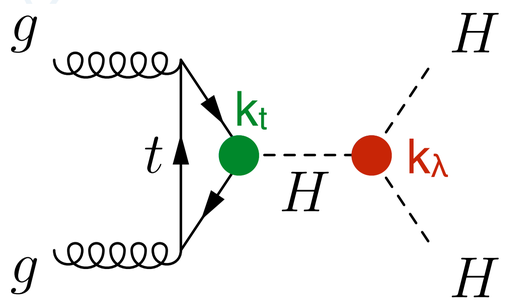
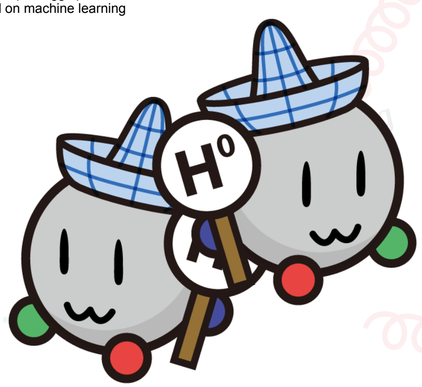
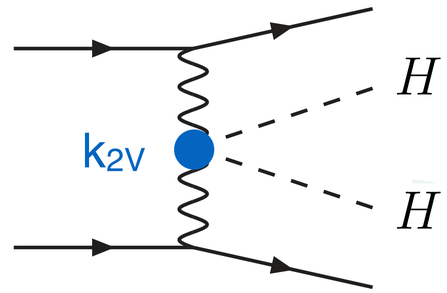
Search for non-resonant Higgs boson pair and triple Higgs production at CMS complemented by a new Level-1 trigger based on machine learning







Search for non-resonant Higgs boson pair production in dilep- ton final states of the bbWW decay mode at CMS

Universität Hamburg
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CLUSTER OF EXCELLENCE
QUANTUM UNIVERSE

FSP CMS
Erforschung von Universum und Materie

Gefördert durch:
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CMS

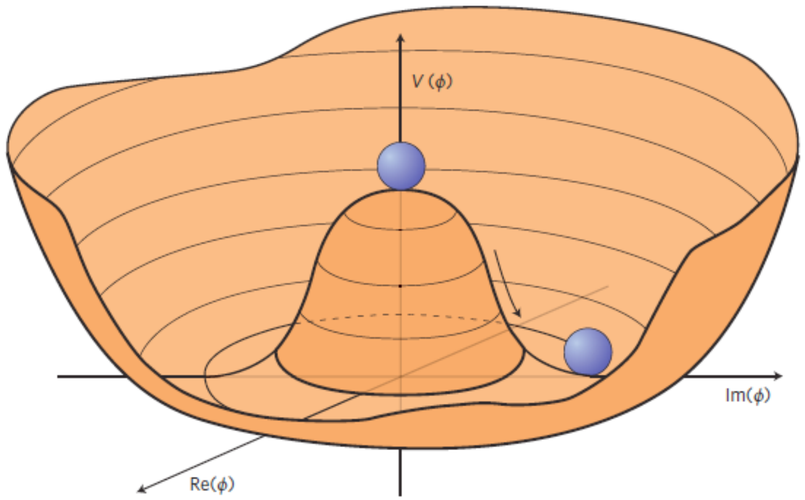
Search for non-resonant Higgs boson pair and triple Higgs production at CMS

Lara Markus

QU Report

10.06.2025

Motivation



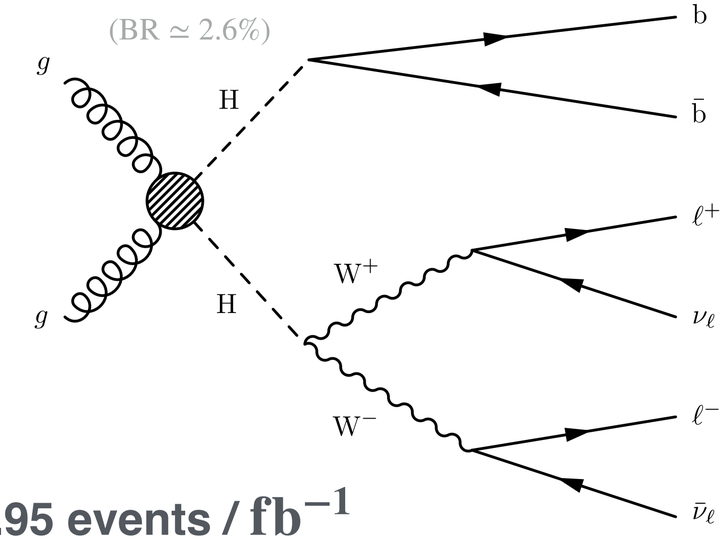
$$V(\phi) = \tfrac{1}{2} m_{\mathrm{H}}^2 \phi^2 + \sqrt{\lambda/2}\, m_{\mathrm{H}} \phi^3 + \tfrac{1}{4} \lambda \phi^4$$

Measuring the **HH production cross section** allows **to characterise** the **shape of the potential**

$$\lambda_{\mathrm{HHH}} = \lambda_{\mathrm{HHHH}} = \lambda = \frac{m_{\mathrm{H}}^2}{2v^2} \approx 0.13$$

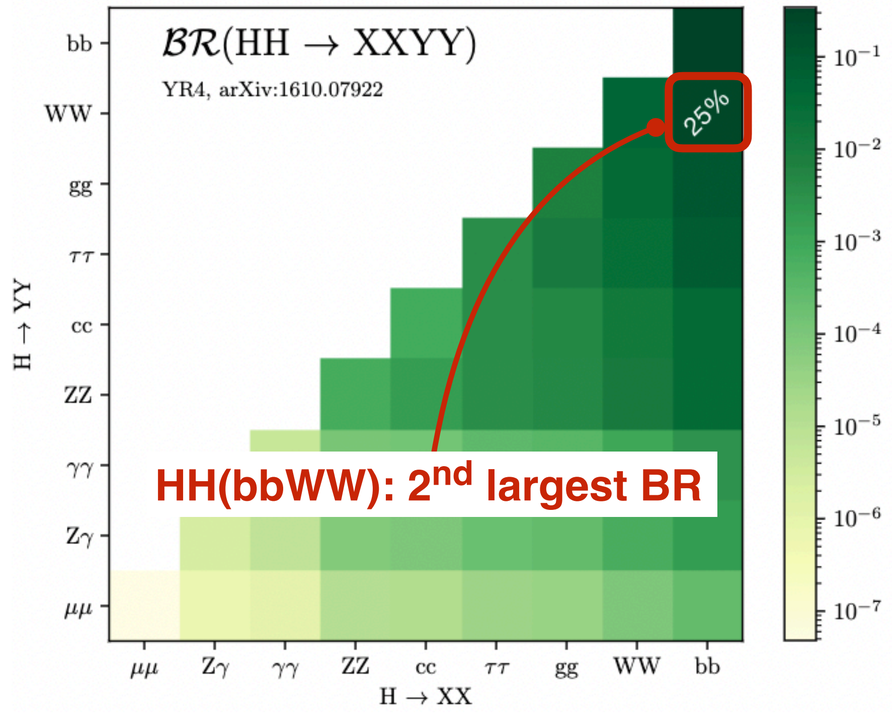
HH → bbWW (DL)

Decay channel: HH → bbWW($2\ell 2\nu$)



Run3: 0.95 events / fb^{-1}

Expected $t\bar{t}$ events: $\sim 100{,}000 \times$ signal

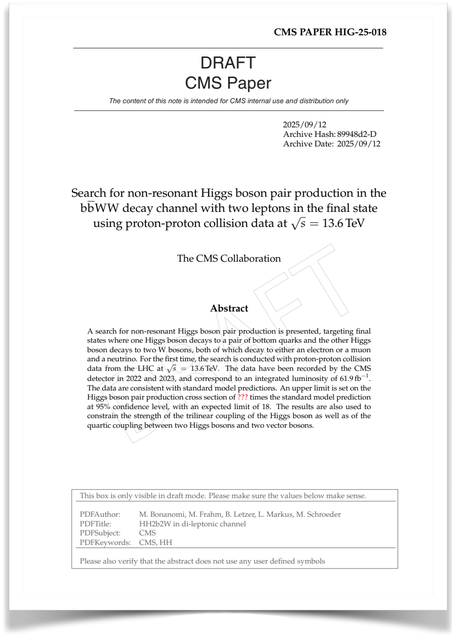


Run-3 search for non-resonant $HH \to bbWW$ (DL)

QU Report
Lara Markus

Analysis is pre-approved targeting a PAS at the end of this year (CADI: HIG-25-018)

- **Contribution:**
  - Studies on ML optimization
  - Derivation of data-driven DY corrections
  - Studies on forward region jets and VBF strategy
  - Task development (e.g. HH Inference tool, analysis framework), review process, …
- **Status & future plans:**
  - Setting up the analysis for 2024 data
  - Started to work on the combination of the DL & SL channel
    Collaboration with Notre Dame University



CMS PAPER HIG-25-018

DRAFT
CMS Paper

The content of this note is intended for CMS internal use and distribution only

2025/09/12
Archive Hash: 89948d2-D
Archive Date: 2025/09/12

Search for non-resonant Higgs boson pair production in the bbWW decay channel with two leptons in the final state using proton-proton collision data at $\sqrt{s} = 13.6$ TeV

The CMS Collaboration

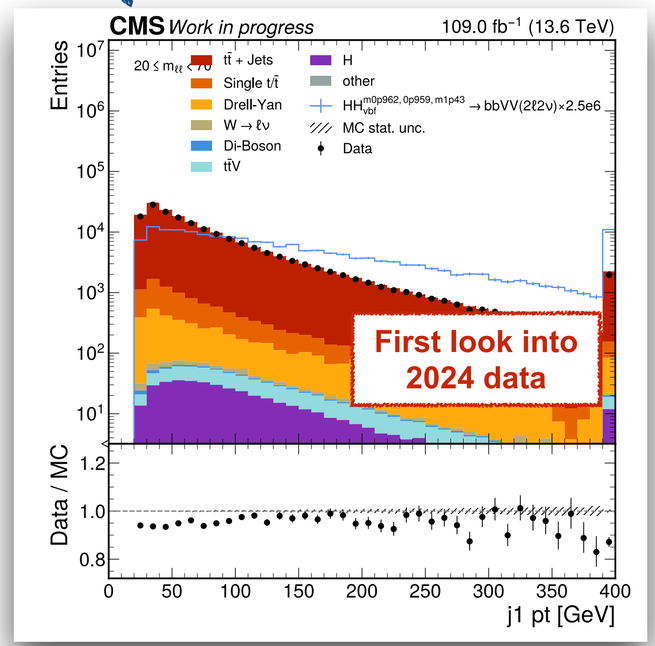
Abstract

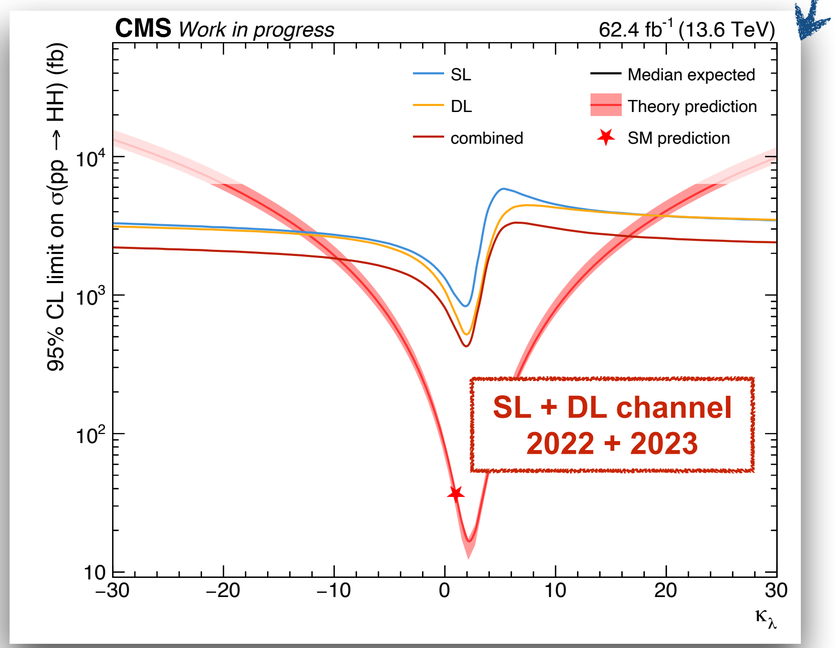
A search for non-resonant Higgs boson pair production is presented, targeting final states where one Higgs boson decays to a pair of bottom quarks and the other Higgs boson decays to two W bosons, both of which decay to either an electron or a muon and a neutrino. For the first time, the search is conducted with proton-proton collision data from the LHC at $\sqrt{s} = 13.6$ TeV. The data have been recorded by the CMS detector in 2022 and 2023, and correspond to an integrated luminosity of 61.9 fb^{-1}. The data are consistent with standard model predictions. An upper limit is set on the Higgs boson pair production cross section of ??? times the standard model prediction at 95% confidence level, with an expected limit of 18. The results are also used to constrain the strength of the trilinear coupling of the Higgs boson as well as of the quartic coupling between two Higgs bosons and two vector bosons.

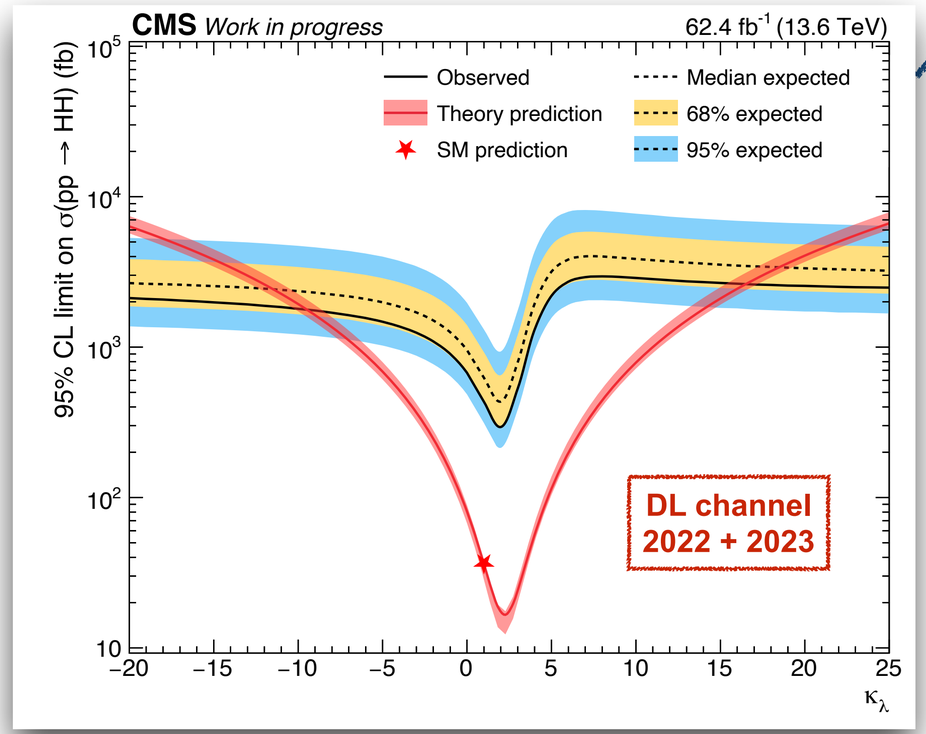
This box is only visible in draft mode. Please make sure the values below make sense.

PDFAuthor: M. Bonanomi, M. Frahm, B. Letzer, L. Markus, M. Schroeder
PDFTitle: HH2b2W in di-leptonic channel
PDFSubject: CMS
PDFKeywords: CMS, HH

Please also verify that the abstract does not use any user defined symbols







Run-3 search for non-resonant HHH → 4b2V

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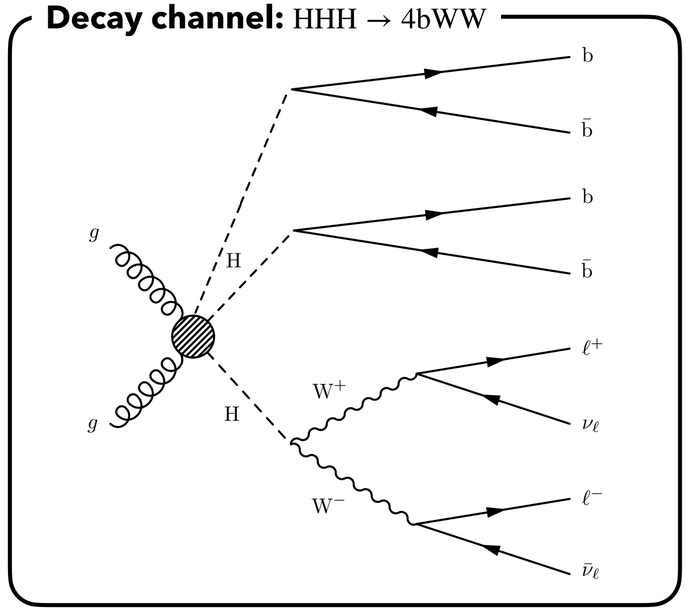
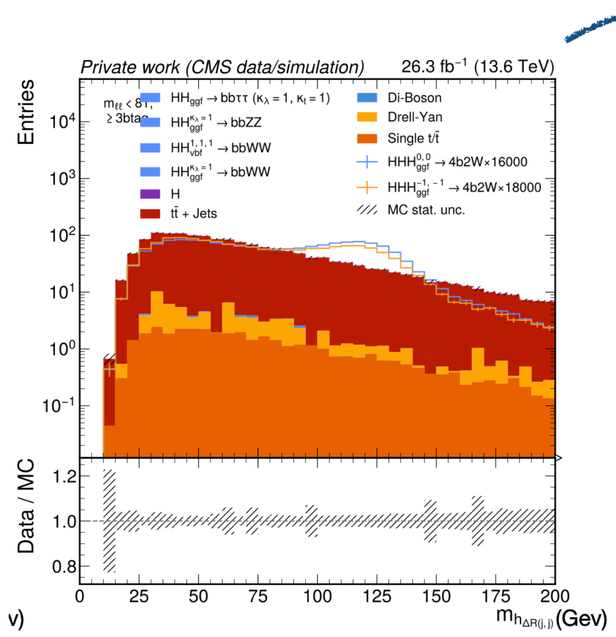
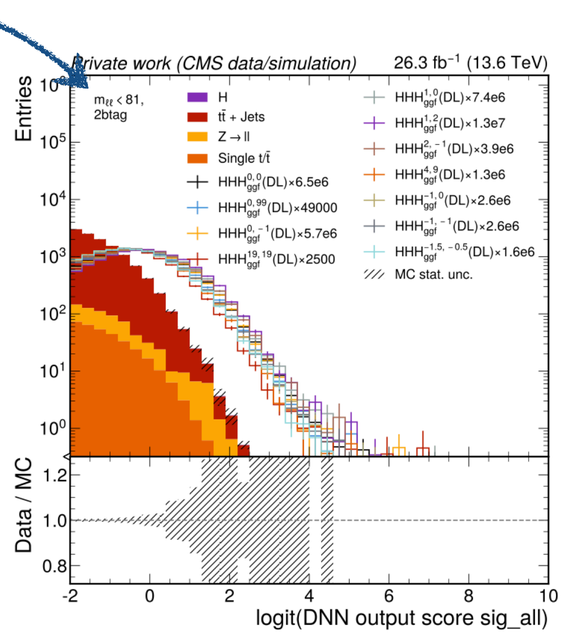
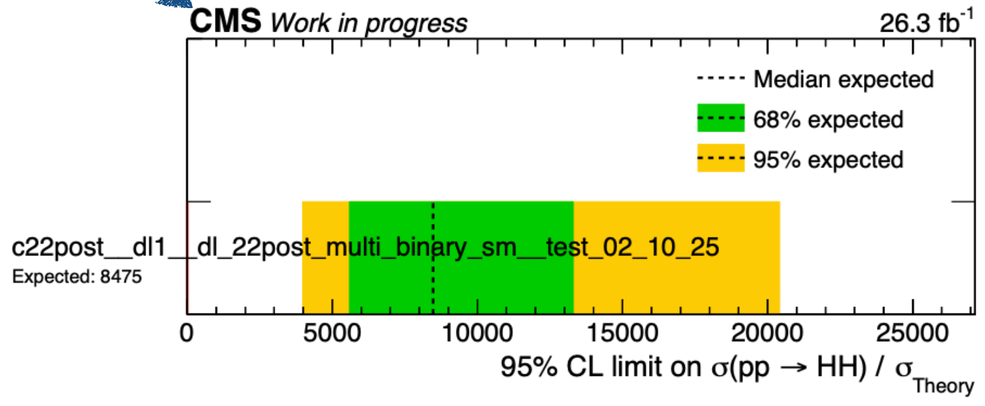
- **Contribution:**
  - DL: Supervision of master thesis by Parth
  - SL + FH: Collaboration with Peking University
  - Active in the newly formed working groups

- **Status & future plans:**
  - Use expertise gathered from HH to set up HHH analysis in columnflow
  - Use more deliberate signal samples (fixed κ 2D modelling)
  - Use state-of-art bkg modeling (e.g. ttbb samples)





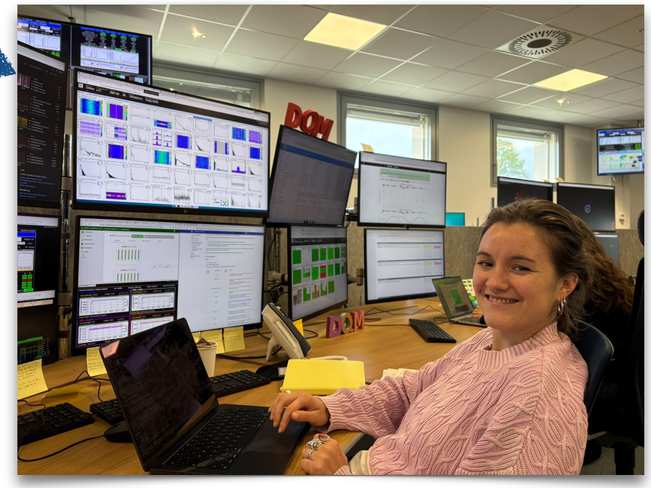


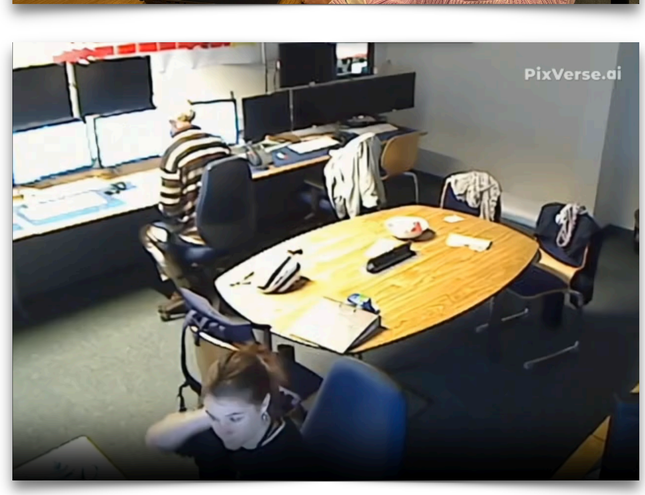


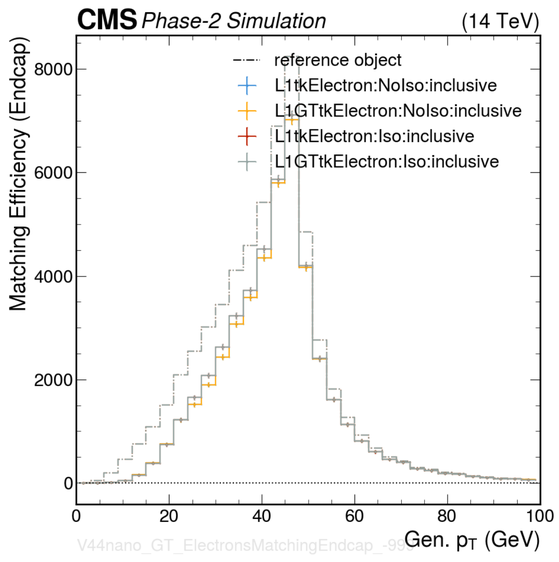
- **Contribution:**
  - Trigger shifts from P5 & Desy ROC
  - Maintenance and development of **Phase 2 — L1 trigger menu tool**

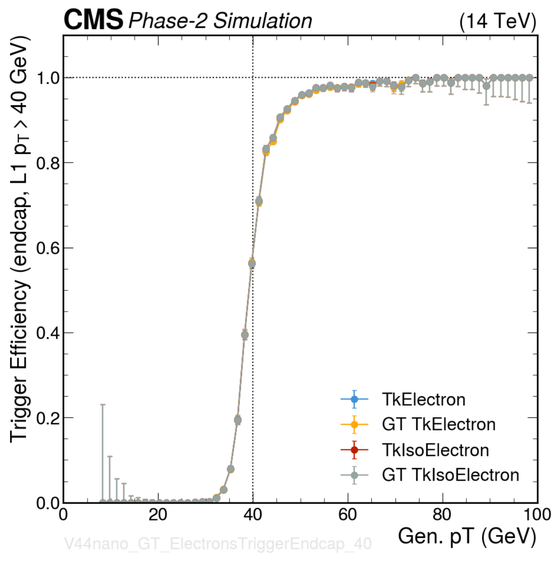
    ⟶ **2 + 1.3 EPR**

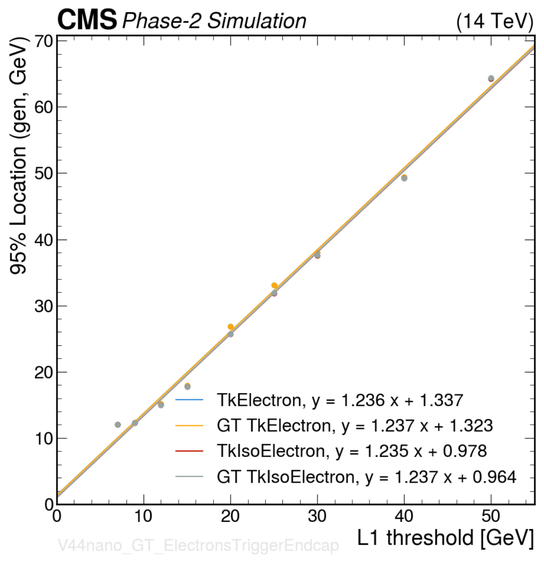
- **Status & future plans:**
  - Focus on Phase 2 — L1 menu tool
  - Get authorship











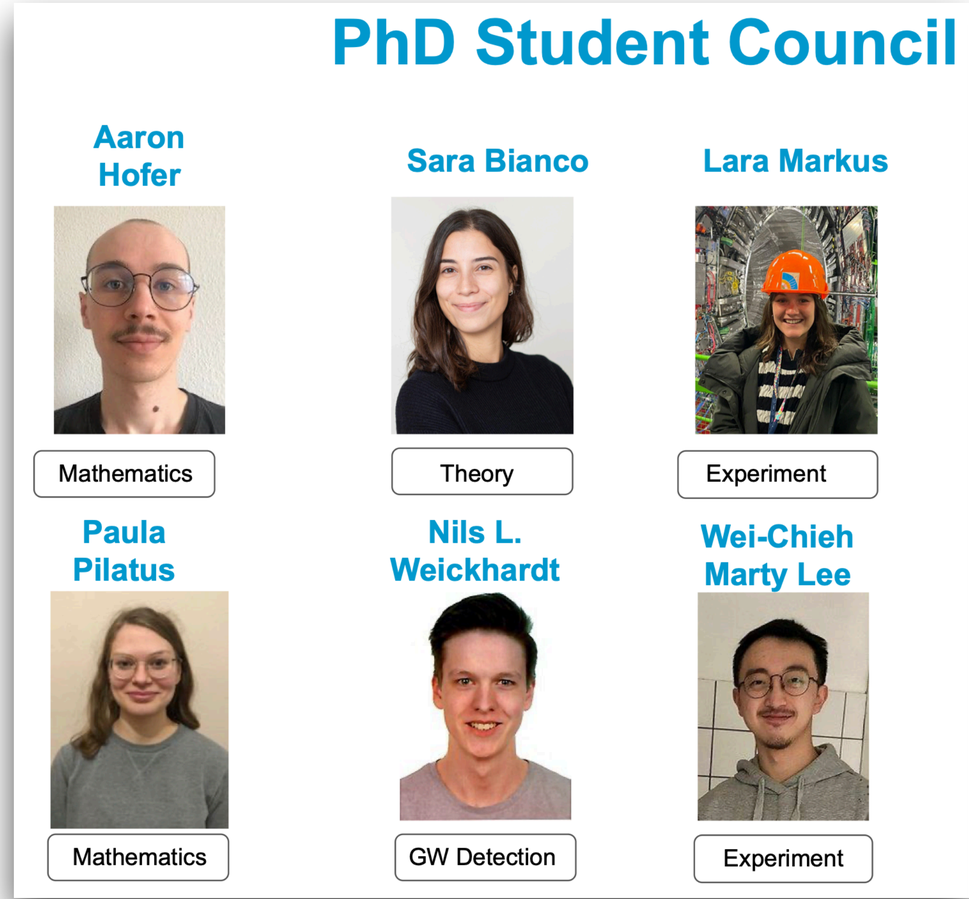
Example: L1 trigger menu tool outputs

- **Conferences with talks**
  - DPG Spring Conferences
  - FSP CMS Germany meetings
  - QU days

- **Schools**
  - Terascale Statistics School 2025
  - 56. Herbstschule of High-Energy-Physics (Maria Laach)

- **Teaching**
  - Exercise group Physik II
  - Supervision of master thesis on HHH analysis (DL)

- **Outreach**
  - Active member of QU Council
  - ATTRACT workshop
  - etc.



Backup

Optimizing ML training for $HH \rightarrow bbWW$ (DL)

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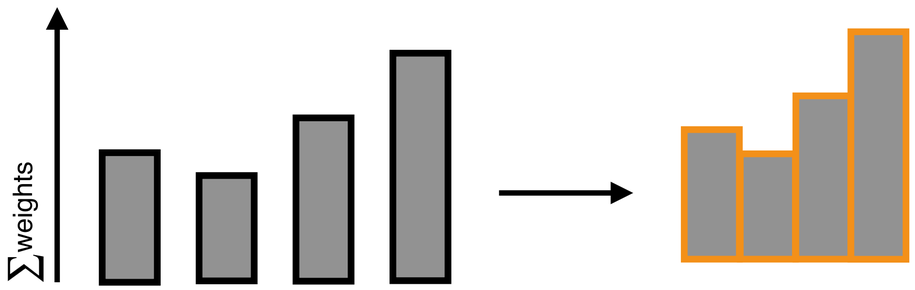
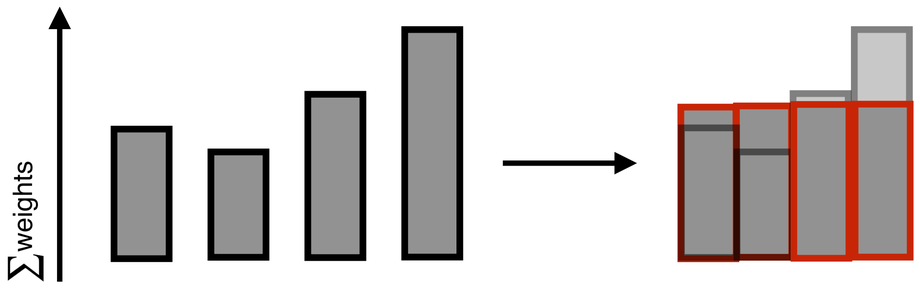
xsec weighting approach (study 1):

- Ratio between weights reflects cross section

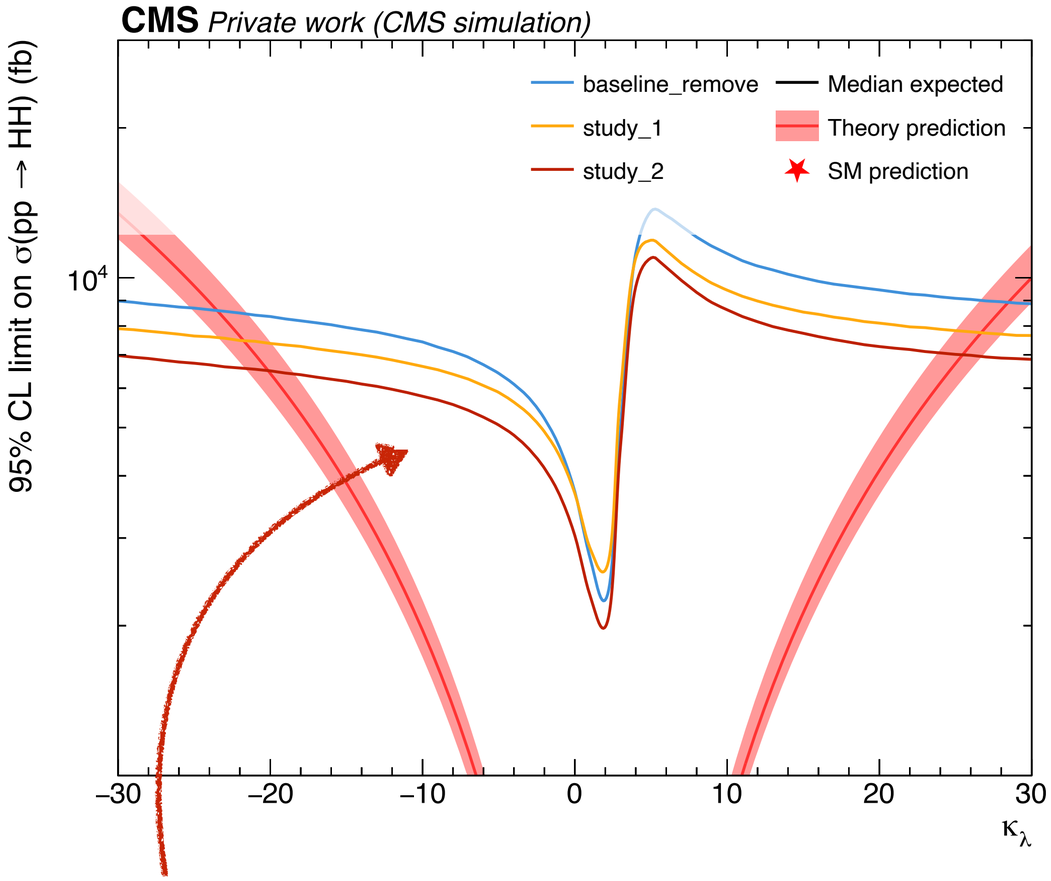


Equal weighting approach (study 2) :

- Each subprocess should be weighted equally
- $\sum$ **weights =** N**events**
- $\sum_{\text{process A}}$ **weights =** $\sum_{\text{process B}}$ **weights = …**



- **Combine signal samples for NN training**



Combining signal samples and applying equal weighting approach enhances sensitivity on κ_λ

Baseline: Only SM signal samples

DY correction for $HH \rightarrow bbWW$ (DL)

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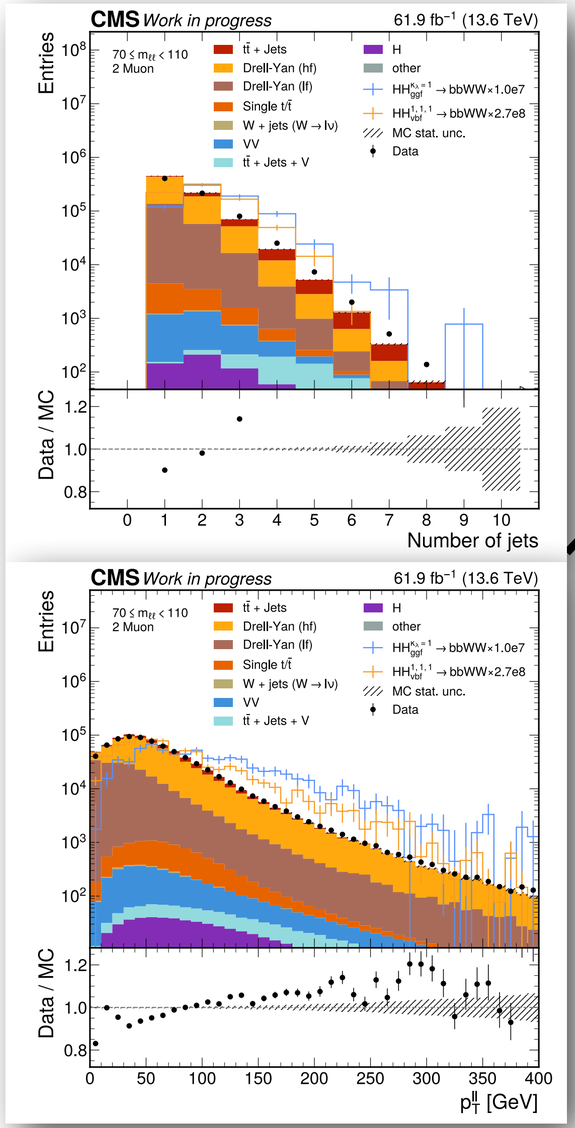
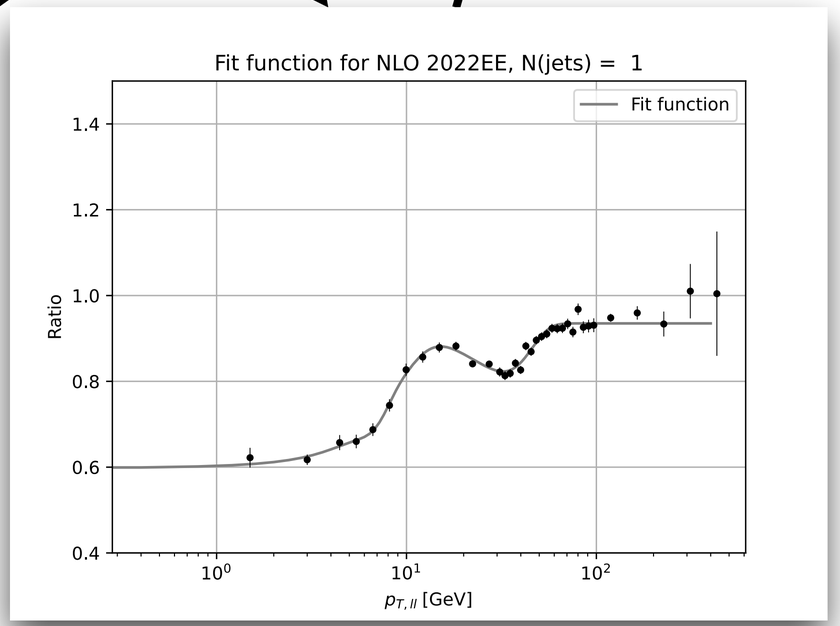
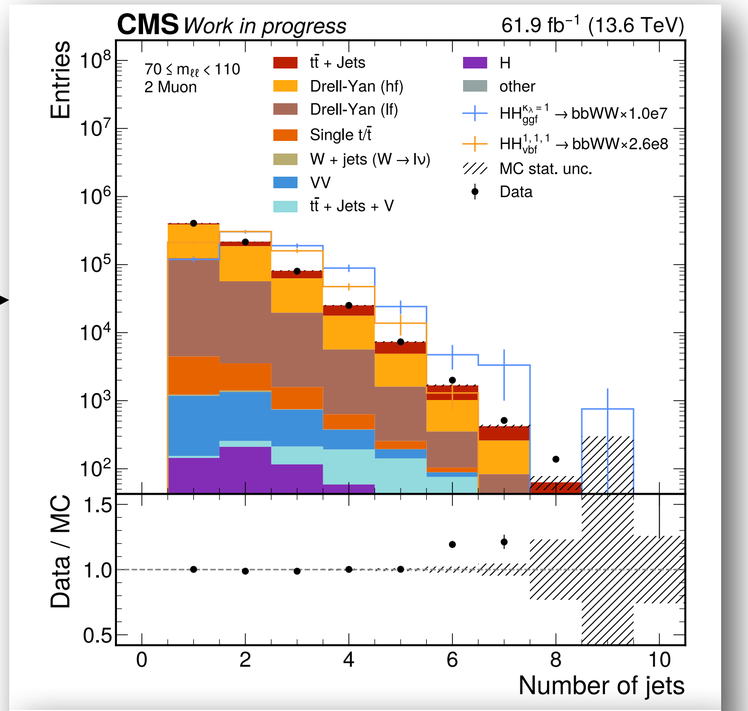
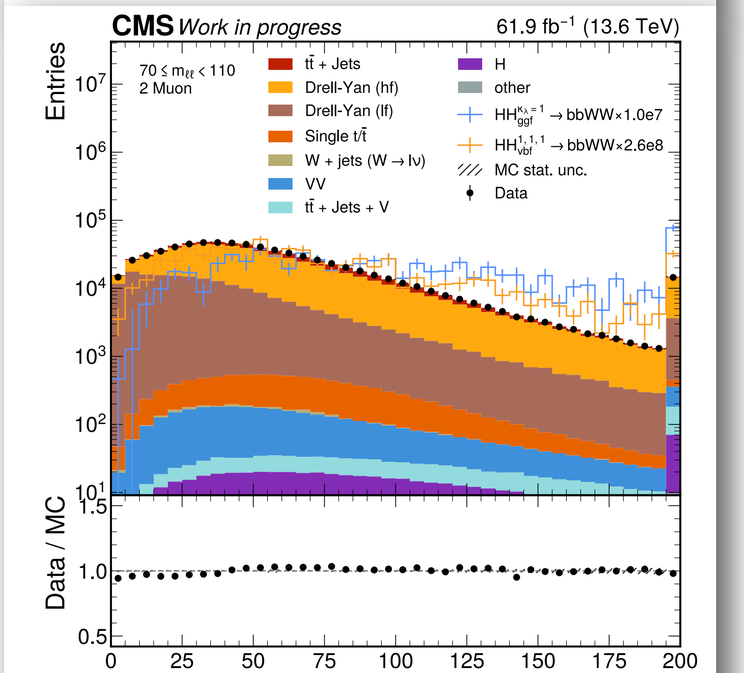
- Data/MC disagreement in DY validation region
- Strategy: $p_T^{\ell\ell}$ corrections in bins of N_{jet}









Technical details on DY correction for $HH \rightarrow bbWW$ (DL)

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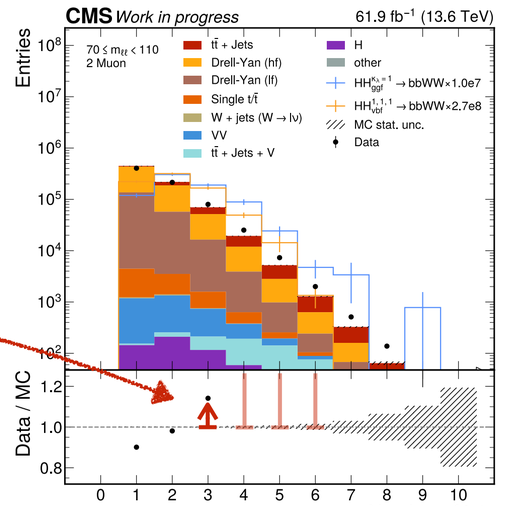
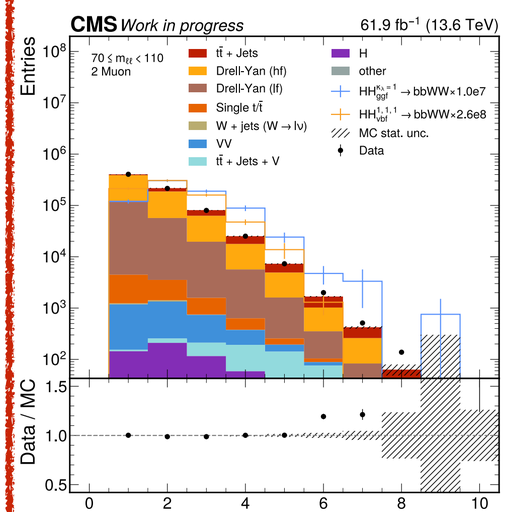
- **Final strategy:**
  - Derived per campaign and in DYVR, *2μ*
    - Purity of DY-jets events: 93.5%
  - Derived in bins of N_{jets} (1, ≥ 2):
    - For $N_{\text{jets}} \geq 2$: add rate factor based on N_{jets}
  - Applied as function of gen-level $p_{\text{T}}^{\ell\ell}$
  - Systematic uncertainty as 50% of the full correction effect

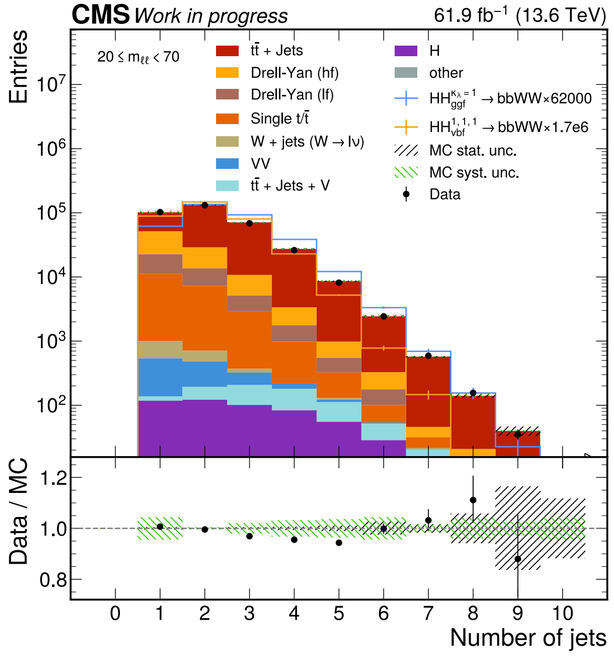
DYVR, 2μ
after DY corrections applied

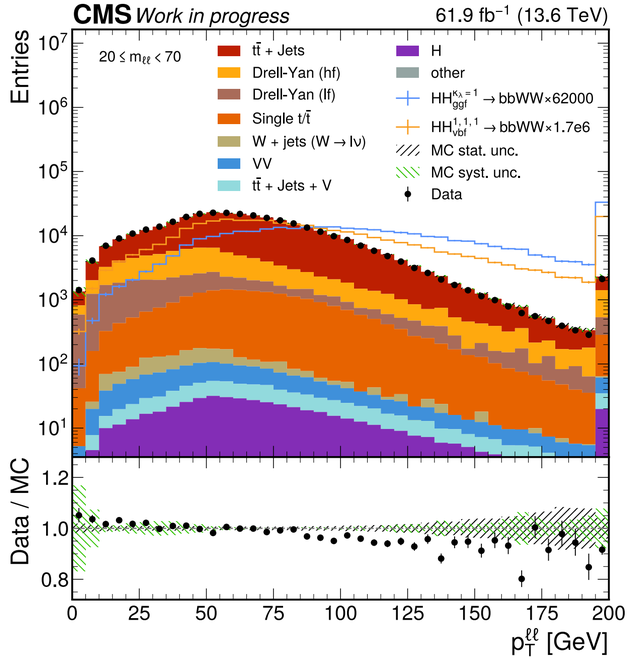


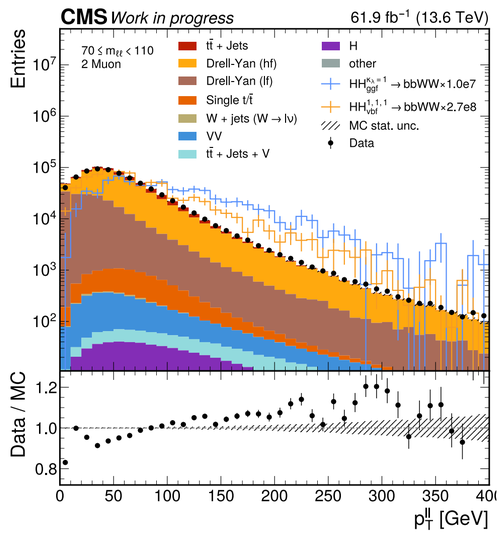


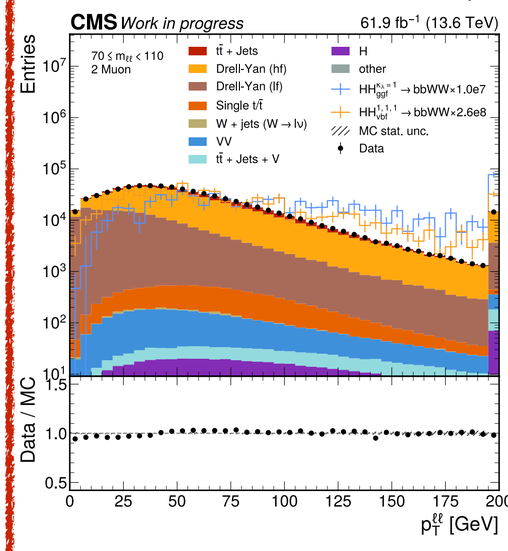
- Application on analysis region:

syst. unc. includes only DY correction unc.









Gen level studies for forward jets $HH \rightarrow bbWW$ (DL)

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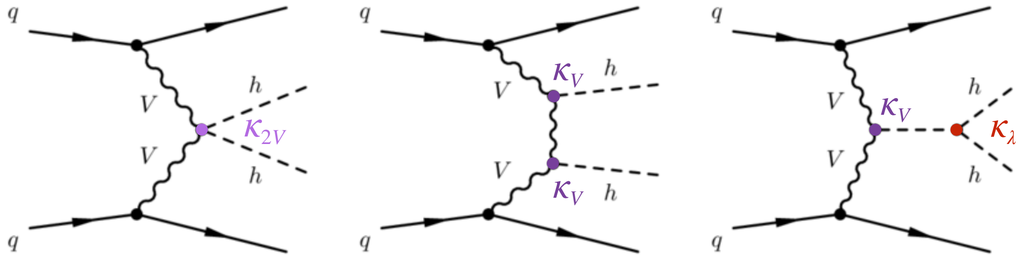
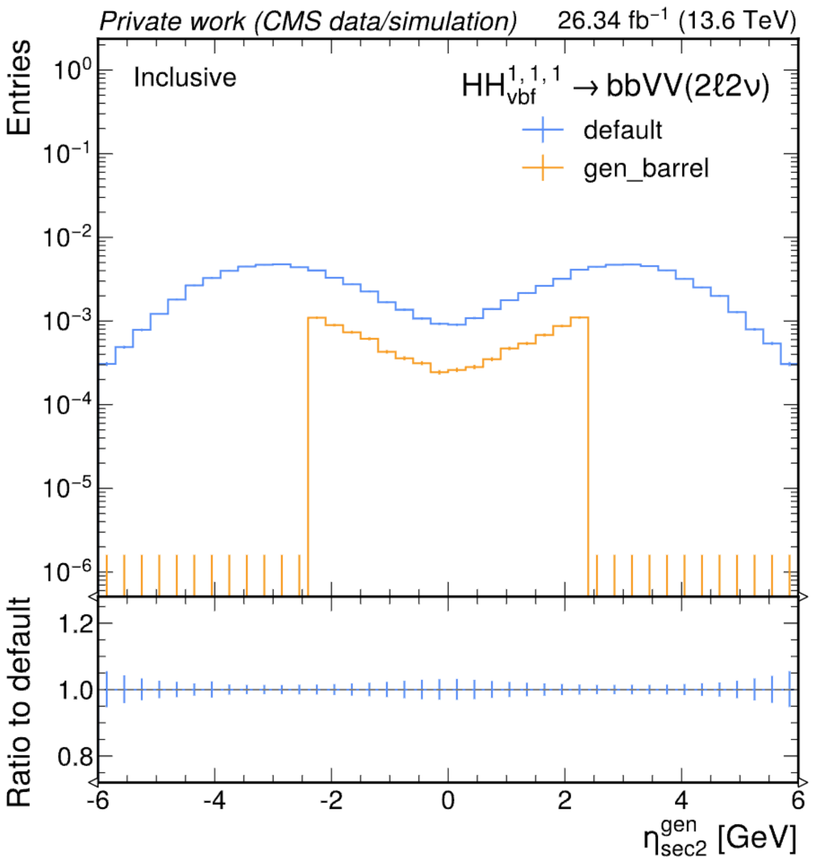
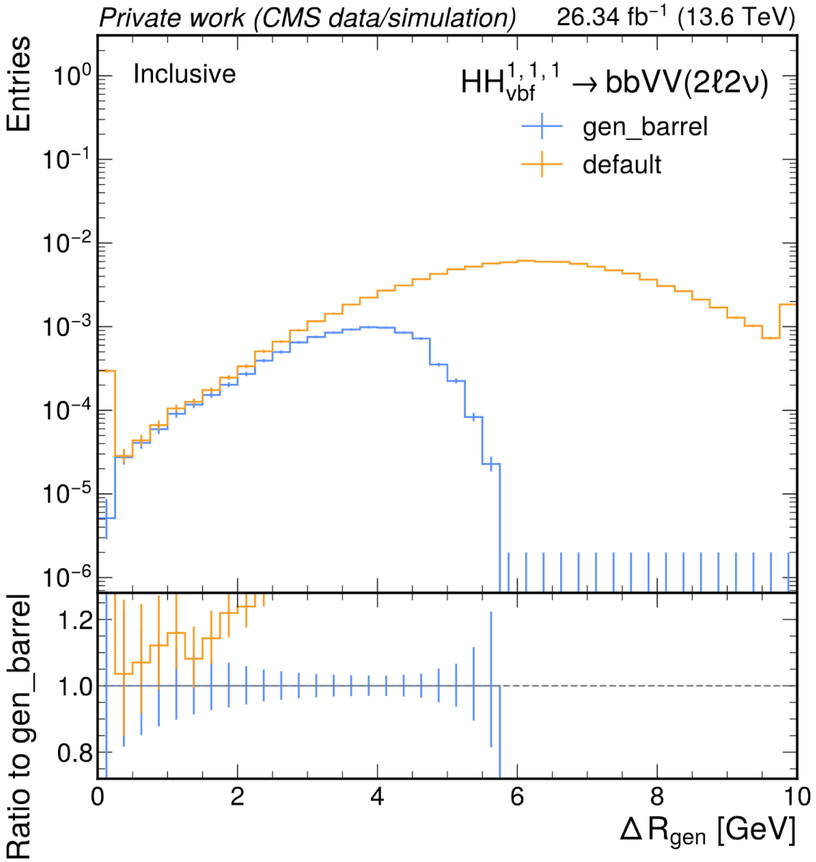
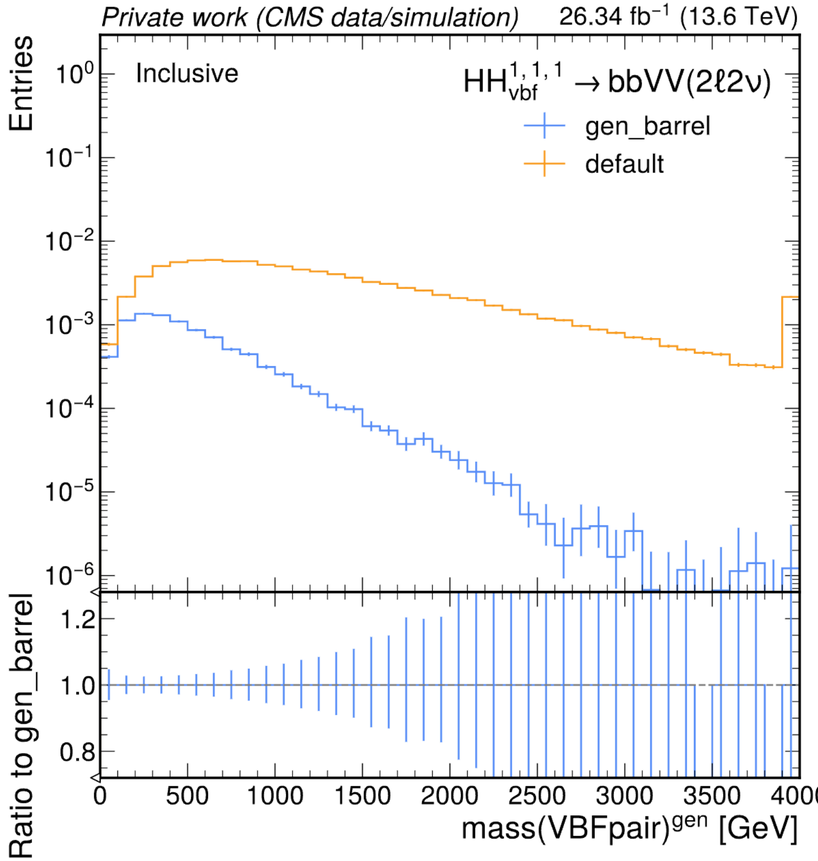
- **Comparison of central and forward jets on Gen level**









VBF strategy on $HH \rightarrow bbWW$ (DL)

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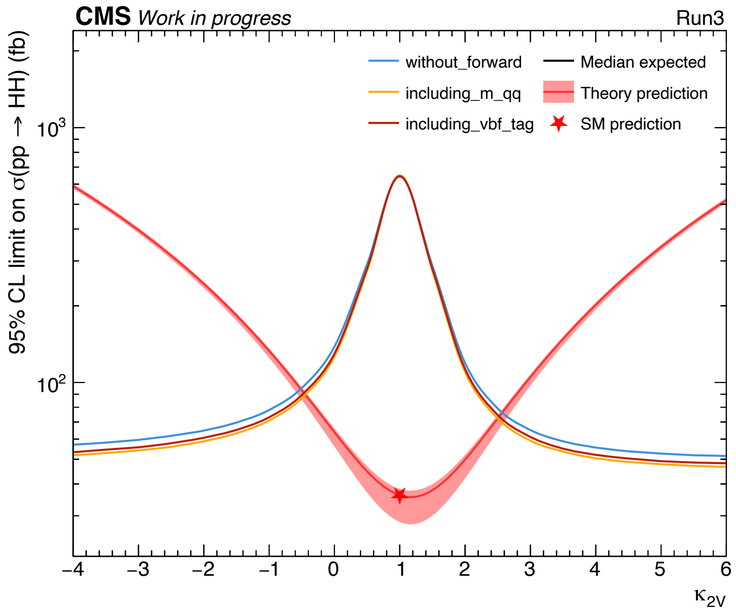
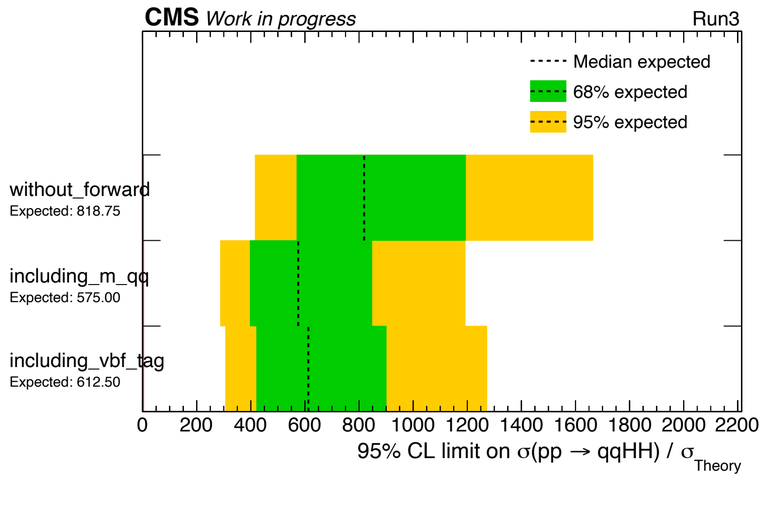
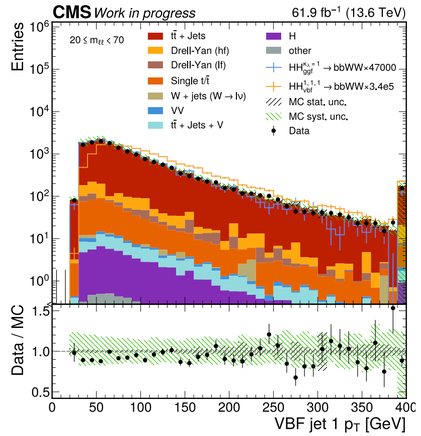
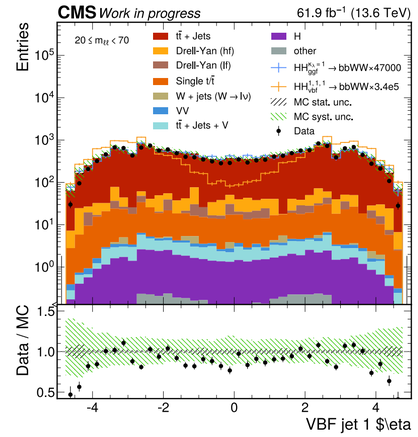
- **Jet selection**
  - Horn region ($2.5 < |\eta| < 3.0$): $p_T \geq 50\,\text{GeV}$, no JER stochastic smearing applied
  - Endcaps ($3.0 < |\eta| < 4.7$): $p_T \geq 30\,\text{GeV}$
- **VBF pair selection**
  - Select all non-btagged jet pairs with $\Delta\eta > 3$ as VBF pair candidates
  - Jet pair with largest $\Delta\eta$ chosen as VBF pair
- Strategy: include VBF pair tag as input feature in ML training for NN_{VBF}

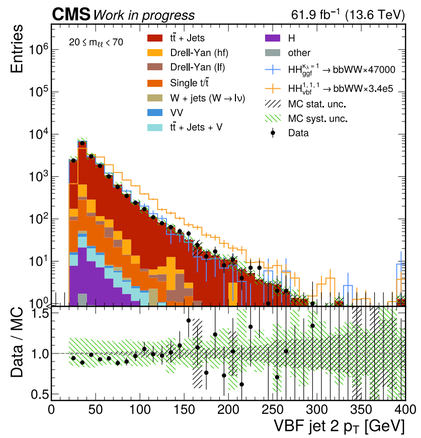
VBF tag definition:
VBF pair present with m_{qq} > 500 GeV & $\Delta\eta$ > 3 → Tag = 1
Else: Tag = 0

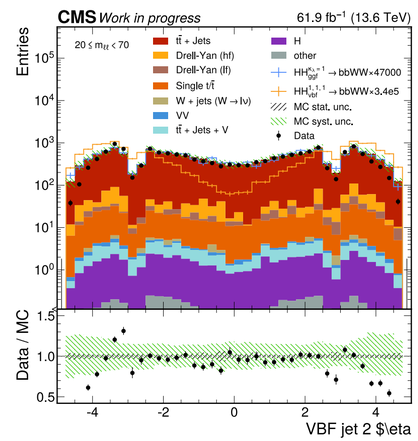


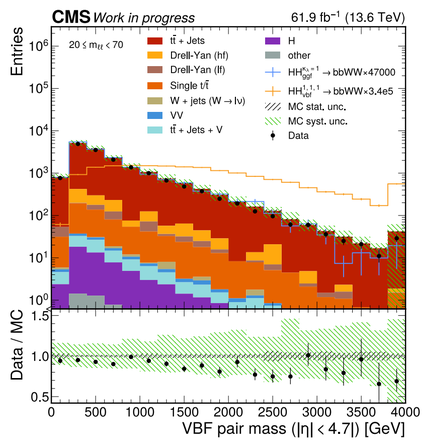


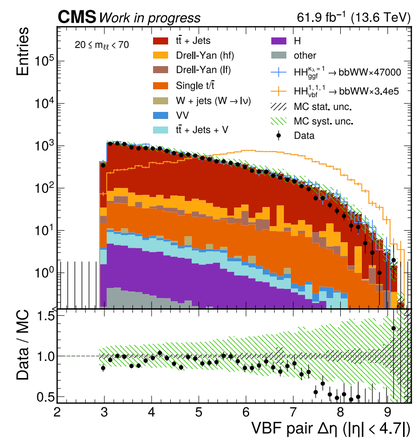












N.B. No additional events selected, additional information used from forward jets

Status integration of 2024 data

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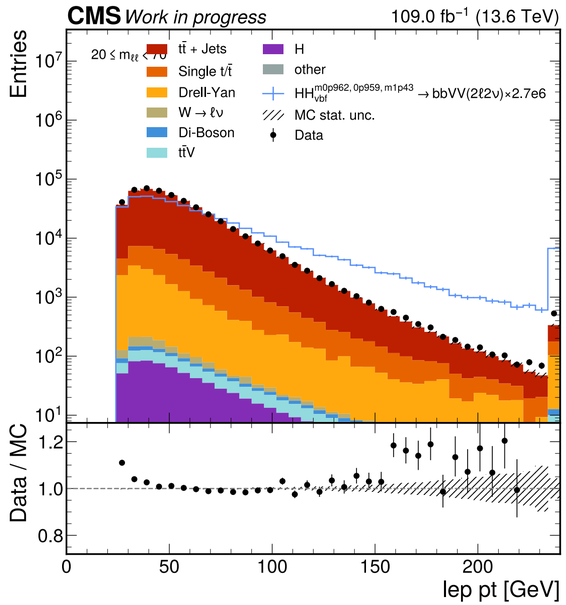
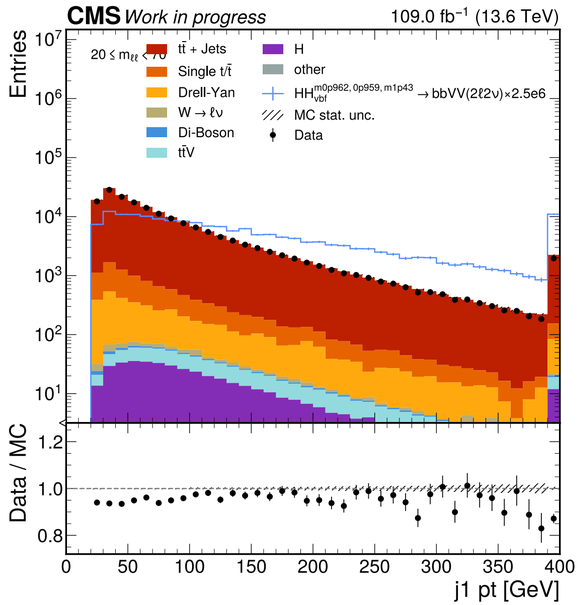
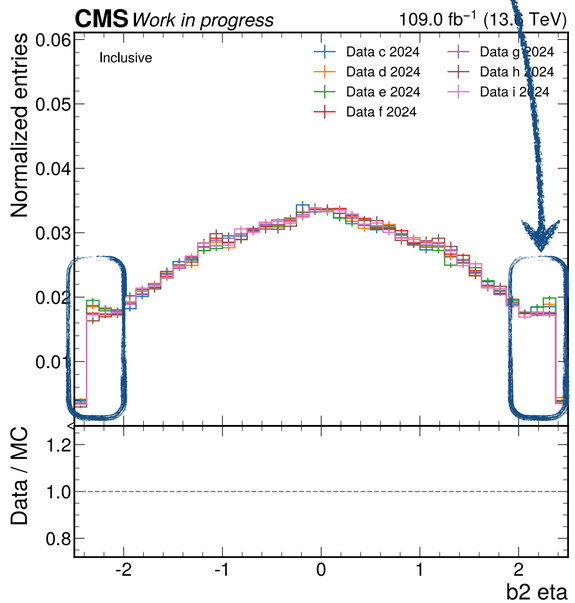
- **Currently missing**
  - Various signal samples (especially SM)
  - DY samples with $m_{\ell\ell}$ 10 to 50 GeV
  - B-tagging scale factors, PU corrections, etc.

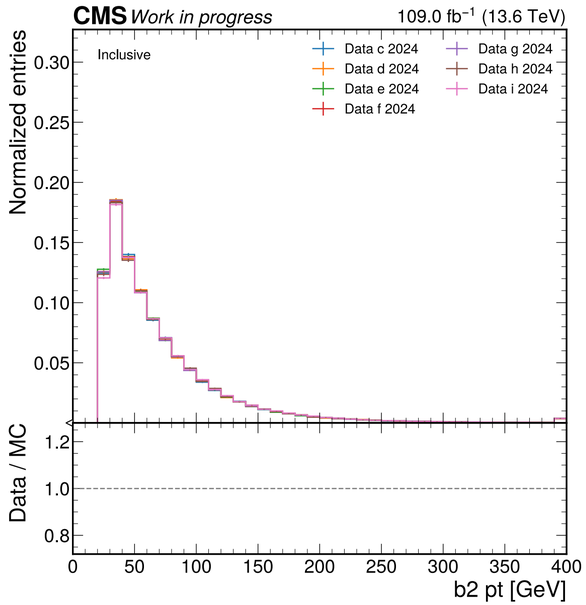
- **For era c,d,e: Horns in data in central region (2.1 < $|\eta|$ < 2.5)**

- **Otherwise: Most observables look already quiet decent**









Calibrations

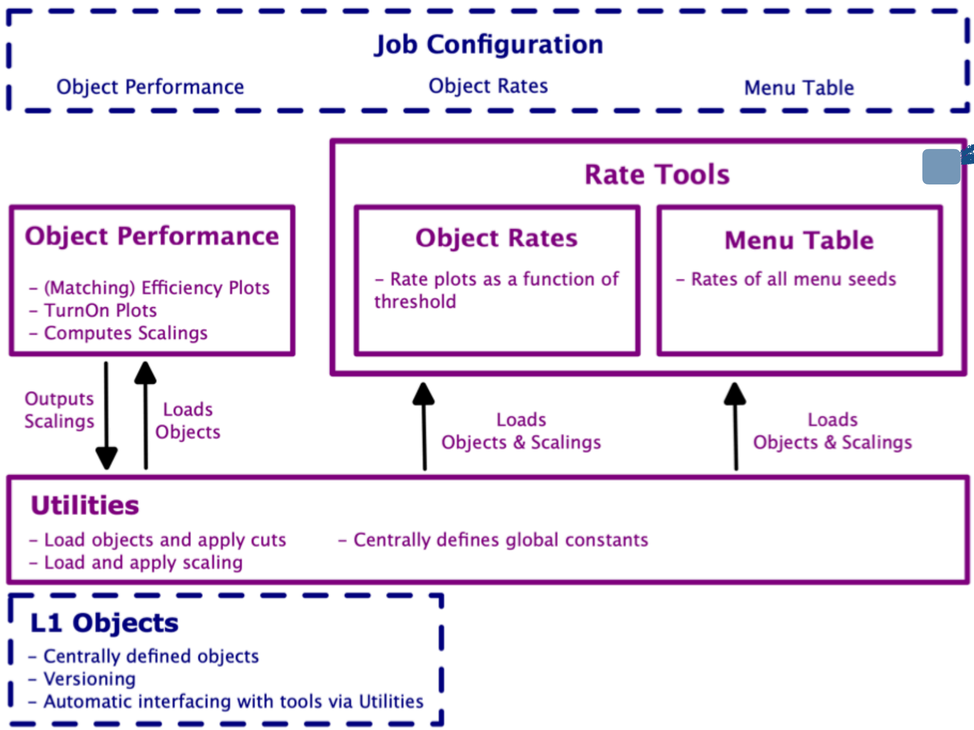
QU Report
Lara Markus

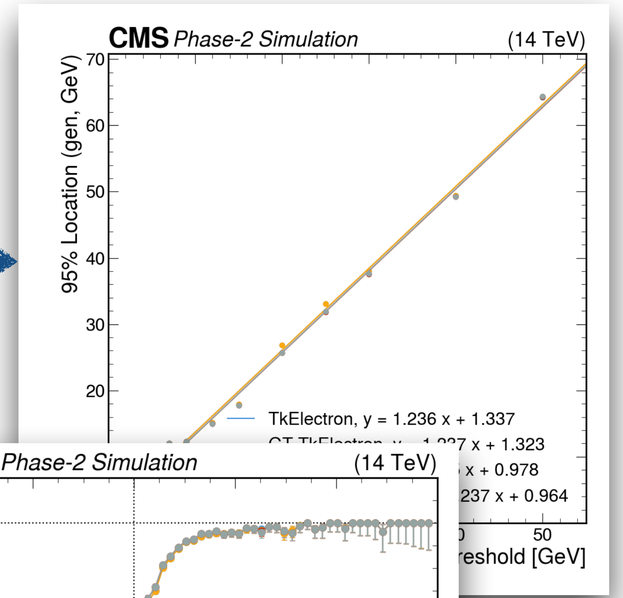
Calibration / Corrections	Impl	Unc.	Comment
JEC	✓	✓	
JER	–	–	Not available atm, using 2023preBPix
MET Type II correction (phi modulation)	✗	✗	Not available
Electron Scale & Smearing	✓	✓	systematics to be processed
B-tag scale factors	–	–	No shape uncertainty available (using kinfit-wp unc atm, but needs to be changed) SF are preliminary (also therefore in the name, no final tag SF available)
Electron scale factors	–	–	ATM only available from pt > 20 GeV, also
Electron reco	✗	✗	Need to find accessible keys
Muon scale factors (id, iso)	✓	✓	
Trigger scale factors	✗	✗	Custom SF need to be derived
Top pt reweighting	✓	✓	
Vector boson pt reweighting	✗	✗	Not needed and not applied before —> custom DY correction instead
recoil corrections	✗	✗	
DY ptll and recoil corrections	✓	✓	
Pileup reweighting	–	–	Preliminary weights used (see link) need to be updated at some point From Guillermo
Factorization / renormalization scales (parton	✓	✓	renorm. included
PDF shape	✓	✓	renorm. included
Initial / final state radiation (ISR/FSR)	✓	✗	systematics via additional samples
Tune / Hdamp	✓	✗	systematics via additional samples
FatJet JEC / JER	✗	✗	Not available
FatJet msoftdrop corrections	✗	✗	Not available
FatJet B-tag scale factors	✗	✗	Not available
Lumi	–	–	Preliminary lumi correction

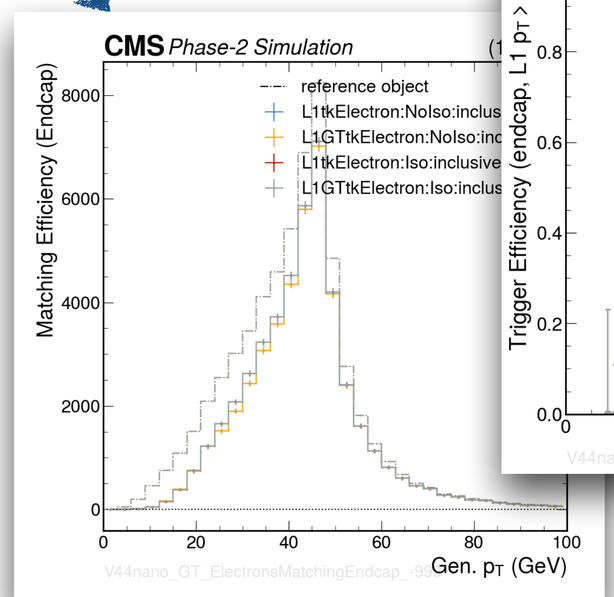
▻ Phase 2 — L1 trigger menu tool

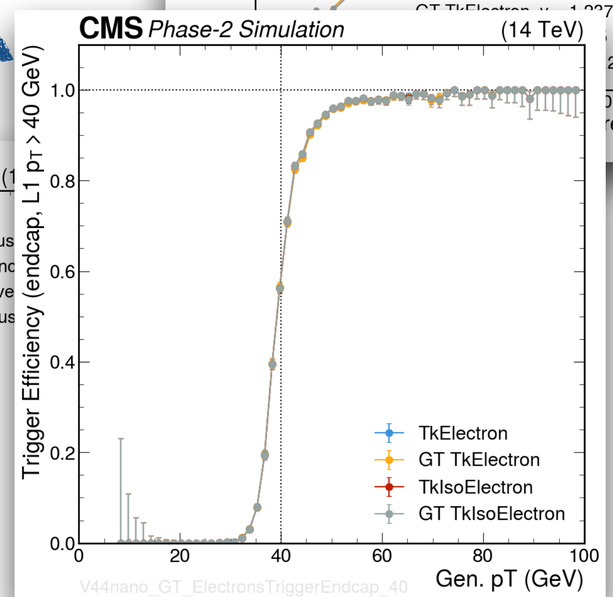
Python based framework for the measuring of matching efficiencies, trigger turn-on curves and scalings for the assessment of

▻ Discussion for a DPS note

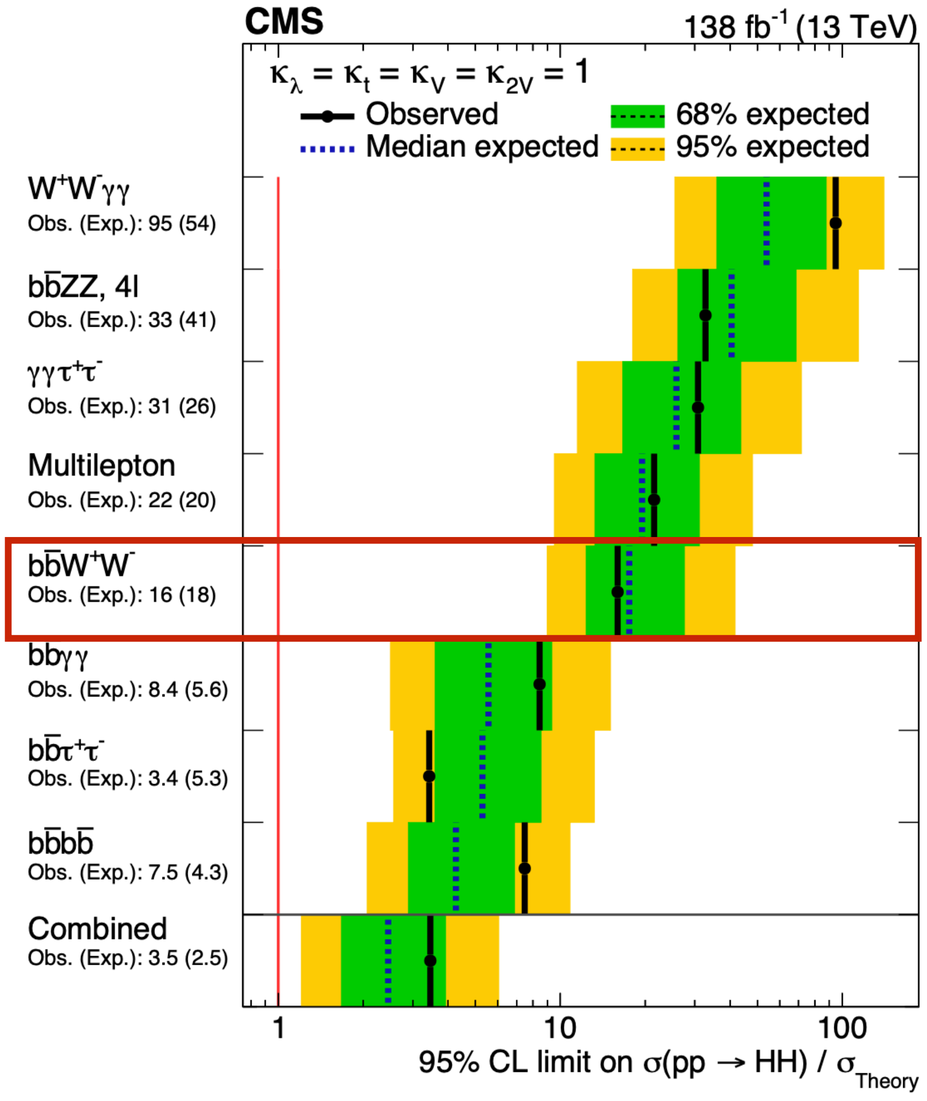








Details on HH → bbWW (DL) analysis



HH combination (arXiv:2510.07527)

Comparing full Run 2 CMS results for $HH \rightarrow bbWW$

(JHEP 07 (2024) 293)

Channel		SM		κ_λ exclusion		κ_{2V} exclusion	
		expected	observed	expected	observed	expected	observed
3	**DL**	**19**	**-**	**(-12, 19)**	**-**	**(-0.5, 2.6)**	**-**
Run 2	Full	18	16	(-8.7, 15.2)	(7.2, 13.8)	(-1.0, 1.4)	(-0.8, 1.3)
	SL	27	28	(-11.5, 18)*	(-11.5,18.5)*	(-1.6, 3.7)*	(-1.5, 3.6)*
	DL	**27**	19	**(-11.5, 18)***	(-8.5, 15.5)*	**(-1.4, 4.4)***	(-1.1, 3.8)*

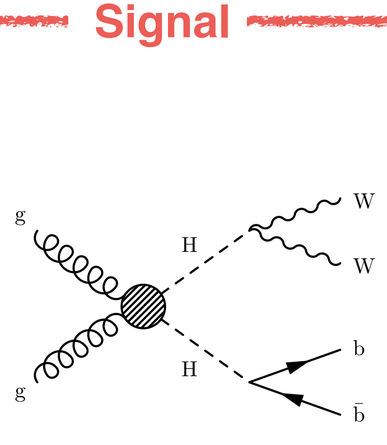
*** taken from:** CMS AN-2020/119 **Version 16**

Object definition and event selection

QU Report
Lara Markus

- **Trigger selection**
  - Dilepton triggers + single lepton triggers to retain efficiency
- **Lepton selection**
  - **2 tight, opposite-charge electron/muon** with $p_{\mathrm{T}} \geq 25\,(15)\,\mathrm{GeV}$ and $|\eta| < (2.5)\,2.4$
    - **electron:** tight Id ($\mathrm{cutBased} \geq 4$) + dxy/dz requirements as recommended
    - **muon:** tight Id + Isolation ($\mathrm{tightId}\ \&\ \mathrm{pfIsoId} \geq 4$)
  - $20 < m_{\ell\ell} \leq 70\,\mathrm{GeV}$
  - Veto additional leptons
- **Jet selection**
  - **AK4 jets:** $p_{\mathrm{T}} \geq 25\,\mathrm{GeV}$, $|\eta| < 2.4$, tight Id, and $\min(\Delta R(j, \ell)) \geq 0.4$
    - At least **1 b-tagged AK4 jet** (particleNet, medium WP)
  - **AK8 jets:** $p_{\mathrm{T}} \geq 200\,\mathrm{GeV}$, $|\eta| < 2.4$, tight Id, and $\min(\Delta R(j, \ell)) \geq 0.8$
- $\boldsymbol{E_{\mathrm{T}}^{\mathrm{miss}} > 40\,\mathrm{GeV}}$

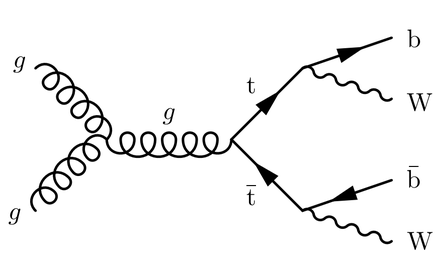
Signal



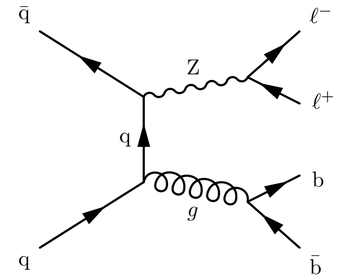
(di-boson, ttV, W+jets, H (<1%))

Background processes

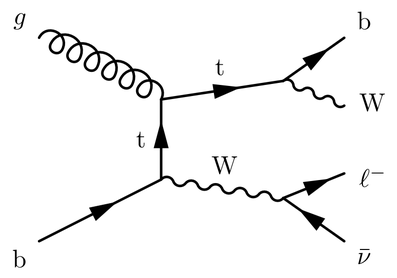
tt̄+jets *(84.8%)*



DY+jets *(7.6%)*



single top *(6.8%)*

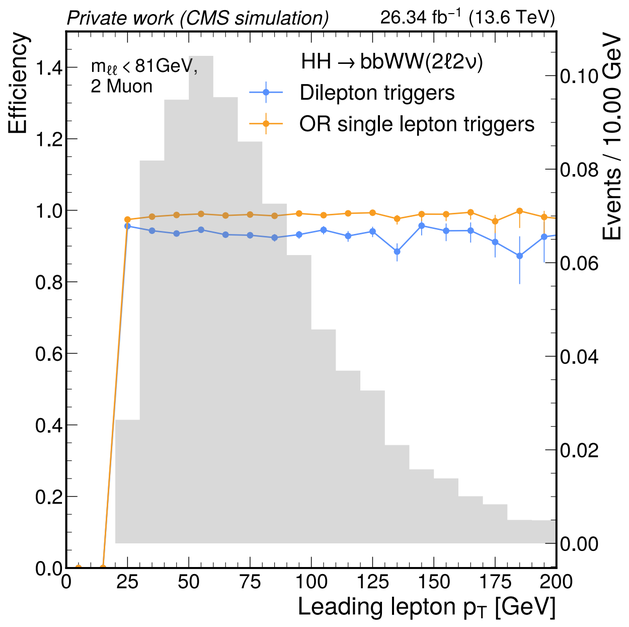


Trigger selection

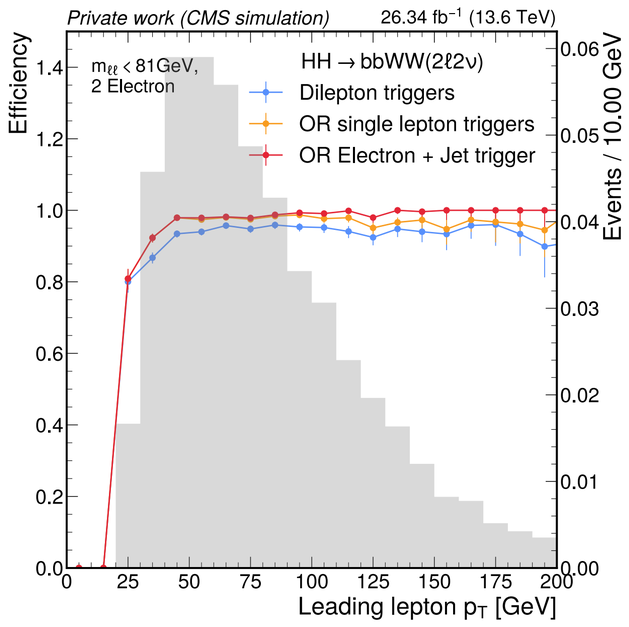
Lepton channel	Offline selection	Trigger combination	Data stream
di-muon	2 tight muons $p_{\mathrm{T}}^{\mathrm{leading(subl.)}} > 25(15)\,\mathrm{GeV}$	Mu17_TrkIsoVVL_Mu8_TrKIsoVVL_DZ_Mass3p8 IsoMu24	Muon Muon
di-electron	2 tight electrons $p_{\mathrm{T}}^{\mathrm{leading(subl.)}} > 25(15)\,\mathrm{GeV}$	Ele23_Ele12_CaloIdL_TrackIdL_IsoVL Ele30_WPTight_Gsf Ele50_CaloIdVT_GsfTrkIdT_PFJet165 DoubleEle33_CaloIdL_MW	EGamma EGamma EGamma EGamma
mixed	1 tight muon, 1 tight electron $p_{\mathrm{T}}^{\mathrm{leading(subl.)}} > 25(15)\,\mathrm{GeV}$	Mu23_TrkIsoVVL_Ele12_CaloIdL_TrackIdL_IsoVL Mu8_TrkIsoVVL_Ele23_CaloIdL_TrackIdL_IsoVL_DZ IsoMu24 Ele30_WPTight_Gsf Ele50_CaloIdVT_GsfTrkIdT_PFJet165	MuonEG MuonEG Muon EGamma EGamma

custom trigger SFs already produced
(one set per lepton channel, binned in leading & subleading lepton p_{T})

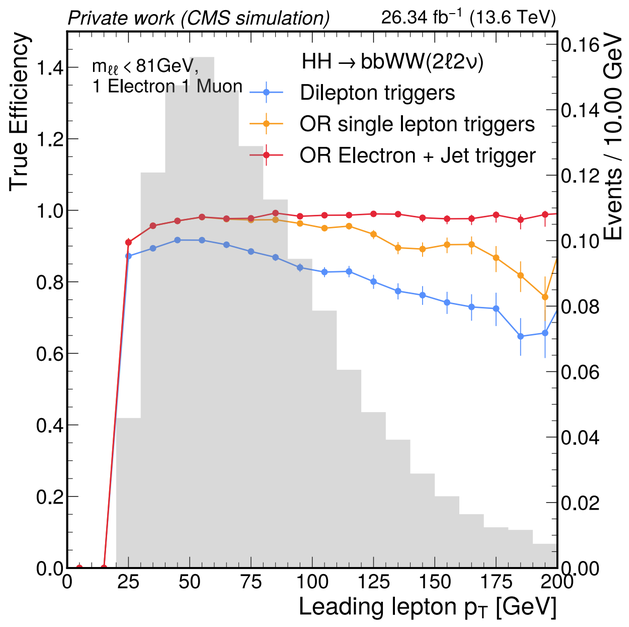
di-muon



di-electron



mixed



DY correction - DY validation region

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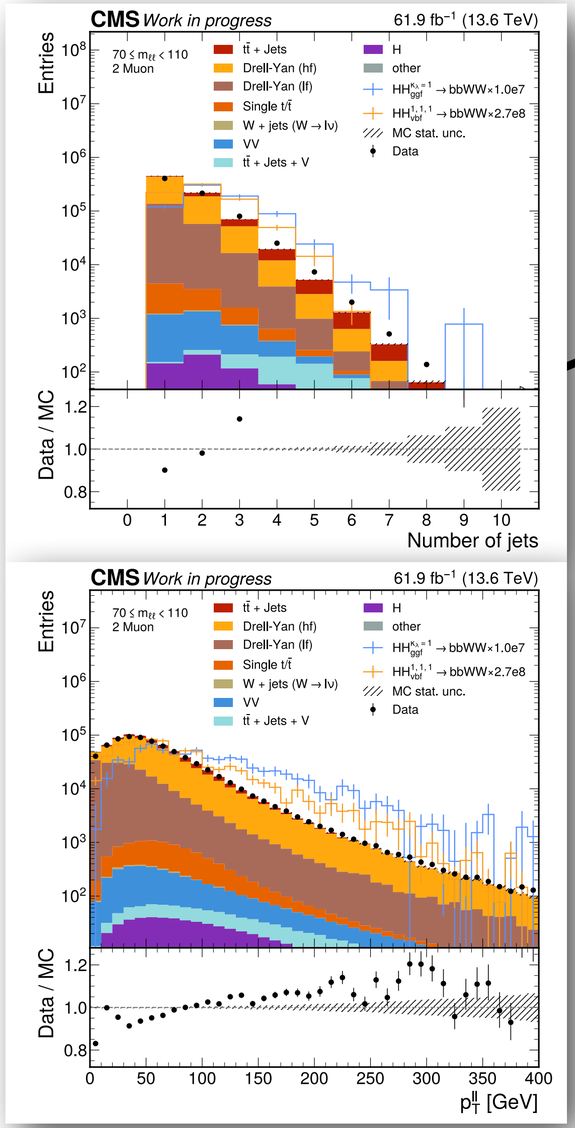
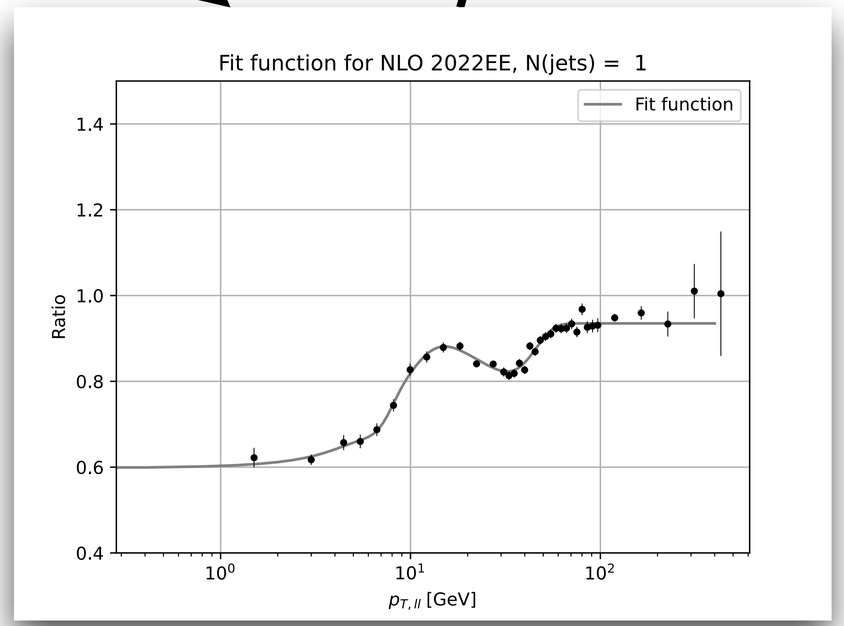
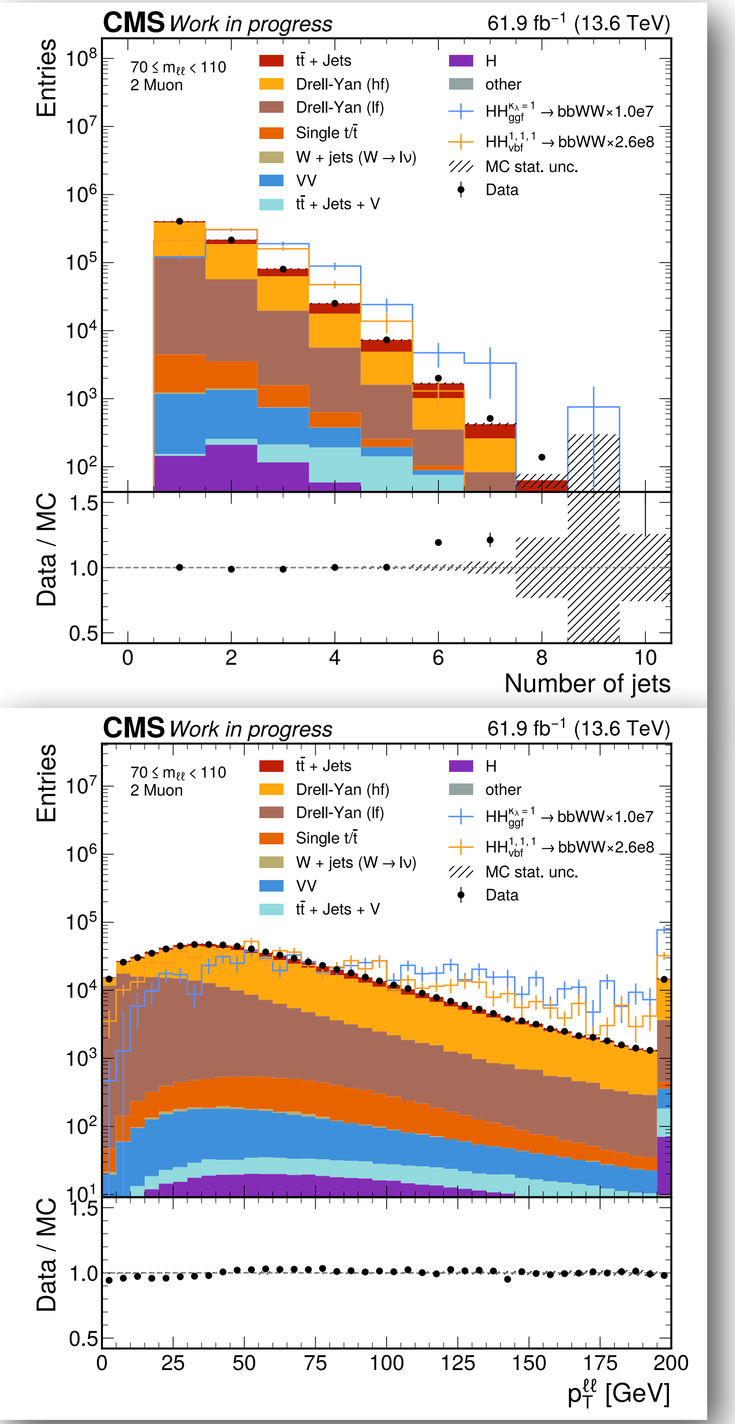
Lara Markus

- Data/MC disagreement in DY validation region
- Strategy: $p_{\mathrm{T}}^{\ell\ell}$ corrections in bins of N_{jet}





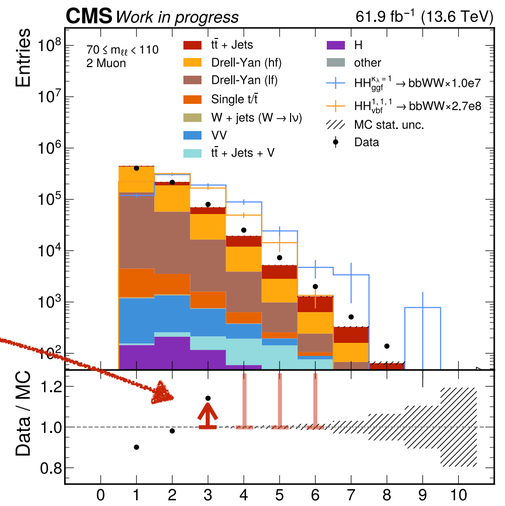


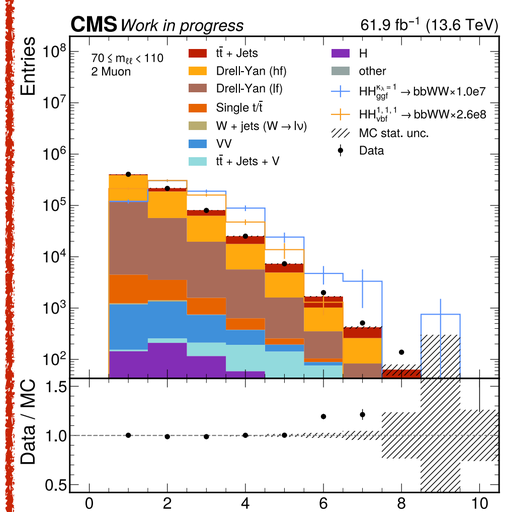
DY correction - technical details

QU Report
Lara Markus

- **Final strategy:**
  - Derived per campaign and in DYVR, 2μ
    - Purity of DY-jets events: 93.5%
  - Derived in bins of N_{jets} (1, ≥ 2):
    - For $N_{\text{jets}} \geq 2$: add rate factor based on N_{jets}
  - Applied as function of gen-level $p_{\text{T}}^{\ell\ell}$
  - Systematic uncertainty as 50% of the full correction effect

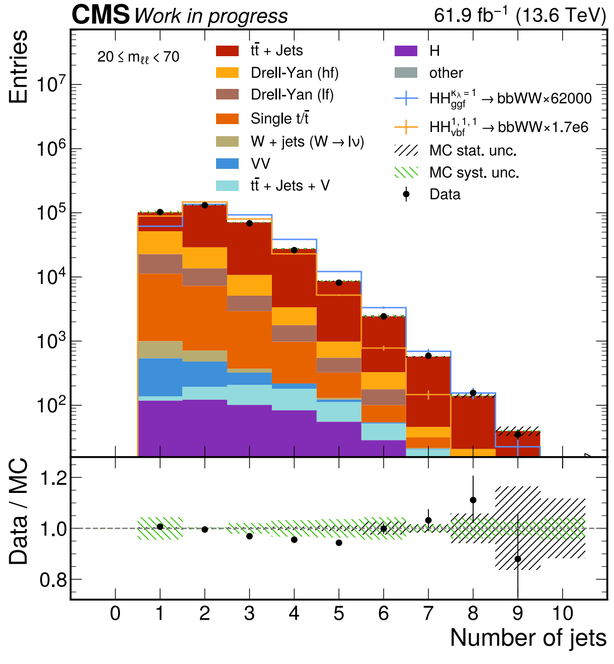
DYVR, 2μ
after DY corrections applied

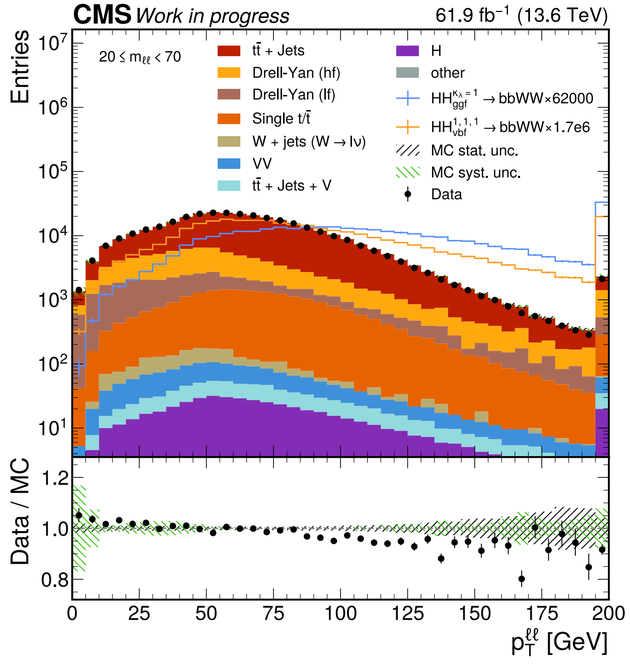


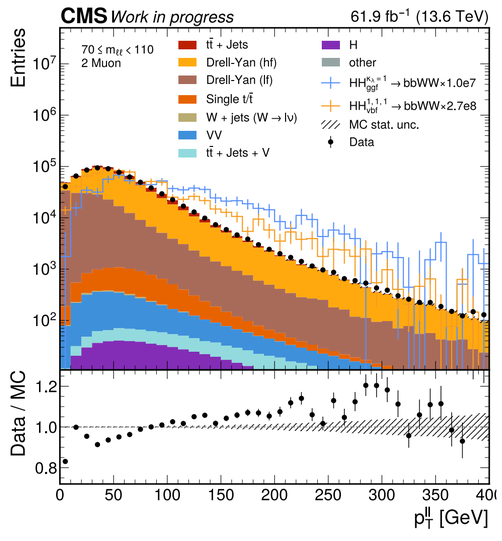


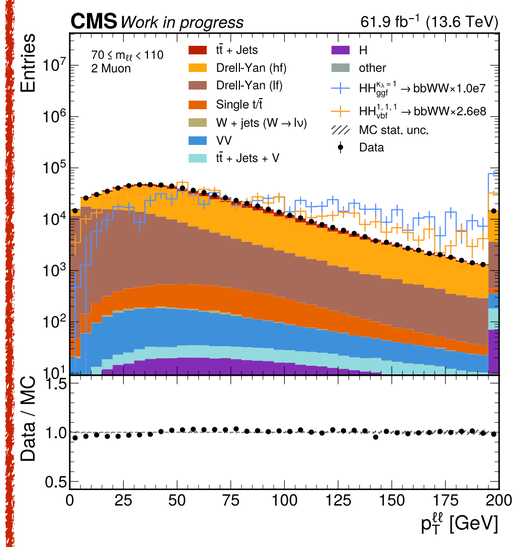
- Application on analysis region:

syst. unc. includes only DY correction unc.





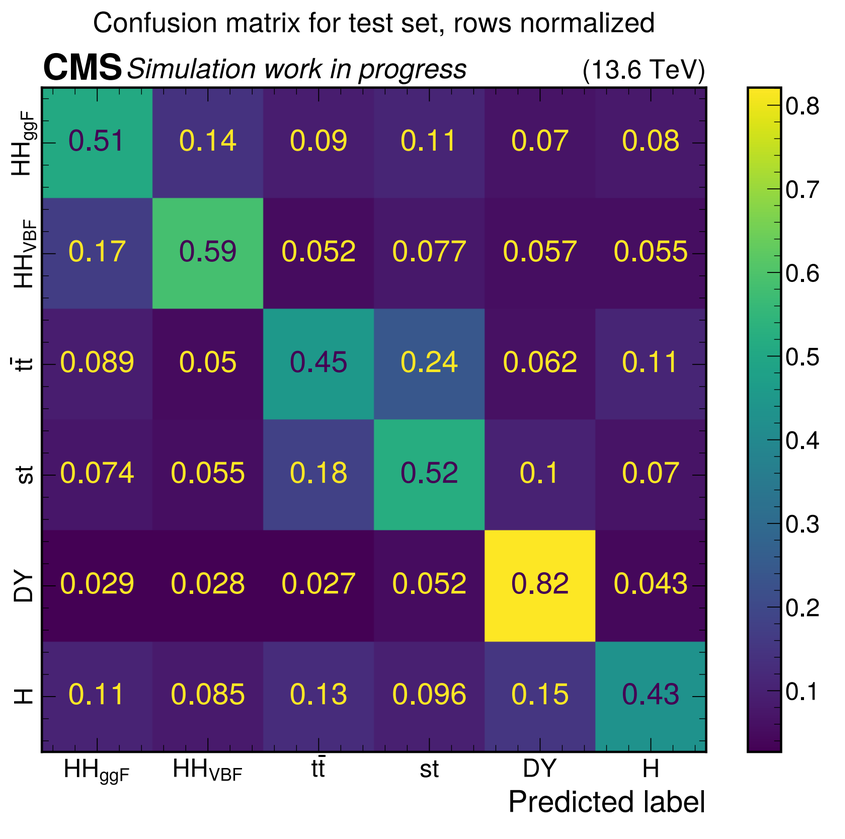




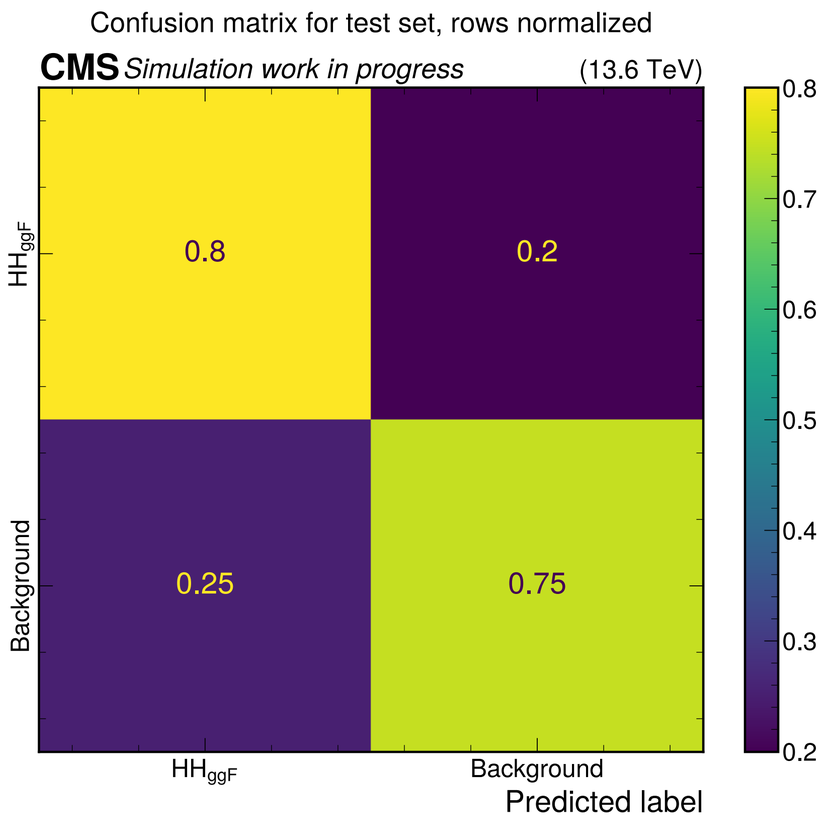
DNN performance

- Multiple different architectures tested by bbWW team
  - Multiclass-only
  - Binary-only
  - Transformer NN
  - Boosted observables
- Best performance obtained with combination of Multiclass + Binary

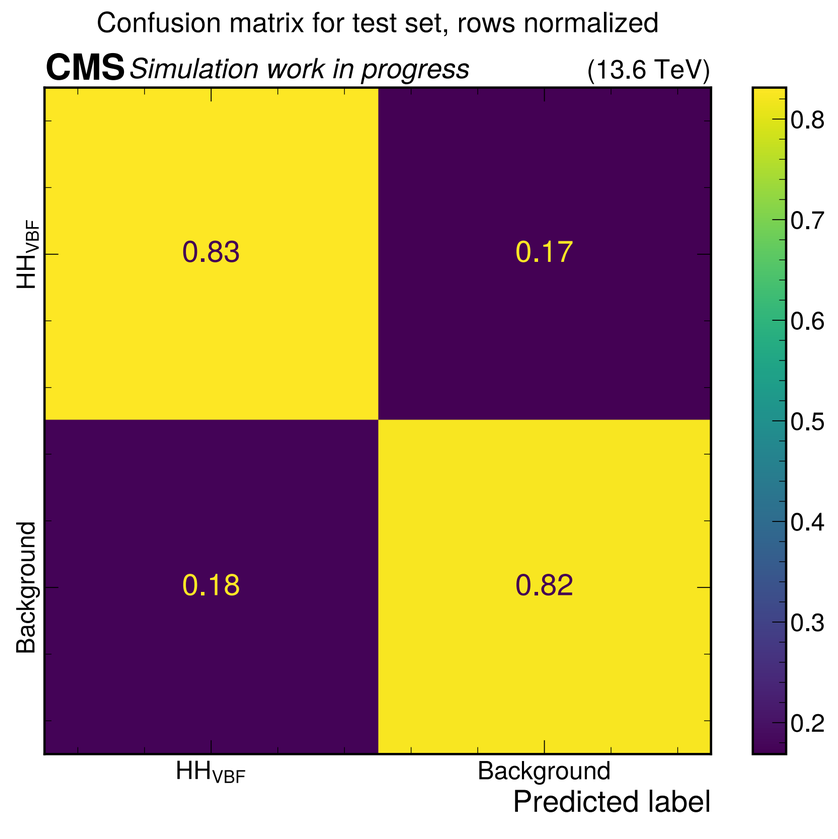
Multiclass DNN



binary ggF DNN



binary VBF DNN



Analysis strategy & categorization

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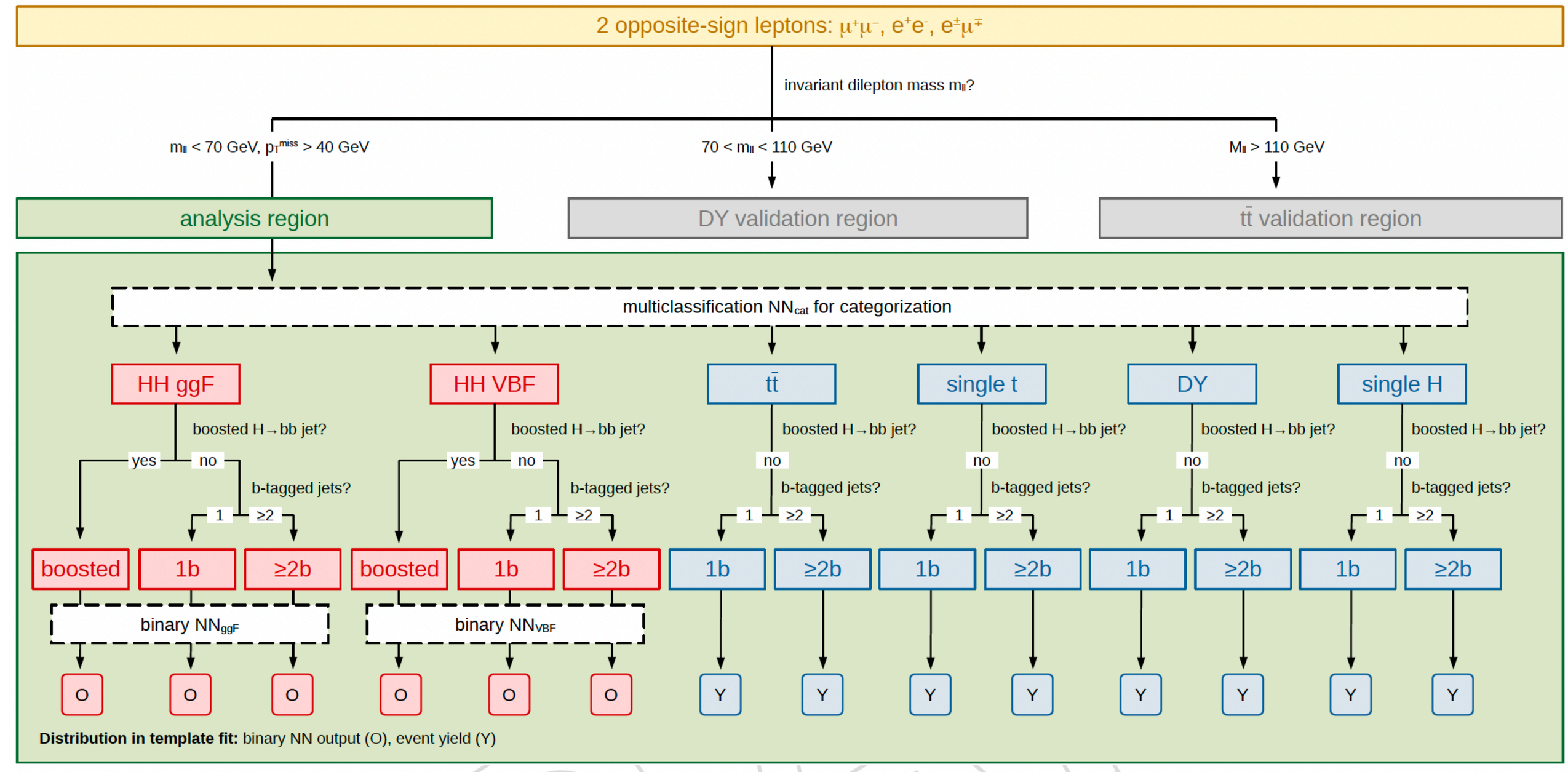
Lara Markus



Binary NN scores (before categorisation & rebinning)

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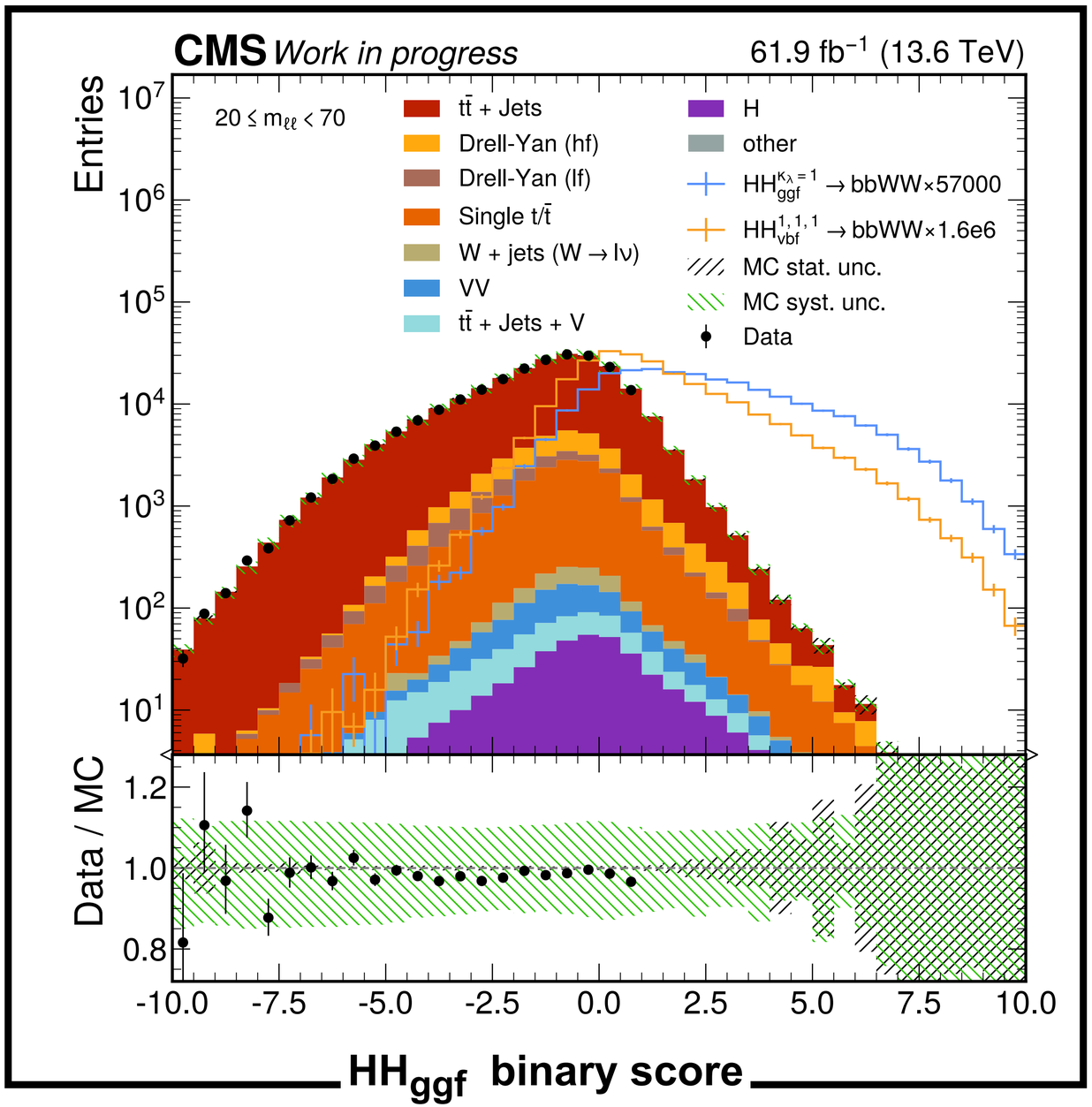
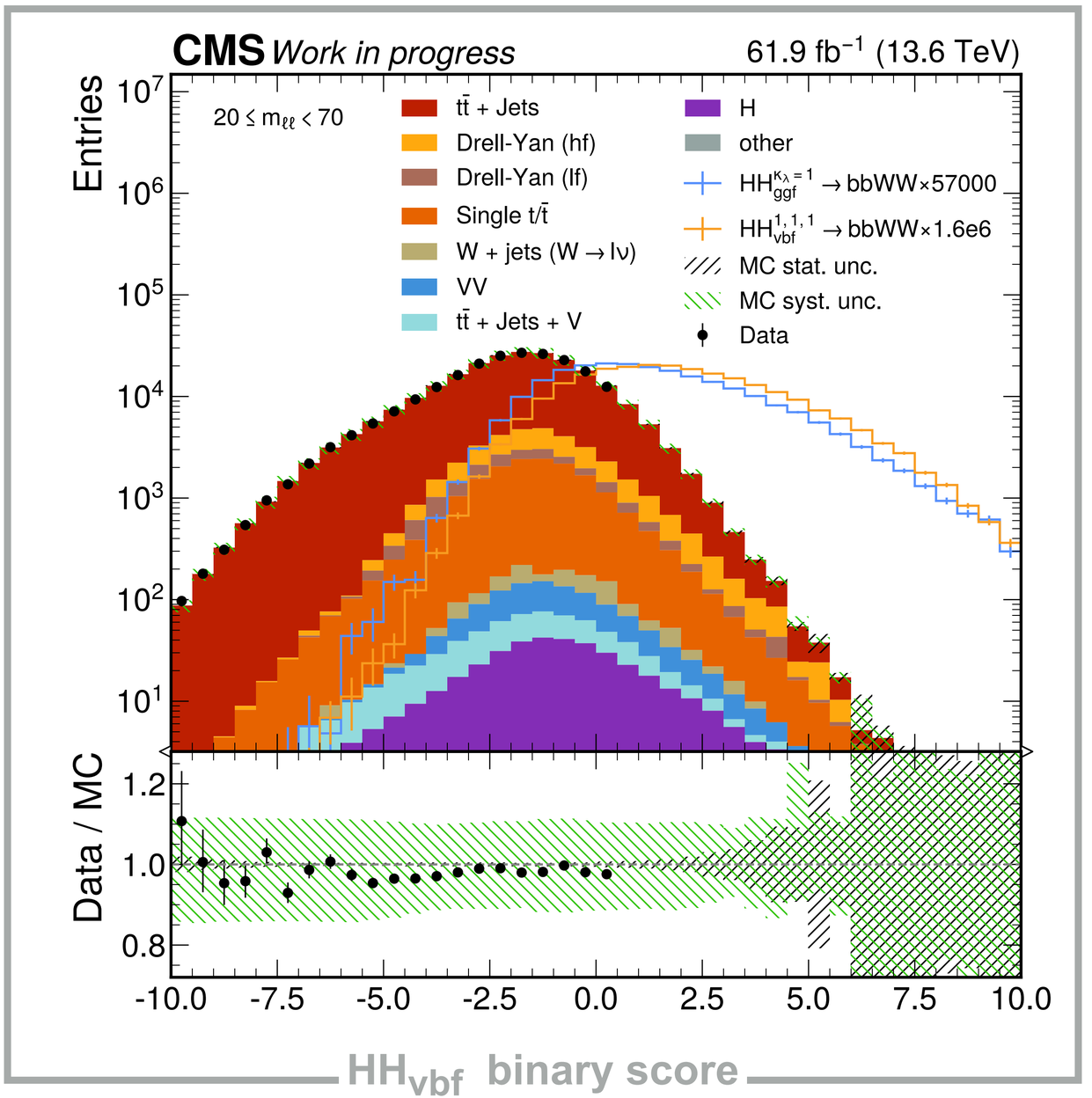
DNN scores are transformed with $\text{logit}(x) = \log \frac{x}{1-x}$

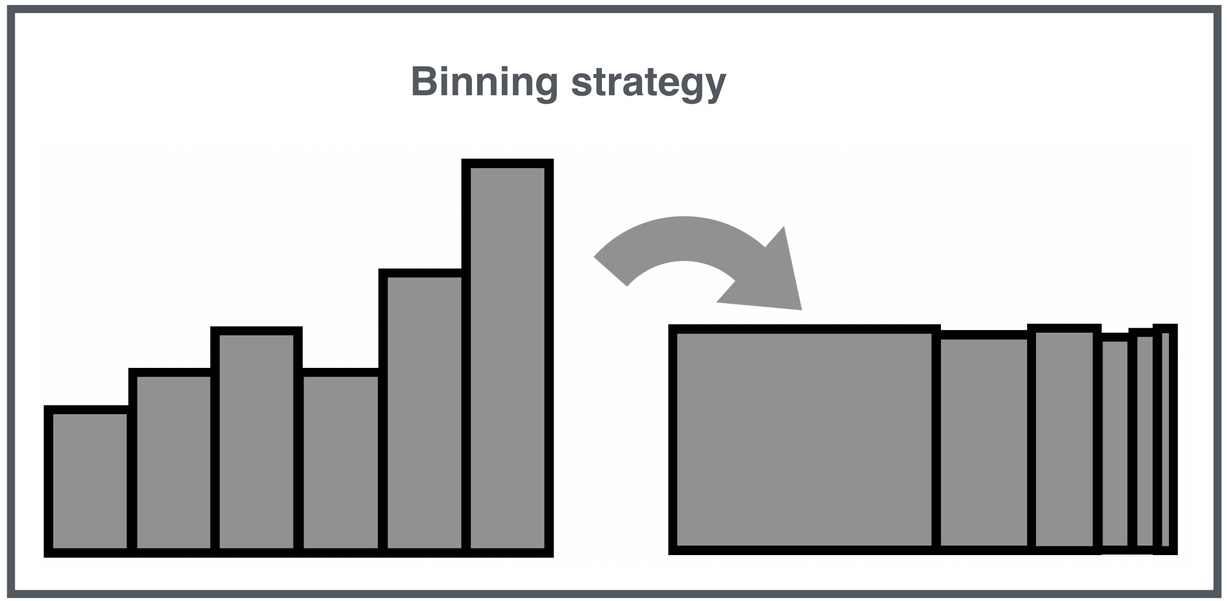
Partial Unblinding for: $s/\sqrt{b} < 0.004$
Sensitive bins blinded





Binning strategy

- Flat signal (ggF or VBF) in signal regions
- Sufficient background MC statistics
  - At least three effective MC background entries in each bin
- Single bin per control region



Minor binning refinements w.r.t ANv8

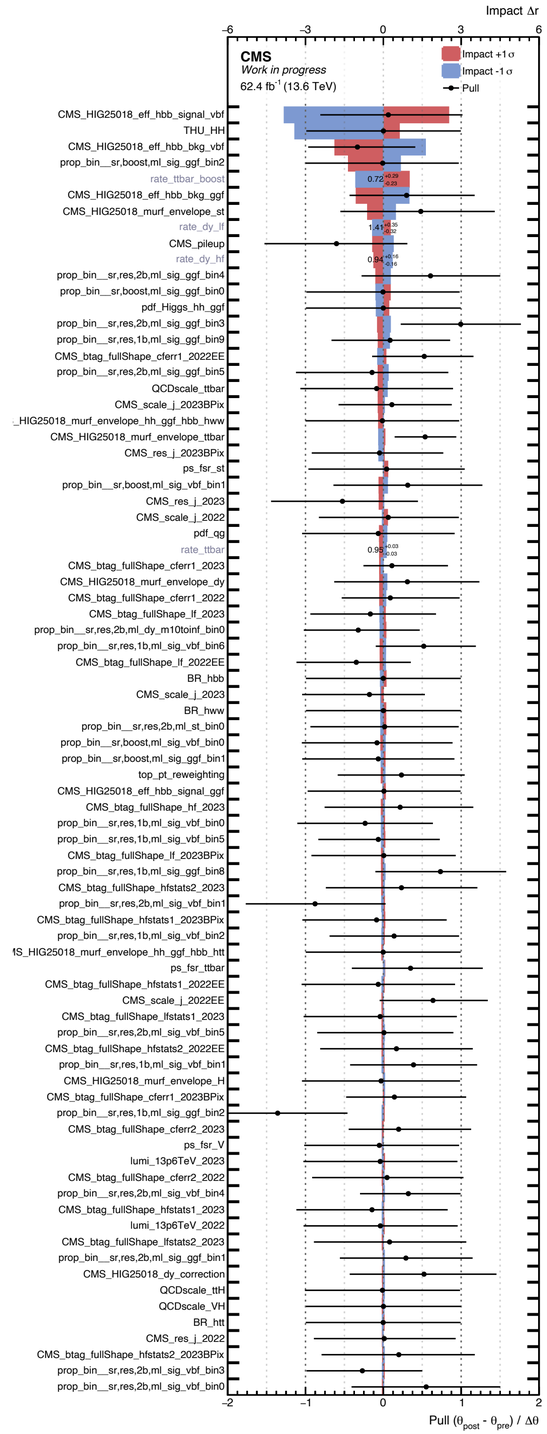
- Fluctuations in minor processes
- No significant degradation of sensitivity in Asimov fits

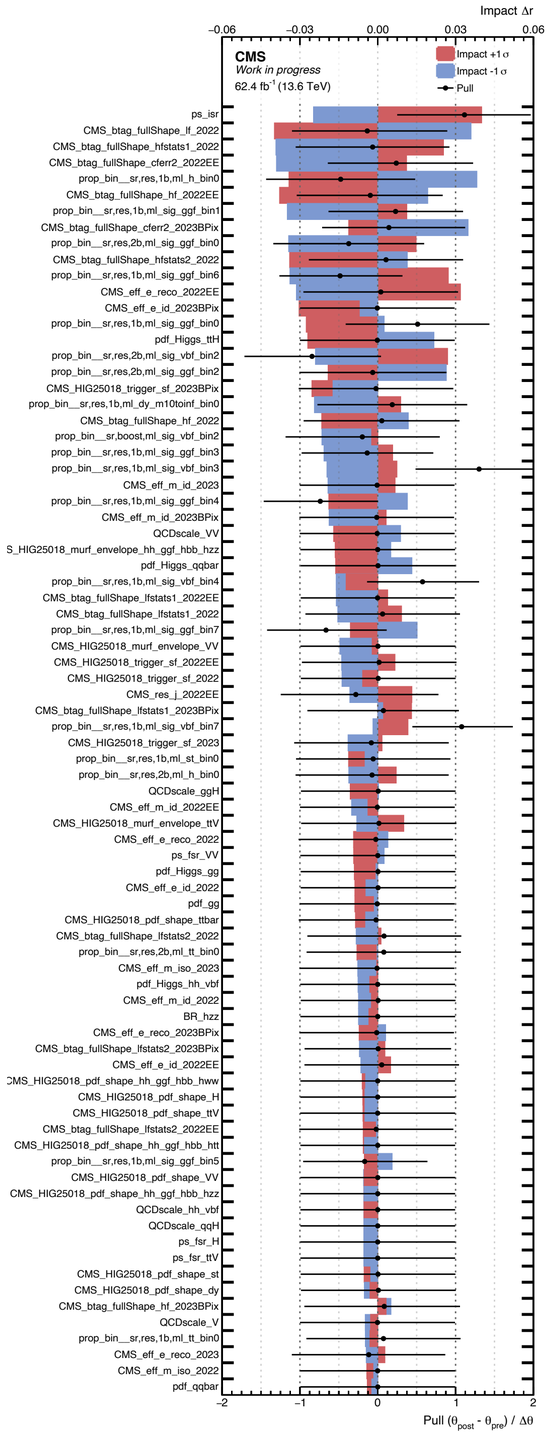
Changed w.r.t ANv8: slight binning adjustment

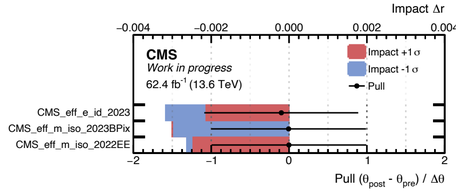
	1b	≥2b	boosted
SR_{ggF}	10	6	3
SR_{VBF}	8	6	3
$t\bar{t}$	1	1	—
single-t	1	1	—
DY	1	1	—
single-H	1	1	—

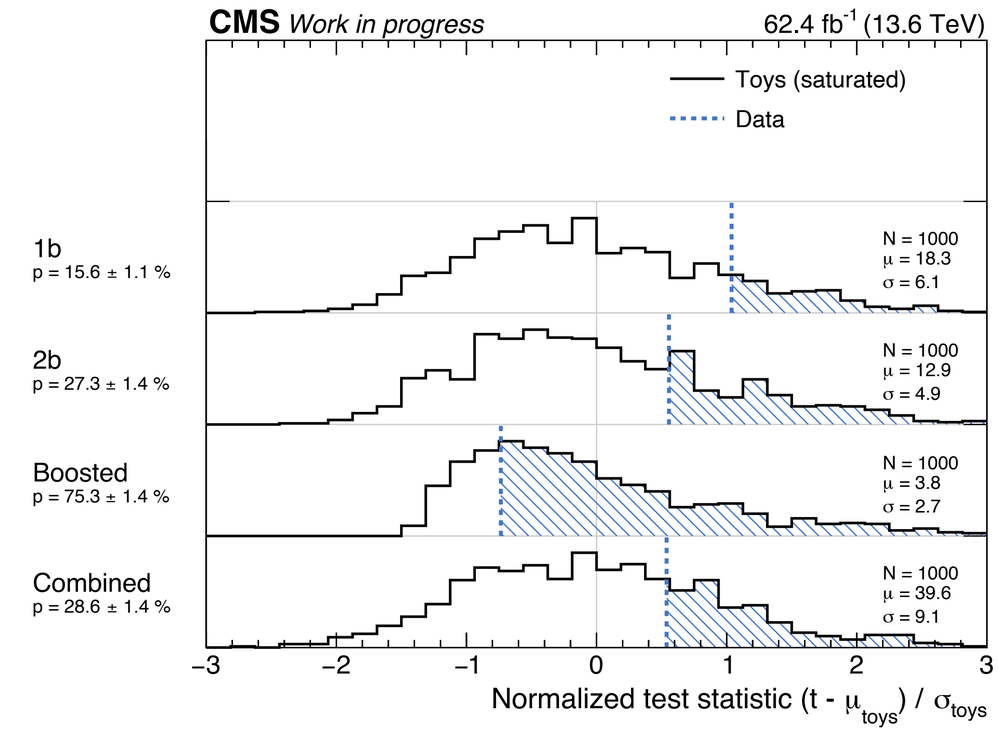
Unblinded Pulls & Impacts + Goodness of Fit

QU Report
Lara Markus









Unblinded prefit & postfit distributions (background-only fit)

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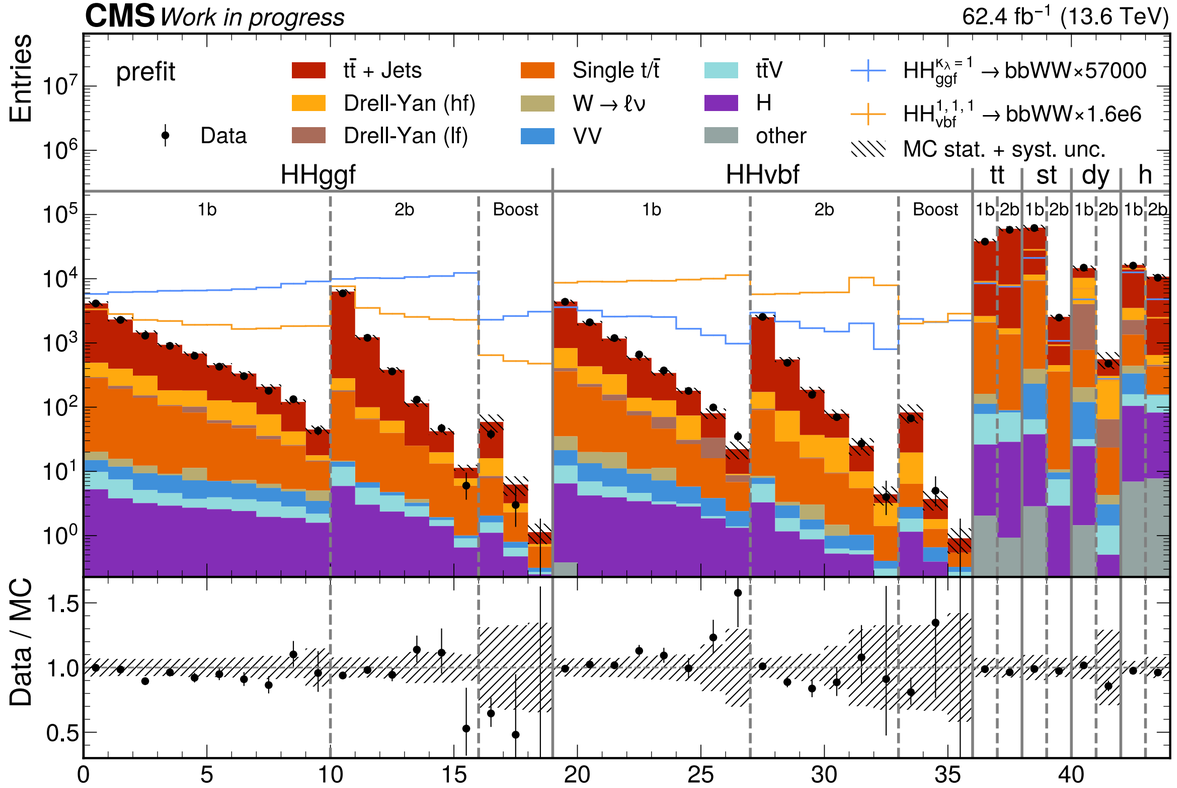
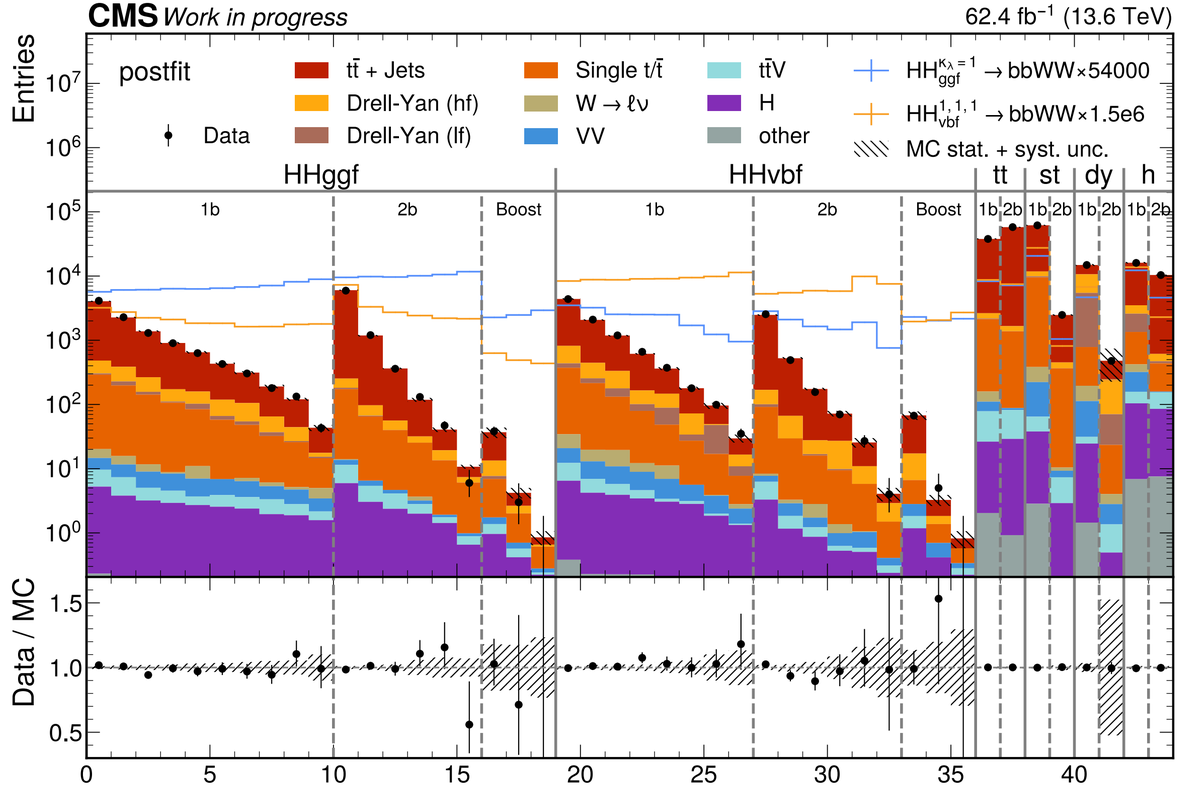
Lara Markus

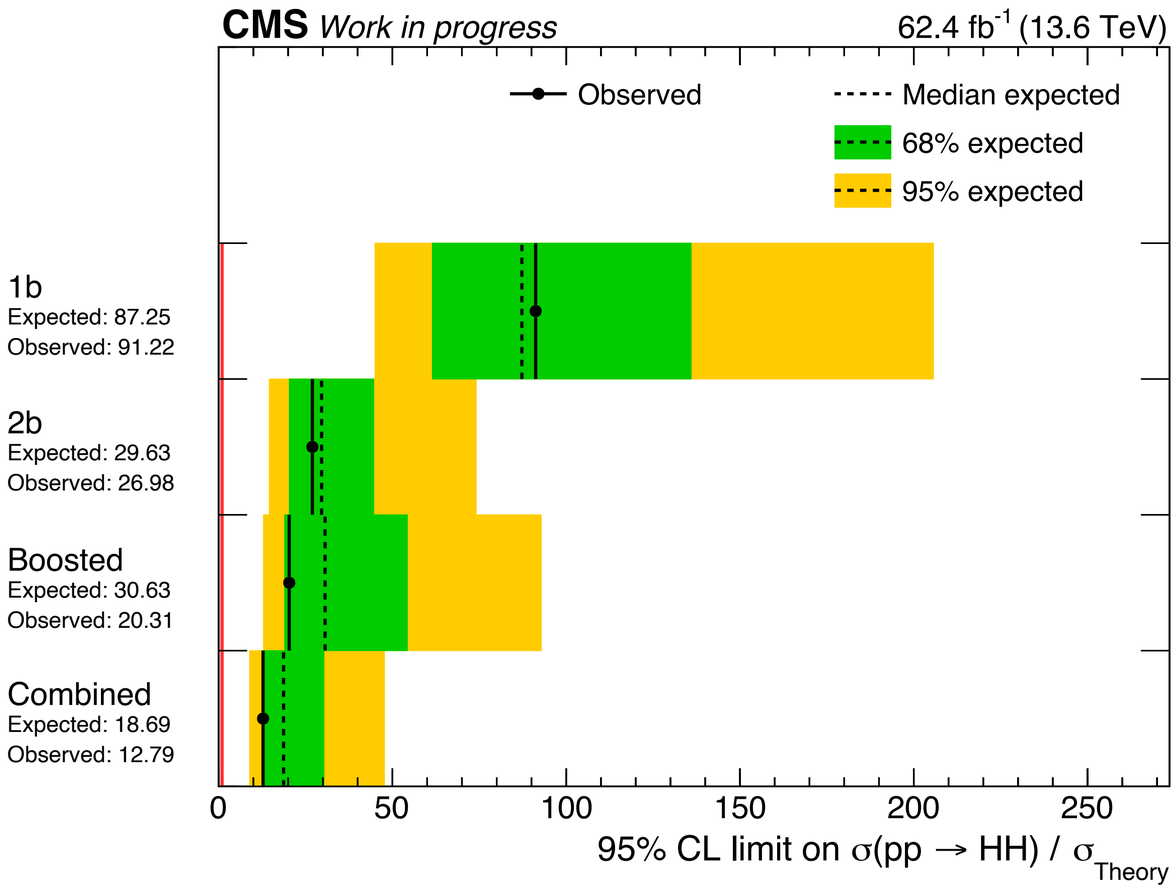


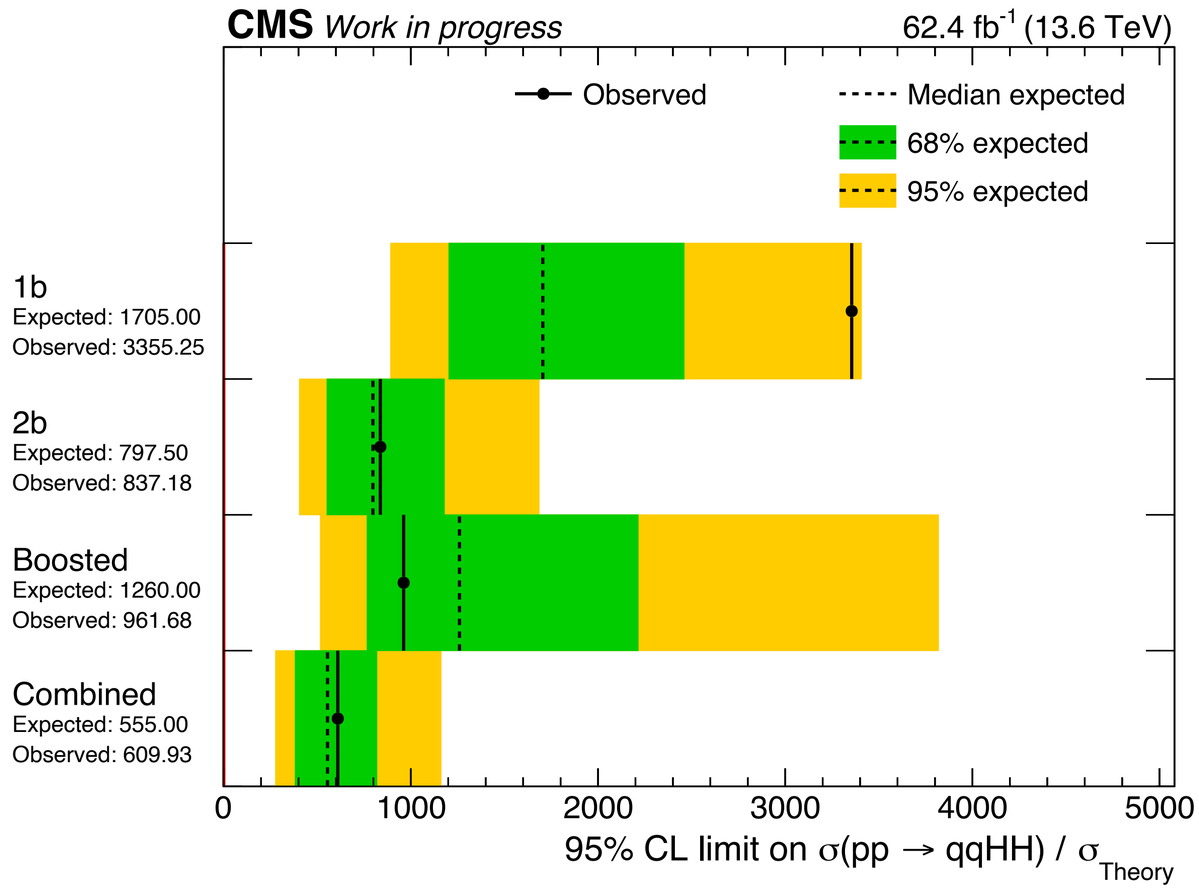


The fit is performed under the background only hypothesis.
The left plot shows prefit distributions, while the right one shows postfit distributions.
Signal is shown with prefit normalization corresponding to the SM expected cross section in both plots.

SM exclusion limits

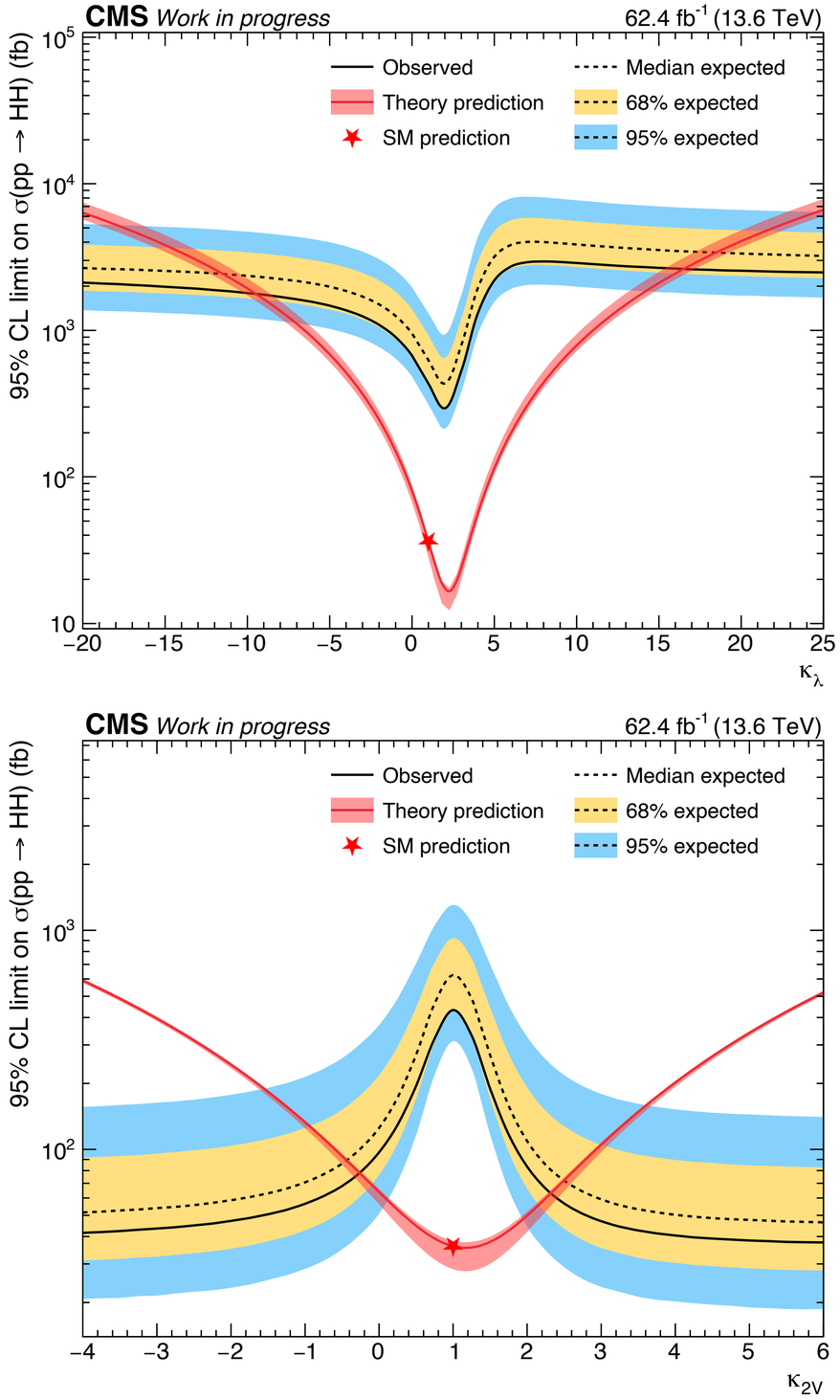
QU Report
Lara Markus



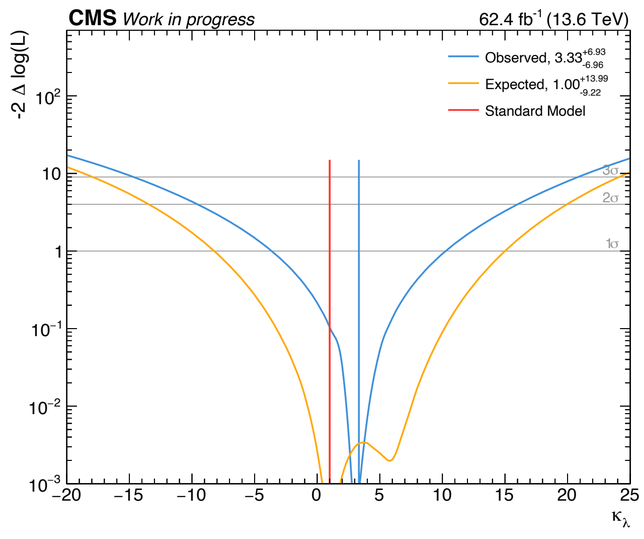


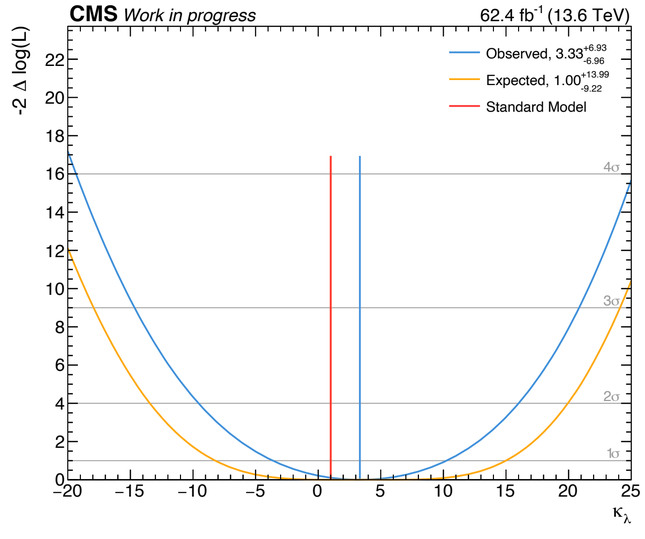
κ_λ and κ_{2V} scans

QU Report
Lara Markus

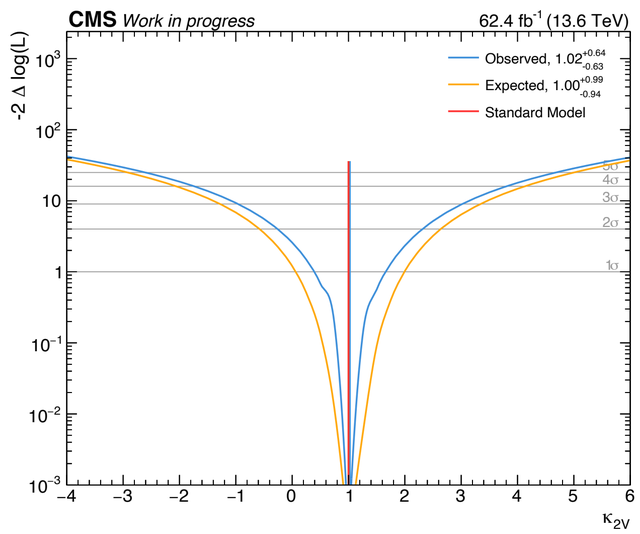


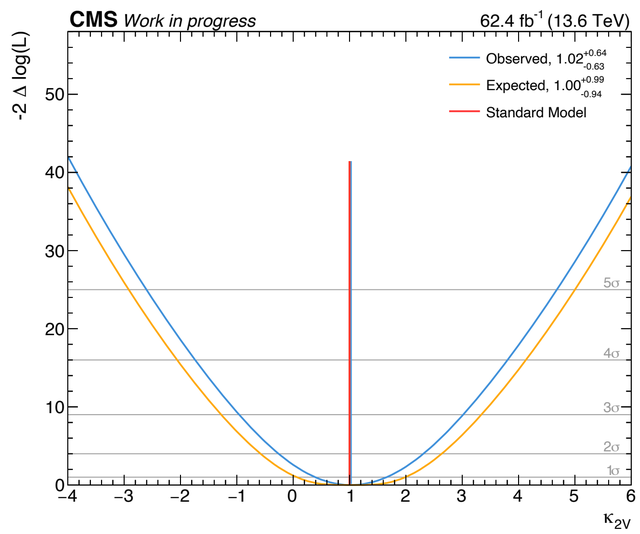
κ_λ Exclusion ranges:
observed: $-9.4 < \kappa_\lambda < 15.9$
expected: $-13.2 < \kappa_\lambda < 19.8$





κ_{2V} Exclusion ranges:
observed: $-0.26 < \kappa_{2V} < 2.31$
expected: $-0.58 < \kappa_{2V} < 2.64$





Details on HHH → 2b4V analysis

Run-3 search for non-resonant HHH → 4b2V

QU Report
Lara Markus

Team:

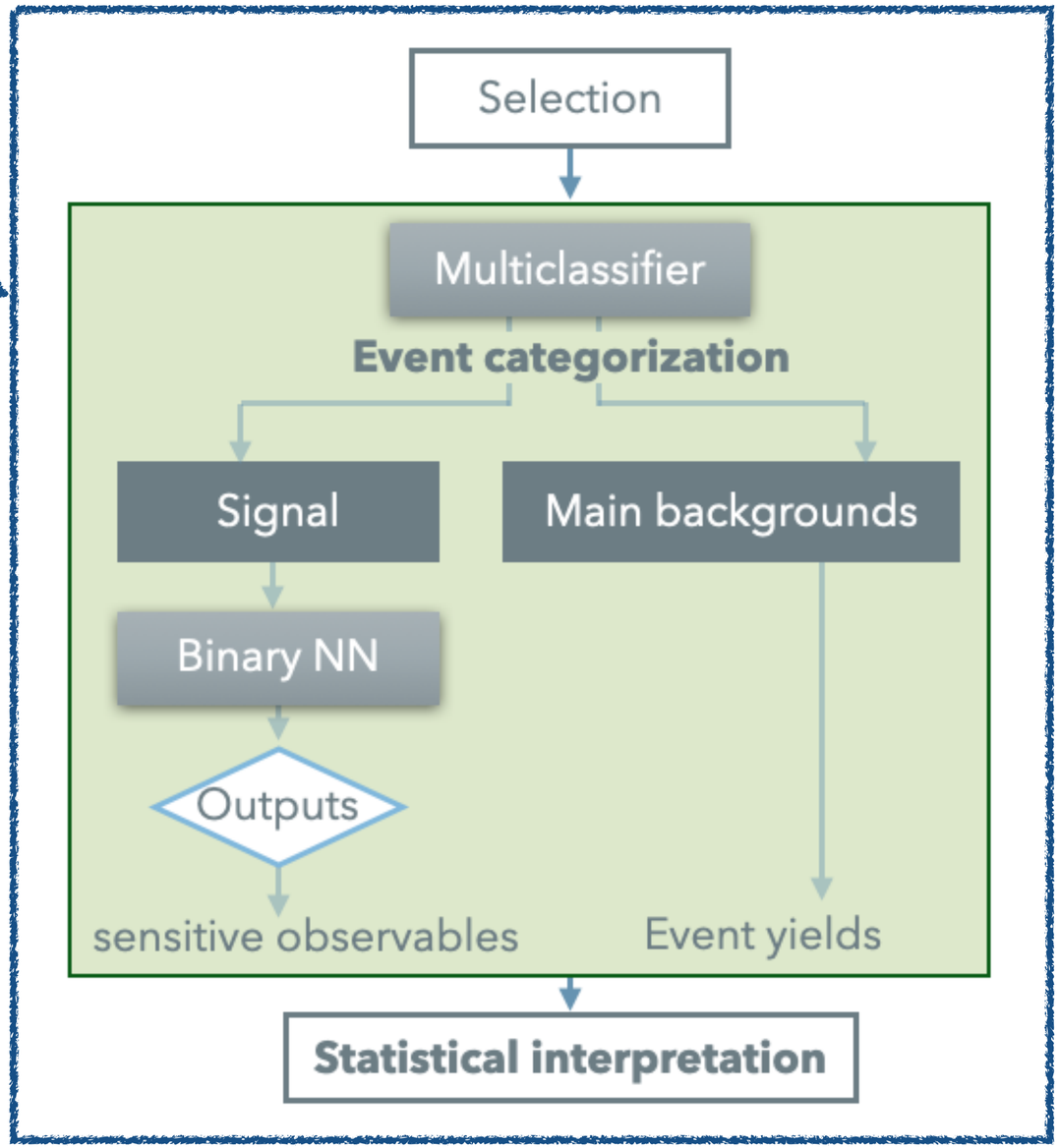
- Matteo Bonanomi (*Staff*), Lara Markus (*PhD*) , Parth Patil (*M. Sc.*), Matthias Schröder (*Staff*) & Emre Toka (*M.Sc.*)
- Collaboration with Alexandra Carvalho (*Postdoc*), Chen Zhou (G*roup leader*) & Xiangran Li (*PhD*) (PKU)

Plans targeting HHH → 4b2V:

- Use expertise gathered from HH → bbWW (DL) (preapproval)
  - Adopt analysis strategy from HH
  - Fully functional analysis framework column flow
- Additionally accepting full hadronic VV states
  - Using gloParT on object classification
  - Veto on 6b and 4b2τ

Timeline:

- Focus on HH analysis for now; start HHH towards next year
  - Explore more advanced strategies (NN)
  - Bkg modelling e.g. ttbb,
    use bkg modeling based on 4b reconstructed H's



Physics coverage - processes and physics

- We want to make a global multi-H approach for the analysis, possibly considering the following:

  - **HHH**
    - **ggHHH:** We will work on fixing the kinematic modelling in κ 2D for SM-like only couplings, while expanding the couplings coverage at least to HEFT – communications with WG4 about SMEFT (but that might be too much)
    - **VBF HHH:** (https://arxiv.org/pdf/1801.10157)
    - **ttHHH:** (new paper coming from Andreas Papafaesnatasiu!) – same EFT couplings probed in ggHHH, but at tree level, so more violent cross section effect
  - **HH**
    - **ggHH:** (**of course!** But now adding kinematics of κ_4 on it along with work ongoing with WG4)
    - **ttHH:** (same objects, also interesting signal)
    - **VHH:** (same objects, also interesting signal)
    - **VVH:** (almost same objects, also interesting signal)
  - We will also keep our eye on the single H – as our sensitivity enhances they become non-negligible!

The work in multi-H signal modelling will be carried following HH meetings, and more details on progress of MC and modelling will follow there, always being advertised here

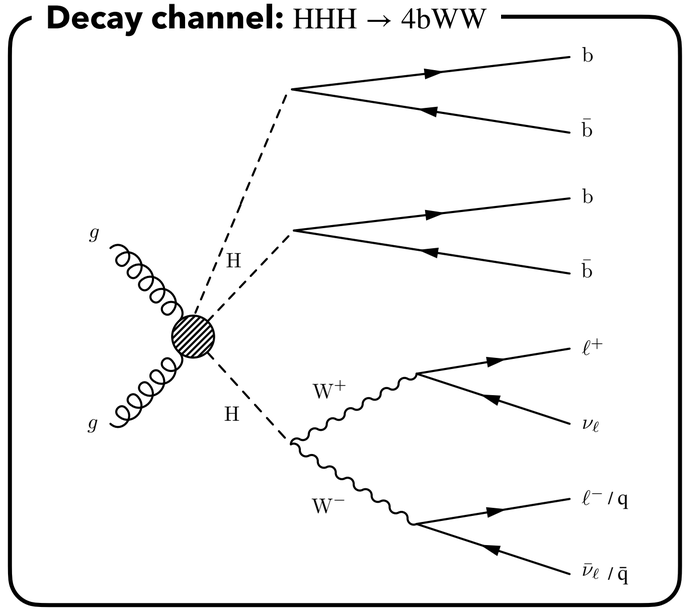
Run-3 search for non-resonant HHH → 4b2V

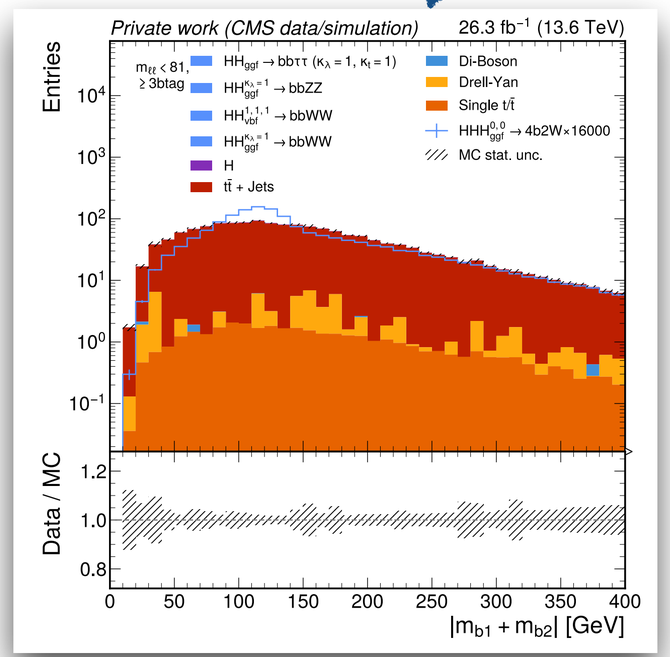
QU Report
Lara Markus

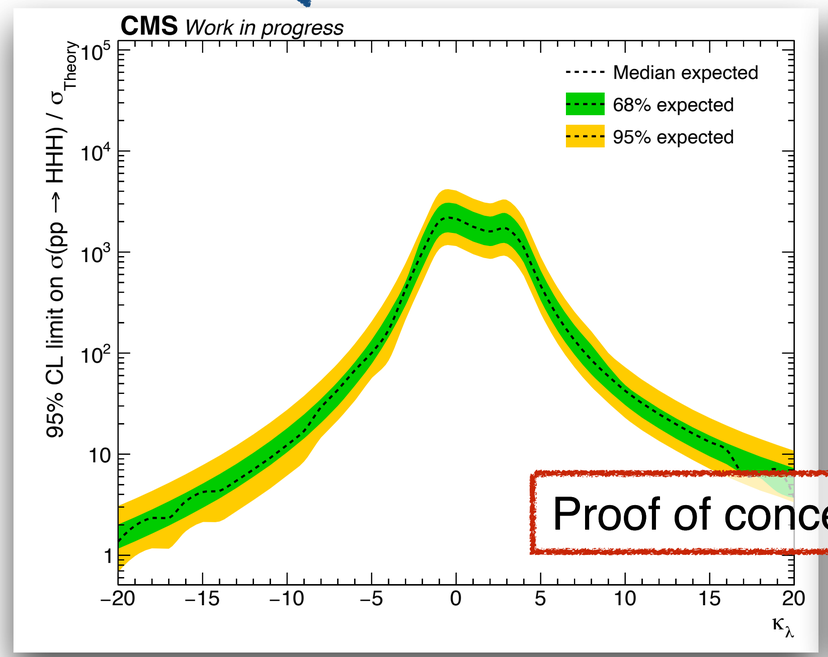
Status today:

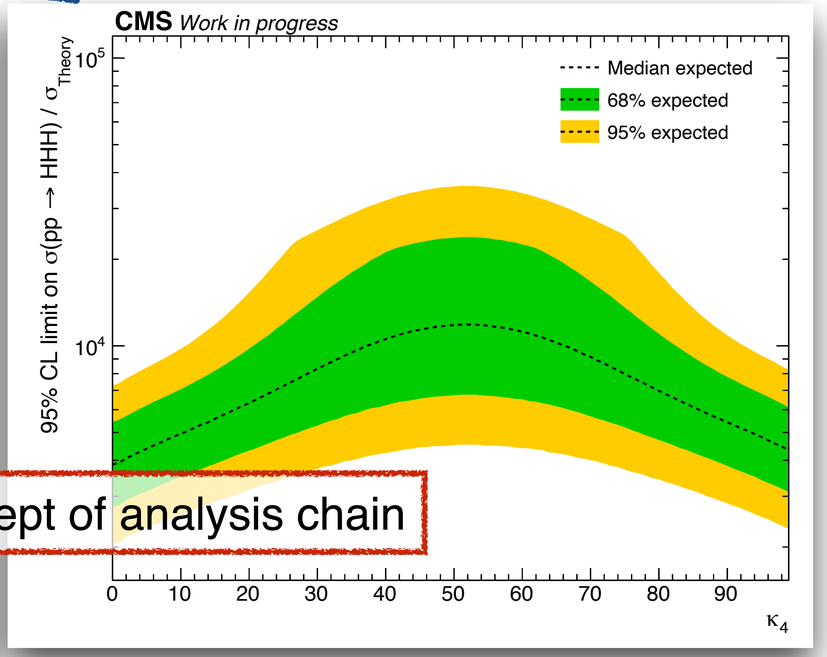
- Signal samples available for 22+23
- Requesting samples for 2024
- Two master theses targeting the HHH → 4b2W doing some first explorative studies
  - HHH → 4b2W single lepton (E.Toka)
  - HHH → 4b2W dilepton (P.Patil)

Decay channel: HHH → 4bWW









Proof of concept of analysis chain