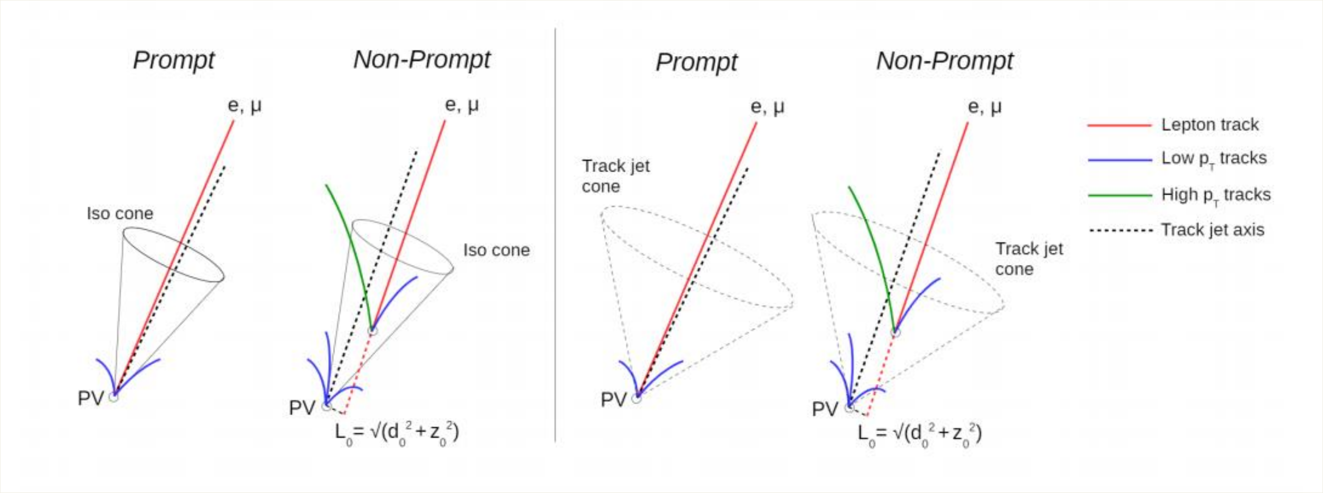

Cells in Layer 3
= 0.0245×0.05
Trigger Tower
Δη = 0.1
2X0
η = 0
470 mm
16X0
Trigger Tower
Δφ = 0.0982
4.3X0
1500 mm
1.7X0
Δφ=0.0245x4
36.8mmx4
=147.3mm
Square cells in Layer 2
Δφ = 0.0245
Δη = 0.025
37.5mm/8 = 4.69 mm
Δη = 0.0031
Strip cells in Layer 1
φ
η

Object


+y
−y
+x
−x
+z
$\vec{p}_T$
ϕ_0
$\vec{p}$
P
ϕ
d_0
V
z_0
θ


hadronic calorimeter
third layer
second layer
electromagnetic calorimeter
first layer (strips)
presampler
TRT (72 layers)
SCT
pixels
beam axis
beam spot
d_0
insertable b-layer
eProbabilityHT

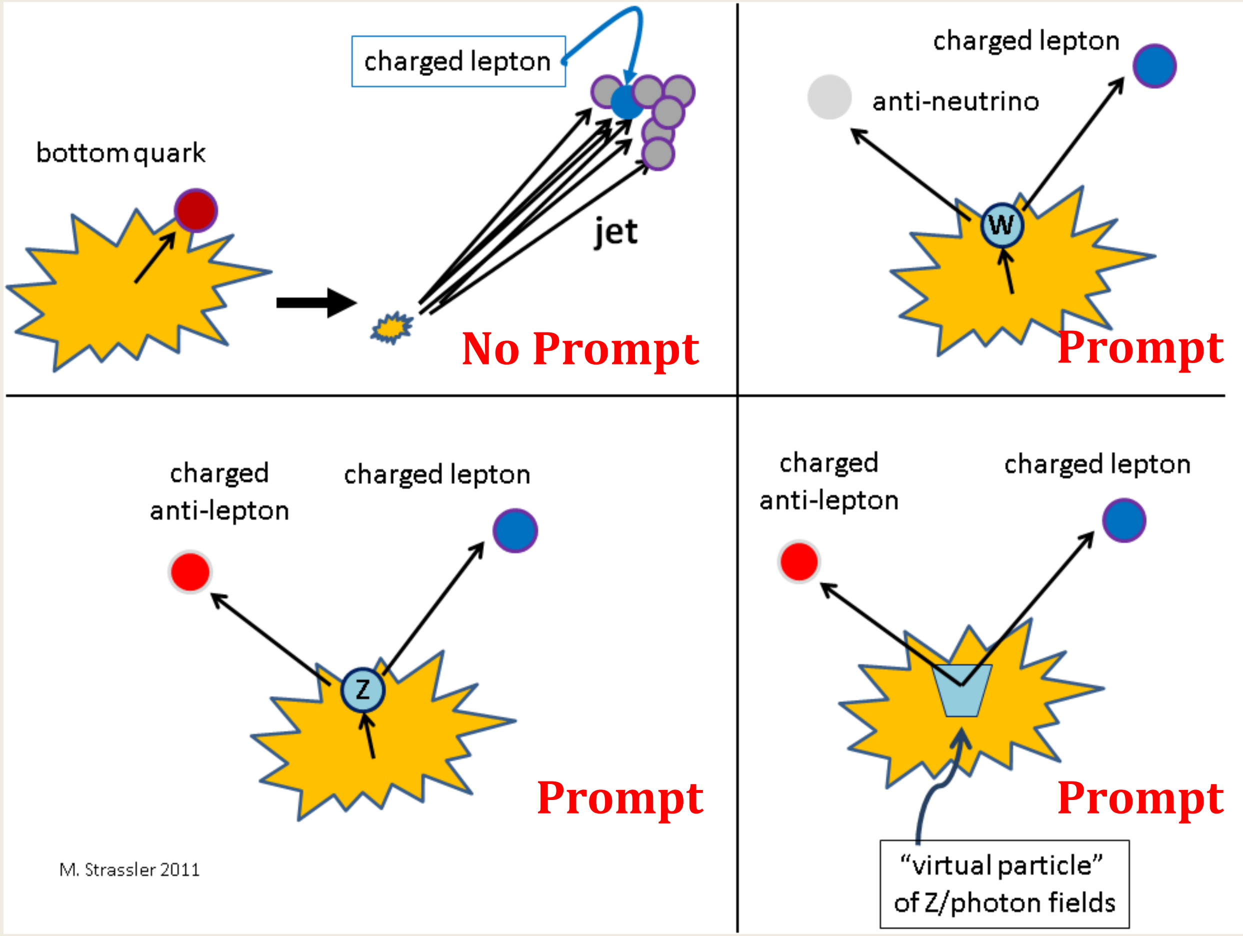

Unrolled RNN
Fully Connected
+
SoftMax
2D unit vector
category
Embed
Merge
S_{d0}
S_{z0}
p_T^{frac}
ΔR
Track 1
Track 2
Track 3
Track 4
Track N
ordered by |Sd0|
Jet


Prompt
Non-Prompt
Prompt
Non-Prompt
e, μ
Iso cone
Track jet cone
PV
$L_0 = \sqrt{(d_0^2 + z_0^2)}$
Lepton track
Low p_T tracks
High p_T tracks
Track jet axis

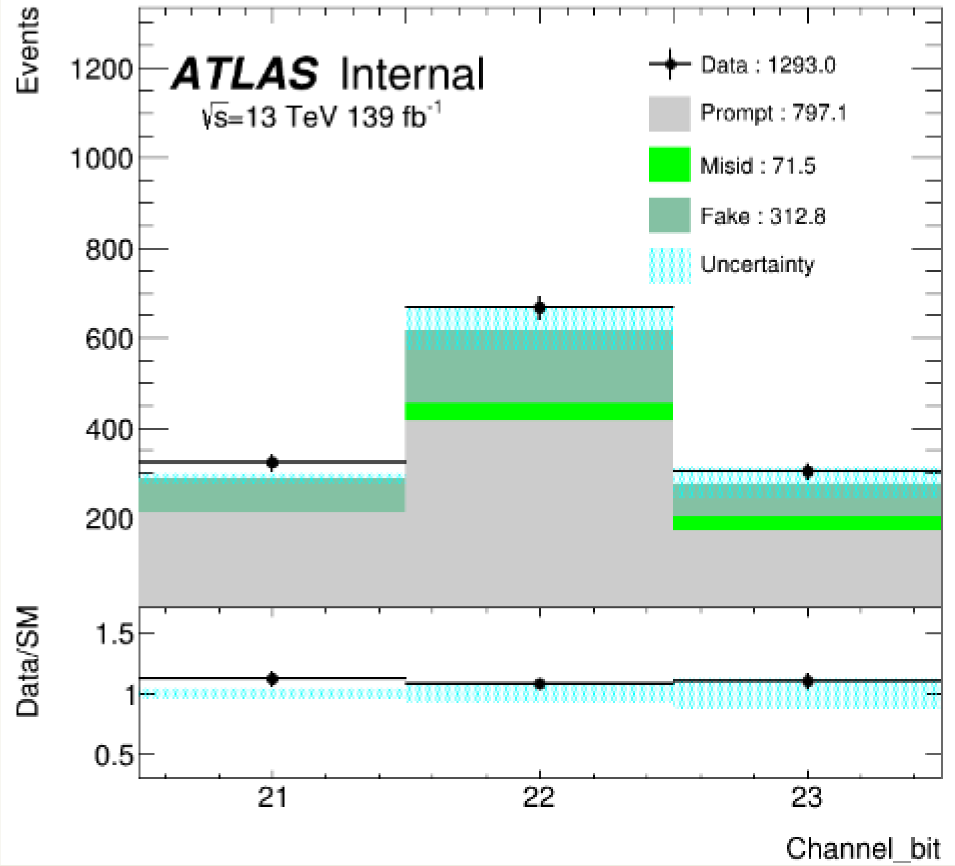
Lepton definitions details.

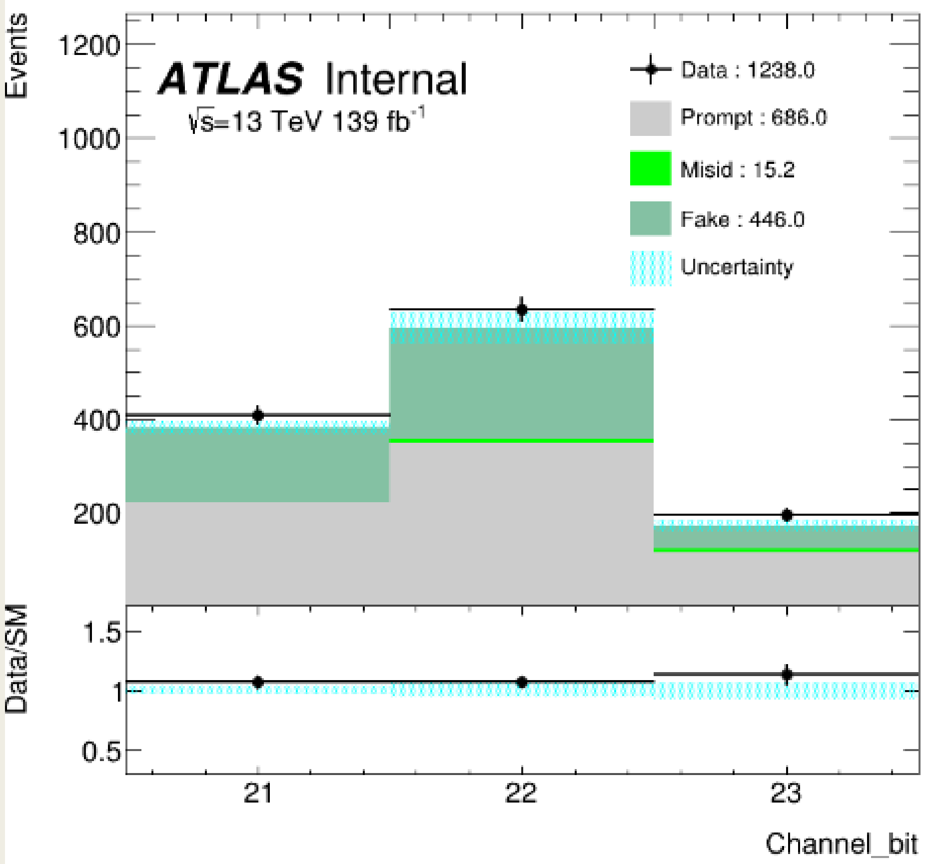
Lepton	Electrons			
Category	*Baseline*	*Candidate*	*Candidate**	*Signal*
$\lvert z_0 \sin\theta \rvert$	< 0.5 *mm*			
$\lvert d_0 \rvert / \sigma(d_0)$	< 5			
Identification	LOOSE			TIGHT
Isolation	No		Loose	Prompt lepton BDT
Electron charge identification	No	Yes		
Lepton	**Muons**			
Category	*Baseline*	*Candidate*	*Candidate**	*Signal*
$\lvert z_0 \sin\theta \rvert$	< 0.5 *mm*			
$\lvert d_0 \rvert / \sigma(d_0)$	< 10	< 3		
Identification	MEDIUM			
Isolation	No		Loose	Prompt lepton BDT

All prompt situation



DEV: Object Selection Improvement





Trigger

2015	Description
HLT_e26_lhmedium_L1EM20VH	≥1 electron with p_T >26 GeV, Medium identification and L1 p_T >20 GeV
HLT_e60_lhmedium	≥1 electron with p_T >60 GeV, Medium identification
HLT_e120_lhloose	≥1 electron with p_T >120 GeV, Loose identification
HLT_mu20_iloose_L1MU15	≥1 CB muon with p_T >20 GeV, Loose isolation and L1 p_T >15 GeV
HLT_mu50	≥1 CB muon with p_T >50 GeV

2016-2018	Description
HLT_e26_lhtight_nod0_ivarloose	≥1 electron with p_T >26 GeV, Tight identification and Loose isolation
HLT_e60_lhmedium_nod0	≥1 electron with p_T >60 GeV, Medium identification
HLT_e140_lhloose_nod0	≥1 electron with p_T >140 GeV, Loose identification
HLT_mu26_ivarmedium	≥1 CB muon with p_T >26 GeV, Medium isolation
HLT_mu50	≥1 CB muon with p_T >50 GeV

Signal Branch Ratios

Signal Production Information

$H^{\pm\pm}H^{\mp\mp} \rightarrow$	$4W \rightarrow$	BR (in %)
$4\,W \rightarrow jj$	$0\ell + 8$ jets	20.1
$3\,W \rightarrow jj,\ 1\,W \rightarrow \nu\ell$	$1\ell + E_T^{miss} + 6$ jets	39.7
$2\,W \rightarrow jj,\ 2\,W \rightarrow \nu\ell$	$2\ell + E_T^{miss} + 4$ jets	29.3 ($2\ell^{sc}$: 14.7)
$1\,W \rightarrow jj,\ 3\,W \rightarrow \nu\ell$	$3\ell + E_T^{miss} + 2$ jets	9.6
$4\,W \rightarrow \nu\ell$	$4\ell + E_T^{miss}$ + no jets	1.2

H^{++} mass (GeV)	200	300	400	500	600
cross section (fb)	81.04	16.48	4.883	1.766	0.726
filter efficiency	0.1089	0.1161	0.1198	0.1249	0.1237

Table: Cross sections (ME LO + PDF LO, k-factor = 1.25 is applied for NLO correction), filter efficiencies of the AFII signal samples (pair-production $pp \rightarrow H^{\pm\pm}H^{\mp\mp}$).

$H^{\pm\pm}H^{\mp} \rightarrow$	$WWWZ \rightarrow$	BR (in %)
$3\,W \rightarrow jj,\ Z \rightarrow jj$	$0\ell + 8$ jets	22.0
$3\,W \rightarrow jj,\ Z \rightarrow \nu\nu$	$0\ell + E_T^{miss} + 6$ jets	6.3
$2\,W \rightarrow jj,\ 1\,W \rightarrow \nu\ell,\ Z \rightarrow jj$	$1\ell + E_T^{miss} + 6$ jets	31.1
$2\,W \rightarrow jj,\ 1\,W \rightarrow \nu\ell,\ Z \rightarrow \nu\nu$	$1\ell + E_T^{miss} + 4$ jets	8.9
$3\,W \rightarrow jj,\ Z \rightarrow \ell\ell$	$2\ell + 6$ jets	3.1 ($2\ell^{sc}$: 0)
$1\,W \rightarrow jj,\ 2\,W \rightarrow \nu\ell,\ Z \rightarrow jj$	$2\ell + E_T^{miss} + 4$ jets	14.6 ($2\ell^{sc}$: 4.7)
$1\,W \rightarrow jj,\ 2\,W \rightarrow \nu\ell,\ Z \rightarrow \nu\nu$	$2\ell + E_T^{miss} + 2$ jets	4.2 ($2\ell^{sc}$: 1.4)
$2\,W \rightarrow jj,\ 1\,W \rightarrow \nu\ell,\ Z \rightarrow \ell\ell$	$3\ell + E_T^{miss} + 4$ jets	4.4
$3\,W \rightarrow \nu\ell,\ Z \rightarrow jj$	$3\ell + E_T^{miss} + 2$ jets	2.3
$3\,W \rightarrow \nu\ell,\ Z \rightarrow \nu\nu$	$3\ell + E_T^{miss}$	0.7
$1\,W \rightarrow jj,\ 2\,W \rightarrow \nu\ell,\ Z \rightarrow \ell\ell$	$4\ell + E_T^{miss} + 2$ jets	2.1
$3\,W \rightarrow \nu\ell,\ Z \rightarrow \ell\ell$	$5\ell + E_T^{miss}$ + no jets	0.3

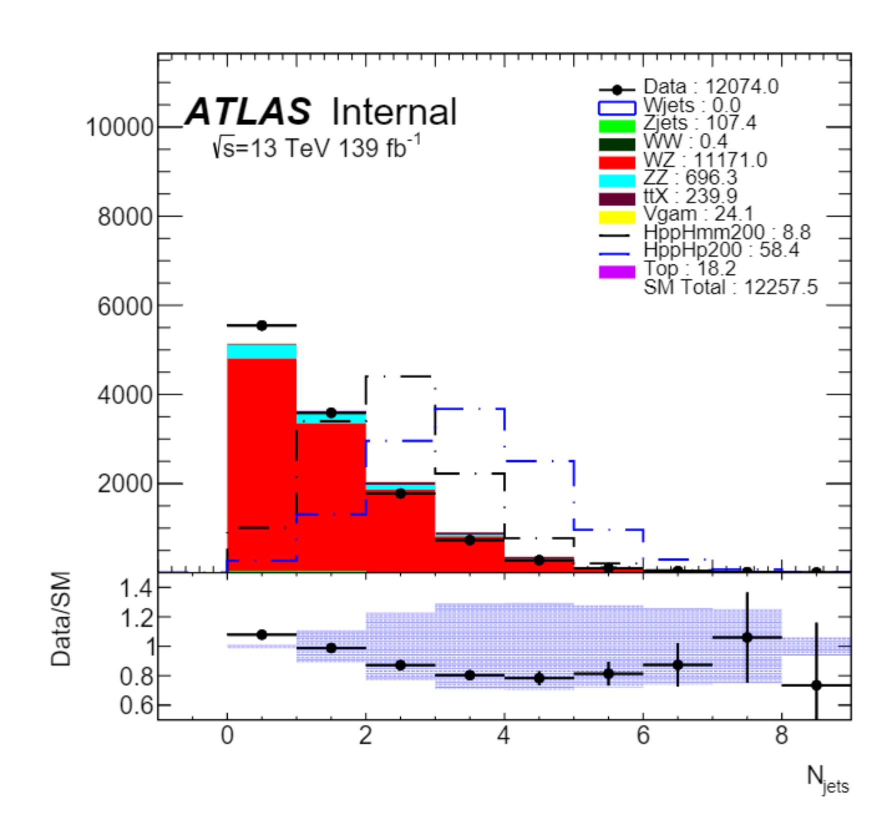
H^{++} mass (GeV)	200	300	400	500	600
H^{+} mass (GeV)	196	295	395	496	602
cross section (fb)	88.66	9.463	2.988	1.175	0.513
filter efficiency	0.2573	0.2814	0.2997	0.3178	0.3278

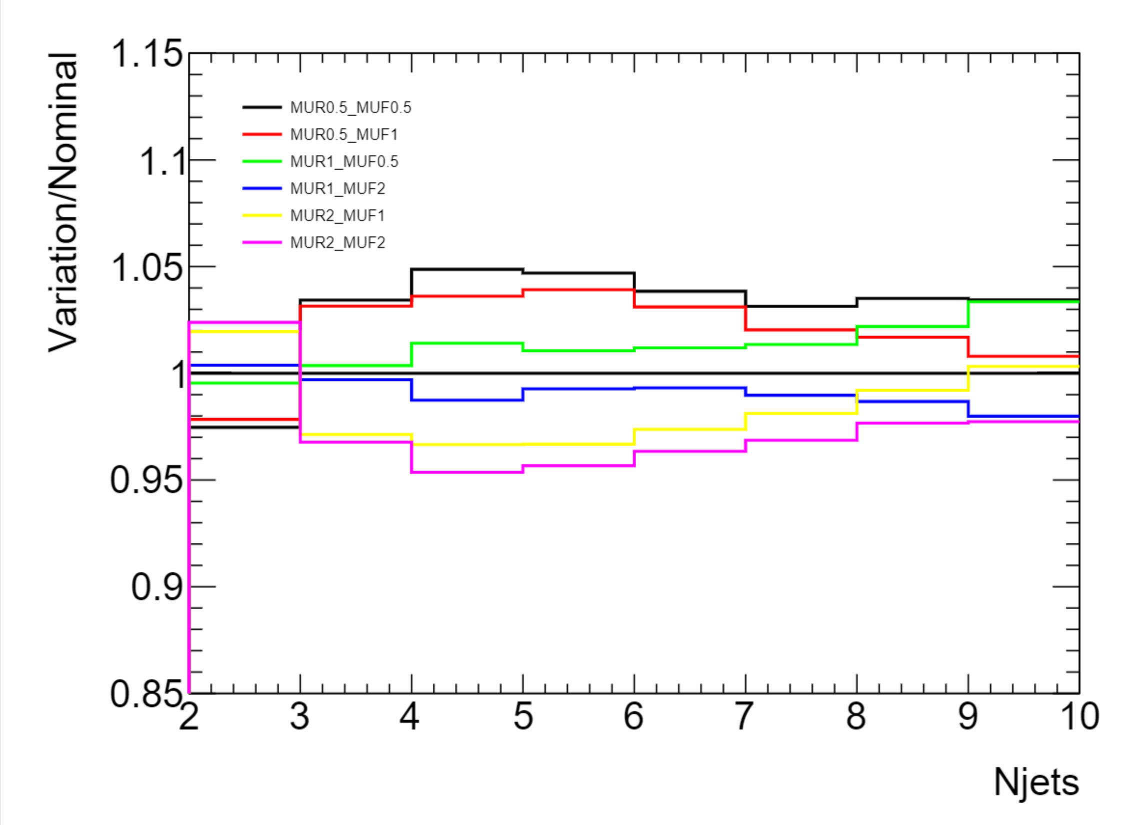
sections (ME LO + PDF LO, k-factor = 1.25 is applied for NLO correction), filter f the AFII signal samples (associate-production $pp \rightarrow H^{\pm\pm}H^{\mp}$).

Background MC

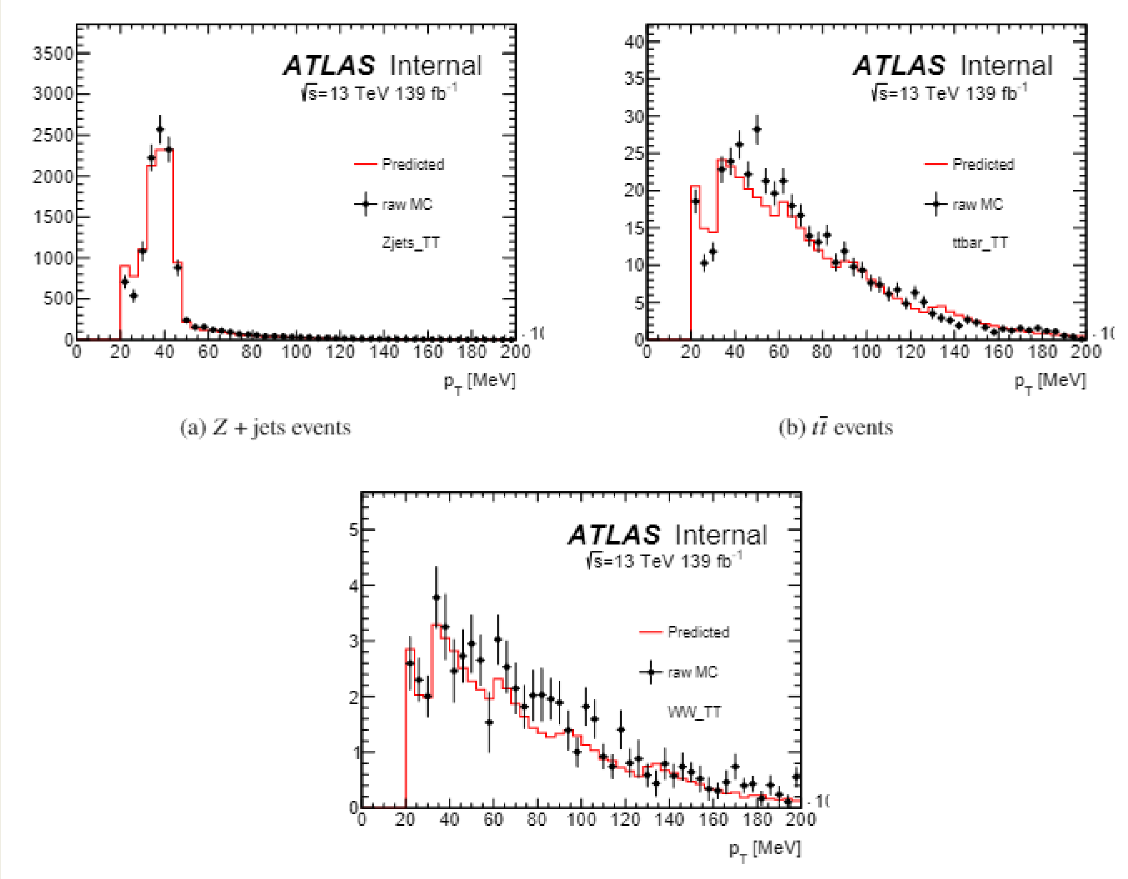
Process	ME Generator	Parton Shower	PDF	Tune
$t\bar{t}H$	POWHEG [146]	PYTHIA 8 [43]	NNPDF30ME [147]	A14 [44]
VH	PYHTIA 8	PYTHIA 8	NNPDF23LO	A14
$t\bar{t}W$	MG5_AMC	PYTHIA 8	NNPDF 3.0 NLO/2.3 LO	A14
$t\bar{t}(Z/\gamma^{*})$	MG5_AMC	PYTHIA 8	MEN30NLO	A14
$t(Z/\gamma^{*})$	MG5_AMC	PYTHIA 8	NNPDF 3.0 LO	A14
$t\bar{t}$	POWHEG [146]	PYTHIA 8	NNPDF 3.0 NLO/2.3 LO	A14
s-, t-channel, Wt single top	POWHEG [148, 149]	PYTHIA 8	NNPDF 3.0 NLO/2.3 LO	A14
VV, $qqVV$, VVV	SHERPA 2.2.2 [150]	SHERPA	NNPDF30NNLO	SHERPA default
$Z \to \ell^{+}\ell^{-}$	SHERPA 2.2.2	SHERPA	NNPDF 3.0 NNLO	SHERPA default
$W \to \ell\nu$	SHERPA 2.2.2	SHERPA	NNPDF 3.0 NNLO	SHERPA default
$Z\gamma$ / $W\gamma$	SHERPA 2.2.4/2.2.2	SHERPA	NNPDF 3.0 NNLO	SHERPA default
$t\bar{t}t\bar{t}$, $t\bar{t}t$	MG5_AMC	PYTHIA 8	NNPDF 2.3 LO	A14
$t\bar{t}W^{+}W^{-}$	MG5_AMC	PYTHIA 8	NNPDF 2.3 LO	A14
$tW(Z/\gamma^{*})$	MG5_AMC	PYTHIA 8	NN30NNLO	A14

WZ QCD shape uncertainty





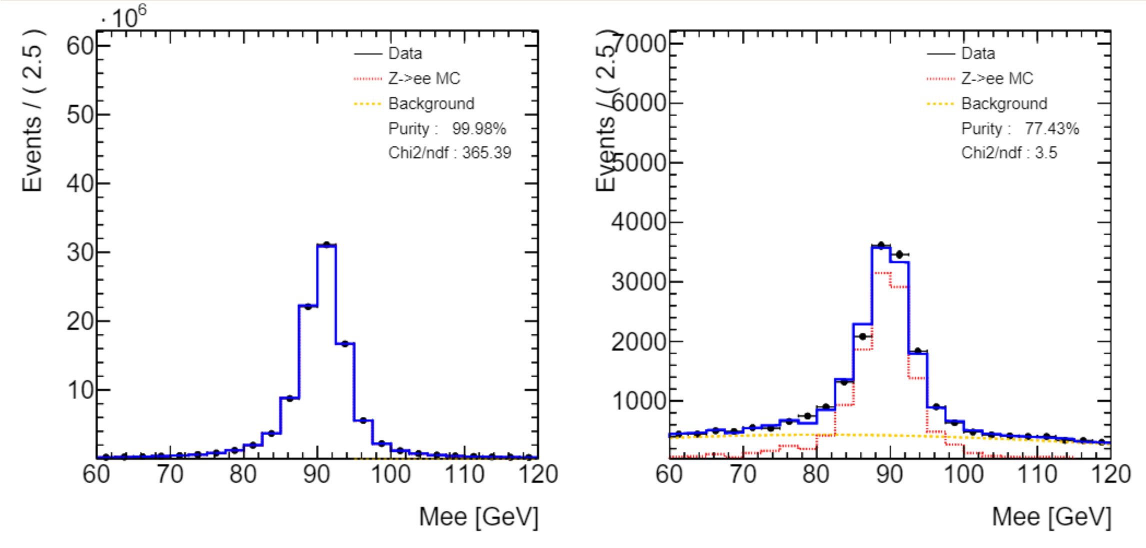
ChargeFlip Unct



(a) Z + jets events

(b) $t\bar{t}$ events

(c) Opposite-sign WW events



(a) all electron pairs

(b) same-sign electron pairs

p_T binned fake factor motivation

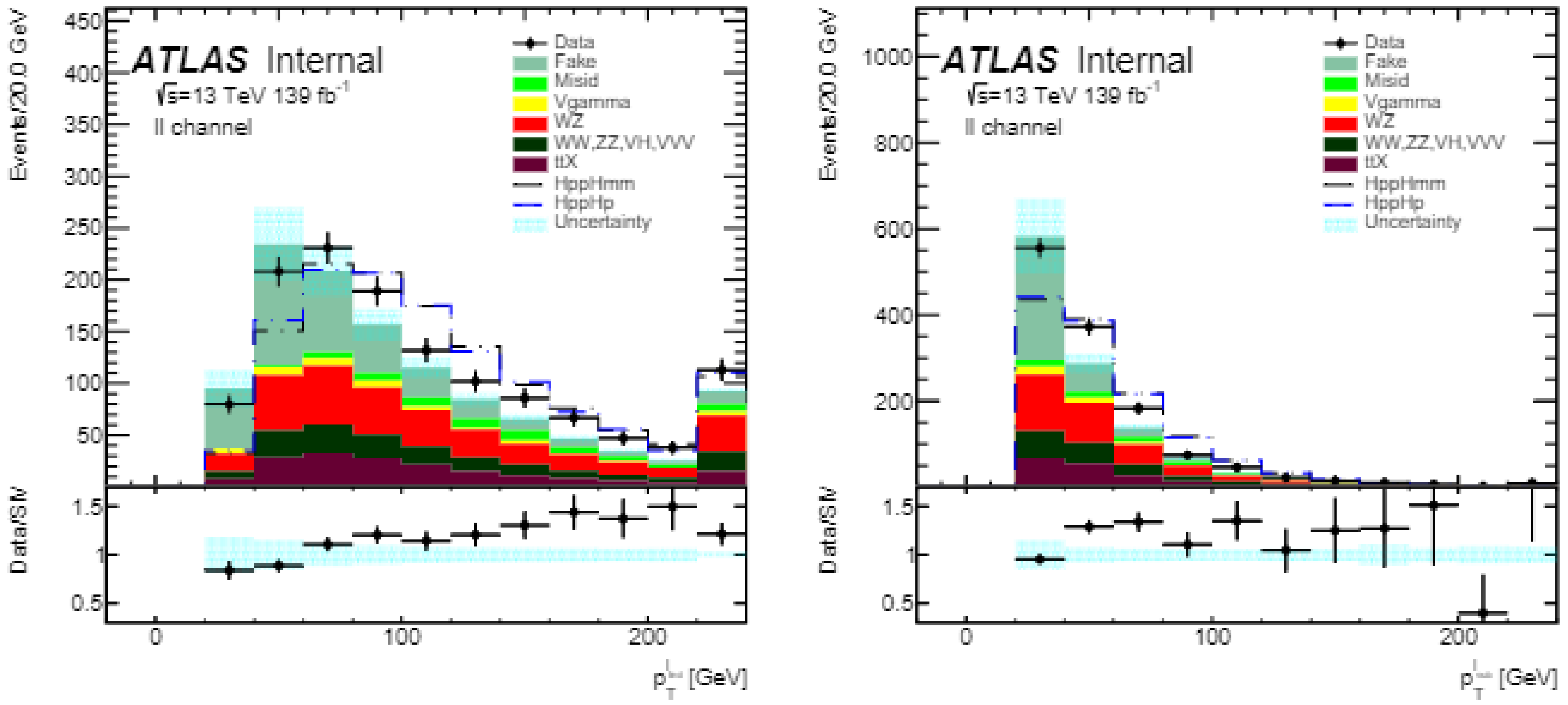


Figure 7.7: $2\ell^{sc}$ channel. Leading lepton p_T and sub-leading lepton p_T distribution at event pre-selection stage. Data-driven fake results were applied with **inclusive fake factors**. The tension found in these distributions

Pt binned method unct

Level	20-40 GeV	40-60 GeV
p_T	ℓ : 30 GeV, ℓ: 50 GeV	ℓ: hadronic decay
Truth info.		ℓ : 30 GeV, ℓ: 50 GeV

FF unct. Breakdown (2l)

Sources	unct(%) [e]	unct(%) [μ]
charge flip	15.9	-
Monte-Carlo closure	19.1	7.3
Prompt-Monte-Carlo theory uncertainty	17.4	15.8
electron efficiency	7.43	-
electron resolution and scale	0.56	0.02
muon scale/ID/sagitta	0.01	0.54
muon efficiency	-	0.75
Pileup reweighting data-scale-factor	0.3	0.63
JET category reduction/energy scale/energy resolution	12.77	10.06
Flavor tagging	0.31	0.28
MET Variation	1.70	2.07
Total global unct	33.74	22.76

Event Selection Yields

	Data	Prompt	Fake	charge flip	Total background
ee	224	113.83±18.78	67.22±19.16	14.06±2.71	195.11±26.97
$\mu\mu$	275	160.37±24.46	93.92 ± 21.39	-	254.29±32.49
$e\mu$	542	299.1±44.46	168.62±42.58	15.81±2.88	483.52±61.63

	WZ	WW,ZZ,VH,VVV	ttX	$V\gamma$
ee	68.67±9.34	18.09±3.66	21.27±4.25	5.8±2.56
$\mu\mu$	91.2±11.83	34.13±6.86	34.5 ± 6.89	0.55 ± 0.57
$e\mu$	172.89±22.09	52.9±10.64	58.8±11.75	15.81±2.88

	Data	Prompt	Fake	Total background
3ℓ	879	730.91 ± 92.71	109.05 ± 64.15	839.96 ± 112.74
Monte-Carlo Composition	WZ	WW,ZZ,VH,VVV	ttX	$V\gamma$
Yield	553.59 ± 57.13	83.6 ± 17.96	77.7 ± 15.63	16.03 ± 5.94

	Data	Prompt Monte-Carlo	Non-prompt Leptons	Total background
Pre-Selection	63	41.8 ± 5.38	24.75 ± 4.86	66.55 ± 7.25
Monte-Carlo	WZ	WW,ZZ,VH,VVV	$t\bar{t}X$	$V\gamma$
Yield	2.9 ± 0.47	31.02 ± 3.66	7.23 ± 1.12	0.66 ± 0.39

Signal Optimization

Instead of ML technique, cut optimization **displays the signal region as a simple list of ranges** and **can be used to test other models.**

Cut Optimization Provided by TMVA.

- Rectangular cuts optimization.
- Maximizes the background rejection $(1/eff_{bkg})$ at given signal efficiency.
- Simulate Anneal algorithm.

100 cut sets will be proposed.

Additional selection.

- Use signal significance (Cowan).
- All cuts are rounded.
- Stability checks were performed.

Optimization were done per mass point, per sub-channel. (500 GeV results will be applied to 600 GeV signal.)

Signal regions

Charged Higgs boson mass	$m_{H^{\pm\pm}} = 200GeV$ $m_{H^{\pm}} = 196GeV$	$m_{H^{\pm\pm}} = 300GeV$ $m_{H^{\pm}} = 295GeV$	$m_{H^{\pm\pm}} = 400GeV$ $m_{H^{\pm}} = 395GeV$	$m_{H^{\pm\pm}} = 500GeV$ or $600GeV$ $m_{H^{\pm}} = 496GeV$ or $602GeV$
Selection criteria	$2lsc$ channel			
m_{jets} [GeV]	[100, 450]	[100, 500]	[300, 700]	[400, 1000]
S [rad.]	<0.3	<0.6	<0.6	<0.9
$\Delta R_{\ell^{\pm}\ell^{\pm}}$ [rad.]	<1.9	<2.1	<2.2	<2.4
$\Delta\phi_{\ell\ell,E_{\text{T}}^{\text{miss}}}$ [rad.]	<0.7	<0.9	<1.0	<1.0
$m_{x\ell}$ [GeV]	[40, 150]	[90, 240]	[130, 340]	[130, 400]
$E_{\text{T}}^{\text{miss}}$ [GeV]	>100	>130	>170	>200
Selection criteria	$3l$ channel			
$\Delta R_{\ell^{\pm}\ell^{\pm}}$ [rad.]	[0.2, 1.7]	[0.0, 2.1]	[0.2, 2.5]	[0.3, 2.8]
$m_{x\ell}$ [GeV]	>160	>190	>240	>310
$E_{\text{T}}^{\text{miss}}$ [GeV]	>30	>55	>80	>90
$\Delta R_{\ell\text{jet}}$ [rad.]	[0.1, 1.5]	[0.1, 2.0]	[0.1,2.3]	[0.5, 2.3]
$p_{\text{T}}^{\text{leading jet}}$ [GeV]	>40	>70	>100	>95
Selection criteria	$4l$ channel			
$m_{x\ell}$ [GeV]	>230	>270	>360	>440
$E_{\text{T}}^{\text{miss}}$ [GeV]	>60	>60	>60	>60
$p_{\text{T}}^{\ell_1}$ [GeV]	>65	>80	>110	>130
$\Delta R_{\ell^{\pm}\ell^{\pm}}^{\text{min}}$ [rad.]	[0.2, 1.2]	[0.2, 2.0]	[0.5, 2.4]	[0.6, 2.4]
$\Delta R_{\ell^{\pm}\ell^{\pm}}^{\text{max}}$ [rad.]	[0.3, 2.0]	[0.5, 2.6]	[0.4, 3.1]	[0.6, 3.1]

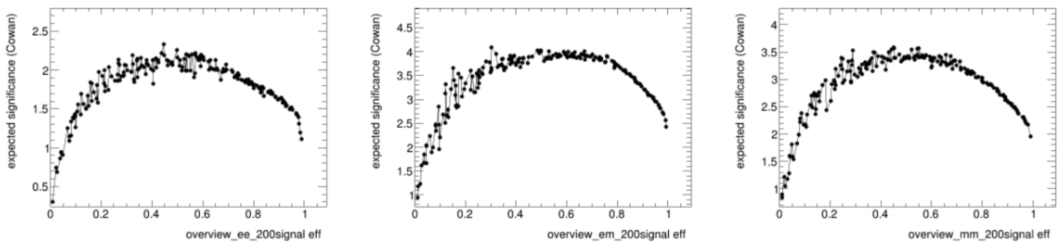
Theoretical Uncertainties ($m_{H^{\pm\pm}}$ = 300 GeV)

Process	Theory uncertainty											
	$2\ell^{sc}$						3ℓ				4ℓ	
	ee		$e\mu$		$\mu\mu$		SFOC0		SFOC12		4ℓ	
	QCD	PDF	QCD	PDF	QCD	PDF	QCD	PDF	QCD	PDF	QCD	PDF
WZ	9.0%										14.8%	0.11%
$t\bar{t}X$	13.0% for QCD, 4.0% for PDF											
ZZ	43.1%	7.7%	27.9%	1.4%	23.6%	1.3%	17.2%	2.1%	26.1%	1.2%	14.9%	2.1%
WW	31.3%	1.0%	24.5%	2.0%	34.1%	1.5%	17.2%	2.6%	41.0%	1.5%	-	-
$V\gamma$	-	-	40.7%	2.5%	-	-	-	-	15.3 %	1.9%	-	-
VVV	7.4%	2.3%	8.4%	2.6%	8.4%	1.3%	10.5%	1.7%	10.5%	1.4%	7.9%	1.4%
Rare process	50%											

Signal Region Stability Check

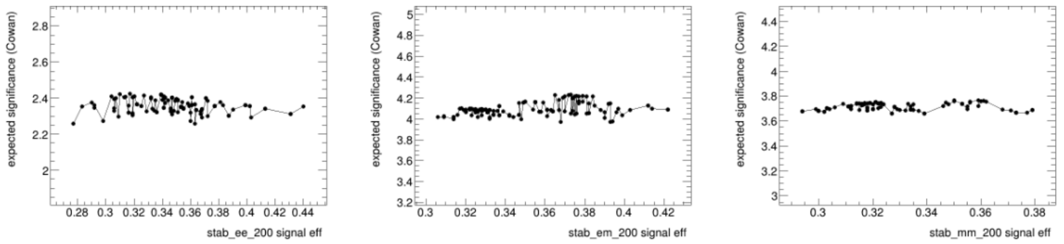
A "temperature for smoothing" is defined:
the R.M.S. in the previous 5 points.

$$Significance = \sqrt{2 * ((sig + bkg) * \log(1 + \frac{sig}{bkg}) - sig)}$$



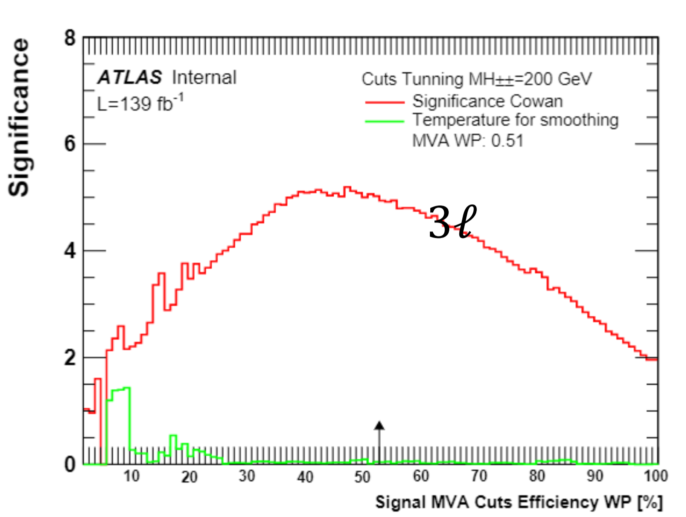
(a) ee channel (b) $e\mu$ channel (c) $\mu\mu$ channel

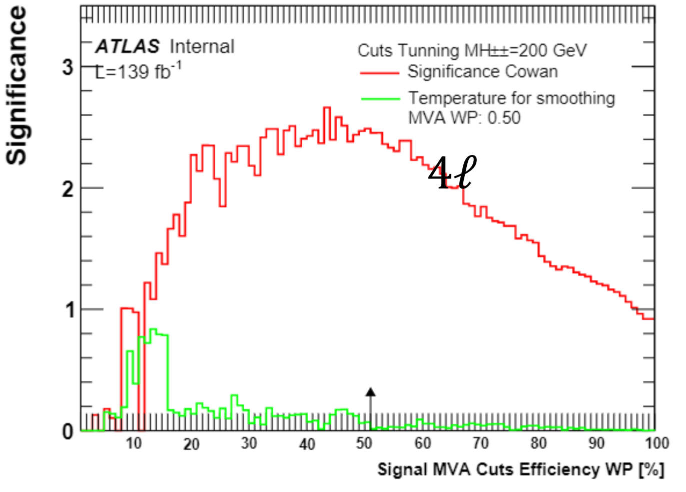
Figure 8.1: $2\ell^{sc}$ channel. Expected significances (Cowan) for different working points (provided by TMVA CutsSA) of the signal selection for the 200 GeV mass point, Left: ee channel, Middle: $e\mu$ channel Right: $\mu\mu$ channel.



(a) ee channel (b) $e\mu$ channel (c) $\mu\mu$ channel

Figure 8.2: $2\ell^{sc}$ channel. Expected significances (Cowan) for different working points (by varying baseline cut value) of the signal selection for the 200 GeV mass point, Left: ee channel, Middle: $e\mu$ channel Right: $\mu\mu$ channel.





Profiling LLH checks ($m_{H^{\pm\pm}}$ = 300 GeV)