EoS PhD Day 2020

Constraints on the anomalous HVV couplings of the Higgs boson in pp collisions at 13TeV

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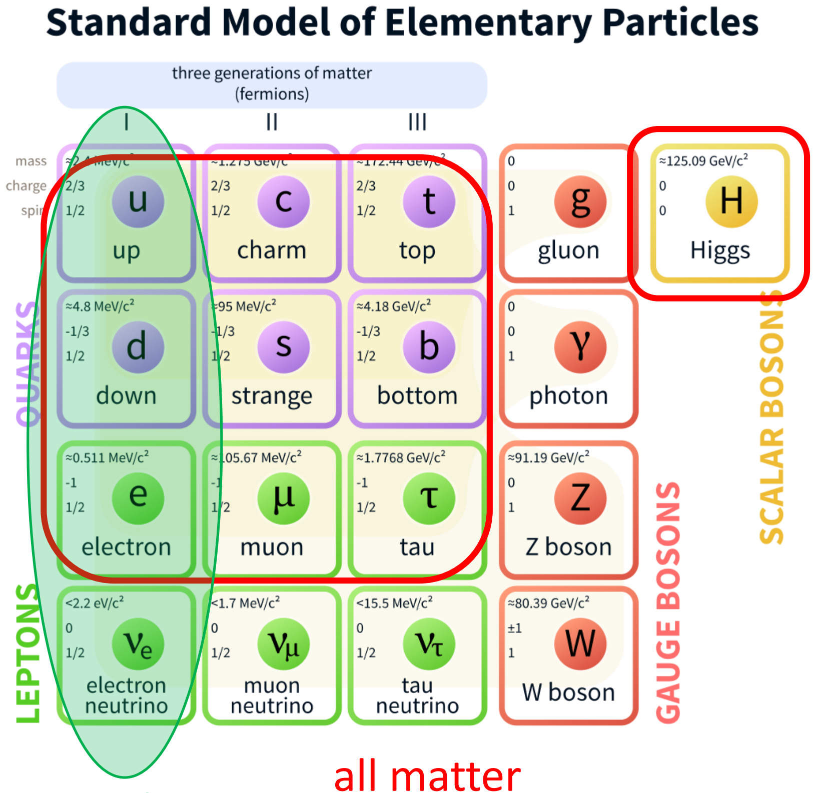
Standard model

- as for now the best theory to describe the fundamental building blocks of our universe
- describes all known **elementary particles** building up matter
- describes 3 (out of 4) fundamental interactions (**electromagnetic**, **weak** and **strong**)
- introduces **Higgs boson** through the process of spontaneous symmetry breaking in $SU(2) \times U(1)$ gauge theory

Source: [1]



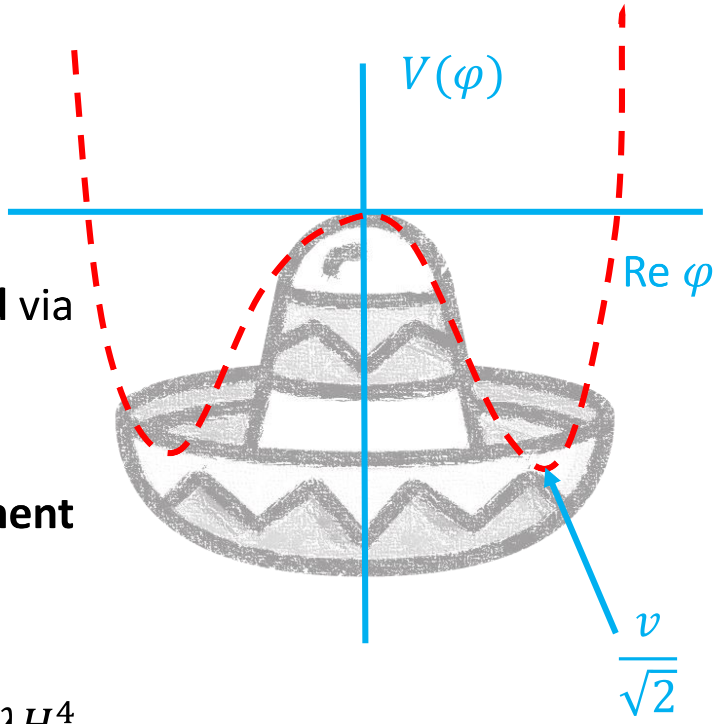
all matter

most of our universe (atoms, β-decay, ...)

Higgs boson

Why missing puzzle piece?

- $W^{\pm}$ and Z^0 **gauge bosons masses are generated** via Brout-Englert-Higgs mechanism



$SU(2)\times U(1)$ local symmetry and U-gauge requirement

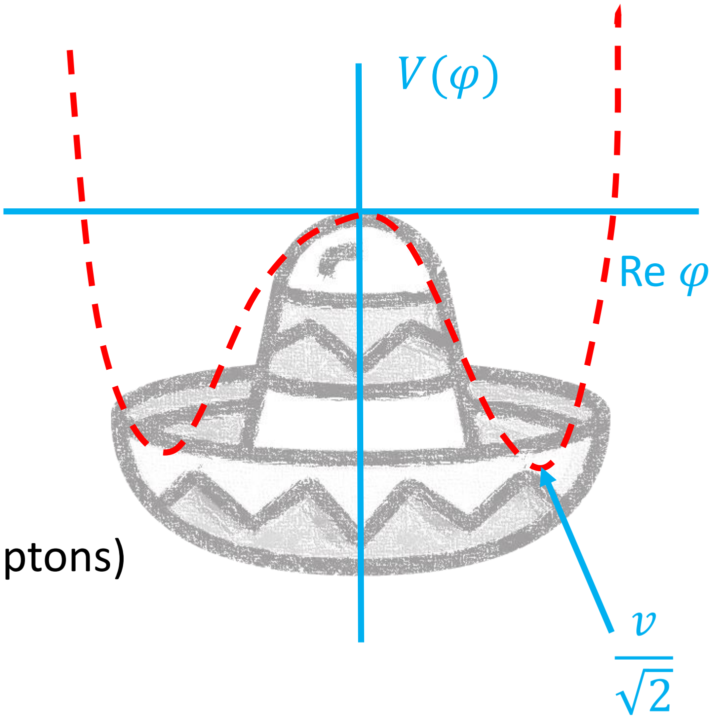
$$\mathcal{L}_{Higgs}^{(U)} = \frac{1}{2}\partial_\mu H \partial^\mu H - \lambda v^2 H^2 - \lambda v H^3 - \frac{1}{4}\lambda H^4 + \frac{1}{8}(v+H)^2\left(g^2 A_\mu^a A^{a\mu} - 4Ygg' A_\mu^3 B^\mu + 4Y^2 g'^2 B_\mu B^\mu\right)$$

$$\boxed{m_W = \frac{1}{2}gv}$$

$$\boxed{m_Z = \frac{1}{2}v\sqrt{(g^2+g'^2)}}$$

A_μ^a ... Yang-Mills fields ⟷ $SU(2)$
B_μ ... Yang-Mills fields ⟷ $U(1)$
Y ... weak hypercharge
g, g' ... coupling constants
v ... „vacuum expectation value“

Higgs boson



Free parameters of the Standard model

- VEV $\boldsymbol{v}$ and Higgs mass $\boldsymbol{m_H}$
- **9 Yukawa couplings** (6 quarks and 3 charged leptons)
- Weinberg weak mixing angle $\boldsymbol{\theta_W}$
- fine structure constant $\boldsymbol{\alpha}$
- strong interaction coupling constant $\boldsymbol{g_3}$
- three mixing angles $\boldsymbol{\theta_{12}}, \boldsymbol{\theta_{23}}, \boldsymbol{\theta_{13}}$ and one CP-violating phase $\boldsymbol{\delta_{13}}$ of the CKM matrix
- neutrino masses, mixing angles, phases, etc.

Higgs boson properties

Or is this resonance really SM Higgs that we measure?

- Higgs boson mass $\boldsymbol{m_H = 125.10 \pm 0.14\mathrm{GeV}}$ [PDG]
- CP-even spin-zero scalar particle $\boldsymbol{J^{CP} = 0^{++}}$
    - **spin-one strongly disfavoured** by Higgs observation in diphoton channel [4] (Landau-Yang theorem)
    - graviton-like **spin-two model disfavoured** in previous studies [5]
    - possible anomalous contribution from **spin-zero** parity conserving CP-odd state $\boldsymbol{J^P = 0^-}$ and CP-even states $\boldsymbol{J^P = 0^+}$
- Higgs boson **couplings** to the other elemental particles are in general **set by their masses**

C = charge conjugation
P = space parity
J = spin

fermions

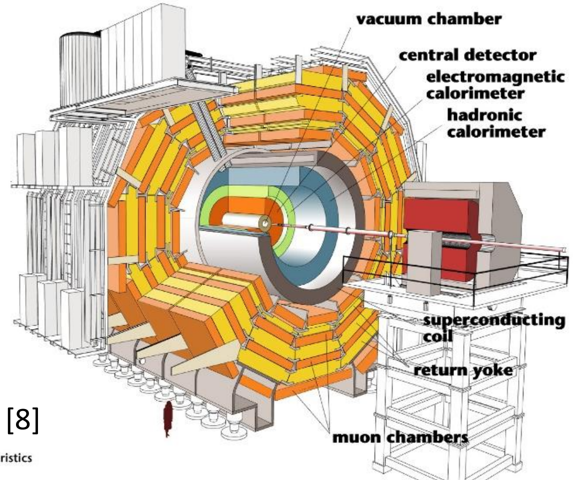
$$g_{Hf\bar{f}}^{SM} = \frac{m_f}{v}$$

vector bosons

$$\boxed{g_{HVV}^{SM} = \frac{2m_V^2}{v}}$$

$H \to VV$ channels suitable for spin-parity studies !

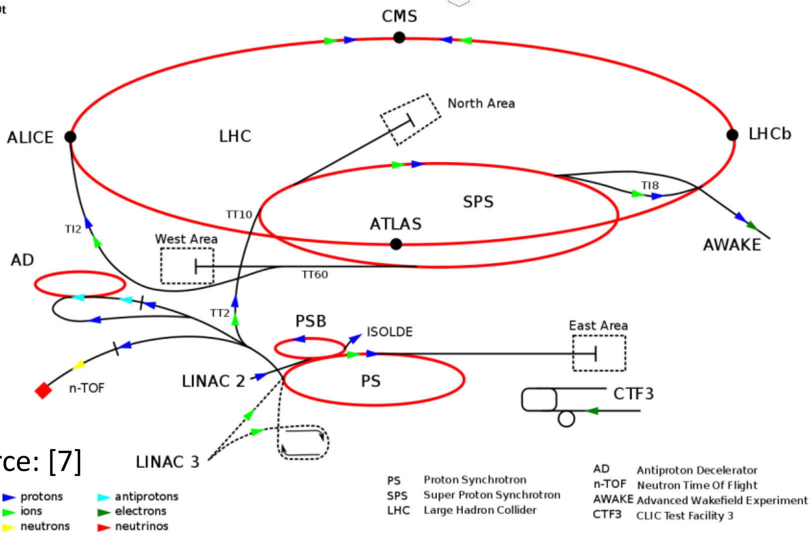
Higgs boson factory



Source: [8]

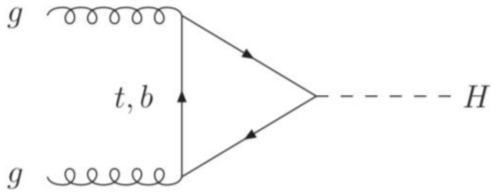
Detector characteristics

Width: 22m
Diameter: 15m
Weight: 14'500t

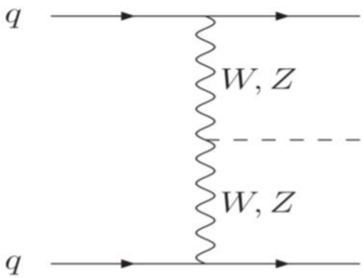


Source: [7]

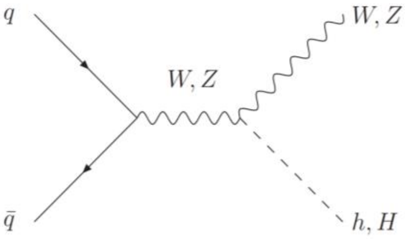
1. ggF (gluon-gluon fusion)



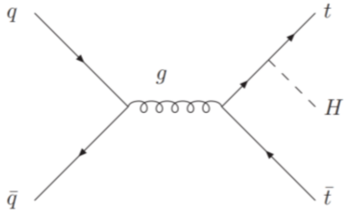
2. VBF (vector-boson fusion)

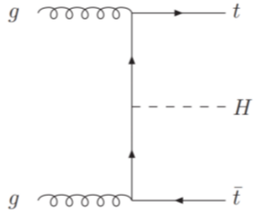


3. Associated VH production

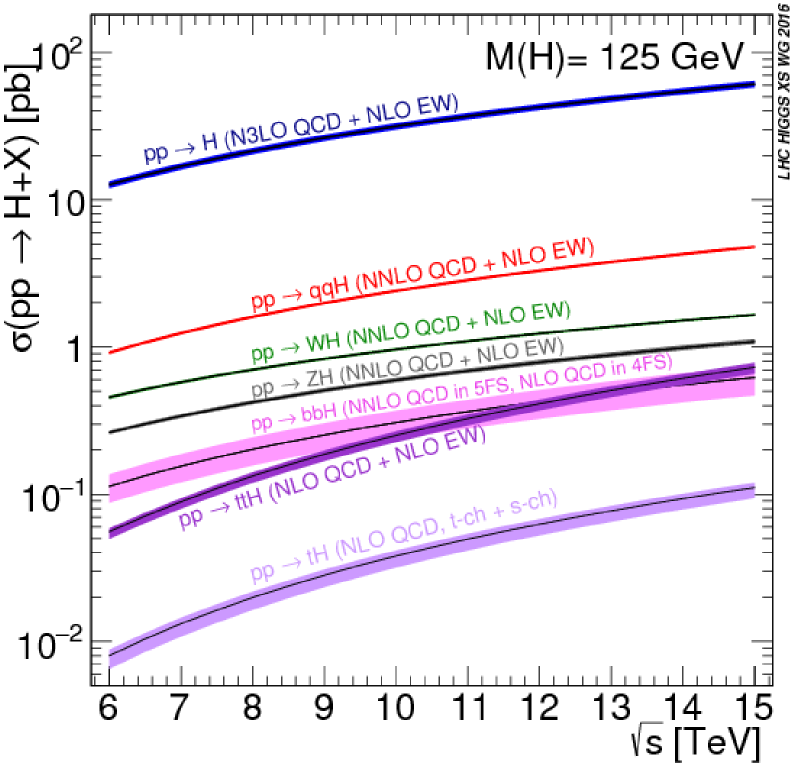


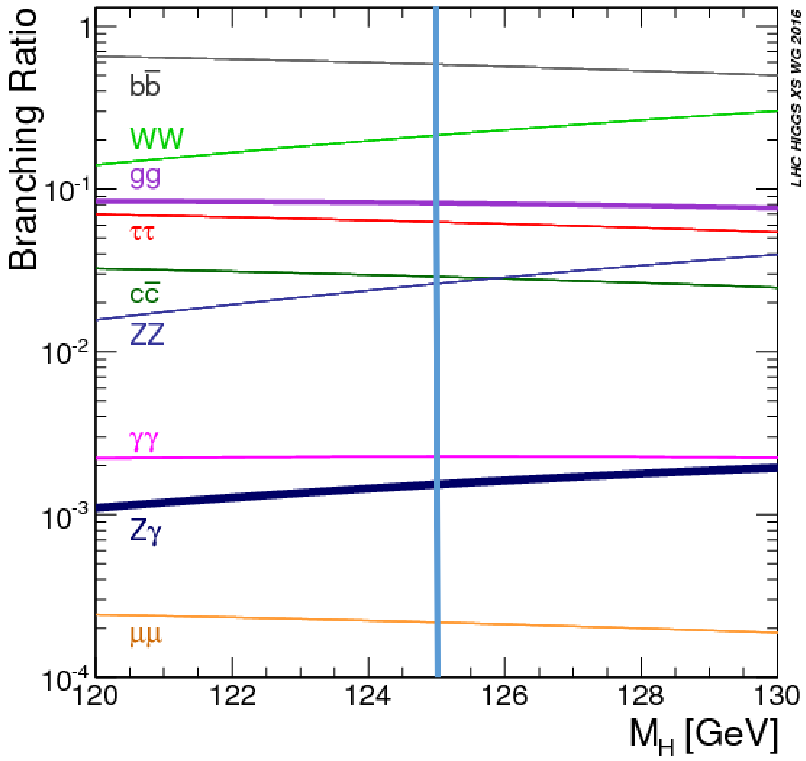
4. ttH production





Higgs boson factory





Source: [9]

$\mathrm{H} \rightarrow \mathrm{WW}^*$ anomalous couplings

$\mathrm{H} \rightarrow \mathrm{VV}$ scattering amplitude – minimum **0-spin expansion of SM** up to $\mathcal{O}(q^2)$:

$$\mathcal{M}(\mathrm{HVV}) \sim \left[a_1^{\mathrm{VV}} + \frac{\kappa_1^{\mathrm{VV}} q_{\mathrm{V1}}^2 + \kappa_2^{\mathrm{VV}} q_{\mathrm{V2}}^2}{\left(\Lambda_1^{\mathrm{VV}}\right)^2} \right] m_{\mathrm{V1}}^2 \epsilon_{\mathrm{V1}}^* \epsilon_{\mathrm{V2}}^* + a_2^{\mathrm{VV}} f_{\mu\nu}^{*(1)} f^{*(2),\mu\nu} + a_3^{\mathrm{VV}} f_{\mu\nu}^{*(1)} \tilde{f}^{*(2),\mu\nu}$$

SM

BSM-loop $0^+_{\Lambda 1}$

SM-loop 0^+_h

SM 3-loop 0^-

$\mathrm{VV} = \mathrm{ZZ}, \mathrm{Z}\gamma, \gamma\gamma, \mathrm{gg}$ and WW

$$f^{(i)\mu\nu} = \varepsilon_{Vi}^{\mu} q_{Vi}^{\nu} - \varepsilon_{Vi}^{\nu} q_{Vi}^{\mu}$$ field strength tensor

$$\tilde{f}_{\mu\nu}^{(i)} = \frac{1}{2} \varepsilon_{\mu\nu\rho\sigma} f^{(i)\rho\sigma}$$ dual field strength tensor

Λ_1 = scale of BSM physics

q_{Vi} = V boson momentum

CP-conserving anomalous couplings

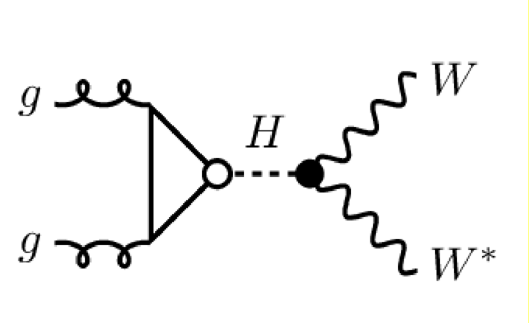
$a_i^{\mathrm{WW}}(q_{\mathrm{W1}}^2, q_{\mathrm{W2}}^2)$

- $a_{\Lambda_1}^{\mathrm{WW}} \leftrightarrow 0^+_{\Lambda_1}$ $\mathcal{O}(10^{-3} - 10^{-2})$
- $a_2^{\mathrm{WW}} \leftrightarrow 0^+_h$ $\mathcal{O}(10^{-3} - 10^{-2})$
- $a_3^{\mathrm{WW}} \leftrightarrow 0^-$ $\mathcal{O}(< 10^{-3})$

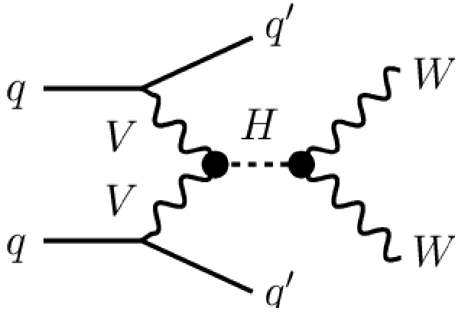
$a_1^{\mathrm{WW}} = 2$

H → WW* analysis strategy

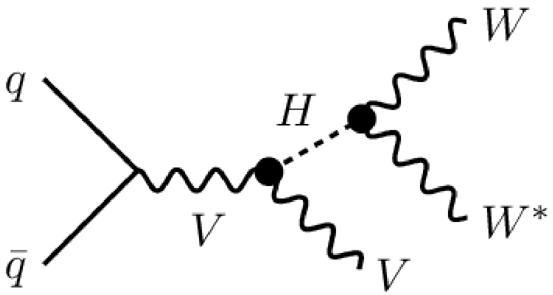
ggH 0-jet and 1-jet



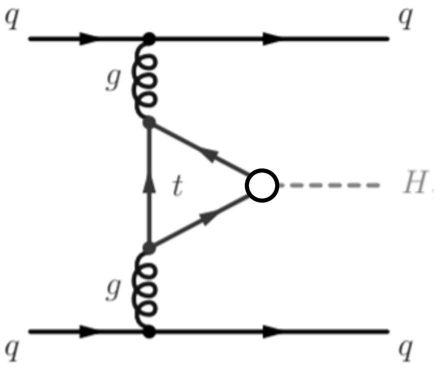
VBF 2-jets



VH 2-jets



(ggH 2-jets)



Categories:

- ggH 0j
- ggH 1j
- (ggH 2j)
- VBF 2j
- WH/ZH 2j

other existing analysis channels

● = HWW vertex (decay or production)

ggH → WW* analysis strategy

ggH signal region

$m^{ll} > 12\text{GeV}$

$m_T^H > 60\text{GeV}$

$m_T^{l_2} > 30\text{GeV}$

no b-jets with $p_T > 20\text{GeV}$

$$m_T^H = \sqrt{2 p_T^{\ell\ell} p_T^{\text{miss}} \left[1 - \cos\Delta\phi(\vec{p}_T^{\,\ell\ell}, \vec{p}_T^{\,\text{miss}})\right]},$$

$$m_T^{\ell_2} = \sqrt{2 p_T^{\ell_2} p_T^{\text{miss}} \left[1 - \cos\Delta\phi(\vec{p}_T^{\,\ell_2}, \vec{p}_T^{\,\text{miss}})\right]},$$

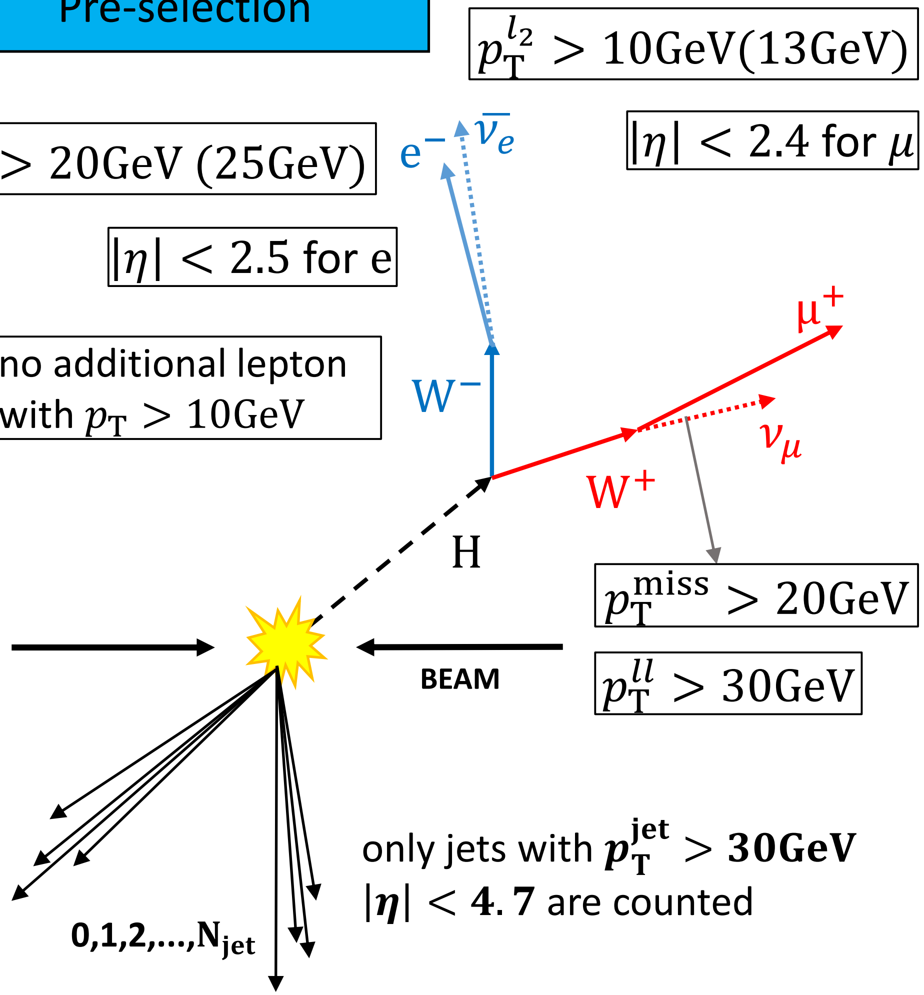
Sub-categories

0-jet $p_T^{\text{jet1}} < 30\text{GeV}$

1-jet $p_T^{\text{jet1}} > 30\text{GeV}$

$p_T^{\text{jet2}} < 30\text{GeV}$

Pre-selection



$p_T^{l_2} > 10\text{GeV}(13\text{GeV})$

$p_T^{l_1} > 20\text{GeV}\ (25\text{GeV})$

$|\eta| < 2.4$ for μ

$|\eta| < 2.5$ for e

no additional lepton with $p_T > 10\text{GeV}$

$p_T^{\text{miss}} > 20\text{GeV}$

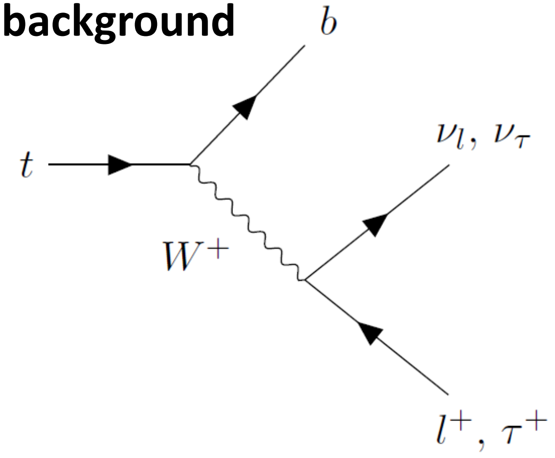
$p_T^{ll} > 30\text{GeV}$

only jets with $p_T^{\text{jet}} > 30\text{GeV}$ $|\eta| < 4.7$ are counted

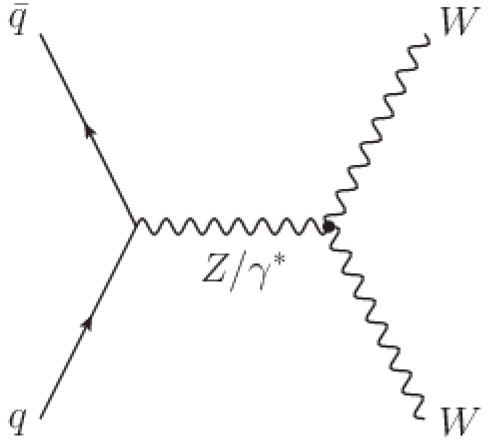
ggH → WW* Backgrounds

Incomplete list of background contributions

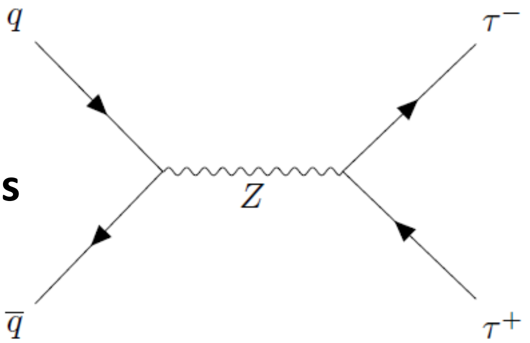
Top background



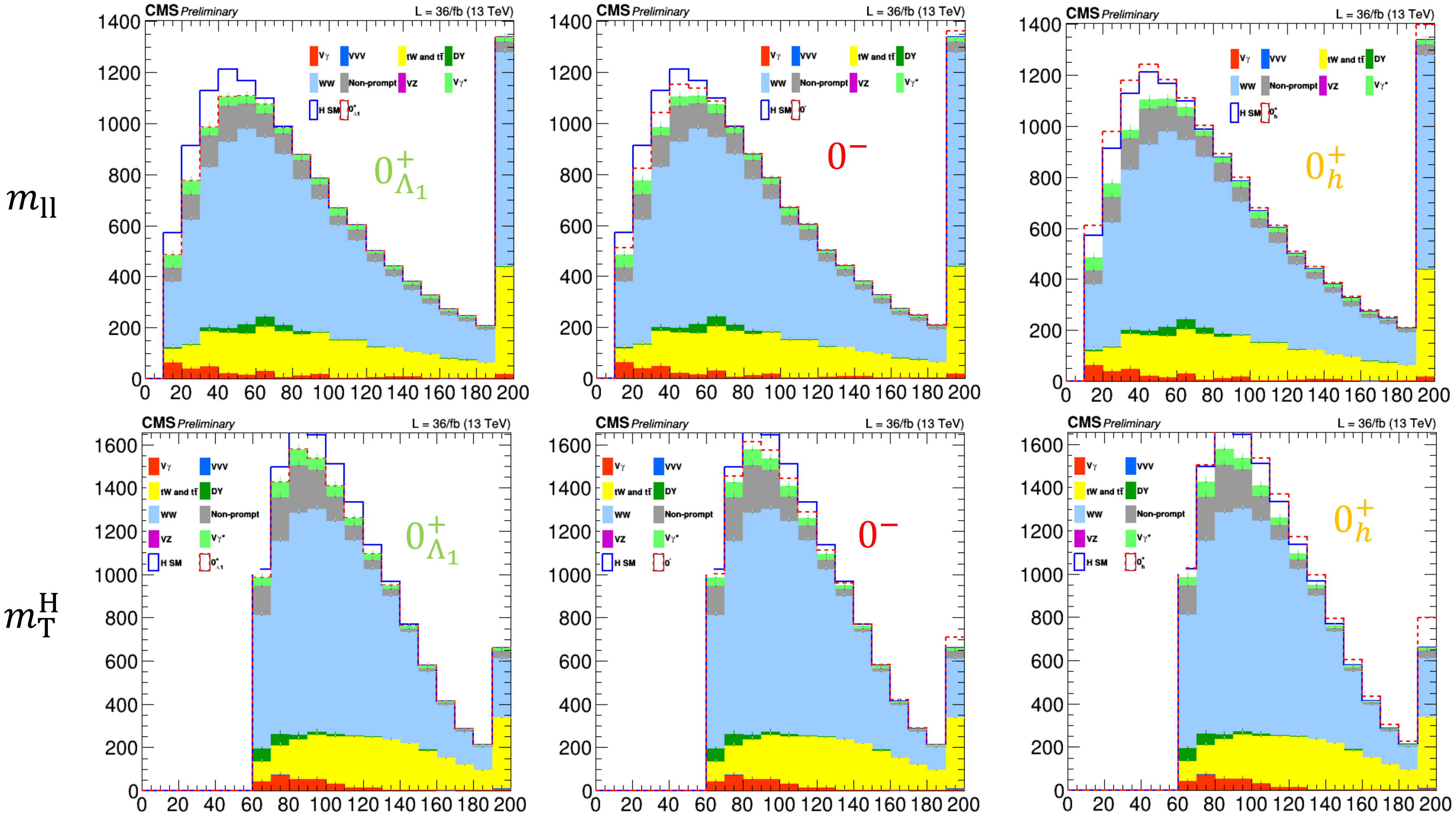
Non-resonant WW background



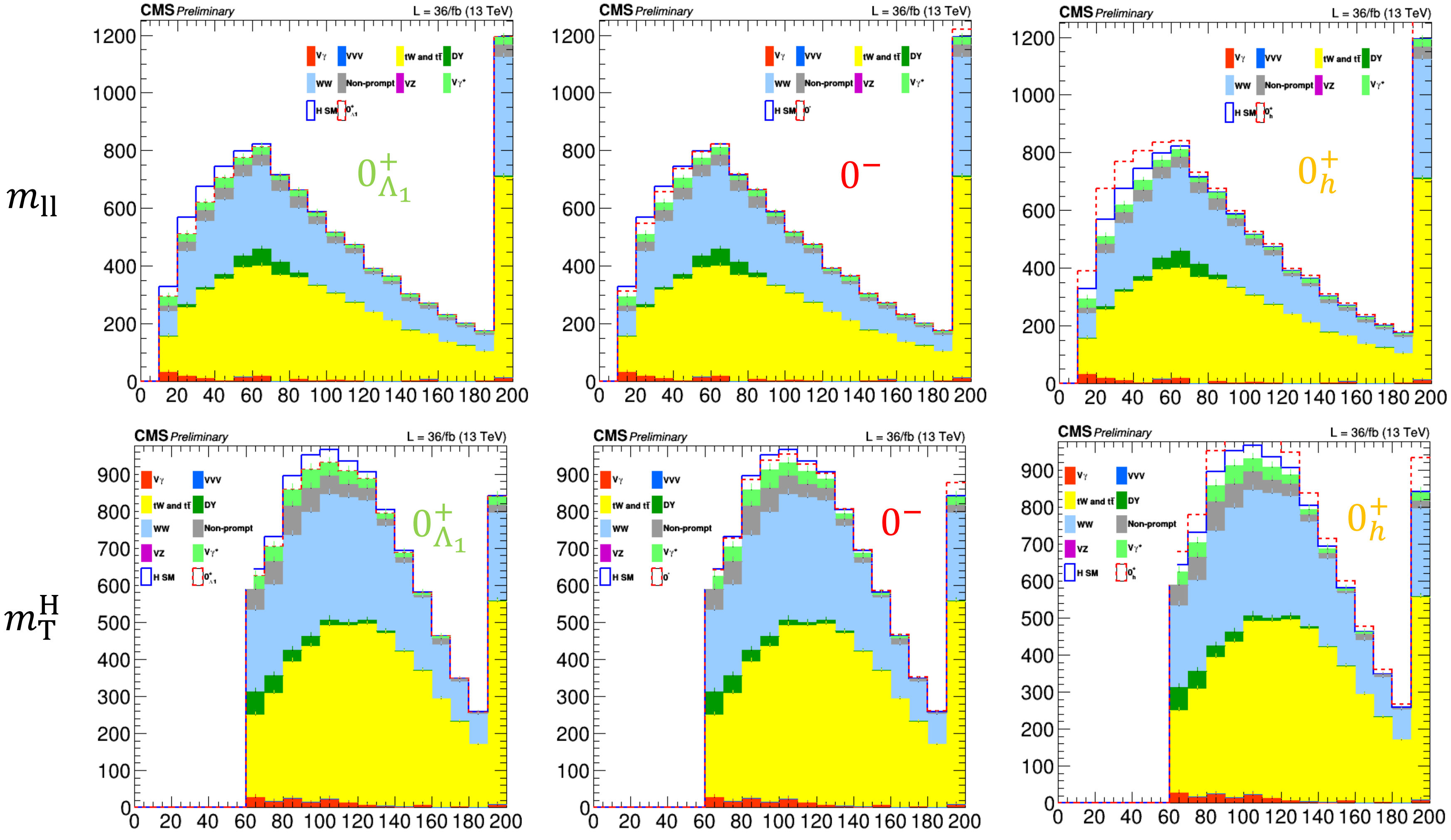
Drell Yan events



ggH → WW^* 0-jet signal region

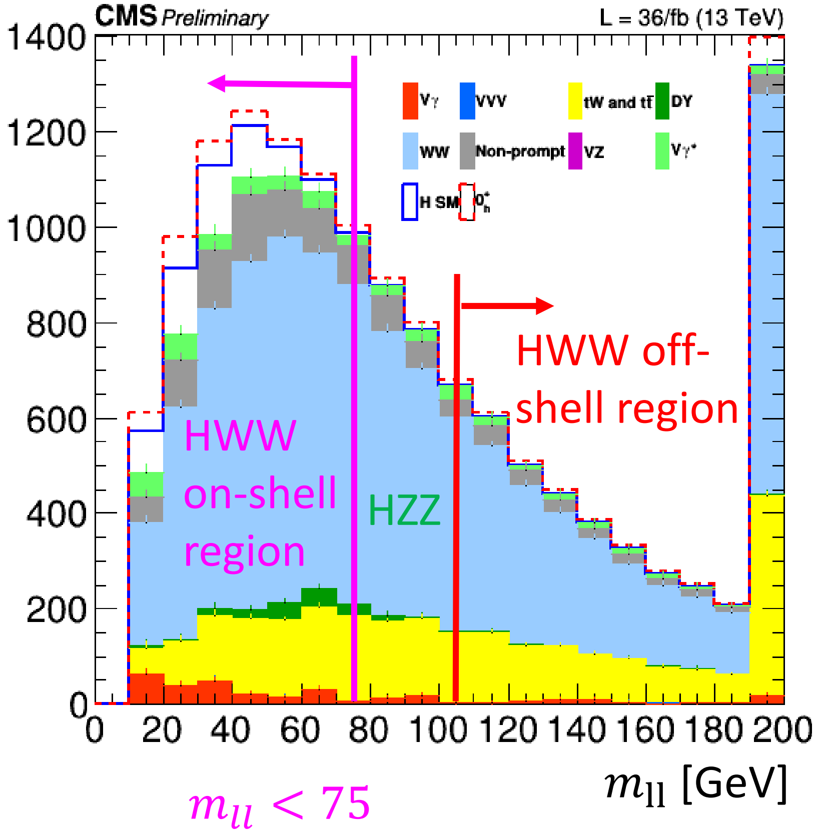


ggH → WW* 1-jet signal region



Side note: $ggH^* \to$ WW off-shell

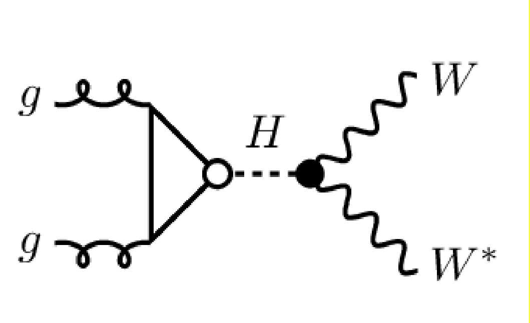
- off-shell HWW phase space needs to be defined in order to carry out orthogonal analysis
- off-shell HZZ requires $75 < m_{\mathrm{ll}} < 105$ to estimate its non-resonant background
- on-shell HWW $m_{\mathrm{ll}} < 75$
- dedicated study in plan (LS scan, error on free floating WW normalisation)



$m_{ll} < 75$

ggH $\to$ WW* analysis strategy

ggH 0-jet and 1-jet



$$\text{ggF}: \mathcal{M}(\mathrm{H} \to \mathrm{WW}^*) = a_1 \mathcal{M}_{\mathrm{SM}}^{\mathrm{decay}} + a_{\mathrm{i}} \mathcal{M}_{\mathrm{AC}}^{\mathrm{decay}}$$

SM + one AC considered

- probability in terms of AC:

$$\mathcal{P} = \mathcal{M}^2(\mathrm{H} \to \mathrm{WW}^*) = a_1^2 * \mathrm{T}_{\mathrm{SM}} + a_{\mathrm{i}}^2 * \mathrm{T}_{\mathrm{AC}} + a_1 a_{\mathrm{i}} * \mathrm{T}_{\mathrm{int}}$$

- probability in terms of effective on-shell XS ratios:

$$\boldsymbol{\mathcal{P}} = \boldsymbol{\mu_F}\left(\left(\mathbf{1} - \boldsymbol{f}_{\mathbf{a_i}}\right) * \mathbf{T}_{\mathbf{SM}} + \boldsymbol{f}_{\mathbf{a_i}} * \mathbf{T}_{\mathbf{AC}} * \boldsymbol{g}^{\mathbf{2}} + \sqrt{\boldsymbol{f}_{\mathbf{a_i}}}\sqrt{\mathbf{1} - \boldsymbol{f}_{\mathbf{a_i}}} * \mathbf{T}_{\mathbf{int}} * \boldsymbol{g}\right)$$

$$f_{\mathrm{ai}} = \frac{|a_{\mathrm{i}}|^2 \sigma_{\mathrm{i}}}{|a_{\mathrm{i}}|^2 \sigma_{\mathrm{i}} + |a_1|^2 \sigma_1} \qquad \phi_{\mathrm{ai}} = \arg(a_{\mathrm{i}}/a_1) \qquad g = \sqrt{\frac{\sigma_1}{\sigma_i}}$$

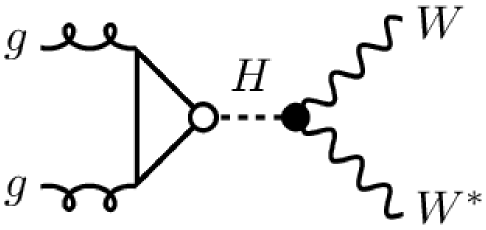
$\sigma_i \leftrightarrow a_i = 1, a_{i \neq j} = 0$

$f_{\mathrm{ai}} \in \langle 0,1 \rangle$

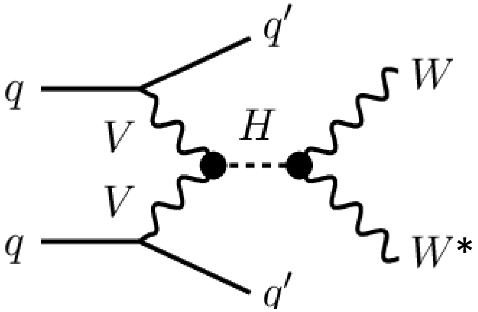
Signal parametrisation (ggH+VBF+VH)

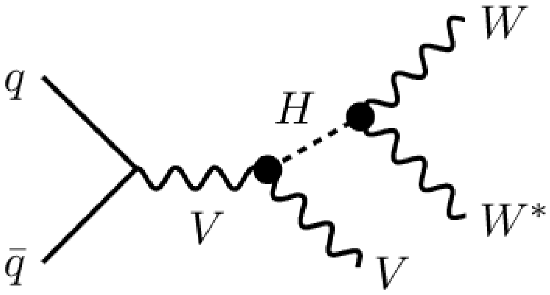
$f_{\mathrm{a1}} = 1 - f_{\mathrm{ai}}$

$$\mathcal{P}_{ggH} = \mu_F \left(f_{\mathrm{a_1}} * \mathrm{T_{SM}} + \sqrt{f_{\mathrm{a_i}}}\sqrt{f_{\mathrm{a_1}}} * g * \mathrm{T_{int}} + f_{\mathrm{a_i}} * g^2 * \mathrm{T_{AC}} \right)$$



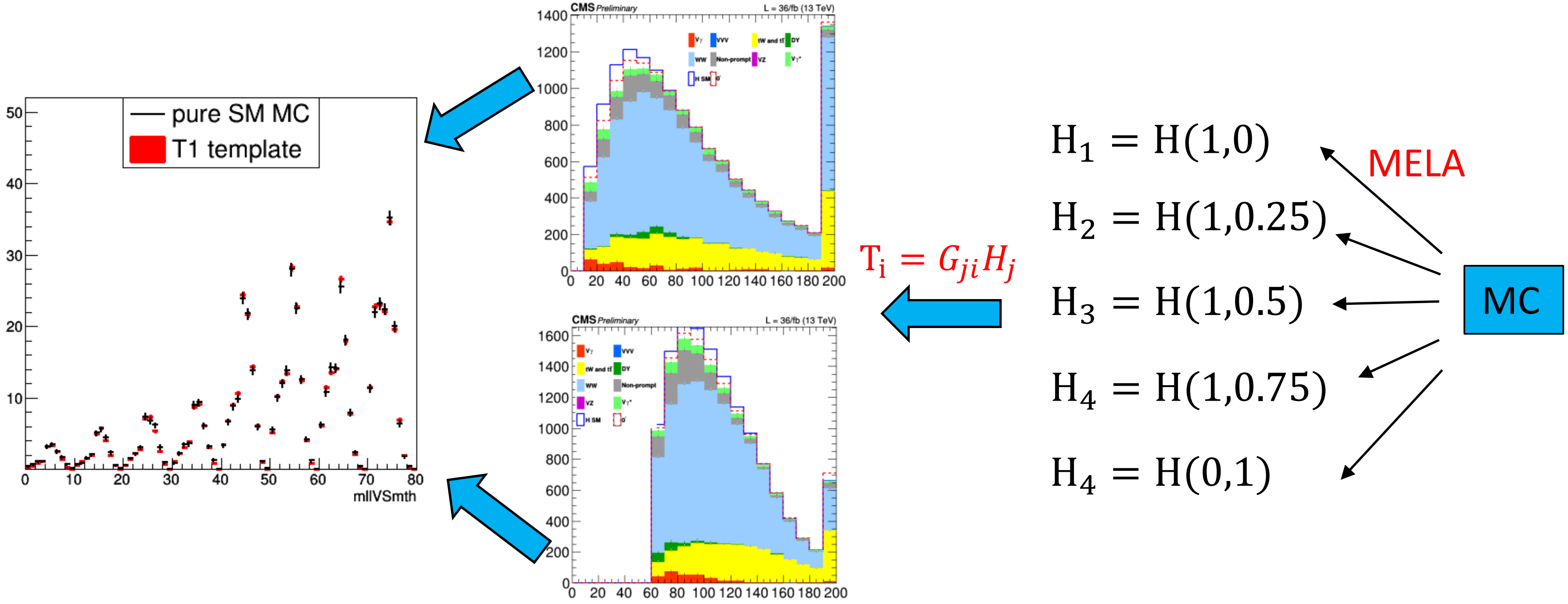
$$\mathcal{P}_{VBF/VH} = \mu_F^2 \left(f_{a_1}^2 * \mathrm{T_1} + \sqrt{f_{a_1}}^3 \sqrt{f_{a_i}} * g * \mathrm{T_2} + f_{a_1} f_{a_i} * g^2 * \mathrm{T_3} + \sqrt{f_{a_1}}\sqrt{f_{a_i}}^3 * g^3 * \mathrm{T_4} + f_{a_i}^2 * g^4 * \mathrm{T_5} \right)$$





Signal templates $T_1 - T_5$

- 3 pure AC samples + 3 mixed SM-AC samples + 1 pure SM sample are **reweighted to considered AC hypothesis** (ggF: $H_1 - H_3$, VBF/VH: $H_1 - H_5$)



$T_i = G_{ji}H_j$

MELA

MC

$H_1 = H(1,0)$

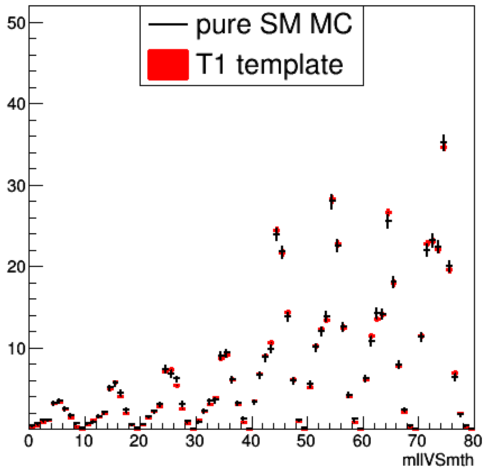
$H_2 = H(1,0.25)$

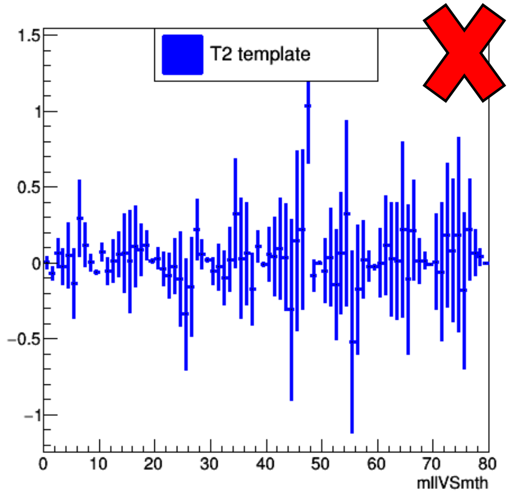
$H_3 = H(1,0.5)$

$H_4 = H(1,0.75)$

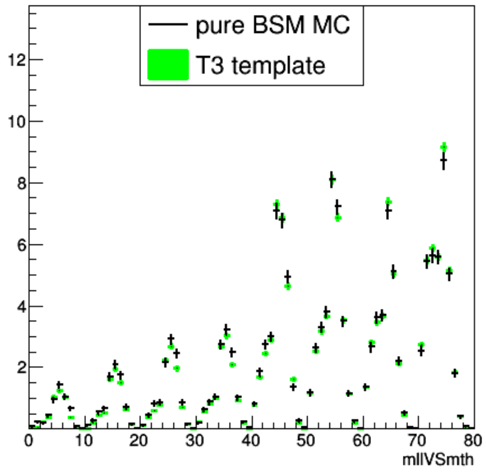
$H_4 = H(0,1)$

$ggH \to WW^*$ 0-jet (ggF templates)



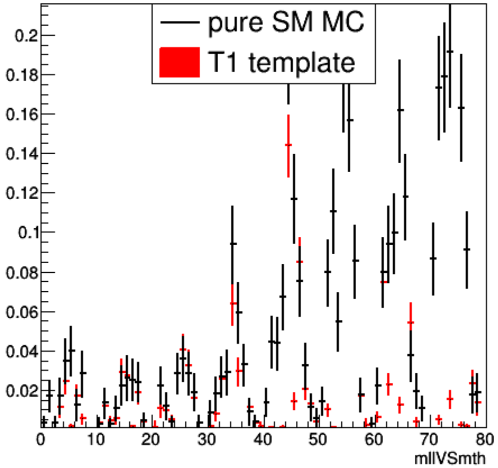


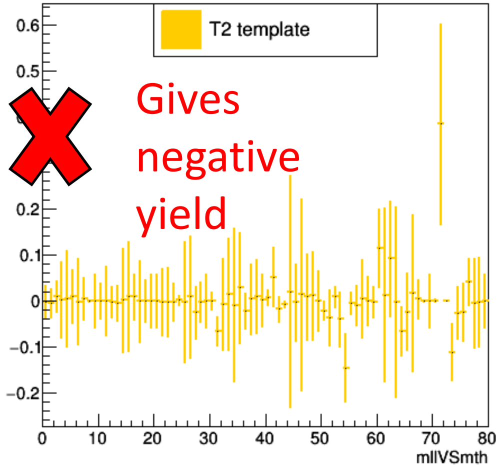
Interference should be identical to zero due to parity flip



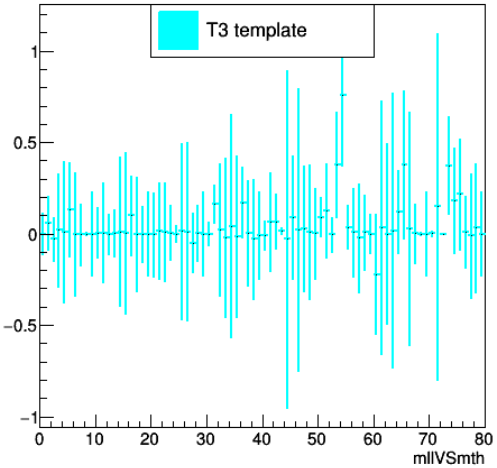
0^-

ggH → WW* 0-jet (VBF templates)

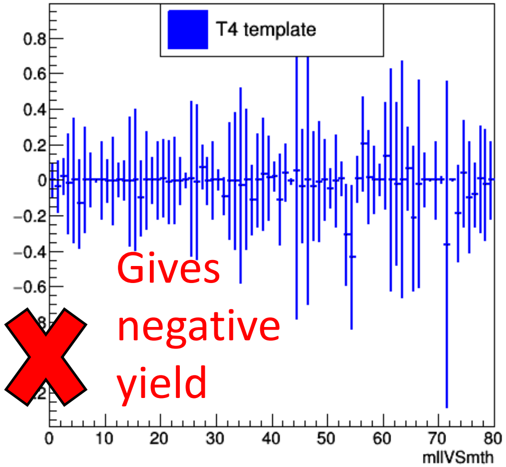




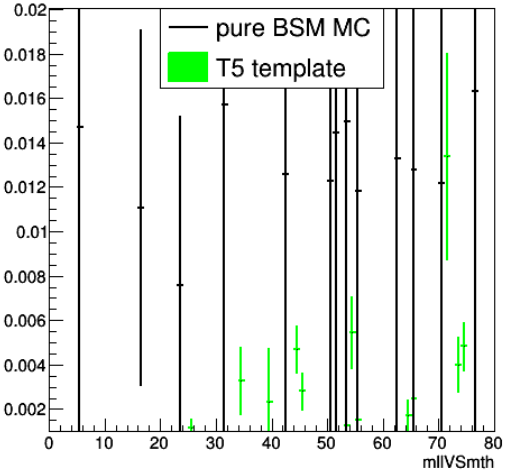
Gives negative yield



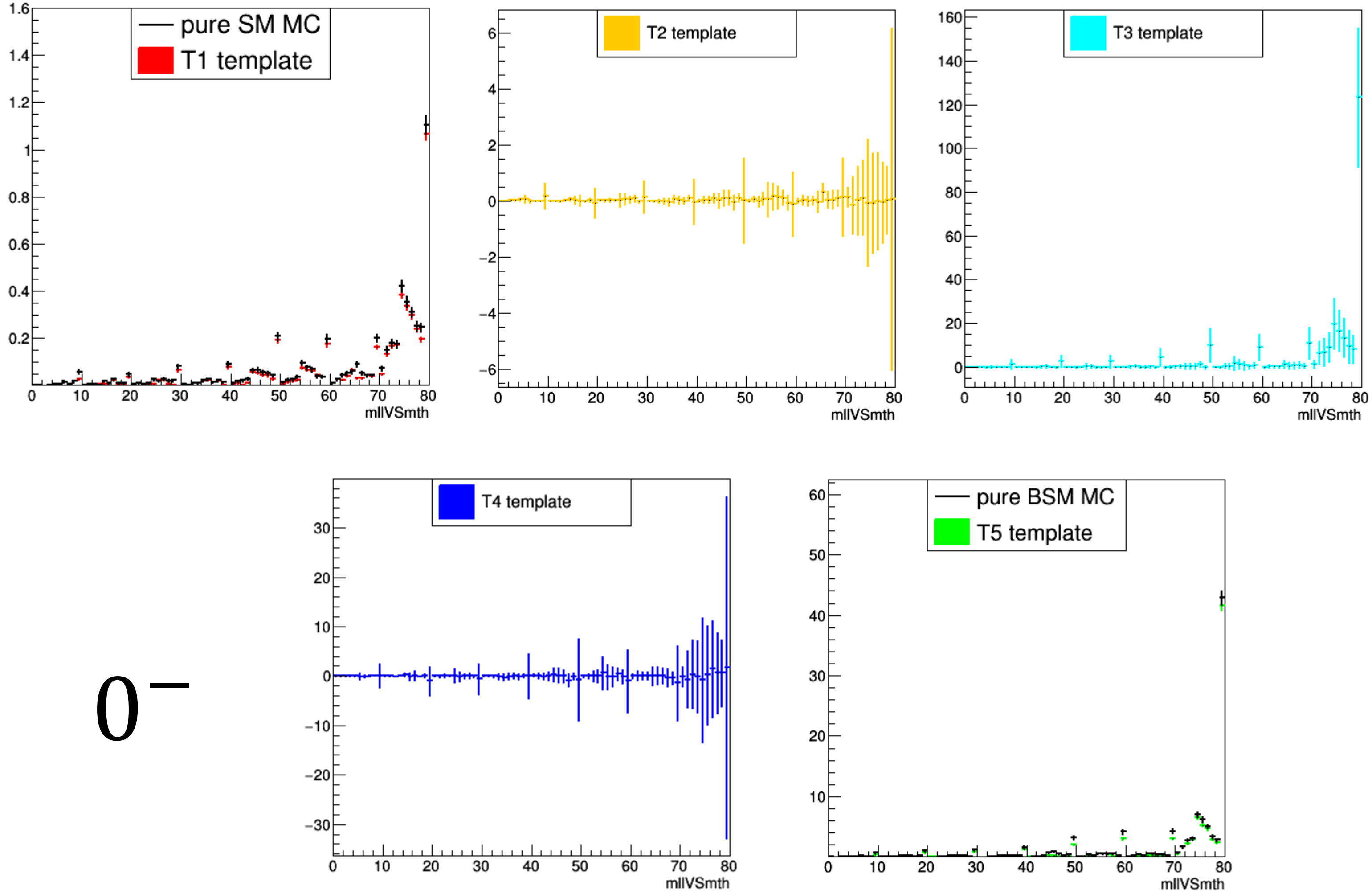
0^-



Gives negative yield



$ggH \rightarrow WW^*$ 0-jet (WH templates)



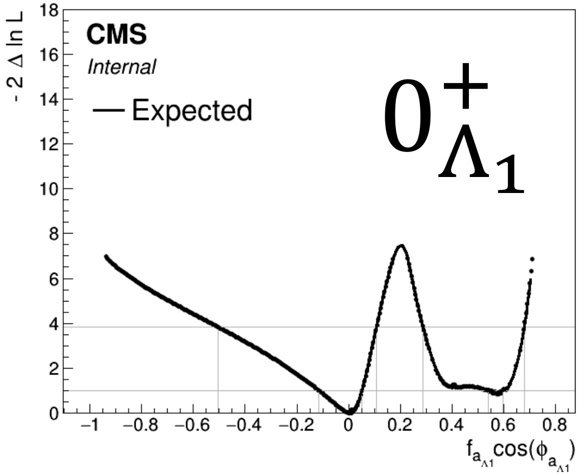
0^-

Nuisance parameters

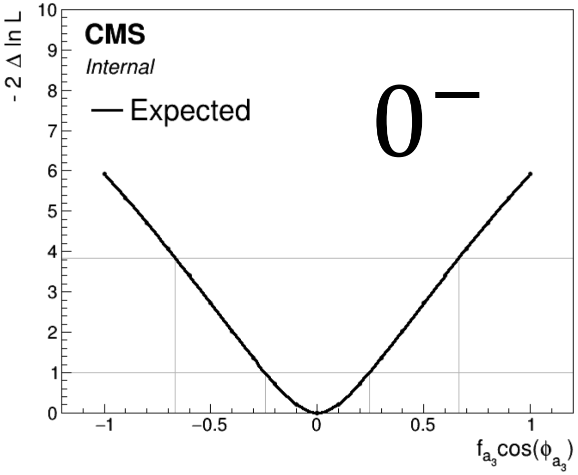
- considering **(almost) all statistic and systematic** uncertainties following main HWW analysis
    - lumi
    - fake
    - btag
    - trigg
    - e/μ eff and energy
    - MET
    - PU
    - PS
    - theory
    - ...
- **JES/JER systematics not included** (were not ready at that time)
- shape-type uncertainties undergo the same template machinery as mentioned above

Preliminary results MC 2016, ggH 0j

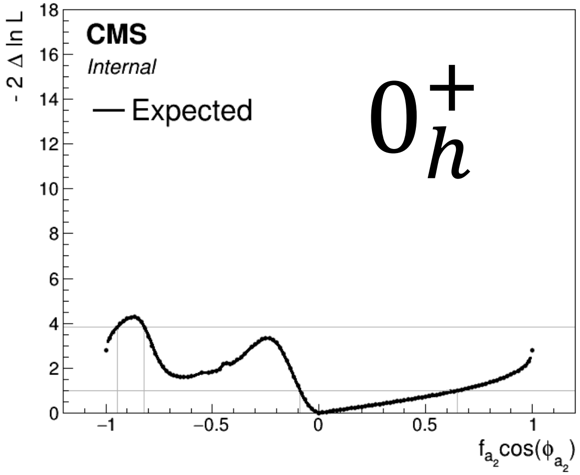
Run2 - 2016



$0^+_{\Lambda_1}$

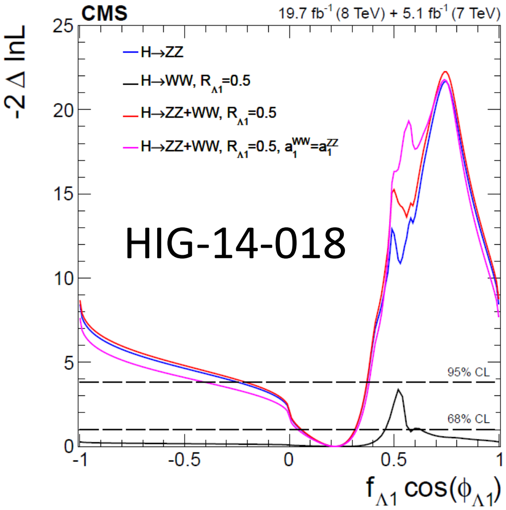


0^-



0^+_h

Run1



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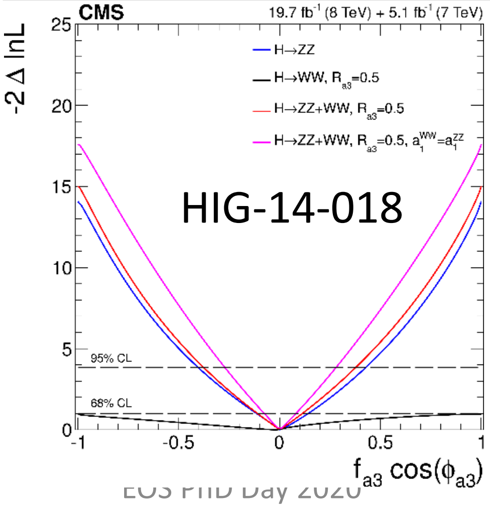

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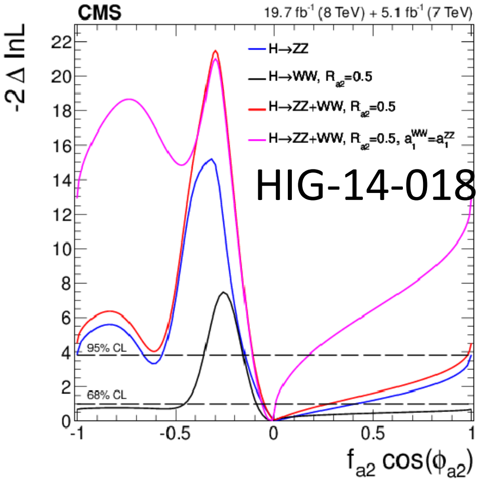
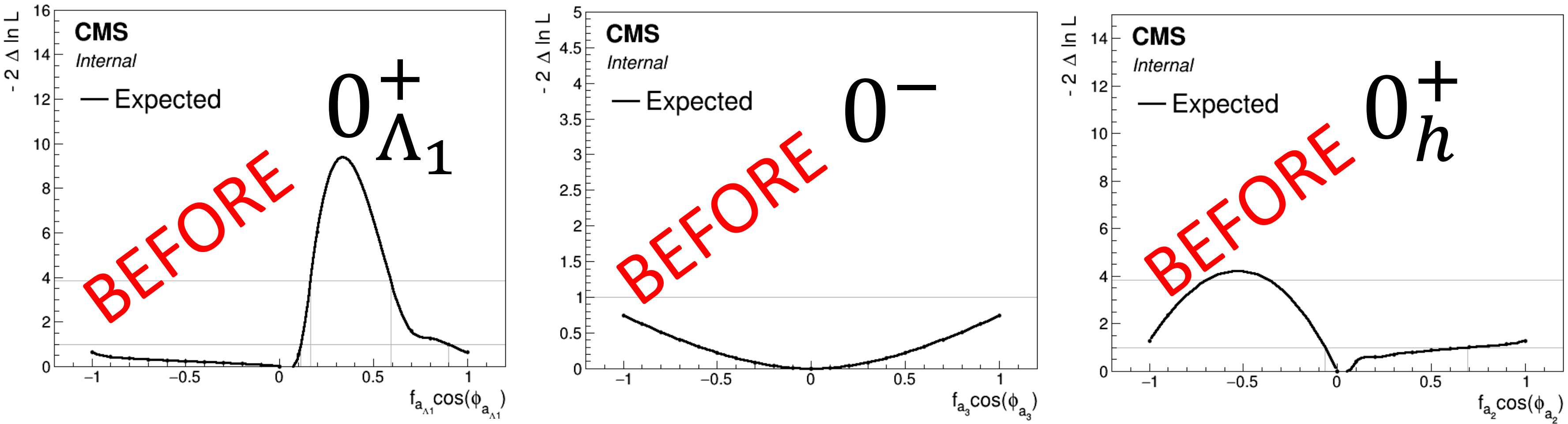


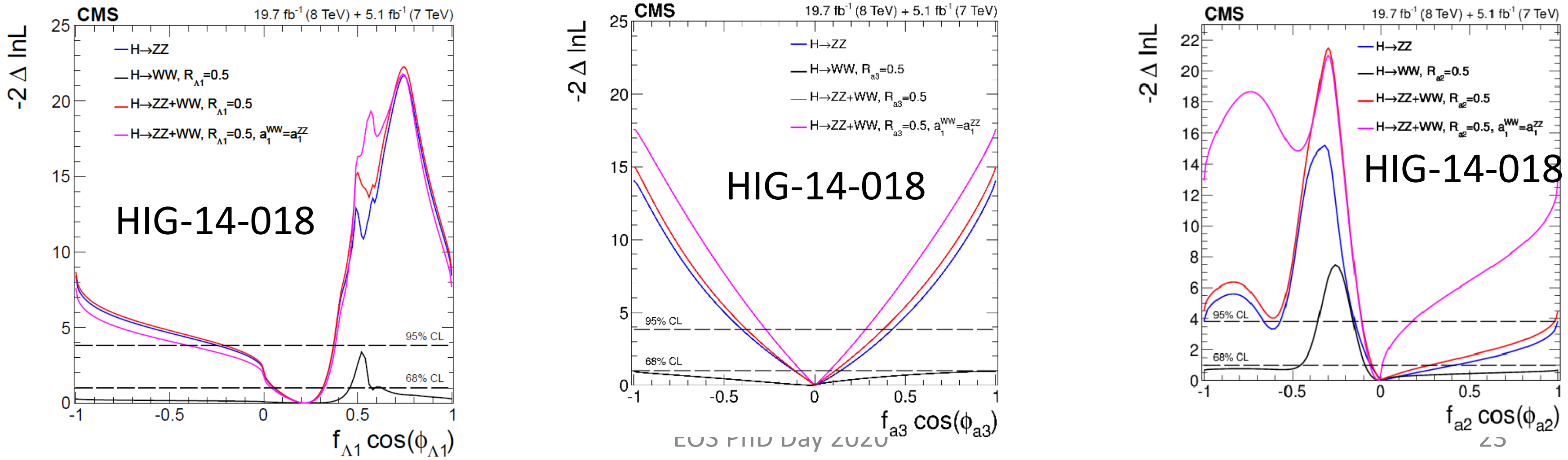
HIG-14-018

No VBF/VH signal MC 2016, ggH 0j

Run2 – 2016 - simplified

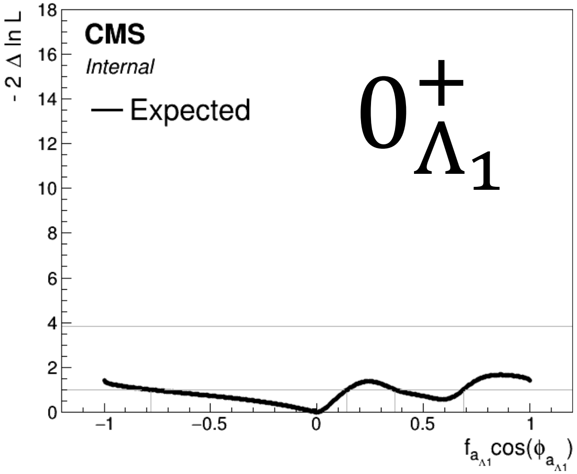


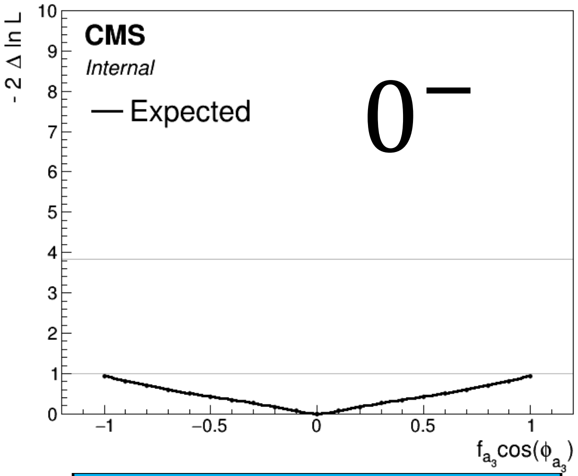
Run1

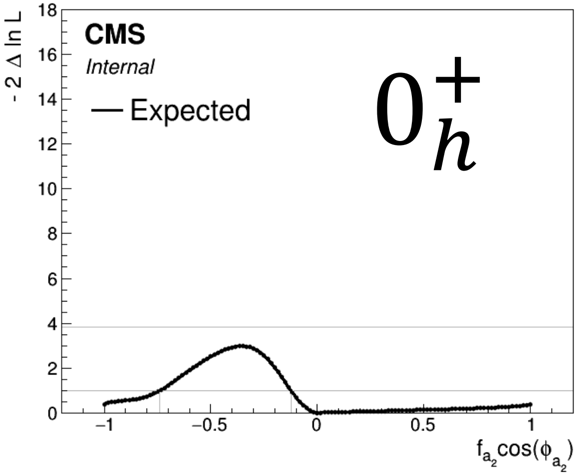


Preliminary results MC 2016, ggH 1j

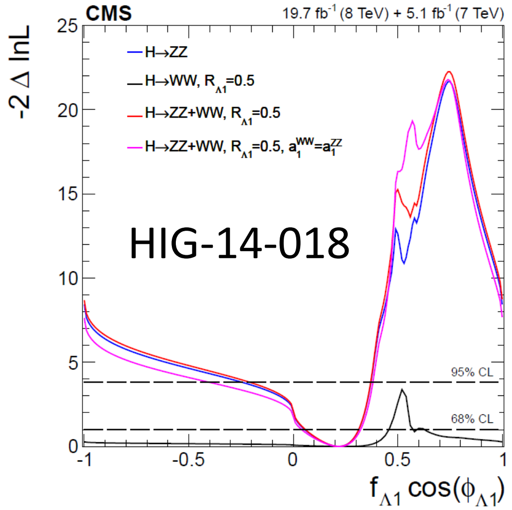
Run2 - 2016

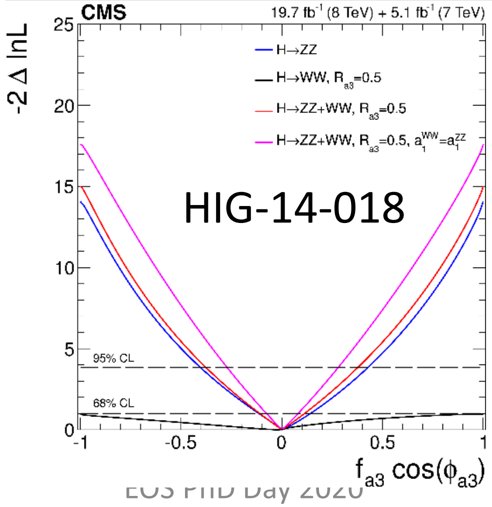


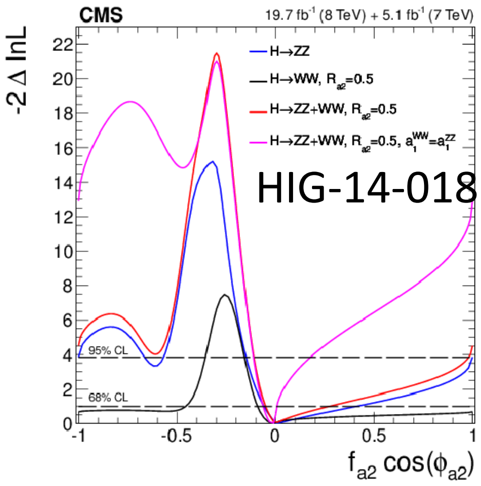




Run1





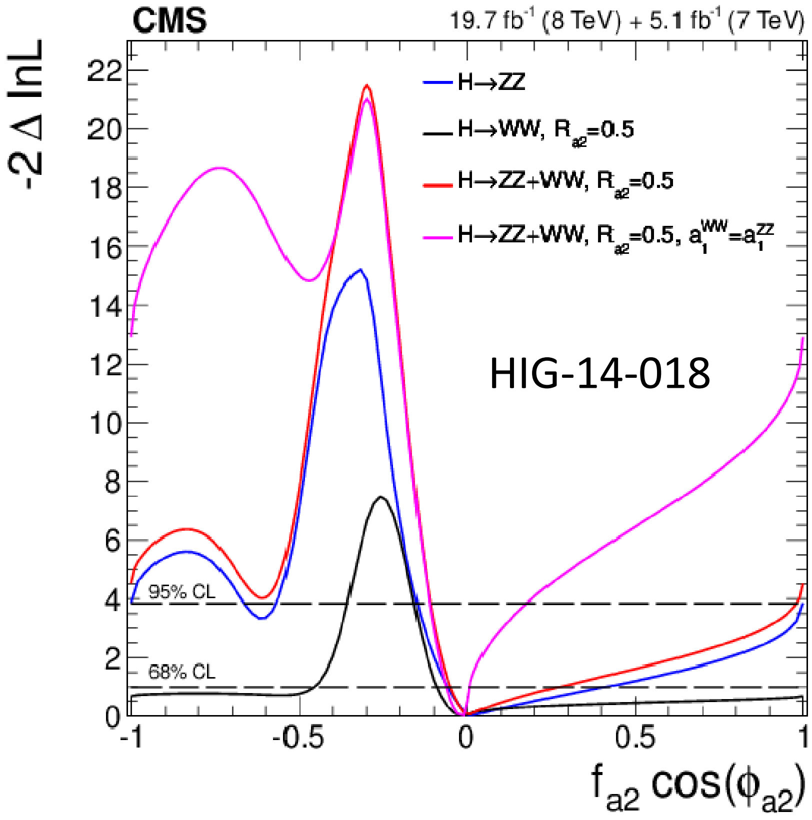


TODO:

- **merged 0j and 1j** categories
- adding JES/JER
- repeating analysis for **2017** and **2018**
- dedicated study on off-shell region (m_{ll} cut)
- can **MVA study** improve 2D kinematic discriminant?

Future plans

- study of the **N-jettiness subtraction method** (possible improvement to the AC studies)
- **ggH+2j** category probing CP-violating scenario
- $\mathbf{H \rightarrow ZZ}$ combination
- writing analysis note



HIG-14-018

Summary:

- likelihood scan performed for the $\mathbf{0^-}, \mathbf{0^+_{\Lambda_1}}$ and $\mathbf{0^+_h}$ models in **ggF 0/1jet channel**
- full signal+background parametrisation
- adding VBF/VH signal is shifting LS shape
- full nuisances applied but JES/JER
- **improved sensitivity in 0-jet channel compared to 1-jet channel**
- anticipated improvement after category merge (compared to Run1)
- interference templates with small, negative or oscillating yields can imply problems

Thank you for your attention

Reference

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URL: https://commons.wikimedia.org/wiki/File:Standard_Model_of_Elementary_Particles.svg

[2] ATLAS Collaboration. Observation of a new particle in the search for the Standard Model Higgs boson with the ATLAS detector at the LHC. Physics Lett. B, 716(1):1 – 29, 2012. URL: http://www.sciencedirect.com/science/article/pii/S037026931200857X, doi:https://doi.org/10.1016/j.physletb.2012.08.020.

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[5] CMS Collaboration. Constraints on the spin-parity and anomalous HVV couplings of the Higgs boson in proton collisions at 7 and 8 TeV. Phys. Rev. D 92, 012004. URL: https://journals.aps.org/prd/abstract/10.1103/PhysRevD.92.012004

[6] CERN. A 2008 aerial image of the LHC site. [22-October-2020] URL: https://www.washington.edu/news/2019/03/05/faser-detector-lhc/

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[10] CMS Collaboration. Constraints on the spin-parity and anomalous HVV couplings of the Higgs boson in proton collisions at 7 and 8 TeV. Phys. Rev. D 92, 012004. URL: https://journals.aps.org/prd/abstract/10.1103/PhysRevD.92.012004

[11] CMS Collaboration. Public CMS Luminosity Information. URL: https://twiki.cern.ch/twiki/bin/view/CMSPublic/LumiPublicResults#Multi_year_plots

[12] CMS Collaboration. Sketches of the CMS Tracker Detector. URL: https://twiki.cern.ch/twiki/bin/view/CMSPublic/DPGResultsTRK

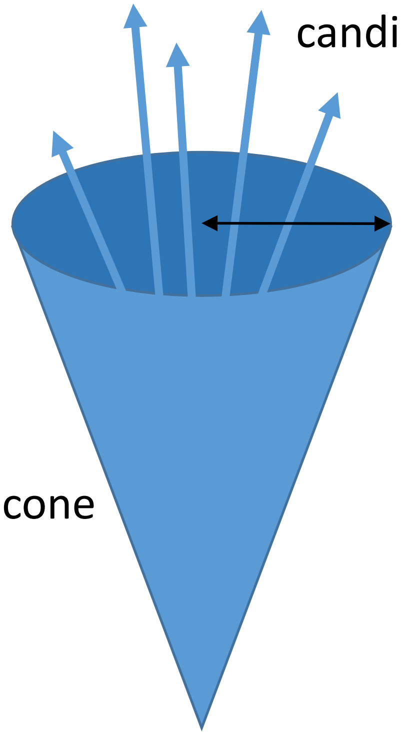
[13] CMS Collaboration. CMS Tracker Detector Performance Results 2015: Alignment. URL: https://twiki.cern.ch/twiki/bin/view/CMSPublic/TkAlignmentPerformance2015

Reference

[14] CMS Collaboration. The Phase-2 Upgrade of the CMS Tracker. *Inspire HEP*. URL: https://inspirehep.net/literature/1614103

Addendum 1

Jet studies



particle-flow (PF) candidates

$\Delta R = \sqrt{\Delta\phi^2 + \Delta\eta^2}$

angular distance parameter

jet cone

„leading vertex“

- jets are reconstructed from PF candidates using anti-kT algorithm within $\Delta R = 0.4$ or 0.8
- Jet $\vec{p} = \sum_{\Delta \mathrm{R}} \vec{p}_{\mathrm{PF}}$
- multiple corrections to jet momentum and energy are applied

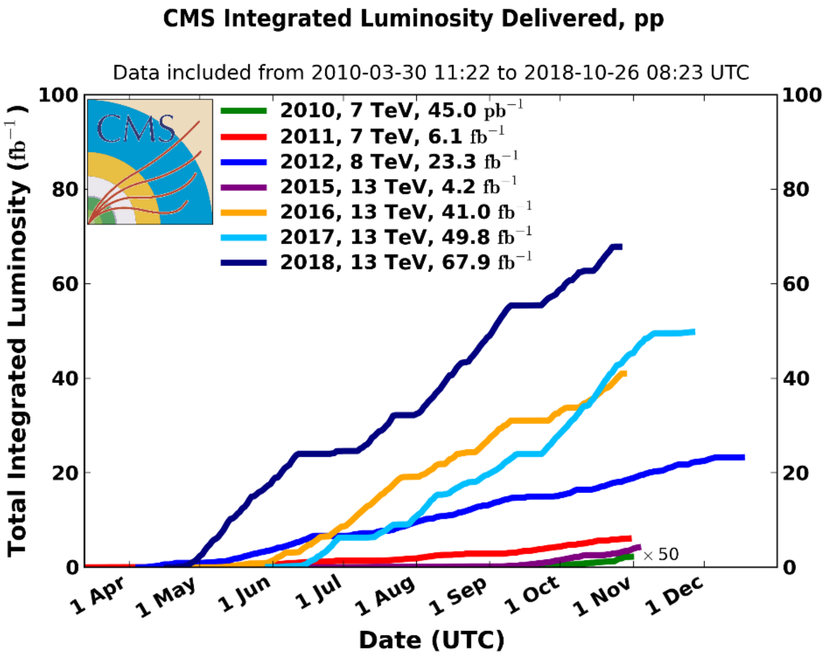
<u>Dictionary:</u>

Reco jets = PF reconstructed jets
Gen jets = Monte Carlo generator particle-level jets

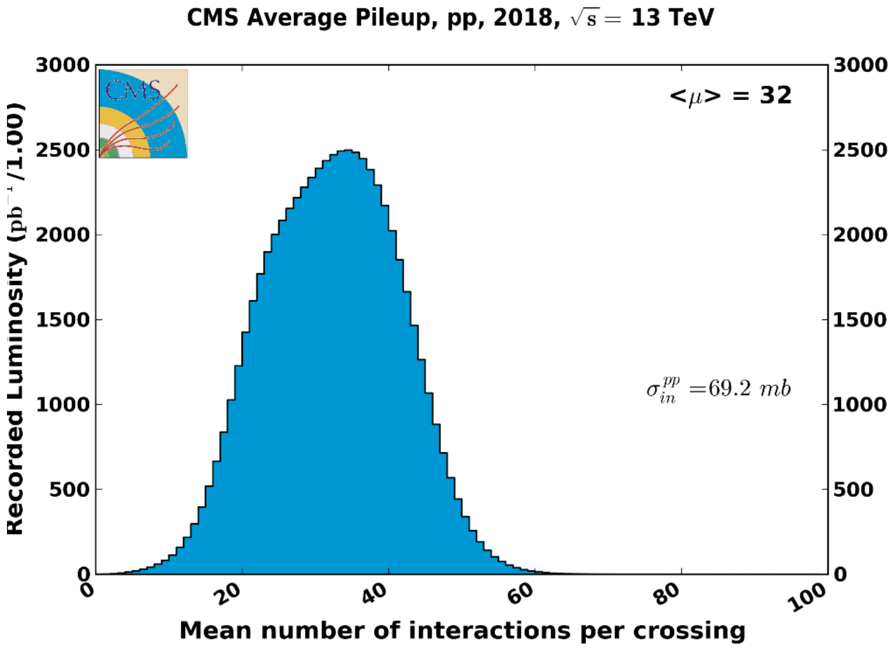
Jet studies

$137\mathrm{fb}^{-1}$ of processed integrated luminosity over Run 2 (2016, 2017, 2018)

pile-up effects



CMS Integrated Luminosity Delivered, pp



CMS Average Pileup, pp, 2018, $\sqrt{s} =$ 13 TeV

Source: [11]

Jet studies

Pile-up Jet Identification Discriminant (PU jet ID)

Hard scatter jets ⟺ Pile-Up jets

- tracks from **„leading vertex“**
- jet shape more **collimated and narrow** as originating from single gluon or quark

- tracks from multiple **PU vertices**
- jet shape is more **broad** due to multiple PU collisions

variables describing jet kinematics and shape

N_{vtx}

$\frac{\sum_{\mathrm{LV}} p_{\mathrm{T}}}{\sum_{\mathrm{all}} p_{\mathrm{T}}}$

$\langle \Delta R^2 \rangle$

…

→ MVA training (Boosted Decision Tree) →

Loose
Medium
Tight

} PU ID

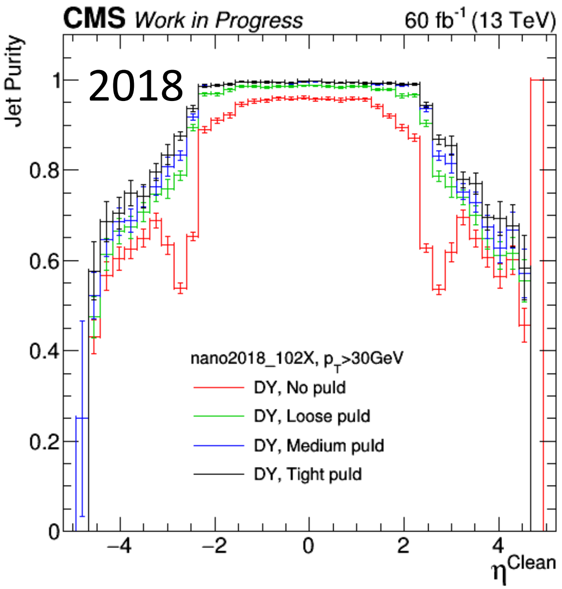
Jet studies - example

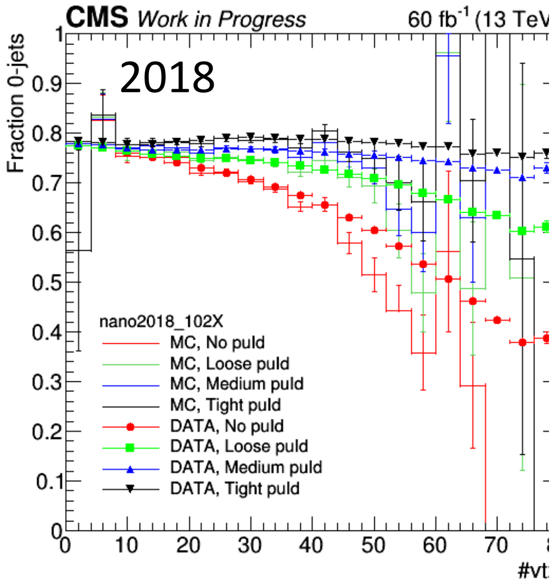
Pile-up Jet Identification Discriminant (PU jet ID)

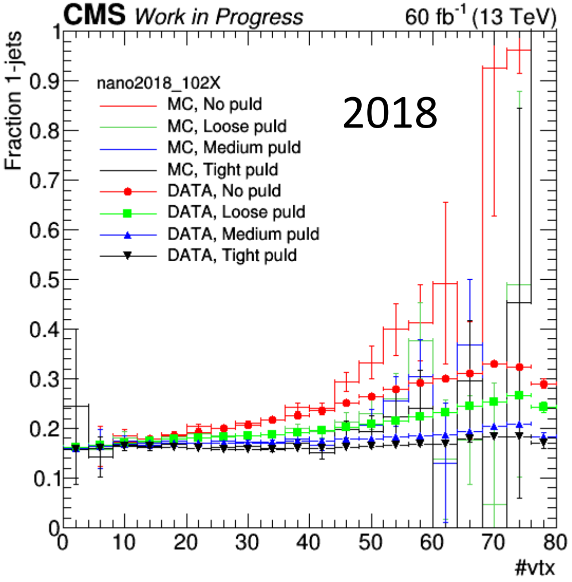
$$\text{Purity} = \frac{\#(\text{Reco \& Gen})}{\#\text{Reco}}(p_T^{Clean}, \eta^{Clean})$$

$$\text{FractionNjets} = \frac{\#(\text{Njets})}{\text{all}}(\#\text{vtx}) \quad N = 0,1$$

- study done for full Run2
- **Loose PU ID** working point was selected (green line)

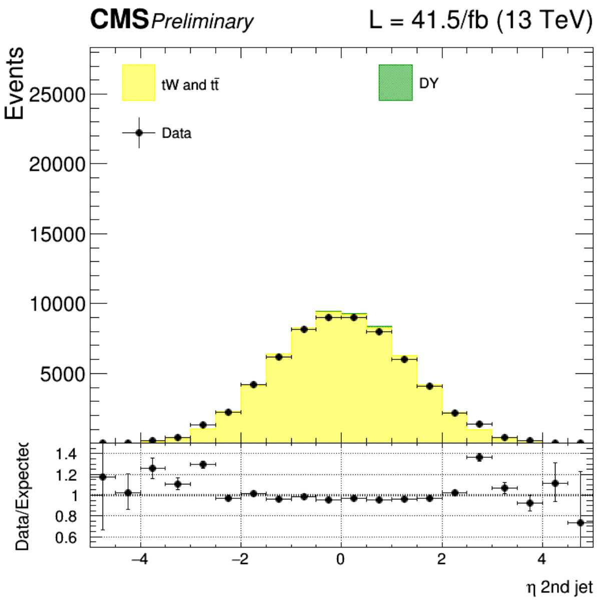


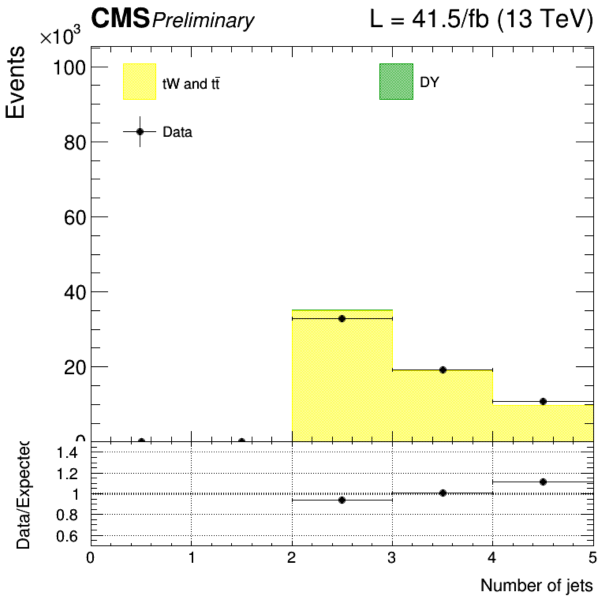




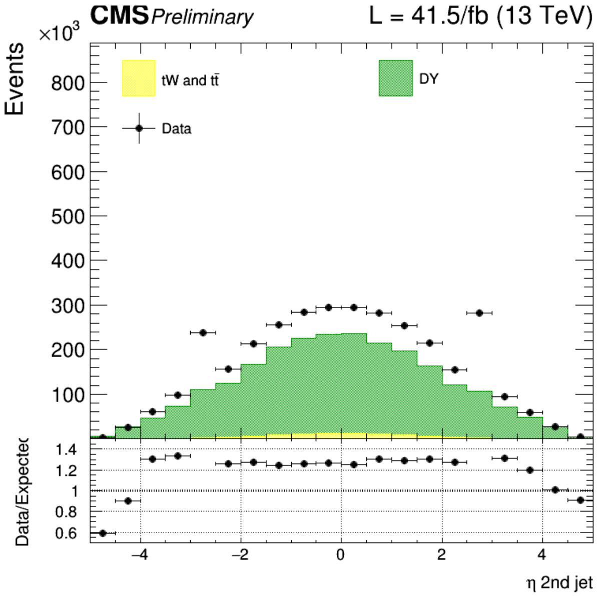
2017 no JERs

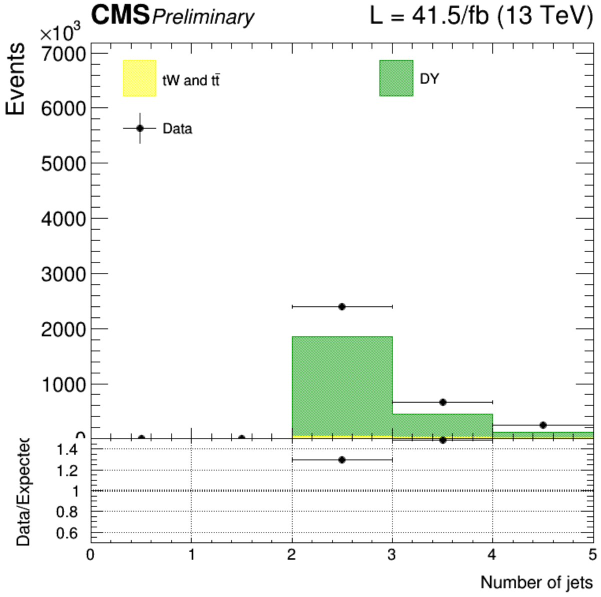
Top2j CR





DYSF2j CR



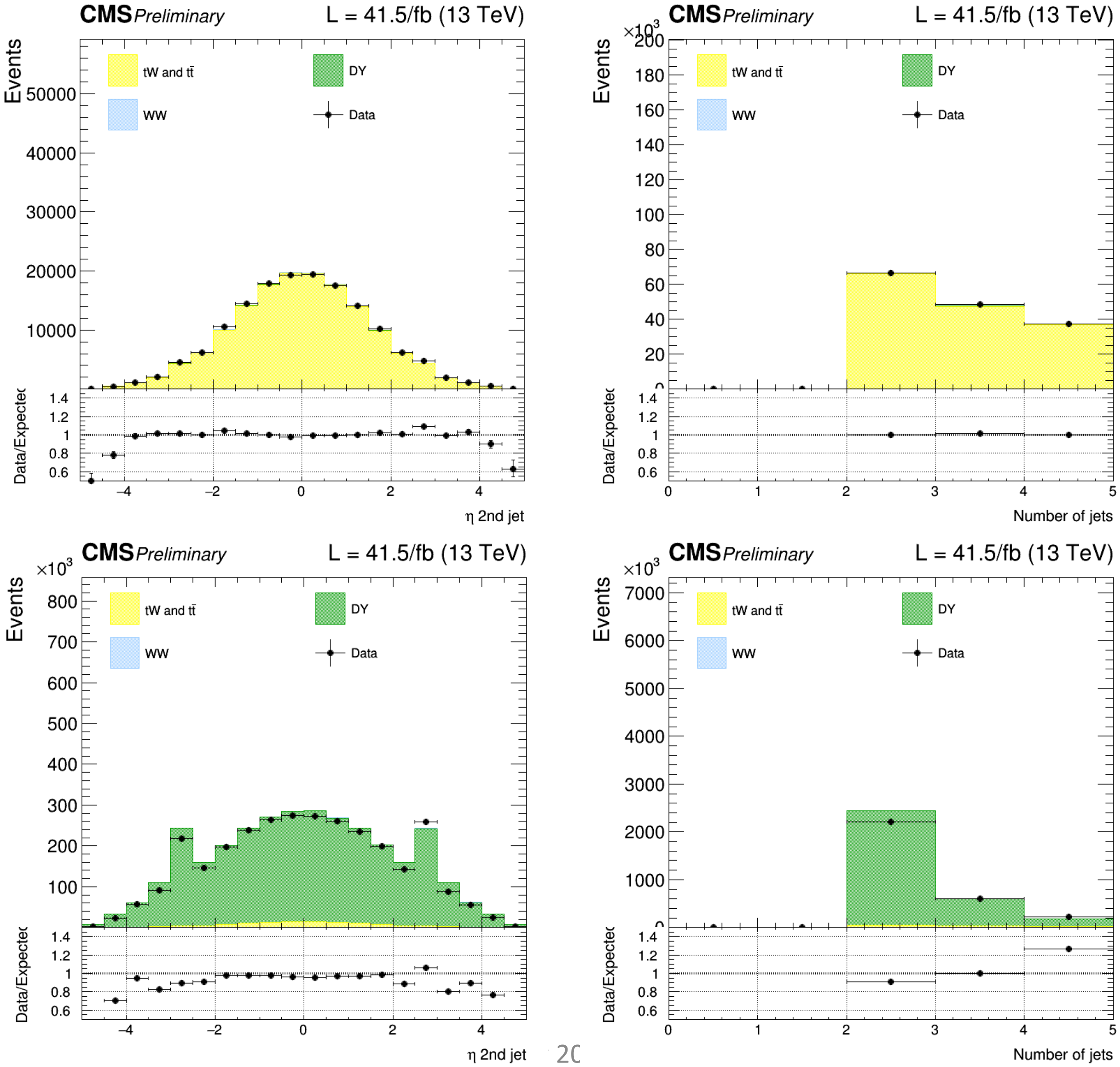


JER17 on 2017

Top2j CR

improvement in 2017

DYSF2j CR



Output

Jet studies contribution to:

- CMS Collaboration, Measurements of differential Higgs boson production cross sections in the leptonic WW decay mode at $\sqrt{s} = 13\ \mathrm{TeV}$
  URL: https://inspirehep.net/literature/1757146
- CMS Collaboration, Measurement of the inclusive and differential Higgs boson production cross sections in the leptonic WW decay mode at $\sqrt{s} = 13\ \mathrm{TeV}$
  URL: https://inspirehep.net/literature/1805274
- CMS internal notes “Higgs to WW leptonic differential measurements using 2016, 2017, and 2018 data sets“ and „Common analysis object definitions and trigger efficiencies for the $\mathrm{H} \to$ WW analysis with full Run-II data “

Addendum 2

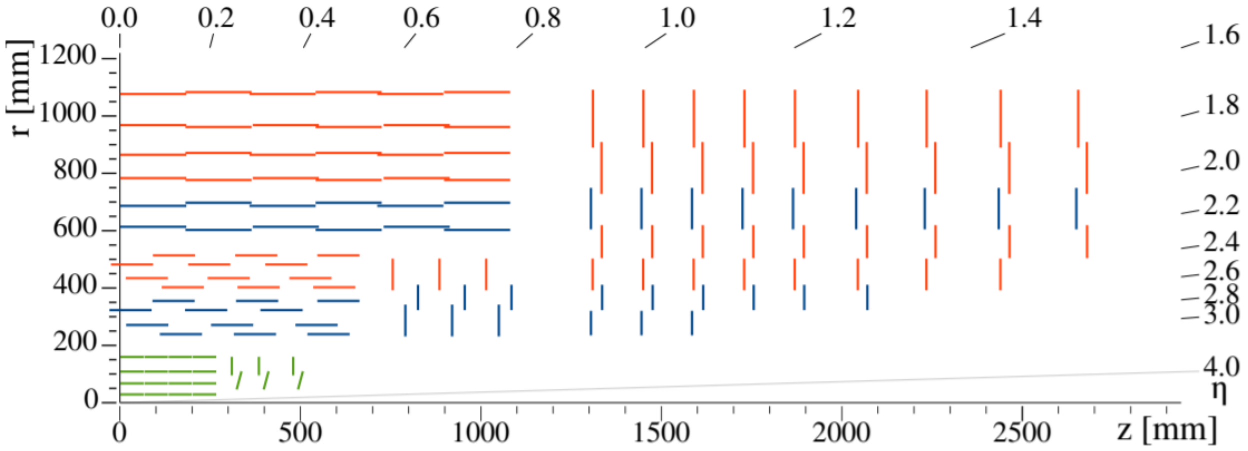
Tracker Alignment

What is it?

- **1856** silicon pixel modules (green)
- **15148** silicon strip modules (orange and blue)

$\sim$200000 parameters needed to describe alignment of the modules

$\sigma_{\mathrm{align}} \sim \sigma_{\mathrm{hit}}$



$\sigma_{p_T} \approx 1.5\%$

$\sigma_{d_z} \approx 45 - 150\mu\mathrm{m}$

$\sigma_{d_{xy}} \approx 25 - 90\mu\mathrm{m}$

Source: [12]

Tracker Alignment

Why do we need it?

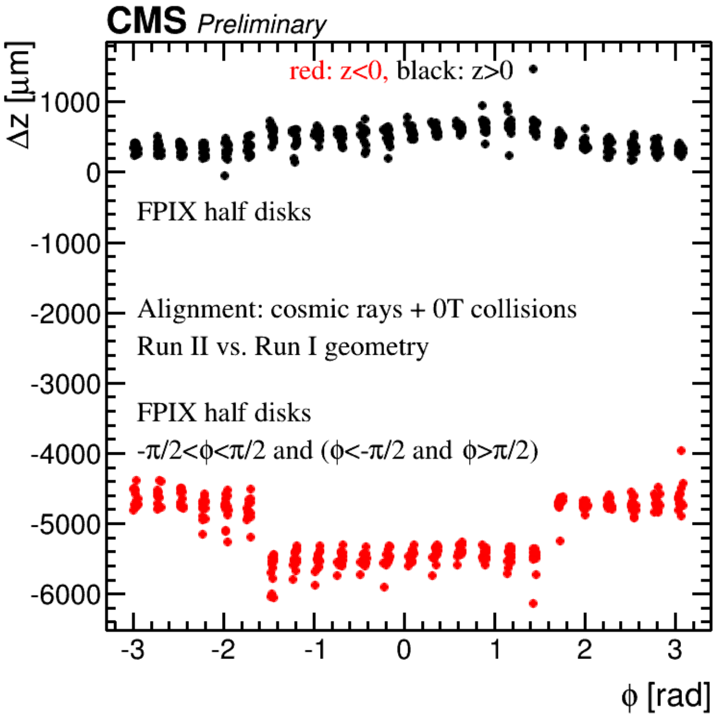
Main misalignment causes:

- magnet cycles
- temperature changes
- ageing (high radiation)
- systematic distortion

Misalignment treatment:

$$\chi^2(p,q) = \sum_j^{tracks} \sum_i^{hits} \left(\frac{m_{ij} - f_{ij}(p,q)}{\sigma_{ij}^m} \right)^2$$

m = measurement
f = prediction
σ = uncertainties
p, q = alignment and track parameters

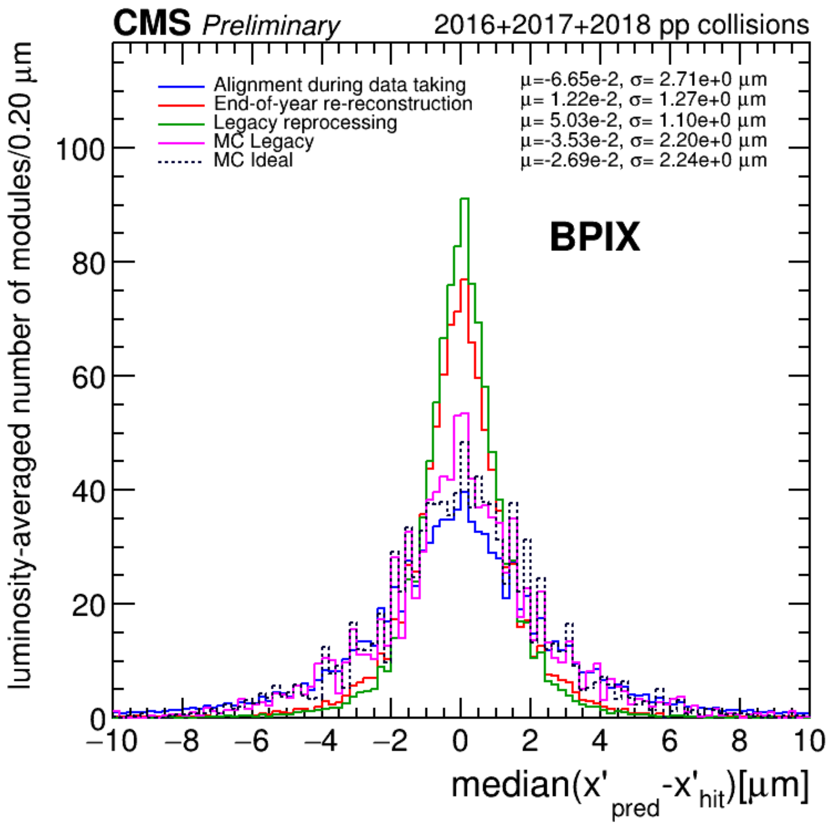


Source: [13]

Tracker Alignment Validation

What is detector performance?

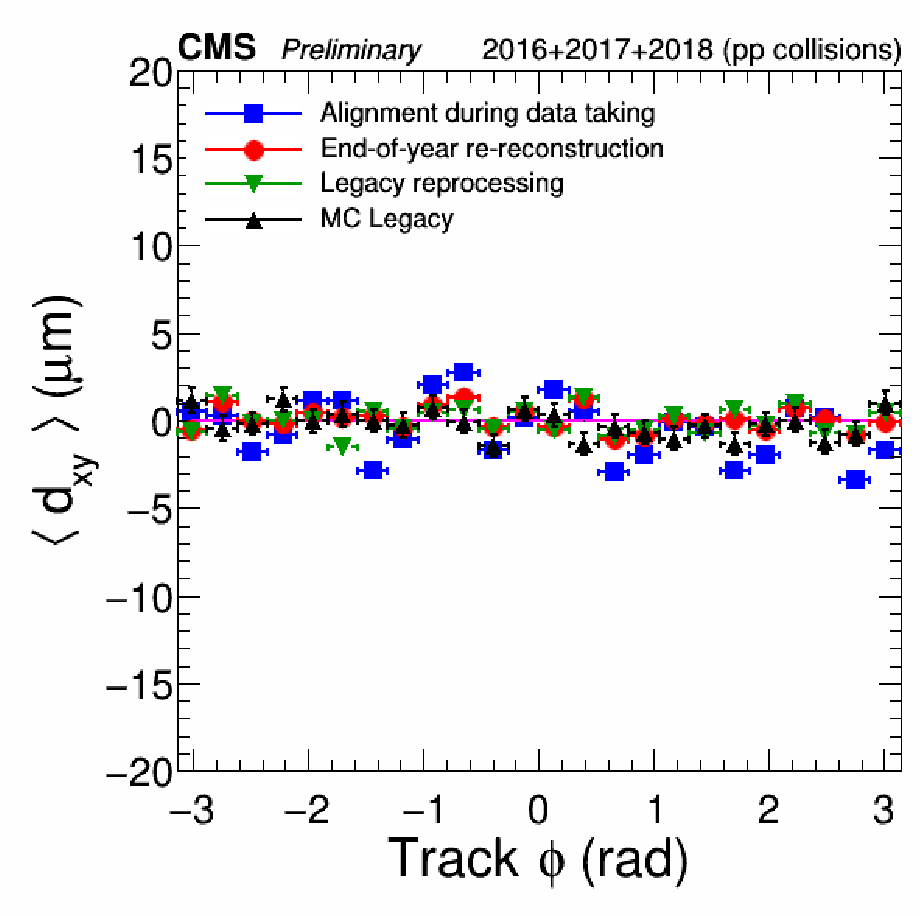
Distributions of median residuals (DMR)



Tracker Alignment Validation

What is detector performance?

Primary vertex validation

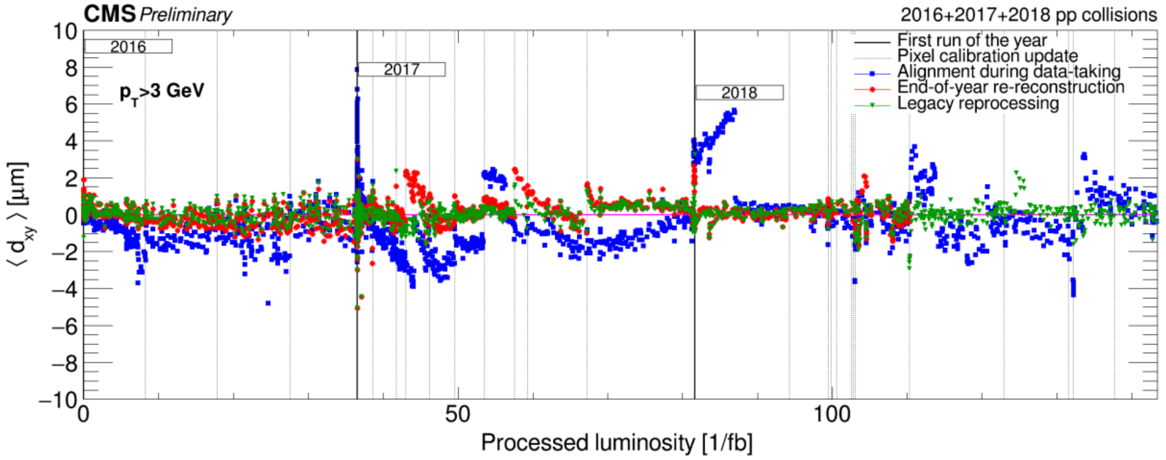


Tracker Alignment Validation

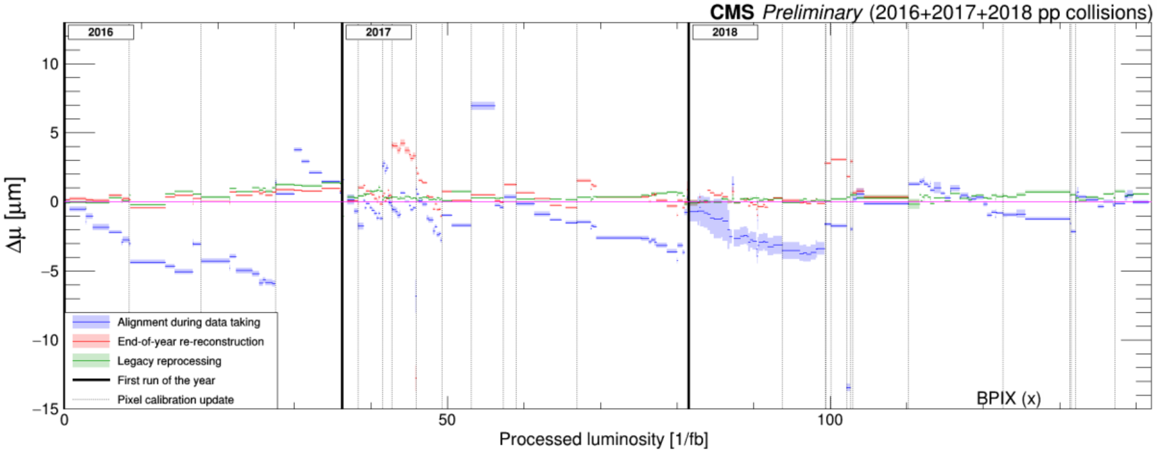
What is detector performance?

Luminosity trends

PV



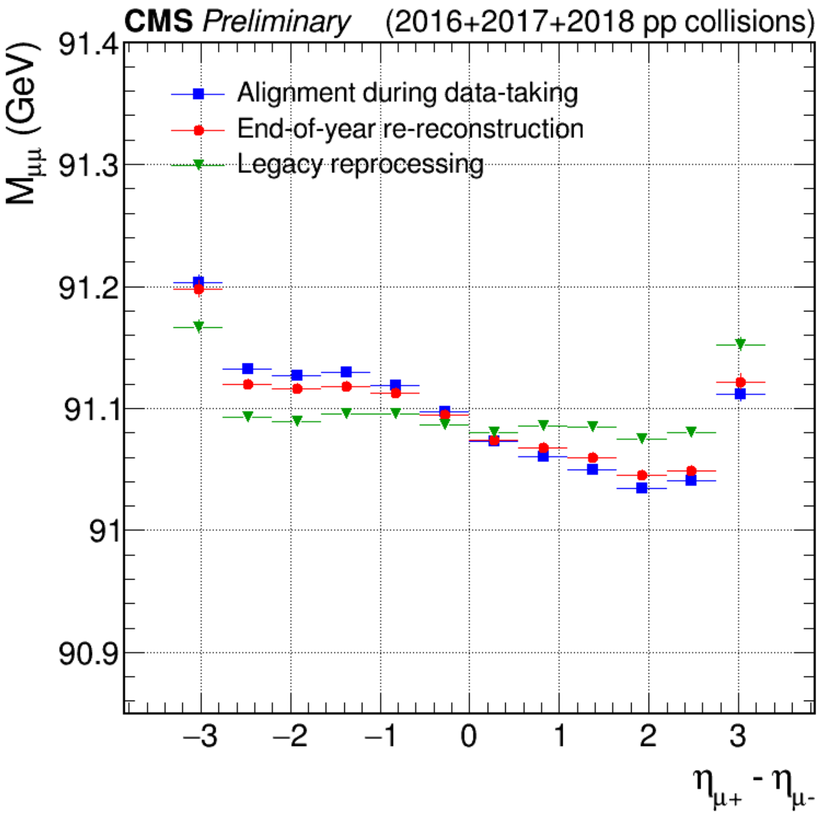
DMR



Tracker Alignment Validation

What is detector performance?

Di-muon mass validation (Zμμ)



Output

Public:

- CMS Collaboration, CMS Tracker Performance results for full Run 2 Legacy reprocessing, URL: http://cds.cern.ch/record/2713208?ln=en

Prepared for publication:

- CMS Collaboration, Alignment Strategies and Performance of CMS silicon tracker during LHC Run-2

Software development

- multipurpose validation tool for luminosity-averaged distributions
- new submission scheduler system of validation code

CMS authorship

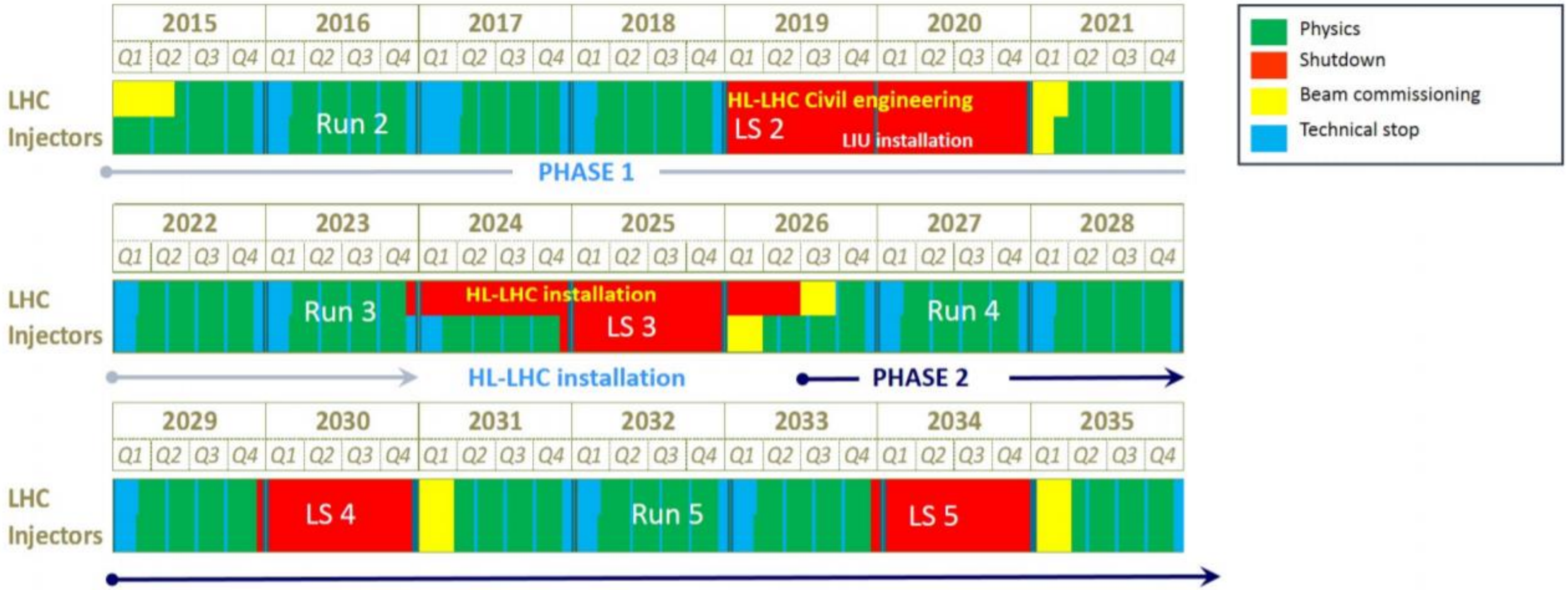
- 5+4 months of service work

Addendum 3

High Luminosity LHC Upgrade

Timeline

- expected $\sim\mathbf{300fb^{-1}}$ of processed luminosity per year

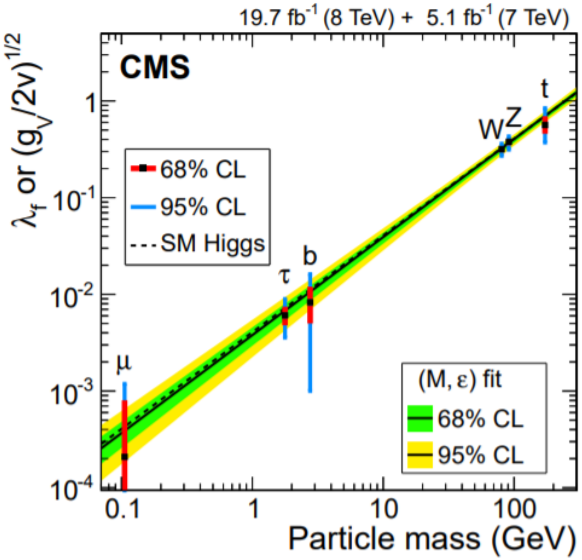


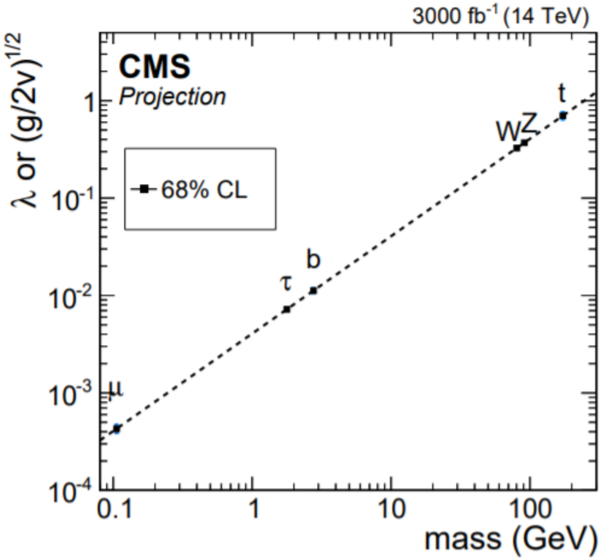
Source: [14]

High Luminosity LHC Upgrade

Physics motivation

- improved sensitivity for SM Yukawa couplings measurements ($\mathrm{H} \rightarrow \mu\mu$)
- **BSM channels with small couplings** will open up
- SM Higgs self-coupling measurement



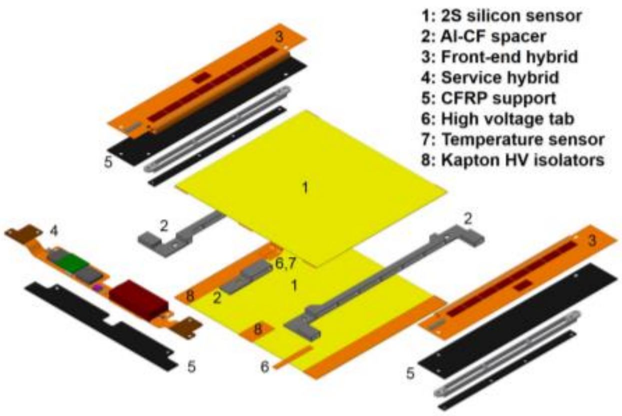


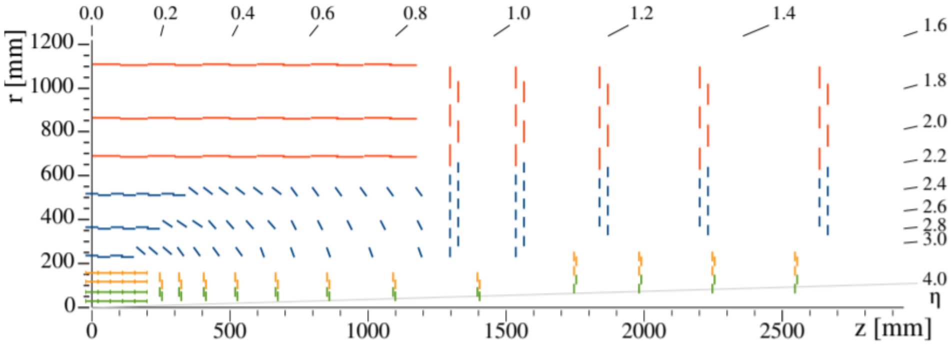
Source: [14]

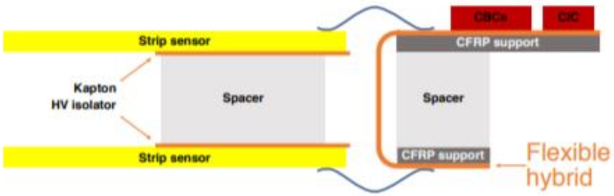
CMS Tracker Phase 2 Upgrade

Belgium Assembly line

- CMS upgrade is necessary to cope with HL upgrade
- tracker is the innermost detector and will need to handle an **increased interaction rate** and **high radiation level**

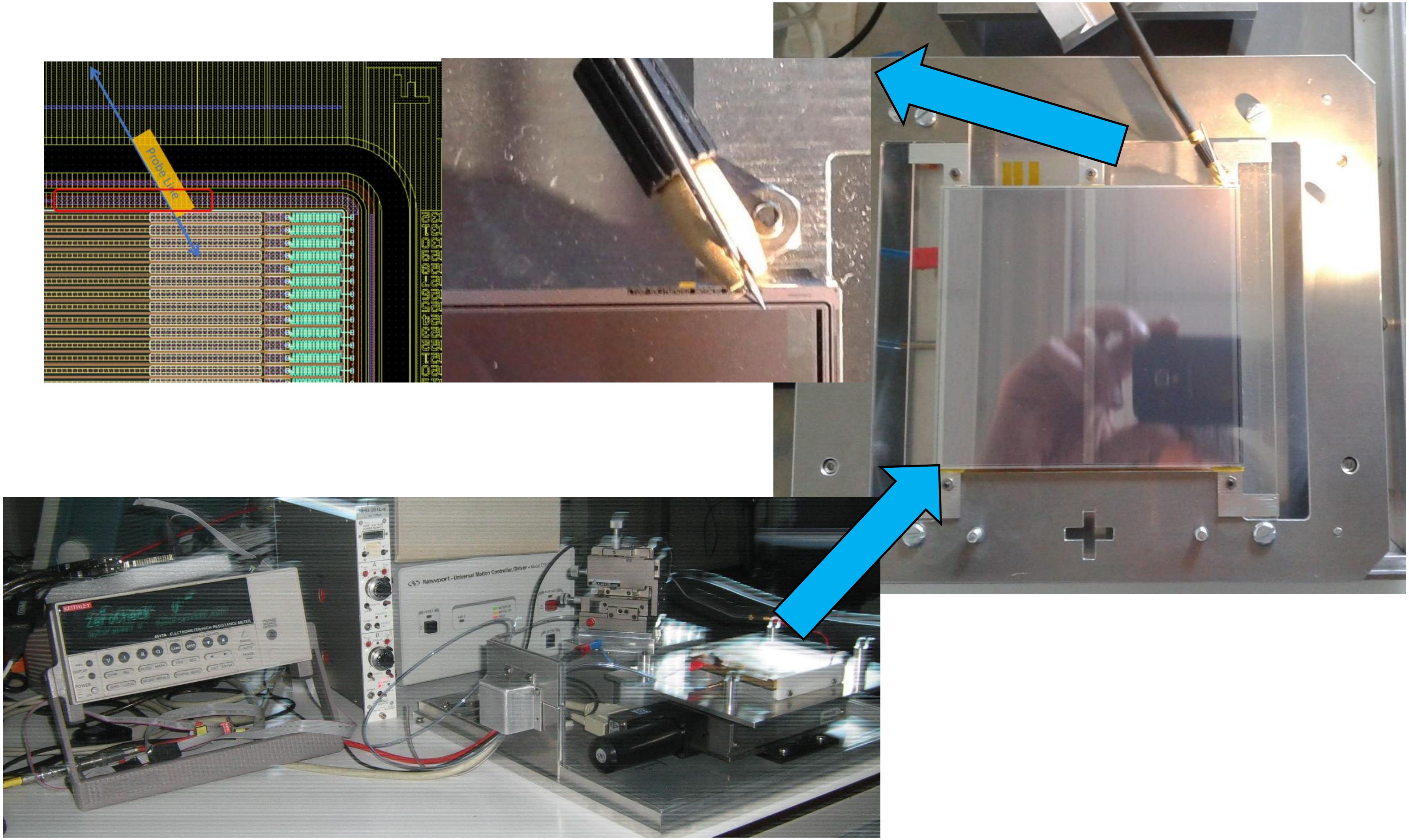




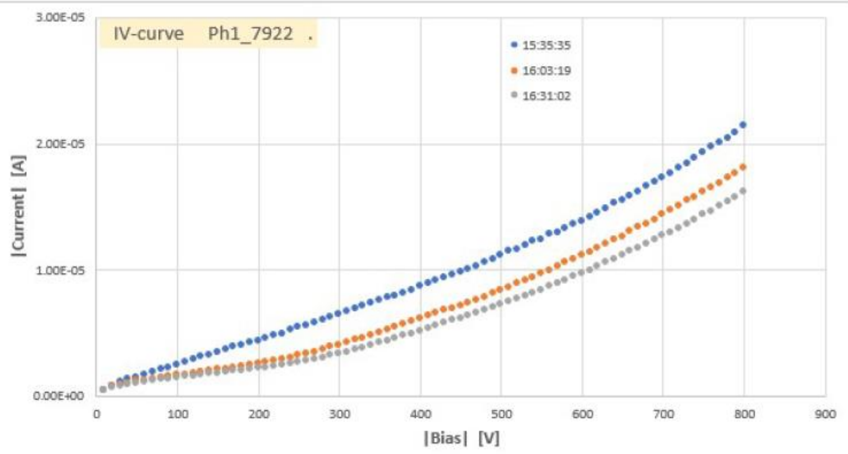


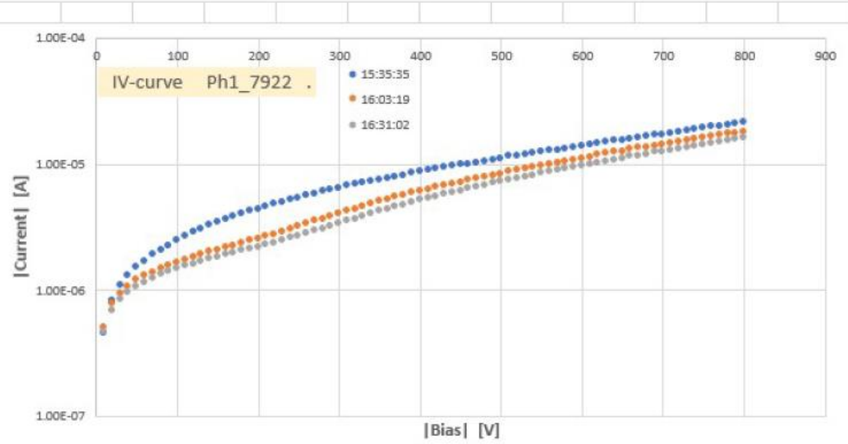
Source: [14]

IV curve testing station

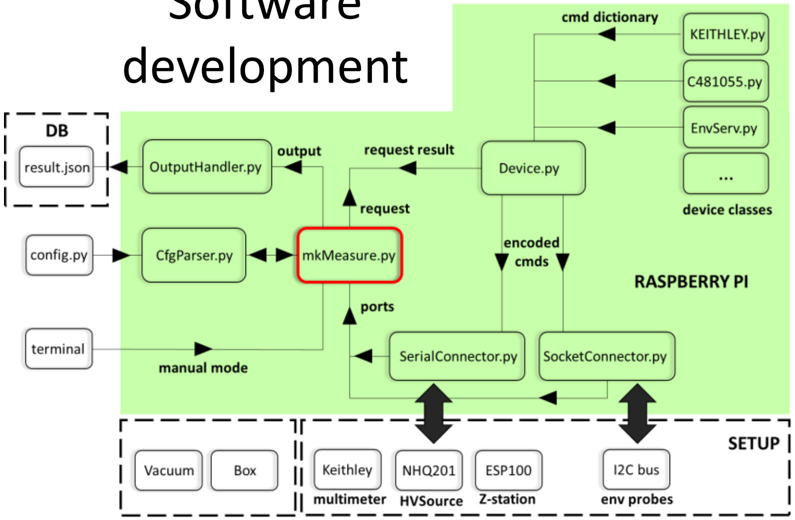


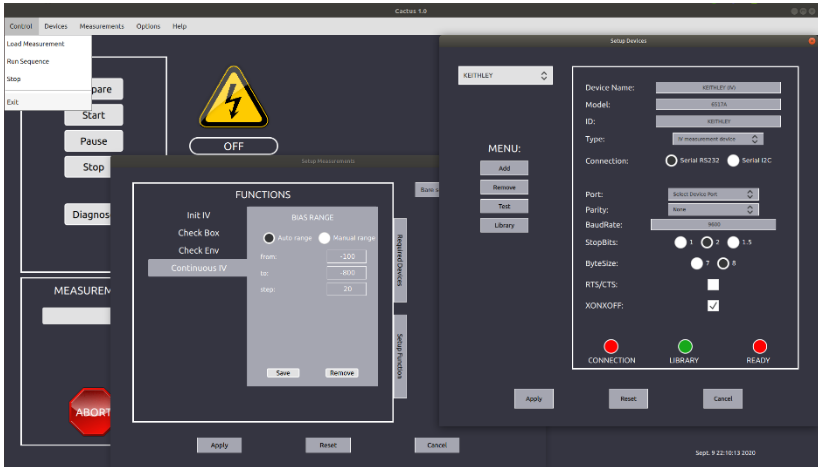
IV curve testing station





Software development





● Auto range ○ Manual range

from: -100

to: -800

step: 20

KEITHLEY

Device Name: KEITHLEY (IV)

Model: 6517A

ID: KEITHLEY

Type: IV measurement device

Connection: ● Serial RS232 ○ Serial I2C

Port: Select Device Port

Parity: None

BaudRate: 9600

StopBits: ○ 1 ● 2 ○ 1.5

ByteSize: ○ 7 ● 8

RTS/CTS: ☐

XONXOFF: ☑

Sept. 9 22:10:13 2020

Backup

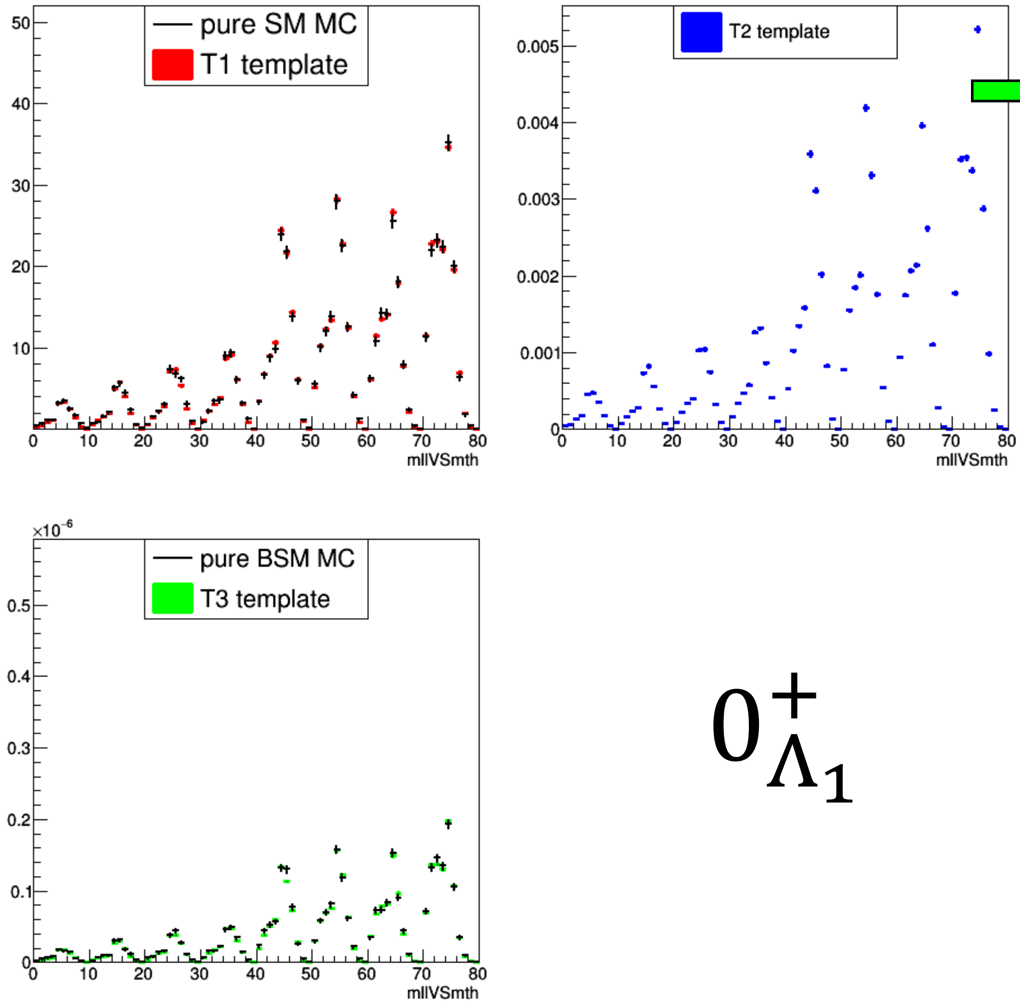
Signal templates $\mathrm{T}_1 - \mathrm{T}_5$

- 3 pure AC samples + 3 mixed SM-AC samples + 1 pure SM sample are **reweighted to considered AC hypothesis** (ggF: $\mathrm{H}_1 - \mathrm{H}_3$, VBF/VH: $\mathrm{H}_1 - \mathrm{H}_5$)
- each hypothesis H_i is created as **a weighted sum** of predictions
- final templates are obtained after some algebraic manipulation

ggF: $\mathrm{T}_2 = (\mathrm{H}_2 - \mathrm{H}_1 - \mathrm{H}_3 * g^2)/g$

VBF/VH: $\mathrm{T}_\mathrm{i} = G_{ji} H_j$

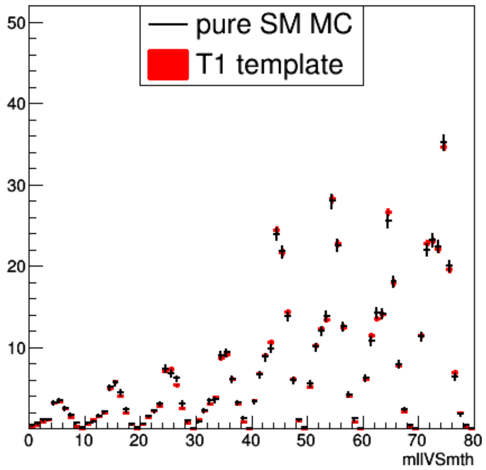
$ggH \rightarrow WW^*$ 0-jet (ggF templates)

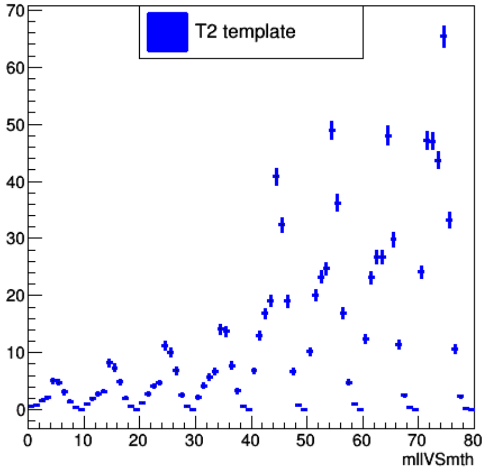


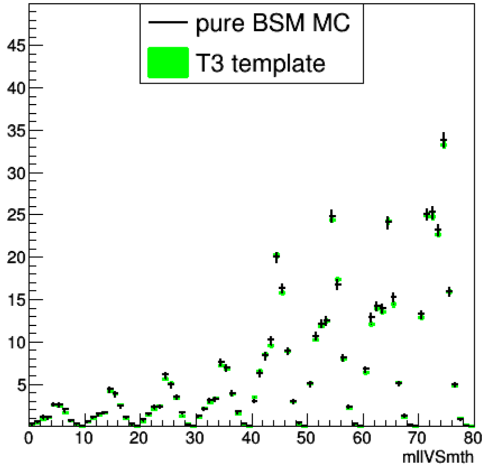
🟩 would be negative

$$0^+_{\Lambda_1}$$

ggH → WW^* 0-jet (ggF templates)

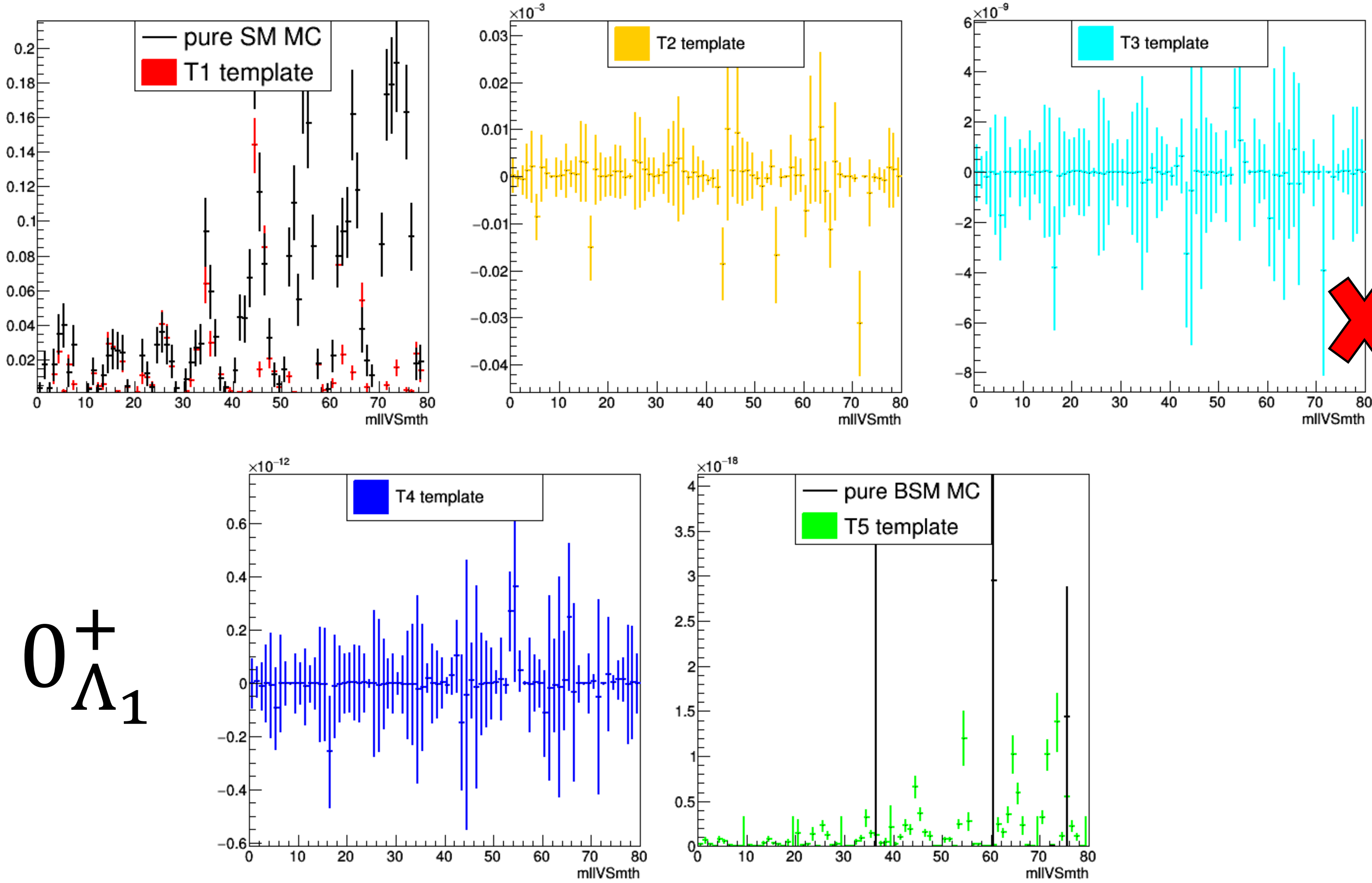






$$0_h^+$$

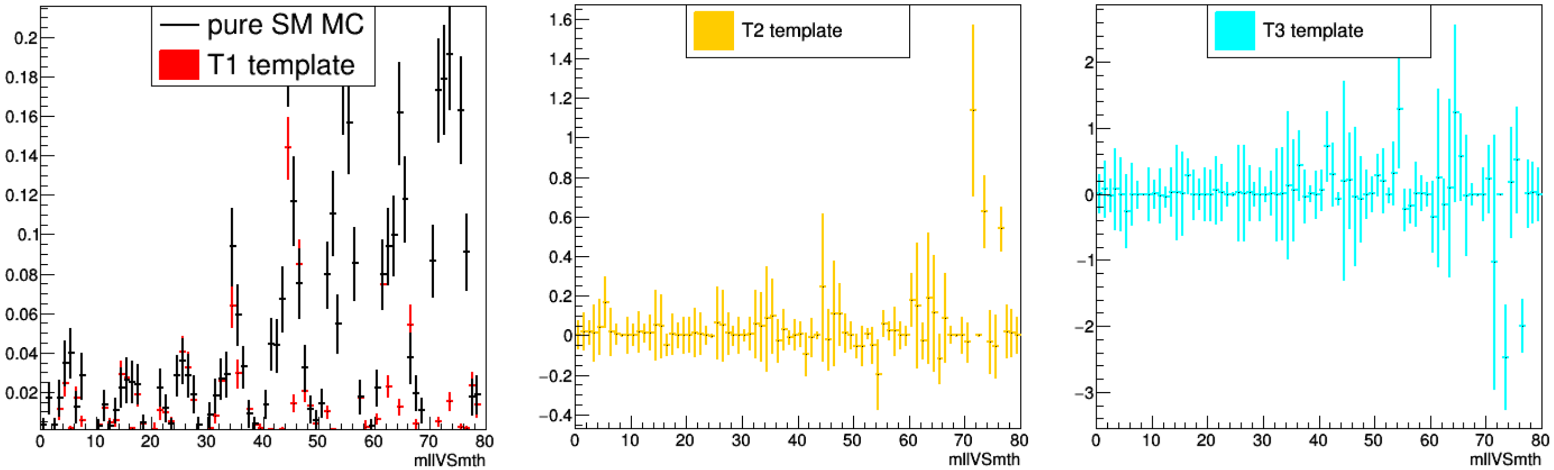
ggH → WW* 0-jet (VBF templates)

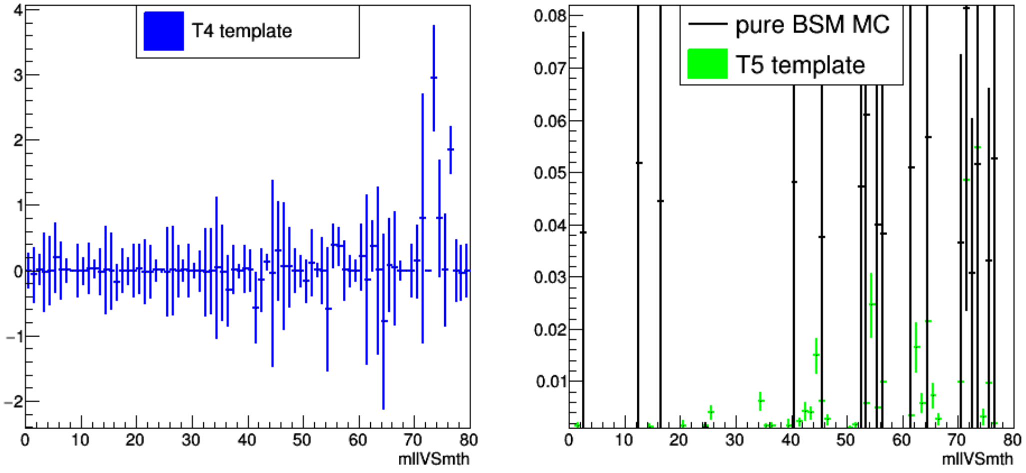


$0^{+}_{\Lambda_1}$

Gives negative yield

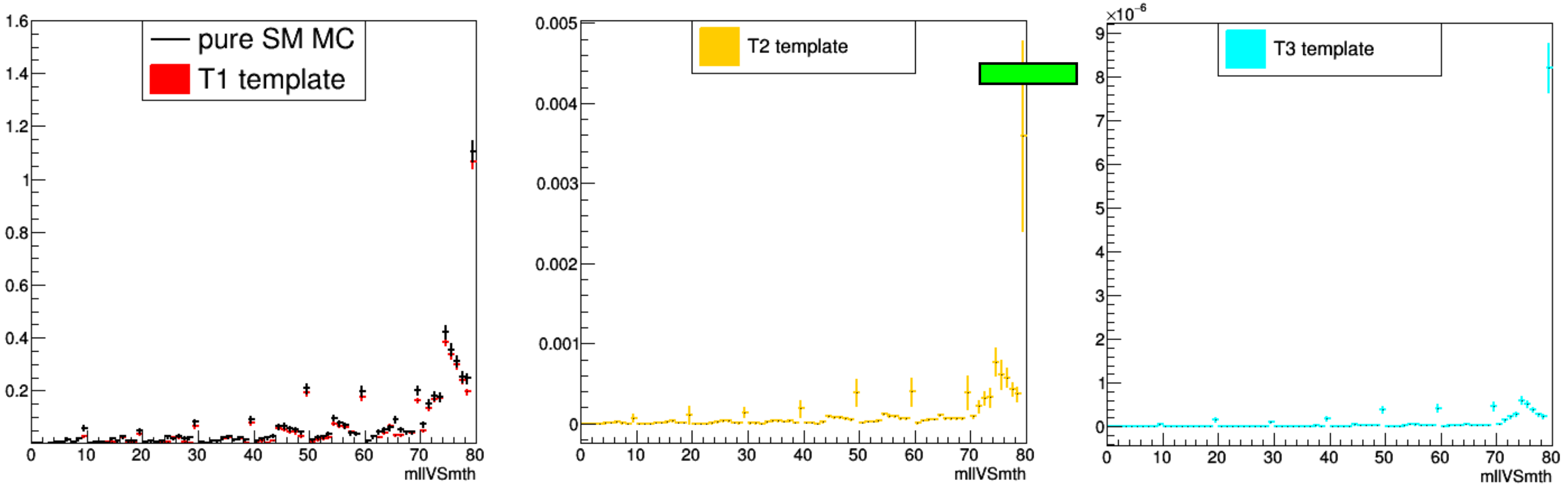
ggH → WW* 0-jet (VBF templates)



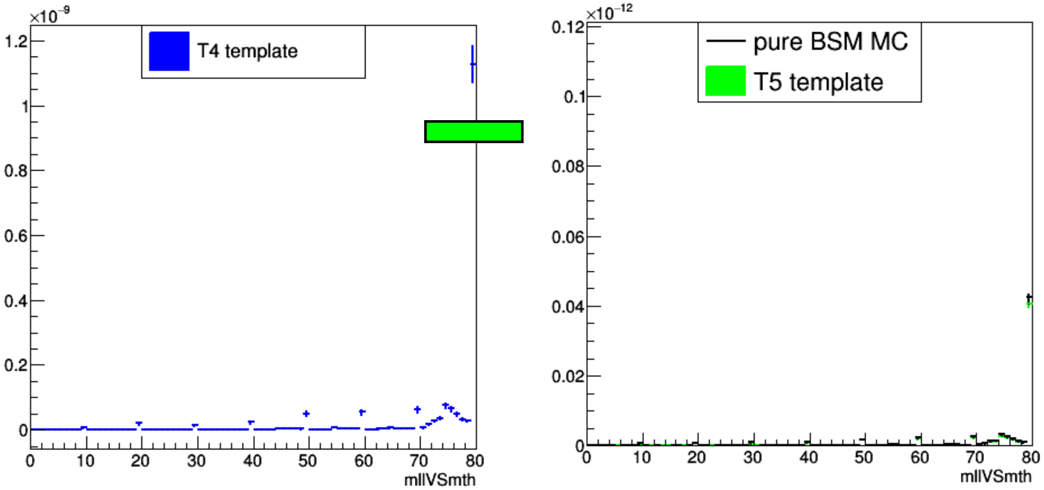


0_h^+

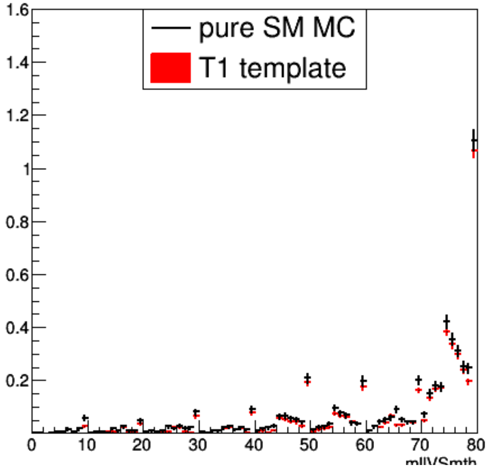
ggH → WW^* 0-jet (WH templates)

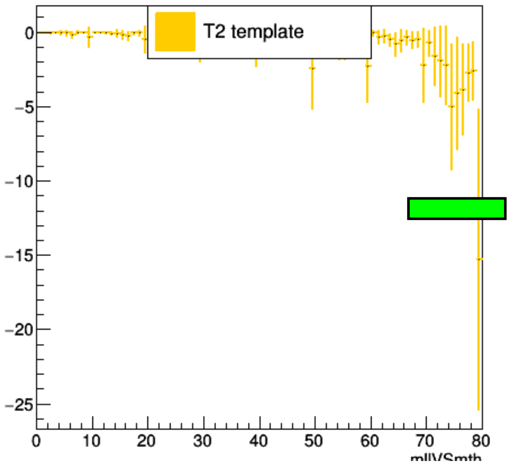


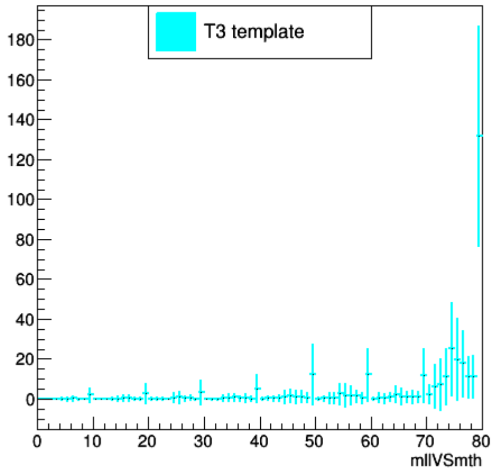
$0^+_{\Lambda_1}$



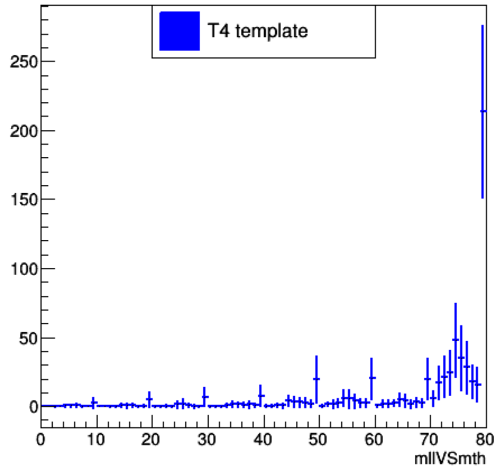
ggH → WW* 0-jet (WH templates)

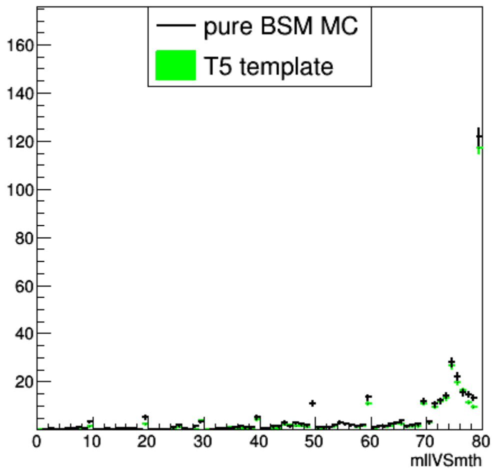






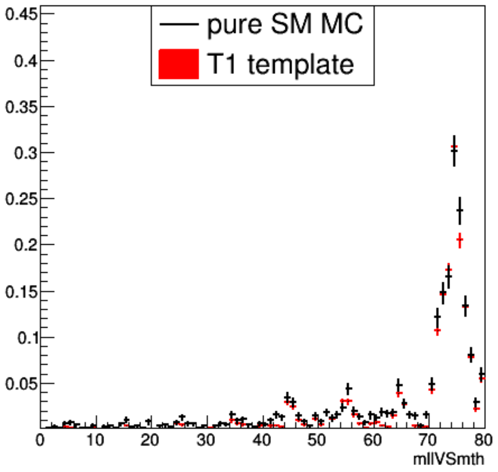
0_h^+

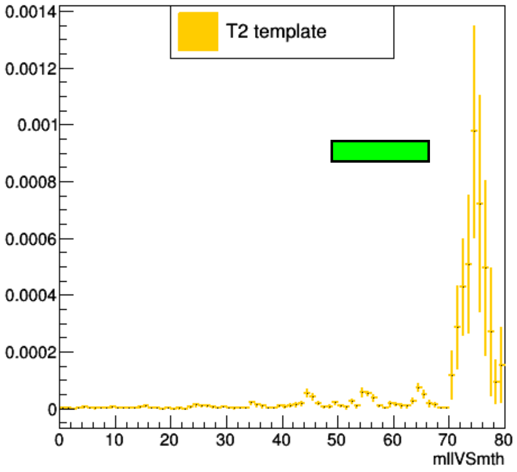


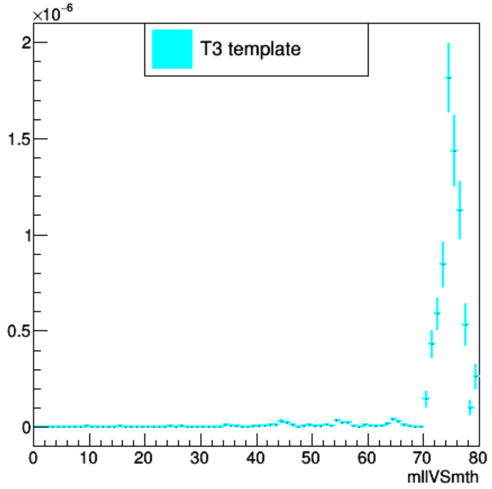


more in backup

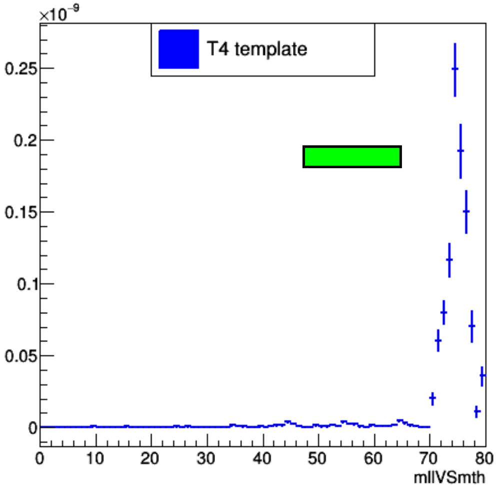
ggH → WW^* 0-jet (ZH templates)

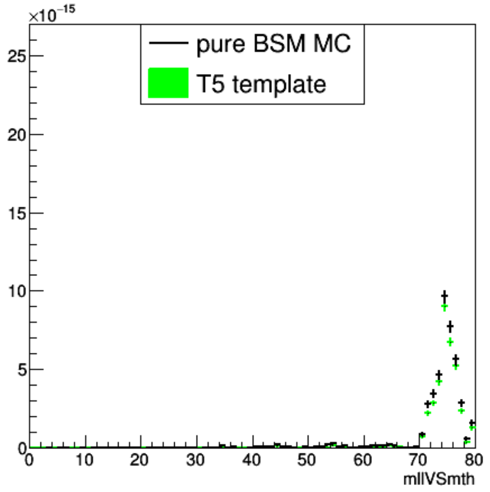




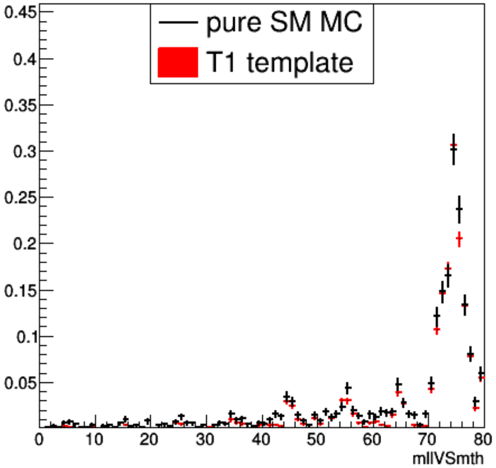


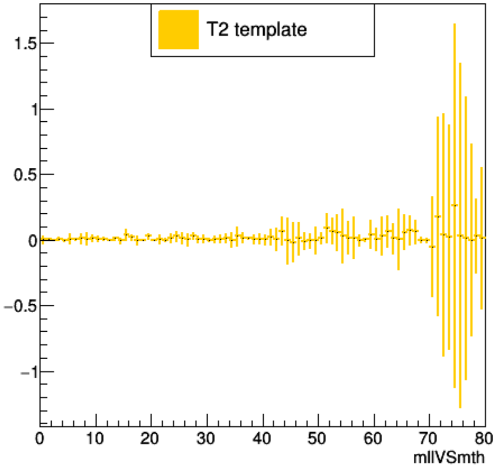
$0^+_{\Lambda_1}$

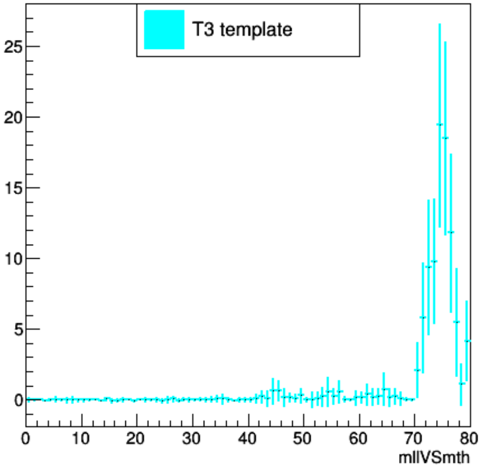




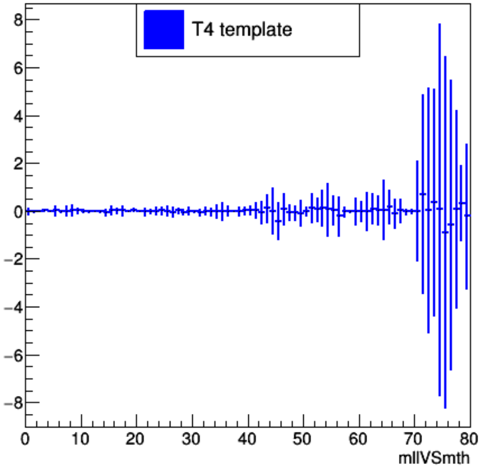
ggH → WW^* 0-jet (ZH templates)

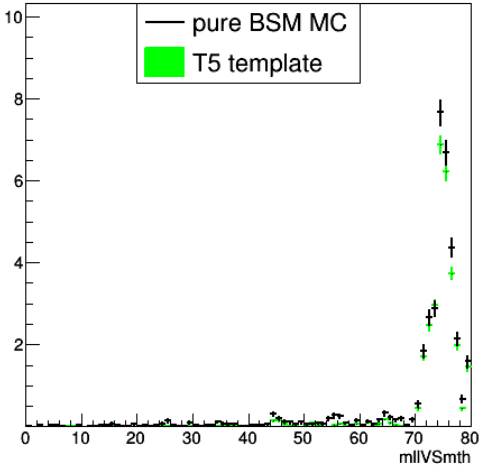




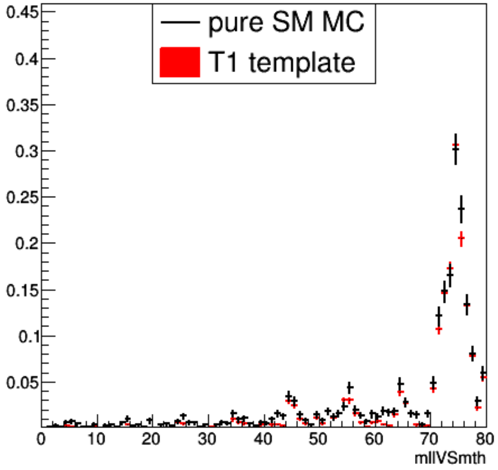


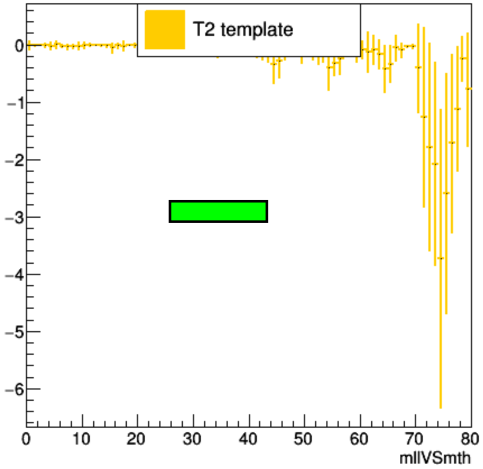
0^-

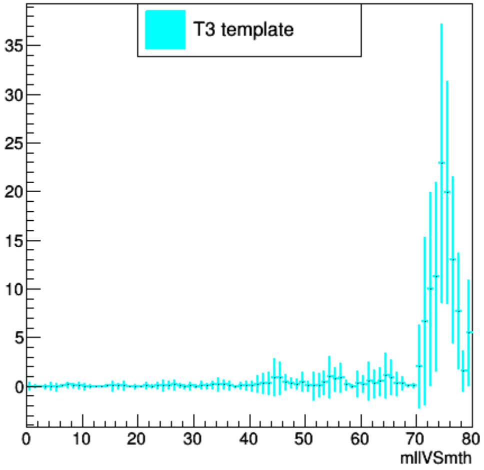




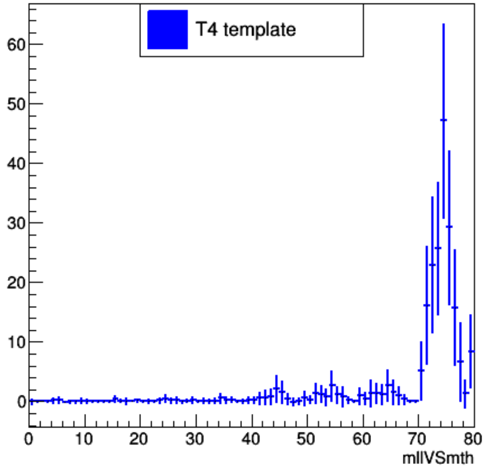
ggH → WW* 0-jet (ZH templates)

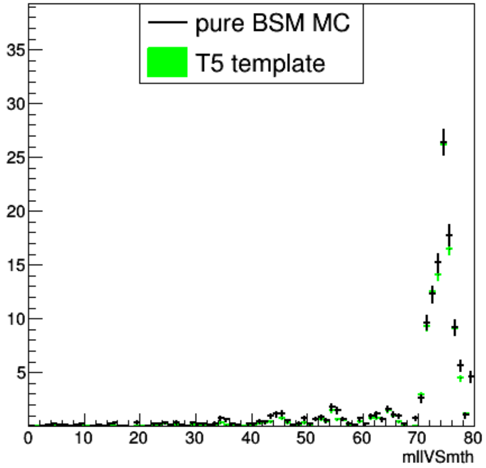






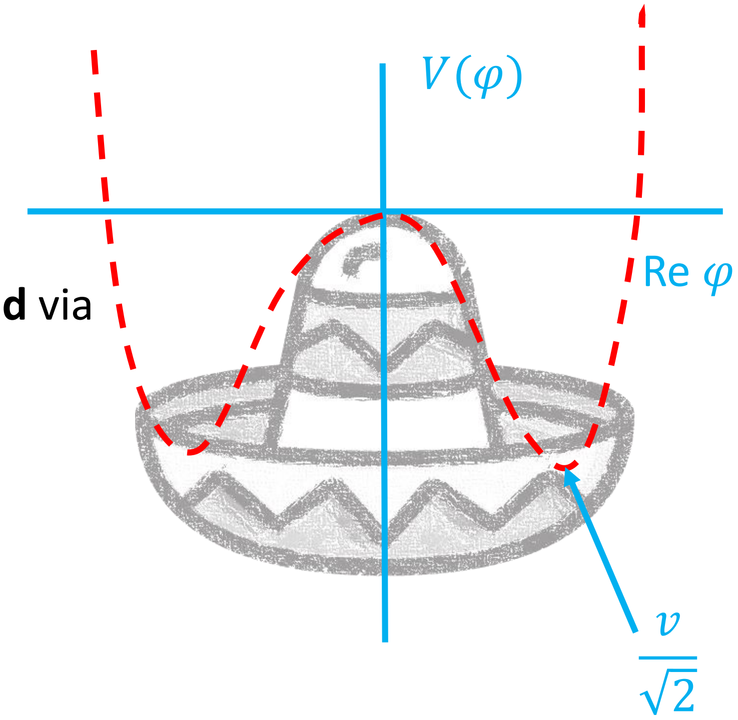
0_h^+





Higgs boson

Why missing puzzle piece?



- $W^{\pm}$ and Z^{0} **gauge bosons masses are generated** via Brout-Englert-Higgs mechanism

- **lepton masses** can be generated through the Yukawa interaction with Higgs boson

$$\mathcal{L}_{Yukawa}^{(U)} = -\frac{1}{\sqrt{2}}k_l v\bar{l}l - \frac{1}{\sqrt{2}}k_l\bar{l}lH$$

$$\boxed{m_l = \frac{1}{\sqrt{2}}k_l v}$$

- one would get **quark masses** in a similar fashion

- interaction though Higgs boson **saves tree unitarity** requirement in electroweak processes such as $e^+e^- \rightarrow W^+W^-$

Higgs boson

Observation of the scalar boson particle of mass $\boldsymbol{m_H \doteq 125\ \mathrm{GeV}}$ by ATLAS [2] and CMS [3] Collaboration in 2012

„The decay to two photons indicates that the new particle is a boson with spin different from one.“ [3]

Kungliga
Svenska Vetenskapsakademien
har den 8 oktober 2013 beslutat att med det
NOBELPRIS
som detta år tillerkännes den
som inom fysikens område gjort den
viktigaste upptäckten eller uppfinningen
gemensamt belöna
François Englert
och Peter W. Higgs
för den teoretiska upptäckten av en mekanism som
bidrar till förståelsen av massans ursprung hos
subatomära partiklar och som nyligen, genom upptäckten av den förutsagda fundamentala partikeln,
bekräftats av ATLAS- och CMS-experimenten
vid CERN's accelerator LHC
STOCKHOLM DEN 10 DECEMBER 2013

The Nobel Prize in Physics 2013

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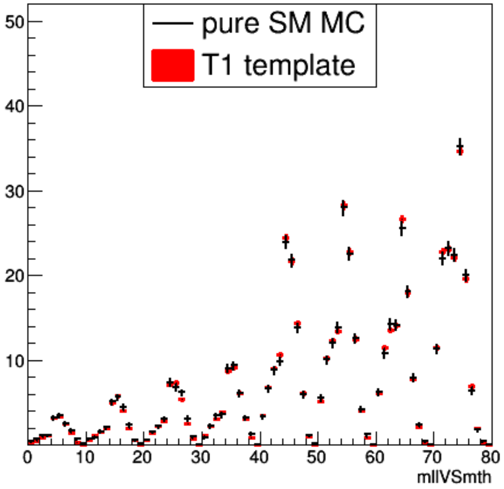
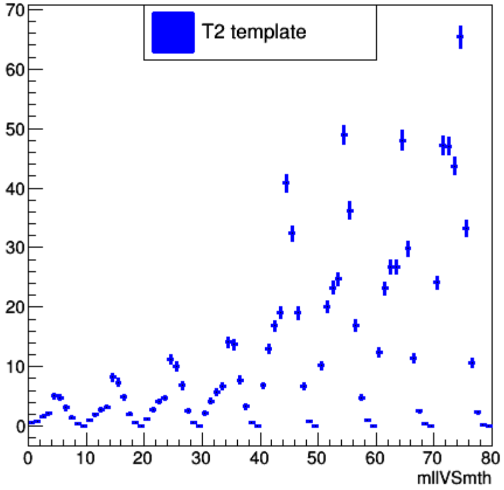
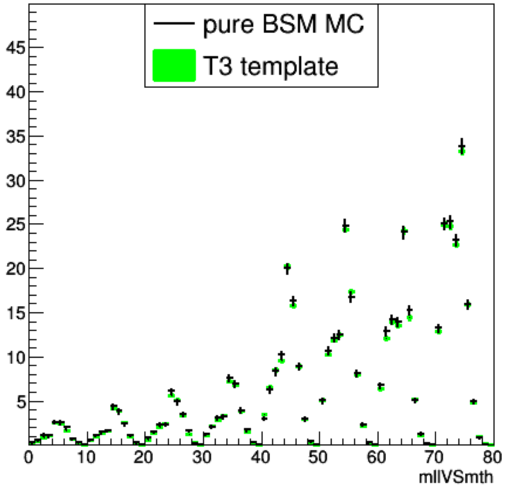
STOCKHOLM DEN 10 DECEMBER 2013

2D – discriminant 0_h^+

ggH templates





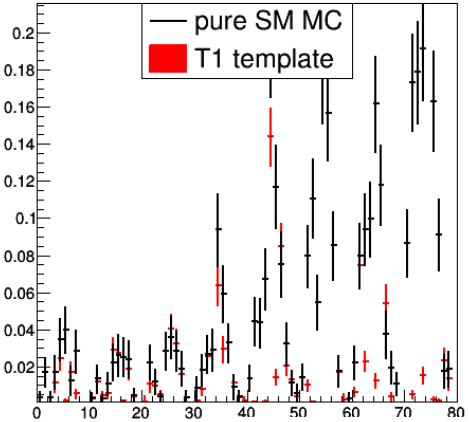


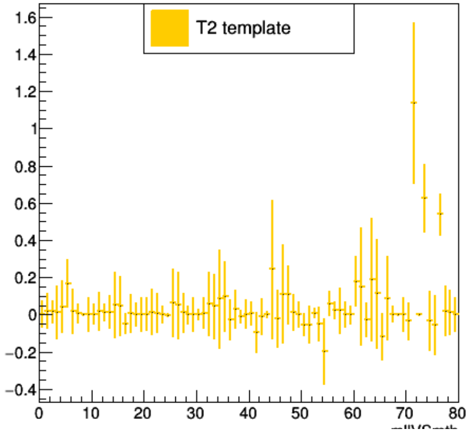
$$T_2 = (\mathrm{MIX} - \mathrm{SM} - g^2\mathrm{BSM})/g$$

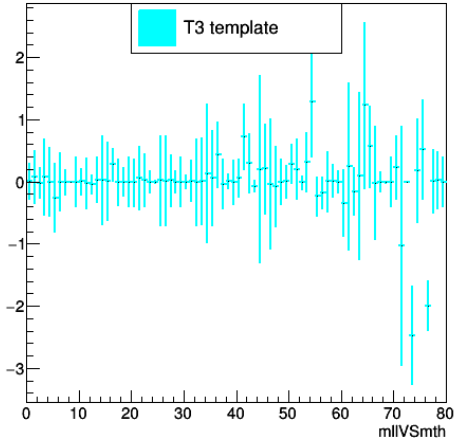
$$g = \sqrt{\frac{\sigma_1}{\sigma_i}}$$

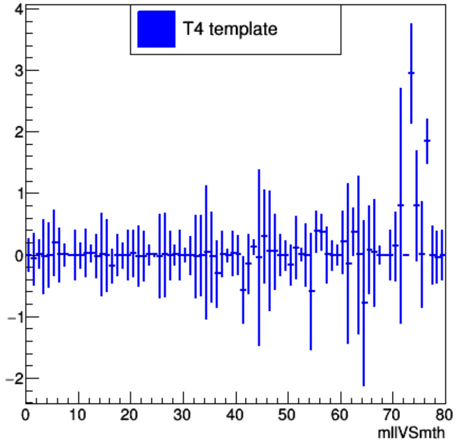
2D – discriminant 0_h^+

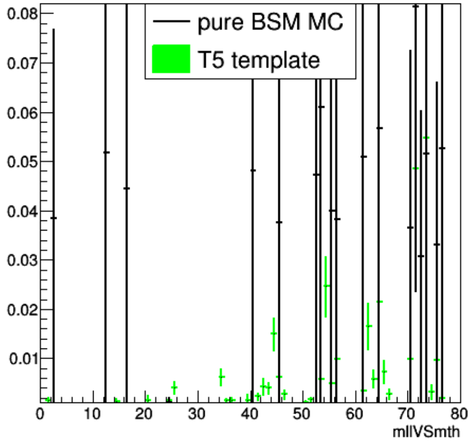
VBF templates











Fit model

$$f_{ai}\cos\theta_{ai} = \pm f_{ai} = f = |f|\mathrm{sign}(f)$$
$$f_1 = 1 - |f_{ai}|$$

ggF:

$$\boldsymbol{\mathcal{P} = \mu_{\mathrm{F}}\left((1-|f|) * \mathrm{T_1} + |f| * \mathrm{T_i} * g^2 + \mathrm{sign}(f)\sqrt{|f|}\sqrt{1-|f|} * \mathrm{T_{1i}} * g\right)}$$

VH, VBF:

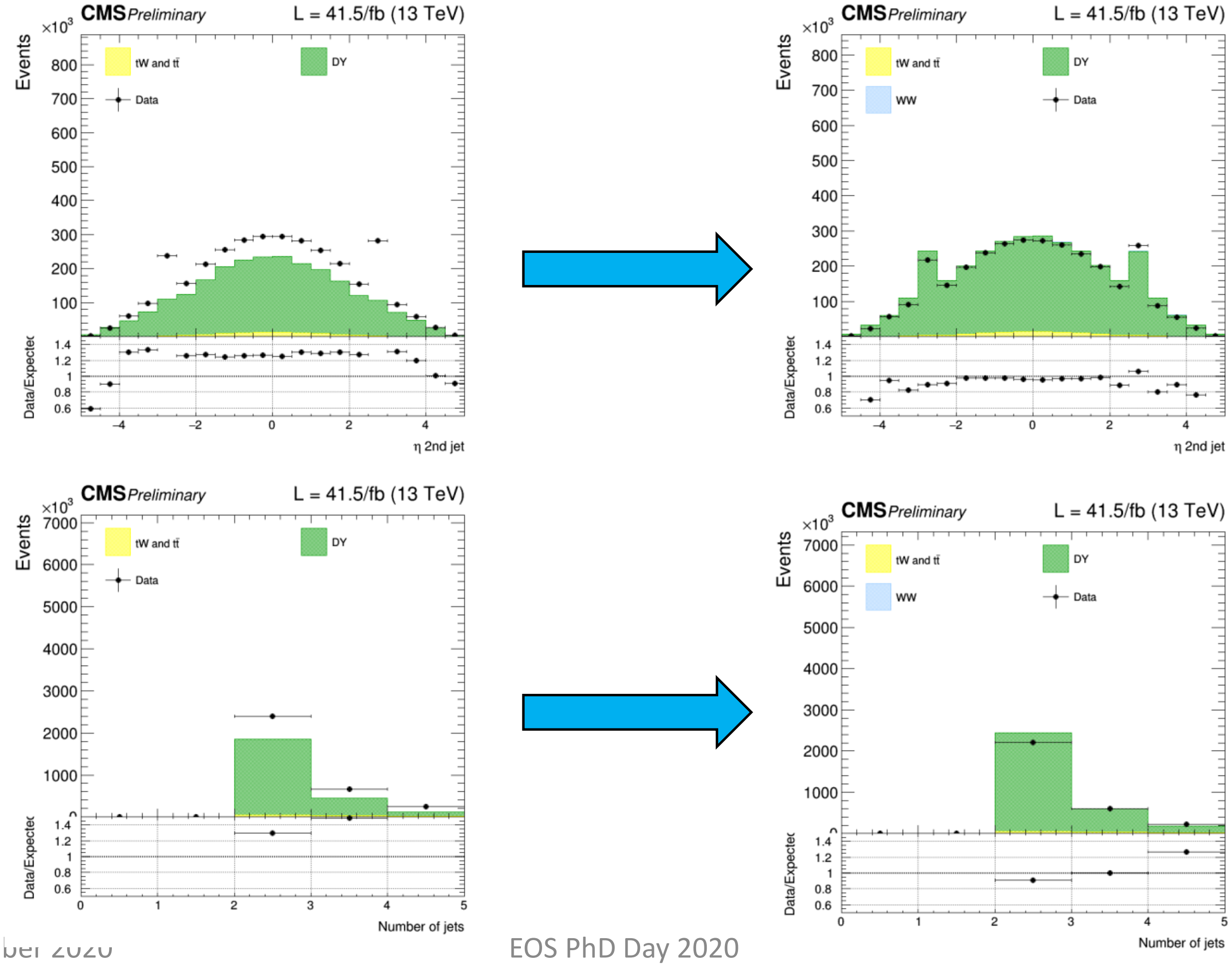
$$\boldsymbol{\mathcal{P} = \mu_F^2\left({f_1}^2 * \mathrm{T_1} + \mathrm{sign}(f)\sqrt{{f_1}^3}\sqrt{|f|} * \mathrm{T_{2i}} * g + f_1|f| * \mathrm{T_{3i}} * g^2\right.}$$

$\mathrm{T_1} \propto \mathrm{SM}$
$\mathrm{T_i} \propto \mathrm{BSM}$
$\mathrm{T_{xi}} \propto \mathrm{SM\&BSM}$

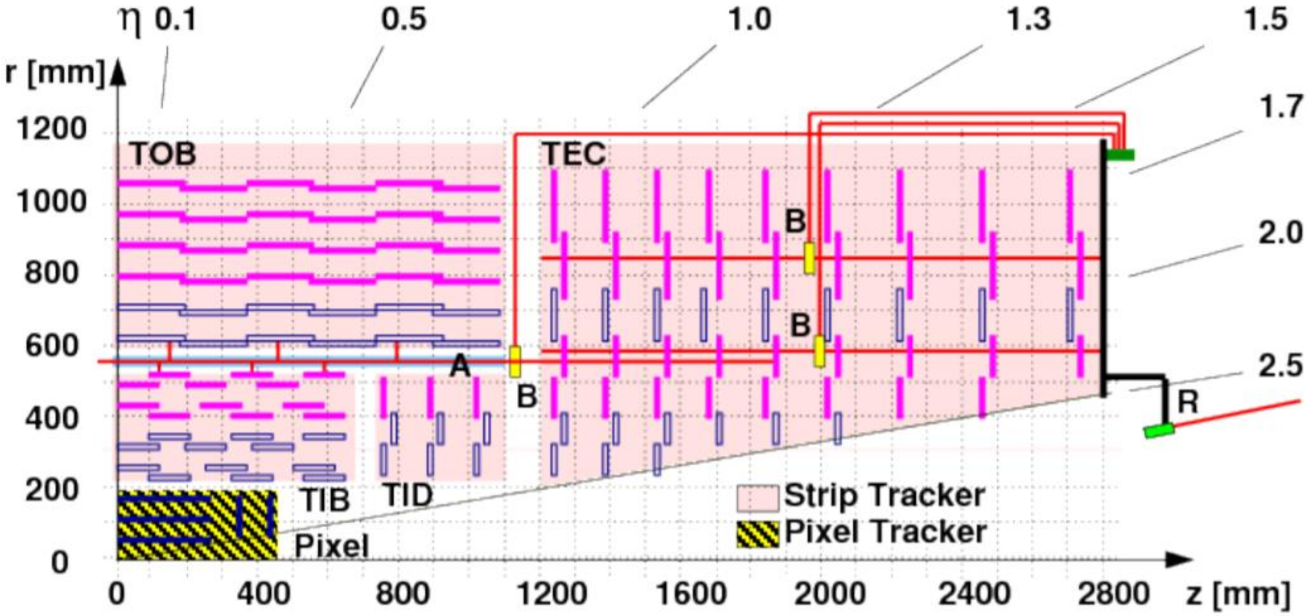
μ_{F} – floating signal strength
f – determines fraction of alternative signal compared to SM signal

Jet studies

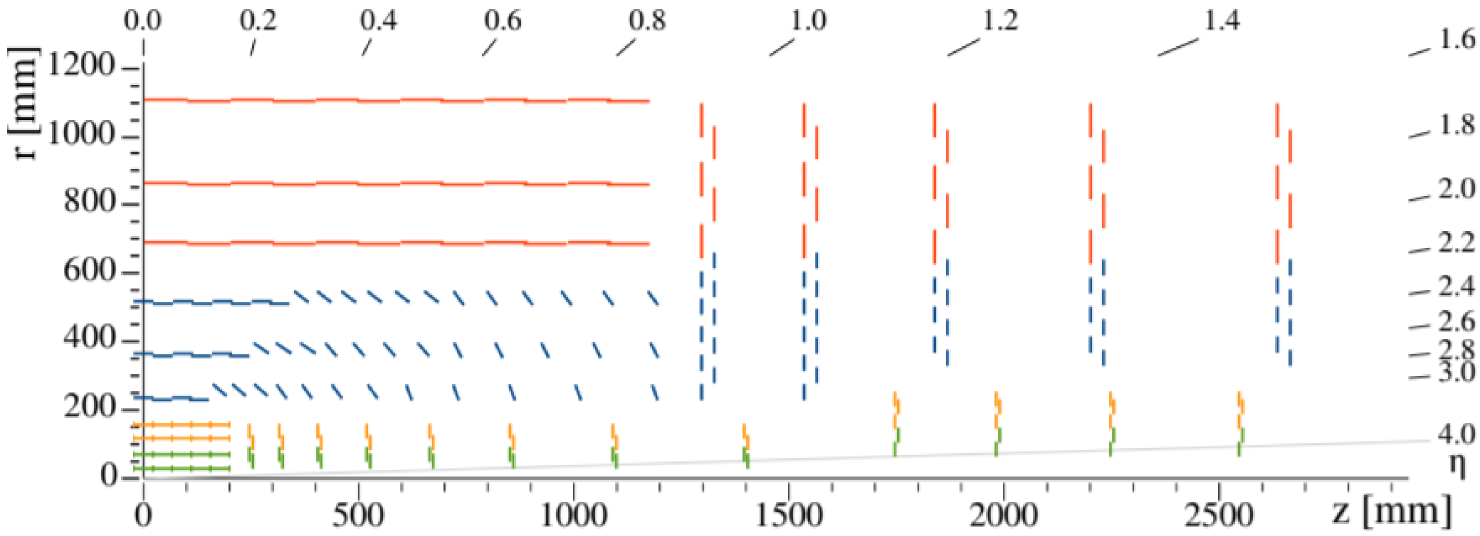
Jet energy resolution smearing



CMS Phase-0 Tracker



CMS Phase-2 Tracker



Data&MC

Maximum Likelihood Method

Profile Likelihood Ratio

$$\lambda(\mu) = \frac{L(\mu, \hat{\hat{\boldsymbol{\theta}}})}{L(\hat{\mu}, \hat{\boldsymbol{\theta}})}$$

$\boldsymbol{\theta}$ are fitted to maximize L for a given value of μ

μ and $\boldsymbol{\theta}$ are both estimated to define maximum of L

$0 < \lambda(\mu) < 1$ Good agreement beween data and prediction

Likelihood function

$$L(\mu, \boldsymbol{\theta}) = \prod_{i=1}^{N} \frac{(\mu\nu_{S,i} + \nu_{B,i})^{n_i}}{n_i!} e^{-(\mu\nu_{S,i}+\nu_{B,i})} \prod_{j=1}^{M} \frac{u_j^{m_j}}{m_j!} e^{-u_j}$$

$$L(\mu, \boldsymbol{\theta}) = \mathrm{Poisson}(\mu\nu_{S,i}(\boldsymbol{\theta}) + \nu_{B,i}(\boldsymbol{\theta})) \times \mathrm{Poisson}(u_j(\boldsymbol{\theta})) \times \mathrm{Gauss}(\boldsymbol{\theta}, 0, 1)$$

constrained by unitary Gauss distibution

Profile Likelihood test statistics

$$q_\mu = -2\ln\lambda(\mu) \longrightarrow \chi^2$$

zero hypothesis ⇔ BKG only ⇔ $\mu = 0$ ⇔ q_0 test statistics

p-value evaluated for q_0^{exp} instead of q_0^{obs} because of blinded regime

Tracker Alignment Validation

What is detector performance?

Distributions of RMS normalized residuals (DRmsNR)