

Searching for exotic Higgs bosons with CMS

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21/01/2020, IJCLab Seminar, Orsay

Outline



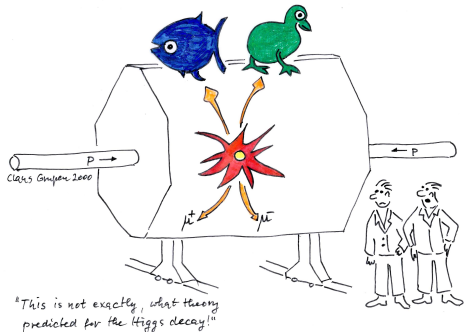
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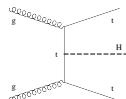
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|---|---|
| <p>1 Introduction</p> <ul style="list-style-type: none"> • (B)SM Higgs @ LHC • The CMS detector <p>2 Invisible Decays</p> <p>3 Heavy Neutral Bosons</p> <p>4 Light Neutral Bosons</p> <p>5 Charged Bosons</p> <p>6 Expectations for Run 3</p> | <p>7 The CMS upgrade for HL-LHC</p> <ul style="list-style-type: none"> • Motivations for an upgrade • Overview of the HGICAL detector <p>8 BSM Higgs @ HL-LHC</p> <p>9 Conclusion</p> |
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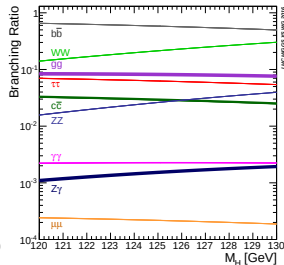


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 - (B)SM Higgs @ LHC
 - The CMS detector
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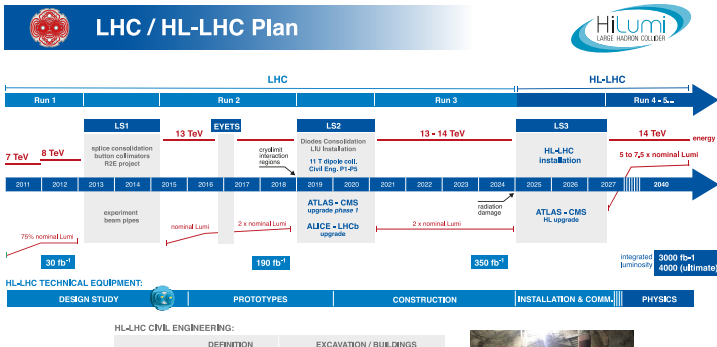


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-
- A black and white line drawing of a steam locomotive pulling a passenger car through a tunnel. A man in a hat and coat is sweeping the tracks with a broom. Two barrels labeled 'WORMS' and 'HIGGS' are on the right.



LHC schedule



● Higgs boson discovery.

● $\langle PU \rangle \simeq 25 - 60$

● New physics ?

● $\langle PU \rangle \simeq 140 - 200$

● Well beyond current experience !

The LHC: A Higgs Factory

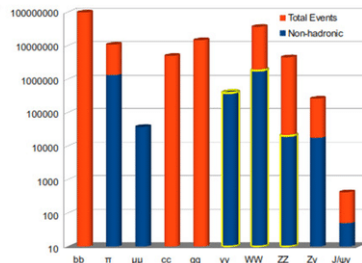
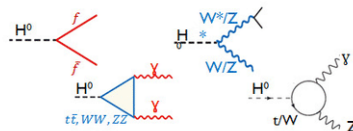
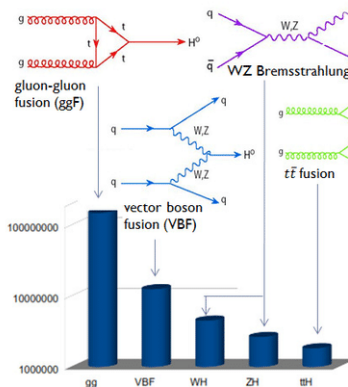


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With 3000 fb^{-1} , expect $\simeq 170\text{M}$ Higgs bosons, and 120k diHiggs events.

Production

Decay



Recap of Beyond Standard Model Higgs



Testing the 125 GeV scalar h

- is it really really SM-like ? $\Rightarrow$ Measure properties: indirect limits on new physics.
- $$\frac{\Gamma_H}{\Gamma_H^{SM}} = \frac{\sum_j BR_{SM}^j \kappa_j^2}{1 - (BR_{undet} + BR_{inv})}$$
- Best indirect limit so far: $BR_{BSM} < 0.34$ @ 95%CL on 8 TeV LHC data (JHEP 08 (2016) 045).
- Search for exotic decays: e.g. invisible, ...
- Search for new production modes: decay product of new particles: e.g. extra-dimensions radions or KK gravitons, heavier Higgses...

More Higgses ?

- Additional EW singlet mixing with SM-h: h, H.
- Two-Higgs Doublet Models (MSSM): H, A, h, H^+ , H^- .
- NMSSM (2HD + singlet): H1, H2, H3, A1, A2, H^+ , H^- .
- Higgs triplet models (SM-doublet + triplet): H, A, h, H^+ , H^- , H^{++} , H^{--} .

Model	w_R^t	d_R^b	e_R^l
Type I	Φ_2	Φ_2	Φ_2
Type II	Φ_2	Φ_1	Φ_1
Lepton-specific	Φ_2	Φ_2	Φ_1
Flipped	Φ_2	Φ_1	Φ_2

BSM Higgs and SUSY



SUSY 2005

Discovery cannot be far off

"The train is already late" (Altarelli): Fine tuning is a problem already.
We expected gauginos in the LEP range
Tevatron "window" is small but low masses are more likely

If masses are low and model is "not too complicated", LHC will fix it and ILC will be "LEP for SUSY"

An era is about to end

Low energy SUSY has provided employment for > 20 years

It will be discovered or die in the next 6 years.



Ian Hinchliffe - SUSY05 - July 2005 - 34

OUTLOOK

LHC phenomenology

- pheno-experimental efforts going very strong
- lots of new tools on the market, waiting to be tested
- ⇒ we will be able to do amazing things at the LHC
- ⇒ we still need the ILC for precision studies

Remember

- errors are tough, but the key to new physics
- we need more serious LHC man power
(you can sign up in the back of this room after the talk)

Thanks to all the people whose work I presented, all those whose great work I did not manage to include, and to T. Falk

Tarun Plehn: Susy at the LHC - p.15

SUSY 2019 - Summary talk by G. Kane

WHAT CLUES DO WE GET FROM THE HIGGS DATA?

- Correct prediction for mass approximately in MSSM (clue 1)
- And associated h decay BR within a few % of SM ones, as in data (clue 2)

So looks like two-doublet decoupling supersymmetry solution

- Plus hierarchy problem → TeV scale supersymmetry (clue 3)

- Plus vacuum stability (clue 4)

- Assume pure Standard Model → then Higgs potential $V = m^2 h^2 + \lambda h^4$

- SM λ runs negative as increase scale, around 10^{12} GeV → vacuum metastable

- Large fluctuations during inflation lead to unphysical AdS vacua (can't just say lifetime of universe long!) [Hook, Kearney, Shukla, Zurek 1404.5953]

- Supersymmetric λ positive definite, $\lambda > 0.1$ in MSSM, vacuum stable

- So higgs not SM

THESE FOUR CLUES POINT TO TeV SUPERSYMMETRY - NOT STANDARD MODEL HIGGS - NOT "NIGHTMARE" WORLD - Don't ignore clues

The higgs mass, decay BR, vacuum stability could have been different

SUSY2215
SUSY: THE NEW HOPE

• QUANTUM MECHANICS AND QFT STILL HOLD
• THE ORBITAL COLLIDER STILL SEES NOTHING
• THREE CENTURIES OF TRIUMPH FOR SUSY AND STRINGS!

The seasonal trends Extremely-weezy constrained SUSY NSFWMSSM FF3C10AC8A9-MSSM MSSM retrograde Anthropic landscaping and trimming it down The problem of condensed matter: They still don't get it Strings - The Perpetual Revolution Number of free parameters: P or NP complete?	Invited seminar How to ensure your model remains predictability-free Forum Is choice moral? "Every time you choose a path of action, a multiverse is killed" Special topic If the universe is not supersymmetric is it necessarily existing?
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The perpetual conference

5 Jan - 5 Mar: Chamoniex	15 Sep - 20 Nov: Jumeirah 1
15 Mar - 30 June: Hainan Island	21 Nov - 24 Dec: Hainan Island
1 July - 15 Sep: Wailea, Maui	

Sponsored by:
The Milner-Zuckerberg Institution

Status of the MSSM

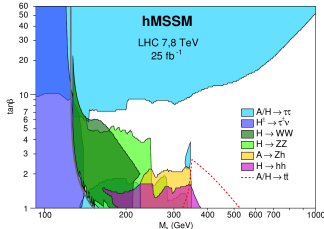


- SM Higgs can be either lightest/heaviest of neutral scalars.
- Many free parameters: need benchmark scenarios.
- Evolve as parameter space constrained by experimental data.
- hMSSM: convenient but assumes independence of Higgs/SUSY sector, not necessarily true, particularly with ($\tan\beta < 1.5, m_A < 200$ GeV).
- New benchmarks available.
- Generally: consider only 2 free parameters, m_A (or $m_{H^\pm}$) and $\tan\beta$.

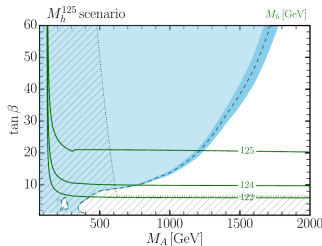


"You've got one foot in the grave. Further testing will determine if it's your left or your right."

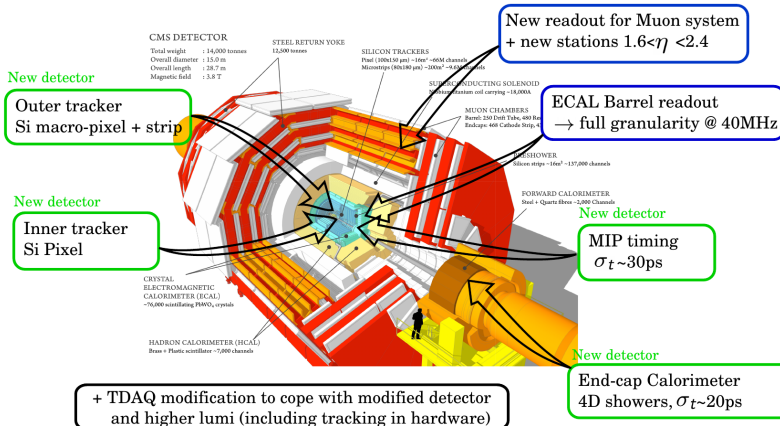
arXiv:1808.07542



arXiv:1502.05653



The CMS Detector and the Upgrade Program



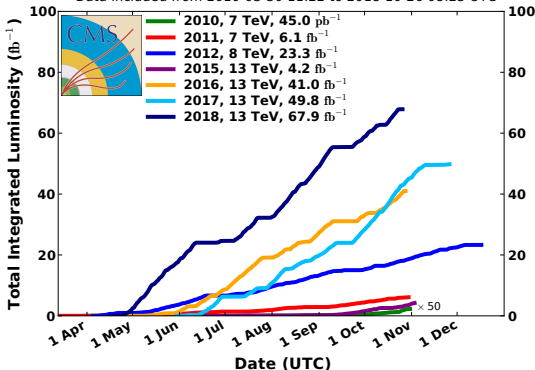
Overview of the data taken so far



- Results presented here: 13 TeV 2016 dataset (plus 7+8 TeV in combinations).
- Still $O(100 \text{ fb}^{-1})$ being analysed before releasing full run II results.
- Lots of updates planned for Moriond 2020.

CMS Integrated Luminosity Delivered, pp

Data included from 2010-03-30 11:22 to 2018-10-26 08:23 UTC



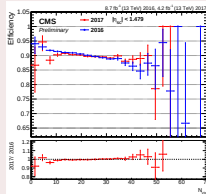
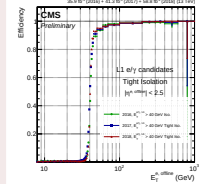
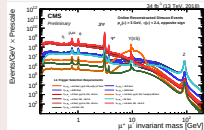
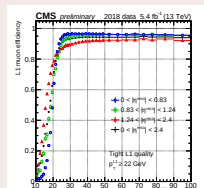
Performance of Triggers in Run 2



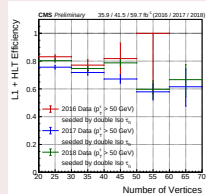
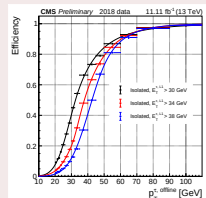
- Level-1 (L1): from 40 MHz to $\simeq 100$ kHz within $4\mu\text{s}$.
- High-Level-Trigger (HLT): particle-flow reconstruction, down to $\simeq 1$ kHz on disk.
- BSM Higgs: wide range of final states ...

Single EM triggers (electron, γ)

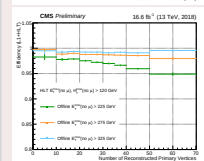
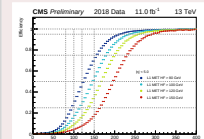
Single muon triggers



Hadronic tau triggers



Jets and missing energy triggers

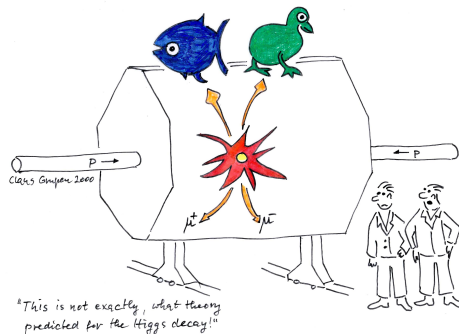


Outline



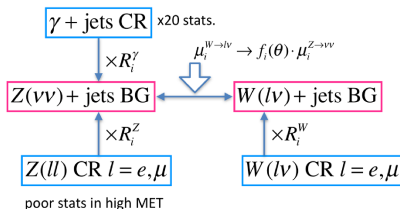
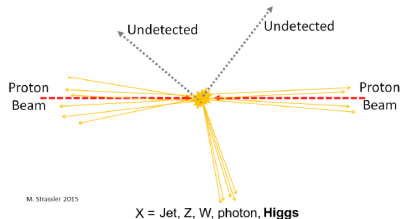
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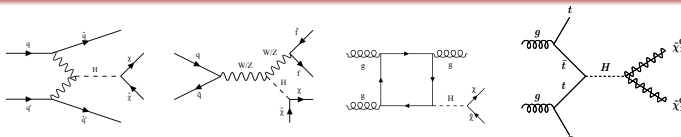


Experimental method

- $H \rightarrow ZZ \rightarrow 4\nu$ in SM: $BR \simeq 0.1\%$
- Any sizable contribution: unequivocal sign of new physics!
- Concentrating on final states with large MET, and a recoil system.
- Dominant backgrounds: $Z(\nu\nu) + \text{jets}$, $W(l\nu) + \text{jets}$, $\gamma + V$, $t\bar{t}$.
- Using control regions to model the recoil: e.g. with identified leptons $\Rightarrow$ cancelling most of the largest experimental systematics from jets and MET.
- Limited stat e.g. in Z CR: use constraints on W/Z, γ/Z ratios $\Rightarrow$ Need control of the theoretical systematics!

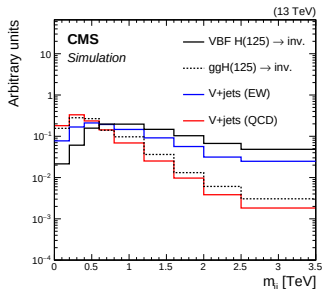


Search for invisible decays



Direct searches for VBFH - ggH - VH production modes

- NEW! VBF+combination, PLB 793 (2019) 520
- monojet/V(had)H: PRD 97 (2018) 092005.
- Z(l)H: EPJC 78 (2018) 291.



NEW! ttH

CMS-PAS-HIG-18-008

- Recast from published stop searches
- All hadronic final states: JHEP 10 (2017) 005
- 1 lepton: JHEP 10 (2017) 019
- 2 leptons: PRD 97 (2018) 032009

VBF H invisible

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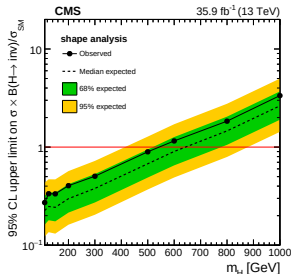
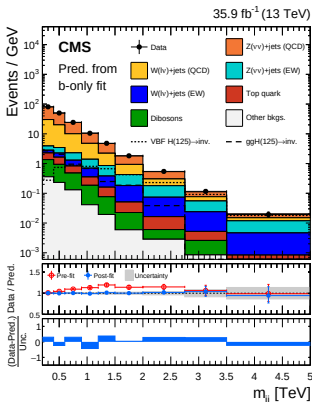


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Observable	Shape analysis	Cut-and-count analysis	Target background
Leading (subleading) jet	$p_T > 80$ (40) GeV, $ \eta < 4.7$	All	All
p_T^{miss}	> 250 GeV	QCD multijet, $t\bar{t}$, γ -jets, V -jets	
$\Delta\phi(\vec{p}_T^{\text{miss}}, \vec{p}_T^{\text{jet}})$	> 0.5 rad	QCD multijet, γ -jets	
Muons (electrons)	$N_{\mu e} = 0$ with $p_T > 10$ GeV, $ \eta < 2.4$ (2.5)	$W(\nu)$ -jets	
τ_s candidates	$N_{\tau_s} = 0$ with $p_T > 18$ GeV, $ \eta < 2.3$	$W(\nu)$ -jets	
Photons	$N_\gamma = 0$ with $p_T > 15$ GeV, $ \eta < 2.5$	γ -jets, $V\gamma$	
b quark jet	$N_{b\text{jet}} = 0$ with $p_T > 20$ GeV, CSVv2 > 0.848	$t\bar{t}$, single top quark	
$\eta_a \eta_b$	< 0	$Z(\nu\bar{\nu})$ -jets, $W(\nu\bar{\nu})$ -jets	
$ \Delta\phi_{jj} $	< 1.5 rad	$Z(\nu\bar{\nu})$ -jets, $W(\nu\bar{\nu})$ -jets	
$ \Delta\eta_{jj} $	> 1	$Z(\nu\bar{\nu})$ -jets, $W(\nu\bar{\nu})$ -jets	
m_{jj}	> 200 GeV	> 1.3 TeV	$Z(\nu\bar{\nu})$ -jets, $W(\nu\bar{\nu})$ -jets

Control regions with 1 or 2 isolated leptons.

Source of uncertainty	Ratios	Uncertainty vs. m_{jj}	Impact on $B(H \rightarrow \text{inv})$
Theoretical uncertainties			
Ren. scale V-jets (EW)	$Z(\nu\bar{\nu})/W(\nu\bar{\nu})$ (EW)	9-12%	48%
Ren. scale V-jets (QCD)	$Z(\nu\bar{\nu})/W(\nu\bar{\nu})$ (QCD)	9-12%	25%
Fac. scale V-jets (EW)	$Z(\nu\bar{\nu})/W(\nu\bar{\nu})$ (EW)	2-7%	4%
Fac. scale V-jets (QCD)	$Z(\nu\bar{\nu})/W(\nu\bar{\nu})$ (QCD)	2-7%	2%
PDF V-jets (QCD)	$Z(\nu\bar{\nu})/W(\nu\bar{\nu})$ (QCD)	0.5-1%	<1%
PDF V-jets (EW)	$Z(\nu\bar{\nu})/W(\nu\bar{\nu})$ (EW)	0.5-1%	<1%
NLO EW corr.	$Z(\nu\bar{\nu})/W(\nu\bar{\nu})$ (QCD)	1-2%	<1%
Experimental uncertainties			
Muon reco. eff.	$Z(\mu\mu)/Z(\nu\bar{\nu})$, $W(\mu\nu)/W(\nu\bar{\nu})$	$\approx 1\%$ (per lepton)	8%
Electron reco. eff.	$Z(ee)/Z(\nu\bar{\nu})$, $W(e\nu)/W(\nu\bar{\nu})$	$\approx 1\%$ (per lepton)	3%
Muon id. eff.	$Z(\mu\mu)/Z(\nu\bar{\nu})$, $W(\mu\nu)/W(\nu\bar{\nu})$	$\approx 1\%$ (per lepton)	8%
Electron id. eff.	$Z(ee)/Z(\nu\bar{\nu})$, $W(e\nu)/W(\nu\bar{\nu})$	$\approx 1.5\%$ (per lepton)	4%
Muon veto	$Z(\nu\bar{\nu})/W(\nu\bar{\nu})$, $W(CR_s)/W(\nu\bar{\nu})$	≈ 2.5 (2%) for EW (QCD)	7%
Electron veto	$Z(\nu\bar{\nu})/W(\nu\bar{\nu})$, $W(CR_s)/W(\nu\bar{\nu})$	≈ 1.5 (1%) for EW (QCD)	5%
τ veto	$Z(\nu\bar{\nu})/W(\nu\bar{\nu})$, $W(CR_s)/W(\nu\bar{\nu})$	≈ 3.5 (3%) for EW (QCD)	13%
Jet energy scale	$Z(CR_s)/Z(\nu\bar{\nu})$, $W(CR_s)/W(\nu\bar{\nu})$	≈ 1 (2%) for Z/Z , W/W	4%
Electron trigger	$Z(ee)/Z(\nu\bar{\nu})$, $W(e\nu)/W(\nu\bar{\nu})$	$\approx 1\%$	<1%
p_T^{miss} trigger	All ratios	$\approx 2\%$	18%



95% CL limit
on BR(inv)
Observed
0.33
Expected
0.25

Combination

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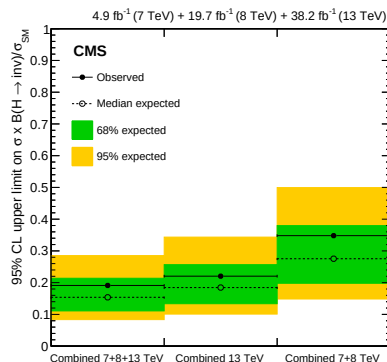
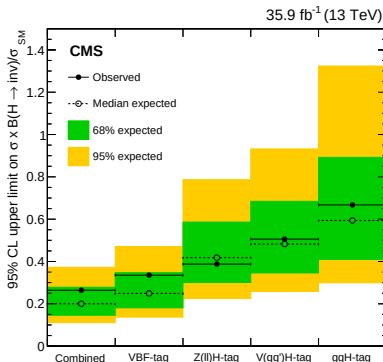
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ttH recast CMS-PAS-HIG-18-008

0.46

0.48

Analysis	Final state	Signal composition	Observed limit	Expected limit
VBF-tag	VBF-jet + p_T^{miss}	52% VBF, 48% ggH	0.33	0.25
VH-tag	$Z(\ell\ell) + p_T^{\text{miss}}$ [?]	79% qqZH, 21% ggZH	0.40	0.42
	$V(\text{qq}') + p_T^{\text{miss}}$ [?]	39% ggH, 6% VBF, 33% WH, 22% ZH	0.50	0.48
ggH-tag	jets + p_T^{miss} [?]	80% ggH, 12% VBF, 5% WH, 3% ZH	0.66	0.59



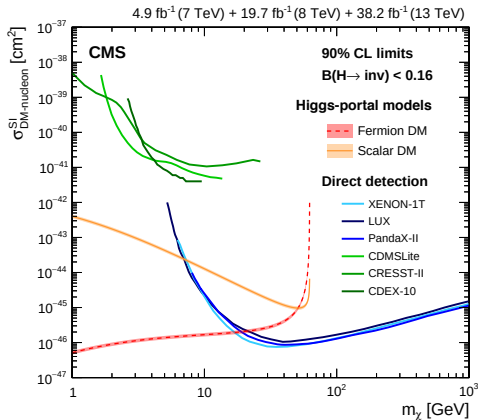
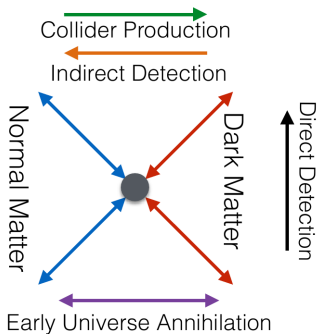
● Best 95% CL limit: observed 0.19, expected 0.15.

Impact on DM

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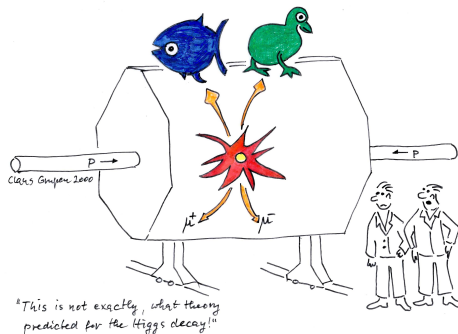


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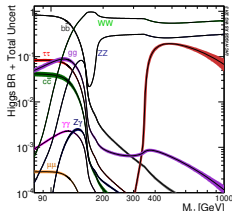
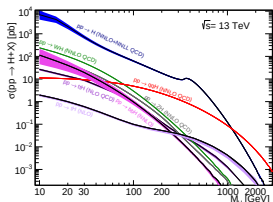


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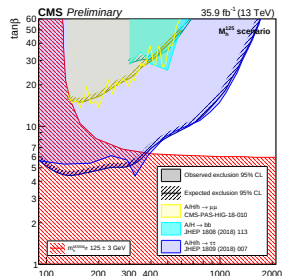
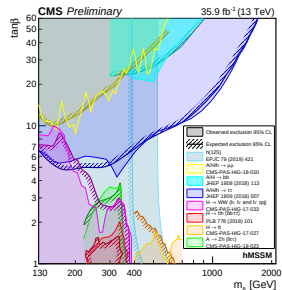
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Summary of existing Run 2 searches



- SM-like: dominant decay to ZZ , WW : JHEP 06 (2018) 127, arXiv:1912.01594.
- Opening of $t\bar{t}$ channel above 300 GeV: NEW! arXiv:1908.01115
- MSSM $H \rightarrow \mu\mu$: NEW! PLB 798 (2019) 134992
- m_A - $\tan\beta$ plane: enhancement of couplings to τ , b : $\tau\tau$ JHEP 09 (2018)007, $b\bar{b}$ JHEP 08 (2018) 113
- Large parameter space already excluded, remaining region of interest at high mass, low $\tan\beta$. Revisit with new benchmark scenarios!

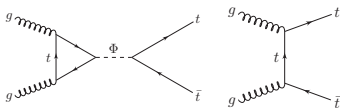


$H \rightarrow t\bar{t}$

arXiv:1908.01115

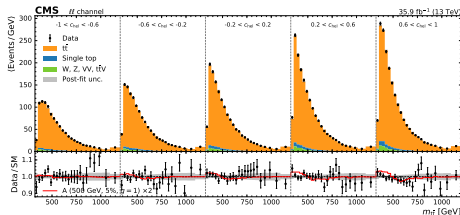
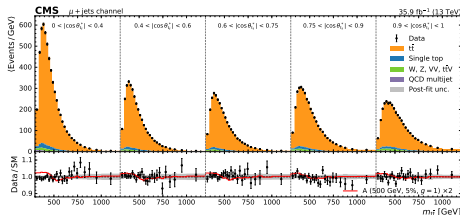
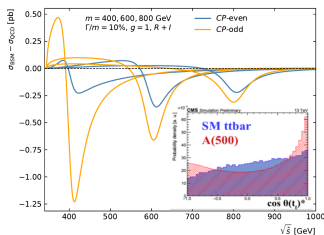


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$$\mathcal{L}_{\text{Yukawa}, H} = \frac{m_t}{v} g_{Ht\bar{t}} t\bar{t}H,$$

$$\mathcal{L}_{\text{Yukawa}, A} = \frac{m_t}{v} i g_{At\bar{t}} t\gamma_5 \bar{t}A,$$



- Signal = resonant+interference terms.
- ggF production of Φ
- Single-lepton and dilepton $t\bar{t}$ decay channels.
- 2D-fit: $m_{t\bar{t}}$ vs $\cos(\theta(t_\ell))^*$ in $t\bar{t}$ frame.

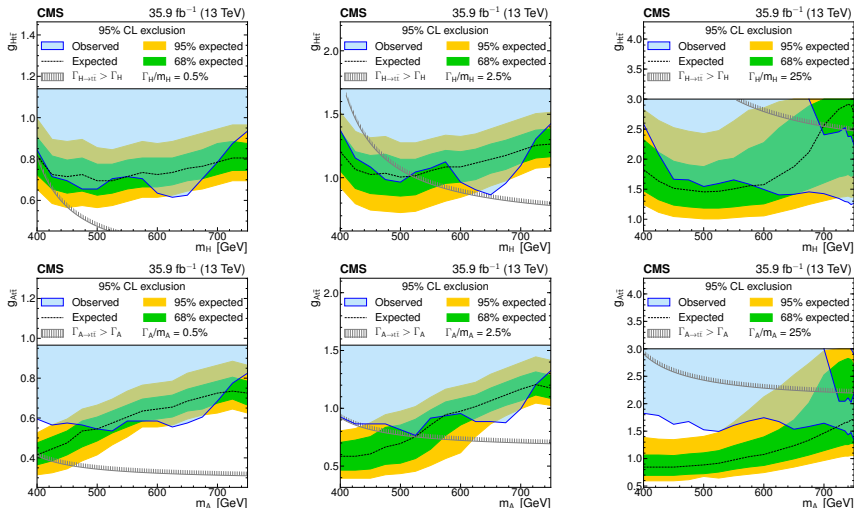
$H \rightarrow t\bar{t}$

arXiv:1908.01115



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Scalar A



Pseudo-scalar H: highest deviation $m_H = 400$ GeV, $\Gamma_H \simeq 0.04$, local $3.5 \pm 0.3\sigma$, global 1.9 . Higher-order EWK corrections for $t\bar{t}$?

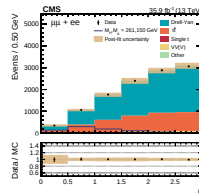
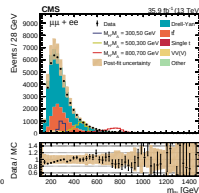
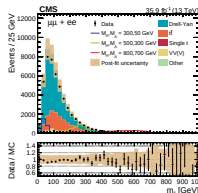
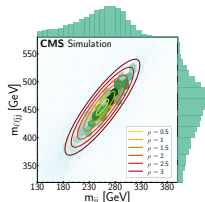
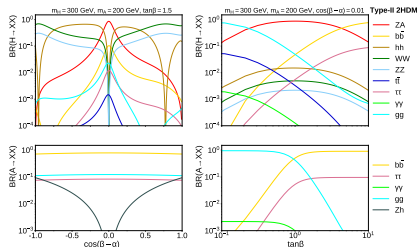
H/A $\rightarrow$ ZA/H

arXiv:1911.03781



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- In 2HDM type-II: can be dominant BR.
- $\cos(\beta - \alpha) \rightarrow 0$: alignment limit $h = \text{SM } H$.
- Final state: $Z \rightarrow \ell\ell$, $H/A \rightarrow b\bar{b}$.
- Signal regions: ellipses parametrised versus M_{jj} and $M_{l\bar{l}}$ for each (m_A, m_H)
- Experimental resolutions through dilatation coefficients ρ .
- Measure data content in ellipses vs ρ
- Use $e\mu$ control region to constrain $t\bar{t}$.

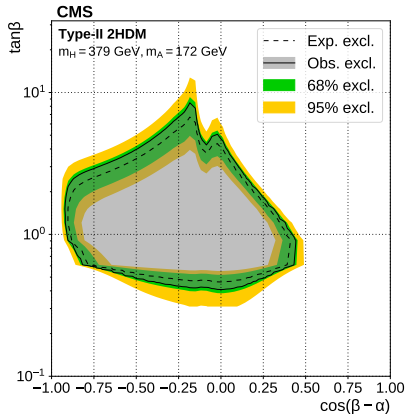
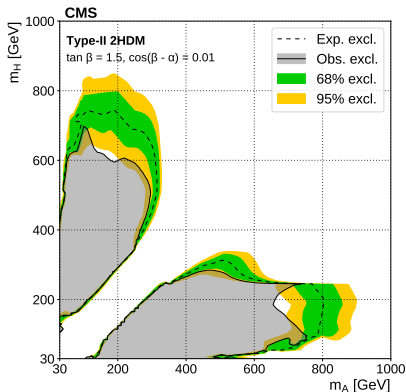


H/A $\rightarrow$ ZA/H

arXiv:1911.03781



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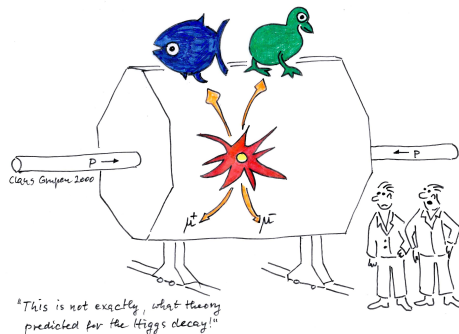
- At $m_H = 627 \text{ GeV}, m_A = 162 \text{ GeV}$: local significance 3.9σ , global 1.3 (2D Look Elsewhere Effects).

Outline



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- 1 Introduction
- 2 Invisible Decays
- 3 Heavy Neutral Bosons
- 4 Light Neutral Bosons**
- 5 Charged Bosons
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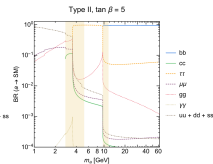
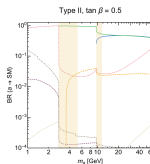
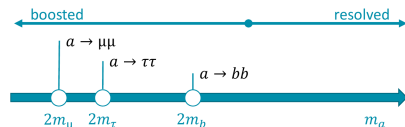
Searches for new light neutral bosons



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- Relevant in 2HDM+S models.
- Either scalar or pseudoscalar: labelled "a", coupling to H_{125} and SM fermions.
- Pair-produced in the decay of the H_{125} : masses below $m_H/2$.
- Other production modes: Za , Wa through charged Higgs.
- Considering SM Higgs production modes, ggF and VBF.
- Dominant branching ratios very dependent on model / parameter space.

- type-I: BR independent of $\tan\beta$, and SM-like ($\propto$ mass)
- type-II: NMSSM, decays to b suppressed for $\tan\beta < 1$, enhanced above 1.
- type-III: decay to quarks suppressed for $\tan\beta > 1$, enhanced below 1.
- type-IV: for $\tan\beta < 1$, bb and $\tau\tau$ BR similar.



Phys. Rev. D 90, 075004 (2014)

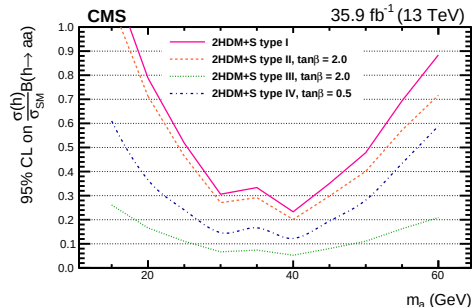
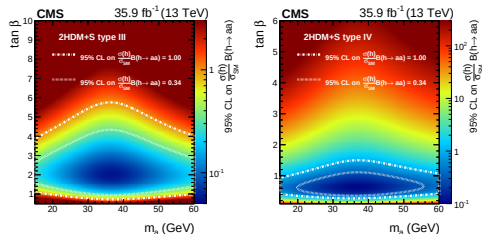
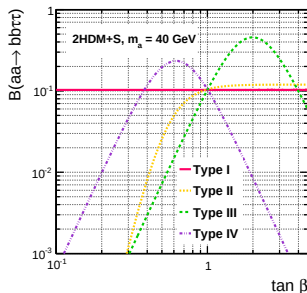
$$H_{125} \rightarrow aa \rightarrow bb\tau\tau$$



Phys. Lett. B 785 (2018) 462

Strategy

- Large BR in 2HD+S models.
- $e\mu$, $e\tau_{had}$, $\mu\tau_{had}$ channels.
- Fit $m_{\tau\tau}^{vis}$ in bins of $m_{b\tau\tau}^{vis}$.

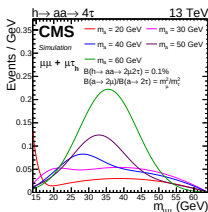
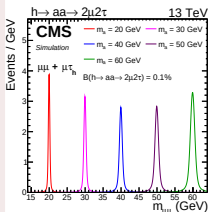


$H_{125} \rightarrow aa \rightarrow \mu\mu\tau\tau$

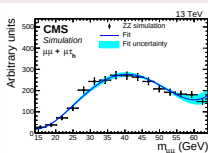
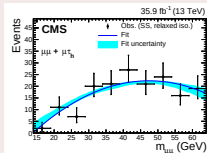
Strategy

$aa \rightarrow \mu\mu\tau\tau$

$aa \rightarrow 4\tau \rightarrow \mu\mu\tau\tau$



- Parametrise signal and background, look for sharp peak in $m_{\mu\mu}$
- $e\mu$, $e\tau_{had}$, $\mu\tau_{had}$, $\tau_{had}\tau_{had}$ channels.

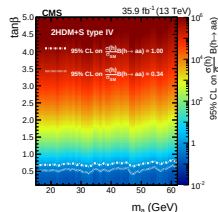
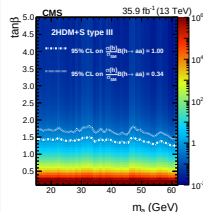


Reducible bkg

Irreducible bkg

JHEP 11 (2018) 018

	$\mu\mu + e\mu$	$\mu\mu + e\tau_h$	$\mu\mu + \mu\tau_h$	$\mu\mu + \tau_h\tau_h$
$ZZ \rightarrow 4\ell$	1.5 ± 0.2	0.5 ± 0.1	1.2 ± 0.2	0.03 ± 0.01
Misidentified τ	13.2 ± 5.5	9.7 ± 2.5	4.0 ± 1.2	1.2 ± 0.5
$h \rightarrow aa \rightarrow 2\mu 2\tau$, $m_a = 20$ GeV	0.39	0.25	0.47	0.10
$h \rightarrow aa \rightarrow 4\tau$, $m_a = 20$ GeV	0.37	0.04	0.24	0.01
$h \rightarrow aa \rightarrow 2\mu 2\tau$, $m_a = 40$ GeV	0.57	0.28	0.68	0.14
$h \rightarrow aa \rightarrow 4\tau$, $m_a = 40$ GeV	0.68	0.09	0.48	0.02
$h \rightarrow aa \rightarrow 2\mu 2\tau$, $m_a = 60$ GeV	0.94	0.85	1.18	0.52
$h \rightarrow aa \rightarrow 4\tau$, $m_a = 60$ GeV	1.27	0.20	0.93	0.05
Observed	17	10	6	1



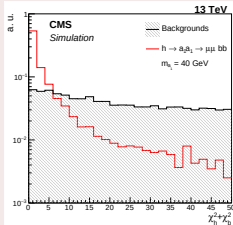
$H_{125} \rightarrow aa \rightarrow \mu\mu bb$



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PLB 795 (2019) 398

Strategy



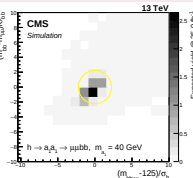
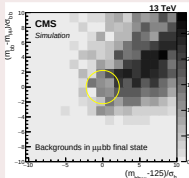
$$\chi_{bb} = \frac{(m_{bb} - m_{\mu\mu})}{\sigma_{bb}}$$

$$\chi_h = \frac{(m_{\mu\mu bb} - 125)}{\sigma_h}$$

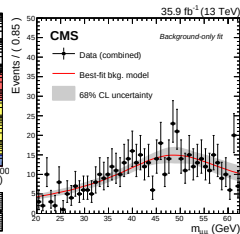
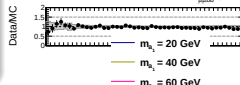
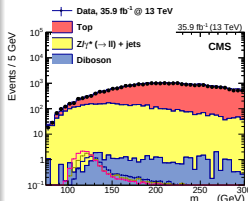
Signal shape:

Voigt + Crystall Ball.

- 2 tight μ $p_T > 20, 9$ GeV, 1b tight (T) + 1b loose (L) $p_T > 20, 15$ GeV, $|\eta^{\mu, b}| < 2.4$.
- Final sel: MET < 60 GeV, $\chi^2 < 5$ (yellow circle), 3 categories TL, TM, TT.



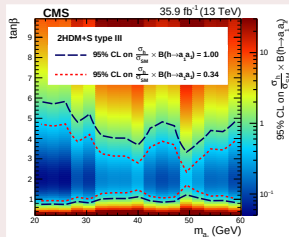
Process	$\mu^+\mu^-\bar{b}\bar{b}$ selection	Final selection
Top (tt, single top quark)	33730 ± 120	198 ± 9
Drell-Yan	5237 ± 77	399 ± 21
Diboson	51 ± 4	1 ± 0.1
Total expected background	39015 ± 140	598 ± 23
Data	36360	610
Signal for $\sigma_h \mathcal{B} \approx 8$ fb		
$m_{a_1} = 20$ GeV	14.0 ± 0.1	6.0 ± 0.1
$m_{a_1} = 40$ GeV	14.8 ± 0.1	7.5 ± 0.1
$m_{a_1} = 60$ GeV	16.7 ± 0.1	10.1 ± 0.1



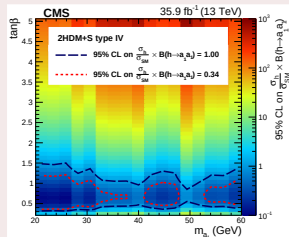
$H_{125} \rightarrow aa \rightarrow \mu\mu bb$

PLB 795 (2019) 398

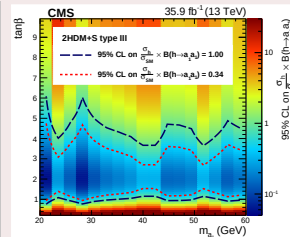
Type III



Type IV



Type III with $\mu\mu\tau\tau$



- Systematics: background shape (discrete profiling method), JES, b-tag SF, ...
- $\mu\mu\tau\tau$ with τ misid'd as b relevant only in particular model with $BR(\tau\tau)$ enhanced: type III with $\tan\beta \simeq 5$.
- $\tau\tau bb$ with $b \rightarrow \mu$ irrelevant due to $m_{\mu\mu}$ constraint.
- Factor 2 improvement wrt 8 TeV analysis, from improvement in analysis technique.

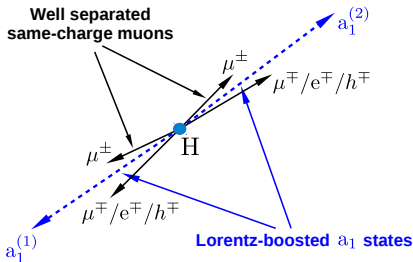
$H_{125} \rightarrow aa \rightarrow 4\tau$

PLB 800 (2019) 135087



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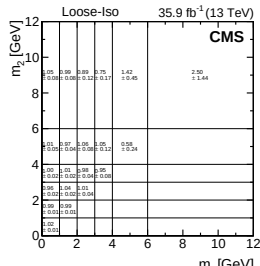
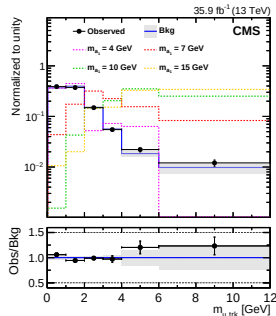
Well separated same-charge muons



- Trigger on same-sign dimuon.
- Require 1 track within $\Delta R = 0.5$ of muons.
- Use correlations between 2 (μ -track) systems.
- Control regions with more tracks for modeling of shape/validation.

$$f_{2D}(i, j) = C(i, j) (f_{1D}(i) \times f_{1D}(j))^{\text{sym}}$$

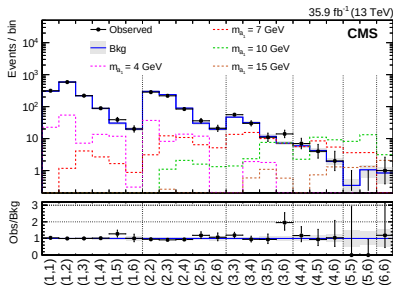
$$C(i, j) = C(i, j)_{\text{data}}^{\text{CR}} \frac{C(i, j)_{\text{MC}}^{\text{sig}}}{C(i, j)_{\text{MC}}^{\text{CR}}}$$



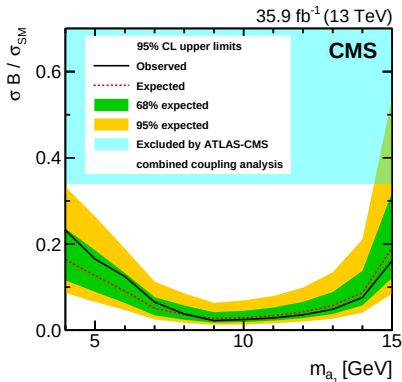
$$H_{125} \rightarrow aa \rightarrow 4\tau$$

PLB 800 (2019) 135087

m_{a_1} [GeV]	Acceptance $\times 10^4$		Number of events	
	4τ	$2\mu 2\tau$	4τ	$2\mu 2\tau$
4	3.29 ± 0.16	89.3 ± 1.4	129.9 ± 6.2	54.7 ± 0.9
7	2.50 ± 0.14	69.0 ± 1.4	98.8 ± 5.5	22.5 ± 0.5
10	1.46 ± 0.11	47.1 ± 1.2	57.8 ± 4.2	14.2 ± 0.4
15	0.21 ± 0.04	3.5 ± 0.3	8.5 ± 1.1	1.0 ± 0.1



- Dominant exp. systematics: on $C(i,j)$ [3–60%] and 1D template, track selection and eff [10–18%], muonID+trig [4%], MC stat in signal [5–10%].
- Theory unc.: signal acceptance [2% scales + 2% PDF], signal cross section [scales/PDF dependent on production mode].



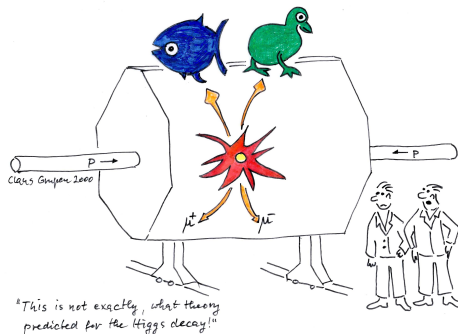
- Degradation at low m_{a_1} : increase of background yields.
- Degradation at high m_{a_1} : increase of $\Delta R(\mu\text{-track}) \Rightarrow$ not anymore boosted final state.

Outline



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- 1 Introduction
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- 5 **Charged Bosons**
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- 7 The CMS upgrade for HL-LHC
- 8 BSM Higgs @ HL-LHC
- 9 Conclusion



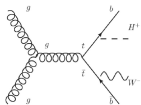
Charged Higgs bosons in the MSSM/2HD models



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Low mass

Low mass

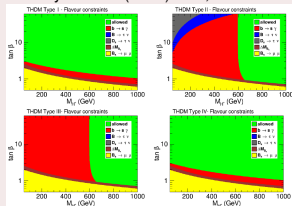


$$\sigma(pp \rightarrow tt) * \text{BR}(t \rightarrow bH^+) * \text{BR}(t \rightarrow bW)$$

NNLO
PRL 110 (2013)

NLO: Phys. Rev. D76
(2007), hep-ph/9301237
NNLO: eg. hep-ph/9806244

Eur.Phys.J. C78 (2018) no.3, 182

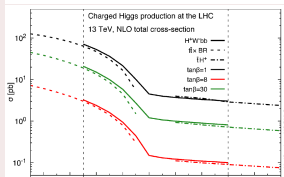
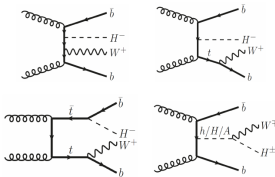


Intermediate mass

Phys.Lett. B772 (2017) 87

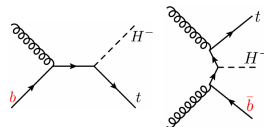
Intermediate mass

NLO $pp \rightarrow H^\pm W^\mp b\bar{b}$



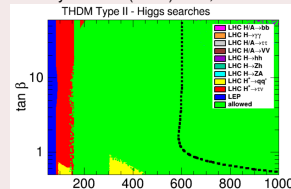
High mass

High mass



Tools: 4FS: MG5_aMCatNLO,
5FS: Prospino

Eur.Phys.J. C78 (2018) no.3, 182



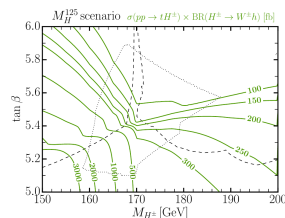
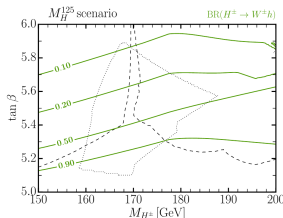
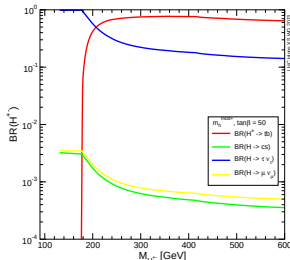
Charged Higgs bosons searches at CMS



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7/8 TeV		13 TeV	
Final State	Ref	Final State	Ref
$H^{\pm} \rightarrow \tau \nu, tb$	JHEP 11 (2015) 018	$H^{\pm} \rightarrow \tau \nu$	JHEP 07 (2019) 142
		$H^{\pm} \rightarrow tb \text{ lep}$	arXiv:1908.09206
		$H^{\pm} \rightarrow tb \text{ had}$	CMS-PAS-HIG-18-015
$H^{\pm} \rightarrow cs$	JHEP 12 (2015) 1	$H^{\pm} \rightarrow cs$	CMS-PAS-HIG-18-021
$H^{\pm} \rightarrow cb$	JHEP 11 (2018) 115	$H^{\pm} \rightarrow Wa$	PRL 123 (2019) 131802
$H^{\pm\pm} \text{ multileptons}$	EPJC 72 (2012) 2189	$H^{\pm\pm} \text{ multileptons}$	CMS-PAS-HIG-16-036
		$VBF H^{\pm} \rightarrow WZ$	PRL 119 (2017) 141802
		$H^{\pm\pm} \rightarrow W^{\pm} W^{\pm}$	PRL 120 (2018) 081801

- New results with 2016 13 TeV data ! Including intermediate mass range.
- But: "standard" decays very constrained now in MSSM-like models.
- New benchmarks: opening decays to $\chi_i^{\pm} \chi_j^0$, Wh, WA.



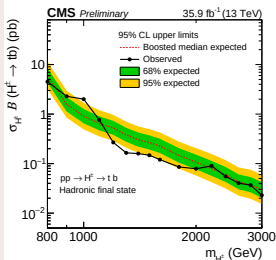
arXiv:1808.07542

$H^{\pm} \rightarrow tb$ combined results

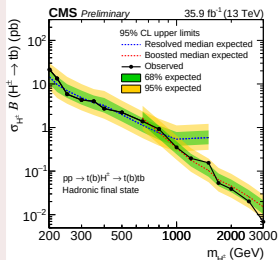
CMS-PAS-HIG-18-015

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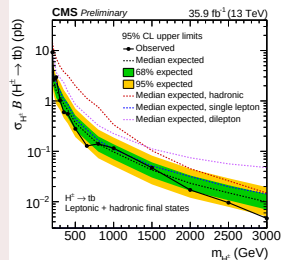
s-channel production



All hadronic



Combined leptonic+hadronic



- In all hadronic channel: no neutrinos = full mass reconstruction possible.
- Best sensitivity still from single lepton channel.
- All hadronic channel contributes most at high $H^{\pm}$ mass.
- No sensitivity in benchmark MSSM models if $m_h^{MSSM} = 125 \pm 3$ GeV.

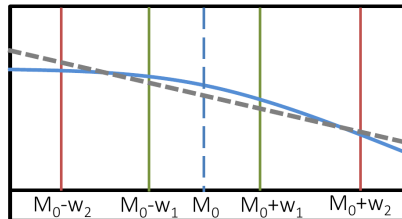
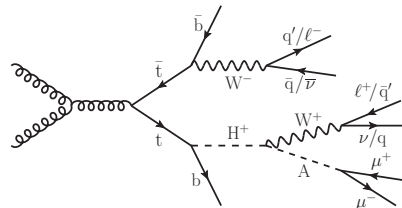
H[±] → W[±]a

PRL 123 (2019) 131802



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- New at the LHC !
- Relevant for low m_A .
- Trigger + low background: target $A \rightarrow \mu\mu$, $W \rightarrow \ell\nu$, $W \rightarrow qq$.
- Select $1e+2\mu$ or 3μ , ≥ 2 jets (≥ 1 b-tag).
- Excellent $m_{\mu\mu}$ resolution, low background yields.
- Strategy: cut&count in narrow mass windows.
- Window width optimised using Asimov significance in 10-GeV steps, linear interpolation in between.
- Background estimation: linear approximation from expectations in larger mass windows.



— True background p.d.f
--- Linear approximation

$m_{\mu\mu}$

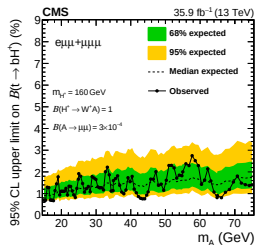
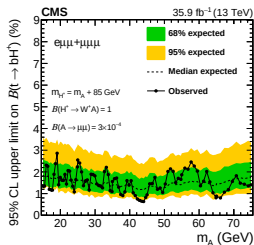
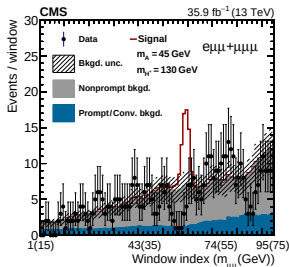
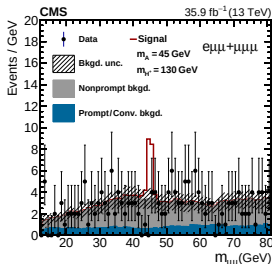
m_A range (GeV)	[15, 25]	[25, 35]	[35, 45]	[45, 55]	[55, 65]	[65, 75]	75
Window index	1–23	24–42	43–59	60–73	74–85	86–94	95
m_A step (GeV)	0.45	0.55	0.6	0.75	0.9	1.15	—
w (GeV)	[0.5, 0.7]	[0.7, 0.8]	[0.8, 1.0]	[1.0, 1.2]	[1.2, 1.5]	[1.5, 1.8]	1.8

$H^{\pm} \rightarrow W^{\pm} a$

PRL 123 (2019) 131802



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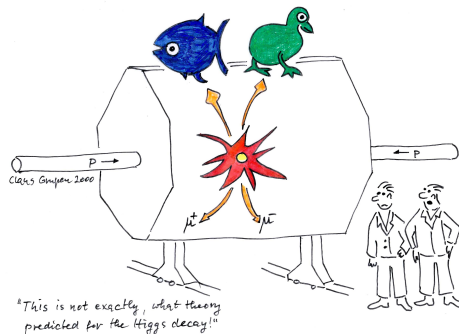


Outline

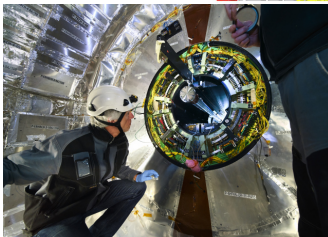
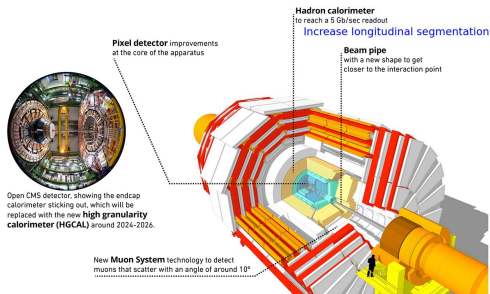


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- 1 Introduction
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- 3 Heavy Neutral Bosons
- 4 Light Neutral Bosons
- 5 Charged Bosons
- 6 **Expectations for Run 3**
- 7 The CMS upgrade for HL-LHC
- 8 BSM Higgs @ HL-LHC
- 9 Conclusion



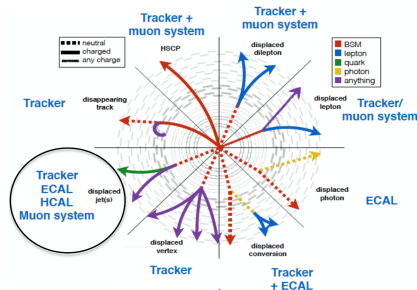
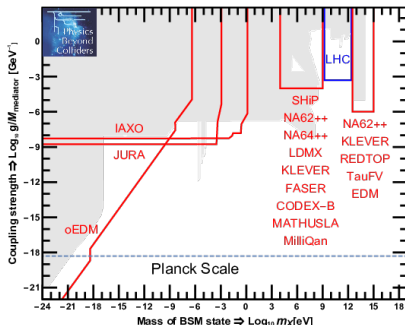
What will be new in Run 3 for CMS



Targeting further long-lived decays

- LHC designed for exploring the high-energy frontier.
- What about also going the other way ?
- Continue developments of triggers to cover blind spots: e.g. long-lived particles.

PBC 2019 report, arXiv:1901.09966

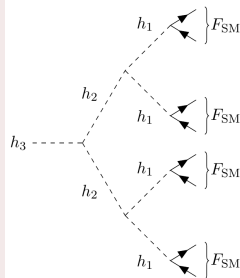
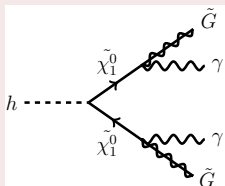


- HCAL upgrade: increased granularity.
- Plans for specific triggers to target displaced jets.
- Target $c\tau$ range 1–5 m.

Gain from increased statistics

Rare processes

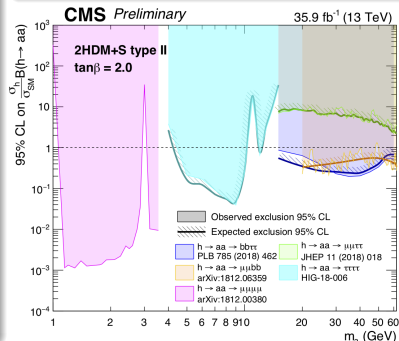
arXiv:1908.08554



- Exotic Higgs: expand further on 4- (6-,8-?) particle final states (e.g. 4b, SUSY cascade decays) or fermions+MET, yet little explored.
- LHC Higgs Working Group on Higgs Exotic Decays.

Uncertainties

- Constraints from precision SM: better theory uncertainties.
- V+Jets/ $t\bar{t}$ backgrounds.
- JET/MET uncertainties.



Outline



1 Introduction

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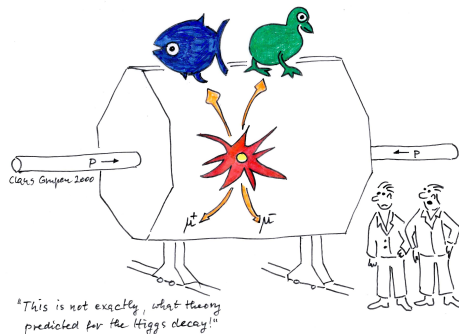
6 Expectations for Run 3

7 The CMS upgrade for HL-LHC

- Motivations for an upgrade
- Overview of the HGCal detector

8 BSM Higgs @ HL-LHC

9 Conclusion

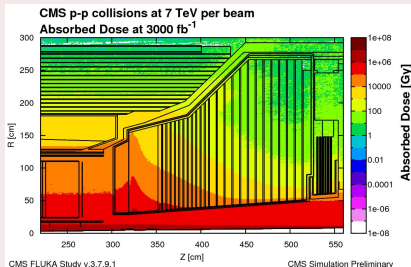


Need for upgrade: radiation damage

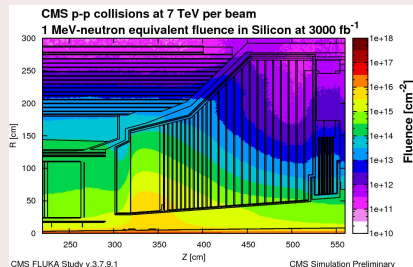


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Dose



Fluence



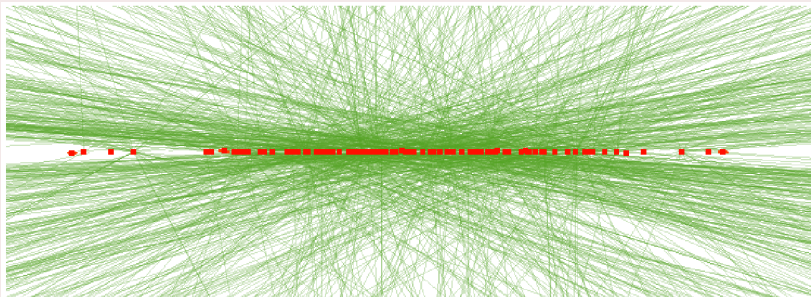
- Current detectors designed for integrated dose equivalent to 300 fb⁻¹.
- Endcap regions will suffer up to 1 MGy and 10¹⁶ neutron/cm².
- Drives choice of sensitive elements.

Motivation for the design: high pileup environment



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High PU environment: expect 200 PU !!

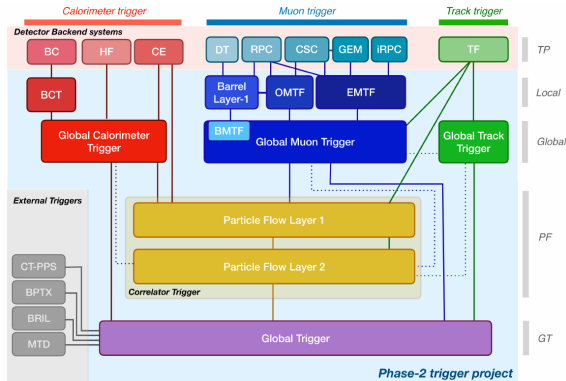


- This is a $t\bar{t}$ event: ability to distinguish the hard scattering $\Rightarrow$ e.g. high granularity.
- Include tracking+particle flow in L1 trigger, and timing information.

Triggering in CMS Phase 2



- Phase-2 L1 Trigger TDR in preparation, followed by HLT TDR.
- Proof of principles for implementation of complicated algorithms in FPGA firmware: e.g. particle-flow at L1, machine-learning trigger algorithms.



Status of the CMS Phase-2 Upgrade

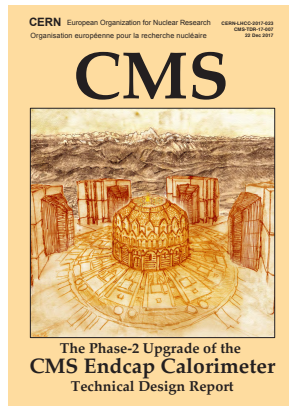


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- TP submitted in June 2015, CERN-LHCC-2015-010.
- Scoping document in Sep 2015, CERN-LHCC-2015-019.
- TDRs:
 - Tracker: CERN-LHCC-2017-009
 - Barrel calorimeter: CERN-LHCC-2017-011
 - End-cap calorimeter: CERN-LHCC-2017-023
 - Muon detectors: CERN-LHCC-2017-012
 - Interim L1 trigger: CERN-LHCC-2017-013

End-cap calorimeter for BSM Higgs

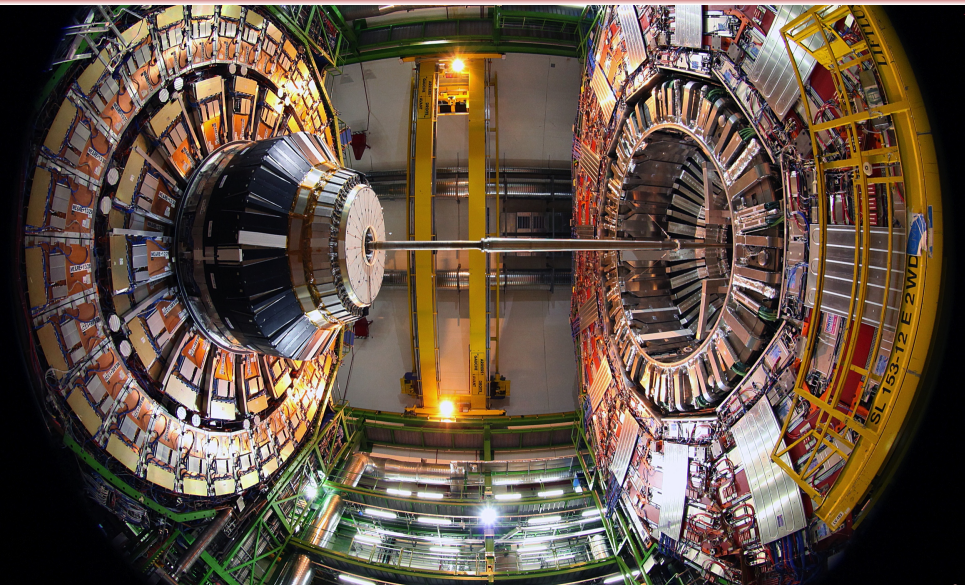
- Identification of b-jets, τ -jets, VBF jets (quark-gluon discrimination), jet substructures for boosted final states.
- Lots of handles for pileup rejection: impact on jet energy and missing energy resolutions.



The HGCAL project



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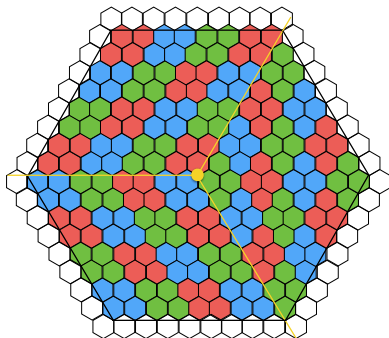


Cell geometry

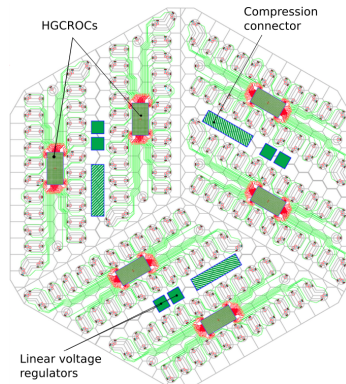


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- use 8-inch wafers
- to maximise active area: hexagonal sensor pads.
- Size: driven by physics and cell capacitance.



- Two sizes: 1 cm^2 (300 and $200 \mu\text{m}$) and 0.5 cm^2 ($120 \mu\text{m}$).
- 192 or 432 diodes per wafer.



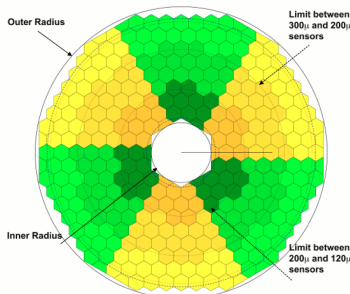
Wafer tiling



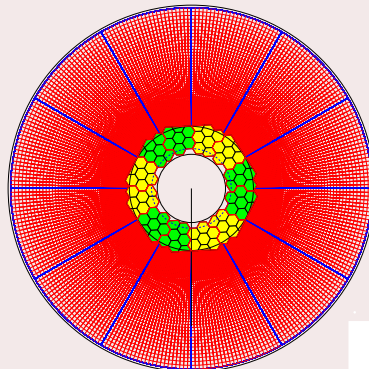
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- Two types of layers: Si only or Si-Scint mixed.
- Scint cell size constant in $\eta - \phi$, 2 granularities for front 4 (1°) and back 12 (1.25°) layers.

Si-only layers: example 9th layer



Si-Scint mixed layers: example 50th layer

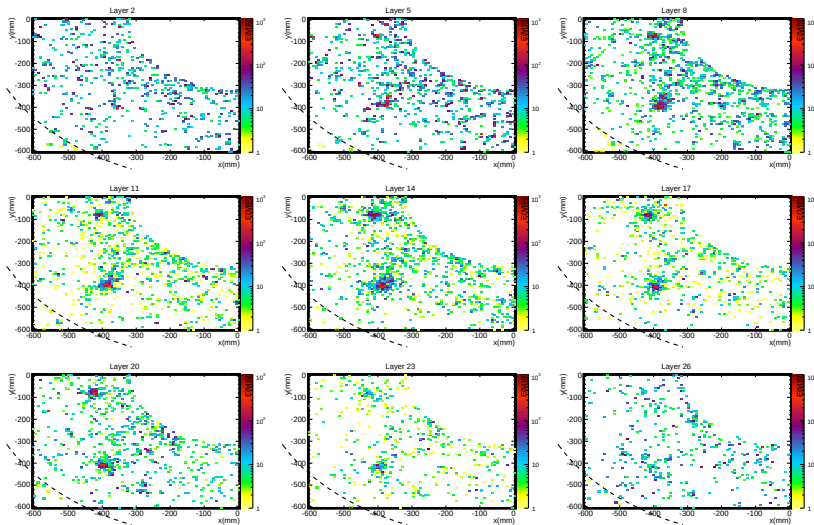


Photon (from a VBF $H \rightarrow \gamma\gamma$ event) in ECAL layers



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$p_T^\gamma = 22 \text{ GeV}$, PU 200

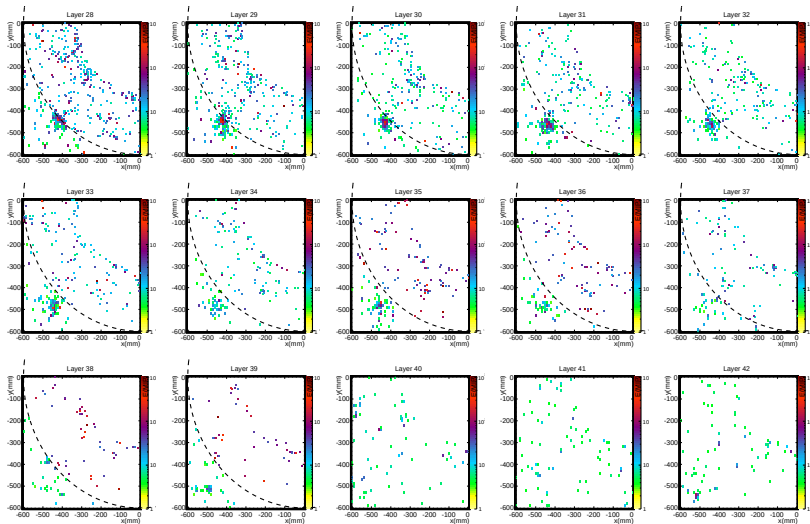


VBF Jet (from the VBF $H \rightarrow \gamma\gamma$ event) in HCAL layers



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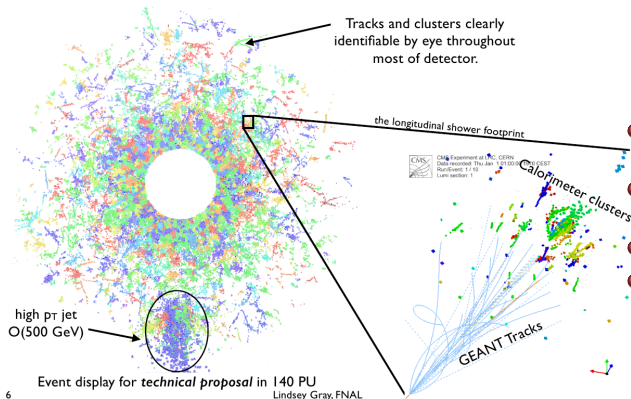
$p_T^{jet} = 118 \text{ GeV}$, max energy carried by $\pi^\pm + \pi^\pm + \gamma$, PU 200



Particle flow and physics performance

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- Particle flow: categorisation into charged EM/hadronic, photons and neutral hadronic deposits.
- High granularity: many handles for particle identification.



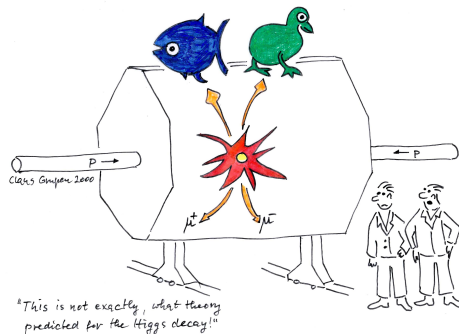
- shower start, longitudinal profile,
- direction to constrain primary vertex,
- layer-by-layer PU rejection,
- possibly timing information.

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Setup for projections



- CERN Yellow Report 2018: CERN-2019-007
- Use latest analysis techniques from 2016 data publications.
- Evolve systematic uncertainties as a function of luminosity, with different scenarios.

Scenario "S1"

- Use run-2 systematic uncertainties.
- Assume same performance of the detector.

Scenario "S2"

- Scale theory uncertainties by factor 2.
- Scale experimental systematics as $\sqrt{\mathcal{L}}$ up to a minimum threshold.
- Floor takes into account upgraded detector capabilities and ageing.

Simulation of the Phase-2 detector



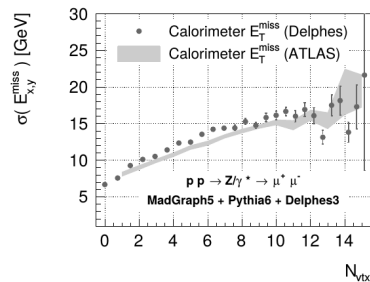
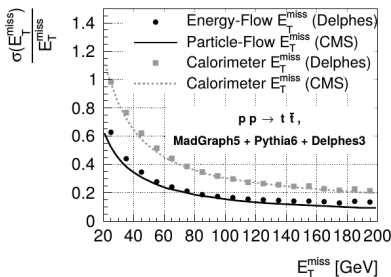
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Full-simulation

- Using Geant-4 with Phase-2 detector geometry.
- Benchmark object performance in 200 PU for fast simulation.
- High-granularity: need challenging clustering algorithm and particle-flow reconstruction $\Rightarrow$ Work in progress.

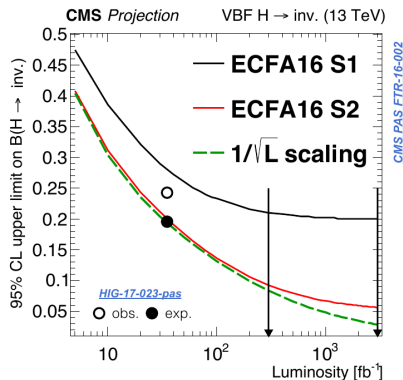
Delphes

- Fast parametrisation of the Phase-2 detector.
- High-statistics samples with 200 PU.
- JHEP 1402 (2014) 057.



Search for Higgs to invisible @ HL-LHC

- Existing ECFA projections for $Z(\ell\ell)H(\text{inv})$: [ATL-PHYS-PUB-2013-014](#), and $VBFH(\text{inv})$: [CMS-PAS-FTR-16-002](#).
- VBF channel drives the limit: studied with Delphes simulation of upgraded detectors in the context of HL-LHC.



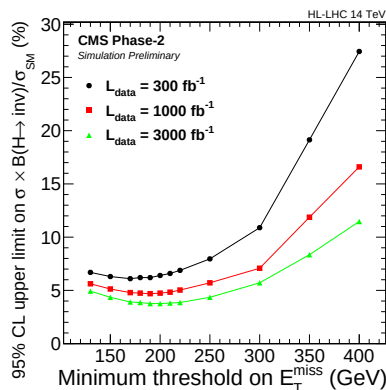
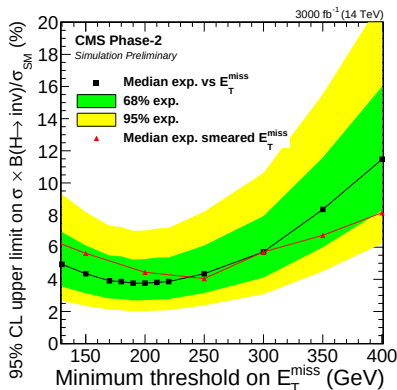
With 3000 fb^{-1} of luminosity

- Ball park: $\text{BR}(\text{inv}) < 6\%$.
- Very optimistic scaling: $\text{BR}(\text{inv}) < 3\%$.

Limits on $\text{BR}(H \rightarrow \text{inv})$



CMS-PAS-FTR-18-016



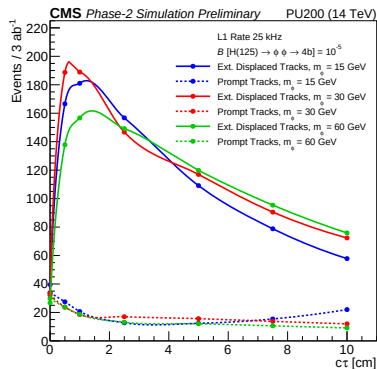
- Little impact from MET smearing after reoptimisation of the selection.
- Final limit $\simeq 4\%$.

Displaced jets



CMS-PAS-FTR-18-018

- Higgs decay to light (pseudo)scalar $h(125) \rightarrow \phi\phi \rightarrow 4j$ (4b).
- Now: triggered by H_T , too high thresholds due to backgrounds : blind spot!
- With upgraded detector: possibility to have L1 tracks.
- Compare standard and displaced L1-track-jet algorithms.
- 10-fold improvement in yields expected from reconstructing displaced vertices.

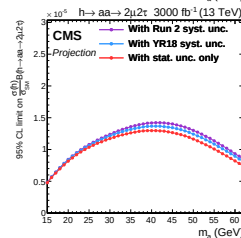
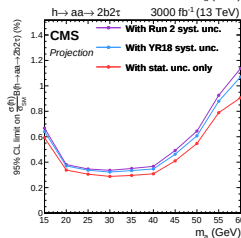
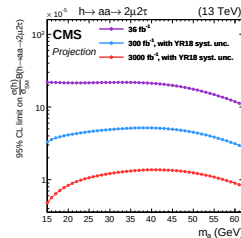
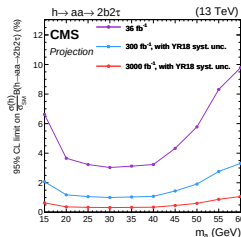


$h \rightarrow aa \rightarrow \mu\mu(bb)\tau\tau$ CMS-PAS-FTR-18-035



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- Projections using same object performance as in Run 2.
- Factor O(10) improvement.

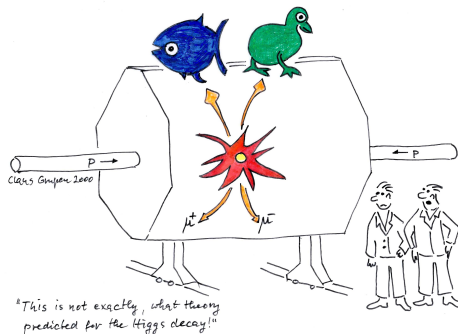


Outline



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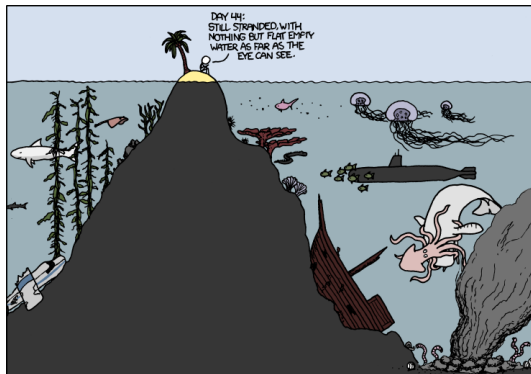
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Conclusion



- Many searches for an extended Higgs sector with run 2 data.
- Still $O(100 \text{ fb}^{-1})$ of data to be analysed!
- Run 3: plans for extended reach thanks to new triggers.
- Feedback loop experiments-theory: evolution of benchmark scenarios.
- HL-LHC: designing detectors capable of dealing with high-pileup conditions
⇒ Challenging projects.



Thank you for your attention



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**KEEP
CALM
AND
KEEP
LOOKING**

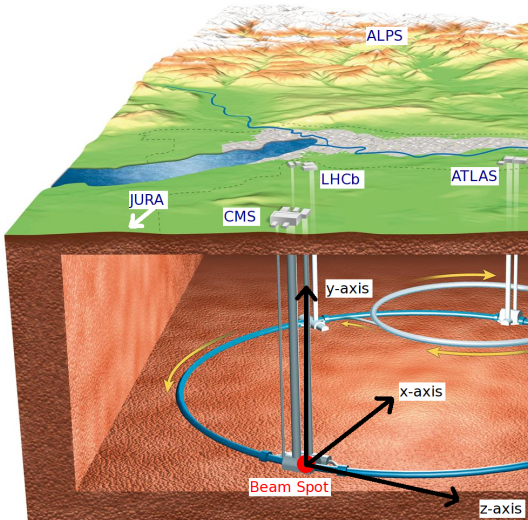


BACKUPS

The coordinate system



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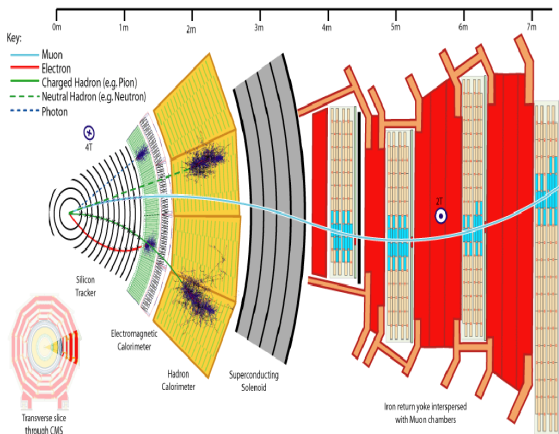
Definitions

- Coordinate system centered on beam spot.
- Transverse plane: x-y.
- Beam axis: z.
- Polar angle θ measured from the z-axis.
- Azimuthal angle Φ measured from the x-axis, in the x-y plane.
- Energy E , Transverse momentum p_T , transverse energy E_T .
- Rapidity: $E = m_T \cosh(y)$,
 $y = \frac{1}{2} \ln \left(\frac{E + p_z}{E - p_z} \right) = \tanh^{-1} \left(\frac{p_z}{E} \right)$.
- Pseudorapidity: $E = E_T \cosh(\eta)$,
 $\eta = -\ln \left(\tan \left(\frac{\theta}{2} \right) \right)$.

What particles look like ...



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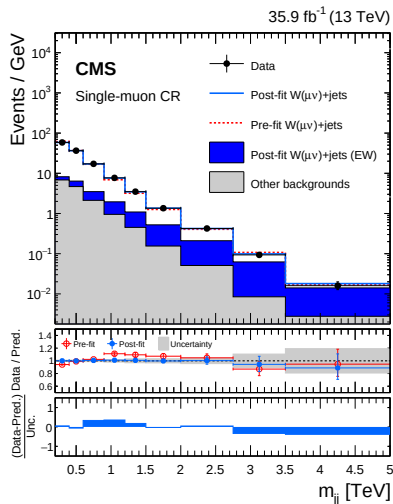
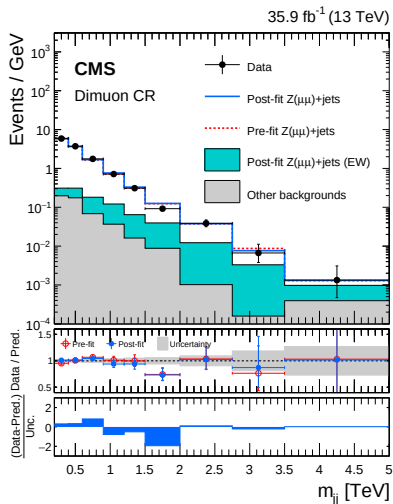
The HE-LHC project

 hadron collider parameters (pp)				
parameter	FCC-hh		HE-LHC	(HL) LHC
collision energy cms [TeV]	100		27	14
dipole field [T]	16		16	8.3
circumference [km]	100		27	27
beam current [A]	0.5		1.12	(1.12) 0.58
bunch intensity [10^{11}]	1 (0.5)		2.2	(2.2) 1.15
bunch spacing [ns]	25 (12.5)		25 (12.5)	25
norm. emittance $\gamma\epsilon_{x,y}$ [μm]	2.2 (2.2)		2.5 (1.25)	(2.5) 3.75
IP $\beta^*_{x,y}$ [m]	1.1	0.3	0.25	(0.15) 0.55
luminosity/IP [$10^{34} \text{ cm}^{-2}\text{s}^{-1}$]	5	30	25	(5) 1
peak #events / bunch Xing	170	1000 (500)	800 (400)	(135) 27
stored energy / beam [GJ]	8.4		1.4	(0.7) 0.36
SR power / beam [kW]	2400		100	(7.3) 3.6
transv. emit. damping time [h]	1.1		3.6	25.8
initial proton burn off time [h]	17.0	3.4	3.0	(15) 40

VBF Invisible: control region plots



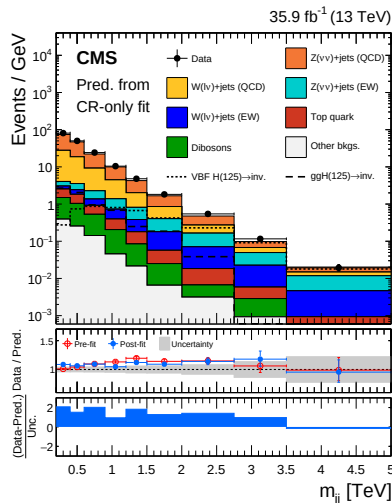
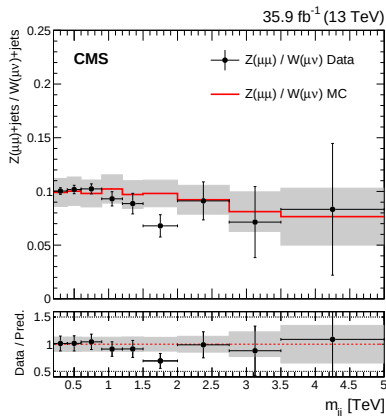
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VBF Invisible: control plots



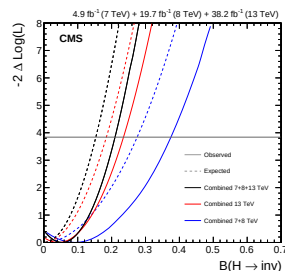
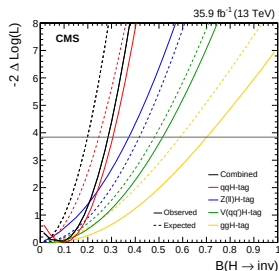
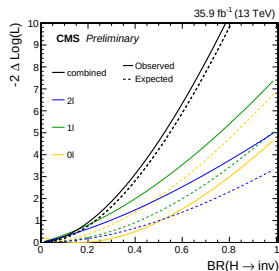
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H invisible: likelihood scans for combinations

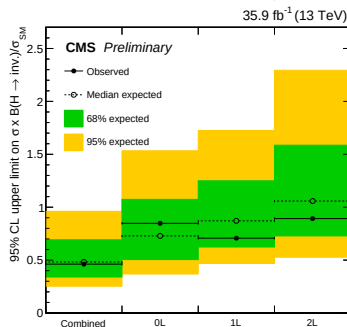
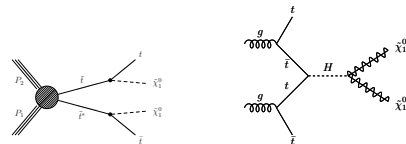
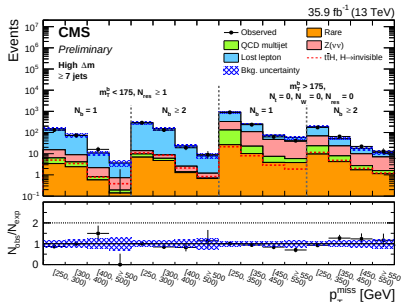


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ttH, H invisible

CMS-PAS-HIG-18-008

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95% CL limit on BR(inv)	
Observed	Expected
0.46	0.48

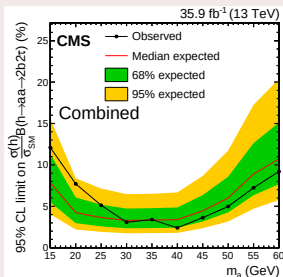
Source	All-hadronic	Semi-leptonic	Di-leptonic
QCD scale cross section	+5.8/-9.2%	+5.8/-9.2%	+5.8/-9.2%
QCD scale acceptance	0.7-14.0%	0.8-30.0%	1.0-7.0%
PDF cross section	3.6%	3.6%	3.6%
PDF acceptance	0.6-3.7%	0.5-4.0%	1.0-1.9%
Sample statistics	1.0-10.0%	1.6-11.2%	3.3-26.4%
Luminosity	2.5%	2.5%	2.5%
Trigger	2.0%	2.0%	0.2-0.5%
Pileup	0.2-2.0%	0.1-2.5%	0.0-3.0%
Jet energy scale	2.8-7.6%	2.8-9.7%	0.0-9.0%
B-tagging scale factor	0.3-3.3%	1.2-1.6%	0.1-1.3%
Lepton efficiency	0.0-0.7%	3.0-3.1%	3.8-5.5%
Unclassified p_T^{miss}	0.2-1.8%	—	0.1-12.3%
Top/W tagging	1.0-20%	—	—

Model-independent limits

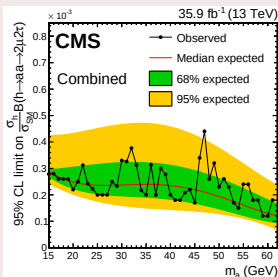


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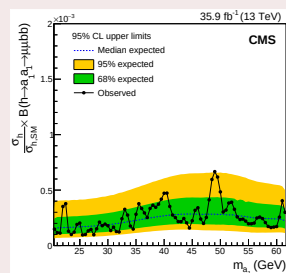
$H_{125} \rightarrow aa \rightarrow bb\tau\tau$



$H_{125} \rightarrow aa \rightarrow \mu\mu\tau\tau$



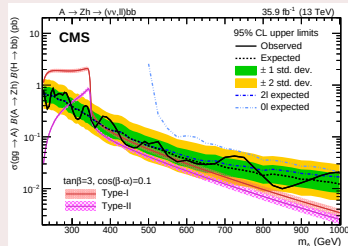
$H_{125} \rightarrow aa \rightarrow \mu\mu bb$



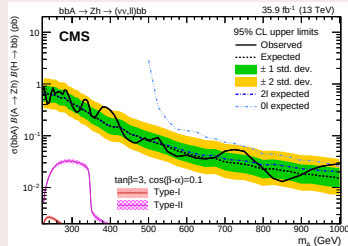
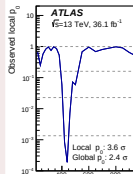
● No significant excess observed.

$H/A \rightarrow ZH_{125}$ Imperial College
London $H \rightarrow bb, Z \rightarrow ee, \mu\mu, \nu\nu$

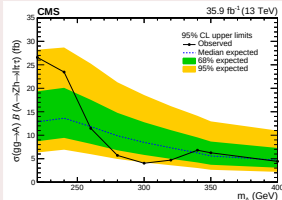
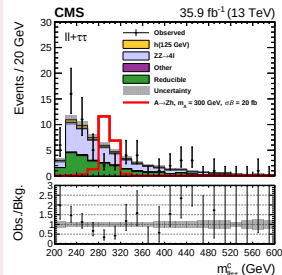
● arXiv:1903.00941 (EPJC)



JHEP 03 (2018) 174

 $H \rightarrow \tau\tau, Z \rightarrow ee, \mu\mu$

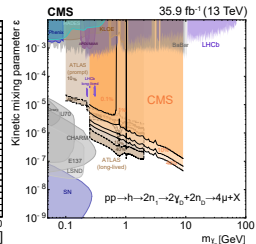
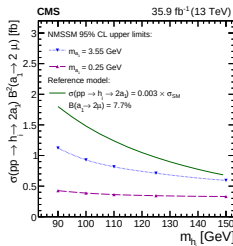
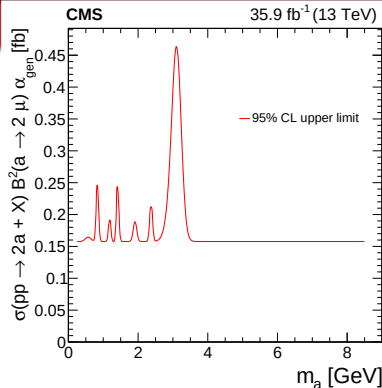
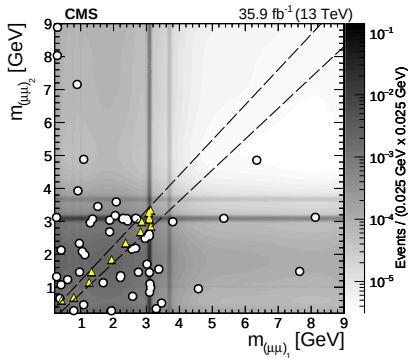
● arXiv:1910.11634



$H_{125} \rightarrow aa \rightarrow 4\mu$ low mass



- PLB 796 (2019) 131
- Using displaced vertices.



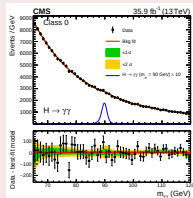
Low mass Higgs to $\gamma\gamma$, $70 < m_H < 110$ GeV



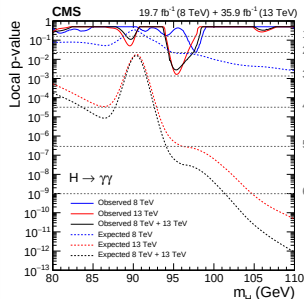
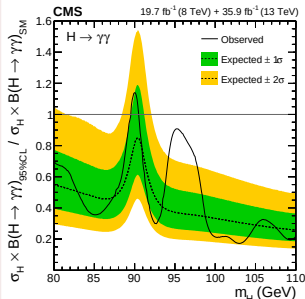
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PLB 796 (2019) 131

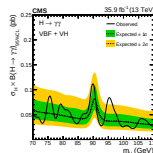
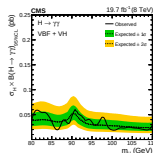
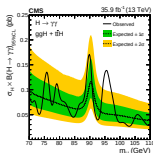
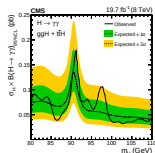
Strategy: bump hunt



Results



- Local (global) significance @ 95.3 GeV : 2.8 (1.3) σ .
- To be checked with more data!



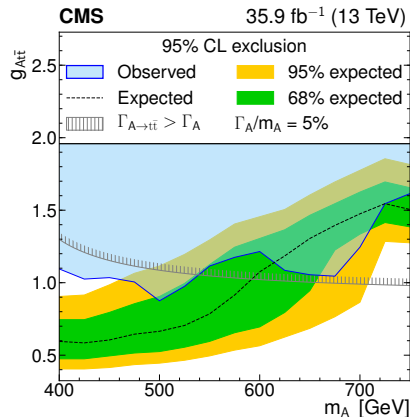
$H \rightarrow t\bar{t}$: systematics

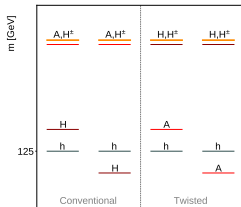


Uncertainty (# of parameters)	Type	Affected process	Correlation
Jet p_T scale (19)	shape	All	All
Jet p_T resolution	shape	All	All
Unclassified p_T^{miss}	shape	All	All
btagging heavy-flavor jets	shape	All	All
btagging light-flavor jets	shape	All	All
Pileup	shape	All	All
Electron identification	shape	All	All
Muon identification	shape	All	All
Single-electron trigger	shape	All	$e, \ell\ell$
Single-muon trigger	shape	All	$\mu, \ell\ell$
Luminosity calibration	norm.	All	All
Renorm. scale SM $t\bar{t}$	shape	SM $t\bar{t}$	All
Fact. scale SM $t\bar{t}$	shape	SM $t\bar{t}$	All
Parton shower FSR $t\bar{t}$	shape	SM $t\bar{t}$	All
h_{damp}	shape	SM $t\bar{t}$	All
Top quark mass	shape	SM $t\bar{t}$	All
Top quark p_T (2)	shape	SM $t\bar{t}$	All
PDF (3)	shape	SM $t\bar{t}$	All
Renorm. scale res. signal	shape	Resonant signal	All
Renorm. scale int. signal	shape	Interference signal	All
Fact. scale res. signal	shape	Resonant signal	All
Fact. scale int. signal	shape	Interference signal	All
SM $t\bar{t}$ norm.	norm.	SM $t\bar{t}$	All
Single top t channel norm.	norm.	Single top t channel	ℓ
Single top s channel norm.	norm.	Single top s channel	ℓ
Single top tW channel norm.	norm.	Single top tW channel	All
W + jets norm.	norm.	W + jets	ℓ
$Z/\gamma^* + \text{jets}$ norm.	norm.	$Z/\gamma^* + \text{jets}$	ℓ
$Z/\gamma^* + \text{jets}$ norm. from data	norm.	$Z/\gamma^* + \text{jets}$	$\ell\ell$
Diboson norm.	norm.	Diboson	All
$t\bar{t}V$ norm.	norm.	$t\bar{t}V$	All
QCD multijet norm. from data, e	norm.	QCD multijet	e
QCD multijet norm. from data, μ	norm.	QCD multijet	μ
MC statistical uncertainty (365)	shape	All	No

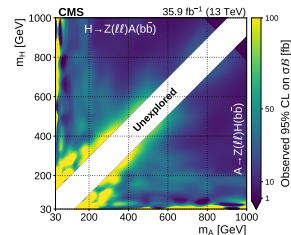
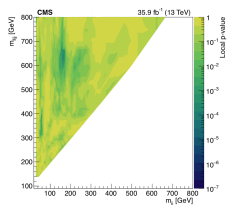
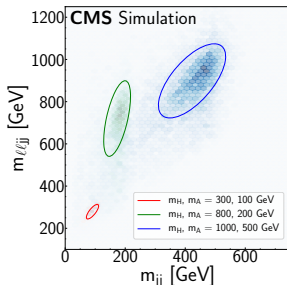
$H \rightarrow t\bar{t}$ Imperial College
London

- Largest excess: $m_A = 400$ GeV, width 4%.
- Local significance: $3.5 \pm 0.3\sigma$.
- With LLE: 1.9σ , p-value = 0.028.
- Driven by dilepton channel.
- Higher order EWK corrections to SM $t\bar{t}$ close to 350 GeV prod threshold expected to play a role.



$H/A \rightarrow ZA/H$ Imperial College
London

Source	Background yield variation	Signal yield variation
Electron identification and isolation	2.7%	2.6%
Integrated luminosity	2.5%	2.5%
Jet energy scale	2.1–2.4%	0.1–0.3%
VV(V) tagging (heavy-flavour jets)	2.3%	2.0%
PDFs	1.0%	0.5%
Pileup	0.3–0.9%	0.7–1.3%
b tagging (light-flavour jets)	0.7–0.8%	<0.1%
Muon identification and isolation	0.5%	0.4%
Trigger efficiency	0.1–0.3%	0.1–0.3%
Jet energy resolution	0.2%	0.2%
Affecting only tt (31.8% of the total bkg.)		
μ_R and μ_F scales	12.2–12.3%	
tt cross section	5.3%	
Affecting only Drell–Yan (64.5% of the total bkg.)		
μ_R and μ_F scales	9.6%	
Drell–Yan cross section	4.9%	
Drell–Yan additional uncertainty	2.1–2.2%	
Simulated sample size	0.5–1.3%	
Affecting only VV (1.1% of the total bkg.)		
μ_R and μ_F scales	4.3–4.8%	
Affecting only signal		1.8%



H to aa to 4 tracks: systematics



Source	Value	Affected sample	Type	Effect on the total yield
Stat. unc. in $C(i, j)$	3–60%	bkg.	bin-by-bin	—
Extrapolation unc. in $C(i, j)$	—	bkg.	shape	—
Unc. in $f_{1D}(i)$	—	bkg.	shape	—
Integrated luminosity	2.5%	signal	norm.	2.5%
Muon id. and trigger efficiency	2% per muon	signal	norm.	4%
Track id. efficiency	4–12% per track	signal	shape	10–18%
MC stat. unc. in signal yields	8–100%	signal	bin-by-bin	5–20%
Theoretical uncertainties in the signal acceptance				
μ_R and μ_F variations		signal	norm.	0.8–2%
PDF		signal	norm.	1–2%
Theoretical uncertainties in the signal cross sections				
$\mu_{R,F}$ variations (ggF)	5–7%	signal	norm.	5–7%
$\mu_{R,F}$ variations (other processes)	0.4–9%	signal	norm.	<0.5%
PDF (ggF)	3.1%	signal	norm.	3.1%
PDF (other processes)	2.1–3.6%	signal	norm.	<0.5%

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

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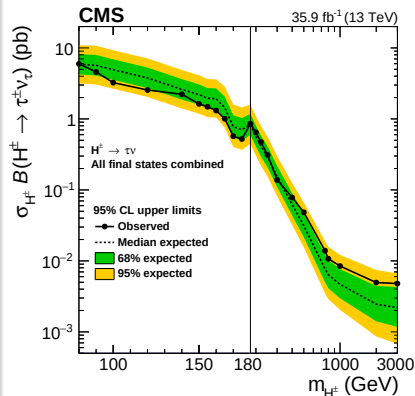
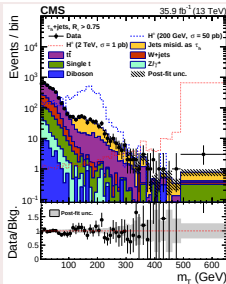
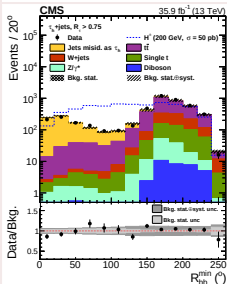


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Strategy

- All hadronic (τ_h +jets) and leptonic ($\ell + \tau_h$, $\ell + n\tau_h$) FS.
- Combination of 36 categories.
- Discriminating variables: R_{bb} , $m_T(\ell, \text{MET})$, $R_\tau = p_T^{\text{track}} / p_T^{\tau_h}$.

$$R_{bb}^{\min} = \min_n \left\{ \sqrt{(180^\circ - \Delta\phi(\tau_h, \vec{p}_T^{\text{miss}}))^2 + (\Delta\phi(\text{jet}_n, \vec{p}_T^{\text{miss}}))^2} \right\}$$



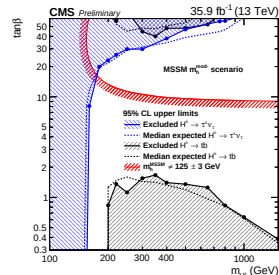
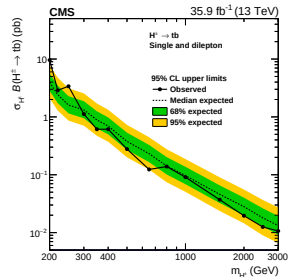
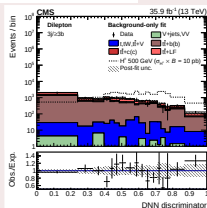
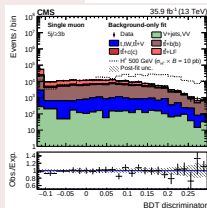
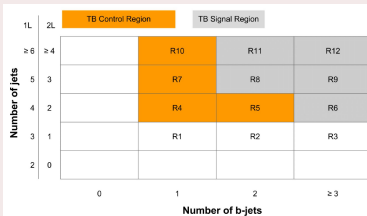
$H^\pm \rightarrow tb$ leptonic

arXiv:1908.09206

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Strategy

- Combination of ℓ +jets and $\ell\ell$ +jets.
- BDT for ℓ +jets, DNN for $\ell\ell$ +jets, both using O(15) discriminating variables.

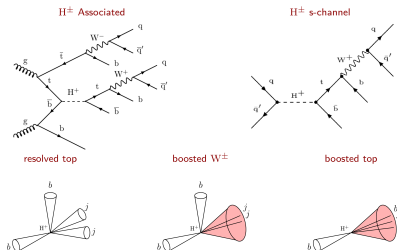


$H^\pm \rightarrow tb$, all hadronic

CMS-PAS-HIG-18-015



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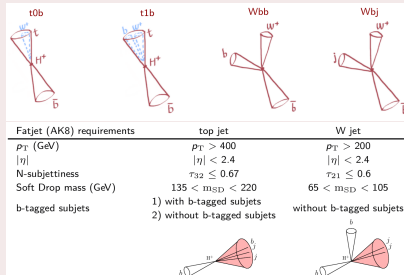


Resolved

- ≥ 7 ak4 jets, $p_T^{6(7)} > 40(30 \text{ GeV})$, $|\eta| < 2.4$,
- ≥ 3 CSV medium b-tag,
- $H_T > 500 \text{ GeV}$,
- 2 top candidates, BDT selection with $\varepsilon_{sig} \simeq 92\%$, $\varepsilon_{bkg} \simeq 6\%$

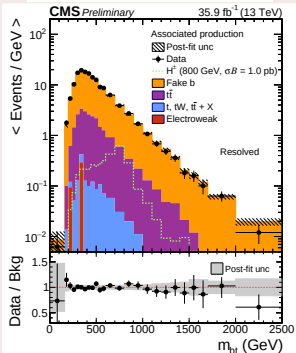
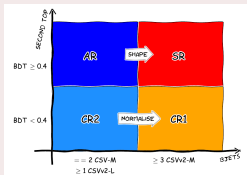
Boosted

- ≥ 1 CSV medium b-tag, $p_T > 40 \text{ GeV}$, $|\eta| < 2.4$,
- ≥ 1 ak8 fatjet with W or top tag,
- $E_T^{miss} < 200 \text{ GeV}$.

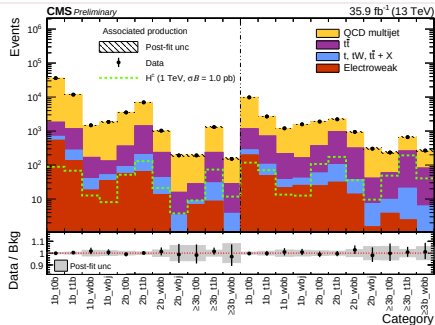
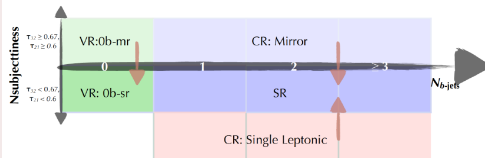


$H^\pm \rightarrow tb$, all hadronicImperial College
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Resolved



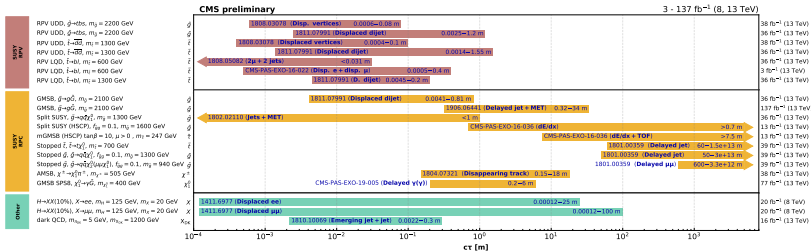
Boosted



On long-lived searches



Overview of CMS long-lived particle searches



Selection of observed exclusion limits at 95% C.L. (theory uncertainties are not included). The y-axis tick labels indicate the studied long-lived particle.

July 2019

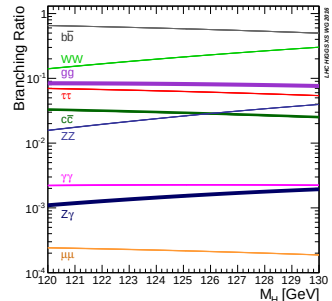
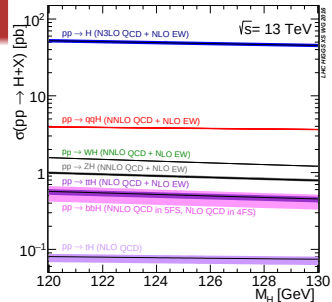
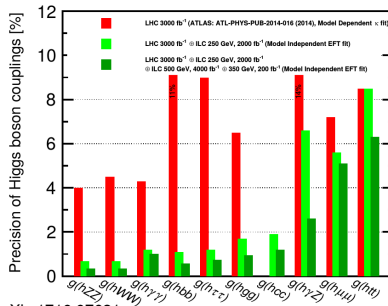
Experimental Systematic Uncertainties



Source	Component	Run 2 uncertainty	Projection minimum uncertainty
Muon ID		1–2%	0.5%
Electron ID		1–2%	0.5%
Photon ID		0.5–2%	0.25–1%
Hadronic tau ID		6%	2.5%
Jet energy scale	Absolute	0.5%	0.1–0.2%
	Relative	0.1–3%	0.1–0.5%
	Pileup	0–2%	Same as Run 2
	Method and sample	0.5–5%	No limit
	Jet flavour	1.5%	0.75%
	Time stability	0.2%	No limit
Jet energy res.		Varies with p_T and η	Half of Run 2
MET scale		Varies with analysis selection	Half of Run 2
b-Tagging	b-/c-jets (syst.)	Varies with p_T and η	Same as Run 2
	light mis-tag (syst.)	Varies with p_T and η	Same as Run 2
	b-/c-jets (stat.)	Varies with p_T and η	No limit
	light mis-tag (stat.)	Varies with p_T and η	No limit
Integrated lumi.		2.5%	1%

Precision Physics at a hadron collider

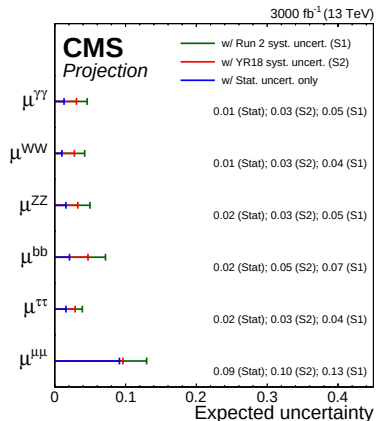
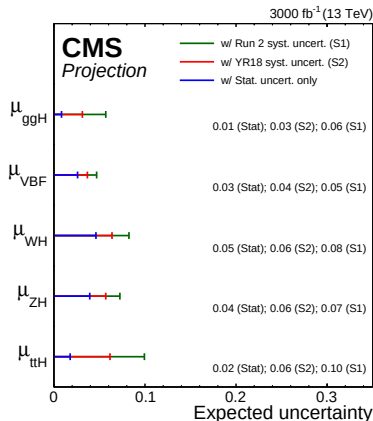
- Overall objective: characterise the Higgs boson properties.
- Also: explore rare decays, constrain BSM decays.
- What can be achieved at HL-LHC?



Expected precision on Higgs signal strengths



CMS-PAS-FTR-18-011



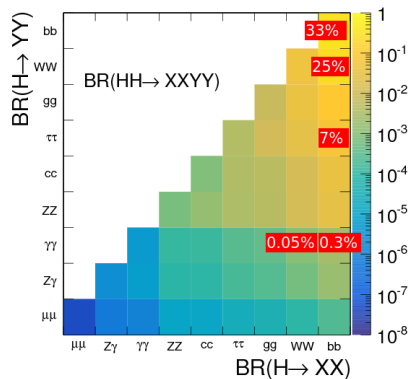
- Expect similar results from ATLAS (in progress) $\Rightarrow$ Combination.
- Sensitive to BSM models with O(5%) predicted deviations.

Di-Higgs production and Higgs self-coupling



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- Non-resonant HH production: benchmark channel.
- Run-2: reaching $O(15 \times \text{SM})$.
- HL-LHC: expect significances at the level of $1-2\sigma$.
- Combining all channels and ATLAS+CMS: evidence ?



Systematics for Higgs to invisible analysis



CMS-PAS-FTR-18-016

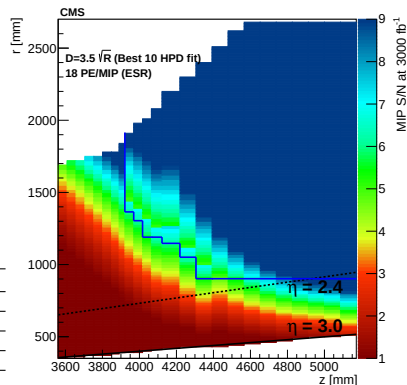
Systematic	From 2016 data	This analysis
e-ID	1%(gsf)⊕1%(idiso)	1%
μ-ID	1%(reco)⊕1%(id)⊕0.5%(iso)	0.5%
e-veto	0.6%(gsf)⊕1.5%(idiso)	1%
μ-veto on QCD V+jets	5%(reco)⊕5%(id)⊕2%(iso)	2%
μ-veto on EWK V+2jets	10%(reco)⊕10%(id)⊕6%(iso)	6%
τ-veto	1–1.5% for QCD–EWK	0.5–0.75%
b-tag-veto	0.1% (sig) 2% (top)	0.05% (sig) 1% (top)
JES	14%(sig) 2%(W/W) 1%(Z/Z)	4.5%(sig) 0.5%(W/W) 0.2%(Z/Z)
Lumi	2.5%	1%
QCD multijet	1.5%	1.5%
Theory on W/Z ratio	12.5%	7%
ggH normalisation	24%	20%
QCDscale_qqH	+0.4%	+0.4%
QCDscale_accept_qqH	−0.3%	−0.3%
pdf_qqbar	2%	1%
pdf_accept_qqbar	2%	1%
pdf_qqbar	1%	1%
QCDscale_ggH2in	40%	20%
QCDscale_YR4_ggH	+4.6%	+2%
pdf_gg	−6.7%	−4%
pdf_gg	3.2%	1.5%
UEPS	16.8%	9%

Choice of sensitive elements



- Requirement to maintain performance up to 3000 fb^{-1} of integrated luminosity $\Rightarrow$ Signal/Noise ≥ 5 for scintillators.
- Radiation-resistant Silicon sensors for higher-dose region.
- Cheaper plastic scintillator in lower-dose region.

	CE-E	CE-H	
	Si	Si	Scintillator
Area (m^2)	368	215	487
Channels (k)	3916	1939	389
Si modules (Tileboards)	16 008	8868	(3960)
Partial modules	1008	1452	—
Weight (t)	23	205	
Si-only planes	28	8	
Mixed (Si+Scint) planes		16	

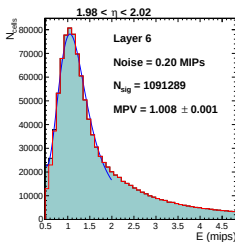
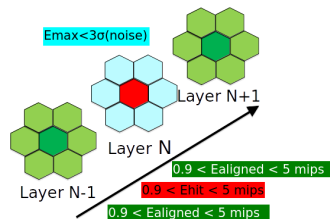


Calibration

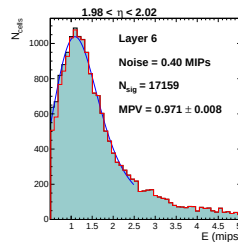
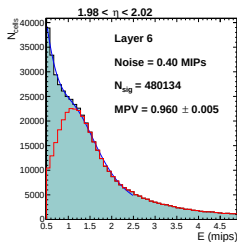


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- Maintain EM energy resolution: intercalibration within 3% to maintain constant term at 0.5%.
- Requires MIP calibration to 3% throughout lifetime of ECAL, i.e. up to $S/N \simeq 2$.
- Looser requirement in HCAL layers.
- Check performance with simple mip-tracking algorithm.



3-layer tracking

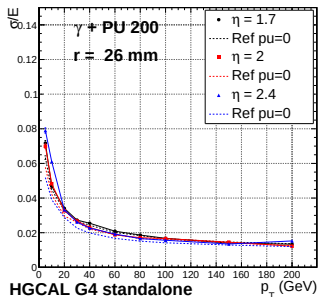
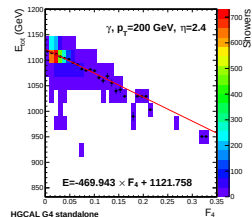


5-layer tracking

Energy resolution of EM showers



- Single photons in standalone setup, unconverted.
- PU impacts larger signal regions.
- Making the most of the high granularity: use deposit in back layers to predict leakage rate, correct for it $\Rightarrow$ improves constant term.



$$\sigma/E = s/\sqrt{E} \oplus c \oplus (n/E)$$

Si (μm)	s ($\sqrt{\text{GeV}}$)	c
300	0.24	0.008
200	0.25	0.008
100	0.28	0.005

$$\sigma/M_{h \rightarrow \gamma\gamma} = 1.6\%$$

