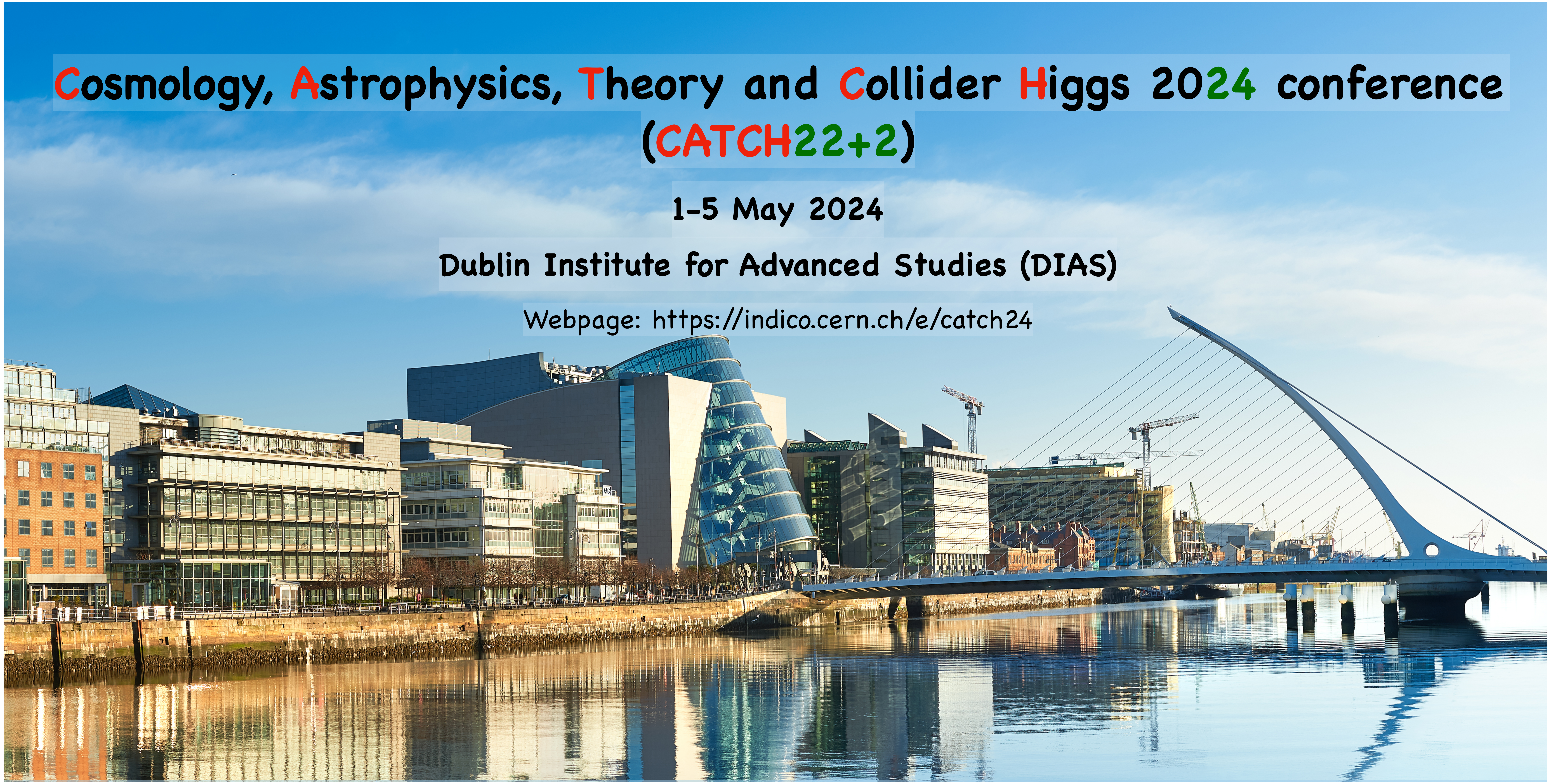
CATCH22+2, Dublin, May 5, 2024

Diphoton jet signals from light fermiophobic Higgs boson at the HL-LHC

Jeonghyeon Song (Konkuk University, Korea)

With D.Wang, J.H. Cho, J. Kim, S. Lee, and P.~Sanyal in Phys.Rev.D 109 (2024) 1, 015017


Cosmology, Astrophysics, Theory and Collider Higgs 2024 conference
(CATCH22+2)
1-5 May 2024
Dublin Institute for Advanced Studies (DIAS)
Webpage: https://indico.cern.ch/e/catch24

What to CATCH?

- Physics Beyond the SM
- Dark matter: theory and experiment
- Flavour physics
- CP-violation
- Inflation
- Baryogenesis
- LHC and future colliders
- Neutrino physics
- Axions and axion-like particles
- Gravitational waves

All revolving around BSM

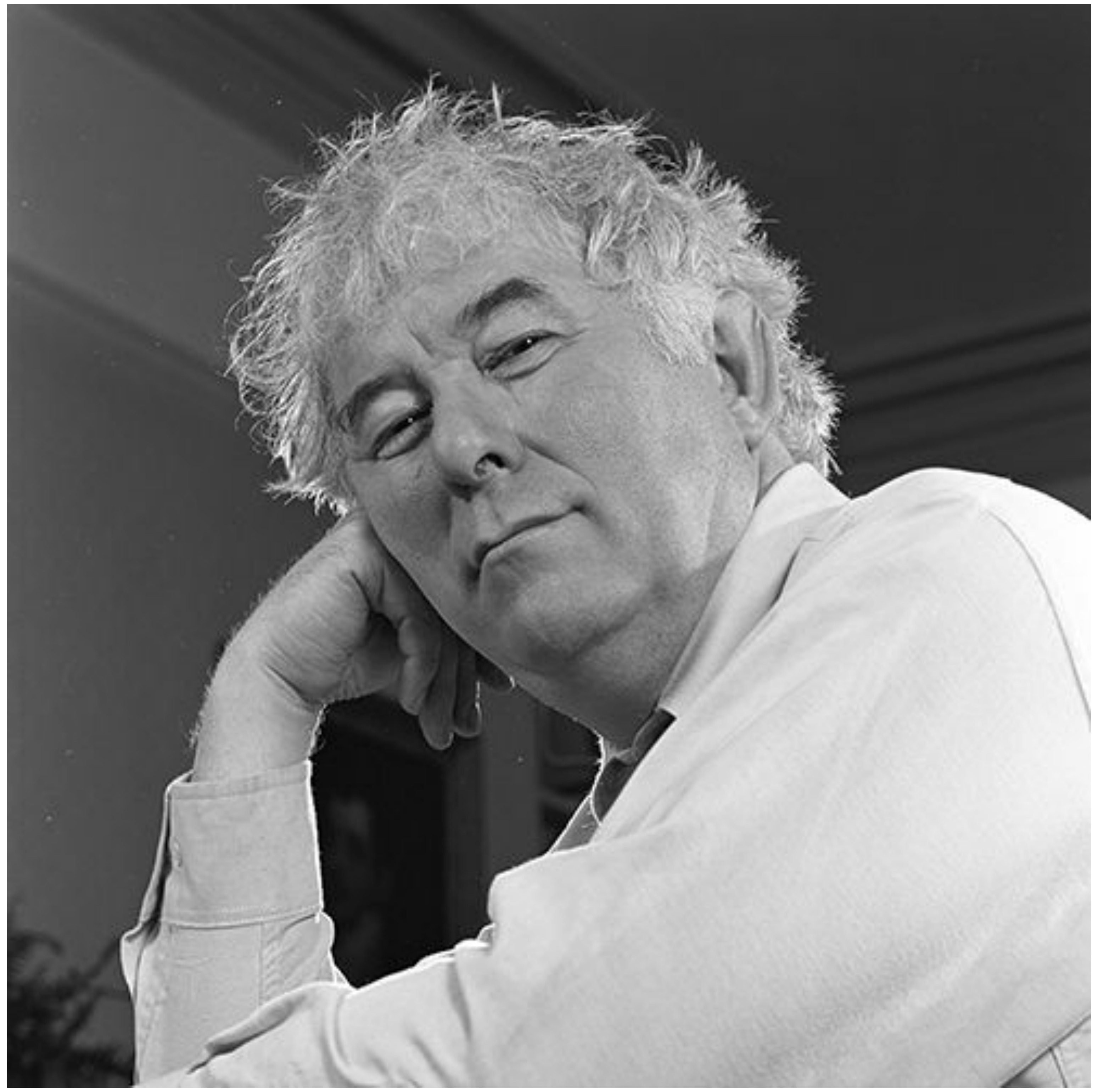
Disappointing situation at the LHC

Abstract

A search for new physics in final states consisting of at least one photon, multiple jets, and large missing transverse momentum is presented, using proton-proton collision events at a center-of-mass energy of 13 TeV. The data correspond to an integrated luminosity of 137 fb^{-1}, recorded by the CMS experiment at the CERN LHC from 2016 to 2018. The events are divided into mutually exclusive bins characterized by the missing transverse momentum, the number of jets, the number of b-tagged jets, and jets consistent with the presence of hadronically decaying W, Z, or Higgs bosons. The observed data are found to be consistent with the prediction from standard model processes. The results are interpreted in the context of simplified models of pair production of supersymmetric particles via strong and electroweak interactions. Depending on the details of the signal models, gluinos and squarks of masses up to 2.35 and 1.43 TeV, respectively, and electroweakinos of masses up to 1.23 TeV are excluded at 95% confidence level

Histories says, Don’t hope

On this side of the grave.



Seamus Heaney, "The Cure at Troy”

Histories says, Don’t hope

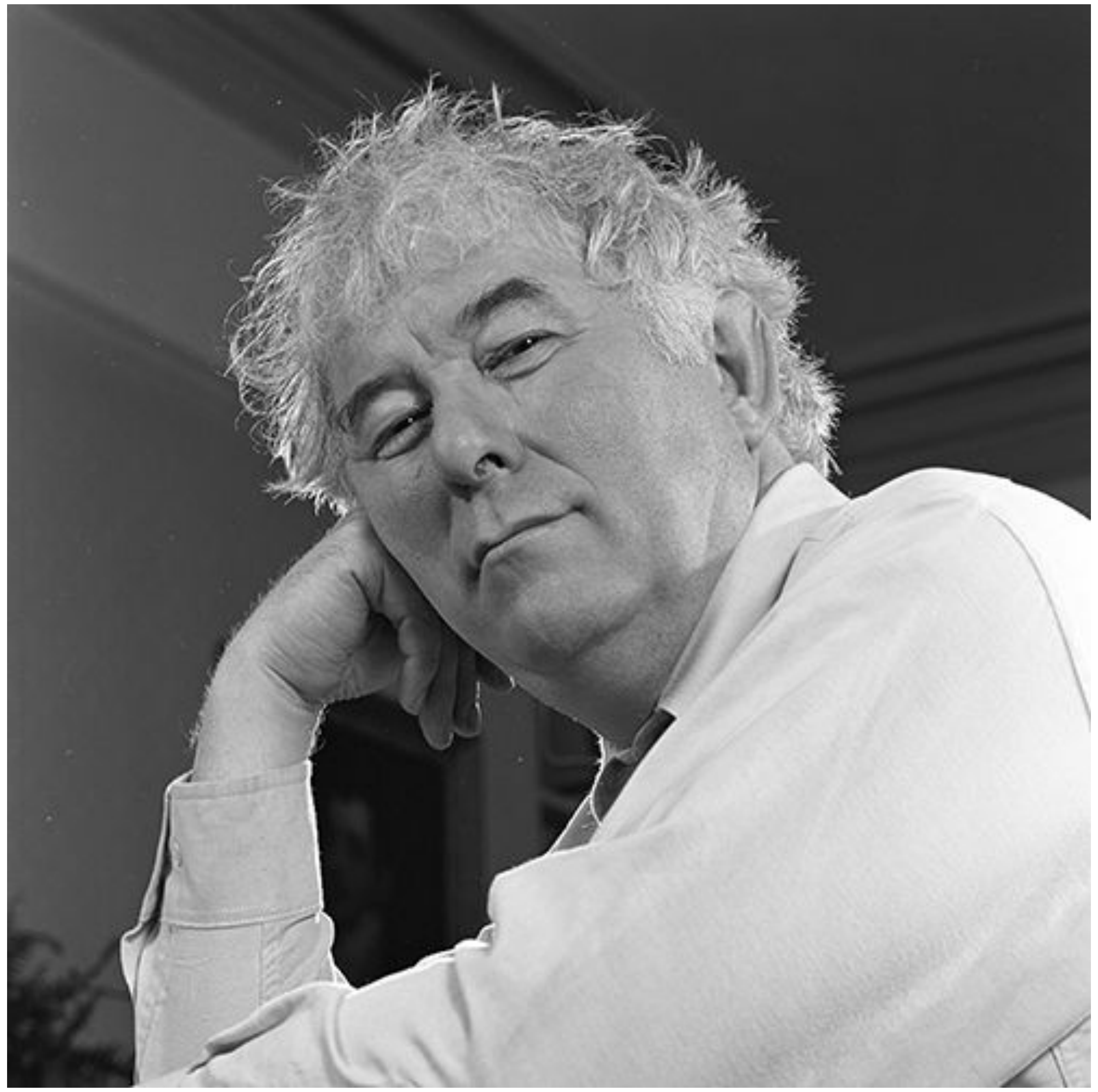
On this side of the grave.

But then, once in a lifetime

The longed-for tidal wave

Of justice can rise up,

and hope and history rhyme….



Seamus Heaney, "The Cure at Troy”

A good example:

Very light fermiophobic Higgs boson in type-I 2HDM

1. Fermiophobic Higgs boson in Type-I 2HDM
2. Jet subparticles and pileups
3. Cut-based analysis
4. Mass reconstruction
5. Machine Learning Techniques
6. Conclusions

1. Fermiophobic Higgs boson in Type-I 2HDM

- Basic theory setup

$$\Phi_i = \begin{pmatrix} w_i^+ \\ \frac{v_i + h_i + i\eta_i}{\sqrt{2}} \end{pmatrix}, \quad i = 1, 2,$$

where $v = \sqrt{v_1^2 + v_2^2} = 246$ GeV.

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$$\Phi_i = \left(\begin{array}{c} w_i^+ \\ \frac{v_i + h_i + i\eta_i}{\sqrt{2}} \end{array} \right), \quad i = 1, 2,$$

where $v \;=\; \sqrt{v_1^2 + v_2^2} \;=\; 246 \text{ GeV}.$

- Discrete Z_2 symmetry to avoid tree-level FCNC

$$\Phi_1 \to \Phi_1, \quad \Phi_2 \to -\Phi_1$$

- Basic theory setup

$$\Phi_i = \begin{pmatrix} w_i^+ \\ \dfrac{v_i + h_i + i\eta_i}{\sqrt{2}} \end{pmatrix}, \quad i = 1, 2,$$

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- Discrete Z_2 symmetry to avoid tree-level FCNC

$$\Phi_1 \to \Phi_1, \quad \Phi_2 \to -\Phi_1$$

- Scalar potential with CP-invariance

Soft braking of Z_2

$$\begin{aligned} V_\Phi = \ & m_{11}^2 \Phi_1^\dagger \Phi_1 + m_{22}^2 \Phi_2^\dagger \Phi_2 - m_{12}^2 (\Phi_1^\dagger \Phi_2 + \text{H.c.}) \\ & + \frac{1}{2}\lambda_1 (\Phi_1^\dagger \Phi_1)^2 + \frac{1}{2}\lambda_2 (\Phi_2^\dagger \Phi_2)^2 + \lambda_3 (\Phi_1^\dagger \Phi_1)(\Phi_2^\dagger \Phi_2) + \lambda_4 (\Phi_1^\dagger \Phi_2)(\Phi_2^\dagger \Phi_1) \\ & + \frac{1}{2}\lambda_5 \left[(\Phi_1^\dagger \Phi_2)^2 + \text{H.c.} \right], \end{aligned}$$

Branco et al.[arXiv:1106.0034]

- Multiple Higgs bosons

$$h,\ H,\ A,\ H^{\pm}$$

- Four types according to the Z_2 parities of the right-handed fermions

	Φ_1	Φ_2	u_R	d_R	ℓ_R	Q_L, L_L
Type I	+	−	−	−	−	+
Type II	+	−	−	+	+	+
Type X	+	−	−	−	+	+
Type Y	+	−	−	+	−	+

Very light fermiophobic Higgs boson

Our setup

$$\text{fermiophobic type-I:} \quad M_H = 125 \text{ GeV}, \quad \alpha = \pi/2.$$

$$\xi_f^h = \frac{c_\alpha}{s_\beta}, \quad \kappa_f^H = \frac{s_\alpha}{s_\beta}, \quad \xi_t^A = -\xi_b^A = -\xi_\tau^A = \frac{1}{t_\beta}.$$

Zero

Akeroyd [hep-ph/9511347]
Barroso et al.[hep-ph/9901293].
Arhrib et al. [0805.1603].
Berger et al. [1203.6645]
Gabrielli et al. [1204.0080].
Delgado et al. [1603.00962]
Kim et al. [2205.01701]

Q. Are there enough viable parameter points?

YEP!

(1) Theoretical requirements

— Scalar potential bounded from below

— Perturbative unitarity of scalar-scalar scattering at tree level

— Vacuum stability

— cutoff scale > 10 TeV

(2) Experimental constraints

— B physics

— Higgs precision data via HiggsSignals

— Direct search bounds at the LEP, Tevatron, and LHC via HiggsBounds

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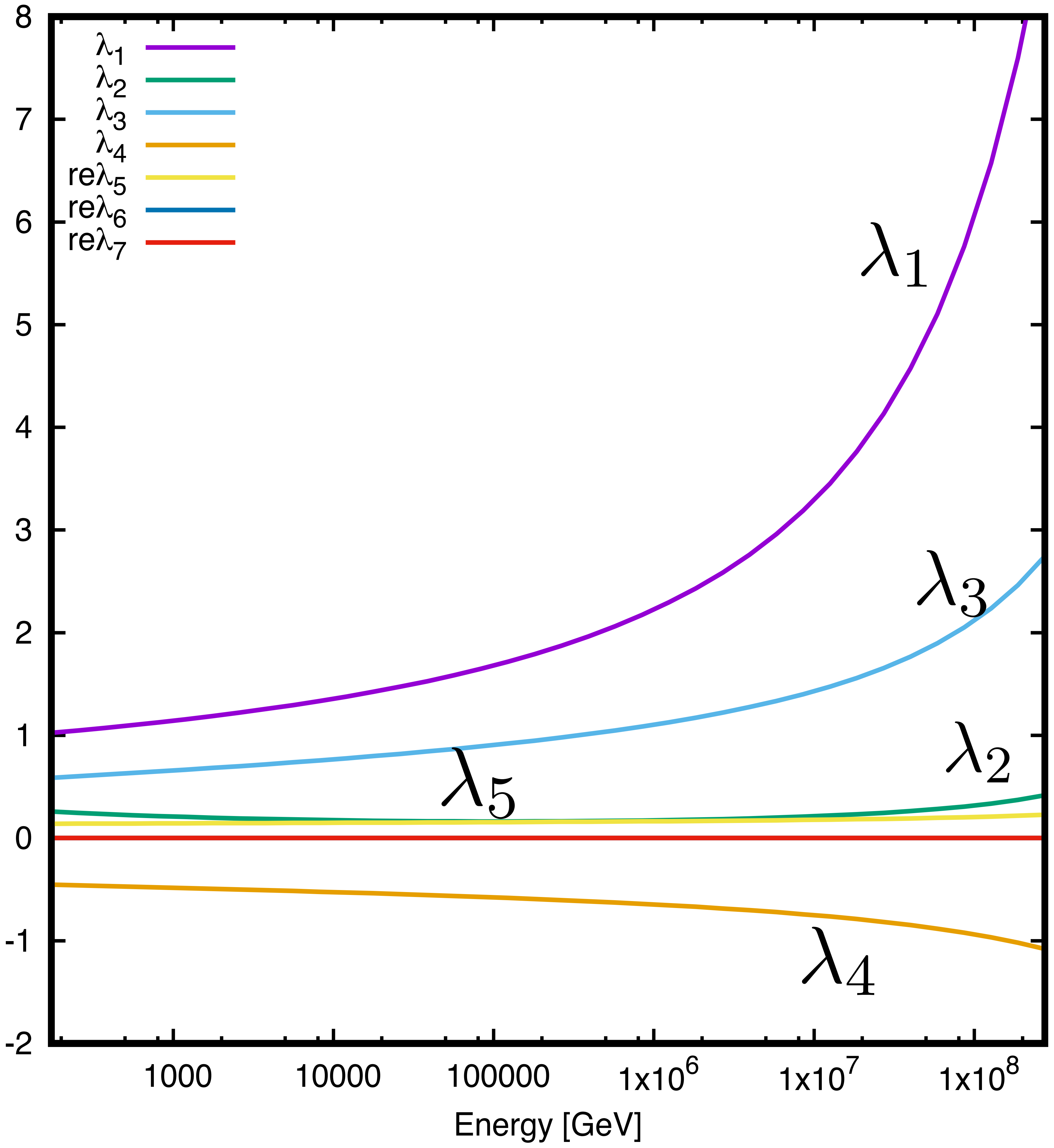
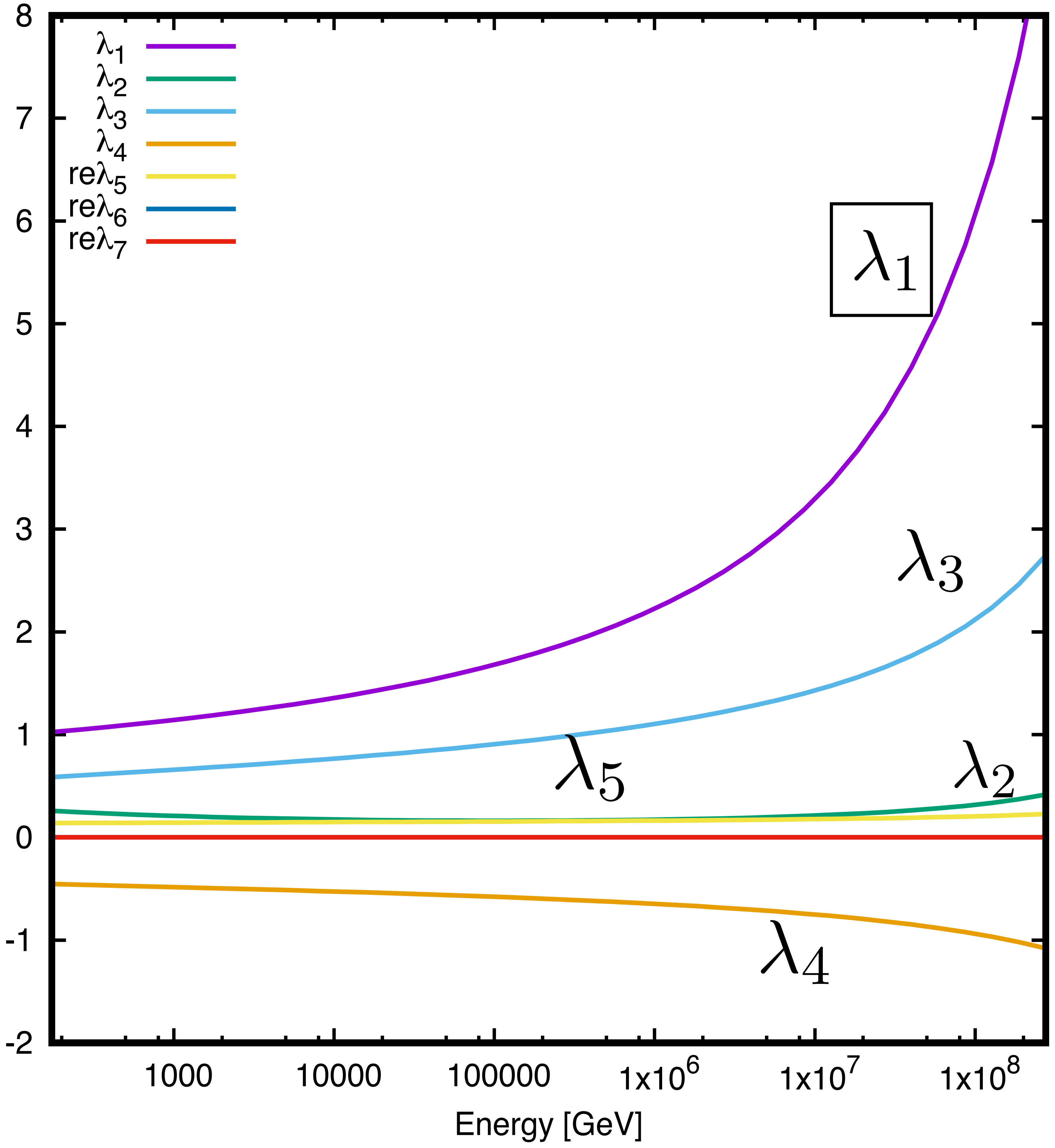
Why imposing cutoff scale > 10 TeV?
Scalar quartic couplings run fast under RGEs!



- Quartic couplings can be very large at high energy scale.
- Stability at EW scale cannot guarantees the stability at higher energy scale.

Oredsson [1810.02588]
Kim et al. [2302.05467]



Theoretical stability is broken at Λ.

⬇

NP is not valid at Λ.

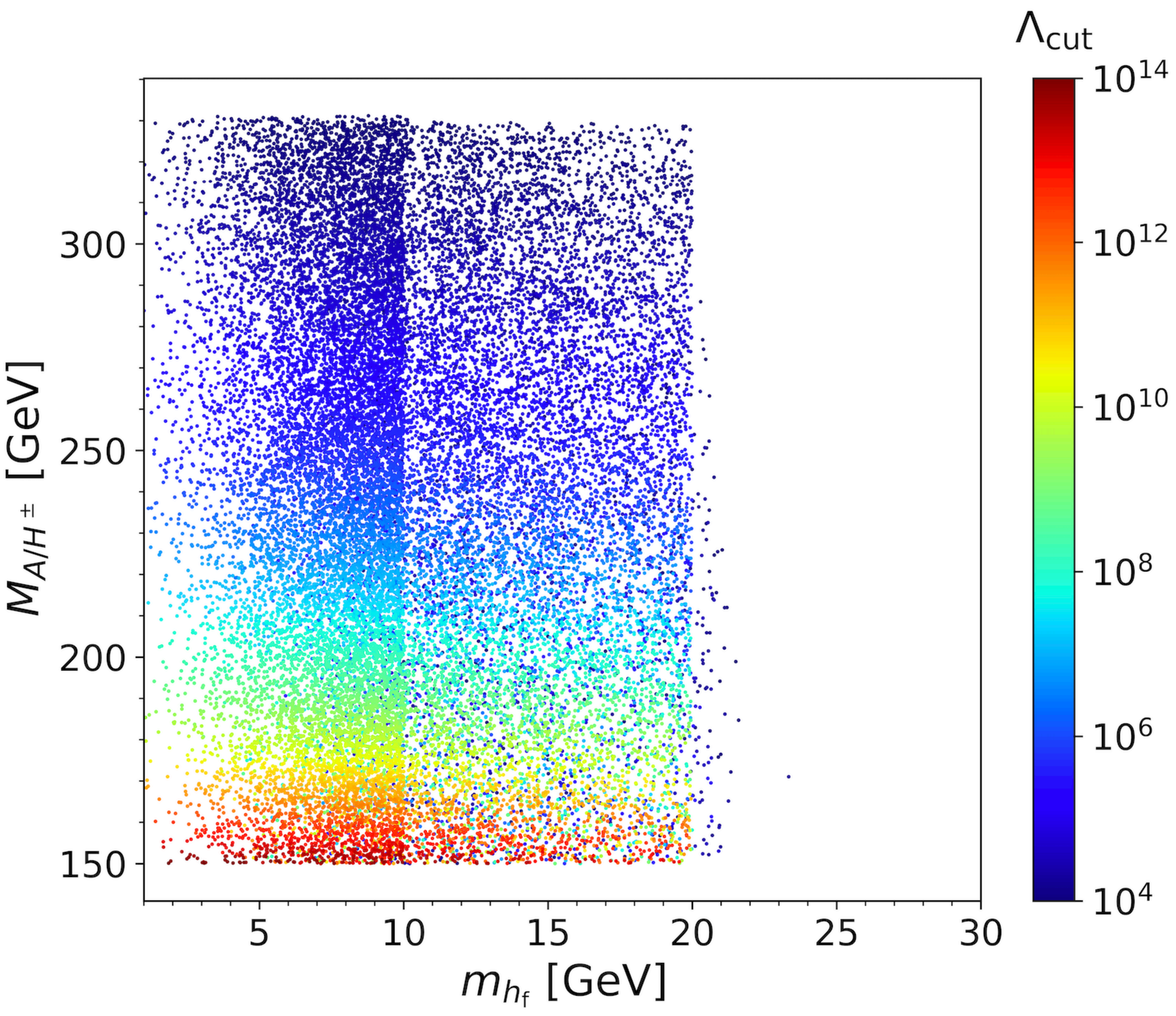
⬇

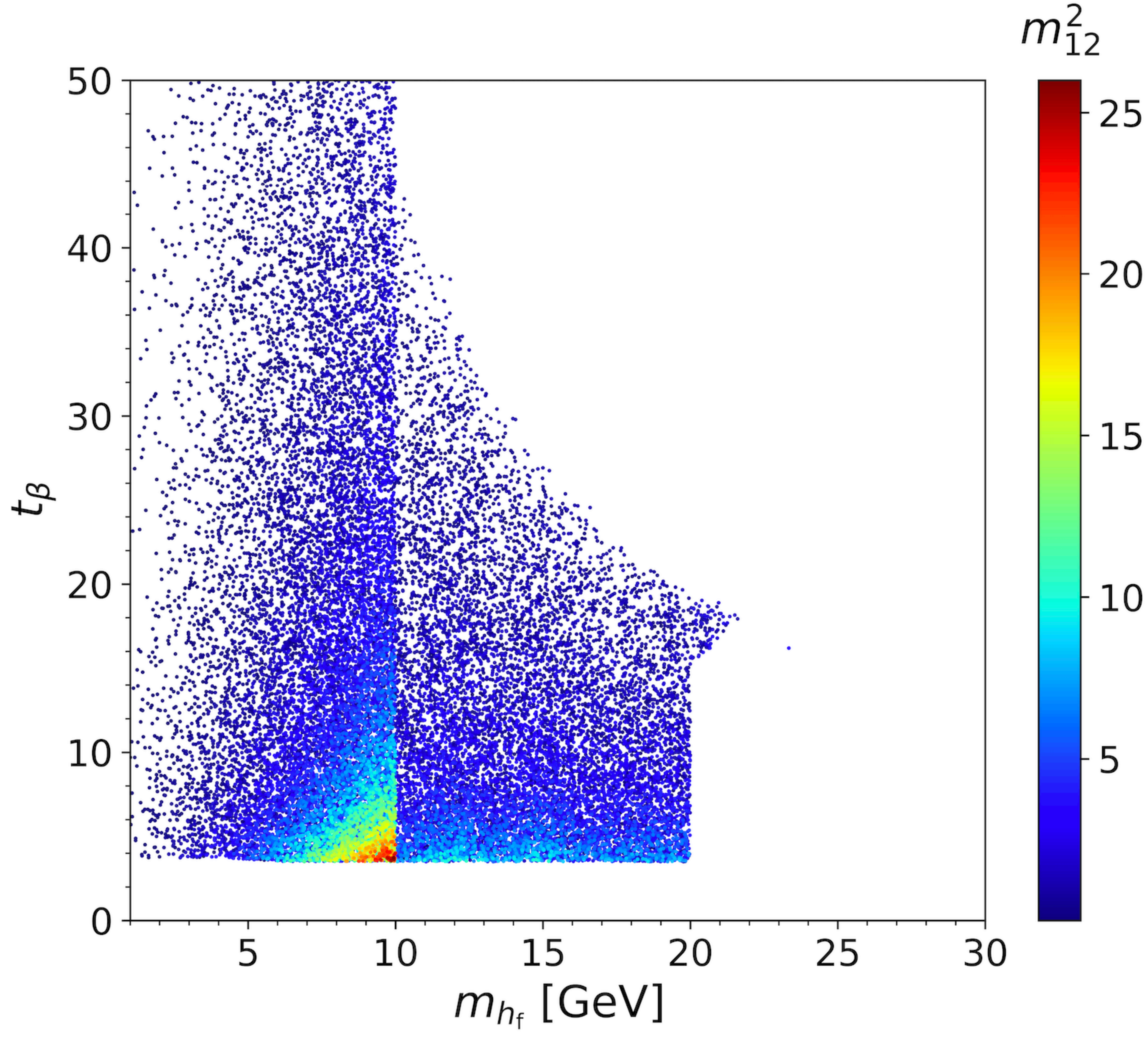
Λ is the cutoff scale of NP.

Let's focus on the light fermiophobic Higgs boson.

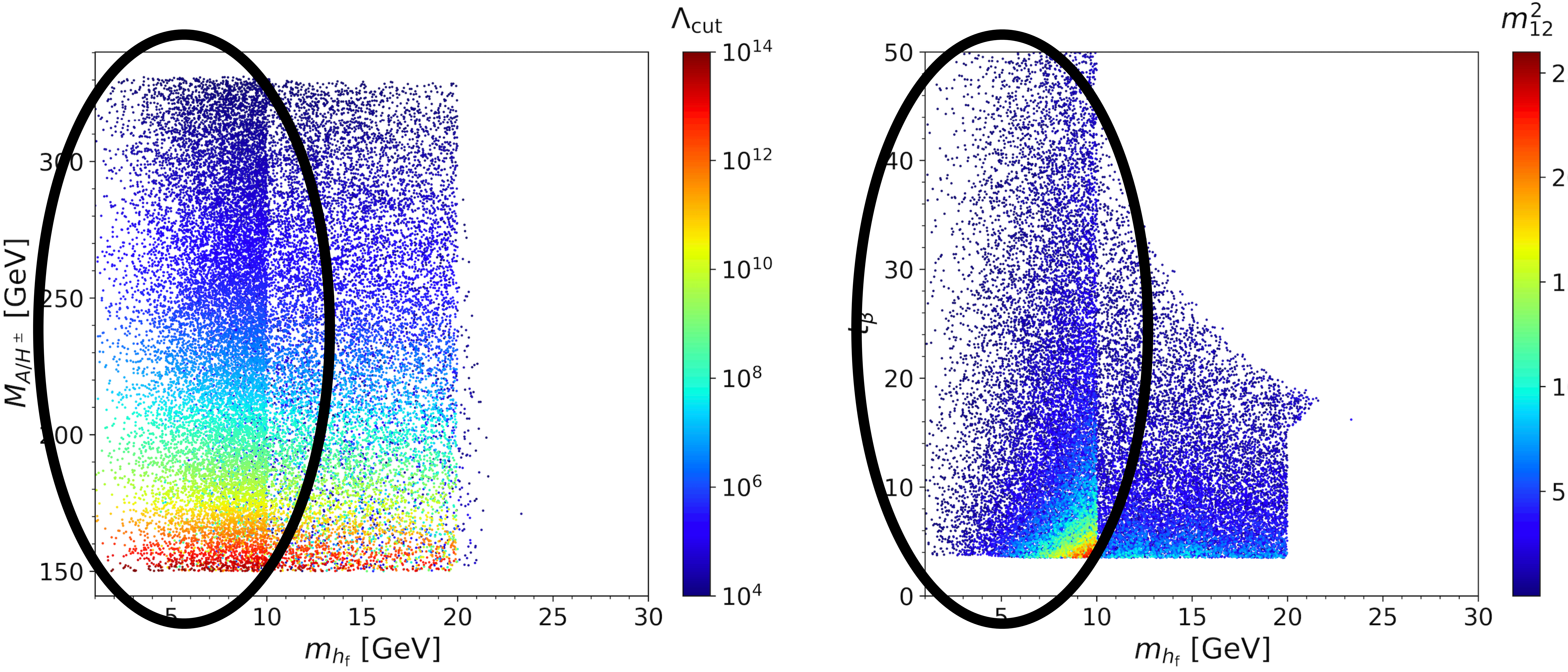
$$m_{h_\mathrm{f}} \in [1, 30]\ \mathrm{GeV}, \qquad M_{A/H^\pm} \in [80, 900]\ \ \mathrm{GeV},$$
$$t_\beta \in [0.5, 50]\,, \qquad m_{12}^2 \in [0, 20000]\ \ \mathrm{GeV}^2.$$

Viable parameter space





Viable parameter space



- Survival rate is high for m_{h_f} in [1,10] GeV.
- NOT studied for the LHC phenomenology.

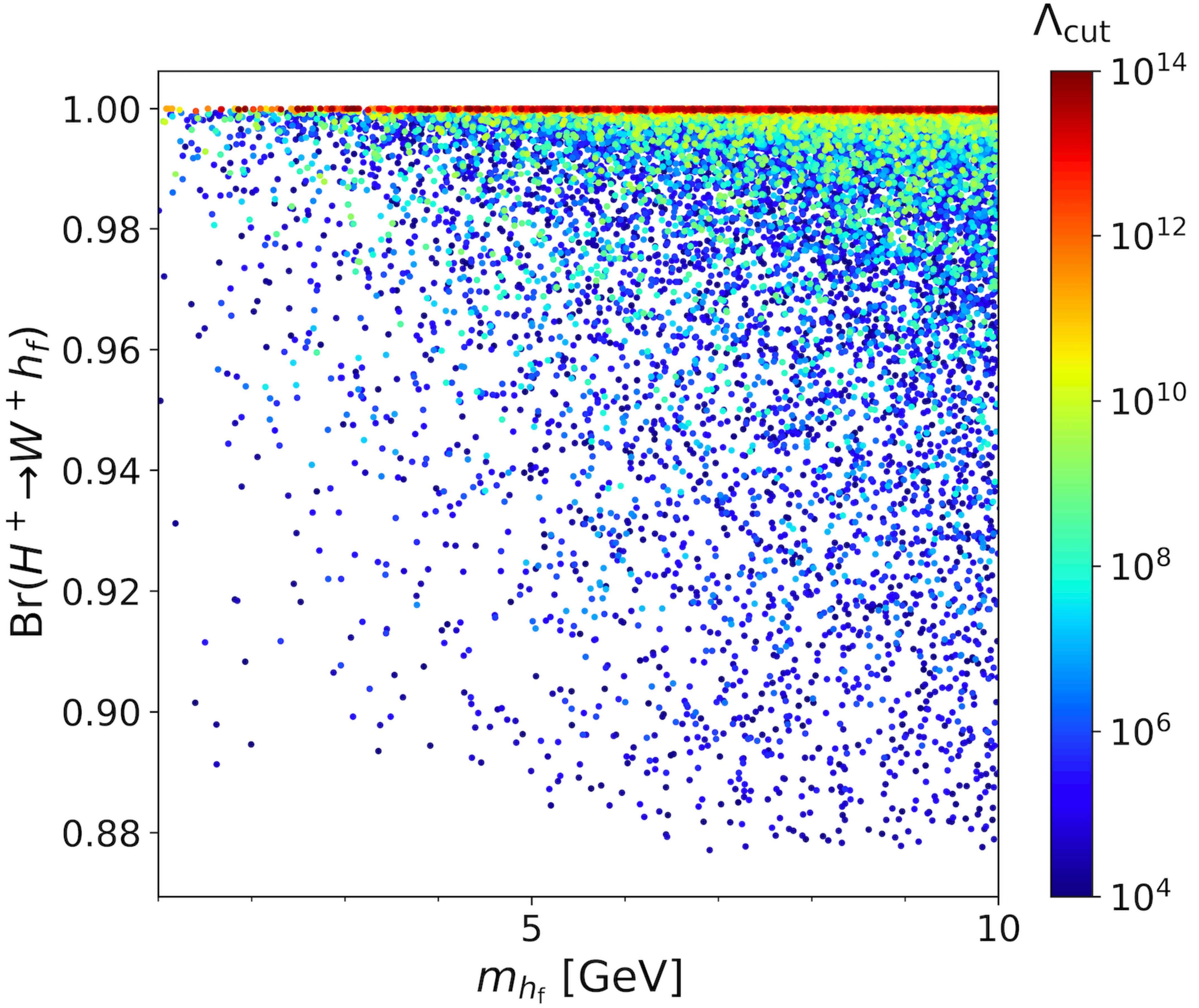
Very light fermion phobic Higgs boson

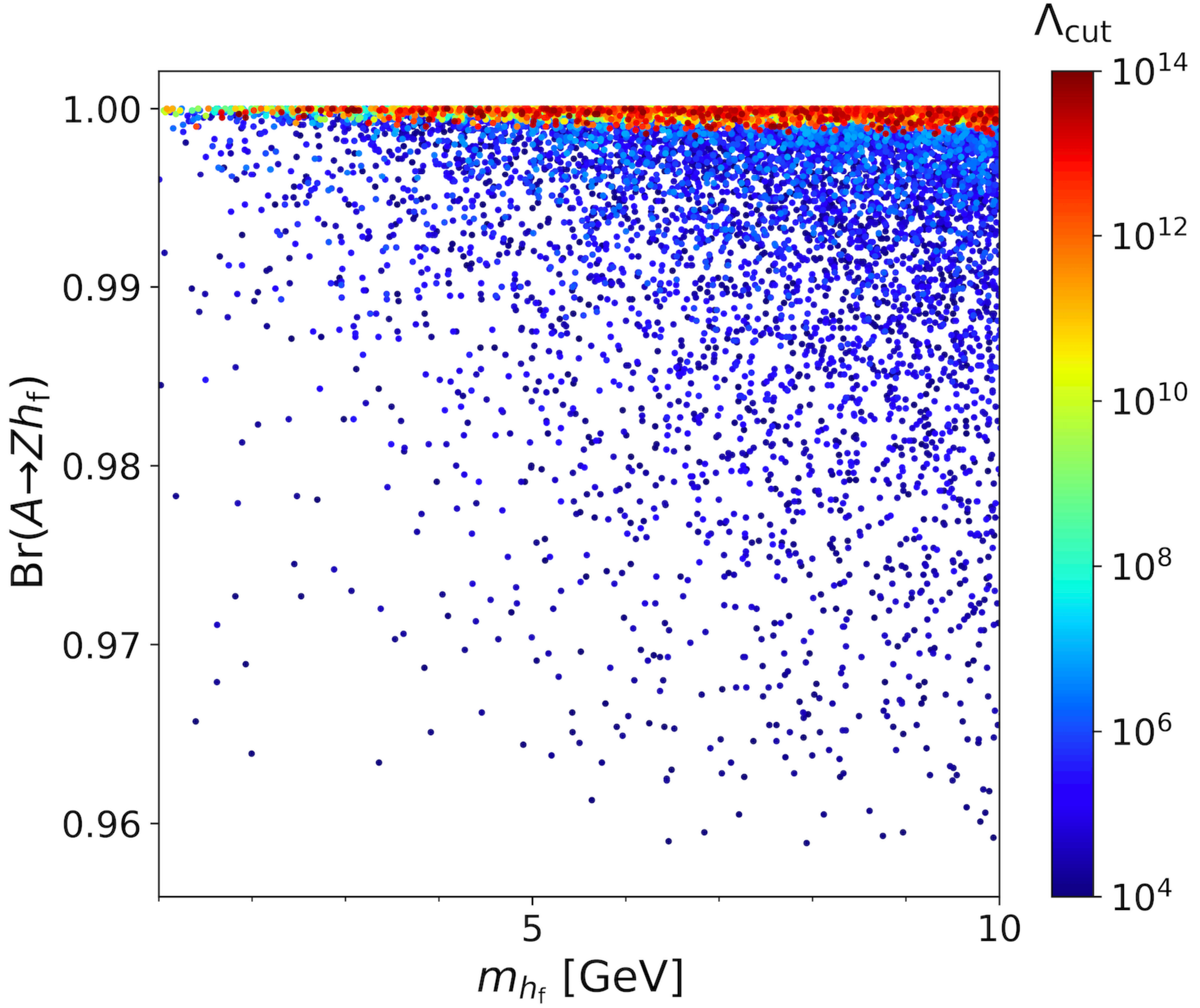
$$m_{h_\mathrm{f}} \in [1, 10]\ \mathrm{GeV}.$$

Practically, one decay mode

$$\mathrm{Br}(h_\mathrm{f} \to \gamma\gamma) \simeq 100\%$$

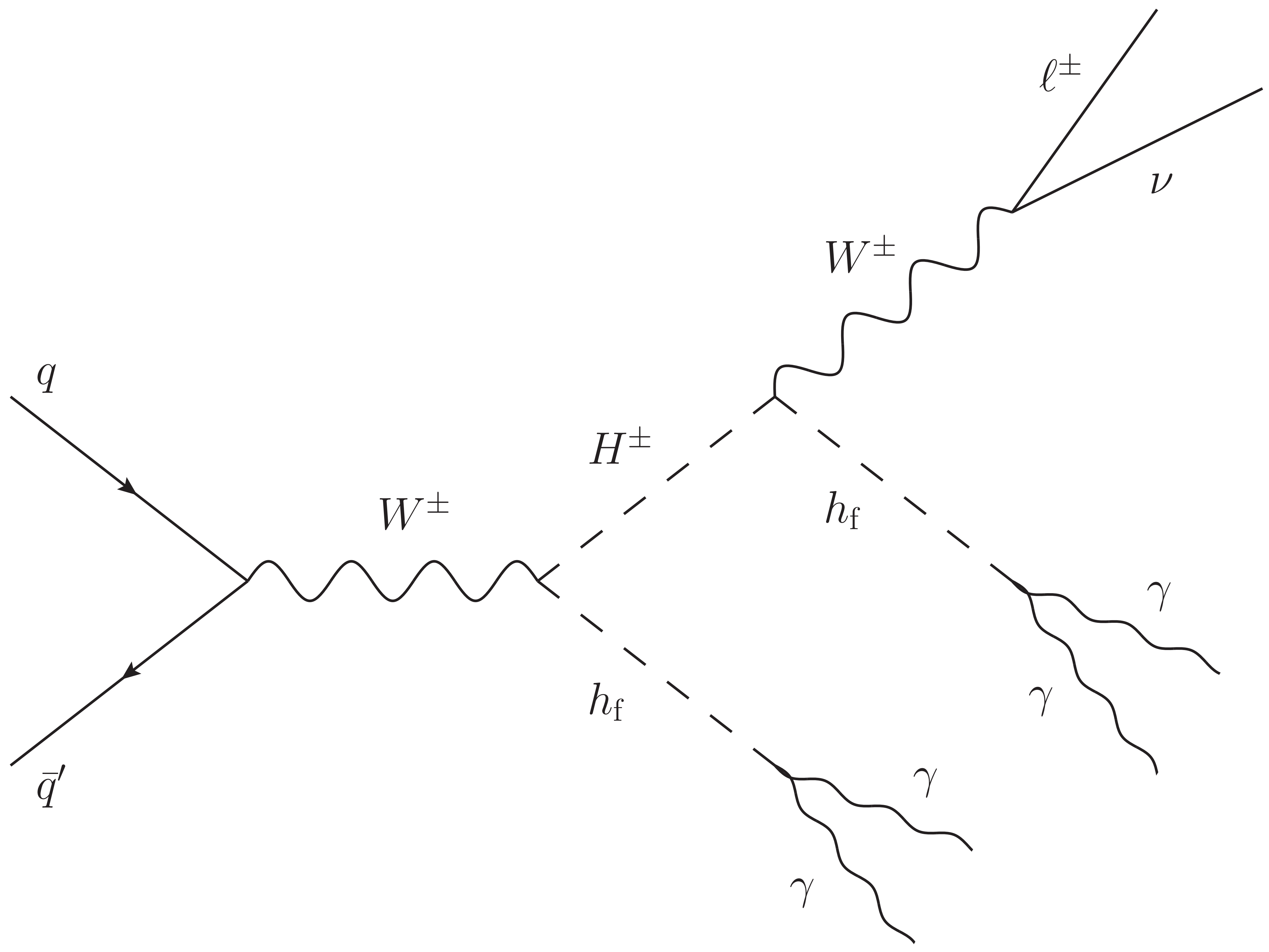
Almost fixed decay modes for $H^{\pm}, A$



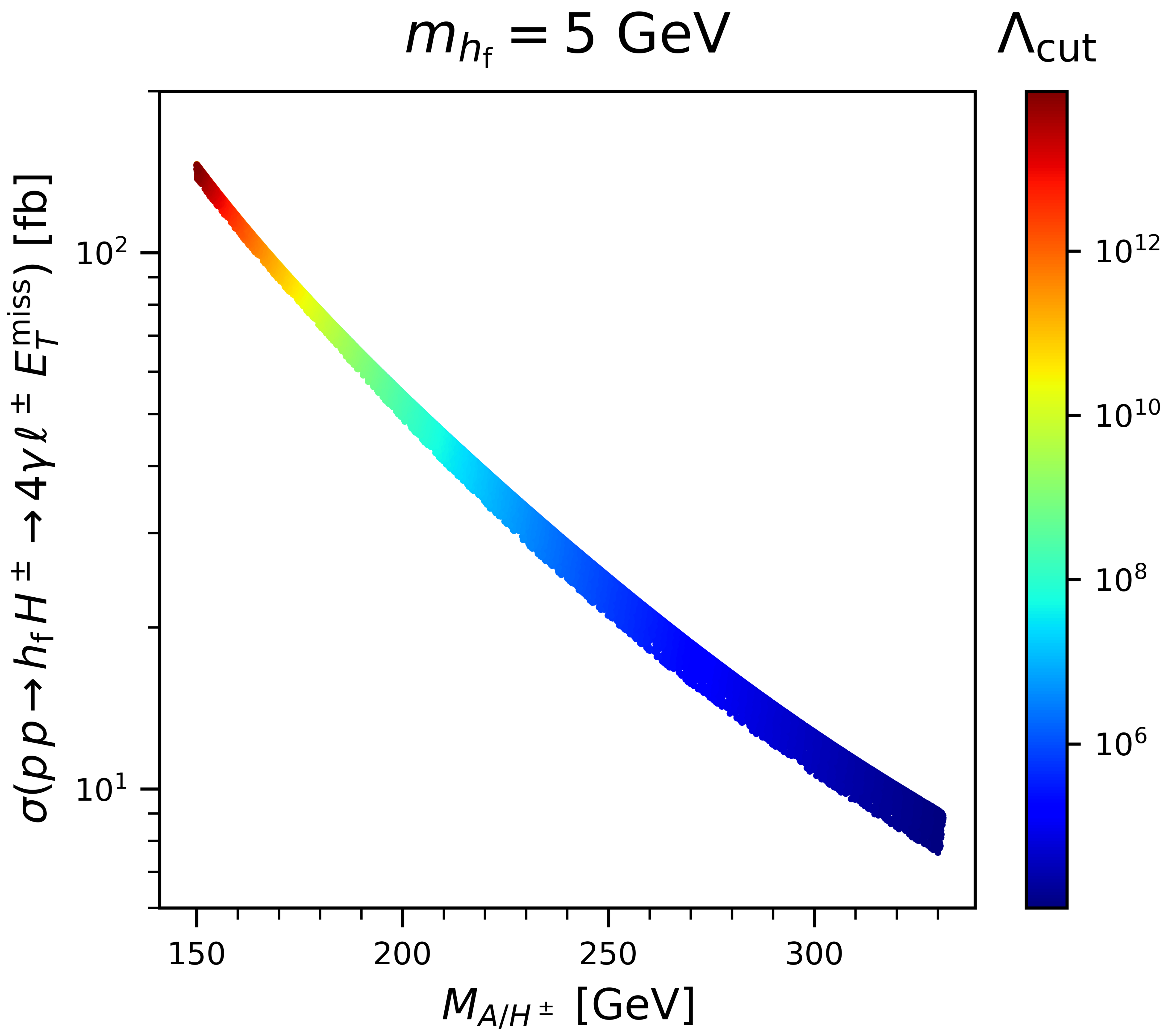


Golden discovery channel for the light h_f

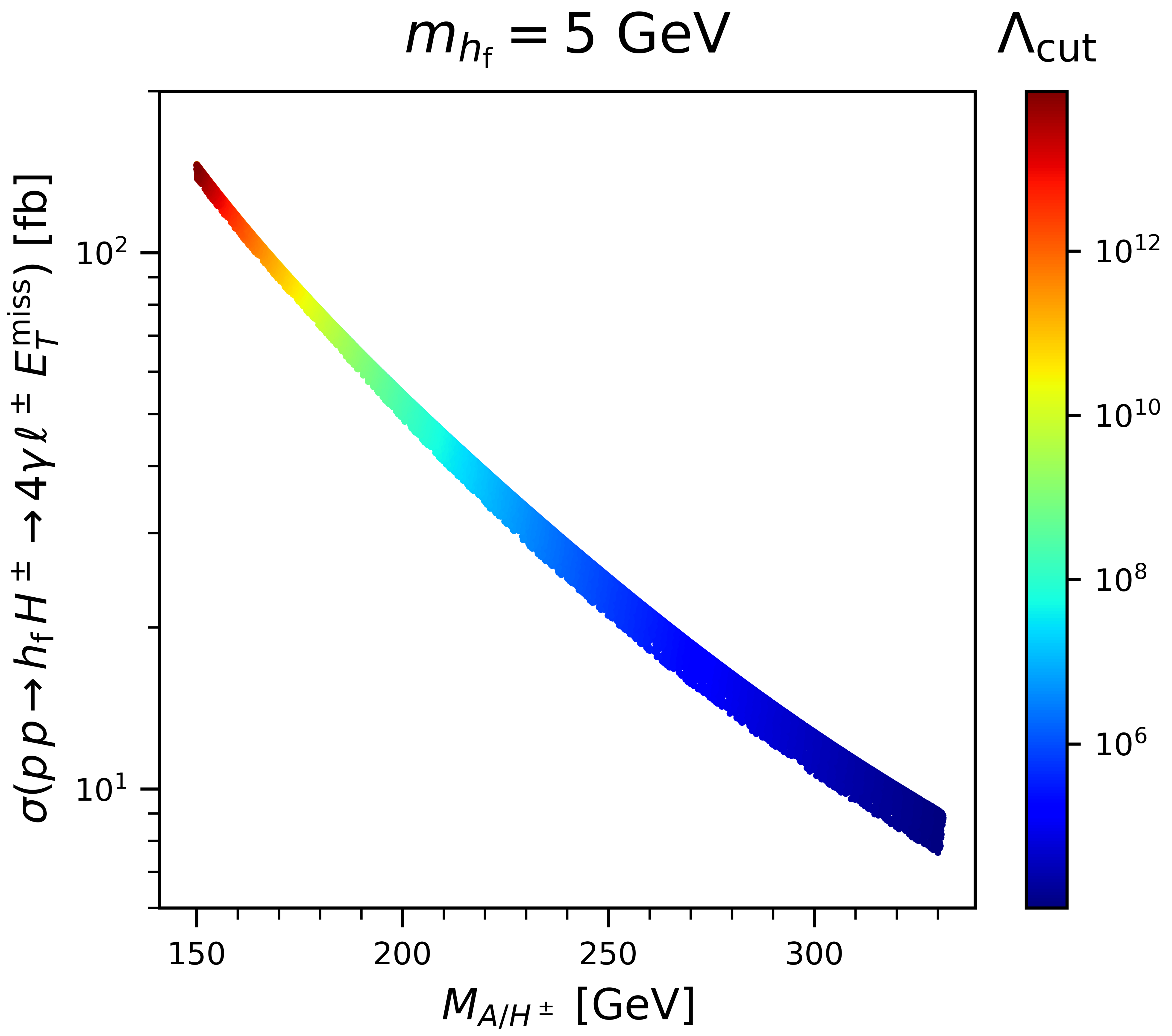
$$pp \to W^* \to h_f H^\pm (\to h_f W^\pm) \to \gamma\gamma + \gamma\gamma + \ell^\pm E_T^{\rm miss}$$



Sizable cross sections



Sizable cross sections

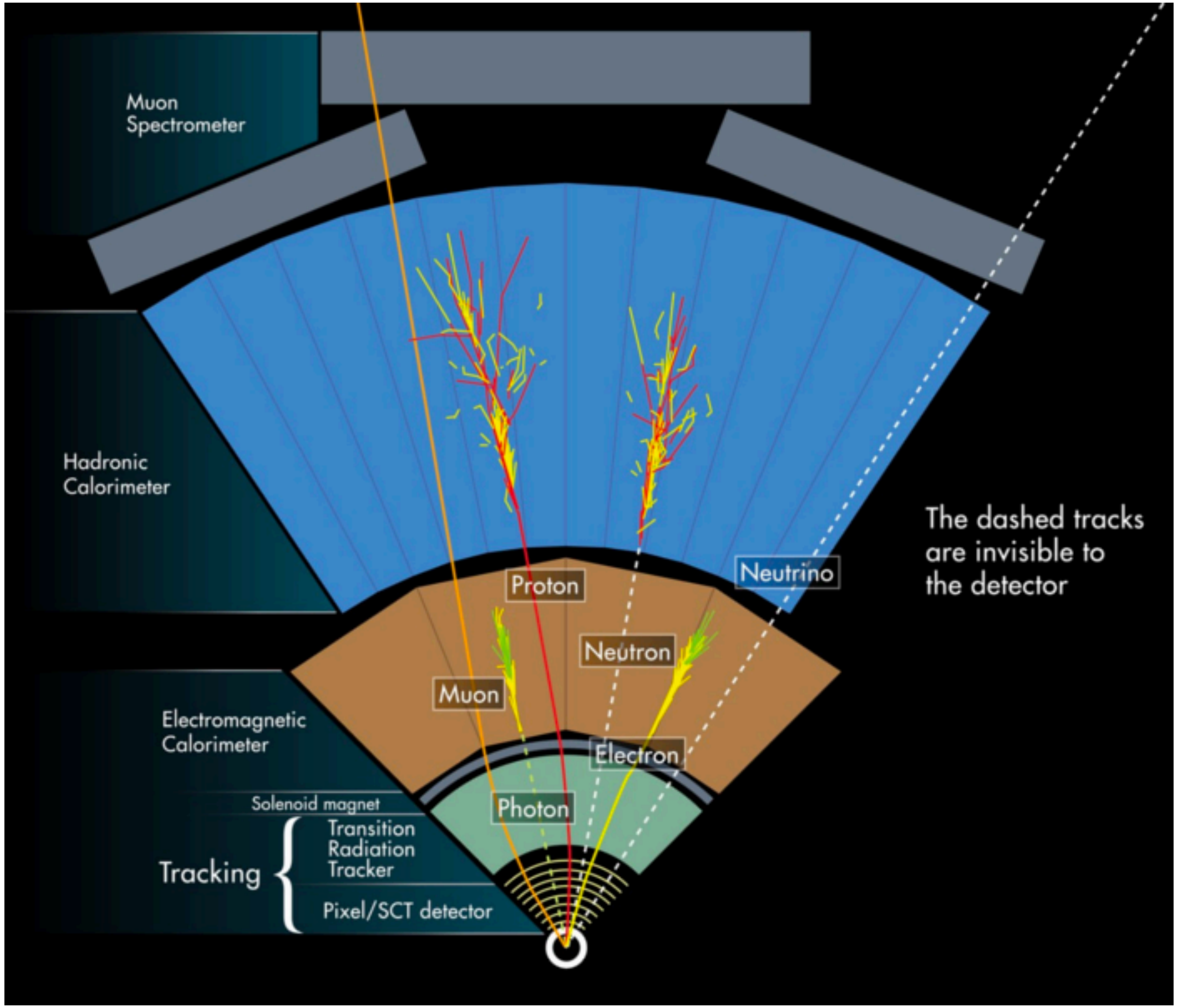


Promising?

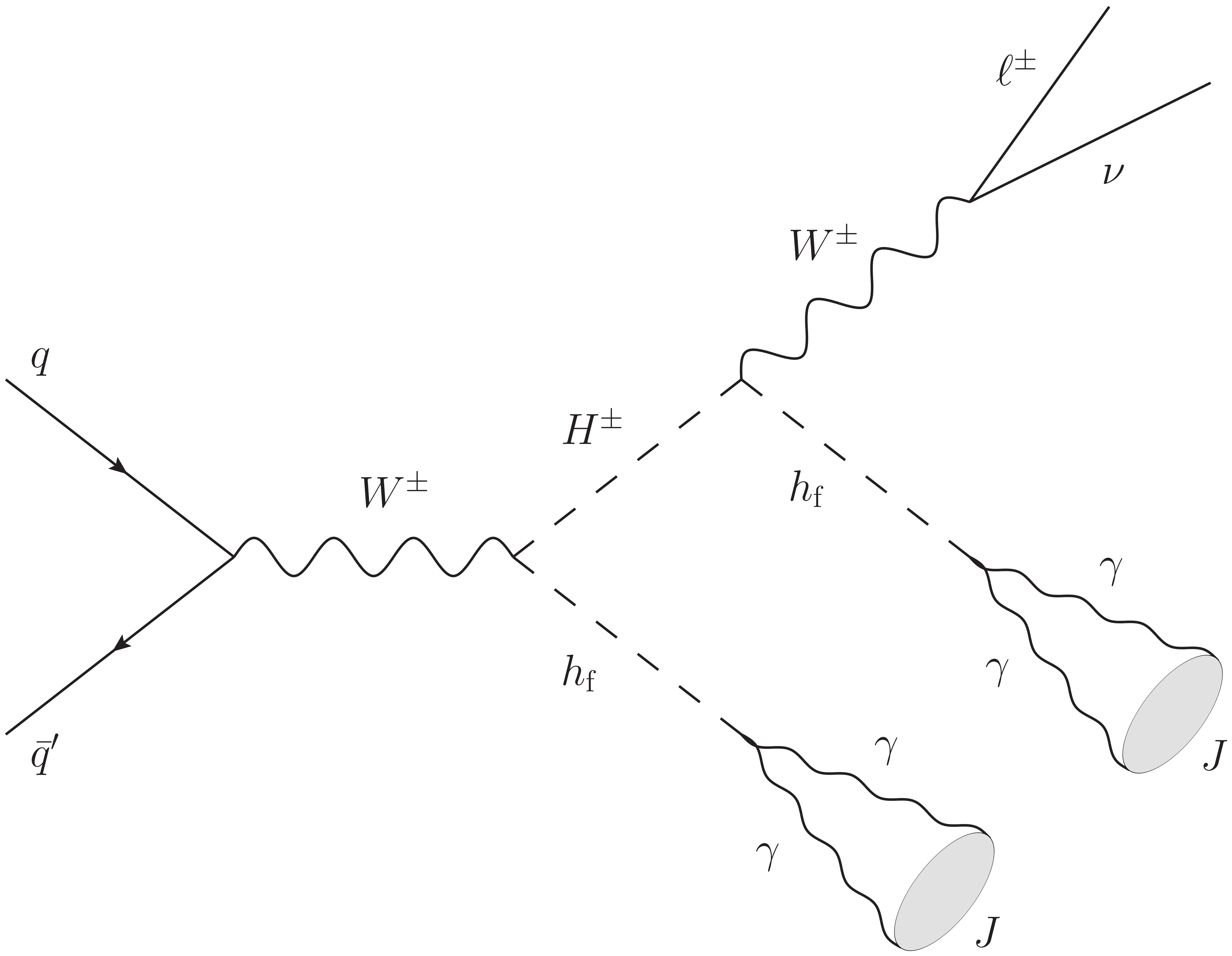
Light mass in [1,10] GeV

➡ Highly collimated two photons

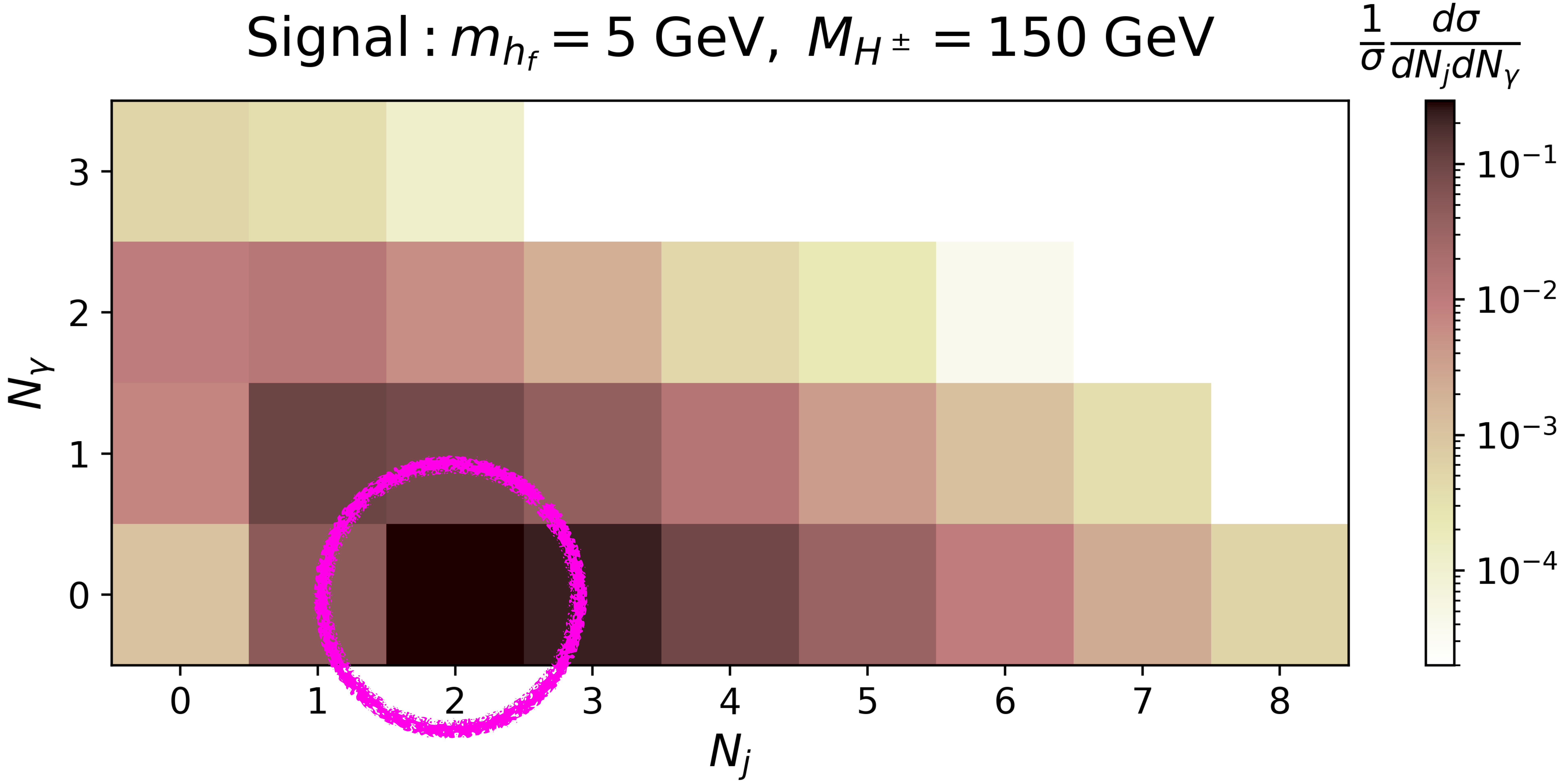
➡ Failing photon isolation!



Two collimated photons are tagged as a jet



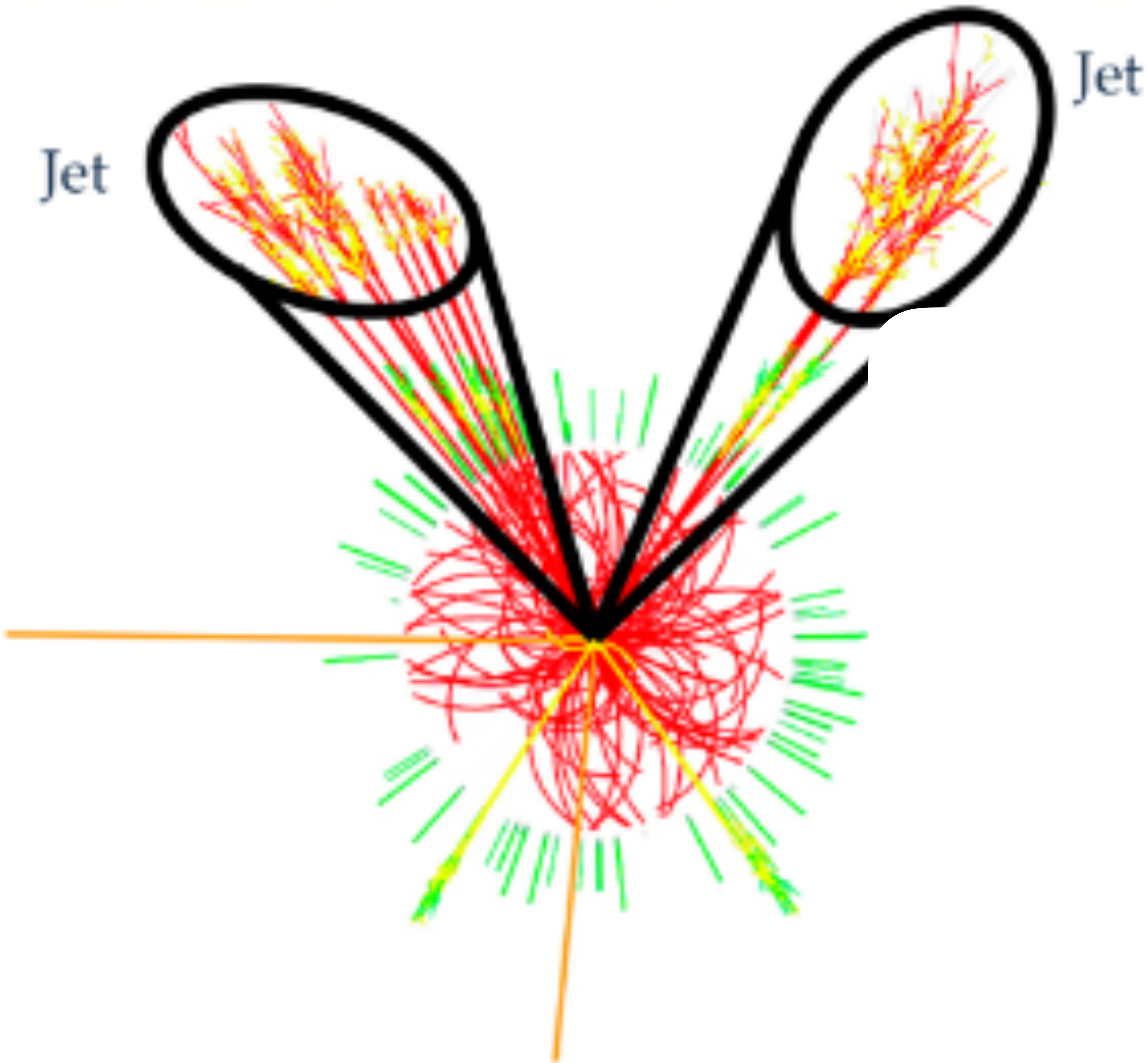
The signal appears as two jets!



Huge QCD backgrounds!!

Background	Cross section [pb]	n_{gen}	Background	Cross section [pb]	n_{gen}
$W^{\pm}(\to L^{\pm}\nu)jj$	3.54×10^3	5×10^8	$W^{\pm}Z$	3.16×10	3×10^6
$Z(\to L^+L^-)jj$	2.67×10^2	5×10^7	$Z(\to L^+L^-)j\gamma$	2.09	10^6
$t\bar{t}(\to b\bar{b}W_{L\nu}W_{jj})$	1.23×10^2	1.2×10^7	ZZ	1.18×10	10^6
$W^{\pm}(\to L^{\pm}\nu)j\gamma$	2.53×10	3×10^6	$W^{\pm}(\to L^{\pm}\nu)\gamma\gamma$	3.28×10^{-2}	10^6
W^+W^-	8.22×10	9×10^6	$Z(\to L^+L^-)\gamma\gamma$	1.12×10^{-2}	10^6

2. Jet subparticles and pileups



A jet consists of many subparticles

Subparticle information from Delphes:
p_T, η, ϕ + EFlow object

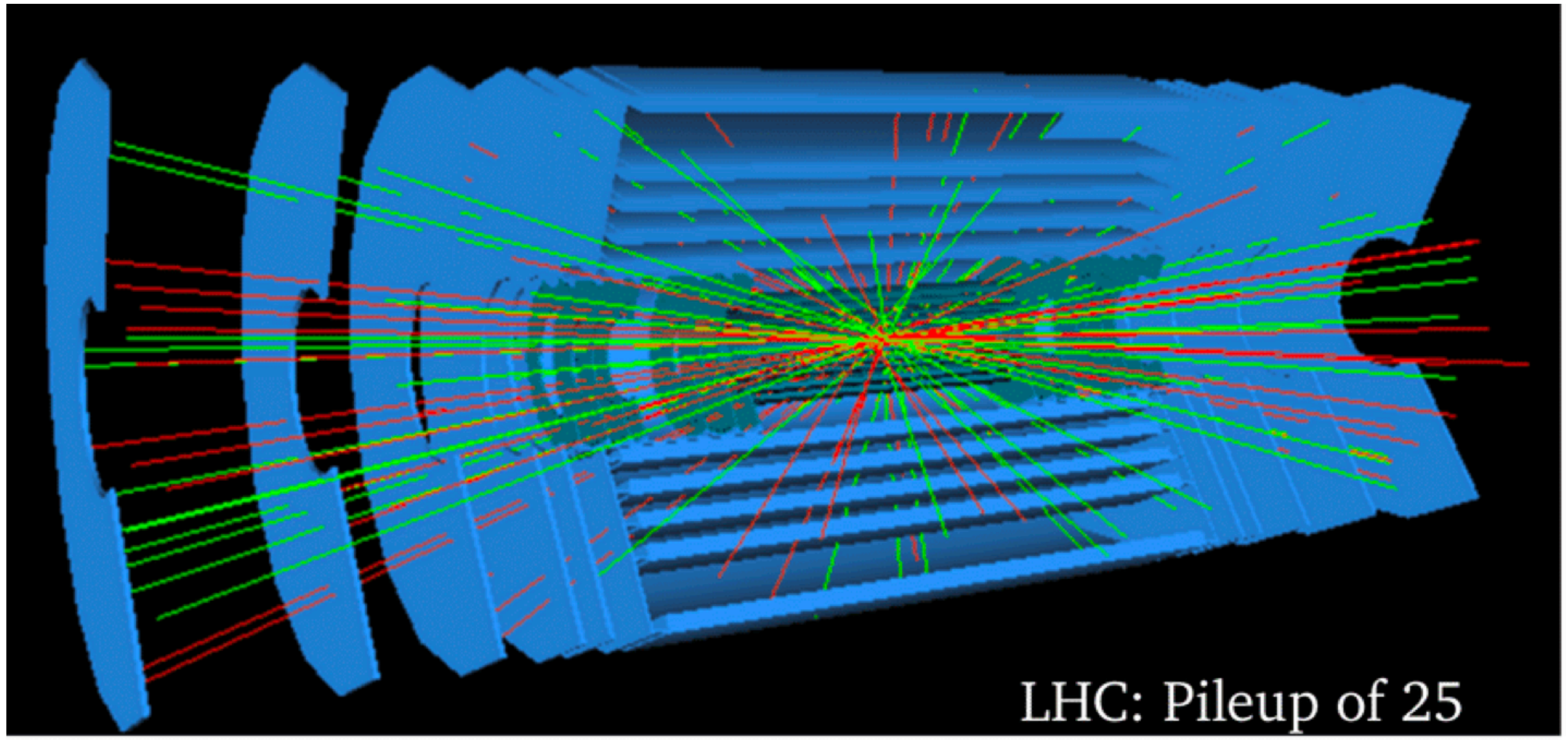
	With track	Without track
ECAL	EFlowElectron	EFlowPhoton
HCAL	EFlowChargedHadron	EFlowNeutralHadron

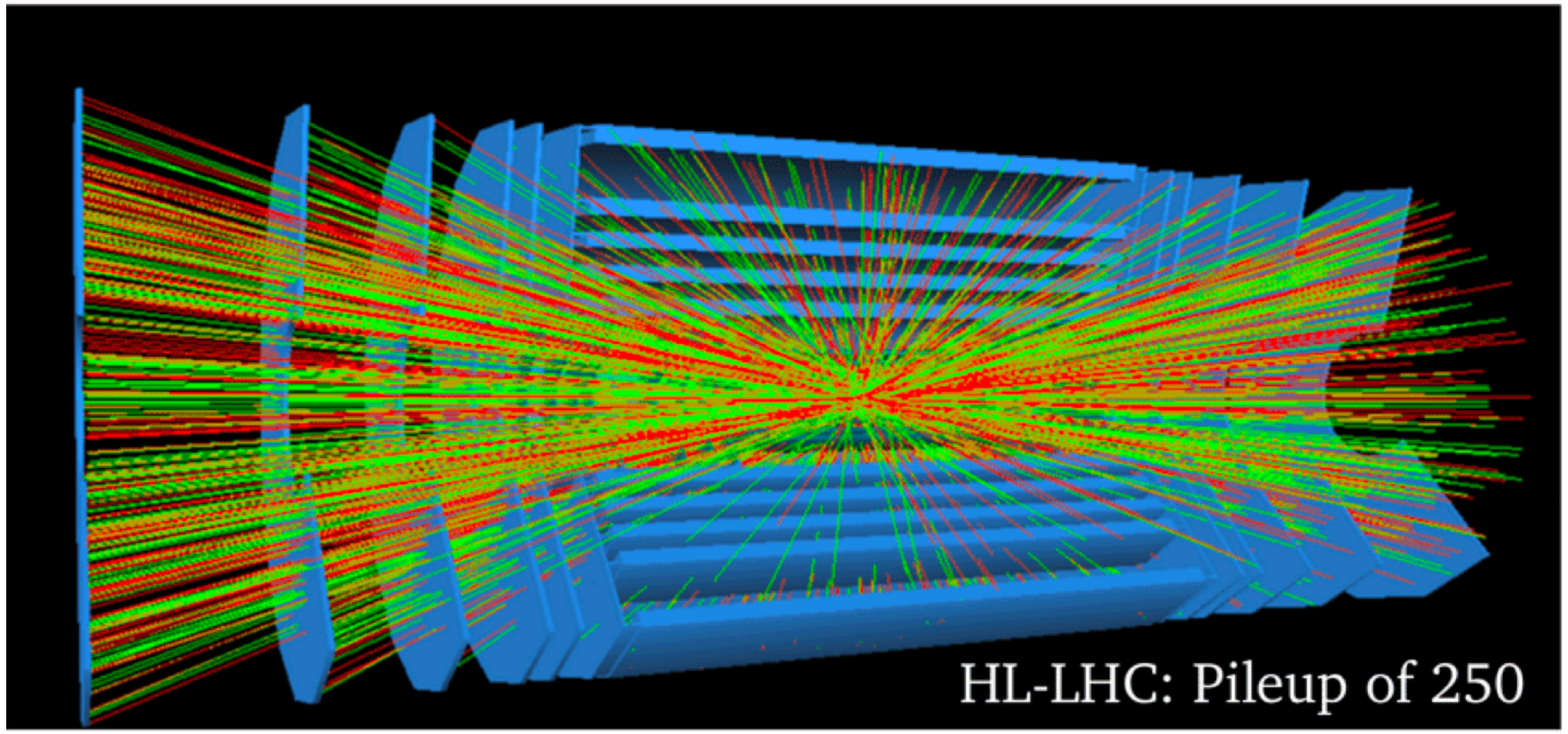
The signal jet should consist of two EFlowPhotons!

Diphoton jet

Distinguishable from QCD jets? BUT

About 200 Pileups at the HL-LHC





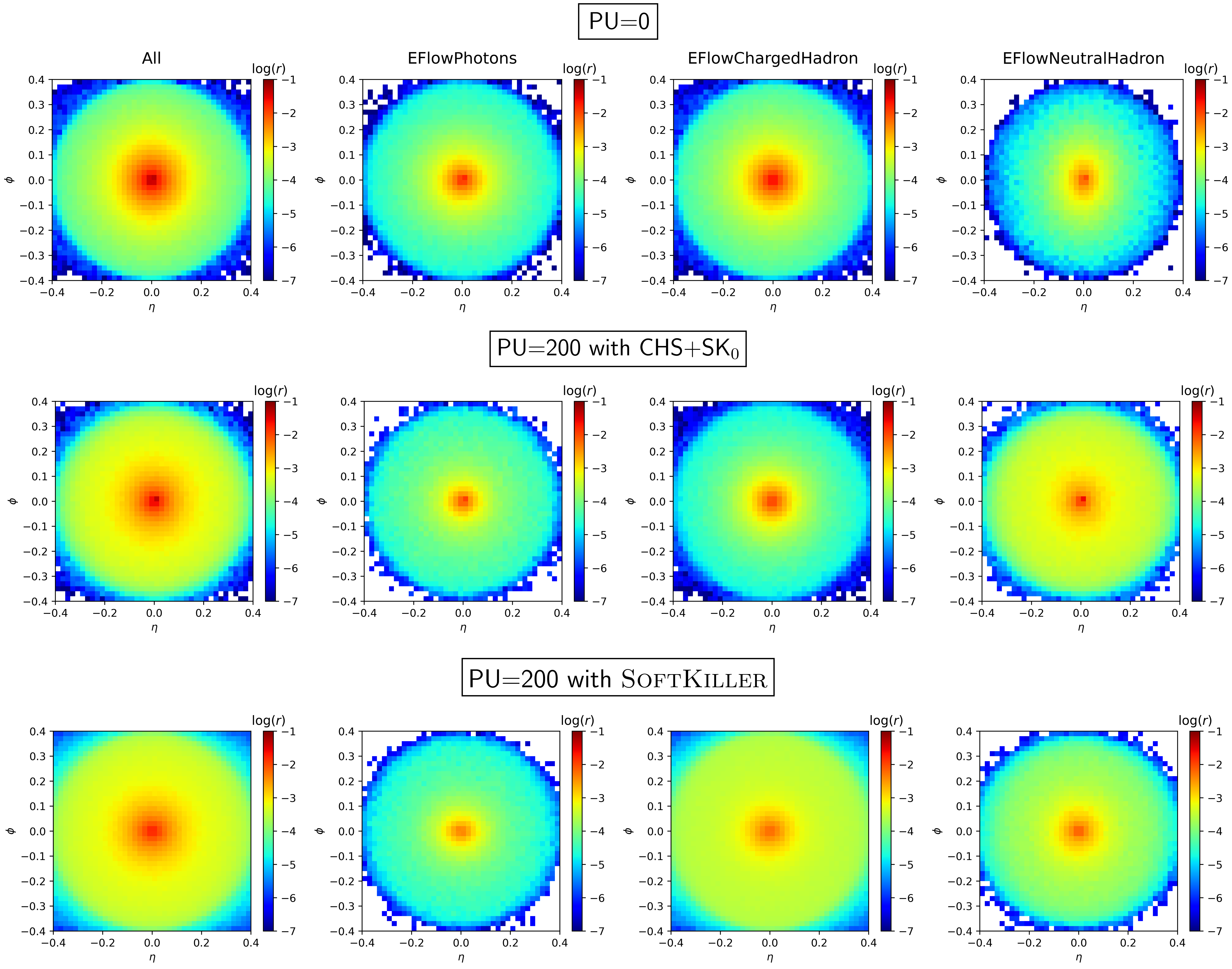
Pileup subtraction is important

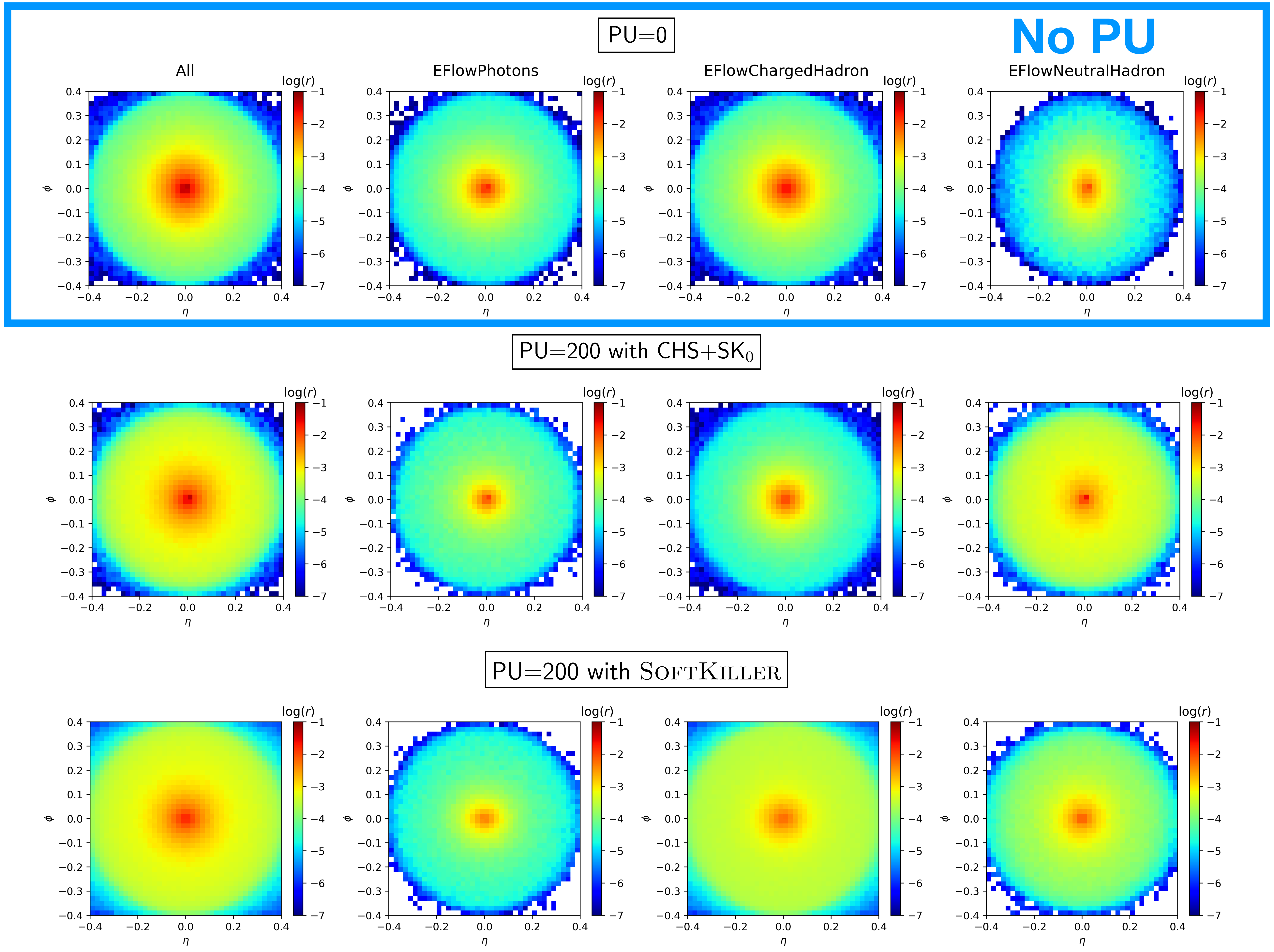
Hybrid method: CHS + SoftKiller0

- Charged Hadron Subtraction (CHS) removes charged pileup particles
- SoftKiller removes neutral pileup particles

CMS-PAS-JME-14-001
Cacciari et al. [1407.0408]

Jet images to demonstrate the excellence of CHS+SK0



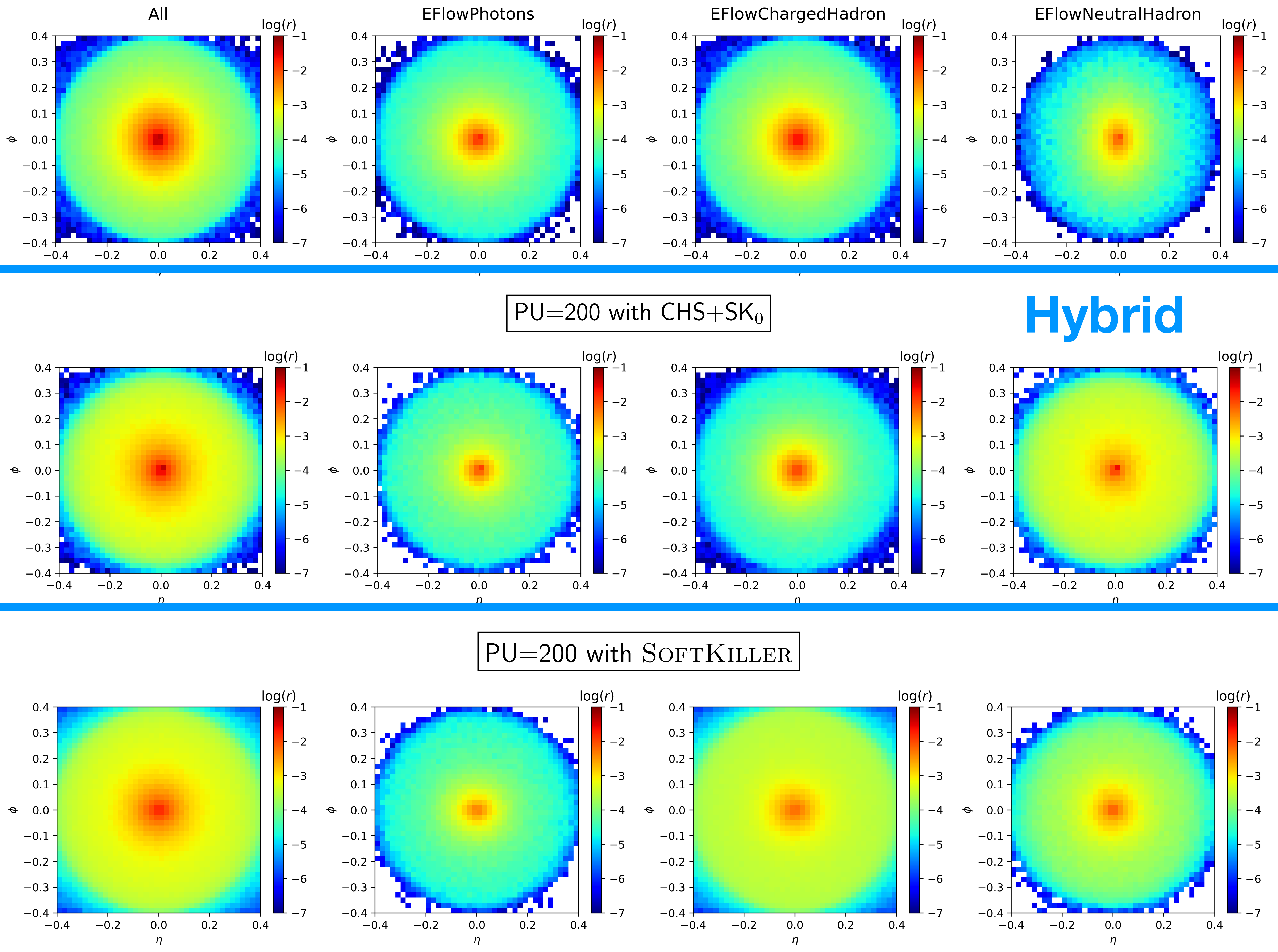

PU=0
No PU
All
EFlowPhotons
EFlowChargedHadron
EFlowNeutralHadron
log(r)
PU=200 with CHS+SK0
PU=200 with SoftKiller
η
ϕ

PU=0

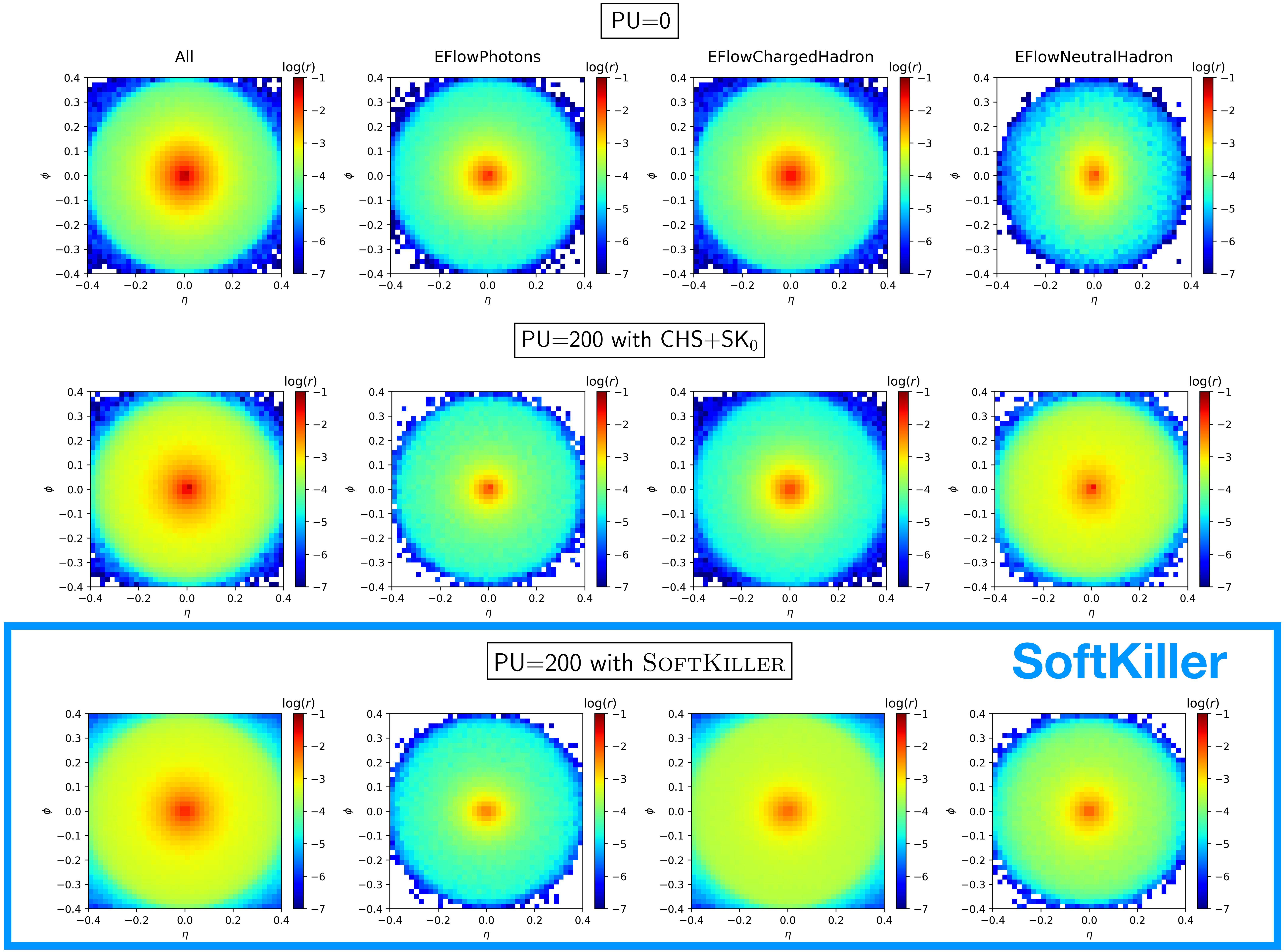
PU=200 with CHS+SK_0

Hybrid

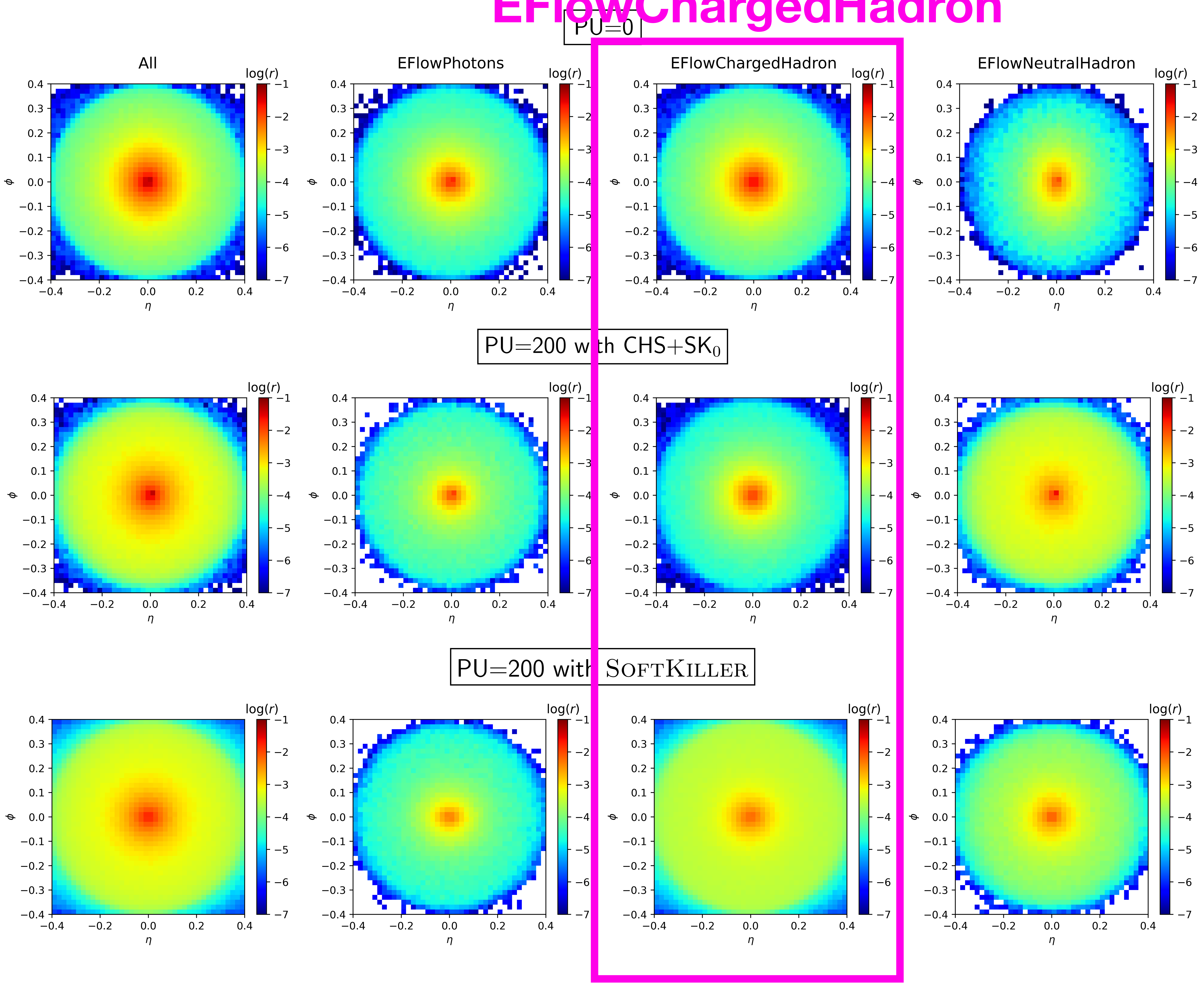
PU=200 with SoftKiller



Jet images to demonstrate the superiority of CHS+SK0



EFlowChargedHadron



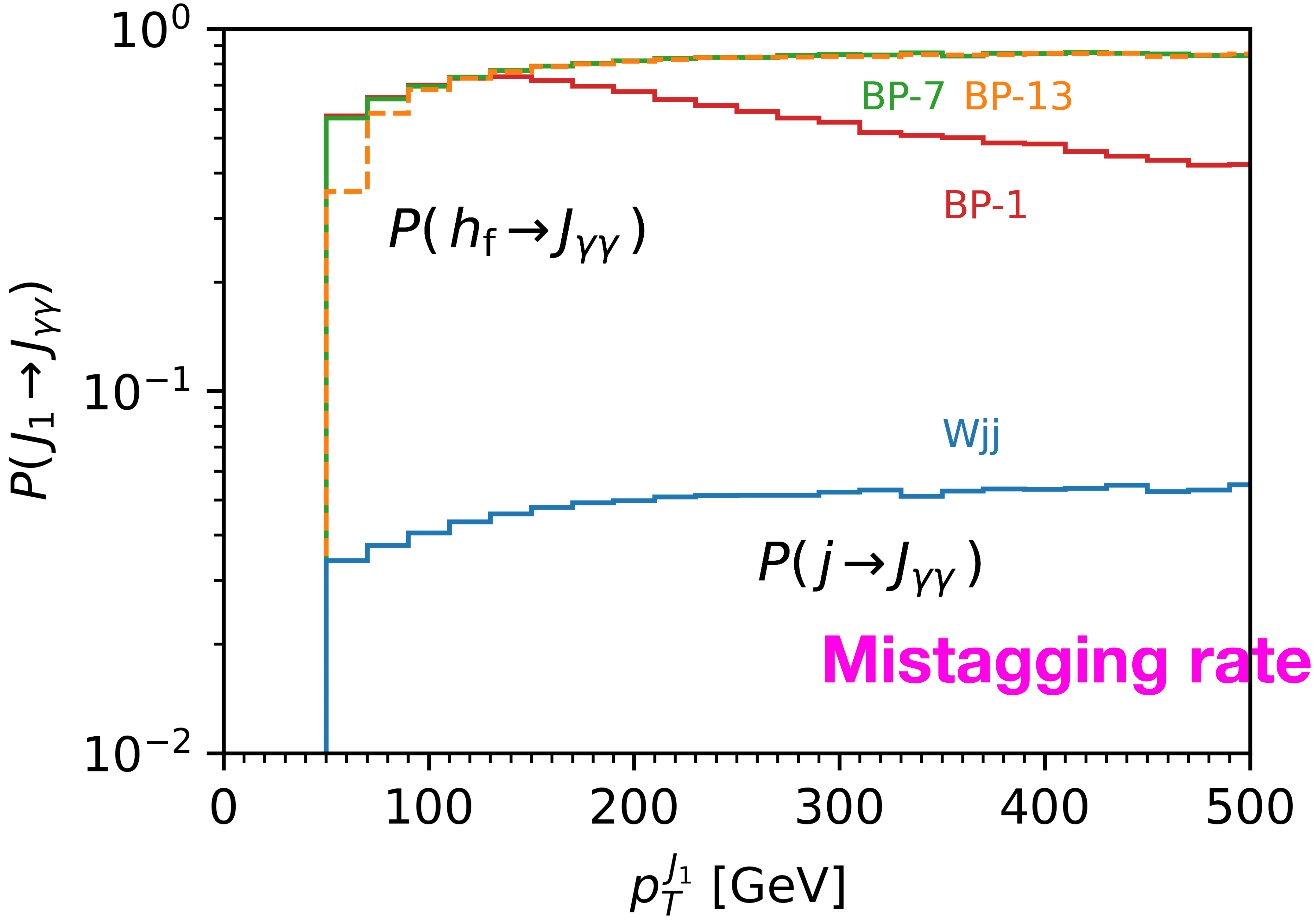
3. Cut-based analysis

18 BPs

BP no.	m_{h_f}	$M_{A/H^\pm}$	$s_{\beta-\alpha}$	m_{12}^2 [GeV^2]	t_β
BP-1	1 GeV	150 GeV	-0.123	0.0786	8.06
BP-2		175 GeV	-0.0909	0.0400	11.0
BP-3		200 GeV	-0.0929	0.0813	10.7
BP-4		250 GeV	-0.0941	0.0494	10.6
BP-5		300 GeV	-0.0985	0.0237	10.1
BP-6		331 GeV	-0.0974	0.0634	10.2
BP-7	5 GeV	150 GeV	-0.0737	0.305	13.5
BP-8		175 GeV	-0.0922	2.20	10.8
BP-9		200 GeV	-0.0983	1.93	10.1
BP-10		250 GeV	-0.0907	1.99	11.0
BP-11		300 GeV	-0.0984	1.84	10.1
BP-12		331 GeV	-0.0920	2.17	10.8
BP-13	10 GeV	150 GeV	-0.0748	1.17	13.3
BP-14		175 GeV	-0.0993	1.70	10.0
BP-15		200 GeV	-0.0919	0.973	10.8
BP-16		250 GeV	-0.0974	0.851	10.2
BP-17		300 GeV	-0.0917	0.0396	10.9
BP-18		328.3 GeV	-0.0979	1.15	10.2

First characteristics of the signal

- For the signal jets, the leading and subleading sub-particles are EFlowPhotons, i.e., diphoton jet.

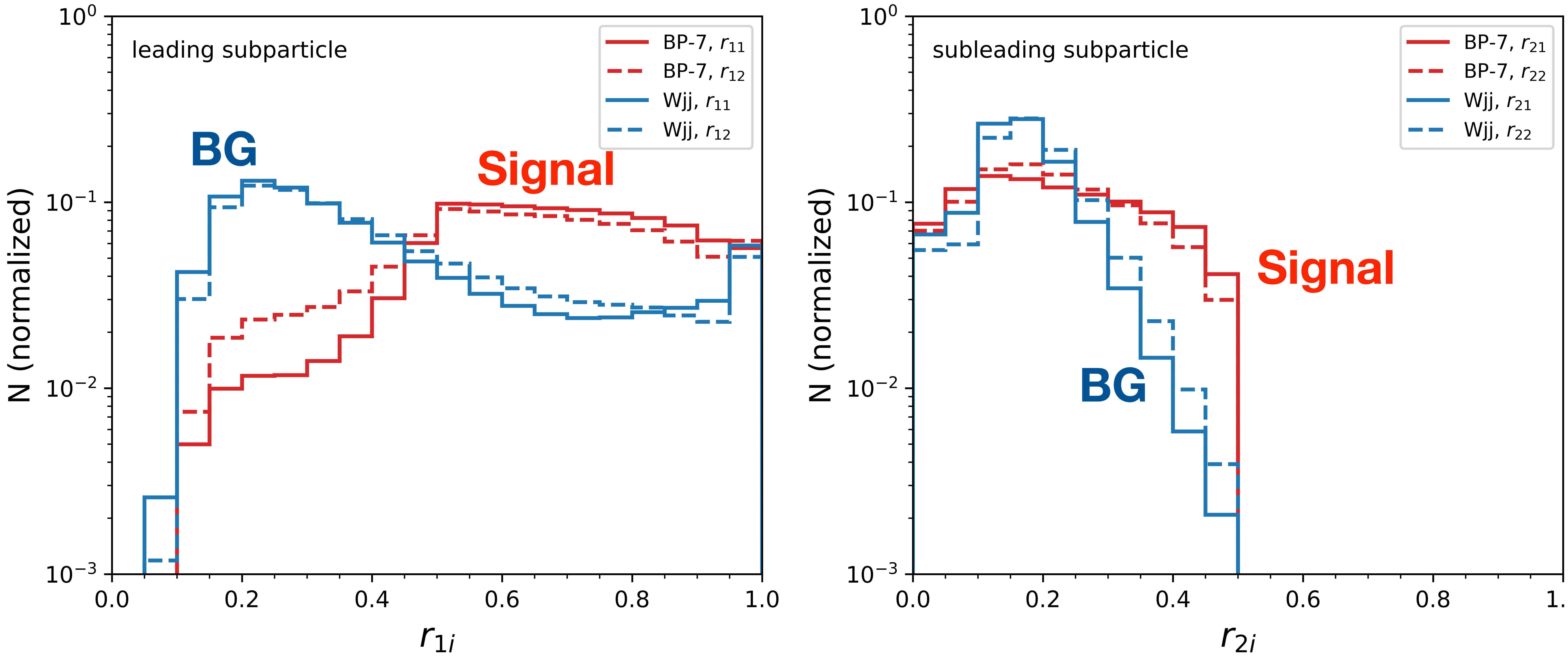


Mistagging rate is only a few percent.

Second characteristics of the signal

$$r_{ij} = \frac{p_T^{s_{ij}}}{p_T^{J_j}}$$

- p_T of two leading subparticles $\simeq p_T/2$ of the mother jet



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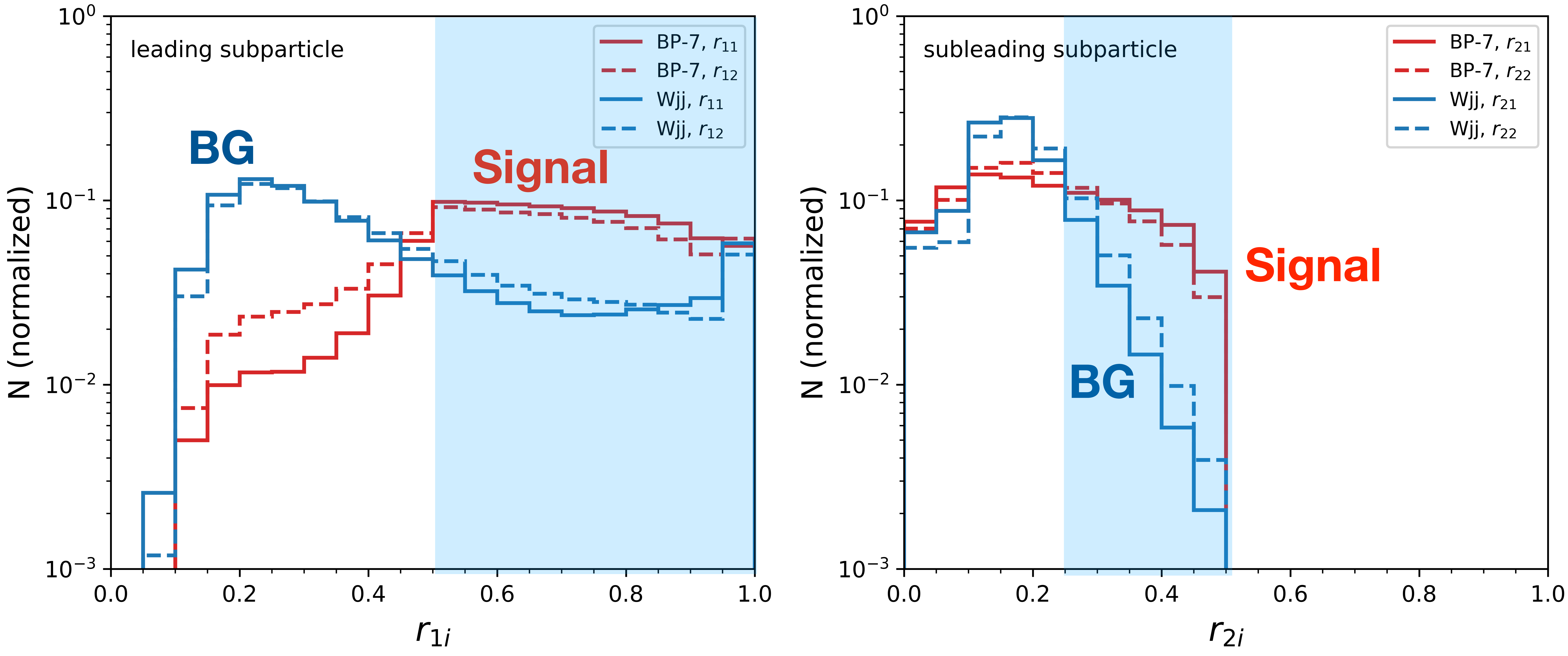
Signal region!



With 10% uncertainty

Cross sections in units of fb at the 14 TeV LHC with $\mathcal{L}_{\rm tot} = 3\ {\rm ab}^{-1}$						
Cut	BP-7	$W^{\pm}jj$	Zjj	$t\bar{t}$	$W^{\pm}j\gamma$	$\mathcal{S}^{10\%}_{\rm BP-7}$
Basic	34.8	372 622	27 727	32 052	3 047	1.09×10^{-3}
$E_T^{\rm miss} > 50$ GeV	29.7	318 407	23 274	27 395	2 610	9.01×10^{-4}
$r_{11} > 0.50$	24.9	102 182	7 843	4 150	1 214	2.15×10^{-3}
$r_{12} > 0.50$	18.7	36 204	2 853	692	541	4.56×10^{-3}
$r_{21} > 0.25$	7.06	4 218	323	62.2	55.8	1.49×10^{-2}
$r_{22} > 0.25$	2.40	840	61.3	8.61	10.1	2.56×10^{-2}
$J_1 \to J_{\gamma\gamma}$	2.29	18.6	2.31	0.205	0.467	1.01
$J_2 \to J_{\gamma\gamma}$	1.98	0.363	0.0589	0.00	0.00849	22.8

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– There must be exactly one lepton with $p_T^{\ell} > 20$ GeV and $|\eta_{\ell}| < 2.5$.

– The leading jet is required to satisfy $p_T^{J_1} > 50$ GeV and $|\eta_{J_1}| < 2.5$.

– The subleading jet should fulfill the conditions $p_T^{J_2} > 30$ GeV and $|\eta_{J_2}| < 2.5$.

– The missing transverse energy should exceed $E_T^{\rm miss} > 10$ GeV.

With 10% uncertainty

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Significances for all 18 benchmark points

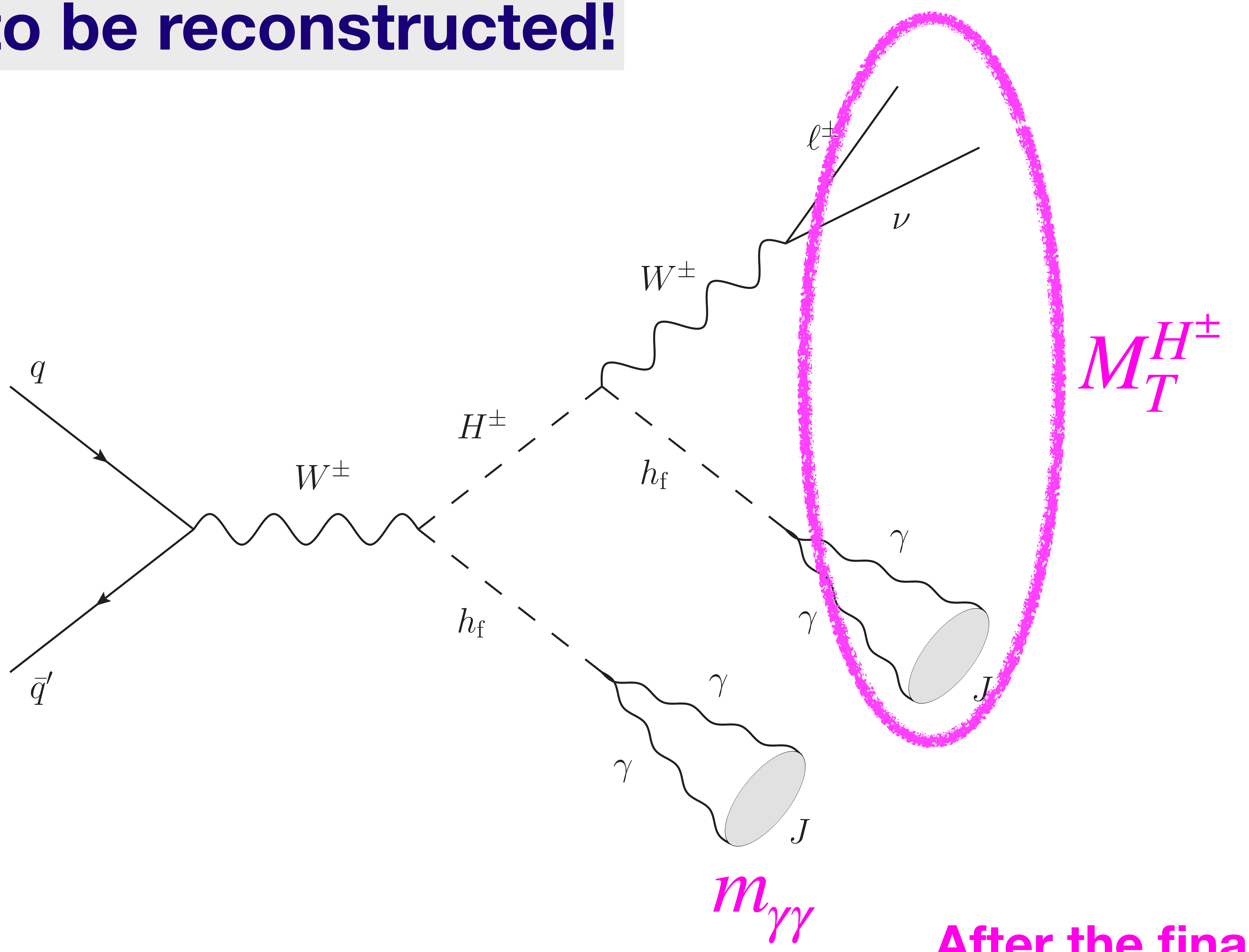
Results in the cut-based analysis at the 14 TeV LHC with $\mathcal{L}_{\text{tot}} = 3\ \text{ab}^{-1}$								
	σ_{final} [fb]	$\mathcal{S}^{10\%}$		σ_{final} [fb]	$\mathcal{S}^{10\%}$		σ_{final} [fb]	$\mathcal{S}^{10\%}$
BP-1	1.46	18.5	BP-7	1.98	22.8	BP-13	1.81	21.5
BP-2	1.19	16.1	BP-8	1.68	20.4	BP-14	1.56	19.4
BP-3	0.927	13.4	BP-9	1.37	17.7	BP-15	1.29	17.1
BP-4	0.529	8.71	BP-10	0.900	13.0	BP-16	0.857	12.7
BP-5	0.303	5.49	BP-11	0.582	9.40	BP-17	0.566	9.19
BP-6	0.216	4.09	BP-12	0.457	7.74	BP-18	0.456	7.72

Most have more than 5σ

4. Mass reconstruction

Although we could observe two diphoton signals with 5σ, can we tell it is from this channel?

Two masses to be reconstructed!



After the final selection

Big obstacle from backgrounds!

Too small background events after the final selection

Background	Cross section [pb]	$n_{\rm gen}$	Background	Cross section [pb]	$n_{\rm gen}$
$W^\pm(\to L^\pm\nu)jj$	3.54×10^3	5×10^8	$W^\pm Z$	3.16×10	3×10^6
$Z(\to L^+L^-)jj$	2.67×10^2	5×10^7	$Z(\to L^+L^-)j\gamma$	2.09	10^6
$t\bar{t}(\to b\bar{b}W_{L\nu}W_{jj})$	1.23×10^2	1.2×10^7	ZZ	1.18×10	10^6
$W^\pm(\to L^\pm\nu)j\gamma$	2.53×10	3×10^6	$W^\pm(\to L^\pm\nu)\gamma\gamma$	3.28×10^{-2}	10^6
W^+W^-	8.22×10	9×10^6	$Z(\to L^+L^-)\gamma\gamma$	1.12×10^{-2}	10^6

Only 51 events after the final selection

Too small background events after the final selection

Background	Cross section [pb]	$n_{\rm gen}$	Background	Cross section [pb]	$n_{\rm gen}$
$W^\pm(\to L^\pm\nu)jj$	3.54×10^3	5×10^8	$W^\pm Z$	3.16×10	3×10^6
$Z(\to L^+L^-)jj$	2.67×10^2	5×10^7	$Z(\to L^+L^-)j\gamma$	2.09	10^6
$t\bar{t}(\to b\bar{b}W_{L\nu}W_{jj})$	1.23×10^2	1.2×10^7	ZZ	1.18×10	10^6
$W^\pm(\to L^\pm\nu)j\gamma$	2.53×10	3×10^6	$W^\pm(\to L^\pm\nu)\gamma\gamma$	3.28×10^{-2}	10^6
W^+W^-	8.22×10	9×10^6	$Z(\to L^+L^-)\gamma\gamma$	1.12×10^{-2}	10^6

Only 4 events

Too small background events after the final selection

No reliable background distributions after the final selection!

Background	Cross section [pb]	n_{gen}	[illegible]	[illegible]	[illegible]
$W^{\pm}(\to L^{\pm}\nu)jj$	[illegible]	[illegible]	[illegible]	[illegible]	[illegible] $\times 10^6$
[illegible]	[illegible]	[illegible]	[illegible]	2.09	10^6
[illegible]	[illegible]	[illegible]	ZZ	1.18×10	10^6
[illegible]	[illegible] $\times 10$	3×10^6	$W^{\pm}(\to L^{\pm}\nu)\gamma\gamma$	3.28×10^{-2}	10^6
W^+W^-	8.22×10	9×10^6	$Z(\to L^+L^-)\gamma\gamma$	1.12×10^{-2}	10^6

Only 4 events

Weighting Factor Method

N : the expected number of events

n : the number of generated events

E_{cut} : the set of events satisfying “cut”

$$n_{\rm cut} \equiv \# E_{\rm cut}.$$

X-section after the final selection in the cut-based analysis

$$\sigma_{\rm final}^{\rm cut\text{-}based} = \sum_{e \in E_{\rm final}} 1 \times \frac{\sigma_{\rm tot}}{n_{\rm gen}} = \frac{n_{\rm final}}{n_{\rm gen}} \sigma_{\rm tot},$$

Either 0 or 1 weighting factor for the entire generated events

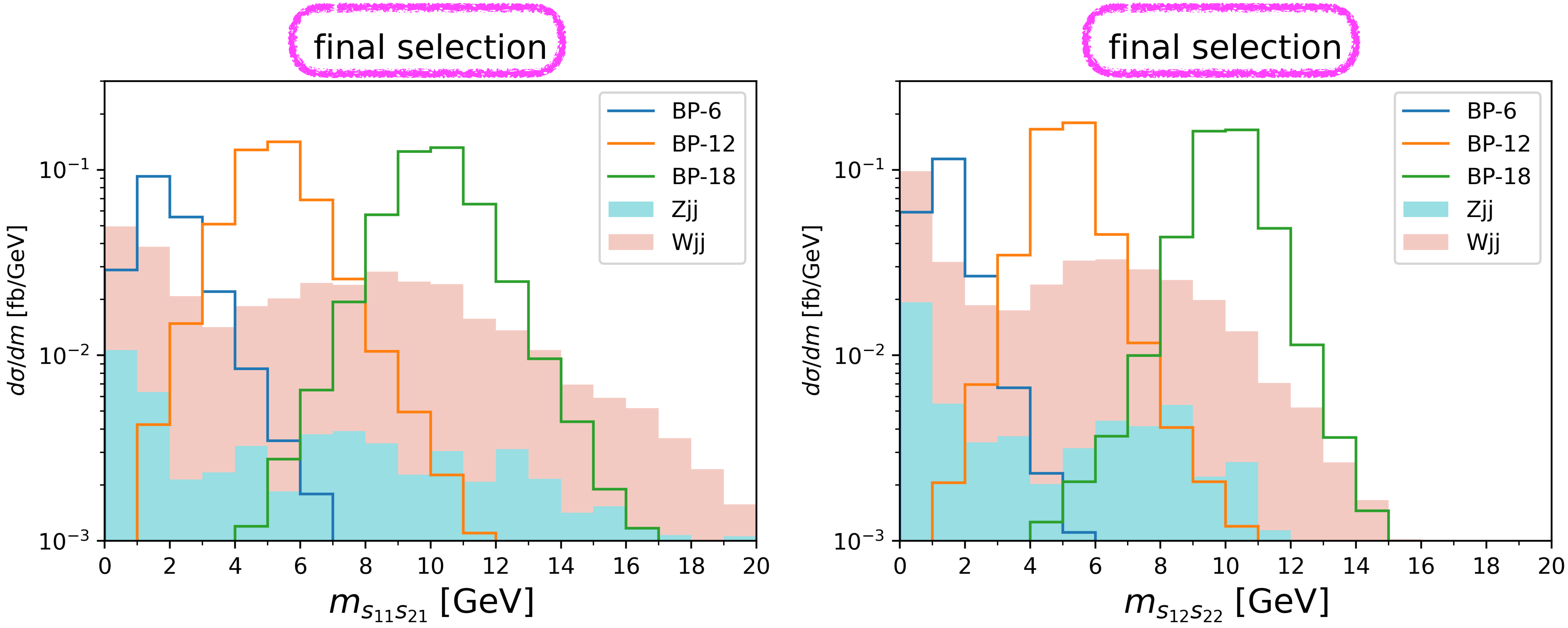
Cut
Basic
$E_T^{\text{miss}} > 50$ GeV
$r_{11} > 0.50$
$r_{12} > 0.50$
$r_{21} > 0.25$
$r_{22} > 0.25$
$J_1 \to J_{\gamma\gamma}$
$J_2 \to J_{\gamma\gamma}$

Weighting Factor Method

$$\sigma_{\text{final}}^{\text{WFM}} = \sum_{e \in E_{r_{22}}} P_e(j_1 \to J_{\gamma\gamma}) P_e(j_2 \to J_{\gamma\gamma}) \times \frac{\sigma_{\text{tot}}}{n_{\text{gen}}}.$$

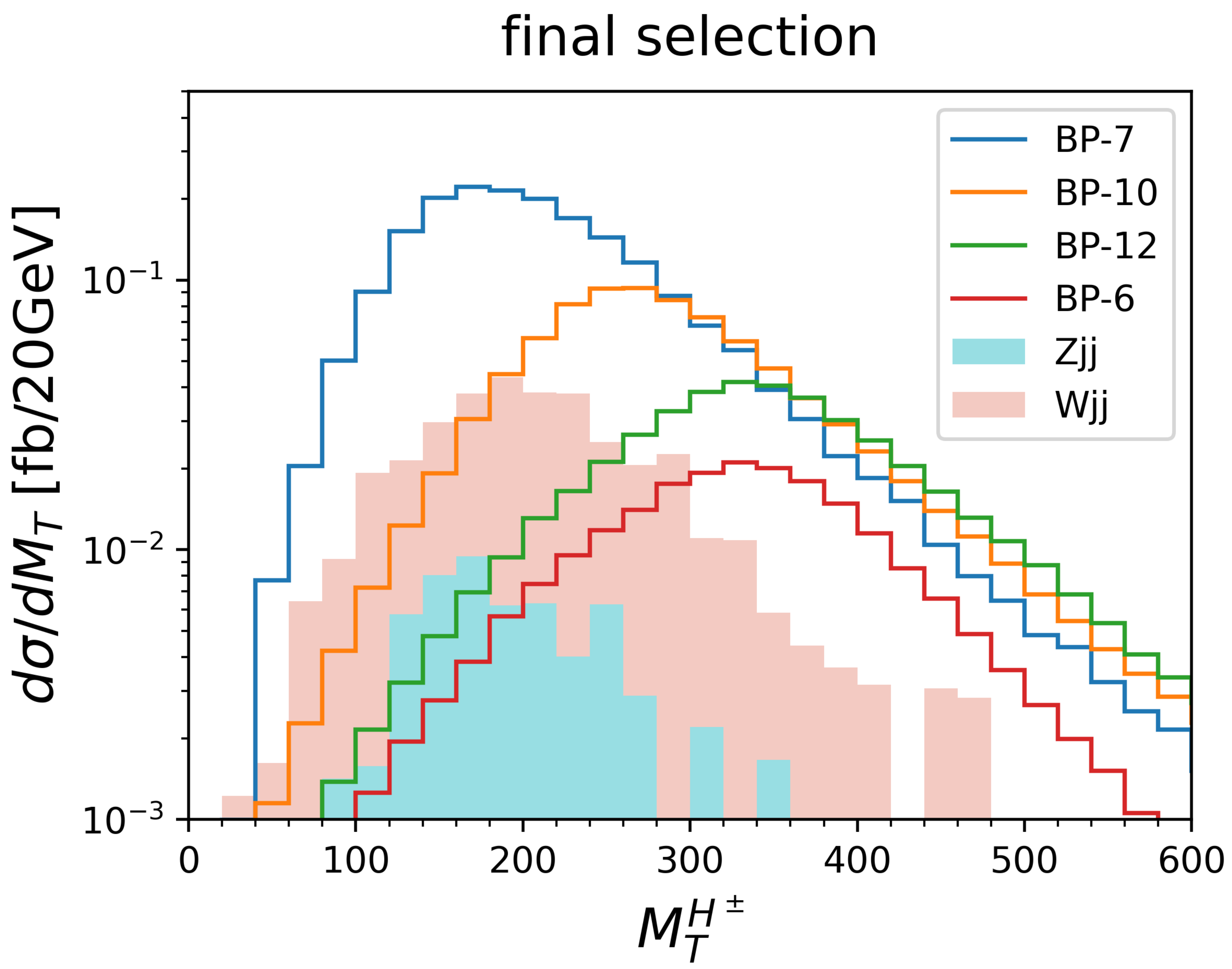
- Covering a larger event sample.
- Instead, we multiply two diphoton tagging efficiencies as a continuous weighting factor.
- Instead of completely being removed, background events can partially survive.

Invariant mass of two leading subparticles



Well-separated resonance peak around m_{h_f}

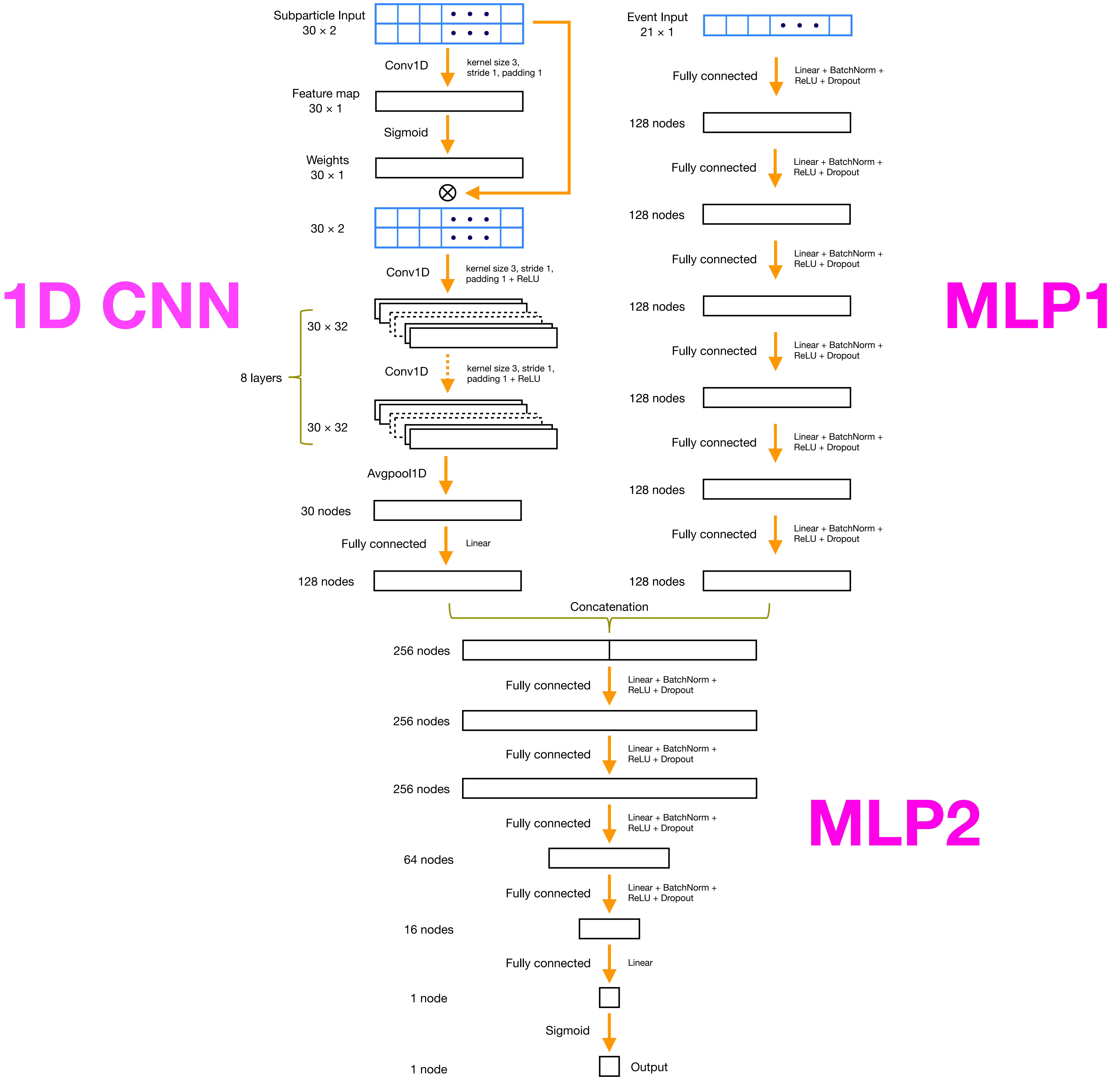
Transverse mass for $H^{\pm}$



5. Machine Learning Techniques

Heavy $M_{H^\pm}$: low significances

Results in the cut-based analysis at the 14 TeV LHC with $\mathcal{L}_{\rm tot} = 3$ ab^{-1}								
	$\sigma_{\rm final}$ [fb]	$\mathcal{S}^{10\%}$		$\sigma_{\rm final}$ [fb]	$\mathcal{S}^{10\%}$		$\sigma_{\rm final}$ [fb]	$\mathcal{S}^{10\%}$
BP-1	1.46	18.5	BP-7	1.98	22.8	BP-13	1.81	21.5
BP-2	1.19	16.1	BP-8	1.68	20.4	BP-14	1.56	19.4
BP-3	0.927	13.4	BP-9	1.37	17.7	BP-15	1.29	17.1
BP-4	0.529	8.71	BP-10	0.900	13.0	BP-16	0.857	12.7
BP-5	0.303	5.49	BP-11	0.582	9.40	BP-17	0.566	9.19
BP-6	0.216	4.09	BP-12	0.457	7.74	BP-18	0.456	7.72



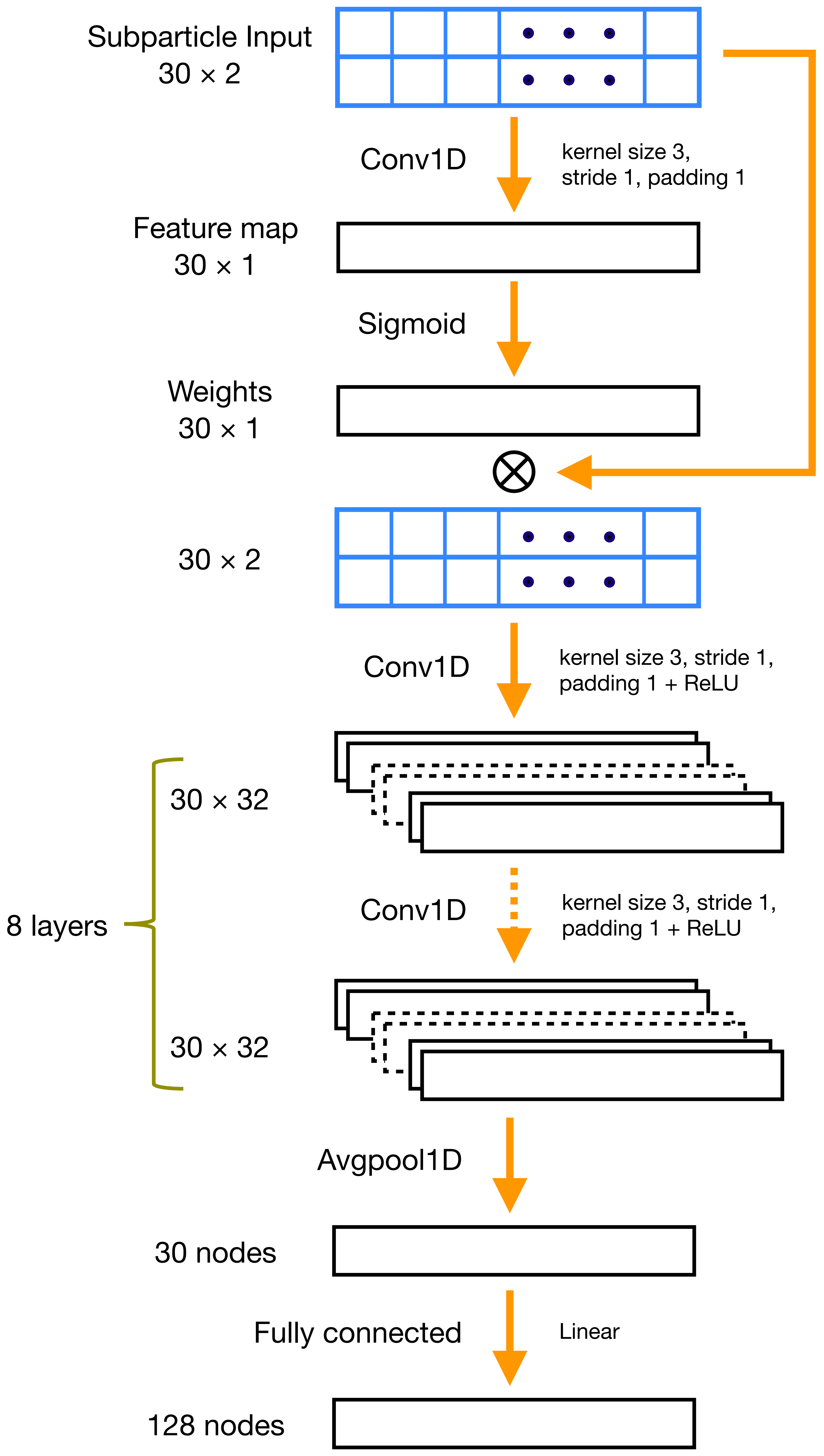
1D CNN
Subparticle Input
30 × 2
Conv1D
kernel size 3,
stride 1, padding 1
Feature map
30 × 1
Sigmoid
Weights
30 × 1
30 × 2
Conv1D
kernel size 3, stride 1,
padding 1 + ReLU
30 × 32
8 layers
Conv1D
kernel size 3, stride 1,
padding 1 + ReLU
30 × 32
Avgpool1D
30 nodes
Fully connected
Linear
128 nodes
MLP1
Event Input
21 × 1
Fully connected
Linear + BatchNorm +
ReLU + Dropout
128 nodes
Fully connected
Linear + BatchNorm +
ReLU + Dropout
128 nodes
Fully connected
Linear + BatchNorm +
ReLU + Dropout
128 nodes
Fully connected
Linear + BatchNorm +
ReLU + Dropout
128 nodes
Fully connected
Linear + BatchNorm +
ReLU + Dropout
128 nodes
Fully connected
Linear + BatchNorm +
ReLU + Dropout
128 nodes
Concatenation
MLP2
256 nodes
Fully connected
Linear + BatchNorm +
ReLU + Dropout
256 nodes
Fully connected
Linear + BatchNorm +
ReLU + Dropout
256 nodes
Fully connected
Linear + BatchNorm +
ReLU + Dropout
64 nodes
Fully connected
Linear + BatchNorm +
ReLU + Dropout
16 nodes
Fully connected
Linear
1 node
Sigmoid
1 node
Output

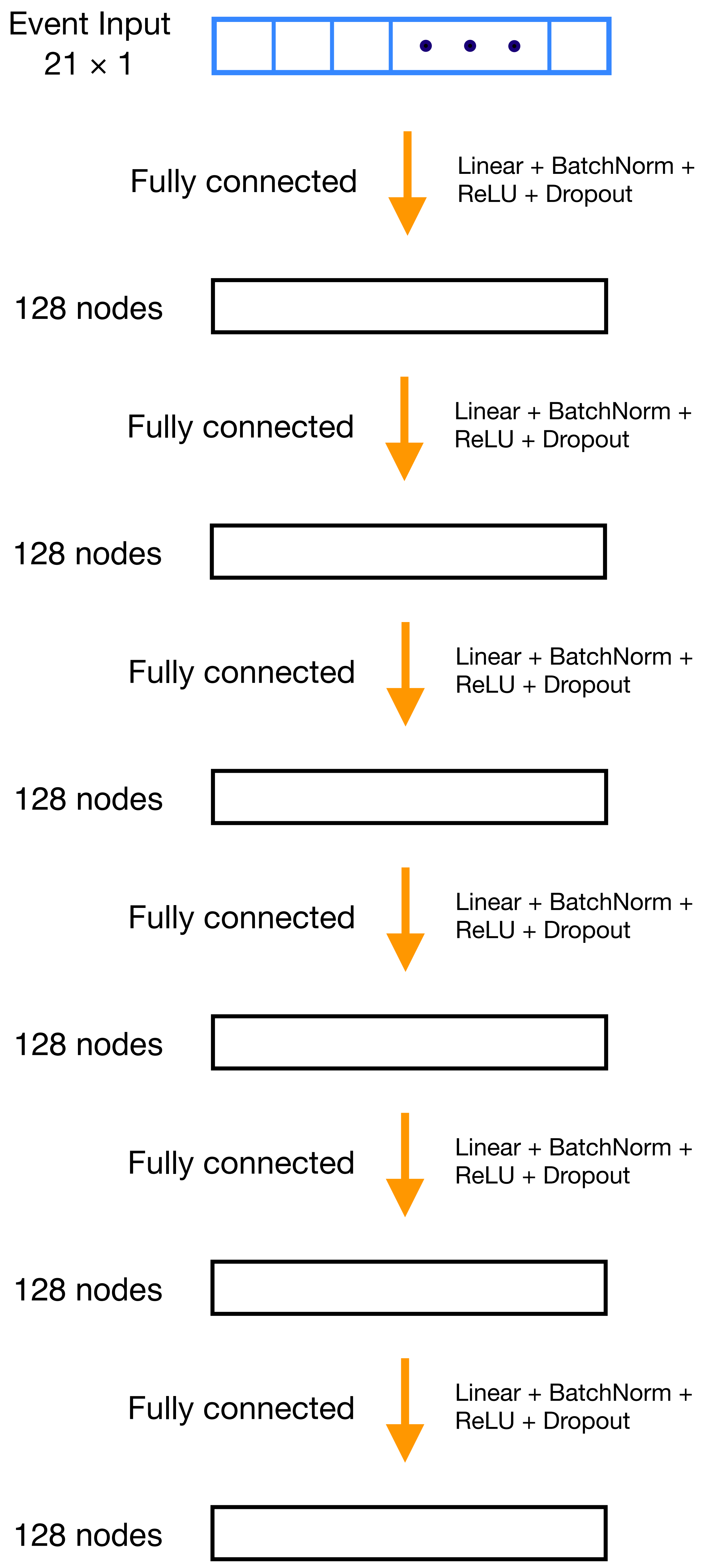
1D CNN

Subparticle features:
For 2 jets, 10 leading subparticles

$$p_T, \eta, \phi$$

$$30 \times 2$$

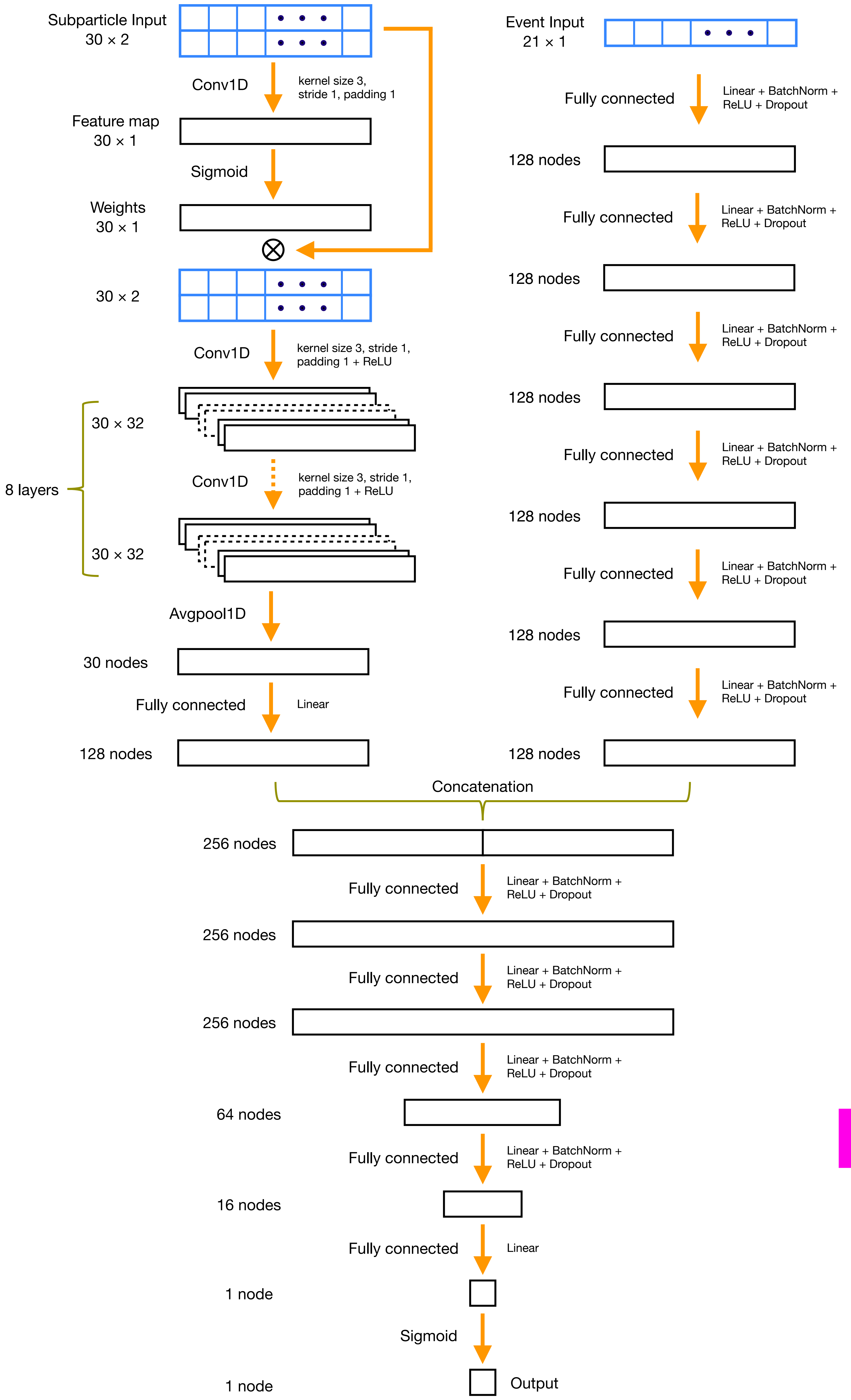




MLP1

Events features:

$$\mathbf{v}_{\text{event}} = \Big[p_T^{J_1}, \eta_{J_1}, \phi_{J_1}, m_{J_1}, p_T^{J_2}, \eta_{J_2}, \phi_{J_2}, m_{J_2}, p_T^{\ell}, \eta_{\ell}, \phi_{\ell}, E_T^{\text{miss}}, \phi_{\vec{E}_T^{\text{miss}}}, \Delta R_{J_1 J_2}, \Delta R_{J_1 \ell}, \Delta R_{J_2 \ell}, \Delta R_{J_1 \vec{E}_T^{\text{miss}}}, \Delta R_{J_2 \vec{E}_T^{\text{miss}}}, \Delta R_{\ell \vec{E}_T^{\text{miss}}}, M_T^{J_1}, M_T^{J_2} \Big],$$



MLP2

Final decision

Impressive enhancement

$$x_{\rm cut} = 0.5: \qquad \mathcal{S}^{10\%}_{\text{BP-6}} = 9.0, \quad \mathcal{S}^{10\%}_{\text{BP-12}} = 15.4, \quad \mathcal{S}^{10\%}_{\text{BP-18}} = 15.0;$$
$$x_{\rm cut} = 0.9: \qquad \mathcal{S}^{10\%}_{\text{BP-6}} = 18.9, \quad \mathcal{S}^{10\%}_{\text{BP-12}} = 33.2, \quad \mathcal{S}^{10\%}_{\text{BP-18}} = 32.4.$$

6. Conclusions

- The very light fermiophobic Higgs boson in type-I 2HDM yields a jet consisting of two photons.
- HL-LHC has a high discovery potential to the very light fermiophobic Higgs boson via probing diphoton jets.
- Mass reconstructions can identify the origin of exotic diphoton jet signals.