Search for high mass Higgs boson production in final states with b-quarks with the LHC Run II data with CMS

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DESY, CMS

LHC physics discussion

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Motivation for the BSM Higgs searches

- **13 TeV** measurements so far indicate **consistency of** the **h(125)** with the Standard Model (**SM**)
- However, several phenomena are not explained by the SM:
  - Dark matter and energy, gravity, neutrino masses…

BSM

- h(125) well may be only one member of an **extended Higgs Sector:**
  - direct searches for **Heavy Higgs** bosons to check this!
- **Heavy neutral Higgs** bosons predicted by several **BSM** extensions:

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BSM

- h(125) well may be only one member of an **extended Higgs Sector:**
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- **Heavy neutral Higgs** bosons predicted by several **BSM** extensions:

2HDM | **MSSM**

Two Higgs Doublet Model (2HDM)

- Higgs sector of CP-conserving **Two Higgs Doublet Model** (2HDM):

2 doublets	CP-even	CP-odd	Charged
Φ_2 Φ_1	h, H	A	$H^{\pm}$

(h, H, A) ≡ ϕ

- **tan β** - ratio of vacuum expectation values ;
- **α** - **mixing** angle between h and H

\+ *other parameters*

- **4 types of 2HDM** with natural flavour and CP conservation, depending on how the 2 Higgs doublet fields couple to SM particles

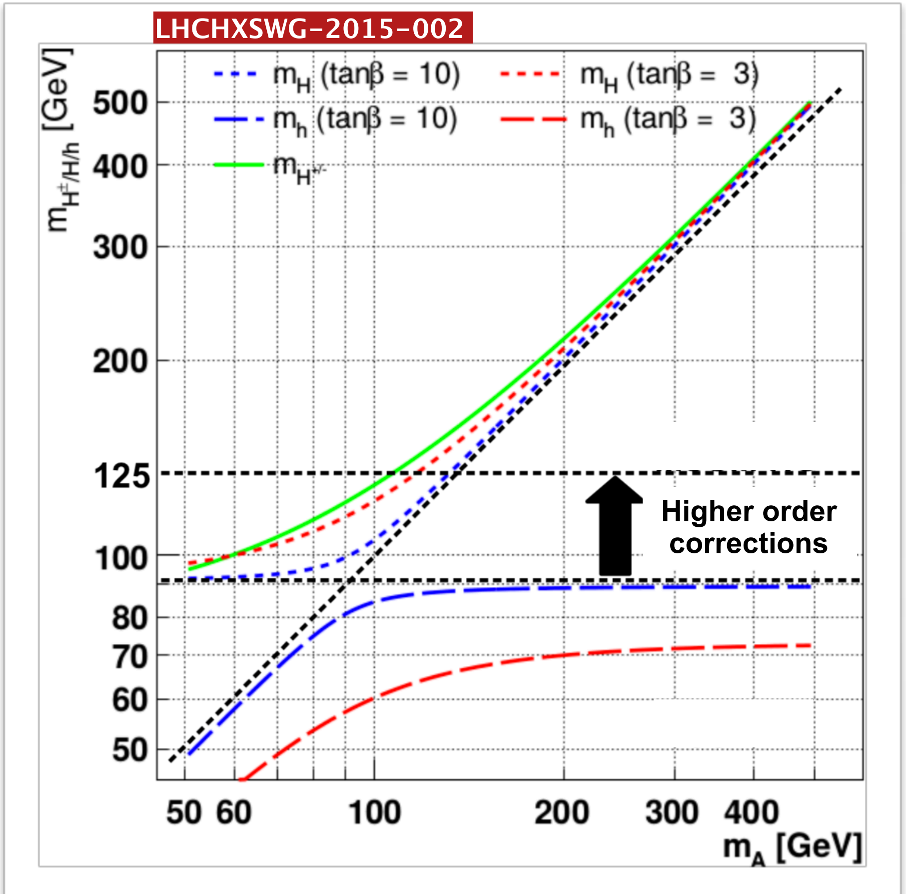
Type I | Flipped | Lepton Specific | Type II

u - (u,c,t)
d - (d,s,b)
ℓ - (e,μ,τ)

all fermion couples to one Higgs boson | quark v.s. lepton | up v.s. down

Minimal Supersymmetric Standard Model (MSSM)

- Two complex Higgs doublets as in **2HDM Type II**, **+** additional constraints from **SUSY**
  - **Two parameters at tree-level**:
    - **m_A** and **tanβ**



$$m^2_{H^\pm} = m^2_A + m^2_W$$

$$m^2_{H,h} = \frac{1}{2}(m^2_A + m^2_Z \pm \sqrt{(m^2_A + m^2_Z)^2 - 4m^2_A m^2_Z cos^2 2\beta})$$

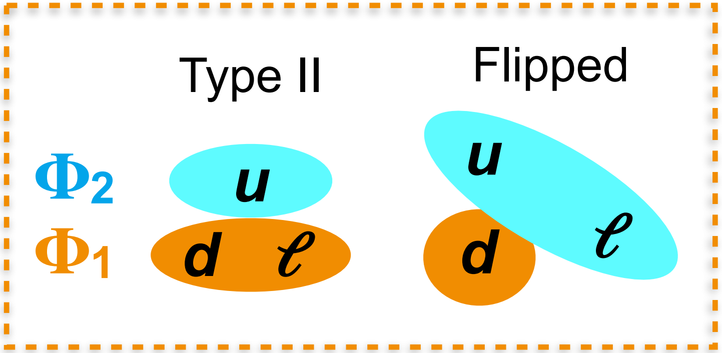
$$tan\alpha = \frac{-(m^2_A + m^2_Z)sin2\beta}{(m^2_Z - m^2_A)cos2\beta + \sqrt{(m^2_A + m^2_Z)^2 - 4m^2_A m^2_Z cos^2 2\beta}}$$

- MSSM **features:**
  - Solve **hierarchy** problem
  - introduce **dark-matter candidate**
- **Compatibility with h(125)** achieved by the HO corrections:
  - **m_h increased** up to 30%
- Variety of **benchmark scenarios** to test different phase-space properties:
  - m_h^{mod+}; low-$\tilde{\tau}$, low-$\tilde{t}$, hMSSM*…

* - M. Carena et al.

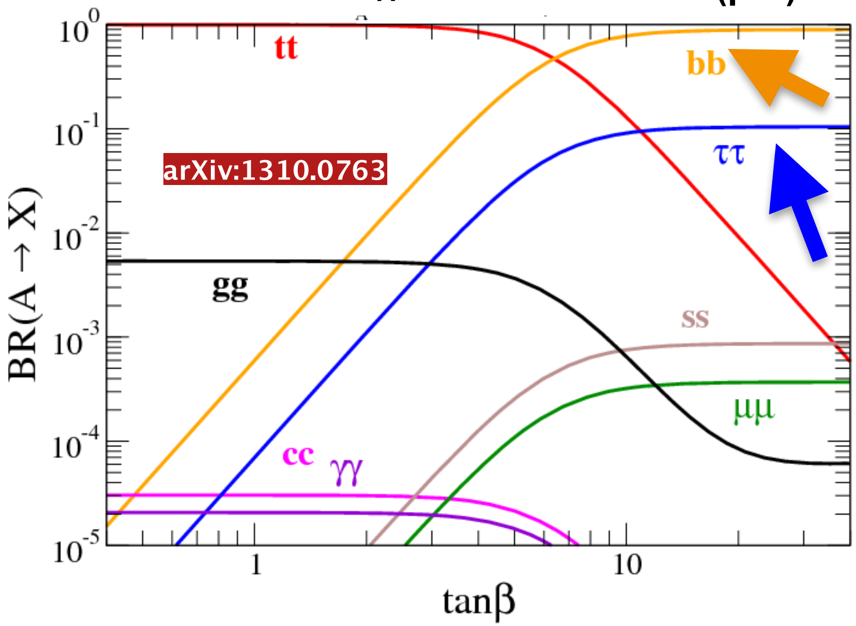
Heavy Higgs bosons and b-couplings

- **Enhanced b-couplings** in various scenarios within 2HDM and MSSM:
- Moreover in **Flipped** scenario **leptons** are **dis-favored**:
  - $A/H \rightarrow \tau\tau$ decay is suppressed
  - **2 decay channels dominate** at high tanβ: $A/H \rightarrow b\bar{b}$, $A \rightarrow Zh$(not shown here)



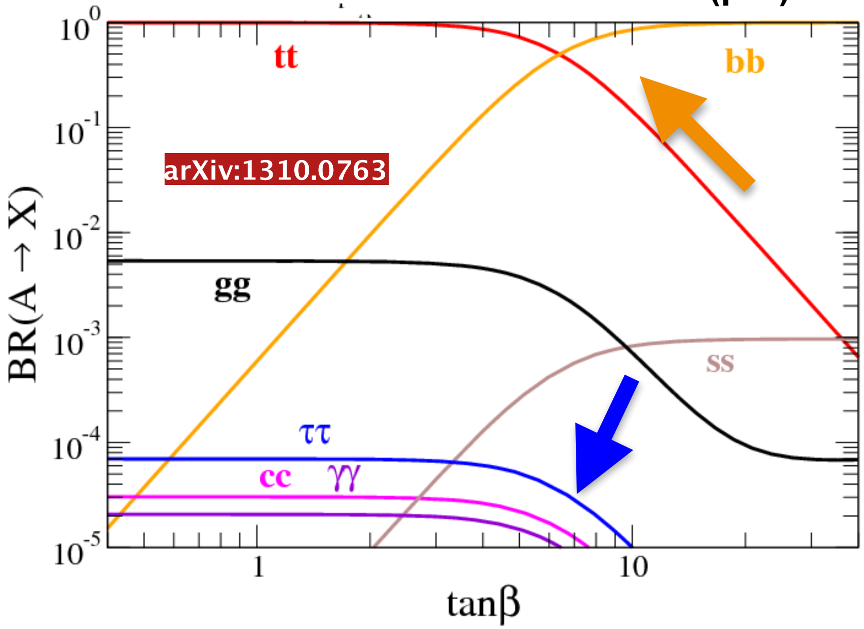
Type-II

A boson **m_A = 400 GeV** **cos(β-α) = 0**



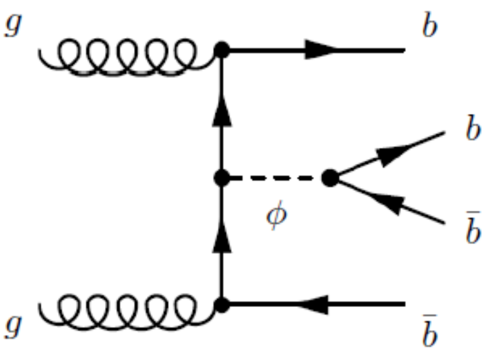
Flipped

A boson **m_A = 400 GeV** **cos(β-α) = 0**

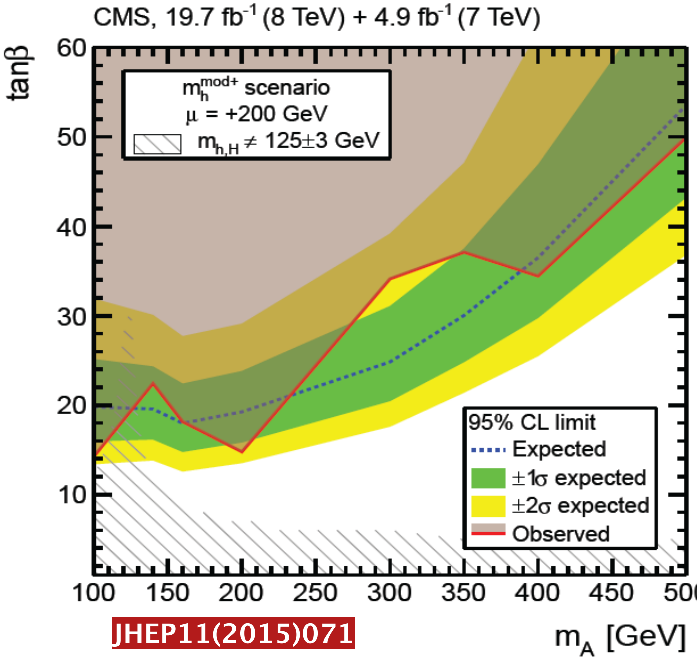


Acknowledgments: Stefan Liebler, Oscar Stal

$b\bar{b}$A/H, A/H→$b\bar{b}$ Analysis



- Search for the **b-associated** production of **degenerate H** and **A** in higher mass region:
  - **cross-section enhanced** by up to ~ $2\tan^2\beta$ both in MSSM and 2HDM models;
  - improved **background control**
- **Unique** analysis **at LHC**
- 7+8 TeV analysis achieved best sensitivity in this channel to date:
  - improve further with 13 TeV data

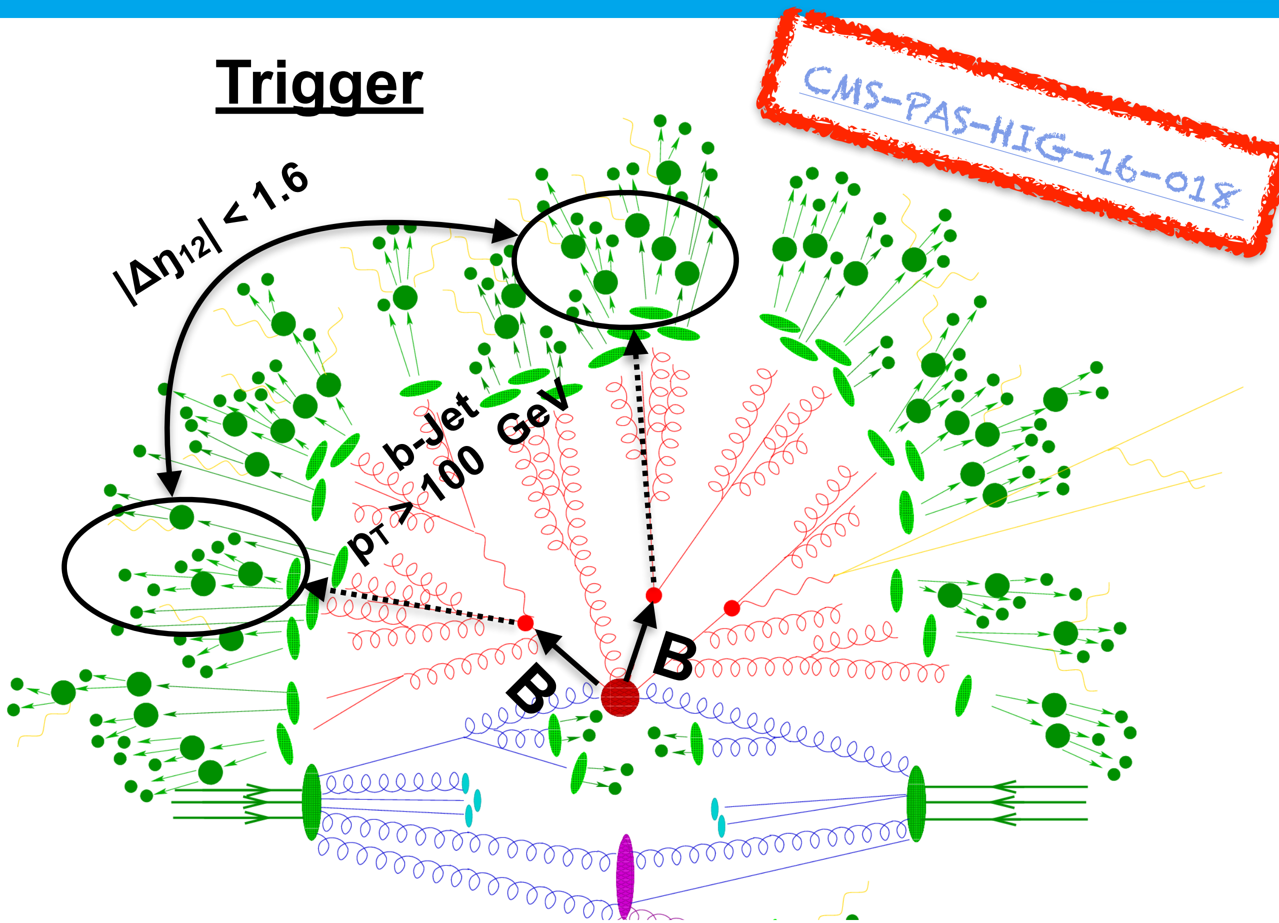


JHEP11(2015)071

13 TeV analysis overview: trigger

Trigger

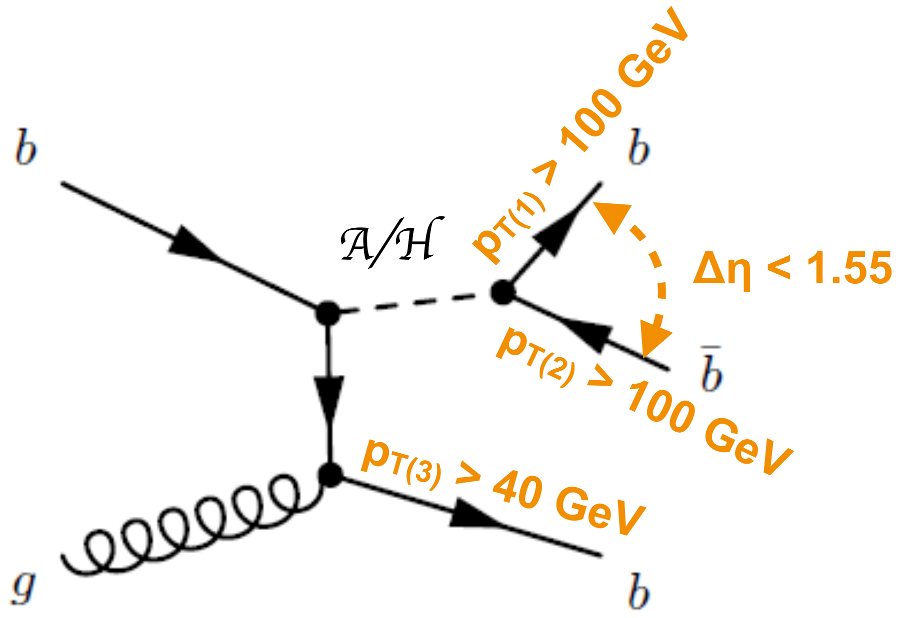
- **Main challenge**: huge background rate from **QCD multi jet** production
- Dedicated **high p_T double b-jet** trigger developed **at DESY**
- **Collected:**
  - 2016 pp at 13 TeV
  - $\int L\, dt$: 35.7 fb^{-1}



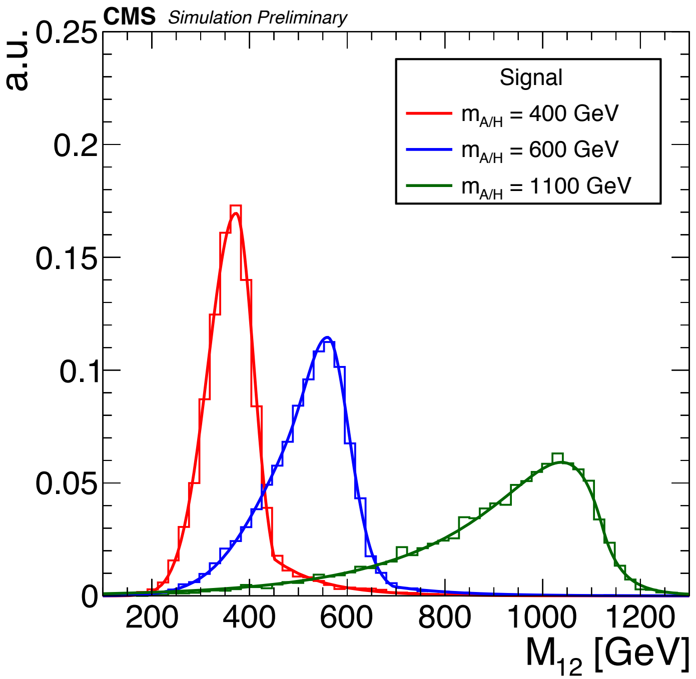
Impact on the analysis	
Double jet with p_T > 100 GeV	limit sensitivity for low $M_{A/H}$
$\|\Delta\eta_{12}\|$ < 1.6	better S vs Bg separation
double b-jet	reduce non $b\bar{b}$ background

13 TeV analysis overview: selection

✱ **Signal** reconstructed **from** the invariant mass of the **two leading b-jets** (M_{12})



Expected Signal Shape



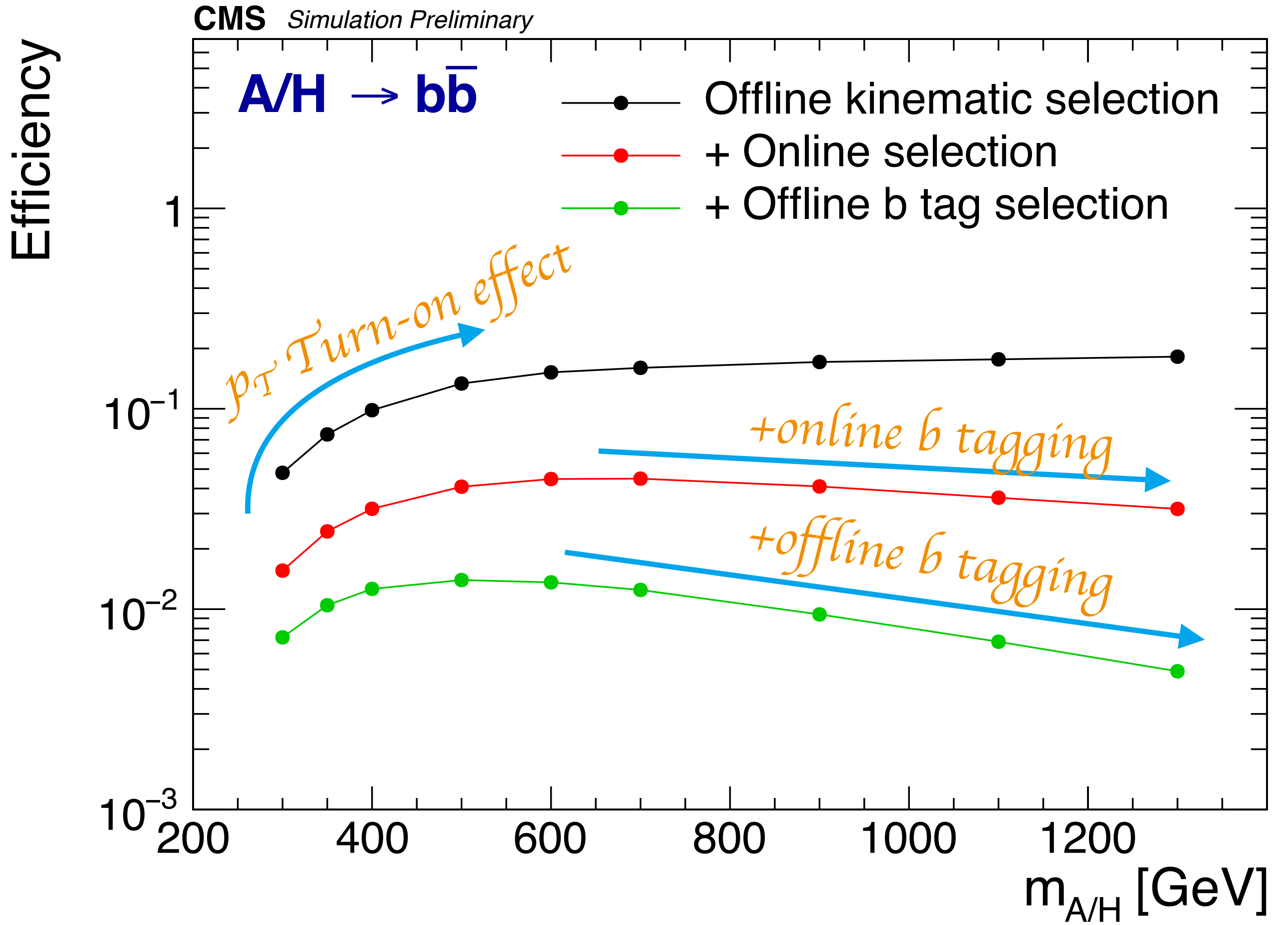
✱Monte Carlo: Pythia 8 LO + MG5 NLO for the corrections

✱Signal masses: $M_{A/H}$ = [300;1300]

- ✱**Sensitive** starting **from $M_{A/H}$ = 300 GeV**, because of the high p_T trigger threshold

Signal Efficiency

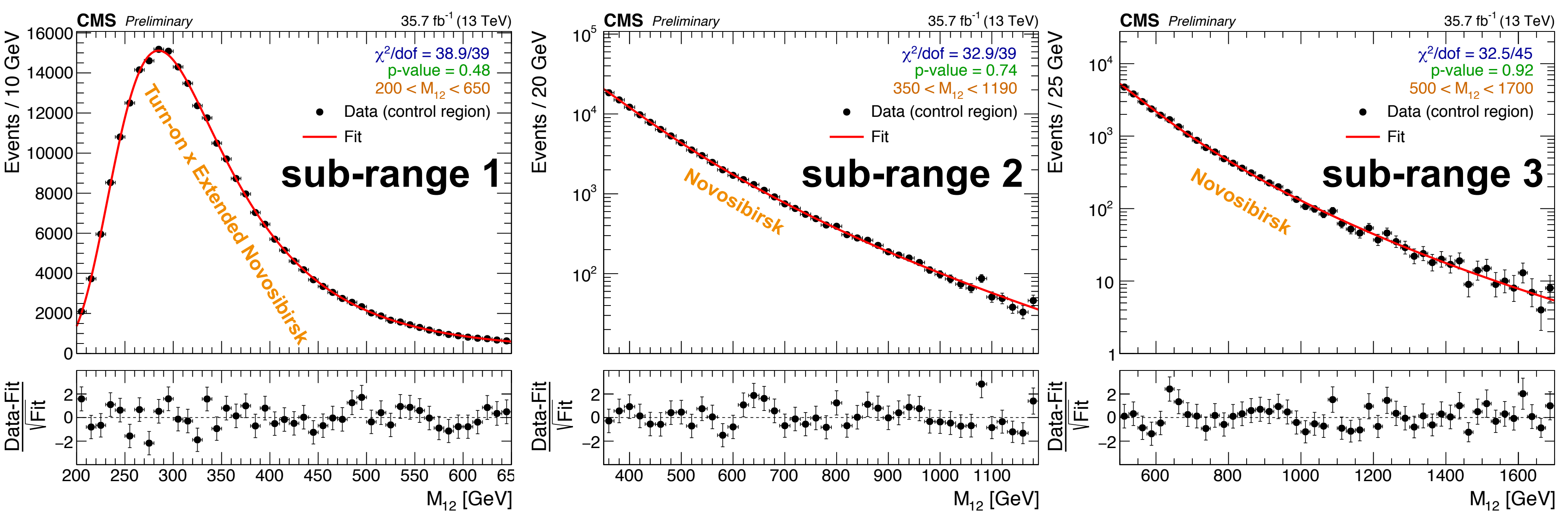
- Effect of the trigger p_T turn-on and triple b tagging



- **Efficiency** up to **1.5%** at 500 GeV mass point

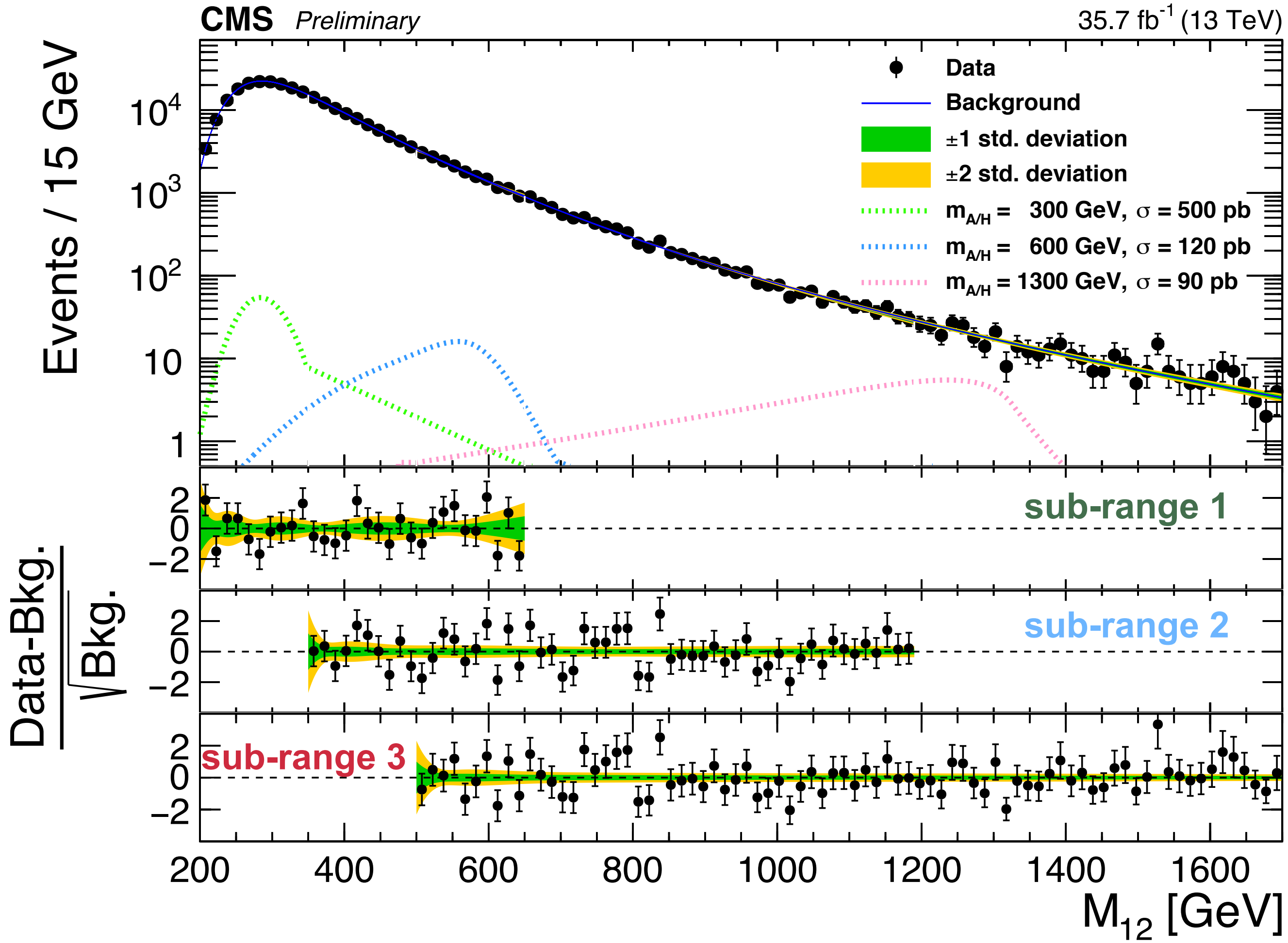
Background estimation: control region

- Model multi jet background using **analytical function**
- **Blinded analysis** → strategy and techniques developed and validated at **control region**
- Find **control region** with a shape of M_{12} similar to the signal region
    - Defined by events in which the **3rd jet is light flavour**
- Main **challenge**:
    - **precise fit** of a **large mass range** including the **background peak region**
- **Divide M_{12}** range into 3 **sub-ranges** to reduce the bias from the choice of the function and simplify the fitting procedure



Background estimation: signal region

- Parameters of the background pdfs allowed to change between CR and SR:
- **Data** is **well fitted** with functions developed in the CR
- **No excess** found → compute **U**pper **L**imits



Systematic uncertainties

- **UL** are calculated using the **profile likelihood method** with systematic uncertainties addressed by the nuisance parameters

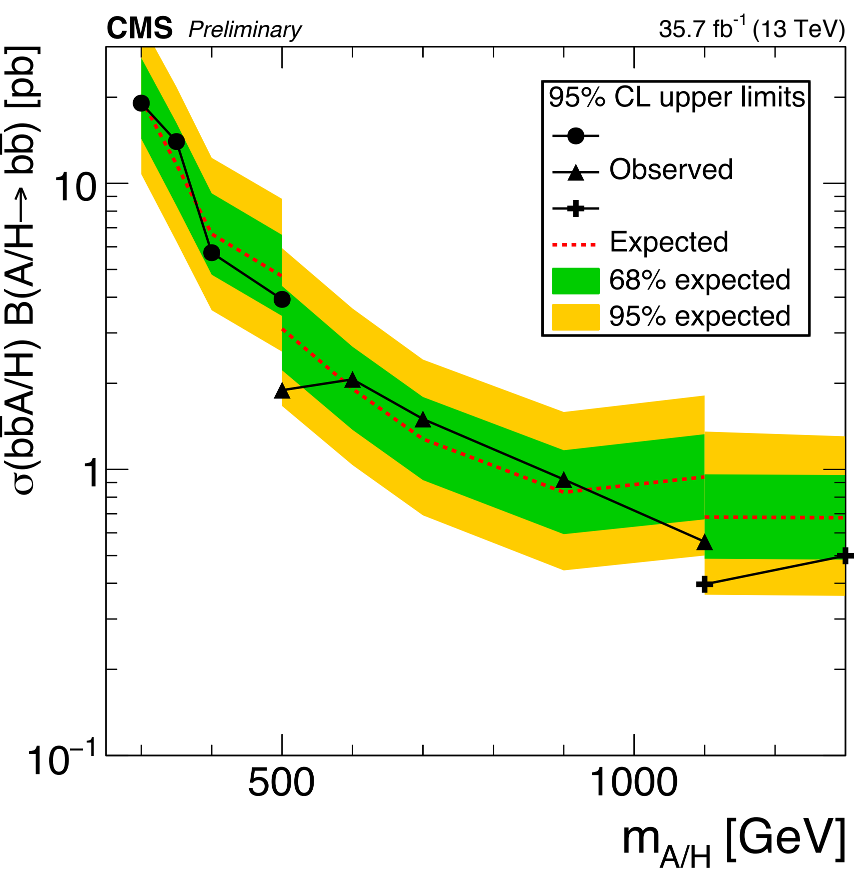
systematic uncertainties	Size	
kinematic trigger efficiency, p/jet	0 - 7 %	} *dominant*
jet energy scale / resolution, p/jet	1 - 6 %	
b-tag efficiency(b/c), p/jet	2 - 5 %	
b-tag efficiency(udsg), p/jet	< 0.3 %	
pileup	4,6 %	
luminosity	2,5 %	
online b-tag efficiency, p/jet	0.8-1.3 %	
background specific, p/sub-range	100 %, 25 % ,20 % Δμ	*dominant*
pdf + α_s, mssm/2hdm cross-section	1 - 6 %	
QCD scale, mssm/2hdm cross-section	1 - 10 %	
NLO correction for the selection eff.	5 %	

- Systematic uncertainties:
  - **normalisation**: log-normal prior;
  - **shape**: gaussian prior.

Model independent upper limits

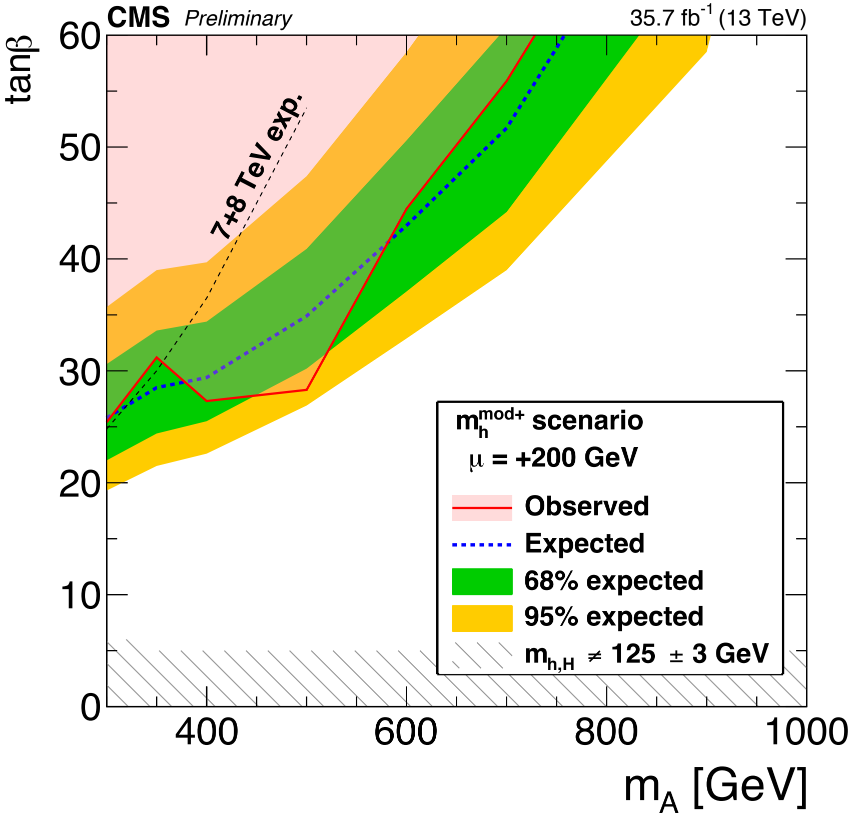
Main features

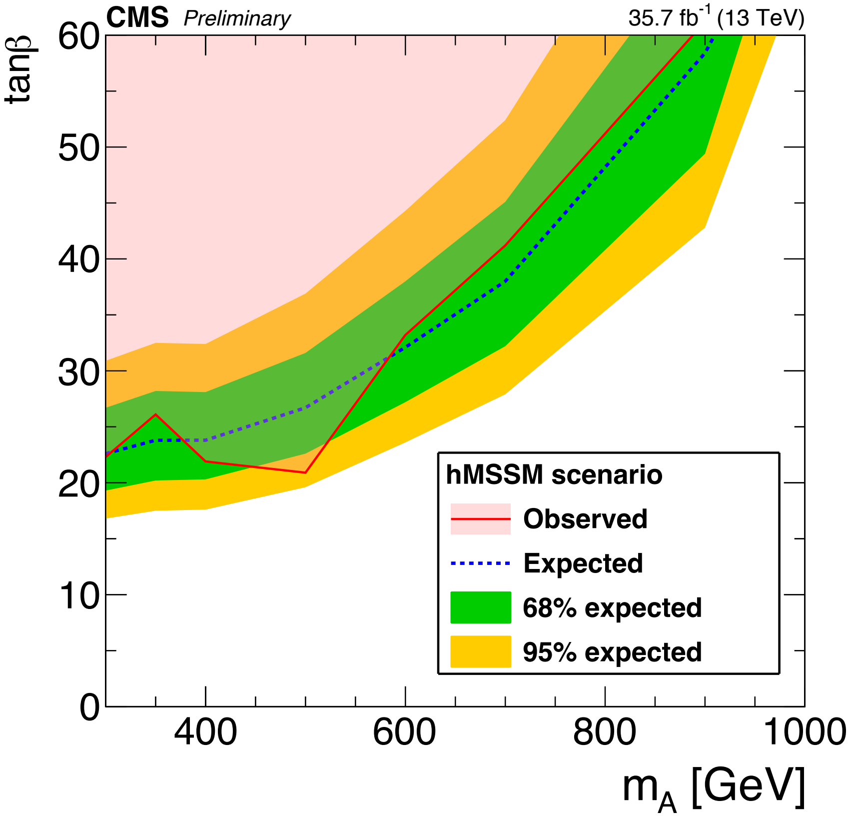
- Sensitivity up to 1300 GeV;
- Improved sensitivity from the sub-range optimisation:
  - steps in the expected limits



MSSM interpretation

- Observed **limits** are translated into exclusion limits **on MSSM** parameters - **tanβ** and **M_A**
- Interpretation within the **m_h^{mod+}** and **hMSSM** benchmark scenarios*.





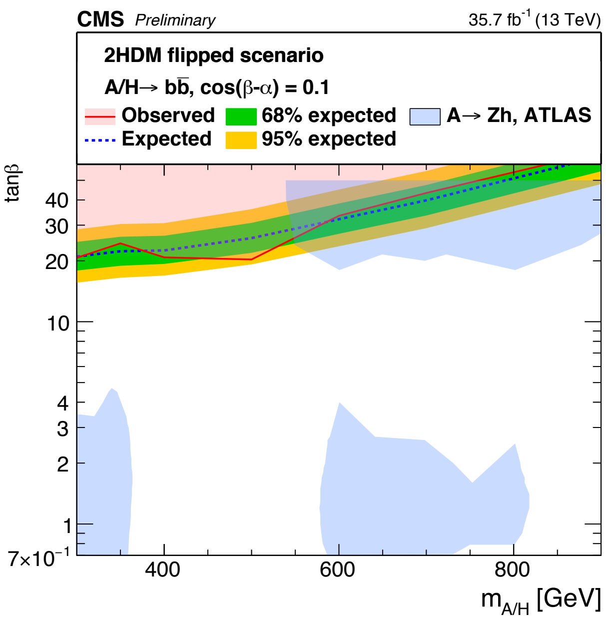
- In spite of higher trigger thresholds, 13 TeV limits for m_h^{mod+} are better than at 7 + 8 TeV everywhere except for the 300 GeV;
- **Now also hMSSM** interpretation: lower tanβ limits than m_h^{mod+} at large M_A

* - τ-phobic, light-$\tilde{t}$ and light-$\tilde{\tau}$ in the backup

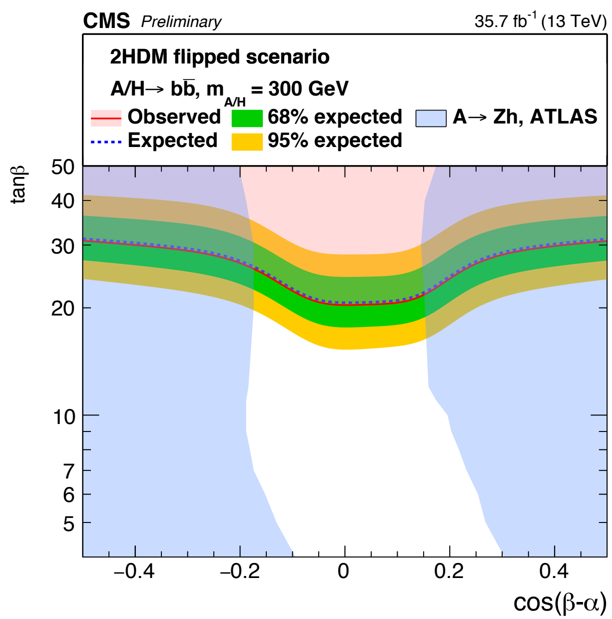
2HDM Interpretation: Flipped scenario

- **Exclusion limits** on **tanβ** vs **M_A** and **cos(β-α)** for 2HDM Flipped and Type-II models:
  - values of cos(β-α) = 0.1 and M_A = 300 GeV were chosen to compare with ATLAS A → Zh analysis [0]
- Our measurements are uniquely sensitive for high values of tanβ and **small |cos(β-α)|** (alignment limit):
  - this is where h couplings are SM-like

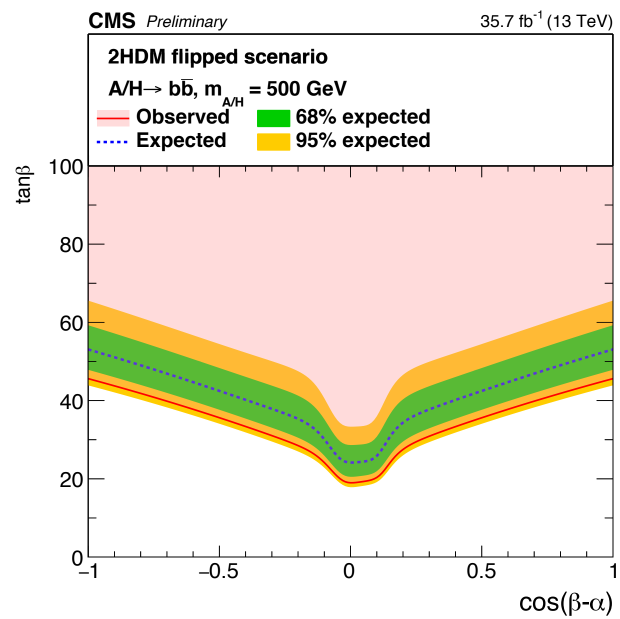
cos(β-α) = 0.1



M_A = 300 GeV



M_A = 500 GeV

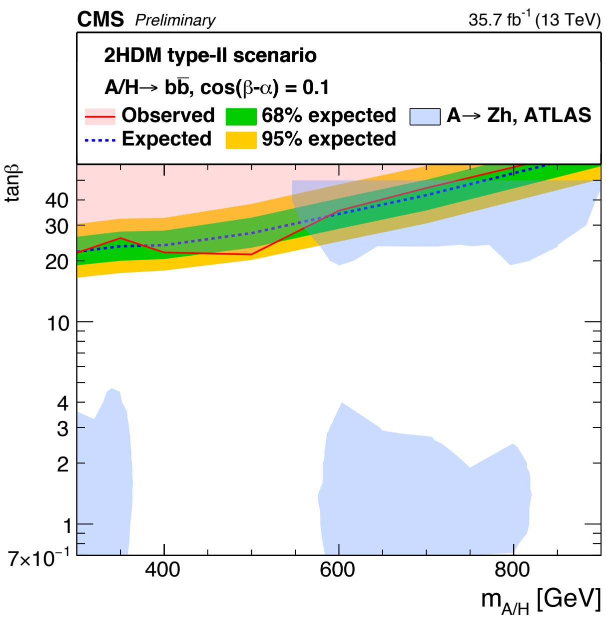


[0] - ATLAS collab., arXiv:1712.06518

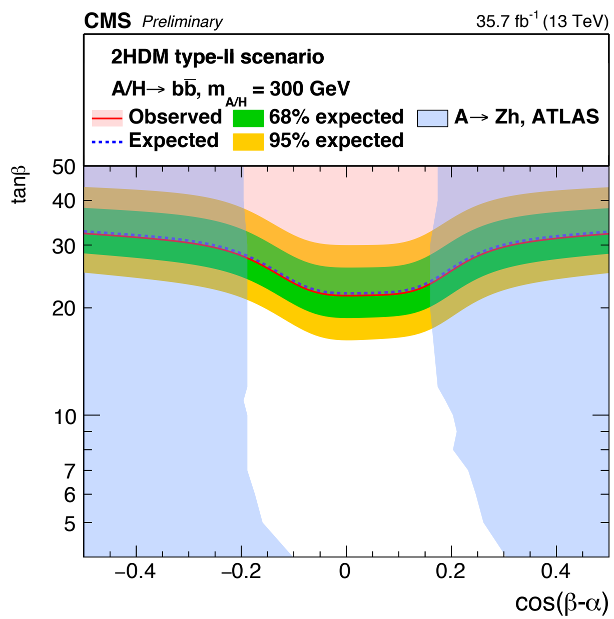
2HDM Interpretation: Type-II scenario

- **Exclusion limits** on **tanβ** vs **M_A** and **cos(β-α)** :
  - values of cos(β-α) = 0.1 and M_A = 300 GeV were chosen to compare with ATLAS A → Zh analysis [0]

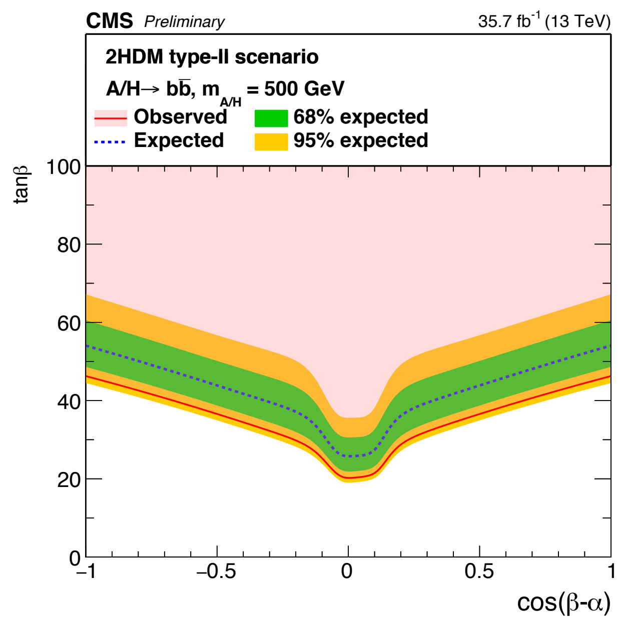
cos(β-α) = 0.1



M_A = 300 GeV



M_A = 500 GeV



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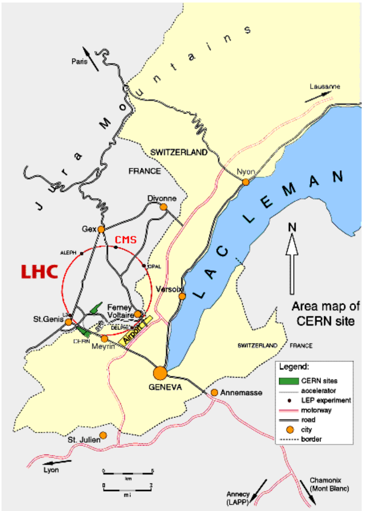
Summary

- A new search for **high mass Higgs** bosons in the **$b\bar{b}$ decay** channel in **association with b-quarks** was presented
  - unique analysis at LHC
- Results interpreted in context of **MSSM**:
  - **improved** limits in m_h^{mod+} and **newly hMSSM** interpretation
- Analysis put strong **constraints** on the relatively unexplored **«Flipped» 2HDM** scenario:
  - **Complements** ATLAS measurements of **$A \rightarrow Zh$**;
  - **Cover alignment limit** for large range of tanβ.
- **Paper submission coming soon**

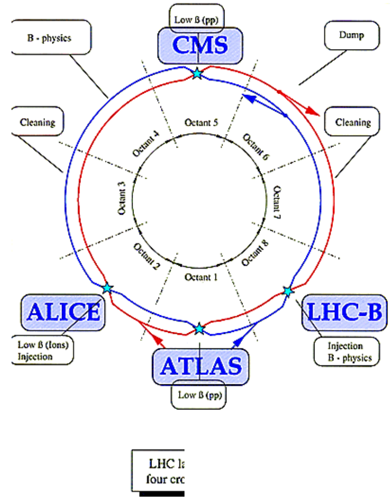
Текст заголовка

BACKUP

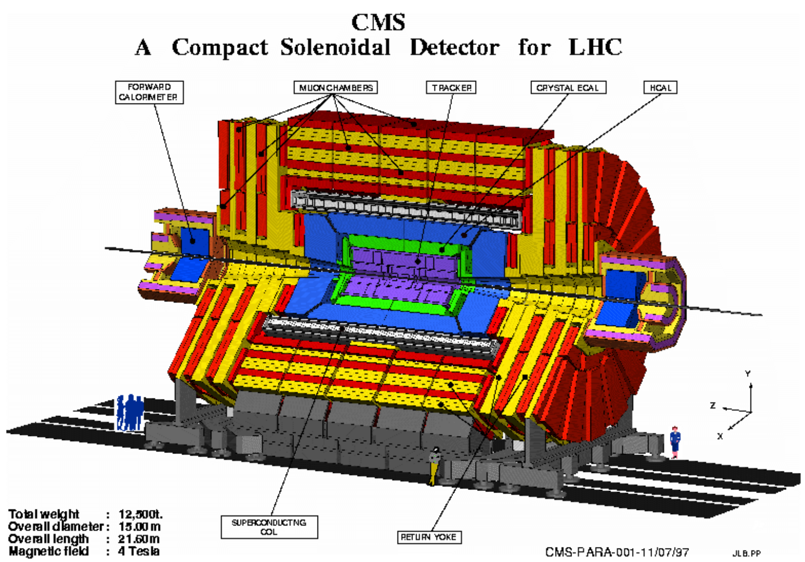
LHC and CMS



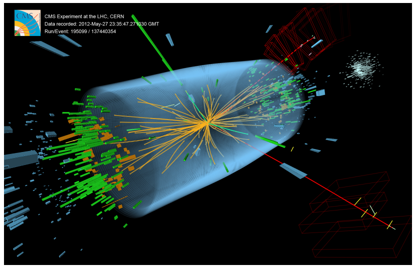
European Center for Nuclear Research (CERN)

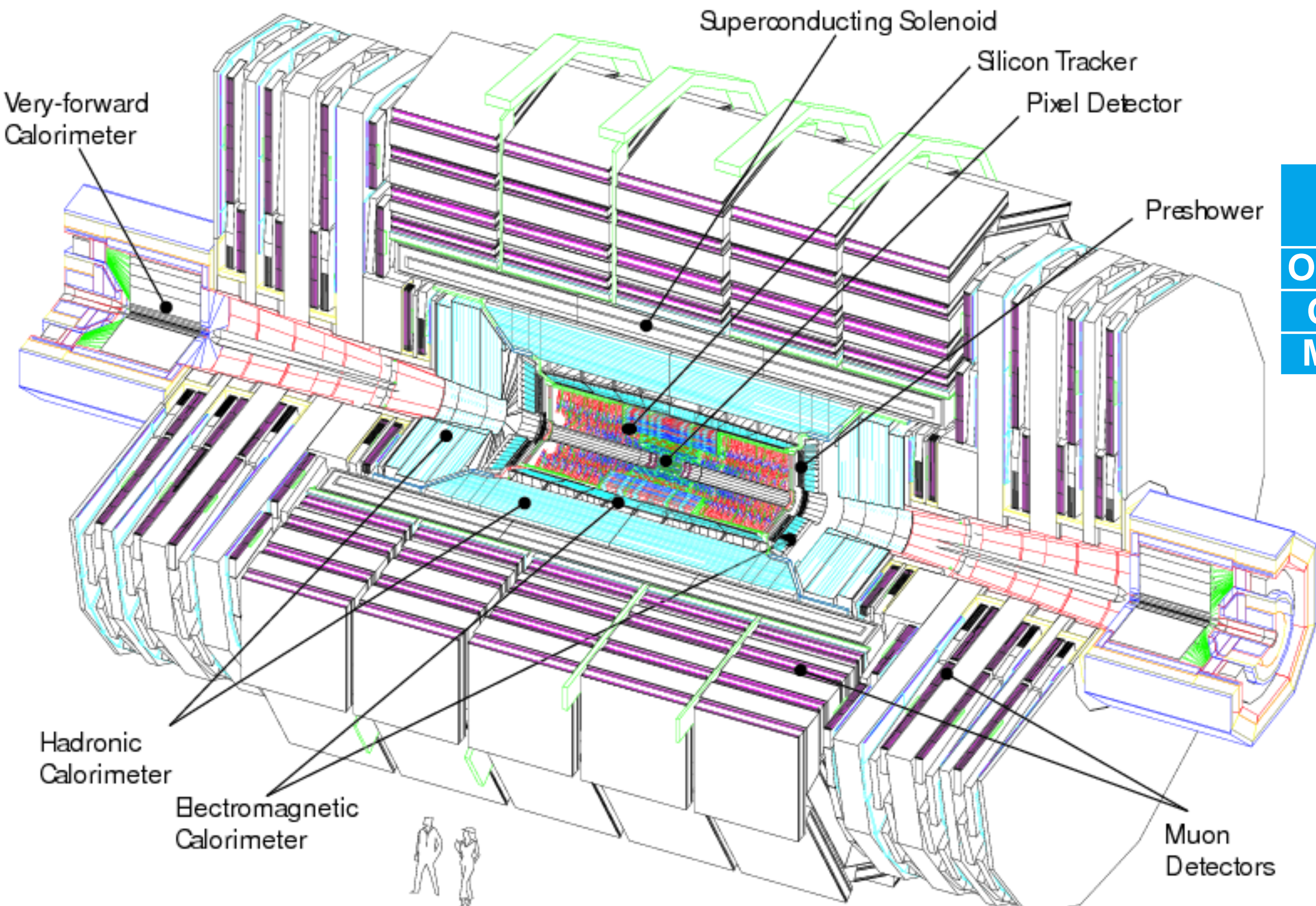


Large Hadron Collider (LHC)



Compact Muon Solenoid





Compact Muon Solenoid

Total weight	12.500 T
Overall diameter	15.0 m
Overall length	21.5 m
Magnetic Field	3.8 T

Two Higgs Doublet Model (2HDM)

- Higgs sector structure and parameters:

$$\Phi_1 = \begin{pmatrix} w_1^+ \\ \frac{v_1+h_1+iz_1}{\sqrt{2}} \end{pmatrix} \qquad \Phi_2 = \begin{pmatrix} w_2^+ \\ \frac{v_2+h_2+iz_2}{\sqrt{2}} \end{pmatrix}$$

- Physical states: **8** - 3 = 5

$$\begin{pmatrix} h_1 \\ h_2 \end{pmatrix} = R(\alpha)\begin{pmatrix} H \\ h \end{pmatrix}, \quad \begin{pmatrix} w_1^\pm \\ w_2^\pm \end{pmatrix} = R(\beta)\begin{pmatrix} G^\pm \\ H^\pm \end{pmatrix}, \quad \begin{pmatrix} z_1 \\ z_2 \end{pmatrix} = R(\beta)\begin{pmatrix} G^0 \\ A \end{pmatrix}$$

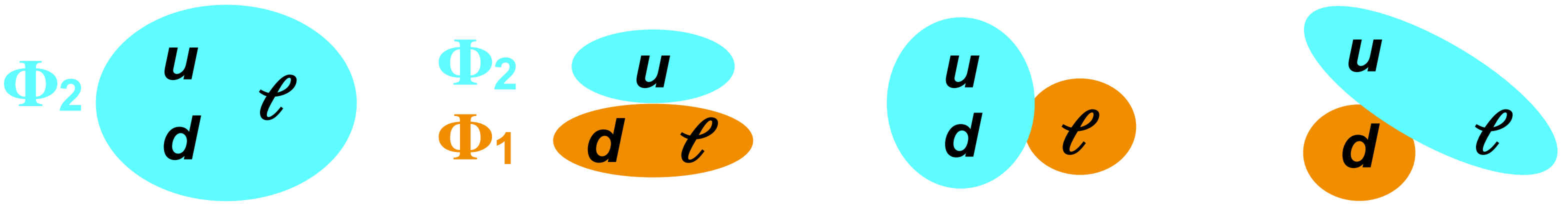
Goldstone bosons

CP-even | Charged | CP-odd

- **tan β** - ratio of vacuum expectation values $tan\beta = \frac{v_2}{v_1}$
- α - **mixing** angle between h and H $R(\alpha) = \begin{pmatrix} cos\alpha & -sin\alpha \\ sin\alpha & cos\alpha \end{pmatrix}$

- **4 types of 2HDM** with natural flavour and CP conservation, depending on how the 2 Higgs doublet fields couple to SM particles

Type I | Type II | Lepton Specific | Flipped



all fermion couples to one Higgs boson | up v.s. down | quark v.s. lepton

u - (u,c,t)
d - (d,s,b)
ℓ - (e,μ,τ)

Two Higgs Doublets Model

- Two Higgs Doublets Model (2HDM) has a large number of free parameters that allow to find specific scenario where A/H→bb will dominate among the other channels.
- Higgs sector of 2HDM models described by parameters: 4 Higgs masses, tan β(ratio of vacuum expectation values vev) and α mixing between the two neutral CP even states h,H

	Type I	Type II	Lepton-specific	Flipped
ξ_h^u	$\cos\alpha/\sin\beta$	$\cos\alpha/\sin\beta$	$\cos\alpha/\sin\beta$	$\cos\alpha/\sin\beta$
ξ_h^d	$\cos\alpha/\sin\beta$	$-\sin\alpha/\cos\beta$	$\cos\alpha/\sin\beta$	$-\sin\alpha/\cos\beta$
ξ_h^ℓ	$\cos\alpha/\sin\beta$	$-\sin\alpha/\cos\beta$	$-\sin\alpha/\cos\beta$	$\cos\alpha/\sin\beta$
ξ_H^u	$\sin\alpha/\sin\beta$	$\sin\alpha/\sin\beta$	$\sin\alpha/\sin\beta$	$\sin\alpha/\sin\beta$
ξ_H^d	$\sin\alpha/\sin\beta$	$\cos\alpha/\cos\beta$	$\sin\alpha/\sin\beta$	$\cos\alpha/\cos\beta$
ξ_H^ℓ	$\sin\alpha/\sin\beta$	$\cos\alpha/\cos\beta$	$\cos\alpha/\cos\beta$	$\sin\alpha/\sin\beta$
ξ_A^u	$\cot\beta$	$\cot\beta$	$\cot\beta$	$\cot\beta$
ξ_A^d	$-\cot\beta$	$\tan\beta$	$-\cot\beta$	$\tan\beta$
ξ_A^ℓ	$-\cot\beta$	$\tan\beta$	$\tan\beta$	$-\cot\beta$

x g_{SM}

- **Type I**: One doublet couples to V(“fermiophobic”), one to fermions
- **Type II**: “MSSM like” model, one doublet couples to up-type quarks, one to
- down-type quarks
- **Lepton-specific**: Higgs bosons have same couplings to quarks as type I and to leptons as in type II
- **Flipped**: Higgs bosons have same couplings to quarks as in type II and to leptons as in type I

Novosibirsk

- Standard Novosibirsk function has been extended to **Super**Novosibirsk function:

$$F(x) = N \cdot exp(-\frac{1}{2\sigma_0^2} ln^2(1 - \frac{\eta}{\sigma_E} \cdot (\sum_{i=1}^{n} p_{(i-1)} \cdot (x - x_p)^i) - \frac{\sigma_0^2}{2}))$$

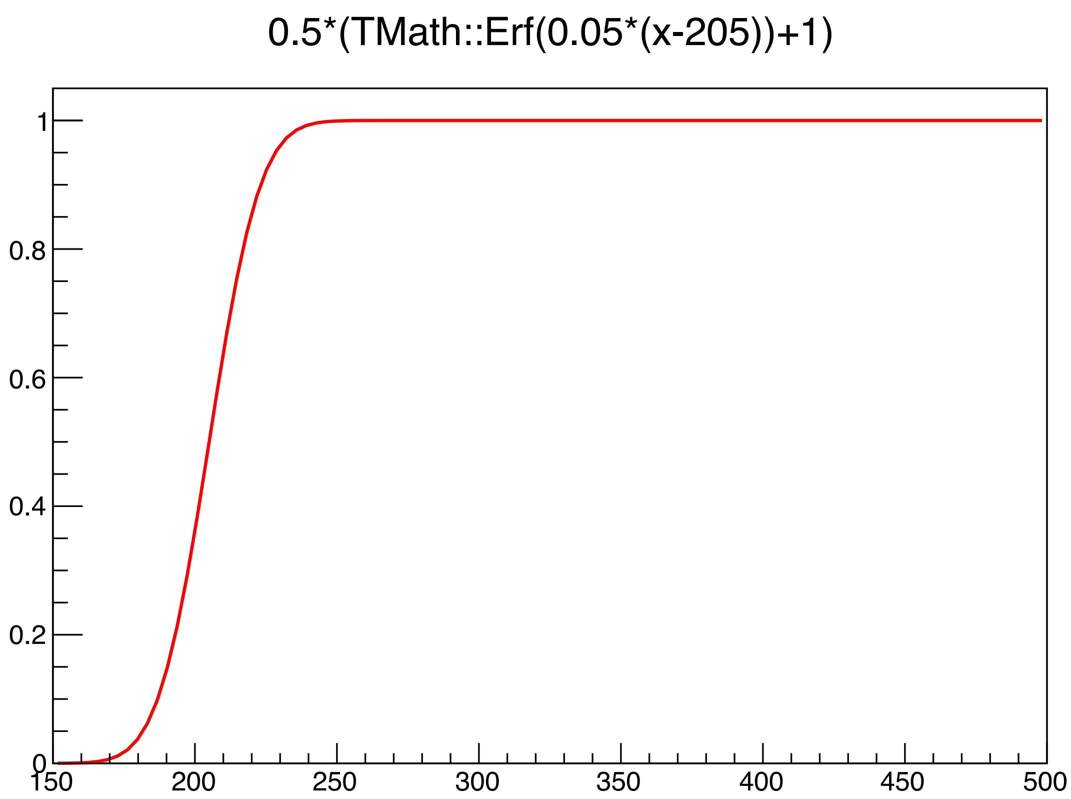
$$\sigma_0 = (2/\epsilon) sinh^{-1}(\eta\epsilon/2)$$

$$\epsilon = 2\sqrt{ln4}) = 2.36$$

- $p_0 = 1$;
- η - tail parameter;
- σ_E - width;
- x_p - peak position

Turn-on functionn

- $F(x) = 0.5*Erf(P_0*(x-P_1))+1)$
  - where $Erf(x) = 2/\sqrt{\pi} * \int e^{-t^2} dt$ — integral between 0 to x
  - P_0 indicates slope of this turn-on function and P_1 is turn-on point



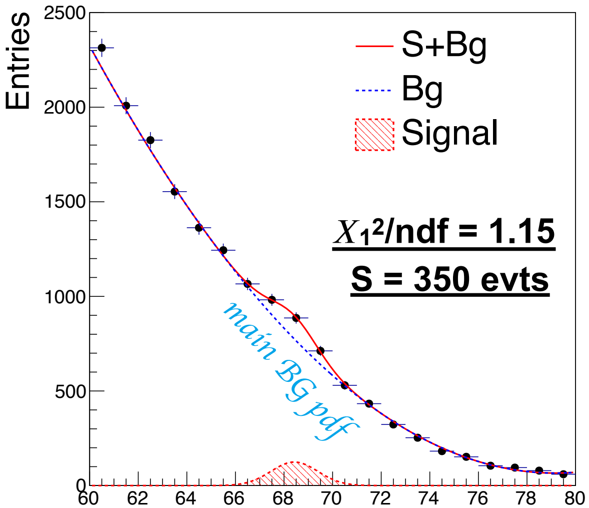
Background estimation: bias

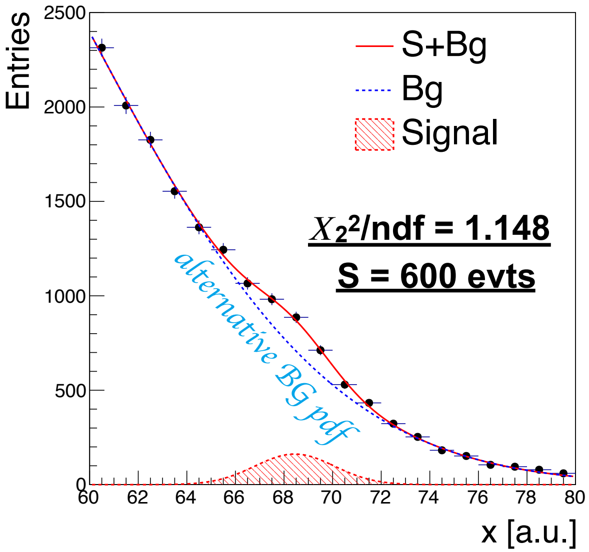
- **Choice** of the particular **fit** function **affects** estimated **signal**:
  - **bias** - measure of this effect;
- **Estimated** by comparison of ***S+Bg* fits** from different functions using "**Toy MC**" method:
  - **generate** toy ***Bg*** sample with pdf_1;
  - **inject** certain amount of **signal**: *S*
  - **fit *S+Bg*** distribution with pdf_2

$$B_{M_{\mathrm{H/A}}} = \left\langle \frac{N_S^{fit} - N_S^{toy}}{\sigma_S^{fit}} \right\rangle .$$

- Calculated **separately** for **each mass** point and for **different amount** of injected **signal**
- Obtained results:
  - sub-range 1: 100%
  - sub-range 2: 25%
  - sub-range 3: 20%

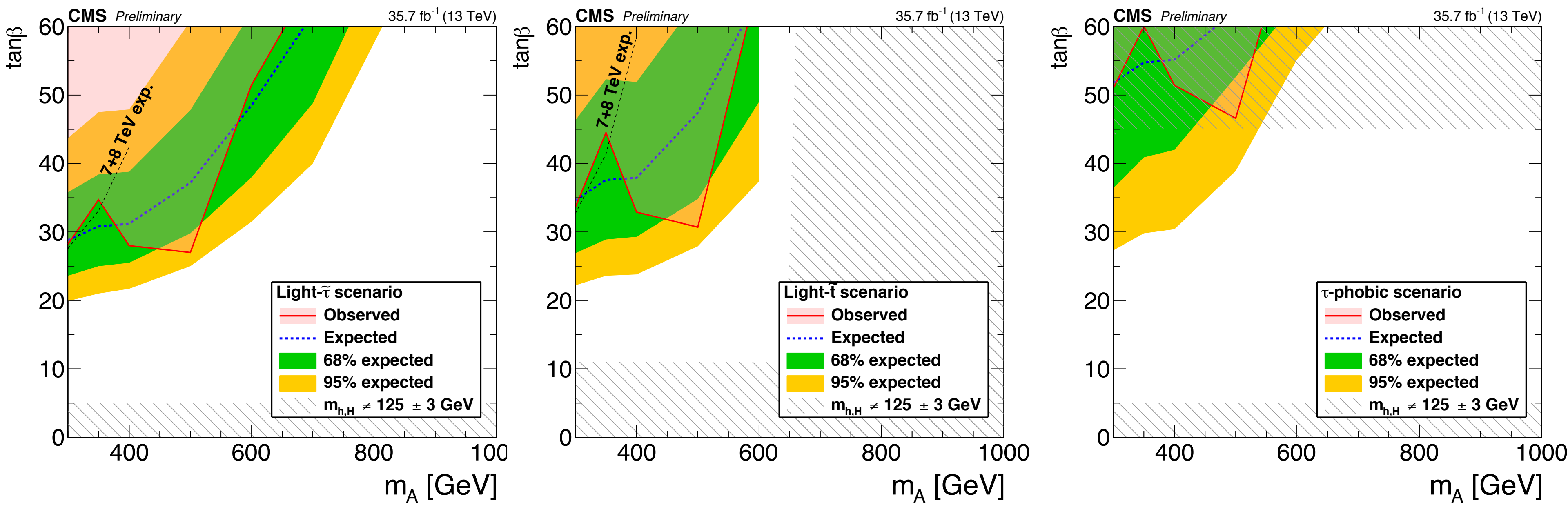
Illustration





MSSM interpretation

- Expected **limits** are translated into exclusion limits **on MSSM** parameters - **tanβ** and **M_A**
- Interpretation performed using **NNLO** cross sections in the **Santander** matching within the **light-$\tilde{\tau}$** ,**light-$\tilde{t}$** and **τ-phobic** benchmark scenarios



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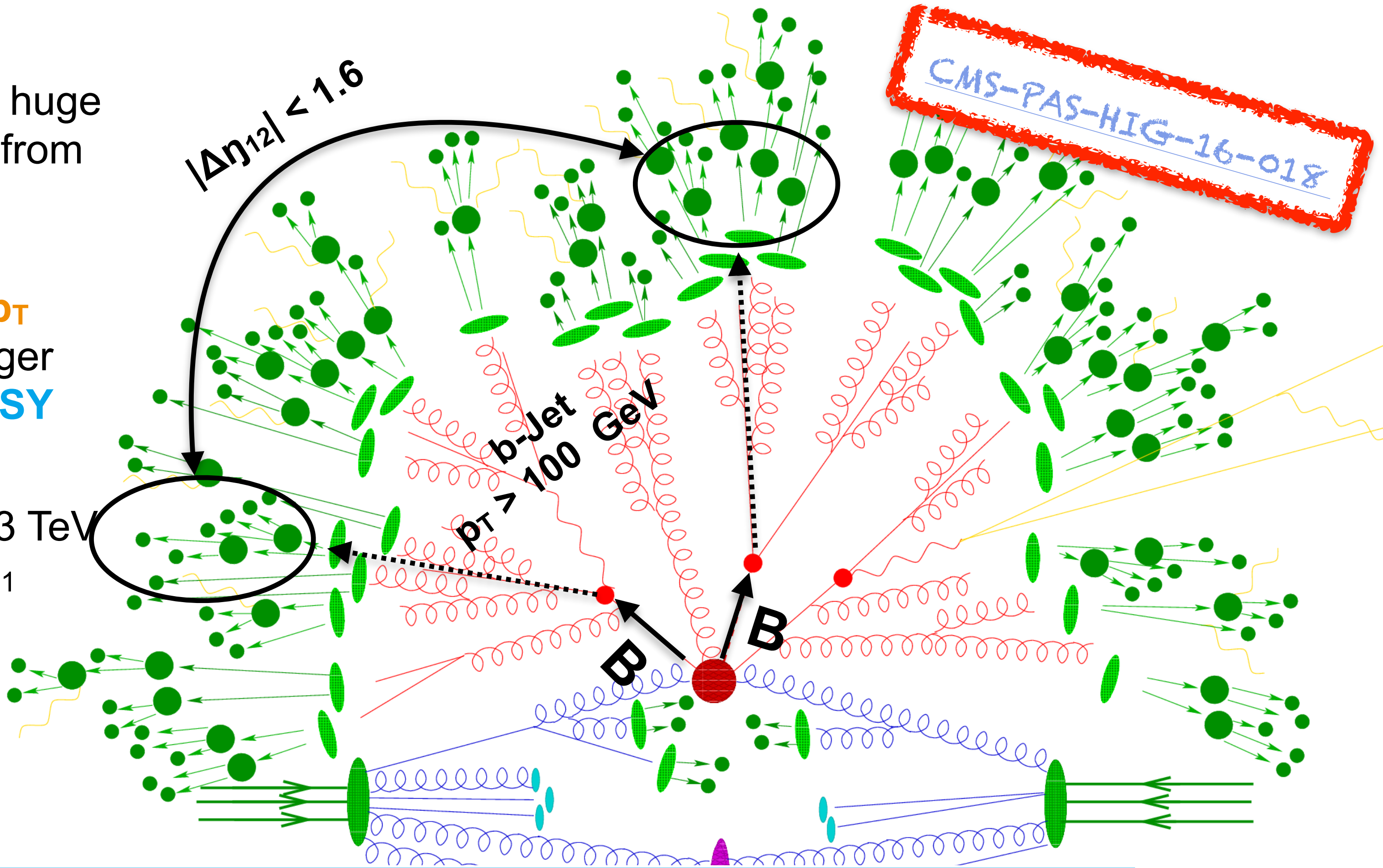

Dedicated Trigger	
Double jet with $p_T > 100$ GeV	reduce rate
$\lvert\Delta\eta_{12}\rvert < 1.6$	
double b-jet	reduce non $b\bar{b}$ background