The Quest for Charged Higgs Boson at ATLAS

… in the Time of Plague

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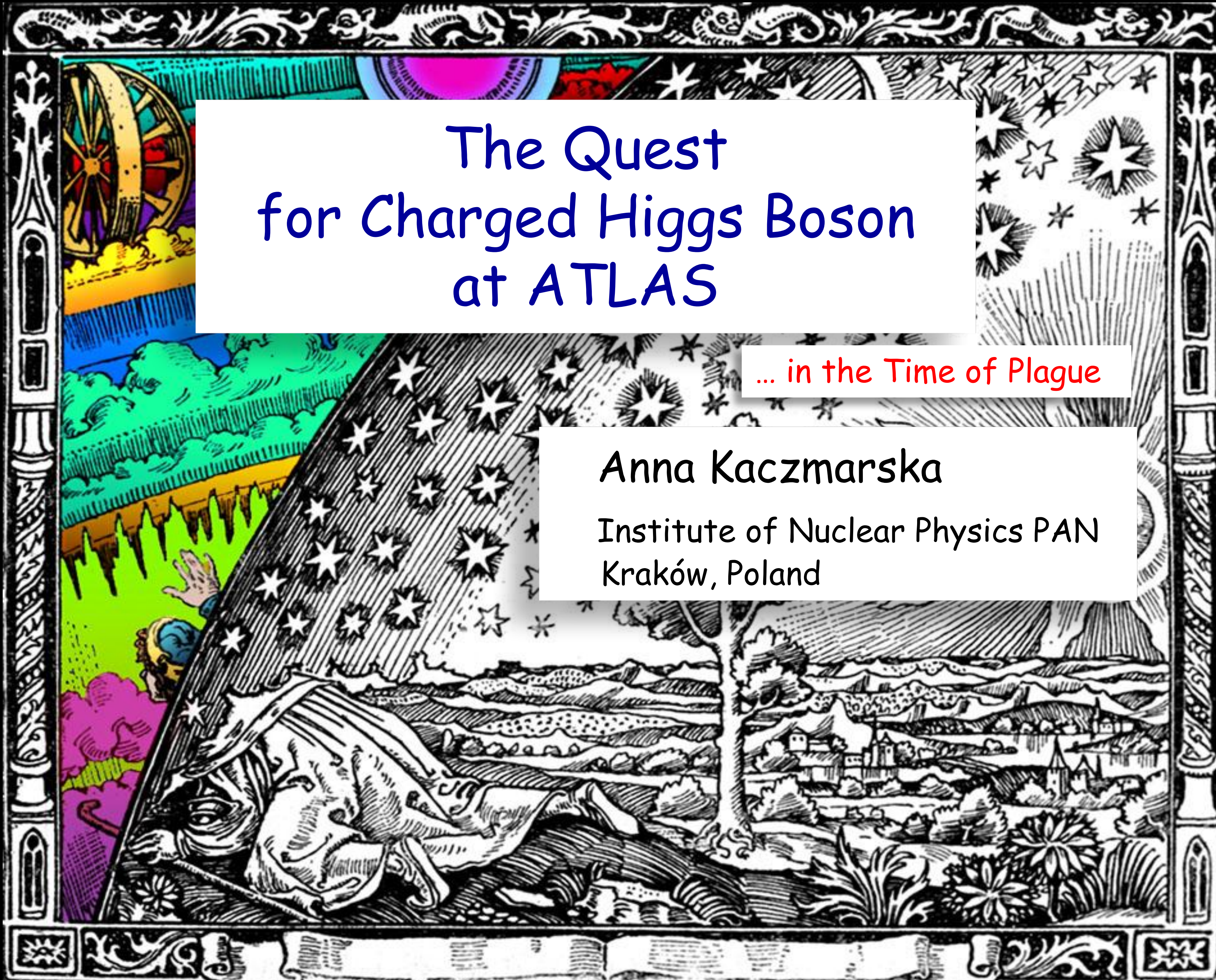
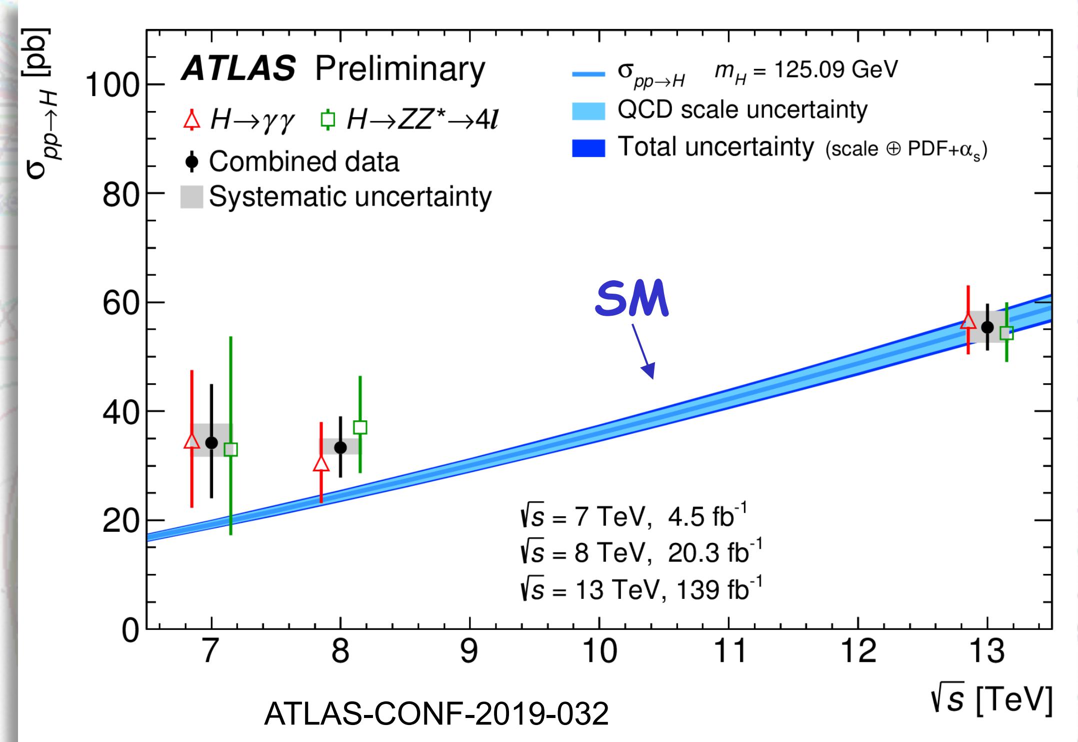


Higgs from the Standard Model

- Discovery of a neutral scalar particle of mass ~125 GeV at the LHC confirmed the predicted electroweak symmetry breaking mechanism of the SM
- Experimental results show consistency with the SM Higgs boson
- The Higgs boson completes the **extremely successful SM**, but at the same time **opens a number of crucial questions** that we need to address



Open questions before 4th July 2012

Electroweak symmetry breaking
- ❑ Does the Higgs boson exist ?

Quarks and leptons
- ❑ Why three families ?
- ❑ Why these masses and mixings ?
- ❑ CP violation in the lepton sector
- ❑ Matter / anti-matter asymmetry
- ❑ Baryon and charged lepton number violation

Physics toward the Planck scale
- ❑ How does gravity play with the other forces ?
- ❑ Are there more than three dimensions of space ?
- ❑ Do all forces unify at high energy ?
- ❑ Are there other forces ?

Dark matter
- ❑ What is it ? WIMP, sterile neutrino , axion, LSP, other hidden sector particle ?
- ❑ Only one type ?
- ❑ Only gravitational or other interactions ?

Neutrinos
- ❑ Why do neutrinos have masses ?
- ❑ Majorana or Dirac ?
- ❑ CP violation
- ❑ Are there more (sterile) neutrinos ?

Two epochs of Universe's accelerated expansion
- ❑ Primordial: Is inflationary model correct? Which (scalar) field ? Role of quantum gravity ?
- ❑ Today: Dark energy or gravity modification ?

courtesy of J. Beacham

Open questions after 4th July 2012

Electroweak symmetry breaking
- ✓ Does the Higgs boson exist ?
- ❑ Is m_h natural or fine-tuned ? If natural: what new physics/symmetry governs this ?
- ❑ Elementary or composite Higgs?
- ❑ Is it alone or does the Higgs have siblings and cousins ?
- ❑ Origin of couplings to fermions ?
- ❑ Coupling to dark matter ?
- ❑ Does it violate CP ?

Dark matter
- ❑ What is it ? WIMP, sterile neutrino , axion, LSP, other hidden sector particle ?
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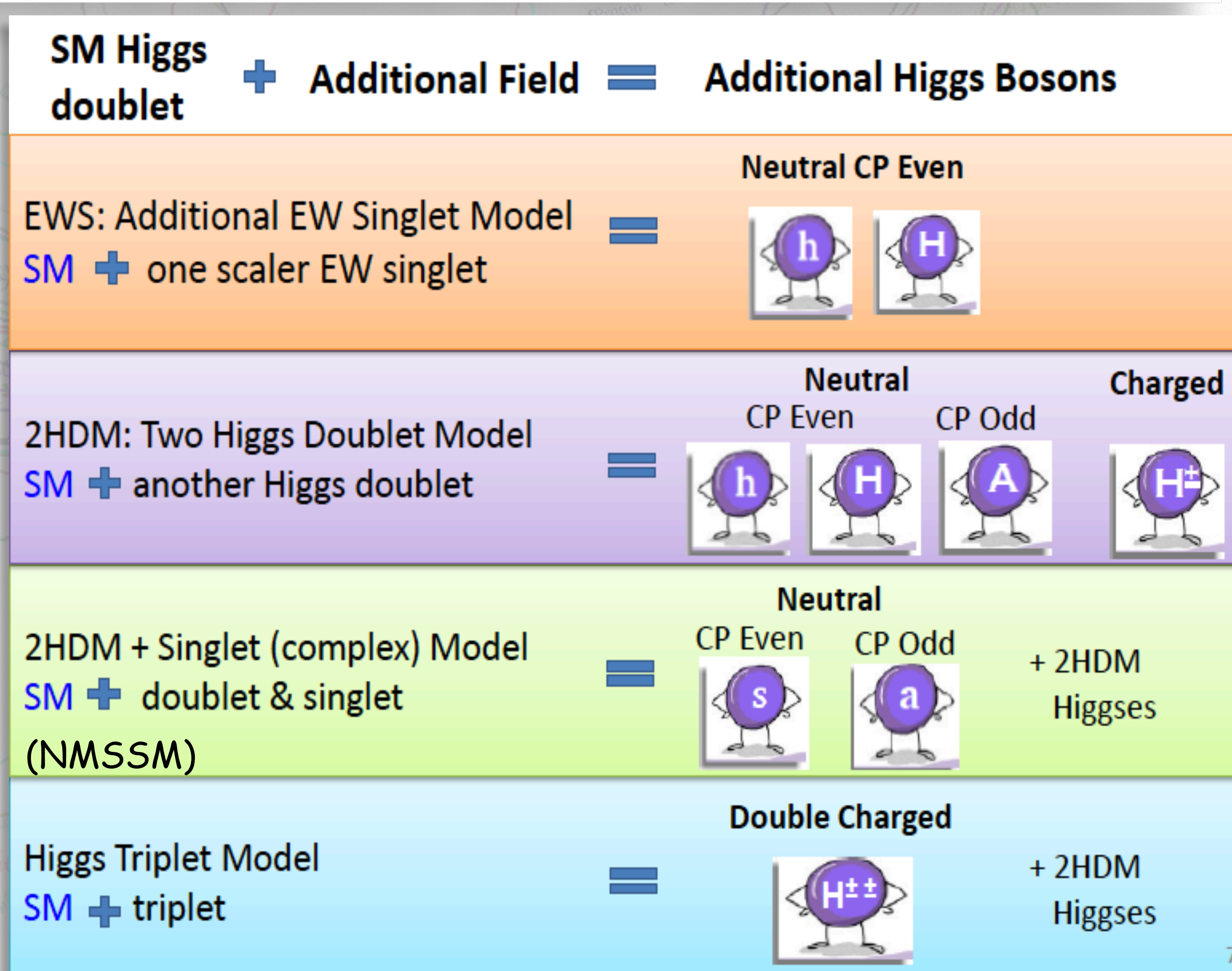
Neutrinos
- ❑ Why do neutrinos have masses ?
- ❑ Majorana or Dirac ?
- ❑ What's the role of h125?
- ❑ CP violation
- ❑ Are there more (sterile) neutrinos ?

courtesy of J. Beacham

Higgs boson(s) Beyond the Standard Model

- So far Higgs looks like from SM, but consistent with SM ≠ incompatible with BSM

- 3 repeated pairs of leptons and quarks, without any reason - why scalar sector should be different?
- Extended scalar sector appears in many extensions of the SM
- They allow for SM-like light Higgs phenomenology with smaller or larger modification of couplings



courtesy of N. Ilic

Two Higgs Doublet Model (2HDM)

Generic class with 2nd Higgs doublet. Four variants to couple SM fermions to the 2HDs (no FCNCs):

- Type I: all quarks and leptons couple to only one doublet
- Type II: one doublet couples to u-type quarks, other to d-type quarks and leptons: „MSSM-like"
- Lepton-specific: couplings to quarks as in the Type I model and to leptons as in Type II
- Flipped: couplings to quarks as in the Type II model and to leptons as in Type I

Model	Type I	Type II	Lepton-specific	Flipped
Φ_1	–	d, ℓ	ℓ	d
Φ_2	u, d, ℓ	u	u, d	u, ℓ

- 5 Higgs bosons: h, H, A, H^+, H^-
- Free parameters: tanβ (ratio between the vevs of the doublets), α (mixing angle between h and H) and m_A
- Minimal Supersymmetric SM (MSSM) is a special case of 2HDM:
  - "type II" with fixed α
  - numerous benchmark models: hMSSM, m_h^{mod+}, etc.
- SM Higgs results give big constraints on 2HDM. Data prefers alignment limit: cos(β- α)=0 – h recovers properties of the SM Higgs

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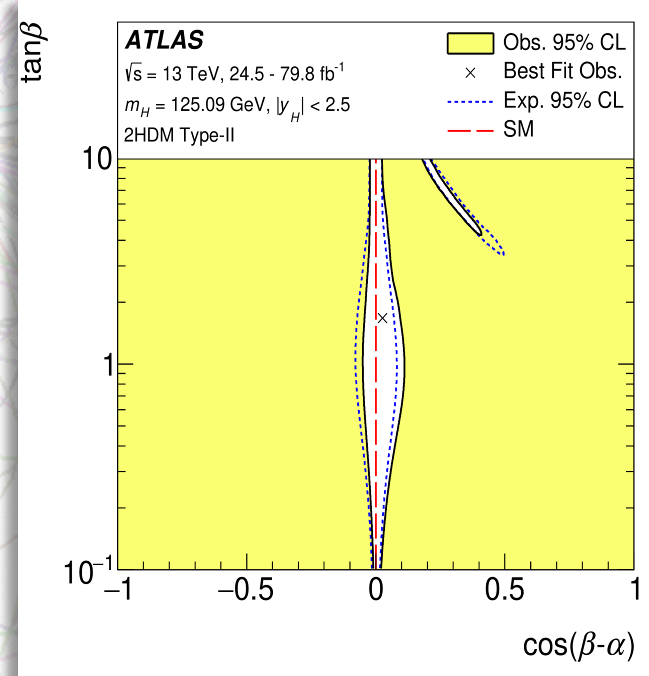


Strategies using Higgs to find New Physics

- Indirectly, by looking for non-standard properties of light Higgs (spin, CP, couplings, LFV decays etc.)
- **Directly, by explicit search for BSM objects**
  - Additional Higgs bosons (neutral and charged, decays to SM particles or to Higgs bosons)
    - $H^{\pm} \rightarrow \tau\nu$ JHEP 09 (2018) 139
    - $H^{\pm} \rightarrow tb$ JHEP 11 (2018) 085
    - $H^{\pm\pm} \rightarrow l^{\pm}l^{\pm}$ Eur. Phys. J. C78 (2018) 199
    - $H^{\pm\pm} \rightarrow W^{\pm}W^{\pm}$ Eur. Phys. J. C (2019) 79

    } **Today**
  - Higgs decays to BSM states (invisible decays, long lived particles etc.)

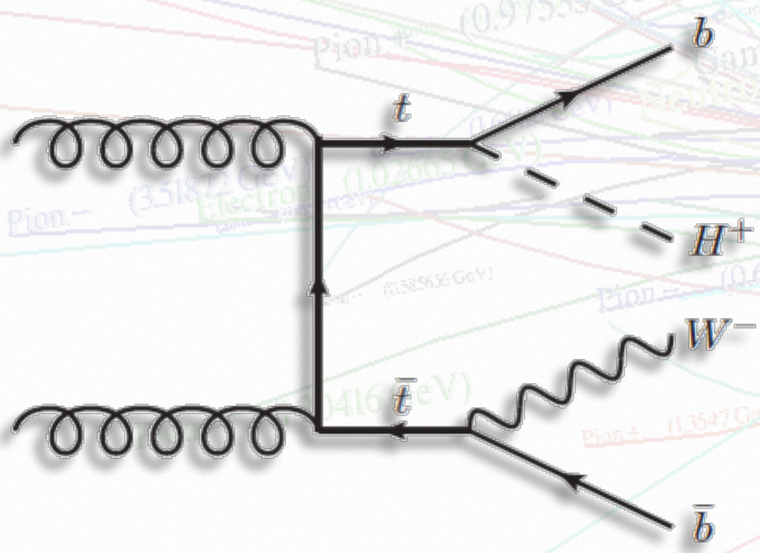
Disclaimer:
Incomplete set of analysed Higgs channels. Only most recent results shown.
New results with full Run-2 dataset coming!

$H^{\pm}$ production modes

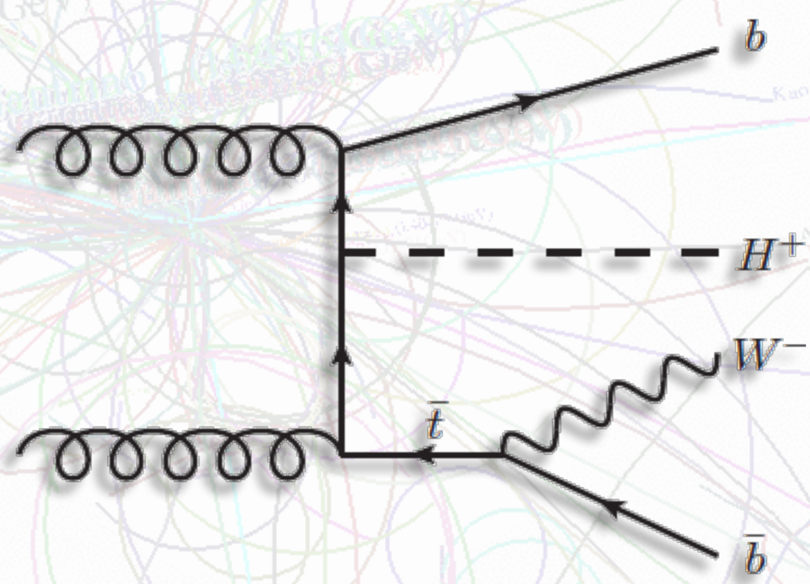
- For $H^{\pm}$ masses below the top-quark mass, the main production mechanism is through the decay of a top-quark, $t \to bH^{\pm}$

- For $H^{\pm}$ masses above the top-quark mass, the leading production mode is $gg \to tbH^{\pm}$

($m_{H+} < m_{top}$)



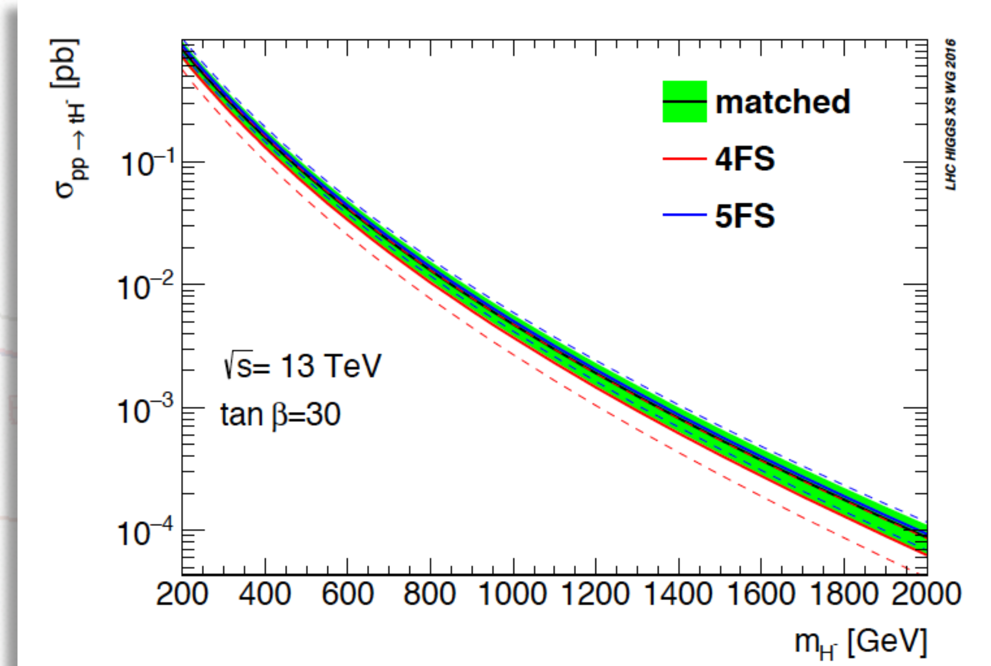
($m_{H+} > m_{top}$)

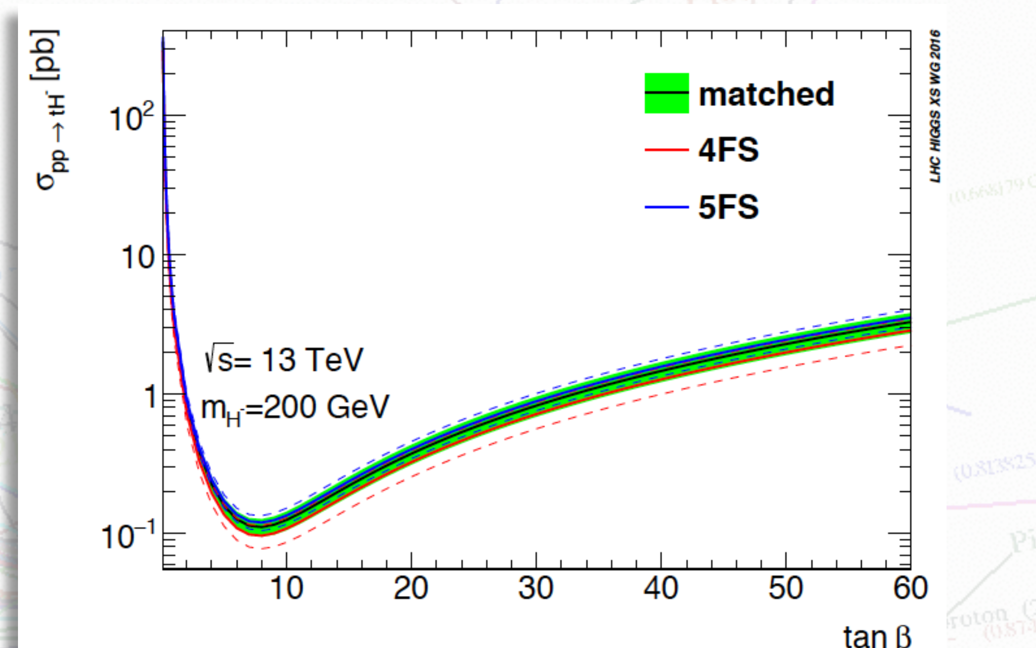


- In the intermediate-mass region ($m_{H+} \sim m_{top}$), accurate theoretical predictions now available

H± production assumptions

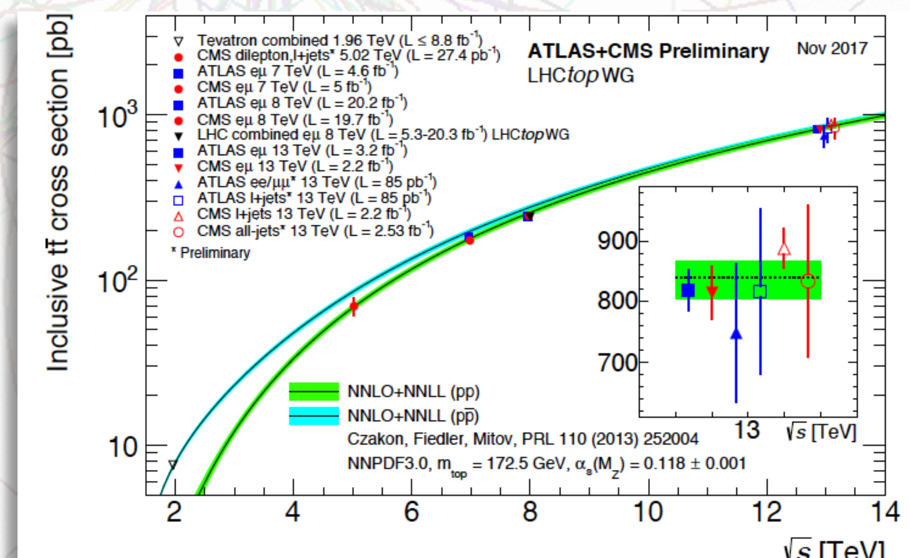
courtesy of B. Burghgrave





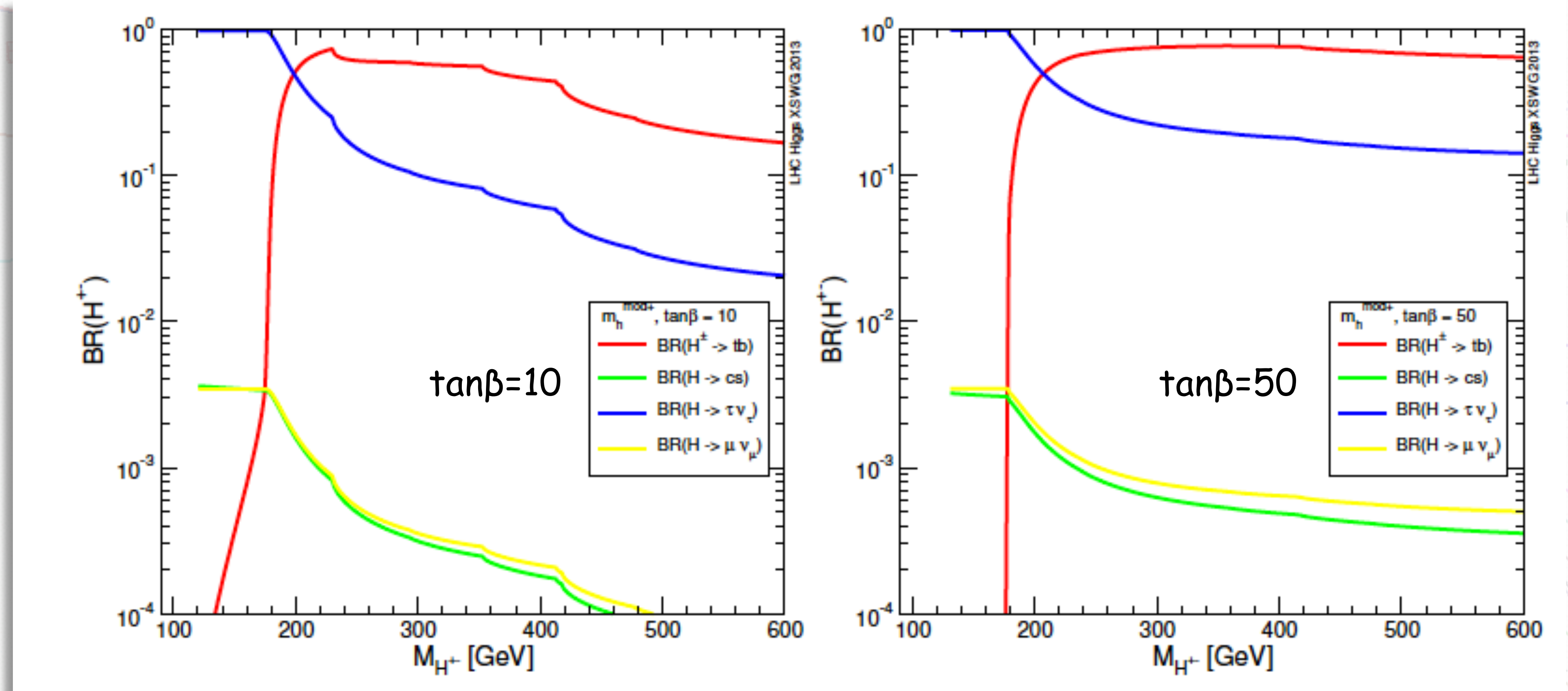
- *Assuming MSSM-like 2HDM, H± production cross section depends on tanβ and $m_{H\pm}$*

- For comparison, ttbar is often the dominant background and its cross section is in general ≥ 3 orders of magnitude higher for $m_{H\pm} \geq m_{top}$

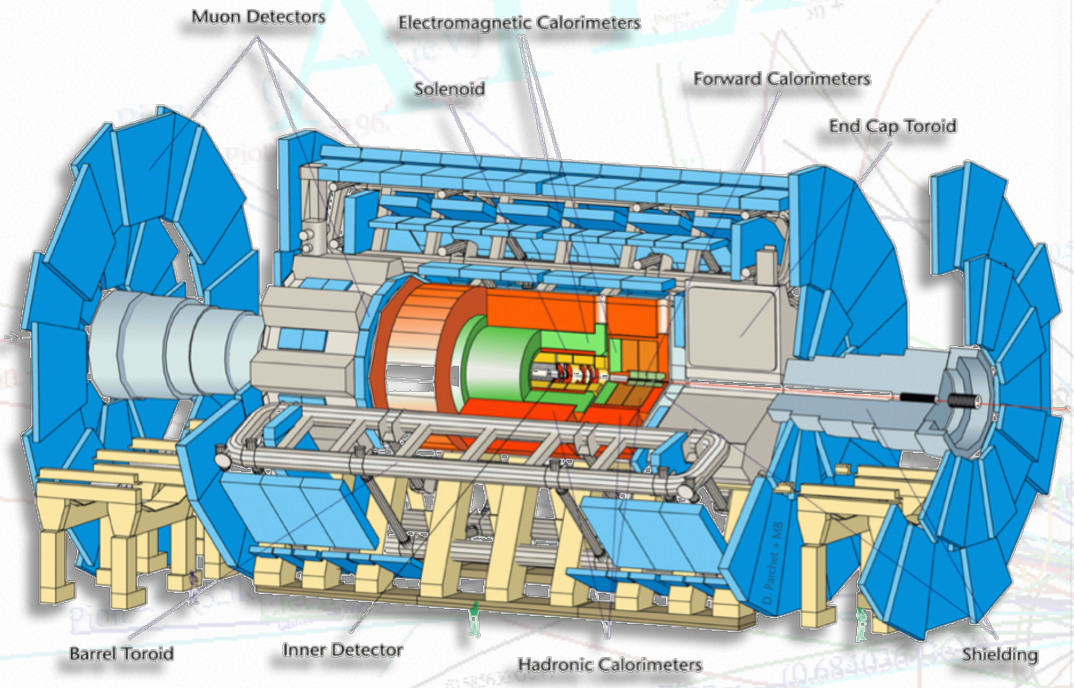


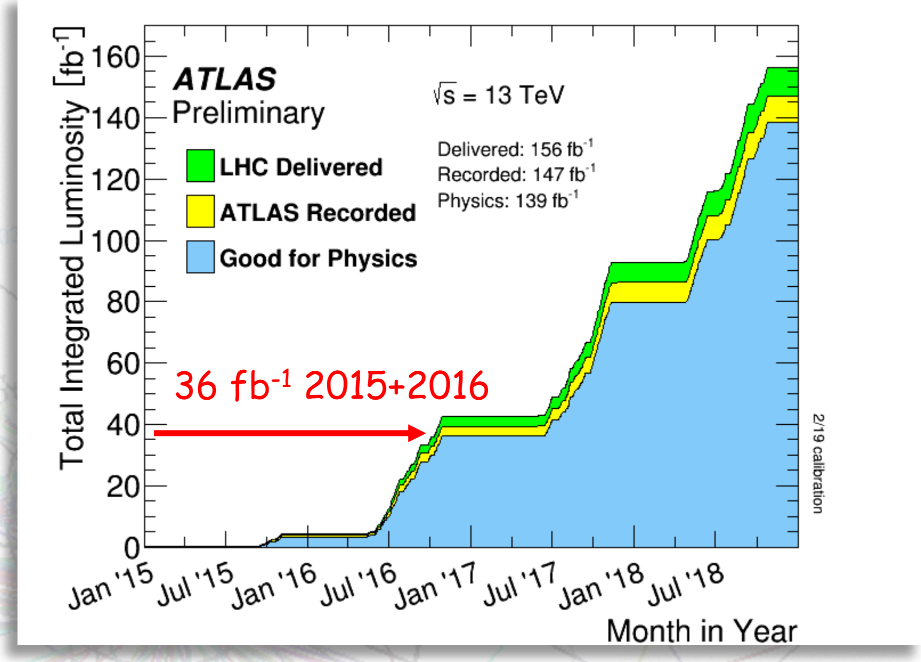
$H^{\pm}$ decay modes

- For $m_{H+} < m_{top}$, the decay $H^{\pm} \to \tau\nu$ usually dominates in a type-II 2HDM
- For $m_{H+} > m_{top}$, the dominant decay is $H^{\pm} \to tb$, however the branching fraction of $H^{\pm} \to \tau\nu$ can reach 10–15% at large values of tanβ in a type-II 2HDM



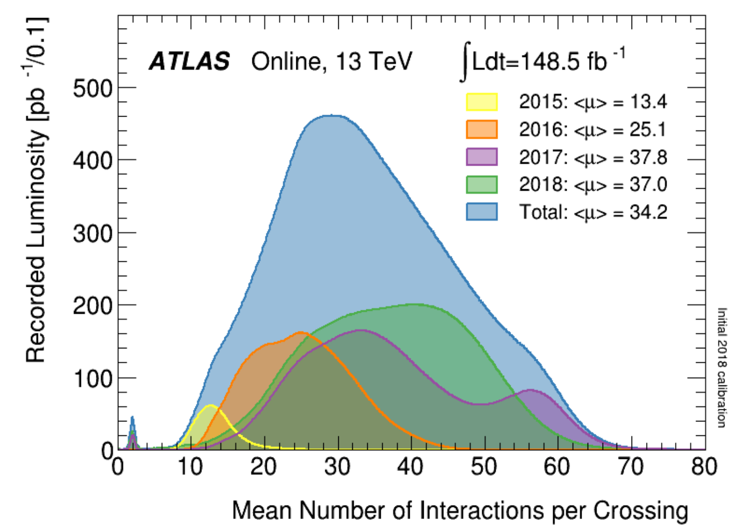
Analysis in ATLAS experiment



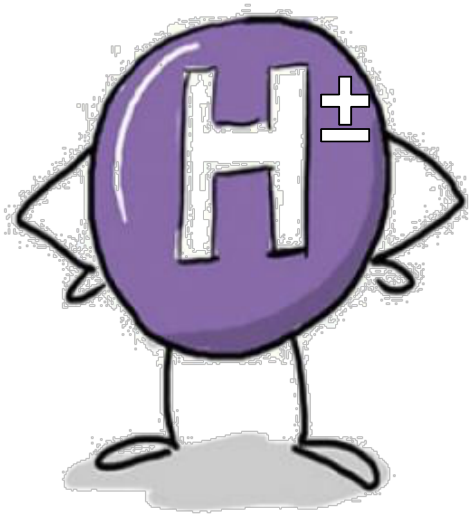


In each analysis we have to:

- understand the detector performance
  - required to be stable even under constantly changing conditions!
- design and validate analysis strategies
  - analysis pipeline fixed before unblinding
- Understand the Standard Model backgrounds
- Model interpretations are the last step and technically the easiest part of analysis

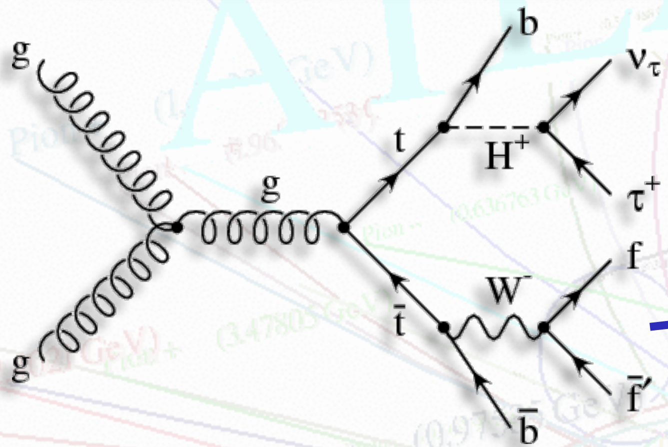


$H^{\pm} \to \tau\nu$ search



36 fb^{-1} @ 13 TeV
JHEP 09 (2018) 139

$H^{\pm}\rightarrow\tau\nu$: Selection



Only consider taus decaying hadronically

W decaying to electron/muon or jets

τ_{had}+jets: $pp\rightarrow bbWH^{\pm}\rightarrow bb(jj)(\tau_{had}\nu)$

τ_{had}+lepton: $pp\rightarrow bbWH^{\pm}\rightarrow bb(l\nu)(\tau_{had}\nu)$

Sensitive at large $m_{H\pm}$

- Select events with a τ_{had} and a hadronic top-quark decay
- E_T^{miss} trigger
  - E_T^{miss} > 150 GeV in analysis

Sensitive at low/intermediate $m_{H\pm}$

- Select events with a τ_{had} and a leptonic top-quark decay
- Single lepton trigger
  - E_T^{miss} > 50 GeV

Dominant backgrounds: SM ttbar production, misidentified jets as fake τ_{had}

Backgrounds with a true τ_{had} :	MC
Backgrounds with e, μ faking τ_{had}:	MC + data-driven corrections
Backgrounds with jets faking τ_{had} :	data-driven fake-factor method

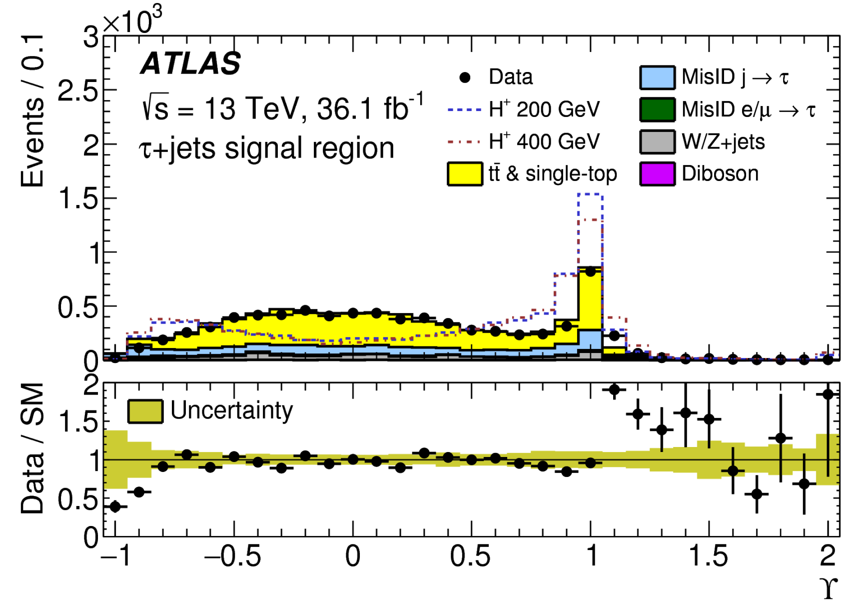
H±→τν: Analysis Strategy

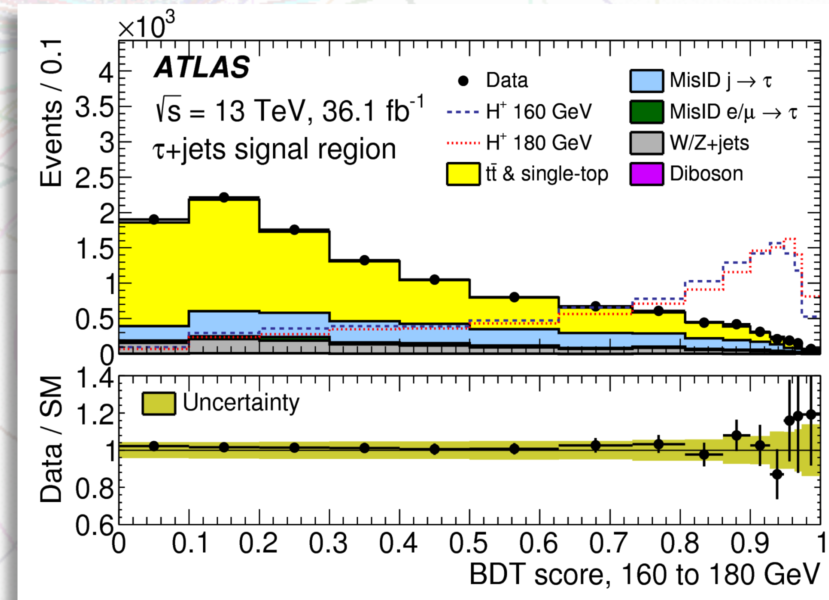
Multivariate discriminant:

- FastBDTs trained in 5 H± mass bins
- Separate training for τ_{had}+jets and τ_{had}+lepton
- Polarisation variable used for 1-prong τ_{had} objects
  - discrimination between H±→τν (signal) and W±→τν (top background)
  - increase of sensitivity for low H± masses

$$\Upsilon = \frac{E_T^{\pi^\pm} - E_T^{\pi^0}}{E_T^\tau} \simeq 2\frac{p_T^{\tau\text{-track}}}{p_T^\tau} - 1$$

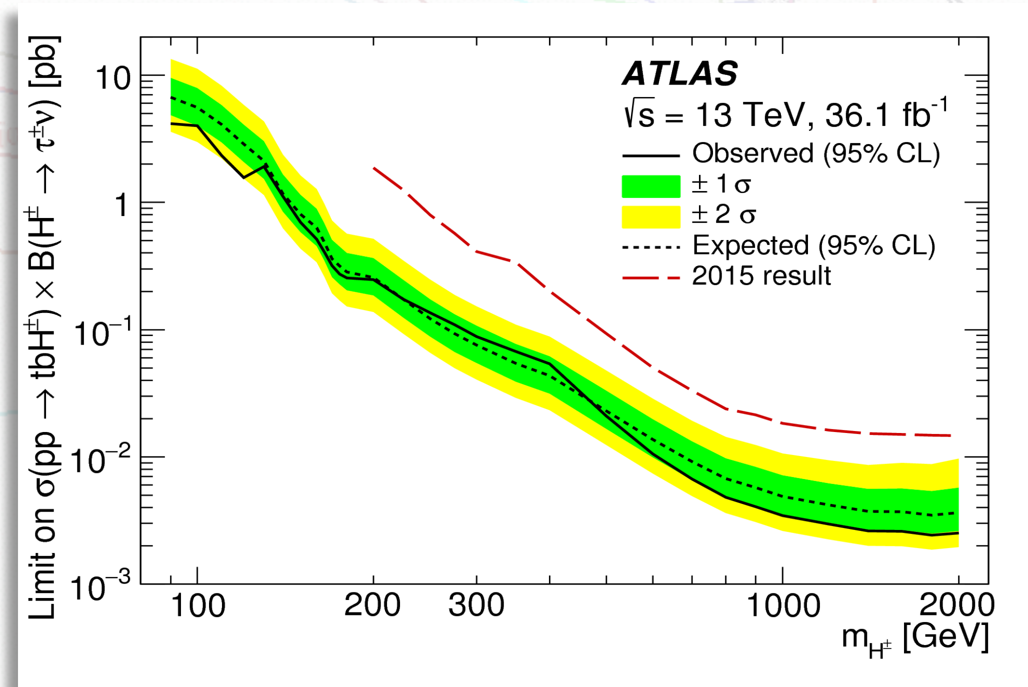
MVA input variable	τ+jets	τ+lepton
E_T^{miss}	✓	✓
p_T^τ	✓	✓
$p_T^{b\text{-jet}}$	✓	✓
p_T^ℓ		✓
$\Delta\phi_{\tau,miss}$	✓	✓
$\Delta\phi_{b\text{-jet},miss}$	✓	✓
$\Delta\phi_{\ell,miss}$		✓
$\Delta R_{\tau,\ell}$		✓
$\Delta R_{b\text{-jet},\ell}$		✓
$\Delta R_{b\text{-jet},\tau}$	✓	
$\Upsilon = 2\frac{p_T^{\tau\text{-track}}}{p_T^\tau} - 1$	✓	✓

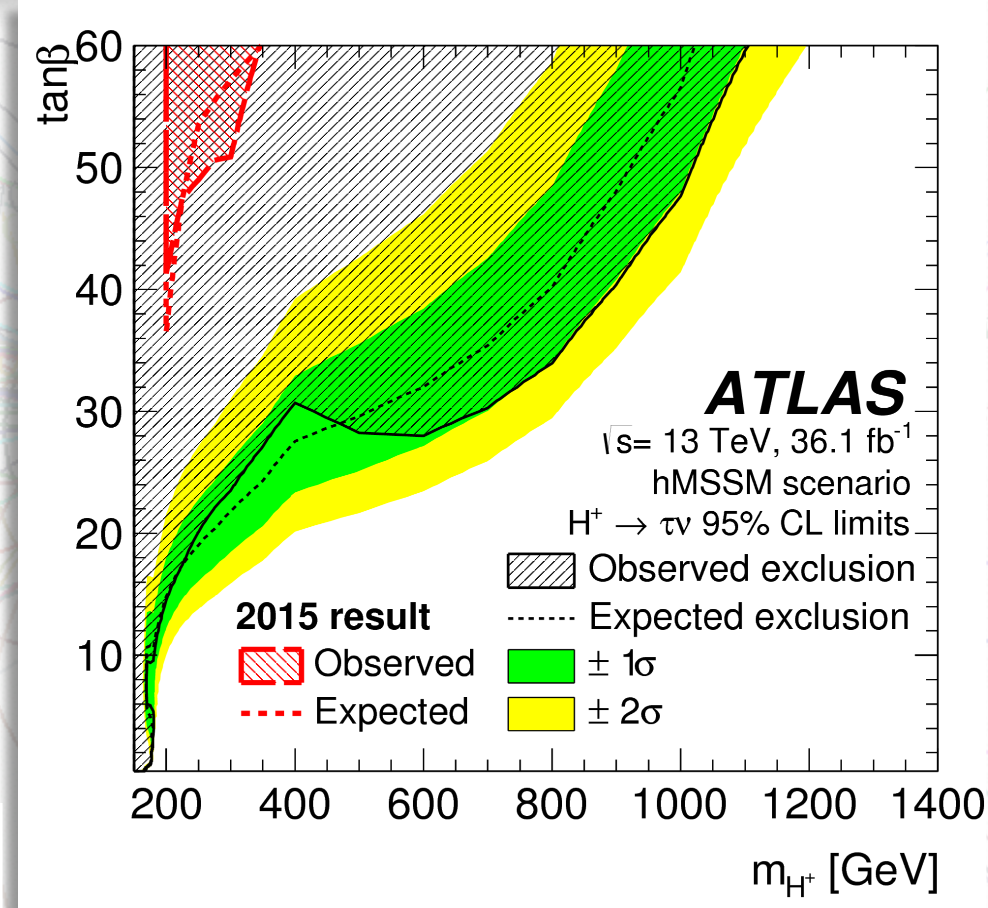




$H^{\pm}\to\tau\nu$: Results

- No statistically significant deviation from the SM predictions
- Exclusion limits obtained from a fit of the BDT distributions





Systematic uncertainties:

- dominant at low $m_{H\pm}$: fake factors method
- dominant at high $m_{H\pm}$: signal modelling

$H^{\pm} \to tb$ search

36 fb^{-1} @ 13 TeV

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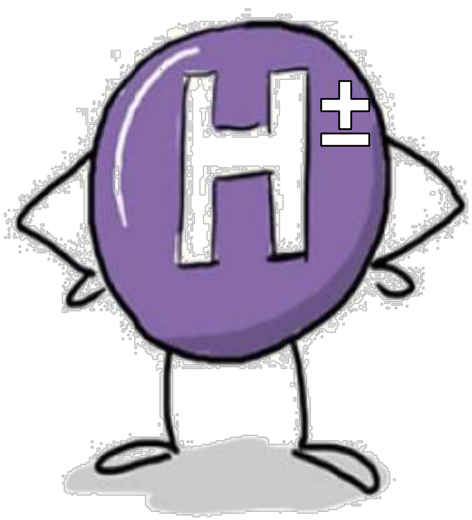
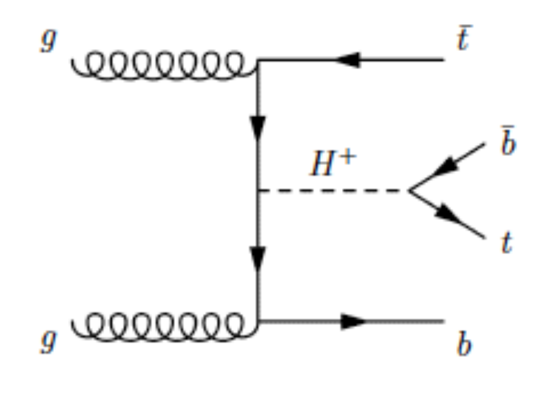


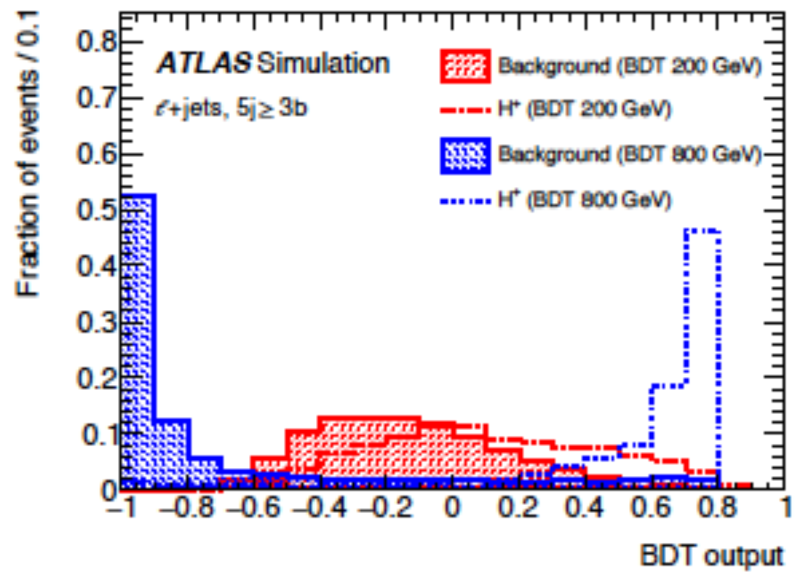
$H^{\pm}\rightarrow tb$: Selection

- At least one leptonic top-quark decay
  - single- and di-lepton (OS) channels
  - single-lepton triggers
- Considers 200 GeV $< m_{H+} <$ 2000 GeV
- Event categorisation in Signal and Control Regions according to the number of jets and b-jets



Single-lepton: CR 5j2b, SR 5j3b, SR 5j4b, CR 6j2b, SR 6j3b, SR 6j4b
Di-lepton: CR 3j2b, CR/SR 3j3b (m_{H+} >/< 1TeV), CR 4j2b, SR 4j3b, SR 4j4b

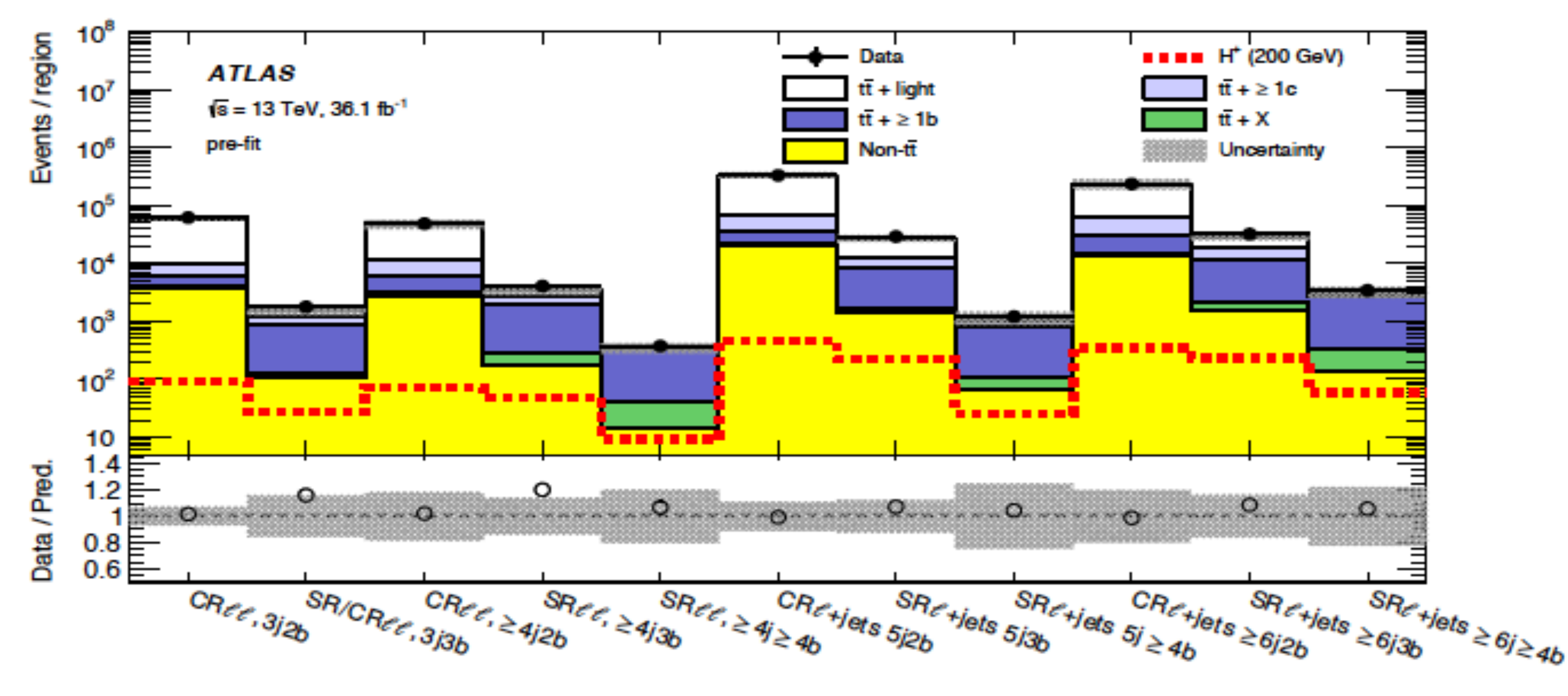
- Separate BDT trained in each SR and for each signal mass hypothesis
- Trained against all backgrounds in single lepton channel
- Trained against ttbar in di-lepton channel



H±→tb: Analysis Strategy

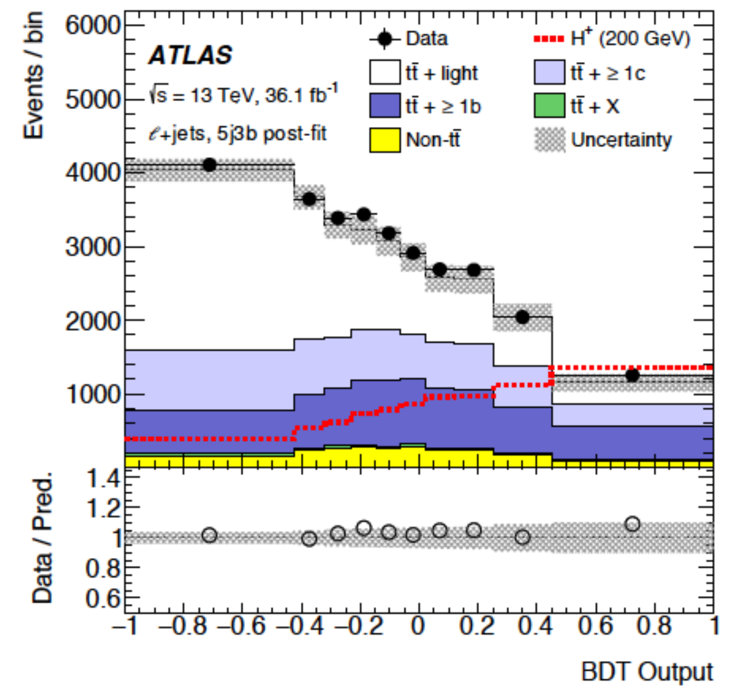
- The dominating background: ttbar +jets
  - Categorised according to the flavour of additional jets (b/c/light)

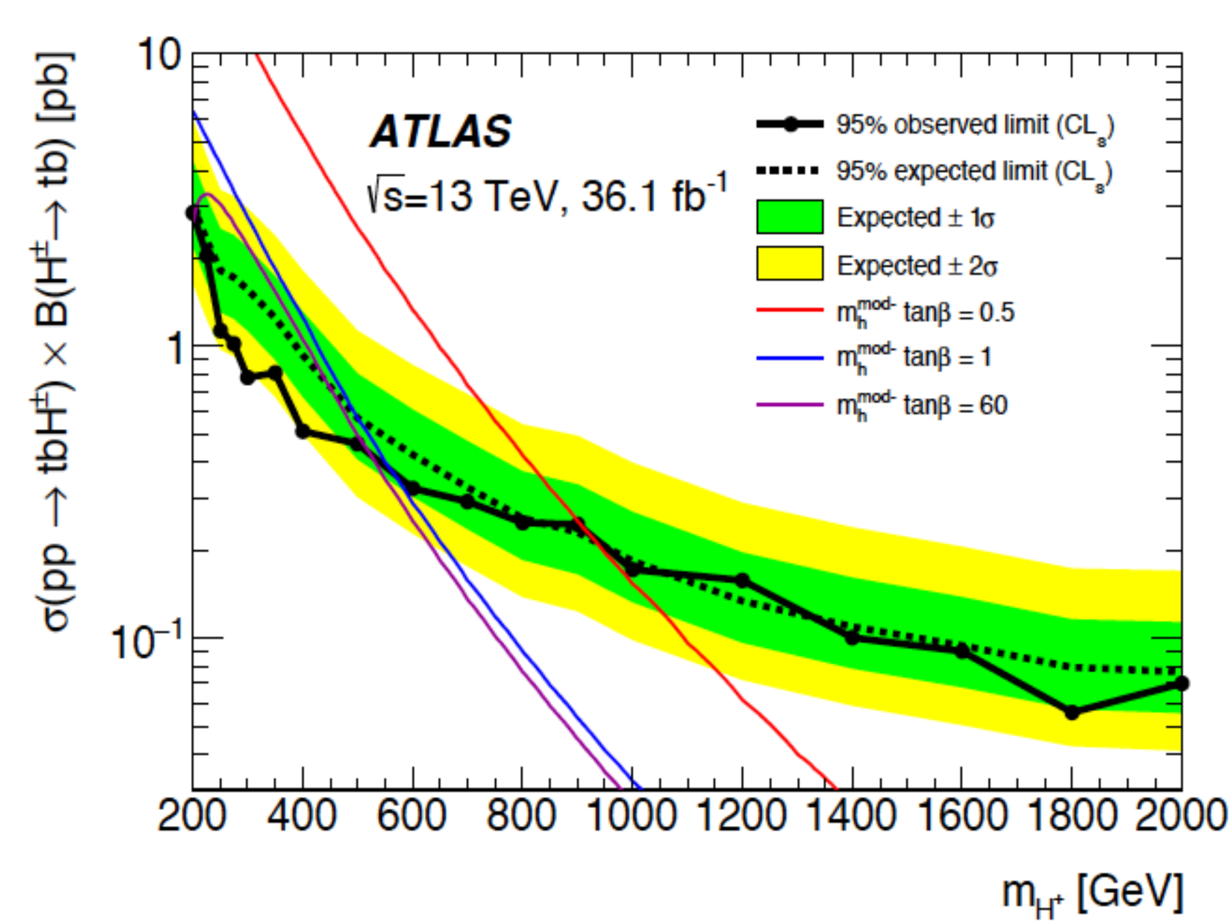
- Prompt leptons modelled with MC
- Non-prompt leptons in ℓℓ modelled with MC and normalised with data in CR
- Non-prompt leptons in ℓ+jets modelled with a data-driven matrix method



H±→tb: Results

- No statistically significant deviation from the SM predictions
- Exclusion limits obtained from a fit of the BDT distributions in SRs and a single bin in CRs

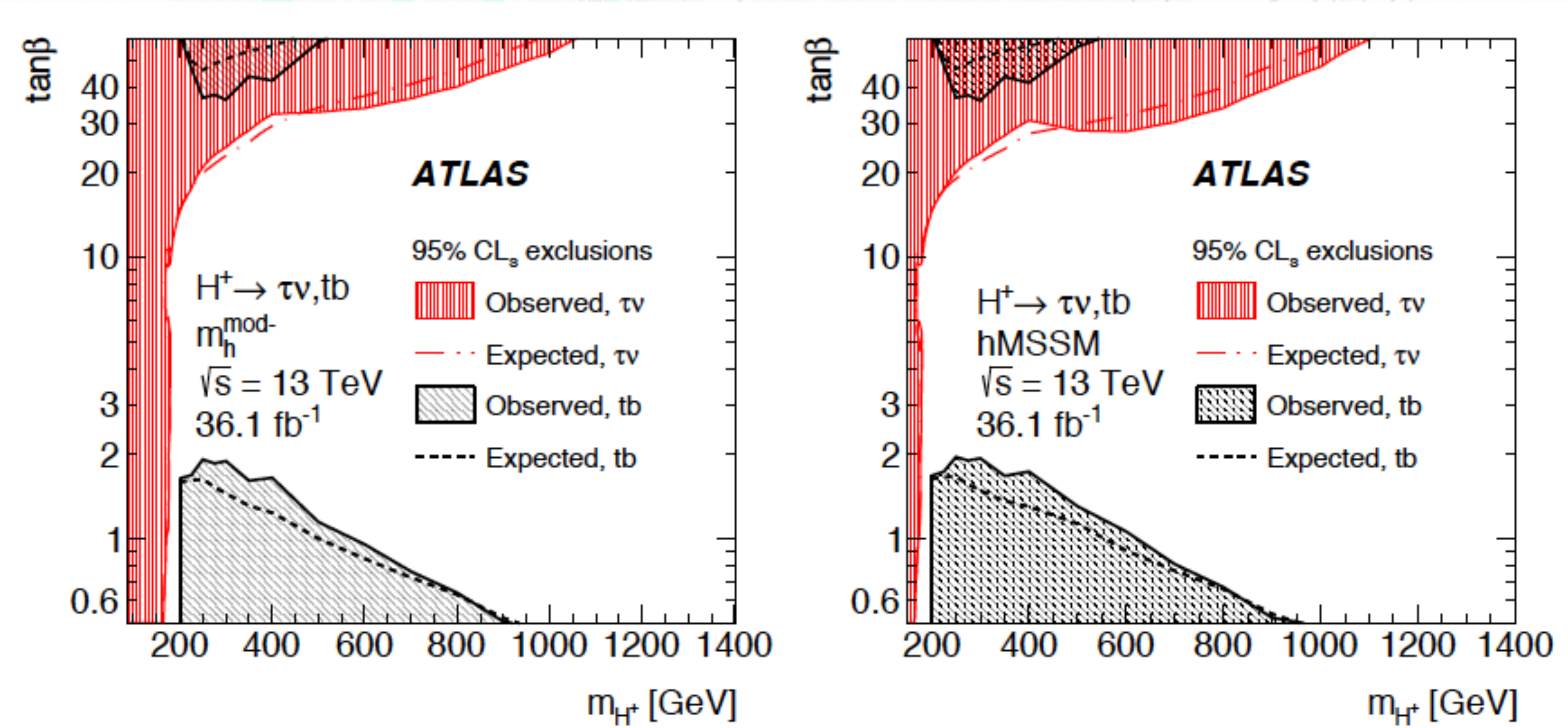




Dominant systematic uncertainties:

- Jet flavour tagging
- Background modelling

$H^{\pm}\to\tau\nu$ and $H^{\pm}\to tb$



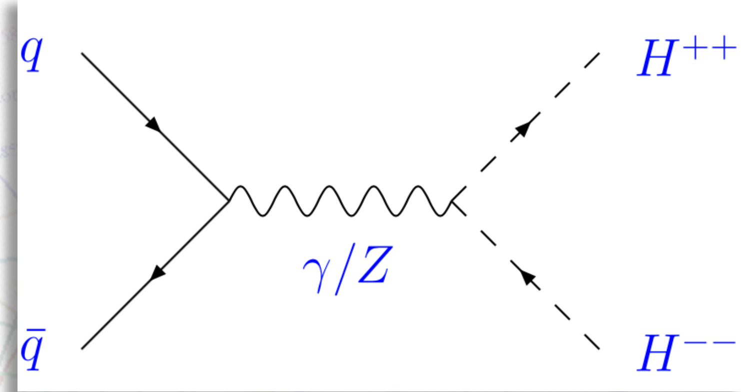
$H^{\pm}\to\tau\nu$ and $H^{\pm}\to tb$ channels are complementary:

- $H^{\pm}\to\tau\nu$: sensitive over a wide mass range and at high tanβ
- $H^{\pm}\to tb$: sensitive at high mass and high or low tanβ

$H^{\pm\pm}$: Production and Decays

$H^{\pm\pm}$ predicted by variety of BSM models:

- Left-Right Symmetric Models (LRSM)
  - addition of two scalar triplets $SU(2)_R$ and $SU(2)_L$
- Higgs Triplet Model (HTM)
  - addition of $SU(2)_L$ scalar triplet
- Zee-Babu models, Georgi–Machacek models



Production at the LHC:
pair-produced $H^{\pm\pm}$ via the Drell–Yan process
(dominant in LRSM and HTM)

Motivations

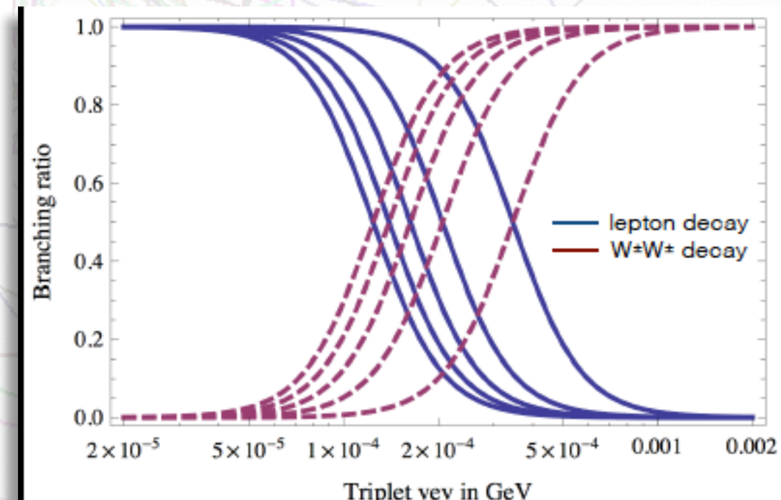
- Restoring parity symmetry in weak interactions at higher energy (LRSM)
- Explain light neutrino masses through see-saw mechanism (type II)

Most unique feature of such models: $H^{\pm\pm}$

- left and right-handed in LRSM or left-handed only in HTM

Decays: $H^{\pm\pm} \to l^{\pm}l^{\pm}$ or $H^{\pm\pm} \to W^{\pm}W^{\pm}$

- BR ~ f($m_{H^{\pm\pm}}$, vev of Higgs triplet)
- Low $m_{H^{\pm\pm}}$ and low vev : $H^{\pm\pm} \to l^{\pm}l^{\pm}$ dominates



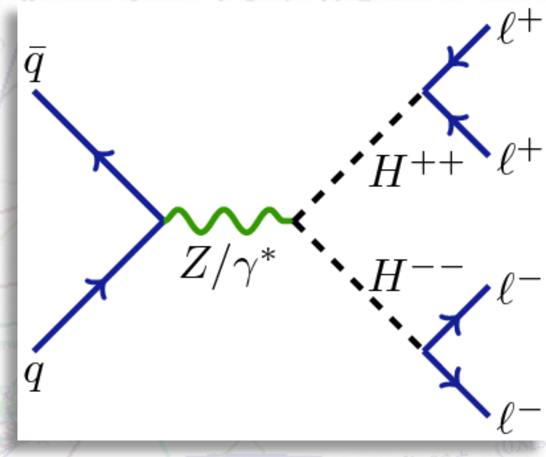
$H^{\pm\pm}H^{\mp\mp} \rightarrow l^{\pm}l^{\pm}l^{\mp}l^{\mp}$ search

36.1 fb^{-1} @ 13 TeV

Eur. Phys. J. C78 (2018) 199

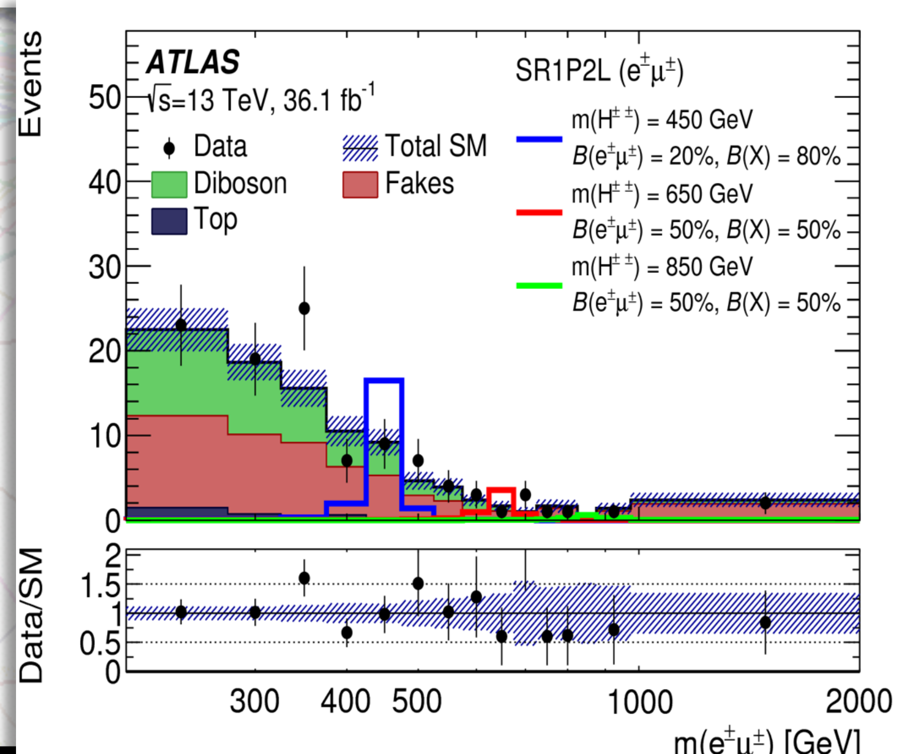
$H^{\pm\pm} \to l^{\pm}l^{\pm}$: Selection and Backgrounds

- Considered decays: $H^{\pm\pm} \to e^{\pm}e^{\pm}, e^{\pm}\mu^{\pm}, \mu^{\pm}\mu^{\pm}$
  - no preference for decays into taus - coupling not proportional to m_{lept} like for the SM Higgs
- Masses studied: 250 - 1300 GeV
- Search for isolated, same sign lepton pairs
- Discrimination observable
  - dilepton invariant mass distribution in all CRs and SRs
  - For SR with 4 leptons $\bar{M} \equiv (m^{++} + m^{--})/2.$



Backgrounds:

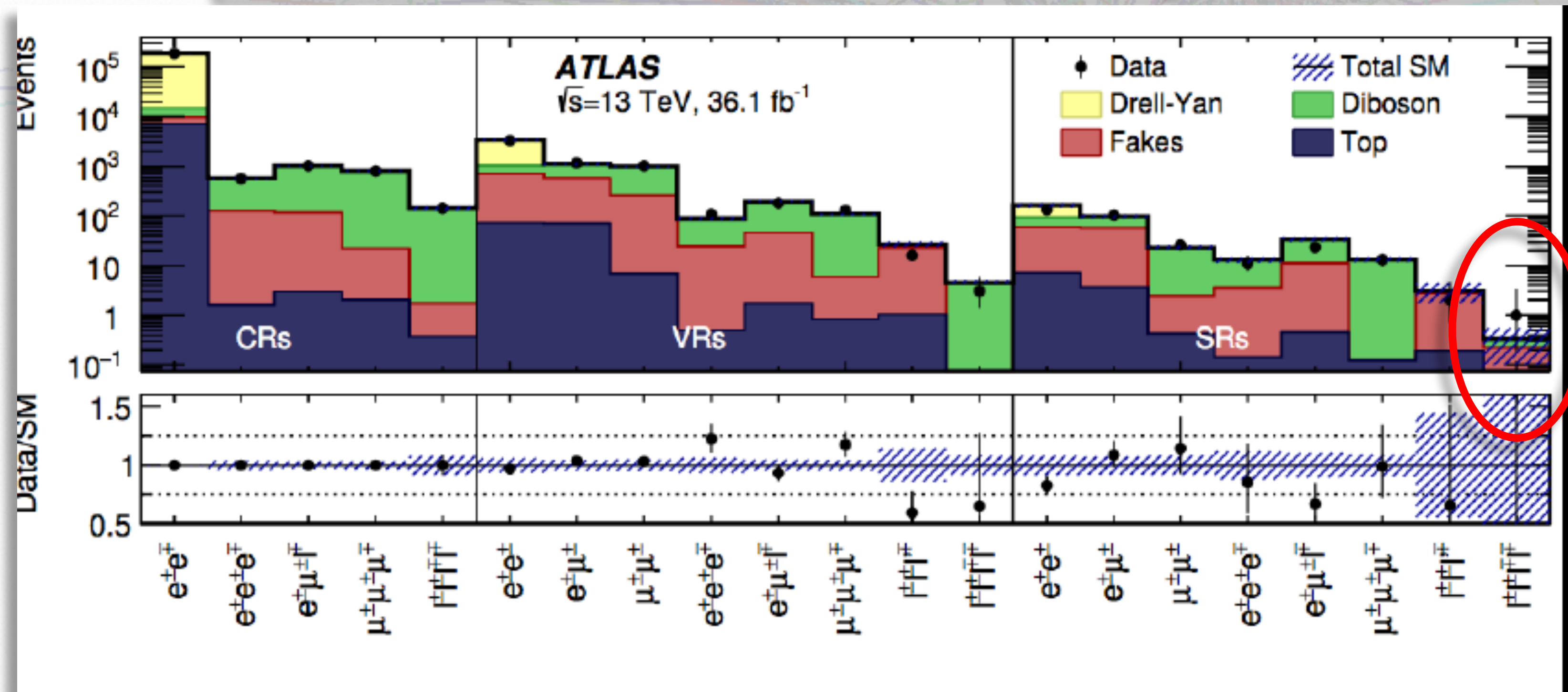
- real prompt leptons: from MC
- oppositely charged leptons with charge mis-ID: from MC but with data-driven correction factors
- non-prompt: estimated from data (fake factors method)
  - jets mis-reconstructed as electrons
  - real e/μ from non-prompt decays, e.g. from heavy flavoured mesons



$H^{\pm\pm} \to l^{\pm}l^{\pm}$: Signal and Control Regions

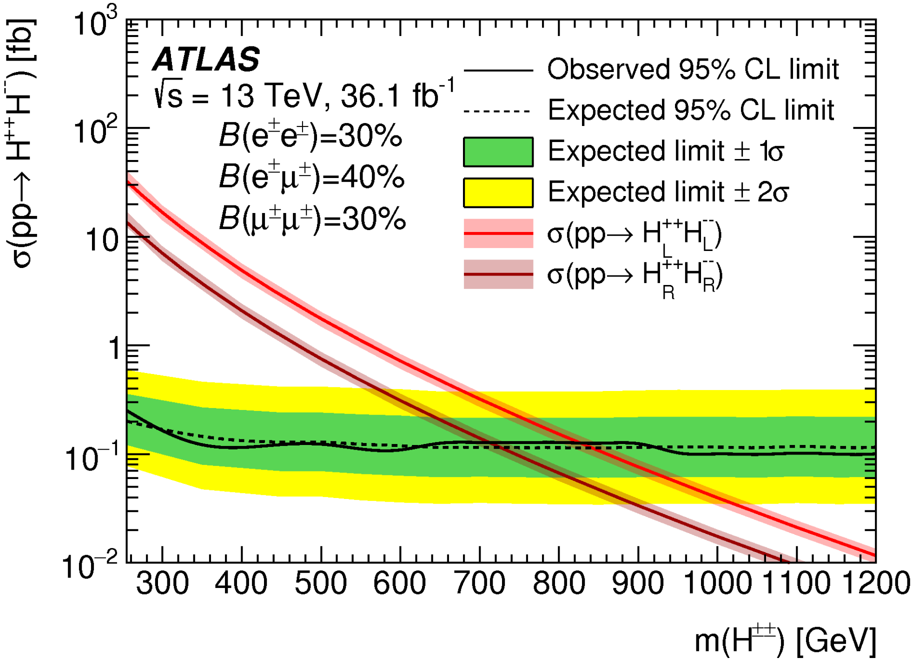
- SRs with 2-, 3-, and 4-leptons and flavour categories
- Control Regions (CRs) to constrain background parameters in the statistical analysis
- Validation Regions (VRs) to check background model against data
- Regions defined by $m(l^{\pm}l^{\pm})$ > 200 GeV in SRs and below 200 GeV in most CRs and VRs

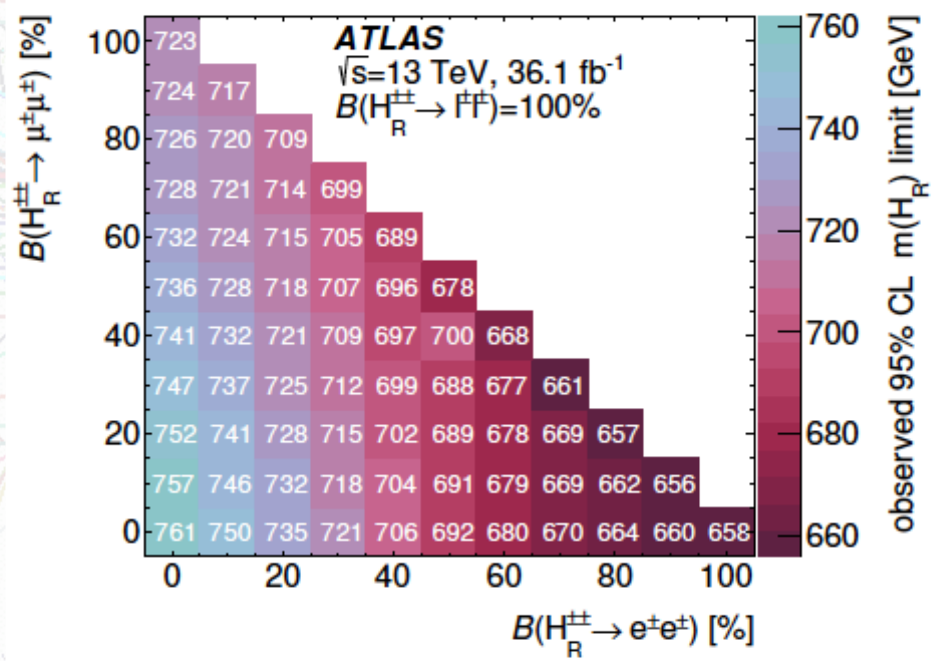
Region / Channel	Control Regions			Validation Regions			Signal Regions		
	OCCR	DBCR	4LCR	SCVR	3LVR	4LVR	1P2L	1P3L	2P4L
Electron channel	$e^{\pm}e^{\mp}$	$e^{\pm}e^{\pm}e^{\mp}$		$e^{\pm}e^{\pm}$	$e^{\pm}e^{\pm}e^{\mp}$		$e^{\pm}e^{\pm}$	$e^{\pm}e^{\pm}e^{\mp}$	
Mixed channel	-	$e^{\pm}\mu^{\pm}\ell^{\mp}$	$\ell^{\pm}\ell^{\pm}$ $\ell^{\mp}\ell^{\mp}$	$e^{\pm}\mu^{\pm}$	$e^{\pm}\mu^{\pm}\ell^{\mp}$ $\ell^{\pm}\ell^{\pm}\ell'^{\mp}$	$\ell^{\pm}\ell^{\pm}$ $\ell^{\mp}\ell^{\mp}$	$e^{\pm}\mu^{\pm}$	$e^{\pm}\mu^{\pm}\ell^{\mp}$ $\ell^{\pm}\ell^{\pm}\ell'^{\mp}$	$\ell^{\pm}\ell^{\pm}$ $\ell^{\mp}\ell^{\mp}$
Muon channel	-	$\mu^{\pm}\mu^{\pm}\mu^{\mp}$		$\mu^{\pm}\mu^{\pm}$	$\mu^{\pm}\mu^{\pm}\mu^{\mp}$		$\mu^{\pm}\mu^{\pm}$	$\mu^{\pm}\mu^{\pm}\mu^{\mp}$	



$H^{\pm\pm} \rightarrow l^{\pm} l^{\pm}$: Results

- No significant excesses observed
- Lower limit evaluated as a function of the branching into electrons and muons
- Separate limits for $H^{\pm\pm}_L$ and $H^{\pm\pm}_R$
- Limits on $H^{\pm\pm}_L$ vary from 770 GeV to 870 GeV, and 660 GeV to 760 GeV for $H^{\pm\pm}_R$ (depending on BR composition)





Systematic uncertainties: fake factor method, statistical uncertainty, theory description

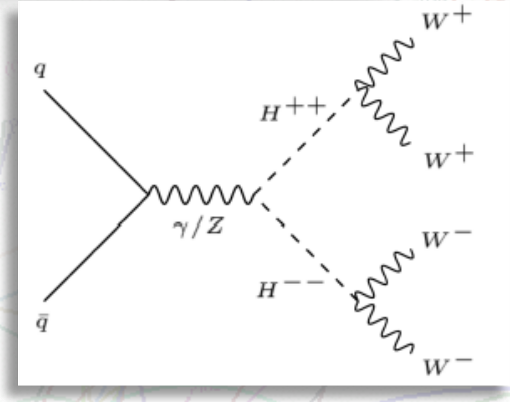
$H^{\pm\pm}H^{\mp\mp} \to W^{\pm}W^{\pm}W^{\mp}W^{\mp}$ search

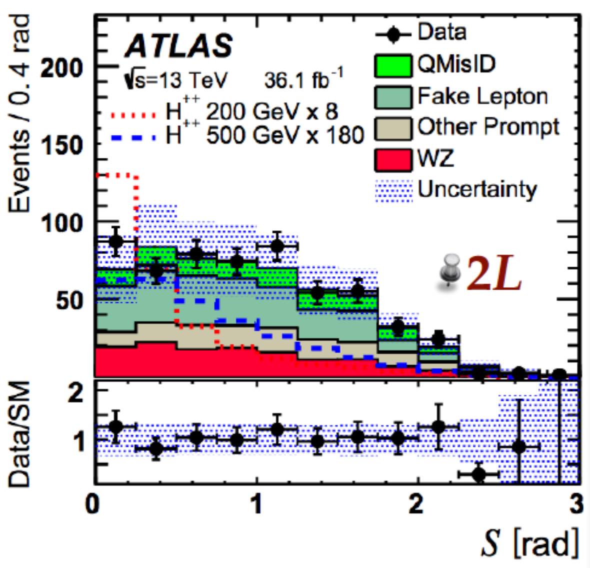
36.1 fb^{-1} @ 13 TeV
Eur. Phys. J. C (2019) 79

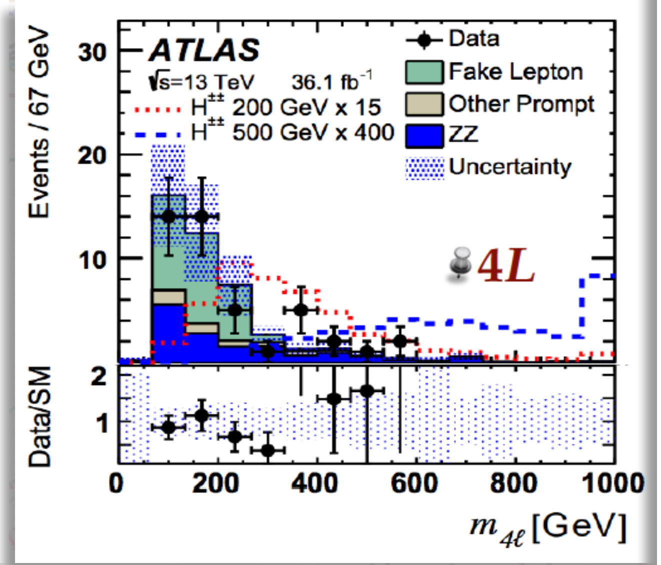
Searched for the first time in ATLAS!

$H^{\pm\pm} \to W^{\pm}W^{\pm}$: Selection and Backgrounds

- Signature: $2L^{SS}$,3L,4L light leptons + missing E_T
- Masses studied: 200-700 GeV
- Dominant backgrounds: dibosons, Z+jets, ttbar
  - Prompt sources estimated from MC
  - Fake estimation: data-driven fake factor method
  - Charge misID: data-driven method





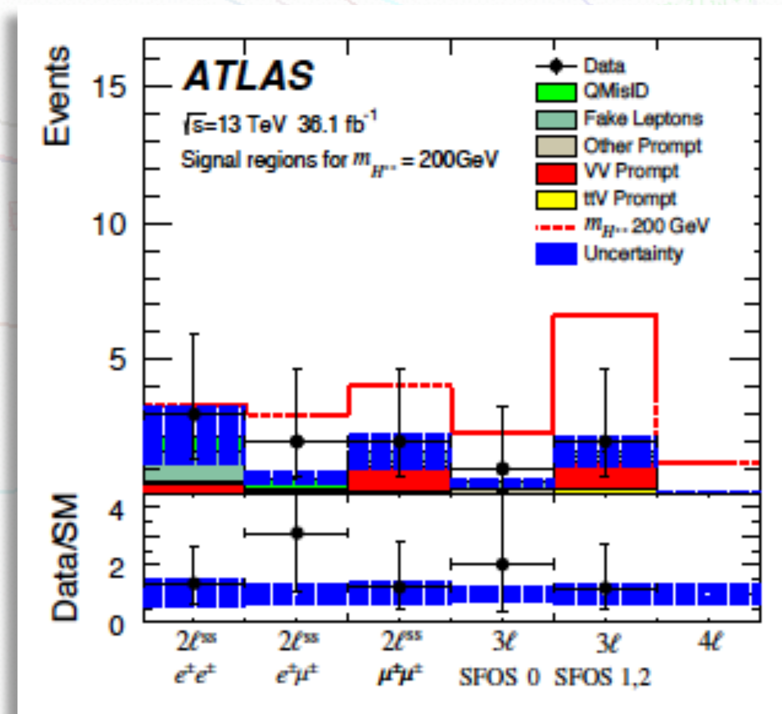


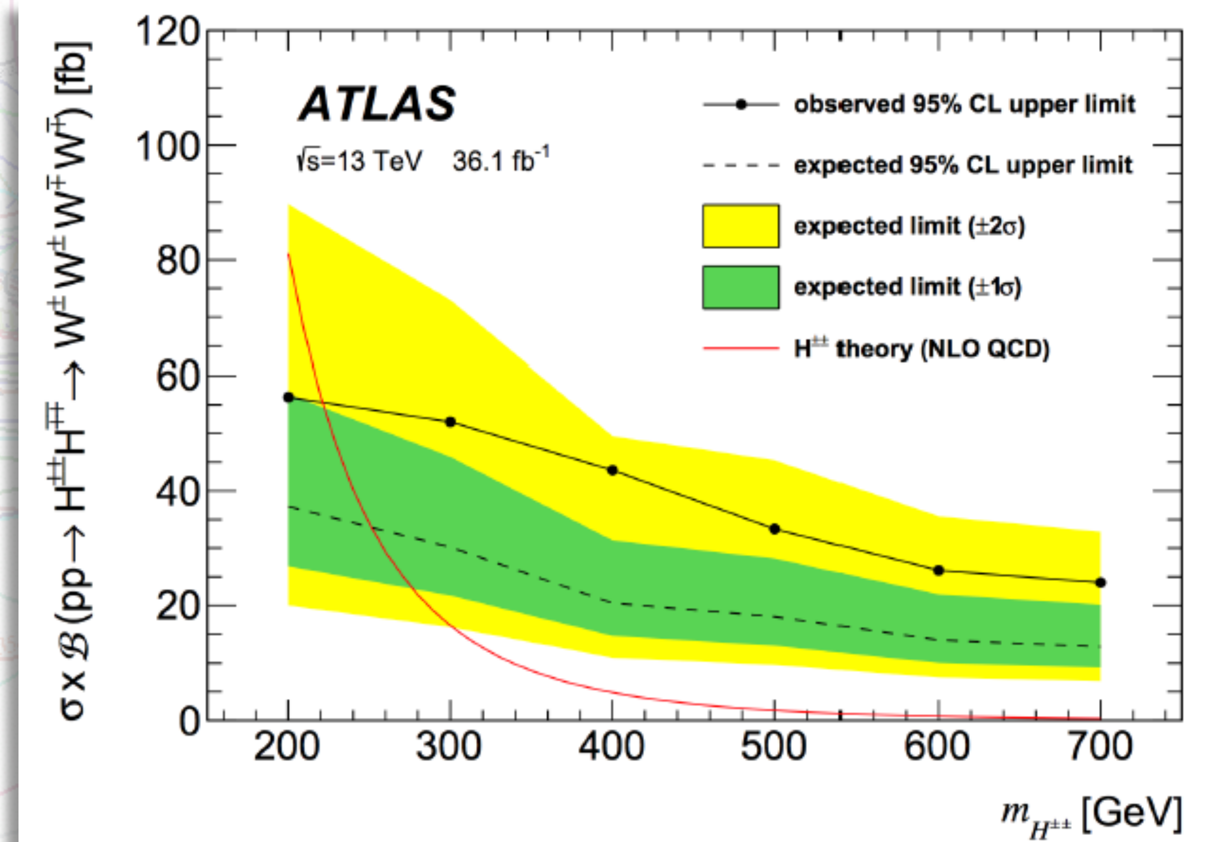
Mass-dependent and channel-dependent cuts on discriminating variables:

- m_{Xl} of all leptons in the event;
- $\Delta R(l^{\pm}l^{\pm})$
- m_{jets} only in the 2L channel
- p_T leading jet
- $\Delta\varphi(l^{\pm}l^{\pm}, E_T^{miss})$ in the 2L channel
- $\Delta R(l, jet)$ any lepton and its closest jet in the 3L channel
- S ($2L^{SS}$) describes the event topology in the transverse plane, using the spread of the φ angles of the leptons, E_T^{miss} and jets

$H^{\pm\pm} \to W^{\pm}W^{\pm}$: Results

Final fit based on six (SRs) bin counting experiment

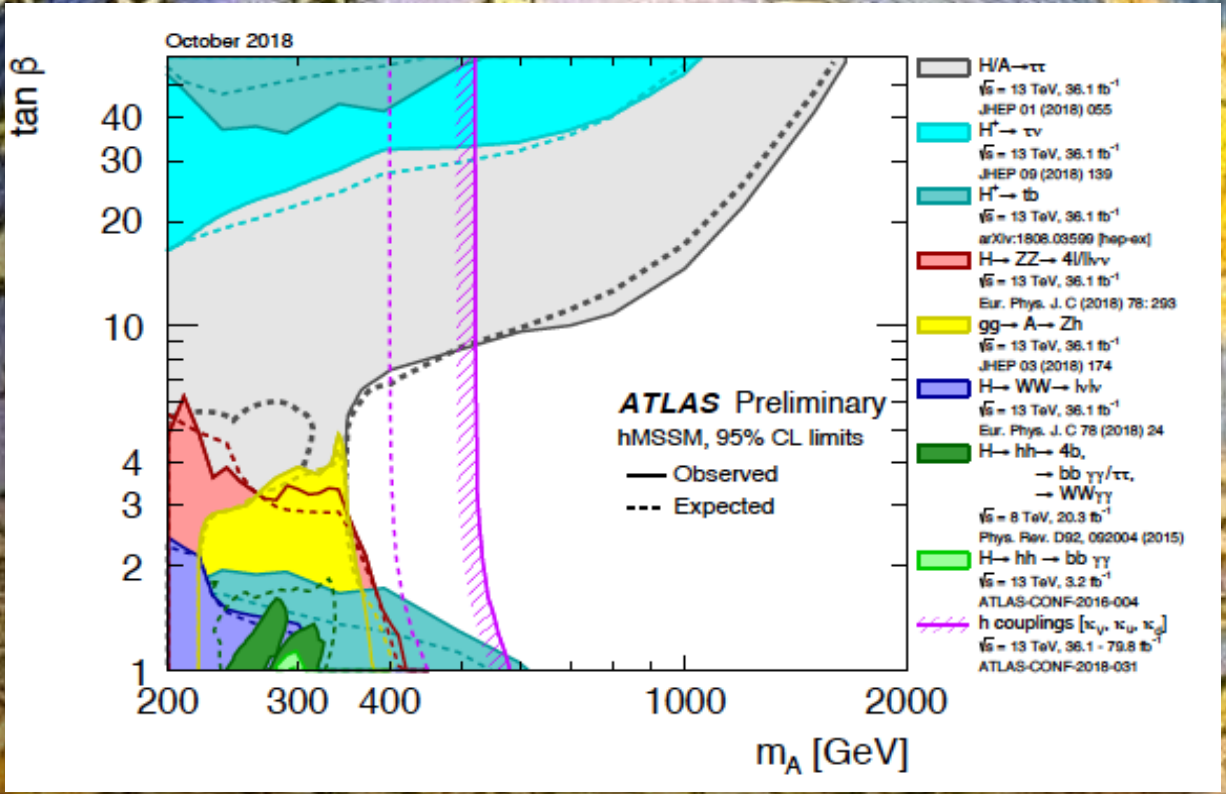


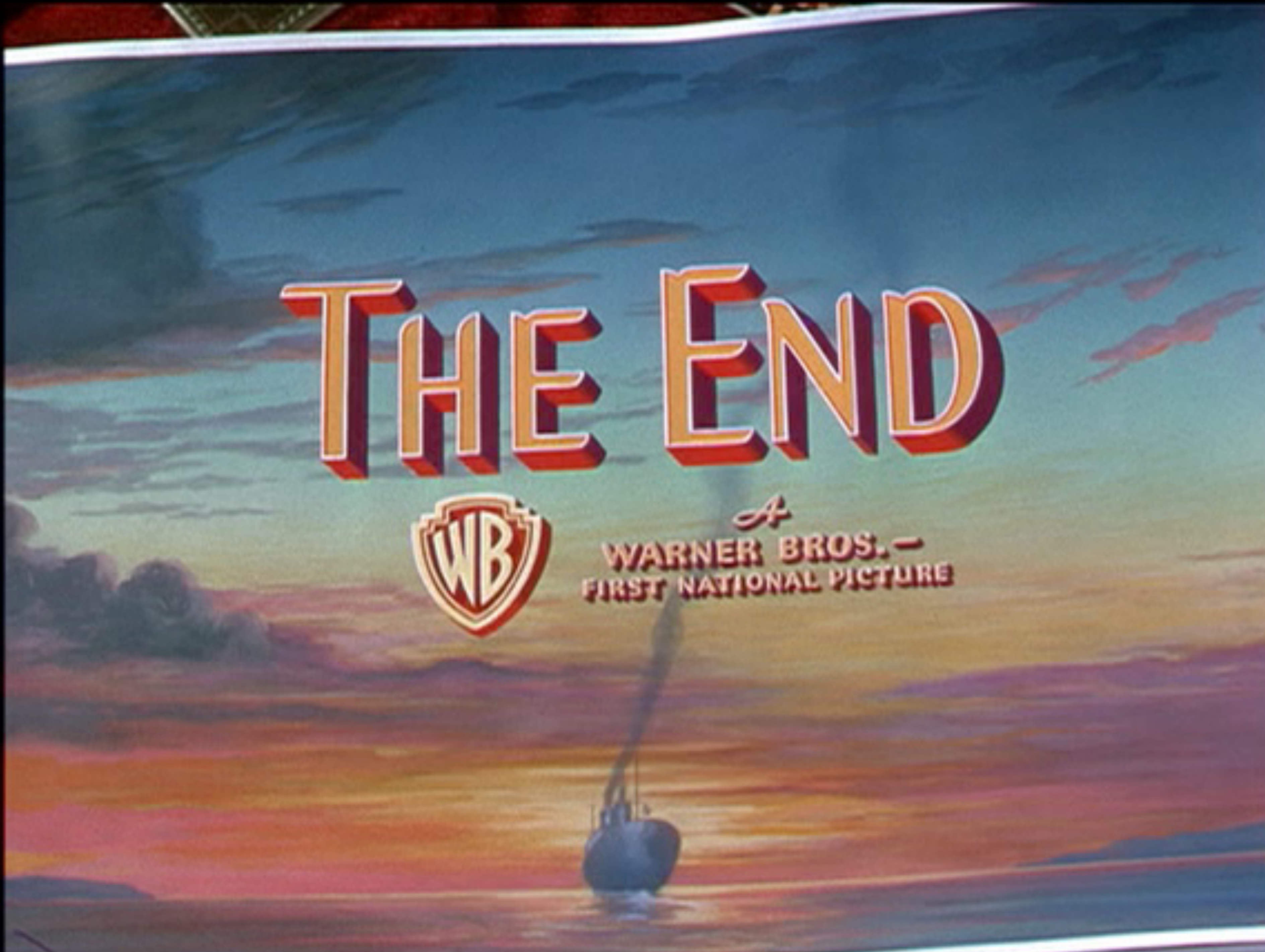


Dominating uncertainties: statistics, data-driven fakes and charge mis-ID

Summary

- There is a plethora of searches for BSM physics in the Higgs sector at the LHC
- Only a small selection of results were presented here
- No evidence for any BSM Higgs Boson… yet
- Dedicated efforts in the combinations help improve sensitivity
- By now only impressive agreement with SM observed, instead of inspiring surprises
- But we have not yet finished! Much more Run2 data (140 fb^{-1}) to analyse!
- We will turn every stone ☺




THE END
A
WARNER BROS.–
FIRST NATIONAL PICTURE

Beyond the Standard Slides

Courtesy of J. Keller

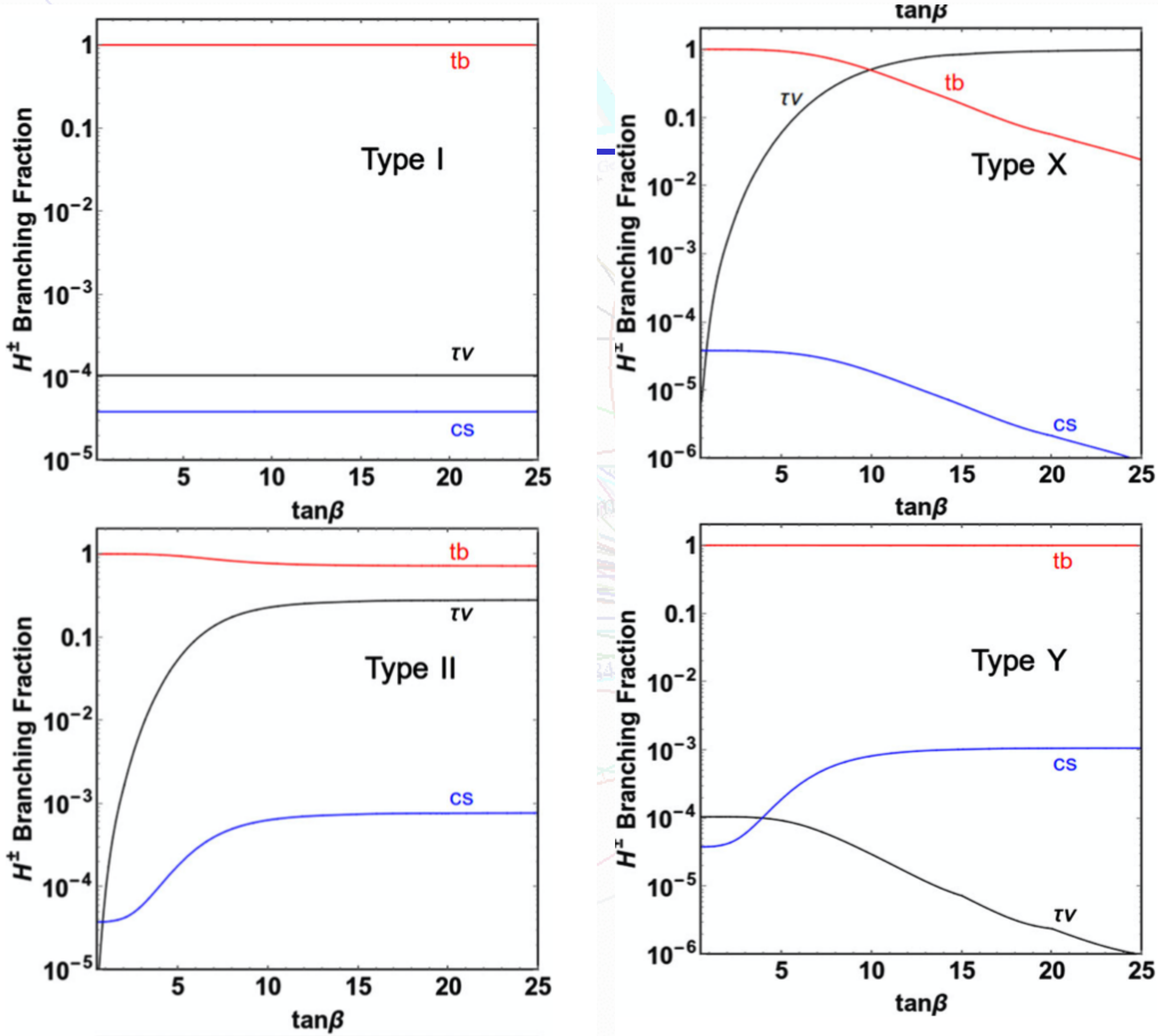


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Fig. 2 Branching fractions of the charged Higgs particle into the dominant fermionic sectors as a function of $\tan\beta$ for $M_{H^\pm} = 250$ GeV. The alignment limit $\sin(\beta - \alpha) \rightarrow 1$ and degenerate $M_{H^\pm}$, M_H and M_A are considered to prevent $H^\pm \rightarrow W^\pm\phi$ ($\phi = h, H, A$) and satisfy the T parameter constraint

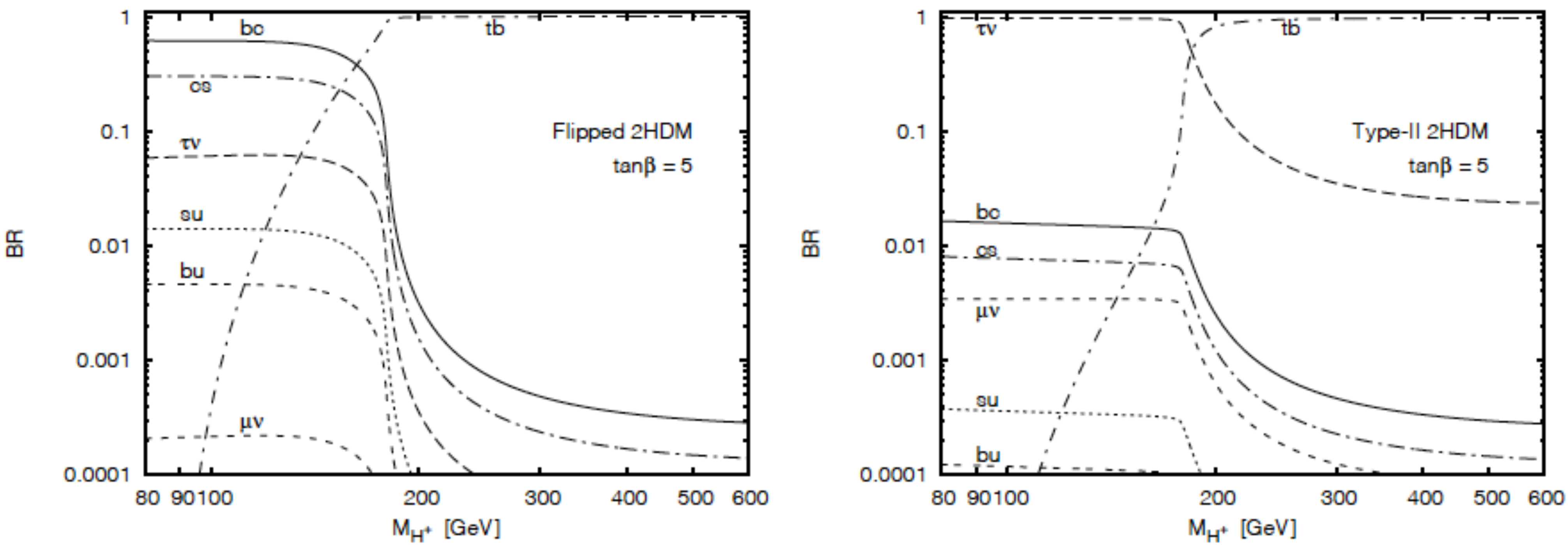


FIG. 2: Charged Higgs branching ratios as a function of M_{H+} for $\tan\beta = 5$ in the flipped (left) and Type-II (right) 2HDMs.

Run 1 Analyses

- VBF $H^{\pm}$ -> $W^{\pm}Z$ -> $q q \ell \ell$ (arxiv:1503.04233)
- Light $H^{\pm}$ -> cs (arxiv:1302.3694)
- Cascade H -> WH^{+} -> WWh (arxiv:1312.1956)
- $H^{\pm}$ -> tau nu (arxiv:1412.6663)
- $H^{\pm}$ -> tb (arxiv:1512.03704)

$H^\pm \rightarrow \tau\nu$: Selection

τ_{had}+jets: $pp \rightarrow bbWH^\pm \rightarrow bb(jj)(\tau_{had}\nu)$

Sensitive at large $m_{H\pm}$

- E_T^{miss} trigger
- Select events with a τ_{had} and a hadronic top-quark decay:
  - 1 τ_{had} object with p_T > 40 GeV,
  - 3 jets with p_T > 25 GeV, including 1 b-tag
  - Electron and muon veto
  - E_T^{miss} > 150 GeV
  - m_T > 50 GeV

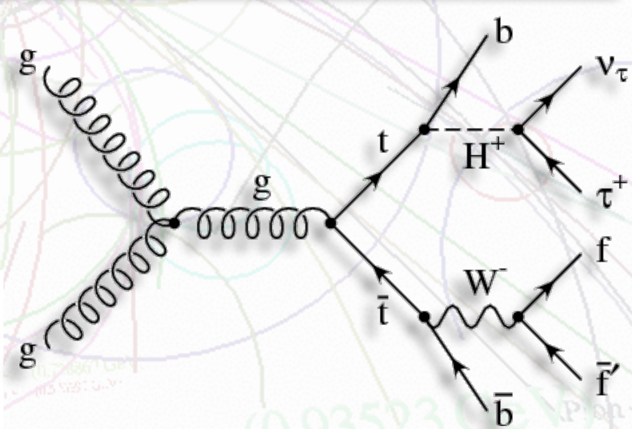
$$m_T = \sqrt{2 p_T^\tau E_T^{miss}(1 - \cos\Delta\phi_{\tau,miss})}$$

τ_{had}+lepton: $pp \rightarrow bbWH^\pm \rightarrow bb(l\nu)(\tau_{had}\nu)$

Sensitive at low/intermediate $m_{H\pm}$

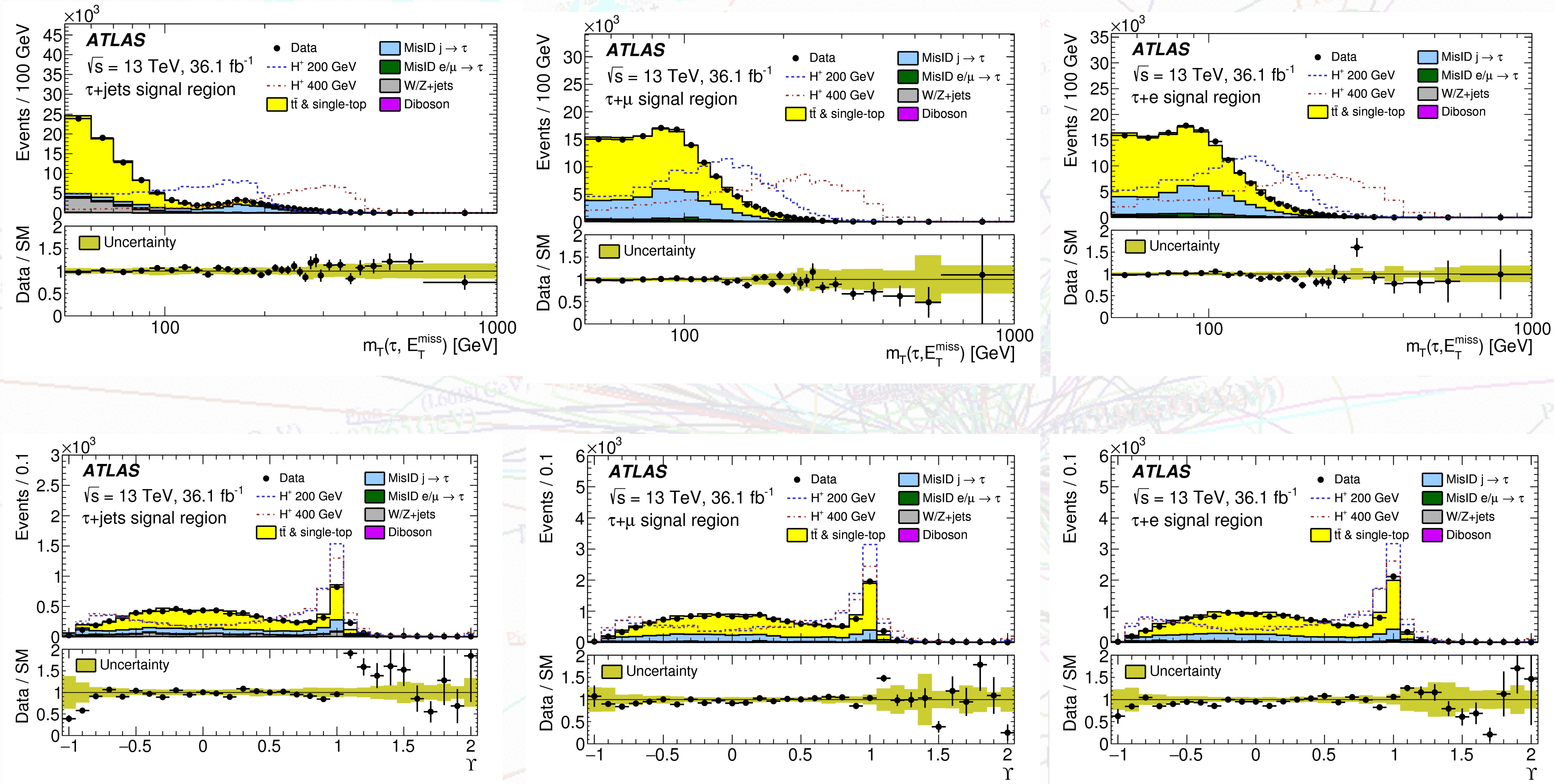
- Single lepton trigger
- Select events with a τ_{had} and a leptonic top-quark decay:
  - 1 τ_{had} object with p_T > 30 GeV,
  - 1 lepton with p_T > 30 GeV
  - Two opposite sign channels: $e+\tau_{had}$, $\mu+\tau_{had}$
  - At least 1 b-tagged jet with p_T > 25 GeV
  - E_T^{miss} > 50 GeV

Dominant backgrounds: SM ttbar production, misidentified jets as fake τ_{had}



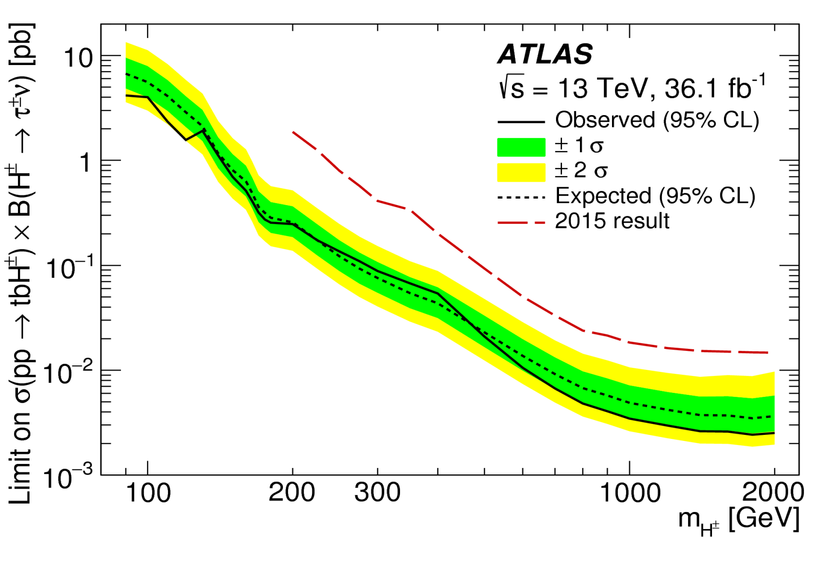
Backgrounds with a true τ_{had} :	MC
Backgrounds with e, μ faking τ_{had}:	MC + data-driven corrections
Backgrounds with jets faking τ_{had} :	data-driven fake-factor method

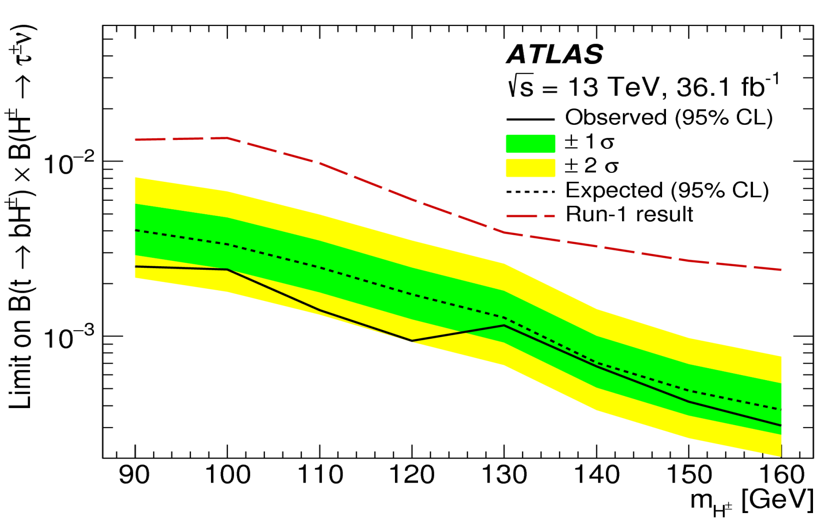
H±→τν: Backgrounds

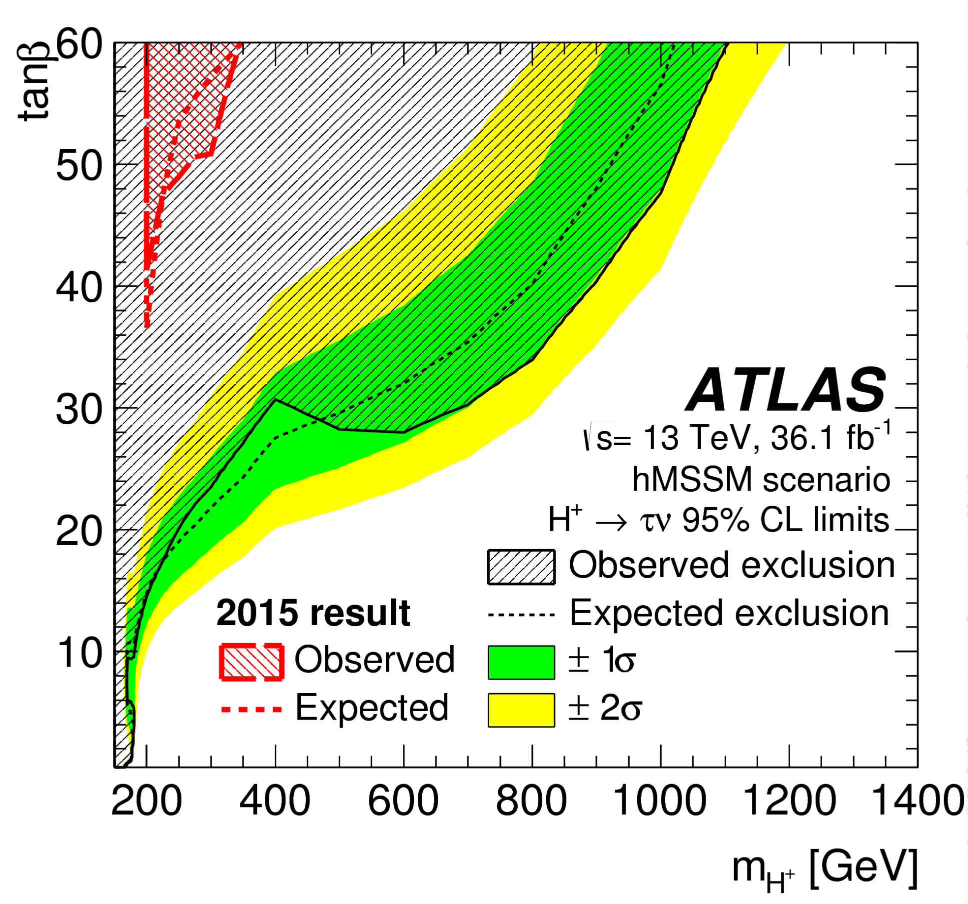


$H^{\pm} \to \tau\nu$: Results

- No statistically significant deviation from the SM predictions
- Exclusion limits obtained from a fit of the BDT distributions







Systematic uncertainties:

- dominant at low $m_{H\pm}$: fake factors method
- dominant at high $m_{H\pm}$: signal modelling

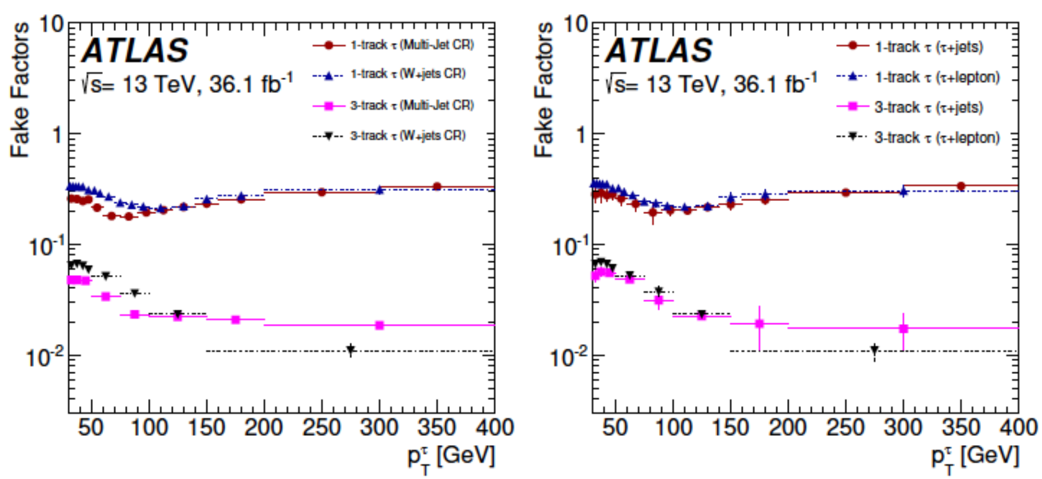
$H^{\pm}\to\tau\nu$: Fake Factors method

- Define an anti-tau region, which is similar to the signal region but where a tau candidate fails the ID-tau requirement, instead of fullfiling it.

$$FF = \frac{N_{\tau-\mathrm{id}}}{N_{\mathrm{anti}-\tau-\mathrm{id}}}$$

$$N^{\tau}_{\mathrm{fakes}} = N^{\mathrm{anti}-\tau}_{\mathrm{fakes}} \times FF$$

- Two control region with different jet compositions are used in order to determine the rate of the fake tau object
  - Multi-jet CR (dominated by gluon-initiated jets)
  - W+jet CR (dominated by quark-initiated jets)
- In the anti-tau regions, the fractions of quark- and gluon-initiated jets misidentified as tau candidates are measured using a template-fit approach, based on variables that are sensitive to the difference in quark- and gluon-fractions between these two types of jets



$H^{\pm}\to\tau\nu$: systematics

Source of systematic uncertainty	Impact on the expected limit (stat. only) in % $m_{H^+} = 170\ GeV$	$m_{H^+} = 1000\ GeV$
Experimental		
luminosity	2.9	0.2
trigger	1.3	<0.1
$\tau_{\text{had-vis}}$	14.6	0.3
jet	16.9	0.2
electron	10.1	0.1
muon	1.1	<0.1
E_T^{miss}	9.9	<0.1
Fake-factor method	20.3	2.7
Υ modelling	0.8	–
Signal and background models		
$t\bar{t}$ modelling	6.3	0.1
W/Z+jets modelling	1.1	<0.1
cross-sections ($W/Z/VV/t$)	9.6	0.4
H^+ signal modelling	2.5	6.4
All	52.1	13.8

- From impact on the expected limit (stat. only) when adding a set of nuisance parameters *ℓ+jets channel*

$p_T(j_1)$	Leading jet transverse momentum
$m(b\text{-pair}^{\Delta R^{\min}})$	Invariant mass of pair of b-tagged jets with smallest ΔR
$p_T(j_5)$	Transverse momentum of fifth jet
H_2	Second Fox–Wolfram moment [128] calculated using all jets and leptons
$\Delta R^{\text{avg}}(b\text{-pair})$	Average ΔR between all b-tagged jet pairs in the event
$\Delta R(\ell, b\text{-pair}^{\Delta R^{\min}})$	ΔR between the lepton and the b-tagged jet pair with smallest ΔR
$m(u\text{-pair}^{\Delta R^{\min}})$	Invariant mass of the non-b-tagged jet-pair with minimum ΔR
H_T^{jets}	Scalar sum of all jets transverse momenta
$m(b\text{-pair}^{p_T^{\max}})$	Invariant mass of the b-tagged jet pair with maximum transverse momentum
$m^{\max}(b\text{-pair})$	Largest invariant mass of any two b-tagged jets
$m^{\max}(j\text{-triplet})$	Largest invariant mass of any three jets
D	Kinematic discriminant based on mass templates (for $m_{H^+} \leq 300$ GeV)

ℓℓ channel, m ≤ 600 GeV		3j3b	≥4j3b	≥4j≥4b
$m((j,b)^{p_T^{\max}})$	Inv. mass of the jet and b-tagged jet with largest p_T	✓		
$\Delta E(j_3, \ell_2)$	Energy difference between the third jet and the subleading lepton	✓		
$E(j_3)$	Energy of third jet	✓		
$\Delta m(j_1+j_2, j_1+j_3+\ell_2+E_T^{\text{miss}})$	Inv. mass difference between j_1+j_2 and $j_1+j_3+\ell_2+E_T^{\text{miss}}$	✓		
$\Delta R(j_2, j_1+\ell_2+E_T^{\text{miss}})$	Angular difference between subleading jet and $j_1+\ell_2+E_T^{\text{miss}}$	✓		
$p_T(b_1)$	p_T of leading b-tagged jet	✓		
$p_T((\ell,b)^{\Delta\eta^{\max}})$	p_T of the pair of lepton and b-tagged jet with largest $\Delta\eta$	✓		
$m((\ell,b)^{\Delta\phi^{\min}})$	Inv. mass of the pair of lepton and b-tagged jet with smallest $\Delta\phi$		✓	
$\Delta E(b_1, \ell_1+E_T^{\text{miss}})$	Energy difference between the leading b-tagged jet and $\ell_1+E_T^{\text{miss}}$		✓	
$\Delta m(j_2+j_3, j_1+\ell_1+\ell_2)$	Inv. mass difference between j_2+j_3 and $j_1+\ell_1+\ell_2$		✓	
$\Delta m(\ell_1+j_3+E_T^{\text{miss}}, j_1+j_2+\ell_2)$	Inv. mass difference between $\ell_1+j_3+E_T^{\text{miss}}$ and $j_1+j_2+\ell_2$		✓	
$\Delta p_T(j_1, j_3)$	p_T difference between leading and third jet		✓	✓
$m^{\min}(b\text{-pair})$	Smallest invariant mass of any b-tagged jet pair		✓	✓
$m^{\min}(\ell, b)$	Smallest invariant mass of any pair of lepton and b-tagged jet		✓	✓
$p_T(b_2+\ell_1+\ell_2+E_T^{\text{miss}})$	p_T of $b_2+\ell_1+\ell_2+E_T^{\text{miss}}$			✓
$\Delta R(\ell_2, j_2+j_3+\ell_1+E_T^{\text{miss}})$	Angular difference between ℓ_2 and $j_2+j_3+\ell_1+E_T^{\text{miss}}$			✓
H_T^{all}	Scalar sum of all jets and leptons transverse energy			✓

ℓℓ channel, m > 600 GeV		3j3b	≥4j3b	≥4j≥4b
$p_T((\ell,b)^{\Delta\eta^{\min}})$	p_T of the pair of lepton and b-tagged jet with smallest $\Delta\eta$	✓		✓
$\Delta p_T(j_1, j_3)$	p_T difference between leading and third jets	✓		✓
$\Delta m(j_2+\ell_1+E_T^{\text{miss}}, j_1+j_3+\ell_1)$	Inv. mass difference between $j_2+\ell_1+E_T^{\text{miss}}$ and $j_1+j_3+\ell_1$	✓		
$p_T((\ell,b)^{\Delta R^{\min}})$	p_T of the pair of lepton and b-tagged jet with smallest ΔR	✓		
$m(j\text{-pair}^{\Delta\eta^{\min}})$	Inv. mass of the jet pair with smallest $\Delta\eta$	✓		
$\Delta p_T(j_1, j_2+E_T^{\text{miss}})$	p_T difference between leading jet and $j_2+E_T^{\text{miss}}$	✓		
$p_T(j_1+j_2+j_3+\ell_1)$	p_T of $j_1+j_2+j_3+\ell_1$	✓		
$\Delta E(\ell_1+E_T^{\text{miss}}, j_1+j_2)$	Energy difference between $\ell_1+E_T^{\text{miss}}$ and j_1+j_2	✓		
$E(j_1)$	Energy of the leading jet	✓	✓	
$p_T^{\max}(j\text{-pair})$	Maximum p_T of any jet pair	✓	✓	
$m(b_1+b_2+\ell_1+\ell_2+E_T^{\text{miss}})$	Inv. mass of $b_1+b_2+\ell_1+\ell_2+E_T^{\text{miss}}$		✓	
$p_T((\ell,b)^{\Delta\eta^{\min}})$	p_T of the lepton-b-jet pair with smallest separation in η		✓	
$\Delta p_T(\ell_2, u_1+b_2+E_T^{\text{miss}})$	p_T difference between subleading lepton and $u_1+b_2+E_T^{\text{miss}}$		✓	
$\Delta p_T(\ell_2, u_1+b_1+E_T^{\text{miss}})$	p_T difference between subleading lepton and $u_1+b_1+E_T^{\text{miss}}$		✓	
$\Delta p_T(\ell_2, \ell_1+E_T^{\text{miss}})$	p_T difference between subleading lepton and $\ell_1+E_T^{\text{miss}}$		✓	
$\Delta p_T(j_1, j_3+\ell_1+E_T^{\text{miss}})$	p_T difference between leading jet and $j_3+\ell_1+E_T^{\text{miss}}$		✓	
$\Delta E(\ell_1, j_2+E_T^{\text{miss}})$	Energy difference between leading lepton and $j_2+E_T^{\text{miss}}$		✓	
$m^{\min}(b\text{-pair})$	Smallest invariant mass of any b-tagged jet pair		✓	✓
H_T^{all}	Scalar sum of all jets and leptons transverse momenta			✓
$p_T(j_3+\ell_1)$	p_T of $j_3+\ell_1$			✓
$\Delta p_T(b_2, b_1+\ell_2)$	p_T difference between subleading b-tagged jet and $b_1+\ell_2$			✓
$\Delta p_T(j_2, j_3+\ell_1+E_T^{\text{miss}})$	p_T difference between subleading jet and $j_3+\ell_1+E_T^{\text{miss}}$			✓
$\Delta E(j_3, j_2+\ell_1+\ell_2+E_T^{\text{miss}})$	Energy difference between third jet and $j_2+\ell_1+\ell_2+E_T^{\text{miss}}$			✓
$\Delta m(j_2+\ell_2+E_T^{\text{miss}}, j_1+\ell_2+E_T^{\text{miss}})$	Inv. mass difference between $j_2+\ell_2+E_T^{\text{miss}}$ and $j_1+\ell_2+E_T^{\text{miss}}$			✓

The BDT variables include various kinematic quantities with the optimal discrimination against the ttbar + >=1b background.

For H+ masses above 400 GeV the most important variables are the scalar sum of the pT of all jets and the leading jet pT.

For a mass at or below 300 GeV, a kinematic discriminant, D is used as an input variable for the BDT.

Kinematic Discriminant D

- $D = P_{H^+}(\mathrm{x})/(P_{H^+}(\mathrm{x}) + P_{t\bar{t}}(\mathrm{x}))$
- $P_{H^+}(\mathrm{x})$ and $P_{t\bar{t}}(\mathrm{x})$ are probability density functions for x under signal and background hypotheses
- x is $E_{\mathrm{T}}^{\mathrm{miss}}$ and four-momentum of e, μ, and jets
- $P_{H^+}(\mathrm{x})$ defined as the product of probability density functions for:
  - the mass of the semileptonically decaying top quark, $m_{b_\ell \ell \nu}$
  - the mass of the hadronically decaying W boson, $m_{q_1 q_2}$
  - the difference between the masses of the hadronically decaying top quark and the hadronically decaying W boson, $m_{b_h q_1 q_2} - m_{q_1 q_2}$
  - the difference between the mass of the charged Higgs boson and the mass of the leptonically or hadronically decaying top quark, $m_{b_{H^+} b_\ell \ell \nu} - m_{b_\ell \ell \nu}$ or $m_{b_{H^+} b_\ell q_1 q_2} - m_{b_\ell q_1 q_2}$, depending on whether or not the top quark from the charged Higgs boson decays leptonically or hadronically
- Where:
  - q_1 and q_2 are quarks from the hadronic W decay
  - ℓ and ν are from the leptonic W decay
  - b_h is the b-quark from the hadronic top quark decay
  - b_ℓ is the b quark from the leptonic top quark decay
  - b_{H^+} is the b-quark from the H^+ decay

courtesy of B. Burghgrave

$H^{\pm} \to tb$: Systematics

Uncertainty Source	$\Delta\mu(H^+_{200})$ [pb]	$\Delta\mu(H^+_{800})$ [pb]
Jet flavour tagging	0.70	0.050
$t\bar{t}+\geq 1b$ modelling	0.65	0.008
Jet energy scale and resolution	0.44	0.031
$t\bar{t}$+light modelling	0.44	0.019
MC statistics	0.37	0.044
$t\bar{t}+\geq 1c$ modelling	0.36	0.032
Other background modelling	0.36	0.039
Luminosity	0.24	0.010
Jet-vertex assoc., pile-up modelling	0.10	0.006
Lepton, $E_{\mathrm{T}}^{\mathrm{miss}}$, ID, isol., trigger	0.08	0.003
H^+ modelling	0.03	0.006
Total systematic uncertainty	1.4	0.11
$t\bar{t}+\geq 1b$ normalisation	0.61	0.022
$t\bar{t}+\geq 1c$ normalisation	0.28	0.012
Total statistical uncertainty	0.69	0.050
Total uncertainty	1.5	0.12

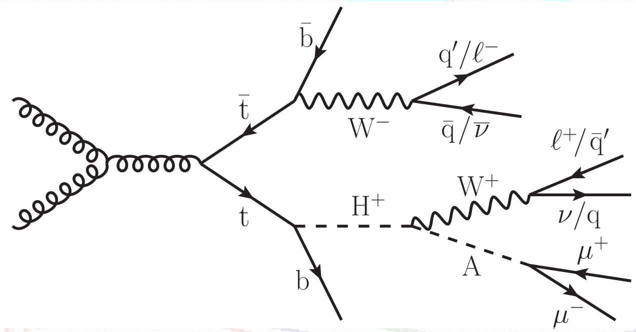
- Uncertainty in terms of effect on $\mu = \sigma(pp \to tbH^{\pm}) \times \mathcal{B}(H^{\pm} \to tb)$ [pb]

$H^{\pm\pm} \to l^{\pm} l^{\pm}$:Signal and Control Regions

Region / Channel	Control Regions			Validation Regions			Signal Regions		
	OCCR	DBCR	4LCR	SCVR	3LVR	4LVR	1P2L	1P3L	2P4L
Electron channel	$e^\pm e^\mp$	$e^\pm e^\pm e^\mp$		$e^\pm e^\pm$	$e^\pm e^\pm e^\mp$		$e^\pm e^\pm$	$e^\pm e^\pm e^\mp$	
Mixed channel	-	$e^\pm \mu^\pm \ell^\mp$	$\ell^\pm \ell^\pm$ $\ell^\mp \ell^\mp$	$e^\pm \mu^\pm$	$e^\pm \mu^\pm \ell^\mp$ $\ell^\pm \ell^\pm \ell'^\mp$	$\ell^\pm \ell^\pm$ $\ell^\mp \ell^\mp$	$e^\pm \mu^\pm$	$e^\pm \mu^\pm \ell^\mp$ $\ell^\pm \ell^\pm \ell'^\mp$	$\ell^\pm \ell^\pm$ $\ell^\mp \ell^\mp$
Muon channel	-	$\mu^\pm \mu^\pm \mu^\mp$		$\mu^\pm \mu^\pm$	$\mu^\pm \mu^\pm \mu^\mp$		$\mu^\pm \mu^\pm$	$\mu^\pm \mu^\pm \mu^\mp$	
$m(e^\pm e^\pm)$ [GeV]	$[130, 2000]$	$[90, 200)$		$[130, 200)$	$[90, 200)$		$[200, \infty)$	$[200, \infty)$	
$m(\ell^\pm \ell^\pm)$ [GeV]	-	$[90, 200)$	$[60, 150)$	$[130, 200)$	$[90, 200)$	$[150, 200)$	$[200, \infty)$	$[200, \infty)$	$[200, \infty)$
$m(\mu^\pm \mu^\pm)$ [GeV]	-	$[60, 200)$		$[60, 200)$	$[60, 200)$		$[200, \infty)$	$[200, \infty)$	
b-jet veto	✓	✓	✓	✓	✓	✓	✓	✓	✓
Z veto	-	inverted	-	-	✓	-	-	✓	✓
$\Delta R(\ell^\pm, \ell^\pm) < 3.5$	-	-	-	-	-	-	✓	✓	-
$p_{\mathrm{T}}(\ell^\pm \ell^\pm) > 100$ GeV	-	-	-	-	-	-	✓	✓	-
$\sum \lvert p_{\mathrm{T}}(\ell) \rvert > 300$ GeV	-	-	-	-	-	-	✓	✓	-
$\Delta M / \bar{M}$ requirement	-	-	-	-	-	-	-	-	✓

Light/Intermediate Charged Higgs bosons: H+-→WA

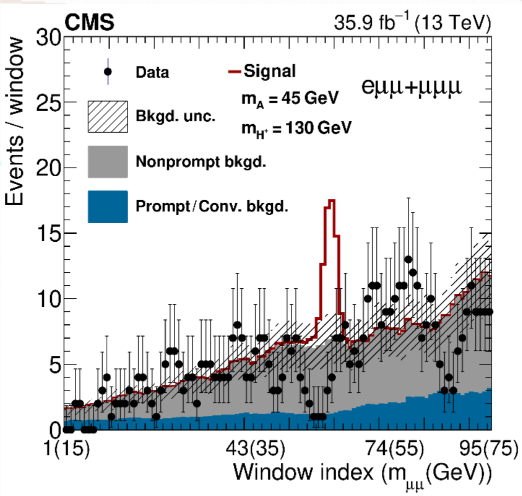
m_A:15 - 75 GeV, $m_{H^\pm}$:100 -160 GeV, $m_{H^\pm} > mA + mW$



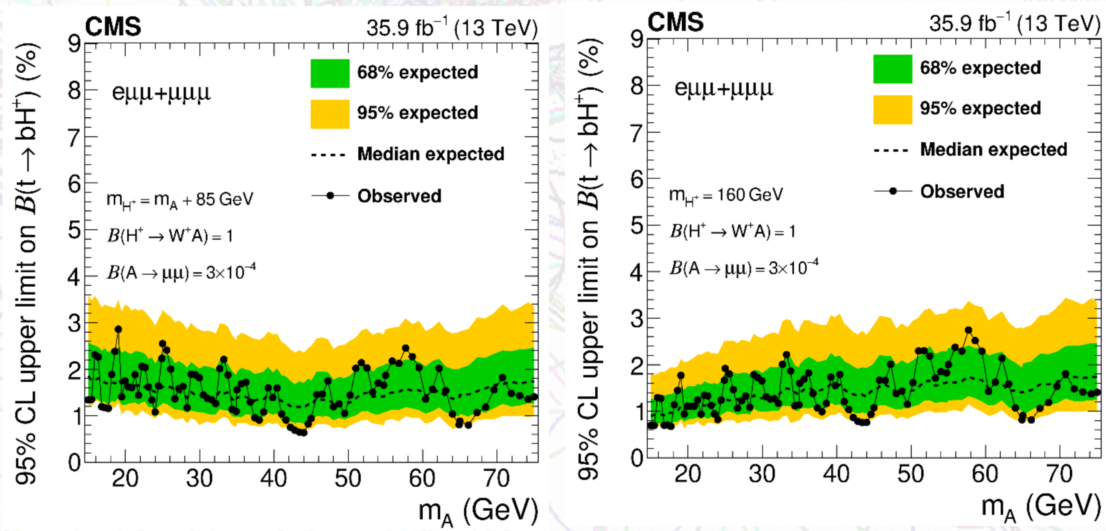
- **Target eμμ or μμμ final states with A→μμ (opposite sign)**
- Assign to A lower-pt of 2 same-sign μ or that having mT least consistent with W
- ***Major background: leptons from semileptonic B-hadron decays***
- Look for excess in variable-width di-μ mass windows intended to maximize

$$\sqrt{2[(n_s + n_b)\ln(1 + n_s/n_b) - n_s]}$$

CMS-HIG-18-020, arXiv:1905.07453, sub. PRL



- **Obtain 95% CL upper limits on B(t→bH+) between 0.63 and 2.9%, variation with m_{H+} values not significant.**



- First model-independent **search for A in this mass range, and first search for H+- in this decay process.**

S. Gascon-Shotkin Higgs Hunting 2019, LPNHE Paris, FR July 30 2019

The Matrix method

Built from two rates:

The real rate: probability that a real lepton identified as a loose lepton gets identified as a tight lepton

The fake rate: probability that a real jet identified as a loose leptons is identified as tight lepton

Single lepton selection: the # of loose and tight leptons can be written as: $N^L = N_R^L + N_F^L; \quad N^T = \varepsilon_R^L N_R + \varepsilon_F^L N_F$

Where ε's are the fraction of events that pass from loose to tight

These are measured in control data samples, depends on kinematics and jet type

In the end results in weights given to each event:

$w = \frac{\varepsilon_F \varepsilon_R}{\varepsilon_R - \varepsilon_F}$ if it fails loose cuts and $\frac{\varepsilon_F}{\varepsilon_R - \varepsilon_F}(\varepsilon_R - 1)$ otherwise

General idea of fake factor method

- Observe number of events in loose and tight selection

$$N^{loose} = N^{loose}_{real} + N^{loose}_{fake}$$
$$N^{tight} = N^{tight}_{real} + N^{tight}_{fake}$$
$$= \epsilon_{real} N^{loose}_{real} + \epsilon_{fake} N^{loose}_{fake}$$

- Matrix form

$$\begin{bmatrix} N^{loose} \\ N^{tight} \end{bmatrix} = \begin{bmatrix} 1 & 1 \\ \epsilon_{real} & \epsilon_{fake} \end{bmatrix} \times \begin{bmatrix} N^{loose}_{real} \\ N^{loose}_{fake} \end{bmatrix}$$

- Fake component

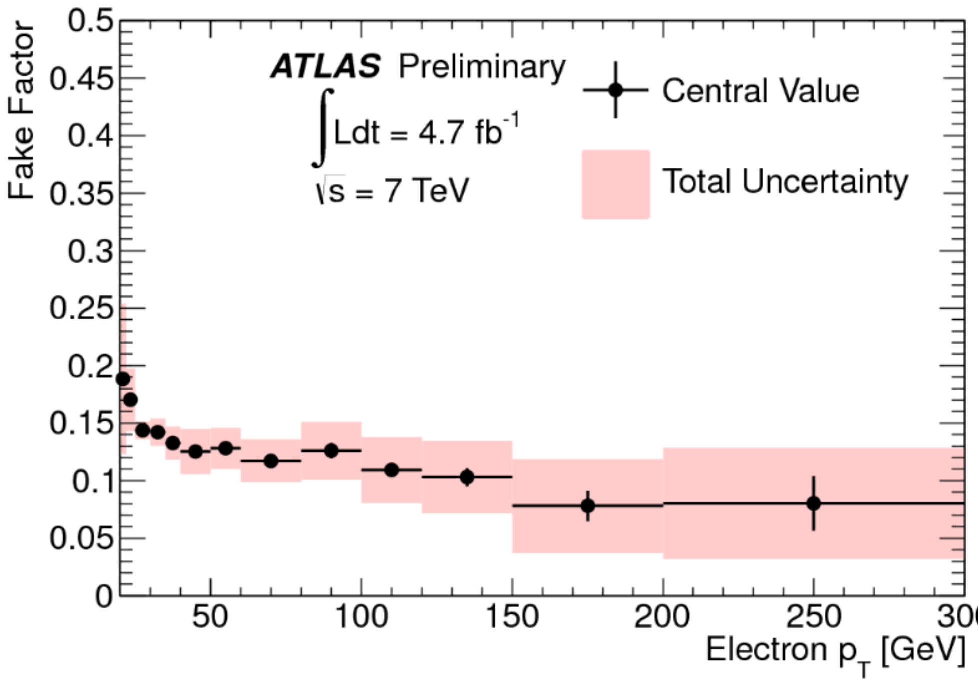
$$\begin{bmatrix} N^{loose}_{real} \\ N^{loose}_{fake} \end{bmatrix} = \frac{1}{\epsilon_{fake} - \epsilon_{real}} \begin{bmatrix} \epsilon_{fake} & -1 \\ -\epsilon_{real} & 1 \end{bmatrix} \times \begin{bmatrix} N^{loose} \\ N^{tight} \end{bmatrix}$$

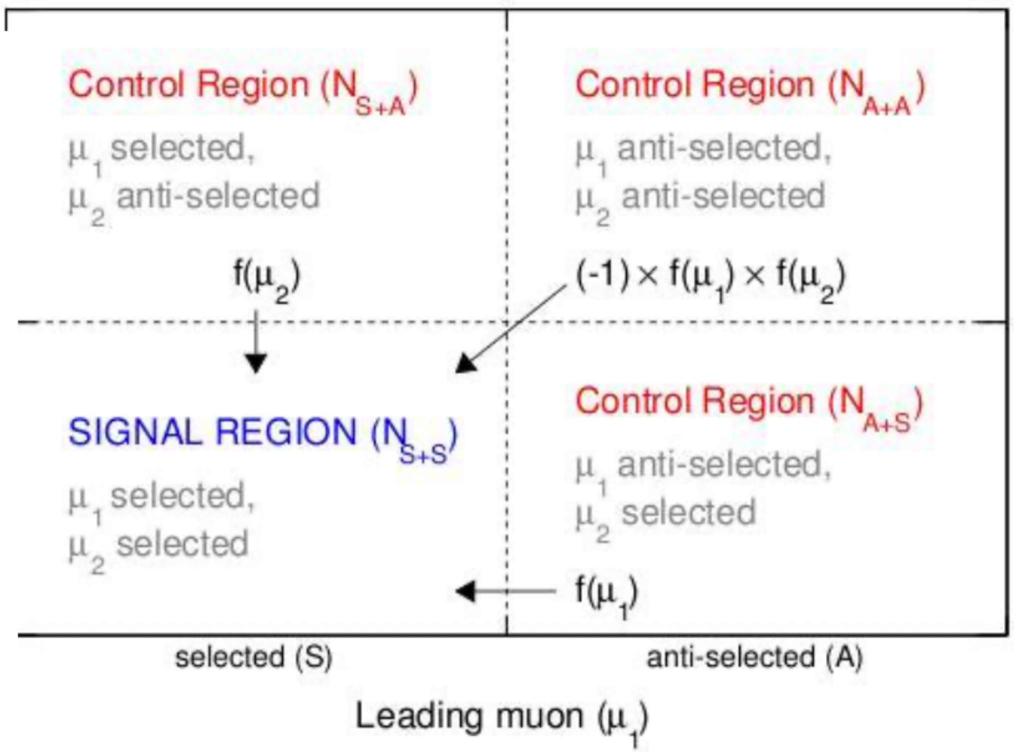
$$N^{tight}_{fake} = \frac{\epsilon_{fake}}{\epsilon_{real} - \epsilon_{fake}} (\epsilon_{real} N^{loose} - N^{tight})$$

Fake factors

Define data control region inverting some selection criteria, then extrapolate this into signal region: $f \equiv \frac{N_{selected}}{N_{Anti-selected}}$

where f= function(p_T , η)

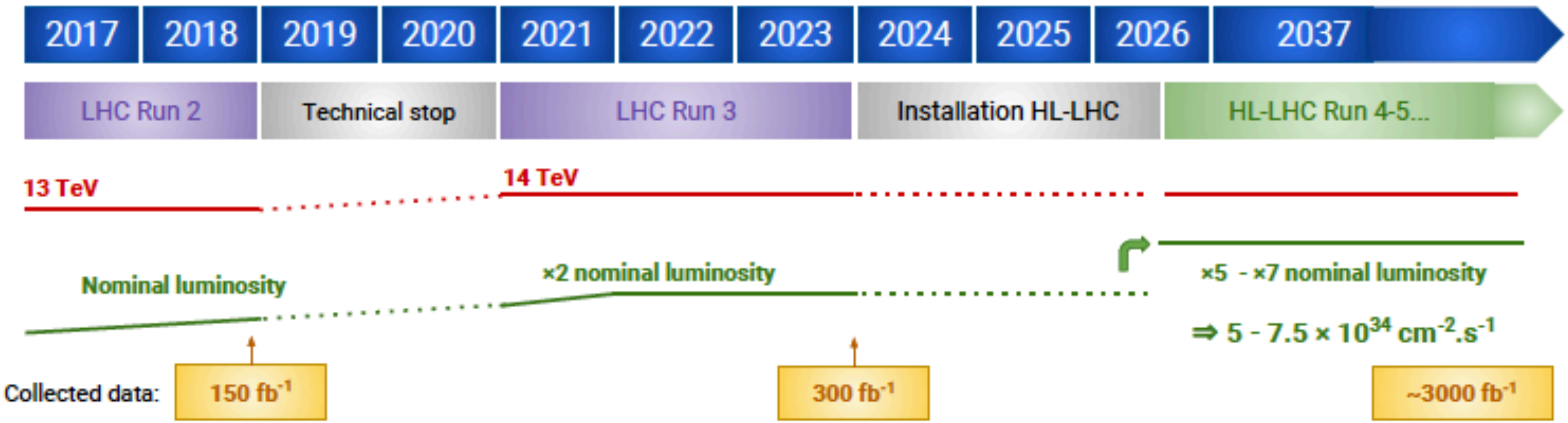




Needs independent sample for measuring f, as well as corrections for other backgrounds

From LHC to High-Lumi LHC

Schedule



Right now Peak lumi = 1.7×10^{34} $cm^{-2}.s^{-1}$

~16 fb^{-1} (2016) ≡ order of 100×10^{12} (trillions) proton-proton collisions

Need of a decisive increase in luminosity

→ to significantly extend statistical sensitivity to new physics

→ to maximize performance for precision measurements

⇒ fully exploit LHC's singular potential

The High-Luminosity LHC program