中国科学院高能物理研究所
Institute of High Energy Physics
Chinese Academy of Sciences

# Search for a heavy resonance X→HH→WWγγ at CMS using Run 2 data

**CMS-B2G-24-010**

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**Shaowei Song**
**IHEP(Beijing)**

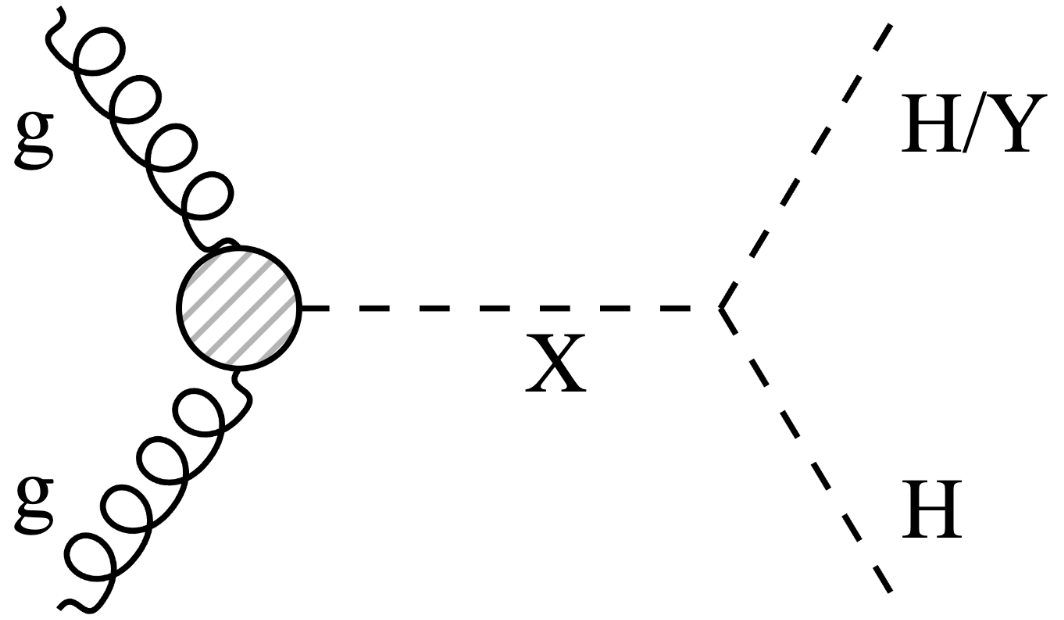

高能物理第十二届全国会员代表大会

主办单位：中国物理学会高能物理分会

# $X \rightarrow HH$ search motivation

Why BSM?

- The SM leaves major open questions:
  - Hierarchy/Naturalness problem: why is the Higgs mass ($m_H$ =125 GeV) stable up to very high scales?
  - Origin of EWSB
  - Dark matter, baryon asymmetry, etc.
- **BSM scenarios predict new Higgs-coupled resonances**
  - Warped Extra Dimensions (**RS1**): Geometric solution to the hierarchy problem, predicts heavy resonances radion(R) and KK graviton(G). **gg → X(R/G) → HH**
  - Extended Higgs Sectors (NMSSM / 2HDM-like): Address Higgs naturalness and SUSY μ-problem. **gg → X → HH/YH** (Y: lighter Higgs boson)



# Introduction of X → HH → WWγγ

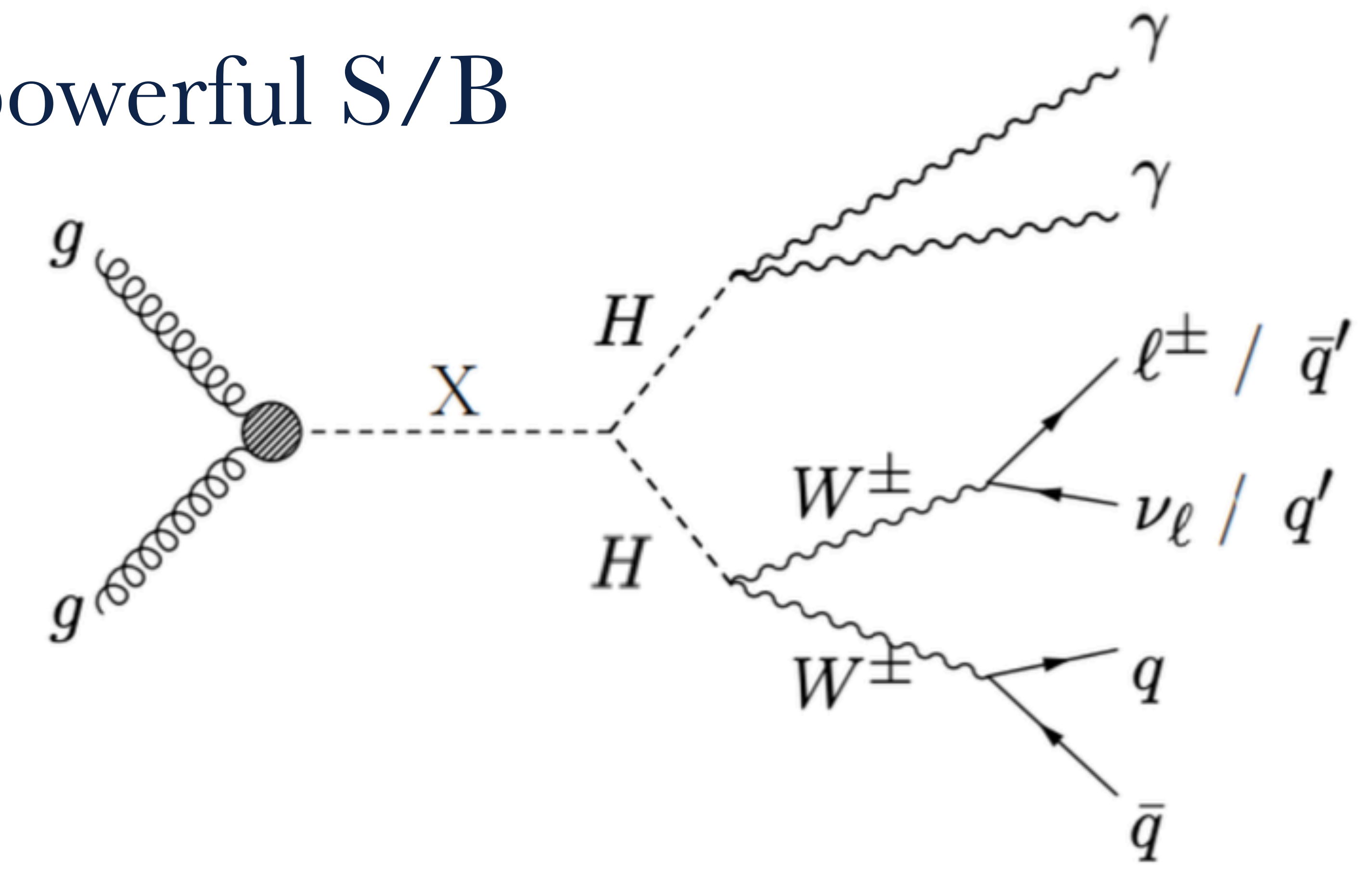
## WWγγ advantage

- H → WW is the second-largest SM Higgs decay mode.
- H → γγ offers a clean final state and excellent mass resolution, providing powerful S/B

## Previous result

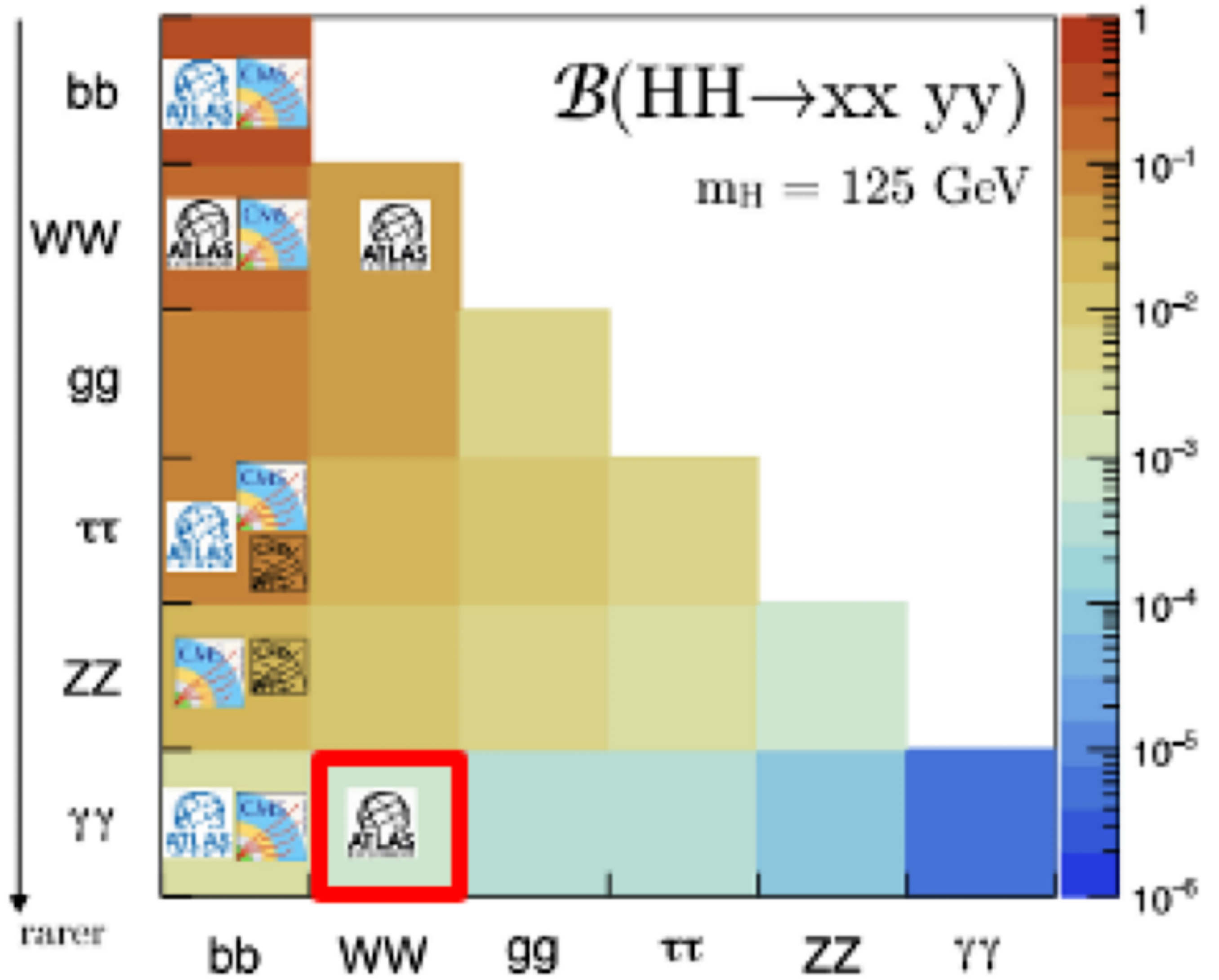
- ATLAS Run 2 (2016 data): X → HH → W(qq)W(lν)γγ [Eur.Phys.J.C]
    - **Semi-leptonic** WW decay **resolved** topology only

## First CMS search for X→HH→WWγγ

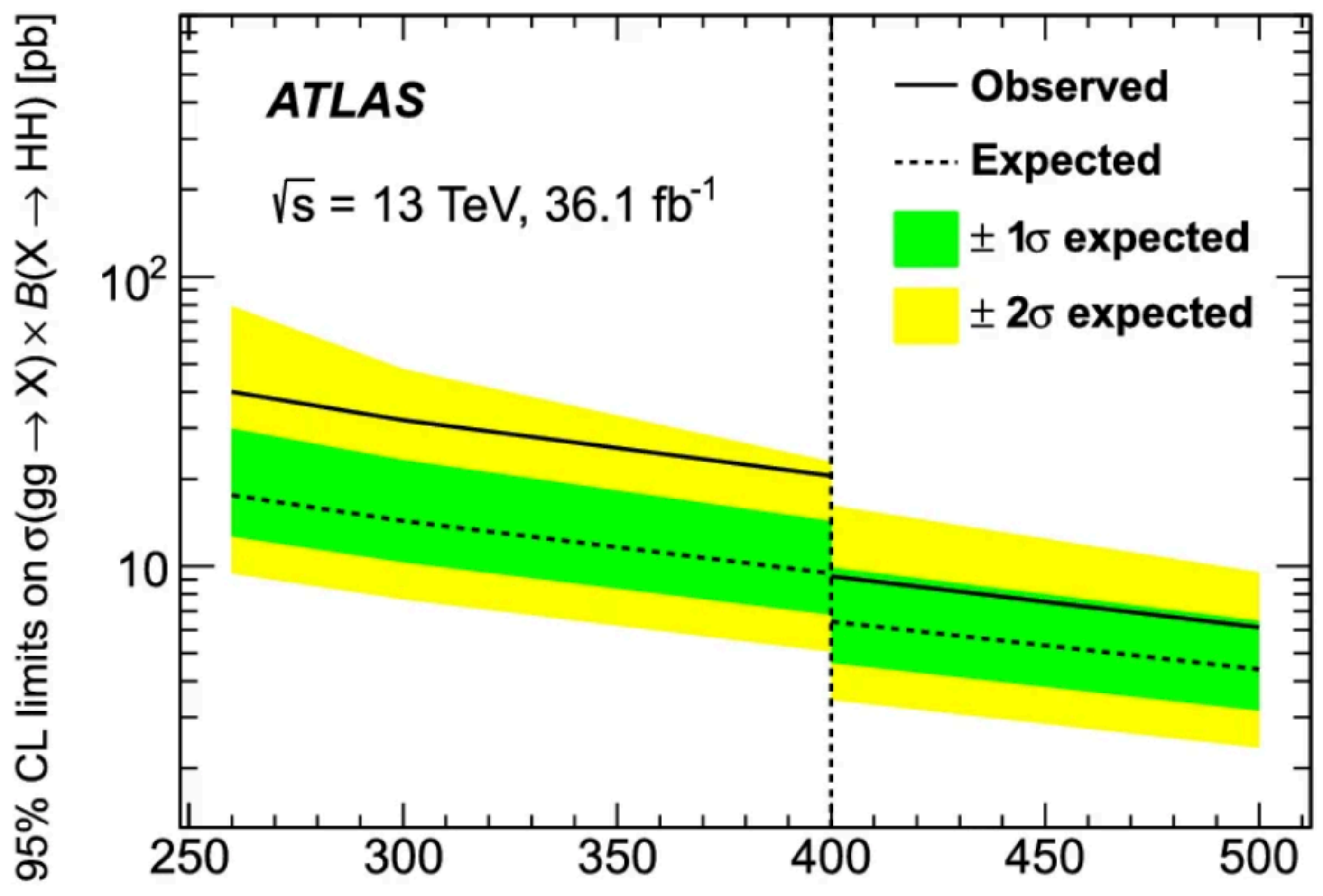



| Decays | h→bb | h→WW | h→ττ | h→ZZ | h→γγ |
|---|---|---|---|---|---|
| h→bb | 34% | | | | |
| h→WW | 25% | 4.6% | | | |
| h→ττ | 7.3% | 2.7% | 0.39% | | |
| h→ZZ | 3.1% | 1.1% | 0.33% | 0.069% | |
| h→γγ | 0.26% | 0.10% | 0.028% | 0.012% | 0.0005% |

Br(HH->xxyy)




Previously studied decay channels in Run2




[Eur.Phys.J.C]

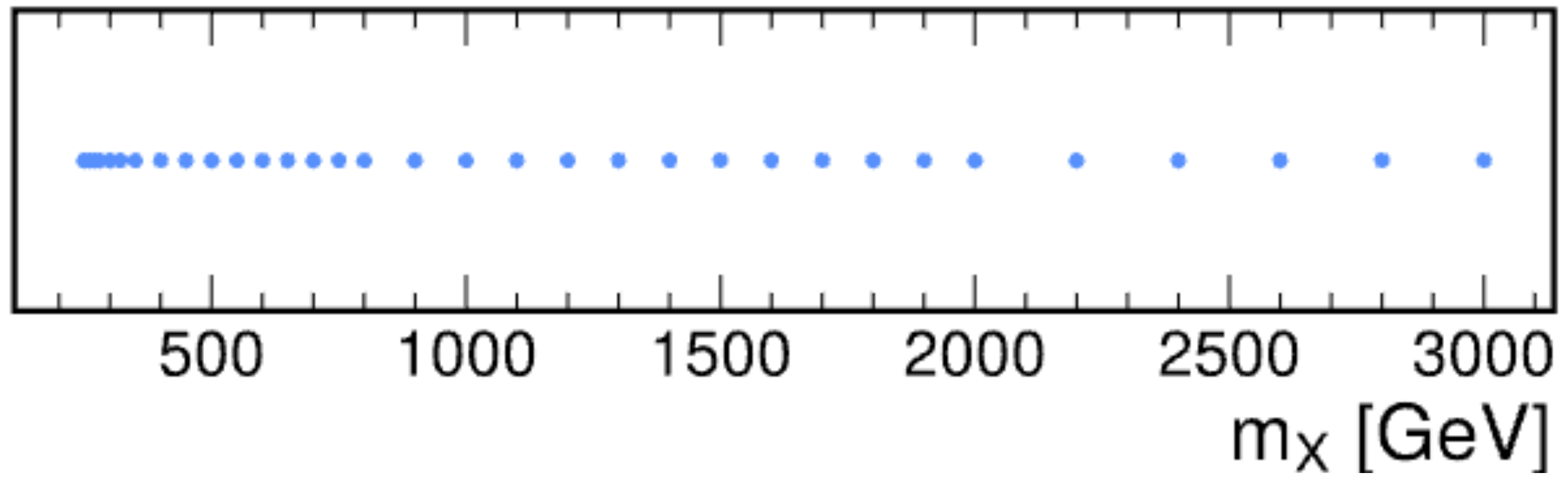
# Signal and background

**Data:** 2016 – 2018 data with 138 $fb^{-1}$ integral luminosity

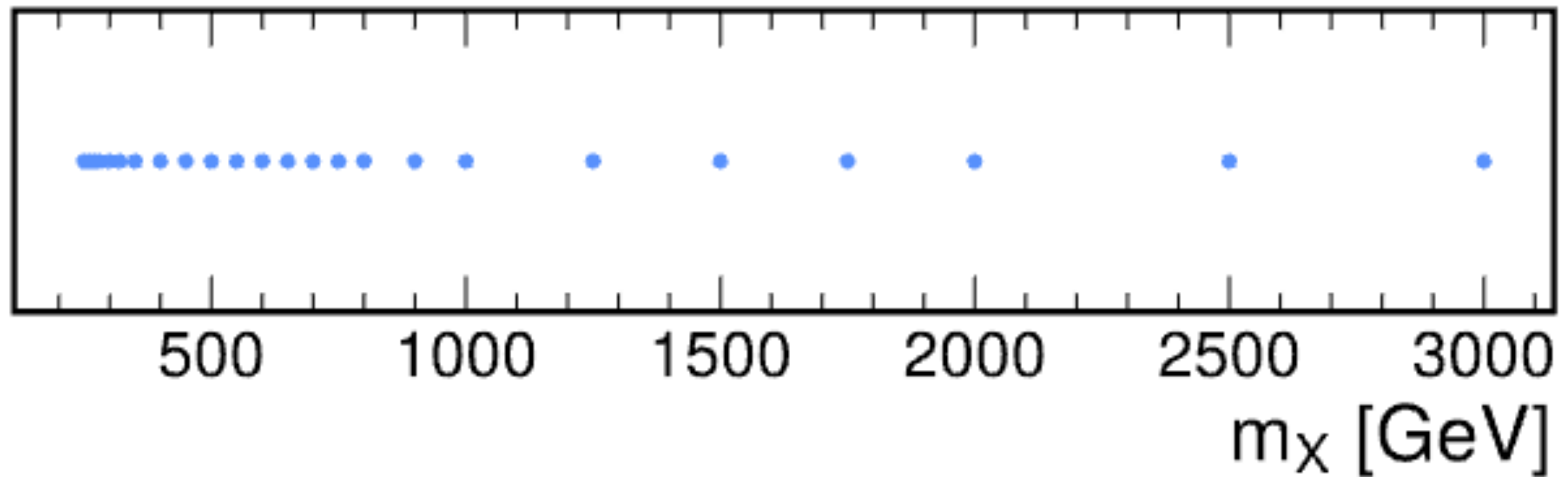
**Signal:** $X \rightarrow HH \rightarrow$ **W(qq)W(qq/lν)**$\gamma\gamma$

- RS radion (J=0) and KK graviton (J=2), $250 \leq m_X \leq 3000$ GeV

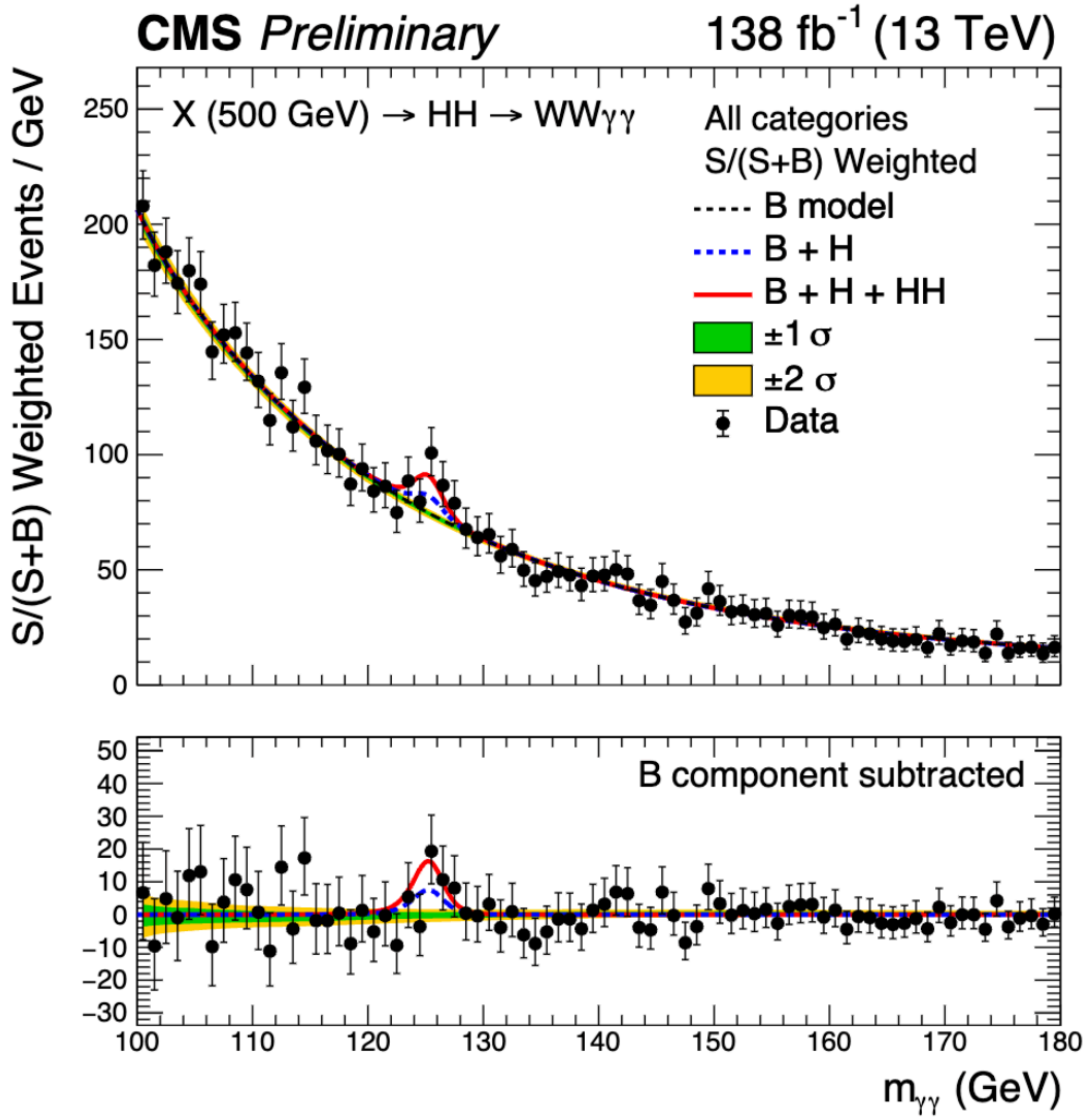
**Extended mX search range(500 GeV → 3 TeV)**




Mass points generated for the radion samples




Mass points generated for the graviton samples



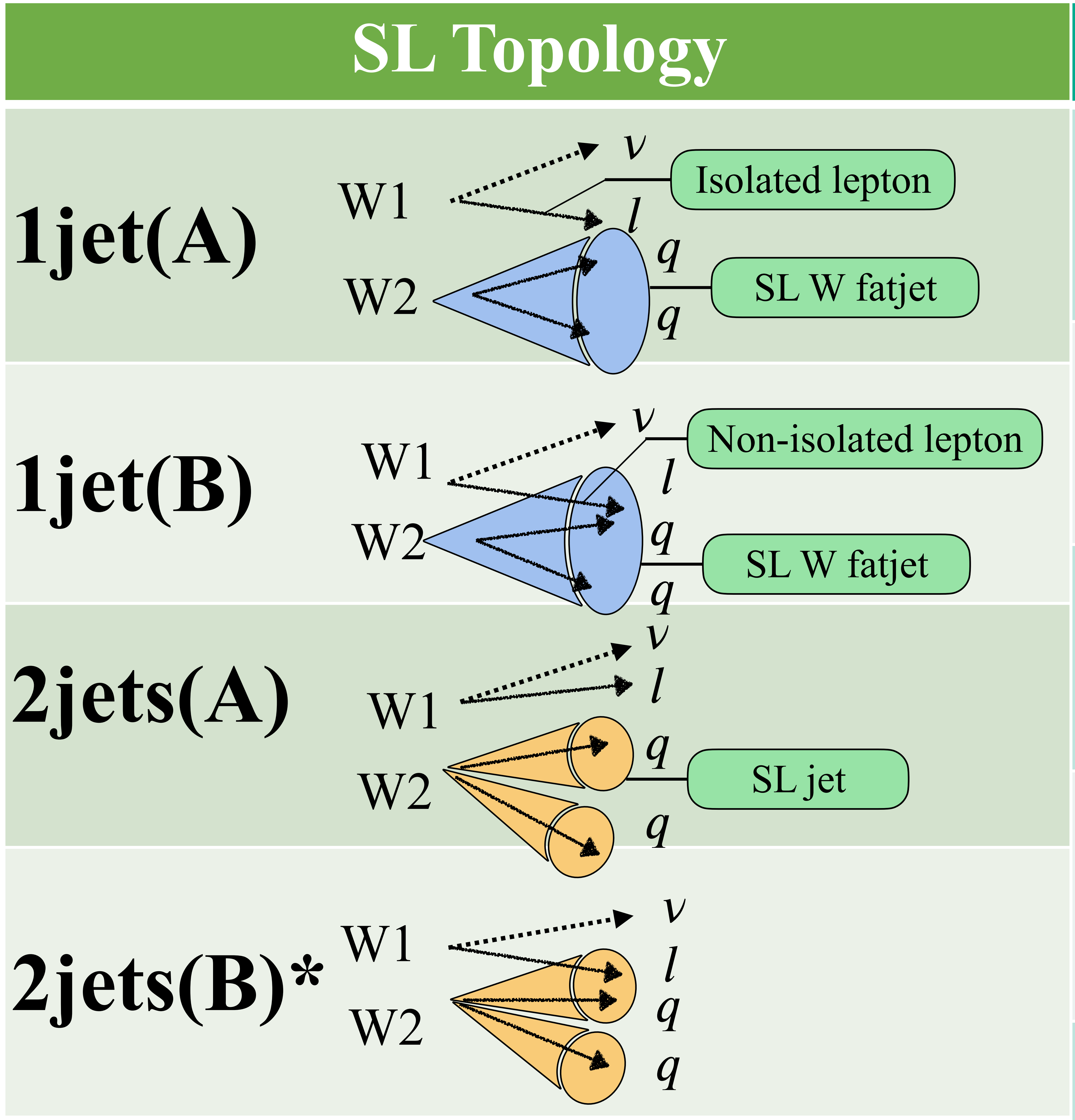

Signal + background models
[CMS-PAS-B2G-24-010]

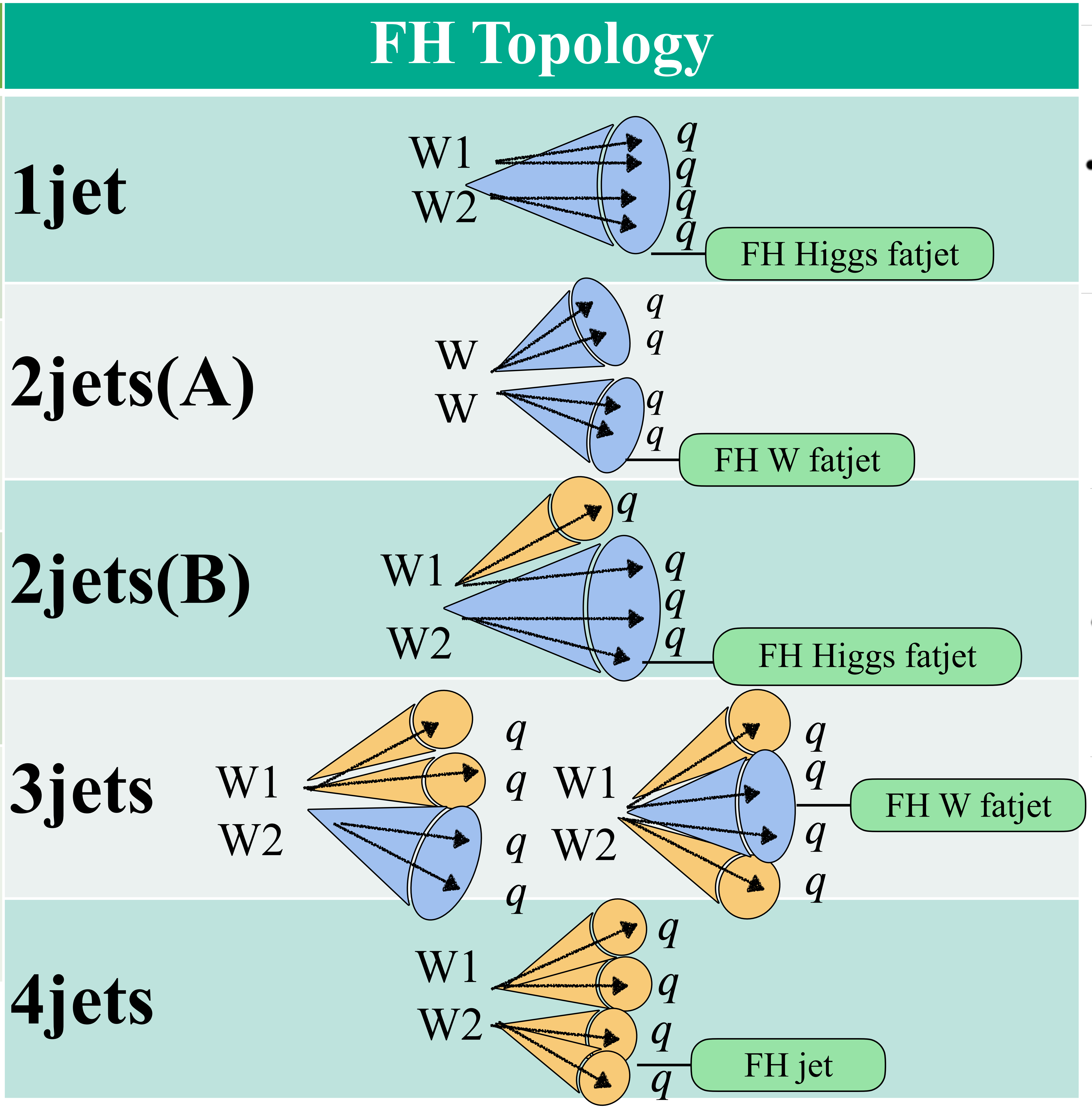
## Background

- **Resonant background:** SM single-Higgs production mechanisms (ggH, VBF, VH, ttH) with $H \rightarrow \gamma\gamma$
- **Continuum background:** SM non-resonant processes (prompt diphoton, real $\gamma$ + jet, and QCD multijet events where jets are misidentified as photons).

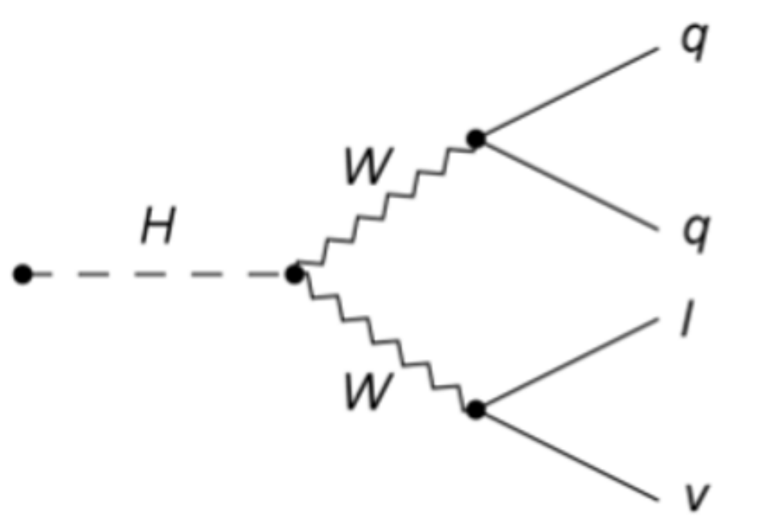
# Signal topologies

Tag all possible topologies of WW semi-leptonic (SL) and fully hadronic (FH) decay

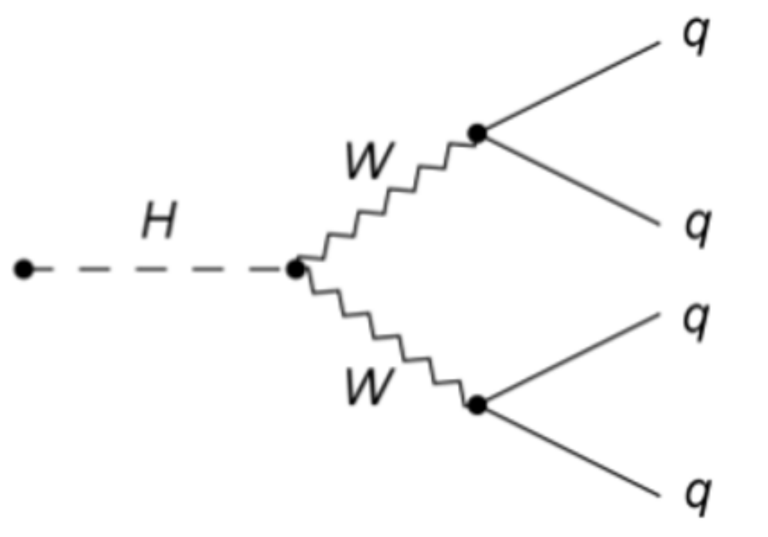



*Not include in final result due to low sensitivity




(a) Semi-Leptonic




(b) Fully-Hadronic

# Analysis strategy

## Event Preselection

- Adopt the standard CMS $H \rightarrow \gamma\gamma$ diphoton triggers and photon selection criteria
- Apply dedicated WW event selection requirements

## Neural Network Training

- A Parameterized Neural Network (PNN) is trained to perform event-level signal–background discrimination.

## Event categorization

- Events are classified using Bayesian optimization based on PNN scores.

## Signal & Background Modeling

- **Signal:** Extracted by fitting the diphoton invariant mass ($m_{\gamma\gamma}$ spectrum) from signal MC events.
- **Continuum background:** Modeled using the *discrete profiling method* fitted to the $m_{\gamma\gamma}$ spectrum in data sidebands (100–115 GeV and 135–180 GeV).
- **Resonant background**: Single-Higgs backgrounds, treated with the same fitting procedure as the signal.

## Statistical analysis

- Extract upper limits on $\sigma(X \rightarrow HH)$ using the diphoton invariant mass.

# Event preselection

**Photon**

- CMS Standard H→γγ preselection
- Photon ID > -0.7

**Lepton**

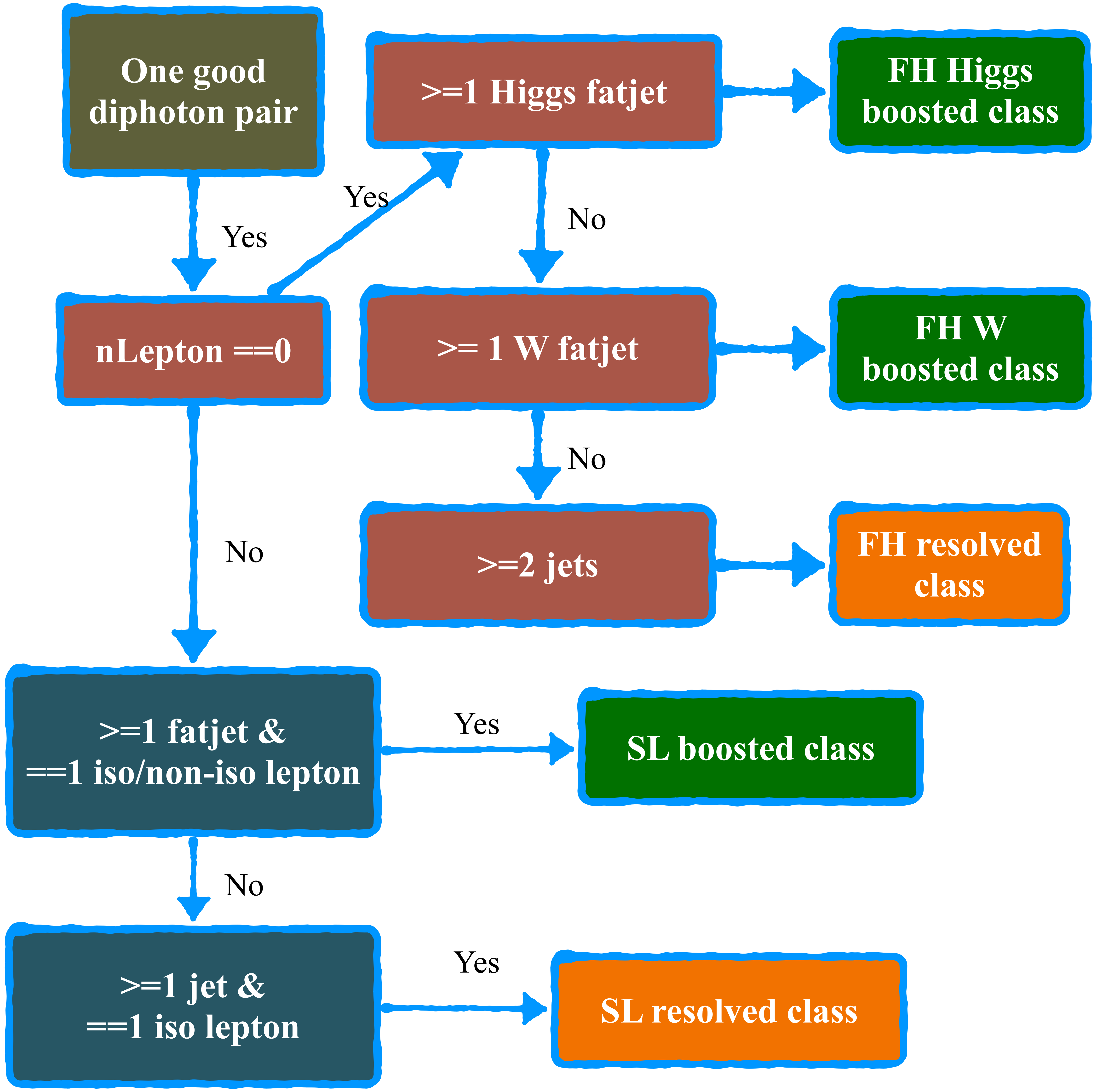
- Basic kinematic and quality requirements ( |$\eta$|, impact parameters)
- Separation from photons ($\Delta R$ cut)
- Z-boson veto (electron only)
- Isolated requirement, well separated from fatjets
- Non-isolated: match to a fatjet ($\Delta R_{l,\ fatjet} < 0.8$)

**Jet**

- Standard tight ID and pileup rejection; basic kinematic requirements; isolated from photons and isolated leptons

**Fatjet**

- High $p_T$, bb fatjet veto
- W fatjets: **ParticleNet** WvsQCD
- Higgs fatjets: **GloParT** Hww



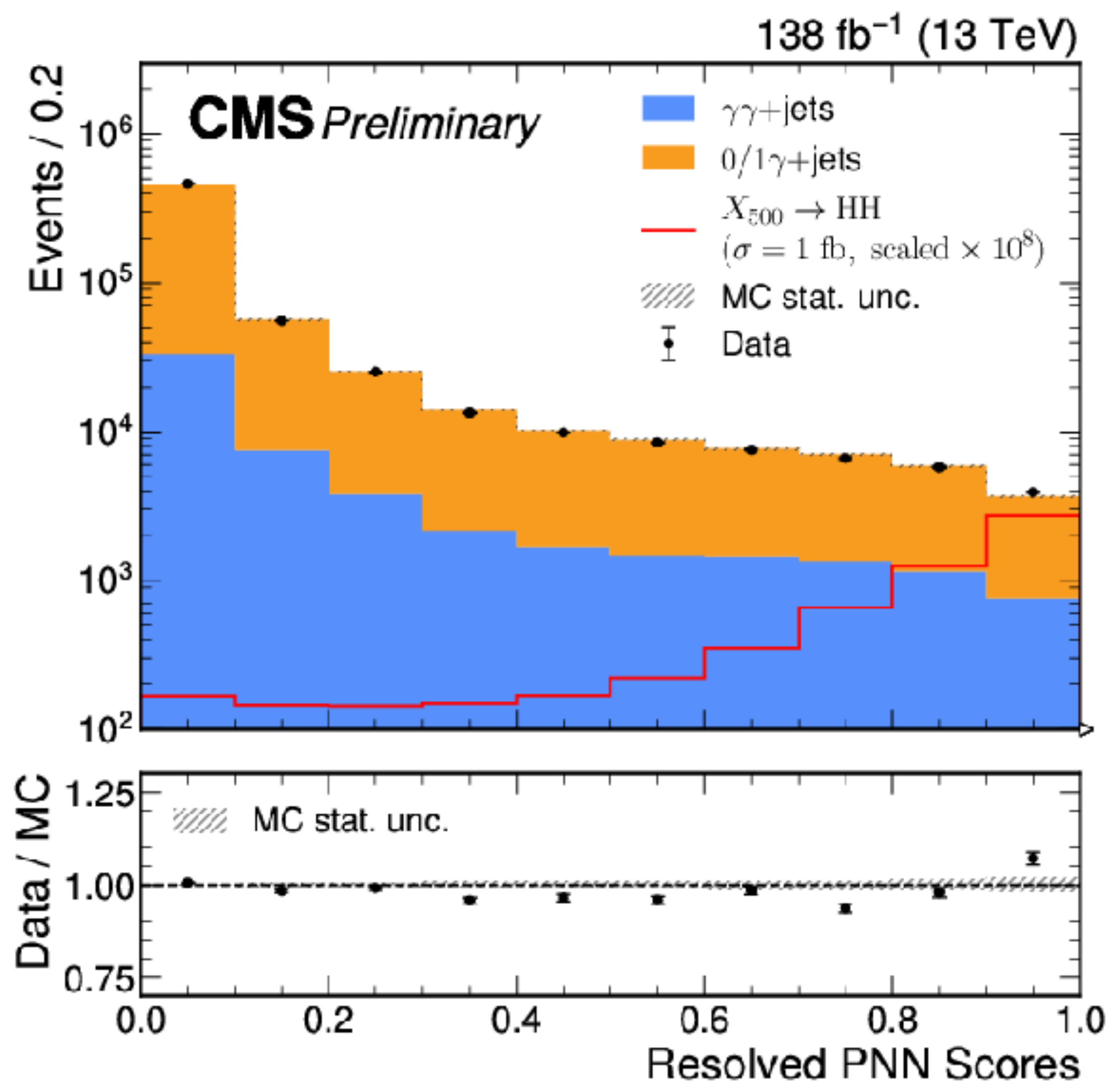
# PNN training

To scan a **continuous range of signal mass hypotheses with a single trained network**, avoiding retraining at each mass point.

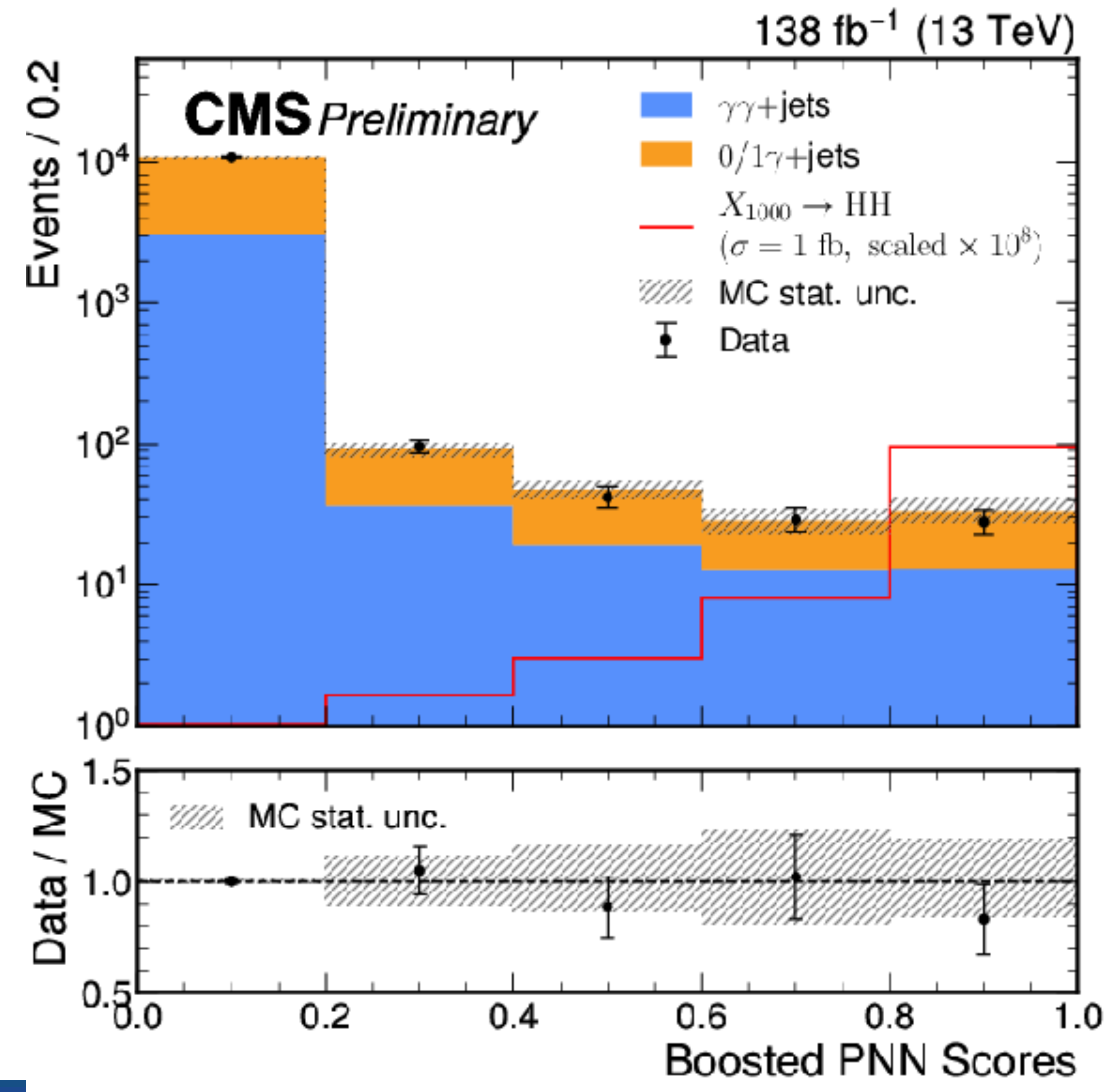
1. Train with $m_X$ as input across all mass points.
2. Duplicate backgrounds for each mass point to remove $m_X$ discrimination.
3. Balance weights: signal across masses, and signal vs. background globally.

- **Resolved training**
  - 5 classes (FH bkg, SL bkg, resonant bbγγ, FH sig, SL sig)
  - Input: Photon, lepton, jet kinematics and multiplicity
- **Boosted training**
  - 5 classes (FH bkg, SL bkg, FH W sig, FH H sig, SL sig)
  - Input: Photon, lepton, jet, fatjet kinematics and multiplicity

**No overtraining, good discriminant power for all signal masses**




[CMS-PAS-B2G-24-010]

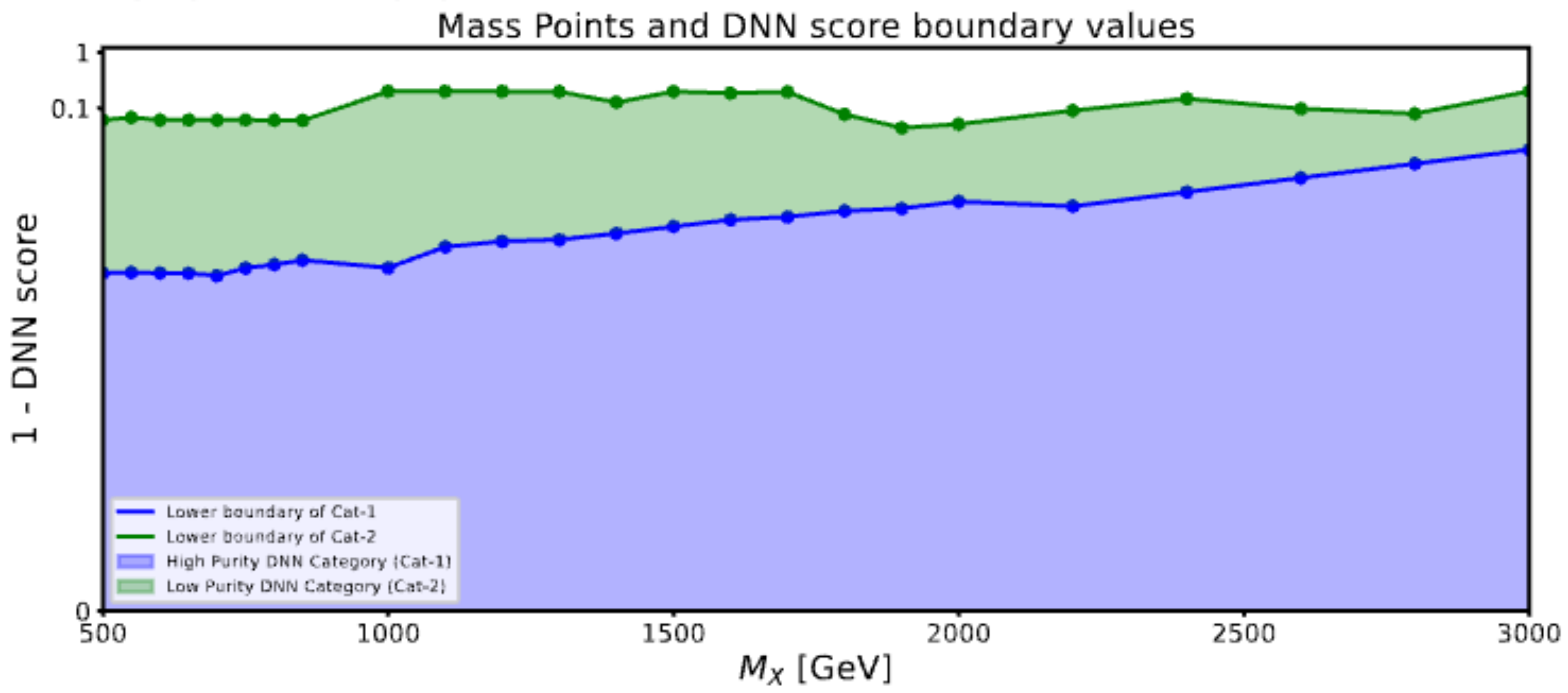



[CMS-PAS-B2G-24-010]

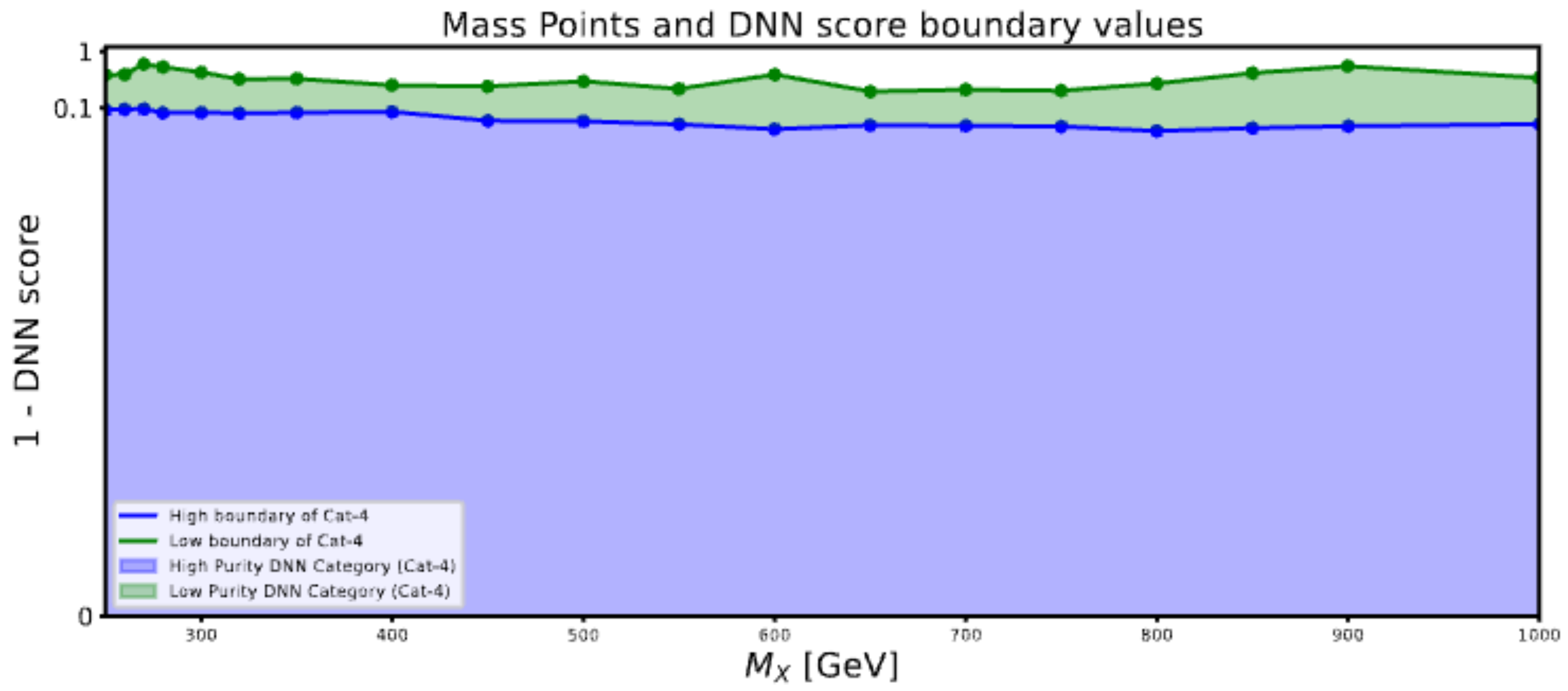
# PNN categorization

## PNN Boundary Optimization (Bayesian)

- **Method**: Bayesian algorithm optimizes PNN score thresholds per mass point to maximize expected significance (1000 iterations).
- **Advantage**: Faster than grid search by leveraging prior knowledge to efficiently sample the parameter space.
- Widely used in HEP (e.g. CMS H→γγ group)
- Outcome:
  - **Resolved (4 cats)**: Orthogonally split by decay topology (FH vs. SL) and PNN score (high vs. low).
  - **Boosted (2 cats)**: Split by PNN score only (high vs. low).




Boosted high/low 1 - PNN boundaries vs mX[CMS-PAS-B2G-24-010]




FH resolved high/low 1 - PNN boundaries vs mX[CMS-PAS-B2G-24-010]

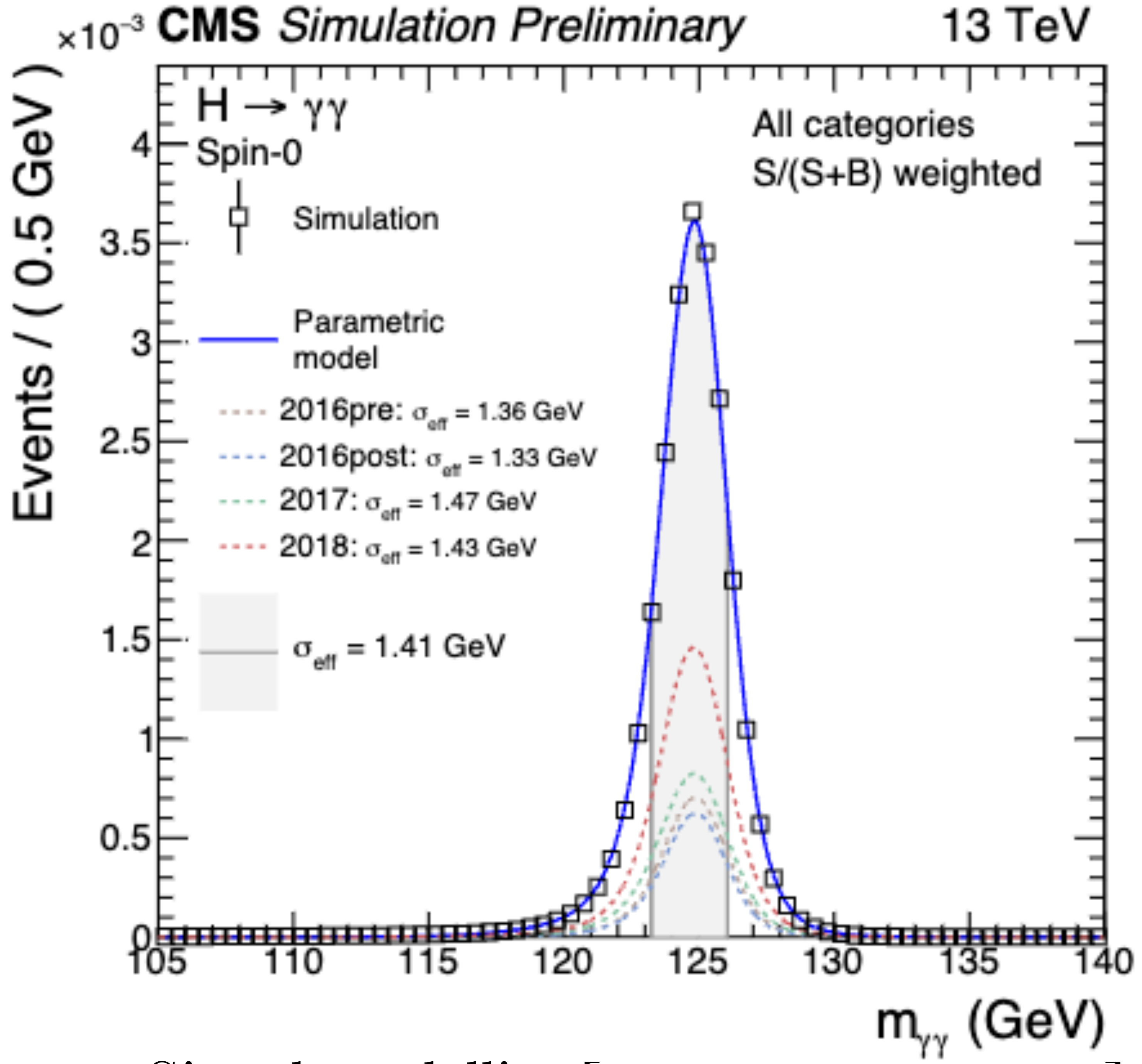
# Signal & background modelling

**Signal model**: Analytic fit to the signal $m_{\gamma\gamma}$ distribution using up to five Gaussian functions.

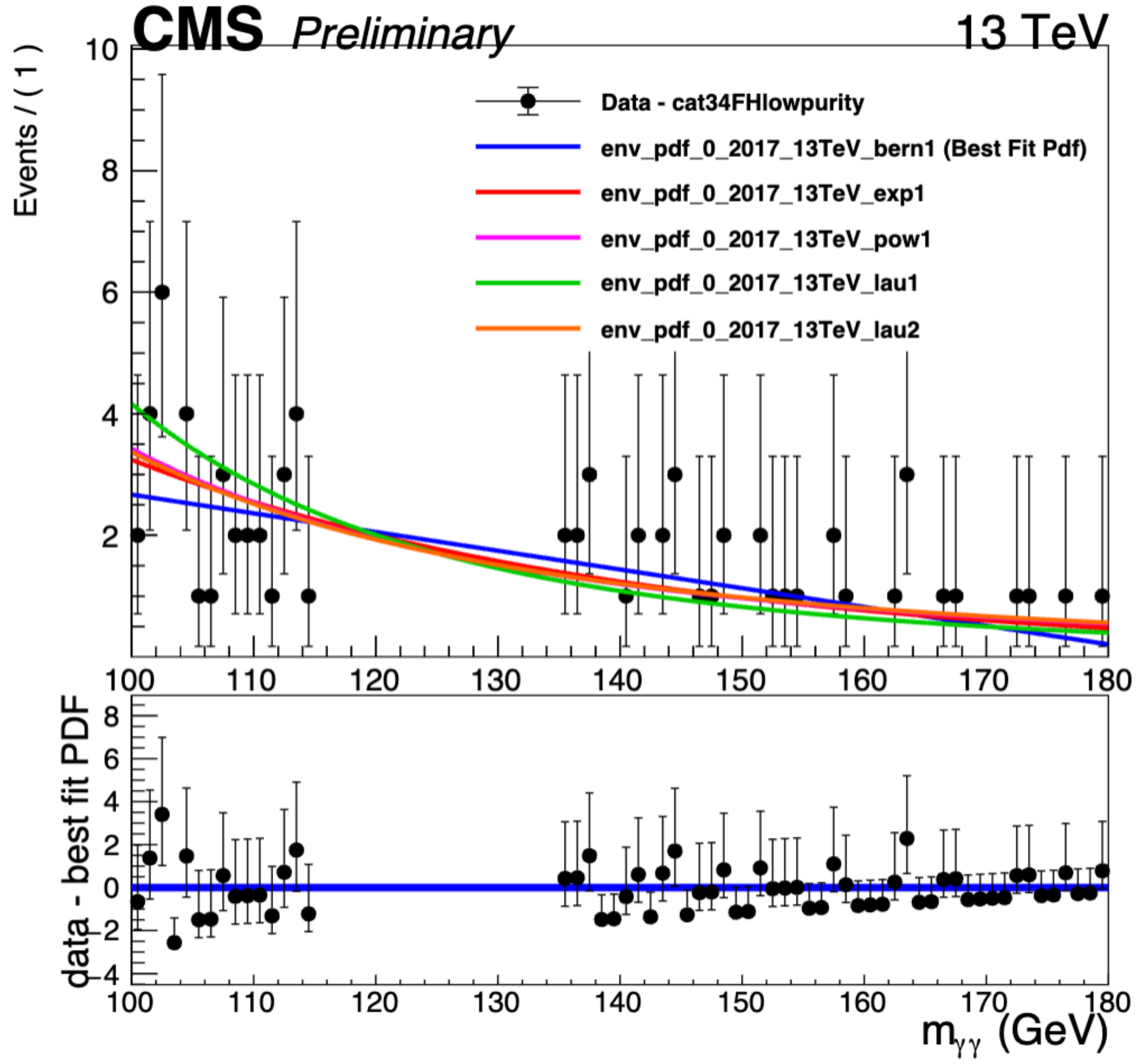
**Continuum background**: Modeled via the discrete profiling method, fitting data sidebands with a set of analytic functions (Bernstein, Laurent, exponential, power law).

**Resonant background**: Single-Higgs processes, modeled with the same fitting strategy as the signal.

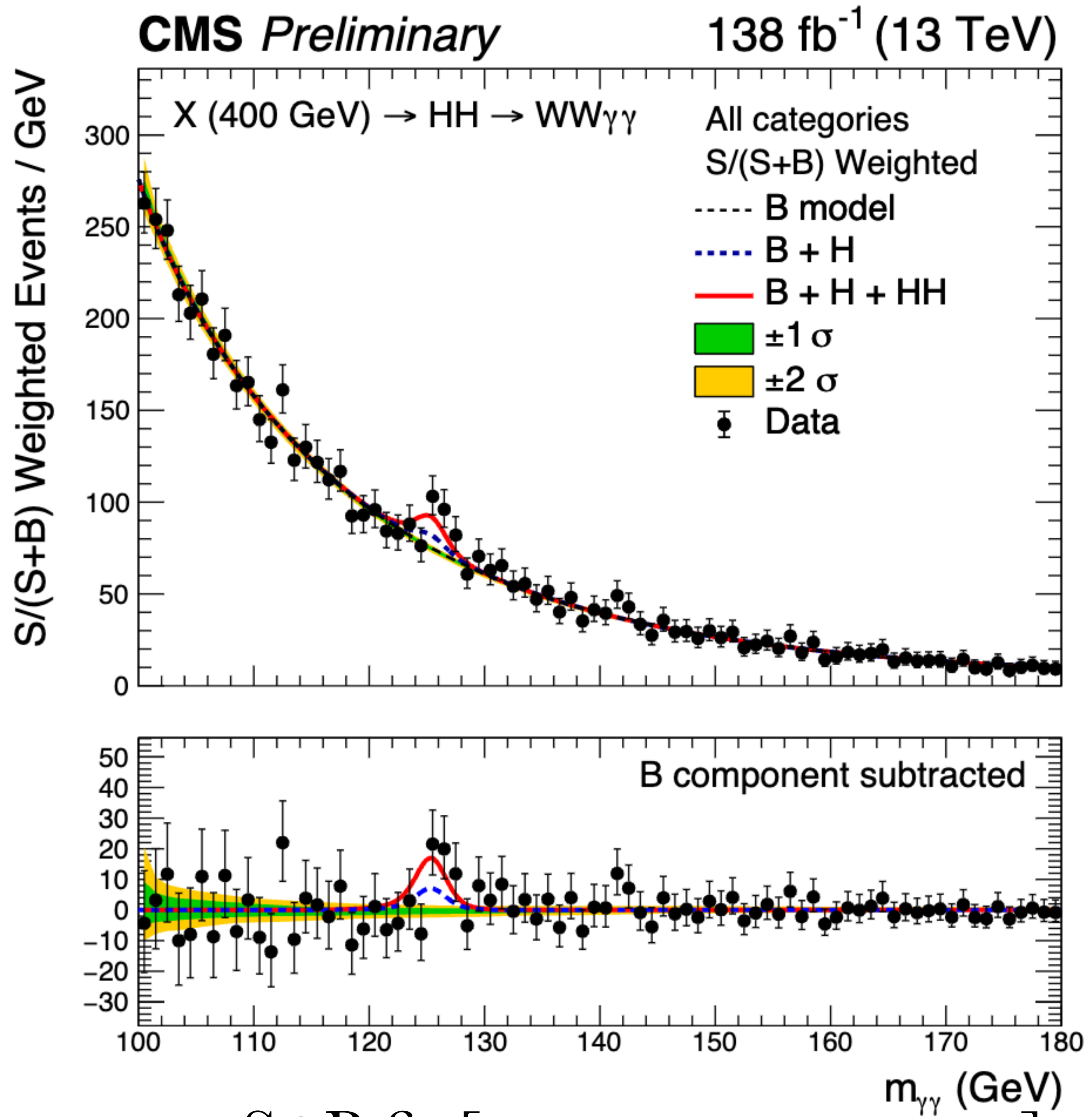
**Final fit**: Simultaneous fit for continuum background + single-Higgs + signal (B+H +HH)




Signal modelling[CMS-PAS-B2G-24-010]




Background modelling



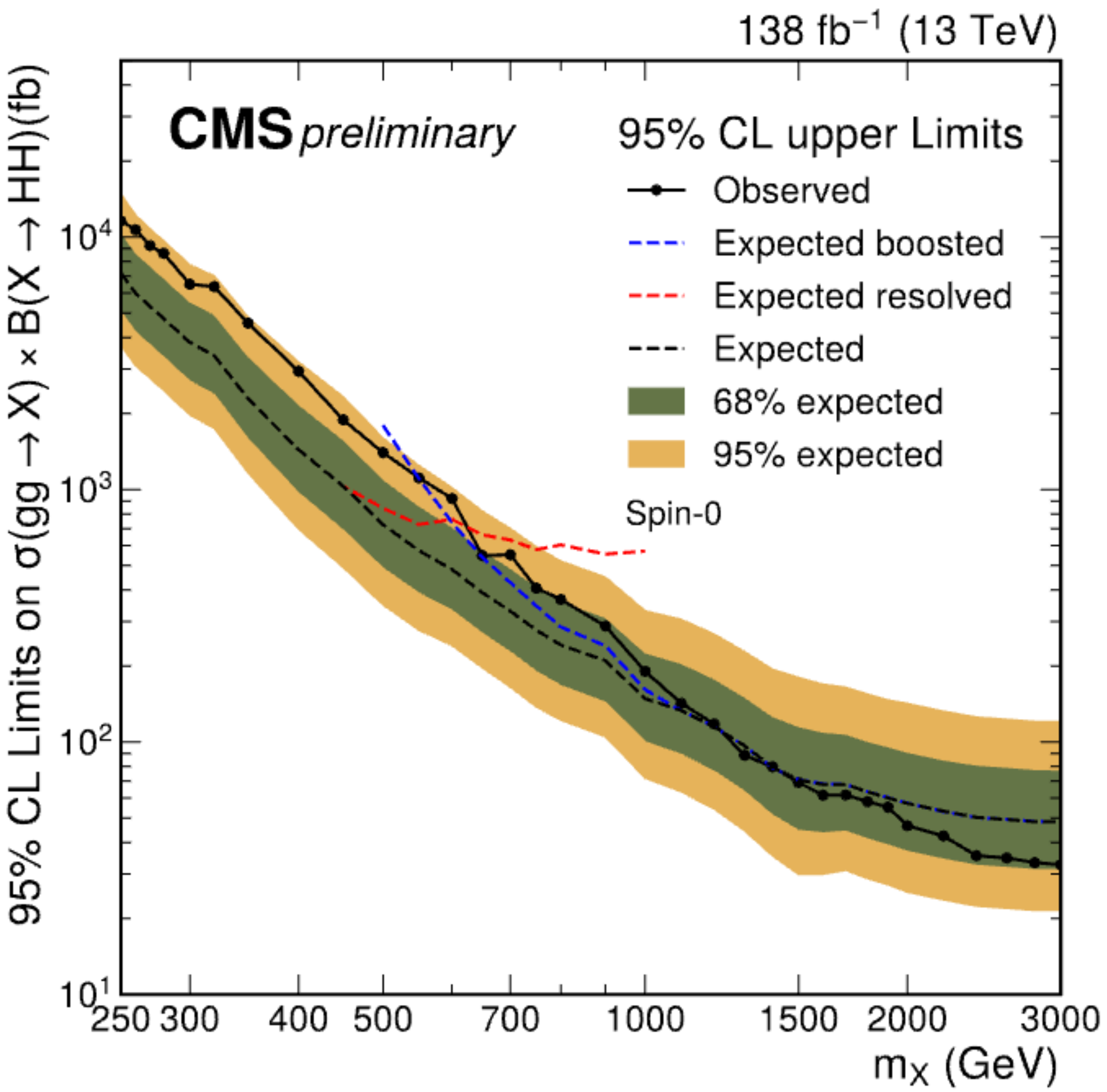

S+B fit [CMS-PAS-B2G-24-010]

# Results

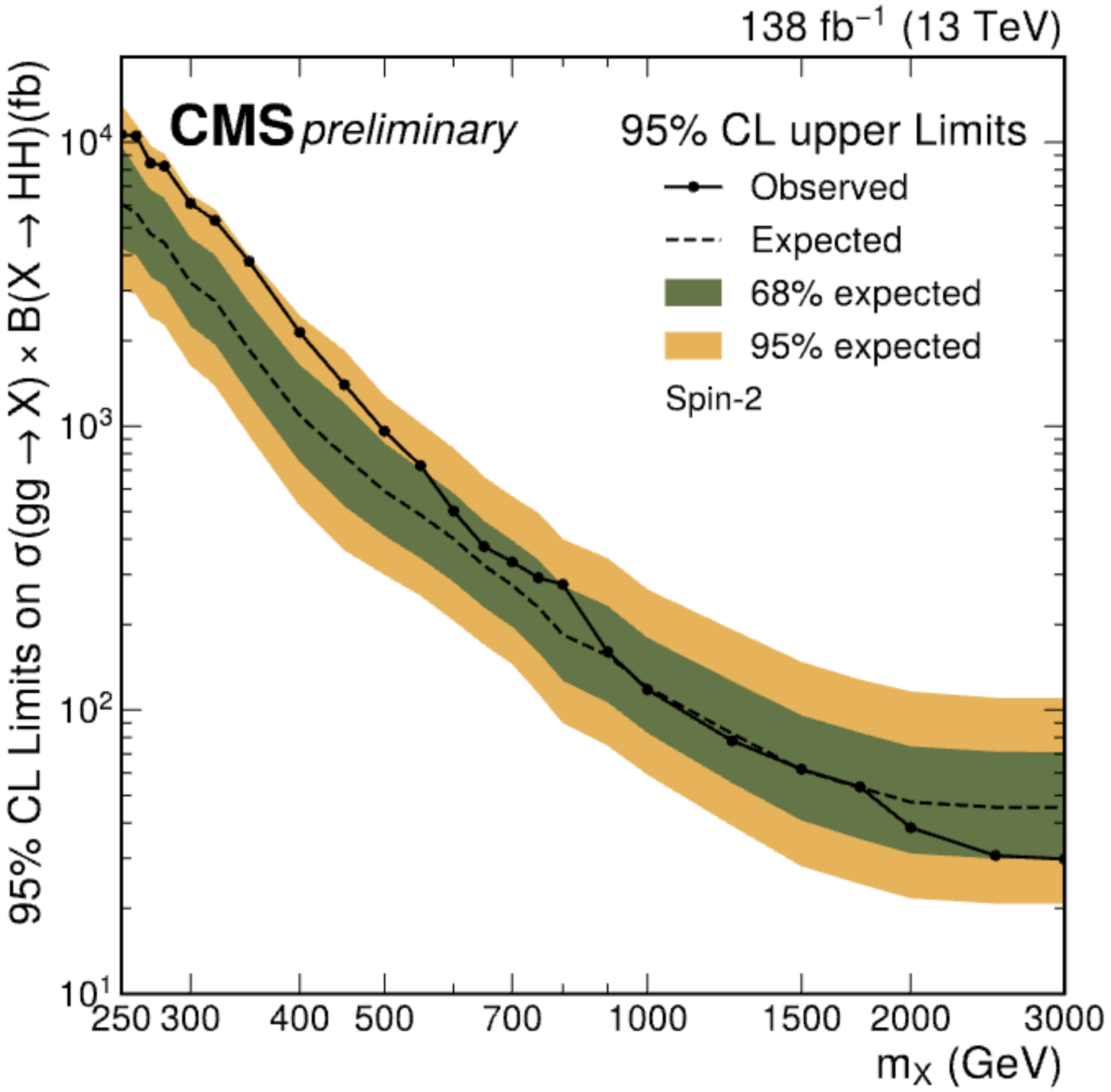
Observed (expected) 95% CL Limit on σ(X→HH) for radion and graviton:

- **Radion**: 32-11600 fb (48-7220 fb)
- **Graviton**: 30-10700 fb (45-6060 fb)

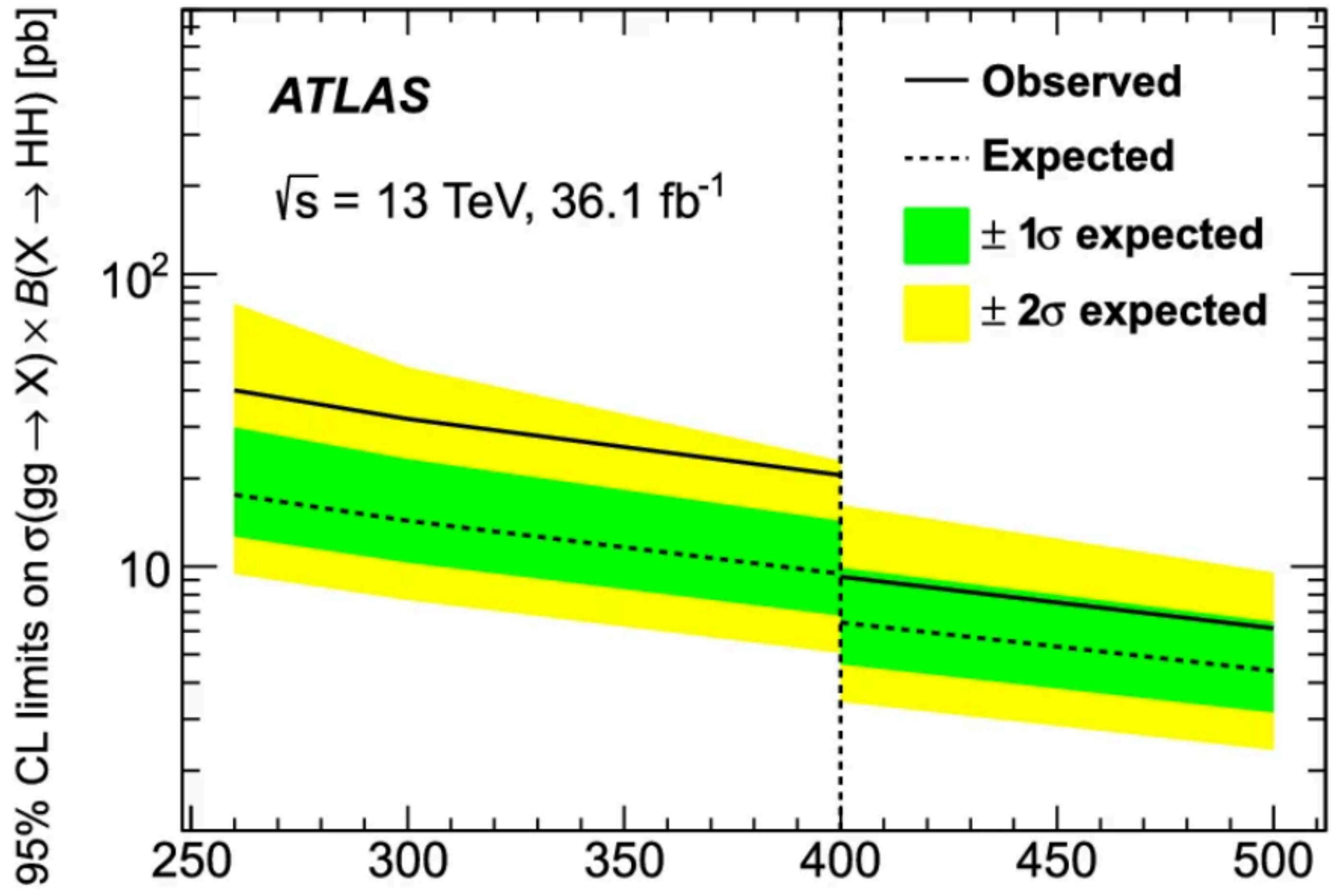
## No excess was observed




Radion [CMS-PAS-B2G-24-010]




Graviton [CMS-PAS-B2G-24-010]




[Eur.Phys.J.C]

# Summary

- This analysis presents the **first CMS search** for a resonance **X→HH→WWγγ** using Run 2 data, **extending the search mass range up to 3 TeV** for both **spin-0 ration and spin-2 graviton** hypotheses.
- First LHC search to probe the **boosted topology** in this final state, and the first to include **fully hadronic WW decays**
- Both fully hadronic and semi-leptonic WW decay modes are considered, **covering all relevant topologies.**
- Advanced ML methods — including a **PNN**, **Bayesian optimization** (per-mass-point boundary tuning), and **ParticleNet/GloParT** (fatjet tagging) — are employed to maximize signal-background separation.
- Observed (expected) 95% CL upper limits on σ(X→HH) are presented, providing the **most stringent constraints** to date for this decay channel.


# Thank you

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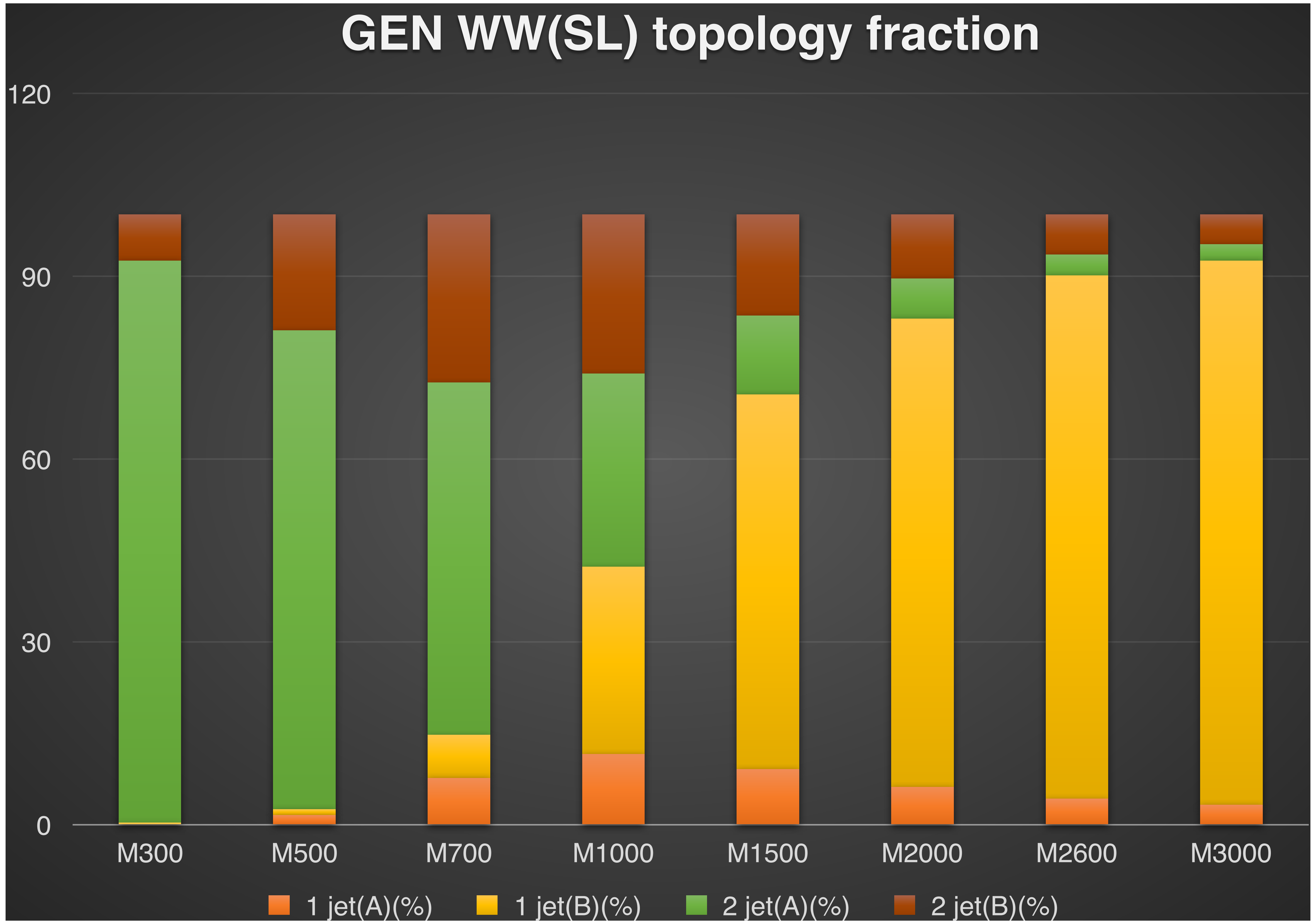
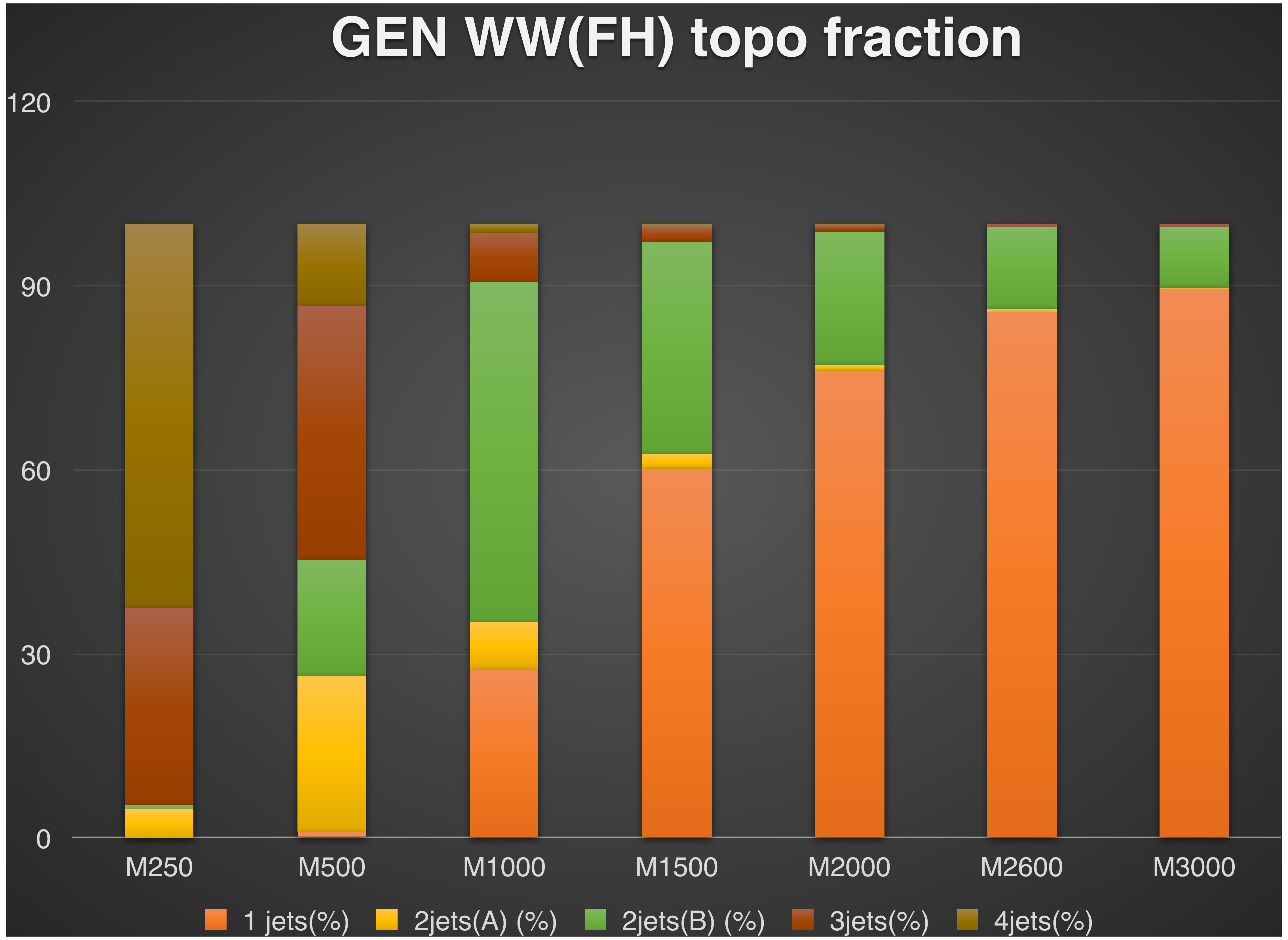
# Datasets and Simulations

Customized NanoAODv9 from Ultra Legacy Summer20MiniAODv2 with modified photon ID, Particle Transformer scores

- Dataset:
  - DoubleEG (2016, 2017) and EGamma (2018)
  - Total lumi = 138 $fb^{-1}$
- Signal simulations:
  - Radion & graviton official X→HH→WWγγ, bbγγ, ZZγγ, ττγγ MADGRAPH5_aMC@NLO, Pythia8
- Background simulations:
  - Non-resonant: official GJet, DiphotonJetsBox
  - Resonant: official single-Higgs (ggH, VBFH, VH, ttH)

# Gen-level WW topology fractions



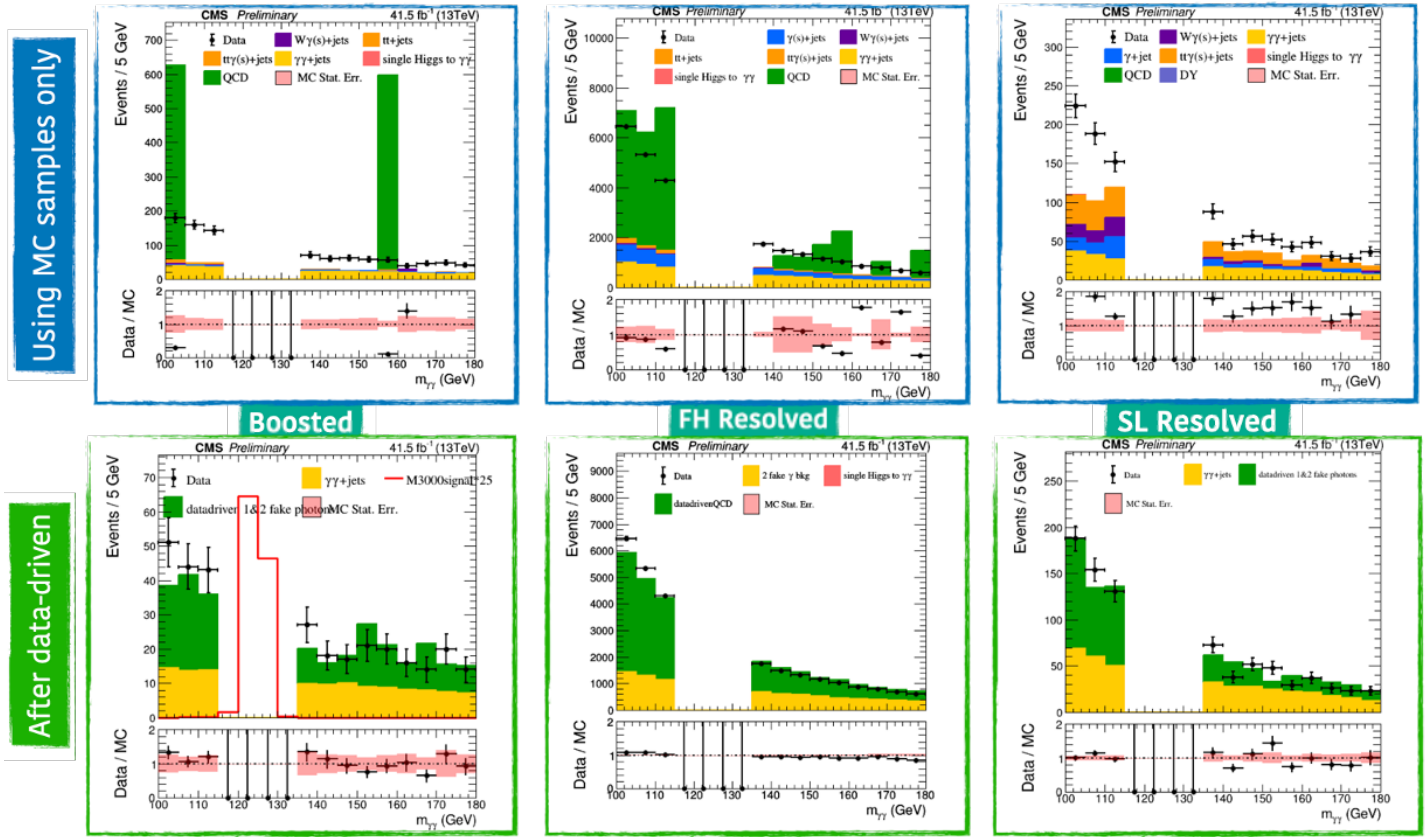
# Background MC

| Sample name | σ [pb] | br |
|---|---|---|
| GluGluHToGG_M125_TuneCP5_13TeV-amcatnloFXFX-pythia8 | 48.58 | 0.00227 |
| VHToGG_M125_TuneCP5_13TeV-amcatnloFXFX-madspin-pythia8 | 2.434 | 0.00227 |
| ttHJetToGG_M125_TuneCP5_13TeV-amcatnloFXFX-madspin-pythia8 | 0.5071 | 0.00228 |
| VBFHToGG_M125_TuneCP5_13TeV-amcatnlo-pythia8 | 4.05 | 0.00227 |
| GJet_Pt-20to40_DoubleEMEnriched_MGG-80toInf_TuneCP5_13TeV_Pythia8 | 232.9 | |
| GJet_Pt-40toInf_DoubleEMEnriched_MGG-80toInf_TuneCP5_13TeV_Pythia8 | 878.1 | |
| GJet_Pt-20toInf_DoubleEMEnriched_MGG-40to80_TuneCP5_13TeV_Pythia8 | 3155 | |
| DiPhotonJetsBox_M40_80-sherpa | 303.2 | |
| DiPhotonJetsBox_MGG-80toInf_13TeV-sherpa | 84.4 | |
| TTJets_TuneCP5_13TeV-madgraphMLM-pythia8 | 833.9 | |
| ttWJets_TuneCP5_13TeV_madgraphMLM_pythia8 | 0.4604 | |
| TTGJets_TuneCP5_13TeV-amcatnloFXFX-madspin-pythia8 | 4.078 | |
| TTGG_0Jets_TuneCP5_13TeV-amcatnlo-madspin-pythia8 | 0.01687 | |
| W1JetsToLNu_TuneCP5_13TeV-madgraphMLM-pythia8 | 8927 | |
| W2JetsToLNu_TuneCP5_13TeV-madgraphMLM-pythia8 | 2809 | |
| W3JetsToLNu_TuneCP5_13TeV-madgraphMLM-pythia8 | 1165.8108 | |
| W4JetsToLNu_TuneCP5_13TeV-madgraphMLM-pythia8 | 592.9176 | |
| WWTo1L1Nu2Q_4f_TuneCP5_13TeV-amcatnloFXFX-pythia8 | 50.95 | |
| WJetsToQQ_HT-200to400_TuneCP5_13TeV-madgraphMLM-pythia8 | 2549 | |
| WJetsToQQ_HT-400to600_TuneCP5_13TeV-madgraphMLM-pythia8 | 276.5 | |
| WJetsToQQ_HT-600to800_TuneCP5_13TeV-madgraphMLM-pythia8 | 59.25 | |
| WJetsToQQ_HT-800toInf_TuneCP5_13TeV-madgraphMLM-pythia8 | 28.75 | |
| WWG_TuneCP5_13TeV-amcatnlo-pythia8 | 0.2147 | |
| QCD_Pt-30to40_DoubleEMEnriched_MGG-80toInf_TuneCP5_13TeV-pythia8 | 24750 | |
| QCD_Pt-30toInf_DoubleEMEnriched_MGG-40to80_TuneCP5_13TeV-pythia8 | 240500 | |
| QCD_Pt-40ToInf_DoubleEMEnriched_MGG-80ToInf_TuneCP5_13TeV-pythia8 | 117400 | |

# Background MC vs datadriven background

In SL channel, the dominant bkg are ttγ(s) + jets, γ + jets, Wγ(s) + jets, γγ + jets

In FH channel, the dominant bkg is QCD, γγ + jets, γ + jets



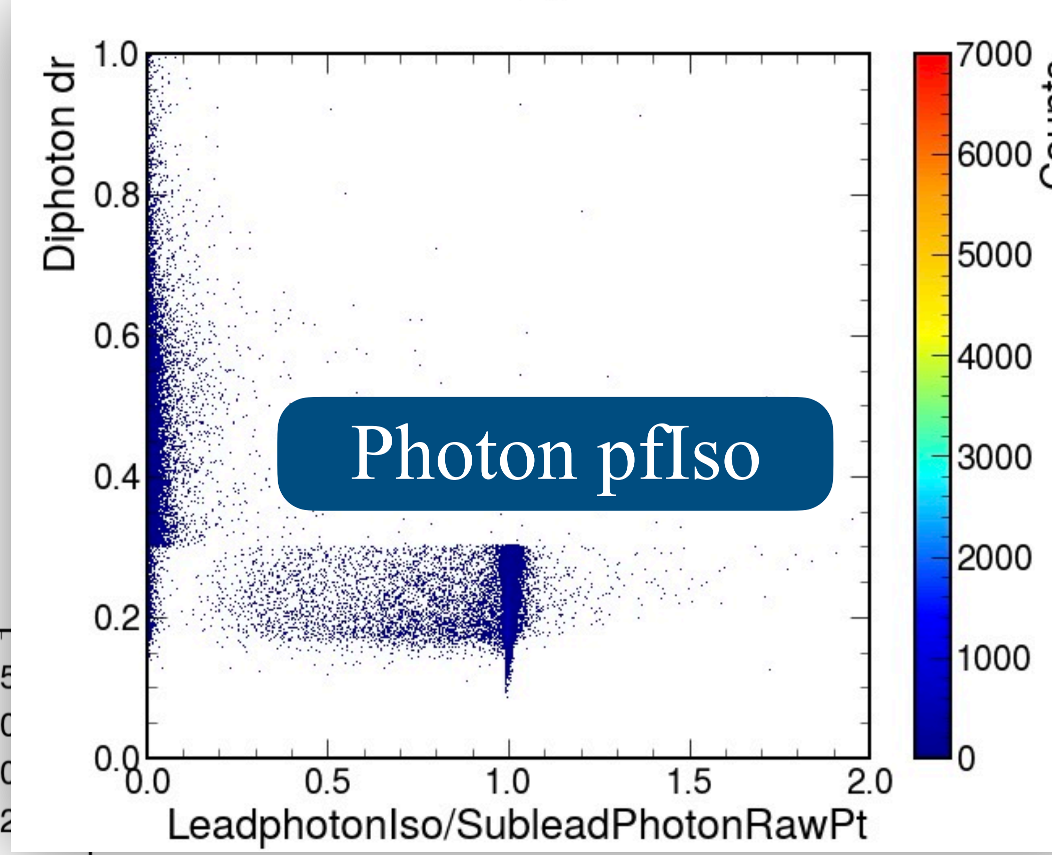
# Object selection H → γγ

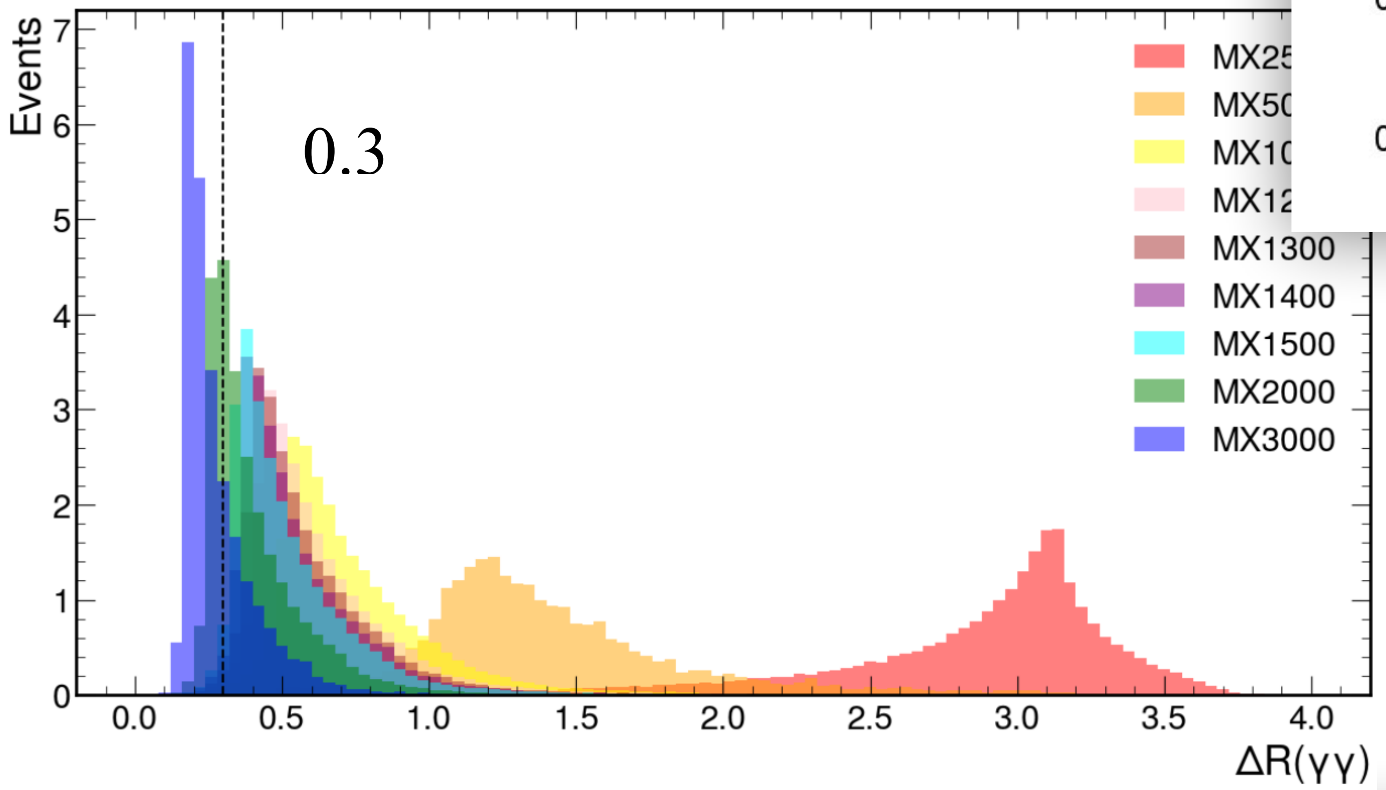
Standard H→γγ preselection (inherited from HIG-16-040)

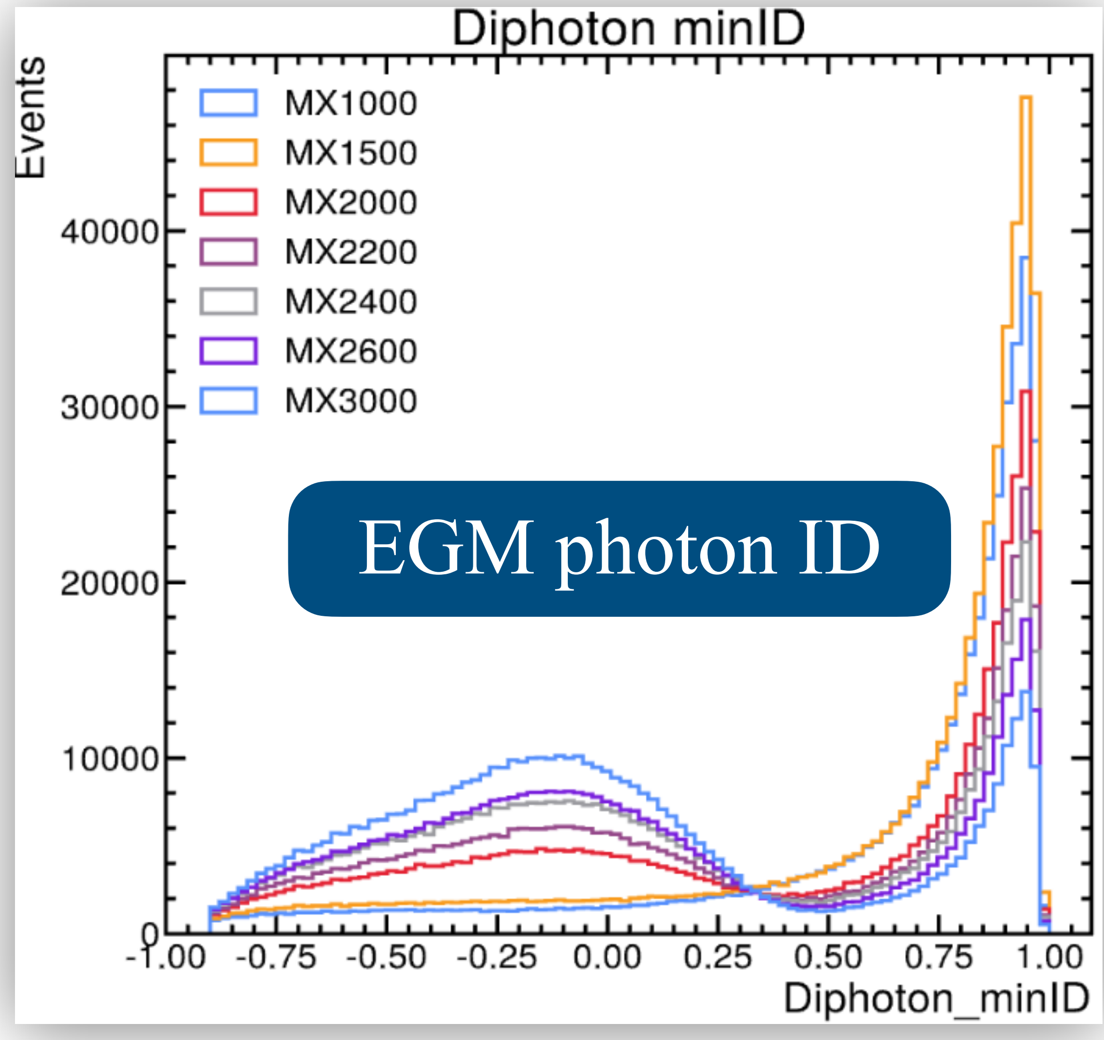
- HLT_Diphoton30_18(22)_R9Id_OR_IsoCaloId_AND_HE_R9Id_Mass90 2016 (2017,2018)
- $100 < m_{\gamma\gamma} < 180$ GeV
- $H/E < 0.08$
- Isolation cuts
- Leading photon $p_T > 35$ GeV, sub-leading photon $p_T > 25$ GeV
- Leading photon $p_{T\gamma\gamma} / m_{\gamma\gamma} > 0.33$, sub-leading photon $p_{T\gamma\gamma} / m_{\gamma\gamma} > 0.25$

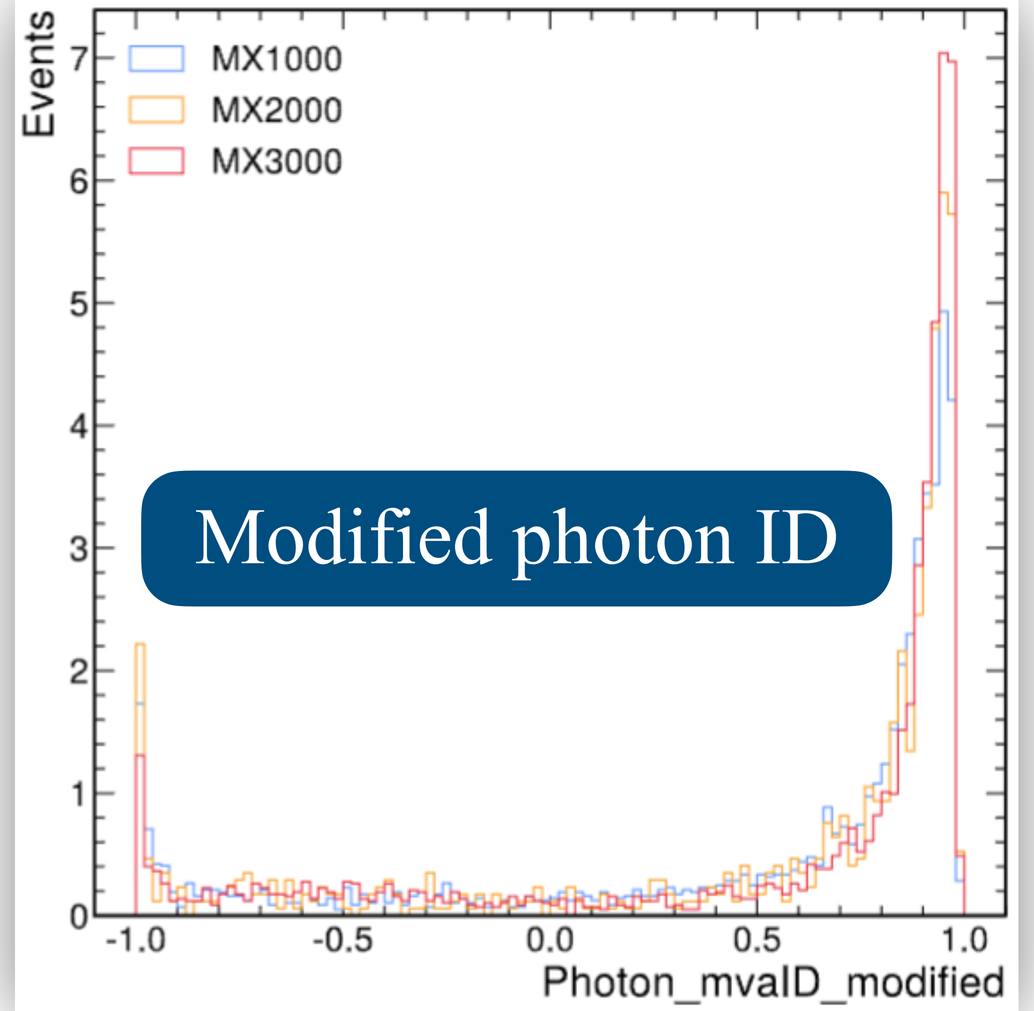
Using modified EGamma photon ID > -0.7 (link) instead of EGM photon ID

- EGamma MVA ID with isolation "pfPhoIso03" (as one of the inputs of the MVA) is no longer suitable for the photons from heavy resonance decays, as they are too close to each other.
  - It will decrease sig. eff. if we use EGamma Photon ID WP90 (> -0.02/-0.26 in EB/EE) requirement, then degrade searching sensitivity of high mass X.
  - The official EGamma photon ID MVA cut and SFs are not proper to use for high mass X .
- Solution: re-evaluate ID by setting pfPhoIso03 = 0.



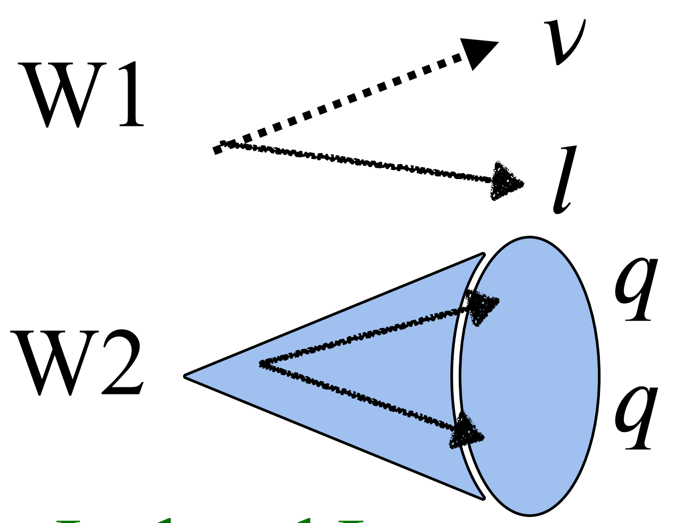



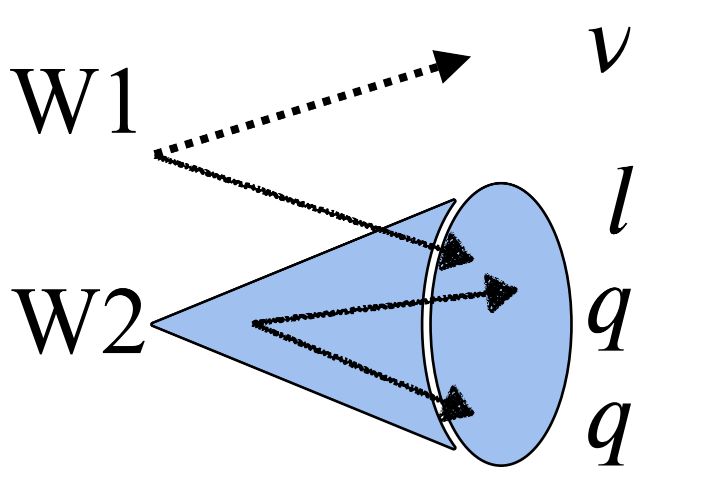
# Object selection: $H \to WW$

**Muon**
- $p_T > 15$ GeV, $|\eta| < 2.4$
- isGlobalMuon
- $\Delta R(\mu,\gamma) > 0.4$
- $|d_{xy}| < 0.045$ cm, $|d_z| < 0.2$ cm
- Isolated Muon: tight ID, $I_\mu < 0.15$
- Non-isolated Muon: high$p_T$ ID, $\Delta R(\mu,\text{fatjet}) < 0.8$

**Electron**
- $p_T > 10$ GeV, $|\eta| < 2.5$ ( $< 1.4442$ or $> 1.566$ )
- $|d_{xy}| < 0.045$ cm, $|d_z| < 0.2$ cm
- $\Delta R(e,\gamma) > 0.4$
- Z veto: $|m_{e\gamma}$ - 91.187$|$ GeV $>$ 5 GeV
- Isolated Electron: mvaFall17V2Iso_WP80
- Non-isolated Electron: mvaFall17V2noIso_WP90, $\Delta R(e,\text{fatjet}) < 0.8$



Isolated Lepton



Non-isolated Lepton

- **AK4 Jet**
  - tight ID, tight PUID
  - $p_T > 20$ GeV, $|\eta| < 2.4$
  - $\Delta R(\text{jet},\gamma) > 0.4$, $\Delta R(\text{jet},\text{lep}_{\text{iso}}) > 0.4$
- **W AK8 Jet**
  - ParticleNet $H_{bb} < 0.9$ (to veto bb fatjet)
  - $p_T > 100$ GeV, $|\eta| < 2.4$
  - loose WP ParticleNet WvsQCD MD tagger
  - $\Delta R(\text{fatjet},\gamma) > 0.8$, $\Delta R(\text{fatjet},\text{lep}_{\text{iso}}) > 0.8$
- **H AK8 Jet**
  - ParticleNet $H_{bb} < 0.9$ (to veto bb fatjet)
  - $p_T > 100$ GeV, $|\eta| < 2.4$
  - FH Higgs AK8 Jet: ParticleTransformer $H_{WW} > 0.2$
  - SL Higgs AK8 Jet:
  - $\Delta R(\text{fatjet},\gamma) > 0.8$, $\Delta R(\text{fatjet},\text{lep}_{\text{noniso}}) < 0.8$

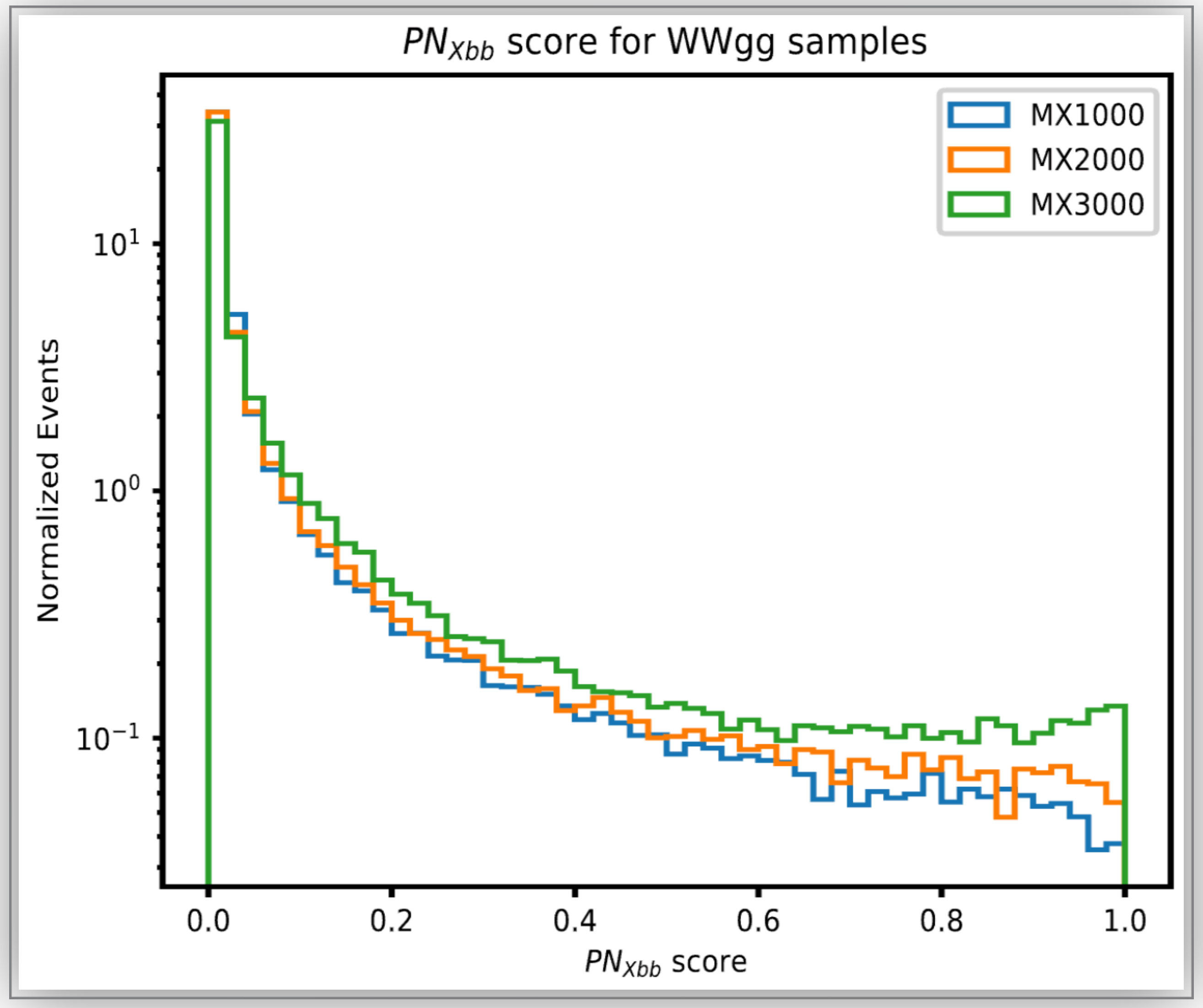
# $H_{bb}$ tagger

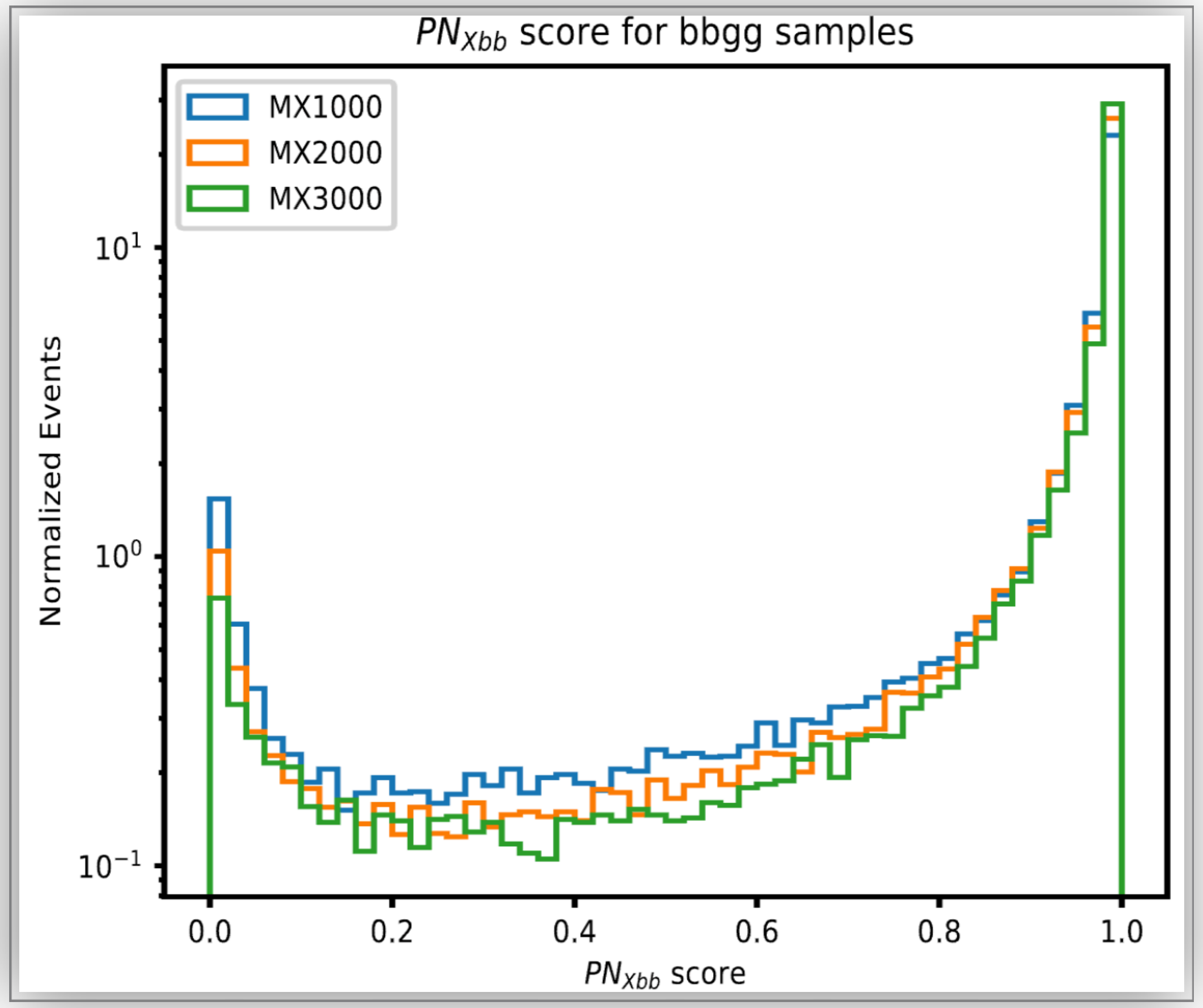
Motivation: Maintain orthogonality to the X→HH→bbγγ (link) analysis

Negligible impact on WWγγ signal, effectively reduce bbγγ signal

**Recalibrated using sfBDT(link) method with similar phase space as signal**

- Selecting signal-like g→bb events with a BDT method




| MC Efficiency in $H_{bb}$<0.9 region | | |
|---|---|---|
| **Mass Point** | **WWγγ** | **bbγγ** |
| MX1000 | 0.995 | 0.189 |
| MX2000 | 0.993 | 0.181 |
| MX3000 | 0.988 | 0.176 |

# Hww Tagger

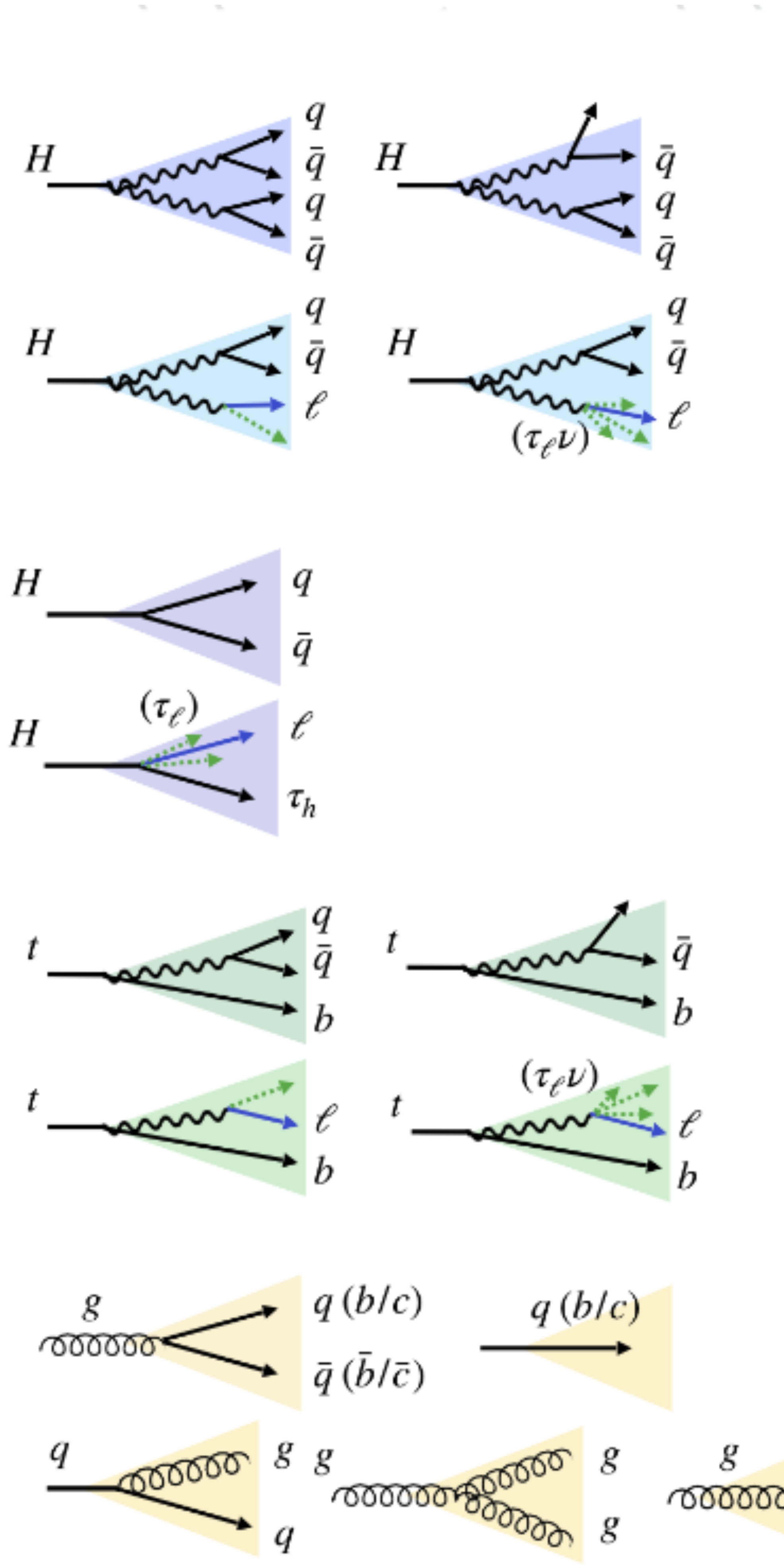
Motivation: to reduce QCD and top background, tag FH Higgs like AK8 Jet.

State-of-art all-inclusive tagger, developed by Tagger dev working group (link)

In our case, construct this tagger as formula [1] to discriminate signal vs QCD & top

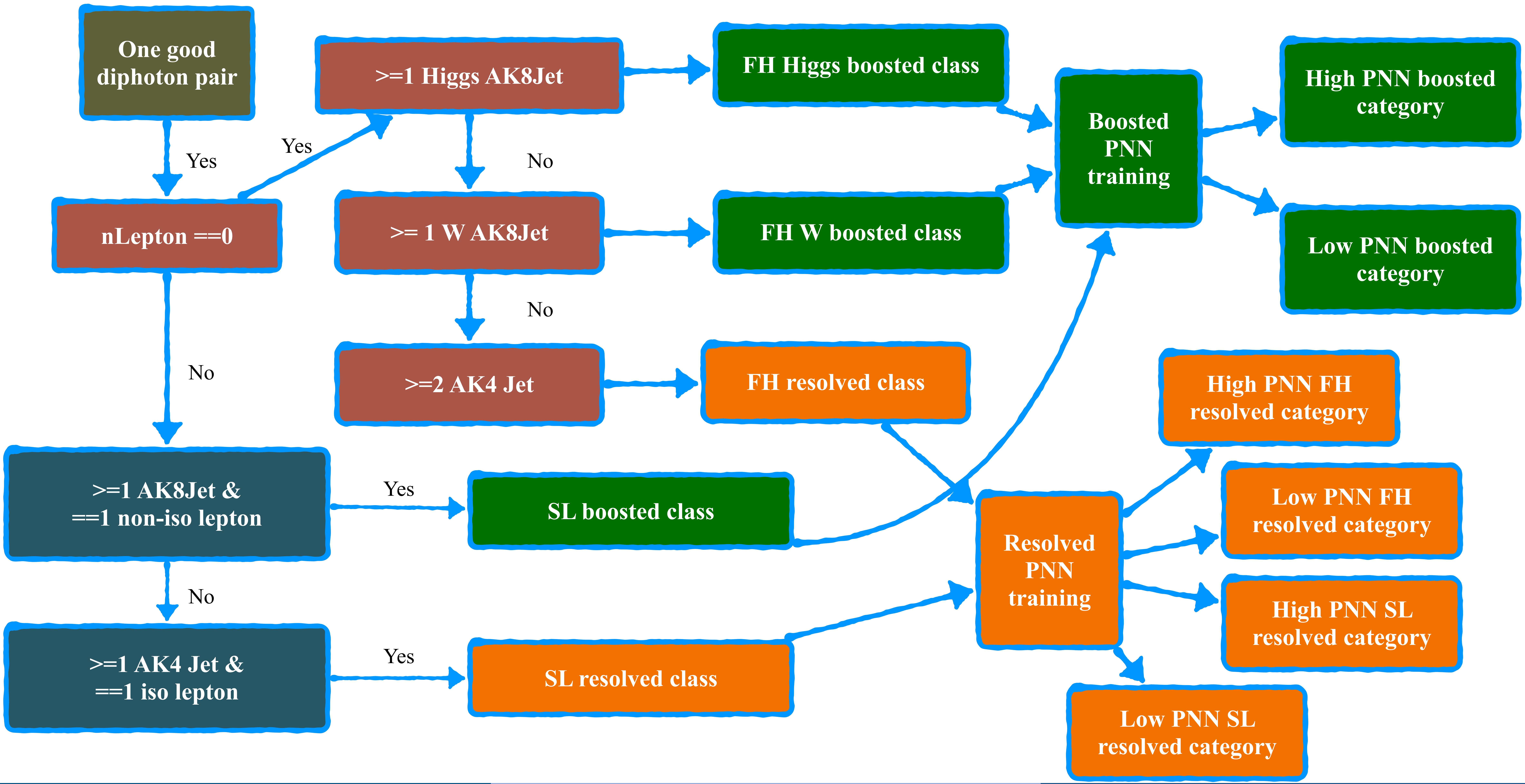
Derive SFs and uncertainty (SFs approval talk) with Lund Jet Plane reweighting method (JME-23-001)

| Process | Final state/ prongness | heavy flavour | # of classes |
|---|---|---|---|
| H→WW (full-hadronic) | qqqq | 0c/1c/2c | 3 |
| | qqq | | 3 |
| H→WW (semi-leptonic) | eνqq | 0c/1c | 2 |
| | μνqq | | 2 |
| | $\tau_e$νqq | | 2 |
| | $\tau_\mu$νqq | | 2 |
| | $\tau_h$νqq | | 2 |
| H→qq | | bb | 1 |
| | | cc | 1 |
| | | ss | 1 |
| | | qq (q=u/d) | 1 |
| H→ττ | $\tau_e\tau_h$ | | 1 |
| | $\tau_\mu\tau_h$ | | 1 |
| | $\tau_h\tau_h$ | | 1 |
| t→bW (hadronic) | bqq | 1b + 0c/1c | 2 |
| | bq | | 2 |
| t→bW (leptonic) | beν | 1b | 1 |
| | bμν | | 1 |
| | b$\tau_e$ν | | 1 |
| | b$\tau_\mu$ν | | 1 |
| | b$\tau_h$ν | | 1 |
| QCD | | b | 1 |
| | | bb | 1 |
| | | c | 1 |
| | | cc | 1 |
| | | others (light) | 1 |




$$H_{WW} = \frac{P_{HWW3q} + P_{HWW4q}}{P_{HWW3q} + P_{HWW4q} + P_{QCD} + P_{Top}} \quad [1]$$

# Event selection flow-chart



# Background estimation for pNN training

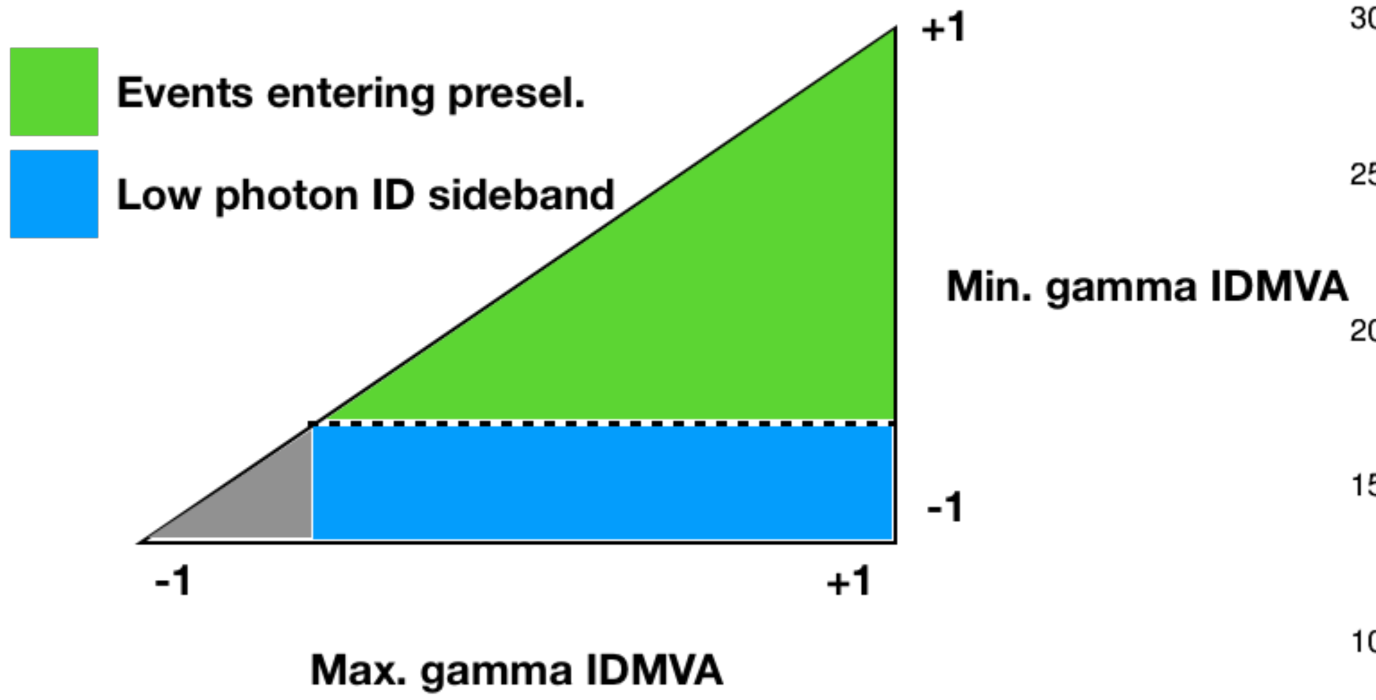
Background components: 2 prompt photons (MC), 1 prompt + 1 fake & 2 fake photons (data-driven)

Data-driven method to derive fake photon(s) background for PNN optimization (inherited from HIG-19-013 (link)

① Fetch a probability distribution function for minimum modified photon ID MVA for non-prompt photons (fake photon PDF) from GJets MC samples

② generate a new value of the minimum modified photon ID MVA in the range [sideband cut value, max modified photon ID MVA]

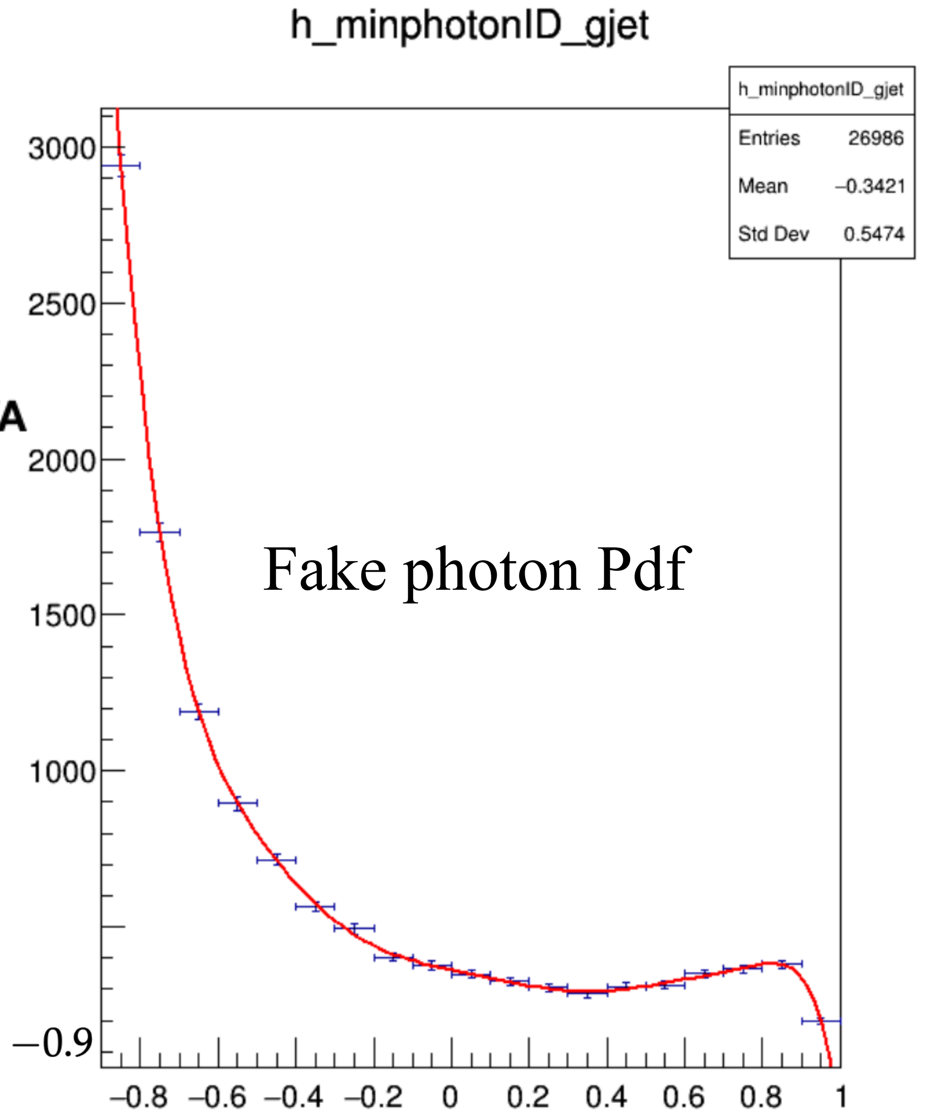
③ assign an additional per-event weight in order to properly reshape the max modified photon ID MVA distribution.

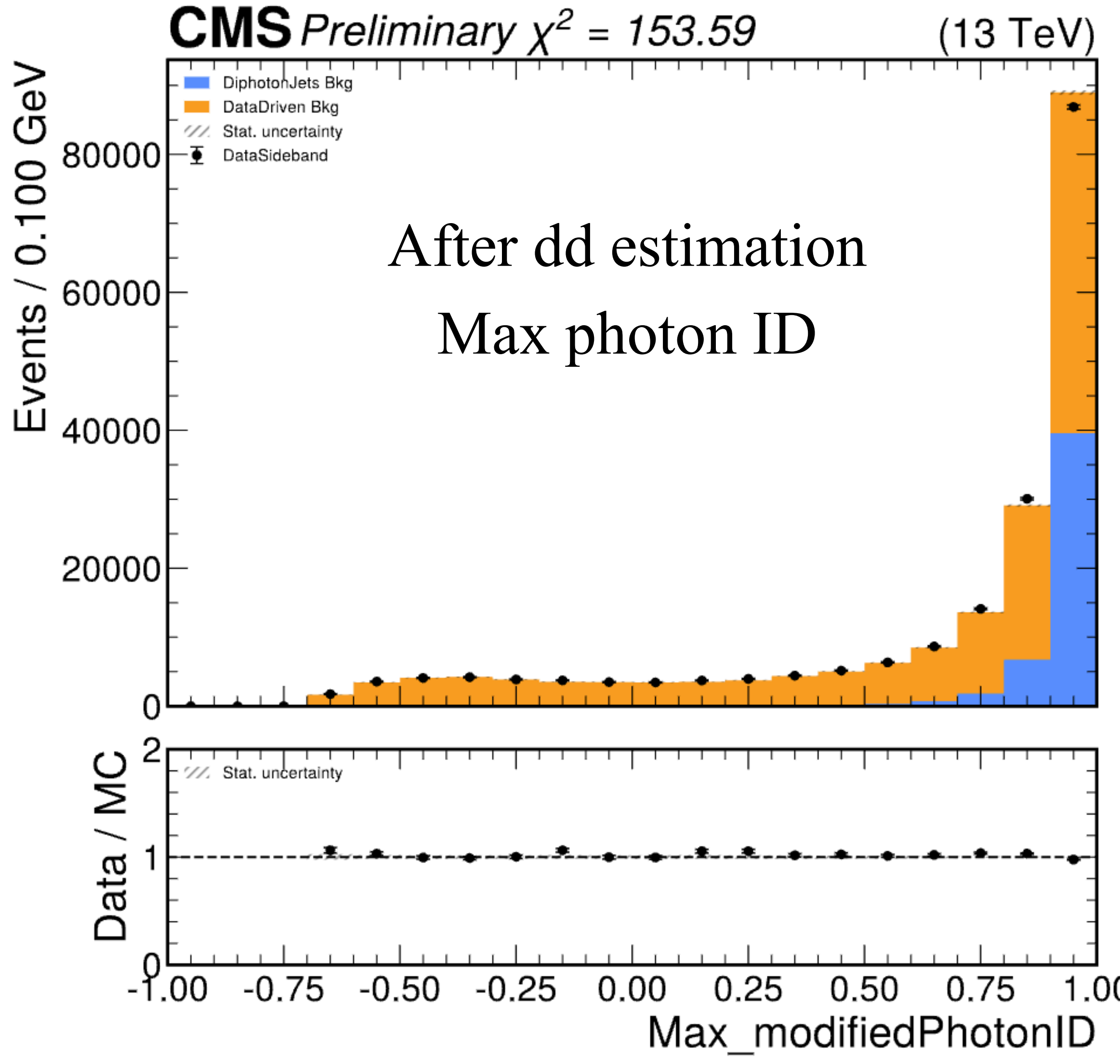


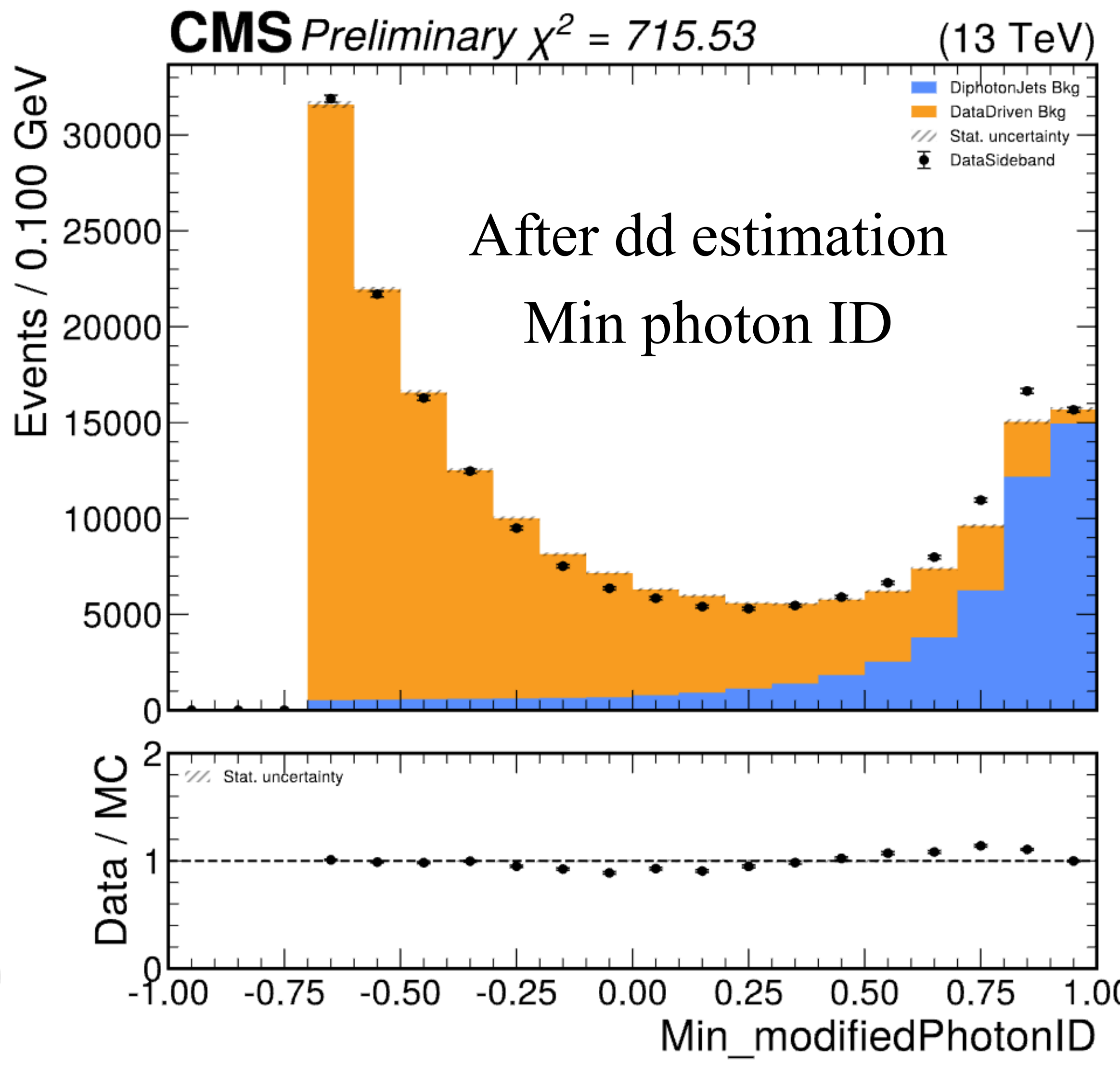

$$w = \frac{\int_B^{\max \gamma\, \mathrm{ID}} \text{fake PDF}}{\int_A^B \text{fake PDF}}$$

$A \equiv$ minimum value of modified photon ID MVA in the low photon ID sideband $= -0.9$

$B \equiv$ preselection cut value on minimum modified photon ID MVA $= -0.7$



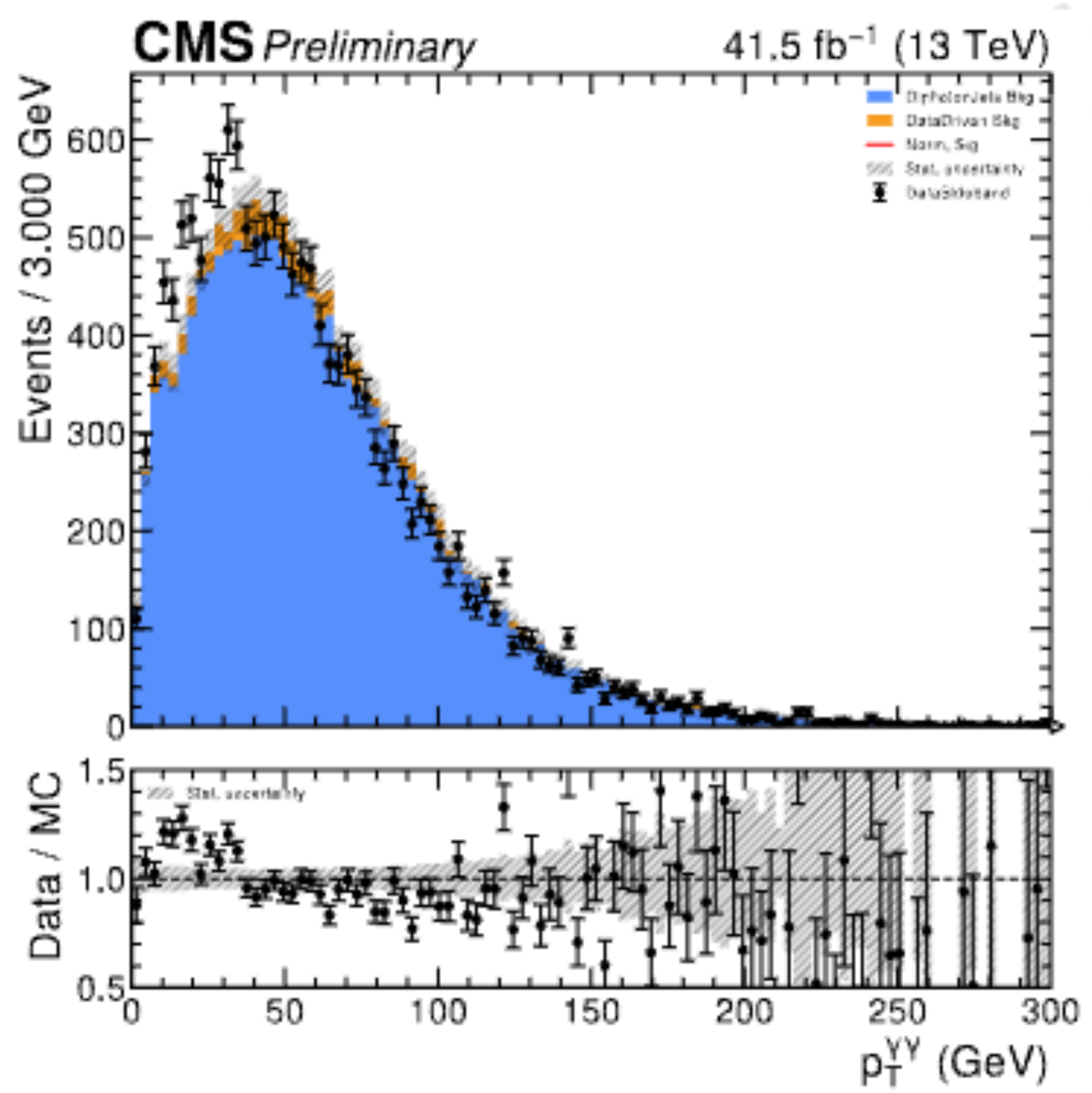



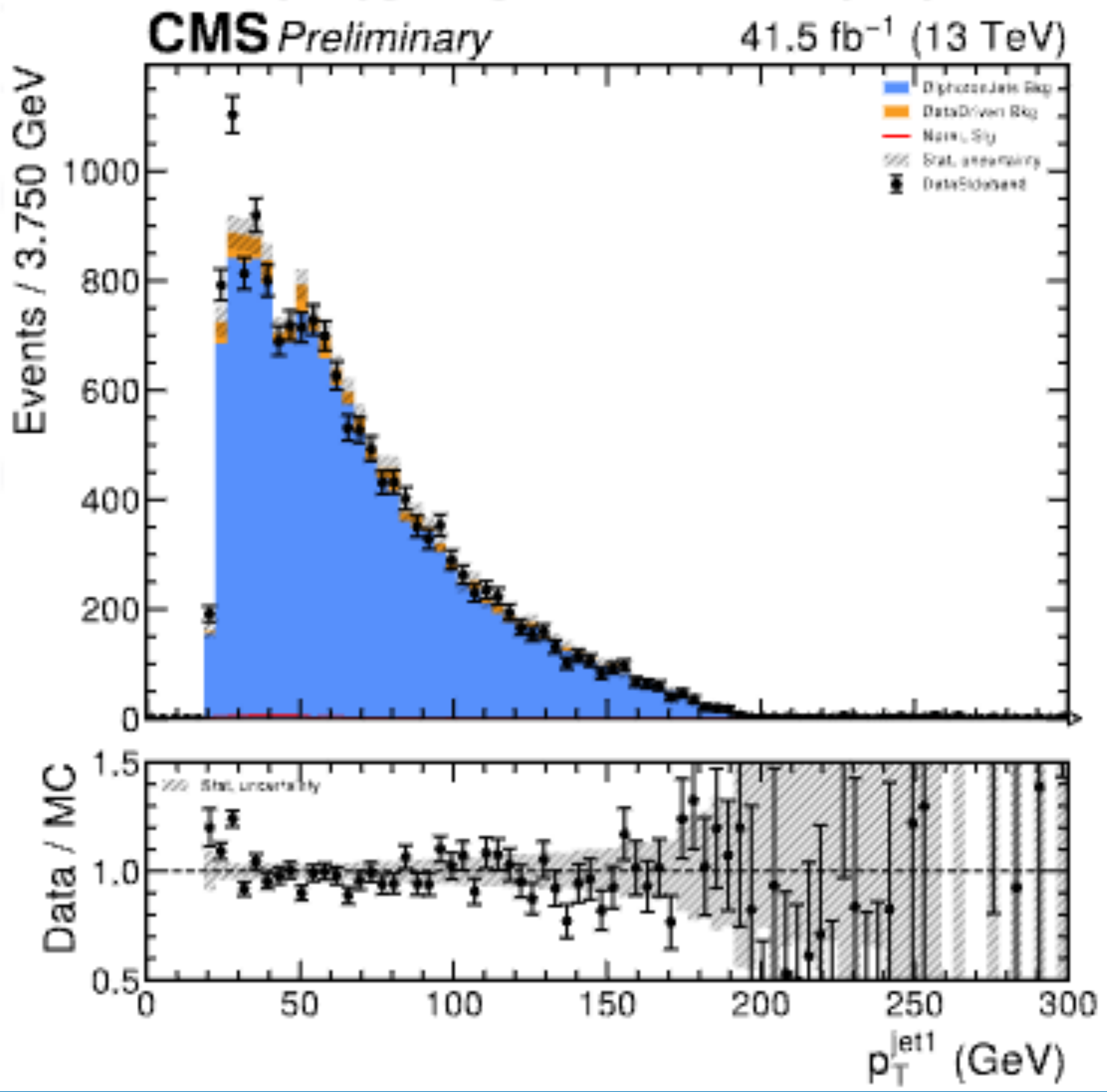

Background modeled from data in low photon ID sideband where minID < -0.9 & max ID > -0.7

# Kinematic reweighting of the MC $\gamma\gamma$ + jets

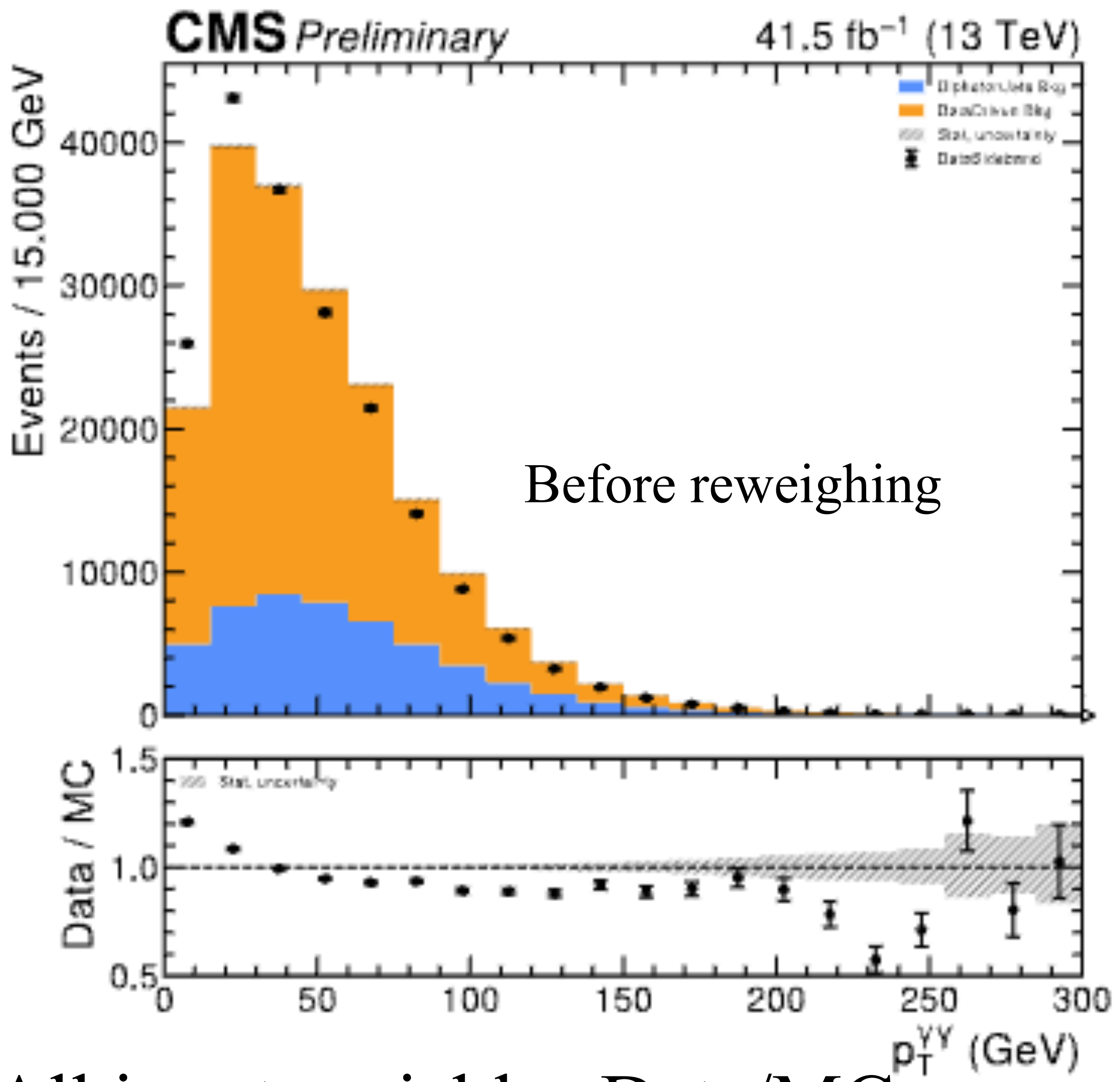
Motivation: mismodeling of the MC $\gamma\gamma$ + jets in the low $p_T$ region of the leading jet and $\gamma\gamma$

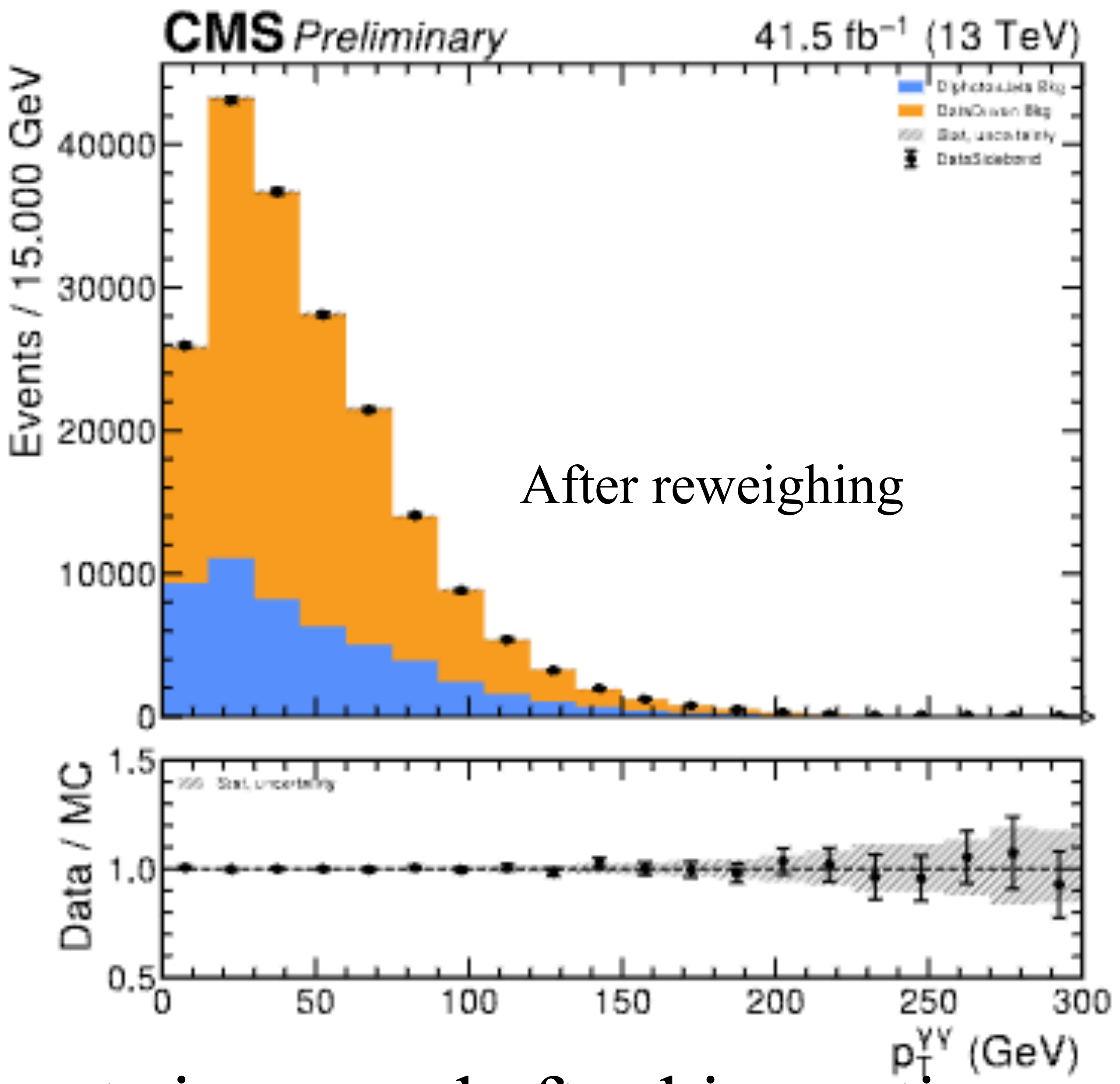
Control plots for $\gamma\gamma$+jets dominated region before reweigthing




1. Derive the bin-by-bin scale factors in the sideband region after subtracting the data-driven background
2. Apply reweighing SFs across the full range, including the signal region

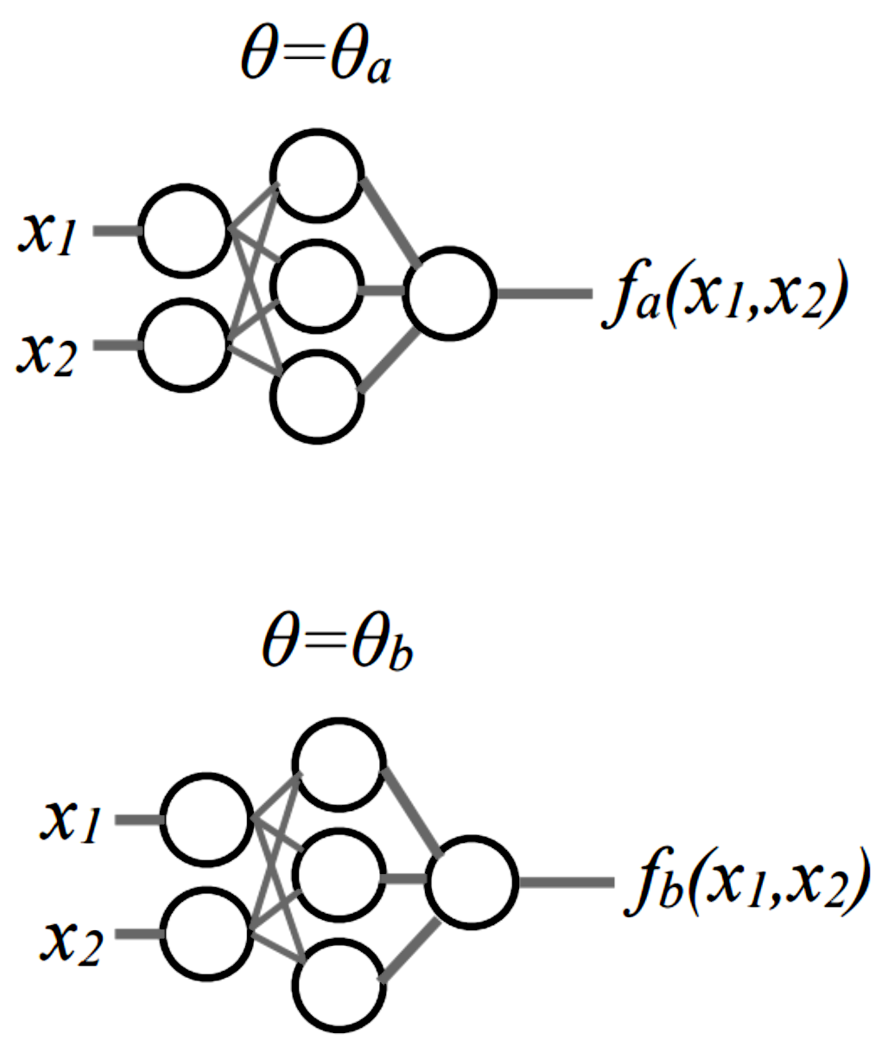


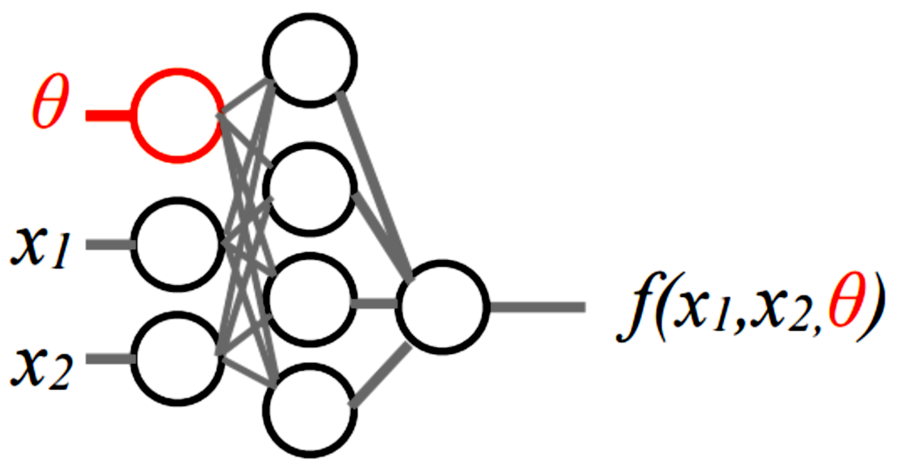

All input variables Data/MC agreements improved after kinematic reweighting

Sideband region: 100 GeV < $m_{\gamma\gamma}$ < 115 GeV or 135 GeV < $m_{\gamma\gamma}$ < 180 GeV
Signal region: 115 GeV ≤ $m_{\gamma\gamma}$ ≤ 135 GeV

# Parameterized Neural Network (pNN)




2 NNs trained on different single mass points




1 pNN trained with signal mass as one input parameter

[Parameterized neural networks for high-energy physics]

1. Include mX as one training feature.
2. Train on all signal MC simultaneously, assigning each event its corresponding mX value.
3. Keep the class balance

- Duplicate background events for each mass point with corresponding mX values, ensuring mX cannot discriminate signal from background.
- Normalize signal datasets to have equal total weights across all mX values.
- Normalize signal and background datasets to have equal total weights collectively.

# Parameterised Neural Network (pNN)

Trained with mass points **[500GeV, 3000GeV]**

**Multi-classifier training** with different signal and backgrounds

- Class0 : FH backgrounds from MC + data-driven background
- Class1 : SL backgrounds from MC + data-driven background
- Class2 : FH Higgs boosted signal
- Class3 : FH W boosted signal
- Class4 : SL W boosted signal

43 input features including:

- Photon and diphoton kinematic variables
- AK8 jet and AK4 jet kinematic variables
- MET kinematic variables
- Number of leptons and jets

Most important features:
$p_{T\gamma\gamma} / m_{\gamma\gamma}$, $\Delta R(\gamma 1, \gamma 2)$, $p_{T\text{fatjet}1}$

PAPER/PAS

| Feature | Description |
|---|---|
| Diphoton_pTom | Transverse momentum of the diphoton system over the mass of the diphoton system |
| Diphoton_dR | Delta R between the two photons |
| Diphoton_eta | Pseudorapidity of the diphoton system |
| Diphoton_phi | Azimuthal angle of the diphoton system |
| LeadPhoton_pTom | Transverse momentum of the leading photon over the mass of the diphoton system |
| LeadPhoton_eta | Pseudorapidity of the leading photon |
| LeadPhoton_phi | Azimuthal angle of the leading photon |
| SubleadPhoton_pTom | Transverse momentum of the subleading photon over the mass of the diphoton system |
| SubleadPhoton_eta | Pseudorapidity of the subleading photon |
| SubleadPhoton_phi | Azimuthal angle of the subleading photon |
| fatjet_1_pT | Transverse momentum of the leading fatjet |
| fatjet_1_eta | Pseudorapidity of the leading fatjet |
| fatjet_1_phi | Azimuthal angle of the leading fatjet |
| fatjet_2_pT | Transverse momentum of the subleading fatjet |
| fatjet_2_eta | Pseudorapidity of the subleading fatjet |
| fatjet_2_phi | Azimuthal angle of the subleading fatjet |
| fatjet_1_2_dR | Delta R between the two fatjets |
| fatjet_1_diphoton_dR | Delta R between the leading fatjet and the diphoton system |
| fatjet_2_diphoton_dR | Delta R between the subleading fatjet and the diphoton system |
| fatjet_1_leadphoton_dR | Delta R between the leading fatjet and the leading photon |
| fatjet_1_subleadphoton_dR | Delta R between the leading fatjet and the subleading photon |
| fatjet_2_leadphoton_dR | Delta R between the subleading fatjet and the leading photon |
| fatjet_2_subleadphoton_dR | Delta R between the subleading fatjet and the subleading photon |
| max_fatjets_mass | Maximum mass of the two fatjets |
| Leading jets_pT | Transverse momentum of the leading jets |
| Subleading jets_pT | Transverse momentum of the subleading jets |
| Third leading jets_pT | Transverse momentum of the third leading jets |
| Leading jets_eta | Pseudorapidity of the leading jets |
| Subleading jets_eta | Pseudorapidity of the subleading jets |
| Third leading jets_eta | Pseudorapidity of the third leading jets |
| Leading jets_phi | Azimuthal angle of the leading jets |
| Subleading jets_phi | Azimuthal angle of the subleading jets |
| Third leading jets_phi | Azimuthal angle of the third leading jets |
| Leading jets_mass | Mass of the leading jets |
| Subleading jets_mass | Mass of the subleading jets |
| Third leading jets_mass | Mass of the third leading jets |
| PuppiMET_pt | Transverse momentum of the missing transverse energy |
| PuppiMET_sumEt | Sum of the transverse energy of the missing transverse energy |
| nGoodAK4jets | Number of good AK4 jets |
| nGoodAK8jets | Number of good AK8 jets |
| nGoodisoleptons | Number of good isolated leptons |
| nGoodnonisoleptons | Number of good non-isolated leptons |
| MX | Invariant mass of the resonance X |

Table 2: Input variables used for the boosted PNN training.

# Parameterised Neural Network (pNN)

Trained with mass points **[250GeV, 1000GeV]**

**Multi-classifier training** with different signal and backgrounds

- Class0 : FH backgrounds from MC + data-driven background
- Class1 : SL backgrounds from MC + data-driven background
- Class2 : bbγγ MC
- Class3 : FH resolved signal
- Class4 : SL resolved signal

41 input features including:

- Photon and diphoton kinematic variables
- Lepton kinematic variables
- Jet, MET kinematic variables
- Reco-level W and H(WW)
- Number of leptons and jets

Most important features：
$p_{T\gamma\gamma}$ / $m_{\gamma\gamma}$, $\Delta R(\gamma 1, \gamma 2)$, $p_{Tjet1}$, jet bscore

PAPER/PAS

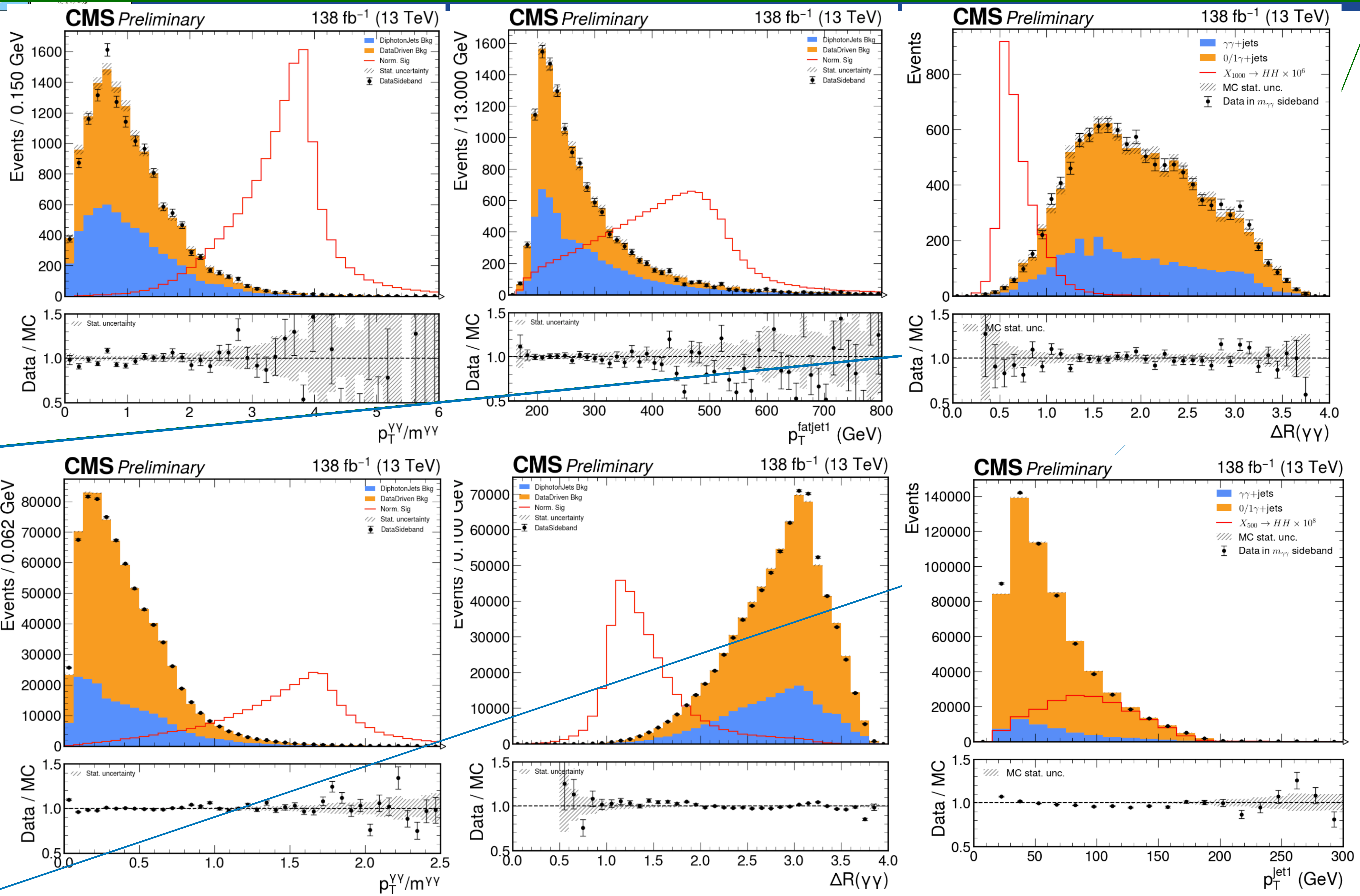
| Feature | Description |
|---|---|
| MX | Invariant mass of the resonance X |
| Diphoton_pTom | Transverse momentum of the diphoton system over the mass of the diphoton system |
| Diphoton_eta | Pseudorapidity of the diphoton system |
| Diphoton_phi | Azimuthal angle of the diphoton system |
| LeadPhoton_pTom | Transverse momentum of the leading photon over the mass of the diphoton system |
| SubleadPhoton_pTom | Transverse momentum of the subleading photon over the mass of the diphoton system |
| LeadPhoton_eta | Pseudorapidity of the leading photon |
| LeadPhoton_phi | Azimuthal angle of the leading photon |
| SubleadPhoton_eta | Pseudorapidity of the subleading photon |
| SubleadPhoton_phi | Azimuthal angle of the subleading photon |
| Diphoton_dR | Delta R between the two photons |
| Diphoton_dEta | Delta pseudorapidity between the two photons |
| jet_1_2_pt | Transverse momentum of the combined leading and subleading jets |
| jet_1_2_mass | Mass of the combined leading and subleading jets |
| jet_1_2_dR | Delta R between the leading and subleading jets |
| jet_1_pt | Transverse momentum of the leading jet |
| jet_1_mass | Mass of the leading jet |
| jet_2_pt | Transverse momentum of the subleading jet |
| jet_2_mass | Mass of the subleading jet |
| photon1_jet1_dR | Delta R between the leading photon and the leading jet |
| photon1_jet2_dR | Delta R between the leading photon and the subleading jet |
| photon1_jet1_2_dR | Delta R between the leading photon and the combined leading and subleading jets |
| Diphoton_jet1_2_dR | Delta R between the diphoton system and the combined leading and subleading jets |
| Diphoton_jet1_dR | Delta R between the diphoton system and the leading jet |
| Diphoton_jet2_dR | Delta R between the diphoton system and the subleading jet |
| photon2_jet1_dR | Delta R between the subleading photon and the leading jet |
| photon2_jet2_dR | Delta R between the subleading photon and the subleading jet |
| photon2_jet1_2_dR | Delta R between the subleading photon and the combined leading and subleading jets |
| Diphoton_jet_1_2_dEta | Delta pseudorapidity between the diphoton system and the combined leading and subleading jets |
| Diphoton_jet_1_dEta | Delta pseudorapidity between the diphoton system and the leading jet |
| Diphoton_jet_2_dEta | Delta pseudorapidity between the diphoton system and the subleading jet |
| Diphoton_jet_1_2_dPhi | Delta phi between the diphoton system and the combined leading and subleading jets |
| Diphoton_jet_1_dPhi | Delta phi between the diphoton system and the leading jet |
| Diphoton_jet_2_dPhi | Delta phi between the diphoton system and the subleading jet |
| PuppiMET_pt | Transverse momentum of the missing transverse energy |
| nGoodAK4jets | Number of good AK4 jets |
| nGoodisoleptons | Number of good isolated leptons |
| leading_bscore | B-tagging score of the leading jet |
| subleading_bscore | B-tagging score of the subleading jet |
| sum_two_max_bscores | Sum of the two highest b-tagging scores |

Table 1: Input variables used for the resolved PNN training.

# Training feature distributions

Boosted

Resolved




Good Data/MC agreement for all variables.

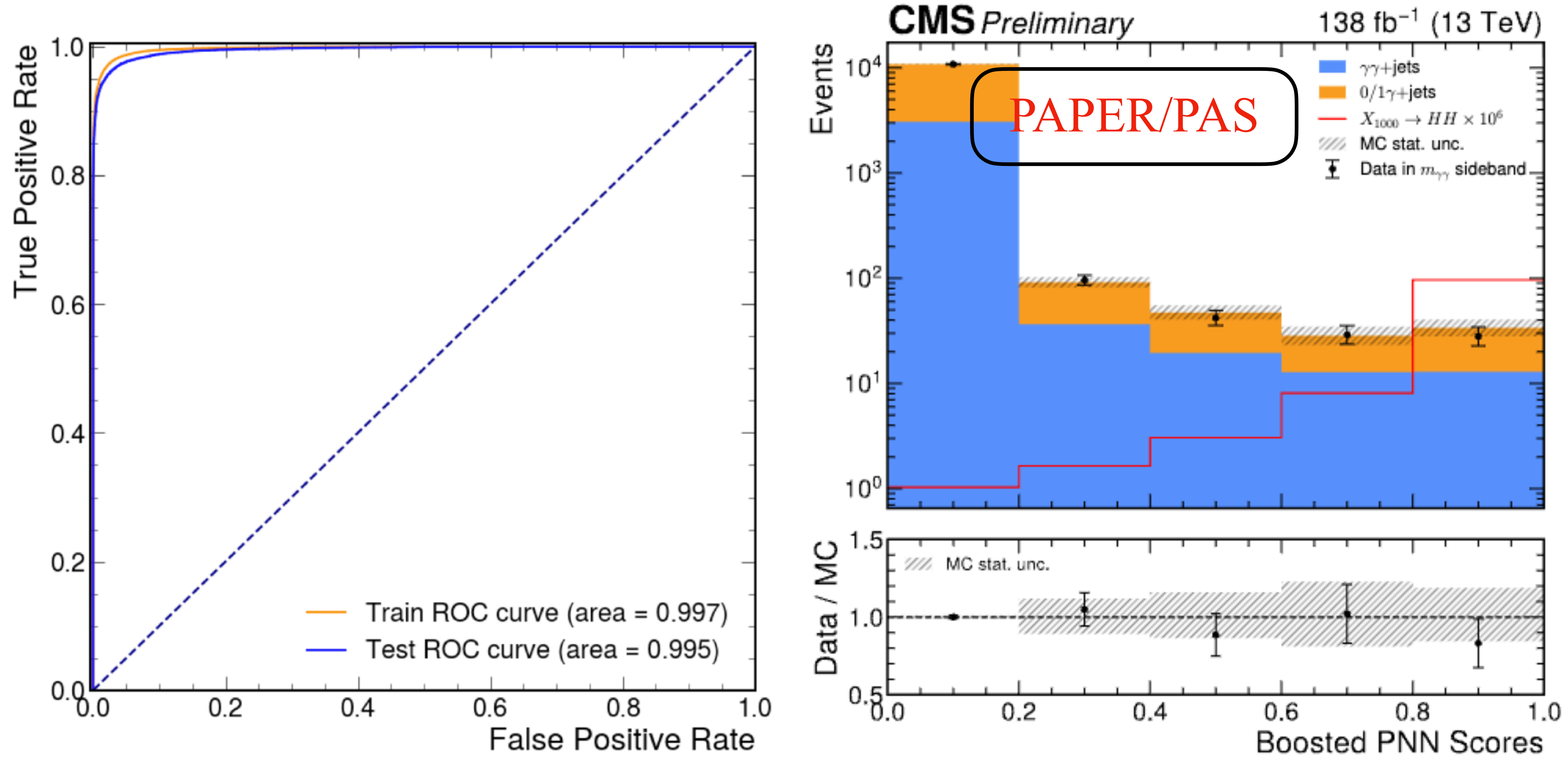
All plots in AN.

# pNN Performance

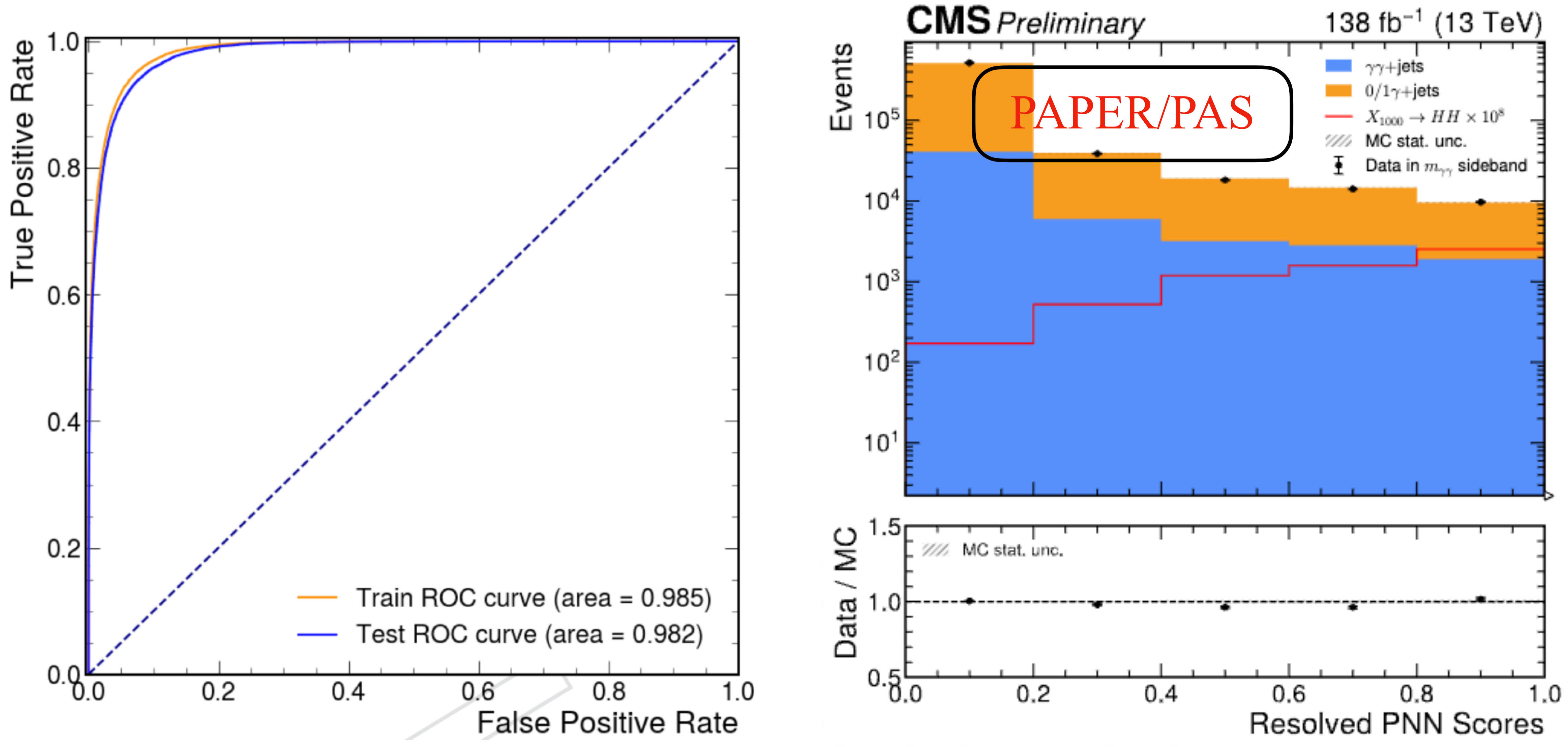
No overtraining

AUC performance for different signal masses are checked

Good discriminant power




Boosted pNN (mX = 1000 GeV)



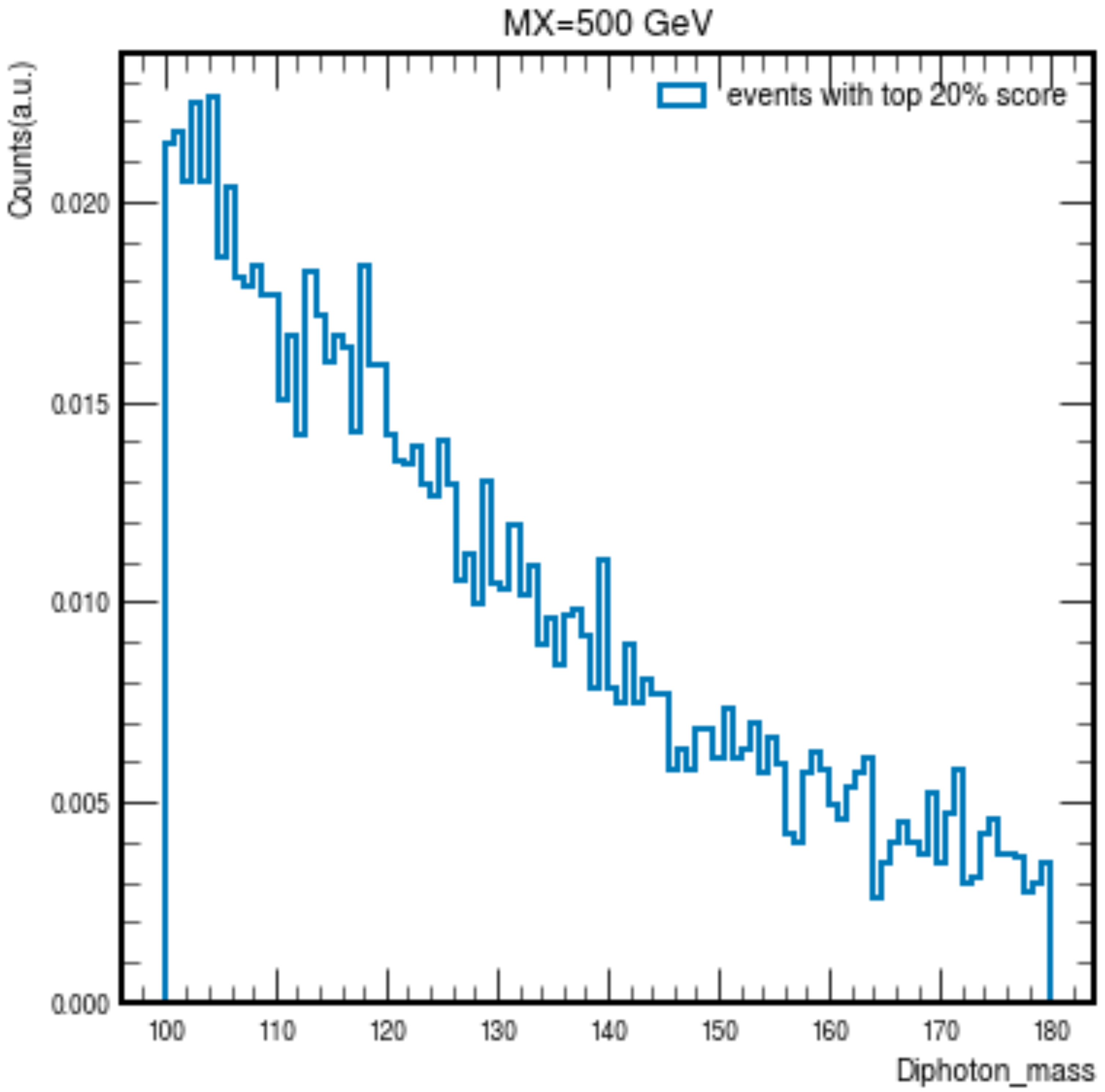

Resolved pNN (mX = 500 GeV)

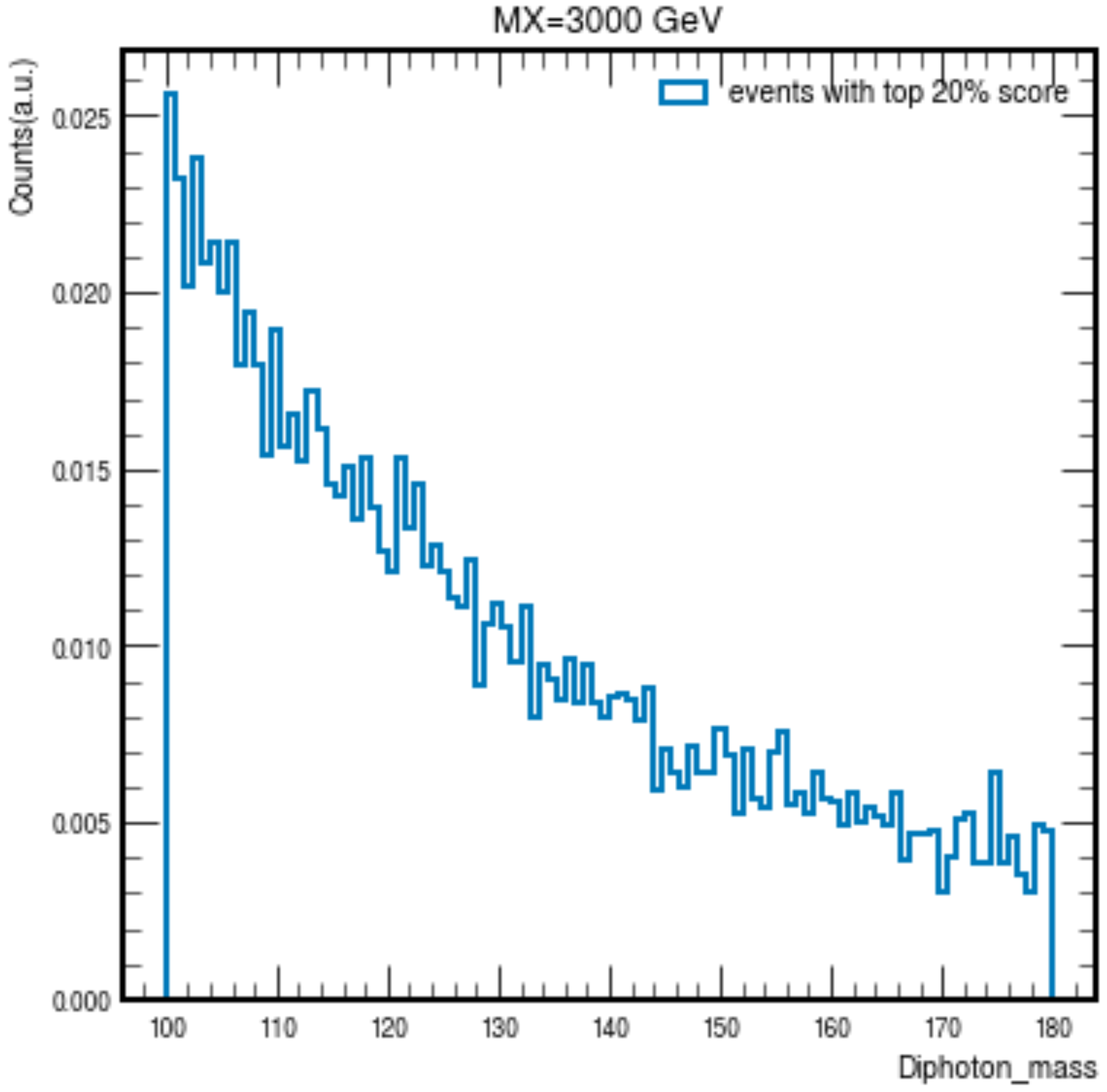
# Correlation check: pNN vs $m_{\gamma\gamma}$

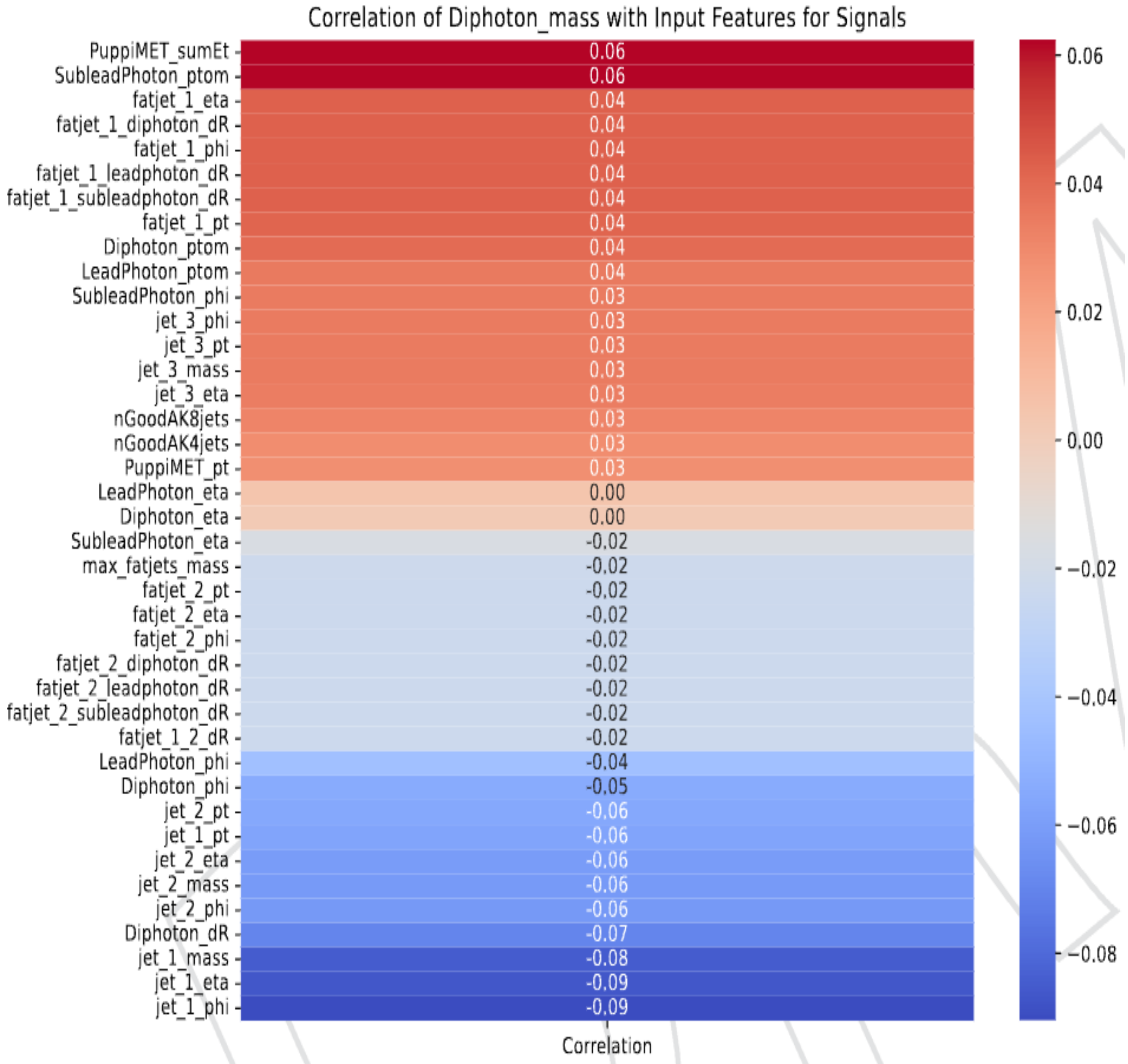
Mass sculpting check

Linear correlation check

No correlation observed



# bbγγ contamination study

Motivation: Remove contamination from bbγγ to be orthogonal with published low mass resonant bbγγ (HIG-21-011) and high mass resonant bbγγ analysis (B2G-24-019).

Low mass (resolved topology):

- Set preselected bbγγ events in the pNN training as one background class to implement bbγγ killer

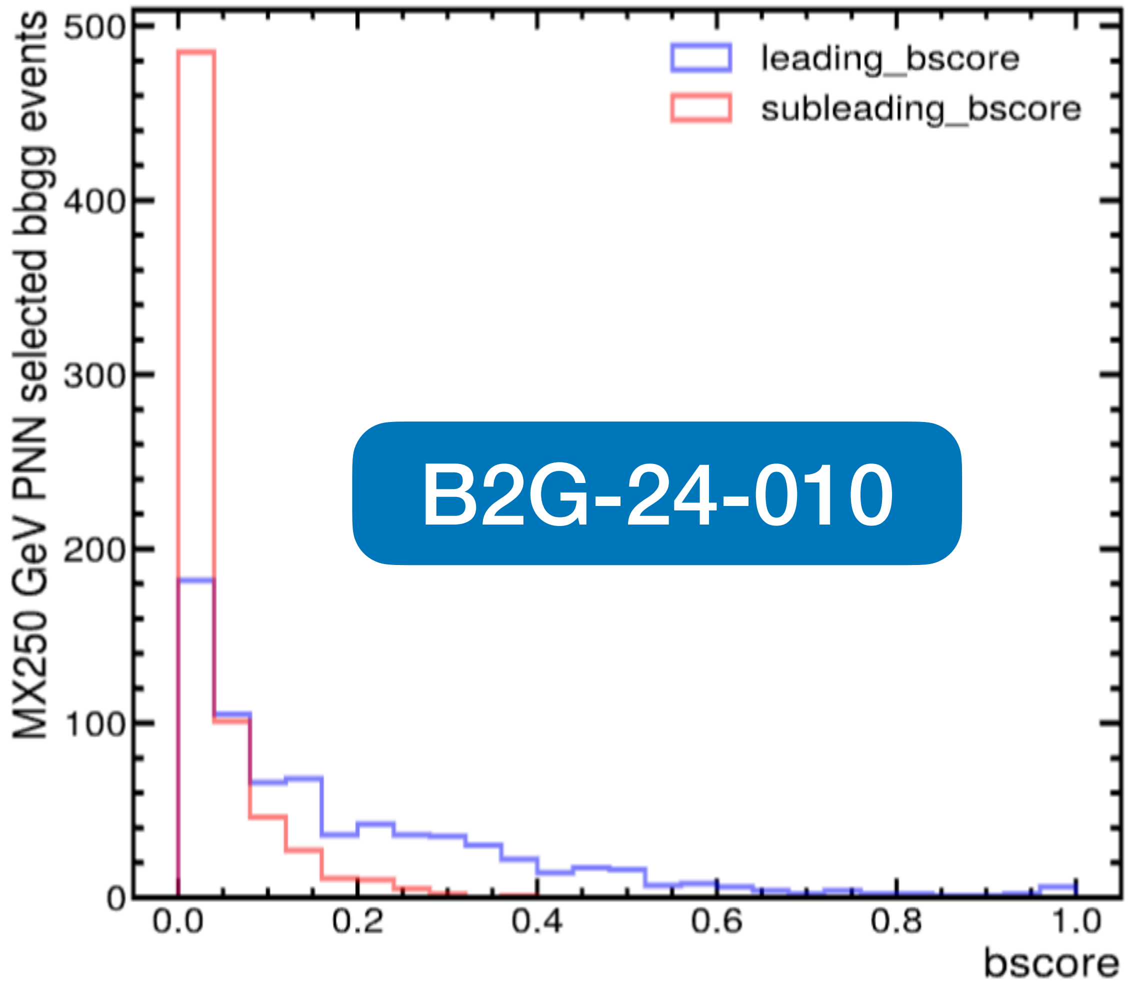
High mass (boosted topology):

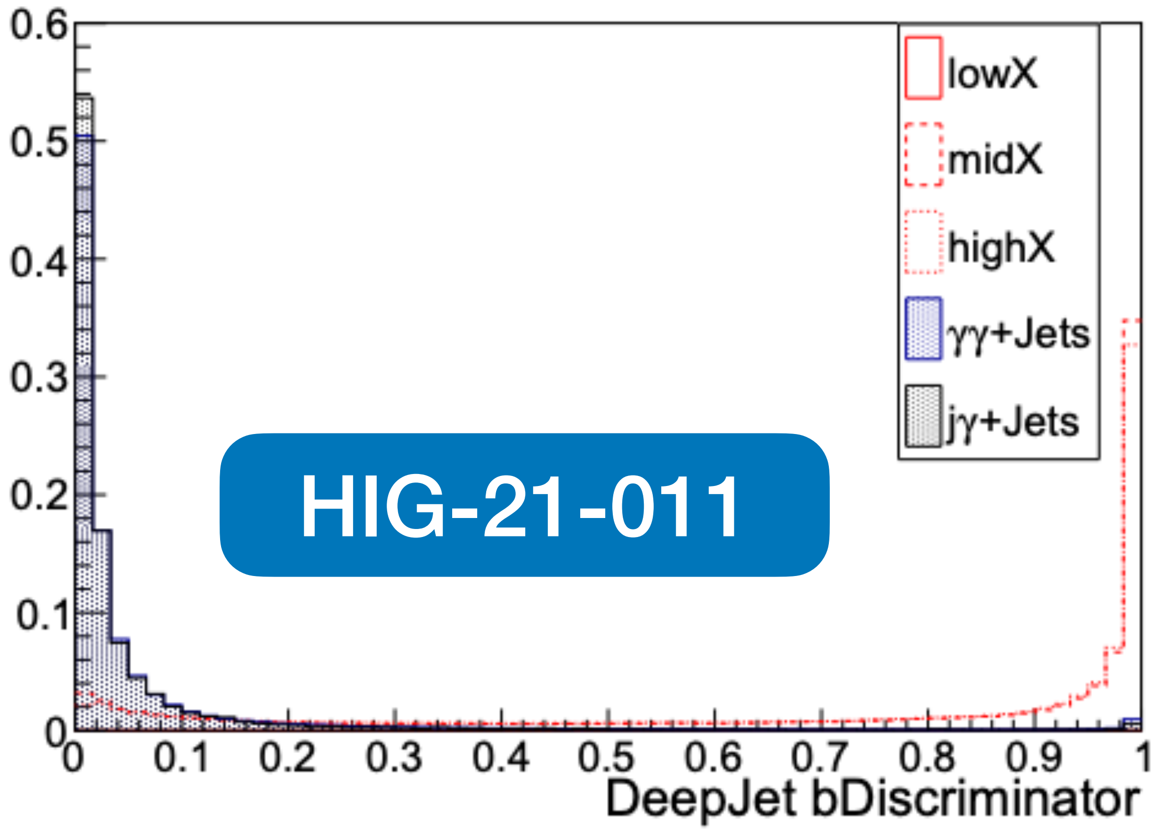
- Reject bbγγ events by applying ParticleNet Hbb $< 0.9$ cut

# bbγγ contamination study

For low mass region, bbgg is rejected by PNN model. The bbgg contribution is less than 10% in the high purity category. All the bbgg events passed the PNN event selection have low btagDeepFlavB scores distribution.

| | MX250 | MX350 | MX400 | MX500 | MX600 | MX700 | MX800 | MX1000 |
|---|---|---|---|---|---|---|---|---|
| highpurity wwgg | 0.075 | 0.062 | 0.147 | 0.154 | 0.195 | 0.481 | 0.46 | 0.525 |
| lowpurity wwgg | 1.933 | 1.962 | 1.698 | 2.011 | 1.698 | 0.709 | 0.676 | 0.347 |
| total wwgg | 2.008 | 2.024 | 1.845 | 2.164 | 1.893 | 1.19 | 1.137 | 0.872 |
| highpurity bbgg | 0.002 | 0.003 | 0.016 | 0.007 | 0.003 | 0.007 | 0.003 | 0.005 |
| lowpurity bbgg | 1.592 | 1.355 | 0.953 | 1.662 | 2.362 | 0.57 | 0.856 | 0.894 |
| total bbgg | 1.594 | 1.358 | 0.968 | 1.669 | 2.365 | 0.578 | 0.859 | 0.899 |
| bbgg/wwgg+bbgg(%) | 55.541 | 50.672 | 46.26 | 55.851 | 68.877 | 59.771 | 69.828 | 77.318 |
| highpurity bbgg/wwgg+bbgg(%) | 2.15 | 4.711 | 9.6 | 4.11 | 1.596 | 1.522 | 0.621 | 0.869 |
| lowpurity bbgg/wwgg+bbgg(%) | 45.171 | 40.849 | 35.944 | 45.256 | 58.172 | 44.579 | 55.862 | 72.074 |

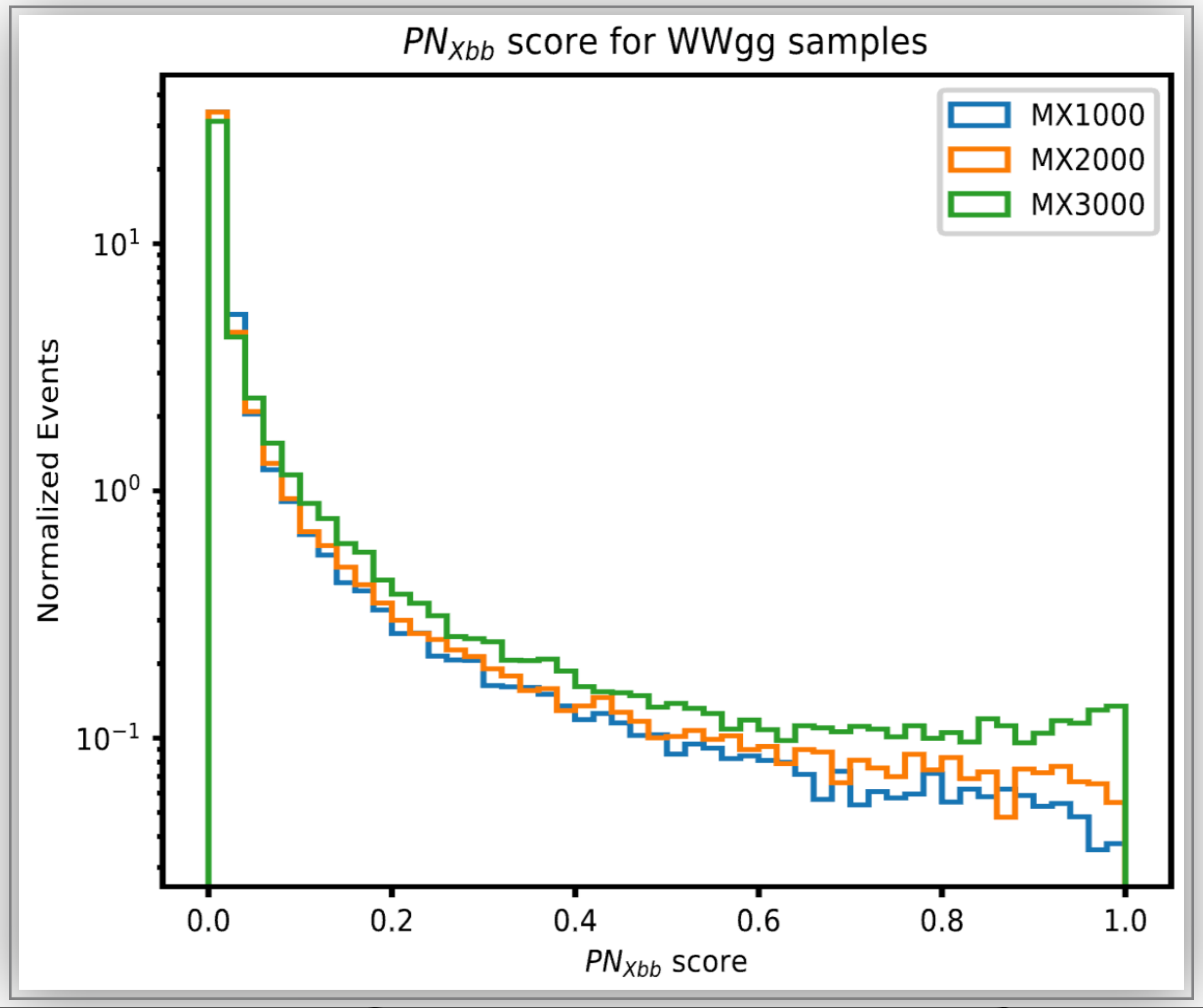


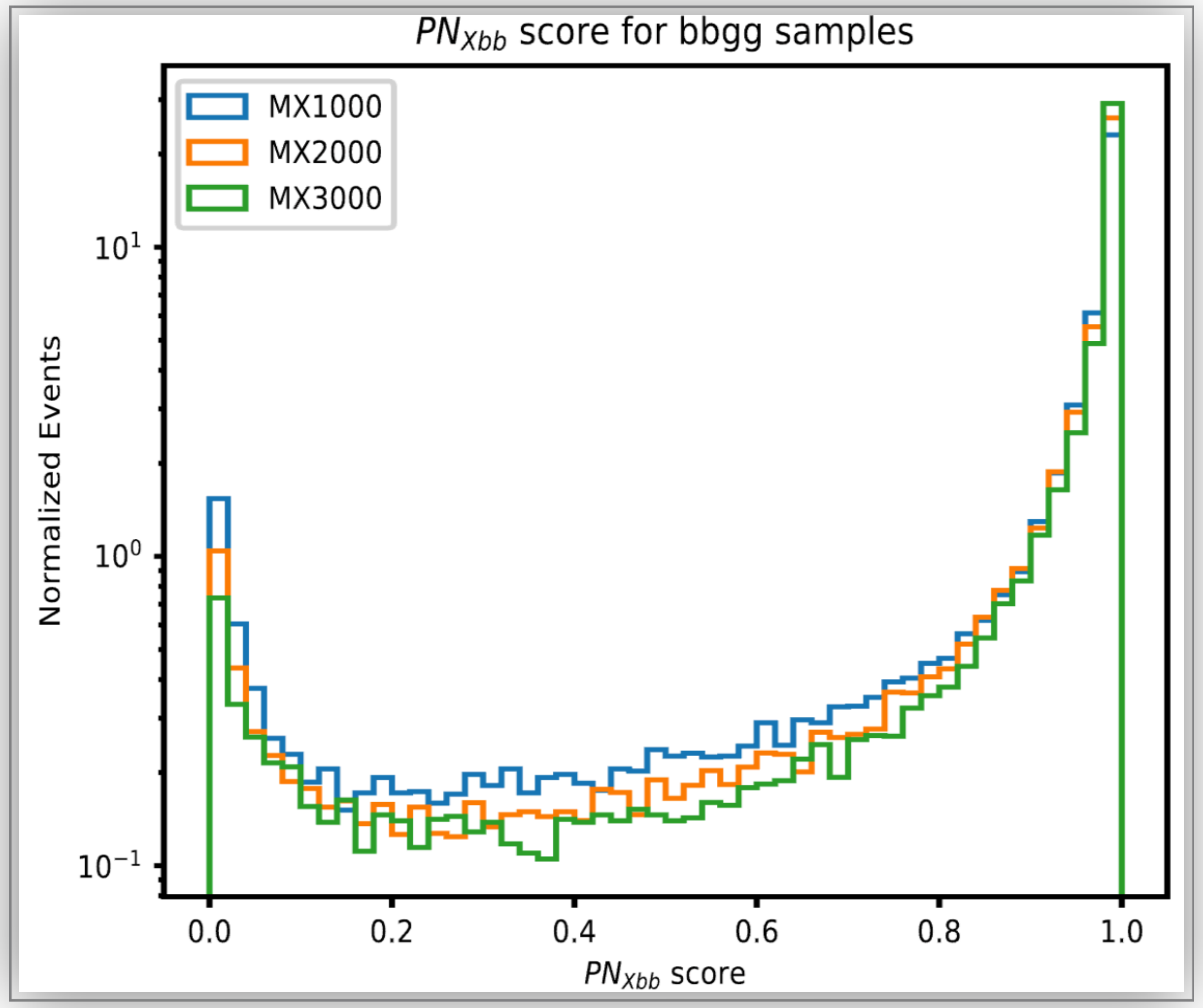



(j) LeadJet DeepJet b-Discriminant

# bbγγ contamination study

ParticleNet Hbb effectively rejected bbγγ events




| Cuts | SL3000 Efficiency% | FH3000 Efficiency% | ZZgg3000 Efficiency% | bbgg3000 Efficiency% |
|---|---|---|---|---|
| Original | 100.0 | 100.0 | 100.0 | 100.0 |
| Diphoton Candidate | 71.788 | 71.79 | 71.805 | 72.082 |
| boosted bbgg Veto | 67.211 | 69.929 | 58.491 | 15.127 |
| SL ZZgg Veto | 67.211 | 69.929 | 58.491 | 15.127 |
| Diphoton minID > -0.7 | 65.881 | 68.358 | 57.291 | 14.853 |
| WWgg Candidate | 63.372 | 63.793 | 49.693 | 9.945 |
| Boosted | 60.92 | 61.442 | 46.131 | 7.6 |
| Resolved | 2.197 | 2.351 | 3.562 | 2.345 |
| Boosted DNN | 60.475 | 61.249 | 45.963 | 7.51 |
| Resolved DNN | 0.0 | 0.0 | 0.0 | 0.0 |
| DNN total | 60.475 | 61.249 | 45.963 | 7.51 |

# Systematics Uncertainties

All relevant systematics uncertainties come from photon, jet, lepton, tagger and theoretical systematic uncertainties

- **Theoretical**
  - $H\rightarrow\gamma\gamma$, $H\rightarrow VV$, bb, $\tau\tau$ branching fractions
  - QCD scale (only single Higgs)
  - PDF (only single Higgs)
- **Experimental**
  - $m_{\gamma\gamma}$ shape related
    - Photon energy scale & smearing
    - Materials
    - FNUF

- **Experimental**
  - Lumi
  - Trigger
  - Diphoton preselection SFs
  - Photon ID SFs
  - Electron/Muon reconstruction, ID, isolation
  - DeepJet btag reshape
  - JER/JES/MET_JER MET_Unclustered
  - Jet Pileup ID
  - L1-prefiring
  - ParticleNet WvsQCD, Hbb tagger efficiency
  - ParT Hww tagger efficiency
  - Electron veto SFs
  - Muon Momentum

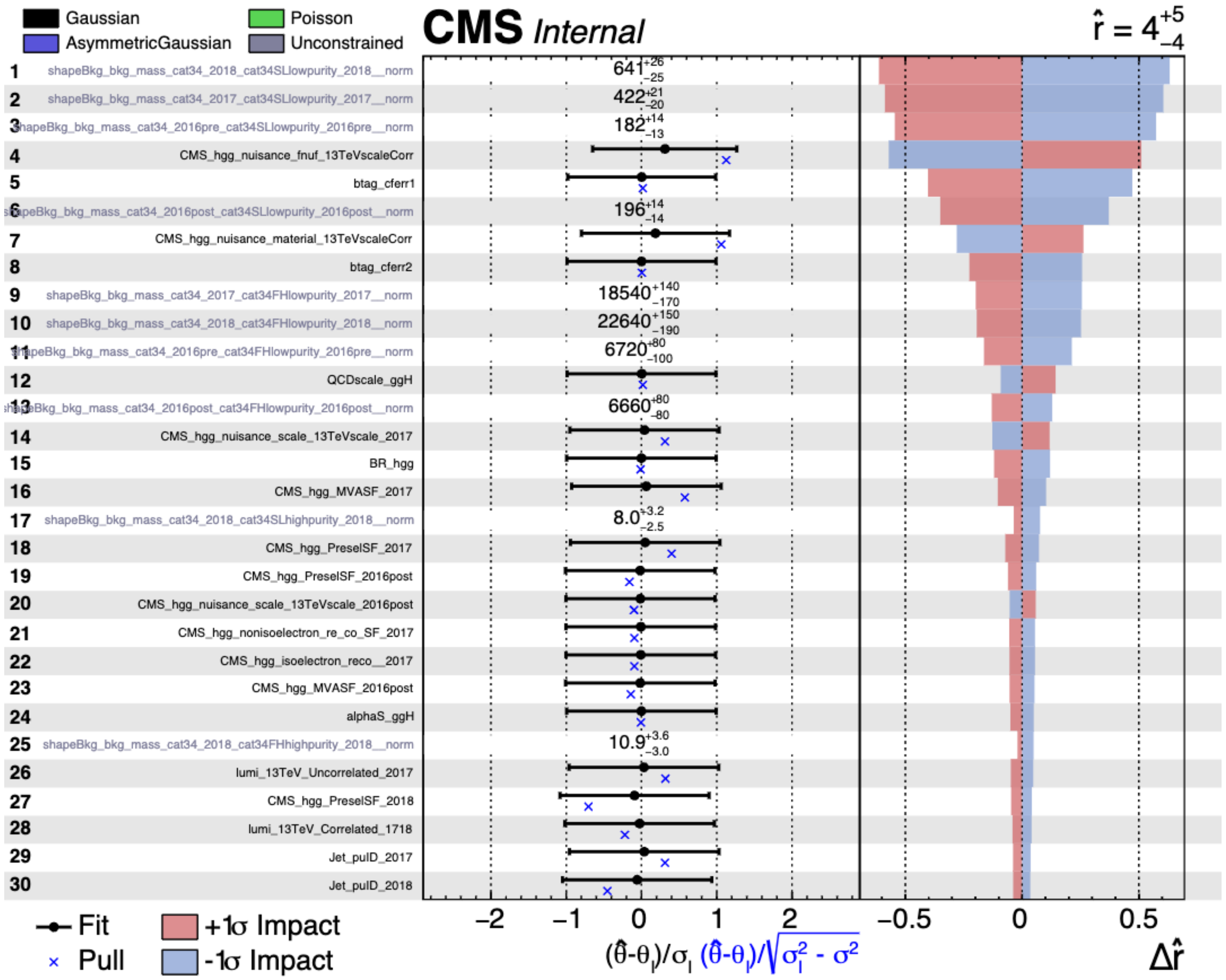
**The systematic uncertainties impact on limit is less than 7%**

# Low-mass X (250GeV) impacts

Statistic uncertainty dominant.

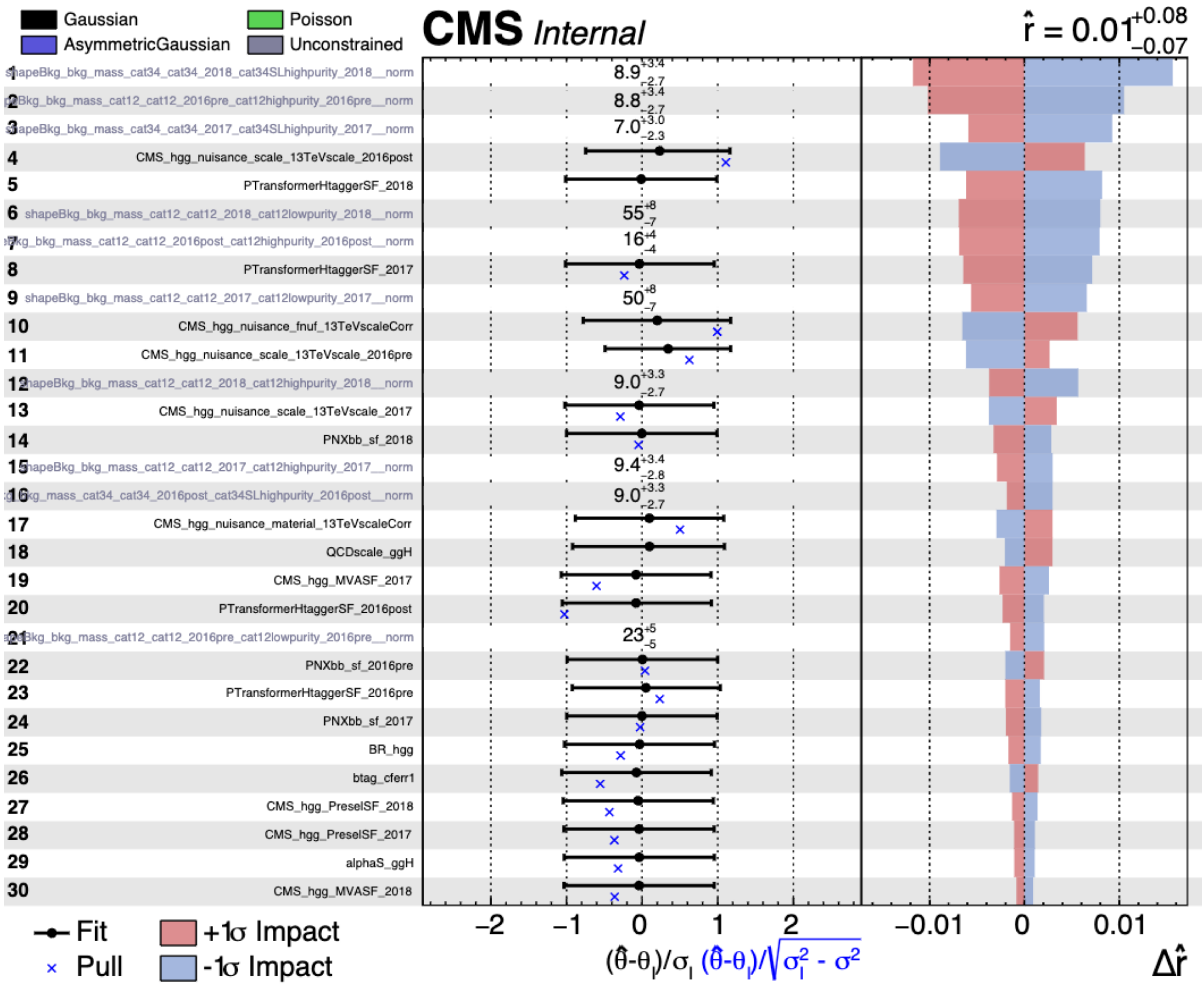
Most impactful nuisances:

- Photon energy scale
- DeepJet btag scale factor
- Theoretical uncertainties

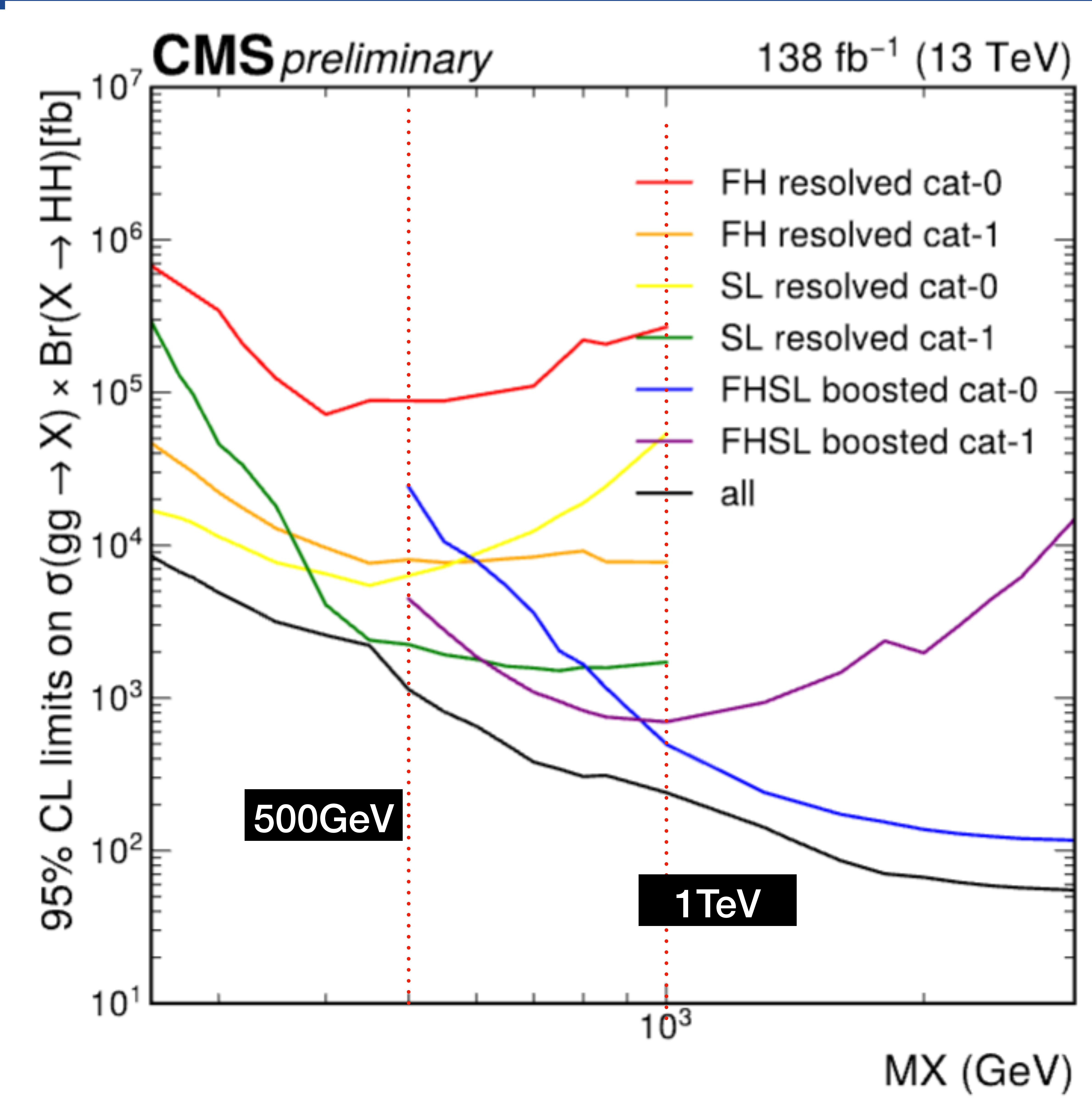


# High-mass X(1 TeV) impacts

- Statistic uncertainty dominant.
- Most impactful nuisances:
  - Photon energy scale
  - ParticleTransformer scale factor



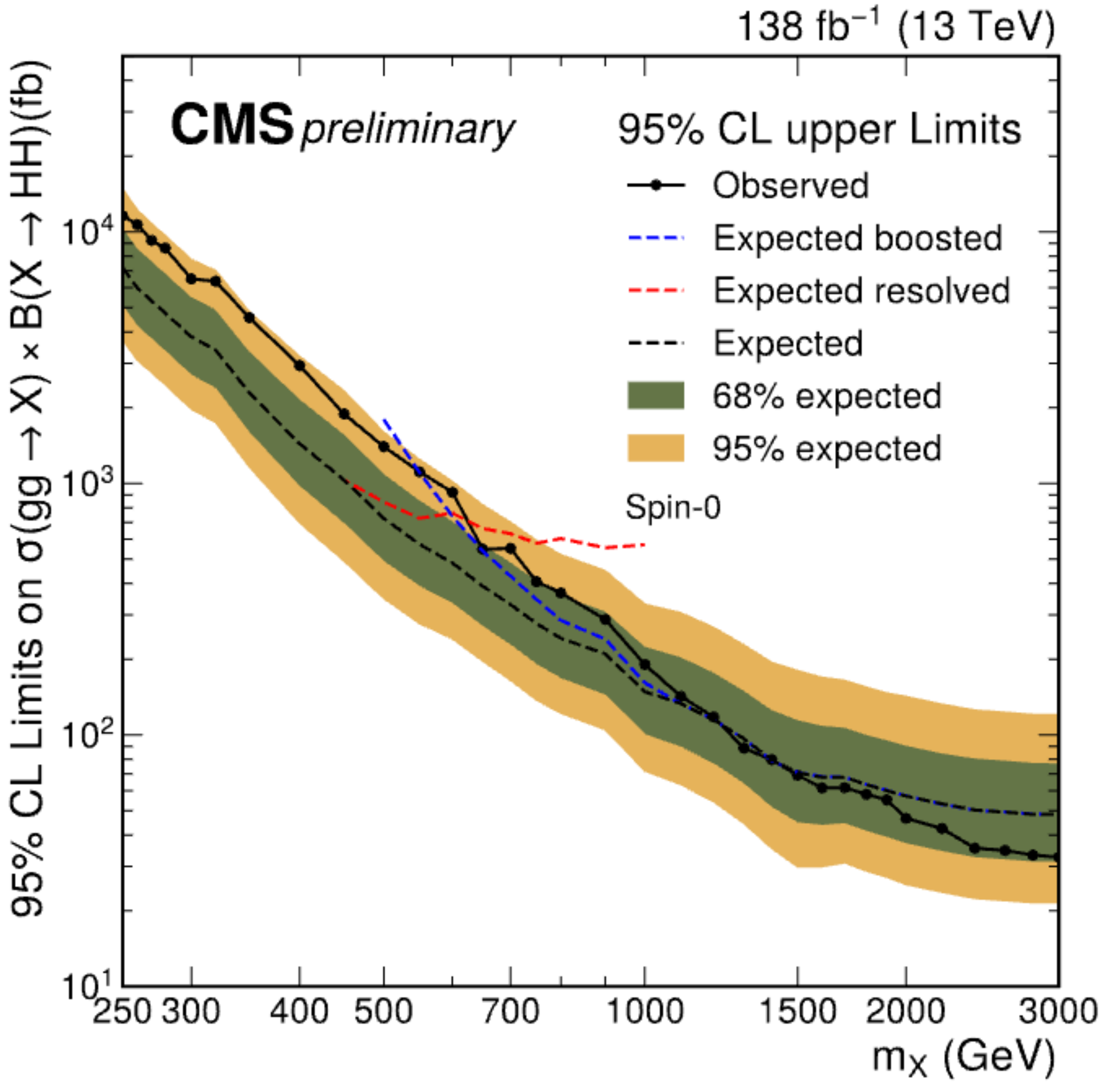
# Results — individual cat



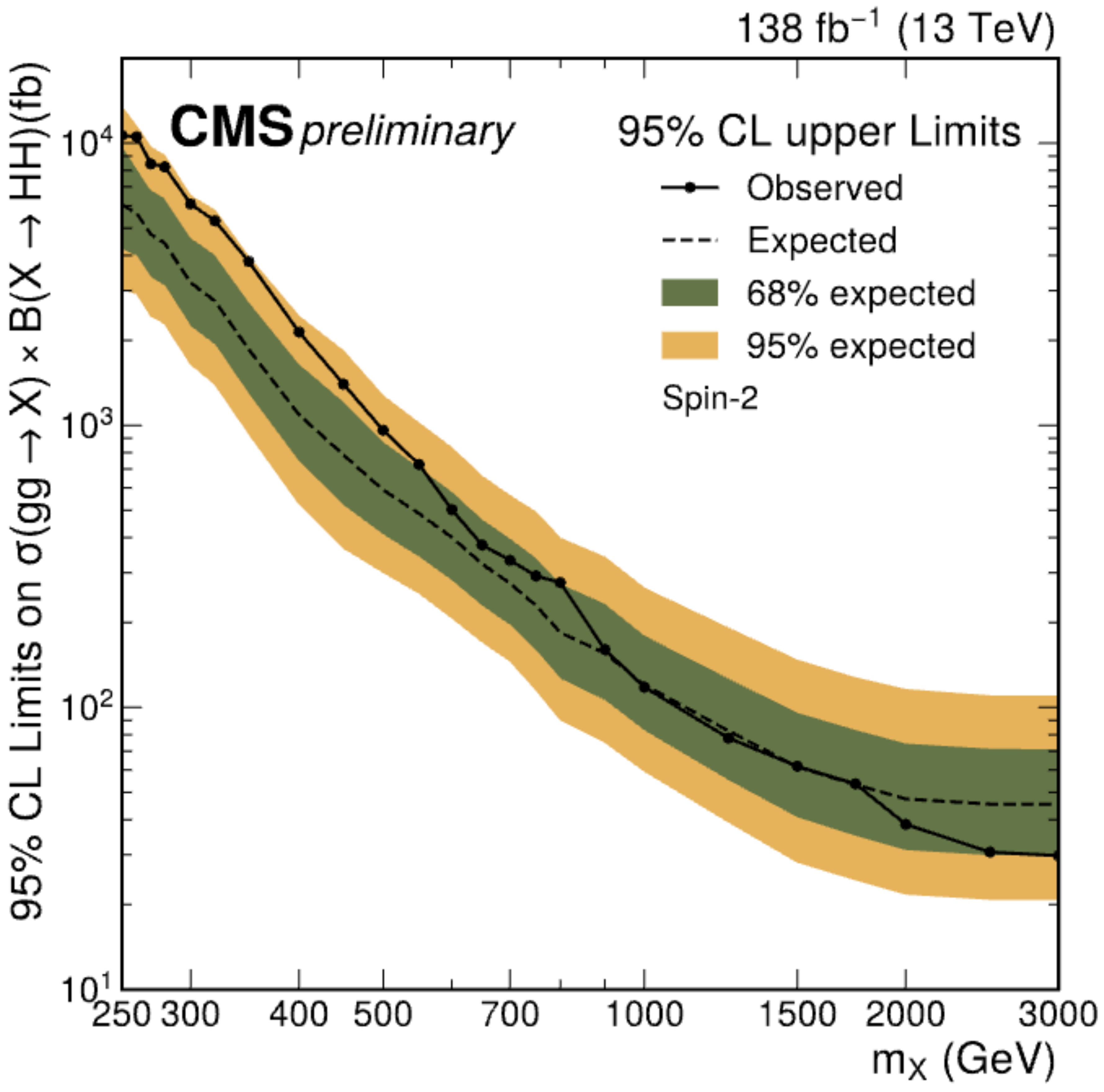
# Results

Observed (expected) 95% CL Limit on σ(X→HH), combining WWγγ, bbγγ, ZZγγ, ττγγ processes, using asymptotic approach

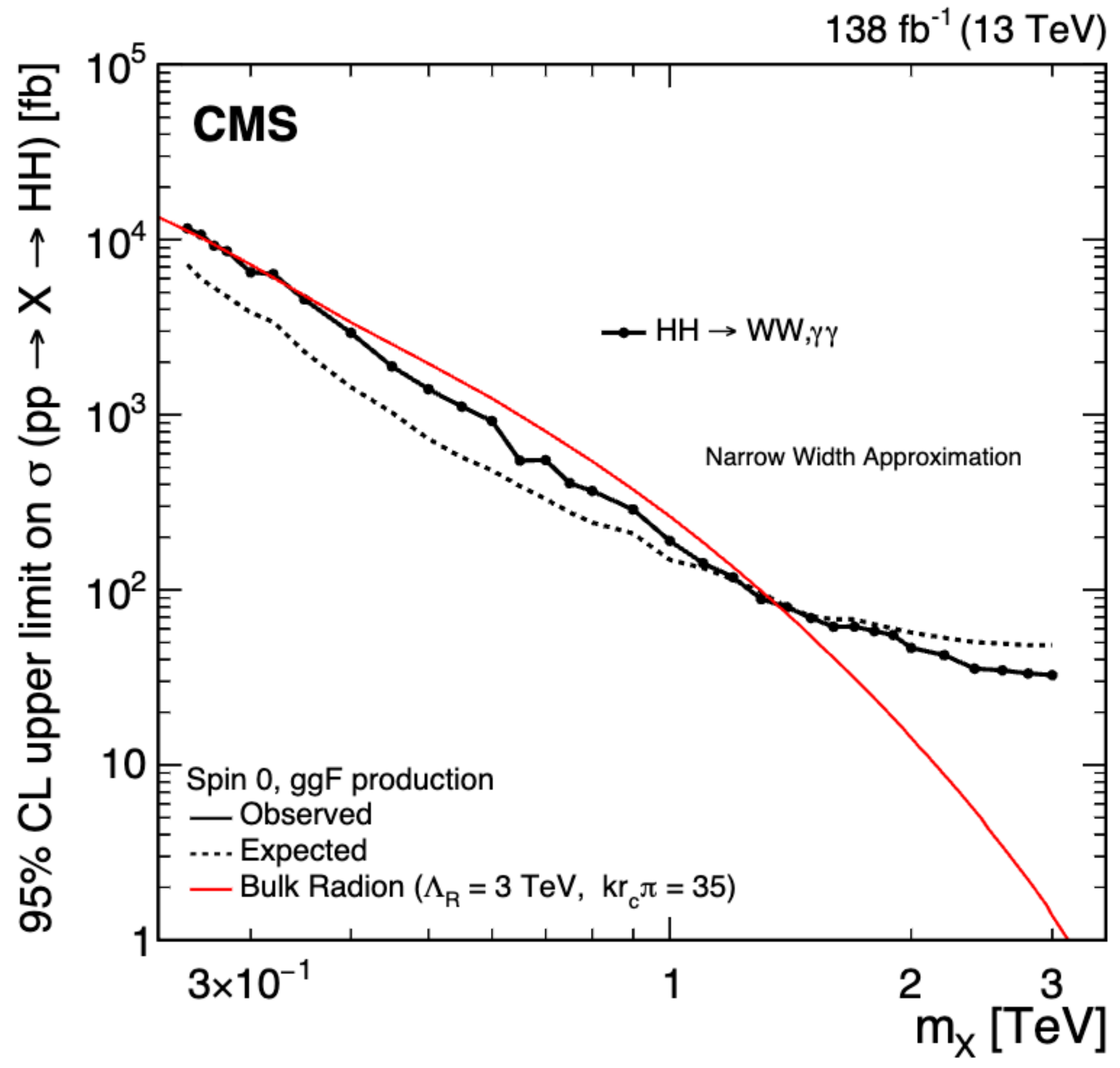
No excess found in radion or graviton




Spin-0 X (Radion)




Spin-2 X (Graviton)




Extra theory line for Radion

# Results comparison with ATLAS

A direct comparison of the 95% CL upper limits on $\sigma(X \to HH)$ at different resonance masses using **only 2016 data** demonstrates the improved performance of the CMS analysis:

| $m_X$ | ATLAS Expected Limit | CMS Expected Limit | Improvement |
|---|---|---|---|
| 260 GeV | $17.6^{+61.5}_{-8.1} pb$ | $11.2^{+13.2}_{-5.6} pb$ | 36% |
| 500 GeV | $4.4^{+5.1}_{-2.0} pb$ | $1.6^{+2.3}_{-0.8} pb$ | 64% |

Eur.Phys.J.C 78 (2018) 1007, 2018.

With similar integrated luminosity and analyzing the same final state (SL resolved only), our analysis still demonstrates superior performance over the ATLAS results:

| $m_X$ | ATLAS Expected Limit | CMS Expected Limit | Improvement |
|---|---|---|---|
| 260 GeV | $17.6^{+61.5}_{-8.1} pb$ | $12.2^{+13.9}_{-6.1} pb$ | 31% |
| 500 GeV | $4.4^{+5.1}_{-2.0} pb$ | $1.9^{+3.0}_{-1.1} pb$ | 57% |

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