Search for Non-Resonant HH production at the LHC

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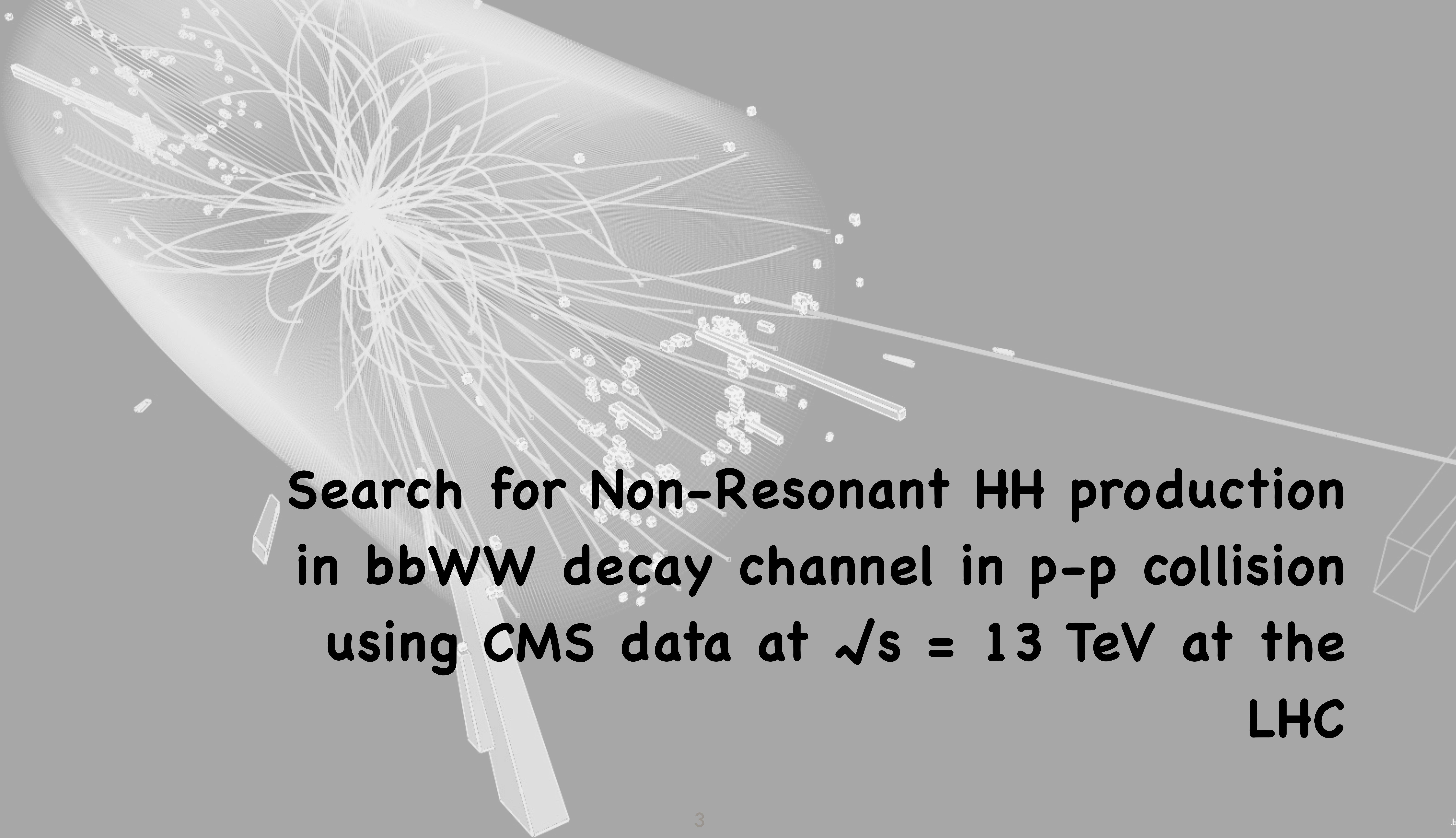
DRS Seminar, IPHC, Strasbourg

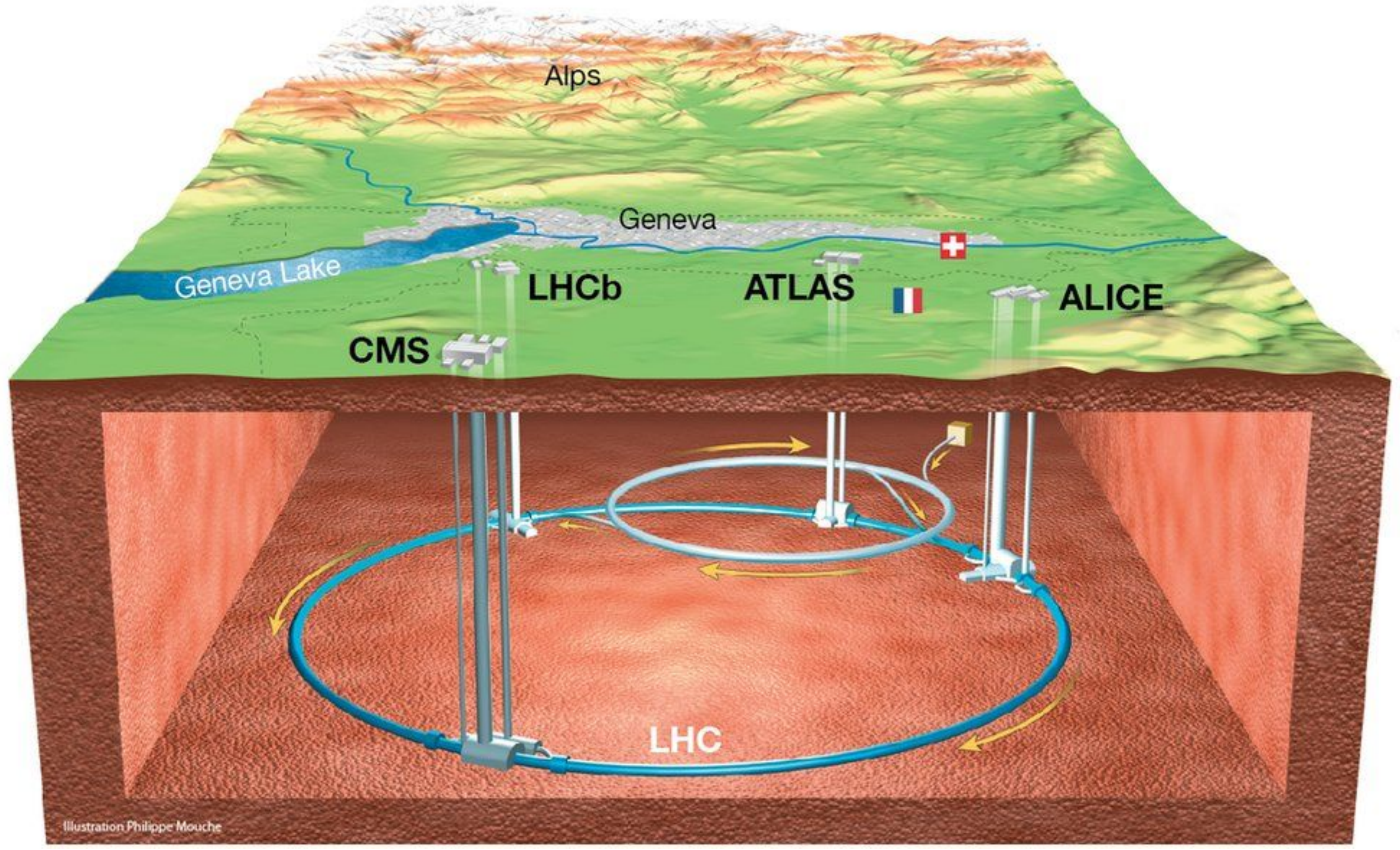
Outline

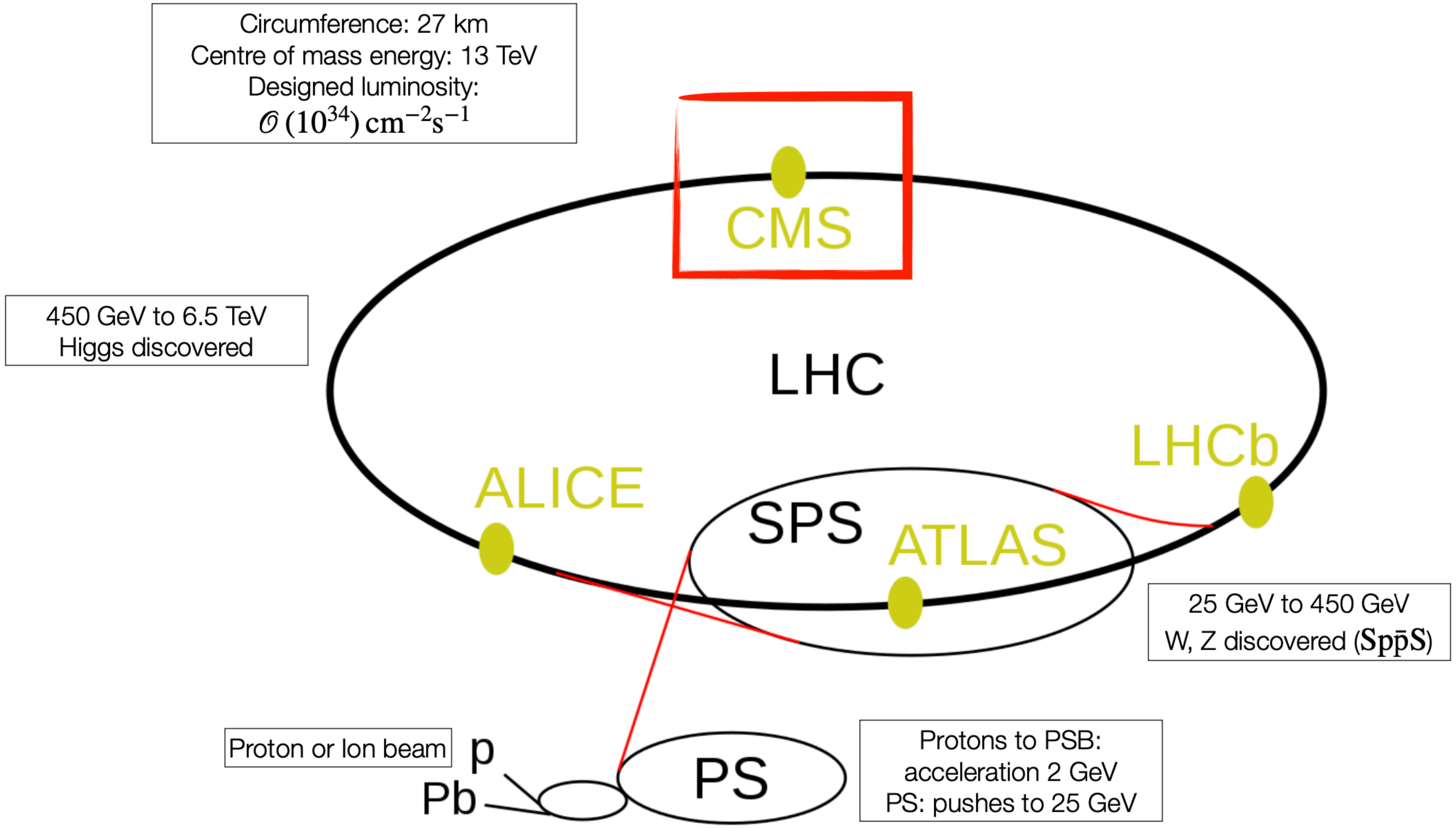
- Non-resonant production of HH in bbWW channel
- Test Beam study of CMS phase 2 tracker 2S module
- A few Phenomenological studies
- Do not let the neutrino escape



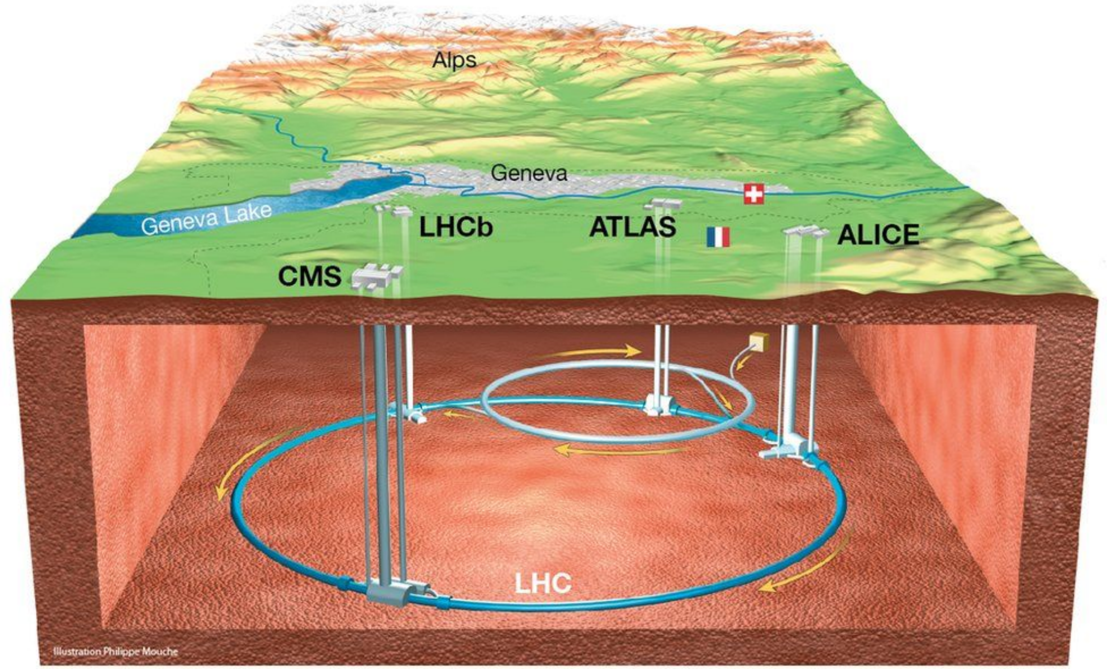
Search for Non-Resonant HH production in bbWW decay channel in p-p collision using CMS data at $\sqrt{s}$ = 13 TeV at the LHC

LHC


Alps
Geneva
Geneva Lake
LHCb
ATLAS
ALICE
CMS
LHC


Circumference: 27 km
Centre of mass energy: 13 TeV
Designed luminosity:
$\mathcal{O}\,(10^{34})\,\mathrm{cm}^{-2}\mathrm{s}^{-1}$
CMS
450 GeV to 6.5 TeV
Higgs discovered
LHC
LHCb
ALICE
SPS
ATLAS
25 GeV to 450 GeV
W, Z discovered ($\mathrm{Sp\bar{p}S}$)
Proton or Ion beam
p
Pb
PS
Protons to PSB:
acceleration 2 GeV
PS: pushes to 25 GeV

CMS


Alps
Geneva
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CMS
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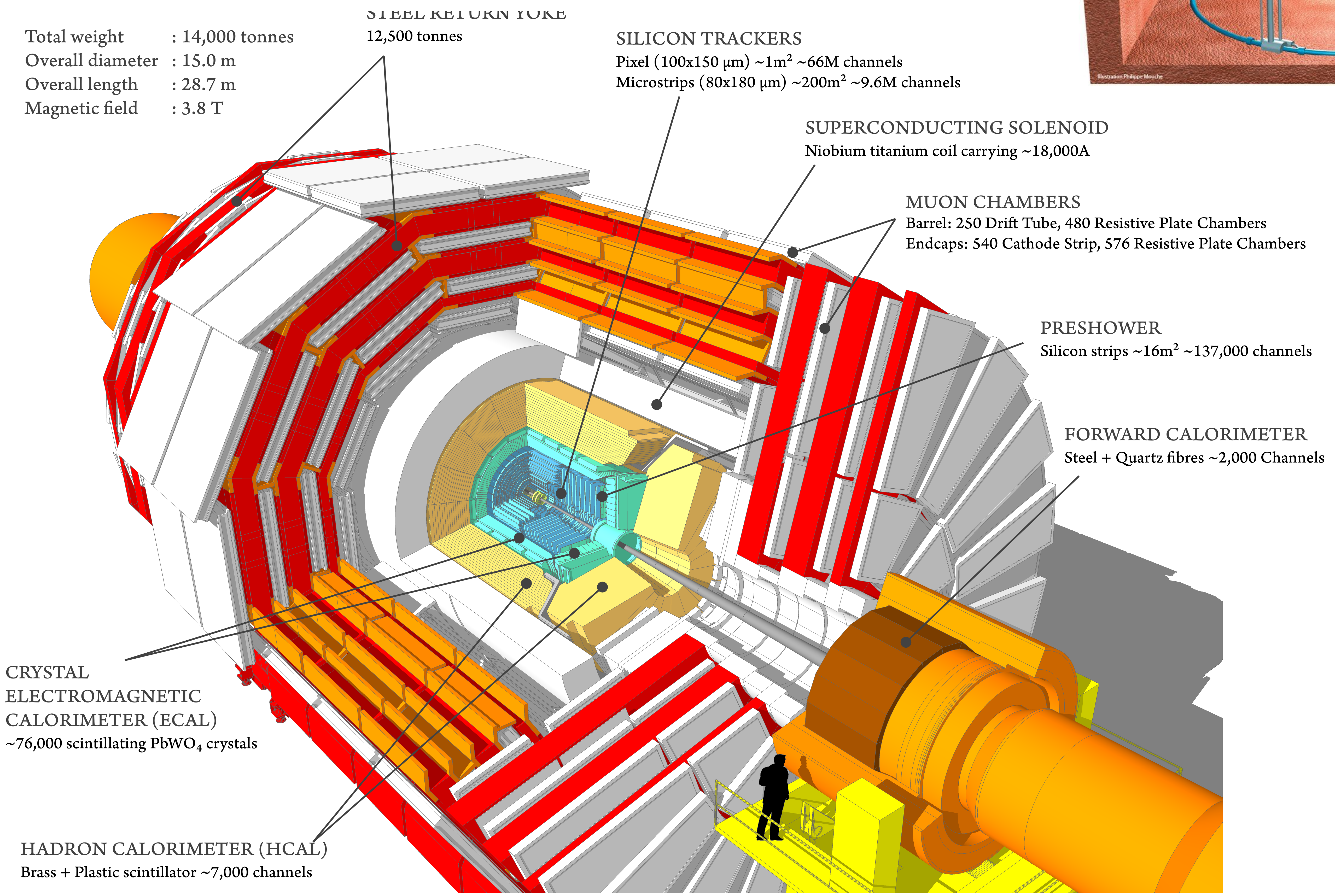
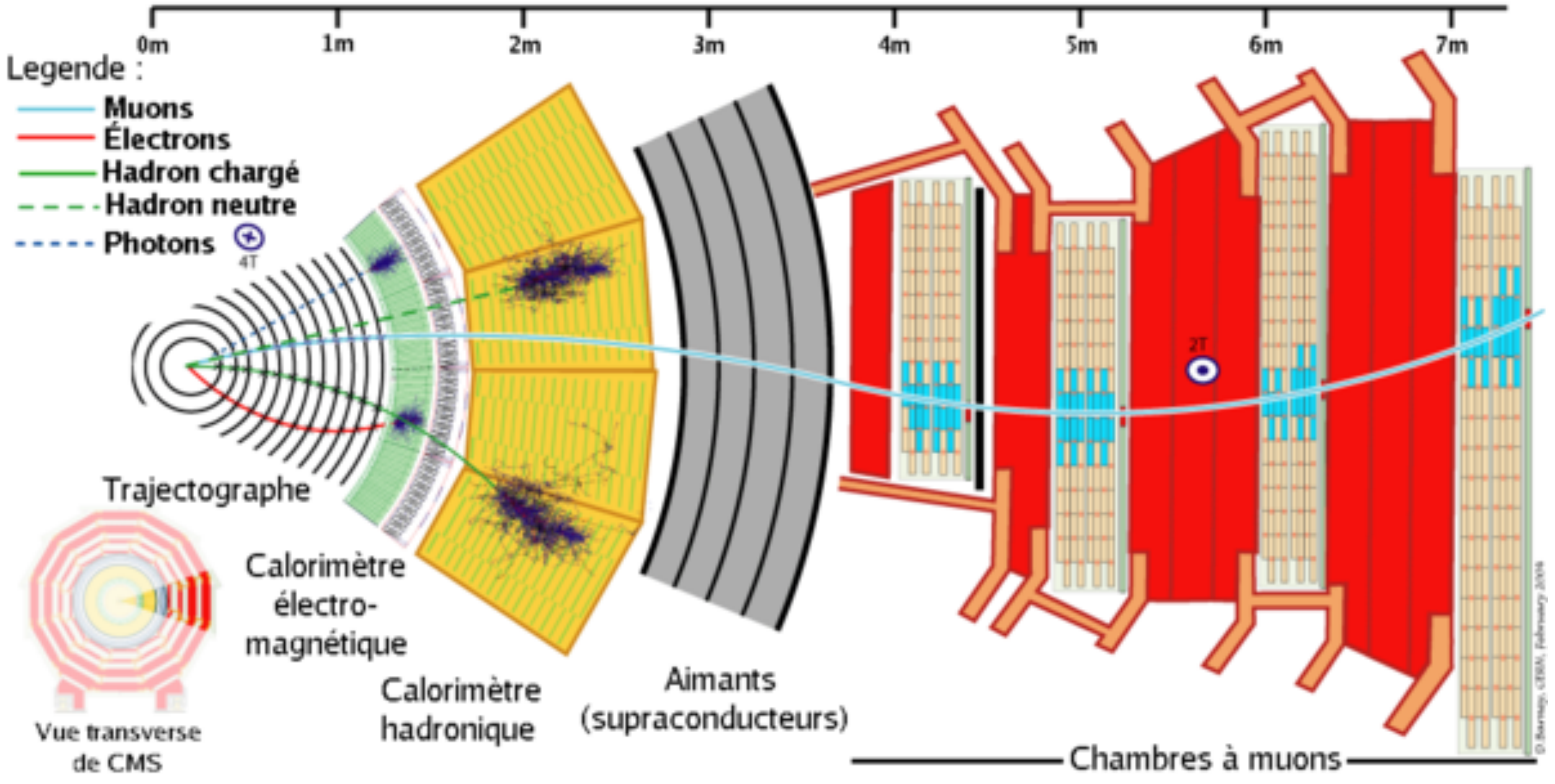
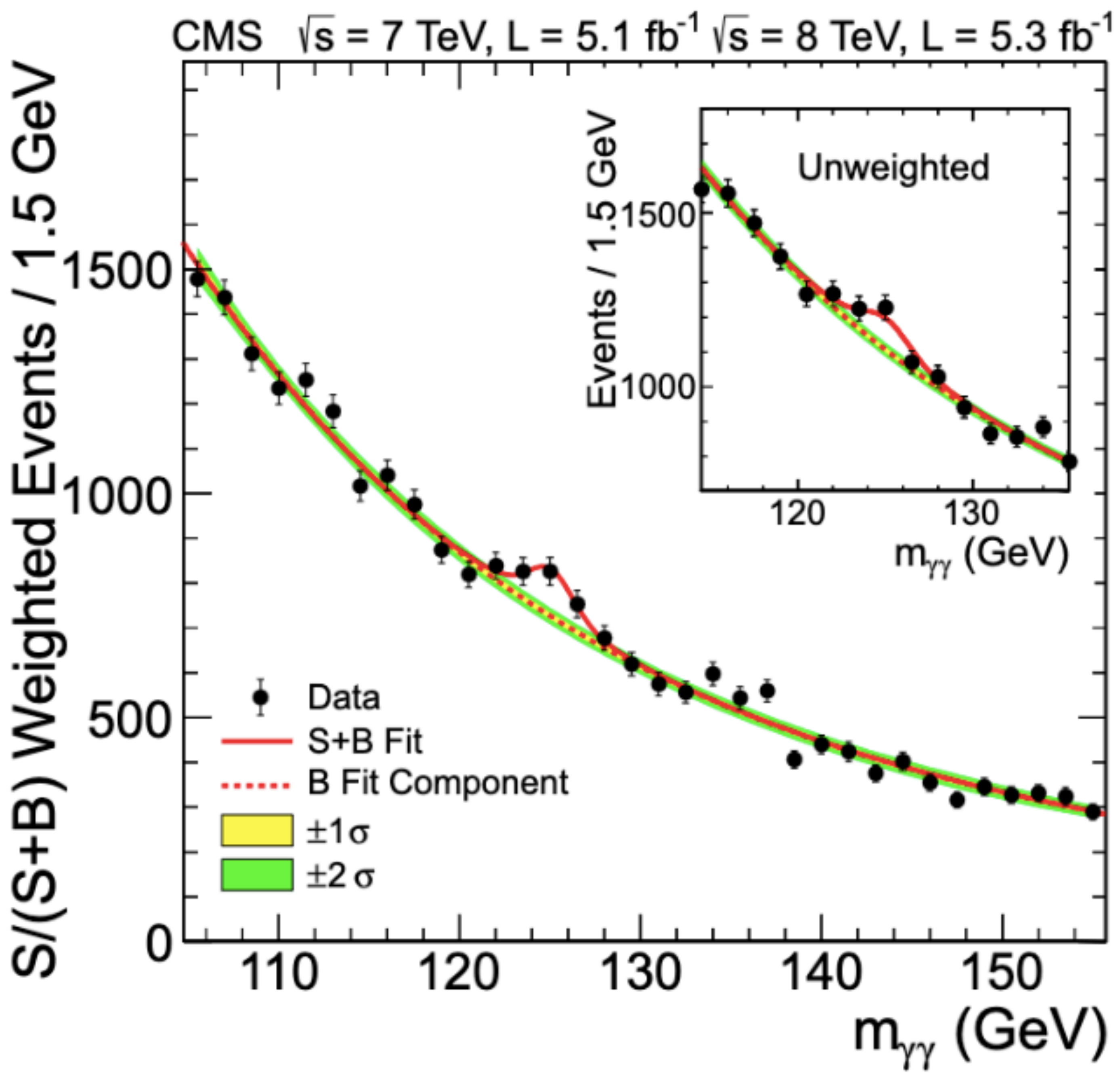
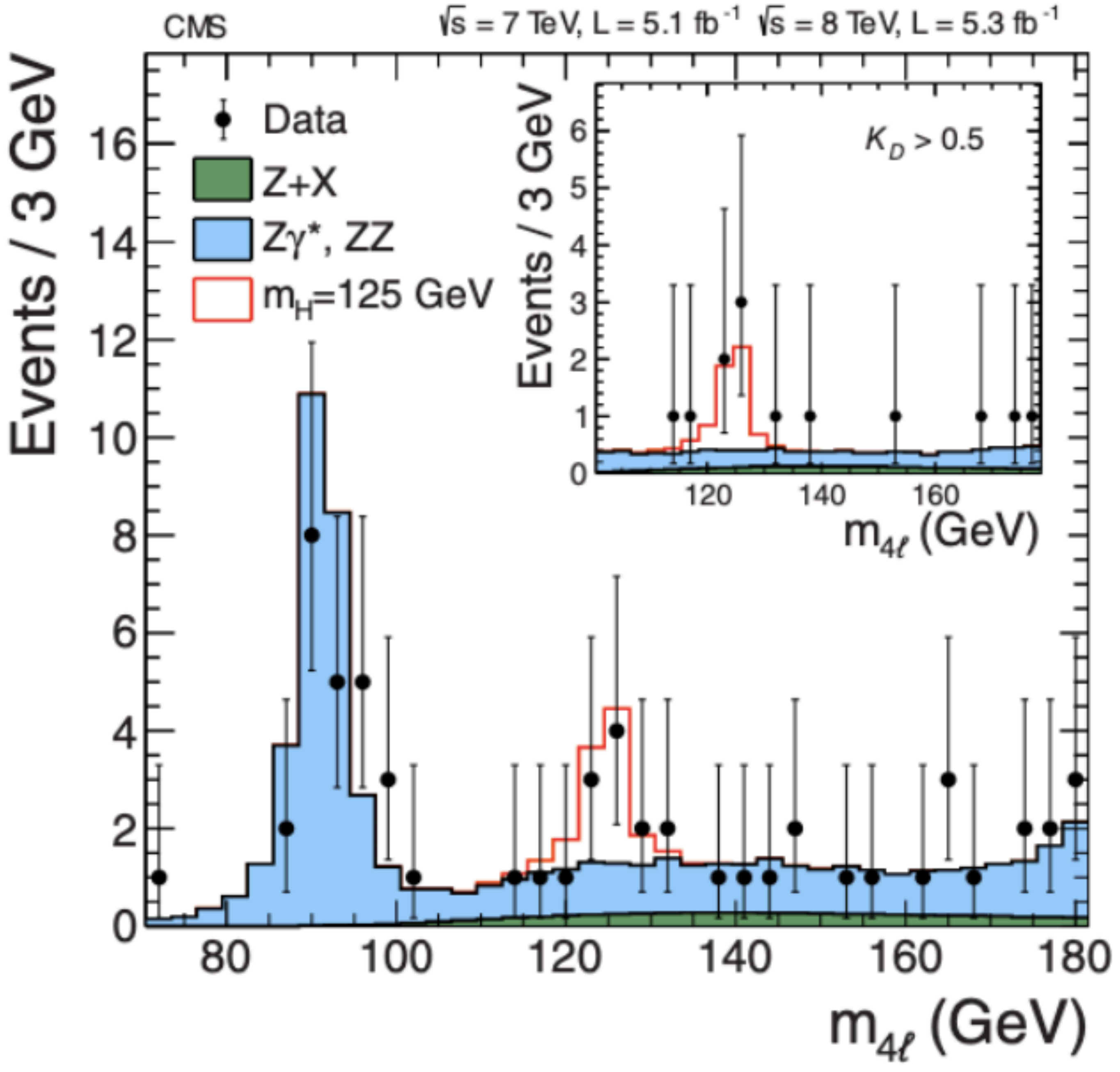

Total weight : 14,000 tonnes
Overall diameter : 15.0 m
Overall length : 28.7 m
Magnetic field : 3.8 T
STEEL RETURN YOKE
12,500 tonnes
SILICON TRACKERS
Pixel (100x150 μm) ~1m² ~66M channels
Microstrips (80x180 μm) ~200m² ~9.6M channels
SUPERCONDUCTING SOLENOID
Niobium titanium coil carrying ~18,000A
MUON CHAMBERS
Barrel: 250 Drift Tube, 480 Resistive Plate Chambers
Endcaps: 540 Cathode Strip, 576 Resistive Plate Chambers
PRESHOWER
Silicon strips ~16m² ~137,000 channels
FORWARD CALORIMETER
Steel + Quartz fibres ~2,000 Channels
CRYSTAL ELECTROMAGNETIC CALORIMETER (ECAL)
~76,000 scintillating PbWO4 crystals
HADRON CALORIMETER (HCAL)
Brass + Plastic scintillator ~7,000 channels


0m
1m
2m
3m
4m
5m
6m
7m
Legende :
Muons
Électrons
Hadron chargé
Hadron neutre
Photons
4T
2T
Trajectographe
Calorimètre électro-magnétique
Calorimètre hadronique
Aimants (supraconducteurs)
Chambres à muons
Vue transverse de CMS

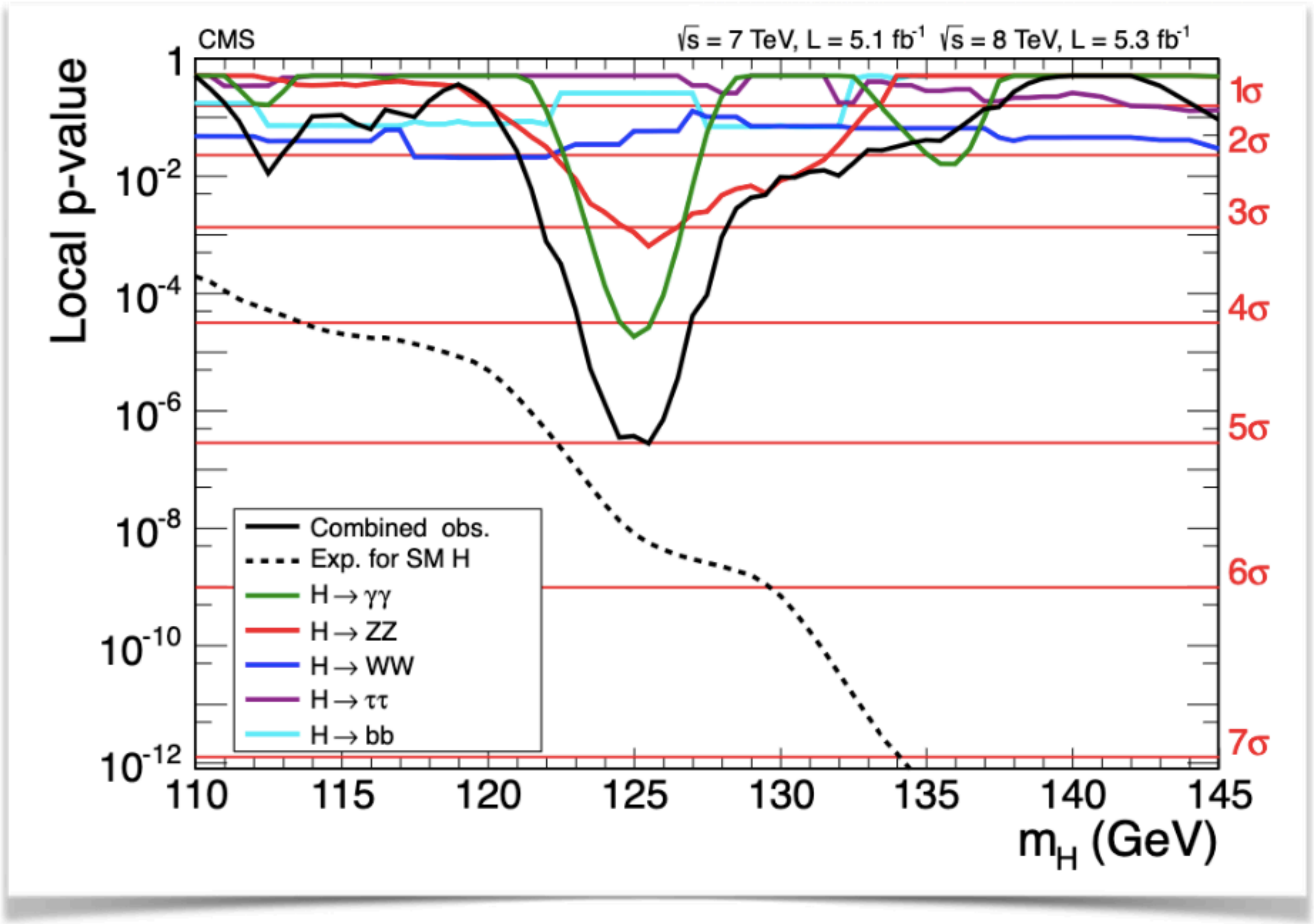
Higgs Discovery



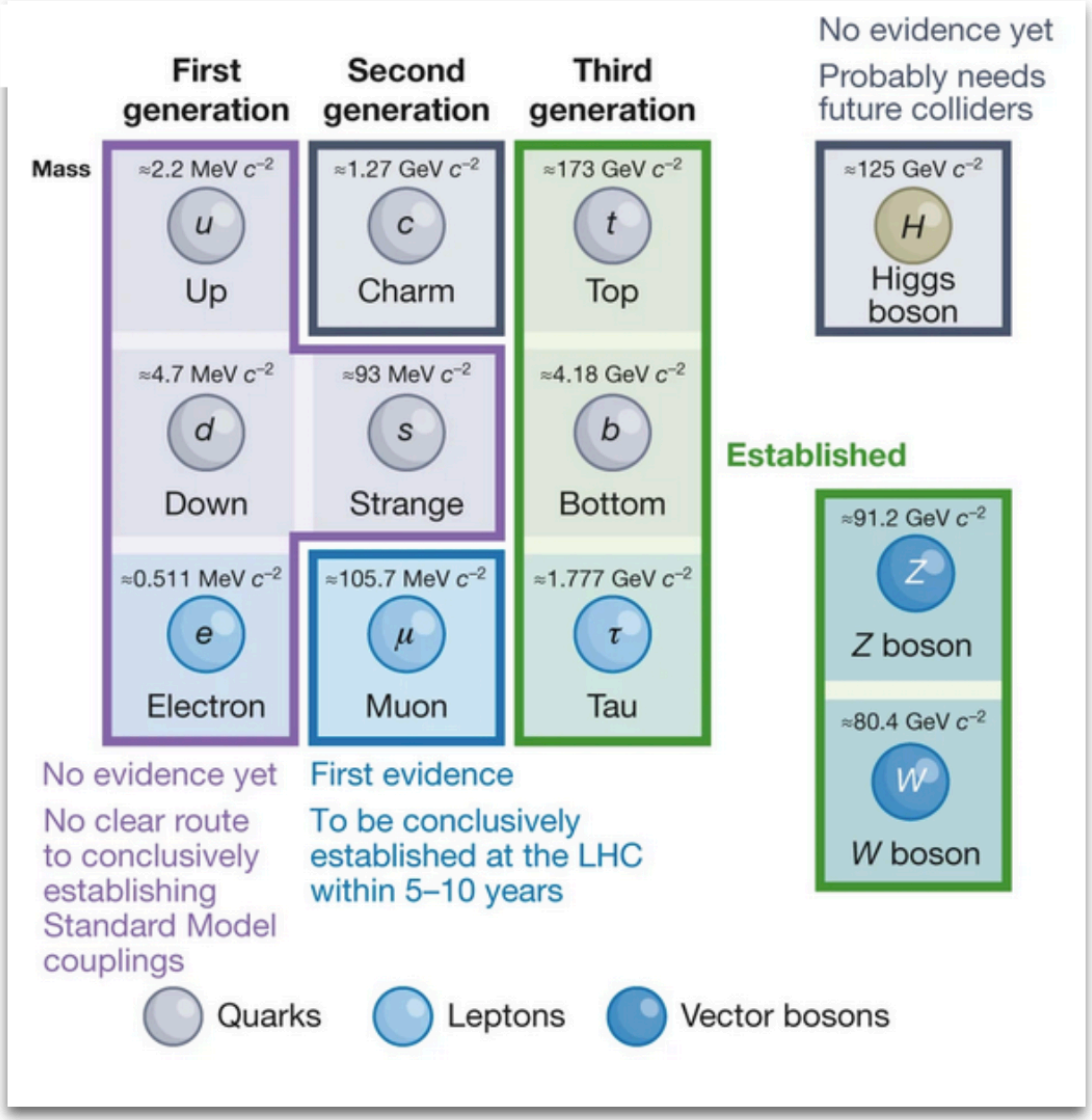
$H \to \gamma\gamma$

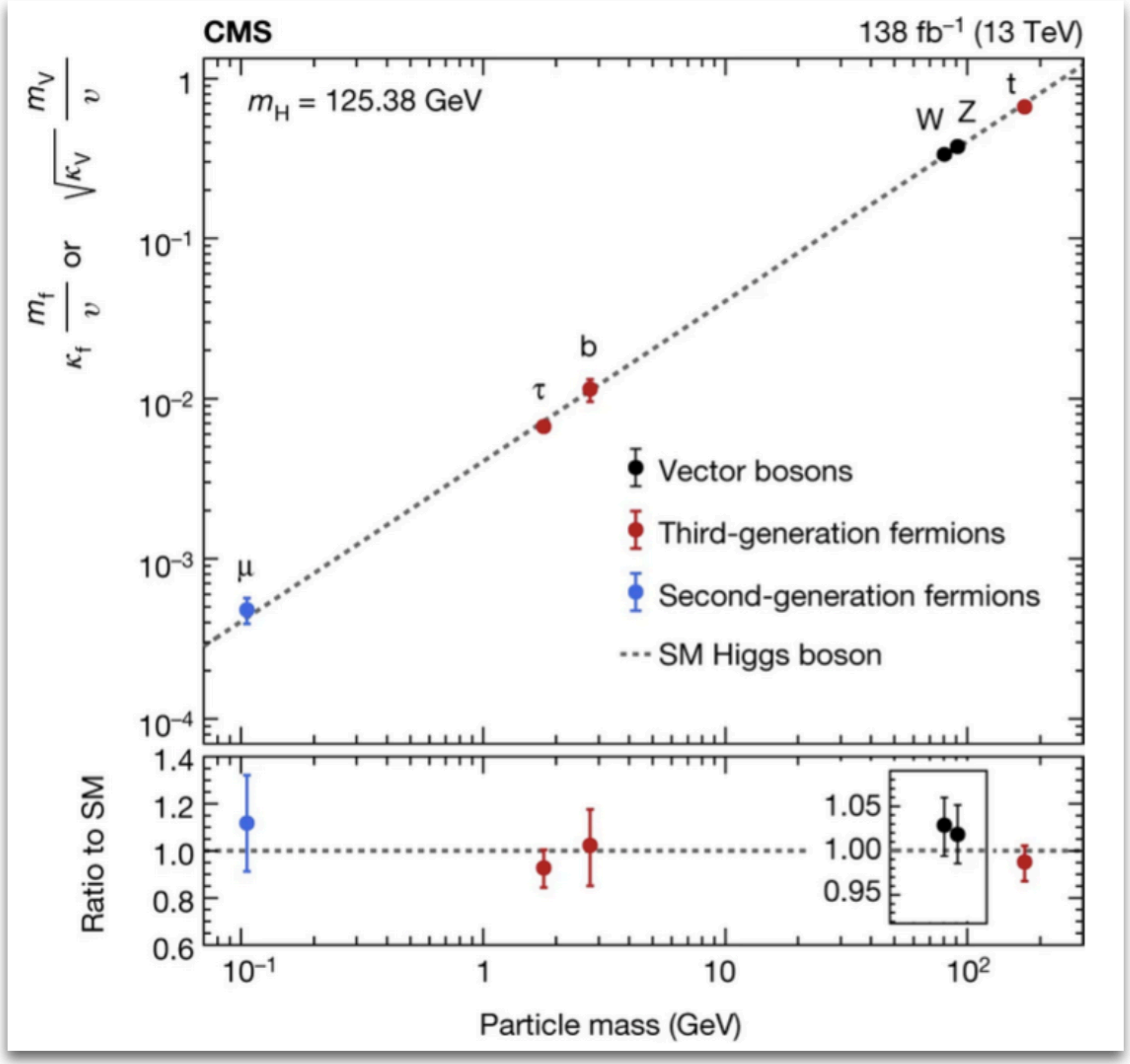


$H \to ZZ \to 4\ell$



Higgs Interactions to SM particles





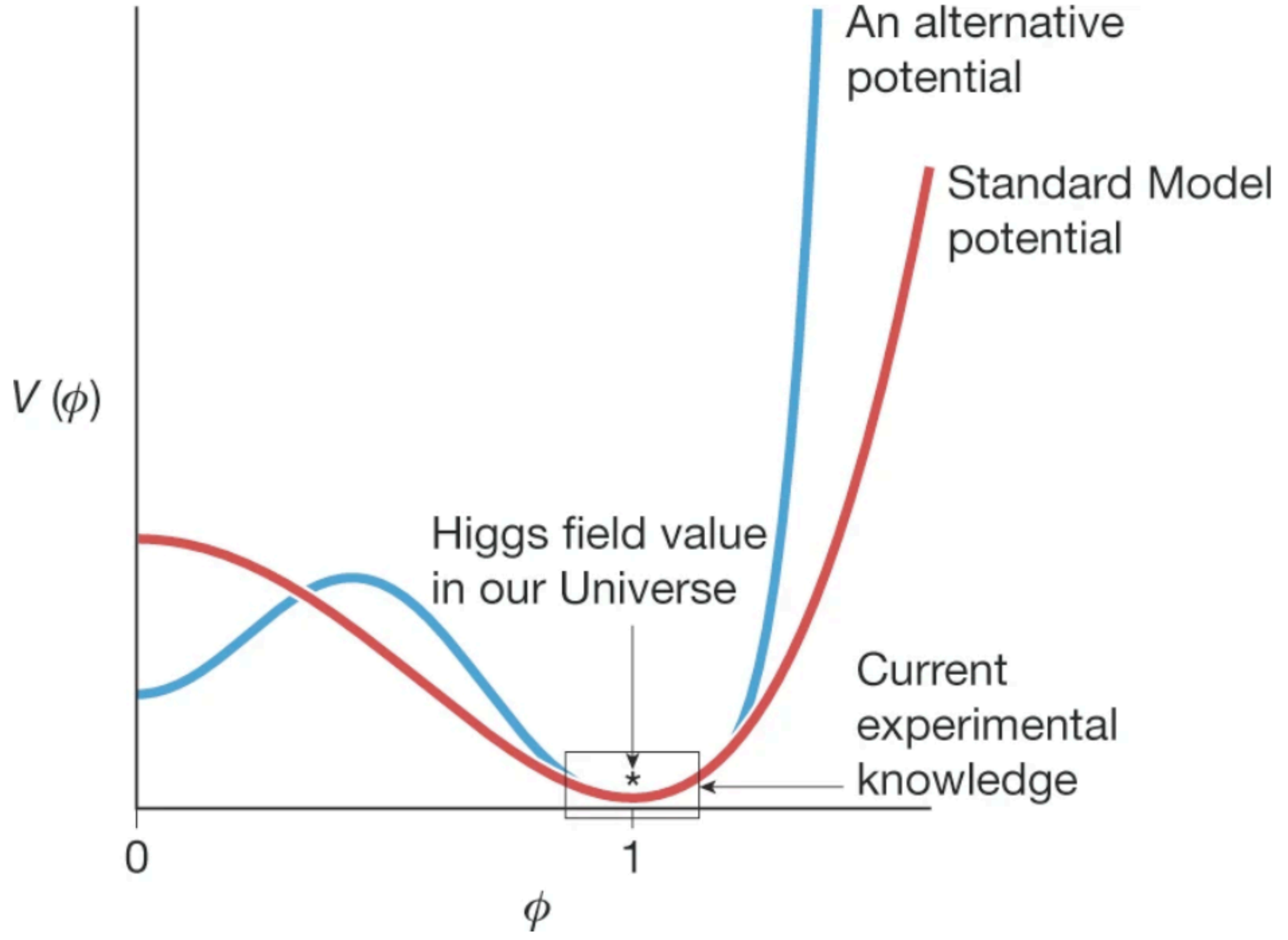
Higgs self-coupling

$$\mathcal{L}_{scalar} = D_\mu \phi^\dagger D^\mu \phi - V(\phi^\dagger \phi) \text{ with } \phi = (\varphi^+ \ \varphi^0)^T \text{ doublet under } SU(2)$$

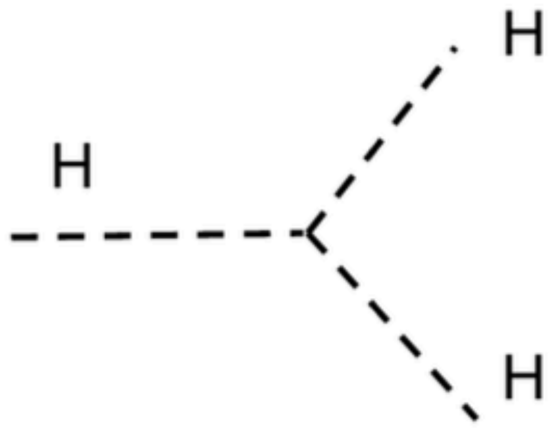
$$V(\phi^\dagger \phi) = -\mu^2(\phi^\dagger \phi) + \lambda(\phi^\dagger \phi)^2$$

$$\begin{aligned}\mathcal{L}_{BEH} = &\frac{1}{2}\partial_\mu \mathrm{H} \partial^\mu \mathrm{H} - \frac{1}{2}\left(2\lambda v^2\right)\mathrm{H}^2 \\ &+ \left(\frac{g^2 v^2}{4}\right) W_\mu^- W^{\mu+} + \frac{1}{2}\left(\frac{(g^2+g'^2)v^2}{4}\right) Z_\mu Z^\mu \\ &+ \left(\frac{g^2 v^2}{4}\right)\frac{2}{v}\mathrm{H} W_\mu^- W^{\mu+} + \left(\frac{(g^2+g'^2)v^2}{4}\right)\frac{1}{v}\mathrm{H} Z_\mu Z^\mu \\ &+ \left(\frac{g^2 v^2}{4}\right)\frac{1}{v^2}\mathrm{H}^2 W_\mu^- W^{\mu+} + \frac{1}{2}\left(\frac{(g^2+g'^2)v^2}{4}\right)\frac{1}{v^2}\mathrm{H}^2 Z_\mu Z^\mu \\ &- \lambda v \mathrm{H}^3 - \frac{\lambda}{4}\mathrm{H}^4 + \frac{\lambda}{4}v^4.\end{aligned}$$

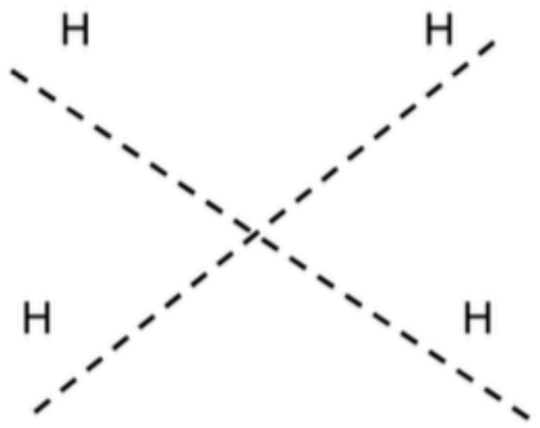
$$V(\mathrm{H}) = \frac{1}{2}m_{\mathrm{H}}^2 \mathrm{H}^2 + \lambda_{\mathrm{HHH}}\mathrm{H}^3 + \lambda_{\mathrm{HHHH}}\mathrm{H}^4 - \frac{1}{4}\lambda v^4$$



$$\lambda_{HHH} = \frac{m_H^2}{2v}$$



$$\lambda_{HHHH} = \frac{m_H^2}{8v^2}$$



Self coupling can be directly probed by studying HH production

Not only SM, possible deviations arising from BSM contributions can be examined

Higgs self-coupling

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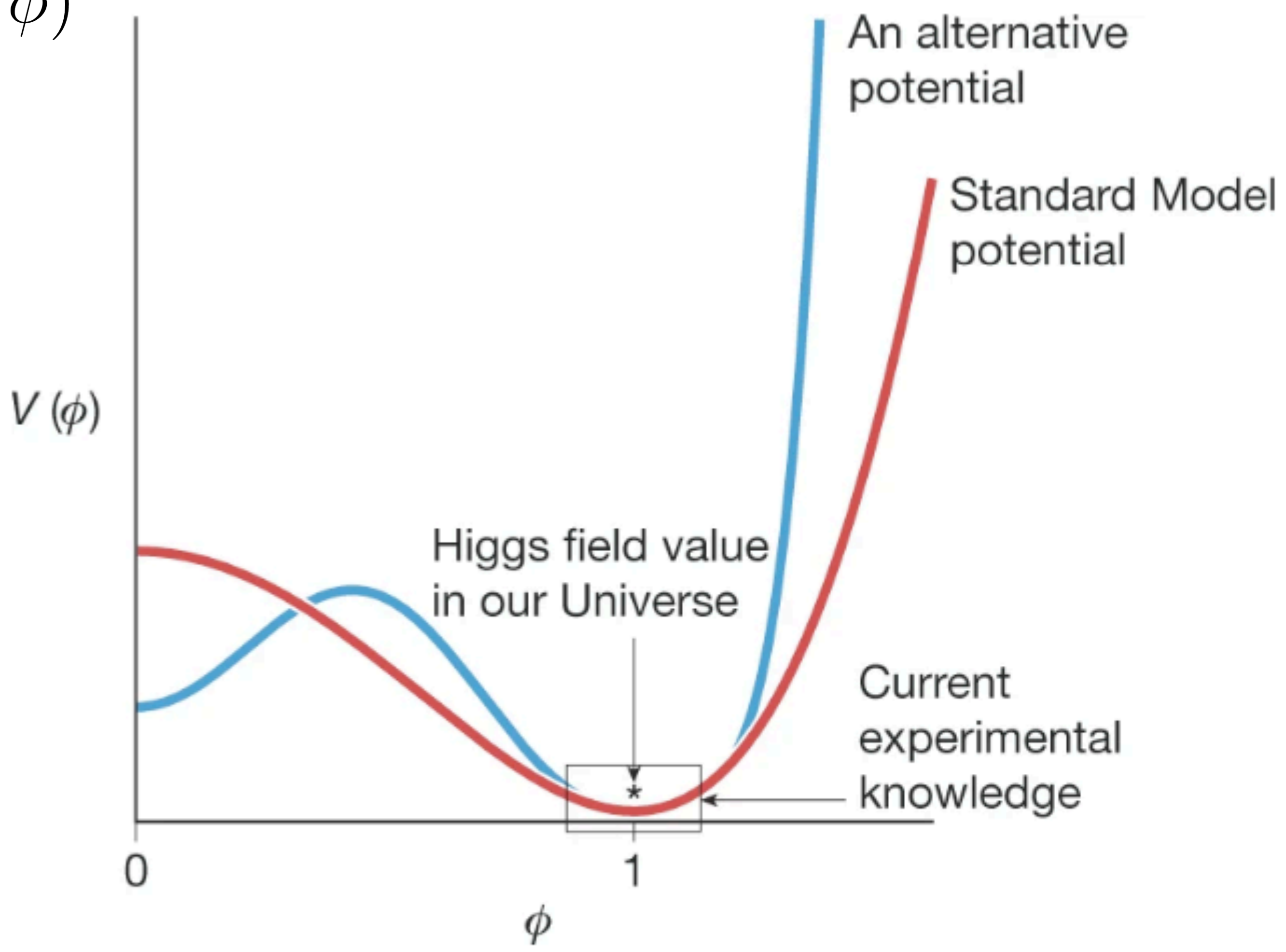
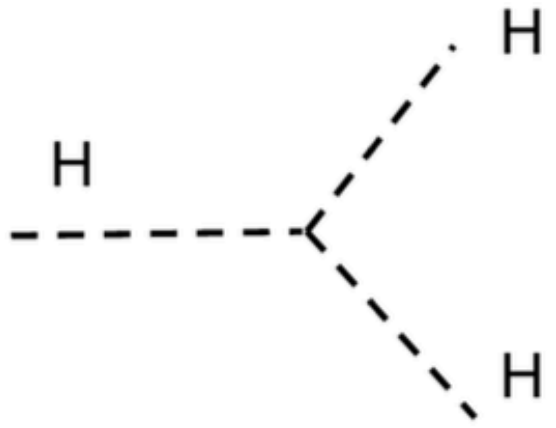
$$\begin{aligned}
\mathcal{L}_{BEH} = & \frac{1}{2}\partial_\mu \mathrm{H} \partial^\mu \mathrm{H} - \frac{1}{2}\left(2\lambda v^2\right)\mathrm{H}^2 \\
& + \left(\frac{g^2 v^2}{4}\right) W_\mu^- W^{\mu +} + \frac{1}{2}\left(\frac{(g^2+g'^2)v^2}{4}\right) Z_\mu Z^\mu \\
& + \left(\frac{g^2 v^2}{4}\right) \frac{2}{v}\mathrm{H} W_\mu^- W^{\mu +} + \left(\frac{(g^2+g'^2)v^2}{4}\right) \frac{1}{v}\mathrm{H} Z_\mu Z^\mu \\
& + \left(\frac{g^2 v^2}{4}\right) \frac{1}{v^2}\mathrm{H}^2 W_\mu^- W^{\mu +} + \frac{1}{2}\left(\frac{(g^2+g'^2)v^2}{4}\right) \frac{1}{v^2}\mathrm{H}^2 Z_\mu Z^\mu \\
& - \lambda v \mathrm{H}^3 - \frac{\lambda}{4}\mathrm{H}^4 + \frac{\lambda}{4} v^4 .
\end{aligned}$$

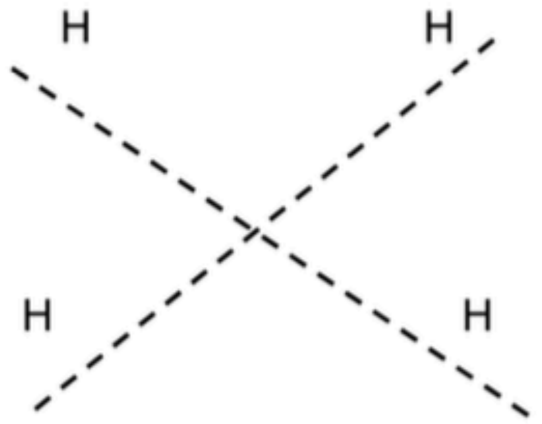


$$V(\mathrm{H}) = \frac{1}{2} m_{\mathrm{H}}^2 \mathrm{H}^2 + \lambda_{\mathrm{HHH}} \mathrm{H}^3 + \lambda_{\mathrm{HHHH}} \mathrm{H}^4 - \frac{1}{4}\lambda v^4$$

$$\lambda_{HHH} = \frac{m_H^2}{2v}$$



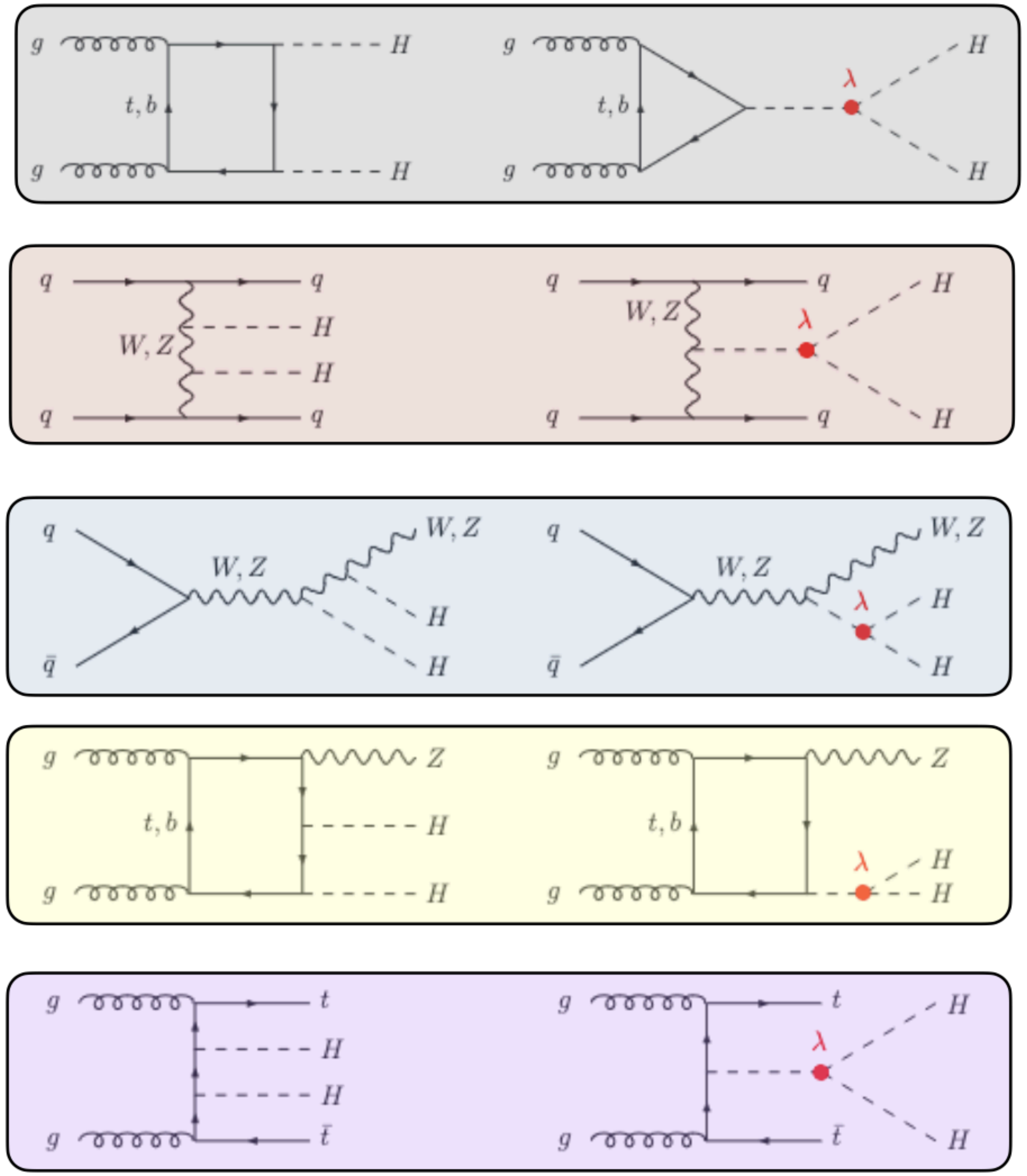
$$\lambda_{HHHH} = \frac{m_H^2}{8v^2}$$

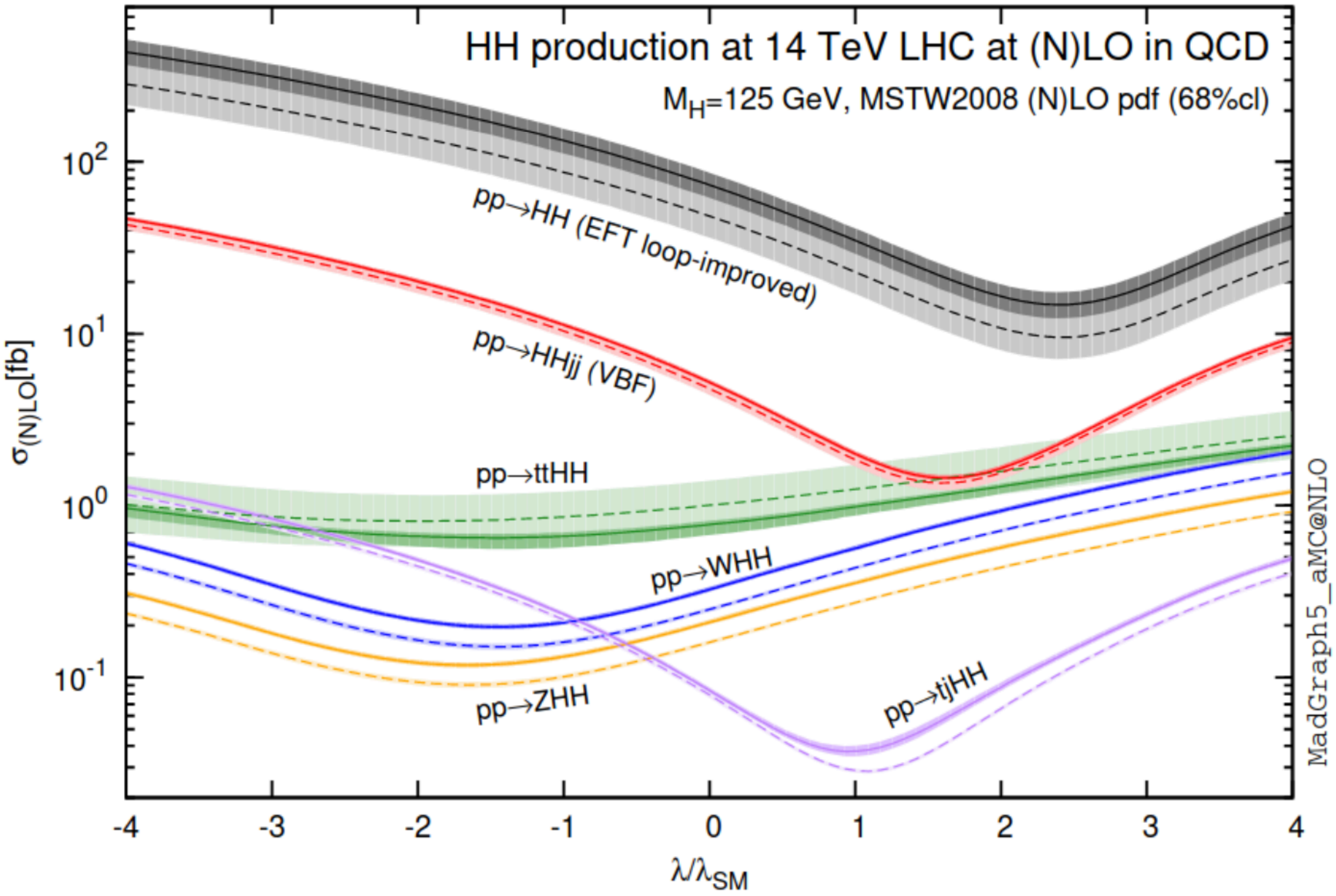


Measurement of the trilinear coupling:

- ☐ Test of the Standard Model
- ☐ Probe the shape of the scalar potential
- ☐ Potentially sensitive to BSM effects :: Need Parameterisation [EFT]

HH Production





$$\sigma(pp \to HH) \sim \frac{\sigma(pp \to H)}{1000}$$

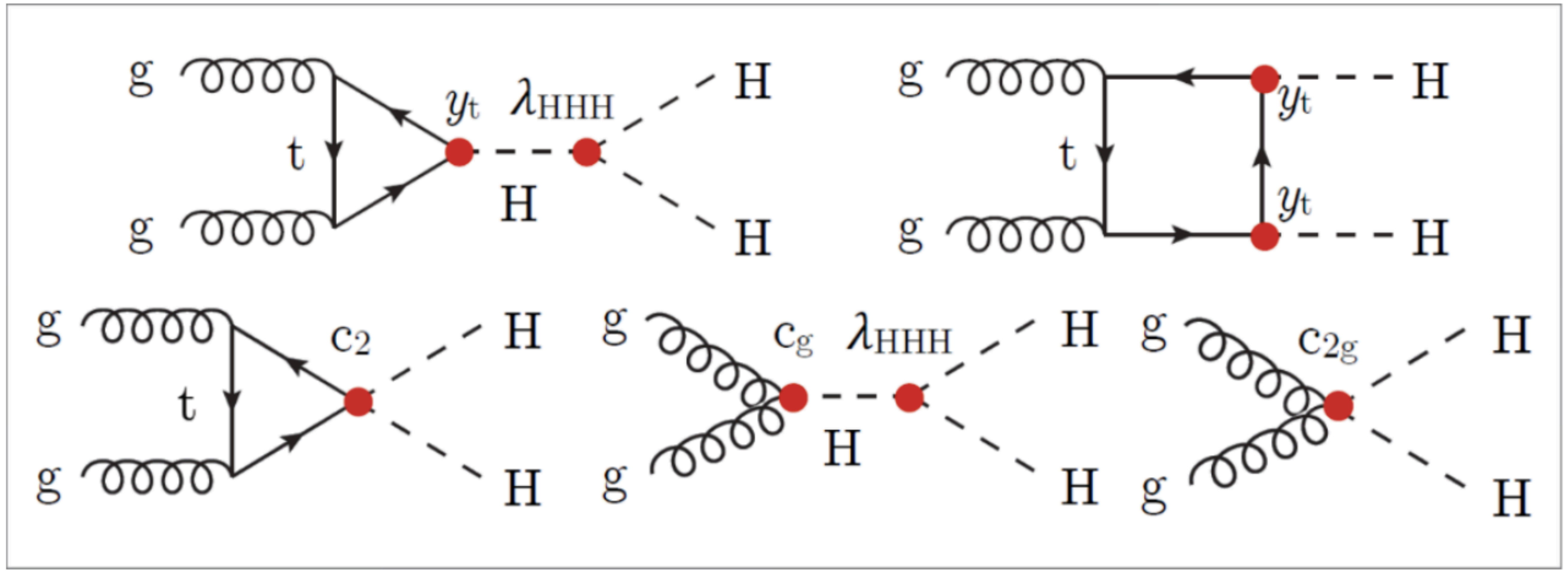
$$\frac{\Delta\sigma}{\sigma} \sim -\frac{\Delta\lambda}{\lambda}$$ around SM

GGF

HH Production [BSM]

$$\mathcal{L}_{\text{SMEFT}} = \mathcal{L}_{SM} + \sum_{d>4}^{\infty} \sum_{i} \frac{c_i^{(d)}}{\Lambda^{d-4}} \mathcal{O}_i^{(d)}$$

- Effective field theory approach



$$\text{SM}: \kappa_t = \kappa_\lambda = 1 \quad \text{and} \quad c_2 = c_g = c_{2g} = 0$$

- EFT Lagrangian for HH GGF production :

2

$$\mathcal{L}^{\text{HH}} = \frac{1}{2}\partial_\mu \text{H} \partial^\mu \text{H} - \frac{1}{2} m_{\text{H}}^2 \text{H}^2 - k_\lambda \lambda^{\text{SM}} \text{H}^3 - \frac{m_t}{v}\left(v + k_t \text{H} + \frac{c_2}{v}\text{HH}\right)(\bar{t}_L t_R + h.c.) + \frac{\alpha_s}{12\pi v}\left(c_g \text{H} - \frac{c_{2g}}{2v}\text{HH}\right) G^a_{\mu\nu} G^{a,\mu\nu}$$

$$R_{\text{HH}} = \sigma_{LO}/\sigma_{LO}^{SM} = A_1\kappa_t^4 + A_2 c_2^2 + (A_3\kappa_t^2 + A_4 c_g^2)\kappa_\lambda^2 + A_5 c_{2g}^2 + (A_6 c_2 + A_7\kappa_t\kappa_\lambda)\kappa_t^2 + (A_8\kappa_t\kappa_\lambda + A_9 c_g\kappa_\lambda)c_2 + A_{10}c_2 c_{2g} + (A_{11}c_g\kappa_\lambda + A_{12}c_{2g})\kappa_t^2 + (A_{13}\kappa_\lambda c_g + A_{14}c_{2g})\kappa_t\kappa_\lambda + A_{15}c_g c_{2g}\kappa_\lambda,$$

HH Production [BSM]

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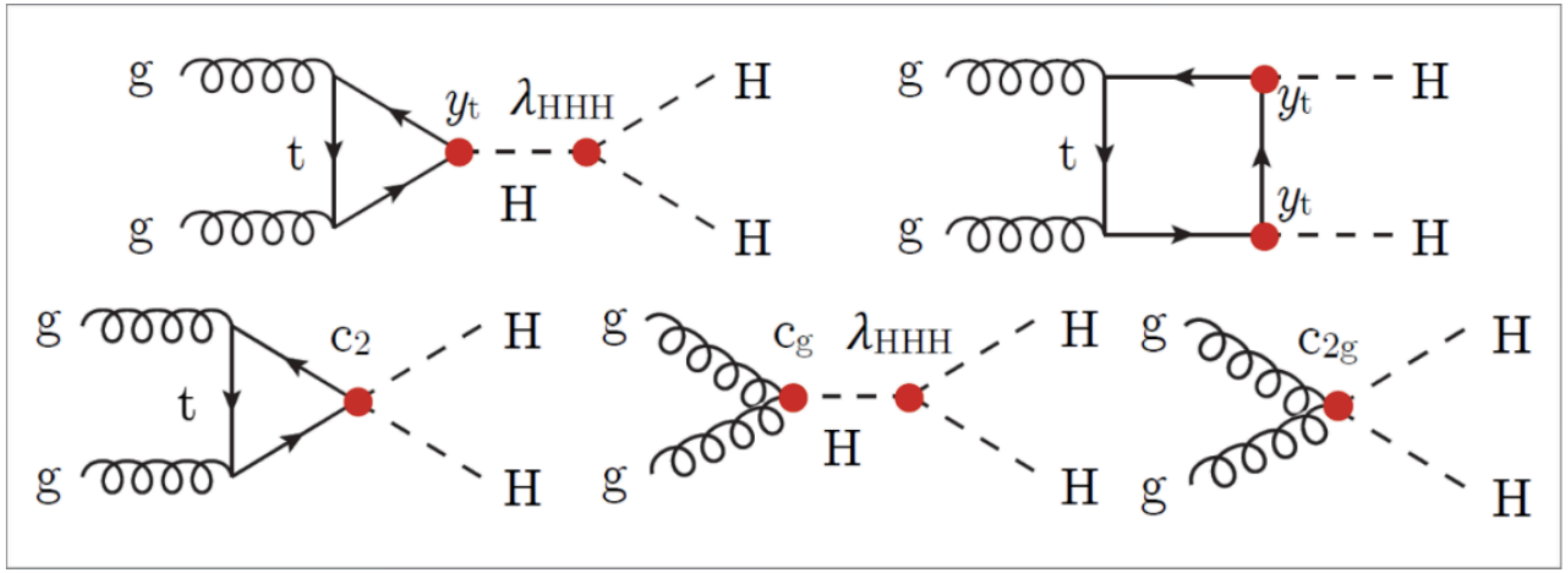
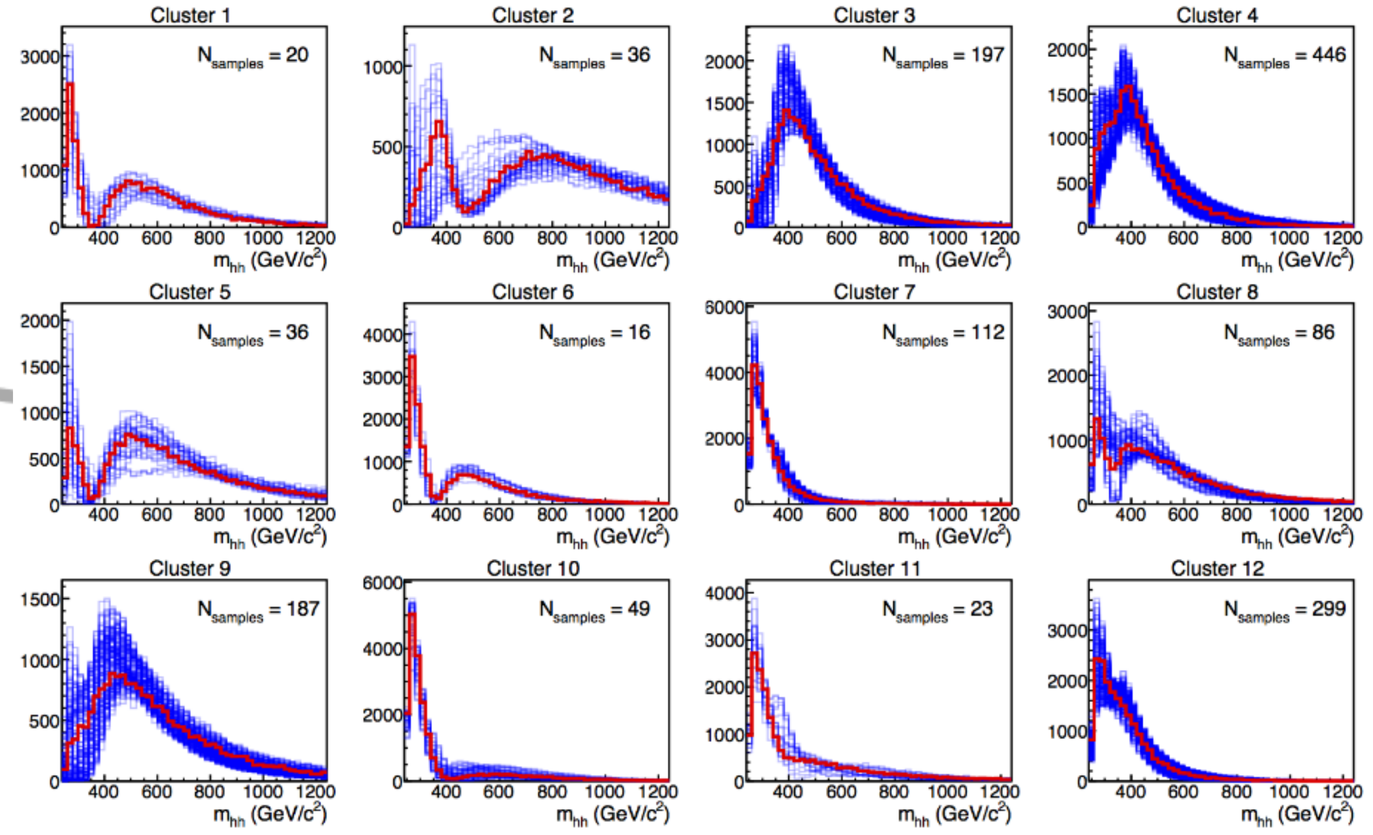
- Effective field theory approach



$$\text{SM} : \kappa_t = \kappa_\lambda = 1 \quad \text{and} \quad c_2 = c_g = c_{2g} = 0$$



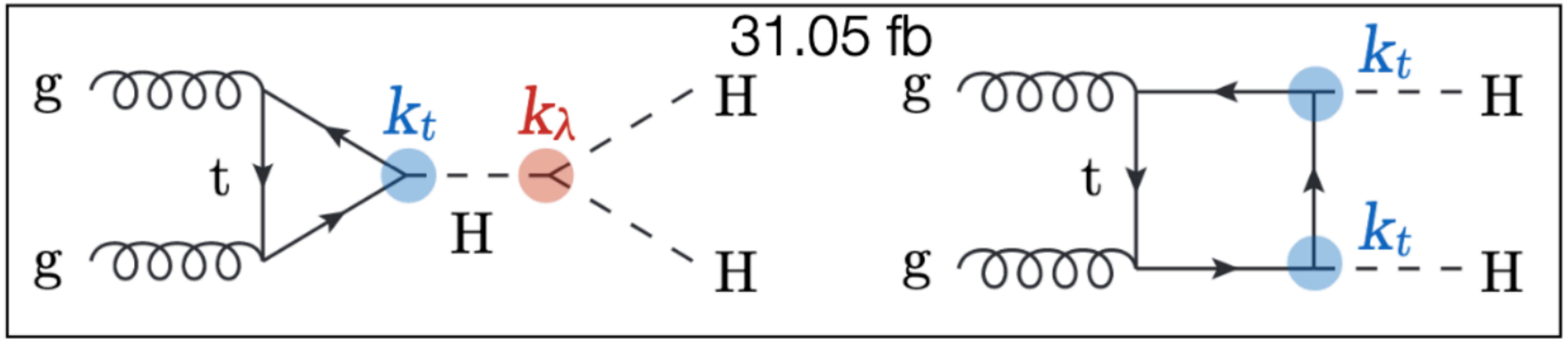
- EFT Lagrangian for HH GGF production :

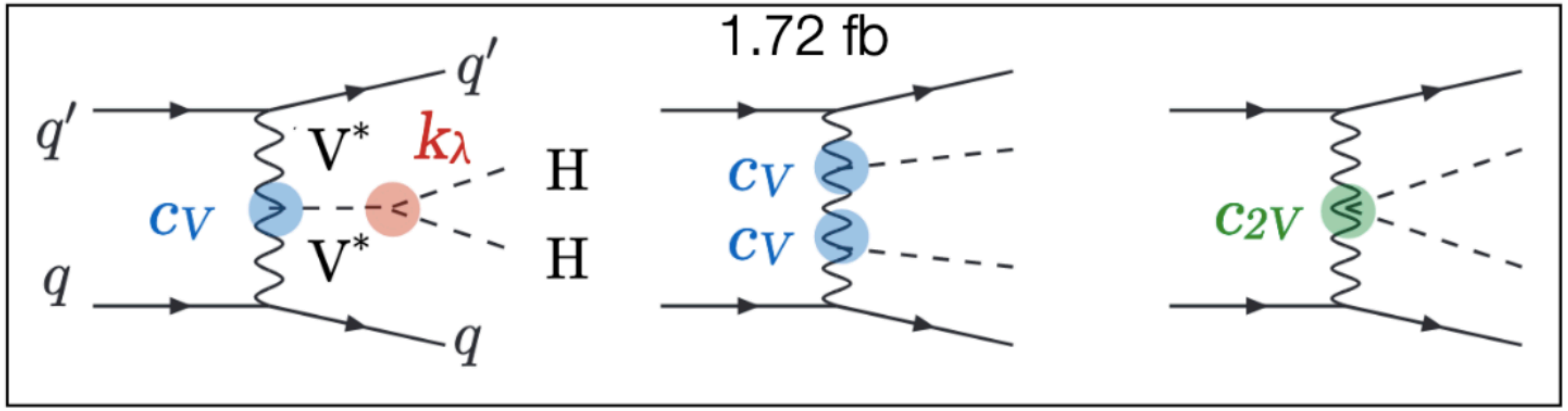
2

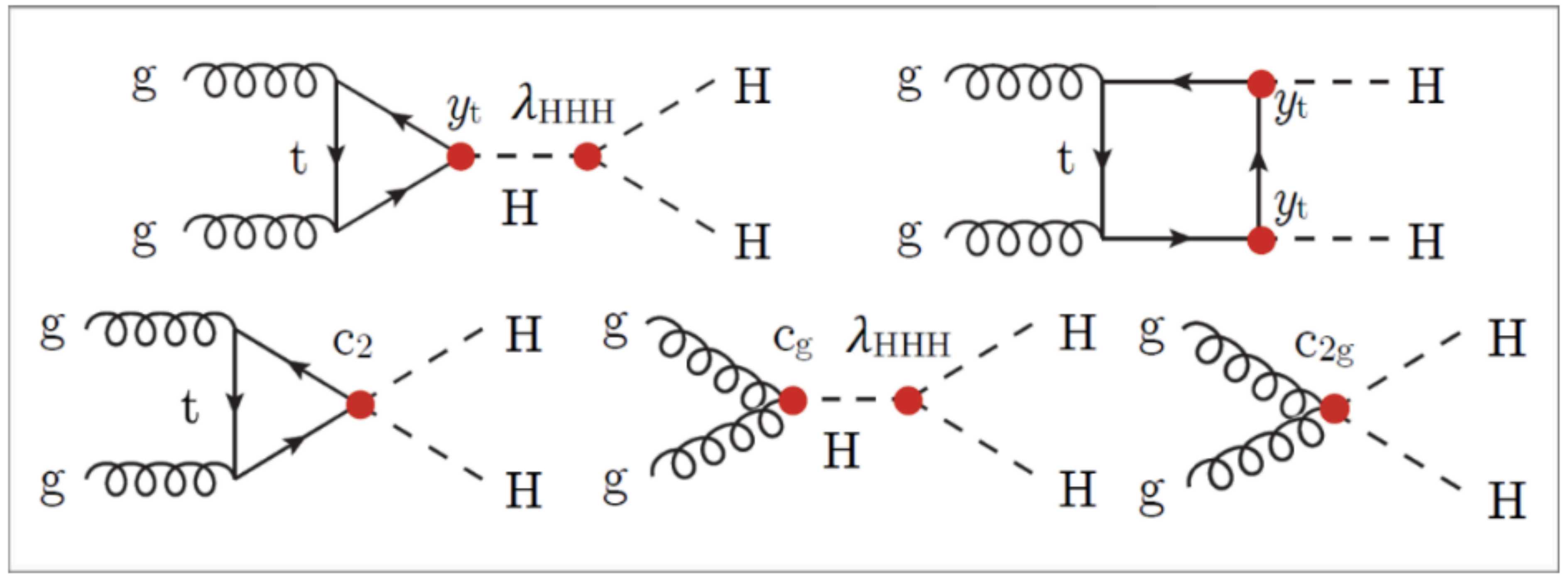
$$\mathcal{L}^{\text{HH}} = \frac{1}{2}\partial_\mu \text{H} \partial^\mu \text{H} - \frac{1}{2} m_{\text{H}}^2 \text{H}^2 - k_\lambda \lambda^{\text{SM}} \text{H}^3 - \frac{m_t}{v}\left(v + k_t \text{H} + \frac{c_2}{v}\text{HH}\right)(\bar{t}_L t_R + h.c.) + \frac{\alpha_s}{12\pi v}\left(c_g \text{H} - \frac{c_{2g}}{2v}\text{HH}\right) G^a_{\mu\nu} G^{a,\mu\nu}$$

- 5D parameter space:
  - Very expensive for a full scan
  - BPs based on the kinematics: $(m_{HH}, cos\theta^*_{HH})$
  - Deviation from the SM couplings $(\kappa_\lambda > 1)$ can be expected

So … Main Motivations !







- ☐ Search for HH
- ☐ Constrain couplings
  - ☐ κ_λ
  - ☐ κ_{2V}
- ☐ EFT Shape Benchmarks

HH Non-Resonant Analyses: Status!

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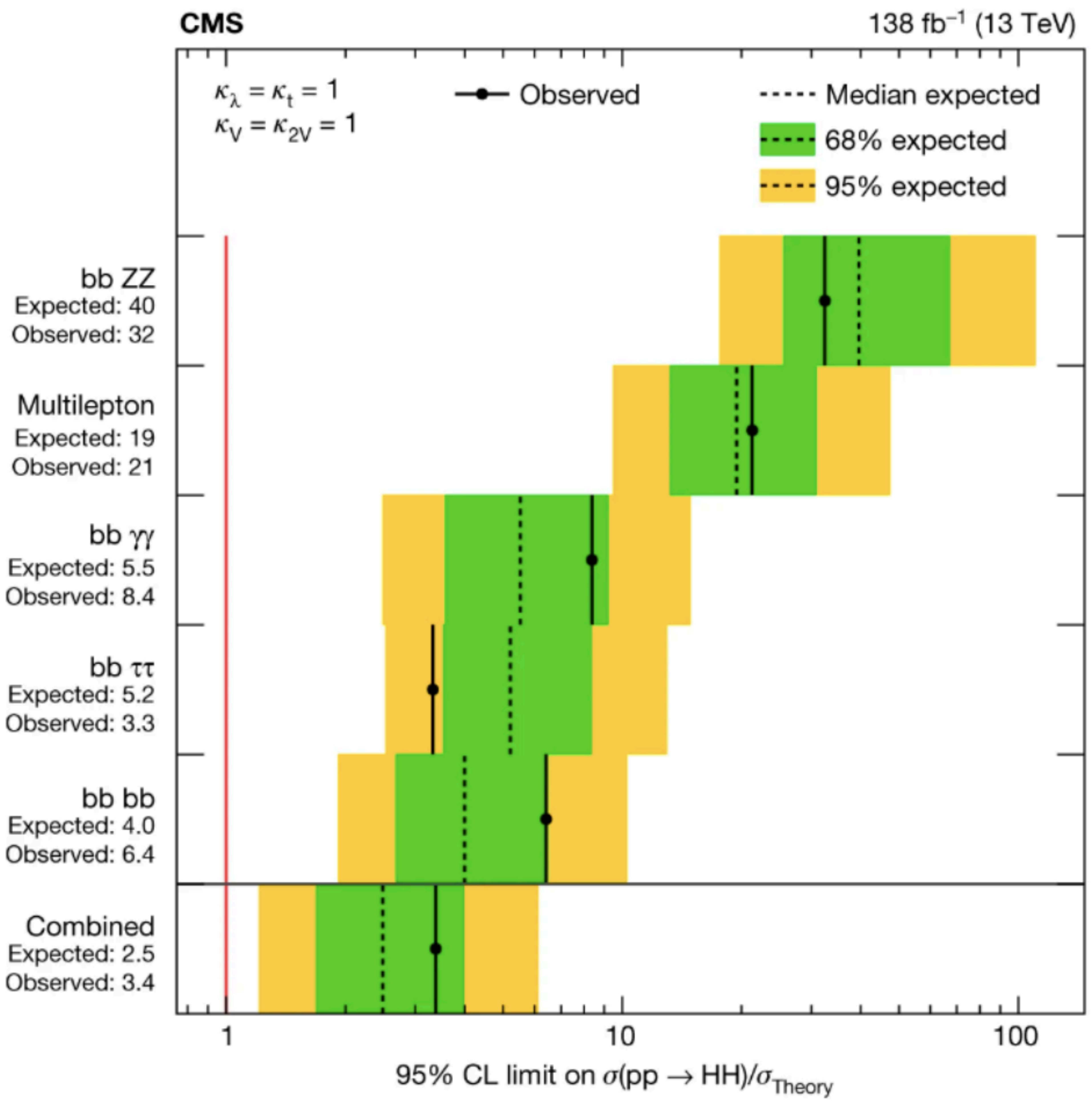
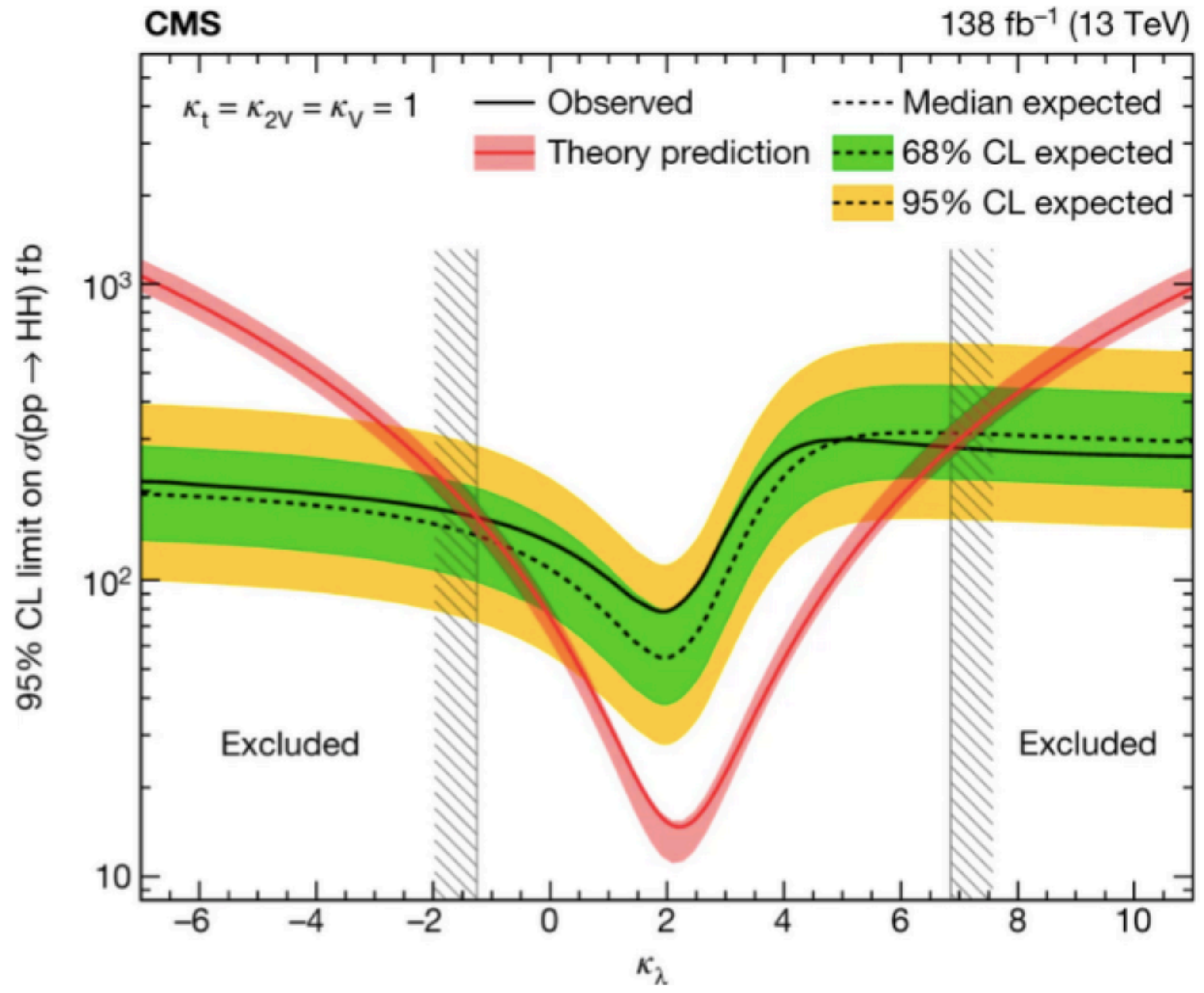
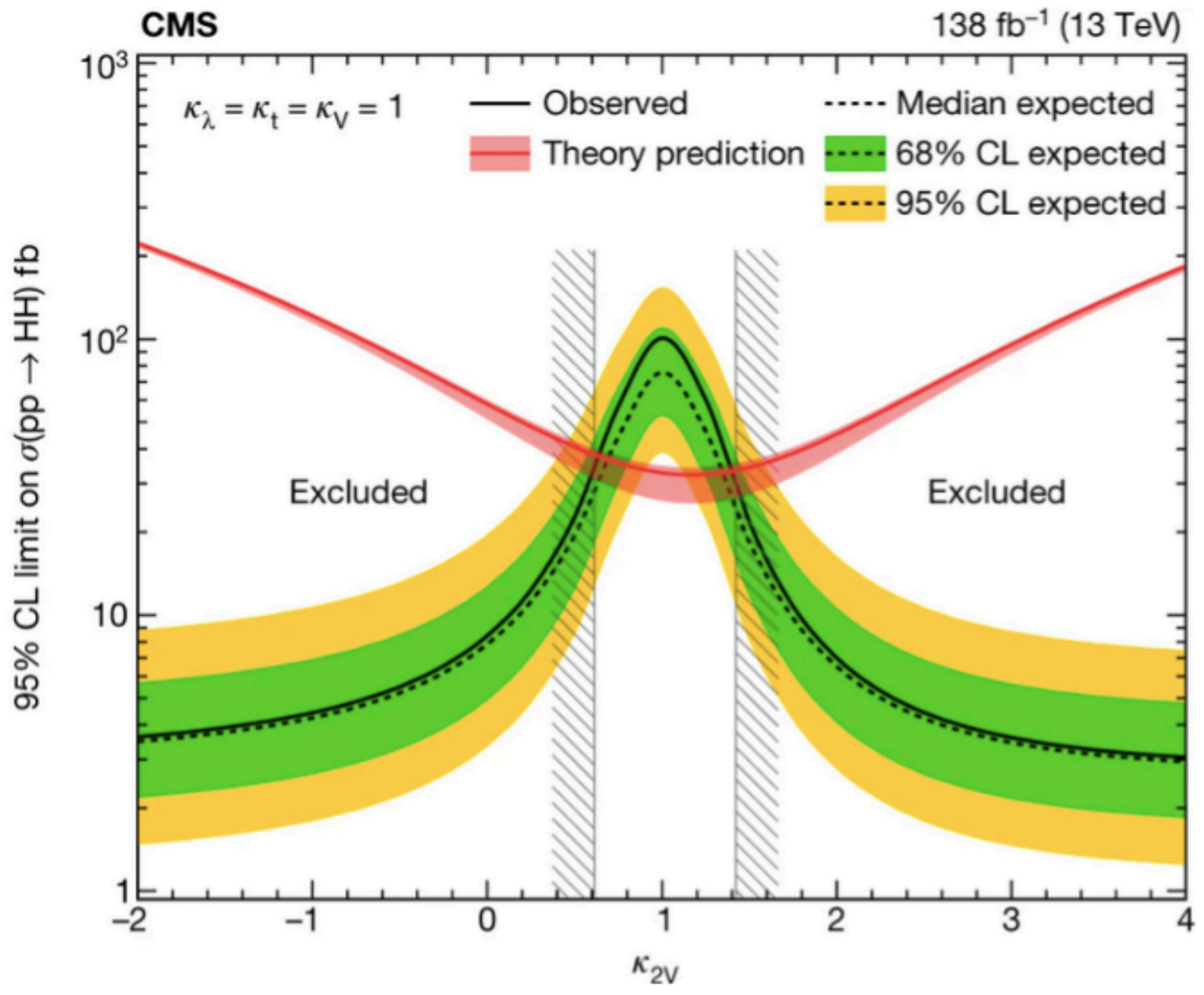
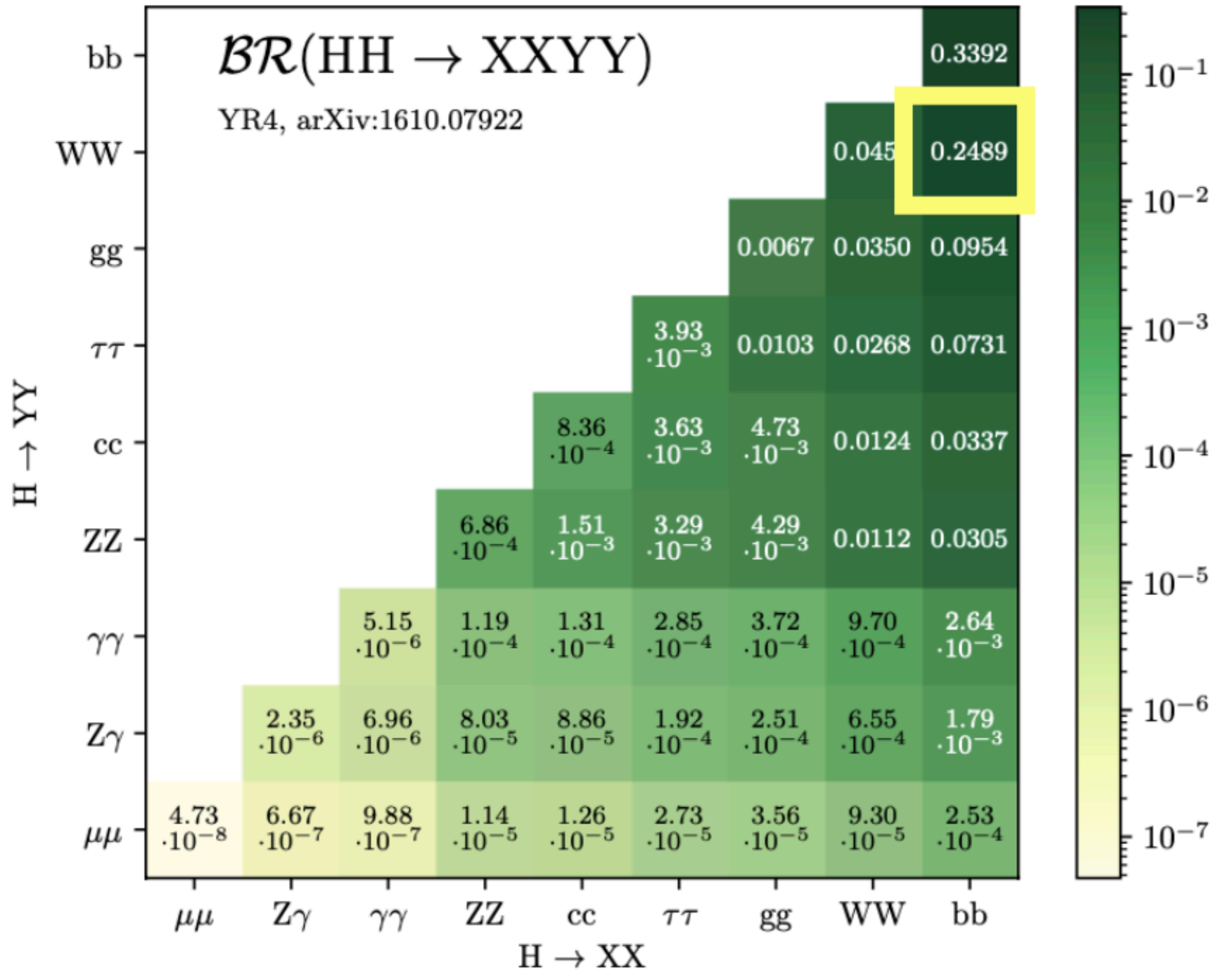






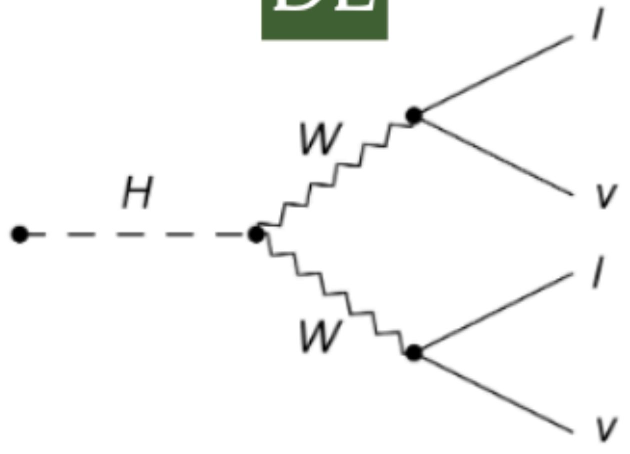
HH -> bbWW



$$N_{HH} \sim \sigma_{HH} \times \mathcal{L} = 31.05\,\text{fb} \times 138\,\text{fb}^{-1} \equiv 4000$$

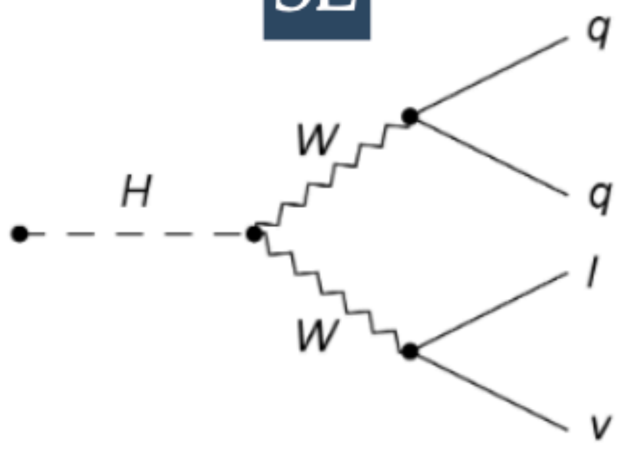
$$N_{HH \to b\bar{b}W^+W^-} = N_{HH} \times BR_{b\bar{b}W^+W^-} \equiv 1000$$

DL



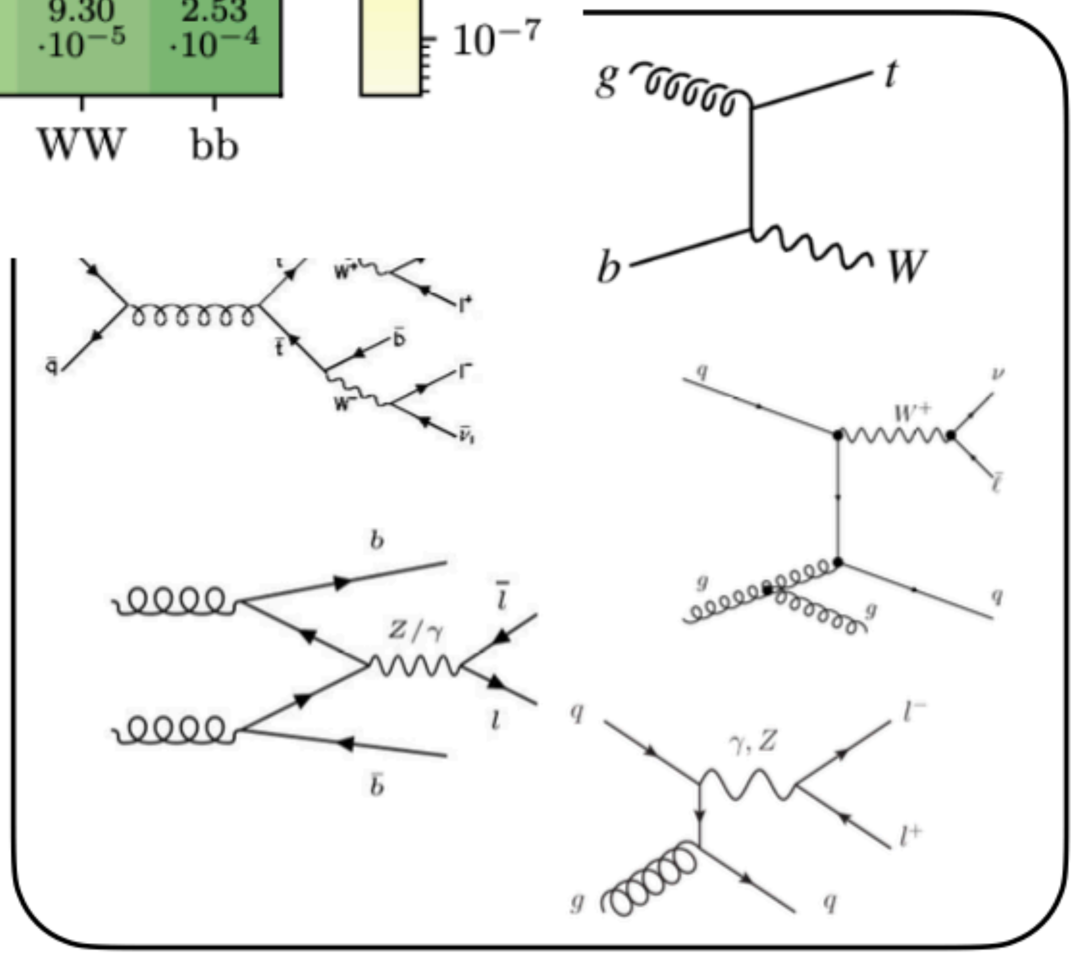
120 events

SL



475 events

$\sim 10^{10}$ background events



Event Selection

- ☐ Lepton triggers
- ☐ 1 (/2) leptons
- ☐ At least one b-tagged jet
- ☐ Kinematic requirements

$\sim 10^{6}$ events

15 events

96 events

HH -> bbWW

Group	Samples	Type	Descriptions
bbWW SL	/GluGluToHHTo2B2VLNu2J_node_cHHH*	NLO	CHHH* : {0, 1, 2.45, 5}
	/VBFHHTo2B2WToLNu2J_CV_*_C2V_*_C3_*	LO	{CV_*_C2V_*_CHHH_*} : (0.5,1,1), (1.5,1,1), (1,0,1), (1,1,0), (1,1,1), (1,1,2), (1,2,1)}
bbWW DL	/GluGluToHHTo2B2VTo2L2Nu_node_cHHH*	NLO	CHHH* : {0, 1, 2.45, 5}
	/VBFHHTo2B2VTo2L2Nu_CV_*_C2V_*_C3_*	LO	{CV_*_C2V_*_CHHH_*} : (0.5,1,1), (1.5,1,1), (1,0,1), (1,1,0), (1,1,1), (1,1,2), (1,2,1)}
bb tautau	/GluGluToHHTo2B2Tau_node_cHHH*	NLO	CHHH* : {0, 1, 2.45, 5}
	/VBFHHTo2B2Tau_CV_*_C2V_*_C3_*	LO	{CV_*_C2V_*_CHHH_*} : (0.5,1,1), (1.5,1,1), (1,0,1), (1,1,0), (1,1,1), (1,1,2), (1,2,1)}

- SM backgrounds:
  - $t\bar{t} + \text{jets}$: Di-leptonic and semi-leptonic decay of $t\bar{t}$ pair. Contribute to both channels, SL and DL
  - Single top: t or $tW + \text{jets}$ contributes significantly
  - $W + \text{jets}$: All jet and p_T binned MC samples are stitched (2106.04360) together. Significant for SL only
  - $Z + \text{jets}$: Data driven estimation, used for DL only. For SL, MC samples are stitched
  - Others: $VV(V), t\bar{t}V(X)$, single Higgs

Datasets	Era	Luminosity (fb-1)
Single Electron	2016, 17	[2016+17+18] 138.1
Single Muon	2016, 17, 18	
Double Egamma	2016, 17	
Muon Egamma	2016, 17, 18	
Egamma	2018	

Analysis Strategy

Baseline Selections

SL

- At least one fakeable lepton
- Single lepton trigger
- $p_T^{\mu} > 25$ GeV or $p_T^{e} > 32$ GeV
- τ_h veto
- $m_{ll} > 12$ GeV & $|m_{ll} - m_Z| > 10$ GeV
- Leading fakeable lepton must be tight
- nAk4-Jets ≥ 3 & nAk4-bJets ≥ 1 & nAk8-Jets = 0 :
  Resolved [nAk4-bJets = 1 or nAk4-bJets ≥ 2]
- nAk8-bJets ≥ 1 & nAk4Jets (Ak8b-cleaned) ≥ 1 :
  Boosted

DL

- At least two fakeable leptons
- Single or double lepton trigger
- lepton-1 $p_T > 25$ GeV, lepton-2 $p_T > 15$ GeV
- Opposite charge
- $m_{ll} > 12$ GeV & $|m_{ll} - m_Z| > 10$ GeV
- Not more than 2 tight leptons
- nAk4-Jets ≥ 2 & nAk4-bJets ≥ 1 & nAk8-Jets = 0 :
  Resolved [nAk4-bJets = 1 or nAk4-bJets ≥ 2]
- nAk8-bJets ≥ 1 : Boosted

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Process	Cross-section [pb]	Total yield	DL channel		SL channel	
			Yield	ϵ [%]	Yield	ϵ [%]
$t\bar{t}$ (fully leptonic)	88.4	$1.2\ 10^7$	$1.5\ 10^6$	12.5	$1.5\ 10^6$	12.5
$t\bar{t}$ (semi leptonic)	365.52	$5.0\ 10^7$	$1.9\ 10^2$	<0.01	$1.1\ 10^7$	21.8
$t\bar{t}$ (fully hadronic)	377.85	$5.2\ 10^7$	0	0.0	$2.9\ 10^2$	<0.01
Drell-Yan	6077.22	$8.4\ 10^8$	$2.0\ 10^5$	0.02	$4.2\ 10^5$	0.05
W+jets	61526.7	$8.5\ 10^9$	$2.1\ 10^2$	<0.01	$2.8\ 10^6$	0.03
ST	292.04	$3.9\ 10^7$	$7.9\ 10^4$	0.2	$1.3\ 10^6$	3.4
WW	62.87	$8.7\ 10^6$	$2.2\ 10^3$	0.03	$5.5\ 10^4$	0.63
ZW	10.03	$1.4\ 10^6$	$1.2\ 10^3$	0.09	$2.2\ 10^3$	0.16
ZZ	6.78	$9.4\ 10^5$	$2.5\ 10^3$	0.27	$5.5\ 10^3$	0.58
$t\bar{t}W$	0.60	$8.3\ 10^4$	$2.1\ 10^3$	2.51	$1.3\ 10^4$	15.36
$t\bar{t}Z$	0.95	$1.3\ 10^5$	$26\ 10^3$	2.00	$1.6\ 10^4$	12.40
HH $\rightarrow$ bbWW (GGF)	0.03105	113.1 / 468.8	15.0	9.56	96.1	20.50
HH $\rightarrow$ bbWW (VBF)	0.00173	6.3 / 26.1	0.55	8.78	3.83	14.69

Analysis Strategy

Baseline Selections

SL

- At least one fakeable lepton
- Single lepton trigger
- $p_T^{\mu} > 25$ GeV or $p_T^{e} > 32$ GeV
- τ_h veto
- $m_{ll} > 12$ GeV & $|m_{ll} - m_Z| > 10$ GeV
- Leading fakeable lepton must be tight
- nAk4-Jets ≥ 3 & nAk4-bJets ≥ 1 & nAk8-Jets = 0 : Resolved [nAk4-bJets = 1 or nAk4-bJets ≥ 2]
- nAk8-bJets ≥ 1 & nAk4Jets (Ak8b-cleaned) ≥ 1 : Boosted

DL

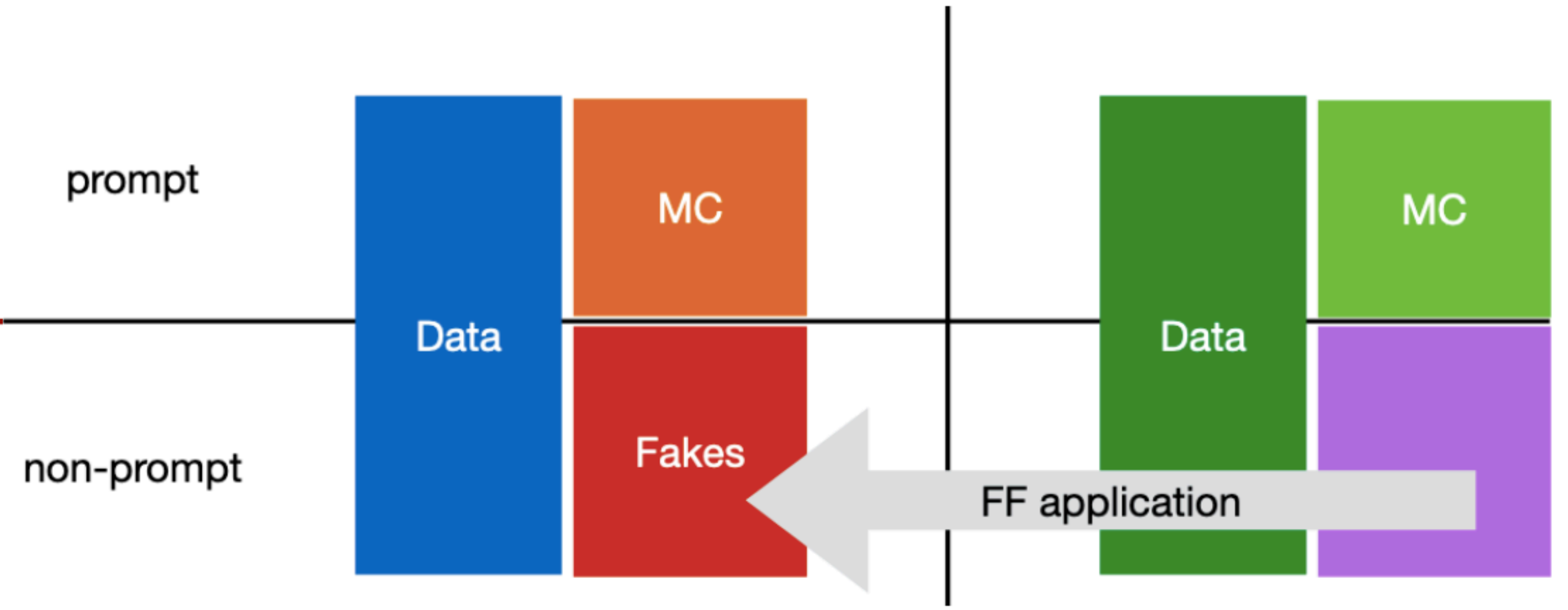
- At least two fakeable leptons
- Single or double lepton trigger
- lepton-1 $p_T > 25$ GeV, lepton-2 $p_T > 15$ GeV
- Opposite charge
- $m_{ll} > 12$ GeV & $|m_{ll} - m_Z| > 10$ GeV
- Not more than 2 tight leptons
- nAk4-Jets ≥ 2 & nAk4-bJets ≥ 1 & nAk8-Jets = 0 : Resolved [nAk4-bJets = 1 or nAk4-bJets ≥ 2]
- nAk8-bJets ≥ 1 : Boosted

Measurement region

$$m_T^{fix} = \sqrt{2 p_T^{fix} E_T^{miss} (1 - \cos\Delta\phi)},$$

$$f_i = \frac{N_{pass}}{N_{pass} + N_{fail}}$$

Fake background:

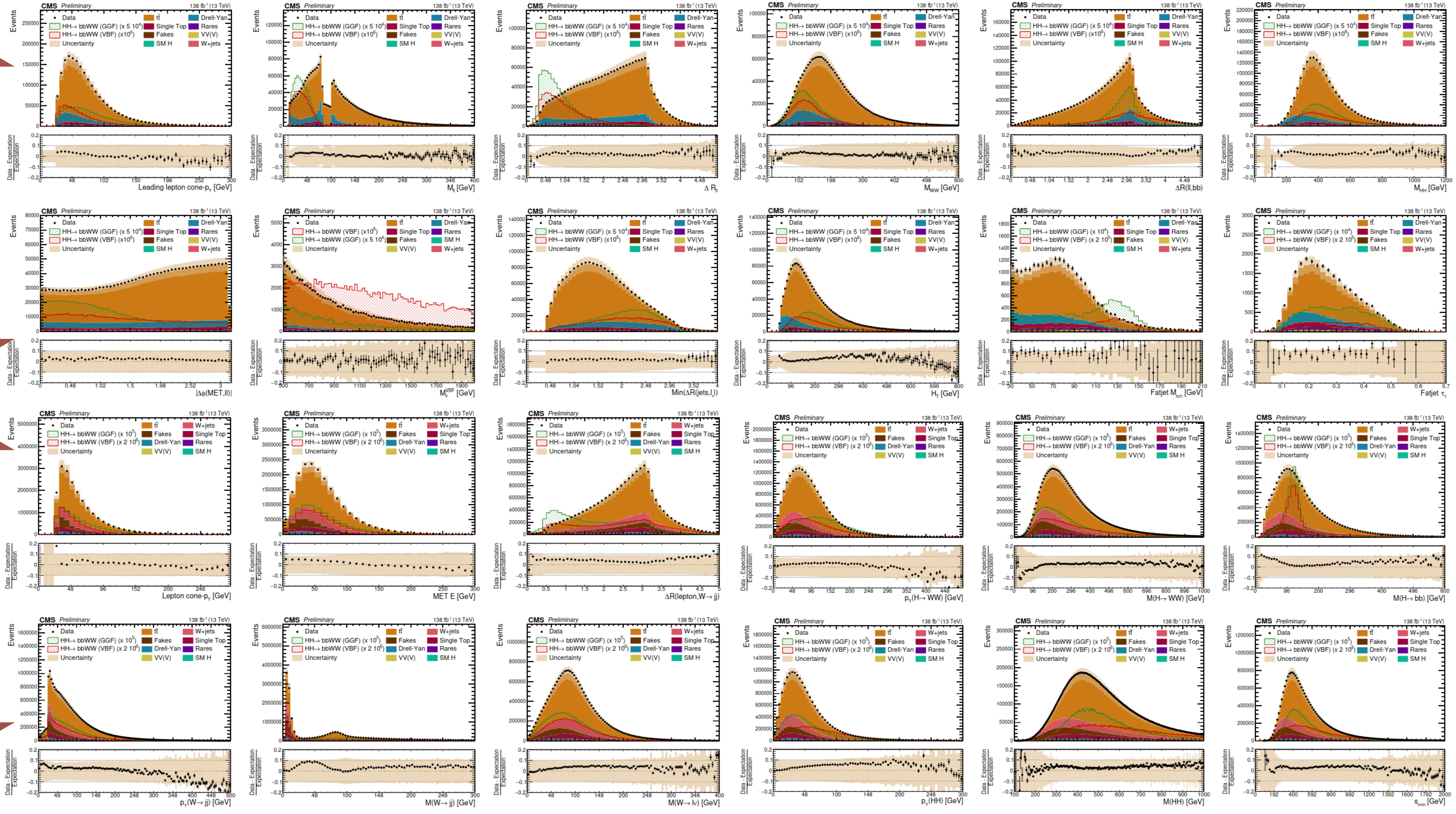


$$w = (-1)^{n+1} \prod_{i=1}^{n} \frac{f_i}{1 - f_i},$$

Analysis Strategy

DL

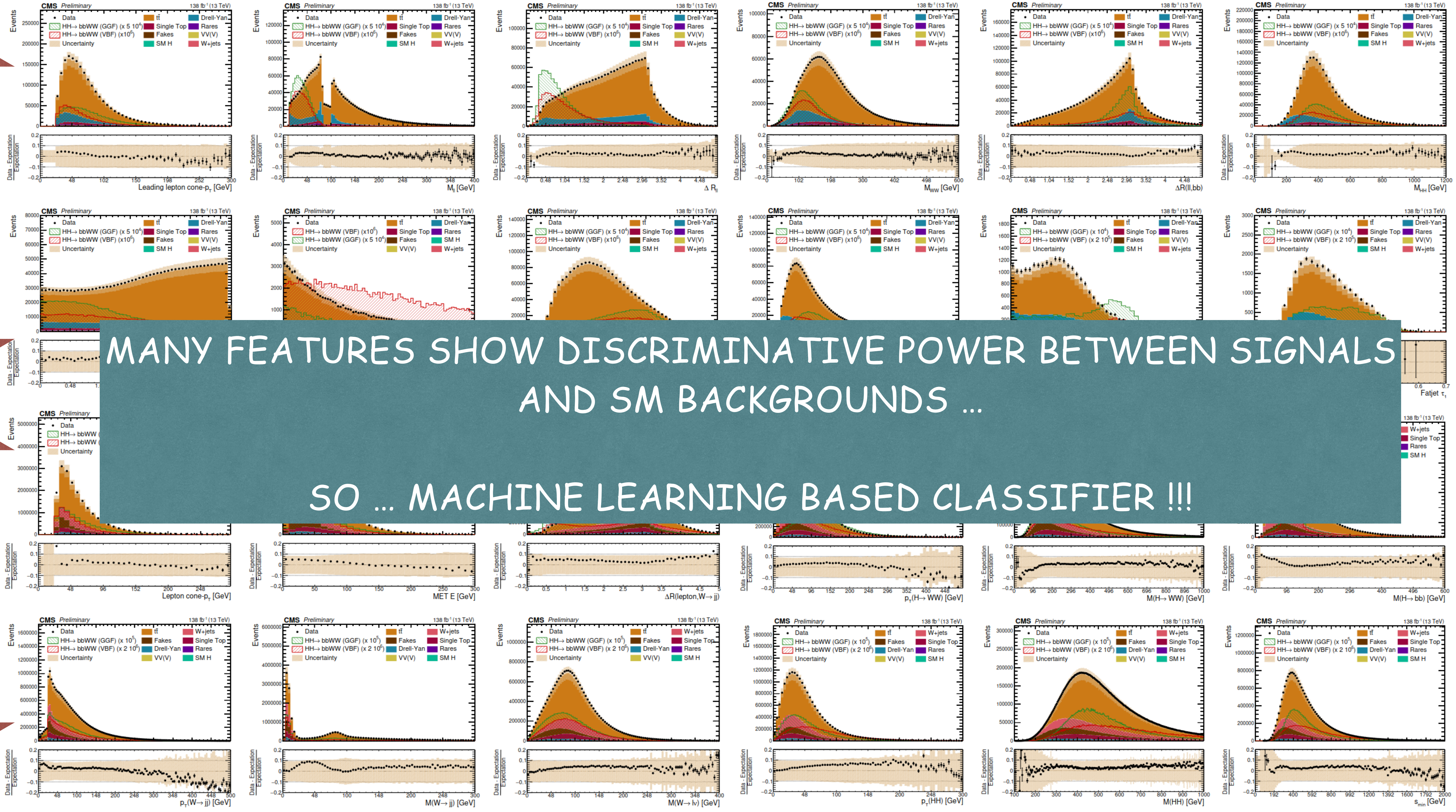
SL



Analysis Strategy

DL

SL



MANY FEATURES SHOW DISCRIMINATIVE POWER BETWEEN SIGNALS AND SM BACKGROUNDS …

SO … MACHINE LEARNING BASED CLASSIFIER !!!

Analysis Strategy

Baseline Selections

SL

- At least one fakeable lepton
- Single lepton trigger
- $p_T^{\mu} > 25$ GeV or $p_T^{e} > 32$ GeV
- τ_h veto
- $m_{ll} > 12$ GeV & $|m_{ll} - m_Z| > 10$ GeV
- Leading fakeable lepton must be tight
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- nAk8-bJets ≥ 1 & nAk4Jets (Ak8b-cleaned) ≥ 1 : Boosted

DL

- At least two fakeable leptons
- Single or double lepton trigger
- lepton-1 $p_T > 25$ GeV, lepton-2 $p_T > 15$ GeV
- Opposite charge
- $m_{ll} > 12$ GeV & $|m_{ll} - m_Z| > 10$ GeV
- Not more than 2 tight leptons
- nAk4-Jets ≥ 2 & nAk4-bJets ≥ 1 & nAk8-Jets = 0 : Resolved [nAk4-bJets = 1 or nAk4-bJets ≥ 2]
- nAk8-bJets ≥ 1 : Boosted

Multivariate Analysis

Multi-class DNN (SL)

Process	Description
HH(GGF)	Gluon fusion Higgs boson pair production
HH(VBF)	Vector boson fusion Higgs boson pair p.
$t\bar{t}$	Top quark pair p.
ST	Single top quark p.
WJets	W boson with additional jets p.
H	Single Higgs boson p.
Other SL	All other, among them Drell-Yan

Multi-class DNN (DL)

Process	Description
HH(GGF)	Gluon fusion Higgs boson pair production
HH(VBF)	Vector boson fusion Higgs boson pair p.
$t\bar{t}$	Top quark pair p.
ST	Single top quark p.
DY	Drell-Yan
H	Single Higgs boson p.
$t\bar{t}$V(X)	Top quark pair associate vector boson p. with possible additional vector or Higgs boson ($t\bar{t}$V, $t\bar{t}$VV, $t\bar{t}$VH)
VV(V)	Multiple vector boson p. (WW, WZ, ZZ, WWW, WWZ, WZZ, ZZZ)
Other DL	All other, among them W boson p. with additional jets

Statistical Analysis

Process Group	Sub-Categories		
HH(GGF)	Resolved 1b	Resolved 2b	Boosted
HH(VBF)	Resolved 1b	Resolved 2b	Boosted
Top + Higgs	Resolved		Boosted
WJets	Inclusive		
Other SL	Inclusive		

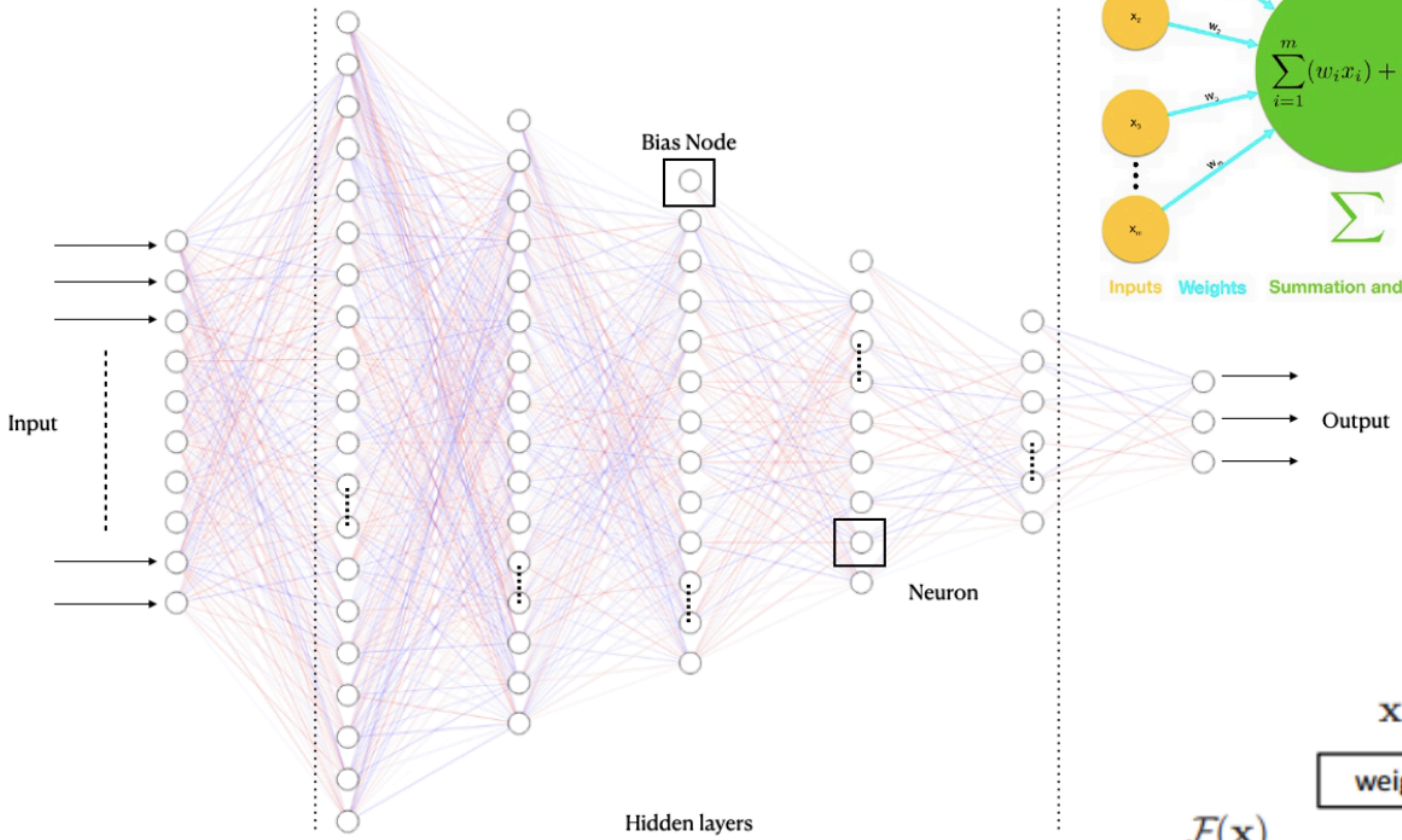
SL Full Run2 limit

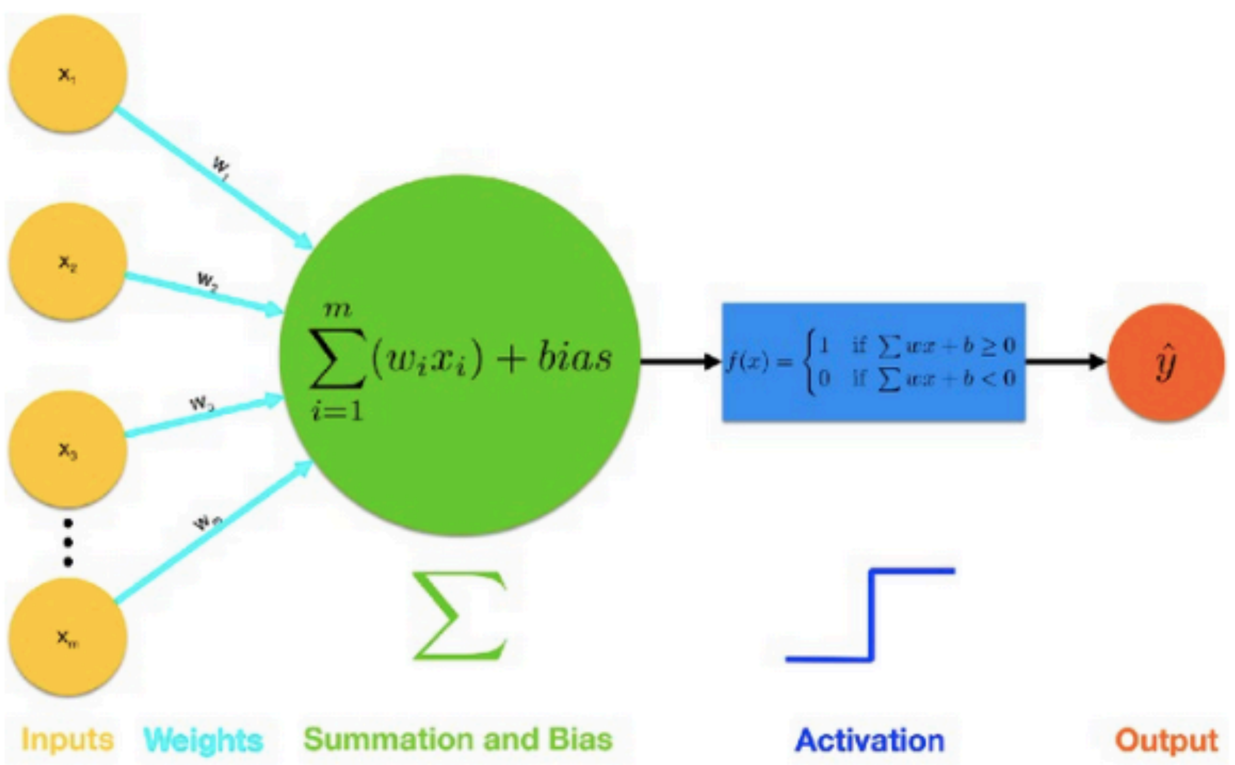
Combined Full Run2 limit

DL Full Run2 limit

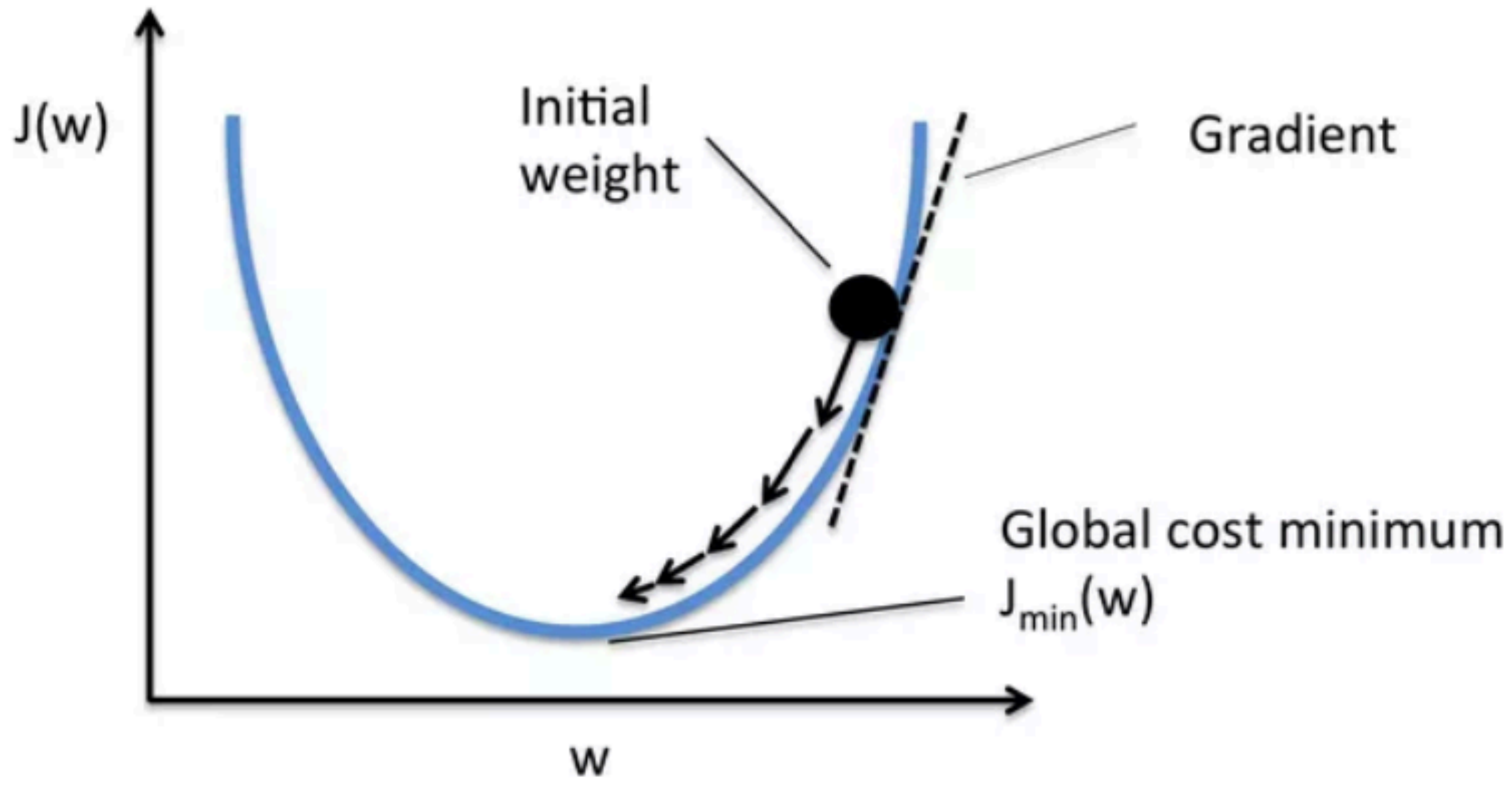
Process Group	Sub-Categories		
HH(GGF)	Resolved 1b	Resolved 2b	Boosted
HH(VBF)	Resolved 1b	Resolved 2b	Boosted
Top + Other	Resolved		Boosted
DY + VV(V)	Inclusive		

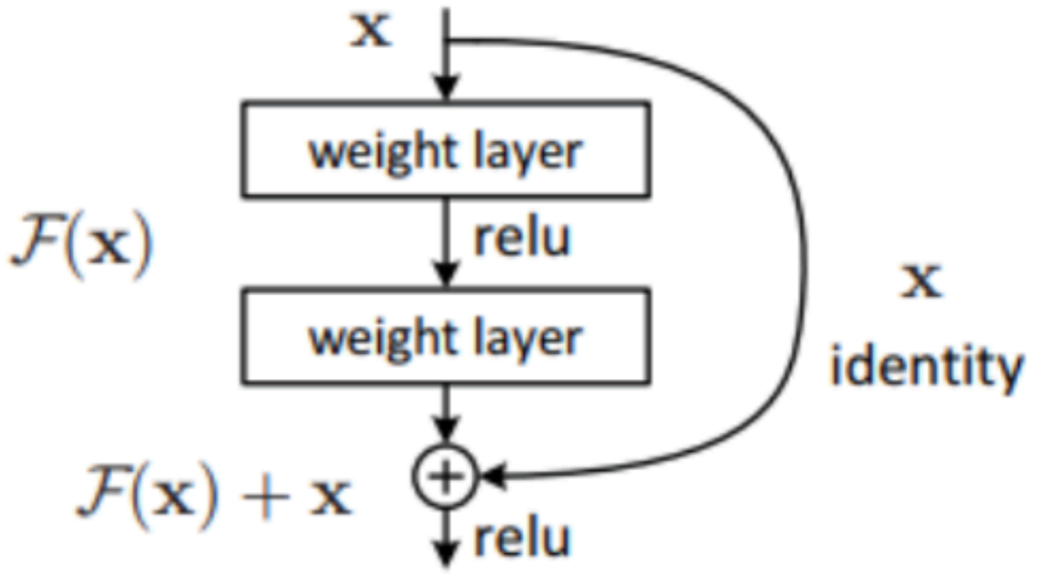
Machine Learning: Neural Network





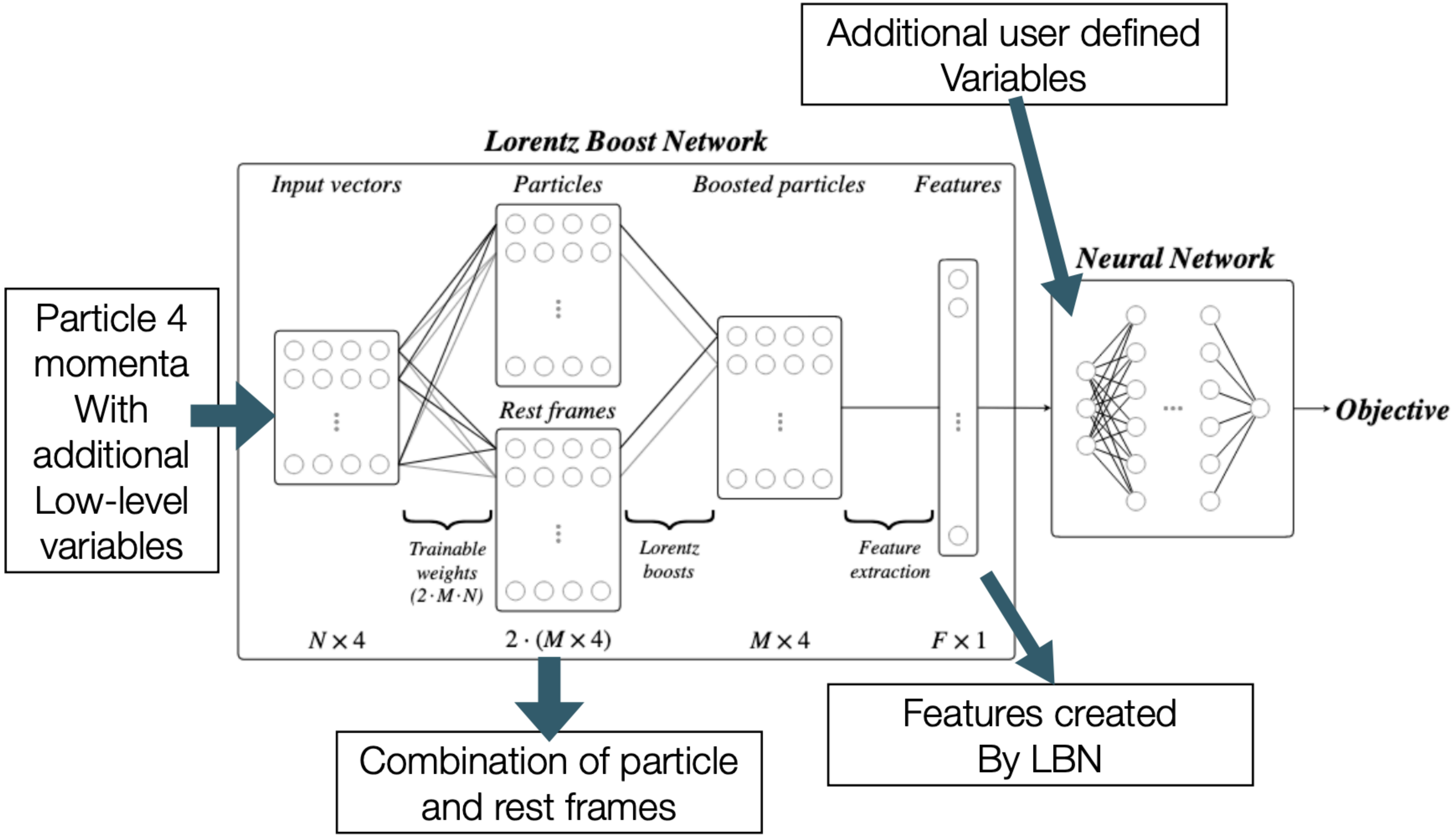
Link





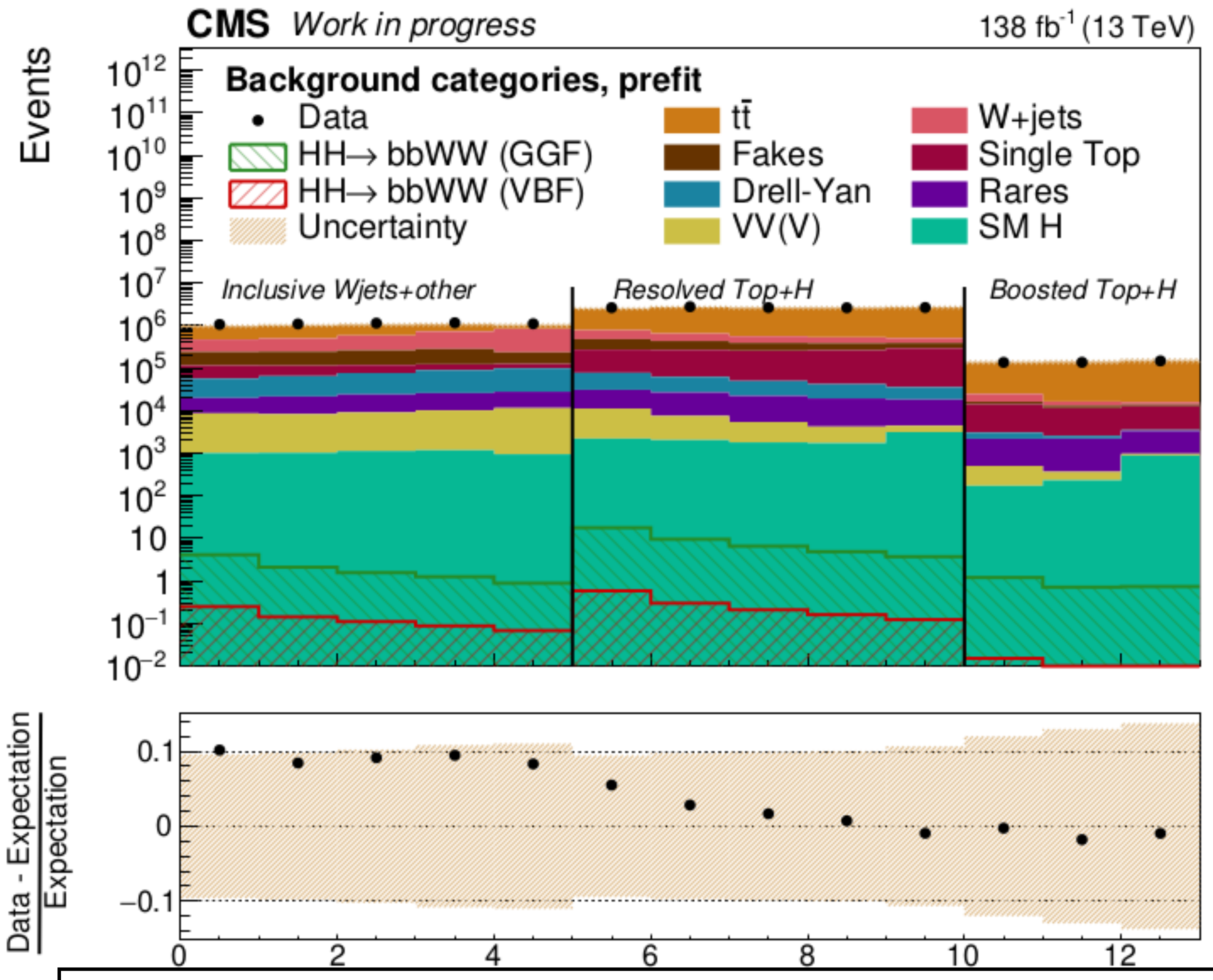
LBN + DNN

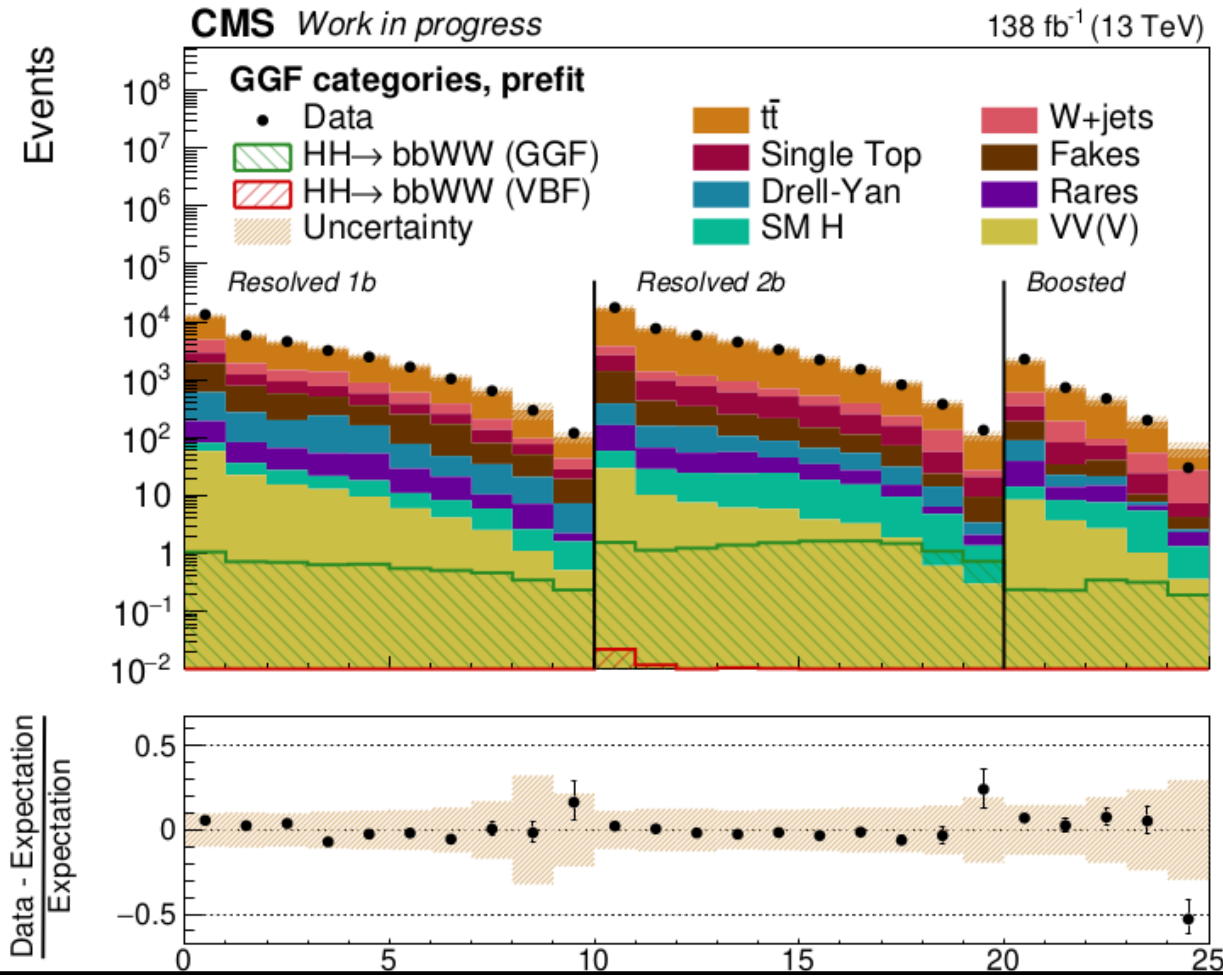
- Lorentz boost network (LBN) as an input pre-processor to the DNN



- Architecture SL(DL):
  - 12 output particles from the LBN
  - 235(239) features extracted: input to NN
  - 3 ResNet blocks
  - Relu activation
  - 7(9) output nodes
  - Dropout: 10%
  - LR ~0.01
  - Batch normalisation

DNN Response





Idea

Let the fit determine the background normalization

No need for much shape information (just enough variation in bin proportions)

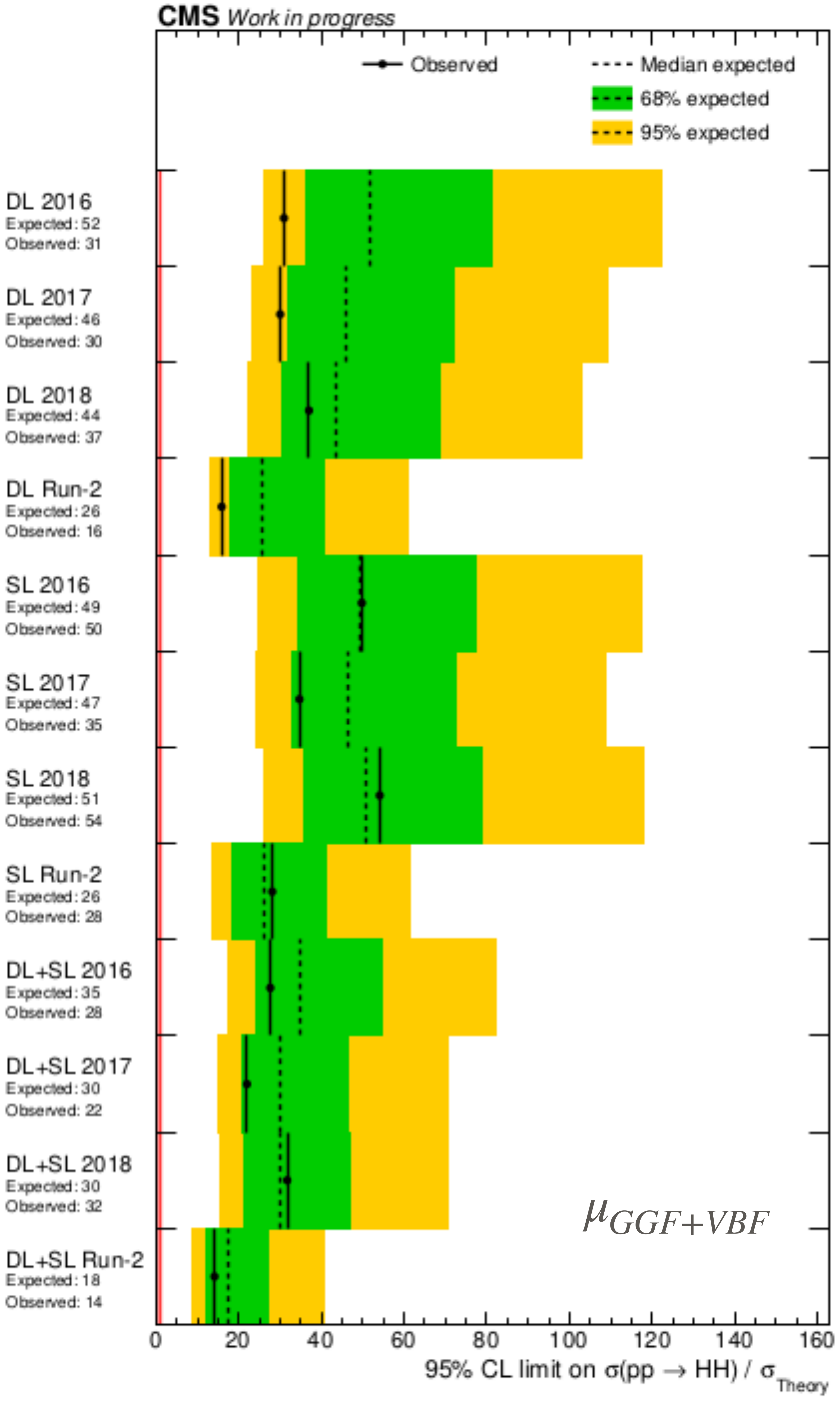
Quantile binning

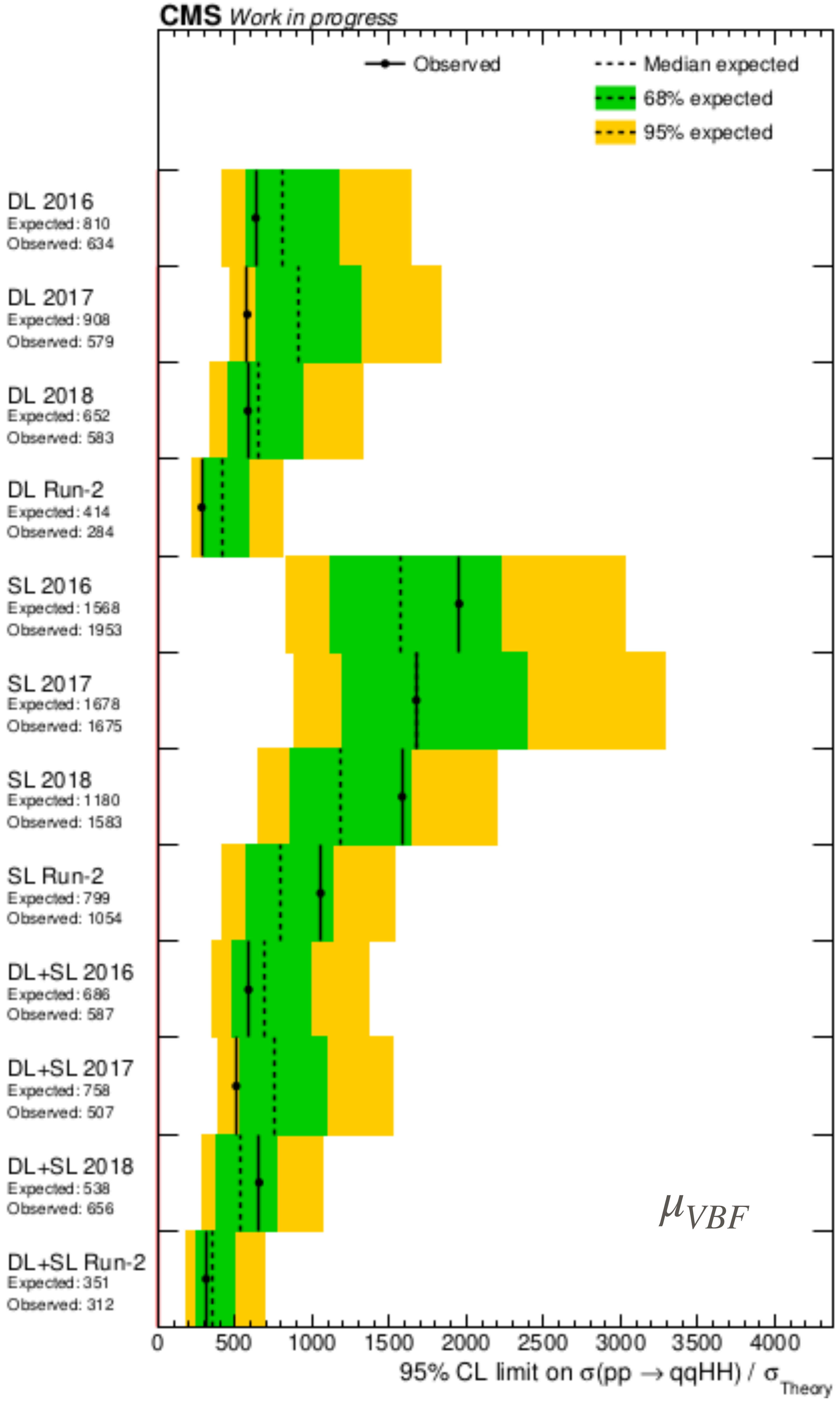
Idea

Quadratically decreasing set of thresholds (aggregated total background bin > threshold → start new bin)

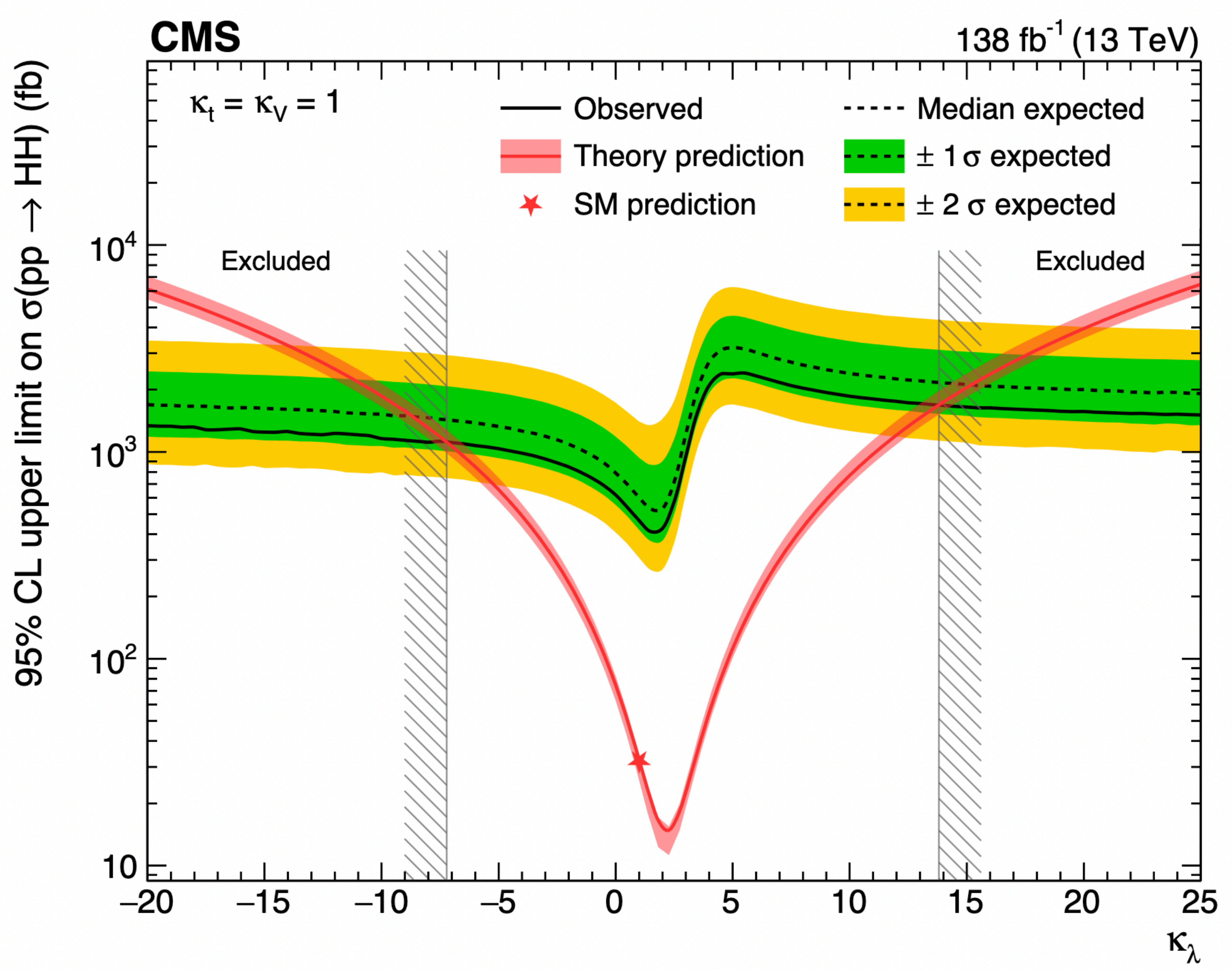
Increase sensitivity to signal in the rightmost bins

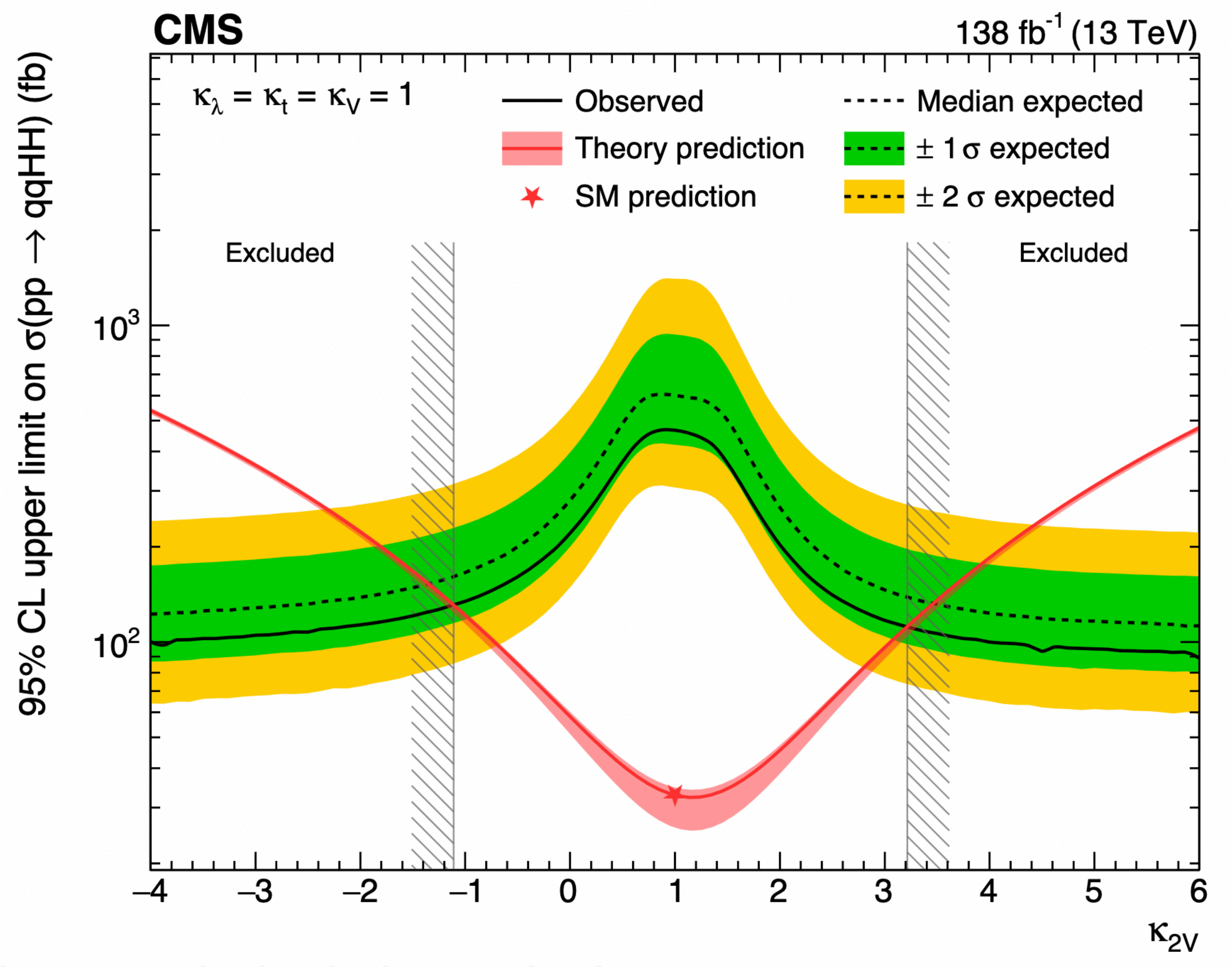
Results


CMS Work in progress
Observed
Median expected
68% expected
95% expected
DL 2016
Expected: 52
Observed: 31
DL 2017
Expected: 46
Observed: 30
DL 2018
Expected: 44
Observed: 37
DL Run-2
Expected: 26
Observed: 16
SL 2016
Expected: 49
Observed: 50
SL 2017
Expected: 47
Observed: 35
SL 2018
Expected: 51
Observed: 54
SL Run-2
Expected: 26
Observed: 28
DL+SL 2016
Expected: 35
Observed: 28
DL+SL 2017
Expected: 30
Observed: 22
DL+SL 2018
Expected: 30
Observed: 32
DL+SL Run-2
Expected: 18
Observed: 14
$\mu_{GGF+VBF}$
0
20
40
60
80
100
120
140
160
95% CL limit on σ(pp → HH) / σ_{Theory}

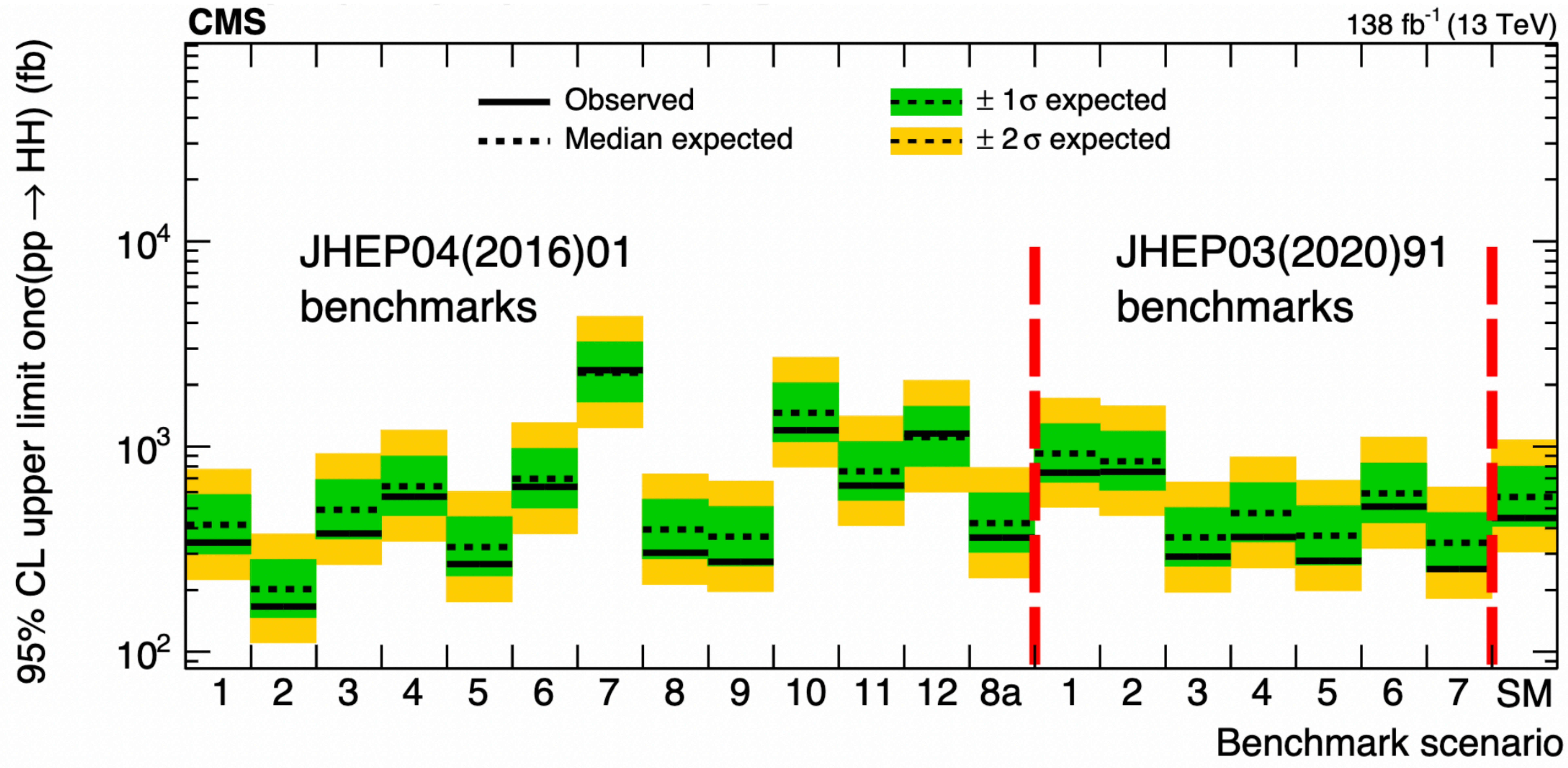

CMS Work in progress
Observed
Median expected
68% expected
95% expected
DL 2016
Expected: 810
Observed: 634
DL 2017
Expected: 908
Observed: 579
DL 2018
Expected: 652
Observed: 583
DL Run-2
Expected: 414
Observed: 284
SL 2016
Expected: 1568
Observed: 1953
SL 2017
Expected: 1678
Observed: 1675
SL 2018
Expected: 1180
Observed: 1583
SL Run-2
Expected: 799
Observed: 1054
DL+SL 2016
Expected: 686
Observed: 587
DL+SL 2017
Expected: 758
Observed: 507
DL+SL 2018
Expected: 538
Observed: 656
DL+SL Run-2
Expected: 351
Observed: 312
μ_{VBF}
0
500
1000
1500
2000
2500
3000
3500
4000
95% CL limit on σ(pp → qqHH) / σ_{Theory}

Results


CMS
138 fb-1 (13 TeV)
κt = κV = 1
Observed
Median expected
Theory prediction
± 1 σ expected
SM prediction
± 2 σ expected
Excluded
Excluded
95% CL upper limit on σ(pp → HH) (fb)
κλ

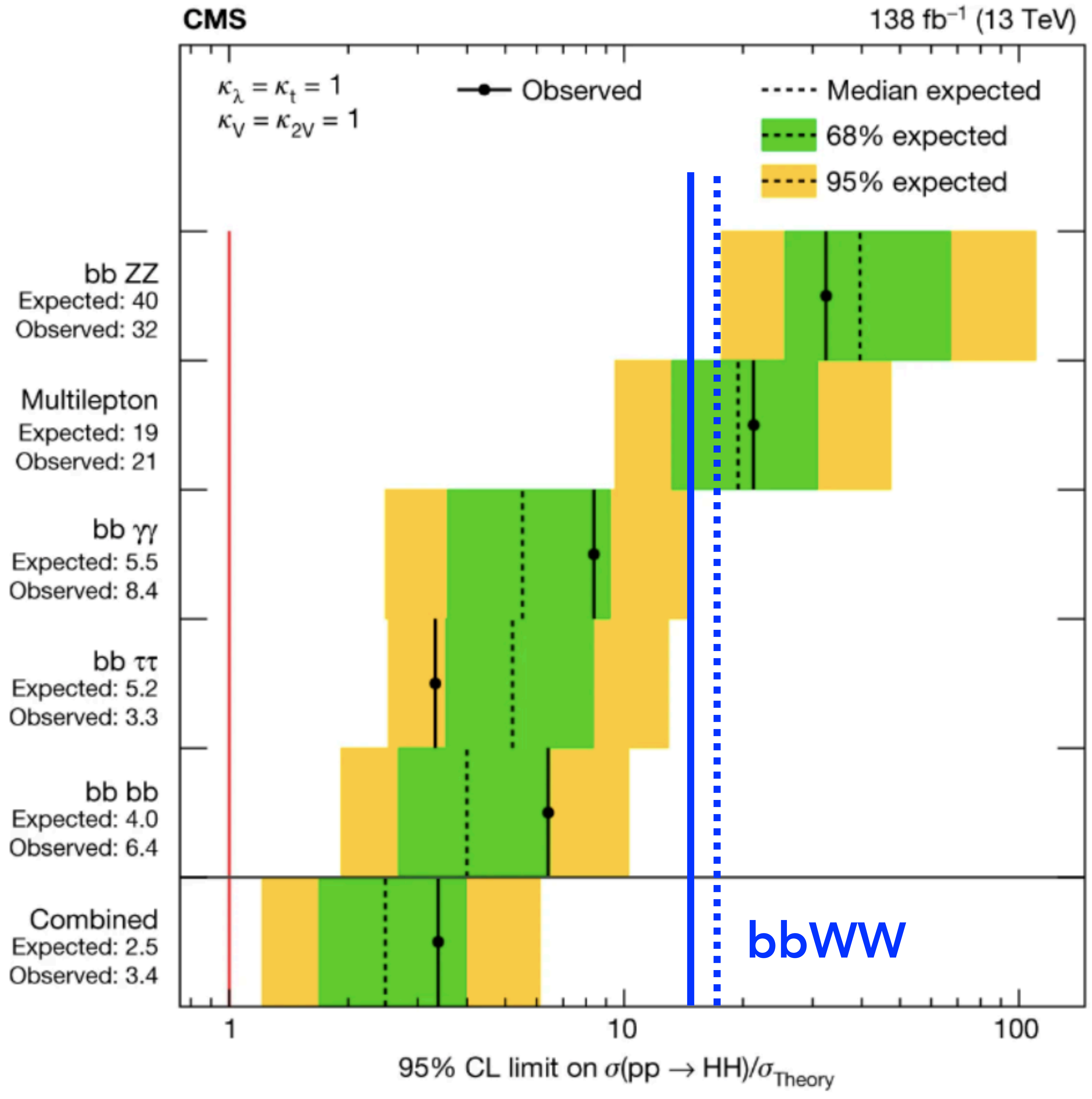

CMS
138 fb-1 (13 TeV)
κλ = κt = κV = 1
Observed
Median expected
Theory prediction
± 1 σ expected
SM prediction
± 2 σ expected
Excluded
Excluded
95% CL upper limit on σ(pp → qqHH) (fb)
κ2V

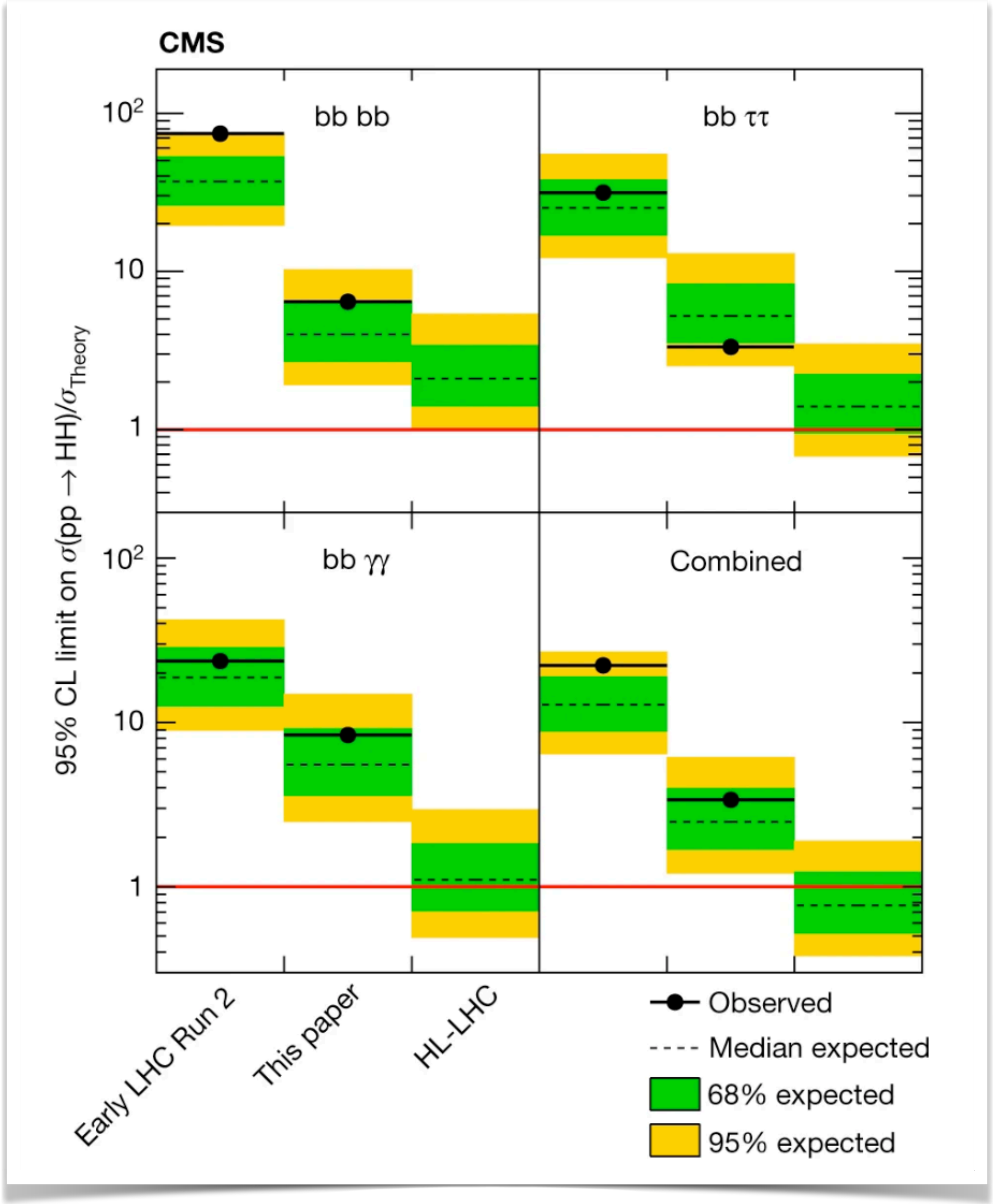
Results



SM point shows the exact same position as in κ_λ scan.
Deviations show the effect of different kinematics.
All are near to the SM with similar sensitivity

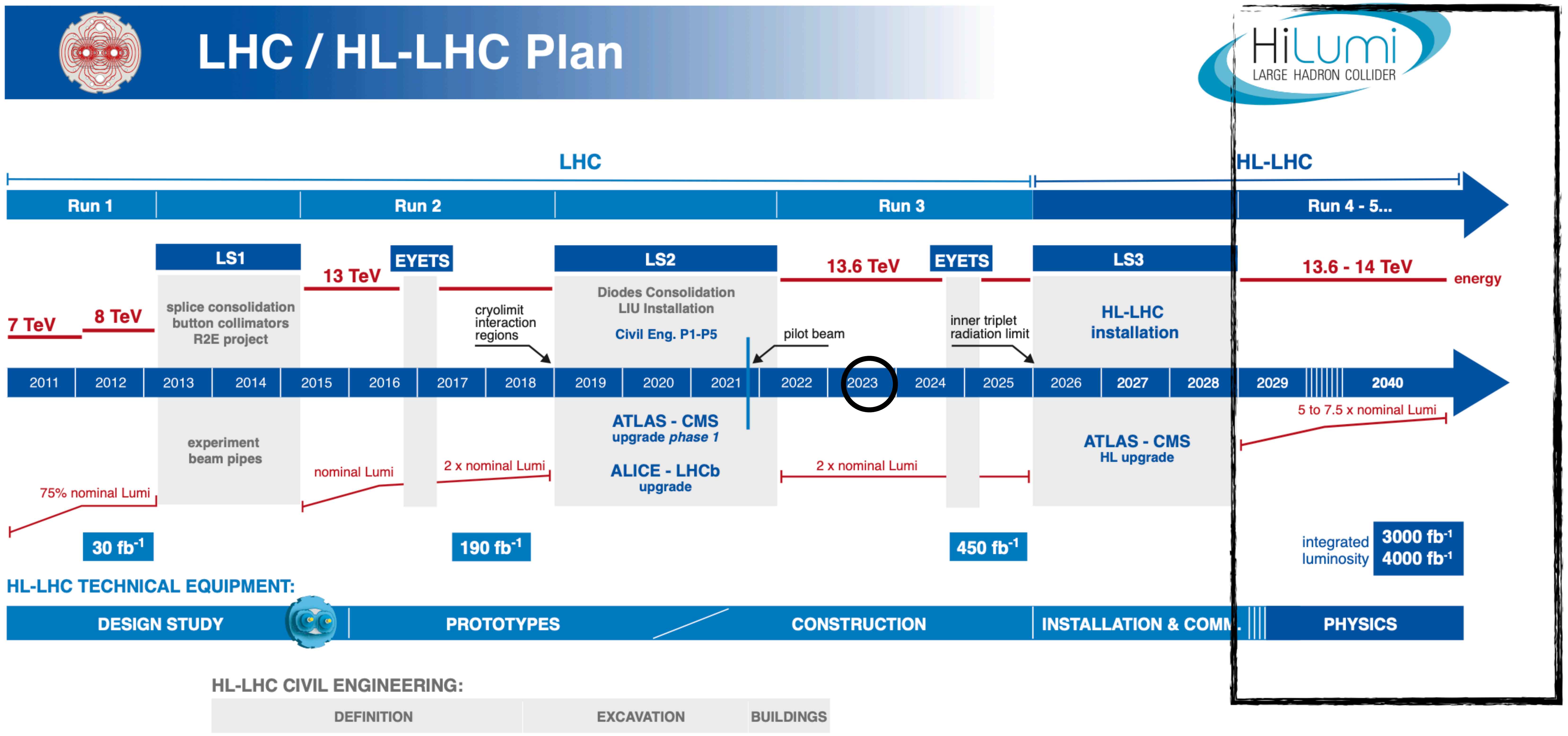
Results


CMS
138 fb^{-1} (13 TeV)
$\kappa_\lambda = \kappa_t = 1$
$\kappa_V = \kappa_{2V} = 1$
Observed
Median expected
68% expected
95% expected
bb ZZ
Expected: 40
Observed: 32
Multilepton
Expected: 19
Observed: 21
bb γγ
Expected: 5.5
Observed: 8.4
bb ττ
Expected: 5.2
Observed: 3.3
bb bb
Expected: 4.0
Observed: 6.4
Combined
Expected: 2.5
Observed: 3.4
bbWW
1
10
100
95% CL limit on σ(pp → HH)/σ$_{Theory}$


CMS
bb bb
bb ττ
bb γγ
Combined
95% CL limit on σ(pp → HH)/σ$_{Theory}$
10^2
10
1
Early LHC Run 2
This paper
HL-LHC
Observed
Median expected
68% expected
95% expected

Performance of the 2S module of new CMS tracker

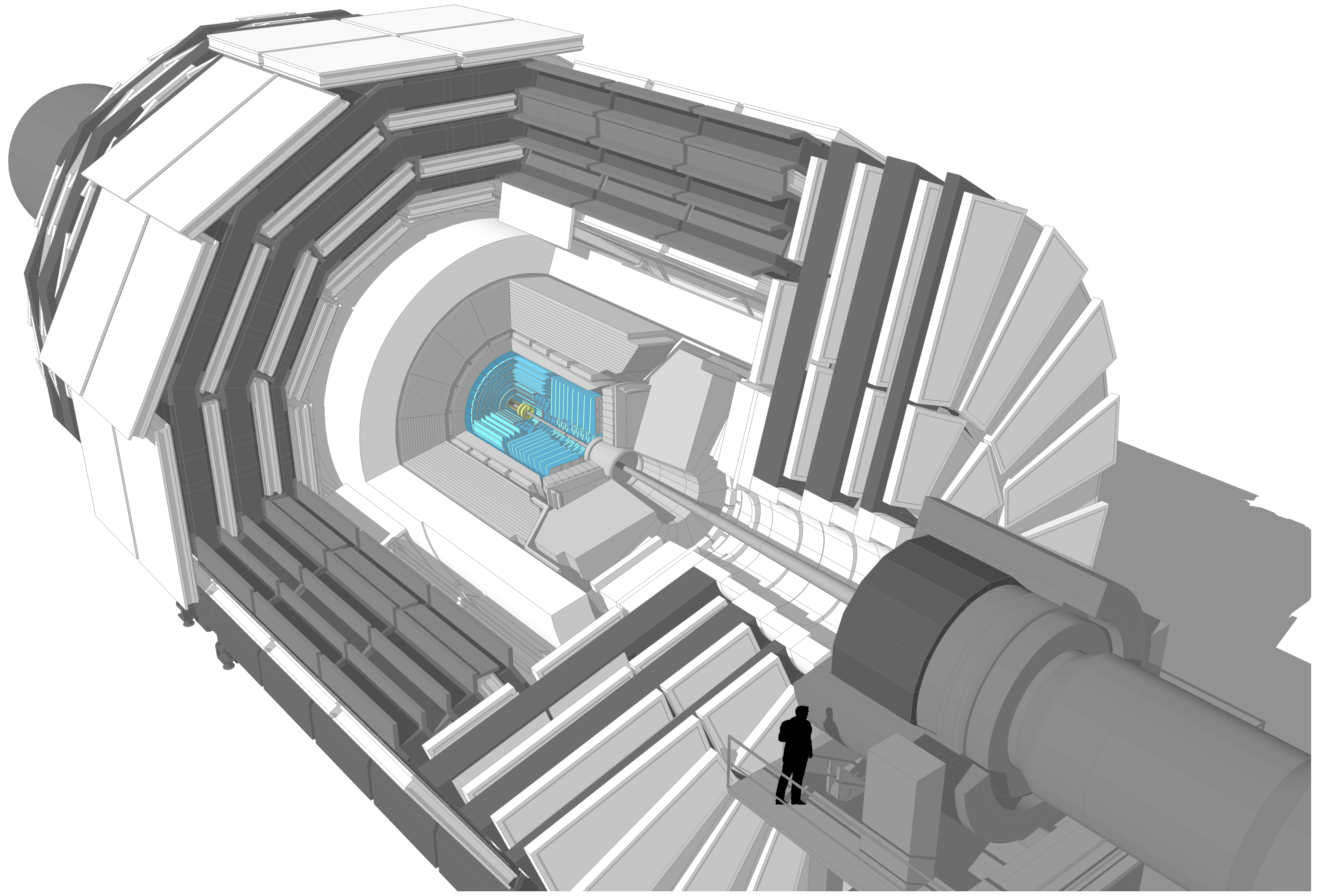
LHC -> HL-LHC

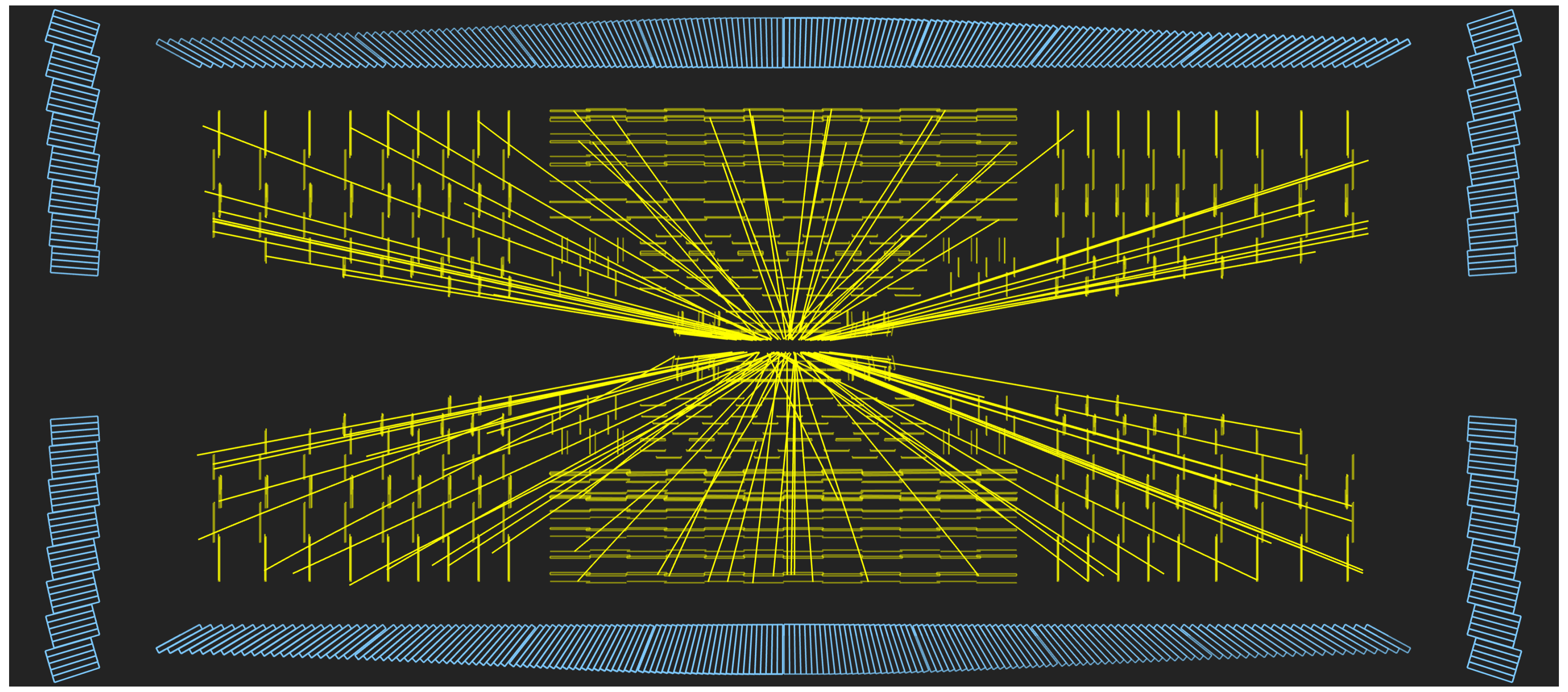


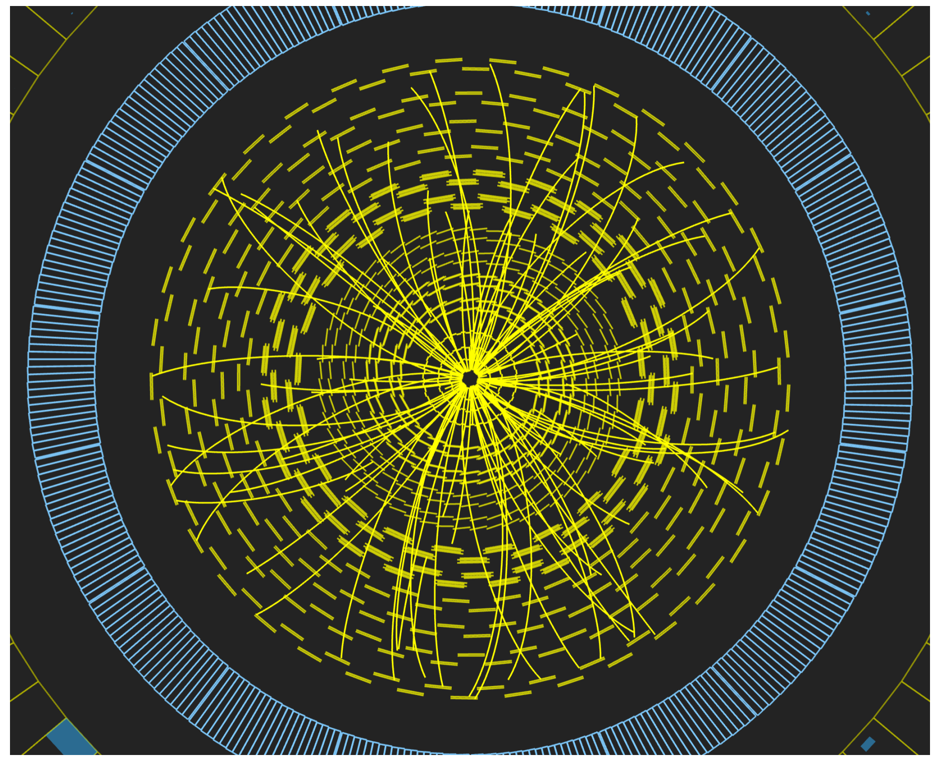
Key changes:

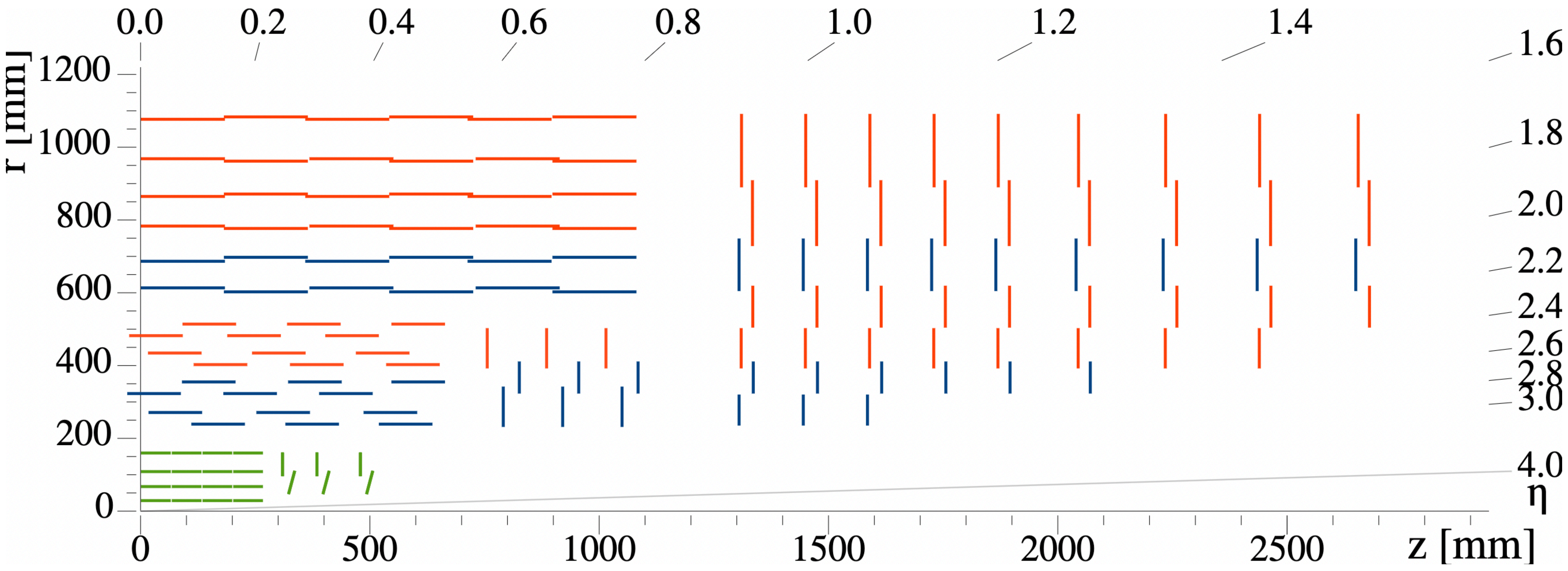
- 5 to 7.5 times higher instantaneous luminosity than the present one
- Expected total integrated luminosity would be > 3000 fb-1
- Level-1 Trigger rate would be 750kHz instead of 100kHz
  - Inclusion of tracking information in L1
- HGCal and MTD installation
- Brand new CMS tracker

Current CMS Tracker

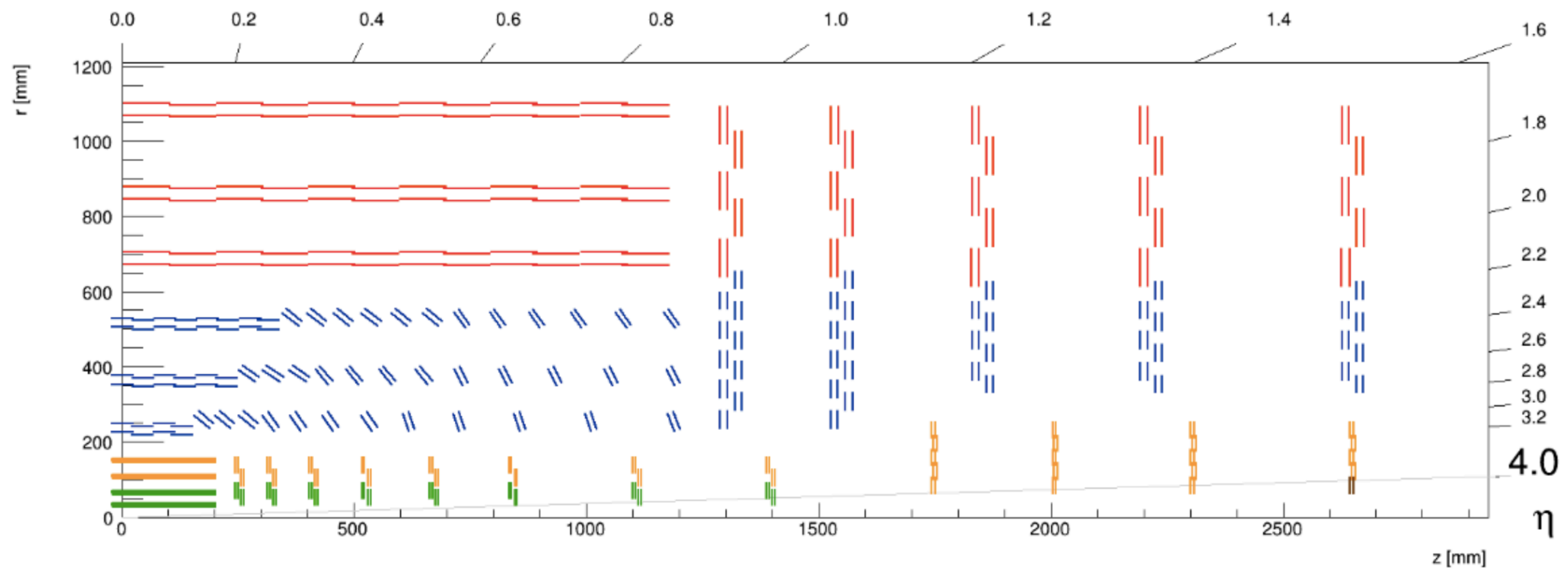








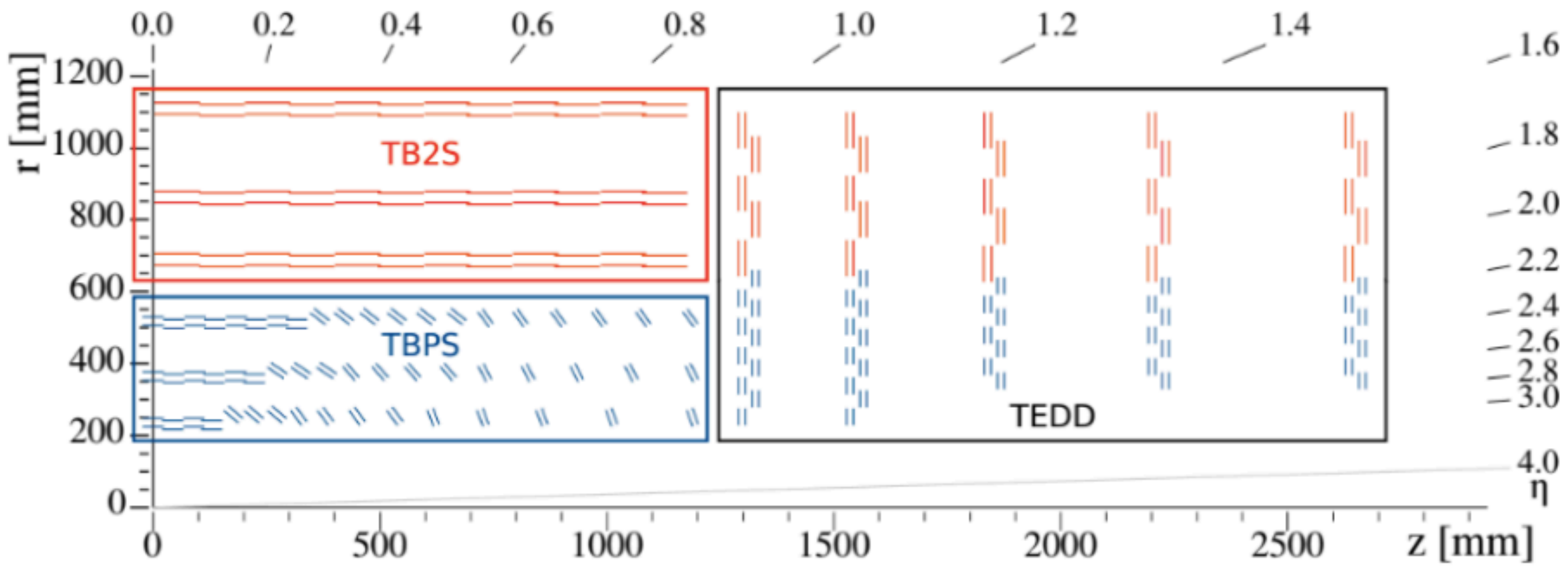
New CMS Tracker

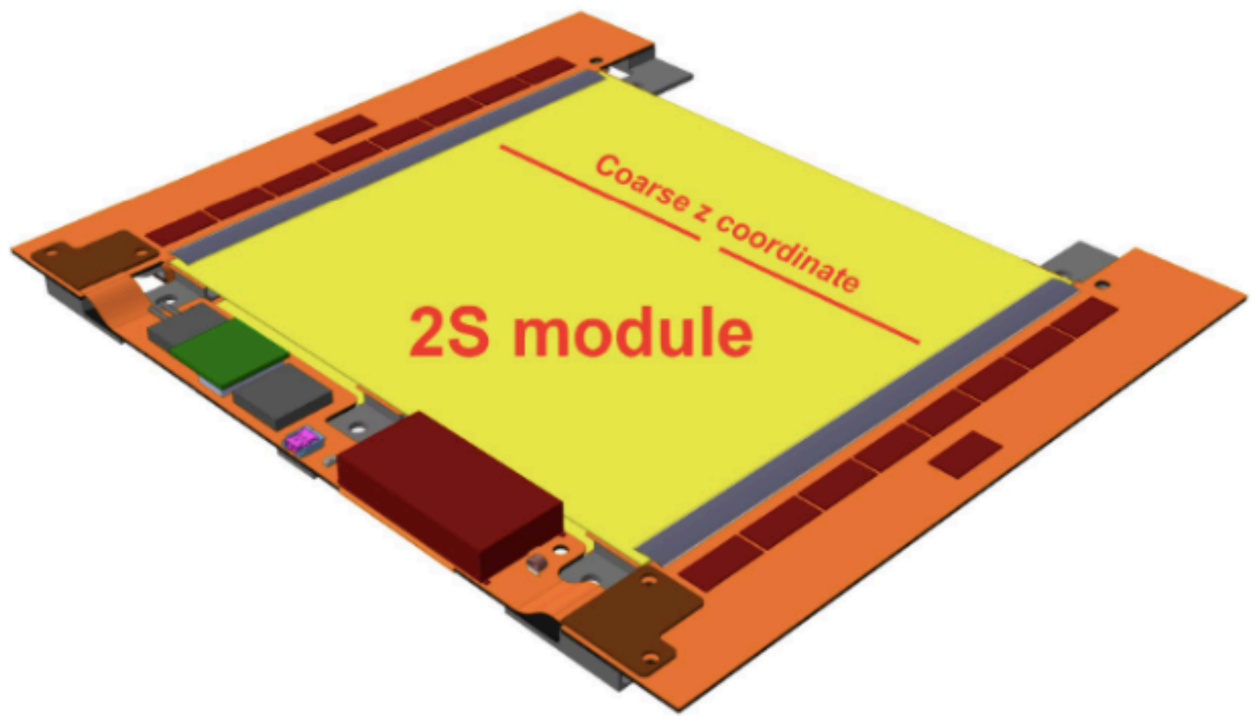


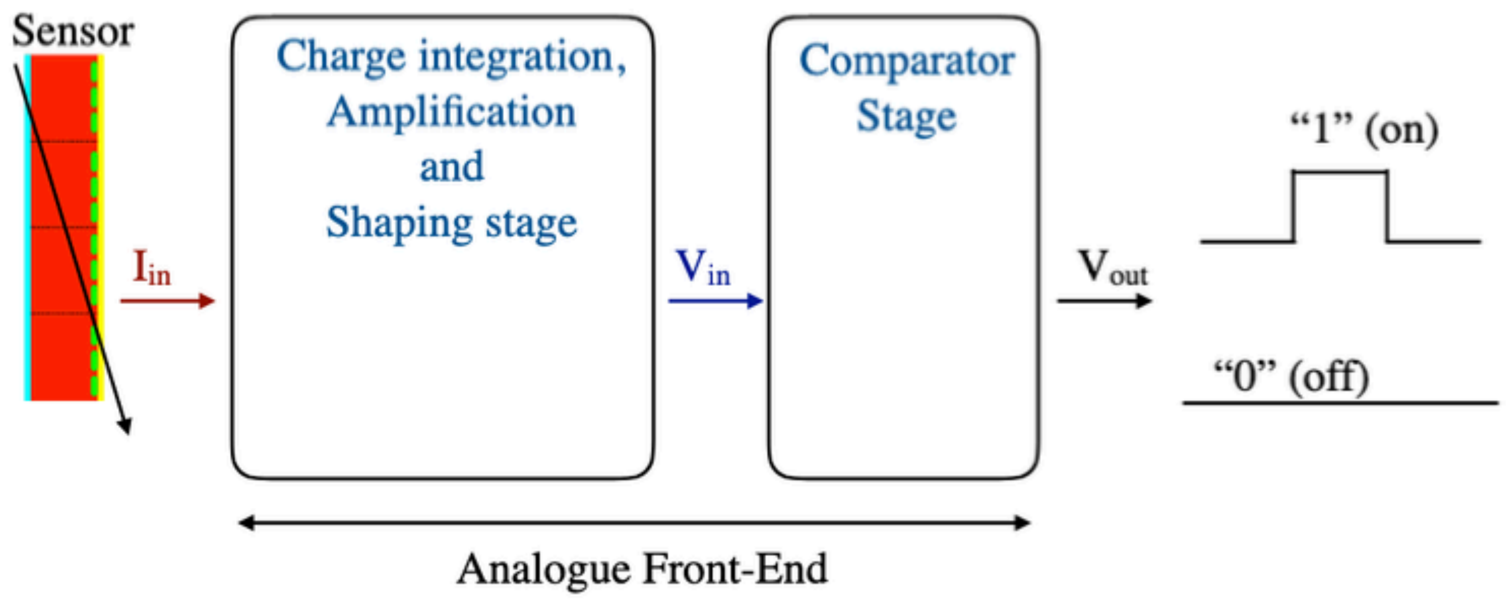
Key Requirements …

- Radiation tolerance
- Higher granularity
- Reduced material budget
- Robust pattern recognition
- Contribution to the Level-1 Trigger
- Extended tracking acceptance

Outer Tracker : 2S pT module

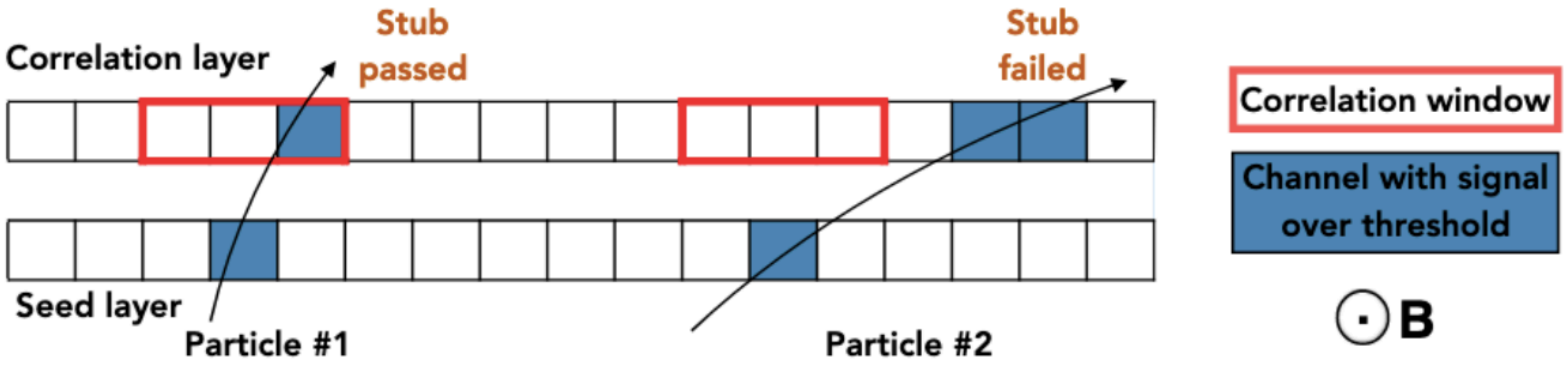




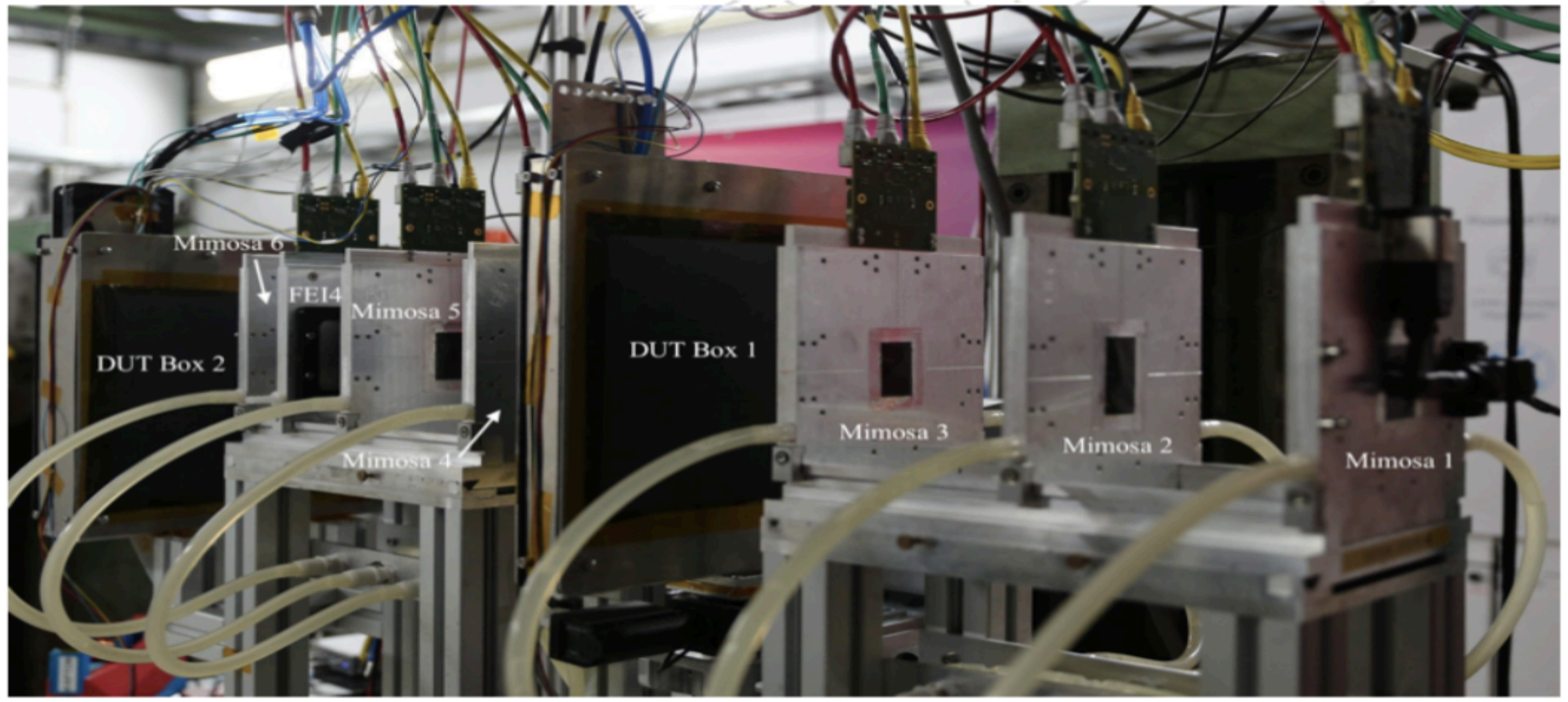


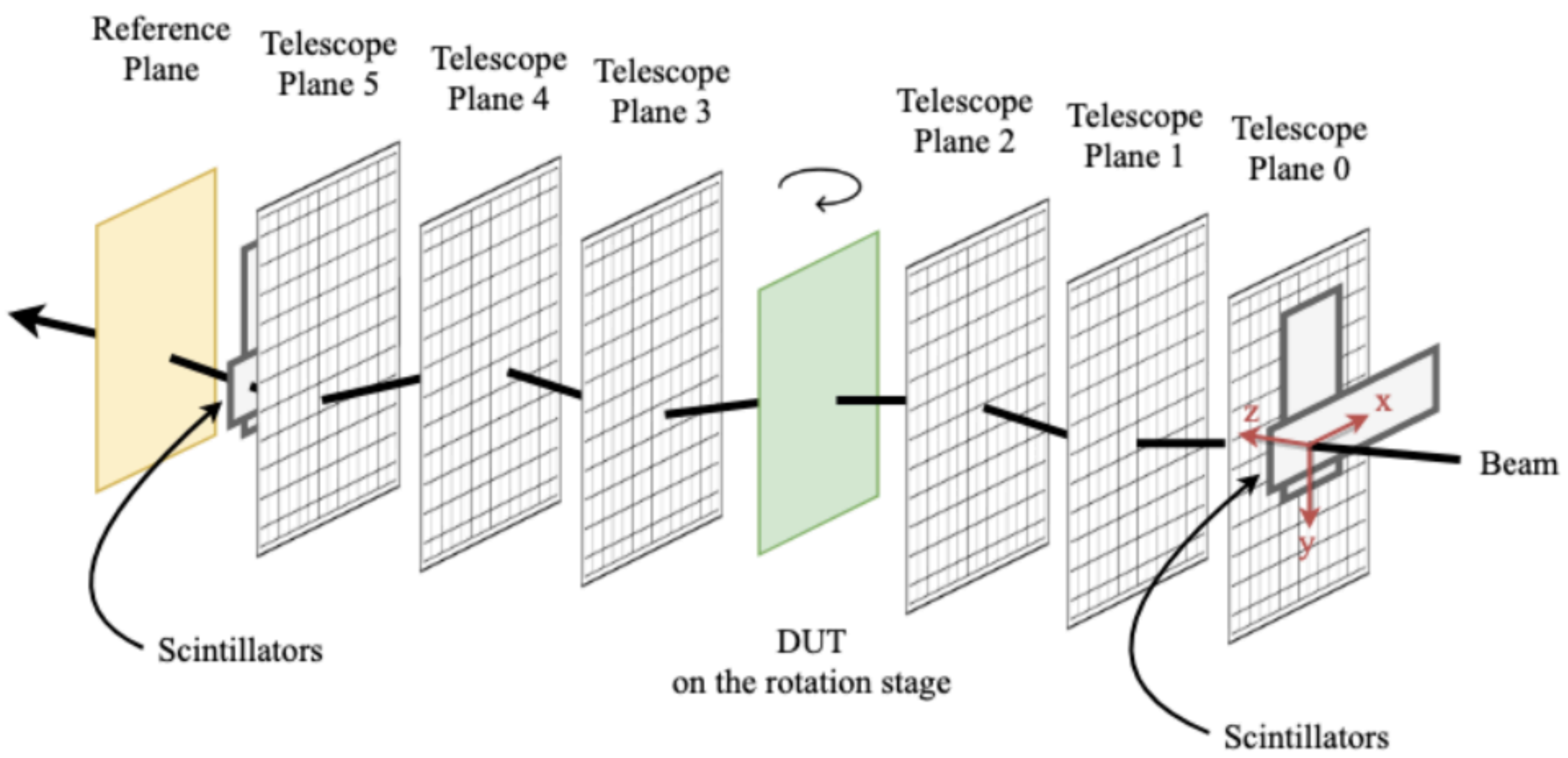
Link

- ☐ 2 parallel sensors with 2 x 1016 Silicon strip detectors
- ☐ Strip length 5cm, pitch: 90 μ
- ☐ 2 2S FEH : 2 x 8 FE chips (CBC3)
- ☐ Position of consecutive hits i.e. clusters with half-strip precision
- ☐ Advantage of on-module track reconstruction above a pT threshold through “Stub” formation



Beam Test

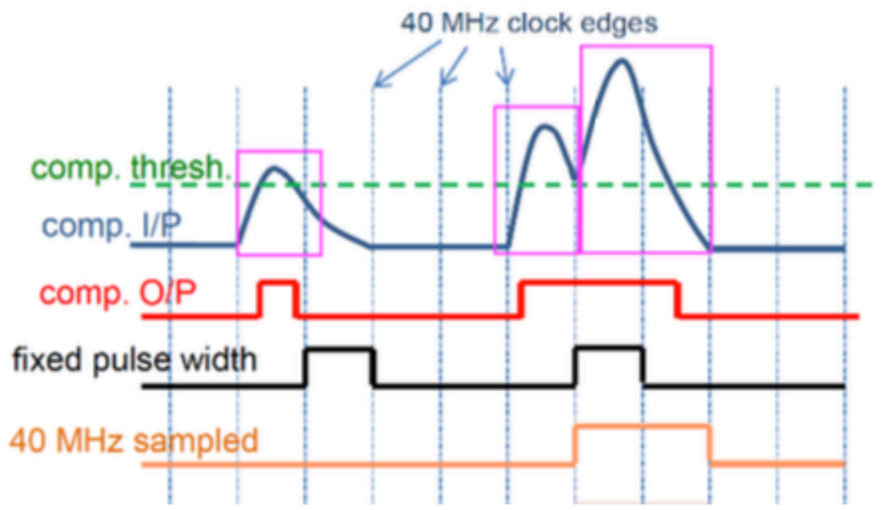




- Proton (120 GeV) / Electron (4 GeV) beam
- DUT: Detector under test (2S module) with resolution ~25 μm
- Telescope system: Six pixel detectors with resolution ~4 μm
- FeI4: Timing layer used for trigger
- Telescope planes reconstruct tracks precisely
- Tracks with hit at FeI4 are selected
- Clusters or stubs matched with the 'selected' tracks describes the performance of a DUT by the track matching efficiencies
- Effect of radiation has been examined using irradiated module
- Mainly two type of scans have been performed:
  - Threshold (V_{CTH}) scan
  - Angular Scan

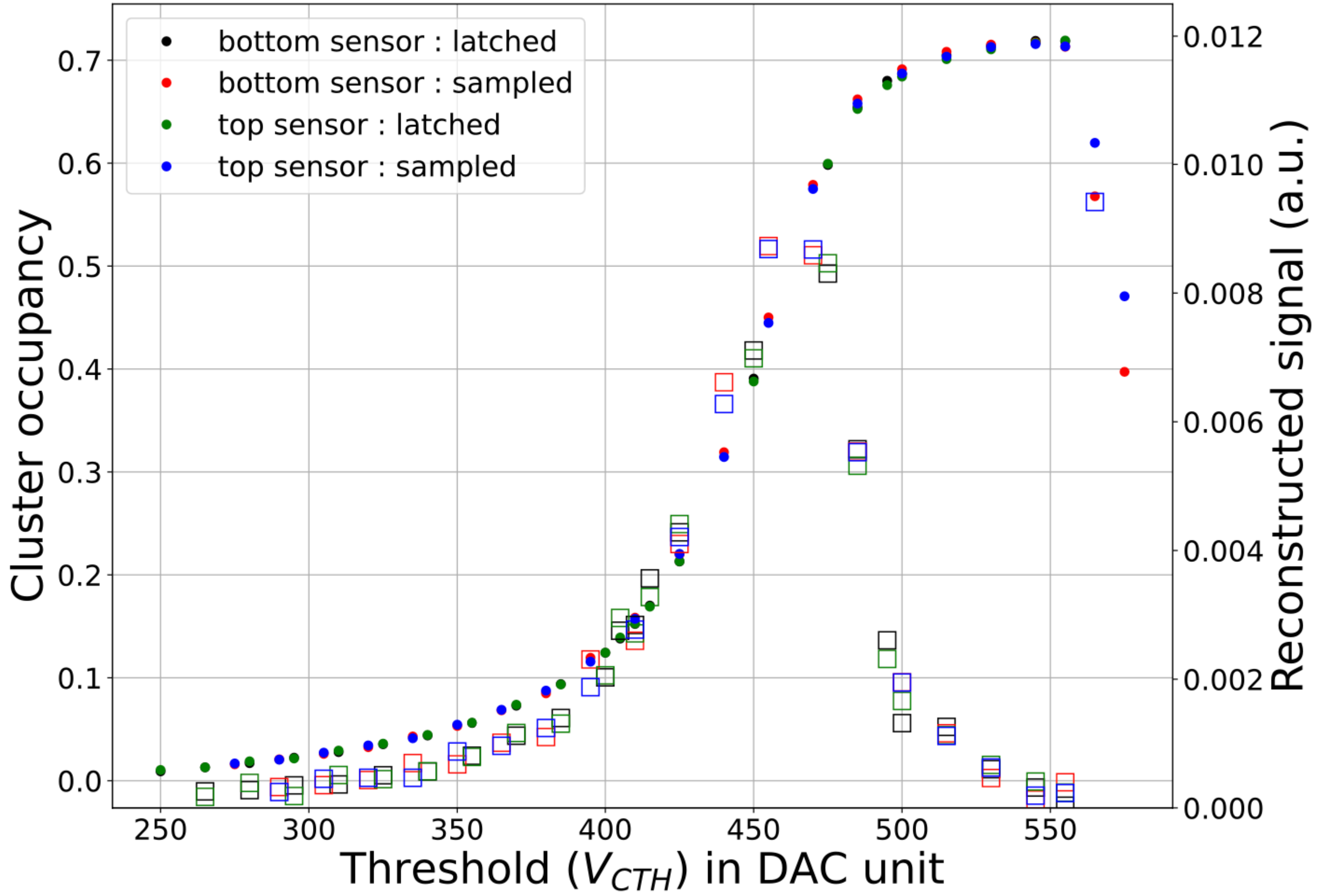
Threshold Scans

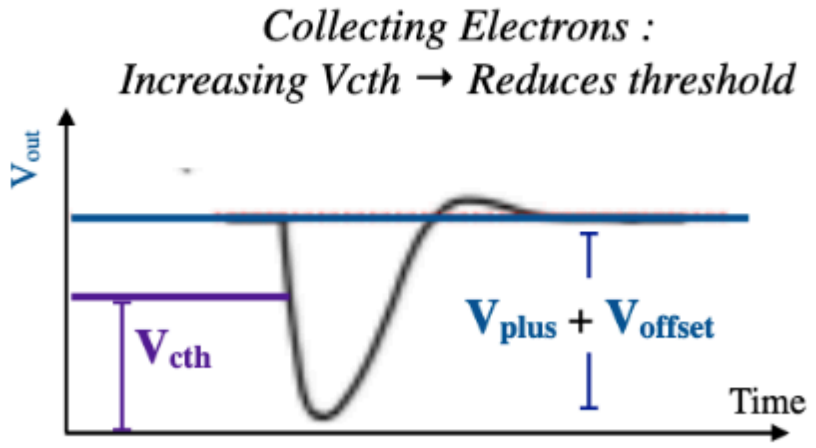
Hit detection logic:



Link

Lower threshold increases the number of clusters





$1\, V_{CTH} = 156\, e^{-}$

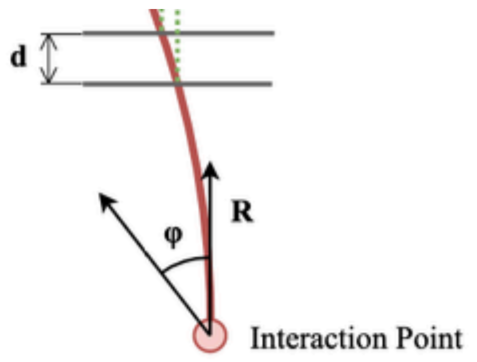
Differential distribution of number of clusters is the reconstructed shape of the signal

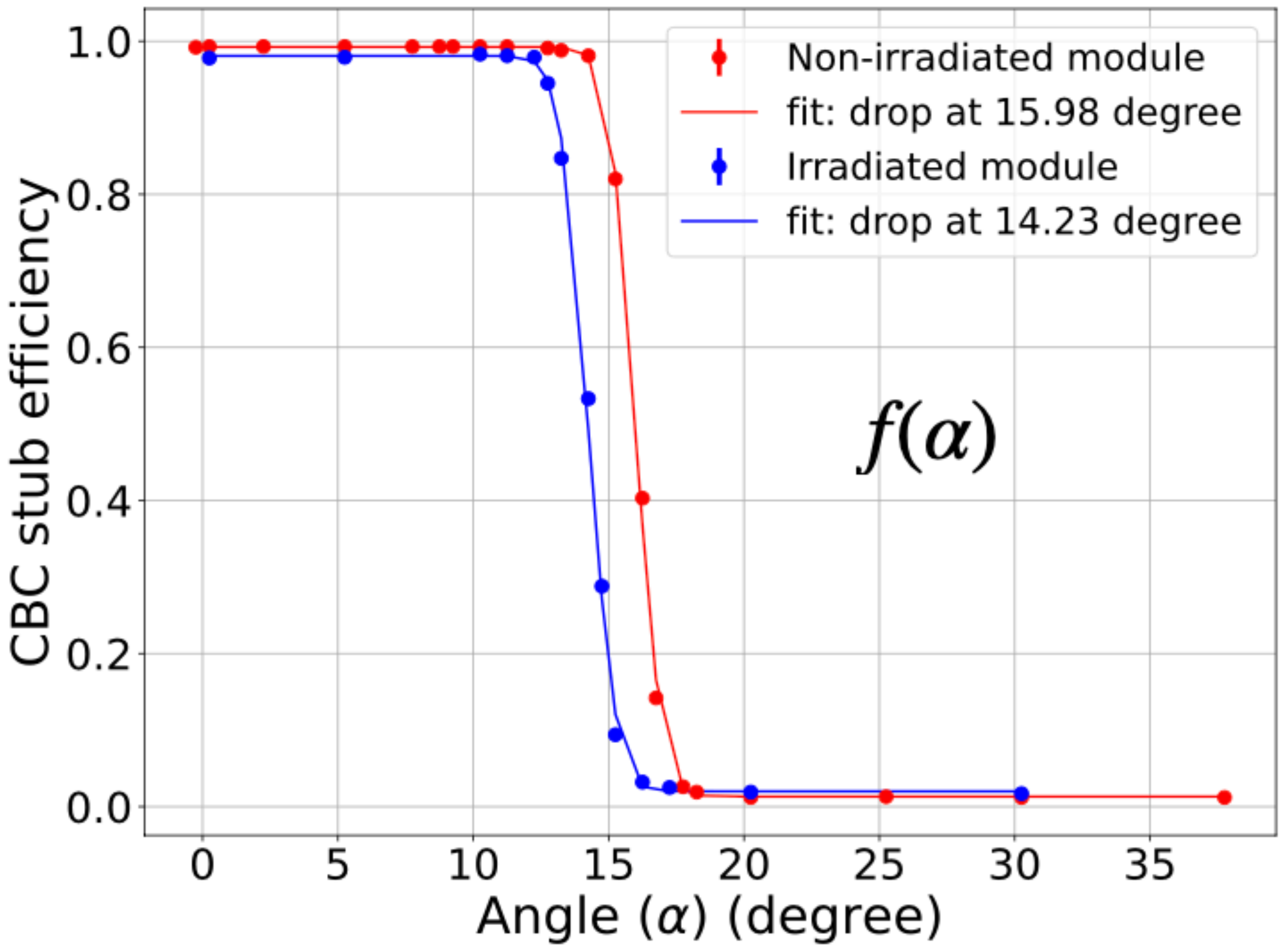
Discriminate signal from pedestal

Angular Scans

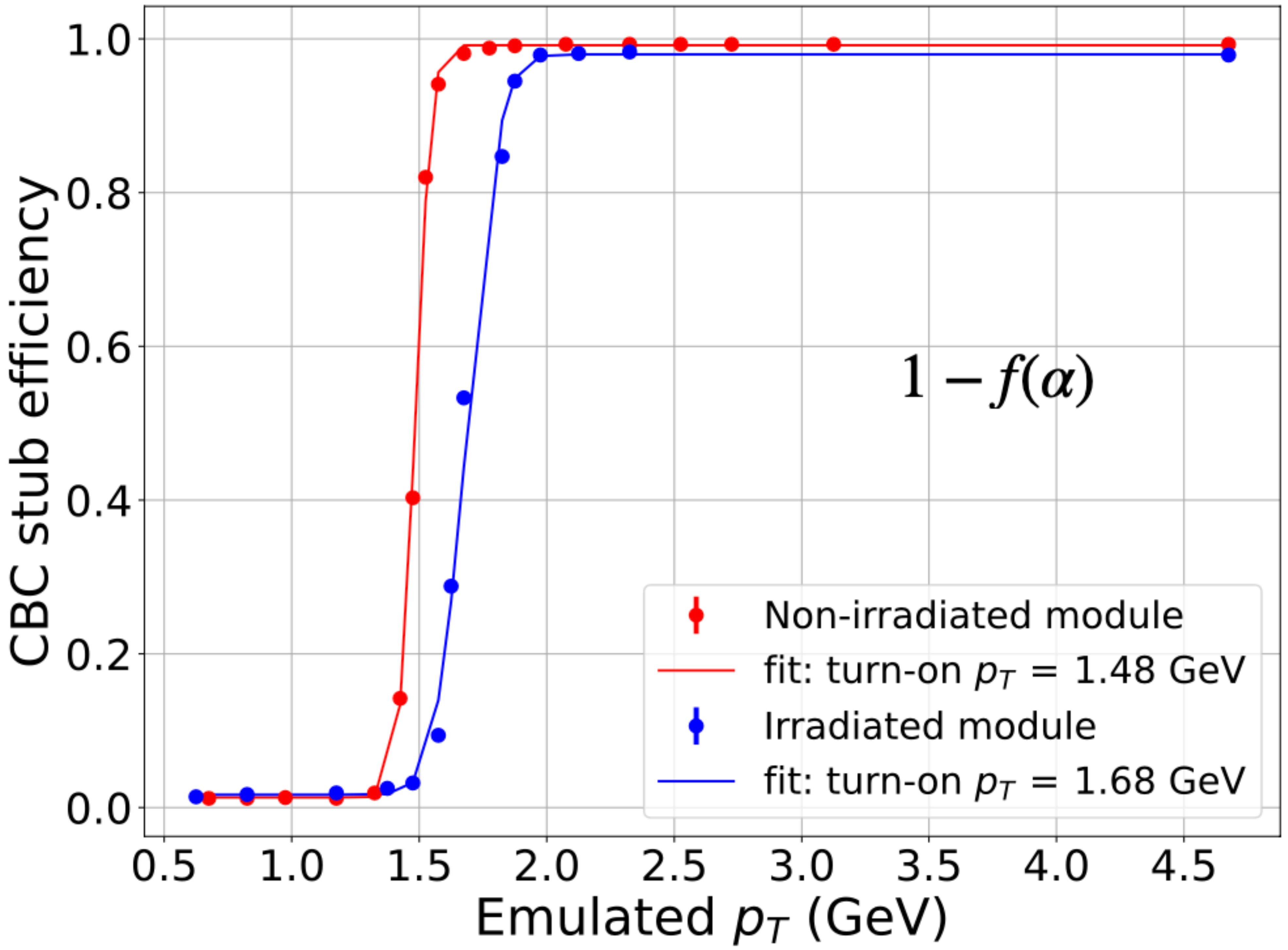
Irradiated with 23 MeV protons
up to a 1 MeV neutron equivalent fluence of $4.6 \times 10^{14}\,\mathrm{n_{eq} cm^{-2}}$.
120% of the max fluence a 2S module expects after 10 years of HL-LHC operation.

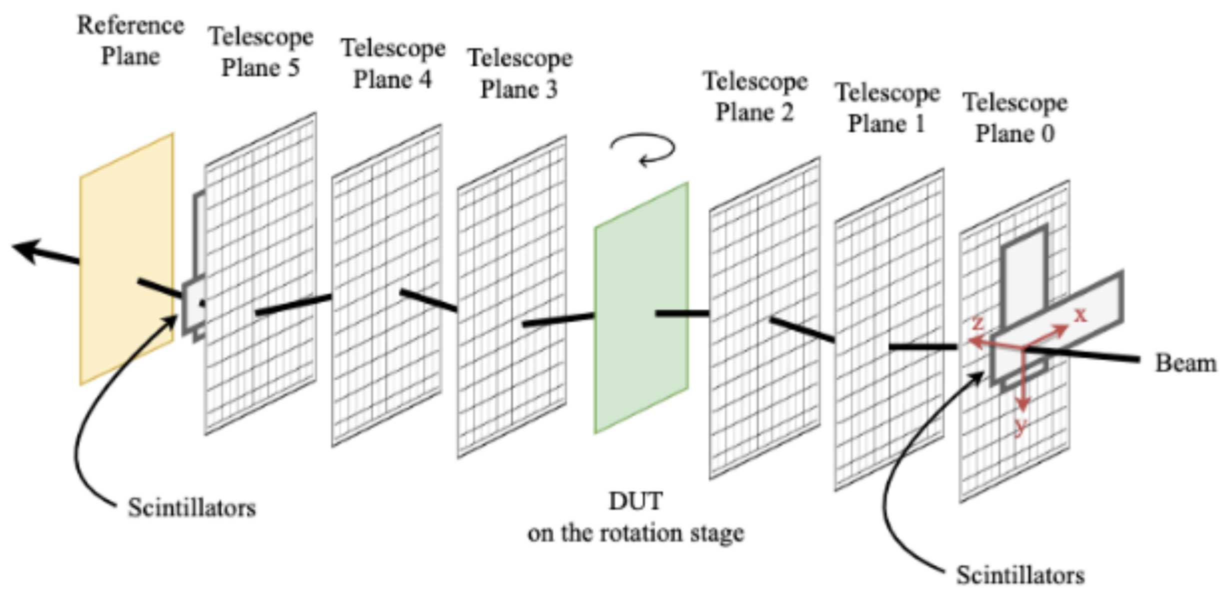
$$f(\alpha) = 1 - \frac{1}{2}(p_0 + p_1 \times erf(\frac{x - p_2}{p_3}))$$





pT can be emulated from incidence angle
In 3.8T B, a 2S module is placed at the 4th layer of outer tracker barrel with a correlation window of ± 5 strips





On-module high pT track finding logic seems perfect

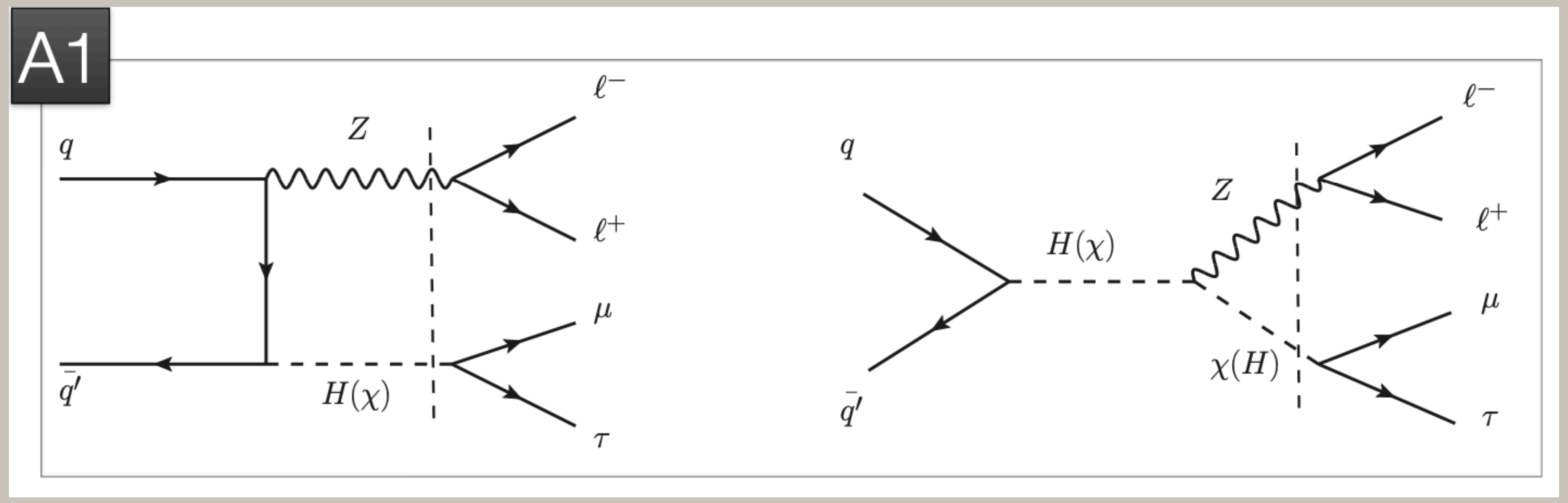
$$p_T[GeV] = \frac{0.57 \times R[m]}{sin(\theta)},$$ R = 0.71m in 3.8T B

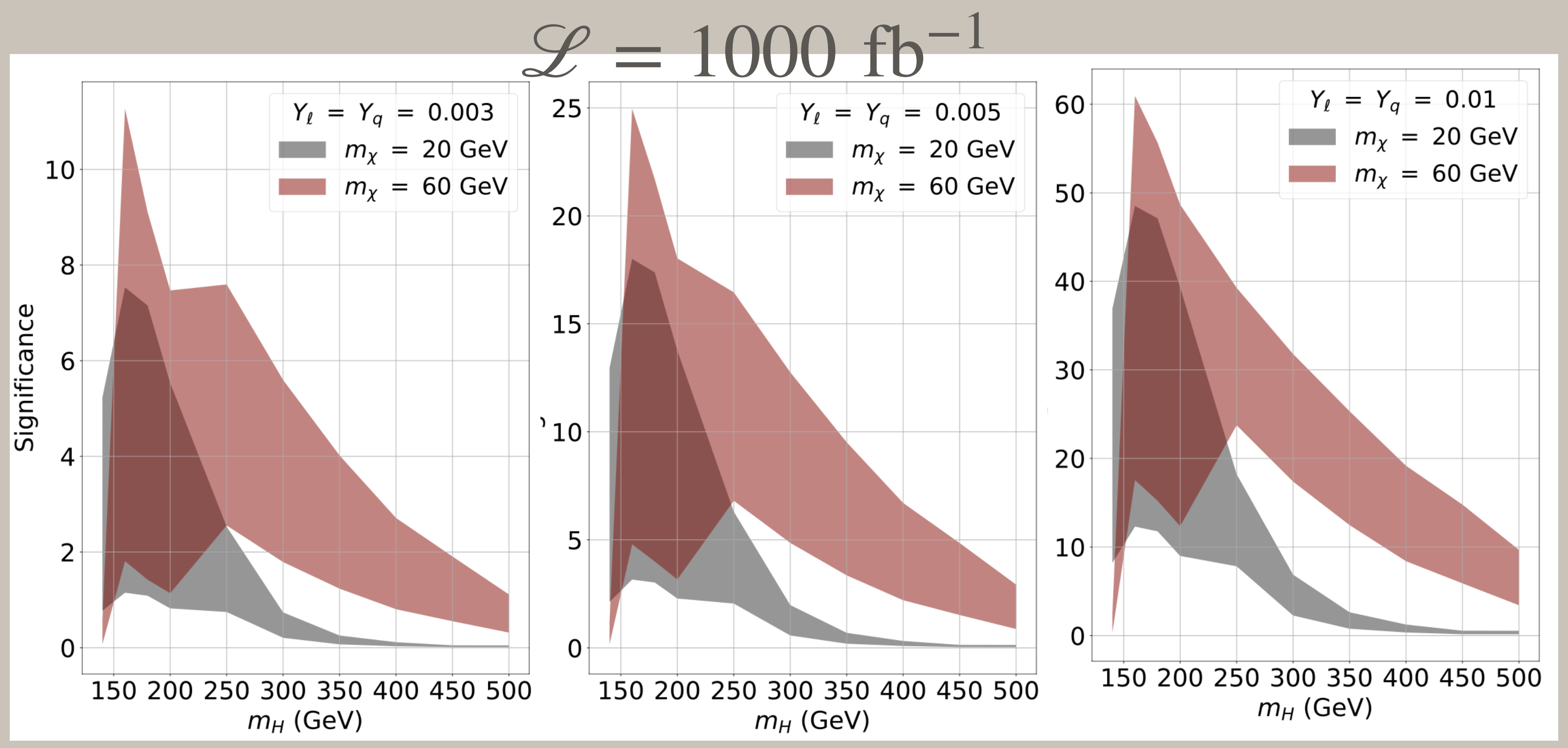
Phenomenological Studies

Search for exotic Higgs boson at the LHC

Flavor models based on Discrete symmetry groups with extended scalar sectors known to yield CP-even and CP-odd spin-0 exotic states

S3 symmetric 3 HDM: 3 CP even, 2 CP odd neutral and 2 sets of charged scalars with purely off-diagonal couplings (No H(X)VV coupling): Particles of interest: CP even heavy scalar H, CP odd light pseudo scalar X … Couplings of interest: Huc, Xmutau





Major Bkgs: WZ+Jets, ZZ+Jets, ttZ+Jets

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Search for exotic Higgs boson at the LHC

Flavor models based on Discrete symmetry groups with extended scalar sectors known to yield CP even and CP odd spin 0 exotic states

S3

sc

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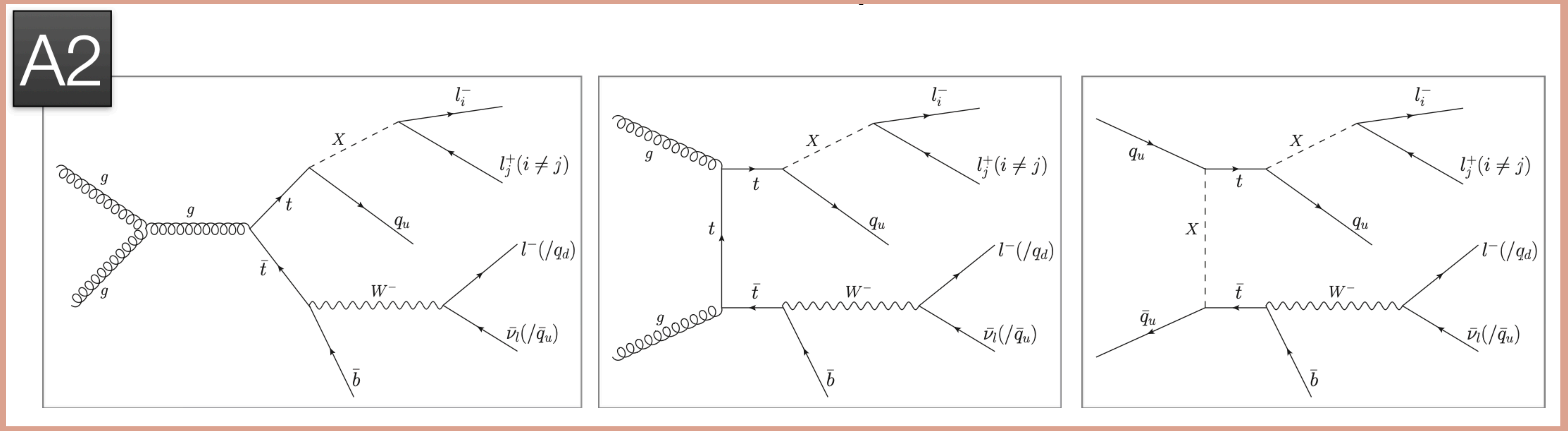
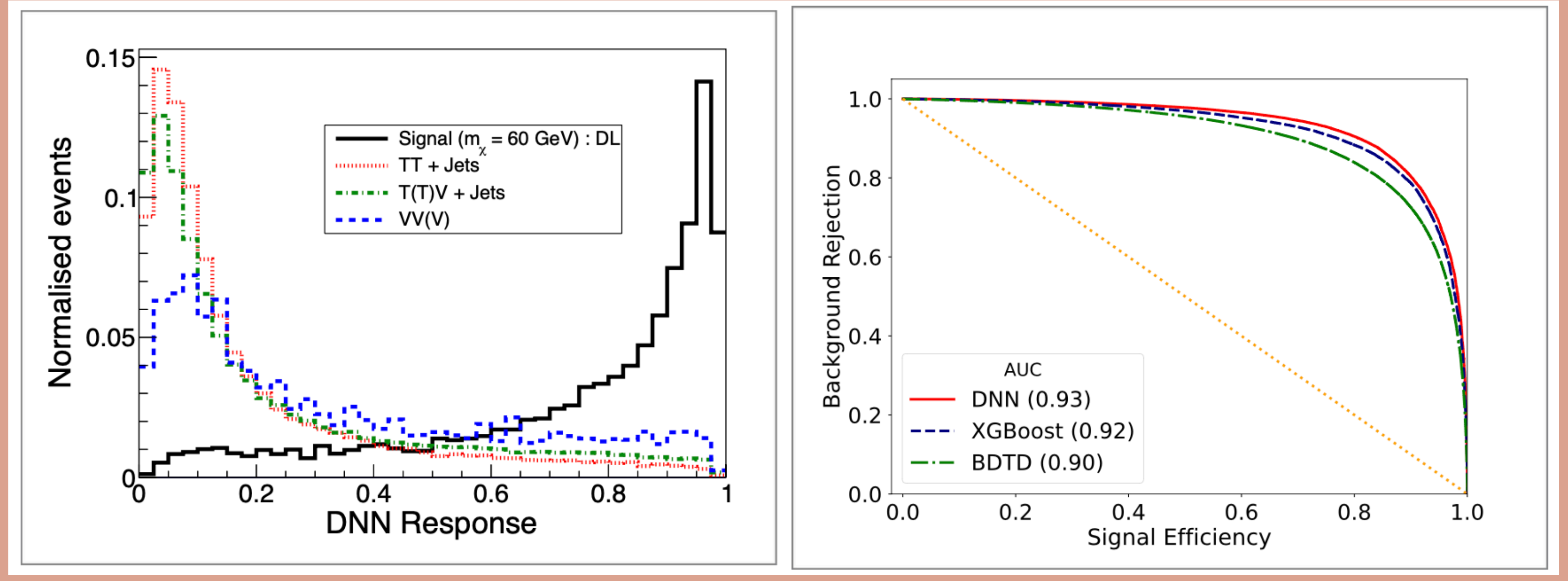
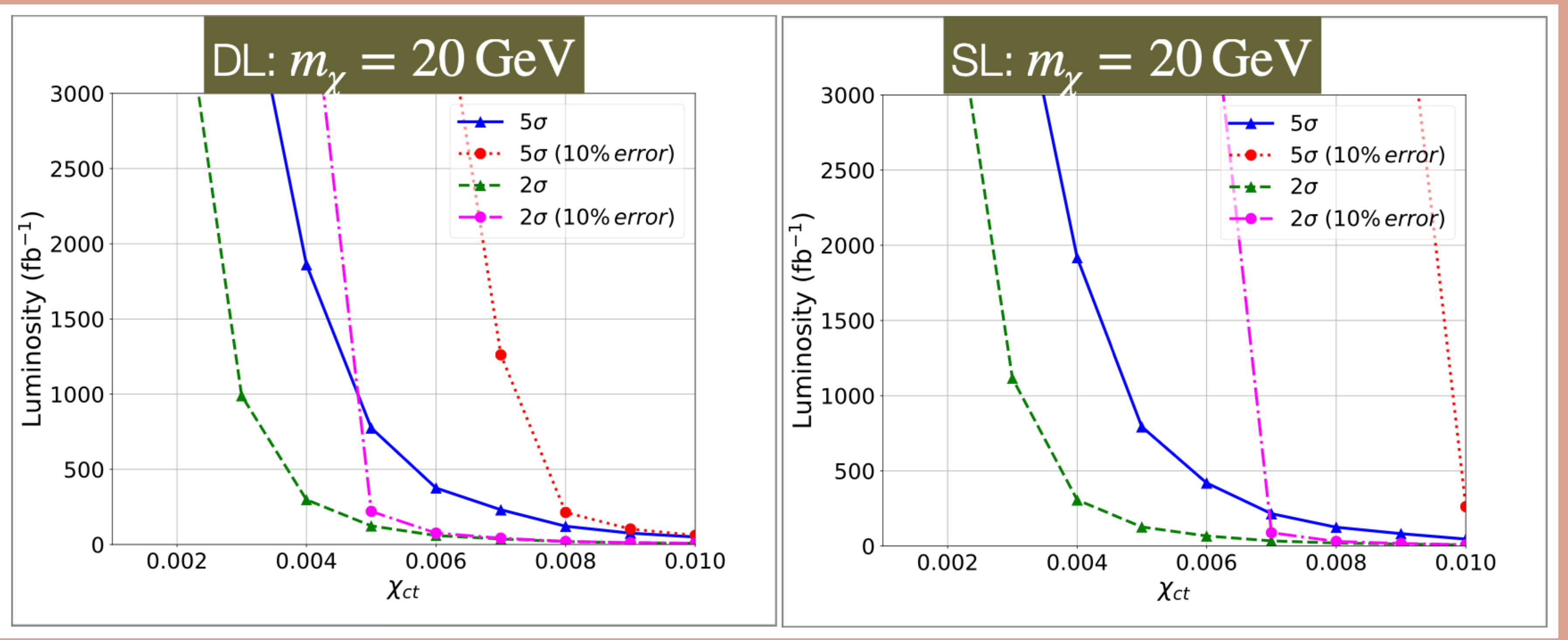
Search for exotic Higgs boson at the LHC

Looking for Xct couplings: a different channel dominated by ttbar background process

2212.09061

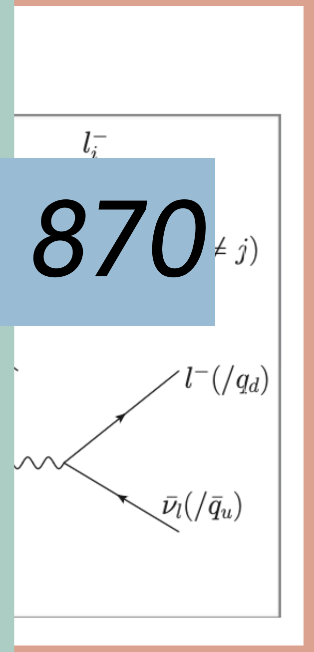






Search for exotic Higgs boson at the LHC

Flavor models based on Discrete symmetry groups with extended scalar



y ttbar

Muon g-2 and W-mass in a framework of colored scalars

Type-X 2HDM is augmented with a color octet isodoublet: able to explain the observed value of W-mass by CDF and g-2 anomalies with minimal flavor violation.

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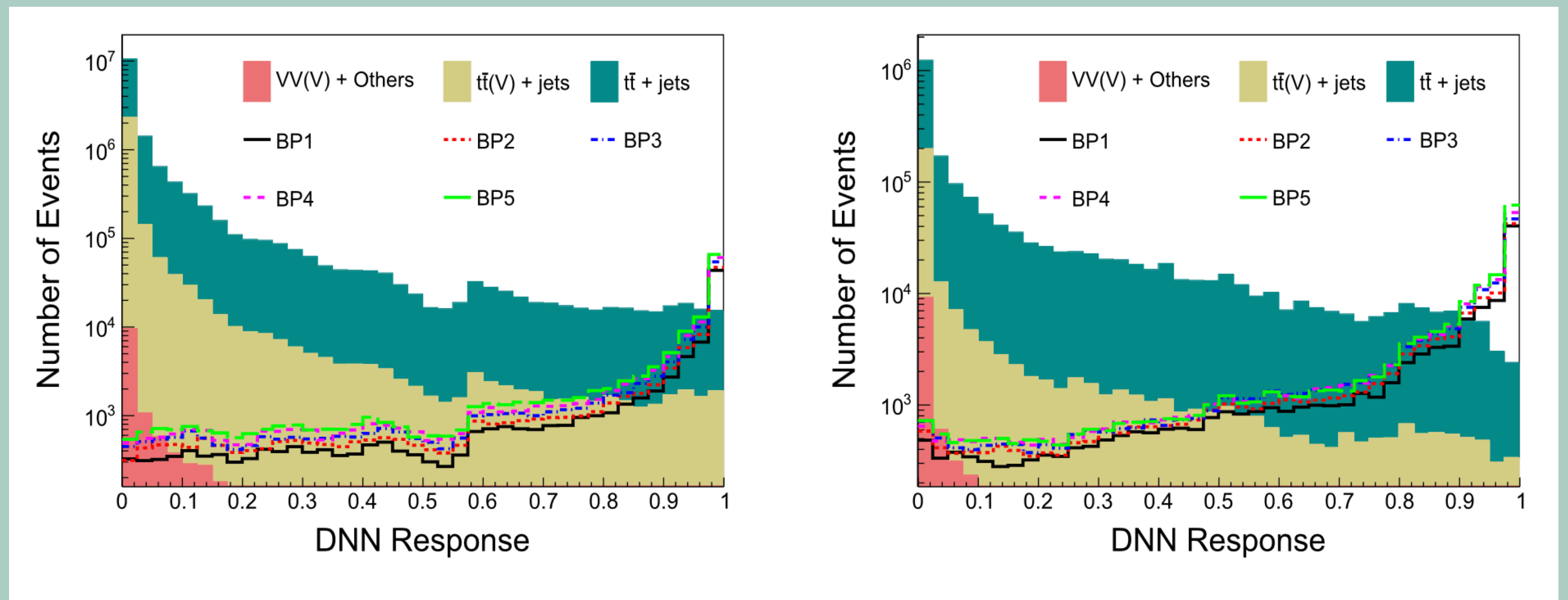
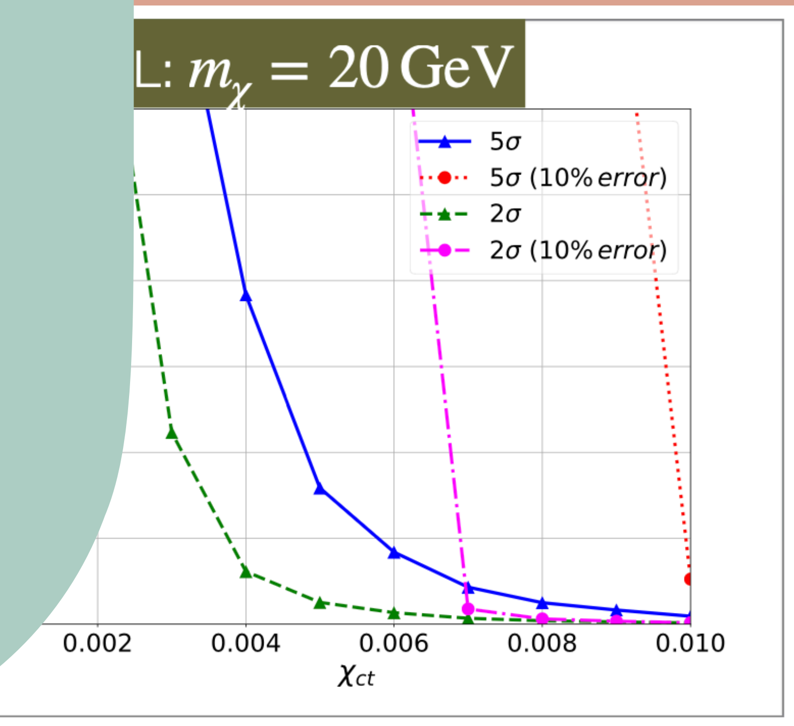
A collider signature in bbtautau final state has been studied



(a) SL (b) NoL

Significance	
$\theta = 0\%$	$\theta = 5\%$
20.1	4.50
34.8	9.56
19.9	4.47
35.2	9.65
17.9	2.47
30.9	8.58
12.1	1.70
22.3	6.37
4.27	0.61
9.19	2.76



Do not let the neutrino escape


CMS Experiment at the LHC, CERN
Data recorded: 2015-Jul-12 06:52:51.677888 GMT
Run / Event / LS: 251562 / 310157776 / 347


CMS Experiment at the LHC, CERN
Data recorded: 2015-Jul-12 06:52:51.677888 GMT
Run / Event / LS: 251562 / 310157776 / 347

Event Selection

- Dataset:
  - DYJetsToLL

- 2 tau candidates of opposite charge
- 12 < Invariant mass of two taus < 200
- No extra electrons or muons

- Muon selection:
  - Pt > 20 GeV
  - |eta| < 2.4
  - |dxy| < 0.045
  - |dz| < 0.2
  - mediumId

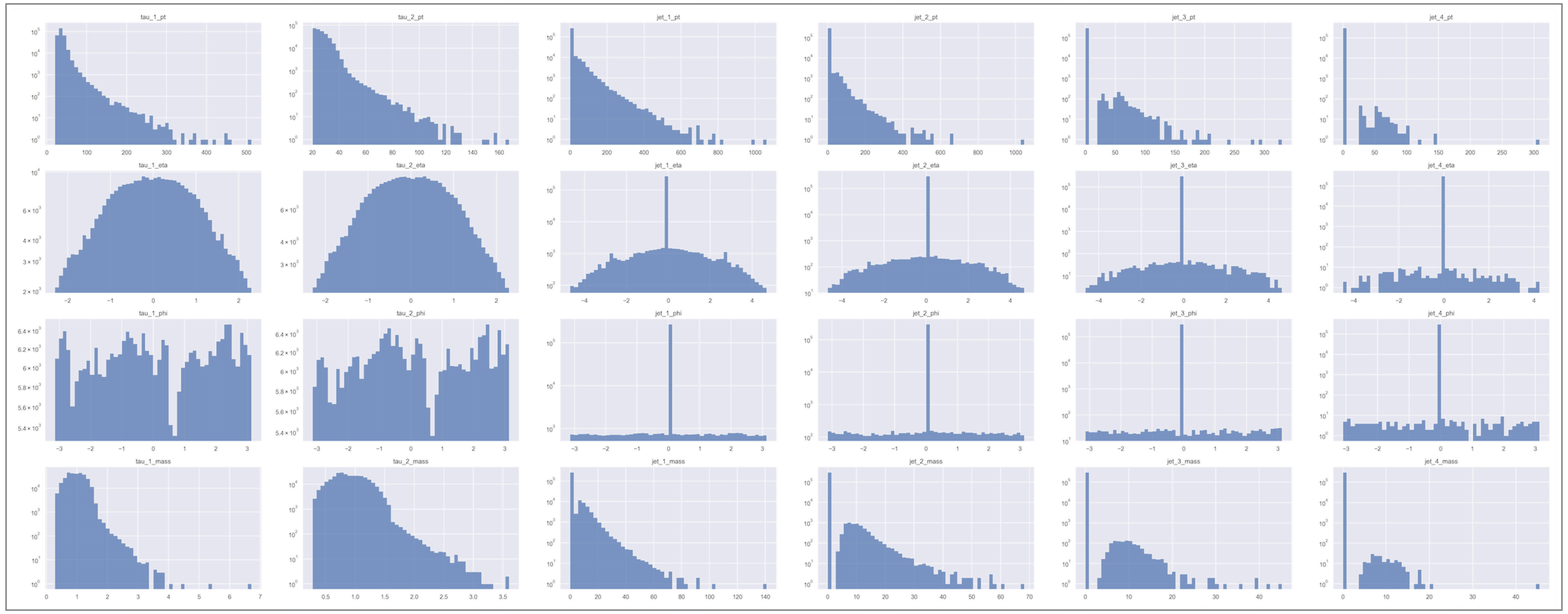
- Electron selection:
  - Pt > 25 GeV
  - |eta| < 2.5
  - |dxy| < 0.045
  - |dz| < 0.2
  - mvaFall17V2Iso_WP80
  - Electron.DeltaR(Muon) > 0.2

- Tau selection:
  - Pt > 20 GeV
  - |eta| < 2.3
  - |dz| < 0.2
  - idDecayModeNewDMs
  - DM: 0, 1, 2, 10, 11
  - idDeepTau2017v2p1VSjet >= 4, idDeepTau2017v2p1VSe >= 2, idDeepTau2017v2p1VSmu >= 1
  - Tau.DeltaR(Muon/Electron) > 0.2

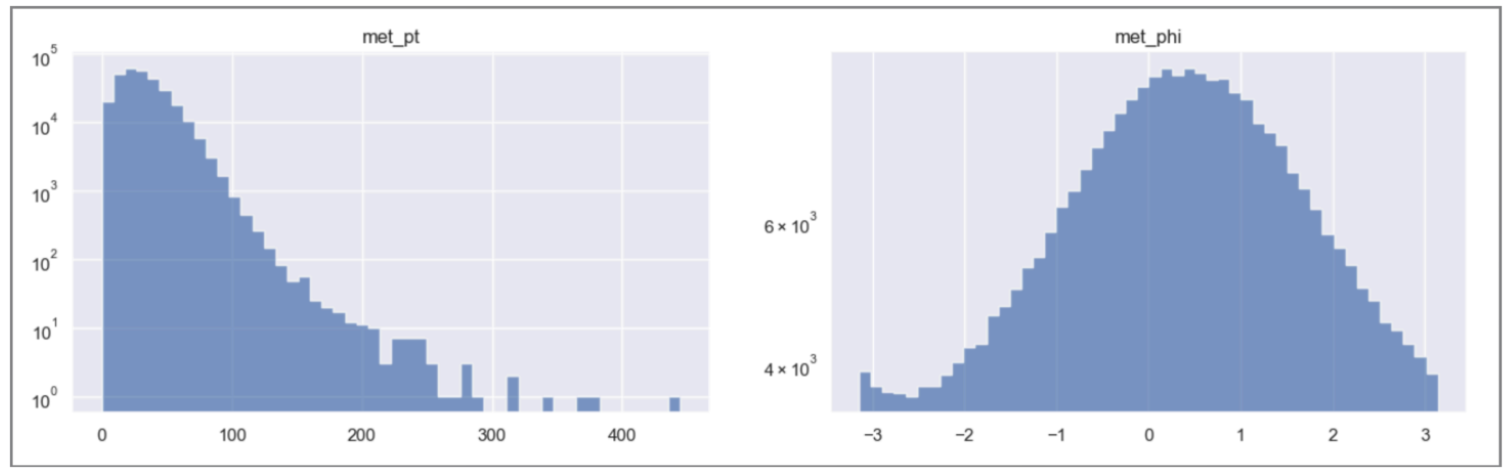
- Jet selection:
  - Pt > 25 GeV
  - |eta| < 4.7
  - jetId == 6
  - puId == 4 if pt > 50 GeV
  - Jet.DeltaR(ele/mu/tau) > 0.2

- Gen tau_nu selection:
  - |PdgId| == 16
  - Flags: isTauDecayProduct | isPromptTauDecayProduct | isDirectTauDecayProduct | isDirectPromptTauDecayProduct
  - |PdgId| of mother == 15
  - Gen.DeltaR(tau) < 0.4
  - Pt > 0.1 GeV

Pt
Eta
Phi
Mass



Tau 1 Tau 2 Jet 1 Jet 2 Jet 3 Jet 4



Networks used

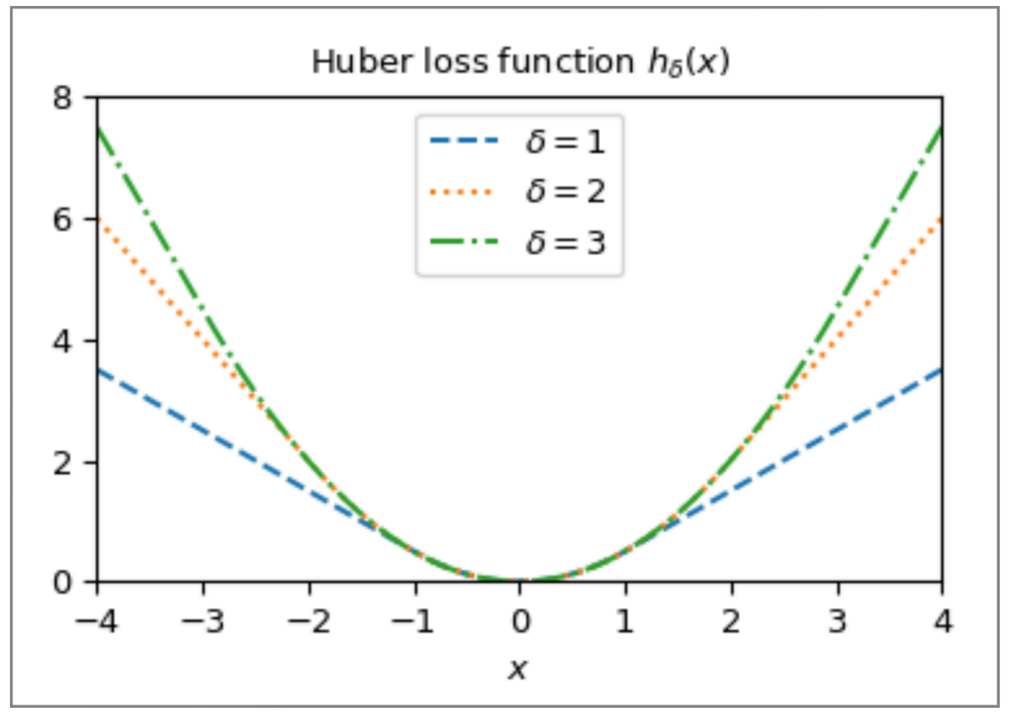
- ResNet: Deep Neural Network with skip connections
  - Initial layer: 512 hidden nodes [4 ResNet blocks with three layers]
  - Activation: selu
  - Batch Normalization
  - Dropout: 10%
  - L2 Regularizer: 0.0001

- LBN: Lorentz Boost Network + ResNet
  - LBN with 2 hadronic taus, 4 leading jets, MET
  - LBN outputs: 5 particles with [“E", "px", "py", "pz", "pt", "eta", "phi", "p", "m", “pair_cos"]
  - Extra features concatenated with LBN output
  - Then the skip connections are the same as mentioned in ResNet

Loss

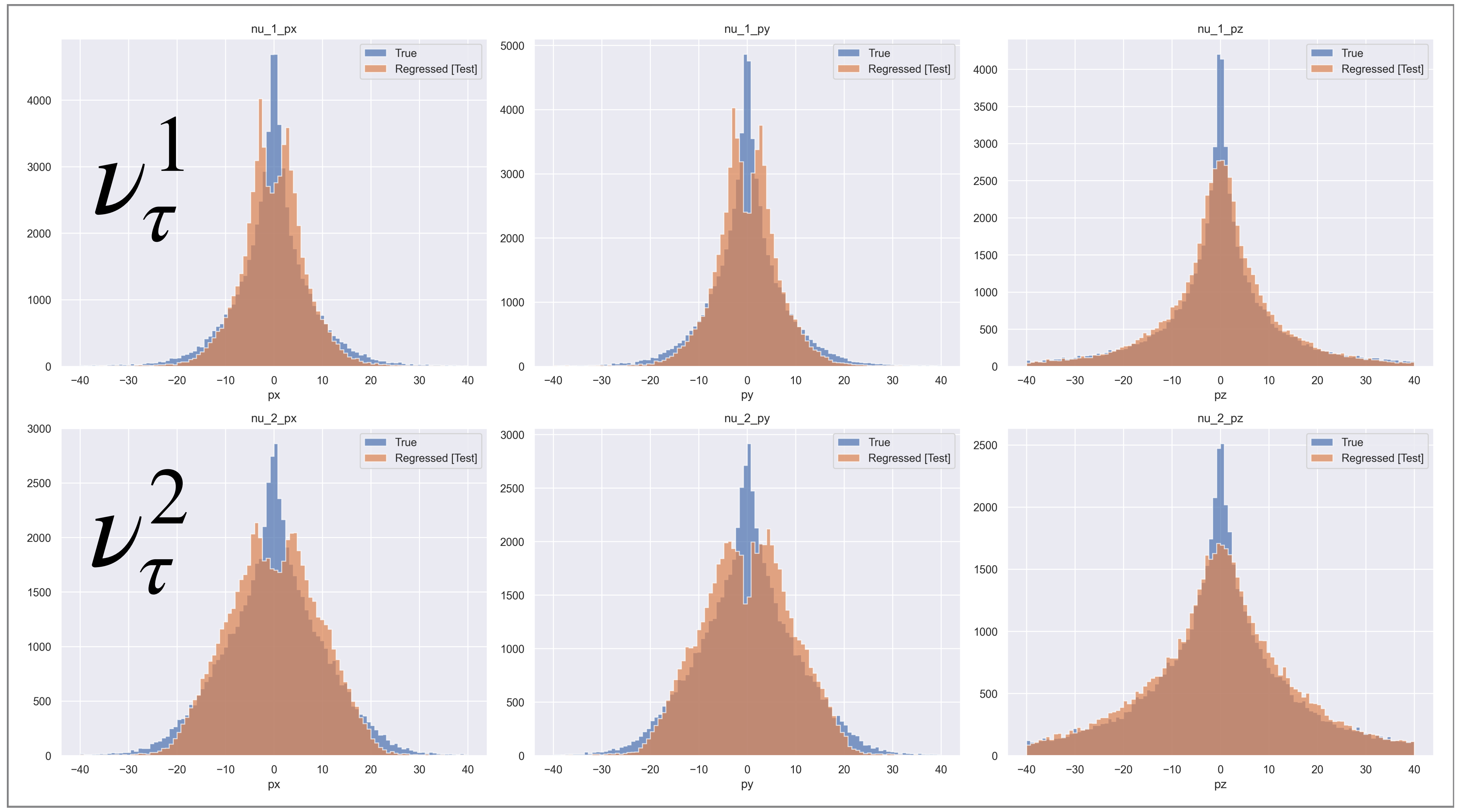
- Two types of loss functions are used
  - Huber: $\delta = 1$

$$L_\delta(a) = \begin{cases} \frac{1}{2}a^2 & \text{for } |a| \le \delta, \\ \delta \cdot \left(|a| - \frac{1}{2}\delta\right), & \text{otherwise.} \end{cases}$$

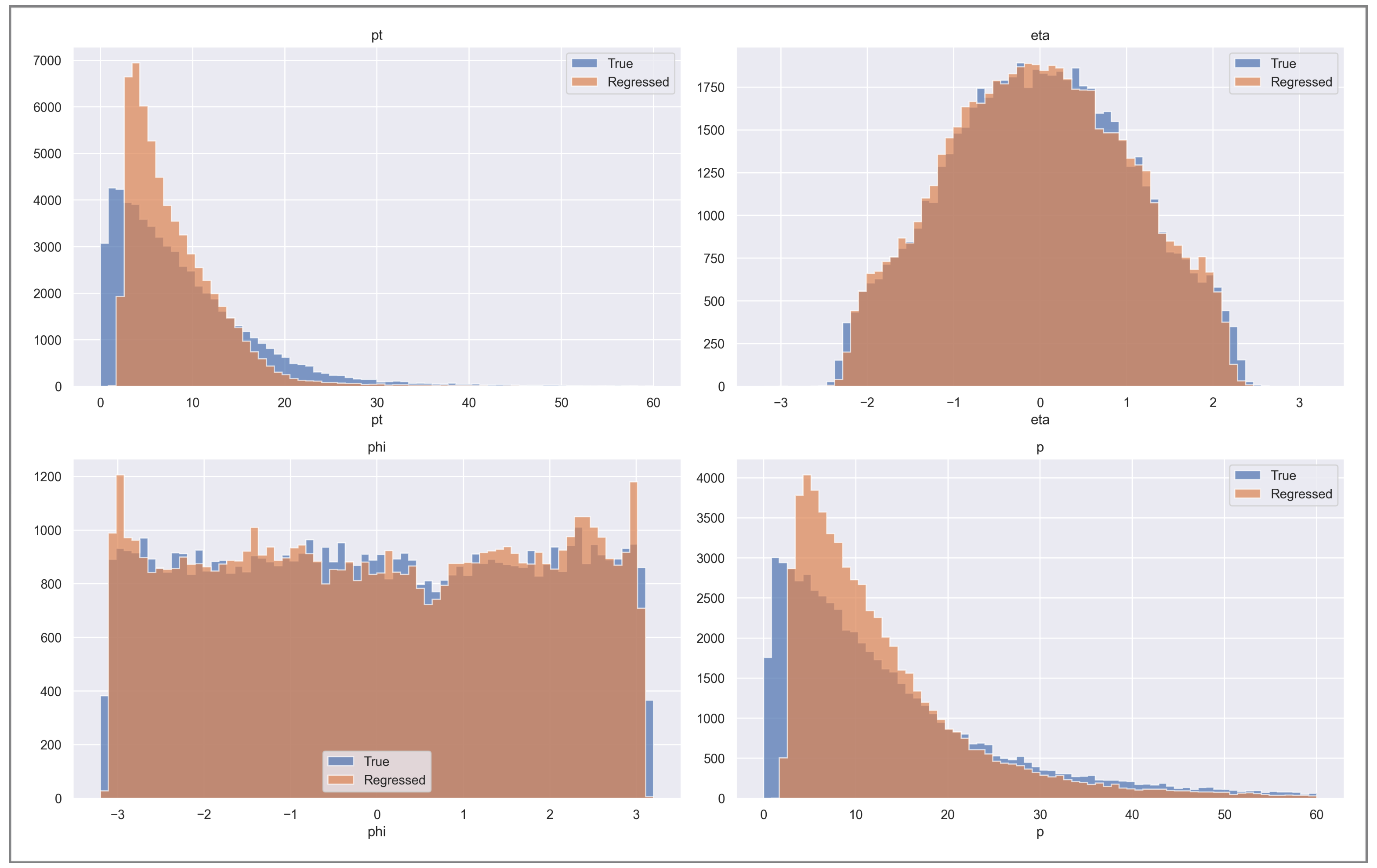


  - Custom MAE loss:
    - Mean of $\sum \alpha \, |y_{pred} - y_{true}| \; + \; \beta \, |\frac{m^{\tau\tau}_{pred}}{m^{\tau\tau}_{true}} - 1|$ $\alpha = 1, \beta = 1$
      - y_pred and y_true include the px, py, pz only.
      - Adding this extra mass constraint in the loss

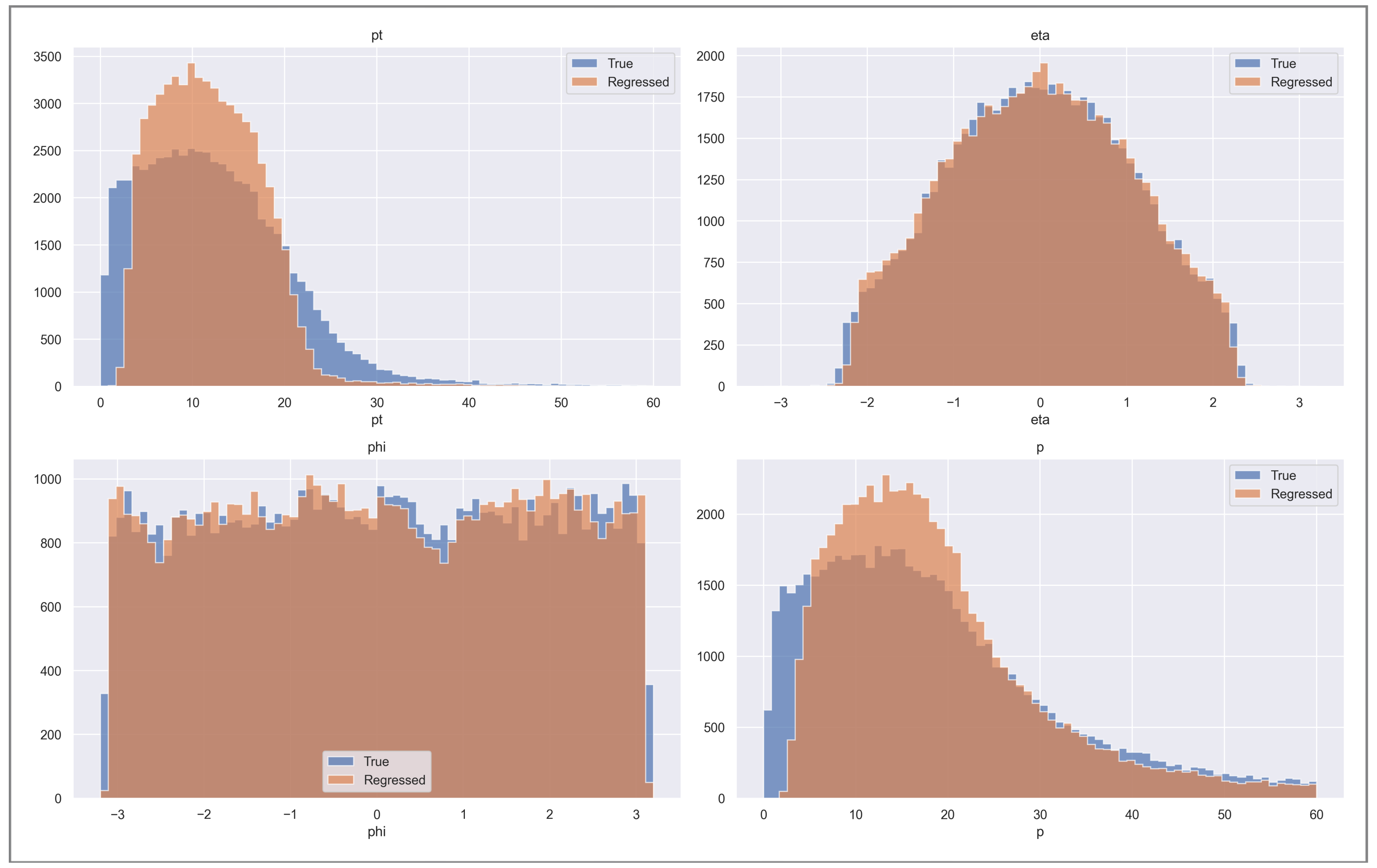
ResNet with Custom Loss

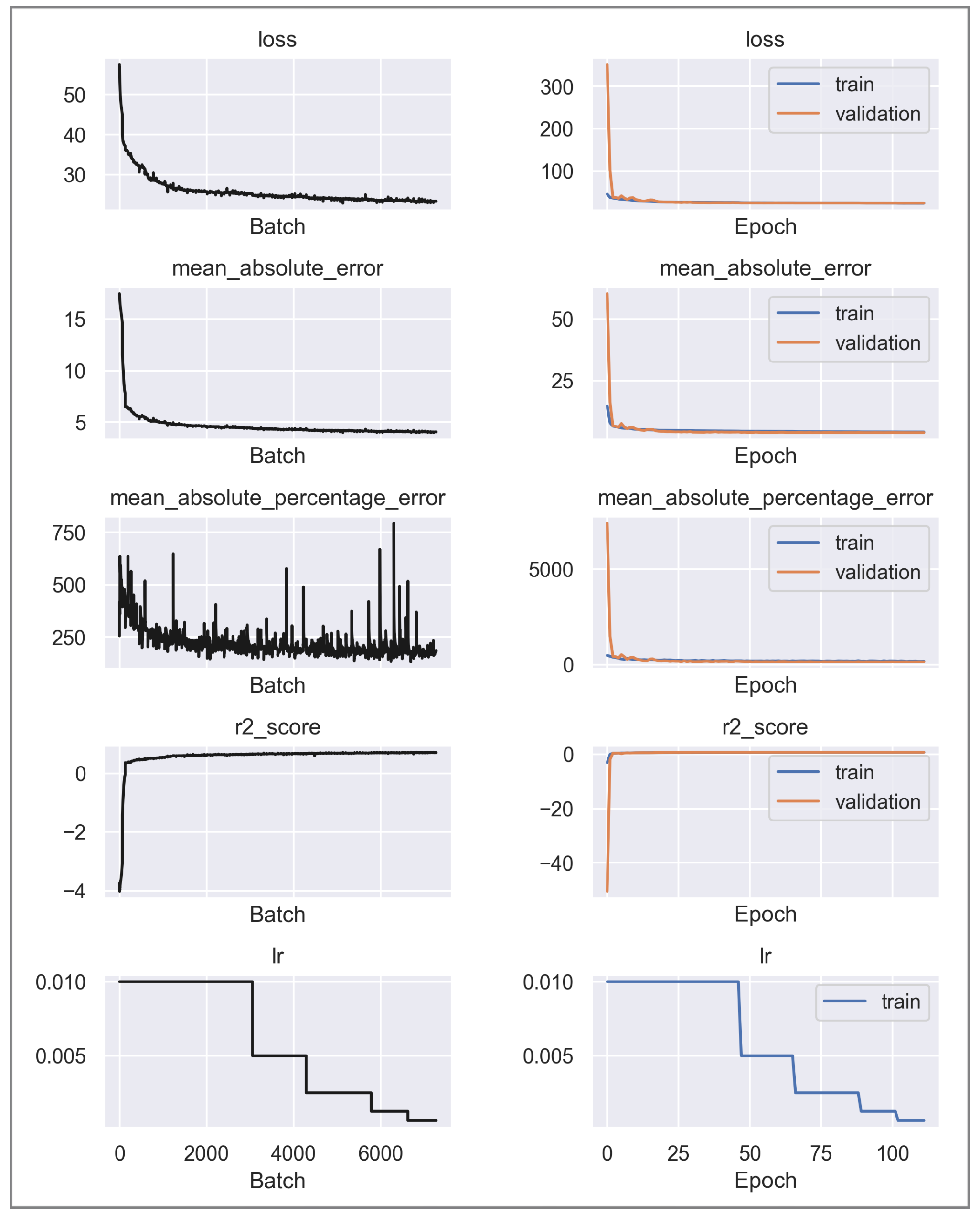


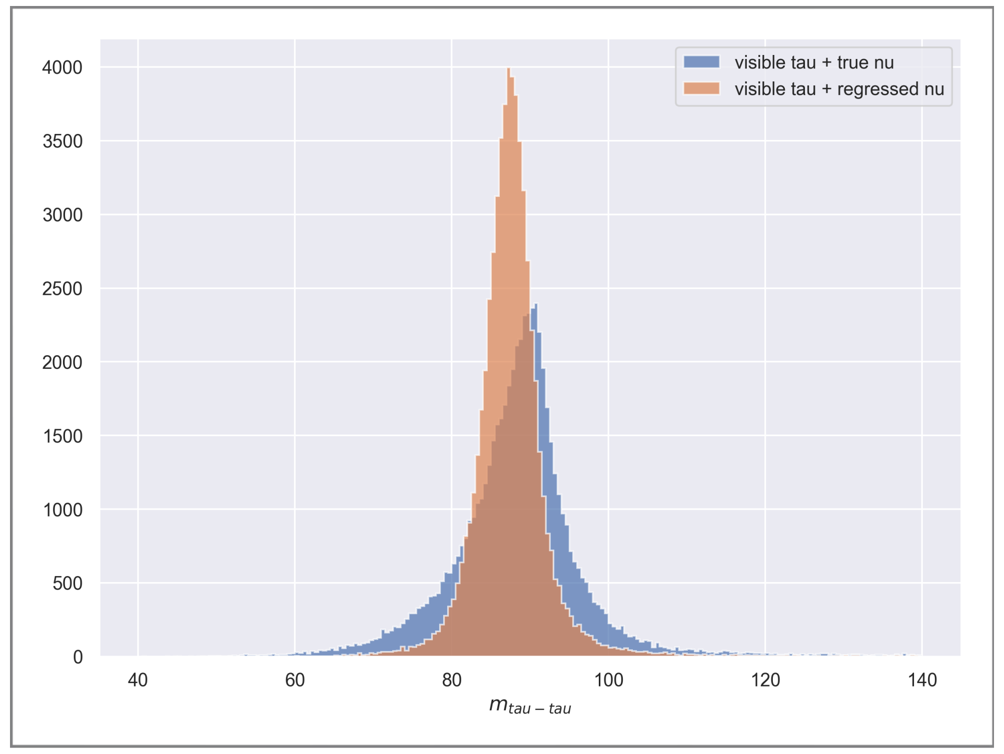
ν_τ^1



ν_τ^2



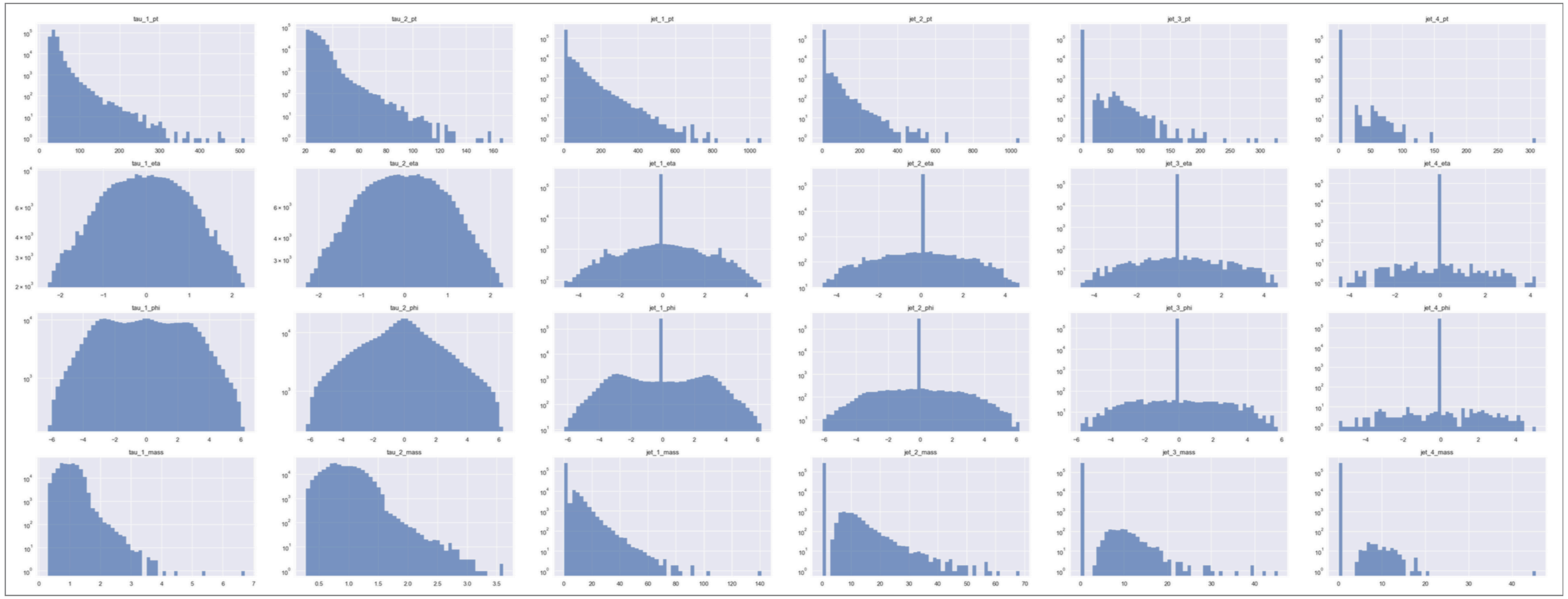


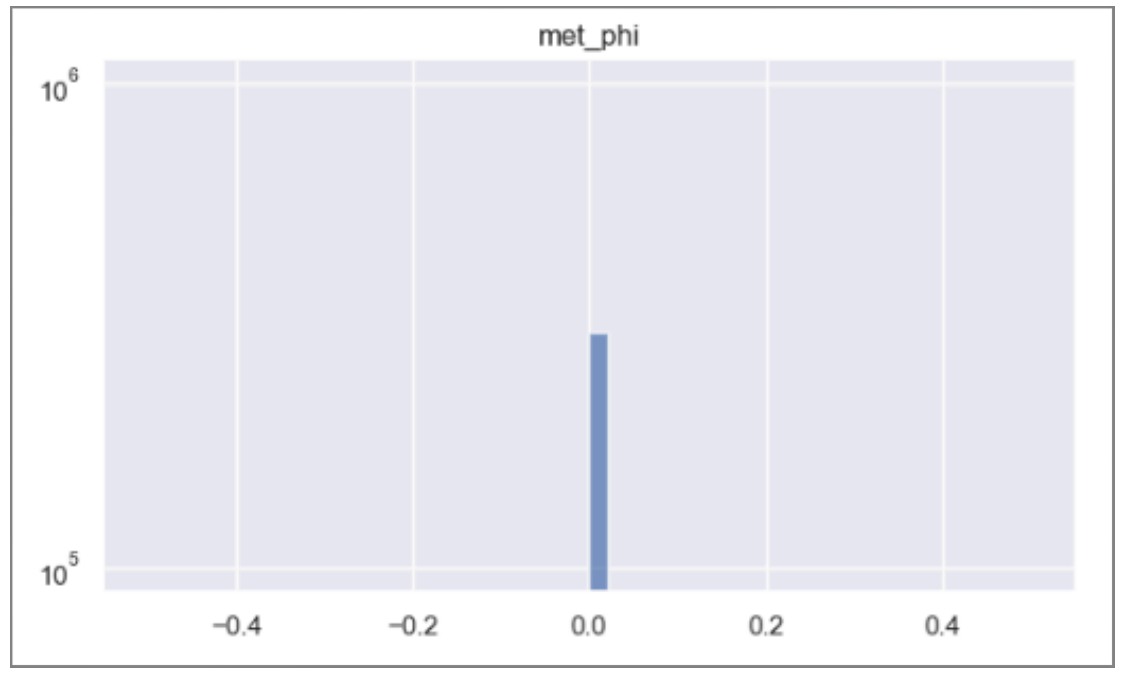


$m_{\tau\tau}$ Full

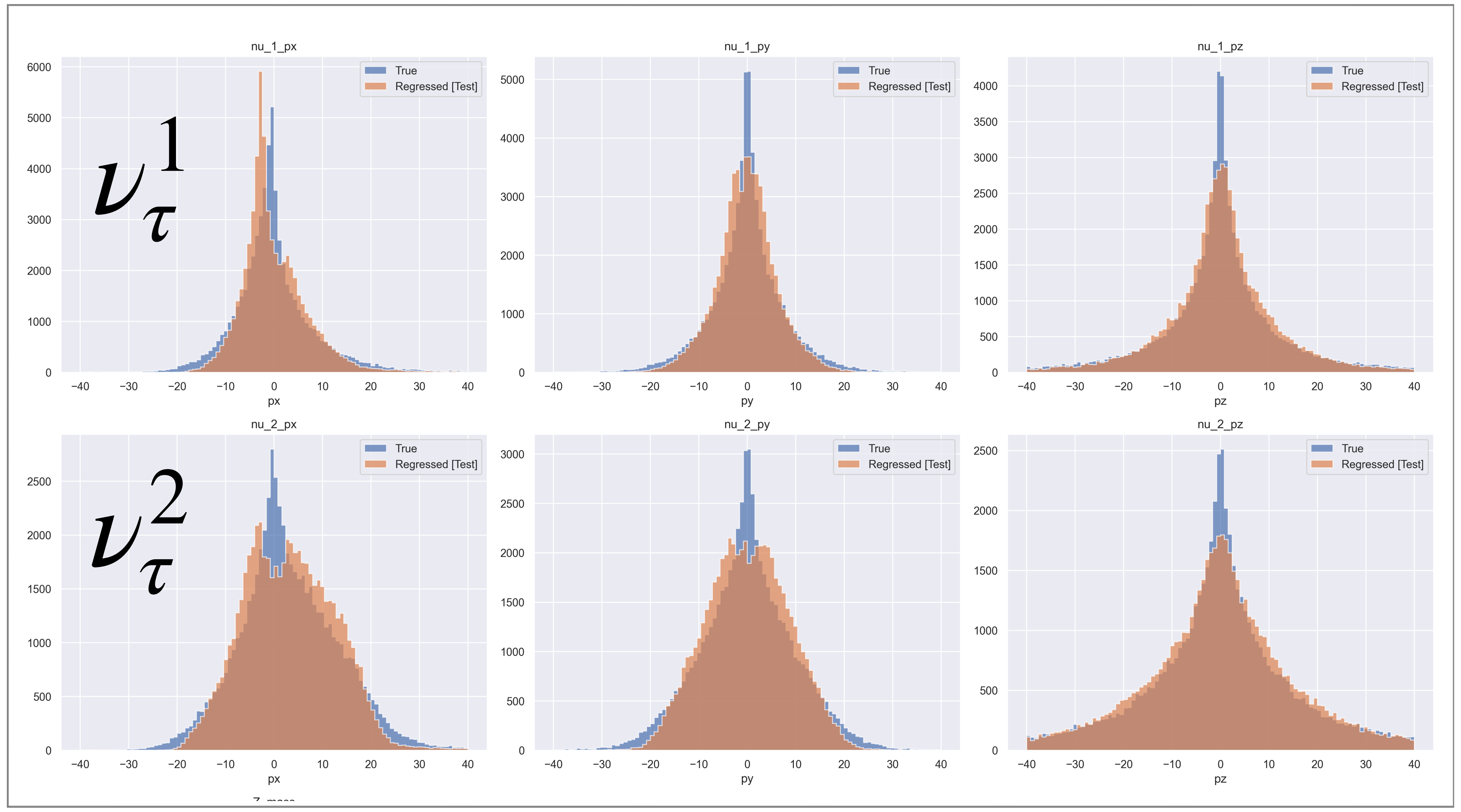
Using scaled input features

- MET is considered as the reference object
- All the objects are rotated to the direction of MET
  - Phi(object) - Phi(MET)
- To help the networks not to focus on the variation of Phi while predicting the shape of px, py and pz

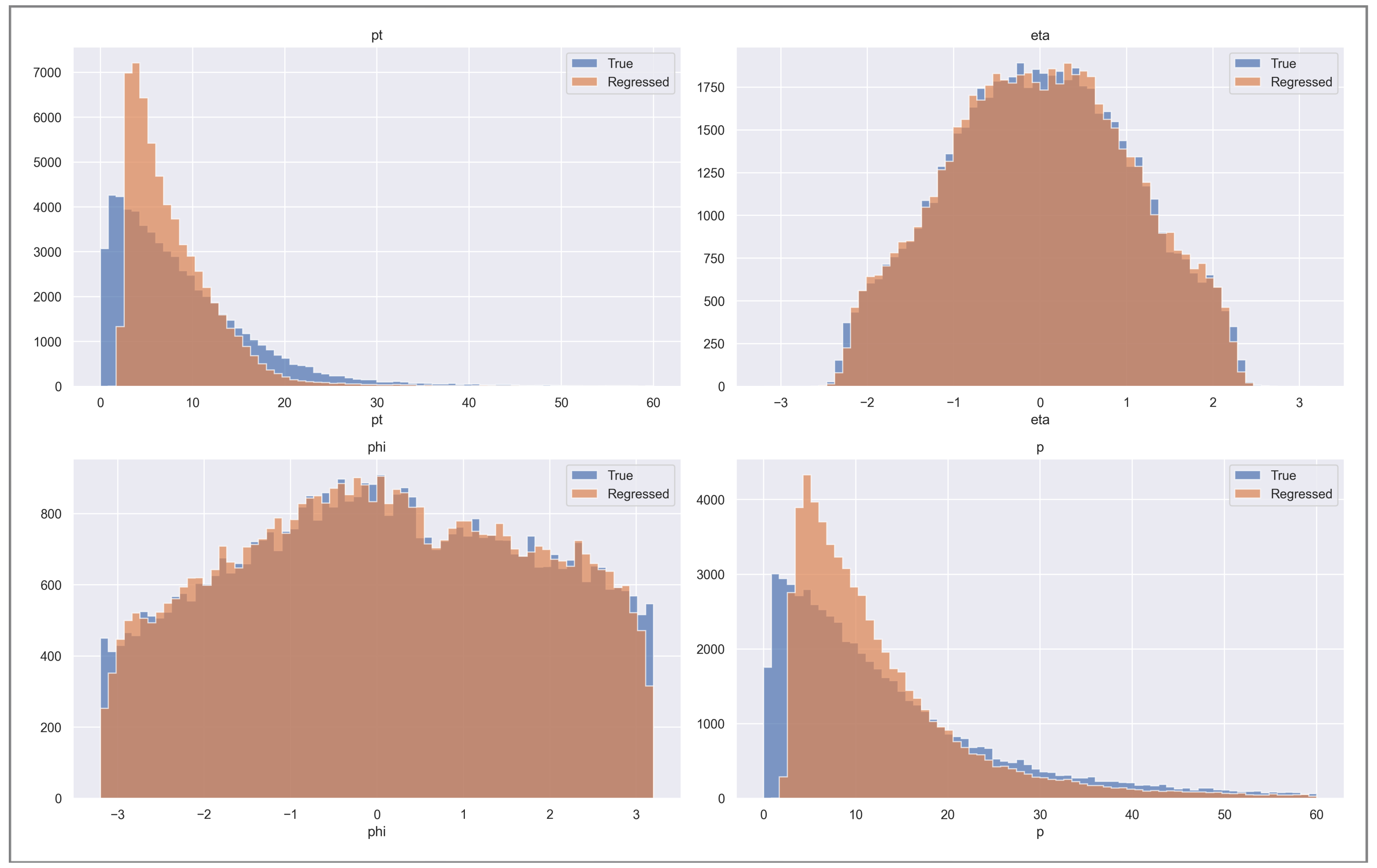




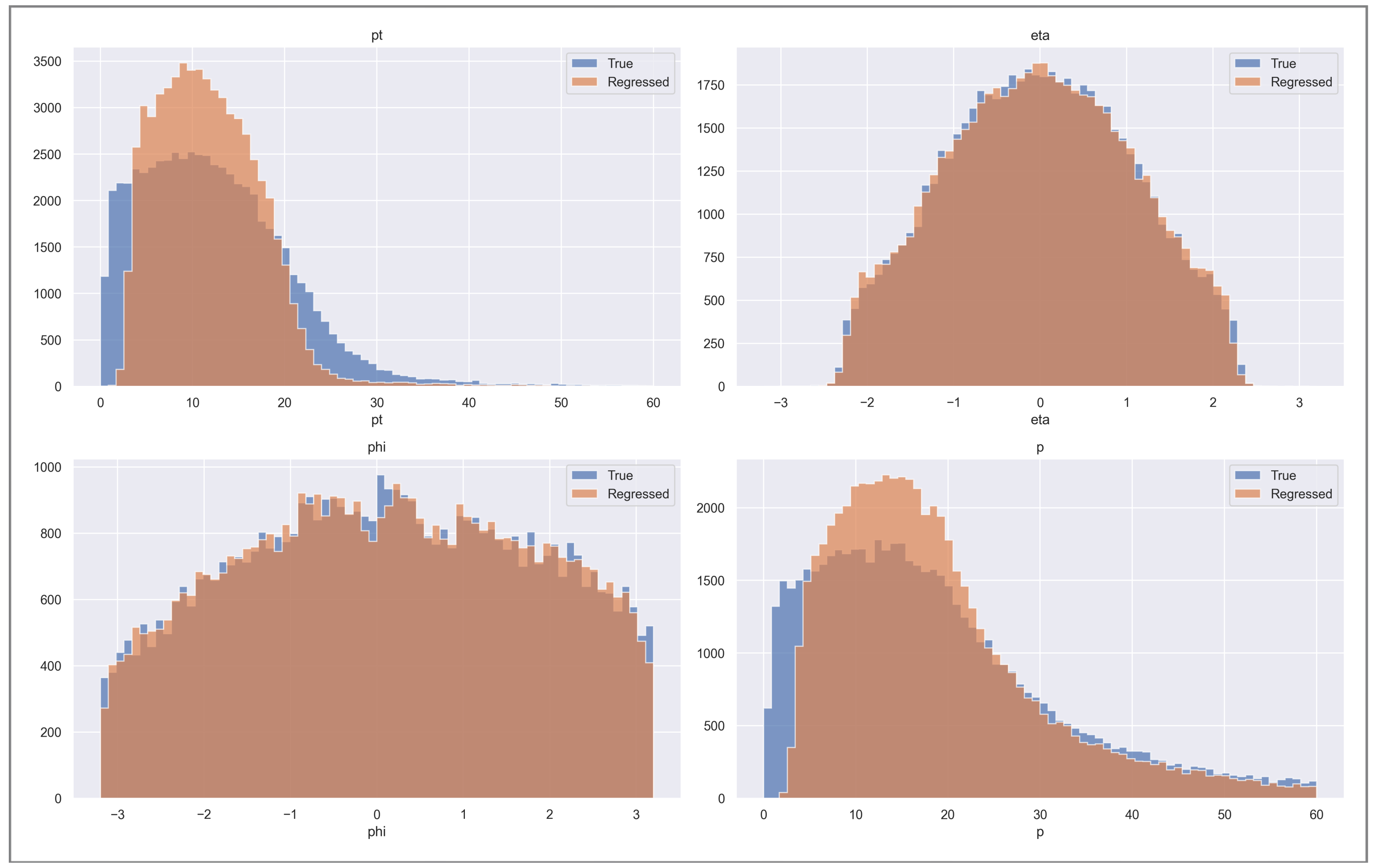
ResNet with Custom Loss

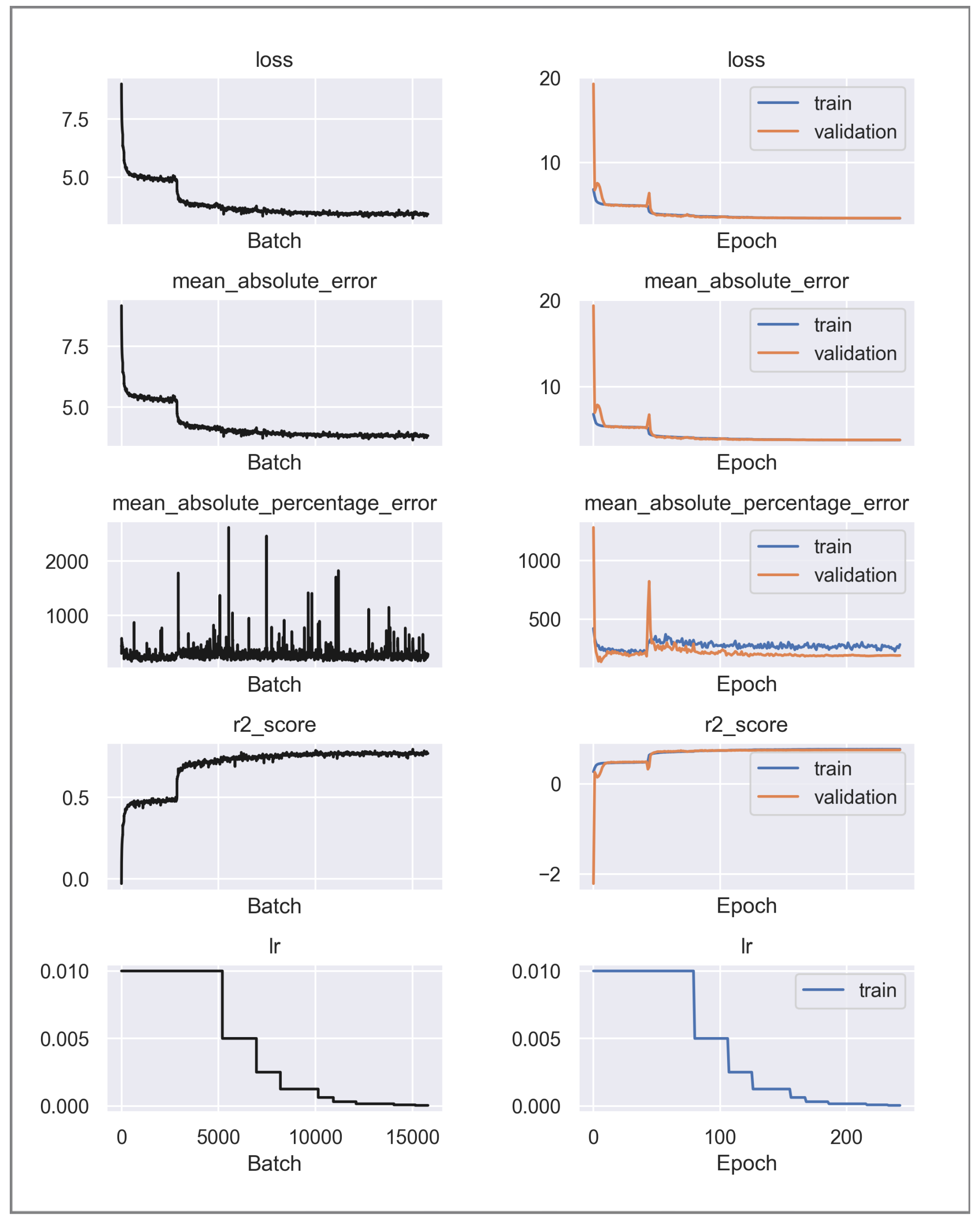


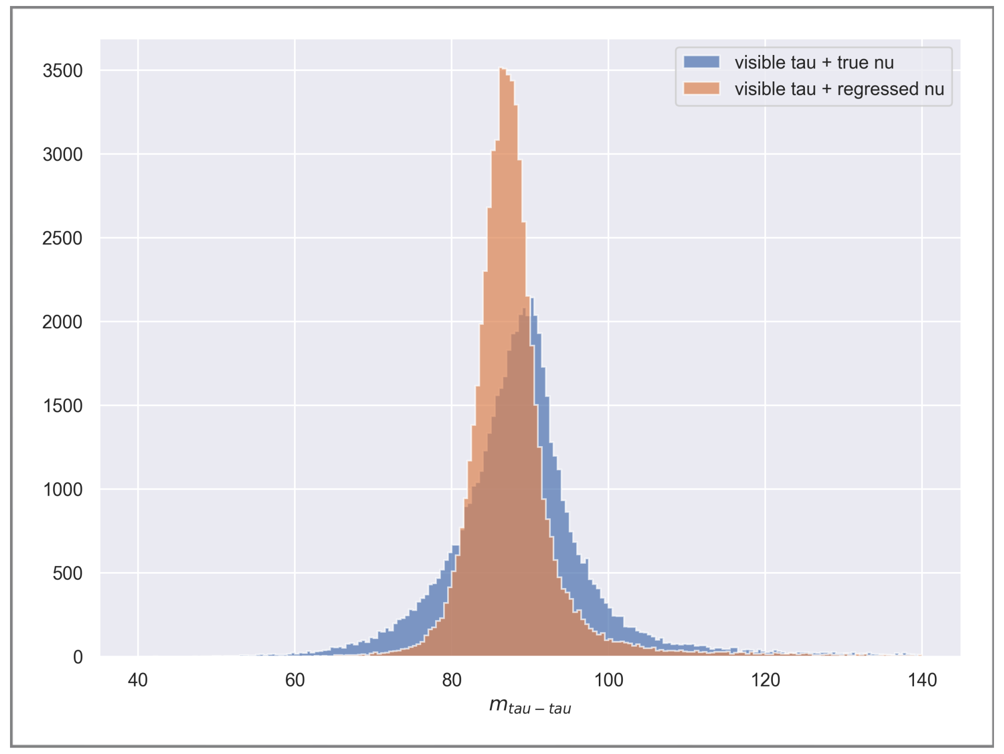
ν_τ^1



ν_τ^2







$m_{\tau\tau}$ Full

Summary

Search for Non-Resonant HH production with full-run2 data

- HH -> bbWW channel
- Challenging for high background yield: Machine learning based classifier is used for better sensitivity
- Currently 5x better results than 2016 & will be added in HH combination

Performance of 2S module for Phase-2 CMS outer tracker

New tracking detector will be installed at the HL-LHC

Outer tracker will have 2S modules

The performance of those modules are tested in beam test experiment

Tracks with pT > 2 GeV can be used in L1 trigger for (un)-irradiated 2S modules

Regression of neutrino momentum

- In Higgs to tau tau analysis for CP violation, it is important to get full tau momenta
- Several ML based approach can be used to regress neutrino momenta
- The plan is to use more granular event information and advanced techniques for better performance.

Thank you for your attention ...

BACKUP

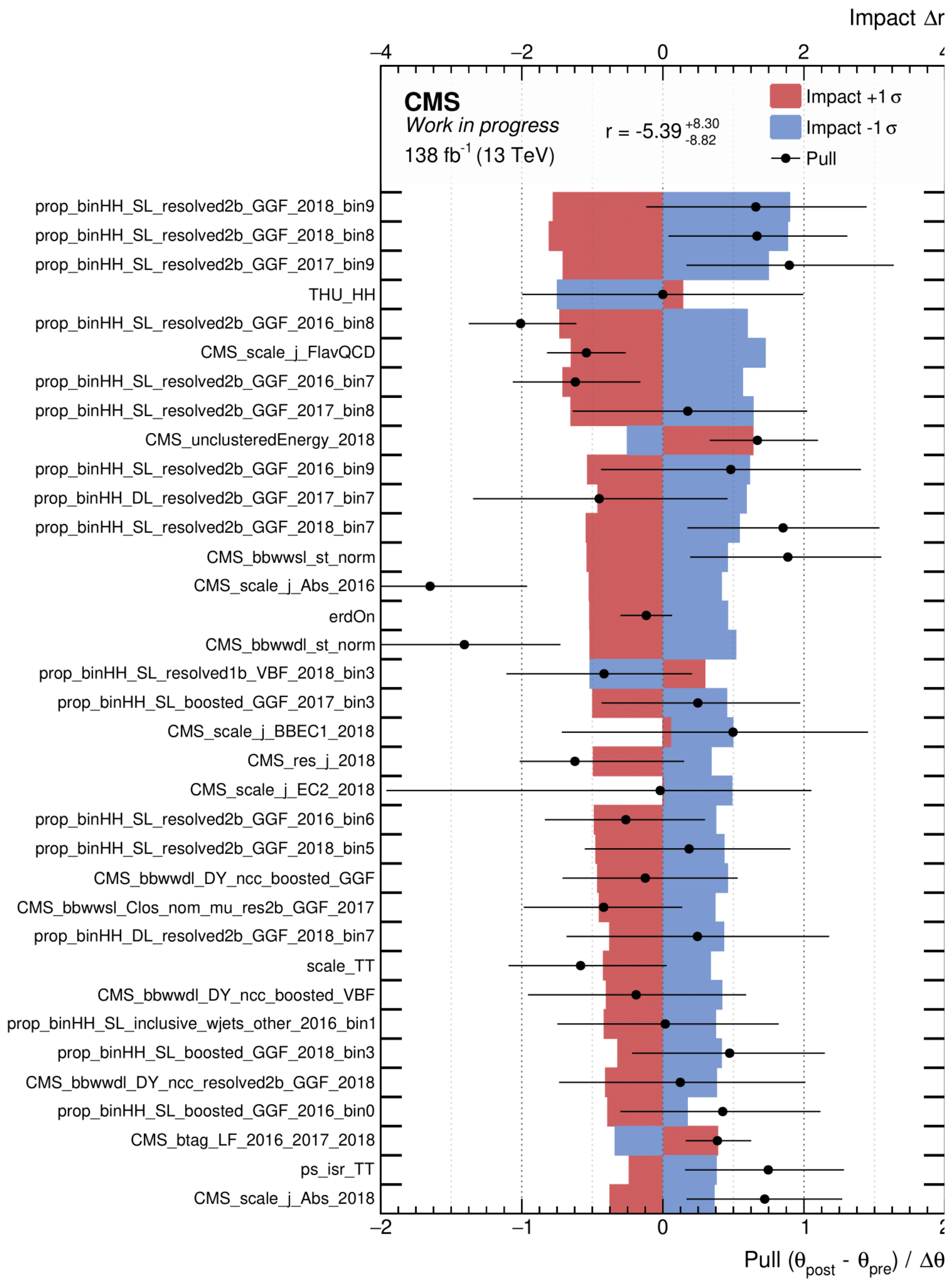
Uncertainties

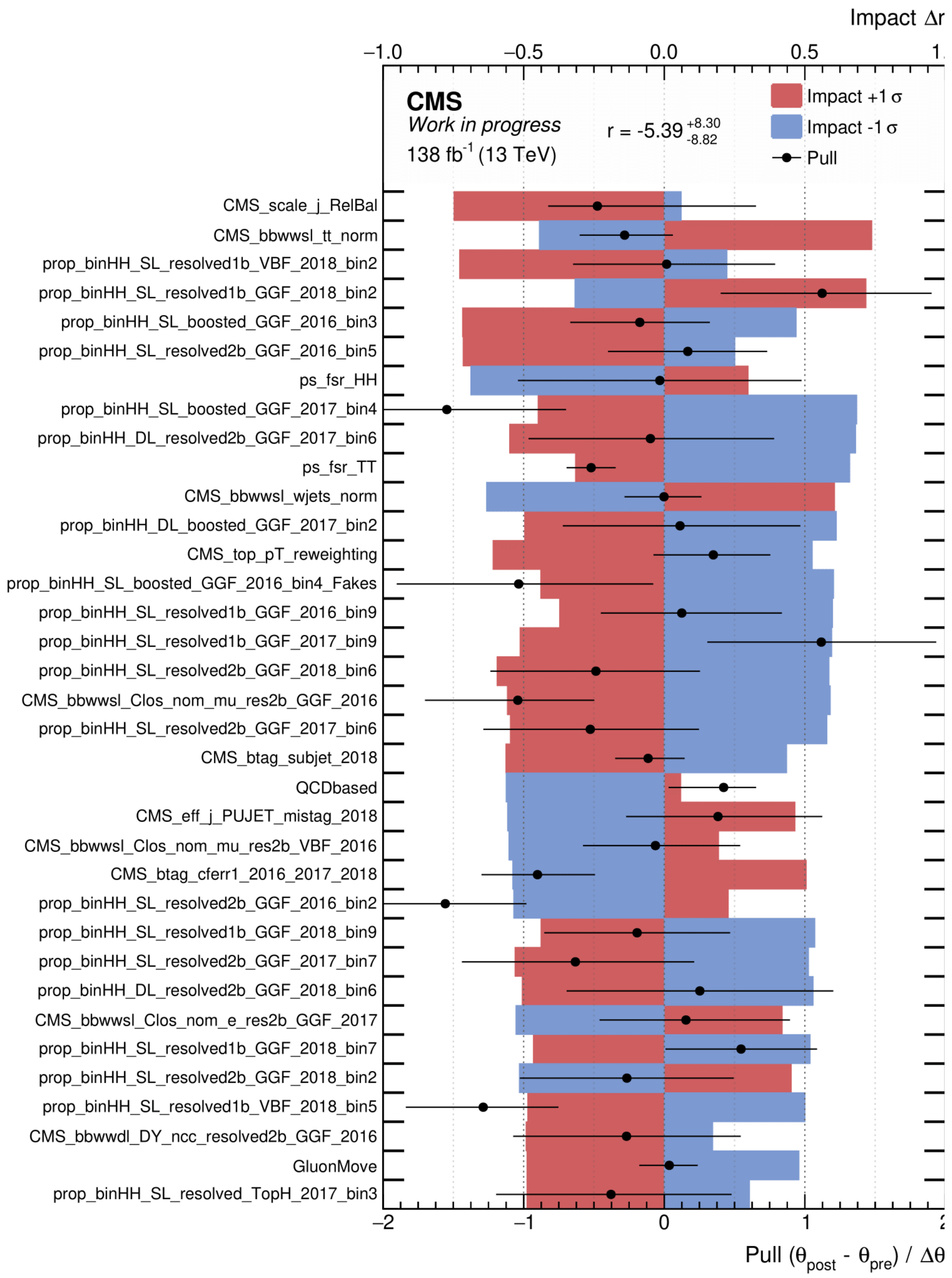
- Normalisation uncertainty sources:
  - Luminosity
  - Branching ratio
  - QCD scale, PDF, α_s, EW corrections
  - HH cross section uncertainties
  - Fake non-closure

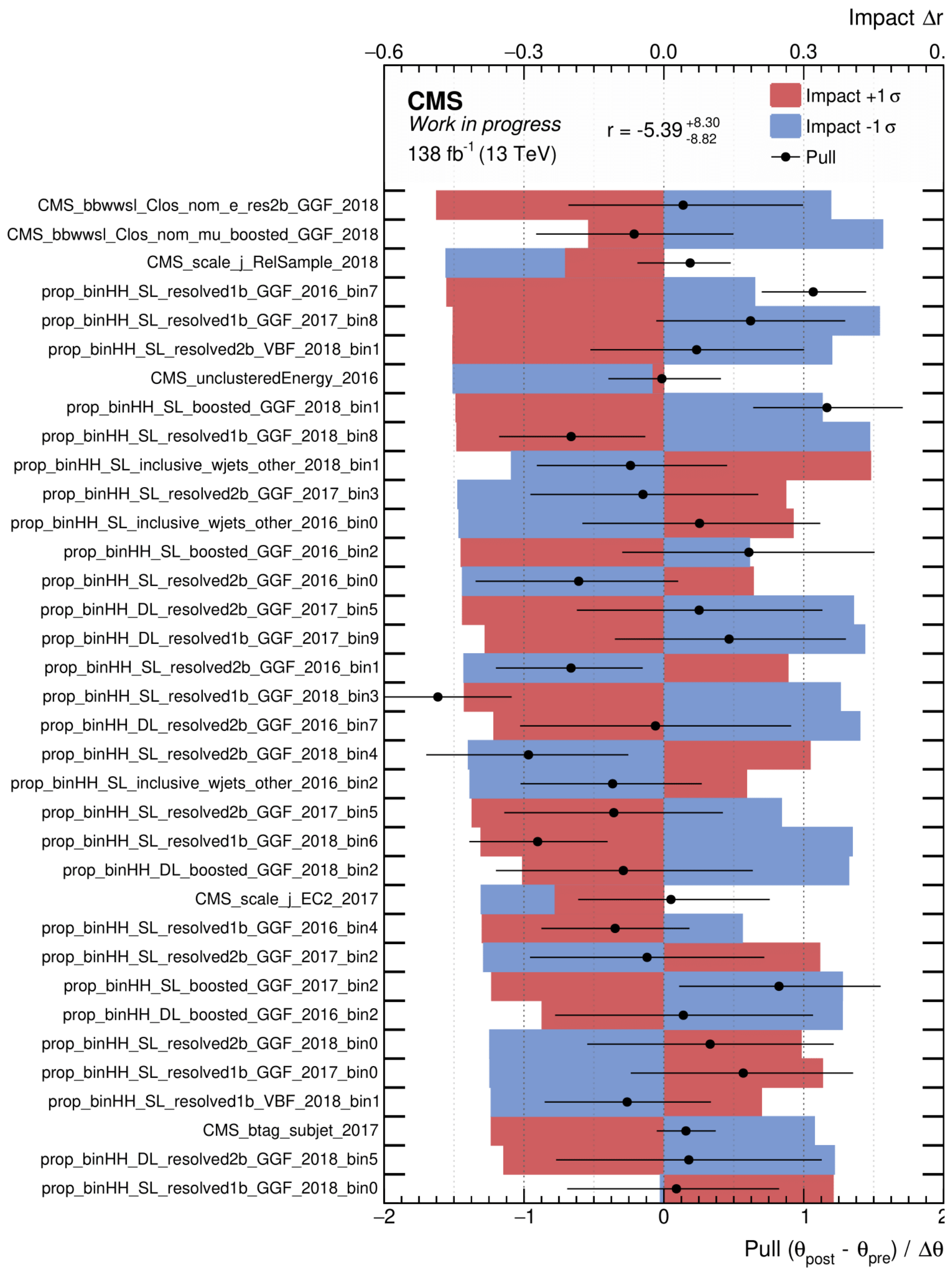
autoMCstats (Barlow-Beeston)

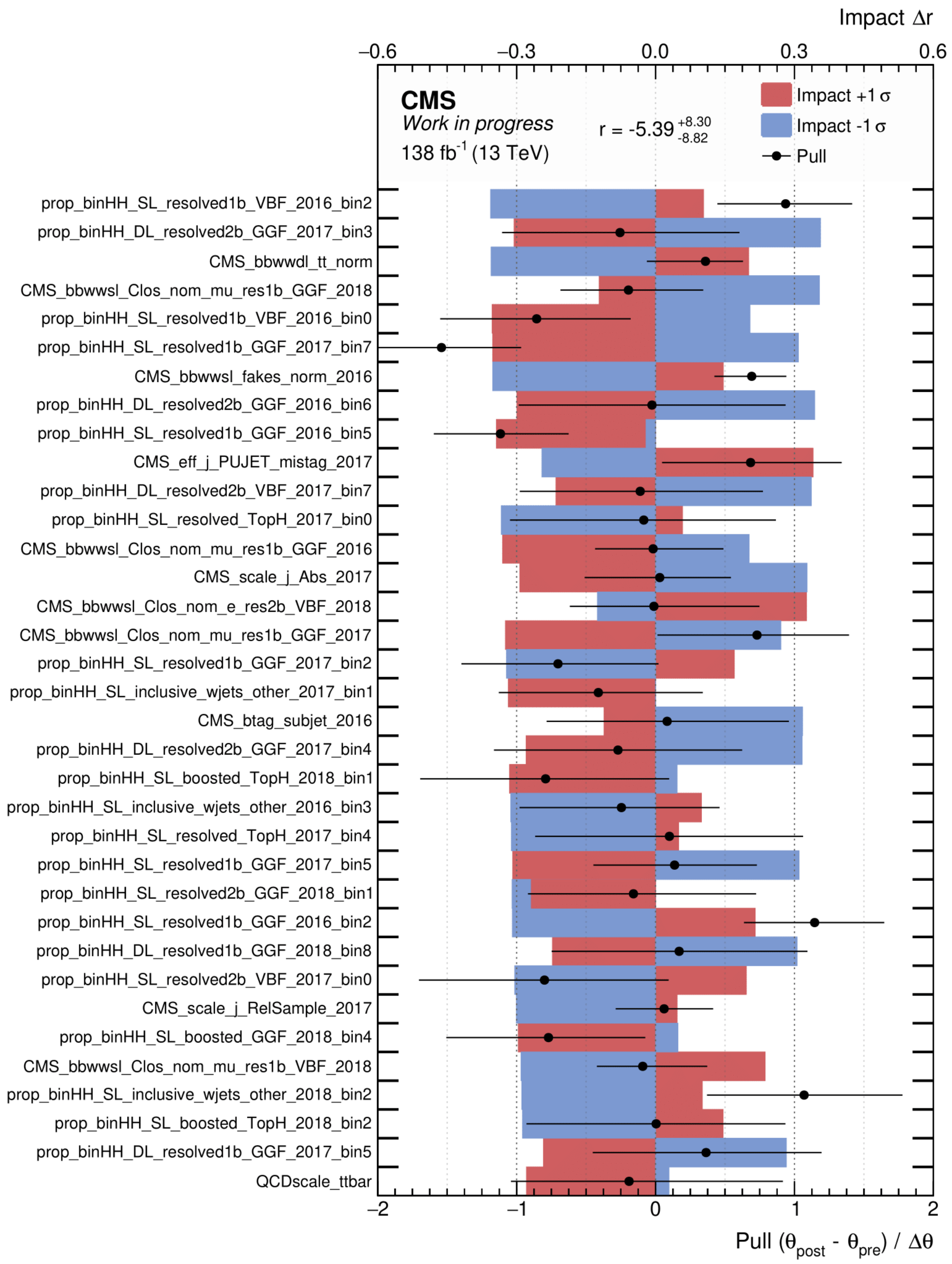
- Shape uncertainty sources:
  - PileUp reweighing
  - Trigger scale factors
  - Electron and Muon scale factor
  - top pT reweighing
  - Jet pileup ID
  - Jet energy resolution, Jet energy scale
  - b-tagging scale factors
  - PDF and PS weights

Uncertainties

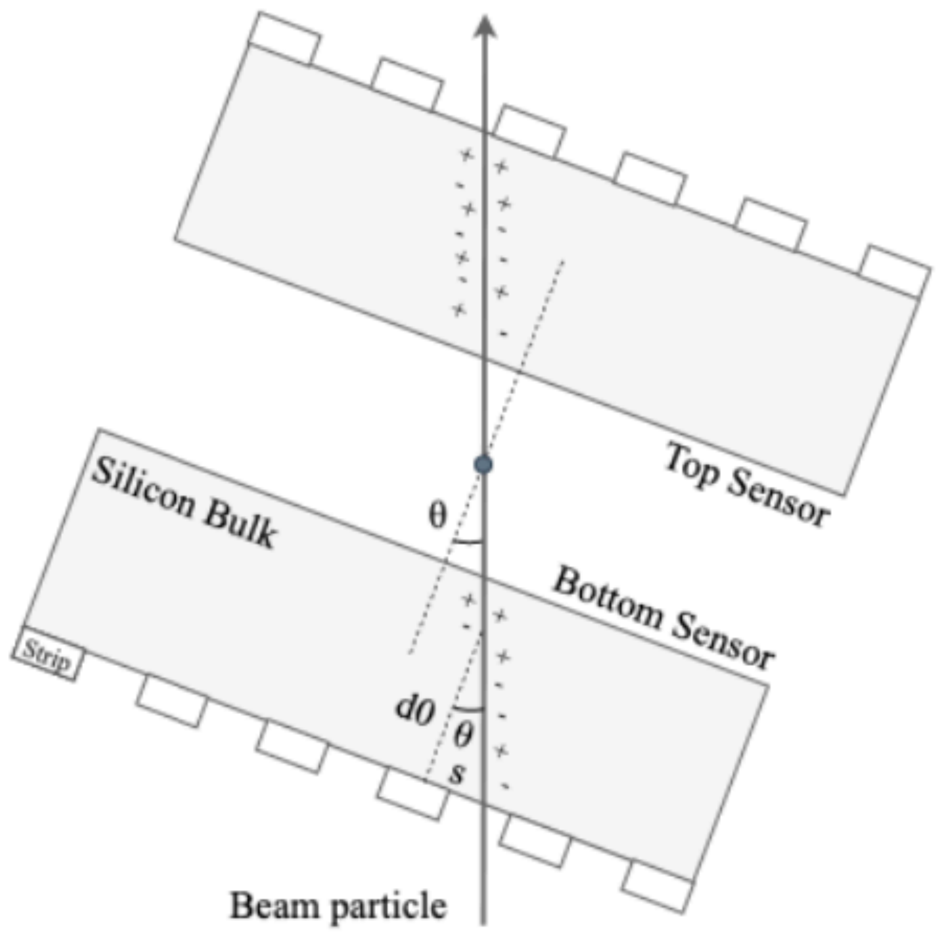




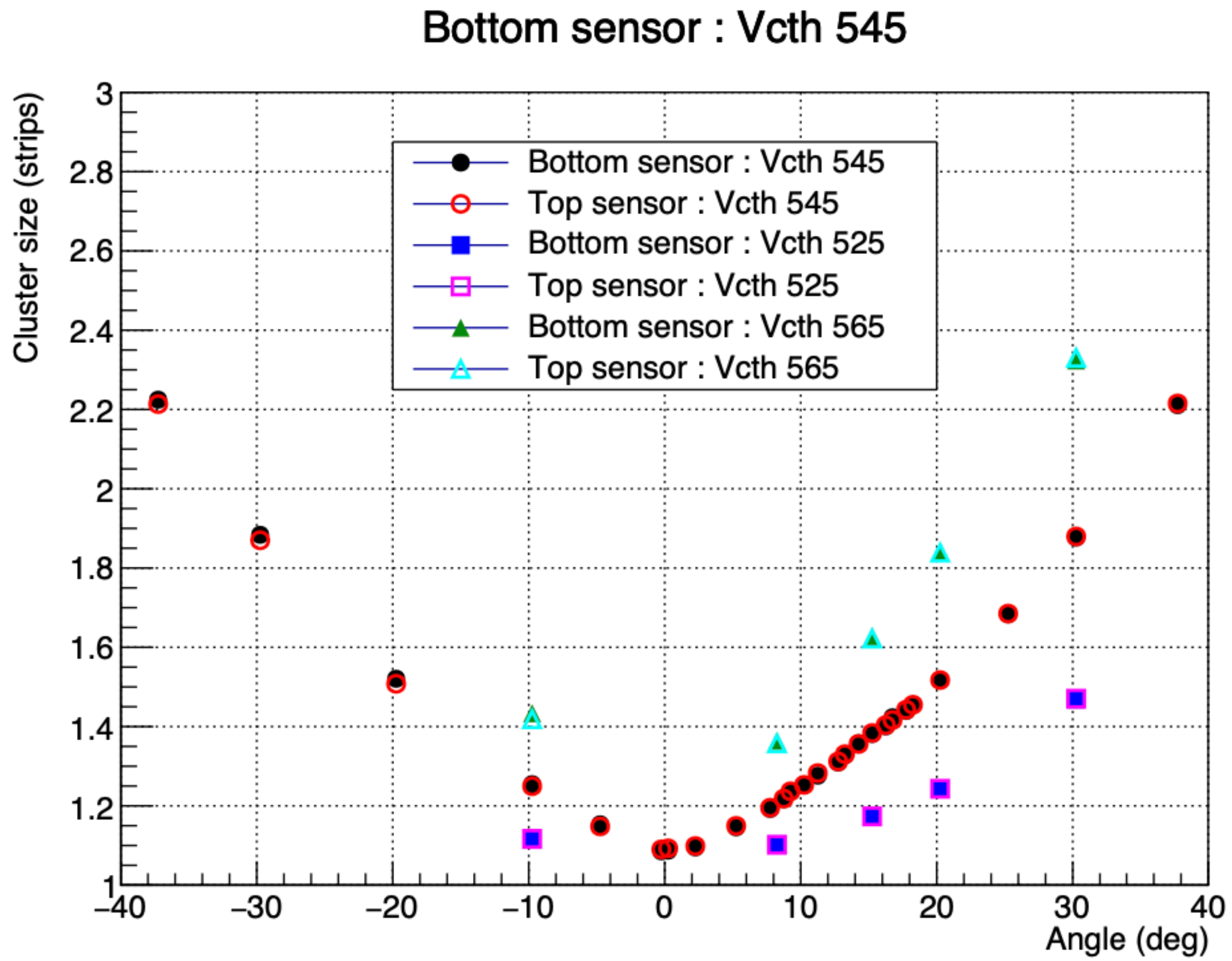


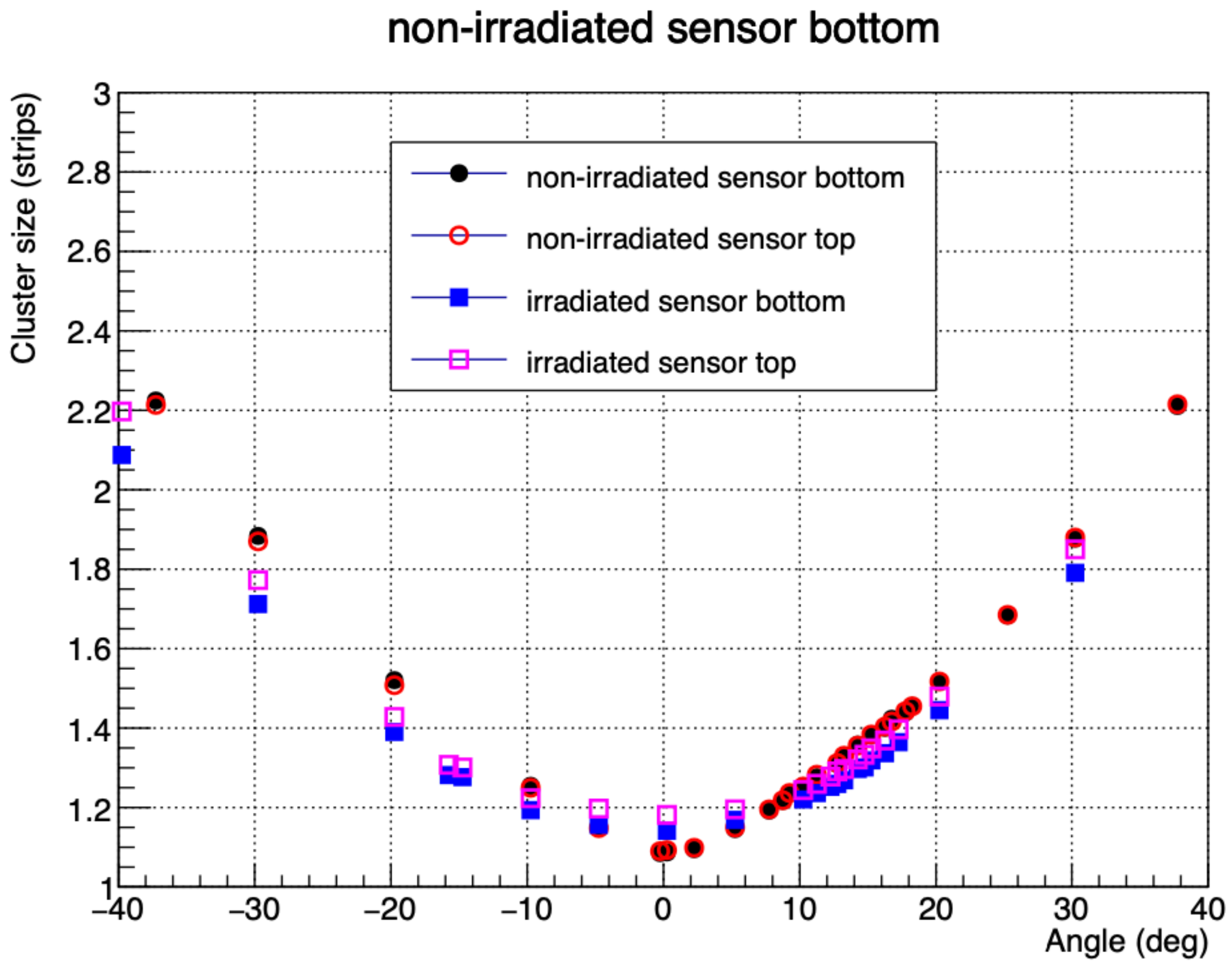


Angular scan: Charge sharing

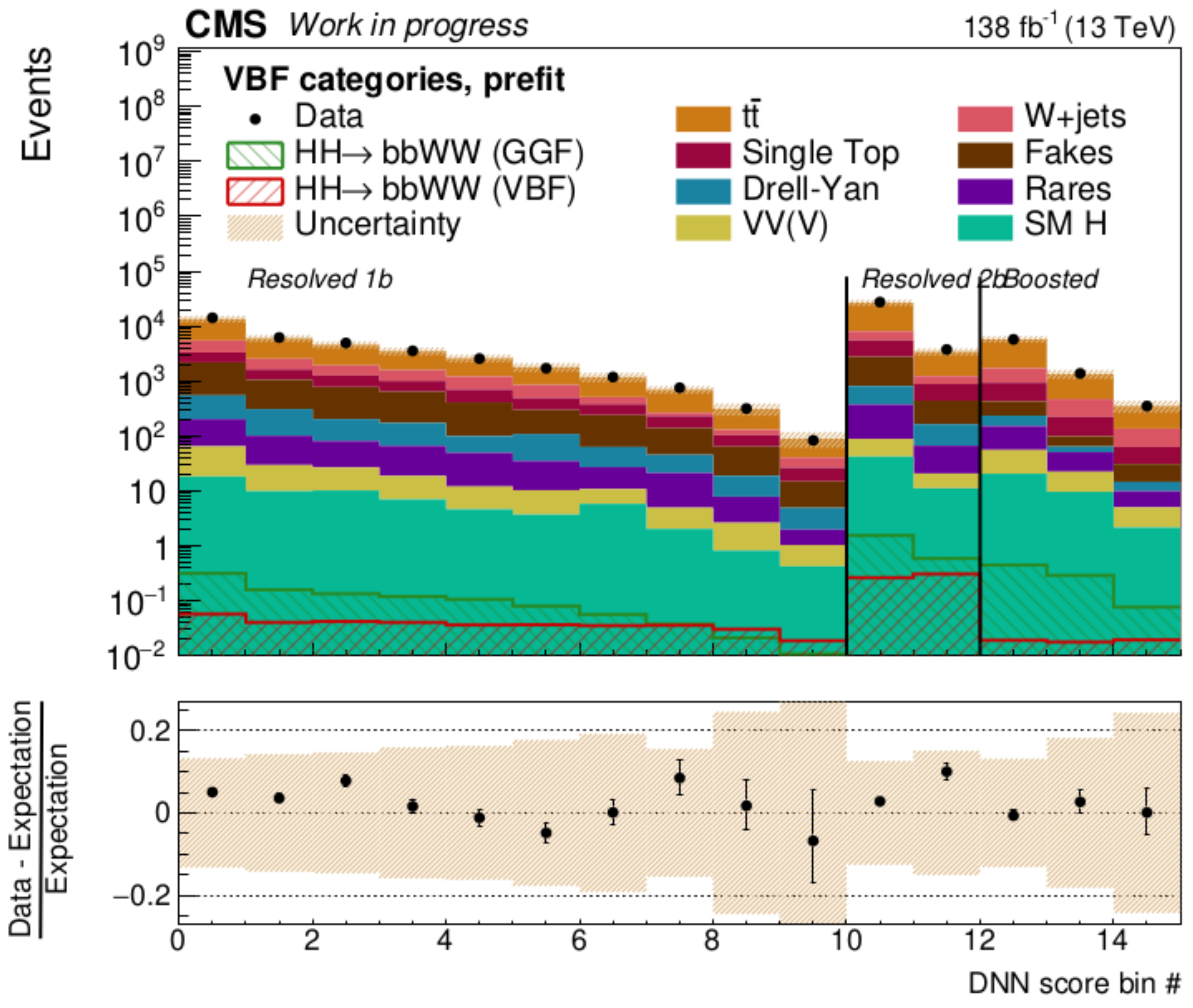


Cluster size Vs. angle





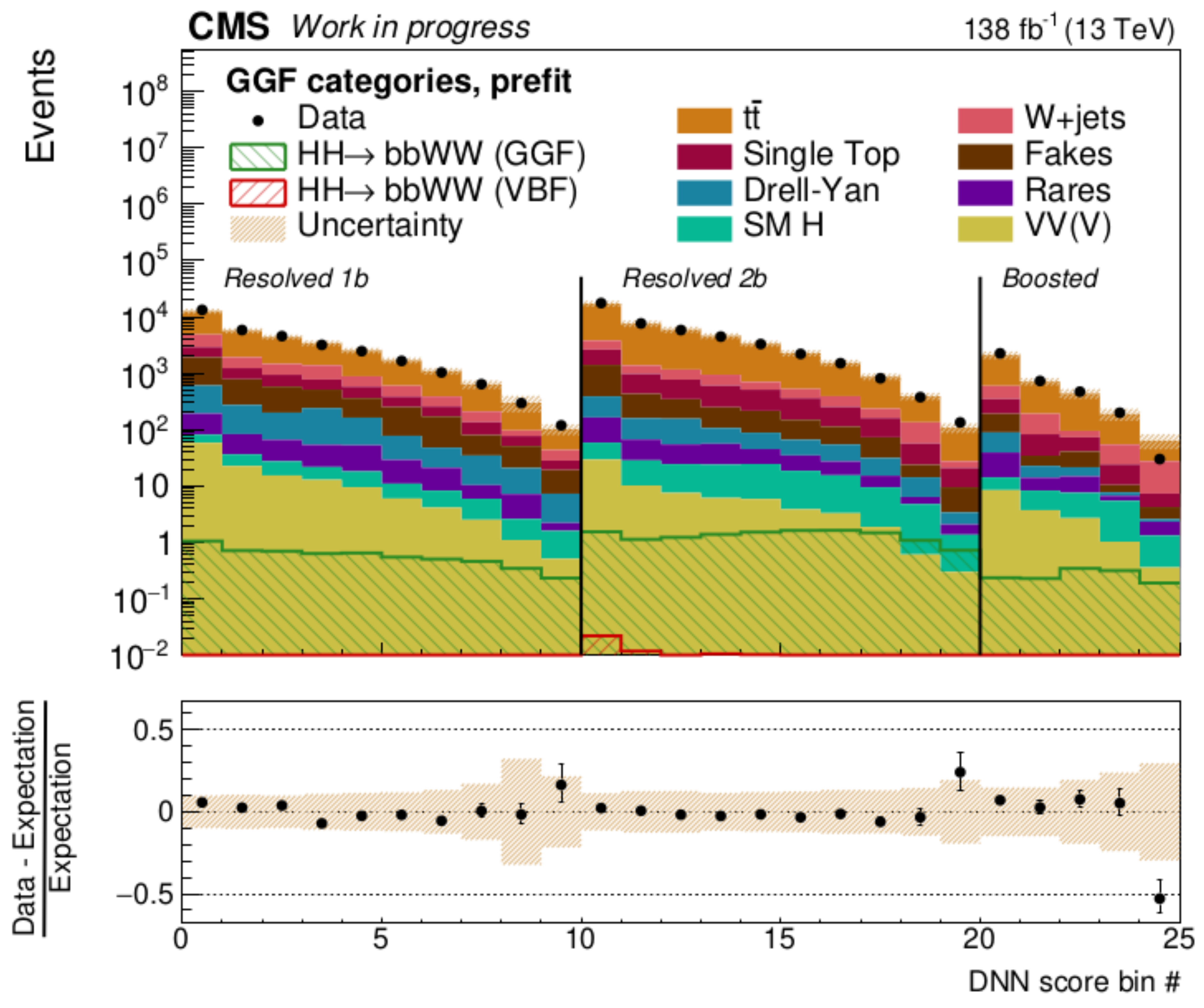
Binning



Idea

Quadratically decreasing set of thresholds (aggregated total background bin > threshold → start new bin)

Increase sensitivity to signal in the rightmost bins



EFT Shape Benchmarks

1608.06578

Benchmark	κ_λ	κ_t	c_2	c_g	c_{2g}
1	7.5	1.0	-1.0	0.0	0.0
2	1.0	1.0	0.5	-0.8	0.6
3	1.0	1.0	-1.5	0.0	-0.8
4	-3.5	1.5	-3.0	0.0	0.0
5	1.0	1.0	0.0	0.8	-1.0
6	2.4	1.0	0.0	0.2	-0.2
7	5.0	1.0	0.0	0.2	-0.2
8	15.0	1.0	0.0	-1.0	1.0
9	1.0	1.0	1.0	-0.6	0.6
10	10.0	1.5	-1.0	0.0	0.0
11	2.4	1.0	0.0	1.0	-1.0
12	15.0	1.0	1.0	0.0	0.0
SM	1.0	1.0	0.0	0.0	0.0

Table 1: Parameter values of the final benchmarks selected by the clustering procedure [1]. The third cluster is the one that contains the SM sample (defined by $\kappa_\lambda = \kappa_t = 1$, $c_2 = c_g = c_{2g} = 0$).

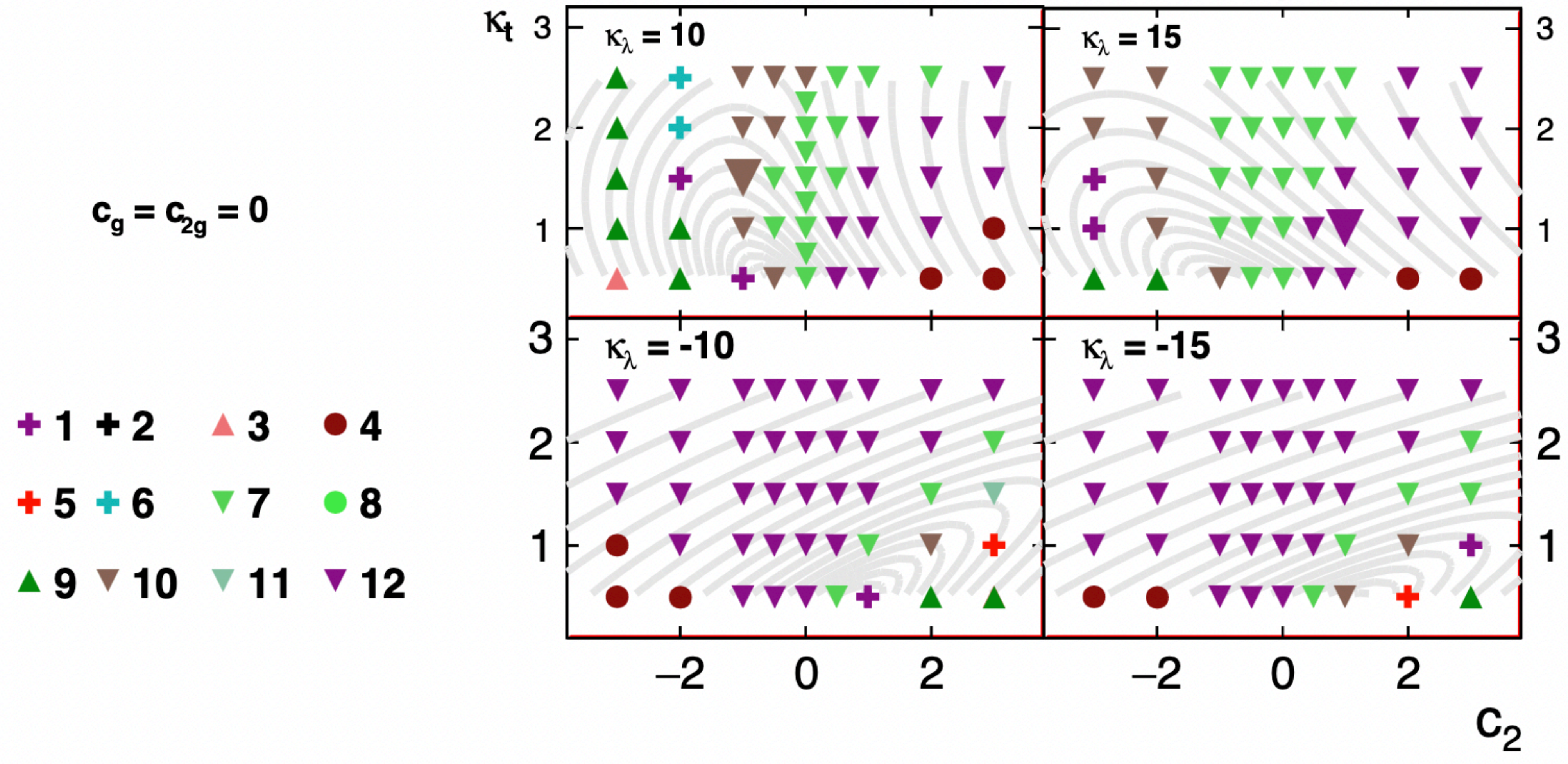
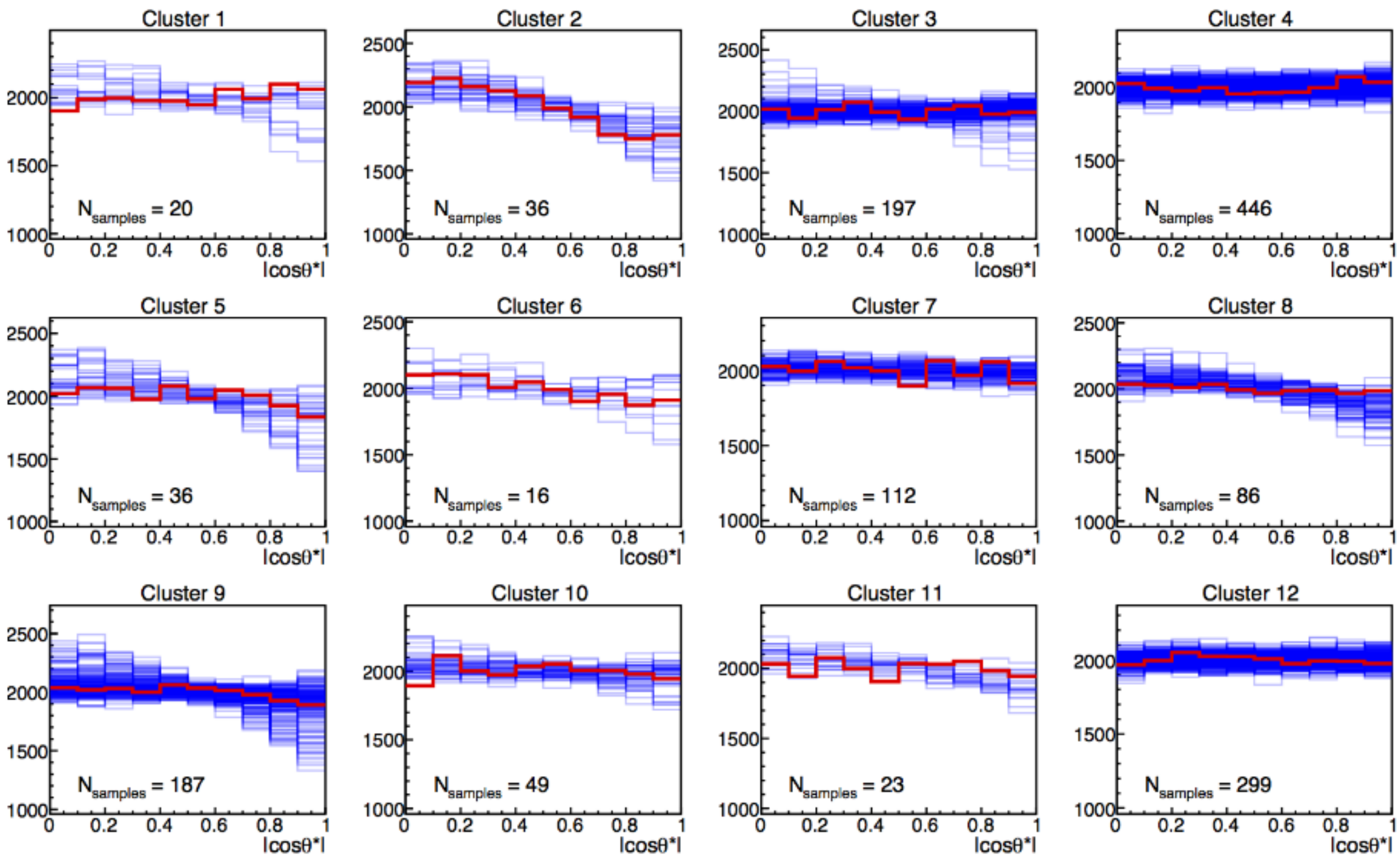


Figure 4: Distribution of points in the $c_2 \times \kappa_t$ plane for different values of κ_λ when $(c_g, c_{2g}) = (0, 0)$. Circles describe clusters whose benchmark has Higgs boson p_T ($p_{T,H}$) peaking around 100 GeV. Downward-pointing triangles describe clusters where $p_{T,H}$ is peaking around 50 GeV or less, while upward-pointing triangles describe ones with $p_{T,H}$ peaking around 150 GeV or more. Finally, crosses describe clusters that show a double peaking structure in the $p_{T,H}$ distribution. Larger markers indicate benchmark points. The gray lines correspond to iso-contours of constant cross section σ_{HH}. See Fig. 8 in Ref. [1] for more details.

EFT Shape Benchmarks

1608.06578



EFT Shape Benchmarks

Table 1.3 | Values obtained from clustering of the 12 benchmarks defined in Ref. [77], with the additional "8a" point from Ref. [82].

Benchmark number	1	2	3	4	5	6	7	8	9	10	11	12	8a
κ_λ	7.5	1.0	1.0	-3.5	1.0	2.4	5.0	15.0	1.0	10.0	2.4	15.0	1.0
κ_t	1.0	1.0	1.0	1.5	1.0	1.0	1.0	1.0	1.0	1.5	1.0	1.0	1.0
c_2	-1.0	0.5	-1.5	-3.0	0.0	0.0	0.0	0.0	1.0	-1.0	0.0	1.0	0.5
c_g	0.0	-0.8	0.0	0.0	0.8	0.2	0.2	-1.0	-0.6	0.0	1.0	0.0	0.8/3
c_{2g}	0.0	0.6	-0.8	0.0	-1.0	-0.2	-0.2	1.0	0.6	0.0	-1.0	0.0	0.0

Table 1.4 | Values obtained from clustering of the 7 benchmarks defined in Ref. [79].

Benchmark number	1	2	3	4	5	6	7
κ_λ	3.94	6.84	2.21	2.79	3.95	5.68	-0.10
κ_t	0.94	0.61	1.05	0.61	1.17	0.83	0.94
c_2	-1./3.	1./3.	-1./3.	1./3.	-1./3.	1./3.	1.
c_g	0.5x1.5	0.0x1.5	0.5x1.5	-0.5x1.5	1./6.x1.5	-0.5x1.5	1./6.x1.5
c_{2g}	1./3.x(-3.)	-1./3.x(-3.)	0.5 x(-3.)	1./6.x(-3.)	-0.5 x(-3.)	1./3.x(-3.)	-1./6.x(-3.)