

INVESTIGATIONS OF ELECTROWEAK SYMMETRY BREAKING MECHANISM FOR HIGGS BOSON DECAYS INTO FOUR FERMIONS

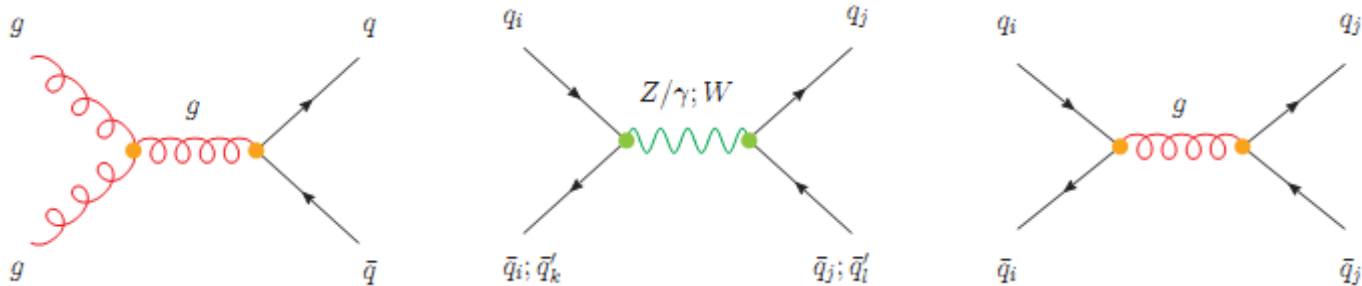
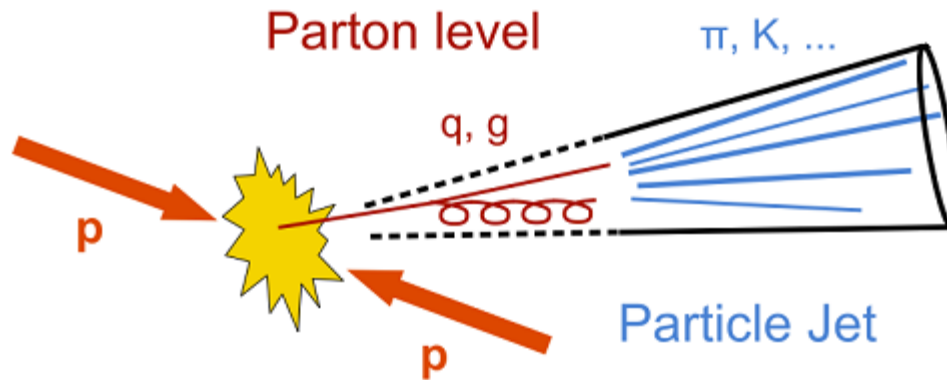
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Plan of the talk

- **Searches for physics beyond SM:**
 - **di-jet resonances;**
 - **Higgs boson decay modes;**
 - **Problems of SM Higgs boson;**
 - **THDM model;**
 - **Experimental parameters;**
 - **PROPHECY 4F 3.0 program with parameters;**
 - **Results of decay width calculations;**
 - **Dark matter production processes;**
- **Conclusions.**

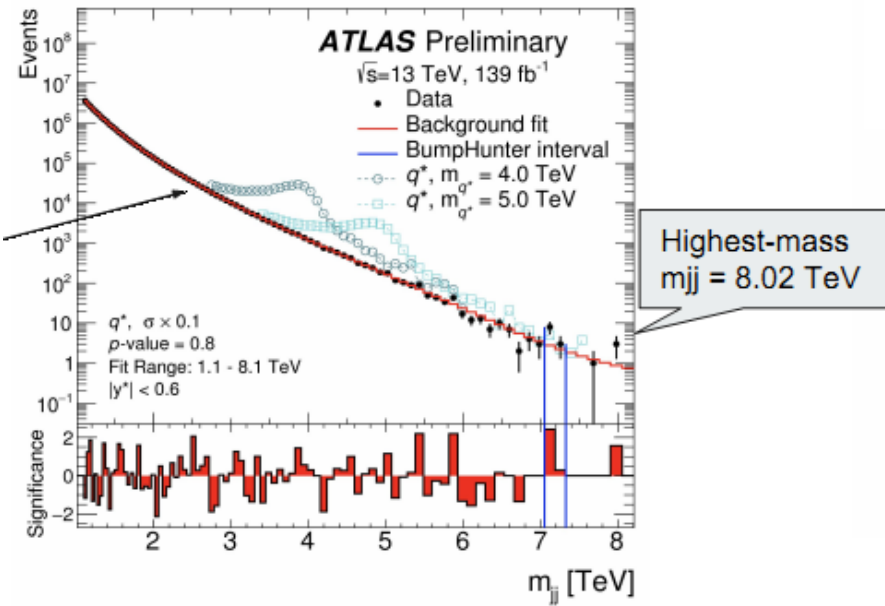
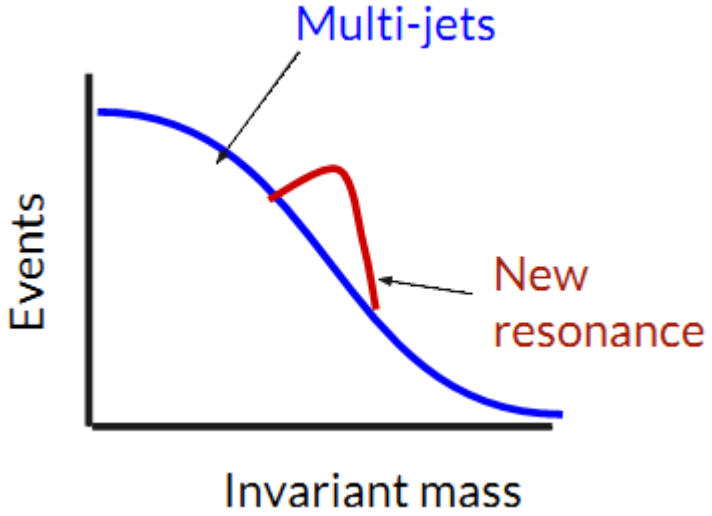
Di-jet resonances



Sample of di-jet processes

Di-jet resonances

- ATLAS Collaboration. "Search for dijet resonances in events with an isolated charged lepton using $\sqrt{s}=13$ TeV proton-proton collision data collected by the ATLAS detector", JHEP 06 (2020) 151.
- ATLAS Collaboration. "Dijet Resonance Search with Weak Supervision Using $\sqrt{s}=13$ TeV pp Collisions in the ATLAS Detector", Phys. Rev. Lett. 125, 131801 – Published 21 September 2020.
- CMS Collaboration. "A search for dijet resonances in proton-proton collisions at $\sqrt{s}=13$ TeV with a new background prediction method," Tech. Rep. CMS-PAS-EXO-19-012, CERN, Geneva, 2019.
- CMS Collaboration. "Search for dijet resonances using events with three jets in proton-proton collisions at $\sqrt{s}=13$ TeV", Physics Letters B, V.805, 10 June 2020, 135448.
- CMS Collaboration. "Search for high mass dijet resonances with a new background prediction method in proton-proton collisions at $\sqrt{s}=13$ TeV", JHEP 05 (2020) 033.



Di-jet resonances

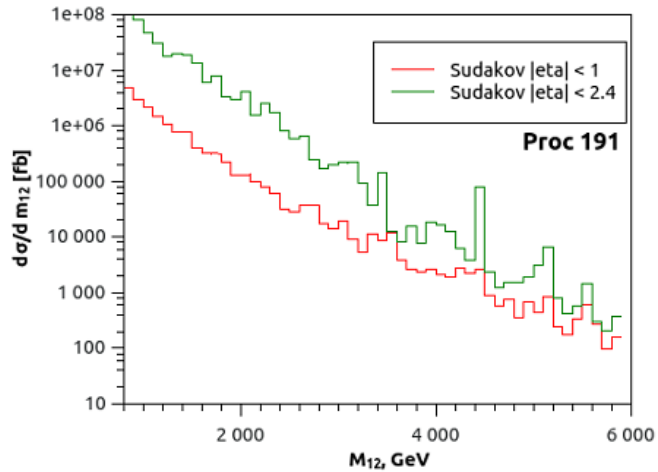


Figure 1: Di-jet mass spectrum for different pseudorapidity regions and with EW corrections at 14 TeV.

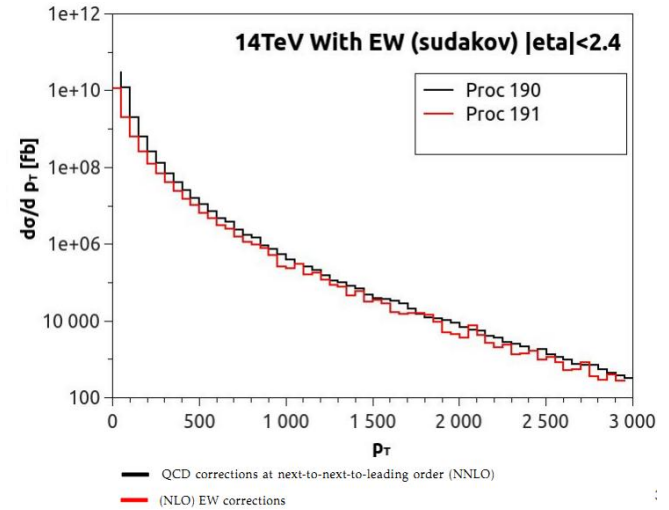


Figure 2: Differential production cross sections with respect to the di-jet transverse momentum p_T .

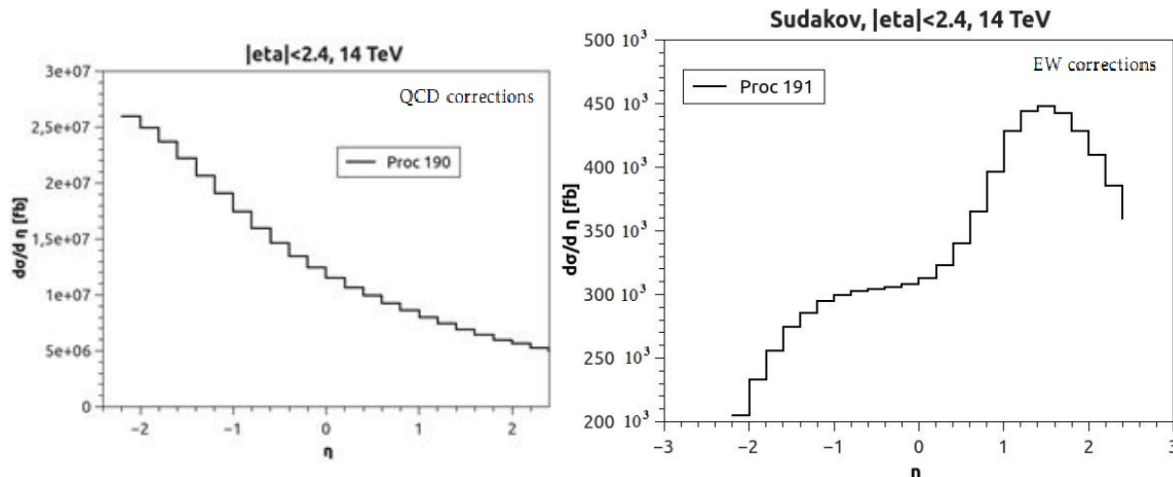


Figure 3: Differential production cross section as function of pseudorapidity calculated for two processes: left 190 (only strong interactions), right 191 (with inclusion of Sudakov EW corrections) at 14 TeV.

Higgs boson decay modes

Problems of SM Higgs boson

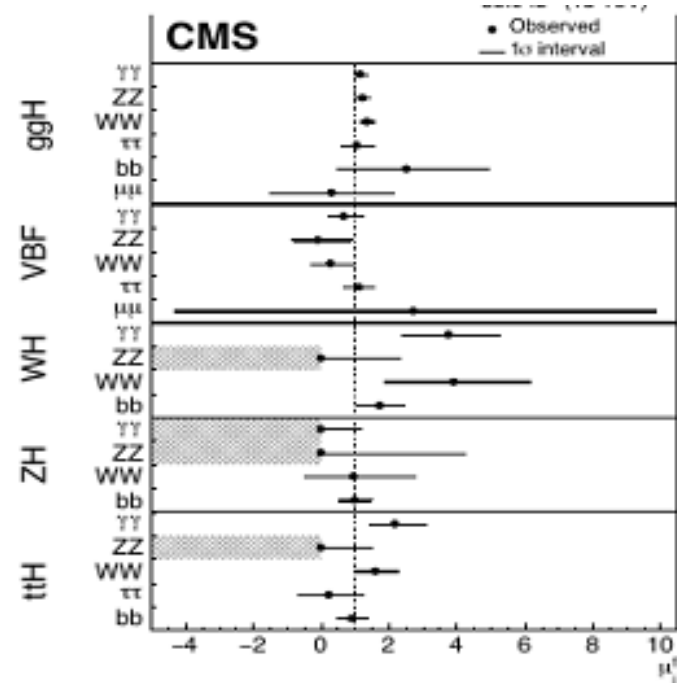
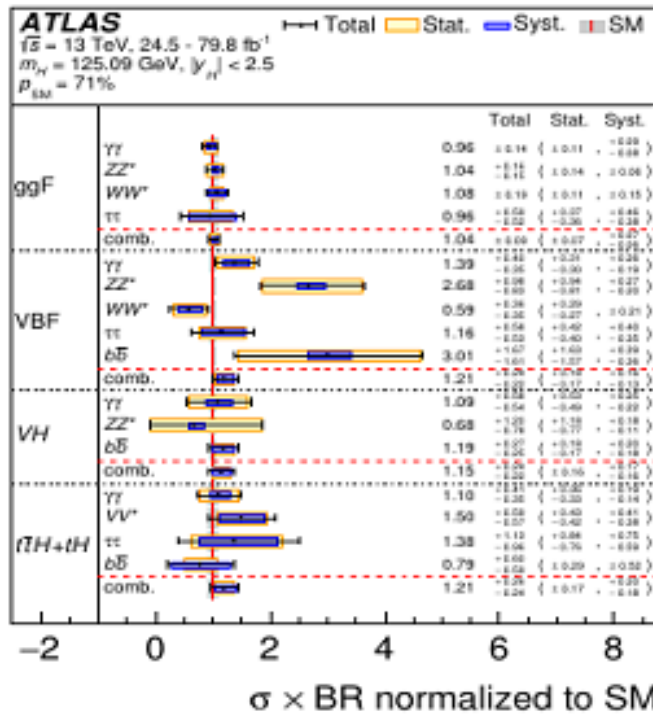


Figure 4 : Combined measurements of the products $\sigma \cdot \text{BR}$, normalised to the SM predictions, for the five main production and five main decay modes. The hatched combinations require more data for a meaningful confidence interval to be provided.

Higgs boson decay modes

Problems of SM Higgs boson

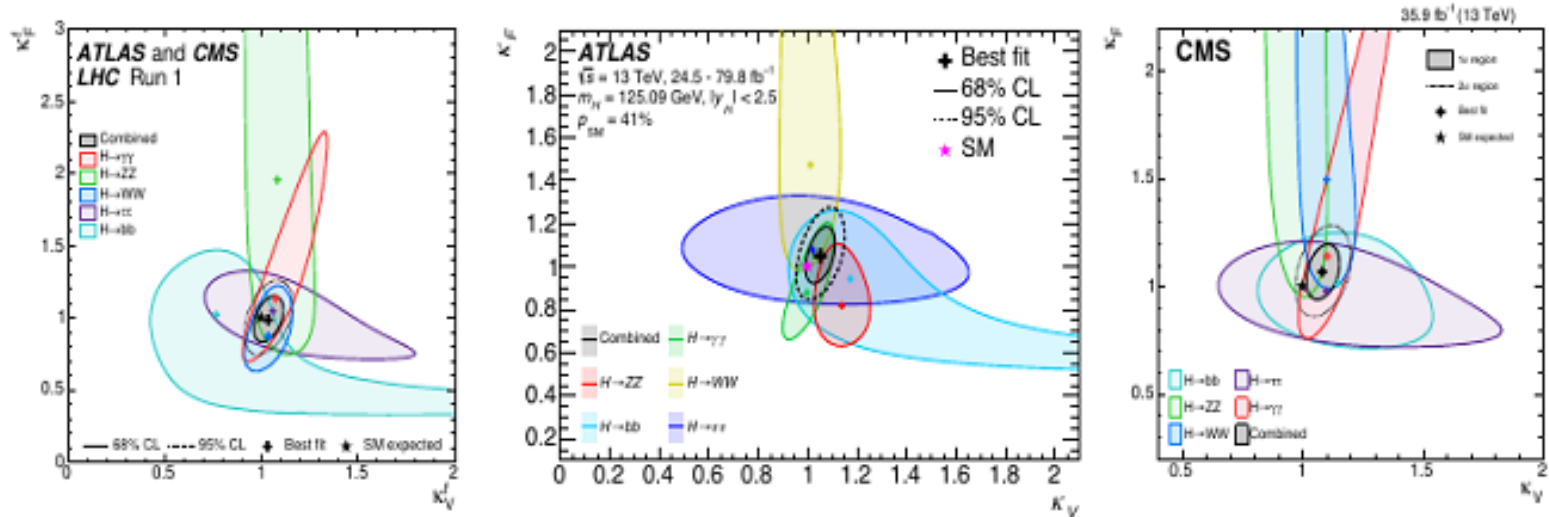


Figure 5 : Likelihood contours in the (κ_F, κ_V) plane for the ATLAS-CMS Run 1 combination (left) and the ATLAS (center) and CMS (right) individual Run 2 combinations.

Table 1. Couplings modifier combined measurements from Run 1 and Run 2

	LHC Run 1	ATLAS Run 2	CMS Run 2
κ_γ	0.87 ± 0.14	1.05 ± 0.09	1.07 ± 0.09
κ_W	0.87 ± 0.13	1.05 ± 0.09	-1.13 ± 0.08
κ_Z	-0.98 ± 0.10	1.11 ± 0.08	1.00 ± 0.07

Table 2. Run 1 observed (expected) direct 95% CL constraints on the width of the 125 GeV resonance from fits to the $\gamma\gamma$ and ZZ mass spectra. The CMS measurement from the $4l$ mass line-shape was performed using Run 2 data.

Experiment	$M_{\gamma\gamma}$	M_{4l}
ATLAS	$< 5.0(6.2) GeV$	$< 2.6(6.2) GeV$
CMS	$< 2.4(3.1) GeV$	$< 1.1(1.6) GeV$

Higgs boson decay modes

Two Higgs Doublet Model, THDM

$$V = m_{11}^2 \Phi_1^\dagger \Phi_1 + m_{22}^2 \Phi_2^\dagger \Phi_2 - m_{12}^2 (\Phi_1^\dagger \Phi_2 + \Phi_2^\dagger \Phi_1) + \frac{\lambda_1}{2} (\Phi_1^\dagger \Phi_1)^2 + \frac{\lambda_2}{2} (\Phi_2^\dagger \Phi_2)^2 \\ + \lambda_3 \Phi_1^\dagger \Phi_1 \Phi_2^\dagger \Phi_2 + \lambda_4 \Phi_1^\dagger \Phi_2 \Phi_2^\dagger \Phi_1 + \frac{\lambda_5}{2} \left[(\Phi_1^\dagger \Phi_2)^2 + (\Phi_2^\dagger \Phi_1)^2 \right],$$

$$\mathcal{L}_{\text{Yukawa}}^{2\text{HDM}} = - \sum_{f=u,d,\ell} \frac{m_f}{v} \left(\xi_h^f \bar{f} f h + \xi_H^f \bar{f} f H - i \xi_A^f \bar{f} \gamma_5 f A \right) \\ - \left\{ \frac{\sqrt{2} V_{ud}}{v} \bar{u} (m_u \xi_A^u P_L + m_d \xi_A^d P_R) d H^+ + \frac{\sqrt{2} m_\ell \xi_A^\ell}{v} \bar{\nu}_L \ell_R H^+ + \text{H.c.} \right\}$$

Parameters of THDM model

Table 3: THDM input parameters in the considered scenarios of a THDM of Type I. The light CP-even Higgs boson has mass $M_{H_2} = 125$ GeV, and $c_{\alpha\beta} = \cos(\alpha - \beta)$.

Scenario	M_{H_1} [GeV]	M_{H^+}, M_{A_0} [GeV]	λ_5	t_β	$c_{\alpha\beta}$	comment
A1	300	460	-1.9	2	0.1	Aa in Refs. [29, 41]
A2	300	460	-1.9	2	0.2	A($c_{\alpha\beta} = 0.2$) in Refs. [29, 41]
B1	600	690	-1.9	4.5	0.15	B1($c_{\alpha\beta} = 0.15$) in Refs. [29, 41]
B2	200	420	-2.5746	3	0.3	BP3 _{B1} in Refs. [29, 41], BP3B1 in Ref. [28]

arxiv: 1808.03466 [hep-ph].

Renormalization of mixing angles

Ansgar Denner, Stefan Dittmaier, Jean-Nicolas Lang

Higgs boson decay modes

PROPHECY 4F 3.0 program with parameters

Prophecy is tool for studying BSM Higgs boson decay via W or Z boson pairs including EW and QCD (NLO) corrections in the framework of THDM model.

$$\Gamma_{H \rightarrow 4f} = \Gamma^{\text{total}} = \Gamma^{\text{leptonic}} + \Gamma^{\text{semi-leptonic}} + \Gamma^{\text{hadronic}}$$

$$\begin{aligned} \Gamma^{\text{leptonic}} = & 3\Gamma^{\nu_e \bar{\nu}_e \nu_\mu \bar{\nu}_\mu} + 3\Gamma^{e^- e^+ \mu^- \mu^+} + 6\Gamma^{\nu_e \bar{\nu}_e \mu^- \mu^+} + 6\Gamma^{\nu_e e^+ \mu^- \bar{\nu}_\mu} \\ & + 3\Gamma^{\nu_e \bar{\nu}_e \nu_e \bar{\nu}_e} + 3\Gamma^{e^- e^+ e^- e^+} + 3\Gamma^{\nu_e e^+ e^- \bar{\nu}_e}, \end{aligned}$$

$$\Gamma^{\text{hadronic}} = \Gamma^{u\bar{u}c\bar{c}} + 3\Gamma^{d\bar{d}s\bar{s}} + 4\Gamma^{u\bar{u}s\bar{s}} + 2\Gamma^{u\bar{d}s\bar{c}} + 2\Gamma^{u\bar{u}u\bar{u}} + 3\Gamma^{d\bar{d}d\bar{d}} + 2\Gamma^{u\bar{d}d\bar{u}},$$

$$\Gamma^{\text{semi-leptonic}} = 6\Gamma^{\nu_e \bar{\nu}_e u\bar{u}} + 9\Gamma^{\nu_e \bar{\nu}_e d\bar{d}} + 6\Gamma^{u\bar{u}e^- e^+} + 9\Gamma^{d\bar{d}e^- e^+} + 12\Gamma^{\nu_e e^+ d\bar{u}}.$$

Parameters

renscheme = 7	! renormalization scheme:
mrenbsm1 = 125d0	! start renormalization scale for THDM MSbar parameters
mrenbsm2 = 361d0	! end renormalization scale for THDM MSbar parameters
cba = 0.15d0	! sin(alpha) in the THDM
sgnsba = +1	! sgn[sin(beta-alpha)], required if cba is input
tb = 4.5d0	! tan(beta) in the THDM
mh0 = 125d0	! mass of the light CP-even Higgs boson in the THDM
mhh = 600d0	! mass of the heavy CP-even Higgs boson in the THDM
ma0 = 690d0	! mass of the CP-odd Higgs boson in the THDM
mhp = 690d0	! mass of the charged Higgs boson in the THDM
lam5 = -1.9d0	! coupling lambda5 in the THDM

Higgs boson decay modes

Table 4. Calculation of decay widths within the THDM model for the decay channel $H \rightarrow \nu_\mu \bar{\mu} e \bar{\nu}_e$.

	EW+QCD/EW	Γ
7-B1	0.00991	0.491
7-B2	0.009296	0.475
5-B1	0.00981	0.4889
5-B2	0.009099	0.4701
SM	0.01025	0.5

Table 5. Calculation of decay widths within the THDM model for the decay channel $H \rightarrow d\bar{d}d\bar{d}$, $H \rightarrow c\bar{c}c\bar{c}$, $H \rightarrow d\bar{d}e\bar{e}$.

	7-B1	SM	Γ	5-B1	Γ
$H \rightarrow d\bar{d}d\bar{d}$	0.00248	0.00259	0.489	0.00246	0.487
$H \rightarrow c\bar{c}u\bar{u}$	0.00288	0.003	0.49	0.00286	0.488
$H \rightarrow d\bar{d}e\bar{e}$	0.00105	0.0011	0.49	0.00105	0.488

Higgs boson decay modes

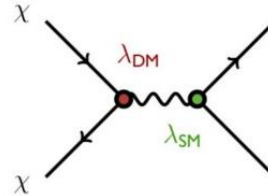
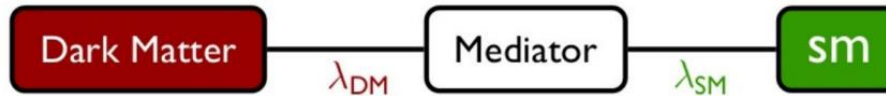
Table 6 . Calculation of decay widths within the THDM model for the decay channel $H \rightarrow \mu\bar{\mu}e\bar{e}$.

	EW+QCD/EW	Γ
7-B1(2)	0.000232	0.490
5-B1(2)	0.0002296	0.4874
SM	0.000241	0.5

Table 7 . Calculation of decay widths within the THDM model for the decay channels $H \rightarrow e\bar{e}e\bar{e}$ and $H \rightarrow \mu\bar{\mu}e\bar{e}$.

	7-B1	SM	Γ
$H \rightarrow e\bar{e}e\bar{e}$	0.000127	0.000133	0.49
$H \rightarrow \mu\bar{\mu}e\bar{e}$	0.000232	0.000241	0.49

Dark matter production processes



842 ' $f(p1) + f(p2) \rightarrow S \rightarrow (X(p3) + X(p4)) + f(p5) + f(p6)$ [Scalar Mediator] ' 'L'

843 ' $f(p1) + f(p2) \rightarrow PS \rightarrow (X(p3) + X(p4)) + f(p5) + f(p6)$ [Pseudo Scalar Mediator] ' 'L'

844 ' $f(p1) + f(p2) \rightarrow GG \rightarrow (X(p3) + X(p4)) + f(p5) + f(p6)$ [Gluonic DM operator] ' 'L'

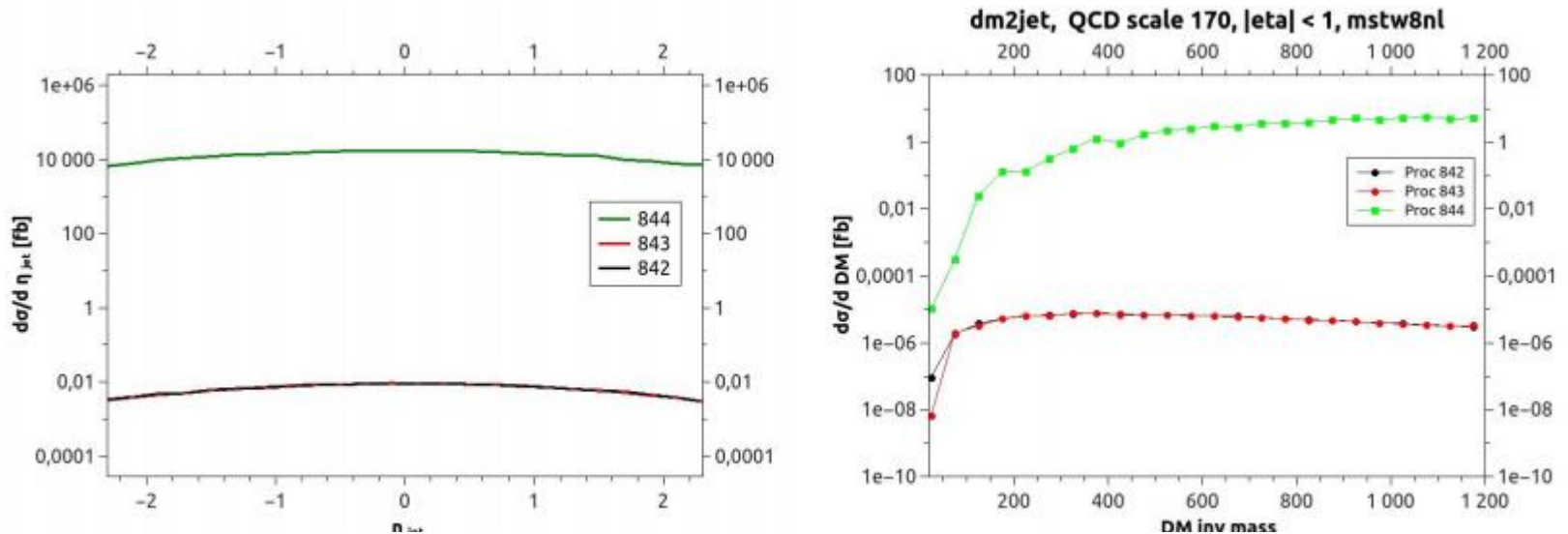


Figure 6 : Invariant mass distributions, angular distribution of 842-844 processes for 14 TeV in proton-proton collisions.

Conclusions

- The latest algorithms (MCFM program, Sep 2019), which included new pdf functions and contributions from different processes, EW and QCD, were used for di-jet searches;
- Sudakov's electroweak corrections do not make a significant contribution to the distributions of inv. mass and momentum, and the largest value of the differential cross section was seen for angles 50 and 130 for two-jet events;
- For investigations of Higgs boson decay modes into four fermions was considered THDM model and with the help of the PROPHECY 4F 3.0 program were calculated decay width and ratio to SM decay width for six channels of Higgs boson decay. The significant deviations in the decay width are seen between quark-lepton modes and quark-quark modes as well as between neutrino lepton modes and lepton-lepton modes;
- Among three considered processes for the formation of Dark matter mediators, the process with a gluon operator prevails, as well as the absence of clear resonances is seen.