Search for Higgs beyond the Standard Model with the ATLAS & CMS Detectors

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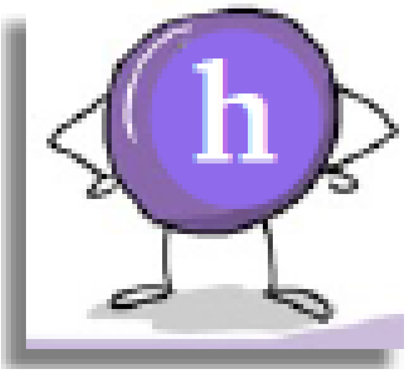
Outline

- Introduction
- Beyond Standard Model Higgs theories
- Results for recently published channels
  - Focus on novel techniques
- Conclusion

Introduction

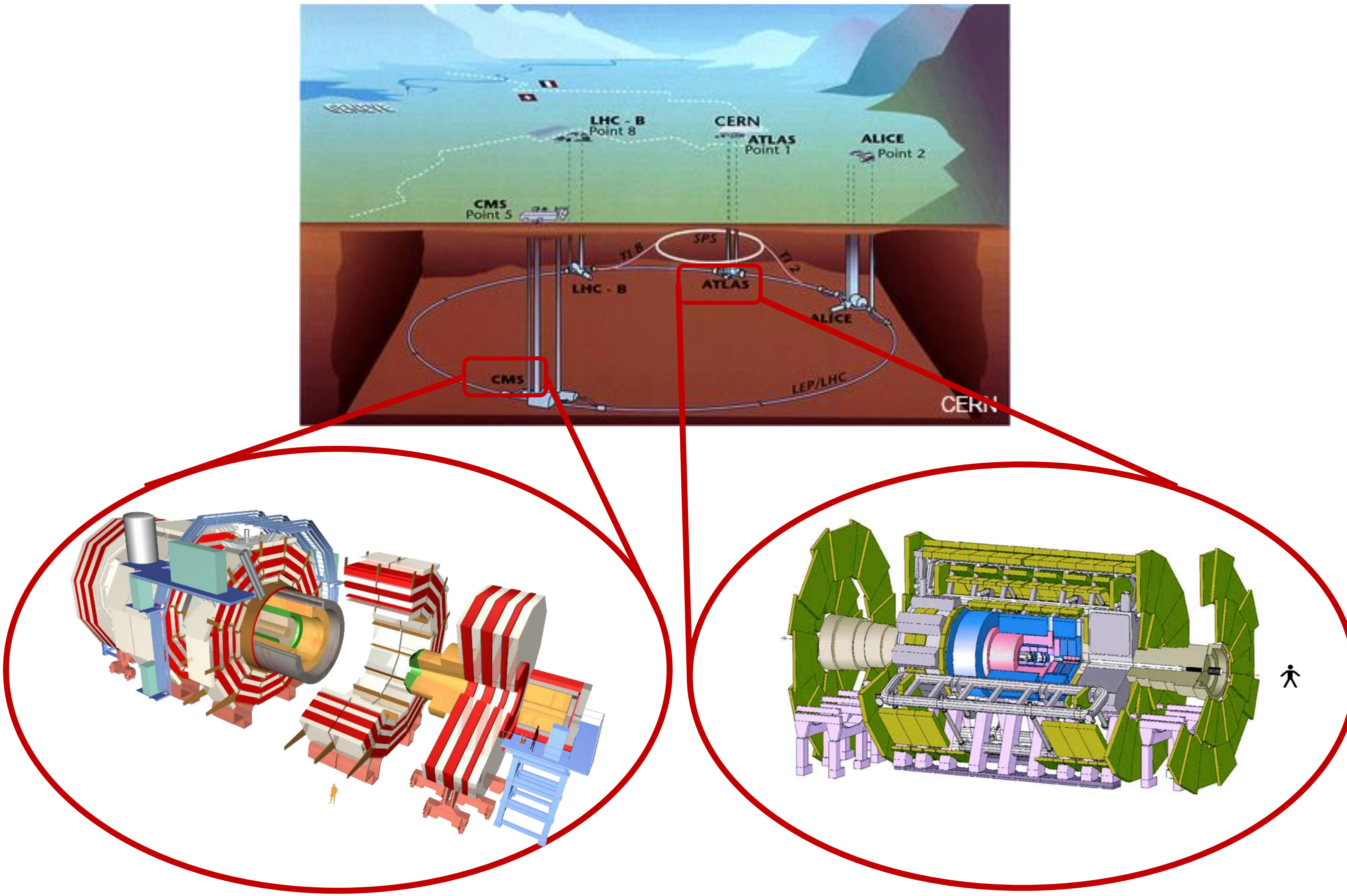
Need to extend SM to address issues like hierarchy problem, quantum gravity, baryon asymmetry, dark matter/energy, neutrino masses



Look for BSM physics by

- Looking for deviations from the SM in Higgs properties measurements
- Directly searching for beyond SM objects
  - Additional Higgs bosons decaying to SM particles
  - SM Higgs decays to BSM states (eg. invisible decays)

Introduction



Beyond Standard Model Higgs Theories

SM Higgs doublet + **Additional Field** = **Additional Higgs Bosons**

Neutral CP Even

EWS: Additional EW Singlet Model =
SM + one scaler EW singlet

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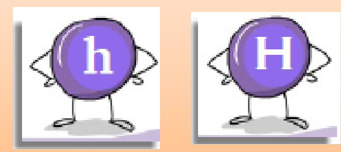
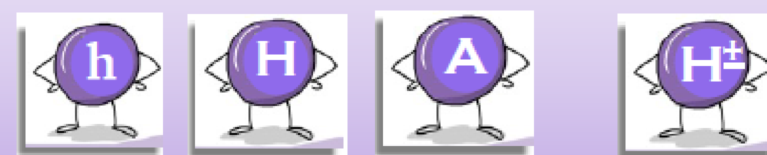


2HDM: Two Higgs Doublet Model 〓
SM ➕ another Higgs doublet

Neutral

CP Even | CP Odd

Charged



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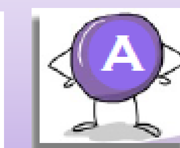

Charged

2HDM + Singlet (complex) Model
SM + doublet & singlet =

Neutral

CP Even

CP Odd

+ 2HDM Higgses

Beyond Standard Model Higgs Theories

SM Higgs doublet ➕ **Additional Field** 〓 **Additional Higgs Bosons**

EWS: Additional EW Singlet Model
SM ➕ one scaler EW singlet 〓

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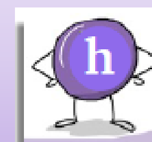
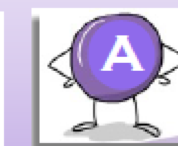


CP Odd



Charged

2HDM + Singlet (complex) Model
SM ➕ doublet & singlet 〓

Neutral

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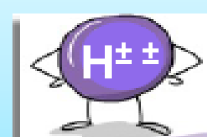
CP Odd

+ 2HDM Higgses

Higgs Triplet Model
SM ➕ triplet 〓

Double Charged



+ 2HDM Higgses

Beyond Standard Model Higgs Theories

EWS significantly constrained by Run 1 Higgs measurements

2HDM: two Higgs doublets Φ_1 and Φ_2

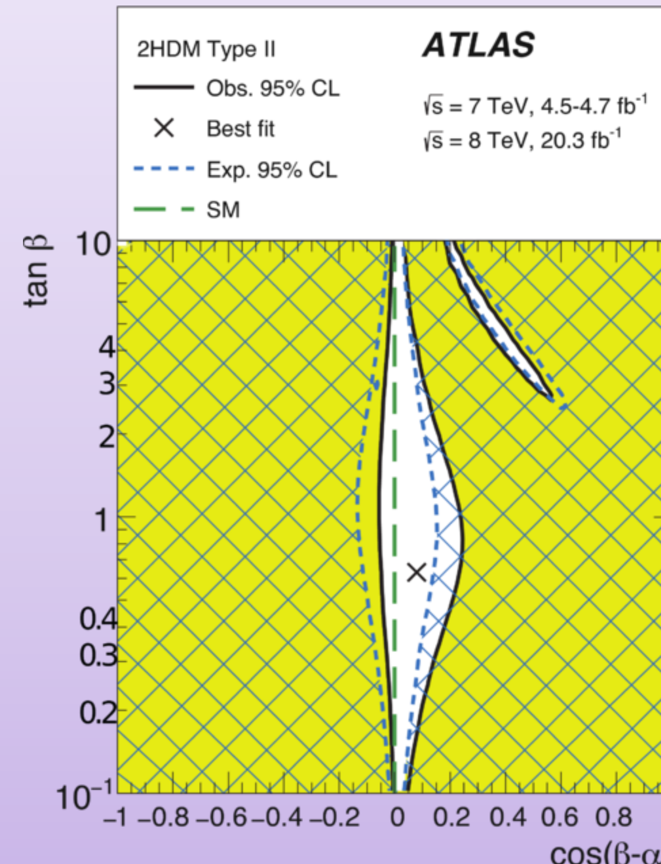
7 parameters:

m_h, m_H, m_A, $m_{H^\pm}$, m_{12}, $tan\beta$, α

Ratio of VEV of Φ_1 and Φ_2

h & H mixing angle

- Models motivated by bounds on FCNC
  - Type I : fermions couple to Φ_2
  - Type II : up type quarks couple to Φ_2, down-type quarks & charged leptons couple to Φ_1 Eg: MSSM
- Run 1 SM Higgs results give big constraints on 2HDM. Data prefers alignment limit: $\cos(\beta - \alpha) = 0$



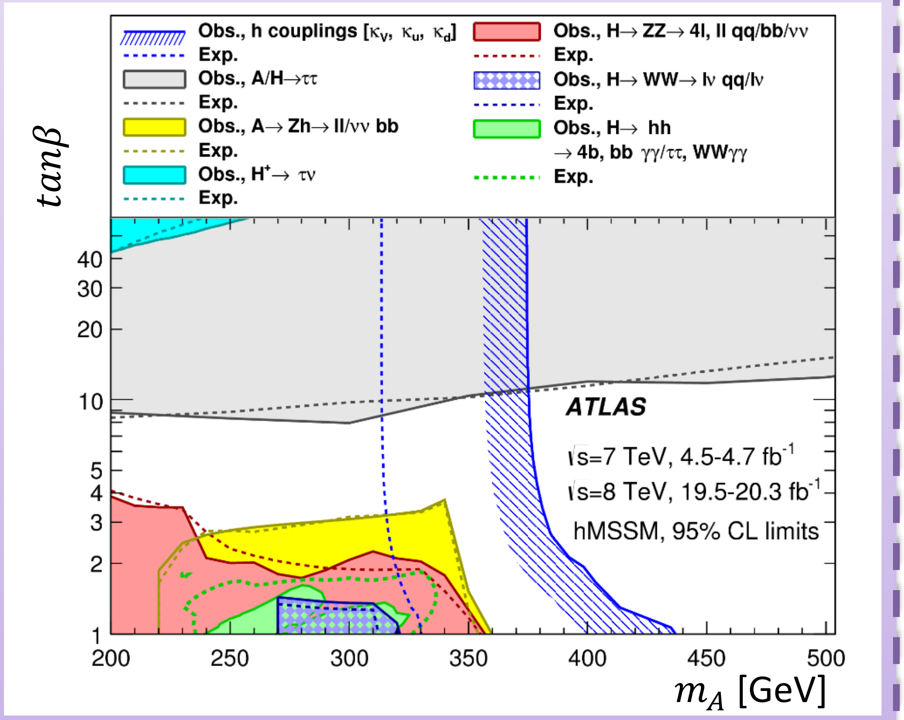
Beyond Standard Model Higgs Theories

2HDM-Minimal Supersymmetric SM (MSSM)

- To reduce parameters define benchmarks defined:

- $m^{\pm}_{h,mod}$: m_h is close to 125 GeV
- hMSSM : measured value of m_h can be used to predict other masses

- In Run 1 excluded many regions of parameter space



~36 fb^{-1}	@13 TeV
15-20 fb^{-1}	@13 TeV
5fb^{-1}	@13 TeV
5-20.3fb^{-1}	@7-8 TeV

Legend

Neutral Heavy Higgs to bosons & fermions

ATLAS

- WV→ $\ell\nu qq$, $\ell\nu\ell\nu$
- ZV → $\ell\ell qq$ /$\nu\nu qq$
- ZZ → 4ℓ, $\ell\ell\nu\nu$
- VV→ 2j
- Z/Wh (w h→bb)
- ZH → (H→bb)
- γZ
- γγ
- ττ → $2\ell, \ell j, jj$
- tt
- 4γ
- WH
- bb

CMS

- ZZ → 4ℓ, $\ell\ell qq$, $\ell\ell\nu\nu$
- γZ
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- ττ → $2\ell, \ell j, jj$
- Zh→ $\ell\ell\tau\tau$
- Zh→ $\ell\ell bb$
- ZA/H →$\ell\ell bb$
- $\gamma\gamma$
- $\mu\mu$
- $\tau\tau$

Neutral Higgs to di-Higgs

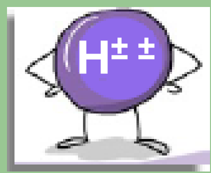
ATLAS:

- hh → bb$\gamma\gamma$
- hh → 4b
- hh → WW$\gamma\gamma$
- hh → bb$\tau\tau$

CMS:

- hh → bb$\gamma\gamma$
- hh → 4b
- hh→ WW/ZZ +2b
- hh → bb$\tau\tau$
- hh→ $\ell\ell\gamma\gamma$

Charged Higgs



ATLAS

- $H^{\pm} \rightarrow \tau\nu$
- $H^{\pm} \rightarrow tb$
- $H^{\pm\pm} \rightarrow \ell\ell$
- $H^{\pm} \rightarrow cs$
- VBF $H^{\pm} \rightarrow WZ$

CMS

- $H^{\pm} \rightarrow \tau\nu$
- $H^{\pm} \rightarrow tb$
- $H^{\pm} \rightarrow ZW$
- $H^{\pm} \rightarrow cs$
- $H^{\pm\pm} \rightarrow 4\ell/3\ell\nu$

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Legend

Higgs exotic with MET

ATLAS

- H $\rightarrow \gamma\gamma$+MET
- H $\rightarrow$ bb+MET
- hZ $\rightarrow$ INV ($\ell\ell$)
- H $\rightarrow Z_d Z_d$
- H $\rightarrow$ Z ($\ell\ell$)+MET
- VBF h $\rightarrow$ INV
- hV$\rightarrow$ INV (had)
- H $\rightarrow \gamma$+MET
- H$\rightarrow$ INV (1 jet)

CMS

- hZ $\rightarrow$ INV ($\ell\ell/bb$)
- hZ $\rightarrow$ INV +$1/2\gamma$
- hj $\rightarrow$ INV +j

Rare decays/ LVF

ATLAS

- $h(125) \to \phi/\rho\gamma$
- $h(Z) \to J/\psi\gamma$ or $\psi/(2S)$ or $\Upsilon(nS)$
- $h \to \tau\mu$ / τe / $e\mu$

CMS

- $h \to \tau\mu$

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Legend

Higgs to light res.

ATLAS

- $aa \to jj\gamma\gamma$
- $aa \to bb\mu\mu$
- $aa \to 4b$
- $aa \to \mu\mu\tau\tau$

CMS

- $aa \to \mu\mu\tau\tau$
- $aa \to bb\tau\tau$
- $aa \to 4\tau, \mu\mu bb, \mu\mu\tau\tau$
- $aa \to 4\mu$

Neutral Heavy Higgs to bosons & fermions

ATLAS	CMS
WV→ $\ell\nu qq$, $\ell\nu\ell\nu$	ZZ → 4ℓ, $\ell\ell qq$, $\ell\ell\nu\nu$
ZV → $\ell\ell qq$ /ννqq	γZ
ZZ → 4ℓ, $\ell\ell\nu\nu$	bb
VV→ 2j	ττ → $2\ell, \ell j, jj$
Z/Wh (w h→bb)	Zh→ $\ell\ell\tau\tau$
ZH → (H→bb)	Zh→ $\ell\ell bb$
$H^{\pm}$→h →bb	ZA/H →$\ell\ell bb$
γZ	$\gamma\gamma$
$\gamma\gamma$	$\mu\mu$
ττ → $2\ell, \ell j, jj$	$\tau\tau$
tt	
4γ	
WH	
bb	

Neutral Higgs to di-Higgs

ATLAS	CMS
hh → bb$\gamma\gamma$	hh → bb$\gamma\gamma$
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hh → bb$\tau\tau$	hh → bb$\tau\tau$
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Why this channel?

- Is unitarisation of WW scattering at high energy ensured ONLY by h ?
- Prominent decay is to W/Z in many BSM models

SM

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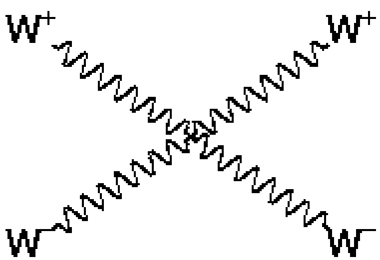
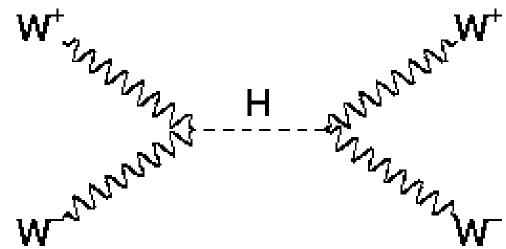
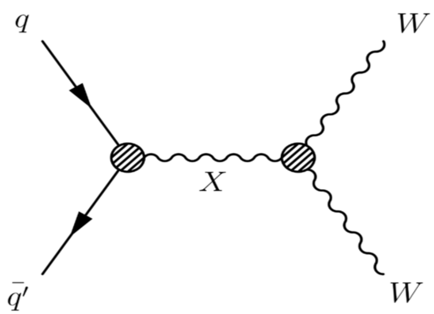
SM

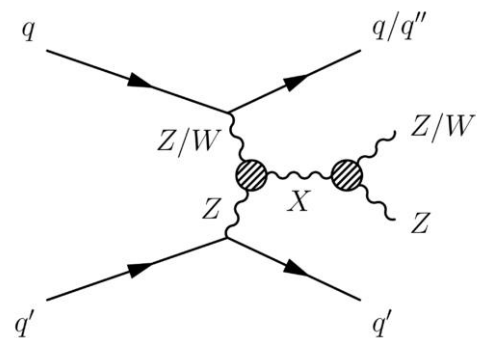




BSM



$q\bar{q}$/ggF production

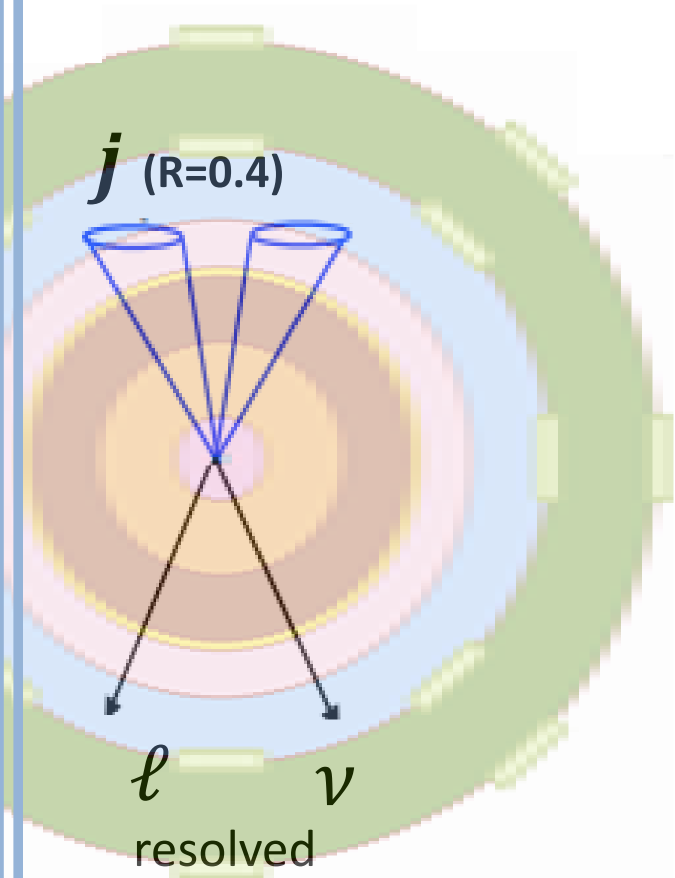


Vector Boson Fusion (VBF)

- Search for H, Z'/W', G_{kk}

WV→ lvqq

- Search in resolved and boosted categories



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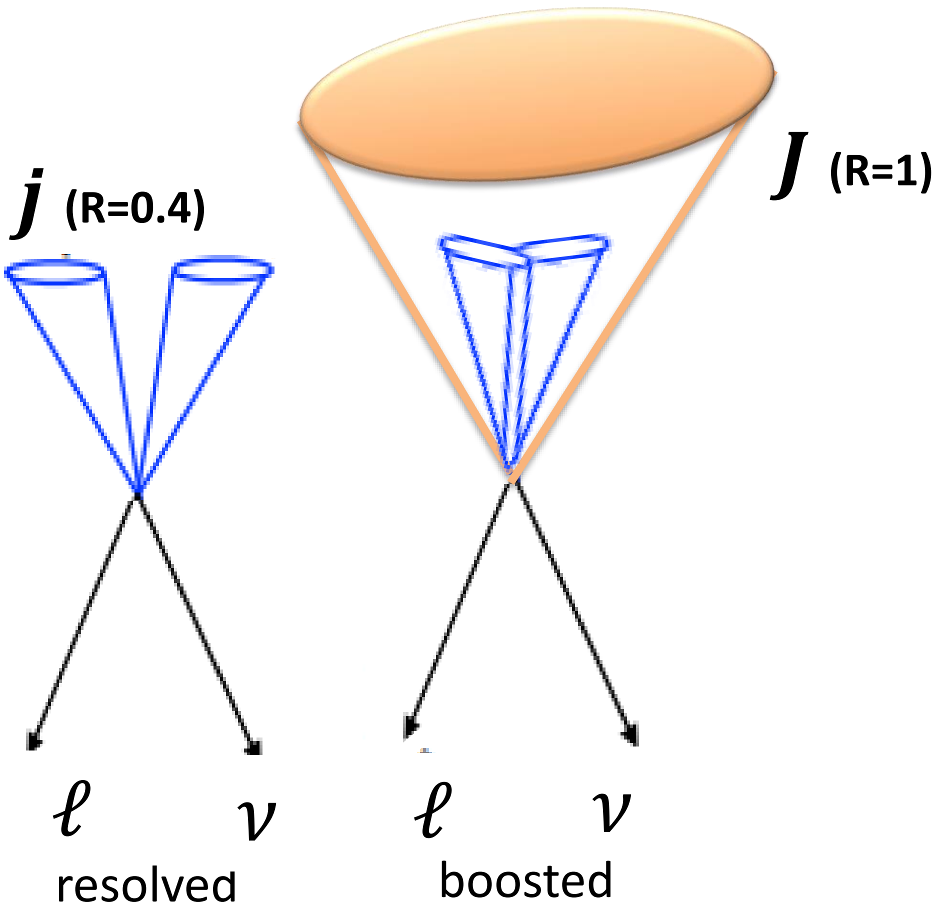
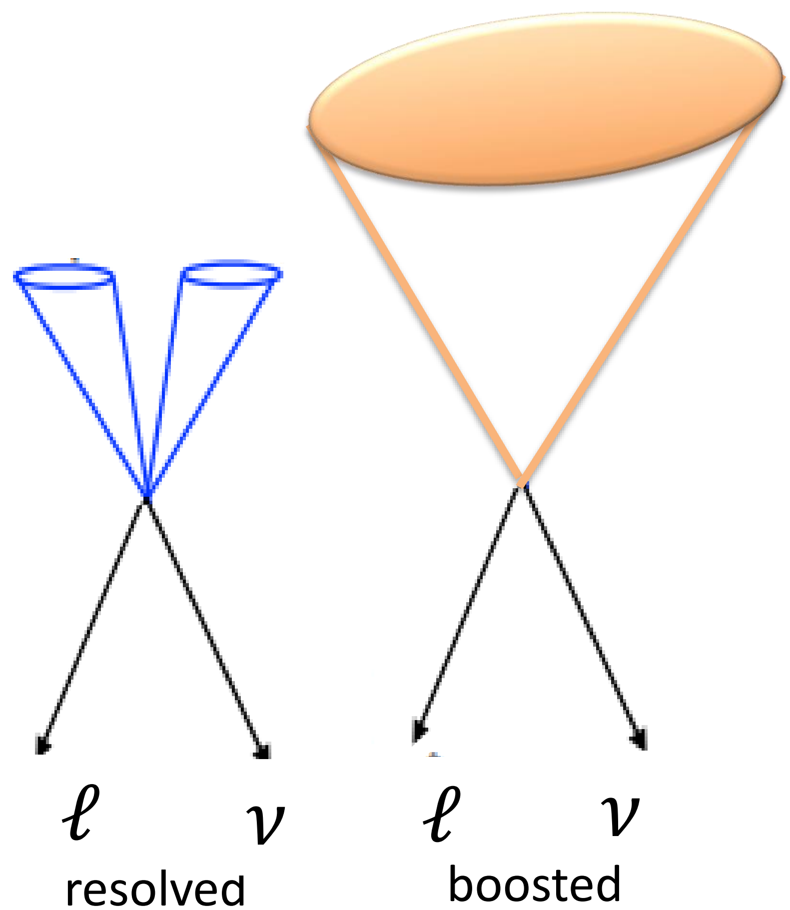
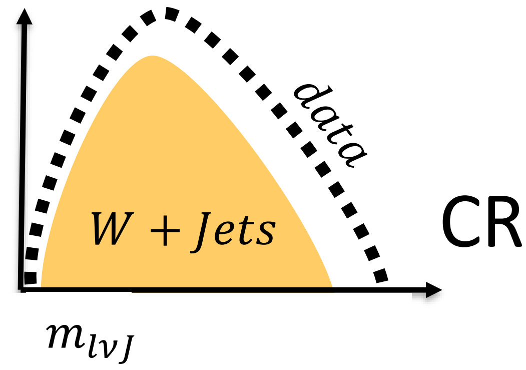


WV→ lvqq

- Background: W+jets and $t\bar{t}$ taken from background-rich control region (CR)
- Signal regions (SR) and CR separated using jet mass, number of b-tagged jets, D_2





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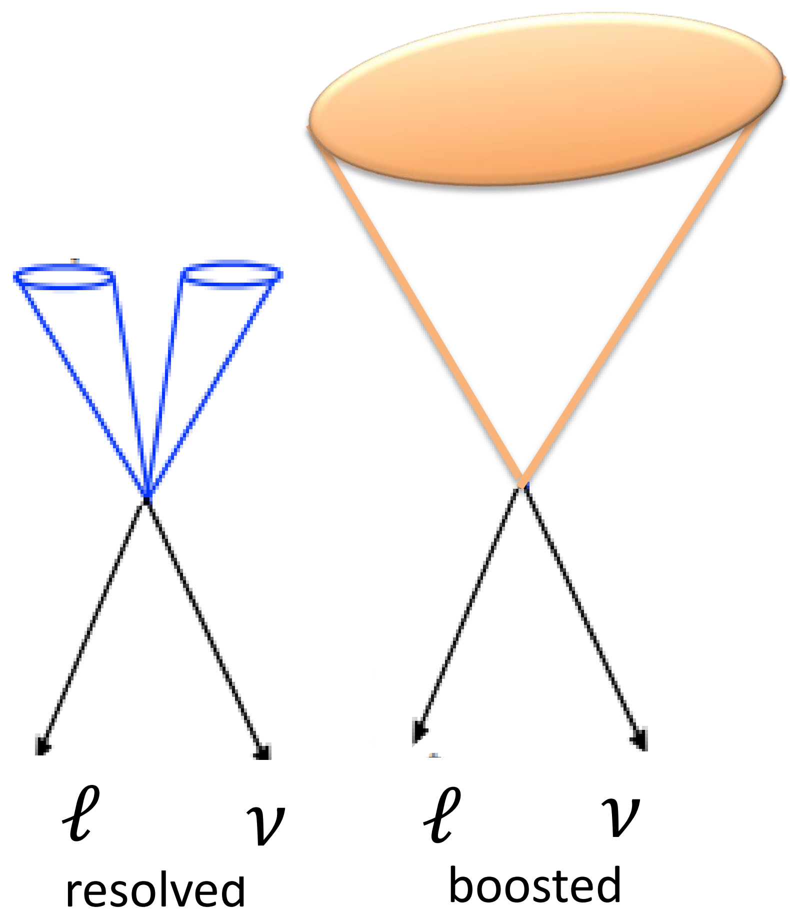

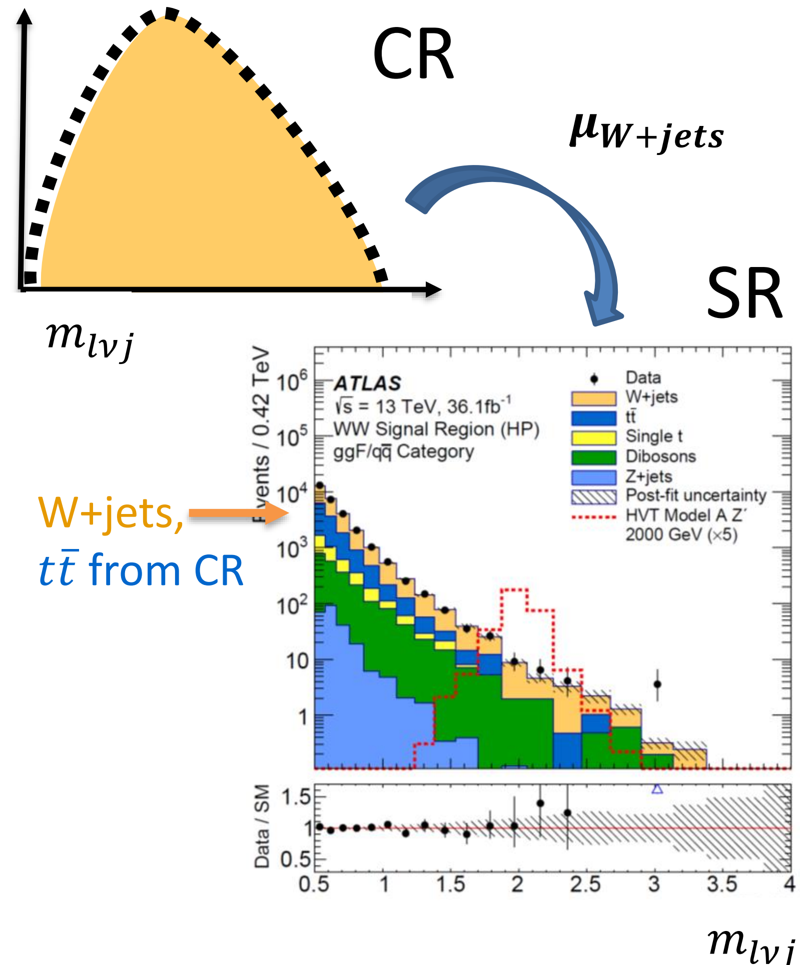

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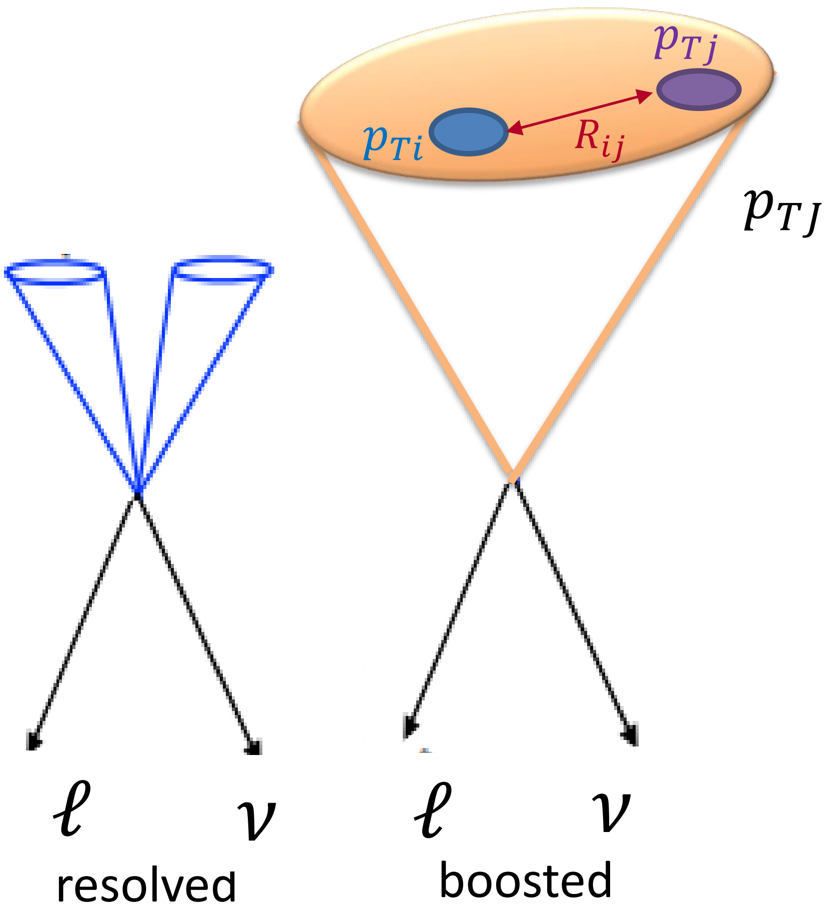

$$e_2 = \frac{1}{p_{TJ}J} \sum p_{Ti}\, p_{Tj}\, R_{ij}$$

Neutral Heavy Higgs to bosons

WV→ lvqq

- Background: W+jets and $t\bar{t}$ taken from background-rich control region (CR)
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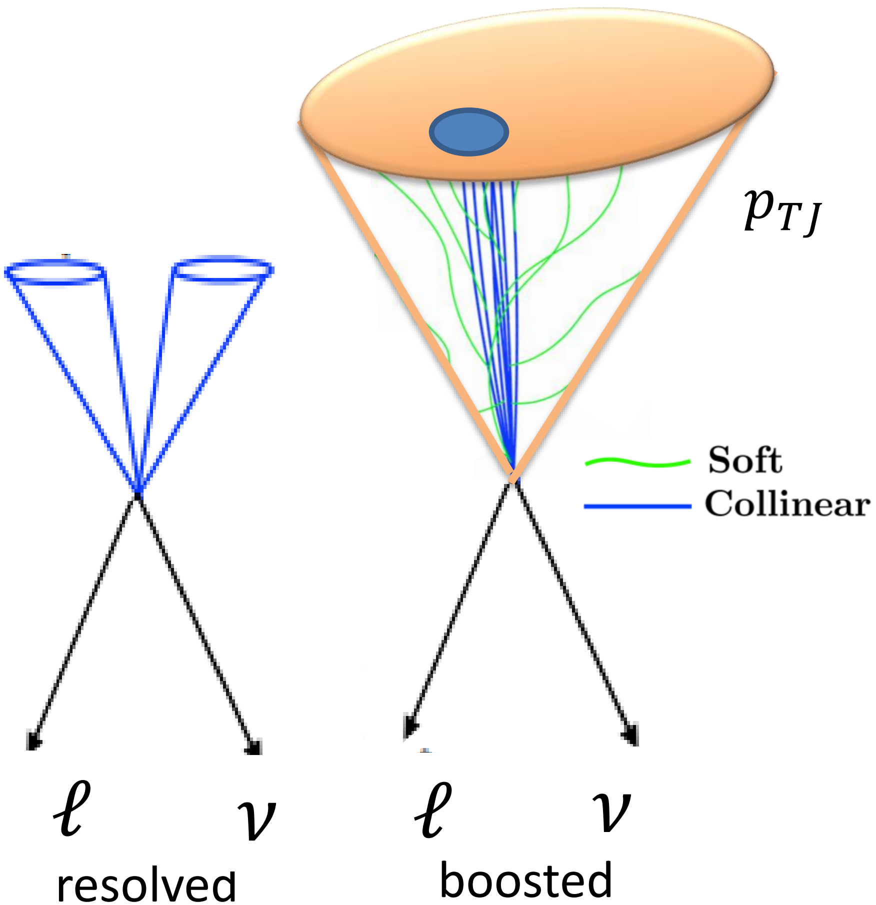

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1-prong jet identification (quark-gluon)

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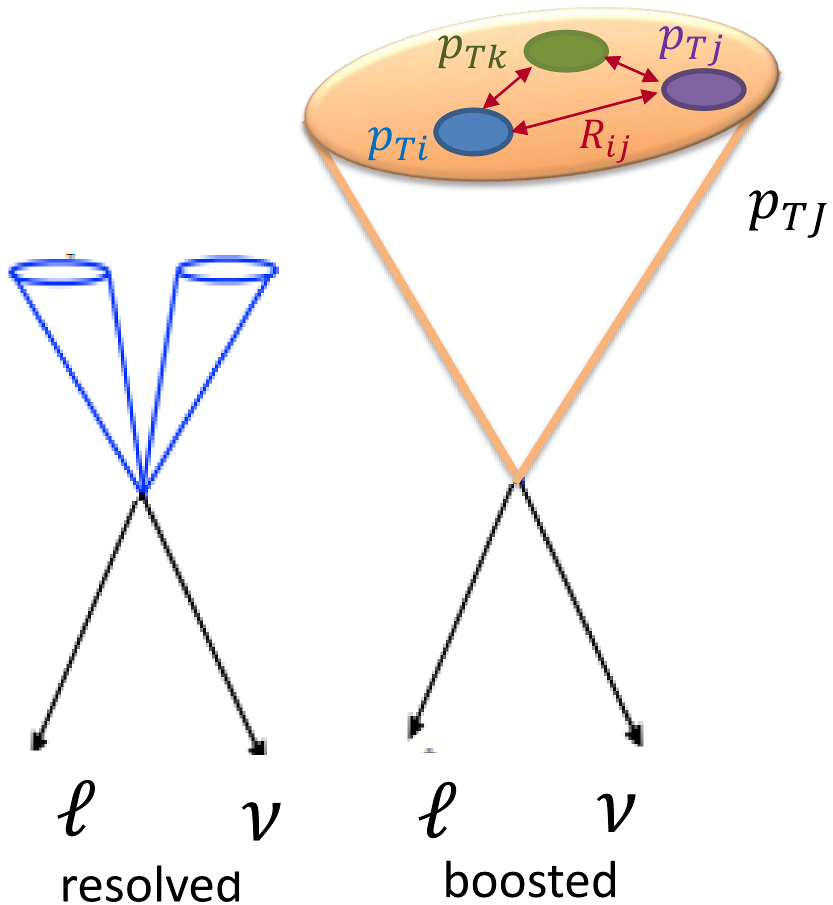

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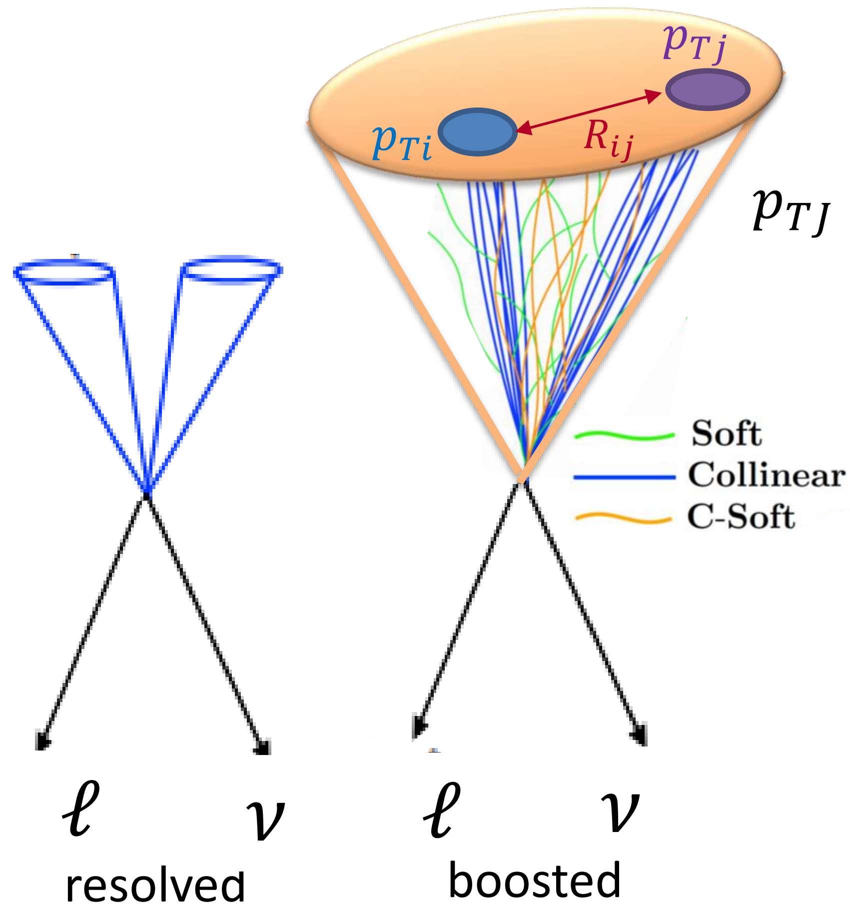

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2-, 3-prong jet identification
(W/Z/H bosons)

WV→ lvqq

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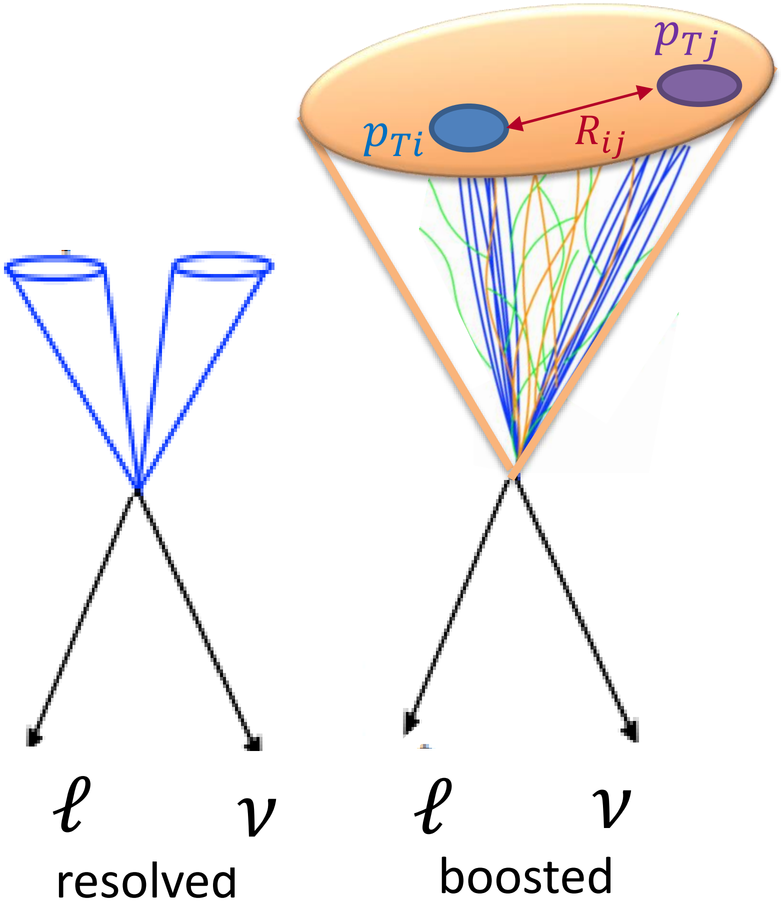

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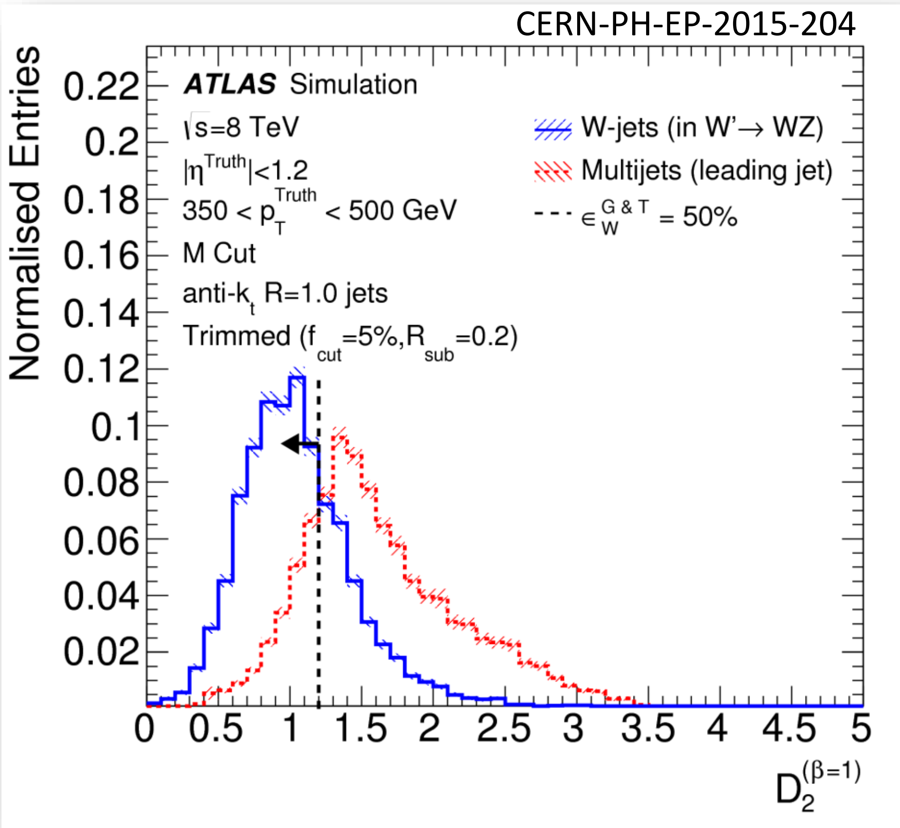
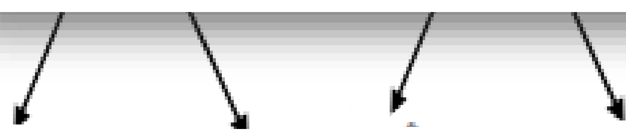
$$\boldsymbol{D_2 = \frac{e_3}{(e_2)^3}}$$

WV→ lvqq





ℓ ν resolved

ℓ ν boosted

background-rich control region (CR)

sing jet mass, number of b-tagged jets, D_2

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$$\boldsymbol{D_2 = \frac{e_3}{(e_2)^3}}$$

Neutral Heavy Higgs to bosons

WV→ lvqq

- Final discriminating variable: transverse mass

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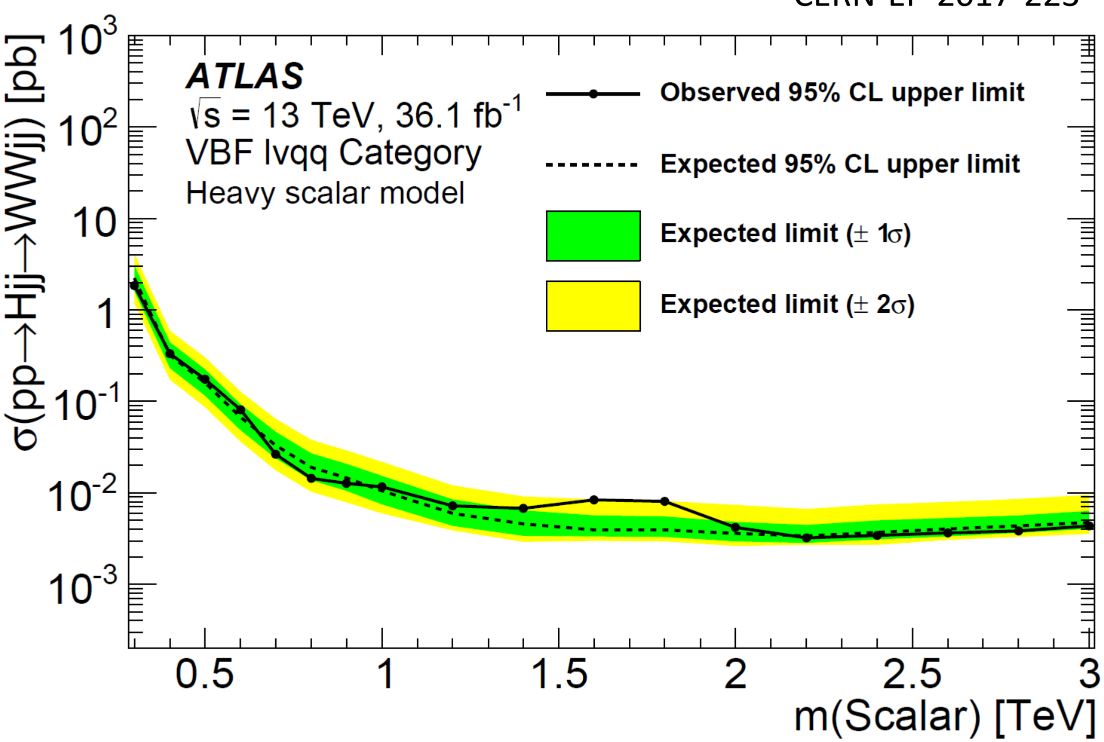

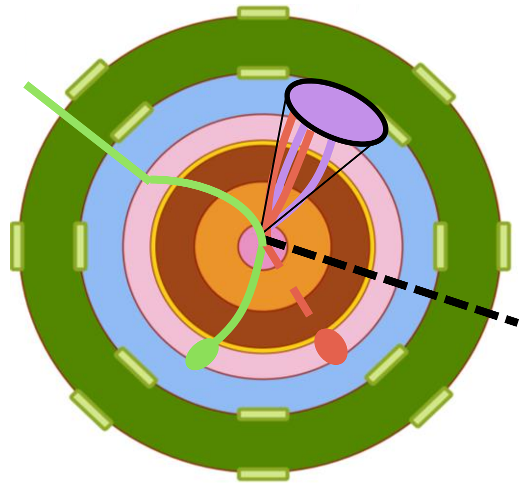

largest local excess : 2.7 σ

Neutral Heavy Higgs to bosons & fermions

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- ZV → $\ell\ell qq$ /$\nu\nu qq$
- ZZ → 4ℓ, $\ell\ell\nu\nu$
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- ZH → (H→bb)
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CMS

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- $\tau\tau$

Neutral Higgs to di-Higgs

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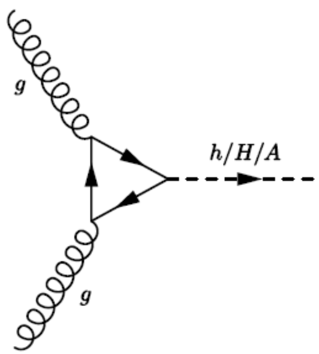
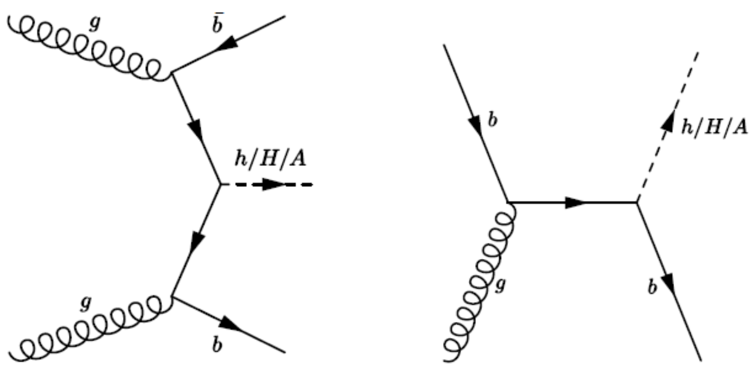
Legend

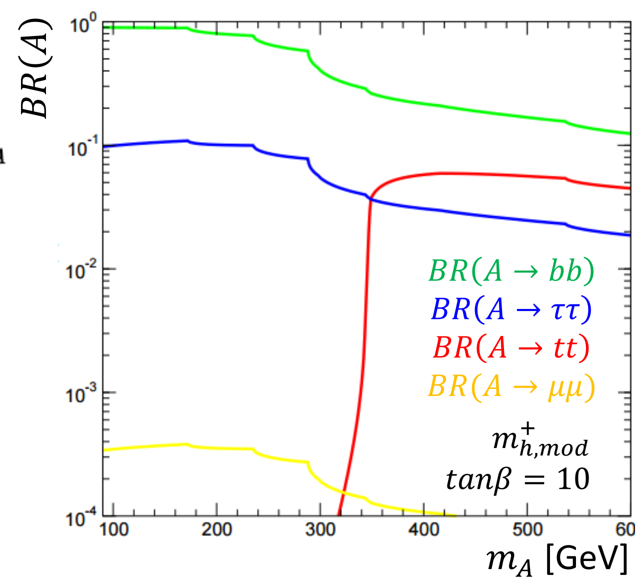
- In MSSM heavy Higgs boson coupling to down-type fermions (τ, b) strongly enhanced for **high tan $\boldsymbol{\beta}$**



gluon-gluon fusion (ggF)



associated b production



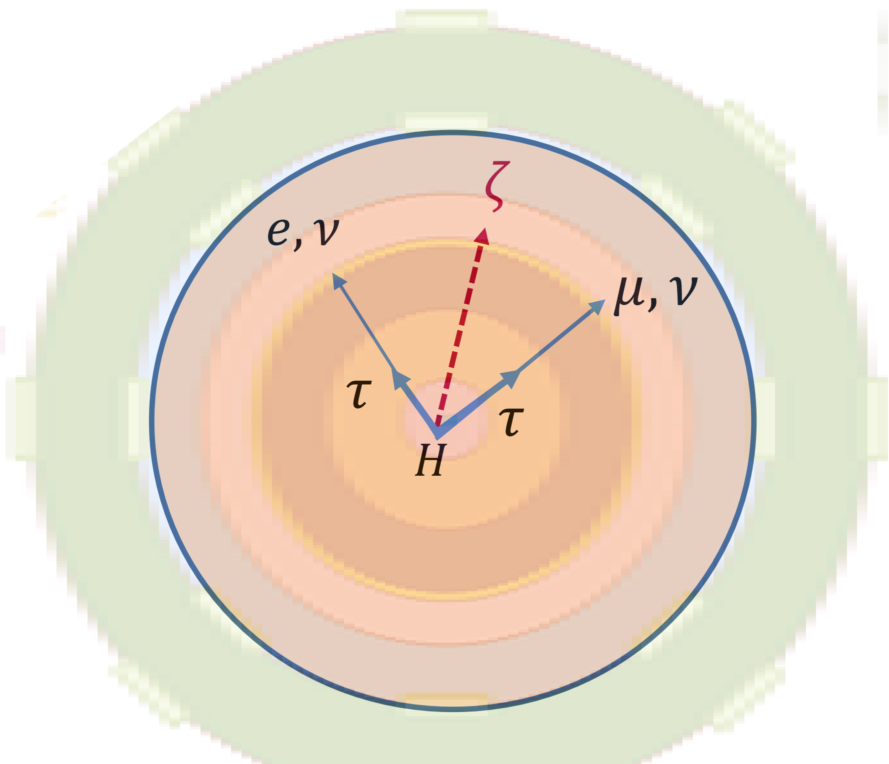
- Search for hMSSM, $m_{h,mod}^{\pm}$

Neutral Higgs to fermions

$\tau\tau \rightarrow 2\ell, \ell j, jj$

- Background: jets/leptons faking τ leptons
- SR and CR separated using number of b-tagged jets, transverse mass, D_ζ

In real $\tau\tau$ events



$\tau\tau \rightarrow 2\ell, \ell j, jj$

- Background: jets/leptons faking τ leptons
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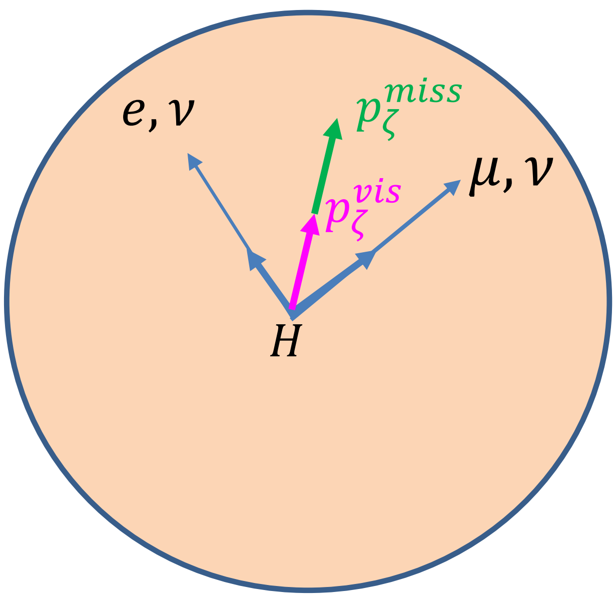
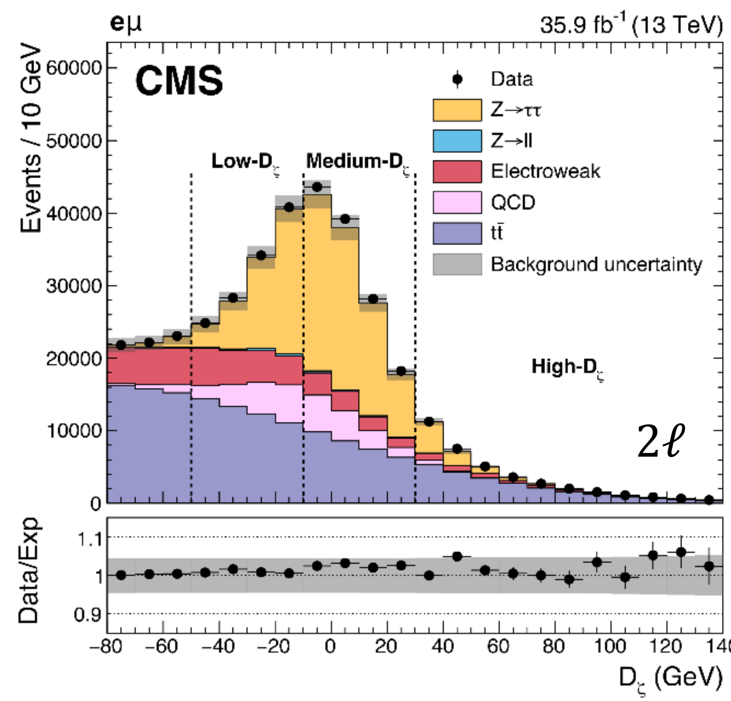
$$D_\zeta = p_\zeta^{miss} - 0.85\, p_\zeta^{visible}$$



Supresses W+jets and $t\bar{t}$



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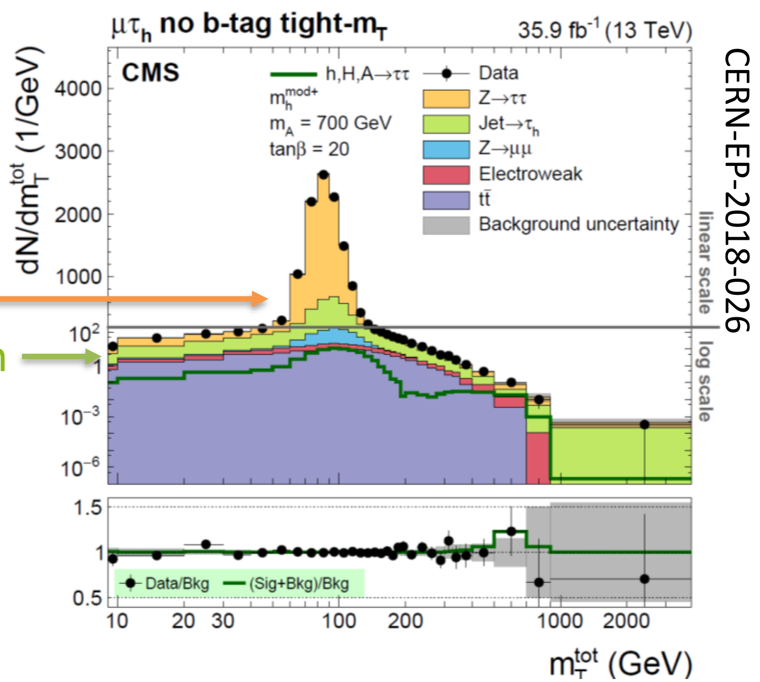
$\tau\tau \rightarrow 2\ell, \ell j, jj$

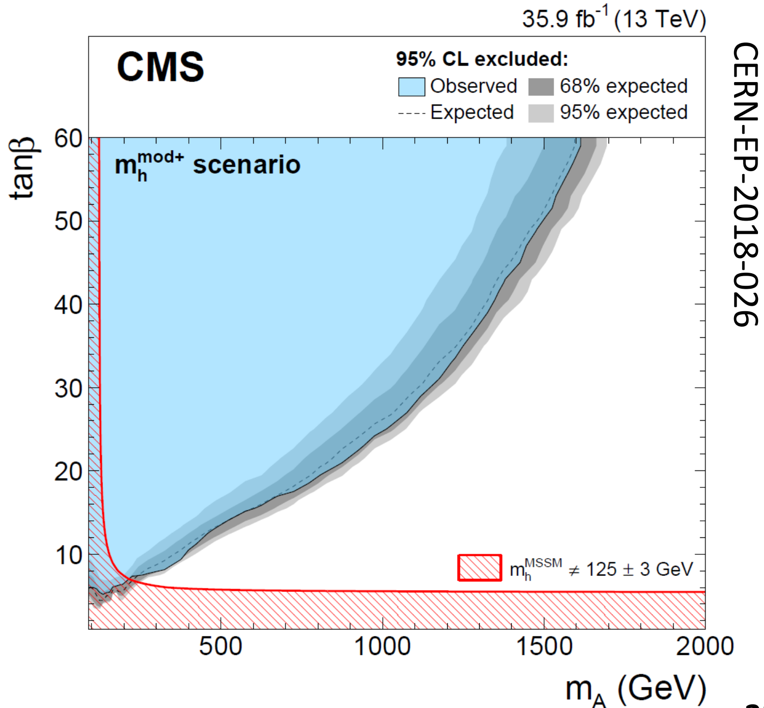
- Final discriminating variable: transverse mass

$$m_{\mathrm{T}}^{\mathrm{tot}} = \sqrt{m_{\mathrm{T}}^2(p_{\mathrm{T}}^{\tau_1}, p_{\mathrm{T}}^{\tau_2}) + m_{\mathrm{T}}^2(p_{\mathrm{T}}^{\tau_1}, p_{\mathrm{T}}^{\mathrm{miss}}) + m_{\mathrm{T}}^2(p_{\mathrm{T}}^{\tau_2}, p_{\mathrm{T}}^{\mathrm{miss}})} \qquad m_{\mathrm{T}} = \sqrt{2\, p_{\mathrm{T}}\, p_{\mathrm{T}}' \,[1 - \cos(\Delta\phi)]}.$$

MC normalized from CR

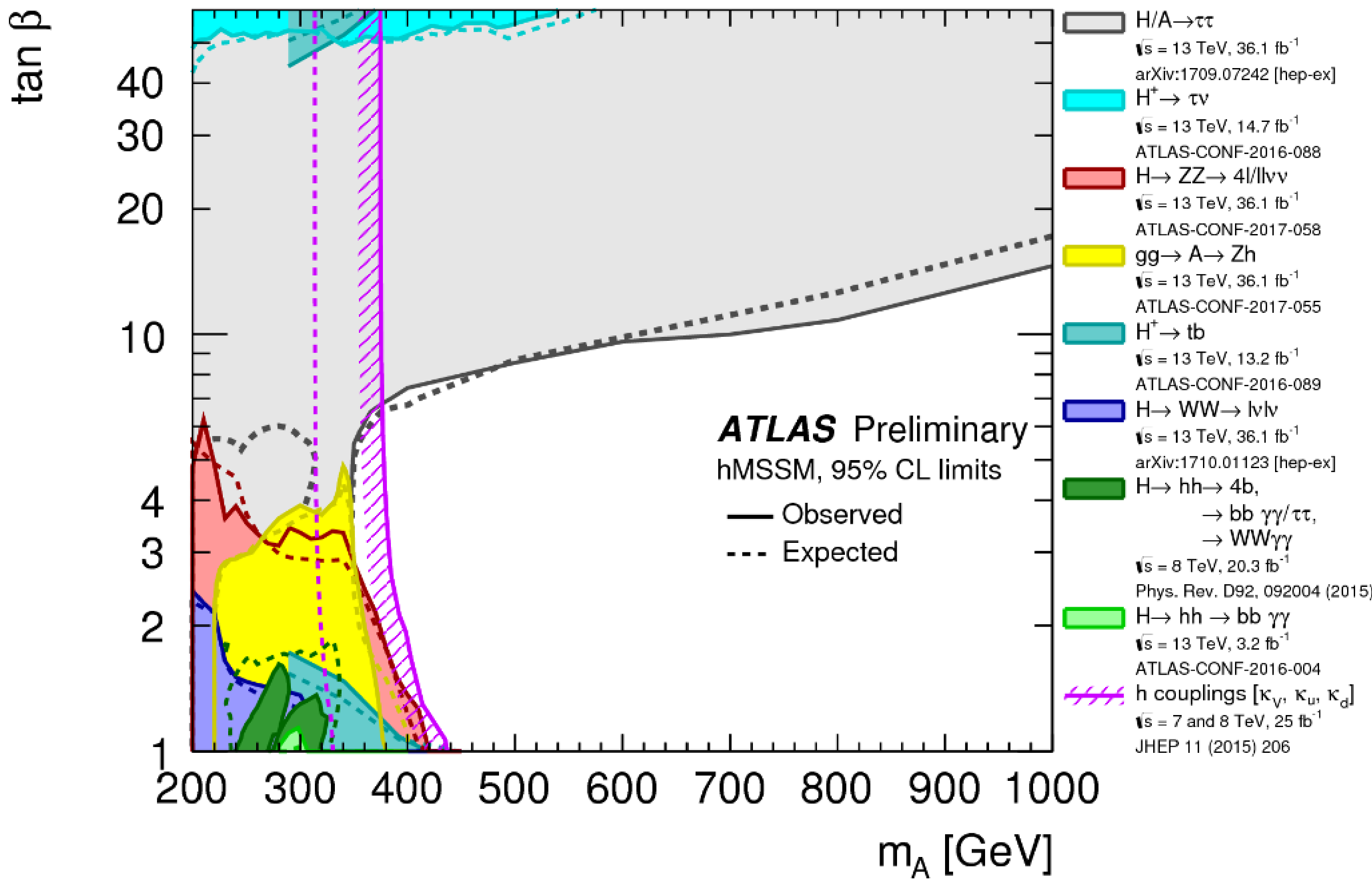
Data-driven method





Neutral Higgs to fermions

ττ → $2\ell, \ell j, jj$



Neutral Heavy Higgs to bosons & fermions

ATLAS

- WV→ $\ell\nu qq$, $\ell\nu\ell\nu$
- ZV → $\ell\ell qq$ /$\nu\nu qq$
- ZZ → 4ℓ, $\ell\ell\nu\nu$
- VV→ 2j
- Z/Wh (w h→bb)
- ZH → (H→bb)
- γZ
- γγ
- ττ → $2\ell, \ell j, jj$
- tt
- 4γ
- WH
- bb

CMS

- ZZ → 4ℓ, $\ell\ell qq$, $\ell\ell\nu\nu$
- γZ
- bb
- ττ → $2\ell, \ell j, jj$
- Zh→ $\ell\ell\tau\tau$
- Zh→ $\ell\ell bb$
- ZA/H →$\ell\ell bb$
- $\gamma\gamma$
- $\mu\mu$
- $\tau\tau$

Neutral Higgs to di-Higgs

ATLAS

- hh → bb$\gamma\gamma$
- hh → 4b
- hh → WW$\gamma\gamma$
- hh → bb$\tau\tau$

CMS

- **hh → bb$\gamma\gamma$**
- hh → 4b
- hh→ WW/ZZ +2b
- hh → bb$\tau\tau$
- hh→ $\ell\ell\gamma\gamma$

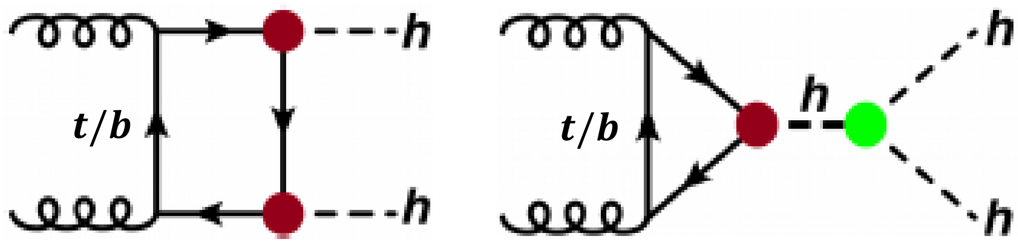
Legend

~36 fb^{-1}	@13 TeV
15-20 fb^{-1}	@13 TeV
5fb^{-1}	@13 TeV
5-20.3fb^{-1}	@7-8 TeV

Legend

Why these channels?

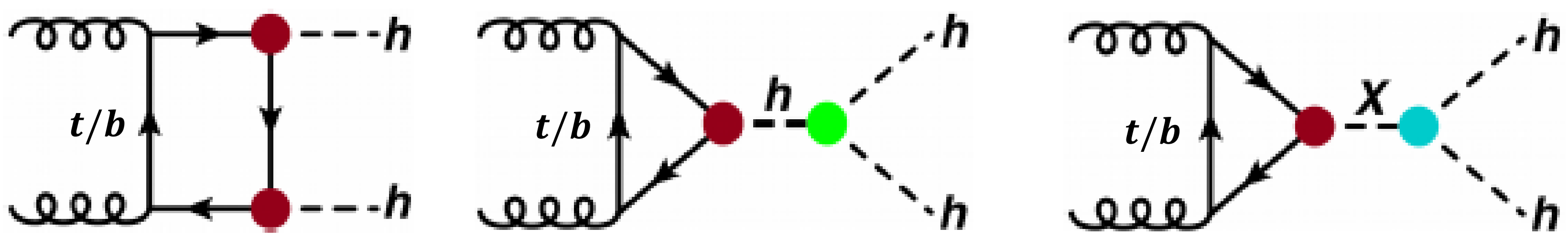
SM Di-Higgs production much lower than single Higgs production



hh → bbγγ

Why this channel?

SM Di-Higgs production much lower than single Higgs production



Di-Higgs production enhanced in BSM models

- Resonant production: 2HDM, radion, G_{kk^*}
- Non resonant production: modified h coupling

- **hh → bbγγ:** low background, good mass resolution

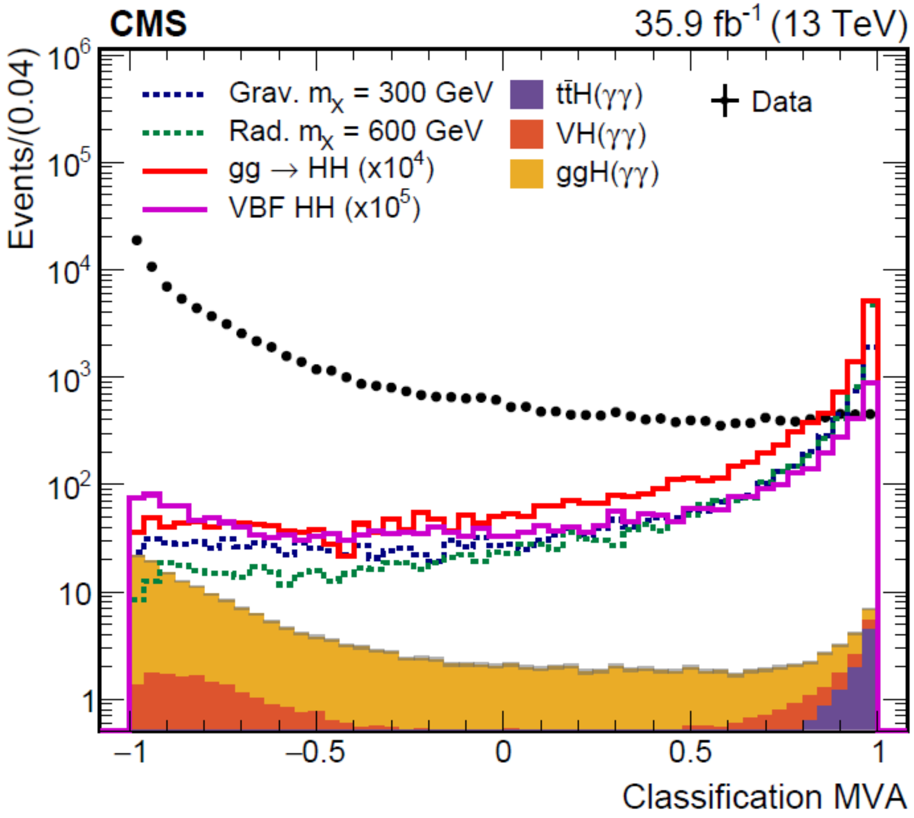
BR	bb	WW
bb	33%	
WW	25%	4.6%
$\tau\tau$	7.4%	2.5%
ZZ	3.1%	1.2%
$\gamma\gamma$	**0.26%**	0.10%

Neutral Higgs to di-Higgs

hh → bbγγ

- To separate different SRs for better sensitivity use Multivariate analysis (MVA)

- Inputs: inputs are b-tagging variables, helicity angles, $p_{\gamma\gamma\,T}/m_{\gamma\gamma jj}$, $p_{jjT}/m_{\gamma\gamma jj}$

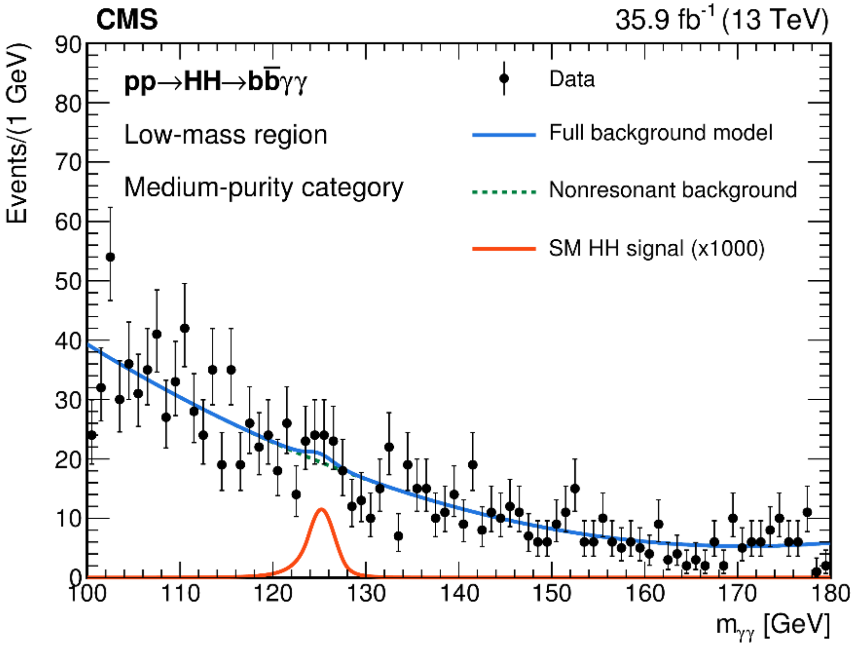


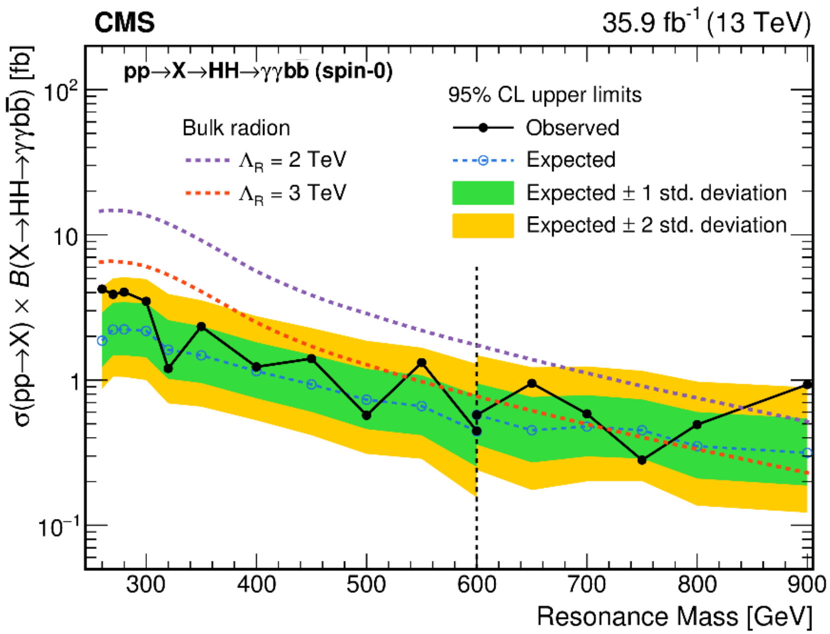
CERN-EP-2017-343

Neutral Higgs to di-Higgs

hh → bbγγ

- Background: γ +jets described using Bernstein polynomials
- Signal obtained by fitting MC in $m_{jj} - m_{\gamma\gamma}$ plane





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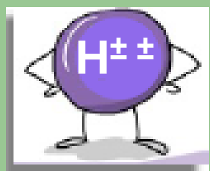
Non resonant production < 24 x SM observed

Charged Higgs



ATLAS

- $H^{\pm} \rightarrow \tau\nu$
- $H^{\pm} \rightarrow tb$
- $H^{\pm\pm} \rightarrow \ell\ell$
- $H^{\pm} \rightarrow cs$
- VBF $H^{\pm} \rightarrow WZ$

CMS

- $H^{\pm} \rightarrow \tau\nu$
- $H^{\pm} \rightarrow tb$
- $H^{\pm} \rightarrow ZW$
- $H^{\pm} \rightarrow cs$
- $H^{\pm\pm} \rightarrow 4\ell/3\ell\nu$

~36 fb^{-1}	@13 TeV
15-20 fb^{-1}	@13 TeV
5fb^{-1}	@13 TeV
5-20.3fb^{-1}	@7-8 TeV

Legend

Higgs exotic with MET

ATLAS

- H $\rightarrow \gamma\gamma$+MET
- H $\rightarrow$ bb+MET
- hZ $\rightarrow$ INV $(\ell\ell)$
- H $\rightarrow Z_d Z_d$
- H $\rightarrow$ Z $(\ell\ell)$+MET
- VBF h $\rightarrow$ INV
- hV$\rightarrow$ INV (had)
- H $\rightarrow \gamma$+MET
- H$\rightarrow$ INV (1 jet)

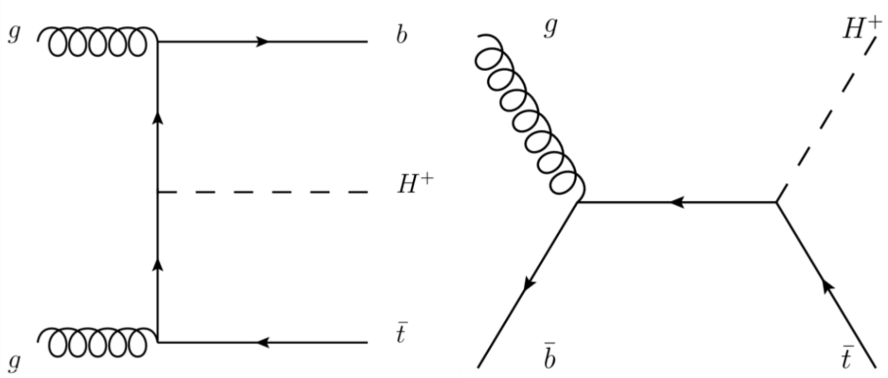
CMS

- hZ $\rightarrow$ INV $(\ell\ell/bb)$
- hZ $\rightarrow$ INV $+1/2\gamma$
- hj $\rightarrow$ INV +j

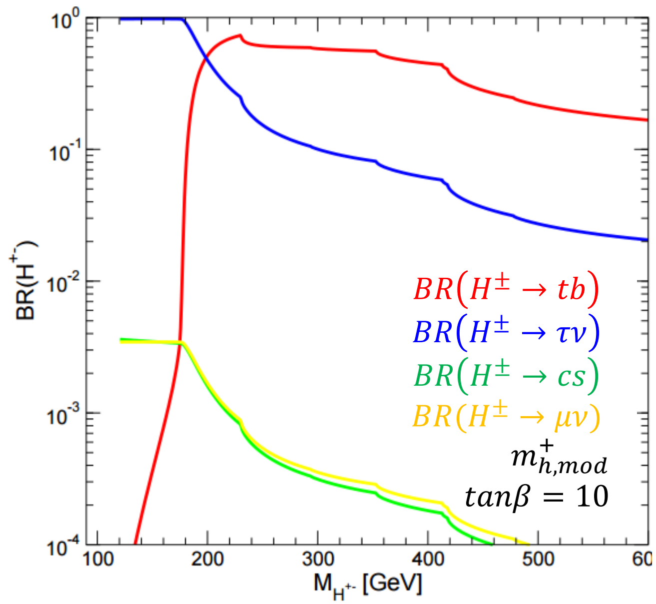
$H^{\pm} \rightarrow \tau\nu$
$H^{\pm} \rightarrow tb$

Why these channels?

- $H^{\pm}$ is in doublet/triplet models
- For $m_{H^{\pm}} > (<)\ m_{top}$, $H^{\pm}$ produced with $t\ (b)$
- $H^{\pm}$ to τν (tb) dominates below (above) top threshold
- ATLAS Run 1: $H^{\pm} \rightarrow tb$ analysis excess of (2.4 σ)
- Test hMSSM and $m_{h,mod}^{\pm}$



4-flavour scheme 5-flavour scheme



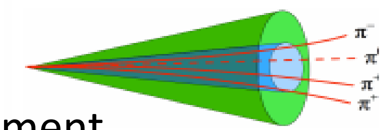
Heavy Charged Higgs

$H^{\pm}$ → τν

- Background: jets/leptons misidentified as τ estimated using Fake Factors

SR – real τ_h

Tight BDT requirement



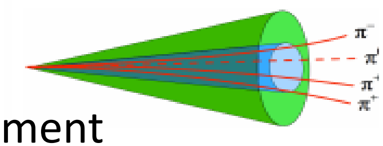
To identify τ

- Find jet, match 1 or 3 tracks to it
- Boosted Decision Tree (BDT) - separate τ from jets that resemble τ using info on hadronic activity
- Likely-hood based veto separates τ from e

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

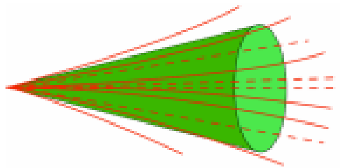
- Background: jets/leptons misidentified as τ estimated using Fake Factors

SR – real τ_h



Tight BDT requirement

Region with jets that resemble (anti-τ_h)



Loose BDT requirement

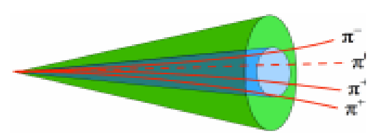
F = **probability of jet faking τ**

Heavy
Charged Higgs

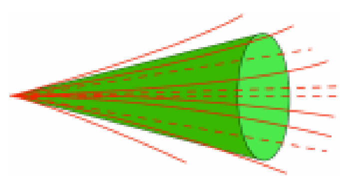
$H^{\pm} \rightarrow \tau\nu$

- Background: jets/leptons misidentified as τ estimated using Fake Factors

SR – real τ_h



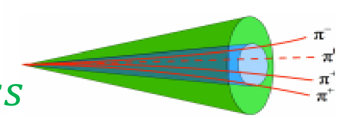
Region with jets that resemble (anti-τ_h)

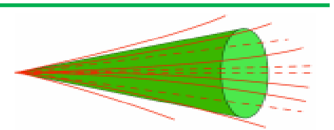


$$F = F_{multi-j} + F_{W+j}$$

Multi-jet region (g-initiated)

$$F_{multi-j} = \frac{N_{pass}}{N_{fail}}$$





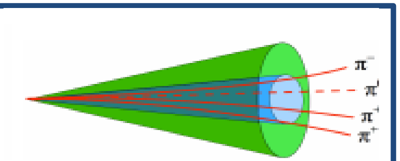
W+jets region (q-initiated)

F_{W+j}

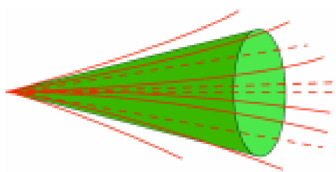
$H^{\pm} \to \tau\nu$

- Background: jets/leptons misidentified as τ estimated using Fake Factors

SR – real τ_h



Region with jets that resemble (anti-τ_h)



$\alpha_{multi-j} f_{multi-j} + \alpha_{W+j} f_{w+j}$

$$\boldsymbol{F} = \alpha_{multi-j} F_{multi-j} + \alpha_{W+j} F_{W+j}$$

Multi-jet region (g-initiated)

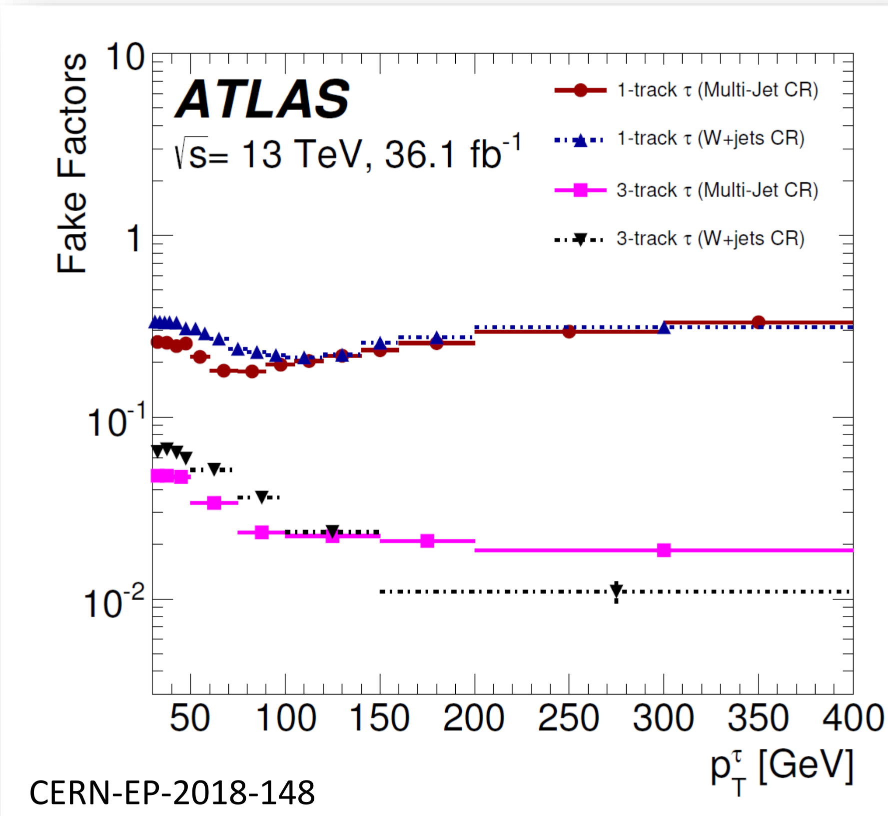
$f_{multi-j} = \frac{N_g}{N_g+N_q}$, template fit in BDT(3p), tau width (1p)

W+jets region (q-initiated)

f_{w+j}

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

- Background: jets/leptons misidentified as τ estimated using Fake Factors



$$F = \alpha_{multi-j} F_{multi-j} + \alpha_{W+j} F_{W+j}$$

$f_{multi-j} = \frac{\quad}{N_g+N_q}$, template fit

in BDT(3p), tau width (1p)

+jets region (q-initiated)

f_{W+j}

Heavy Charged Higgs

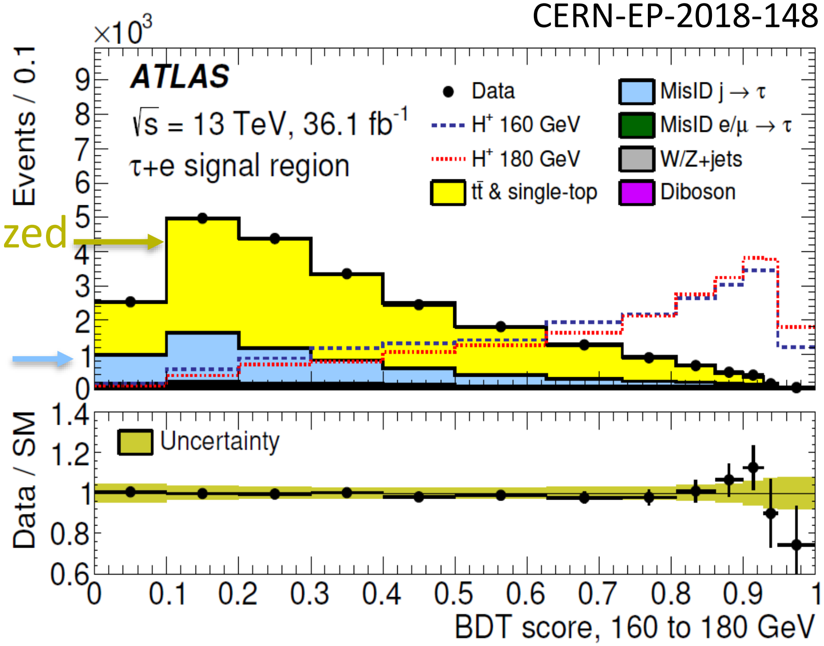
$H^{\pm} \rightarrow \tau\nu$
$H^{\pm} \rightarrow tb$

- BDT is discriminating variable
  - Inputs: transverse mass, missing transverse energy, momentum of objects, separation between objects

CERN-EP-2018-148

MC normalized from CR

Fake-factor method



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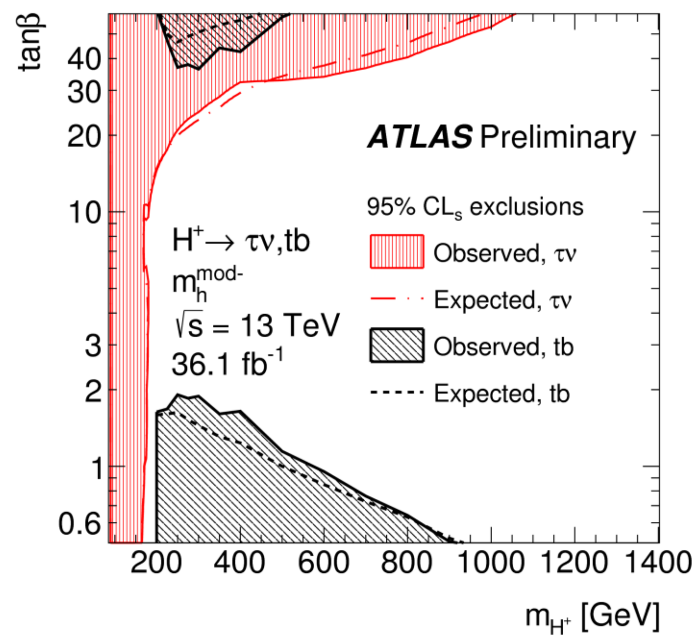
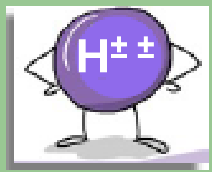


$H^{\pm} \rightarrow tb$ analysis excess went away

Charged Higgs



ATLAS

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- $H^{\pm} \rightarrow tb$
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- VBF $H^{\pm} \rightarrow WZ$

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~36 fb^{-1}	@13 TeV
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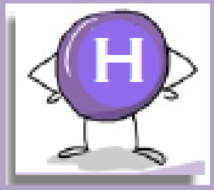
Legend

Higgs exotic with MET



ATLAS

- H → $\gamma\gamma$+MET
- H → bb+MET
- hZ → INV ($\ell\ell$)
- **H → $Z_d Z_d$**
- H → Z ($\ell\ell$)+MET
- VBF h → INV
- hV→ INV (had)
- H → γ+MET
- H→ INV (1 jet)

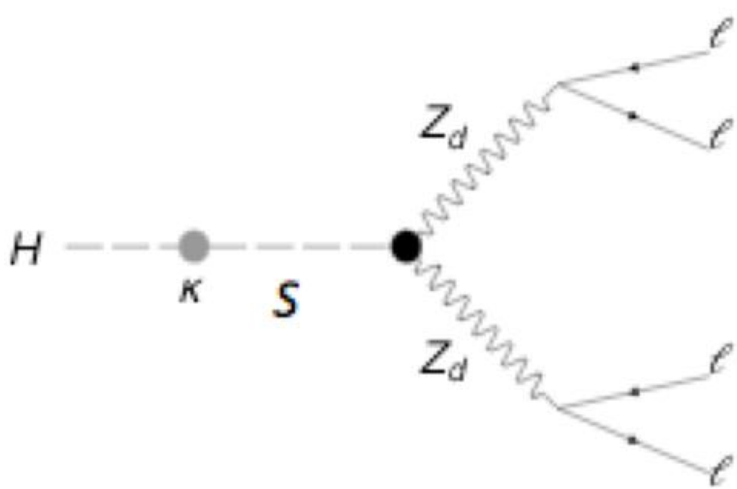
CMS

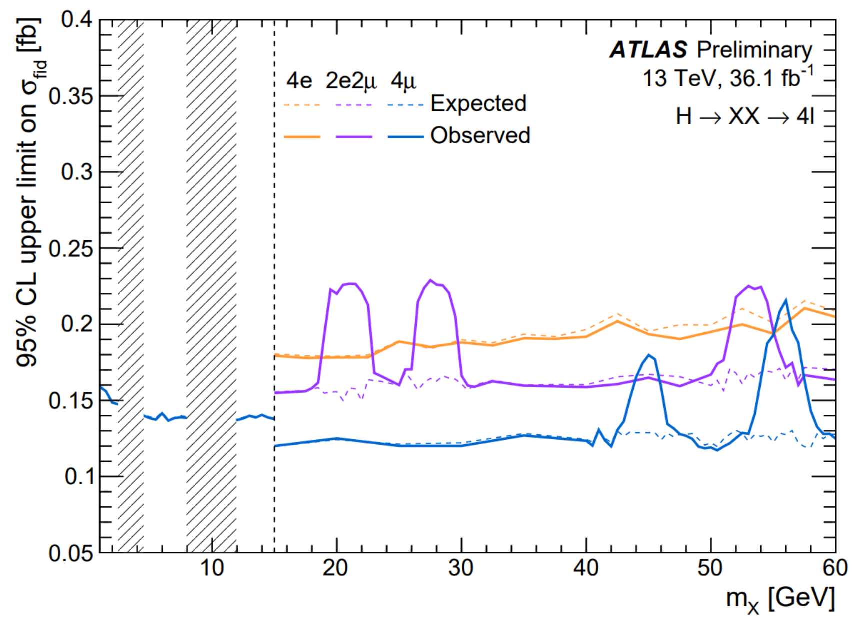
- hZ → INV ($\ell\ell/bb$)
- hZ → INV +$1/2\gamma$
- hj → INV +j

Higgs exotic with MET

h(125)→ aa/$Z_{dark}Z_{dark}$

- Look for 2HDM H→ aa process
- Dark sector in SM extensions provides DM candidate, explains positron excesses
- 4ℓ final states have low background. Optimize for different mass regions





Rare decays/ LVF

ATLAS

h(125) → $\phi/\rho\gamma$
h(Z) → J/ψγ or ψ/(2S) or Υ(nS)

h → τμ / τe / eμ

CMS

h → τμ

Higgs to light res.

ATLAS

aa → $jj\gamma\gamma$
aa → bb$\mu\mu$
aa → 4b

aa → μμττ

CMS

aa → μμττ
aa → $bb\tau\tau$

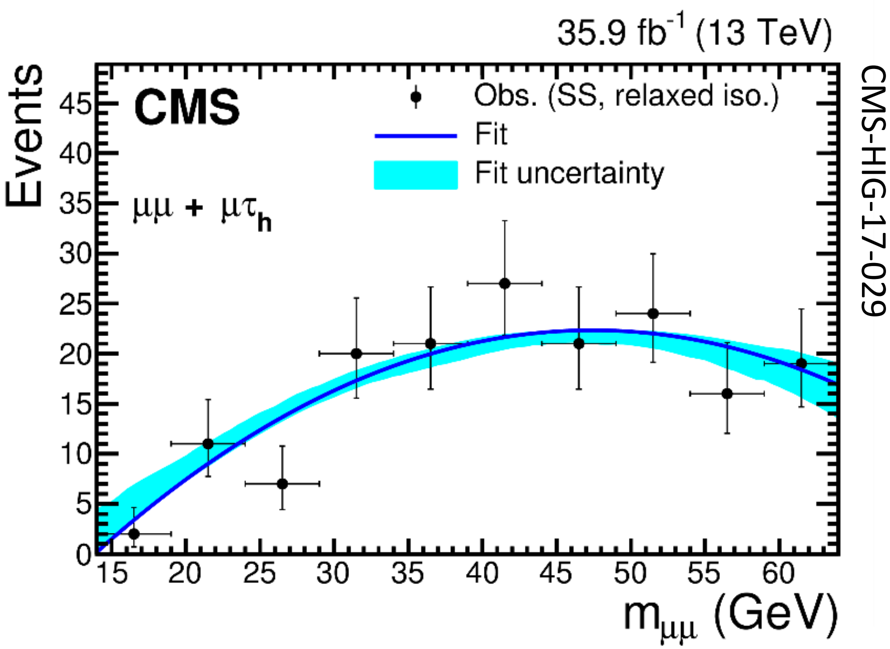
aa →$4\tau, \mu\mu bb, \mu\mu\tau\tau$
aa →4μ

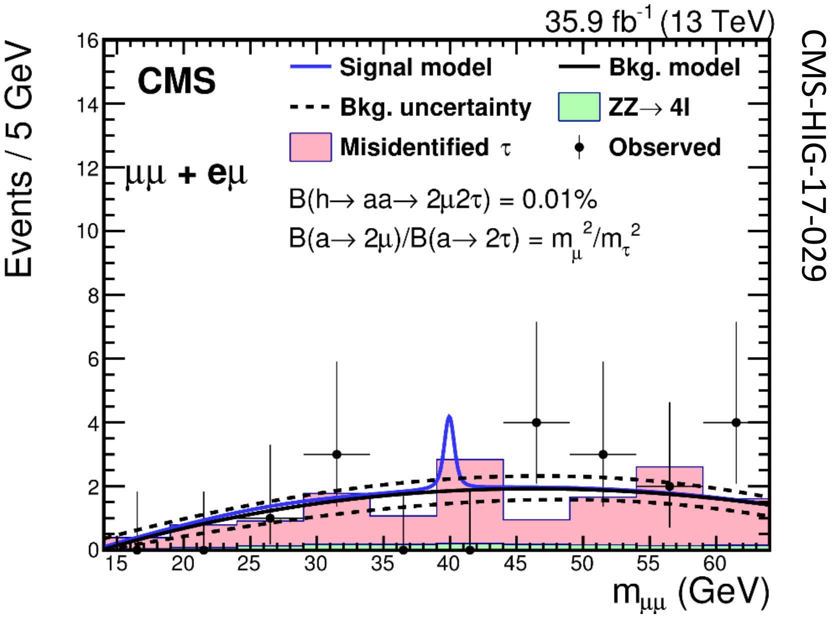
~36 fb^{-1}	@13 TeV
15-20 fb^{-1}	@13 TeV
5fb^{-1}	@13 TeV
5-20.3fb^{-1}	@7-8 TeV

Legend

Higgs to light res aa → $\mu\mu\tau\tau$

- Main background: Jets misidentified as τ estimated from CR
- Signal and background parameterized by different functions (Voigt/ Gaussian, Bernstein polynomials)
- Fit to in dimuon mass (excellent resolution!)





Conclusions

- Many ATLAS & CMS searches for beyond Standard Model physics were explored
- No discoveries yet of BSM Higgs sector
- Significant excesses not found, but many stringent limits set in several models