CMS Recent Results & Prospects for probing Higgs CP using $H \rightarrow \tau\tau$

Yuta Takahashi (CERN)
Physics Seminar @ KEK
30 September 2015
Outlook

• Introduction

• CMS status & First results at 13TeV

• Improvement of the tau identification

• Prospective study for measuring Higgs CP using $H \rightarrow \tau\tau$
What we learned from LHC run-1?

SM describes all observations very well.

A fundamental scalar (aka Higgs boson) with $m_H = 125$ GeV that couples to mass.

No new physics (yet)

- *the* Higgs boson?
- First scalar of many?
- Elementary or composite?
- Couples to Dark matter?
- etc…

Direct search

Precise measurement of the Higgs properties (couplings, CP, exotic decays, …)
Run-2 might give us an answer

<table>
<thead>
<tr>
<th>Minimum bias</th>
<th>ZZ</th>
<th>WH</th>
<th>H (ggF)</th>
<th>H (VBF)</th>
<th>tt</th>
<th>ttH</th>
<th>stop pair (0.7 TeV)</th>
<th>stop pair (0.9 TeV)</th>
<th>gluino pair (1.5 TeV)</th>
<th>gluino pair (2.5 TeV)</th>
<th>Z' SSM (3 TeV)</th>
<th>Q* (4 TeV)</th>
<th>QBH (6 TeV)</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>1.1</td>
<td>2.1</td>
<td>2.1</td>
<td>2.6</td>
<td>3.9</td>
<td>4.7</td>
<td>11</td>
<td>16</td>
<td>72</td>
<td>5700 (13 / 8: 2700)</td>
<td>13</td>
<td>87</td>
<td>12000</td>
</tr>
</tbody>
</table>

230 pb\(^{-1}\) (13 TeV) = run-1 (20 fb\(^{-1}\), 8 TeV) → Large benefit for NP search

System mass (GeV)

\[\sigma(13\text{TeV}) / \sigma(8\text{TeV})\]
We are in run-2 (until 2018)

We are here (1.1 fb⁻¹ so far)

July: 100 pb⁻¹ of data with 50ns bunch spacing

Aug: Start 25ns run

3 - 4 fb⁻¹

L_{peak} = 10^{34} (1/cm²s)

100 fb⁻¹ @ 2018
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CMS detector

CMS : diameter 15m x length 22m
(ATLAS : diameter 25m x length 44m)

Strong B field (3.8T) + Total absorption type ECAL
→ Nice e/γ resolution (σ_{mγγ}/m_{γγ} ~ 0.8%)
Upgrade during long shutdown

New photo sensors for the Outermost HCAL

New beam pipe for 4th pixel layer

4th muon station

DAQ Trigger

Commissioning crew of Hadron calorimeter
Several recovery campaigns have re-established an almost perfect status.

➡ Please note that the scale starts at 90%!

96 – 100% eff.

1092 pb⁻¹ (~35% with B = 0T)

- Magnet has been operated intermittently due to problems in cryogenic system (clogging effects of contaminants in compressor)
- Magnet can be operated but continuous up-time is still limited
- A strategy for complete component replacement or cleaning during the end of the year shutdown
Selected physics results @ 13TeV


- Charged hadron multiplicity v.s $\eta$ (FSQ-15-001)
- Di-jet bump search (EXO-15-001)
- $Tt\bar{b}$ cross-section
  - Di-lepton (TOP-15-003)
  - Semi-lepton (TOP-15-005)
  - Differential (TOP-15-010)
- Single-top (TOP-15-004)
- Ridge analysis (FSQ-15-002)
- $W$, $Z$ inclusive cross-section (SMP-15-004)
- $W'$, $Z'$ search (DP-2015-037, DP-2015-039)
Charged Hadron multiplicity v.s $\eta$

- First publication from LHC after 1.5h of data-taking
- 0.5% pp interaction per bunch crossing (clean), $B = 0T$

Counting experiment using pixel detector

Relevant to the relative weight of soft / hard scattering

$$\frac{dN_{ch}}{d\eta_{|\eta| < 0.5}} = 5.49 \pm 0.01 \text{ (stat)} \pm 0.17 \text{ (sys)}$$

Relevant to tune theory / MC predictions at 13 TeV
Search for di-jet resonance

Classical bump search

CMS EXO-12-059

CMS Run-1
8 TeV

19.7 fb⁻¹ (8 TeV)

σ(13TeV) / σ(8TeV)

- One of the most beneficial analysis by jumping 8 → 13 TeV
- Quite simply analysis, hence suitable for an early analysis
Search for di-jet resonance

2 jets ($p_T > 60$ and $30$ GeV) and $|\Delta \eta_{jj}| < 1.3$ (to kill t-channel prod.)

Background fitted by

$$\frac{d\sigma}{dm_{jj}} = p_0 \frac{(1 - x)^{p_1}}{xp_2^2}, \quad x = \frac{m_{jj}}{\sqrt{s}}$$

$q^* (4.5$ TeV) $\rightarrow$ qg

For $M_{jj} > 3.5$ TeV,
- 4 events obs.
  (4.6 Bkg. exp, 0.8 sig. exp)

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<td>2.7</td>
</tr>
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</table>
• Fundamental for most of the physics analysis
  \[ \sigma_{tt}(13\text{TeV}) \sim 800\text{pb} \rightarrow 1\text{Hz} @ L = 10^{34} \text{ (/cm}^2\text{s)} \rightarrow \text{Top-factory} \]
• Di-lepton, lep + jets used to extract cross-section

- Opposite-sign e + muon with $p_T > 20 \text{ GeV}$
- $\geq 2$ jets with $p_T > 30 \text{ GeV}$

\[
\sigma_{tt} (e\mu) = 722 \pm 60 \text{ (stat)} \pm 62 \text{ (sys)} \pm 93 \text{ (lum)} \text{ pb} \\
\sigma_{tt} (l+j) = 836 \pm 27 \text{ (stat)} \pm 84 \text{ (sys)} \pm 100 \text{ (lum)} \text{ pb} \\
\]

\[ \sigma_{tt}^{\text{NNLO}} = 832^{+40}_{-46} \text{ pb} \]
**W', Z'**: early look at 13TeV

**W' → μν**
- 1 muon (> 55 GeV),
- $\Delta\phi (\mu, \nu) > 2.5$ rad

**Z' → μμ**
- 2 muons ($p_T > 48$ GeV),
- Opposite-sign

**Z' → ee**
- 2 electrons ($E_T > 35$ GeV)
- Early alignment data used

Electrons are not affected by miss-alignment

2.9 TeV

Exp. Bkg (M > 2 TeV) ~ 0.007
Spectacular ee event

Back-to-back

Energy balanced (resonance-like)

- Run-1 upper limit: $\sigma = 4.4$ fb @ 13TeV
- If this is signal, 1 event @ 42pb$^{-1}$ $\rightarrow \sigma = 24$ fb (we are just lucky ?)

Negative Colins-Soper angle (DY bkg peaks towards positive)

<table>
<thead>
<tr>
<th></th>
<th>electron 0</th>
<th>electron 1</th>
</tr>
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<tbody>
<tr>
<td>$E_T$</td>
<td>1260 GeV</td>
<td>1280 GeV</td>
</tr>
<tr>
<td>$\eta$</td>
<td>-0.24</td>
<td>-1.31</td>
</tr>
<tr>
<td>$\phi$</td>
<td>-2.74 rad</td>
<td>0.42 rad</td>
</tr>
<tr>
<td>charge</td>
<td>-1</td>
<td>+1</td>
</tr>
<tr>
<td>mass</td>
<td>2.91 TeV</td>
<td></td>
</tr>
<tr>
<td>$\cos \theta^s_{cs}$</td>
<td>-0.49</td>
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Tau ID plays an important role

CMS, 4.9 fb$^{-1}$ at 7 TeV, 19.7 fb$^{-1}$ at 8 TeV

**Run-1**

- Tau ID efficiency: 50 – 60% @ 1% fake rate
- Tau energy scale: 0.95 – 1

High tau ID eff. up to high $p_T$ (for heavy Higgs analysis) is needed
**τ_h identification @ CMS run-1**

$$\tau^- \rightarrow \pi^- \pi^0 \nu \quad (Br = 26\%)$$

1. Reconstruct π⁰ from observed γ, e± within a fixed-size window (strip)

2. Calculate m(π⁻ + strip), See compatibility with tau

3. To separate real taus from QCD jets, require the energy deposit in isolation annulus < 2 GeV
Limitation of run-1 $\tau_h$ ID

- $e^+/e^-$ sometimes goes outside strip
- This will produce energy deposit in the isolation annulus, causing isolation cuts ($< 2\text{GeV}$) to fail
- The effect is more pronounced at higher tau $p_T$, as the decay product becomes higher $p_T$
Better $\tau_h$ Identification for run-2

The extent by which $e^+/e^-$ goes outside strip depends on $p_T(e)$

$\rightarrow$ low $p_T$ electron can easily go outside strip

$\rightarrow$ Dynamically change the strip size as a function of $p_T(e)$
Performance improvement

- Efficiency improved
- Efficiency drop recovered

Isolation efficiency

- Dynamic
- Standard (run-1)
- VBF

Energy response

- Better energy response compared to run-1
- Run-1
- New tau ID
With a re-optimization of the new algorithm ...

$\tau^-$ → $\pi^- \pi^0 \nu$

- Proposal
- Pioneered all the development
- adopted as the default algorithm for CMS run-2

$\Delta \kappa < \sim 5\%$ (32)

$\Gamma_d = \Gamma(h \rightarrow \pi^+ + \pi^- + 2\nu)$

$gg: 1.514^{+0.551}_{-0.476}$

$ZZ: 1.549^{+0.953}_{-0.661}$

$WW: 0.623^{+0.593}_{-0.479}$

$\tau^{\pm} \rightarrow \pi^{\pm}$

$\tau^{\pm} \rightarrow \pi^{\pm} \pi^0 \nu$

$\tau^{\pm} \rightarrow \pi^{\pm} \pi^0 \pi^0 \nu$

$\tau^{\pm} \rightarrow \pi^{\pm} \pi^+ \pi^- \nu$

$\sim 30\%$ reduction of the fake rate at the same efficiency point (and high efficiency at high tau $p_T$)
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Why Higgs CP is interesting?

- SM: One Higgs, CP eigenstate; CP even
- BSM models
  - MSSM: 3 Higgs, CP eigenstate; even ($h^0, H^0$) and odd (A)
- More generally
  - Observed Higgs does not necessarily to be CP eigenstate
    → Mixed state of CP even and odd

\[ |H\rangle = \cos \alpha |\text{even}\rangle + \sin \alpha |\text{odd}\rangle \]

\( \alpha : \) CP mixing angle

\[ \begin{cases} \text{SM: } \alpha = 0 \\ \text{CP odd: } \alpha = \pi/2 \\ \text{Max. mixing: } \alpha = \pi/4 \end{cases} \]

Measuring the CP property (mixing angle) = probe for NP
What do we know about CP?

- Higgs decays are used
  - $H \rightarrow \gamma\gamma : C = +1$
  - Kinematic distributions in bosonic decay to test $J^P$

$H \rightarrow ZZ \rightarrow 4l$

Shape analysis

Hypothesis test

SM favors ($J^P = 0^+$)

Specific $J^P$ (in x-axis)

$C = +1, P = +1$

$\rightarrow$ Higgs is CP even (?)
This is not the end of the story

\[ \mathcal{L} = \begin{cases} 
\cos(\alpha) & \text{CP even} \\
\sin(\alpha) & \text{CP odd} 
\end{cases} \]

If \( \Lambda \) is large (seems to be), contribution of this term to the final distribution \( \sim 0 \) (irrespective of \( \alpha \))

Final Data distribution looks like “CP even”
\rightarrow Hypothesis test always prefers CP even (shape analysis !)

We can constrain \( \alpha \) by the signal rate (\( \mu \)-value) \( \propto f(\alpha, \Lambda) \)
\rightarrow We have to assume \( \Lambda \) (model dependent)
On the other hand – fermionic coupling

\[ \mathcal{L} = \begin{cases} \cos(\alpha) & \text{CP even} \\ \frac{m_f h f_i \bar{f}_i}{v} & f \\ \frac{m_f i\gamma_5 A f_i \bar{f}_i}{v} & \text{CP odd} \end{cases} + \sin(\alpha) \]

- Both CP even and odd can decay into $\bar{f}f$ in tree level (no suppression)
  - Both CP even and odd can contribute to the final distribution equally
- Hypothesis test can evaluate CP without any assumption about NP (model independent)

Conclusion: Higgs CP can be better studied using fermionic coupling
2 methods using fermionic coupling

**Tau polarization method**
- Studied in the context of ILC
- Use $H \rightarrow \tau\tau$ and look at $\Delta\phi$
e.g. between tau decay planes (difficult, especially at high PU)

**Gluon fusion + 2 jets method (I want to do this)**
- A priori easier than polarization method
- Irrespective of Higgs decay (combinable)
- Not much studied yet

VBF doesn’t show this (flat)
($|M|^2$ does not depend on $\alpha$)
Gluon fusion + 2 jets includes “not-interesting” events

Exhibit modulation

Doesn’t bring CP info. (gluon split)

• More VBF-like selection ($\Delta R_{jj}$, $m_{jj}$), we get less gluon-fusion

→ Need optimization

$\Delta R_{jj} > 0.6$

$ m_{jj} > 200$ GeV

CP odd    CP even
Feasibility study using $H \rightarrow \tau\tau$

- Same event selection used for $H \rightarrow \tau\tau$ analysis in run-1
- $\geq 2$ jets $\rightarrow$ calculate $\Delta\phi(jj)$ using leading, sub-leading jet
- Apply VBF like selection to reject not-interesting events
  - $\Delta R(jj) > 0.6$, $m_{jj} > 200$ GeV

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Sensitivity check using run-1 data

Hypothesis test of data with SM ($\alpha=0$) v.s various $\alpha$

5 Higgs signal:
(75% VBF, 25% ggH)
Data: blinded

Exclude pure CP odd at 2$\sigma$
(encouraging !)
Summary

• CMS is in full swing
  – Highly operative after upgrade (both h/w and s/w) during long shutdown period
  – Cryogenics issue is still there but believed to be solved soon
  – Preliminary physics results seem encouraging

• New tau identification is developed and will improve physics performance with tau in run-2

• Higgs CP property can be a nice probe for NP
  – Fermionic coupling will allow model-independent measurement of the Higgs CP property
  – Feasibility study using run-1 data with $\tau\tau$ final state suggests that run-2 data will provide interesting results
Thank you for your attention
Spare slide
Projection studies

H → τμτh

Luminosity (/fb)

Expected Significance

S. Smith (summer student) & Yuta Takahashi
Hadron mass $m_{h}$ reconstructed by the hadron-plus-strips algorithm as shown in the legend. The mass distribution of the intermediate $h$ resonance. The $Z$ production is then split according to the decay mode $h \rightarrow \tau \tau$, $h \rightarrow \mu \mu$, and $h \rightarrow gg$. All generated events are processed through a detailed $\nu\nu$–$\nu\nu$ and $Z\rightarrow \tau\tau$ event reconstruction with the same $Z$ resolution, Particle Flow [1].

$\tau^- \rightarrow \pi^- \nu$ (12%)

$\tau^- \rightarrow \pi^- \pi^0 \nu$ (11%)

$\tau^- \rightarrow \pi^- \pi^+ \pi^- \nu$ (10%)

$\tau^- \rightarrow \pi^- \pi^0 \nu$ (26%)

Photon cluster (2 photons from $\pi^0 \rightarrow \gamma\gamma$)

Make full use of substructures inside jets to reconstruct $\tau_h$
- Observed limits at 95% CL on cross section of $qq$, $qg$, $gg$ resonances
- Get worse when there are gluons in the final state because radiation increases and resolution degrades
- Extend to 7 TeV in di-jet mass for the first time
- Plateaus at high mass due to absence of events

Confirms Run2 is already more sensitive than Run1 for $M > 5$ TeV

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Ttbar differential cross-section

Can’t draw conclusive statement (yet)
→ Need more data
Particle Identification @ 13TeV

- Use standard candles (W, Z)

\[ Z \rightarrow \mu\mu / ee \]

\[ 13 \text{ TeV} \quad 40/pb \]

\[ m(\mu^+\mu^-) \text{ [GeV]} \]

- Opposite-sign di-lepton
- \( p_T > 20, 10 \text{ GeV} \)
- \(|\eta| < 2.4 \)

- More to be done; Scale factor (data/MC), energy scale, resolution, etc…
PU mitigation (50ns $\rightarrow$ 25ns)

ECAL cluster offset
50 ns data

pile-up invariant

25 ns data

Missing $E_T$
25 ns data

Run1 reco.

Large tails of run1
Reco. removed

Improve ID eff.
at the same fake rate
**Tau polarization method**

- Use $H \rightarrow \tau\tau$ and look for $\Delta \phi$ between tau decay planes at the Higgs rest frame.

   ![Diagram showing the tau plane reconstruction](image)

   *Tau plane is reconstructed by impact parameter vector and $\pi^\pm$ momentum*

- Difficult to reconstruct Higgs rest frame
- Only specific tau decay ($\tau^\pm \rightarrow \pi^\pm \nu$, $\tau^\pm \rightarrow \pi^\pm \pi^0 \nu$) is sensitive

Large data (at least 300 fb$^{-1}$) is needed to address the question.
Cross-section for ggH+2jets

TABLE I. The gluon fusion and weak boson fusion signal cross sections at the generator level before event selection and Higgs decay for 8 (left) and 14 TeV (right).

<table>
<thead>
<tr>
<th>$\alpha$</th>
<th>8 TeV GF cross section (fb)</th>
<th>8 TeV WBF cross section (fb)</th>
<th>14 TeV GF cross section (fb)</th>
<th>14 TeV WBF cross section (fb)</th>
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<tr>
<td>0.00</td>
<td>250</td>
<td>467</td>
<td>1141</td>
<td>1481</td>
</tr>
<tr>
<td>0.30</td>
<td>278</td>
<td>426</td>
<td>1268</td>
<td>1351</td>
</tr>
<tr>
<td>0.60</td>
<td>352</td>
<td>318</td>
<td>1606</td>
<td>1009</td>
</tr>
<tr>
<td>0.90</td>
<td>447</td>
<td>181</td>
<td>2038</td>
<td>572</td>
</tr>
<tr>
<td>1.20</td>
<td>529</td>
<td>61</td>
<td>2411</td>
<td>194</td>
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Magnet cryogenics issues

- The restart of the CMS magnet after LS1 was more complicated than anticipated due to problems with the cryogenic system in providing liquid Helium.
- Inefficiencies of the oil separation system of the compressors for the warm Helium required several interventions and delayed the start of routine operation of the cryogenic system.
- The data delivered during the first two weeks of LHC re-commissioning with beams at low luminosity have been collected with $B=0$
- Currently the magnet can be operated, but the continuous up-time is still limited by the performance of the cryogenic system requiring more frequent maintenance than usual.
- A comprehensive program to re-establish its nominal performance is underway. These recovery activities for the cryogenic system will be synchronized with the accelerator schedule in order to run for adequately long periods.
- A consolidation and repair program is being organized for the next short technical stops and the long TS at the end of the year.
Magnet cryogenics

• Cryo cold box instabilities since March
  – Suspected oil contamination from compressor plant

• Many invasive campaigns of cleaning and replacement since Apr 1\textsuperscript{st}
  – Many thanks to TE and EN departments for exceptional effort

• Cold box opened on 1\textsuperscript{st} Sep., restarted on 8\textsuperscript{th} Sep [ramped to 3.8 T on 15\textsuperscript{th} Sep]
  – Insertion of additional 10 and 30 µm filters
    • augment filters which were clogging by much larger surface area filters used in the main LHC cryo plants.
  – Work ongoing to clear remaining contamination

• Precautionary preparations for comprehensive cleaning campaign (YETS 2015-16 or sooner)
Single top cross section

- t-channel single top cross section @13 TeV measured:
  - $\mu + \text{jet channel}$
  
  \[ \sigma_{t\text{-ch.}} = 274 \pm 98 \text{ (stat.)} \pm 52 \text{ (syst.)} \pm 33 \text{ (lumi.)} \text{ pb} \]

Data / MC

Events / 15 GeV

\[ |V_{tb}| = 1.12 \pm 0.24 \text{ (exp.)} \pm 0.02 \text{ (theo.)} \]

TOP-15-004
Run-1 $Z'$ limit

- First of all, this could be DY Bkg. (bkg. uncertainty being checked)
- We excluded a cross-section of 0.22 fb at inv. mass 3 TeV
  - translate into 4.4 fb @ 13 TeV
- Cross-section of 1 events @ 65 pb$^{-1}$ is ~24 fb (but 4 fb is within 1 sigma)

- In the case of true NP, there are many possibilities not excluded by data
  - Not narrow resonance
  - Reflection of something at high mass
  - Spin2 particle ...
- Still, most natural explanation is relatively narrow $Z'$ resonance
- 1 event with several hundreds of pb$^{-1}$ (we are lucky if this is true)
ee event

• There are non-negligible uncertainties in the background at high-mass
  – In particular, for the contribution of the gg → dilepton process. But even assuming a large contribution in relative terms with respect to DY, its contribution will be small in absolute term

• Follow up on-going
  – Analyze 0T runs for di-electron channels
  – Analyze Di-muon channel (alignment matters)
  – Di-tau …
Particle flow

• Attempt to reconstruct all stable particles in an event
  – Photons
  – Charged and neutral hadrons
  – Electrons
  – Muons

• Information from sub-detectors is combined in best possible way, based on resolution

• List of particles is returned, as if it came from a MC generator

• Higher-level physics objects can be built from list of particles
  – Hadronic taus
  – (b-tagged) Jets
  – Missing transverse energy
Collins-Soper angle

- CS frame = The rest frame of the lepton pairs
- CS angle is manifestly covariant under rotation about the Z’-axis in the CS frame

\[ h_1 + h_2 \rightarrow \gamma^* + x \rightarrow l^+ + l^- + x \ (q + \bar{q} \rightarrow \gamma^*) \]

\[ \Theta \text{ and } \Phi \text{ are the decay polar and azimuthal angles of the } \mu^+ \text{ in the dilepton rest-frame} \]

Collins-Soper frame

In case of \( H \rightarrow \gamma\gamma \)

\[ \cos \theta_{CS}^* = 2 \times \frac{E_{\gamma}^2 p_{z_{\gamma}}^{\gamma_1} - E_{\gamma}^{\gamma_1} p_{z_{\gamma}}^{\gamma_2}}{m_{\gamma\gamma} \sqrt{m_{\gamma\gamma}^2 + (p_T^{\gamma\gamma})^2}}. \]
(DY events with similar kinematics present a positive FB asymmetry)
Feasibility study

- Tag a Higgs boson + 2 jets
  - Use $H \to \tau\tau$ final state

Reconstruct $\Delta \phi(jj)$ using leading and sub-leading jets

To enhance $\Delta \phi(jj)$ discrimination power, apply:
  - $\Delta R(jj) > 0.6, mjj > 200$ GeV, Higgs $p_T > 70$ GeV

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Inclusive

$\Delta R_{jj} > 0.6$

$M_{jj} > 200 \text{ GeV}$

Higgs $p_T > 70 \text{ GeV}$

VBF-like selection helps separating “interesting” events. But, more VBF-like selection, less gluon-fusion $\rightarrow$ Need optimization
Sensitivity check using run-1 data

- Likelihood fit of $\Delta \phi$ with signal & bkg. template
  - Signal template with several mixing angle ($0 - \pi/2$)
Expected sensitivity

20 fb\(^{-1}\), 8TeV

50 fb\(^{-1}\), 14TeV

Exclusion limit w.r.t. SM (CP even, \(\alpha = 0\))

Exclude pure CP odd with 2\(\sigma\) level (completely model independent)

\(\alpha > 0.9\) rad excluded with 3\(\sigma\) at 50 fb\(^{-1}\) at 14TeV

- Encouraging results for run-2
- Feasibility study on-going with realistic detector simulation
Run-2 will continue until 2018

- Run-1: 7–8 TeV
- Run-2: 13–14 TeV

- Peak luminosity
- Integrated luminosity

- PU~20
- PU~40

- 30 fb$^{-1}$
- 100 fb$^{-1}$
- 300 fb$^{-1}$
- 3000 fb$^{-1}$

4th pixel layer

High-luminosity LHC Preparation on-going
<table>
<thead>
<tr>
<th>mass range</th>
<th>SM Bkg Expection</th>
</tr>
</thead>
<tbody>
<tr>
<td>&gt;1 TeV</td>
<td>0.21</td>
</tr>
<tr>
<td>&gt; 2 TeV</td>
<td>0.007</td>
</tr>
<tr>
<td>&gt; 2.5 TeV</td>
<td>0.002</td>
</tr>
</tbody>
</table>